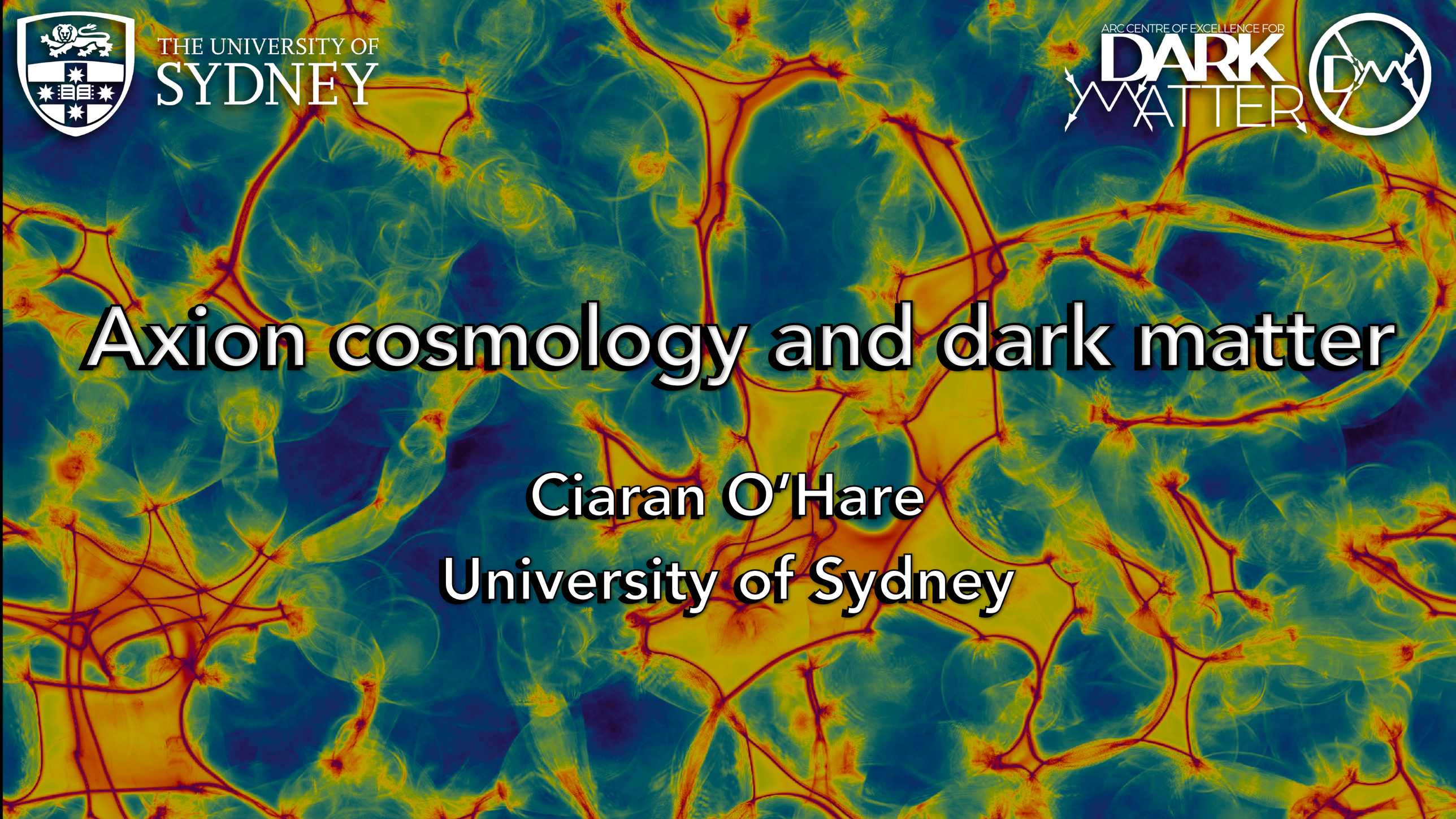

THE UNIVERSITY OF
SYDNEY
ARC CENTRE OF EXCELLENCE FOR
DARK
MATTER
Axion cosmology and dark matter
Ciaran O'Hare
University of Sydney

Outline

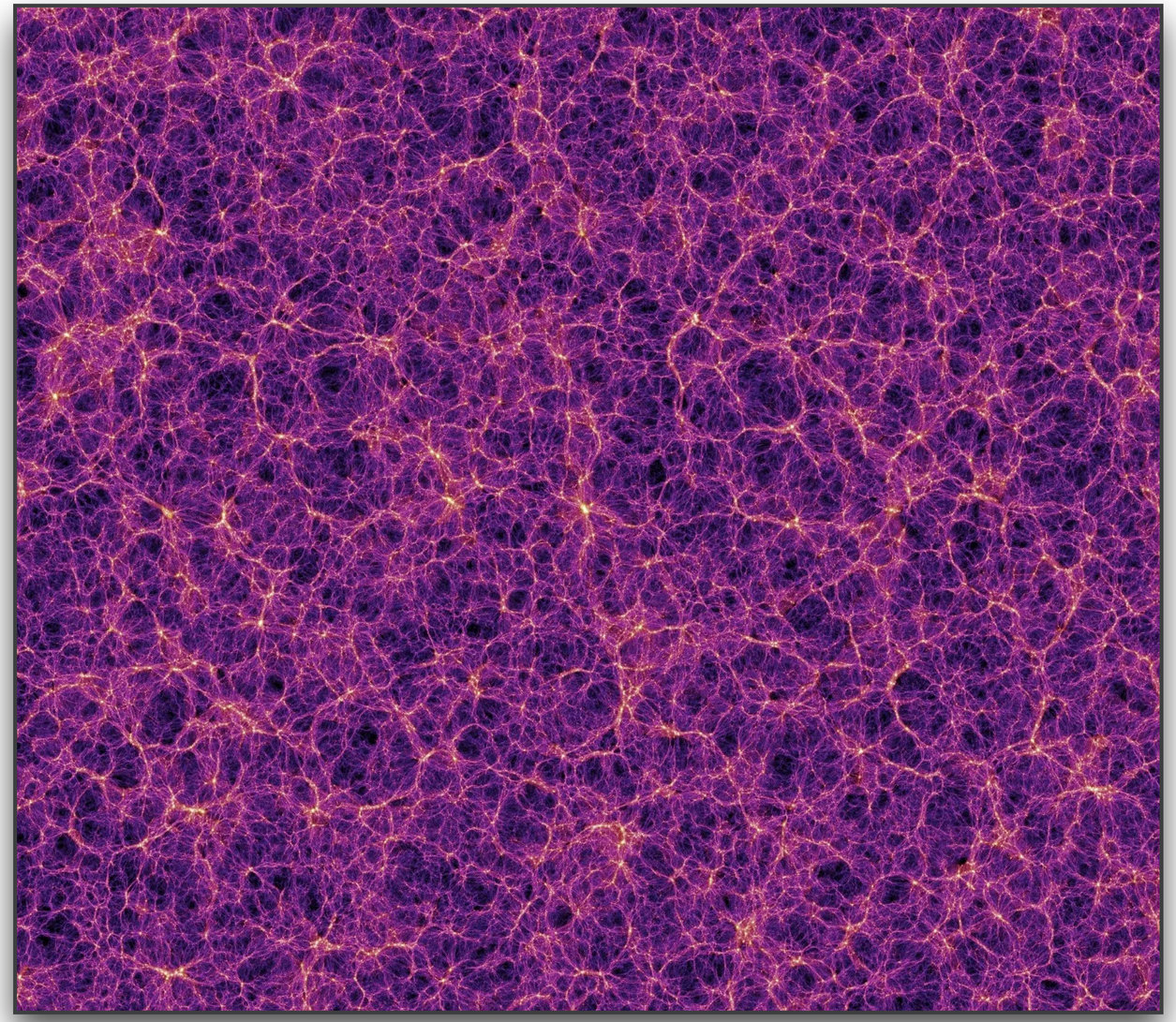
1. Cosmology basics

2. How cosmology can tell us where to look for the axion

3. How cosmology can tell us where *not* to look

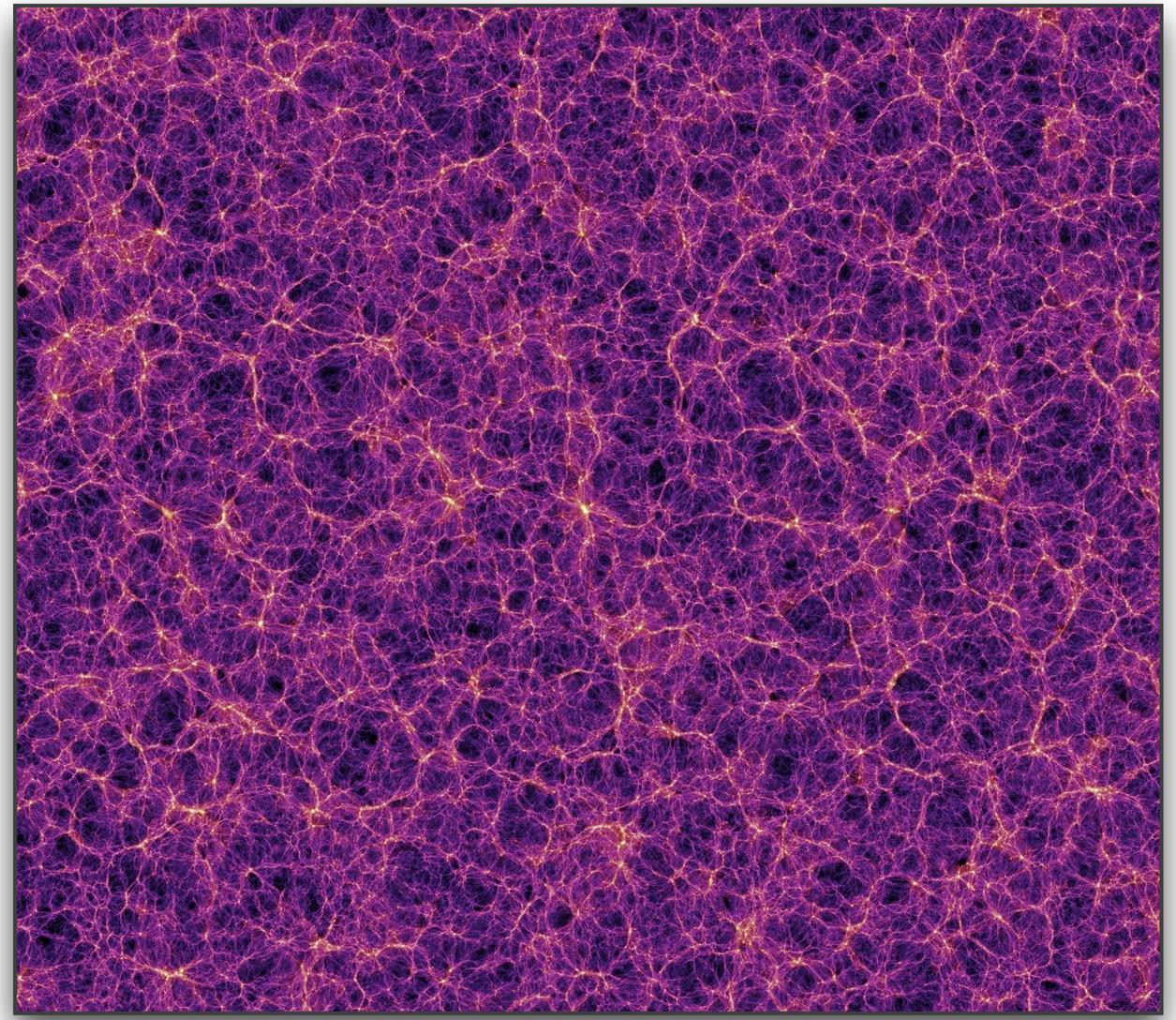
4. “Near-field cosmology” a.k.a direct detection

How well do you know your Universe?



How well do you know your Universe?

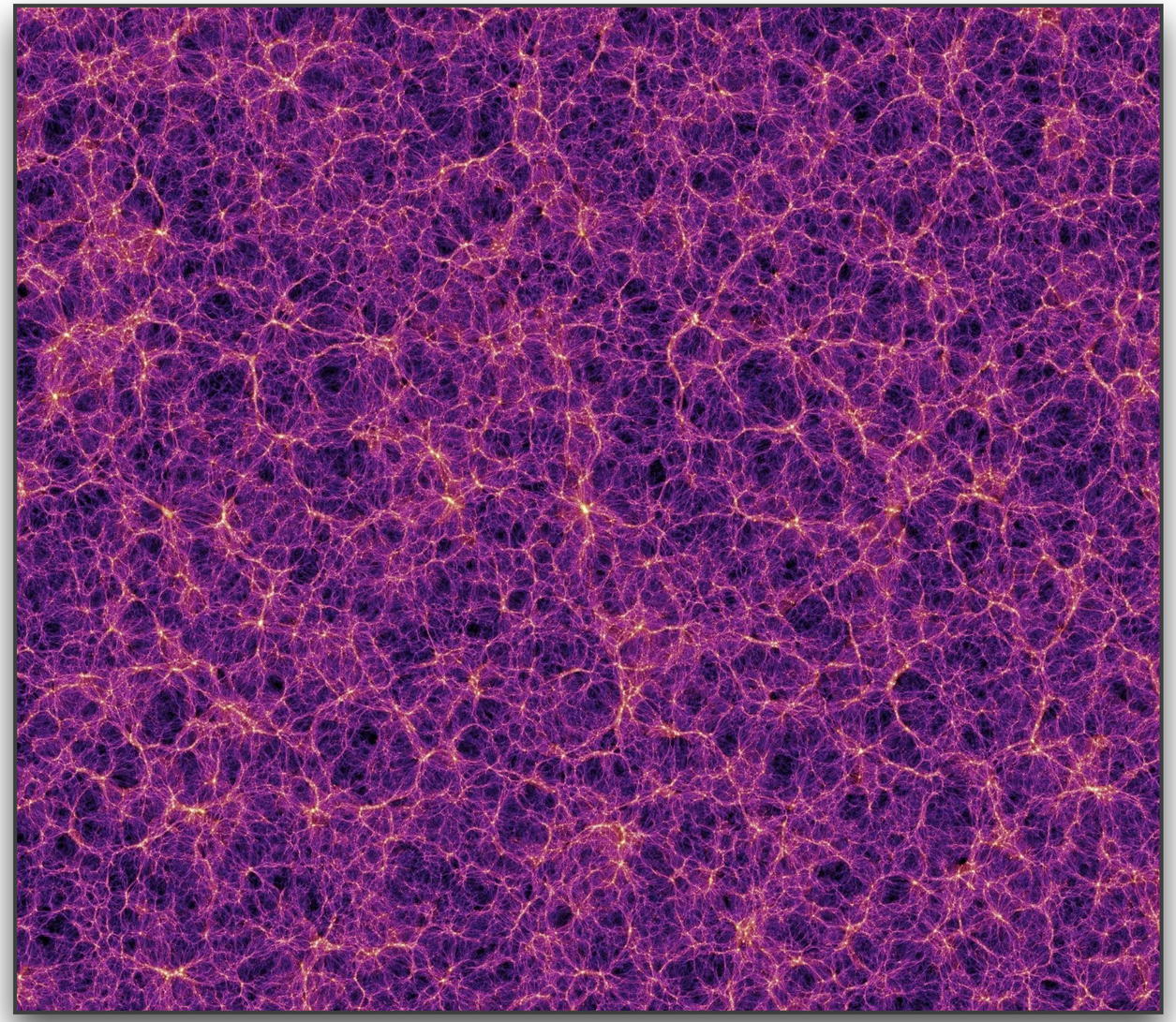
Age of Universe



How well do you know your Universe?

Age of Universe

→ 13.8 Gyr



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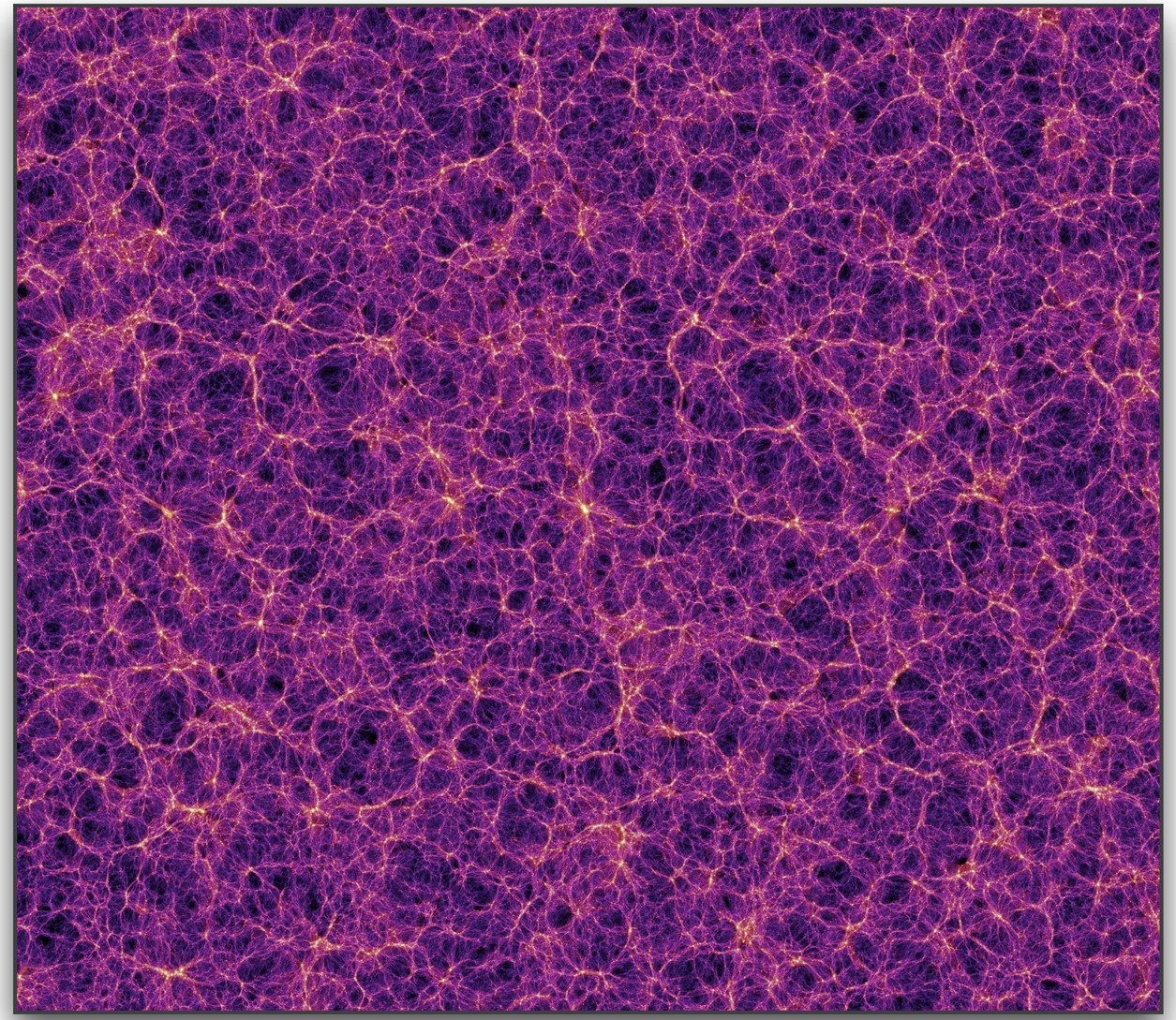
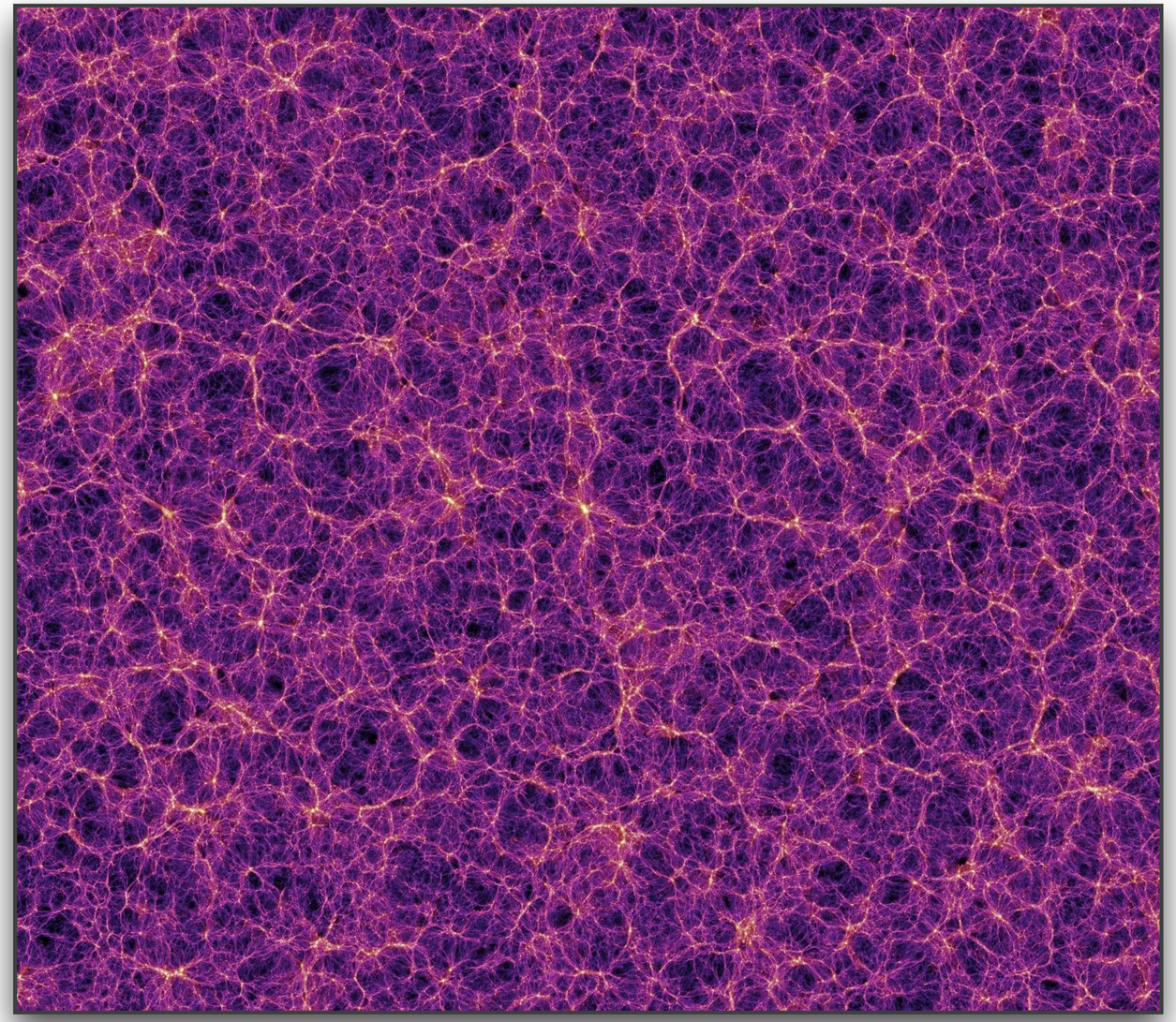
Radius of *observable* Universe



How well do you know your Universe?

Age of Universe
→ 13.8 Gyr

Radius of *observable* Universe
→ 93 billion ly/28 Gpc



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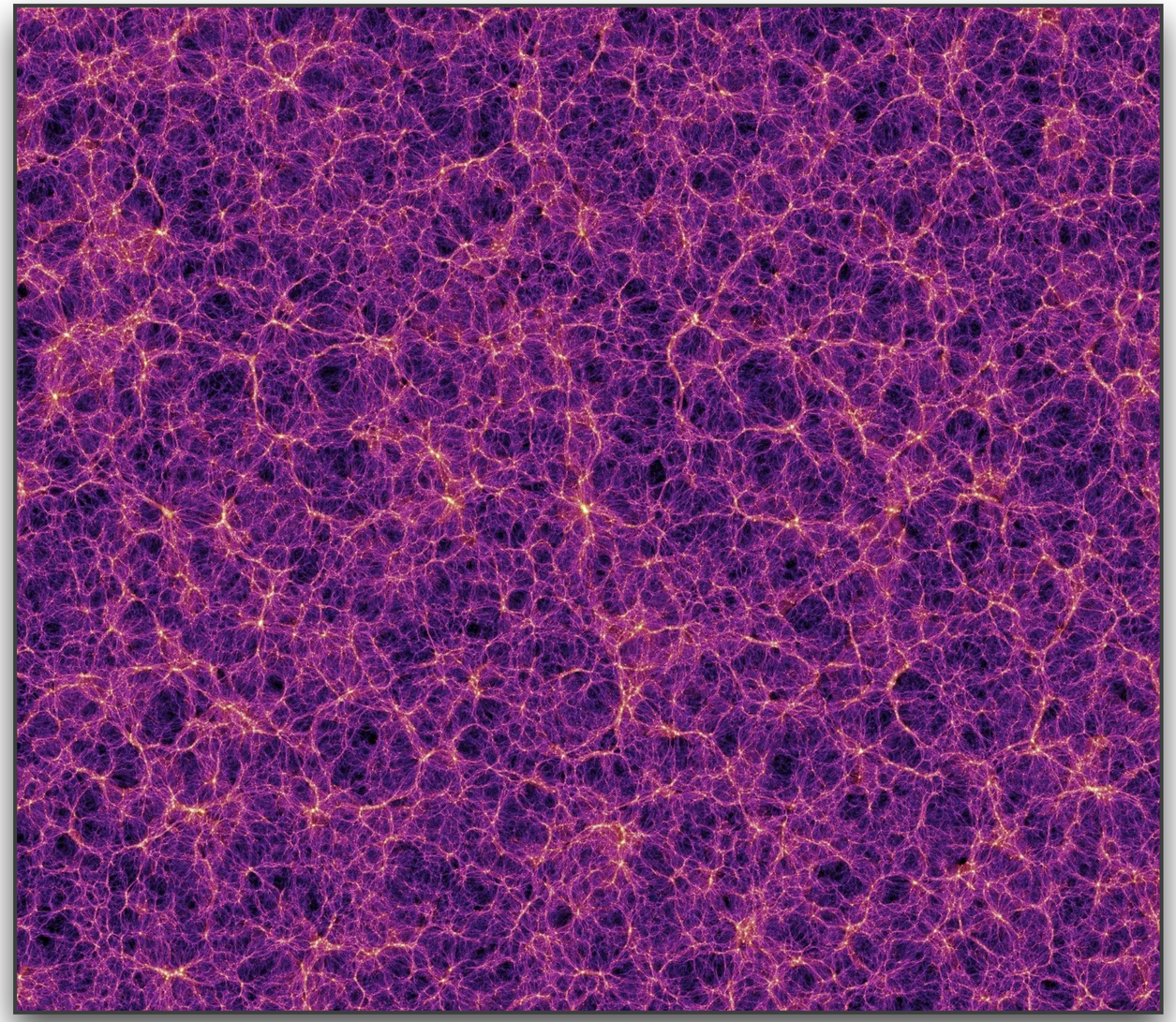
Average density of Universe [g/cm^3]

→ $\rho_c = 3H_0^2 M_{\rm Pl}^2 =$



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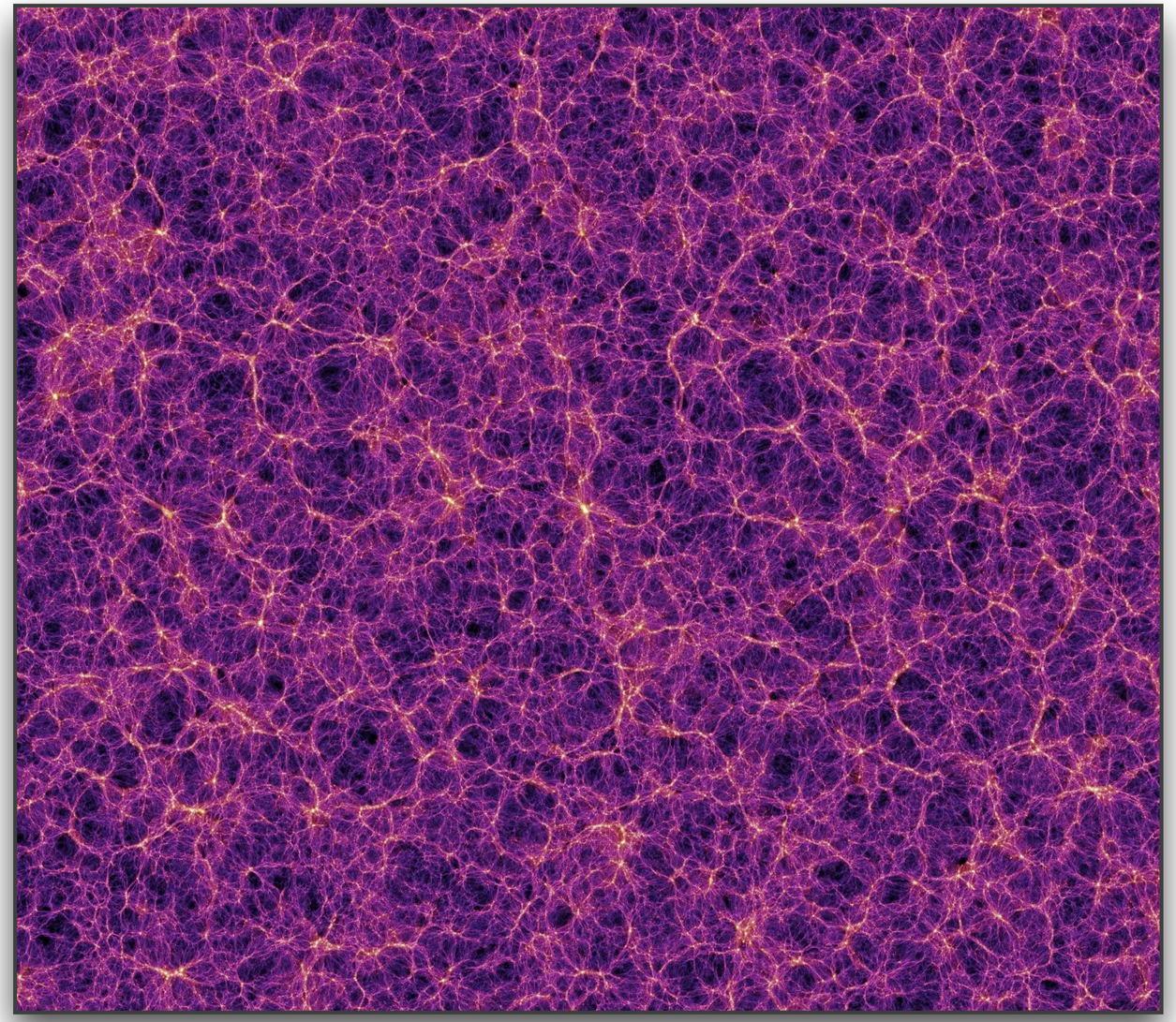

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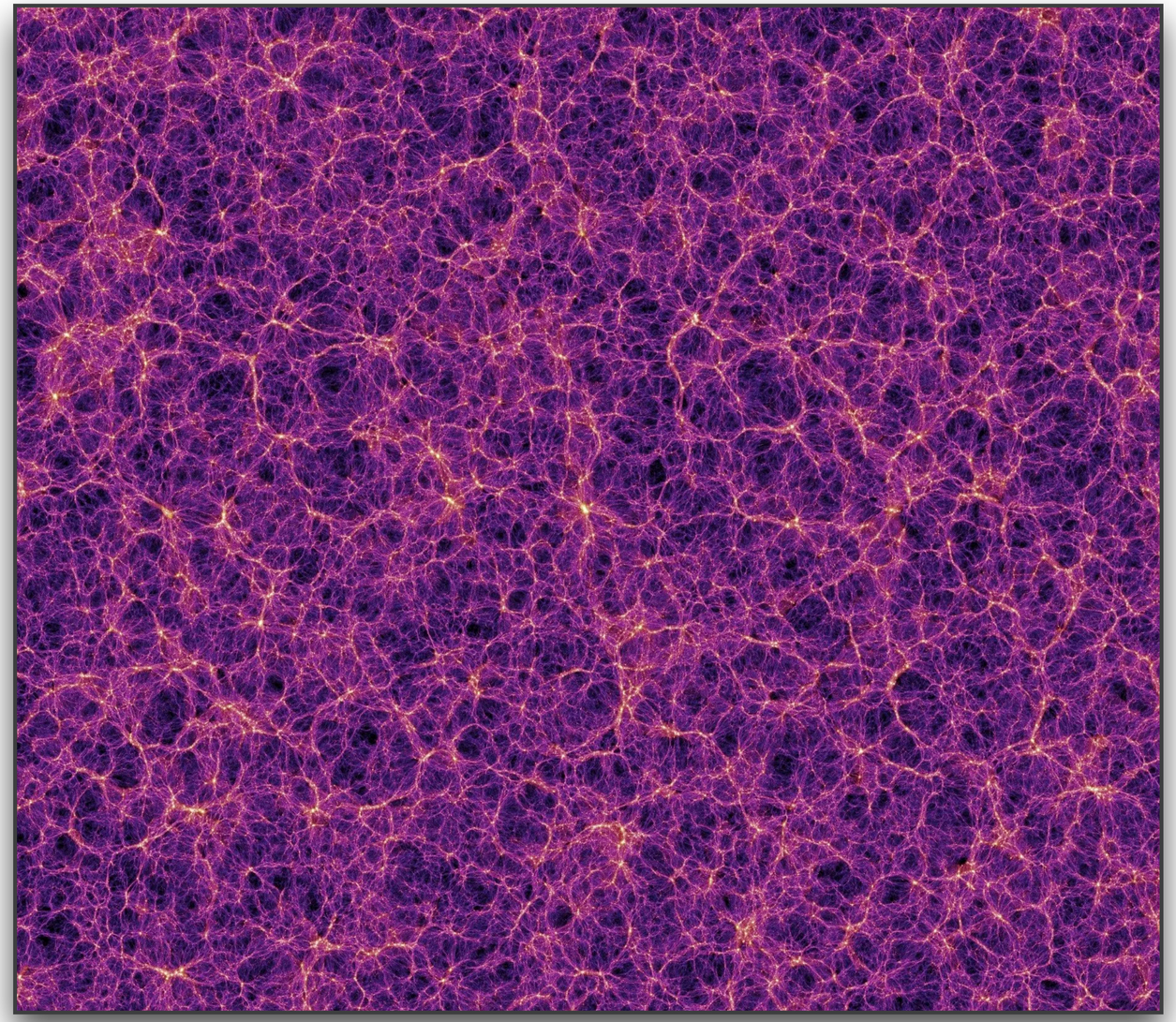

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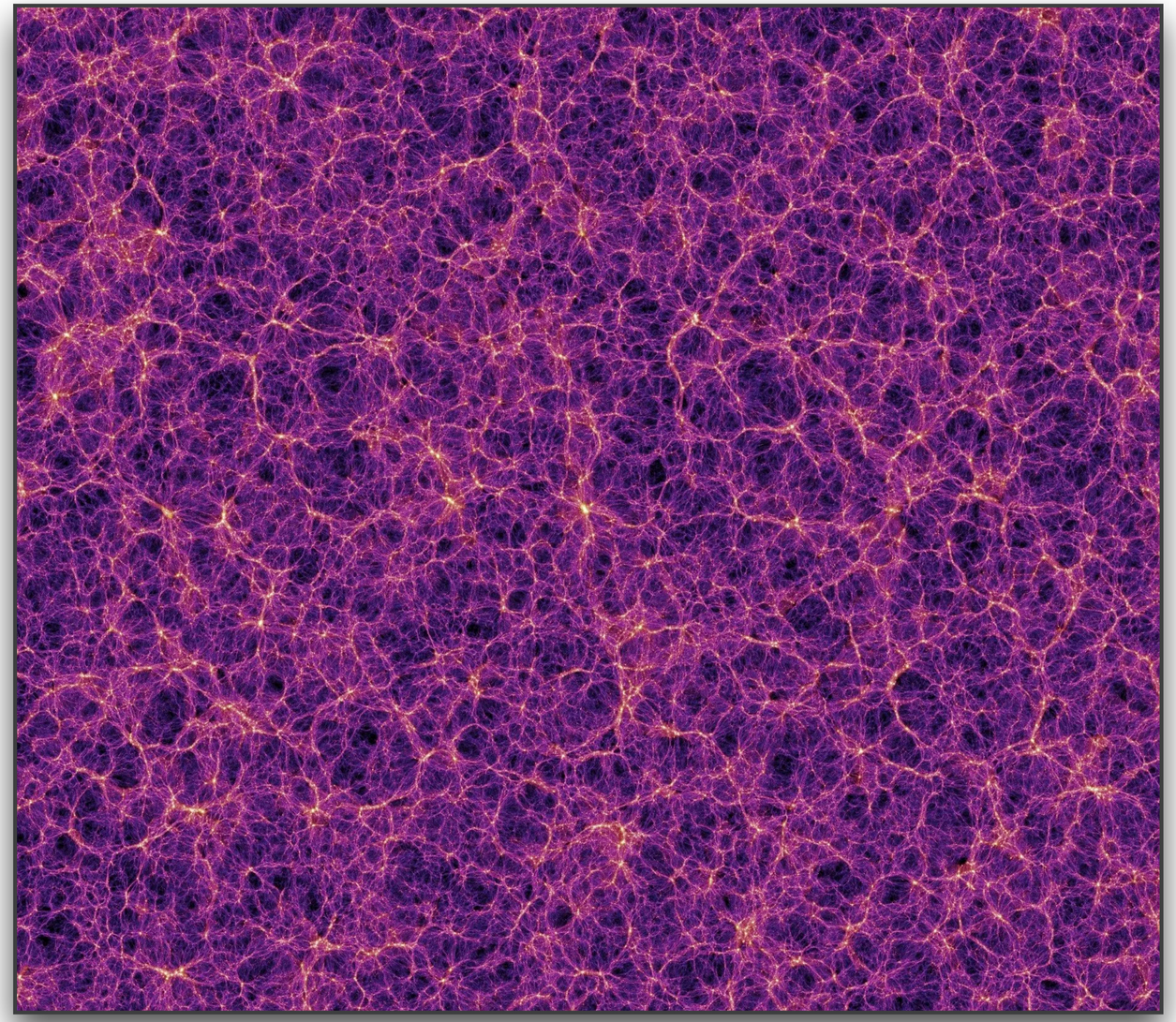
→ $\rho_c = 3H_0^2 M_{\rm Pl}^2 = 9 \times 10^{-30}\ g/{\rm cm}^3$

Average number of photons [cm^{-3}]
→ ~ 411



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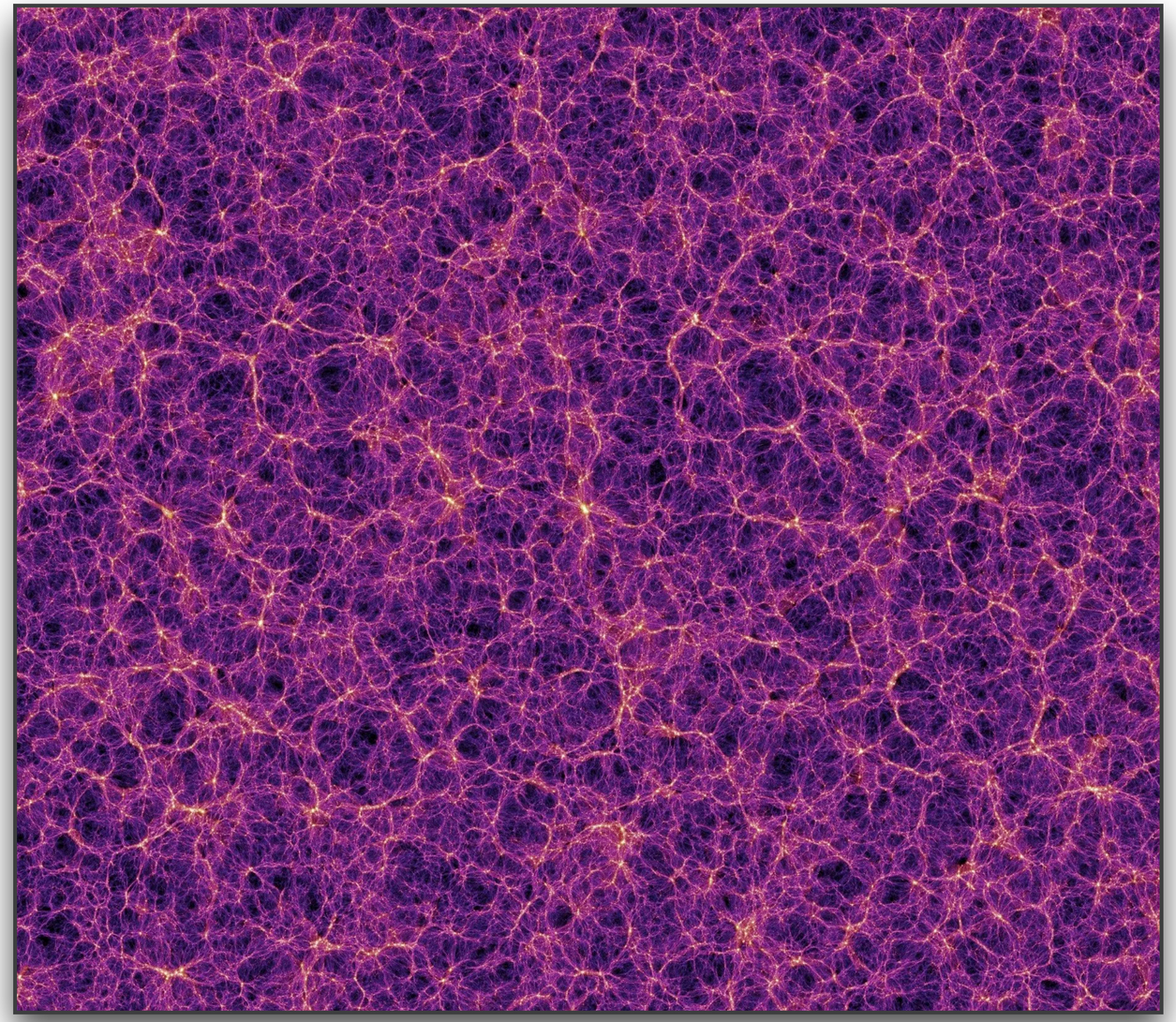

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Average number of photons [cm^{-3}]
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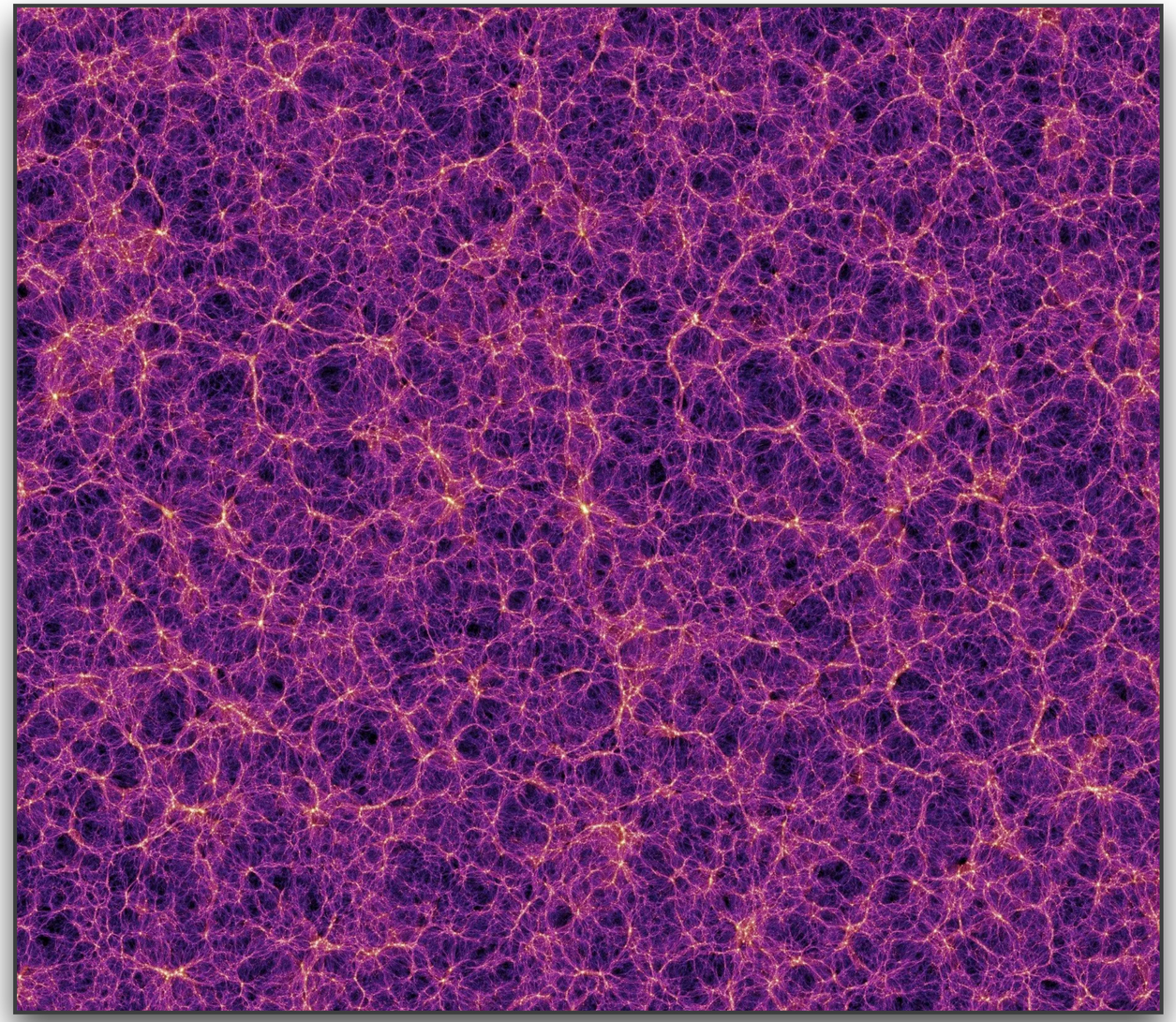
Average number of neutrinos [cm^{-3}]
→ ~ 336



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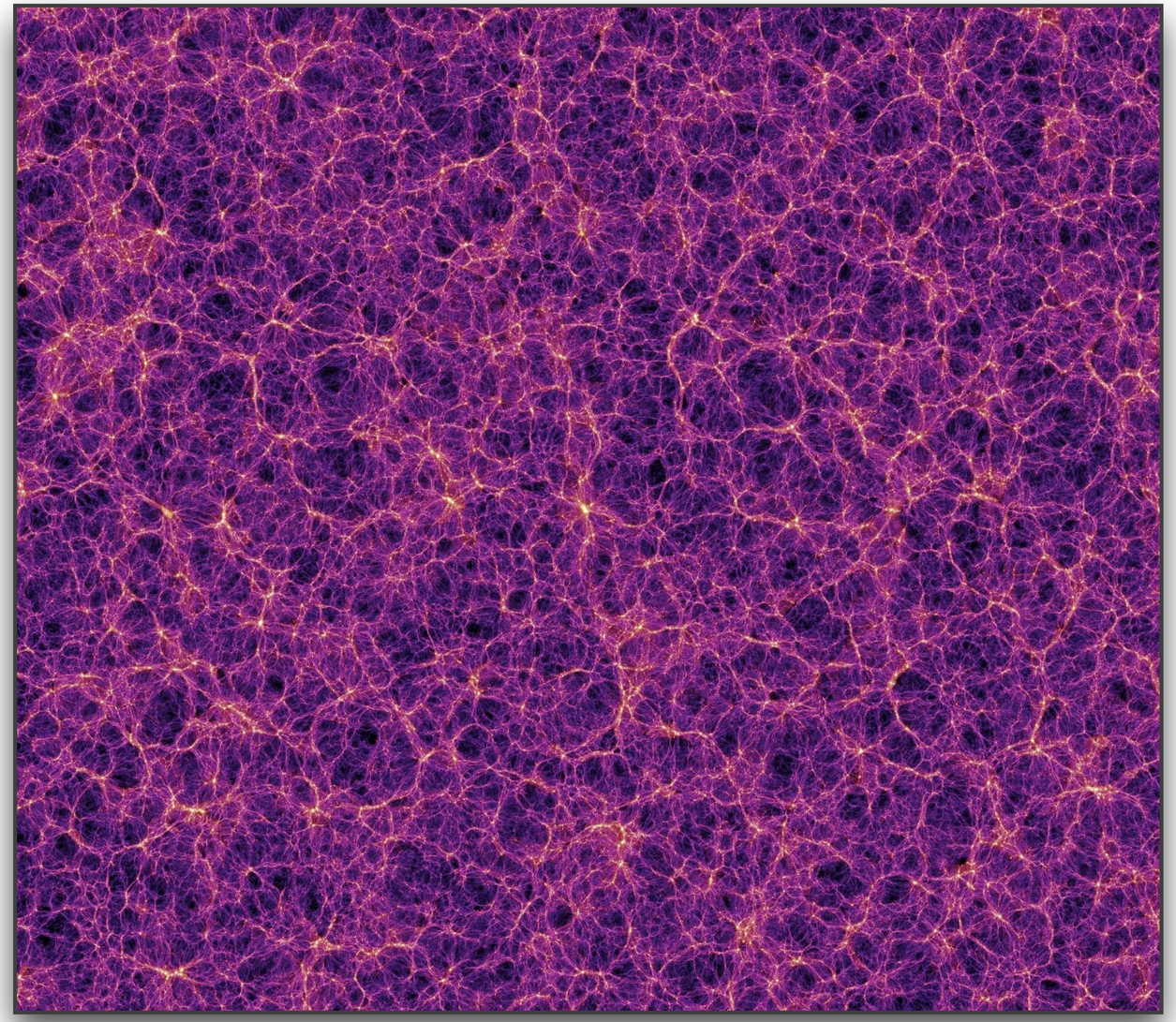
Energy density of components

$$\Omega = \frac{\rho}{\rho_c} \quad \rightarrow \quad \Omega_{\rm rad} = \qquad \Omega_b =$$
$$\Omega_{\rm DM} = \qquad \Omega_\Lambda =$$



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Average number of photons [cm^{-3}]
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Average number of neutrinos [cm^{-3}]
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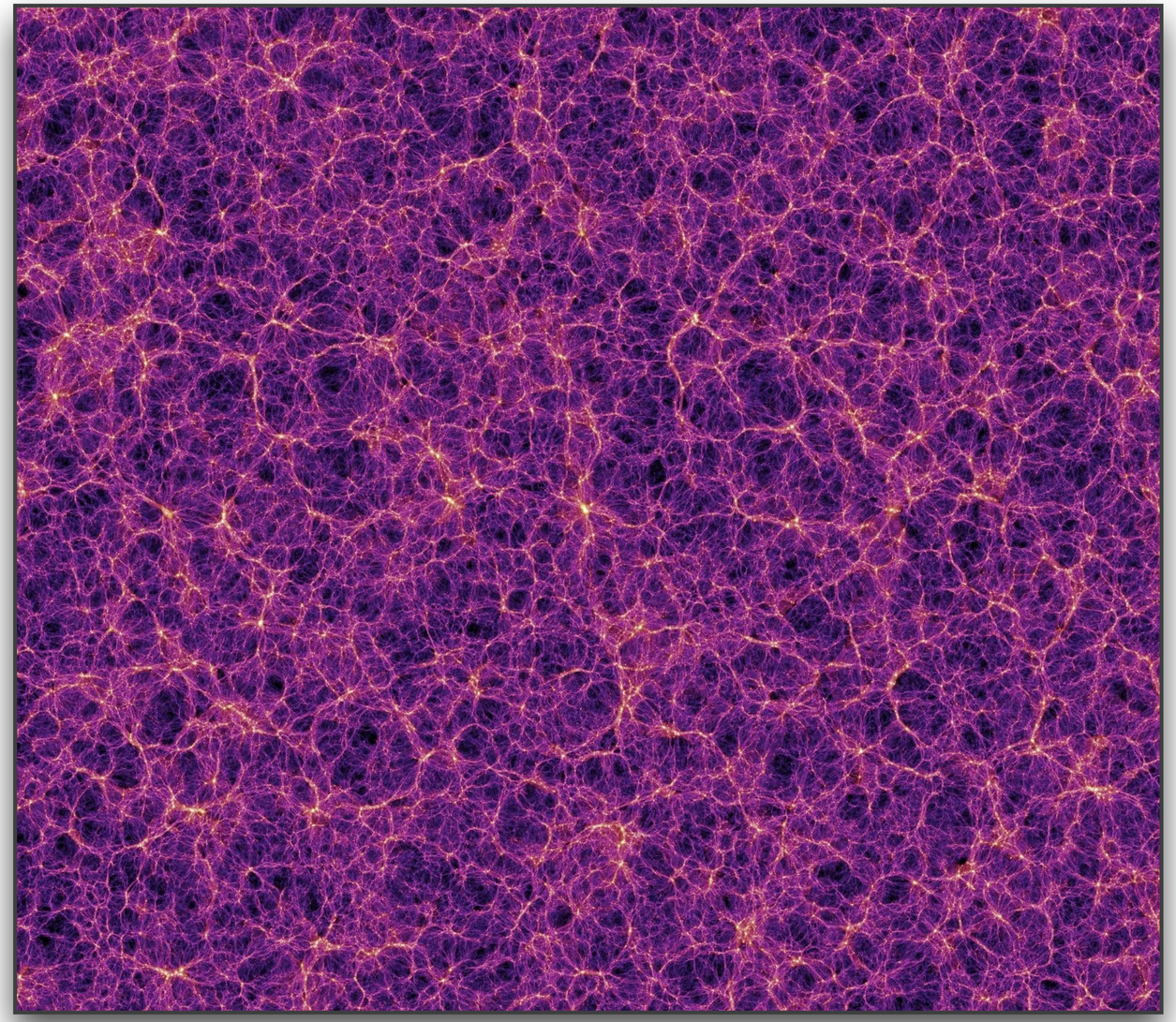
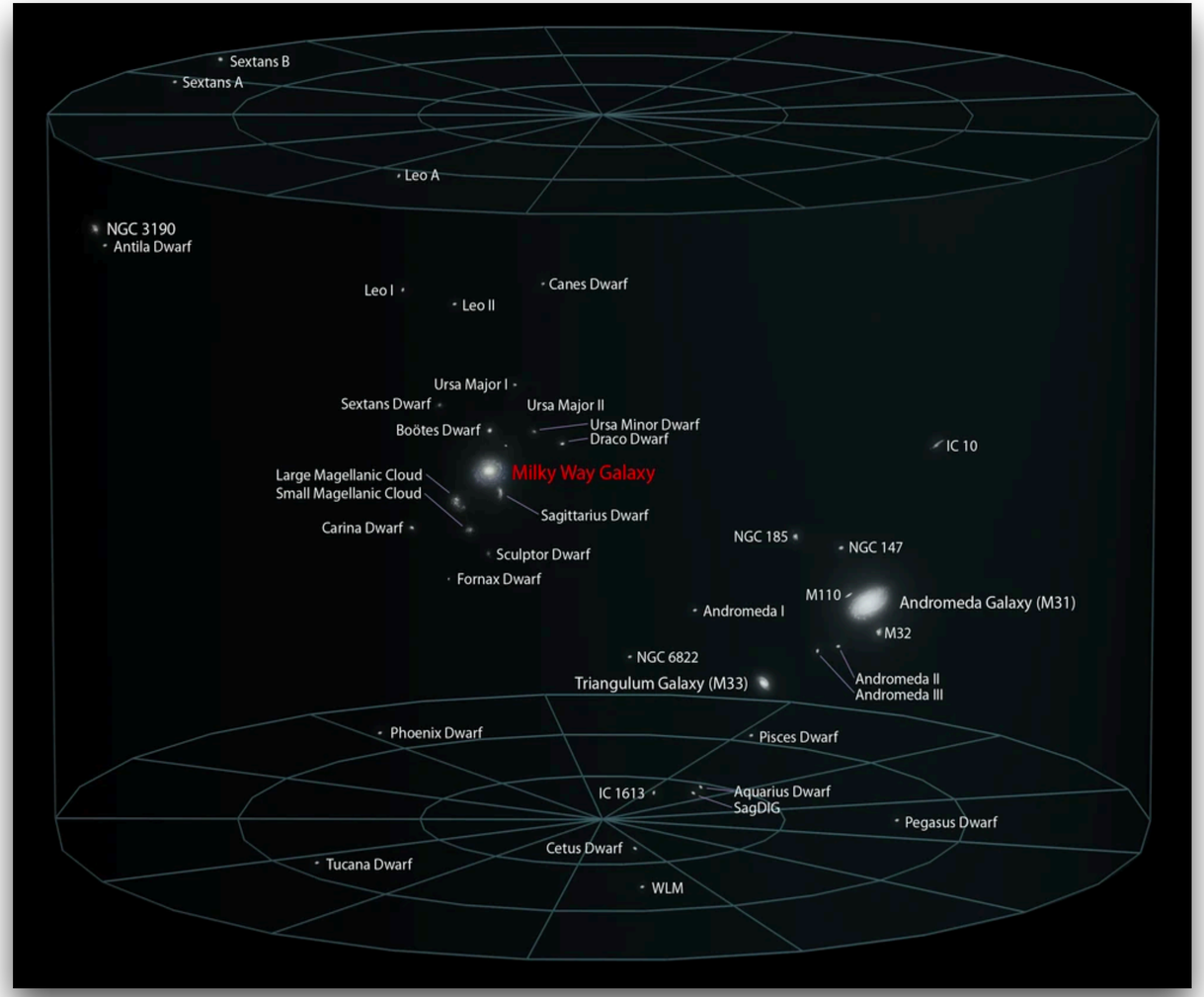
Energy density of components

$$\Omega = \frac{\rho}{\rho_c} \quad \rightarrow \quad \Omega_{\rm rad} = 0.0015 \quad \Omega_b = 0.05 \quad \Omega_{\rm DM} = 0.26 \quad \Omega_\Lambda = 0.69$$

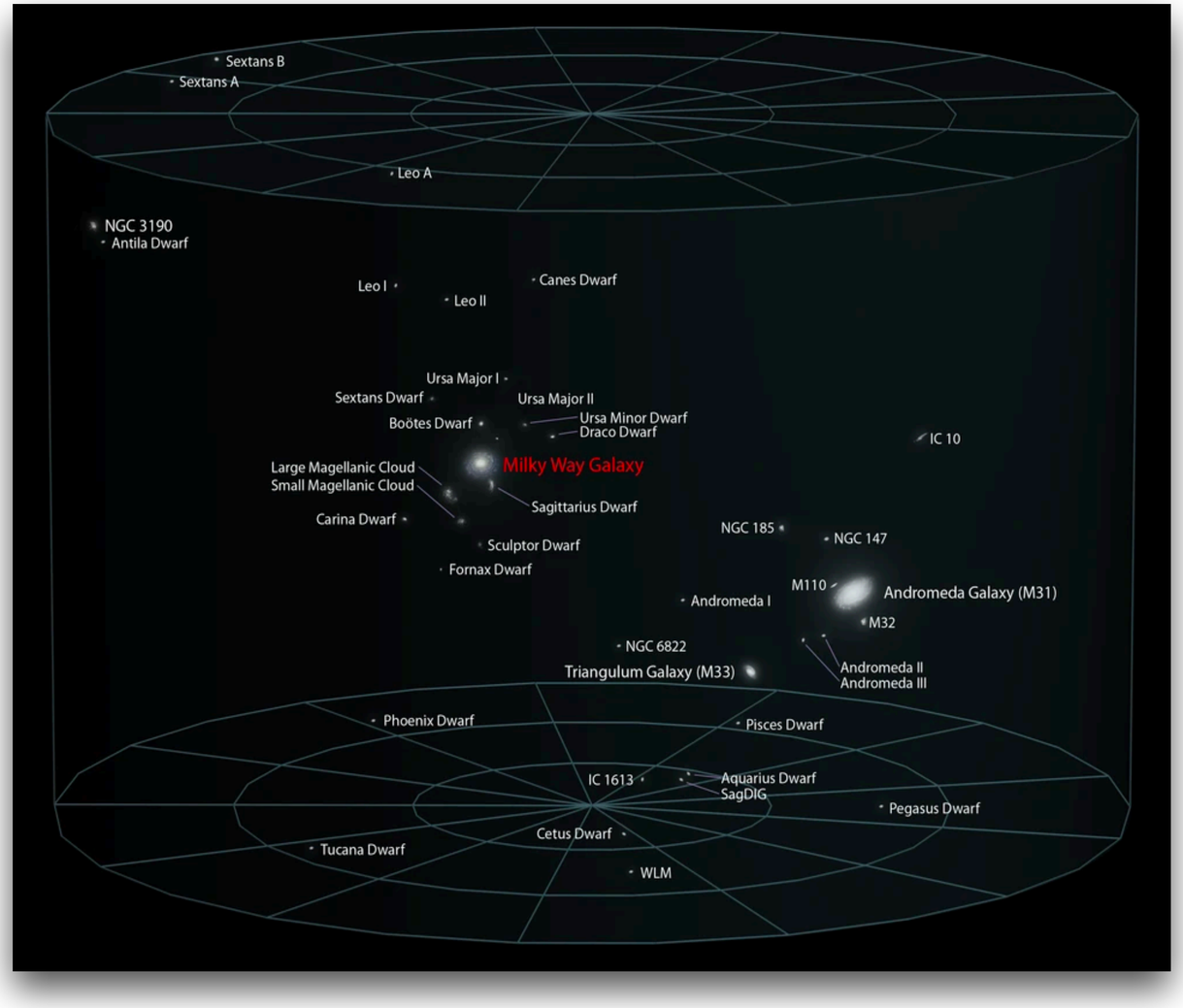


How well do you know your Local group?



How well do you know your Local group?

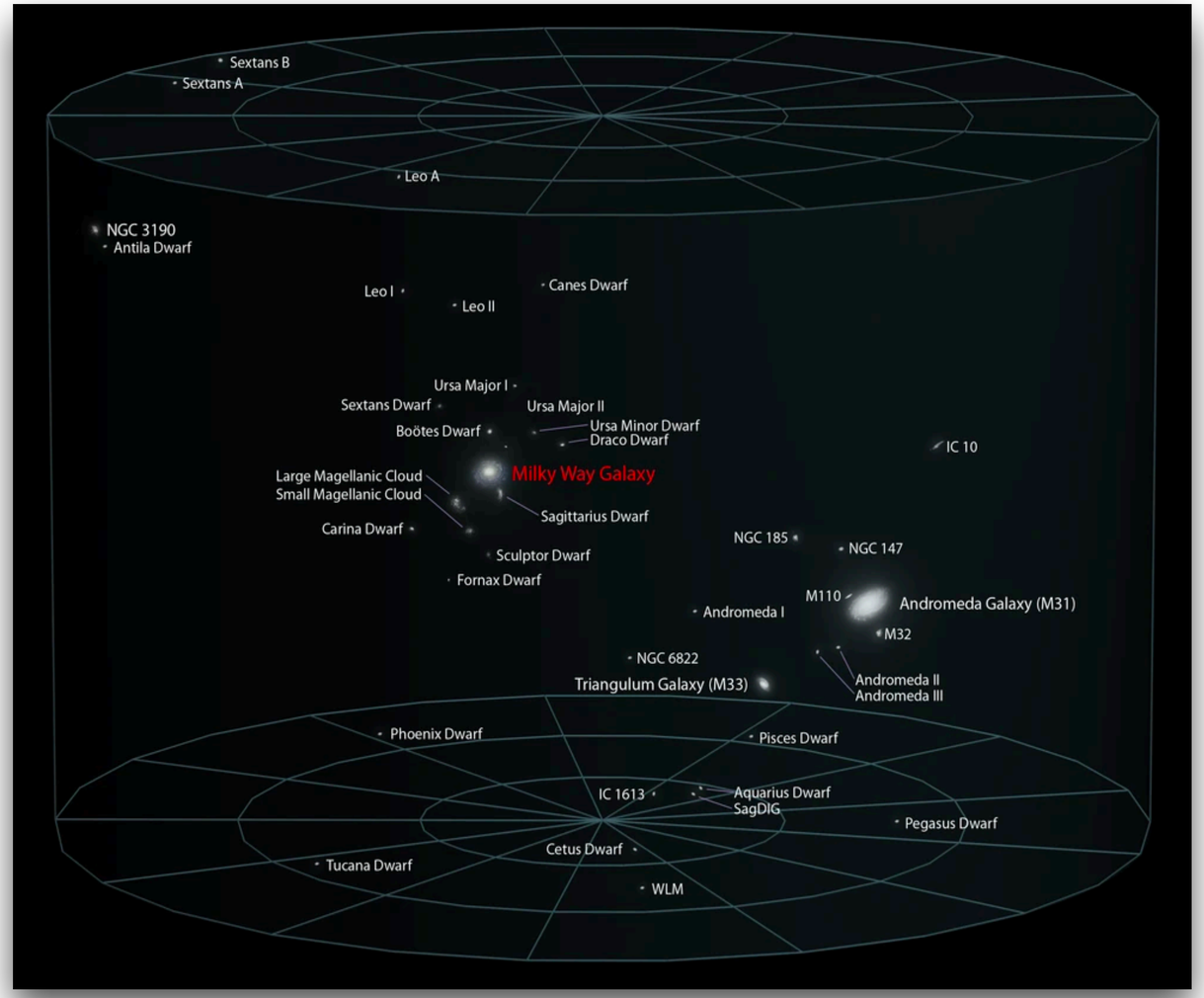
Distance to nearest major galaxy



How well do you know your Local group?

Distance to nearest major galaxy

→ 765 kpc / 250 million ly (Andromeda/M31)



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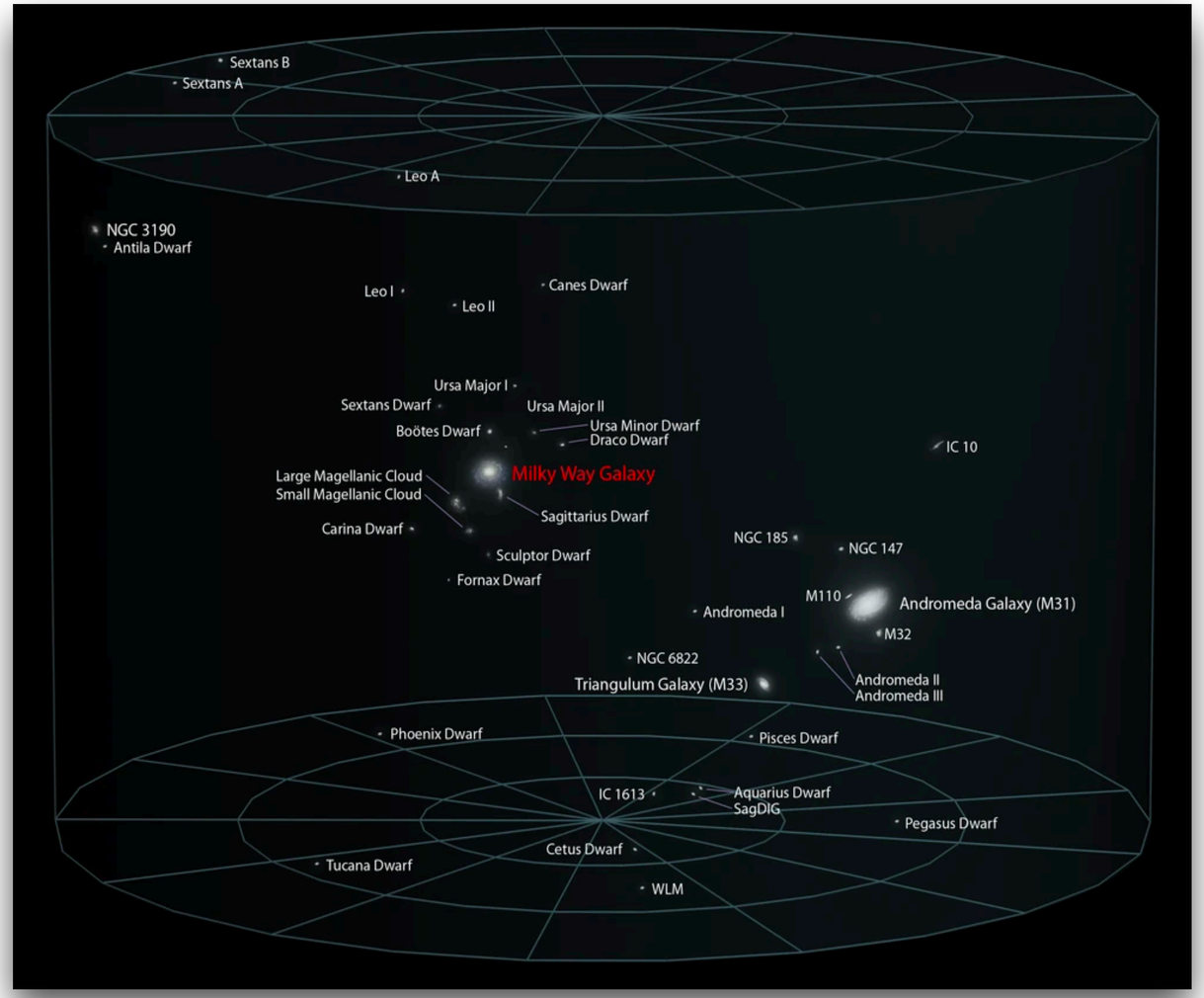
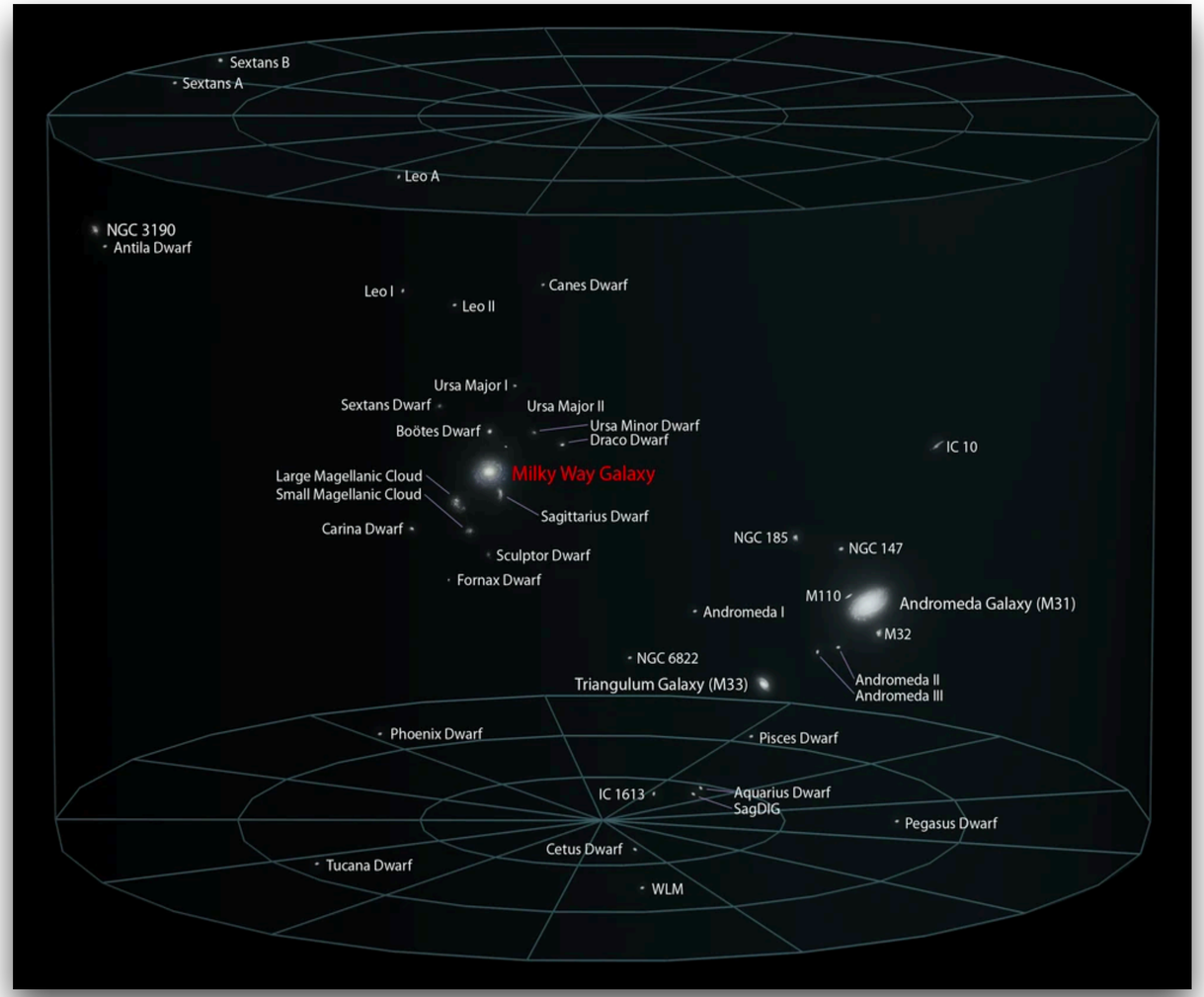
Radius of Milky Way's DM halo



How well do you know your Local group?

Distance to nearest major galaxy
→ 765 kpc / 250 million ly (Andromeda/M31)

Radius of Milky Way's DM halo
→~200 kpc



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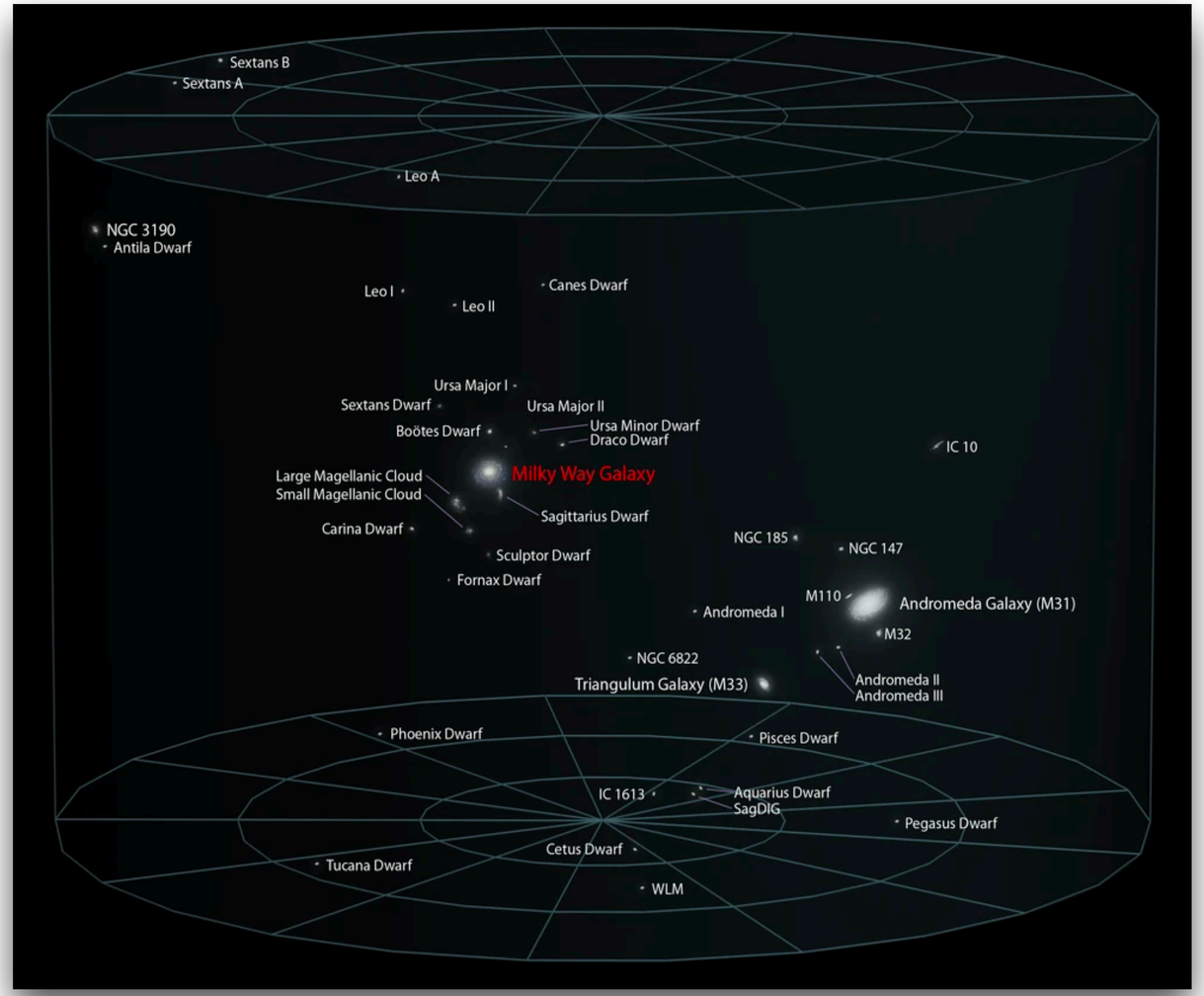
Mass of Milky Way



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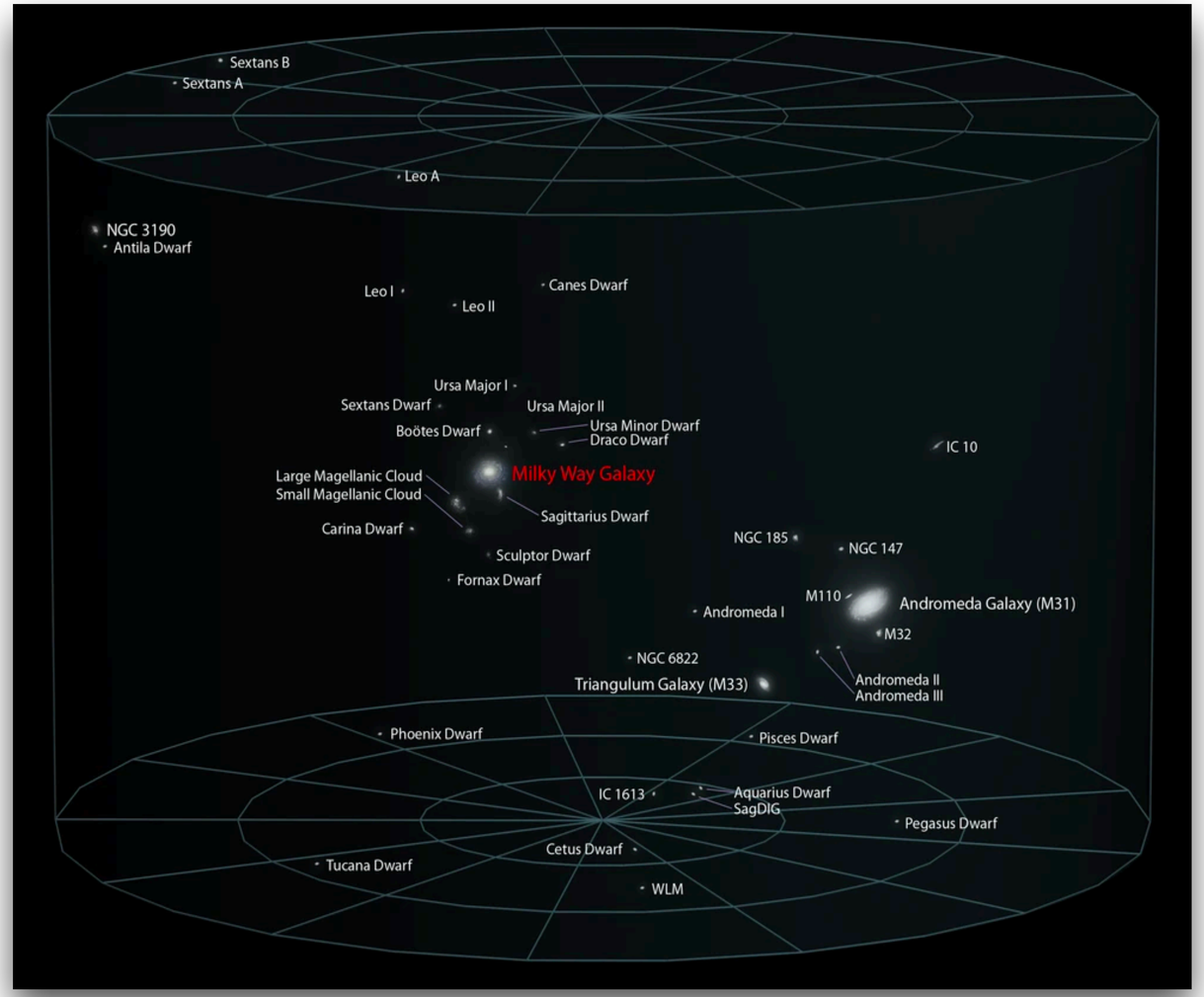
Radius of Milky Way's DM halo

→~200 kpc

Mass of Milky Way

→ $\sim 10^{11-12}\, M_{\odot}$



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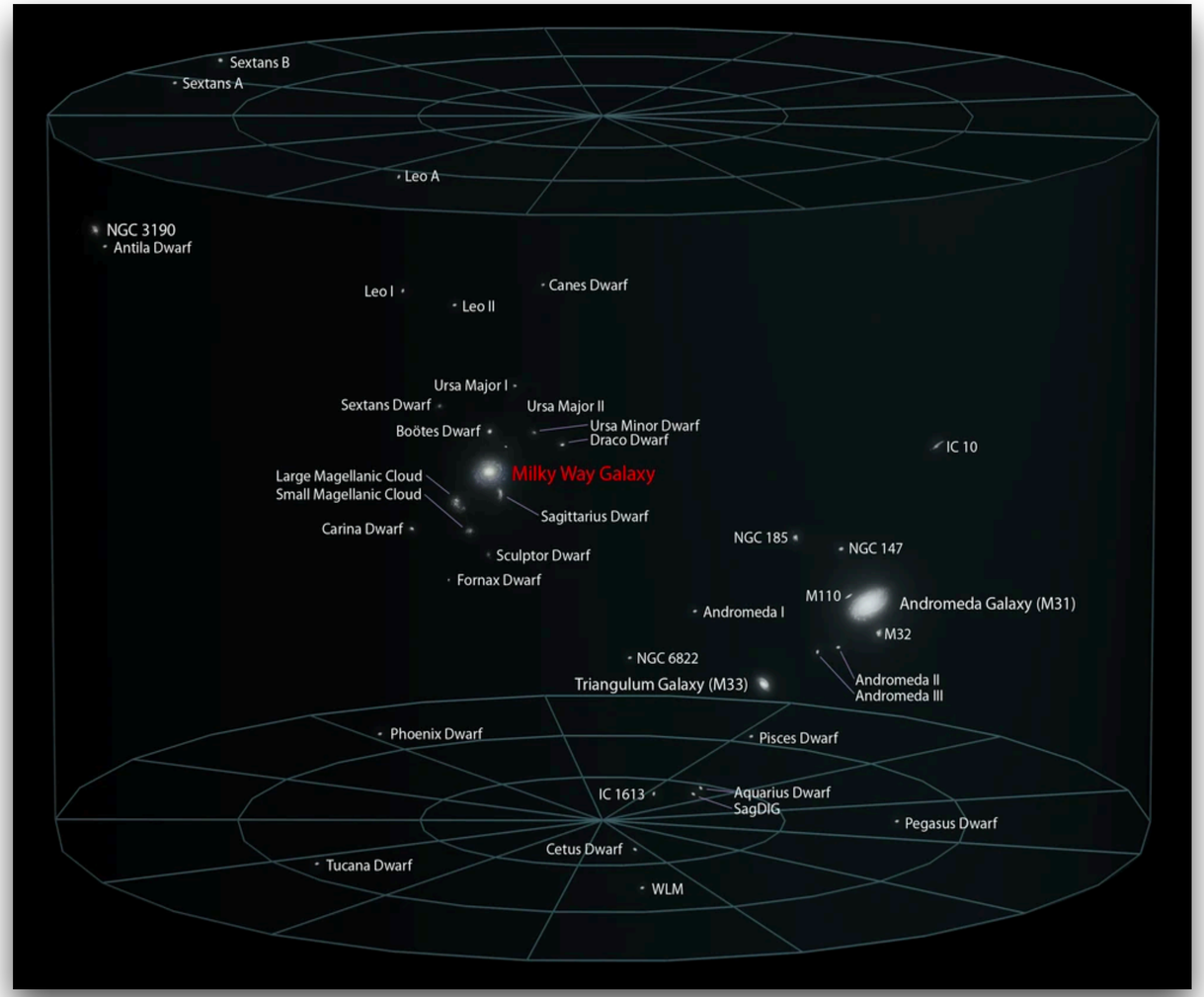
Velocity of Milky Way



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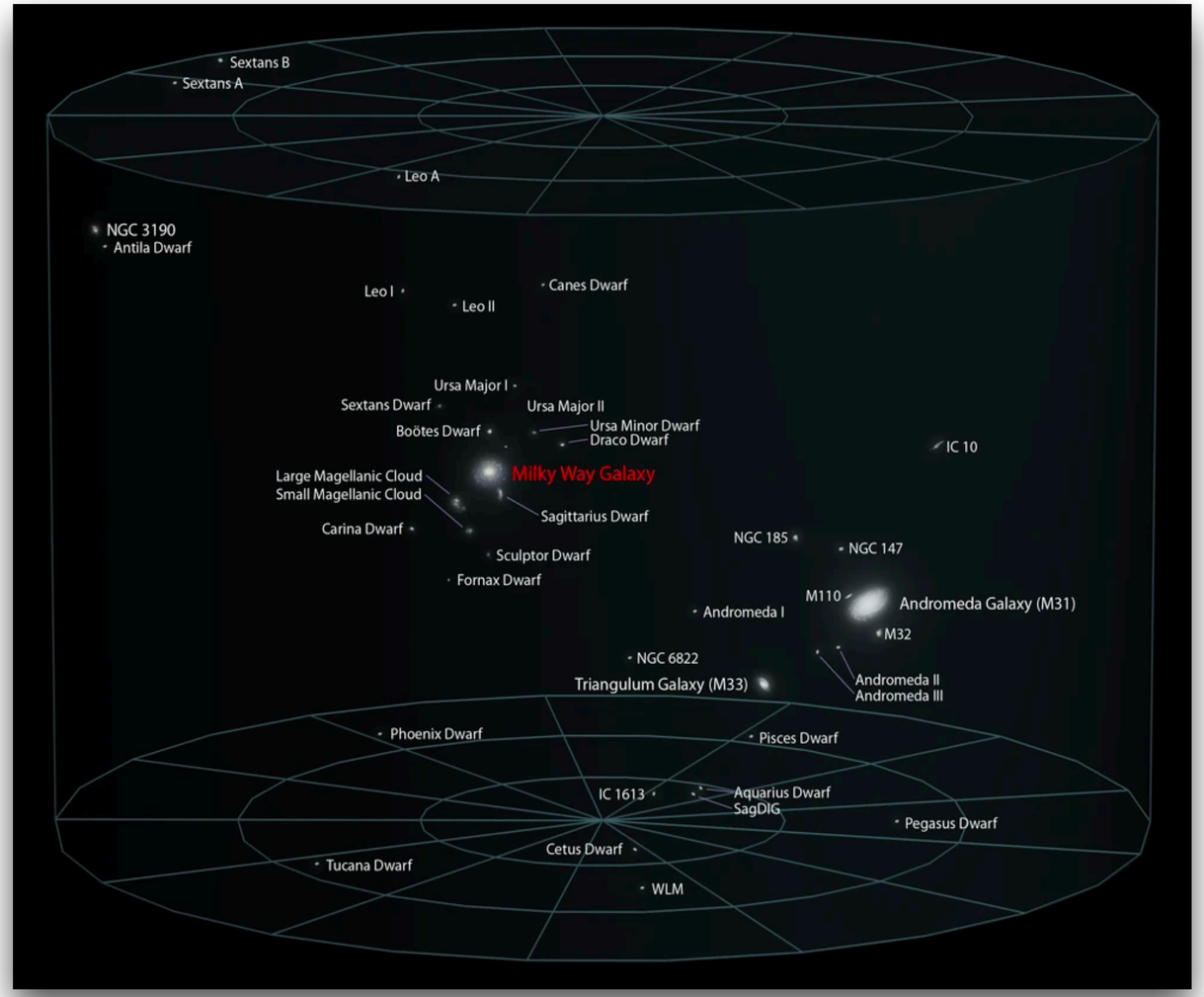
Velocity of Milky Way

→ ~ 600 km/s



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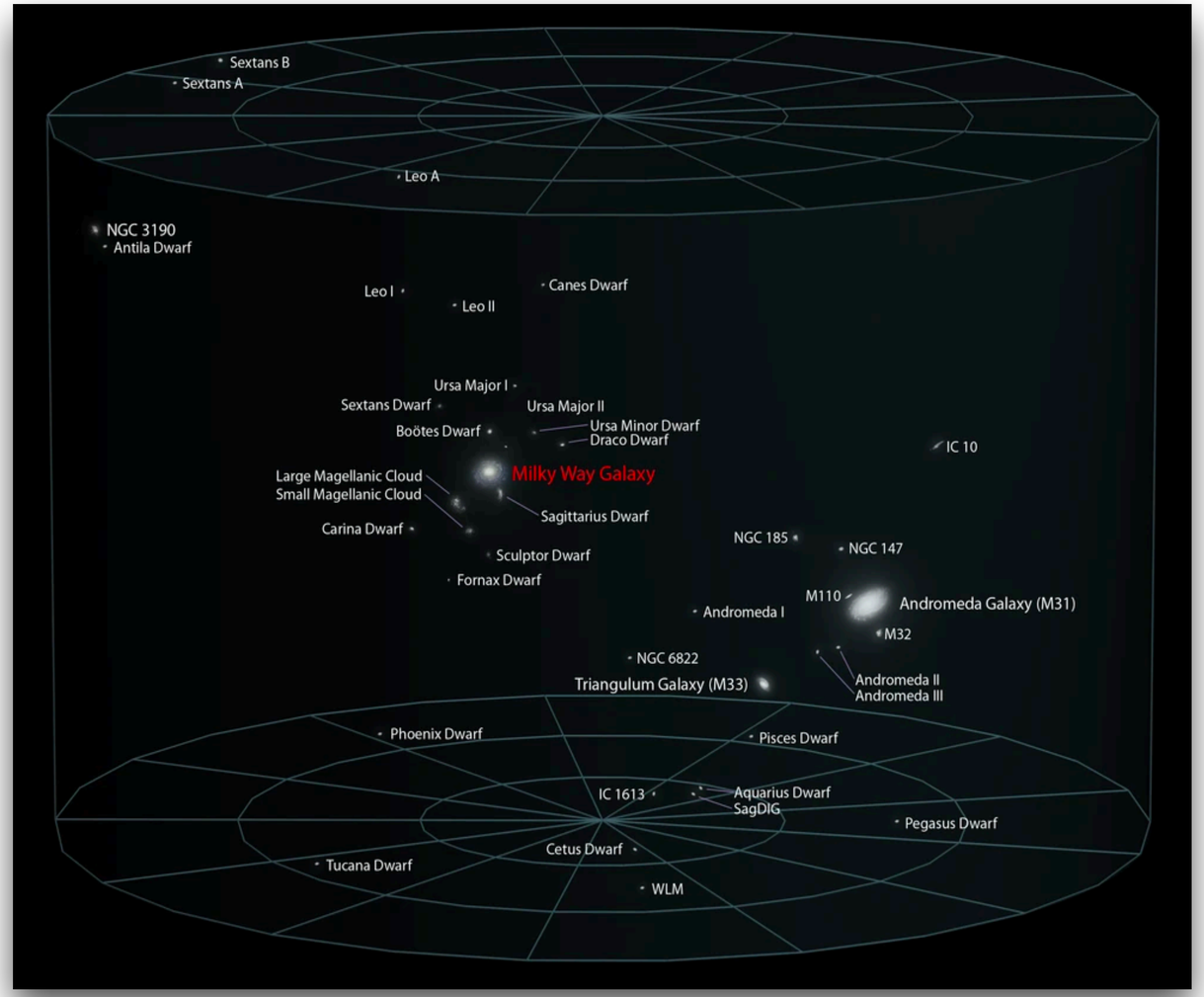
What our galaxy will be called in 4.5 bn years



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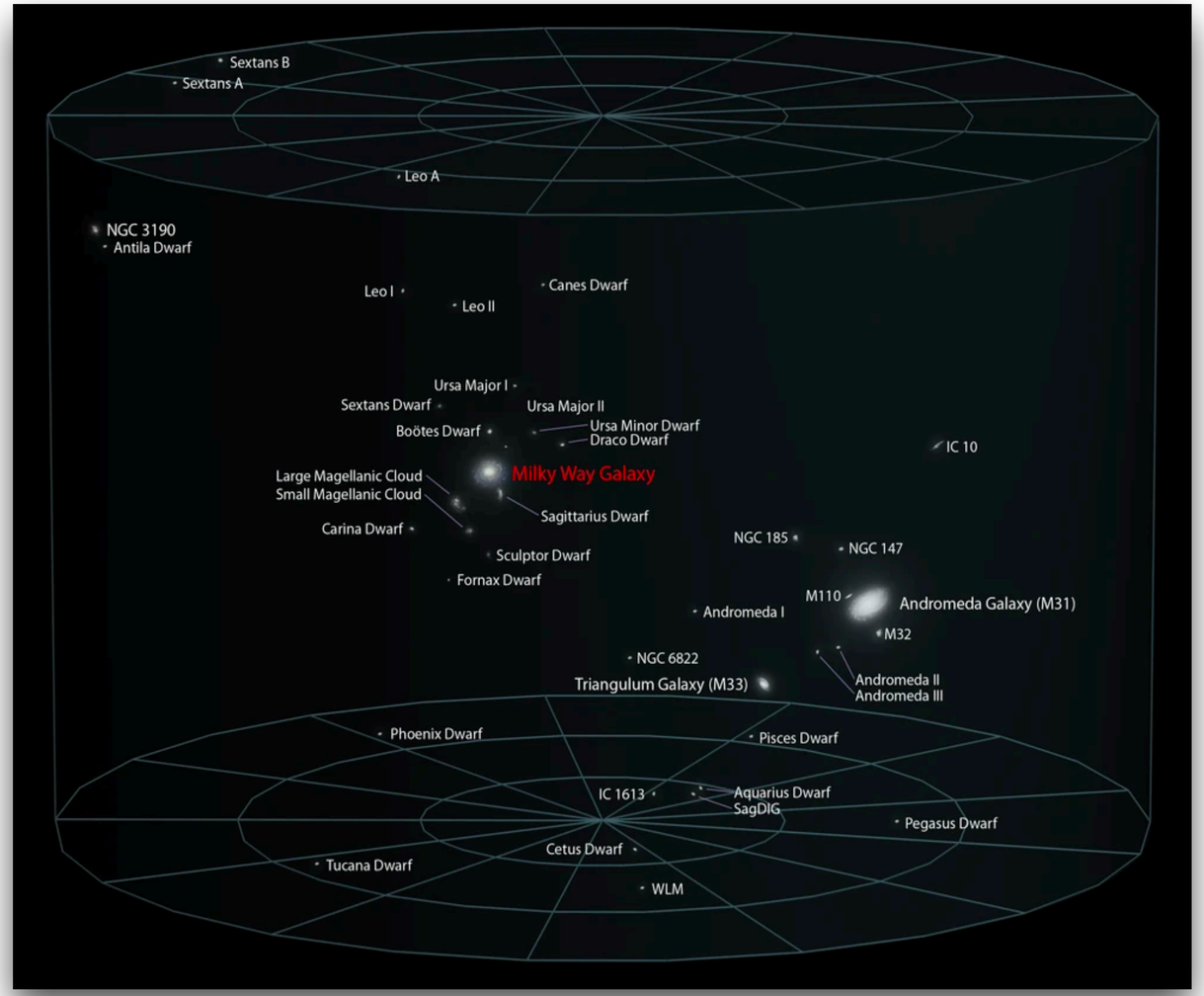
What our galaxy will be called in 4.5 bn years
→ Milkdromeda



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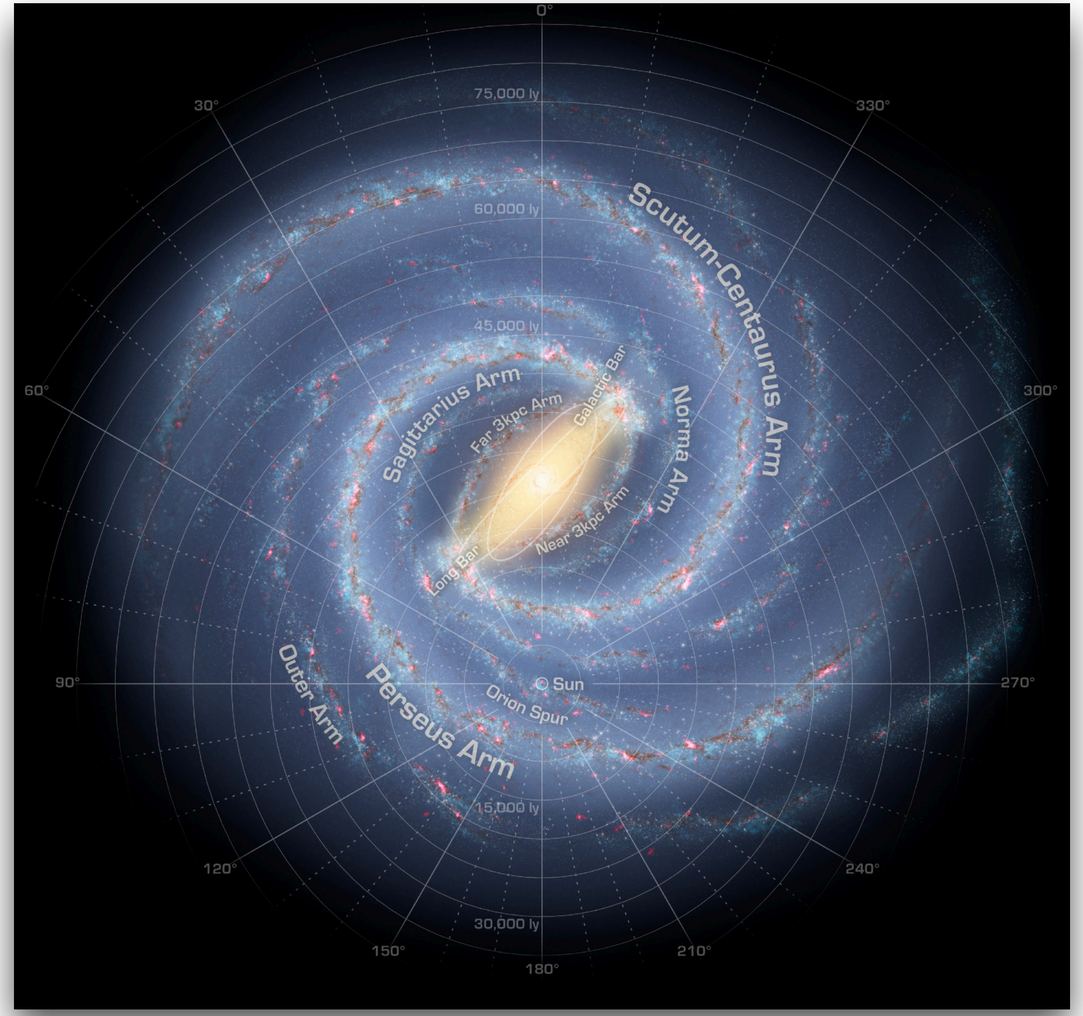
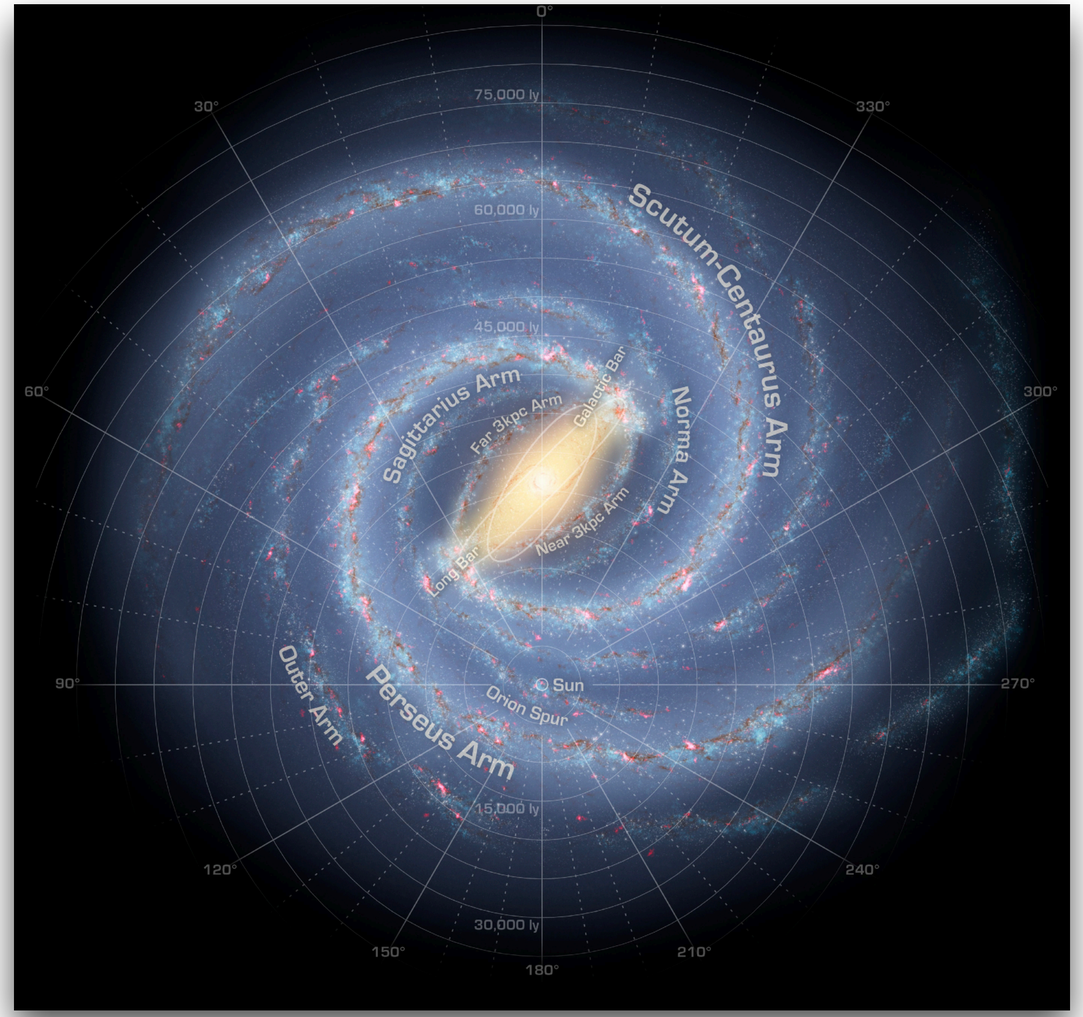


How well do you know your galaxy?

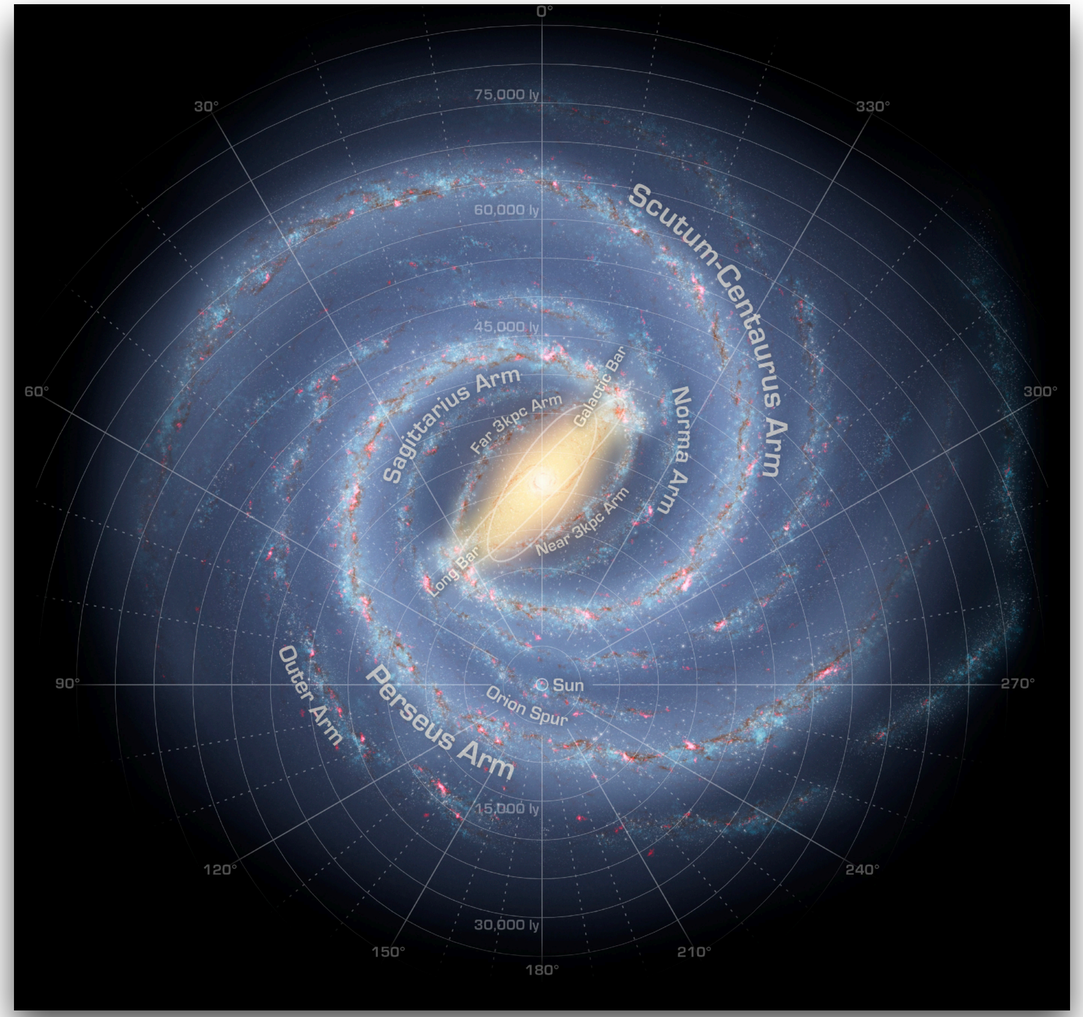
Diameter of Milky Way disk



How well do you know your galaxy?

Diameter of Milky Way disk

→ ~30 kpc

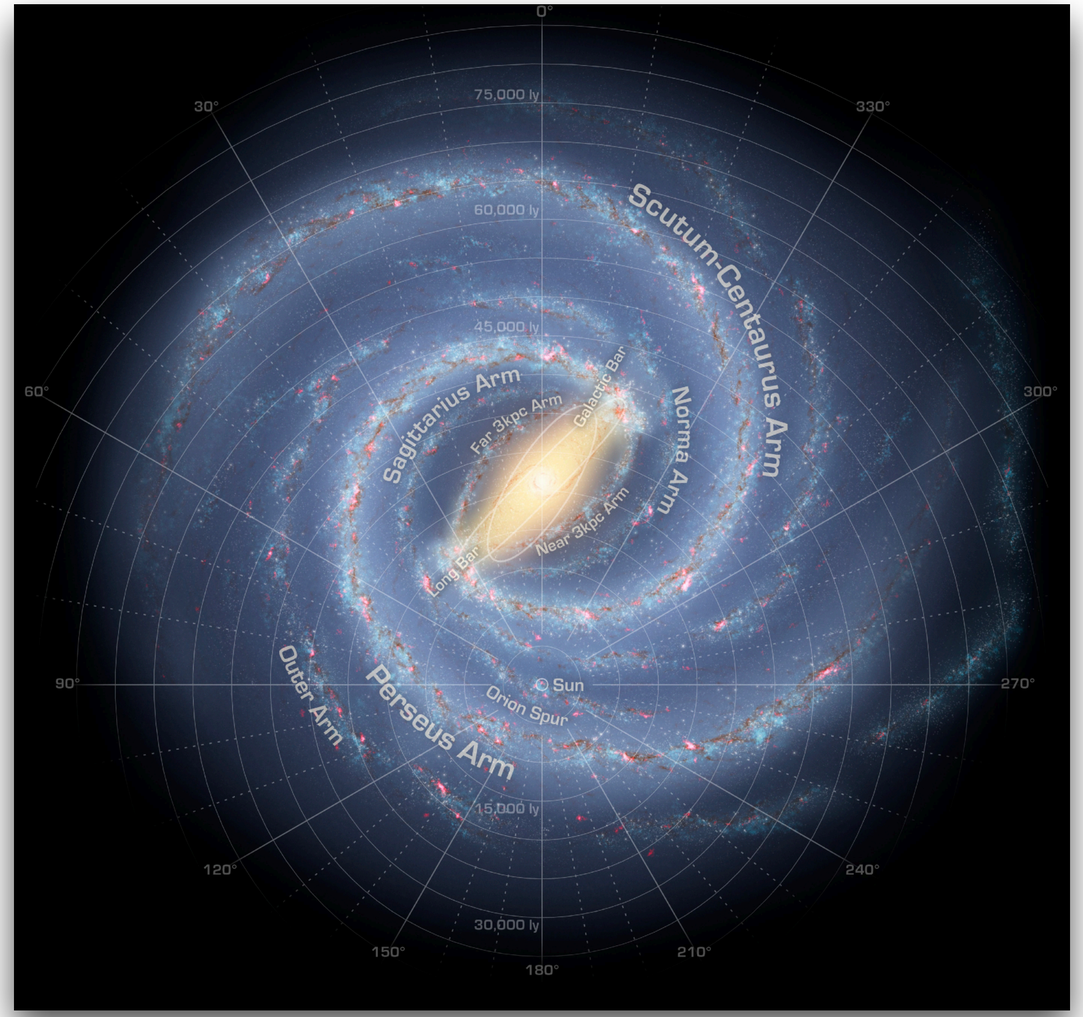


How well do you know your galaxy?

Diameter of Milky Way disk

→ ~30 kpc

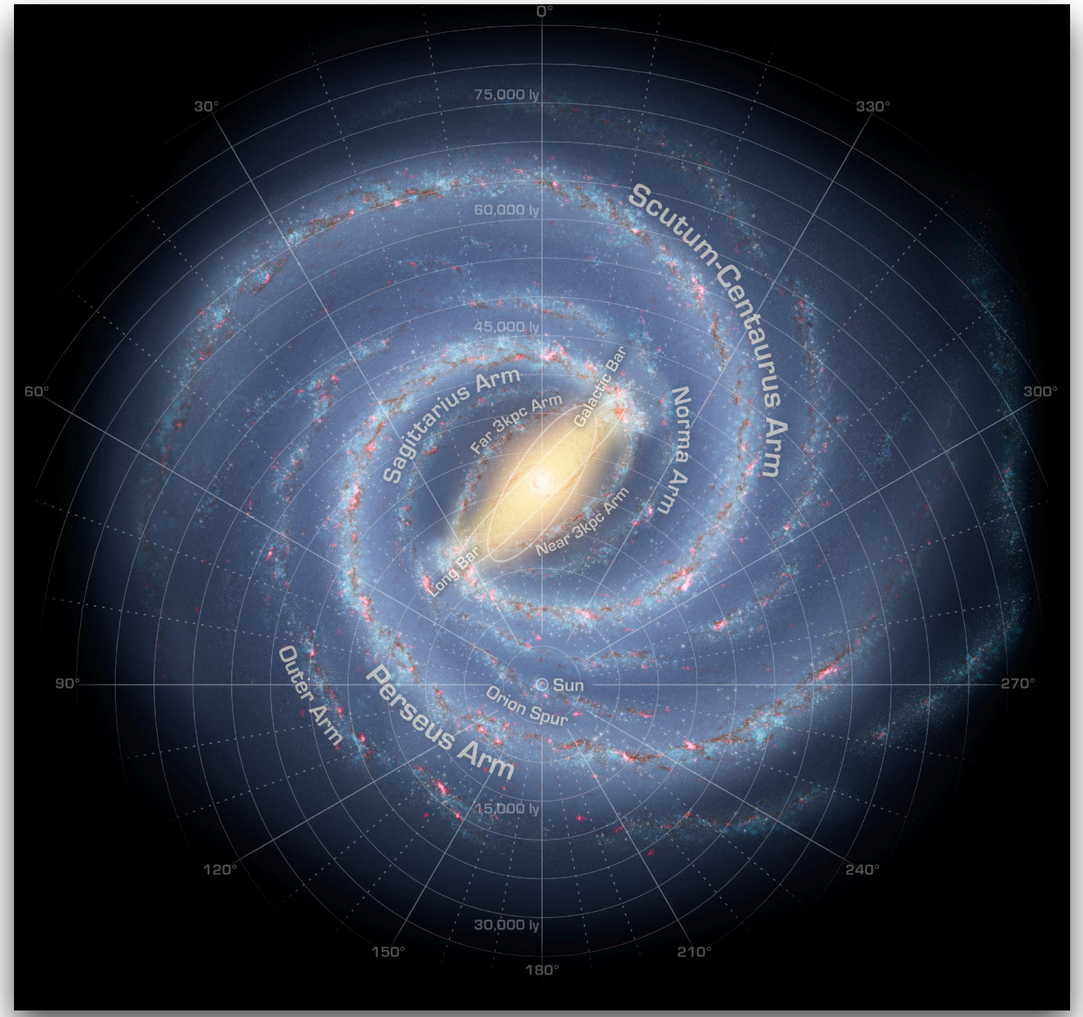
Radius of solar orbit



How well do you know your galaxy?

Diameter of Milky Way disk
→ ~30 kpc

Radius of solar orbit
→ 8 kpc



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Diameter of Milky Way disk
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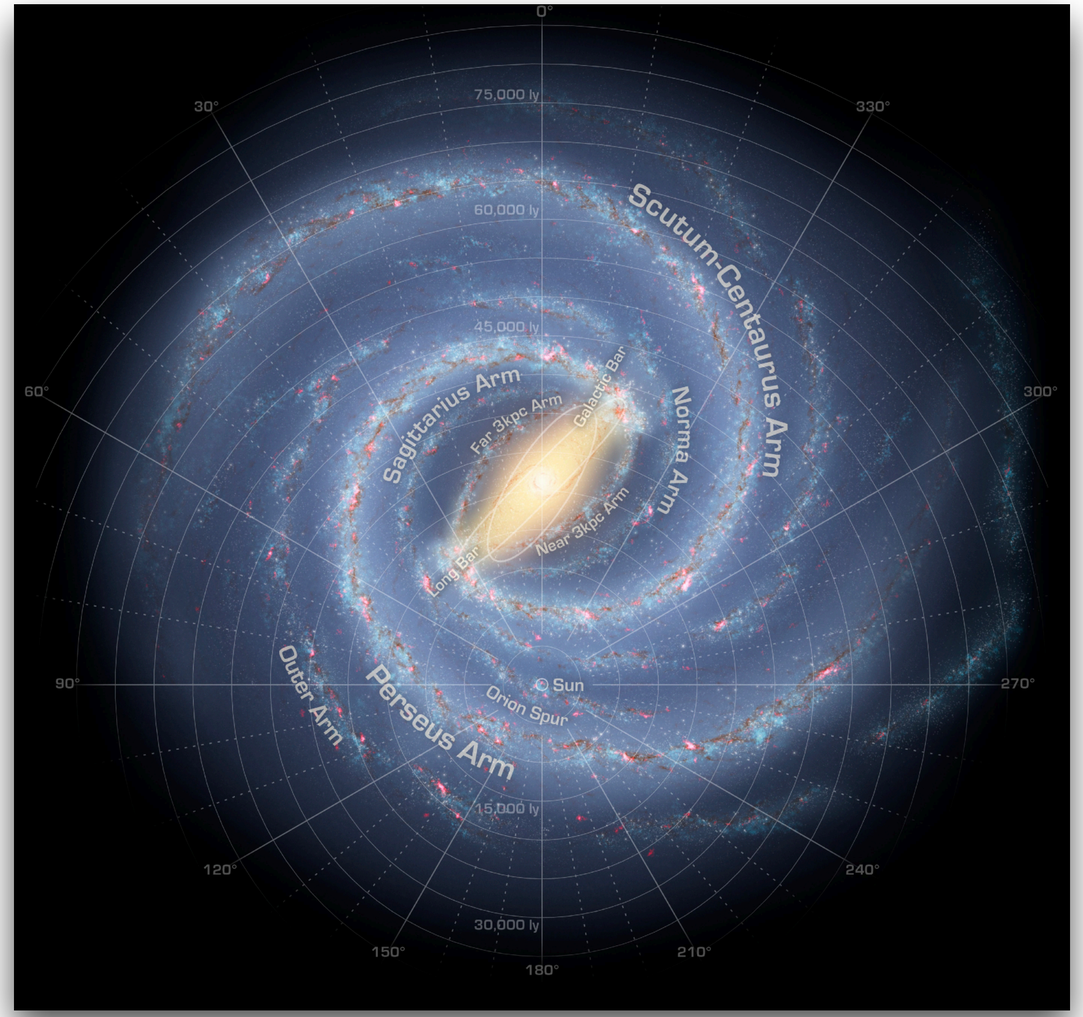
Radius of solar orbit
→ 8 kpc

How many birthdays has the Sun had?



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Diameter of Milky Way disk
→ ~30 kpc

Radius of solar orbit
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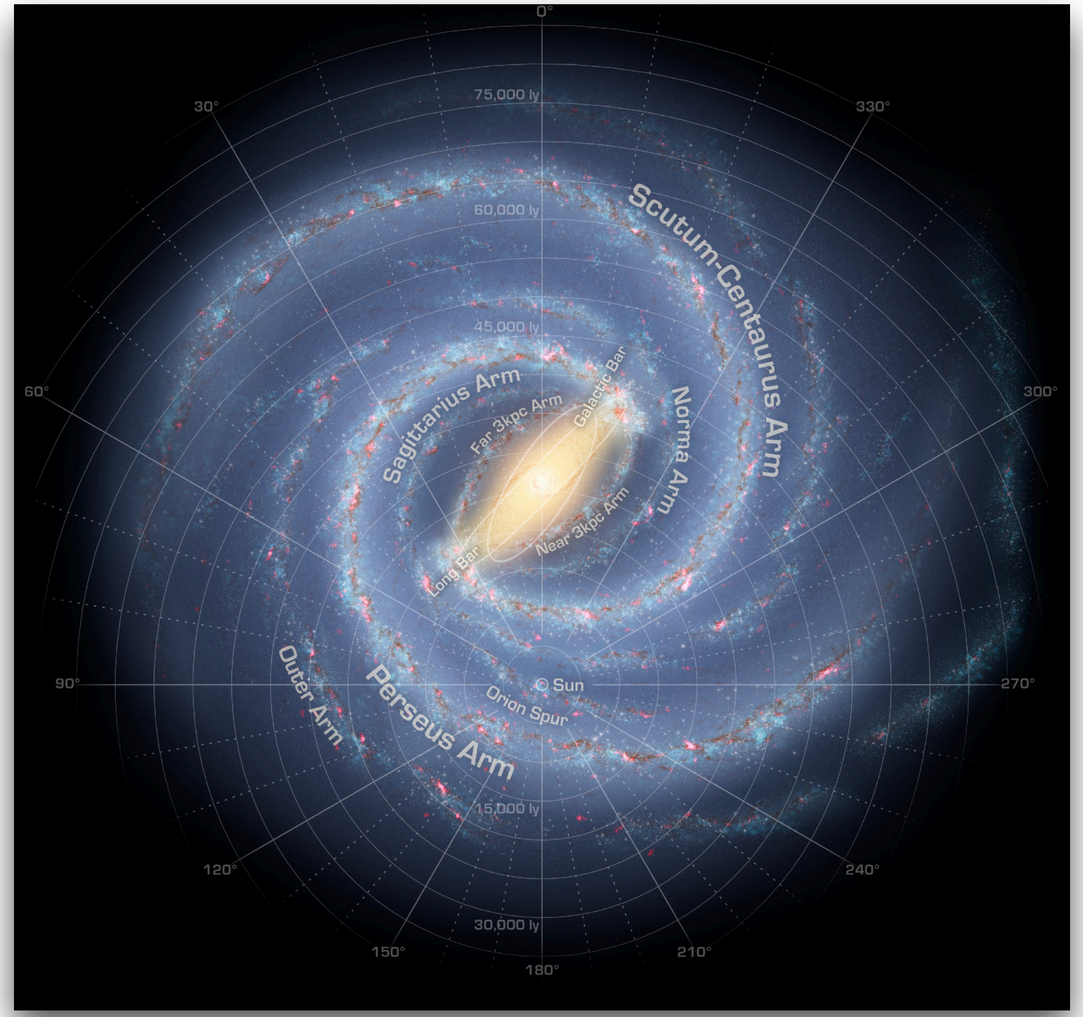
How many birthdays has the Sun had?
→ Solar age/Solar orbit = 4.6 Gyr/230 Myr = 20



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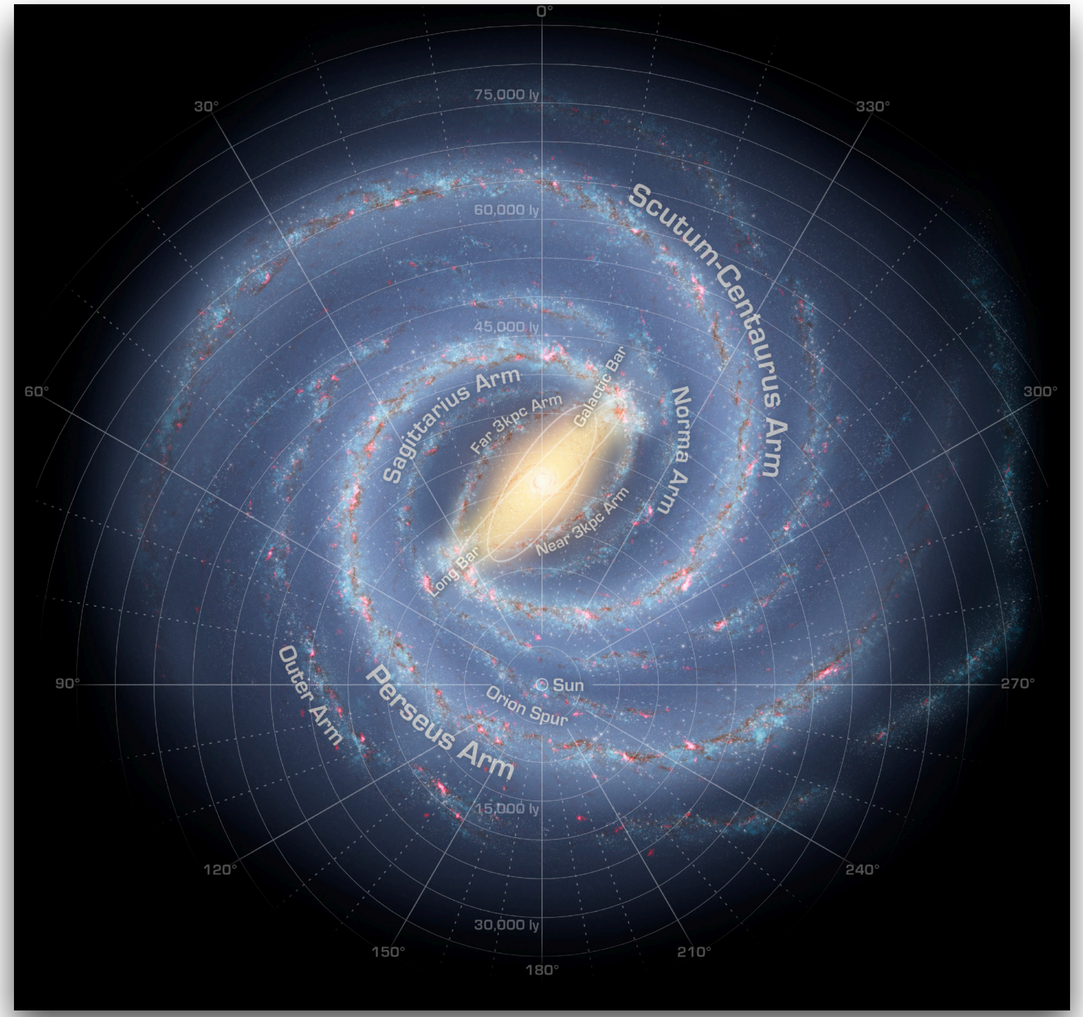
Density of dark matter at Solar position [GeV/cm^3]



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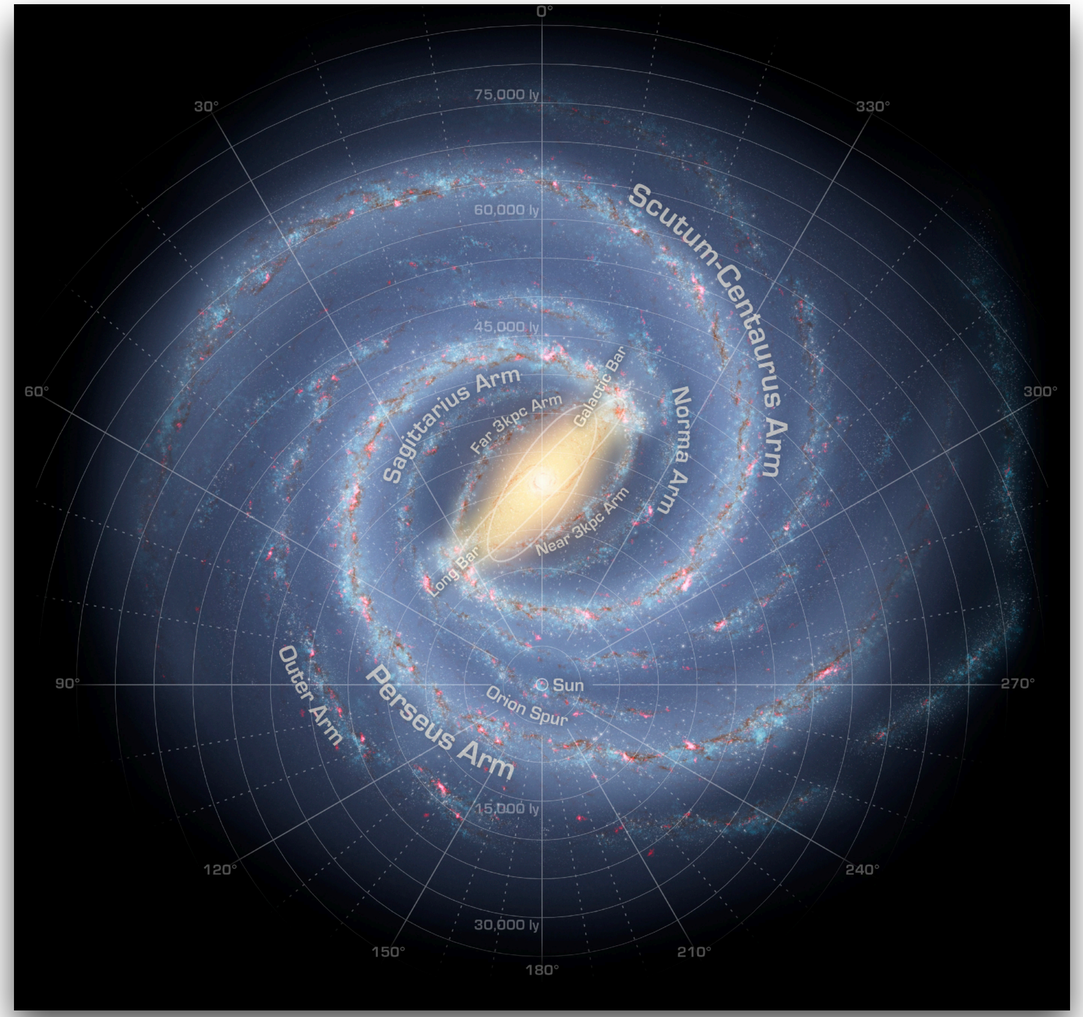
Density of dark matter at Solar position [GeV/cm^3]
→ ~ 0.3—0.7 GeV/cm^3



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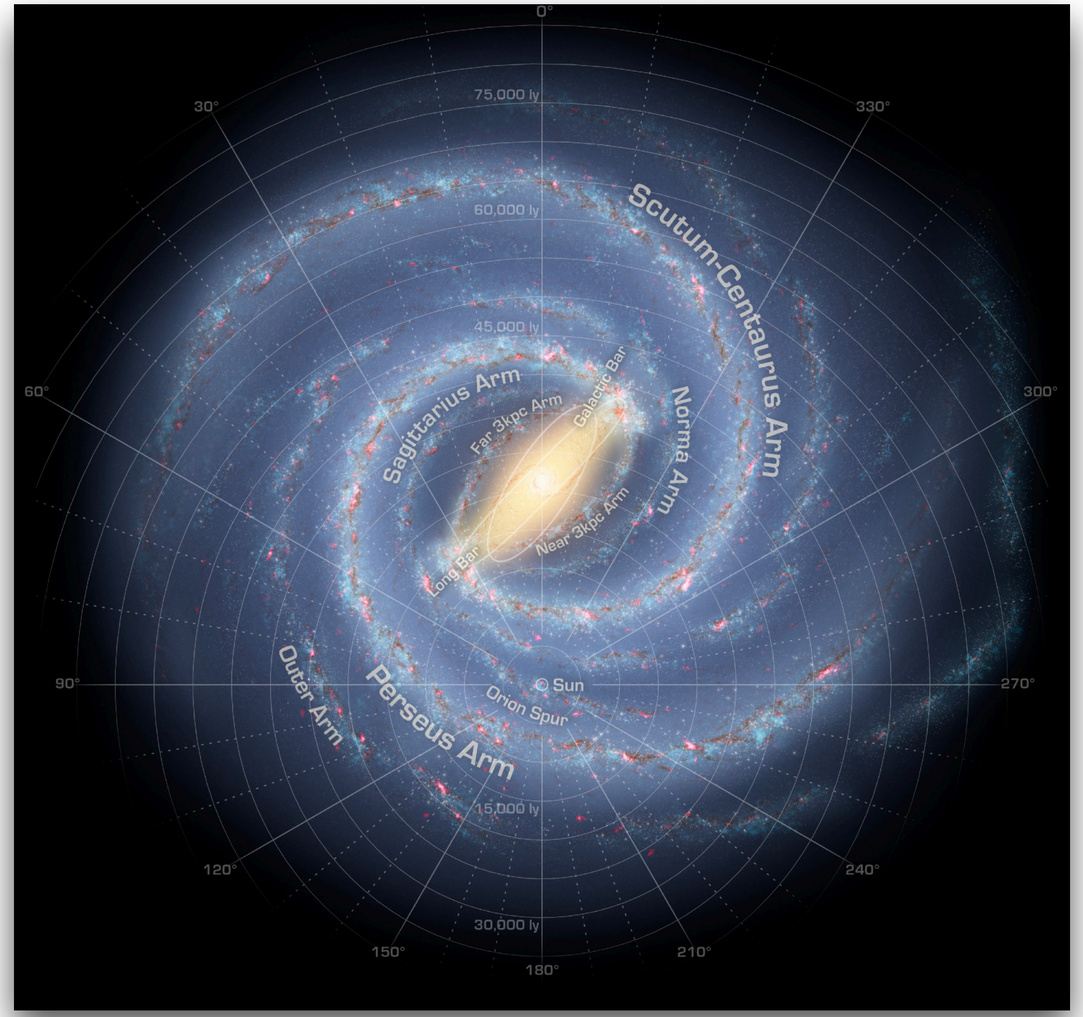
Number density of dark matter at Solar position [cm^{-3}]



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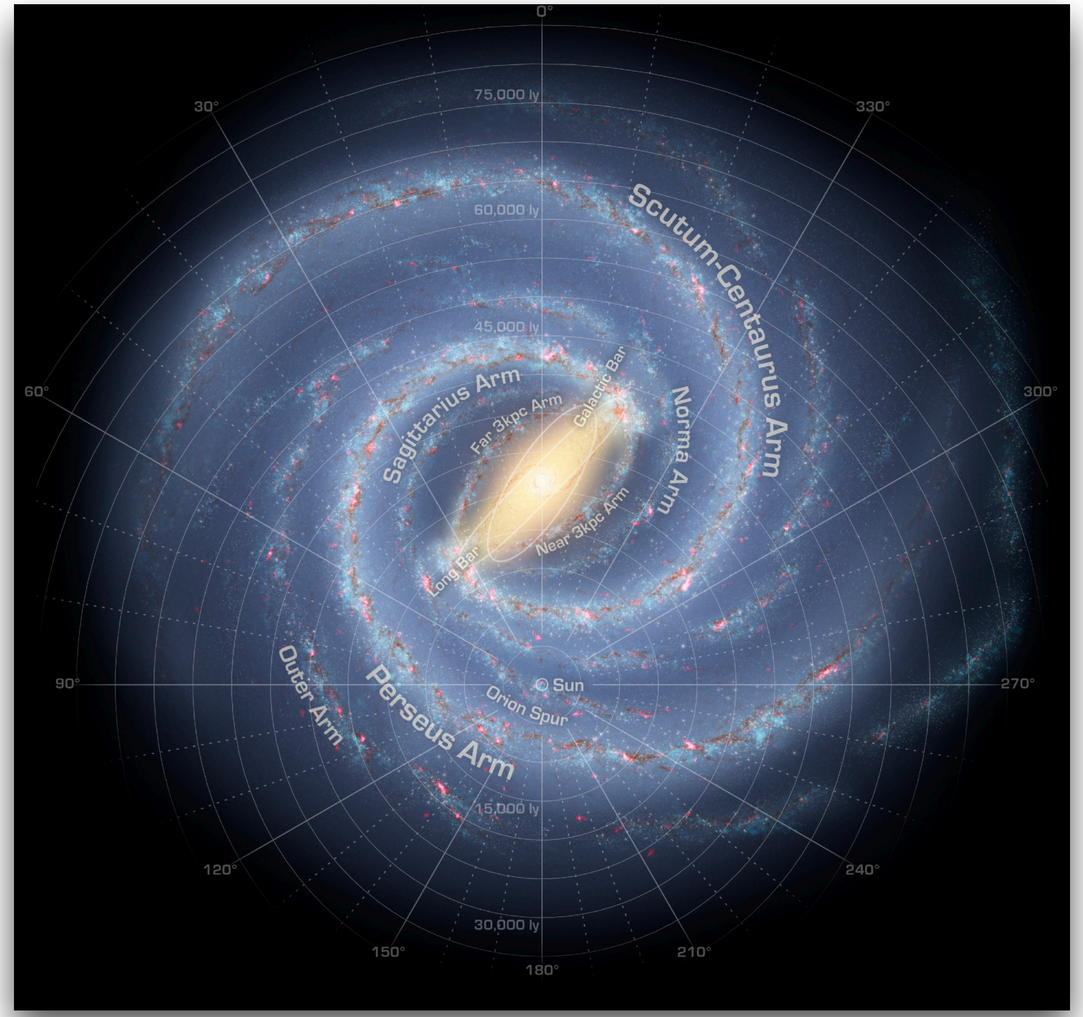
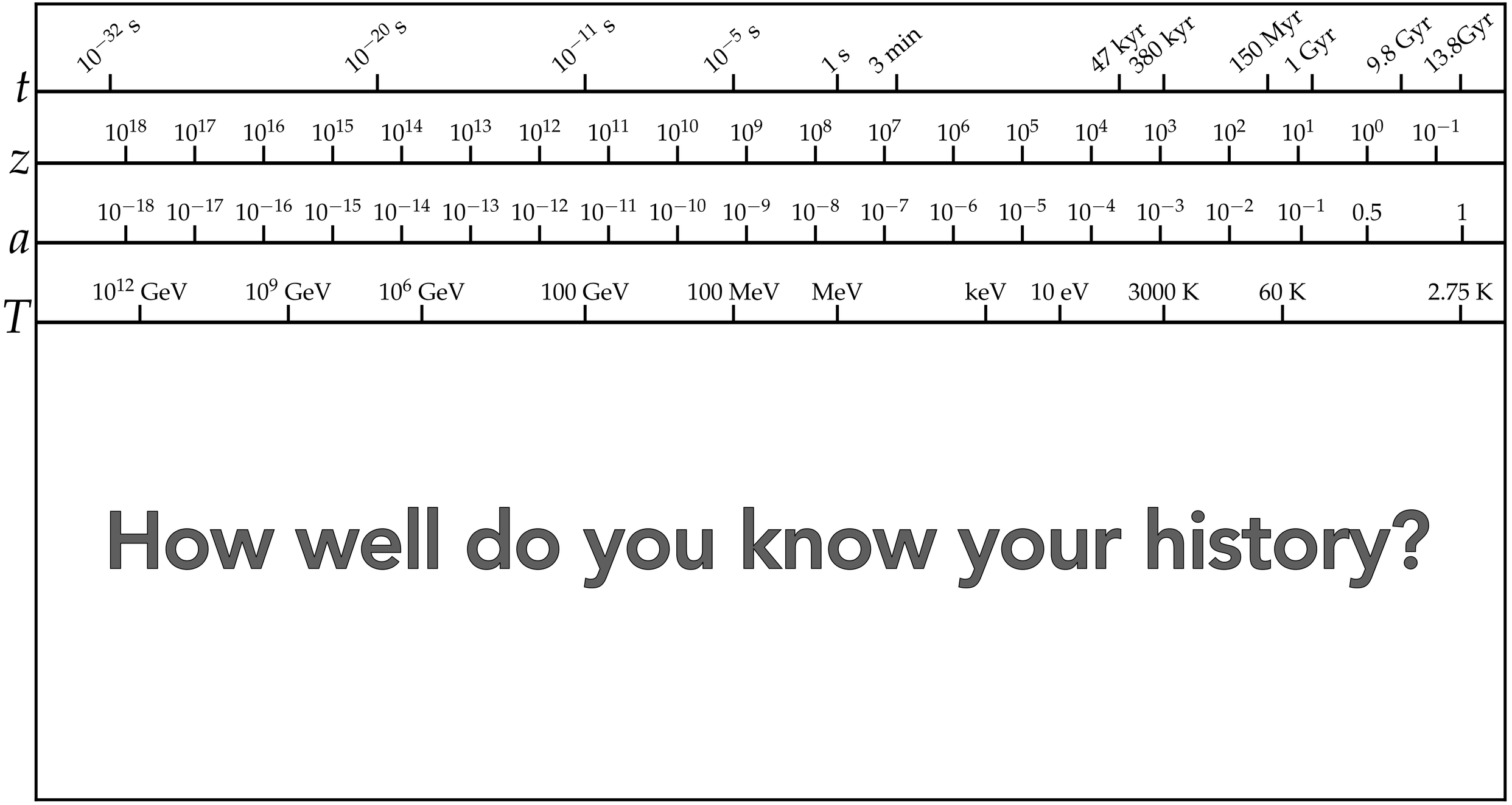
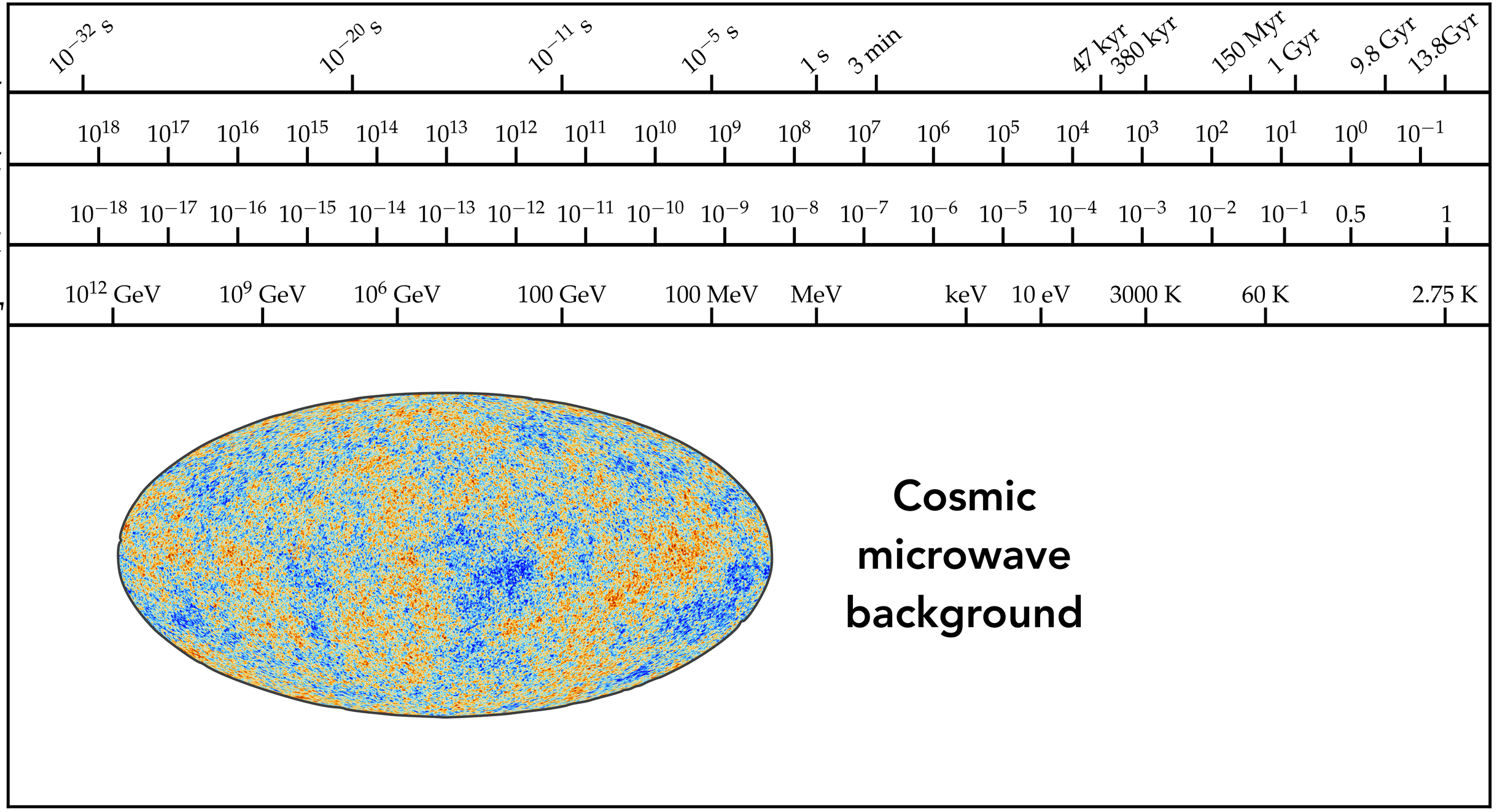
Number density of dark matter at Solar position [cm^{-3}]
→ ?





How well do you know your history?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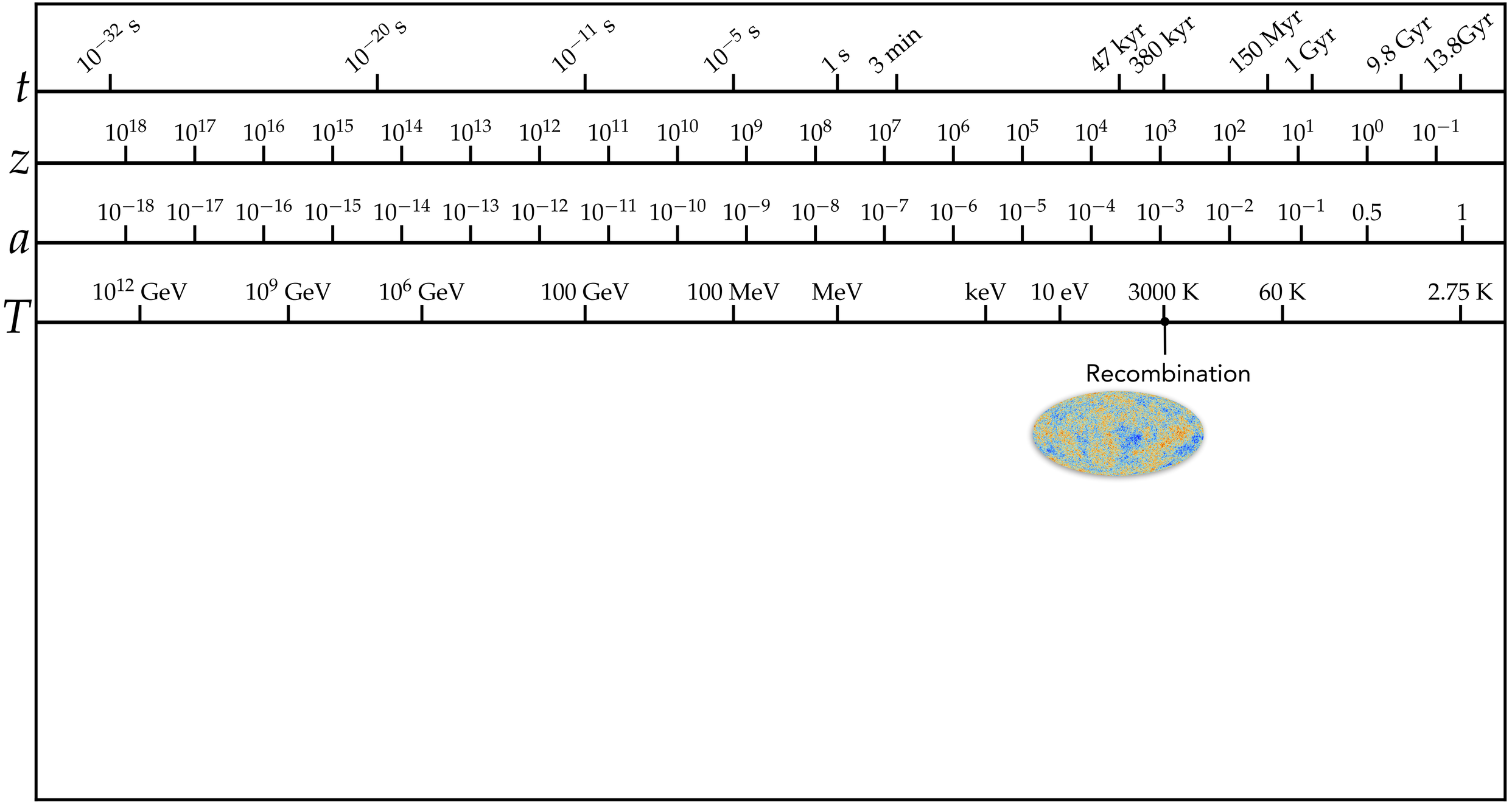
10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
z
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Cosmic microwave background


t
10^{-32} s
10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
z
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
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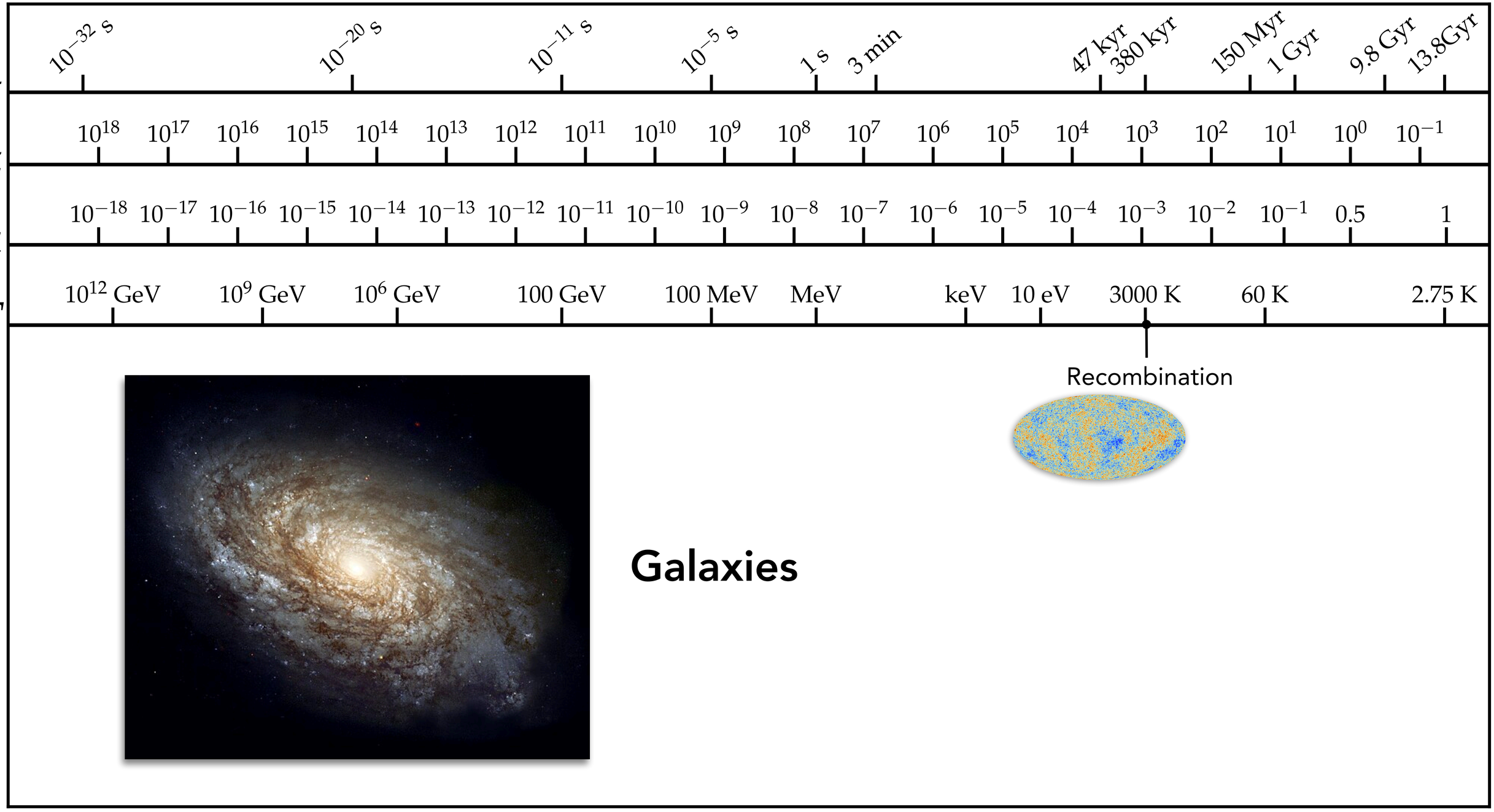
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Recombination


t
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10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
z
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a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
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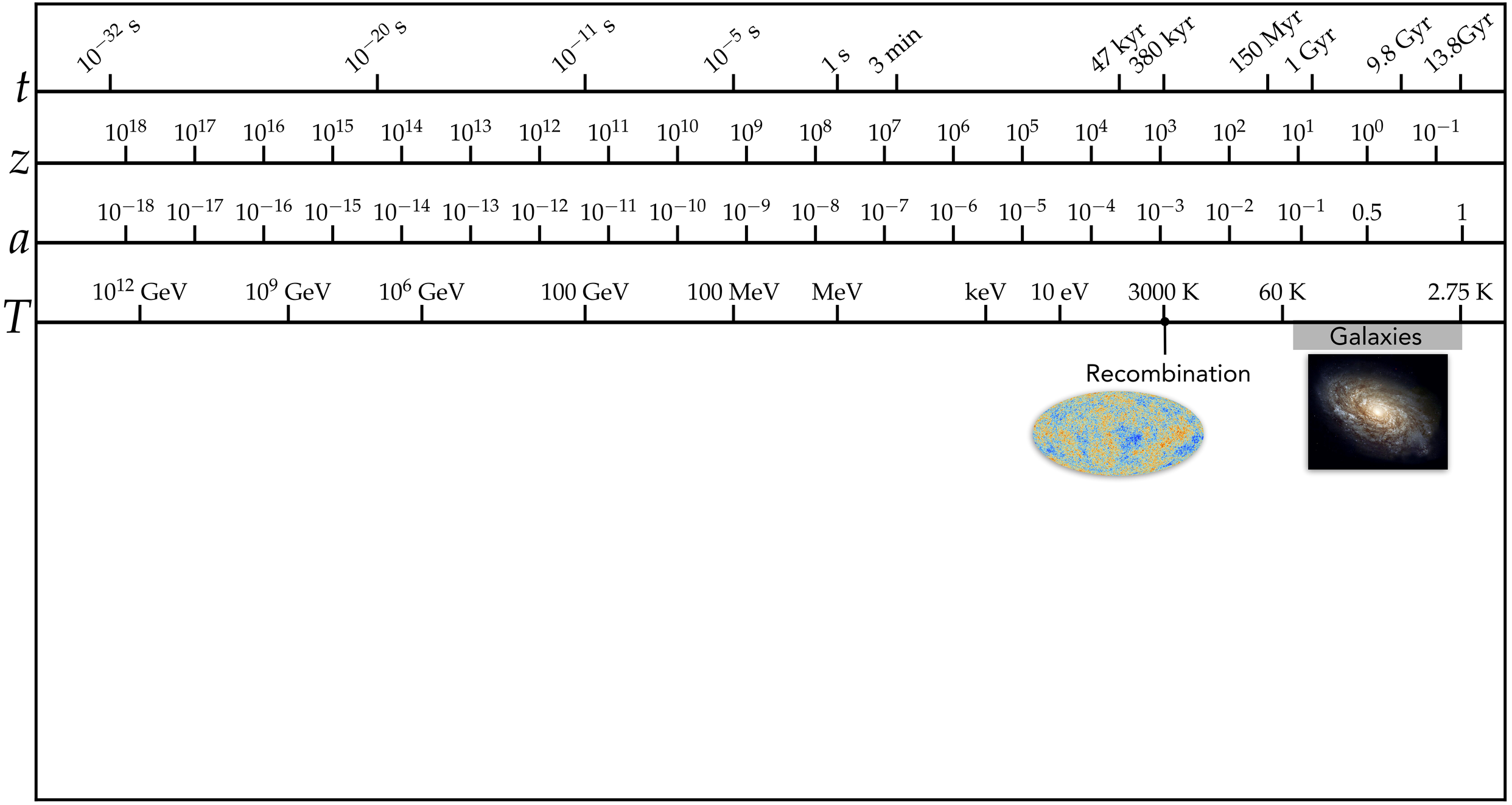
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Recombination
Galaxies


t
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10^{-20} s
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47 kyr
380 kyr
150 Myr
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9.8 Gyr
13.8Gyr
z
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a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
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10^{9} GeV
10^{6} GeV
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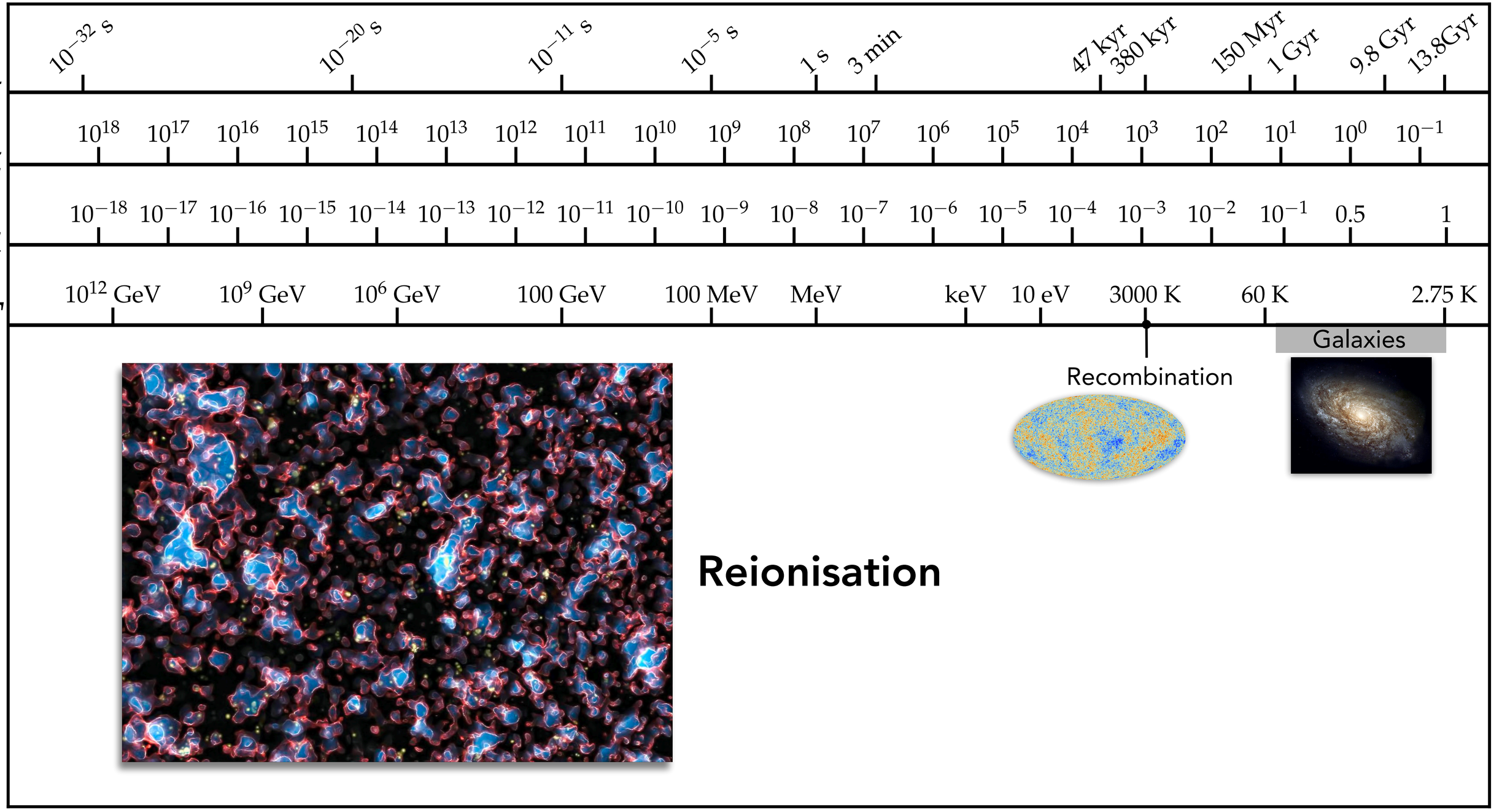
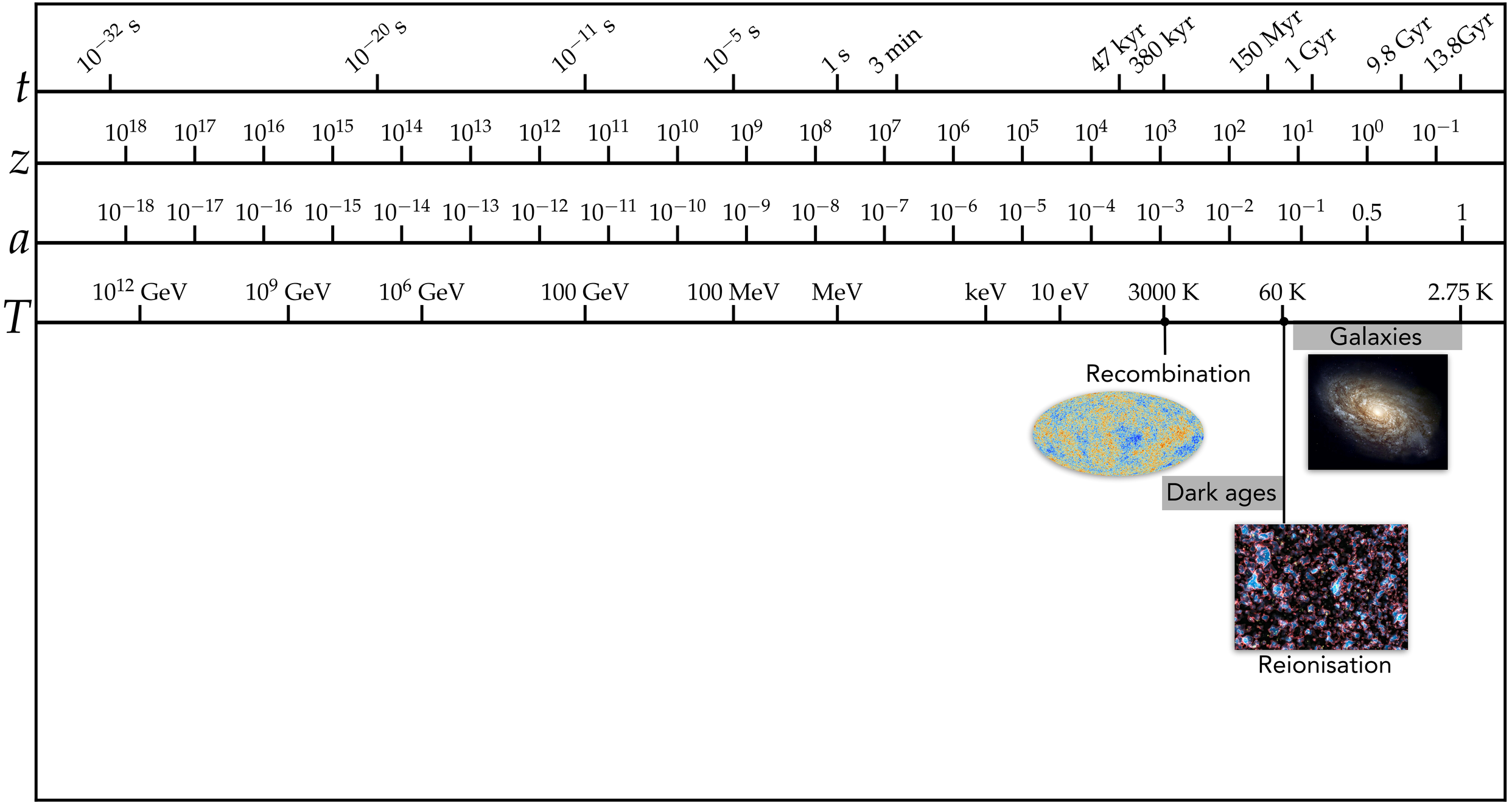
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Recombination
Galaxies



Reionisation


t
10^{-32} s
10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
z
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a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
10^{12} GeV
10^{9} GeV
10^{6} GeV
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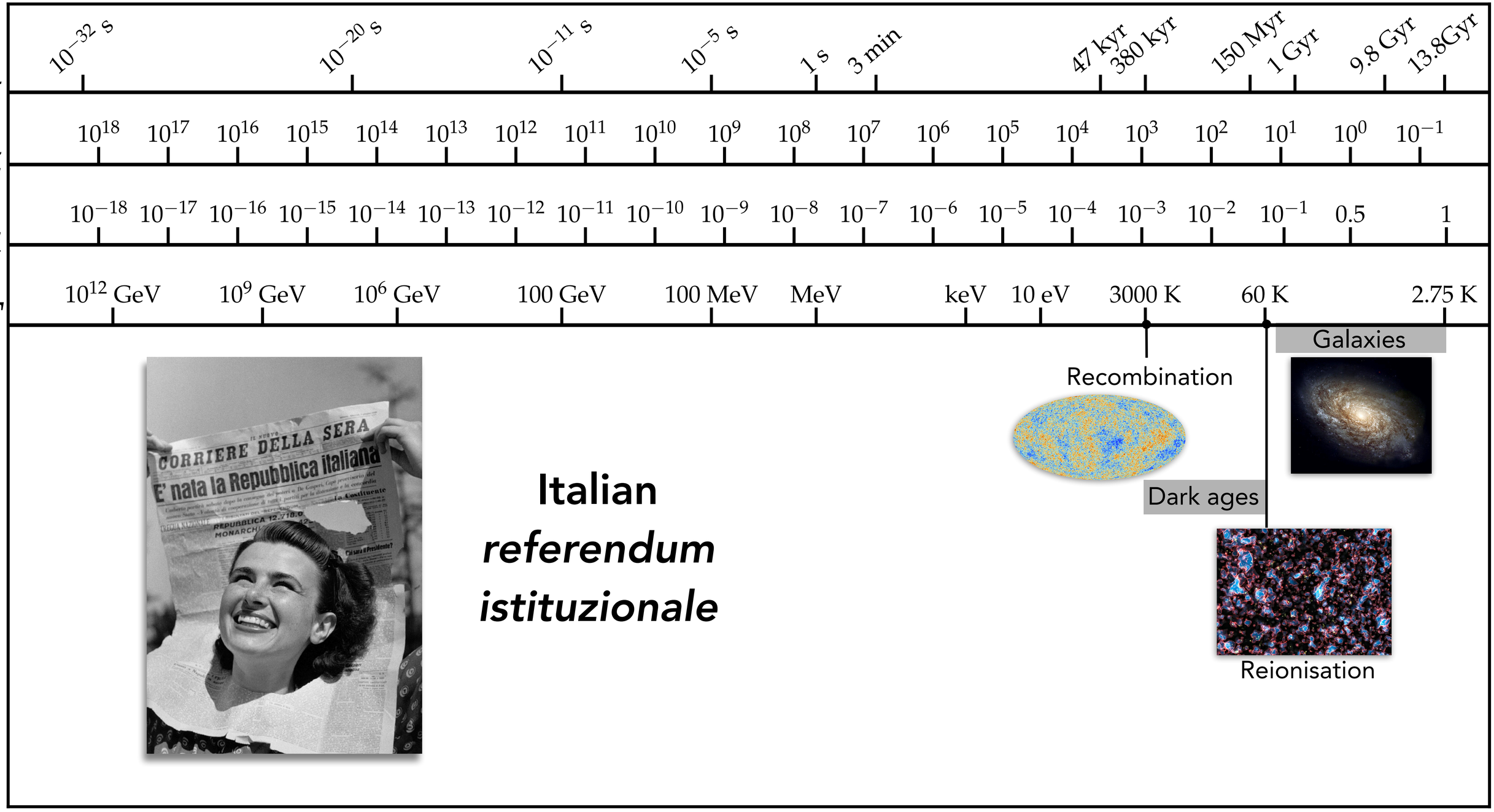
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Recombination
Galaxies
Dark ages
Reionisation


t
z
a
T
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10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
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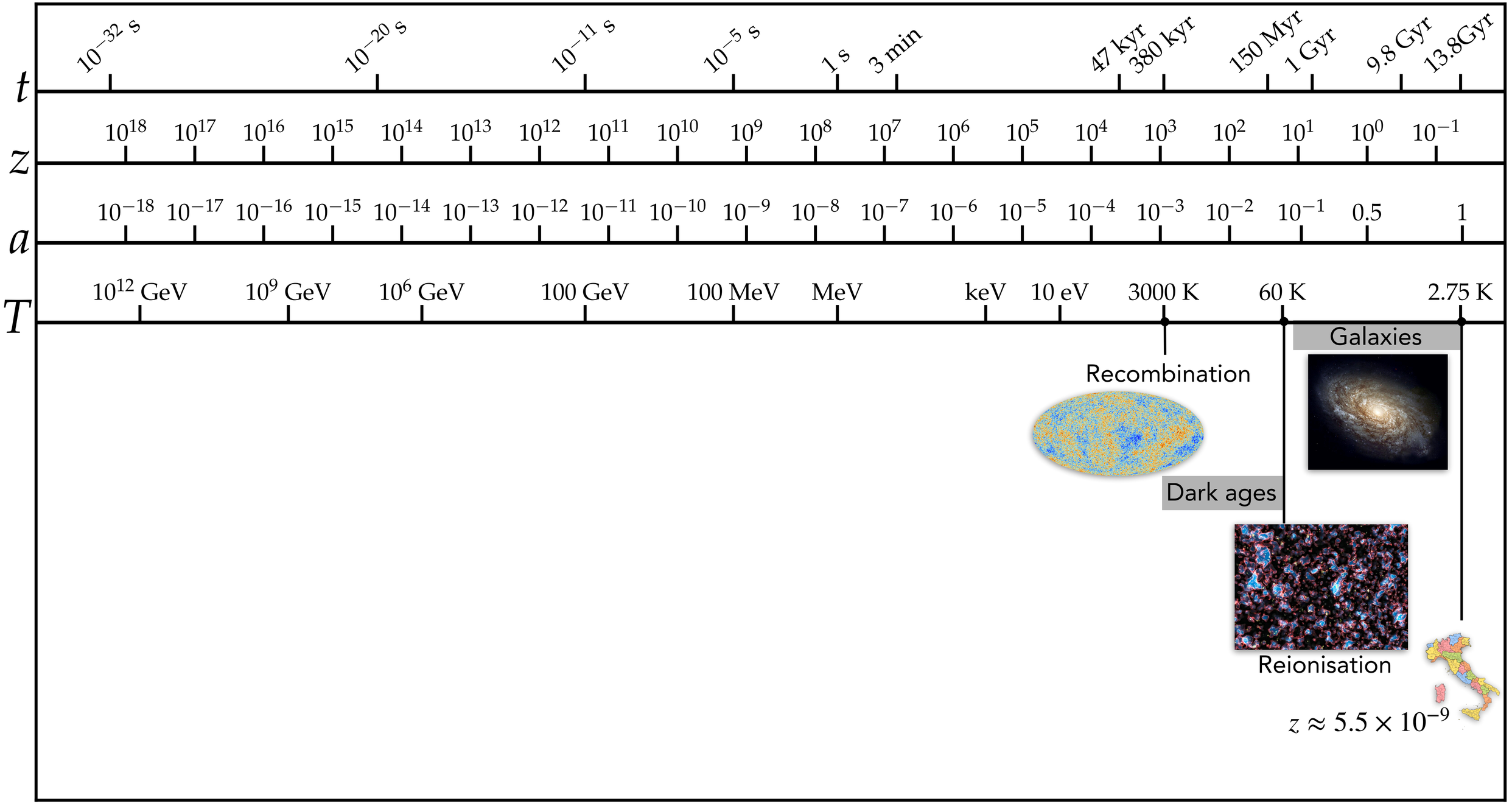
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Recombination
Galaxies
Dark ages
Reionisation
CORRIERE DELLA SERA
E' nata la Repubblica italiana
Italian
referendum
istituzionale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1 s
3 min
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380 kyr
150 Myr
1 Gyr
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13.8Gyr
z
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a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
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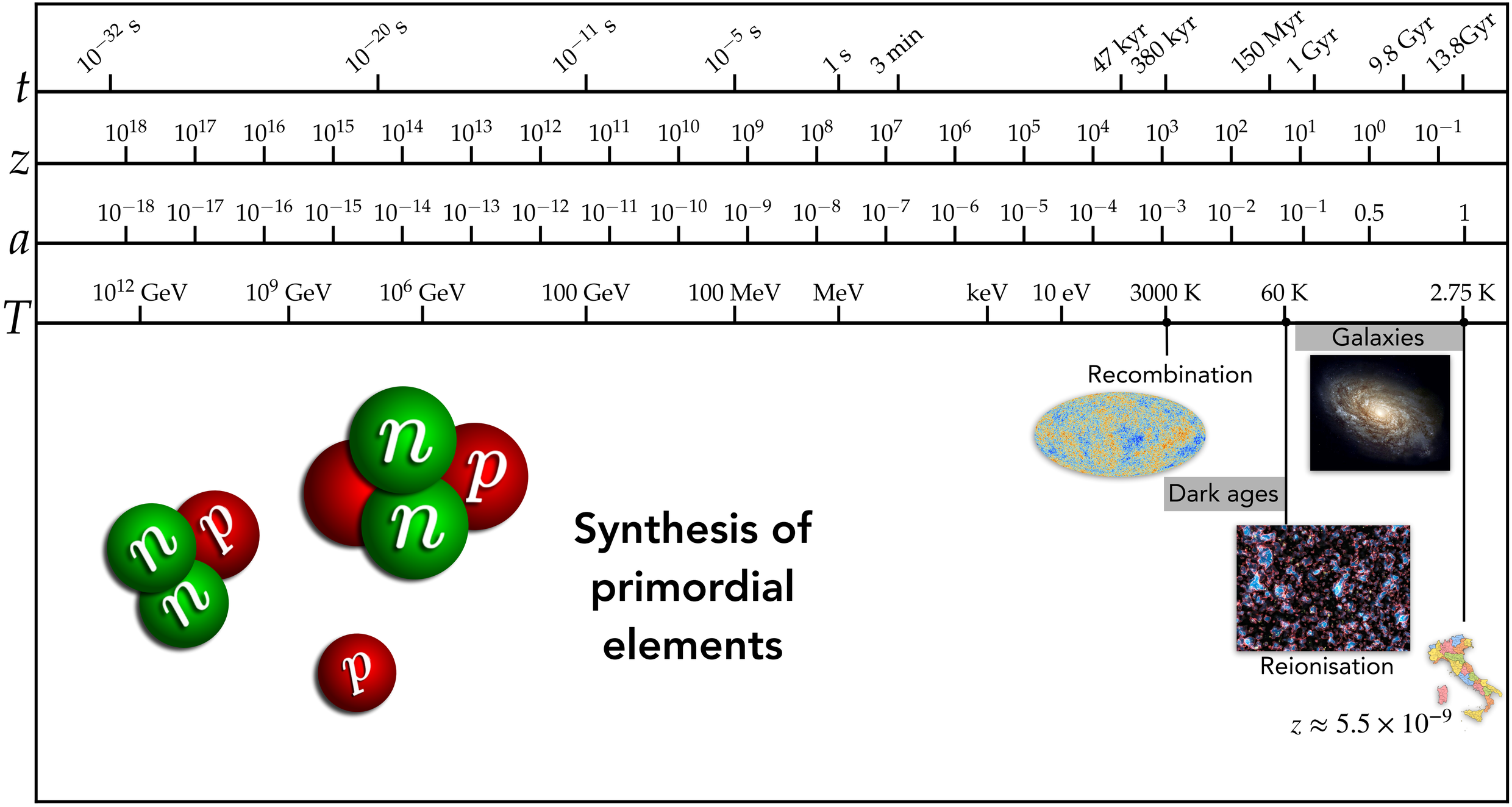
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Recombination
Galaxies
Dark ages
Reionisation
$z \approx 5.5 \times 10^{-9}$


t
z
a
T
10^{-32} s
10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
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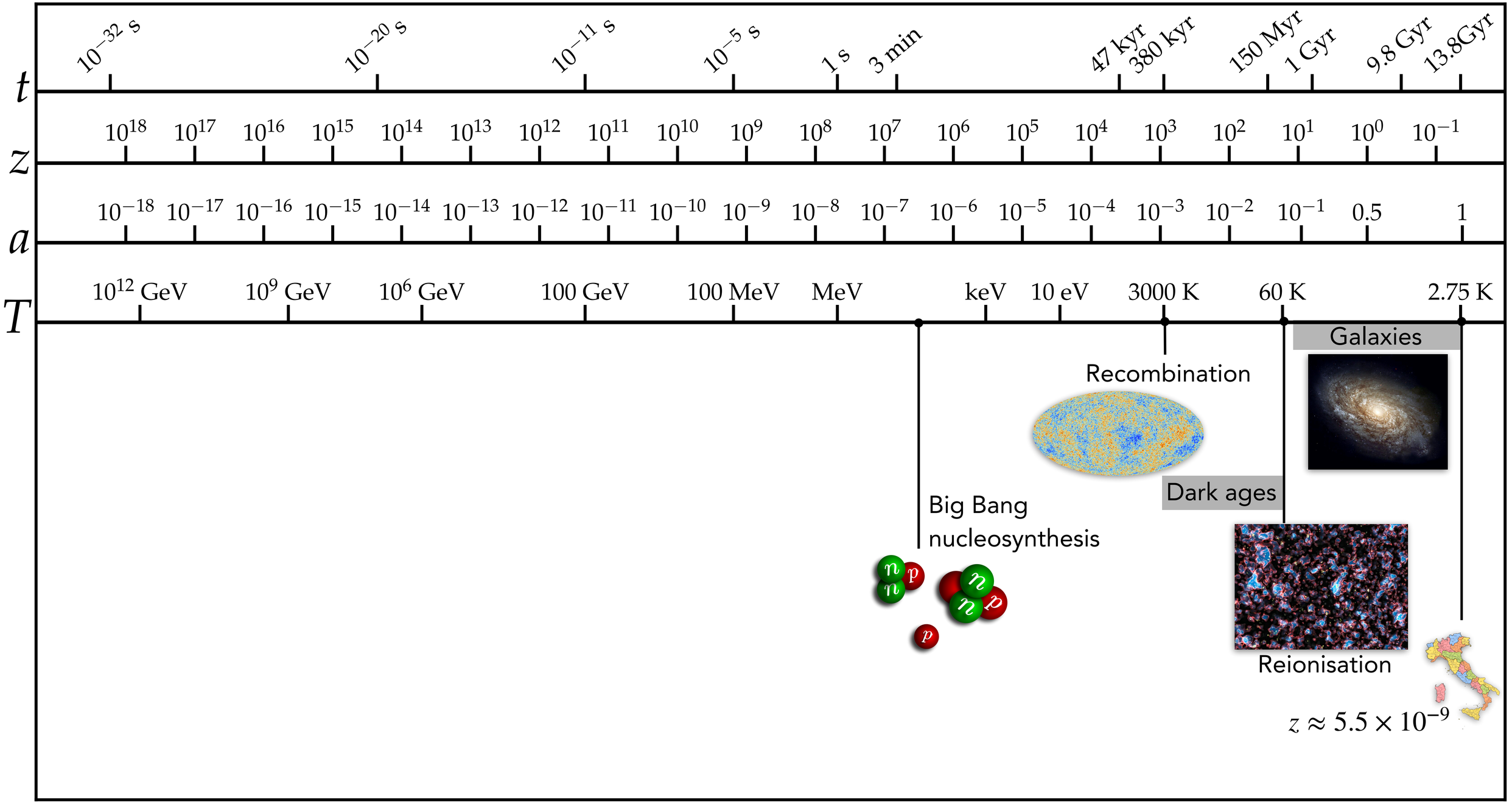
1 Gyr
9.8 Gyr
13.8Gyr
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Recombination
Galaxies
Dark ages
Reionisation
$z \approx 5.5 \times 10^{-9}$
Synthesis of primordial elements


t
10^{-32} s
10^{-20} s
10^{-11} s
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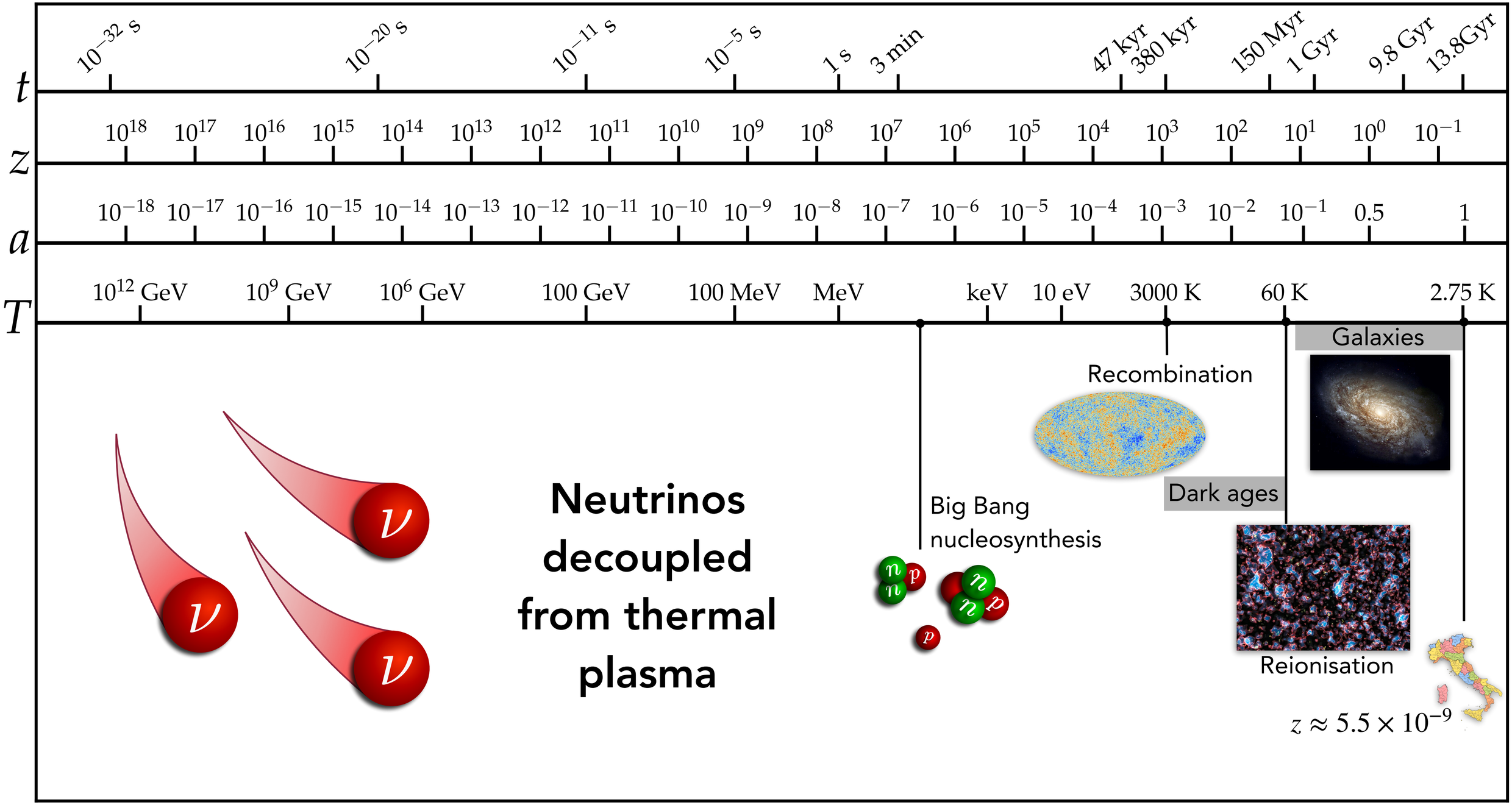
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
z
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Galaxies
Recombination
Dark ages
Big Bang
nucleosynthesis
n
p
Reionisation
$z \approx 5.5 \times 10^{-9}$


t
10^{-32} s
10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
z
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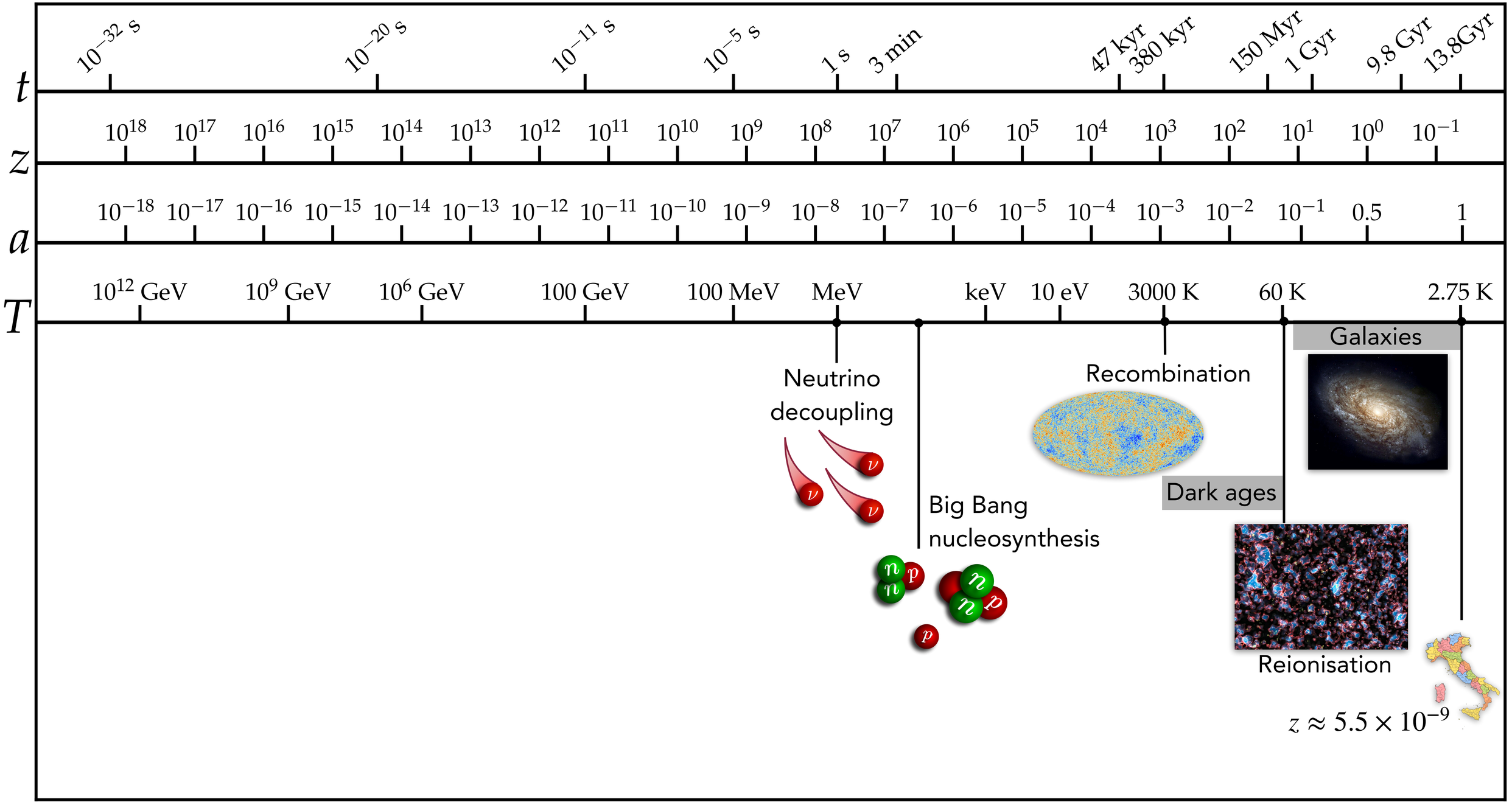
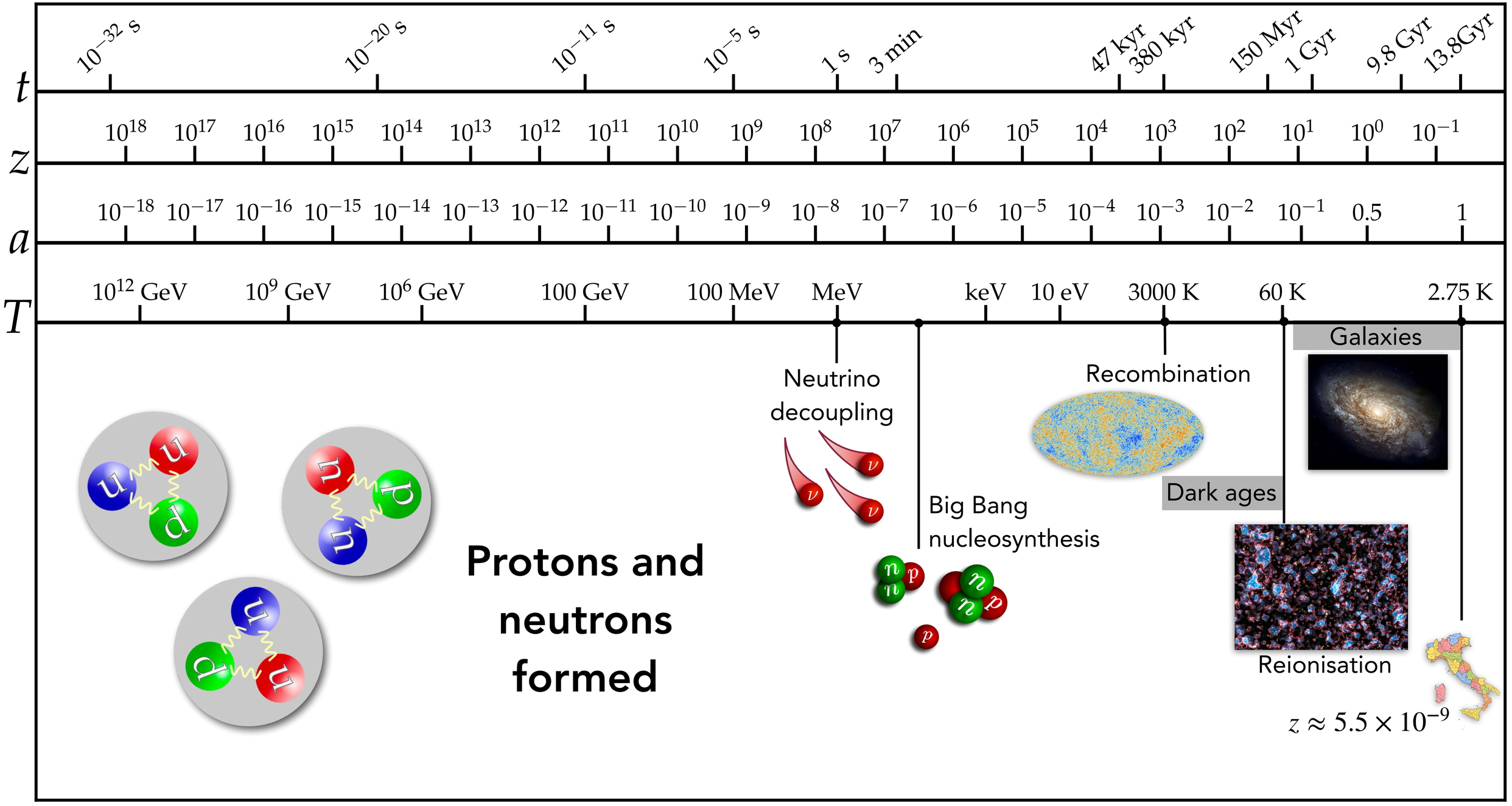
a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Galaxies
Recombination
Dark ages
Big Bang nucleosynthesis
Reionisation
$z \approx 5.5 \times 10^{-9}$
Neutrinos decoupled from thermal plasma


t
10^{-32} s
10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
z
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Neutrino decoupling
Big Bang nucleosynthesis
Recombination
Dark ages
Reionisation
Galaxies
$z \approx 5.5 \times 10^{-9}$


t
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10^{-32} s
10^{-20} s
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47 kyr
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150 Myr
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10^{12} GeV
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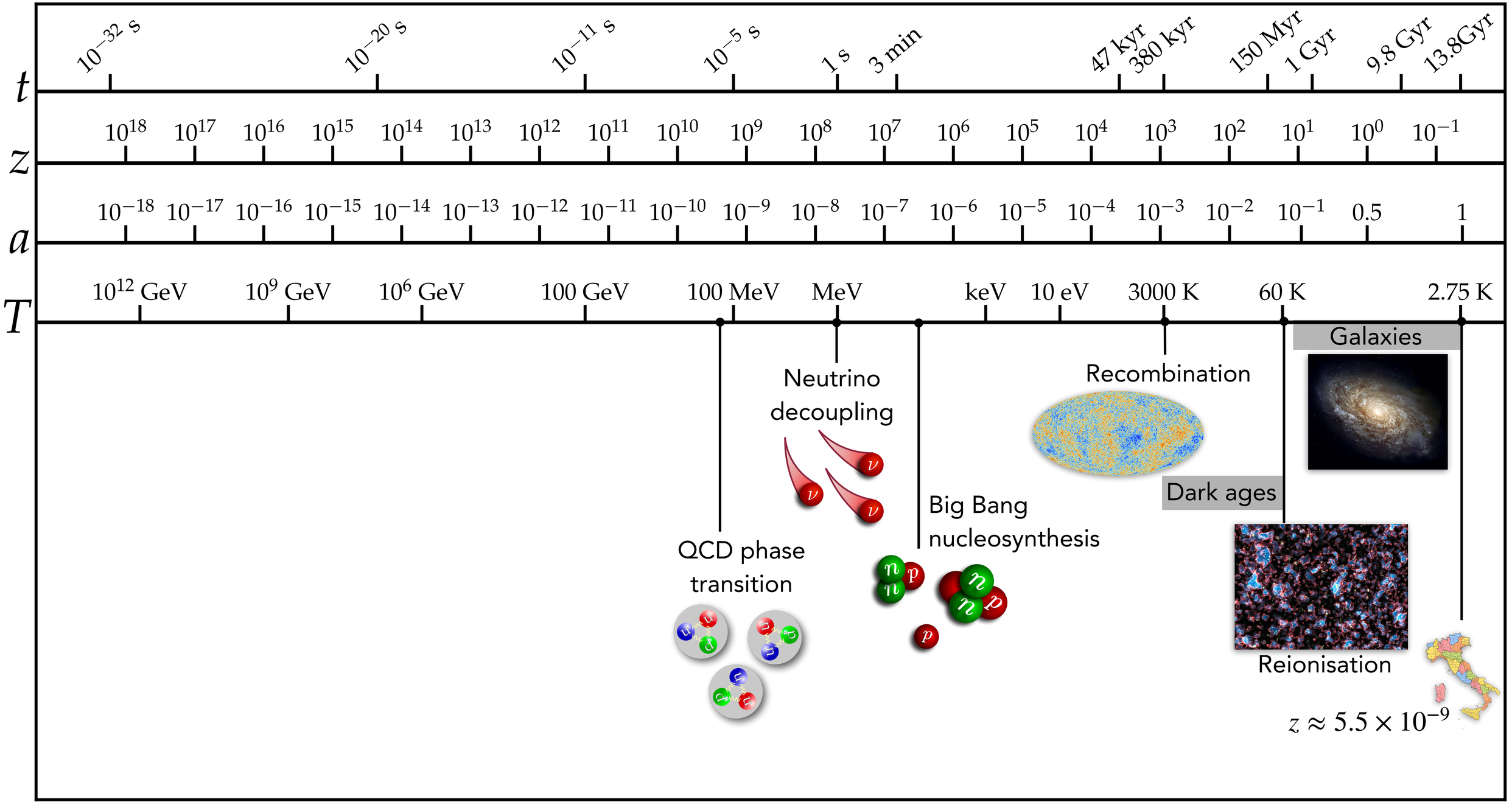
10 eV
3000 K
60 K
2.75 K
Neutrino decoupling
Big Bang nucleosynthesis
Recombination
Galaxies
Dark ages
Reionisation
$z \approx 5.5 \times 10^{-9}$
Protons and neutrons formed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a
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10^{-20} s
10^{-11} s
10^{-5} s
1 s
3 min
47 kyr
380 kyr
150 Myr
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10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
10^{12} GeV
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10^{6} GeV
100 GeV
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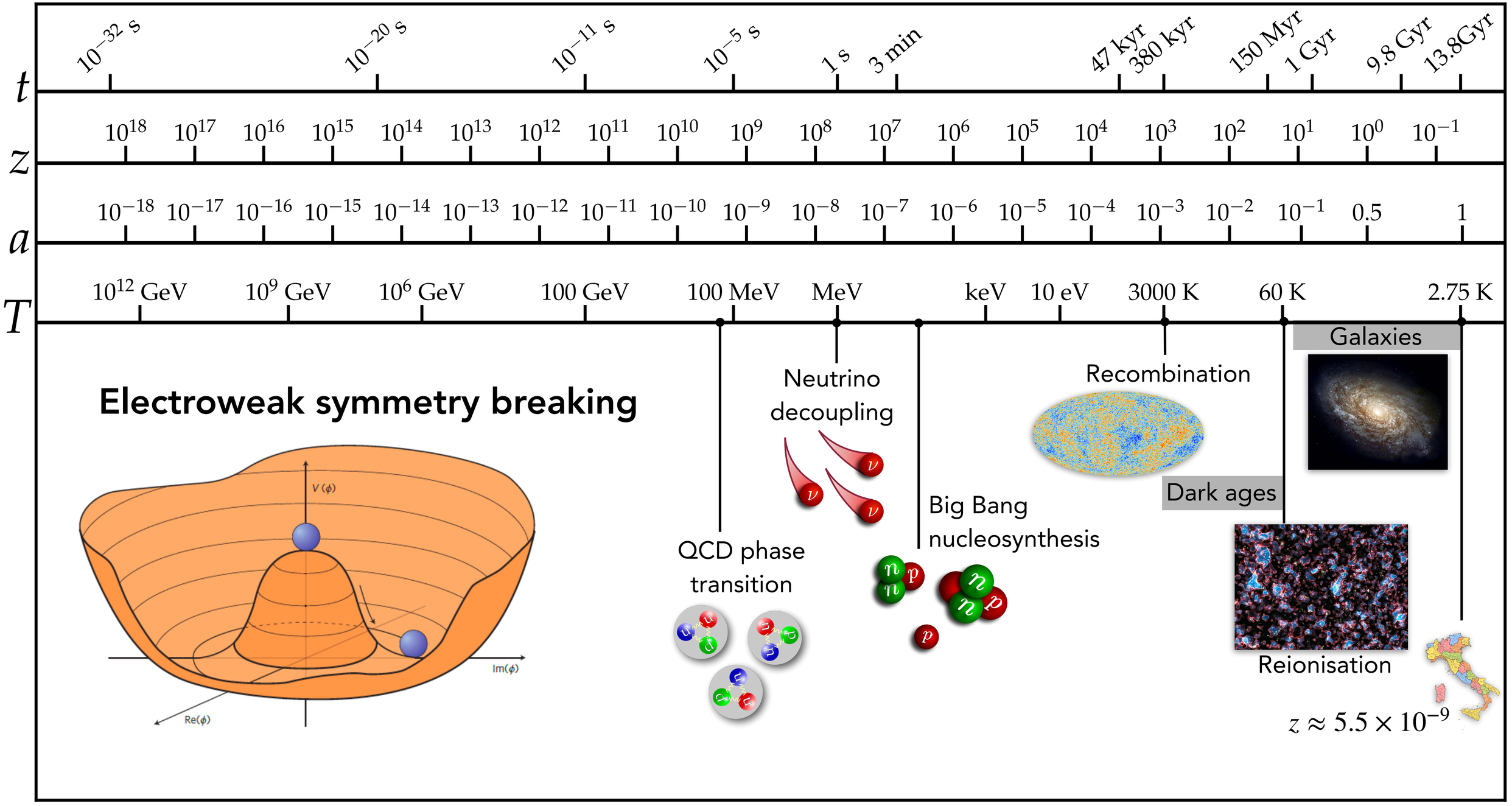
keV
10 eV
3000 K
60 K
2.75 K
Galaxies
Recombination
Neutrino decoupling
Dark ages
Big Bang nucleosynthesis
QCD phase transition
Reionisation
$z \approx 5.5 \times 10^{-9}$


t
10^{-32} s
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47 kyr
380 kyr
150 Myr
1 Gyr
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z
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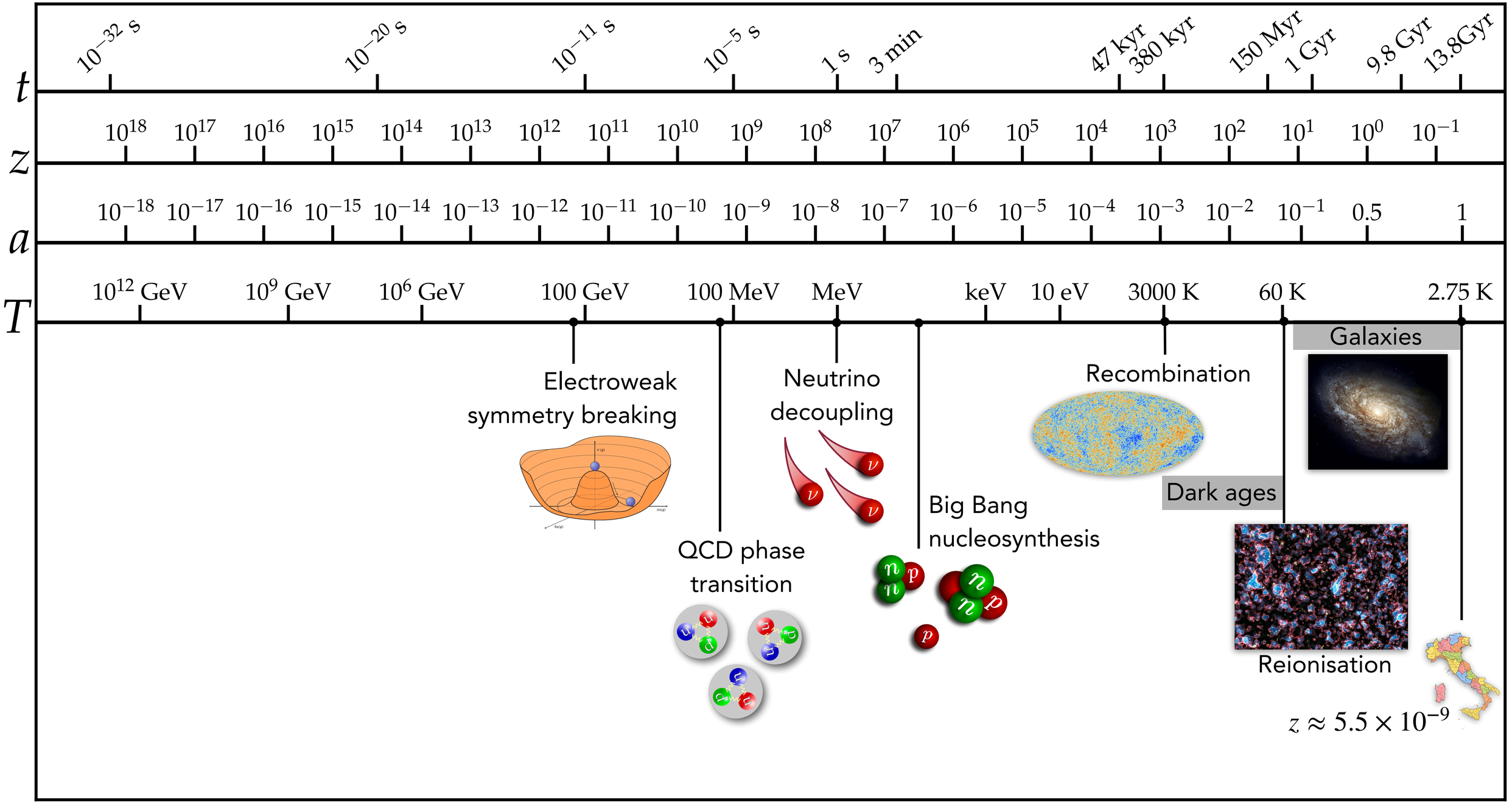
a
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
T
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Electroweak symmetry breaking
V(ϕ)
Im(ϕ)
Re(ϕ)
QCD phase transition
Neutrino decoupling
Big Bang nucleosynthesis
Recombination
Dark ages
Galaxies
Reionisation
$z \approx 5.5 \times 10^{-9}$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z
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T
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10^{-11} s
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47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
10^{12} GeV
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100 GeV
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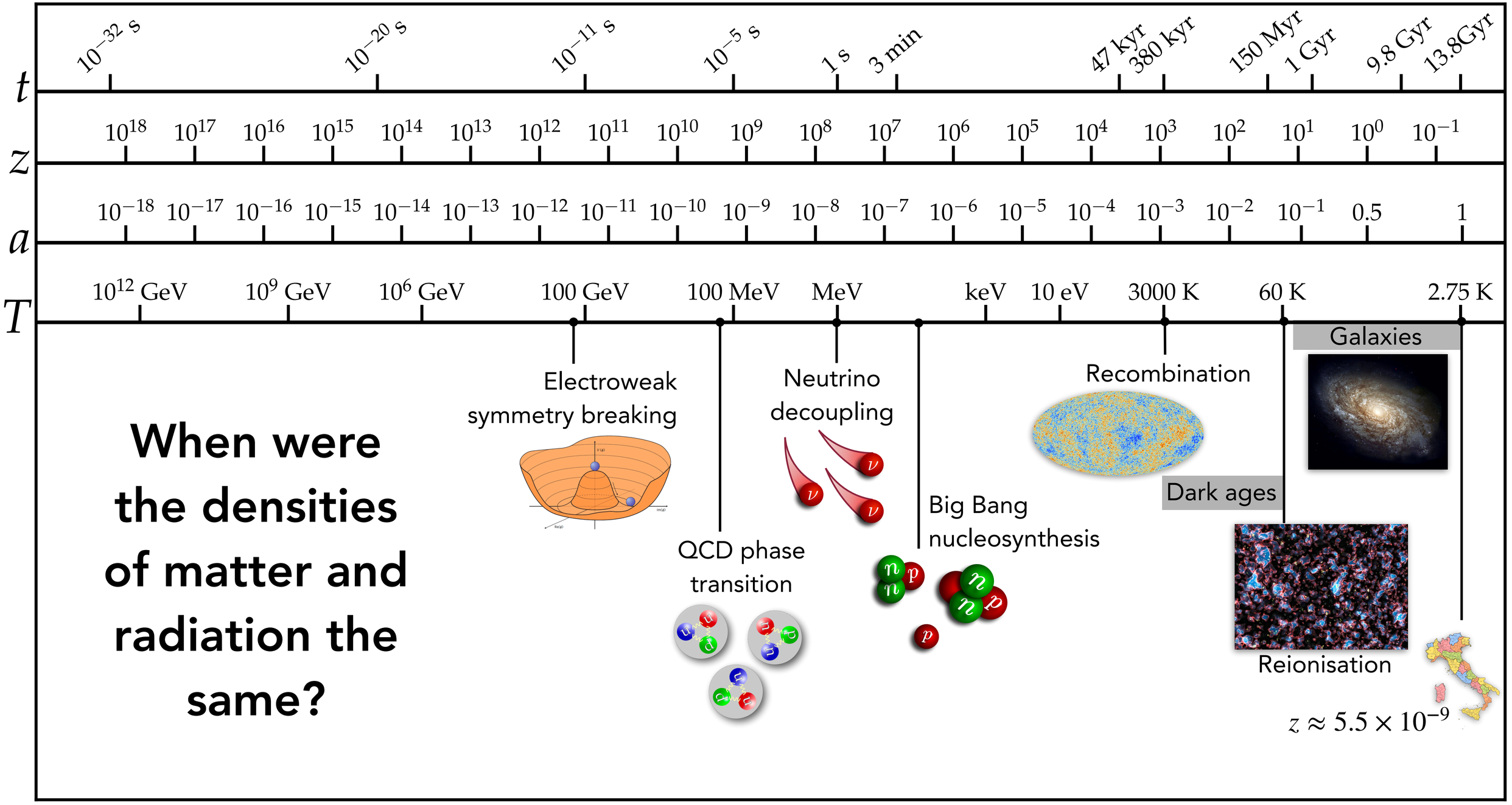
keV
10 eV
3000 K
60 K
2.75 K
Electroweak symmetry breaking
QCD phase transition
Neutrino decoupling
Big Bang nucleosynthesis
Recombination
Dark ages
Reionisation
Galaxies
$z \approx 5.5 \times 10^{-9}$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10^{-20} s
10^{-11} s
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3 min
47 kyr
380 kyr
150 Myr
1 Gyr
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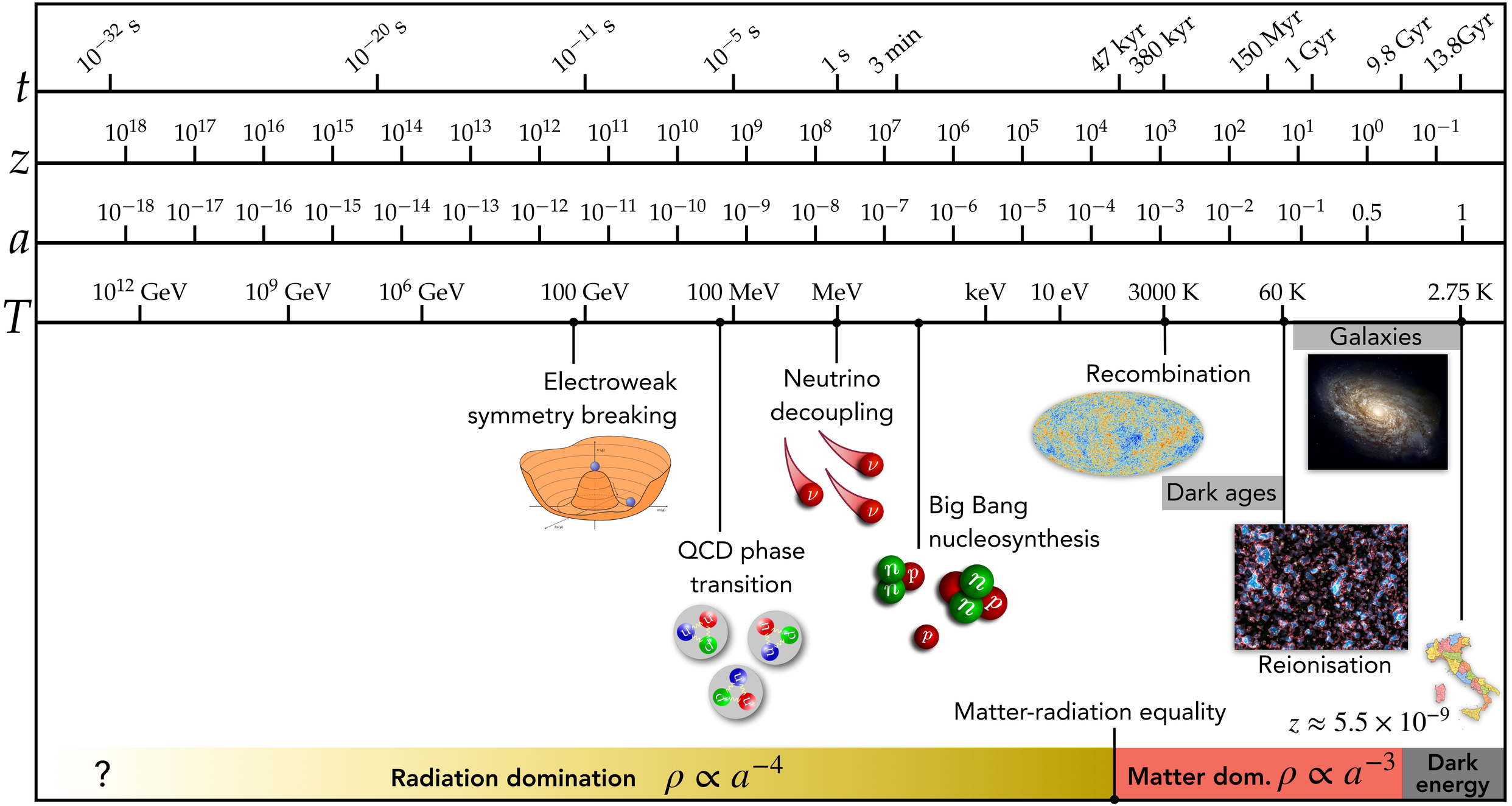
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
When were the densities of matter and radiation the same?
Electroweak symmetry breaking
QCD phase transition
Neutrino decoupling
Big Bang nucleosynthesis
Recombination
Dark ages
Reionisation
Galaxies
$z \approx 5.5 \times 10^{-9}$


t
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10^{-11} s
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3 min
47 kyr
380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}
10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0.5 1
10^{12} GeV
10^{9} GeV
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
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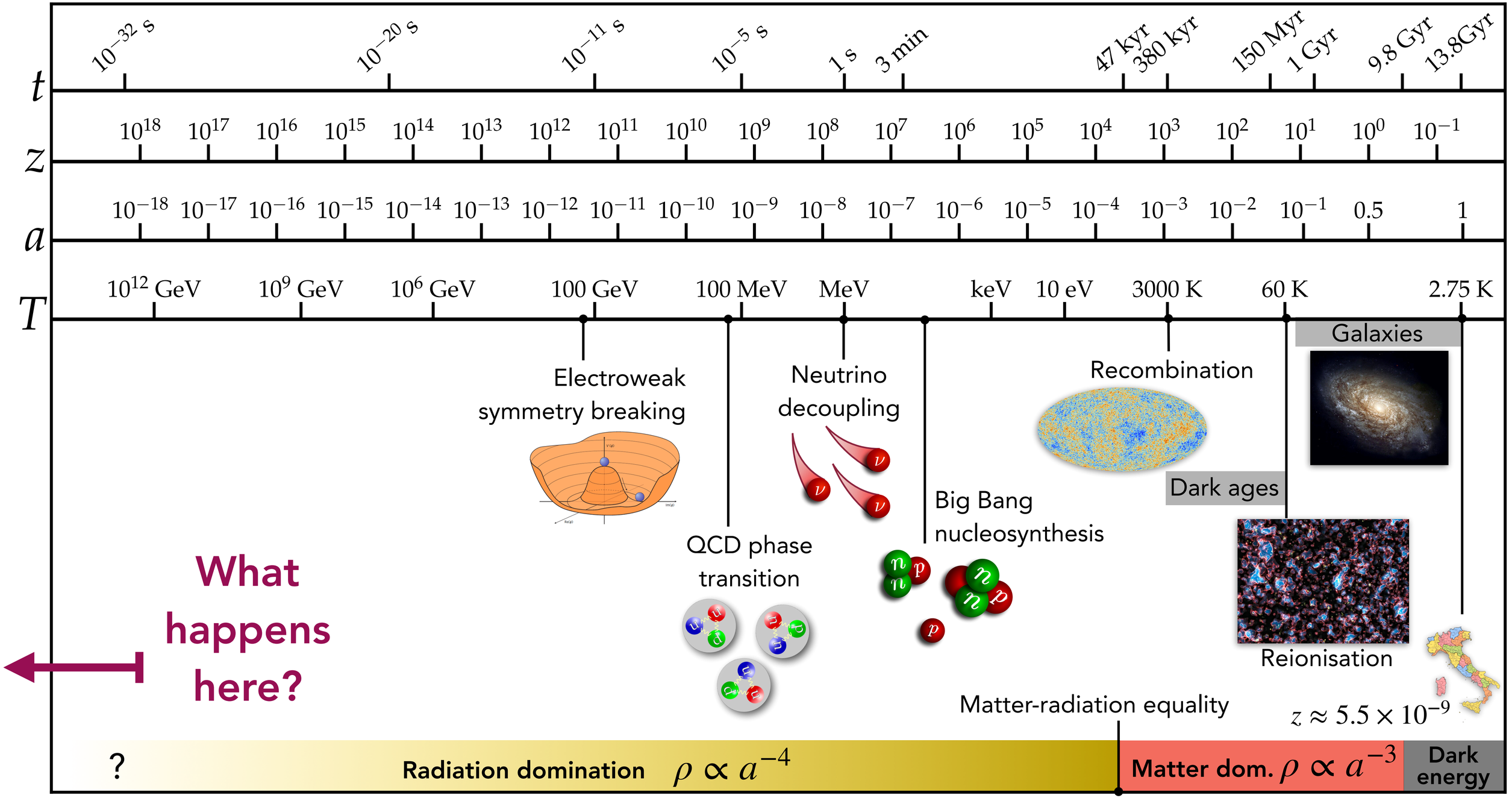
Electroweak symmetry breaking
Neutrino decoupling
QCD phase transition
Big Bang nucleosynthesis
Recombination
Galaxies
Dark ages
Reionisation
$z \approx 5.5 \times 10^{-9}$
Matter-radiation equality
?
Radiation domination $\rho \propto a^{-4}$
Matter dom. $\rho \propto a^{-3}$
Dark energy


t
z
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10^{-11} s
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3 min
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380 kyr
150 Myr
1 Gyr
9.8 Gyr
13.8Gyr
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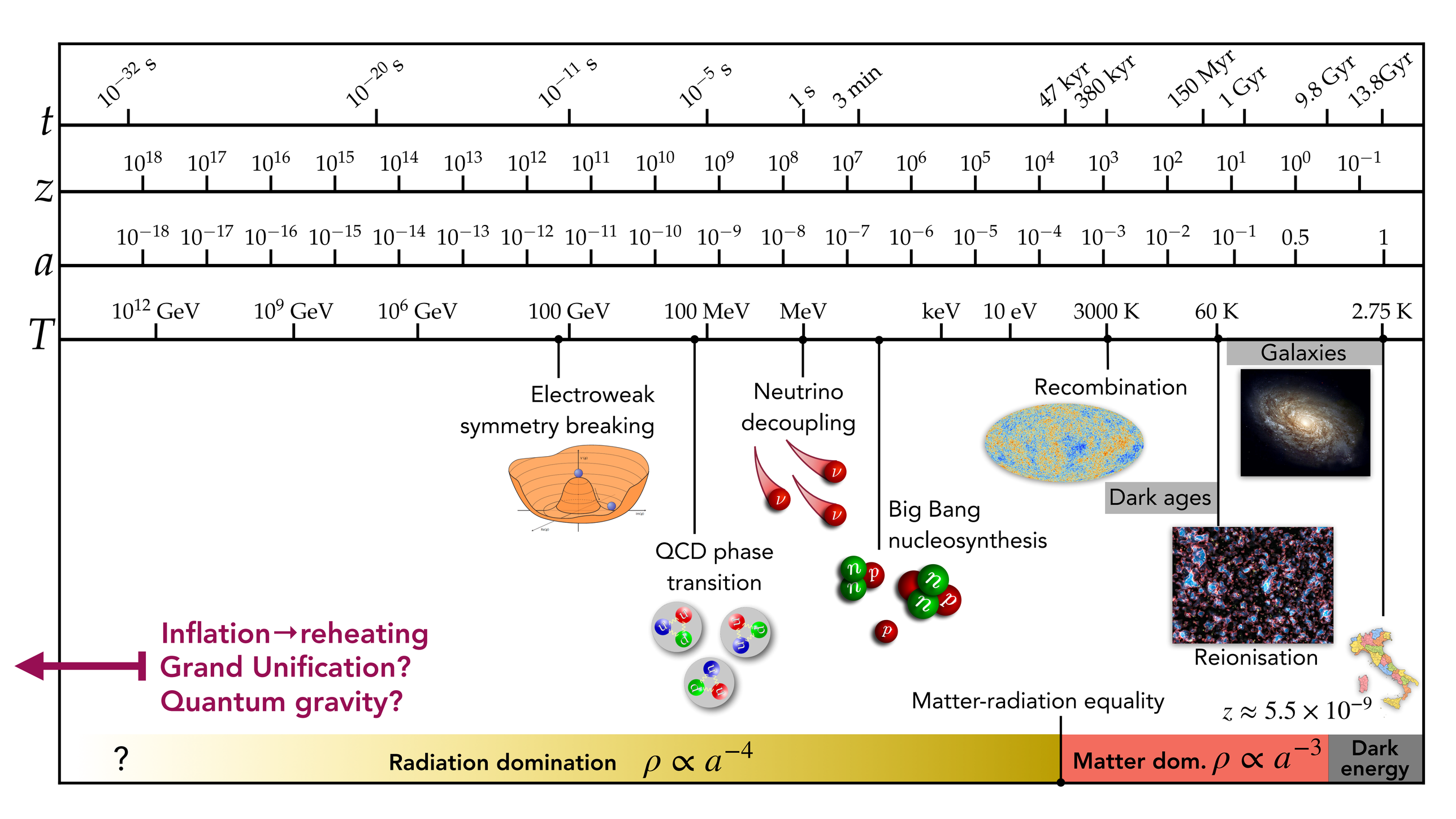
10^{6} GeV
100 GeV
100 MeV
MeV
keV
10 eV
3000 K
60 K
2.75 K
Electroweak symmetry breaking
Neutrino decoupling
QCD phase transition
Big Bang nucleosynthesis
Recombination
Galaxies
Dark ages
Reionisation
What happens here?
Matter-radiation equality
$z \approx 5.5 \times 10^{-9}$
?
Radiation domination $\rho \propto a^{-4}$
Matter dom. $\rho \propto a^{-3}$
Dark energy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Grand Unification?
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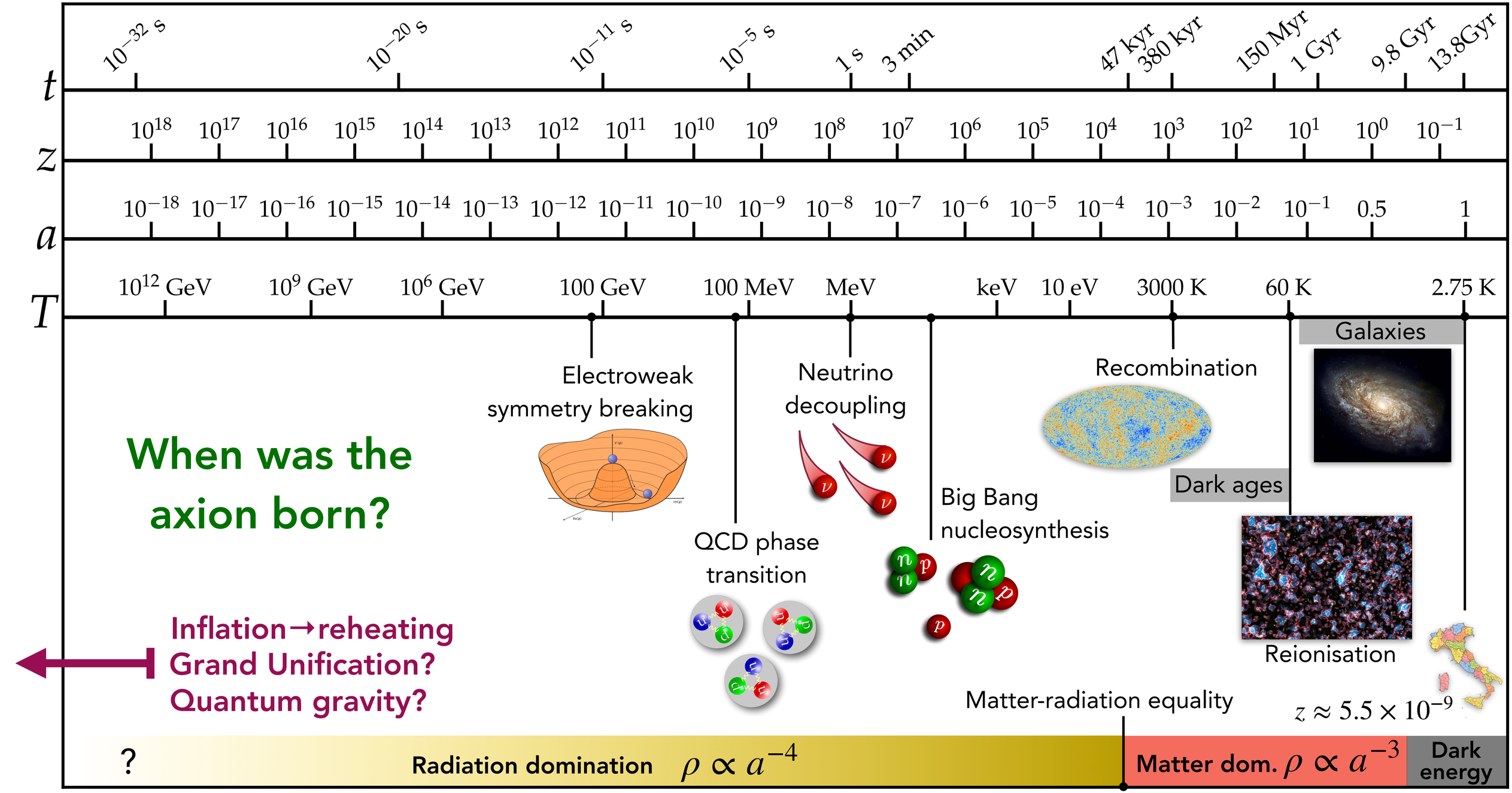
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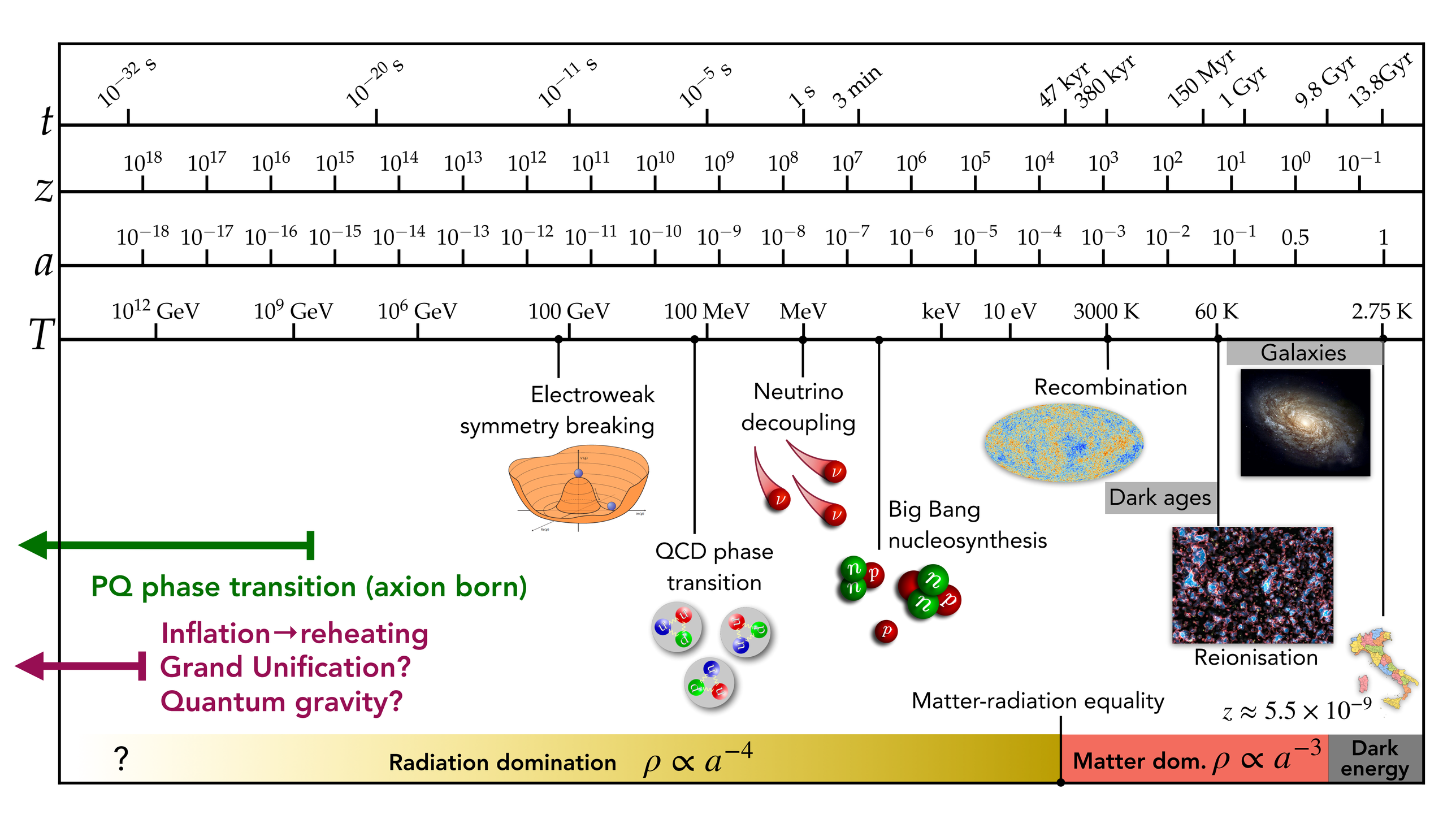
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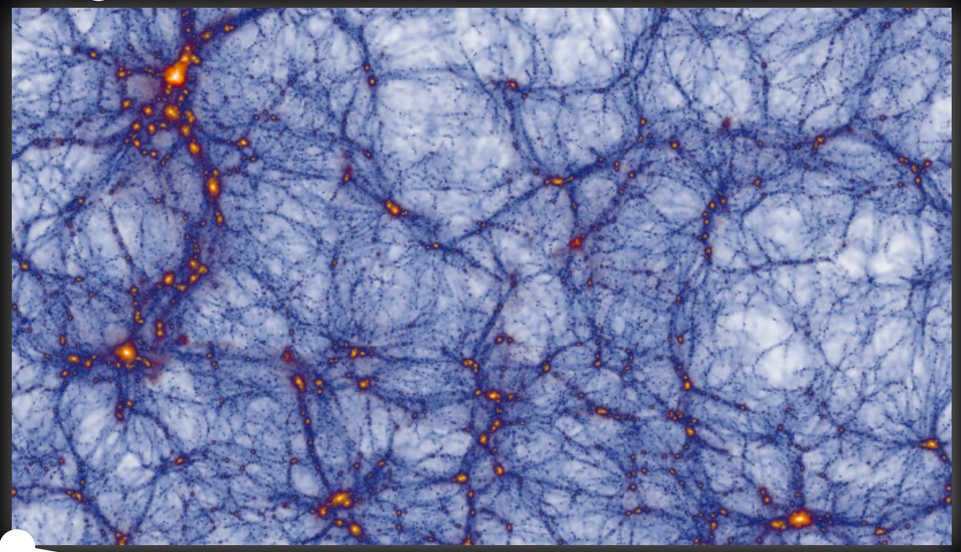
Evidence for dark matter across scales

Large-scale structure

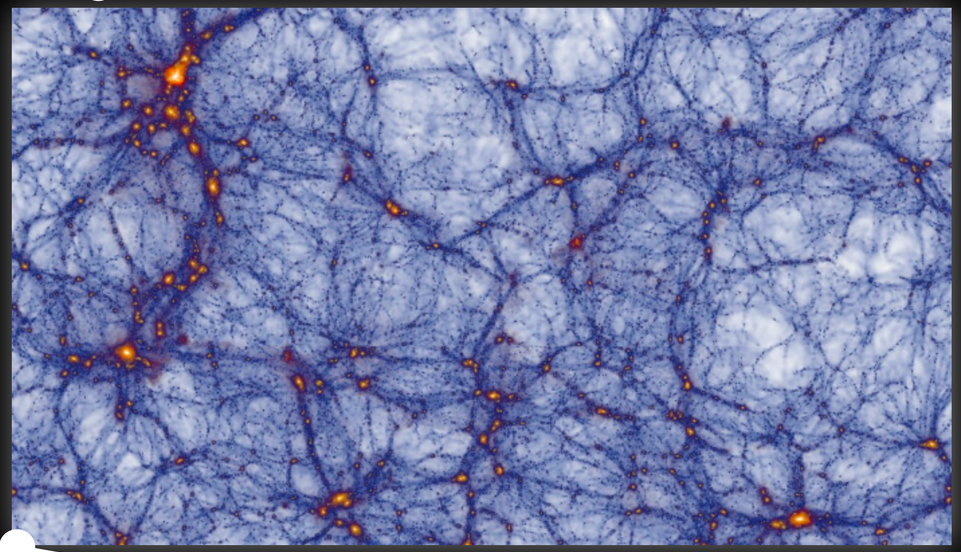


L > Gpc

M > $10^{22}\,M_{\odot}$

Evidence for dark matter across scales

Large-scale structure



L > Gpc

M > $10^{22}\,M_{\odot}$

Large-scale structure: consistent with hierarchical mergers of halos seeded by collisionless matter

Evidence for dark matter across scales

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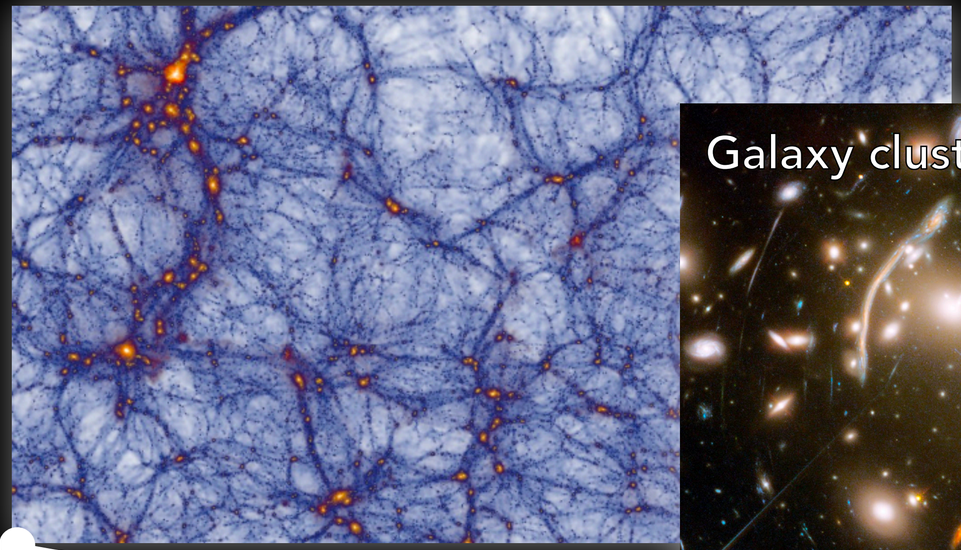
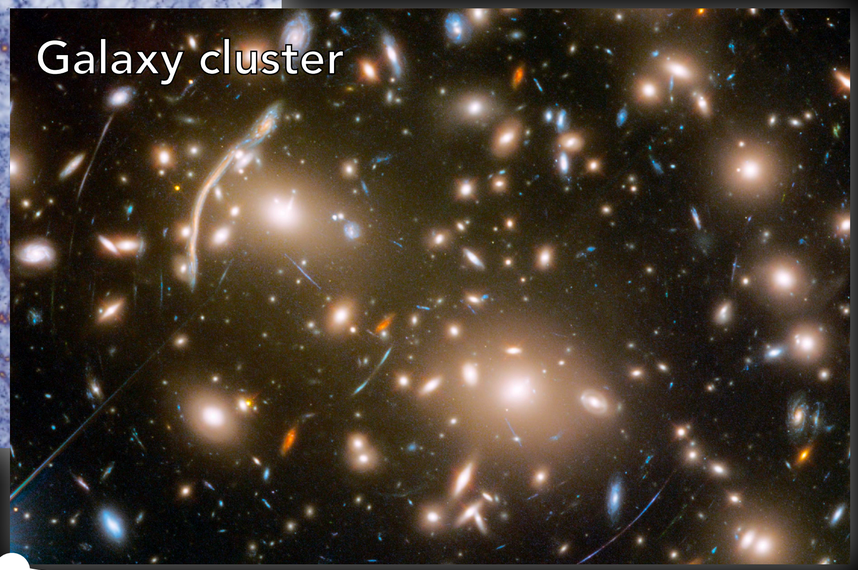




L > Gpc

M > $10^{22}\,M_{\odot}$

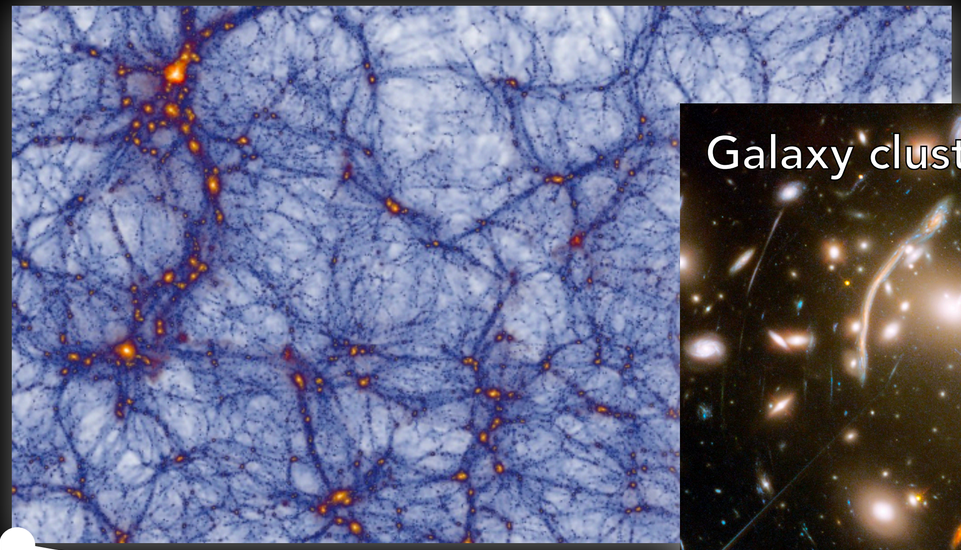
L ~ Mpc

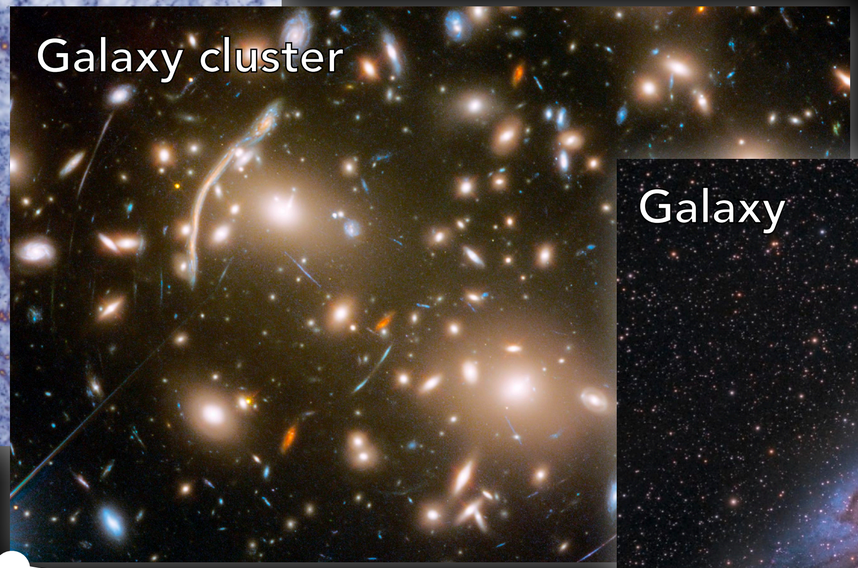
M ~ $10^{14}\,M_{\odot}$

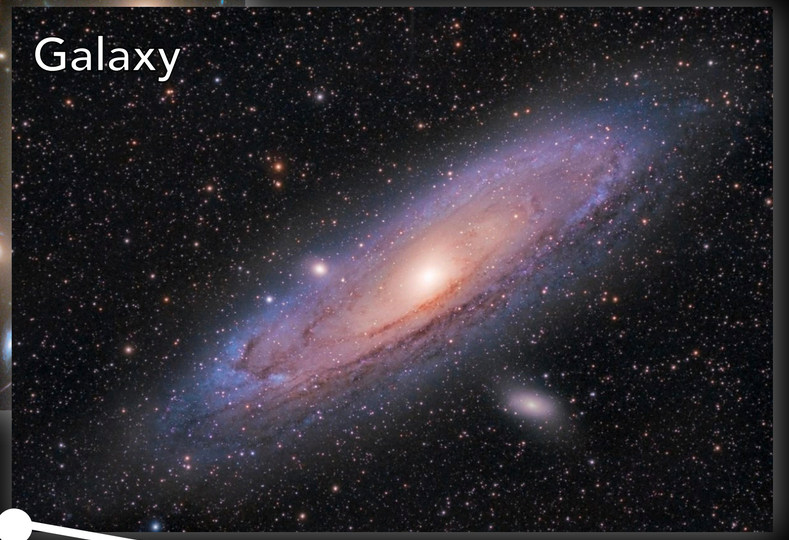
Galaxy clusters: strong gravitational lensing reveals mass much larger than one inferred from luminosity

Evidence for dark matter across scales

Large-scale structure







L > Gpc

M > $10^{22}\,M_\odot$

L ~ Mpc

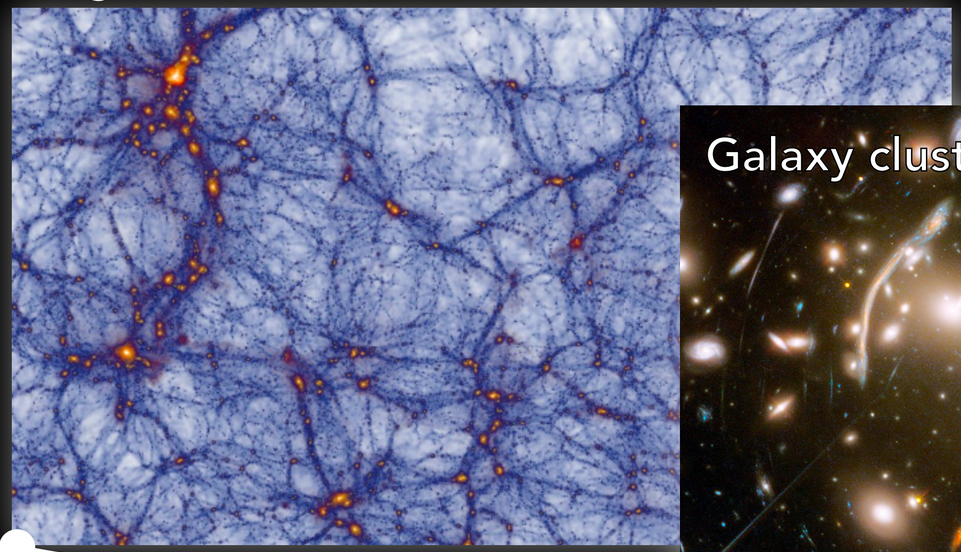
M ~ $10^{14}\,M_\odot$

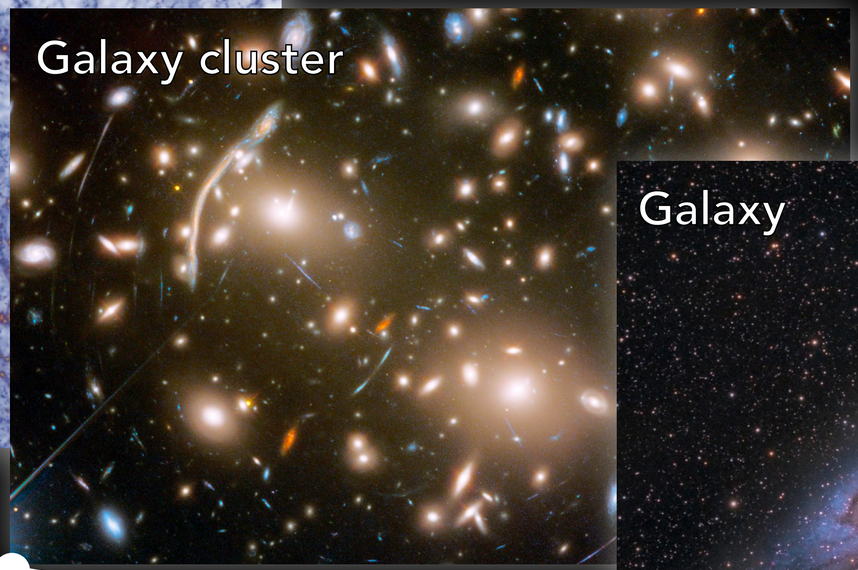
L ~ 100 kpc

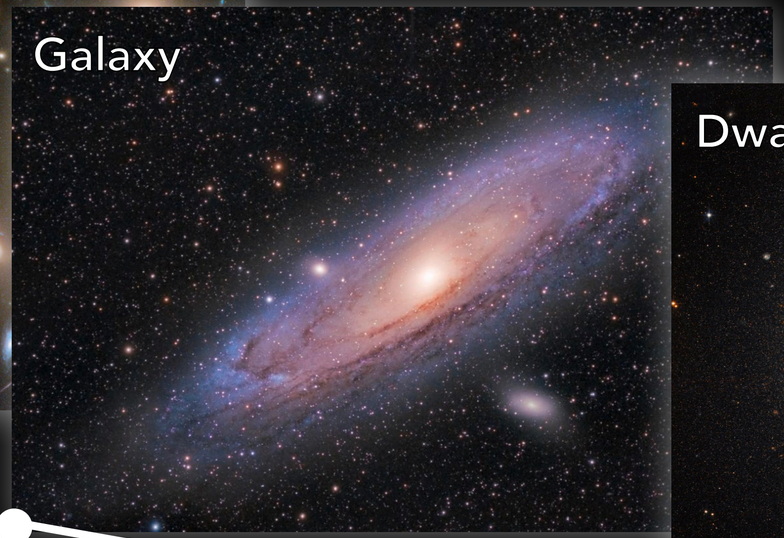
M ~ $10^{12}\,M_\odot$

Galaxies: rotation profiles reveal considerable unseen mass contribution extending beyond visible structure

Evidence for dark matter across scales







L > Gpc
M > $10^{22}\,M_\odot$

L ~ Mpc
M ~ $10^{14}\,M_\odot$

L ~ 100 kpc
M ~ $10^{12}\,M_\odot$

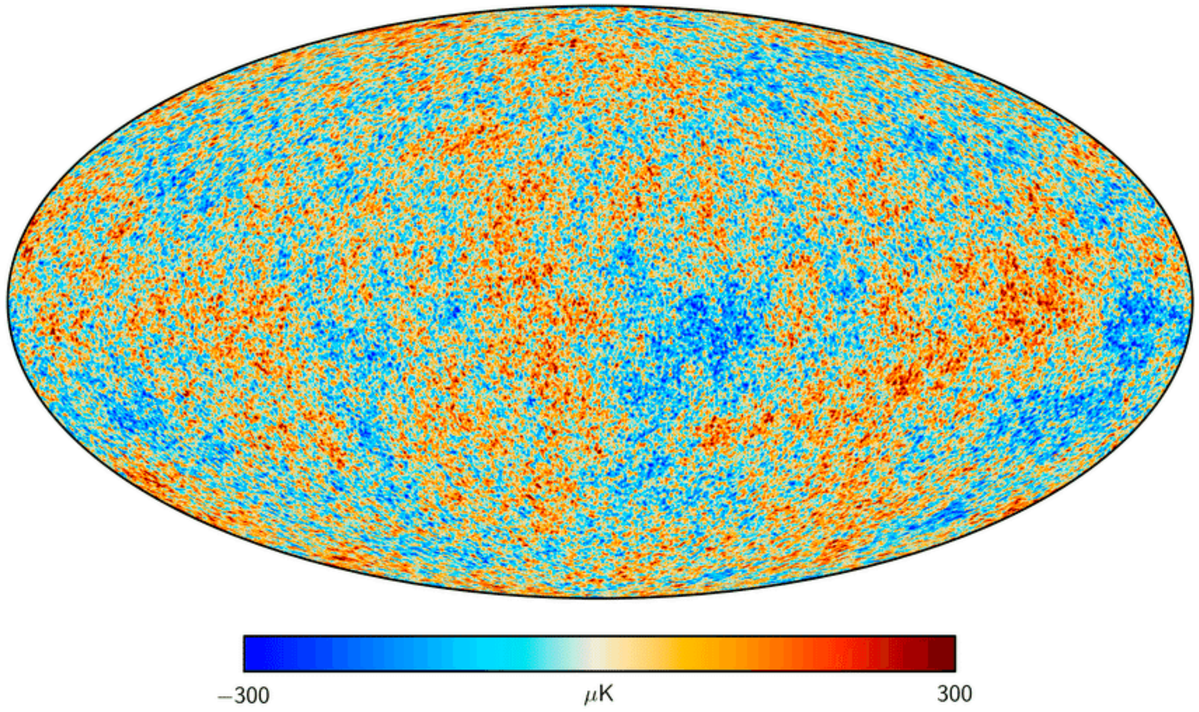
L ~ 1-10 kpc
M ~ $10^{6-8}\,M_\odot$

Dwarf galaxies: Stellar kinematics reveal mass-to-light ratios significantly larger than $1 M_\odot / L_\odot$

The cosmic microwave background

Fluctuations in photon temp. across sky

$$\frac{\delta T}{T} = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$



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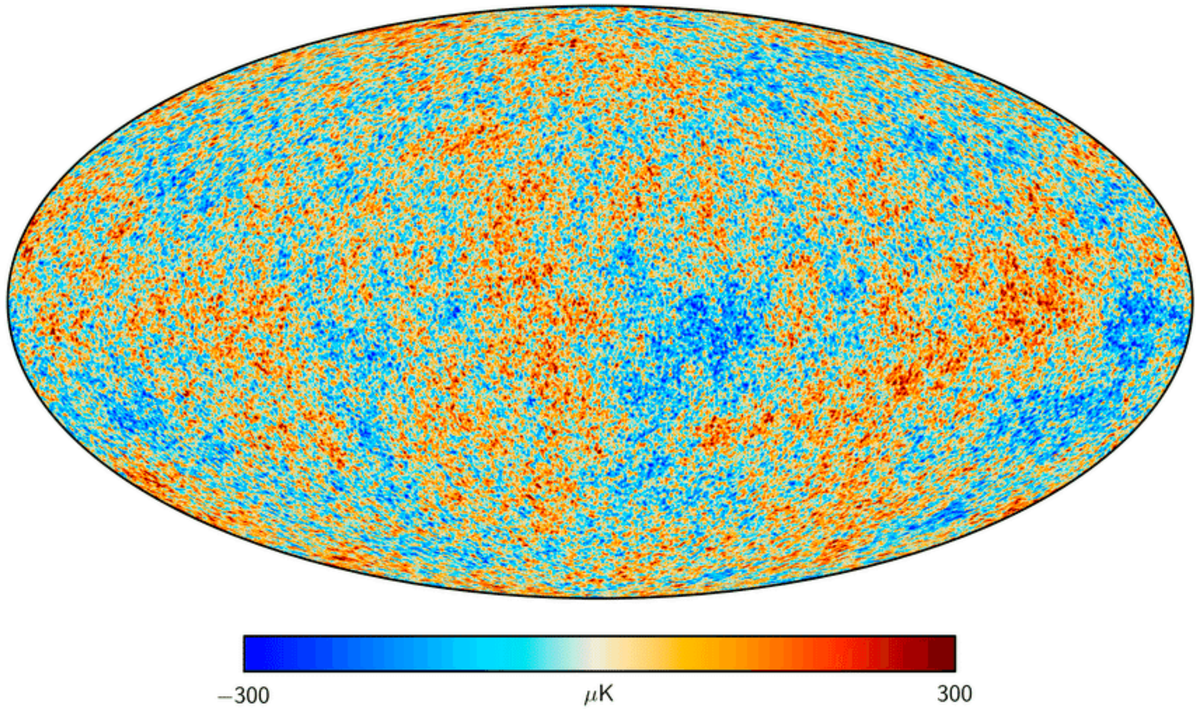
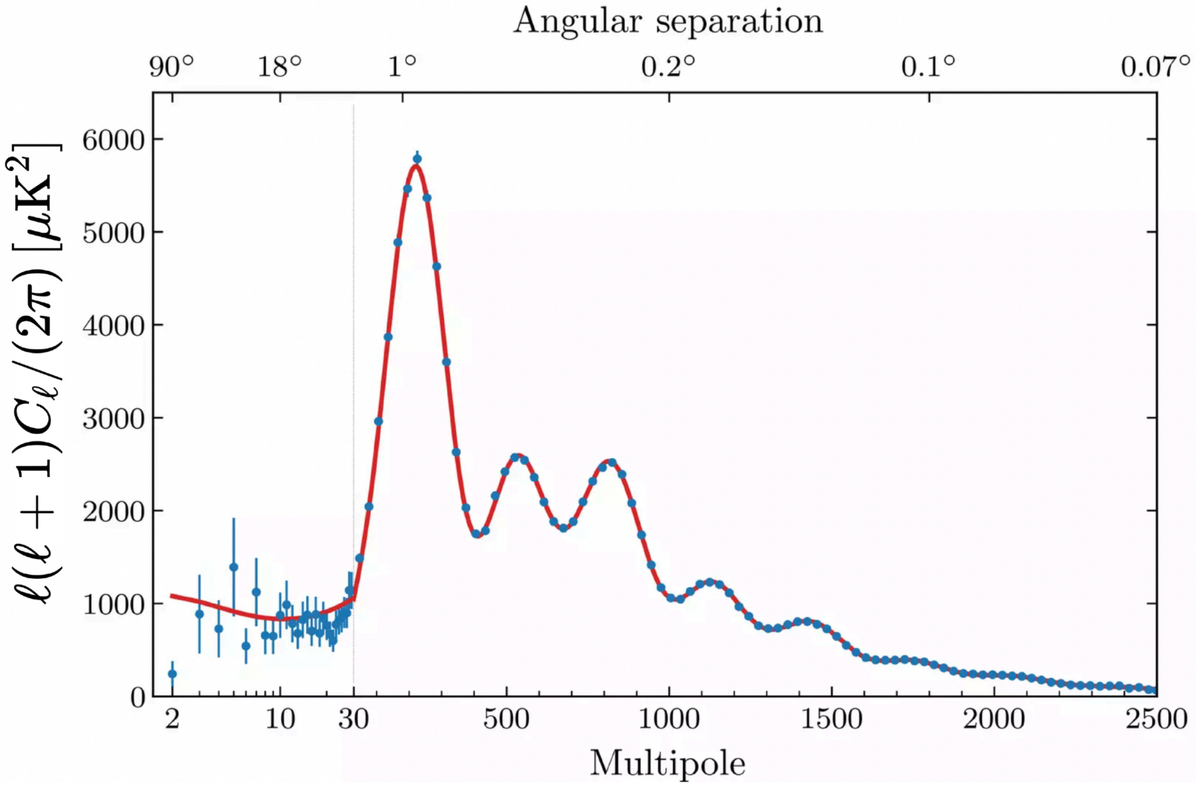


Power spectrum of angular correlations vs multipole number

$$\langle a_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$$



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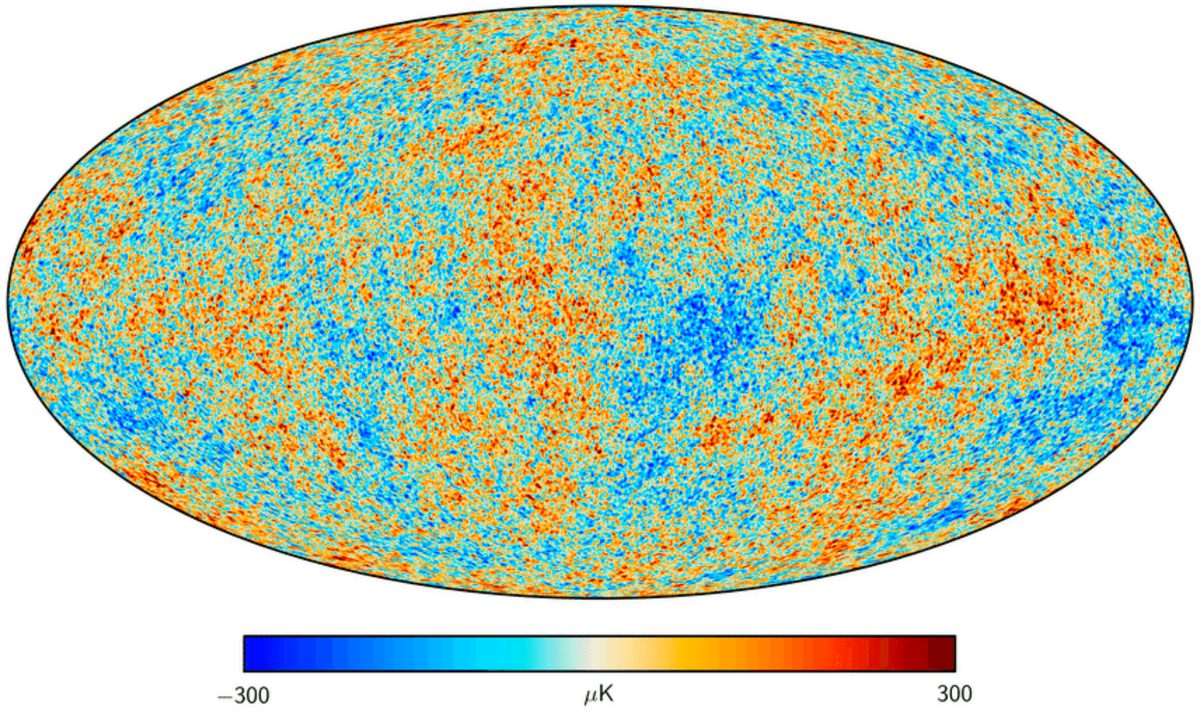

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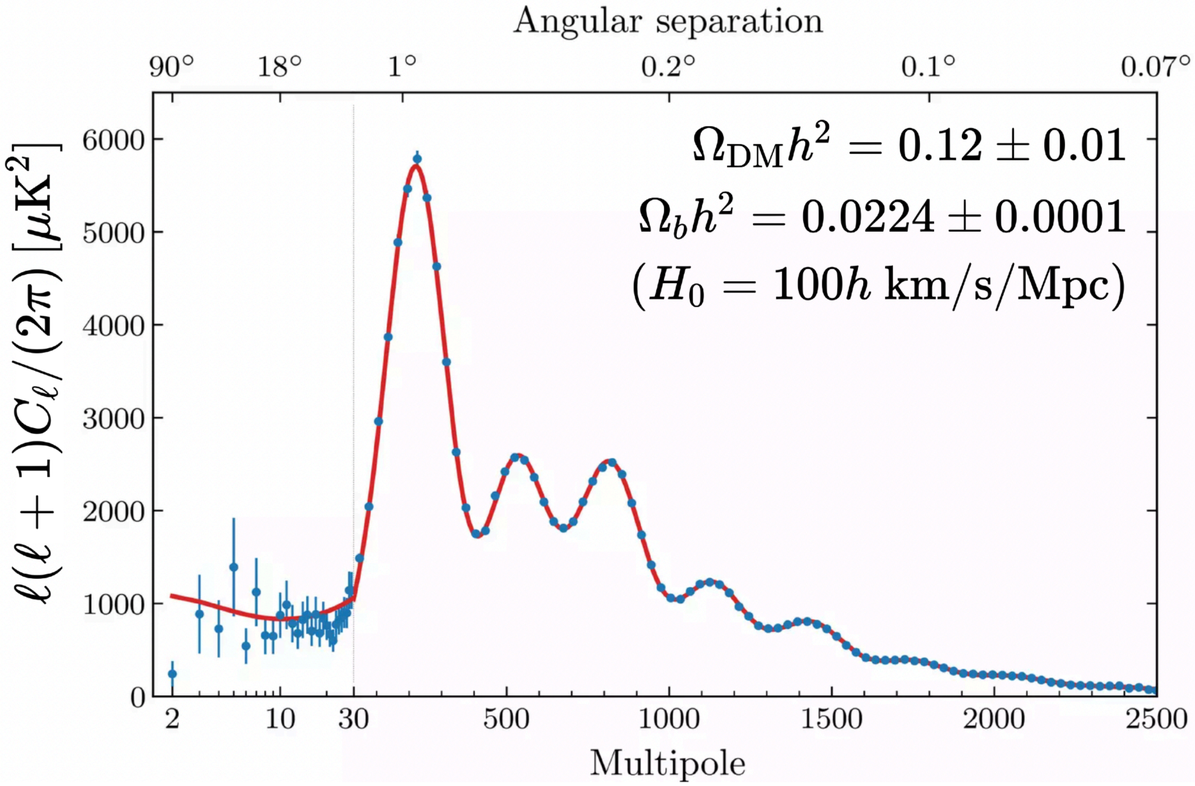
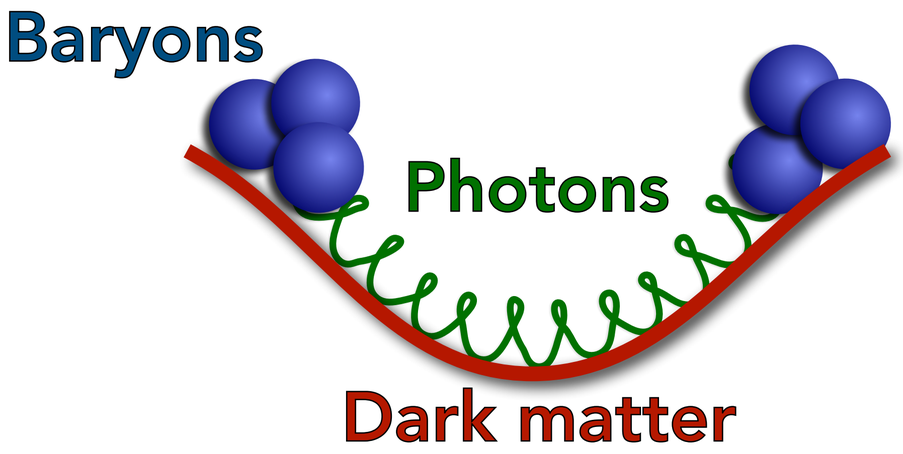
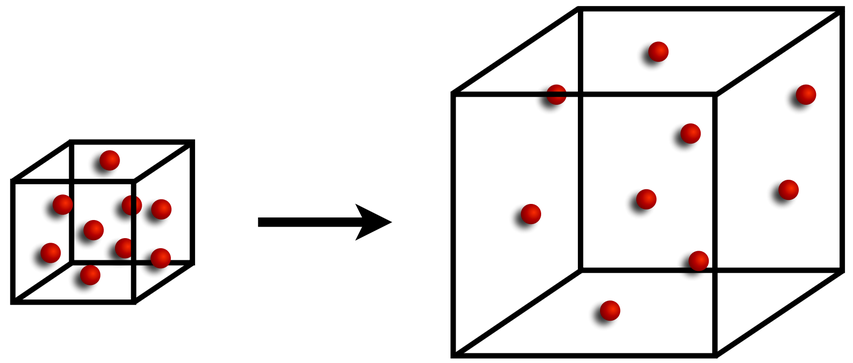


Minimal definition of dark matter

Dissipation-less, source of gravitational potential **(dark)**



Energy density dilutes with expansion **(matter)**

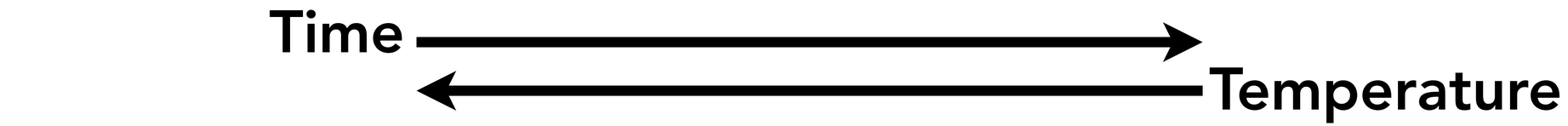


$$\rho \propto \frac{1}{a^3} = \frac{1}{V}$$

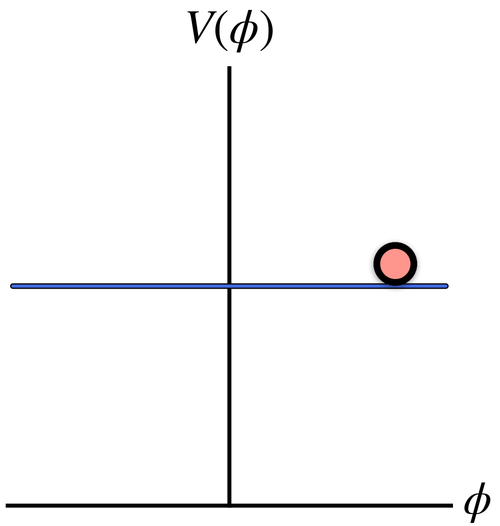
How can a scalar field be the dark matter?

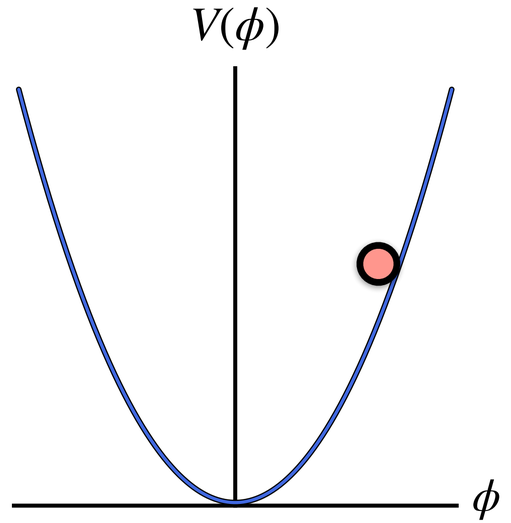
→ the misalignment mechanism

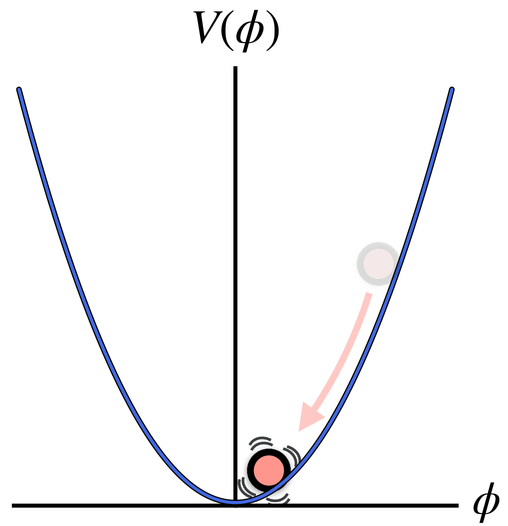
Misalignment mechanism



Symmetry broken



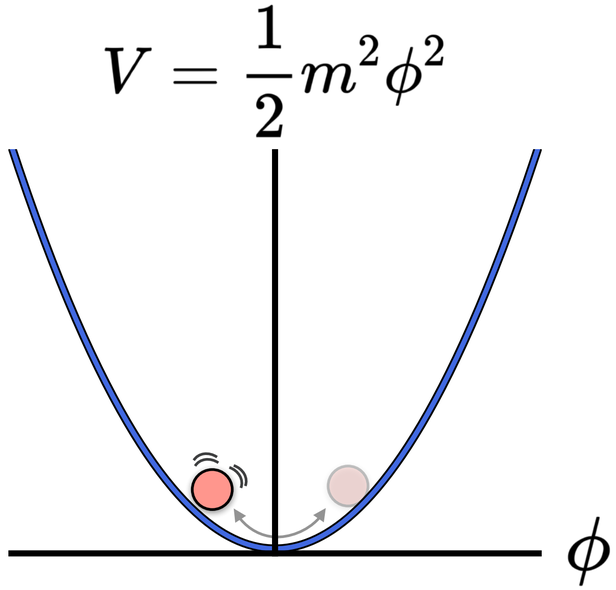




Misalignment mechanism for a generic scalar

Imagine our scalar field's potential is just given by its mass

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{2}(\partial_\mu\phi\partial^\mu\phi) - \frac{1}{2}m^2\phi^2\right]$$



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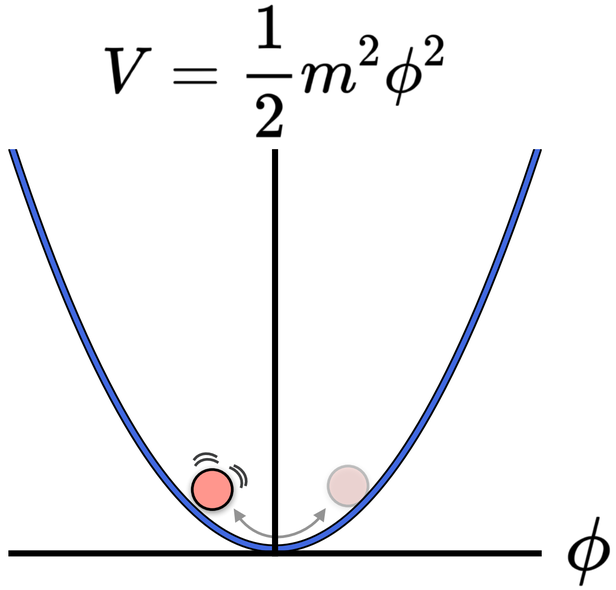

Euler-Lagrange equation:

$$\partial_\mu \frac{\partial\sqrt{-g}\mathcal{L}}{\partial(\partial_\mu\phi)} = \frac{\partial\sqrt{-g}\mathcal{L}}{\partial\phi}$$

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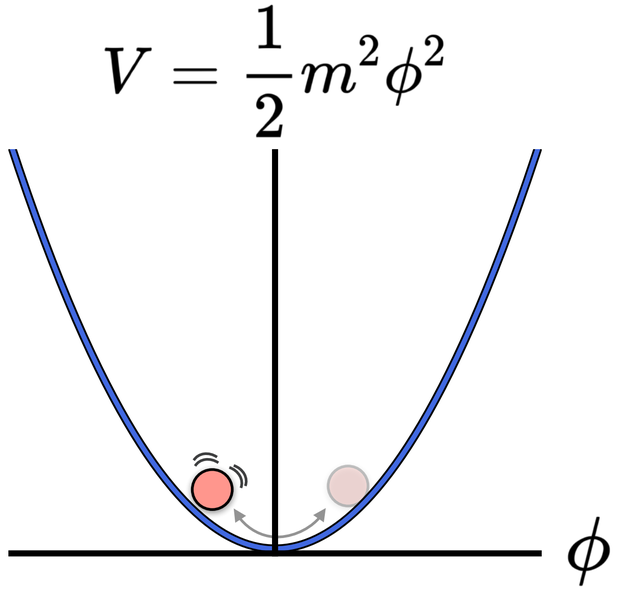

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(Klein-Gordon equation)

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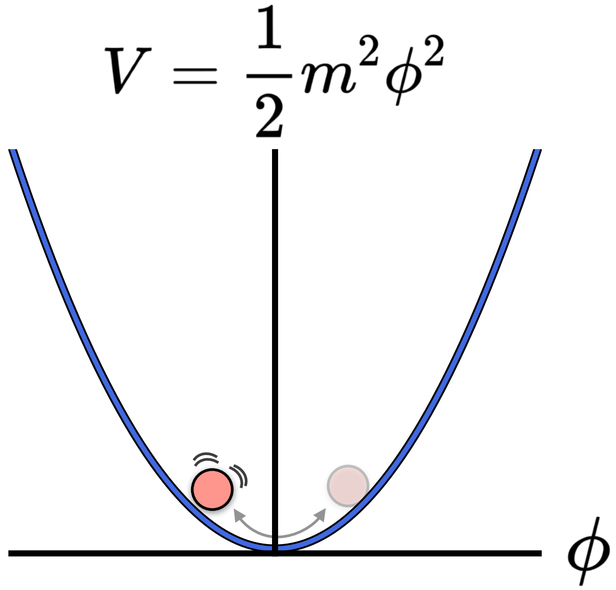

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Put in FRW metric $g = \mathrm{diag}(-1, a^2, a^2, a^2)$ where $H = \dot{a}/a$

$$\Box = -\partial_t^2 - 3H\partial_t$$

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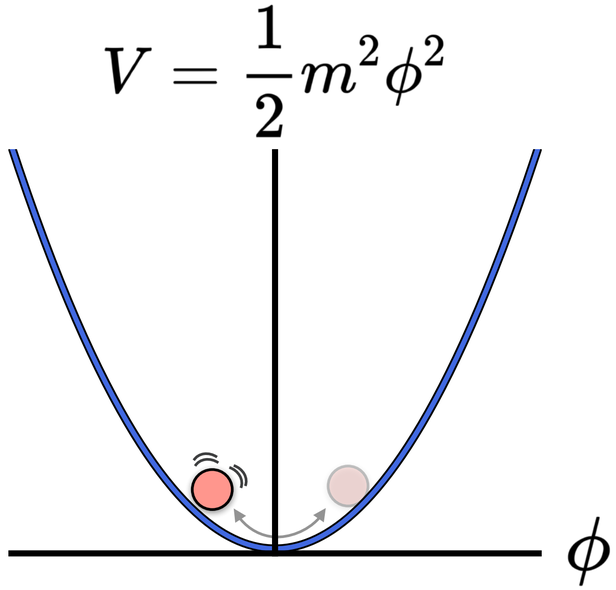

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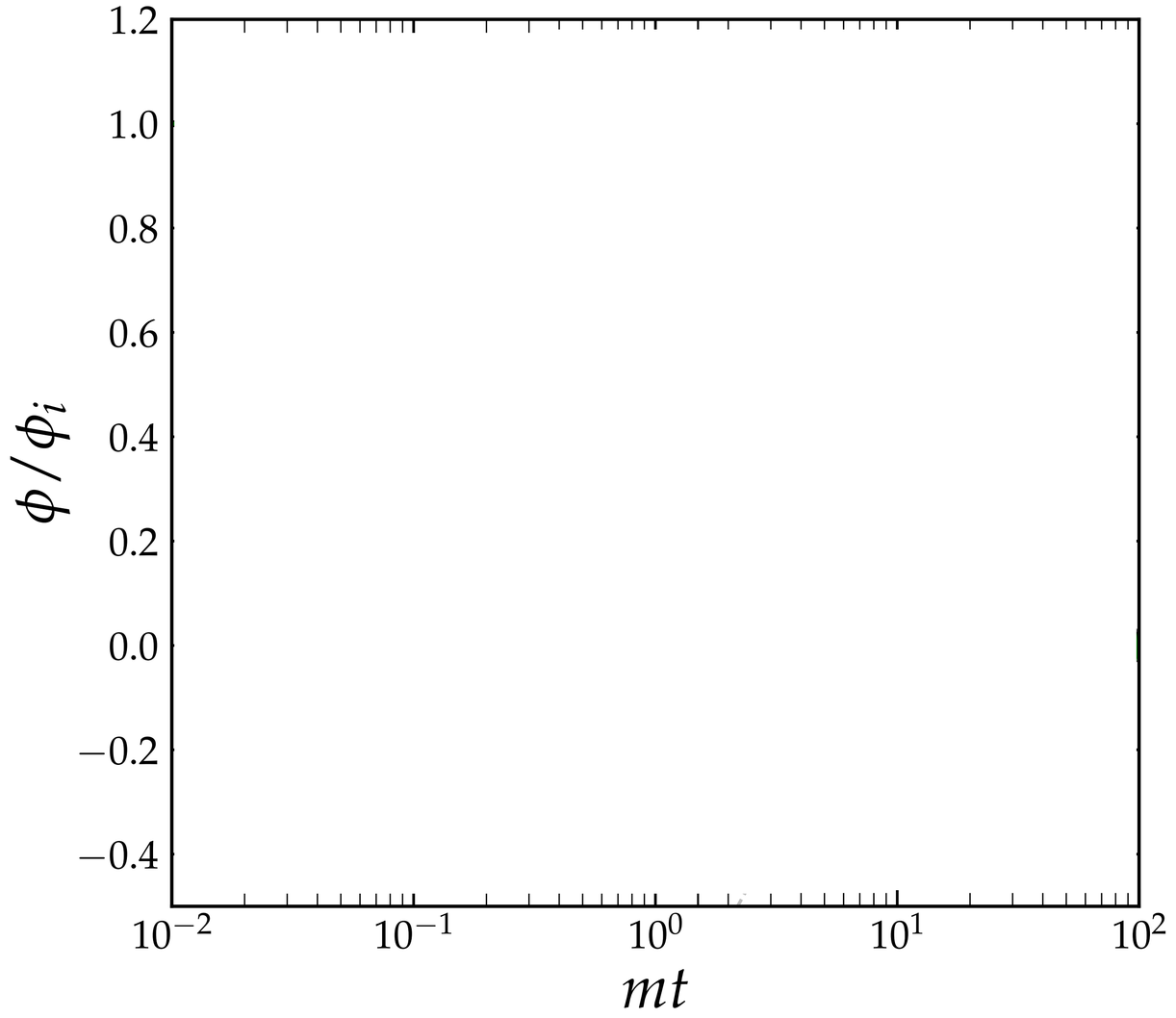
Damped harmonic oscillator

Misalignment mechanism for a generic scalar

$$\ddot{\phi} + 3H(t)\dot{\phi} + m^2\phi = 0$$

Taking radiation domination $H(t) = 1/2t$ and enforcing the boundary condition $\dot{\phi}(t_i) = 0$, we get a general solution:

$$\phi = \phi_i \left(\frac{2}{mt}\right)^{\frac{1}{4}} \Gamma\left(\frac{5}{4}\right) J_{\frac{1}{4}}(mt)$$



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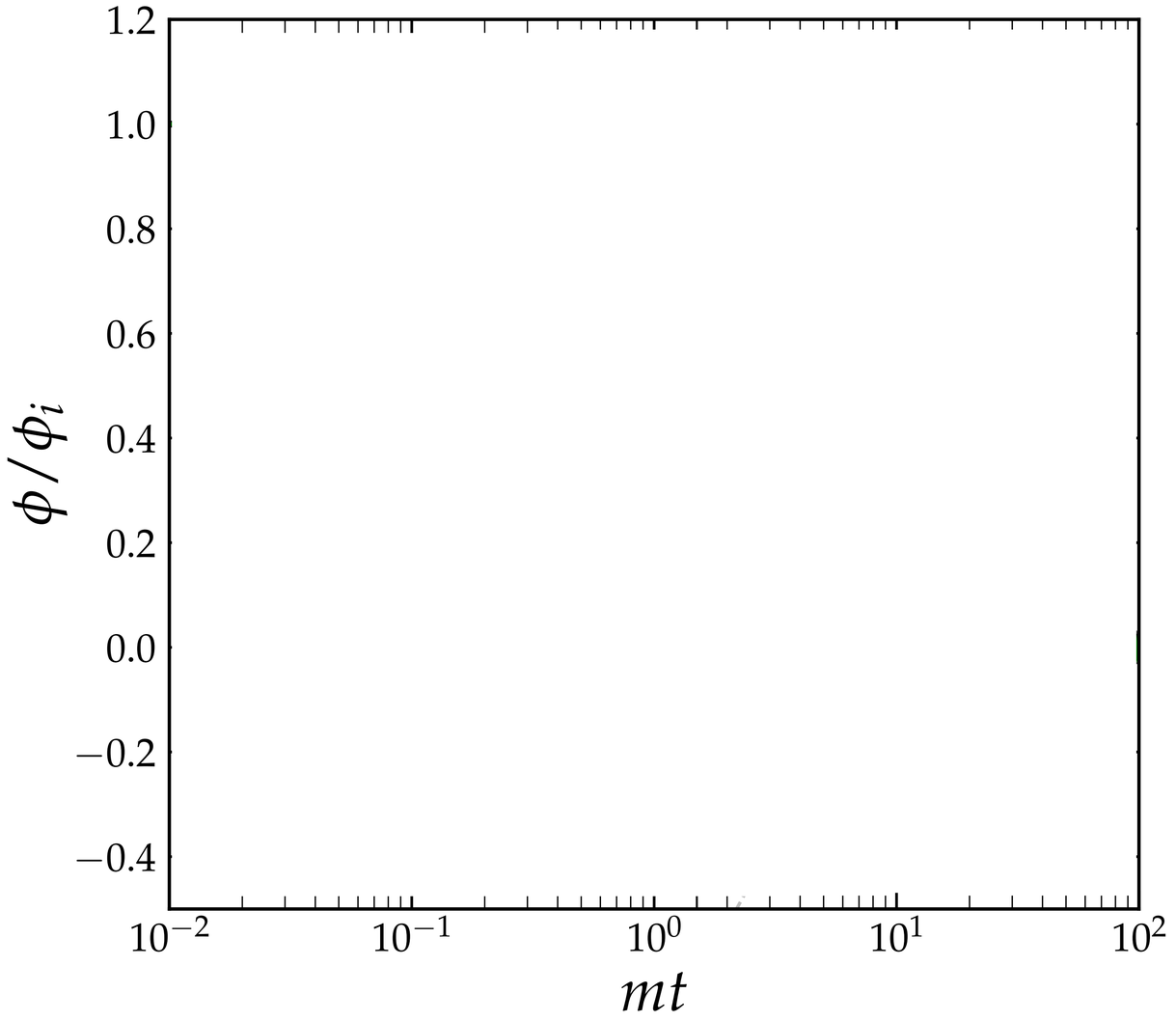
Two regimes:



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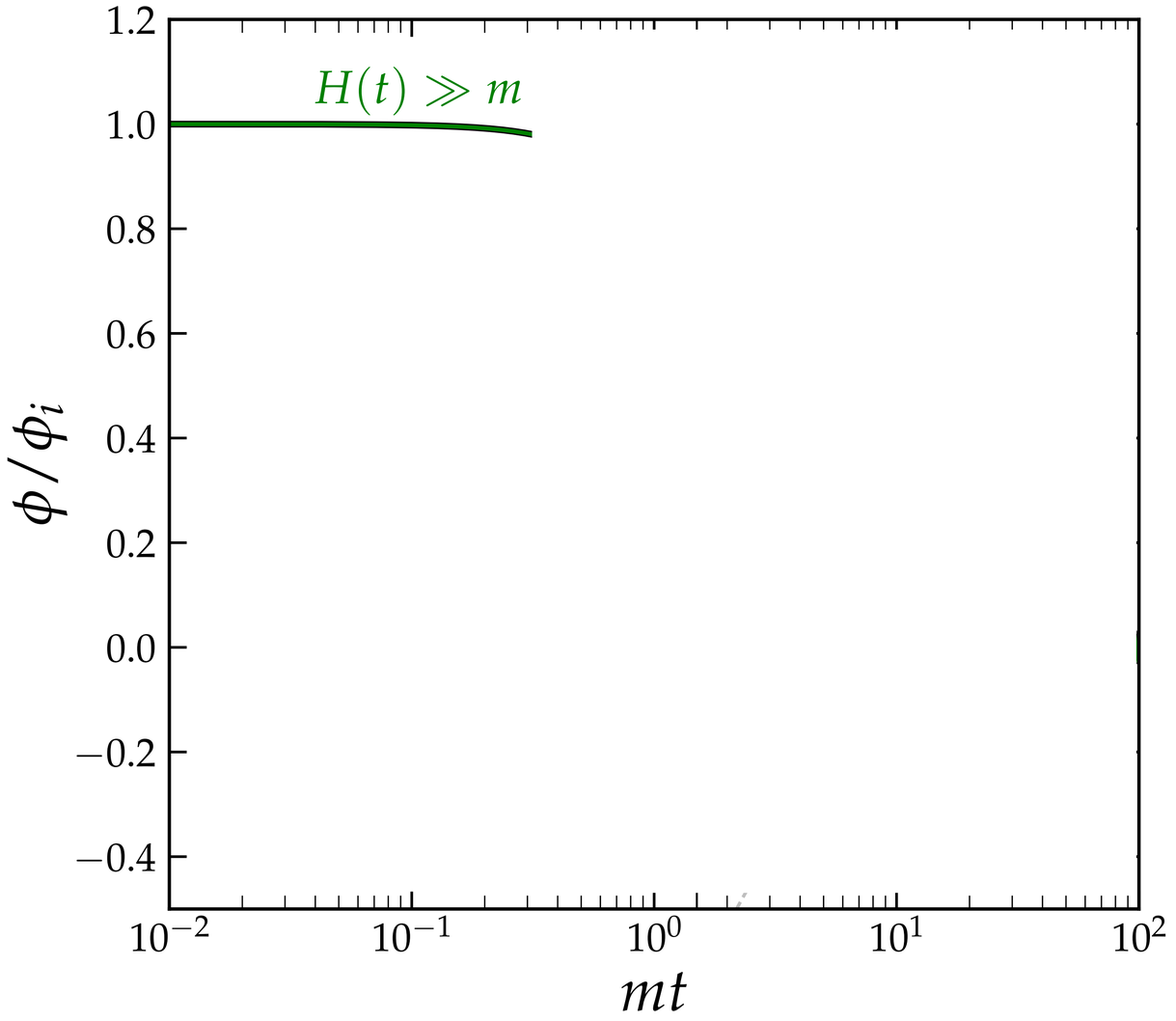
- $3H(t) \gg m \rightarrow$ overdamped oscillator



Misalignment mechanism for a generic scalar

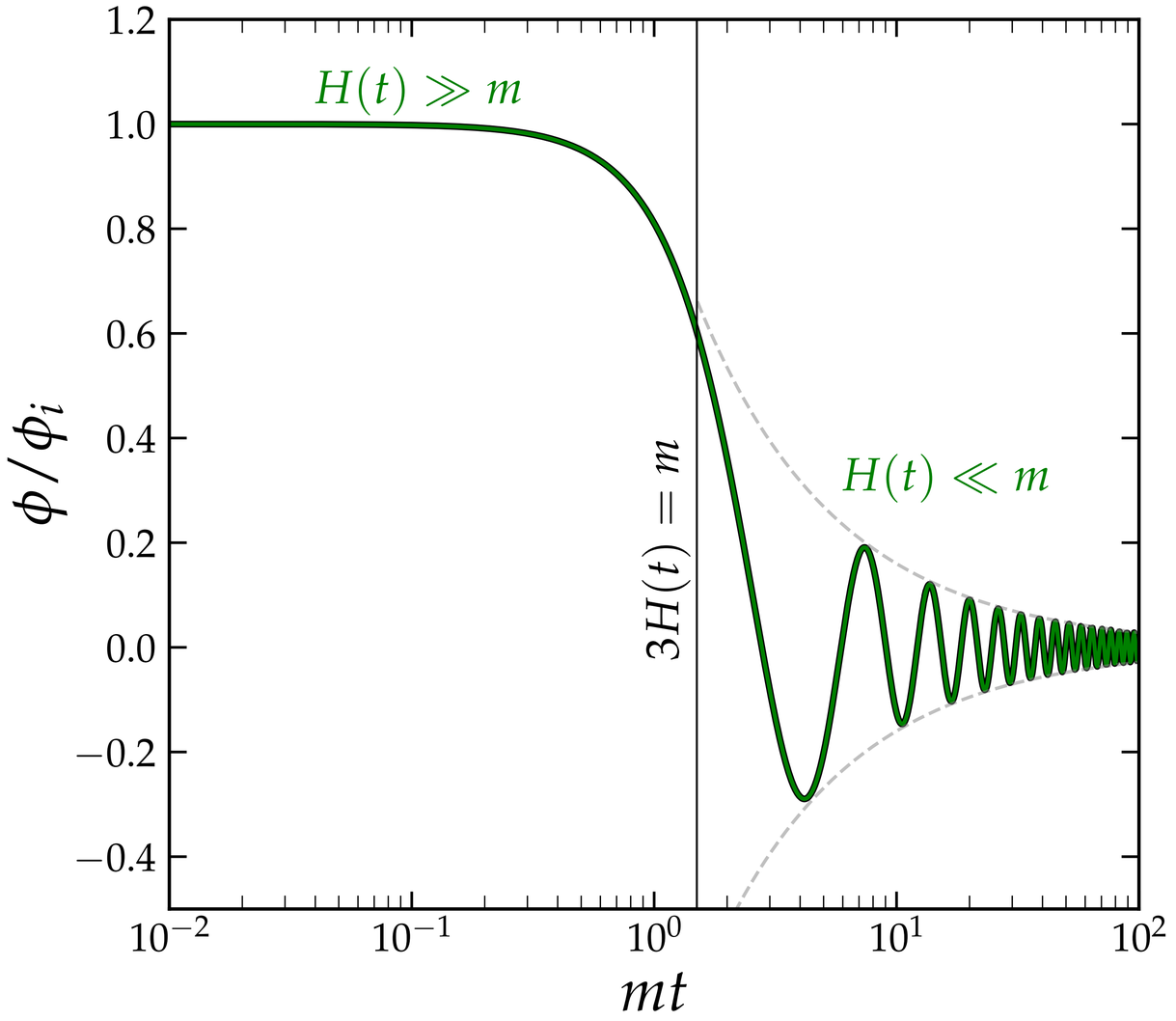
$$\ddot{\phi} + 3H(t)\dot{\phi} + m^2\phi = 0$$

Taking radiation domination $H(t) = 1/2t$ and enforcing the boundary condition $\dot{\phi}(t_i) = 0$, we get a general solution:

$$\phi = \phi_i \left(\frac{2}{mt}\right)^{\frac{1}{4}} \Gamma\left(\frac{5}{4}\right) J_{\frac{1}{4}}(mt)$$

Two regimes:

- $3H(t) \gg m \rightarrow$ overdamped oscillator
- $3H(t) \ll m \rightarrow$ damped harmonic oscillator



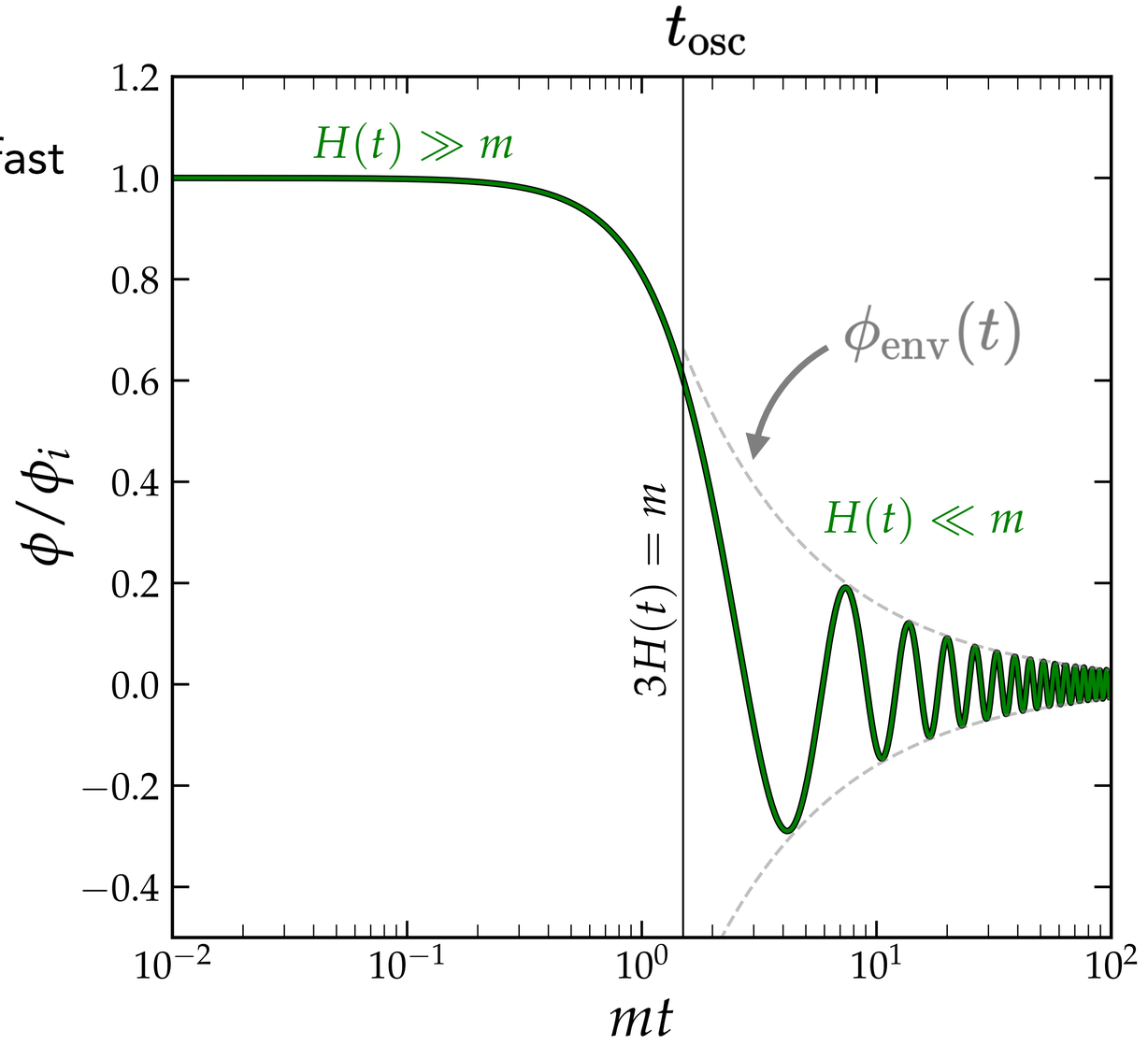
Misalignment mechanism for a generic scalar

At late times, the damping takes place over cosmological timescales, while the oscillations are fast
→ Make a WKB approximation $\dot{\phi}_{\rm env}/\phi_{\rm env} < m$

$$\phi(t) = \phi_{\rm env}(t)\cos mt$$

$$\rightarrow\ \phi \propto \underbrace{\phi_i a(t)^{-3/2}}_{\text{Envelope}}\cos(mt)$$

Envelope
decays as $a^{-3/2}$



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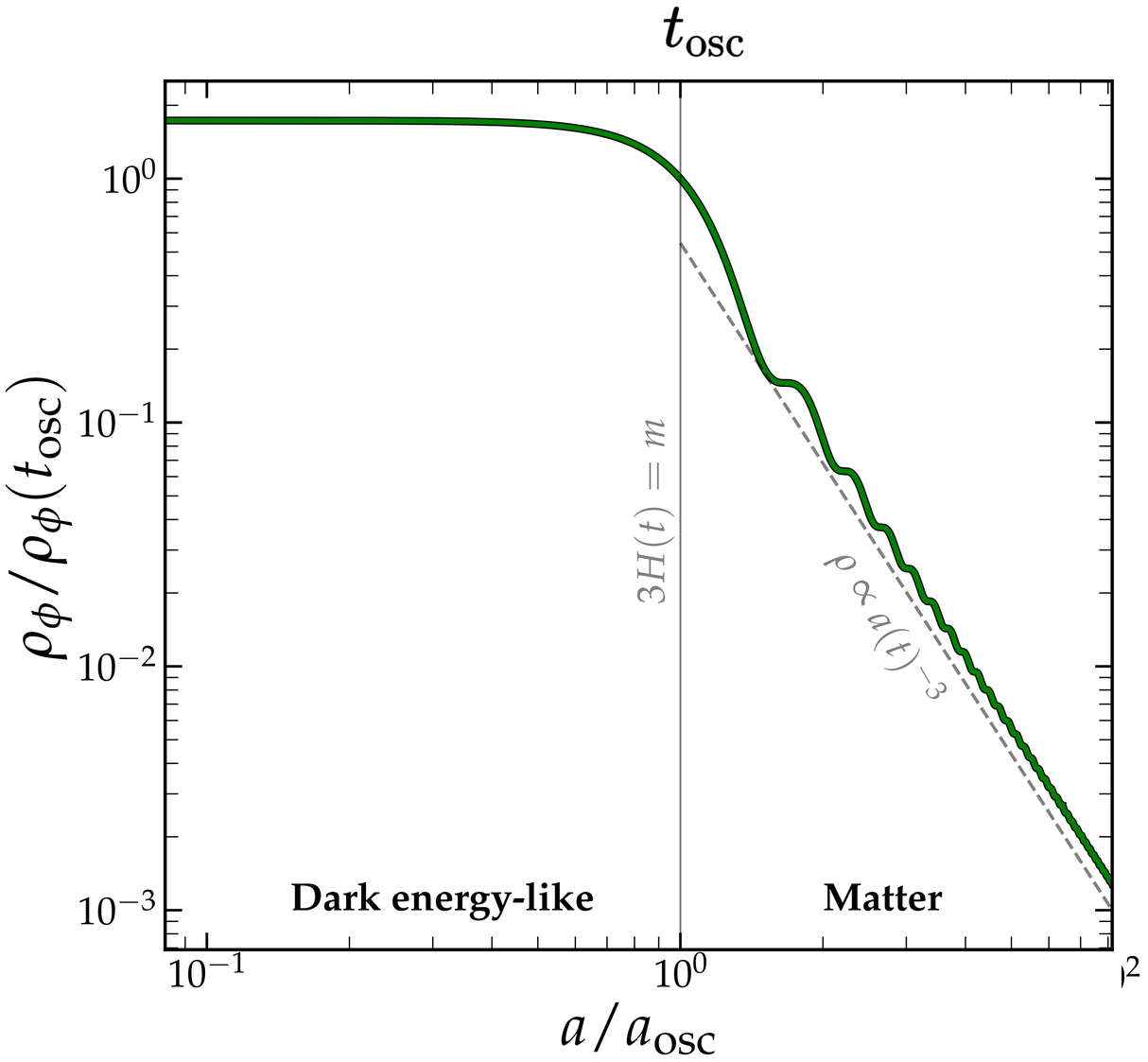
Look at the energy density in the scalar field

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 \implies \rho_\phi \propto a^{-3}$$



Misalignment mechanism for a generic scalar

We want to force this to be equal to the abundance of dark matter today

$$\Omega_\phi h^2 = \frac{\rho_\phi}{\rho_c} h^2 = \frac{\rho_\phi}{3 H_0^2 M_{\rm Pl}^2} h^2 \to 0.12$$

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The density in our scalar field is:

$$\rho_\phi^{\rm today} = \frac{1}{2} m^2 \phi_i^2 \left(\frac{a_{\rm today}}{a_{\rm osc}} \right)^{-3}$$, where $$\left(\frac{a_{\rm today}}{a_{\rm osc}} \right)^{-3} \sim \left(\frac{T_{\rm today}}{T_{\rm osc}} \right)^3$$

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Assume we're late enough that $g_* = 3.4 = \text{const}.$

To get these temperatures, use Friedmann eq: $3H^2 M_{\rm Pl}^2 = \frac{\pi^2}{30} g_* T^4$

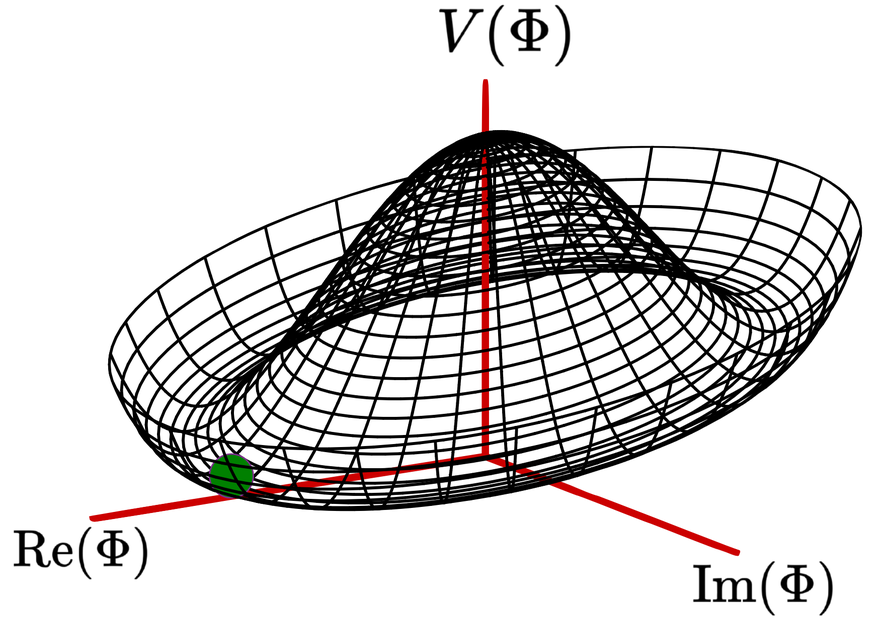
$$\Longrightarrow \boxed{\Omega_\phi h^2 = 0.12 \left(\frac{\phi_i}{4.7 \times 10^{16}\,{\rm GeV}}\right)^2 \left(\frac{m}{10^{-21}{\rm eV}}\right)^{\frac{1}{2}}}$$

Now, the axion case: How do we adapt this?

Axion is the Goldstone (θ) appearing after the $\mathrm{U}(1)_{\mathrm{PQ}}$ is broken at scale f_a.

We write it as the phase of a complex scalar field: $\Phi(t) = \rho\, e^{i\theta}$

$$V(\Phi) = V_{\mathrm{PQ}}(\rho) + V_{\mathrm{QCD}}(\theta) = \frac{\lambda}{8}\left(\rho^2 - f_a^2\right)^2 + \Lambda_{\mathrm{QCD}}^4(1 - \cos\theta)$$



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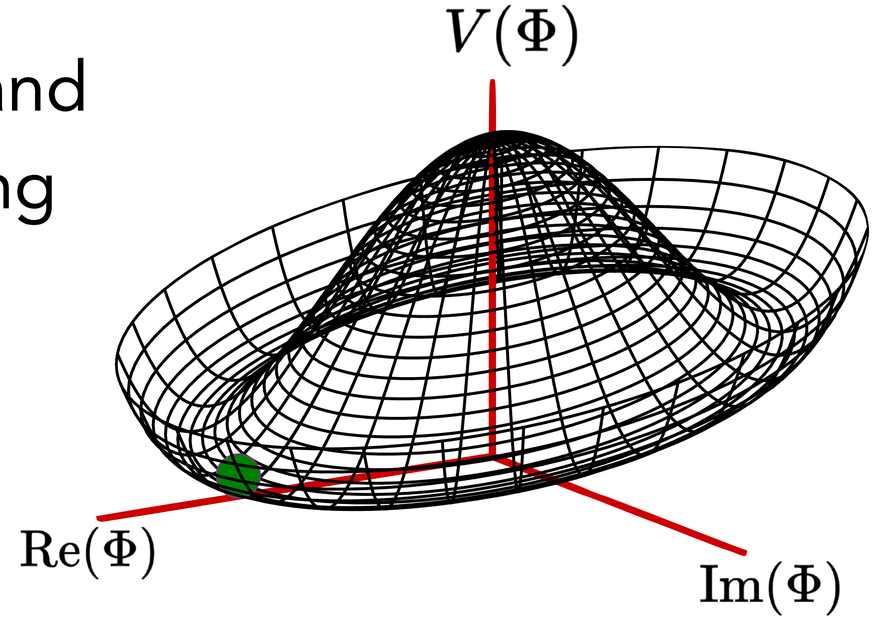
So our scalar field is now an angle in units of f_a and with a mass set by the explicit symmetry-breaking term generated by QCD

$$\phi \to f_a\theta \qquad\qquad m \to m_a \approx \frac{\Lambda_{\mathrm{QCD}}^2}{f_a}$$



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To convert this to the axion case, can I just replace:

$$\phi_i \to \theta_i f_a \approx \mathcal{O}(1) f_a \qquad m \to m_a \approx 6\,\mu\mathrm{eV} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \ ?$$

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No! If you do this, you will not get what is quoted in the literature

$$\Omega_a h^2 \approx 0.12\,\theta_{\mathrm{i}}^2 \left(\frac{f_a}{9 \times 10^{11}\mathrm{GeV}} \right)^{1.165} \implies \textbf{Why?}$$

The QCD axion

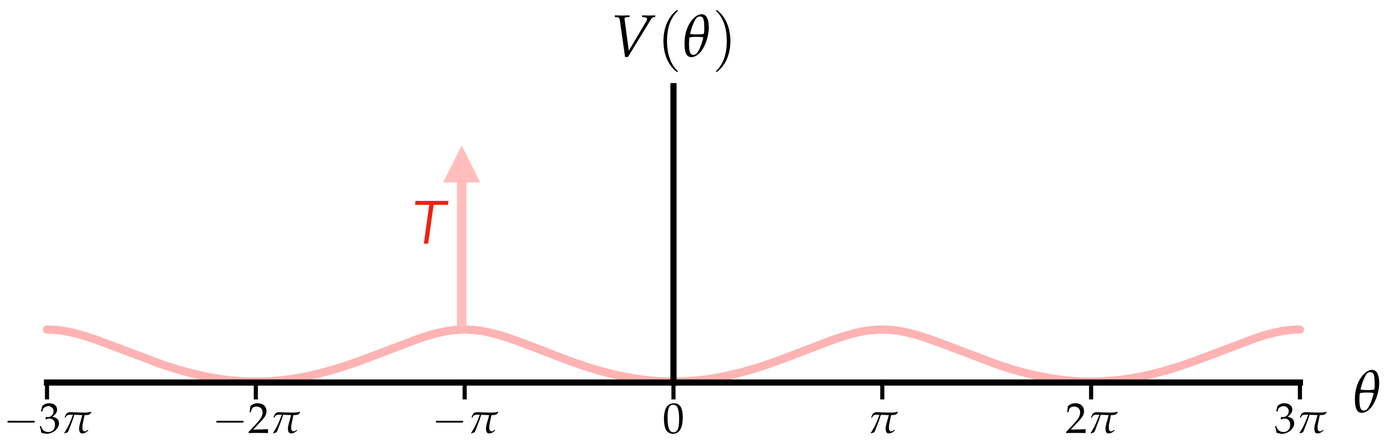
Mass is generated by instantons whose effects are temperature-dependent

In the literature this dependence is called the “topological susceptibility”, $\chi(T)$

$$V(\theta) \approx \chi(T)(1-\cos\theta) = m_a^2(T) f_a^2 (1-\cos\theta)$$

Axion mass grows as temperature drops,

reaching a constant when $T < T_{\mathrm{QCD}}$



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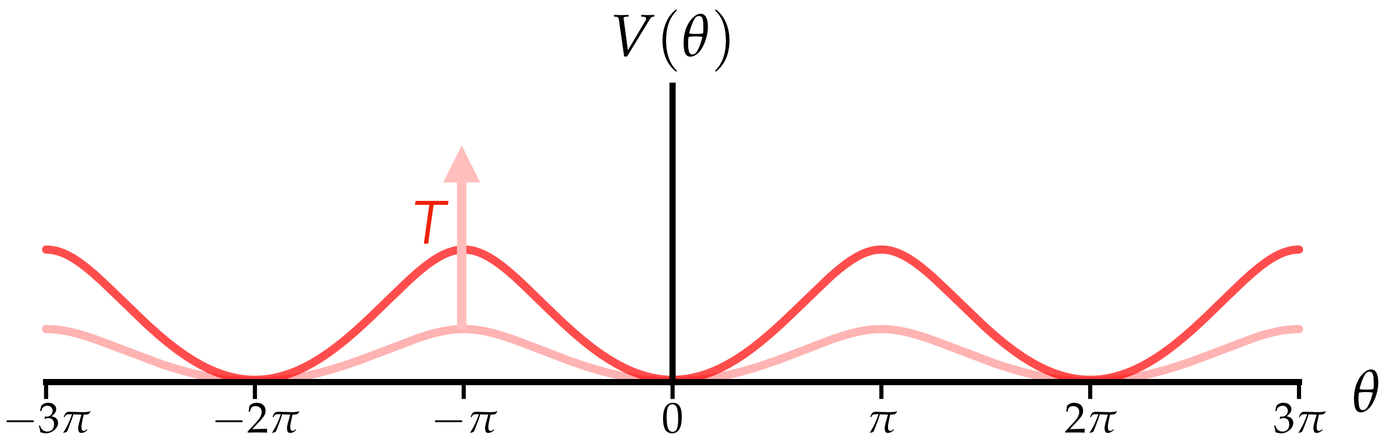

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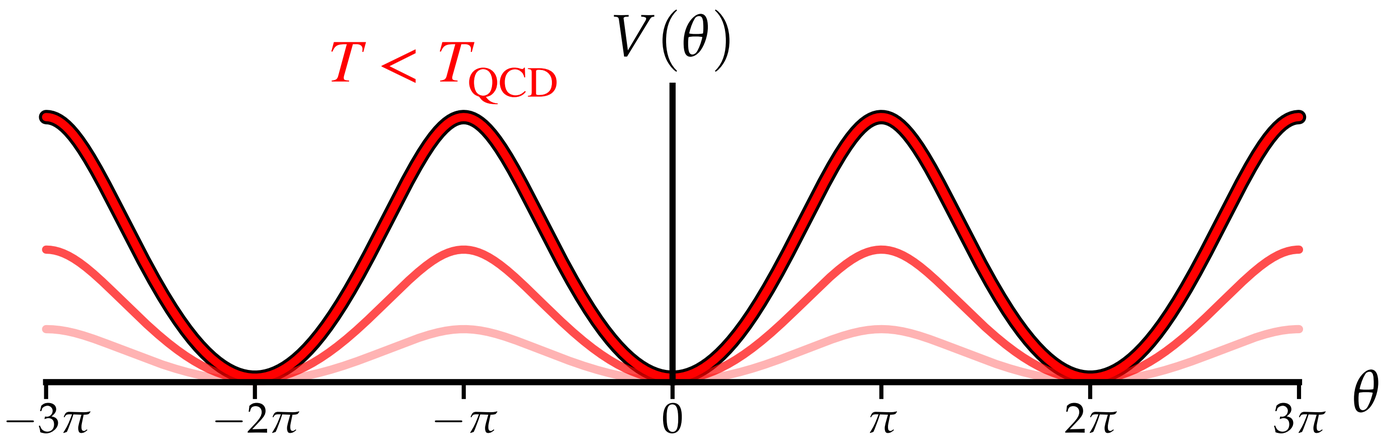

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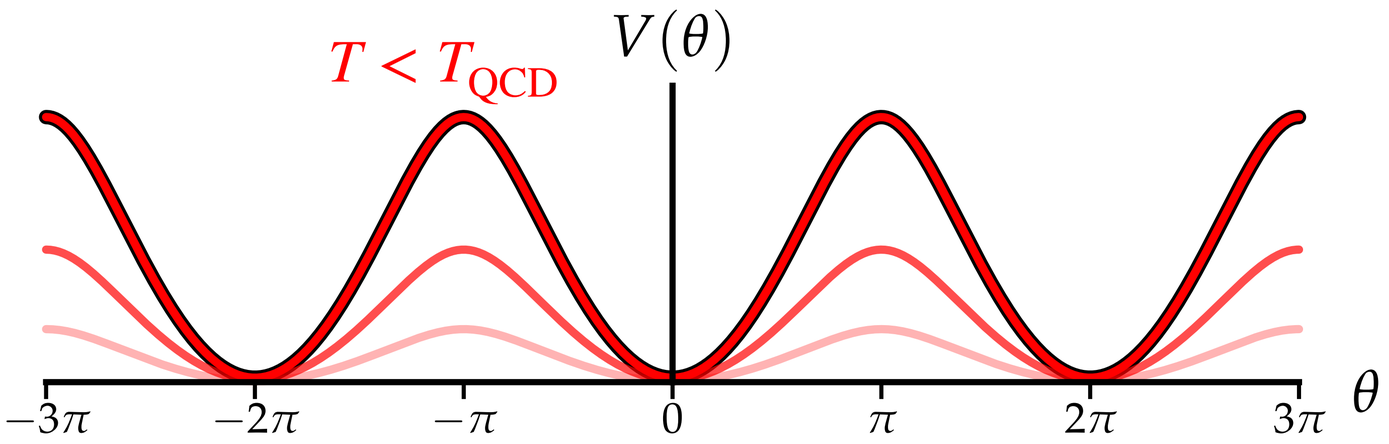
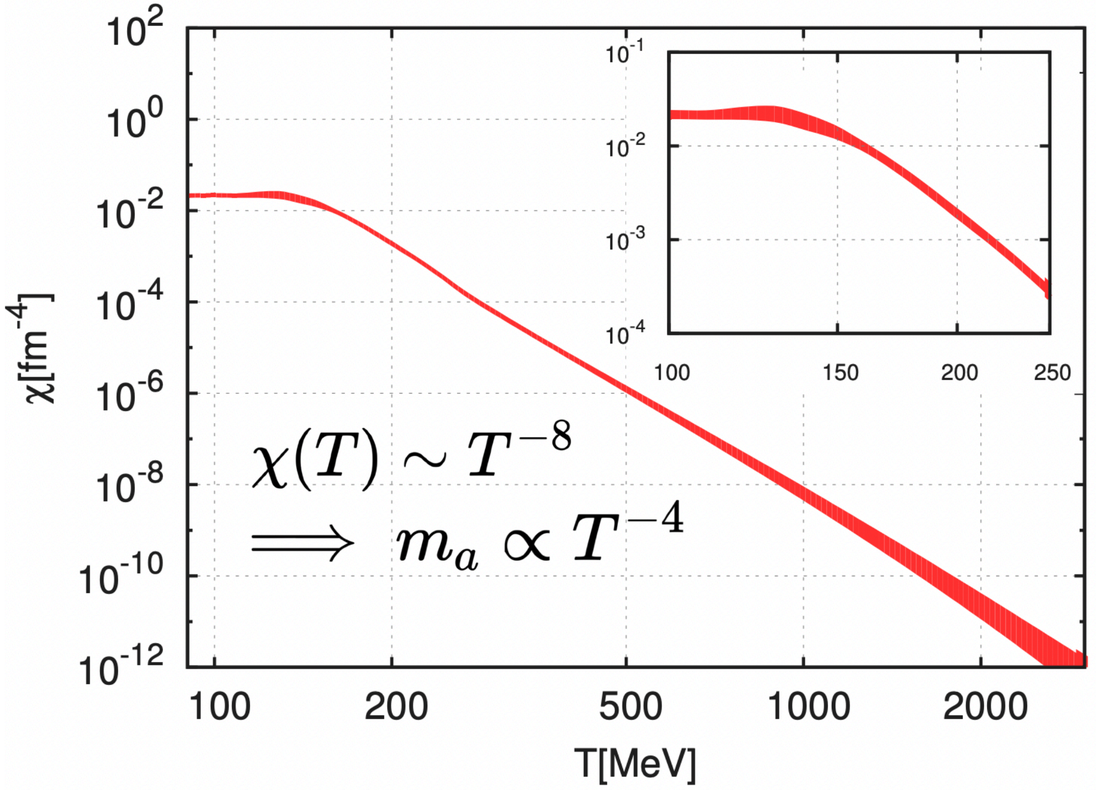


Lattice QCD calculation, Borsanyi+ [1606.07494]



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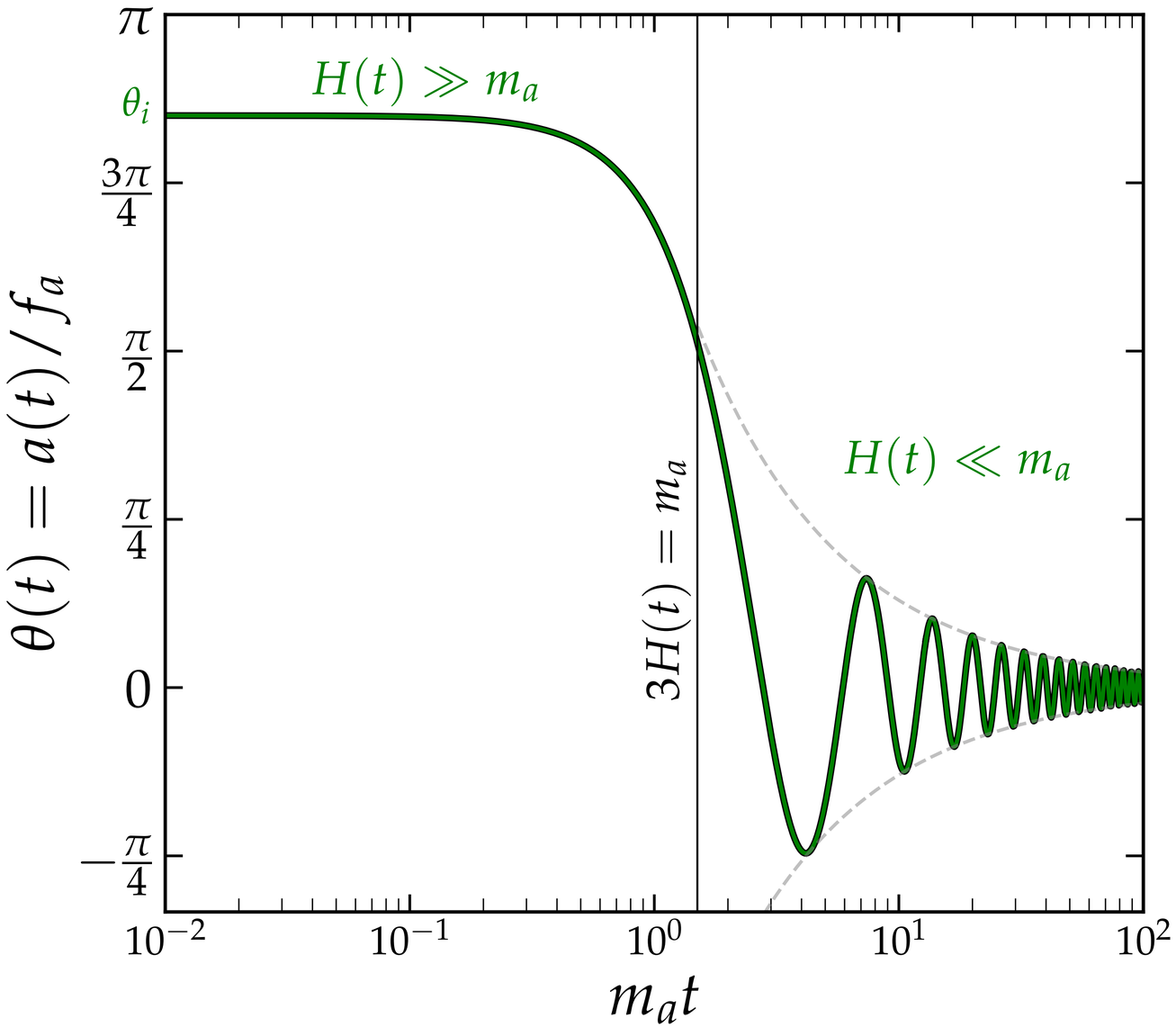
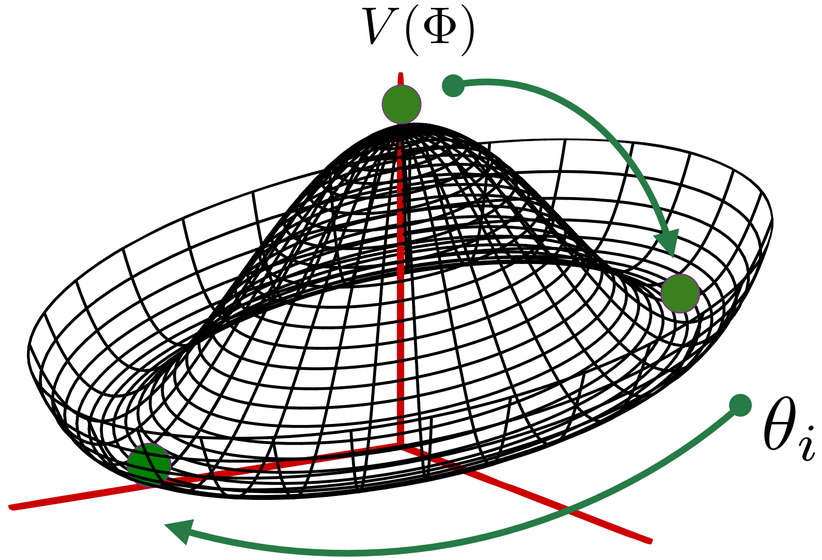


The tilt comes on gradually as the temperature drops



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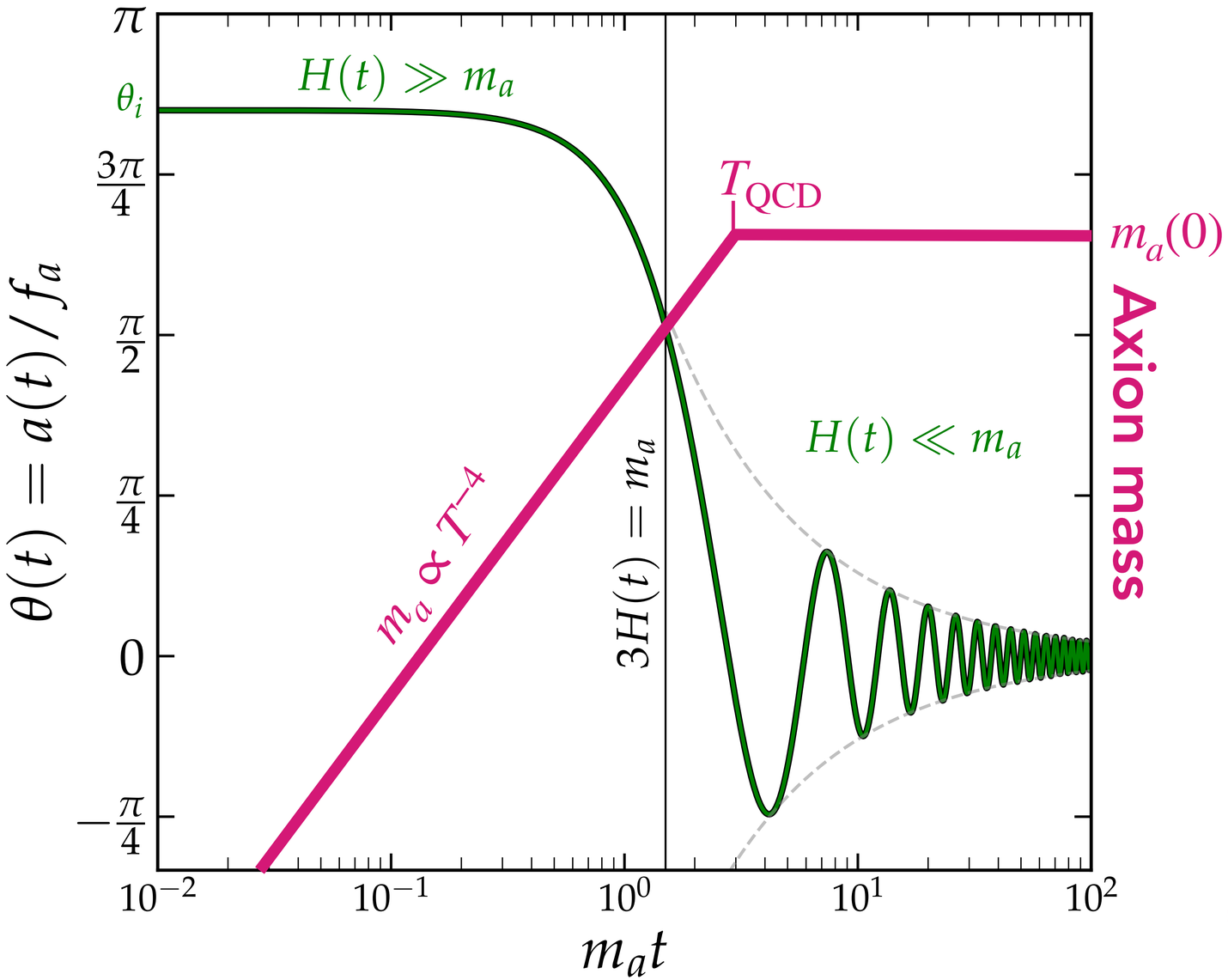

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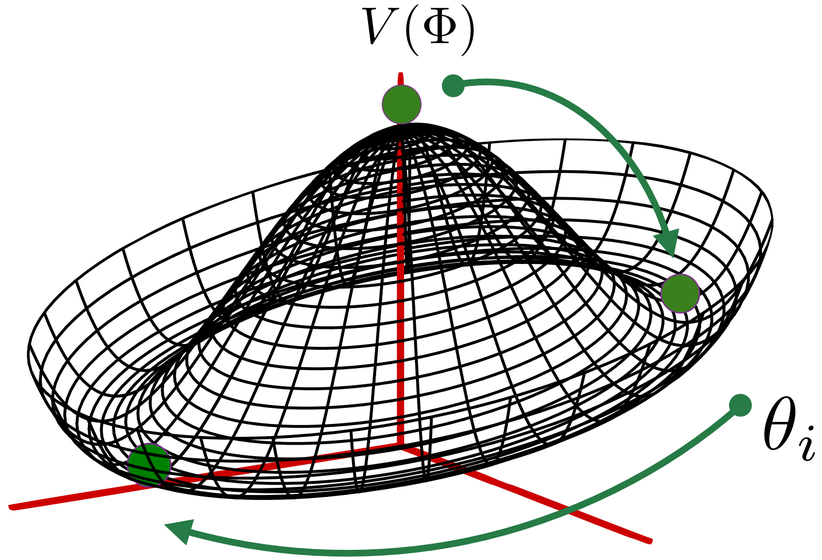


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$$

$$\ddot{\theta} + 3H\dot{\theta} + m_a(T)^2 \sin(\theta) = 0$$

QCD axion abundance

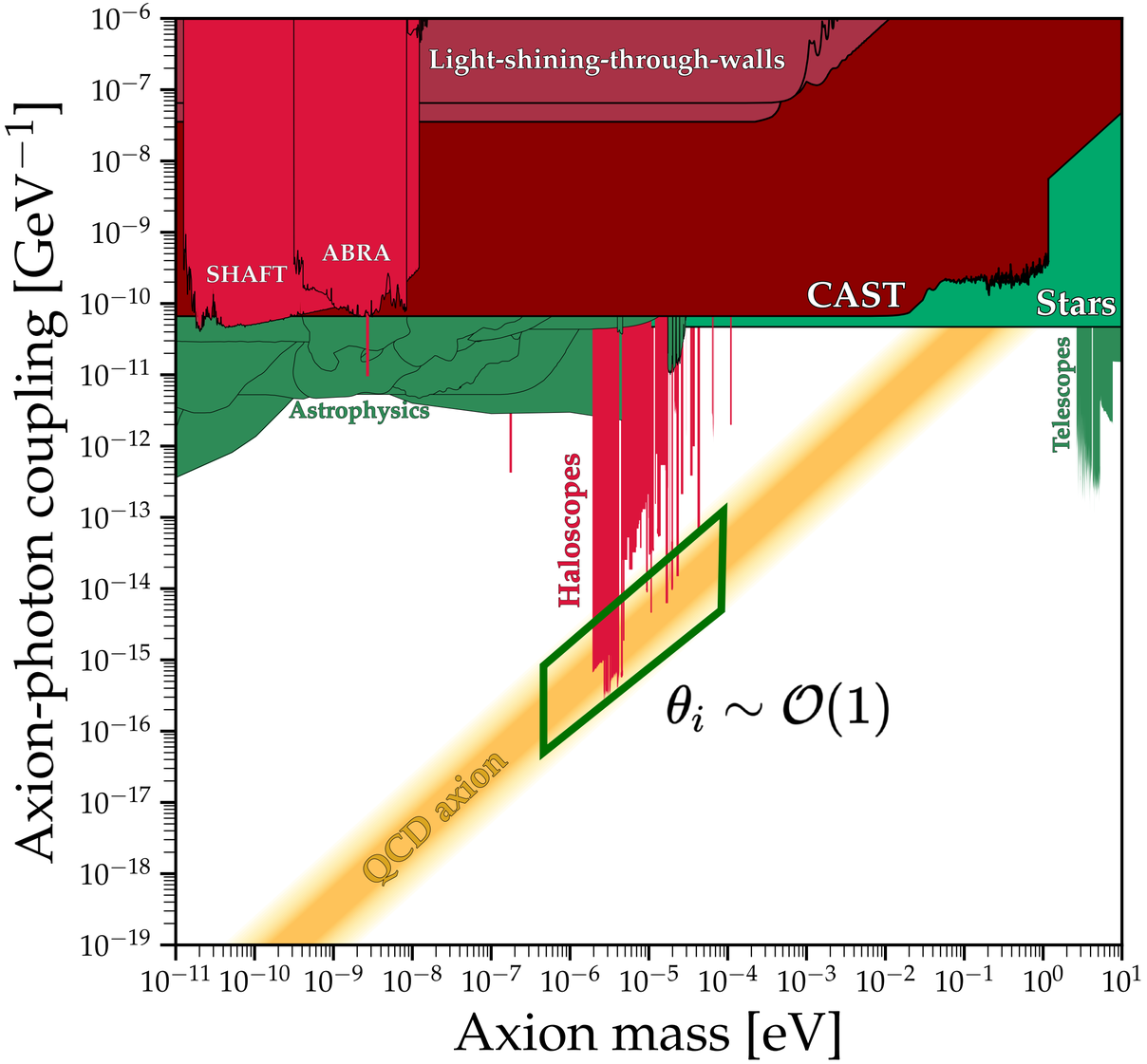
- Full calculation leads to:

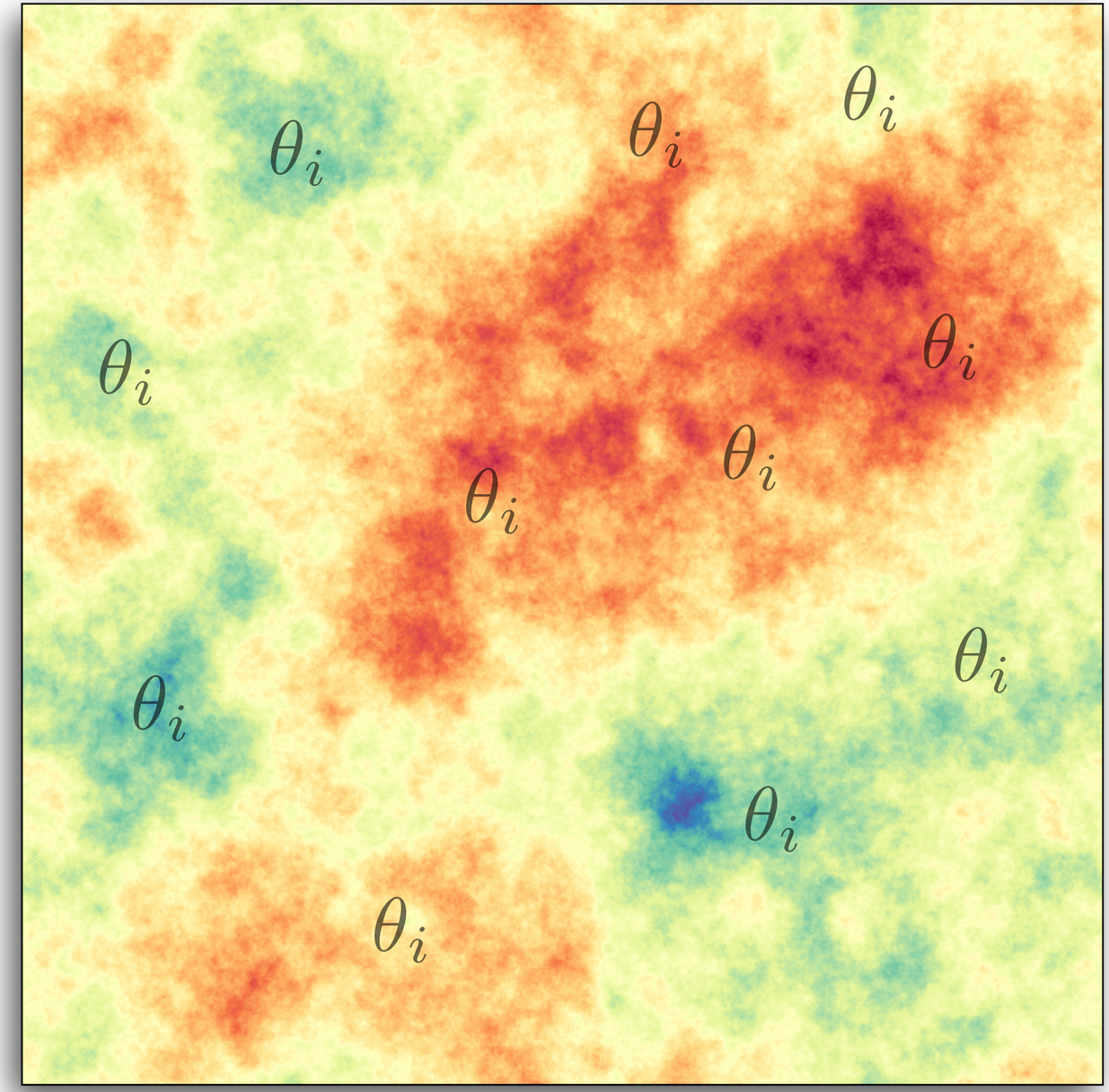
$$\Omega_a h^2 \approx 0.12\,\theta_i^2 \left(\frac{7.26\,\mu\text{eV}}{m_a}\right)^{\frac{n+6}{n+4}}$$

where $n \sim 8$

- Seems to prefer the "classic QCD axion window": $\mathcal{O}$(1—10) μeV

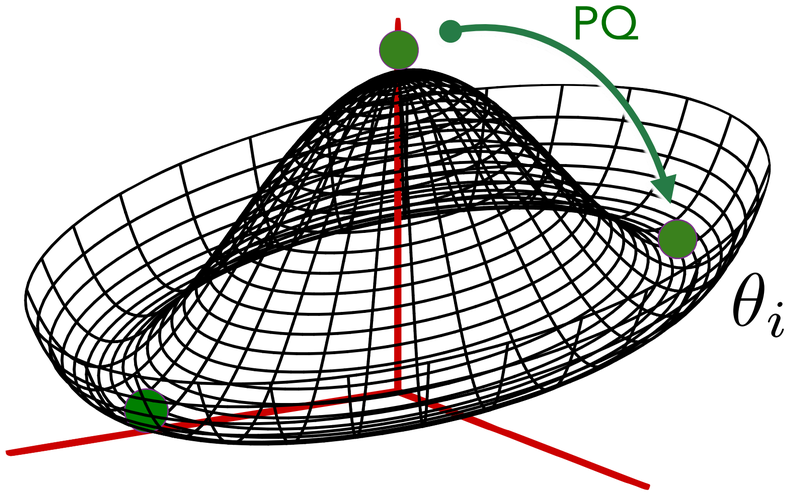
→ **but what should we pick for θ_i ?**





The issue is that $T_{\rm PQ} \gg T_{\rm QCD}$

The Universe should be filled with random θ_i everywhere since the axion didn't know about the preferred angle when the PQ phase transition happened



When did inflation happen?

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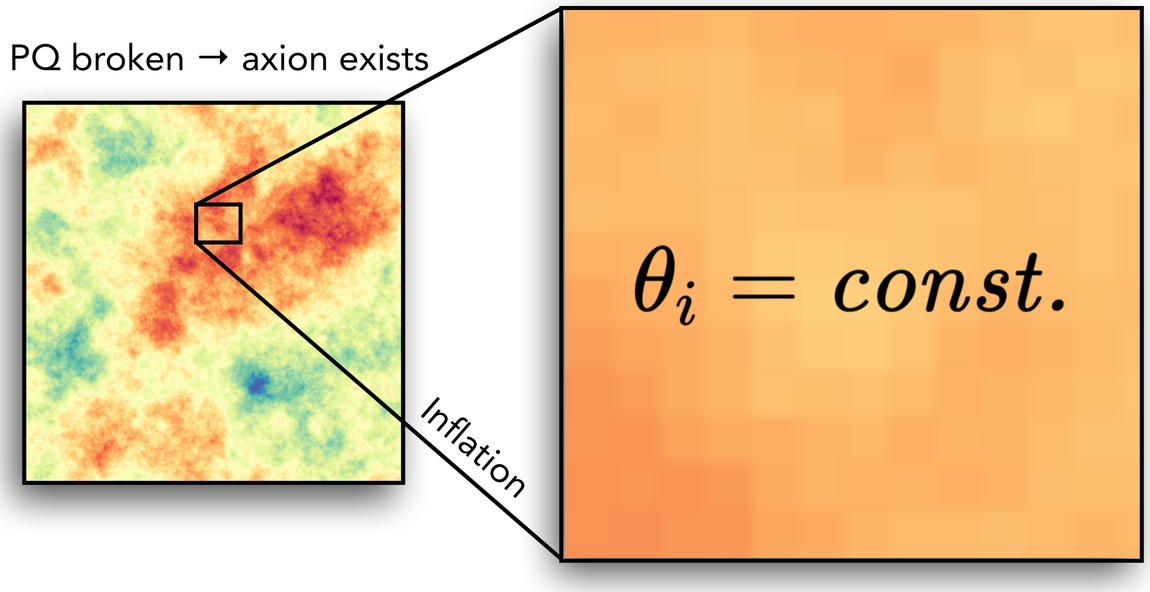
Option 1:

PQ is broken *before and during* inflation



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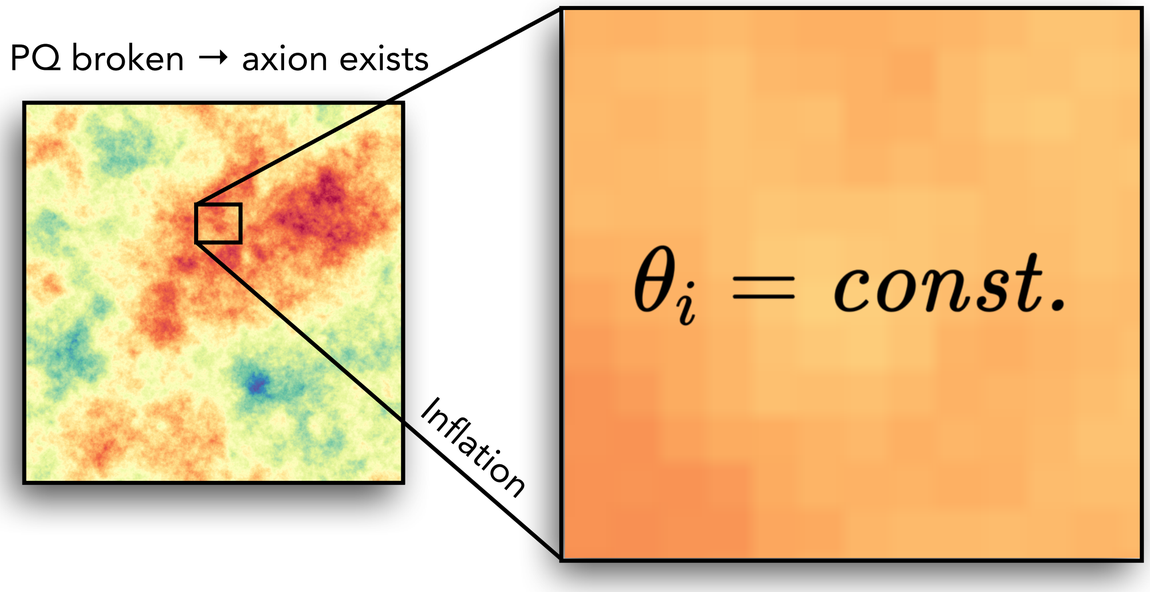
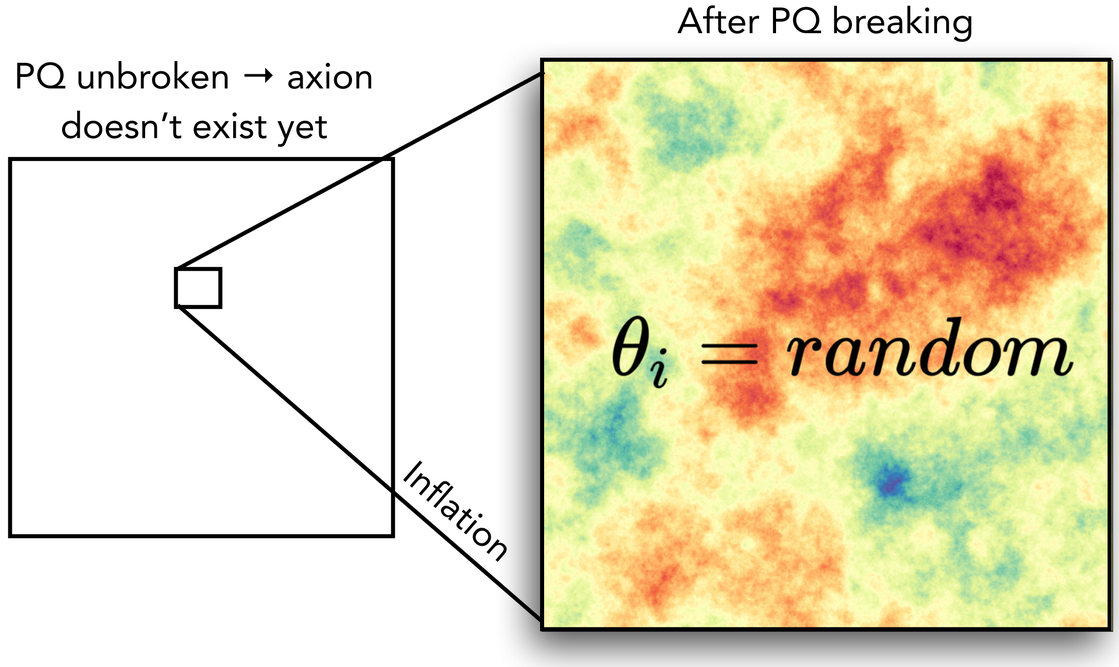


Option 2:

PQ is broken *after* inflation



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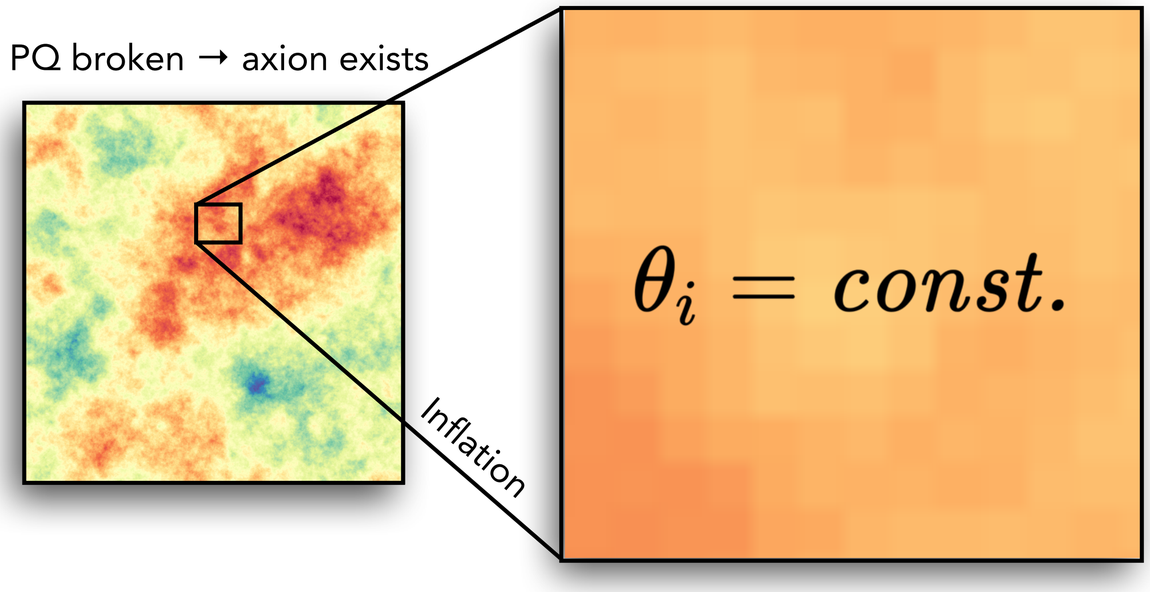

Pre-inflationary scenario

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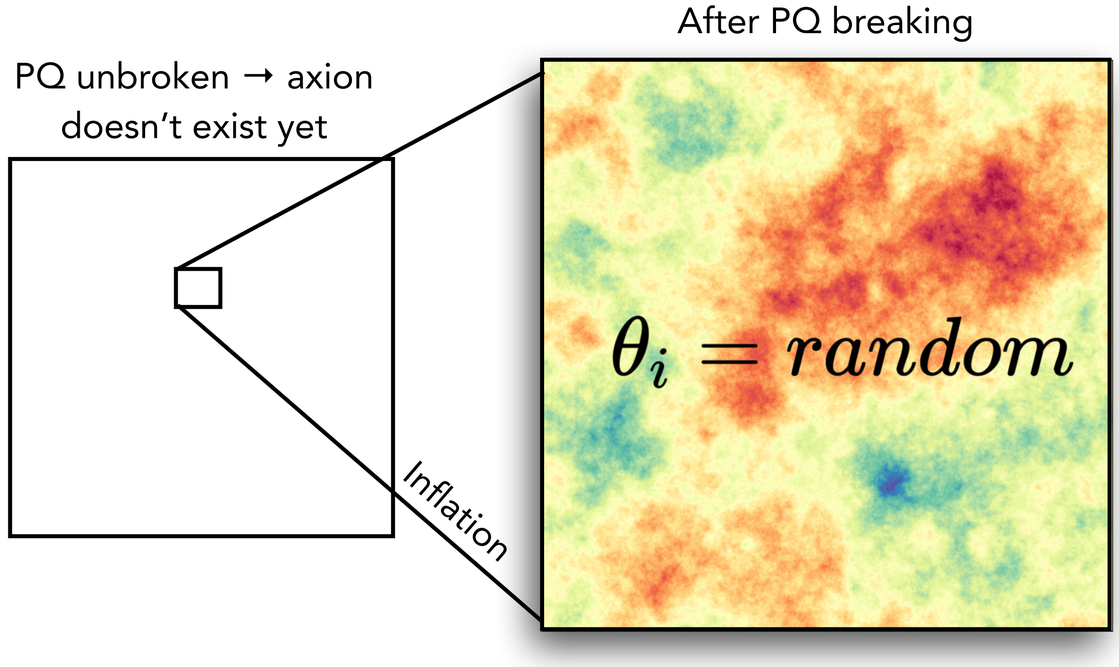

Post-inflationary scenario

Pre-inflationary axions

$$\Omega_a h^2 \approx 0.12\,\theta_i^2 \left(\frac{7.26\,\mu\text{eV}}{m_a}\right)^{\frac{n+6}{n+4}}$$

Our Universe could have been given any value of $\theta_i \in [-\pi, \pi]$. So we can make any axion mass work as long as we choose the θ_i that gives $\Omega_a h^2 = 0.12$

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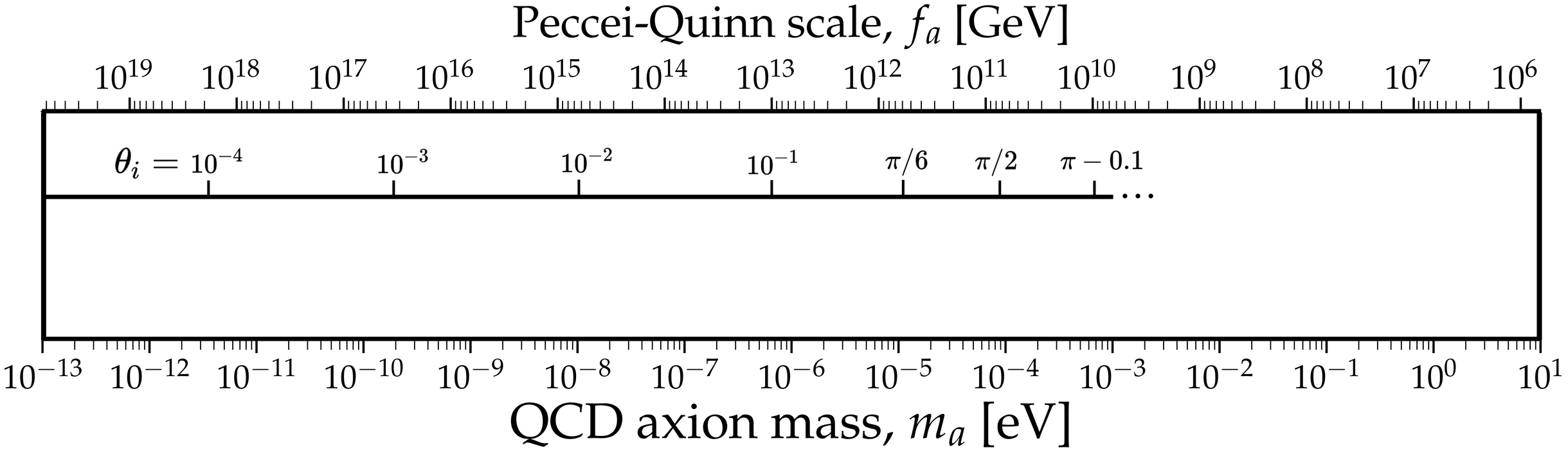

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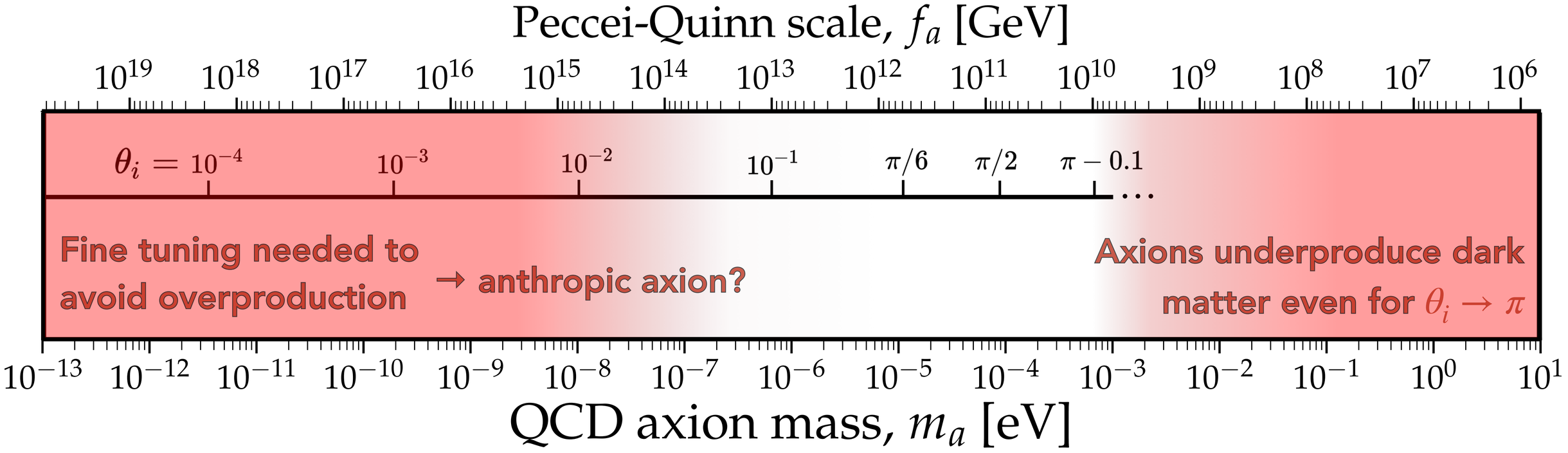


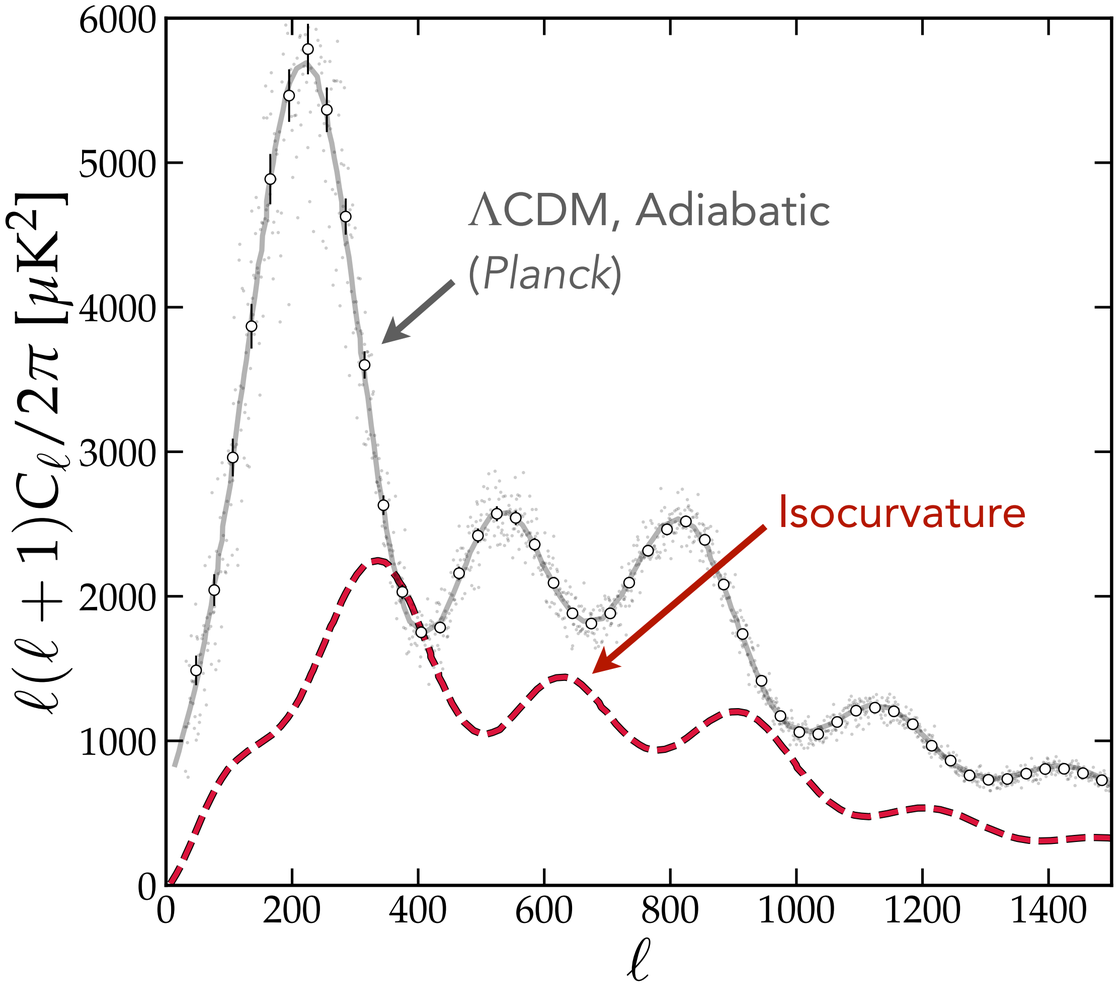
Pre-inflationary axions: isocurvature

- Axion exists as scalar d.o.f *during* inflation
  → quantum fluctuations are also inflated

$$\sigma_{\rm axion} \sim H_I/2\pi$$

- Fluctuations eventually become matter perturbations when the axion gets a mass
- This is bad: they will be *uncorrelated* with curvature fluctuations from inflaton. Such fluctuations are called **isocurvature**
- *Planck* bounds power in isocurvature to be less than <4% compared to primordial curvature perturbations.

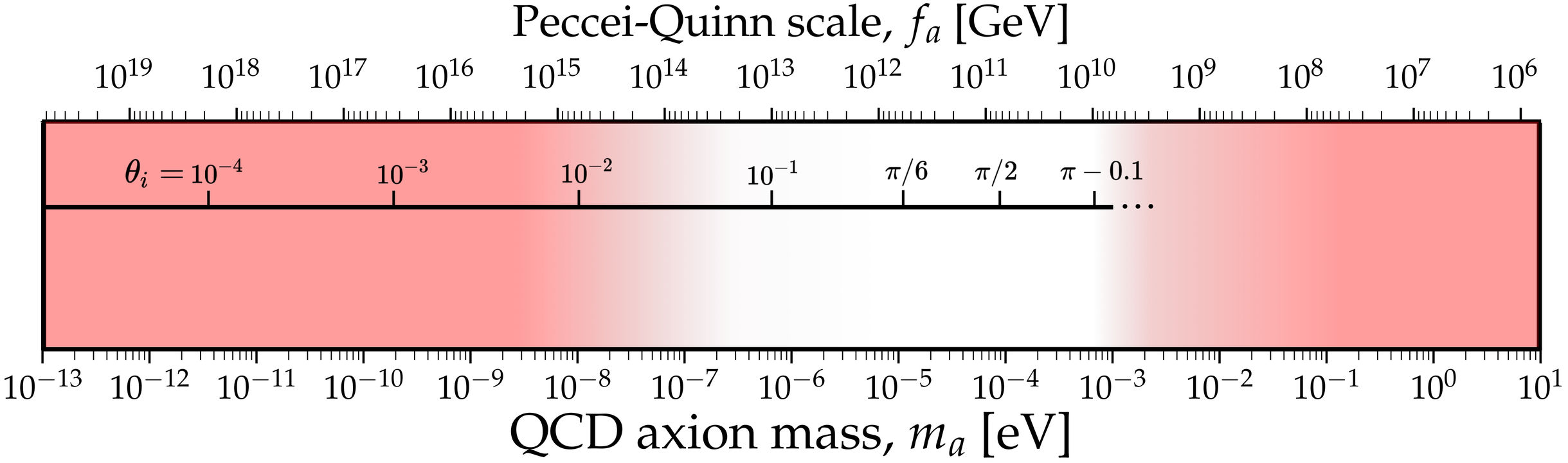
$$\beta(k_0) \equiv \frac{\Delta_a^2(k_0)}{\Delta_{\mathcal{R}}^2(k_0) + \Delta_a^2(k_0)} < 0.038$$



Pre-inflationary axions

For a given f_a the scale of inflation must be below some maximum value or axion produces too much isocurvature

$$H_I \lesssim 2.8 \times 10^8\,\mathrm{GeV} \times \theta_i \left(\frac{f_a}{10^{11}\,\mathrm{GeV}} \right)$$



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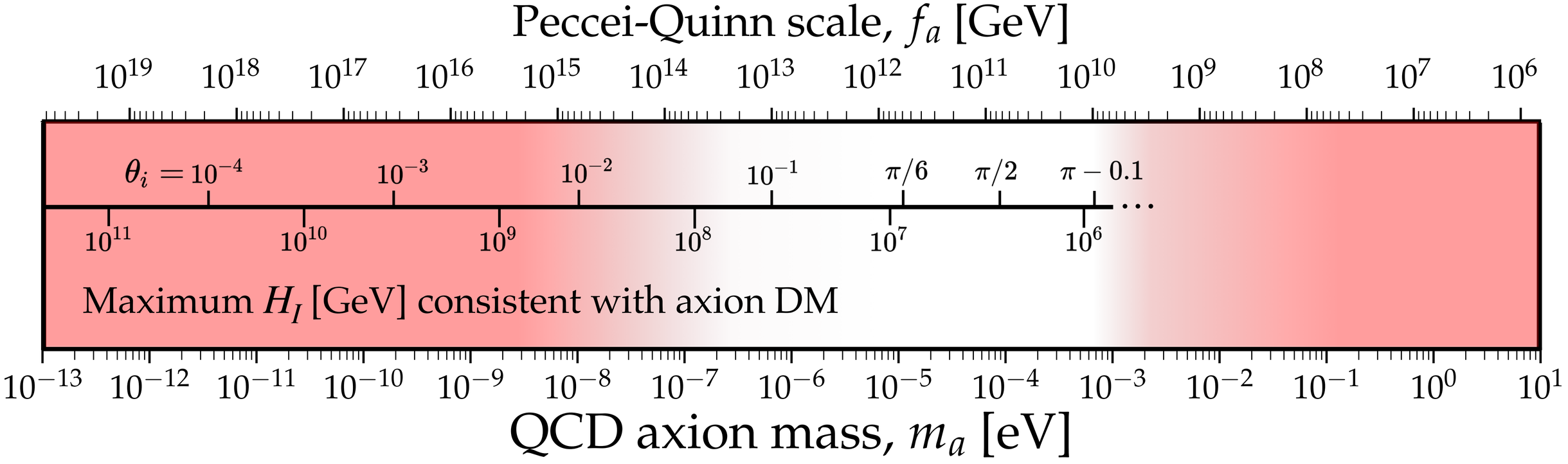
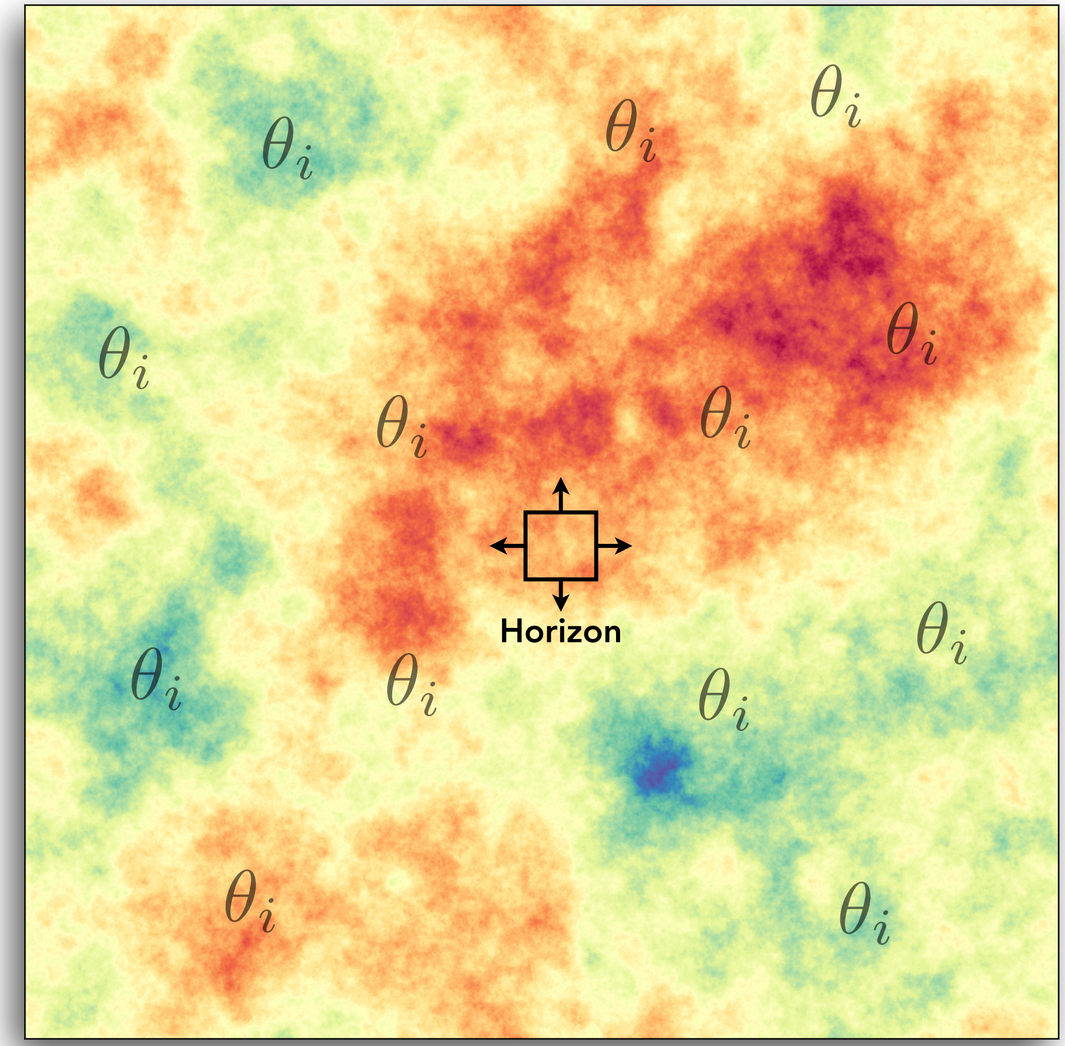


Post-inflationary scenario



Inflation has already happened *before* axion was born

→ Universe filled with many values of θ_i

→ Different value in every causal patch

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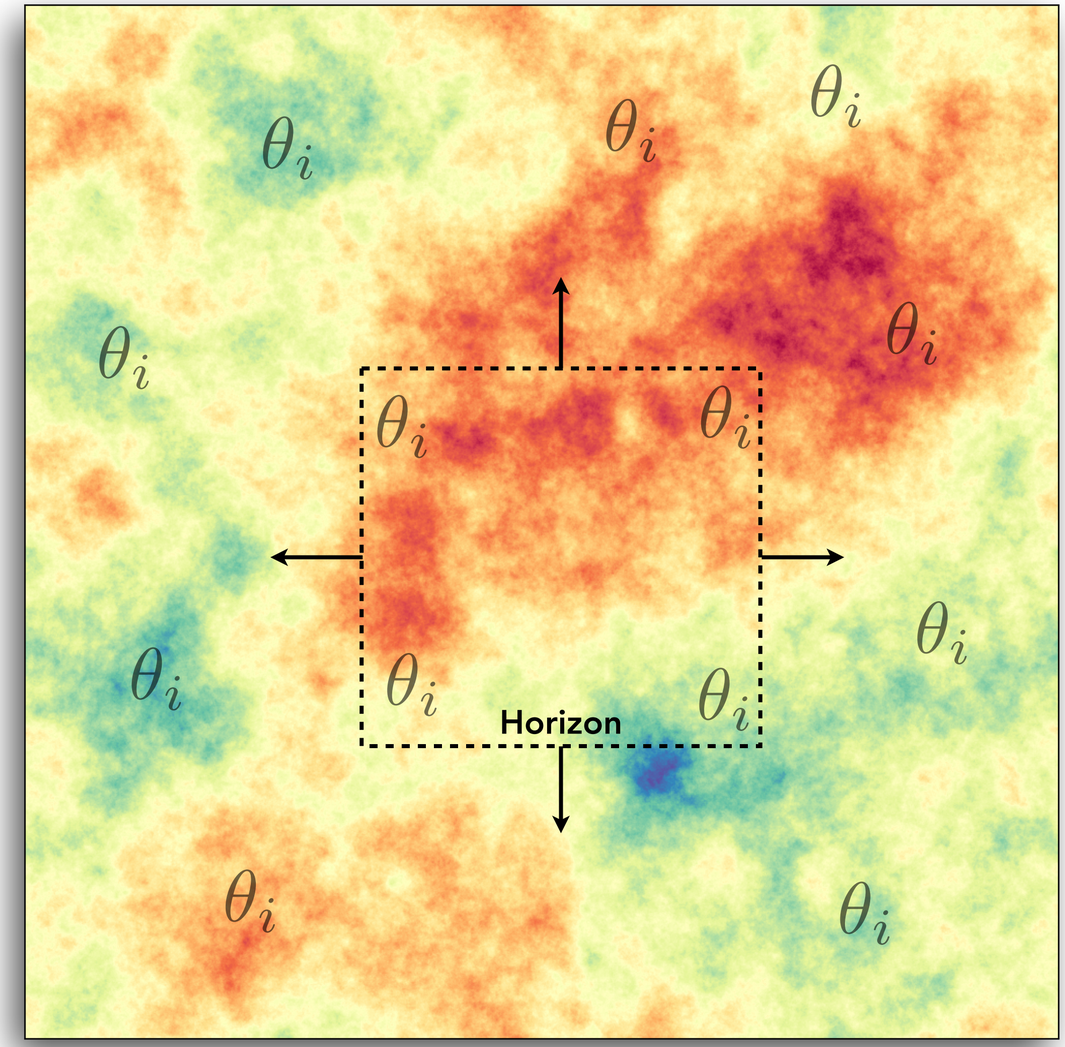


Inflation has already happened *before* axion was born

→ Universe filled with many values of θ_i

→ Different value in every causal patch

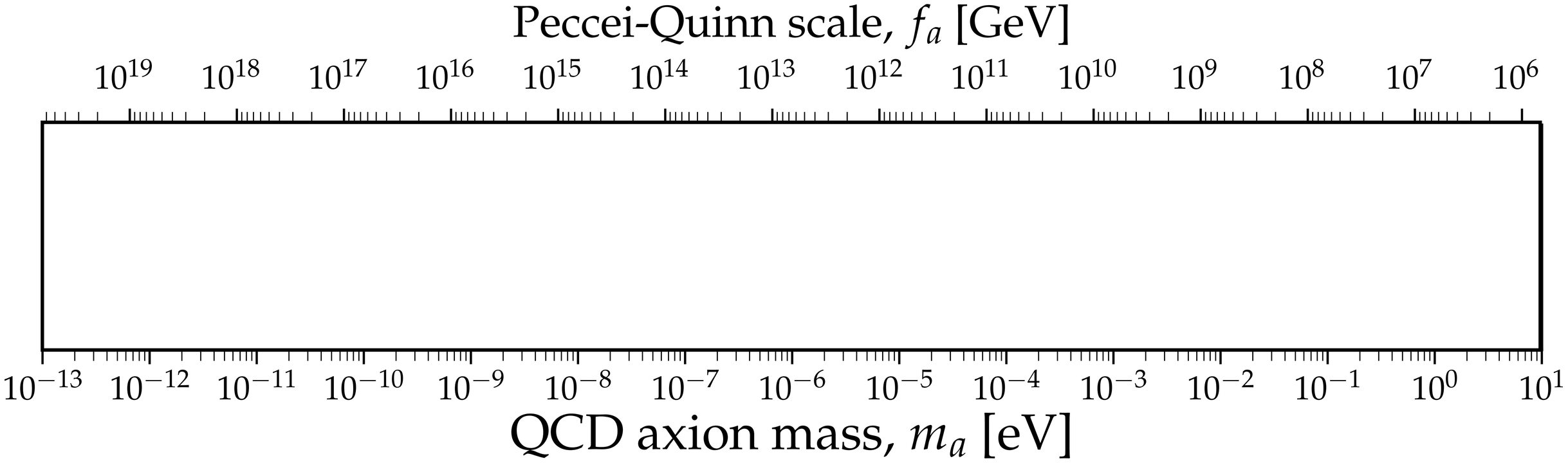
→ Patches come into contact as horizon grows.

Post-inflationary scenario

- We have an ensemble of every possible θ_i sampled across our Universe.
- Stochastic average:

$$\langle \theta_i^2 \rangle \approx \left(\frac{\pi}{\sqrt{3}} \right)^2 \approx (1.81)^2$$

$$\Omega_a h^2 \approx 0.12 \frac{\langle \theta_i^2 \rangle}{(1.81)^2} \left(\frac{20 \mu\text{eV}}{m_a} \right)^{\frac{n+6}{n+4}}$$

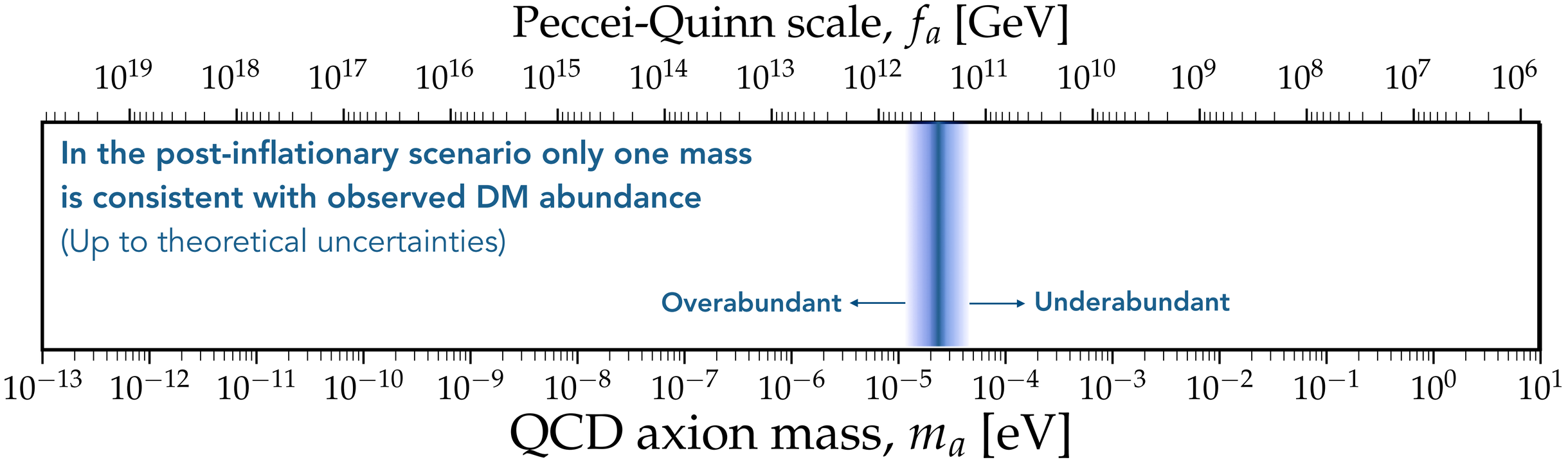


Post-inflationary scenario

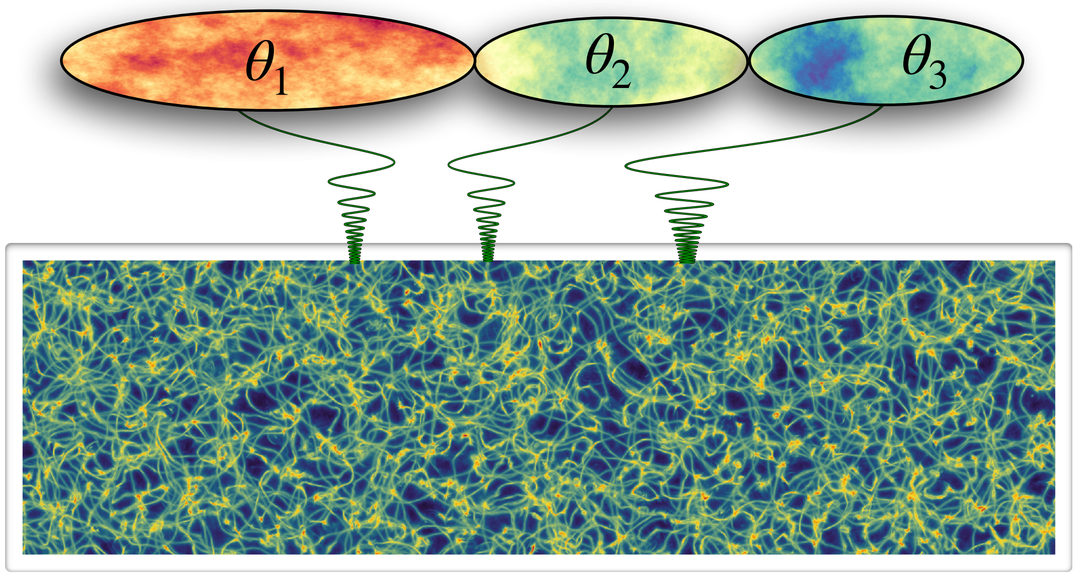
- We have an ensemble of every possible θ_i sampled across our Universe.
- Stochastic average:

$$\langle \theta_i^2 \rangle \approx \left(\frac{\pi}{\sqrt{3}} \right)^2 \approx (1.81)^2$$

$$\Omega_a h^2 \approx 0.12 \frac{\langle \theta_i^2 \rangle}{(1.81)^2} \left(\frac{20 \mu\text{eV}}{m_a} \right)^{\frac{n+6}{n+4}}$$



But there's a complication: $\nabla\theta$



Different patches meet up

→ Field gradients!

$$\ddot{\theta} + 3H\dot{\theta} - \frac{1}{a^2}\nabla^2\theta + m_a^2\theta = 0$$

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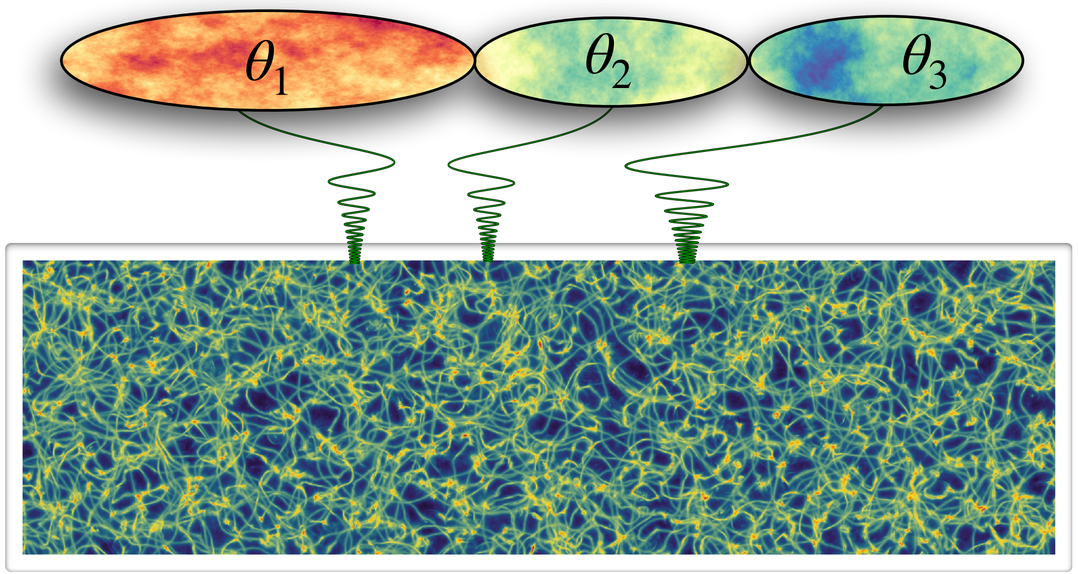

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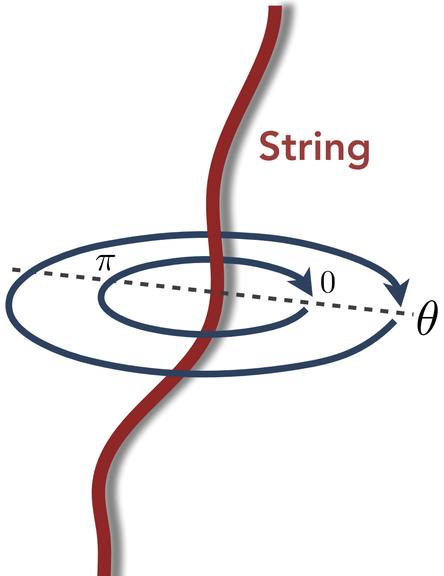
⇒ **Cosmic strings**

from axion field

winding around 2π



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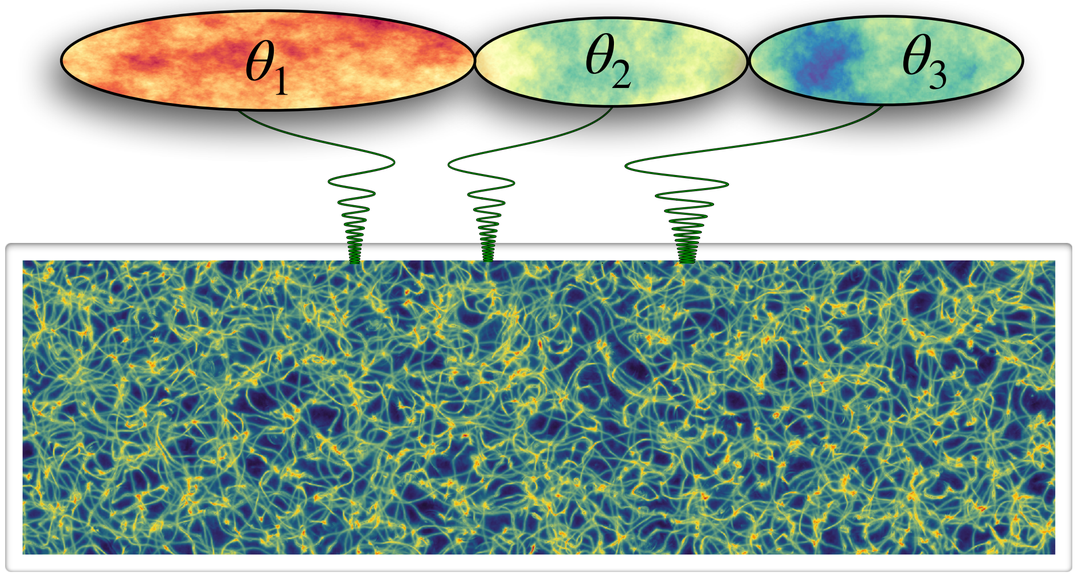

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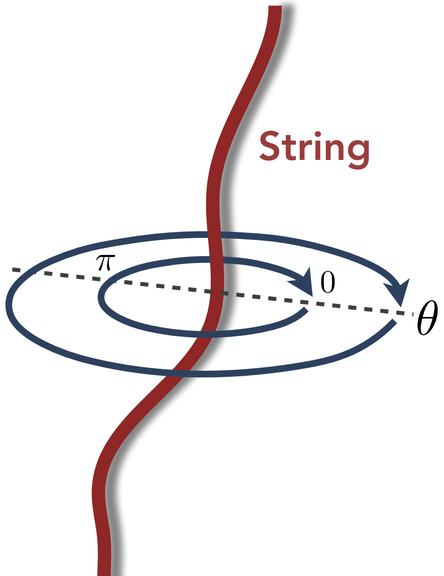
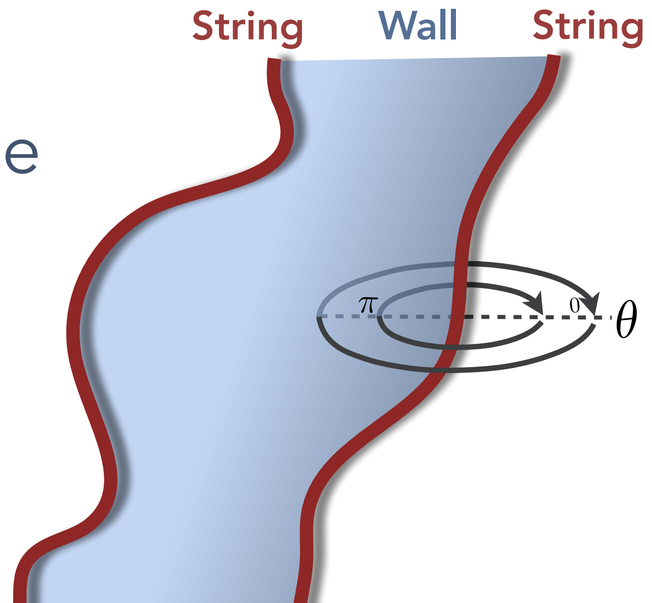


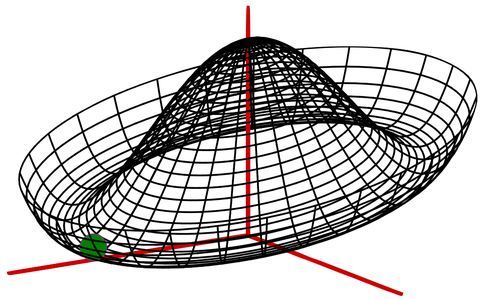
⇒ **Domain walls**

between true/false

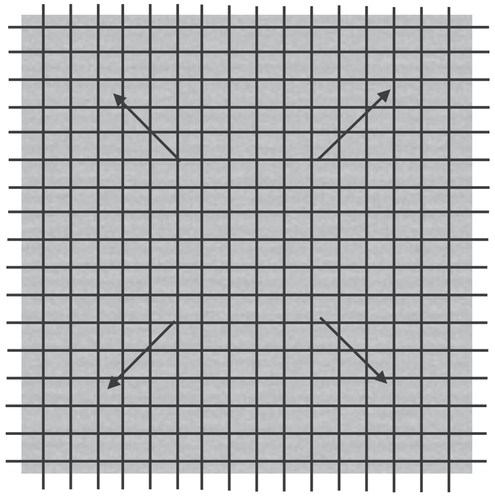
vacuum (0 and π)



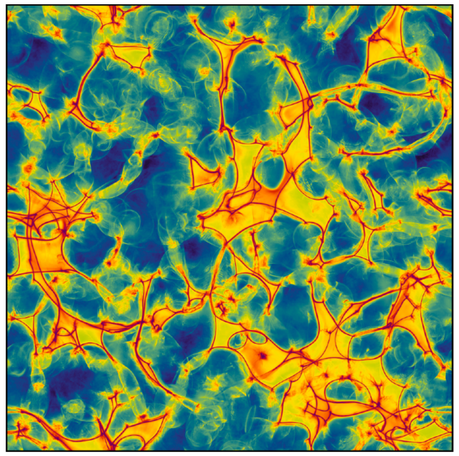
Brute force solution: simulate



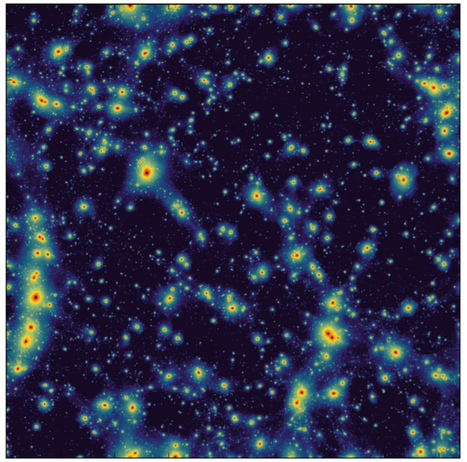
Evolve the axion field…



…on an expanding lattice…



…to measure the relic abundance of axions…



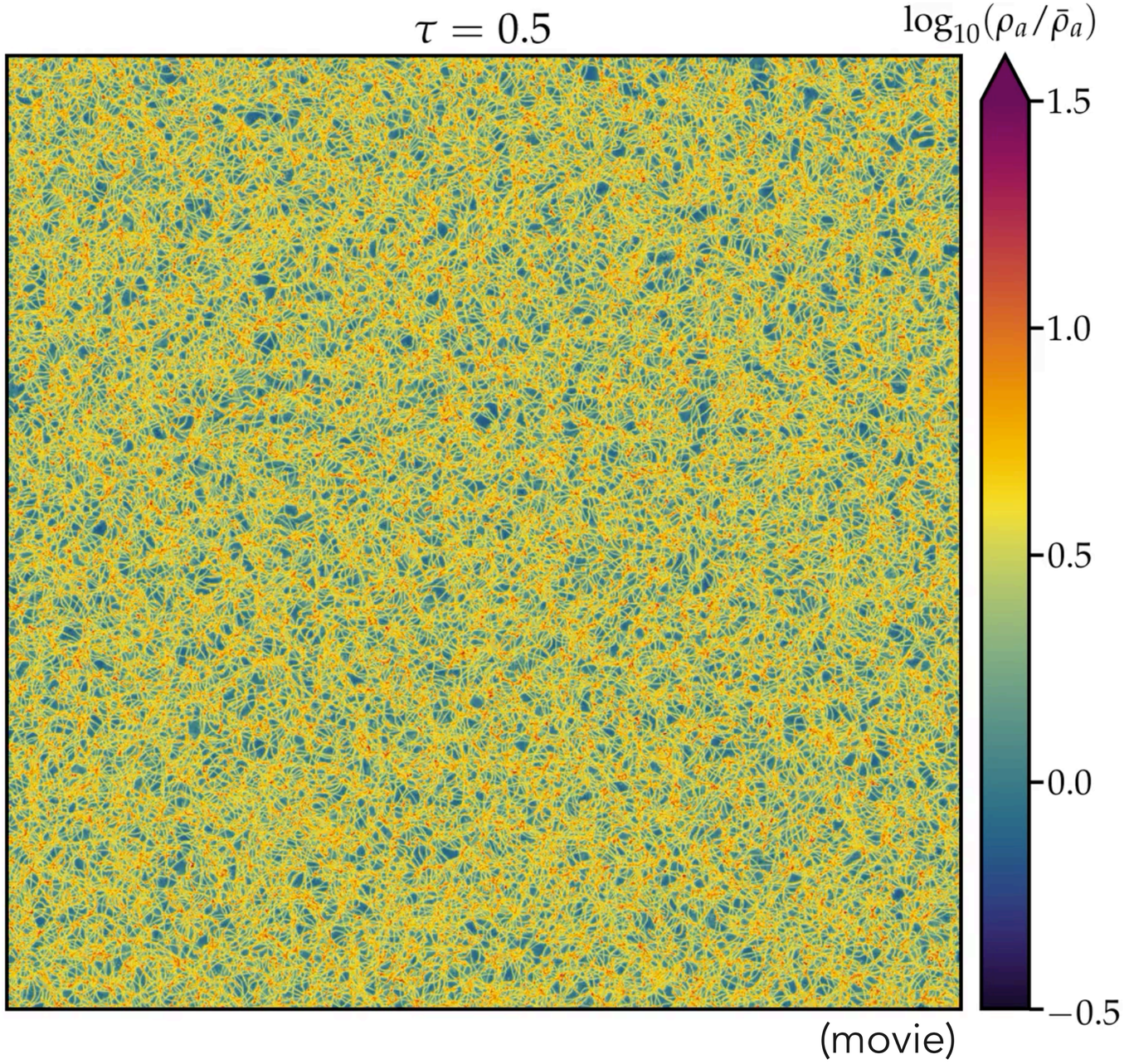
…and predict its present day distribution

Gorghetto+[2007.04990], Buschmann+ [2108.05368], Vaquero+ [1809.09241], O'Hare+ [2112.05117]

Evolution of the axion field in the post-inflationary scenario

Projection through 3D co-moving box, coloured by integrated axion energy density:

$$\rho_a = \frac{1}{2}\dot{a}^2 + \frac{1}{2R^2}(\nabla a)^2 + \chi\left(1 - \cos a/f_a\right)$$



(movie)

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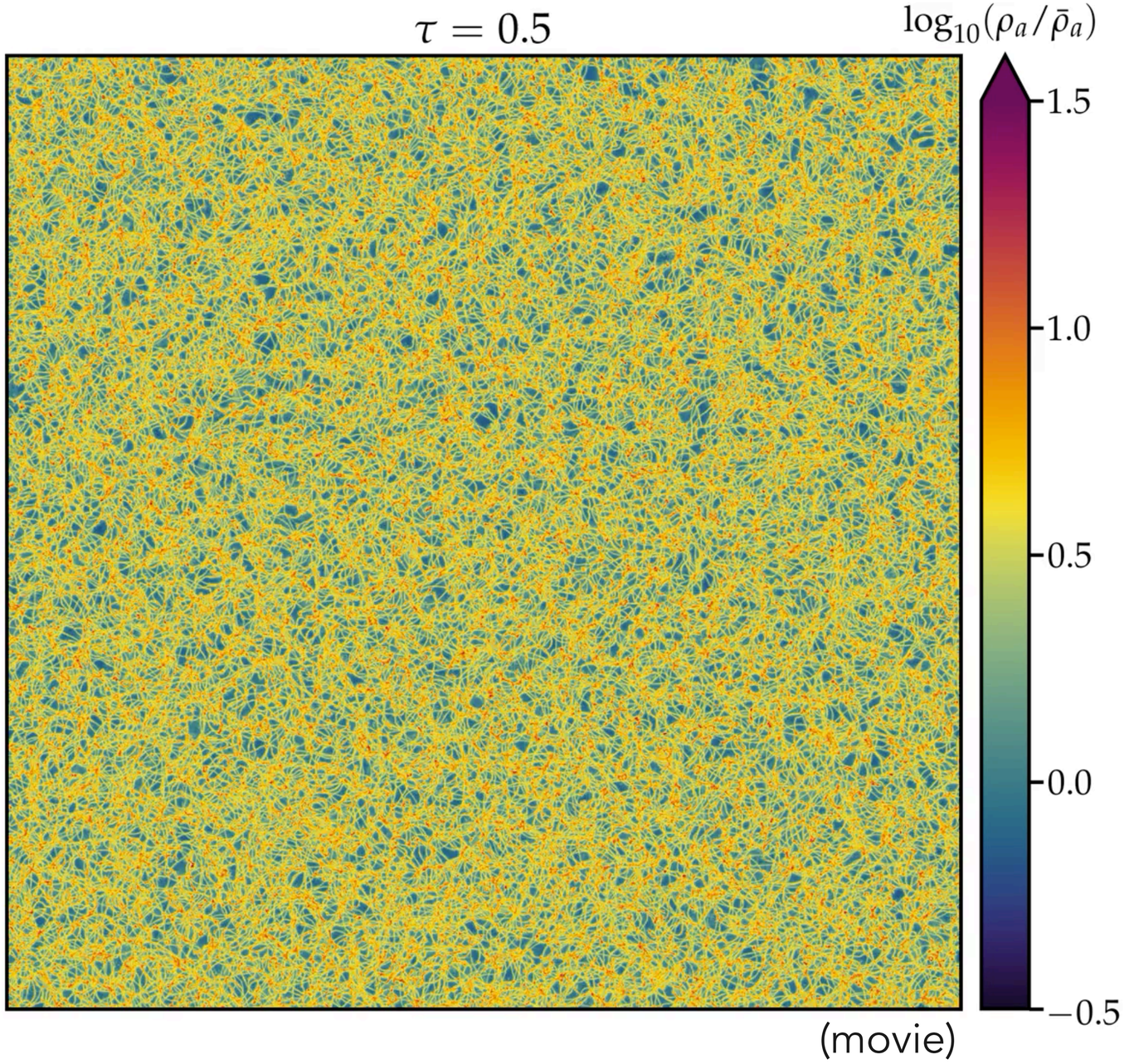

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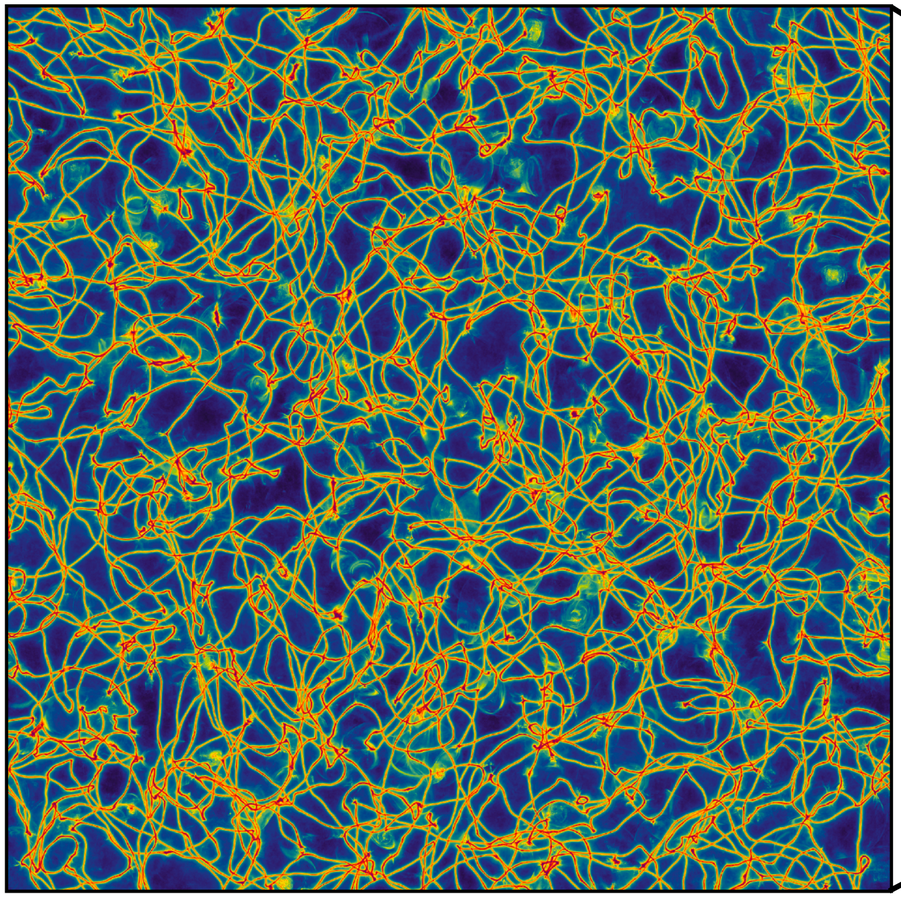
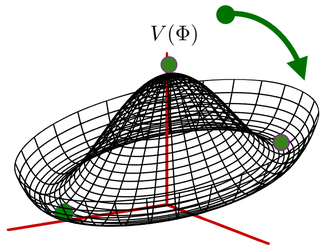




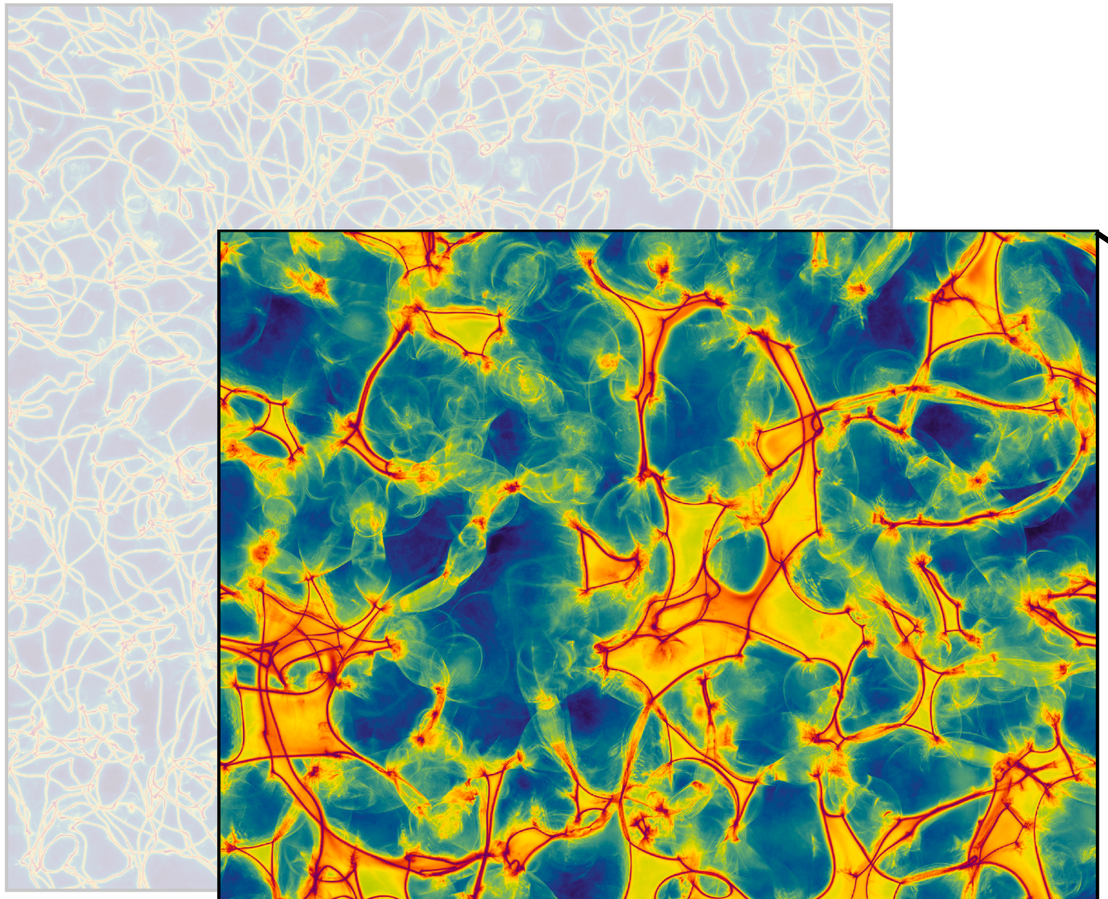
PQ

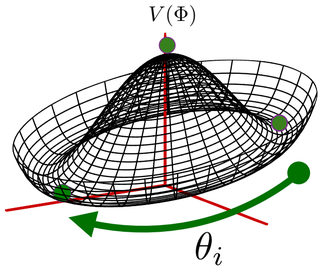
QCD

z_{eq}

String network scaling

Evolution of the axion field in the post-inflationary scenario





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String network scaling

Domain walls attached to strings
→ network collapses

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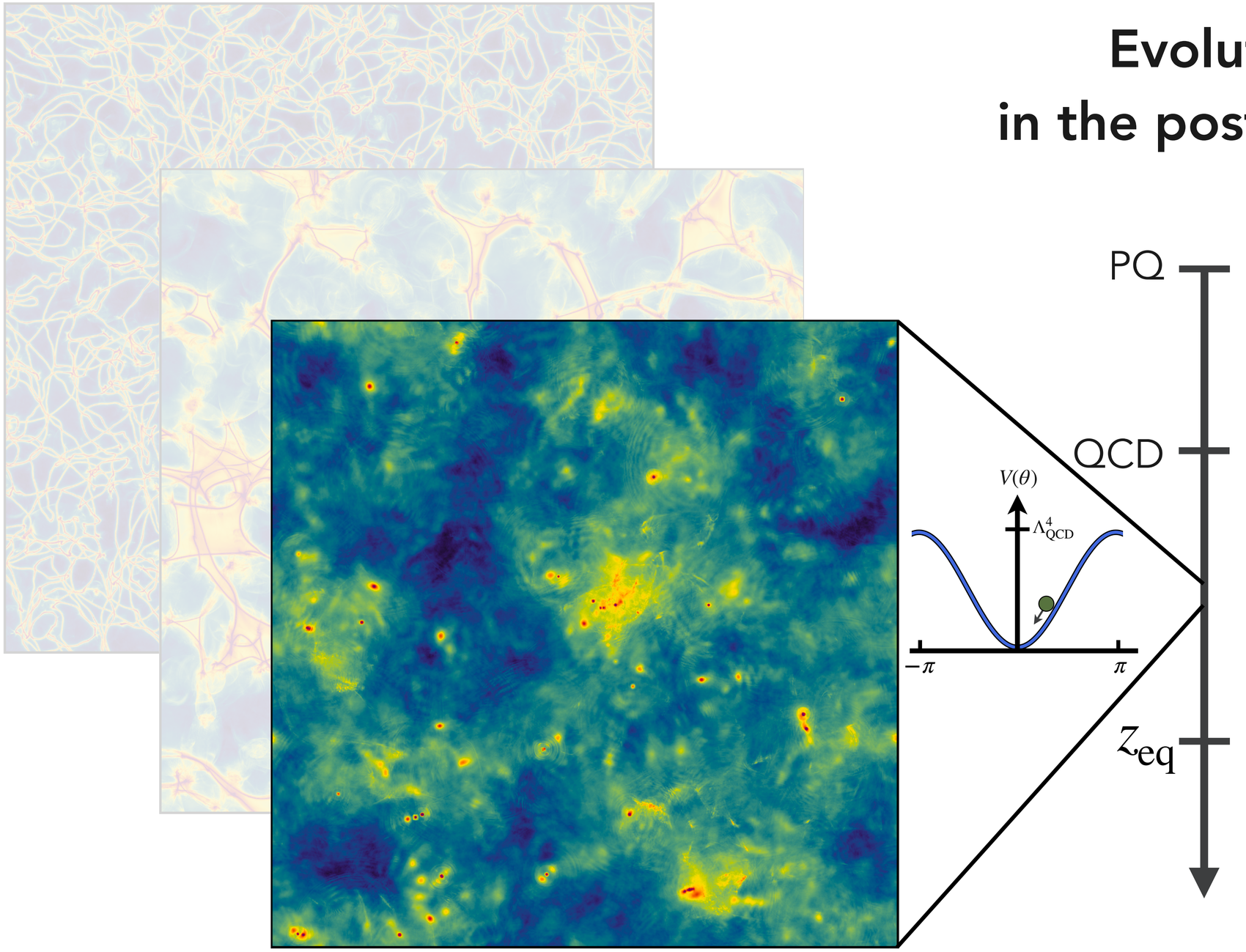


String network scaling

Domain walls attached to strings
→ network collapses

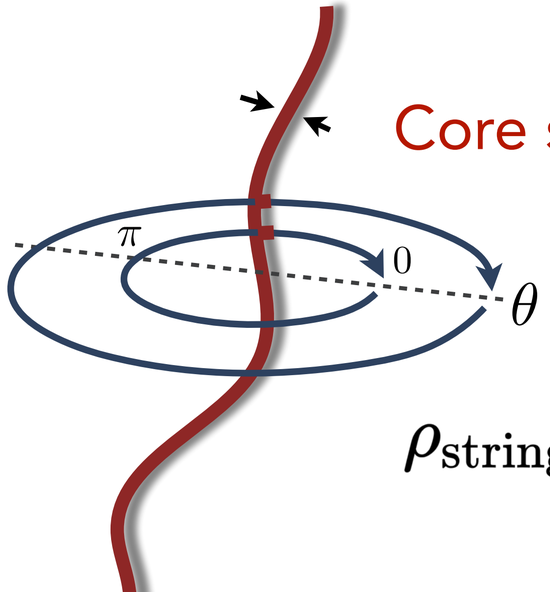
Inhomogeneous distribution of axions free streams until non-relativistic

Seeds of structure gravitationally collapse into miniclusters and halos

Axion string network

Network is expected to enter a "scaling solution" where strings straighten and loops collapse at roughly the same rate as the horizon grows

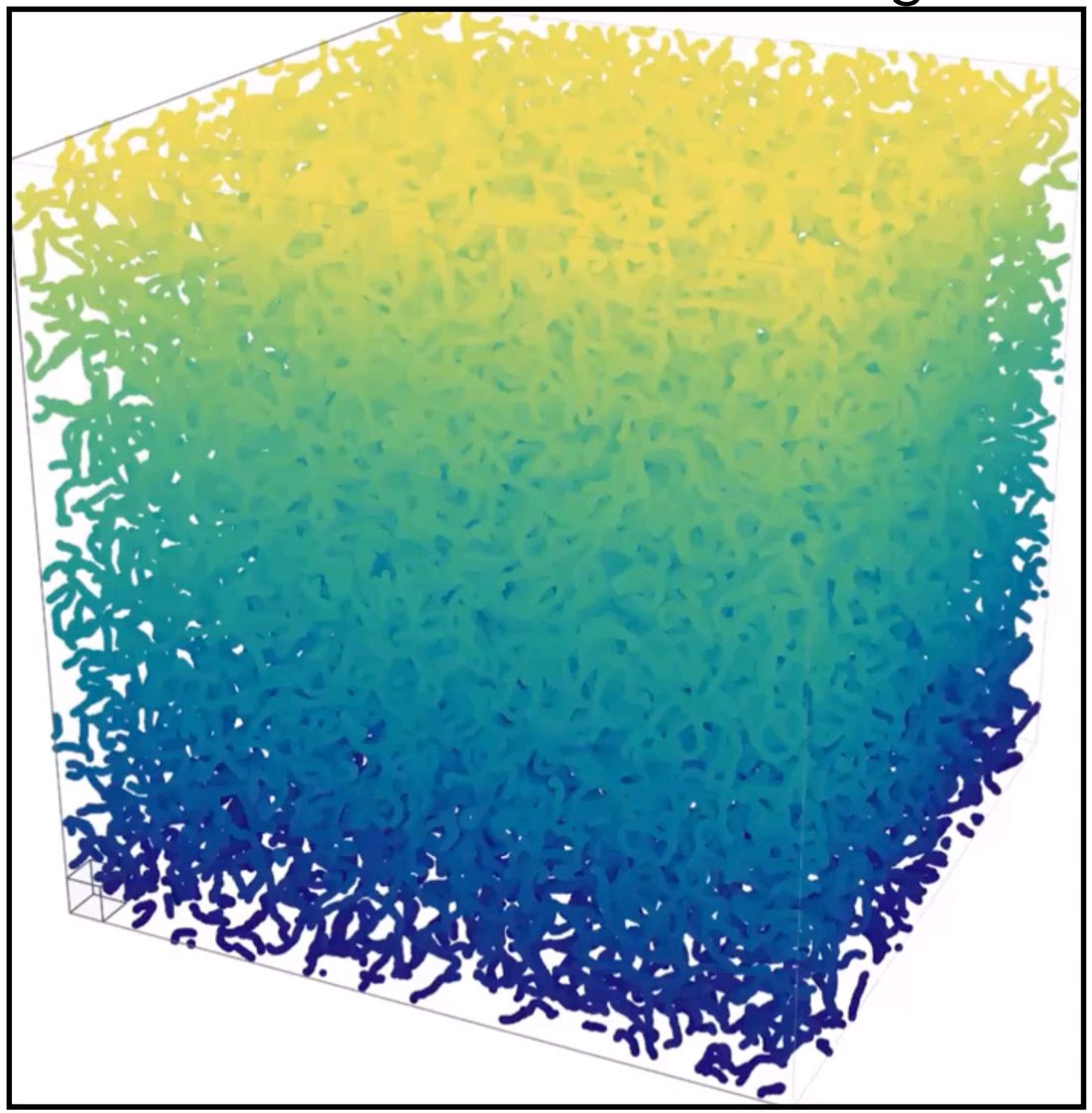
→ Number of strings per Hubble volume, $\xi(t)$ = const. + log-violations



Core size set by $m_r \sim \sqrt{\lambda} f_a$

$$\rho_{\text{strings}} \sim \xi \times f_a^2 H^2 \log \frac{m_r}{H}$$

M. Gorghetto



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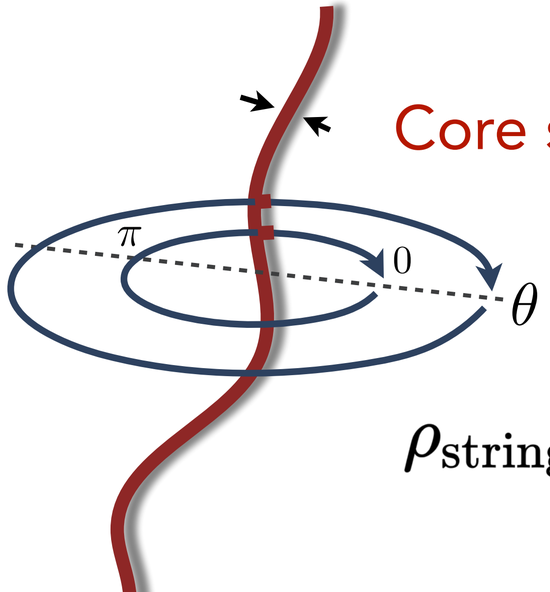

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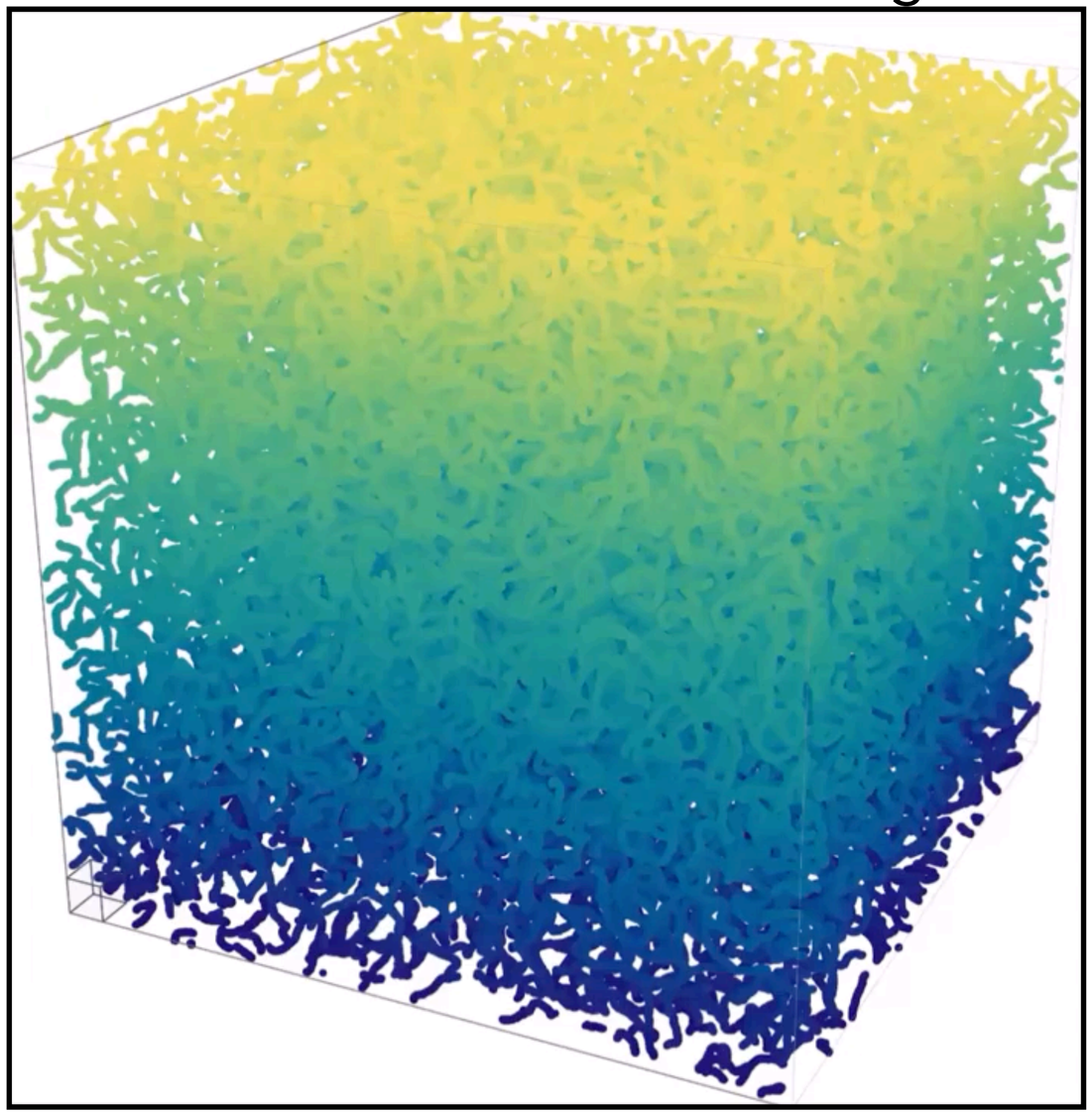
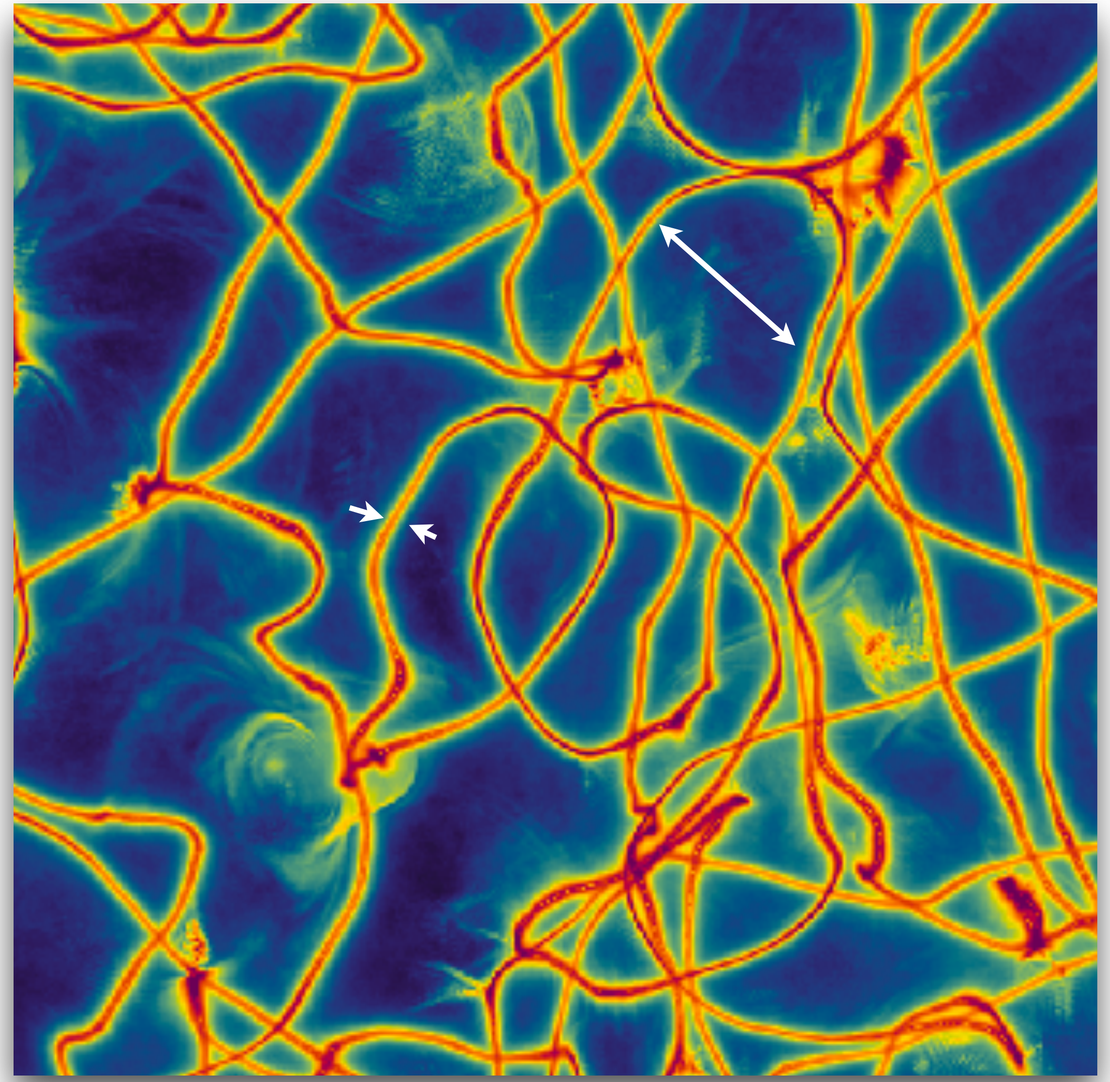


Axion string simulation limitations



Required dynamical range:

Largest scale = Inter-string spacing ~ $H(t)^{-1}$

Smallest scale = string core size = $m_r^{-1} \sim f_a^{-1}$

- Dynamical range is a function of time, so m_r/H gets larger (strings shrink in co-moving coords)
- For physical QCD axion models need to get to $\log(m_r/H) \rightarrow \sim 70$
- With ~8000^3 lattice sites can do up to $\log(m_r/H)$~6—9

Axion string radiation uncertainties

Currently not fully understood what will be the ultimate spectrum of axions radiated from strings

Num. density of axions when they become DM $= \int_{k_{\rm IR}}^{k_{\rm UV}} \frac{{\rm d}k}{k} \frac{\partial \rho_{\rm string}}{\partial k}$

UV dominated (q<1)

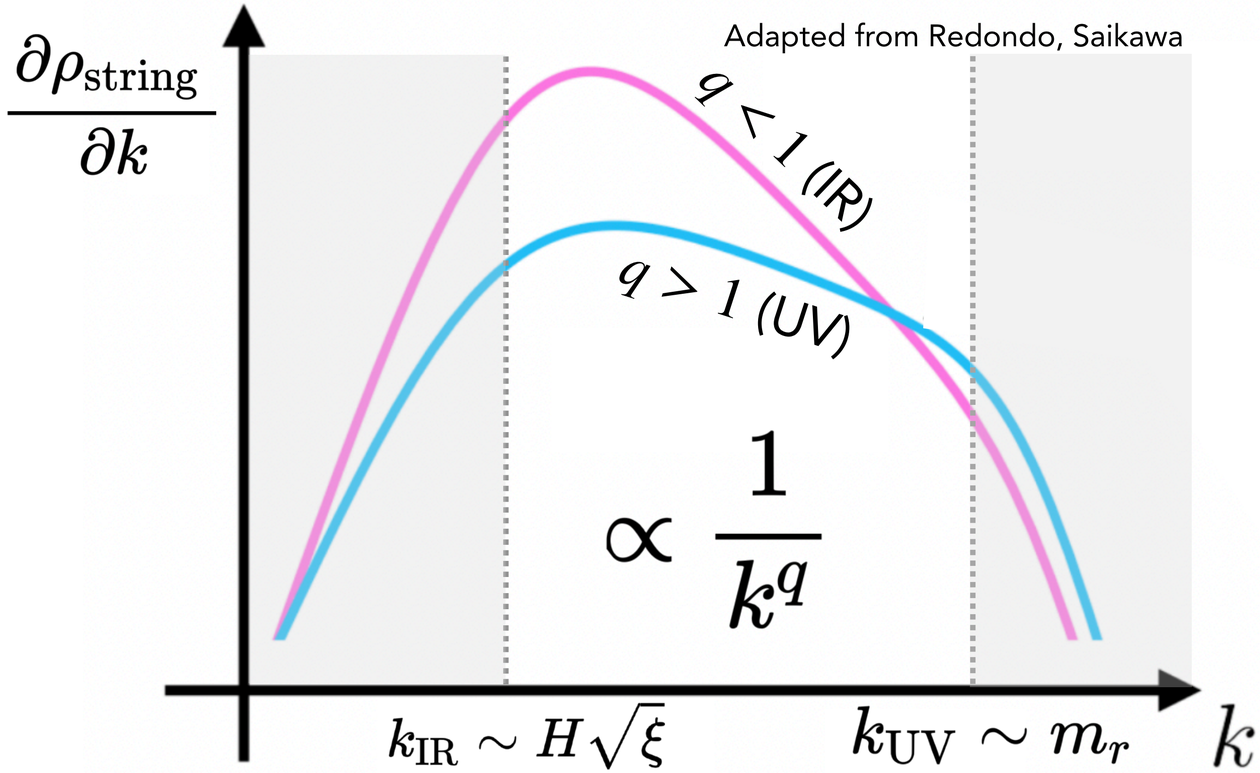
→ Most radiation comes from string cusps and loops (fewer axions)

IR dominated (q>1)

→ More radiation comes from straightening of long strings (more axions)

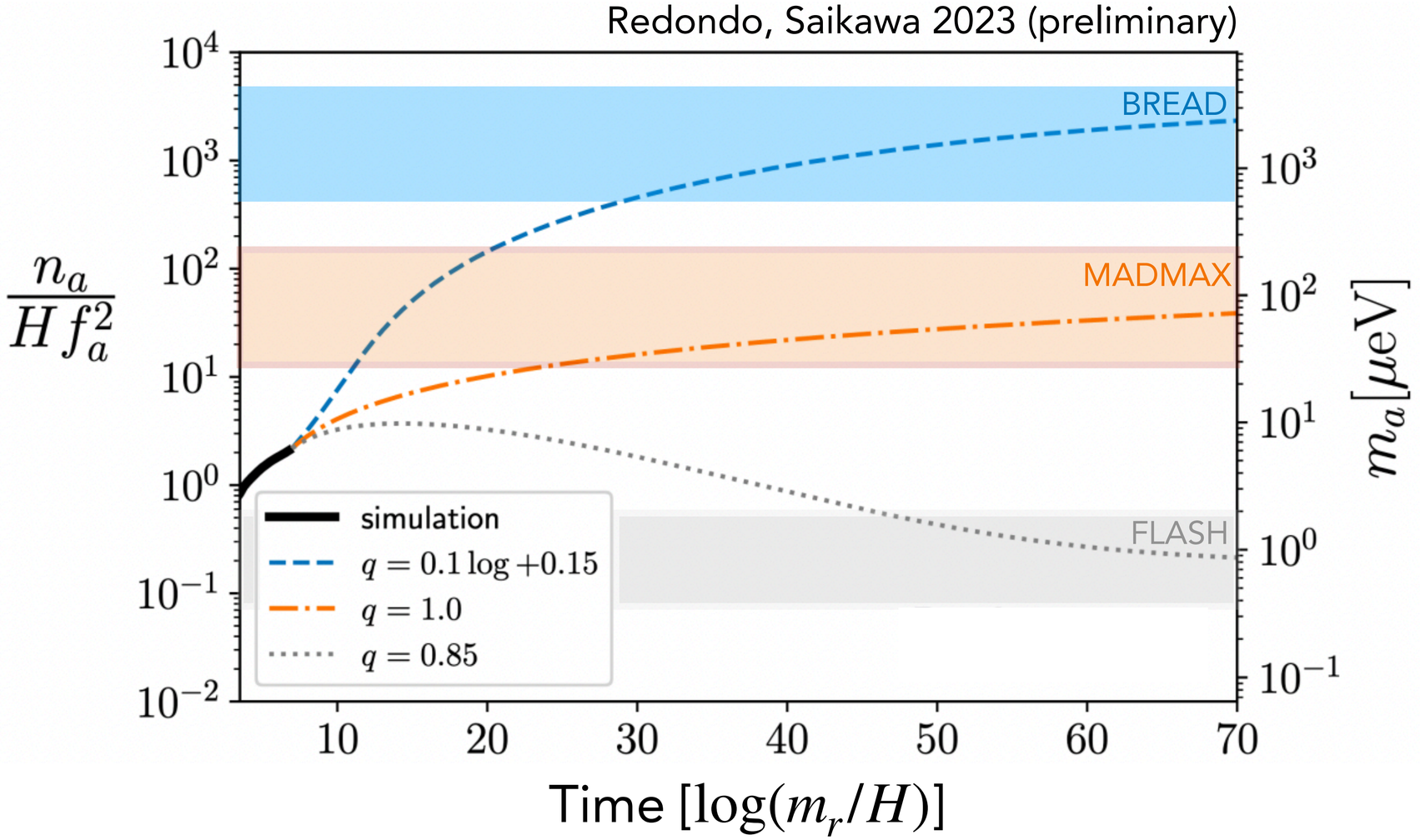
Scale invariant (q=1)? e.g. [2108.05368]

→ Equal axions from each decade in k



Axion string radiation uncertainties

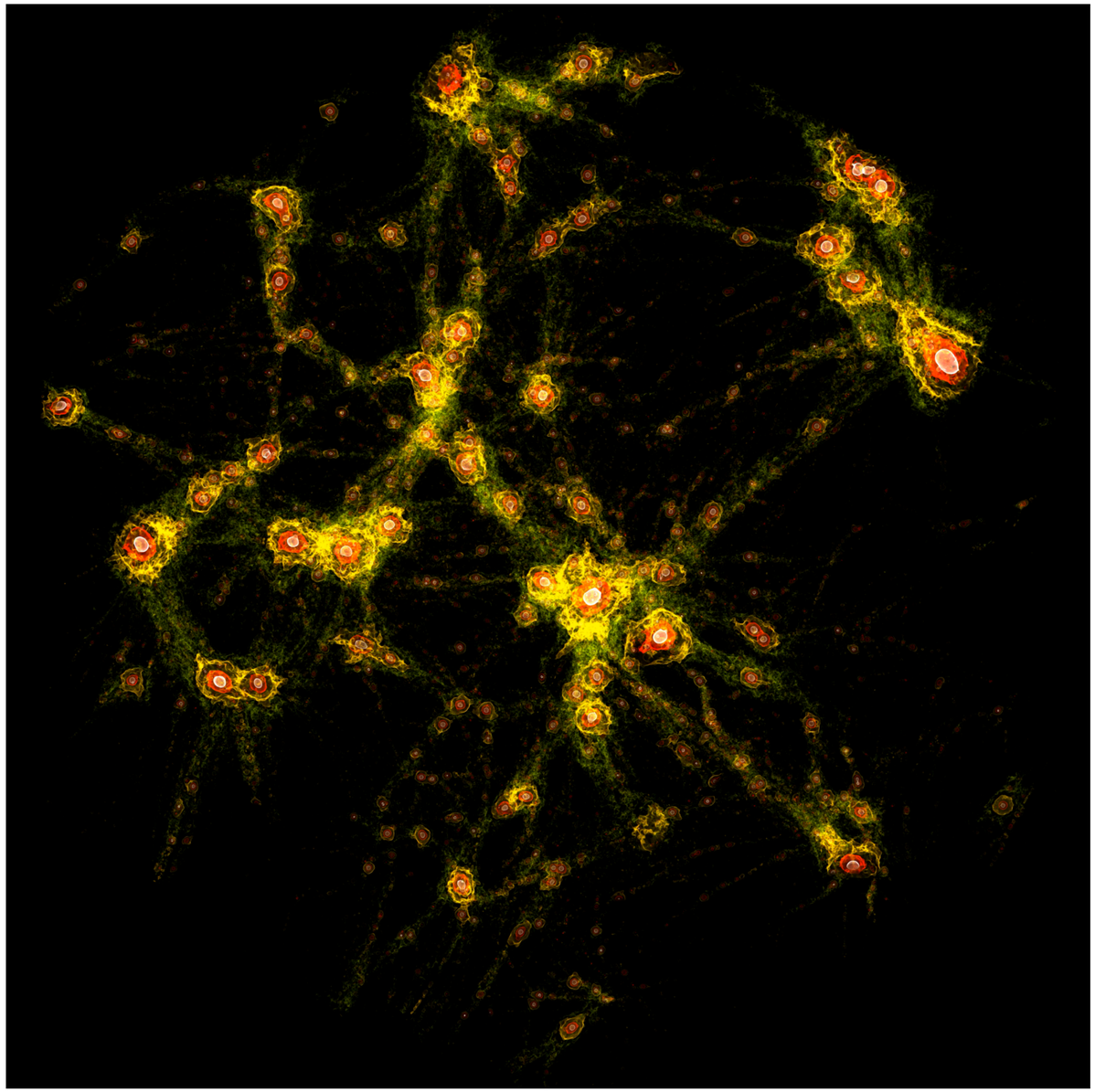
Extrapolating beyond the end of the simulations could be treacherous and has large consequences for axion mass prediction



After t_{QCD} axion field forms quasi-stable solitons that lay down small-scale perturbations

These eventually form AU—mpc gravitationally bound clumps of axions with masses
$M \in [10^{-15}, 10^{-9}]\ M_{\odot}$

→ **axion miniclusters**



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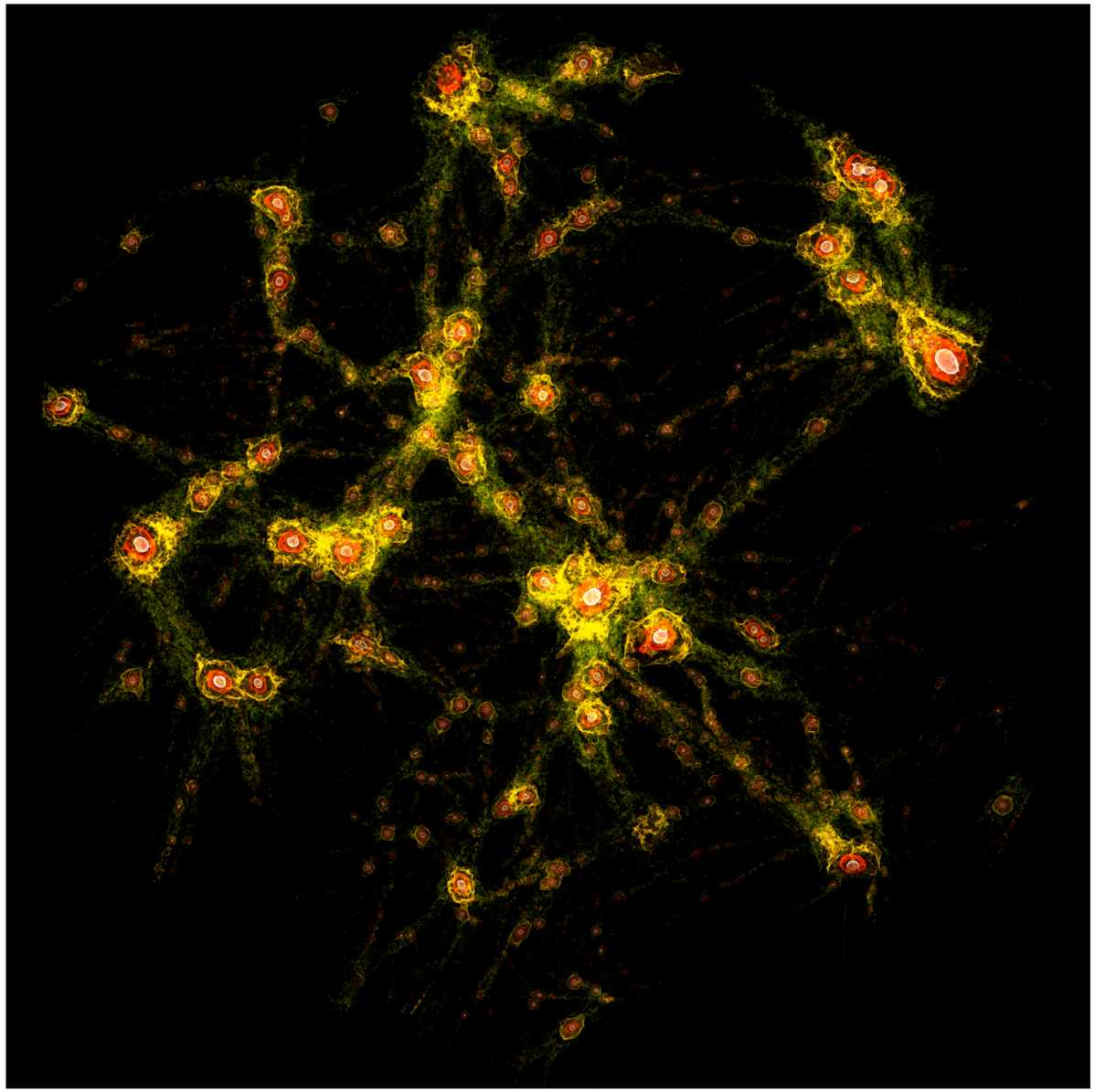
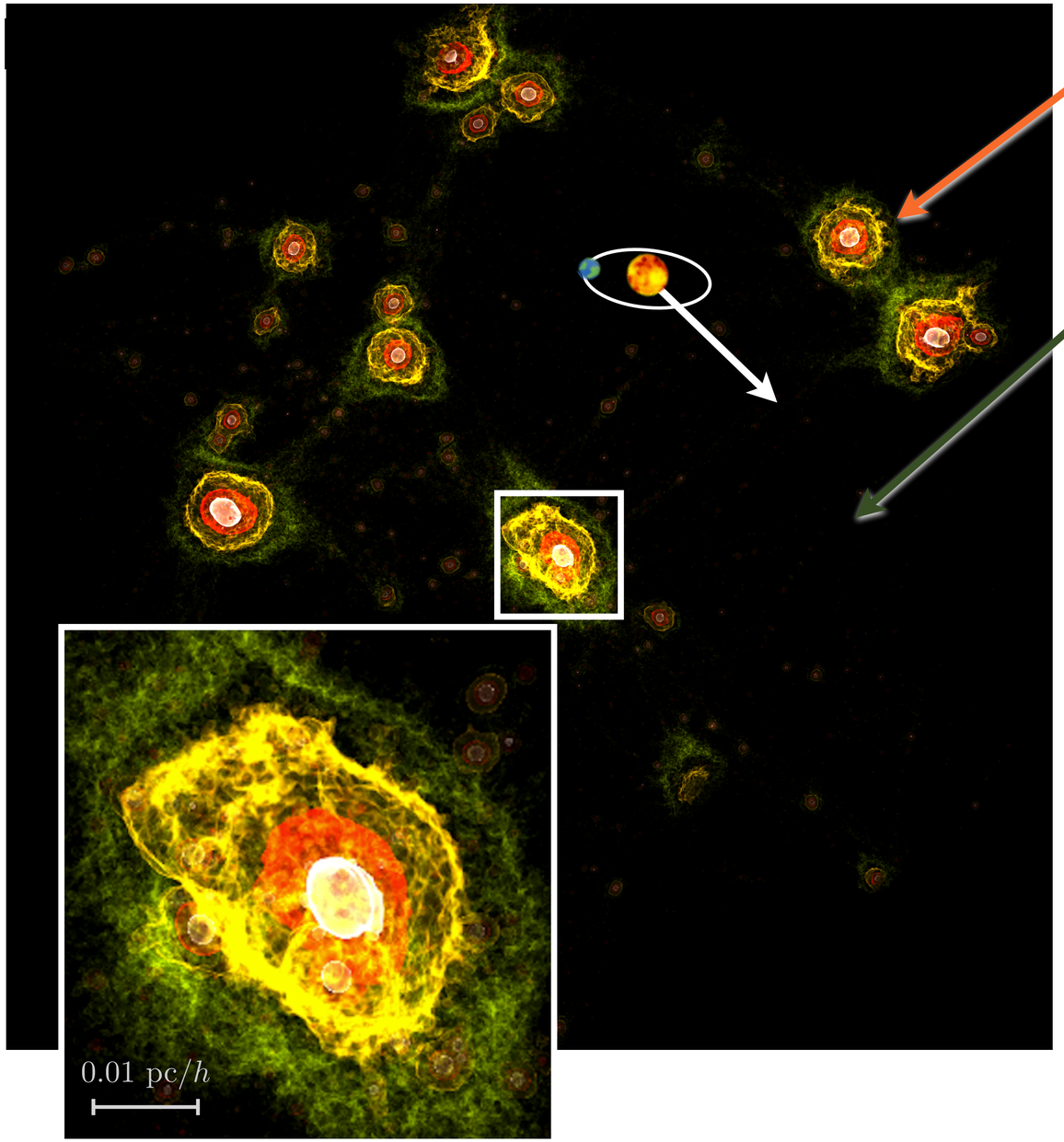




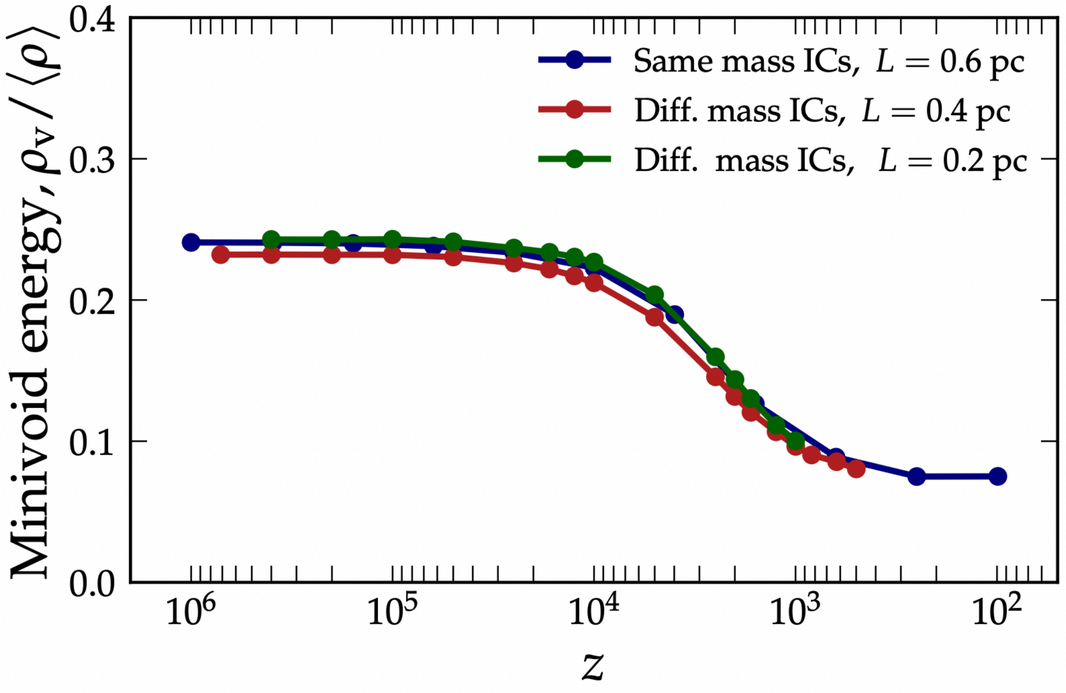
Miniclusters

Minivoids

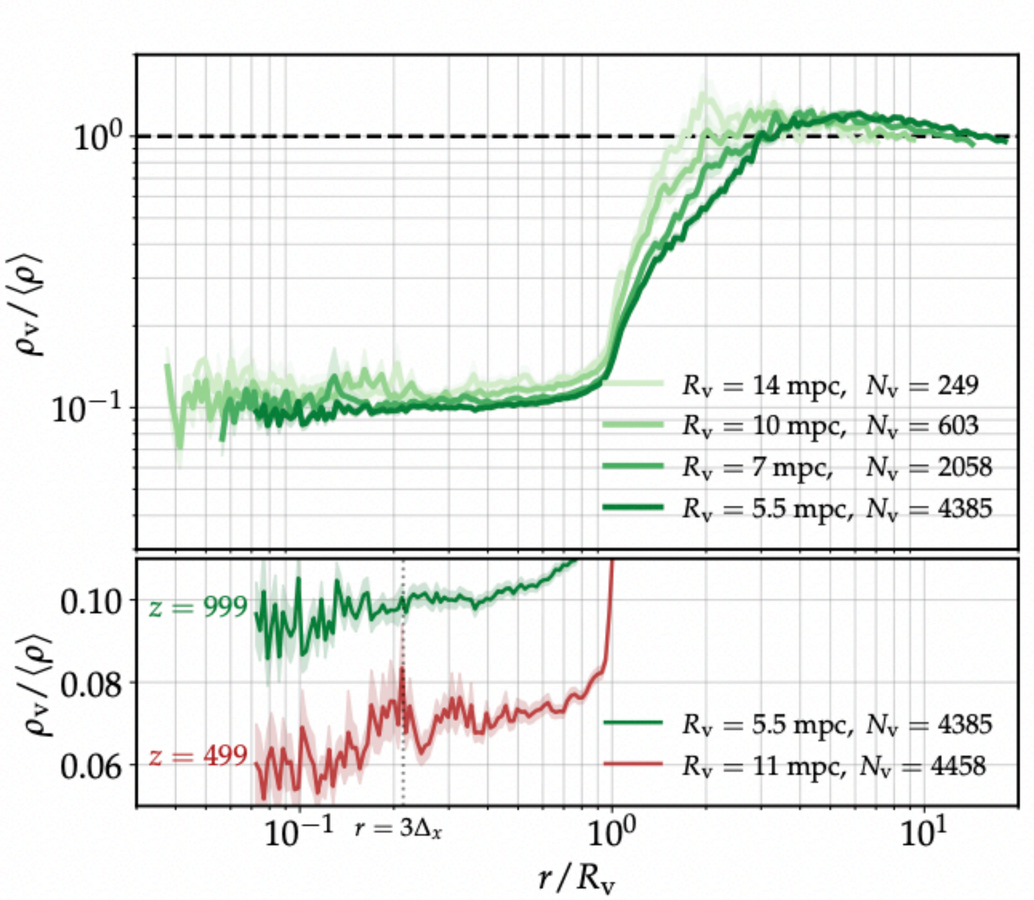
Miniclusters contain >80% of the axions but make up <1% of the volume

Earth travels through galaxy at about 0.2 mpc per year, so experiments are much more likely to sample the mini*voids* than the mini*clusters*

Minivoids are mostly stable by final simulation time (z~100)



Typical "worst case scenario" density would be inside the minivoids ~10% of large-scale average density

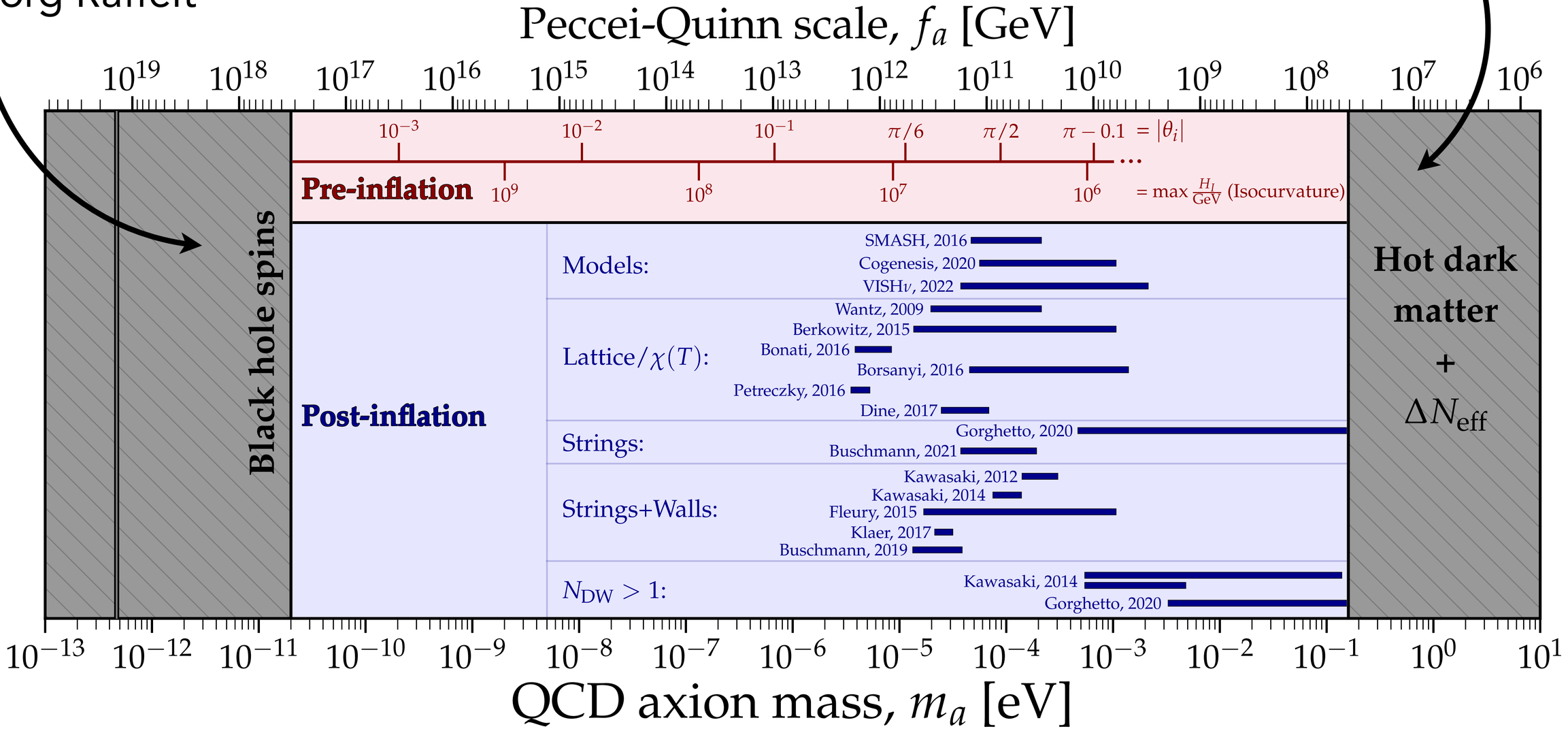


Eggemeier, CAJO+ [2212.00560]

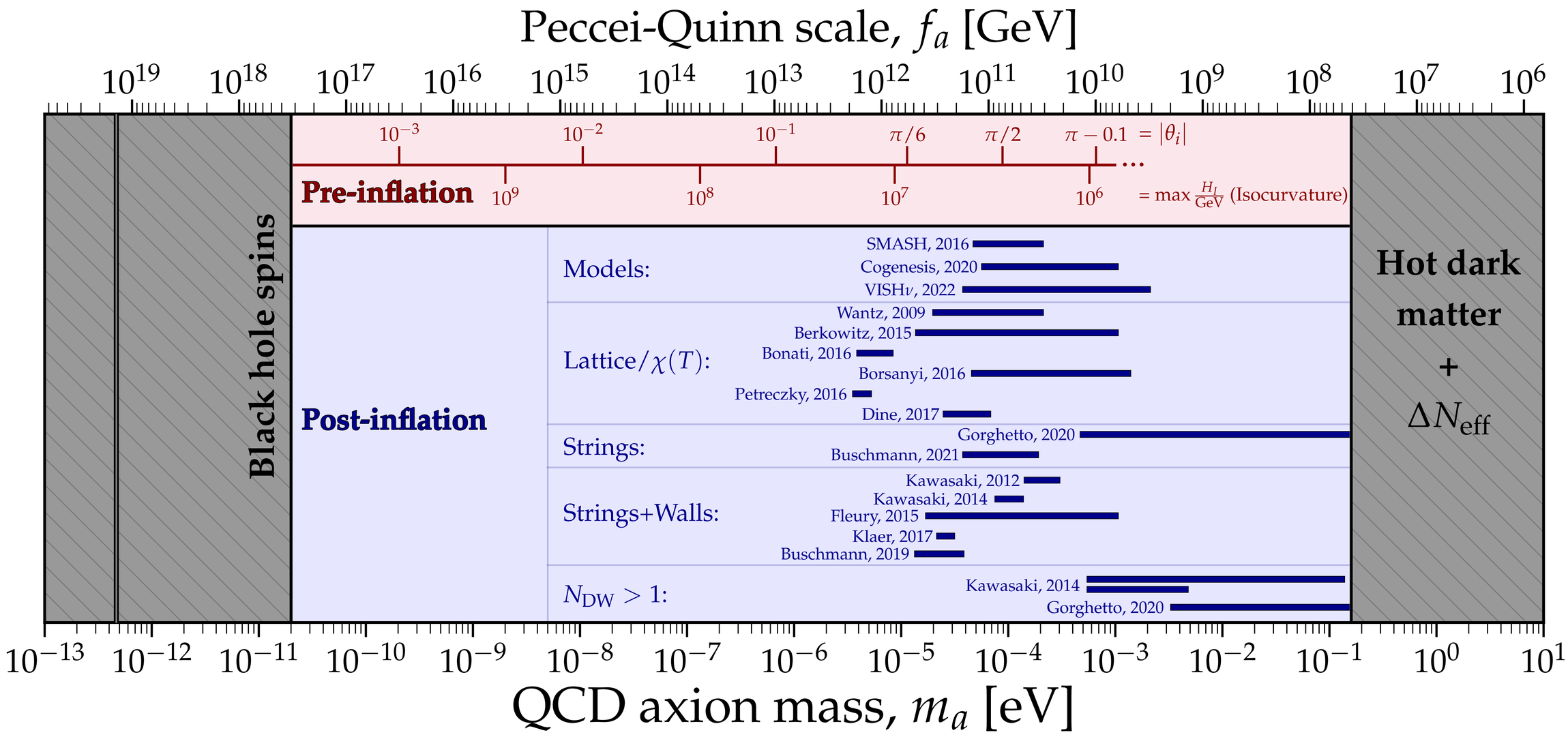
Summary of axion mass post-dictions

See lecture by Georg Raffelt

Next lecture



github.com/cajohare/AxionLimits



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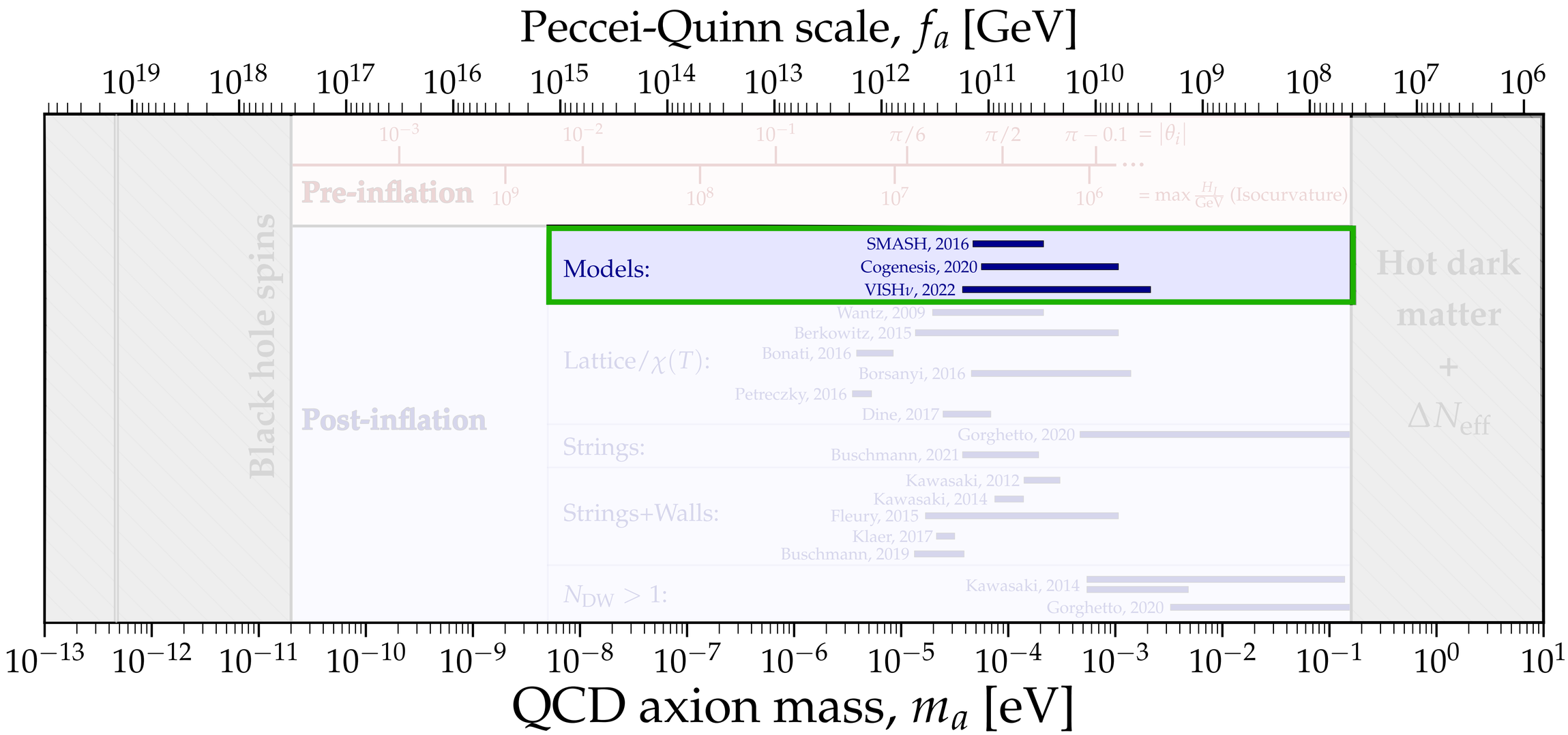

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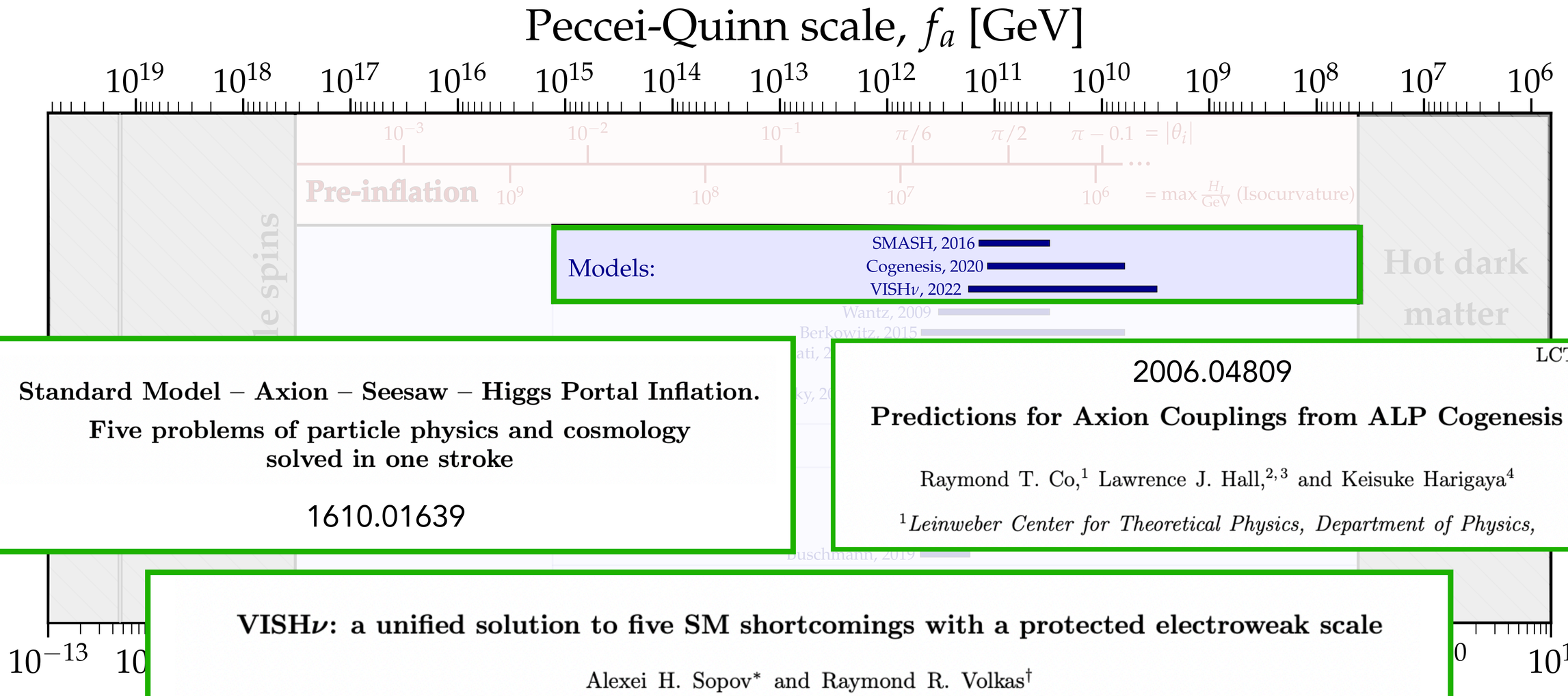


Standard Model – Axion – Seesaw – Higgs Portal Inflation.
Five problems of particle physics and cosmology solved in one stroke

1610.01639

LCTP

2006.04809

Predictions for Axion Couplings from ALP Cogenesis

Raymond T. Co,[1] Lawrence J. Hall,[2,3] and Keisuke Harigaya[4]

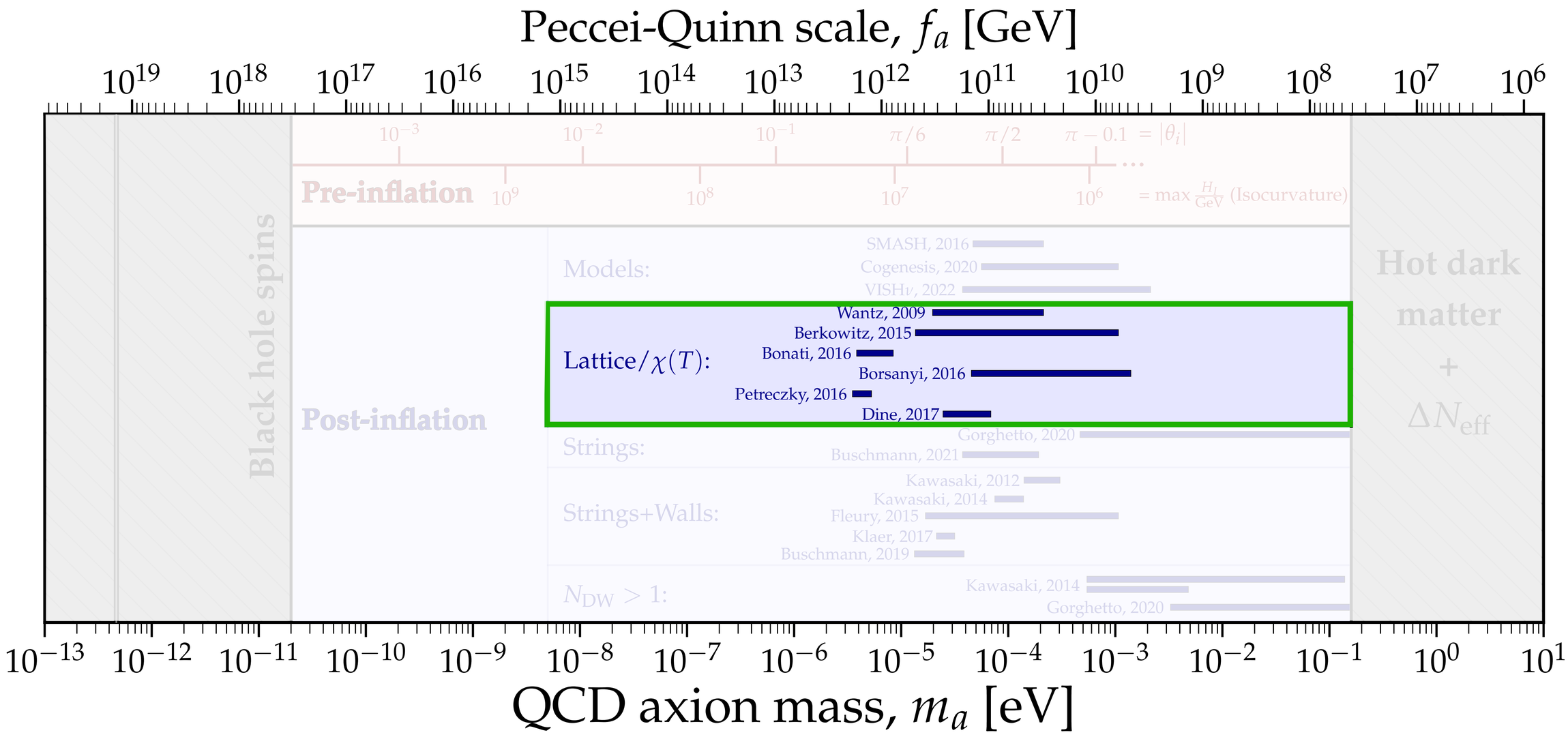
[1] *Leinweber Center for Theoretical Physics, Department of Physics,*

VISHν: a unified solution to five SM shortcomings with a protected electroweak scale

Alexei H. Sopov* and Raymond R. Volkas†
ARC Centre of Excellence for Dark Matter Particle Physics, School of Physics,
The University of Melbourne, Victoria 3010, Australia

2206.11598

github.com/cajohare/AxionLimits



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Borsanyi+ [1606.07494]

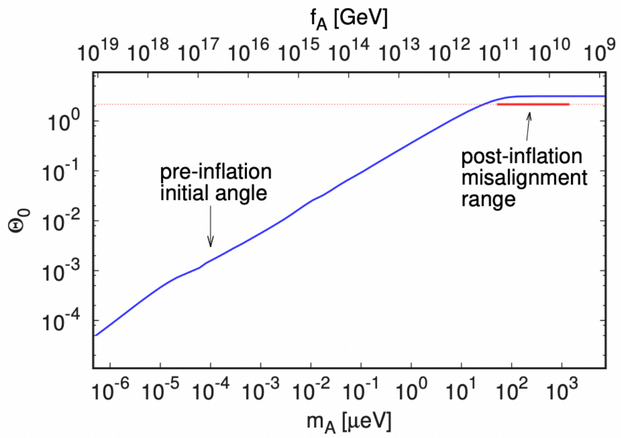


Figure 3: Relation between the axion's mass and the initial angle θ_0 in the pre-inflation scenario. The post-inflation scenario corresponds to $\theta_0 = 2.155$ with a strict lower bound on the axion's mass of m_A=28(2)μeV. The thick red line shows our result on the axion's mass for the post-inflation case.

ei-Quinn scale, f_a [GeV]

10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6}

10^{-1} $\pi/6$ $\pi/2$ $\pi - 0.1$ $= |\theta_i|$ …

10^{8} 10^{7} 10^{6} $= \max \frac{H_I}{\mathrm{GeV}}$ (Isocurvature)

lels:

SMASH, 2016
Cogenesis, 2020
VISHν, 2022

Lattice/$\chi(T)$:

Wantz, 2009
Berkowitz, 2015
Bonati, 2016
Borsanyi, 2016
Petreczky, 2016
Dine, 2017

Strings:

Gorghetto, 2020
Buschmann, 2021

Strings+Walls:

Kawasaki, 2012
Kawasaki, 2014
Fleury, 2015
Klaer, 2017
Buschmann, 2019

$N_{\mathrm{DW}} > 1$:

Kawasaki, 2014
Gorghetto, 2020

Black ho

Post-inflation

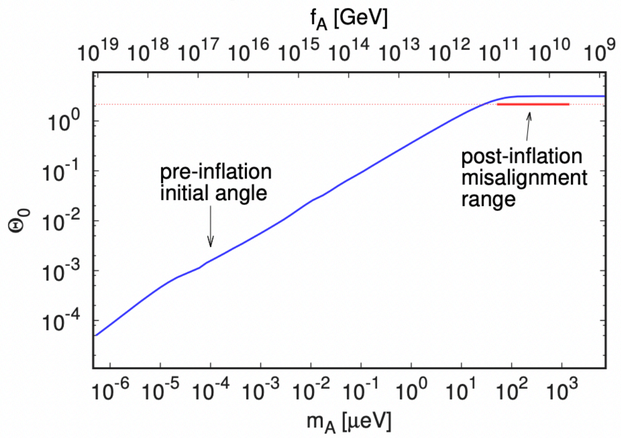
Hot dark matter + ΔN_{eff}

10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}

QCD axion mass, m_a [eV]

github.com/cajohare/AxionLimits

Borsanyi+ [1606.07494]



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Minimum mass for post-inflationary scenario.
Strings add more axions
→ drive m_a prediction down

10^{14} 10^{8} 10^{7} 10^{6}

Hot dark matter + $\Delta N_{\rm eff}$

Post-inflation

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Gorghetto, 2020

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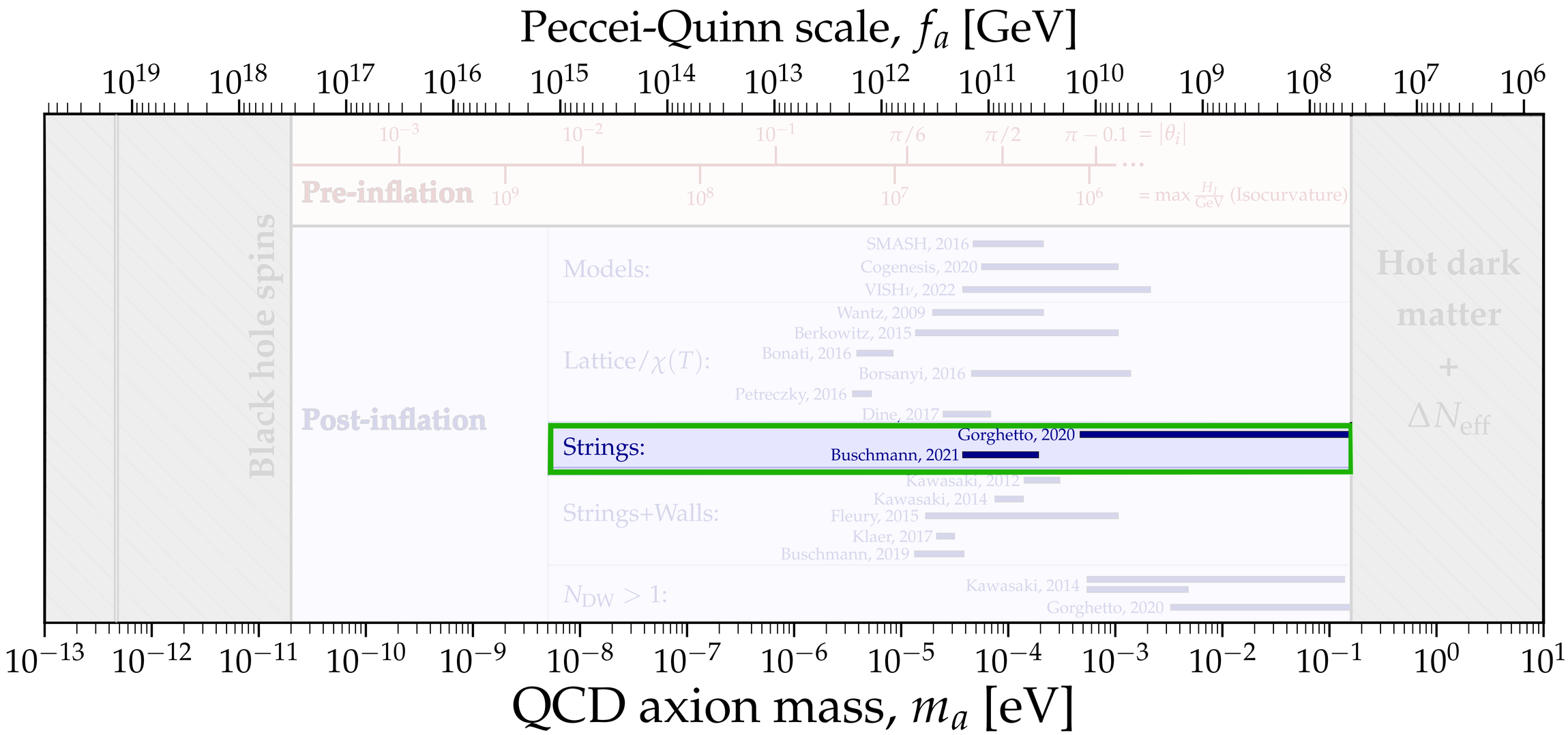
QCD axion mass, m_a [eV]

github.com/cajohare/AxionLimits



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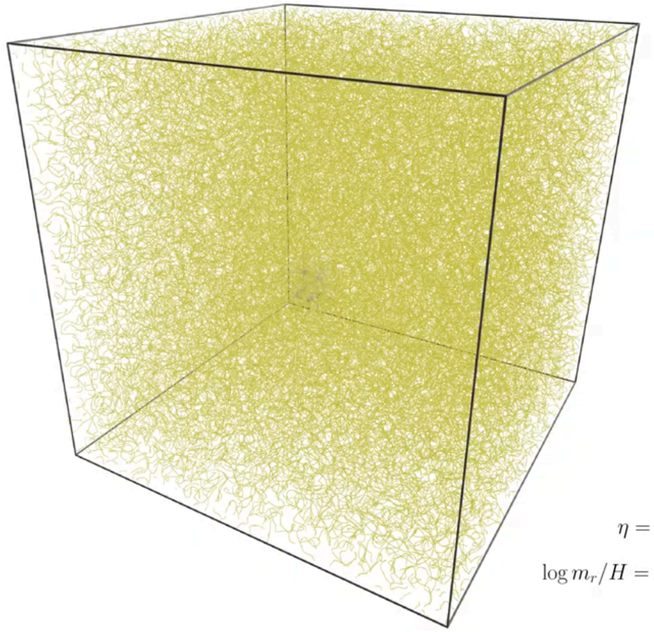
M. Buschmann



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Hot dark matter + ΔN_{eff}

Post-inflation

Models:
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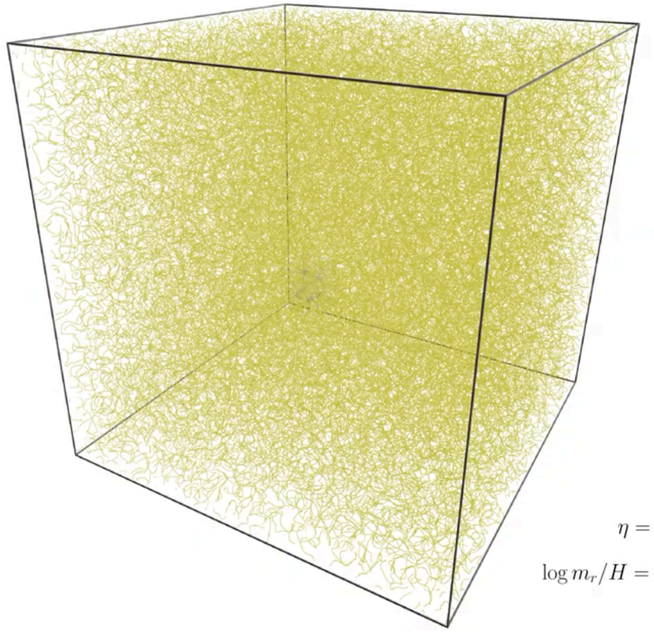

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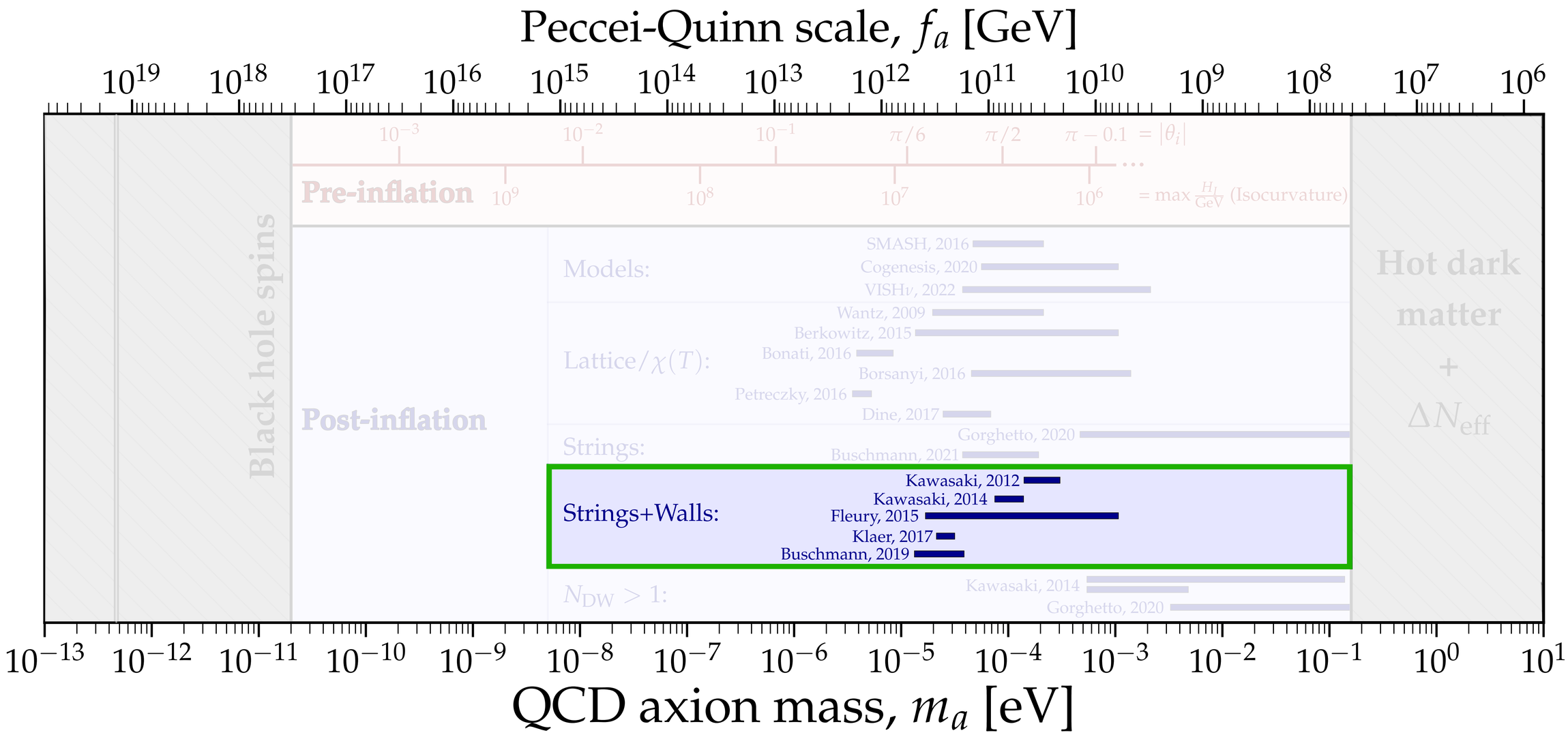

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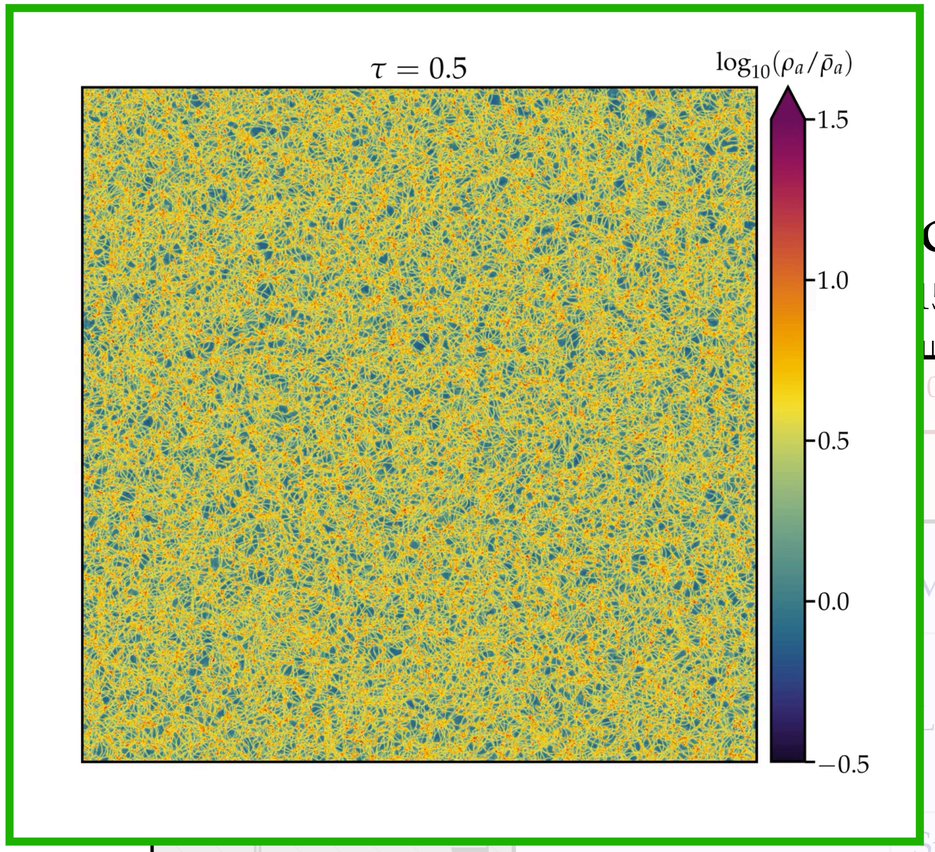

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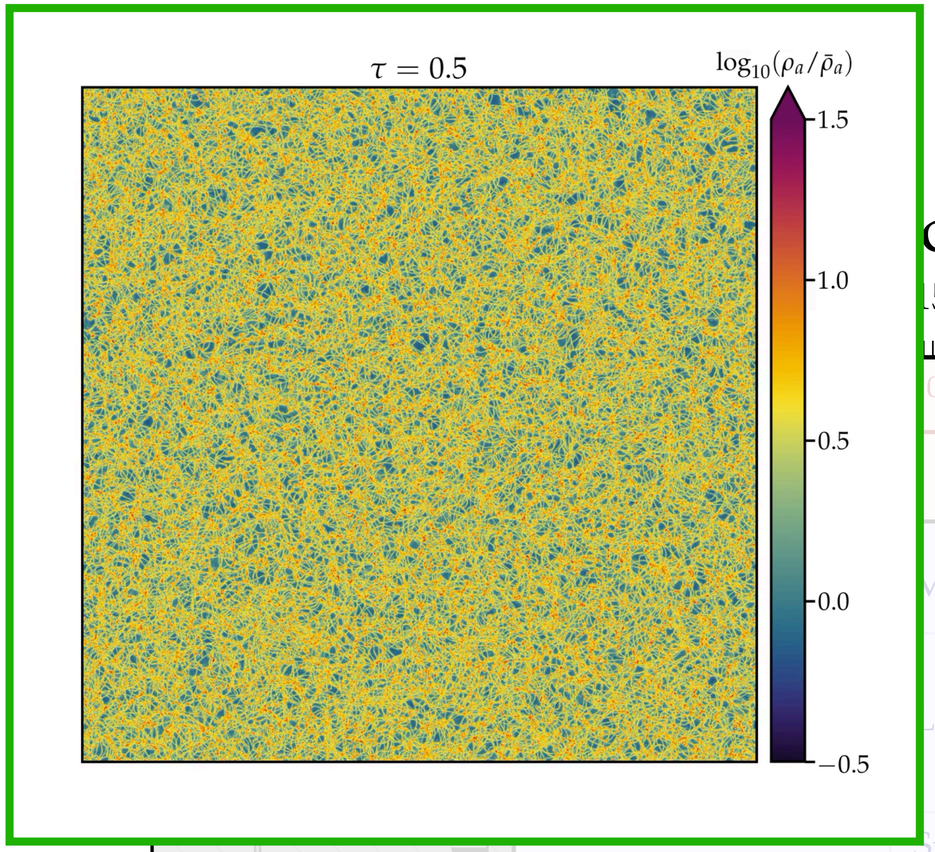

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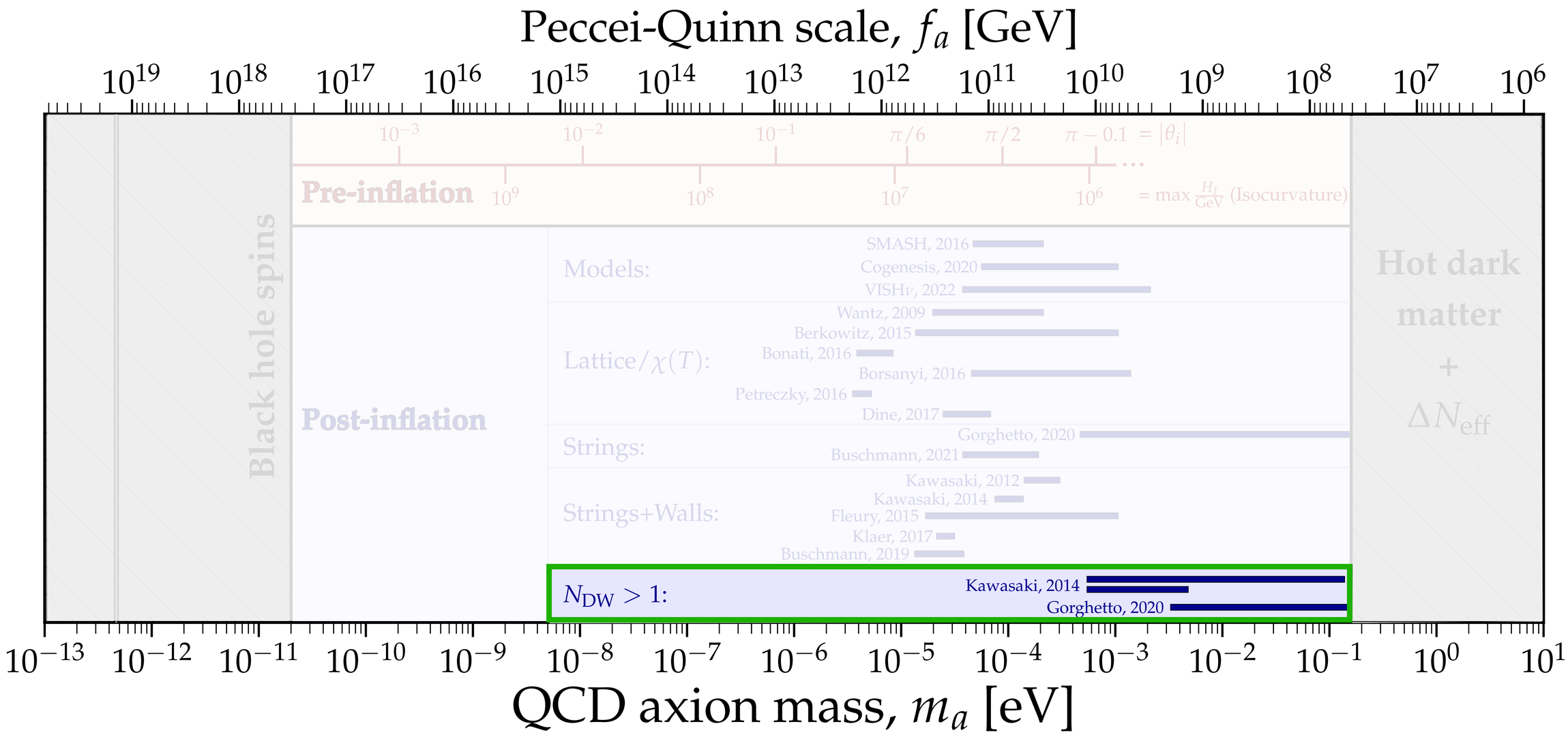

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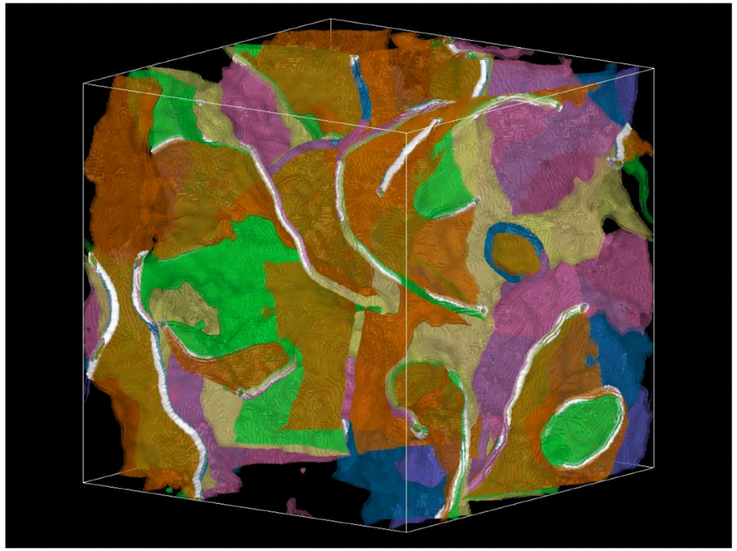
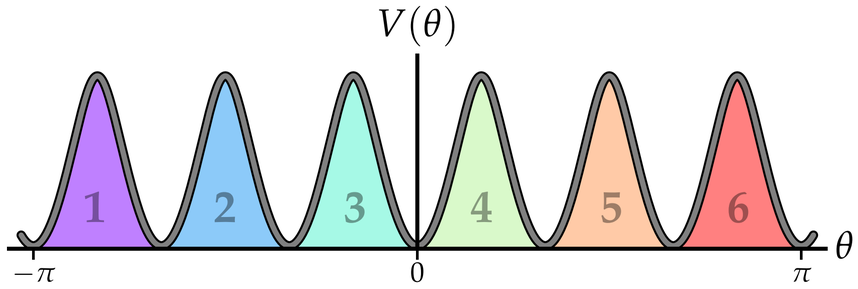


(e) $N_{\rm DW} = 6$

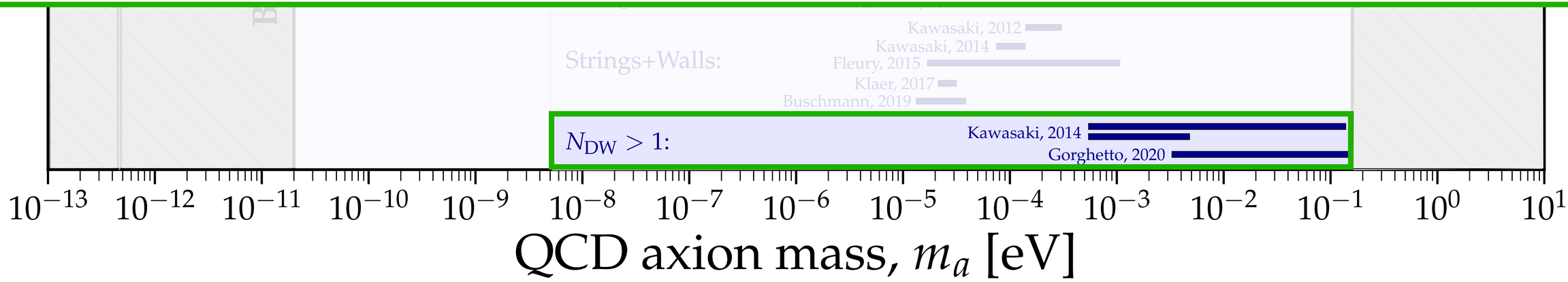
Hiramatsu+ [1207.3166]

Axion models with domain wall number > 1

$$V(\theta) \approx -\chi(T)\cos(N_{\rm DW}\theta)$$

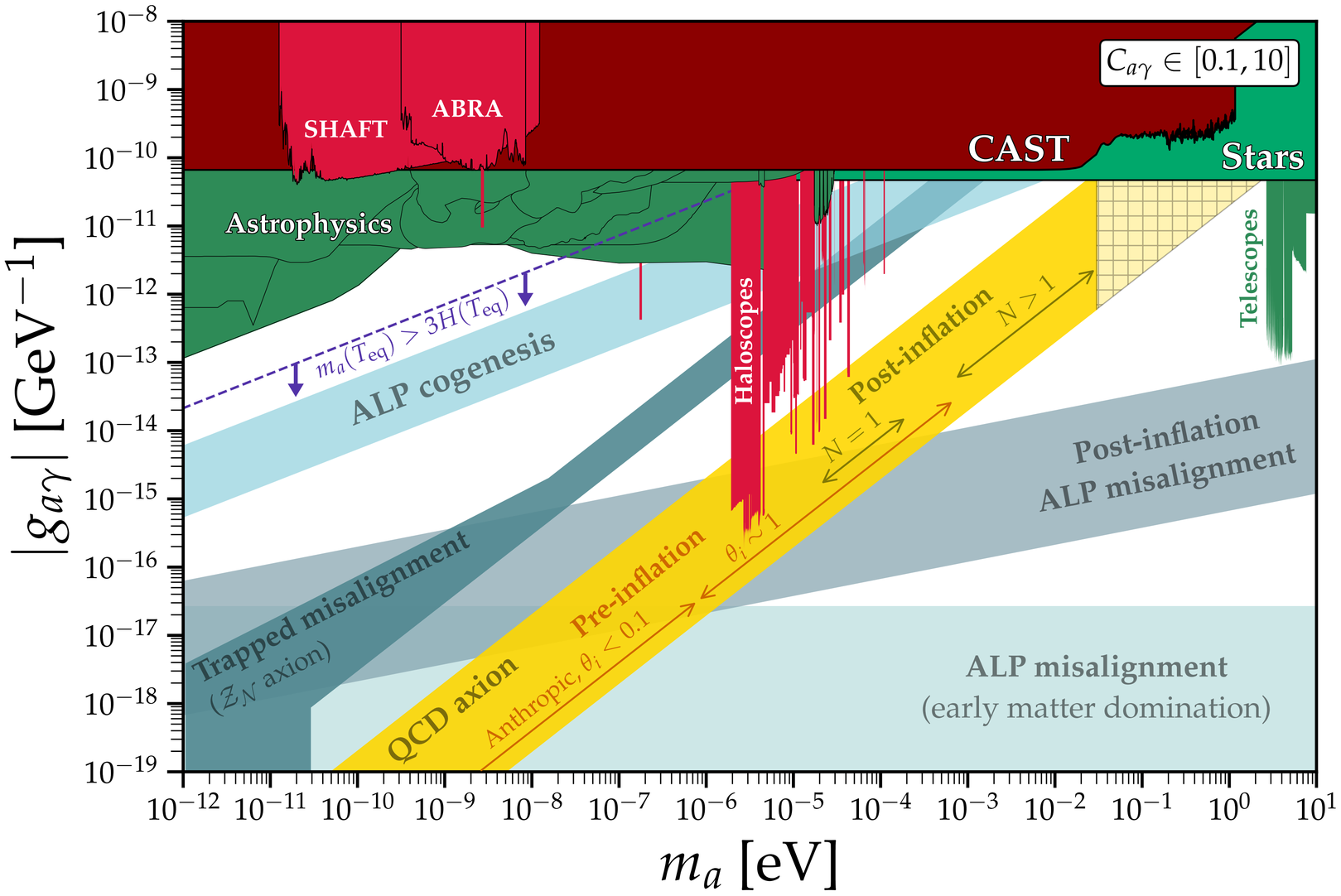


- Axion cycles around $N_{\rm DW}$ times between $(-\pi, \pi)$
- In general get more axions from wall decay, so preferred m_a is higher
- On their own $N_{\rm DW} > 1$ models are not allowed. Domain wall network gets stuck and overwhelms the cosmic energy density.
- Must have some "bias" to tip the scales to preferring one minimum



github.com/cajohare/AxionLimits

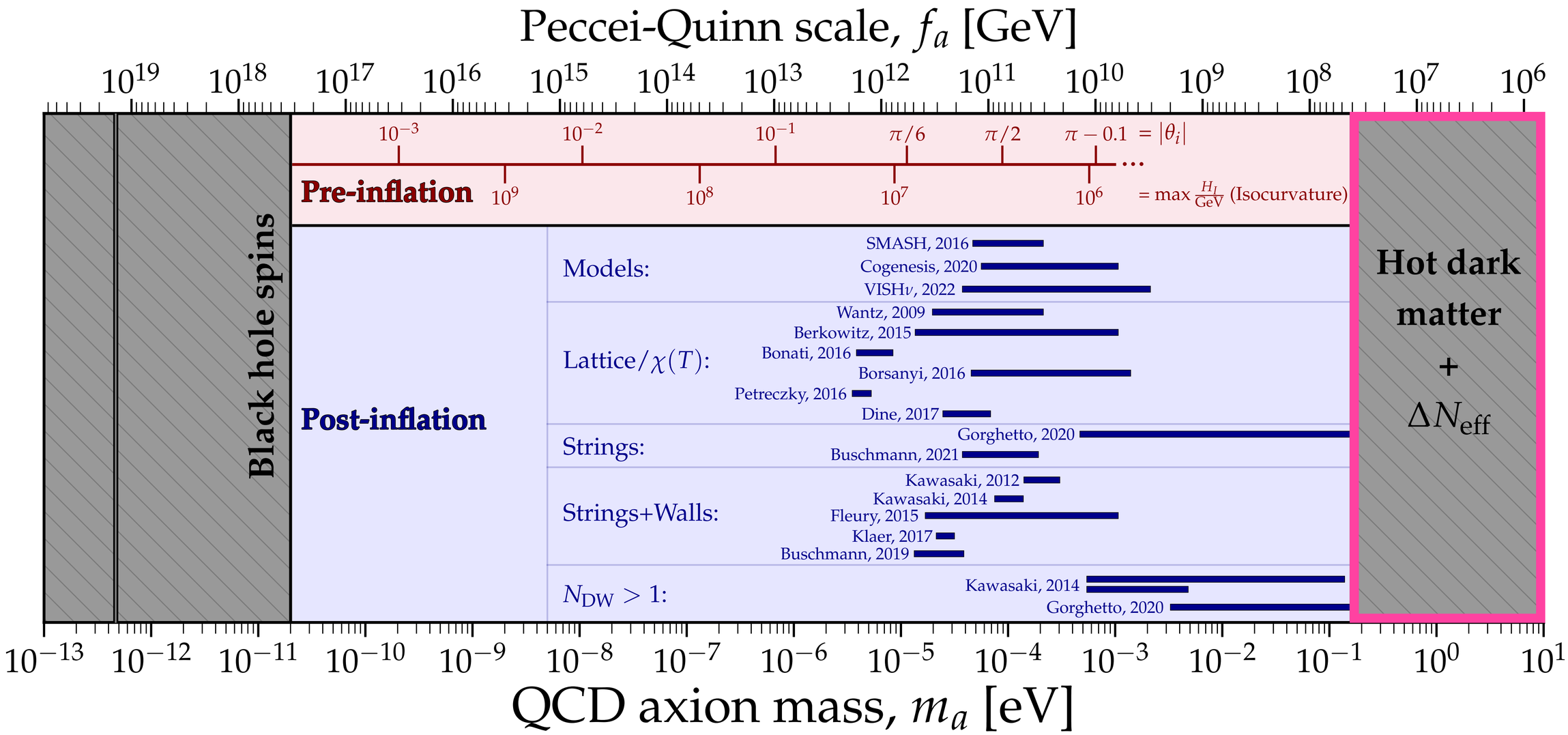
Non-standard axion/ALP post-dictions



- QCD axion with a non-standard mass,
  → e.g. [2102.01082]
- ALP with a temperature-independent mass
  → e.g. [2112.05117]
- Axions in non-standard cosmologies
  → e.g. [1911.07853]
- Variants of misalignment mechanism: axion rotations, parametric resonance etc.
  → e.g. [2006.04809]

github.com/cajohare/AxionLimits

How cosmology can bound the axion parameter space

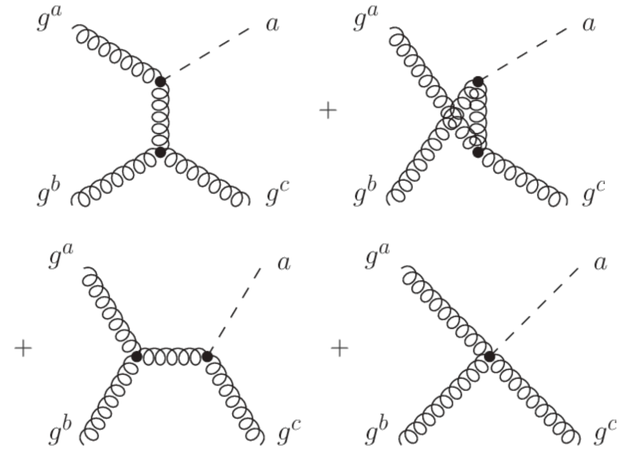


github.com/cajohare/AxionLimits

Thermal production of axions

At very high temperatures even axions can be in thermal equilibrium with SM bath

Via e.g. $g + g \leftrightarrow g + a$ (high T) or $\pi + \pi \leftrightarrow \pi + a$ (low T)



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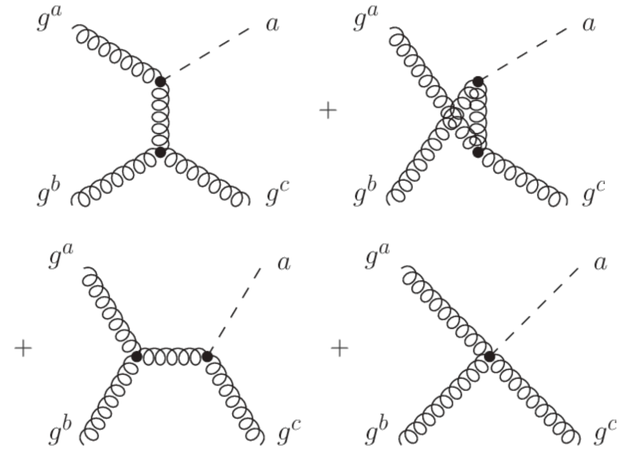
Production rate: $\Gamma \sim n\langle\sigma v\rangle \sim 10^{-4}\dfrac{T^3}{f_a^2}$



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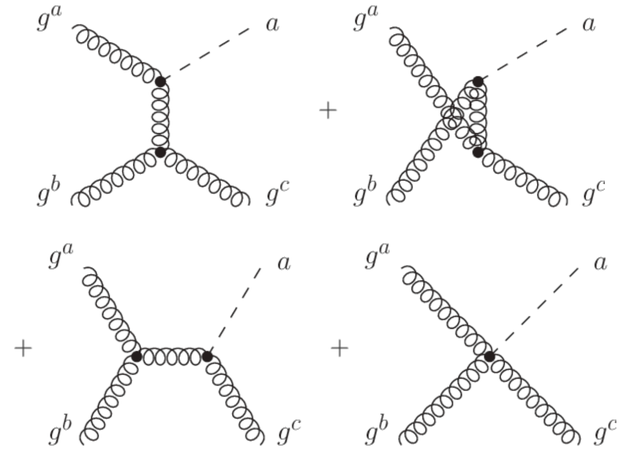

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Axions "freeze-out" when

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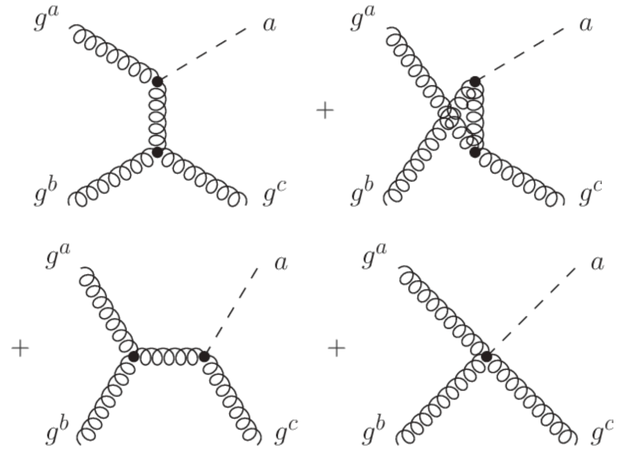

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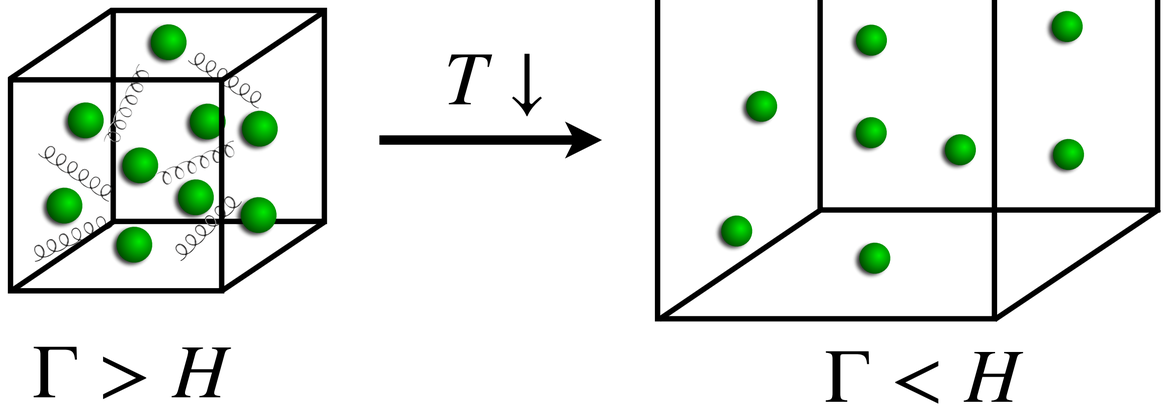
$\Downarrow$

$$T_d \sim 10^8\,\text{GeV}\left(\frac{f_a}{10^{11}\,\text{GeV}}\right)^2$$



$\Gamma > H$

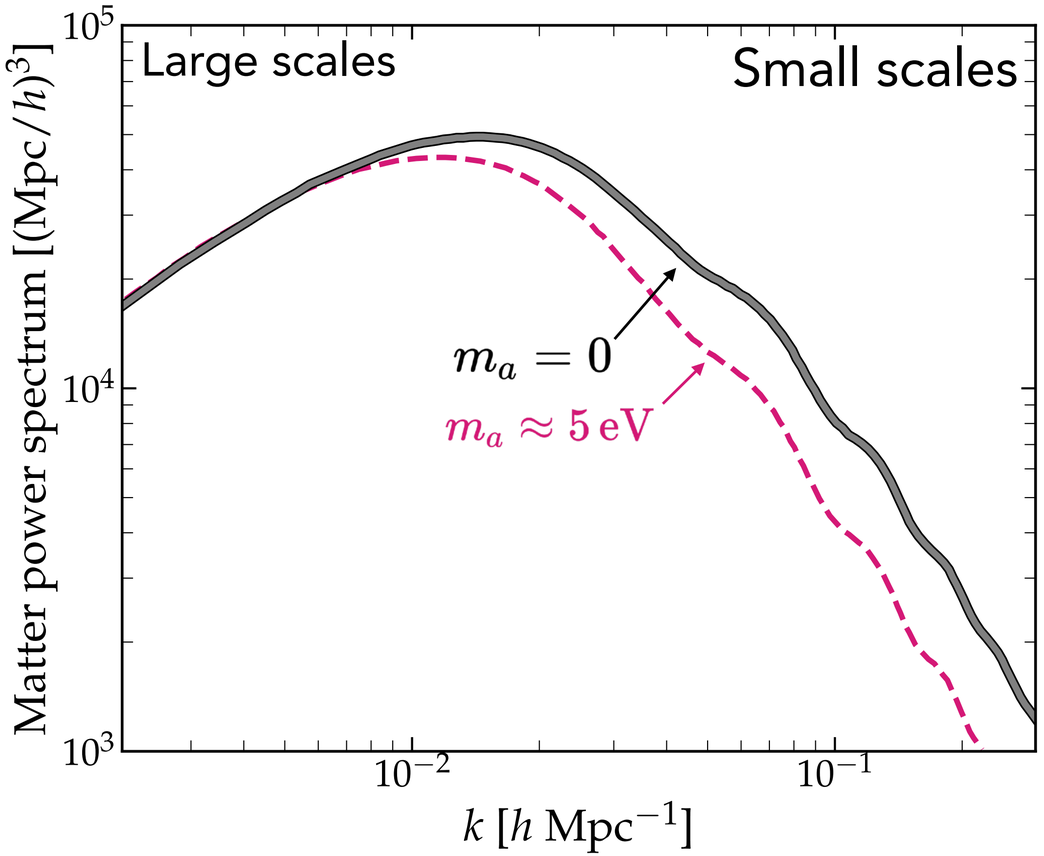
thermal eq. maintained

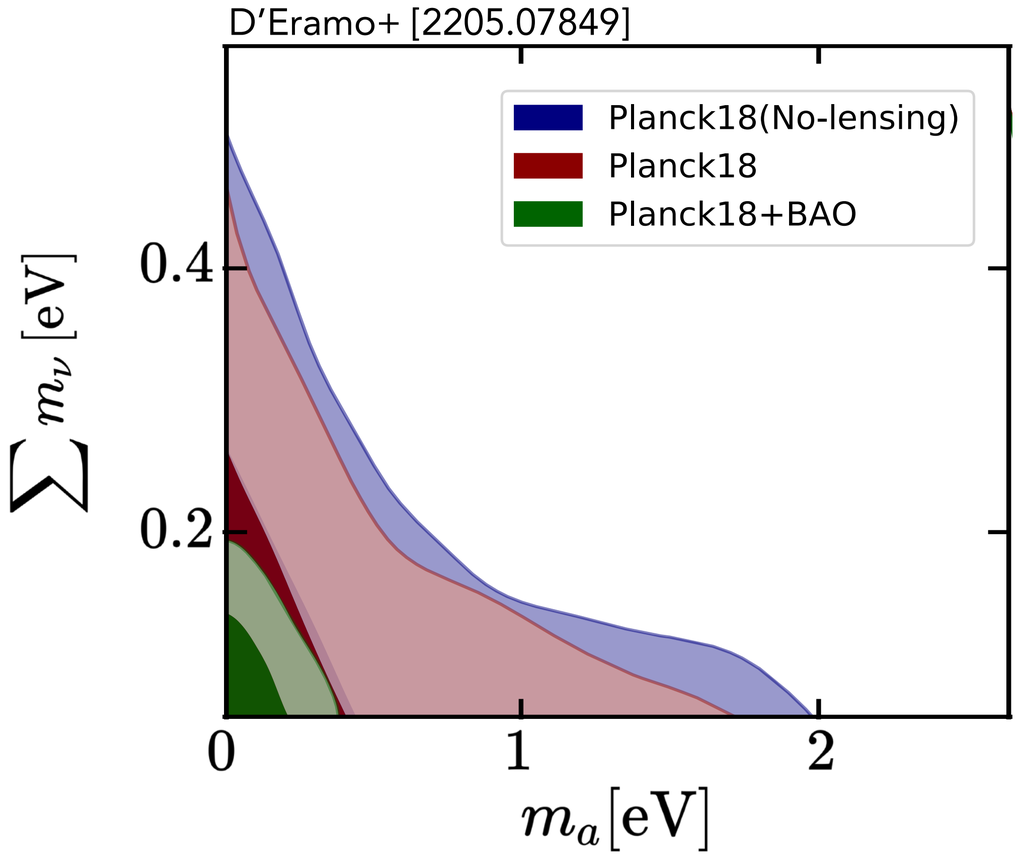
$\Gamma < H$

Production can't keep up with expansion

Hot dark matter axions

If they are heavy enough then the thermal axion background contributes a form of **hot dark matter** (similar to neutrinos) which is heavily constrained by LSS+CMB





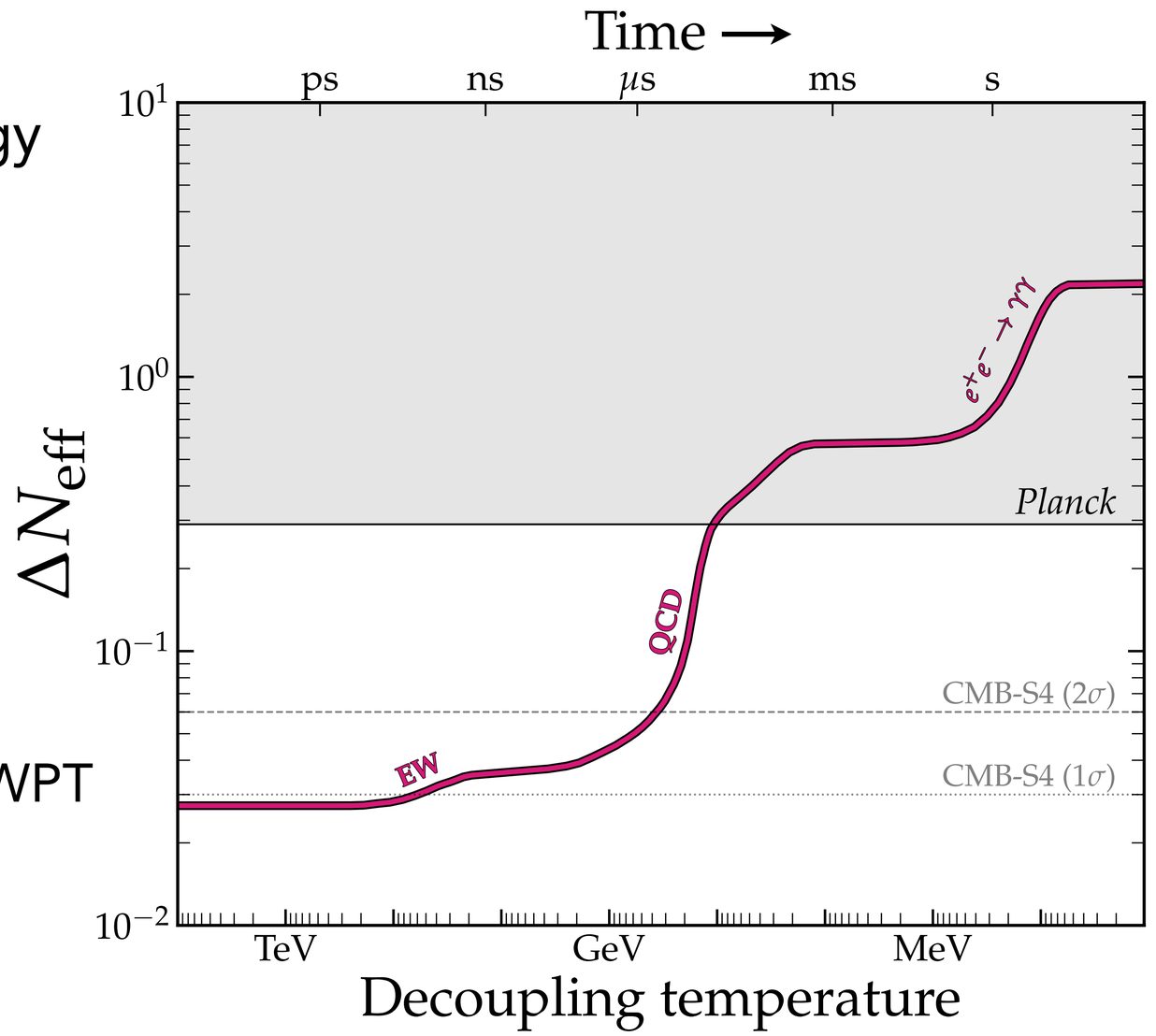
Thermal axions and $N_{\rm eff}$

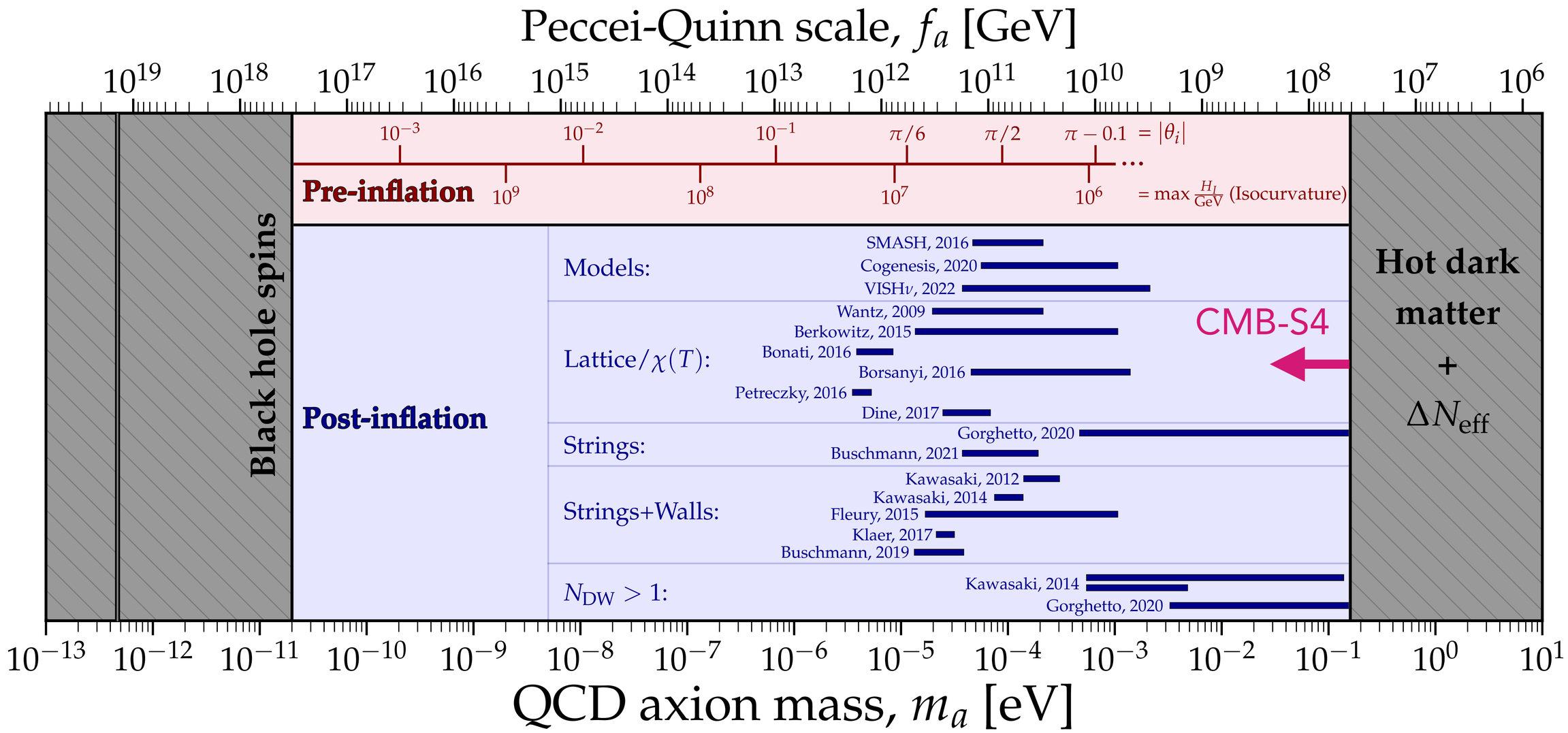
Quantify effects of new relativistic species on early-Universe expansion rate via energy density in units of a single neutrino ($\Delta N_{\rm eff}$)

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}(N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff})\right]\rho_\gamma$$

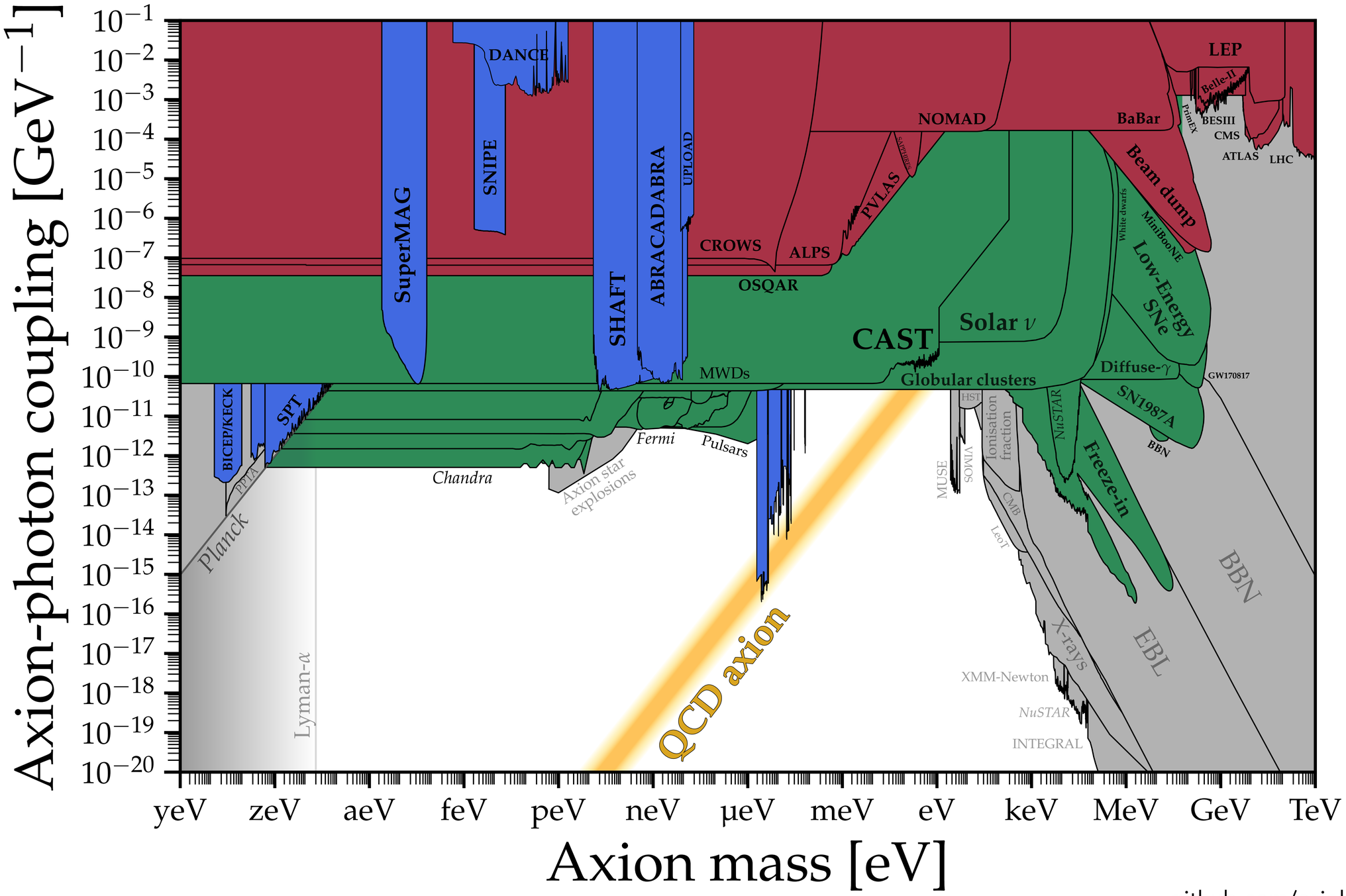
$$N_{\rm eff}^{\rm SM} = 3.044$$

- CMB-Stage 4 is targeting $\Delta N_{\rm eff} = 0.03$
- Could constrain axions decoupling before EWPT
- Quite plausible we could detect a relic population of thermal axions





github.com/cajohare/AxionLimits



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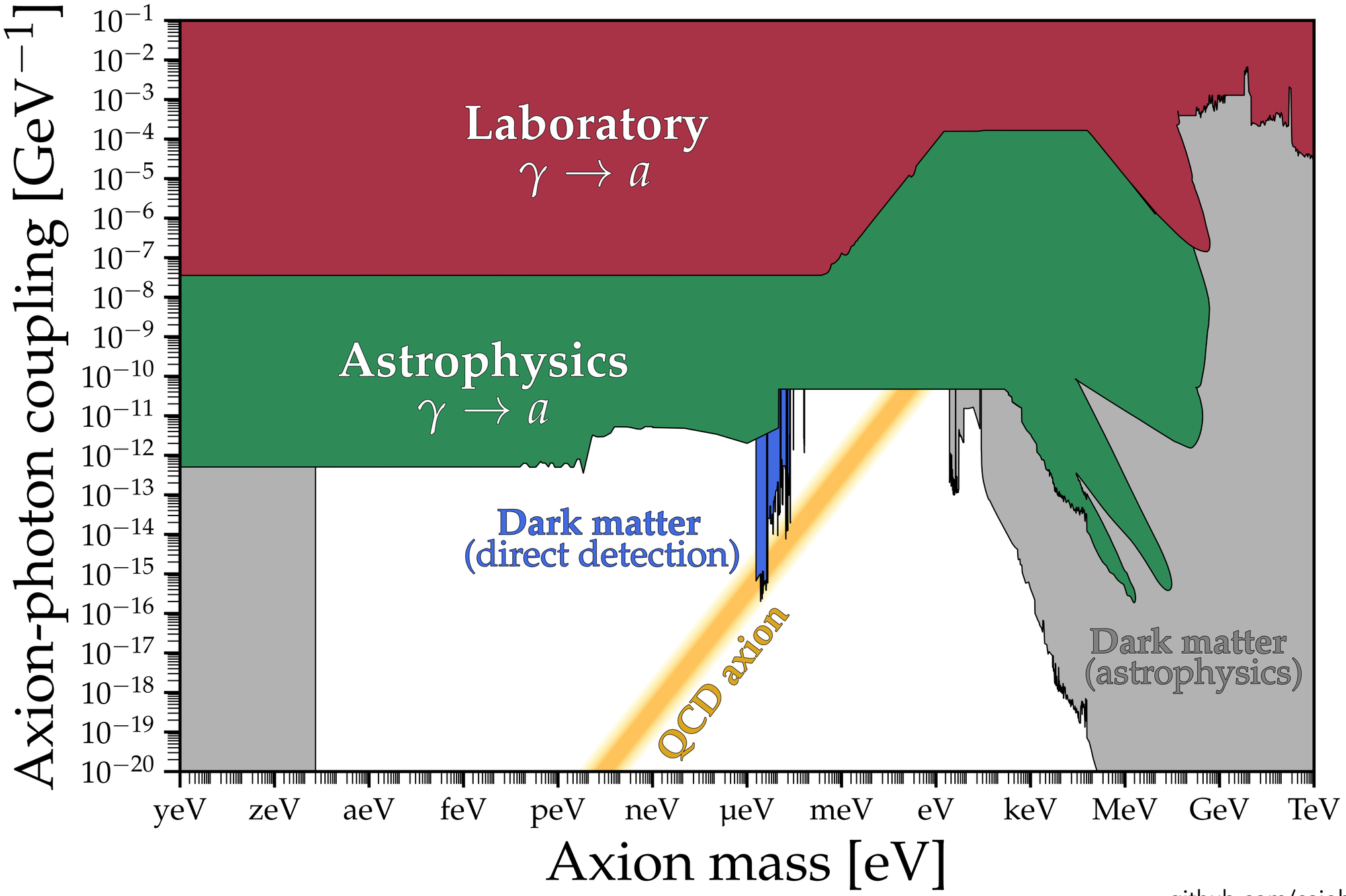

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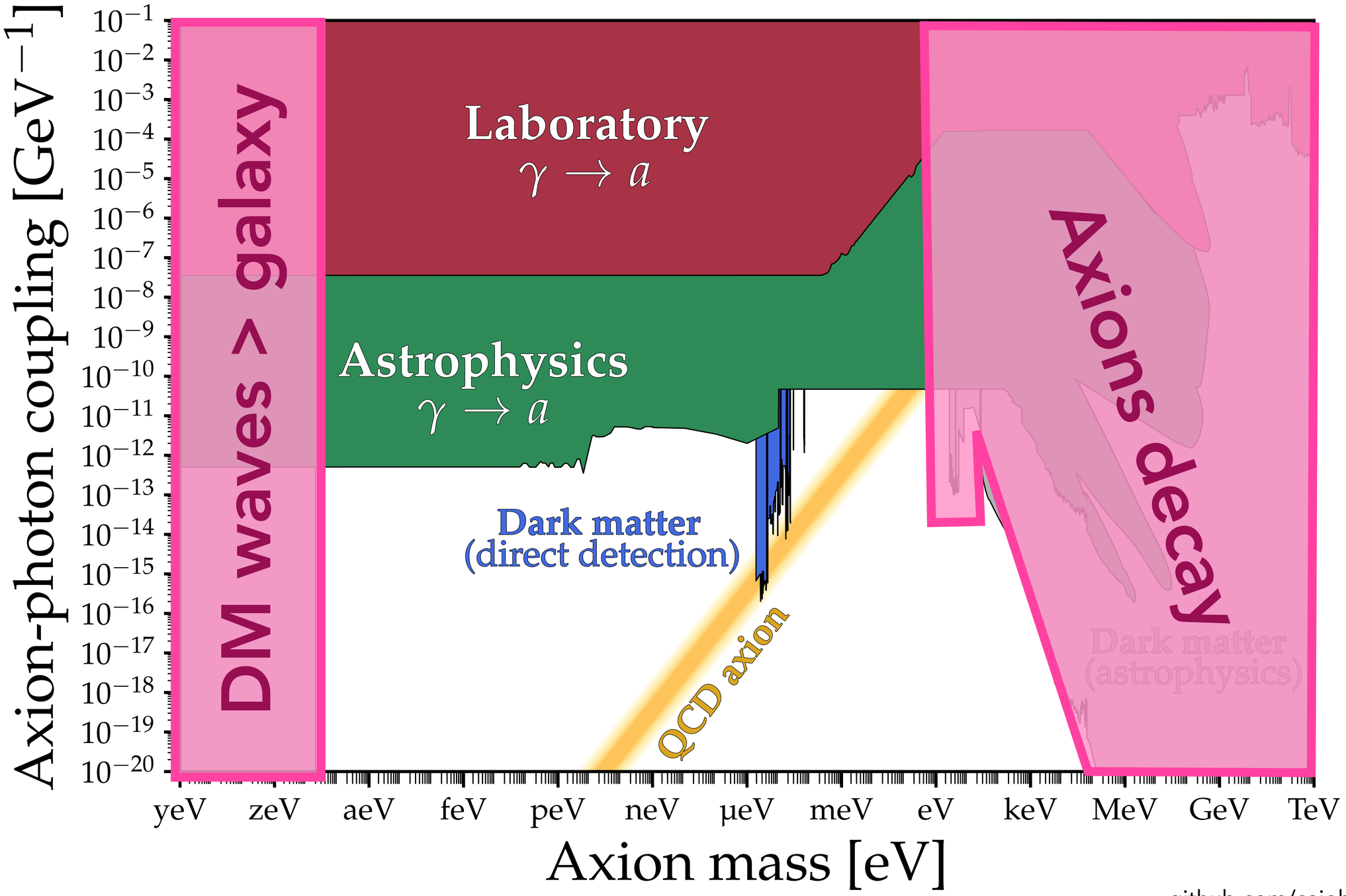

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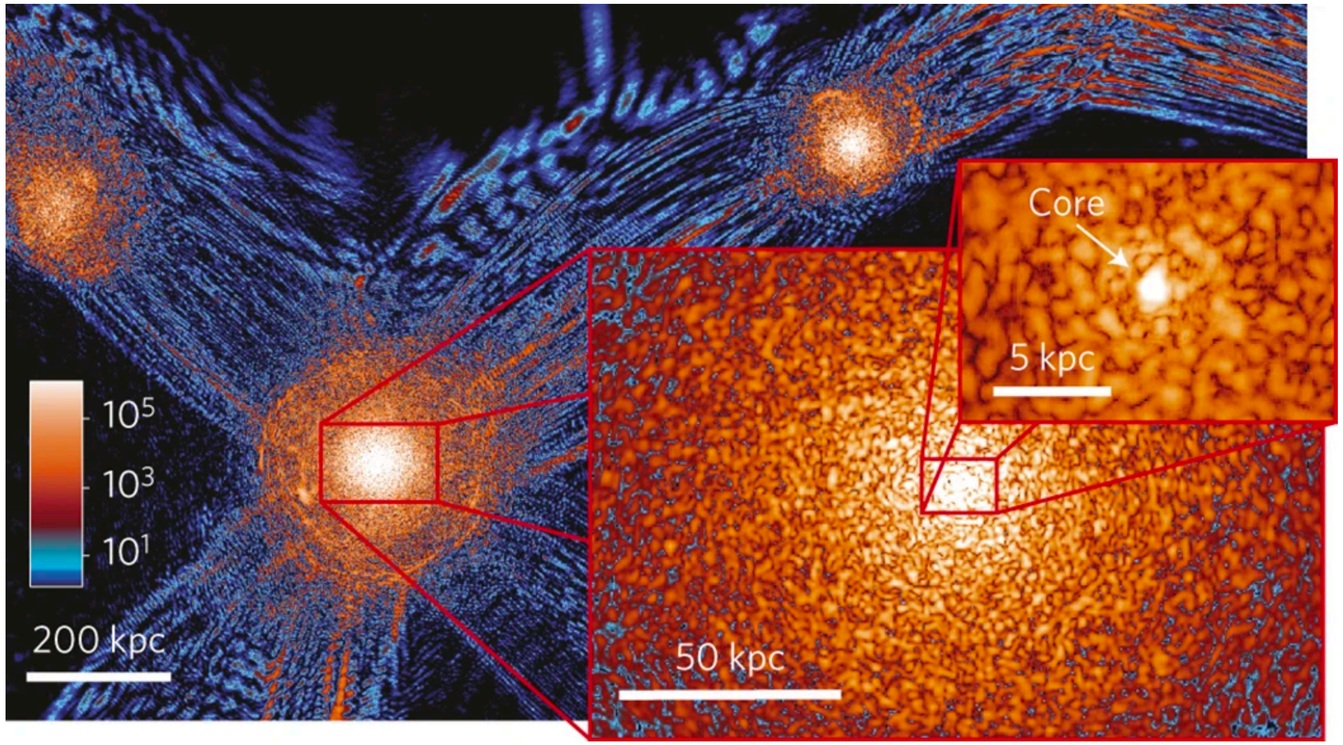
Lower bound on the axion mass: fuzzy dark matter

- Wave-like DM has a finite "incompressible" size given by its wave coherence length $\lambda = 1/m_\phi v$.
- Perturbations below an effective Jeans scale ($1/k_J$) cannot grow due to wave effects
- For very small m_ϕ this could become of comparable size to DM halos that we know exist

Schive+ [1406.6586]



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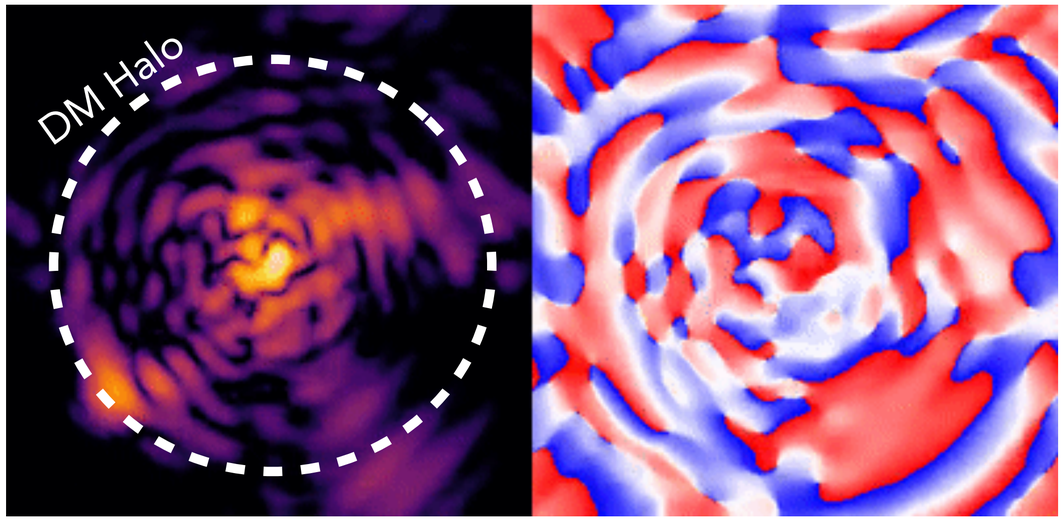

P. Mocz

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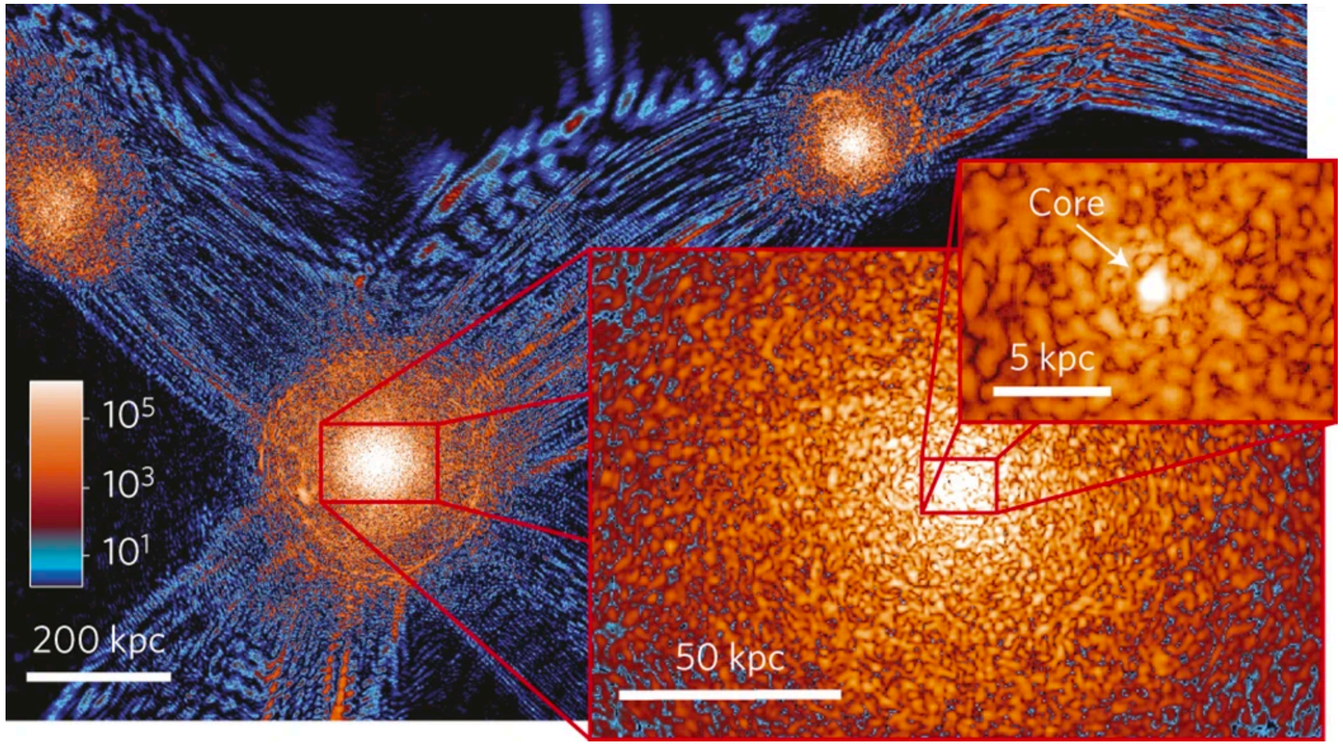

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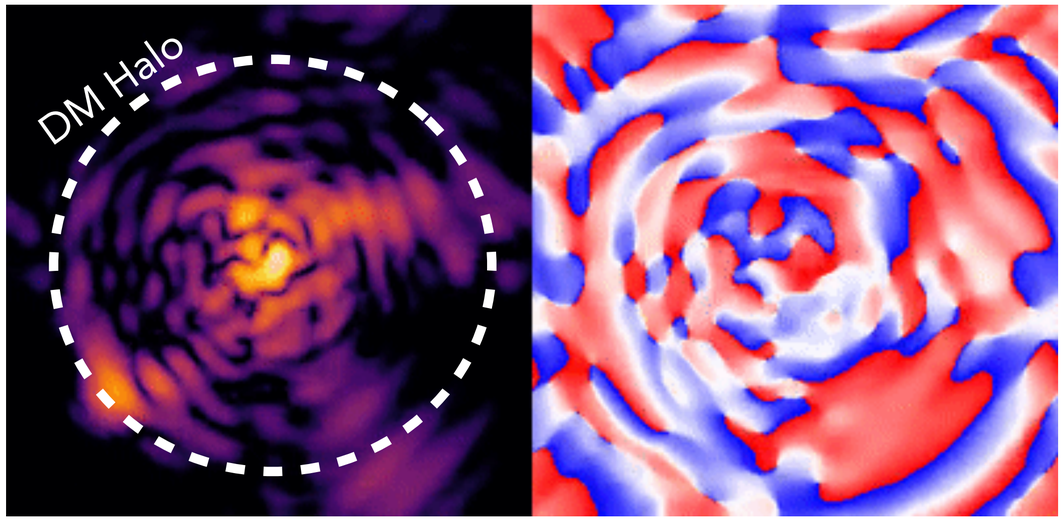

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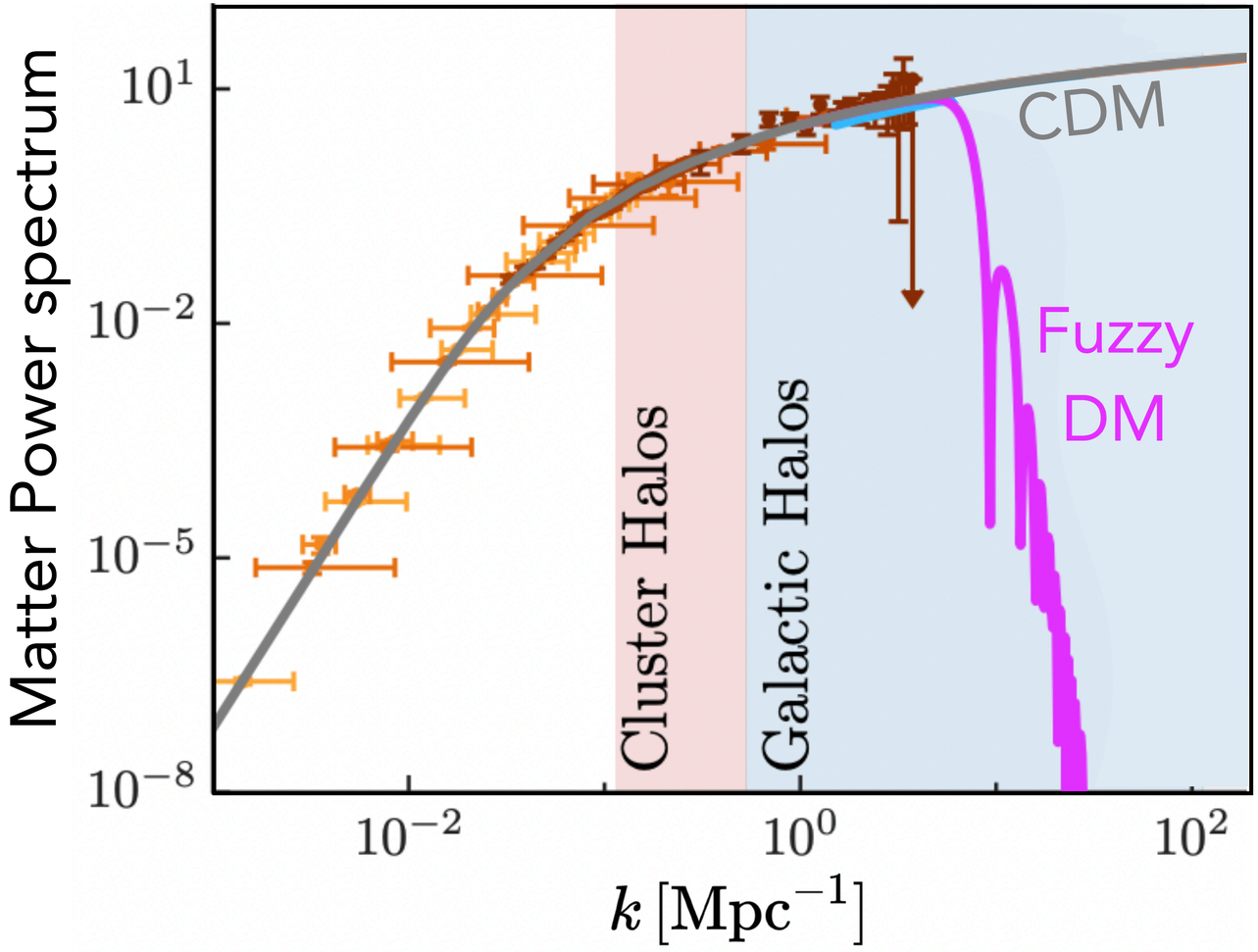
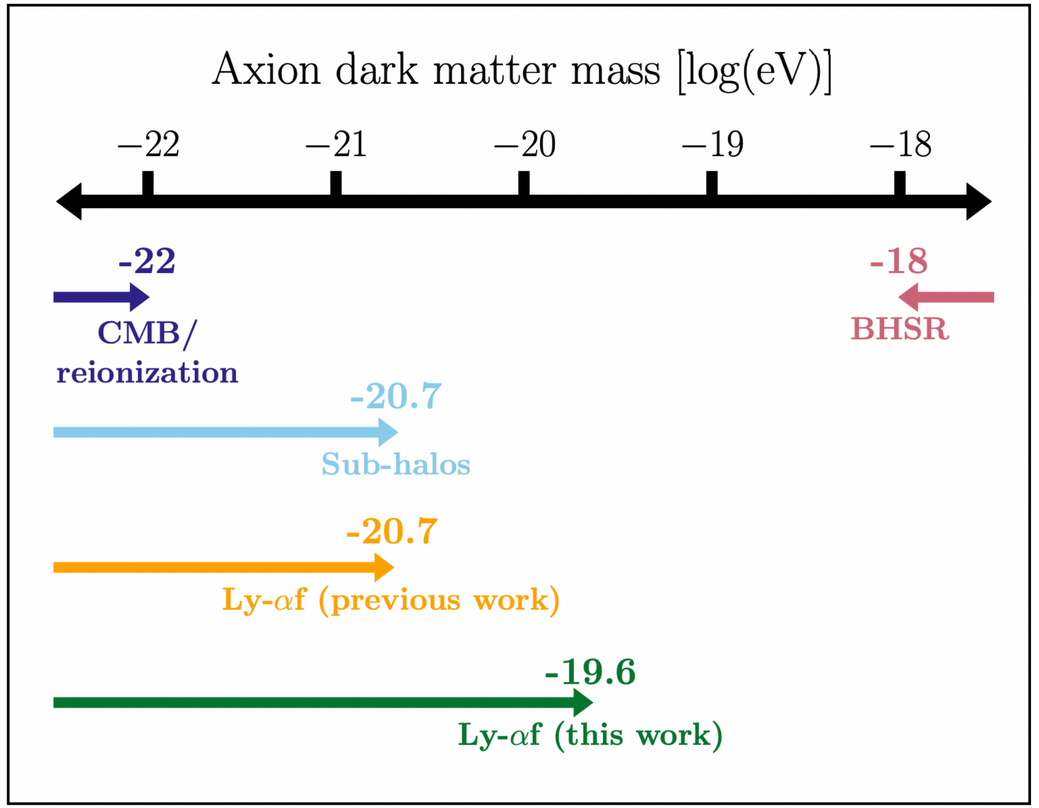
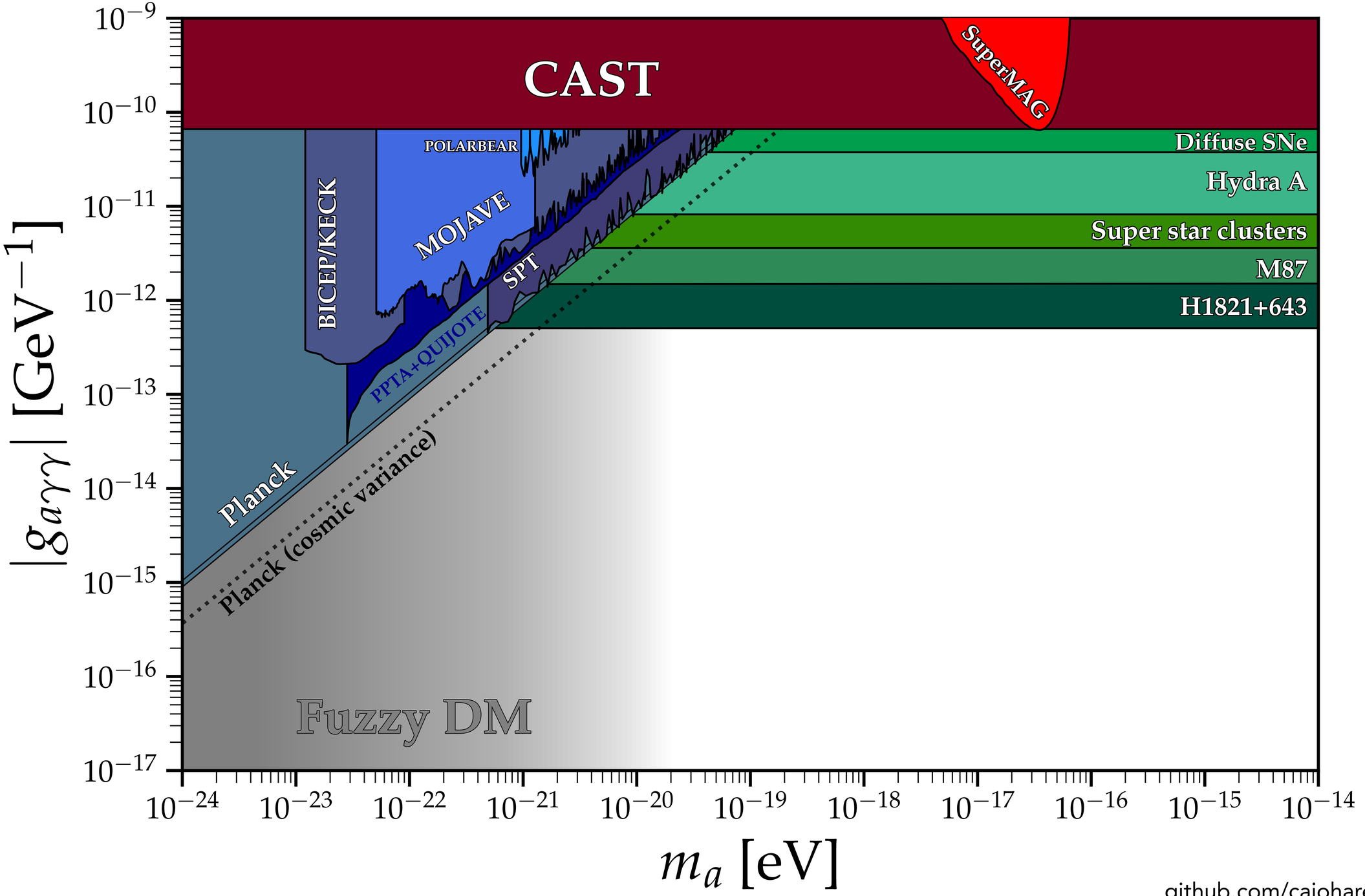
Adapted from [2203.07354]



Rogers+ [2007.12705]





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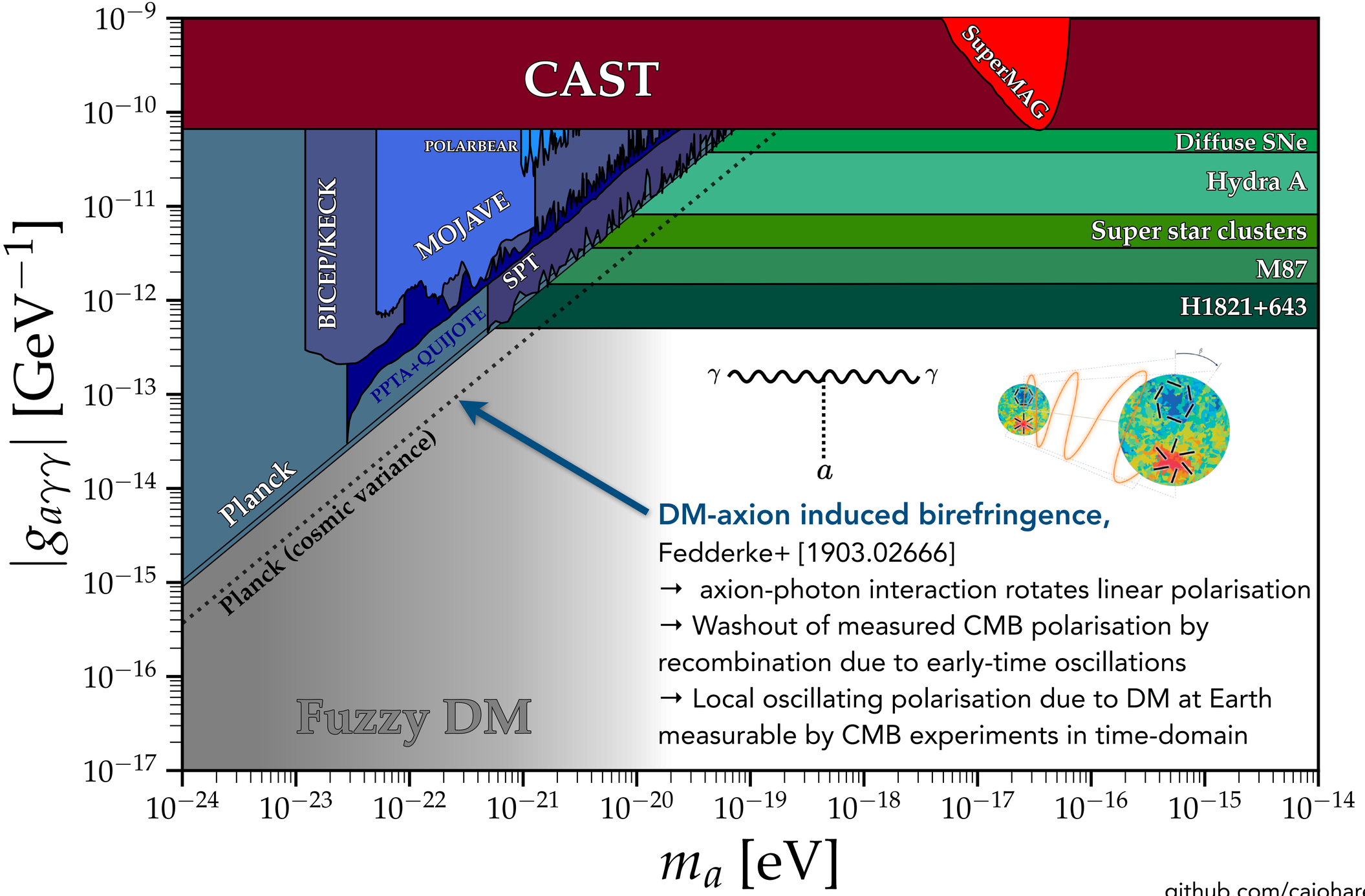

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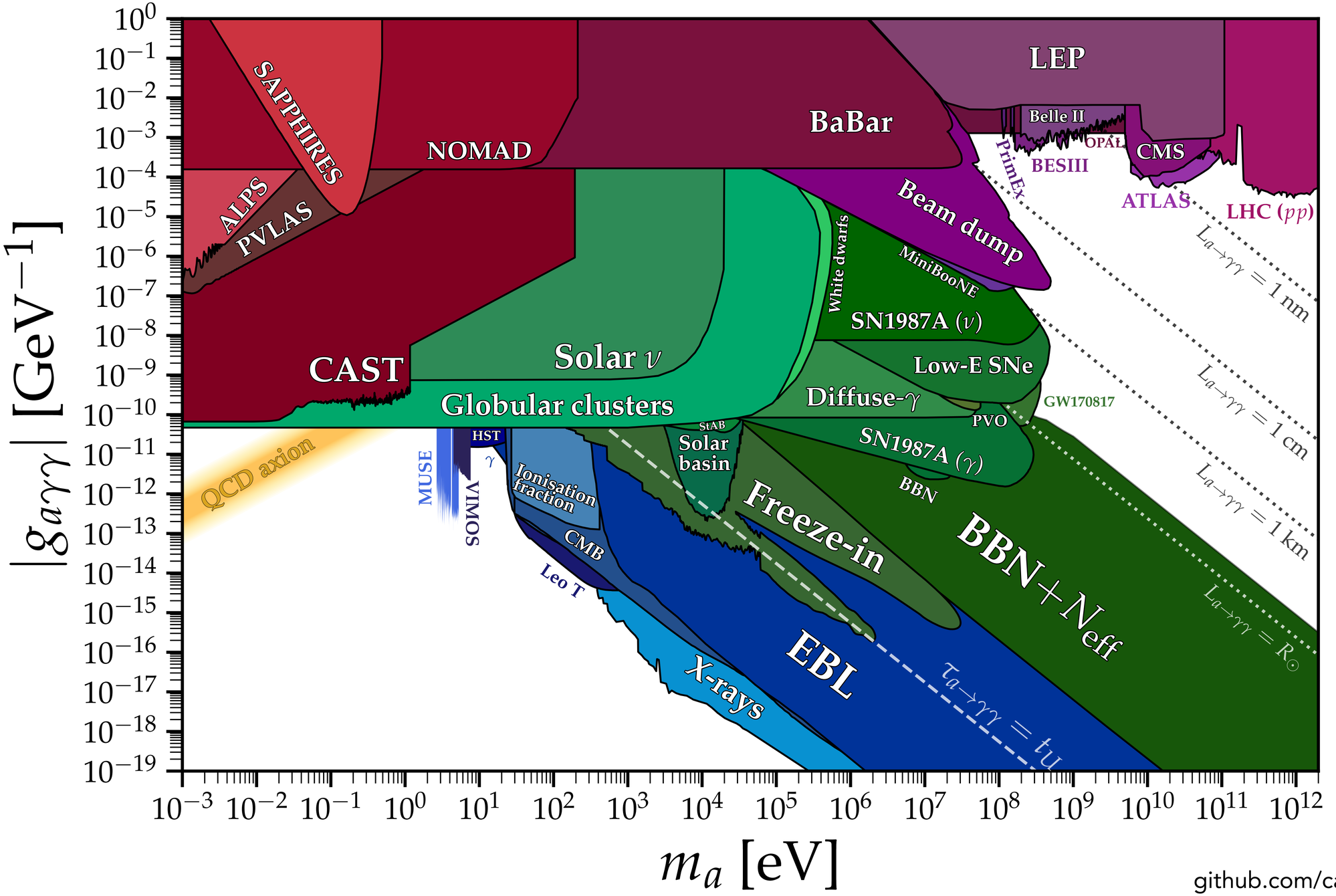

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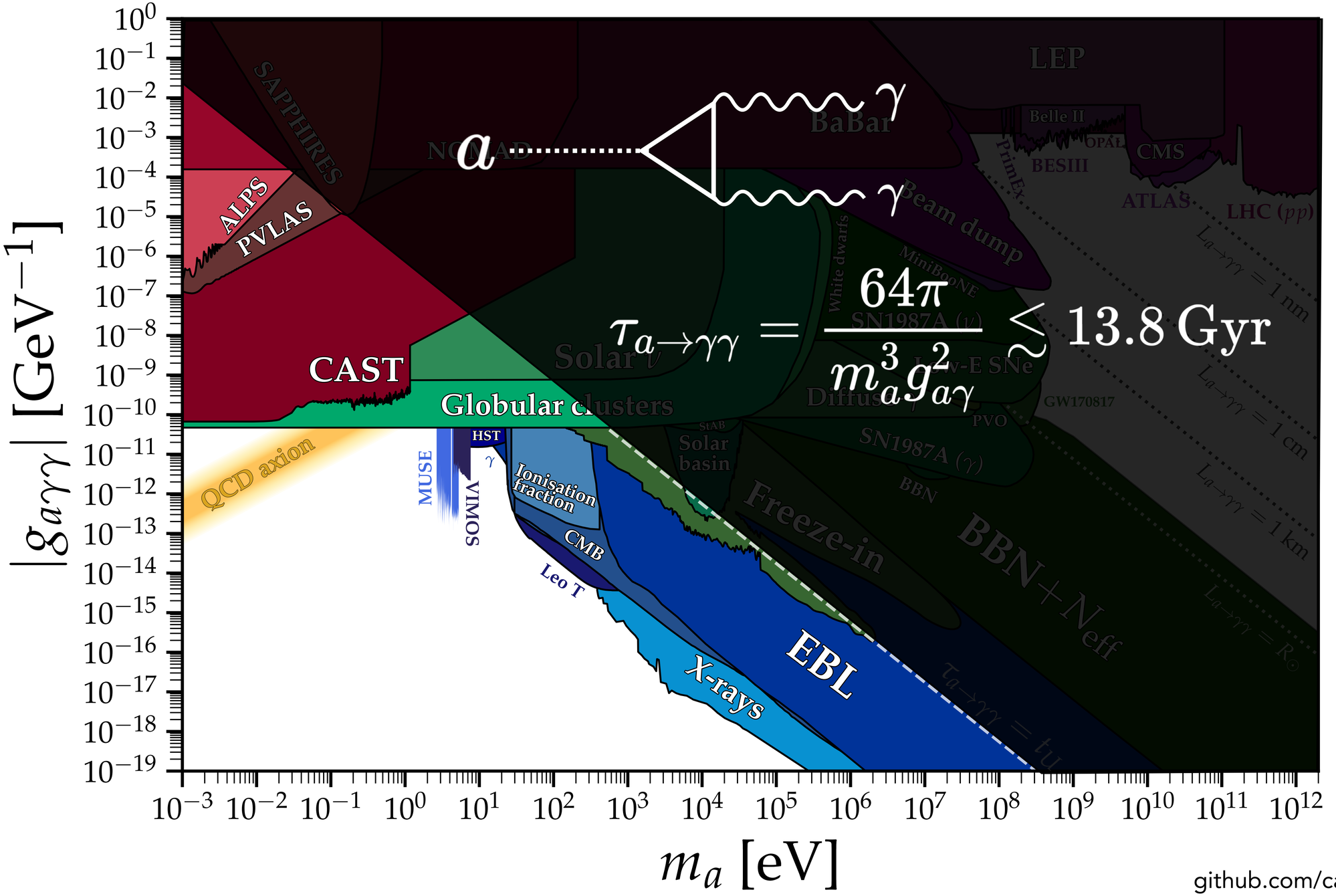

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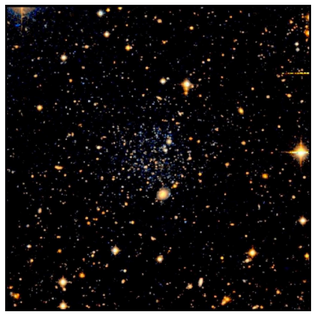
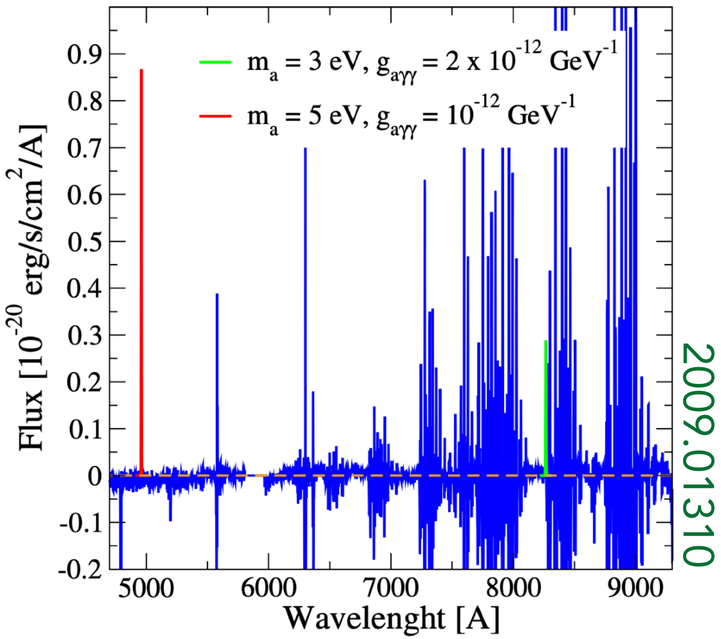
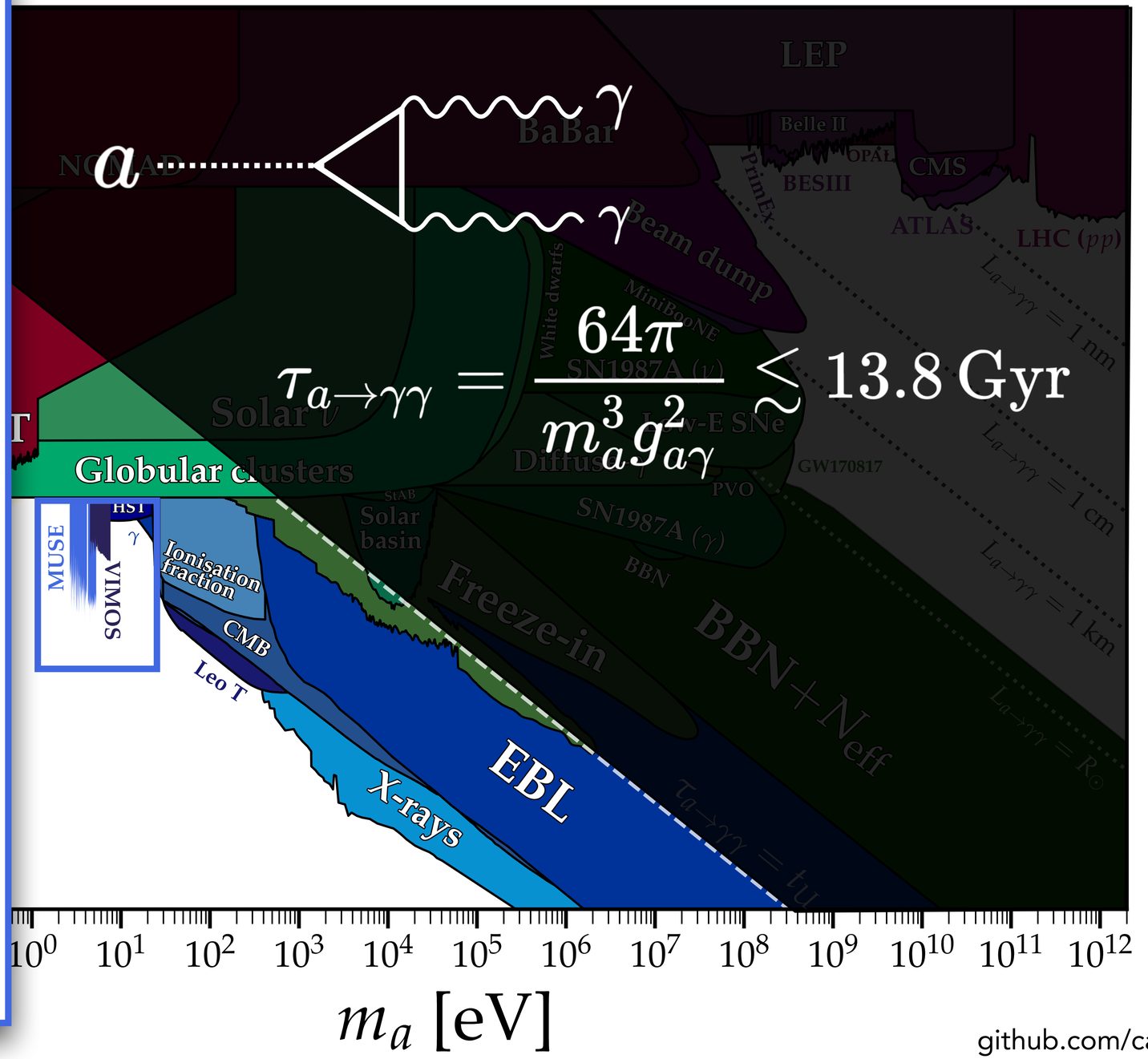
Search for **axion decay line** at $\omega_\gamma = m_a/2$ in galaxy spectra (e.g. MW dwarf spheroidals w/ high DM densities)
See recent Todorello+ [2307.07403]



Leo-T dwarf

$M \sim 8 \times 10^6\, M_\odot$





github.com/cajohare/AxionLimits

“Near-field cosmology”

→ The structure and formation history of our own dark matter halo

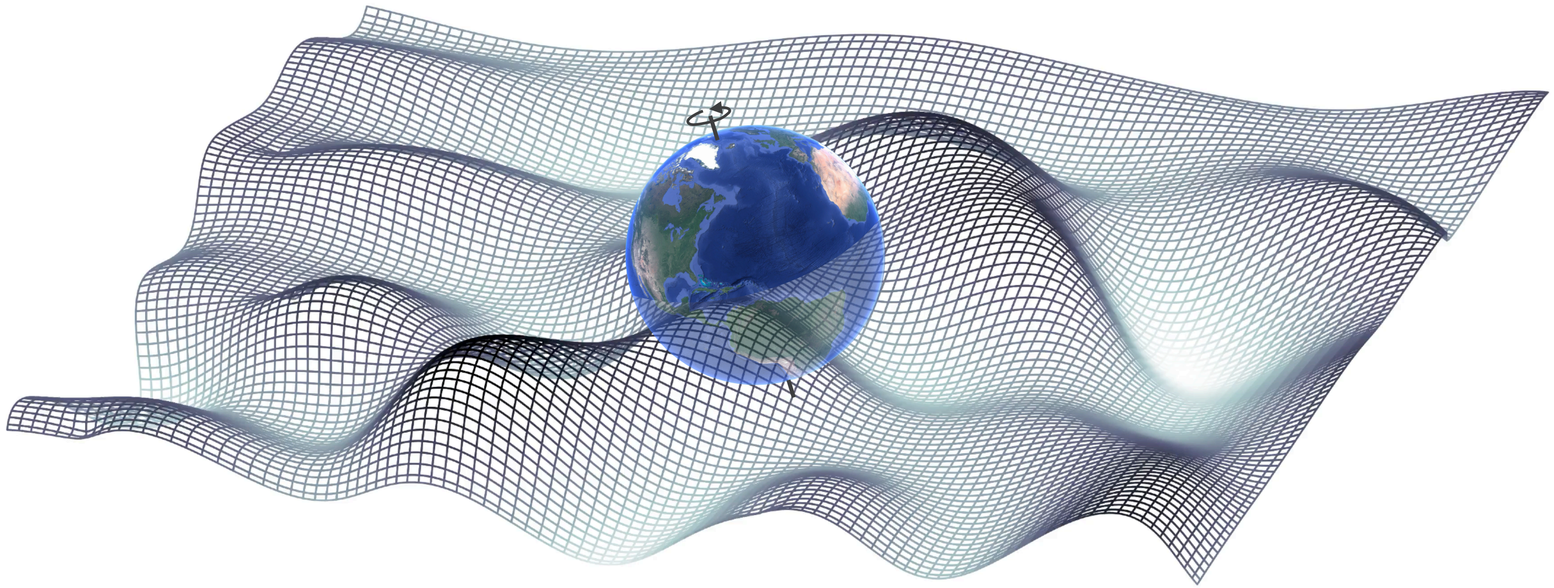
Axions in our galaxy: Wave-like dark matter

We know the local mass density of DM ($\rho_{\rm DM} \approx 0.4$ GeV/cm^3), but not the number density

Occupancy = Number of particles per de Broglie volume: $\mathcal{N} \approx (\rho_{\rm DM}/m) \times \lambda_{\rm dB}^3$

Typical DM velocity in galaxy v = 300 km/s = $10^{-3}c$

$$\implies \quad \mathcal{N} \approx 10^{32} \left(\frac{100\,\mu\text{eV}}{m_a} \right)^4$$



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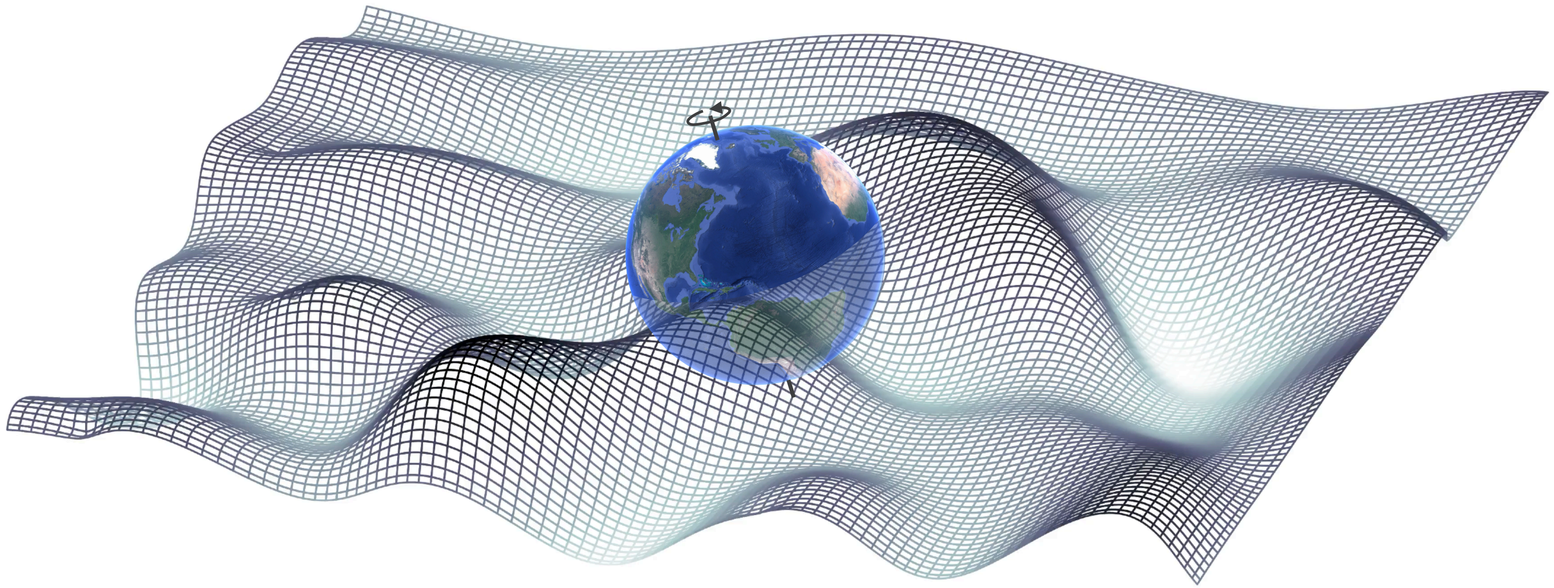

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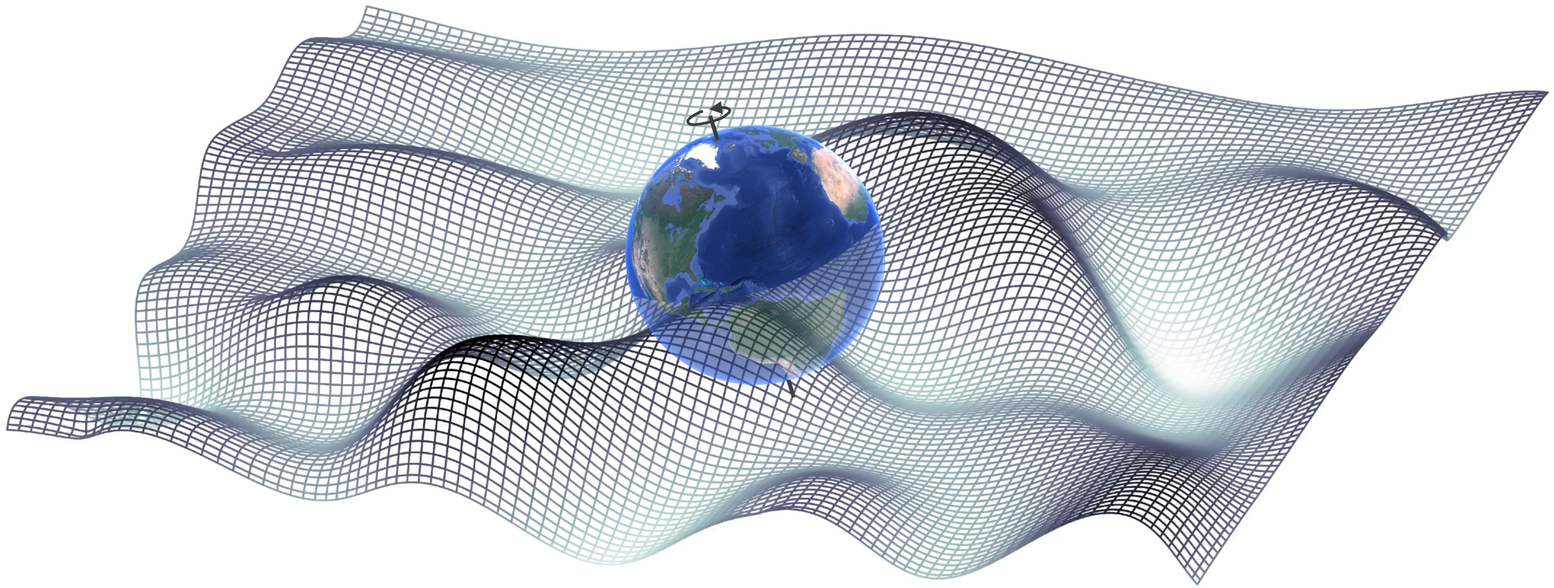
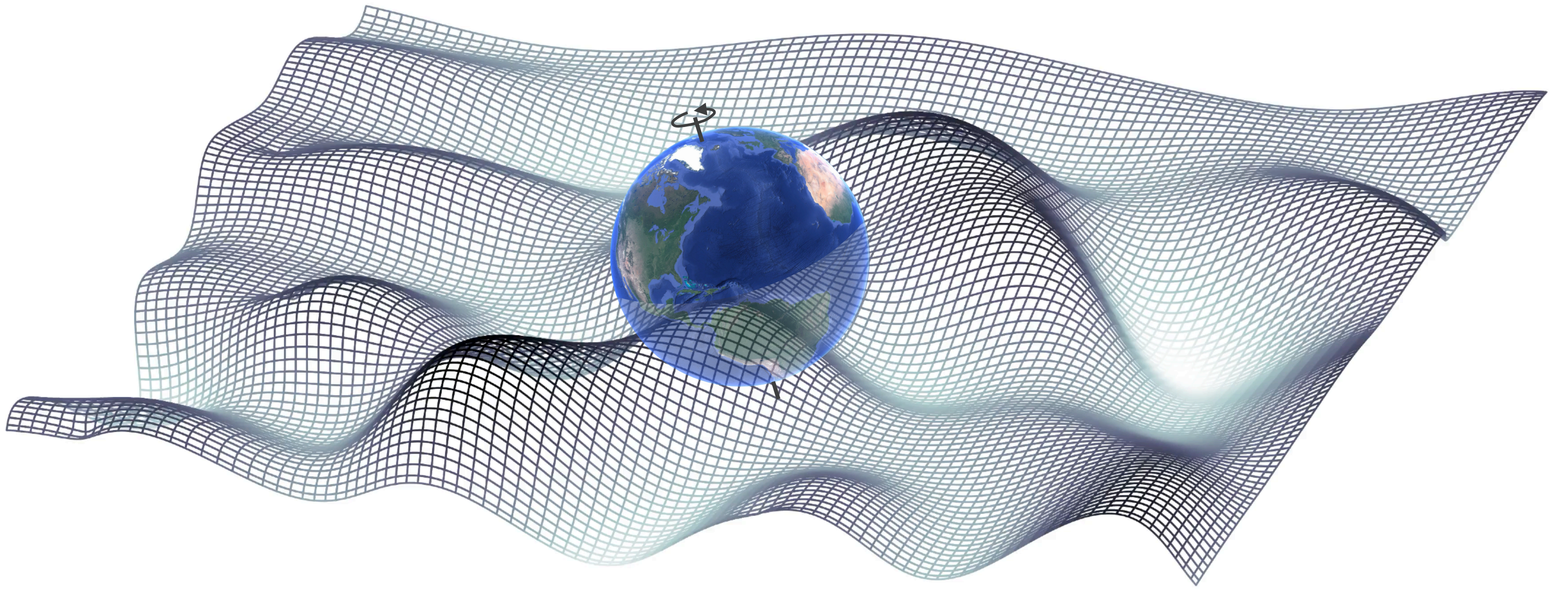
Macroscopically occupied ground state

↓

Classical field

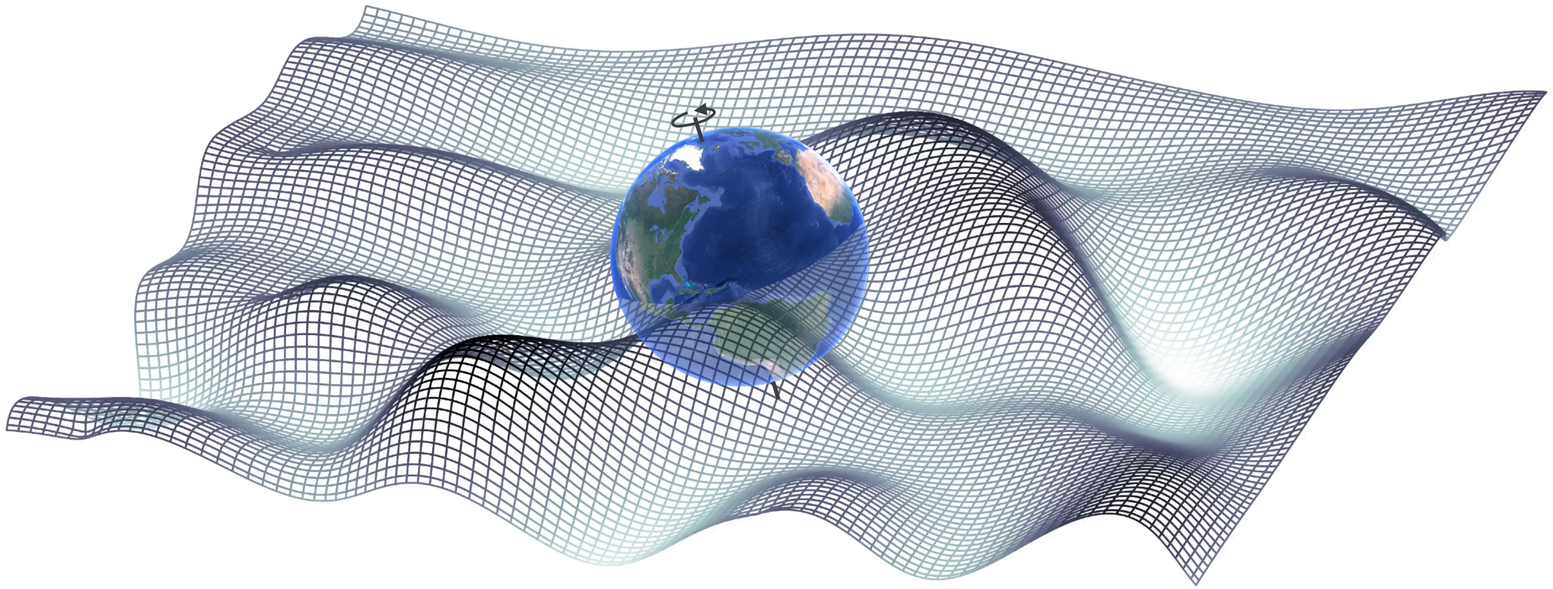


Wave-like dark matter



$$\phi(t) \approx A \cos \omega t$$

Wave-like dark matter



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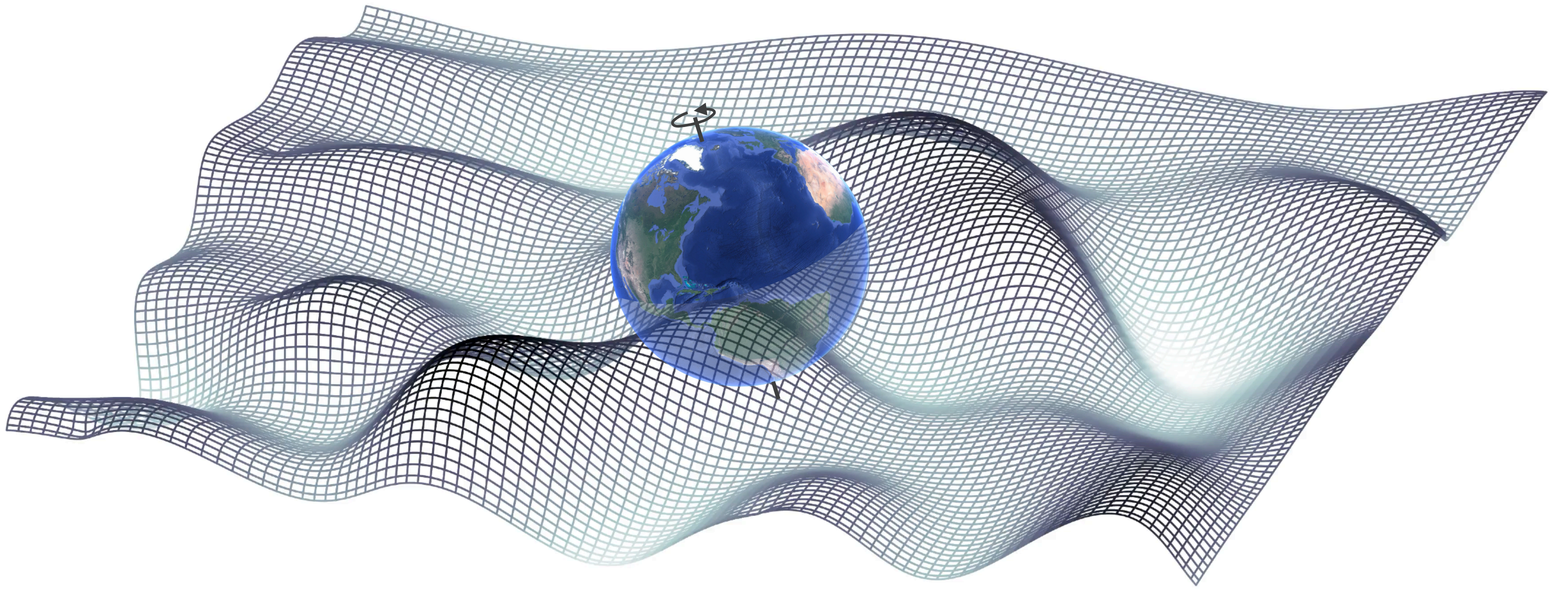

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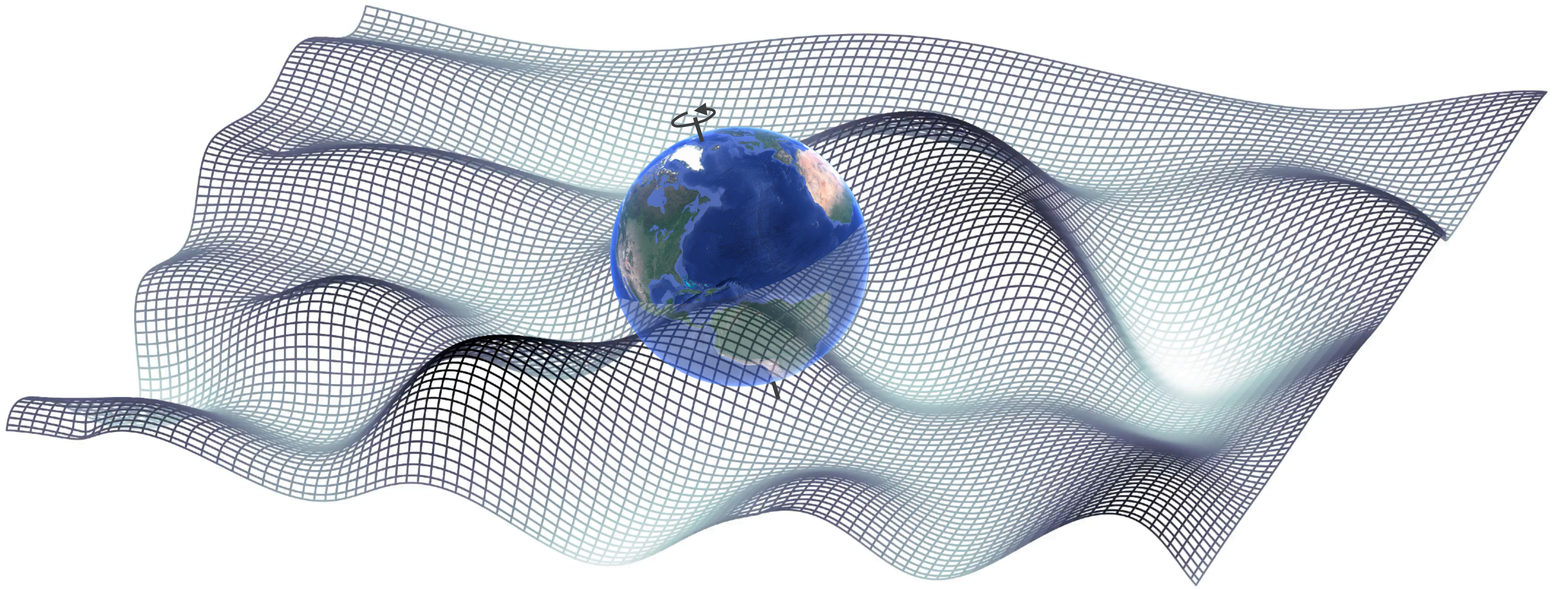

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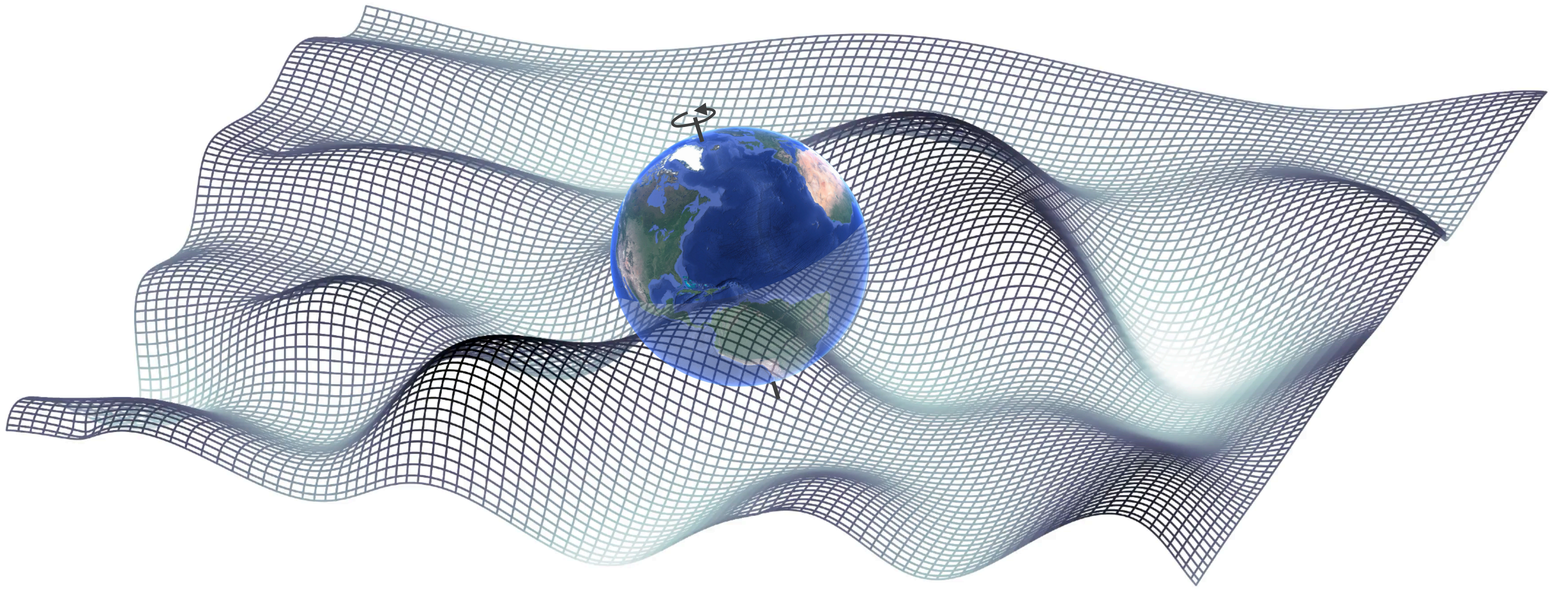
$$\approx m\underbrace{\left(1 + 10^{-6}\right)}$$

Oscillation remains coherent for 10^6 cycles

Wave-like dark matter



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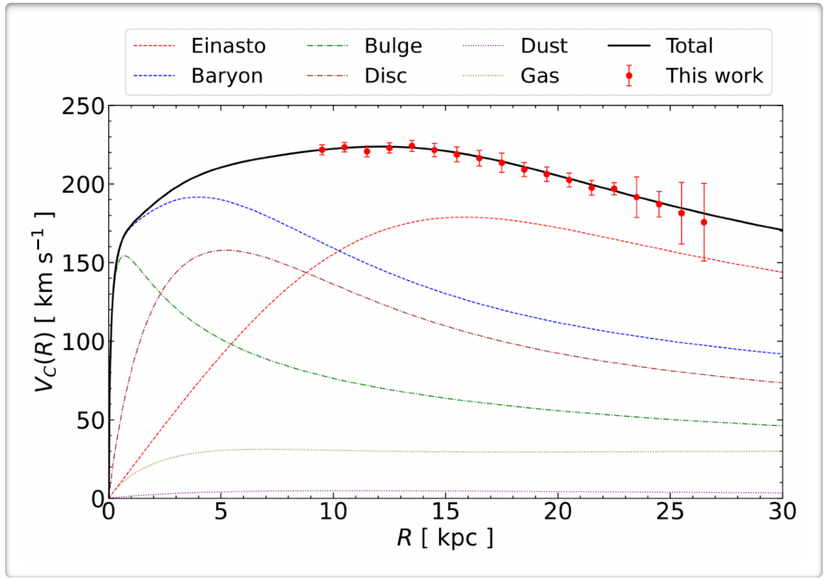
How do we know what to put in for density and velocity?


Dark Matter Halo
8 kpc
Galactic Bulge
Galactic Disk
(You are here)

[2309.00048]



$\rho(R = 8\,\mathrm{kpc}) \approx 0.4$ GeV/cm^3

Dark Matter Halo

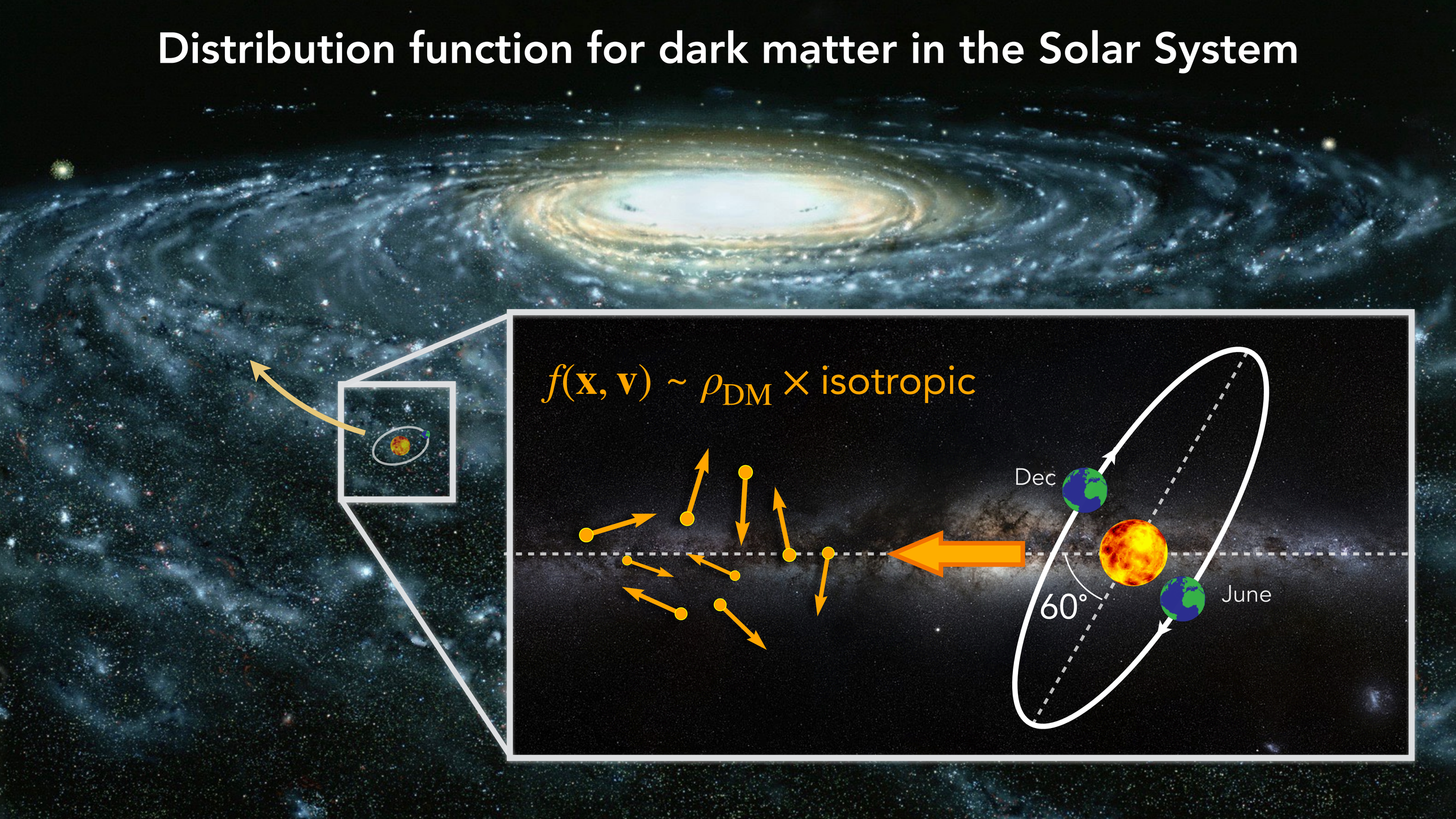
Galactic Bulge

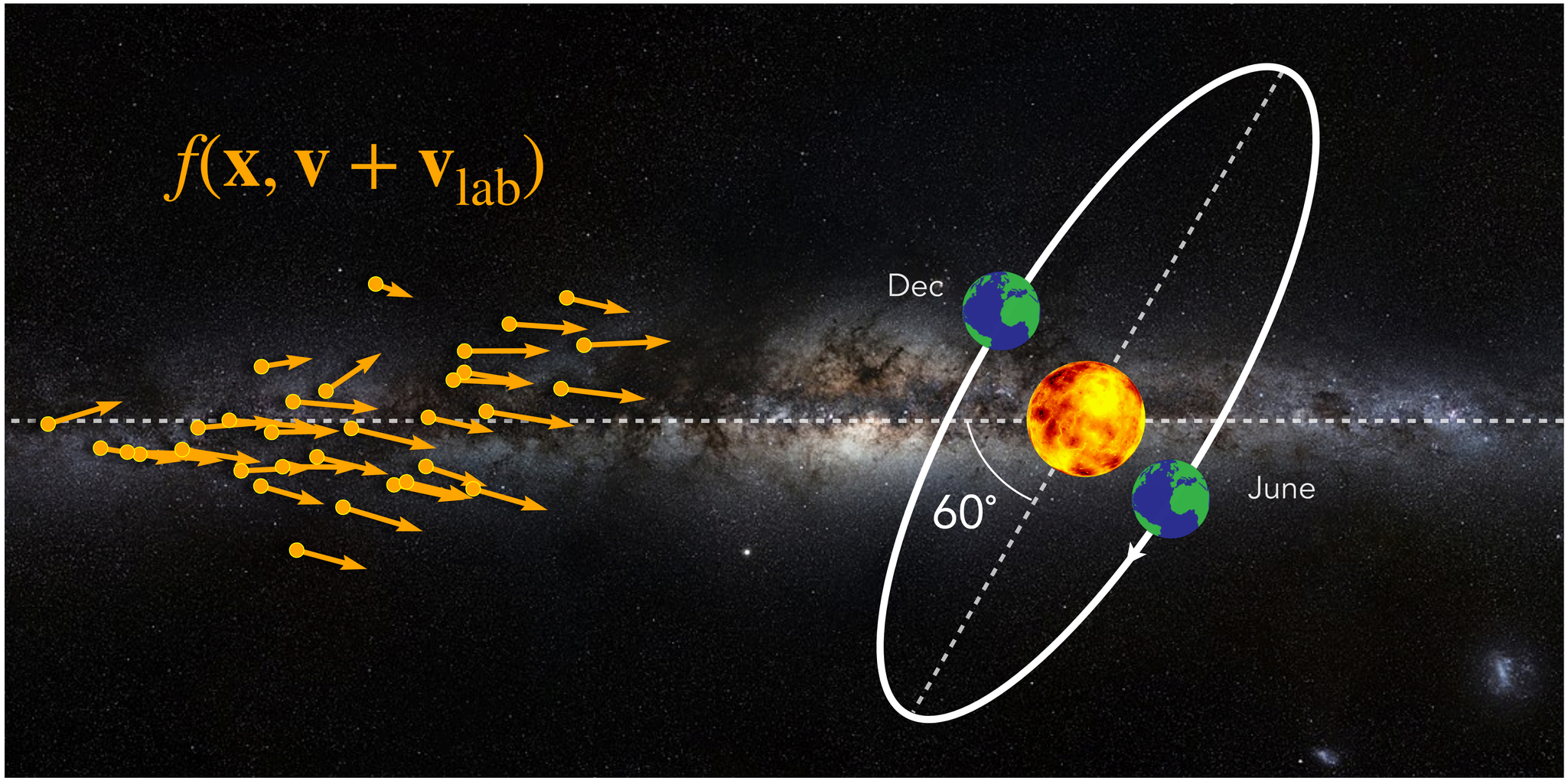
8 kpc

Galactic Disk

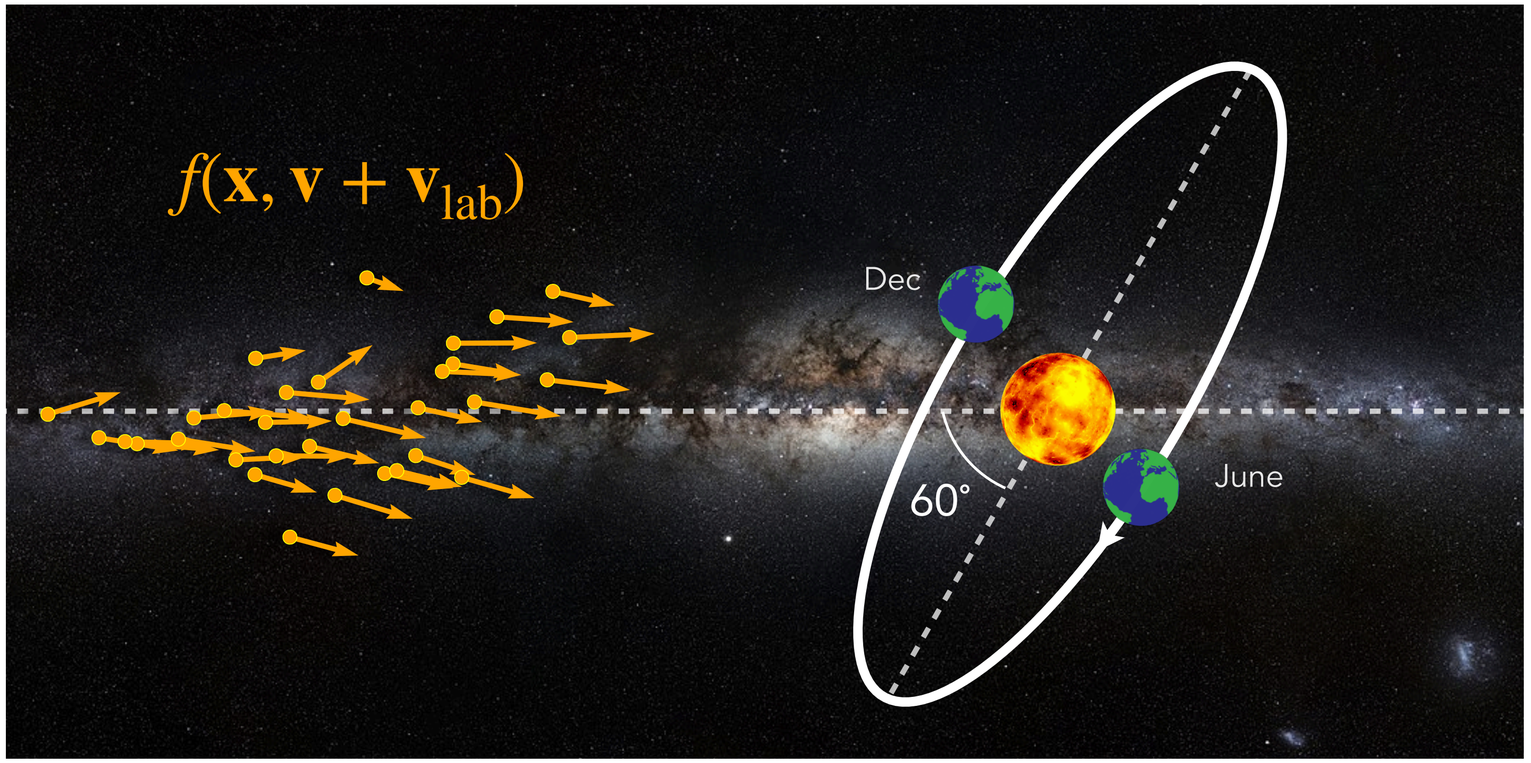
(You are here)

Distribution function for dark matter in the Solar System





Assuming the dark matter does not co-rotate with the disk, most effects come about from our laboratory's motion **through** the dark matter: $v_{\rm lab} \sim 300$ km/s



Sun/Earth motion leads to characteristic signals independent of DM model

→ Annual modulation
→ Gravitational focusing by Sun
→ Direction-dependence

$$\mathbf{v}_{\rm lab} = \underbrace{\mathbf{v}_{\rm LSR} + \mathbf{v}_{\rm pec}}_{\text{Sun:}} + \underbrace{\mathbf{v}_{\oplus,\,\rm rev.}(t)}_{\text{Earth:}}$$

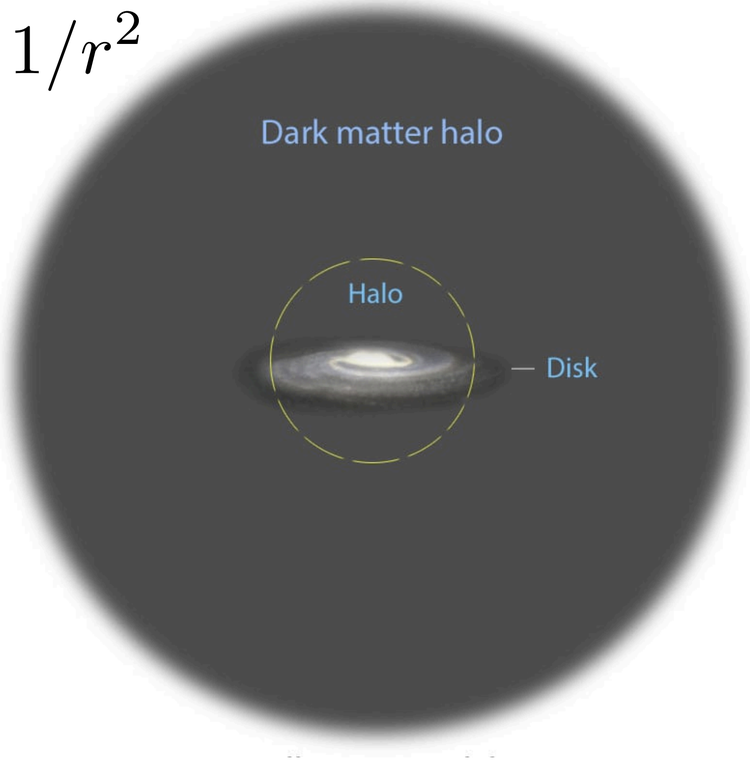
260 km/s

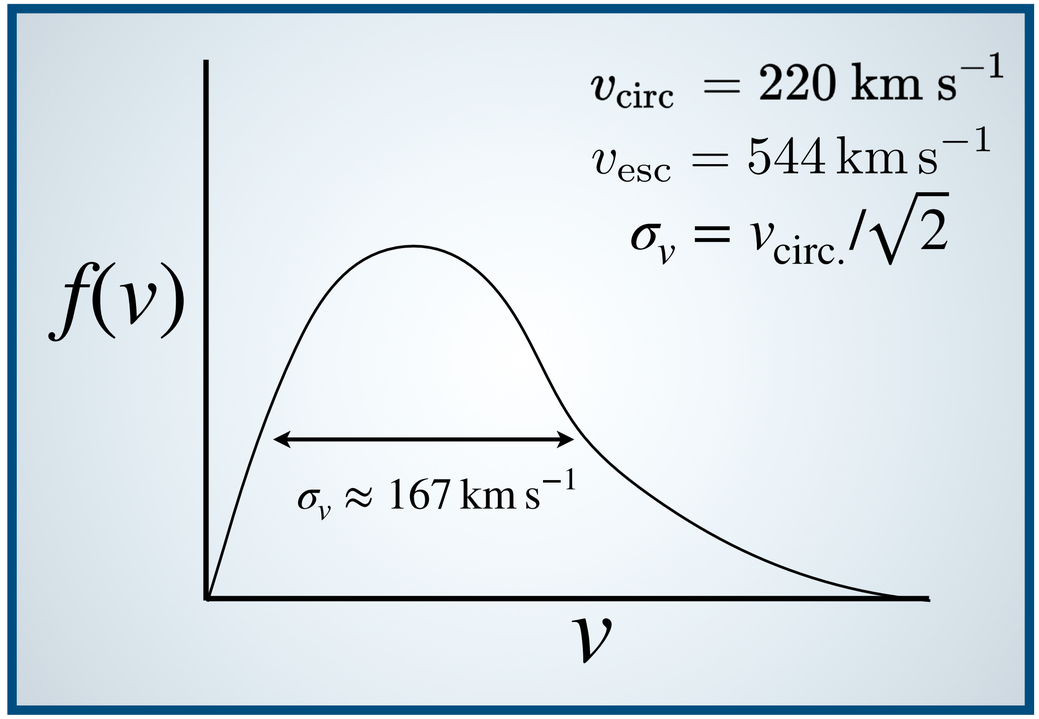
± 15 km/s (left-right)
± 20 km/s (up-down)

Usual assumption for $f(\mathbf{x}, \mathbf{v})$: the Standard Halo Model (SHM)

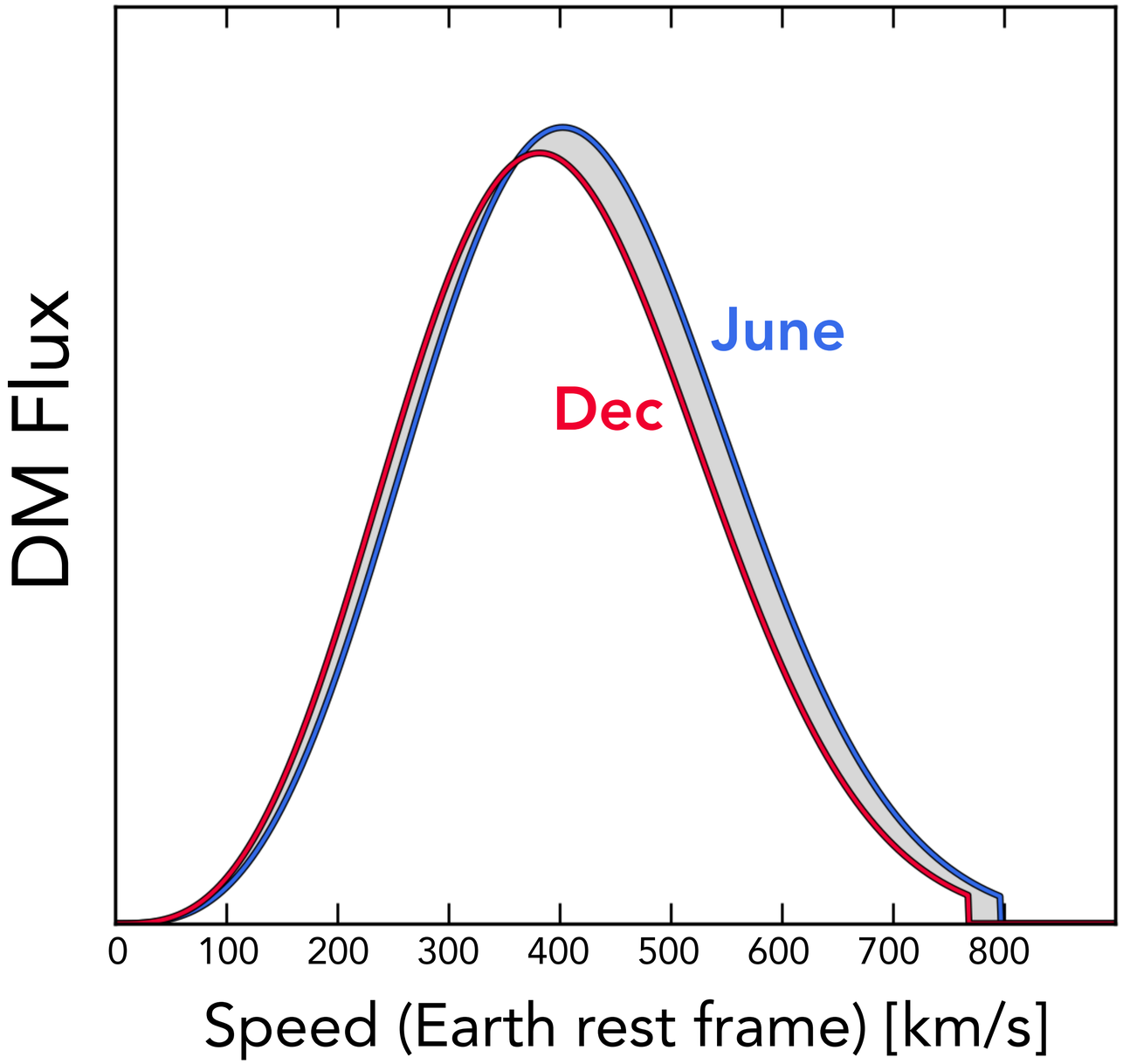
- Infinite isothermal sphere → Simplest halo model that gives a flat rotation curve
- Truncate at $v > v_{\rm esc}$ so as to not include unbound particles

$\rho \sim 1/r^2$





1. Annual modulation

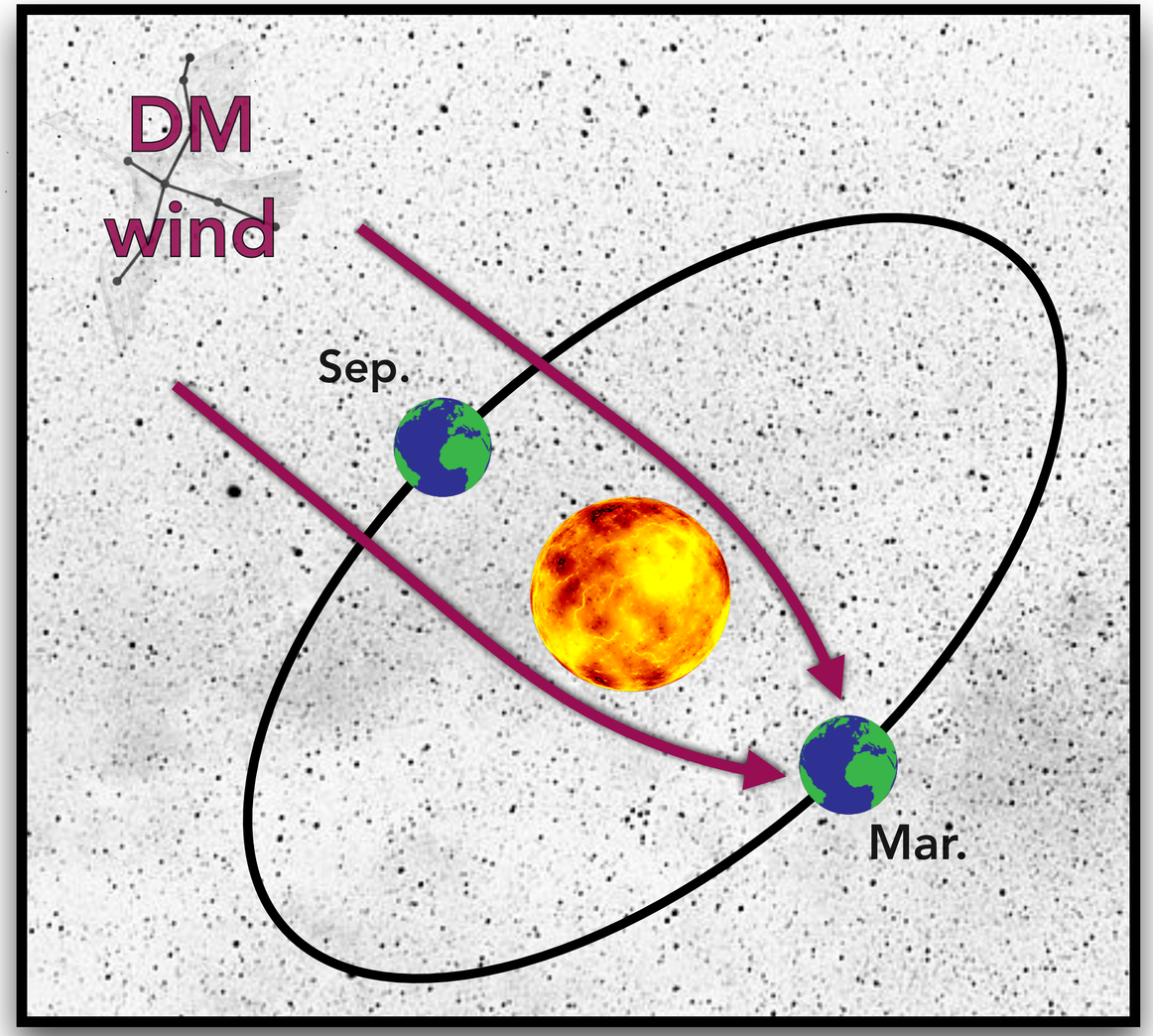


$$\mathbf{v}_{\rm lab} = \mathbf{v}_{\rm LSR} + \mathbf{v}_{\rm pec} + \mathbf{v}_{\oplus,\,\rm rev.}(t)$$

$$\text{DM Flux} \propto v\, f(\mathbf{v} + \mathbf{v}_{\rm lab})$$

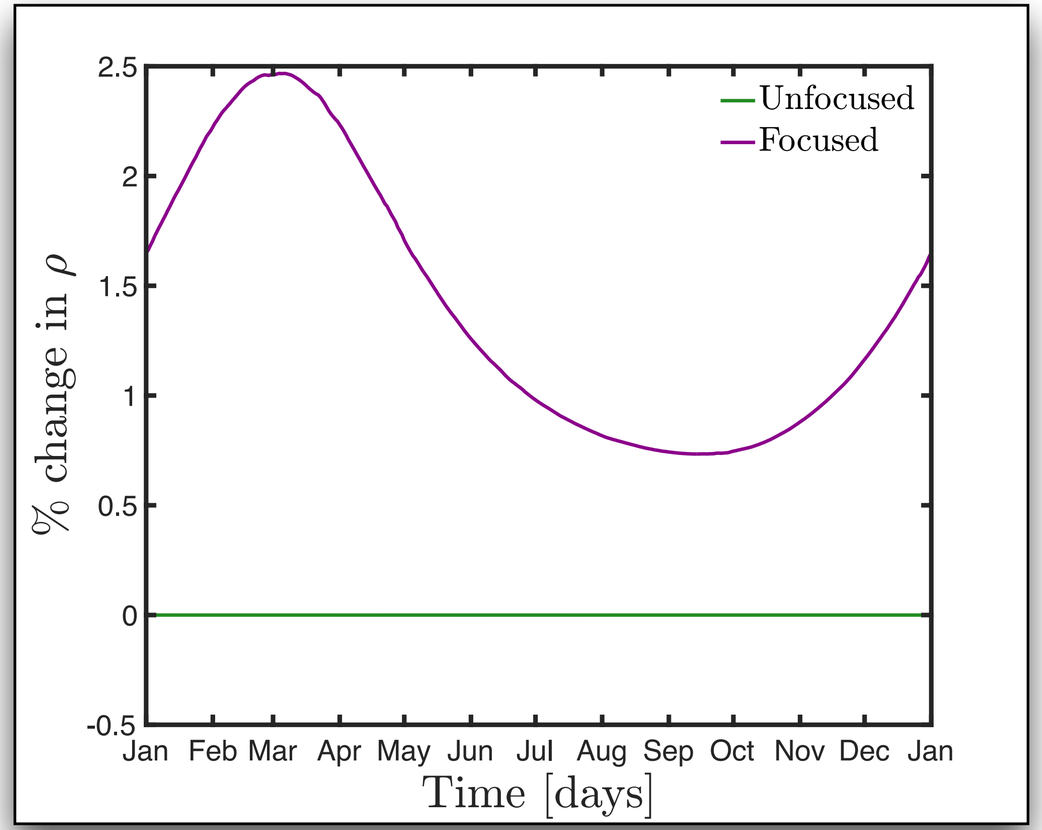
- Integrated flux is maximum during June and minimum in December (few % modulation)
- If sampling over distribution at lower-speeds only, phase is flipped (maximum in Dec.)

2. Gravitational focusing



- Additional ~2% modulation in DM **density**
- Distortion to $f(v)$ at small speeds:

$$v < v_{\rm esc} = \sqrt{2GM_\odot/r} \approx 40\,{\rm km/s}$$



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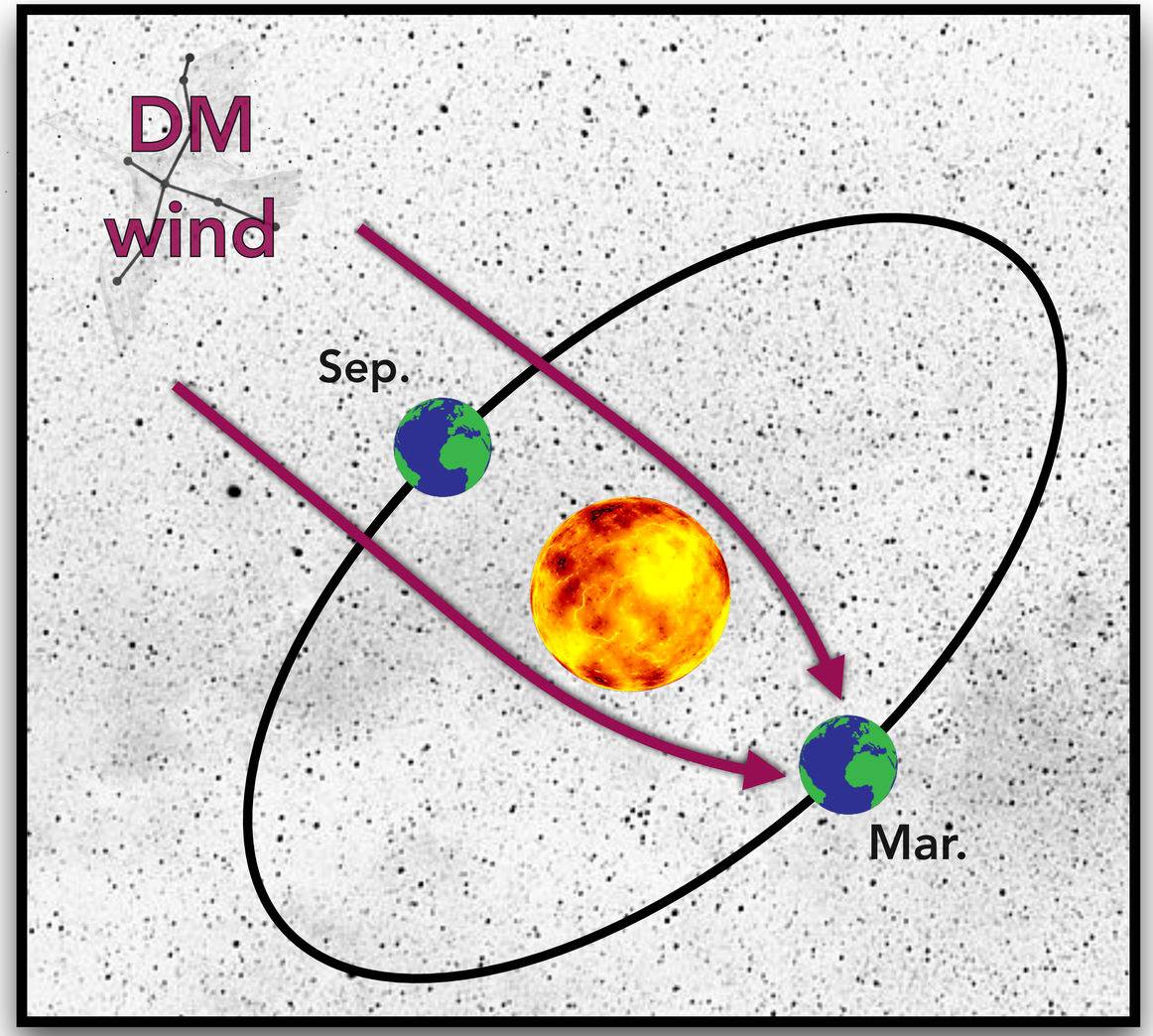

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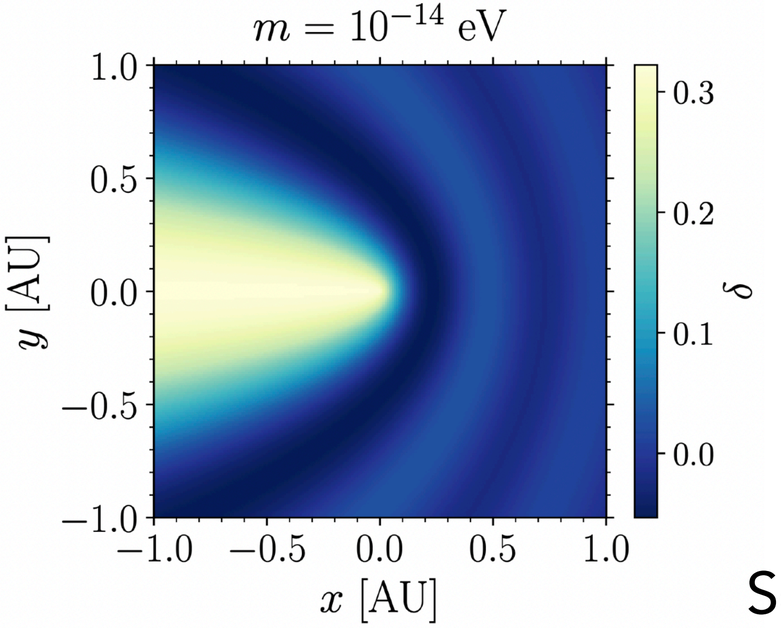
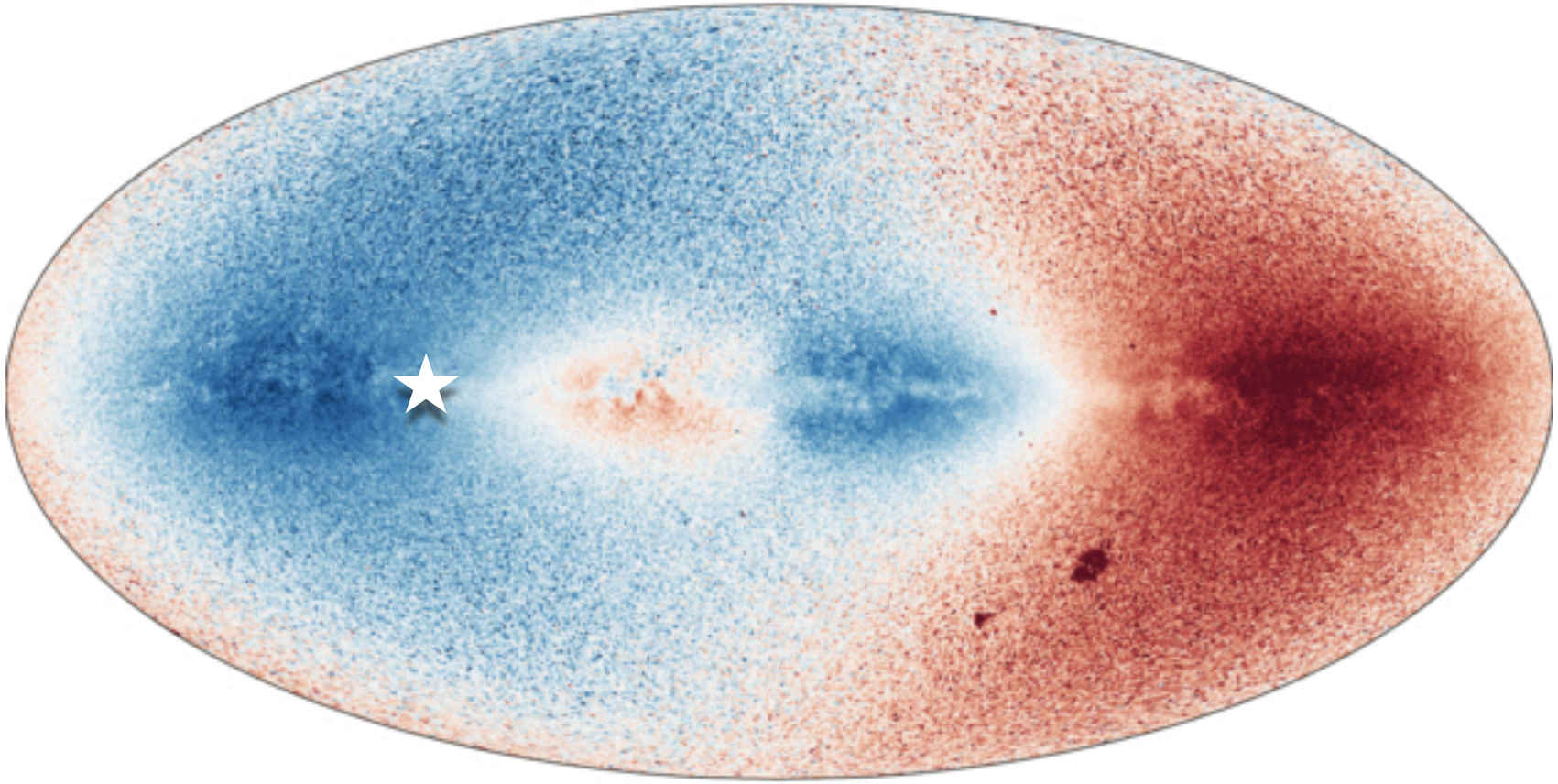


Distinct effects for the wave-like case relevant for low-mass axions

See [2112.05718]

3. Directionality



Gaia RVS galactic coordinates skymap of stellar line-of-sight velocities

Blue = moving towards us

Red = moving away from us

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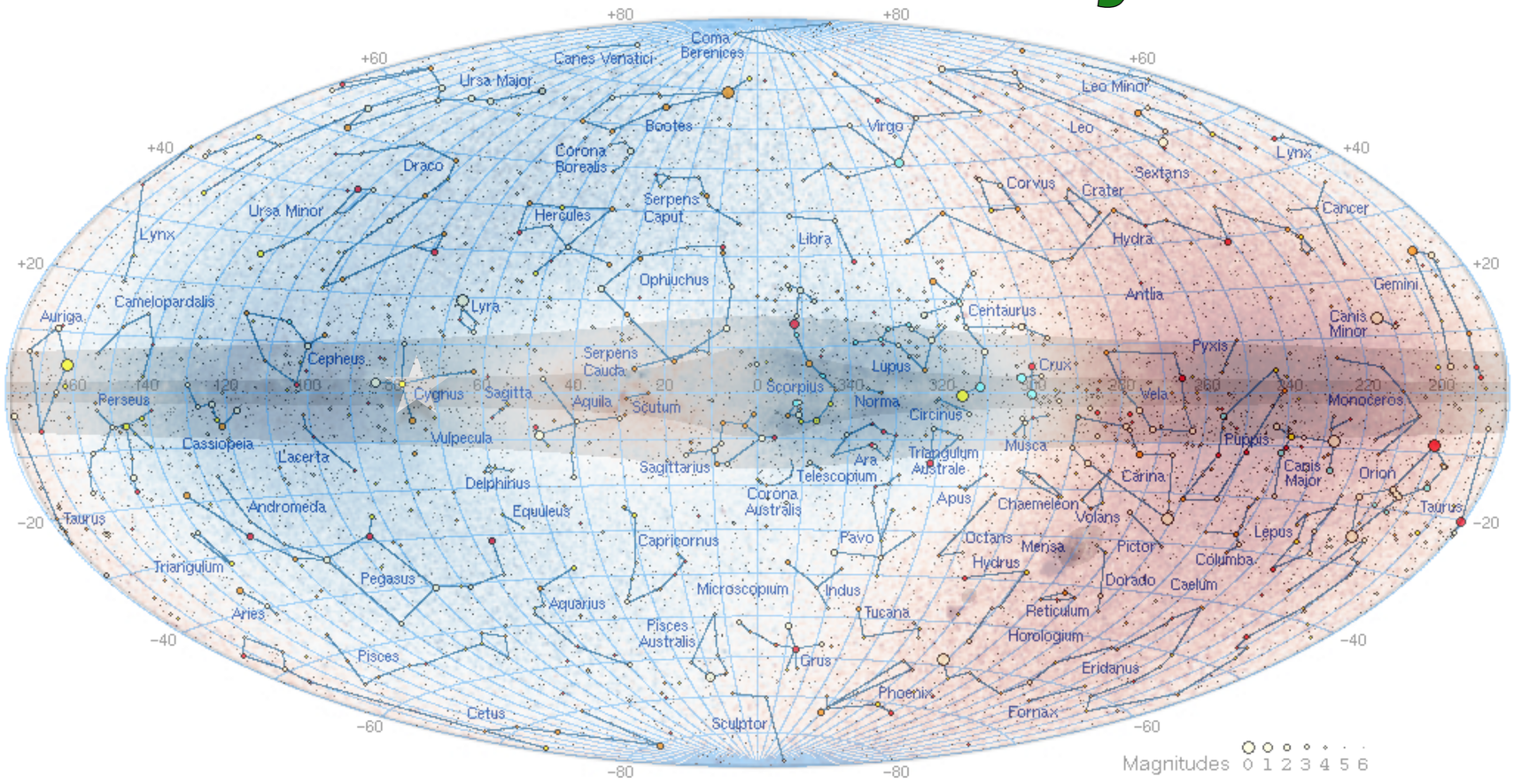

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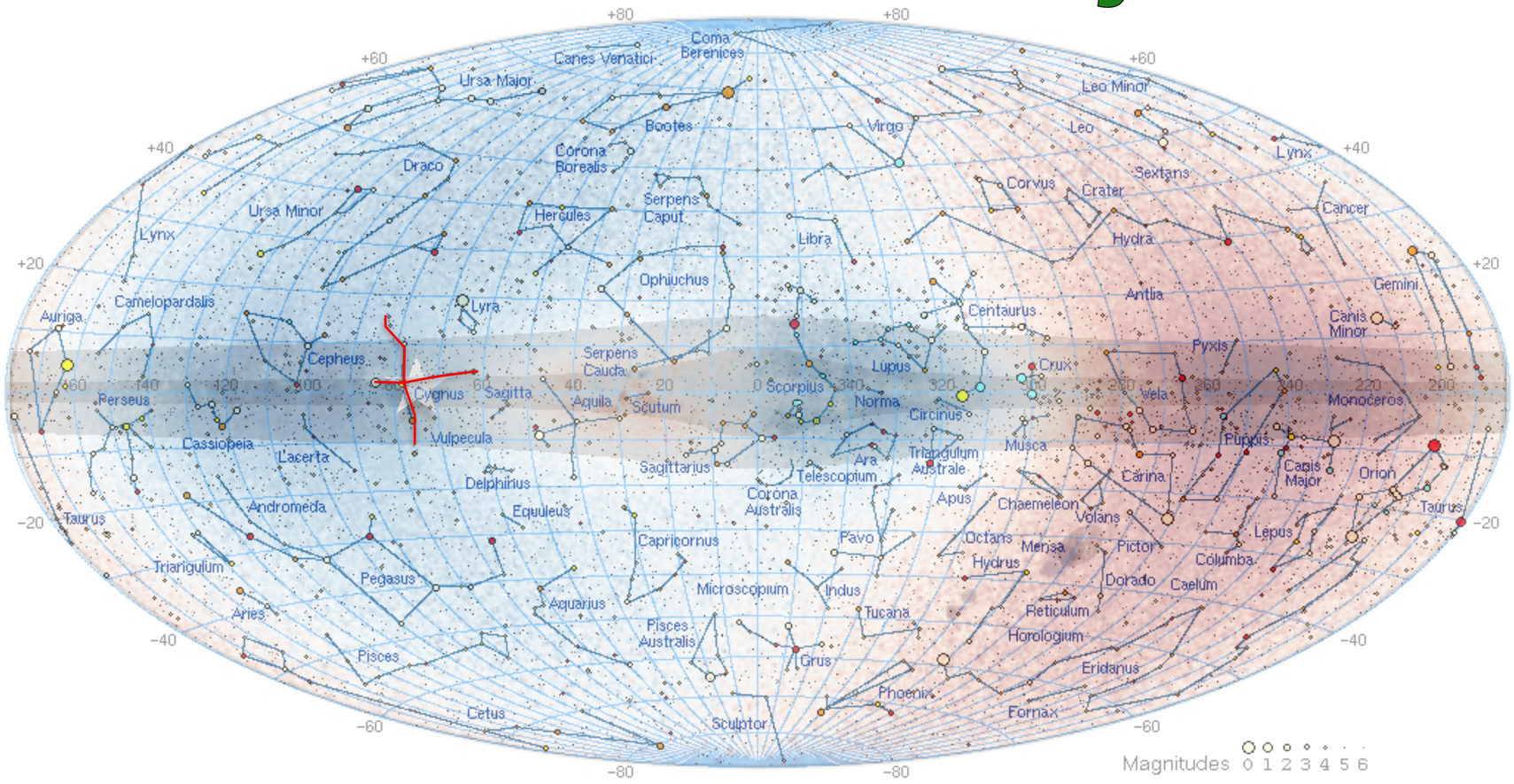

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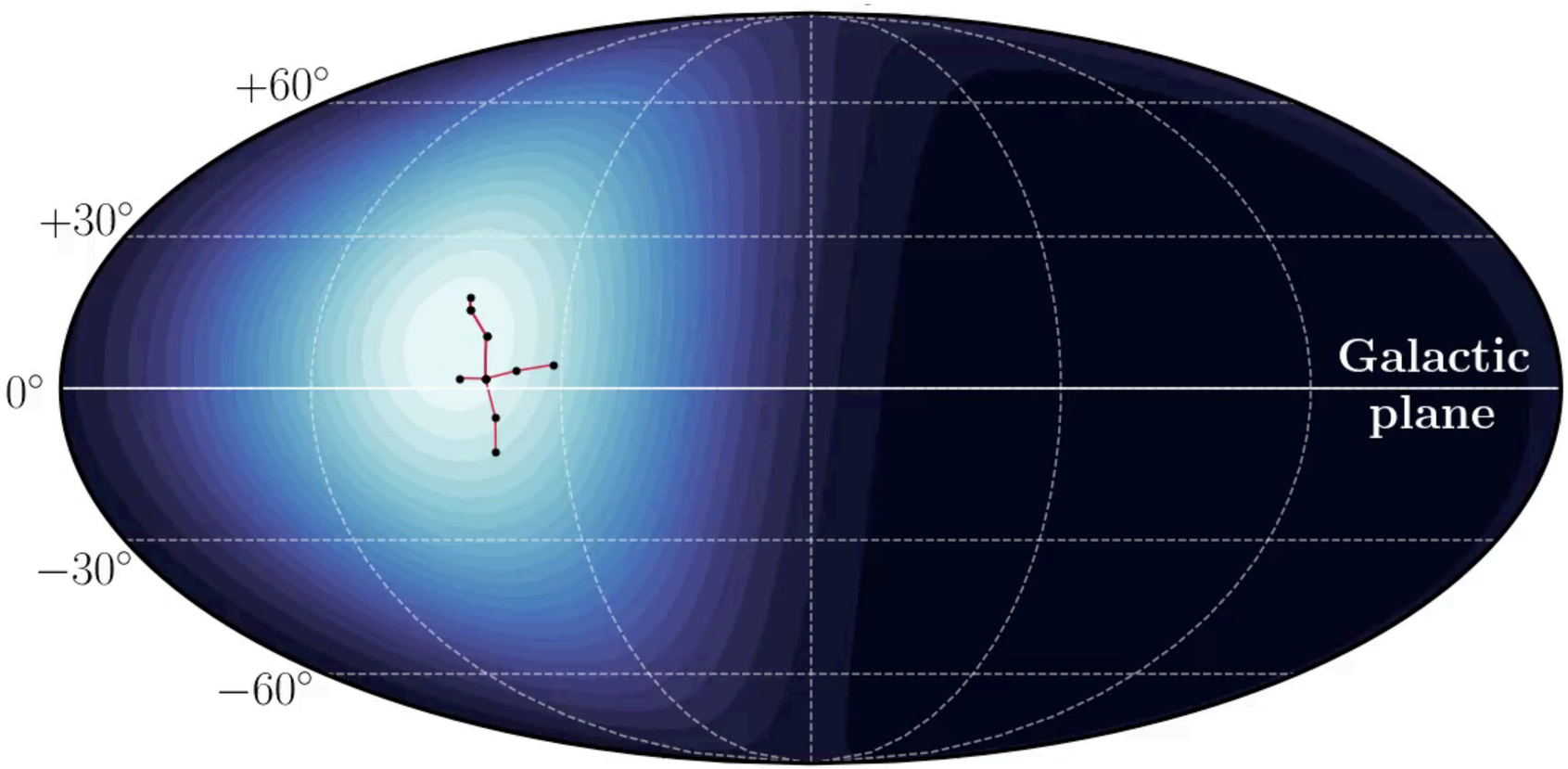

The dark matter flux on Earth is highly anisotropic towards constellation of Cygnus

$$\Phi_{\text{forward}}/\Phi_{\text{backward}} \sim O(10)$$

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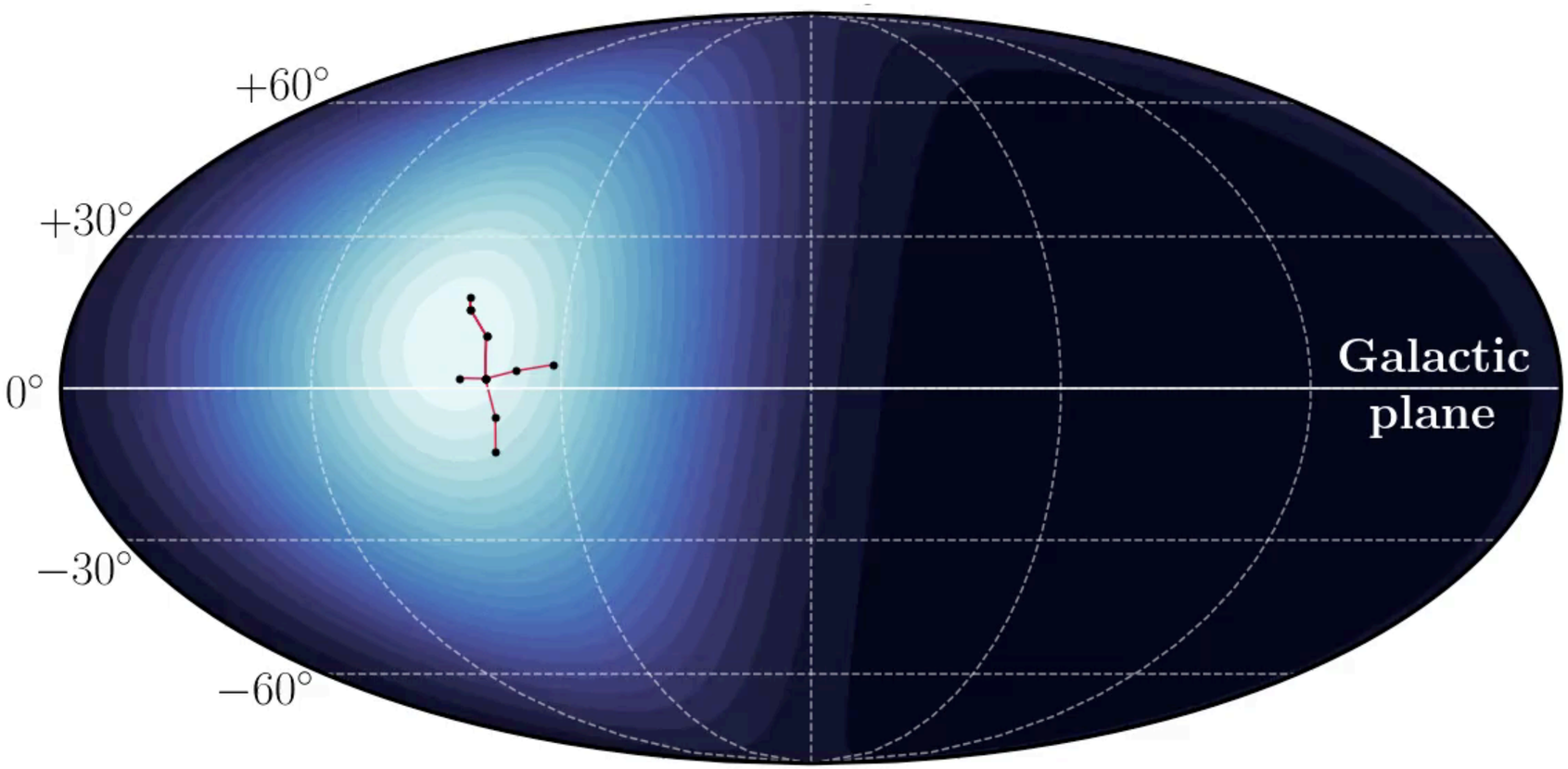

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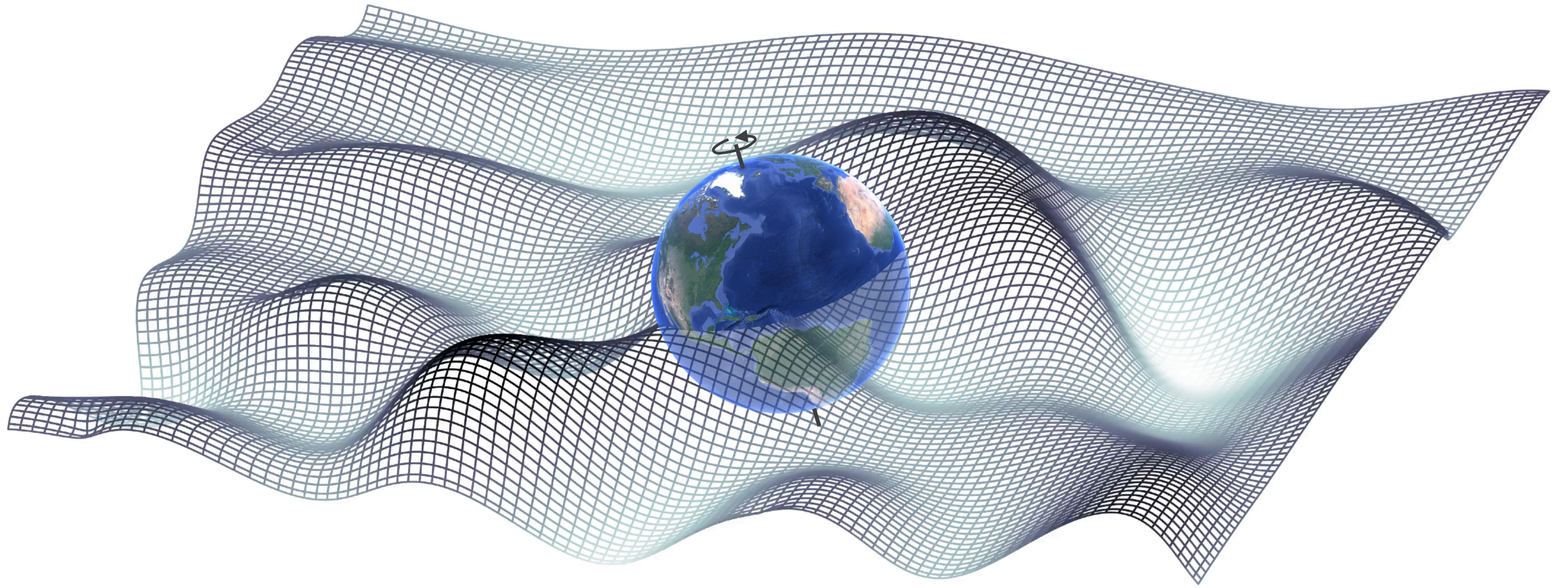
How do the speed distribution, annual modulation, directionality manifest in the wave-like case?



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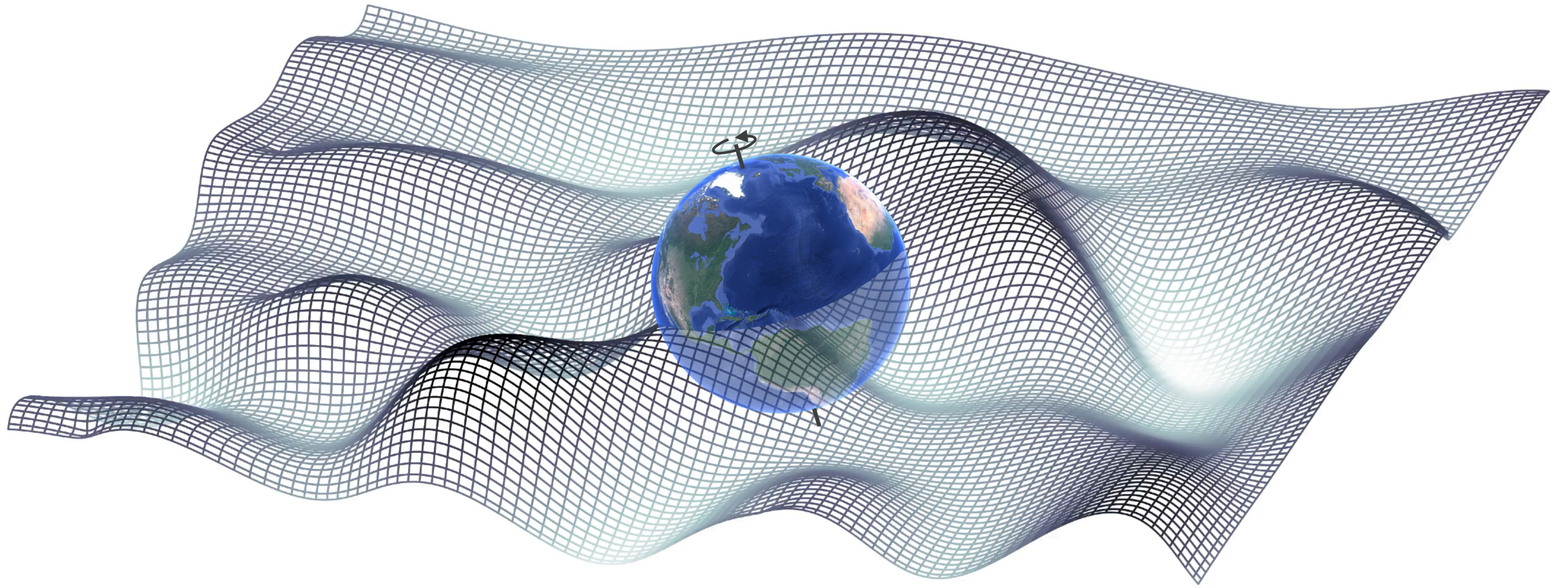

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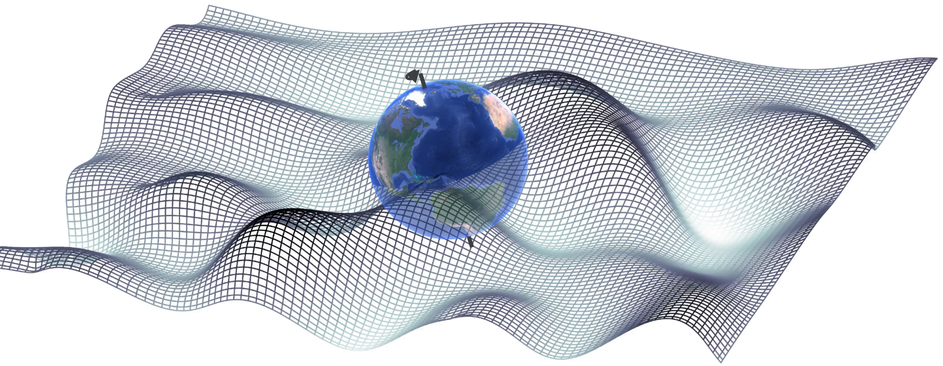
Wave-like dark matter, properly



Superposition of plane waves in some box of volume, *V*

$$\phi(t, \mathbf{x}) = \sqrt{V} \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \phi(\mathbf{p}) e^{-i(\omega t - \mathbf{p}\cdot\mathbf{x} + \beta(\mathbf{p}))}$$

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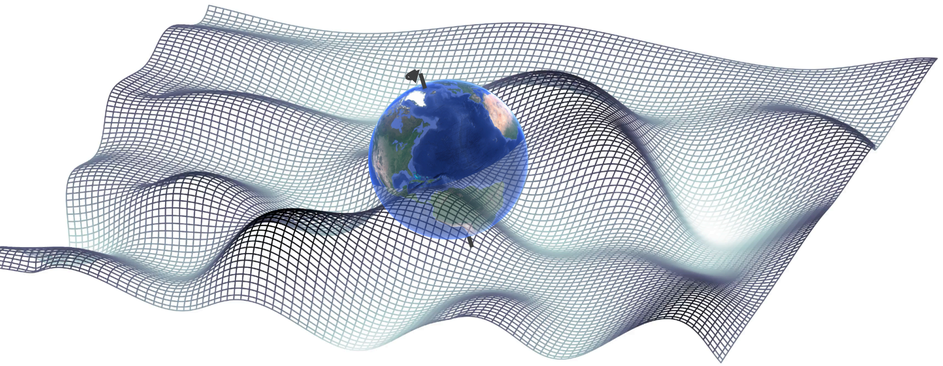

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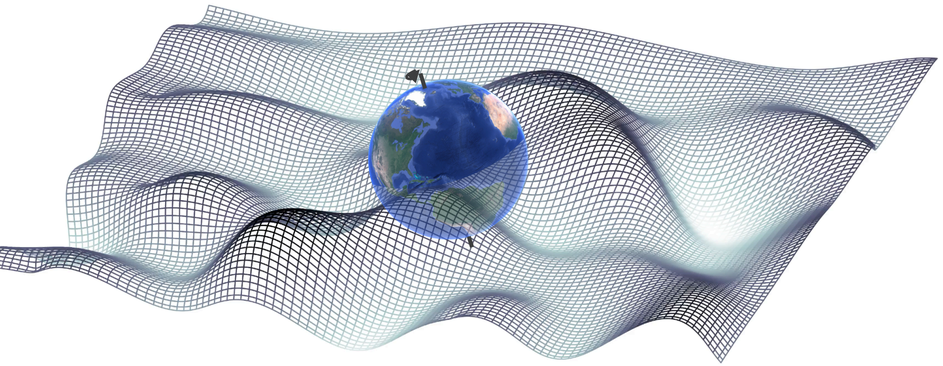

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Only when we measure over some **short enough** time/length scale do we have:

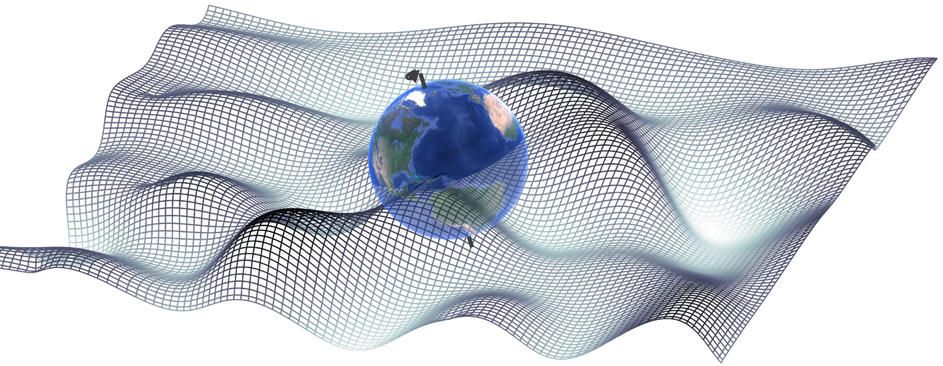
$$\phi = \phi_0 \cos(\omega t - \mathbf{p} \cdot \mathbf{x} + \beta)$$

Random amplitude

Random draw from the velocity distribution

Arbitrary phase

Wave-like dark matter, properly



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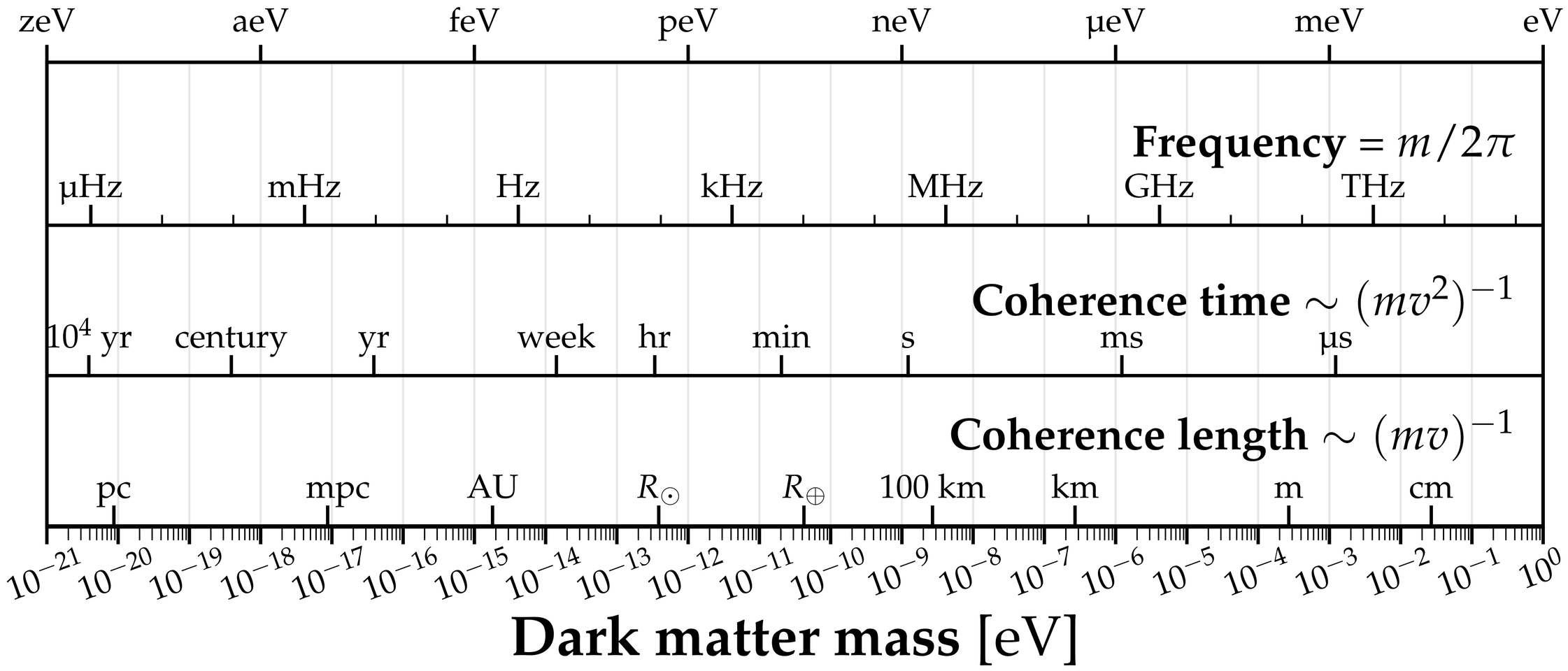
Random draw from the velocity distribution

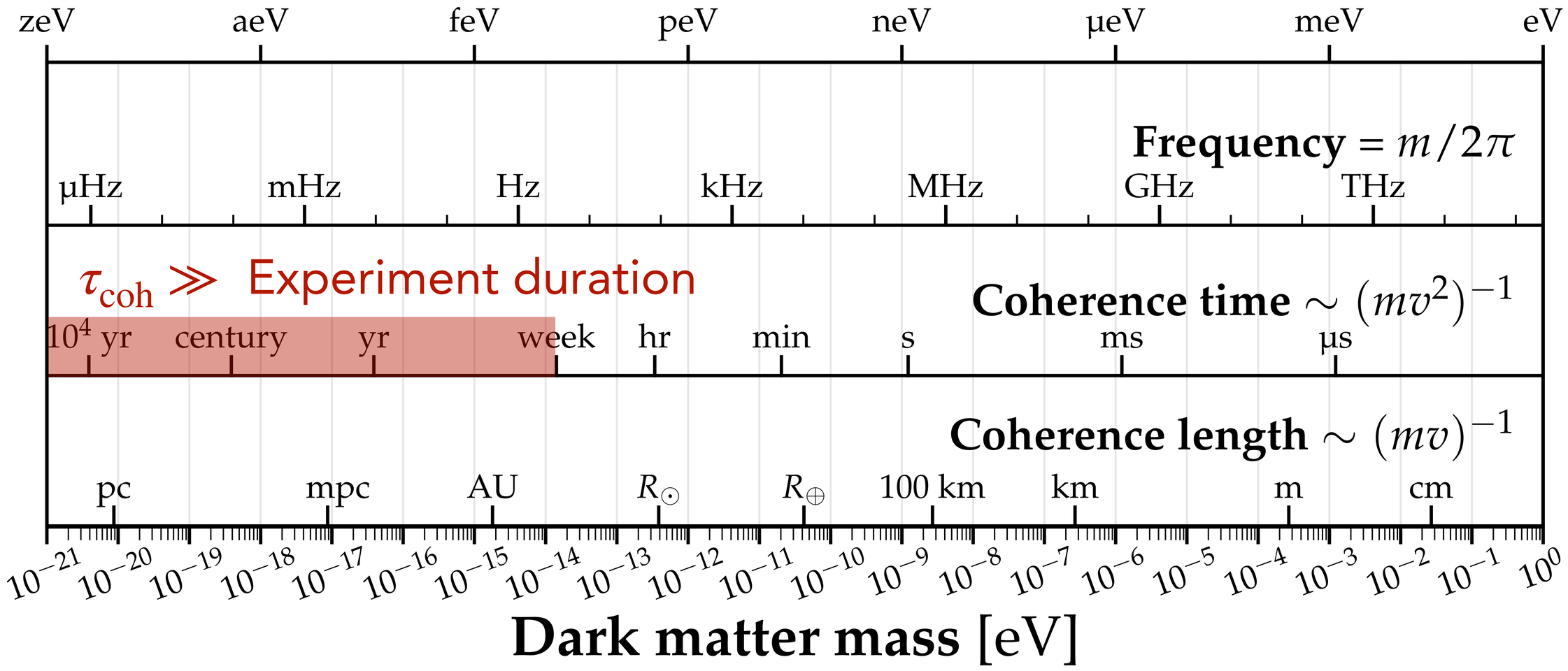
Arbitrary phase

What is considered "short enough"?

→ Coherence length and coherence time: the length/timescale over which field will be out of phase with itself

$$\lambda_{\mathrm{coh}} \sim \frac{2\pi}{mv} \qquad \tau_{\mathrm{coh}} \sim \frac{2\pi}{mv^2}$$


zeV
aeV
feV
peV
neV
μeV
meV
eV
Frequency = $m/2\pi$
μHz
mHz
Hz
kHz
MHz
GHz
THz
Coherence time ~ $(mv^2)^{-1}$
10^4 yr
century
yr
week
hr
min
s
ms
μs
Coherence length ~ $(mv)^{-1}$
pc
mpc
AU
$R_\odot$
$R_\oplus$
100 km
km
m
cm
10^{-21} 10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
Dark matter mass [eV]


zeV
aeV
feV
peV
neV
μeV
meV
eV
Frequency = $m/2\pi$
μHz
mHz
Hz
kHz
MHz
GHz
THz
$\tau_{\rm coh} \gg$ Experiment duration
Coherence time $\sim (mv^2)^{-1}$
10^4 yr
century
yr
week
hr
min
s
ms
μs
Coherence length $\sim (mv)^{-1}$
pc
mpc
AU
$R_\odot$
$R_\oplus$
100 km
km
m
cm
10^{-21} 10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
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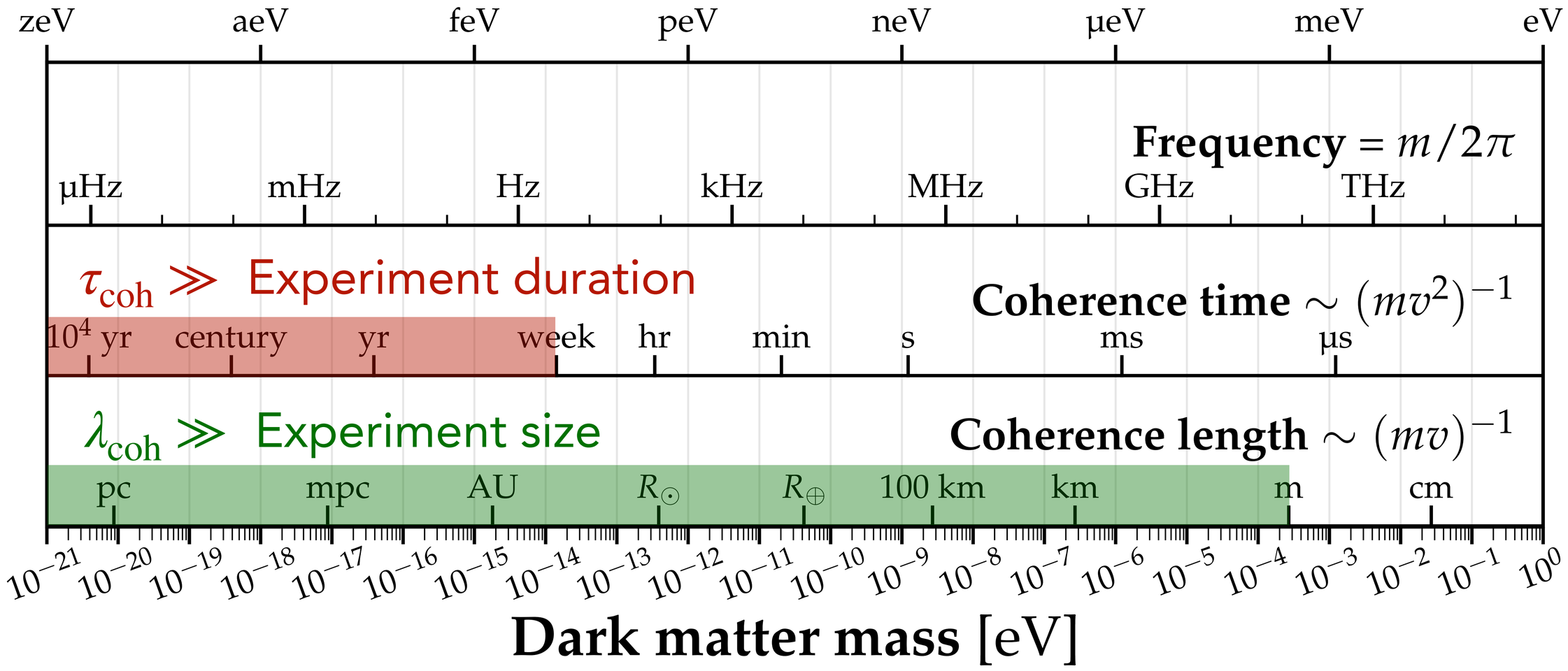
zeV
aeV
feV
peV
neV
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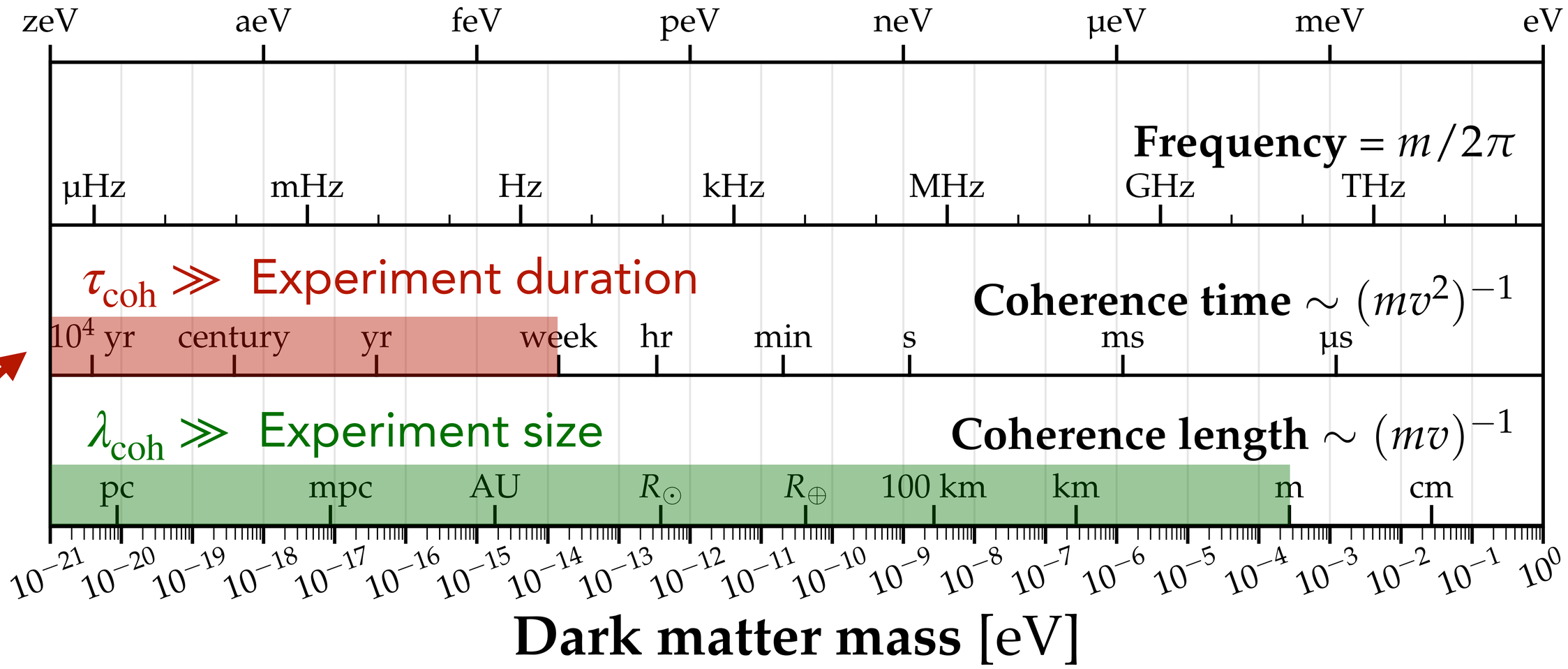
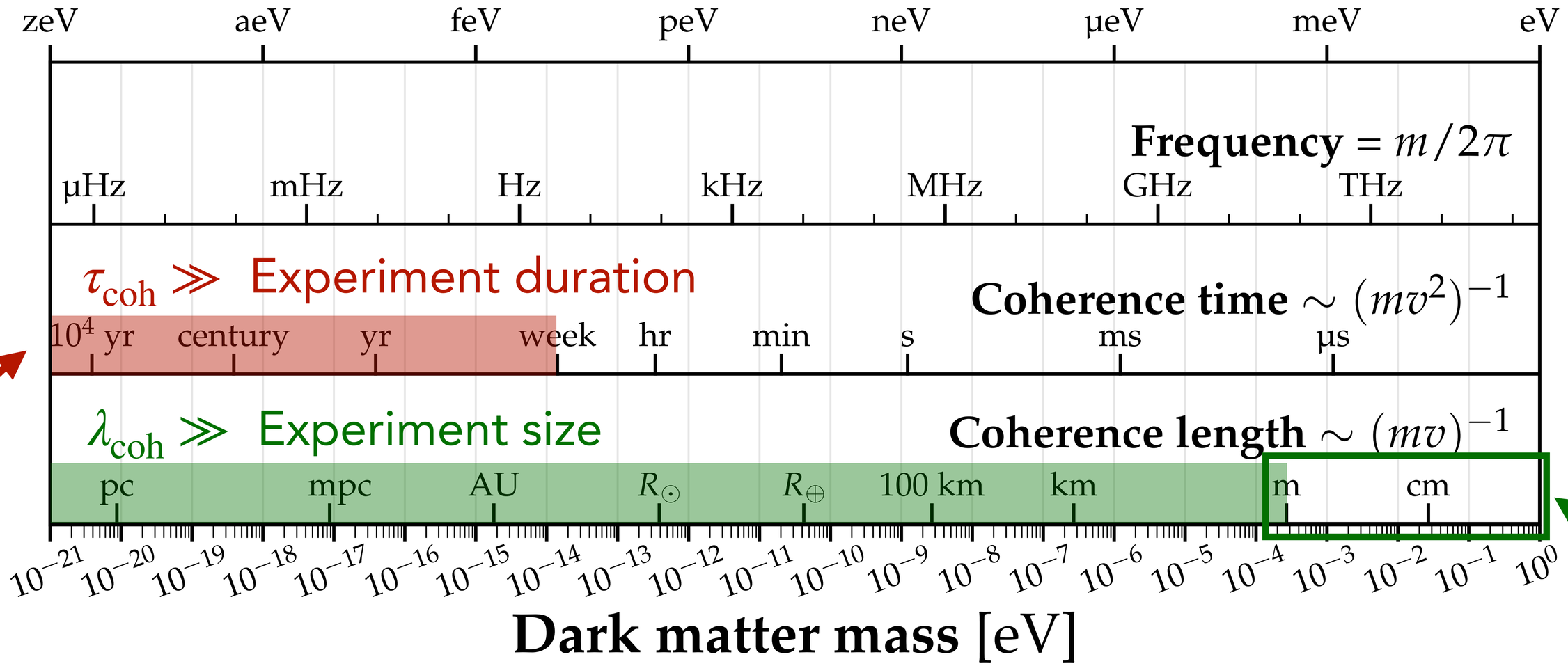
meV
eV
Frequency = $m/2\pi$
μHz
mHz
Hz
kHz
MHz
GHz
THz
$\tau_{\rm coh} \gg$ Experiment duration
Coherence time $\sim (mv^2)^{-1}$
10^4 yr
century
yr
week
hr
min
s
ms
μs
$\lambda_{\rm coh} \gg$ Experiment size
Coherence length $\sim (mv)^{-1}$
pc
mpc
AU
$R_\odot$
$R_\oplus$
100 km
km
m
cm
10^{-21} 10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
Dark matter mass [eV]



~week-long integration will observe almost perfectly monochromatic signal

(Worry instead about random amplitude)



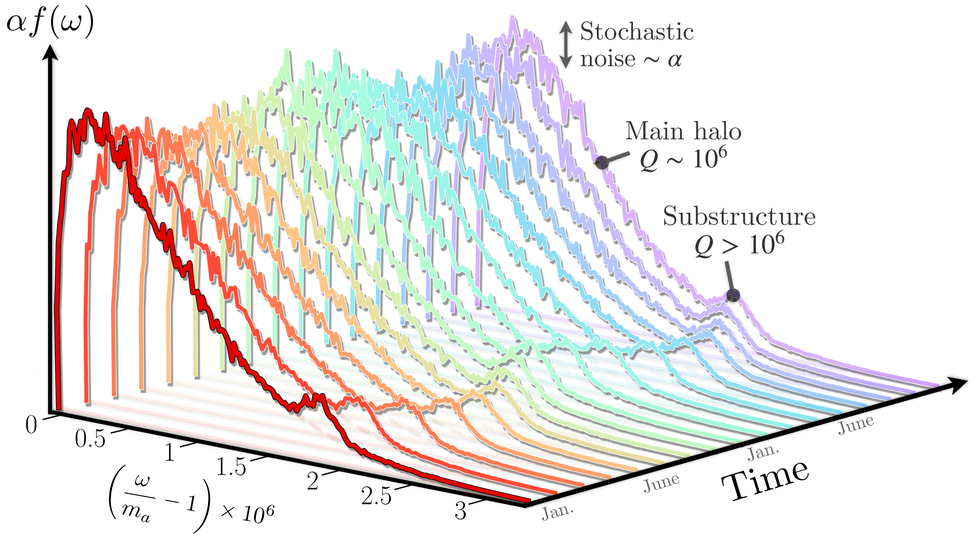
~week-long integration will observe almost perfectly monochromatic signal

(Worry instead about random amplitude)

Field oscillations are out of phase in different parts of <m-scale experiment

Wave-like dark matter

How do the speed distribution, annual modulation, directionality manifest in the wave-like case?



→ Speed distribution leads to a distinctive “lineshape” in frequency that will modulate over the year

$$f(\omega, t) = f(v, t)\frac{\mathrm{d}v}{\mathrm{d}\omega}$$

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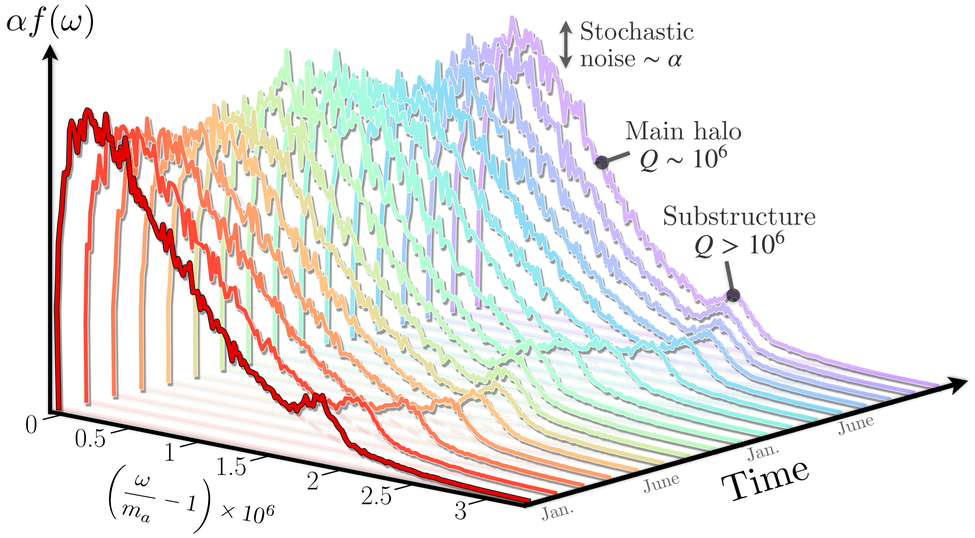

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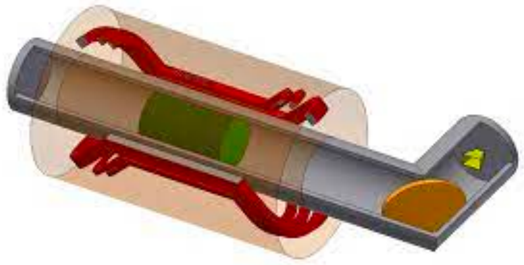
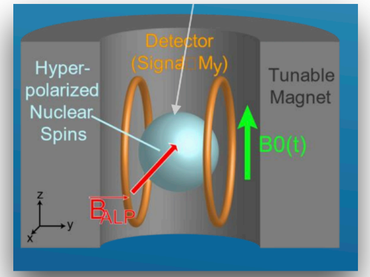


MADMAX



CASPEr-Gradient

→ Directionality could appear in two forms:

→ Experiments that are larger than coherence length

→ Experiments that measure the field-gradient:

$$\nabla\phi = \sqrt{2\rho}\,\mathbf{v}\sin(\omega t - m_a\mathbf{v}\cdot\mathbf{x} + \beta)$$

But how much do we trust our assumptions?

Is the DM halo spherical?

Is the DM speed distribution Maxwellian?

Is the DM halo stationary?

But how much do we trust our assumptions?

Is the DM halo spherical? → No

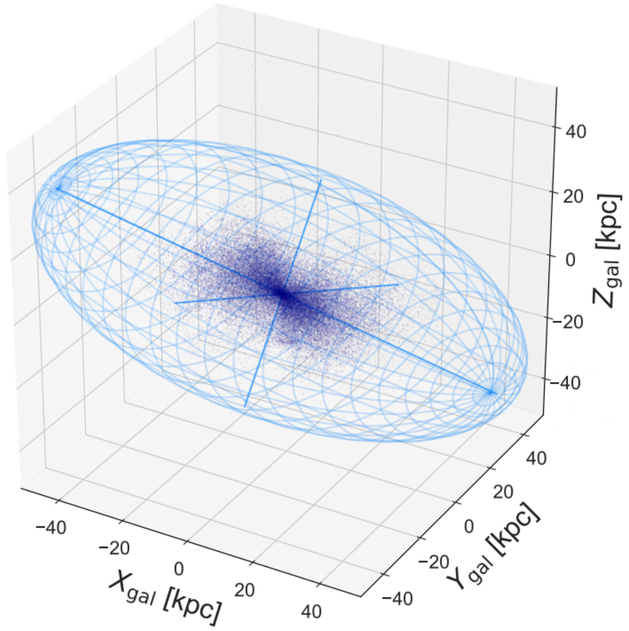
Is the DM speed distribution Maxwellian? → Probably not

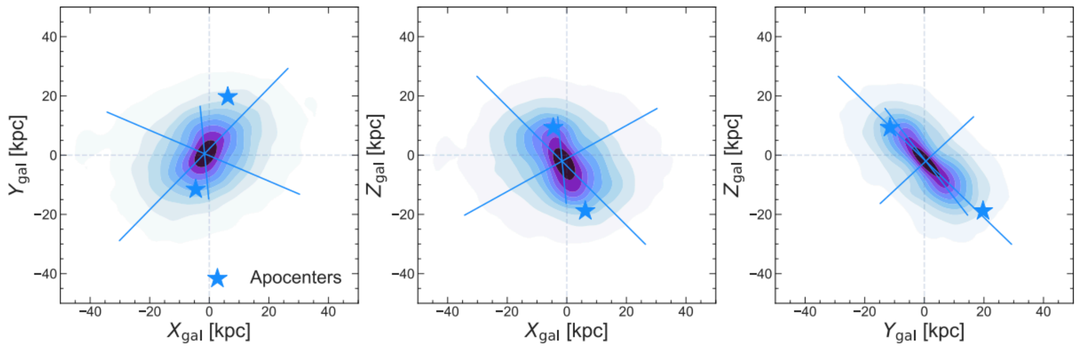
Is the DM halo stationary? → Probably not

Han+ [2208.04327]
Naidu+[2103.03251]
(H3 survey)

Triaxial axis ratio
10 : 7.9 : 4.5
Major axis at ~35°
from disk plane

Iorio & Belokurov
2019
10 : 7.9 : 4.5-6.6
~20°





Iorio & Belokurov
[1804.11347] (RR Lyraes)

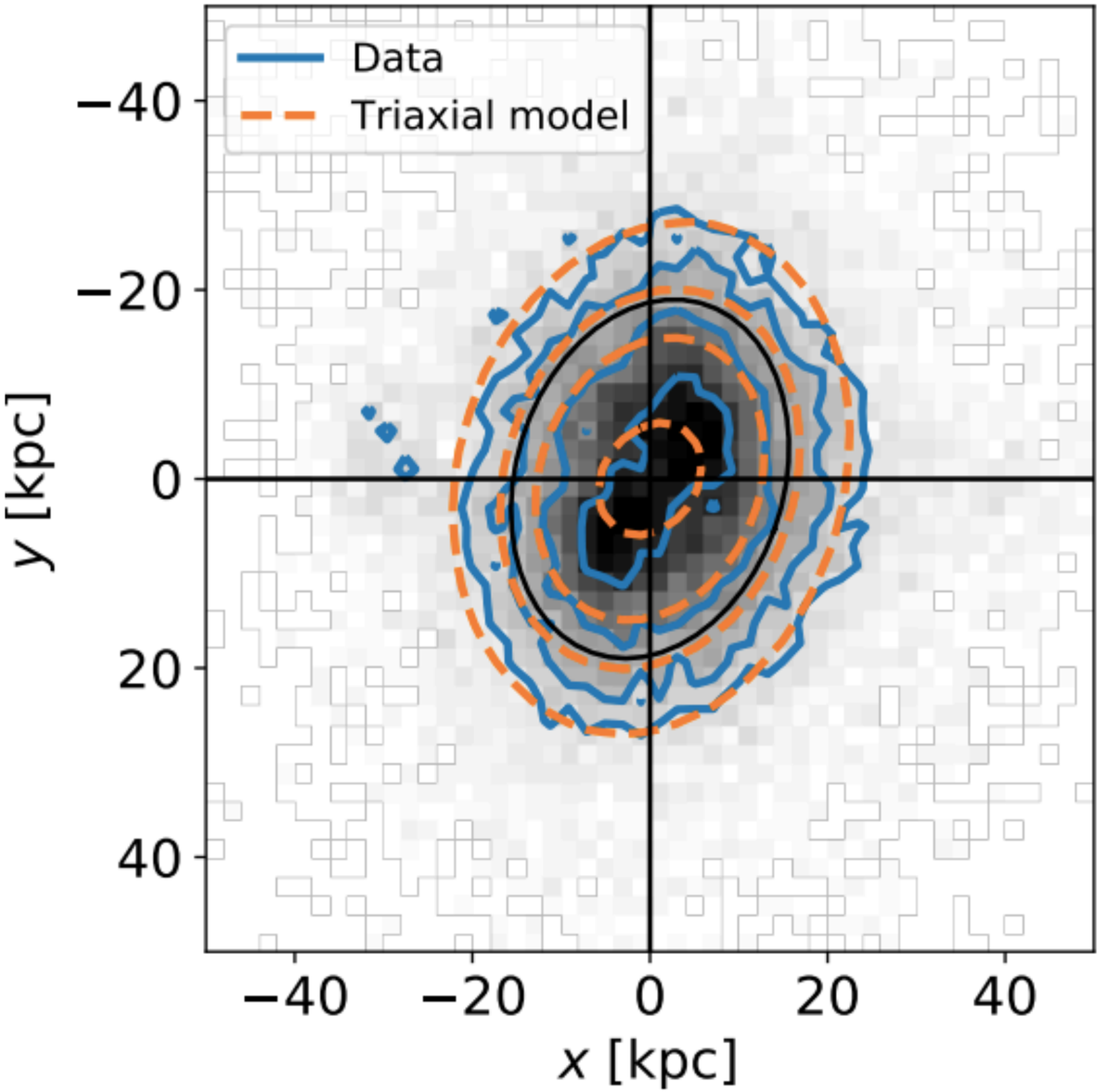


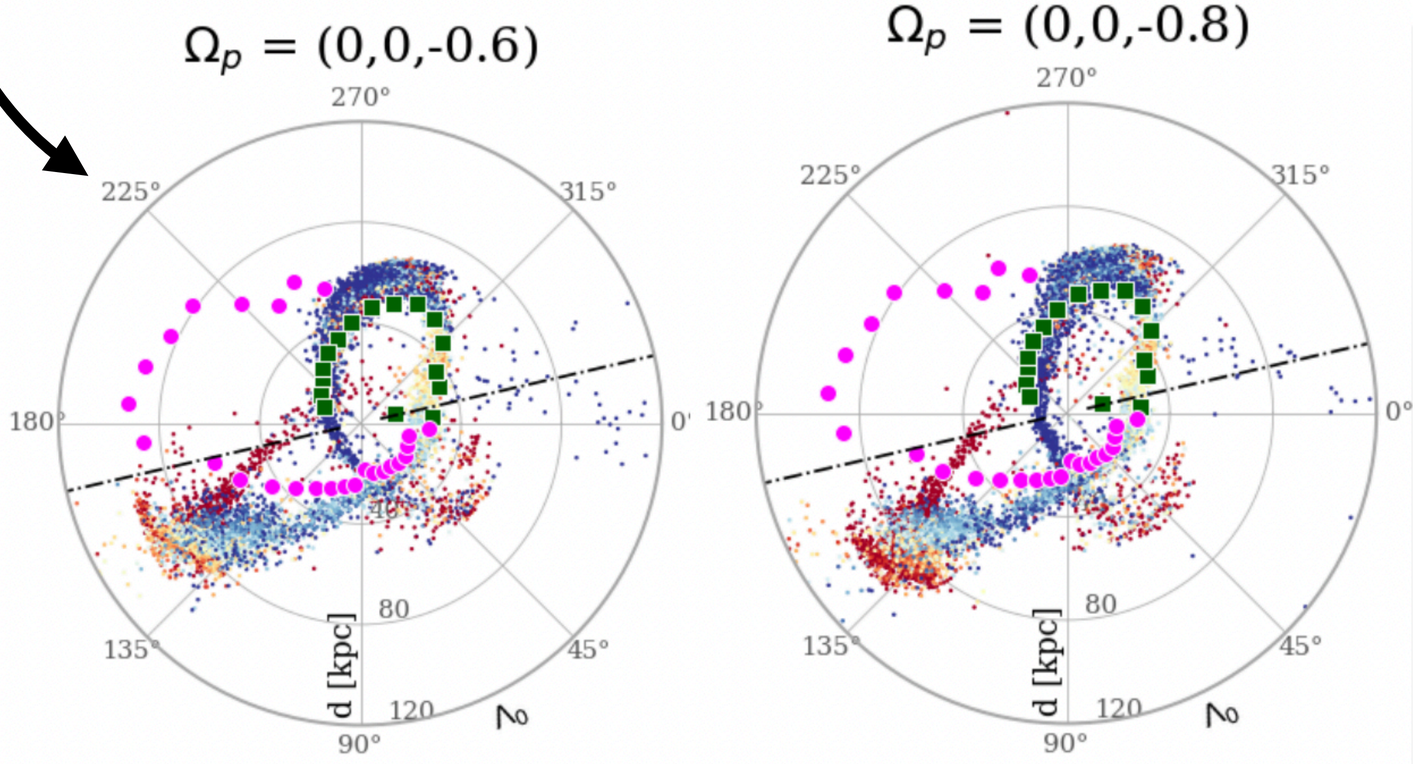
Figure rotation/tumbling of DM halo

Simulations find typical pattern speeds for triaxial halos in the range:

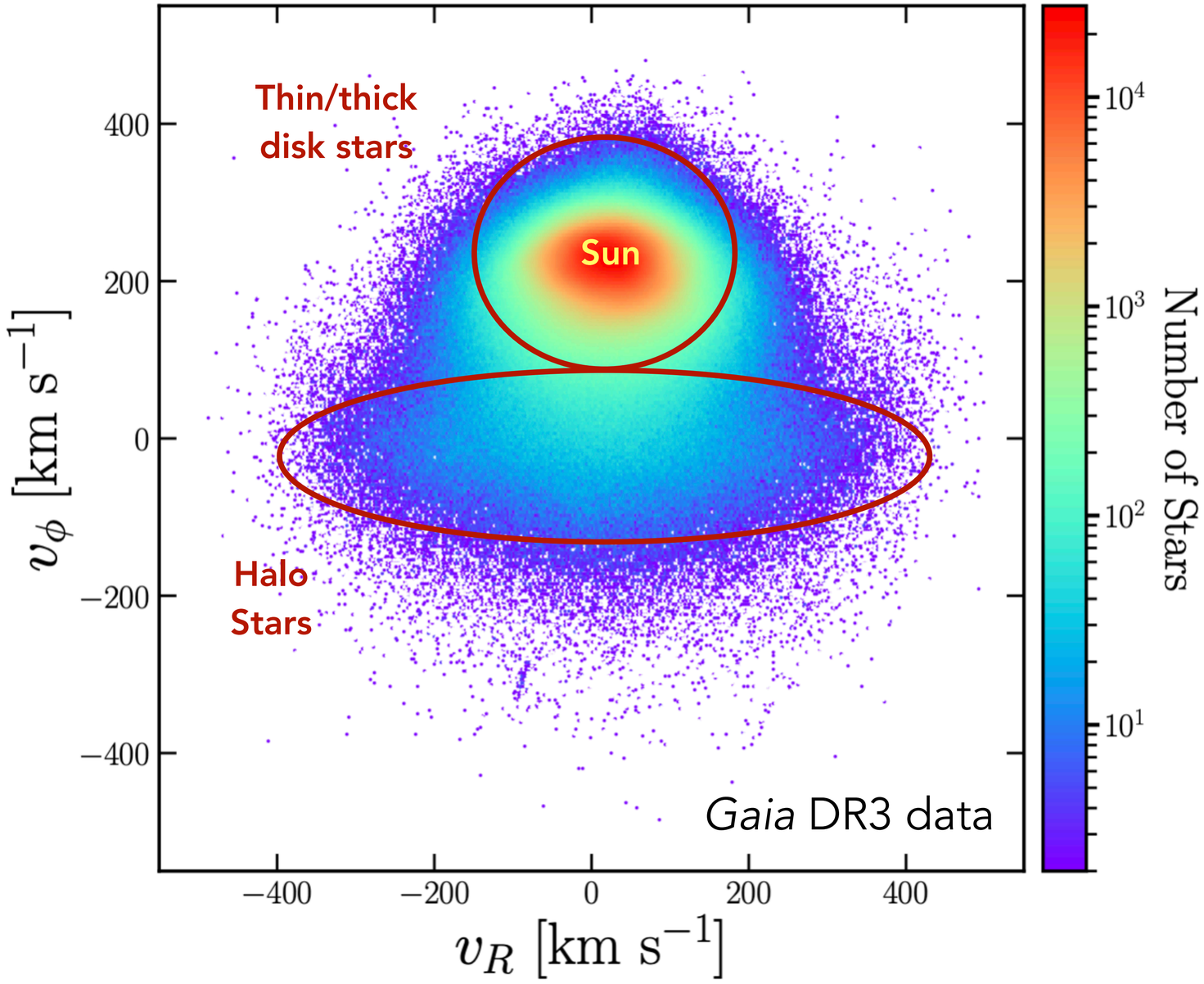
$$\Omega_p \sim 0.15 - 0.6\,\mathrm{km\,s^{-1}kpc^{-1}} \sim 9^\circ - 35^\circ \mathrm{Gyr}^{-1}$$

→ MW spin cannot be anomalously large or the Sagittarius stream would look measurably different from the way it does (Valluri et al. 2009.09004)

Even extreme figure rotation would not reduce directionality of DM flux in Solar System

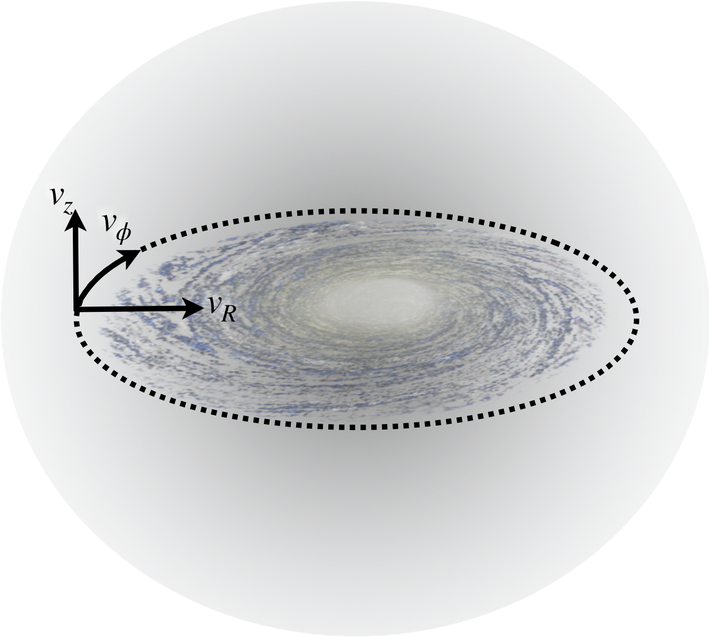


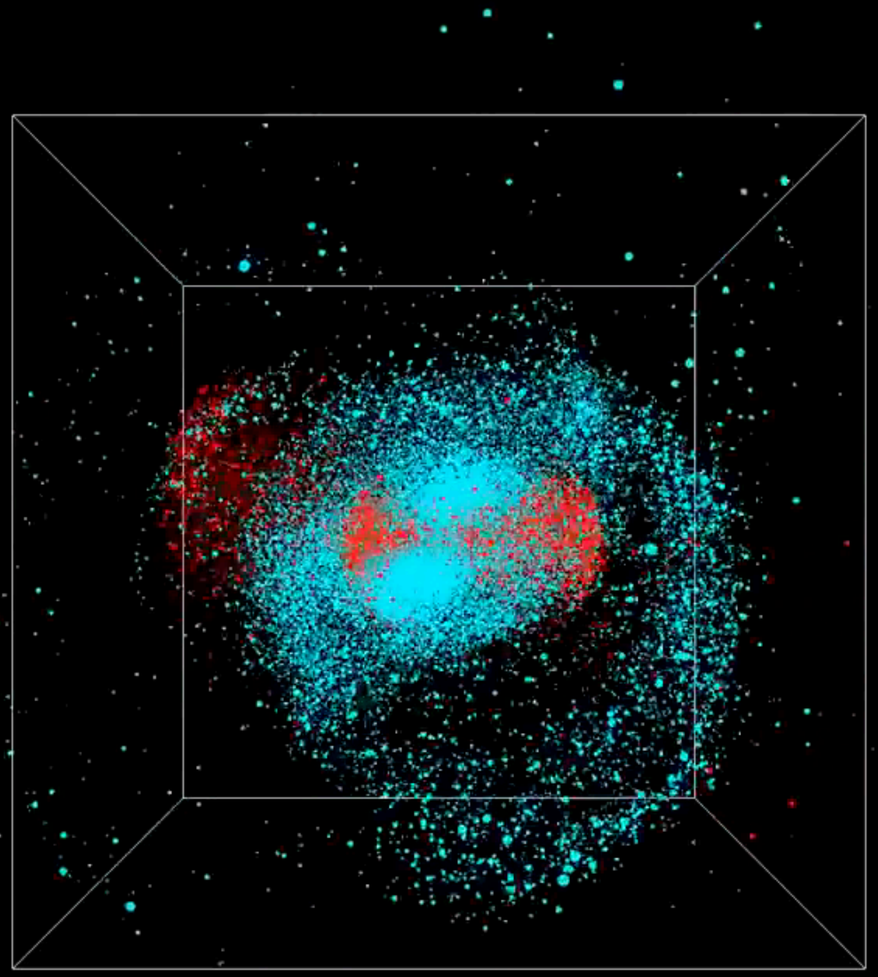
Velocity distribution of the MW stellar halo



Substantial evidence for recent merger event with a dwarf galaxy filling much of the inner halo

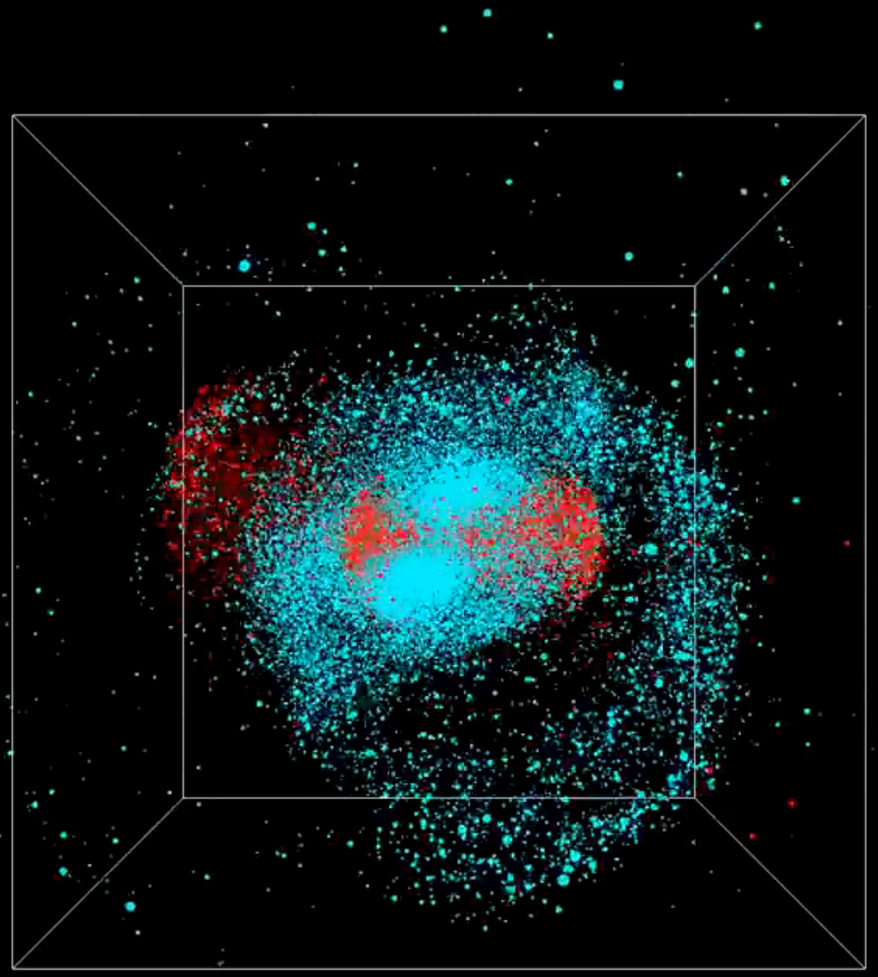
→ **The Gaia-Sausage-Enceladus (GSE)**





The GSE Merger:
Stars+DM brought in on **highly radial orbits** by a $10^{9\text{-}10}\ M_\odot$ stellar mass galaxy merging with the MW 8-10 billion years ago

Helmi et al. [1806.06038]



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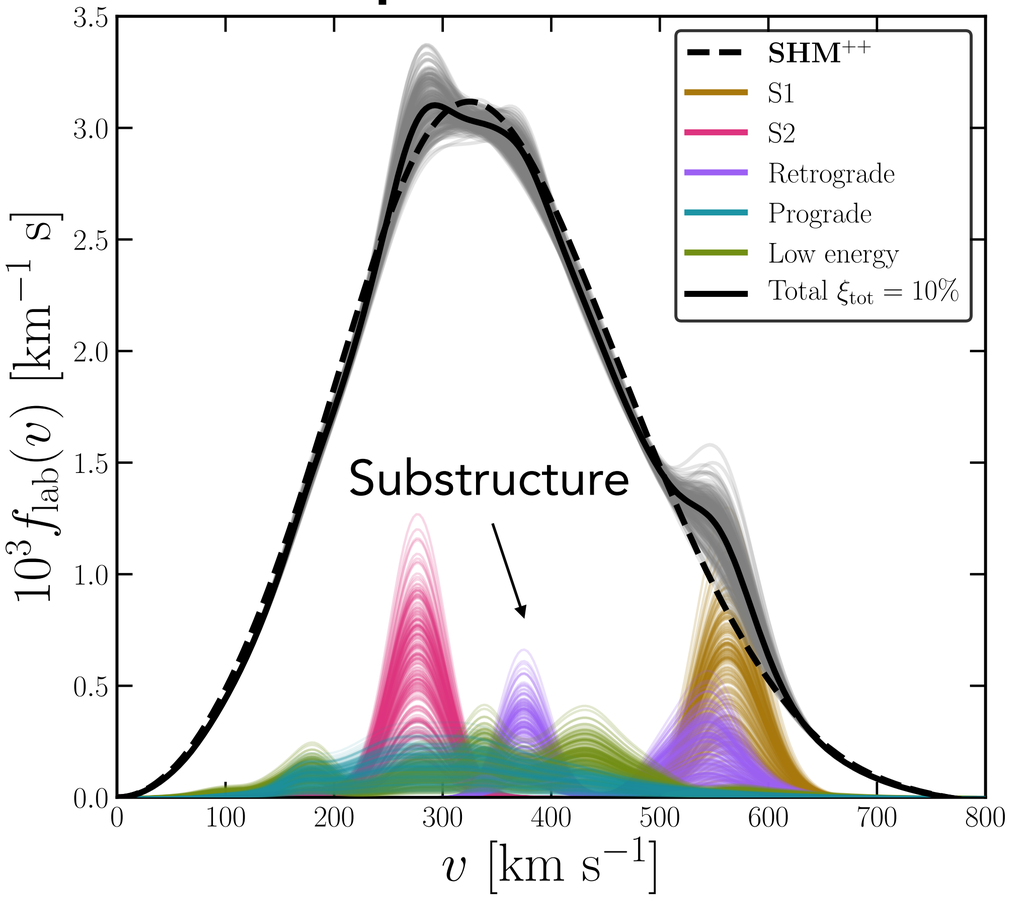
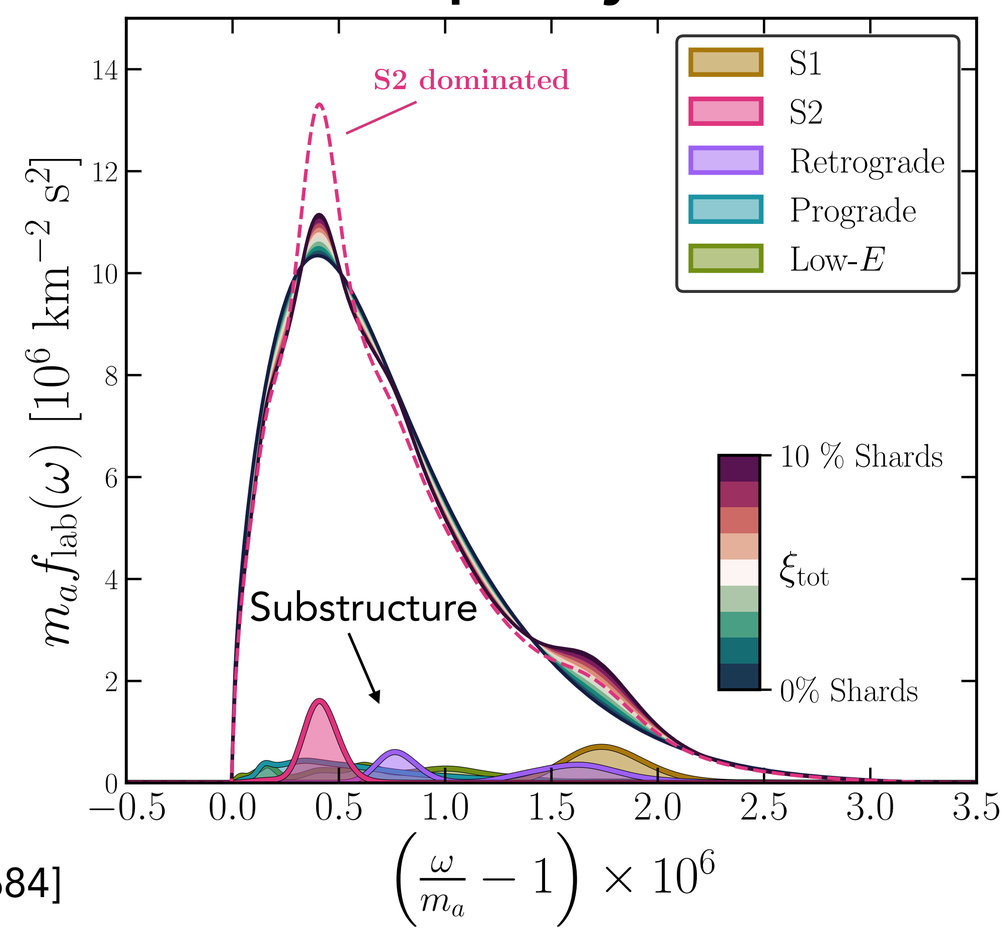
Ultimately the relevance of these structures for dark matter is only something that direct detection can reveal. That's why we call our experiments "**Haloscopes**"

DM speed distribution



Wave DM frequency distribution



O'Hare+ [1909.04684]