Dark Matter

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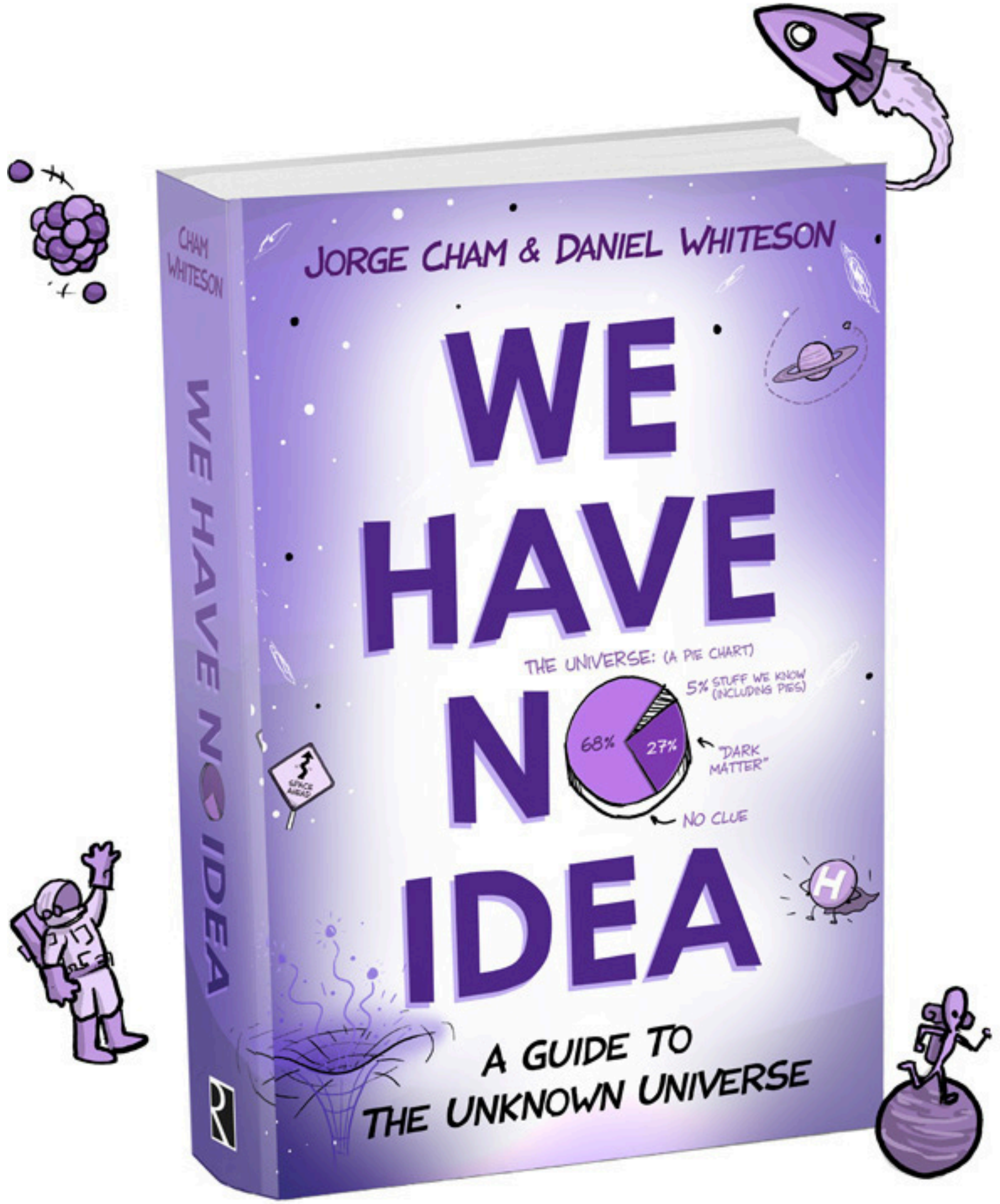
What you often hear:

“scientists have no idea what dark matter is”



Papers from last Friday with the words "**dark matter**" in the title

arXiv:2103.09822 [pdf, other]
Accidentally Asymmetric Dark Matter
Pouya Asadi, Eric David Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, Juri Smirnov

arXiv:2103.08715 [pdf, other]
Dark matter searches using accelerometer-based networks
Nataniel L. Figueroa, Dmitry Budker, Ernst M. Rasel

arXiv:2103.07592 (replaced) [pdf, other]
Flux-mediated Dark Matter
Yoo-Jin Kang, Hyun Min Lee, Adriana G. Menkara, Jiseon Song

arXiv:2103.09827 [pdf, other]
Thermal Squeezeout of Dark Matter
Pouya Asadi, Eric David Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, Juri Smirnov

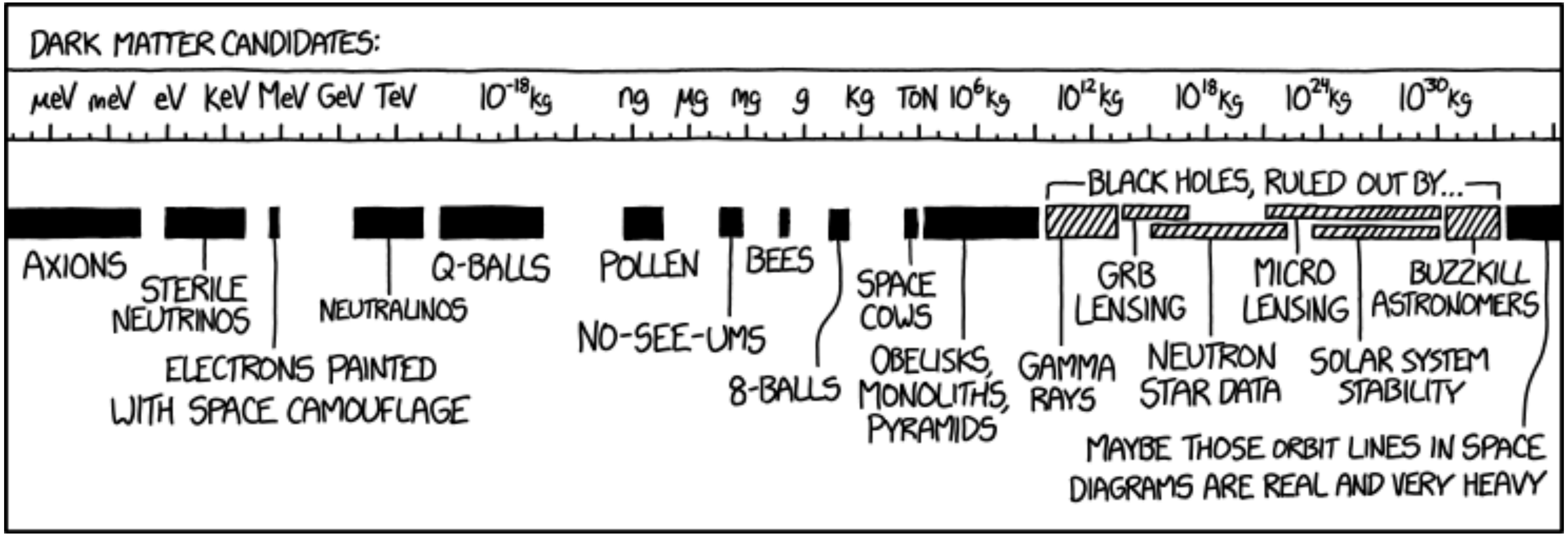
arXiv:2103.10392 [pdf, other]
Production and signatures of multi-flavour dark matter scenarios with t-channel mediators
Johannes Herms, Alejandro Ibarra

arXiv:2103.09835 [pdf, other]
Systematic approach to B-physics anomalies and t-channel dark matter
Giorgio Arcadi, Lorenzo Calibbi, Marco Fedele, Federico Mescia

arXiv:2103.08873 [pdf, ps, other]
Majorana Fermion Dark Matter in Minimally Extended Left-Right Symmetric Model
M. J. Neves, Nobuchika Okada, Satomi Okada

arXiv:2103.09810 [pdf, other]
Probing Mild-Tempered neutralino dark matter through top-squark production at the LHC
Monoranjan Guchait, Arnab Roy, Seema Sharma

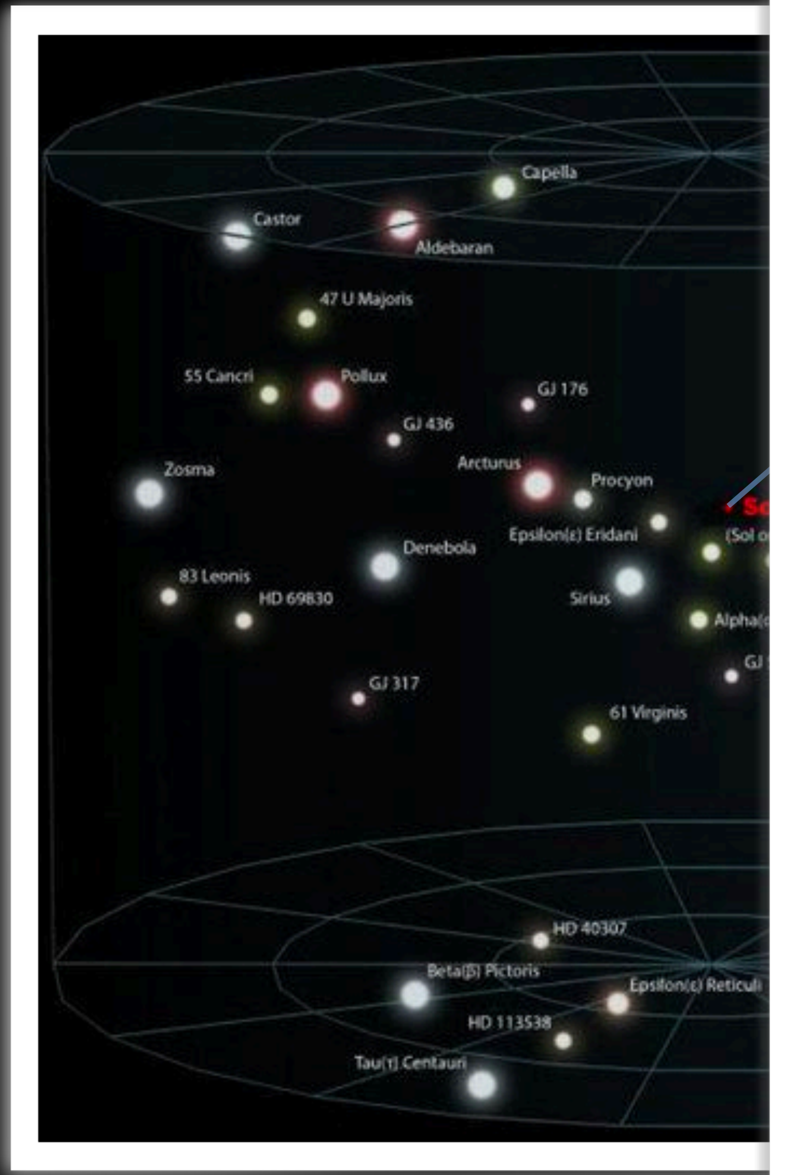
arXiv:2103.08626 [pdf, other]
Sterile Neutrino Dark Matter from Generalized CPT-Symmetric Early-Universe Cosmologies
Adam Duran, Logan Morrison, Stefano Profumo

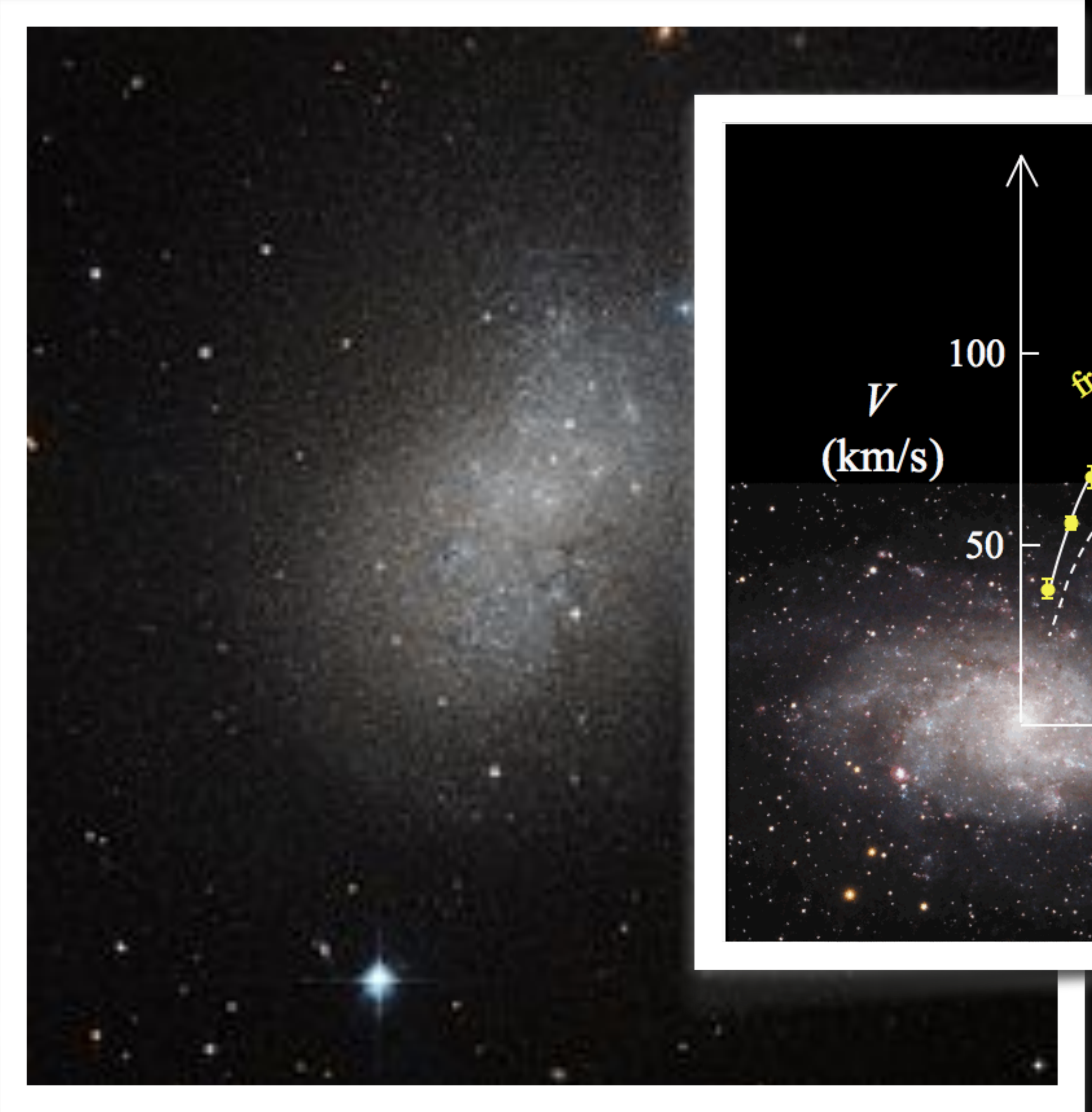


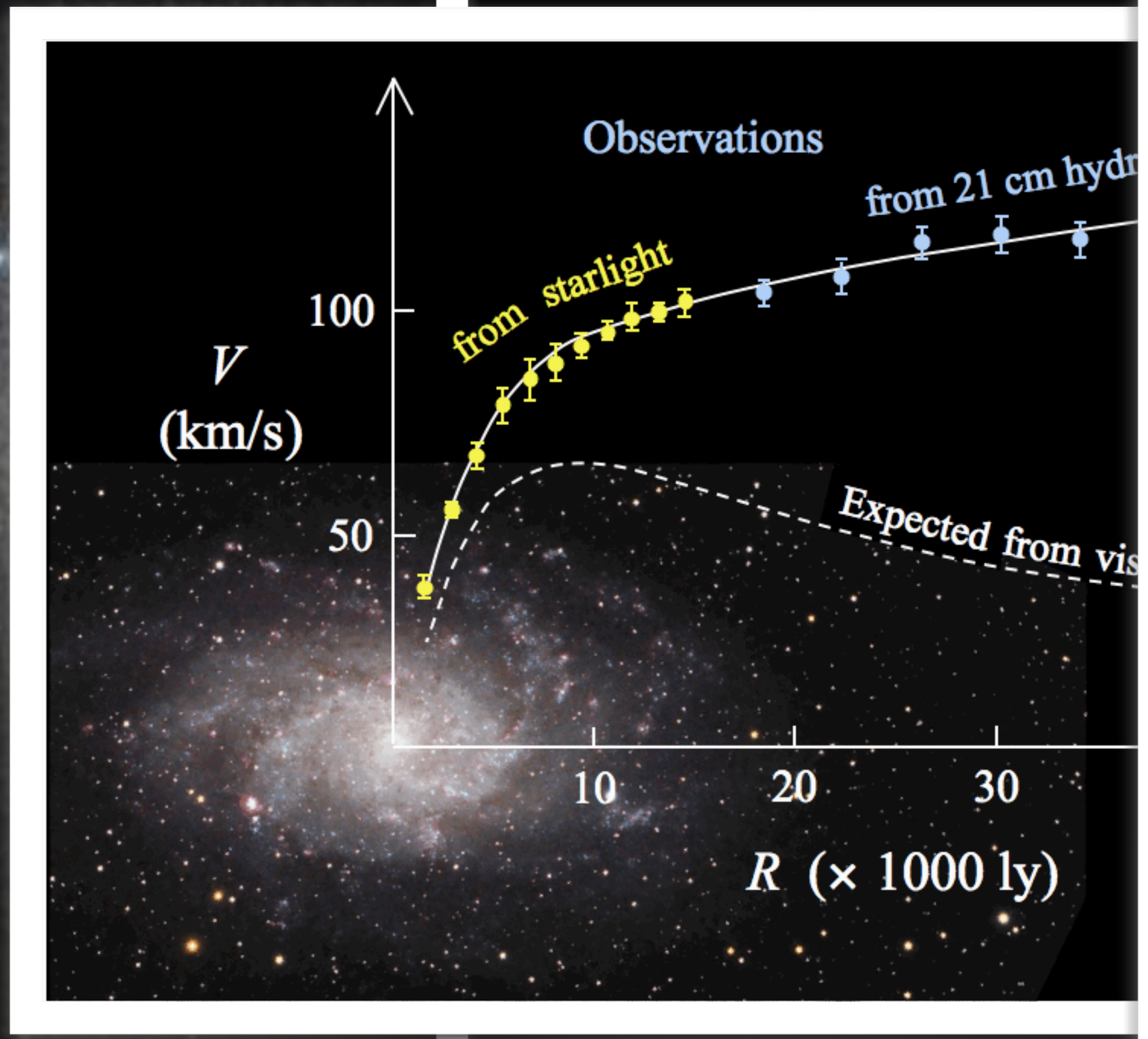
xkcd.com/2035

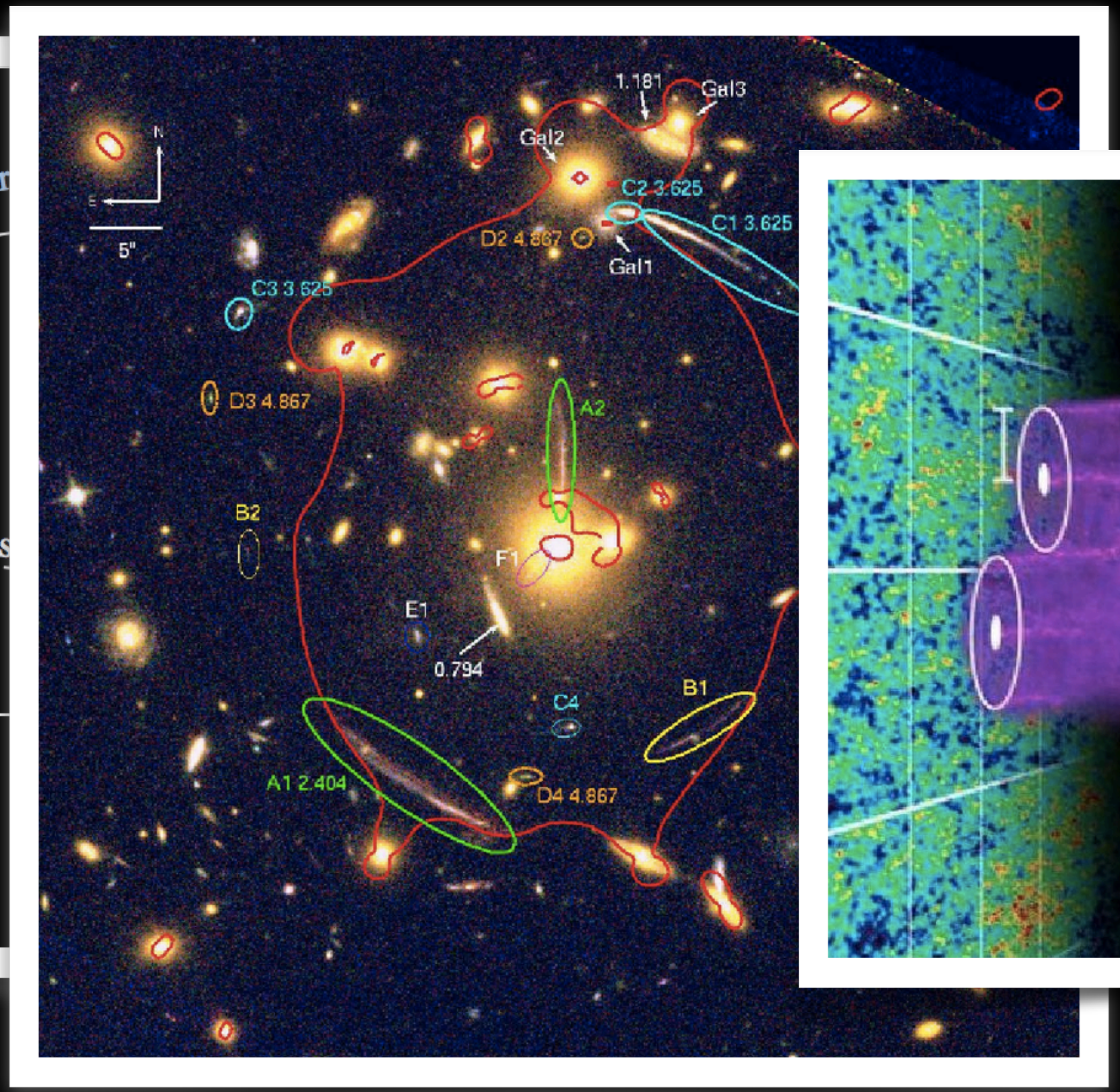
Evidence for dark matter (you will learn about this if you haven't already)

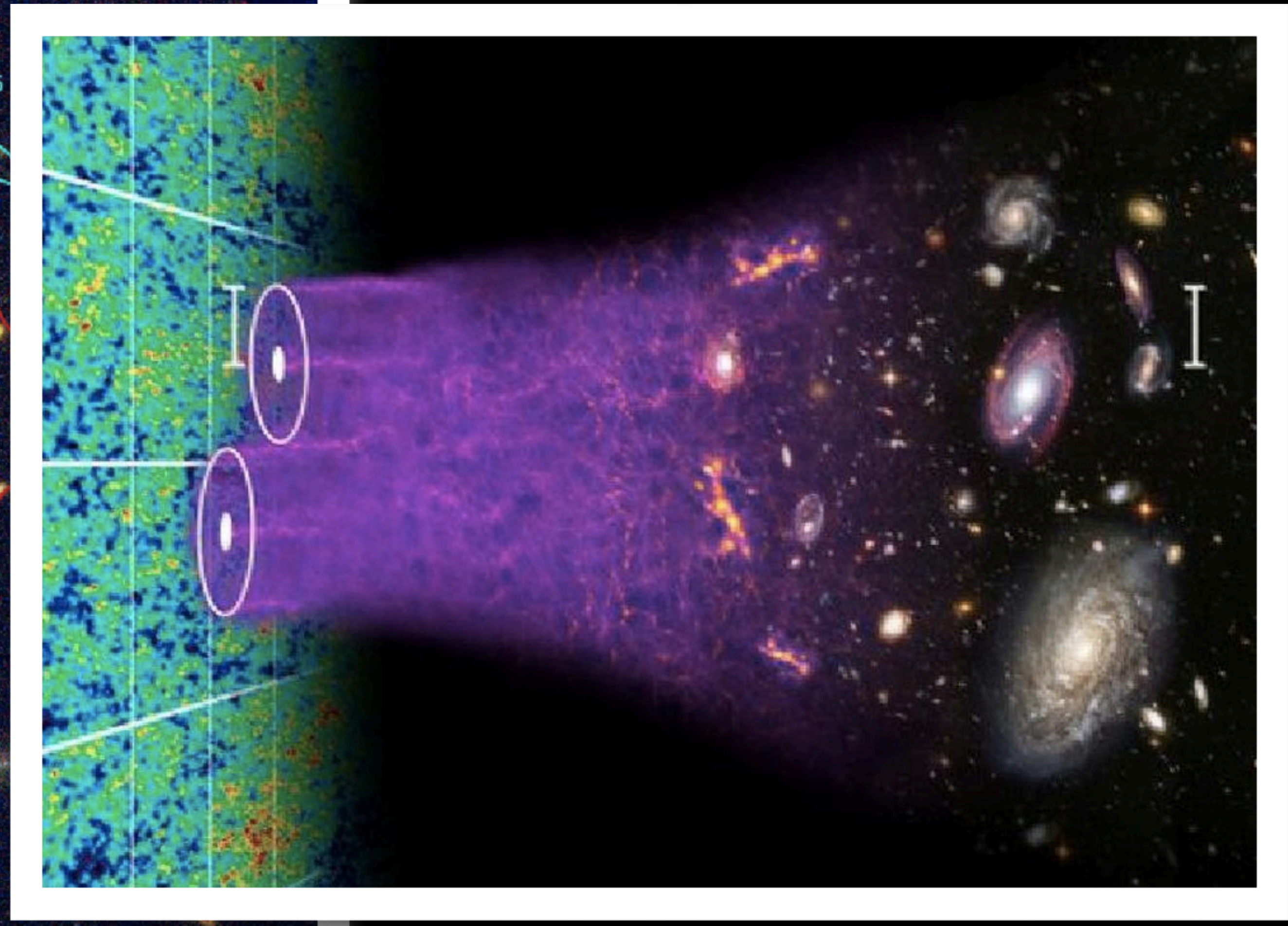
~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	Seeds large scale structure





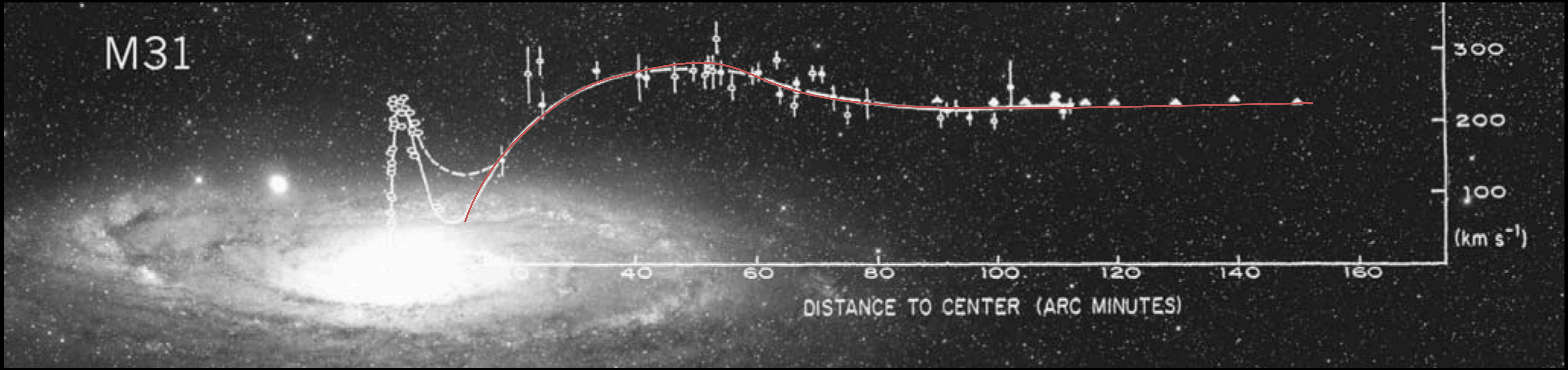






Rotation of stars around a galaxy

e.g. Andromeda (Rubin & Ford 1970s)



v ↑

r ⟶

$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2} \longrightarrow v(r) = \sqrt{\frac{GM(r)}{r}}$$

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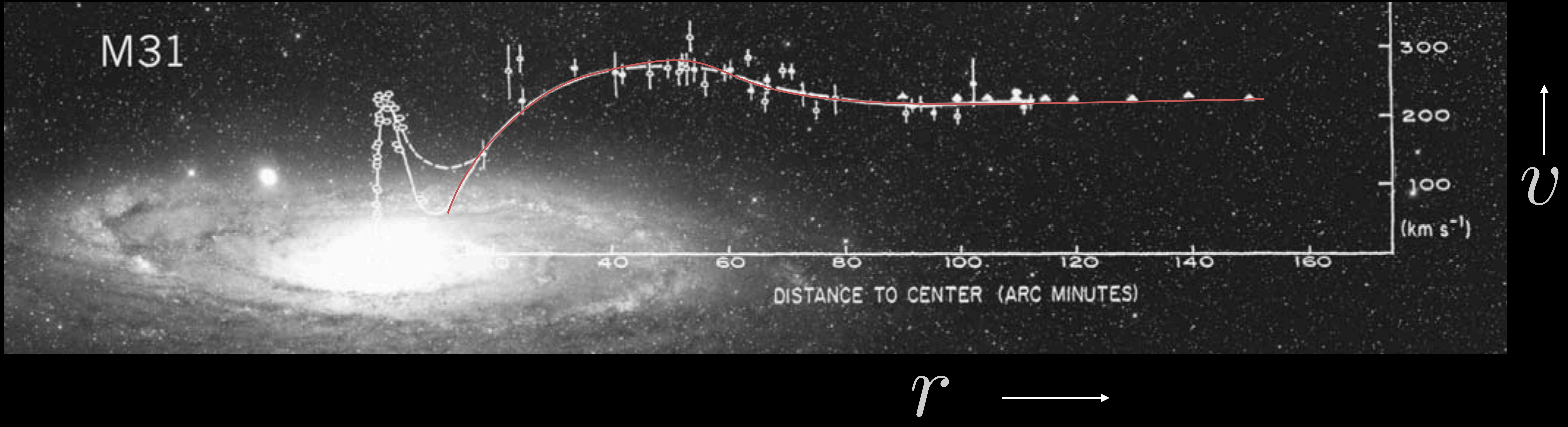


$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2} \longrightarrow v(r) = \sqrt{\frac{GM(r)}{r}}$$

Observation: $v(r)$~const → flattening of rotation curves at large radii

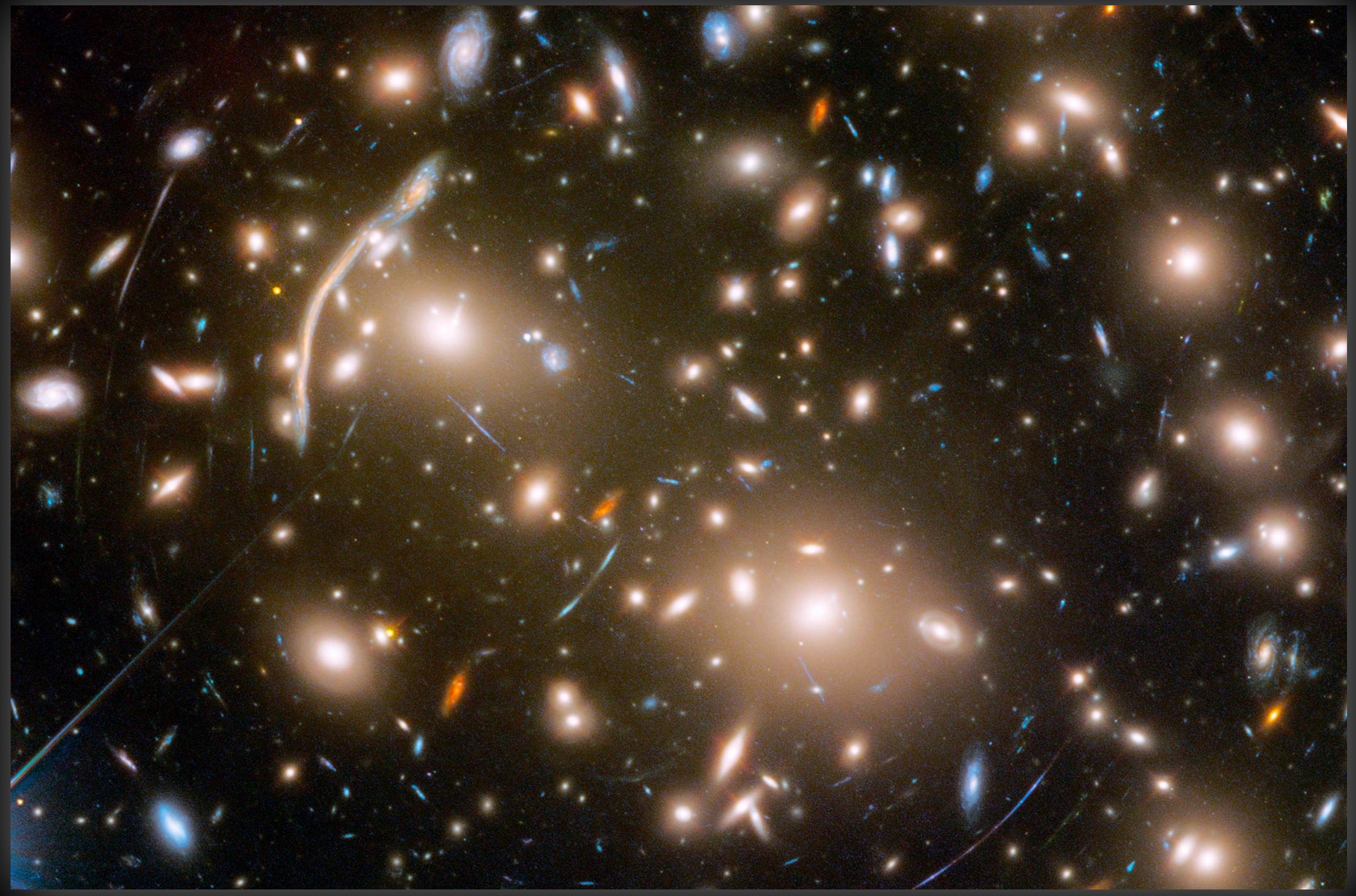
Implication: $M(r)$~increasing → galactic disks embedded in halos of invisible matter.

→ **That includes our own galaxy**

Why is dark matter a problem for physics?

For describing **astrophysical systems** “dark matter” is just a label given to a set of observations

It is actually an incredibly elegant solution → you can explain the dynamics of structures across the Universe if you just make 85% of all mass invisible



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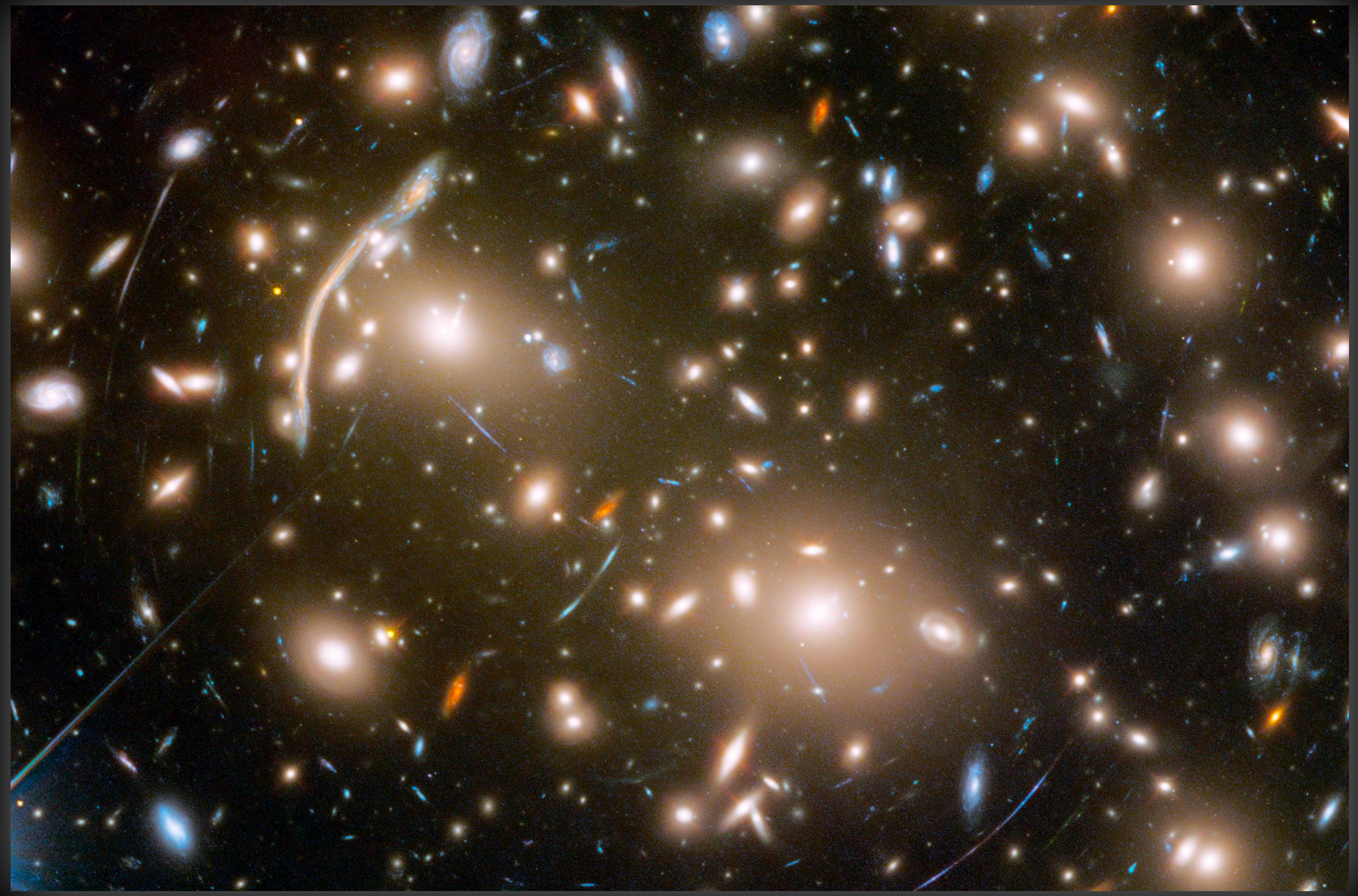
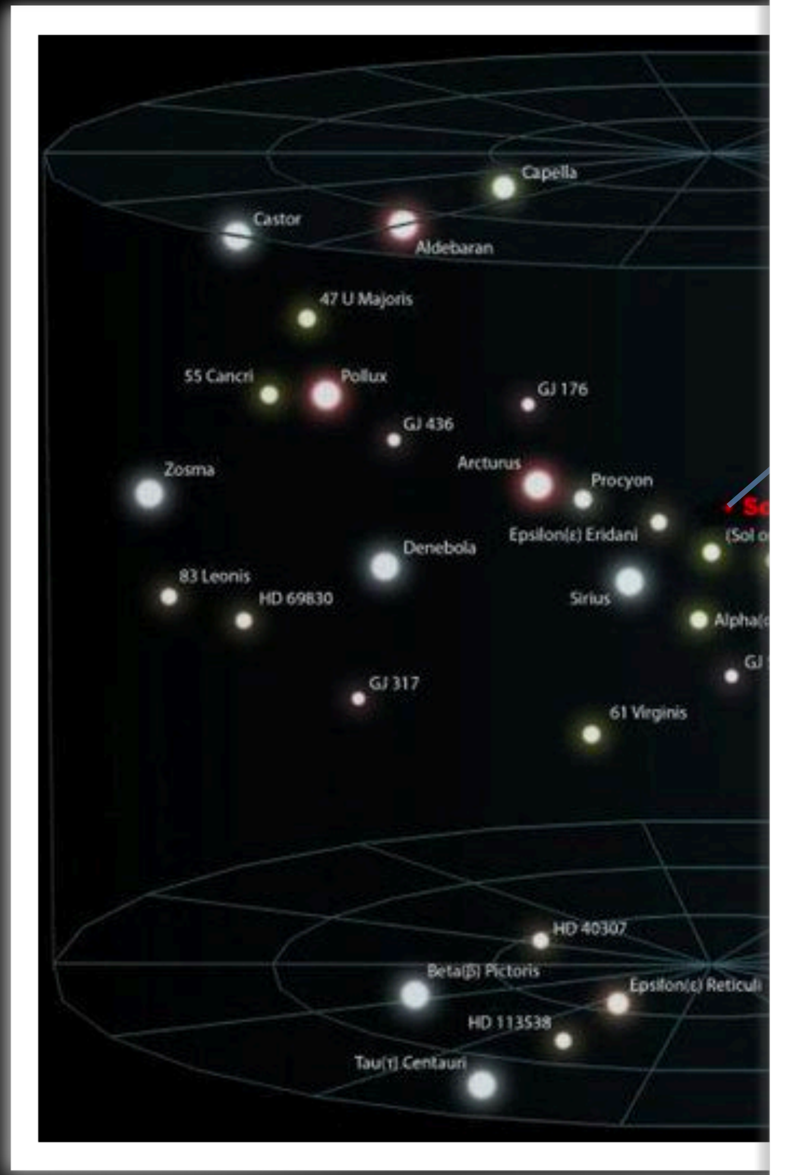
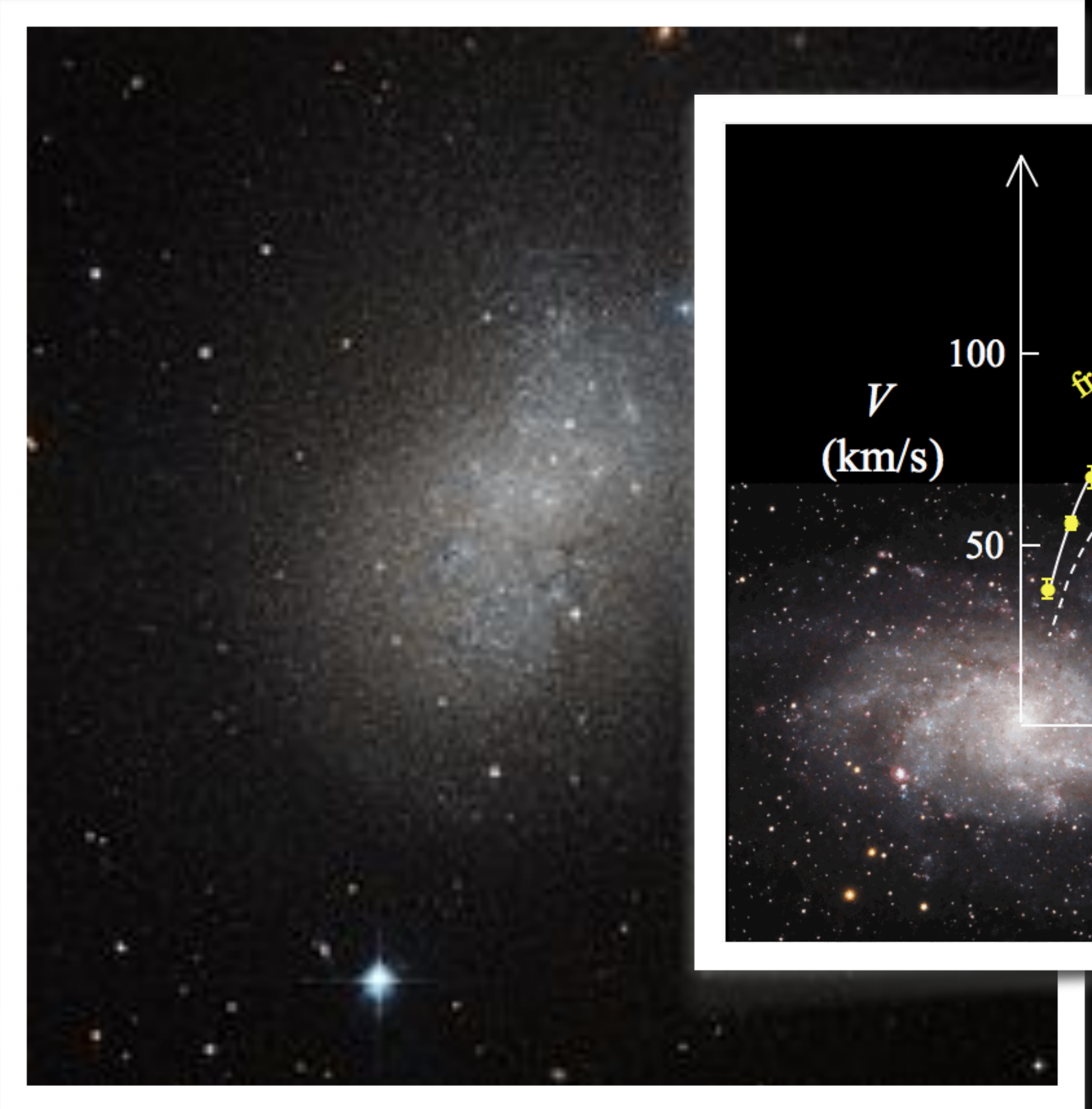


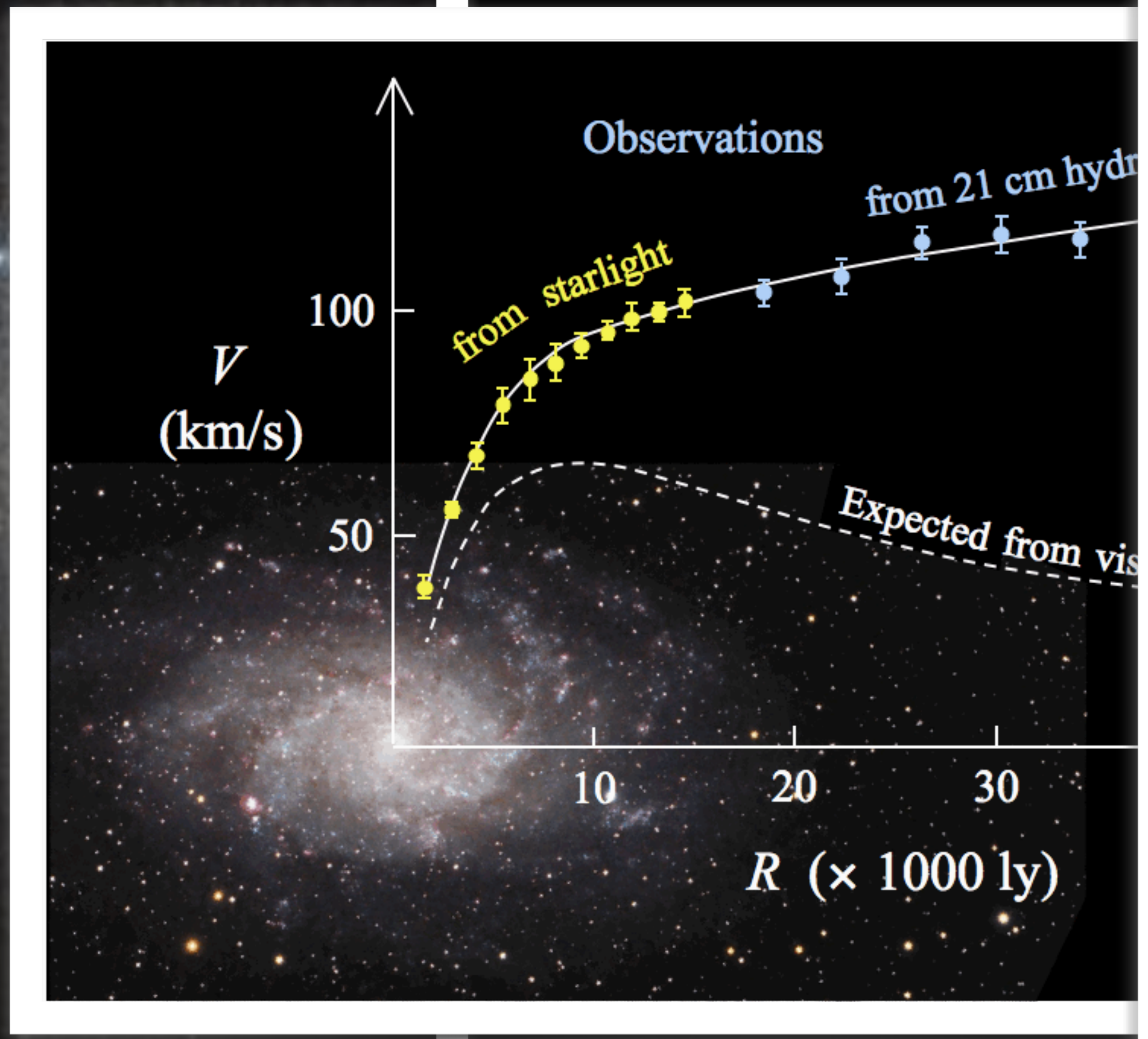
The problem lies with **particle physics** we have no fundamental explanation for what the identity of dark matter is, how it was created, or how it connects to the rest of physics - the “Standard Model”

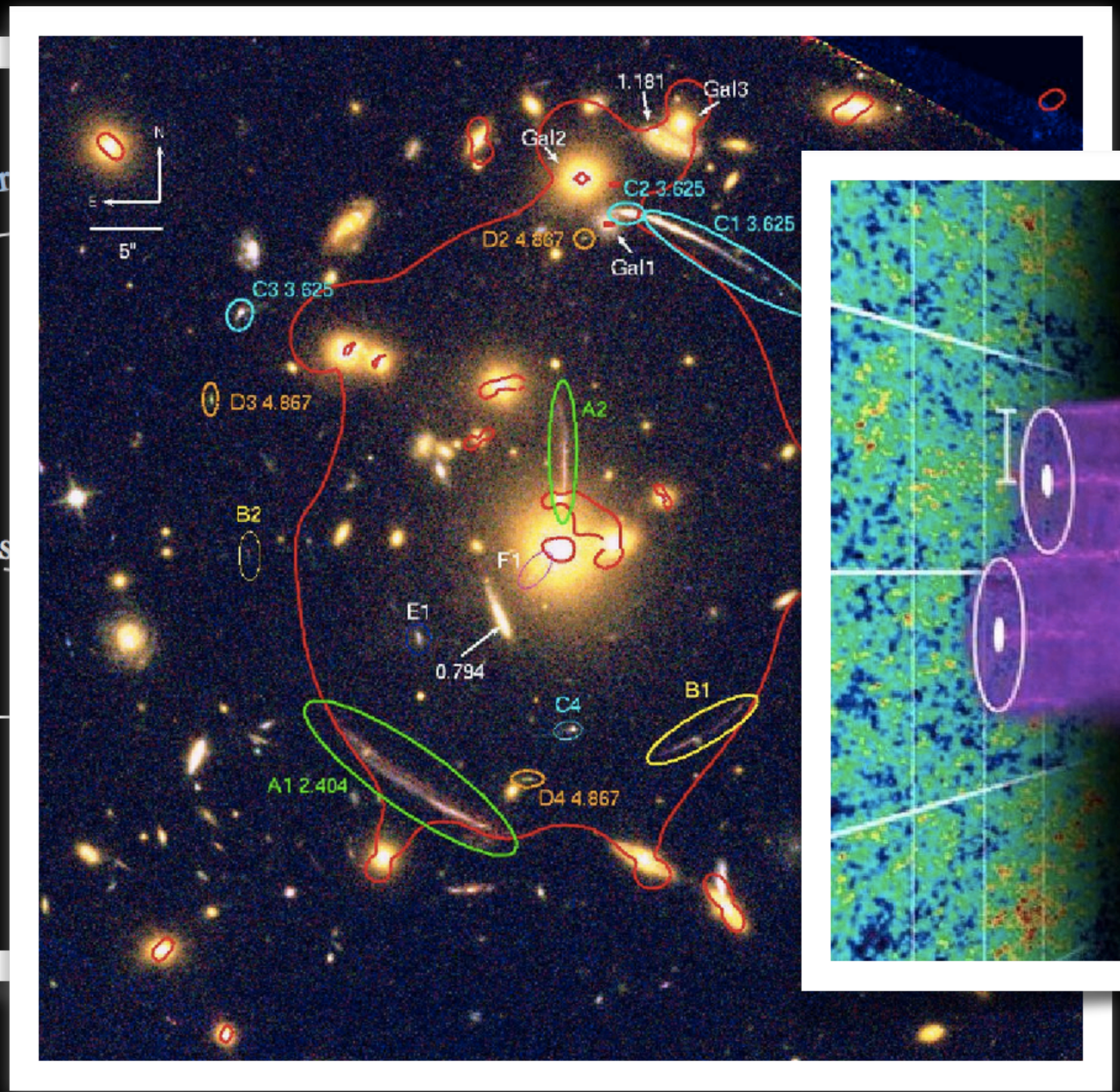
Which piece of evidence is the most relevant for particle physics if we want to figure out what dark matter is?

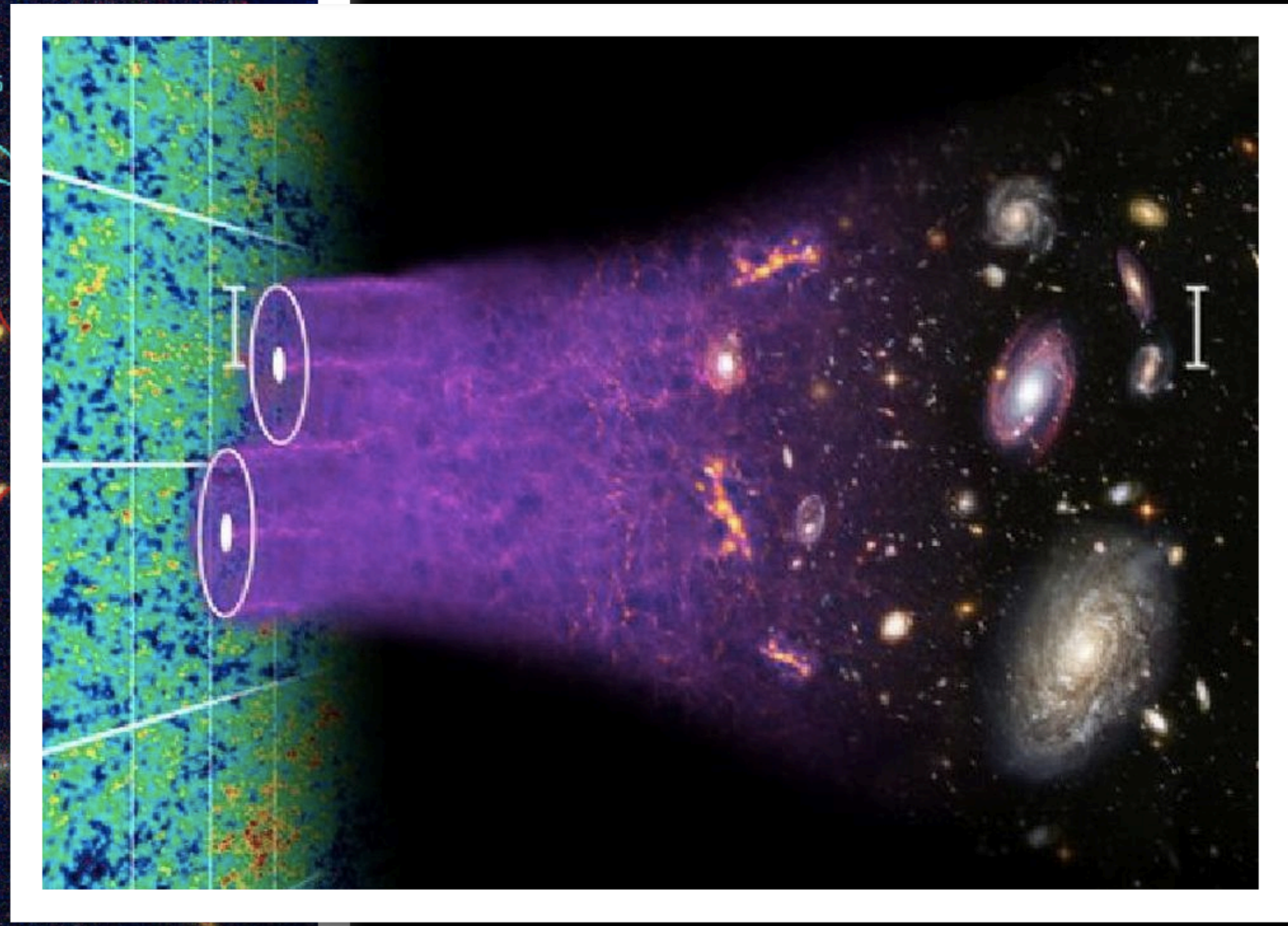
~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	Seeds large scale structure











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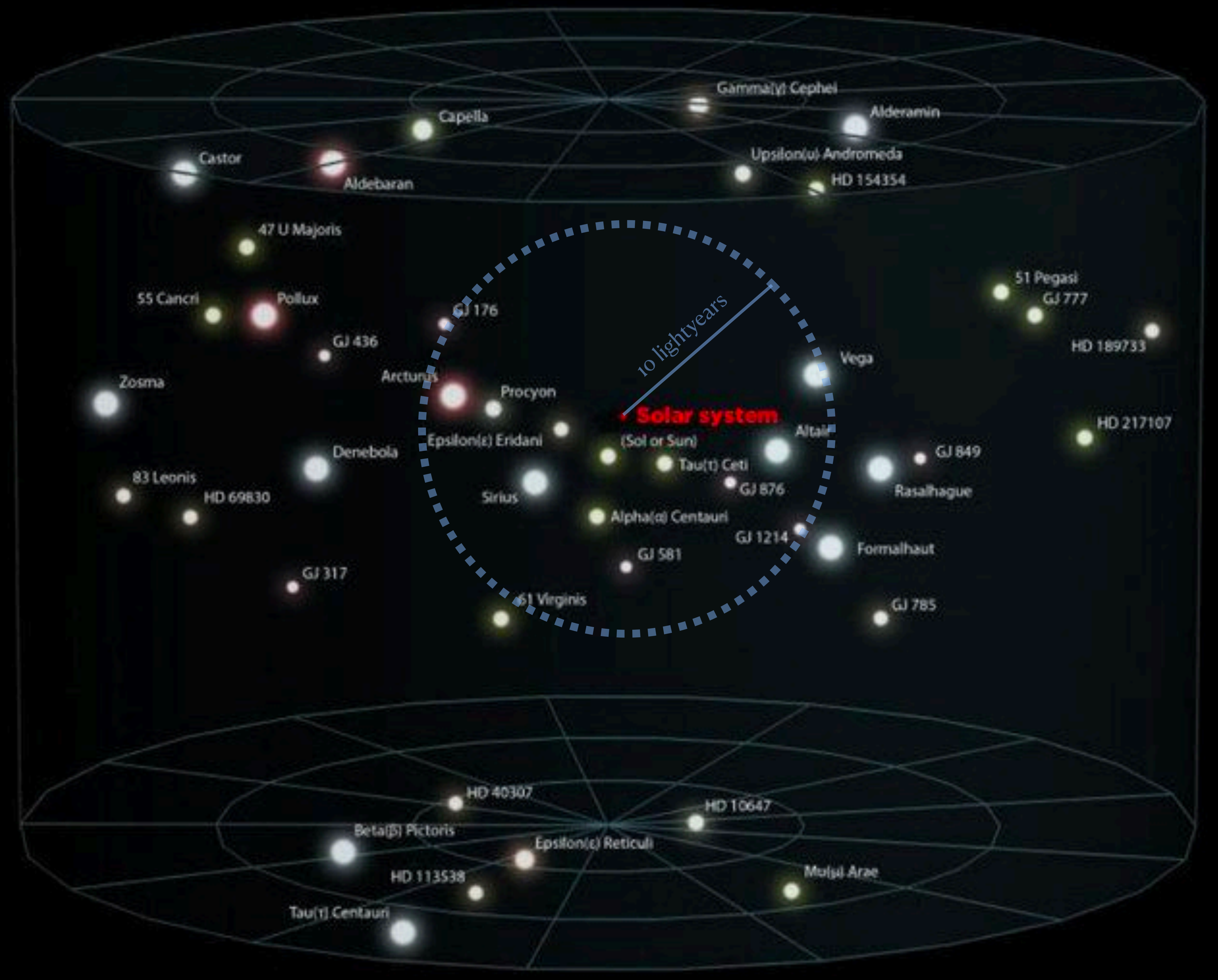
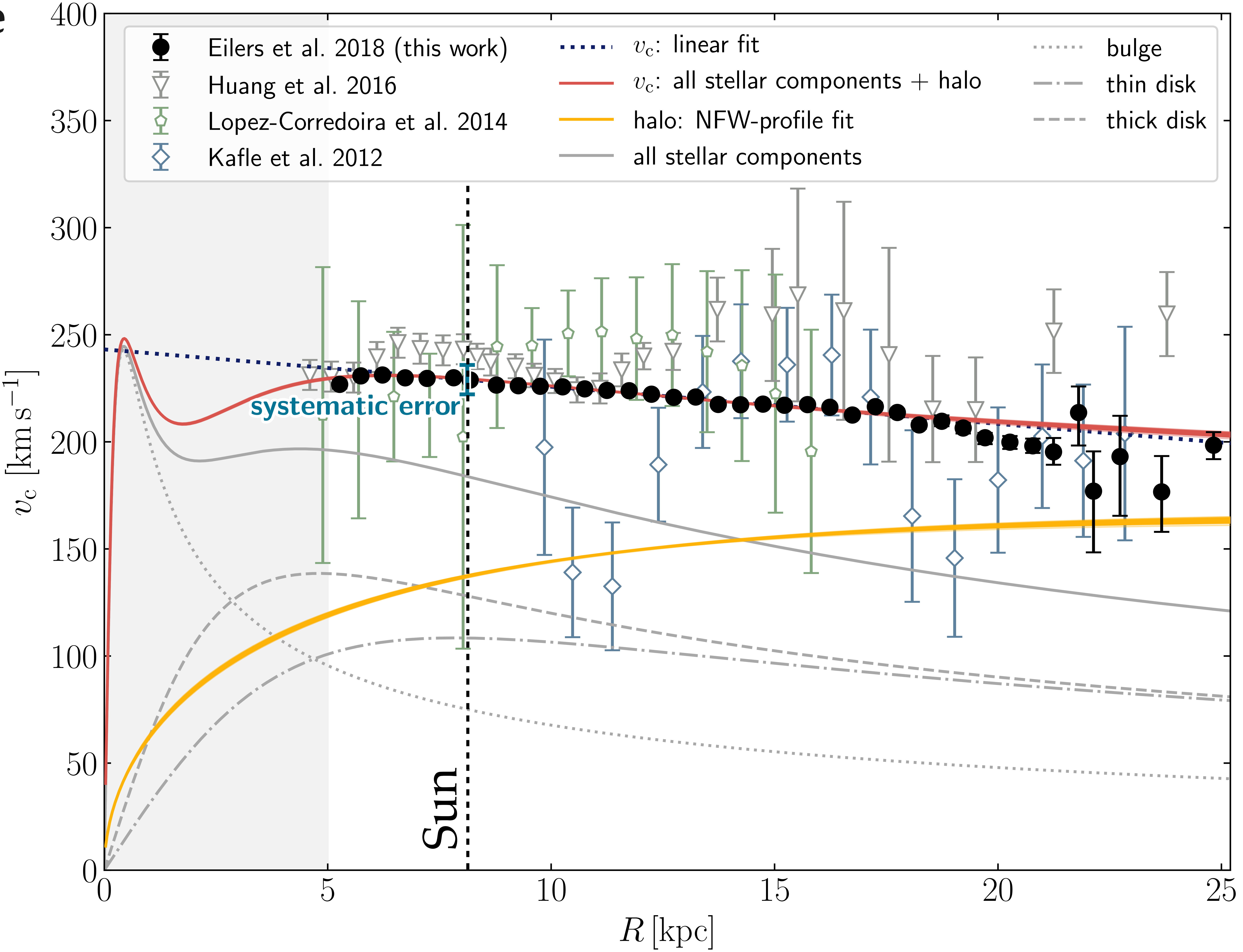
~100 pc ~kpc ~100 kpc ~Mpc >Gpc

Nearby stars → infer local density of dark matter **inside the Solar System**



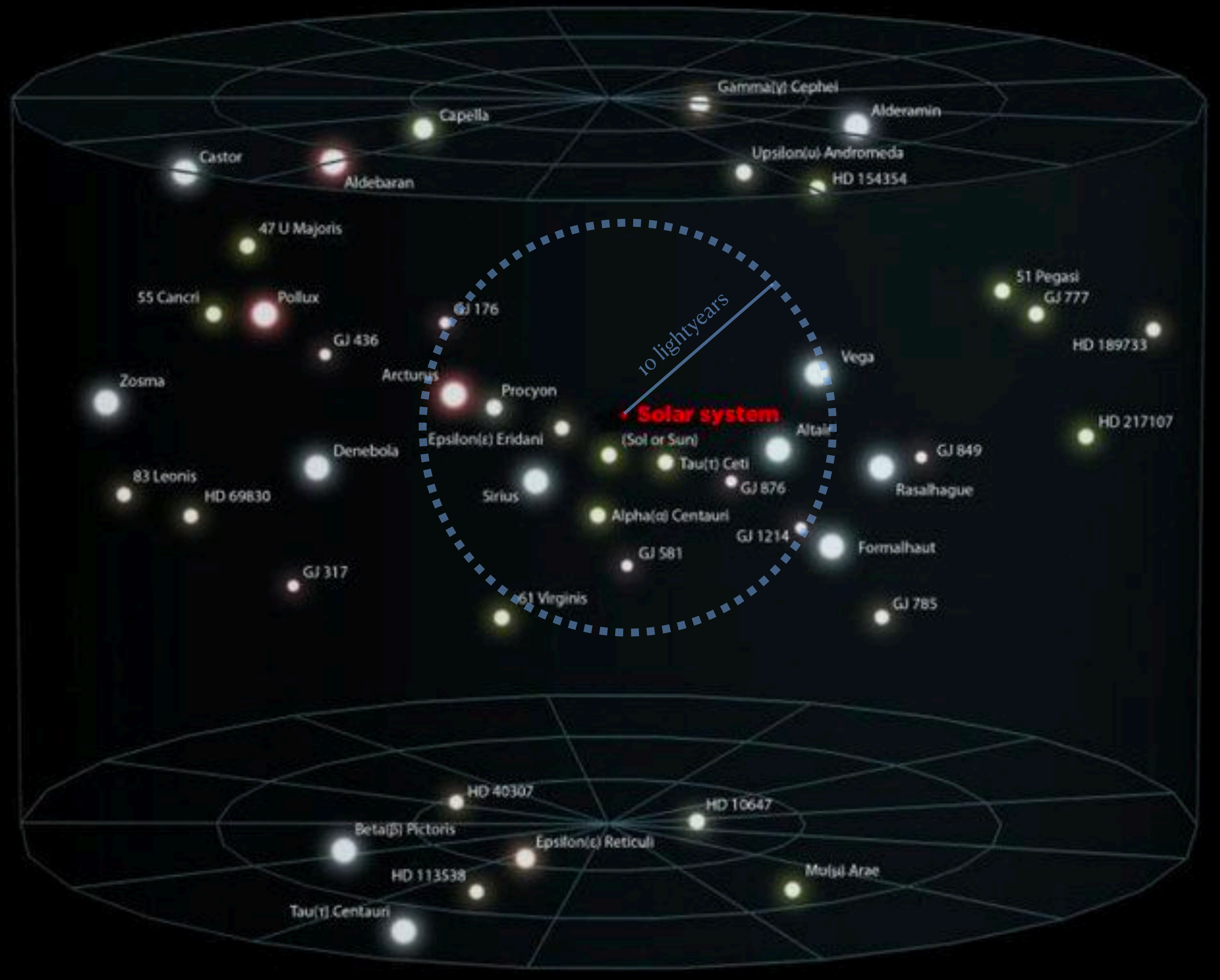
We can measure the local dark matter density from the rotation curve of our <u>own</u> galaxy



<u>The answer:</u>

$$0.01 \pm 0.001\ M_\odot / \mathrm{pc}^3$$

~100 pc | ~kpc | ~100 kpc | ~Mpc | >Gpc



<u>Local density of dark matter</u> (i.e. in this room!)

$$\rho_{\rm dm} \approx 0.4\,{\rm GeV/cm^3} \longleftarrow \textit{Particle physicist's unit}$$

$$\approx 0.01\,{\rm M_\odot/pc^3} \longleftarrow \textit{Astrophysicist's unit}$$

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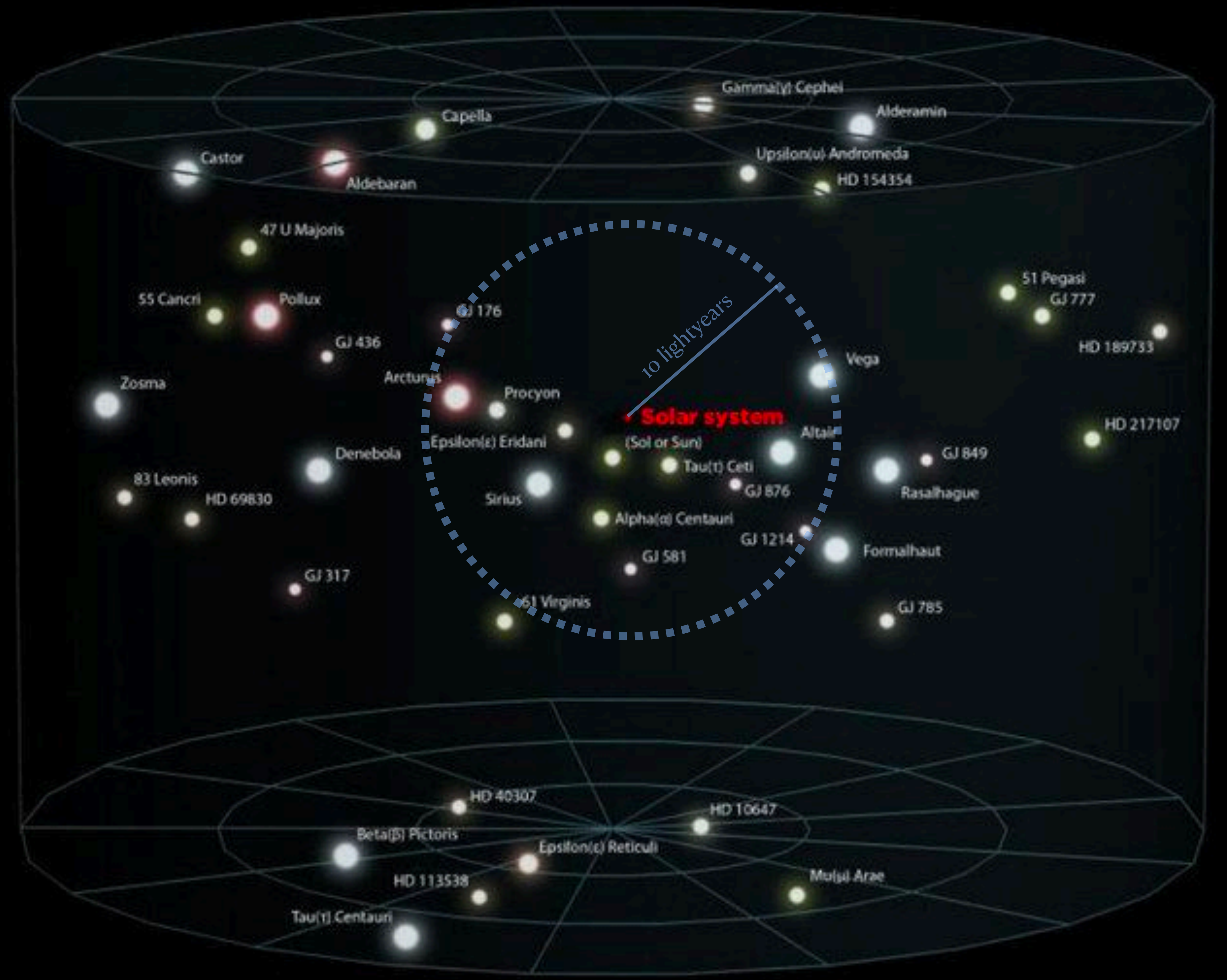

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$\approx$ 2 protons/teaspoon

$\approx$ 1 sand grain/Sydney harbour

$\approx$ 1 cockatoo/Earth

$\approx$ 1 asteroid/Solar System

Note about units:

Particle physicist's mass: $\text{eV} = 1.76 \times 10^{-36}\,\text{kg}$

(i.e. the rest mass energy, technically eV/c^2 but we tend to set $c = 1$)

e.g. electron = 511 keV

proton = 938 MeV

neutrino < 0.3 eV

Astronomer's mass: $M_\odot = 2 \times 10^{30}\,\text{kg}$

e.g. Moon = $10^{-8}\,M_\odot$

Sun = $1\,M_\odot$

Supermassive Black Hole $\approx 10^6\,M_\odot$

How do you come up with a theory of dark matter?

The bare minimum (i.e. assuming no interactions)

→ Is it a particle, or an object?

→ Mass

→ Statistical properties, i.e. spin: fermionic vs bosonic

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These are cannot be independently chosen, take for example the density of DM particles in the solar system

de Broglie wavelength: $\lambda_{\rm dB} = \frac{2\pi}{p} \approx \frac{2\pi}{mv}$

DM density: $\rho_{\rm DM} \approx 0.4\,{\rm GeV\,cm^{-3}}$

⟶

<u>Local occupation number:</u>

(i.e. number of particles you have to cram into a quantum state to make up DM)

$$\mathcal{N} \approx (\rho_{\rm DM}/m) \times \lambda_{\rm db}^3$$

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$\mathcal{N} \approx (\rho_{\rm DM}/m) \times \lambda_{\rm db}^3$

$m = 100\,{\rm GeV}$ ⟶ $\mathcal{N} \approx 10^{-36}$ ⟶ Particle-like dark matter (fermionic or bosonic)

$m = 1\,\mu{\rm eV}$ ⟶ $\mathcal{N} \approx 10^{32}$ ⟶ Wave-like dark matter (only bosonic allowed, due to Pauli exclusion principle)

Wave-like
Particle-like
Object-like
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
kg
$M_\oplus$
$M_\odot$
$10^6\,M_\odot$

Wave-like **Particle-like** **Object-like**

$m \gtrsim 10^{-21}$ eV
de Broglie wavelength must **fit inside** dwarf galaxies ~ 100 pc

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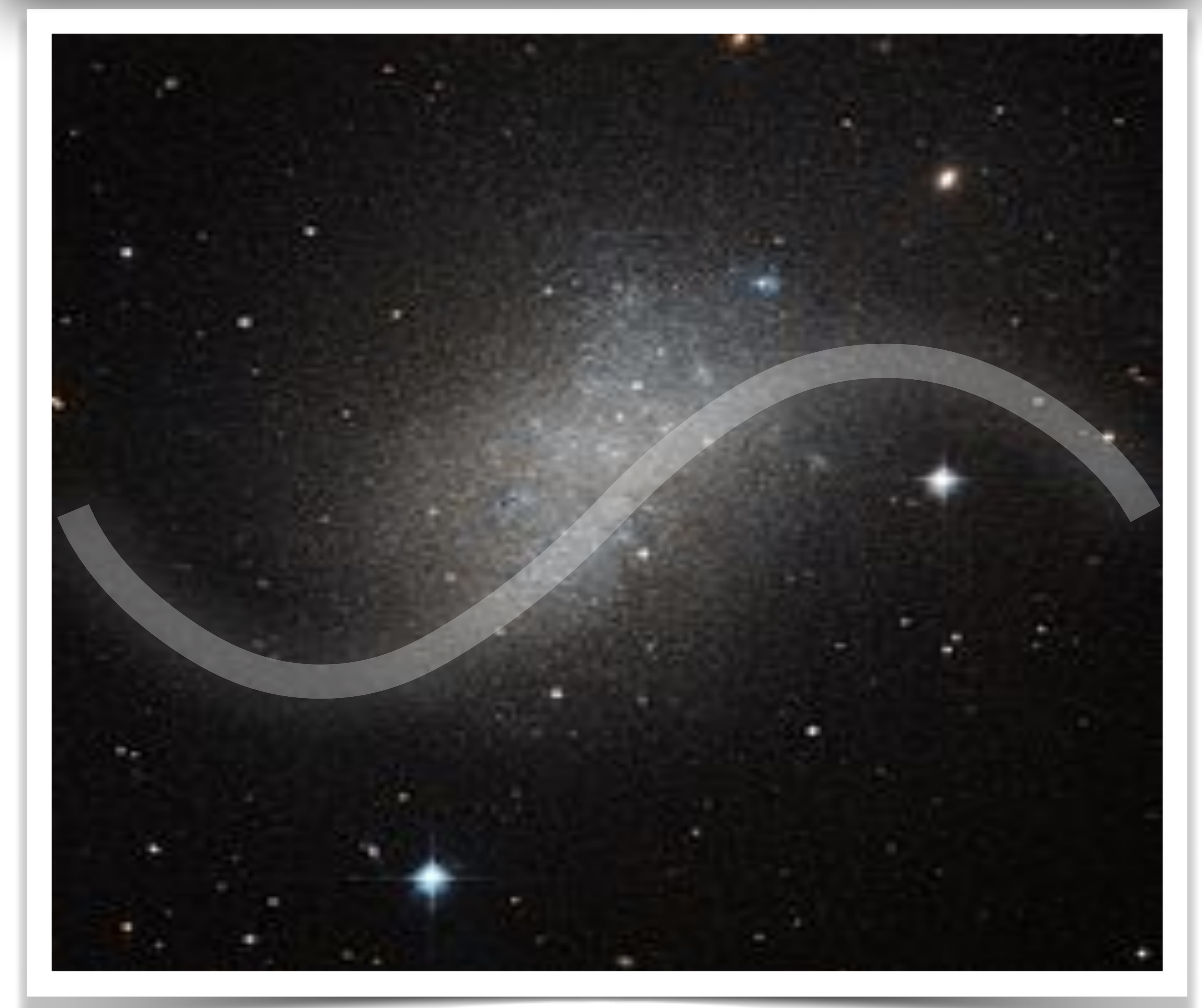
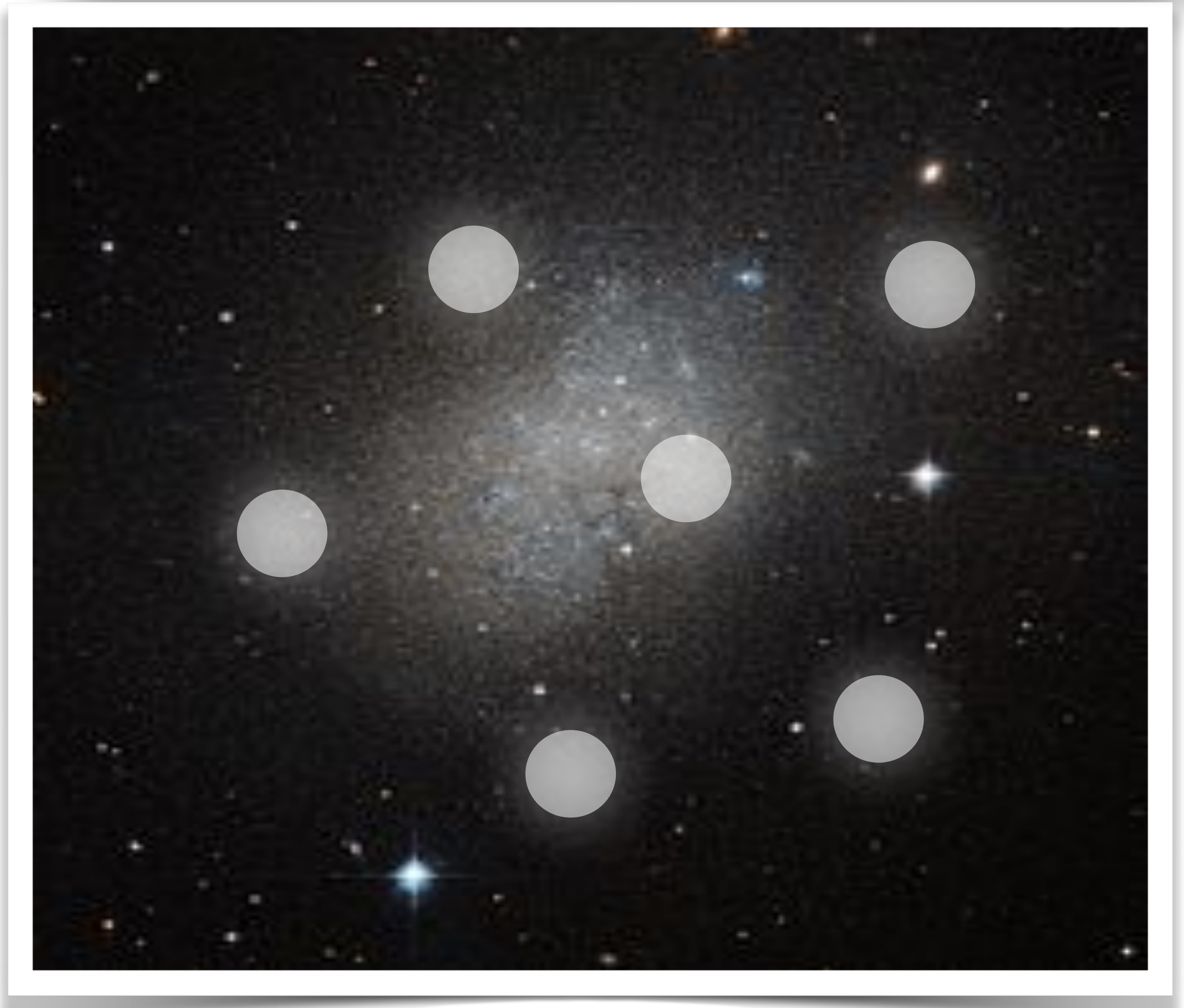


Possible mass range only bounded by ~75 orders of magnitude, but it's a start



How to come up with a theory of dark matter

Observationally driven → Narrow down the possibilities based on astrophysics/particle physics data

Theoretically driven → Find a mathematically well-behaved and aesthetically nice theory

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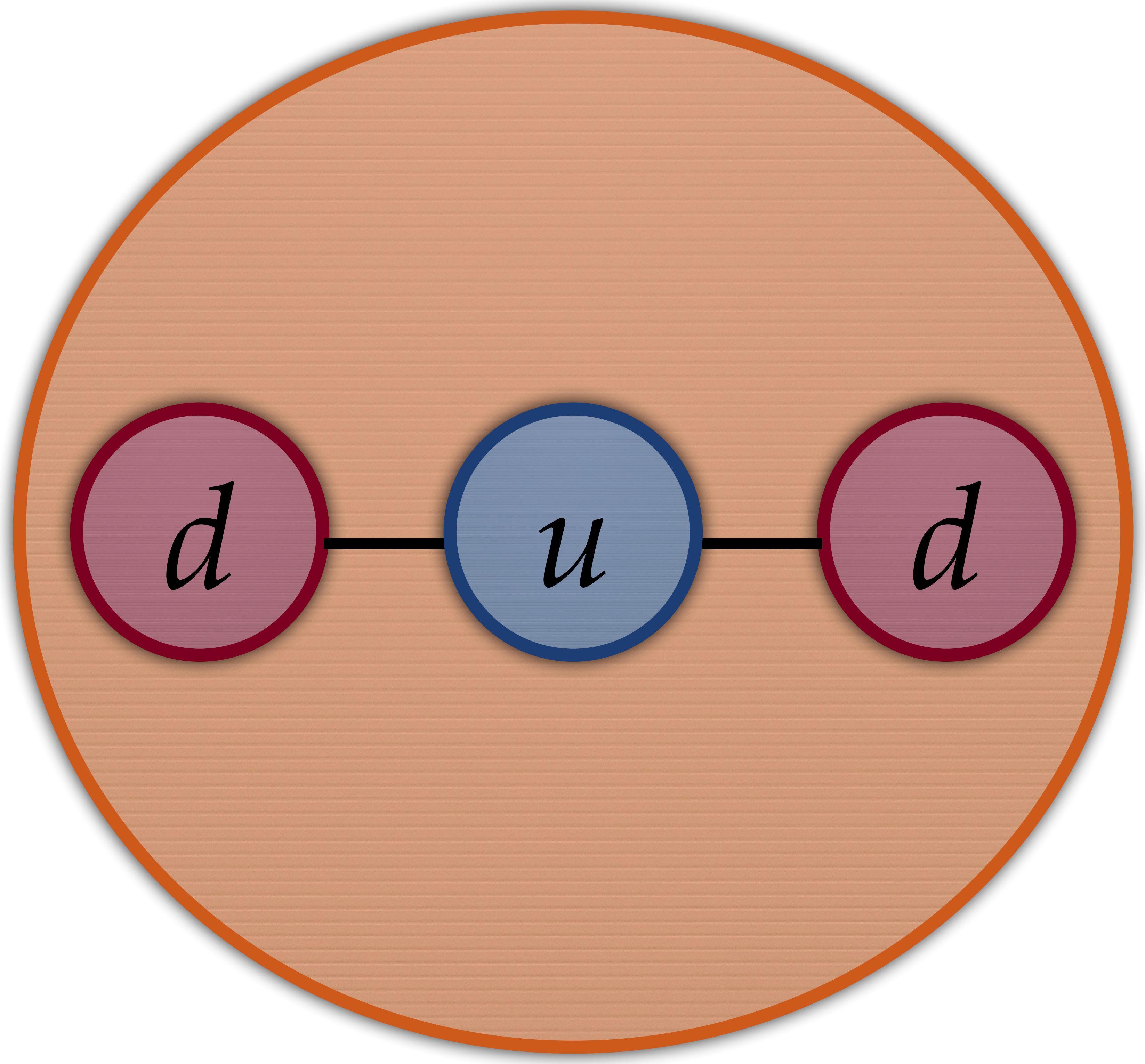
One strategy: try to find theories that solve other problems in physics at the same time

Problem #1: "The Strong CP problem"

Experimental tests of the electric dipole moment of the neutron suggest that its quark content is arranged in a very specific way, but **the theory of the strong force does not explain why**

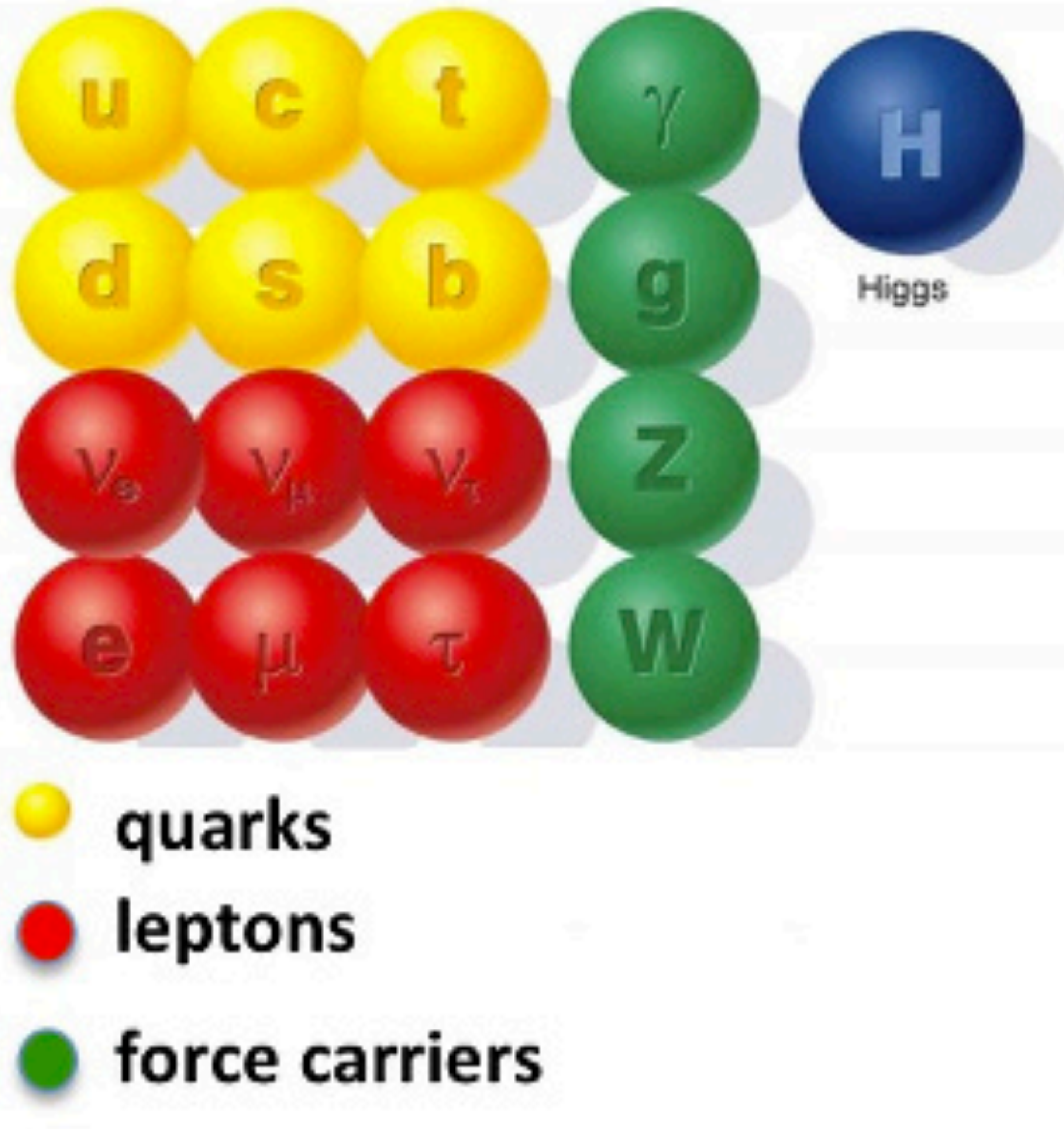


<u>Clue:</u> We need a new force that acts on nucleons (remember that forces have mediator particles)

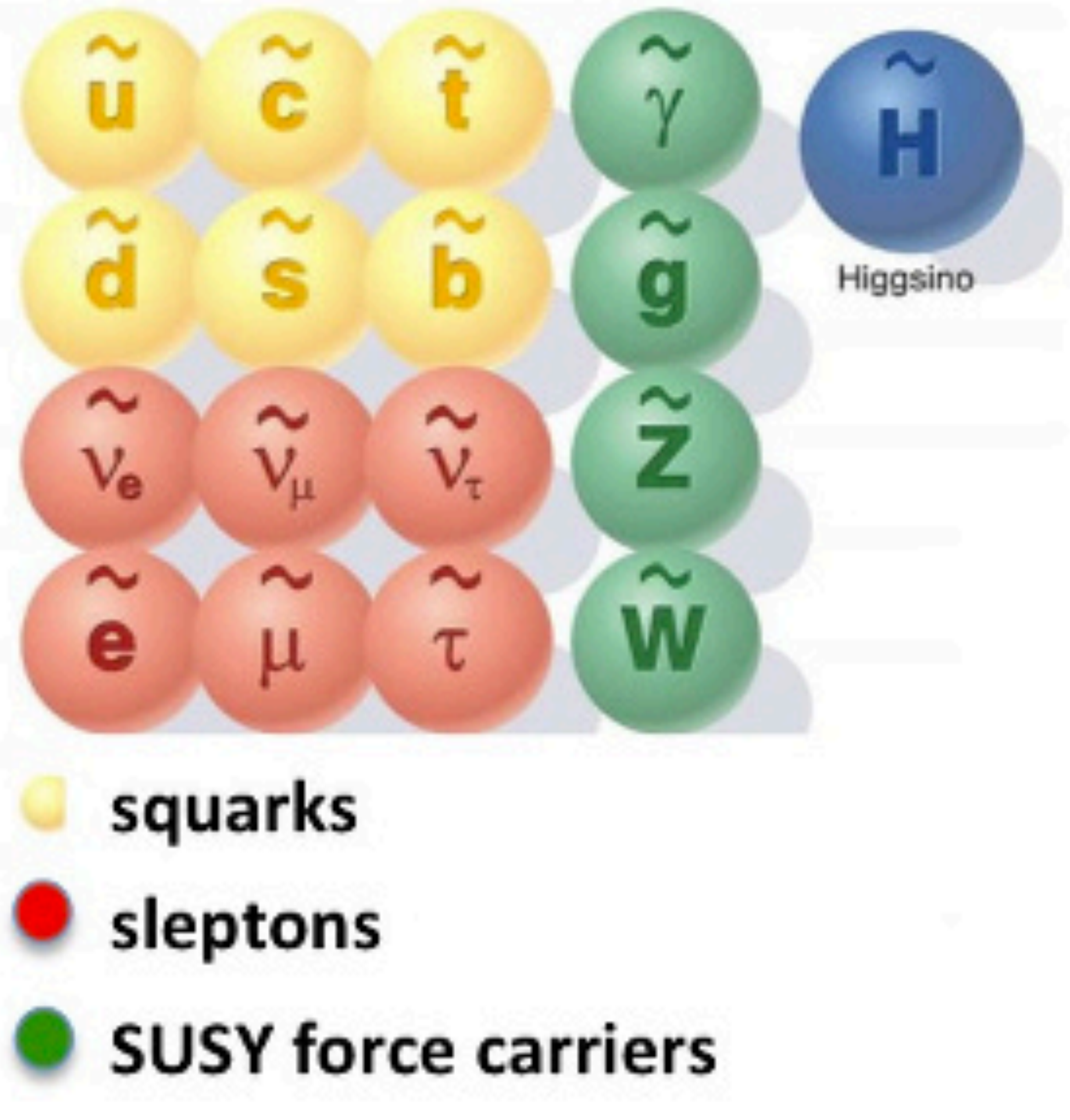
Problem #2: How to extend the symmetries of the Standard Model?

- "Supersymmetry" posits a fundamental symmetry of nature between bosons and fermions.
- Solves several problems in particle physics, most notably a hierarchy problem associated with the calculation of the Higgs boson mass
- This the most "natural" way to expand the symmetries of the Standard Model from a mathematical perspective

Standard Model particles



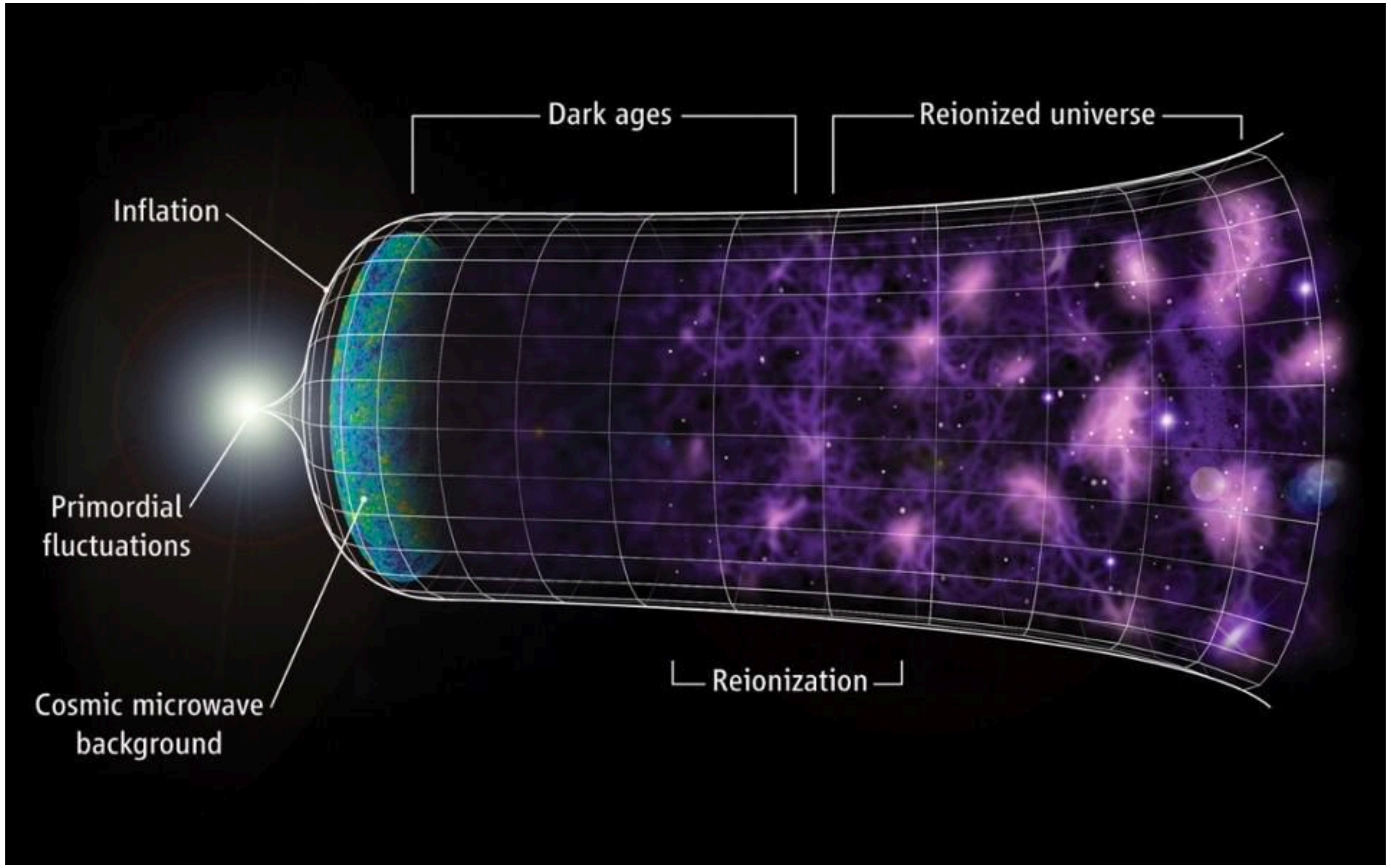
Supersymmetric partners



Clue: The lightest supersymmetric particle is **stable**

Problem #3: Where does the structure in the Universe come from?

- The theory of **inflation** invokes a period of exponential expansion, just after the Big Bang
- Explains why the Universe is flat and homogenous on large scales
- Predicts that tiny primordial quantum fluctuations are blown up to macroscopic sizes
- These fluctuations then seed all of the structure in the Universe



<u>Clue:</u> Some of these fluctuations in the primordial plasma could have been so large that they collapsed straight away…

Problem	**Solution**	**Dark Matter candidate**
#1: The electric dipole moment of the neutron		
#2: How to extend the symmetries of the Standard Model?		
#3: Where does the Universe's structure come from?		

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Problem	Solution	Dark Matter candidate
#1: The electric dipole moment of the neutron	A new force acting on quarks	Axions
#2: How to extend the symmetries of the Standard Model?	Supersymmetry	Weakly Interacting Massive Particles (WIMPs)
#3: Where does the Universe's structure come from?	Inflation	Primordial black holes

Classic dark matter candidates

Definition: very light particle that interacts with quarks and photons

Motivation: the strong CP problem

Type: Wave-like

Definition: heavy particle that can interact with itself and other particles

Motivation: Supersymmetry

Type: Particle-like

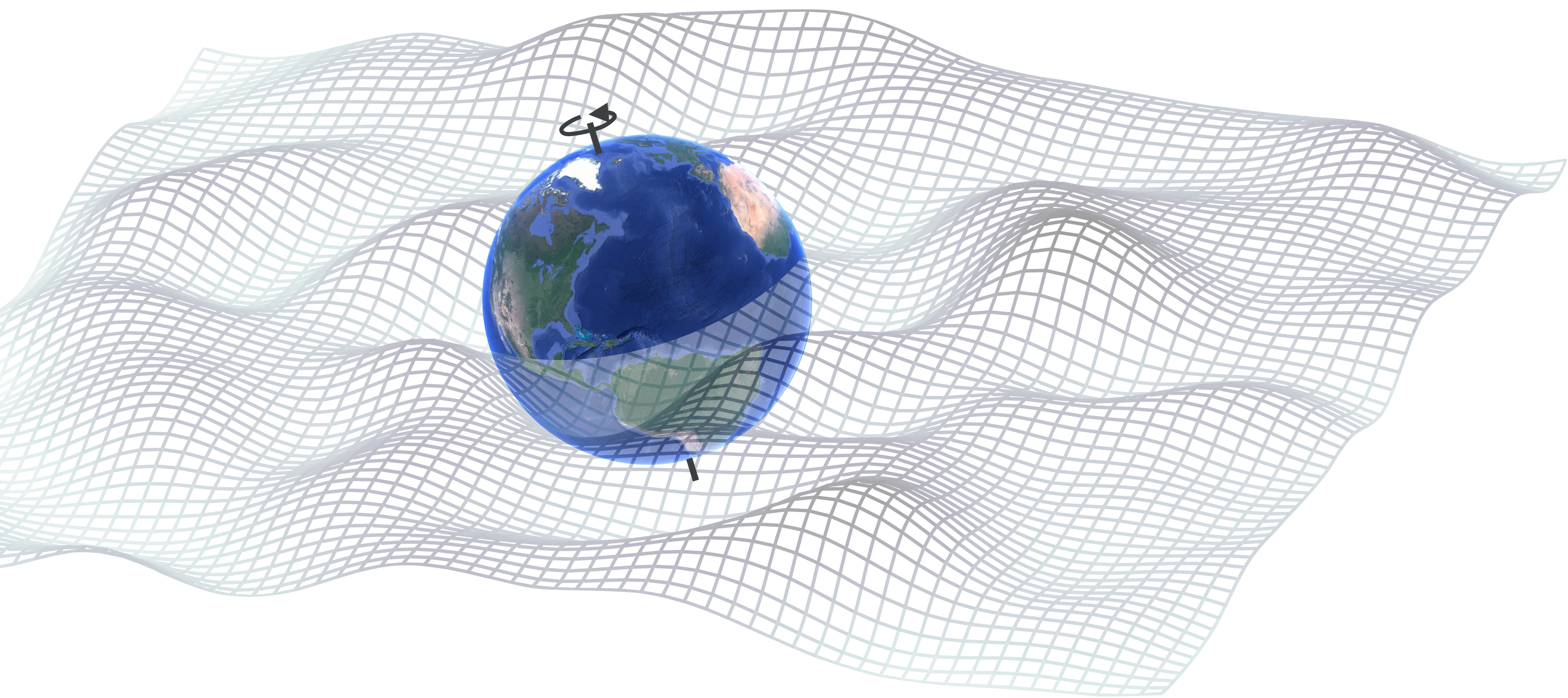
Definition: black holes formed very early in the Universe

Motivation: inflation

Signatures: Object-like

How to think about different types of dark matter

Wave-like (e.g. axions)

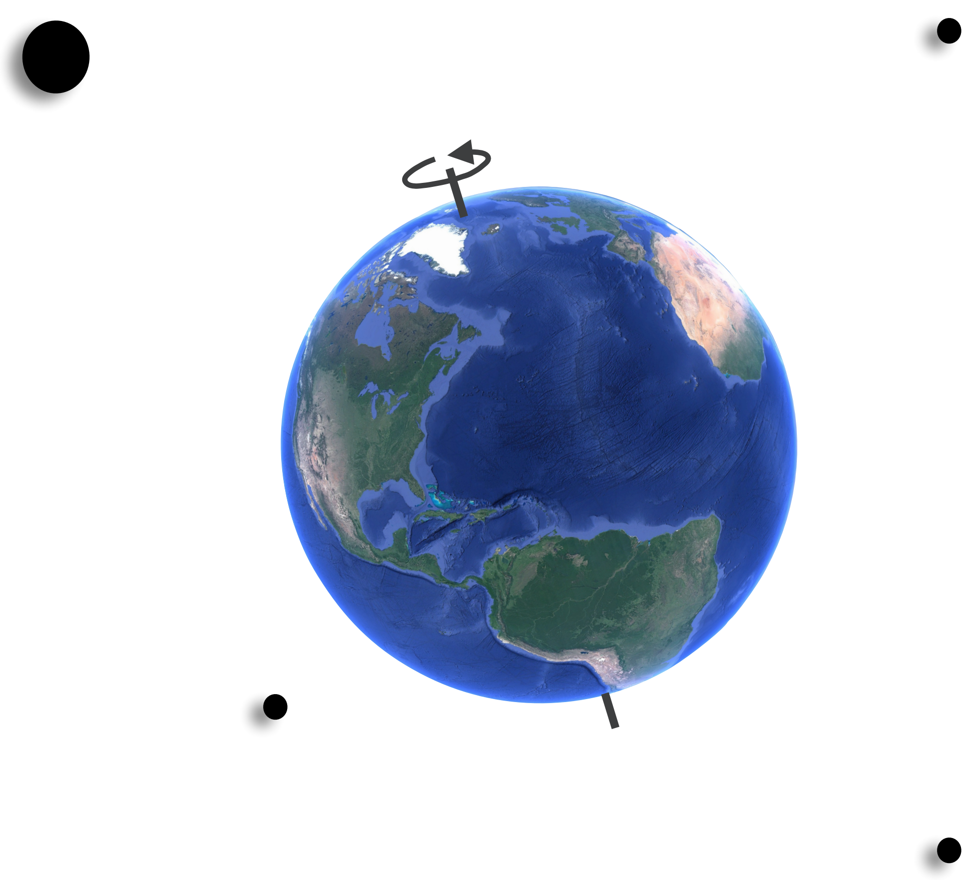


Continuously oscillating and fluctuating field that can couple to other fields (e.g. the electromagnetic one)

Particle-like (e.g. WIMPs)

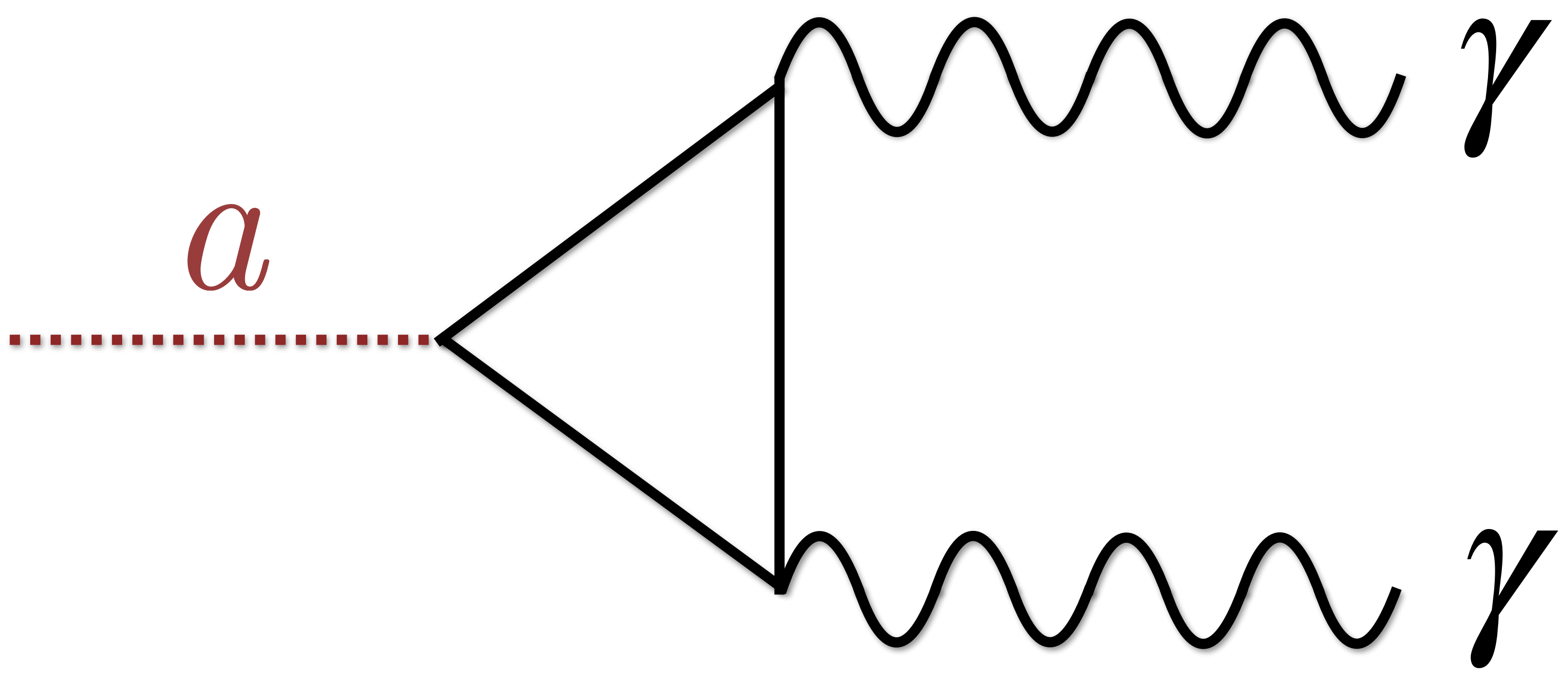
Discrete particles occasionally colliding with each other or other stuff

Object-like (e.g. black holes)



Very sparse population of heavy bodies exerting distant gravitational interactions

How to detect the axion



The **axion** couples to quarks, but it also couples to the photon → therefore violates Maxwell's equations

$$\nabla \cdot \mathbf{E} = \rho_q$$

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

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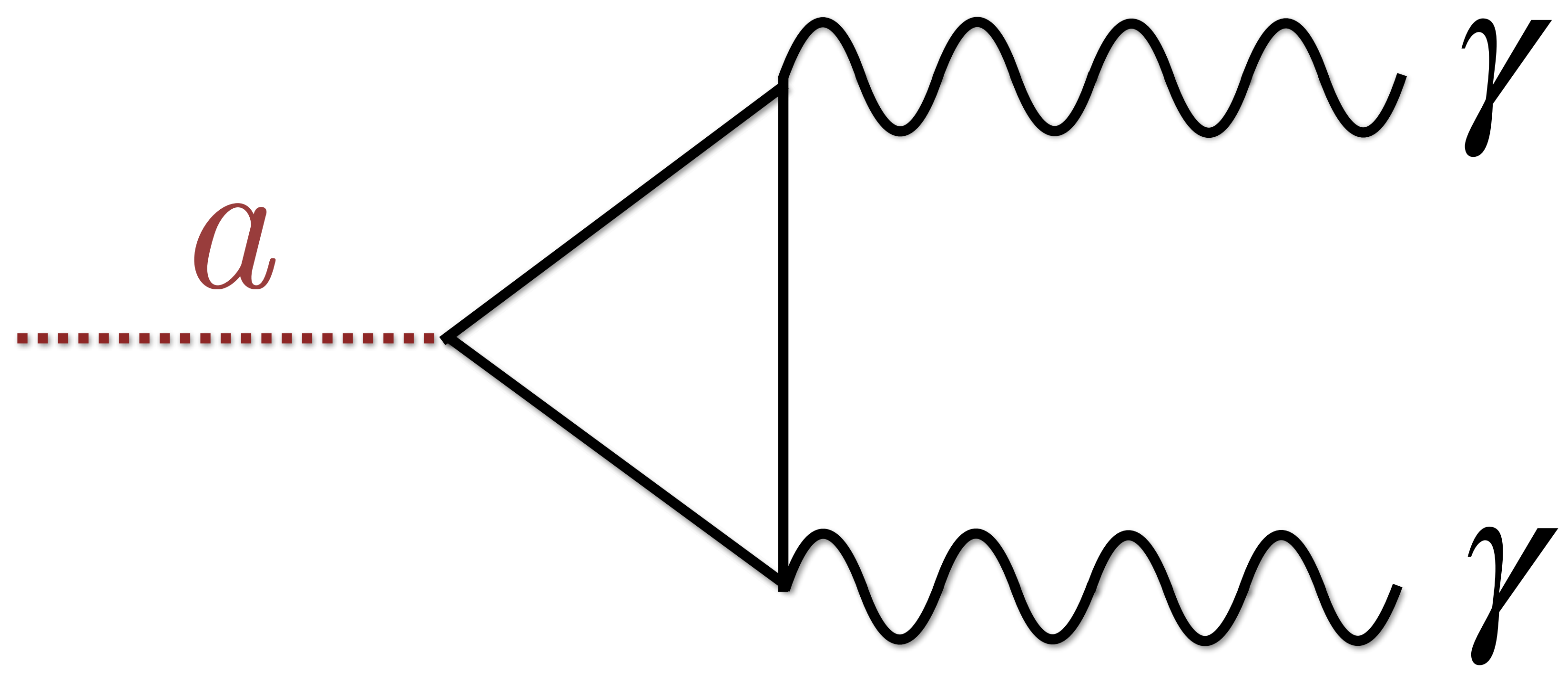


$$\nabla \cdot \mathbf{E} = \rho_q - g_{a\gamma}\mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma}(\mathbf{B}\,\dot{a} - \mathbf{E} \times \nabla a)$$

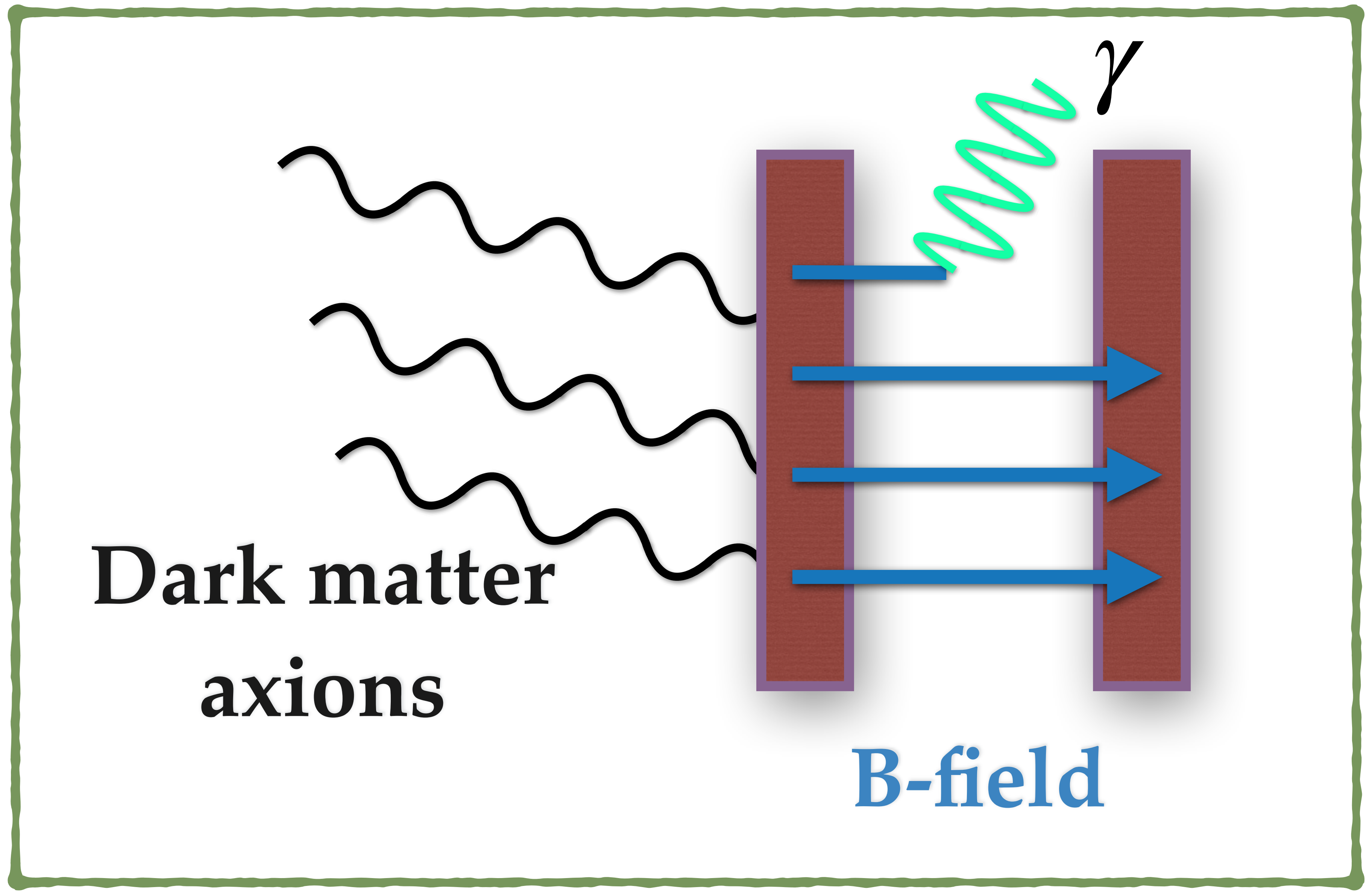
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

Okay as long as the coupling $g_{a\gamma}$ is <u>very small</u>

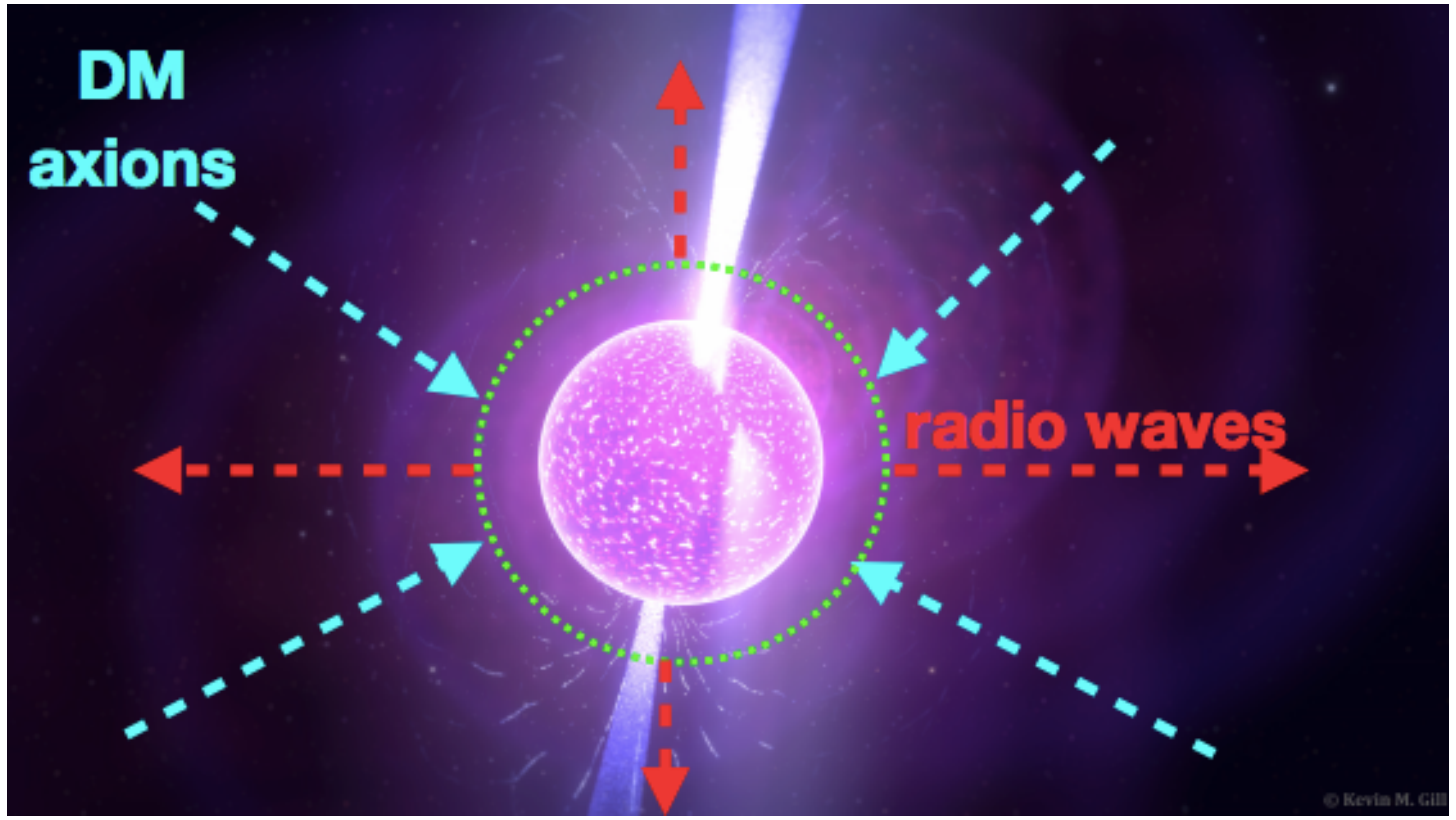
Key feature: axions can turn into photons inside magnetic fields
→ the stronger the B-field, the more photons you get

Detecting axions *directly*



→ If you have a big enough magnet then dark matter axions could flow into your lab and convert into photons

Detecting axions *indirectly*

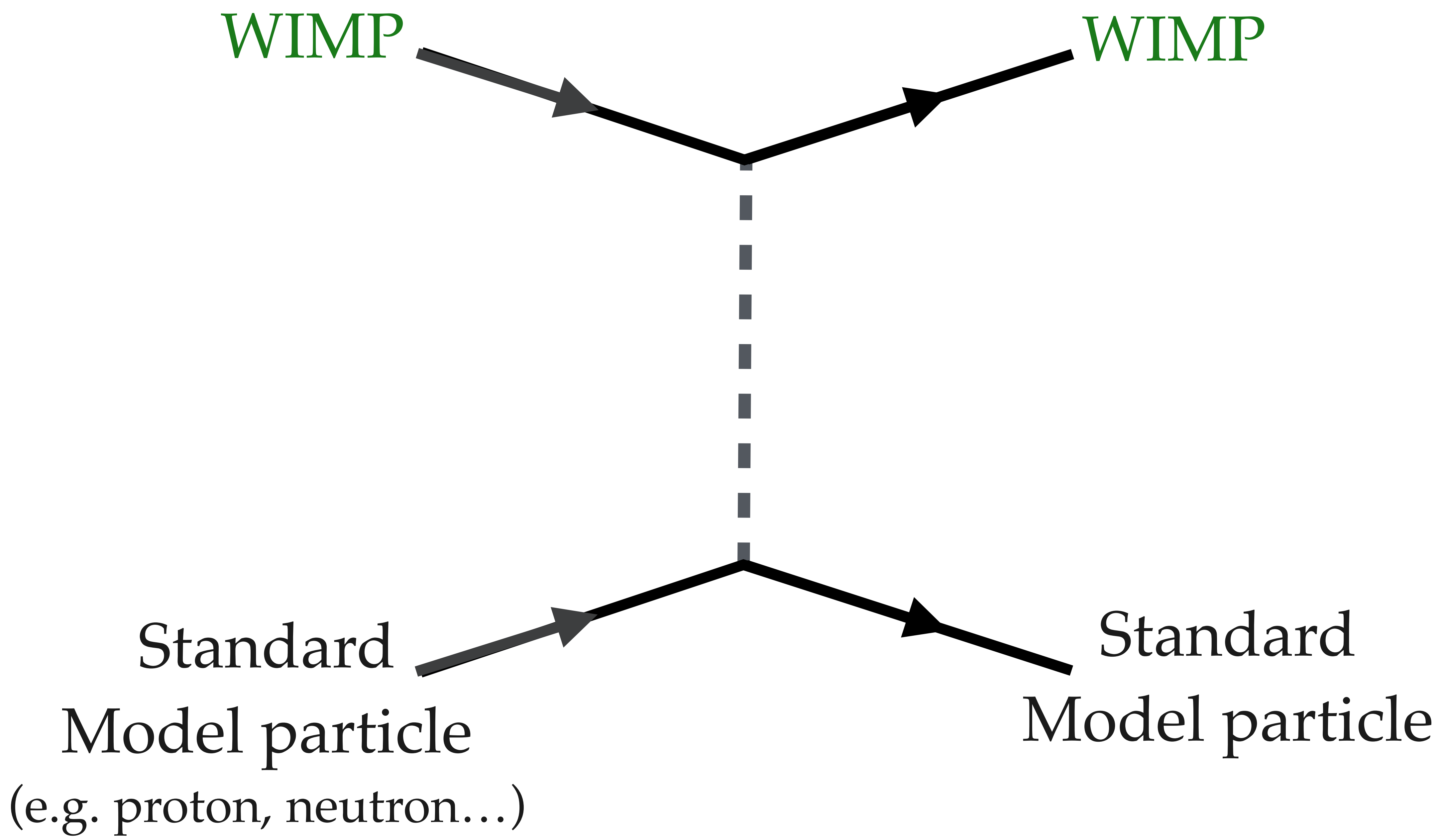


→ Dark matter could fall onto a neutron star (B~10^{10} T) and convert into radio waves

= excluded already
Axions
WIMPs
Primordial black holes
zeV aeV feV peV neV μeV meV eV
keV MeV GeV TeV
10^−18 10^−12 10^−9 10^−3 10^3 M⊙
Big magnets
Direct searches:
(Looking for axions streaming in from space and converting into photons in the lab)
Neutron stars
Red giants
Indirect searches
(Looking for axions interacting with stellar objects):
Sheath
Main Coil
Main Coil Leads
Test Coil Leads
To SQUID
Mirror
~2m
10 T dipole magnet
Horn antenna (+ receiver)
80 adjustable dielectric discs
Parabolic
Seperate cryogenic volume
Schematics of experimental concept
AF-TI crystal
DM axion wave
Photon counter
Induced Axion-Polaritons

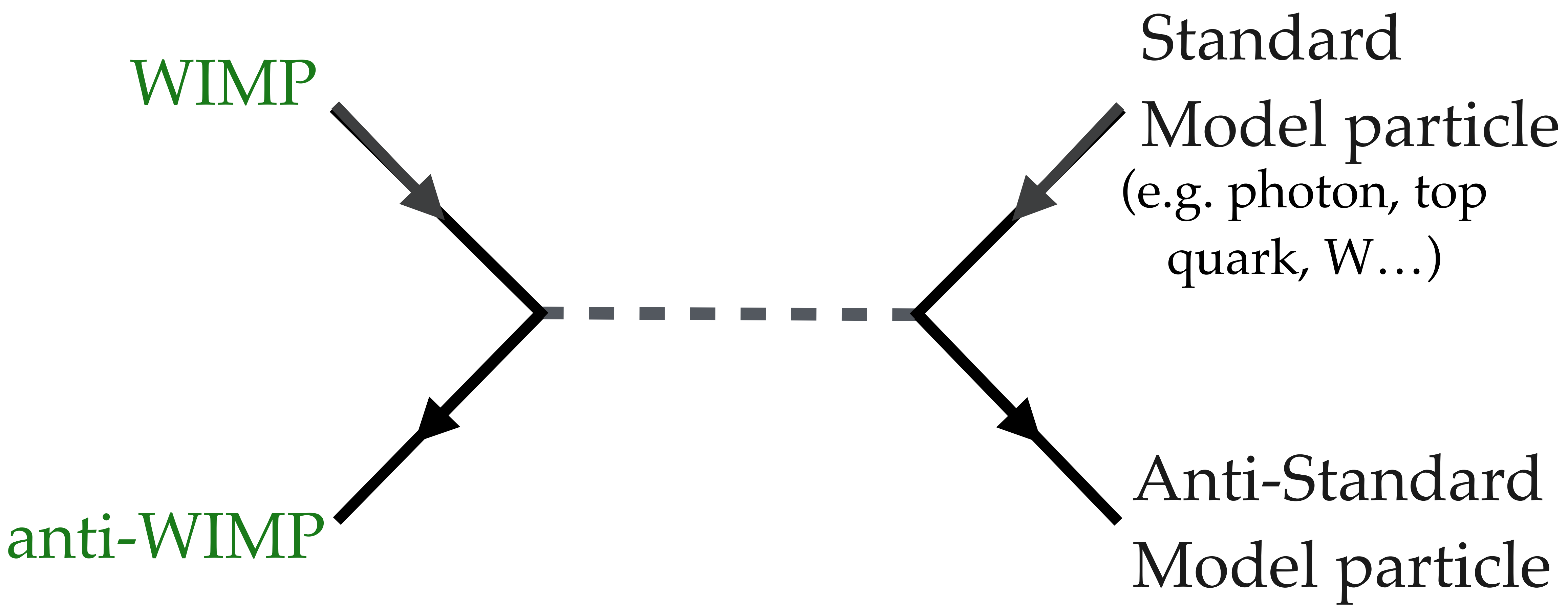
WIMPs couple feebly to other particles in the Standard Model

Detecting WIMPs *directly*



→ Interaction between galactic WIMPs and normal particles in the laboratory

Detecting WIMPs *indirectly*

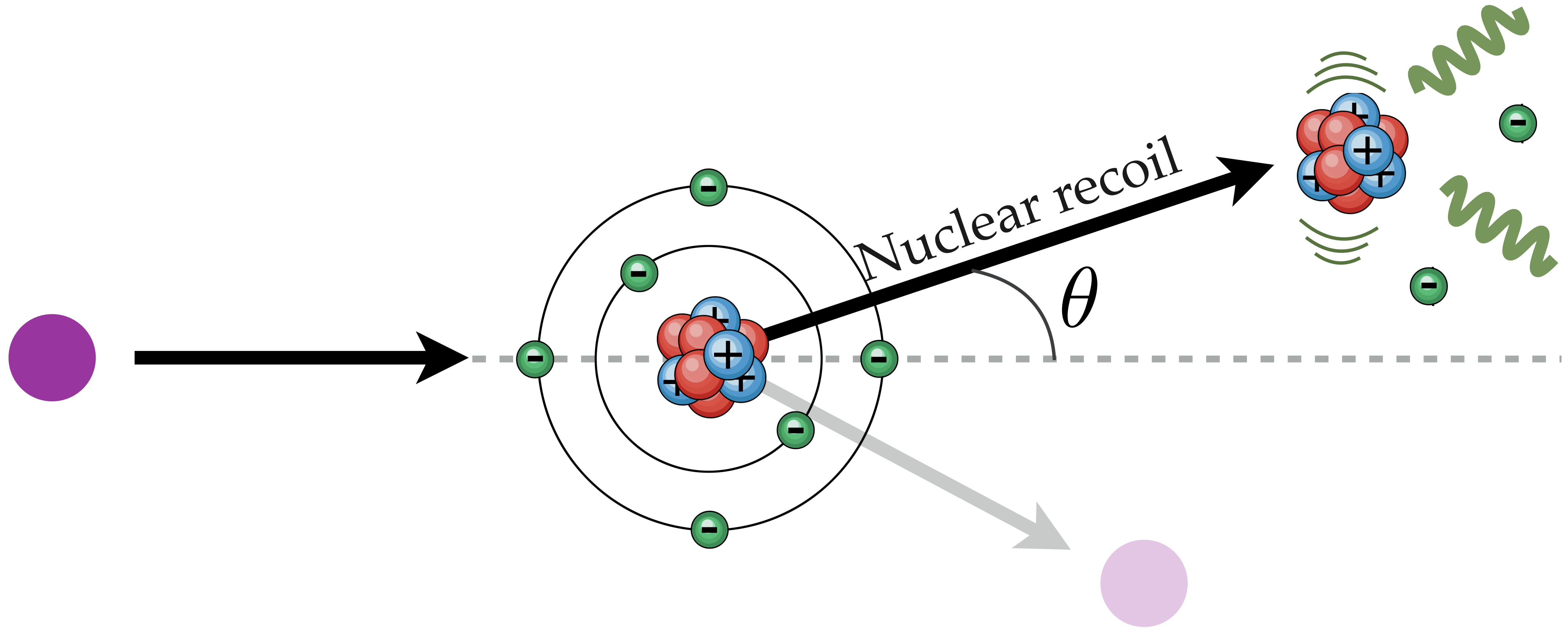


→ Annihilation of WIMPs in space

(WIMPs can be their own antiparticles)

Typical direct WIMP interaction: nuclear scattering

WIMP floating in from Milky Way halo
v ~ 300 km/s



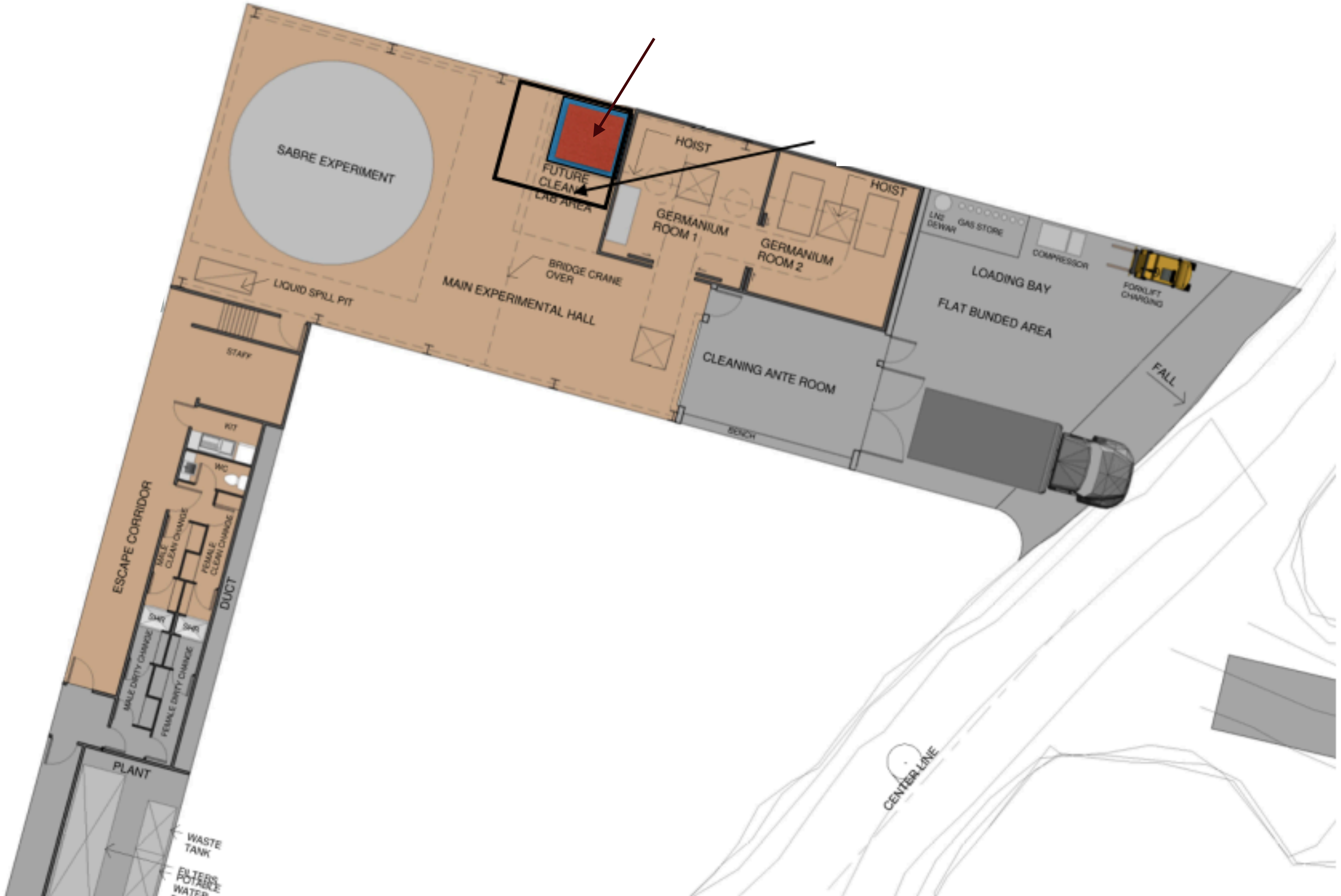
Recoil dumps energy in the form of ionisation, heat or photons

Main issue: how to shield from cosmic rays?

Less than 1 WIMP event per year per ton of detector material. Will be drowned out unless your lab is **underground**

Stawell underground physics lab (SUPL)

- Construction began in old Victoria gold mine last year
- SUPL will be the first underground lab in the Southern Hemisphere
- First experiment it will host is **SABRE,** more on that later…



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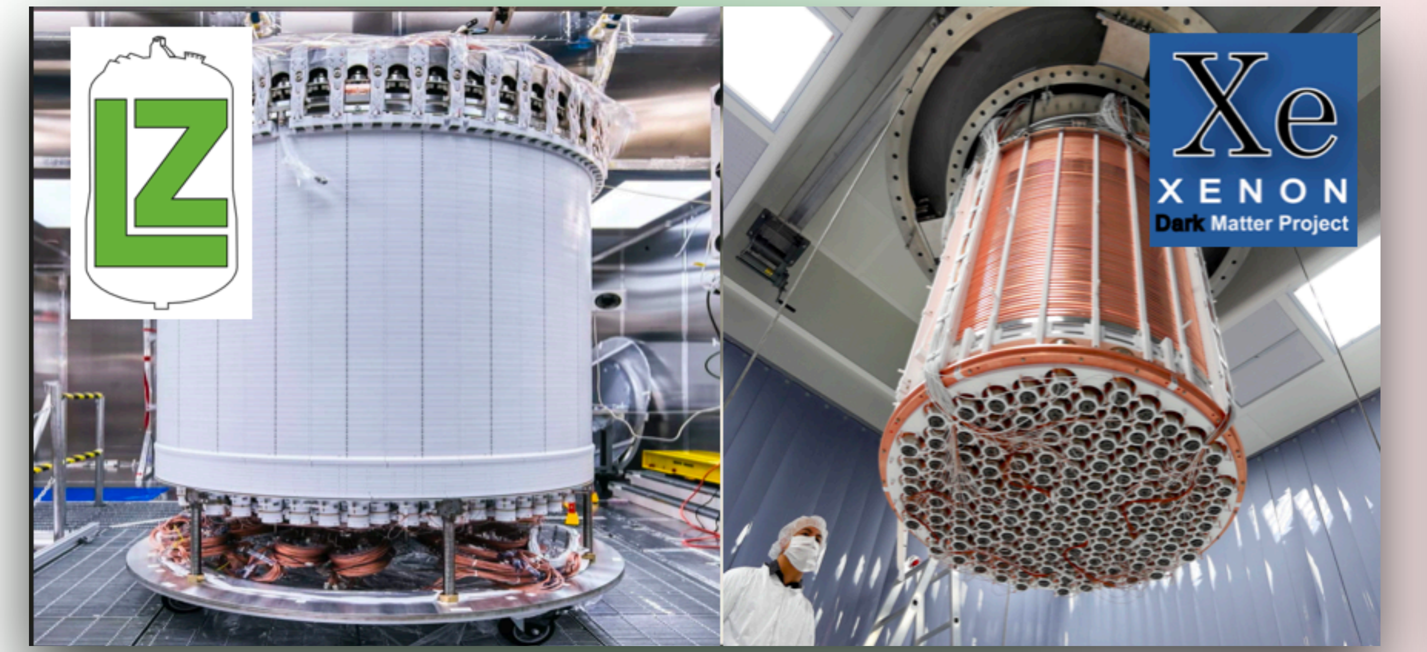
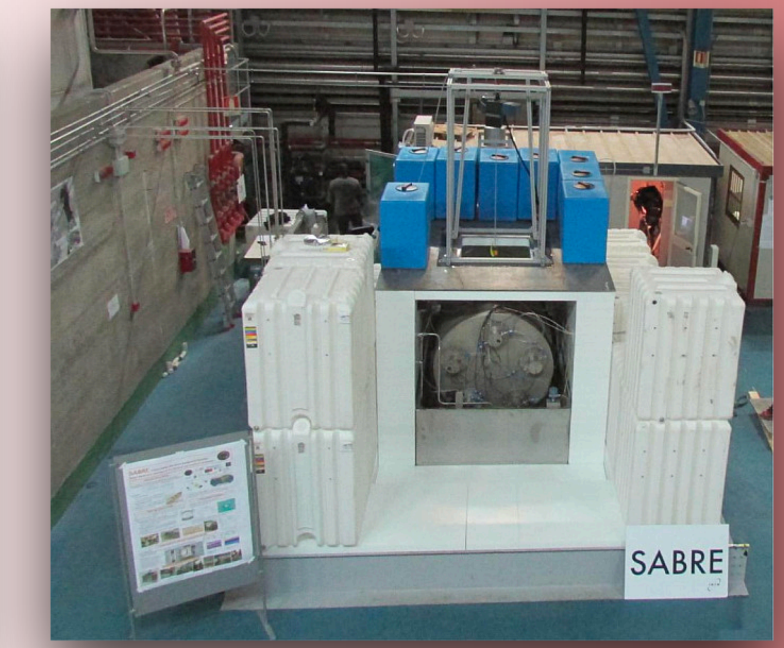
Searches

Direct searches:
(Looking for WIMPs scattering underground) →

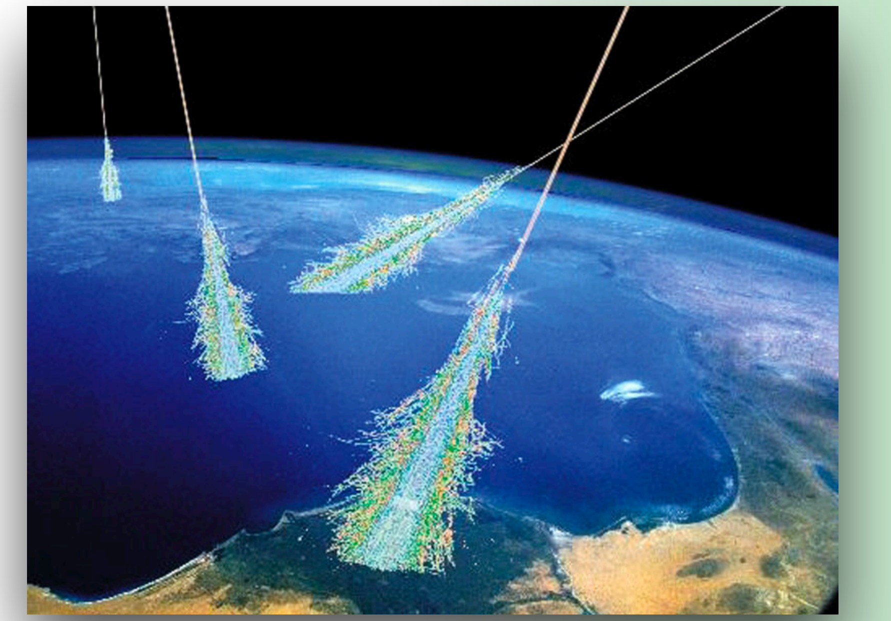
Underground detectors



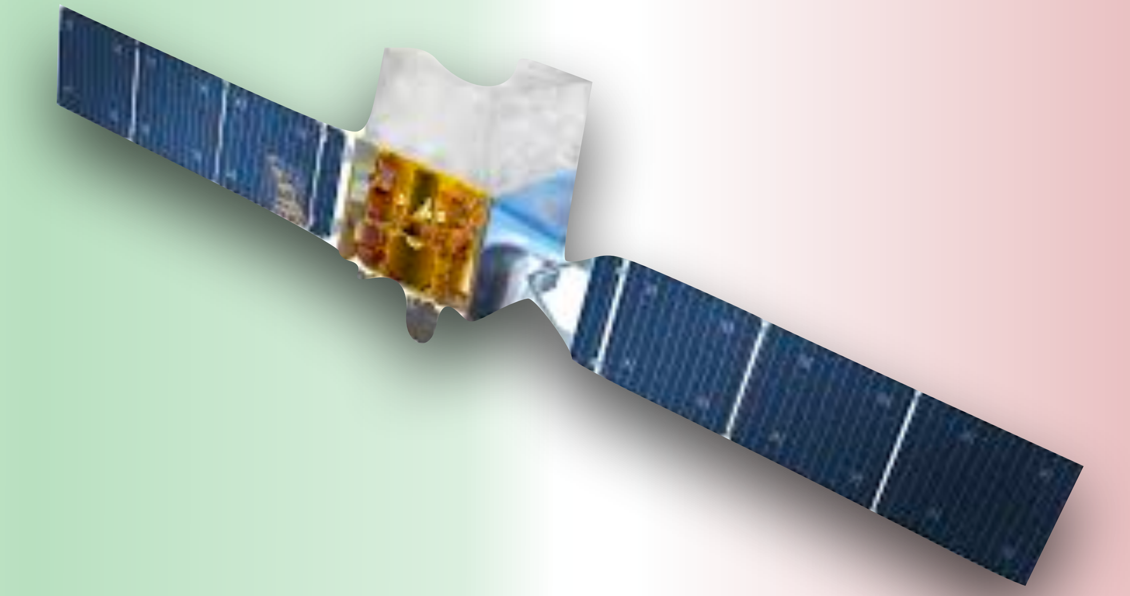


Indirect searches
(Looking for WIMPs annihilating in space): →

Cosmic rays



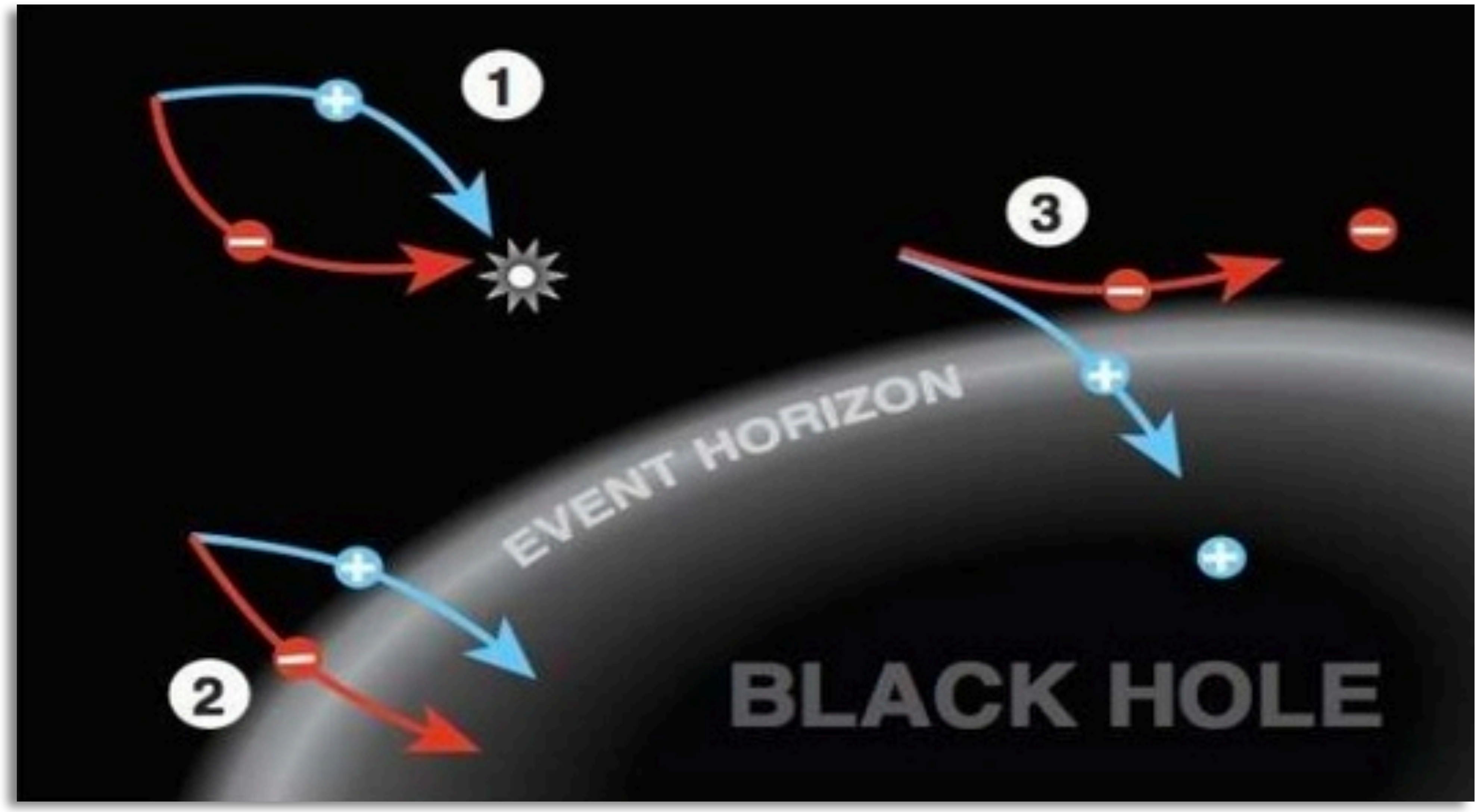
Gamma rays



Primordial black holes form from the collapse of very large density fluctuations left over by inflation

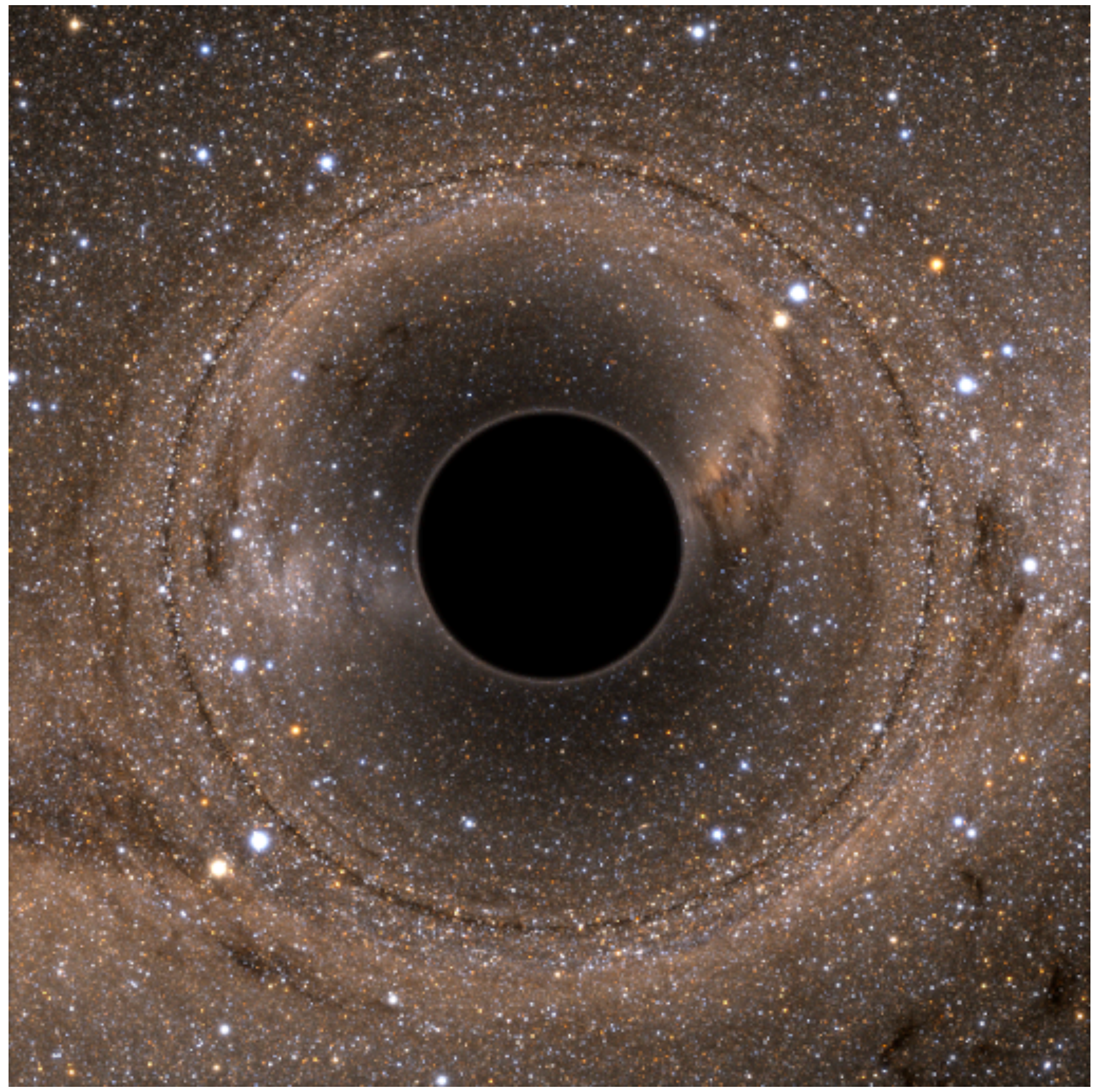
Ways to observe primordial black holes

Hawking radiation



Black hole horizons evaporate via the emission of high energy particles
→ the lighter the black hole, the faster it evaporates

Gravitational lensing



Black holes could pass in front of stars and bend their light
→ "microlensing"

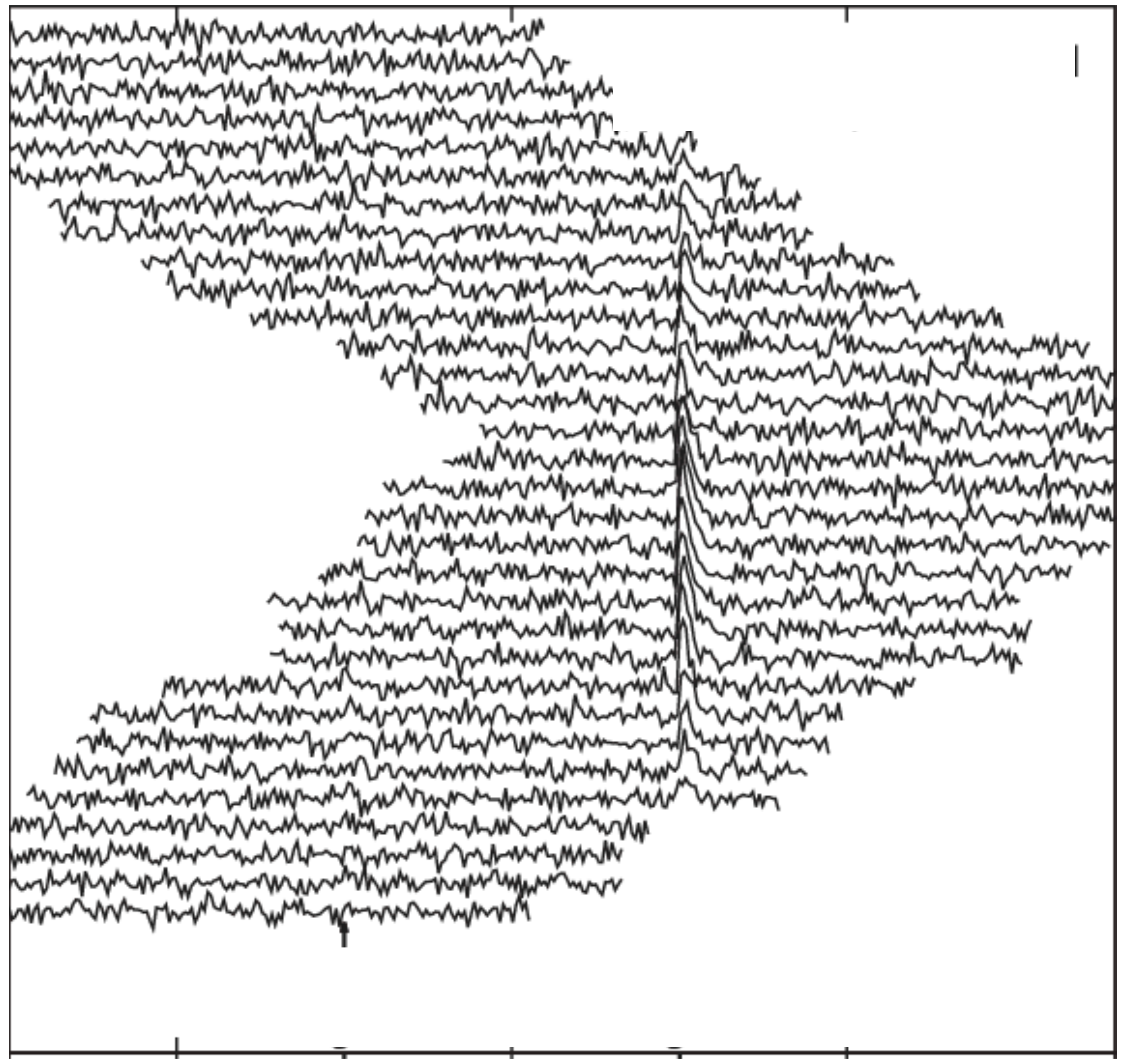

= excluded already
Axions
WIMPs
Primordial black holes
zeV aeV feV peV neV μeV meV eV
keV MeV GeV TeV
10^−18 10^−12 10^−9 10^−3 10^3 M_⊙
Microlensing
star
lens
view from Earth
Hawking radiation
EVENT HORIZON
BLACK HOLE
Accretion
Gravitational waves

Searches (very incomplete summary)

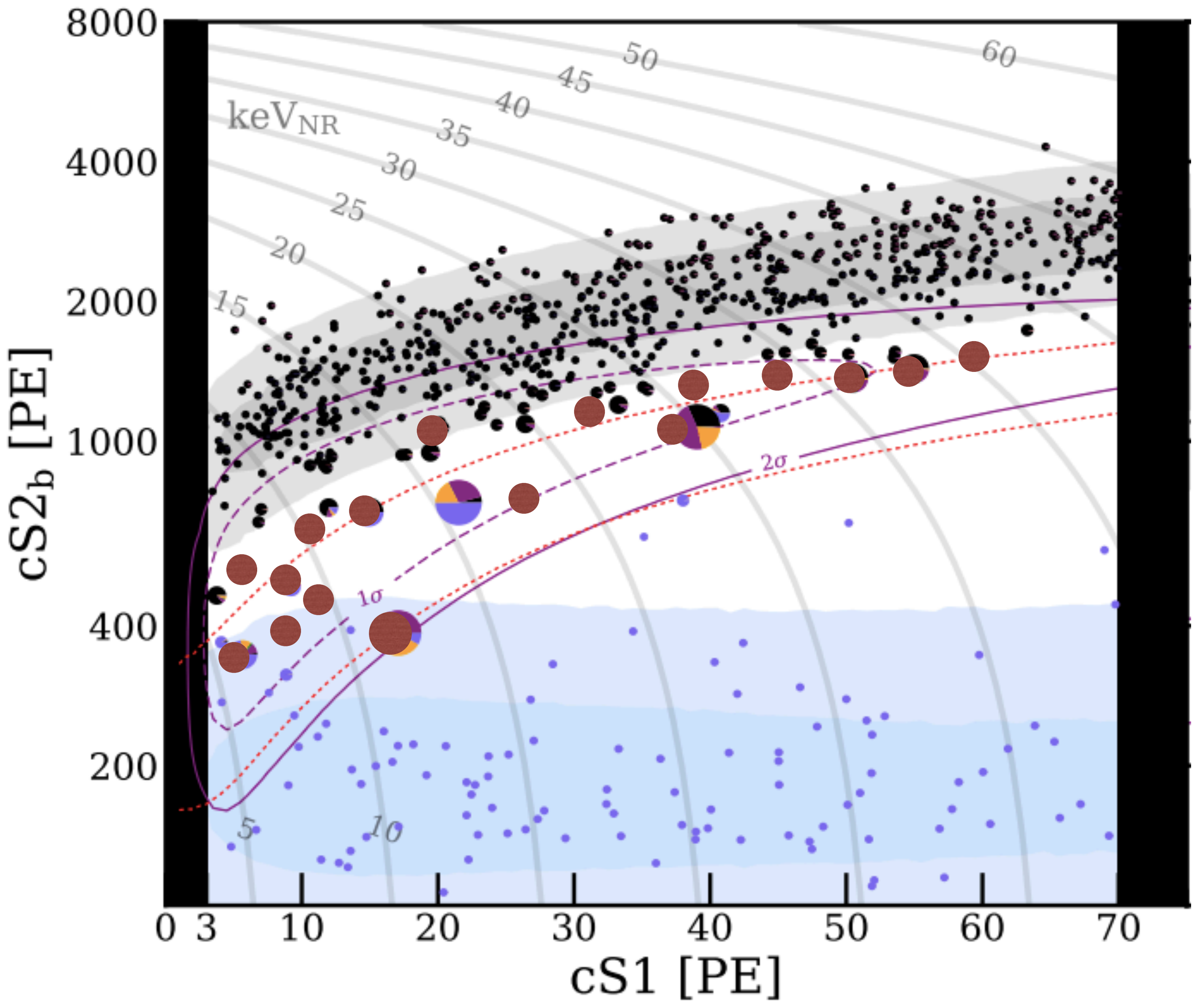
This is what a "discovery" of dark matter could look like

→ How do we know when we have seen it?

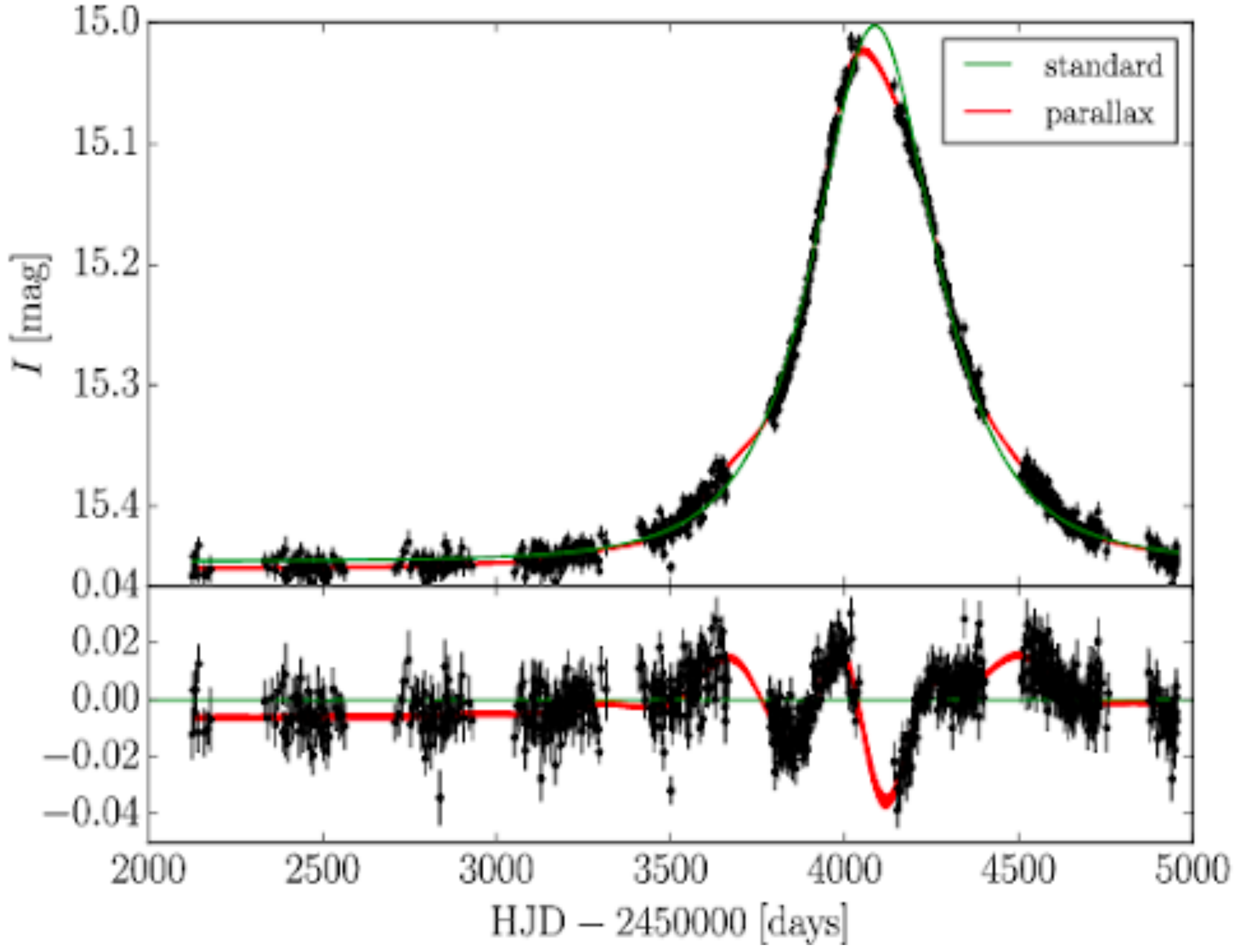
Axions



WIMPs



Primordial black holes



"What if it was just some radio noise nearby?"

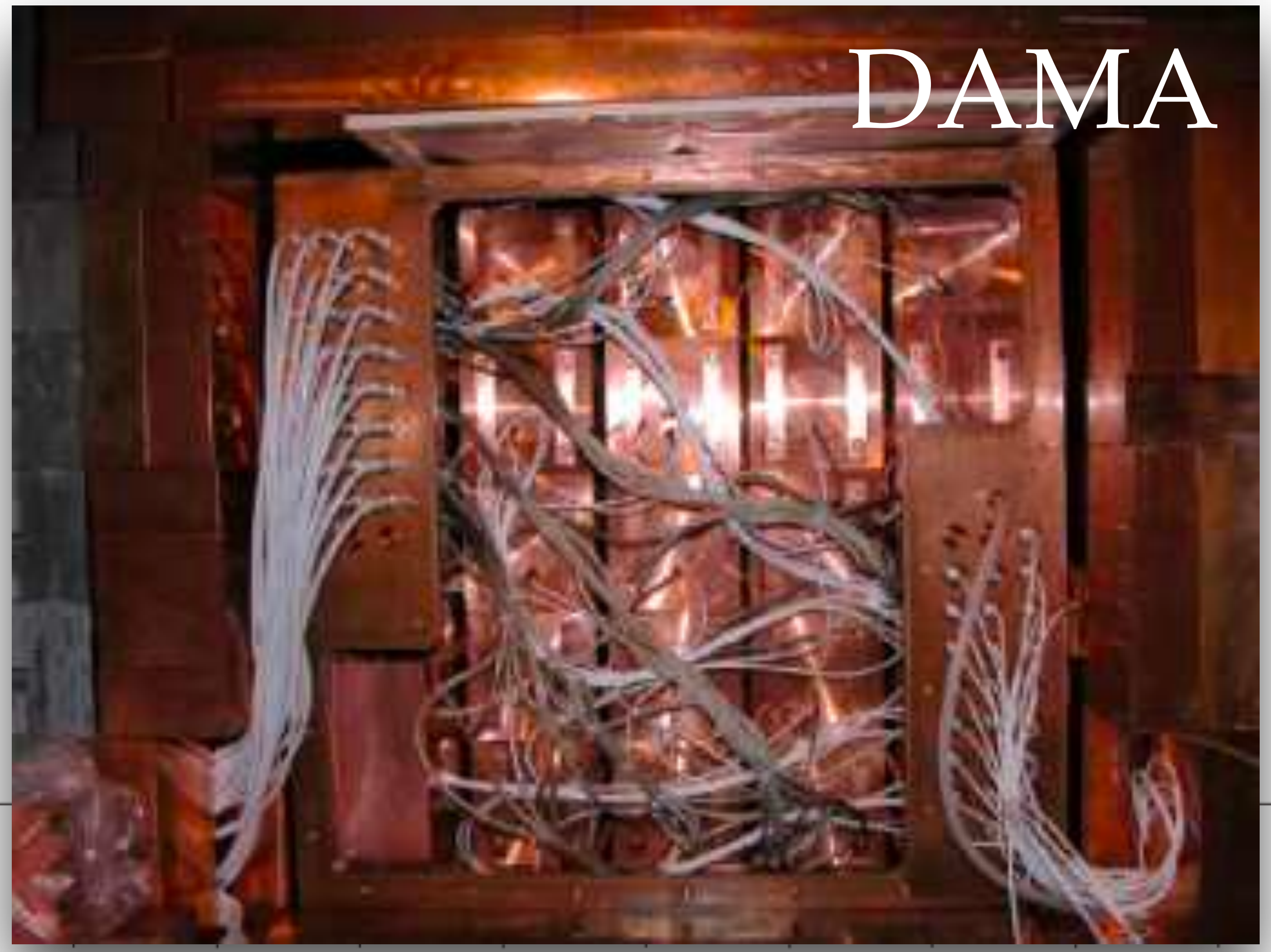
"What if some radioactive substance leaked into the detector?"

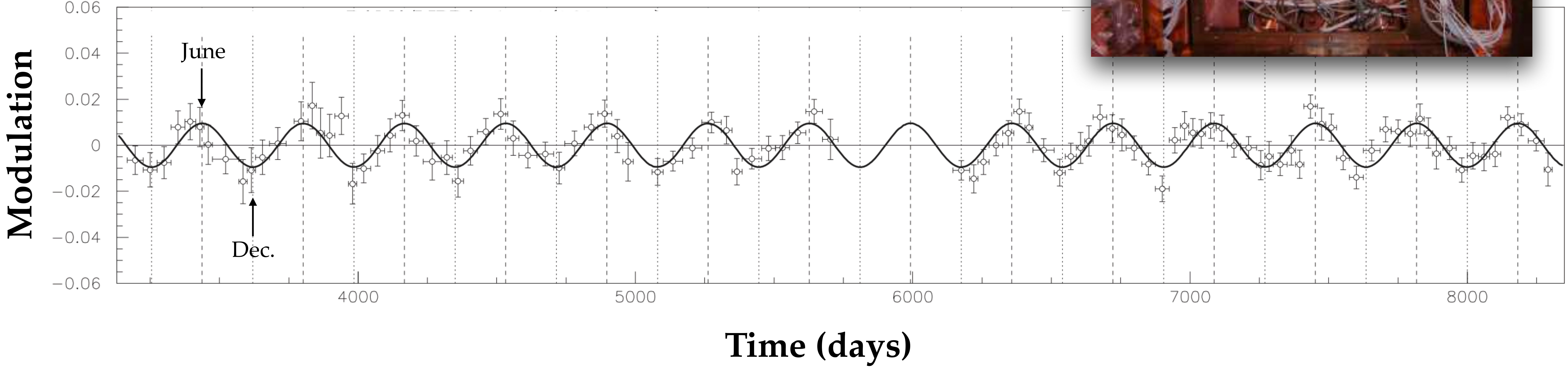
"What if there were just more compact bodies in the galaxy than we thought?"

A smoking gun: the dark matter “wind”

The flux of dark matter on Earth should modulate annually

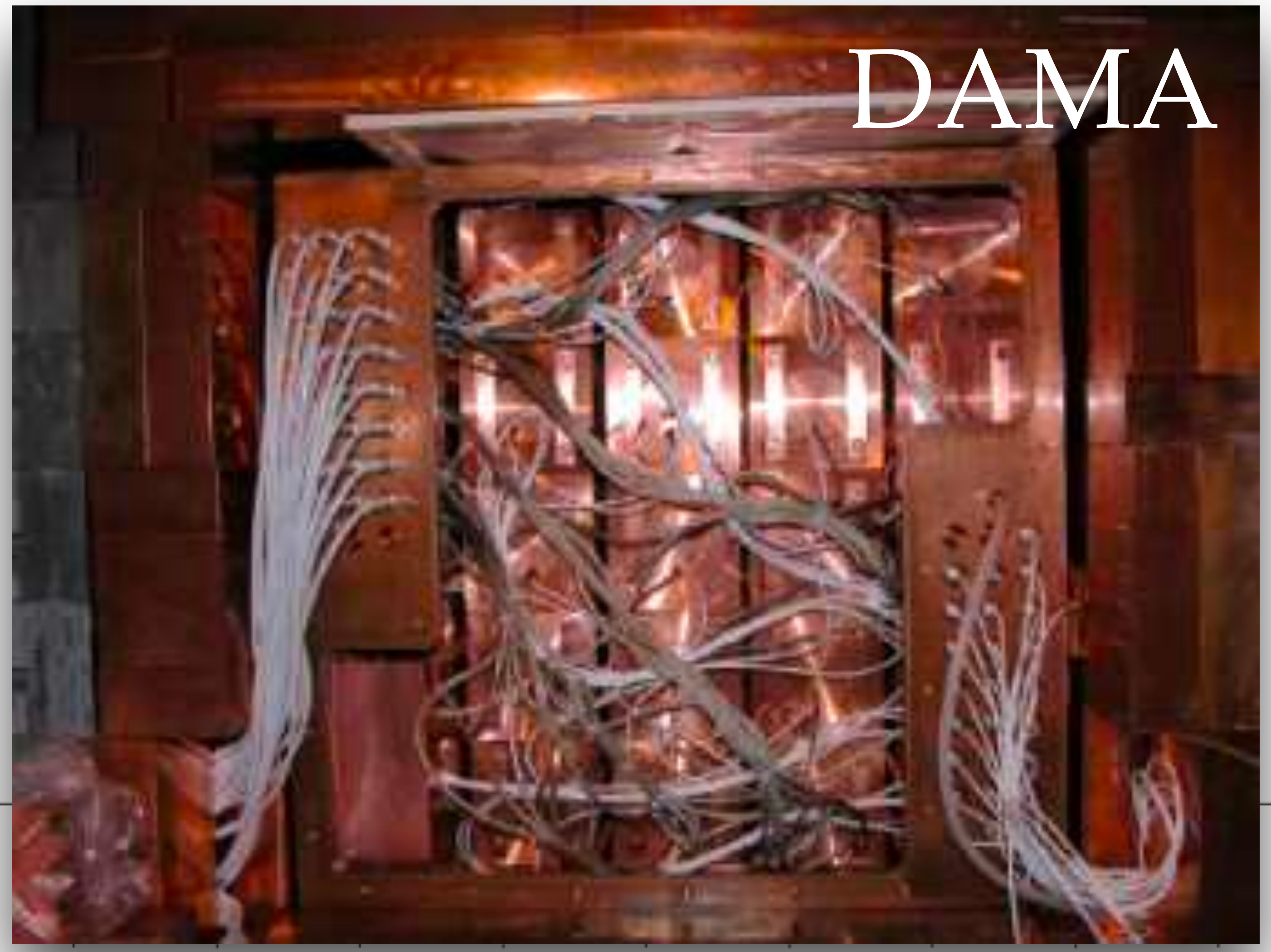
Dark matter observed already by the *DAMA* experiment?

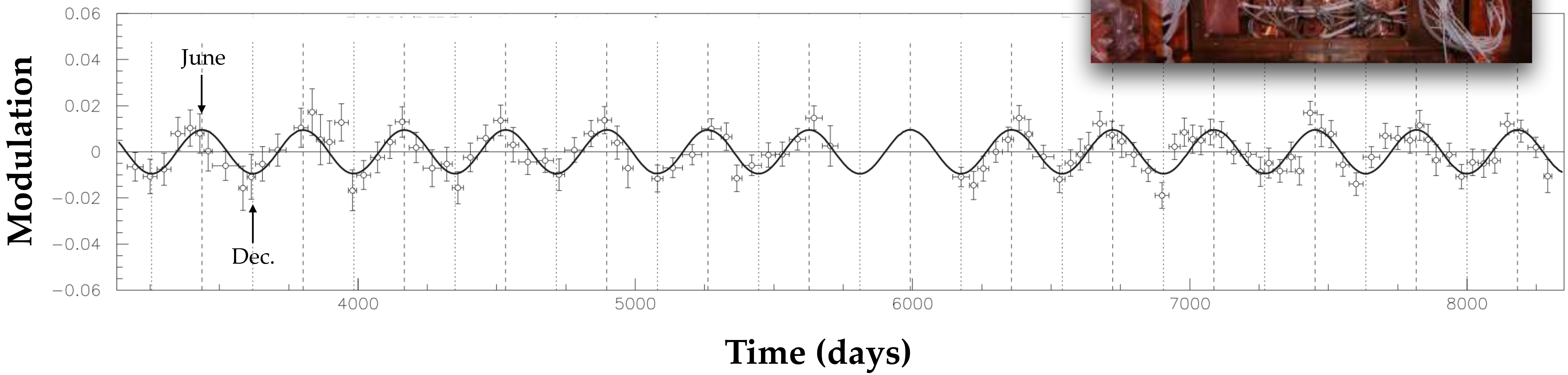




12.9σ significant observation of an annual modulation in line with what would be expected from dark matter

Dark matter observed already by the *DAMA* experiment?

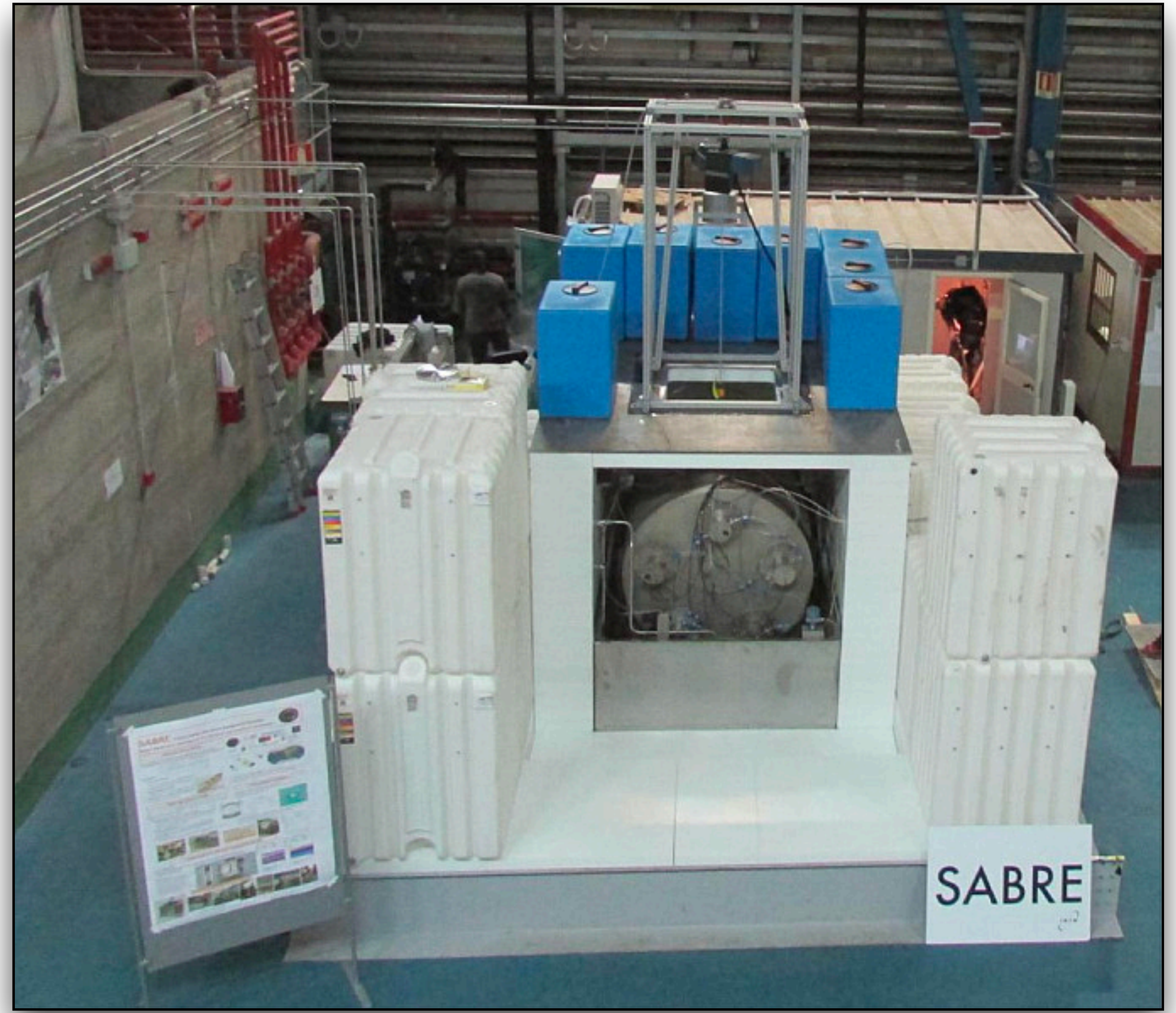




12.9σ significant observation of an annual modulation in line with what would be expected from dark matter

However: currently very hard to come up with a dark matter model that explains this and all the other null-results from other experiments

New Australian dark matter efforts



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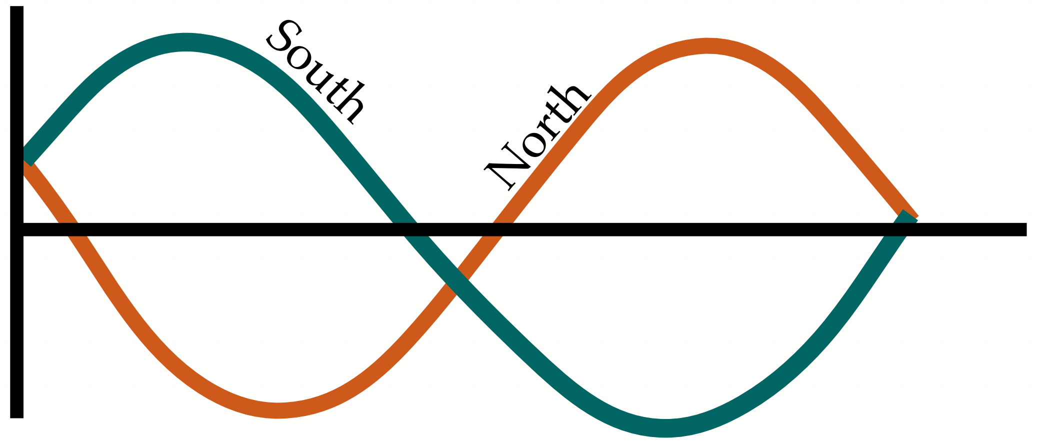
SABRE

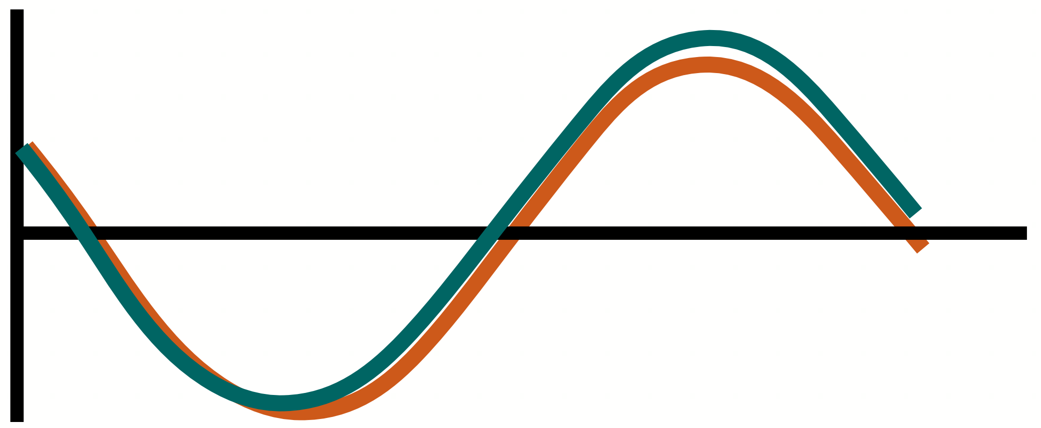
SABRE

- Put two identical experiments in the Northern and Southern Hemispheres

- If the signal is dark matter then the annual modulation should be the same, but if it is a seasonal effect then the modulation will be flipped



Seasonal effect

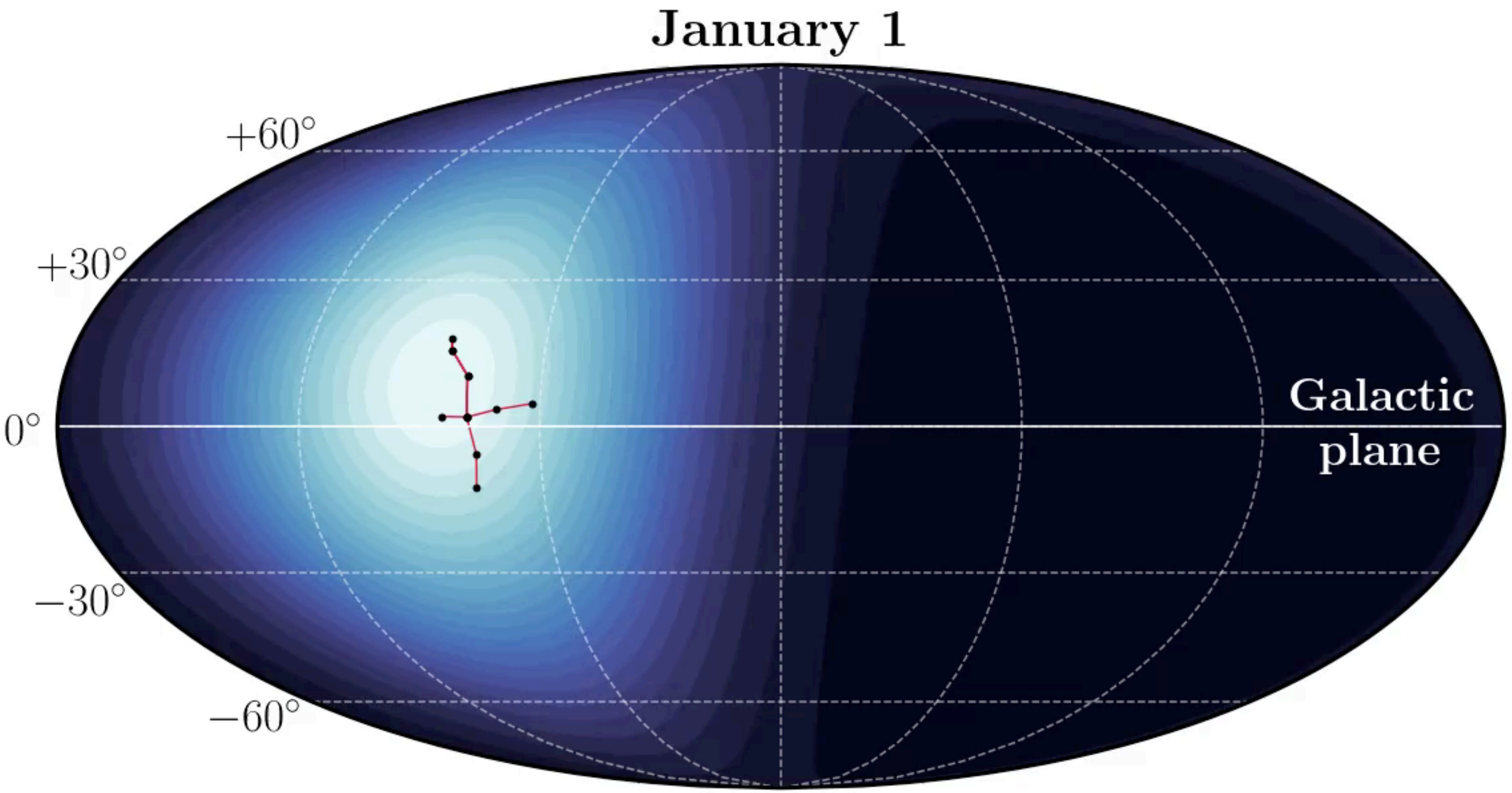


Dark matter

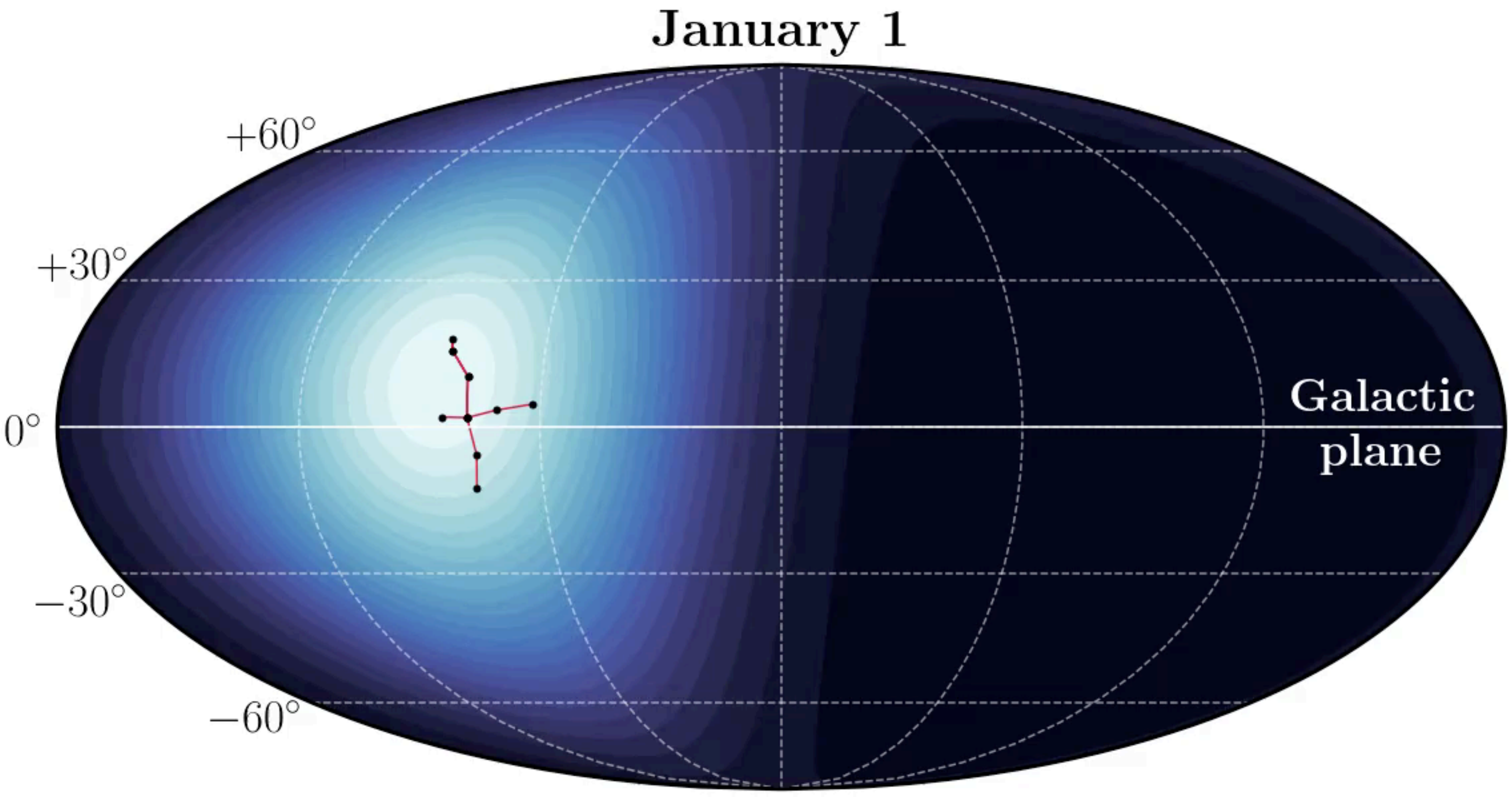
The dark matter "wind"

The flux of dark matter on Earth also be strongly <u>directional</u>

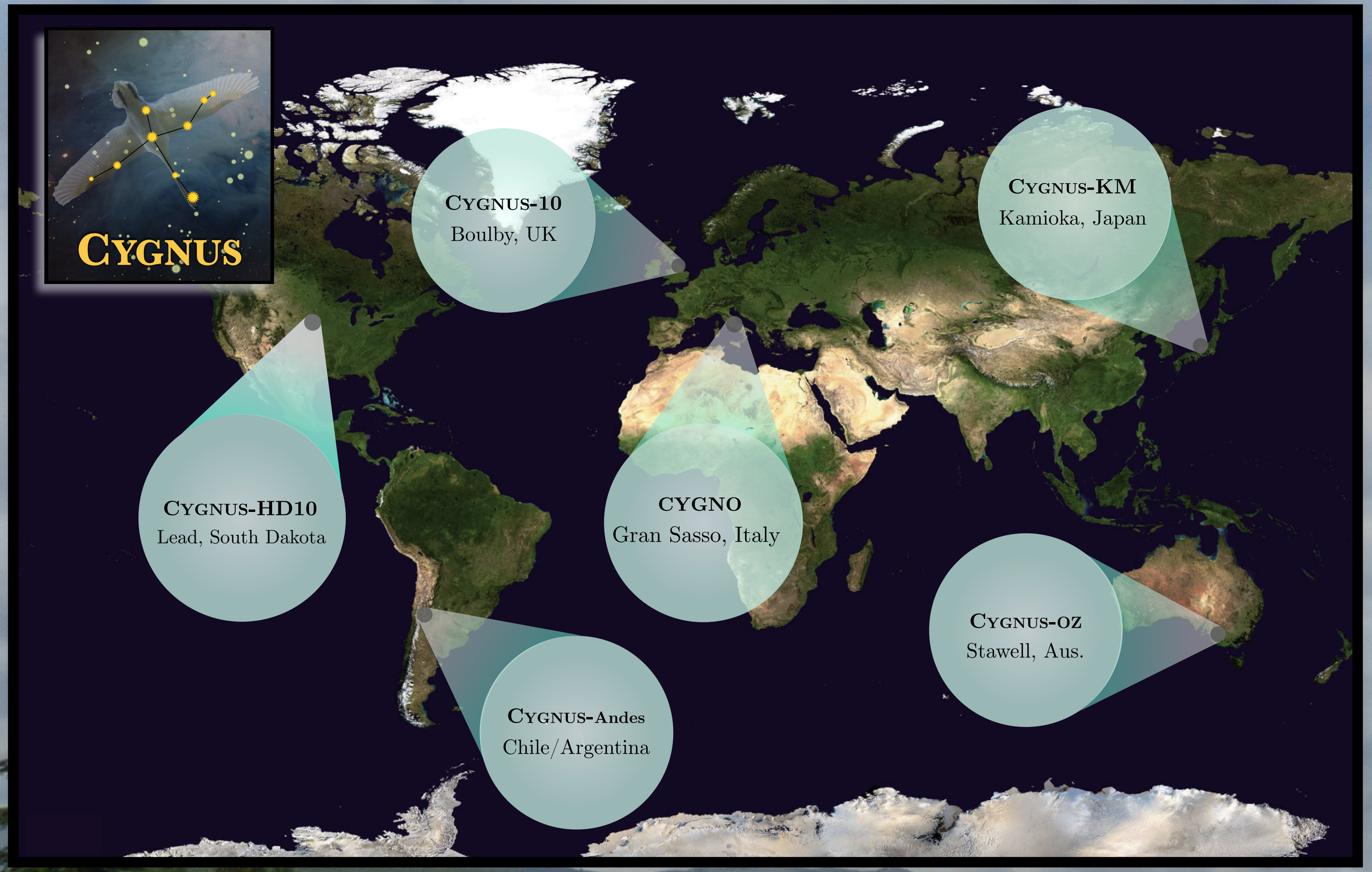
Should see a dipole in dark matter interactions peaking towards the constellation of Cygnus

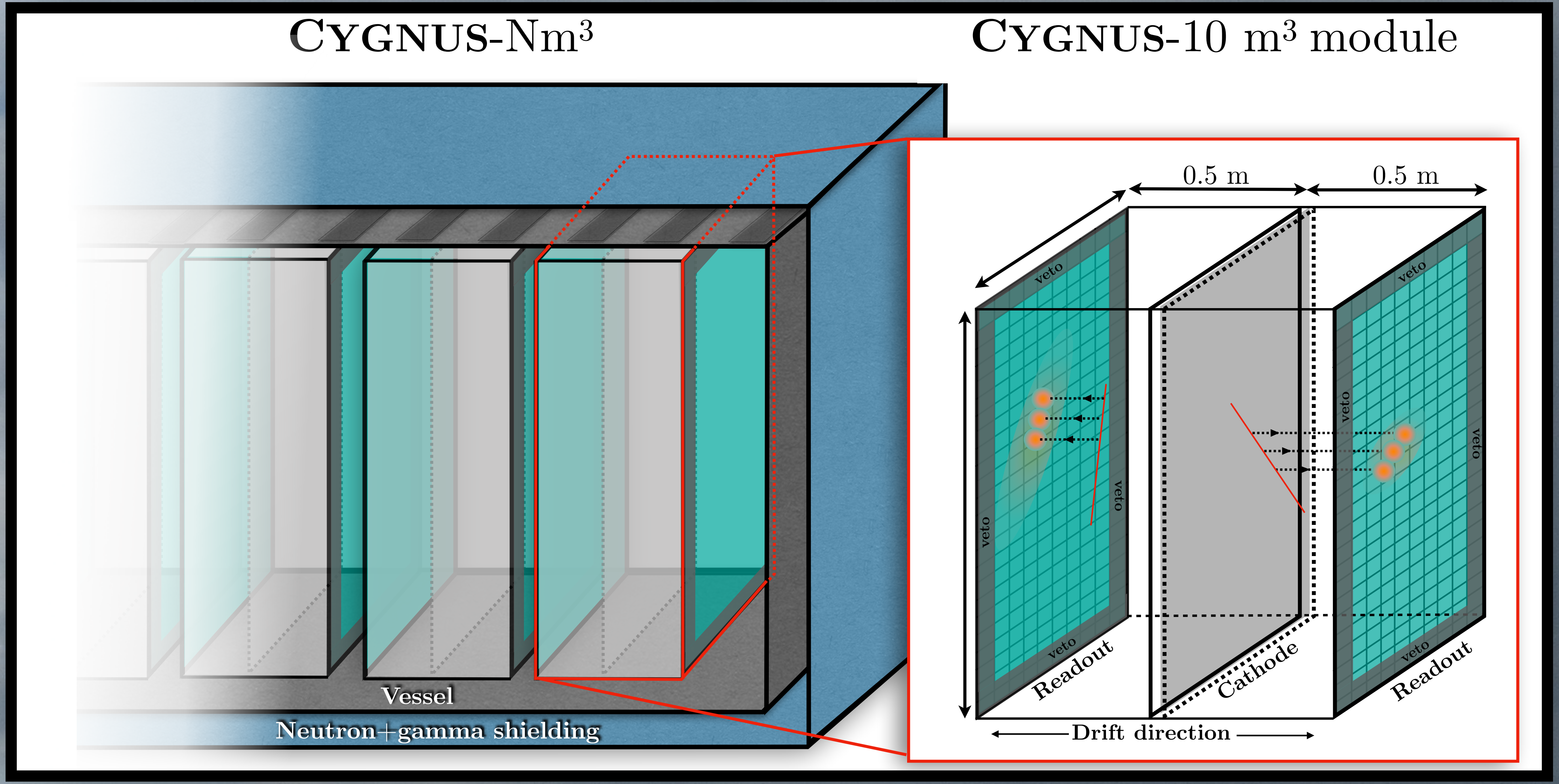


Should see a dipole in dark matter interactions peaking towards the constellation of Cygnus



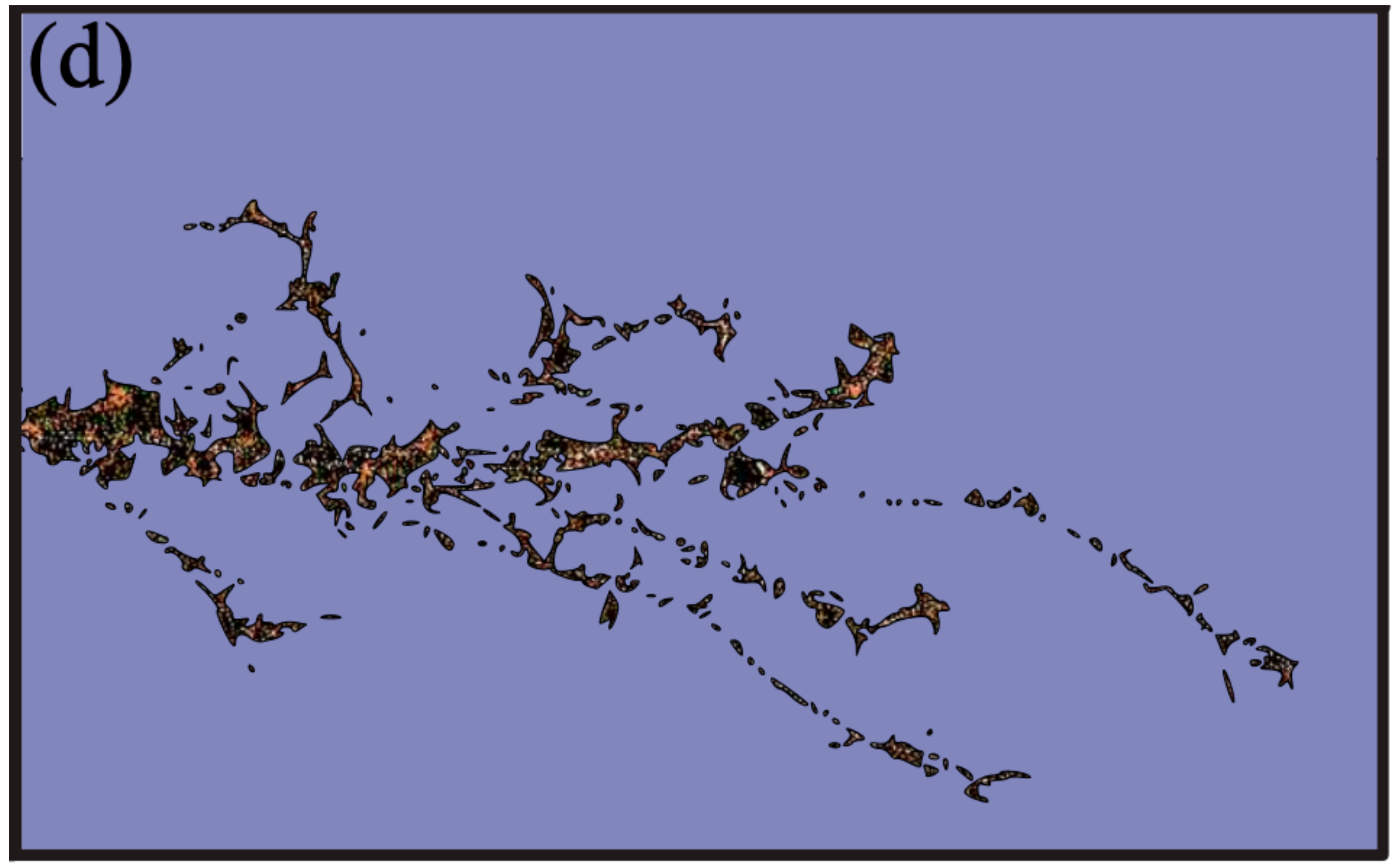
CYGNUS



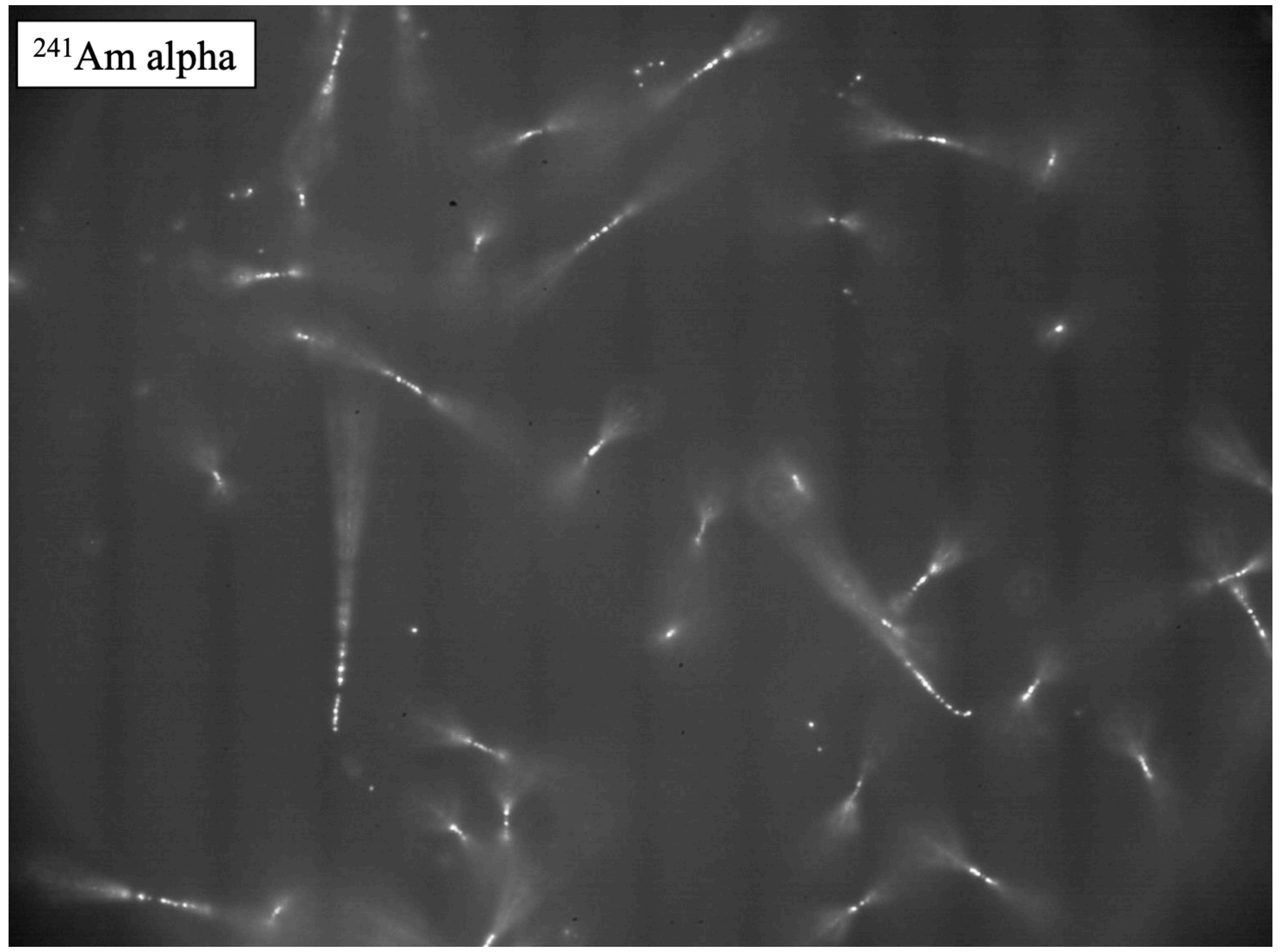


- **Brand new collaboration: >50** members from US, UK, Aus., Japan, Italy, Spain, China
- **Focus**: Towards a world-wide directional dark matter search campaign

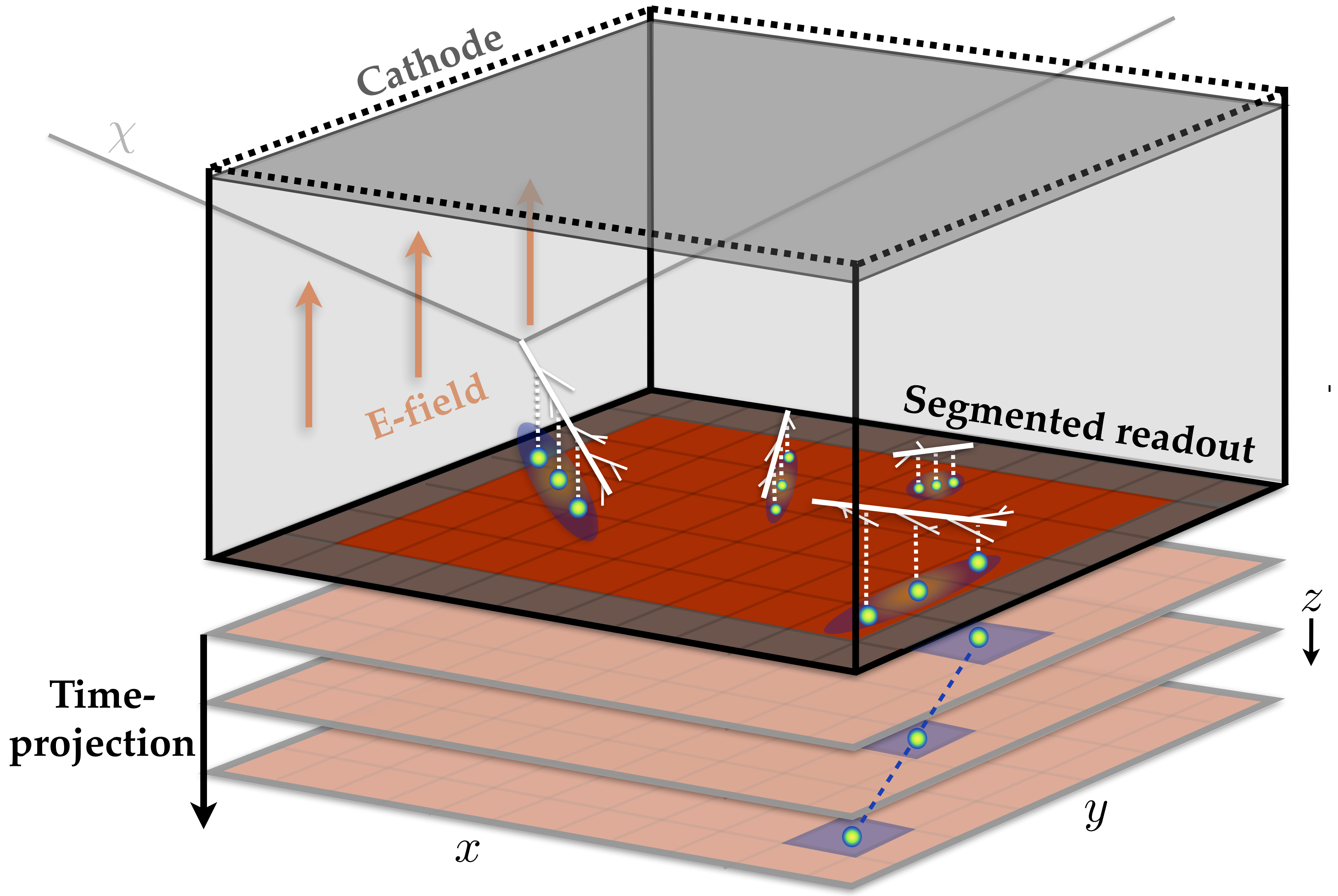
Crystal defect spectroscopy



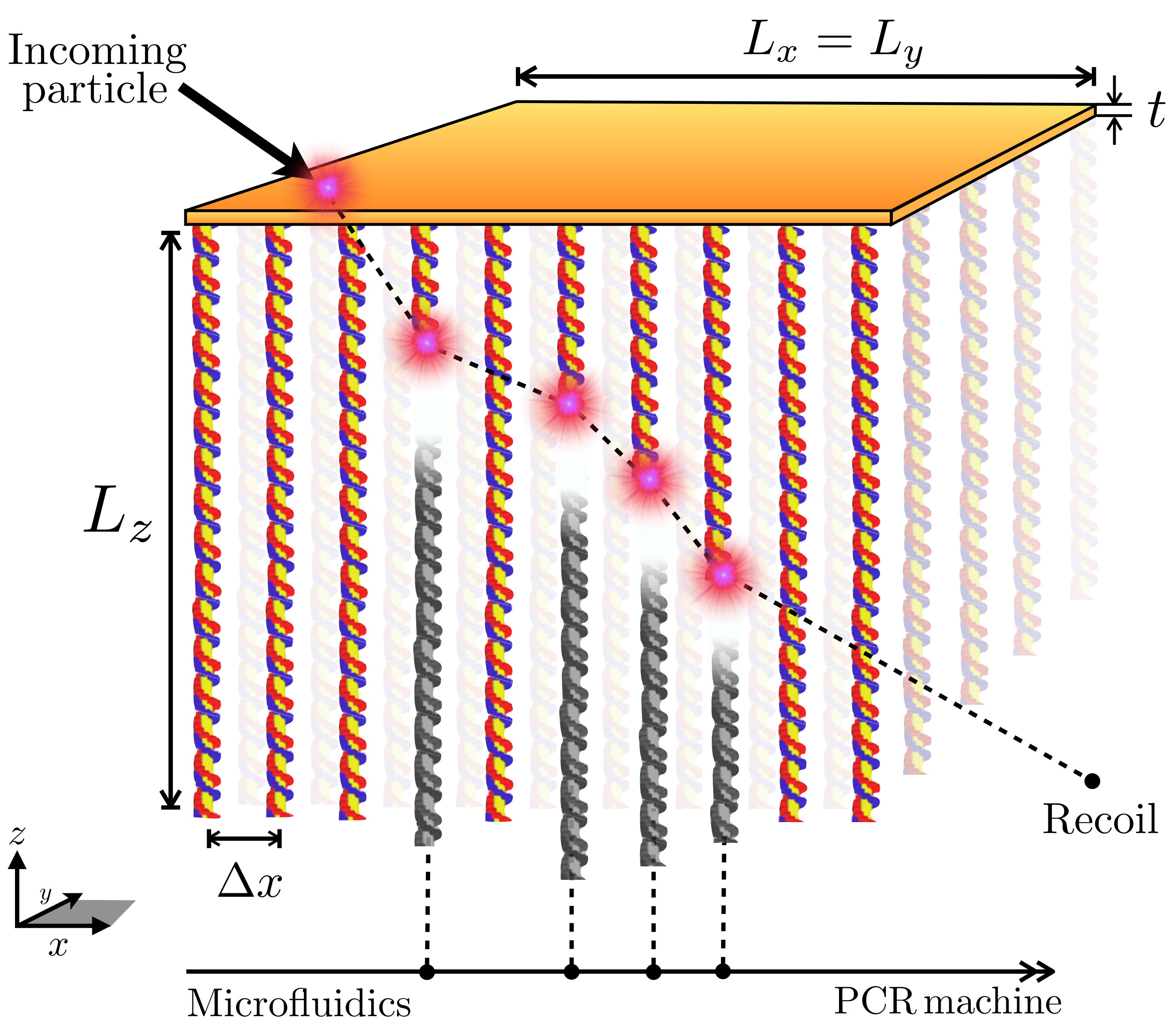
Nuclear Emulsions



Time projection chamber



DNA



Summary

Abundant evidence that the Universe is full of dark matter

We have many good ideas for what it could be and many ways to test those ideas in the laboratory or with astrophysical data

But we are far (>10 years) away from having explored all of our options.
We may get lucky, but potentially have a lot of work ahead…

Many opportunities for undergrad/summer/honours projects at any stage.
Please get in touch if you would like to be involved with research

ciaran.ohare@sydney.edu.au **celine.boehm@sydney.edu.au**

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THE UNIVERSITY OF SYDNEY
Australian Government
Australian Research Council
Sydney CPPC

Moving off the beaten path…

Moving off the beaten path…