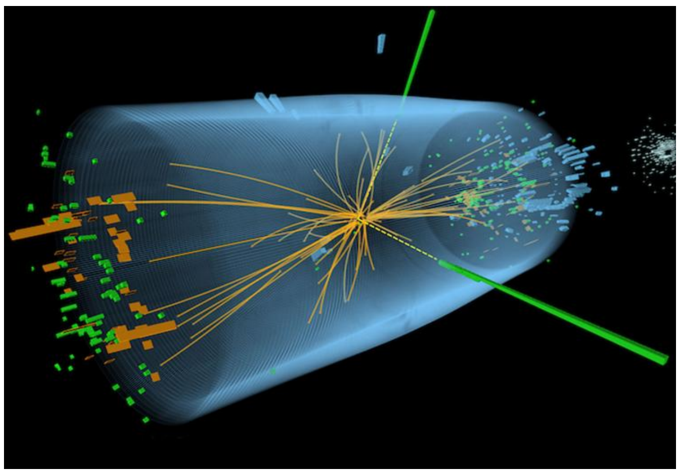
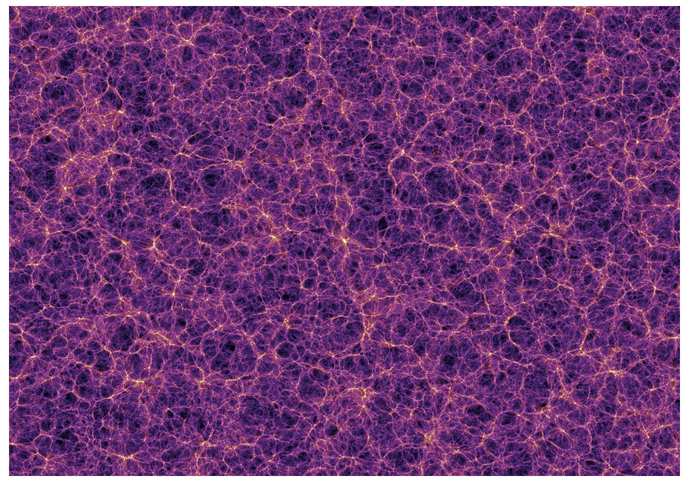
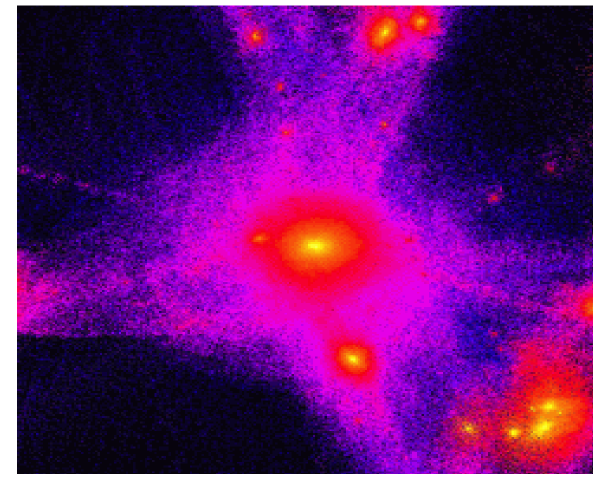
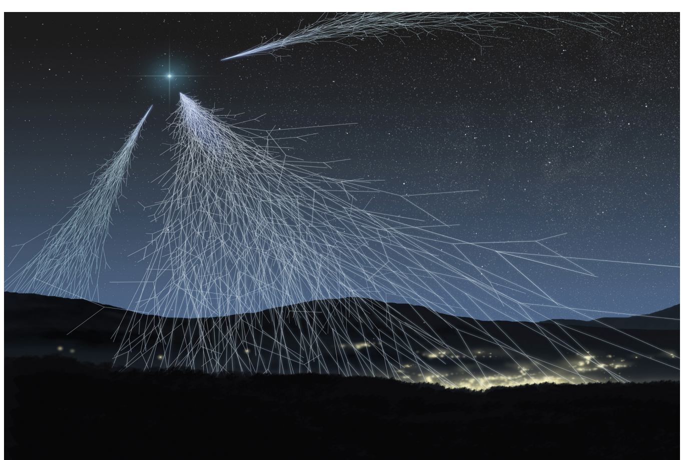
The Dark Side

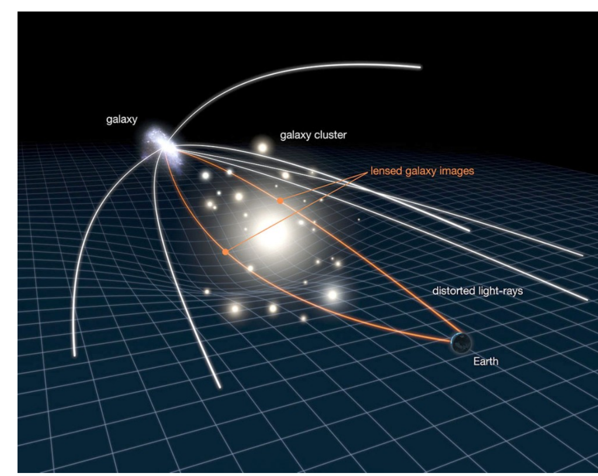
Ciaran O'Hare





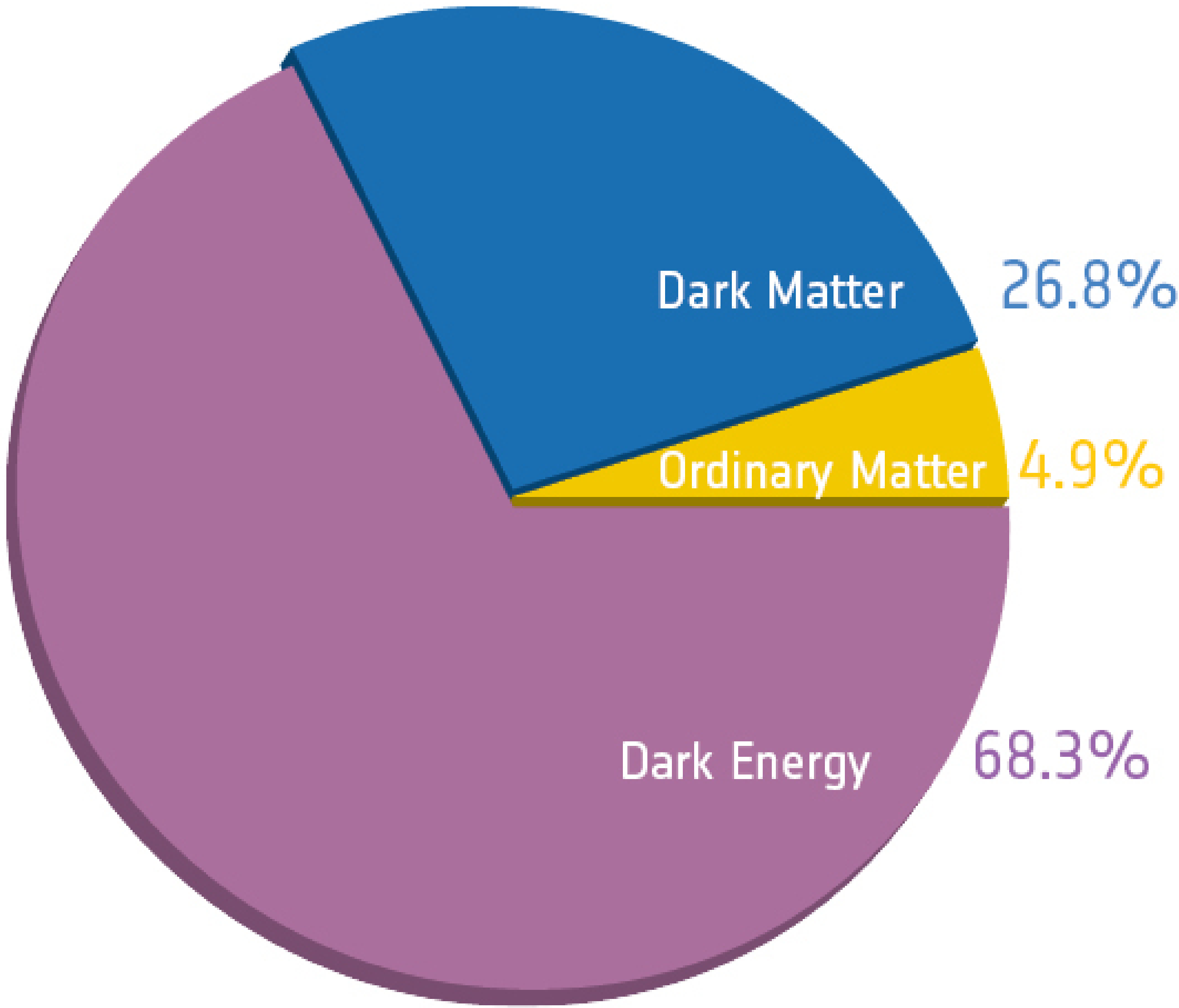






University of Manchester, March 2017

The University of Nottingham



Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%

Part 1: Dark matter

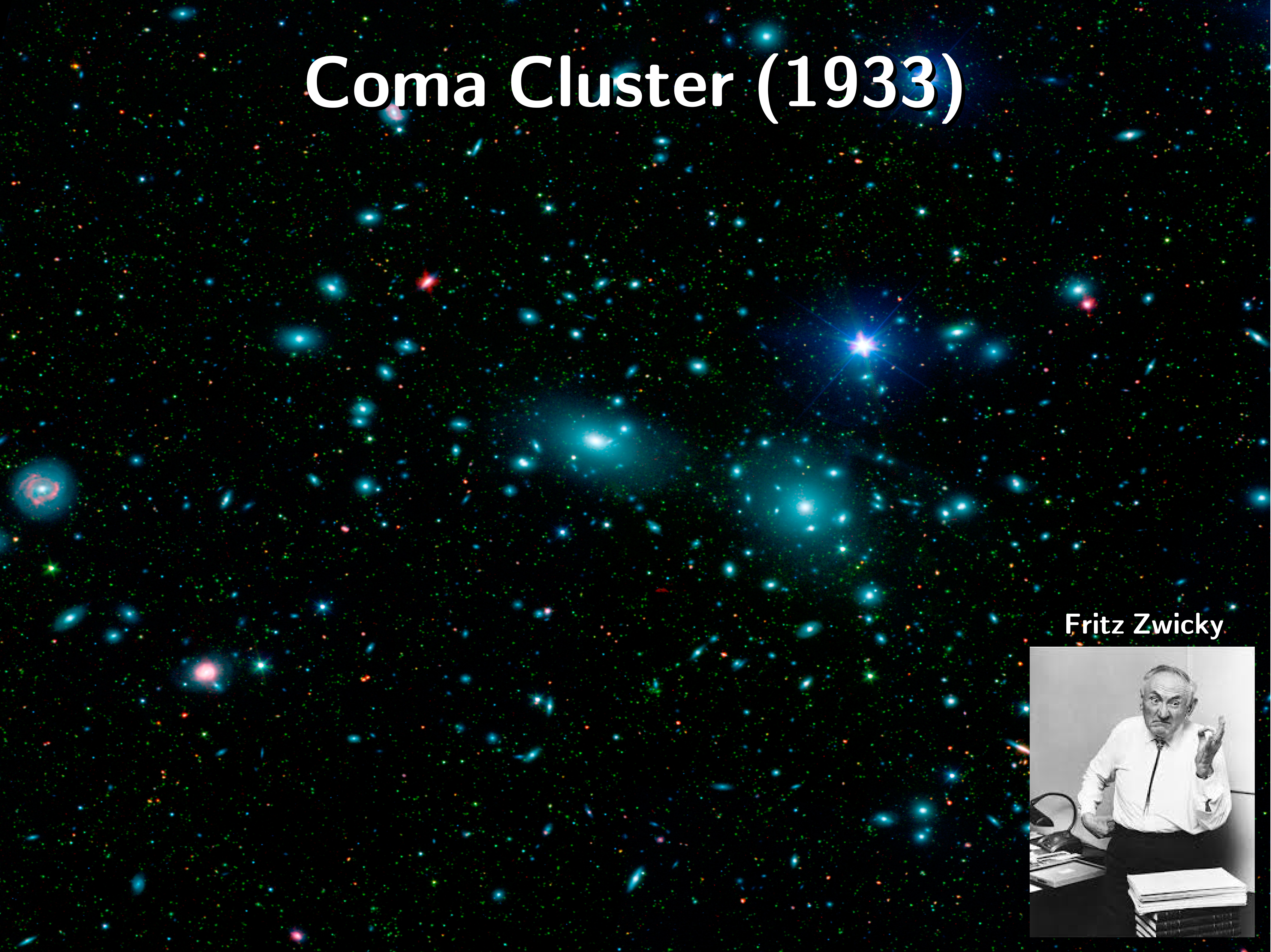
- Why we think it exists
- What we think it is
- How we're going to find out

Part 2: Dark energy

- Why we think it exists
- What we think it is
- How we're going to find out

Part 1: Dark matter

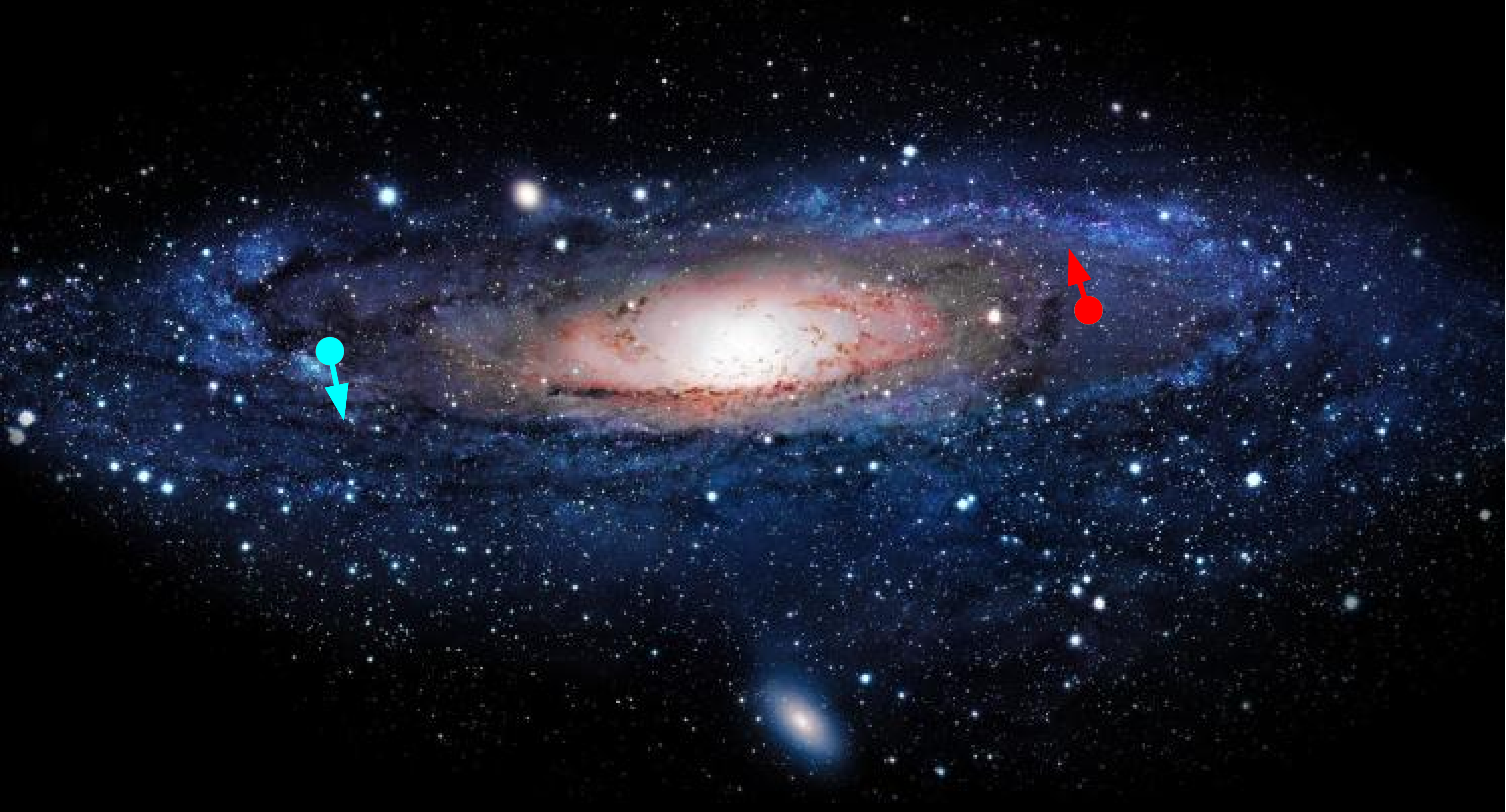
Coma Cluster (1933)



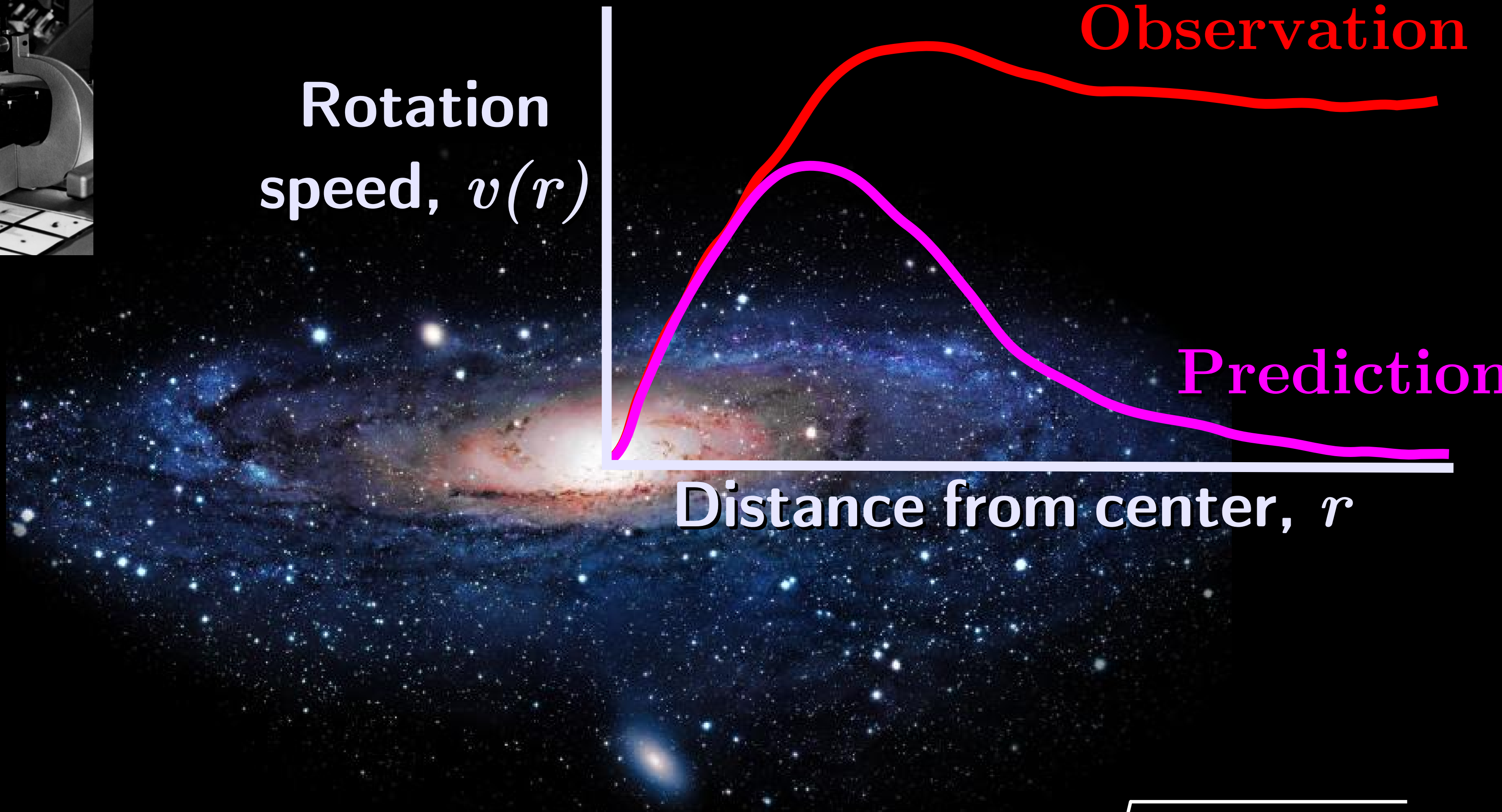
Fritz Zwicky

Blue shifted = coming towards us

Red shifted = moving away from us



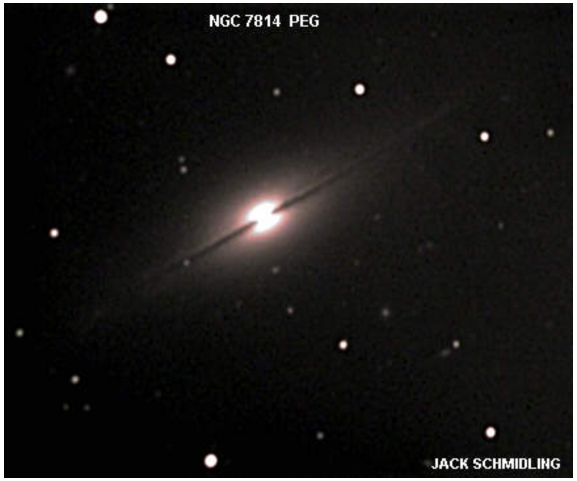
Vera Rubin (1970s)

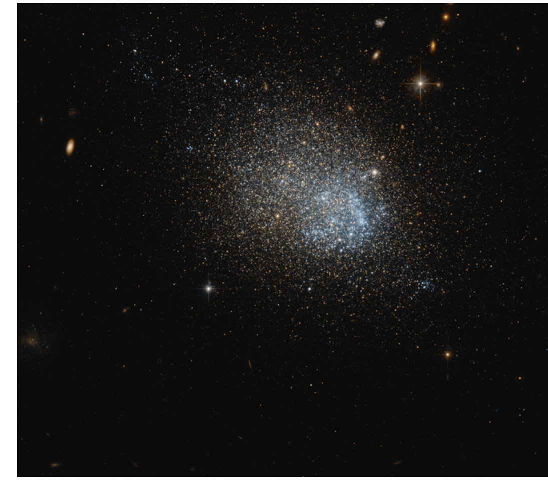


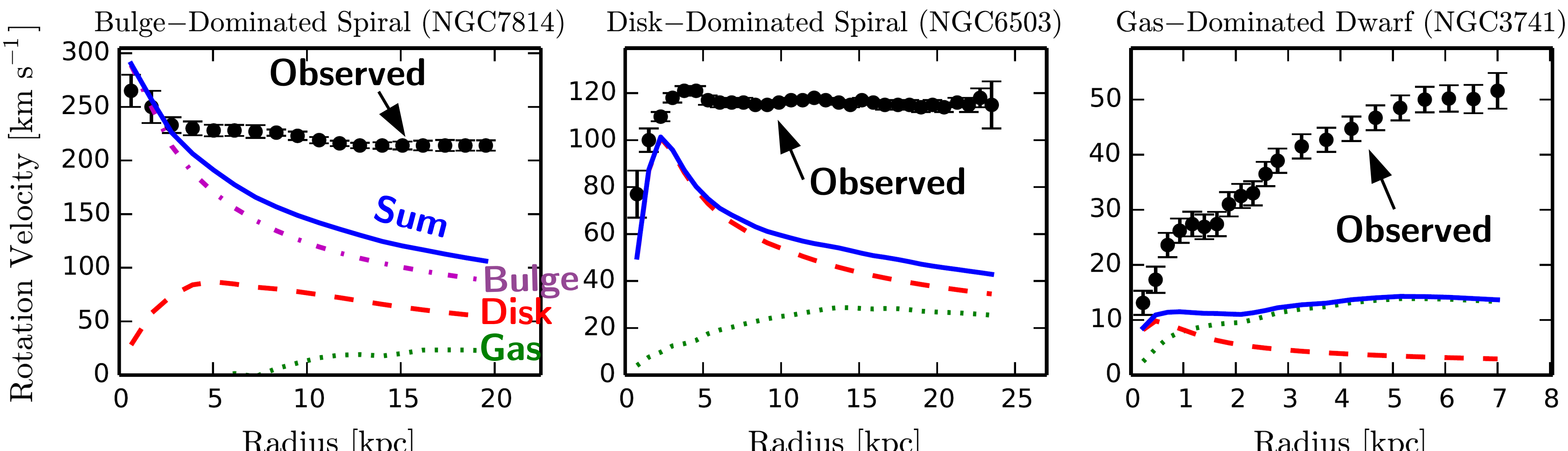
$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2} \longrightarrow v(r) = \sqrt{\frac{GM(r)}{r}}$$

$v(r)$ ~ constant $\longrightarrow$ $M(r)$ increasing?

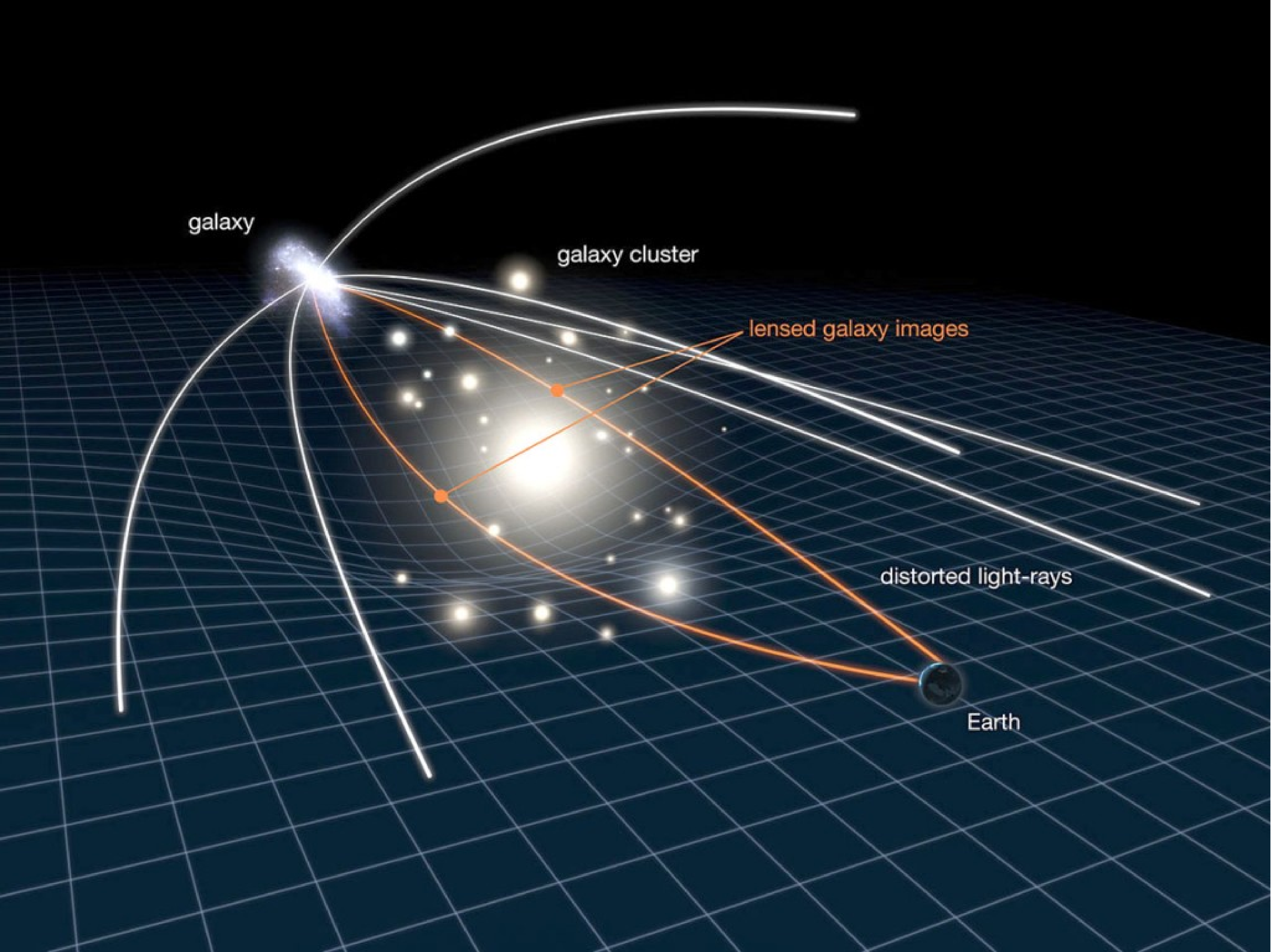
SPARC Catalogue data, McGaugh *et al.* 2016



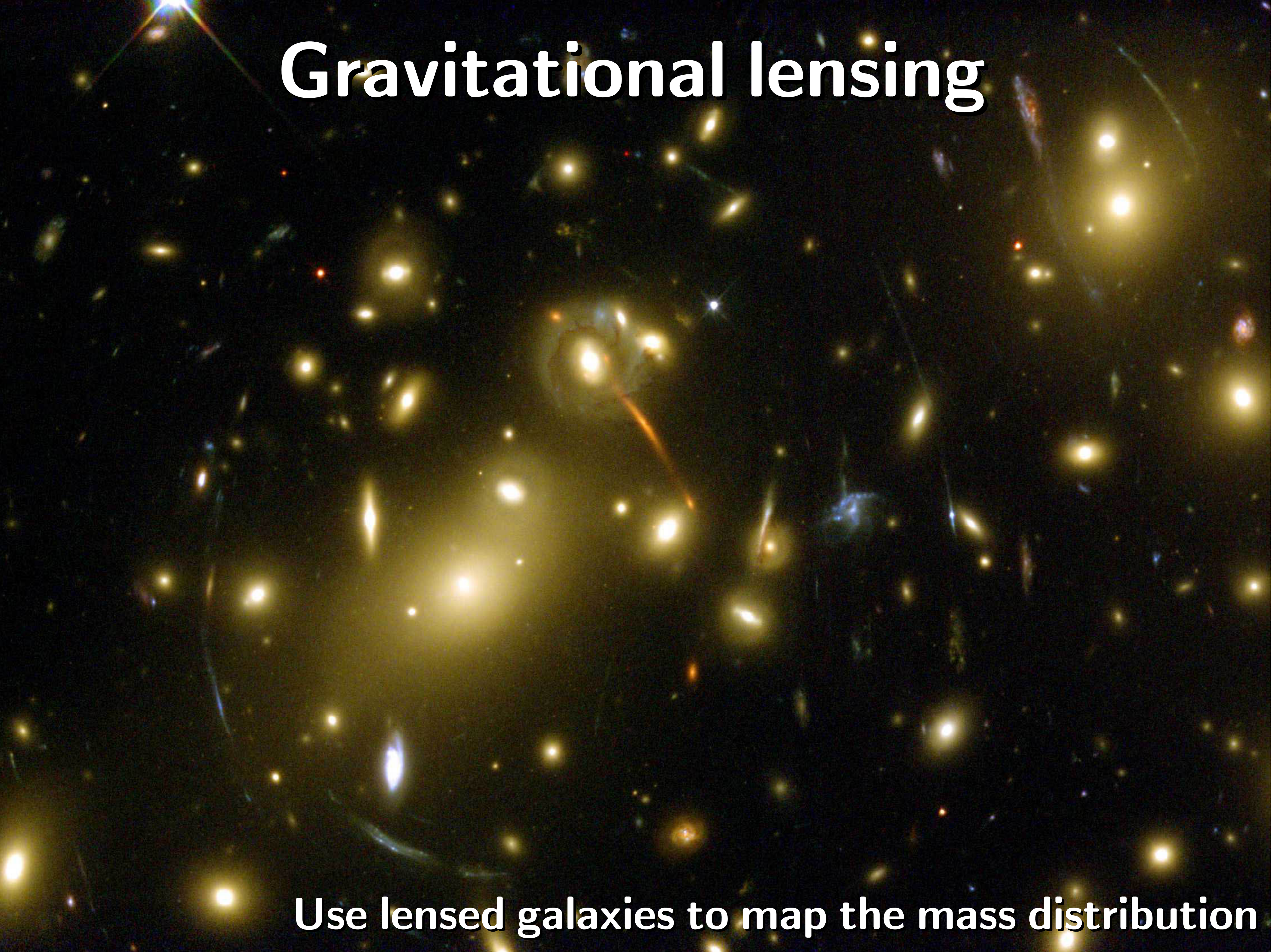




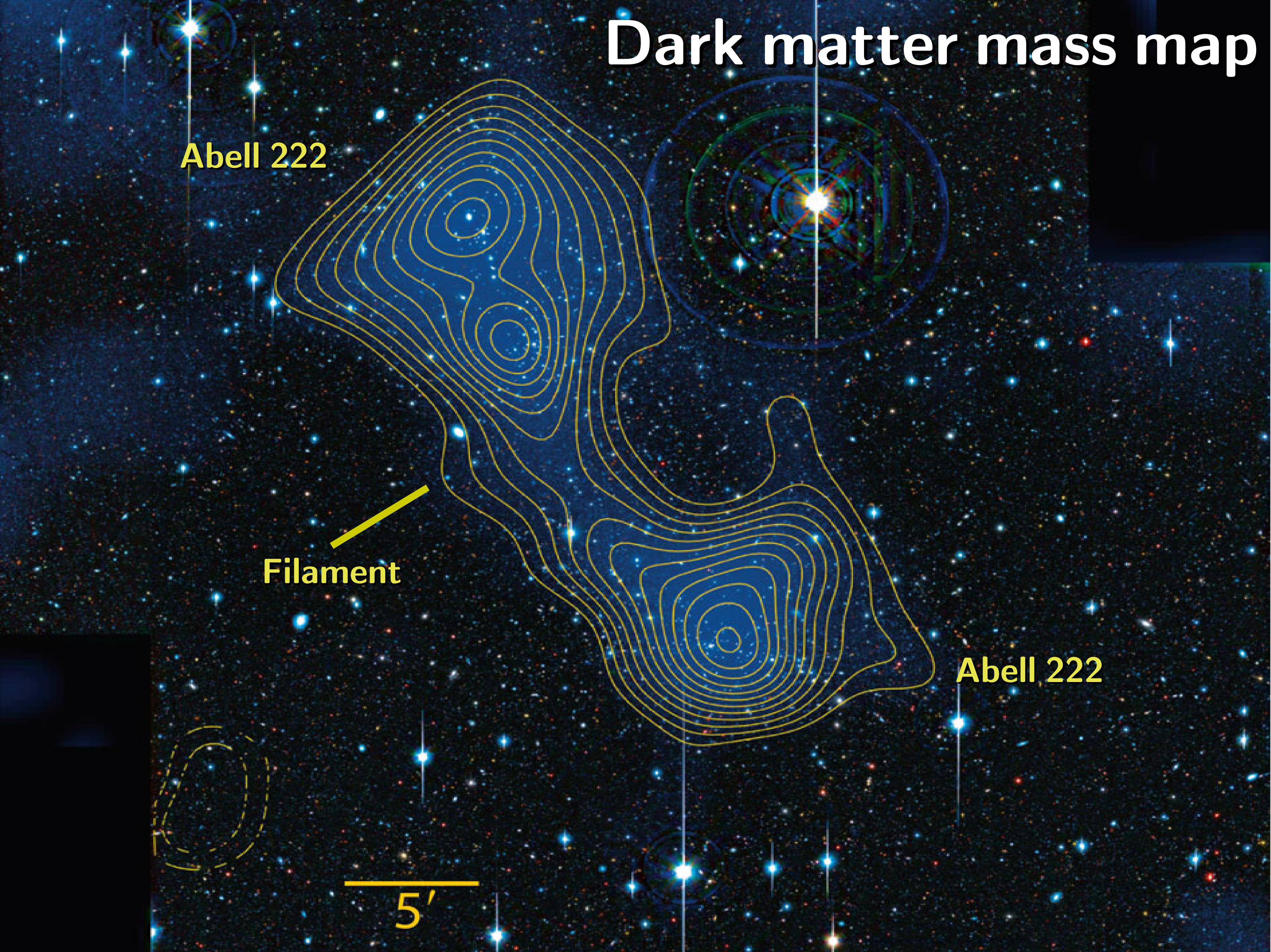
80-90% of galactic mass is invisible

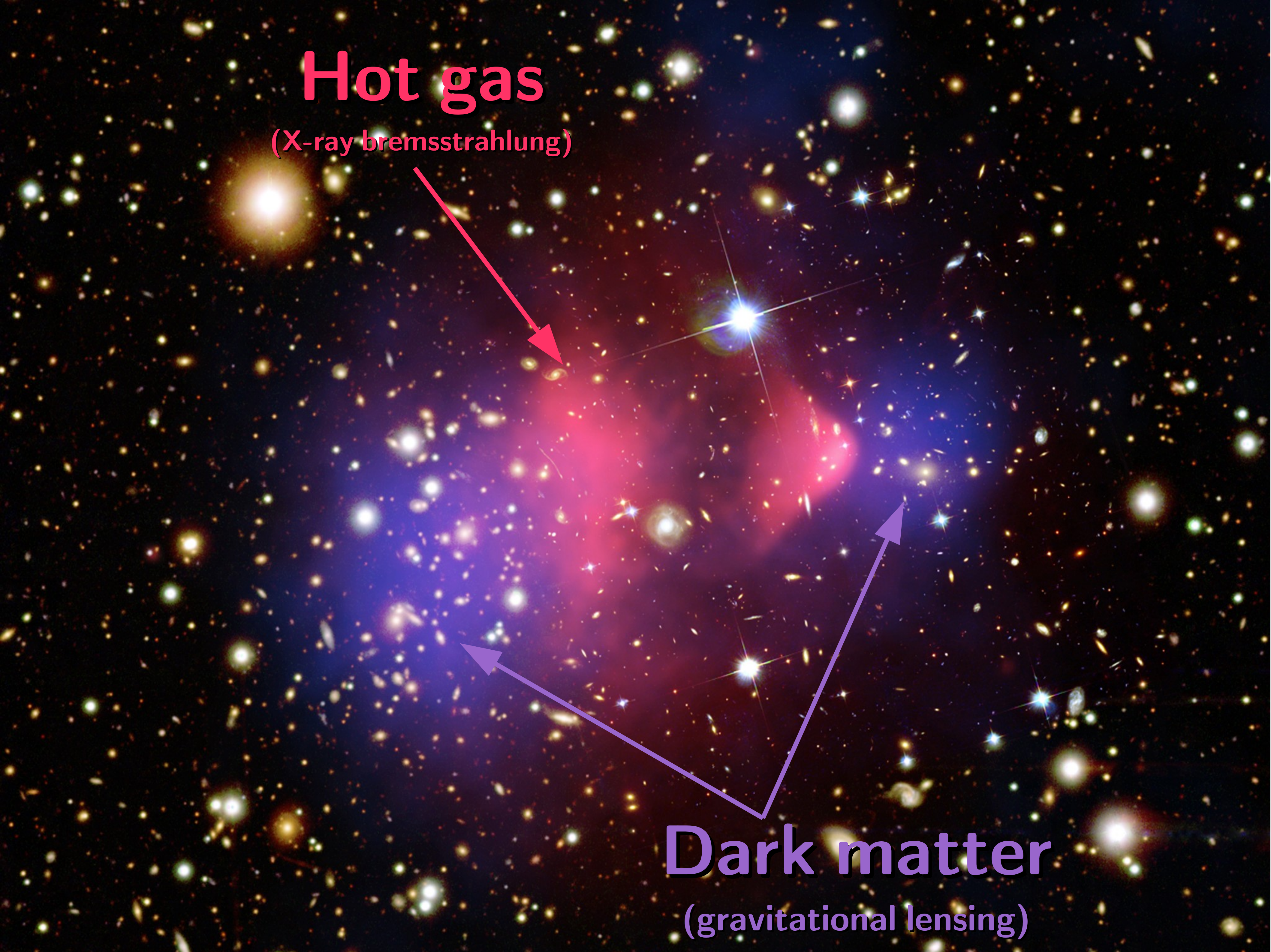

galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

Gravitational lensing

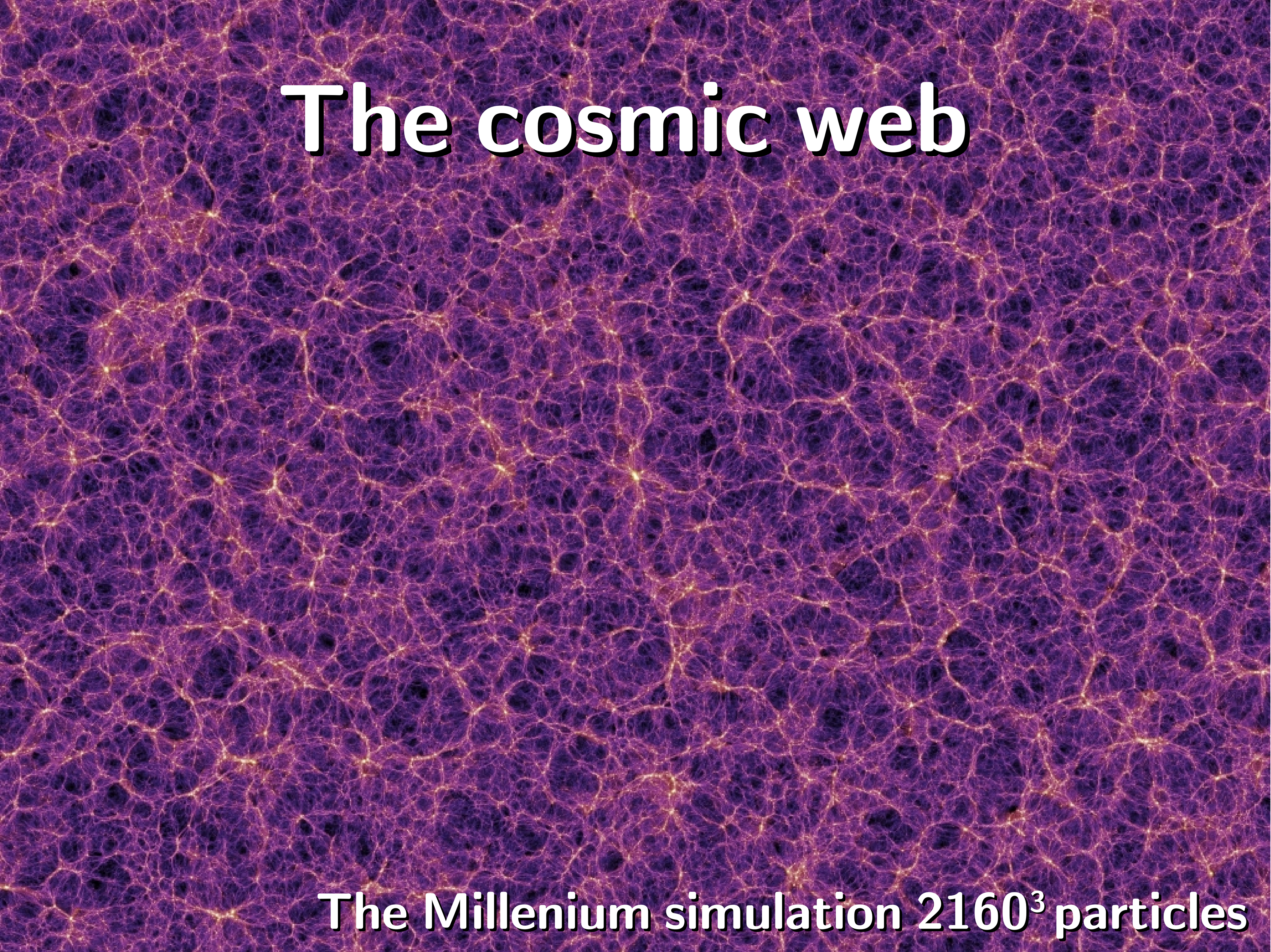


Use lensed galaxies to map the mass distribution


Dark matter mass map
Abell 222
Filament
Abell 222
5′

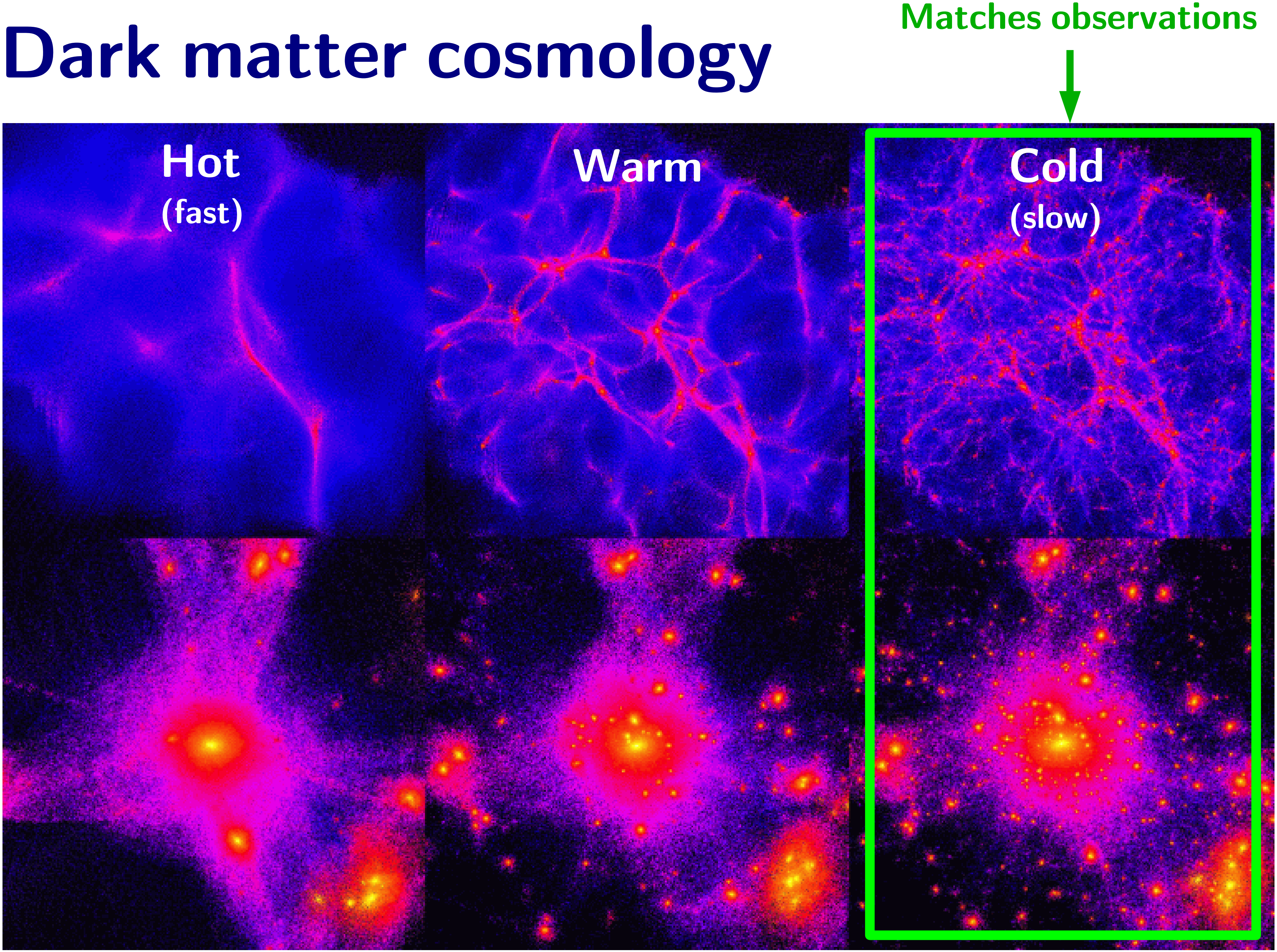

Hot gas
(X-ray bremsstrahlung)
Dark matter
(gravitational lensing)

The cosmic web



The Millenium simulation 2160^3 particles

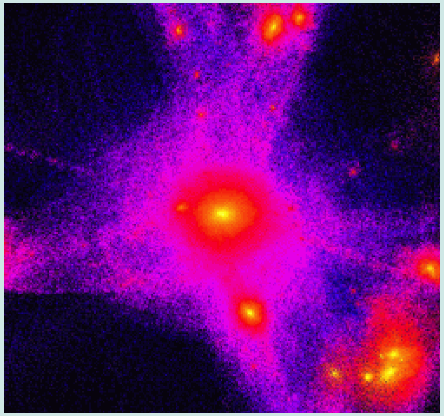
Dark matter cosmology



Dark matter seems to be particles, what do we know about it already?

- Massive
- Stable
- Invisible
- Cold

What out there has these properties:

Dust	✓ Massive ✓ Stable ✗ Invisible ✓ Cold		Absorbs starlight (and glows in the infra-red)
Small objects (planets, brown dwarfs, asteroids)	✓ Massive ✓ Stable ✓ Invisible ✓ Cold		Good DM candidate... (but nowhere near enough of them)
Neutrinos	✓ Massive ✓ Stable ✓ Invisible ✗ Cold		Too hot! Don't form enough galaxies

Nothing we know about has these properties

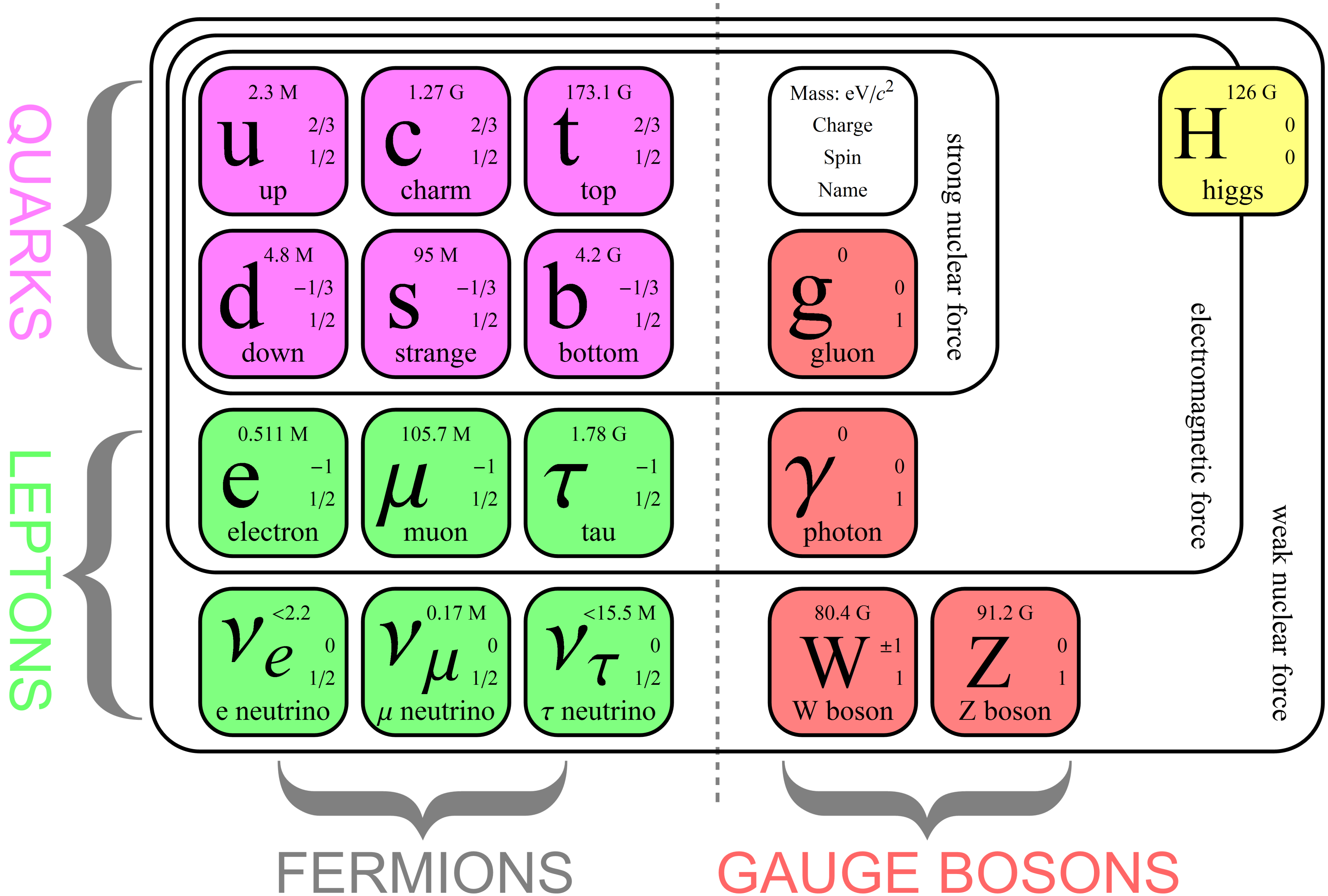
- Massive
- Stable
- Invisible
- Cold

→ Dark matter must be exotic

The standard model

Dark matter must be exotic, but what is exotic?

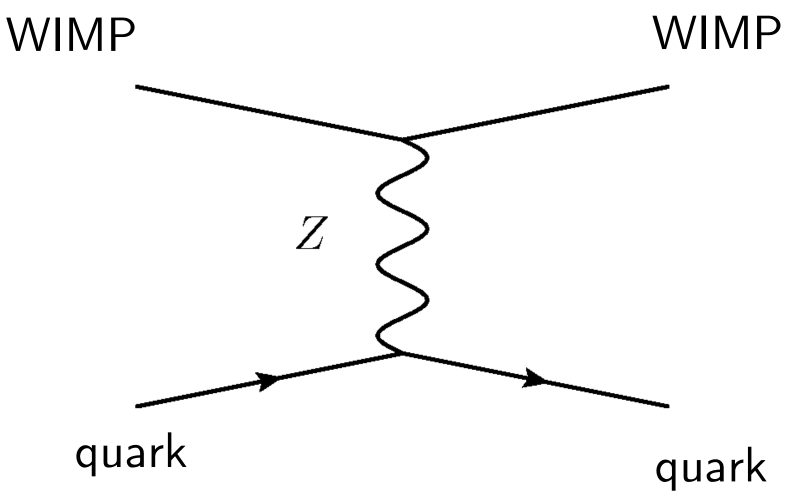
It's none of these...



WIMPs

Weakly Interacting Massive Particles

- Massive
- Stable
- Invisible
- Cold
- Interact via the Weak force



→ Nice, simple, *testable* assumption

→ Show up in supersymmetry and string theory

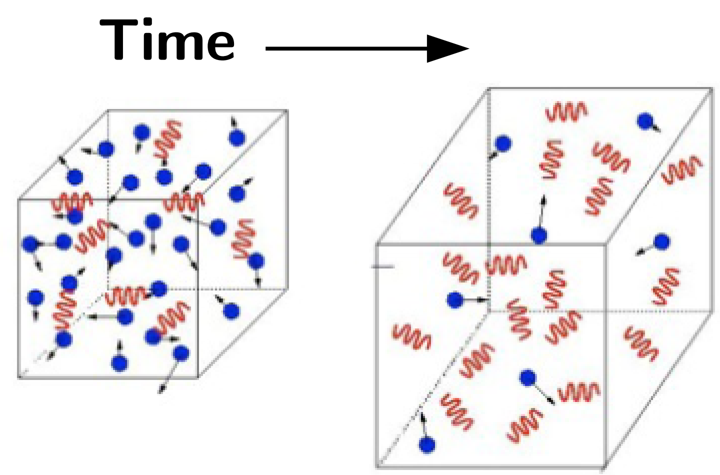
Weakly Interacting Massive Particles

- They are their own anti-particle
- They annihilate each other if density is high enough
- "freeze out" soon after the Big Bang

WIMPs

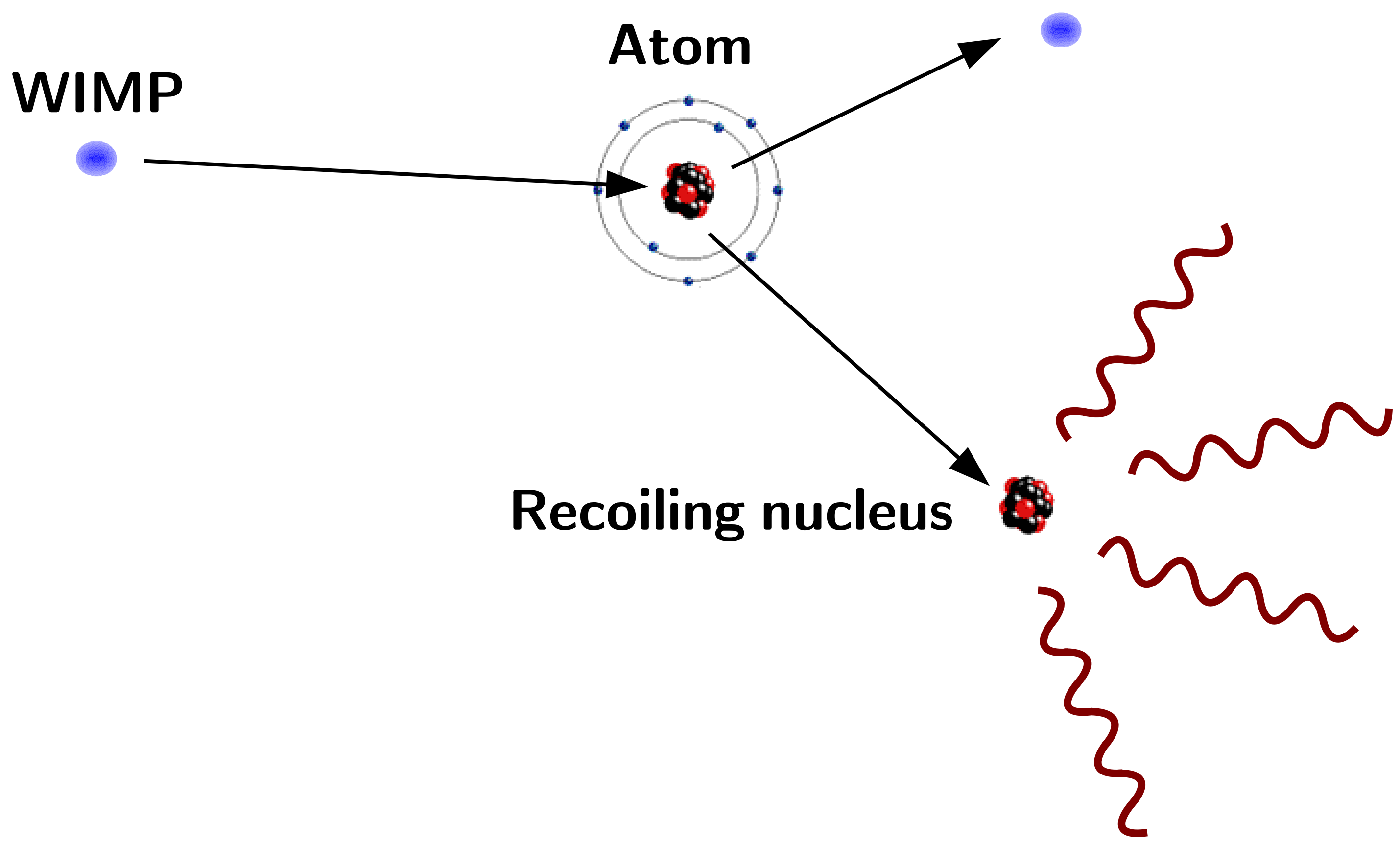
$$\chi + \chi \leftrightarrow X + \bar{X}$$

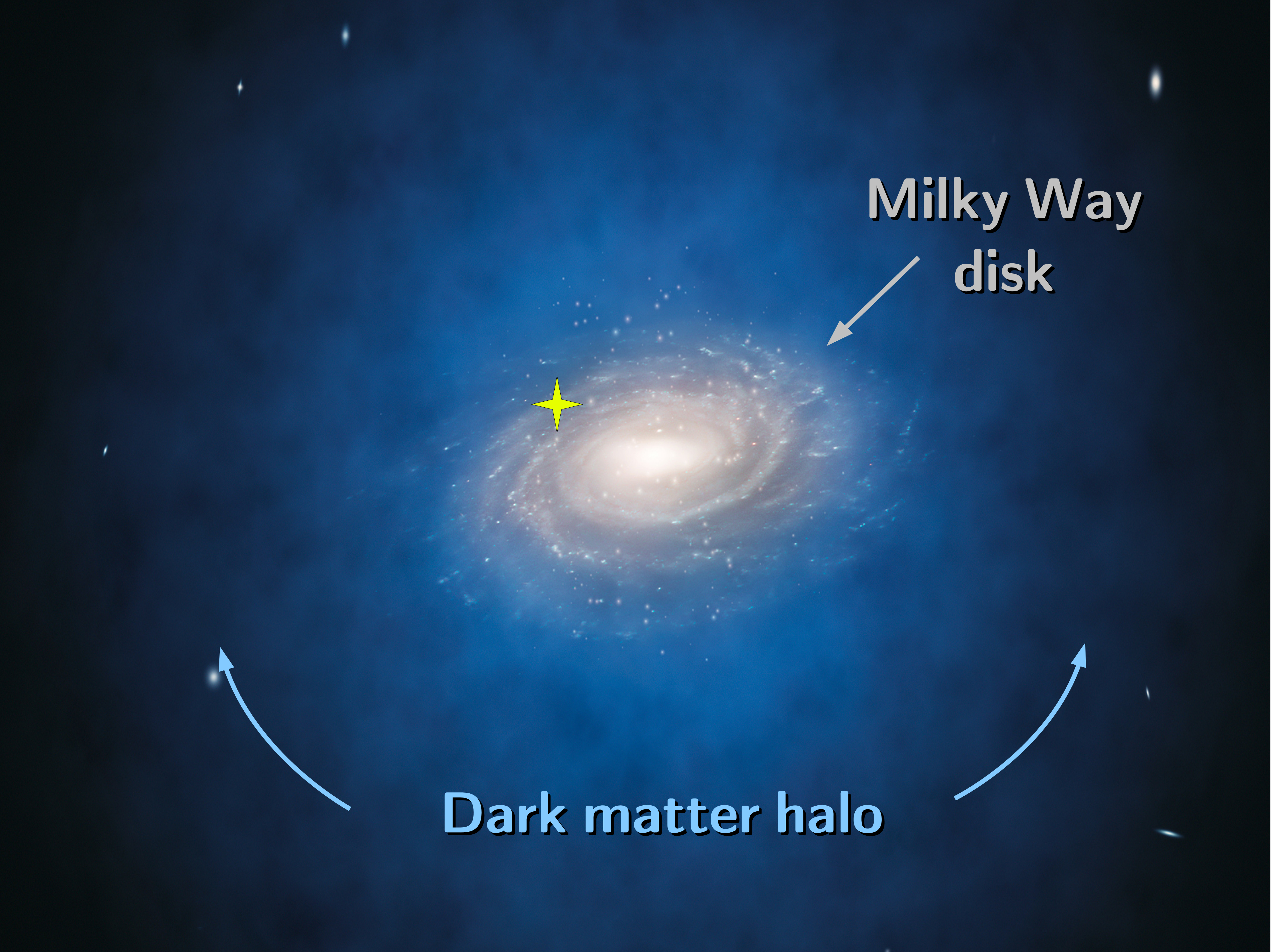
Standard model particles



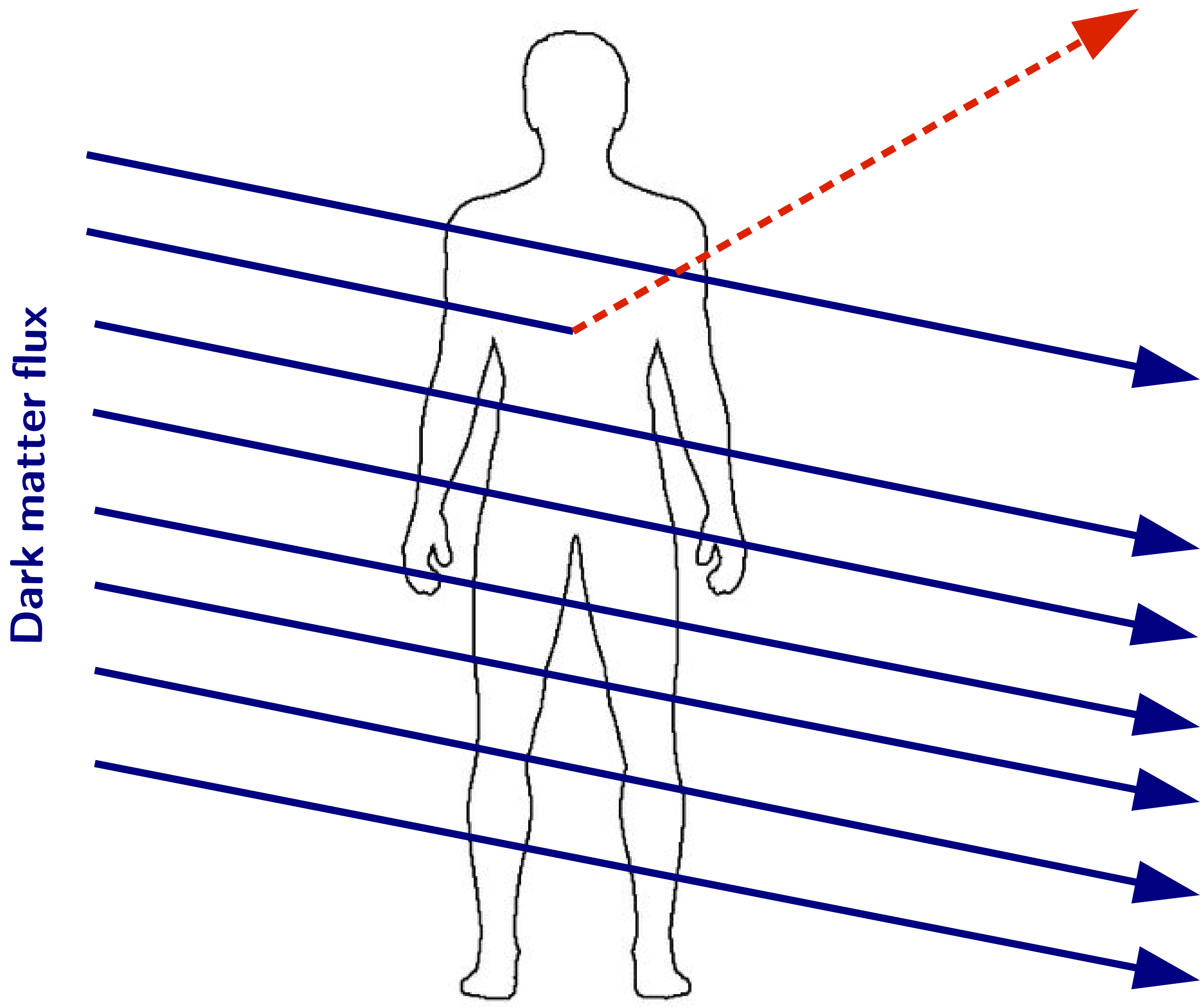
Calculated freeze out density matches observed value!

Can we detect these interactions?



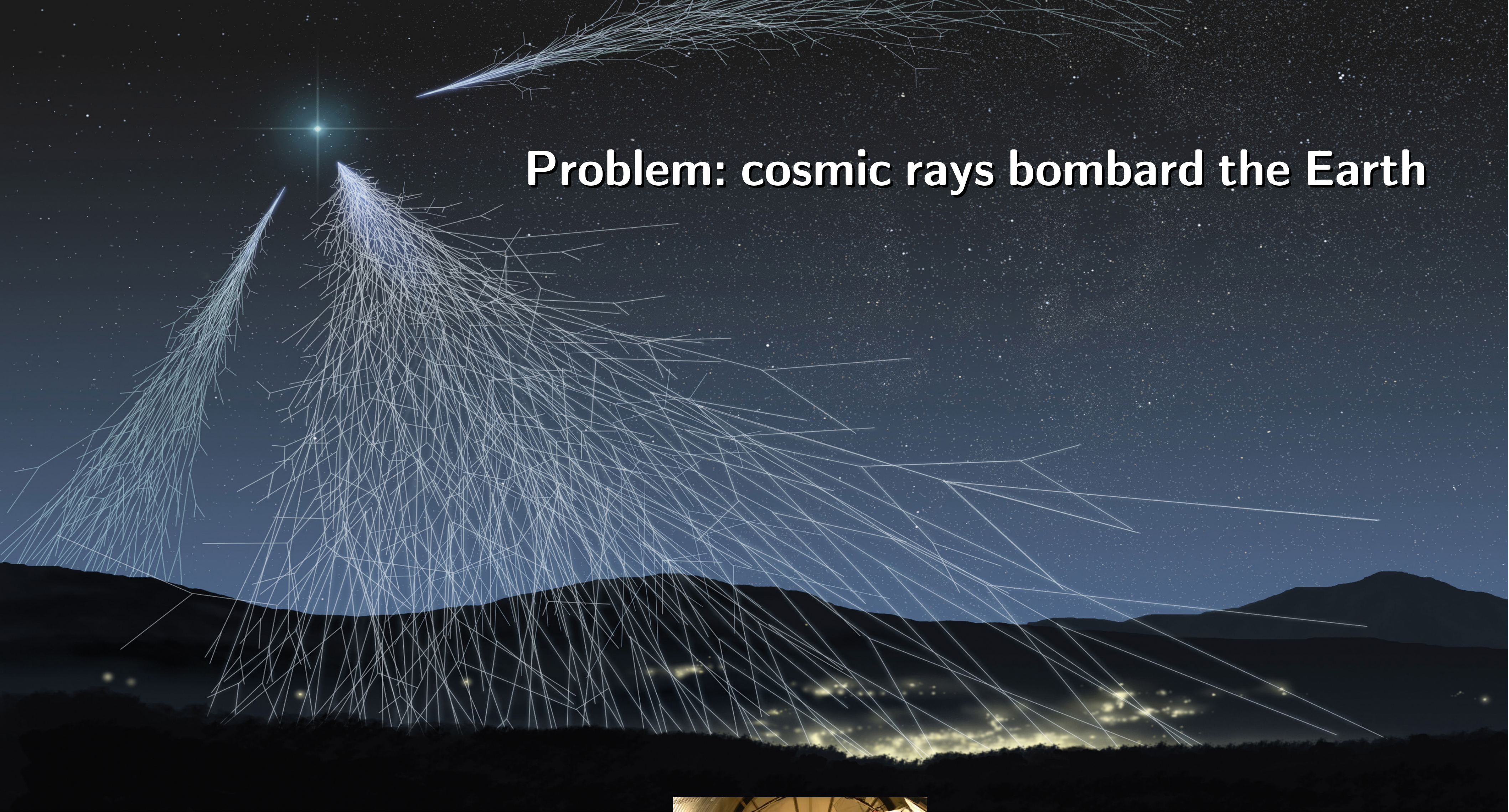

Milky Way
disk
Dark matter halo

Thousands of dark matter particles fly through your body every ***second***



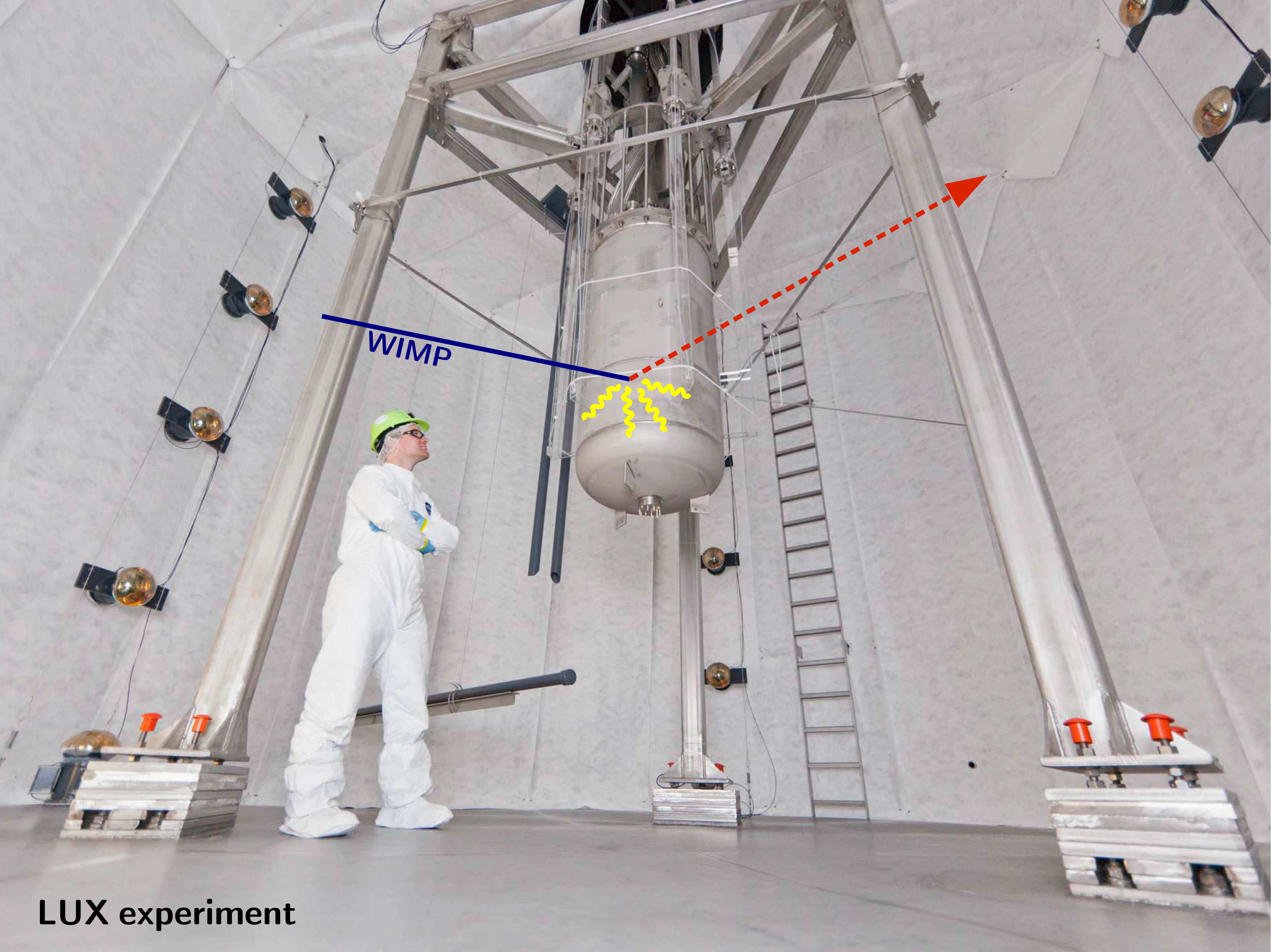
Interactions are extremely rare

→ expect only a couple per ***year***



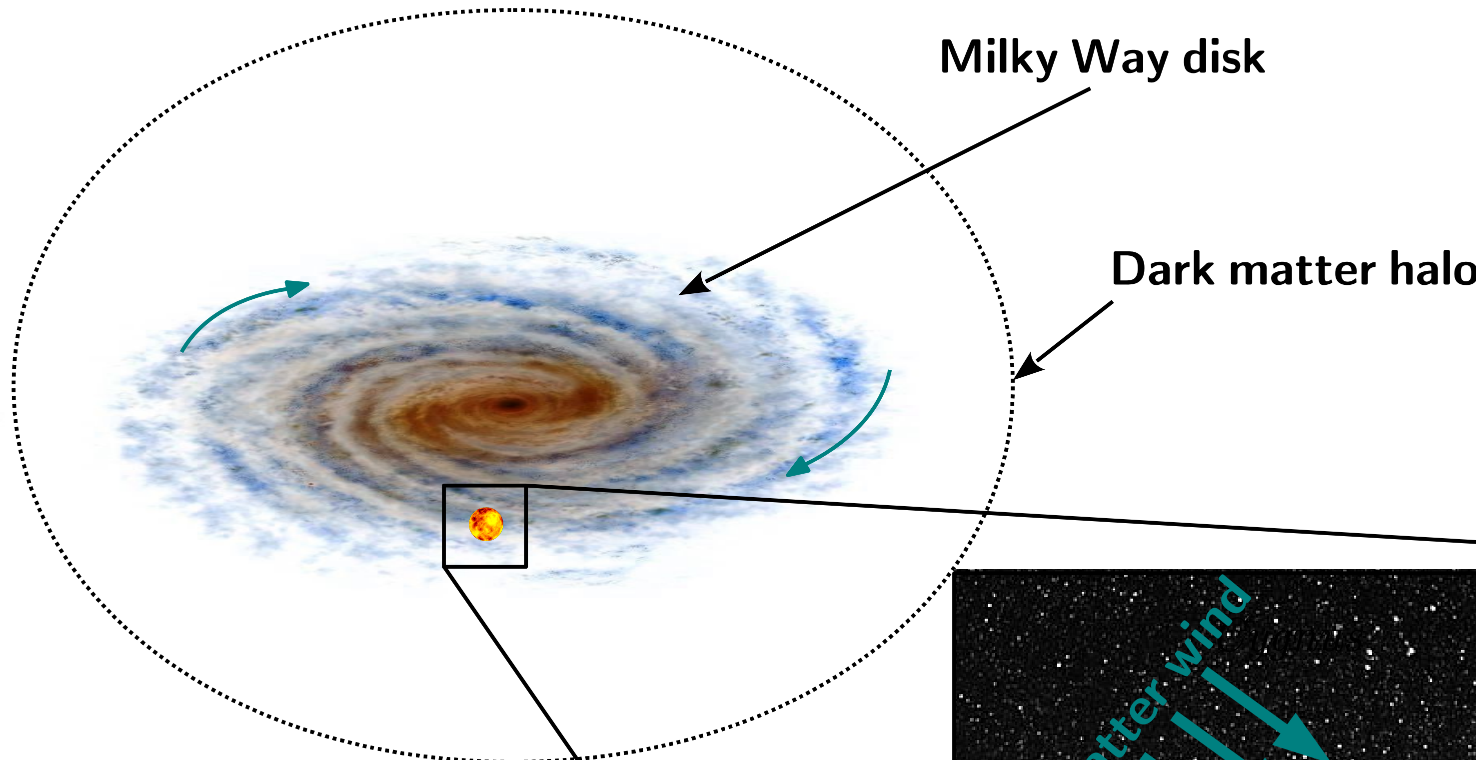
Problem: cosmic rays bombard the Earth

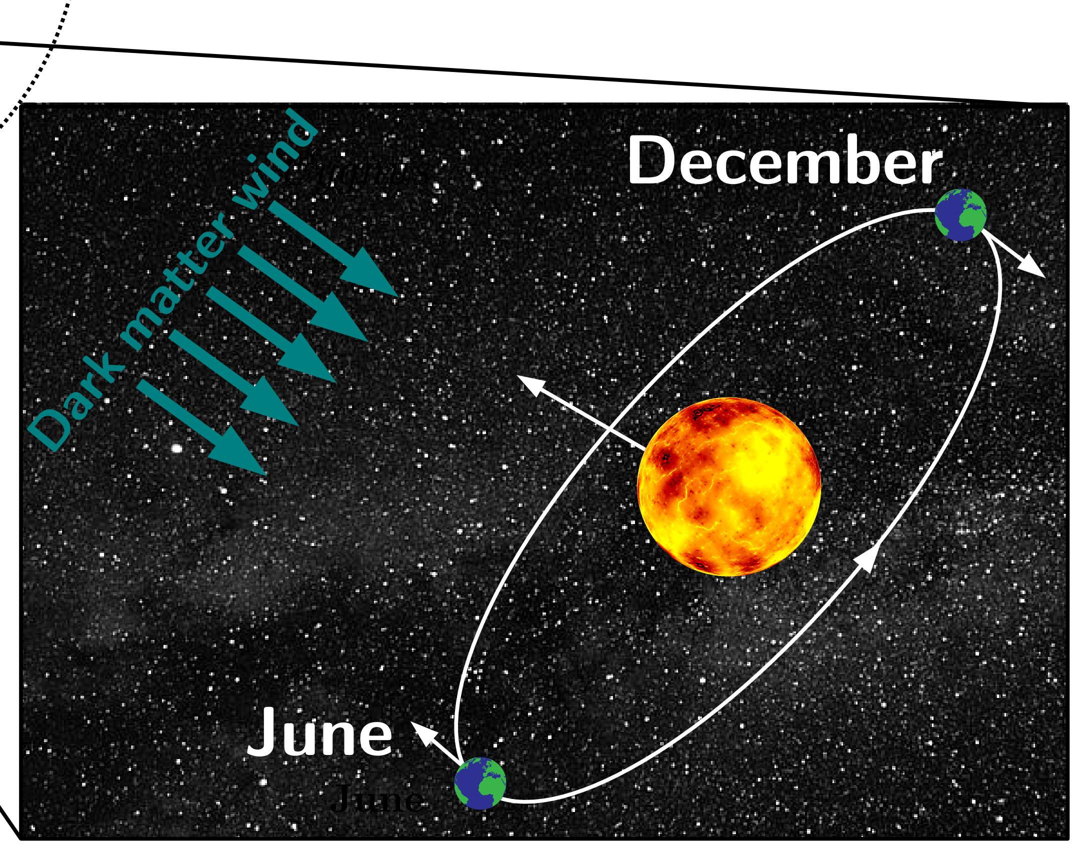
Solution: build detectors underground



LUX experiment

Annual modulation



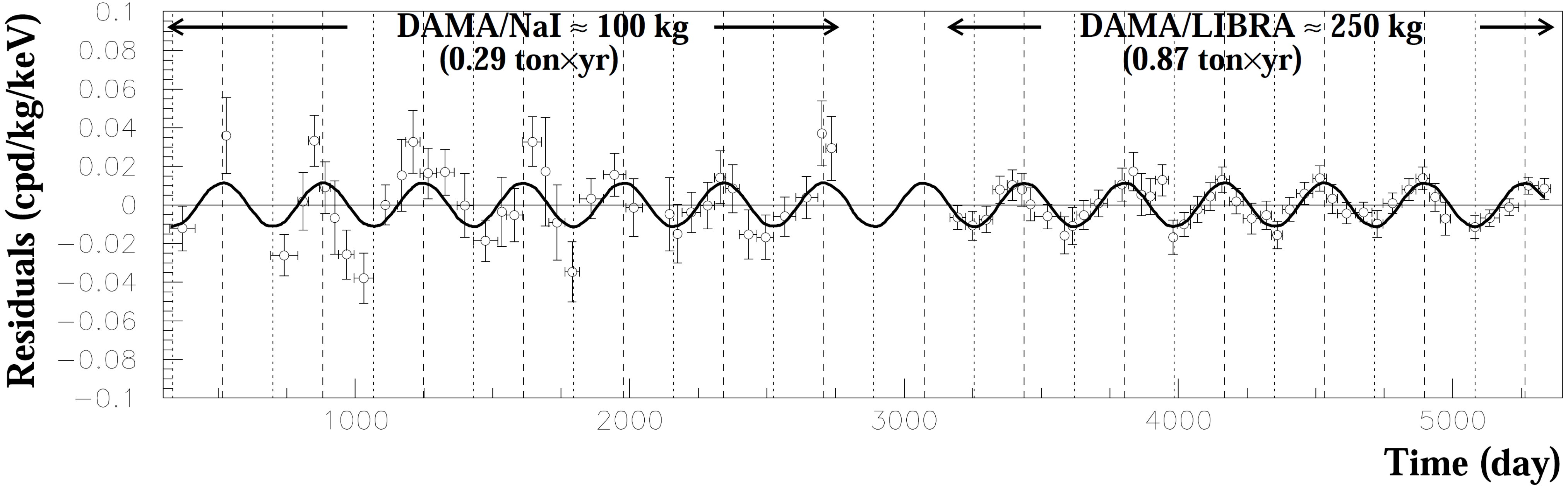


- **Expect to see more events in June and fewer in December → “*smoking gun*” for dark matter**

DAMA/LIBRA Experiment

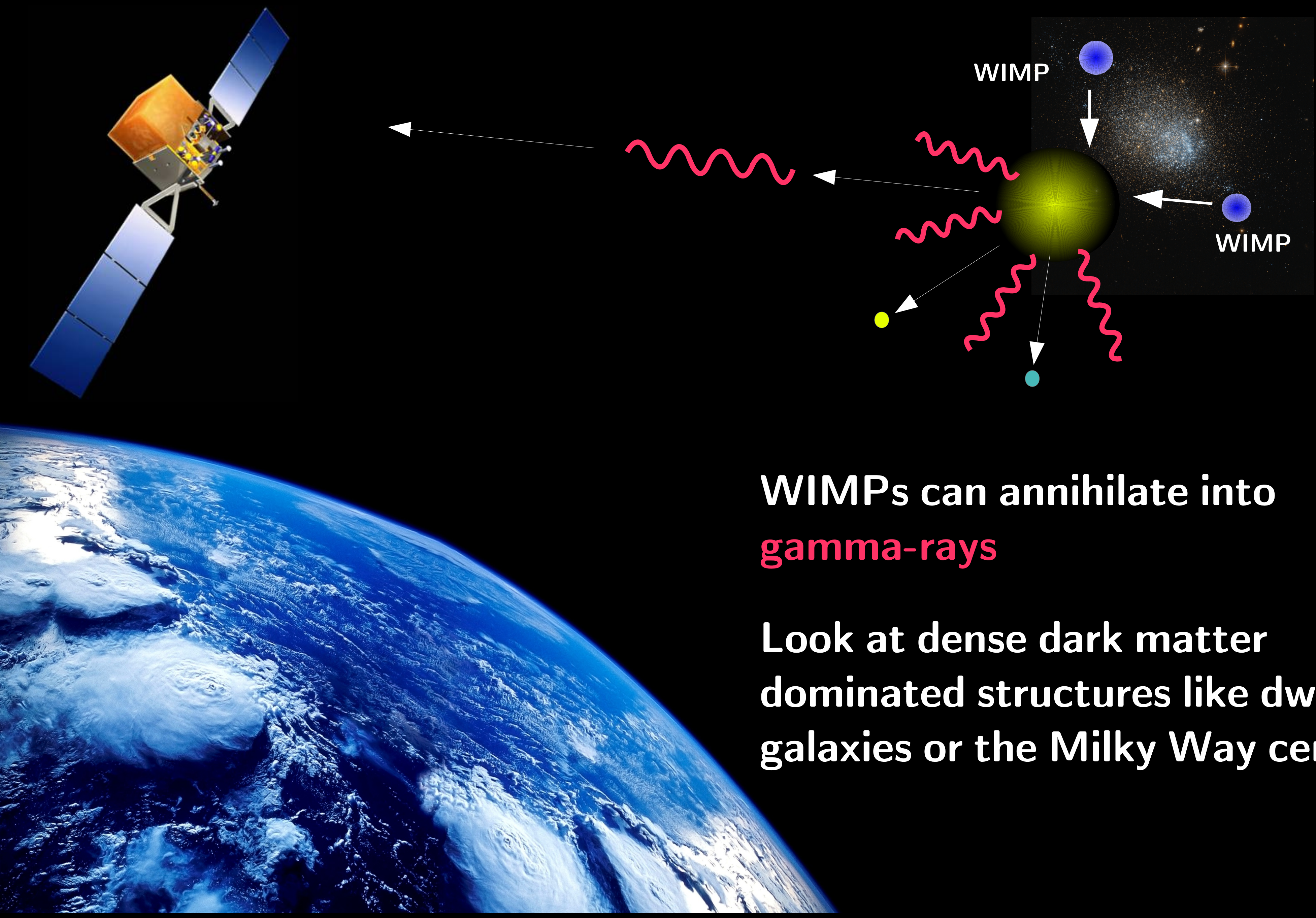
- The DAMA/LIBRA experiment report a 9.6σ annual modulation over 12 years of data consistent with the detection of dark matter

Count rate



- Signal corresponds to WIMP models already **ruled out**!
- No one really knows what the modulation actually is...

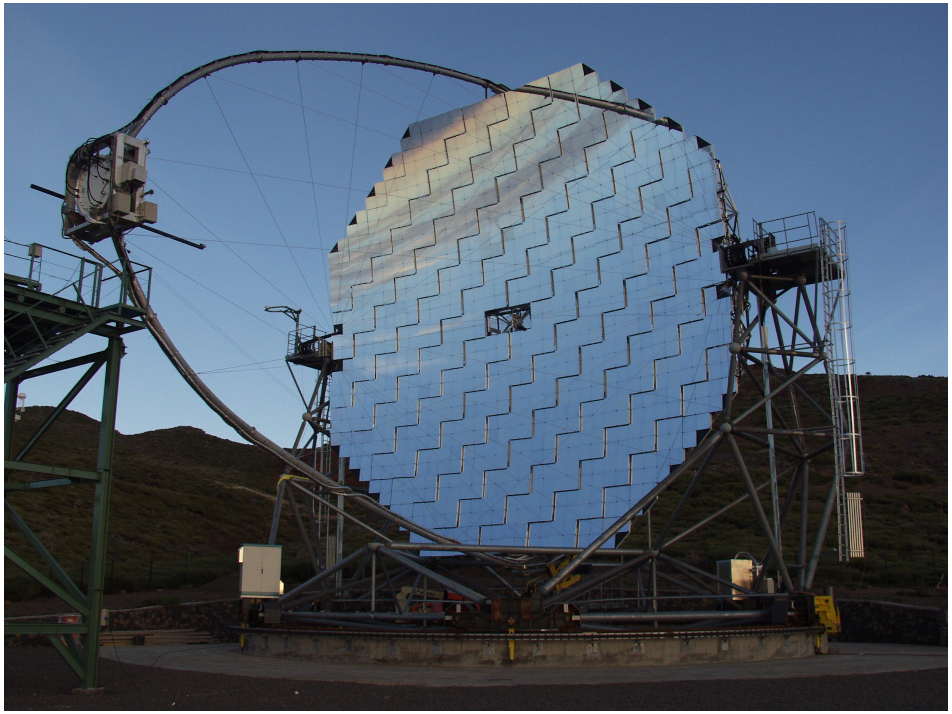
Indirect detection of dark matter



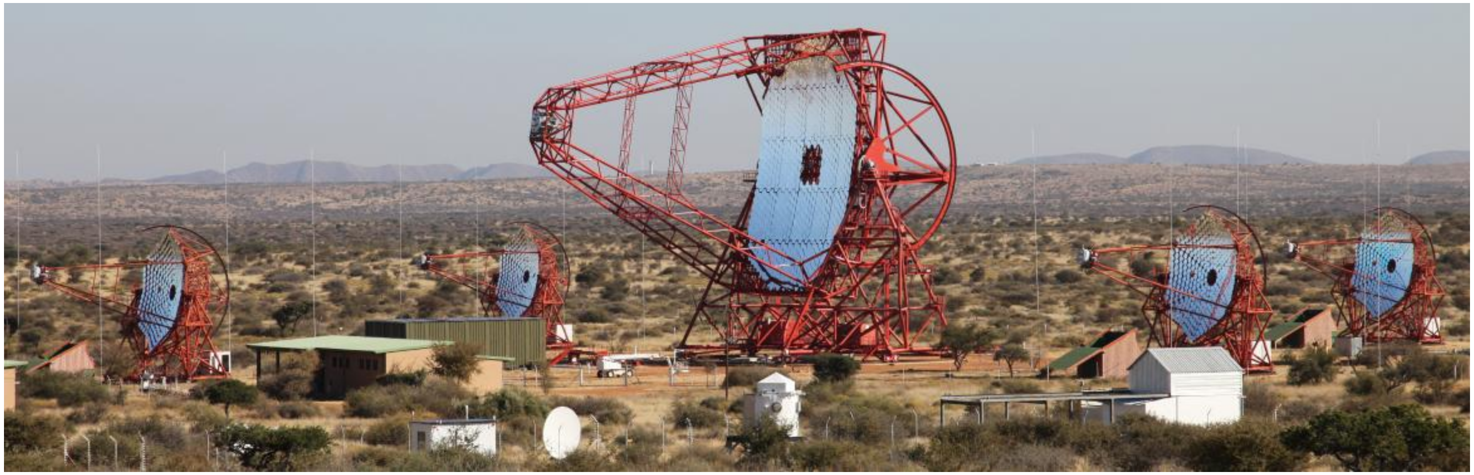
WIMPs can annihilate into gamma-rays

Look at dense dark matter dominated structures like dwarf galaxies or the Milky Way center

Fermi space telescope

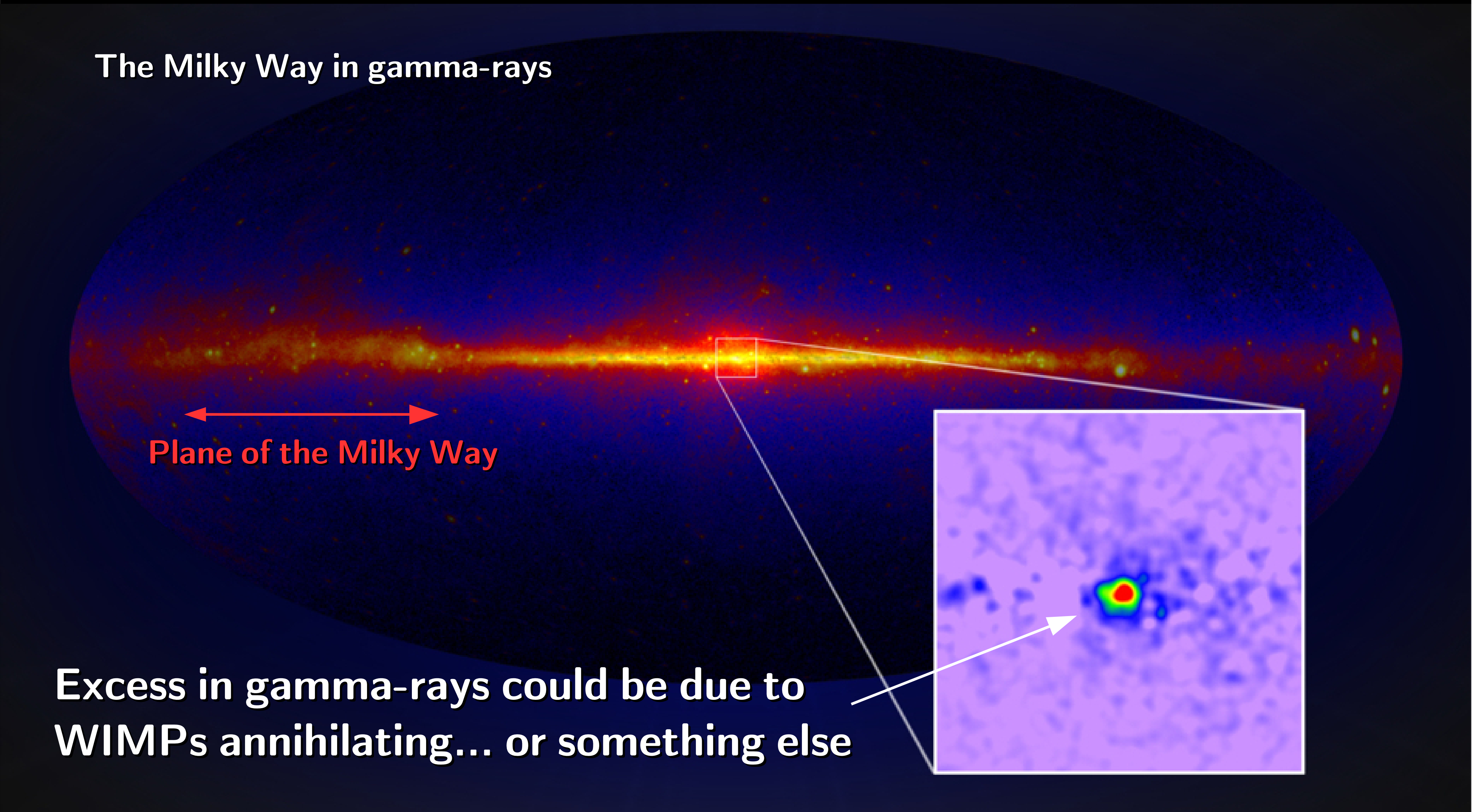


MAGIC



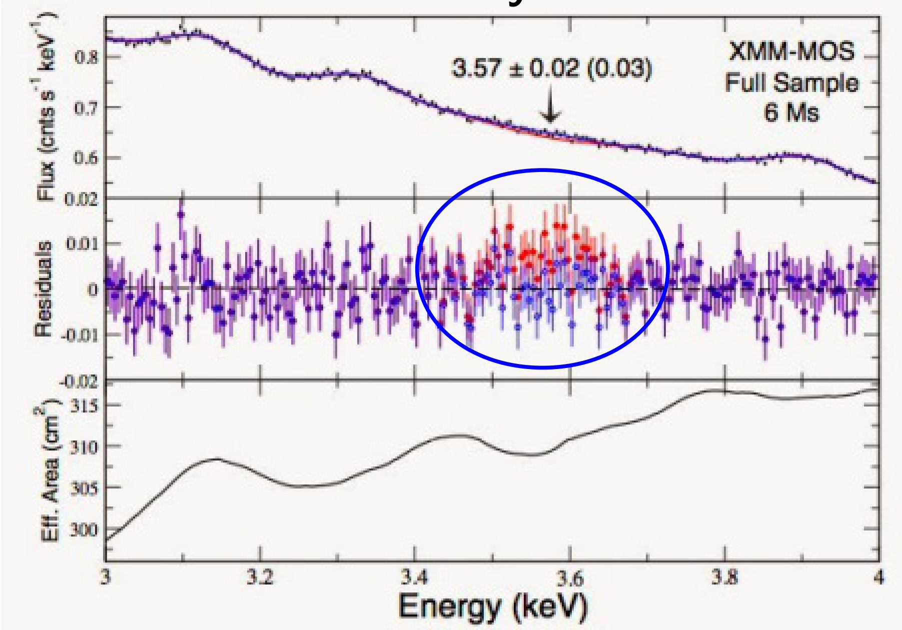
H.E.S.S.

Galactic center excess

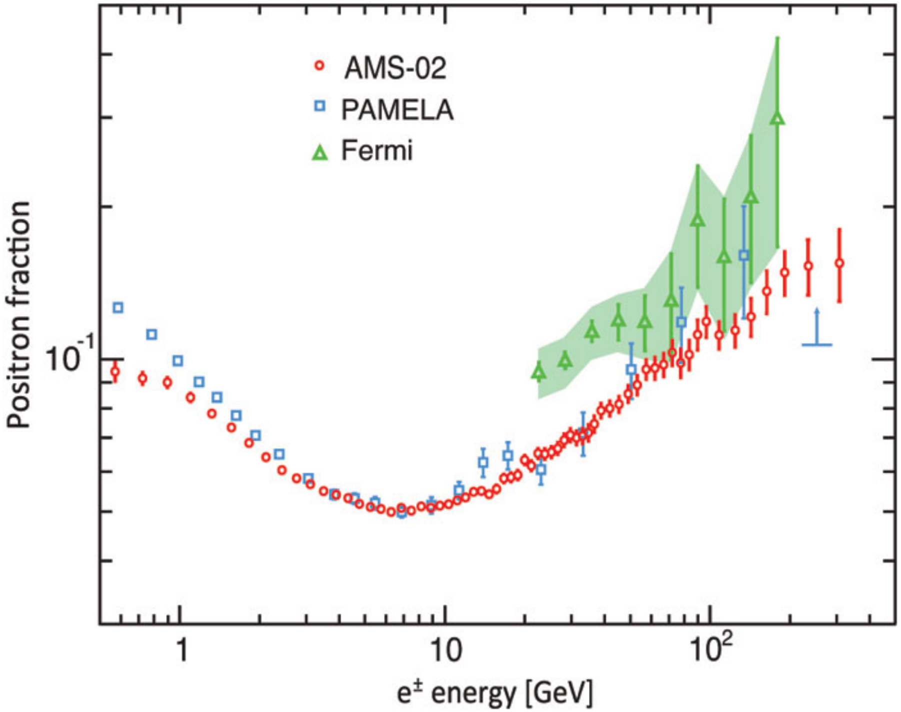


Astrophysics is a messy business and there have been lots of hints...

3.5 keV X-ray line...



Cosmic ray positron excess...

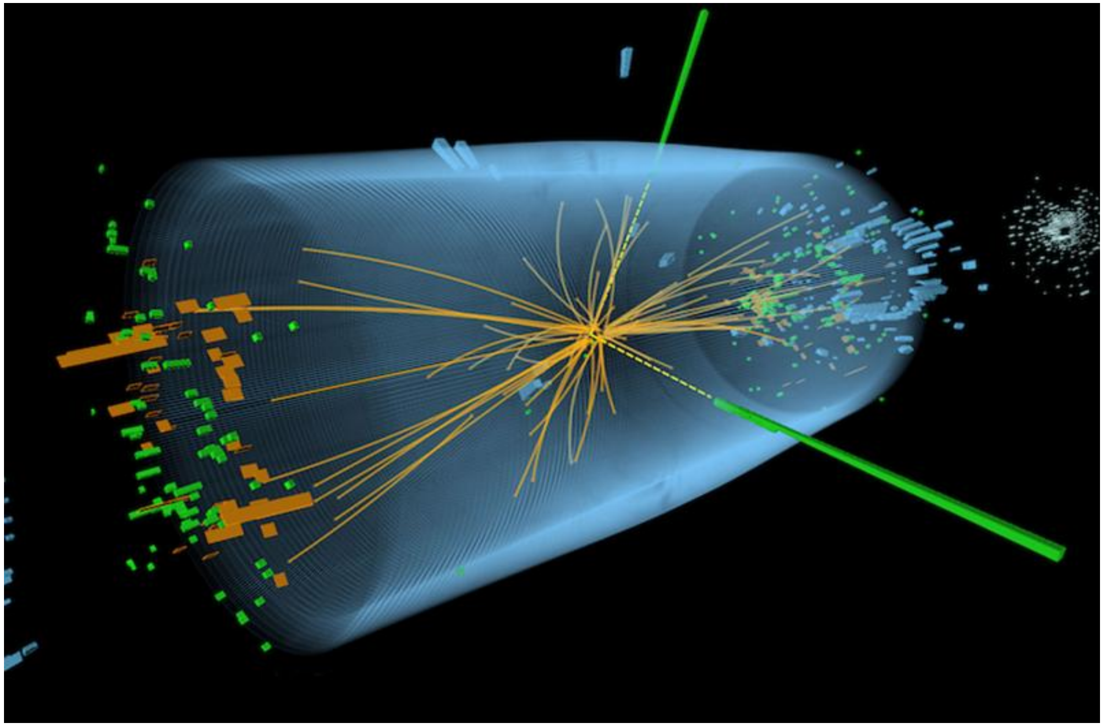


- Statistical noise?
- Pulsars?
- High energy outbursts?

...probably a bit of all the above

Dark matter production

Can we create dark matter in the LHC?



Look for missing energy in particle collisions:

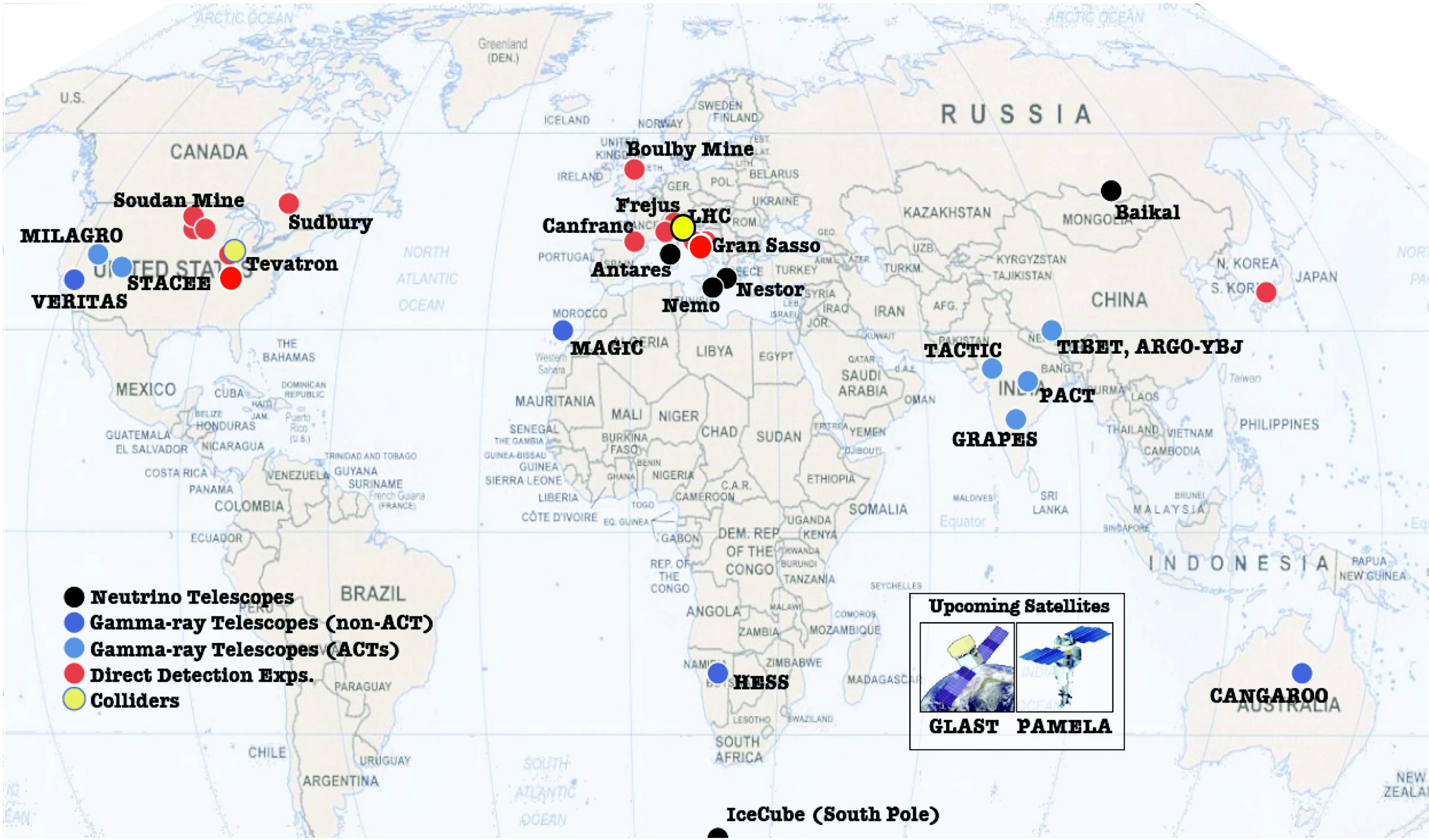
$E_{\mathrm{initial}} =$ energy of initial beams

$E_{\mathrm{final}} =$ energy of debris

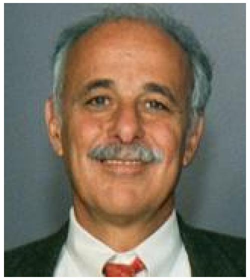
$$E_{\mathrm{initial}} - E_{\mathrm{final}} \propto m_{\mathrm{dm}} c^2$$

But, no new particles so far...

Experiments looking for WIMPs



Axions

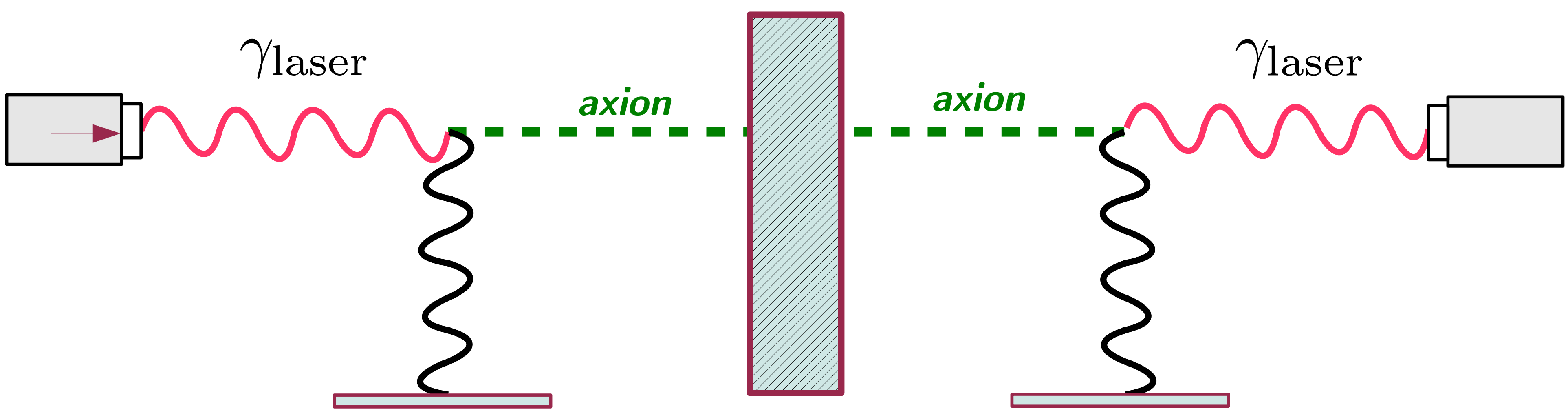


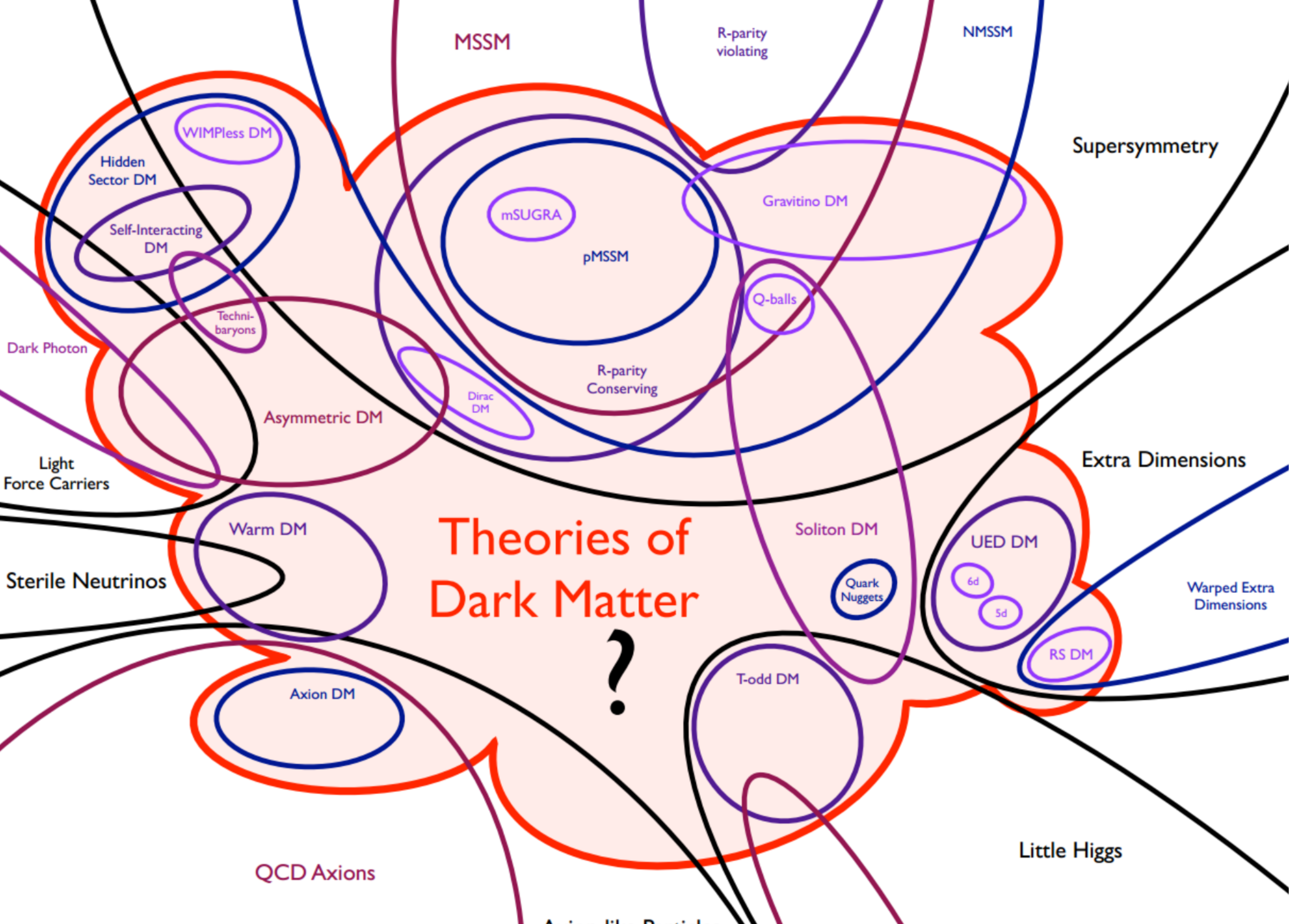
Roberto Peccei

Helen Quinn

- Introduced by Peccei & Quinn to solve another problem in particle physics (it's involved in explaining why the neutron doesn't have a dipole moment)
- Are a good dark matter candidate with very light mass ($m <$ eV)
- Convert in photons inside magnetic fields:

  → *"light-shining-through-a-wall"* experiment





Ask me at the end if you really want to know…

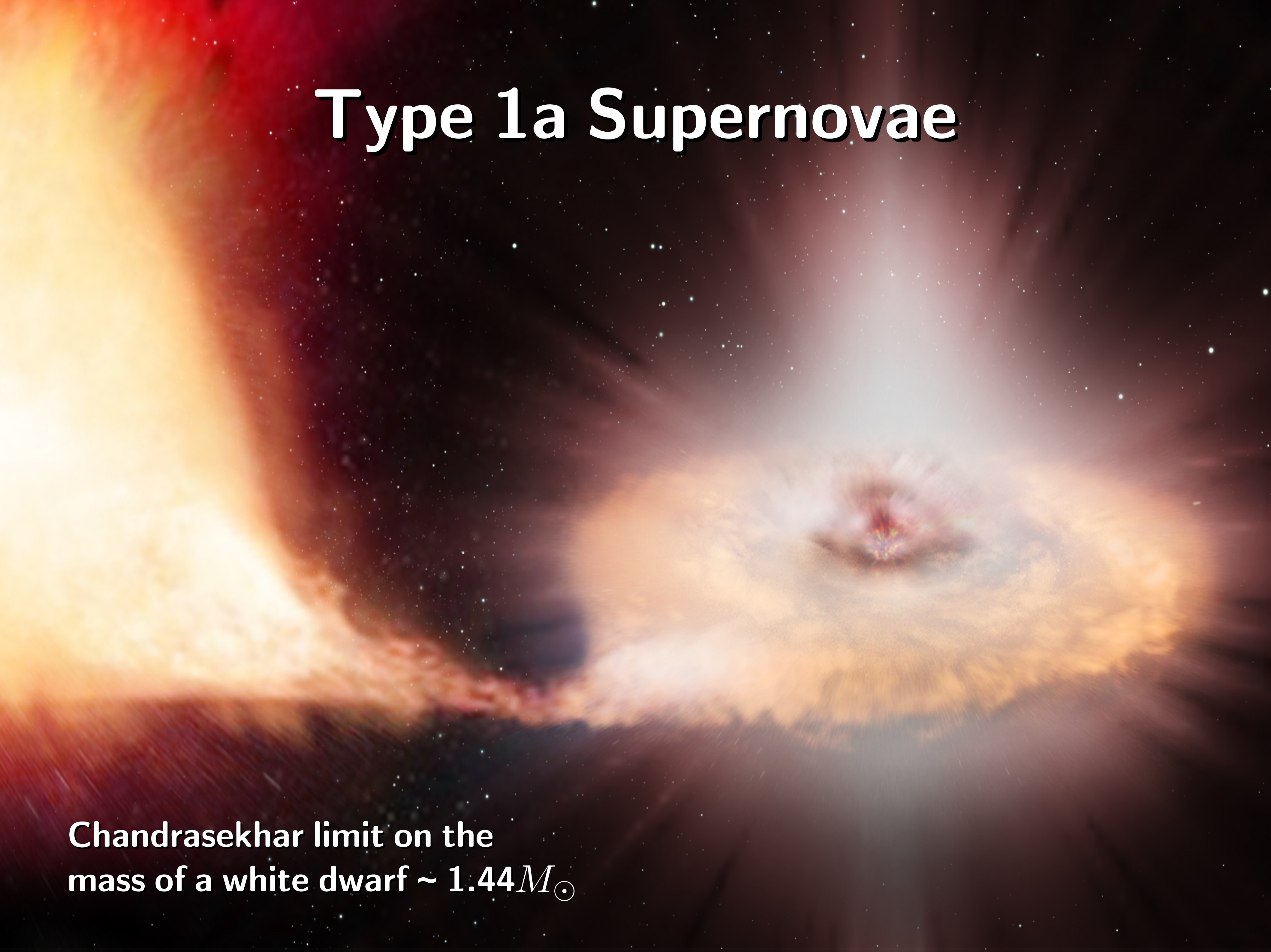
Dark Matter

- Plenty of evidence for dark matter
- Best candidate is the WIMP (but I think axions are nice too)
- We are working on experiments to detect it
  - Direct detection in underground labs
  - Indirect detection in space
  - Production in colliders

Good prospects for detection in the next few years so stay tuned!

Part 2: Dark Energy

Type 1a Supernovae

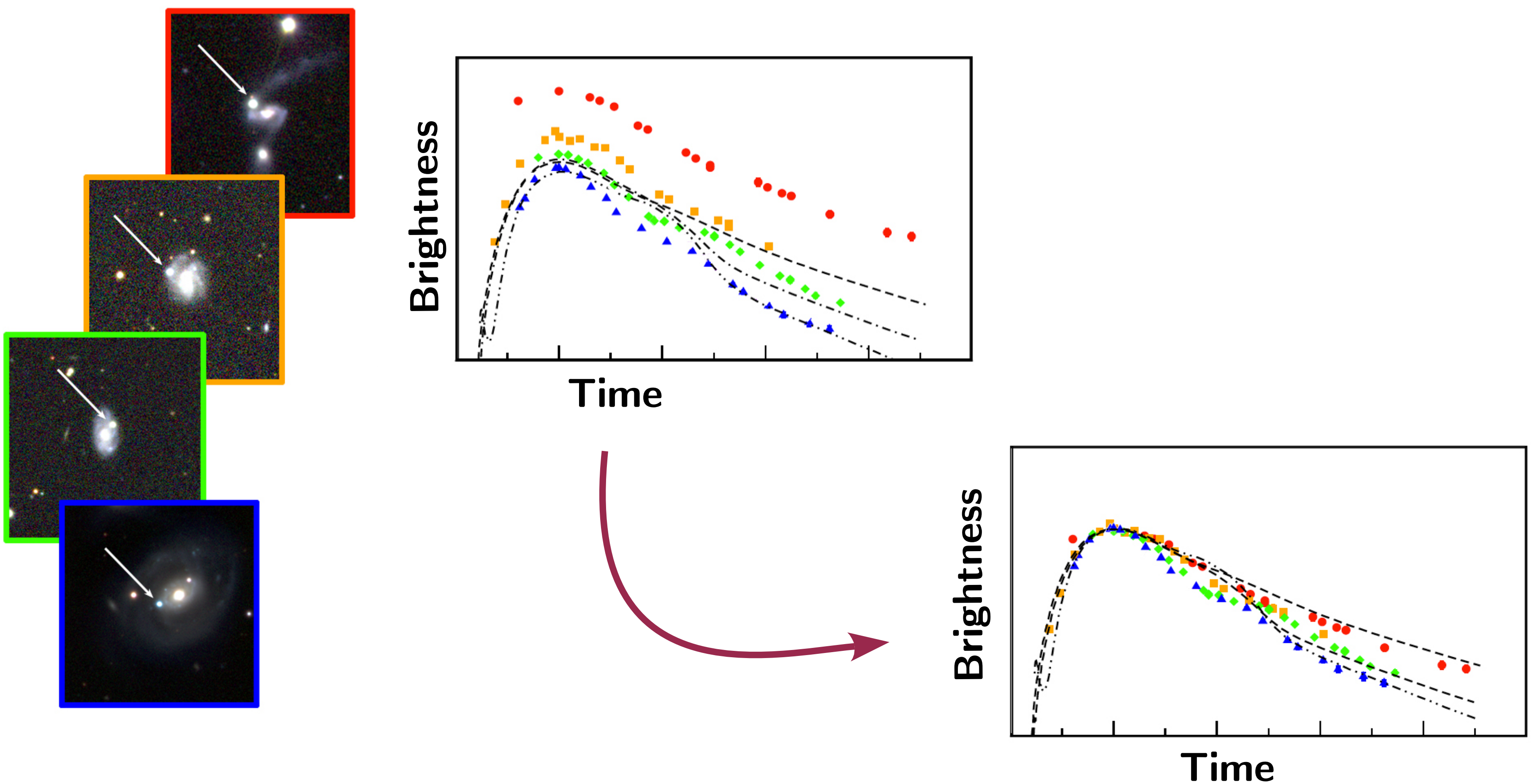


Chandrasekhar limit on the mass of a white dwarf ~ $1.44 M_\odot$

- **Type 1a all have characteristic light curves**
  → can be used as *standard candles*

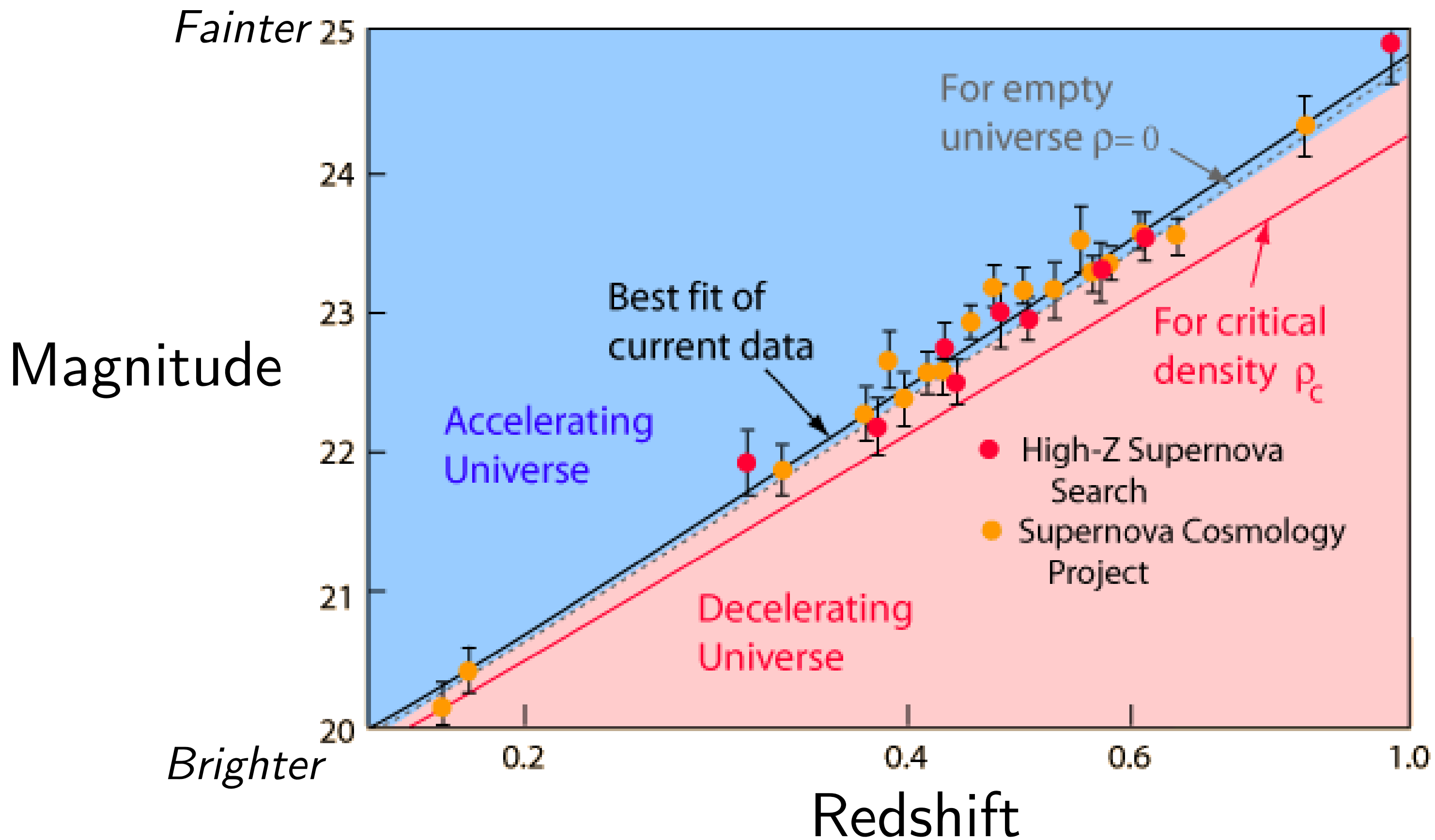
$$5\log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right) = m - M$$

$d =$ **Distance**
$m =$ **apparent magnitude**
$M =$ **absolute magnitude**



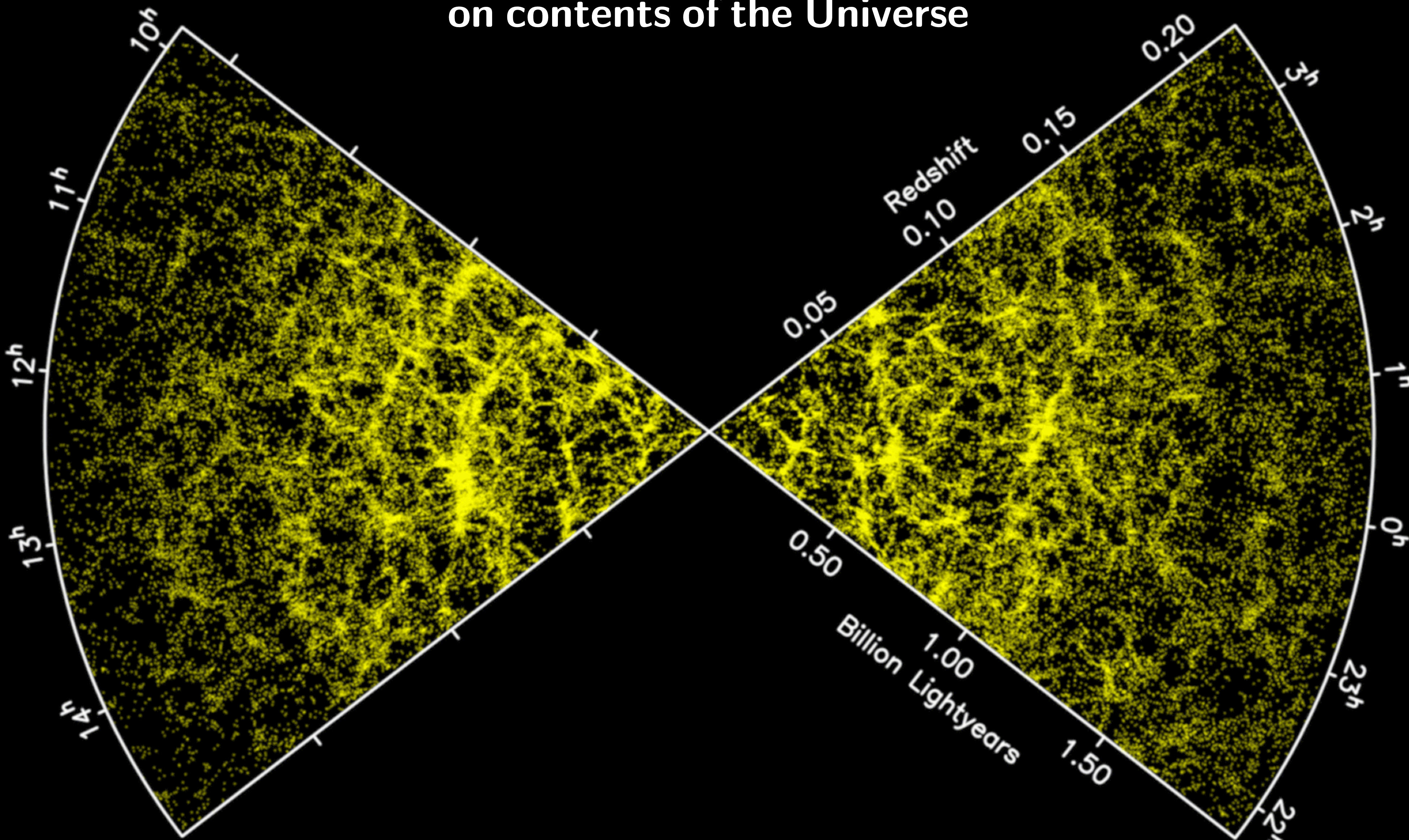
Cosmic acceleration

• Higher redshift supernovae are dimmer than expected
→ Expansion of the Universe is ***accelerating***

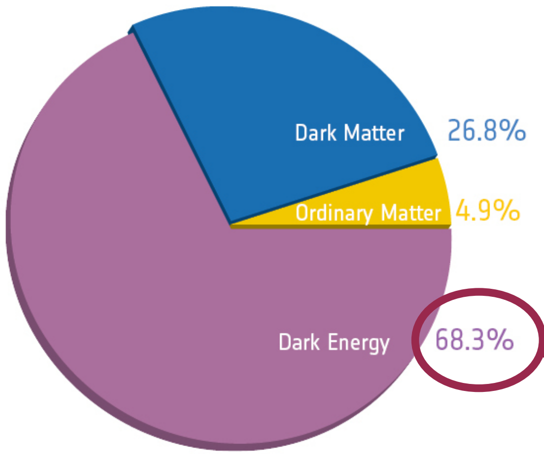


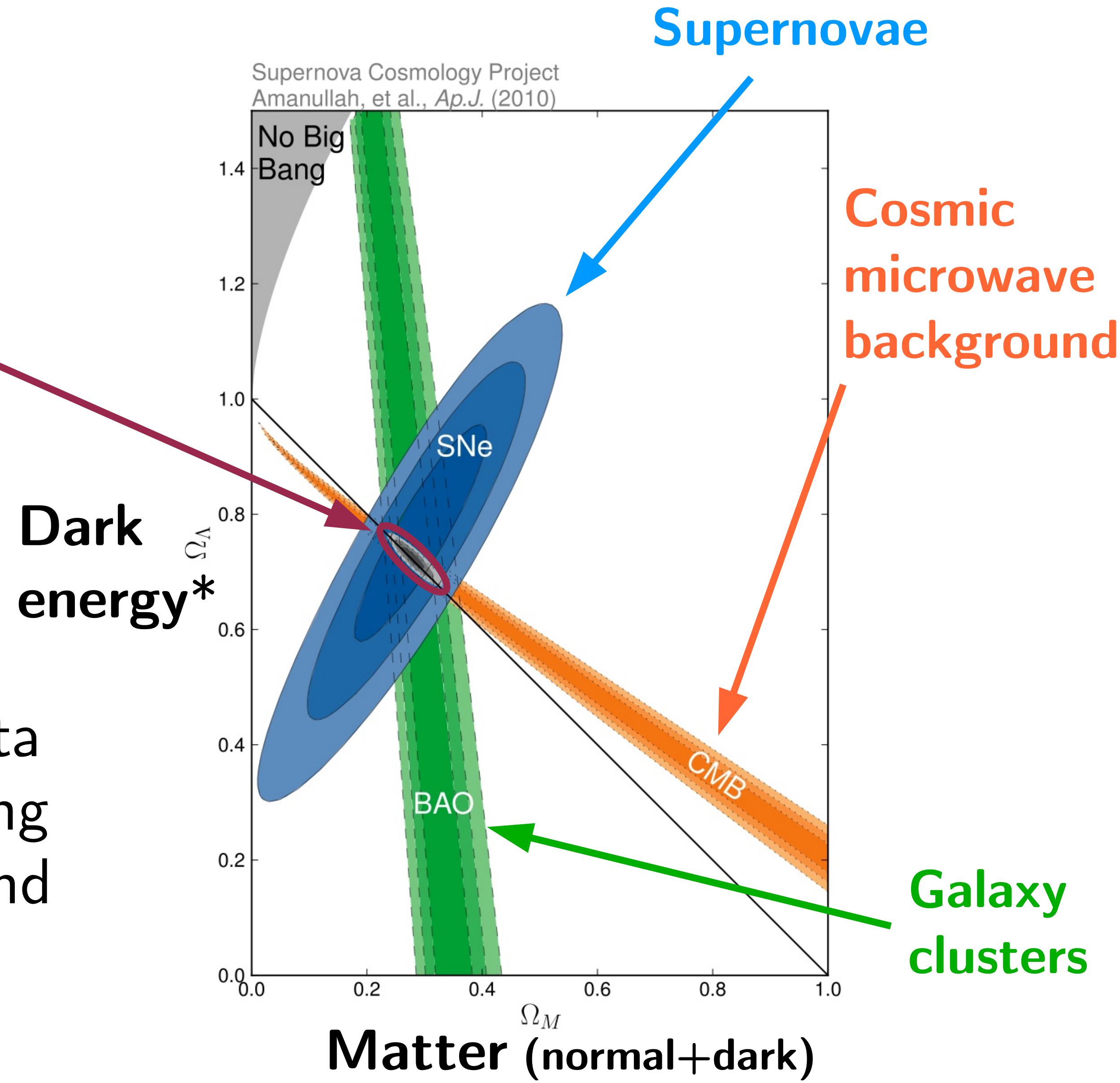
Large scale structure

Distribution of structure dependent on contents of the Universe



Cosmological data



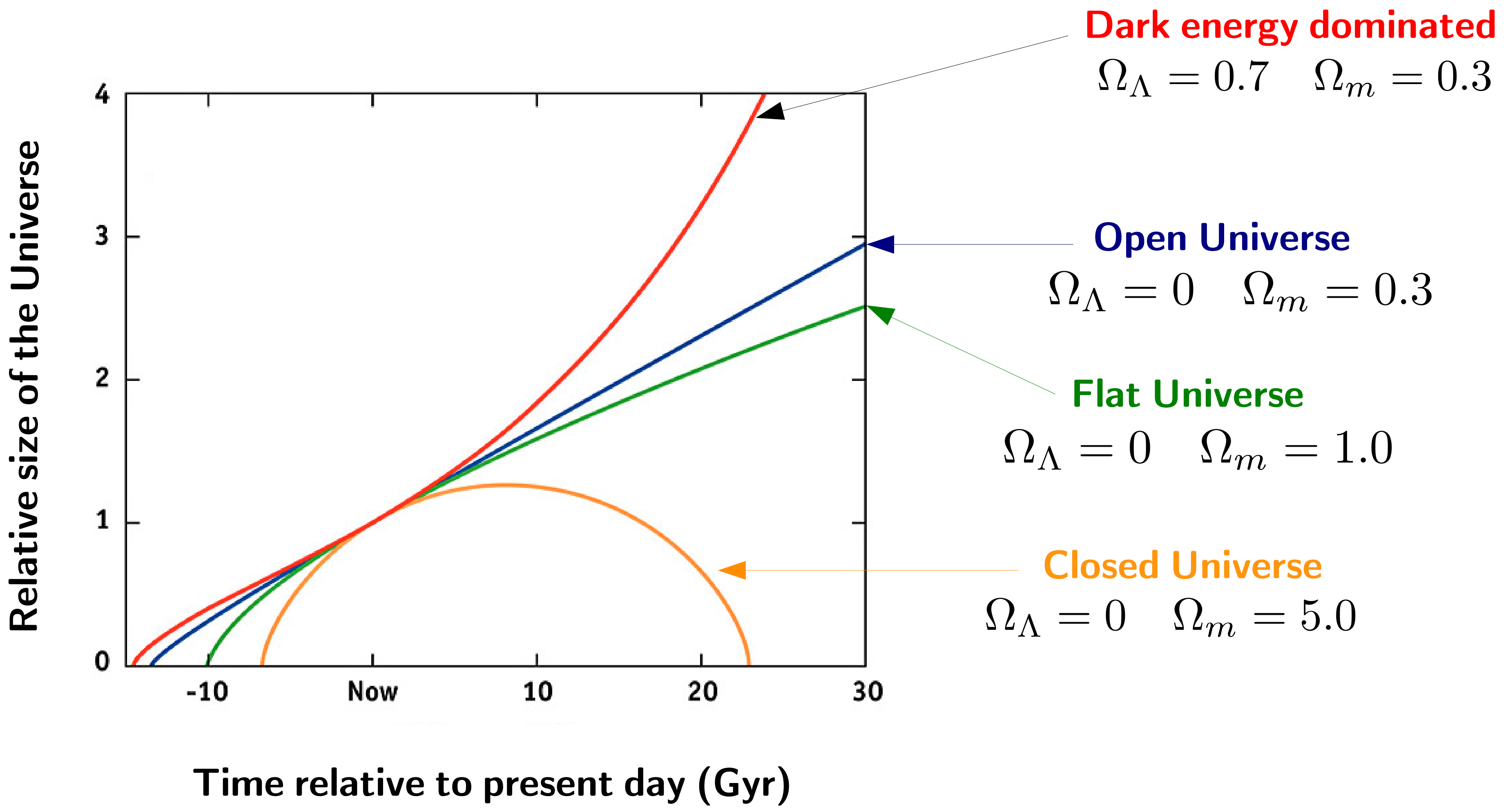


Combining all available data gives us the most compelling evidence for dark matter and dark energy

*actually this plot is only for dark energy in the form of a cosmological constant

Expansion of the Universe

- Our Universe is dominated by dark energy



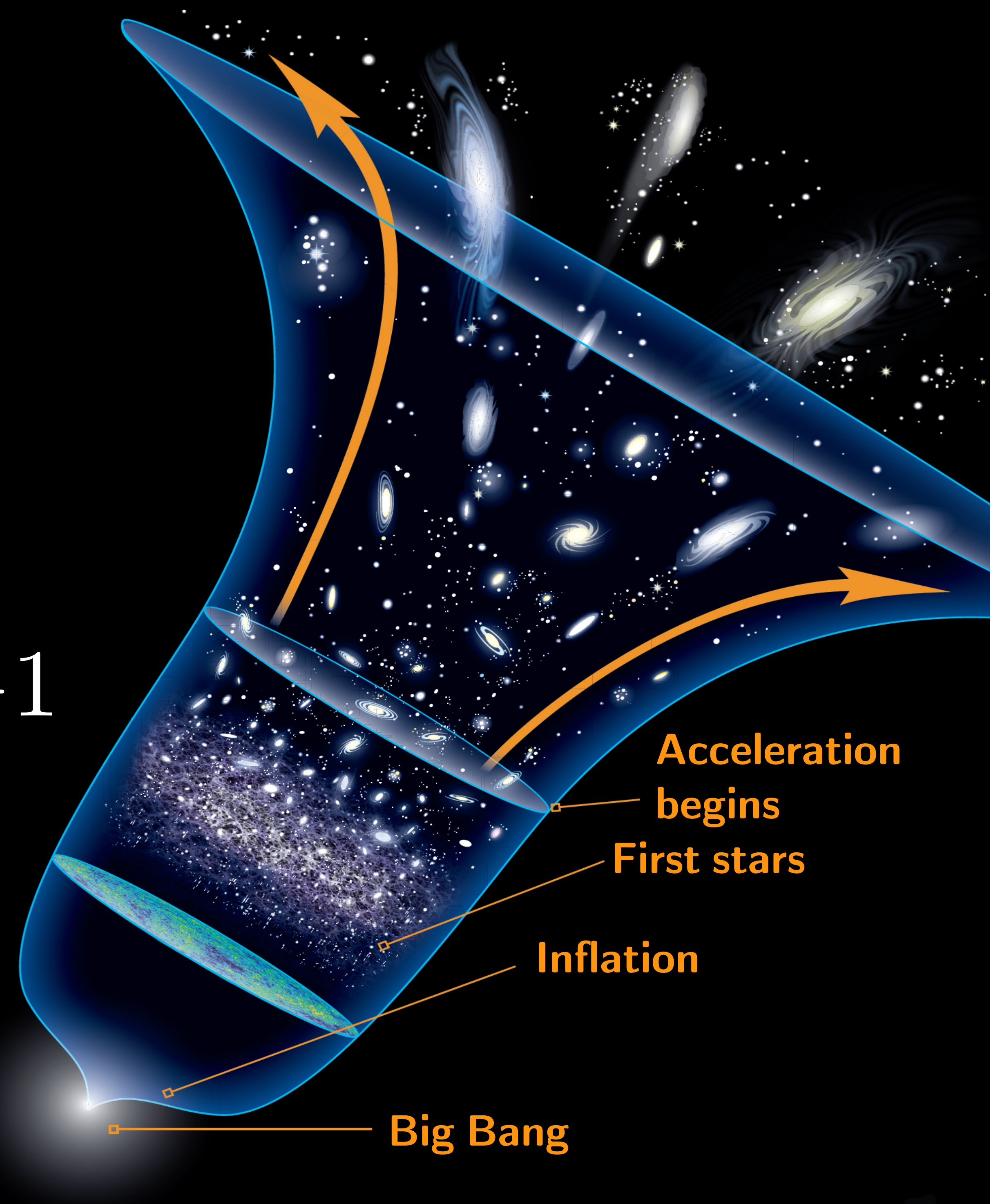
- The expansion of the Universe has begun to **accelerate**
- Needs something with negative pressure

"Equation of state"

$$w = \frac{\text{Pressure}}{\text{Density}} = -1$$

↓

Dark energy



Cosmological constant

- Einstein's field equations permit a extra constant term

Curvature of spacetime = Matter and energy

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

- $\mathbf{\Lambda}$: cosmological constant has an equation of state $w =$ -1

→ the ΛCDM model

The problem with Λ

Predicted value of Λ from the zero point vacuum energy is 10^{120} times bigger than the observed value!

Why?*

1. **Maybe GR isn't the complete description of gravity?**

2. **Maybe dark energy is a new 'thing'?**

* depending on your perspective these two questions often amount to the same idea

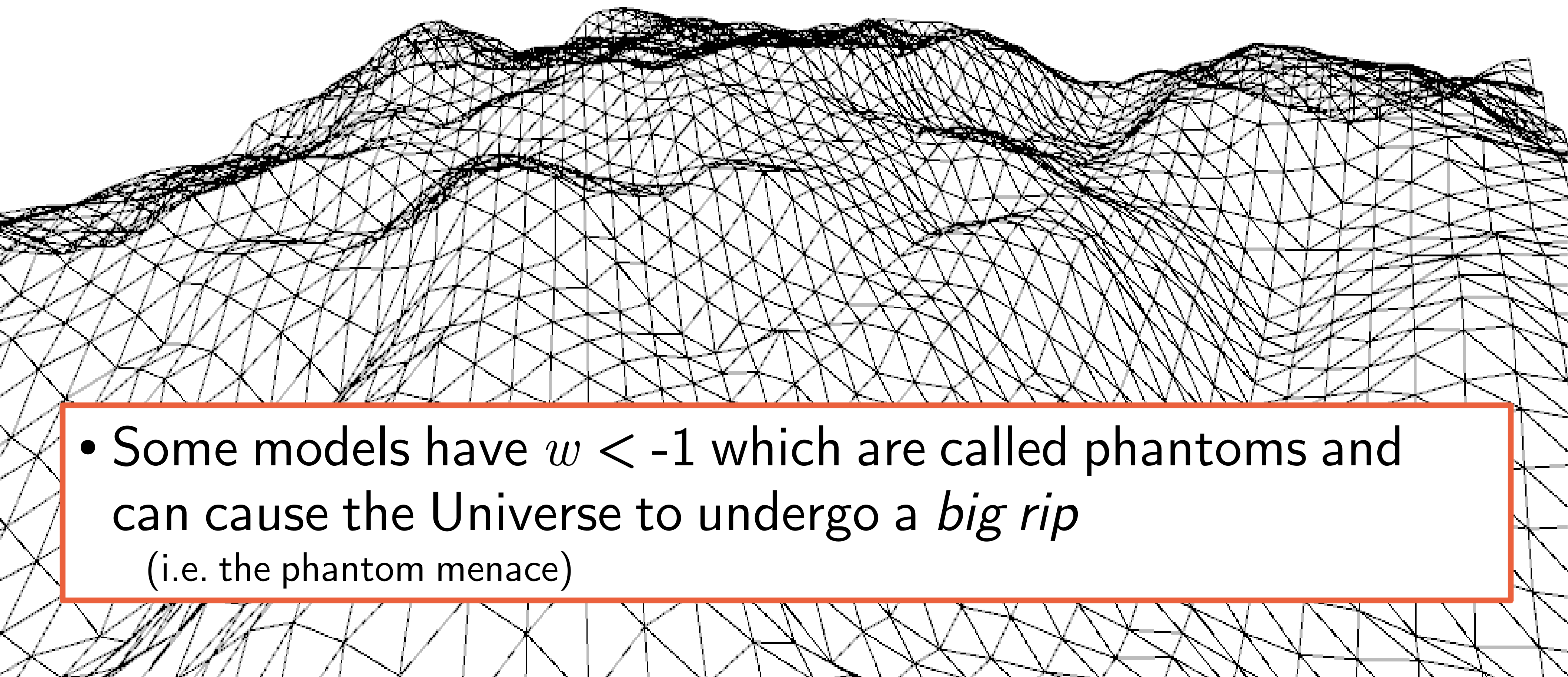
Quintessence

the "aether"

Quintessence

the "aether"

- Energy field that permeates the Universe
- Like the cosmological constant but can vary in spacetime and couple to matter



- Some models have $w <$ -1 which are called phantoms and can cause the Universe to undergo a *big rip*
  (i.e. the phantom menace)

Appeasing the Phantom Menace?

Mariam Bouhmadi-López,[1,*] Yaser Tavakoli,[2,†] and Paulo Vargas Moniz[2,1,‡]
[1] *Centro Multidisciplinar de Astrofísica - CENTRA, Departamento de Física, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal*
[2] *Departamento de Física, Faculdade de Ciências – UBI, Rua Marquês d'Avila e Bolama, 6200 Covilhã, Portugal*
(Dated: January 19, 2010)

An induced gravity brane-world model is considered herein. A Gauss-Bonnet term is provided for the bulk, whereas phantom matter is present on the brane. It is shown that a combination of infra-red and ultra-violet modifications to general relativity replaces a *big rip* singularity: A *sudden*

Type I singularities and the Phantom Menace

Tapan Naskar [a,1] **and John Ward** [b,c,2]

[a] *IUCAA, Post bag 4, Ganeshkhind, Pune 411007, India*

[b] *Center For Research in String theory, Department of Physics, Queen Mary University of London, Mile End Road, London, E1 4NS, UK.*

[c] *Science Institute, University of Iceland, Taeknigardi, Dunhaga 5 IS-107 Reykjavik, Iceland.*

Scalar perturbations and the possible self-destruction of the *phantom menace*

J.C. Fabris[*] and S.V.B. Gonçalves[†]
Departamento de Física Universidade Federal do Espírito Santo
CEP29060-900 Vitória, Espírito Santo, Brazil

January 16, 2014

A Phantom Menace?

Cosmological Consequences of a Dark Energy Component

with Super-Negative Equation of State

R. R. Caldwell[1]

Department of Physics & Astronomy, Dartmouth College, Hanover, NH 03755

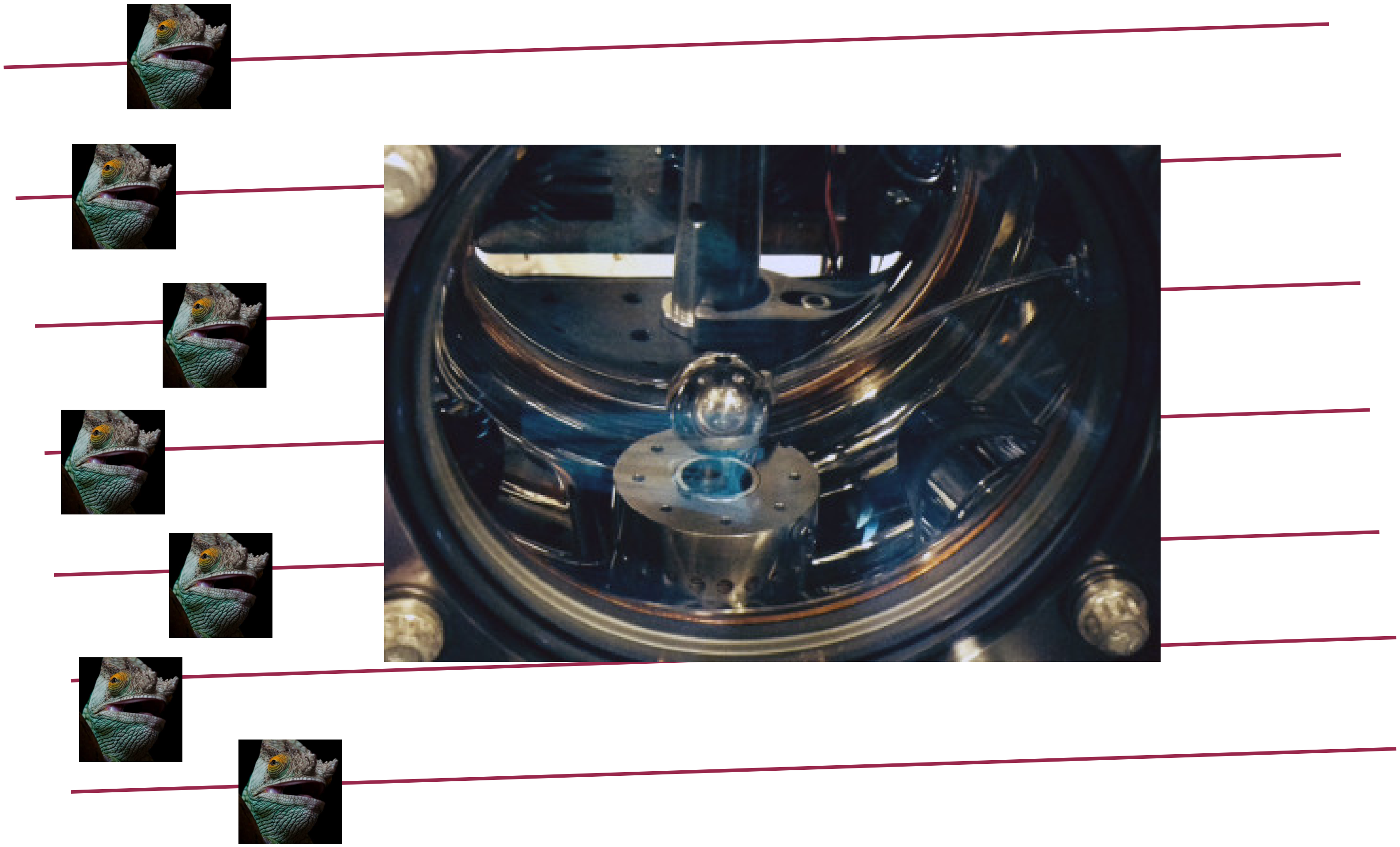
The phantom menaced: constraints on low-energy effective ghosts

James M. Cline, Sangyong Jeon, Guy D. Moore
Physics Department, McGill University, 3600 University Street, Montréal, Québec, Canada H3A 2T8
e-mail: ghostbusters@physics.mcgill.ca
(Dated: November, 2003)

It has been suggested that a scalar field with negative kinetic energy, or "ghost," could be the source of the observed late-time cosmological acceleration. Naively, such theories should be ruled out by the catastrophic quantum instability of the vacuum. We derive phenomenological bounds on

Searching for fifth forces

- Dark energy might be measurable in the lab as a **"fifth force"**
- One popular model is called the chameleon because it changes value depending on its environment



Part 1: Dark matter

- Why we think it exists → a wealth of gravitational evidence
- What we think it is → possibly a WIMP, or maybe an axion
- How we're going to find out → $>$50 experiments working on it
- When we're going to find out → probably in the next 10 years

Part 2: Dark energy

- Why we think it exists → cosmic acceleration + more...
- What we think it is → ...
- How we're going to find out → cosmology, or in the lab, somehow
- When we're going to find out → ¯_(ツ)_/¯