Dark Matter

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Sutton Trust Summer School July 2015

The University of Nottingham

Outline

Part I: a brief tour of the Universe

Part II: the evidence for dark matter

Question sheet part I

Part III: what is dark matter made of?

Part IV: how are we going to find it?

Question sheet part II

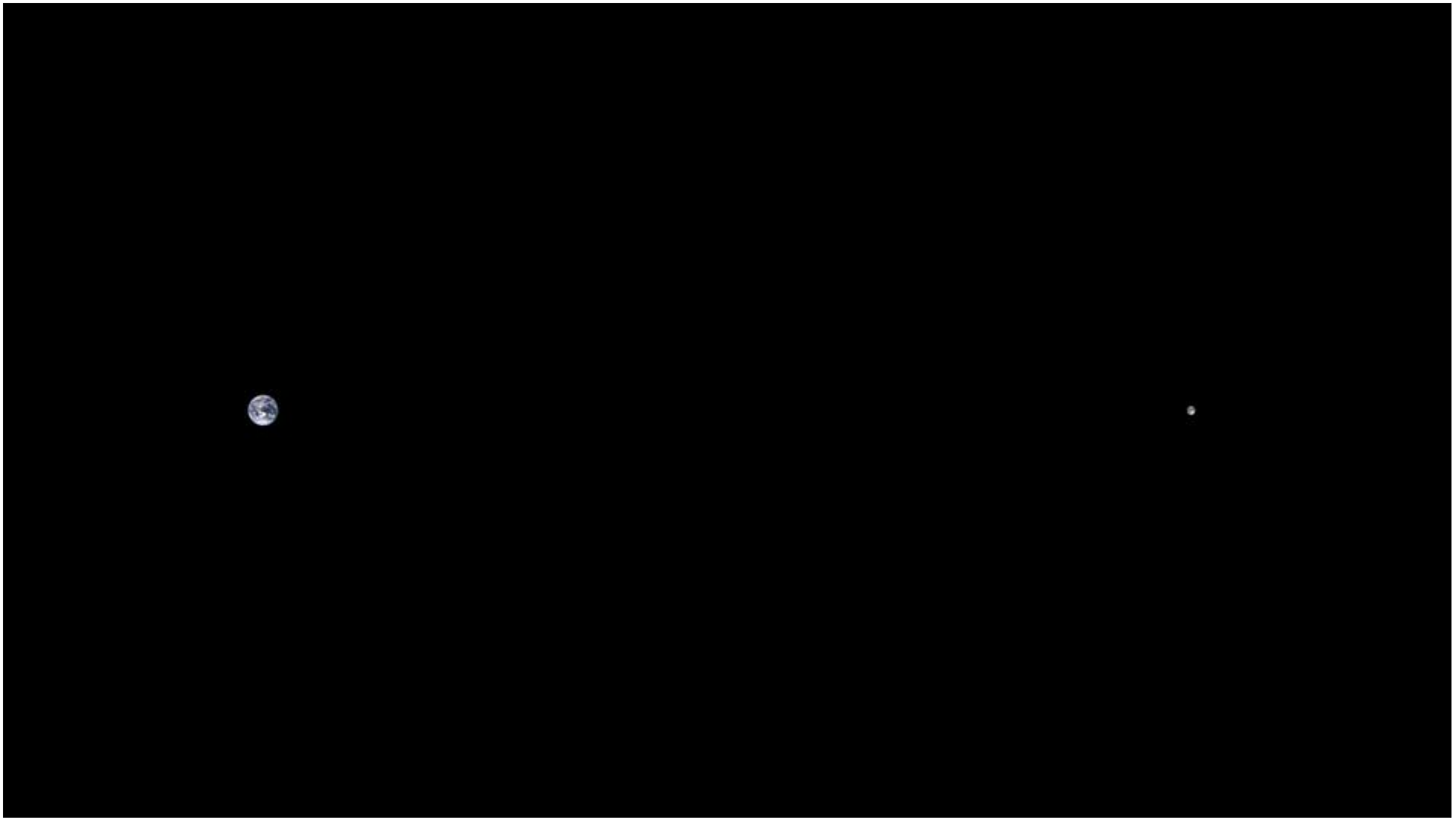
Part I

A brief tour...

The Earth

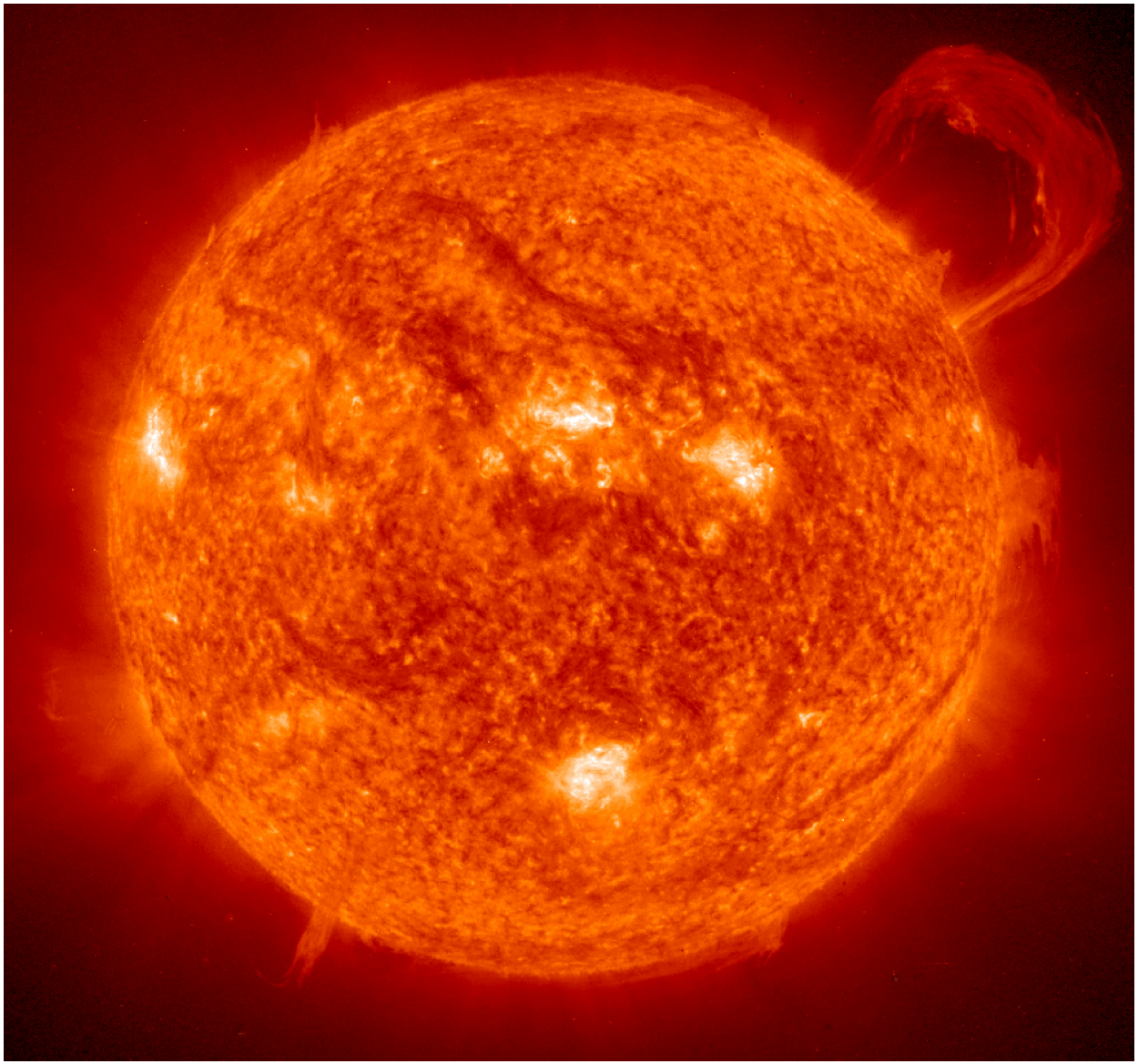
Diameter: 12,700 km or 0.04 light-seconds

The Moon



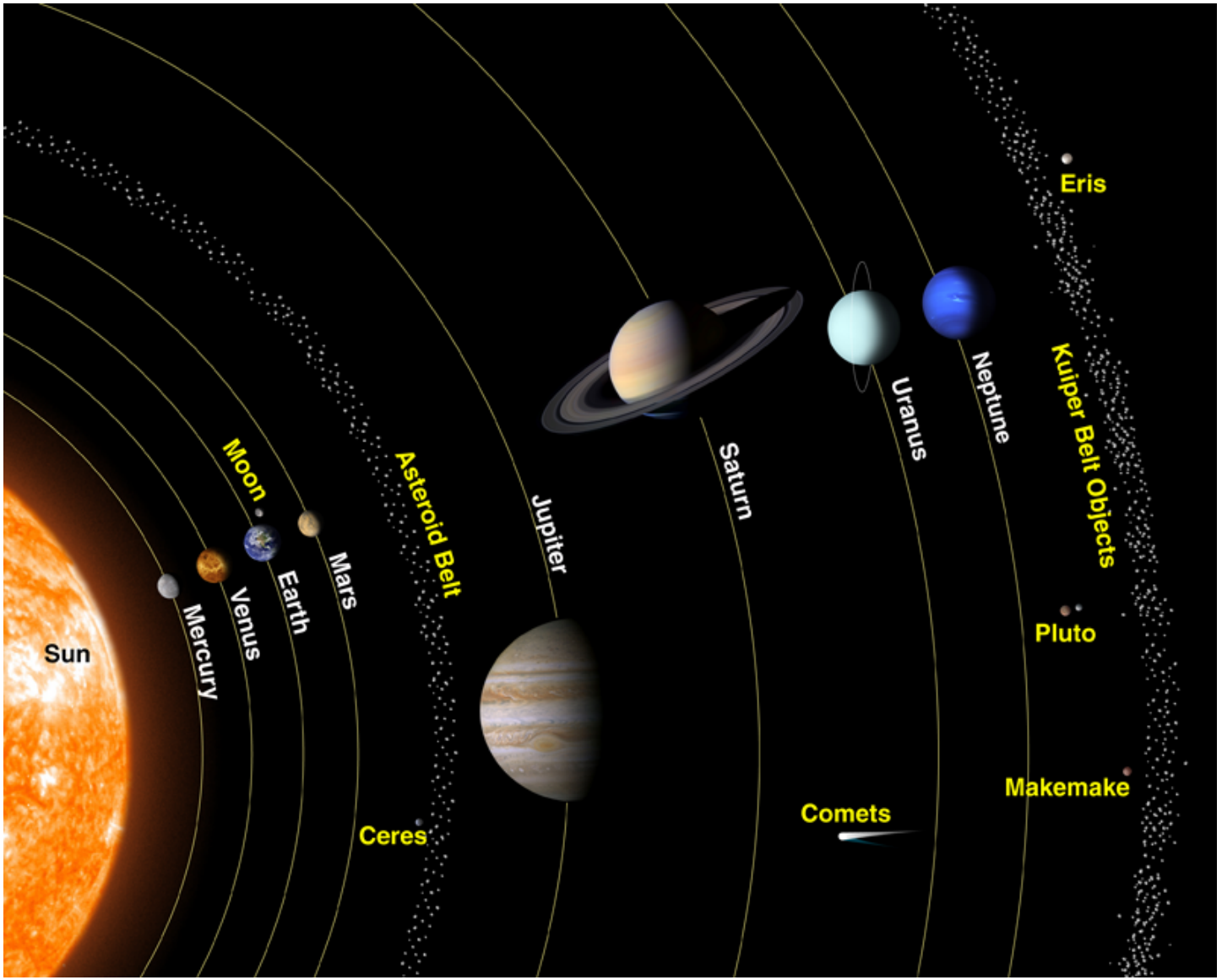
Distance: 384,000 km or 1.3 light-seconds

The Sun



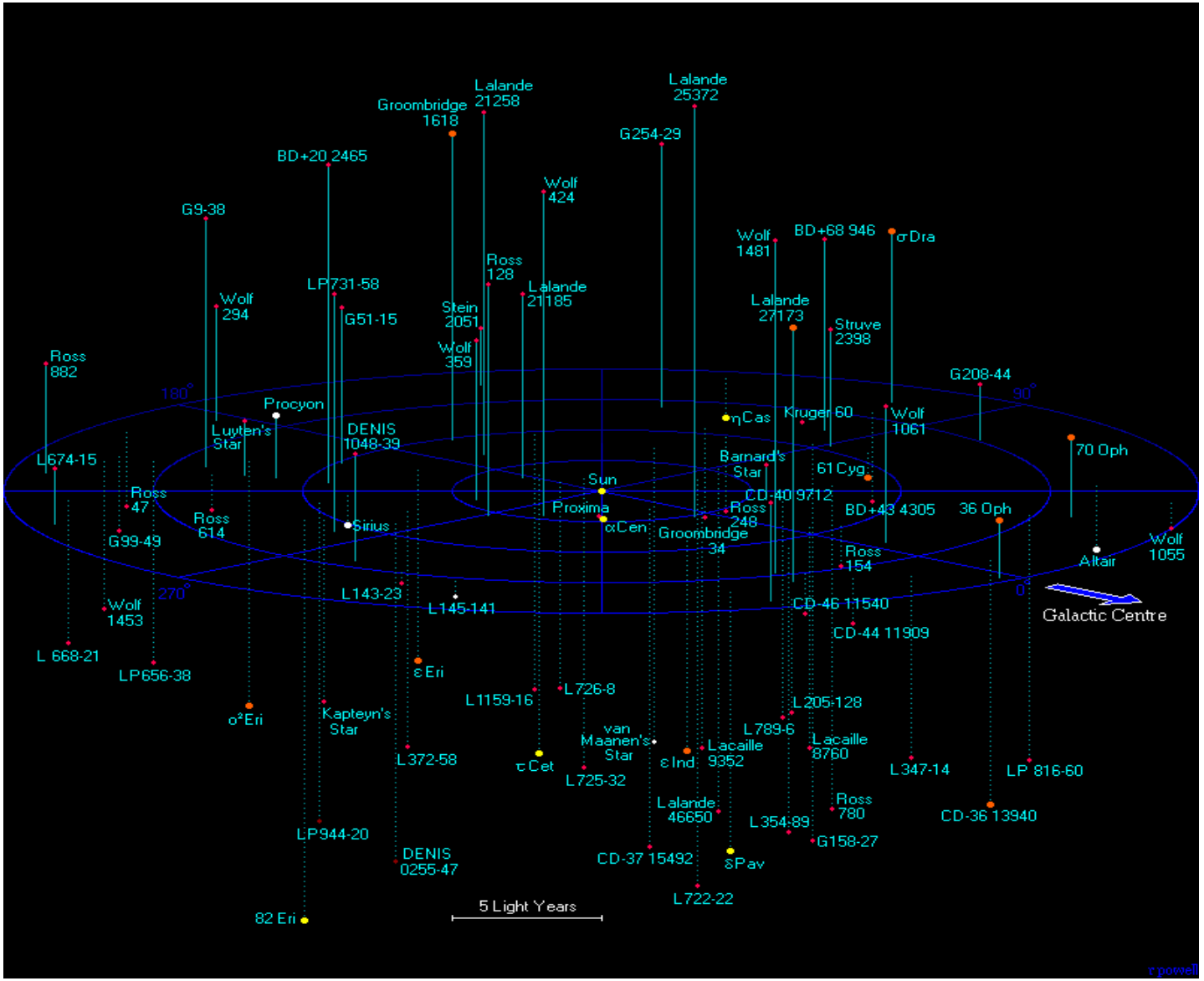
Distance: 150,000,000 km or 8 light-minutes

The Solar System



Distance to Neptune: 4 light-hours

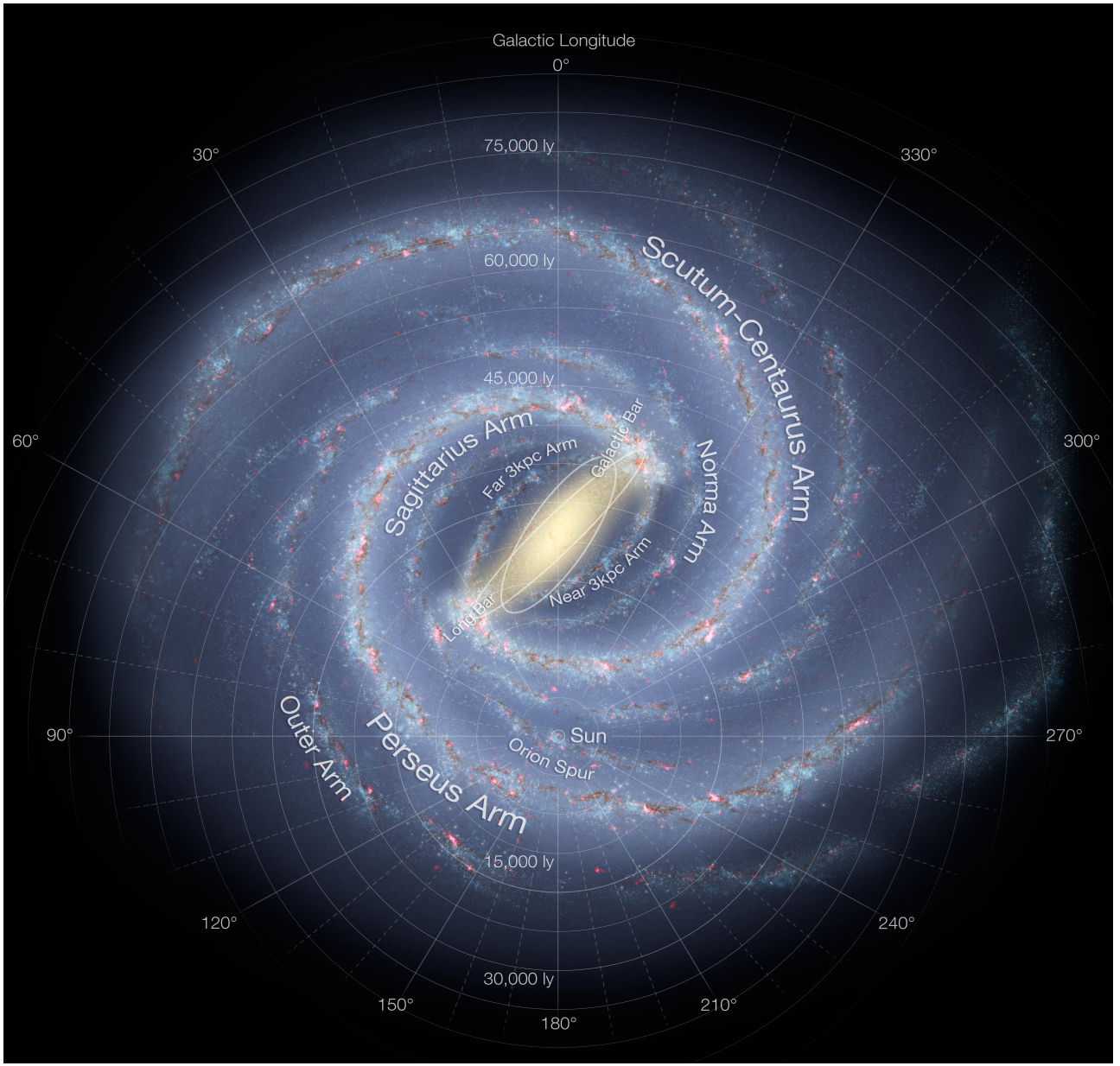
The Solar neighborhood



Distance to nearest star: 4 light-years

The Milky Way

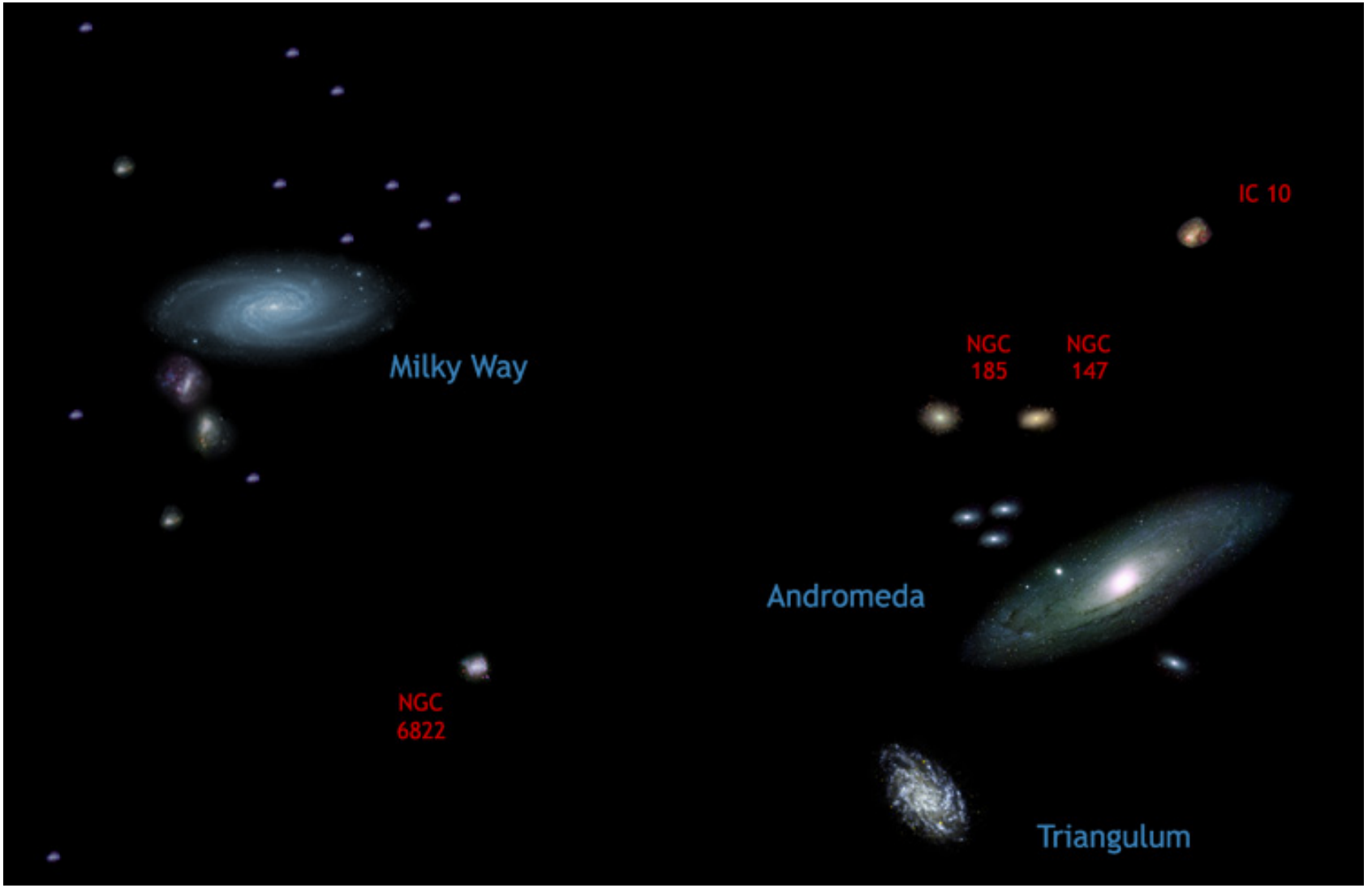
The Milky Way



100,000
light-years
diameter

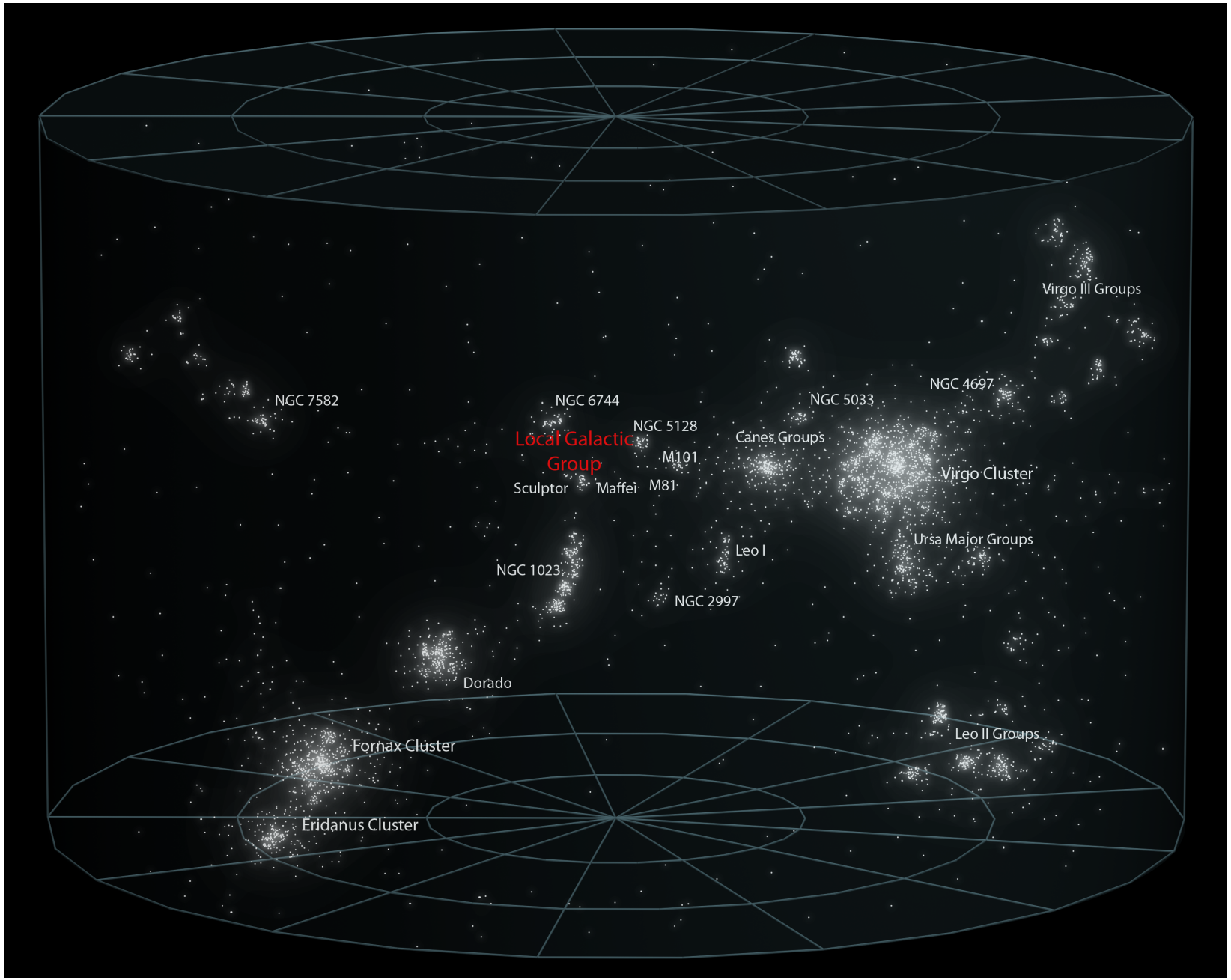
around 300 billion stars

The local group

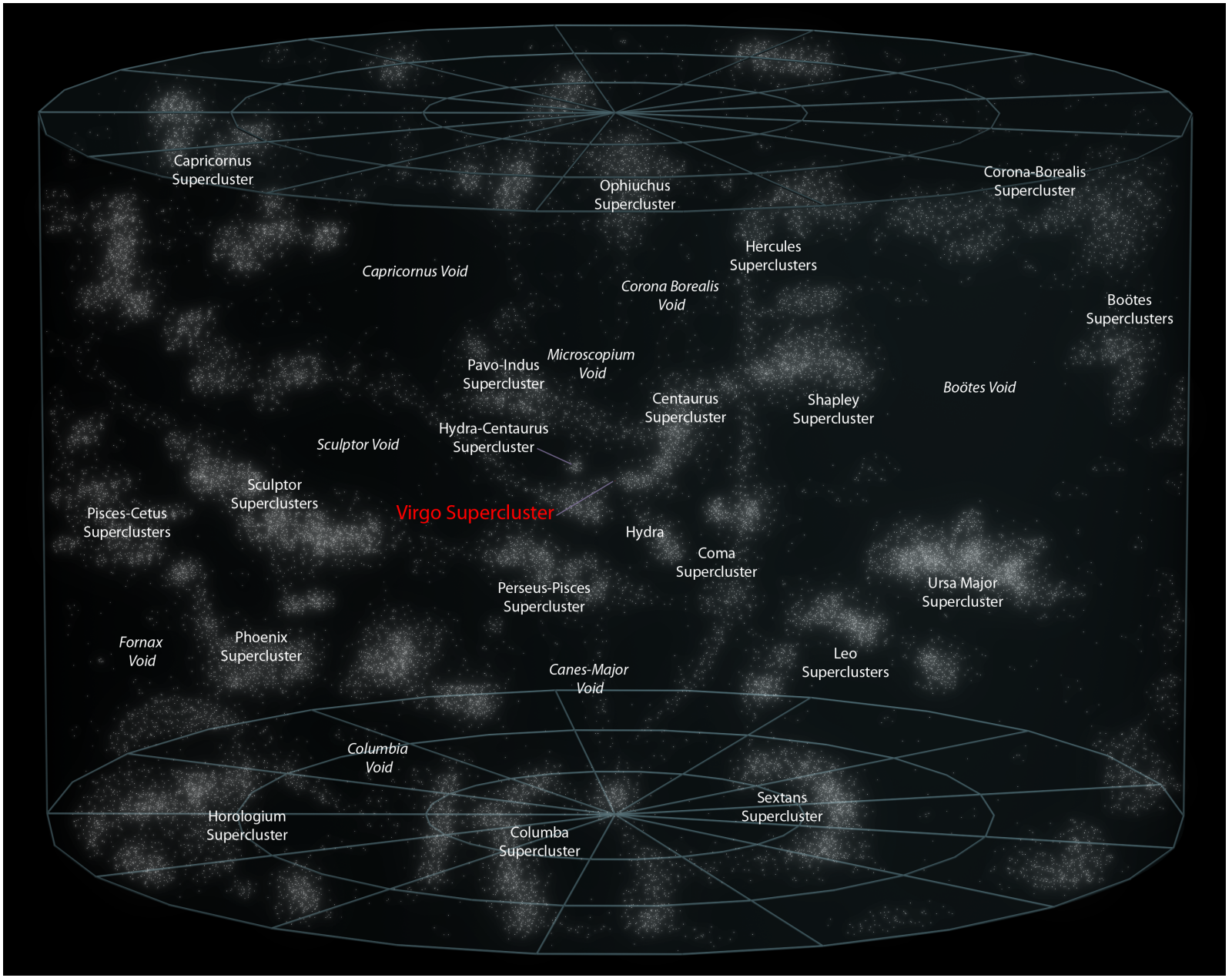


54 Galaxies, stretches over 10 million light-years

Virgo "supercluster"

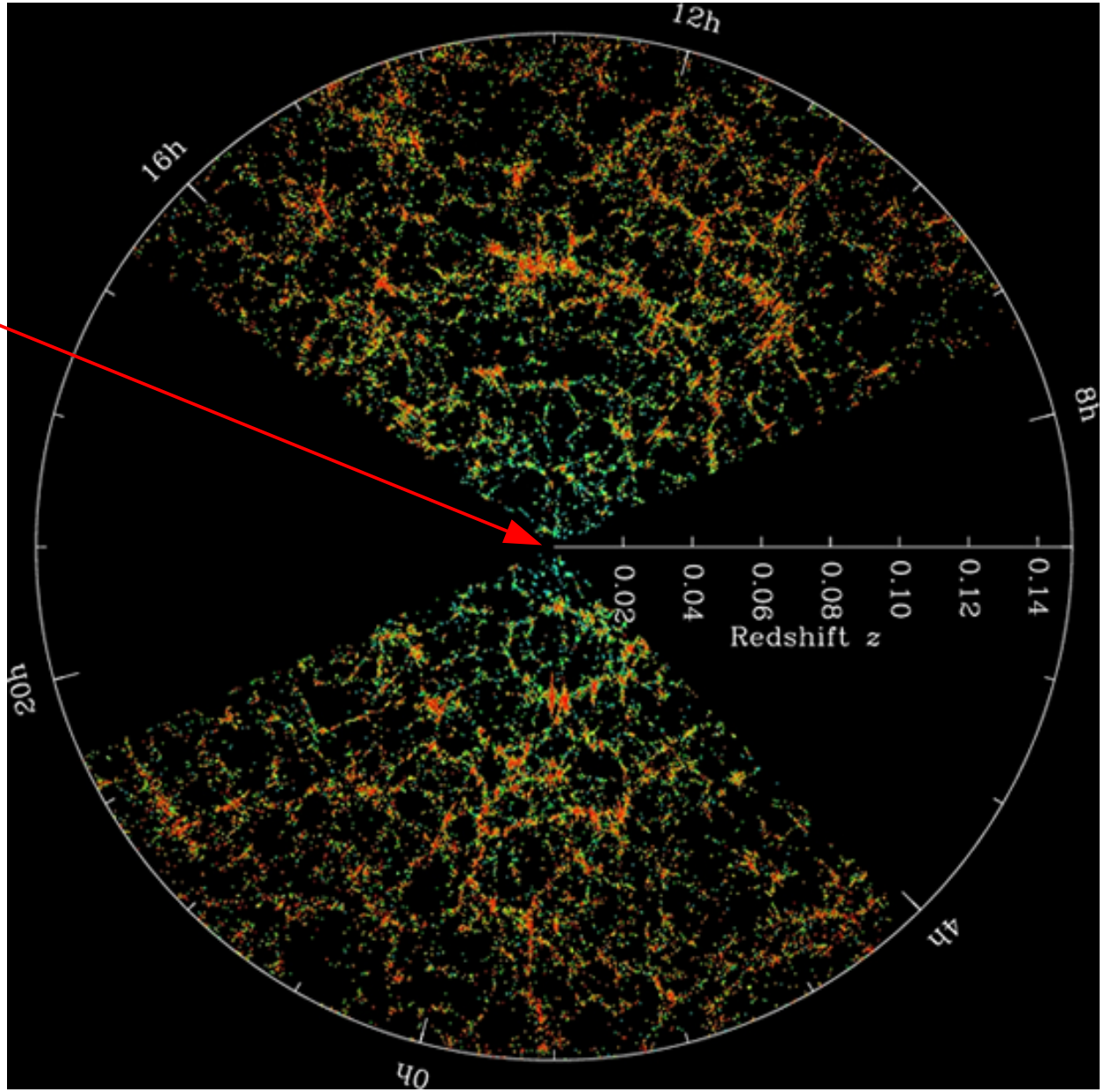


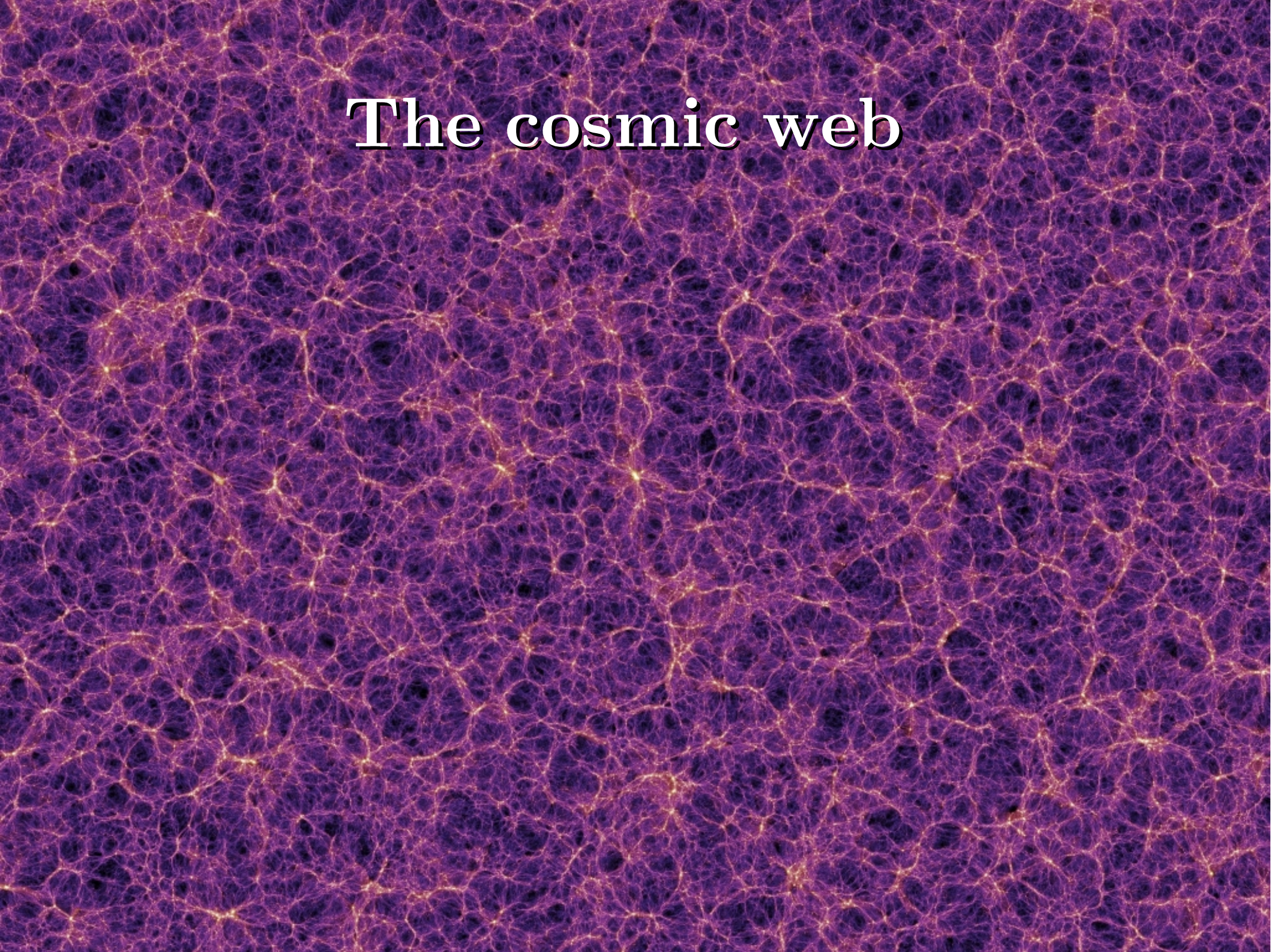
Local superclusters



The observable Universe

We are here




The cosmic web

Part II

The evidence for dark matter...

Circular rotation speeds

Force of gravity

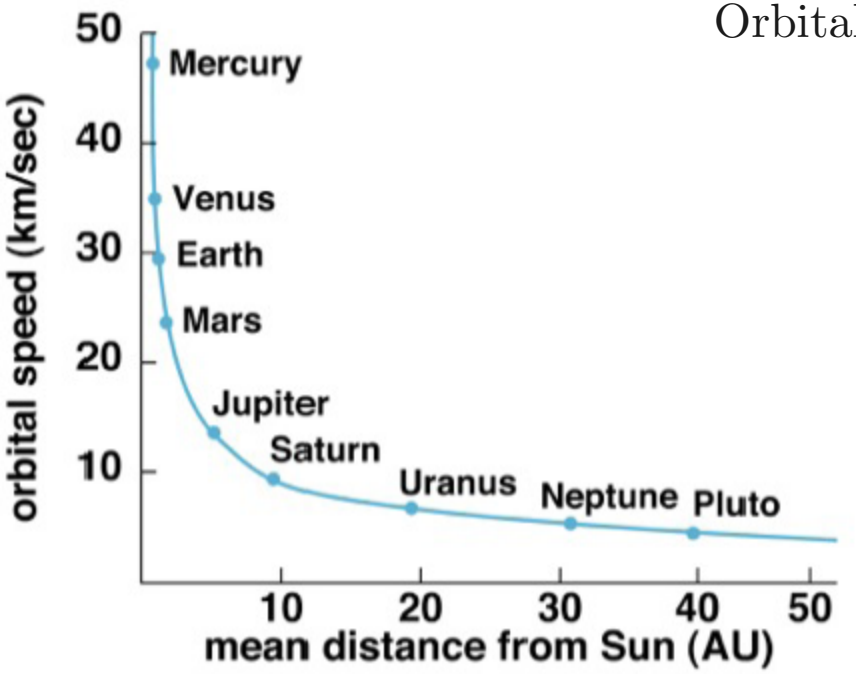
$$F = \frac{GMm}{r^2}$$

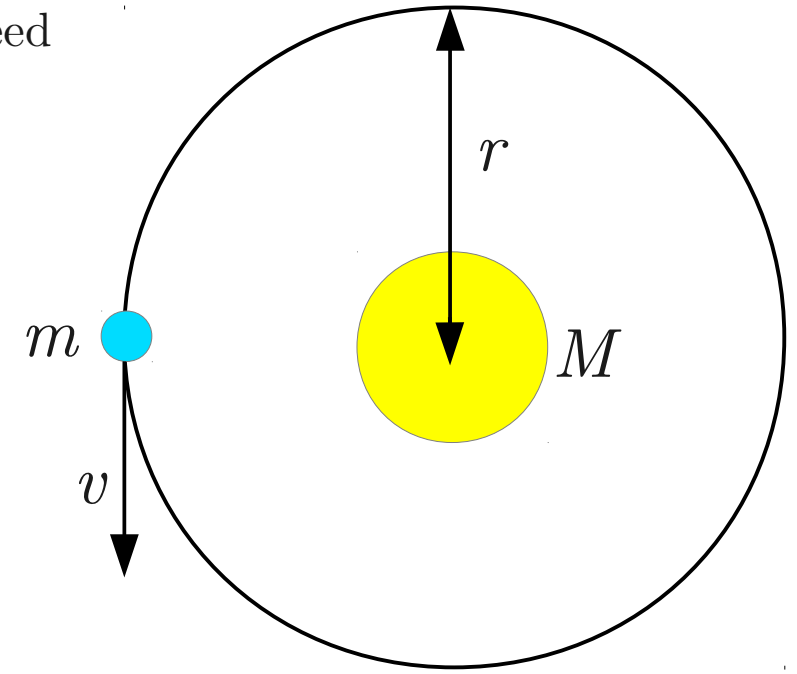
Centripetal force

$$F = \frac{mv^2}{r}$$

$$v = \sqrt{\frac{GM}{r}}$$

Orbital rotation speed





Circular rotation speeds

Orbital rotation speed

$$v = \sqrt{\frac{GM}{r}}$$

Use speed and radius to measure mass

$$M = \frac{v^2 r}{G}$$

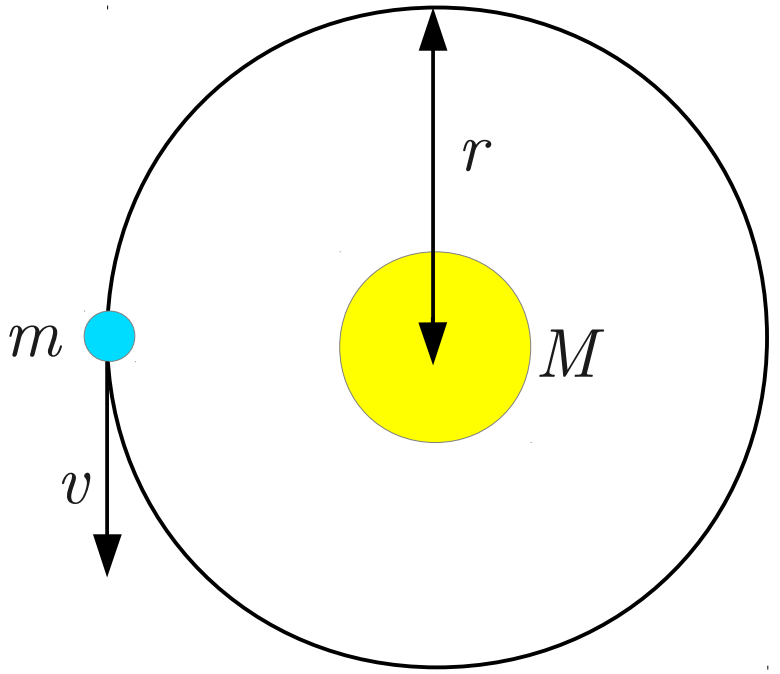
Weigh the sun

Earth's orbital radius: $r = 1$ AU

Earth's orbital speed: $v = 2\ \pi$ r/1 year

$$M = \frac{v^2 r}{G}$$

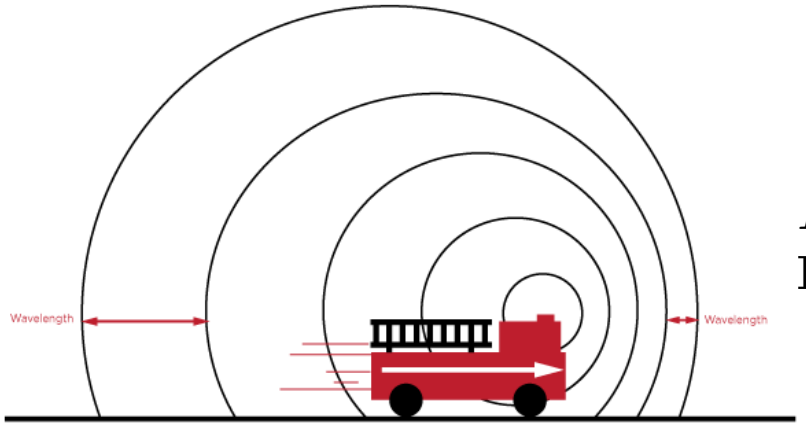
Mass of the sun: $M = 2$ x 10^{30} kg



How do we measure speeds in space?

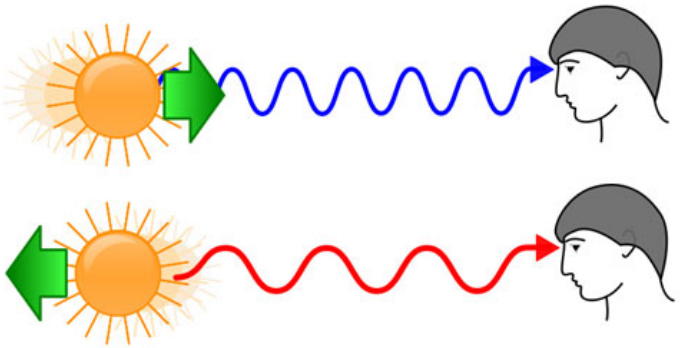
Doppler effect

Sound:



Higher pitch = coming towards us
Lower pitch = moving away from us

Light:



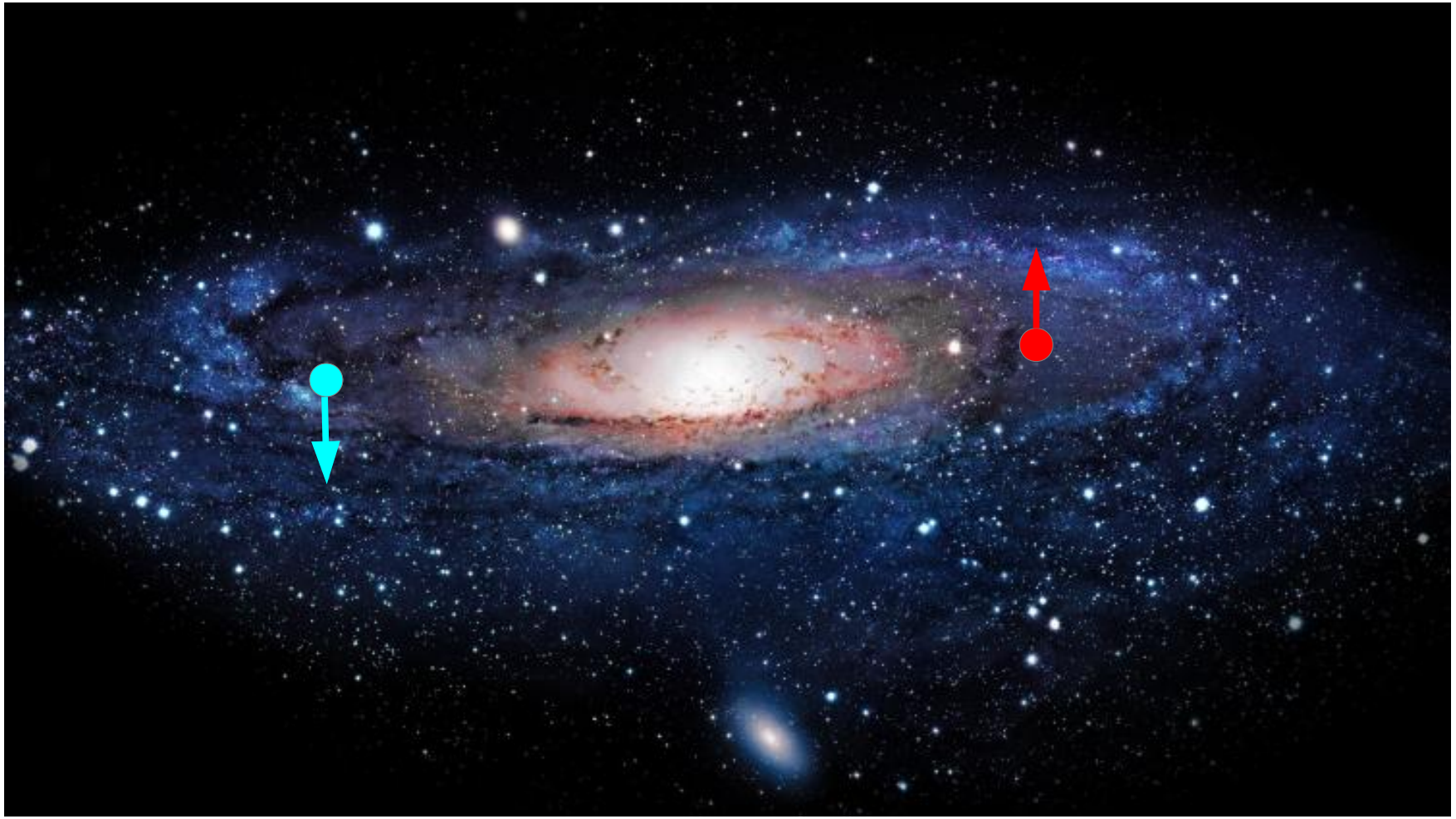
Blue shifted = coming towards us
Red shifted = moving away from us

Galaxies

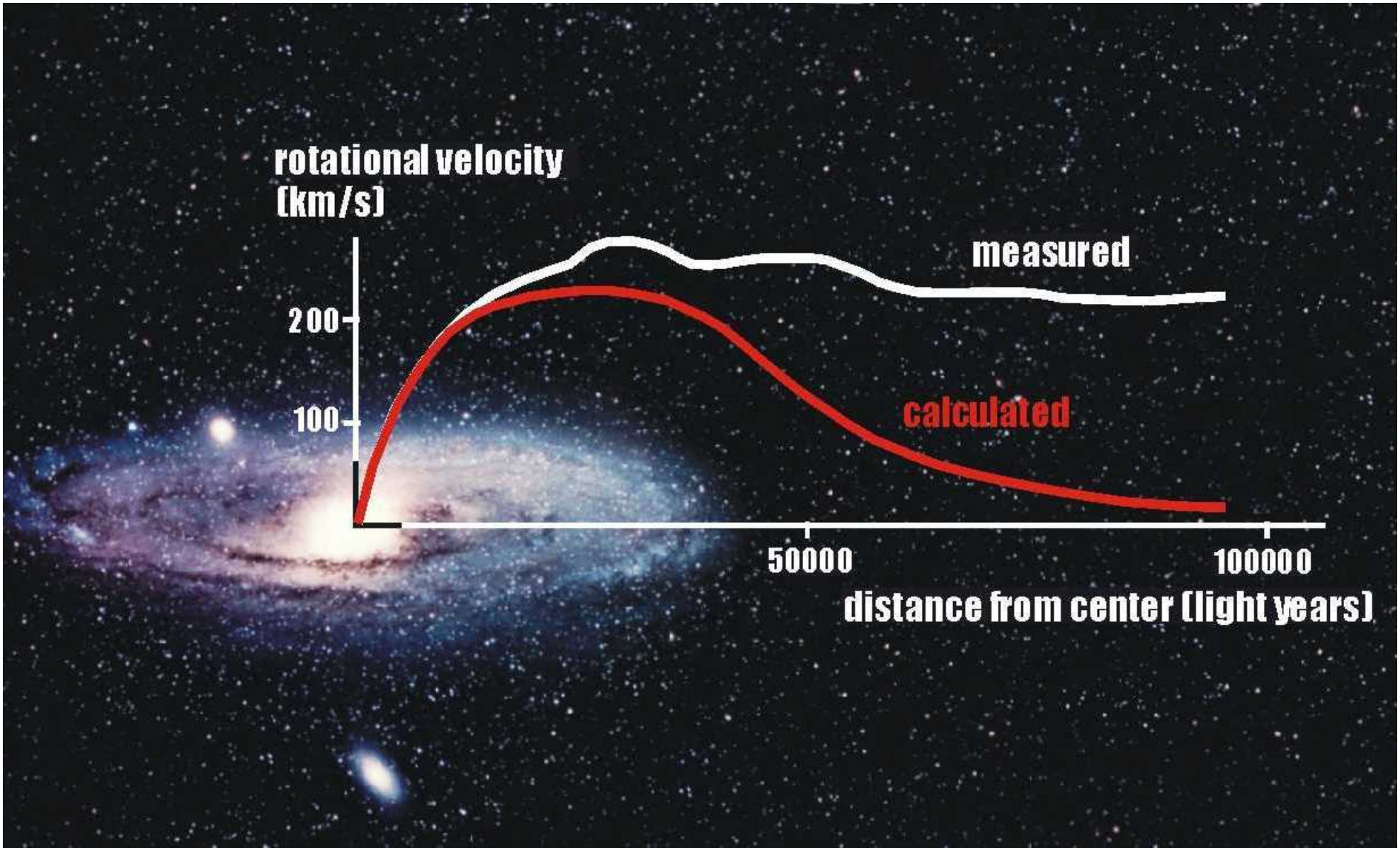
We can measure the rotation of galaxies

Blue shifted = coming towards us

Red shifted = moving away from us



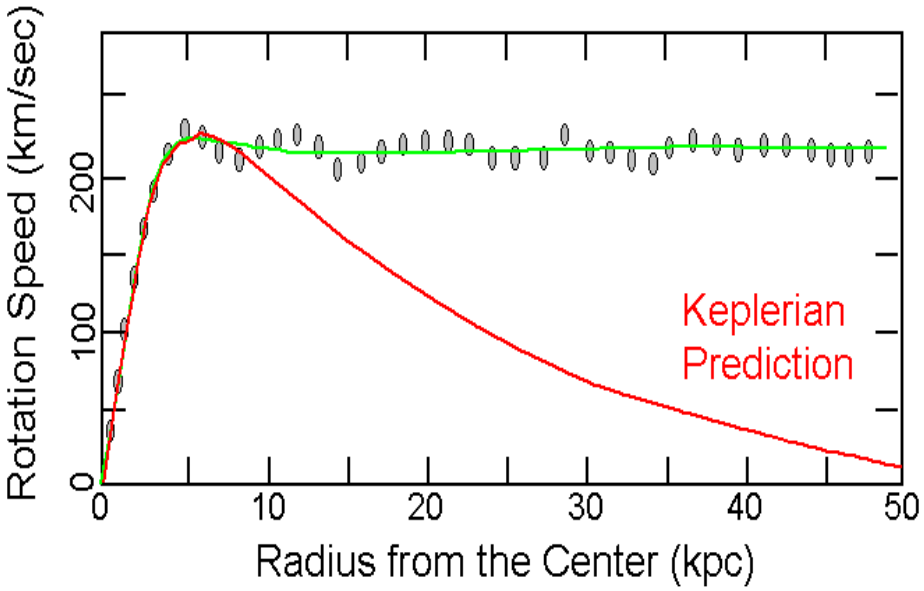
Galaxy rotation



Galaxy rotation

$$v = \sqrt{\frac{GM}{r}}$$

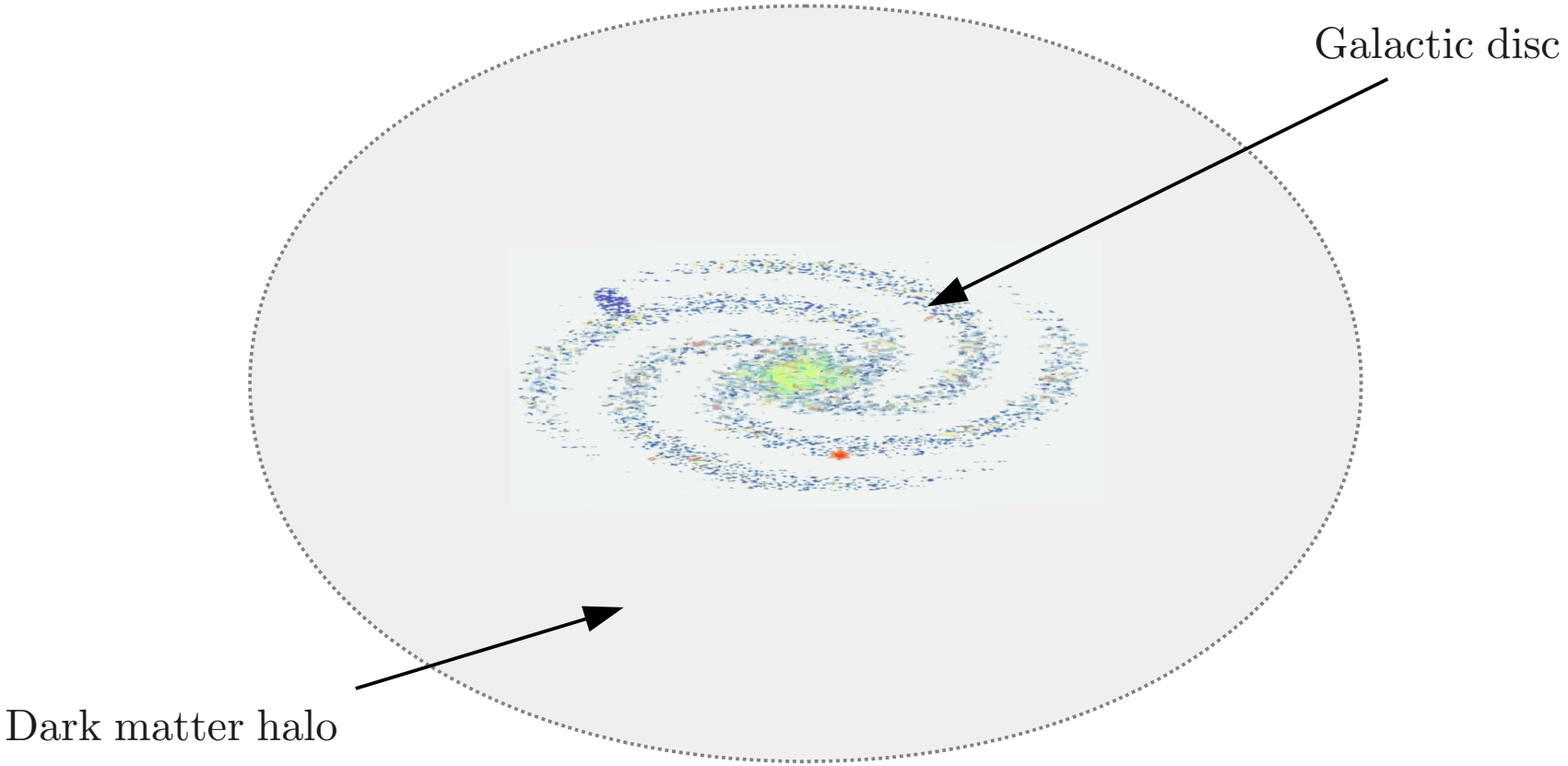
$v(r) = constant$ with increasing r



M must also be increasing with r

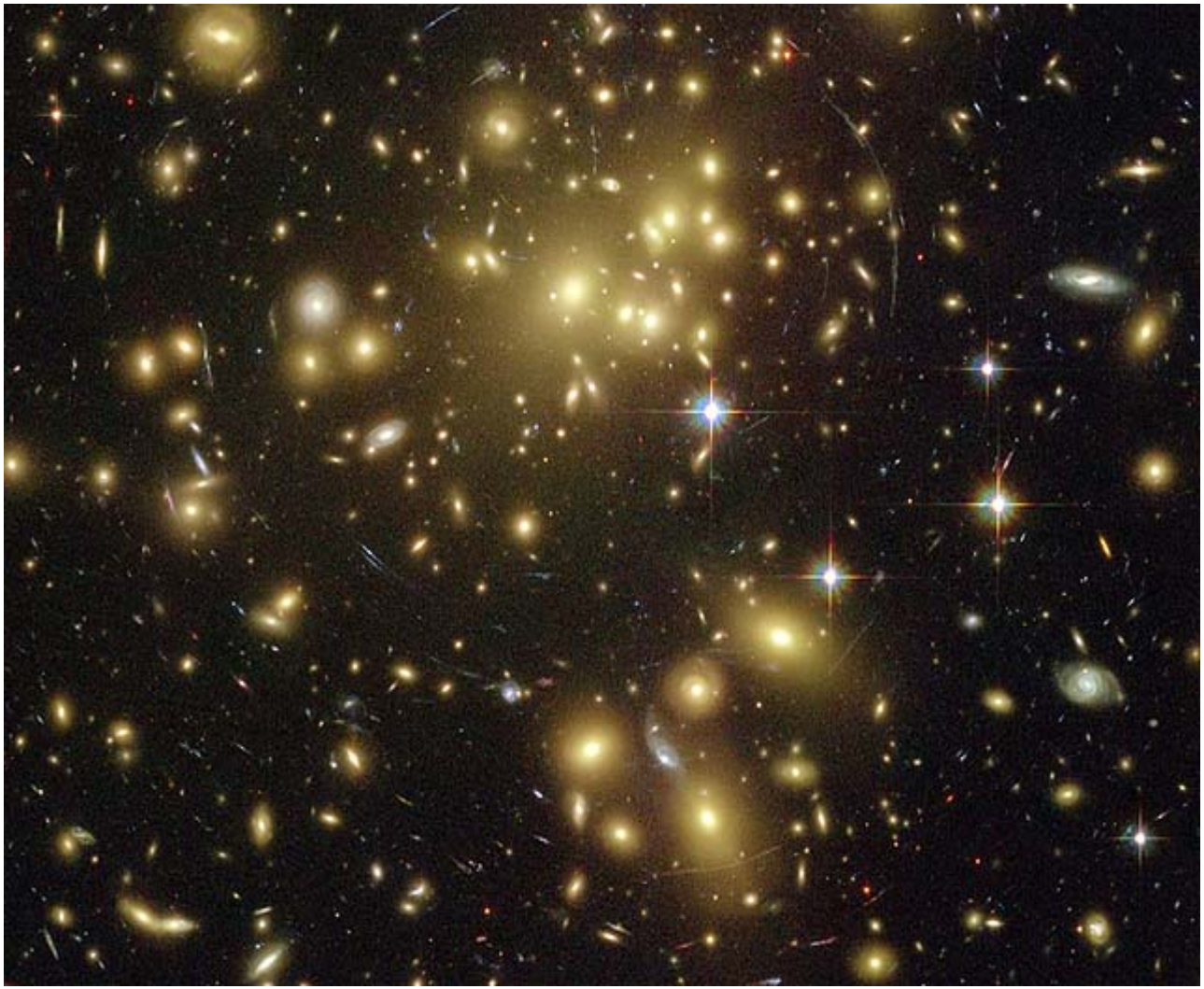
Dark matter halos

- Conclusion: galaxies are embedded in a halo of invisible mass – dark matter



Galaxy clusters

- Galaxies gravitationally bound together
- between **50-1,000** galaxies of all sizes

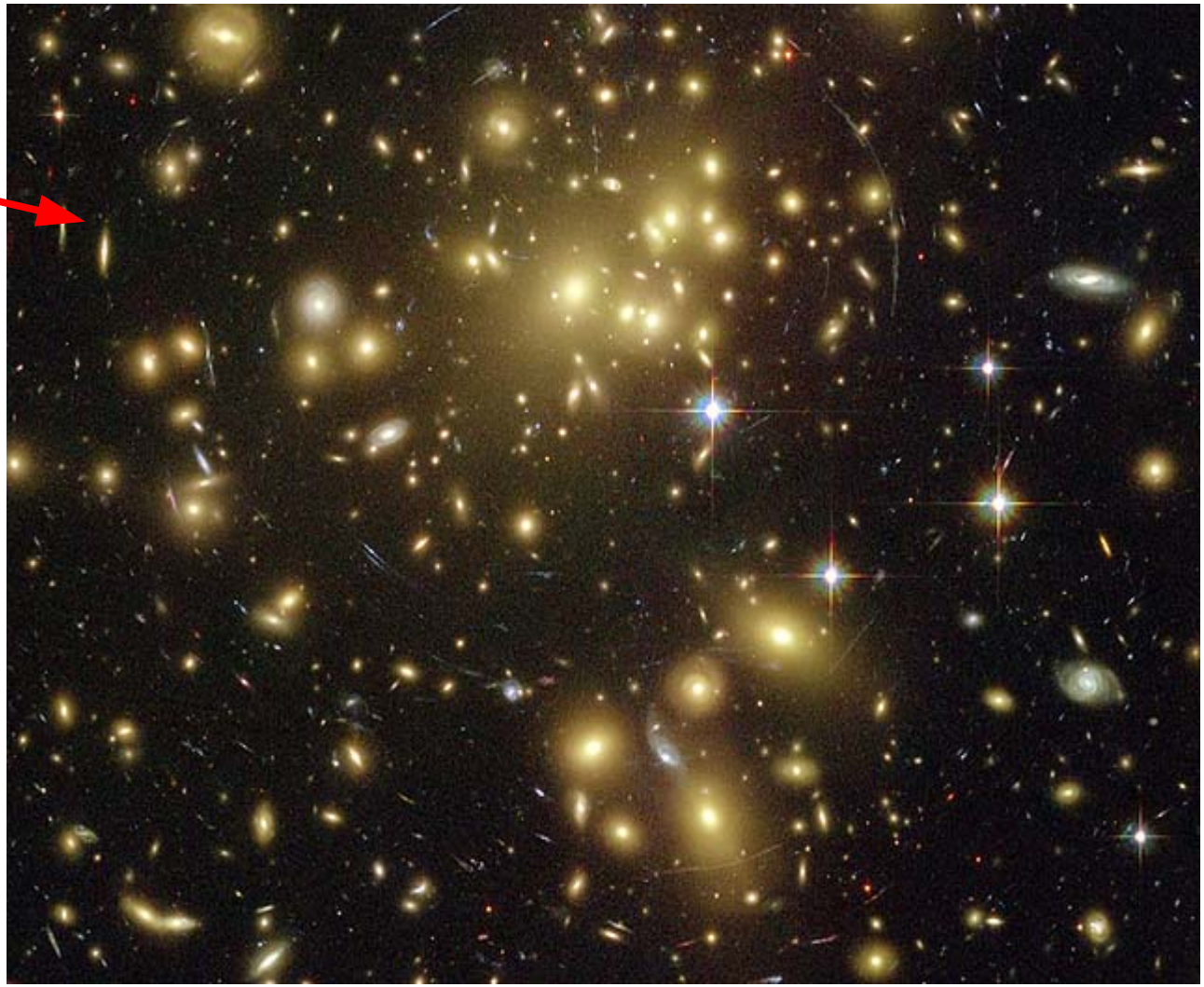


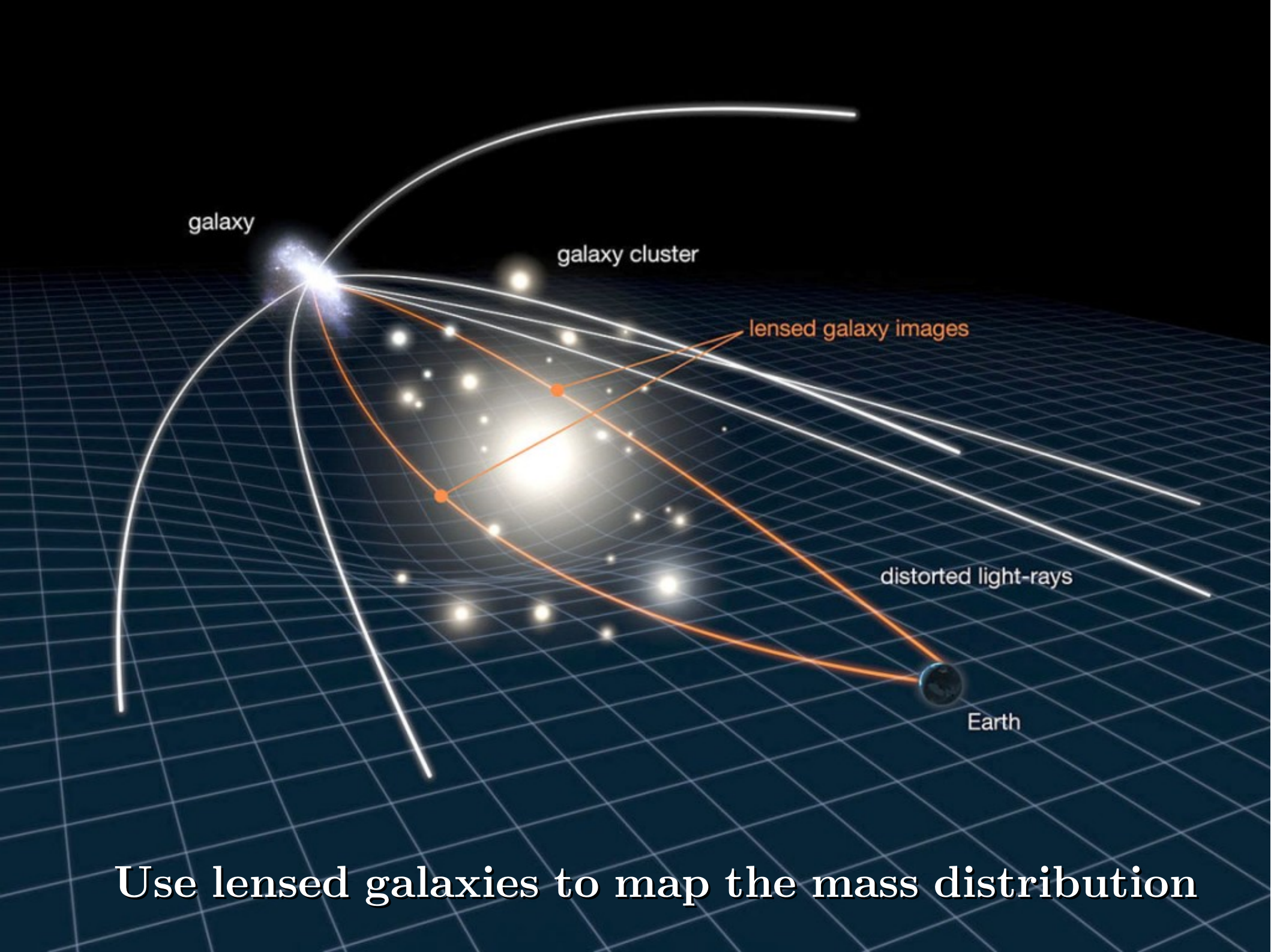
Composition
- 90% dark matter
- 9% hot plasma
- 1% galaxies

Gravitational lensing

- Einstein's general relativity says that light is bent by gravitational fields

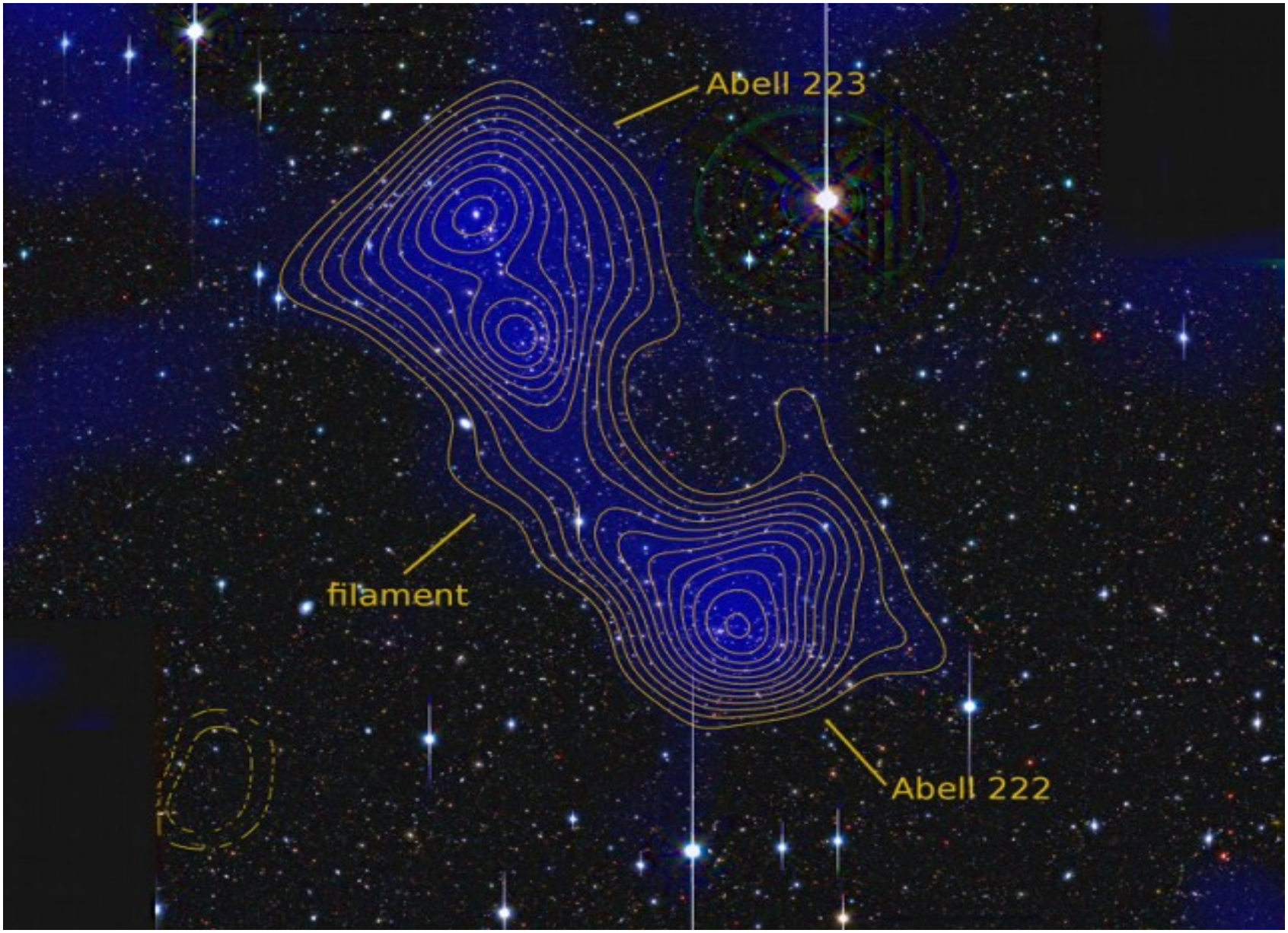
Normally too small to notice – but galaxy clusters are *very* massive **10^{14} – 10^{15} solar masses!**





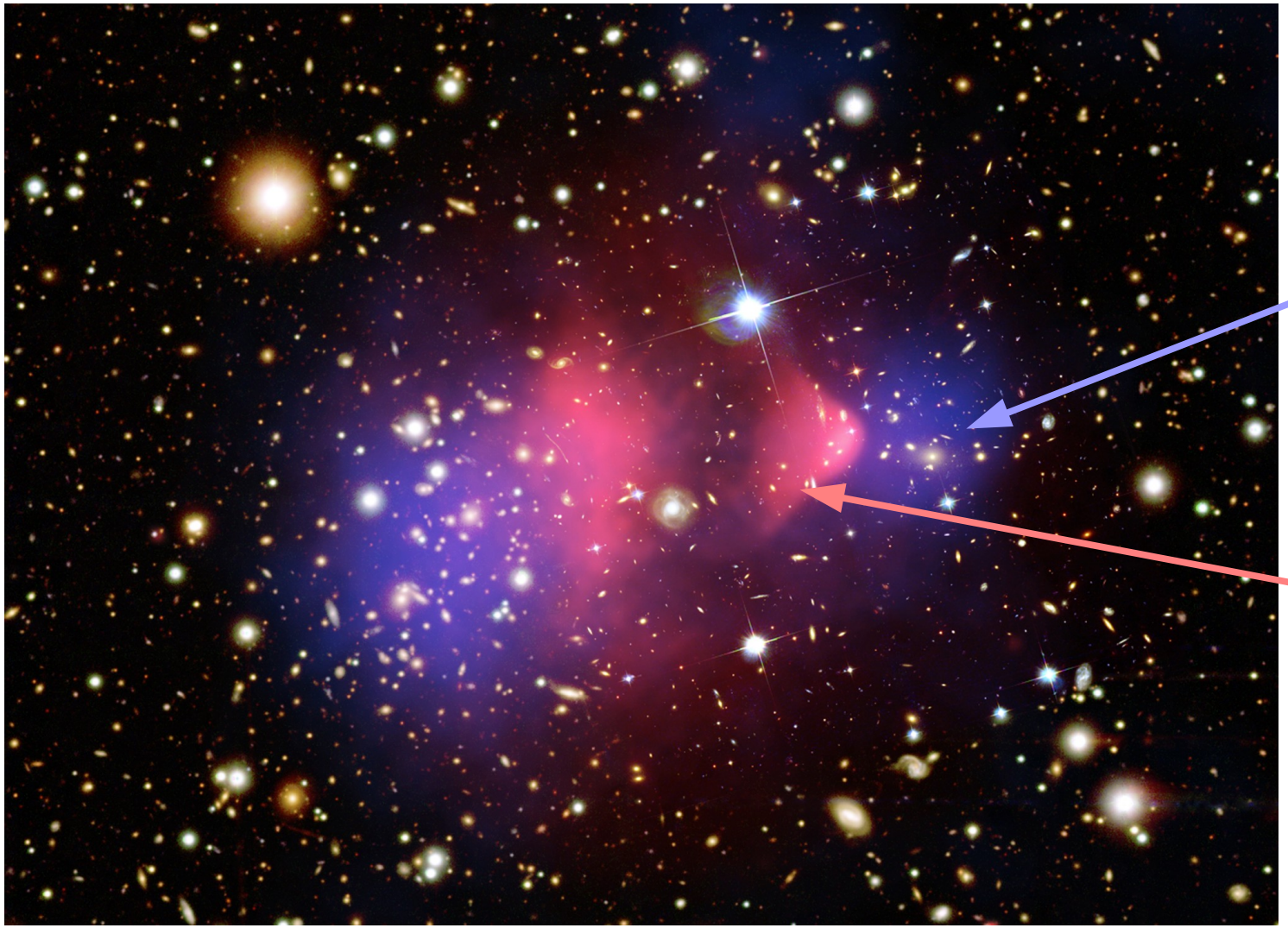
Use lensed galaxies to map the mass distribution

More evidence for dark matter



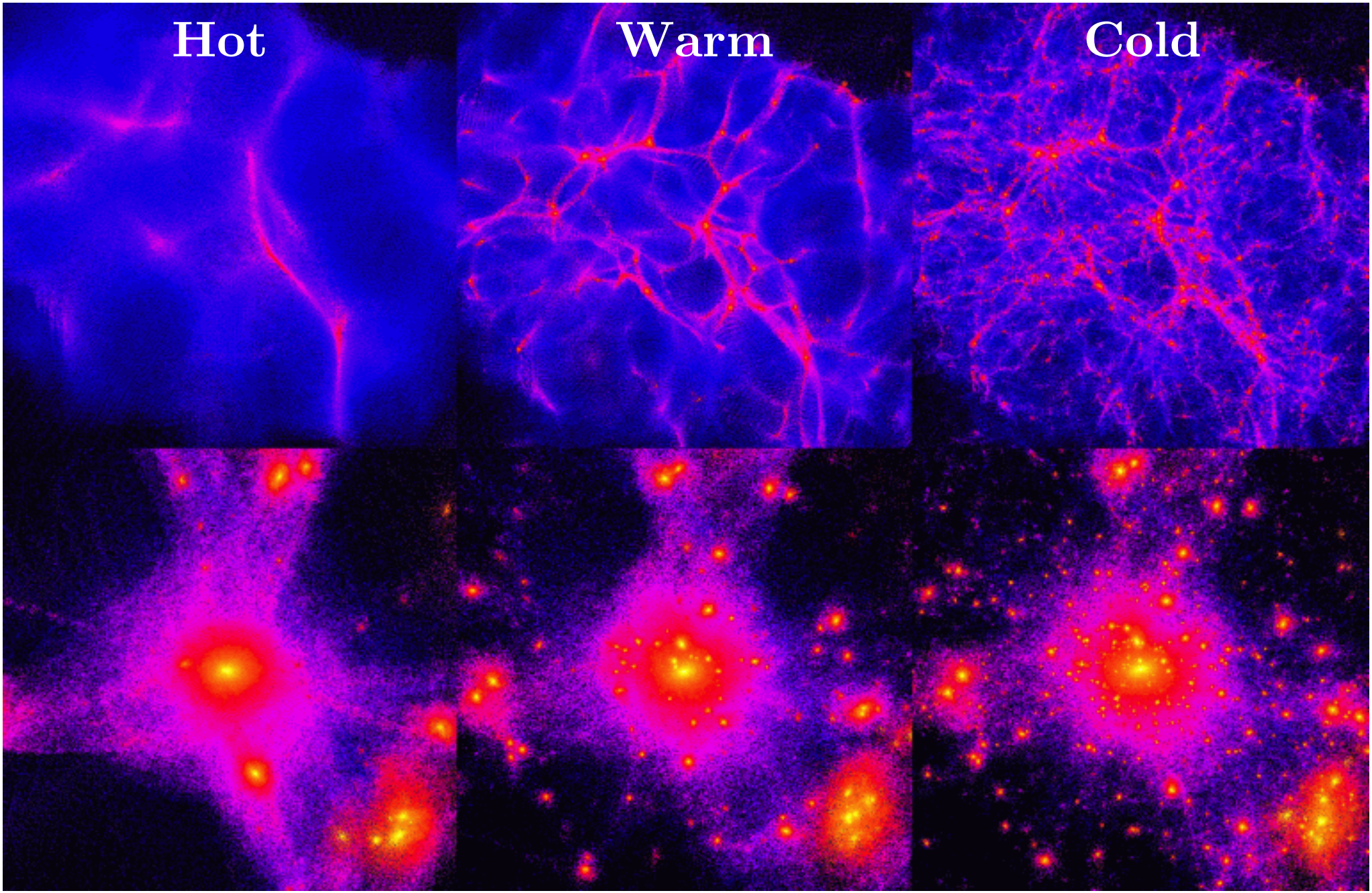
Is it definitely a particle?

- Bullet cluster - colliding clusters of galaxies



- Good evidence that dark matter is a ***particle***

Dark matter cosmology



Movie...

Summary so far...

- Around 5 times more dark matter than normal matter
- It exists in halos around galaxies
- Contributes most of the mass in galaxy clusters
- Does not interact with normal matter
- Seeds the formation of structure in the Universe(!)

It's probably a particle – but what is it?

Part III

What is dark matter made of...

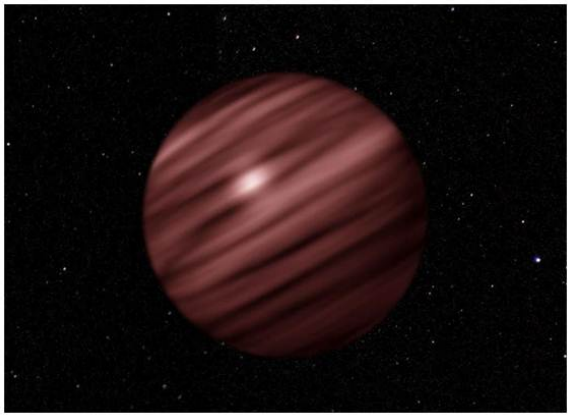
Known properties

- Massive
- Stable
- Invisible
- Cold

What out there has these properties

What about stuff that isn't stars?

- Planets, rocky objects
- Brown dwarfs
- Gas, dust
- Black holes



Fall under the umbrella term MACHOs

But there isn't enough to account for dark matter

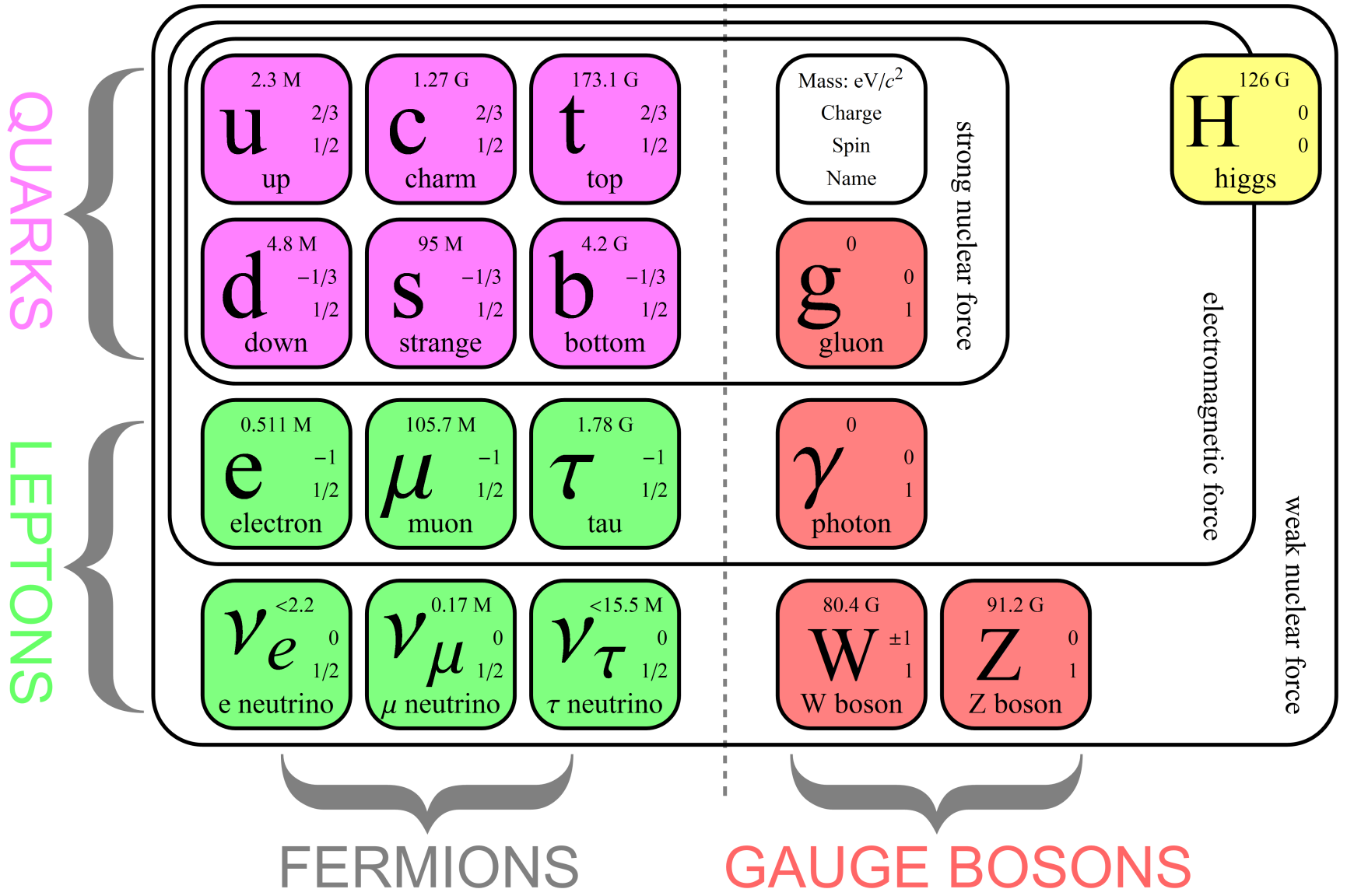
Known properties

- Massive
- Stable
- Invisible
- Cold

Nothing we know about has these properties
Dark matter must be exotic

The standard model

- Dark matter must be exotic, but what is exotic?

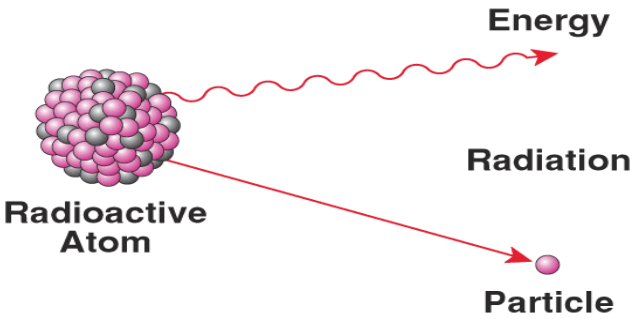


Four forces

Gravity

- Particle: graviton (not discovered)
- ***Very*** weak, infinite range

Weak

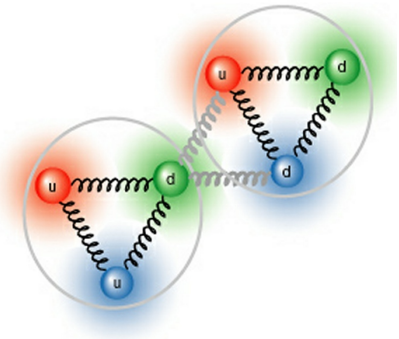


- Particles: W and Z bosons
- Weak, very short range

Electromagnetism

- Particle: photon
- Strong, infinite range

Strong



- Particle: gluon
- Very strong, very short range

Particle candidates

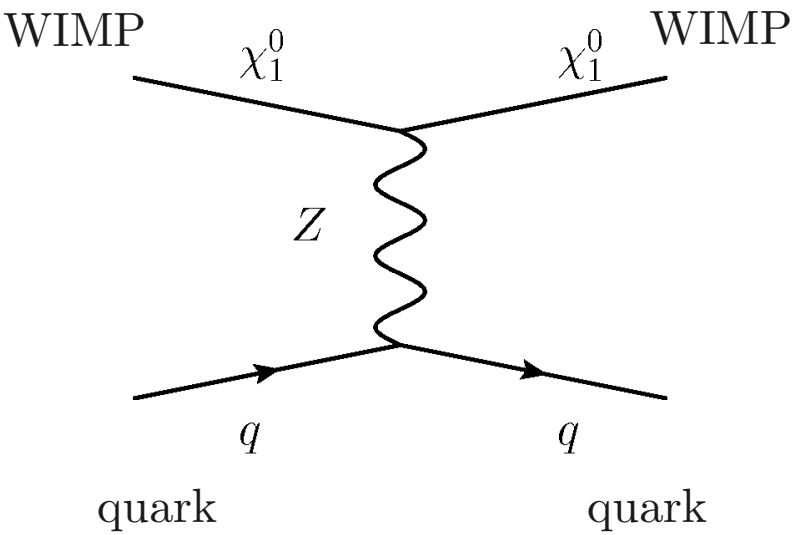
- Theorists have come up with a range of different candidates for dark matter
- The favourite at the moment is the **WIMP**

Weakly **I**nteracting **M**assive **P**article

- These show up in models of ***string theory*** and ***supersymmetry***

Weakly **I**nteracting **M**assive **P**articles

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



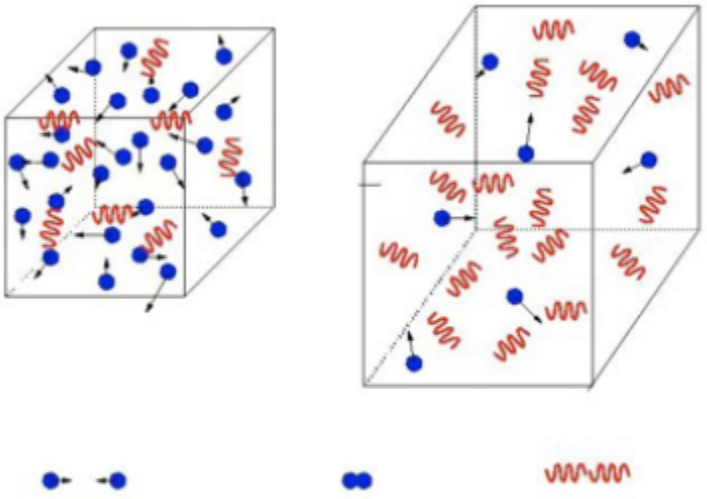
Weakly **I**nteracting **M**assive **P**articles

- They are their own anti-particle
- They annihilate each other if density is high enough
- "freeze out" as Universe expands

WIMPs

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

Standard model particles

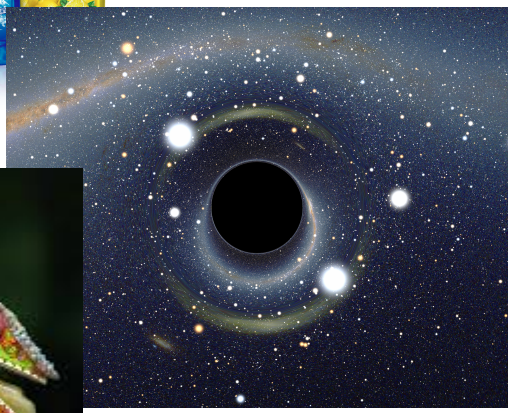


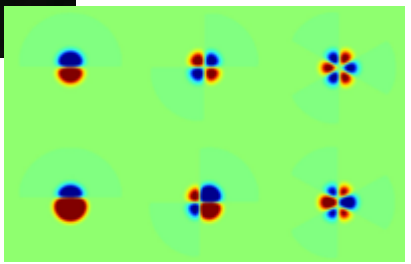
Calculated freeze out number matches observed value!

But what if it's not a WIMP?

- Well, physicists are inventive...
  - ***Axions***
  - ***Primordial black holes***
  - ***SIMPs***
  - ***ALPs***
  - ***WIMPZILLAs***
  - ***Chameleons***
  - ***WISPs***
  - ***CHAMPs***
  - ***Q-balls***
  - ***MACHOs***
  - ***RAMBOs***

  the list goes on...





Part IV

What are we doing to find it?

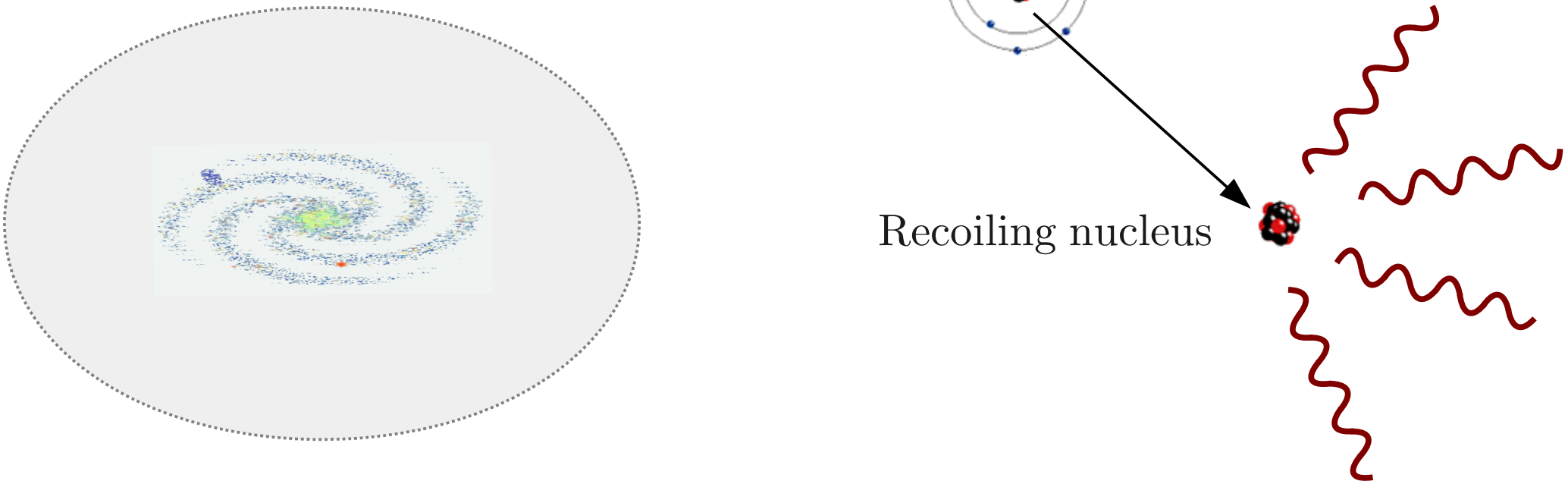
Detecting dark matter

- If dark matter is a WIMP it will have weak interactions with normal matter – we can detect these

  - Direct detection
  - Indirect detection
  - Production

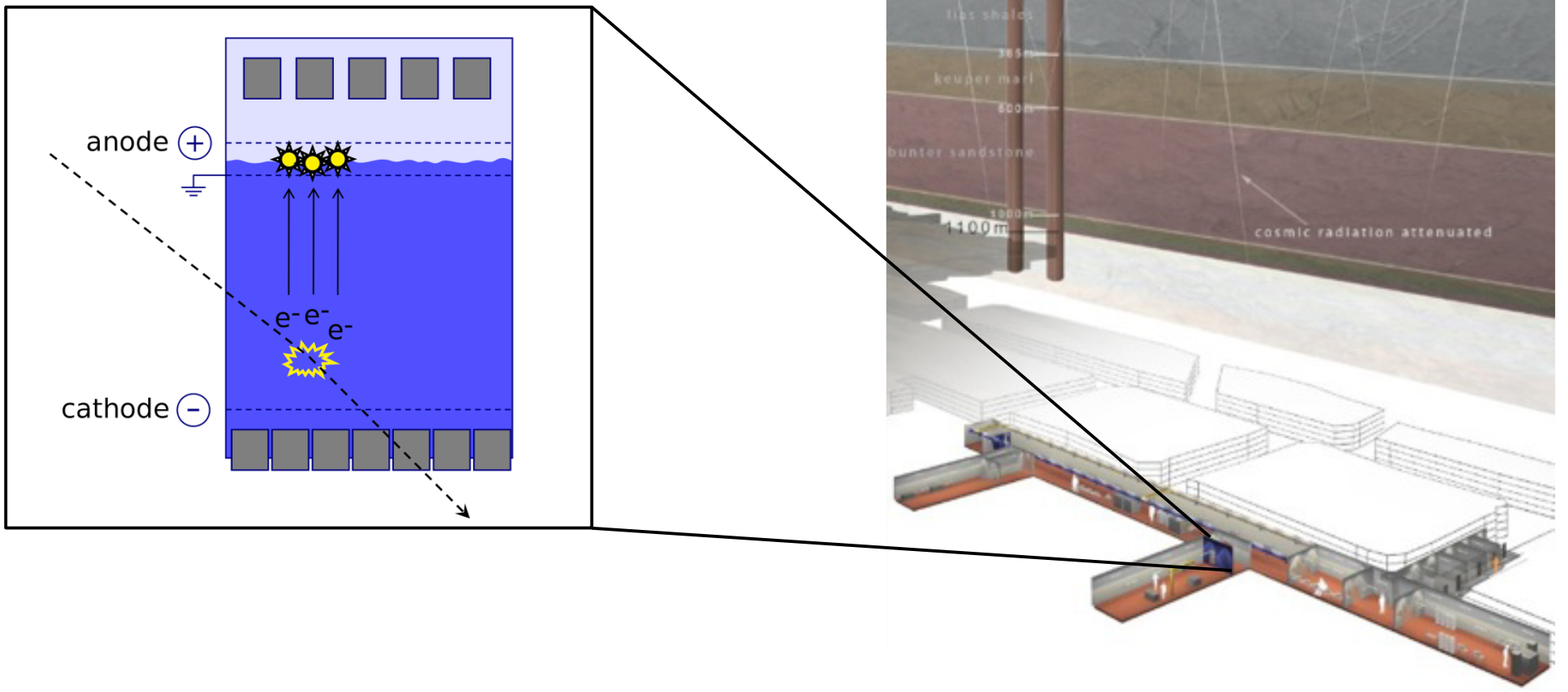
1. Direct detection

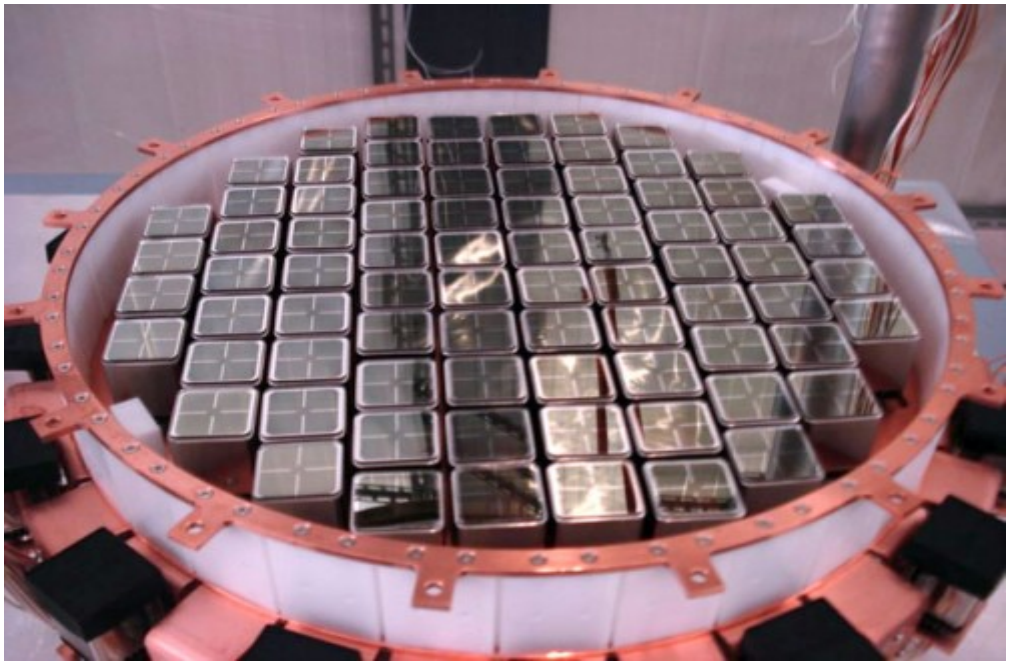
- Wait for a WIMP in our own Galactic halo to hit a nucleus on Earth



1. Direct detection

- WIMPs interact ***very*** rarely (see question sheet)
- Need to bury experiments deep underground to shield from backgrounds

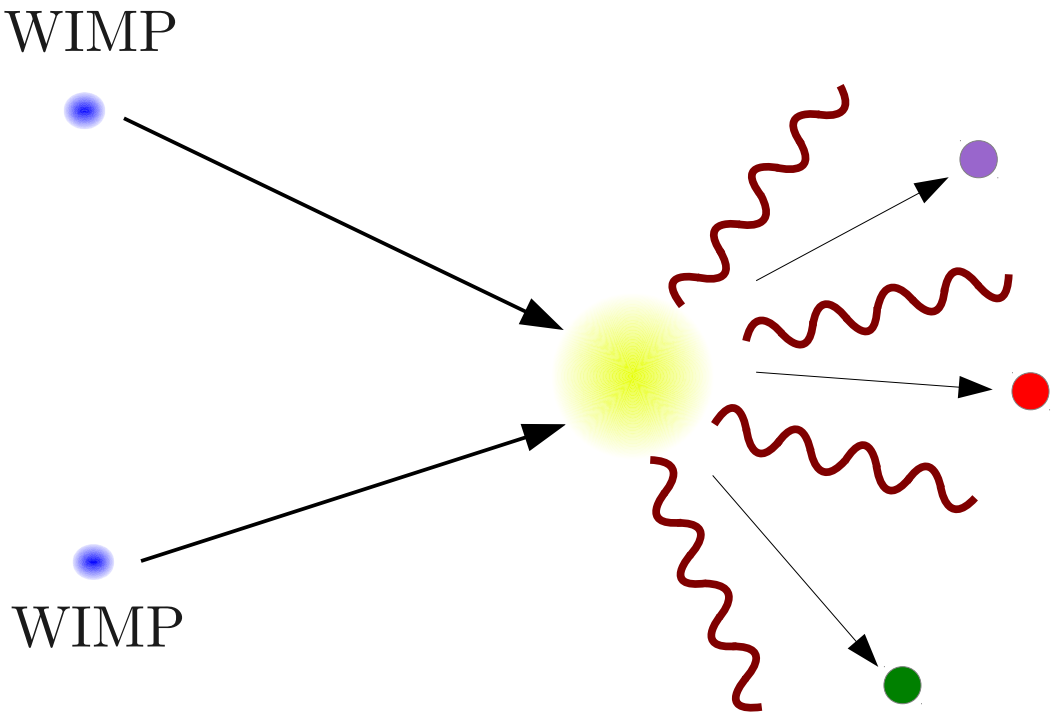





HOMESTAKE
LUX
APRIL 19-20, 2013

2. Indirect detection

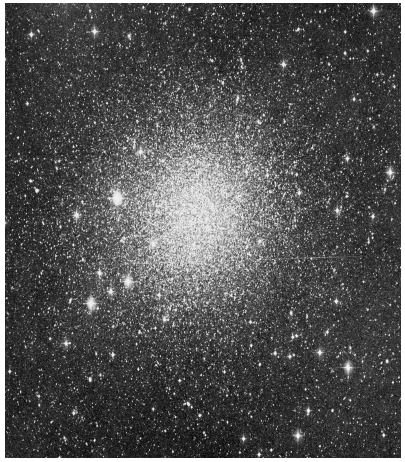
- WIMPs are their own anti-particle
- Look for WIMP annihilations in space



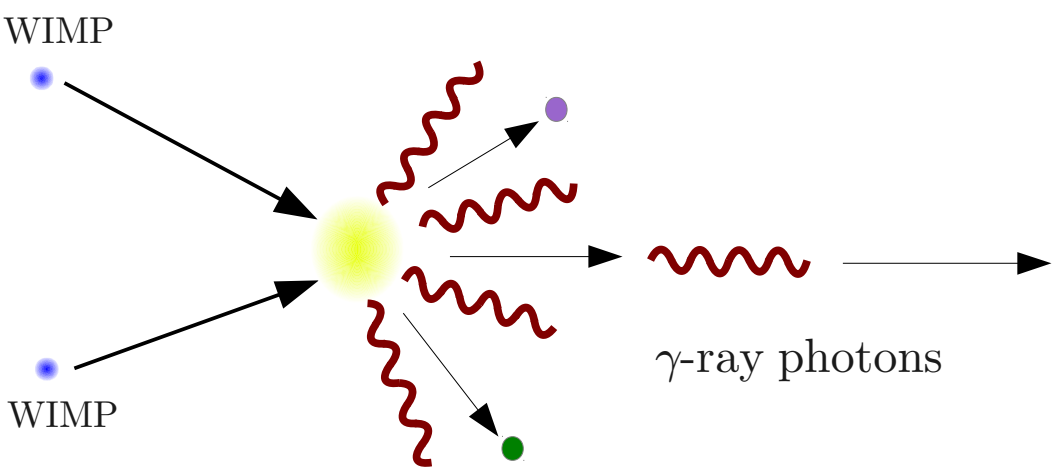
Photons, electrons, positrons, neutrinos...

2. Indirect detection

- Normally very rare but in dense clouds of dark matter we expect see dark matter annihilating

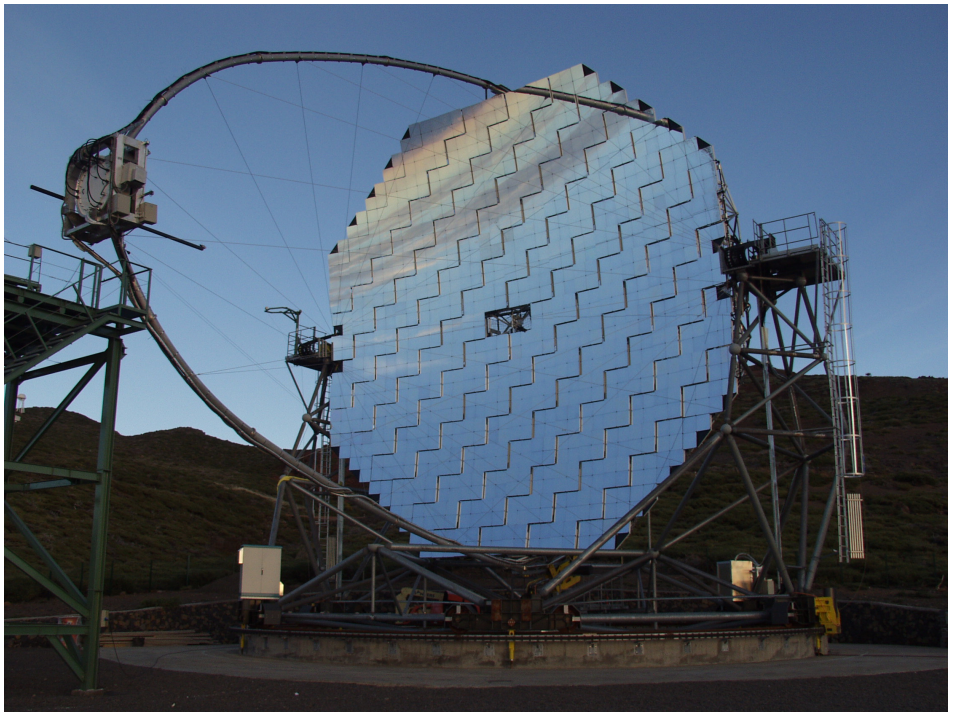


Dark matter halo

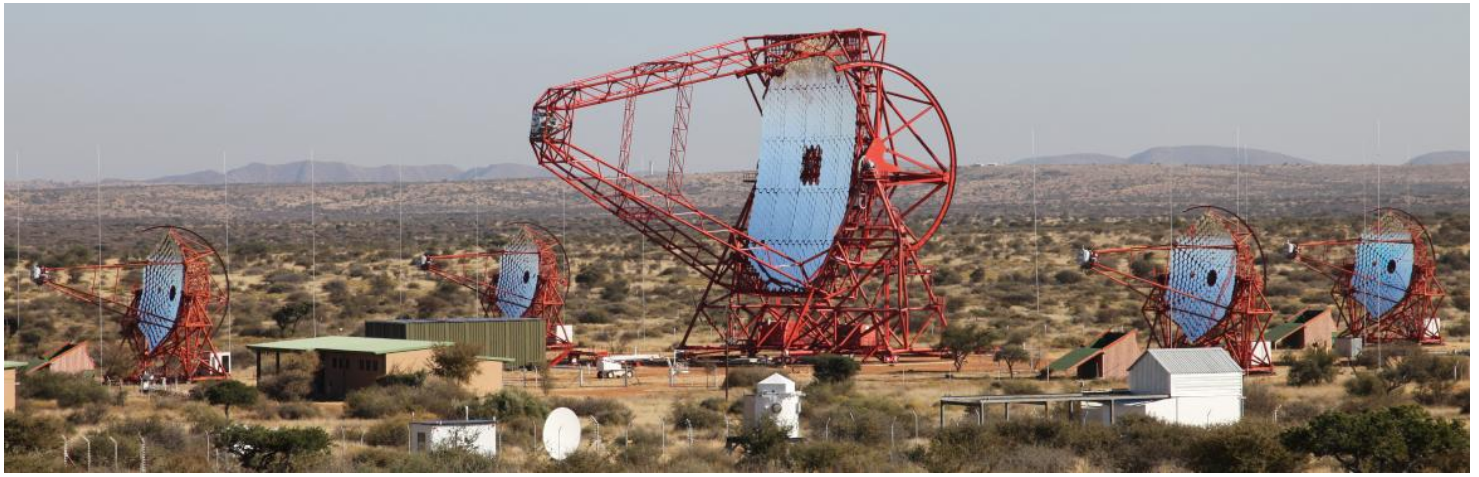


Telescope

Fermi telescope



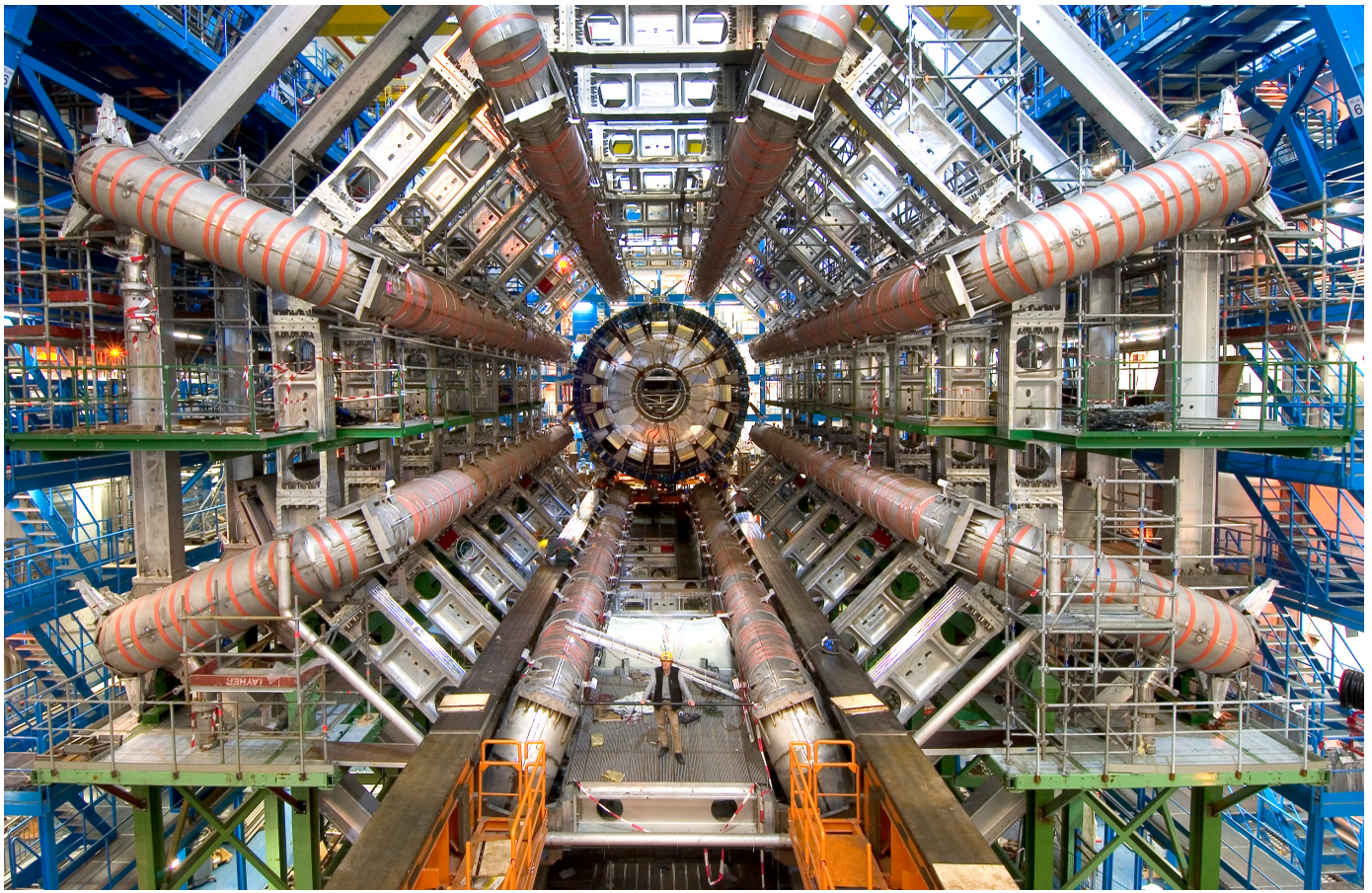
MAGIC



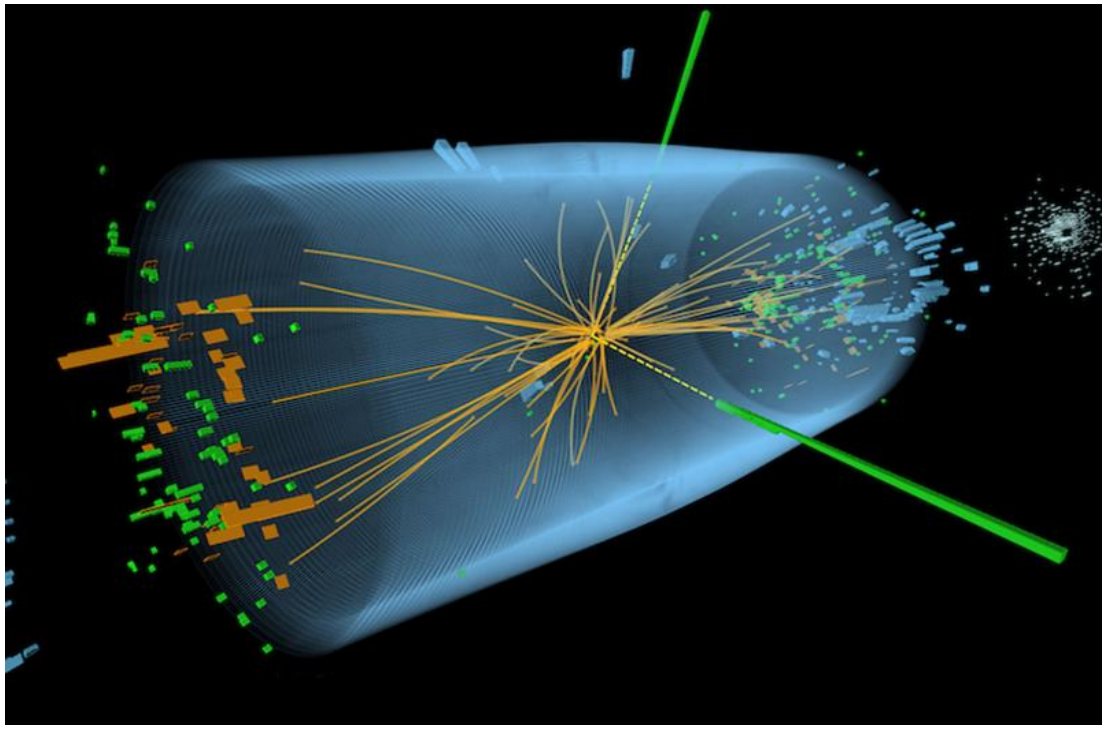
HESS

3. Dark matter production

- Large Hadron Collider recreates conditions a few seconds after the Big Bang
- Can we create dark matter in the LHC?



3. Dark matter production



- Look for missing energy in particle collisions

E_{initial} = energy of initial beams

E_{final} = energy of debris

$E_{initial}$ - E_{final} = $\text{m}_{\text{dm}}\text{c}^2$

LHC started its 14 TeV run on June 3 so stay tuned!

Summary

- Best dark matter candidate is the WIMP
- We are working on experiments to detect it
  - Direct detection – in underground labs
  - Indirect detection – in space
  - Production – at the LHC

Good prospects for discovery in the next few years!

Extra stuff

- Detecting dark matter in the lab
- Extra dimensions
- Supersymmetry
- Primordial black holes
- Axions
- Dark matter inside stars
- Dark energy