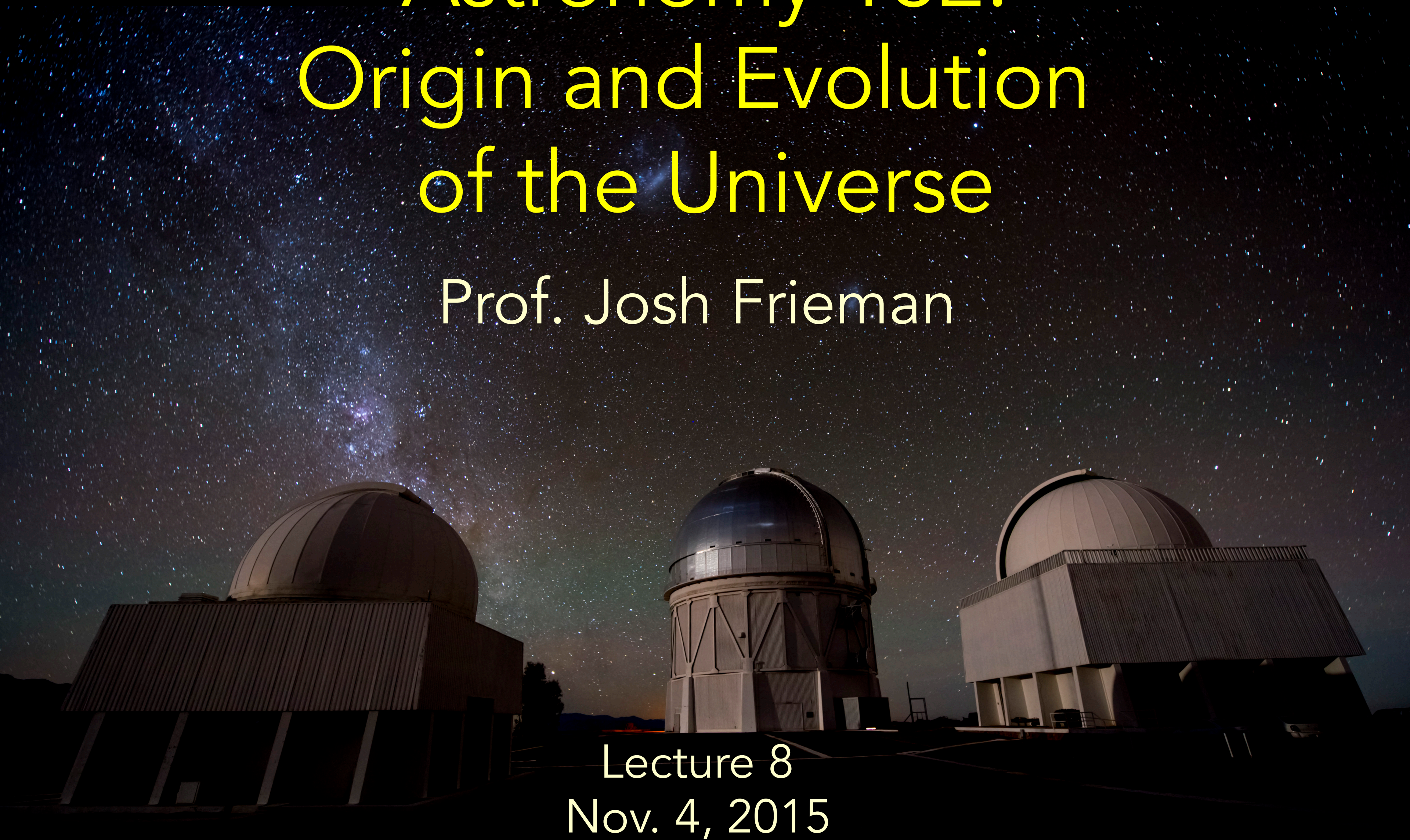
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 8

Nov. 4, 2015

Today

- Dark Side of the Universe I: Dark Matter
- Dark Side of the Universe II: Dark Energy

Assignments

- This week: read Hawley and Holcomb, Chapters 13, 15.
- This Fri., Nov. 6: Essay due on HH, Chapter 8.

The Light-Beam Rider

By WALTER ISAACSON OCT. 30, 2015

THIS month marks the 100th anniversary of the General Theory of Relativity, the most beautiful theory in the history of science, and in its honor we should take a moment to celebrate the visualized "thought experiments" that were the navigation lights guiding Albert Einstein to his brilliant creation. Einstein relished what he called Gedankenexperimente, ideas that he twirled around in his head rather than in a lab. That's what teachers call daydreaming, but if you're Einstein you get to call them Gedankenexperimente.

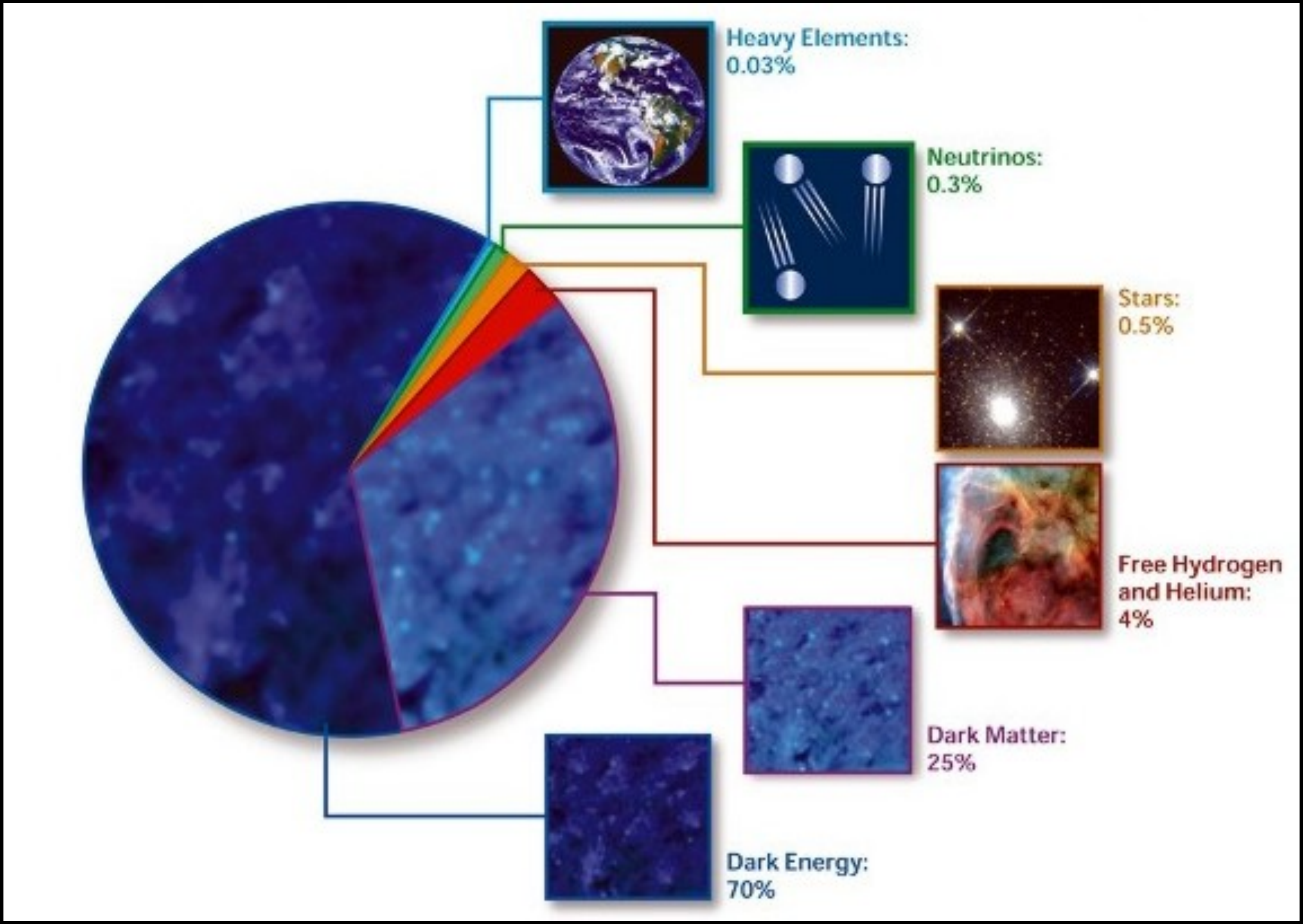
As these thought experiments remind us, creativity is based on imagination. If we hope to inspire kids to love science, we need to do more than drill them in math and memorized formulas. We should stimulate their minds' eyes as well. Even let them daydream.

Contents of the Universe

- To determine the evolution of the Universe, we need to know what forms of matter and energy there are:
    - Ordinary (baryonic) matter (stars, gas, planets, …, made of atoms)
    - Neutrinos
    - Electromagnetic Radiation (Cosmic Microwave Background)
    - Dark Matter
    - Dark Energy
- and how much there is of each:

$$\Omega_i = \frac{\rho_i}{\rho_{crit}} = \frac{\rho_i}{(3H_0^2/8\pi G)}$$

Contents of the Universe



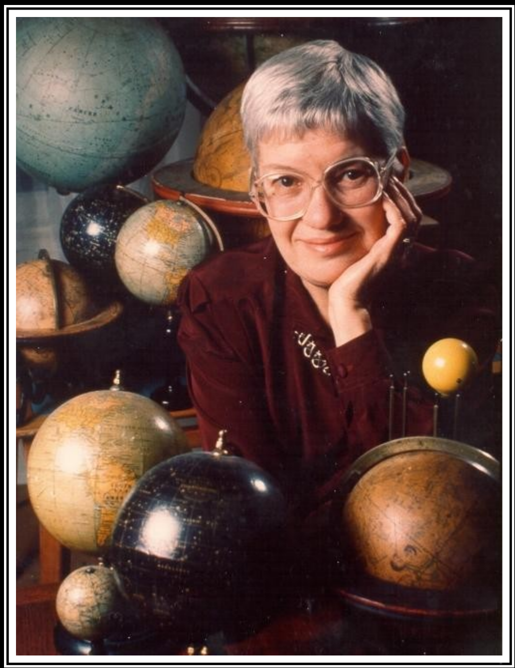
Dark Matter

- A component that does not interact with (emit or absorb) light but whose presence is inferred from its gravitational effect on luminous matter or light.
- 1930's: initial evidence for dark matter (clusters)
- 1970's-80's: mounting evidence for dark matter (spiral galaxy rotation curves)
- 1990's-2000's: confirmation via gravitational lensing and cosmological measurements

Dark Matter (F. Zwicky)

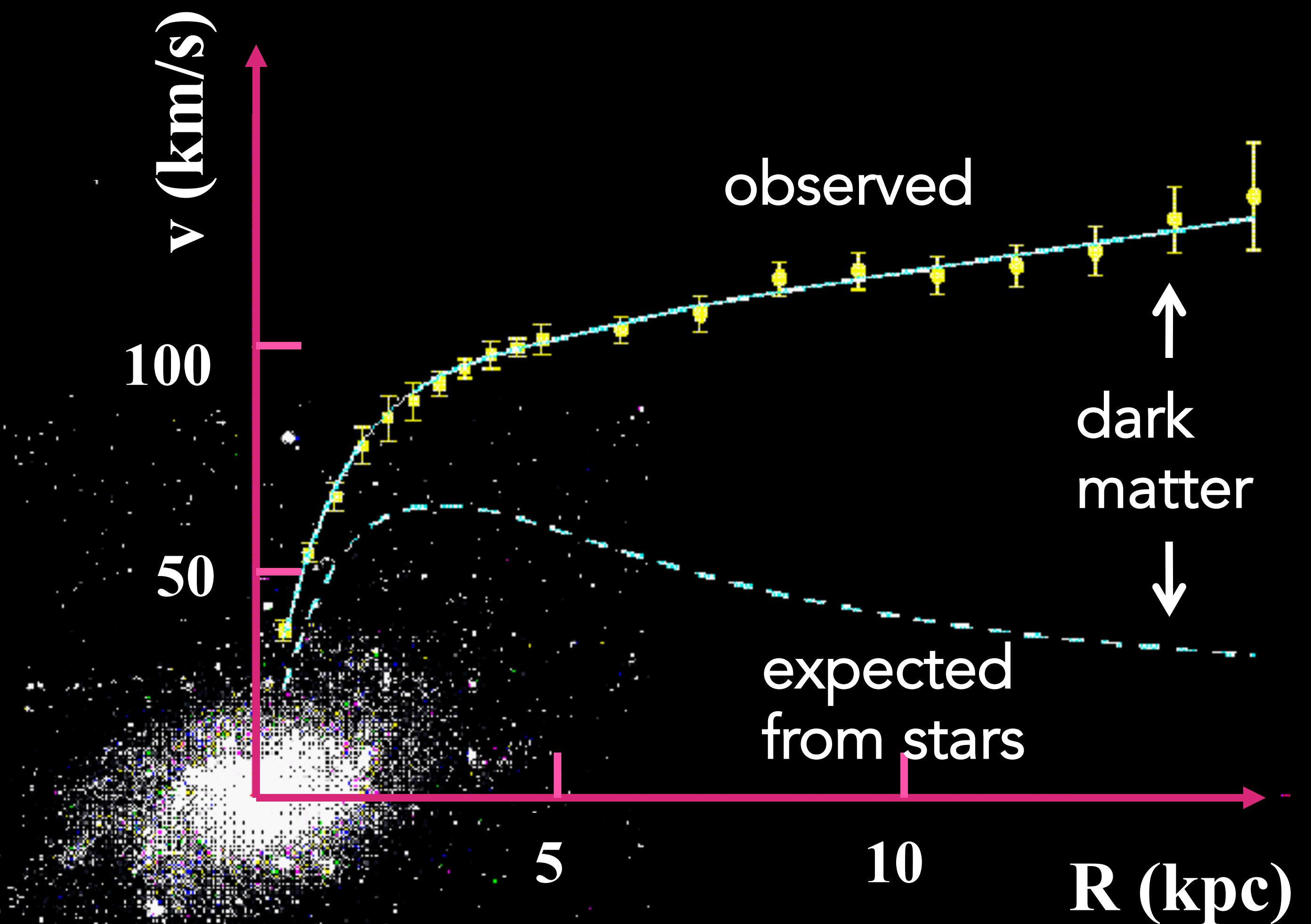
- The galaxies in Coma cluster are moving around faster than we can explain.
- The gravity of something *that we can't see* must be keeping the galaxies from flying off into space: Dark Matter
- Clusters are mostly made of dark matter: galaxies are like sprinkles on dark matter ice cream.
- We know dark matter is there because it exerts gravitational pull on the galaxies we can see in clusters.

Rotation of Stars around Galaxies



Vera Rubin
(1970's)

Galaxies surrounded by halos of dark matter



M33 rotation curve
(contrast Solar System)

Dark Matter (V. Rubin)

- The stars in a galaxy are moving around faster than we can explain.
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- Galaxies are mostly made of dark matter: stars are like sprinkles on dark matter ice cream.
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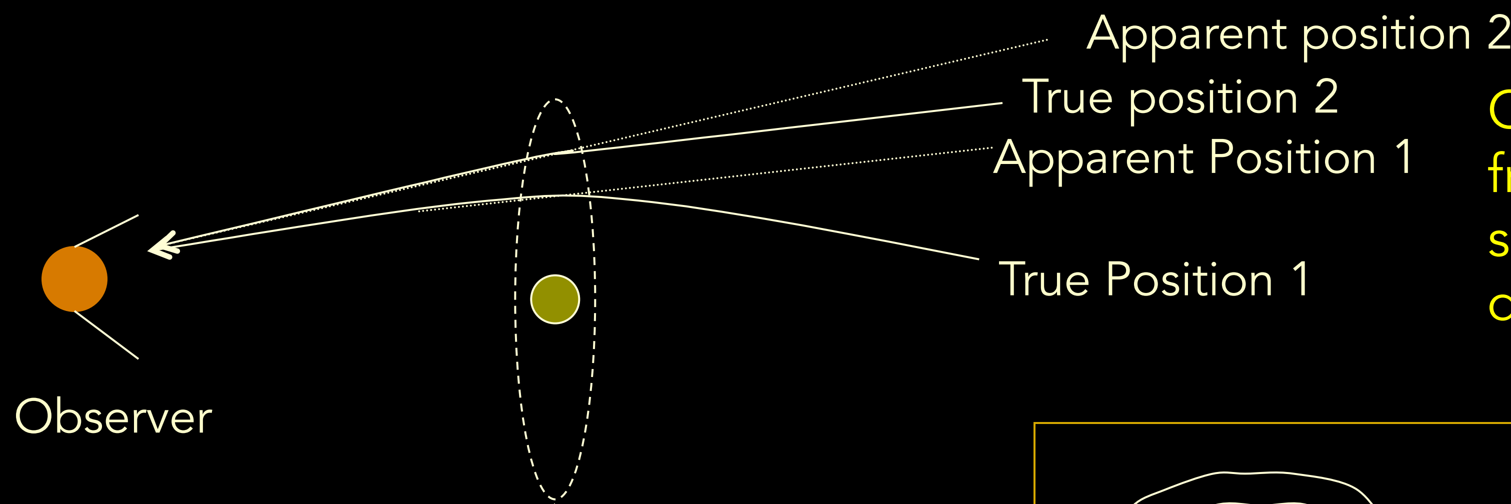
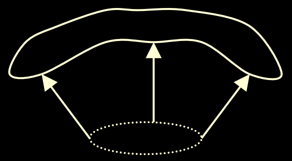
Gravitational Lensing



Objects farther from the line of sight are distorted less.

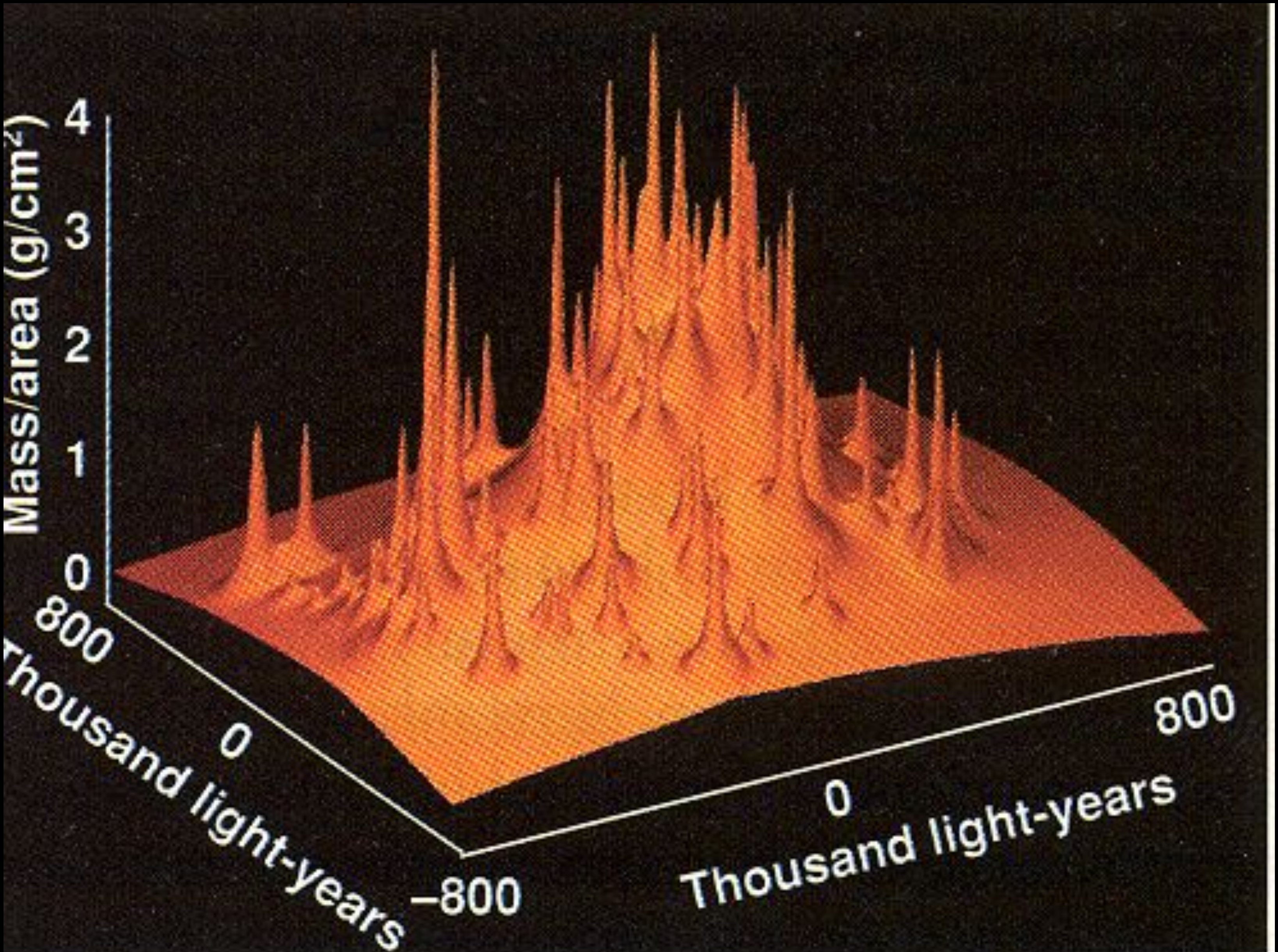


"Looking into" the lens: extended objects are tangentially distorted...

“Seeing” Dark Matter in a Cluster

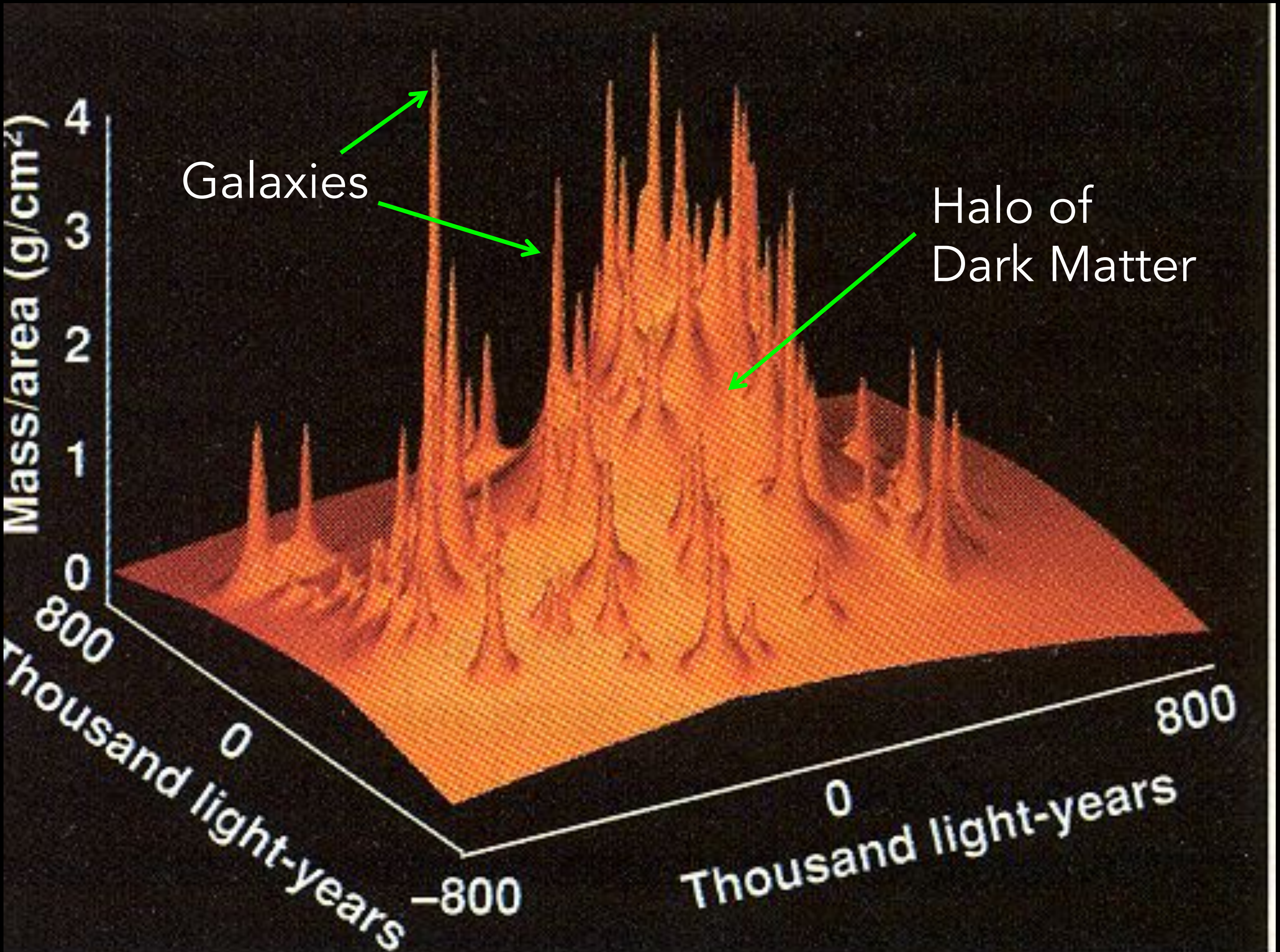
Mass Distribution in a Cluster of Galaxies

inferred from gravitational lensing



Mass Distribution in a Cluster of Galaxies

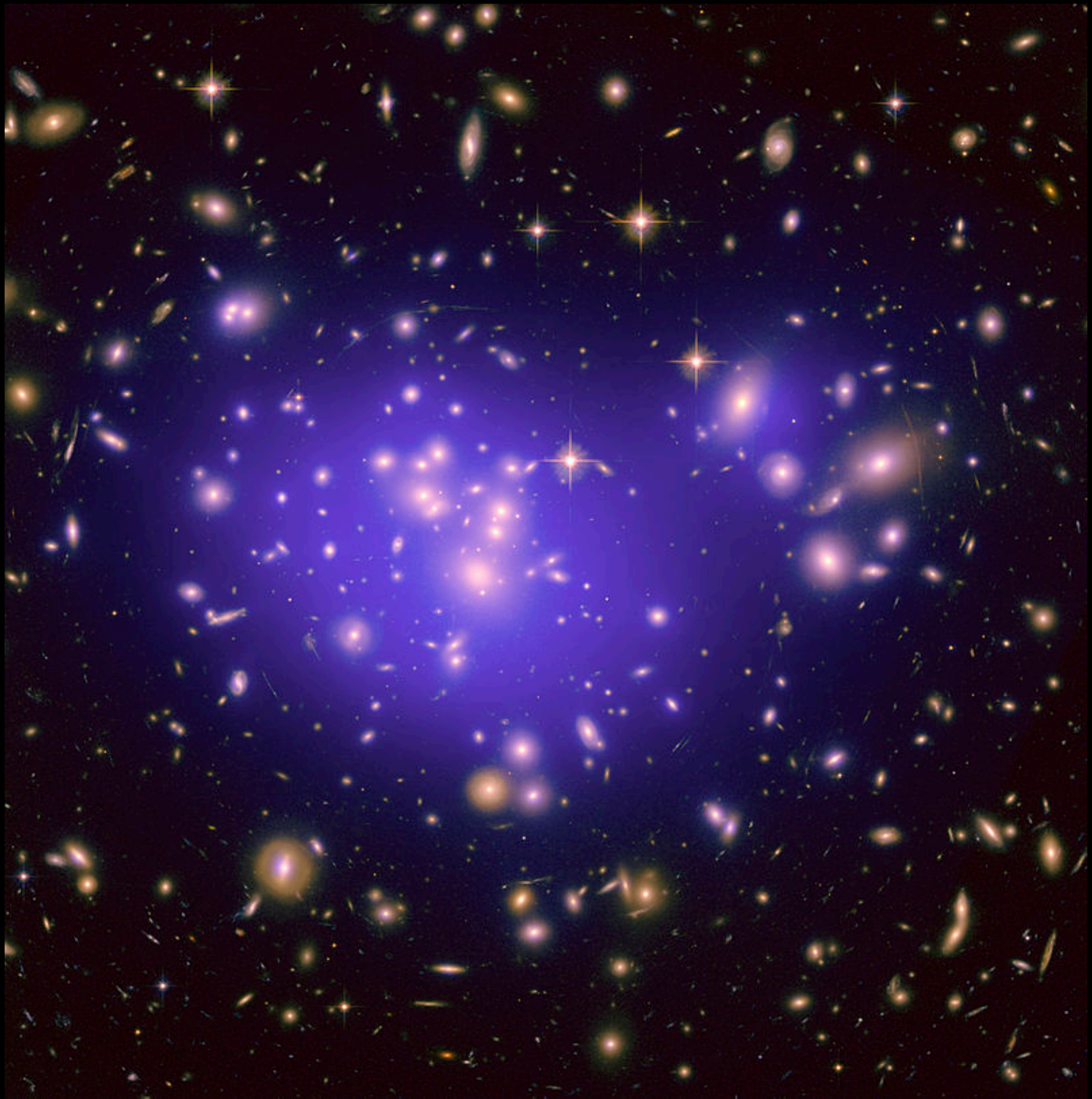
inferred from gravitational lensing



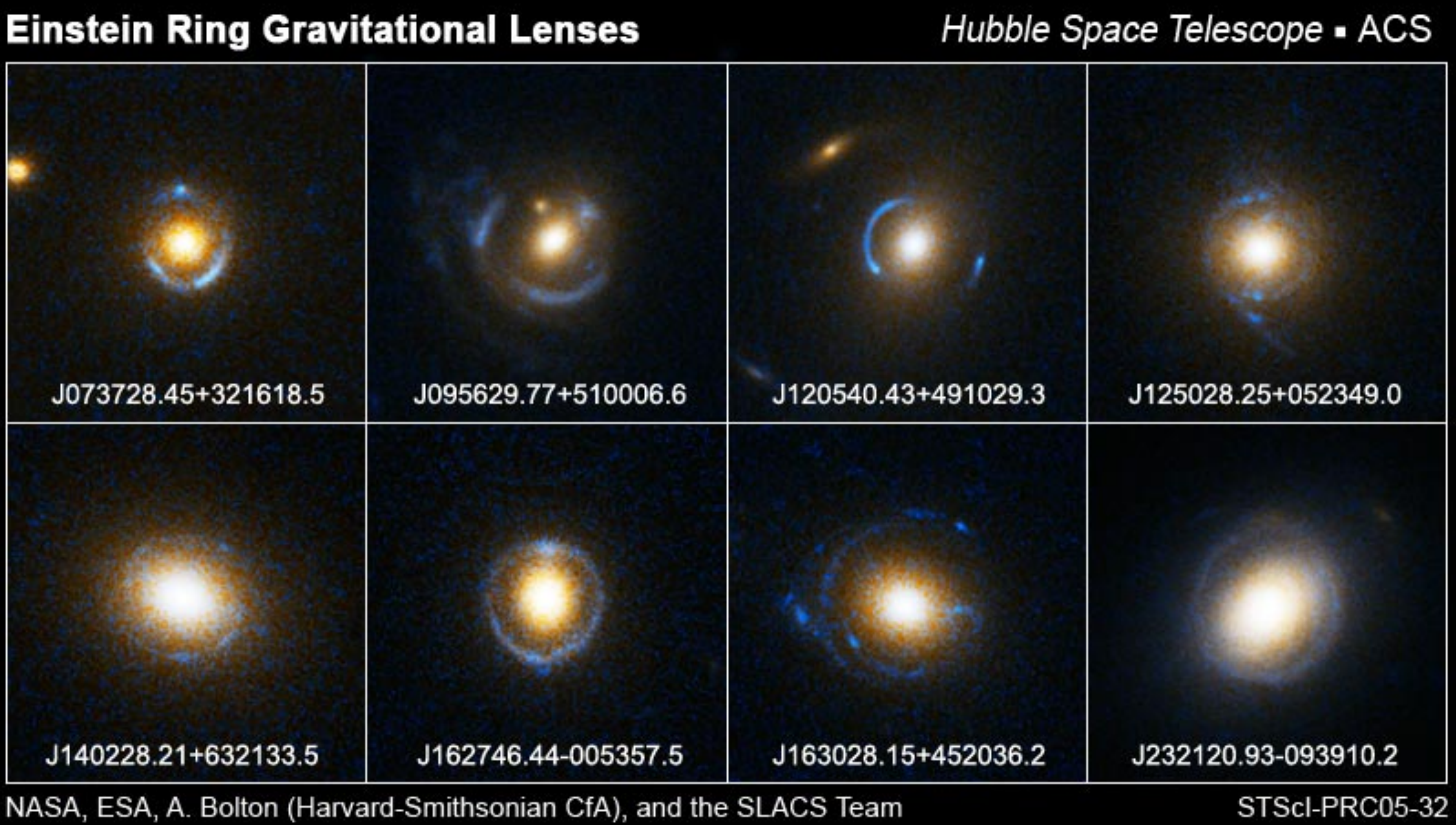
Mass Distribution in a Cluster of Galaxies

inferred from gravitational lensing

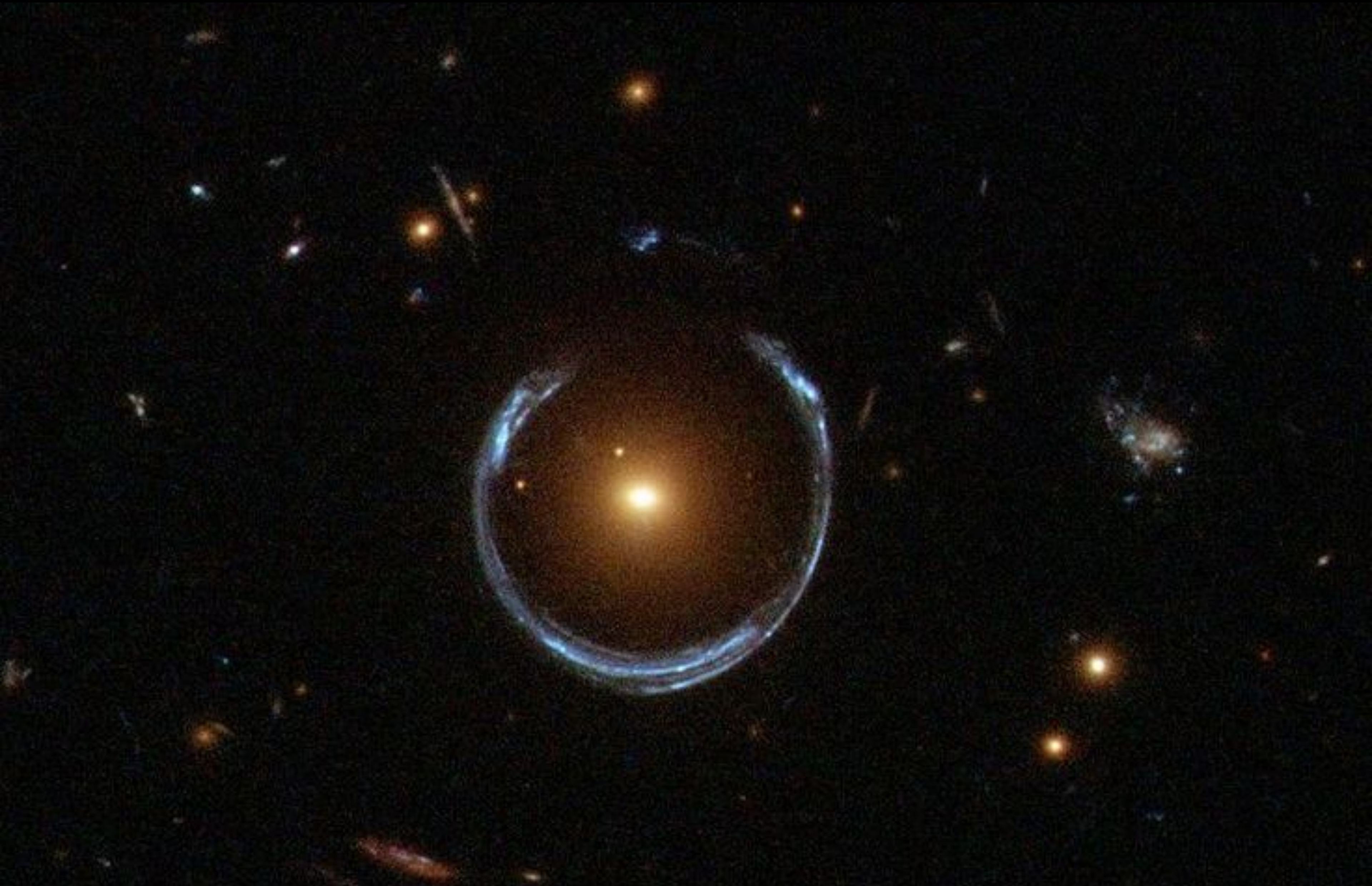
Purple: mass inferred from gravitational lensing: extended halo of dark matter



Gravitational Lensing by Dark Matter in Galaxies



Gravitational Lensing by Dark Matter in Galaxies

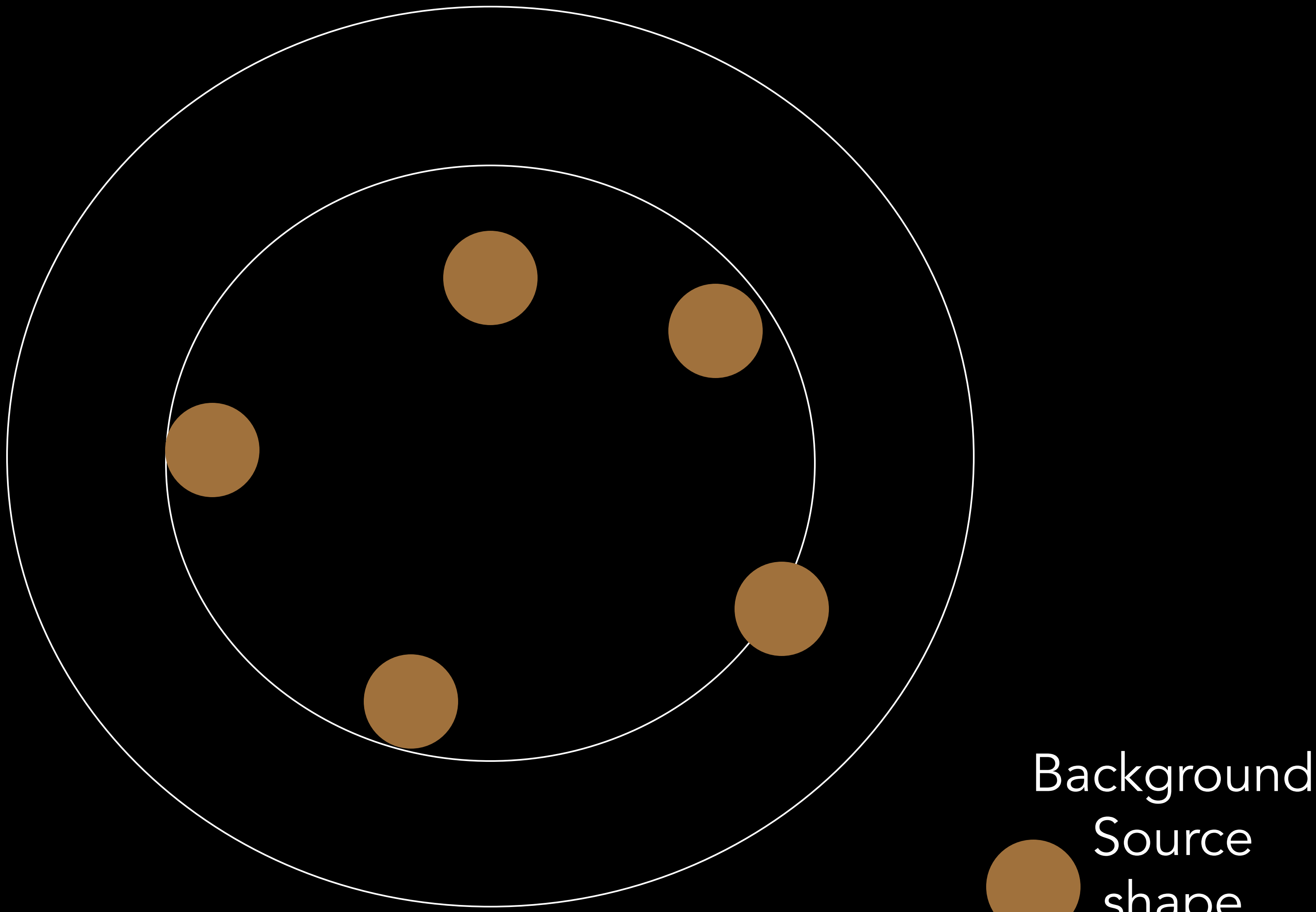


Evidence for Dark Matter from Weak Lensing by Galaxies

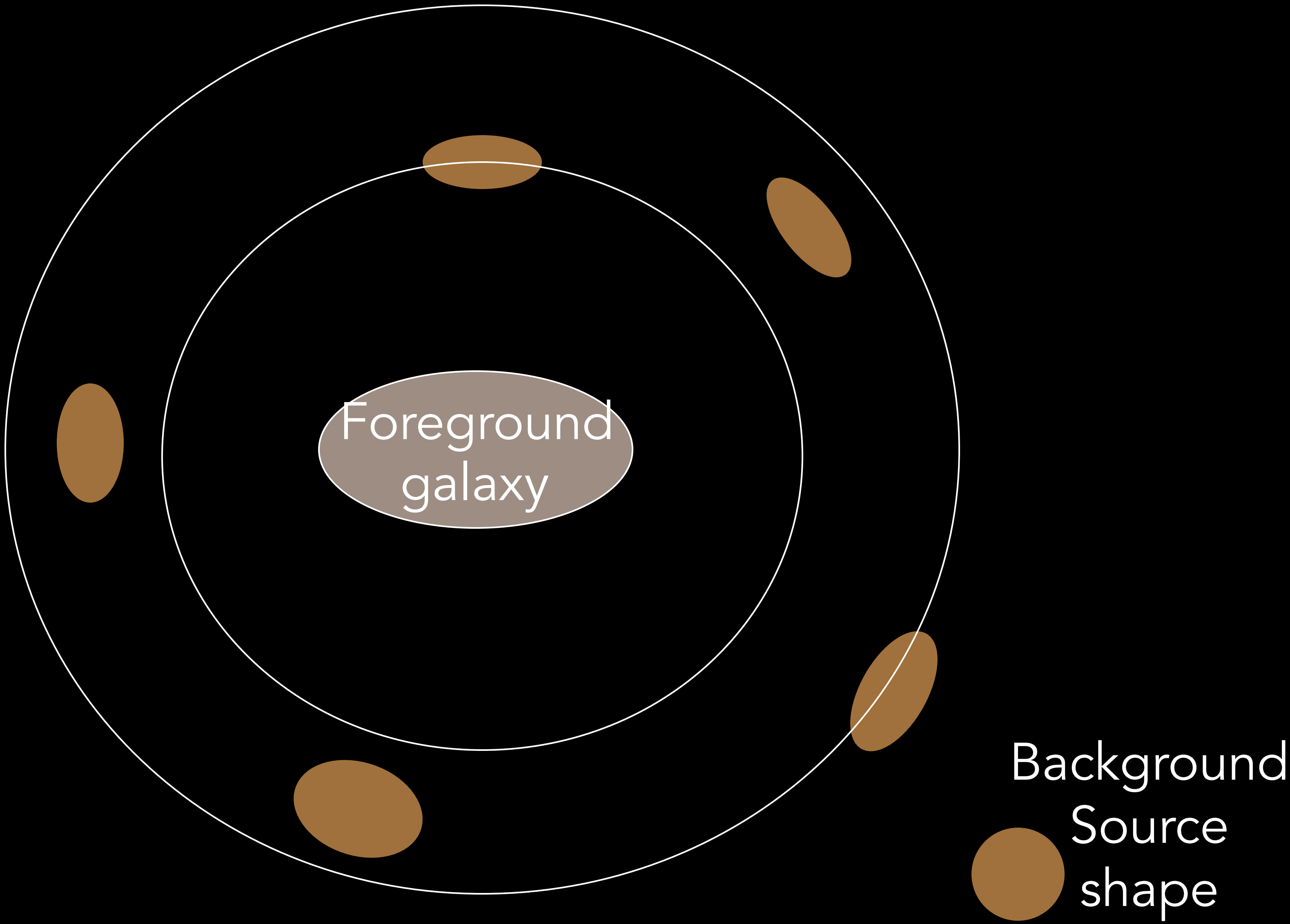
Galaxy-galaxy lensing:

- Measure the shapes of a large sample of distant `background' galaxies, the images of which are very weakly distorted by the Dark Matter halos of a foreground population of galaxies
- Instead of probing the mass of individual objects, this method probes the *average* mass of a population of galaxies.

Weak Lensing of Faint Galaxies: distortion of shapes

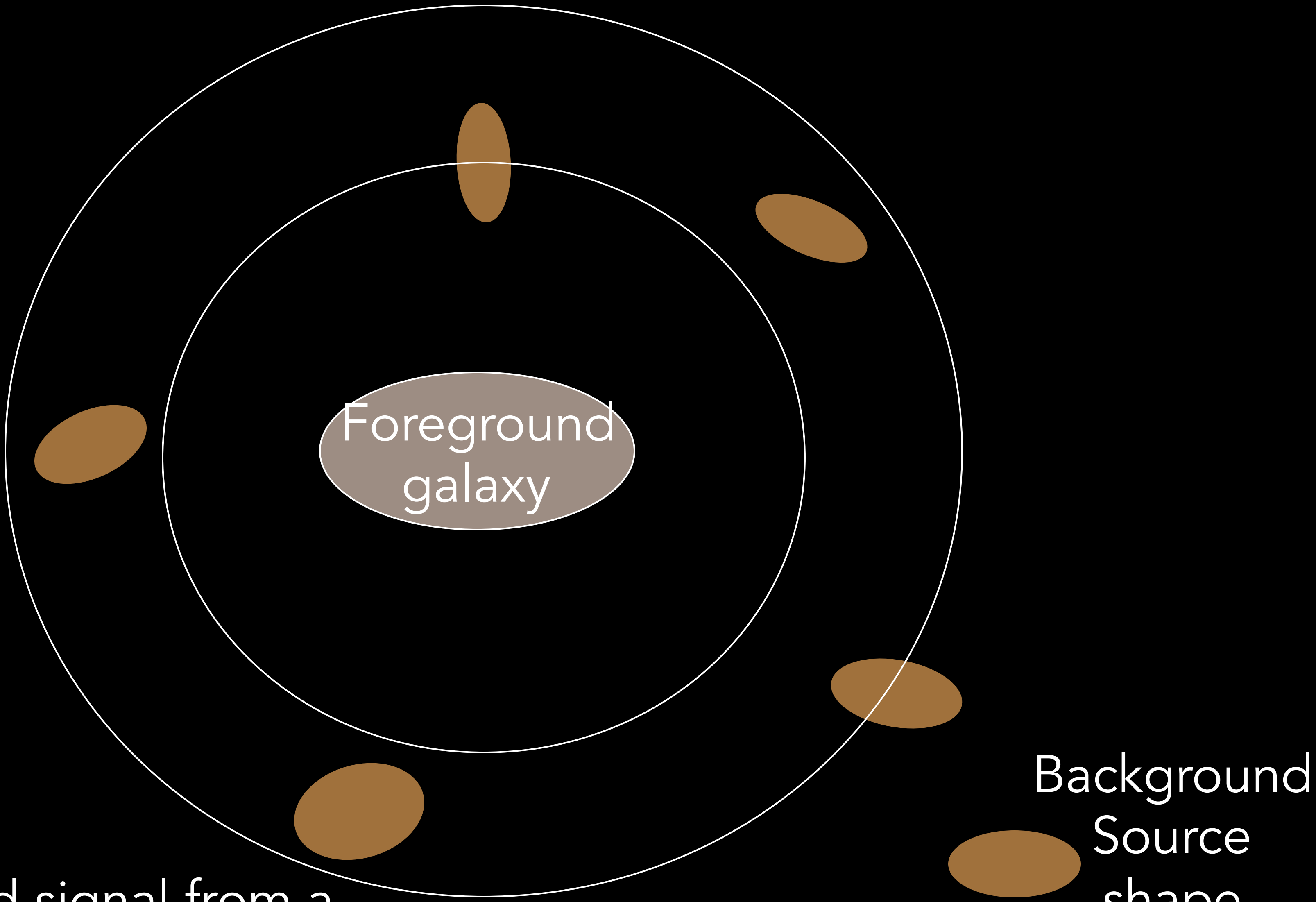


Weak Lensing of Faint Galaxies: distortion of shapes



Note: the effect has been greatly exaggerated here

Lensing of real (elliptically shaped) galaxies



Must add signal from a
large number of foreground galaxies

Weak Gravitational Lensing Indicates:

Luminous Galaxies are surrounded by Extended Massive Halos of Dark Matter

December 14, 1999

Science Times

The New York Times

Galaxies' Vastness Surprises Scientists

By JAMES GLANZ

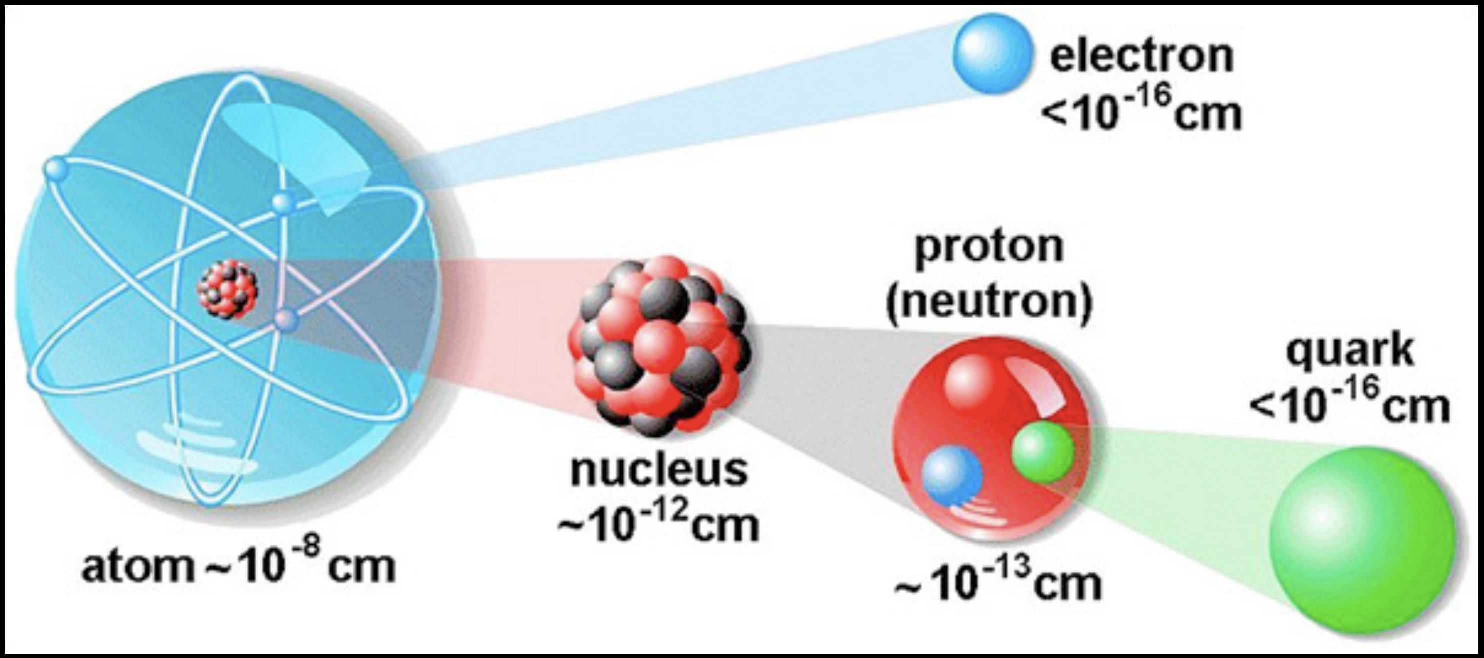
Using a technique akin to overlaying thousands of faint X-ray images to create one sharp picture, astronomers have discovered that typical galaxies may be twice as large and contain twice as much mass as suggested by previous measurements. The new observations, which have emerged from a five-year census of the heavens called the Sloan Digital Sky Survey, indicate that an average galaxy extends invisibly for well over a million light-years into space and weighs the equivalent of at

A portrait of a woman far different from the cavewoman stereotype is emerging from these Stone Age Venuses: above is Venus of Willendorf in Austria; at right, the back and front views of Venus of Kostenki in Russia; far right, Venus of Lespugue, with prominent buttocks and a "grass" skirt, in southwest France.

By NATALIE ANGIER

Ah, the poor Stone Age woman of our kitschy imagination. When she isn't getting bonked over the head with a club and

"Normal" (Baryonic) Matter: stuff made of atoms



1 1/10,000 1/100,000 1/100,000,000

Dark Matter

- What is dark matter made of?
  - Very faint stars, planets, black holes, and other things made of atoms (baryons) can't do it: there aren't enough baryons in the Universe to account for all the dark matter we infer in galaxies.
  - Evidence for this comes from Cosmic Microwave Background and from Big Bang Nucleosynthesis, which tell us baryons make up only 4% of the mass density of the Universe (while dark matter is 25%).

Dark Matter

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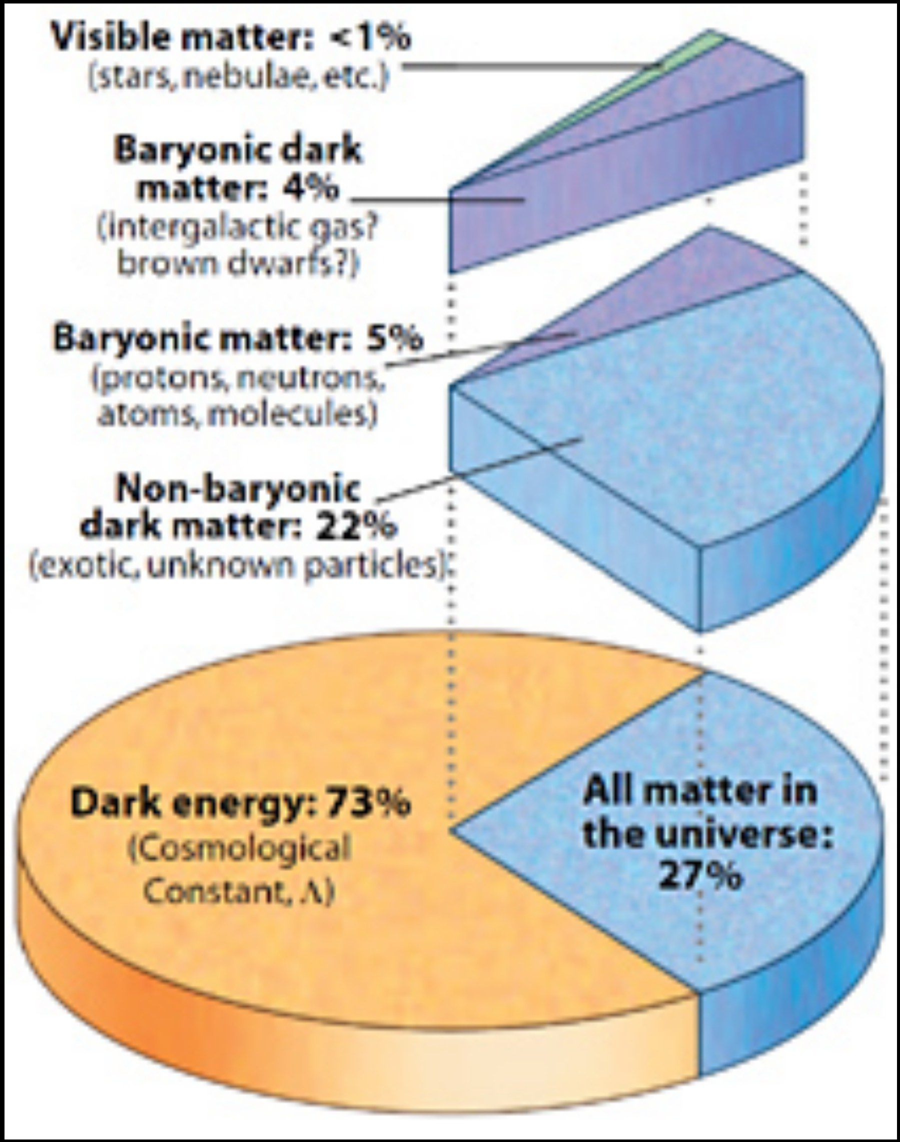
  - Dark matter must be made of something other than atoms (or quarks): perhaps a new kind of elementary particle that we've never seen before.

Dark Matter

- What is dark matter made of?
  - Dark matter must be made of something other than atoms (or quarks): perhaps a new kind of elementary particle that we've never seen before.
  - Even so, luminous matter (stars and hot gas) make up only a fraction of that 4%, so there is a smaller amount of dark (or at least so far unseen) baryonic matter as well.

Dark Matter

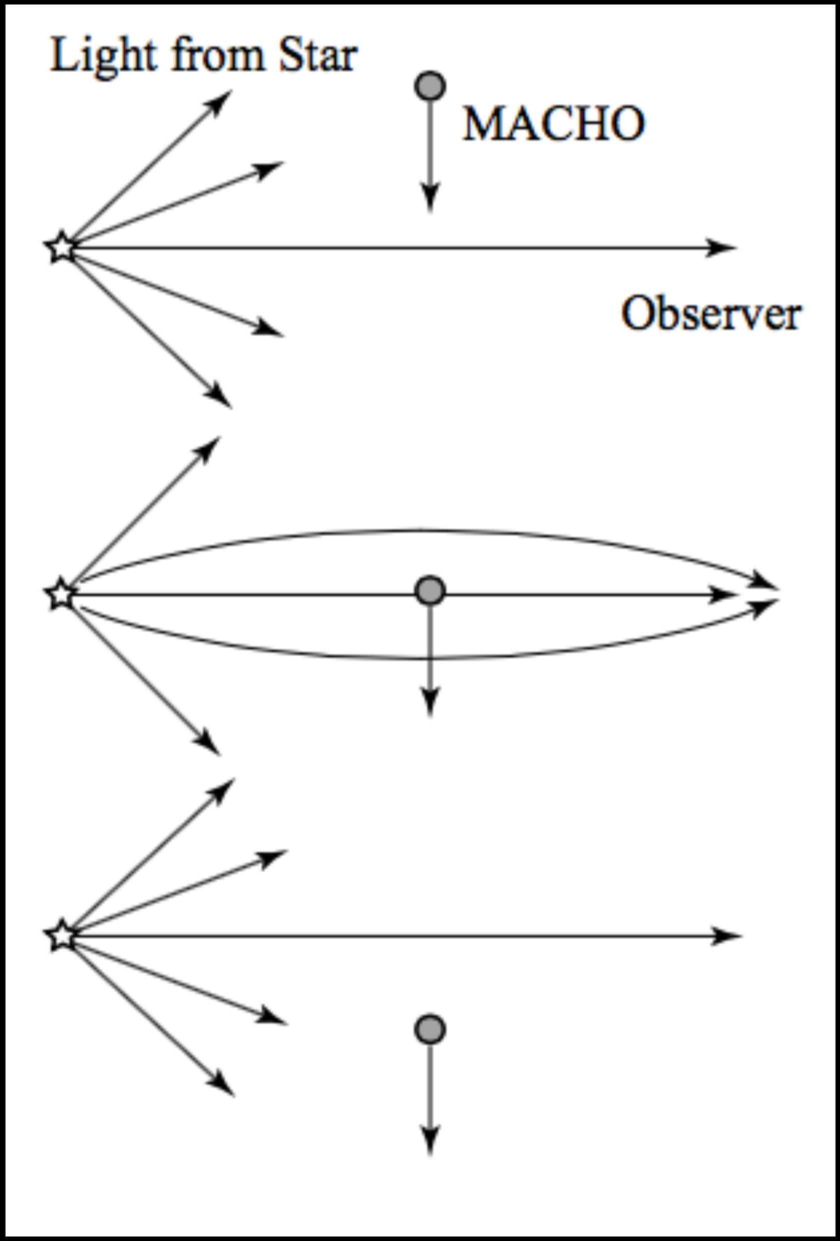

Visible matter: <1%
(stars, nebulae, etc.)
Baryonic dark matter: 4%
(intergalactic gas? brown dwarfs?)
Baryonic matter: 5%
(protons, neutrons, atoms, molecules)
Non-baryonic dark matter: 22%
(exotic, unknown particles)
Dark energy: 73%
(Cosmological Constant, Λ)
All matter in the universe: 27%

Baryonic Dark Matter

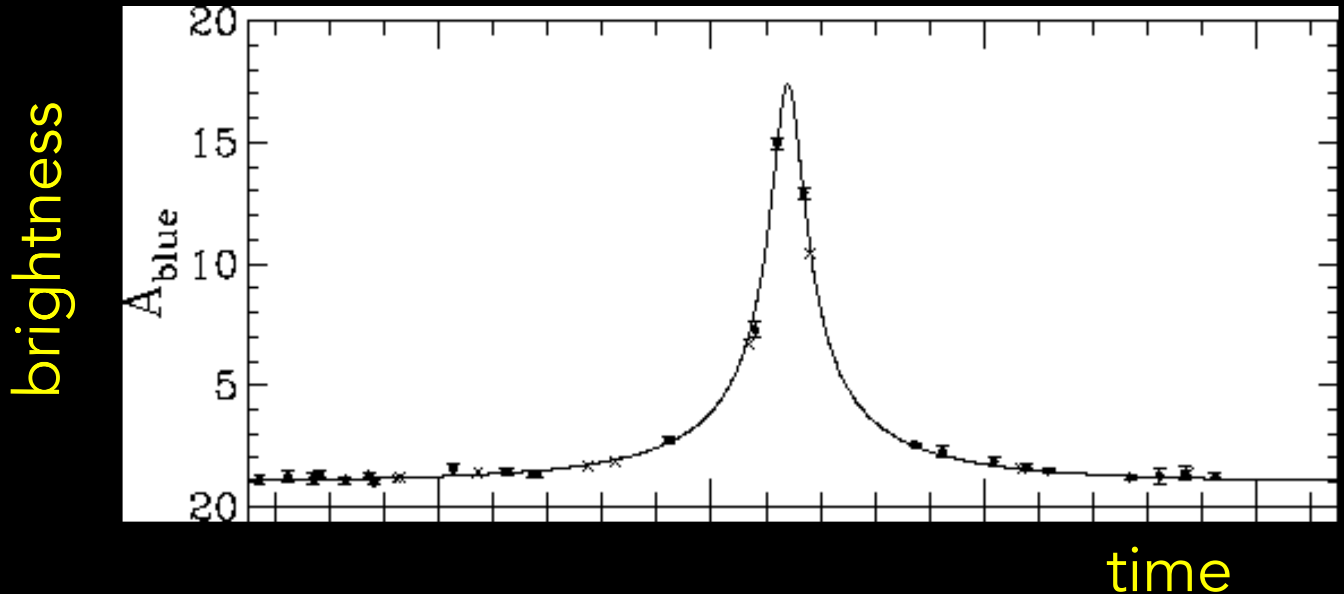
- Nucleosynthesis and CMB indicate $\Omega_{baryons} = 0.04$, substantially larger than the density of luminous matter (stars & hot gas in galaxies & clusters); $\Omega_{stars} \sim 0.005$.
- Some possibilities for `hiding' baryons in dark objects:
  - Massive Astrophysical Compact Halo Objects (MACHOs), masses from small planets to stars
  - Brown Dwarfs: objects with mass < 1/10 that of the Sun, do not get hot enough to undergo thermonuclear burning, so they do not shine
  - White Dwarfs: old stars of relatively low mass that have used up their nuclear fuel and collapsed
  - Neutron Stars: intermediate mass stars that have used up their fuel
  - Black Holes: Likely end-state of higher-mass stars
  - Cold or warm gas
  - Dust

Gravitational Microlensing

- MACHO in the dark halo of the Milky Way will occasionally cross the line of sight to a distant star
- Gravitational lensing (light bending) does not cause multiple images of the distant star (the bending angle is too small to cause resolved images) but focusing does lead to an observable *brightening* of the star.



MACHO Searches



Duration of brightening constrains MACHO mass

Background star appears brighter when lensed by the foreground MACHO. MACHO project monitored brightness of ~a million stars from the Large Magellanic Cloud over period of years. Found a number of microlens events but showed the dark halo of the Milky Way is not made of MACHOs.

Non-baryonic Dark Matter

Evidence on the amount of Dark Matter from Big Bang Nucleosynthesis and CMB indicate the Universe is dominated by an exotic Dark Matter component, made of some new, as-yet undiscovered elementary particle.

In order for it to be dark matter, this particle should be weakly interacting (i.e., not interact with or emit light) and naturally have an abundance in the Universe of $\Omega_{\text{dark matter}} = 0.25$.

Models of Elementary Particle Physics provide a number of Dark Matter candidates, new particles with these requisite properties:

WEAKLY INTERACTING MASSIVE PARTICLES (WIMPs)

(Some) Dark Matter Candidates

Neutrinos (mass ~ few electron Volts ~ 10^{-5} electron's mass)
known to exist, should be as abundant as CMB photons.

Supersymmetric Particles (mass ~ 10-100 x proton mass)
Favorite candidate of particle physics theorists

Axions (mass ~ 10^{-5} electron Volts ~ 10^{-10} electron mass)
Hypothetical particle that arises in theories that seek to explain certain features of the strong interactions

Note: these candidates involve physics beyond the well-tested Standard Model of Particle Physics. Thus, determining the nature of the Dark Matter should tell us about fundamental physics.

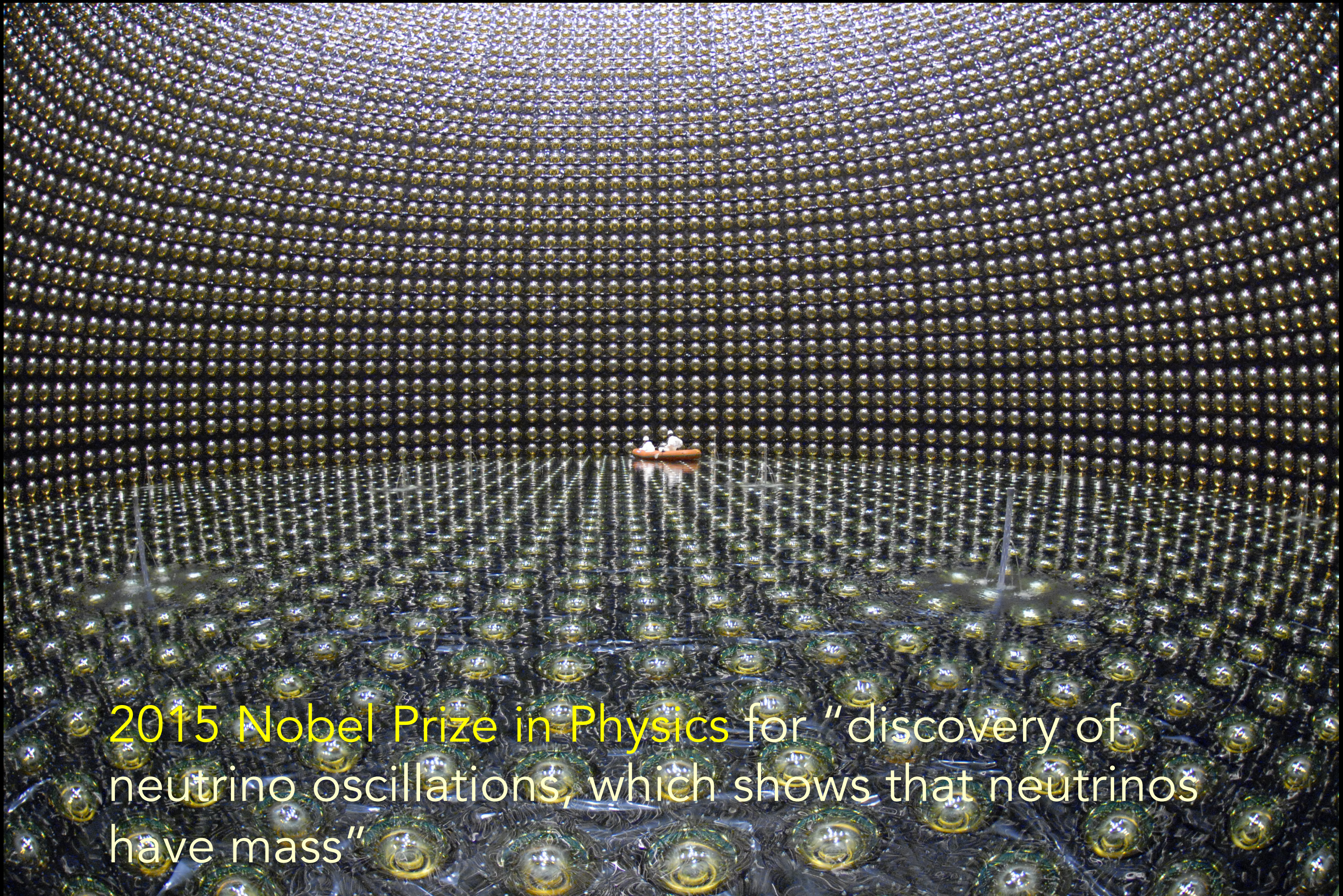
Detecting Dark Matter: Neutrinos

Substantial experimental efforts over last decades to determine the masses of the neutrinos (3 types of neutrinos we know of, ν_e ν_μ ν_τ) : use neutrinos generated (i) by the Sun, (ii) by cosmic rays hitting the Earth's atmosphere, and (iii) by particle accelerators (like Fermilab) on Earth. Massive neutrinos transmute (oscillate) into each other as they travel, depending on their masses. Requires massive underground detectors, since neutrinos interact only weakly and to avoid `backgrounds' caused by other particles.

Result: neutrinos are too light to be more than a tiny fraction of the dark matter.

Note: about 10^{14} neutrinos from the Sun pass through your body every second

SuperKamiokande Neutrino Experiment (Japan)



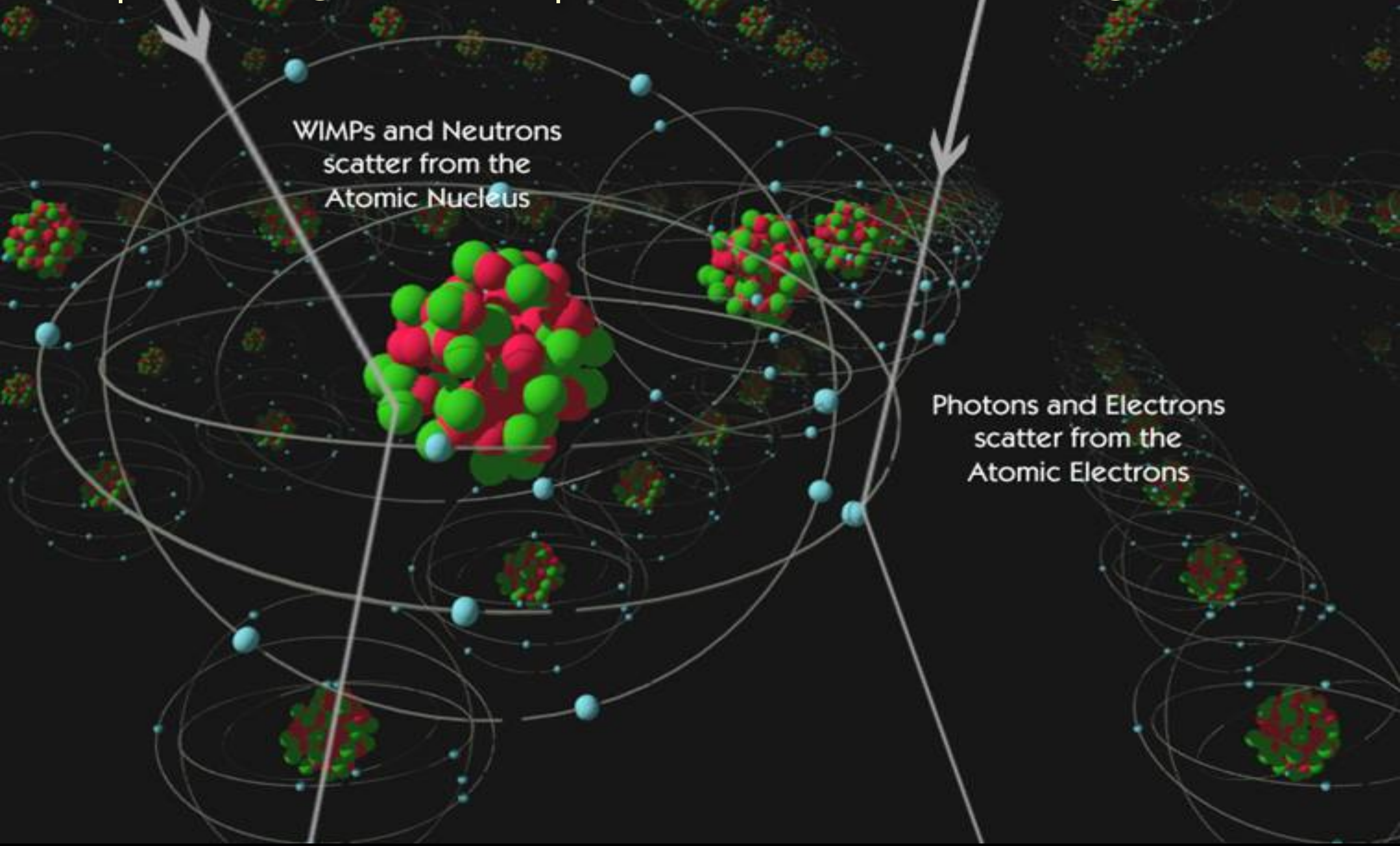
Detecting Dark Matter: WIMPs

- Weakly interacting Dark Matter particles, e.g., those predicted by Supersymmetry, travelling through the Milky Way halo: as the Earth orbits through the galaxy, it continually runs into this `spray' of particles.
- Occasionally, one of these WIMPs would knock into a nucleus in a detector, and one can look for the signature of such an event.
- For example, in a `bolometric' detector (operated at very low Temperature), the `recoiling' nucleus scatters with other nuclei in the detector, and the whole detector heats up by a miniscule but measurable amount.
- One experiment has claimed a detection, but others exclude that detection as due to dark matter.
- About 10^9 WIMPs would pass through your body every second.

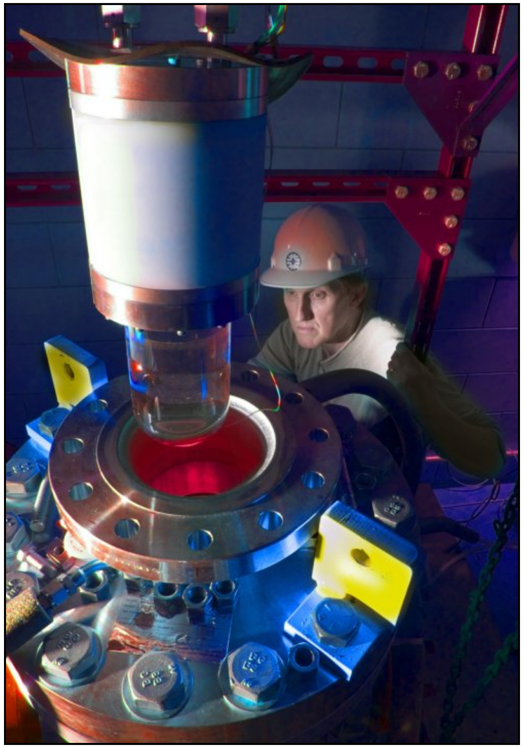
What is the (non-baryonic) Dark Matter?

It might be a Weakly Interacting Massive Particle (WIMP)

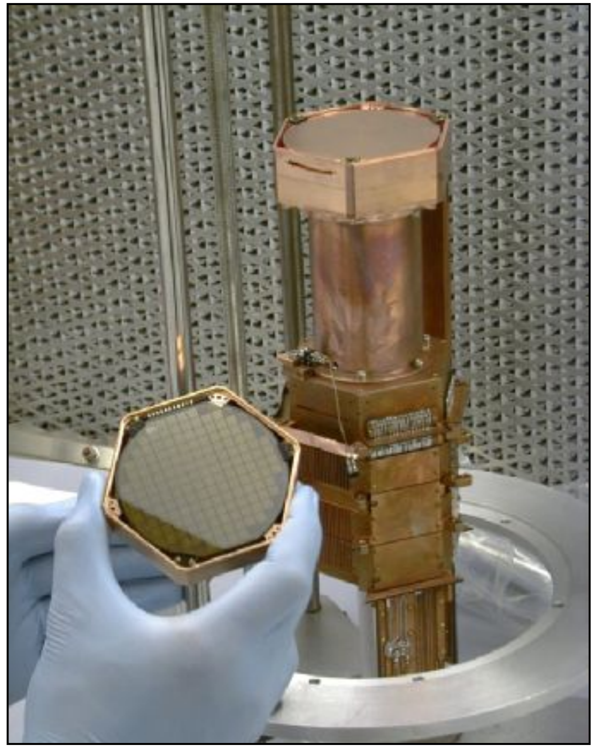
Deep underground experiments are searching for them



COUPP

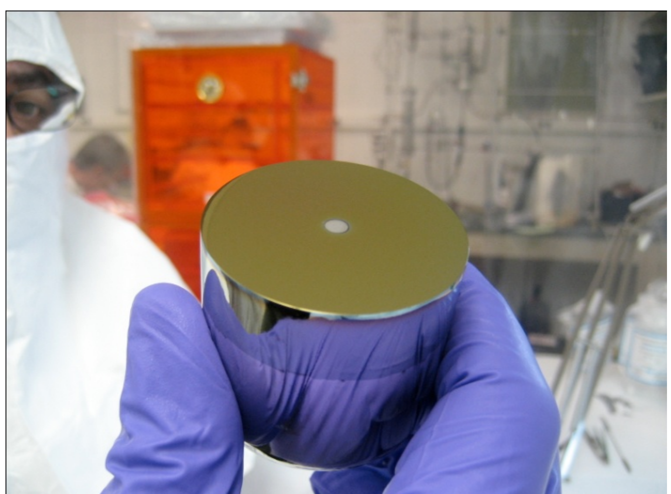


CDMS



XENON

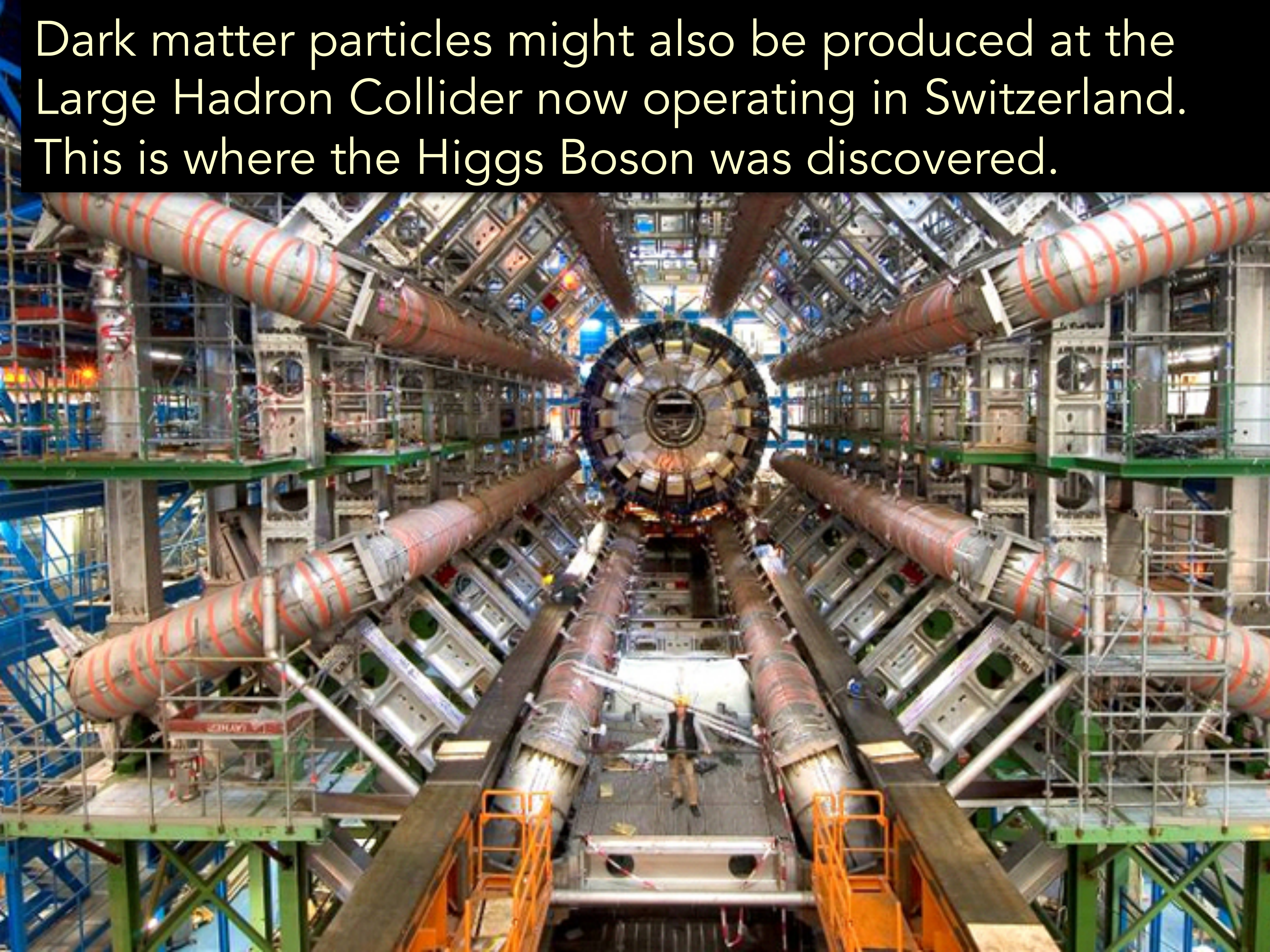
CoGeNT



DAMA/LIBRA

Experiments to search for Dark Matter particles

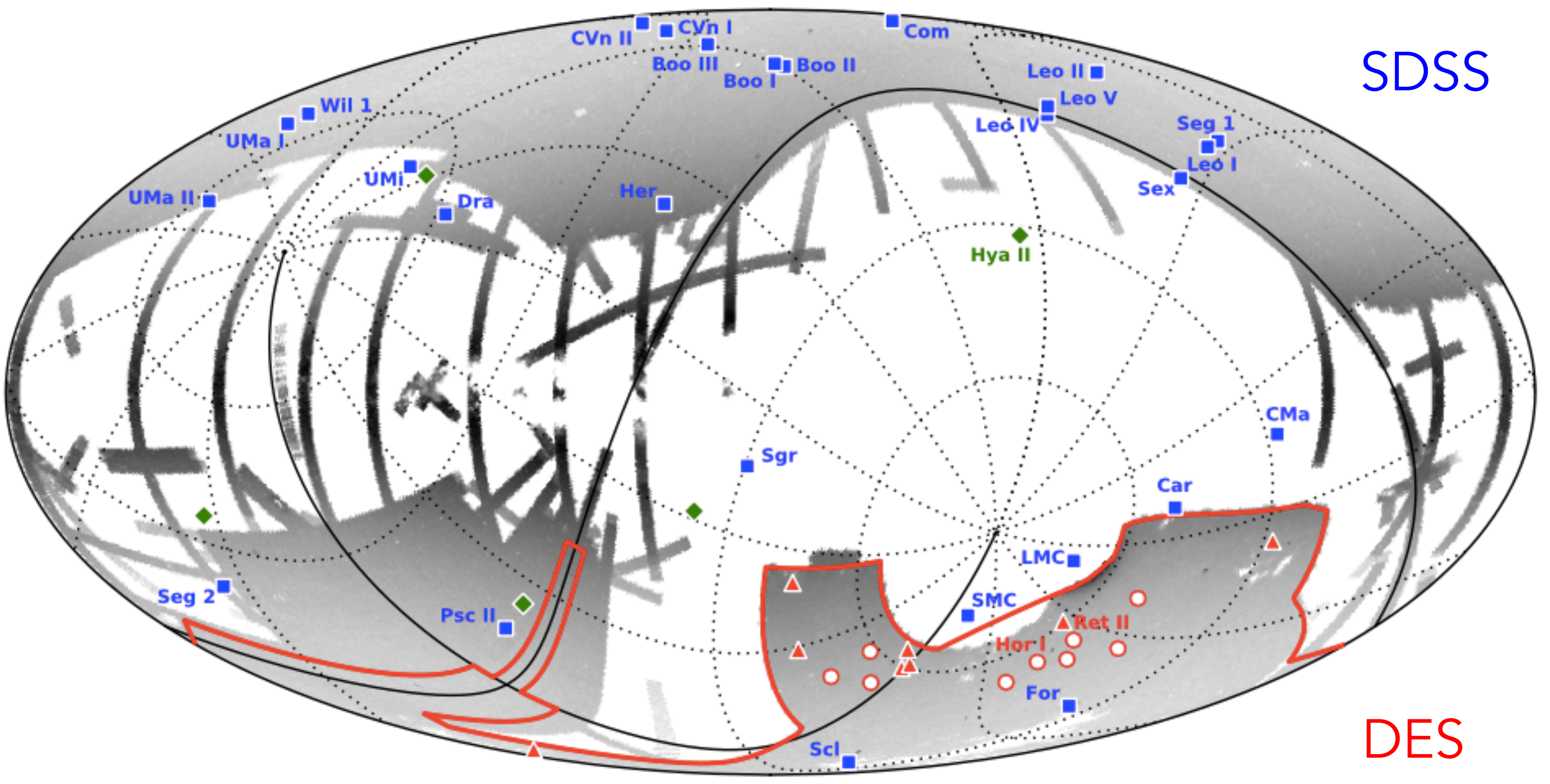
Dark matter particles might also be produced at the Large Hadron Collider now operating in Switzerland. This is where the Higgs Boson was discovered.



Dark Matter Annihilation

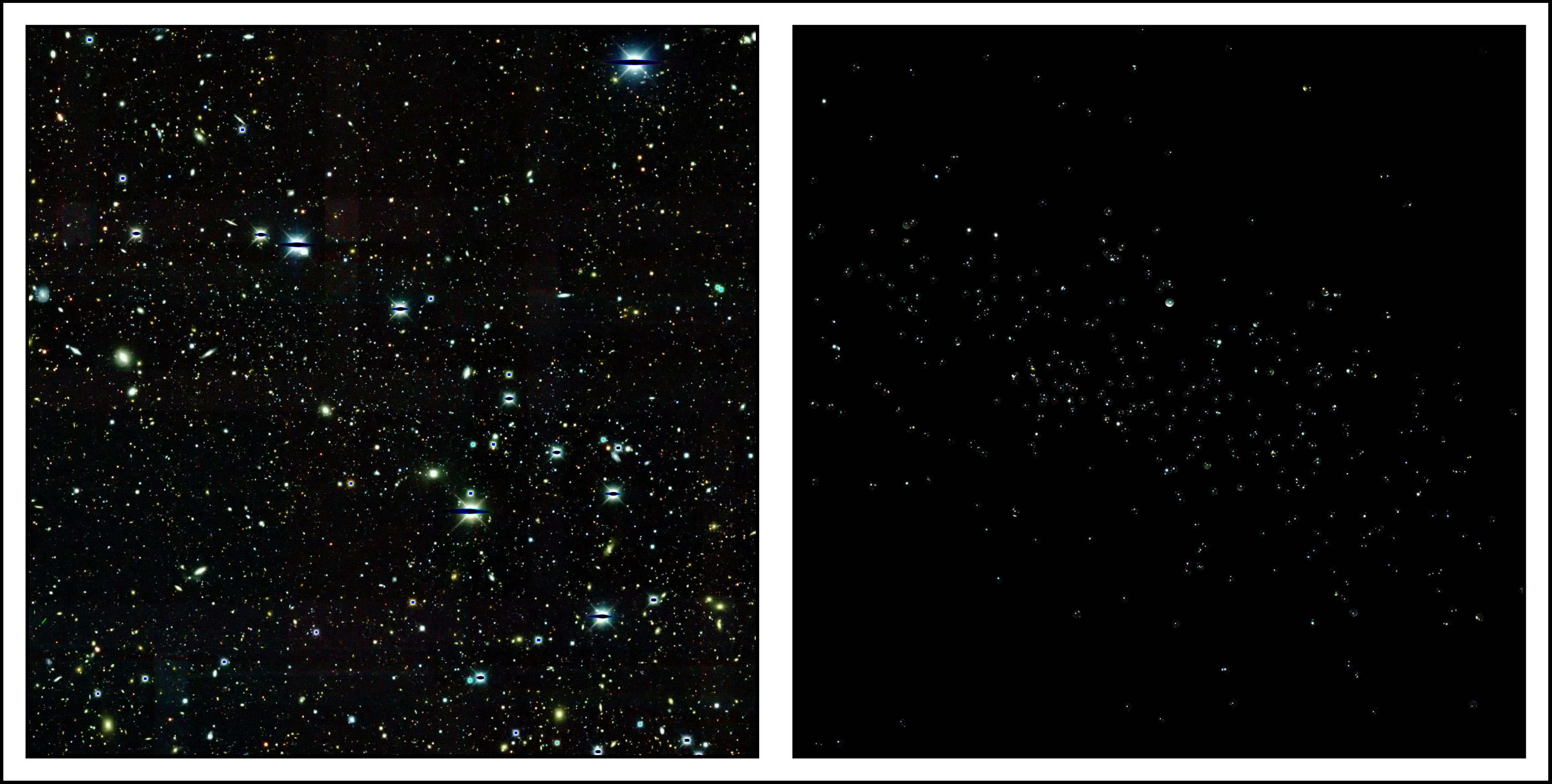
- In addition to direct DM detection experiments and DM production at the LHC, a third method to discover WIMP DM could be via annihilation of DM particles and anti-particles in nearby dwarf galaxies.
- Our Milky Way Galaxy is surrounded by ~20 dwarf satellite galaxies.
- In last 10 years, astronomers have discovered an additional ~40 ultra-faint dwarf galaxy satellites: the most dark matter-dominated systems known, they contain relatively few stars.
- WIMPs and anti-WIMPs annihilating in these galaxies would produce intense beams of gamma rays observable with gamma ray satellites: Fermi satellite.

New Faint Milky Way Dwarfs found

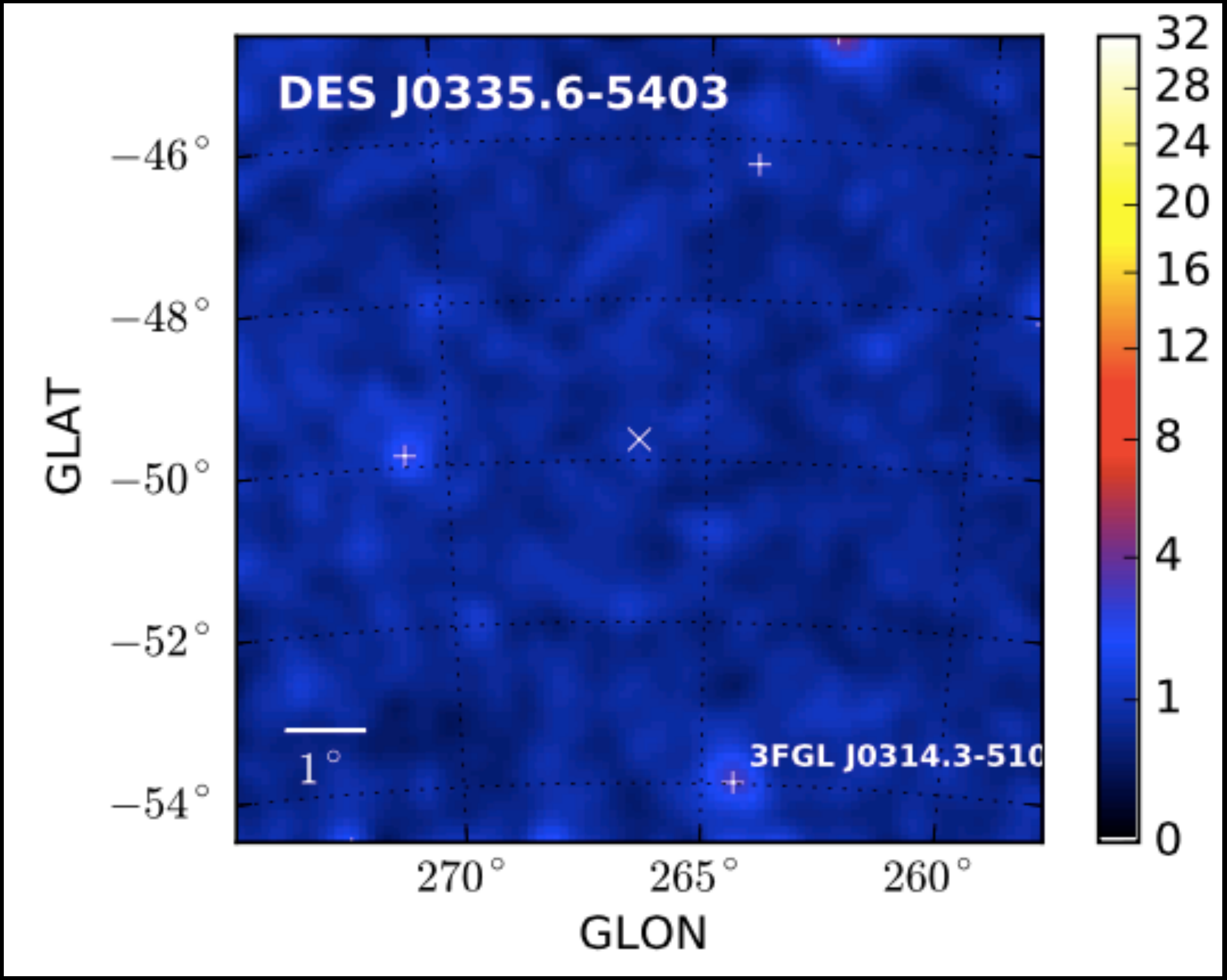


Nearest of the new Dwarfs found by DES

Reticulum 2, ~90 thousand light-years from Earth



Fermi Map for Reticulum 2 region



No evidence for DM annihilation

Detecting Dark Matter: Axions

- Like WIMPs, axions would be traveling through the Galaxy and continually bombarding Earth: about 10^{24} passing through you every second.
- Axion detection: place a finely tuned microwave cavity in a very strong magnetic field. An axion can convert into a microwave photon, which can be detected, in a strong magnetic field. Experiments on-going to search for them, nothing seen yet.

Dark Matter Properties: Clustering

Three `types' of Dark Matter distinguished by the objects they can be found in:

- Cold DM: clusters on all scales; particles slowly moving,... Candidates: Supersymmetric WIMPs, axions, …
- Hot DM: these particles moved at near the speed of light early on, and can only cluster in objects as big as clusters (or larger): would not expect to find them in individual galaxy halos
  Candidate: neutrinos
- Warm DM: clusters on scales of galaxies or larger.
  Candidate: heavy neutrinos (in certain cases)

Dark Matter & Large-scale Structure

These 3 different types of DM (cold, hot, warm) lead to different scenarios for the formation of galaxies and large-scale structures in the Universe (as we will discuss later in the course).

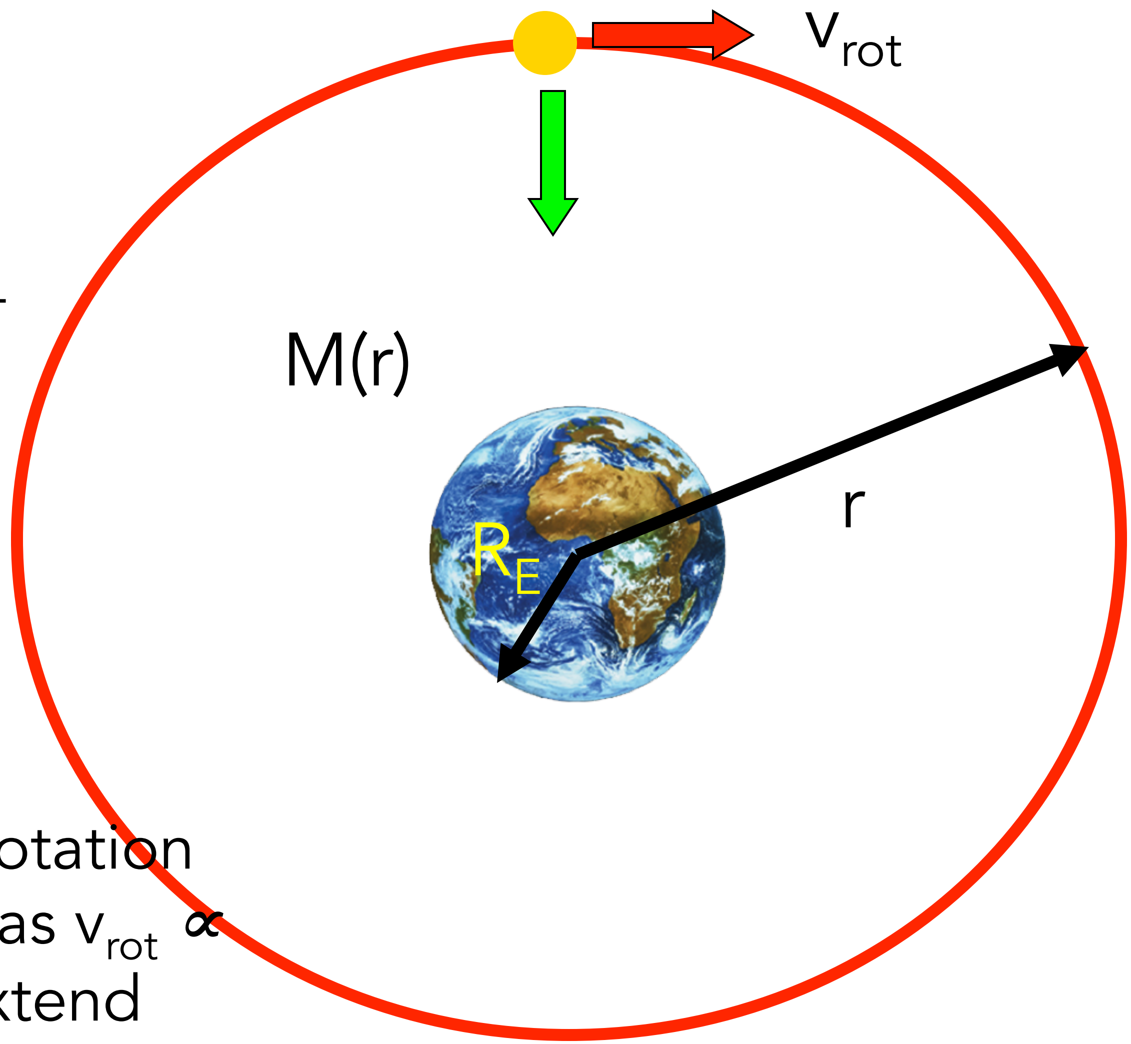
Observations of the large-scale distribution of galaxies (from galaxy surveys) indicate that the bulk of the DM is cold (or at most slightly warm).

How do we determine Masses of Astrophysical Objects?

Recall Newtonian acceleration:

$$a = \frac{F}{m} = \frac{GMm}{r^2 m} = \frac{GM}{r^2}$$

For body in circular motion, $a = v_{rot}^2/r$, so $v_{rot}^2 = GM(r)/r$



Dark Matter: galaxy rotation curves do not fall off as $v_{rot} \propto r^{-1/2}$, so mass must extend farther than stars

Alternative to Dark Matter?

Recall Newtonian acceleration:

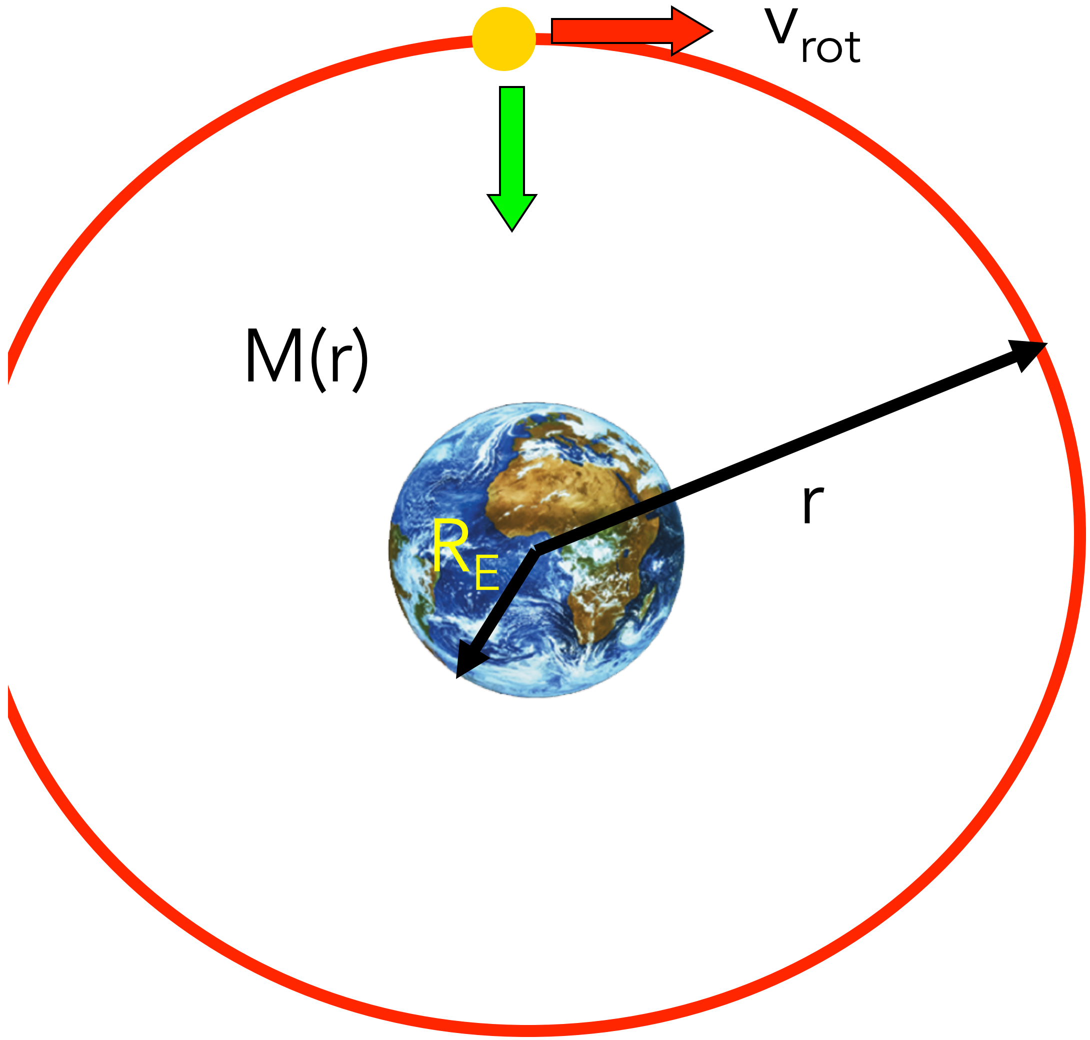
$$a = \frac{F}{m} = \frac{GMm}{r^2 m} = \frac{GM}{r^2}$$

Modify law of inertia for very small acceleration:

$$F = ma\, f(a/a_0)$$

$f(x) \neq 1$ for x<<1

Modified Newtonian Dynamics (MOND)



Bullet Cluster

- Two clusters of galaxies that collided and will merge
- Blue: dark matter inferred from weak lensing
- Red: hot gas seen in X-rays
- Clear separation of dark matter from hot (baryonic) gas
- Modification of Newton's law would not predict this