Outline: Evidence for Big Bang theory

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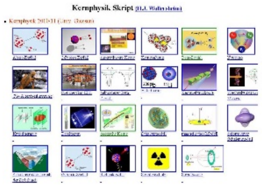
web-page: https://web-docs.gsi.de/~wolle/ and click on



1. 3 pillars of Big Bang theory
2. Hubble expansion
3. nucleosynthesis
4. cosmic microwave background radiation

Question:

Is the mass in the universe all observable through emission or absorption of electromagnetic radiation ?

Dark Matter

...is matter that does not shine or absorb light, and has therefore escaped direct detection by electromagnetic transducers like telescopes, radio antennas, x-ray satellites...

It turns out that there is strong experimental evidence that there is more than 4 times as much dark matter as luminous matter in the observable universe

The father of Dark Matter

- In 1933, Fritz Zwicky checked out the Coma Cluster.

  The galaxies were flying around too fast (*160! as measured by the Doppler effect) for their visible mass to keep them together, so he proposed dark matter was present.

The mother of Dark Matter

- A few decades later, Vera Rubin started to notice FLAT rotation curves in spiral galaxies.

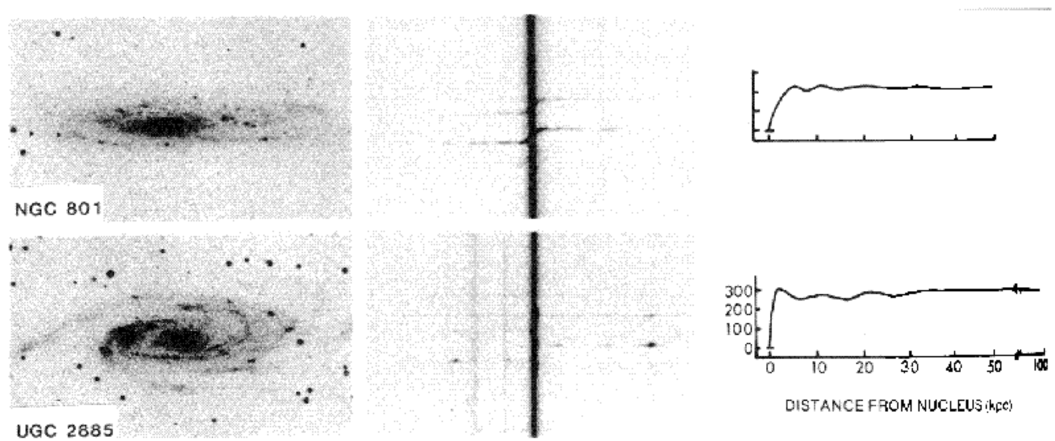
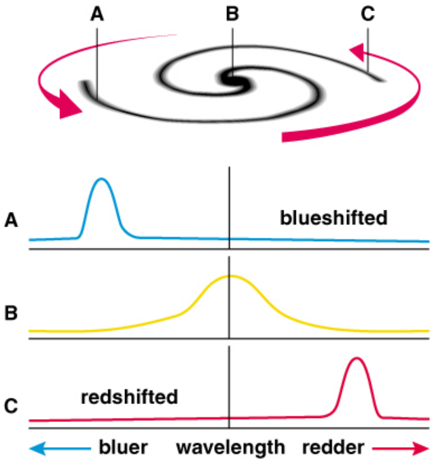
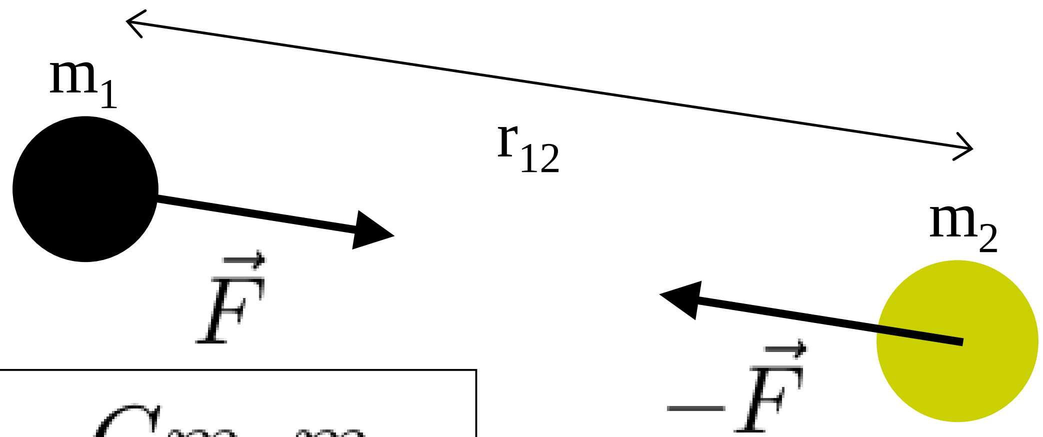


Figure 10-1. Photographs, spectra, and rotation curves for five Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each spectrum is continuum emission from the nucleus. The distance scales are based on a Hubble constant $h = 0.5$. Reproduced from Rubin (1983), by permission of *Science*.

see: Binney, Tremaine (1994) *Galactic Dynamics* p.600



Use the fact that massive objects, even if they emit no light, exert gravitational forces on other massive objects.



$$\left|\vec{F}\right| = \frac{G m_1 m_2}{r_{12}^2}$$

Study the motions (dynamics) of visible objects like stars in galaxies, and look for effects that are not explicable by the mass of the other light emitting or absorbing objects around them.

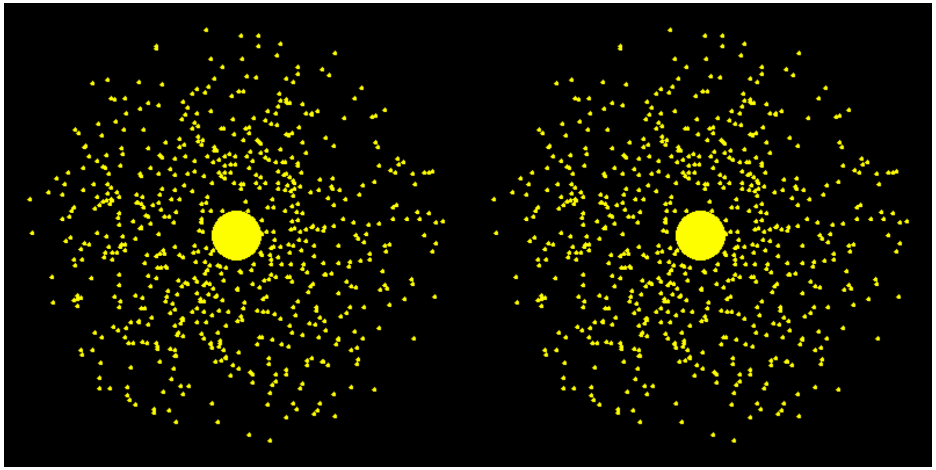
Rotation of stars around Galactic centres

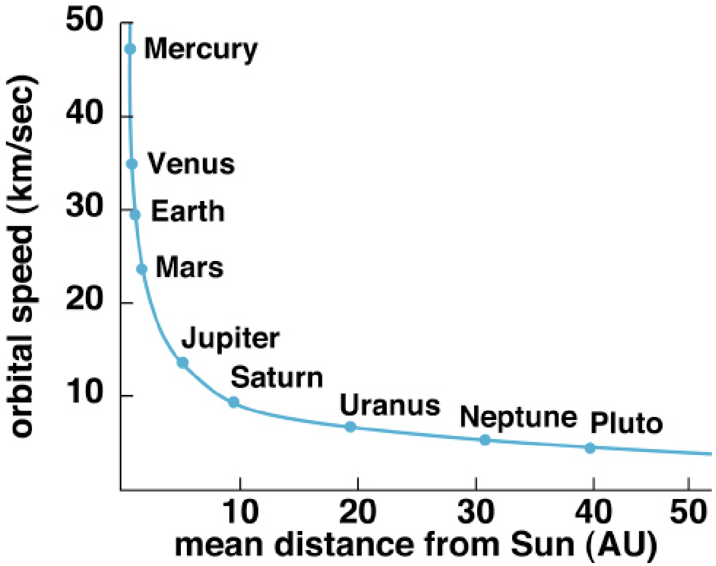
We can measure how fast stars rotate around galactic centres by looking at the frequency shift of known spectral lines originating in the stars due to the Doppler effect.

Star's motion towards you, relative to the galactic centre alters wavelength of light

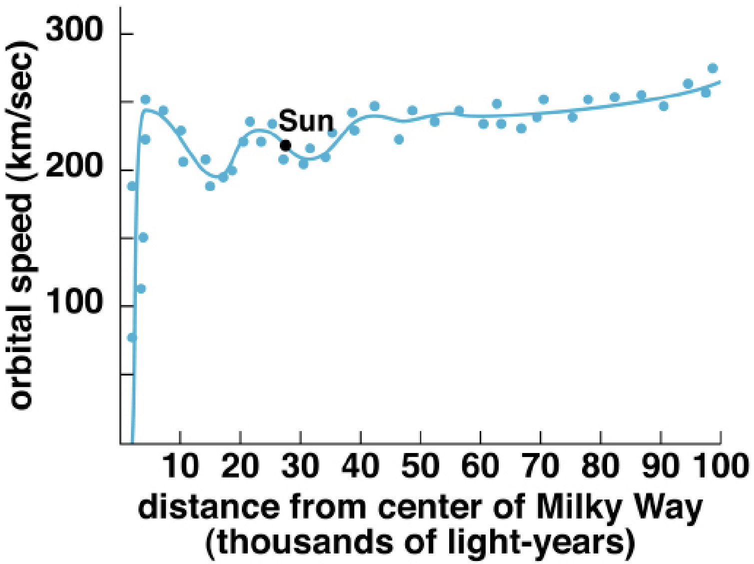
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Flat rotation curves





(b)



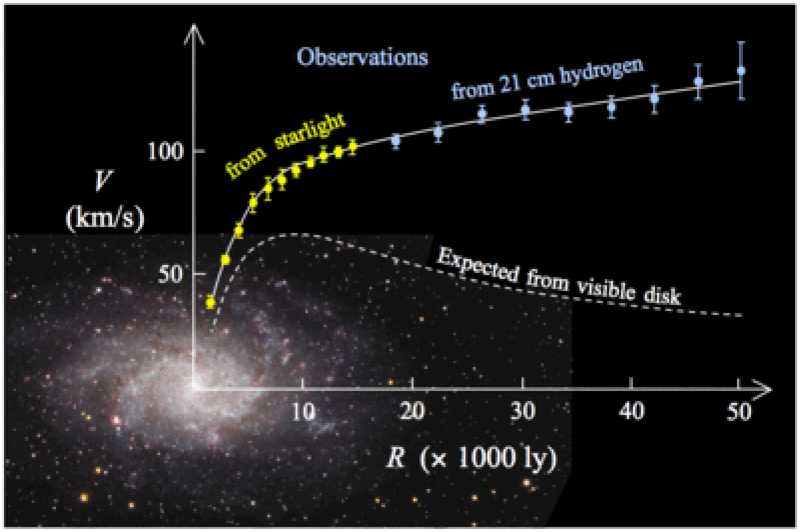
(c)

$v \approx \sqrt{G\,M(r)\,/\,r}$

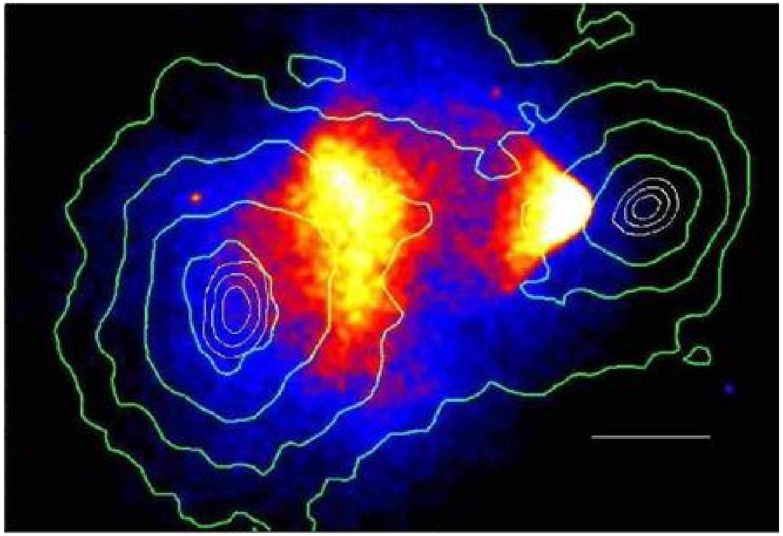
following Rieke, images from Bennett and Pryke

Why do we need DM?

• Galaxy rotation curve (Wikipedia)

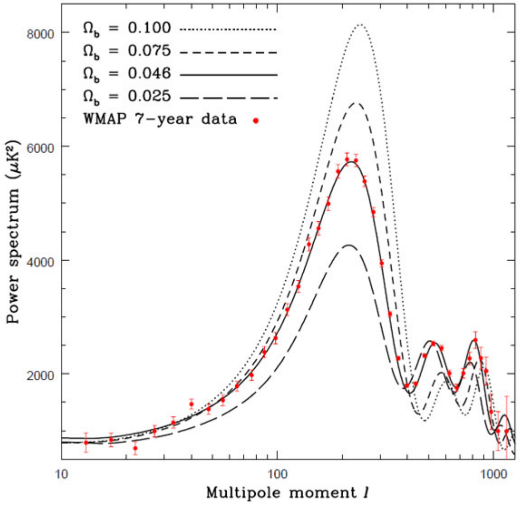


• Bullet Cluster (Deep Chandra)

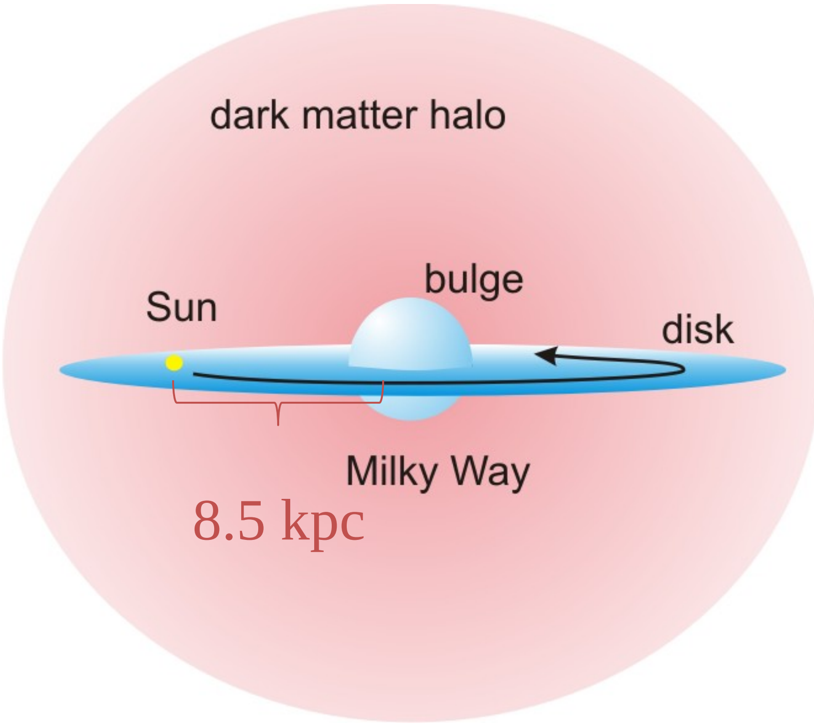


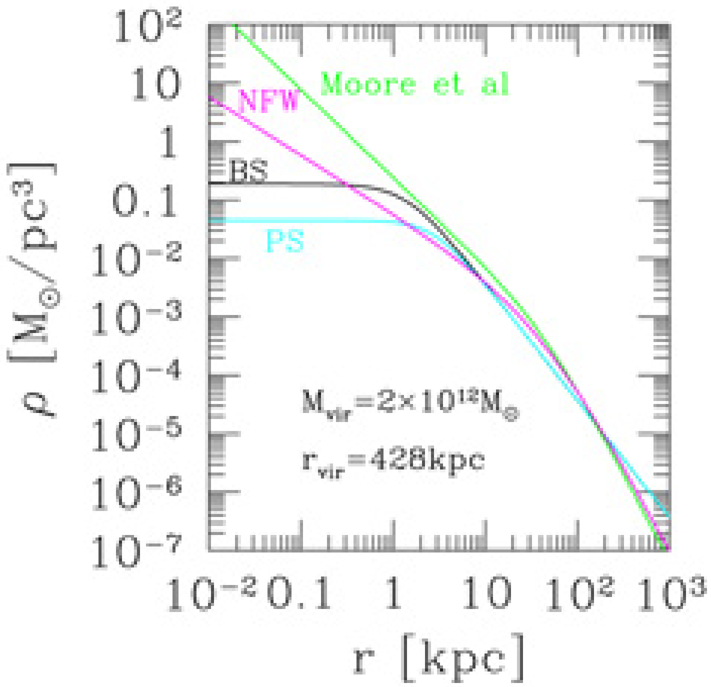
• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)



Some basic facts we roughly know so far:





Local DM energy density: $\rho_{\rm DM} \simeq 0.4 {\rm GeV/cm^3}$

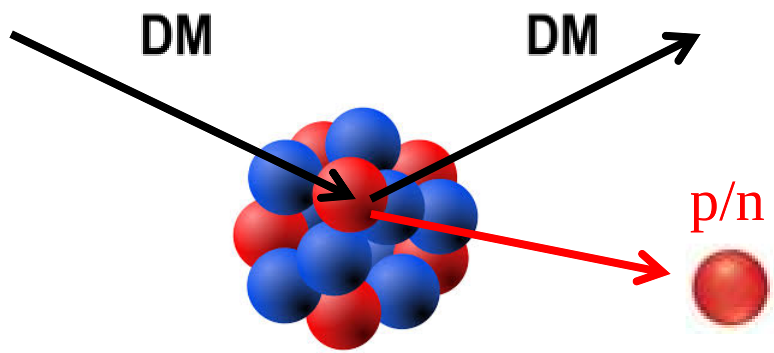
Local DM velocity: $v_{\rm vir} \sim 10^{-3} c$

Boosted dark matter channels

Boosted DM detection:

⇨ DM particle is energetic enough to knock a nucleon out!

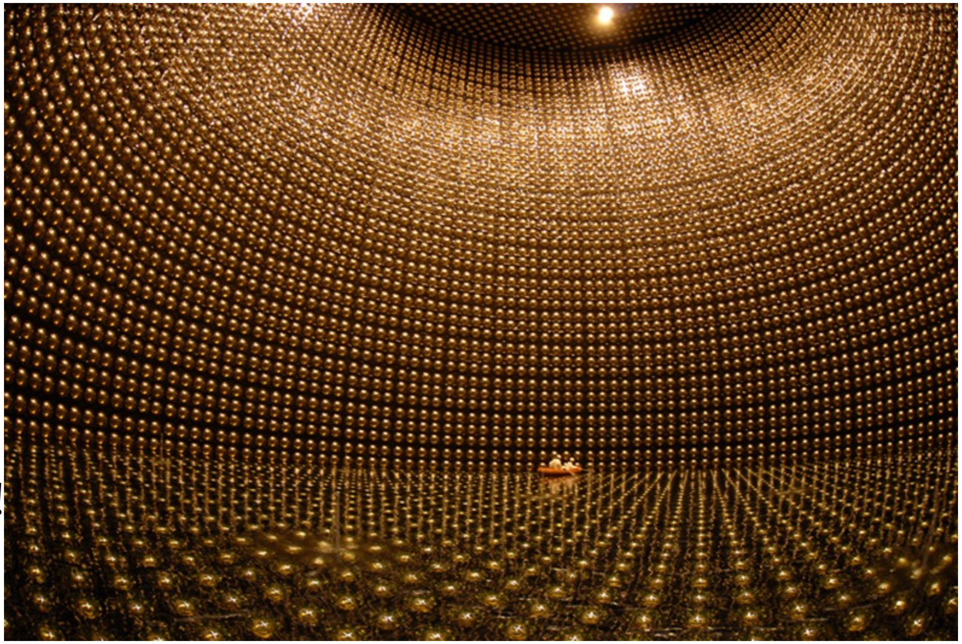
v ~ O(1) c



Looking for proton/neutron knocked out of a nucleus.
Similar to neutrino neutral current interaction!

$$\sigma_{\nu p \to \nu p}(E) \simeq 6 \times 10^{-46} \mathrm{cm}^2 \left(\frac{E_\nu}{\mathrm{MeV}} \right)^2$$

DM-nucleon scattering cross section can be less constrained!



Large Volume Neutrino Experiments
Super-K ~ 50K ton! DUNE ~ 68K ton!

Boosted dark matter channels

Boosted DM detection:

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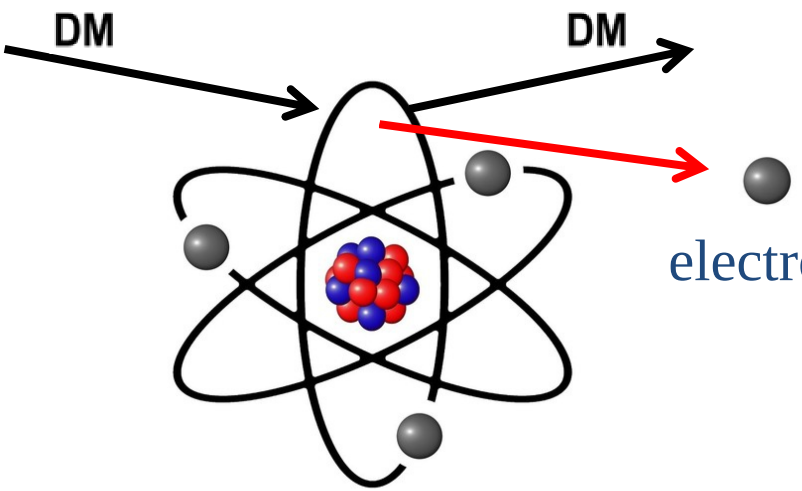
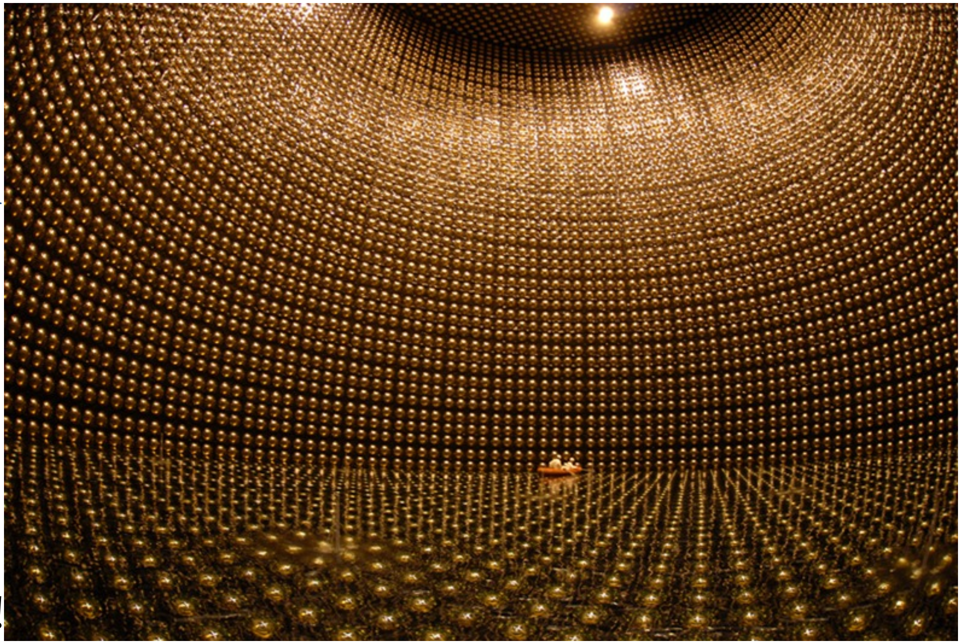
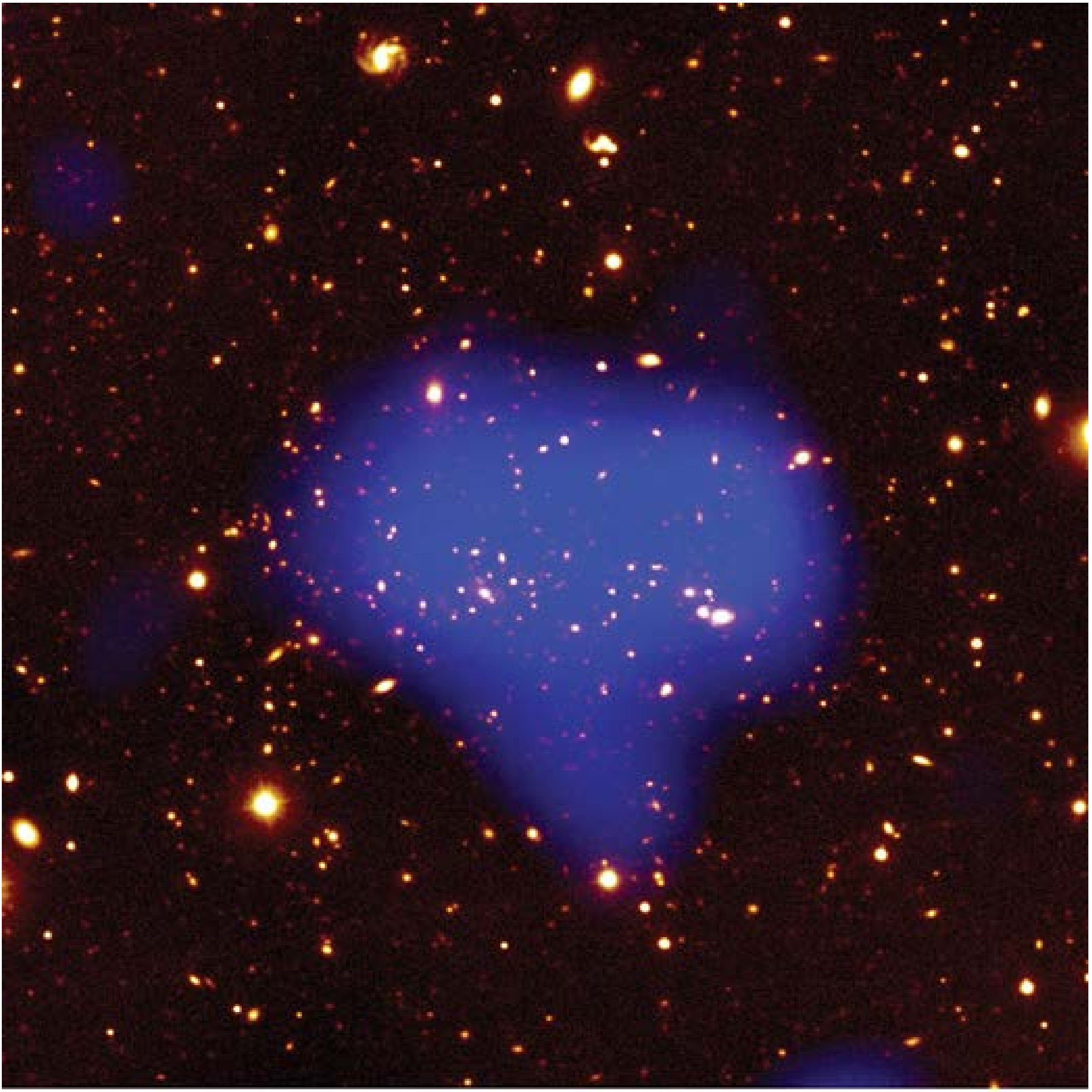




Looking for electron
knocked out of an atom.
Similar to neutrino neutral current interaction!

DM-nucleon scattering cross section
can be less constrained!

Large Volume Neutrino Experiments
Super-K ~ 50K ton! DUNE ~ 68K ton!



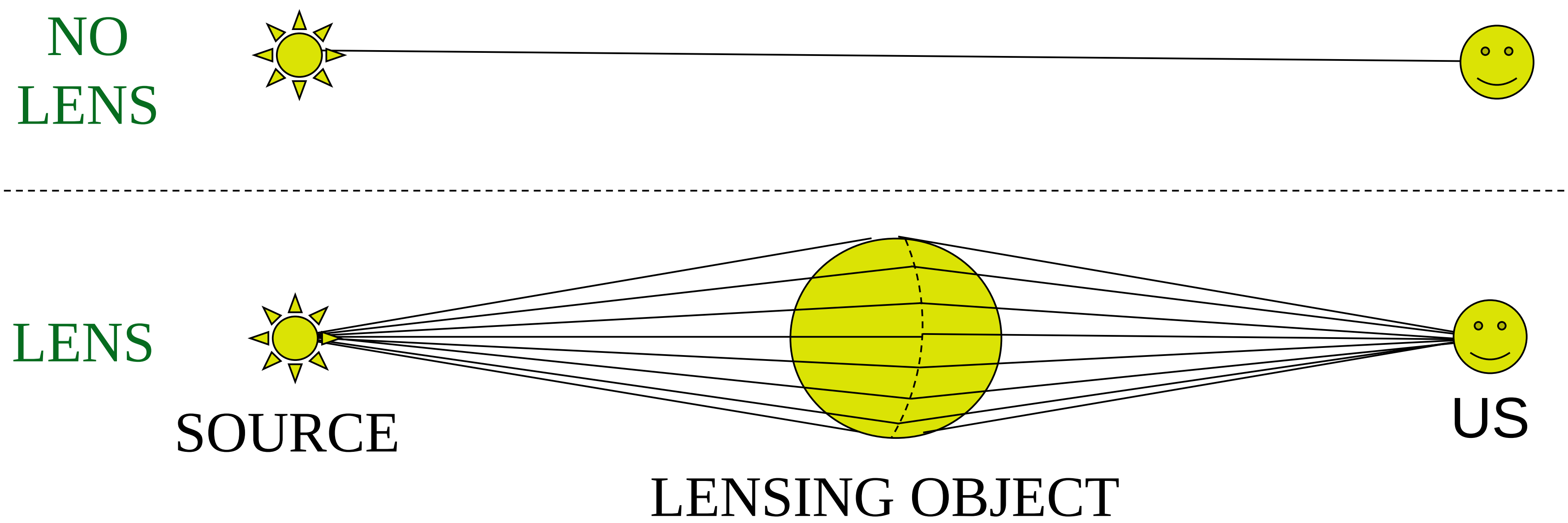
Clusters contain large amounts hot gas: emits x-rays

Temperature of hot gas tells us cluster mass:

85% dark matter
13% hot gas
2% stars

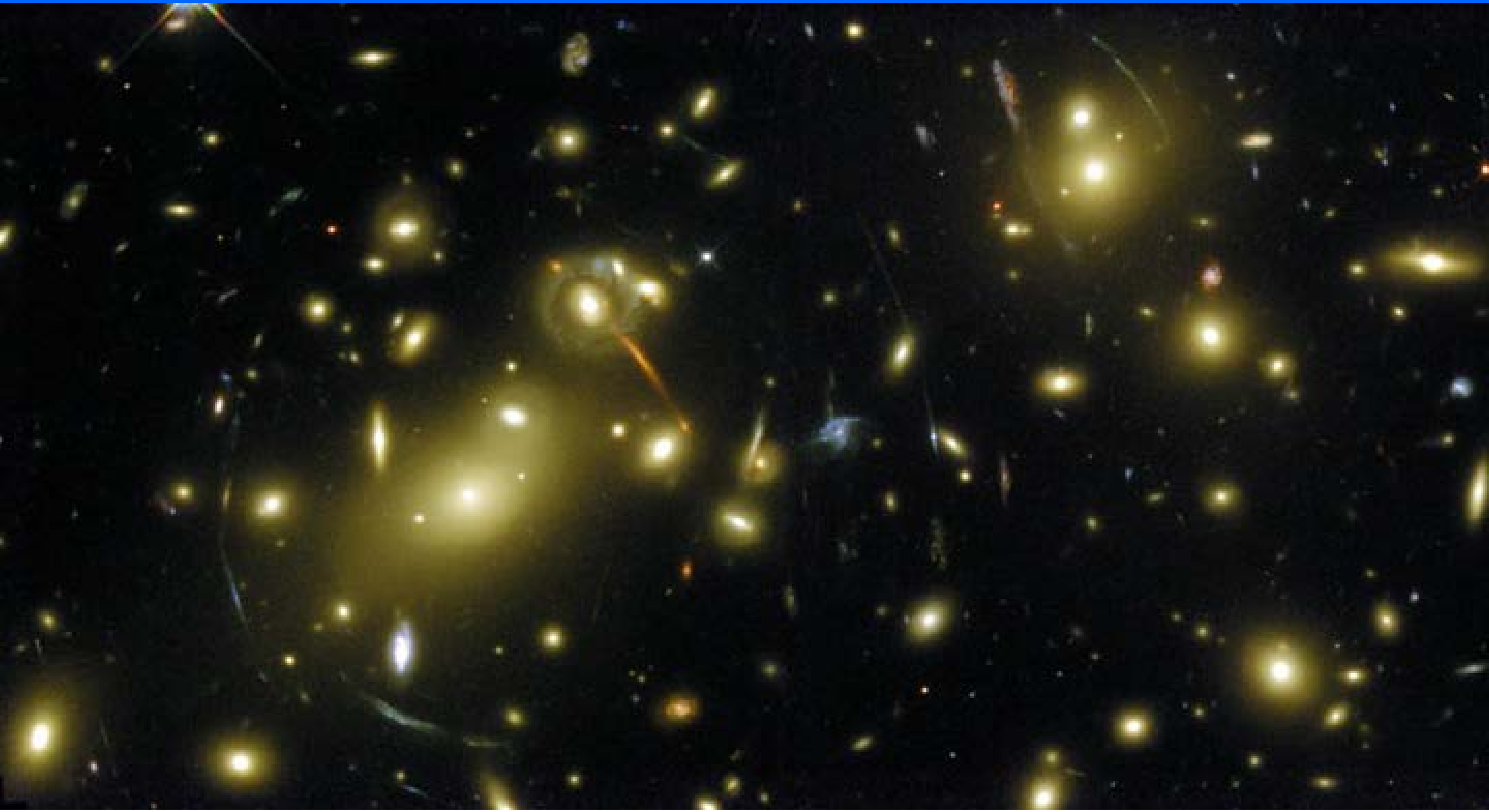
Gravitational lensing of light

Bending of light in gravitational fields can make lenses out of massive objects



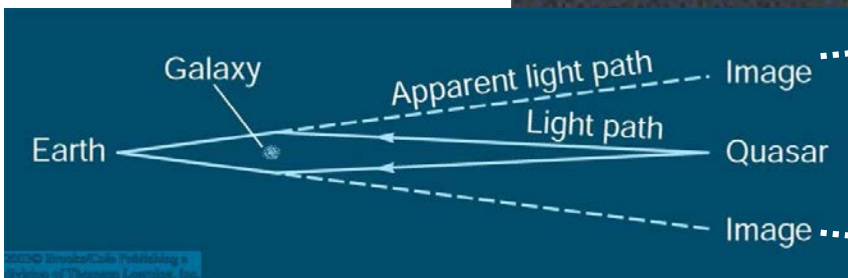
Strong or close lens, expect a ring of light, or a ring of images in the presence of the lens. When not resolved, expect increased intensity.

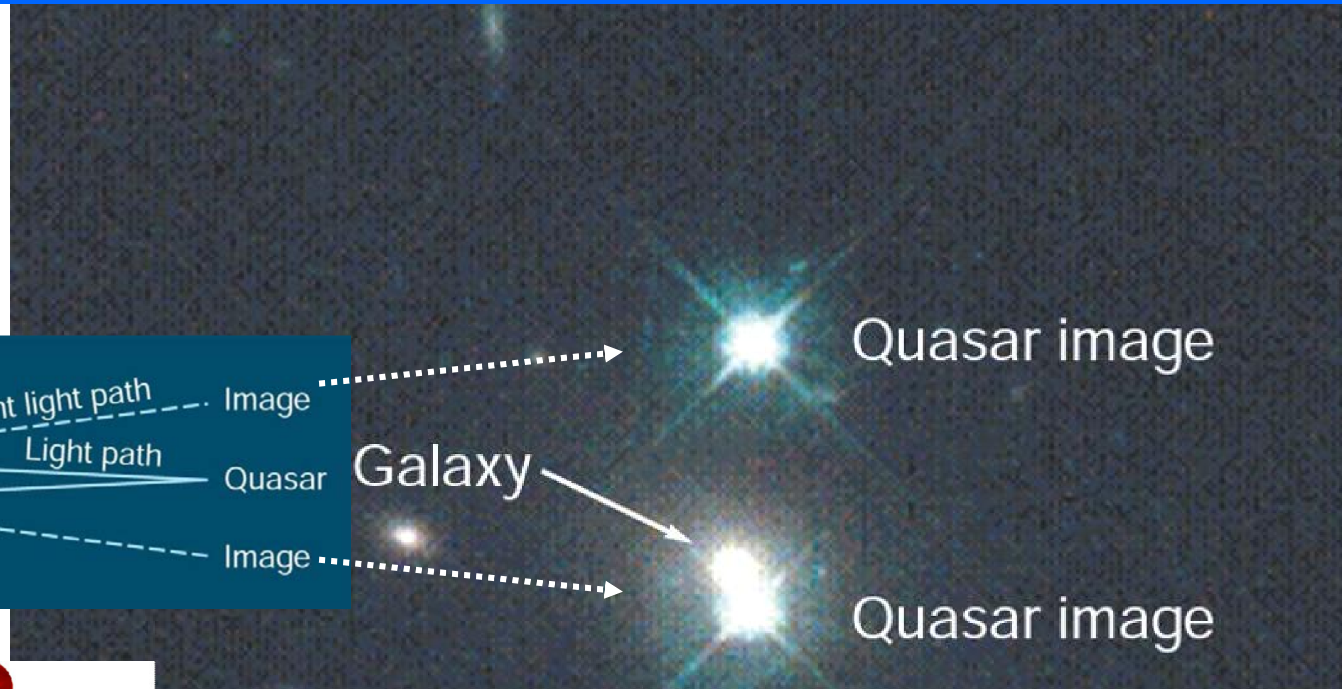
Gravitational lensing of light



Gravitational lensing of background galaxies also tells us the mass

Probing Dark Matter with distant Quasars



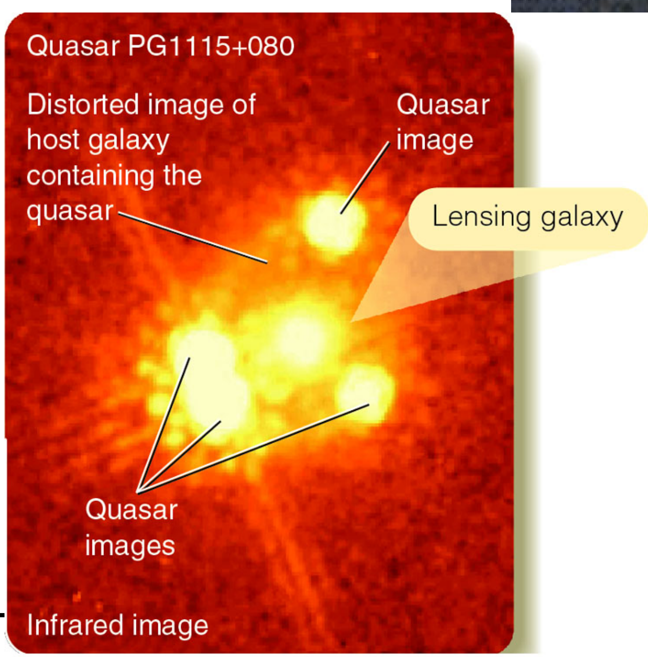


Light from a distant quasar is bent around a foreground galaxy

→ two images of the same quasar!

Light from a quasar behind a galaxy cluster is bent by the mass in the cluster.

Use to probe the distribution of matter in the cluste



Galaxy Cluster 0024-1654 Hubble Deep Field

← 1.4 million light years →

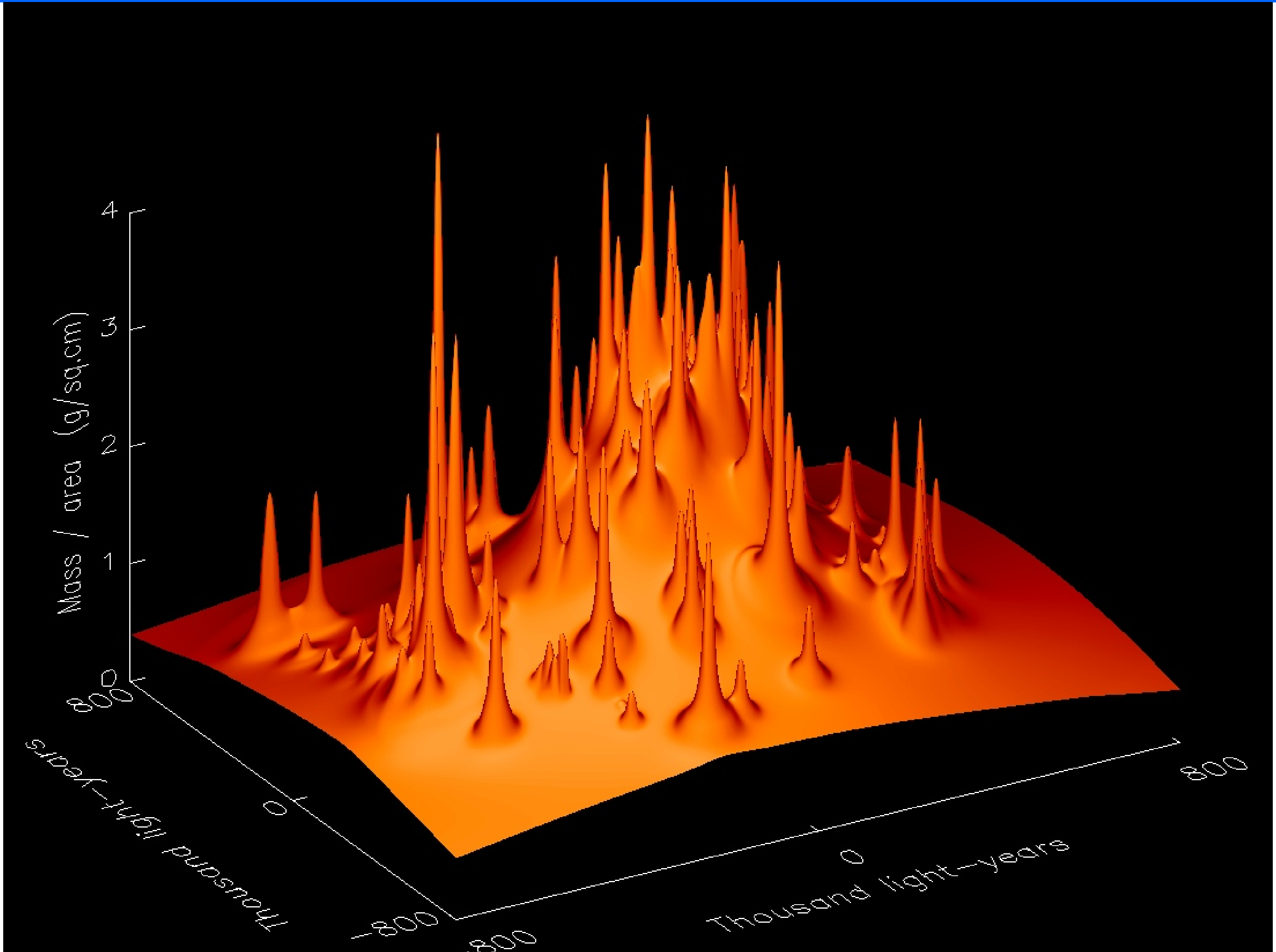
Gravitational Lens HST • WFPC2

Galaxy Cluster 0024+1654

PRC96-10 • ST ScI OPO • April 24, 1996

W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA

Reconstructed Matter Distribution Galaxy Cluster 0024-1654



[Tyson et al., Ap. J. **498** L107-110, 1998]

What could constitute the Dark Matter (1)?

IDEA 1 : Rocks

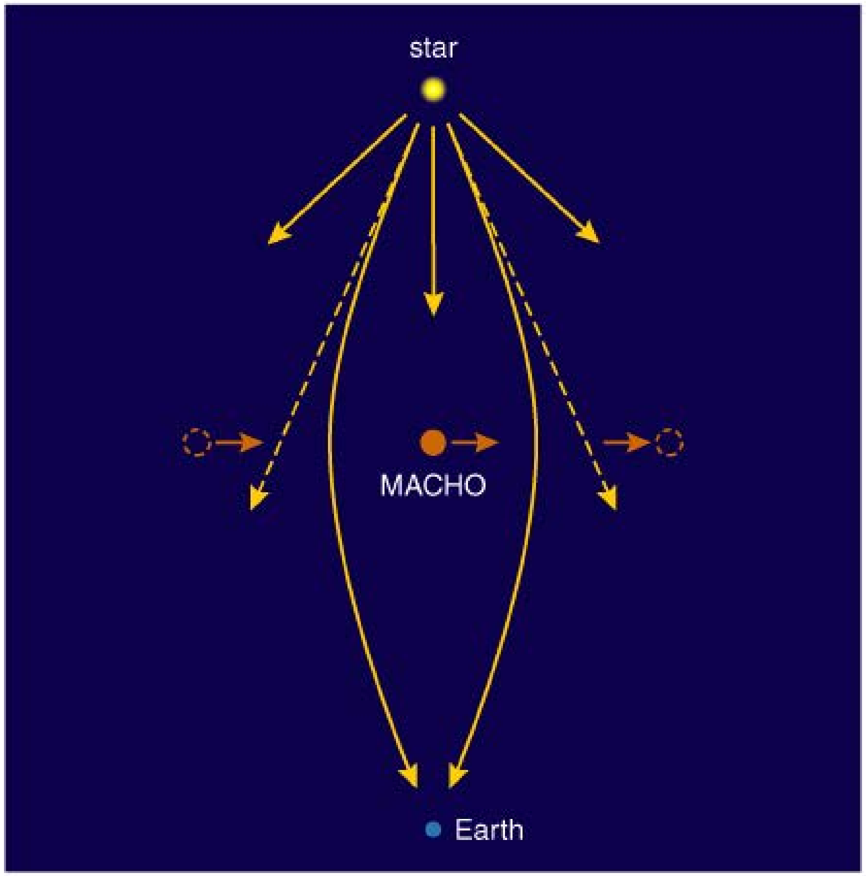
- from pebbles to giant planets like Jupiter.
If there are enough of them, they could make up the dark matter.

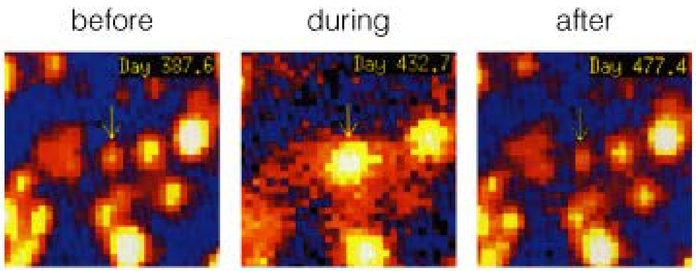
Jupiter-size and above planets are a serious contender, and are called MACHOs by the community - **MA**ssive **C**ompact **H**alo **O**bjects.

IDEA 2: Neutrinos

Light, neutral particles of which at least some have a small mass. Produced in enormous numbers in stars and possibly at the big bang. If there are enough of them, they could (maybe) be the dark matter.

MAssive Compact Halo Objects





MACHOs do not cause enough lensing events to explain all the dark matter

What could constitute the Dark Matter (2)?

IDEA 3: Black Holes

Don't emit significant amounts of light, can be very massive.
Would need lots of them.

IDEA 4: Cosmic Strings

Dense filamentary structures that some theorists think could thread the universe, giving rise to its present-day lumpiness. Currently disfavored by cosmological data, but may come back into vogue sometime.

What could constitute the Dark Matter (3)?

IDEA 5: Axions

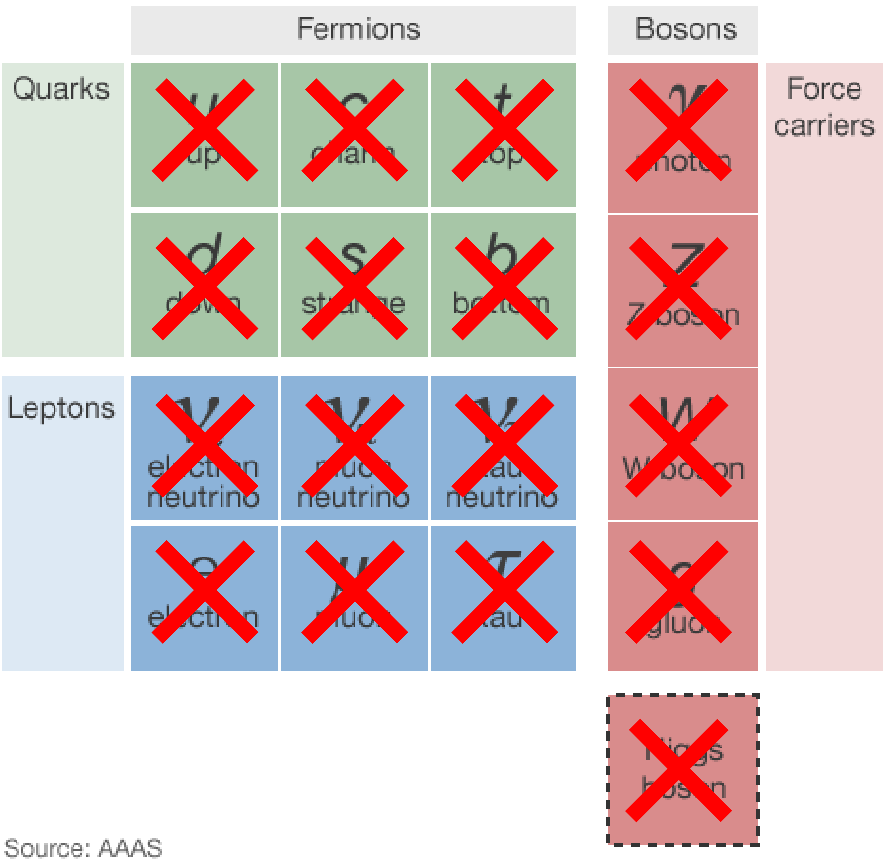
Very light particles, mass around 1/1,000,000,000,000 of an electron. Needed for building most realistic models of the neutron from standard model particle physics. Not detected. To be the dark matter, there should be around 10,000,000,000,000 per cubic centimeter here on Earth.

IDEA 6: WIMPS (**W**eakly **I**nteracting **M**assive **P**articles)

Particles having mass roughly that of an atomic nucleus, could be as light as carbon or as heavy as 7 nuclei of xenon. Need a few per liter to constitute dark matter. Unlike nucleus, only interact WEAKLY with other matter, through the same mechanism that is responsible for nuclear beta-decay.

Could be left over from Big Bang

Dark matter



Source: AAAS

Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Dark Matter
26.8%

Normal Matter
4.9%

Dark Energy
68.3%