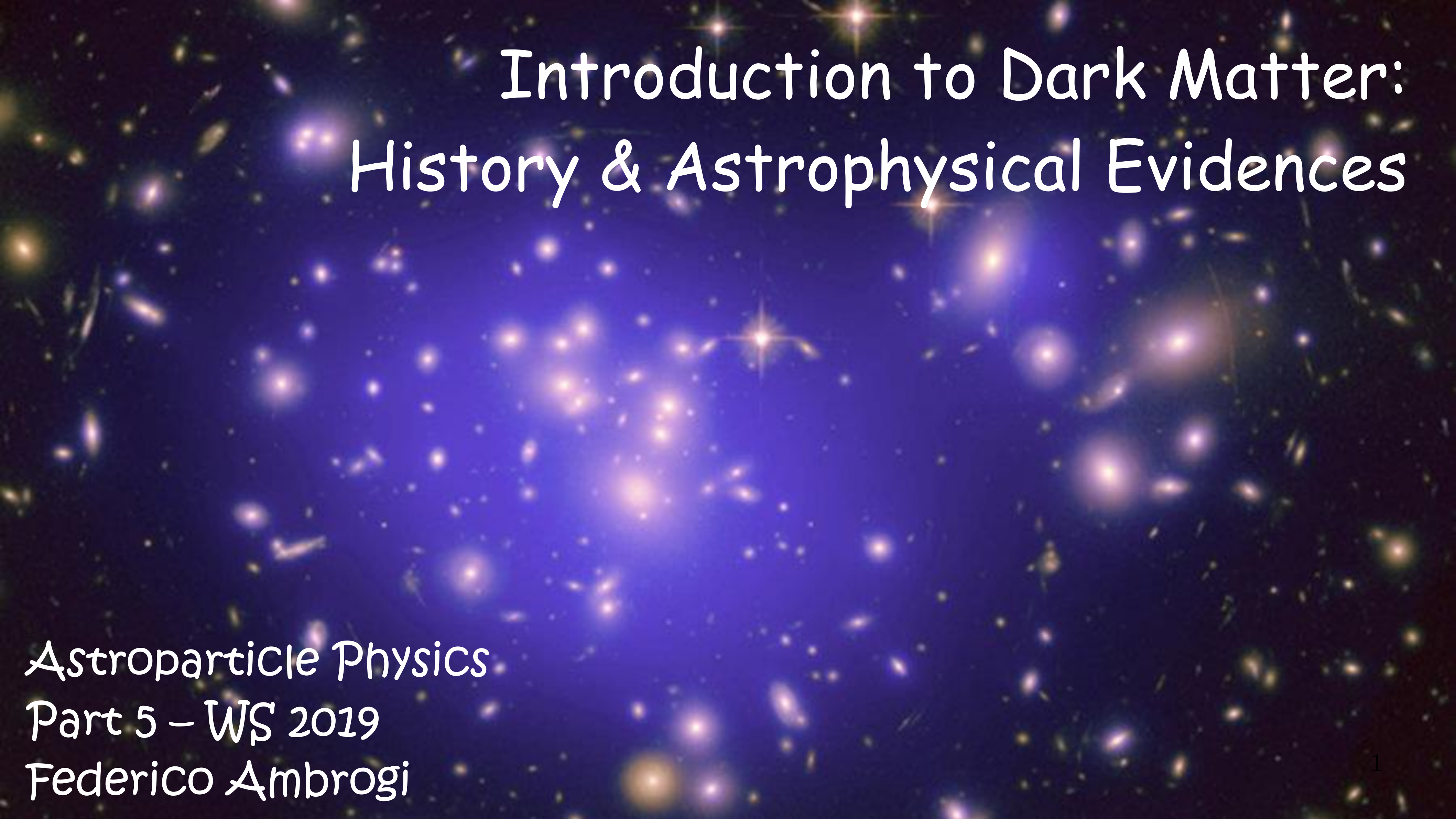
Introduction to Dark Matter: History & Astrophysical Evidences



Astroparticle Physics
Part 5 – WS 2019

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Overview

Why do we talk about dark matter i.e. what are the evidences for Dark Matter existence?

What do we think Dark matter is?

What is the role of Dark Matter in the evolution of the Universe?

How can we search for Dark Matter?

Introduction: An Astrophysical Puzzle

http://hosting.astro.cornell.edu/academics/courses/astro201/vt.htm

https://arxiv.org/pdf/1605.04909.pdf

- Dark Matter is a building block of modern Cosmology and of the LambdaCDM model
- Pioneer of DM studies: the Swiss-American astronomer Fritz Zwicky (**1933**)
- He studied the velocity dispersion of galaxies inside the Coma cluster

(a large cluster of galaxies with more than 1,000 identified galaxies) and found a gravitational anomaly

- He was the first to use the virial theorem to determine the mass of a galaxy cluster
- He estimated the total mass M_{tot} of Coma as

$$M_{tot} = 800 * \langle m \rangle$$

where $\langle m \rangle = 10^9$ Mo is the average mass of the galaxies in a radius of the system equal to 10^6 light-years

- He calculated the potential energy, the average kinetic energy, applied the virial theorem,

obtained a velocity dispersion of ~ 80 km/s

!!! The observed average velocity dispersion along the line-of-sight was approximately 1000 km/s >> 80 km/s !!!

Virial Theorem:

$$K = -\frac{1}{2}P$$

http://hosting.astro.cornell.edu/academics/courses/astro201/vt.htm

Gravitational Potential Energy:

$$P \sim -\frac{1}{2}G\frac{N^2m^2}{R_{tot}} = -\frac{1}{2}G\frac{M_{tot}^2}{R_{tot}}$$

Kinetic Energy: $K = \frac{1}{2}mv^2$

Assuming the system is composed of N galaxies with average mass <m> = m:

$$K_{tot} = \frac{1}{2}mNv^2 = \frac{1}{2}M_{tot}v^2$$

Apply the Virial Theorem:

$$\frac{1}{2}M_{tot}v^2 = +\frac{1}{4}G\frac{M_{tot}^2}{R_{tot}} \Rightarrow M_{tot} = 2\frac{R_{tot}v^2}{G}$$

Introduction: An Astrophysical Puzzle

Objects	Distance (in kpc)	Luminosity (in sol. lum.)	Mass (in sol. mass)	Mass/Lum. f
Solar Neighborhood	—	—	—	4
Triangulum Nebula, M33	480	1.4×10^9	5×10^9	4
Large Magellanic Cloud	44	1.2×10^9	2×10^9	2
Andromeda Nebula	460	9×10^9	1.4×10^{11}	16
Globular Cluster, M92	11	1.7×10^5	$<8 \times 10^5$	<5
Elliptical Galaxy, NGC 3115	2100	9×10^8	9×10^{10}	100
Elliptical Galaxy, M32	460	1.1×10^8	2.5×10^{10}	200
Average S in Double Gal.	—	1.3×10^9	7×10^{10}	50
Average E in Double Gal.	—	8×10^8	2.6×10^{11}	300
Average in Coma Cluster	25000	5×10^8	4×10^{11}	800

FIG. 1. A snapshot of the dark matter problem in the 1950s: the distance, mass, luminosity, and mass-to-light ratio of several galaxies and clusters of galaxies, as compiled by M. Schwarzschild in 1954 [282].

Several galaxies showed an 'excess of mass' wrt the total visible luminous emission

- Useful astronomical quantity: Mass to Light ratio, M/L
- It is defined as the ratio of the mass and the luminosity of an object
- Typically use the Solar value $M_\odot / L_\odot$ ~ 5100 kg/W
- Segue 1 dwarf spheroidal galaxy: **M/L > 3.400,** contains only a few hundred stars, yet has a large mass
- "Segue 1: The Darkest Galaxy" *(Ideal objects to study DM annihilation with indirect searches)*

Optical image of an "Ultra faint" dwarf galaxy

“If this would be confirmed, we would get the surprising result that dark matter (dunkle materie) is present in much greater amount than luminous matter“

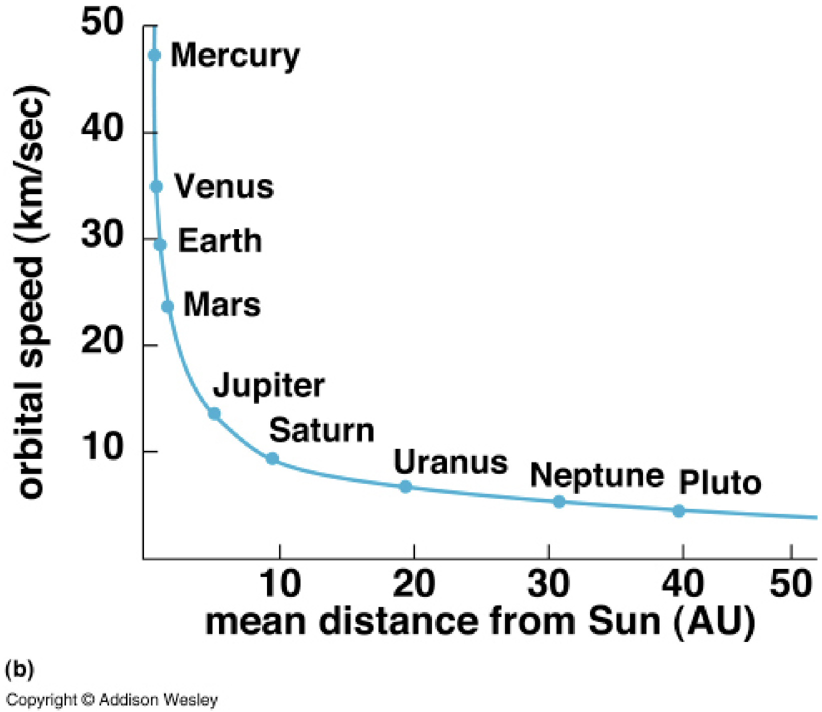
“ [In order to derive the mass of galaxies from their luminosity] we must know how much dark matter is incorporated in nebulae in the form of cool and cold stars, macroscopic and microscopic solid bodies, and gases“

- Consider the mean orbital speed of planets around the Sun. The gravitational attractive force must be equal to the centripetal force:

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

$$v(r) = \sqrt{\frac{G\,M}{r}}$$

$$v(r) \propto \sqrt{1/r}$$



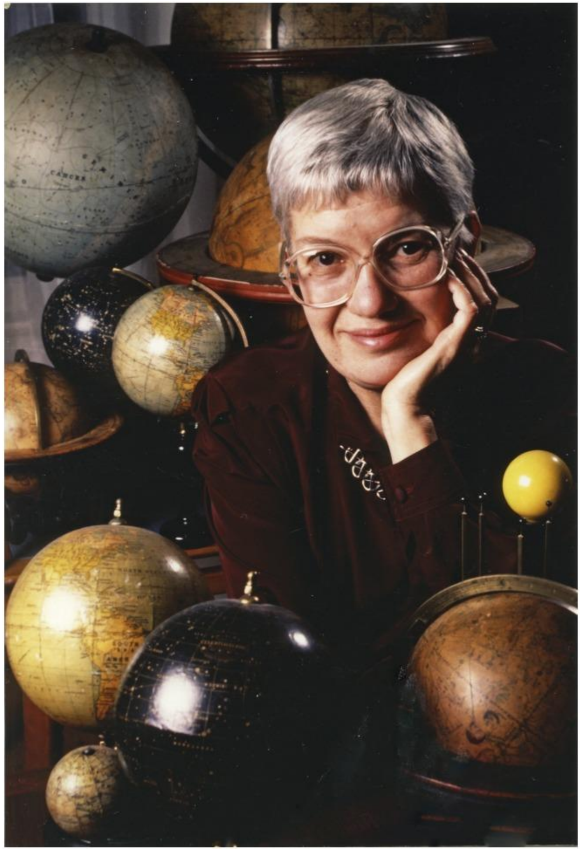
- This is observed for the planets in the solar system (sometimes called “Keplerian fall”)

- This should also holds for other dynamical system e.g. the motion of stars in spiral galaxies orbitating around the galactic centre (i.e. supermassive black hole), or blob of hydrogen

Rotation Velocity of Spiral Galaxies

Vera C. Rubin: Pioneering American astronomer (1928–2016)

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5338491/



“Vera Cooper Rubin, an icon of astronomy whose work revolutionized our understanding of the universe by confirming the existence of dark matter”

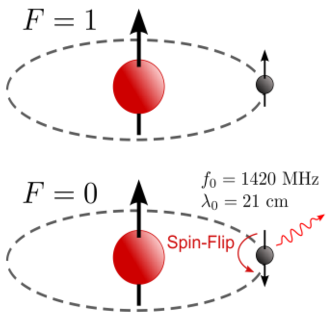
“Her research showed that spiral galaxies rotate quickly enough that they should fly apart, if the gravity of their constituent stars was all that was holding them together; because they stay intact, a large amount of unseen mass must be holding them together, a conundrum that became known as the galaxy rotation problem.

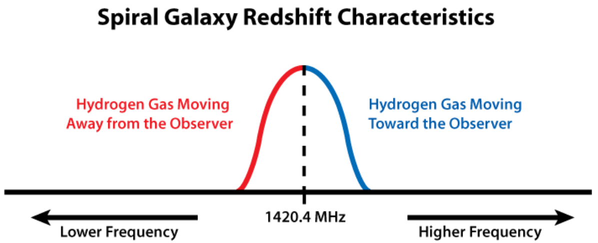
Rubin's calculations showed that galaxies must contain at least five to ten times as much dark matter as ordinary matter. Rubin's results were confirmed over subsequent decades, and became the first persuasive results supporting the theory of dark matter, initially proposed by Fritz Zwicky in the 1930s.

This data was confirmed by radio astronomers, the discovery of the cosmic microwave background, and images of gravitational lensing.”

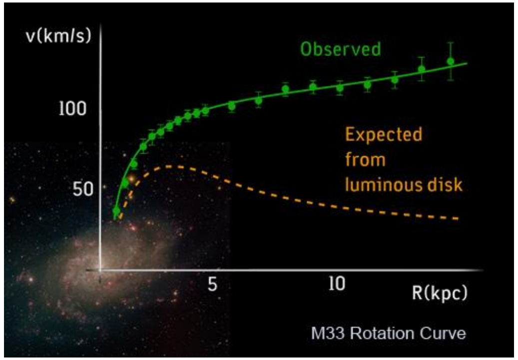
http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/velcurv.html

- However: this behavior is not observed in the case of spiral galaxies; instead of the expected fall, the rotation curves all seem to flatten with increasing distance from the centre
- Idea: use the neutral hydrogen clouds 21cm radio emission to map the rotational velocity

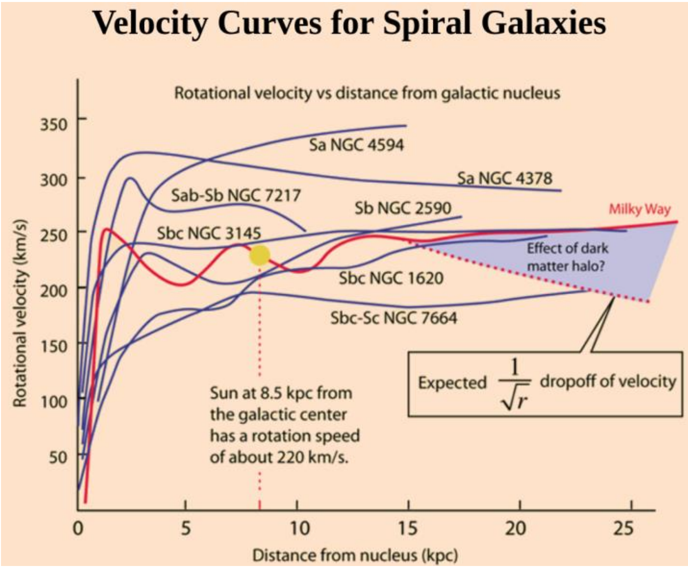




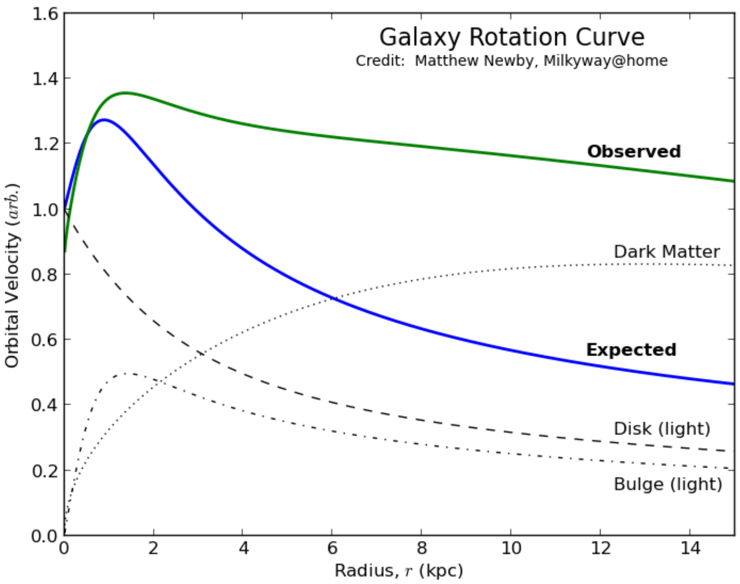
Hyperfine splitting or "spin flip": transition to two different spin states of the electron. The motion wrt the observer will cause blue or red-shift (Doppler effect)



Triangulum Galaxy



Rotation Velocity



How to explain this

- Observe the luminous matter distributions of the two components of the galaxy (i.e. the bulge and the disk)

- Calculate the gravitational potential, and resulting velocity distribution of start as a function of the distance

- Add the contributions→ they do not match the observations

- Add a hypotetical distribution of matter, that is not observed, to produce velocites compatible with observations

- Calculations/simulations suggest a presence of a halo of non-visible matter, that surrounds the galaxy, and explain the flattening of the rotation curves

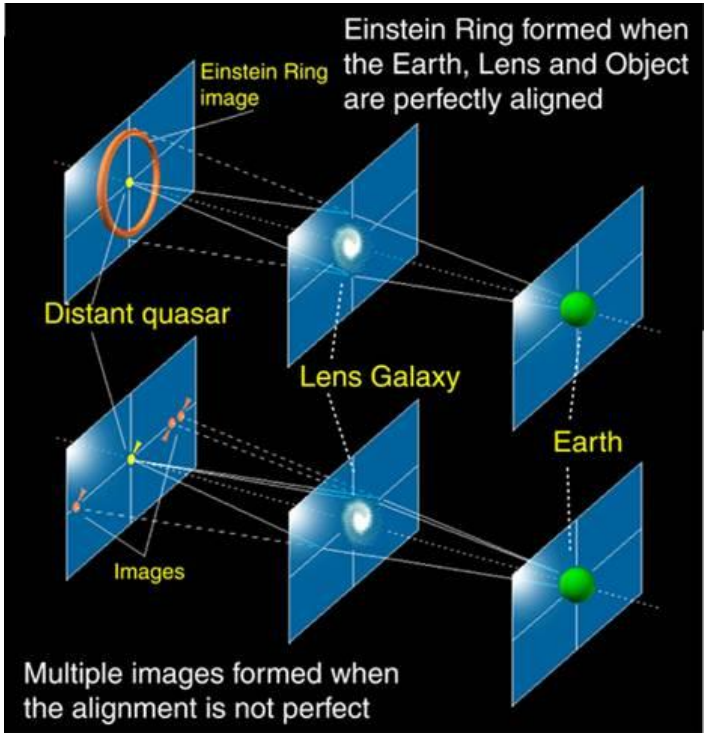
- The halo component dominates at large radii, while it is less important near the centre

- Yet, another prediction from Einstein general relativity

- In the presence of a large mass, the space-time is distorted and particles e.g. photons follow accordingly different geodetics

- The image of a distant source (like a quasar) appears on the sky at a different position, or at multiple positions, or distorted due to the intense gravitational field caused by a massive astrophysics placed in between the source and the observer

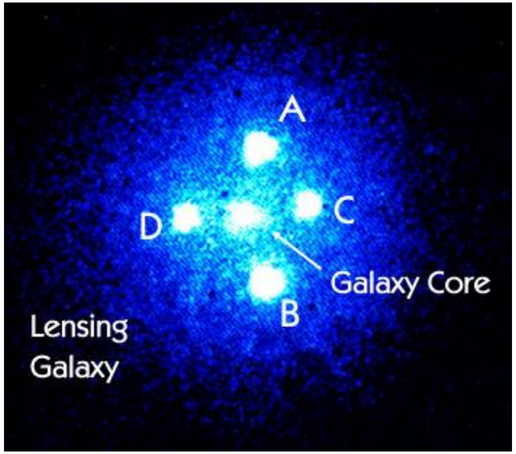
- Depending on the alignment of the luminous source – lensing object – observer, multiple effects are possible



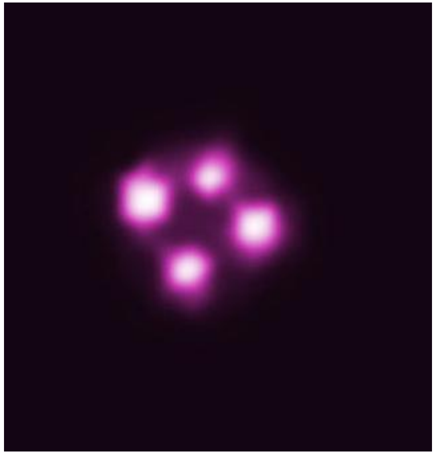
http://www.astronomy.com/news/2015/04/alma-sees-einstein-ring-in-stunning-image-of-lensed-galaxy

- The Einstein Cross (Q2237+030 or QSO 2237+0305) is a gravitationally lensed quasar

- Due to strong gravitational lensing caused by the lensing galaxy (Huchra's Lens), the light coming form the quasar splits into four different images



The above long-exposure photograph shows the position of the lensed images of the quasar



Chandra satellite X-Ray observation

Constraining Quasar Relativistic Reflection Regions and Spins with Microlensing

"The X-rays detected by Chandra are produced when the accretion disk surrounding the black hole creates a multimillion-degree cloud, or corona above the disk near the black hole. X-rays from this corona reflect off the inner edge of the accretion disk, and the strong gravitational forces near the black hole distort the reflected X-ray spectrum, that is, the amount of X-rays seen at different energies. The large distortions seen in the X-ray spectra of the quasars studied here imply that the inner edge of the disk must be close to the black holes, giving further evidence that they must be spinning rapidly."

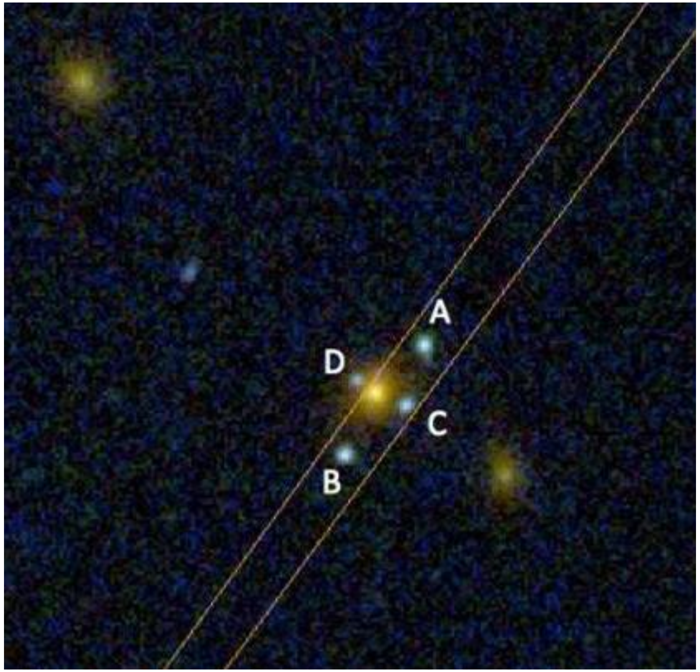
https://arxiv.org/pdf/1901.06007.pdf

https://chandra.harvard.edu/blog/node/731

https://phys.org/news/2019-03-einstein.html

!!! New Einstein Cross (March 2019) found by The Hubble Space Telescope https://phys.org/news/2019-03-einstein.html

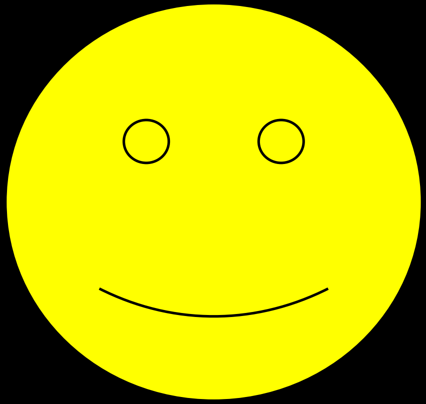
“ The object acting as a lens turns out to be an elliptical galaxy located at a distance of approximately 7 billion light years (z = 0.556), while the source is at least 20 billion light years away (z = 3.03). "Normally the source is a quasar, it was with great surprise that we realized the source in this case was another galaxy, in fact a galaxy with very intense emission lines which indicates it is a young object still forming large amounts of stars"



[…] Gravitational lenses are important because they allow the study of the Universe in a unique way. Because the light of the different images, initially the same light, follows different paths in the Universe, thus any spectral differences must be due to the material that is between us and the source. Moreover, if the source is variable, we can see a time delay (one image illuminates before the others), which provides valuable information about the shape of the Universe.

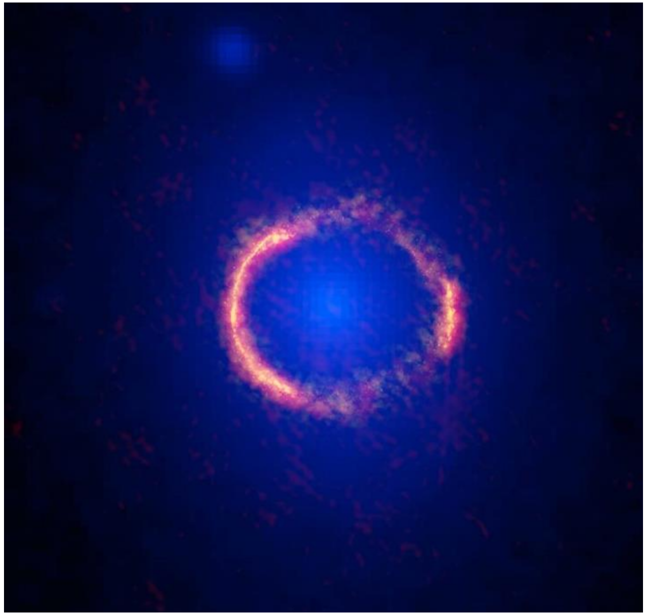
Of course, the mass of the lens responsible for bending the light can be accurately derived, providing an important independent method to weight galaxies.

Finally, as with a normal glass lens, the gravitational lens concentrates toward us the light from the source, making it possible to see intrinsically unreachable objects. In this case it could be calculated that the source is 5 times brighter than it would be without the lens. “



Atacama Large Millimiter Array (ALMA, Chile)

https://public.nrao.edu/news/alma-ring-lens/#PRimage3

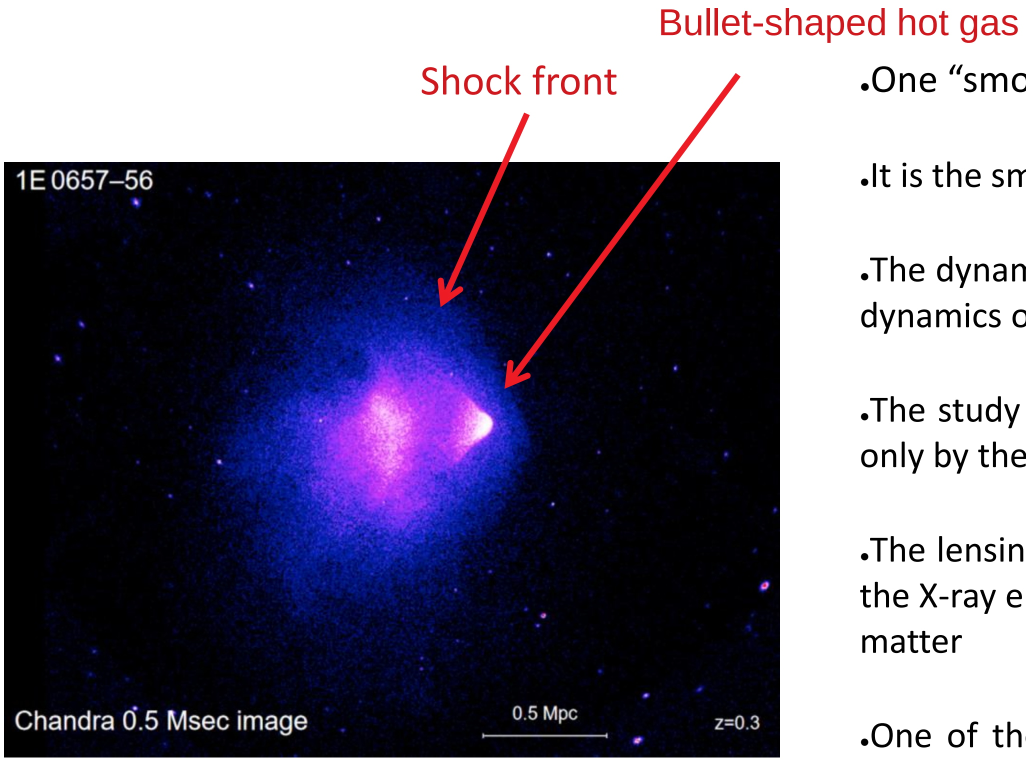


ALMA/Hubble composite image of the gravitationally lensed galaxy SDP.81. The bright orange central region of the ring (ALMA's highest resolution observation ever) reveals the glowing dust in this distant galaxy.

The surrounding lower-resolution portions of the ring trace the millimeter wavelength light emitted by carbon monoxide.

The diffuse blue element at the center of the ring is from the intervening lensing galaxy, as seen with the Hubble Space Telescope.

Bullet Cluster (1E 0657–56)



- One "smoking gun" of the existence of Dark Matter
- It is the smallest cluster of a two cluster systems, which is bullet-shaped
- The dynamics of visible components (starts and hot gas) is different from the dynamics of Dark Matter
- The study of gravitational lensing produced by the system can be explained only by the presence of two DM Halos
- The lensing is strongest in two separated regions, which do not overlap with the X-ray emission (from the hot gas) i.e. the centre of mass ODF the baryonic matter
- One of the strongest evidence against alternative gravitation theories (like MOND, Modified Newtonian Dynamics)
- It is possible to derive a model independent DM annihilation / interaction cross section upper limit

Bullet Cluster (1E 0657–56)

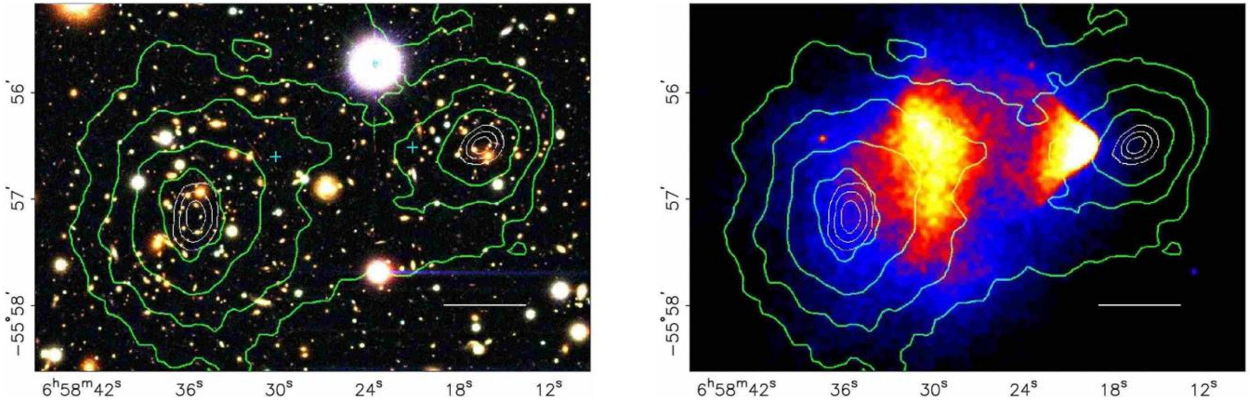


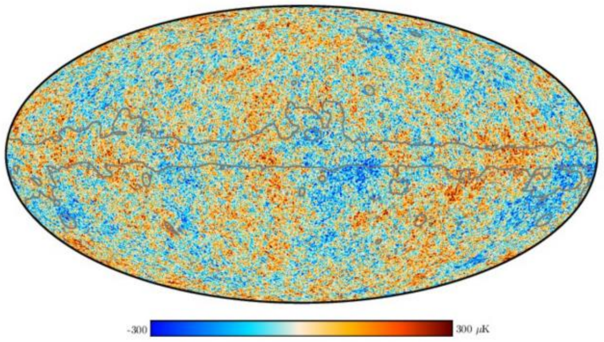
FIG. 1.— Shown above in the top panel is a color image from the Magellan images of the merging cluster 1E0657−558, with the white bar indicating 200 kpc at the distance of the cluster. In the bottom panel is a 500 ks Chandra image of the cluster. Shown in green contours in both panels are the weak lensing κ reconstruction with the outer contour level at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue +s show the location of the centers used to measure the masses of the plasma clouds in Table 2.

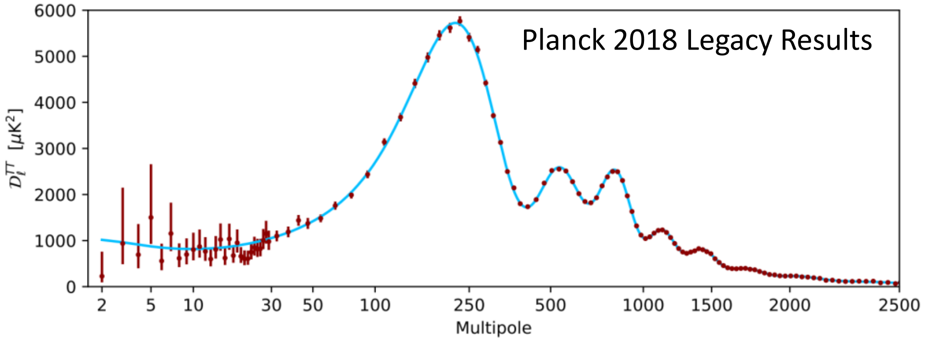
A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER

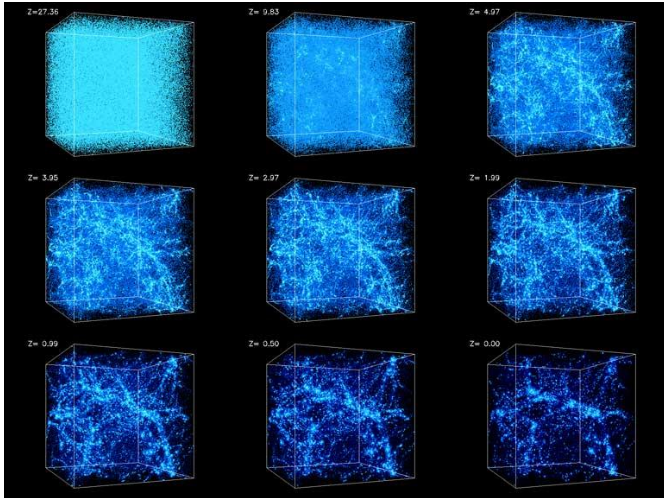
https://arxiv.org/pdf/astro-ph/0608407.pdf

“We present new weak lensing observations of 1E0657−558 (z= 0.296), a unique cluster merger, that enable a direct detection of dark matter, independent of assumptions regarding the nature of the gravitational force law. Due to the collision of two clusters, the dissipationless stellar component and the fluid-like X-ray emitting plasma are spatially segregated. By using both wide-field ground based images and HST/ACS images of the cluster cores, we create gravitational lensing maps which show that the gravitational potential does not trace the plasma distribution, the dominant baryonic mass component, but rather approximately traces the distribution of galaxies. An 8σ significance spatial offset of the center of the total mass from the center of the baryonic maspeaks cannot be explained with an alteration of the gravitational force law, and thus proves that the majority of the matter in the system is unseen.”

CMB Spectrum



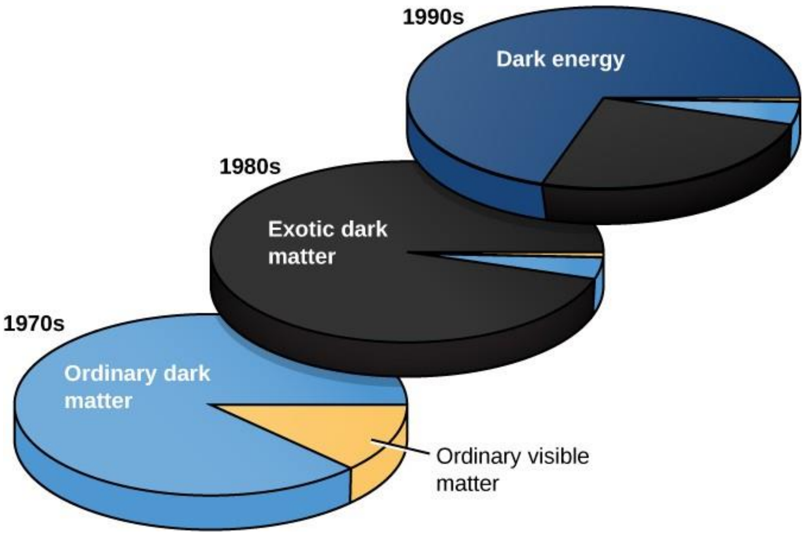


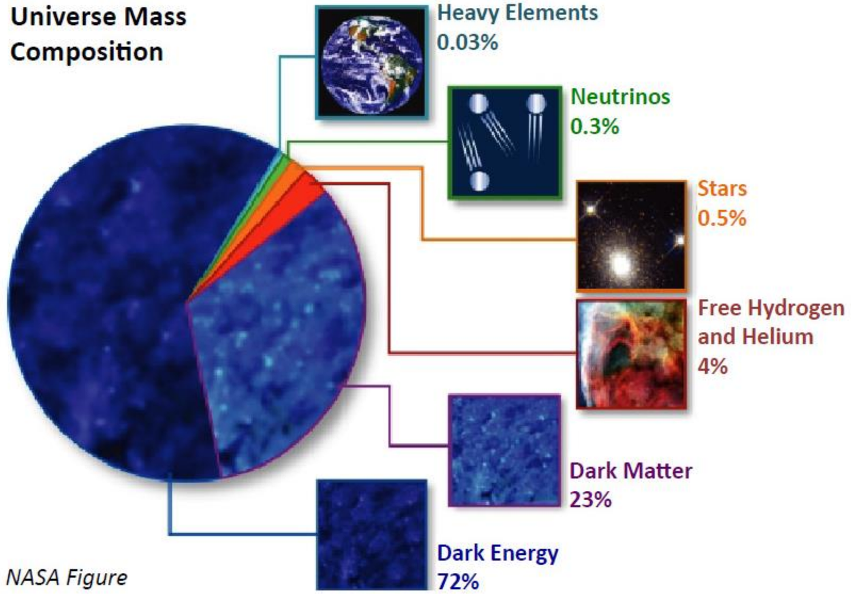


Large Scale Structure of the Universe and Structure Formation

Component	Parameter	TT+lowE 68% limits
Baryonic component	$\Omega_b h^2$	0.02212 ± 0.00022
DM component	$\Omega_c h^2$	0.1206 ± 0.0021
	$100\theta_{MC}$	1.04077 ± 0.00047
	τ	0.0522 ± 0.0080
	$\ln(10^{10} A_s)$	3.040 ± 0.016
	n_s	0.9626 ± 0.0057
	H_0 [km s^{-1} Mpc^{-1}]	66.88 ± 0.92
Dark Energy component	Ω_Λ	0.679 ± 0.013
DM + Baryons	Ω_m	0.321 ± 0.013
	Age [Gyr]	13.830 ± 0.037

DM in the Cosmic Microwave Background and in Cosmology





(Numbers ~ change according to the experiment taken into account)