Astroparticle Physics – the Dark Side of the Universe

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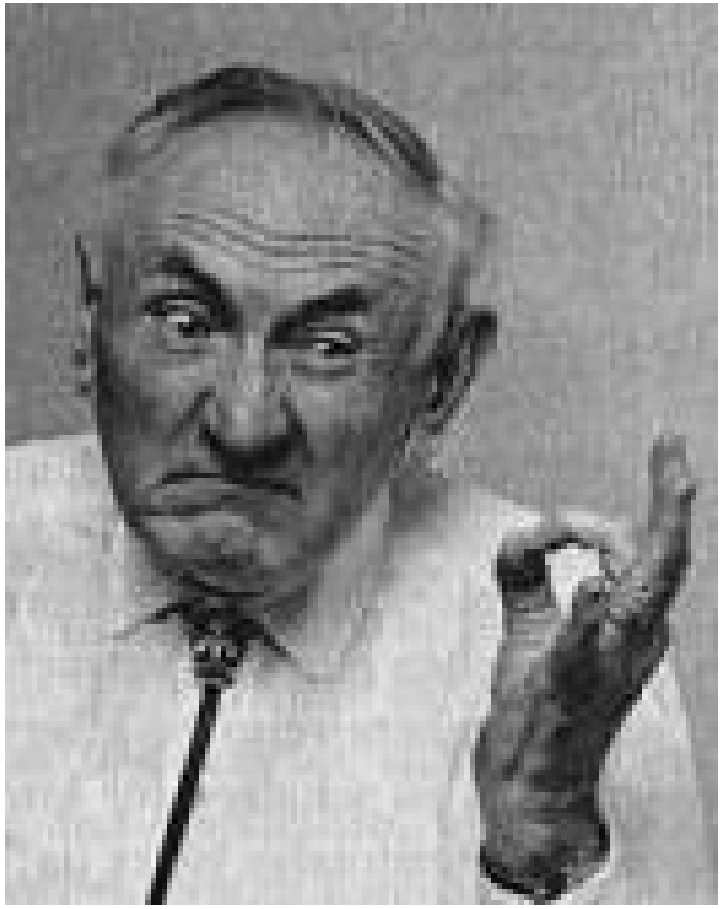
(1) Evidence for Dark Matter

The Father of Dark Matter



In 1933 Fritz Zwicky studied two neighbouring galaxy clusters, Coma und Virgo. The velocities of the individual galaxies that belonged to a cluster were 10 to 100 times higher than expected. The more mass there is in the galaxy cluster, the stronger are the forces exerted on each single galaxy and the higher is their speed.

Virial theorem for potential energy

$V(r) = \alpha r^{n}$

$2 \langle T \rangle = n \langle V_{tot} \rangle$

Dark matter at the scale of galaxy clusters!

The Mother of Dark Matter

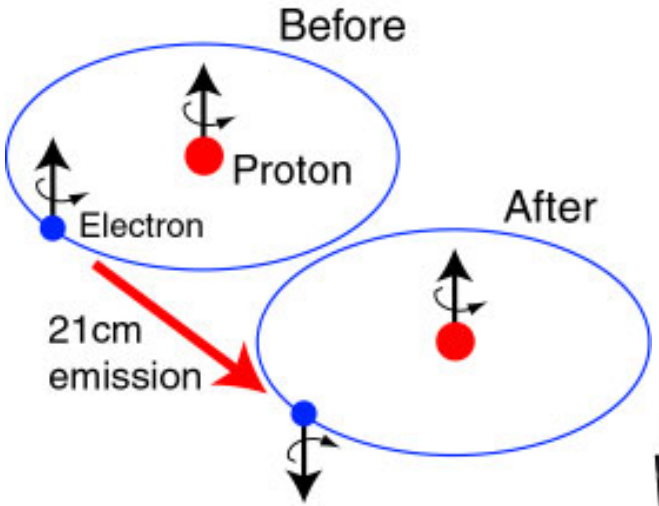
Vera Rubin found 1975 that the velocities of hydrogen gas clouds did not decrease with increasing distance from the galactic center, but either stayed constant or increased slightly.

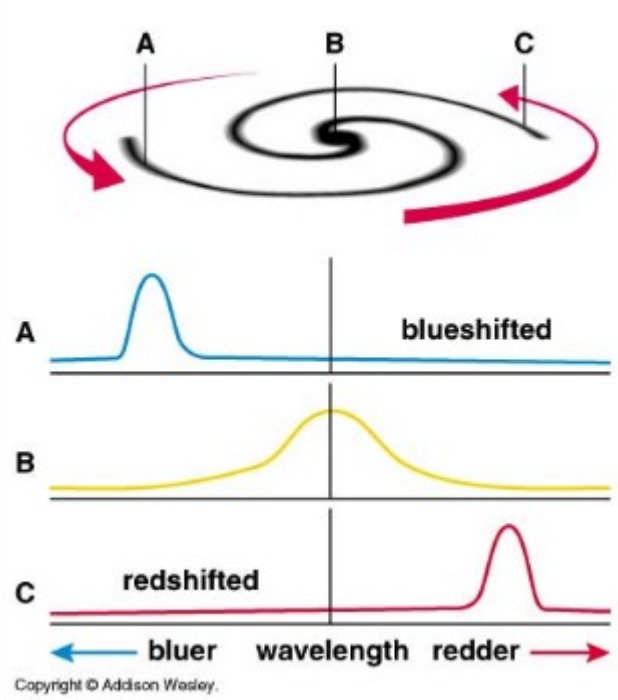
She showed that dark matter is not a phenomenon restricted to the Coma and Virgo clusters.

Dark matter at the scale of galaxies!

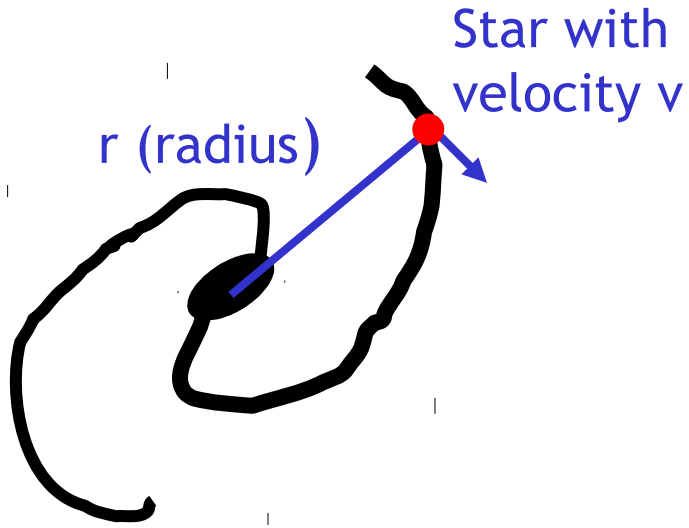
The Mother of Dark Matter

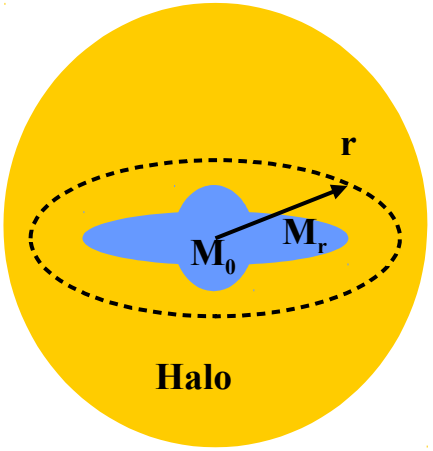
21 cm
Hydrogen line





Rotation speeds





Gravitational force equals centrifugal force:

$G\ m\ M_r\ /\ r^2 = mv^2\ /\ r$

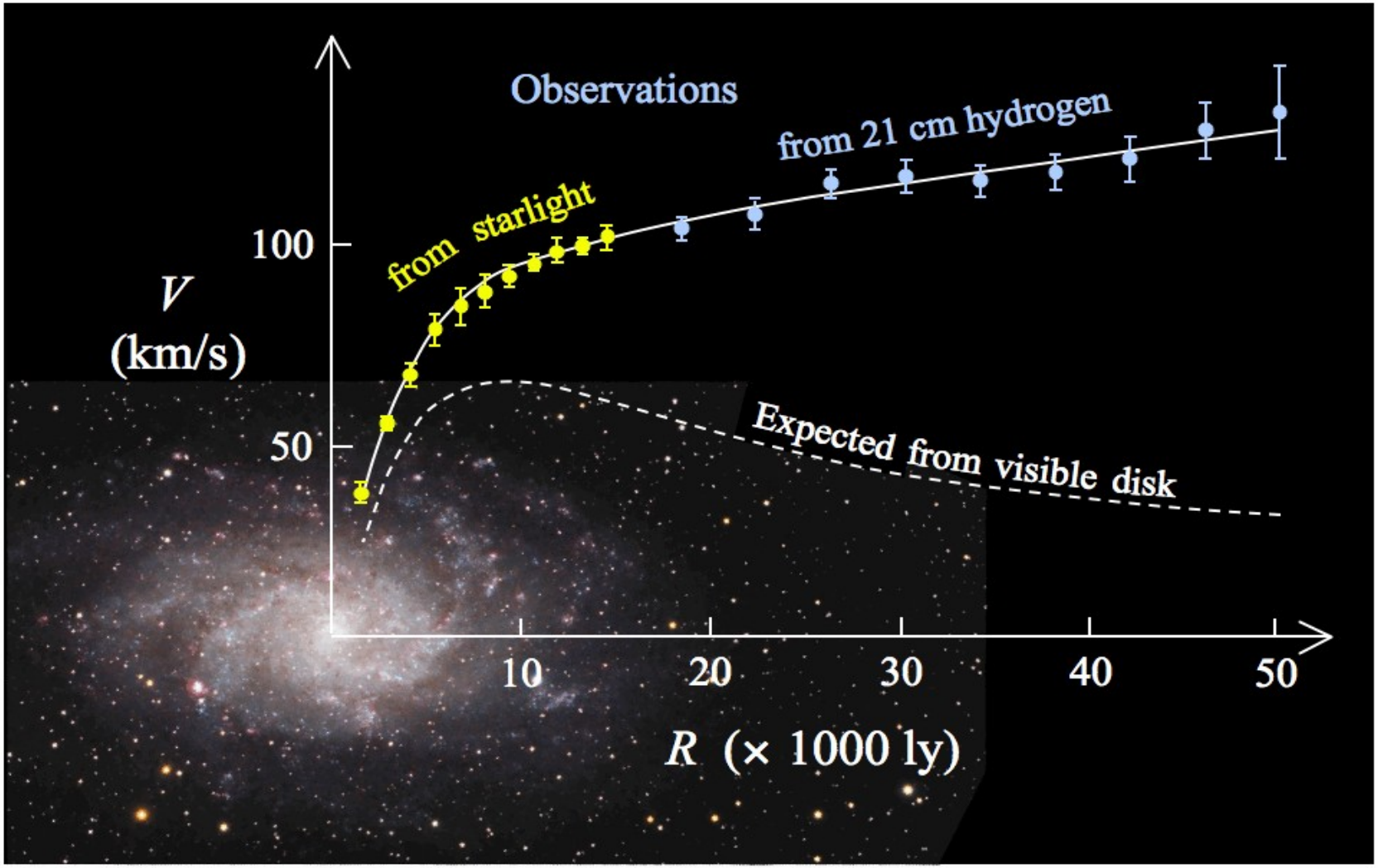
Mass inside radius r: $M_r = v^2\ r\ /\ G$

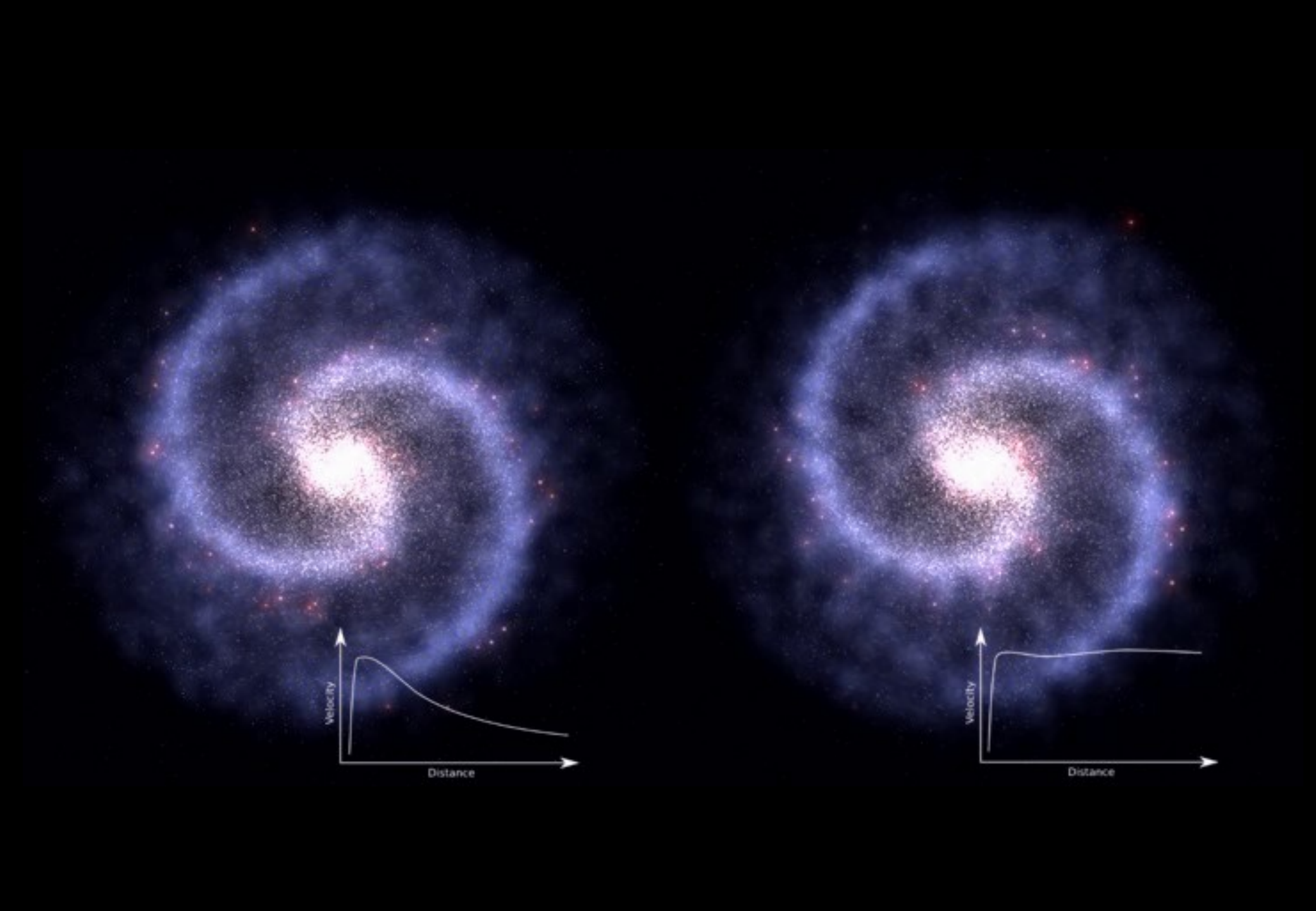
If star is inside hub (central mass M_0): $M_r \sim r^3 \rightarrow v \sim r$

If star far outside hub (assuming no DM): $M_r \sim \text{const} \rightarrow v \sim 1/\sqrt{r}$

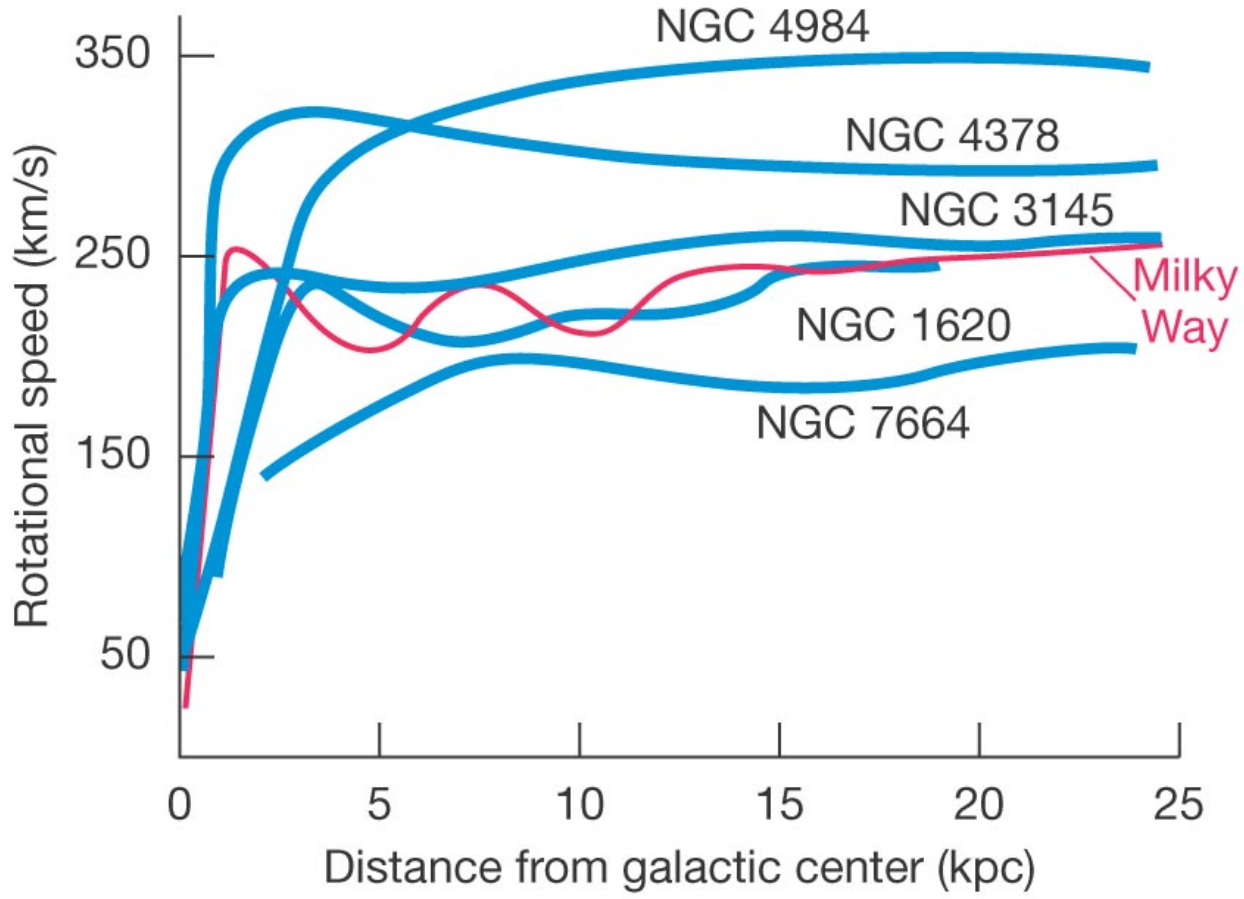
$G = 6.7 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$

Galaxy rotation curve




Velocity
Distance
Velocity
Distance

Galaxy rotation curves

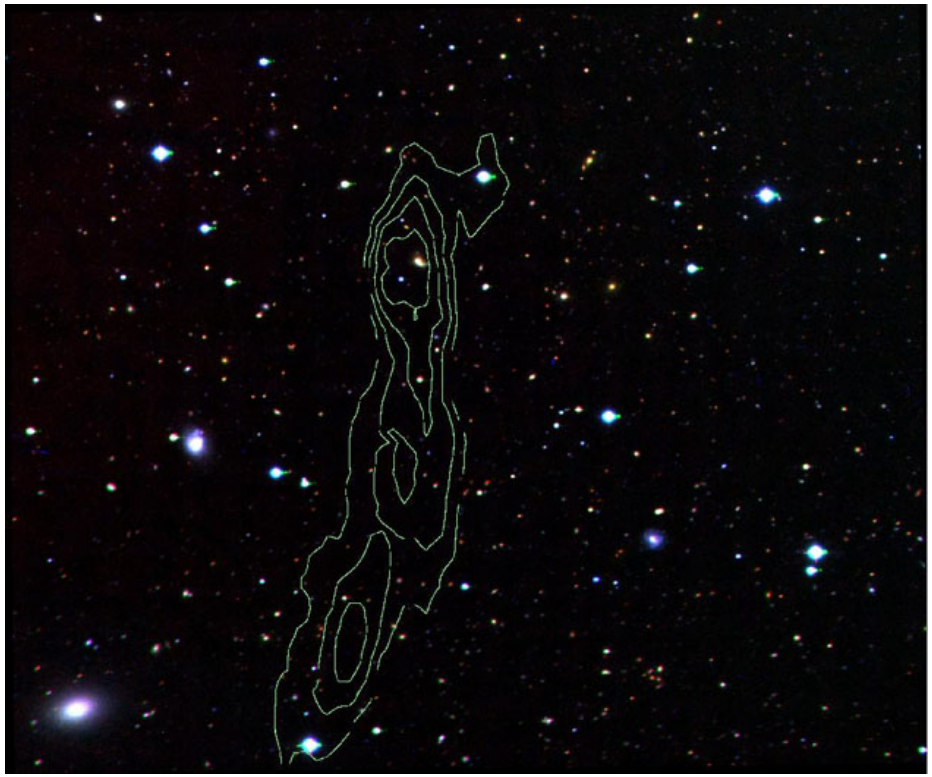


Rotation curves of numerous spiral galaxies are flat. To explain this a massive halo (10:1) is required.

Galaxy rotation curves

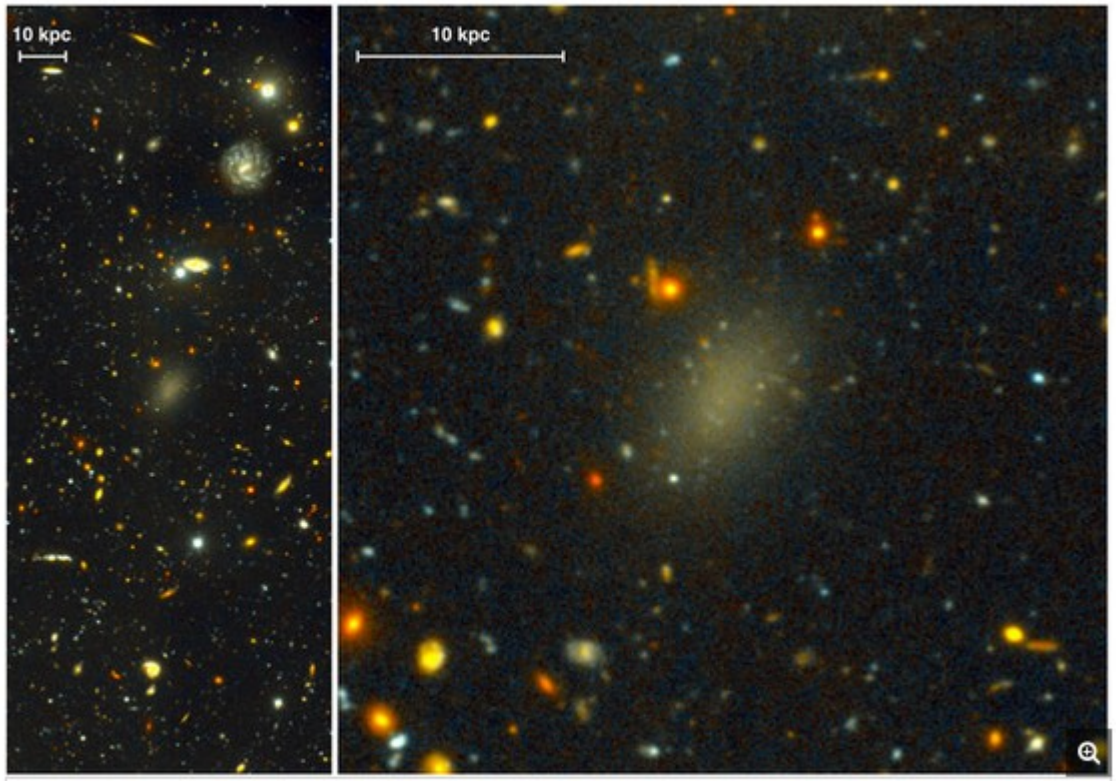
Astronomers discovered that the galaxy VIRGOHI21 practically totally consists of Dark Matter!

No stars, only 21 cm hydrogen-line emission; hydrogen is rotating and $M_H:M_{total} \sim 1:10^3$



arXiv:astro-ph/0502312v1

Dragonfly 44

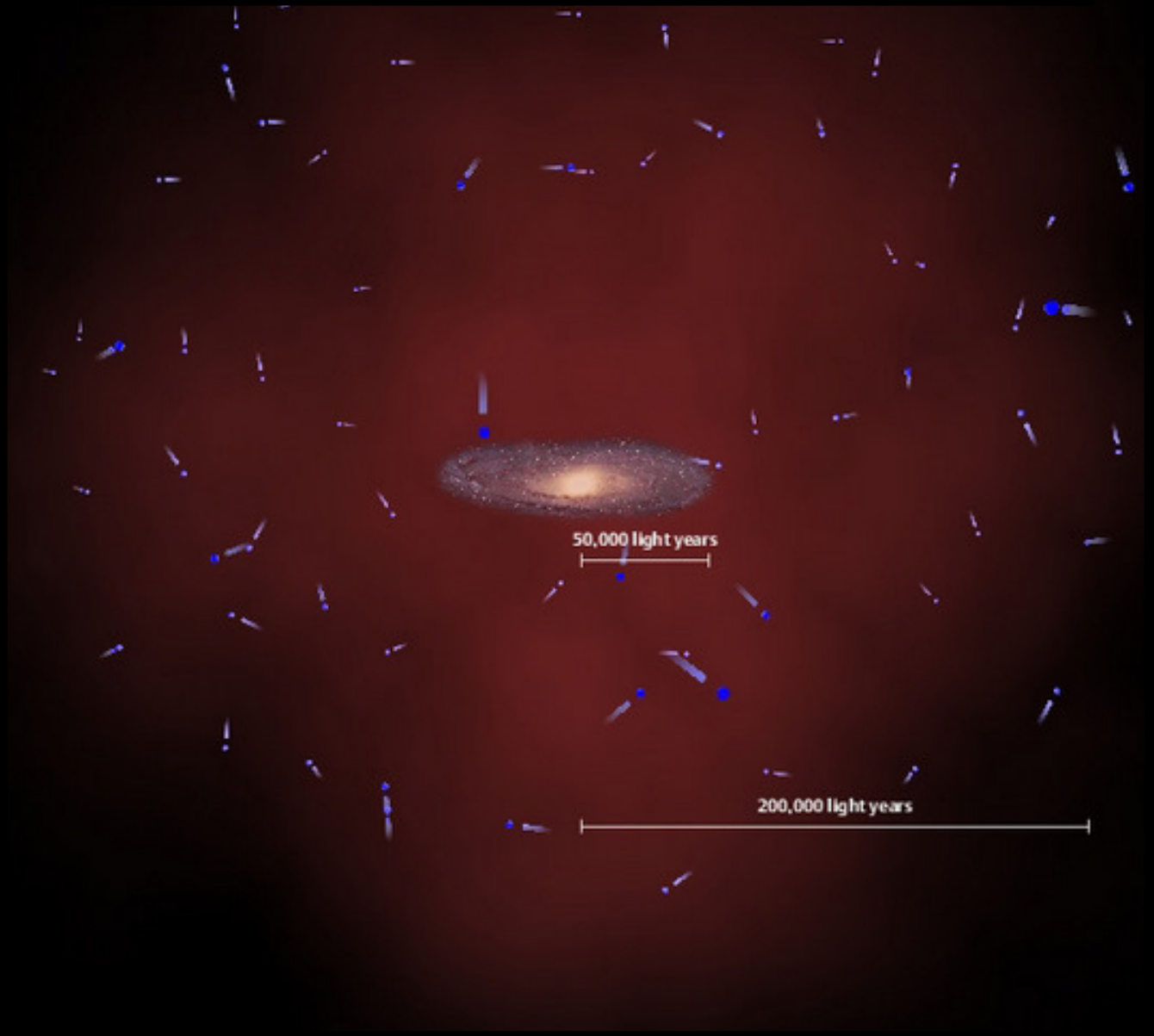


Astronomers photographed the ultradiffuse galaxy Dragonfly 44 using the Gemini Multi-Object Spectrograph (GMOS) on the 8-meter Gemini North telescope in Mauna Kea, Hawaii.

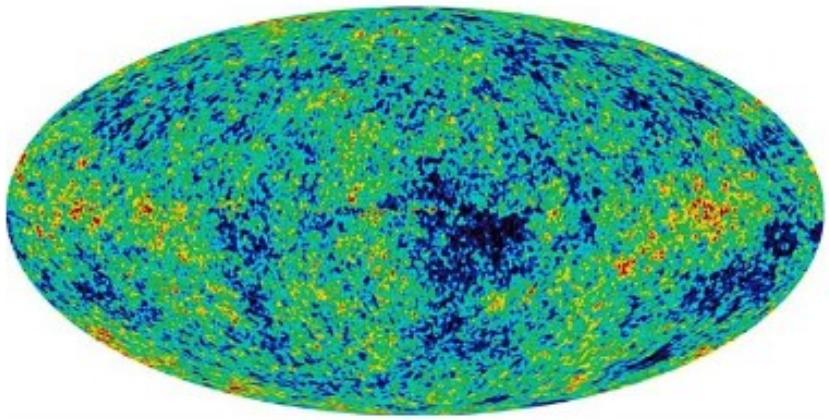
Credit: Pieter van Dokkum, Roberto Abraham, Gemini Observatory/AURA

Ultra-diffuse galaxy in the coma cluster (non-rotating) seems to have the mass of the milky way, but 99% dark matter. arXiv:1504.03320

Dark matter halo



Dark Matter in the Cosmic Microwave Background



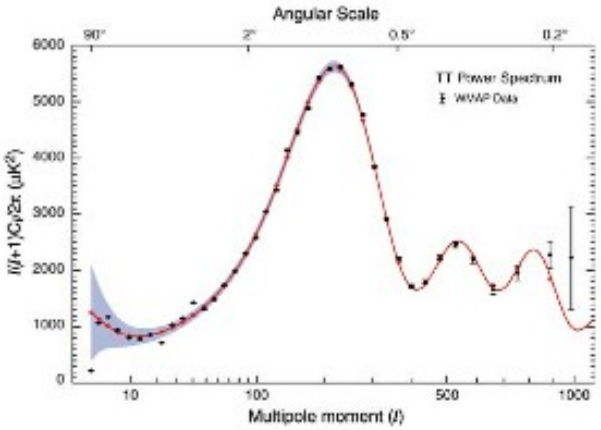


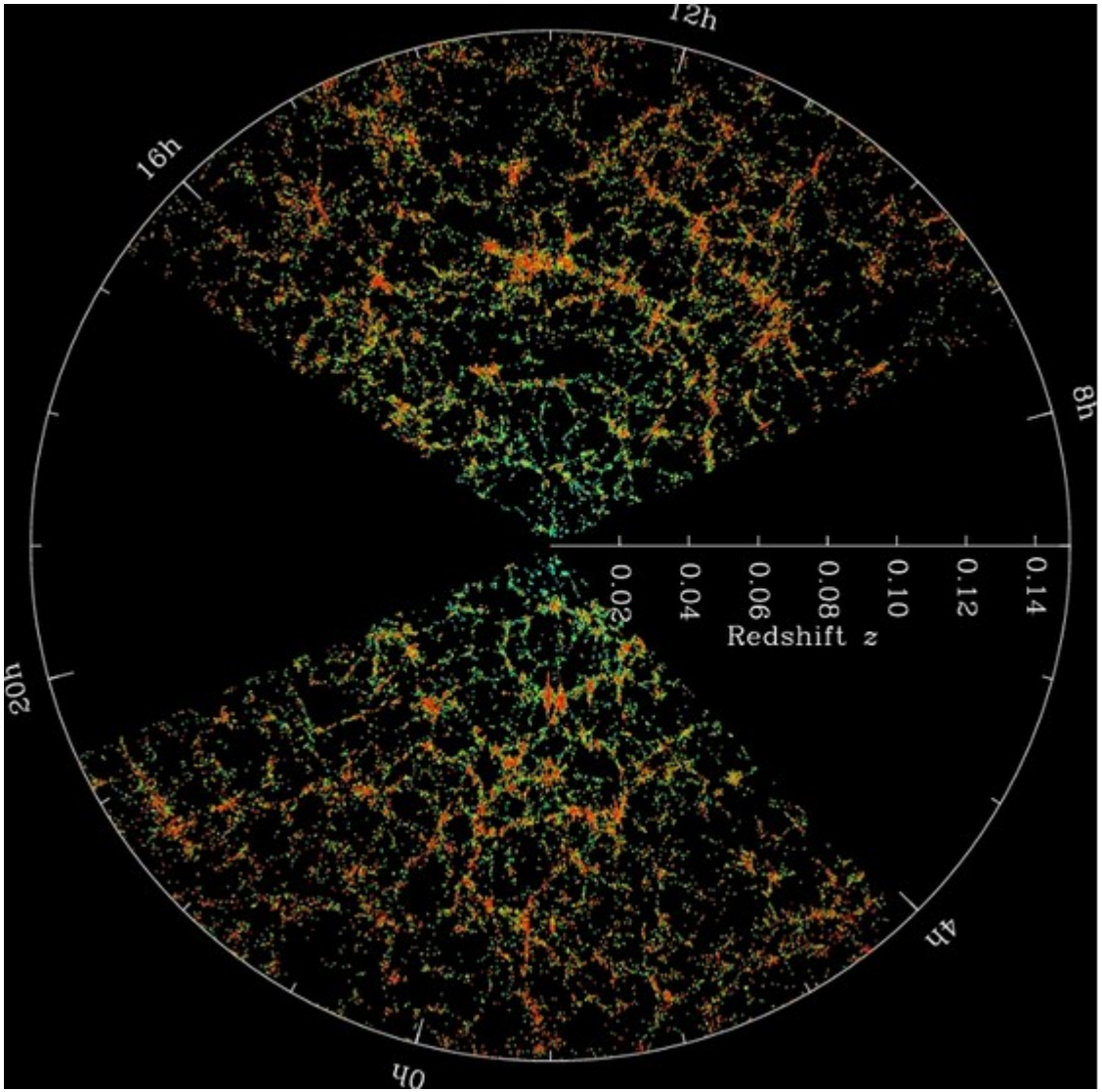
Table 3: Goodness of Fit, $\Delta\chi^2_{eff} \equiv -2\ln\mathcal{L}$, for WMAP data only relative to a Power-Law ΛCDM model. $\Delta\chi^2_{eff} > 0$ is a worse fit to the data.

	Model	$-\Delta(2\ln\mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	6	5
M2	No Reionization ($\tau = 0$)	7.4	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	**Power Law ΛCDM**	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	-1	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d\ln k \neq 0$)	−4	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	−2	7
M11	Running Spectral Index & Tensor Modes	−4	8
M12	Sharp cutoff	−1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	−22	20

WMAP
(Spergel et al 2006)

Dark matter at the scale of the universe!

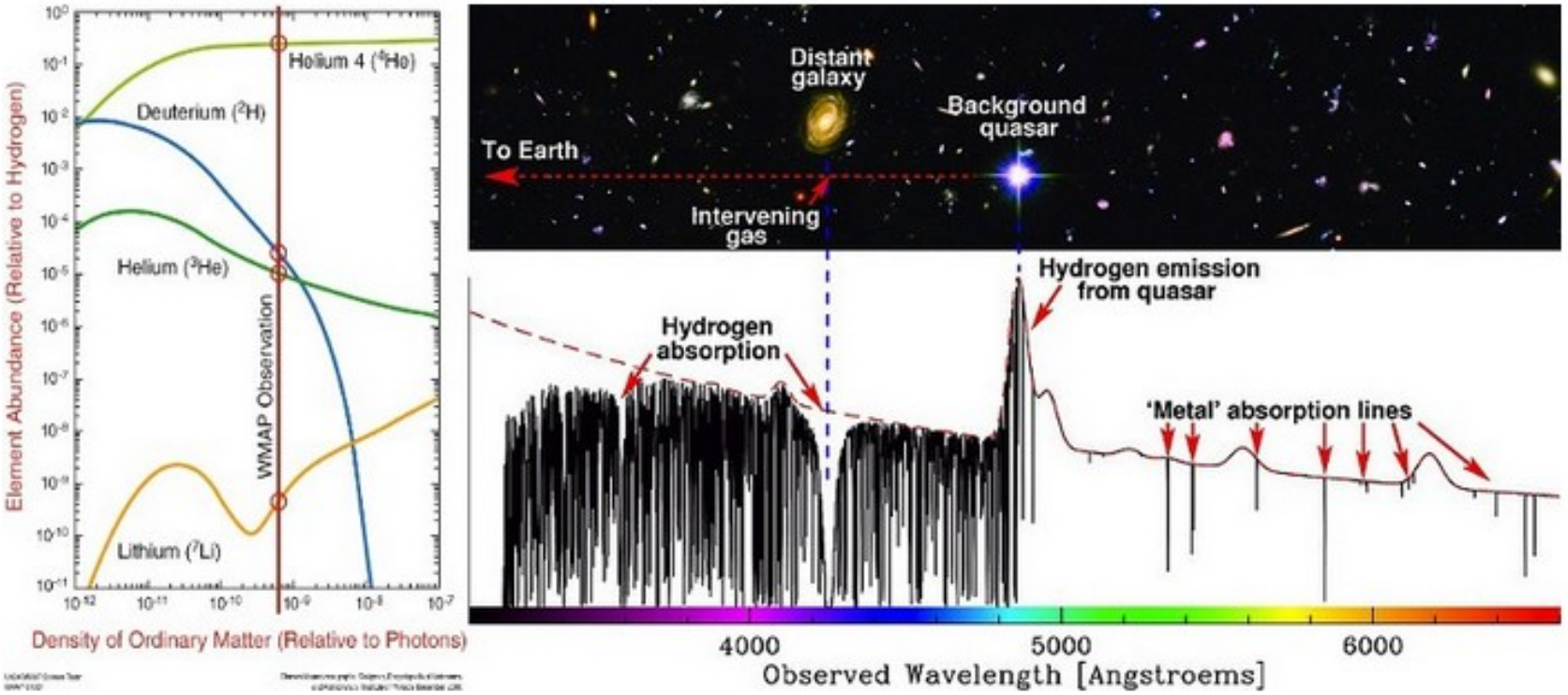
Large structure formation



Dark matter at the scale of the universe!

https://arxiv.org/abs/1203.6594
http://www.sdss.org/science/

Big Bang Nucleosynthesis and Dark Matter

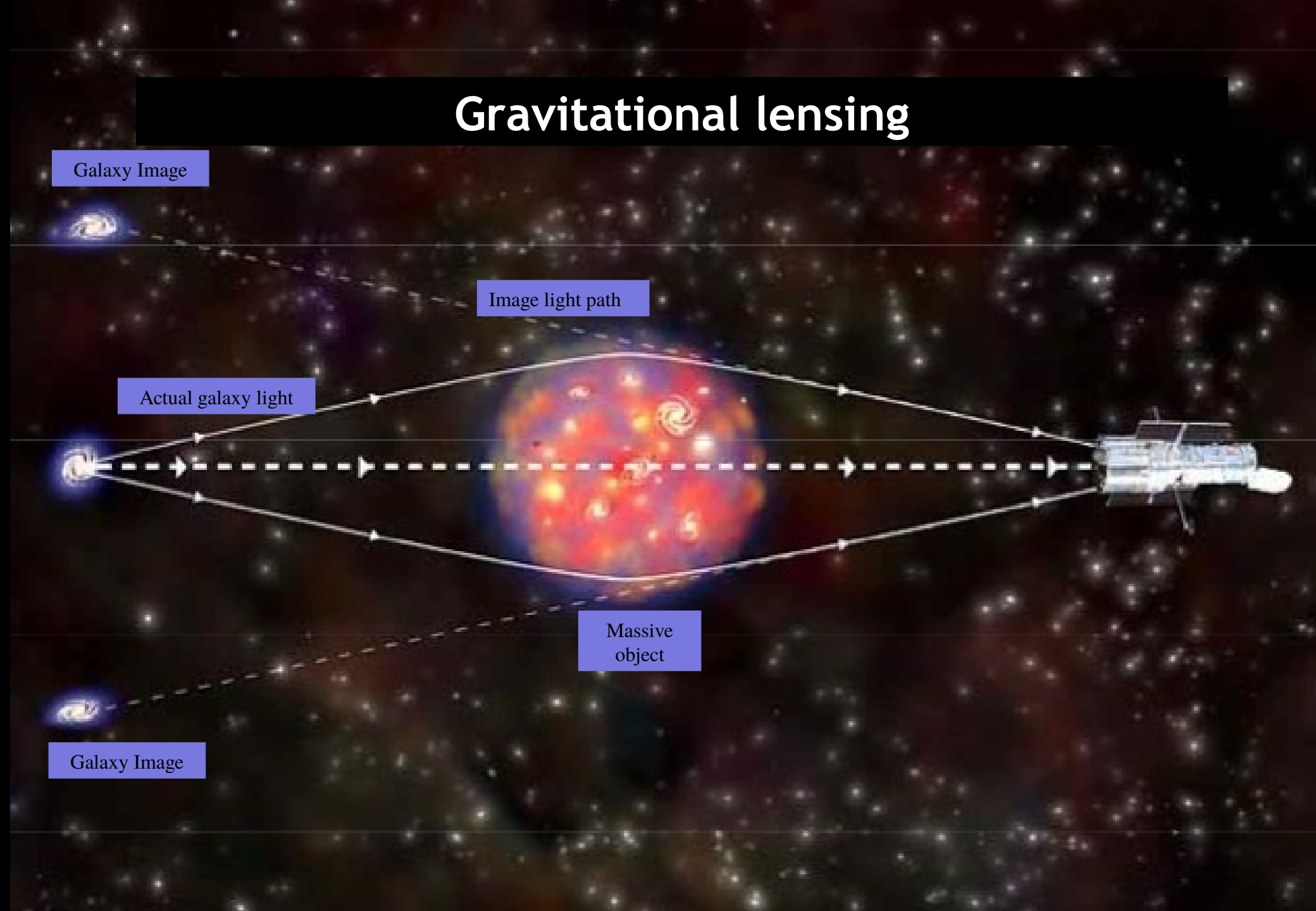


Images credit: NASA / WMAP science team, Gary Steigman (L), of Big Bang Nucleosynthesis and the baryon-to-photon ratio; Michael Murphy, Swinburne U.; HUDF: NASA, ESA, S. Beckwith (STScI) et al. (R), of the Lyman-alpha forest from intervening intergalactic clumps of non-luminous matter.

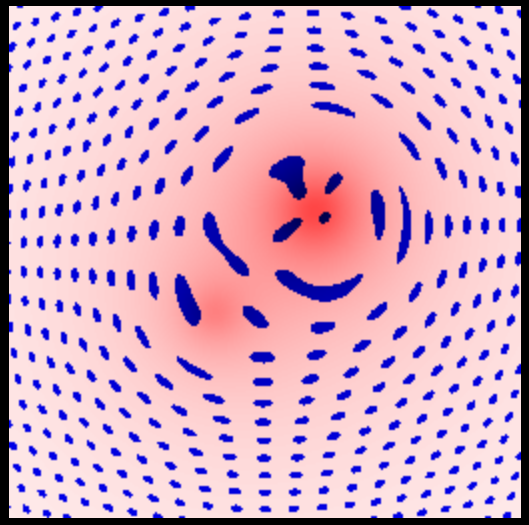
Dark matter at the scale of the universe!

Gravitational Lensing

Gravitational lensing



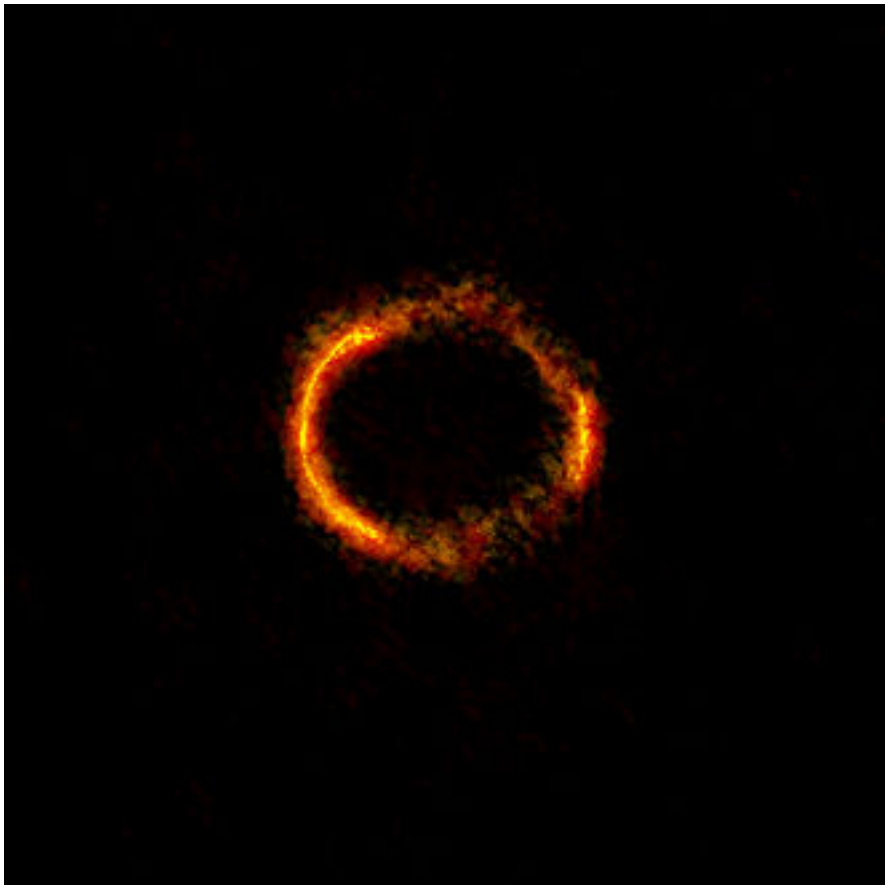
Strong gravitational lensing



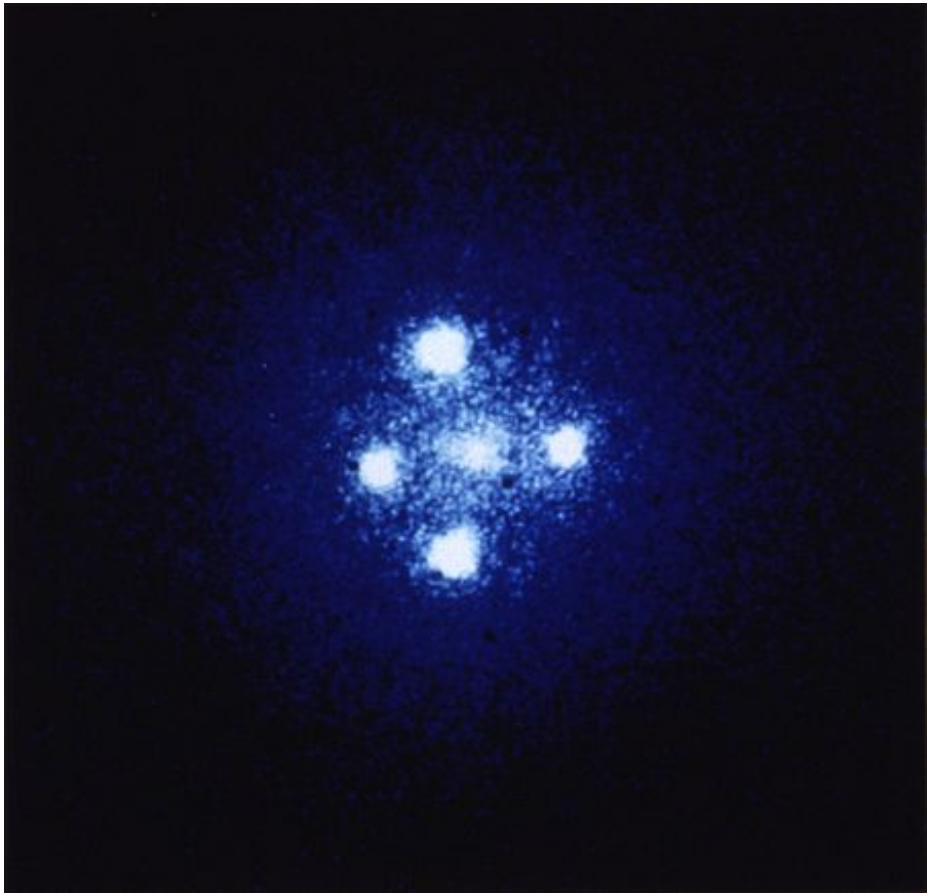
Distortion of the background object (regular pattern) by a distributed mass

Hubble Space Telescope

Einstein Rings and Crosses



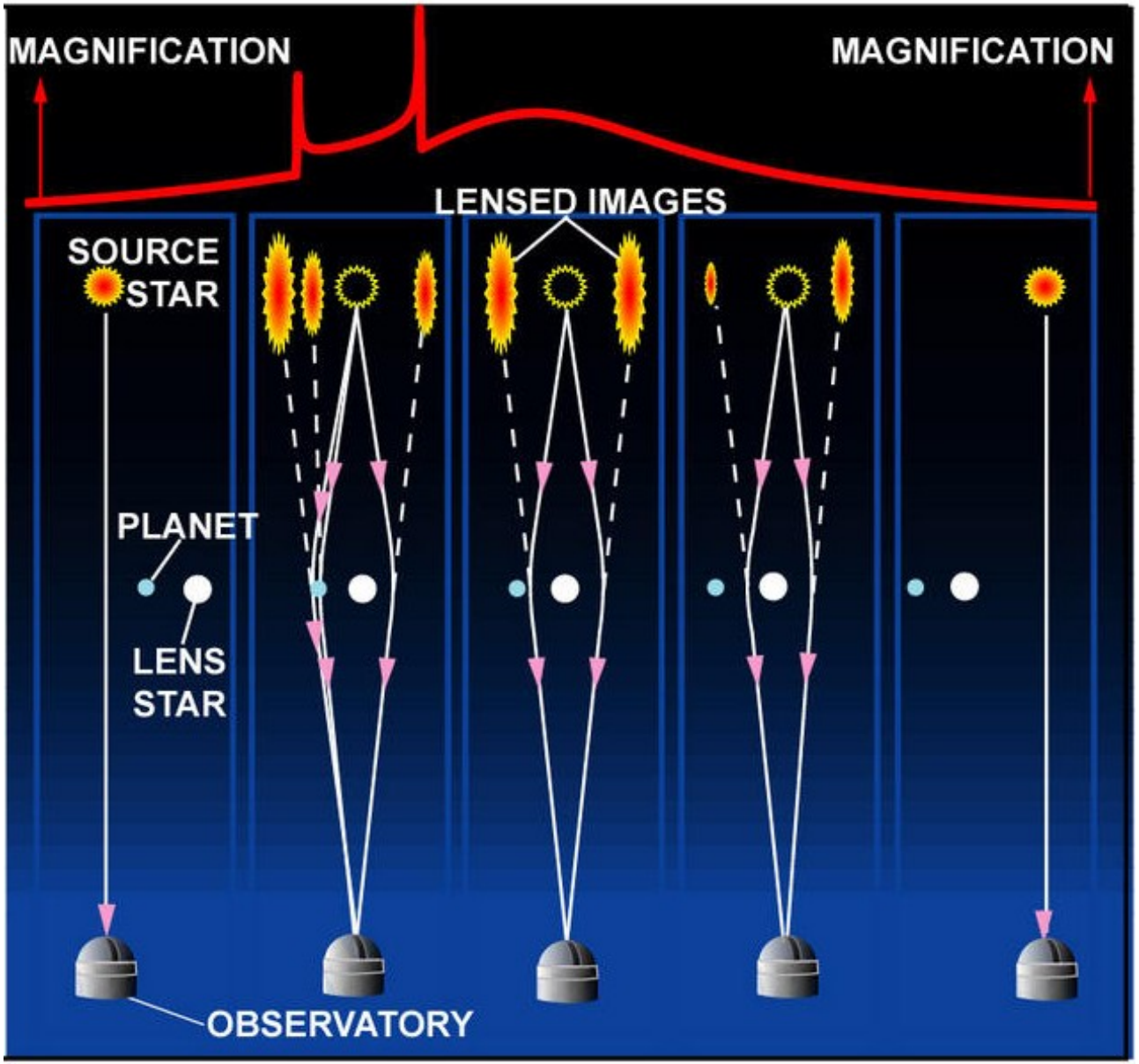
Einstein Ring: Gravitationally lensed galaxy SDP 81, taken by ALMA



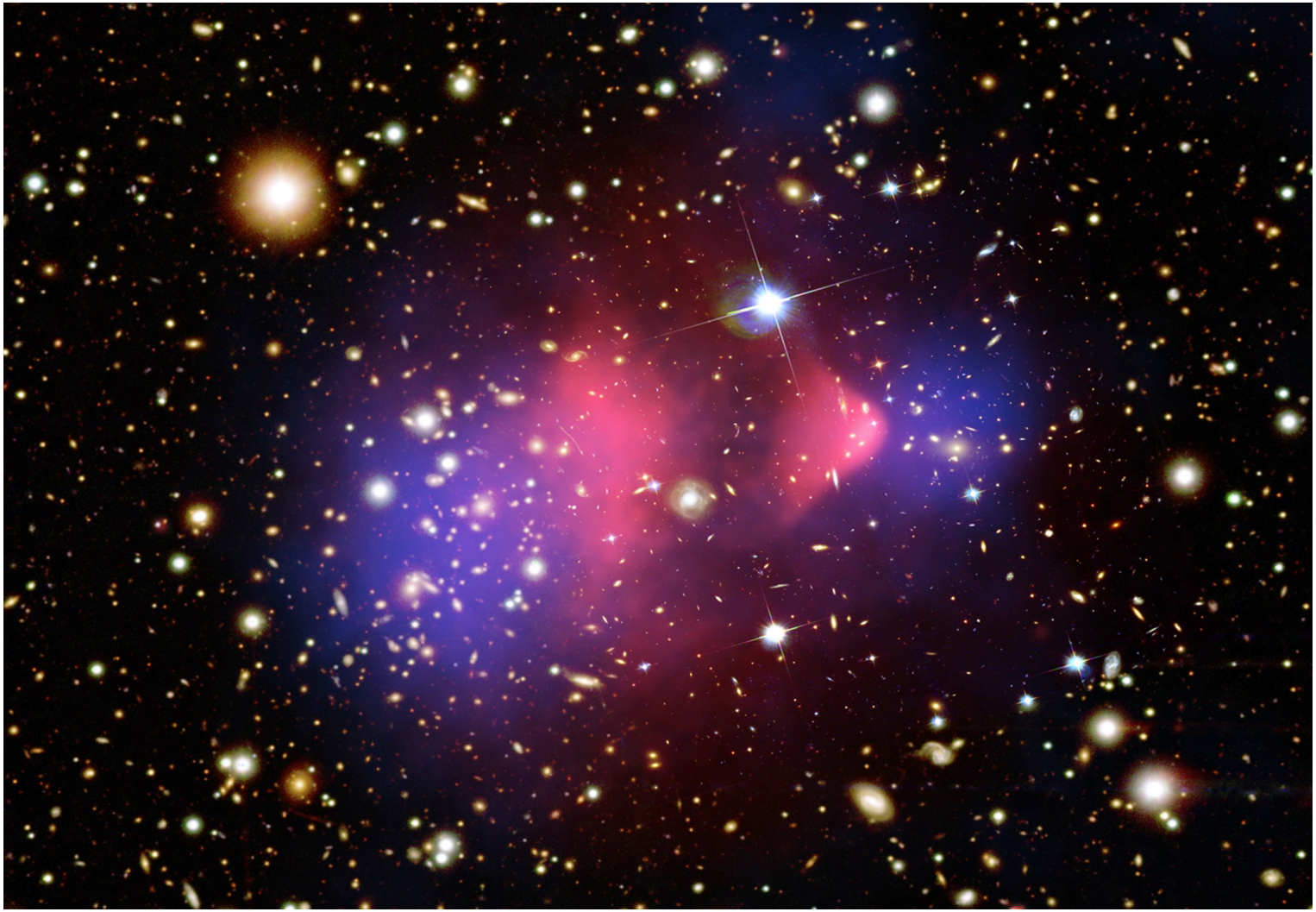
Einstein Cross: The same Quasar (QSO 2237+0305) seen four times.

Gravitational microlensing

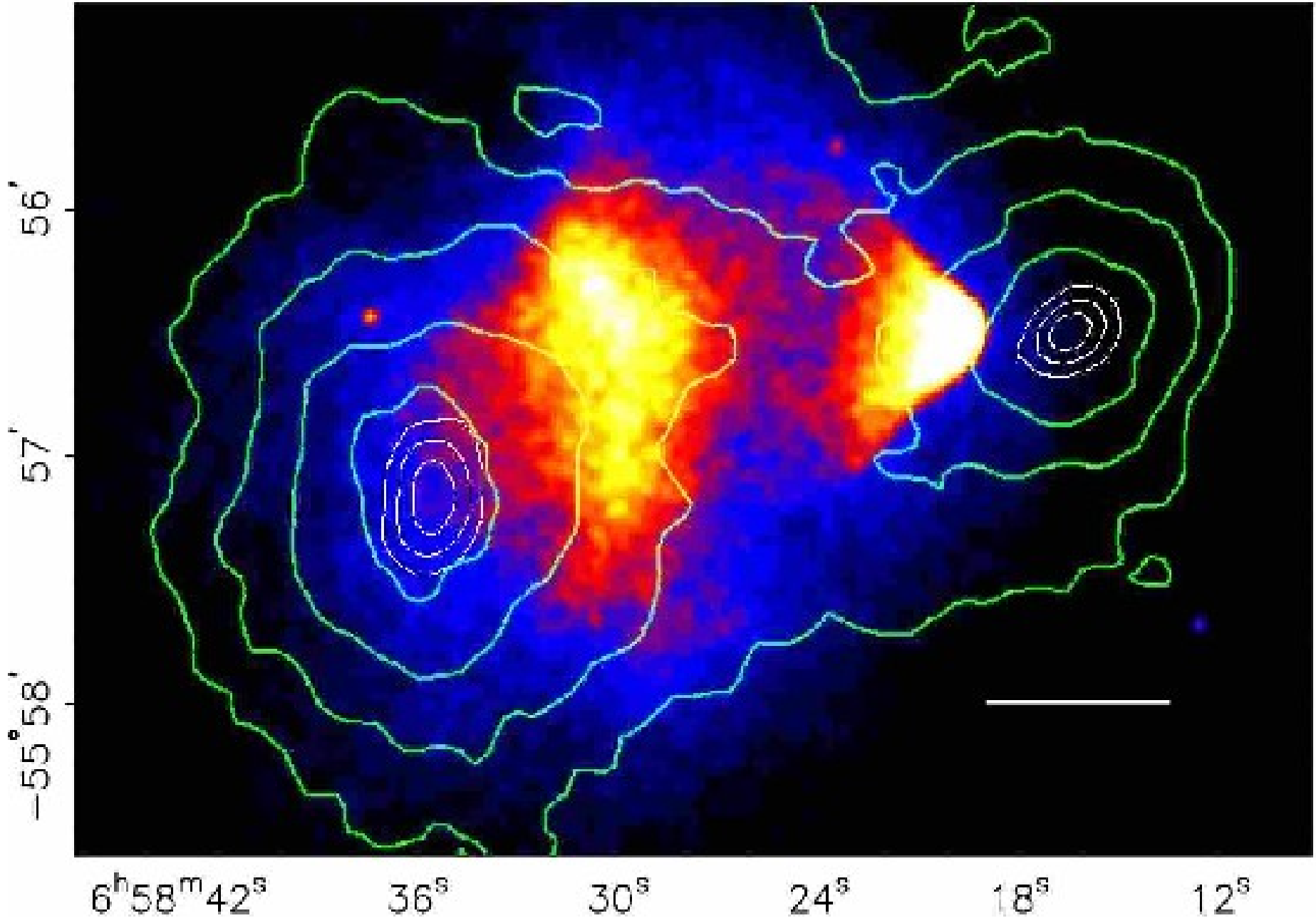
Technique also used to find extrasolar planets



Bullet cluster

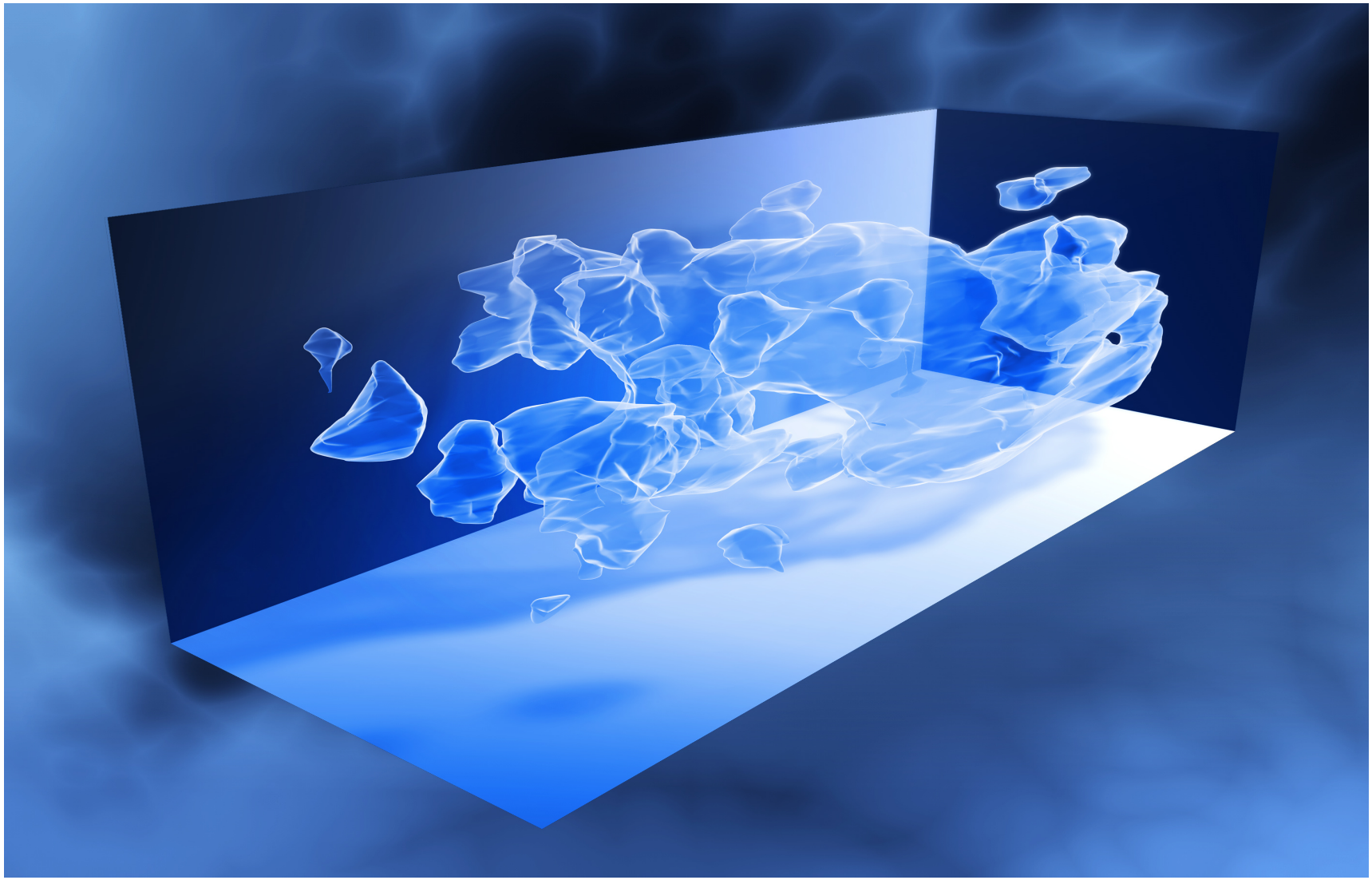


1E 0657-558: cosmic collision of two galaxy clusters



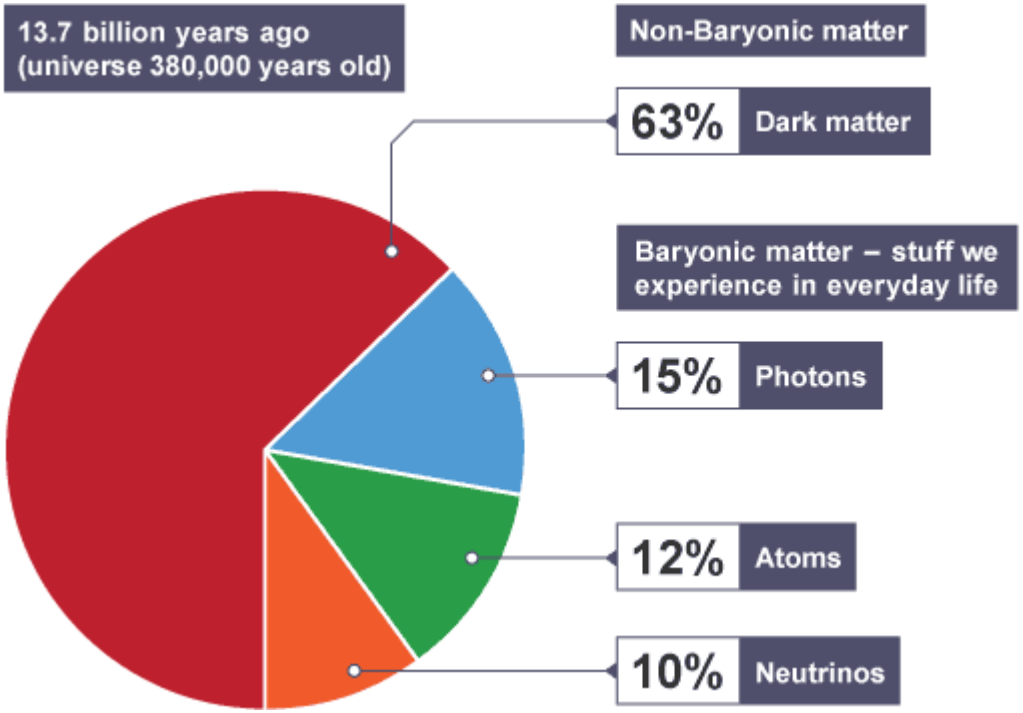
Dark Matter again at the scale of galaxy clusters!

Map of Dark Matter



"Hubble Maps the Cosmic Web of "Clumpy" Dark Matter in 3-D" (Press release). NASA. 7 January 2007.

Matter Content Of The Universe



Density of dark matter in universe O (1 keV / cm^3)
Galactic density of dark matter ~ 0.3 GeV / cm^3