Astrophysical & Cosmological Evidence for non-baryonic Dark Matter

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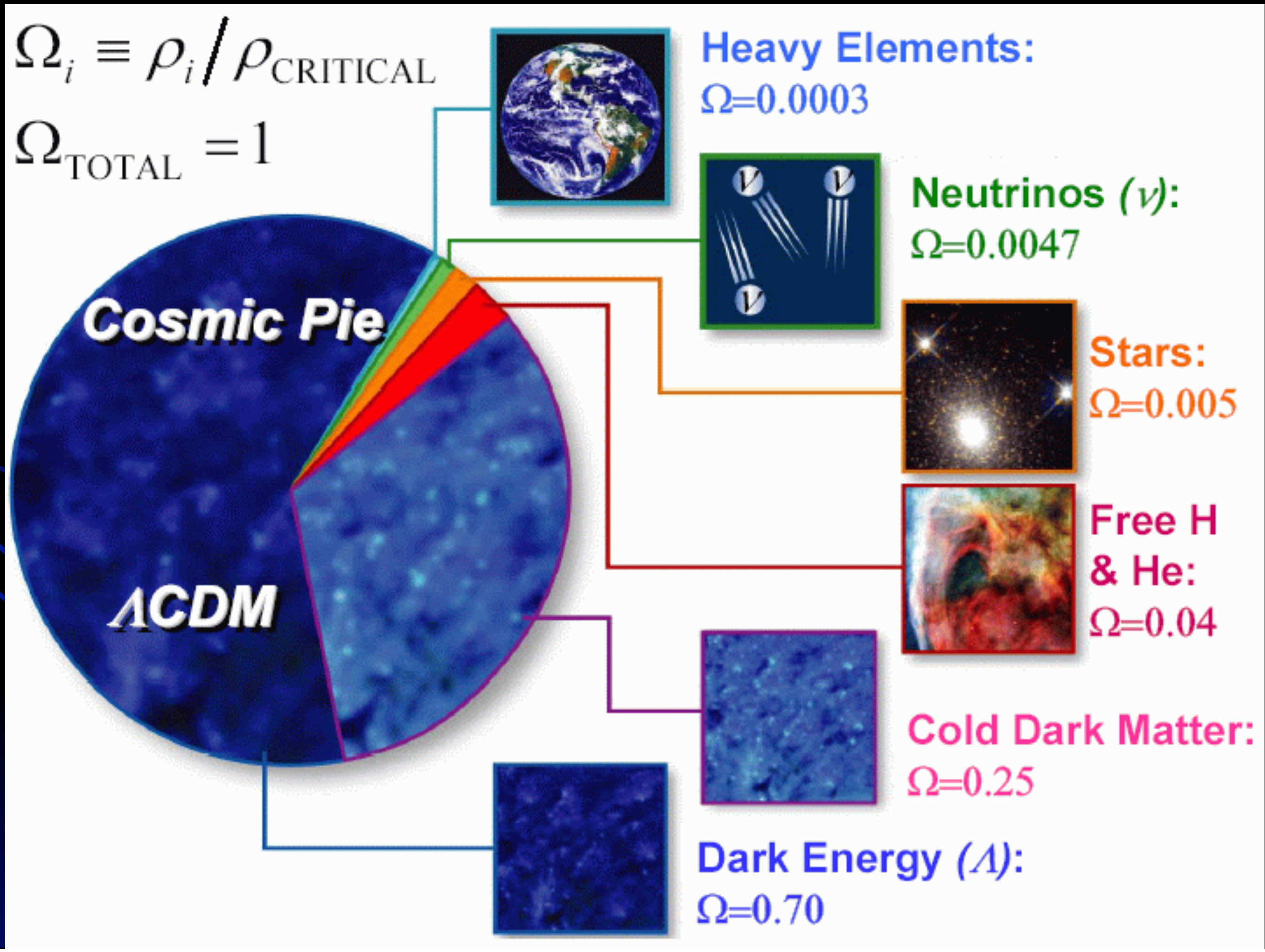
The 2 Main Questions of Contemporary Cosmology:
Dark Matter & Dark Energy

95% of the Energy-Density in the Universe is of an unknown form !



The Dark Universe 1: Dark Matter

It is an unknown type of matter which interacts gravitationally with all types of matter, but it does not emit electromagnetic radiation.

We know of its existence from the gravitational effects that it has on its surroundings. It has been measured with a variety of independent methods, while its existence is also necessary in order to form cosmic structures without violating the observed amplitude of the CMB temperature fluctuations $\langle \delta T/T \rangle \sim 10^{-5}$.

The Dark Universe 1: Dark Matter

Astrophysical Evidence for Dark Matter:

- Spiral Galaxies (Rotation Curves)
- Clusters of Galaxies (Virial Theorem, X-ray Emission, Gravitational Lensing)

Cosmological Evidence for Dark Matter:

- Structure Formation
- Primordial Nucleosynthesis (BBPN)
- Join BBPN & Cluster DM
- Cluster M/L vs Global M/L
- SNIa Hubble function + CMB T Fluctuations

ASTROPHYSICAL EVIDENCES OF DARK MATTER

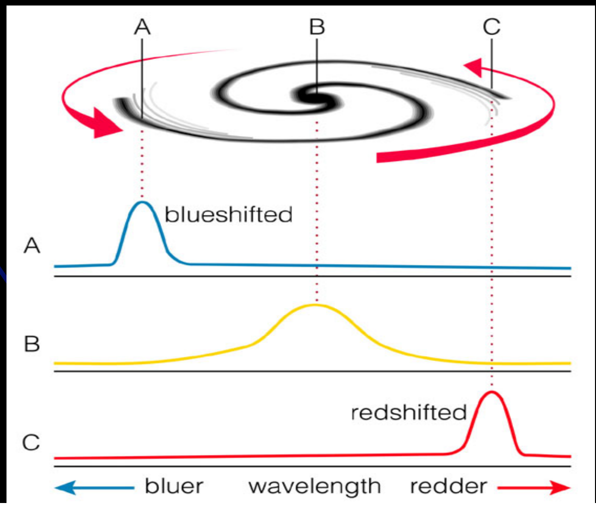
Astrophysical Indications for the Existence of Dark Matter: Rotation Curves of Spirals

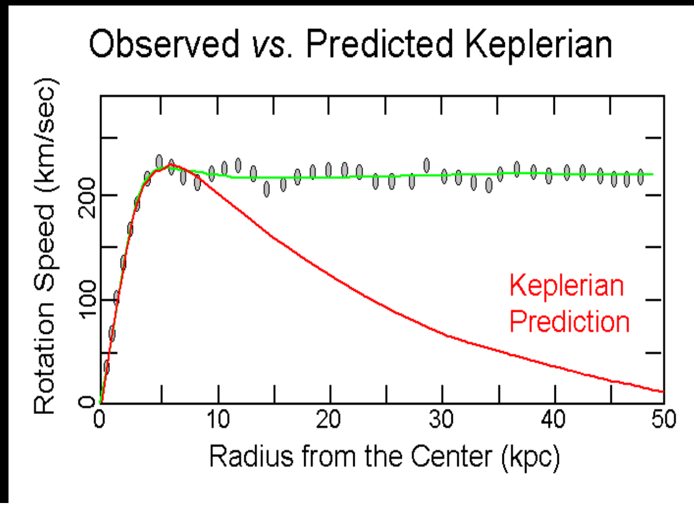
~1970: Vera Rubin, Ken Freeman measured the rotational velocity of Spiral Galaxies using the 21cm radiation of atomic Hydrogen

What do we expect classically for the rotation curve. From Dynamical arguments we have:

$$\frac{GM(r)m}{r^2} = \frac{mv(r)^2}{r} \Rightarrow v(r) \propto r^{-1/2} (Keplerian)$$

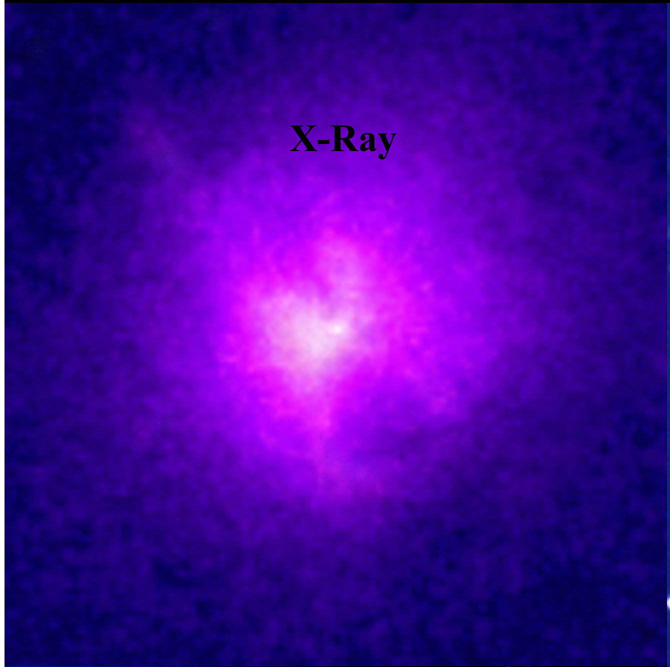
$$instead \Rightarrow v(r) = const. \Rightarrow M(r) \propto r$$

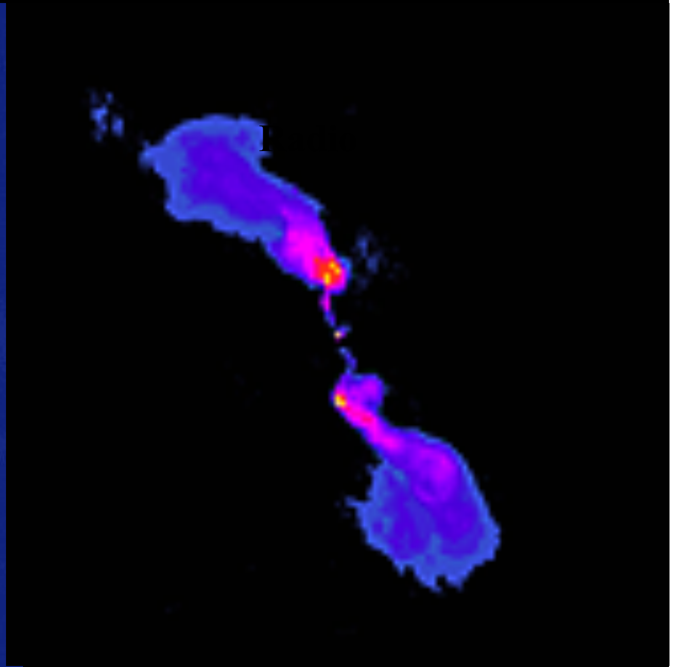




Astrophysical Indications for the Existence of Dark Matter: Clusters of Galaxies

WHAT ARE CLUSTERS OF GALAXIES: THE LARGEST SELF-GRAVITATING, BOUND, MULTICOMPONENT SYSTEMS WITH 100s OF GALAXIES, HOT X-ray EMITTING ICM, RADIO-PLASMAS AND DARK MATTER, WHICH EVOLVE IN A TIGHTLY COUPLED MANNER. DM IS DYNAMICALLY DOMINANT COMPONENT!

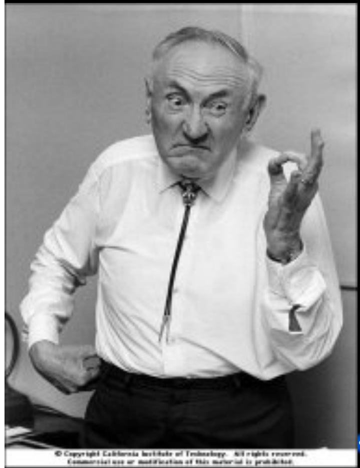




$$S = S_o\left[1 + (r/r_c)^2\right]^{-3\beta+1/2}$$

$$\rho = \rho_o\left[1 + (r/r_c)^2\right]^{-3/2}$$

Cluster Mass Measurement: 1. Virial Theorem

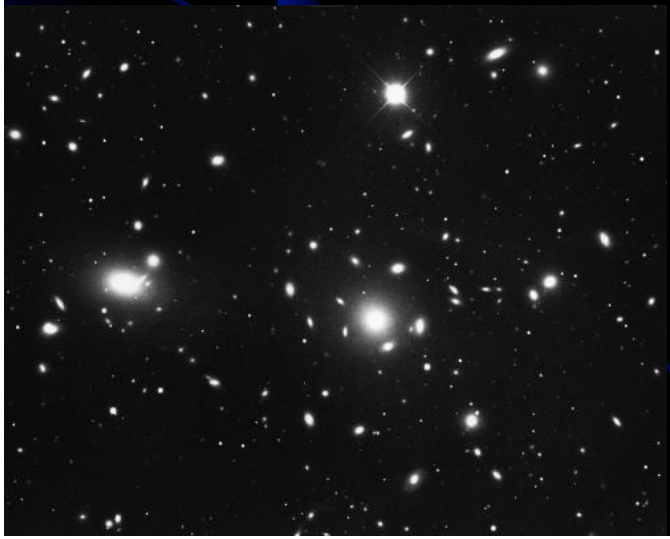


First such indication came from the study of the motions of galaxies in the Coma cluster, back in 1933 by Fritz Zwicky. He found that the galaxies mean velocity were larger than their escape velocity, that implied that the Coma cluster should not have existed as such.

The virial theorem relates the average kinetic and potential energy of galaxies in a cluster which is in dynamical equilibrium:

$$U=2K \Rightarrow M=3\sigma^2 r/G \quad (+\Lambda r^3/5G)$$

$K = \frac{1}{2} M v^2$ $\qquad$ $U \sim GM^2/r$ $\qquad$ $v^2=3\sigma^2$



Assumption: The galaxy distribution is Virialized" and in a spherically symmetric potential well.

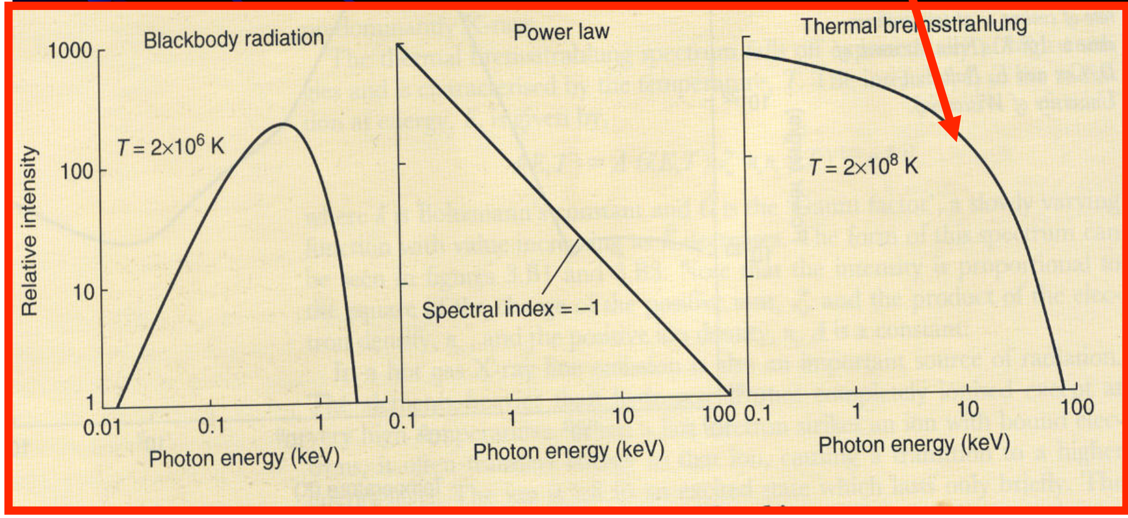
Mass Measurement: 2. X-ray Emission

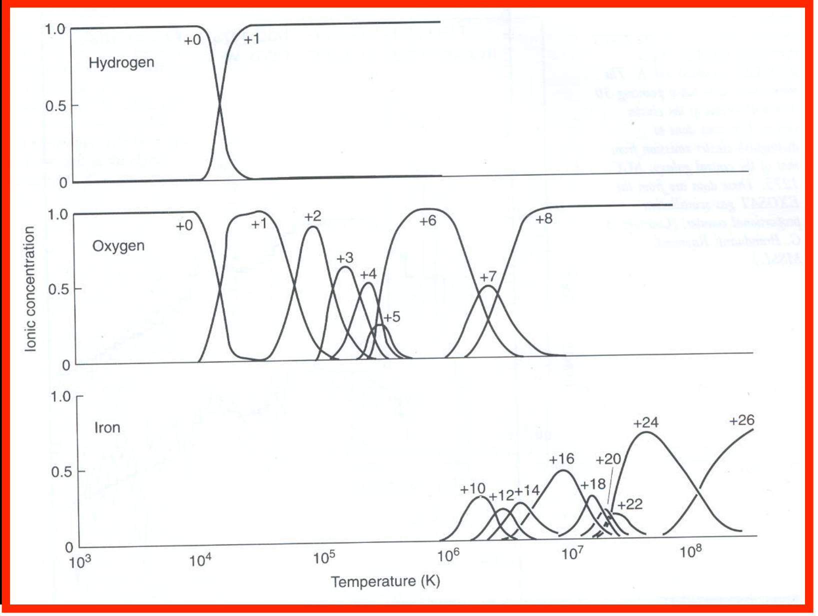
Cluster gas thermalizes to >10^6 K making clusters strong X-ray sources

Bremsstrahlung radiation: The hot, thin (transparent to its own radiation) plasma emits electromagnetic radiation due to e^- trajectory change and acceleration when passing near a positive ion

Line emission due to the fact that metals are not completely ionised and so when a fast e^- strikes ions with bound e^- it causes transition to higher energy level. Excitation lasts little and ions decay to ground state with emission of photon with characteristic energy δE.

$$I(E) \propto n_e n_i (kT)^{-1/2} exp(-E/kT)$$





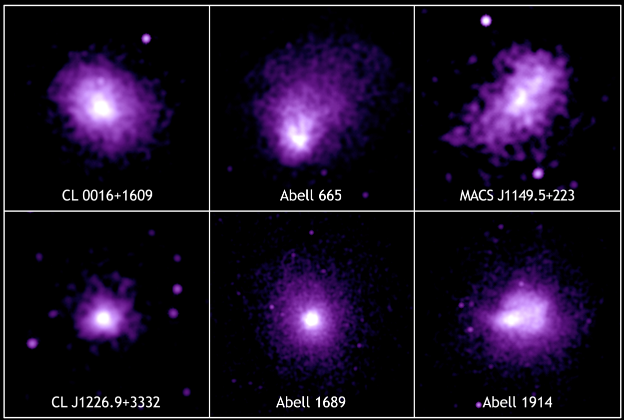
Cluster Mass Measurement: 2. X-ray Emission

Main Idea: Use of the hot gas in clusters of galaxies as a tracer of the total gravitational potential.

From Conservation of Momentum equation (Euler's equation) we have that:

$$\partial u / \partial t + (u \cdot \nabla) u = (1/\rho)\nabla P - \nabla \Phi$$

+ *Hydrostatic equilibrium in spherical potential* →



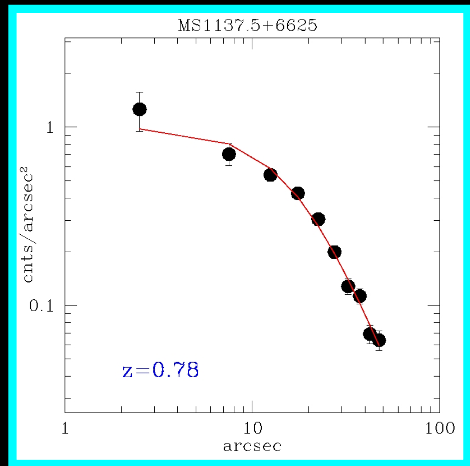
$$dP/dr = -GM(r)\rho(r)/r^2$$

$$P = k\rho T / \mu m_u$$

$$M(<r) = \frac{kTr}{mG}\left(\frac{d\ln\rho}{d\ln r} - \frac{d\ln T}{d\ln r}\right)$$

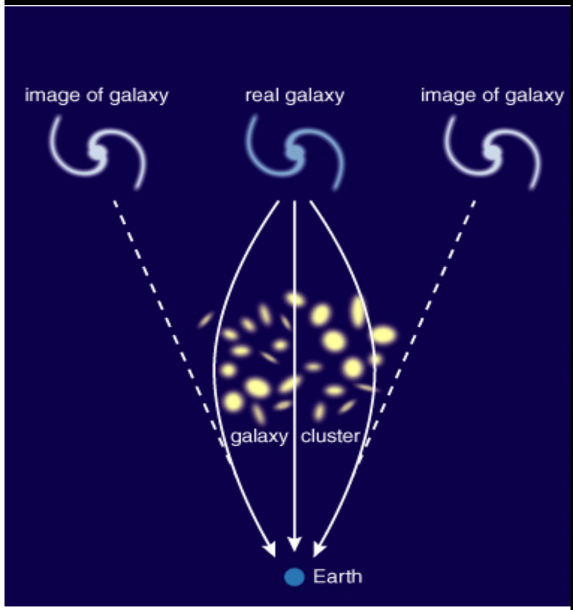
Deproject gas density ρ(r) and temperature profile T(r) to obtain gravitating mass.

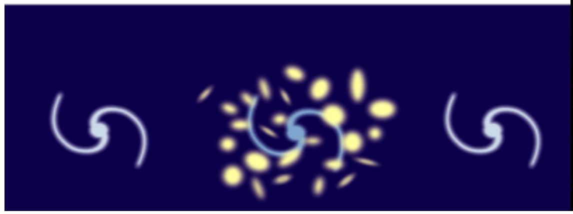
Data provided from X-ray observatories (XMM & Chandra)



Mass Measurement: 3. Gravitational Lensing

- Based on GR: Radiation is deflected in gravitational fields
- Just as for conventional lenses, images will form at extrema in the light travel time surface (Fermat).
- Normally there will be just one deflected image but, for sufficiently deep gravitational potentials, multiple images form.

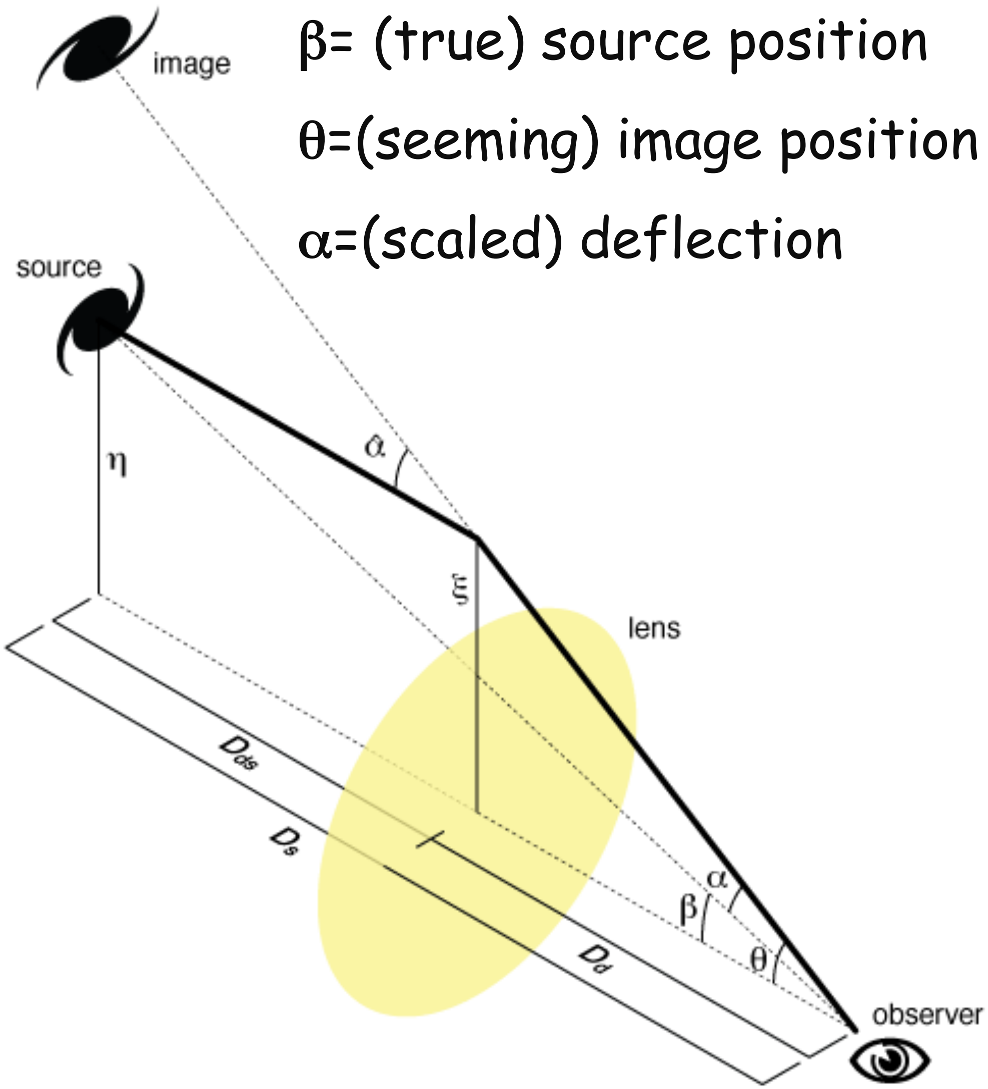




Galaxy Cluster Abell 2218 **HST** • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Mass Measurement: 3. Strong Gravitational Lensing

From simple geometry we get Lens Equation: $$\beta = \theta - \alpha \frac{D_{\rm ds}}{D_{\rm s}}$$



β= (true) source position

θ=(seeming) image position

α=(scaled) deflection

$$D_\theta = \frac{1}{1+z}\int_0^z \frac{c}{H(z)}{\rm d}z$$

$$H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_Q \exp\left(3\int_0^z \frac{1+{\rm w}(x)}{1+x}{\rm d}x\right)\right]^{\frac{1}{2}},$$

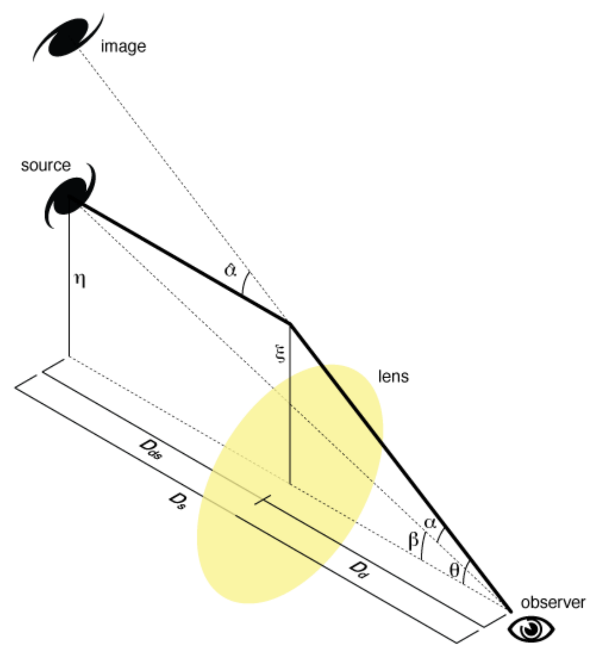
For a point mass lens the deflection, α, is given by a simple equation:

$$\alpha = \frac{4GM}{c^2\xi}$$

Images are formed at angles where the deflection eq. and the lens eq. are satisfied simultaneously.

Mass Measurement: 3. Gravitational Strong Lensing

In the case of a well aligned lens-source configuration (β~0) the deflection, α, is α~θ, (the so-called Einstein Ring), which implies that combining the Lens and deflection equations, we have:

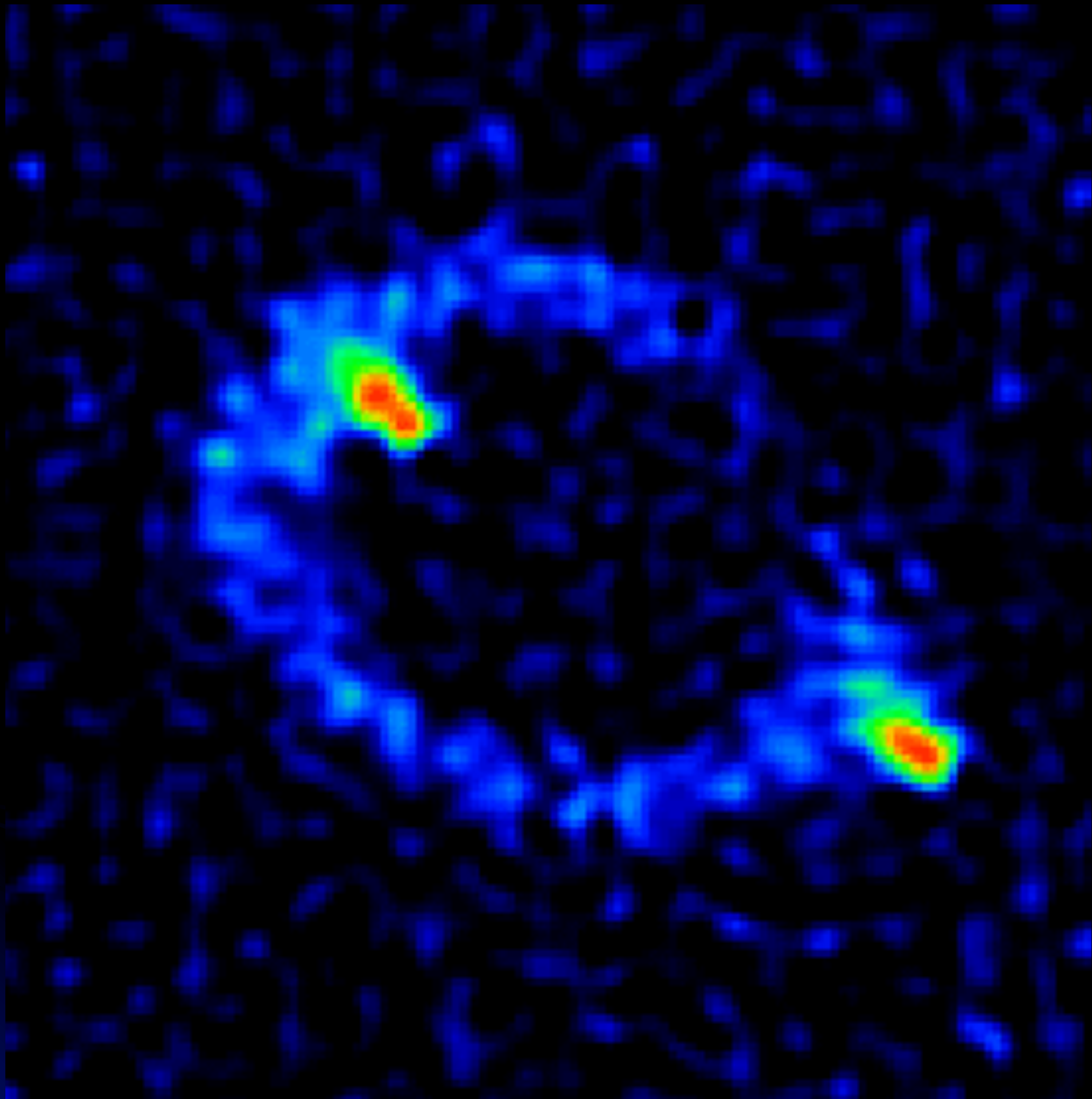


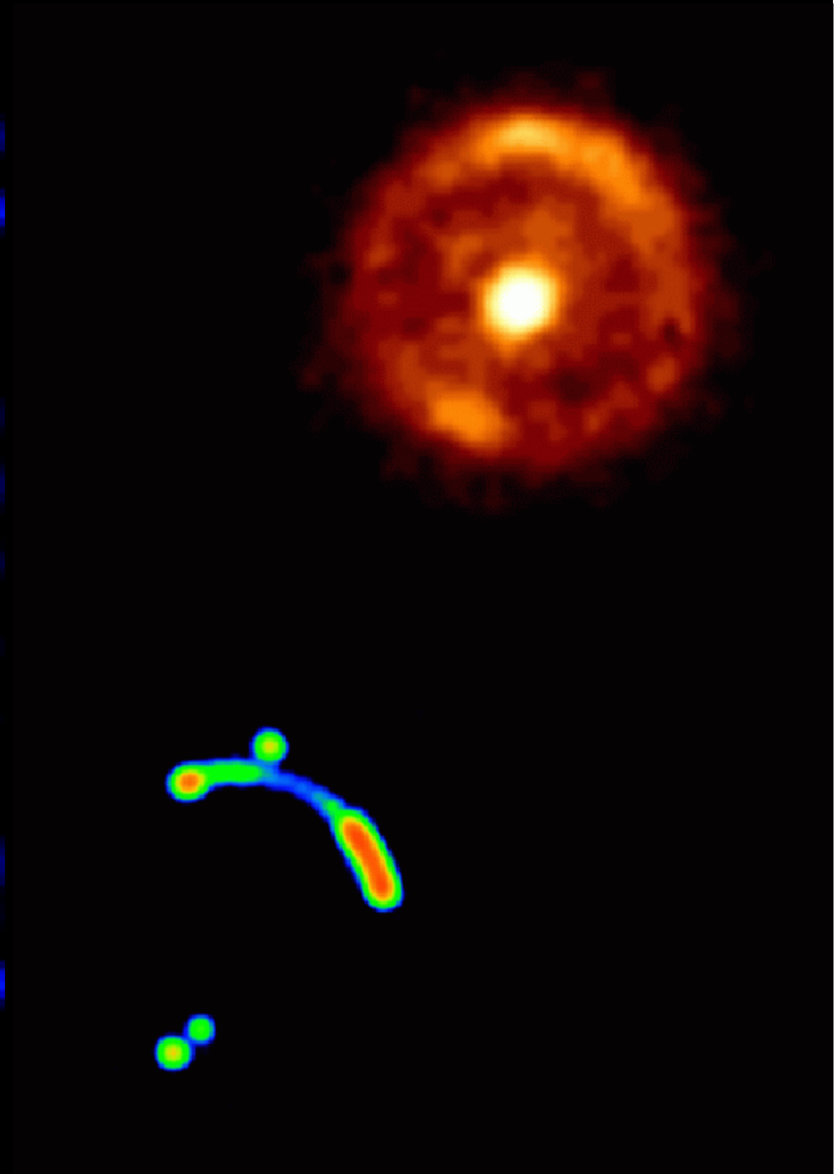
$$\beta = \theta - \frac{4GM(\theta)}{c^2\theta}\frac{D_{\rm ds}}{D_{\rm s}D_{\rm d}}$$

$$\xi = \theta D_{\rm d}$$

$$\beta = 0 \rightarrow \theta_E = \left[\frac{4GM(\theta)}{c^2}\frac{D_{\rm ds}}{D_{\rm s}D_{\rm d}}\right]^{1/2}$$

Therefore, measuring θ_E observationally, we can estimate the mass of the lens (cluster of galaxy in this case) if we know angular diameter distances of source and lens (which of course depends on the cosmological model)



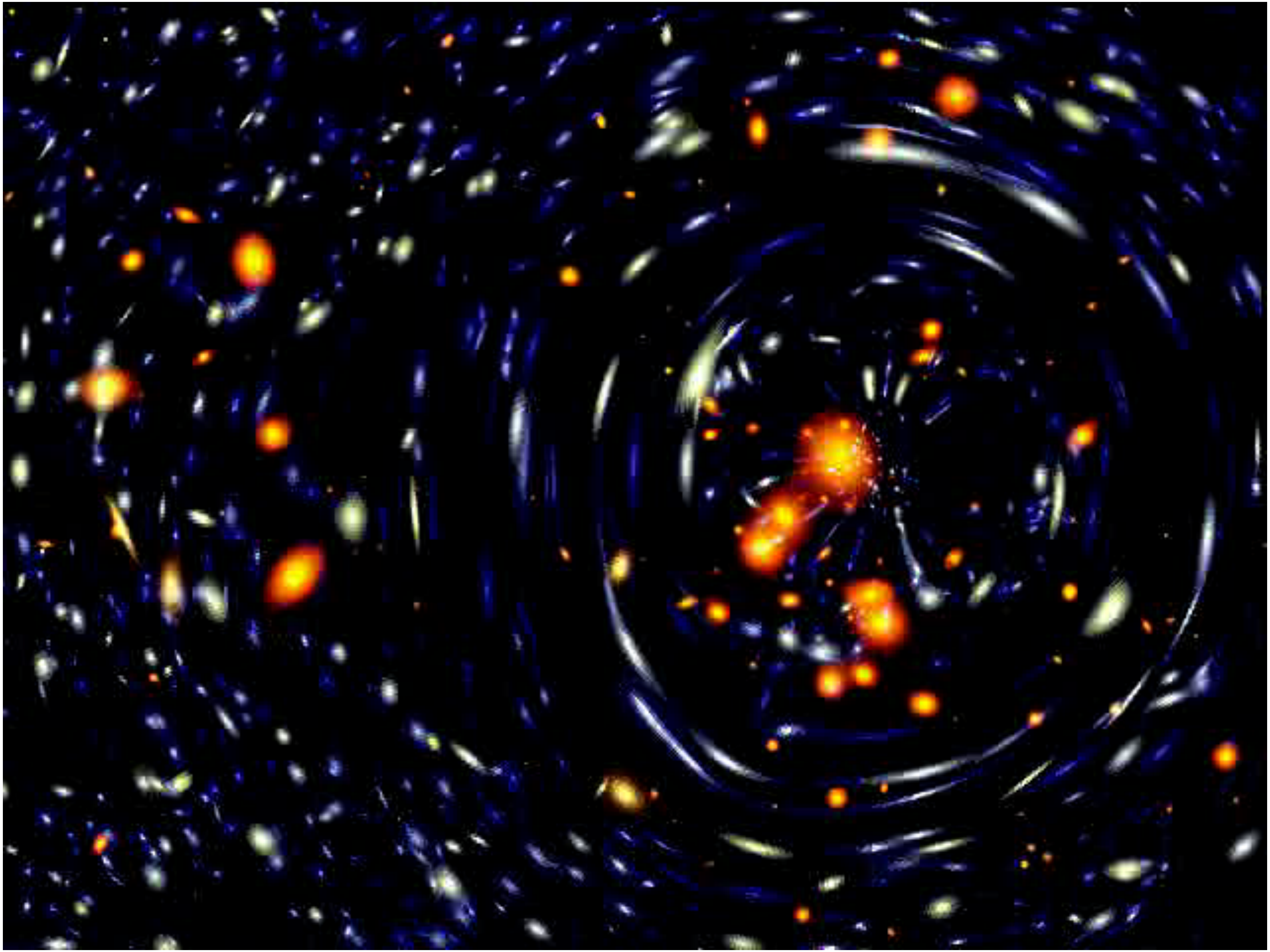


First Einstein ring observed by VLA

Quasar lensed by galaxy

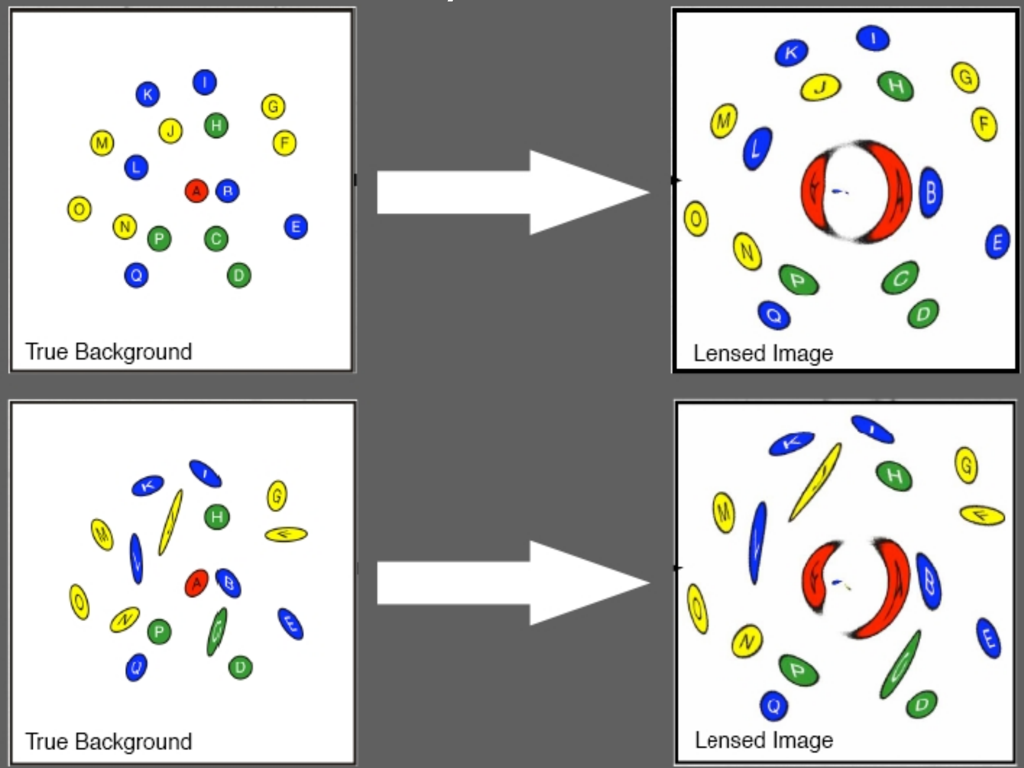
upper: Hubble

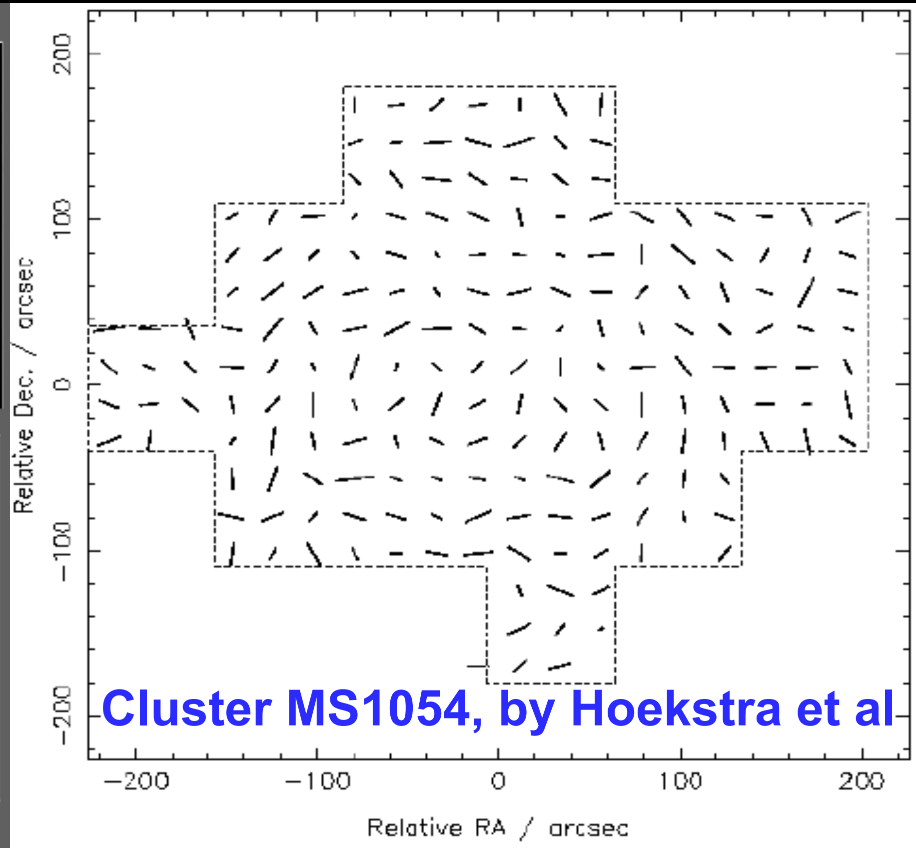
lower: Merlin



Mass Measurement: 3. Gravitational Weak Lensing

In this case the distortions of background sources are much smaller and can only be detected by analyzing large numbers of sources to find coherent distortions of only a few percent. The lensing shows up statistically as a preferred stretching of the background objects perpendicular to the direction to the center of the lens. By measuring the shapes and orientations of large numbers of distant galaxies, their orientations can be averaged to measure the shear of the lensing field. Since galaxies are intrinsically elliptical and the weak gravitational lensing signal is small, a very large number of galaxies must be used in these surveys.

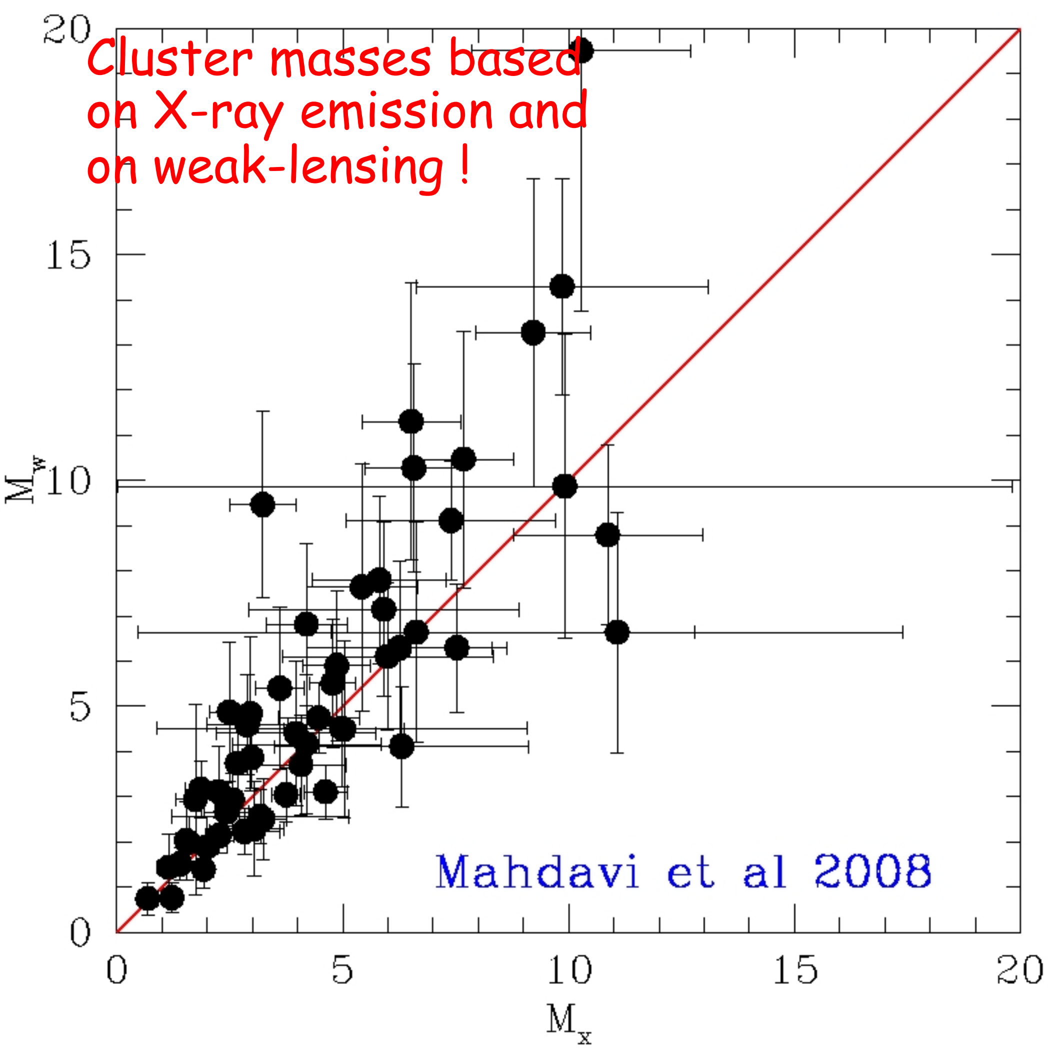




Cluster MS1054, by Hoekstra et al

Mass Measurement: Comparison

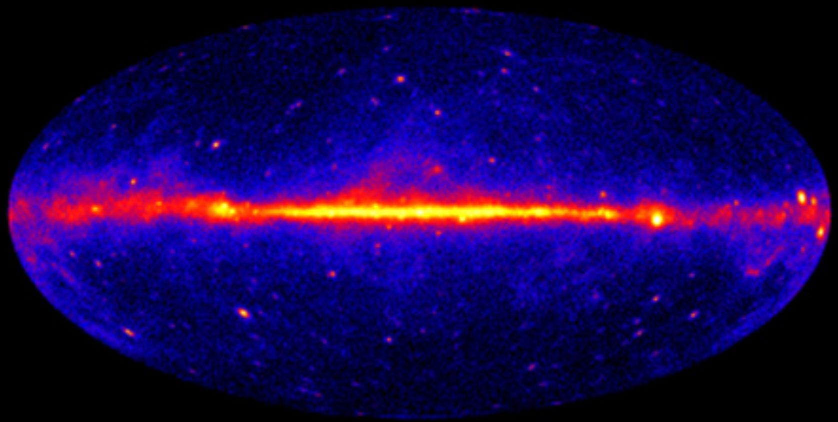
(1) Reasonable agreement of Cluster Masses between methods.
(2) Weak evidence for validity of General Relativity on cluster scales



FINAL RESULTS ARE:

- 15% of total gravitating mass is in Stars and Gas
- 85% of total gravitating mass is in Dark Form.

High Energy emission from annihilation of WIMPs

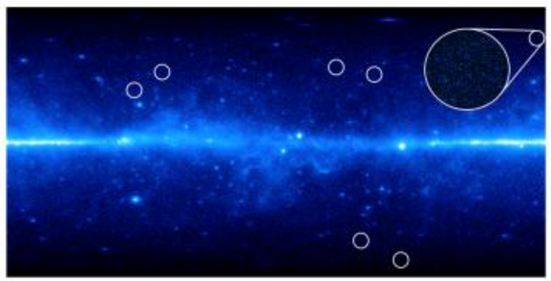


The high-density of DM particles (WIMPs) in the center and halo of our Galaxy and other galaxies, could produce γ-ray emission due to particle annihilations.

Some years ago INTEGRAL detected excess of γ-ray (E~511 keV) possible due to electron-positron annihilation, produced in WIMP annihilations, but could be explained astrophysically.

However, FERMI has found excess in inner 100 ly of the Galaxy that cannot be explained astrophysically – There is also an unexplained MW glow from WMAP.

Koussiapas & Geringer-Sameth, a year ago, using FERMI obs of nearby dwarf galaxies do not confirm and put a lower limit in the mass of WIMPs of 40 GeV (since the lack of annihilation based emission indicates low density and thus high-mass of WIMPs).



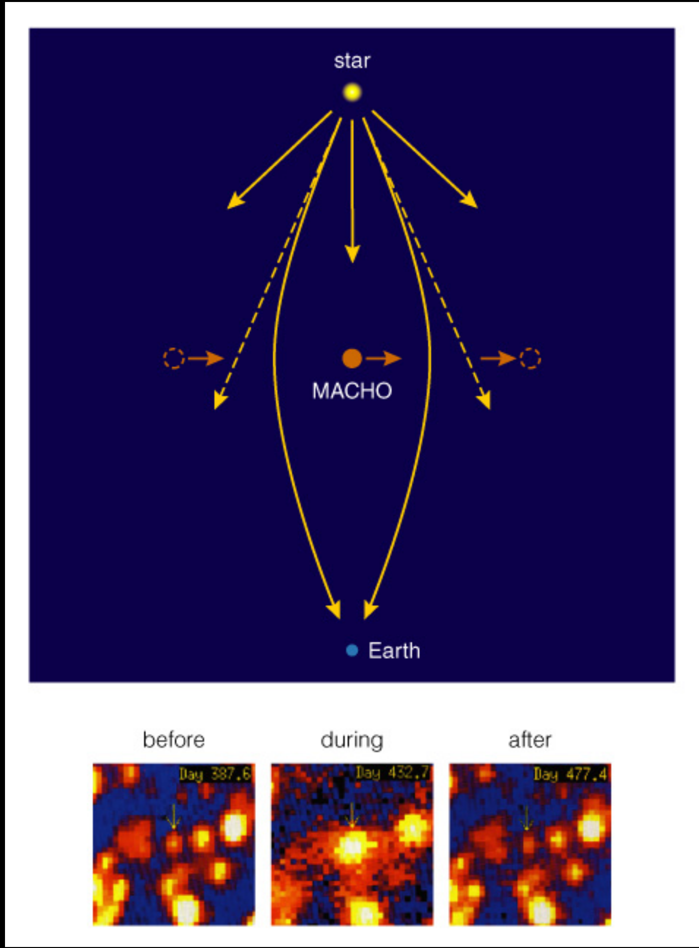
COULD THERE BE A TRADITIONAL EXPLANATION:

1. Could Dark Baryons constitute the Dark Matter ?

Suggestions exist that failed stars, hot Jupiters etc that have masses below thermonuclear limit, could constitute the DM, ie., Massive Compact Halo Object: MACHOS

These could be detected via gravitational microlensing by the large number of halo stars.

Large observational programs have failed to provide the necessary numbers (not even close…)



2. Could Modification of Gravity make the trick ?

Could explain rotation curves but not the whole range of DM indications…

2. Could Modification of Gravity make the trick ?

Could explain rotation curves and Tully-Fisher relation but not the whole range of DM indications…

1) The intensity of the gravitational field becomes larger at larger scales. But this implies that we should see an effect which is larger at larger galaxies. Not observed.

$$\gamma = \frac{GM}{r^2}\left(1 + \frac{r}{r_o}\right)$$

2) Variation of gravity law at low accelerations: with $\mu = \gamma / \gamma_0$ for $\gamma \ll \gamma_0$ and $\mu = 1$ for $\gamma \gg \gamma_0$.

$$\gamma\mu = \frac{GM}{r^2}$$

Therefore

$$\gamma = \frac{v^2}{r} = \sqrt{\frac{\gamma_0 GM}{r^2}} \Rightarrow v^4 = GM\gamma_0 \propto L$$

Which reproduces the rotation curves of spirals but also the Tully-Fisher relation ($v^4 \approx L$).

But cannot reproduce Cluster data.

MOG (J.W.Moffat):

The modified weak field acceleration law from static spherically symmetric solution of F.E. based on Riemannian geometry and a massive vector field (phion field), is:

$$a(r) = -\frac{G(r)M}{r^2}$$

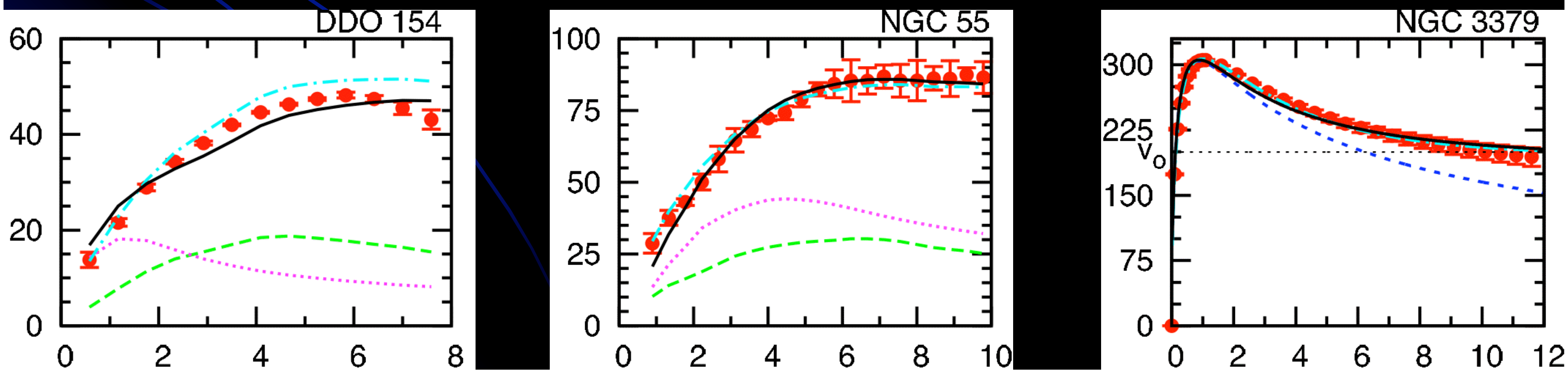
$$G(r) = G_0\left[1 + \alpha(r)\left(1 - \exp(-r/\lambda(r))\left(1 + \frac{r}{\lambda(r)}\right)\right)\right]$$

Assume the following parametric forms for the "running" of the constants:

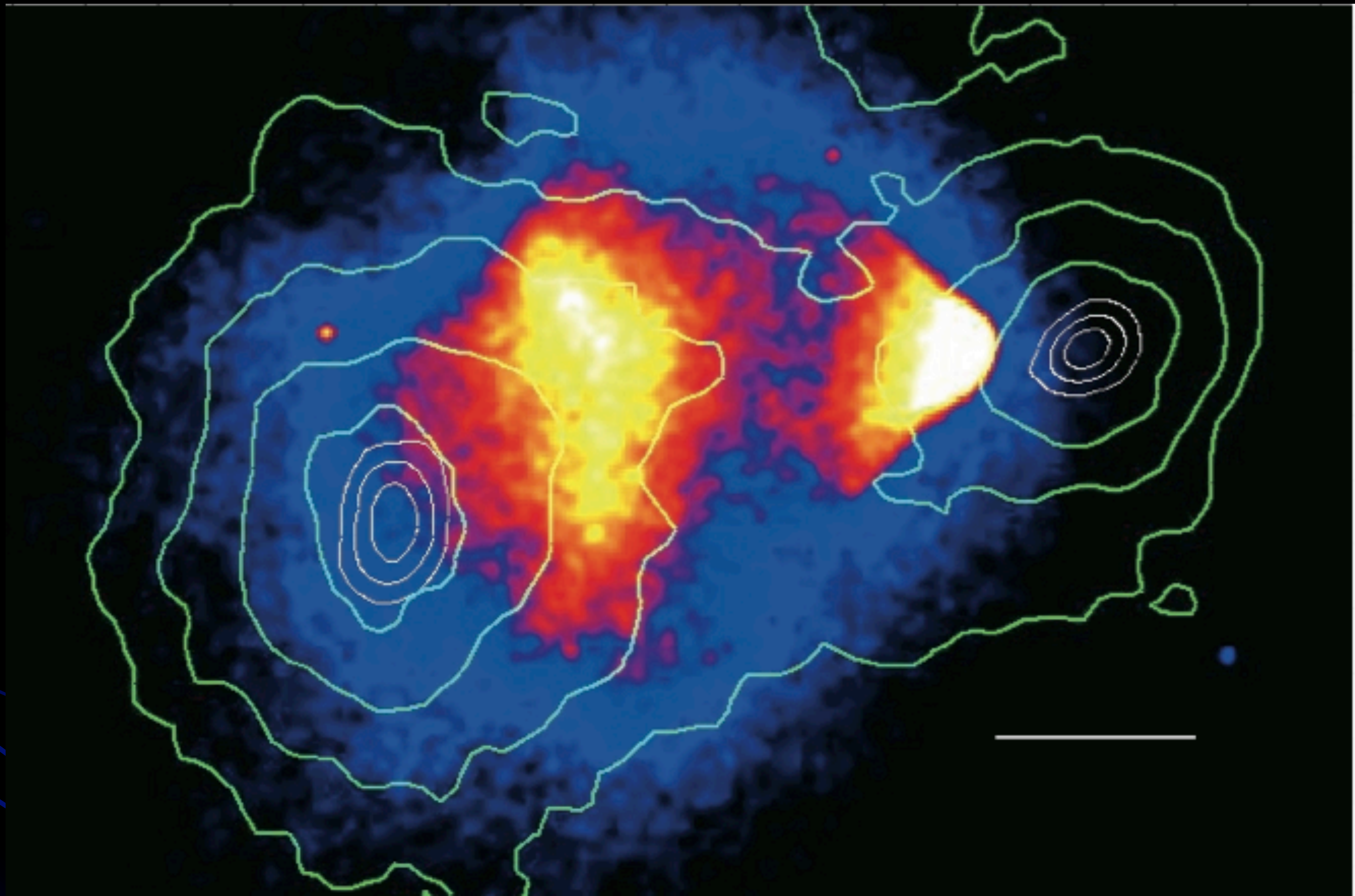
$$\alpha(r) = \alpha_\infty(1 - \exp(-r/\bar{r}))^{b/2}$$

$$\lambda(r) = \lambda_\infty(1 - \exp(-r/\bar{r}))^{-b}$$

Successfully reproduces R.C. and some cluster mass profiles, with M/L free parameter and a global fit of constants (for R.C. but individual for Clusters)



Final blow to M.G. is the Bullet Cluster.



The gravitational Potential, measured by grav.lensing (green contours) coincides with the distribution of galaxies (white contours) and not with the dominant baryonic component, which is the gas (yellow-red).

COSMOLOGICAL EVIDENCES OF DARK MATTER

Some Basics of Dynamical Cosmology

Friedman's equation: The basic equation of the dynamical evolution of the Universe

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda c^2}{3} + \frac{kc^2}{R^2}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[\rho_m + \rho_\Lambda + \rho_k\right]$$

$$\rho_{\text{total}} = \left[\rho_m + \rho_\Lambda + \rho_k\right] = \frac{3H^2}{8\pi G}$$

Definition of the parametrized density parameter Ω: It is the fractional contribution to global energy density of the Universe.

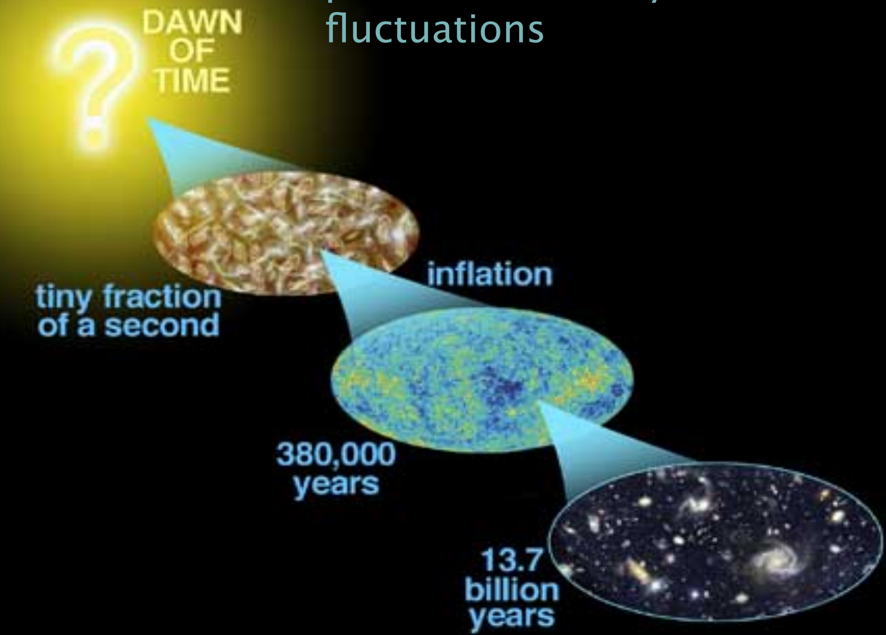
$$\Omega_i(a) = \frac{\rho_i}{\rho_{\text{total}}} = \frac{8\pi G\rho_i}{3H^2}$$

Important relation among Ω's

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

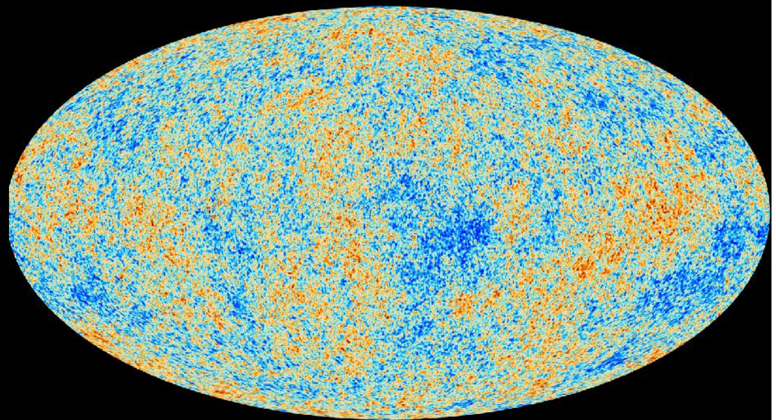
Cosmological Indications for the Existence of Dark Matter: Structure Formation

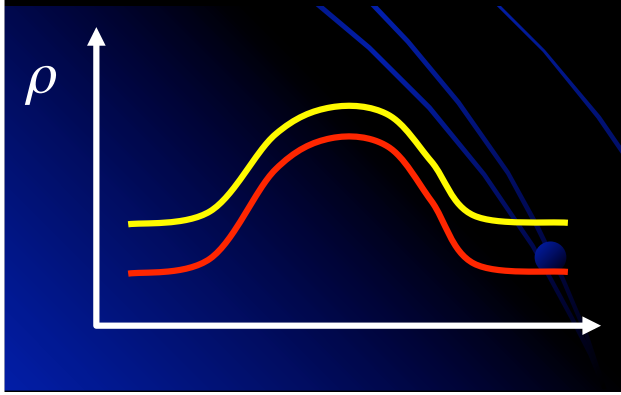
Origin of LSS today – primordial density fluctuations



Density perturbation

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} = \frac{\delta\rho}{\bar{\rho}}$$





ADIABATIC FLUCTUATIONS

Fluctuations in matter and radiation (changes in volume in the early Universe ➠ change in number densities)

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho}{\rho}$$

Cosmological Indications for the Existence of Dark Matter: Structure Formation

Formal Jeans Theory in an expanding background and in comoving coordinates, Using Continuity Equation, Euler's Equation & Poisson's Equation and Linear Perturbation Theory we obtain the basic differential equation for the growth of density perturbations:

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta$$

➔

$$\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}\Omega_m H^2\delta = 0$$

Matter Era (Ω_m=1, H=2/3t)

$$\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}\Omega_m H^2\delta = \ddot{\delta} + \frac{4}{3t}\dot{\delta} - \frac{2}{3t^2}\delta = 0$$

Solution:

$$\delta(t) \approx A\,t^{2/3} + B\,t^{-1}$$

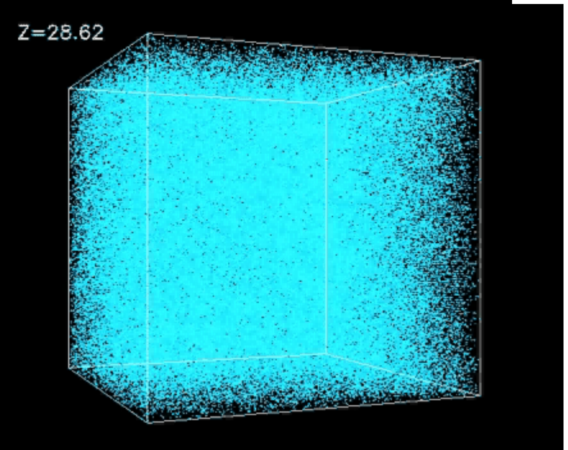
Growing mode and a decaying mode

Cosmological Indications for the Existence of Dark Matter: Structure Formation

Density fluctuations in a flat, matter dominated Universe grow as

$$\delta \propto A\,t^{2/3} \propto R(t) \propto \frac{1}{(1+z)}, \qquad \delta << 1$$

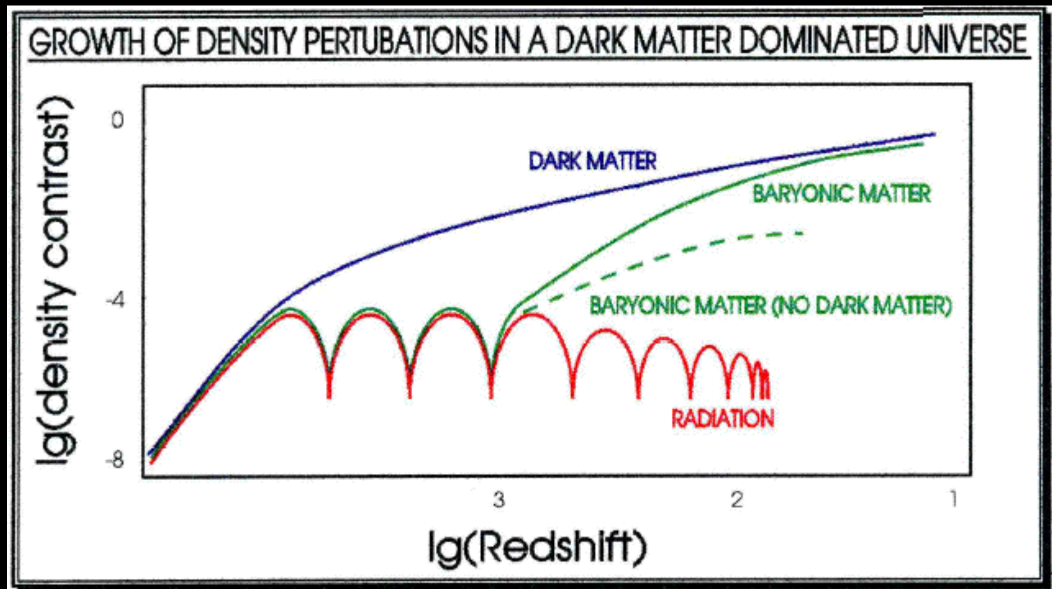
- Baryonic Matter fluctuations can ONLY have grown by a factor $(1+z_{dec}) \sim 1000$ by today
- for $\delta \sim 1$ (just entering non-linearity today) require $\delta \sim 0.001$ at recombination
- $\delta \sim 0.001 \Rightarrow \delta T/T \sim 0.003$ at recombination
- But CMB $\Rightarrow \delta T/T \sim 10^{-5}$!!!



MATTER PERTURBATIONS DON'T HAVE TIME TO GROW IN A BARYON DOMINATED UNIVERSE

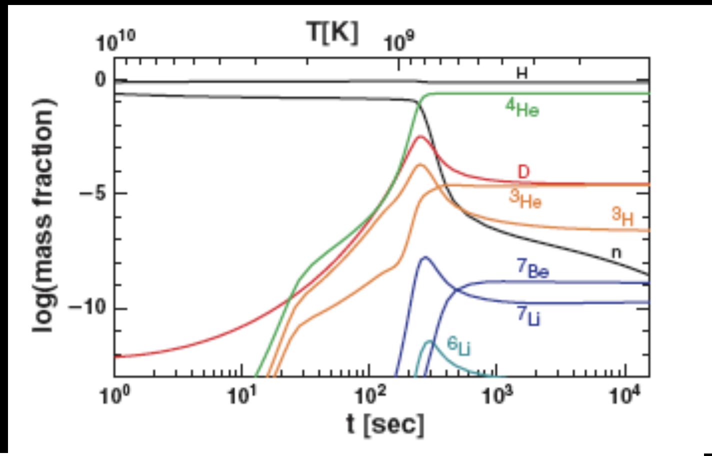
⇒ **DARK MATTER**

Dark Matter Condenses at earlier time
Matter then falls into DM gravitational wells



Cosmological Indications for the Existence of Dark Matter: Primordial Nucleosynthesis

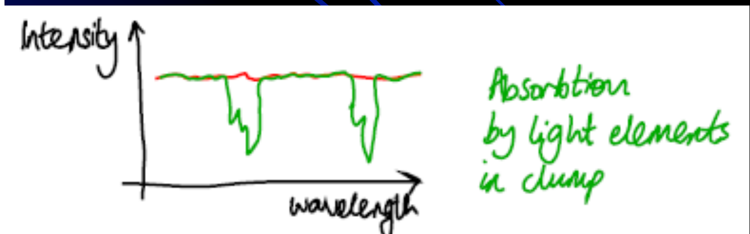
- In the first 3 minutes, the Universe was hot enough for nuclear reactions to take place
- Protons and neutrons formed ^{2}H, ^{3}He & ^{4}He. ^{2}H is reactive and was used up quickly
- ^{4}He is most stable and, within 3 minutes, made up 25% of the Universe

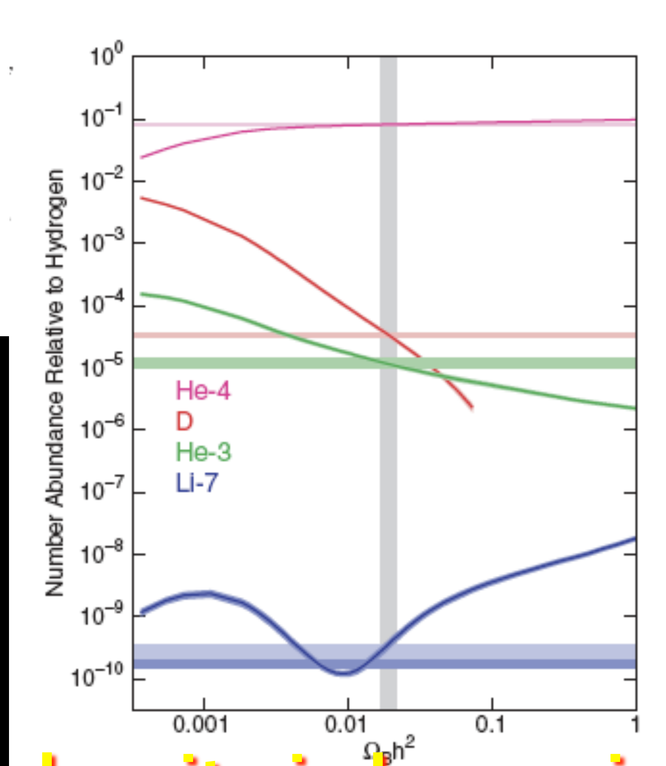


- Quasar spectra

$$^2H + {}^2H \rightleftarrows {}^3H + p$$
$$^2H + {}^2H \rightleftarrows {}^3He + n$$
$$^3H + {}^2H \rightleftarrows {}^4He + n$$
$$^3He + {}^2H \rightleftarrows {}^4He + p$$

- Measure absorption lines





→ Ω_b = 0.048 ~4.8% of critical density is baryonic !

Cosmological Indications for the Existence of Dark Matter: Join Cluster DM & BBPN

BASIC HYPOTHESIS is that the DM and Baryonic mix in Clusters of galaxies corresponds to the Universal value.

Then compare estimate of Total Cluster Mass with baryonic mass (galaxies and gas) to BBPN value to get Ω_b.

First application by White et al. 1993, Nature: "*The baryon content of galaxy clusters – A challenge to cosmological orthodoxy*".

$$\frac{M_b}{M_{Total}} = \frac{\Omega_b}{\Omega_m} \approx 0.15 \Rightarrow \Omega_m \approx \frac{0.048}{0.15} \approx 0.32$$

27% of total mass-energy density is DARK MATTER

Cosmological Indications for the Existence of Dark Matter: Measuring the values of Ω_i

JUST A FEW BASIC METHODS (many more…)

- M/L & baryonic matter in Clusters of Galaxies → Ω_m
- Temperature fluctuations of the CMB → Ω_κ
- Hubble diagram (SN Ia) → $\Omega_m + \Omega_\Lambda$

Cosmological Indications for the Existence of Dark Matter: Ω_m from Cluster M/L vs Universal Value

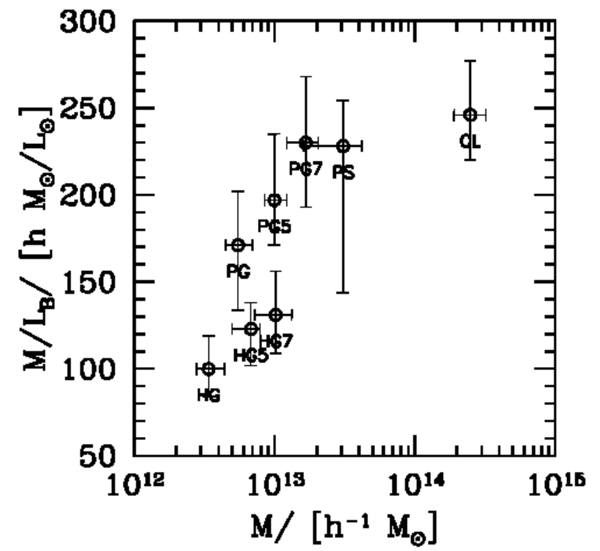
Estimate Cluster MASS to LIGHT ratio and compare with GLOBAL VALUE, assuming that mean $(M/L)_{clusters} = (M/L)_{global}$ on average

A. Determine Mass of clusters

B. Determine luminosity of clusters

C. Determine Global M/L of Universe

$$\frac{M}{L} \approx 340h \frac{M_\oplus}{L_\oplus}$$



→ From total galaxy luminosity function, Φ(L), integrate to low luminosities. Schechter Function, analytical and well behaved.→ **Derive mean Luminosity density of Universe and then compare with mean Mass density of Universe to derive Global M/L (*SDSS, Blanton et al 2003*)**

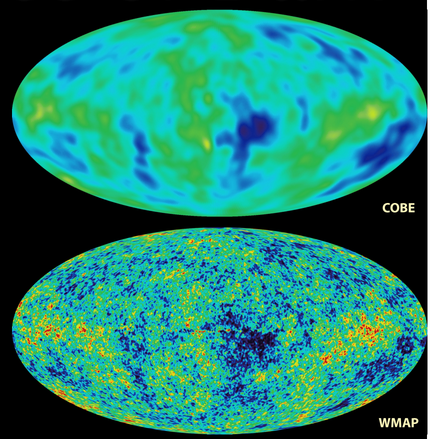
$$\Phi(L) = C\left(\frac{L}{L^*}\right)^a \exp(-L/L^*)$$

$$< L >= \int L\Phi(L)dL \propto L^*\Gamma(a+2)$$

$$\left(\frac{M}{L}\right) = \frac{\rho_0}{< L >} = \frac{\rho_{crit}\Omega_m}{< L >} \approx 1520\Omega_m h \frac{M_\oplus}{L_\oplus}$$

Preliminary Result: $\Omega_m \approx 0.23$

Cosmological Indications for the Existence of Dark Matter: Ω_k from $\delta T/T$



Different angular size on the last scattering surface of the same characteristic scale for different geometries !

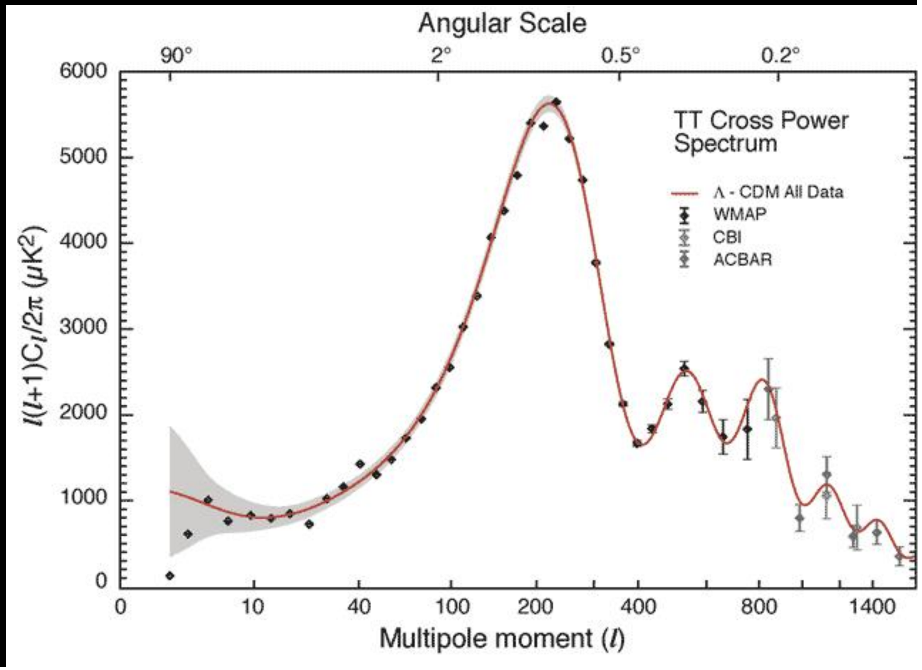
- Spherical Harmonic expansion →

$$\Delta T/T(\theta,\varphi)=\Sigma a_{lm} Y_{lm}(\theta,\varphi).$$

  Then the Power-Spectrum ($C_l = <|a_{lm}|^2>$) represents the amplitude of the contribution of fluctuations from different angular scales (note that $\theta=\pi/l$).
- Fluctuations at $\theta<2^o$ are due to the oscillations of the photo-baryonic fluid before recombination

Fluctuations at the scale of the acoustic horizon (at recombination) create a very strong peak in the power-spectrum at : $l \sim 220/(1-\Omega_k)^{1/2}$

→ $\Omega_k \approx 0$

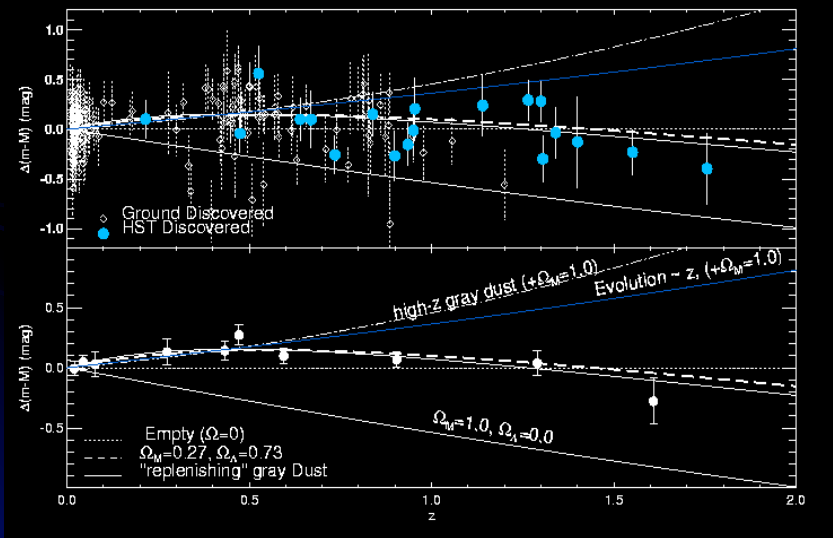


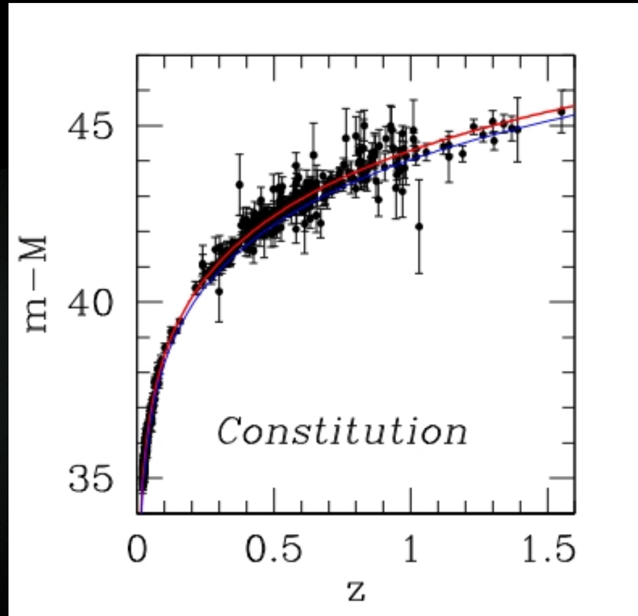
Cosmological Indications for the Existence of Dark Matter: $\Omega_m+\Omega_\Lambda$ from SNIa Hubble function

Supernova Ia's appear dimmer than what expected in decelerating Universes, therefore they are further away and this implies accelerated expansion of the Universe ➔ $\Omega_\Lambda > 0$ and more detailed theoretical calculation $\Omega_\Lambda > 1/3$.

$$m - M = 5\log_{10} D_L + 25$$

$$D_L = (1+z)\int_0^z \frac{c}{H(z)}\mathrm{d}z$$





$0.8\,\Omega_m - 0.6\Omega_\Lambda \approx 0.2$ SNIa)

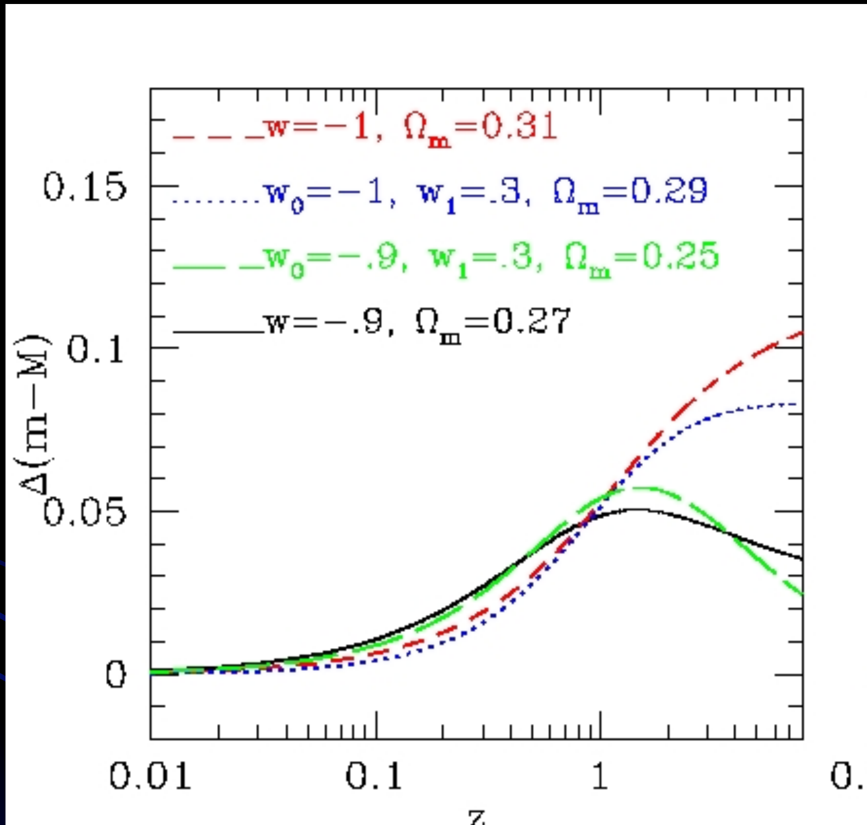
$\Omega_m + \Omega_\Lambda = 1 - \Omega_\kappa$ (from theory)

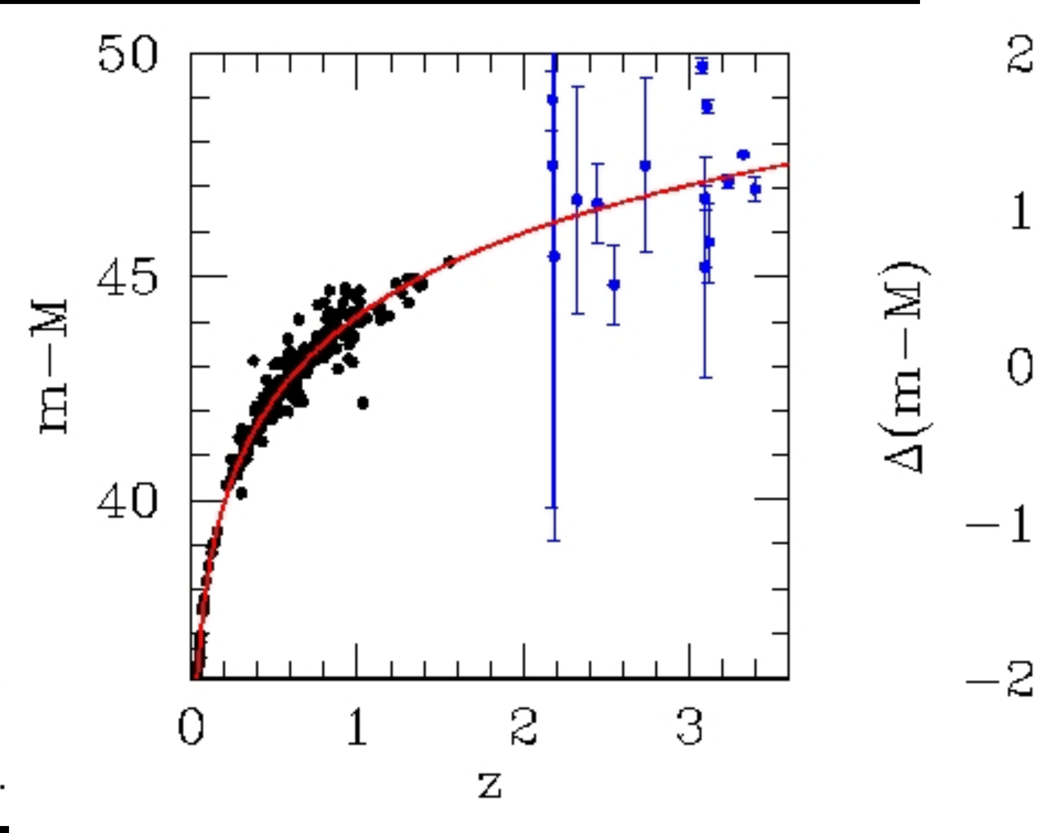
$1 - \Omega_\kappa = 1$ (from CMB $\Delta T/T$)

$\Omega_m \sim 0.27,\ \Omega_\Lambda \sim 0.73$

Alternative high-z distance Indicator – HII gals

M.Plionis, R.Chavez, R.Terlevich, E.Terlevich, F.Bressolin, S.Basilakos & J.Melnick 2011-2012





Necessary: Increase number of high-z starburst galaxies having spectroscopy and reduce significantly the random and systematic sources of scatter.

Cosmological Indications for the Existence of Dark Matter: Clustering of extragalactic sources – AGN

Model AGN Spatial Correlations

$$\xi_{th}(r,z) = b^2(z)D^2(z)\frac{1}{2\pi^2}\int_0^\infty k^2 P(k)\frac{\sin(kr)}{kr}\mathrm{d}k$$

- **P(k)** is the Cold Dark Matter power spectrum.
- **b(z)** is the evolution of bias, with bias being:

$$\delta_{\mathrm{tracer}} = b\delta_{\mathrm{matter}}$$

Linear Perturbation Theory

- (Peebles 1993) for w=-1 and w=-1/3

$$D(z) = \frac{5\Omega_{\mathrm{m}}E(z)}{2}\int_z^\infty \frac{(1+x)}{E^3(x)}$$

- (Silveira & Waga 1994) for w≠ -1
- (Linder & Chan 2007) for w(z)

Limber's Integral Equation

$$w_{th}(\theta) = 2\frac{H_0}{c}\int_0^\infty \left(\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}z}\right)^2 E(z)\mathrm{d}z\int_0^\infty \xi_{th}(r,z)\mathrm{d}u$$

- **dN/dz** is the redshift distribution of the X-ray selected AGN (predicted by the integral of their Luminosity Function).

Minimization procedure between theory & observations

$$\chi^2_{\mathrm{AGN}}(\mathbf{p}) = \sum_{i=1}^{n}\frac{[w_{\mathrm{th}}(\theta_i,\mathbf{p}) - w_{\mathrm{obs}}(\theta_i)]^2}{\sigma_i^2}$$

$$\mathbf{p} = \mathbf{p}(\Omega_m, \sigma_8, w, M_h)$$

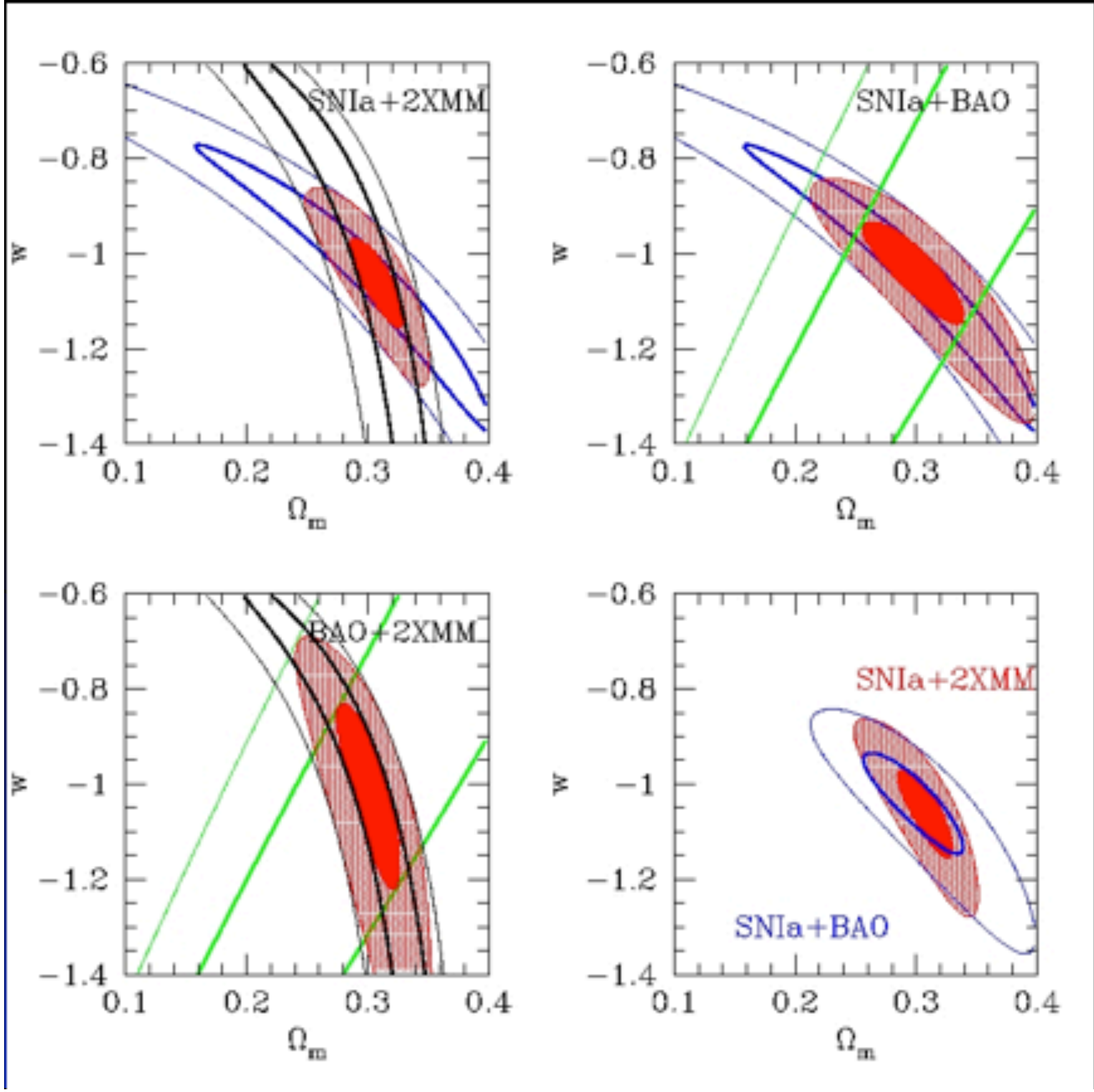
Dark Energy is manifested in the expansion rate of the Universe, via:

$$E(z)=\{\Omega_m(1+z)^3 + \Omega_w \exp\int dz[1+w(z)]/(1+z)\}^{1/2}$$

Equation of state w: Λ cosmology: w = -1 (p_{VAC}=- wρ_{VAC} = -Λ/8πG) but for variable time-dependent equation of states: **$w(z)=w_0+w_a$ [z/(1+z)]**

Precision Cosmology using Hubble expansion + X-ray AGN Clustering Probes

(Basilakos & Plionis 2009; Plionis et al. 2011)

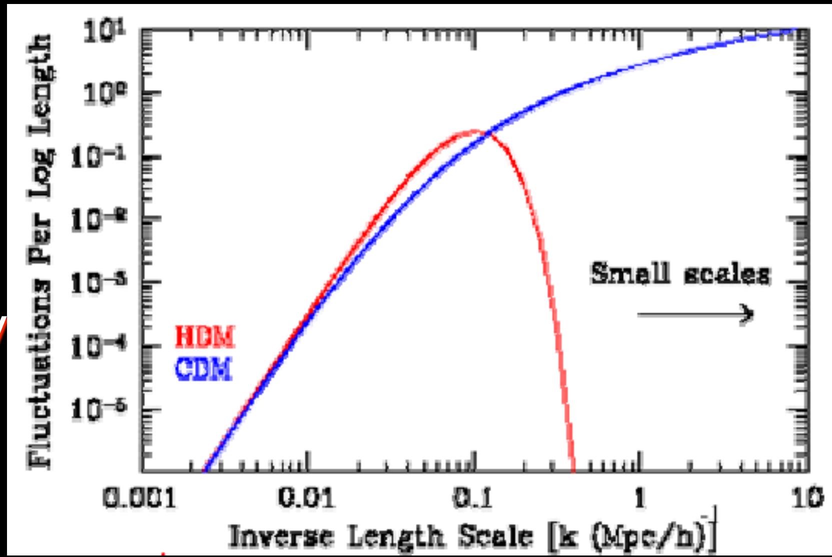


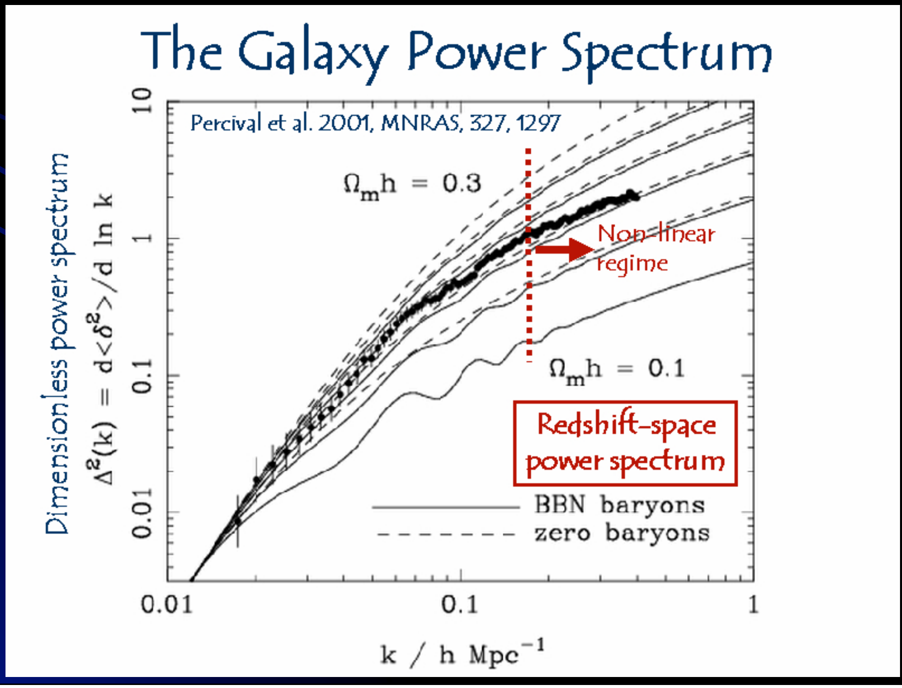
Example of our methodology:
The joint likelihood analysis, of the 2XMM clustering and the SNIa Hubble relation, and under the priors of a flat universe, h=0.704 and σ_8=0.81 provide significantly more stringent QDE constraints, as indicated by the fact that the *Figure of Merit increases by a factor ~2,* with respect to that of the joint SNIa-BAO analysis.

Ω_m=0.31±0.01, w=-1.06±0.05

Nature of the dark matter—Hot or cold

- Hot dark matter is relativistic at the collapse epoch and free-streaming out the galaxy-sized over density. Larger structure forms early and fragments to smaller ones.
- Cold DM is non-relativistic at de-coupling, forms structure in a hierarchical, bottom-up scenario.
- HDM is tightly bound from observation and LSS formation theory





Conclusions

Dark Matter, of a Coldish type which self-interacts gravitationally, definitely exists !

It constitutes ~26.5% of total mass-energy density + 4.8% baryons + 69% DE….. !

Important Issue: Direct Detection of DM, its mass and type. Many candidates:

- Axions, Neutralinos, Gravitinos, Axinos, Kaluza-Klein Photons, Kaluza-Klein Neutrinos, Heavy Fourth Generation Neutrinos, Mirror Photons, Mirror Nuclei, Stable States in Little Higgs Theories, WIMPzillas, Cryptons, Sterile Neutrinos, Sneutrinos, Light Scalars, Q-Balls, D-Matter, Brane World Dark Matter, Primordial Black Holes, …