Dark matter

- Astrophysical motivations.
- Distribution.
- Simulations

Dark matter

- What shines and doesn't matter... stars!

Dark matter

- What shines and doesn't matter... stars!
- 99% of astronomical information comes from stars

Dark matter

- What shines and doesn't matter... stars!
- 99% of astronomical information comes from stars
- yet only 0.3% (with a factor of 2 of uncertainty) of the content of the Universe

$$\text{i.e. } \Omega_* \sim 0.003$$

Dark matter

- Dark matter is needed, unless one allows new law for gravitation.

Dark matter

- Dark matter is needed, unless one allows new law for gravitation.
- There is several times more dark matter than visible matter...

Dark matter

- Dark matter is needed, unless one allows new law for gravitation.
- There is several times more dark matter than visible matter...
- We don't know much about it (nothing special, as we do not see it...)

Dark matter

- Dark matter is needed, unless one allows new law for gravitation.
- There is several times more dark matter than visible matter...
- We don't know much about it (nothing special, as we do not see it...)

"There are some astrophysical problems to which dark matter is not the solution..." Virginia Trimble.

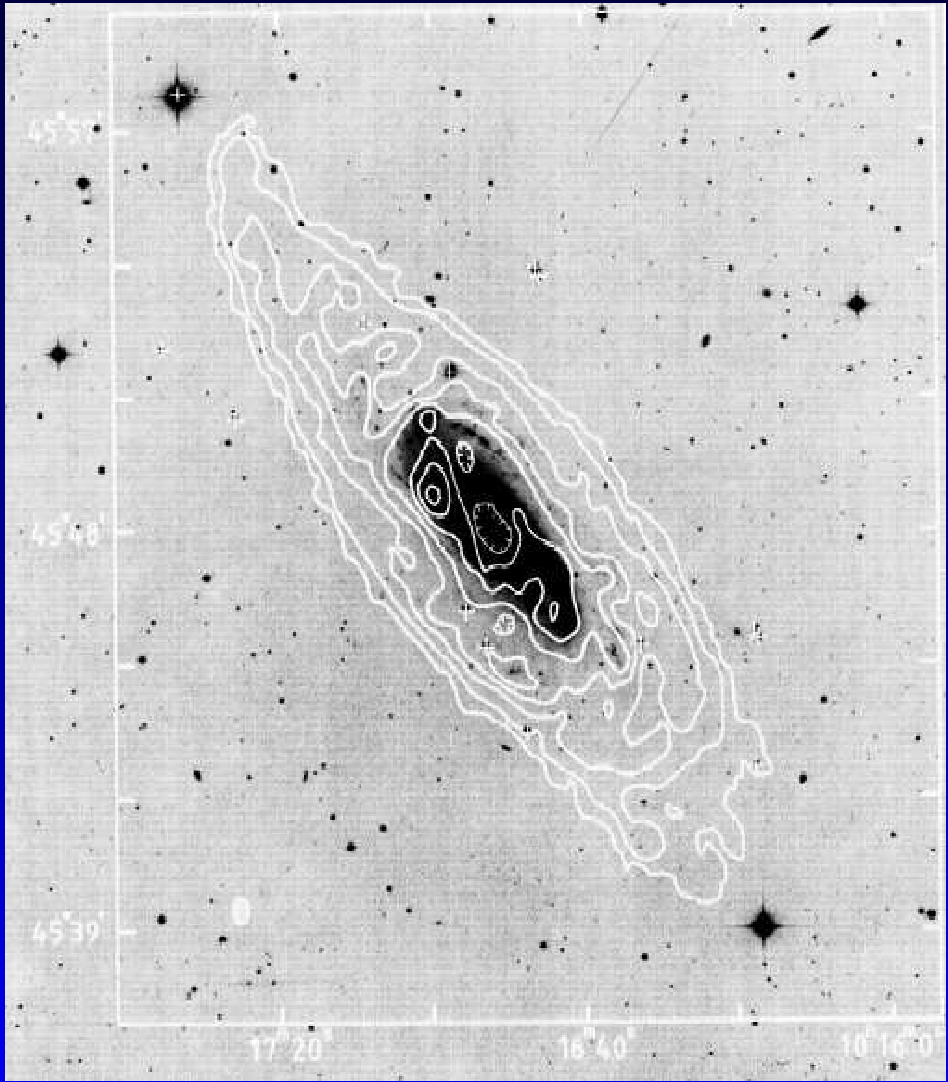
Dark Matter

Robust evidence I: galaxy rotation curves

Typical galaxy NGC 3198 (may mean best case...)

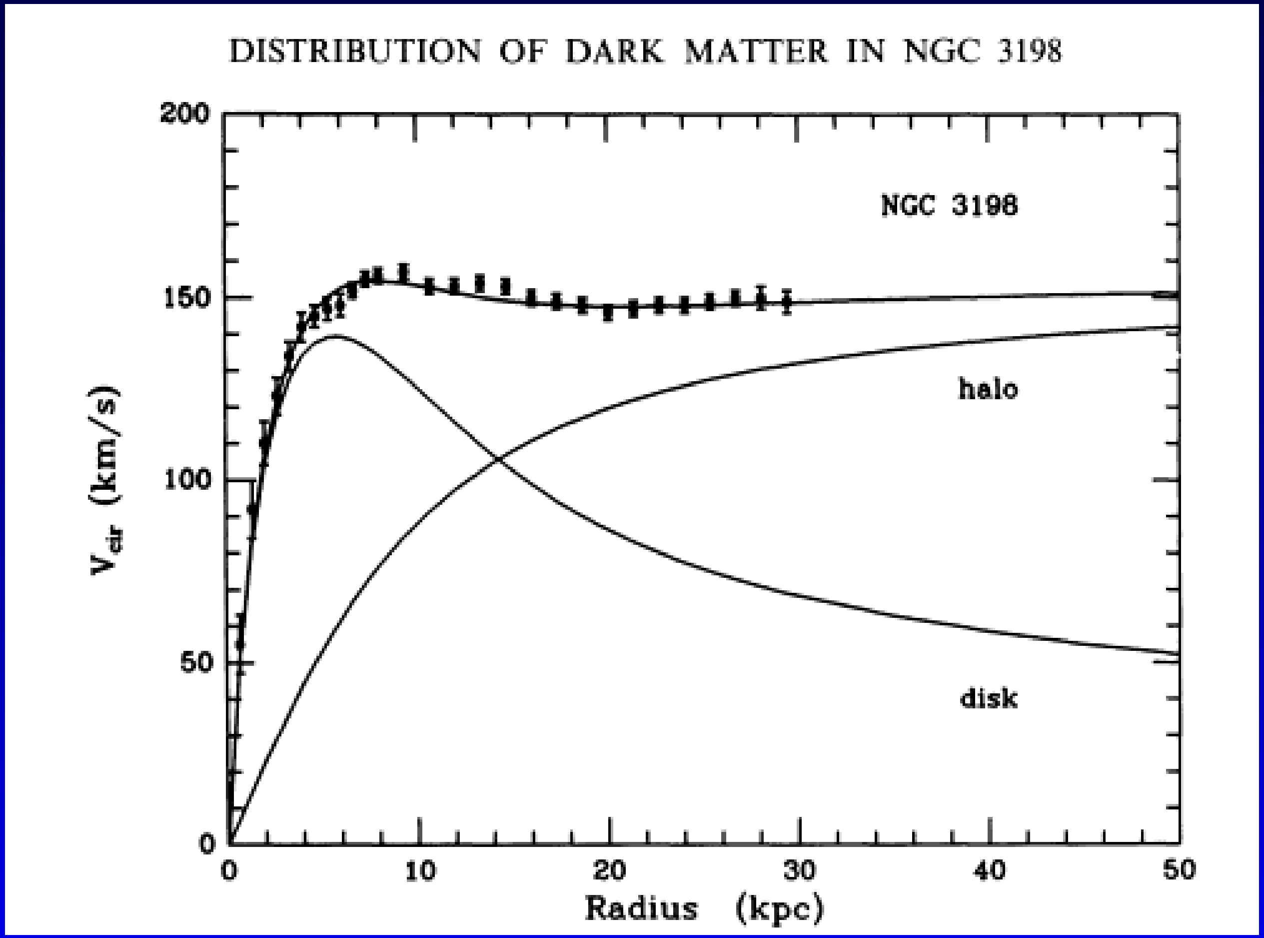
Dark Matter

NGC 3198: optical + HI view



Dark Matter

NGC 3198 : rotation curve



Dark Matter

rotation curve traces mass:

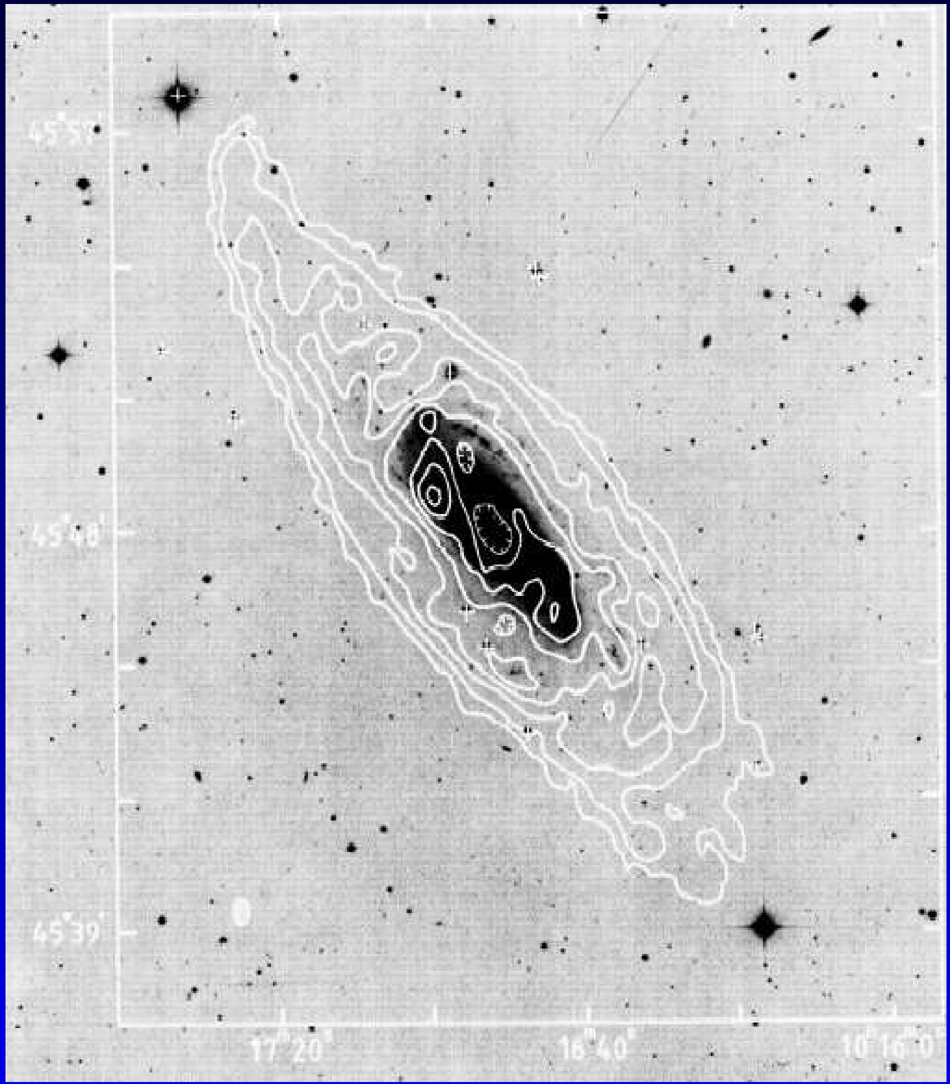
$$V^2 = \alpha \frac{GM}{R}$$

with $\alpha \sim 1$.

So $v \sim \mathrm{cste}$ means $M \propto R$

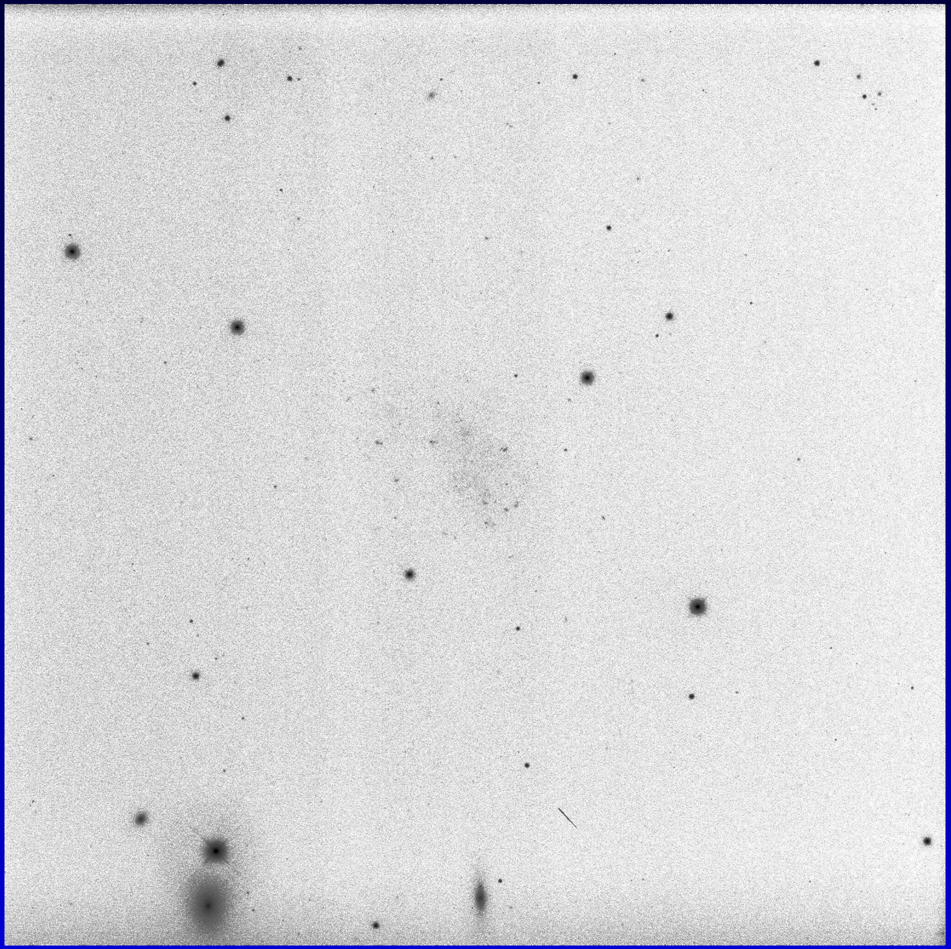
Dark Matter

HI view : mass grows where ”nothing ” is seen



Dark Matter

Flat rotation curve, a general feature of disk galaxies:



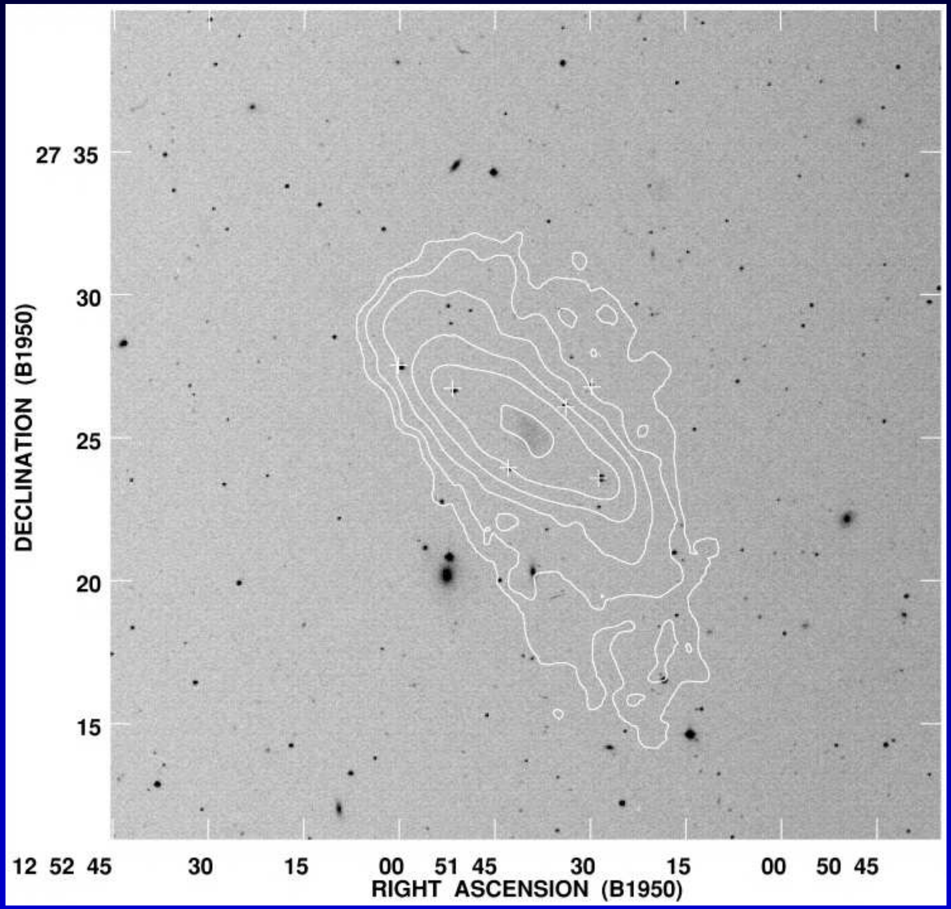
DDO154: a dwarf galaxy...

Dark Matter

DDO154: modern view...

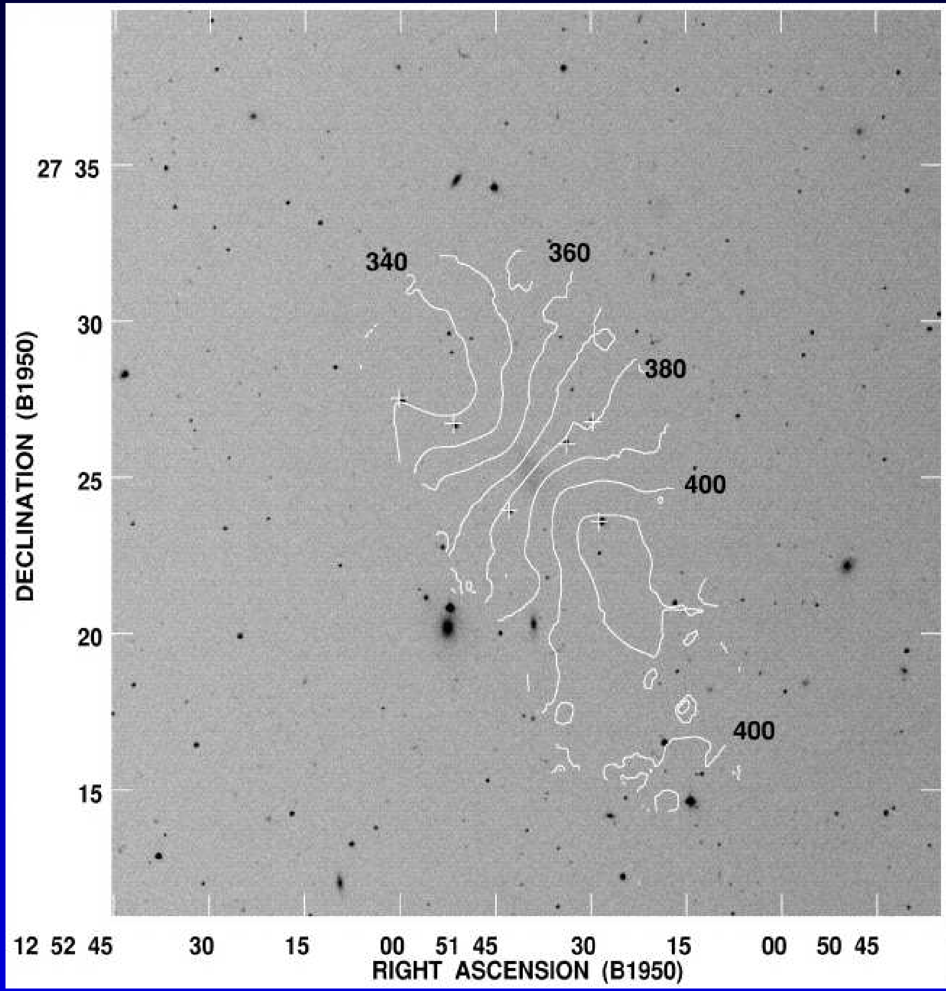
Dark Matter

DDO154: large HI extension



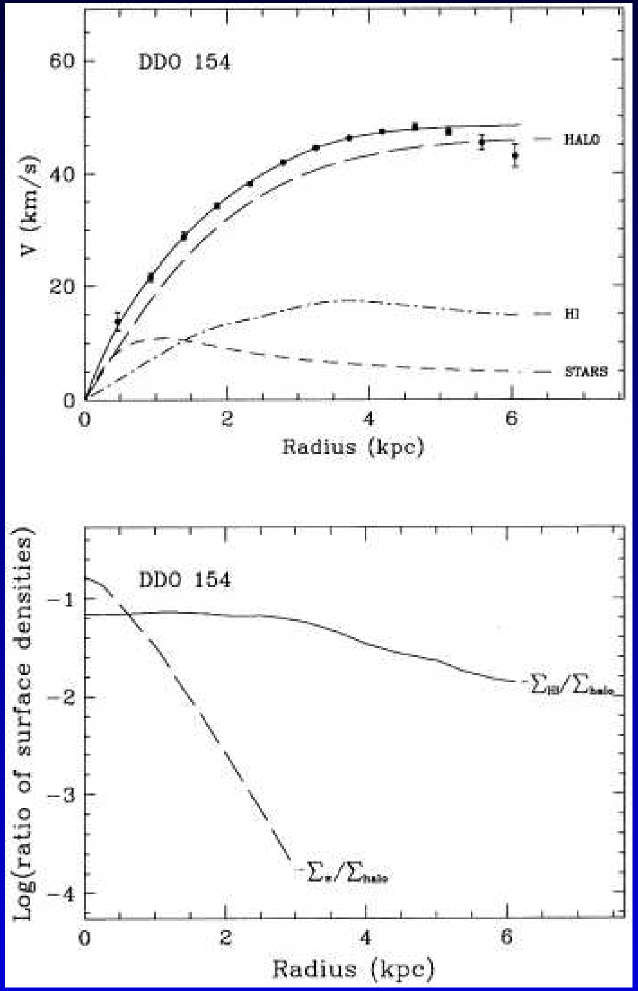
Dark Matter

DDO154:velocity field



Dark Matter

DDO154: rotation curve



Dark Matter: Galaxies

"Observed" amount of dark matter in galaxies:

$$\frac{M_{tot}}{M_{vis}} \approx 5 - 10$$

so :

$$\Omega_{gal} \approx 0.015 - 0.03$$

Note : we do not know how far galaxies extend.

Dark Matter

Robust evidence II: Clusters.

Early discovery:

1933

F.Zwicky

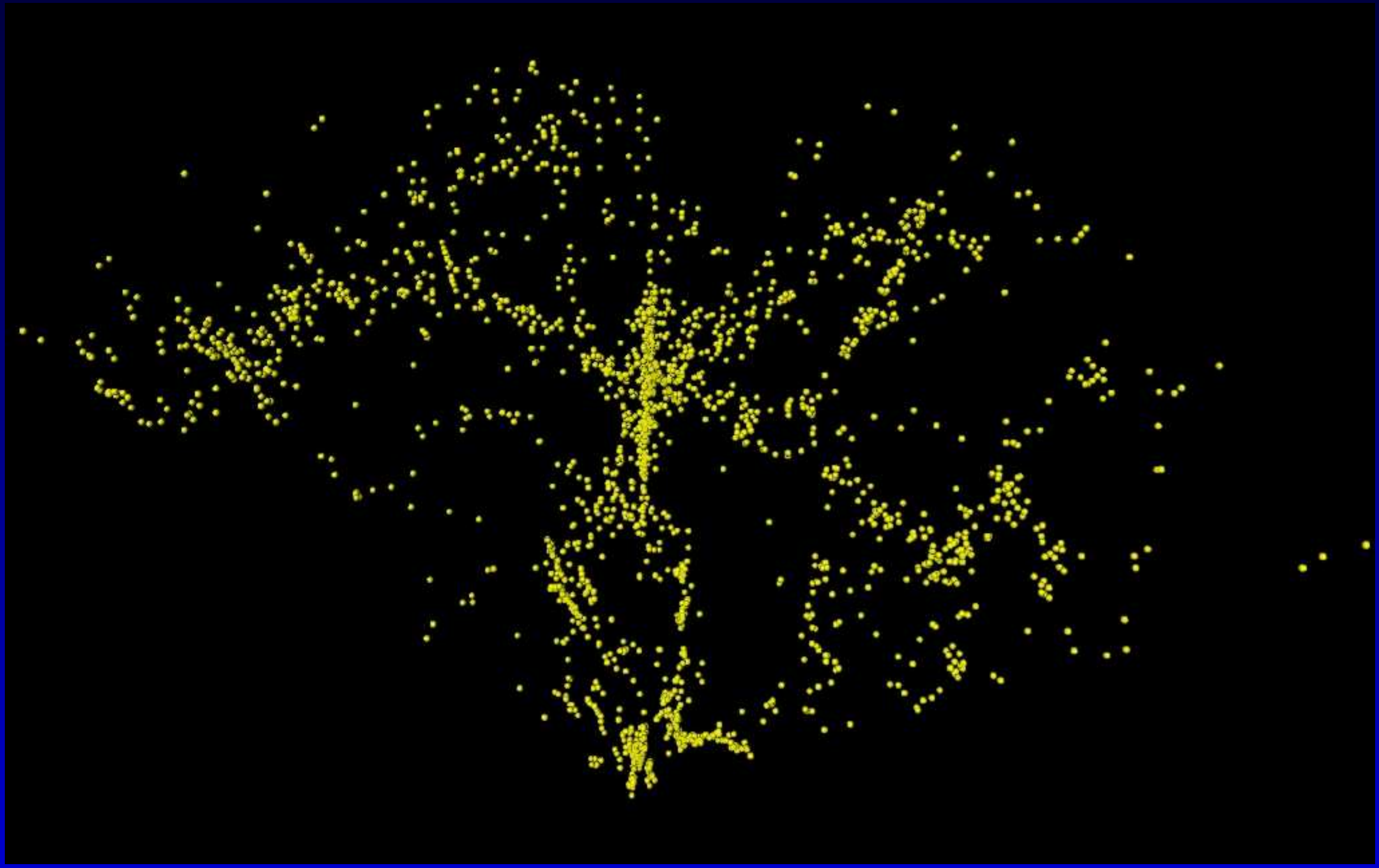
Velocity dispersion in galaxy clusters.

Dark Matter

Typical Cluster: Coma.

Dark Matter

Velocity dispersion in galaxy clusters.



$$D = H_0^{-1} V$$

Dark Matter

Velocity dispersion in galaxy clusters.

but actual V:

$$V = H_0 D_{true} + V_{pec}\cos(\theta)$$

so:

$$D = D_{true} + H_0^{-1} V_{pec}\cos(\theta)$$

Measures $\sigma_{1D} = 1/3\sigma$

Infers mass:

$$\sigma^2 = \alpha' \frac{GM}{R}$$

Dark matter

Typical velocity dispersion $\sim 1000\mathrm{km/s}$ (massive clusters).

Dark matter

Typical velocity dispersion $\sim 1000\mathrm{km/s}$ (massive clusters).

So typical mass $M \sim 10^{15} \mathrm{M}_\odot$ ($R \sim 3$ Mpc).

$$\frac{M_{tot}}{M_*} \approx 100$$

and :

$$\Omega_{DM} \approx 0.3$$

Dark matter

Typical velocity dispersion $\sim 1000\mathrm{km/s}$ (massive clusters).

So typical mass $M \sim 10^{15}\mathrm{M}_\odot$ ($R \sim 3$ Mpc).

$$\frac{M_{tot}}{M_*} \approx 100$$

and :

$$\Omega_{DM} \approx 0.3$$

relies on an extrapolation: $100 - 10^5$

M/L

Astrophysicists used the "M/L" ratio:

$$M/L = \frac{M/M_\odot}{L/L_\odot}$$

so :

$$\rho = \rho_L \times M/L$$

and :

$$\Omega_0 = \frac{8\pi G\rho}{H_0^2}$$

M/L

so :

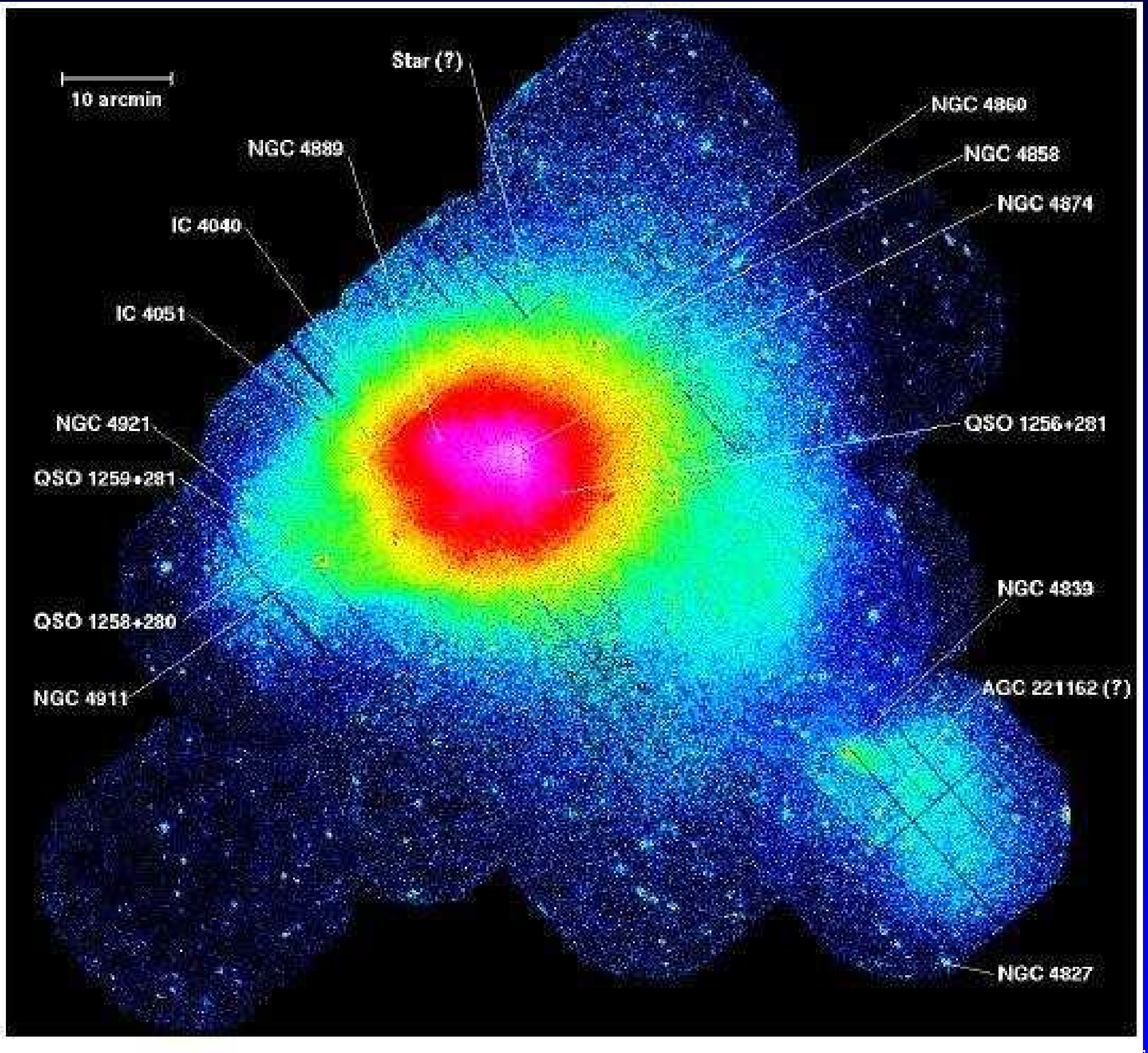
$$\Omega_0 = \frac{8\pi G M/L \rho_L}{3H_0^2} = \frac{M/L}{M/L)_c}$$

with:

$$M/L)_c = \frac{3H_0^2}{8\pi G \rho_L}$$

Dark Matter

An other vision of clusters: X-ray.



Coma Cluster of galaxies

Dark Matter

- diffuse X-ray emission comes from bremsstrahlung emission.

Dark Matter

- diffuse X-ray emission comes from bremsstrahlung emission.
- This emission is $\propto n_e^2 T^{1/2}$ and probes the inter cluster medium (ICM).

Dark Matter

- diffuse X-ray emission comes from bremsstrahlung emission.
- This emission is $\propto n_e^2 T^{1/2}$ and probes the inter cluster medium (ICM).
- The emissivity profile allows to infer gas mass.

Dark Matter

Masses in clusters:

$$\frac{M_{gas}}{M_*} \approx 10$$

and therefore :

Dark Matter

Masses in clusters:

$$\frac{M_{gas}}{M_*} \approx 10$$

and therefore :

- Gas is the dominant baryonic content of clusters.

Dark Matter

Masses in clusters:

$$\frac{M_{gas}}{M_*} \approx 10$$

and therefore :

- Gas is the dominant baryonic content of clusters.
- Visible matter is a small fraction ($\sim 10 - 20\%$) of the total mass.

Dark Matter

Masses in clusters: X-ray spectrum provides the temperature of the gas.

Dark Matter

Masses in clusters: X-ray spectrum provides the temperature of the gas.
This allows an estimation of the mass:

$$\frac{dP_{gas}}{dr} = \frac{-\rho_{gas} G M_{grav}(r)}{r^2}$$

where : $P_{gas} = nkT = \rho_{gas} kT/\mu m_p$. So:

Dark Matter

Masses in clusters: X-ray spectrum provides the temperature of the gas.
This allows an estimation of the mass:

$$\frac{dP_{gas}}{dr} = \frac{-\rho_{gas} G M_{grav}(r)}{r^2}$$

where : $P_{gas} = nkT = \rho_{gas} kT/\mu m_p$. So:

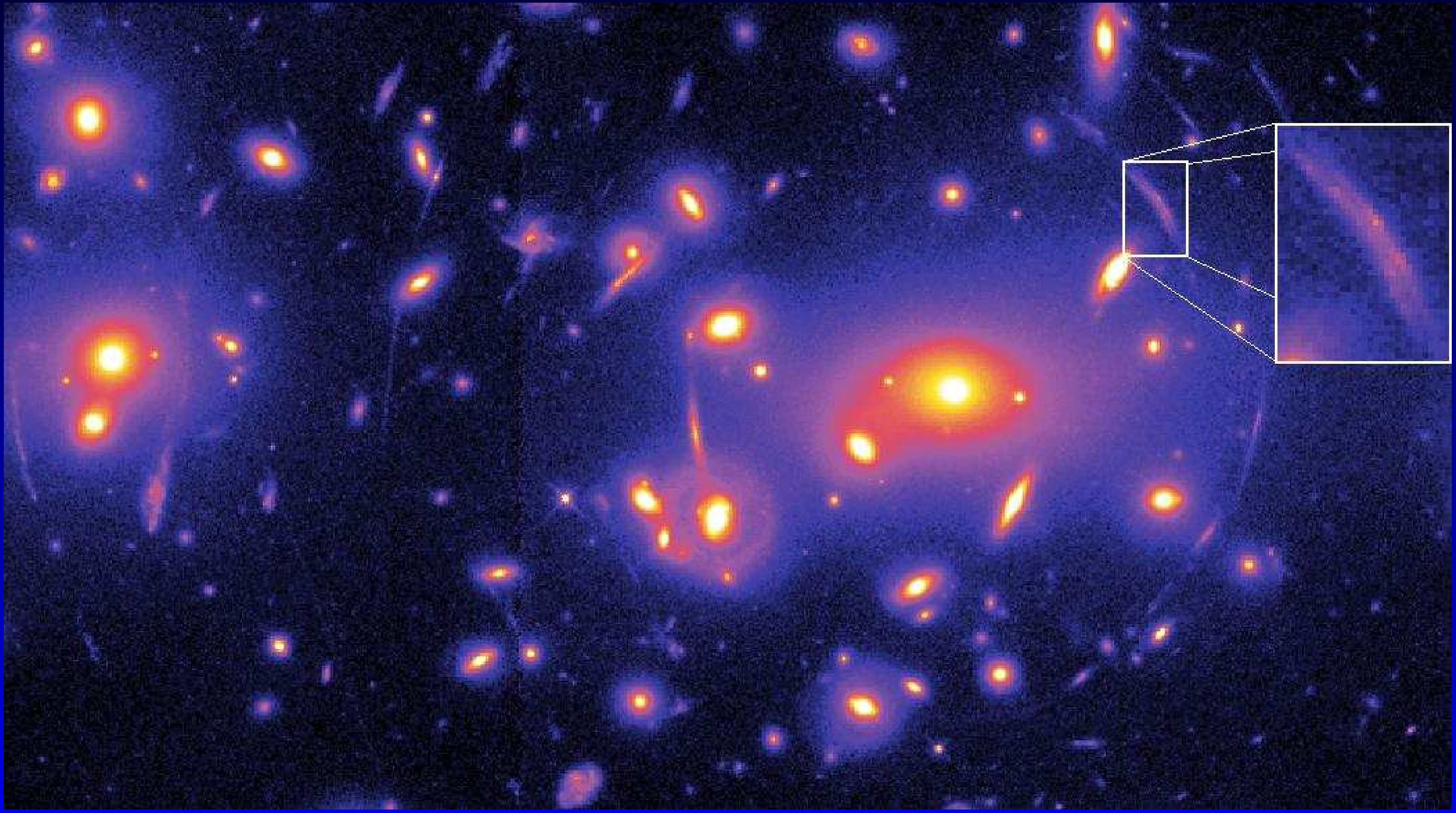
$$M_{grav}(r) = \frac{-kT}{G\mu m_p}\left(\frac{d\ln\rho_{gas}}{d\ln r} + \frac{d\ln T}{d\ln r}\right) r$$

Dark Matter

Cluster mass from lensing (strong regime)

Dark Matter

Cluster mass from lensing (strong regime)

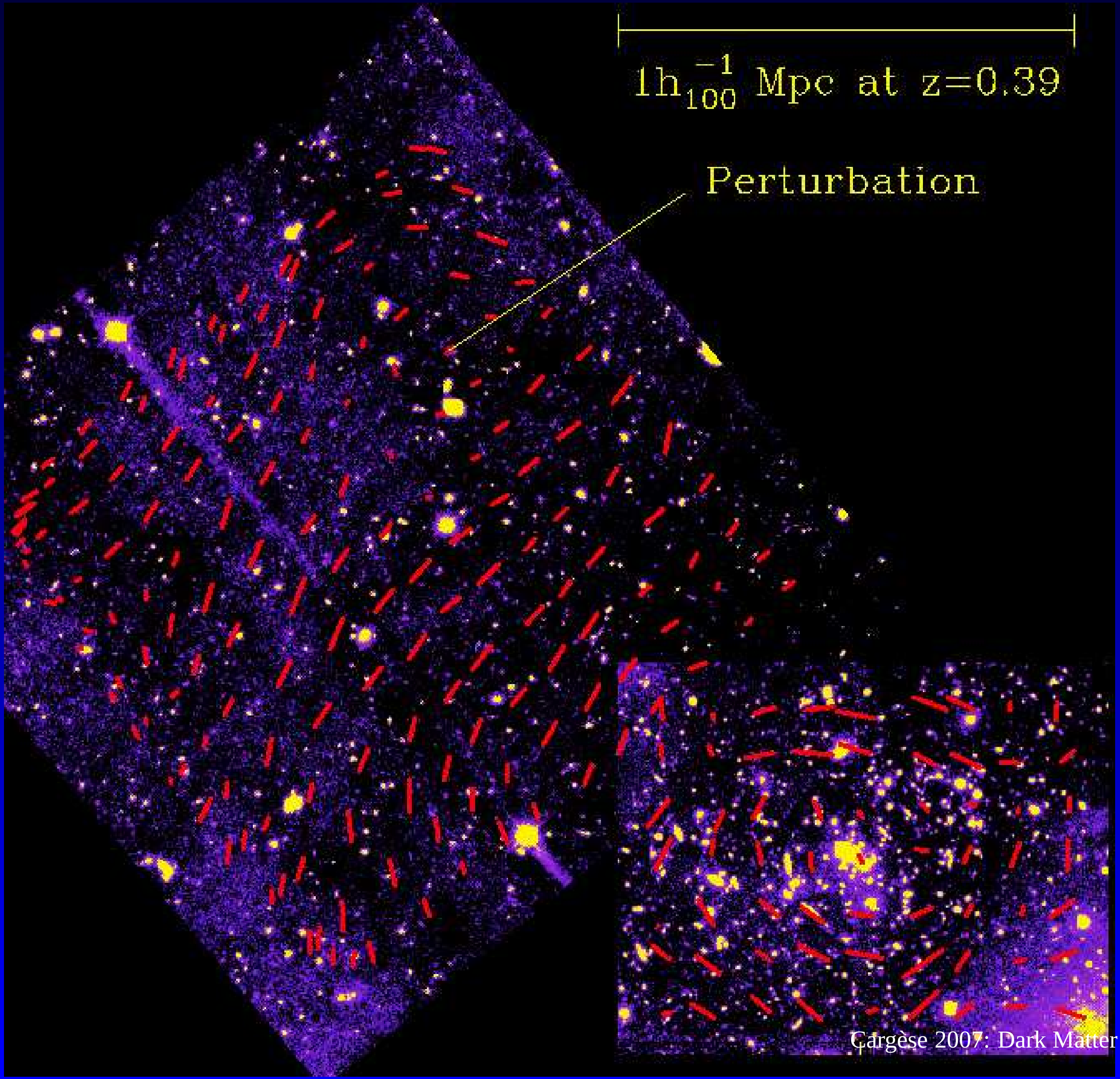


Dark Matter

Cluster mass from lensing (weak regime):

Dark Matter

Cluster mass from lensing (weak regime):



Dark Matter

(crude) Conclusion on cluster masses :

Dark Matter

(crude) Conclusion on cluster masses :

- Masses obtained by the various methods agree

Dark Matter

(crude) Conclusion on cluster masses :

- Masses obtained by the various methods agree

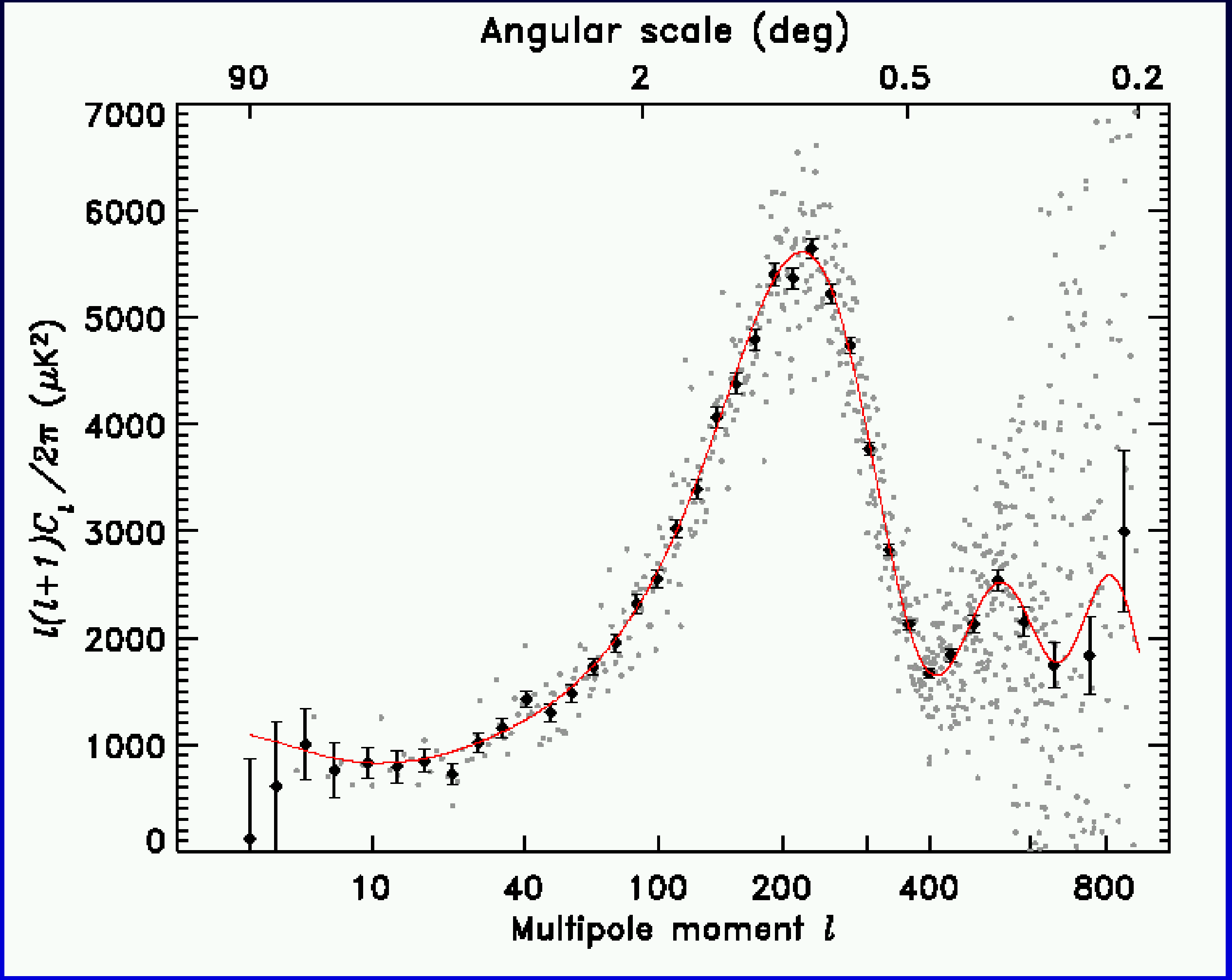
(some debate within a factor of two)

Dark Matter

Robust evidence III: CMB.

Dark Matter

Robust evidence III: CMB.



Dark Matter

Robust evidence III: CMB.

Dark Matter

Robust evidence III: CMB.

Table 10. Basic and Derived Cosmological Parameters: Running Spectral Index Model[a]

	Mean and 68% Confidence Errors
Amplitude of fluctuations	$A = 0.83^{+0.09}_{-0.08}$
Spectral Index at $k = 0.05$ Mpc^{-1}	$n_s = 0.93 \pm 0.03$
Derivative of Spectral Index	$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
Hubble Constant	$h = 0.71^{+0.04}_{-0.03}$
Baryon Density	$\Omega_b h^2 = 0.0224 \pm 0.0009$
Matter Density	$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$
Optical Depth	$\tau = 0.17 \pm 0.06$
Matter Power Spectrum Normalization	$\sigma_8 = 0.84 \pm 0.04$
Characteristic Amplitude of Velocity Fluctuations	$\sigma_8 \Omega_m^{0.6} = 0.38^{+0.04}_{-0.05}$
Baryon Density/Critical Density	$\Omega_b = 0.044 \pm 0.004$
Matter Density/Critical Density	$\Omega_m = 0.27 \pm 0.04$
Age of the Universe	$t_0 = 13.7 \pm 0.2$ Gyr
Reionization Redshift[b]	$z_r = 17 \pm 4$
Decoupling Redshift	$z_{dec} = 1089 \pm 1$
Age of the Universe at Decoupling	$t_{dec} = 379^{+8}_{-7}$ kyr
Thickness of Surface of Last Scatter	$\Delta z_{dec} = 195 \pm 2$
Thickness of Surface of Last Scatter	$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
Redshift of Matter/Radiation Equality	$z_{eq} = 3233^{+194}_{-210}$
Sound Horizon at Decoupling	$r_s = 147 \pm 2$ Mpc
Angular Diameter Distance to the Decoupling Surface	$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
Acoustic Angular Scale[c]	$\ell_A = 301 \pm 1$
Current Density of Baryons	$n_b = (2.5 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/Photon Ratio	$\eta = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$

Dark Matter: standard view.

- Visible matter (stars+gas) is $\sim 0.002 - 0.01$

Dark Matter: standard view.

- Visible matter (stars+gas) is $\sim 0.002 - 0.01$
- Baryonic matter is ~ 0.05, so most baryons are dark,

Dark Matter: standard view.

- Visible matter (stars+gas) is $\sim 0.002 - 0.01$
- Baryonic matter is ~ 0.05, so most baryons are dark,
- Galaxies represent a small fraction of total mass $\sim 0.02 - 0.05$,

Dark Matter: standard view.

- Visible matter (stars+gas) is $\sim 0.002 - 0.01$
- Baryonic matter is ~ 0.05, so most baryons are dark,
- Galaxies represent a small fraction of total mass $\sim 0.02 - 0.05$,
- Most of dark matter should be non baryonic : $\Omega_{nb} \sim 0.2 - 0.25$.

Dark Matter: alternative view.

Newtonnian gravity law fails on large scale...

Dark Matter: alternative view.

Newtonnian gravity law fails on large scale...

(this is an heretic point of view...)

Dark Matter: alternative view.

Newtonnian gravity law fails on large scale...

(this is an heretic point of view...)

Simplest is MOND (Milgrom 1983):

$$a = g$$

Dark Matter: alternative view.

Newtonnian gravity law fails on large scale...

(this is an heretic point of view...)

Simplest is MOND (Milgrom 1983):

$$\mu(a/a_0)a = g$$

with:

$$\mu = \frac{x}{1+x}$$

Alternative view

- When g is large compare to a_0 $a \sim g$.

Alternative view

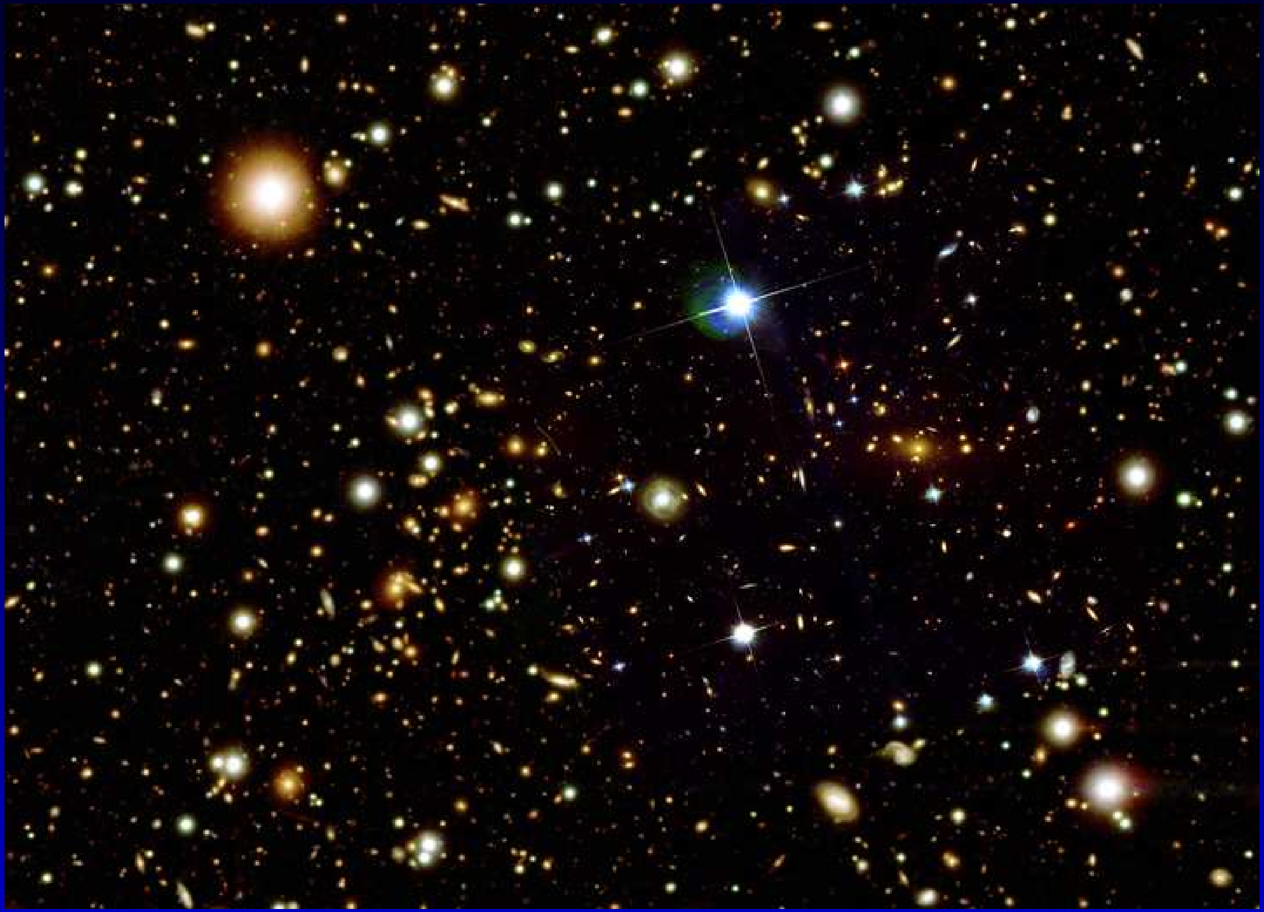
- When g is large compare to a_0 $a \sim g$.
- When g is small compare to a_0 $a \sim \sqrt{g a_0}$.

Alternative view

- When g is large compare to a_0 $a \sim g$.
- When g is small compare to a_0
  $a \sim \sqrt{g a_0}$.
- Efficient for rotation curves

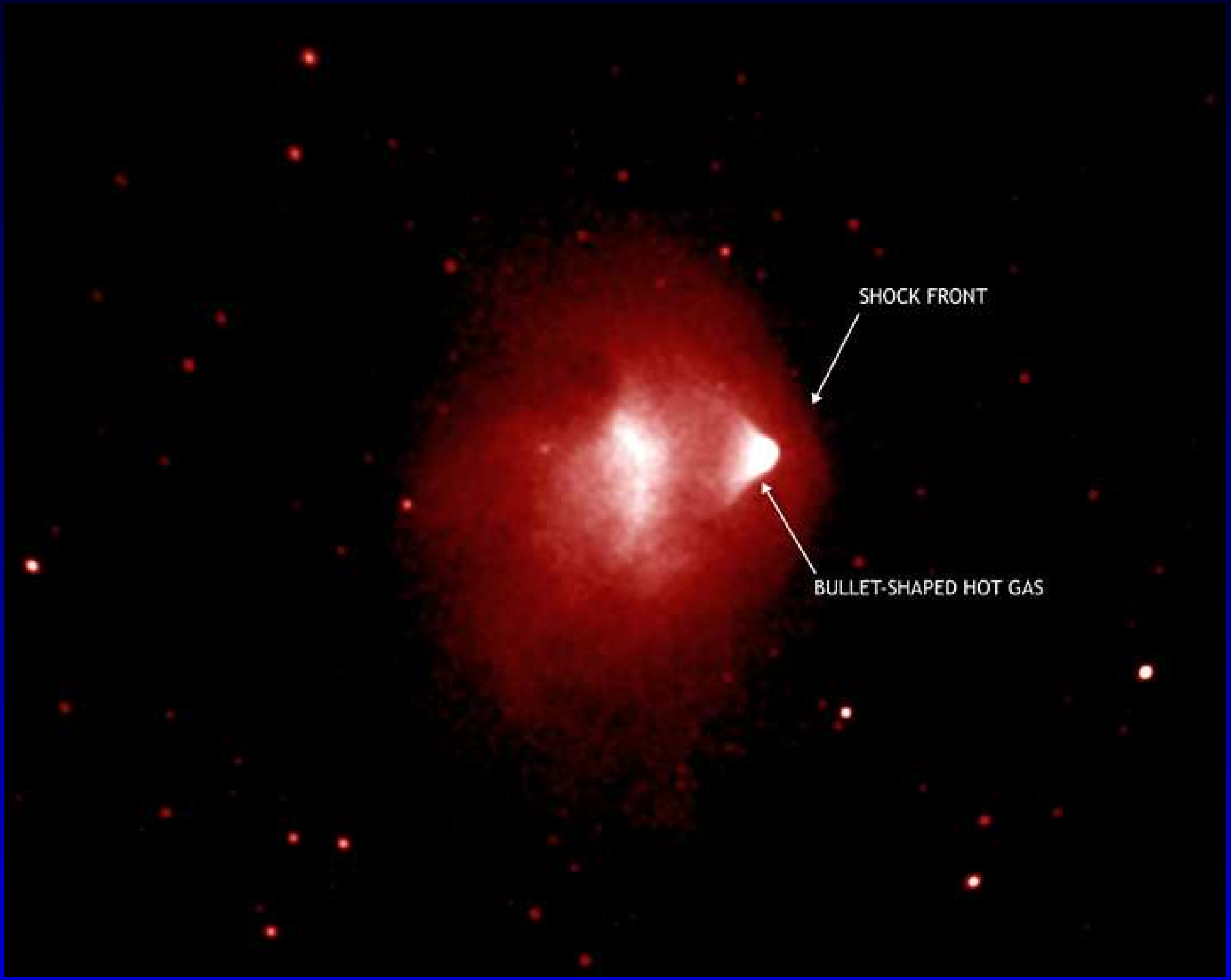
The Bullet cluster

The Bullet cluster



The Bullet cluster: xray

The Bullet cluster: xray

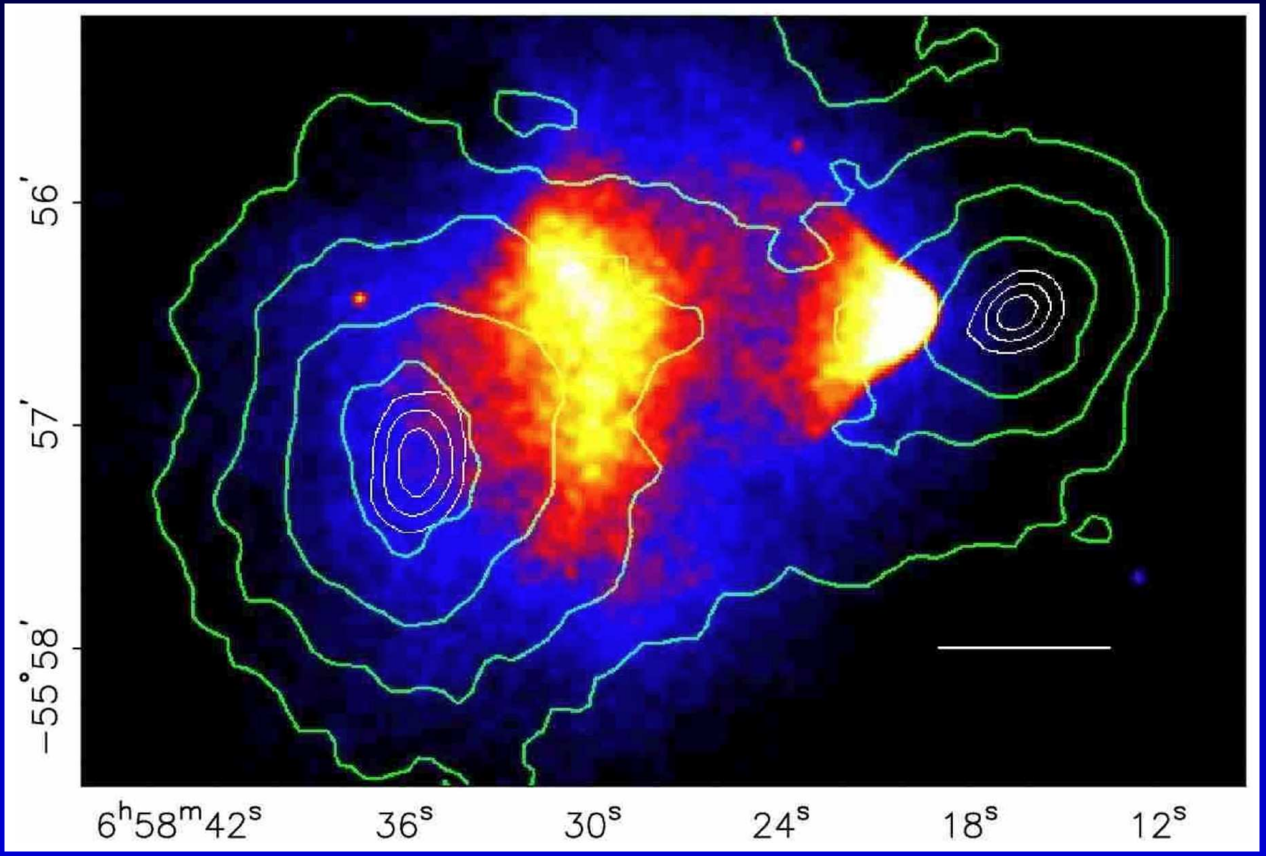


The Bullet cluster

Standard history: Simulation.

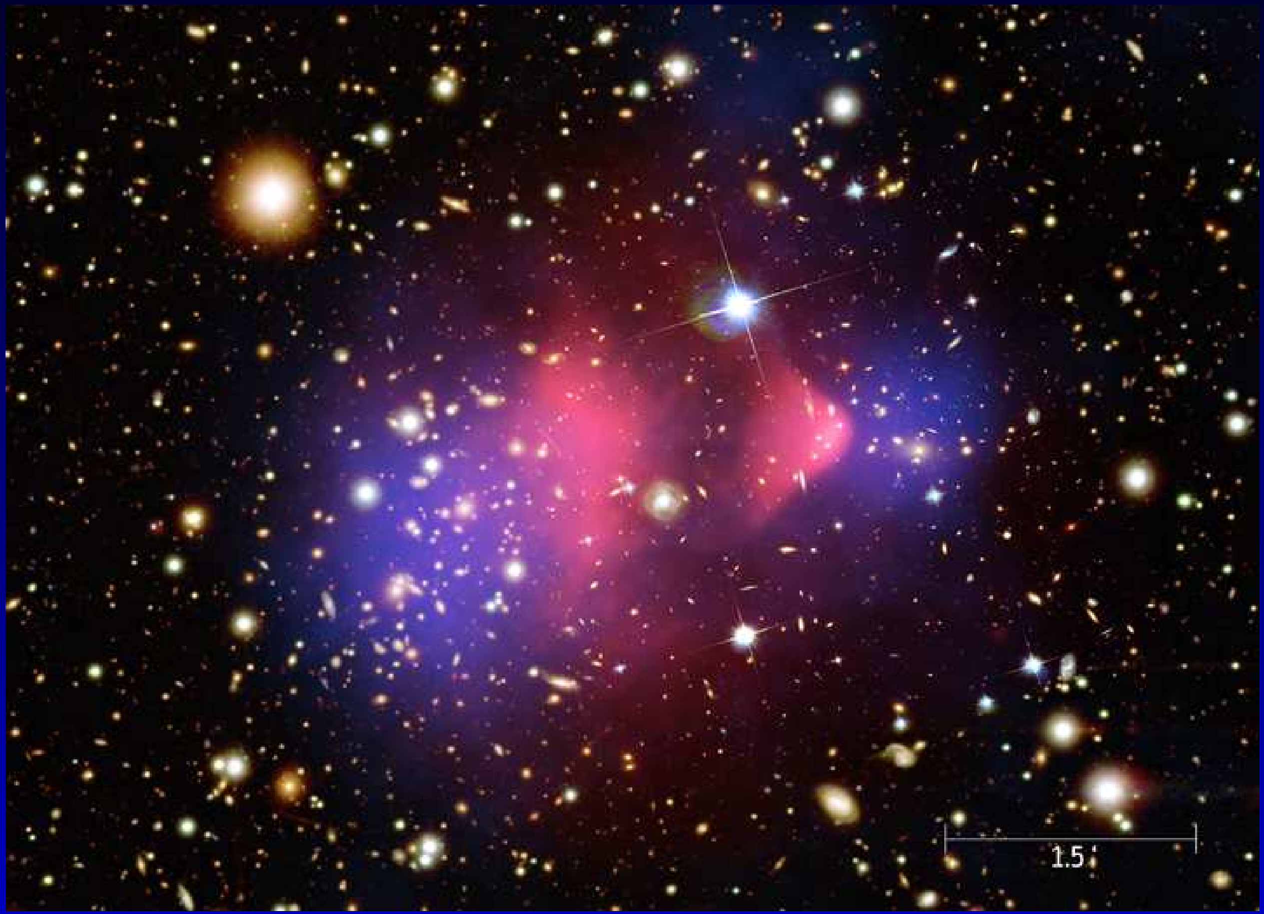
The Bullet cluster:
Where the mass is

The Bullet cluster:
Where the mass is



The Bullet cluster

The Bullet cluster



The Global picture

Alternative view

- Surprisingly good for galaxies.

Alternative view

- Surprisingly good for galaxies.
- Consistent with PIONEER anomaly

Alternative view

- Surprisingly good for galaxies.
- Consistent with PIONEER anomaly
- Relativistic formulation now exists (TeVeS)

Alternative view

- Surprisingly good for galaxies.
- Consistent with PIONEER anomaly
- Relativistic formulation now exists (TeVeS)
- Needs dark matter on cluster scales ($m_\nu \sim \mathrm{few} \quad \mathrm{eV}$?)

Dark Matter: Summary

- Evidences for dark matter are huge!

Dark Matter: Summary

- Evidences for dark matter are huge!
- Visible matter is less than 1%

Dark Matter: Summary

- Evidences for dark matter are huge!
- Visible matter is less than 1%
- most baryons should be dark (gas ?)