Dark Matter I

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References And Credits

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- L. Bergstrom, Rep.Prog.Phys. **63**(2000)793.
- G. Bertone et. al., Phy.Rep. **405**(2005)279.
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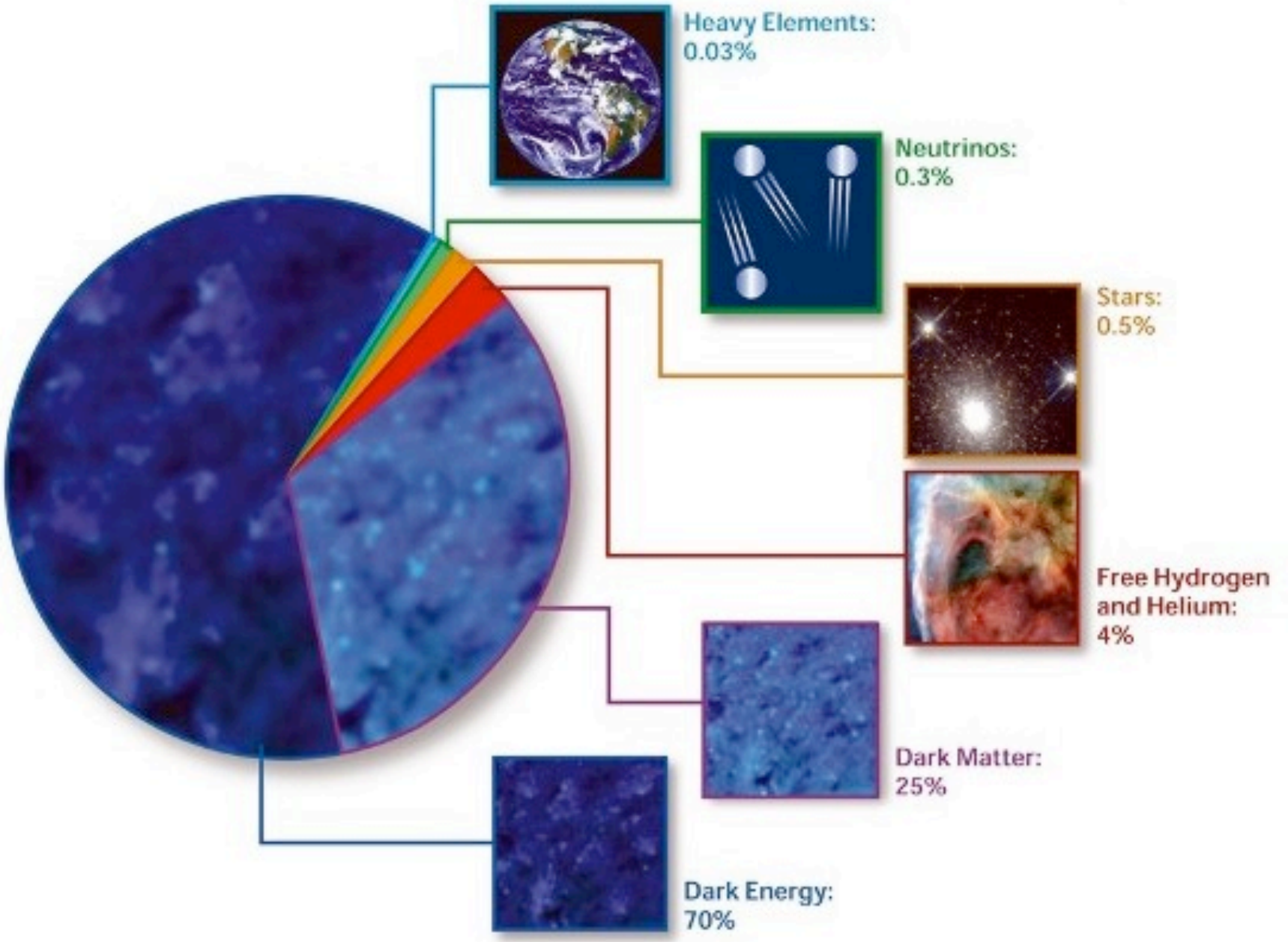
Composition of Present Universe

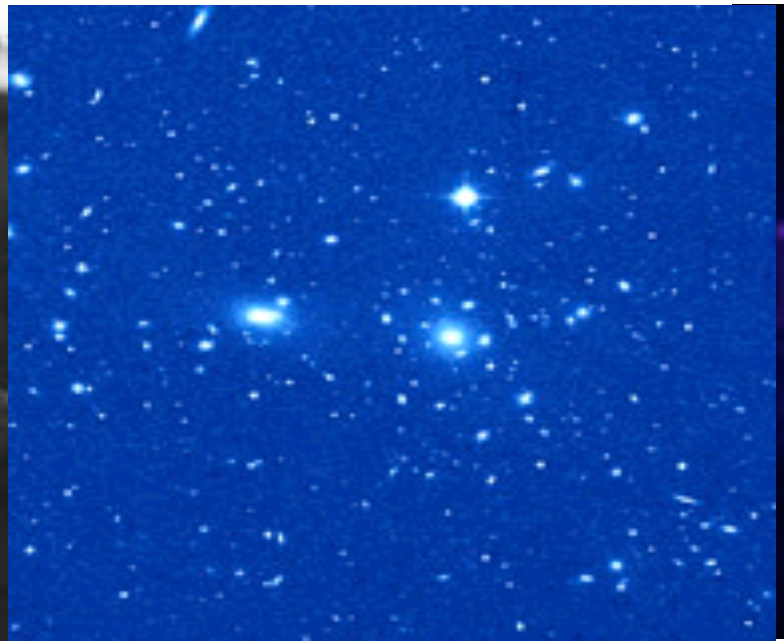


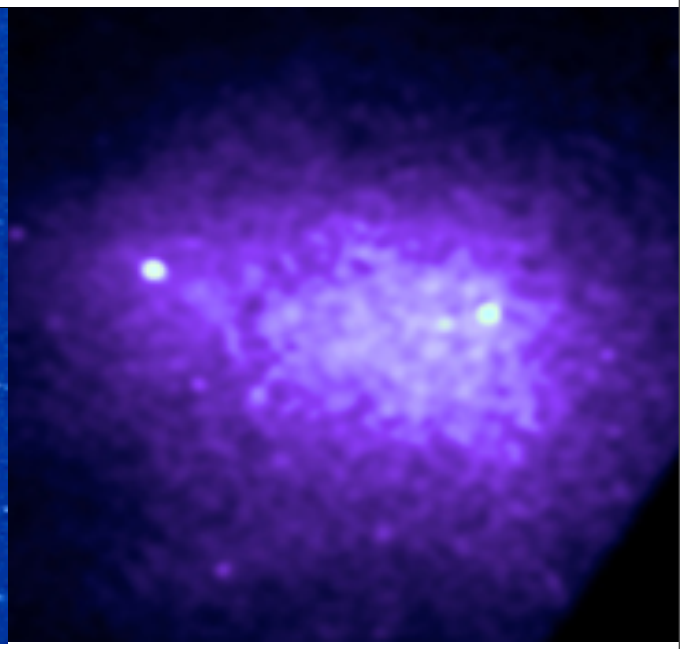
Evidence Of Dark Matter

Historic Evidence For Dark Matter

- Velocities in COMA (1937)
- Velocities in Local Group (1959)
- Galactic rotation curves (1970s)
- Studies of CMB (1980s)
- Gravitational weak lensing
- Crossing of galaxies (2006)

First Evidence of Dark Matter





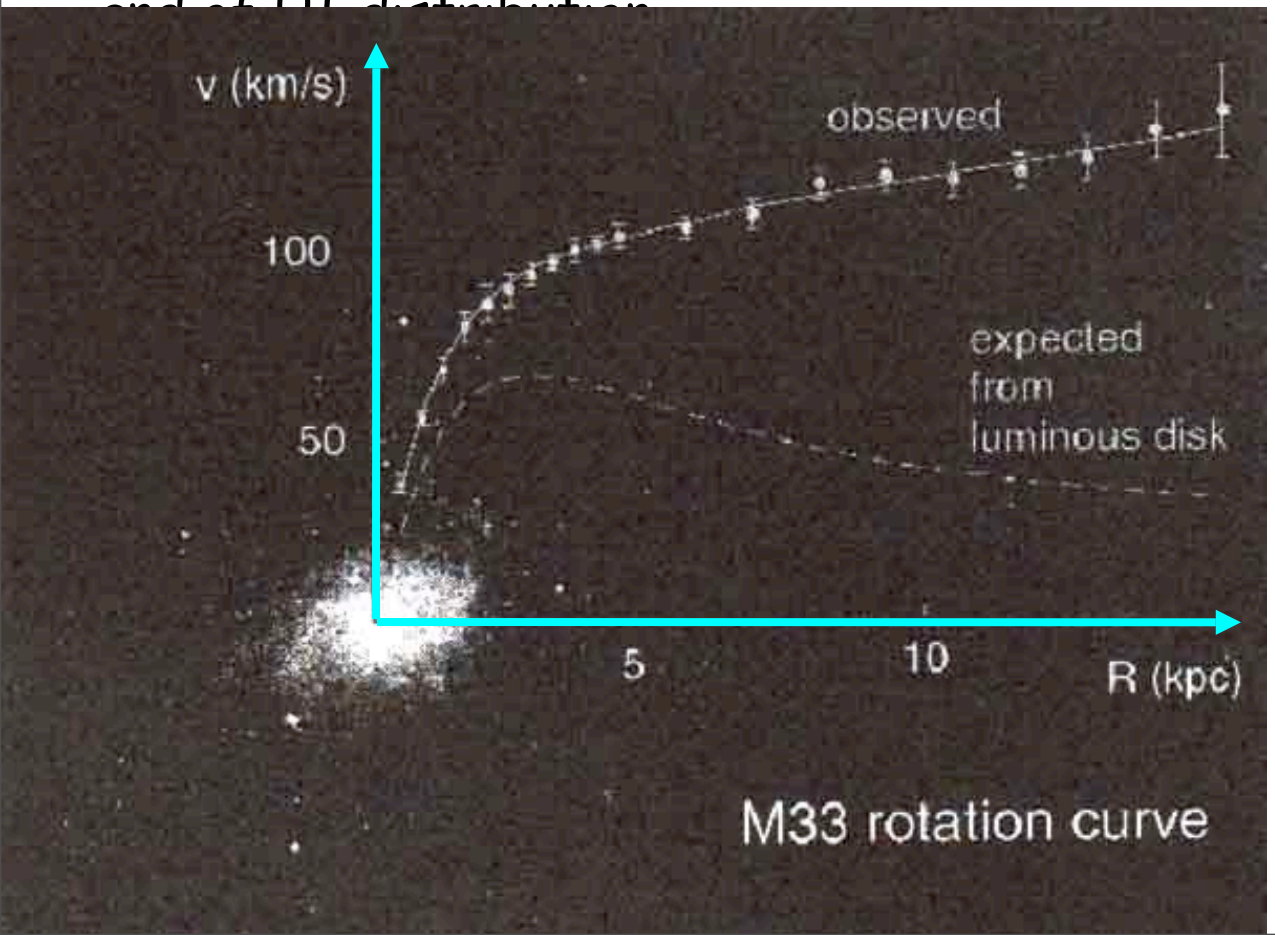
- Fritz Zwicky measured the mass of 8 galaxies in the COMA Cluster in 1937.
- Light from COMA suggested that $M \sim 10^{13} M_o$
- Measured velocities, ~ 1200 km/s, implied $M \sim 5 \times 10^{14} M_o$, 50 times more massive than expected [ApJ **86**, (1937) 217].

Evidence From Galactic Rotation Curves

- The velocity of a rotating galaxy is

$$\frac{v_{rot}^2}{R} = \frac{GM(R)}{R^2}$$

- Measured v_{rot} by the Doppler shift of star light and of HI distribution



Vera Rubin (1974)

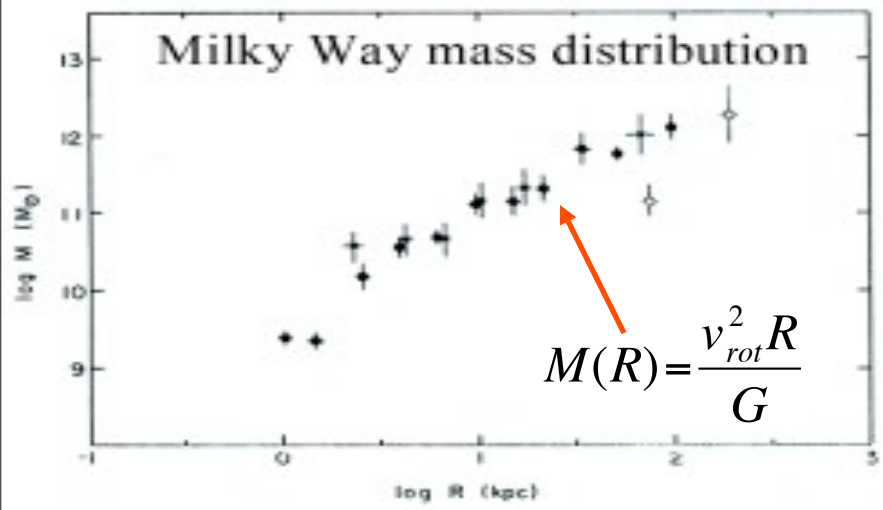
Found:

- M increases linearly with R for R > ~5 kpc.
- For large R, halos of some galaxies even overlap.
- $M_{halo} > 10 \times (M_{lum} + M_{gas})$

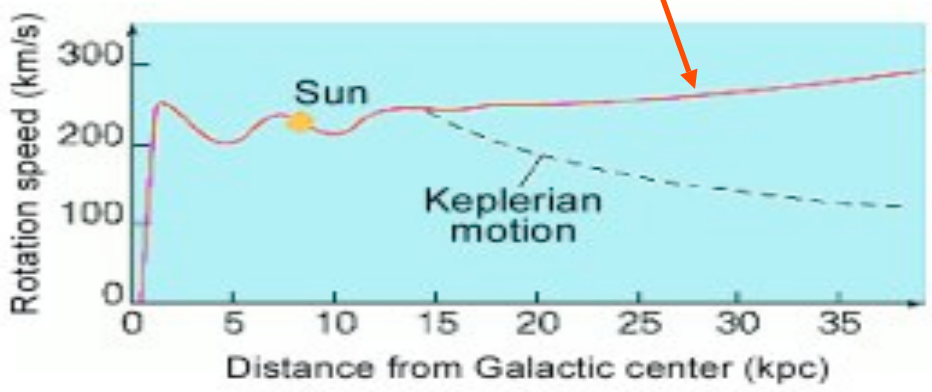
DARK MATTER IN MILKY WAY

From 2MASS two Micron All Sky Survey:

only 5-10% of matter visible!



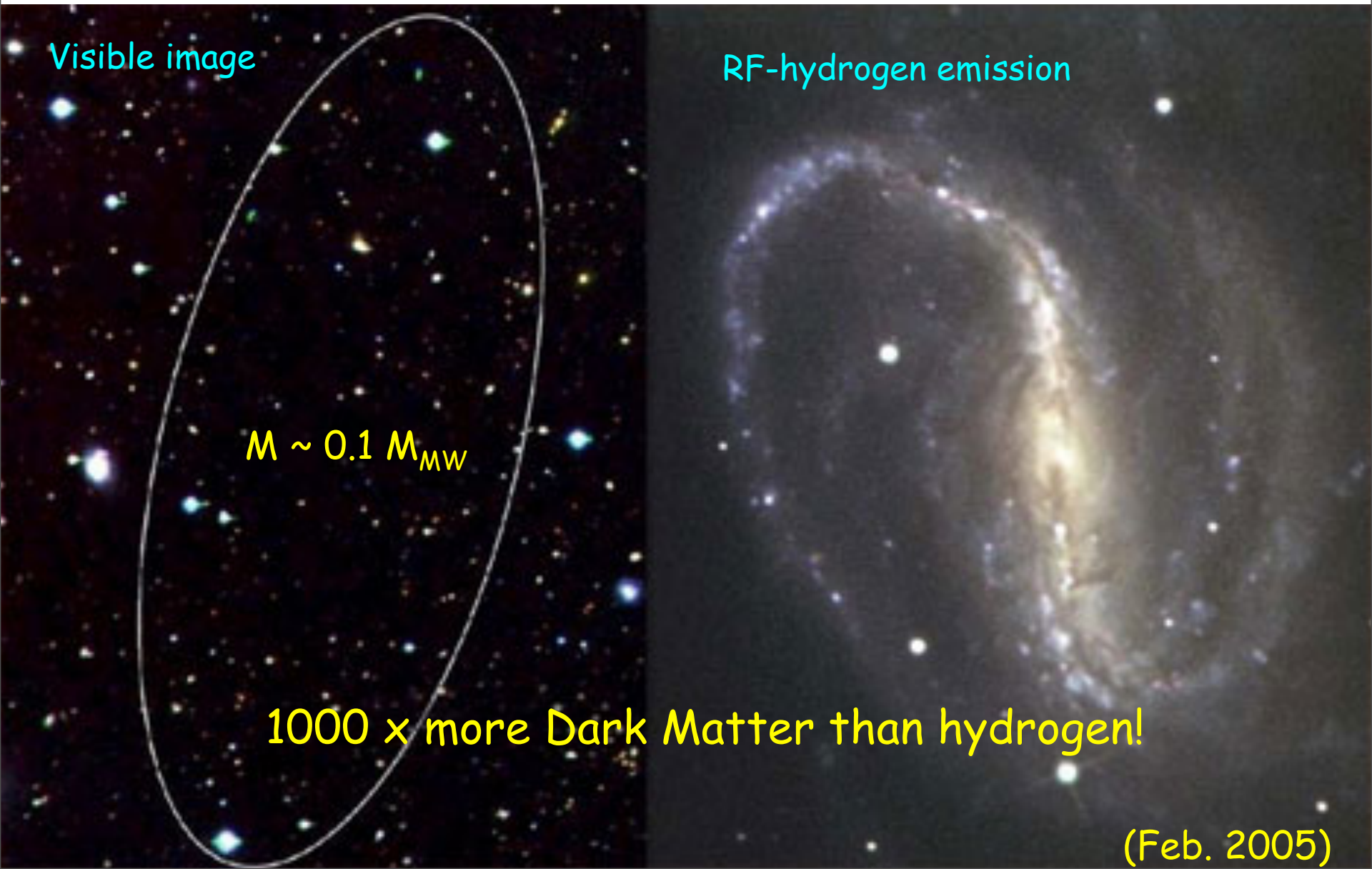
Mass increases up to 200 kpc



Schematic flat rotation curve for the Milky Way galaxy

1kpc = 3.259 x 10^3 Ly

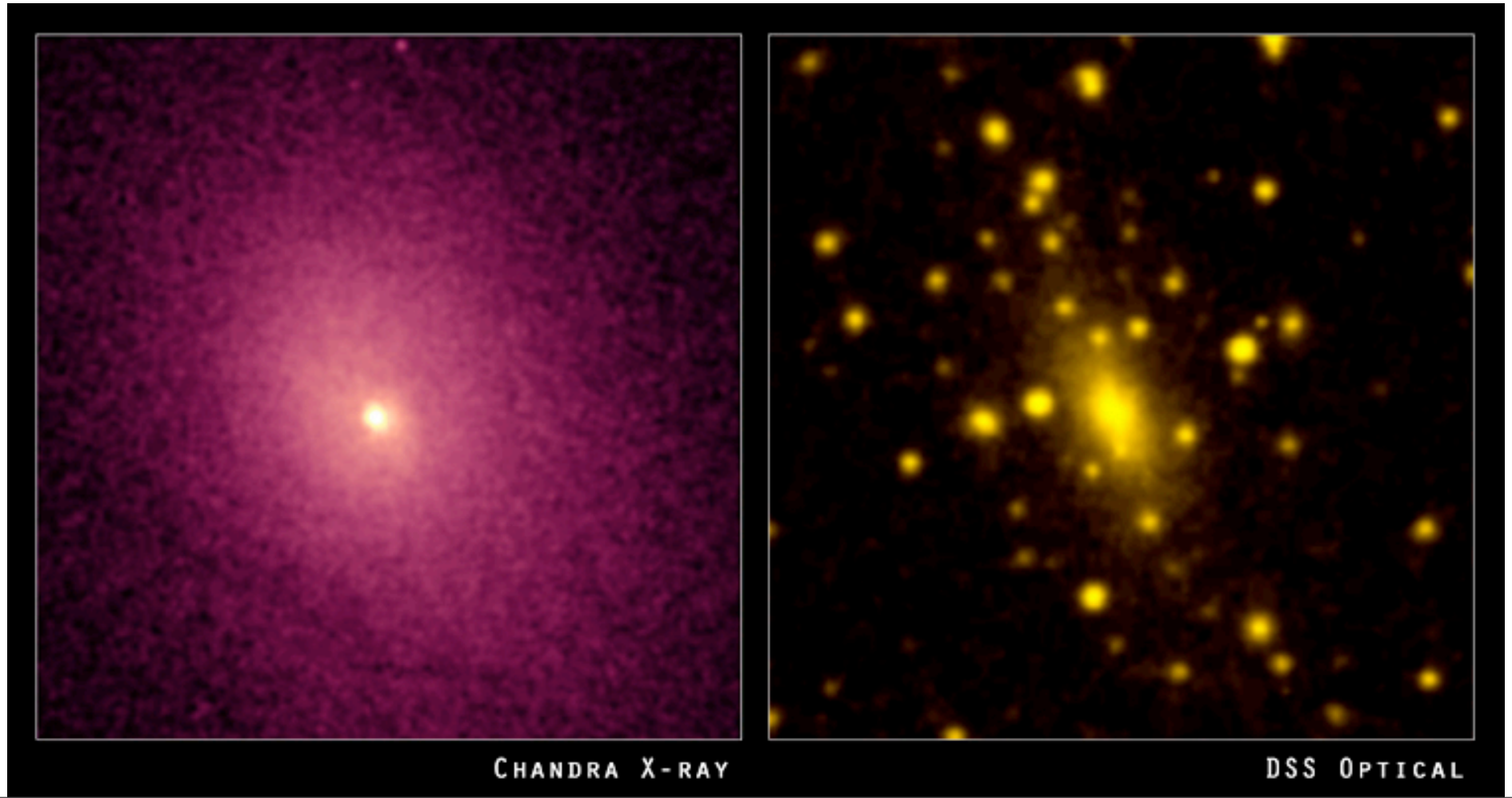
VIRGO HI21: A GALAXY OF DARK MATTER !



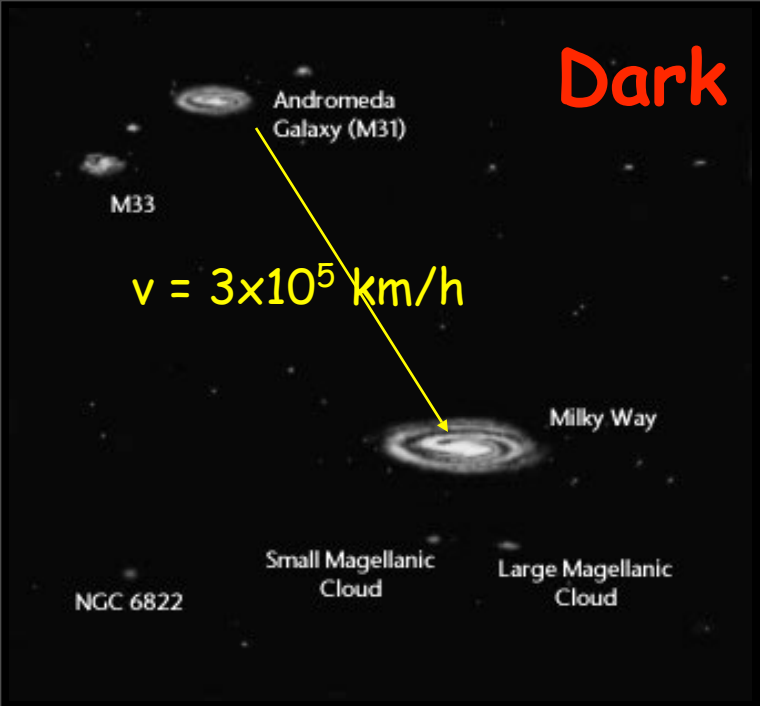
DARK MATTER AROUND OTHER GALAXIES

Abell 2029:

- A cluster of thousands of galaxies surrounded by gigantic clouds of hot gas, T~ 10^6 K.



Dark Matter At Larger Scales



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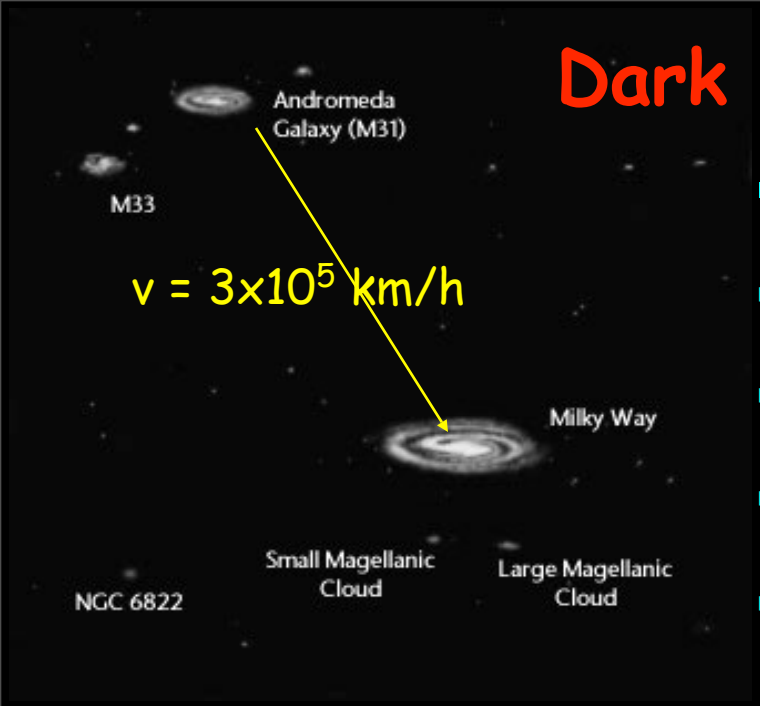
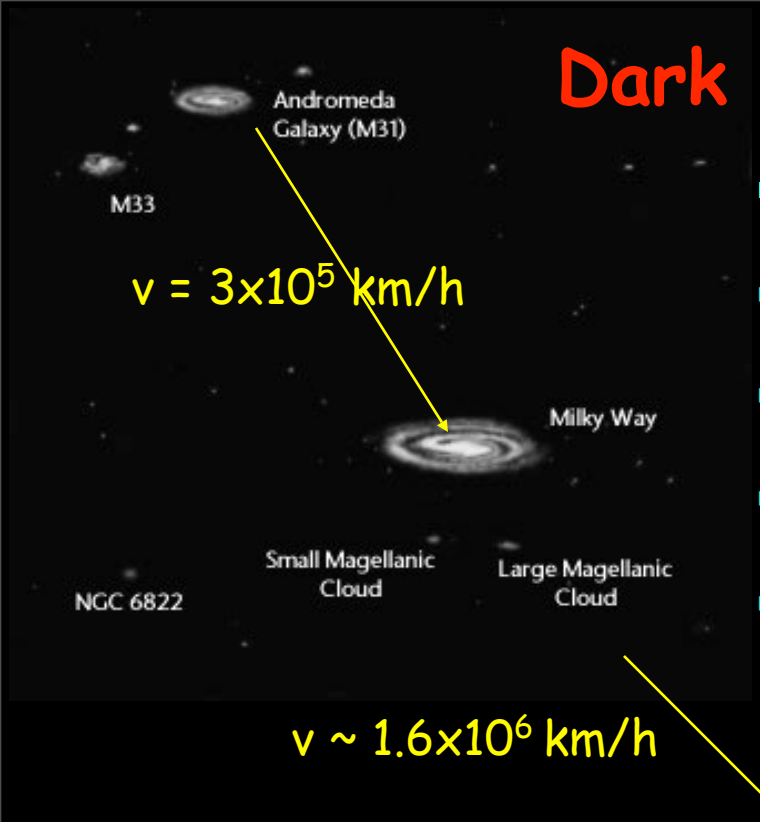


- Size of Local group: 2.2 MLy
- Milky Way & M31 dominate Local Group
- Enormous gravit. pull between the two galaxies
- Invisible mass > 10 x M_{MW}
- Local Group at the fringe of Virgo cluster

Dark Matter At Larger Scales



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v ~ 1.6x10^6 km/h

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v ~ 1.6x10^6 km/h

- Size of Virgo cluster 50 MLy
- Local group pulled towards Virgo cluster
- Invisible mass > 10 x M_{vis}

Dark Matter At Larger Scales

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v ~ 1.6x10^6 km/h

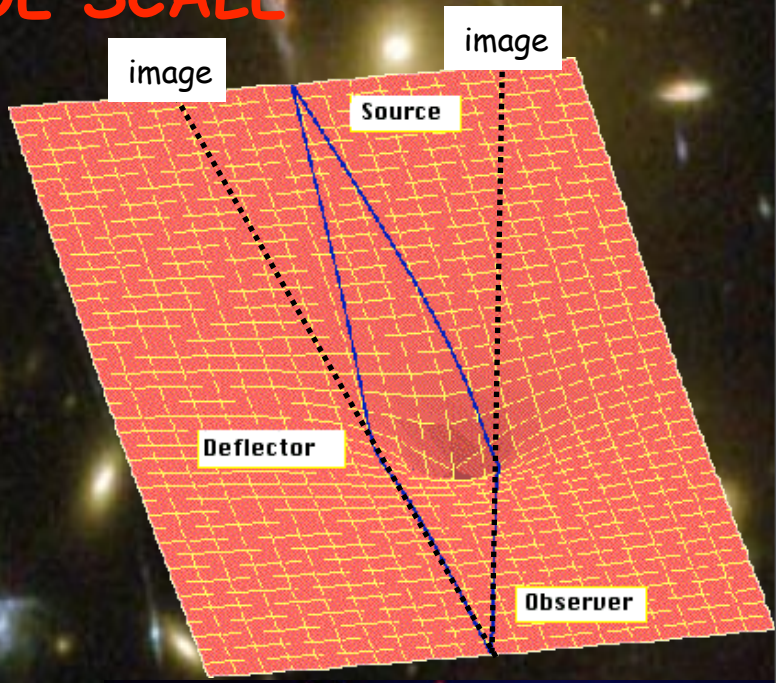
- Size of Virgo cluster 50 MLy
- Local group pulled towards Virgo cluster
- Invisible mass > 10 x M_{vis}

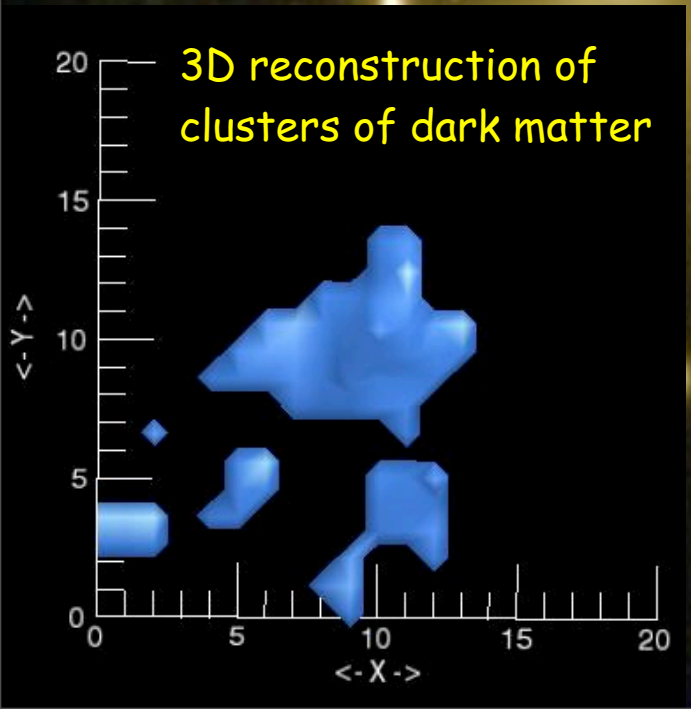
v ~ 2 x 10^6 km/h

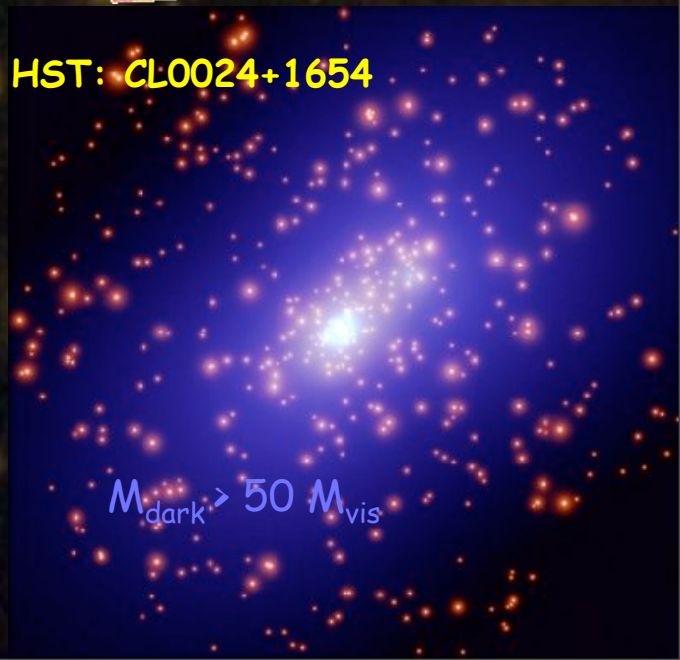
Virgo Cluster is pulled towards an invisible "Great Attractor"

DARK MATTER AT LARGE SCALE

Gravitational lensing provides evidence of large masses between



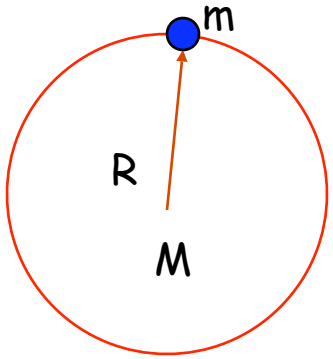





IE0657-56 : THE BULLET CLUSTER (3.4 x 10⁹ LY)
Gas: x-ray
Dark matter: lensing
$M_{dm} \sim 50(M_{vis} + M_{gas})$
M. Markewitch et al (August 2006) : data gathered with HST, Magellan, Chandra

How much Dark Matter in the Universe ?

Dynamics Of The Universe



M = mass of the Universe

R = radius of the Universe

m = mass of a galaxy at R

- From Newtonian mechanics:

$$E_{kin} = \frac{m}{2}\dot{R}^2 \qquad E_{pot} = -G\frac{mM}{R}$$

- Include the potential energy of the vacuum:

$$E^{v}_{pot} = -G\frac{m}{R}(\rho_v \frac{4}{3}\pi R^3)$$

With energy density of vacuum $\rho_v = c^2\Lambda/8\pi G$

Λ = cosmological constant

- The total energy of the system:

$$E_{kin} + E_{pot} = E_{tot}$$

$$\rightarrow \quad \frac{m}{2}\dot{R}^2 + (-\frac{GMm}{R} - \frac{1}{6}m\Lambda c^2 R^2) = E_{tot}$$

Dynamic Of The Universe (Cont.)

- E_{tot} depends on the geometry of space.
- From Einstein's equation:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

implies

$$\frac{m}{2}\dot{R}^2 + \left(-\frac{GMm}{R} - \frac{1}{6} m\Lambda c^2 R^2\right) = E_{tot} = -k\frac{mc^2}{2}$$

where k is the curvature of space:

k < 0 (open)

k = 0 (flat)

k > 0 (closed)

- The force acting on the galaxy is:

$$F = -\frac{dE_{pot}}{dR} = -G\frac{Mm}{R^2} + \frac{1}{3} m\Lambda c^2 R$$

attractive repulsive

Hubble's Law And Critical Density

- Substitute the Hubble's law

$$\dot{R}(t) = H(t)R(t)$$

H(present) = H_0 = 71 km s^{-1}Mpc^{-1}

into

$$\frac{m}{2}\dot{R}^2 + \left(-\frac{GMm}{R} - \frac{1}{6}m\Lambda c^2R^2\right) = E_{tot} = -k\frac{mc^2}{2}$$

and yields

$$\boxed{\left(\frac{\dot{R}}{R}\right)^2 = H(t)^2 = \left[\frac{8\pi}{3}G(\rho + \rho_V) - \frac{kc^2}{R^2}\right]}$$

Friedmann equation

$\rho_v = c^2\Lambda/8\pi G$

- For Λ = 0, the critical density of the Universe is defined as

$$\boxed{\rho_c = \frac{3H^2}{8\pi G}} \quad \Rightarrow \quad k = 0 \text{ (flat)}$$

More On Critical Density

$$\rho_c = \frac{3H^2}{8\pi G}$$

- At present, $\rho_c = 1.9 \times 10^{-26}$ kg/m^3 (~ 1 proton/m^3)
- Mass and energy parameters:

$\Omega_m = \rho_0/\rho_c$ $\Omega_\Lambda = \rho_v/\rho_c$

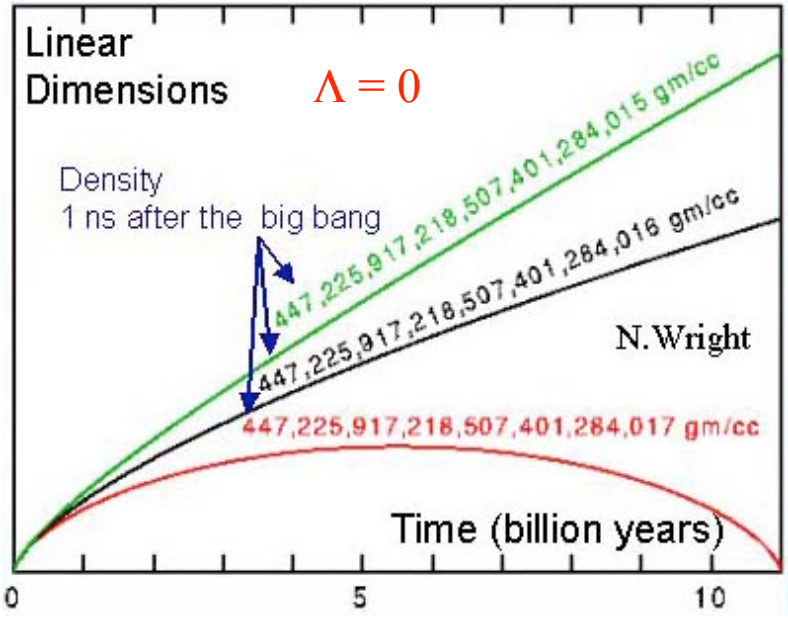
where ρ_0 is the present value.

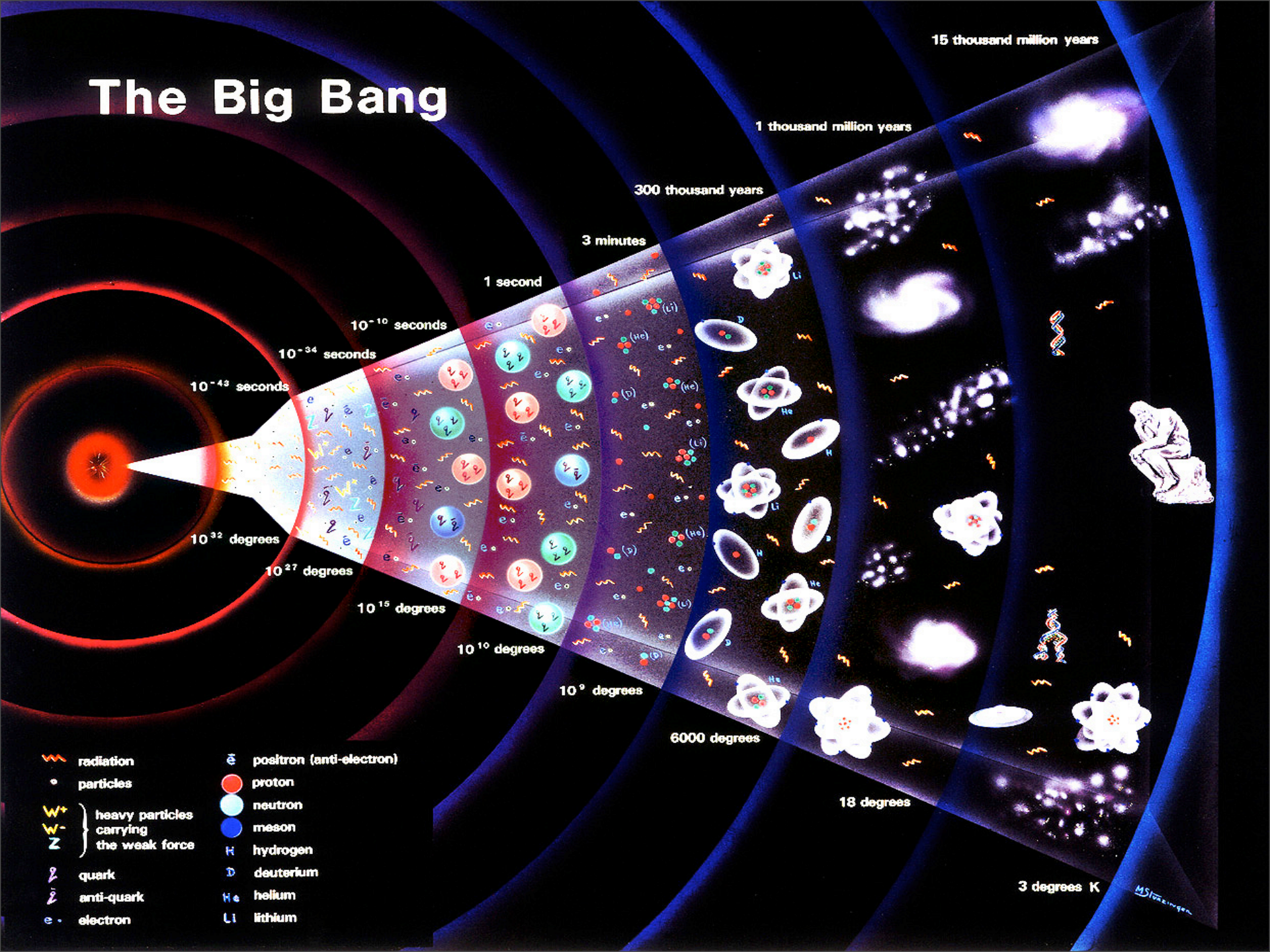
$$\Omega_{tot} = \Omega_m + \Omega_\Lambda$$

$\Omega_{tot} > 1$ closed Universe

$\Omega_{tot} < 1$ open Universe

$\Omega_{tot} = 1$ flat Universe




The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e- electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

Determining Ω_b

- From Big Bang nucleosynthesis:

$n + p \rightarrow D$

$p + D \rightarrow {}^3He$

$n + D \rightarrow T$

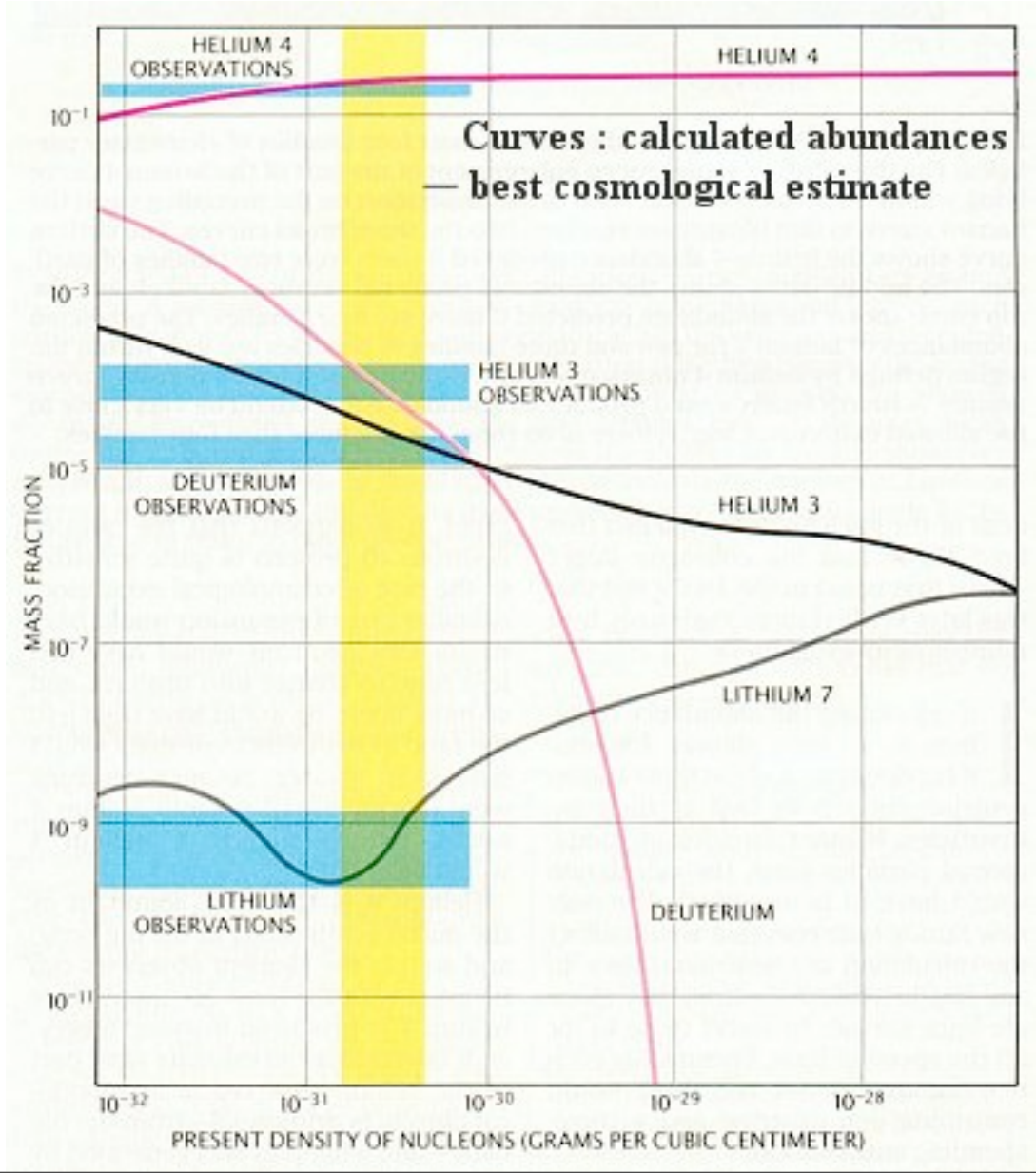
$T + p \rightarrow {}^4He$

${}^3He + n \rightarrow {}^4He$

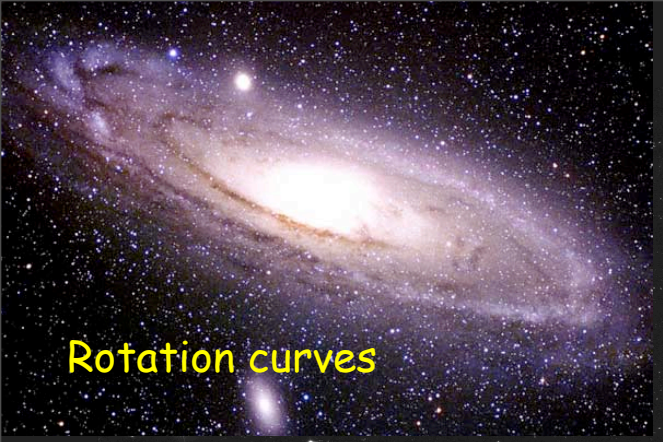
$D + D \rightarrow {}^4He$

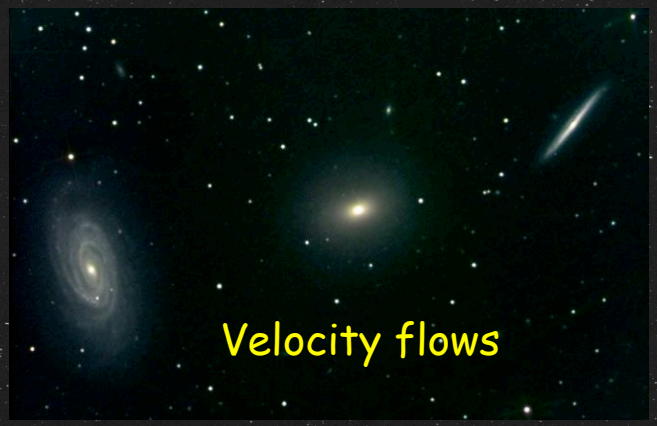
${}^4He + T \rightarrow {}^7Li$

- Heavier elements were formed at $t \sim 10^6$ yr.
- Get D/H from quasar absorption lines.
- $\Omega_b = 0.04 \pm 0.007$

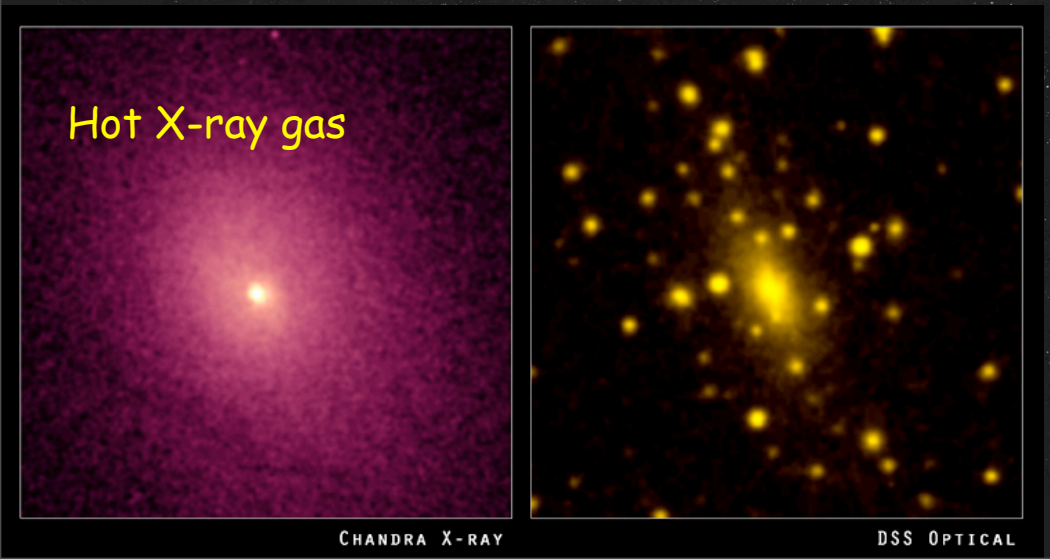


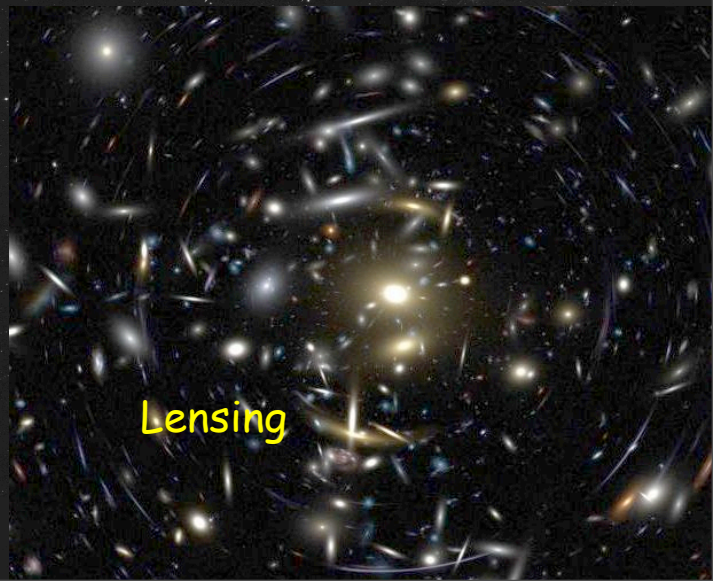
Determining Ω_m





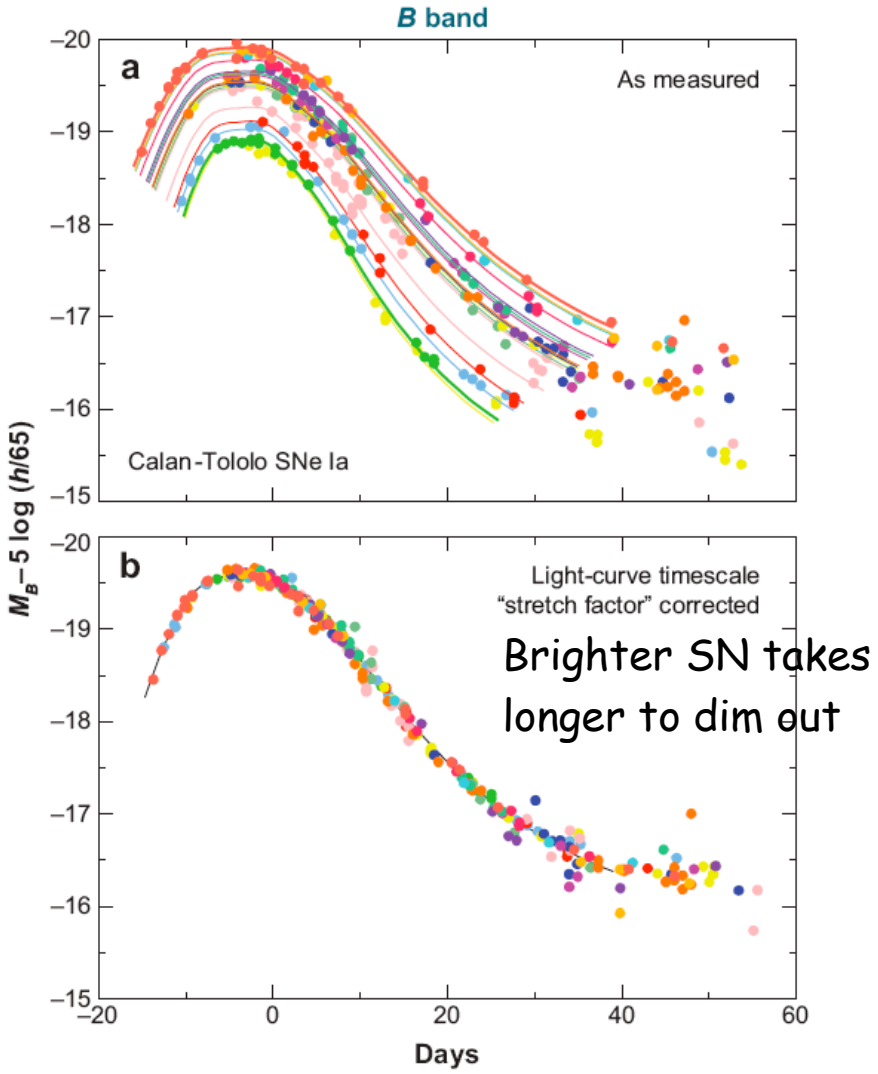
$\Omega_m \sim 0.2\text{-}0.3$



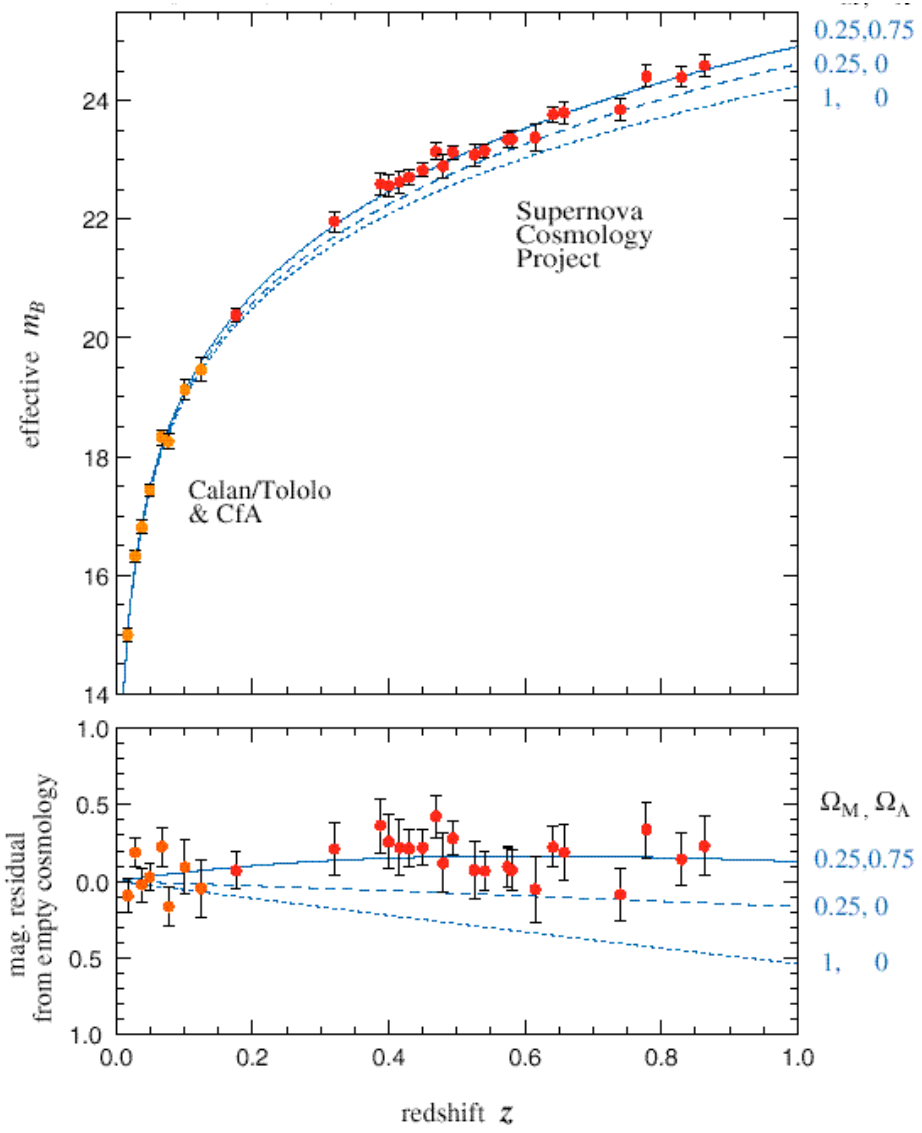


Evidence Of Ω_Λ

- From studying Type 1A supernovae as a function of

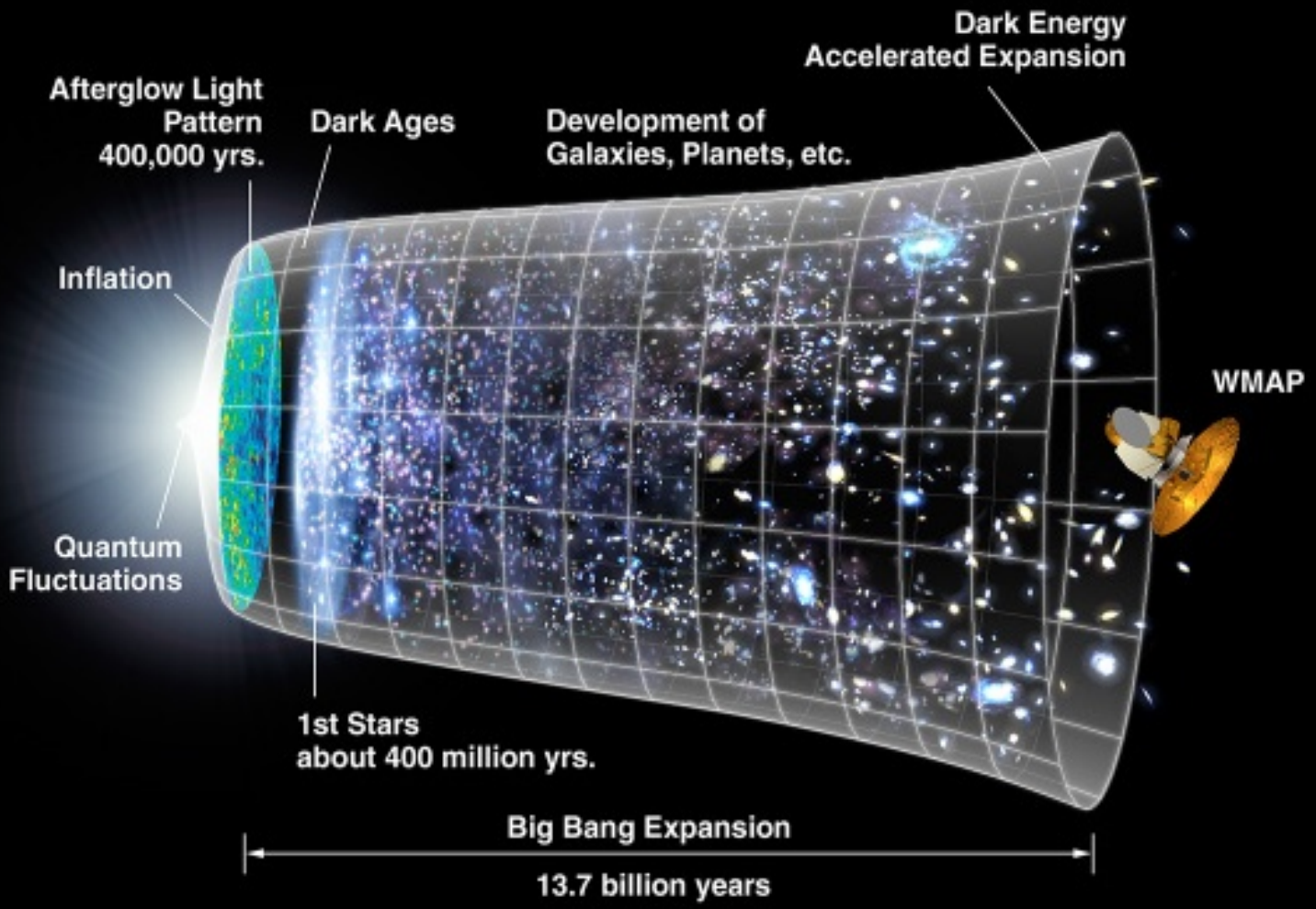


Brighter SN takes longer to dim out



$\Omega_m = 0.3, \quad \Omega_\Lambda = 0.7$

Ω_{tot} From Inflation Of The Universe

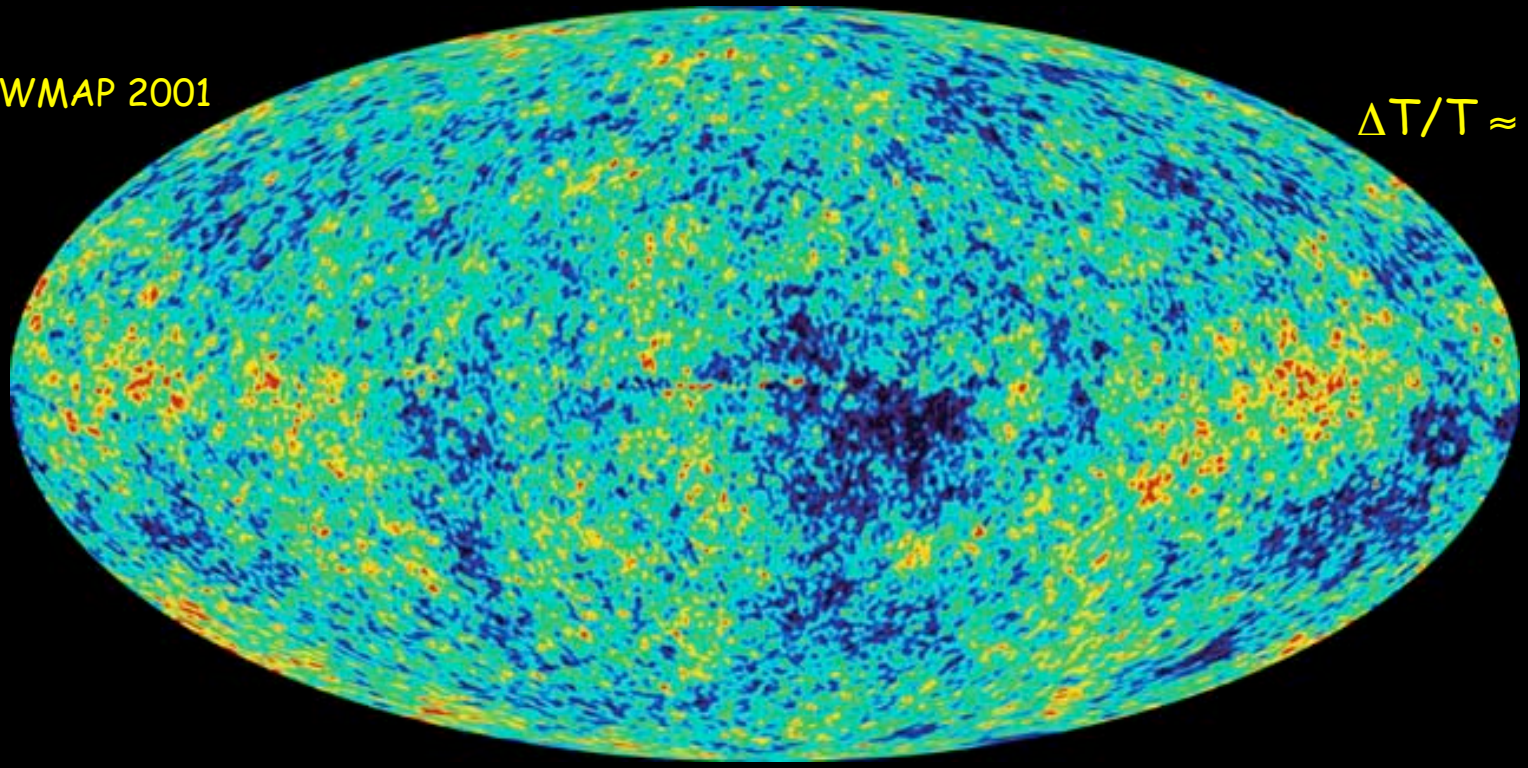


At $t \sim 10^{-35}$ s, the Universe inflated by 10^{50}, leading to a flat space:

$$\Omega_{tot} = 1$$

Anisotropy Of Cosmic Microwave Background

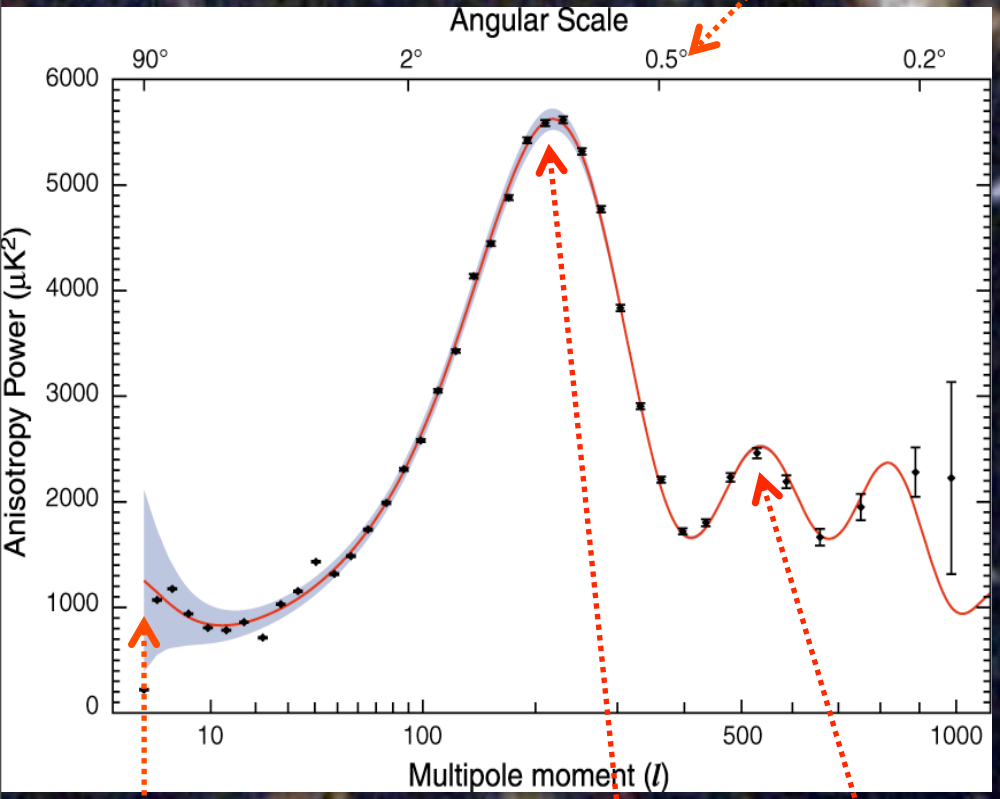
Image of early Universe imprinted on the temp. anisotropy of CMB



- 300 ky after Big Bang, photons decouple from matter: $T \approx 6000$ K
- Before decoupling: plasma oscill. of photon-baryon fluid generated sound waves
- CMB: snap shot of sound waves when rad. decoupled
- Today, light is red shifted by 1/1000, $T \approx 3$K
- Small $\Delta T/T$ implies visible Universe once causally connected $\rightarrow$ Inflation!

Expansion in spherical harmonics of CMB temp. field

Angular diameter of the moon



Multipole development ⇔ angular scale

l number of cycles in the sky

- $\theta = \pi / l$
- $l_{peak} = 200 / \sqrt{\Omega_{tot}}$
- $l_{peak} = 197 \pm 6$ (0.9^0)

Curvature of Universe: Ω_{tot}

"Cosmic variance"
(only one Universe)

Baryon density small: Ω_b

Summary of Results

WMAP Results:

$\Omega_{tot} = 1.02 \pm 0.02$

$\Omega_b = 0.04 \pm 0.004$

$\Omega_m = 0.27 \pm 0.04$

$\Omega_\Lambda = 0.73 \pm 0.04$

$H_0 = 71 \pm 4$ km/sec/Mpc

$T_0 = 13.7 \pm 0.02$ Gyr

Other :

Inflation : $\Omega_{tot} = 1$

BBN: $\Omega_b = 0.039$

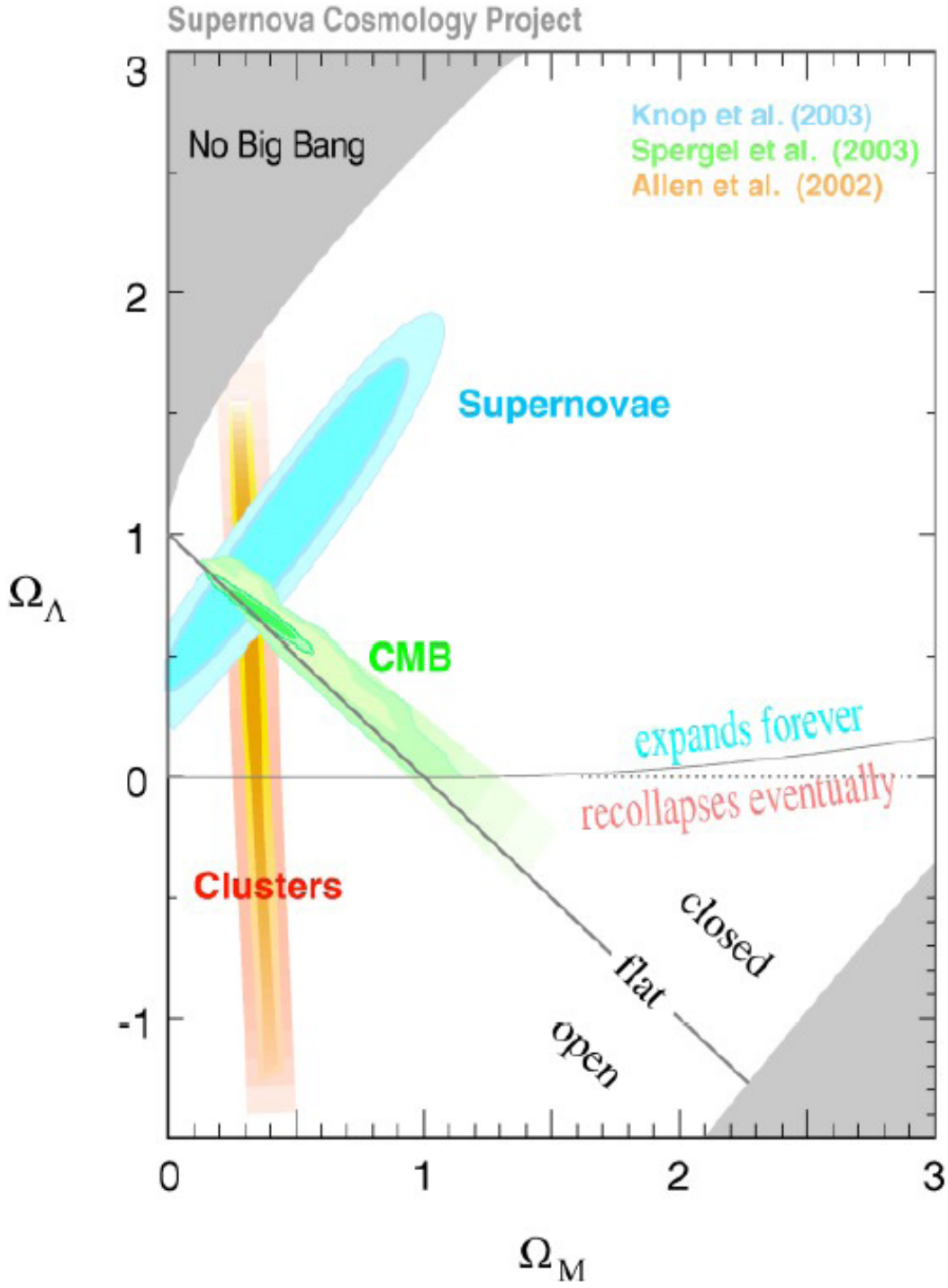
clusters of galaxies, lensing

hot x-ray gas : $\Omega_m = 0.3$

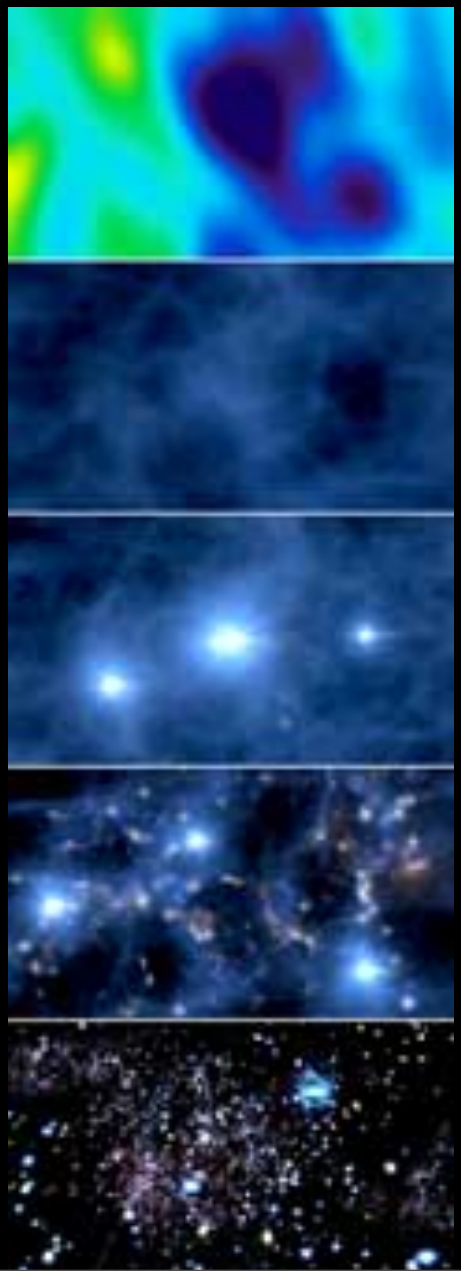
SN1a –redshift : $\Omega_\Lambda = 0.7$

Hubble: $H_0 = 72 \pm 4$ km/sec/Mpc

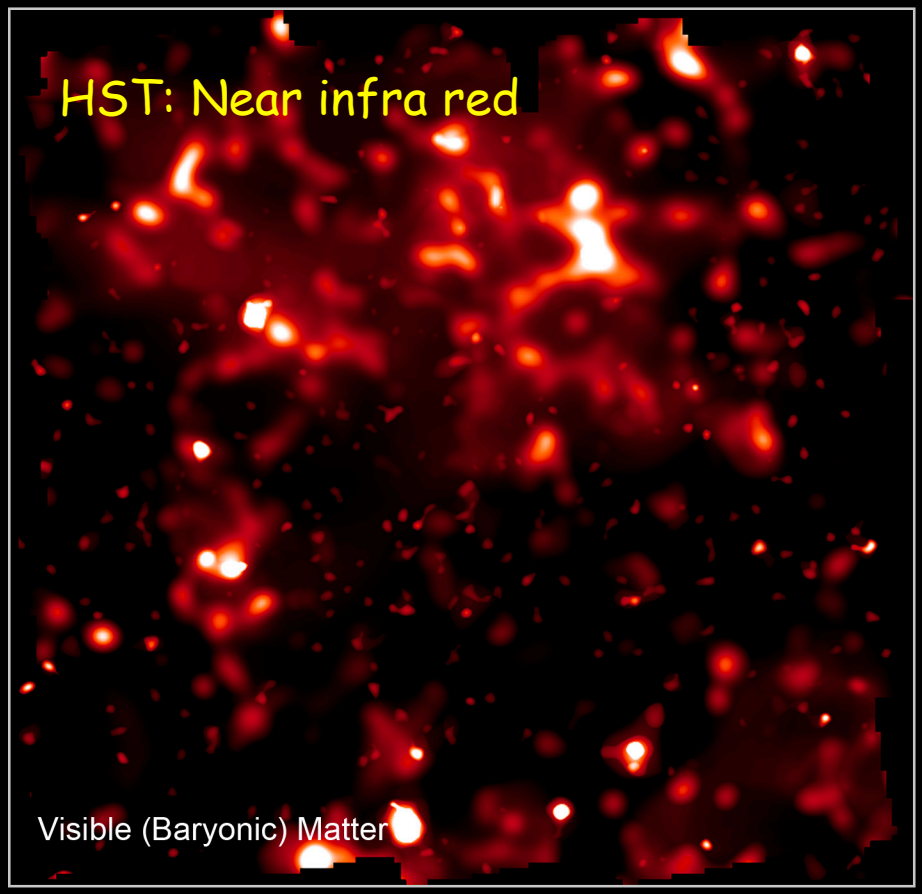
Hubble: 11 Gyr

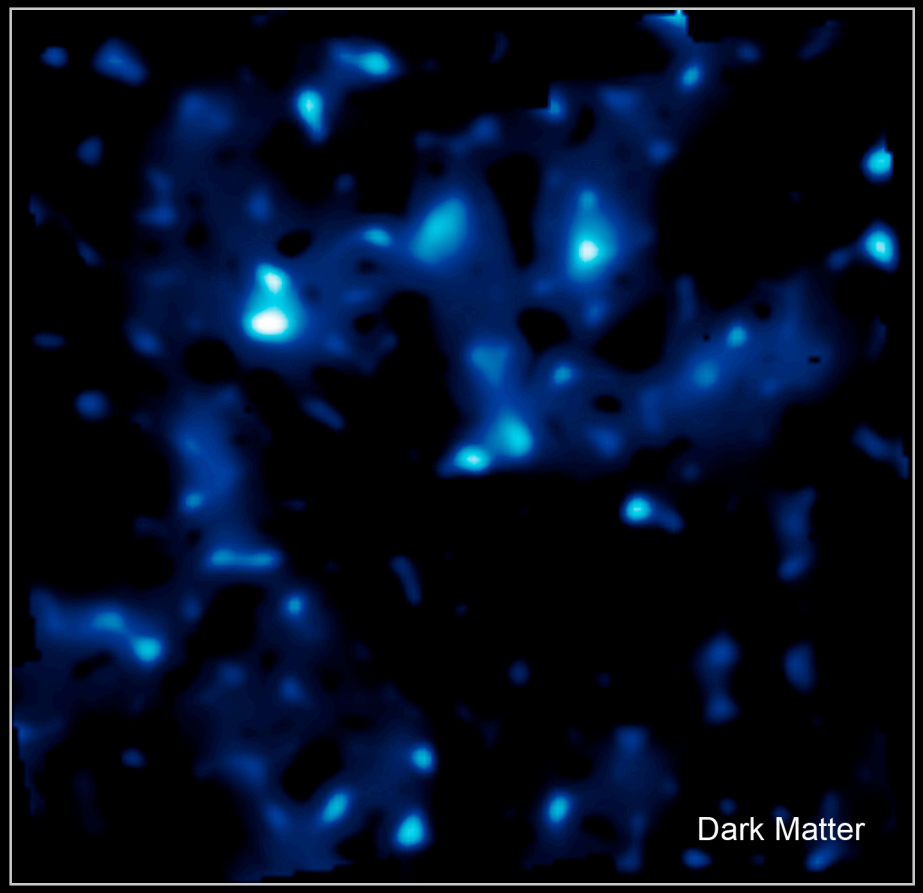

Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

Dark Matter: Development of Structure



- Big Bang created dark matter and ordinary matter
- Dark matter decoupled early
- Dark matter formed clumps
- Ordinary matter flowed in
- Galaxies formed and thus trace

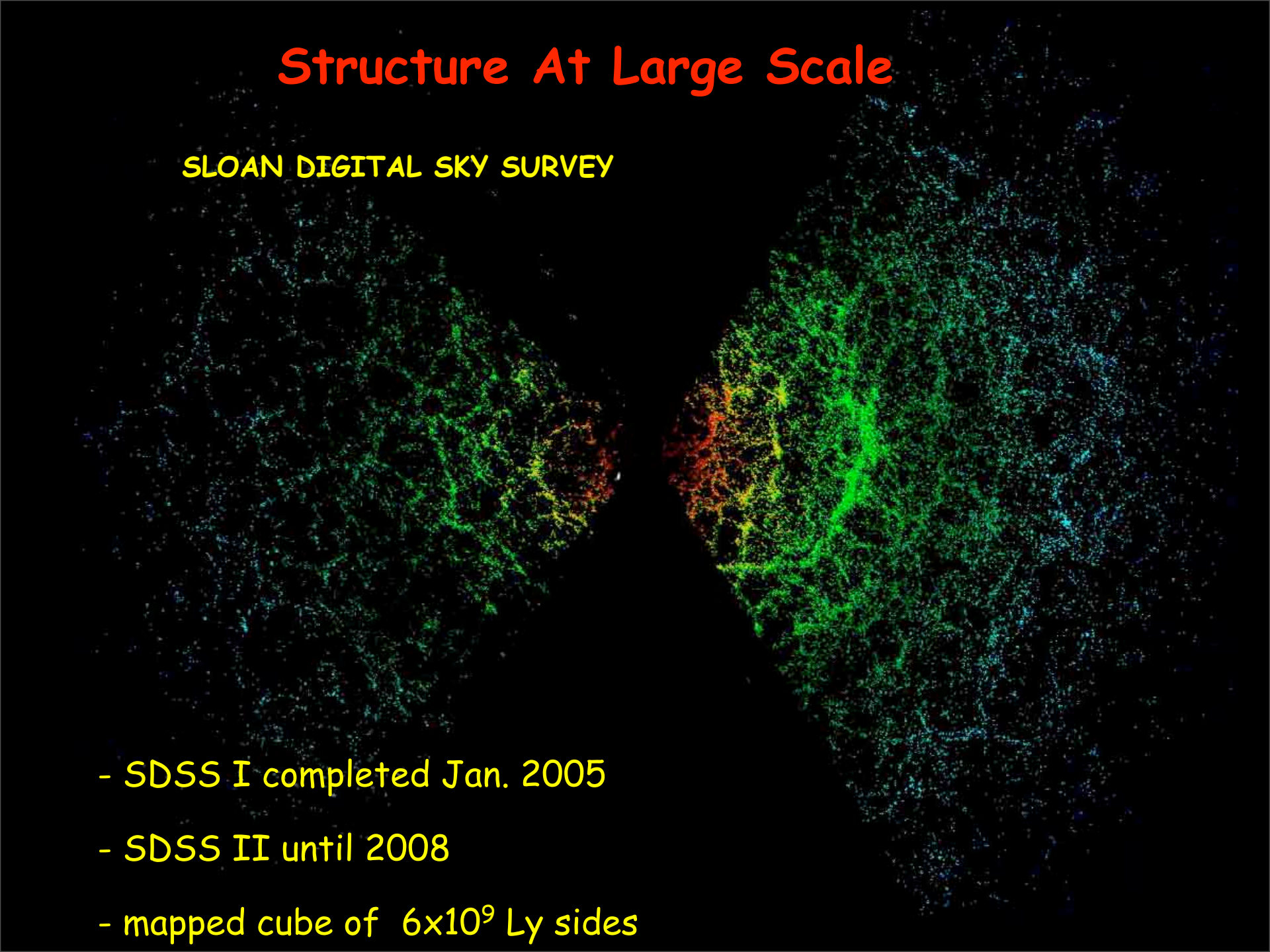




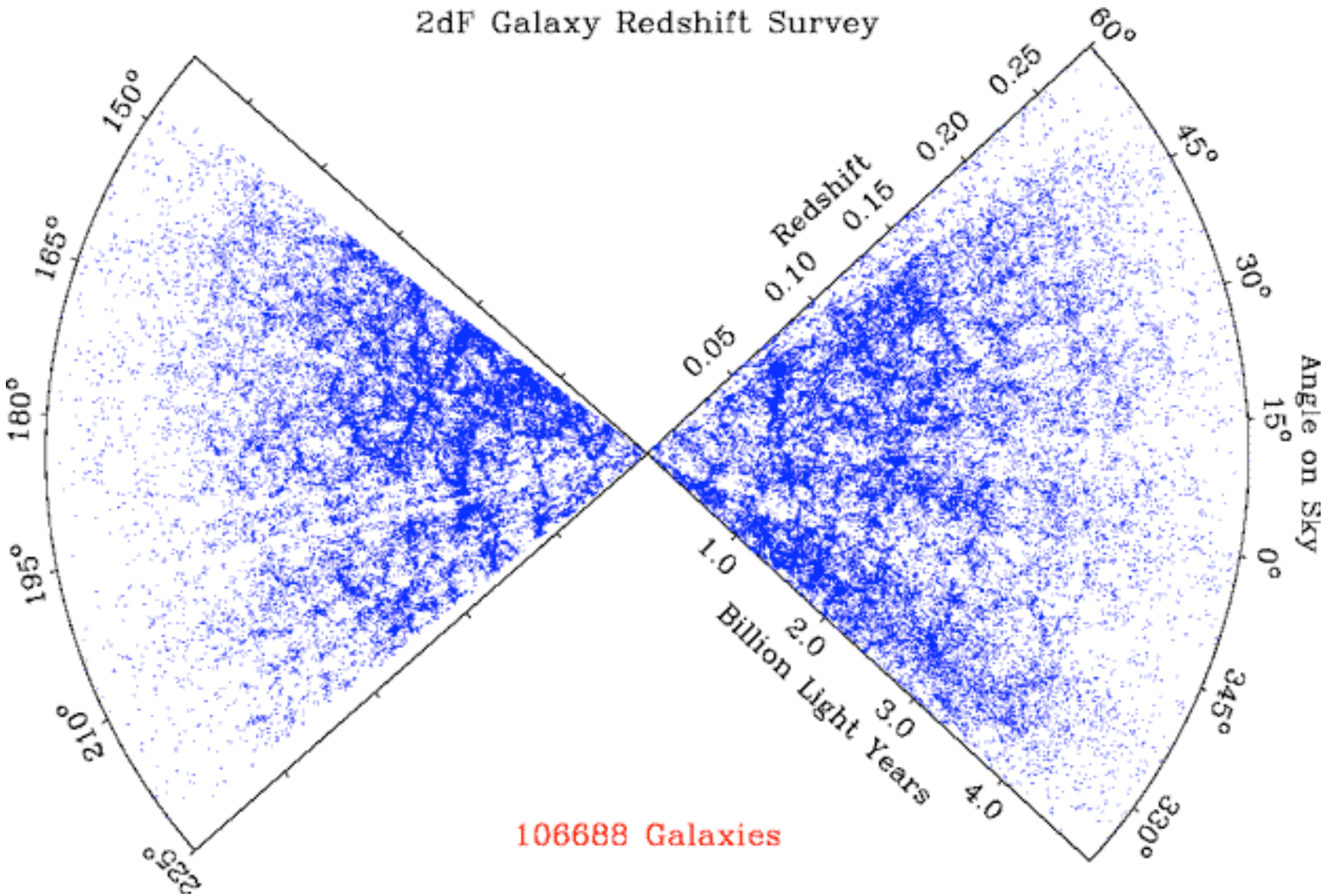
Dark matter is six times more abundant than ordinary matter

Growing clumpiness of Dark matter & ordinary matter flowing in

Structure At Large Scale

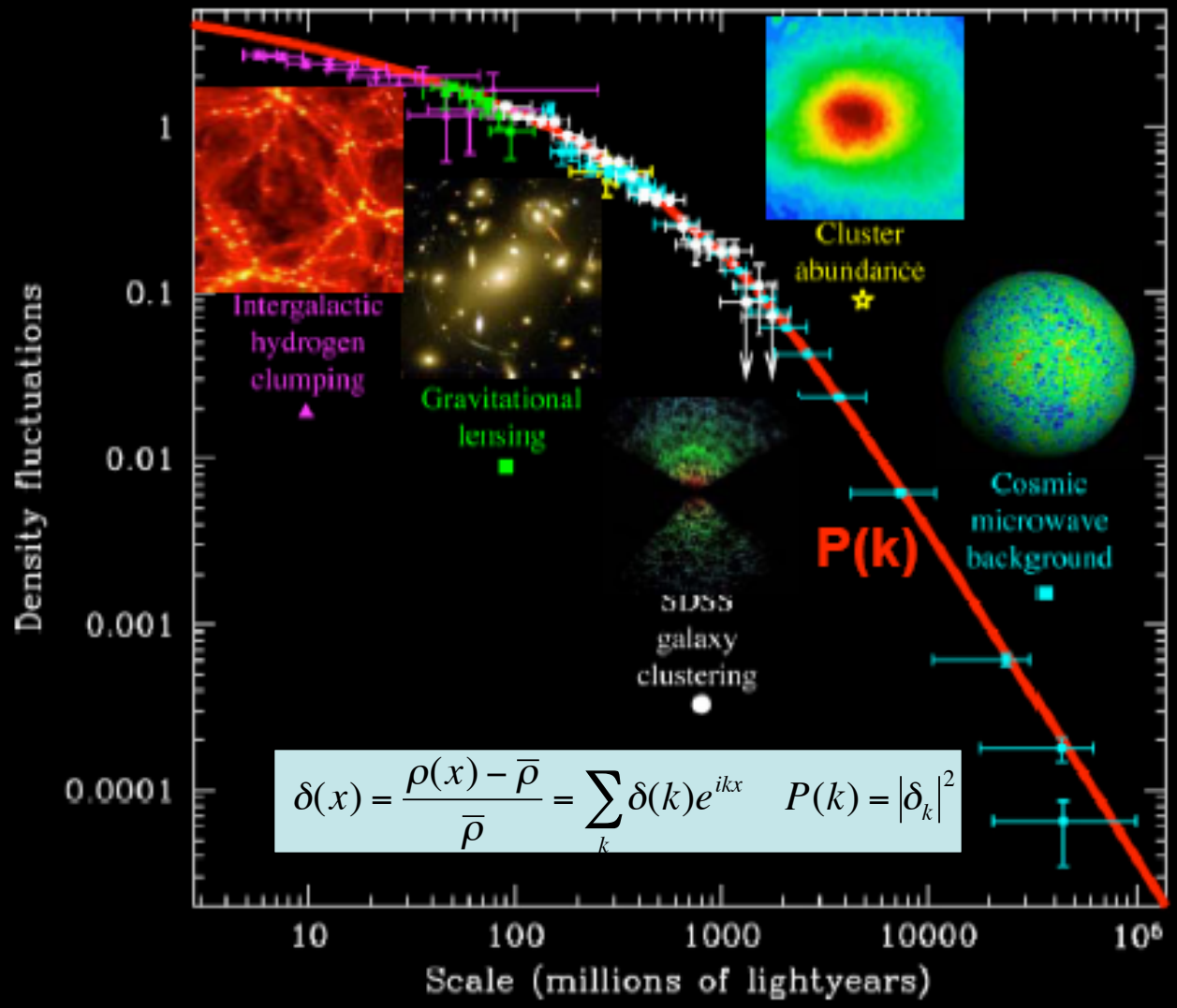


- SDSS I completed Jan. 2005
- SDSS II until 2008
- mapped cube of 6×10^9 Ly sides



Any structure formed by ordinary matter from Big Bang nucleosynthesis would be thinned out by expansion.

Ω Parameters From Large-scale Structure



Best fit:

$\Omega_b = 5\%$

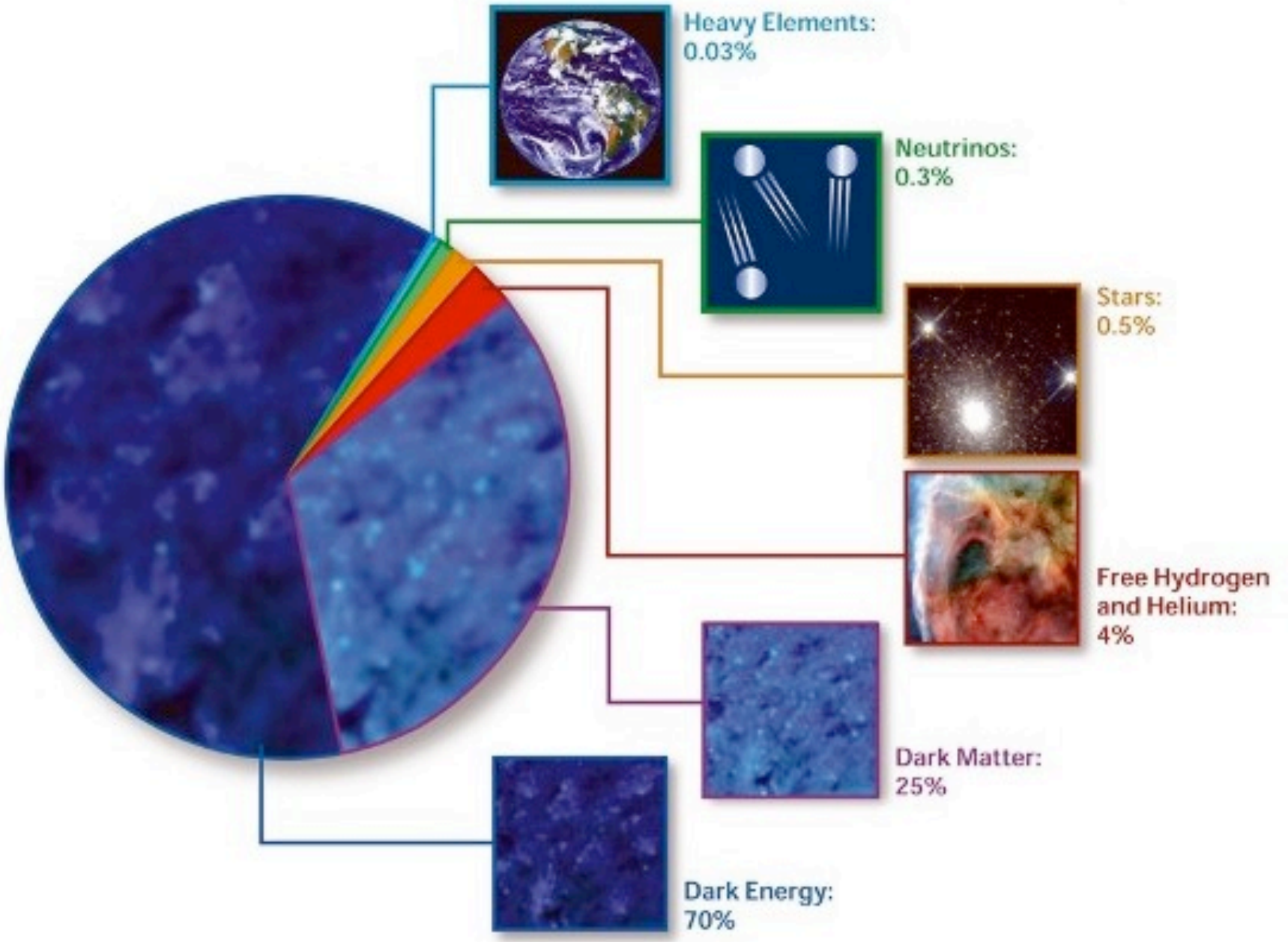
$\Omega_{dm} = 25\%$

$\Omega_\Lambda = 70\%$

Max Tegmark

The larger the scale we average the more uniform the Universe becomes!

Composition of Present Universe



Summary

- There are compelling evidences that dark matter exists.
- Dark matter makes up about 23% of the contents of the present Universe.
- Dark matter plays a key role in the evolution of the Universe
  - Provides the seed to form structures
  - Prevents dark energy from tearing the structures of baryonic matter apart
- But, what is the nature of dark matter?