The case for Dark Matter

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DESY
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Outline

- Introduction & global evidence
- Dark Matter: local evidence
- Dark Matter and perturbations
- Dark Matter: particle properties
- Outlook

Introduction

Einstein's legacy: Energy is Geometry

$$\boxed{\mathcal{R}^{\nu}_{\mu} - \frac{1}{2}\delta^{\nu}_{\mu}\mathcal{R} \; = \; 8\pi G_N \, T^{\nu}_{\mu} + \Lambda\delta^{\nu}_{\mu}}$$

Einstein's Tensor:
Geometry of Space-time

Energy-momentum Tensor:
ALL the Physics content

The birth of Cosmology as a science:
the Universe's dynamics and fate is determined
by its Energy (Particle) content,
both the known and the unknown....

Standard Cosmology

Cosmological Principle (nowadays also experimental result...):

The Universe is homogeneous and isotropic
on large scales (i.e. larger than ~100 Mpc)

It is described by the Friedmann-Robertson-Walker Metric:

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-\kappa r^2} + r^2 d\Omega\right)$$

- Only one dynamical variable: the scale factor $a(t)$
- One constant parameter: the spatial curvature κ

Friedmann equation:

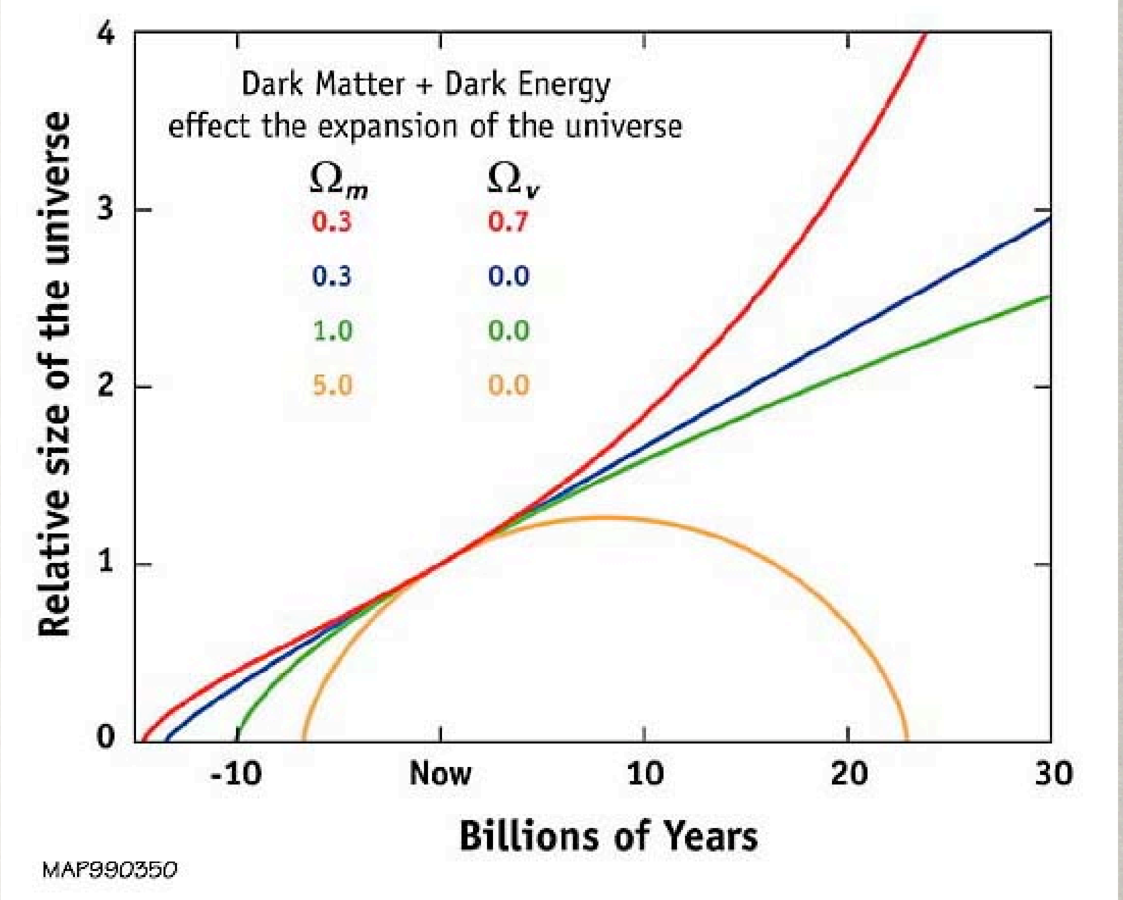
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho + \Lambda - \frac{\kappa}{a^2}$$

- The energy density & curvature decree the time evolution of the scale factor
- Key parameter is the critical density:

$$\rho_c = \frac{3H^2}{8\pi G_N} \qquad \Omega_i = \frac{\rho_i}{\rho_c}$$

Ω_i :density in $\sim 10^4 \mathrm{eV/cm}^3$

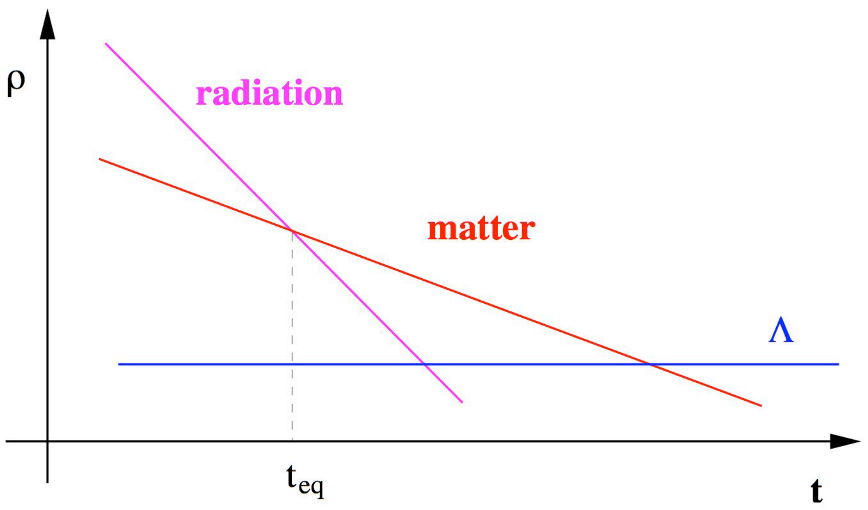
~ 10 protons/m3



Different energy types

Depending on the pressure and the equation of state, the energy densities give different expansion rates:

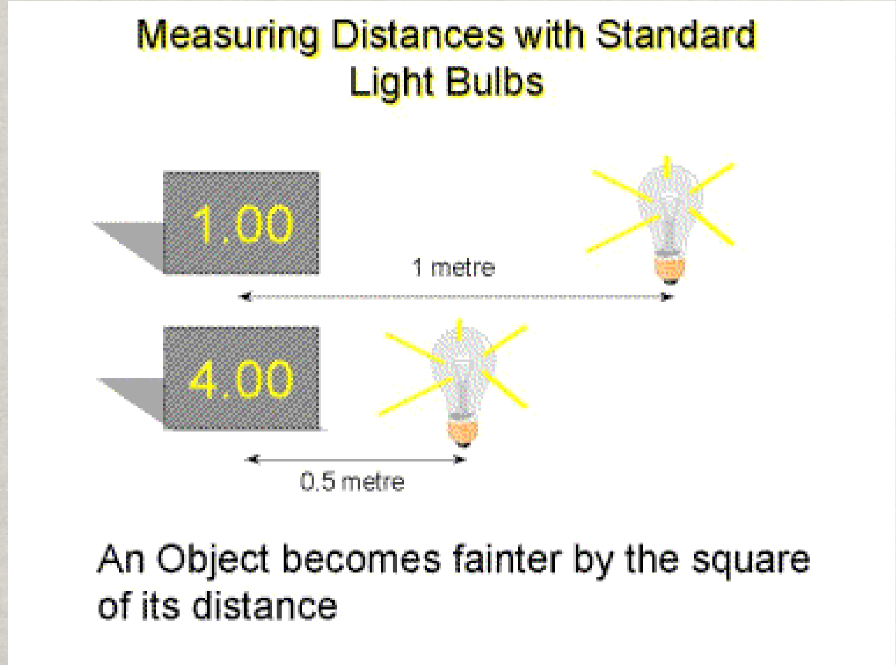
Type	p/ρ	$\rho(a)$	$a(t)$
Generic	w	$a^{-3(1+w)}$	$t^{2/(3(1+w))}$
Radiation	$1/3$	$\propto a^{-4}$	$\propto t^{1/2}$
Matter	0	$\propto a^{-3}$	$\propto t^{2/3}$
Λ	-1	const.	e^{Ht}
Curvature	$-1/3$	$\propto a^{-2}$	$\propto t^{1}$

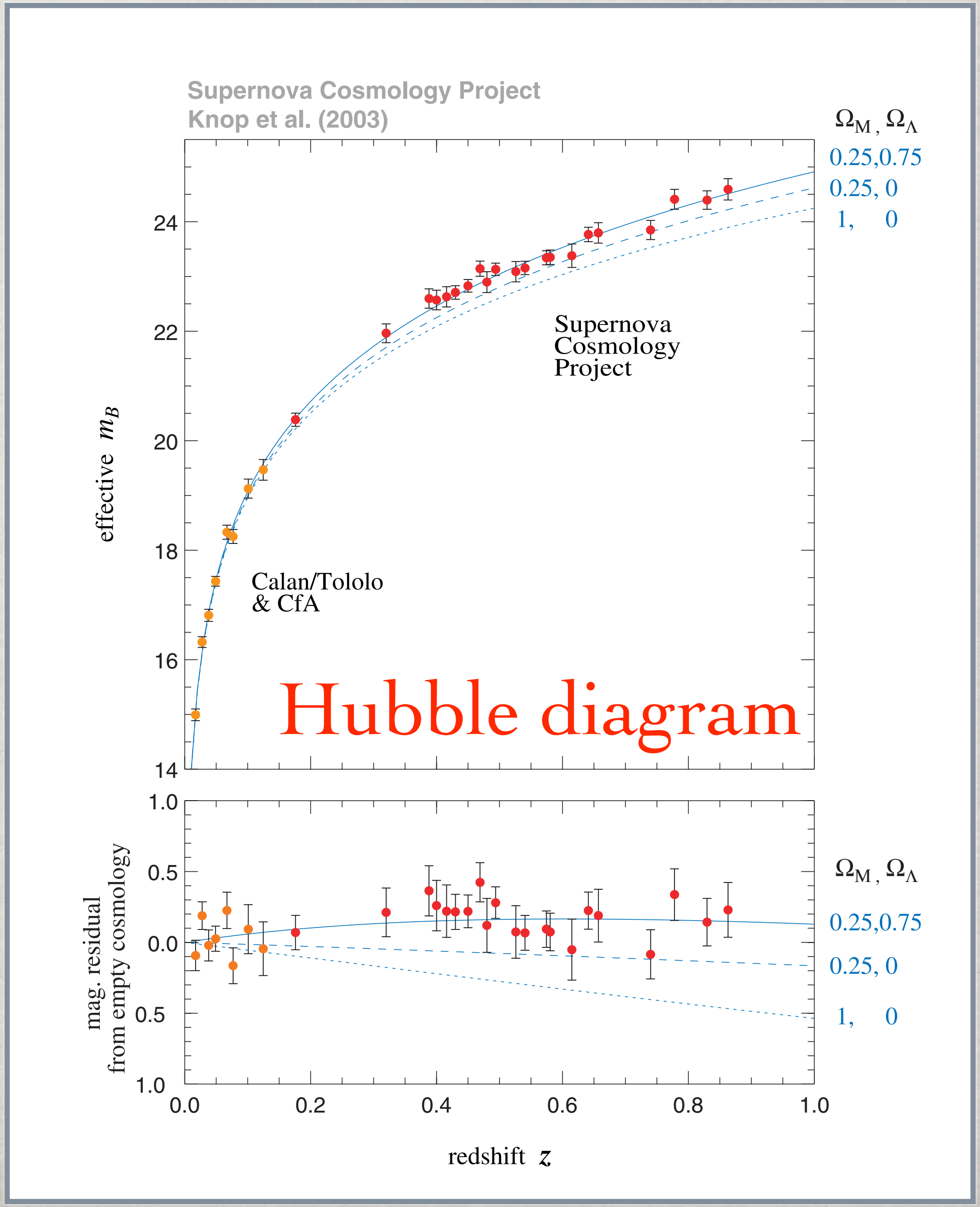


Different epochs of the Universe history

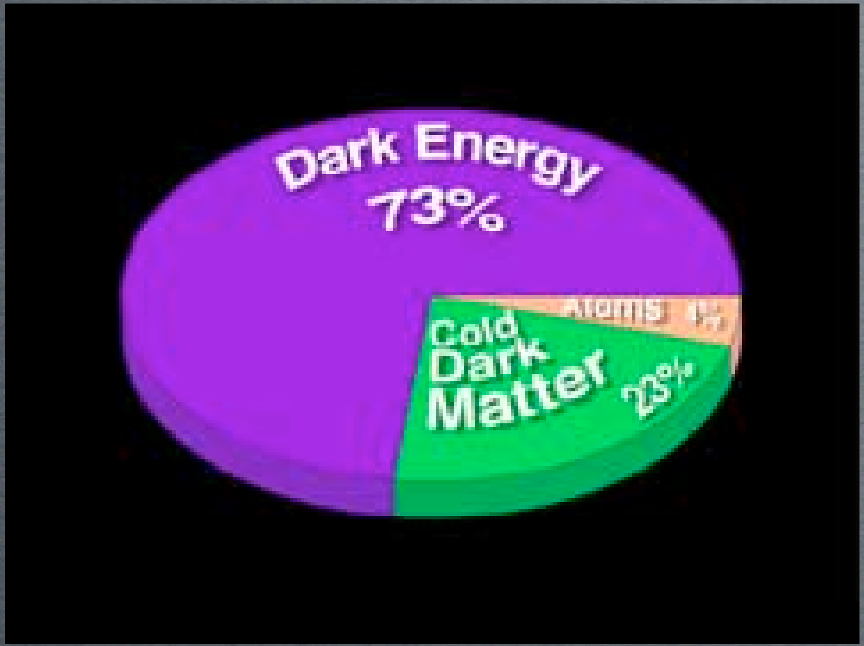
How can we measure the expansion of the Universe ?

Standard Candle



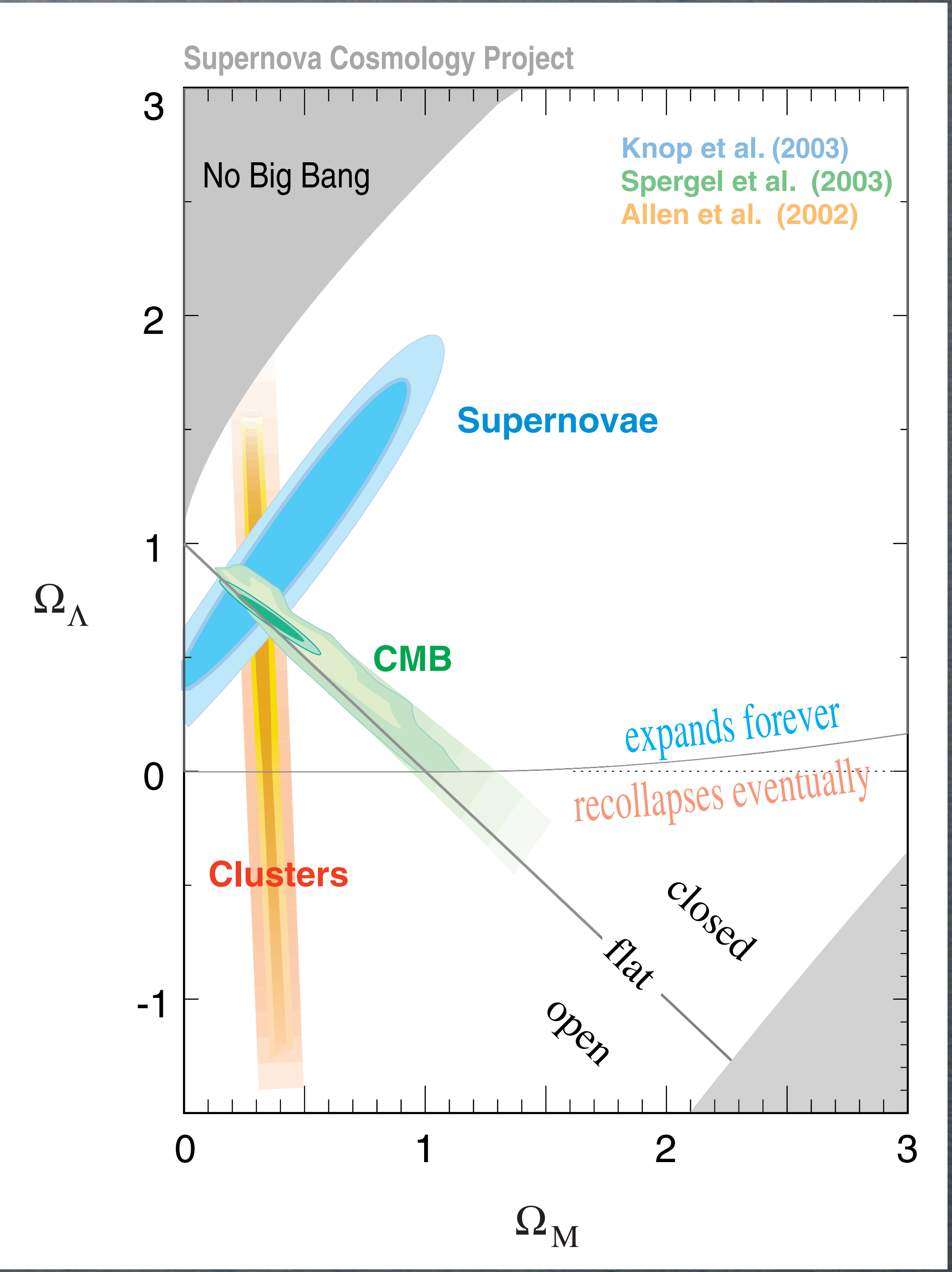


ENERGY CONTENT



with traces of photons,

neutrinos & ... ?



Dark Matter: local evidence

DARK MATTER EVIDENCE

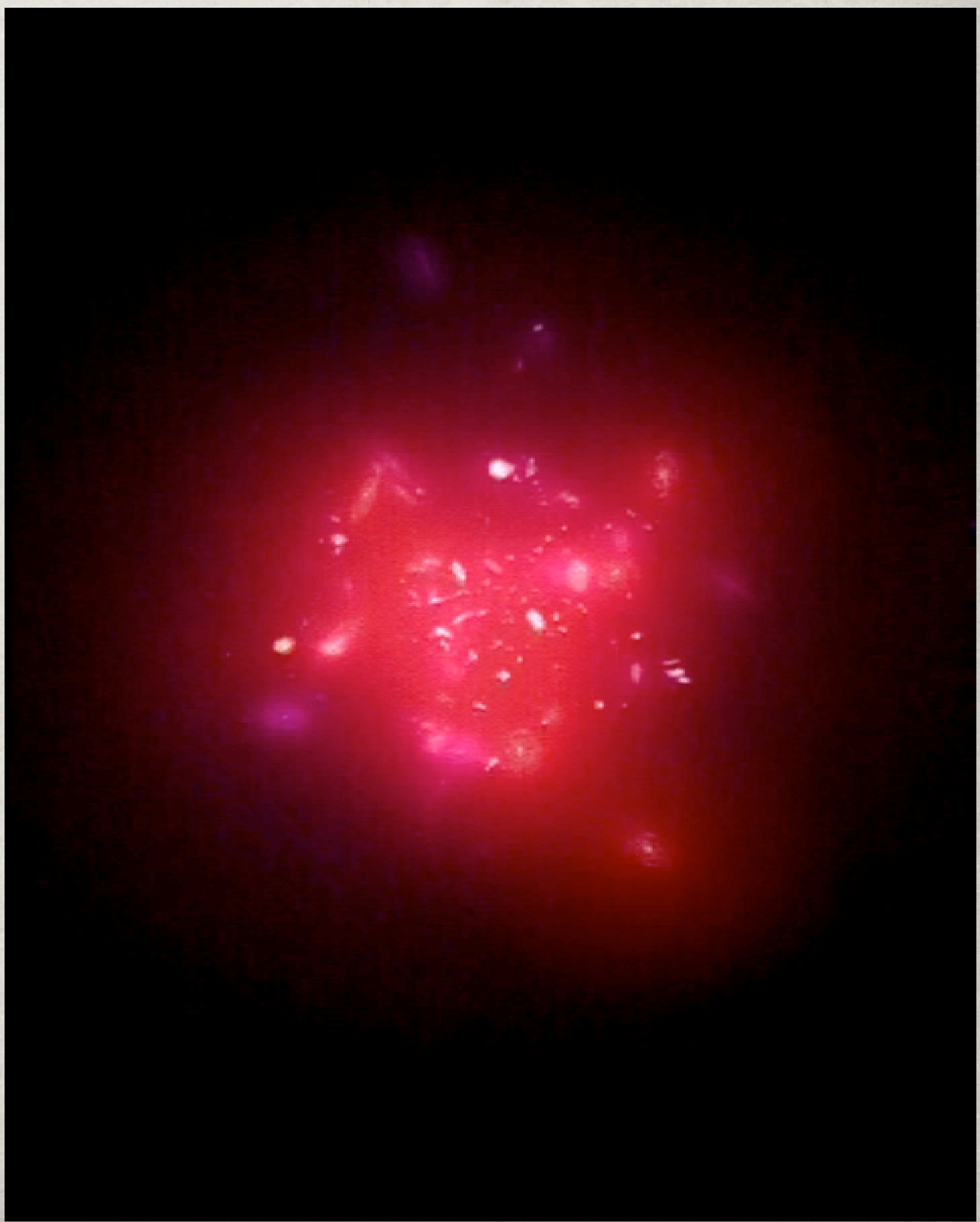
CLUSTER SCALES:

The early history of
Dark Matter:
In 1933 F. Zwicky found
the first evidence for DM
in the velocity dispersion
of the galaxies in the
COMA cluster...
Already then he called it
DARK MATTER !

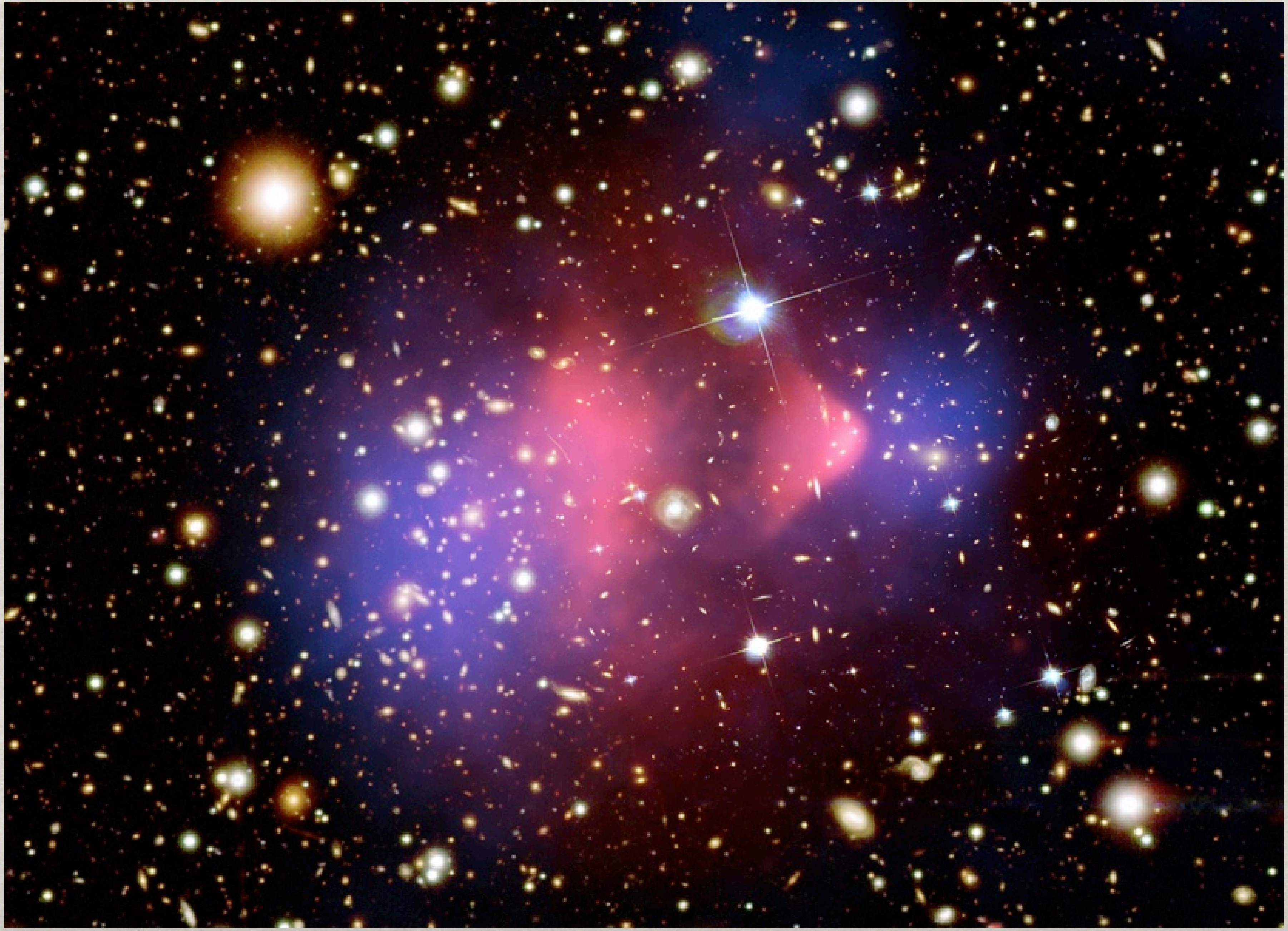
DARK MATTER EVIDENCE

CLUSTER SCALES:

Nowadays even stronger result from X-ray emission: the temperature of the cluster gas is too high, requires a factor 5 more matter than the visible baryonic matter...

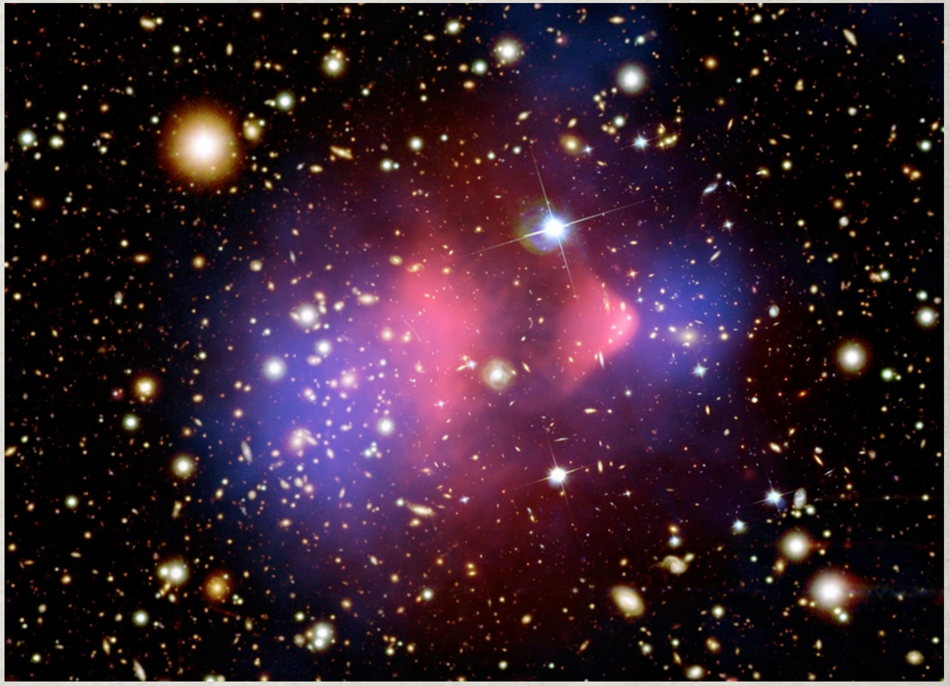


Even more impressive: strong gravitational lensing SEES DM, e.g. in the BULLET CLUSTER 1E 0657-56



DARK MATTER EVIDENCE

CLUSTER SCALES:



Systems like the Bullett cluster allow to restrict the self-interaction cross-section of Dark Matter to be smaller than the gas at the level

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb$$

[Markevitch et al 03]

One order of magnitude stronger contraint by required a sufficiently large core... [Yoshida, Springer & White 00]

DARK MATTER EVIDENCE

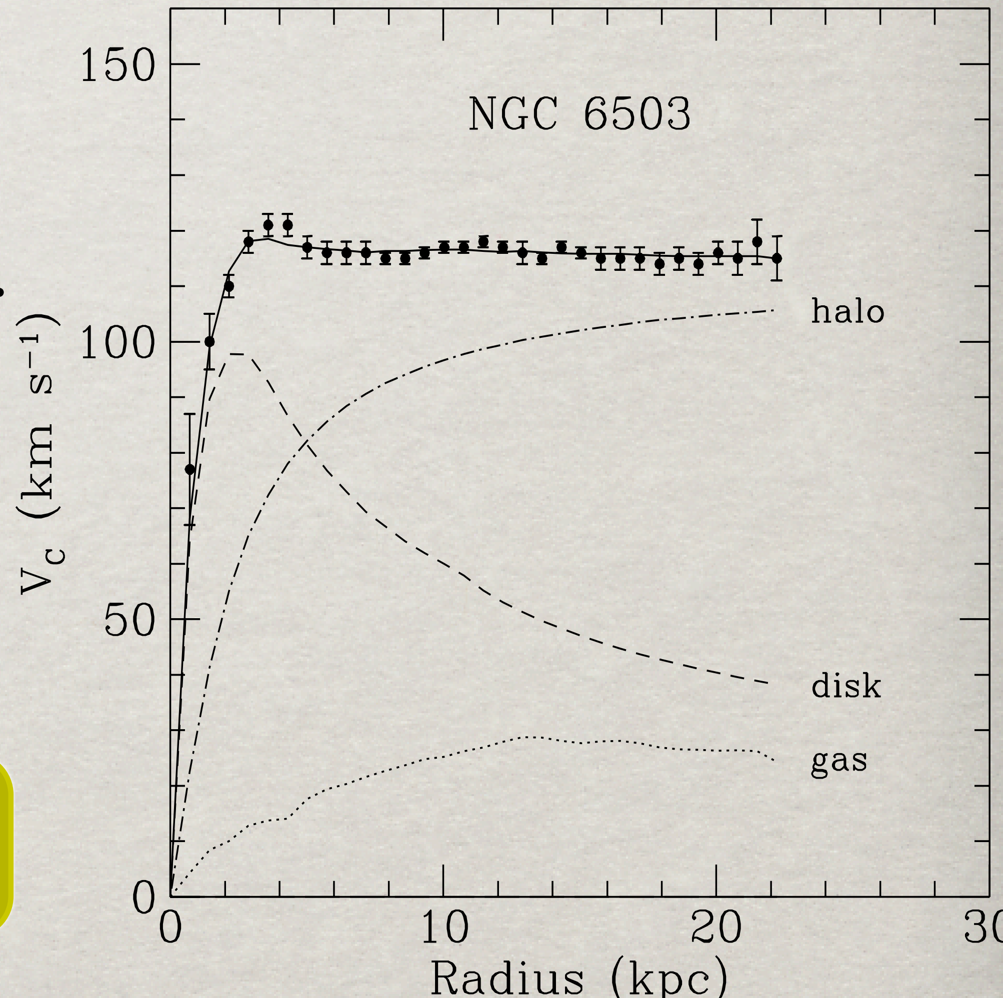
GALACTIC SCALES:

the stars in the outer part of galaxies are faster than expected...

$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{tot}}{r}$$

But instead it is constant ! Need

$$M(r) \propto r, \text{ i.e. } \rho_{DM} \propto r^{-2}$$



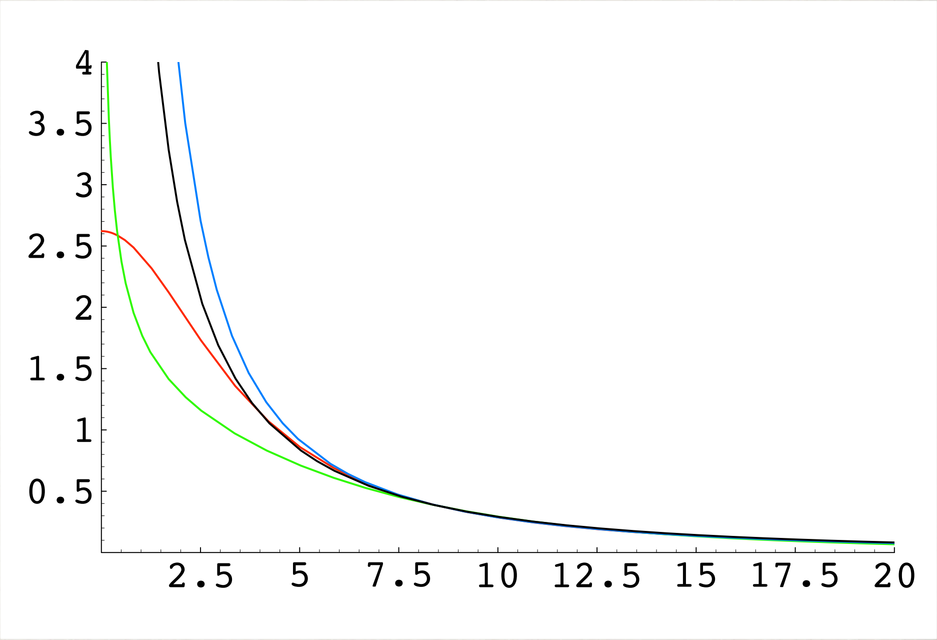
Unfortunately the density in the internal region of the galaxies is much more uncertain...

DARK MATTER EVIDENCE

GALACTIC SCALES:

Many profiles, inpired by data or numerical simulations: Isothermal, NFW, Moore, Kratsov, Einasto, etc....

$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma [1 + (r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$



Critical for indirect detection !

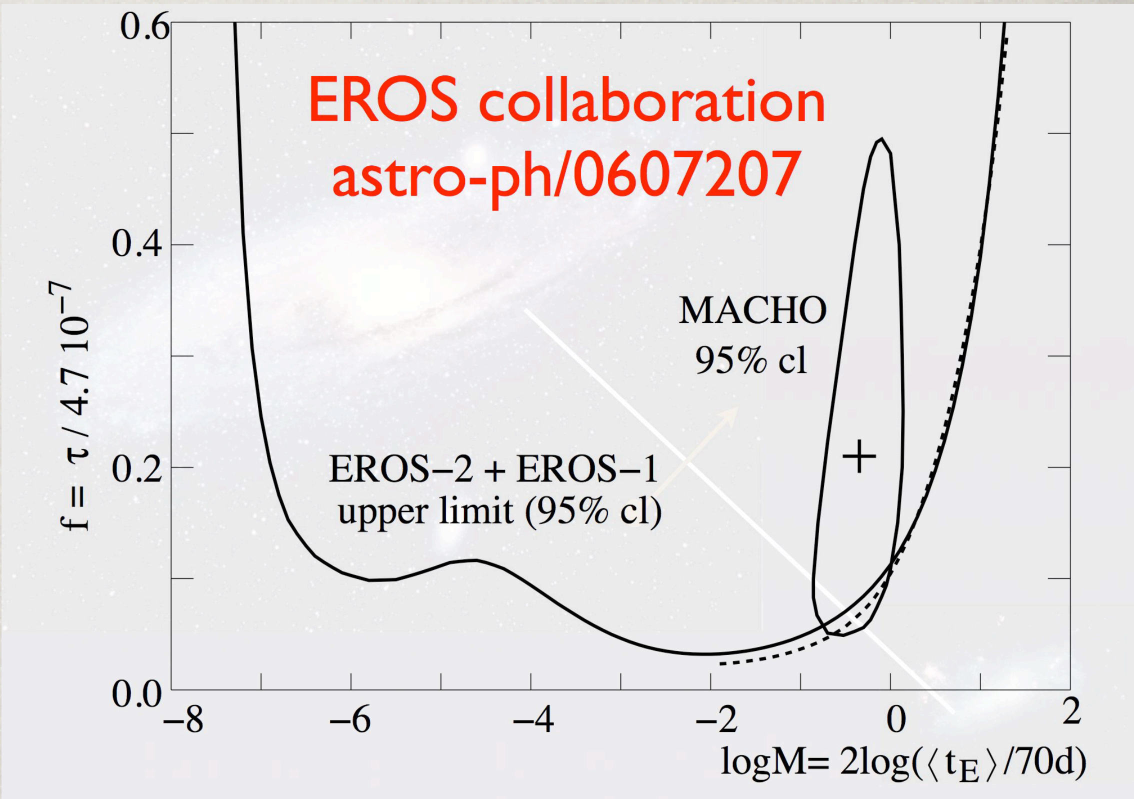
Other important fact: DARK MATTER is still here !
It is either stable or extremely long-lived. The decay into photon or charged particles must have a lifetime above 10^26 s, into neutrinos it can be a couple of orders of magnitude shorter.

DARK MATTER EVIDENCE

GALACTIC SCALES:

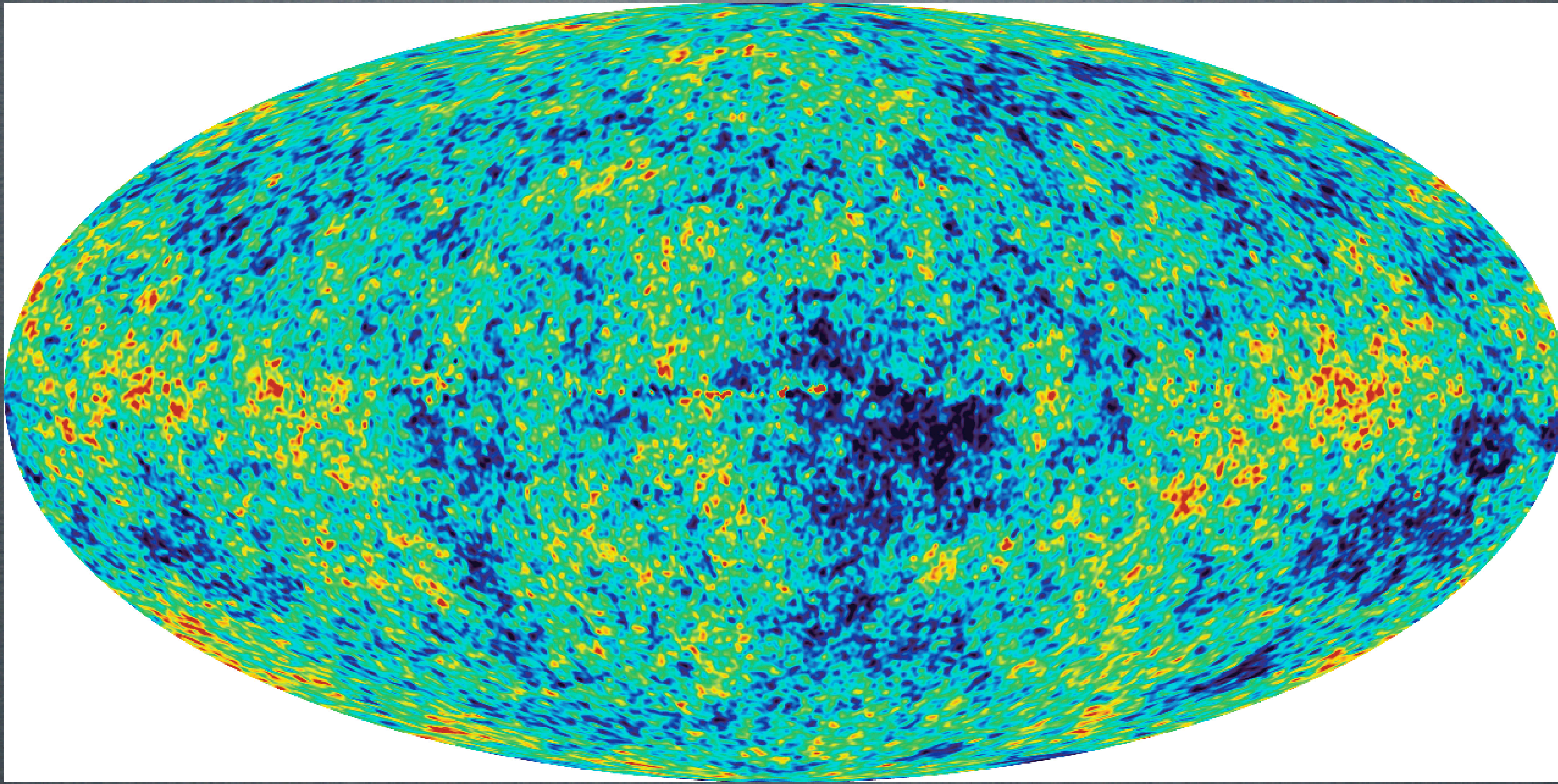
Faint planets, MACHOS ?
No evidence from the EROS collaboration between 10^{-7} and 20 solar masses.

Still clumps of Dark Matter, which are much less concentrated may be there...



Dark Matter and perturbations

1/2 Physics Nobel Prize 2006 to G. Smoot for COBE:
The Universe is NOT perfectly homogeneous !

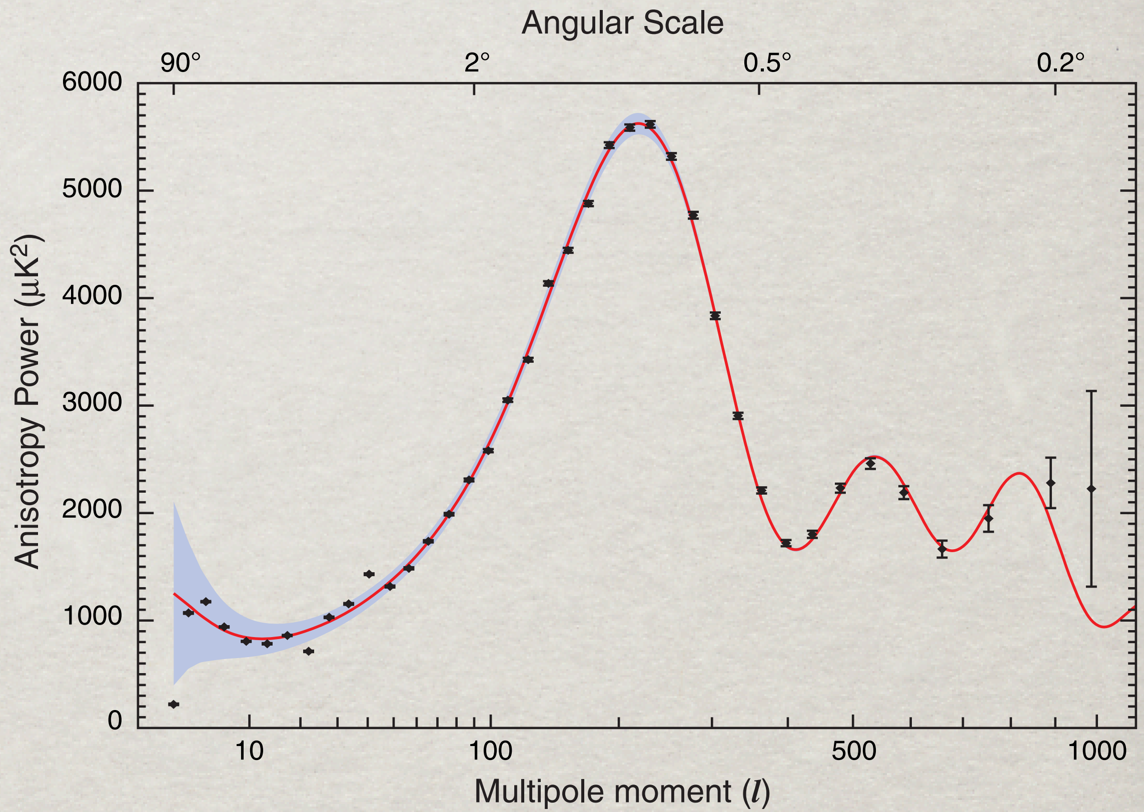


Tiny ripples on the black body spectrum at level of 0.01%...

DARK MATTER EVIDENCE

HORIZON SCALES:

From the position and height of the CMB anisotropy acoustic oscillations peaks we can determine very precisely the curvature of the Universe and other background parameters.



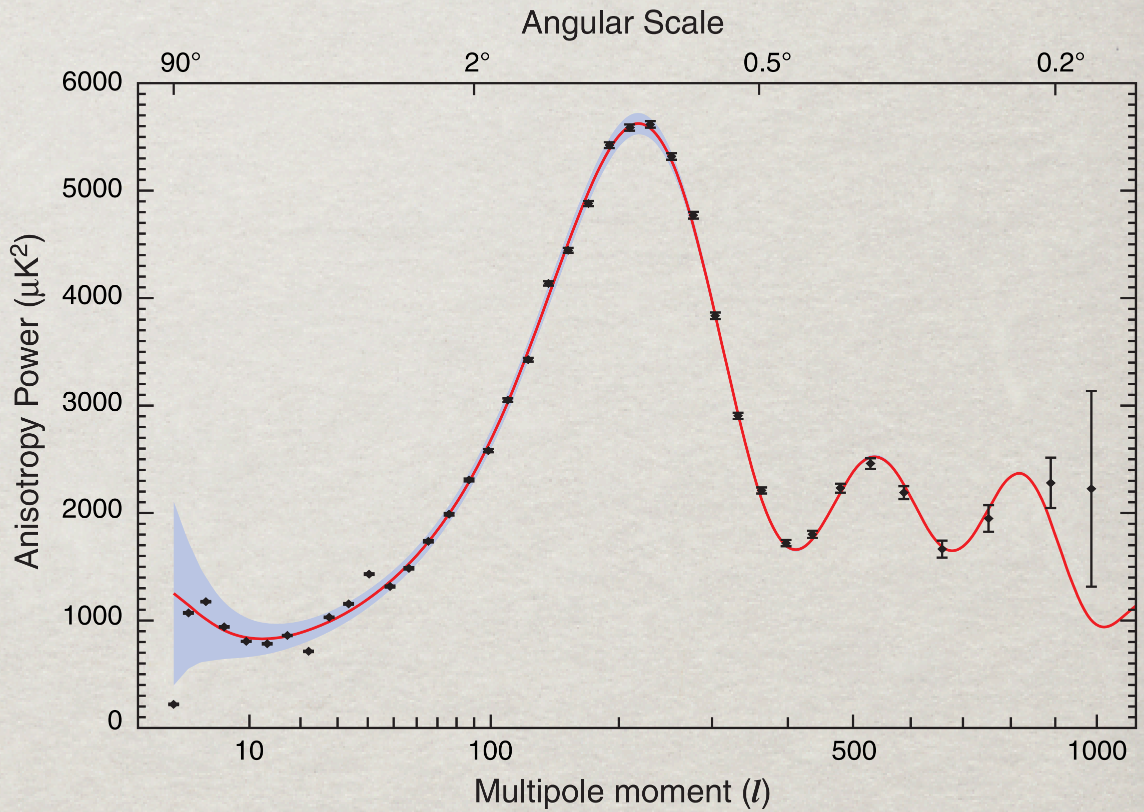
Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
???	0.1-0.13	Cold

DARK MATTER →

DARK MATTER EVIDENCE

HORIZON SCALES:

Moreover
Dark Matter must be non-baryonic, decoupled from the baryon-photon plasma and also not all neutrinos.



DARK MATTER →

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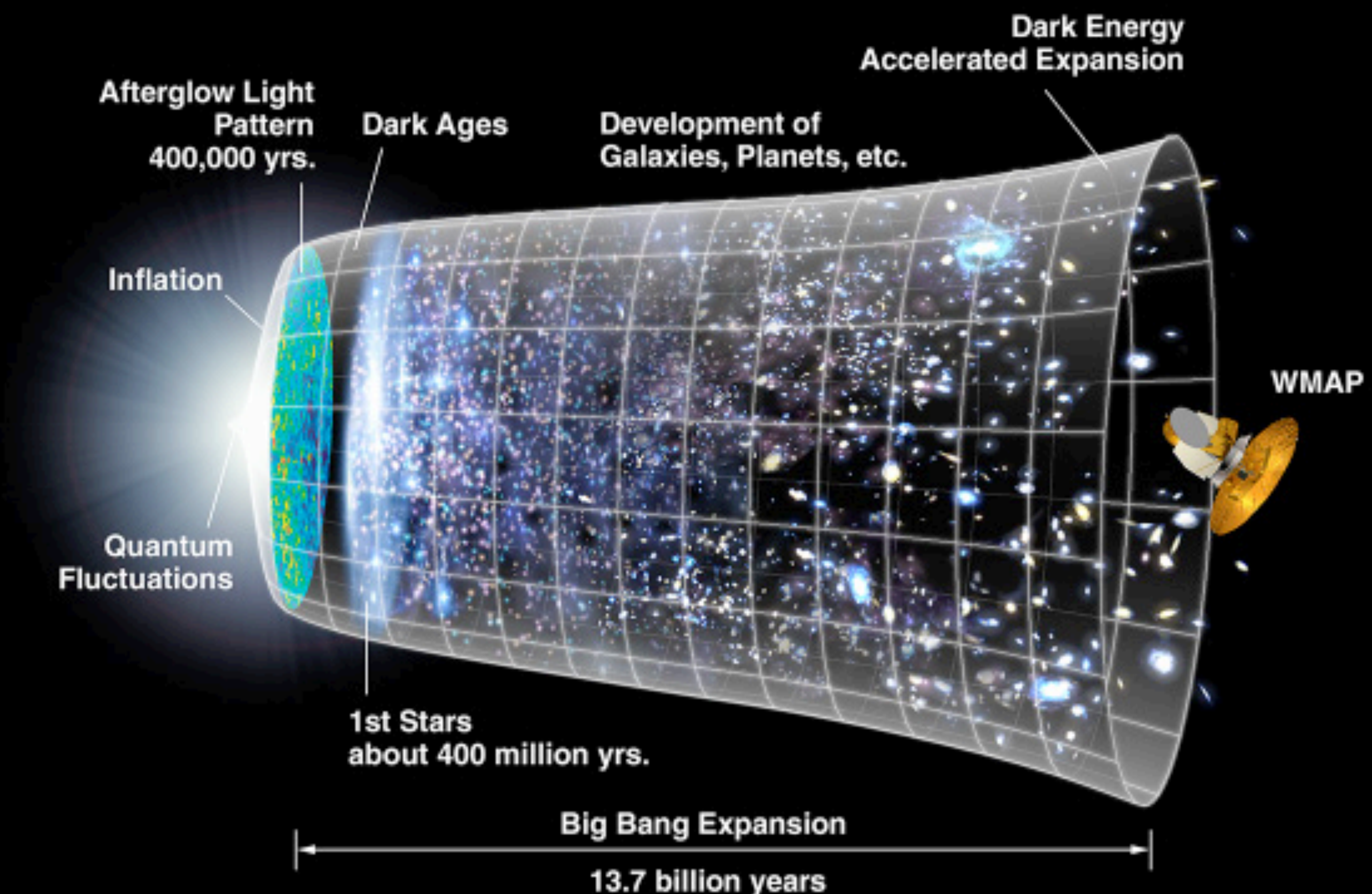
Following the fluctuations



These small fluctuations are amplified by gravity & are the origin of the structure we see today

NASA/WMAP Science Team

Following the fluctuations

What happens after such perturbations ”re-enter” the horizon ?

In the Newtonian limit we have for the density perturbations of a matter fluid $\delta = \frac{\delta\rho}{\rho}$

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(\frac{{c_s}^2 k^2}{a^2} - 4\pi G\rho\right)\delta_k = 0,$$

where $c_s = \delta p / \delta \rho$ is the sound speed in the plasma. Again a linear equation with a negative ”mass” term... The fluctuations with negative mass grow and those have k below k_J ,i.e. a physical wavelength larger than the Jeans length:

$$\lambda_J = \frac{2\pi a}{k} = c_s \sqrt{\frac{\pi}{G\rho}} \simeq \frac{c_s}{H} \quad \text{sound horizon}$$

How strongly do they grow ? The growing solution is

$$\delta_k \sim C_1 H \int \frac{dt}{a^2 H^2} + C_2 H \sim C_1 t^{2/3} + C_2 t^{-1} \quad \text{for matter dominance}$$

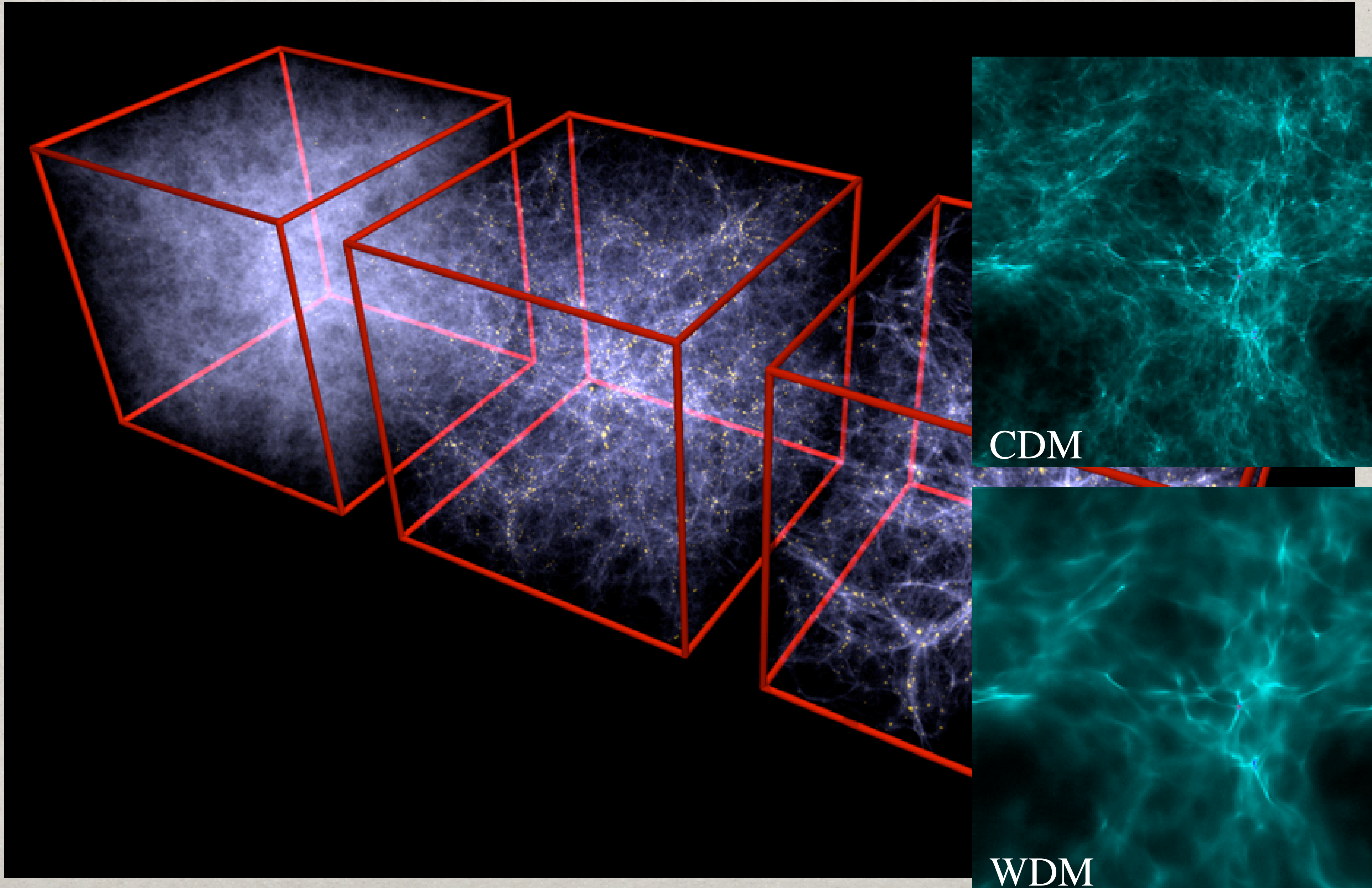
NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large...

Non Linear regime

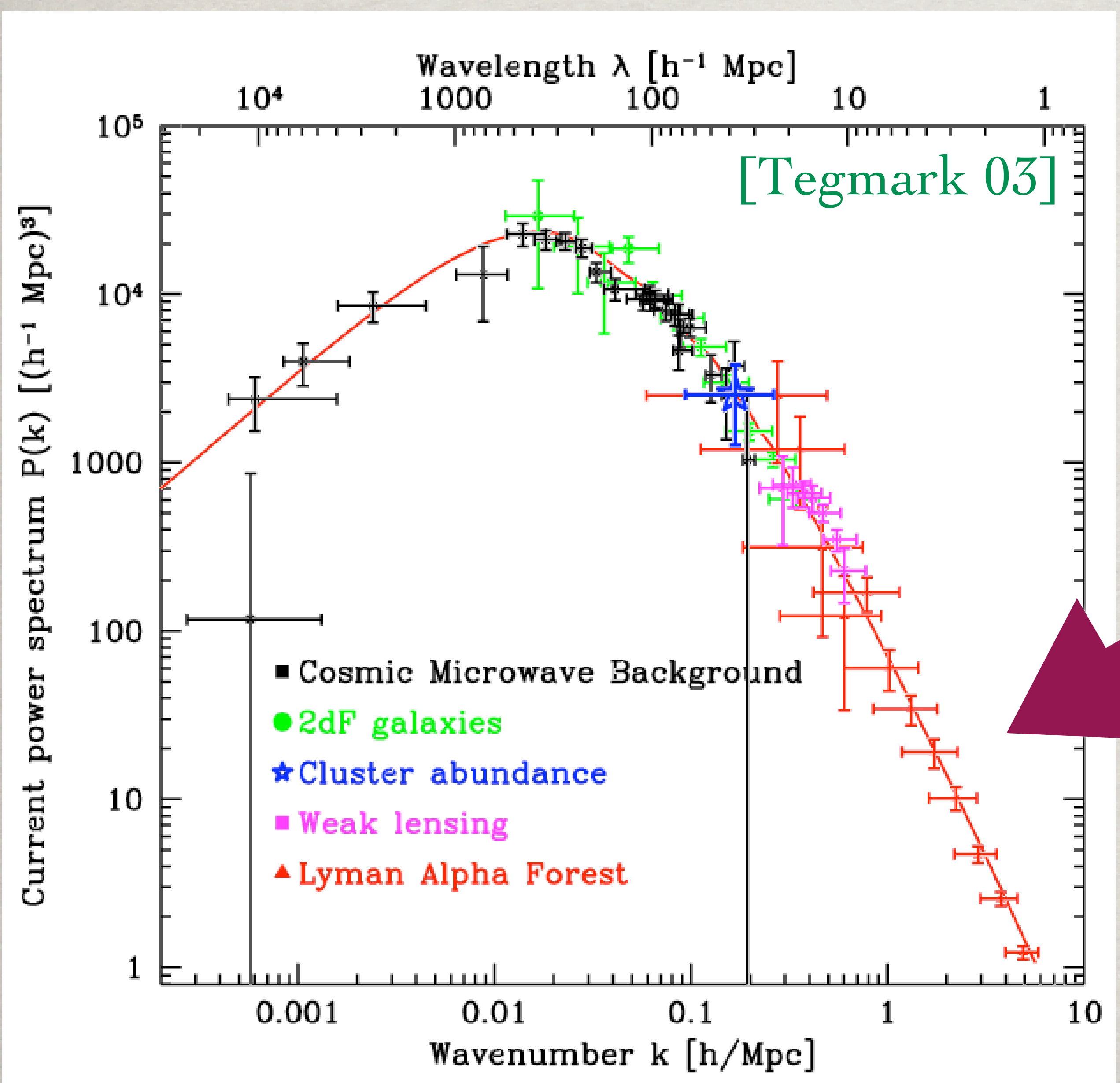
Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



WDM & the Power spectrum



WARM DM suppresses perturbations on scales smaller than its free-streaming length:

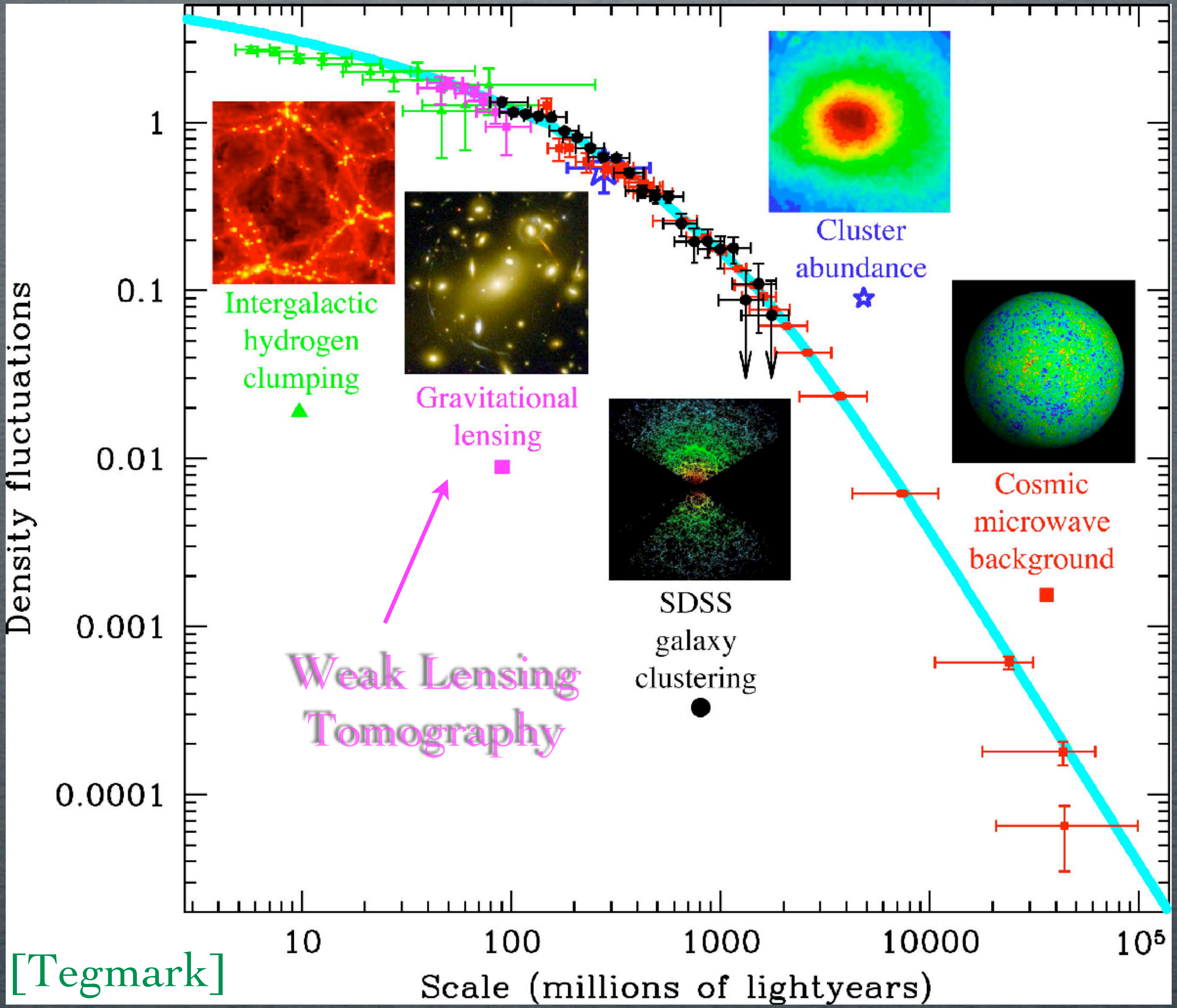
$$\lambda_{FS} \sim \text{Mpc} \left(\frac{m_{WDM}}{1\text{keV}} \right)$$

Compare with the data:

$$m_{WDM} > 4 \text{ keV}$$

[Viel et al. '07]

MEASURE FLUCTUATION ON ALL SCALES



[Tegmark]

Dark Matter: Particle Properties

DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (non-baryonic & decoupled from the baryon-photon plasma, electrically neutral !)
- It must have the right density profile to "fill in" the galaxy rotation curves.
- No pressure and small free-streaming velocity, it must cluster & cause structure formation.

⬇

COLD DARK MATTER

DARK MATTER PROPERTIES

- Electrically neutral, non-baryonic, possibly electroweak interacting, but could even be only gravitationally interacting.

- It must still be around us: either stable or very very long lived, i.e. it is the lightest particle with a conserved charge (R-, KK-, T-parity, etc...) or its interaction and decay is strongly suppressed !

- If it is a thermal relic, must be sufficiently massive to be cold..., but it may even be a condensate...

⬇

LOOK FOR PARTICLE DM CANDIDATES !

Neutrino as (prototype) DM

- Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

$$\Omega_\nu h^2 \sim \frac{\sum_i m_{\nu_i}}{93\ \mathrm{eV}}$$

but $m_\nu \leq 2\ \mathrm{eV}$ (Tritium β decay) so $\Omega_\nu h^2 \leq 0.07$

- Unfortunately the small mass also means that neutrinos are HOT DM... Their free-streaming is non negligible and the LSS data actually constrain

$m_\nu \leq 0.27 \sim 1\ \mathrm{eV}$ ➡ $\boxed{\Omega_\nu \ll \Omega_{DM}}$

NEED to go beyond the Standard Model !

OPEN QUESTIONS & OUTLOOK

Outlook

Since the discovery of Zwicky, we have learned a lot about Dark Matter, in particular what it is not: not baryonic, not hot, not made of neutrinos, etc...

The next decade hopefully should bring us some more clear answers:

- Accelerator and DM direct detection experiments may find out if Dark Matter is supersymmetric...

- Indirect detection may discover if DM in the halo is annihilating or decaying...

EXCITING TIMES ARE JUST BEGINNING...