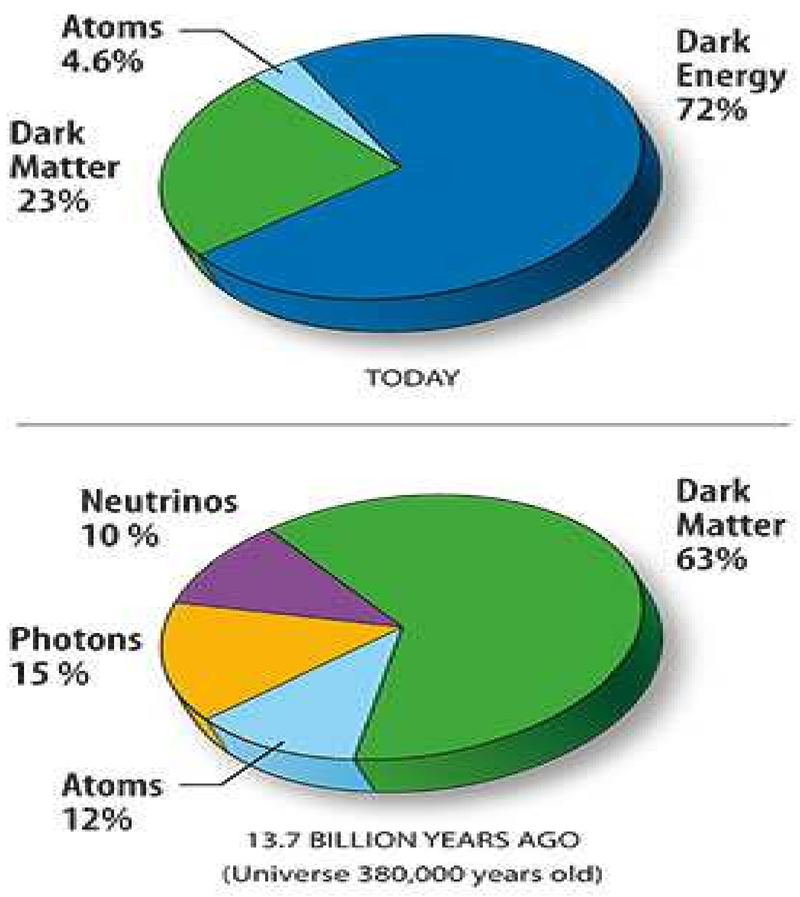
Shining (some) light on DARK MATTER



Q: What is Dark Matter?

SA: We don't know!!

LA: Whatever it is:

- It does not SHINE: it does NOT interact electromagnetically or strongly
- It does interact with all other matter and radiation GRAVITATIONALLY
- It is stable, or at least it has a lifetime > 13.7 billion years!

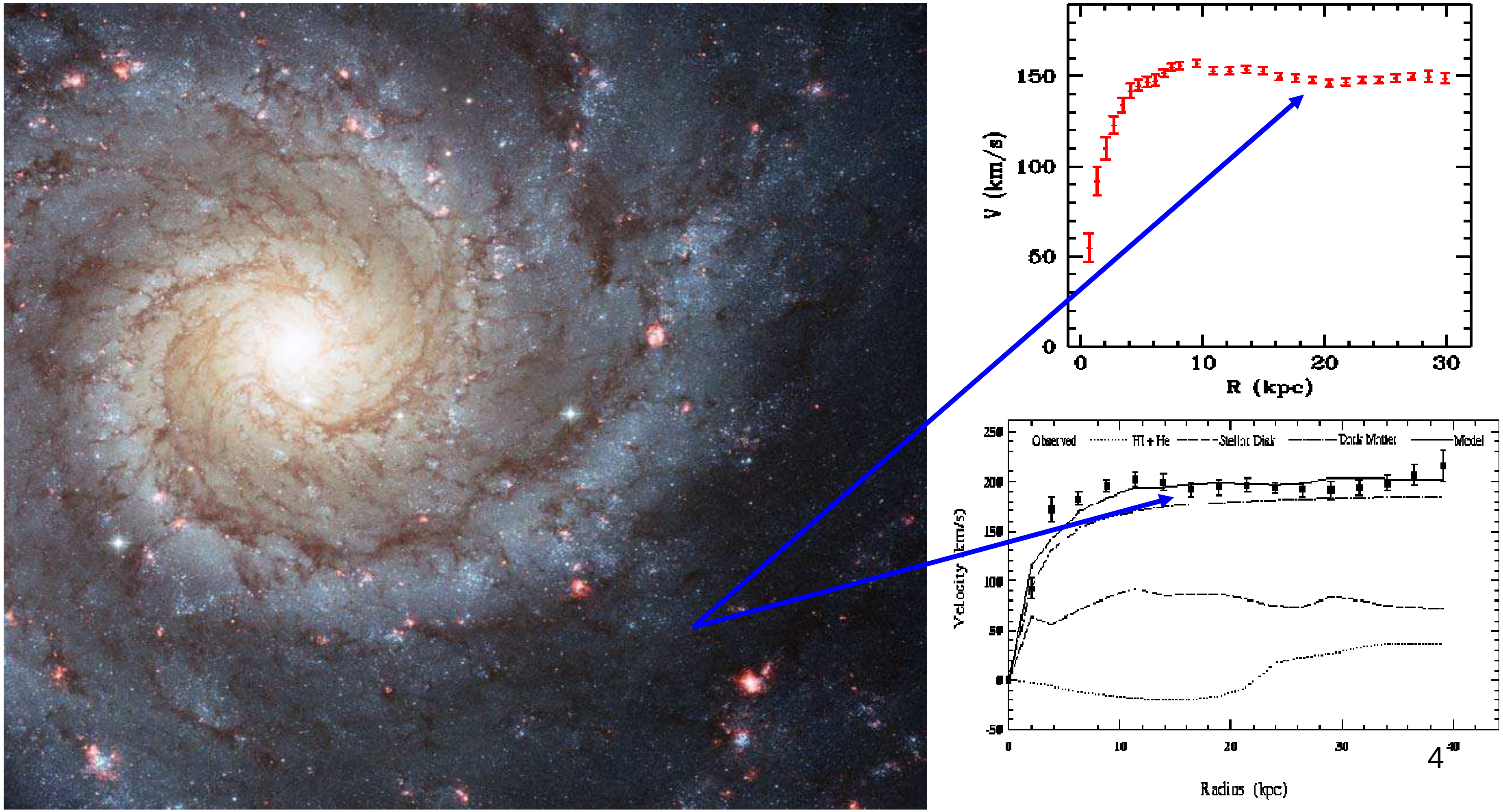
Gimme the evidence:

- Galaxies: rotational velocity curves
- Gravitational lensing: smoke and bullets
- Cosmic Microwave Background
- Large scale structure: simulations vs observations
- Type Ia Supernovae

$$\frac{V^2}{R} = \frac{GM(R)}{R^2} \Rightarrow V(R) = \sqrt{\frac{GM(R)}{R}}$$

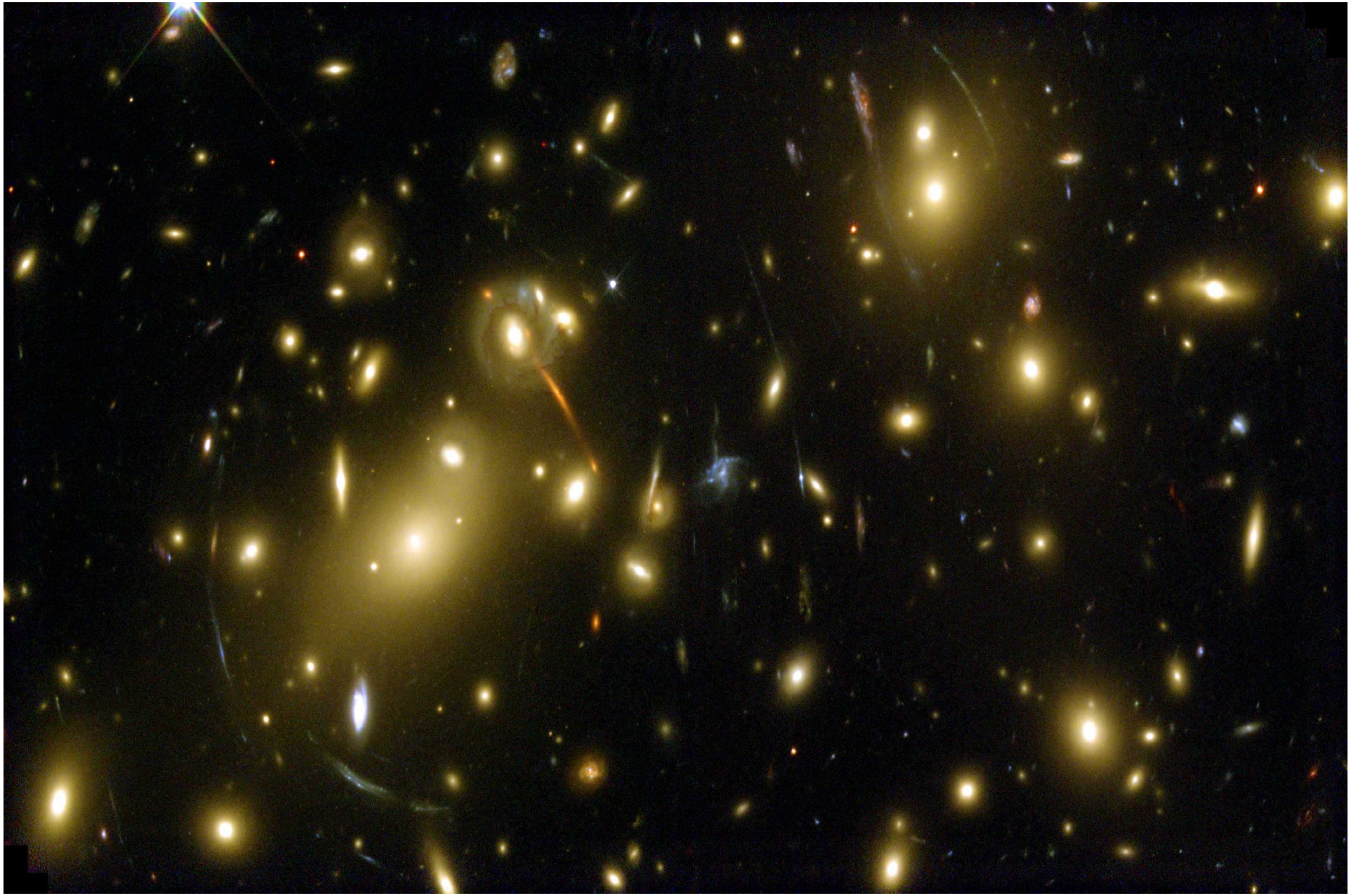
$\approx R$ In the galaxy

$\approx \frac{1}{\sqrt{R}}$ Outside the galaxy

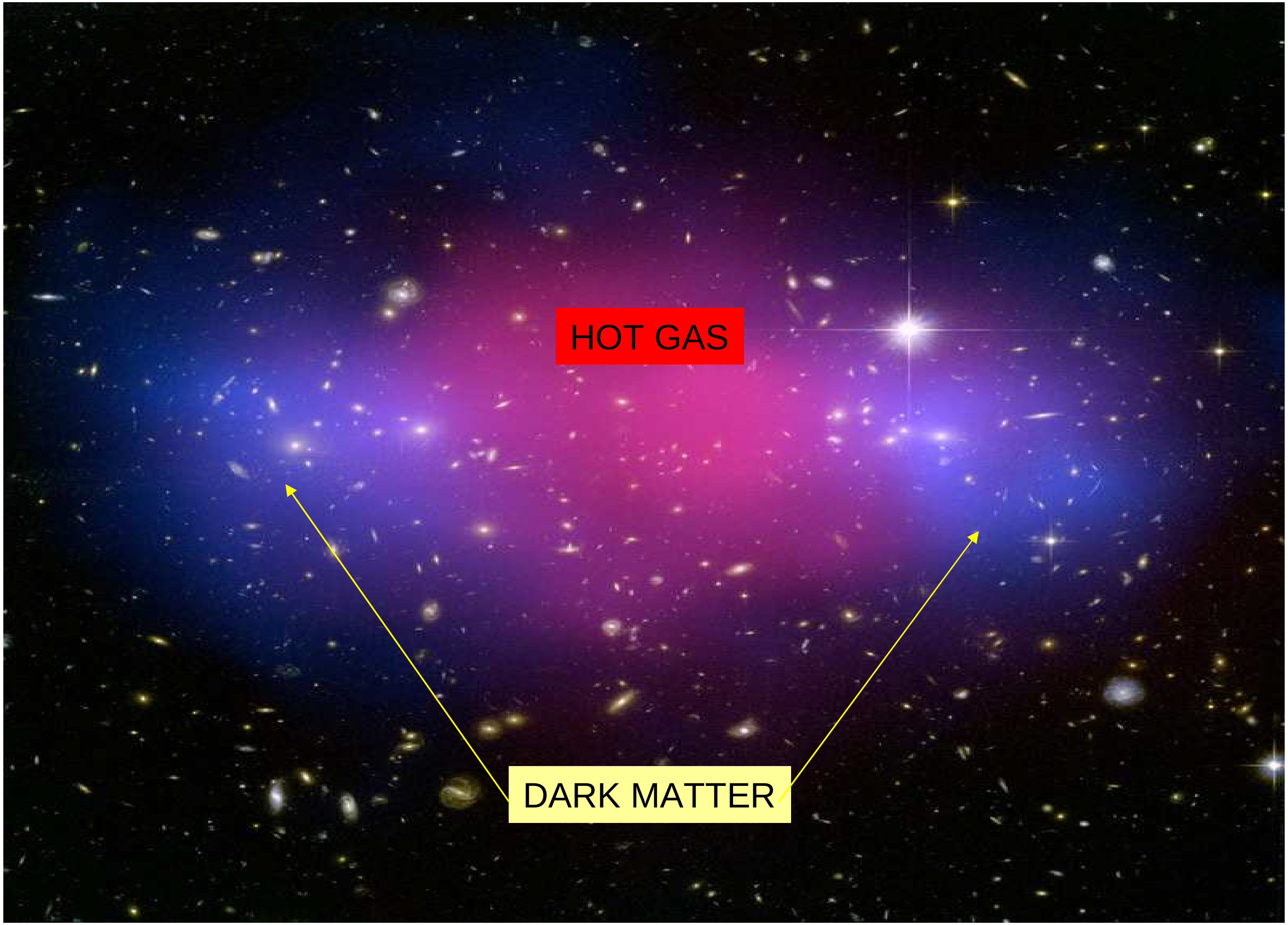


Gravitational Lensing: Einstein’s equivalence principle → Matter acts as a lens

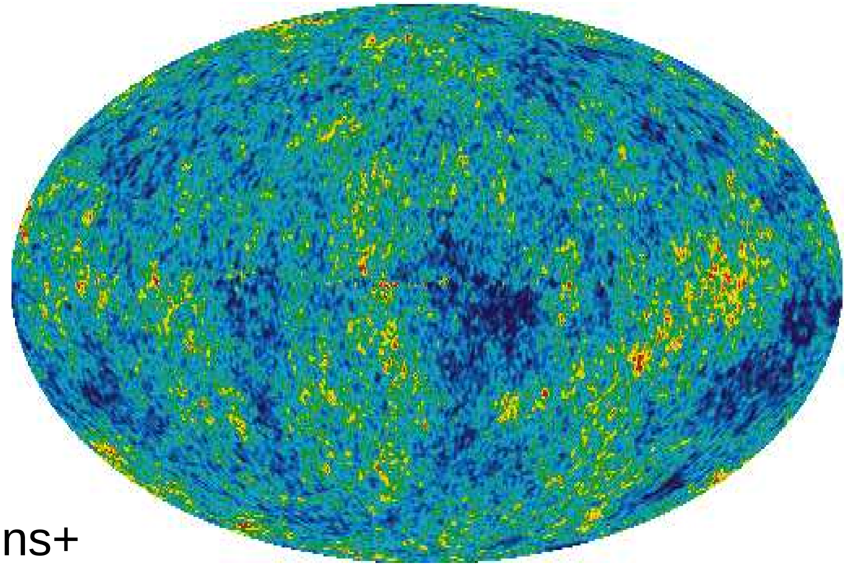
(go to a freely falling elevator)



Smoke from bullets: The bullet cluster



CMB: listen to the story



1992: COBE confirms CMB at T =2.73 K + fluctuations $\frac{\Delta T}{T} ; 10^{-5}$

The origin of temperature fluctuations: Photons+

electrons and protons tightly coupled by Thompson scattering: a **photon-baryon fluid**

Gravity vs radiation-baryon pressure: a primer on galaxy formation:….consider…..

Acoustic oscillations in the photon-baryon fluid: $\frac{\delta\rho}{\rho} \sim \frac{\Delta T}{T}$

Sound waves (seeded by primordial fluctuations) a result from the competition between gravity's attraction and pressure restoring forces

speed of sound ⟶ **photons + baryons**

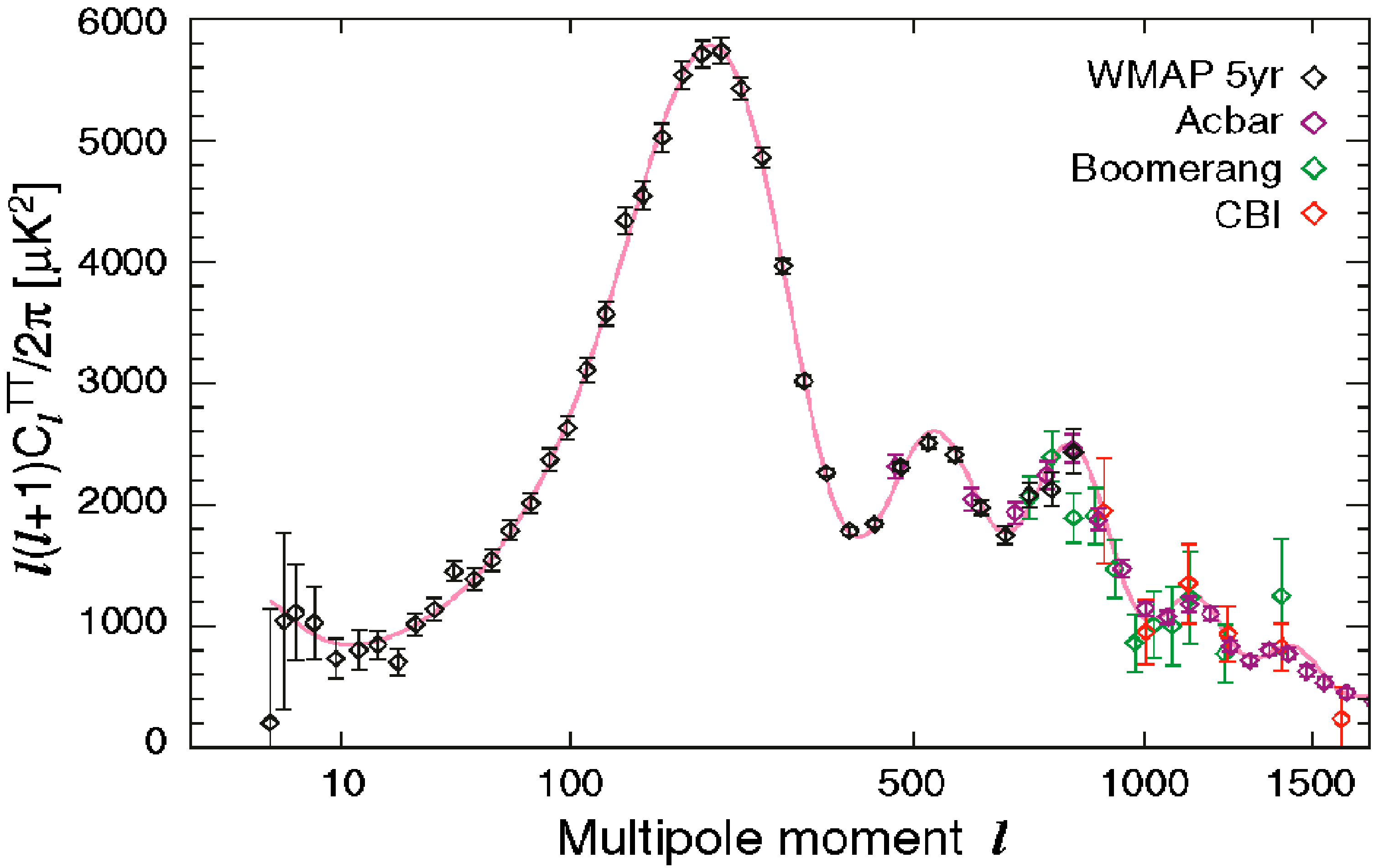
Expansion ⟶ **DM + DE**

Re-combination: $\mathrm{e} + p \Leftrightarrow \mathrm{H} + \gamma$

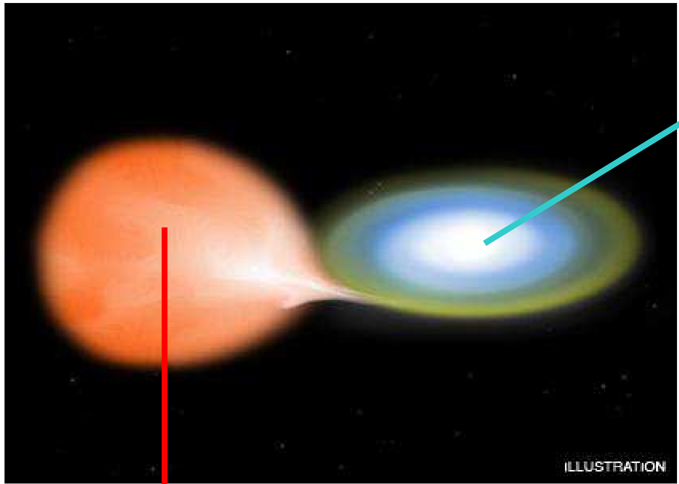
At T ~ 3000 K the reaction goes right, H, forms and the Universe becomes transparent, photons are ``liberated'' from the plasma and travel freely for about 13.7 billion years. Acoustic waves have been imprinted on their temperature.

$\frac{\Delta T}{T} \propto \frac{\delta\rho}{\rho}$ ⟶ Seeds for galaxy formation

Peaks + valleys tell the story: DM + DE + baryons…



SnIa: Carbon-Oxygen white dwarfs in binary systems:



White Dwarf:

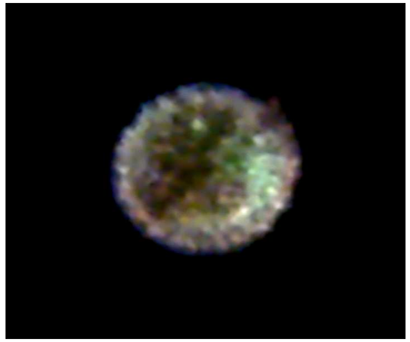
Composition: C+0

Mass ~ 1.4 M_e

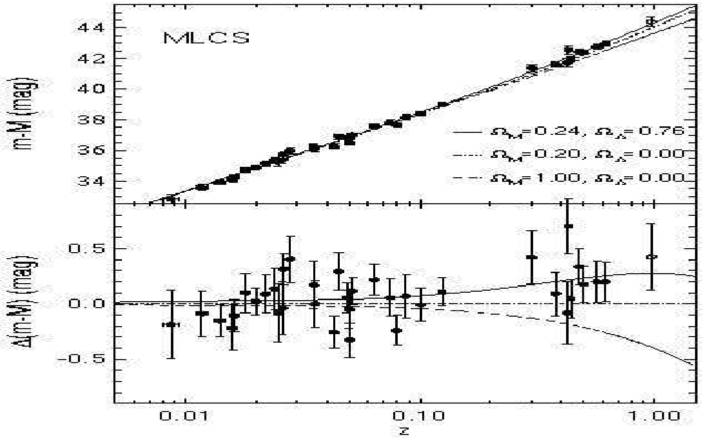
Red Giant

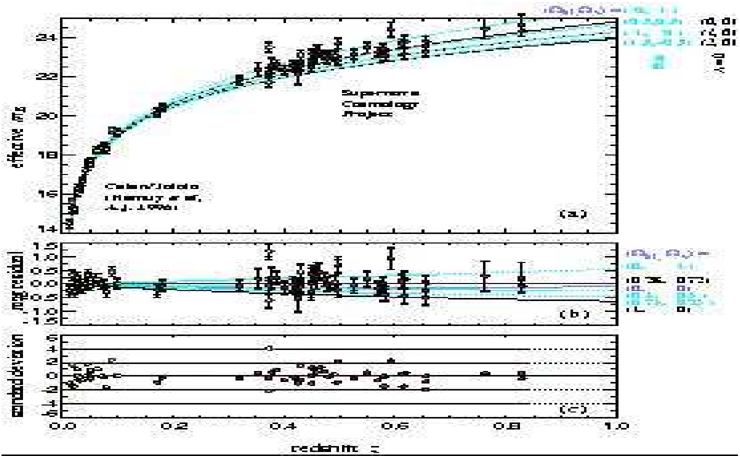
Mass accretion :
Thermonuclear run-away of a Fermi degenerate core

Sn Ia explosion:standard candles !!



Measure apparent magnitude and redshift: Hubble expansion—decceleration parameter: extract DM-DE contributions

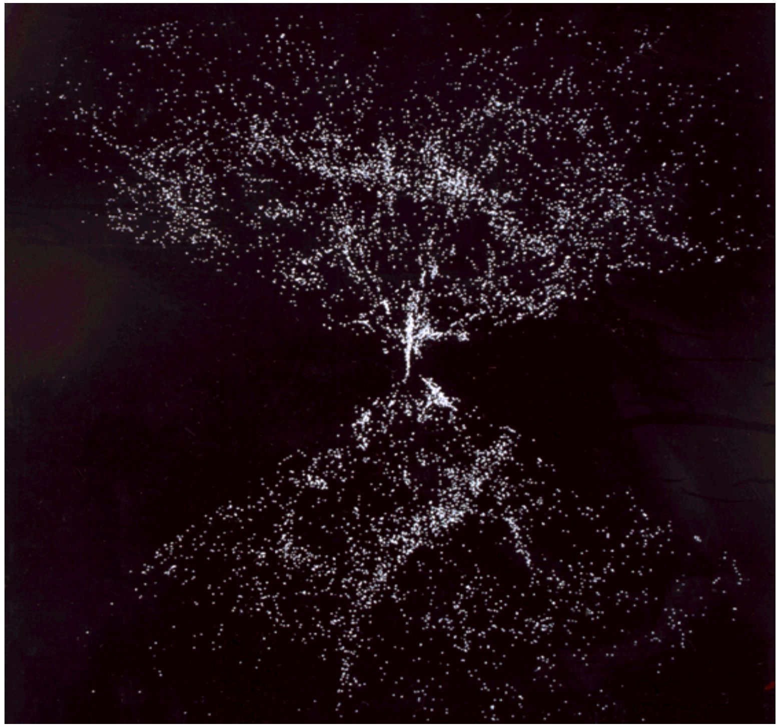


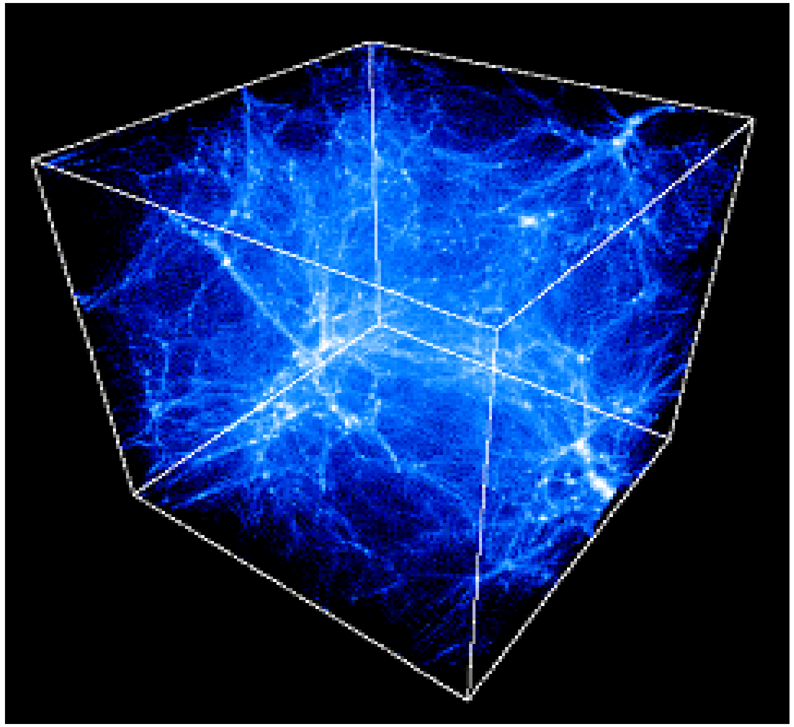


Large Scale Structure: Observations vs. Simulations

Observations: SDSS, CfA,
Deep field surveys:

Large scale (truly) simulations:
particles with gravitational
interactions only





Physics of DM

DM: NOT Standard Model particles, the ONLY SM stable particles are p, e, these SHINE, ``atoms'' → DM = Physics Beyond the SM!!

DM particles interact very weakly → DECOUPLING AND FREEZE OUT

$\Gamma \sim n\sigma v$ = reaction (or production) rate

$H = \frac{\dot{R}}{R}$ Hubble=expansion rate

$\Gamma > H$ → LTE

$\Gamma < H$ → OUT OF LTE: DECOUPLING AND FREEZE OUT

DM distribution function: after decoupling….

$$\frac{df(p)}{dt} = 0$$

f(p) →

- DM abundance
- <v^2> = velocity dispersion
- (conserved) phase space density

Thermal relics: f(p) = MB, FD, BE

$$\langle v^2 \rangle \sim \frac{k_B T}{M}$$

T → Temperature today

M → DM particle mass

Fluids vs collisionless particles: free streaming

Fluids: $\lambda_J \sim \frac{c_s}{\sqrt{G\rho}}$

$\lambda > \lambda_J$ ⟹ Gravitational collapse

$\lambda < \lambda_J$ ⟹ Acoustic oscillations (sound)

Collisionless Particles: $\lambda_{fs} \sim \sqrt{\frac{\langle v^2 \rangle}{G\rho}}$

$\lambda > \lambda_{fs}$ ⟹ Gravitational collapse

$\lambda < \lambda_{fs}$ ⟹ (Landau) damping (free streaming)

Structures **cannot** form with $\lambda < \lambda_{fs}$!!

Cold DM (CDM):

- ❖ light NON-THERMAL M < 1 eV
- ❖ Heavy, thermal M ~ GeV – TeV
- ❖ small $\lambda_{fs} \lesssim 0.1\text{pc}$
- ❖small structures form first and merge hierarchically: bottom-up

Hot DM (HDM):

- ❖ M $\lesssim 1\text{eV}$
- ❖large $\lambda_{fs} > 1\text{Mpc}$ (clusters of galaxies)
- ❖large structures form first and fragment: top-down

Warm DM (WDM):

``In between'' CDM and HDM: M $\sim 1\text{keV}$

Particle Physics Candidates: All beyond the Standard Model

CDM:

- Thermal, heavy: W(eakly)I(nteracting)M(assive)P(articles): the LSP, neutralino (mixed s-partner) M ~50 GeV—1 TeV
- Light, NON-thermal: Scalar or Pseudoscalar condensates, Axions, M< 1 eV (small velocity as a BEC)

HDM: ``Standard Model'' neutrinos M < 1 eV

WDM: ``Sterile'' neutrino, SU(2) singlet, only interaction through mixing with ``active'' (SM) neutrino, M ~ 1 keV

Observations + numerical simulations: DM is COLD AND COLLISIONLESS: LSS=hierarchical merger of DM ``halos''

N-body simulations: predictions for CDM

- ``Cuspy'' density profiles: $\rho(r) \sim \frac{1}{r^{\gamma}}$, $\gamma = 1$: Navarro-Frenk-White (NFW), $\gamma \sim 1.2$ Via Lactea simulation
- Many ``satellites'': DM clumps left over from mergers

Observing DM (sub) structure: Dwarf Spheroidal Galaxies (dSphs):

Low luminosity satellite galaxies, DM dominated (low baryon, gas, content)

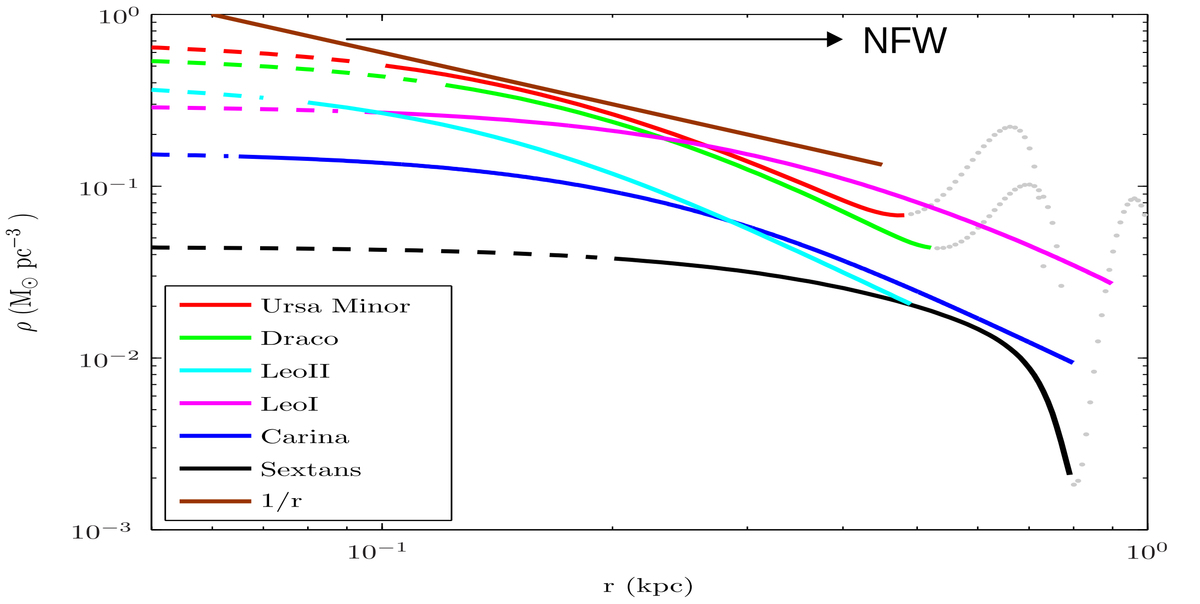


Fig. 4.— Derived inner mass distributions from isotropic Jeans' equation analyses for six dSph galaxies. The modelling is reliable in each case out to radii of log (r)kpc∼ 0.5. The unphysical behaviour at larger radii is explained in the text. The general similarity of the inner mass profiles is striking, as is their shallow profile, and their similar central mass densities. Also shown is an r^{-1} density profile, predicted by many CDM numerical simulations (eg Navarro, Frenk & White 1997). The individual dynamical analyses are described in full as follows: Ursa Minor (Wilkinson et al. (2004)); Draco (Wilkinson et al. (2004)); LeoII (Koch et al. (2007)); LeoI (Koch et al. (2006)); Carina (Wilkinson et al. (2006), and Wilkinson et al in preparation); Sextans (Kleyna et al. (2004)).

Cores vs cusps??, ``Missing satellite'' problem?, is there a problem at small scales?? ***<u>Maybe WDM instead of CDM or mixture? : CONTROVERSIAL!!</u>***

DETECTION:

Direct:

Accelerator: The LHC will search for the LSP, missing energy ⟶ mass, perhaps X-section.

Non Accelerator: WIMP-nucleus/nucleon scattering: ***DA***(rk)***MA***(tter)/LIBRA (Grand Sasso), ***C***(yogenic)***D***(ark)***M***(atter)***S***(earch) (Soudan), Xenon…..

nucleus/nucleon recoil deposits energy in a semiconductor (Ge), listen to the phonons (CDMS).

Telltale: seasonal variation as the Earth moving around the sun``sweeps'' through the DM halo.

Axion-Photon conversion in B-fields (Primakoff) (CDMS,Pvlas)

Indirect

Wimp-Wimp annihilation → e^+e^- ***Excess positrons*** — Pamela, Heat (satellites)

Wimp-Wimp annihilation → $\gamma\,\gamma$ ***hard gammas (>50 GeV)*** — Glast/Fermi (FGST) (sat).

Wimp-Wimp annihilation → $\bar{\nu}\nu$ — Amanda,Antares,IceCube

(neutrino detectors)

Sterile neutrinos: $\nu_s \rightarrow \nu_a + \gamma$

X-ray background: Chandra, XMM/Newton, Integral (sats), constrain M, mixing angle

→ M from Lyman-alpha forest, phase space density of dSphs, ~ 1-10 keV

Reports:

DAMA/NaI –DAMA/LIBRA report annual modulation consistent with DM signal

Negative results from CDMS, CDMSII,Xenon…controversial!!

Pamela, Heat report excess of positrons, DM signal expected from WIMP annihilation (???)

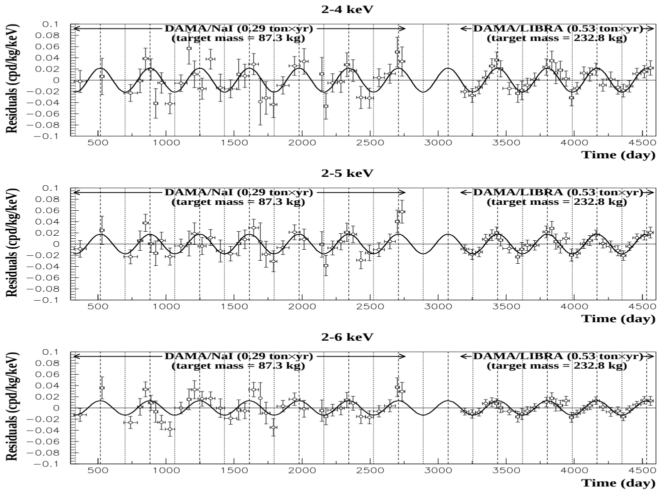


Figure 2: Model-independent residual rate of the *single-hit* scintillation events, measured by the new DAMA/LIBRA experiment in the (2 – 4), (2 – 5) and (2 – 6) keV energy intervals as a function of the time. The residuals measured by DAMA/NaI and already published in ref. [4, 5] are also shown. The zero of the time scale is January 1^{st} of the first year of data taking of the former DAMA/NaI experiment. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves represent the cosinusoidal functions behaviours $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, with a phase $t_0=152.5$ day (June 2^{nd}) and with modulation amplitudes, A, equal to the central values obtained by best fit over the whole data, that is: (0.0215 ± 0.0026) cpd/kg/keV, (0.0176 ± 0.0020) cpd/kg/keV and (0.0129 ± 0.0016) cpd/kg/keV for the (2 – 4) keV, for the (2 – 5) keV and for the (2 – 6) keV energy intervals, respectively. See text. The dashed vertical lines correspond to the maximum of the signal (June 2^{nd}), while the dotted vertical lines correspond to the minimum. The total exposure is 0.82 ton×yr.

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X-ray Bckrd (Chandra,XMM Newton, Integral), constrain mass/mixing angle of sterile neutrinos: M ~ keV, also Lyman-alpha (although some tension)!

Summary: Dark Matter, a mystery we can believe in…

- A window to physics beyond the standard model
- A convergence between particle physics, statistical mechanics, astrophysics, cosmology
- Satellites, accelerators, underground (and under-ice) detectors are the instruments for discovery.
- Large scale numerical simulations yield unprecedented picture of structure (and galaxy) formation.

Knowledge will emerge NOT from a single approach but by a combination of space and earth based observations.

We live in an exciting time, breakthroughs and discoveries are right around the corner. !!