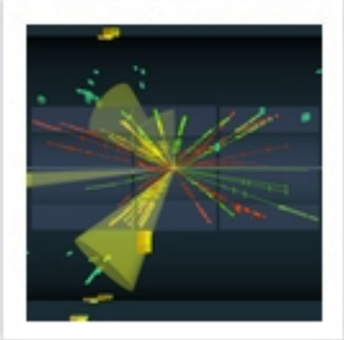

TAE 2023 - International Workshop on High Energy Physics
Sep 03 - 16, 2023

CENTRO DE CIENCIAS
DE BENASQUE
PEDRO PASCUAL

Dark Matter

María Martínez
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mariam@unizar.es

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Bibliography

An Introduction:

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Some lectures:

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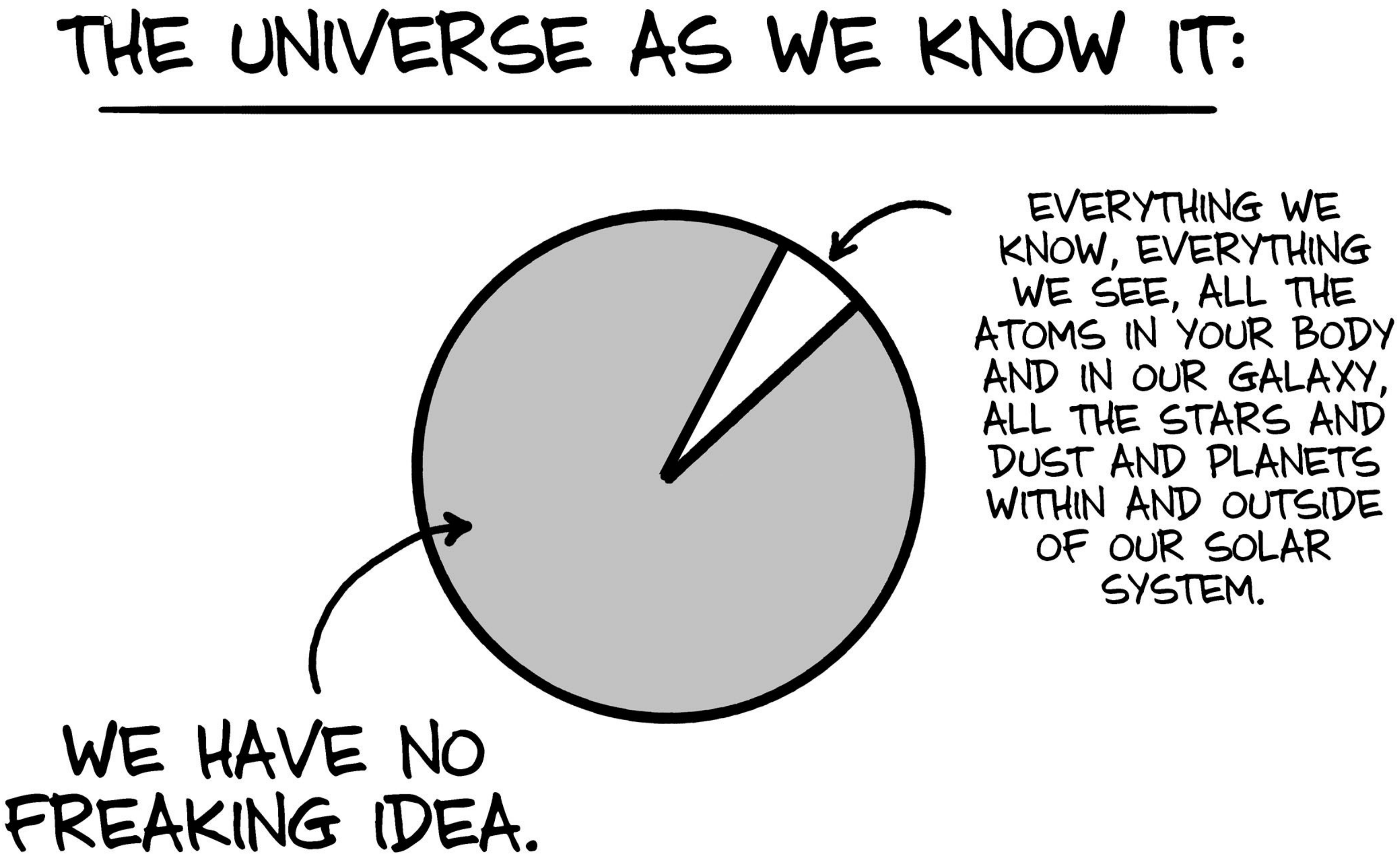
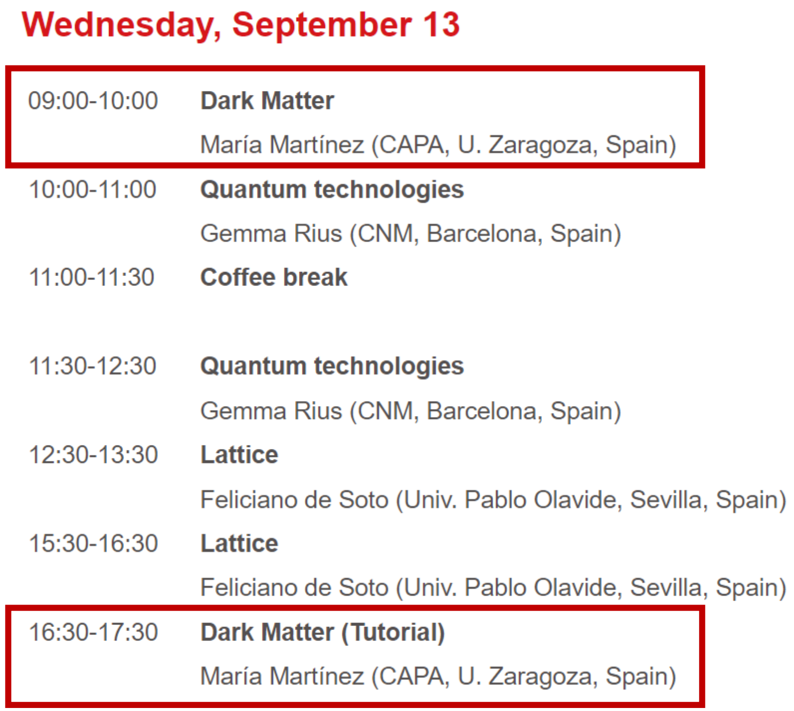


https://phdcomics.com/noidea/

Presentation



Wednesday, September 13

09:00-10:00	**Dark Matter** María Martínez (CAPA, U. Zaragoza, Spain)
10:00-11:00	**Quantum technologies** Gemma Rius (CNM, Barcelona, Spain)
11:00-11:30	**Coffee break**
11:30-12:30	**Quantum technologies** Gemma Rius (CNM, Barcelona, Spain)
12:30-13:30	**Lattice** Feliciano de Soto (Univ. Pablo Olavide, Sevilla, Spain)
15:30-16:30	**Lattice** Feliciano de Soto (Univ. Pablo Olavide, Sevilla, Spain)
16:30-17:30	**Dark Matter (Tutorial)** María Martínez (CAPA, U. Zaragoza, Spain)

Thursday, September 14

09:00-10:00	**Future detectors** Ivan Vila (IFCA, CSIC, Santander, Spain)
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3h theory + 1h tutorial

Aim: to provide you with a general idea of the dark matter problem status / best candidates / detection prospects

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Friday, September 15

09:00-10:00	**Axions** Maurizio Giannotti (CAPA, U. Zaragoza, Spain)
10:00-11:00	**Axions** Maurizio Giannotti (CAPA, U. Zaragoza, Spain)
11:00-11:30	**Coffee break**
11:30-12:30	**Flavour / LHCb** Jeremy Peter Dalseno (IGFAE, U.Santiago de Compostela)
12:30-13:30	**Flavour / LHCb** Jeremy Peter Dalseno (IGFAE, U. Santiago de Compostela)
15:30-16:30	**Cosmology** Jacobo Asorey (IPARCOS, U. Complutense, Madrid, Spain)
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Axions: one of the most promising DM candidate

3h theory + 1h tutorial

Aim: to provide you with a general idea of the dark matter problem status / best candidates / detection prospects

Program

I. Dark Matter evidences
II. Dark Matter candidates
III. Dark Matter (WIMPs & light DM) detection

Please, don’t be afraid to interrupt and ask during the lectures
I’ll be around till Friday afternoon
After that: mariam@unizar.es

Lecture I

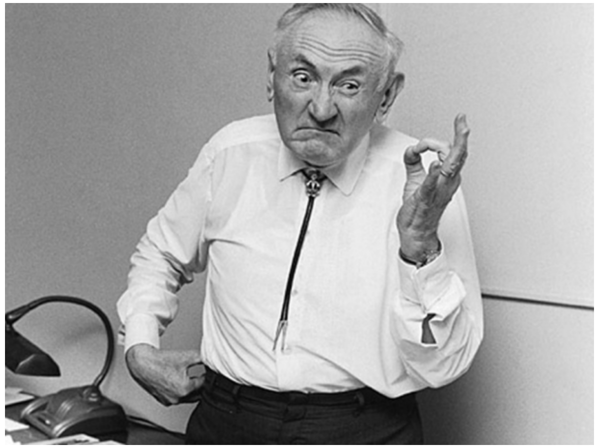
Dark Matter Evidences

Brief history of Dark Matter

1930s: First evidences, but no body cares
1970s: Serious evidences: galaxy rotation curves are flat!
1980s: People convince themselves that there are a lot of invisible matter around… or gravity doesn’t work as we thought (MOND)
1980-1984: light neutrinos (hot dark matter) proposed & ruled out as DM
1984: Cold dark matter theory (CDM) [THE DARK MATTER DETECTION RACE STARTS!]
1992: First COBE data agrees with CDM
1998: SNIa: first evidence of Dark Energy
2000: ΛCDM becomes the standard cosmological model
2003-2008: WMAP & LSS confirm ΛCDM predictions
2004: Cluster bullet observation discards (completely?) MOND
2013: PLANCK data release:
4.82%±0.05% ordinary matter, 26.8%±0.4% dark matter and 69%±1% dark energy

Early days

- Discrepancies between the quantity of gravitating and luminous matter: Öpik (1915), Kapteyn (1922), Jeans (1922), Oort (1932)
- Most solid evidence provided by Fritz Zwicky, 1933. Using the Virial theorem in the Coma Cluster, Zwicky finds that galaxies are moving too rapidly to remain bound solely by the visible mass.



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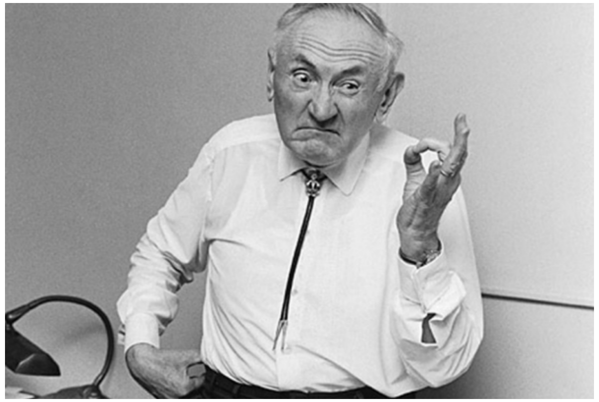
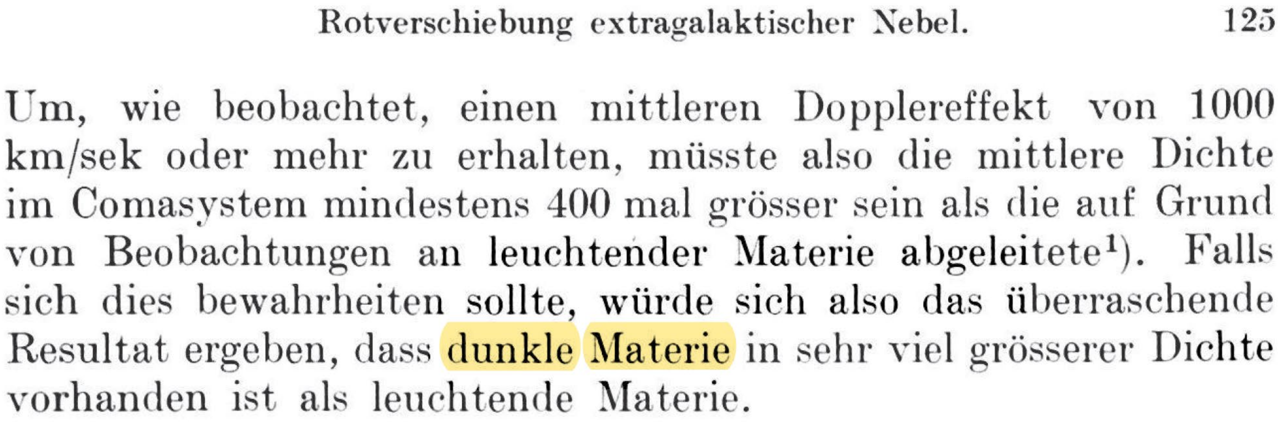


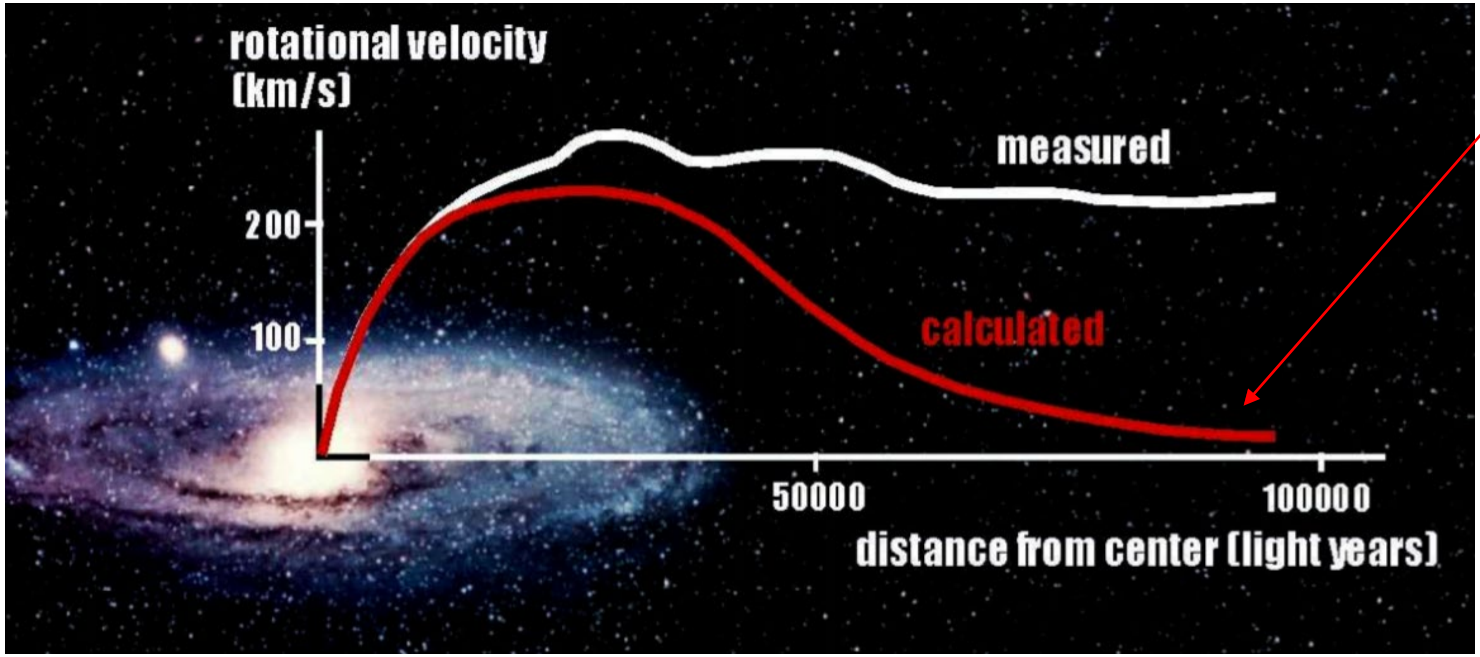


Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete1). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Galaxy rotation curves

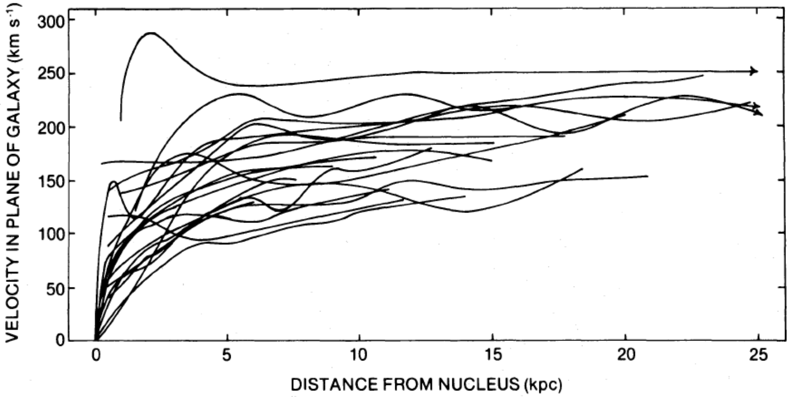
Vera Rubin et al. (1970-1980)



Newton predicts:

$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

…but measured curves remain flat



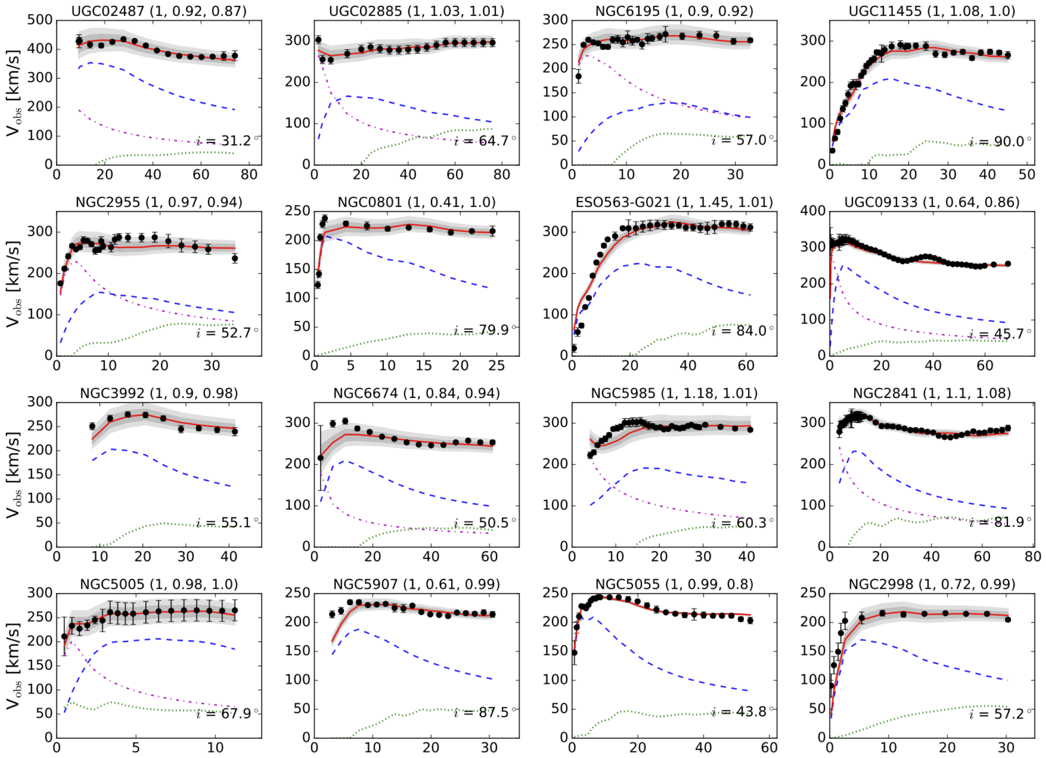
V. C. Rubin, N. Thonnard, and W. K. Ford, Jr., “Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 (R = 4kpc)to UGC 2885 (R = 122 kpc)," Astrophys. J. 238 (1980) 471.

Galaxy rotation curves

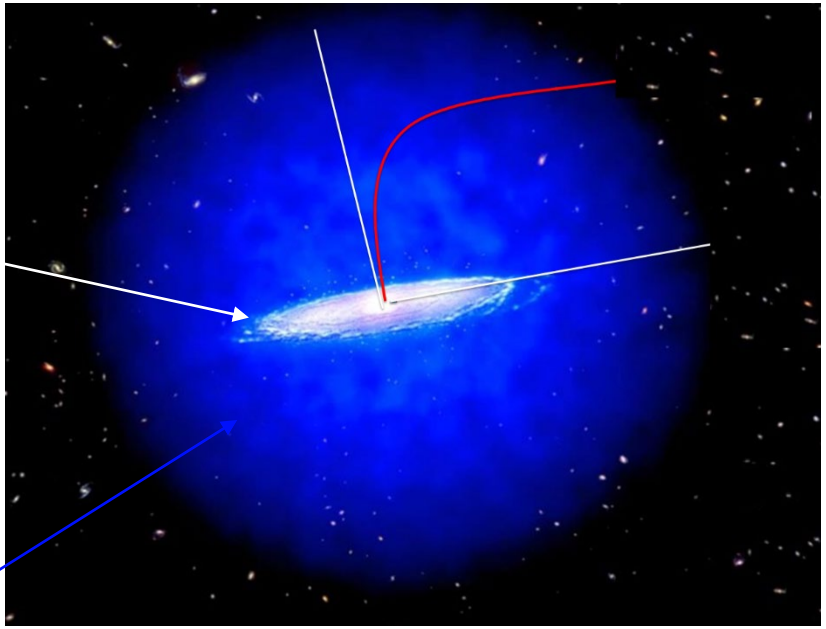
Two possibilities to solve the problem:

Modify gravity law

MOND (MOdified Newtonian Dynamics)



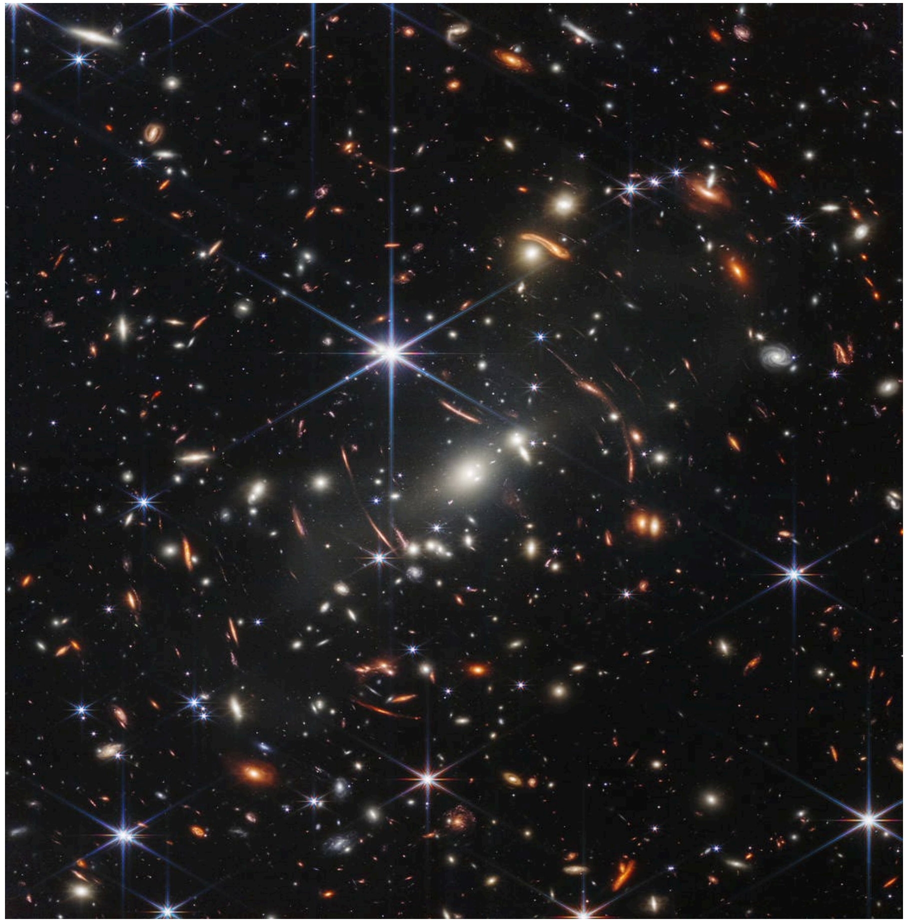
Add more matter (DM)



Galaxy (luminous stars)

Dark Matter

Gravitational lensing

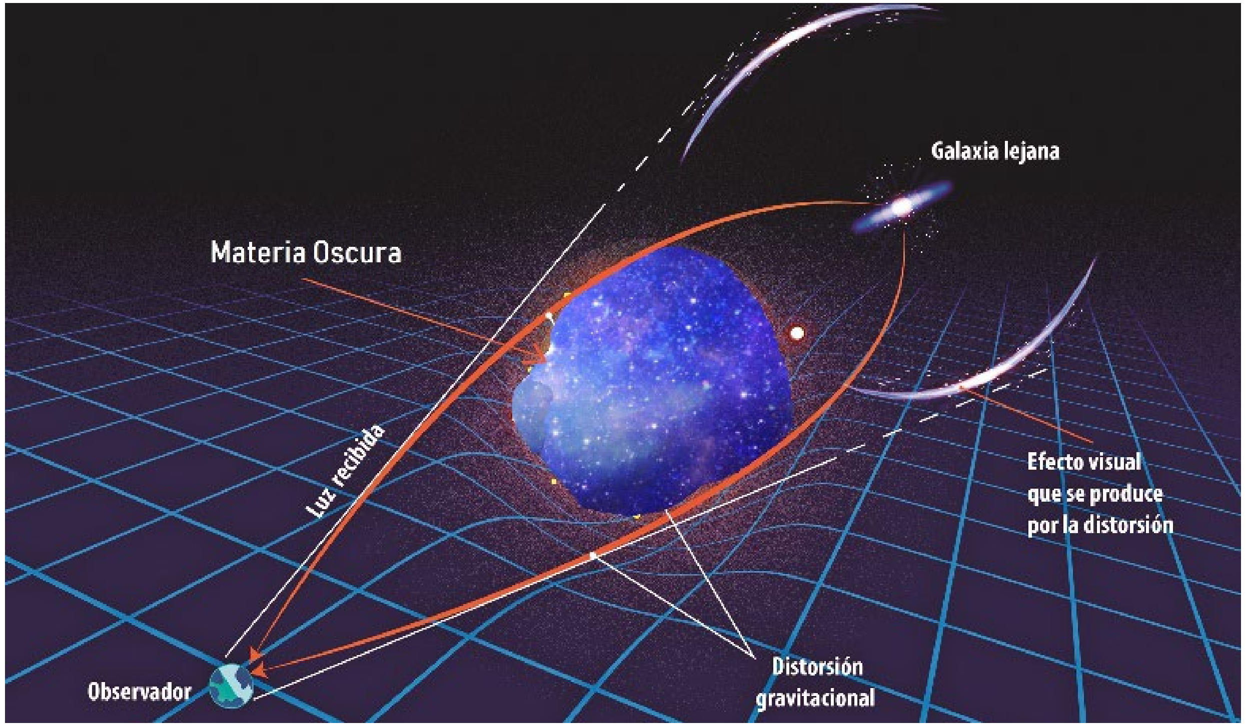


JWST, galaxy cluster SMACS 0723

https://www.nasa.gov/webbfirstimages

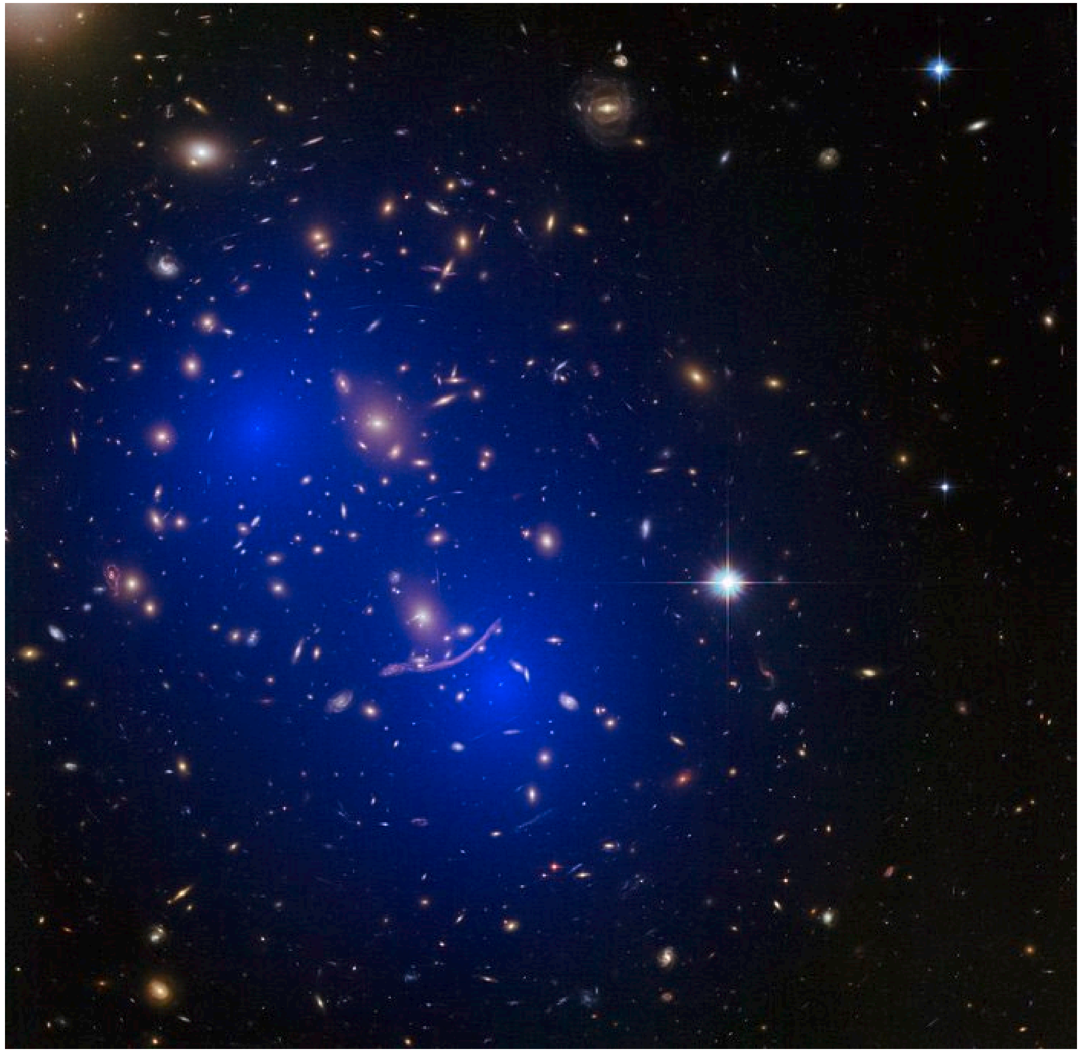
Credits: NASA, ESA, CSA, and STScI

DM gravity deflects the light from a distant source
From these distortions we can infer a DM map



Gravitational lensing

Galaxy cluster Abell 370 with dark matter map



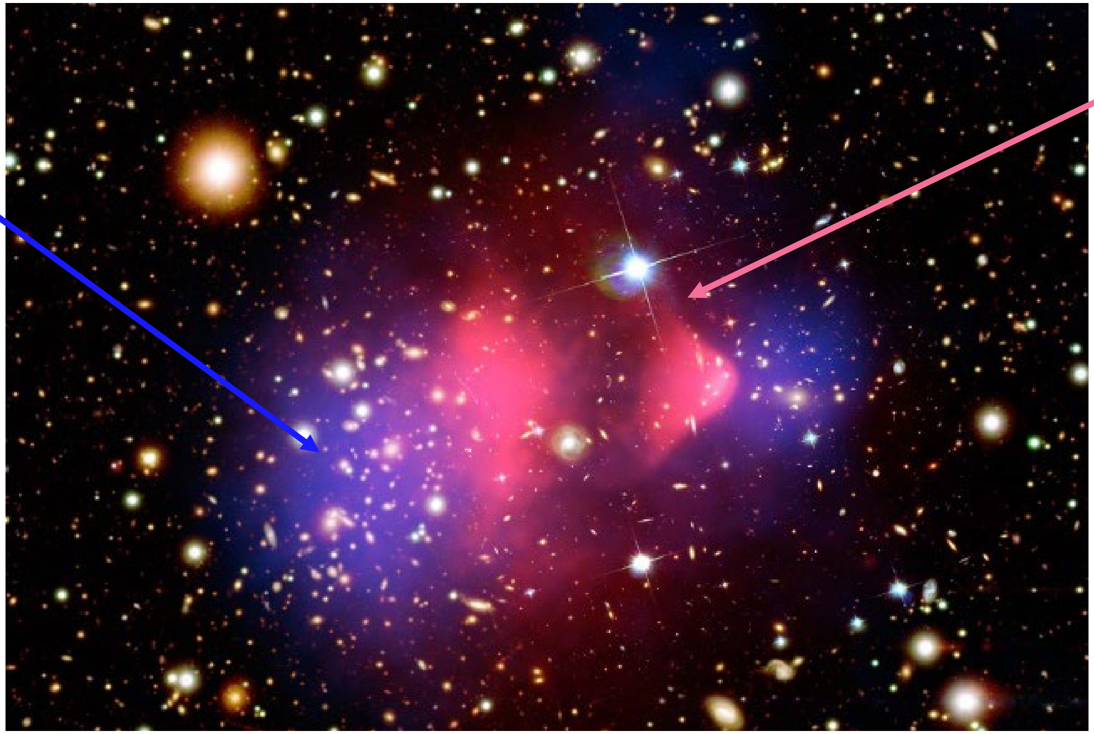
NASA, ESA, D. Harvey (École Polytechnique Fédérale de Lausanne, Switzerland), R. Massey (Durham University, UK), the Hubble SM4 ERO Team and ST-ECF

Bullet cluster (2004)

https://viewspace.org/interactives/unveiling_invisible_universe/dark_matter/bullet_cluster

bullet cluster (1E0657-558) (2004)

Gravitational lensing shows that most of the total mass moved ballistically, indicating that DM self-interactions are indeed weak



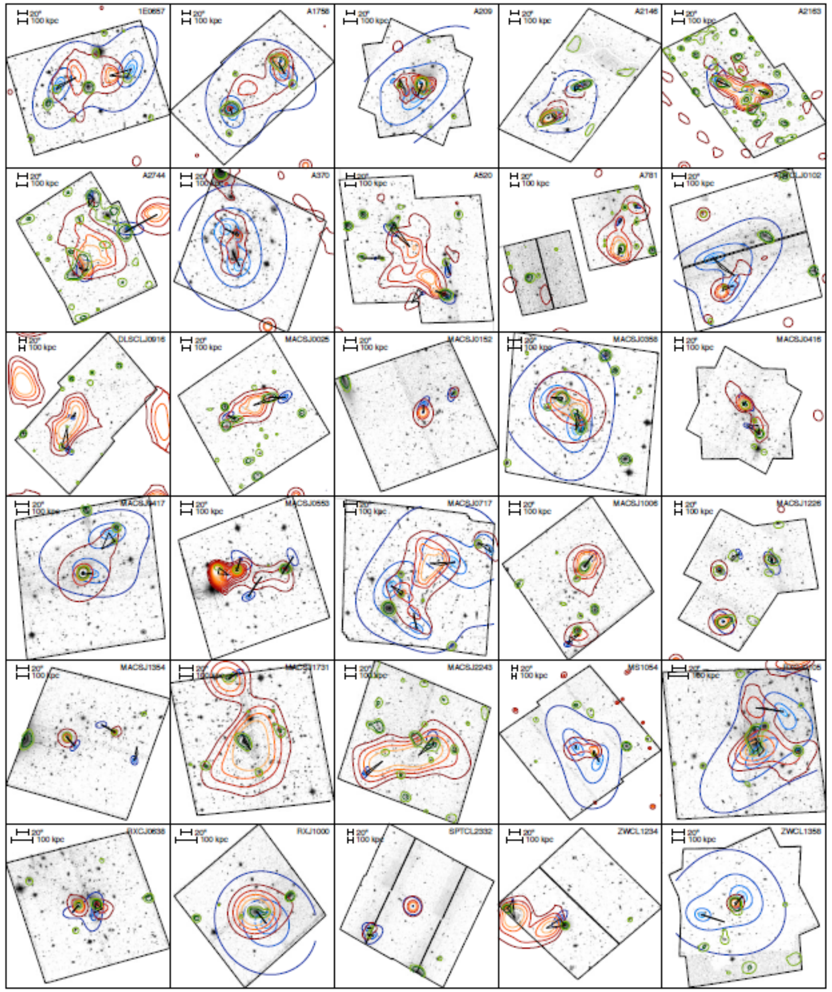
hot gas forming most of the clusters' baryonic mass is shocked and decelerated

Constrain in self-interacting cross section for long-range forces

$$\sigma_{DM}/m < 1.25\ cm^2/g$$

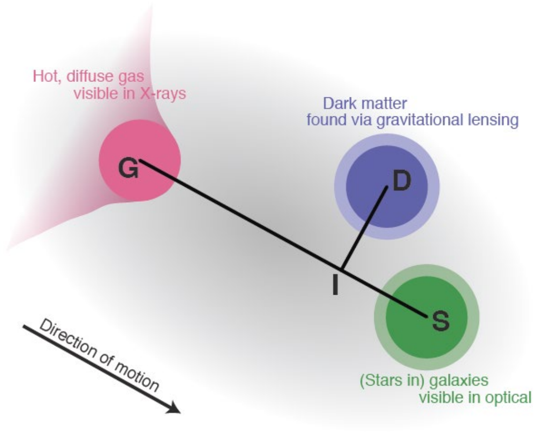
Direct evidence of DM is of a different nature (collisionless, non-baryonic) that visible matter.
Cannot be explained with MOND (need 2-3 times more mass)

Colliding galaxy clusters



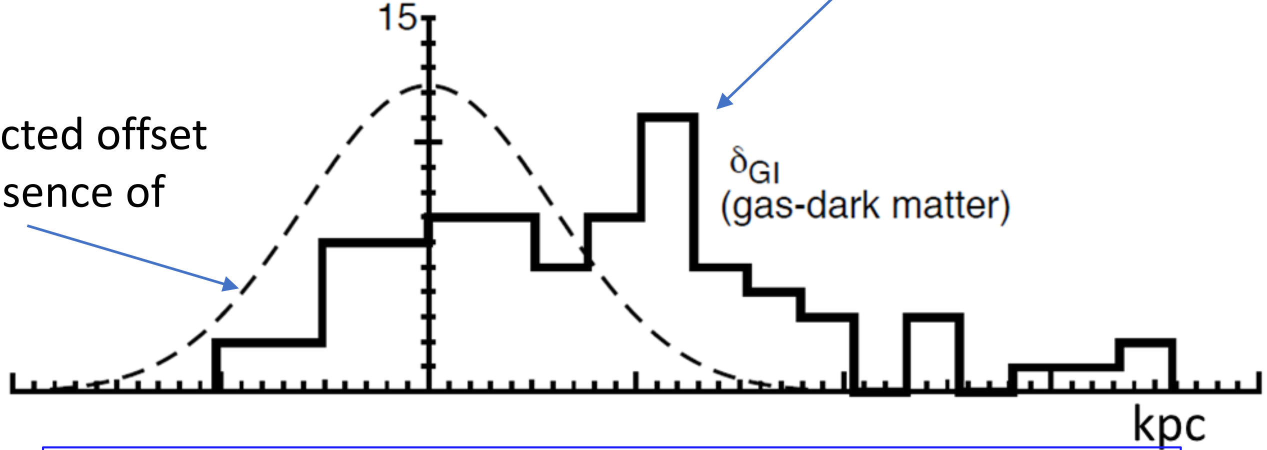
Harvey et al., Science, 1503.07675

Harvey et al studied 72 colliding galaxy clusters



Observed offset between gas and mass

Expected offset in absence of DM



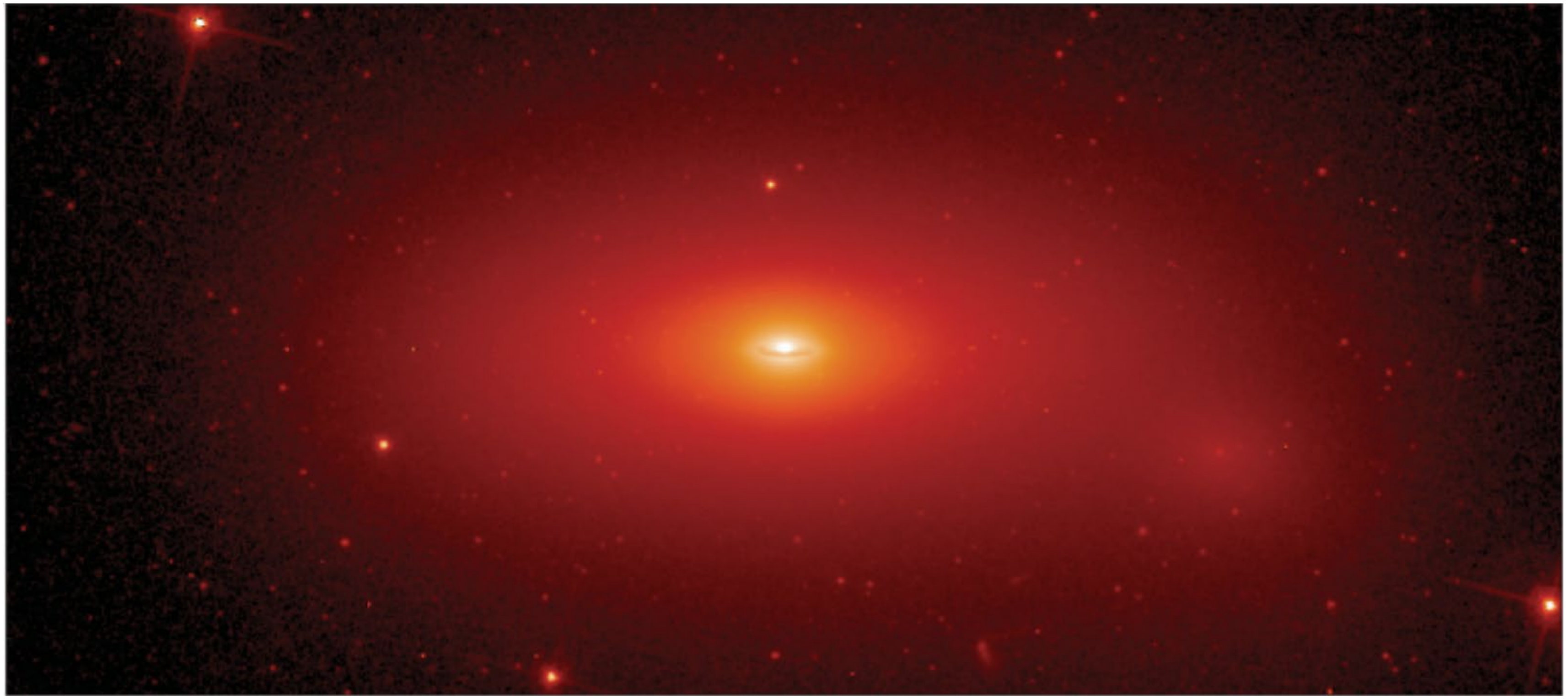
> *"The hypothesis that dark matter does not exist is inconsistent with the data at 7.6 statistical significance"*

$\sigma_{DM}/m < 0.47\ cm^2/g$ (95% CL)

Galaxies without DM

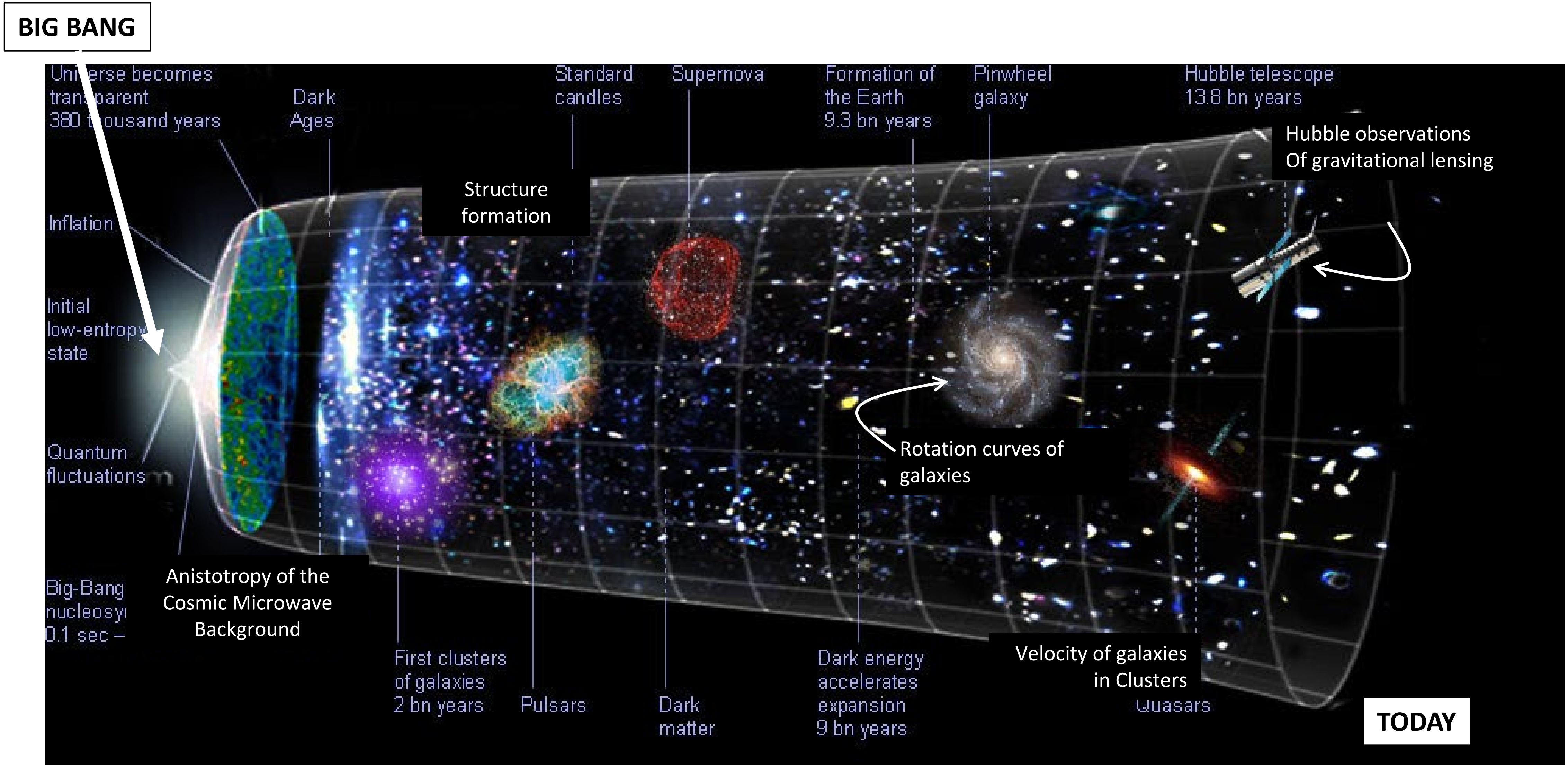
“The massive relic galaxy NGC 1277 is dark matter deficient”

Comeron et al, Astron.Astrophys. 675 (2023) A143, 2303.11360



“Although the dark matter in a specific galaxy can be lost, a modified law of gravity must be universal, it cannot have exceptions, so that a galaxy without dark matter is a refutation of this type of alternatives to dark matter”
I. Trujillo

Dark Matter Evidences at cosmological scales



BIG BANG

Structure formation

Hubble observations
Of gravitational lensing

Rotation curves of galaxies

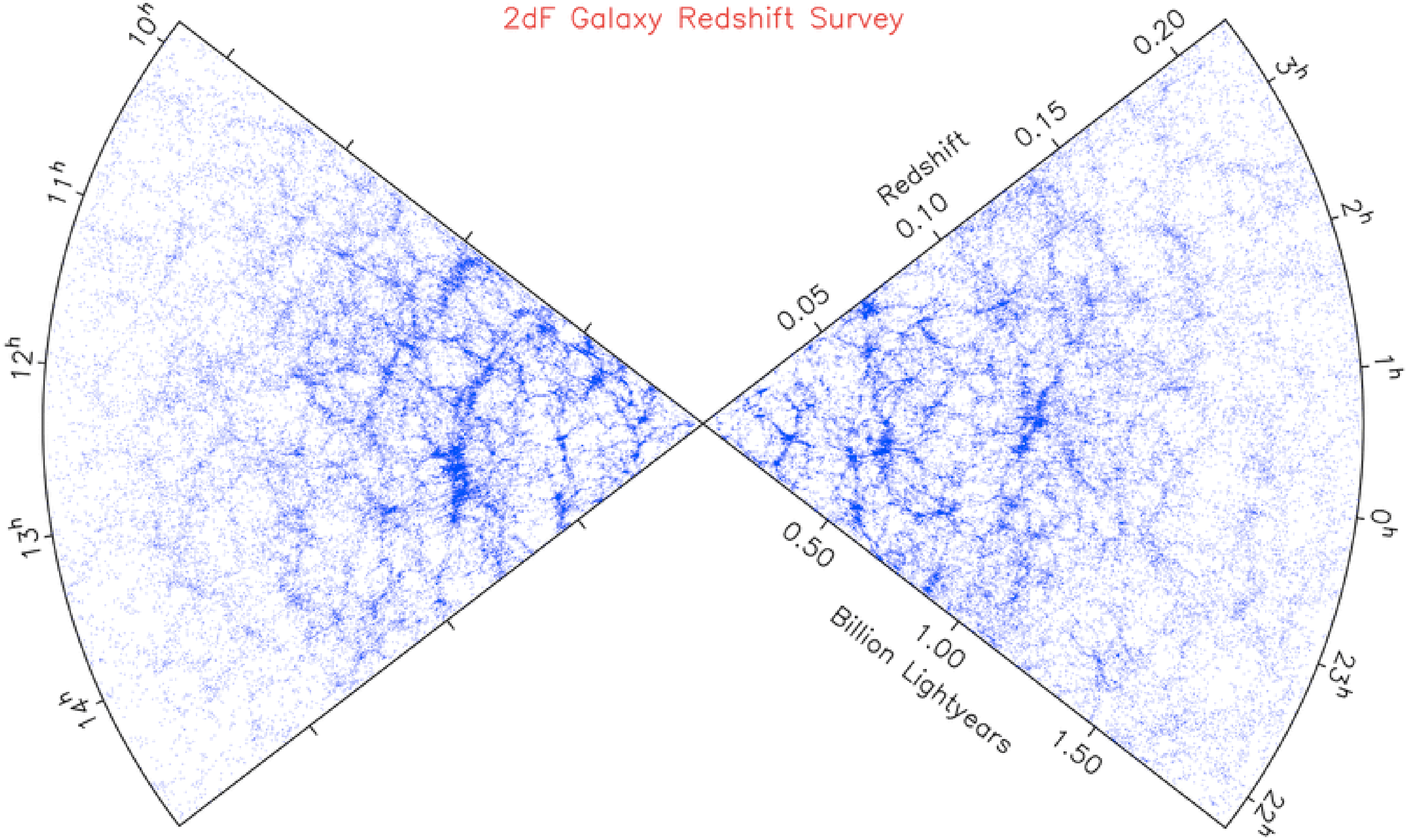
Anistotropy of the Cosmic Microwave Background

Velocity of galaxies in Clusters

TODAY

Large Scale Structure (LSS)

. Large galaxy surveys are mapping the Universe, like the 2-degree Field Galaxy Redshift Survey (2dFGRS), or the Sloan Digital Sky Survey (SDSS2). Astronomers observe galaxies located at varying distances from Earth, representing different points in the universe's past, thanks to the time it takes for their light to reach us. Through these observations, we can discern that gravity is gradually drawing more and more matter together over time, causing the universe to become increasingly clustered

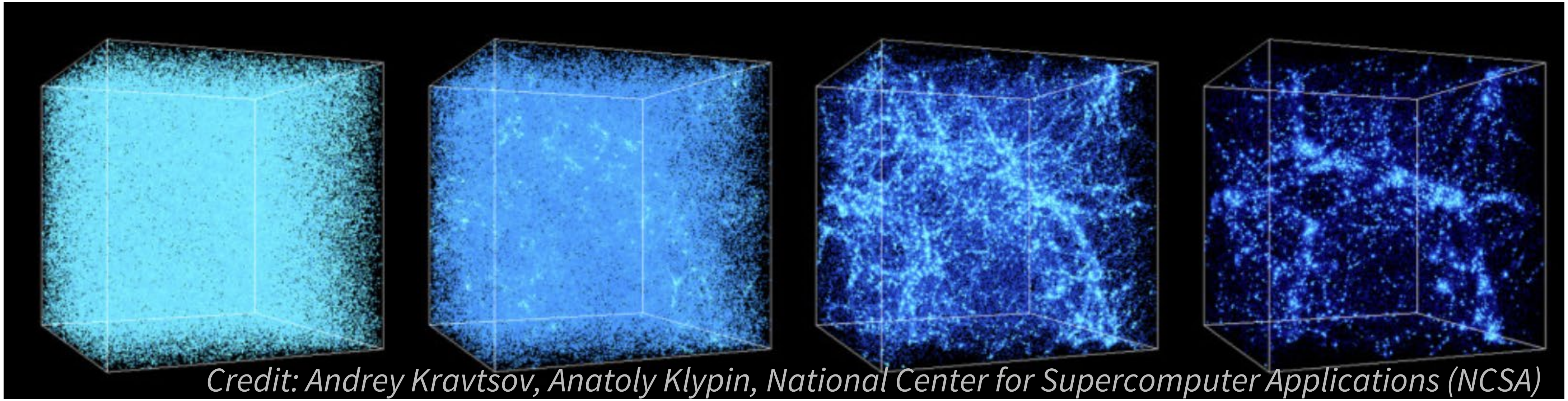


N-body simulations

Numerical simulations for the large-scale structure of the Universe

- pioneering work in the 1980s
- currently testing the ΛCDM model.

Simulations of the expanding Universe (boxes growing in size)



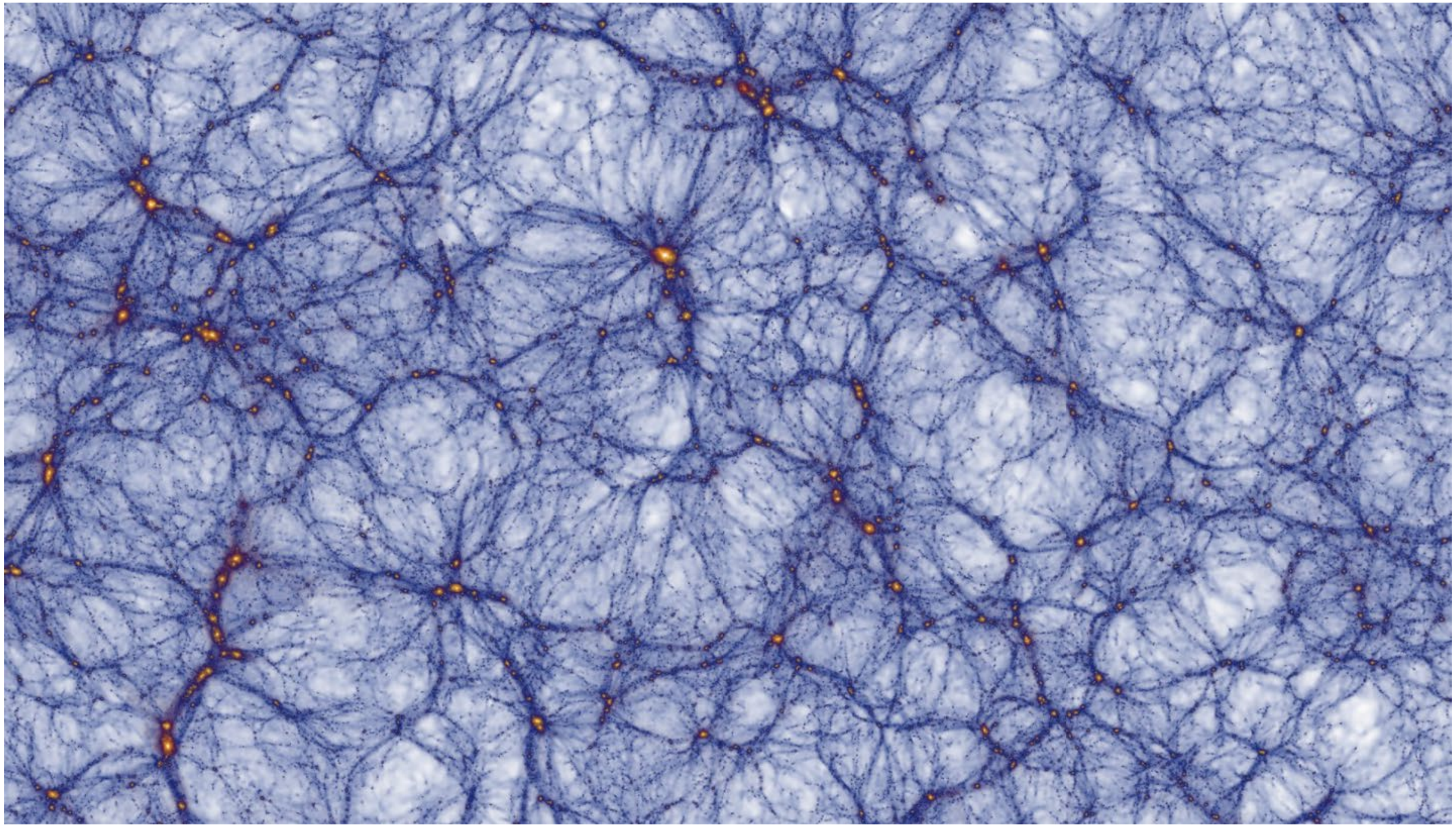
Credit: Andrey Kravtsov, Anatoly Klypin, National Center for Supercomputer Applications (NCSA)

As the Universe expands, gravity pulls together matter into large scale patterns. At present day, structures are much more clustered than in the early in the Universe.

N-body simulations

Millenium XXL simulation
http://galformod.mpa-garching.mpg.de/mxxlbrowser

The simulation follows the nonlinear growth of dark matter structures within a cubical region 4.1096 Gpc on a side. This simulated volume is equivalent to that of the whole observable Universe up to redshift 0.72. The particle mass in the MXXL is $m_p = 8.456\times10^9\ M_{sun}$



Cold, Warm, hot DM

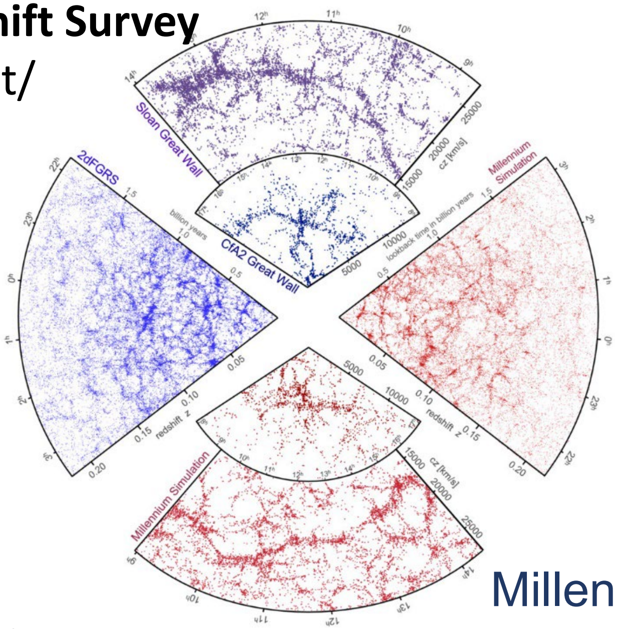
COLD (CDM)
WARM (WDM)
HOT (HDM)

It was moving at

NON-RELATIVISTIC
SEMI-RELATIVISTIC
RELATIVISTIC

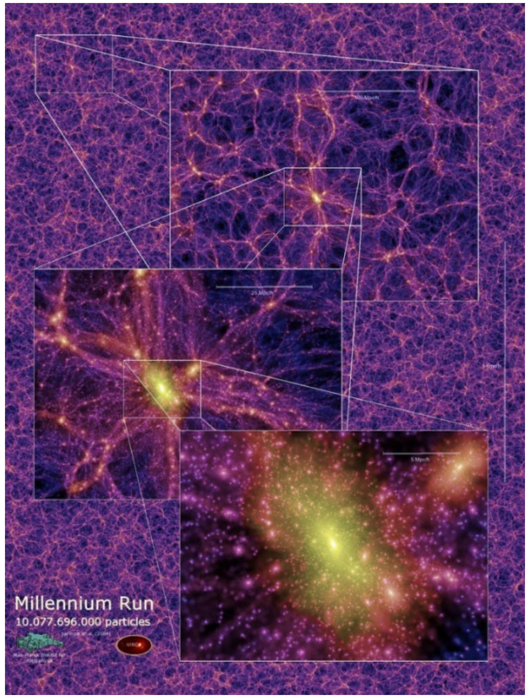
speeds when the structures began to form (T~K)

The 2dF Galaxy Redshift Survey
http://www.2dfgrs.net/

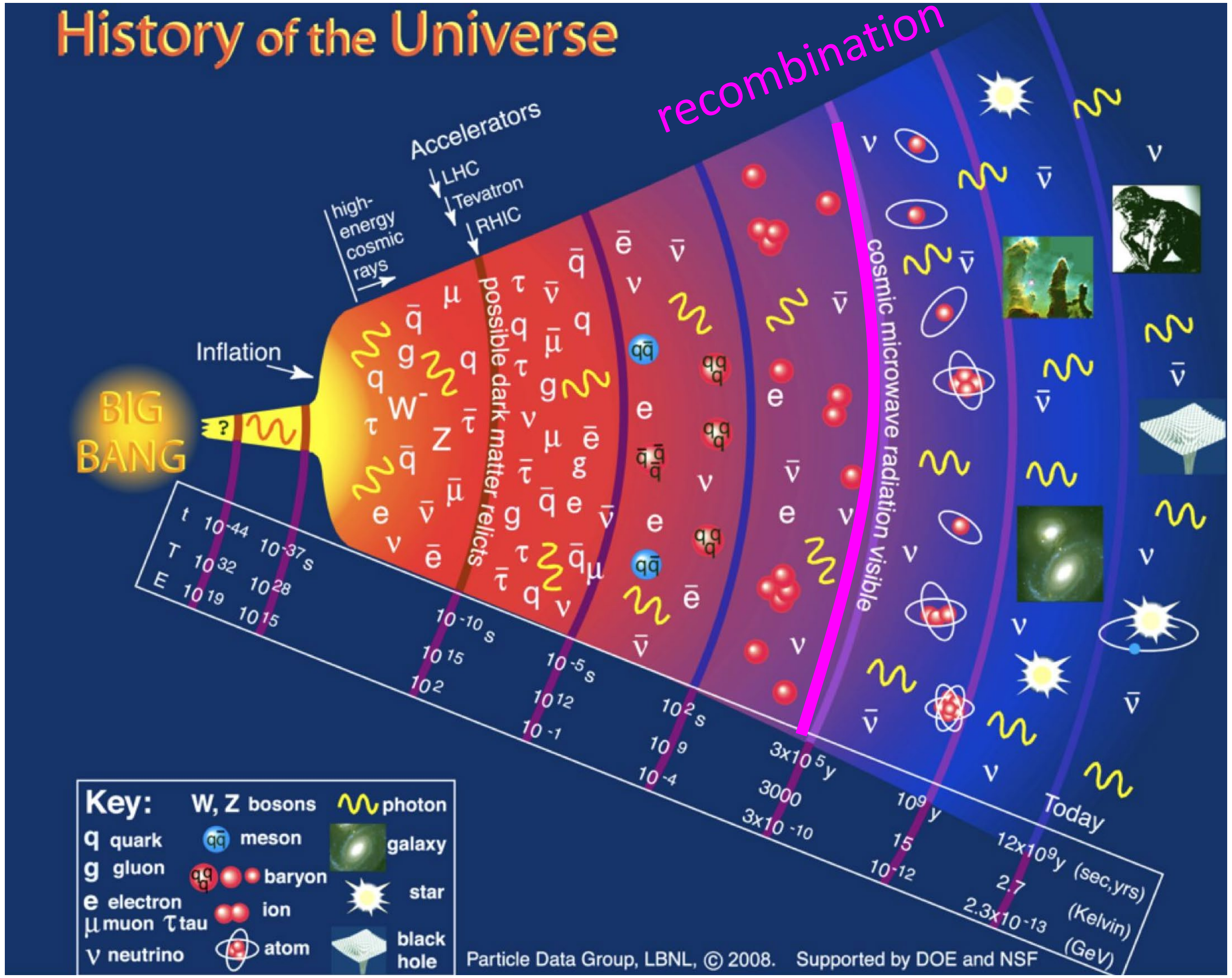


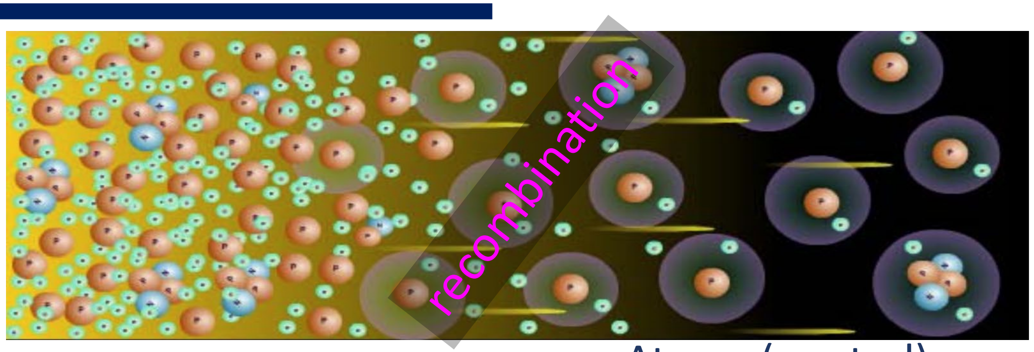
The comparison of the observed distribution of galaxies as a function of their distance (redshift) with the predictions of N-body simulations indicates **that cold (or at most warm) dark matter is required** to form the structures we see today.

Millenium simulation
http://galformod.mpa-garching.mpg.de/mxxlbrowser



Cosmic Microwave Background (CMB) (t ~300.000 y)



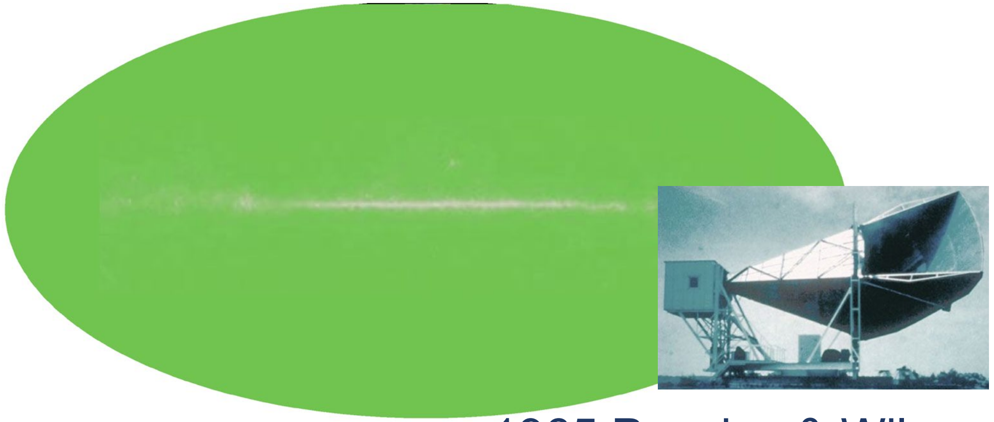


Plasma (e, baryons)
→ Light trapped

$T_R \sim 3000\ K$

Atoms (neutral)
→ Freely propagating photons with blackbody distribution of frequencies

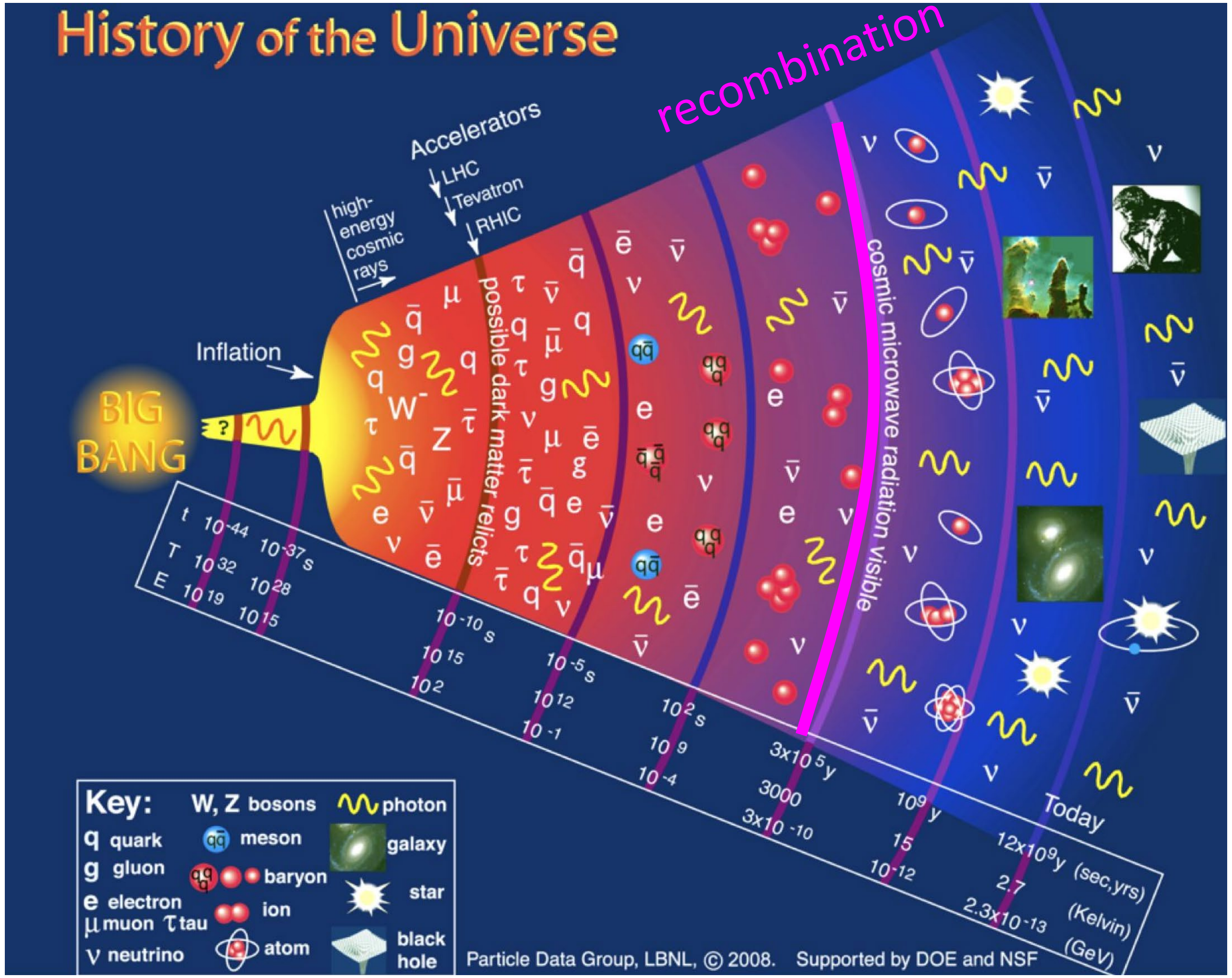
We can detect these photons today shifted to $T \sim 2.73\ K$ (Cosmic microwave background)

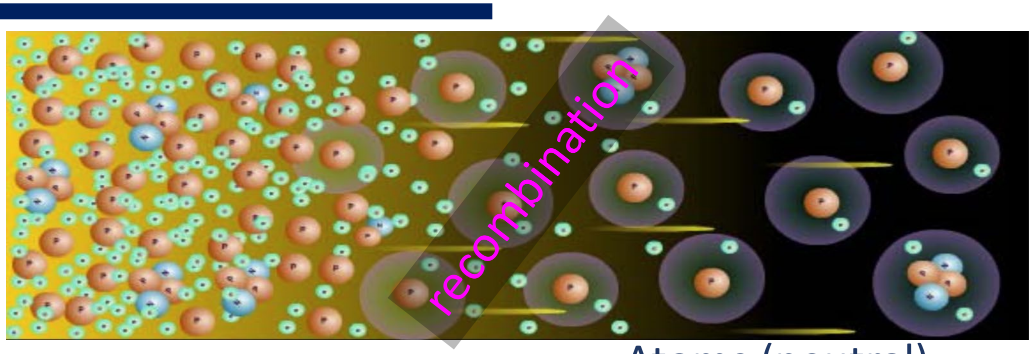


1965 Penzias & Wilson

T= 2.725±0.001 K

Cosmic Microwave Background (CMB) (t ~300.000 y)





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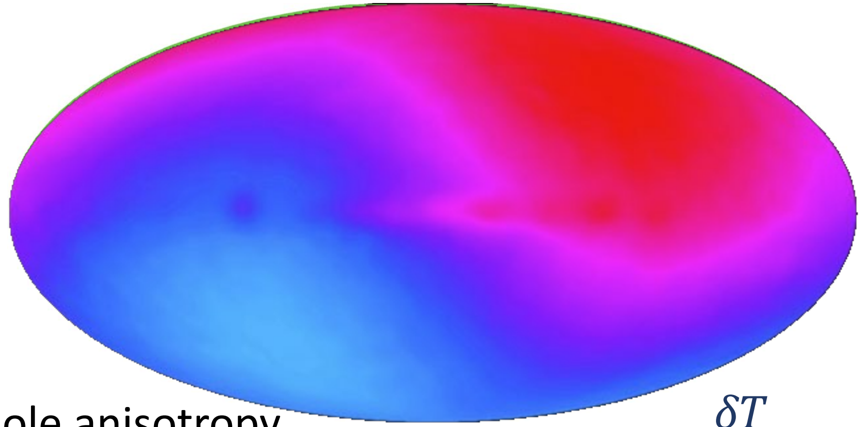
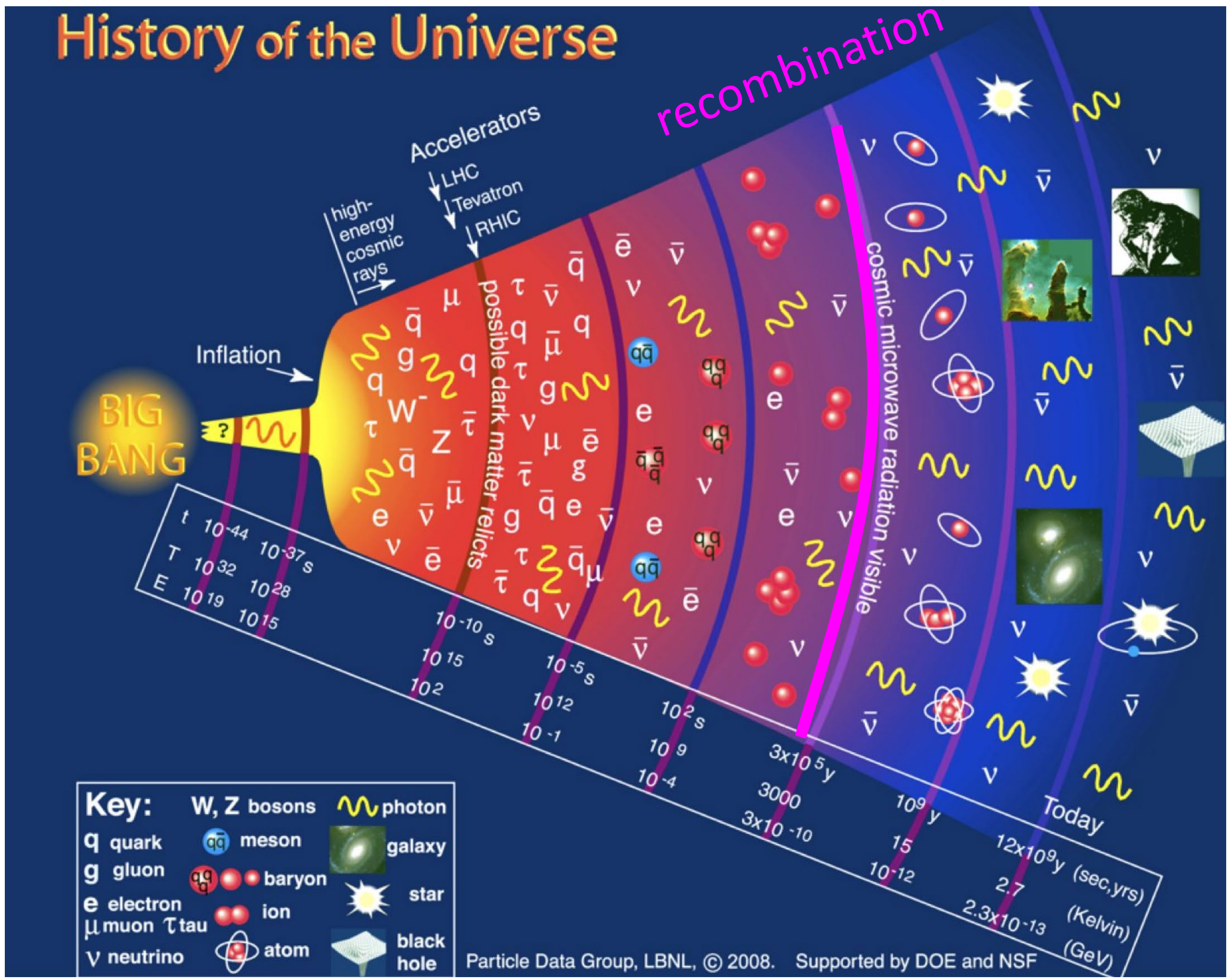
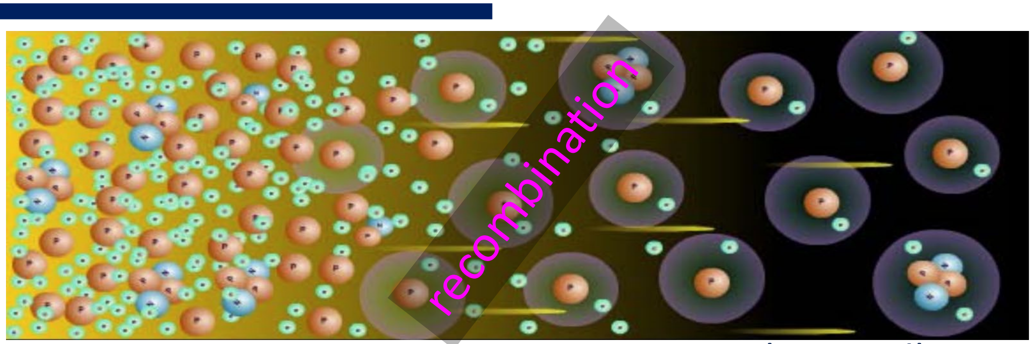


1970: Dipole anisotropy
Due to the movement of the Earth

$$\frac{\delta T}{T} \simeq 10^{-3}$$

Cosmic Microwave Background (CMB) (t ~300.000 y)





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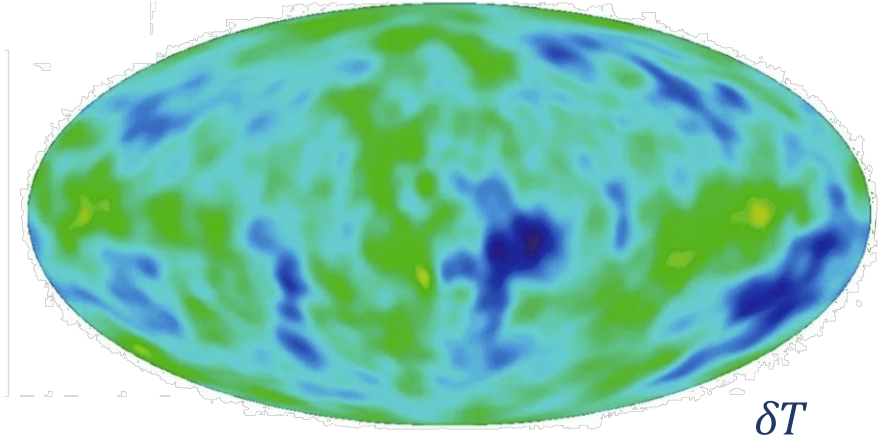
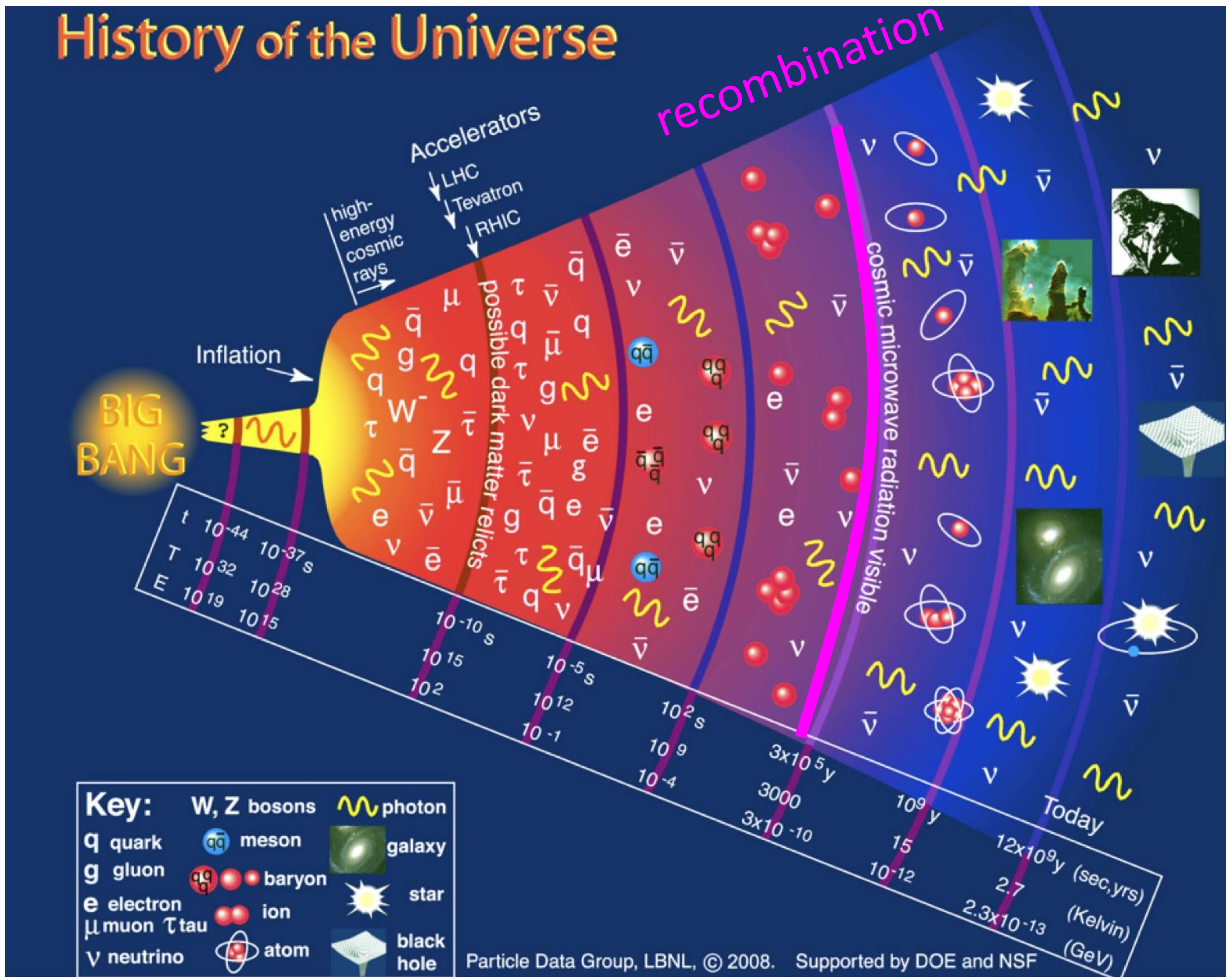


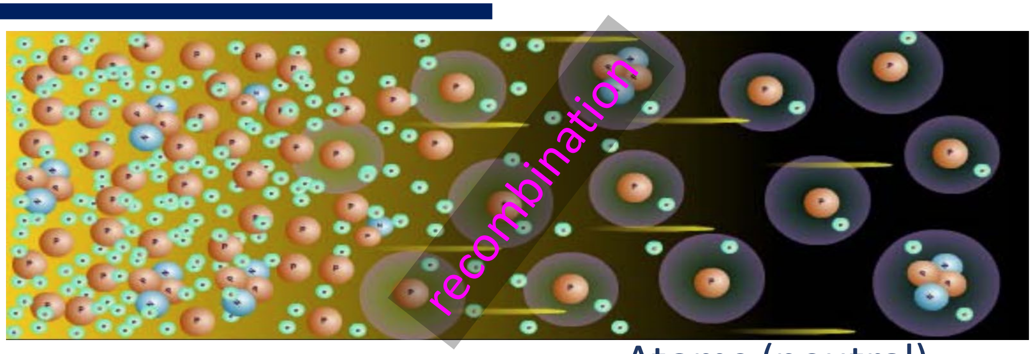
COBE (1992)

$$\frac{\delta T}{T} \simeq 10^{-5}$$

Cosmic Microwave Background (CMB) (t ~300.000 y)



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF



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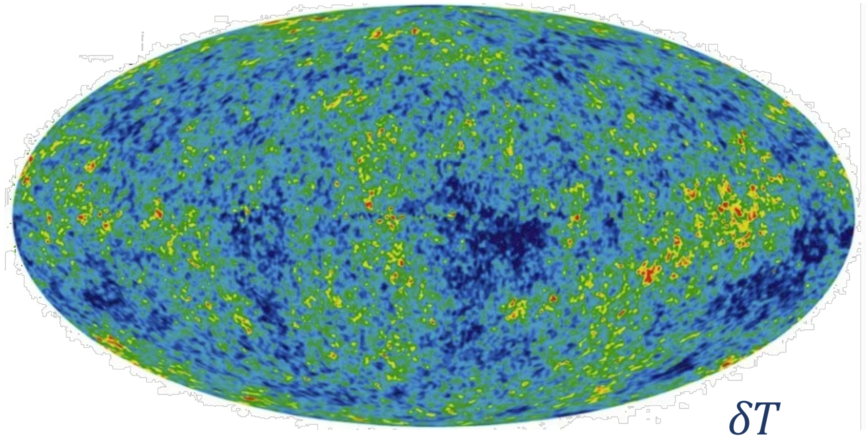
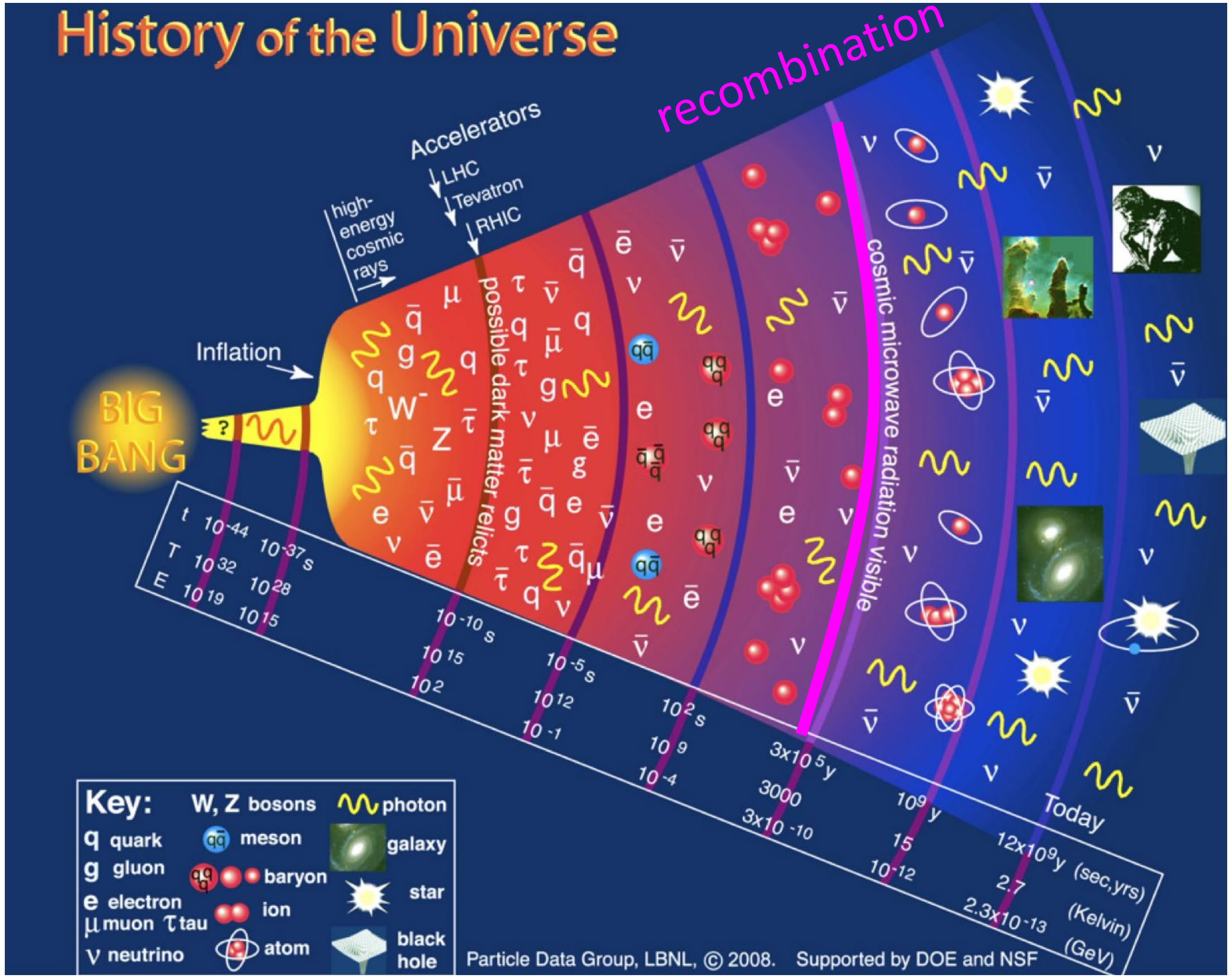
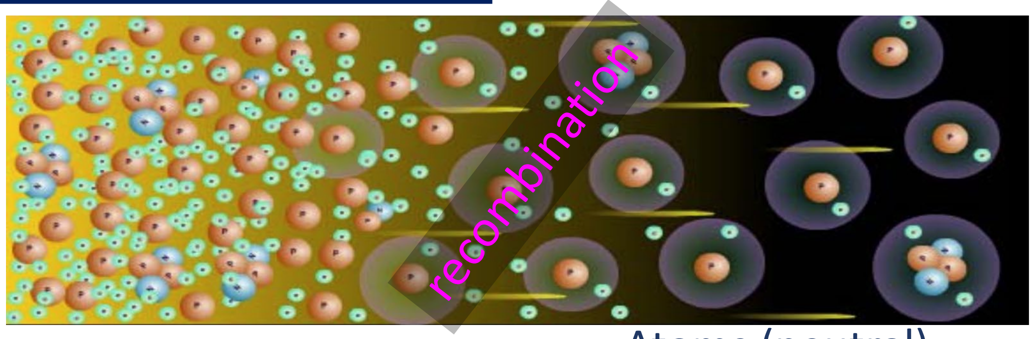


WMAP (2003)

$$\frac{\delta T}{T} \simeq 10^{-5}$$

Cosmic Microwave Background (CMB) (t ~300.000 y)





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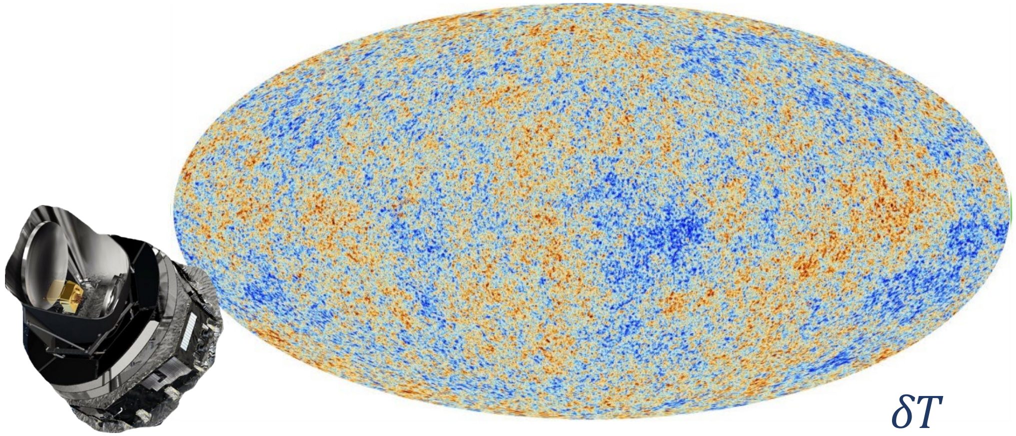
Atoms (neutral)
→ Freely propagating photons with blackbody distribution of frequencies

We can detect these photons today shifted to $T \sim 2.73\ K$ (Cosmic microwave background)



PLANCK (2013)

$$\frac{\delta T}{T} \simeq 10^{-5}$$

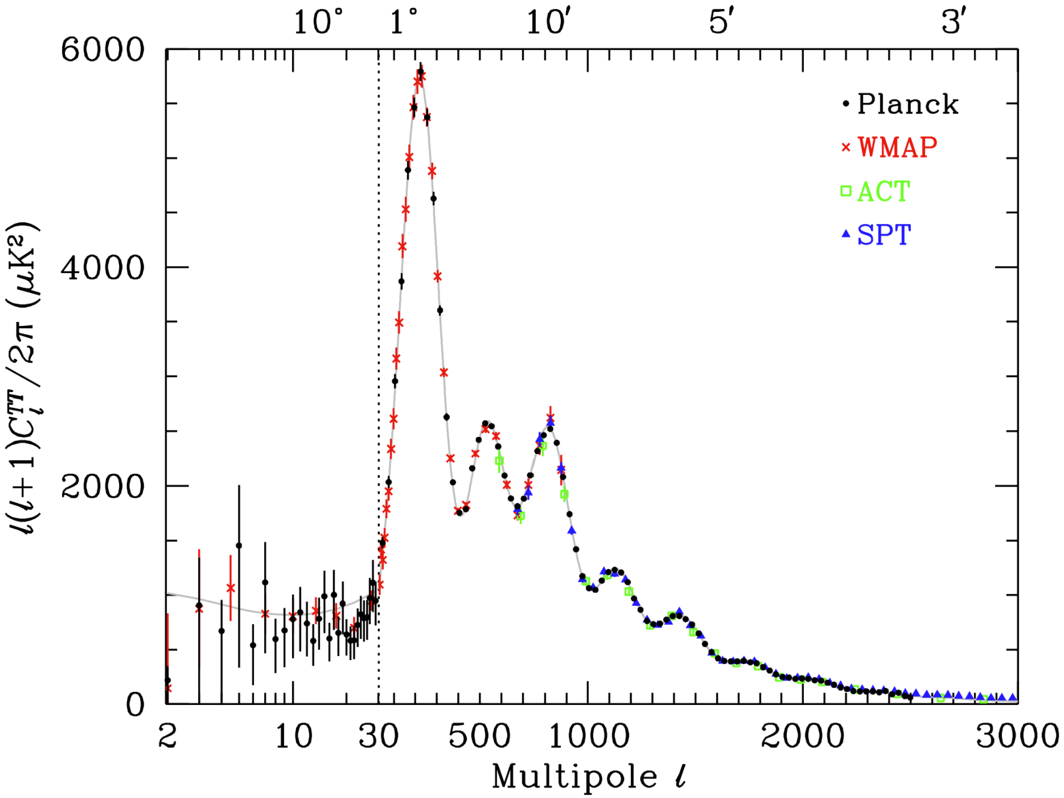
Information in the CMB

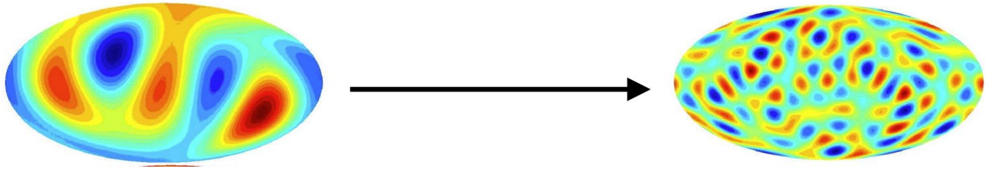
The surface of last scattering appears to us as a spherical surface at

$$1 + z_R = \frac{a(t_0)}{a(t_R)} = \frac{T_R}{T_0} \sim 1100$$

The anisotropies in the CMB can be described by an expansion in spherical harmonics:

$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$



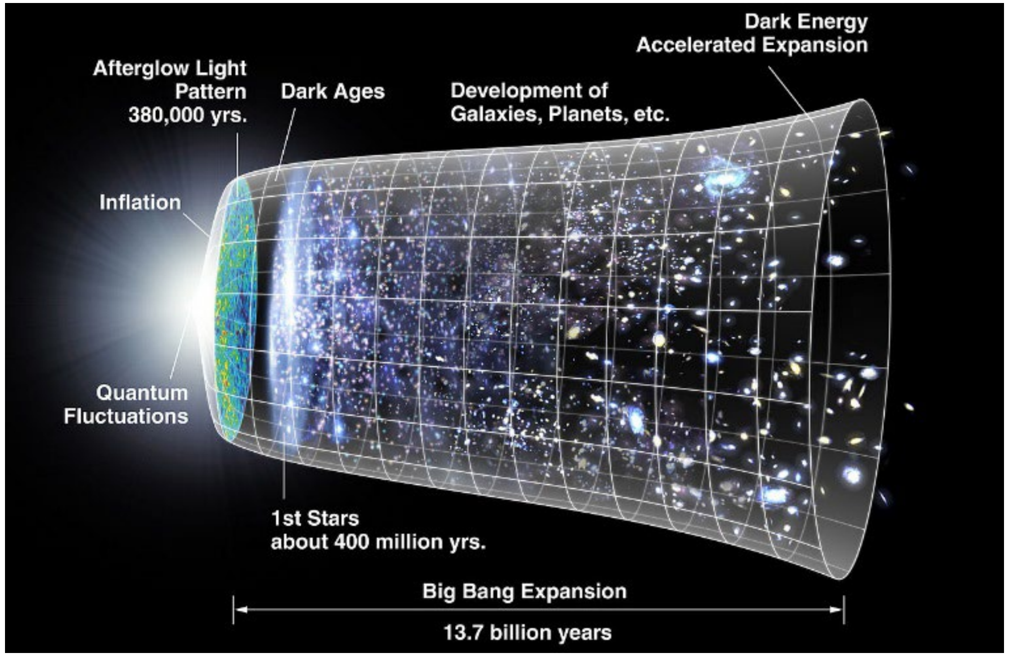


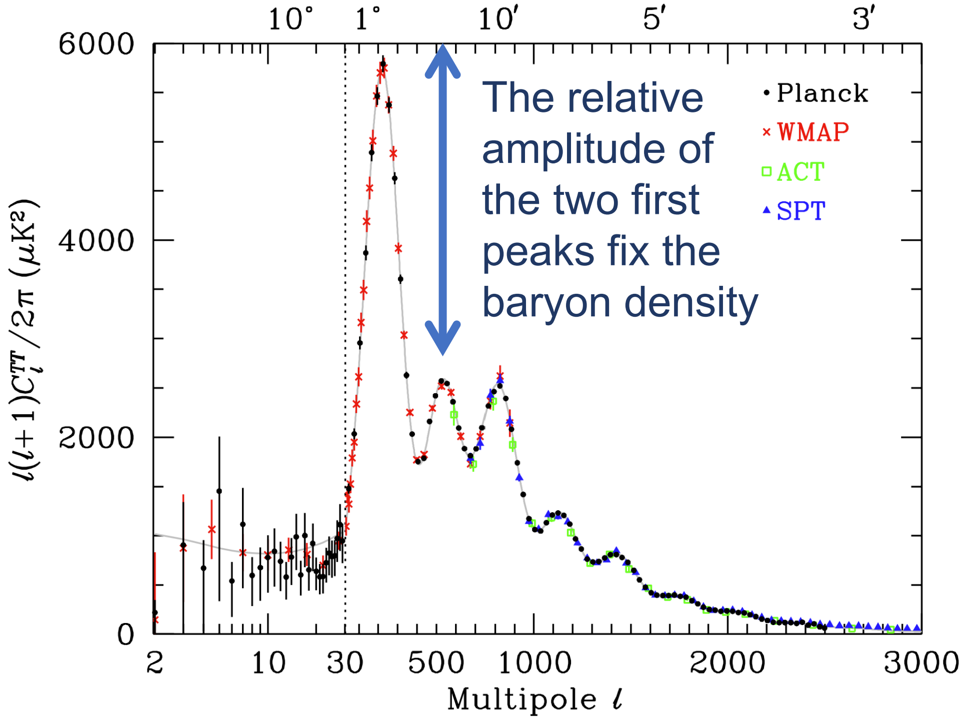
Large scales

Small scales

CMB & structure formation

The formation of structures occurs from small density perturbations, which also give rise to the anisotropies of the CMB.



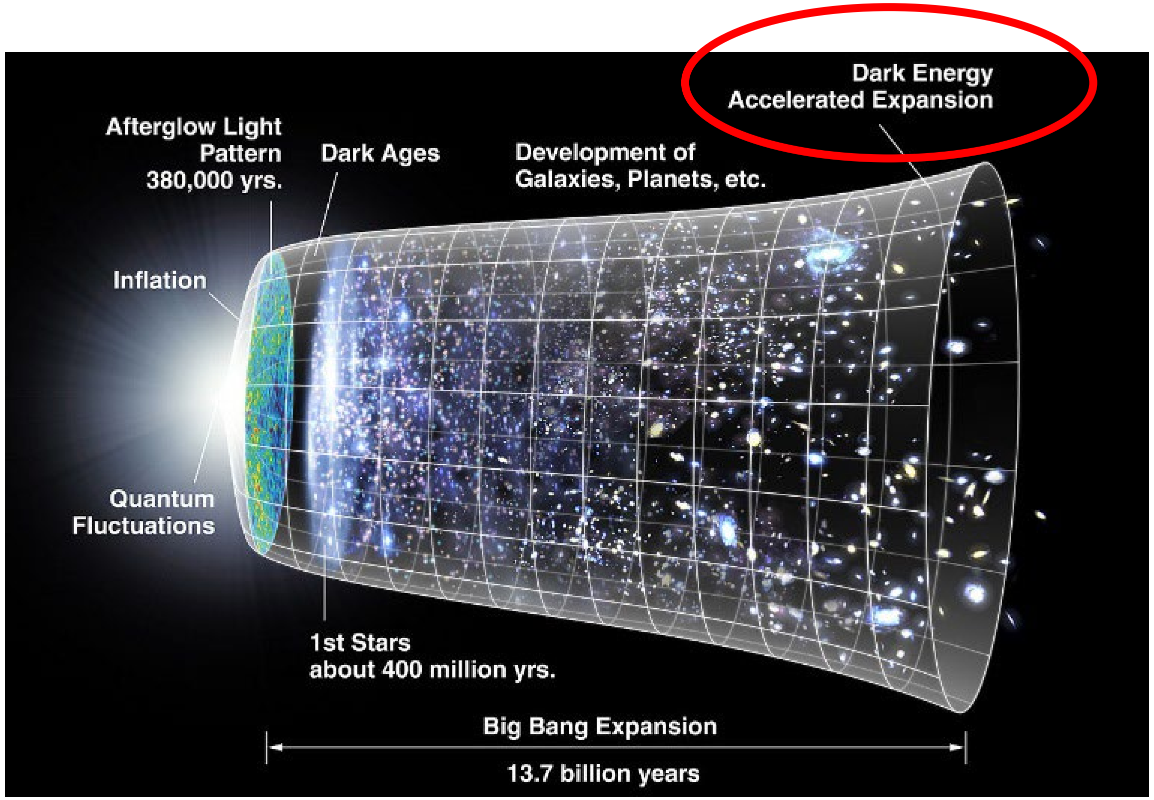


The relative amplitude of the two first peaks fix the baryon density

Until recombination, baryonic matter is strongly coupled to photons. In a universe dominated by baryonic matter, perturbations can only grow AFTER RECOMBINATION, and there is no time to form the structures we see.

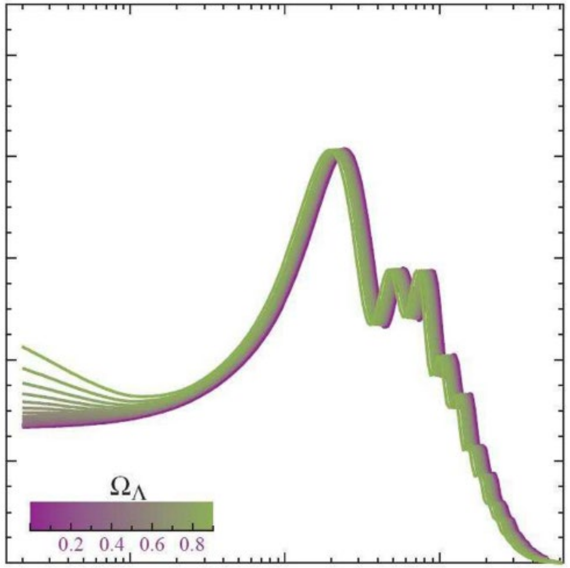
In order for perturbations to grow and form structures, **non-baryonic dark matter is required**

Accelerated expansion: Dark energy



The universe is undergoing accelerated expansion. The first evidence emerged in the 1990s from observations of supernovas. The simplest model to explain dark energy assumes a vacuum energy given by Einstein's cosmological constant Λ (although calculations of vacuum energy from quantum fluctuations produce results many orders of magnitude higher than what is observed).

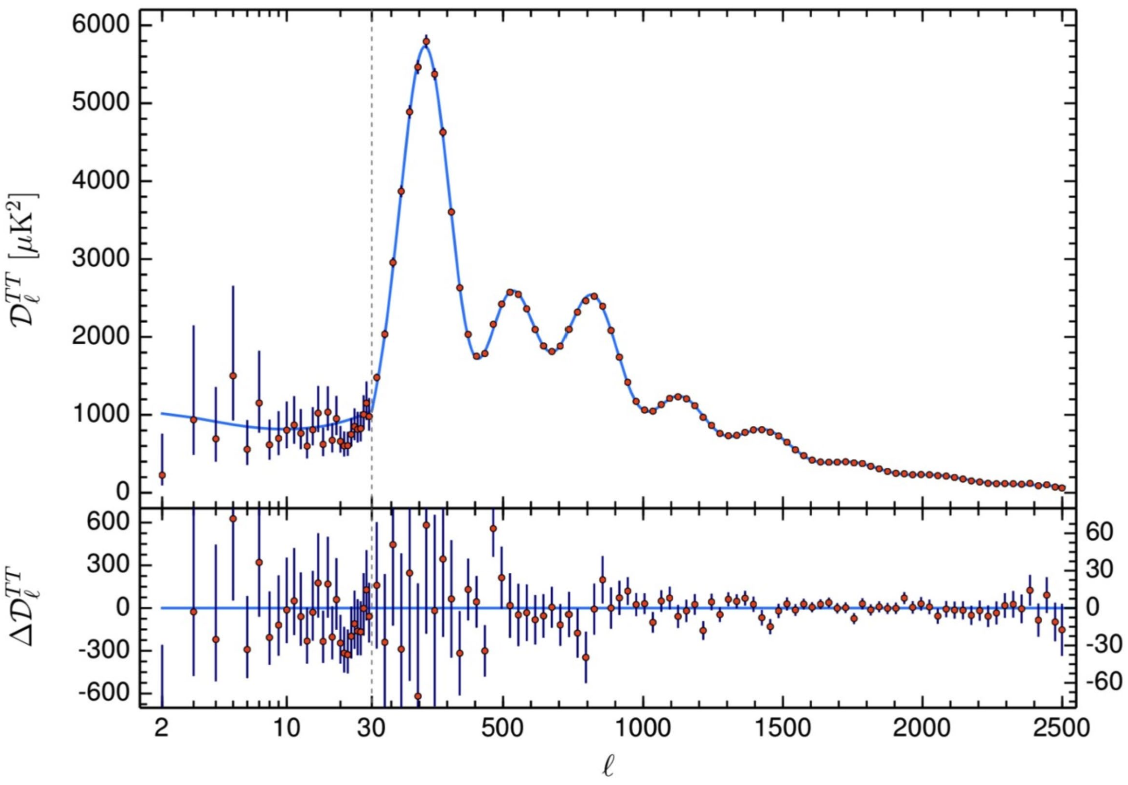
From the CMB anisotropies one can also obtain information about the amount of dark energy in the Universe



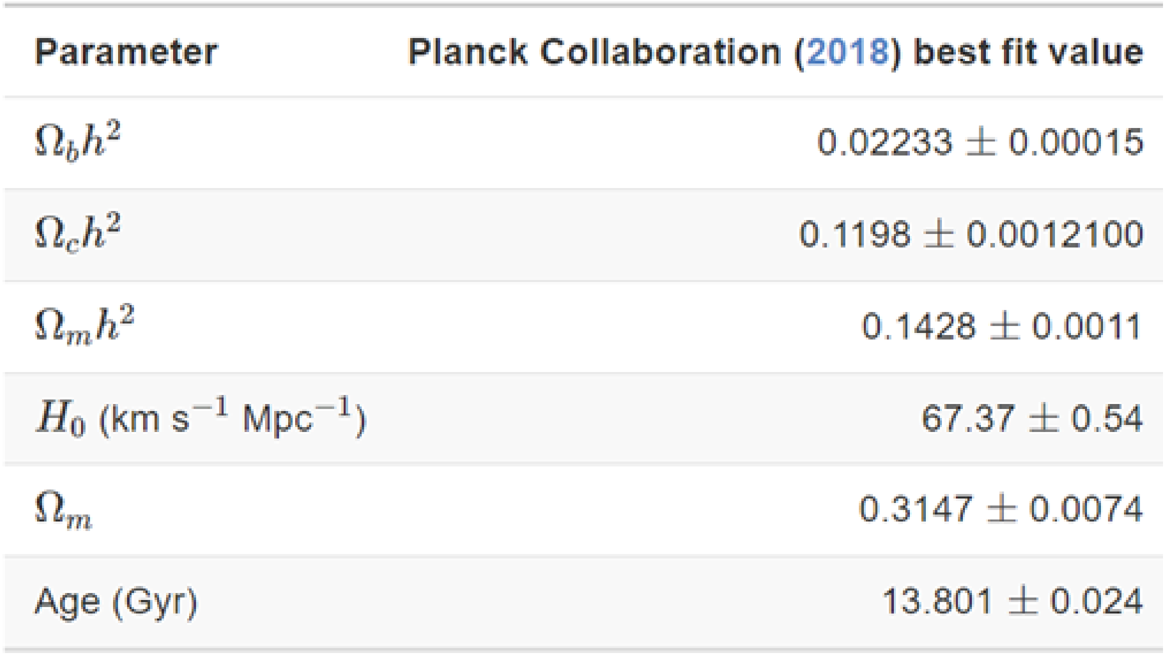
ΛCDM model

Parametrization of the Universe with three main ingredients:

- A cosmological constant (Λ) associated with dark energy
- Ordinary matter
- An unknown matter component that is non-baryonic, cold, dissipationless (does not emit photons) and collisionless



Results of the fit of the Planck 2018 data to the ΛCDM model



Parameter	**Planck Collaboration (2018) best fit value**
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012100
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 (km s^{-1} Mpc^{-1})	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age (Gyr)	13.801 ± 0.024

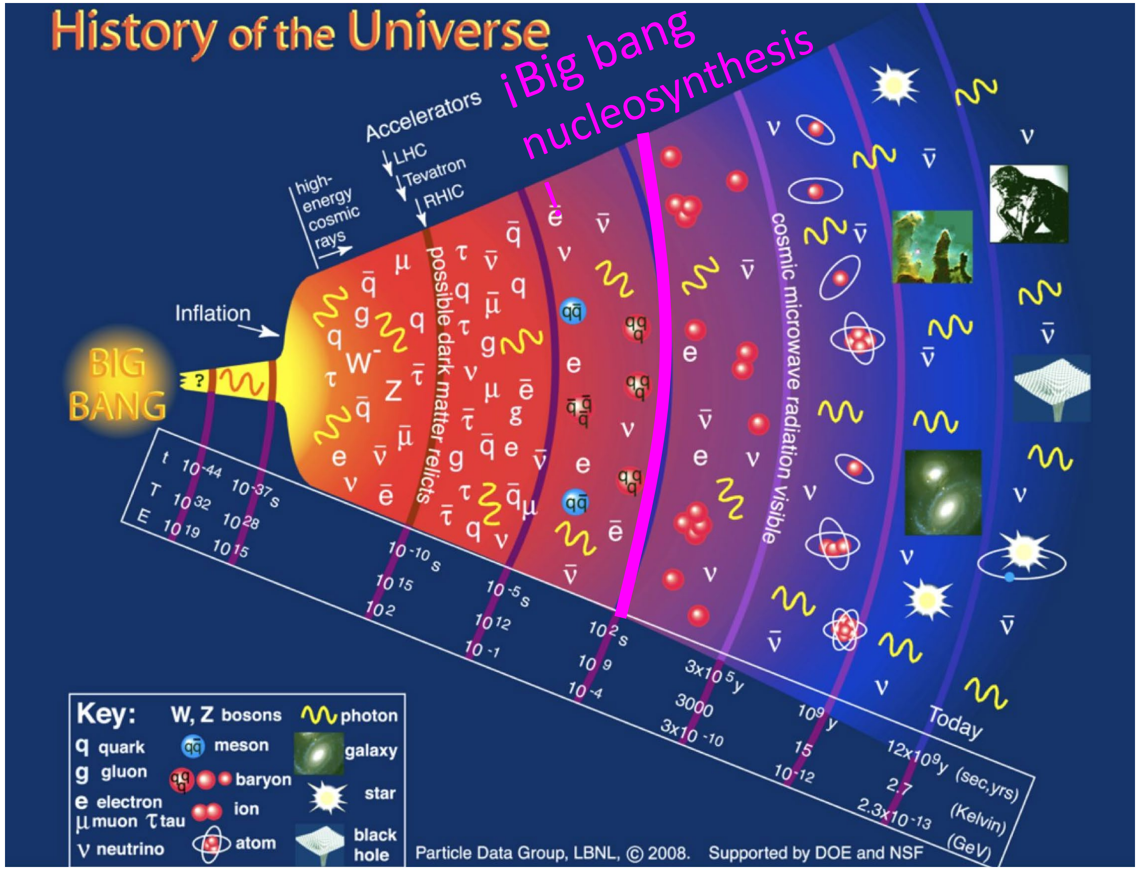
Ω_i $\equiv$ ratio of the energy density of each component to the "critical density" ρ_c

$\rho_c = \frac{3H_0^2}{8\pi G_N}$ (value of the total energy density needed for the Universe to be spatially flat)

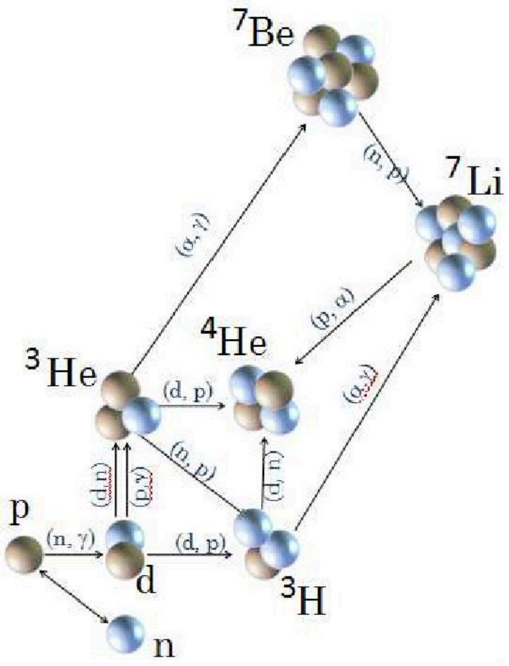
$h \equiv$ present expansion rate of the Universe (H_0) in units of $100\ km\ s^{-1} Mpc^{-1}$ km

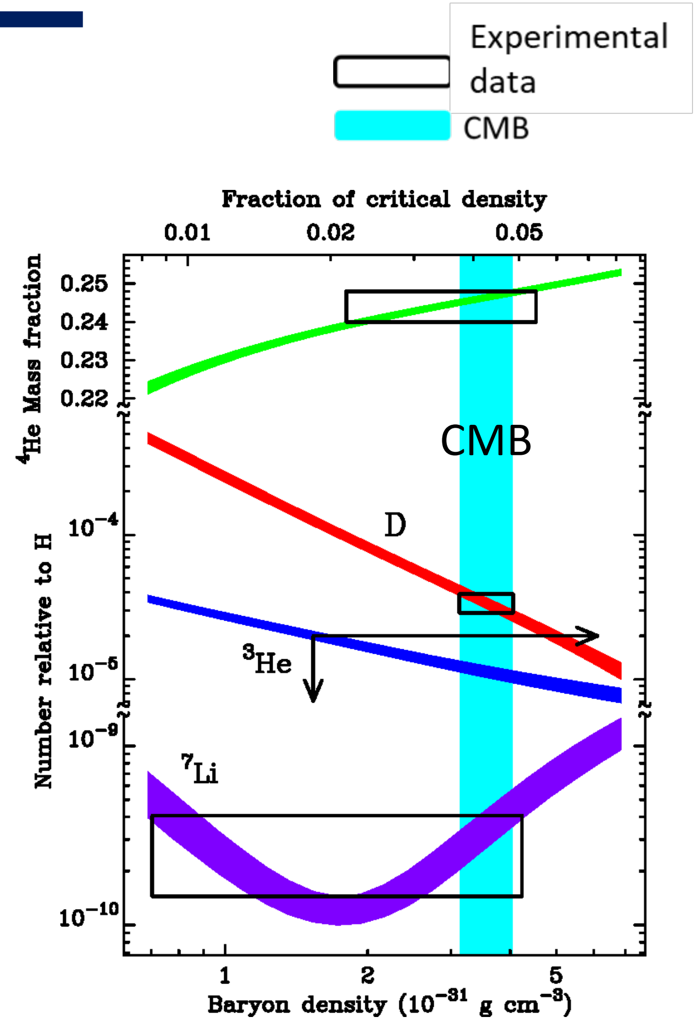
Big bang nucleosynthesis (t < 20 min)

The study of the abundance of light nuclei in the Universe formed in the first minutes after the Big Bang confirms the prediction of the CMB

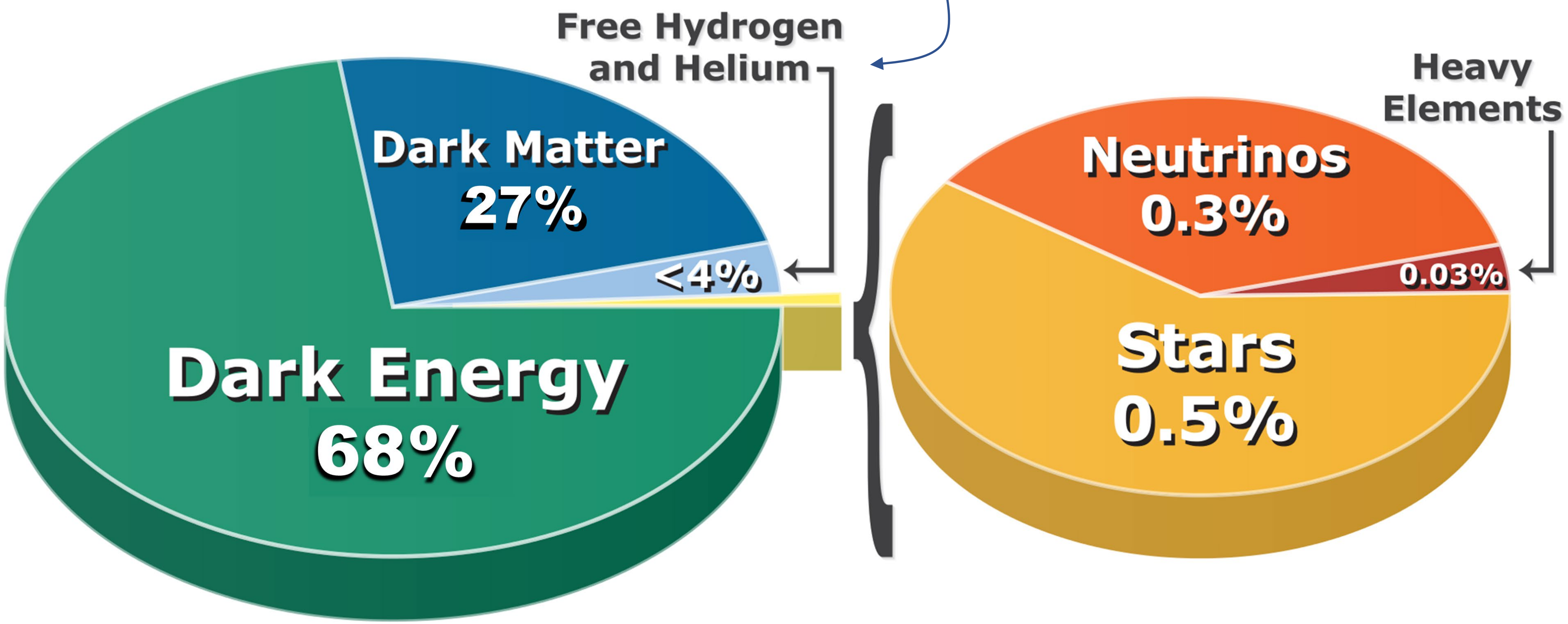


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF





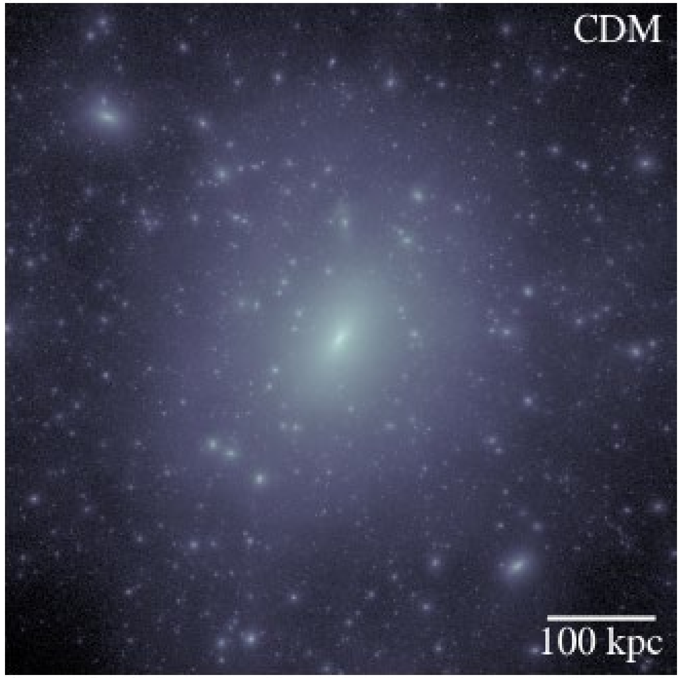
ΛCDM



- ΛCDM is the standard Cosmological model
- As for today, MOND theories does not consistently explain all the data, as the ΛCDM model does

Challenges of the ΛCDM model

Currently N-body simulations don’t agree with observations at small scale (galaxy halos). There are a number of problems that could give clues for the DM nature.

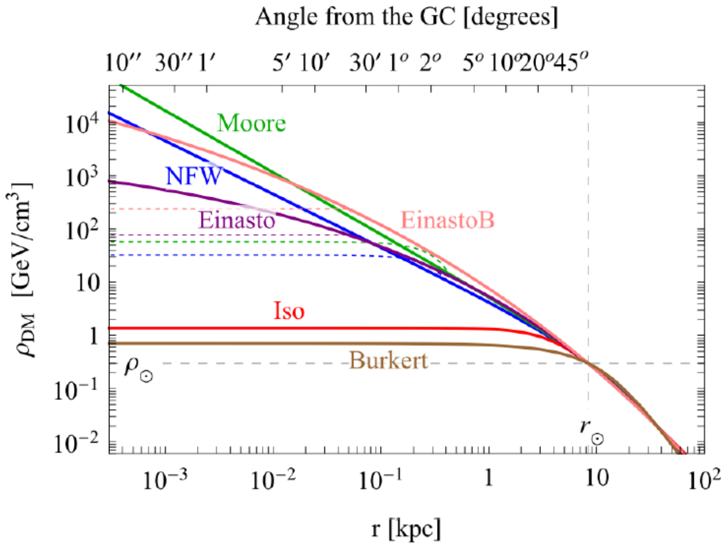


Milky Way-like N-body simulation (CDM-only)

From N-body simulations:

- The dark matter profiles of individual halos are cuspy and dense
- There are many more small halos than large ones
- Substructure is abundant and almost self-similar

The “cuspy” density profile is well described by NFW law



$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

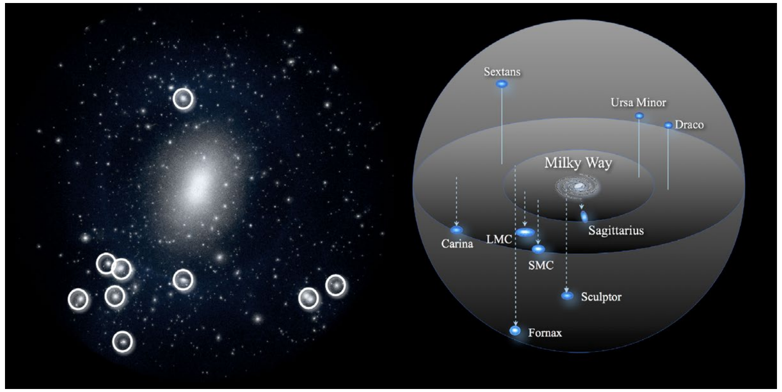
J S. Bullock and M Boylan-Kolchin, Annu. Rev. Astron. Astrophys 2017 55:343-87, 1707.04256

Challenges of the ΛCDM model

Currently N-body simulations don't agree with observations at small scale (galaxy halos). There are a number of problems that could give clues for the DM nature.

"missing satellites" problem: N-body high-resolution simulation of haloes of similar size as the Milky Way predict O(1000) subhaloes with masses $\gtrsim 10^7$ $M_\odot$ (large enough to galaxy formation). The observed number of satellites of the Milky Way appeared to be far too low. Currently, there are $\sim$ 100 satellite galaxies of the Milky Way. Other galaxies show a similar under-abundance.

Milky Way-like galaxy Simulation



Milky Way satellites

Possible solutions: these dwarf galaxies have had their stars stripped from them during tidal interactions , or galaxy formation becomes inefficient at low masses

Challenges of the ΛCDM model

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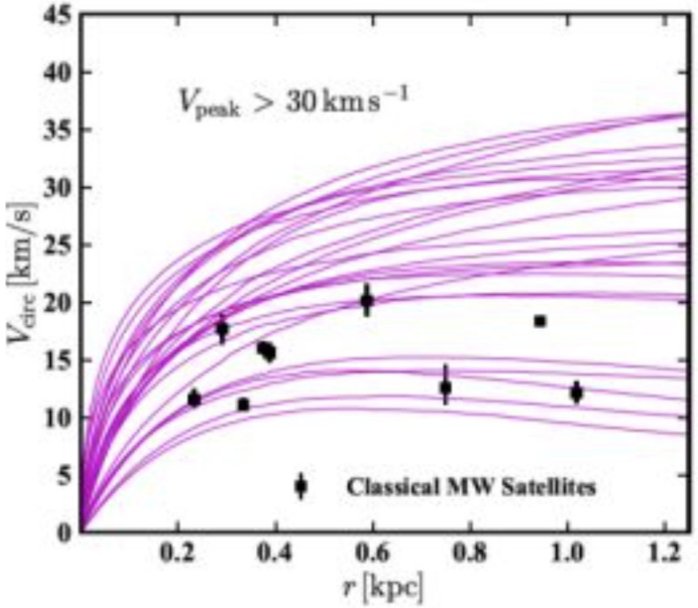
The “too-big-to-fail” problem: The local Universe contains too few galaxies with large central densities ($\sim 10^{10}\ M_\odot$) compared to ΛCDM predictions. Large DM haloes should form galaxies efficiently (they are too massive to have failed to form stars!)



● circular velocities of classical MW satellite galaxies ($M_\star \simeq 10^{5-7}\ M_\odot$)

— circular velocity of sub-halos from a DM-only Aquarius simulations.

Challenges of the ΛCDM model

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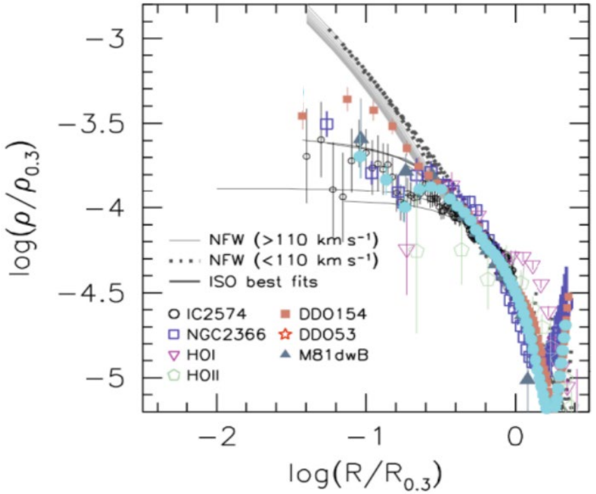
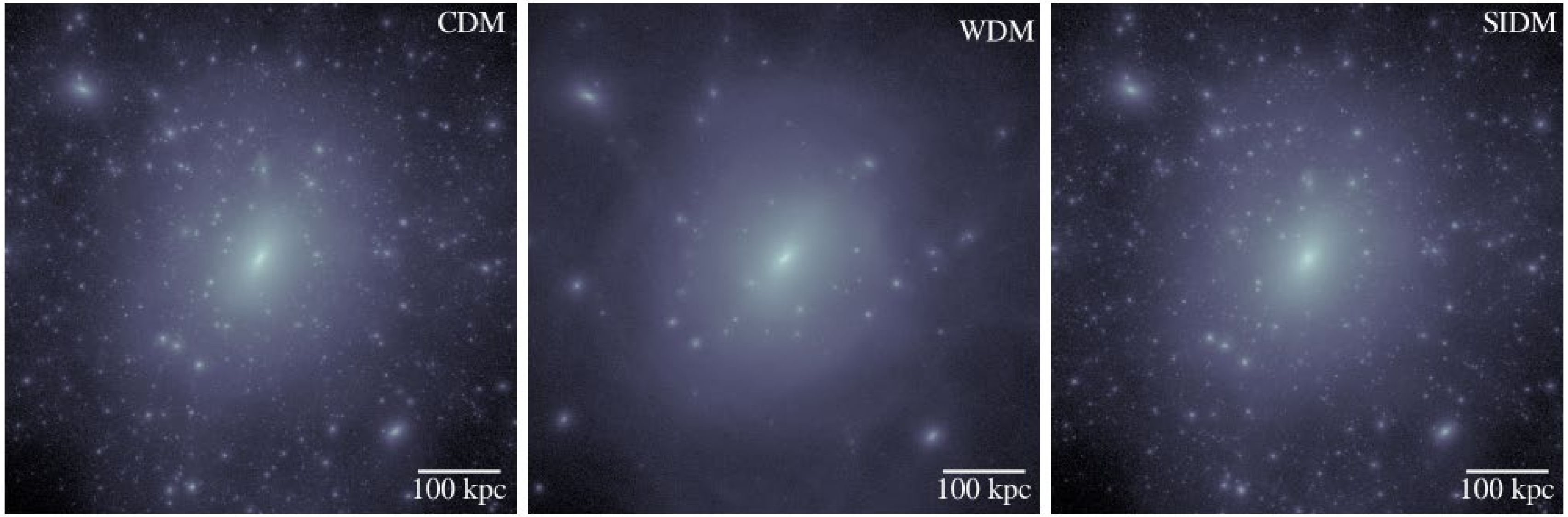
"cusp vs. core" problem: The central profiles of dwarf galaxies is observed to be much shallower than predicted in DM-only simulations, where it rise steeply at small radii.

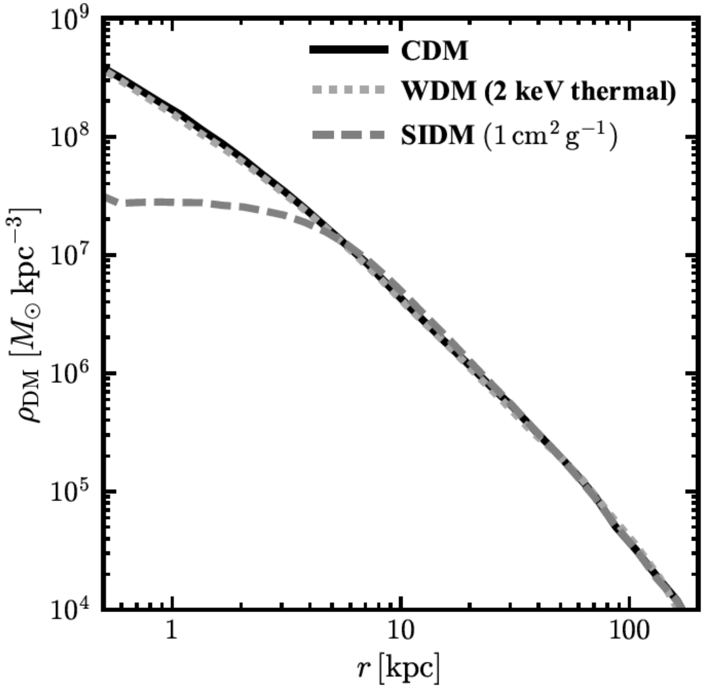


A possible explanation is that usually simulations do not include baryons. Baryonic feedback modifies the structure of DM haloes, smoothing the central cusps and producing more core-like profiles.

WDM / SIDM ?

Warm DM or Self-interacting DM induce behaviors that are qualitatively different from the CDM counterparts at large and small scales, improving agreement with data, but it requires much higher resolution than in a CDM simulation.





CDM (left), 2keV WDM (middle) , SIDM with $\sigma/m = 1\ cm^2/g$ (right)

More accurate simulation studies that properly describe cold/warm dark matter models are needed