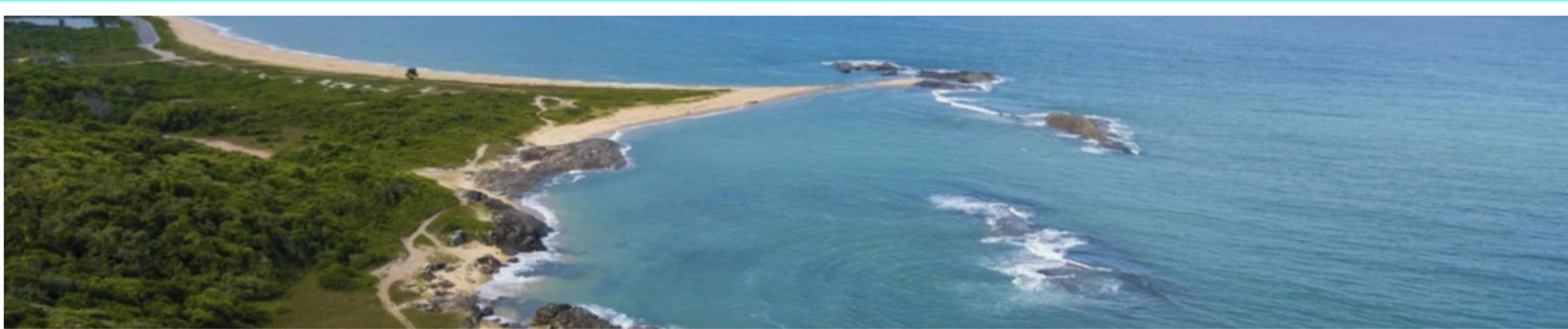


Mini-couse on Dark Matter



Quantum Summer 2025

Iriri, ES, Brazil. April 07-11, 2025.

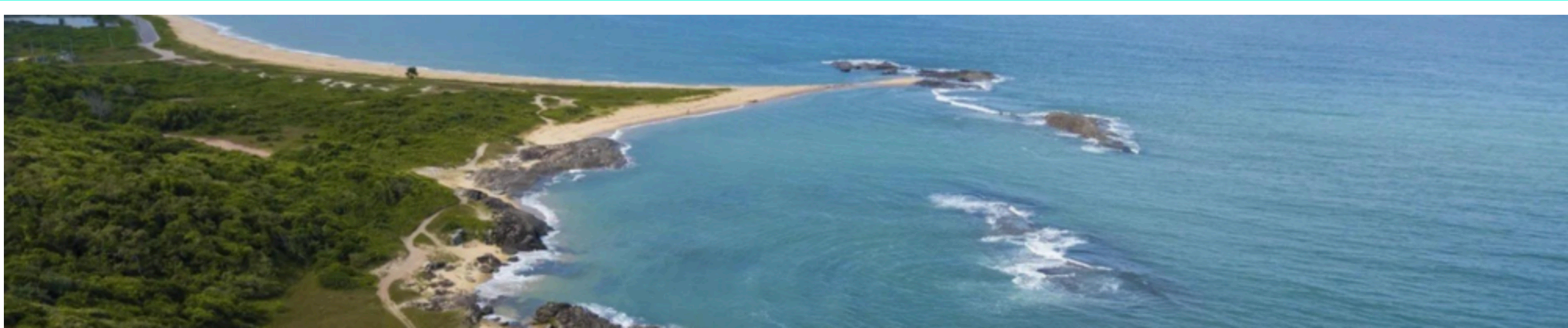
Diana López Nacir



Outline

- **Lecture 1:** Evidence for Dark Matter (DM) and its properties
- **Lecture 2:** DM inhomogeneities in the standard CDM model and others (WDM, SI-WDM)
- **Lecture 3:** Ultralight DM (spin 0 and 1). Can the spin of ULDM be distinguished on cosmological scales?

Lecture 1: Evidence for Dark Matter (DM) and its properties



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Traditional method to estimate ρ_m from M/L of Galaxy Clusters

Idea:

$$\rho_m \simeq (M/L)\mathcal{L}$$

$\mathcal{L}$ = **Total luminosity
density**

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- **M** : Use the virial theorem $2T + V = 0$ to estimate the mass M of galaxy clusters:

$$T = \frac{1}{2}M\langle v^2 \rangle$$

$$V = -\frac{1}{2}GM^2\left\langle \frac{1}{r} \right\rangle$$

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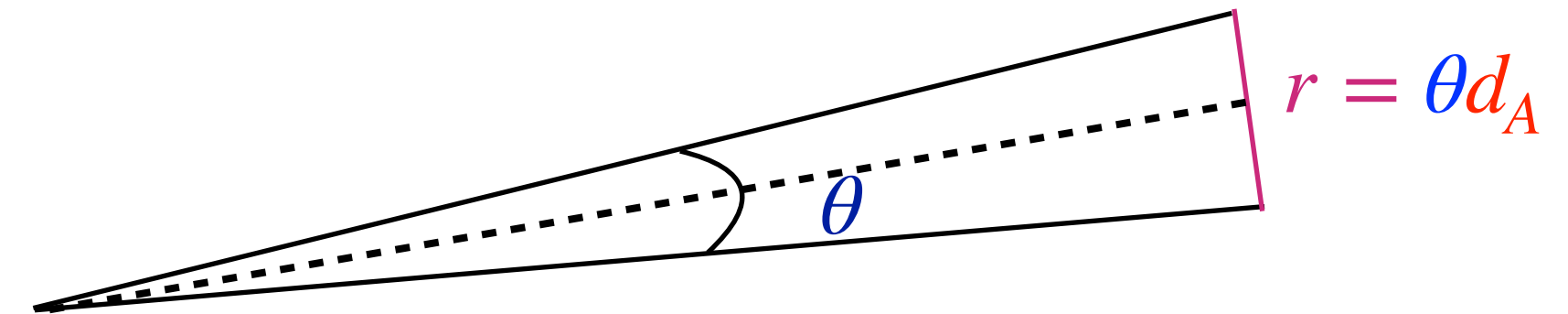
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Average (weighted with the mass) of $v^2 \sim$ velocity dispersion square:
- of the galaxies (from the Doppler broadening of spectral lines)

Average of the inverse distance separation:

- by measuring the angular separations θ and the z of the cluster:

$$M = \frac{2\langle v^2 \rangle}{G\langle 1/r \rangle}$$



Hubble's law: $z \ll 1$, $d_A \sim \frac{z}{H_0} \rightarrow r \simeq \theta \frac{z}{H_0}$

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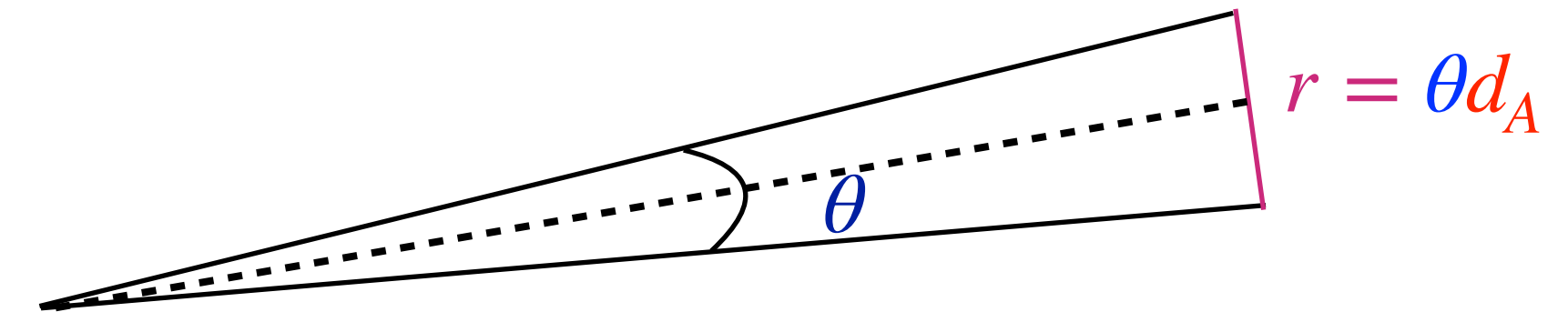
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 $L = 4\pi d_L^2 \ell \simeq 4\pi z^2 / H_0^2 \ell$

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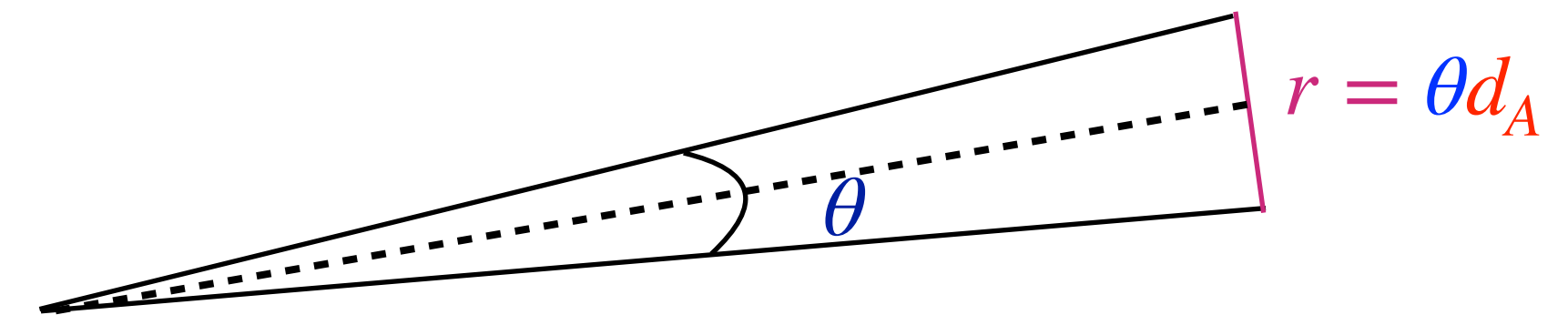
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Results: - The values of M/L estimated in this way typically give, e.g., for rich galaxy clusters $M/L = 200 - 300 h M_\odot / L_\odot$

- For virialized galaxies M/L can be estimated using the virial theory for stars and typically give $M/L = 10 - 20 h M_\odot / L_\odot$

The luminosities of clusters are given by that of galaxies $\rightarrow$ **most of the mass of clusters is NOT luminous matter.**

Historically, it was **Zwicky's studies of the Coma cluster in ~1930** that first lead to this conclusion (see for instance **G. Bertone y D. Hooper, "A History of Dark Matter": [arXiv:1605.04909](https://arxiv.org/abs/1605.04909)**)

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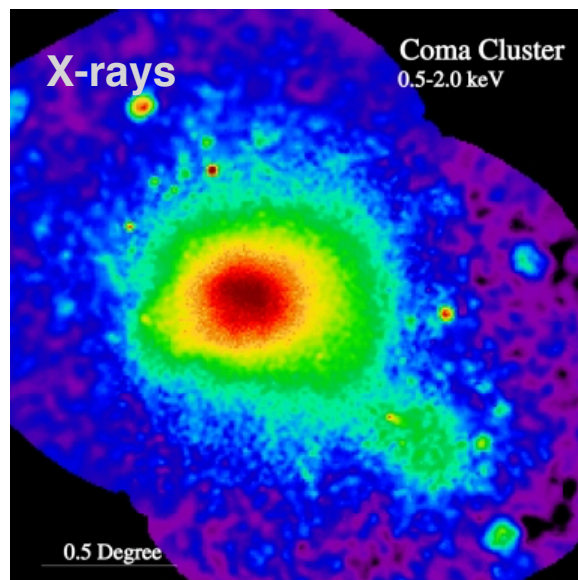
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Average (weighted with the mass) of $v^2 \sim$ velocity dispersion square:

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- of the intergalactic ionized gas (from the X-ray spectrum of the gas)

Average of the inverse distance separation:

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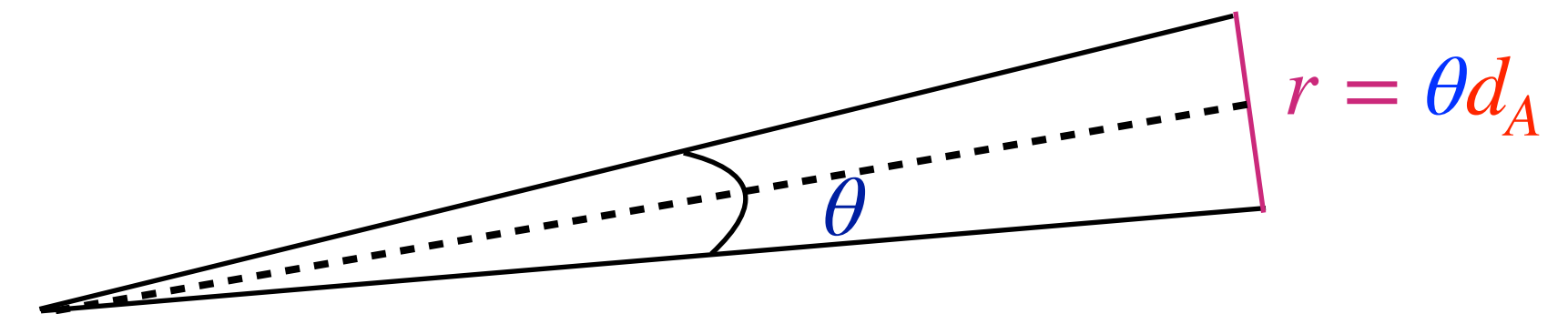


Hydrostatic equilibrium

$$\frac{dP}{dr} = -\rho_{gas} \frac{M(< r)G}{r^2}$$

$$PV = Nk_B T$$

$$M = \frac{2 \langle v^2 \rangle}{G \langle 1/r \rangle}$$



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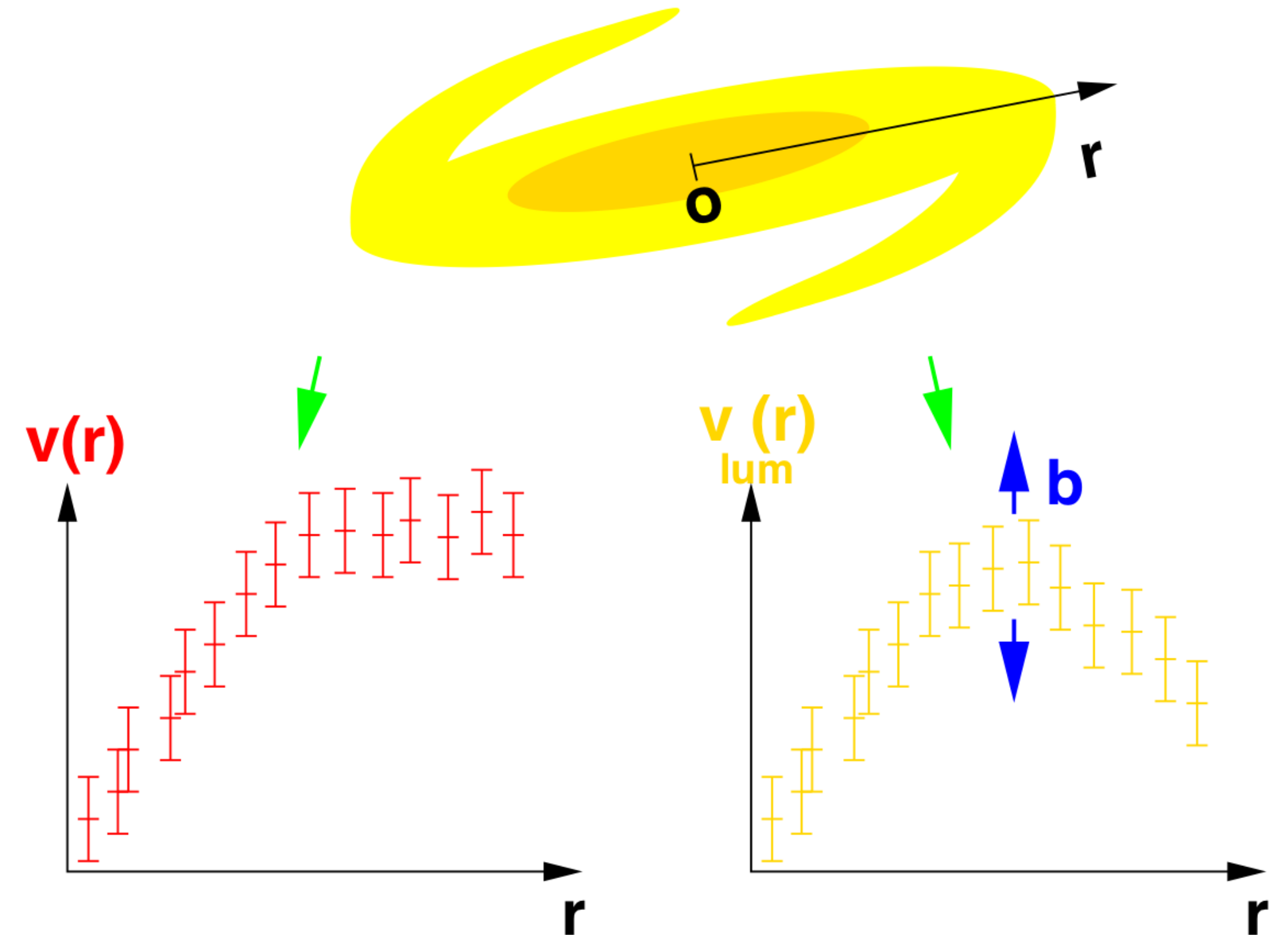
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Dark Matter on galactic scales

Rotation curves (1970) as evidence for DM: Measurements of $v(r)$ (circ. vel.) and $L(r)$ (luminosity) at different r

Newtonian prediction:

$$\left. \begin{aligned} \Delta\Phi_L &= 4\pi\rho_L(r) \\ v_L^2(r) &= r \frac{\partial\Phi_L(r)}{\partial r} \end{aligned} \right\} \text{ Assuming } \rho(r) = \rho_L(r) = bL(r), b \text{ bias,} \\ \text{we can compute } v_L(r) \text{ up to a factor } b.$$



Credit: https://lesgourg.github.io/courses/DMDE_EPFL.pdf

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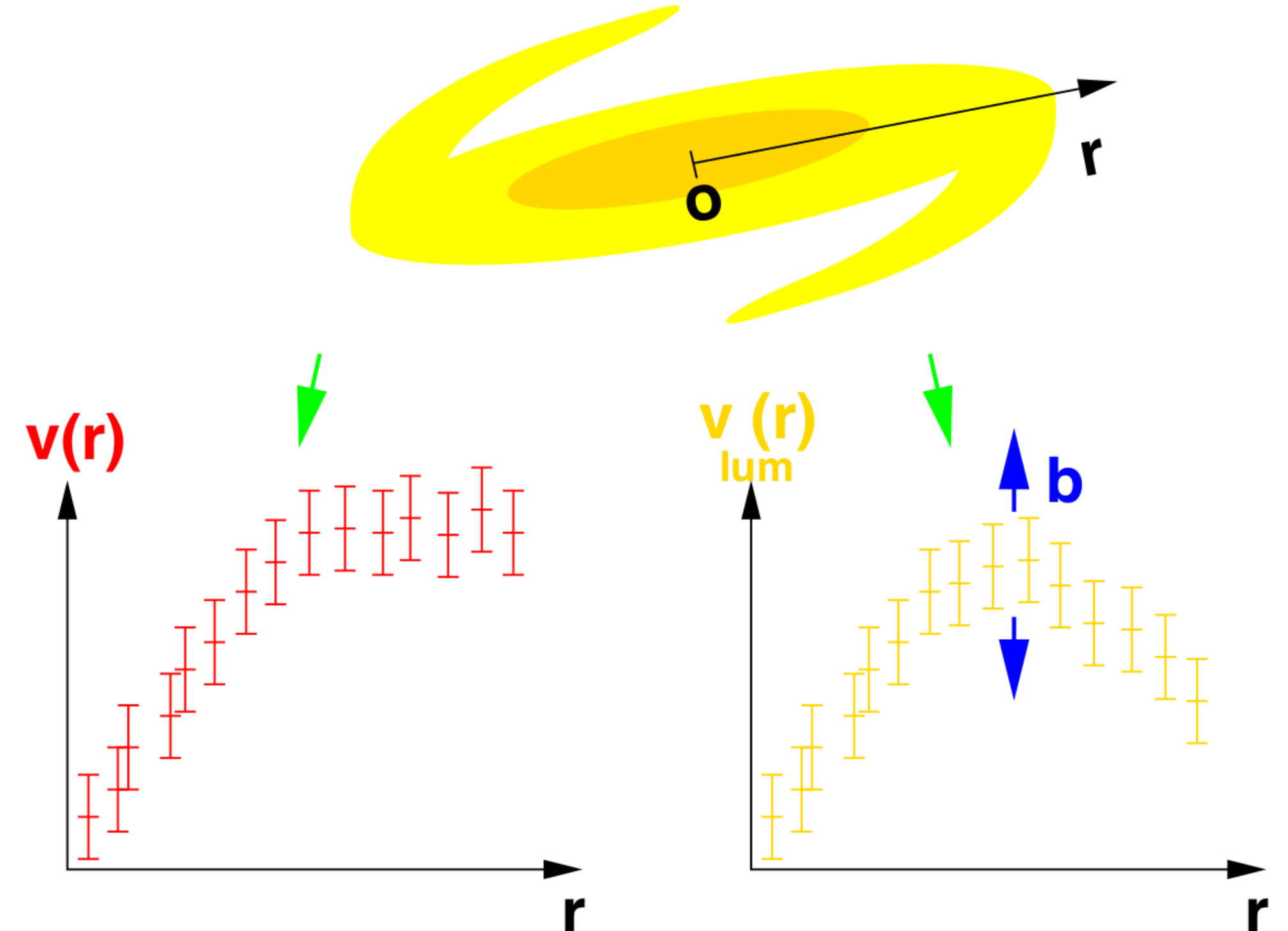
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Exercise: Given a spherically symmetric $\rho(r)$, compute $v(r)$ in terms of $M(r) = 4\pi \int_0^r dr' r'^2 \rho(r')$. **Result:** $v^2(r) = \frac{GM(r)}{r}$

- If $\rho(r) \simeq 0$ for $r > r_0 \rightarrow M(r) \simeq \text{cte}$ y $v(r) \sim \frac{1}{\sqrt{r}}$.
- $v(r) \sim \text{cte}$ for $r > r_0 \leftarrow M(r) \simeq r$ y $\rho(r) \sim \frac{1}{r^2}$.



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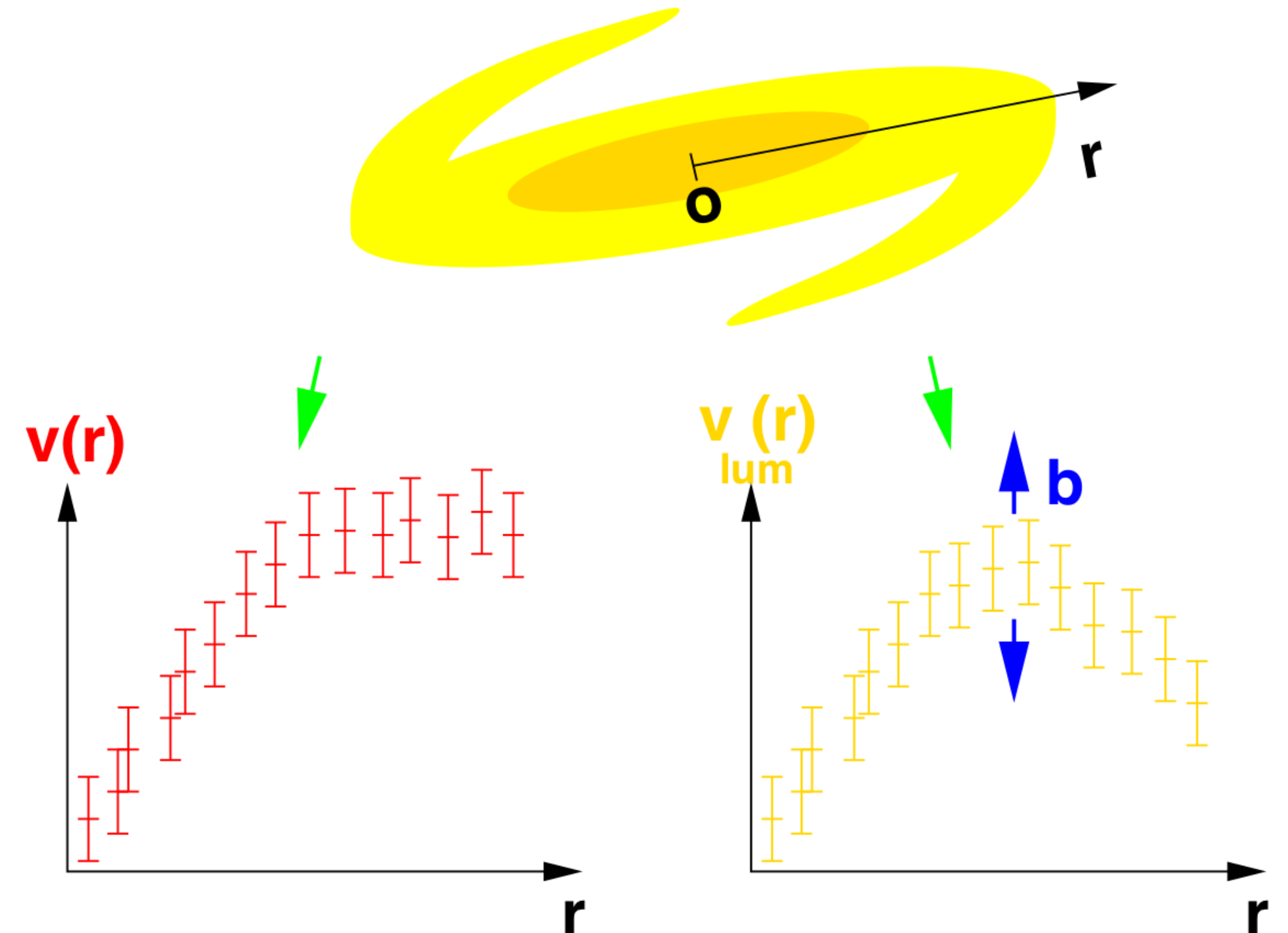
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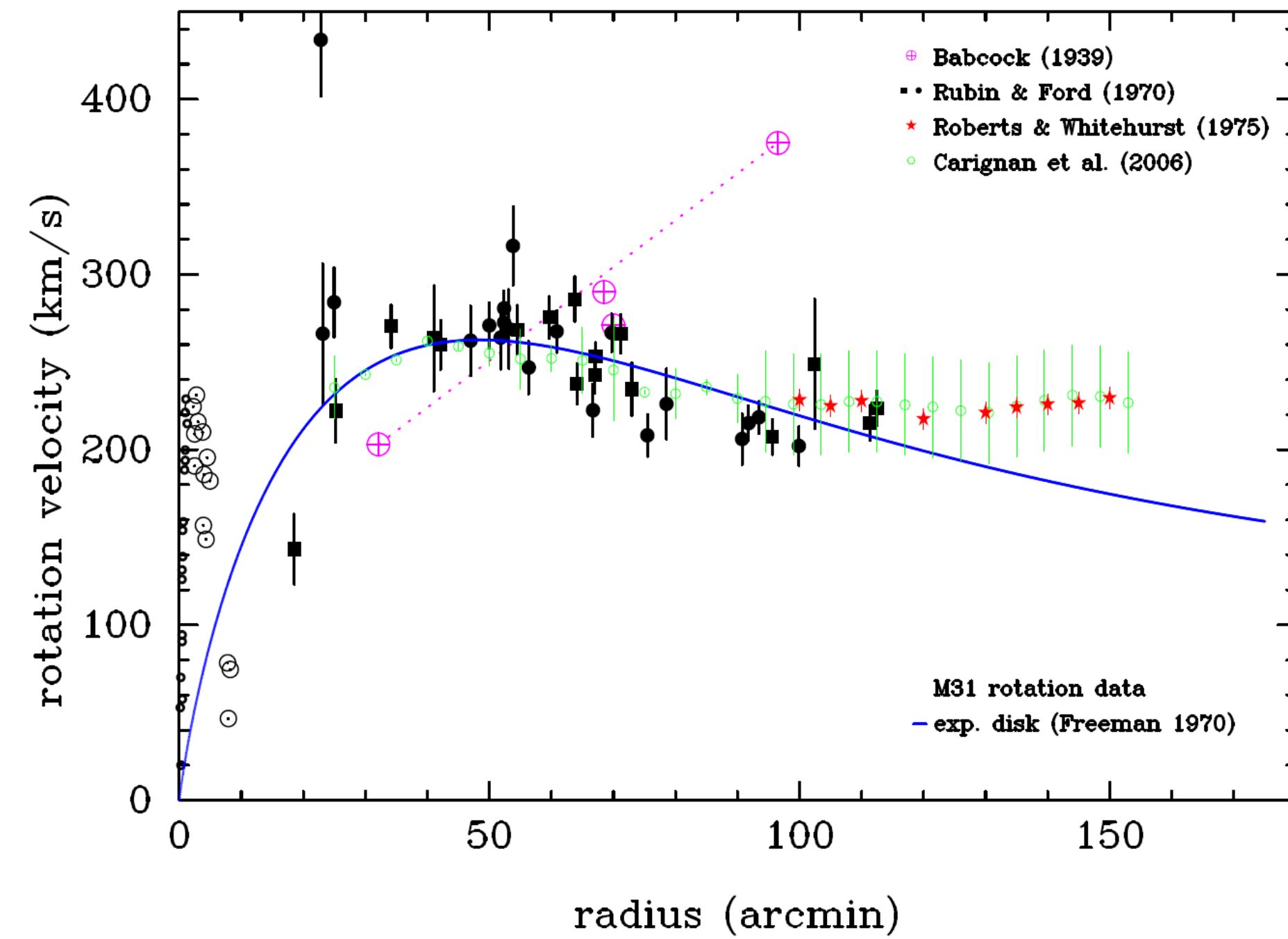
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→ Using measurements of rotation curves and the theory of gravity, one can characterize the distribution of matter and the so-called **dark matter halos**.

Rotation curves



Andromeda Galaxy, Messier 31 o NGC 224



FIG. 4. Rotation curve data for M31. The purple points are emission line data in the outer parts from Babcock 1939 [31]. The black points are from Rubin and Ford 1970 [267] (squares for the SW data, filled circles for the NE data, and open circles for the data in the inner parts – the presence of non-circular motions in the inner parts makes the modelling of those data uncertain). The red points are the 21-cm HI line data from Roberts and Whitehurst 1975 [261]. The green points are 21-cm HI line data from Carignan et al. [73]. The black solid line corresponds to the rotation curve of an exponential disc with a scalelength according to the value given in Freeman 1970 [126], suitably scaled in velocity. 21-cm data demonstrate clearly the mass discrepancy in the outer parts. Figure courtesy of Albert Bosma.

Rotation curves

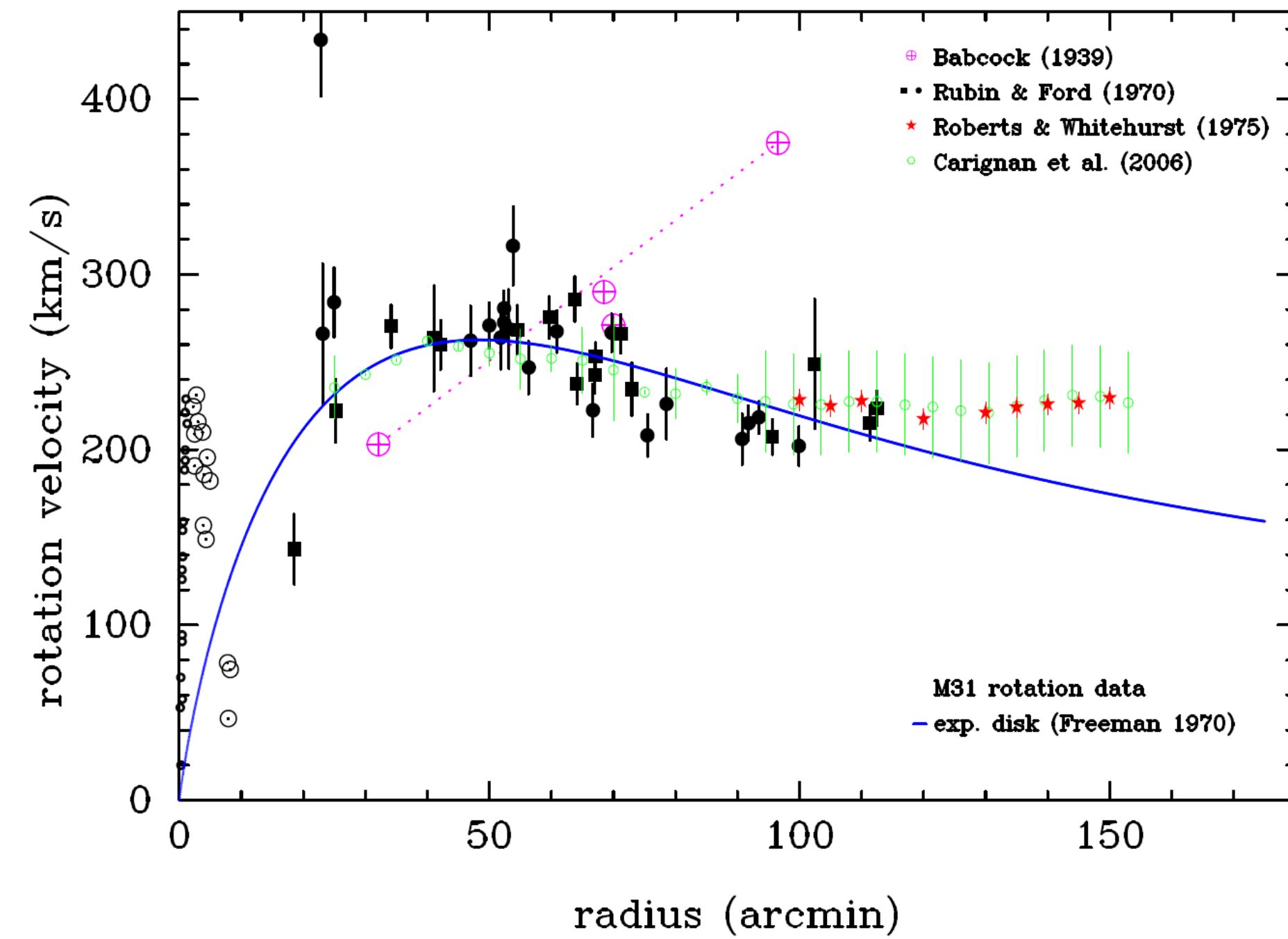
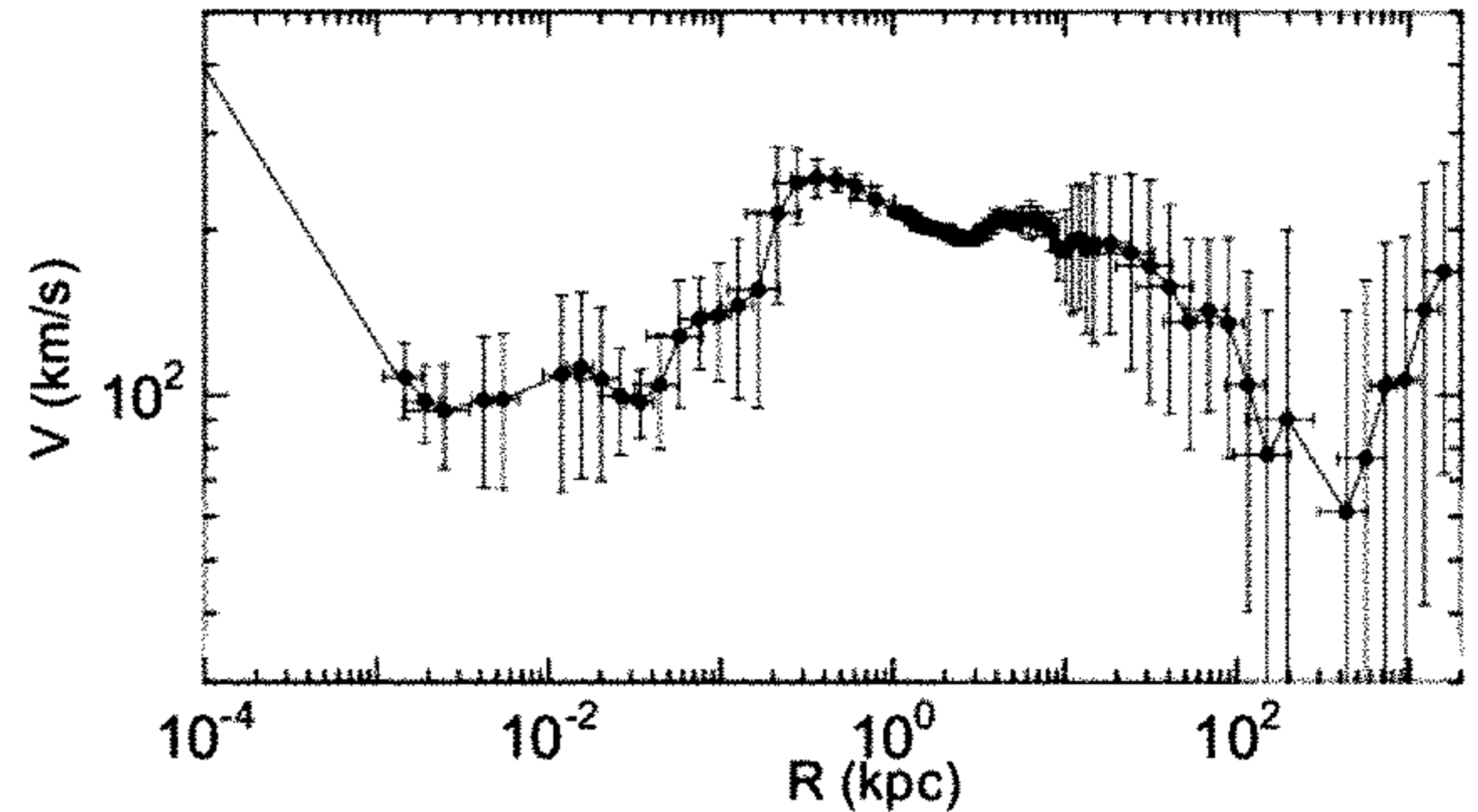


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Milky Way



Y. Sofue, PASJ 65 (2013) 118.

Rotation curves

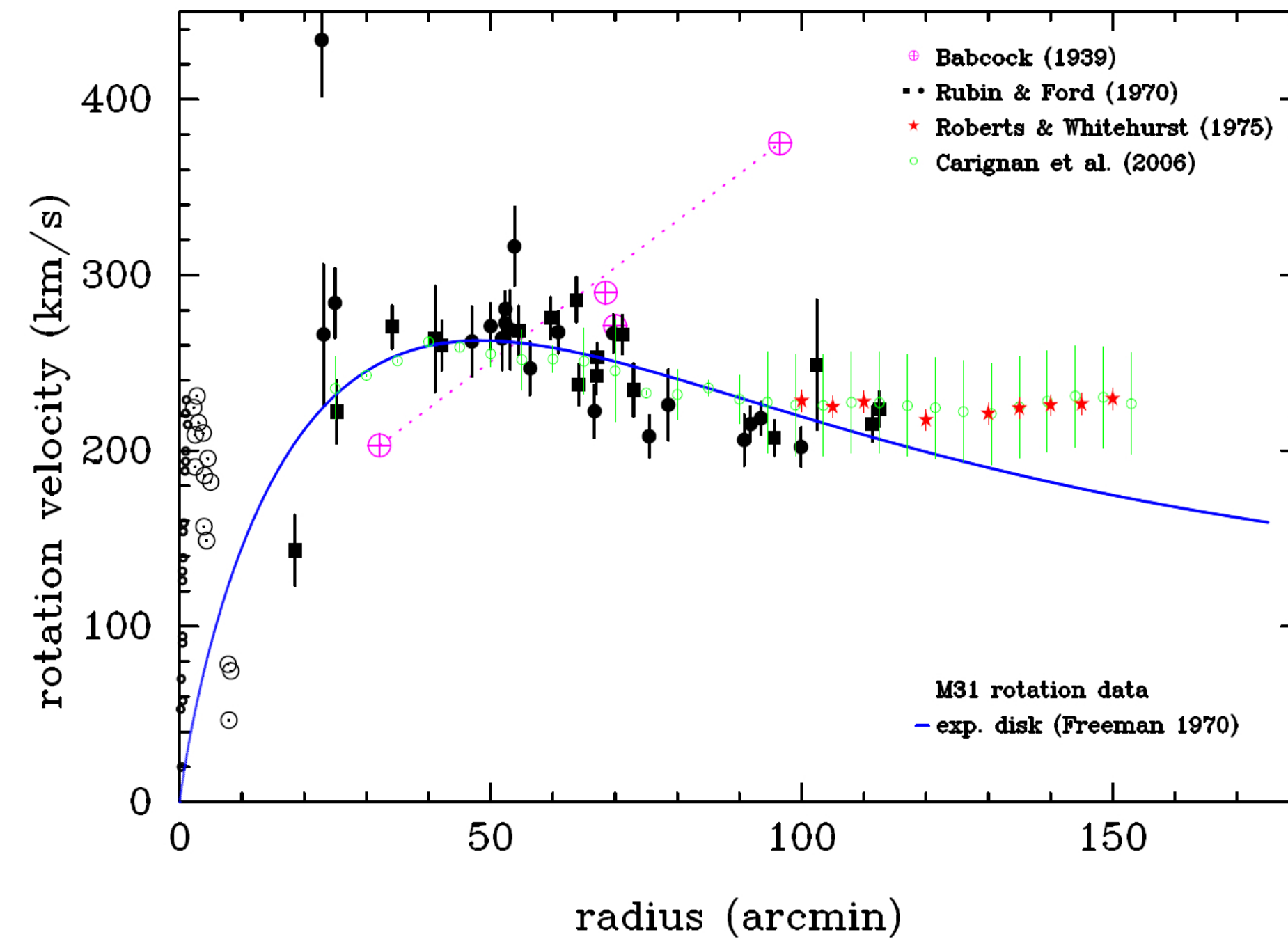


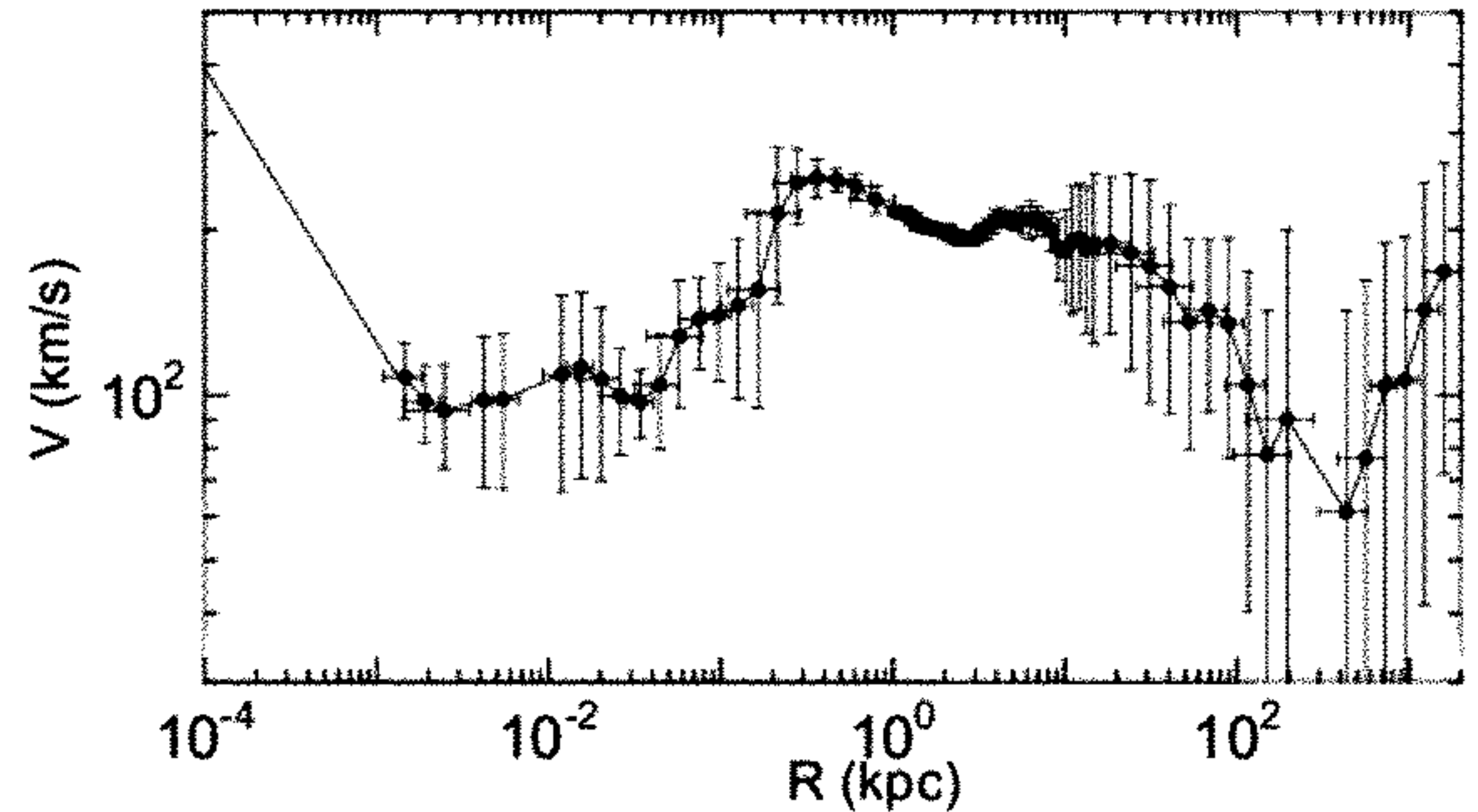
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DM exists or the laws of gravity are different?

Andromeda Galaxy, Messier 31 o NGC 224

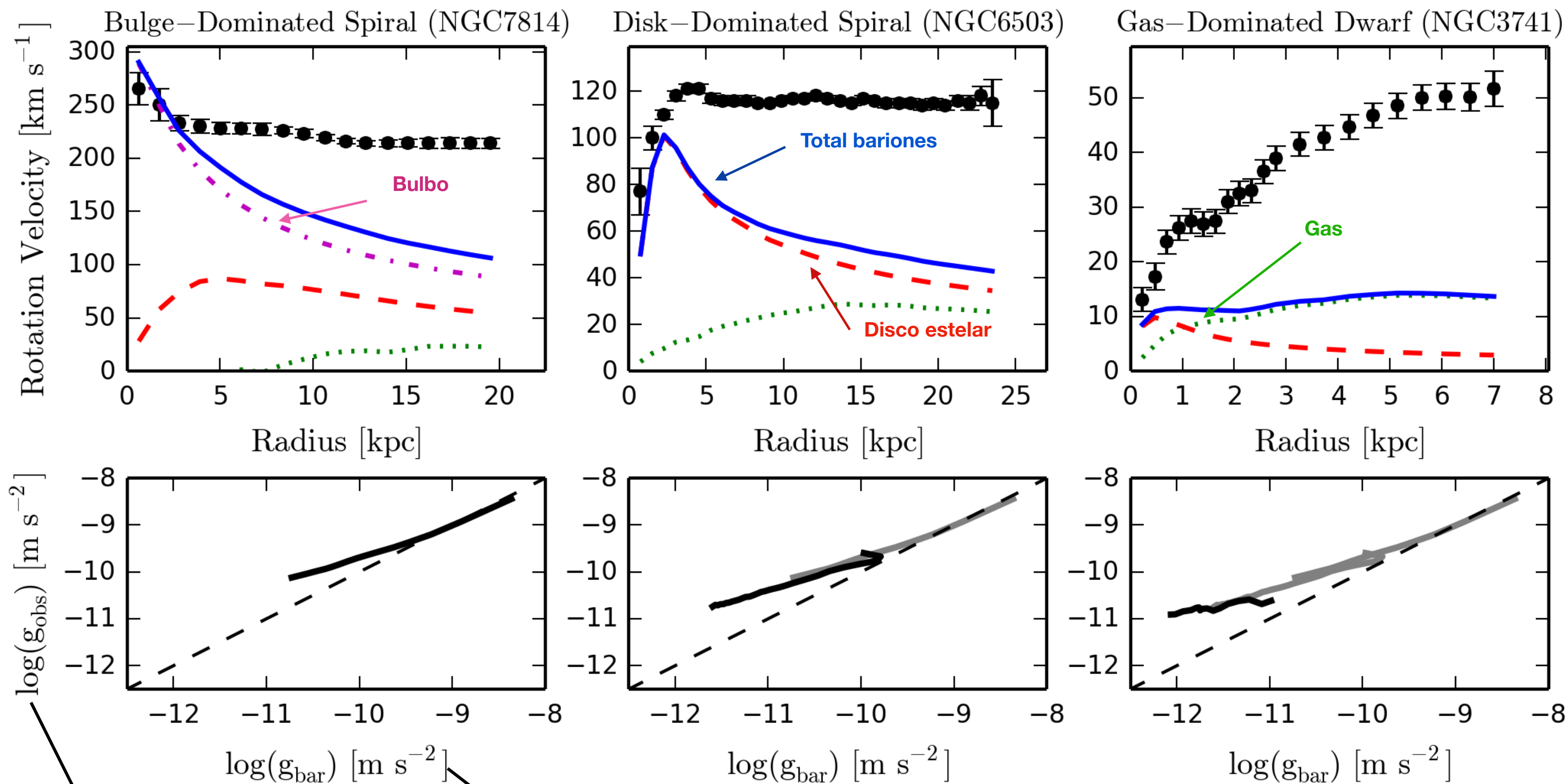


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It is crucial to analyze statistical properties...



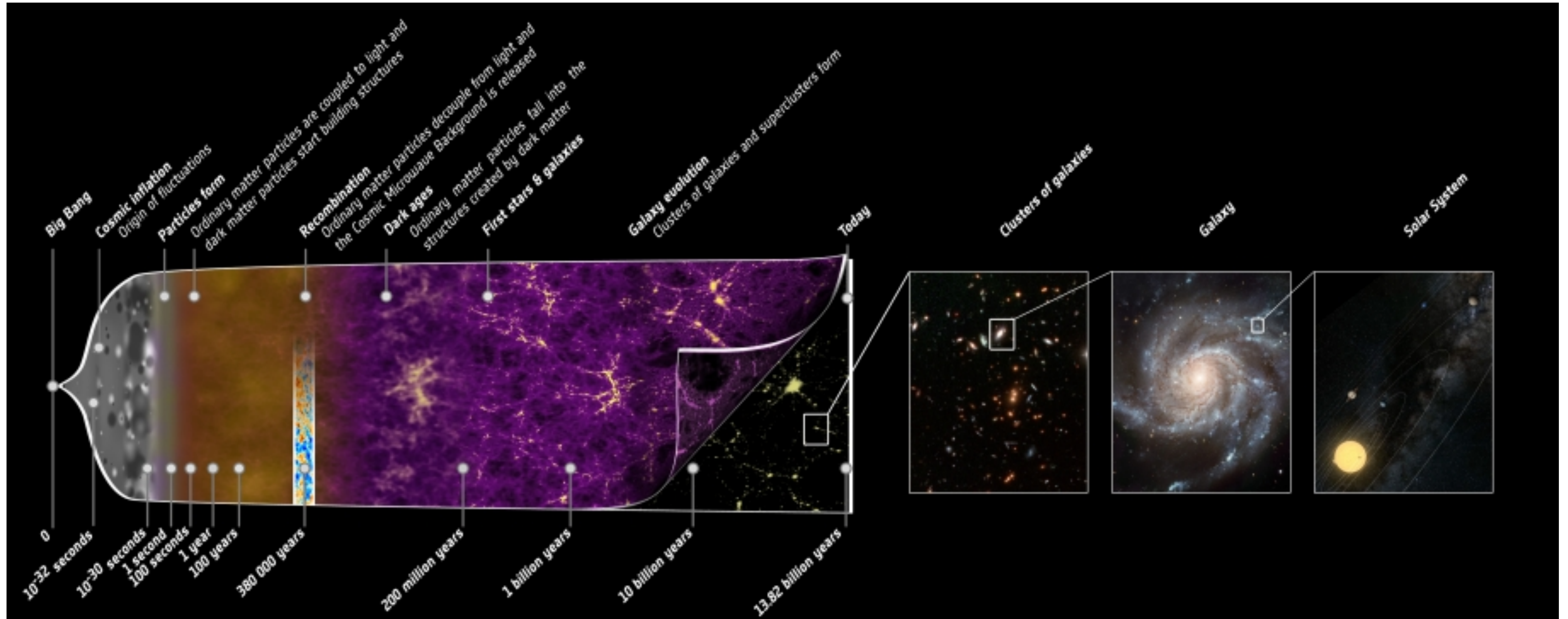
$$V_{\text{obs}}^2 / R = -\nabla \Phi_{\text{tot}}$$

$$V_{\text{bar}}^2 / R = -\nabla \Phi_{\text{bar}}$$

$$\nabla^2 \Phi_{\text{bar}} = 4\pi G \rho_{\text{bar}}$$

McGaugh, Lelli, Schombert (2016)

We have a standard cosmological framework



In textbooks such as:

- Modern Cosmology, Scott Dodelson and Fabian Schmidt, ACADEMIC PRESS, Second Edition, 2021.
- Cosmology, Steven Weinberg, OXFORD UNIVERSITY PRESS, 2008.

The standard cosmological framework

$\hbar = c = 1$

- Spatial isotropy + homogeneity

Friedmann-Lemaître-Robertson-Walker (FLRW):

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

$a(t)$ = scale factor

$K = 0, 1, -1$

- General relativity: $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G \sum_I T_{\mu\nu}^I - g_{\mu\nu}\Lambda \equiv 8\pi GT_{\mu\nu}$

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-00 component gives the **Friedman eq.:**

$T_{00} = -\rho(t)$ = Energy density of the universe

$$R_{00} - \frac{1}{2}g_{00}R = 8\pi GT_{00} \rightarrow \left(\frac{1}{a} \frac{da}{dt} \right)^2 = H^2(t) = \frac{8\pi G}{3} \rho(t) - \frac{K}{a^2}$$

(*)

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Critical density at t

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-ij are equivalent to $\nabla_\mu T^\mu_\nu = 0$ (conservation of total energy):

Physical volume: $V(t) = V_0 a^3(t) \rightarrow d(a^3 \rho(t)) = -p da^3$

$$\frac{d\rho}{dt}(t) = -3H(t)[P(t) + \rho(t)]$$

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Note: If $P(t) = w \rho(t)$ ($w = cte$) $\rightarrow \frac{\dot{\rho}}{\rho} = -3(1+w) \frac{\dot{a}}{a} \rightarrow \rho(t) = \rho(t_0) \left(\frac{a(t_0)}{a(t)} \right)^{3(1+w)}$

The standard Λ CDM model-Background level

- 3 components (Λ , matter, radiation)

$$\rightarrow G_{\mu\nu} = 8\pi G \sum_{I=\Lambda, m, r} T_{I\mu\nu}, \quad \nabla_\mu T^\mu_{I\nu} = 0$$

$$d(a^3 \rho_I(t)) = -p_I da^3$$

- Spatially flat geometry ($K=0$):

$$\rho(t_0) = \rho_{cr} = \frac{3H_0^2}{8\pi G} = 1.88h^2 \times 10^{-29} \frac{g}{cm^3}$$

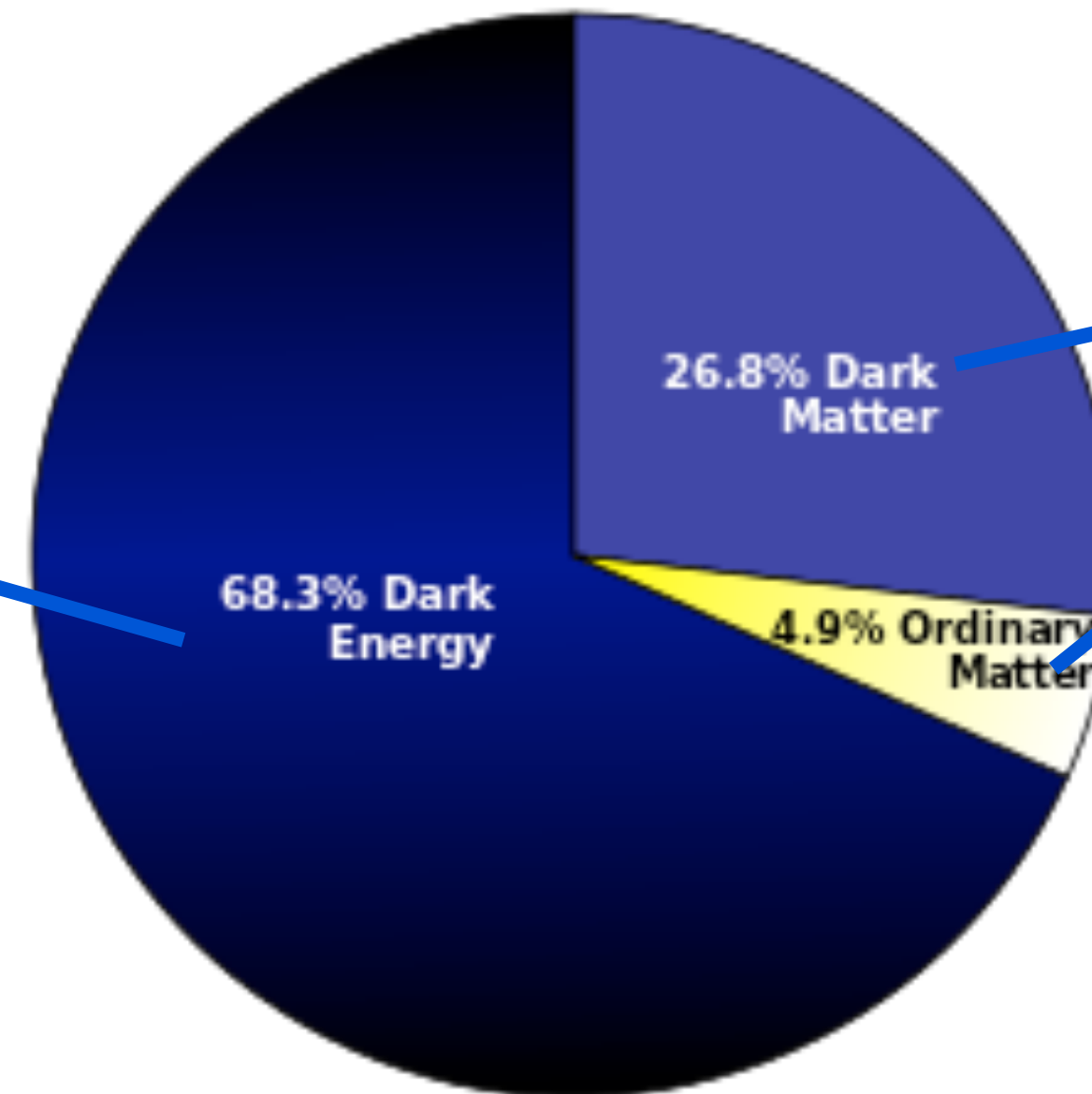
$$h \equiv \frac{H_0}{100 \frac{km/s}{Mpc}}$$

Dark Energy

$$p_{DE} \simeq -\rho_{DE}$$

$$(\Lambda\text{CDM: } p_\Lambda = -\rho_\Lambda)$$

$$ds^2 = -dt^2 + a^2(t) \delta_{ij} dx^i dx^j$$



Non-relativistic matter

$$p_m \simeq 0 \rightarrow \rho_m \propto a^{-3}$$

Radiation ($\sim 0.01\%$)

$$p_r = \frac{1}{3}\rho_r \rightarrow \rho_r \propto a^{-4}$$

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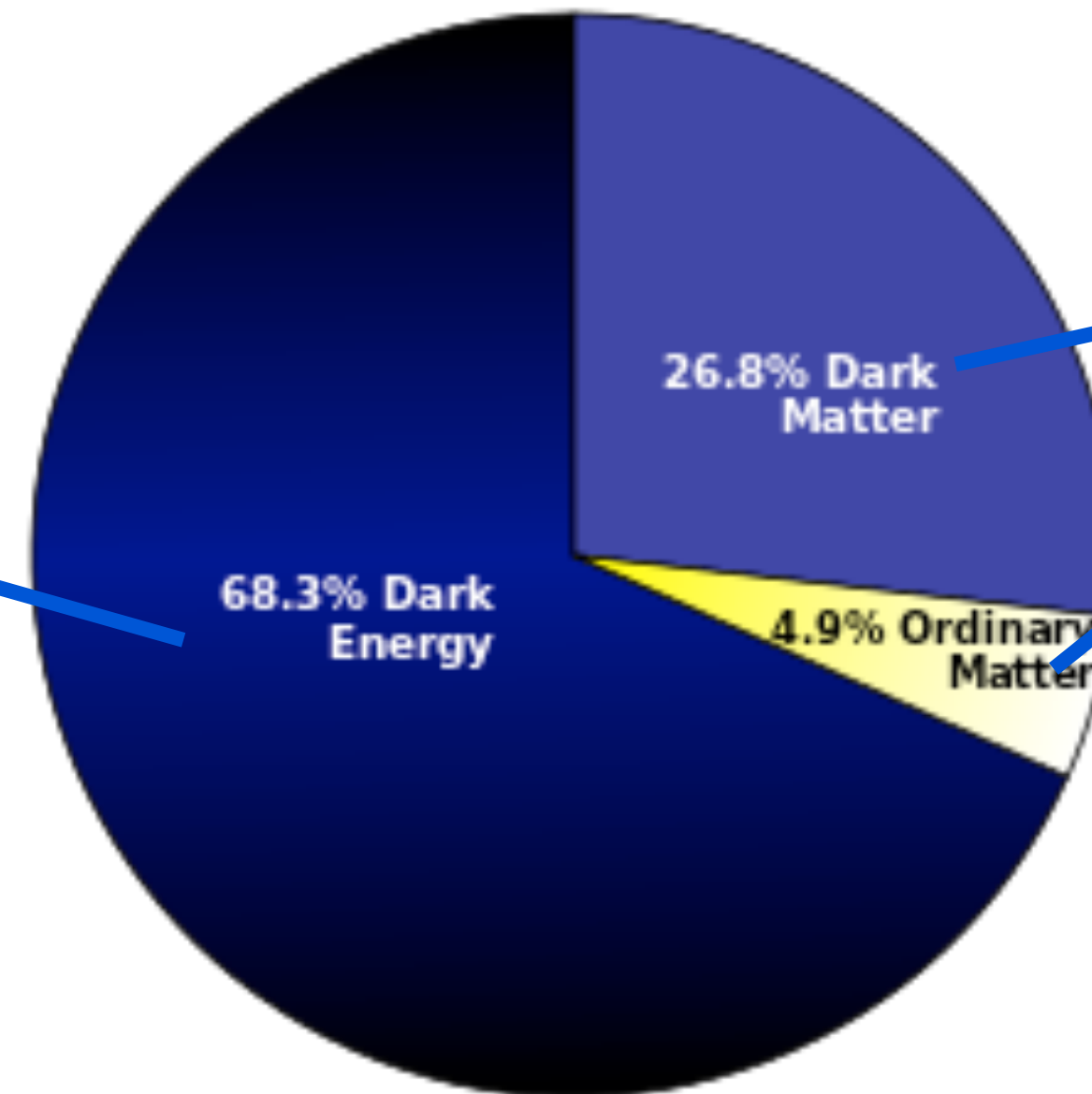
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Non-relativistic matter

$$p_m \simeq 0 \rightarrow \rho_m \propto a^{-3}$$

Radiation ($\sim 0.01\%$)

$$p_r = \frac{1}{3}\rho_r \rightarrow \rho_r \propto a^{-4}$$

- Friedman equations:

$$H^2(t) = \frac{8\pi G}{3} [\rho_\Lambda + \rho_m(t) + \rho_r(t)] \rightarrow 1 = \frac{8\pi G}{3H^2} [\rho_\Lambda + \rho_m(t) + \rho_r(t)] \equiv \Omega_\Lambda(t) + \Omega_m(t) + \Omega_r(t)$$

Λ CDM model

$$\Omega_r(a) + \Omega_\Lambda(a) + \Omega_m(a) = 1$$

Friedman eq.

$$\Omega_I(a) := \frac{\rho_I(a)}{\rho_{\text{cr}}(a)}$$

$$\rho_{\text{cr}}(a) := \frac{3H^2}{8\pi G}$$

Λ CDM model

$$\Omega_r(a) + \Omega_\Lambda(a) + \Omega_m(a) = 1$$

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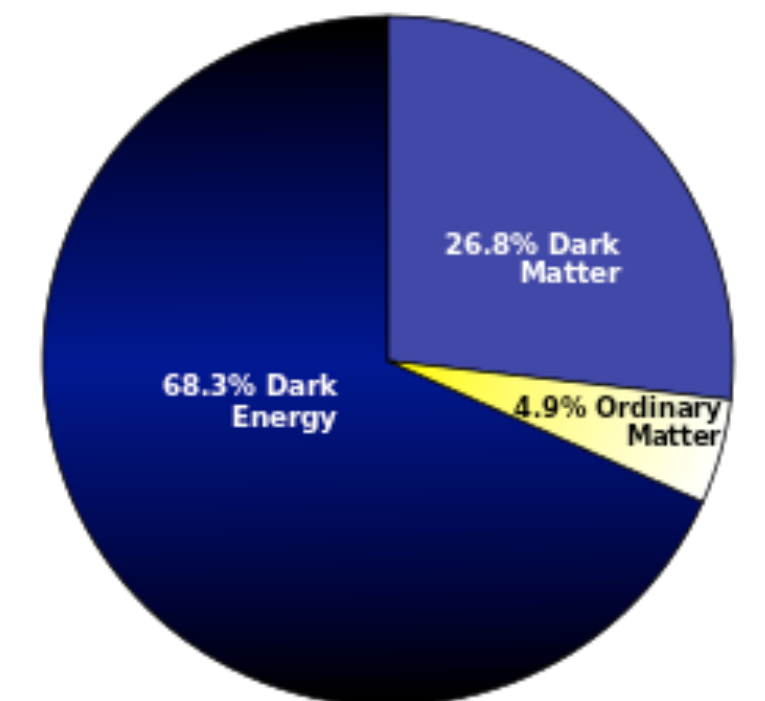
$$\rho_{\text{cr}}(a) := \frac{3H^2}{8\pi G}$$

Redshift:

$$\frac{\nu}{\nu_{\text{obs}}} = \frac{1}{a(t)} \equiv 1 + z$$

Today $z = 0$

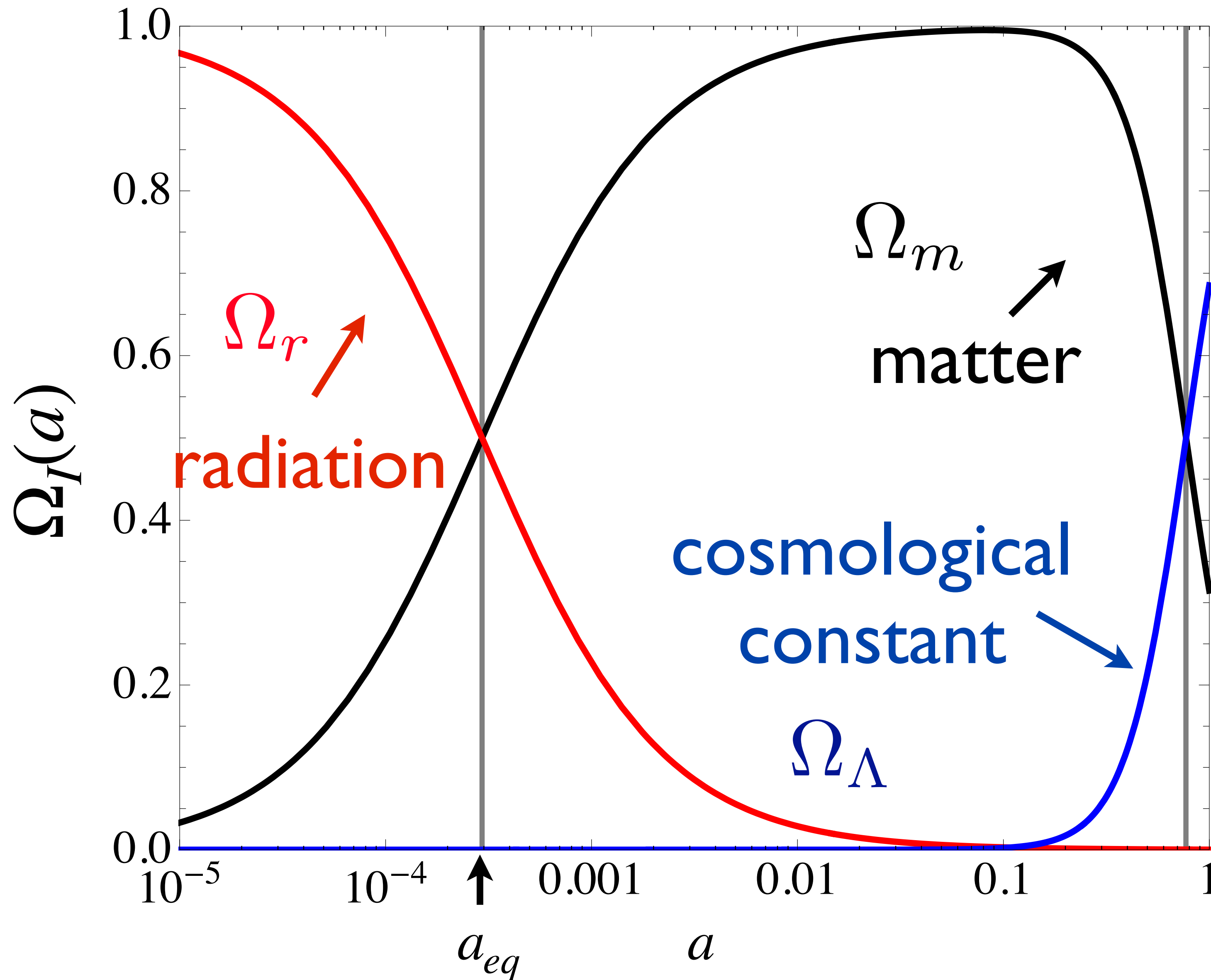
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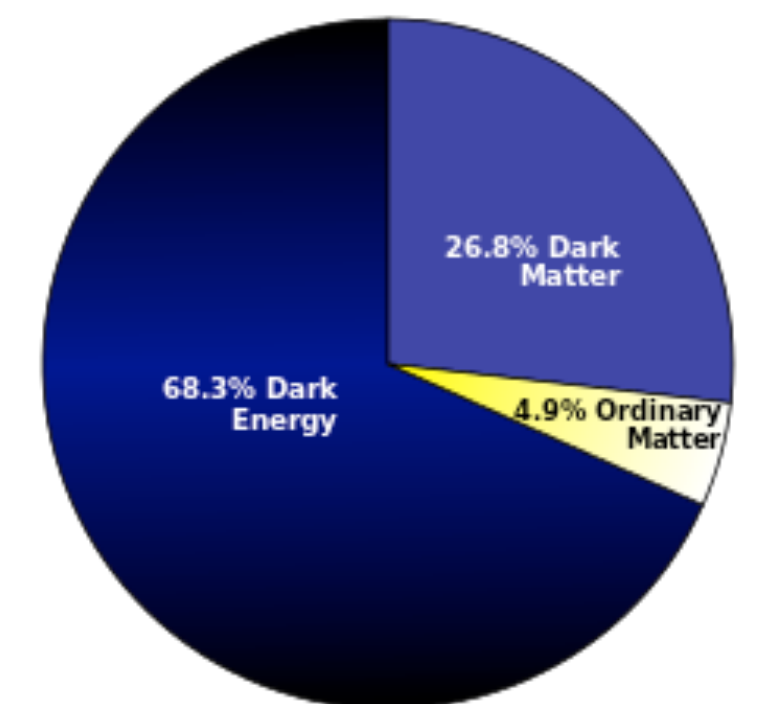
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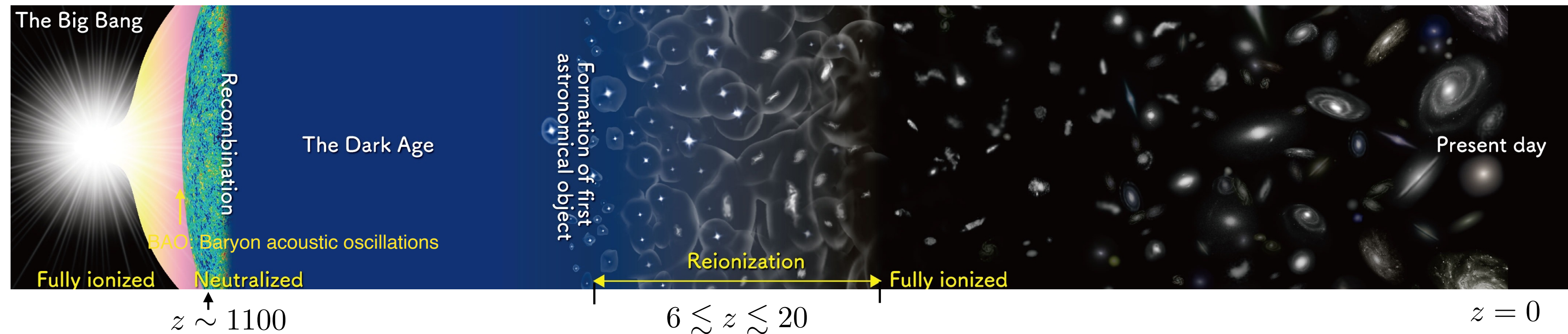
$\leftarrow a = 1$



The Λ CDM model

- Main observational pillars:

- The Hubble diagram and the expansion of the universe + discovery of the acceleration
- Primordial nucleosynthesis (BBN) and the abundance of light elements
- The cosmic background radiation (CMB): its spectrum and anisotropies
- The large-scale structure of the matter distribution (LSS). The distribution of matter is not random; it has structure.



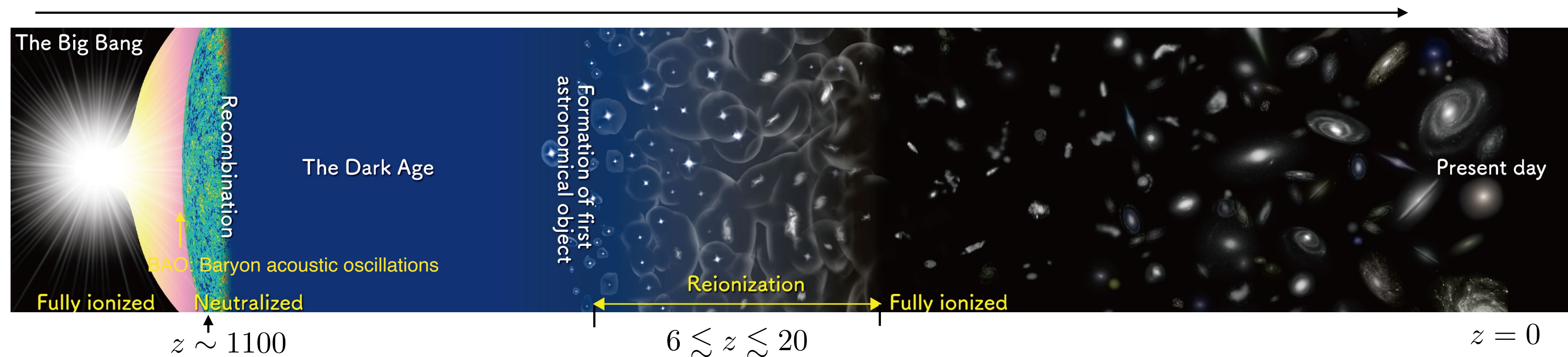
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Evolution of primordial perturbations with characteristic properties: gaussian and adiabatic initial conditions



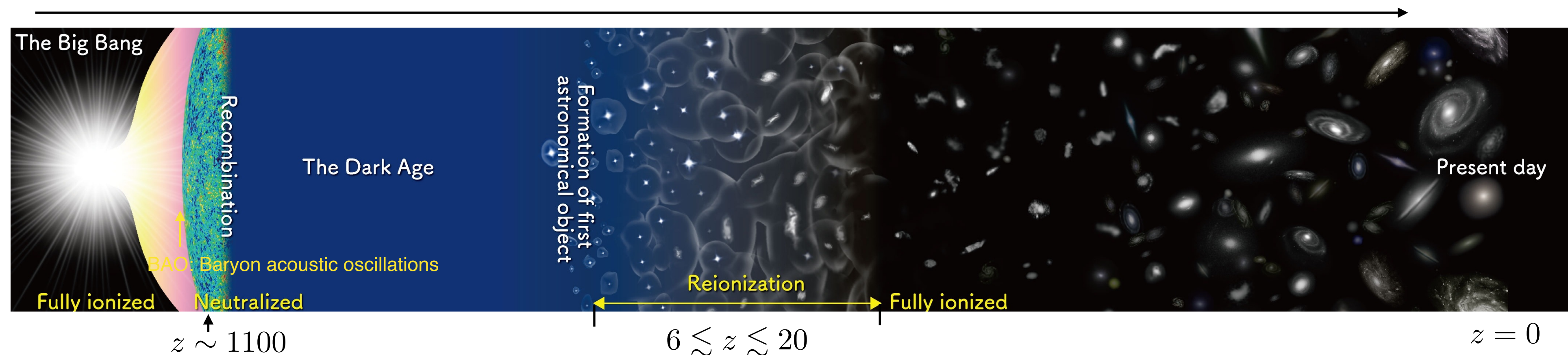
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Evolution of primordial perturbations with characteristic properties: gaussian and adiabatic initial conditions



What do these observations tell us about DM and its properties?

• Supernovae (SN) Ia

“Standard Candles”

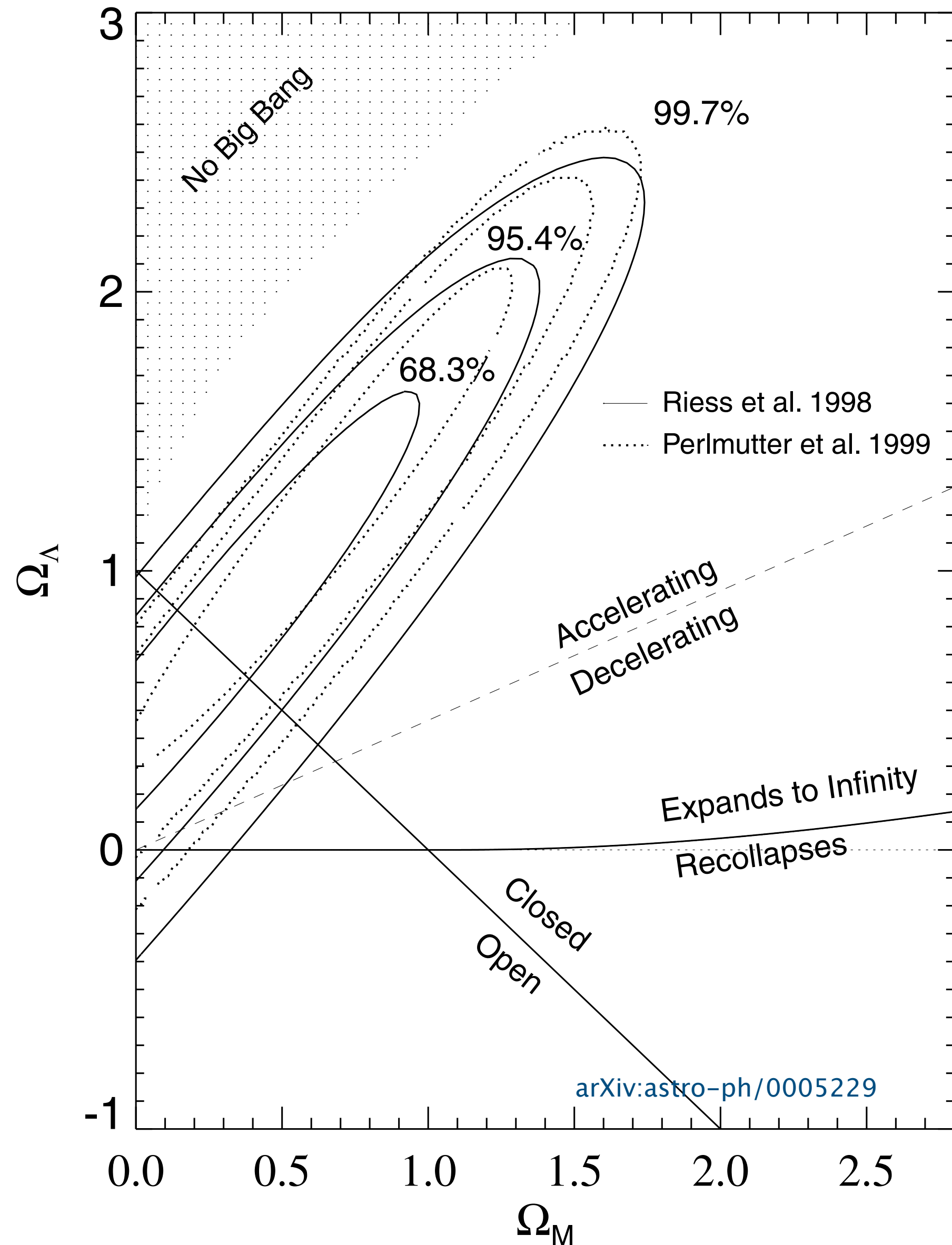


FIG. 2.—SNe Ia joint confidence intervals for $(\Omega_M, \Omega_\Lambda)$ from Perlmutter et al. (1999; SCP) and Riess et al. (1998; HZT). Regions representing specific cosmological scenarios are indicated.

➔ ...in ~2 decades, several teams searched for and characterized supernovae

Recent compilations of Spectroscopically-classified SNIas from different surveys:

Pantheon + [arXiv:2202.04077]:

$\simeq 1500$ SNIas

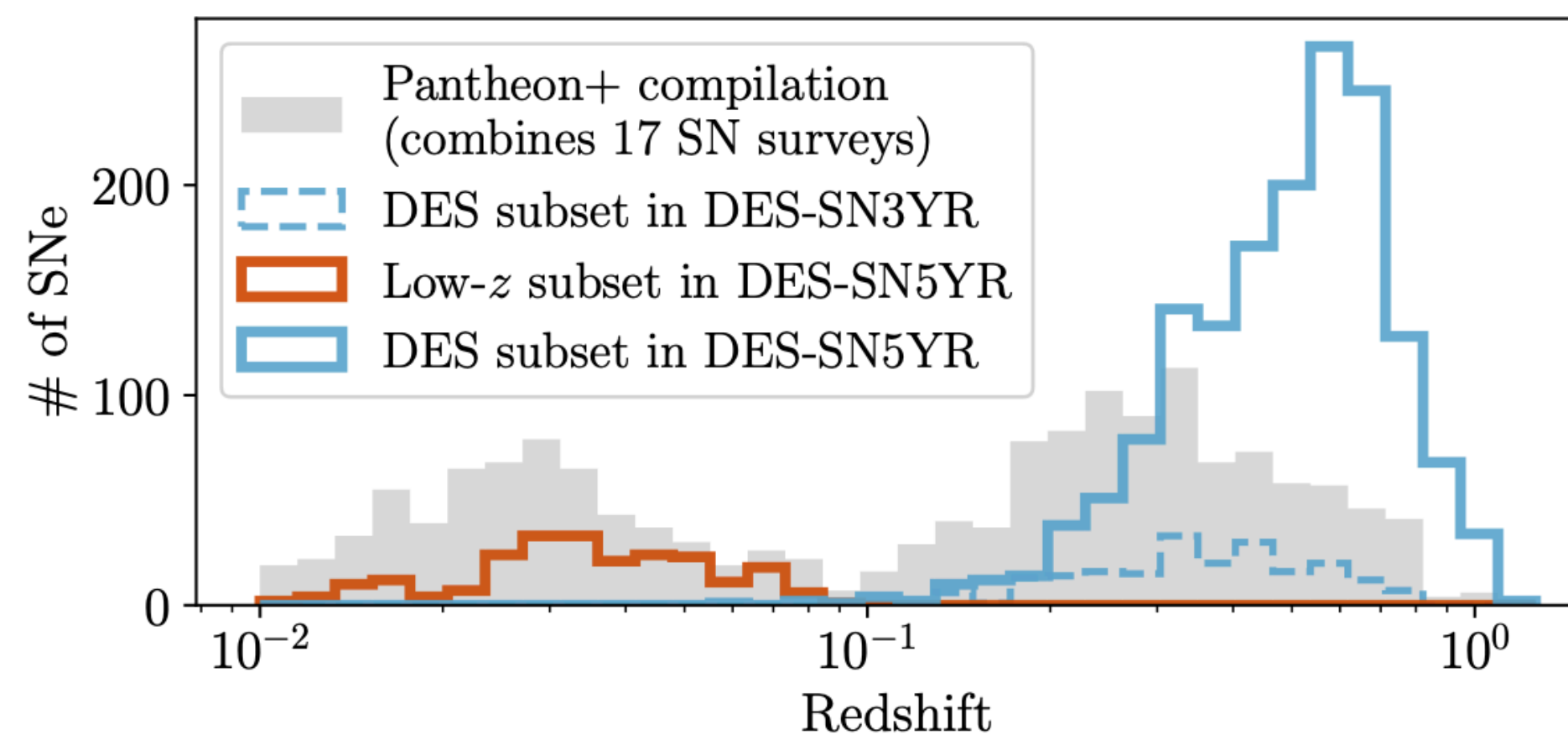
$$\Omega_m = 0.334 \pm 0.018$$

Union3: (Updated Bayesian Framework)

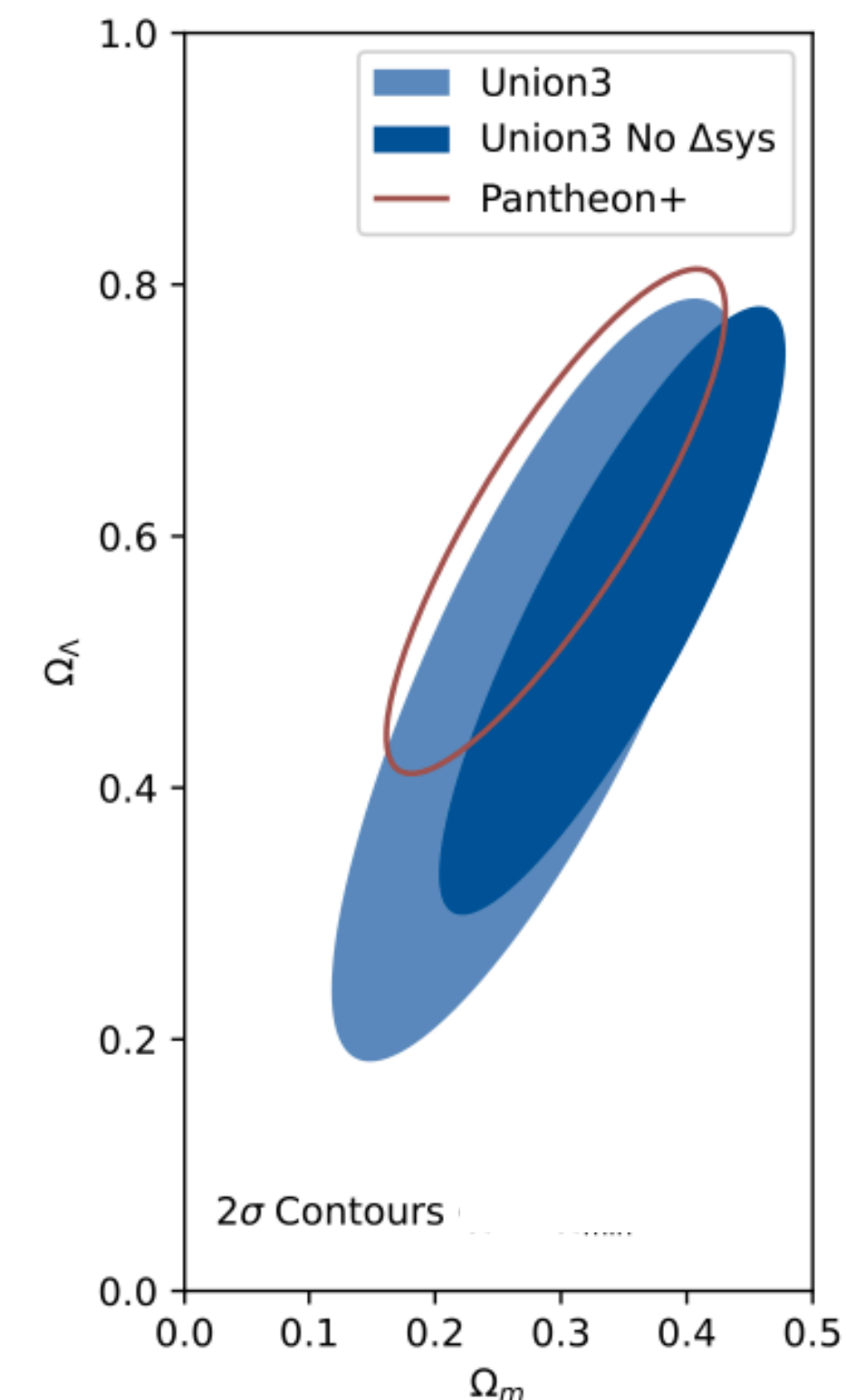
$\simeq 2000$ SNIas

$$\Omega_m = 0.356^{+0.028}_{-0.026}$$

DES Photometrically-classified SNIas



arXiv:2311.12098



DES-SN:

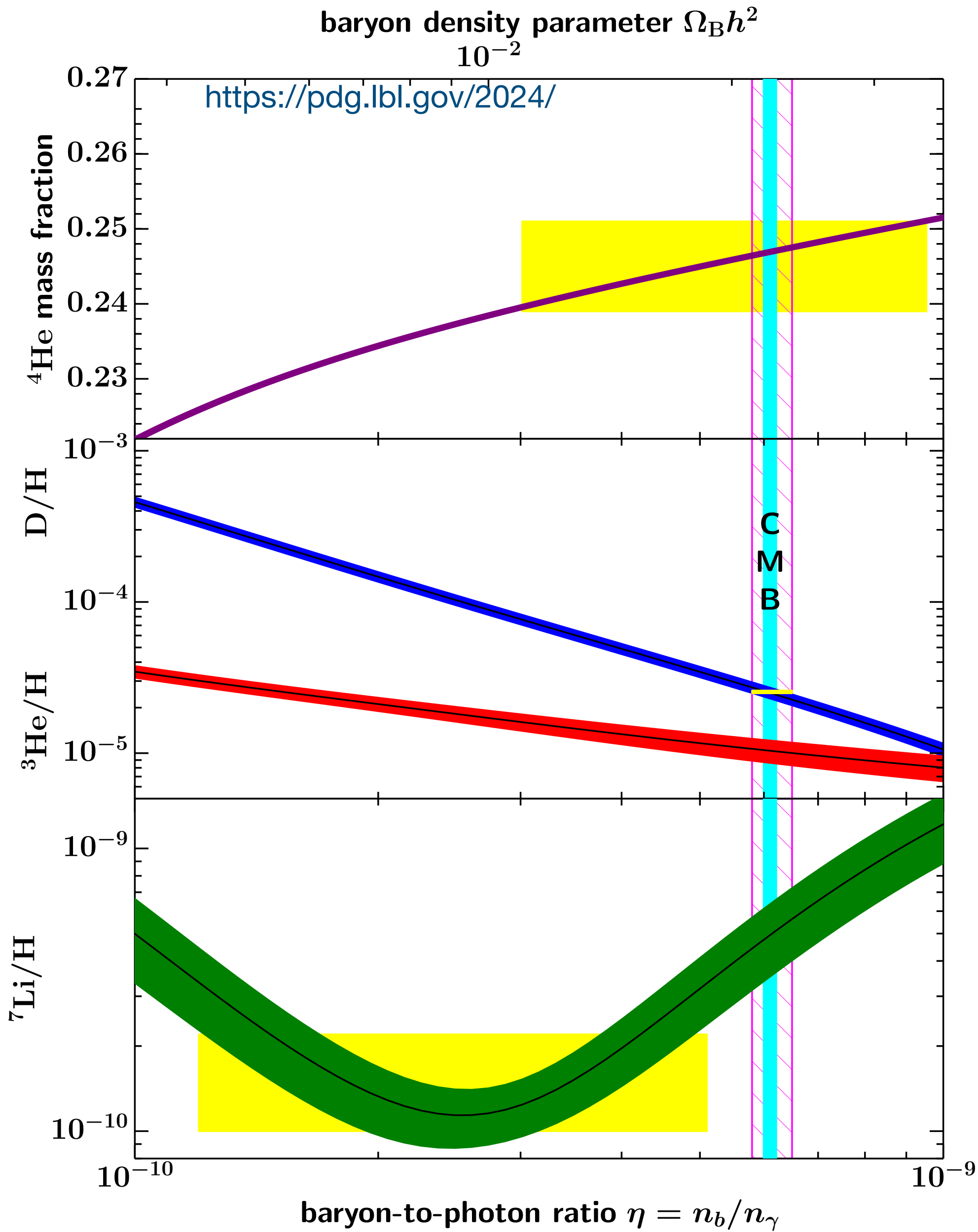
$\simeq 1600$ SNIas

$$\Omega_m = 0.352 \pm 0.017$$

[arXiv:2401.02929]

- Primordial nucleosynthesis (BBN):** process in which nuclei of the lightest elements are formed from neutrons and protons.

“Baryonic” matter in cosmology: Ordinary matter, made of protons and neutrons. It also contains electrons, but their mass is 2000 times smaller and they do not contribute significantly to the energy density of the universe.

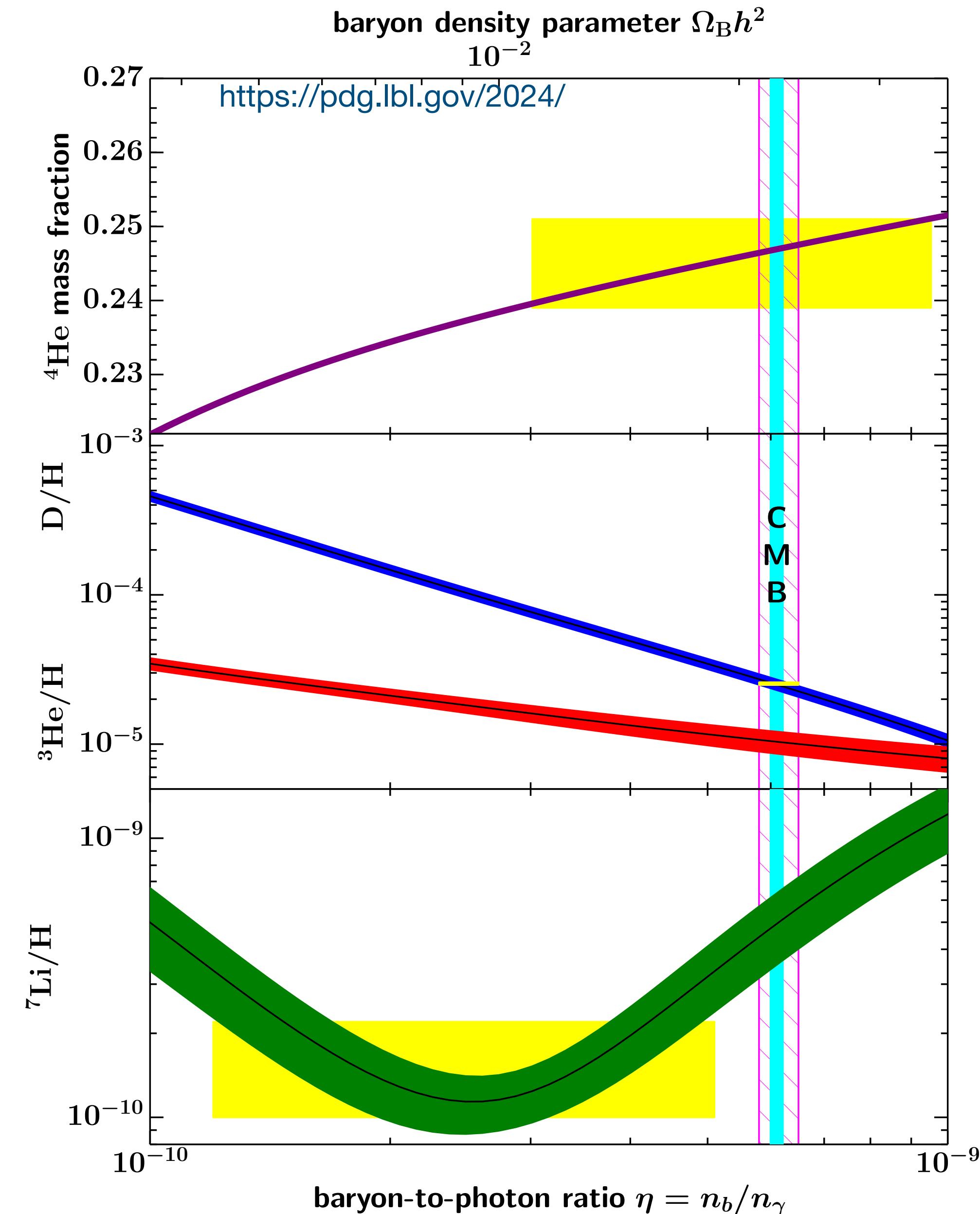


Combining with CMB (cyan band): $\Omega_b h^2 = 0.02233 \pm 0.00014$

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- The Standard Model indicates that this occurred when the universe had a temperature $T \sim 1$ MeV.
- The most abundant element is H .
- The observed abundance of 4He , is significantly larger than what could have been produced in stars. Heavier nuclei are produced in astrophysical processes.
- The relative abundance of deuterium $D = {}^2H$ is sensitive to $\rho_b \propto \Omega_b h^2$



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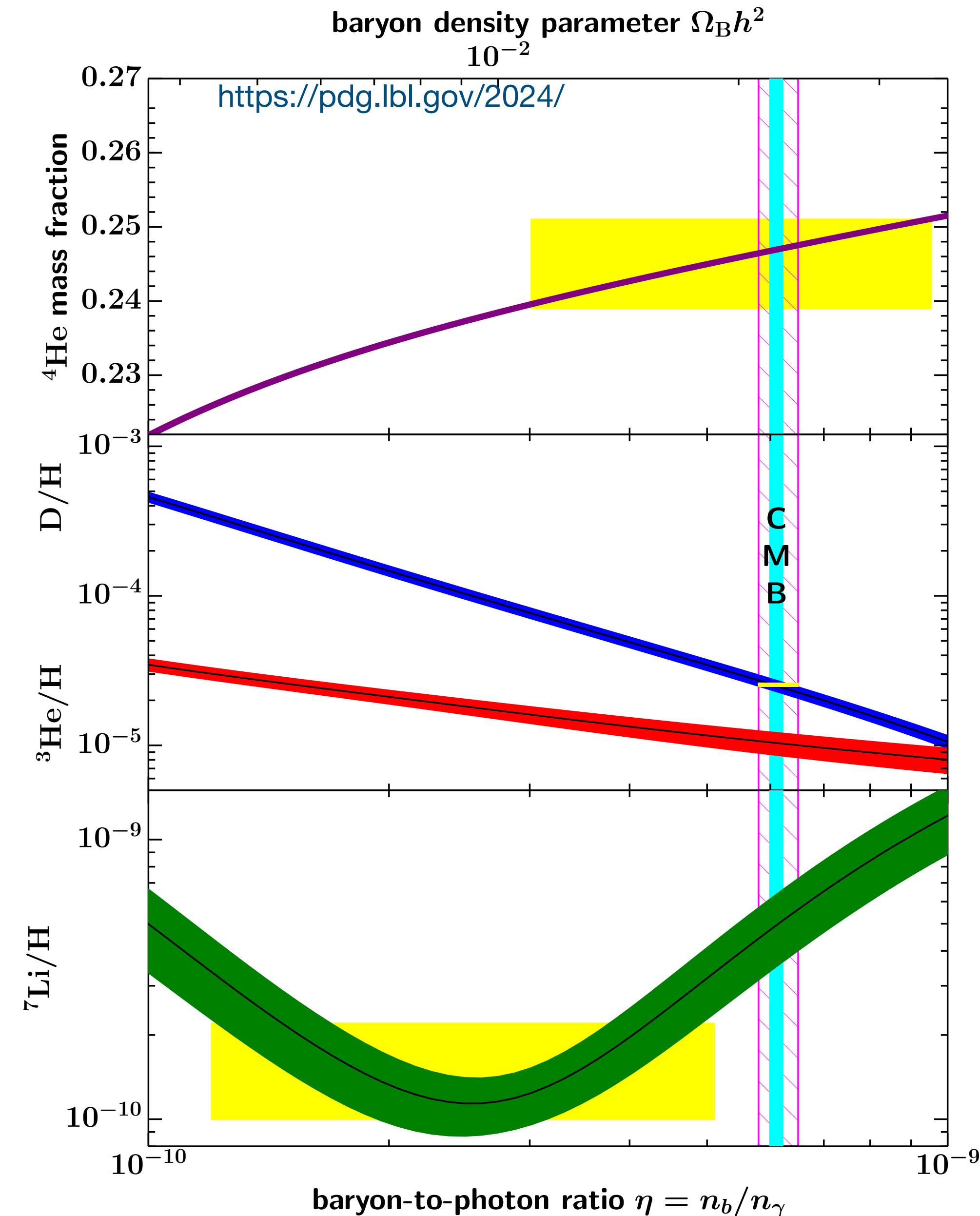
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- Combining (4He y D), the result is:

$$\Omega_b h^2 = 0.02205 \pm 0.00043$$

$h = \frac{H_0}{100 \frac{\text{km/s}}{\text{Mpc}}}$

$$\eta \equiv \frac{n_b}{n_\gamma} = 274 \times 10^{-10} \Omega_b h^2 \simeq 6 \times 10^{-10} \left(\frac{\Omega_b h^2}{0.022} \right)$$

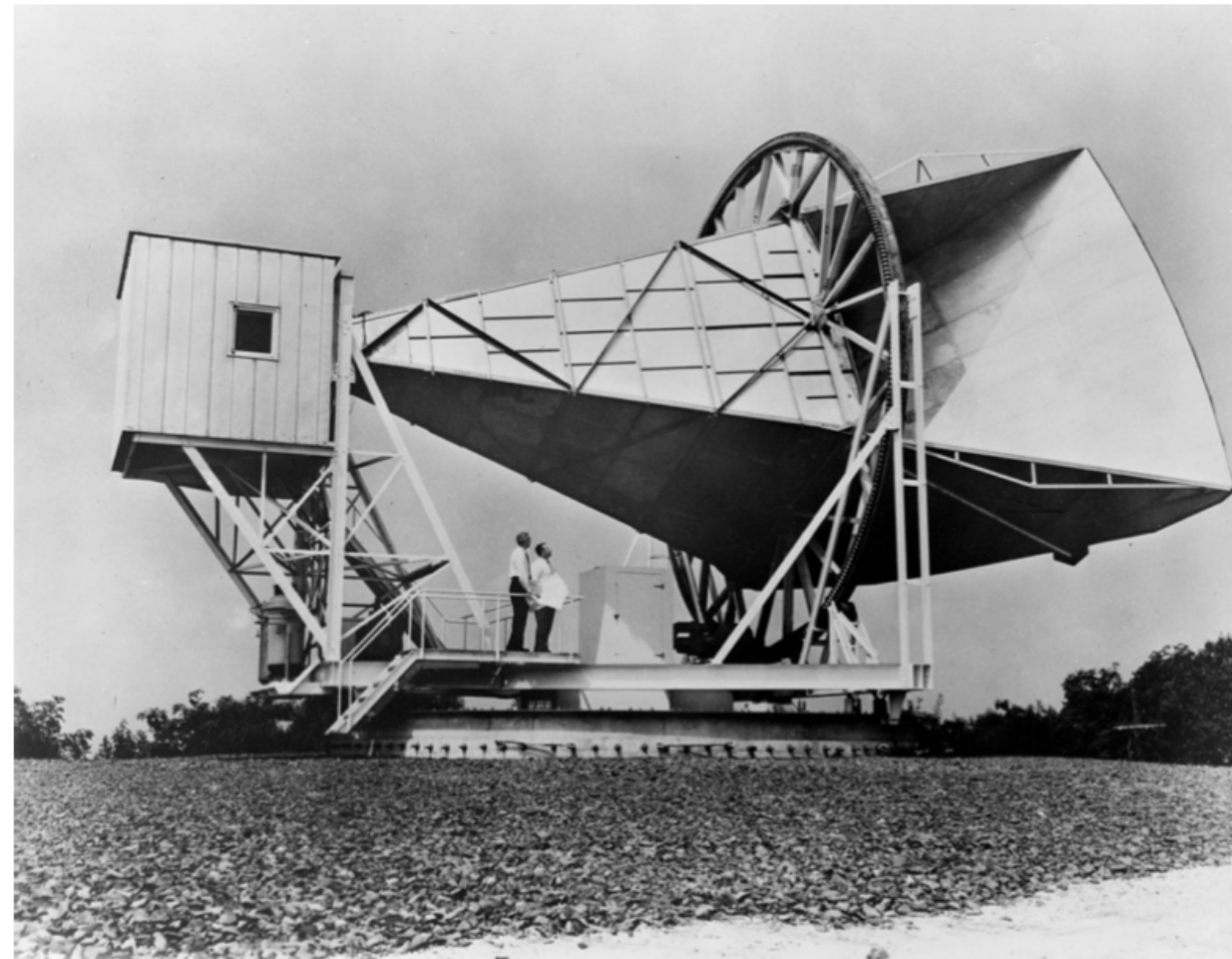
Baryonic matter is only $\sim 5\%$ of the critical density!



Combining with CMB (cyan band): $\Omega_b h^2 = 0.02233 \pm 0.00014$

The cosmic background radiation (CMB)

- There were predictions of the existence of a radiation with T around 5 o 10 K (*)



- In 1965 Penzias and Wilson were studying radiation with a radio antenna and they found an excess of $3.5 \pm 1 \text{ K}$ for $\lambda \sim 7.5 \text{ cm}$. -> **Nobel prize 1978!**

- Only one frequency was measured in the classical region $h\nu \ll k_B T$, where Rayleigh-Jeans formula applies: $h\nu n_\nu(\nu) \simeq 8\pi\nu^2 k_B T^4$.

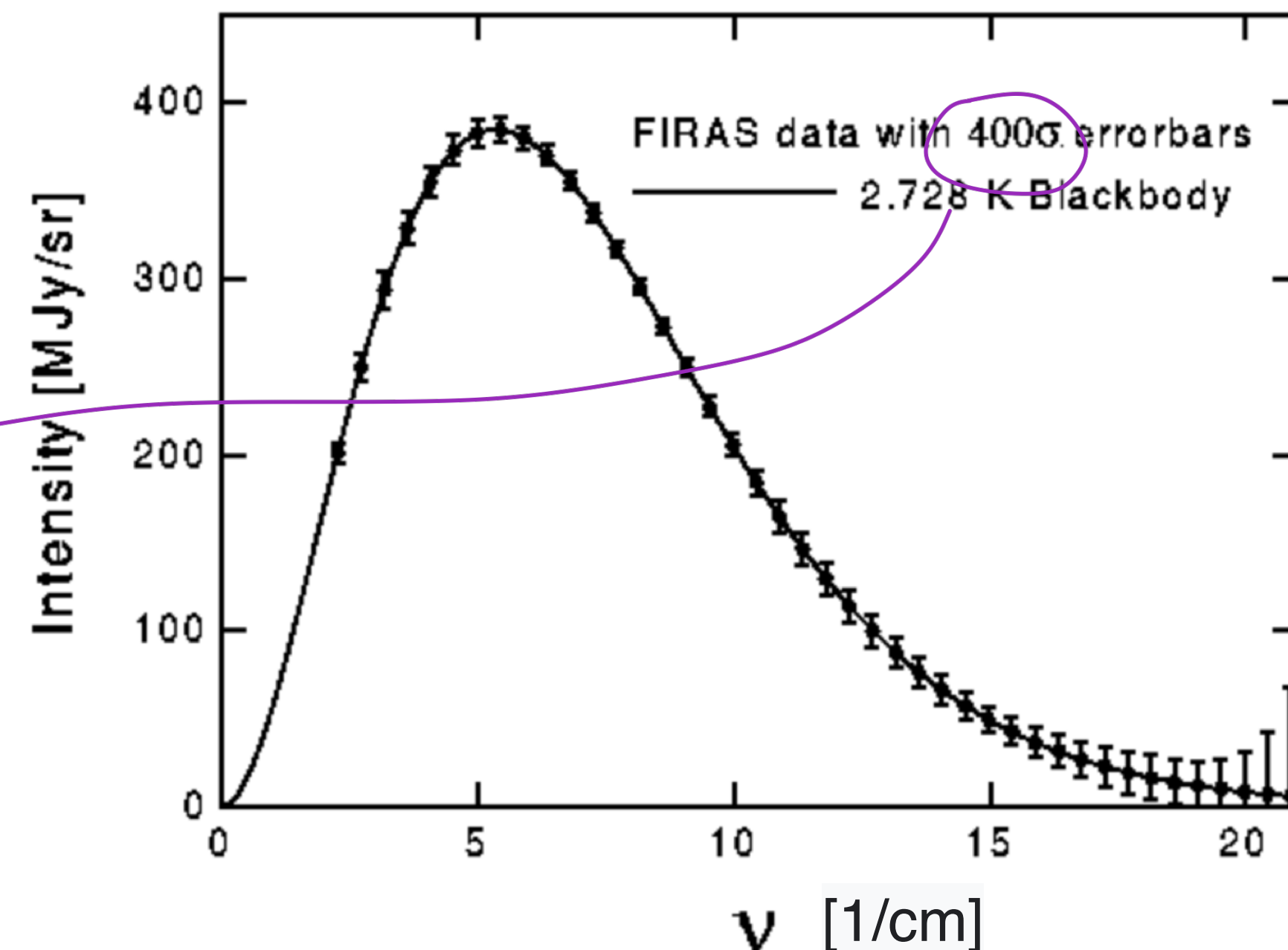
- To determine whether it has a blackbody spectrum it was needed to measure for smaller values of λ and the atmosphere becomes more and more opaque for $\lambda \lesssim 0.3 \text{ cm}$.

- In 1989, COBE satellite was launched with an instrument (spectrophotometer) called FIRAS dedicated to measuring the CMB spectrum.



Result: Almost a perfect blackbody spectrum!

Note: errors increased by a factor of 400!

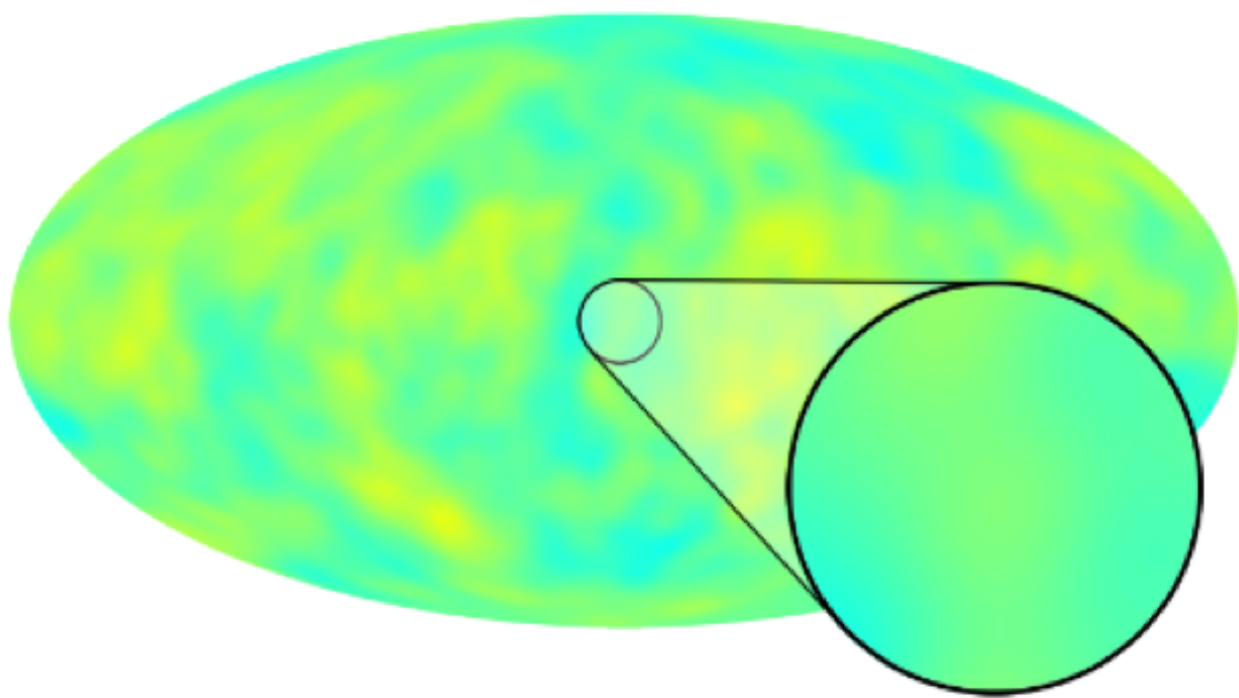


$$\rho_{\gamma 0} = \frac{4\sigma}{c} T_0^4 \simeq 4.64 \times 10^{-34} \frac{\text{g}}{\text{cm}^3}$$

The Cosmic Background Explorer Satellite (COBE)

(*) For a historical summary see for instance Golden Webinars - James E. Peebles - [here](#)

COBE had other instruments on board: Final data from 1996



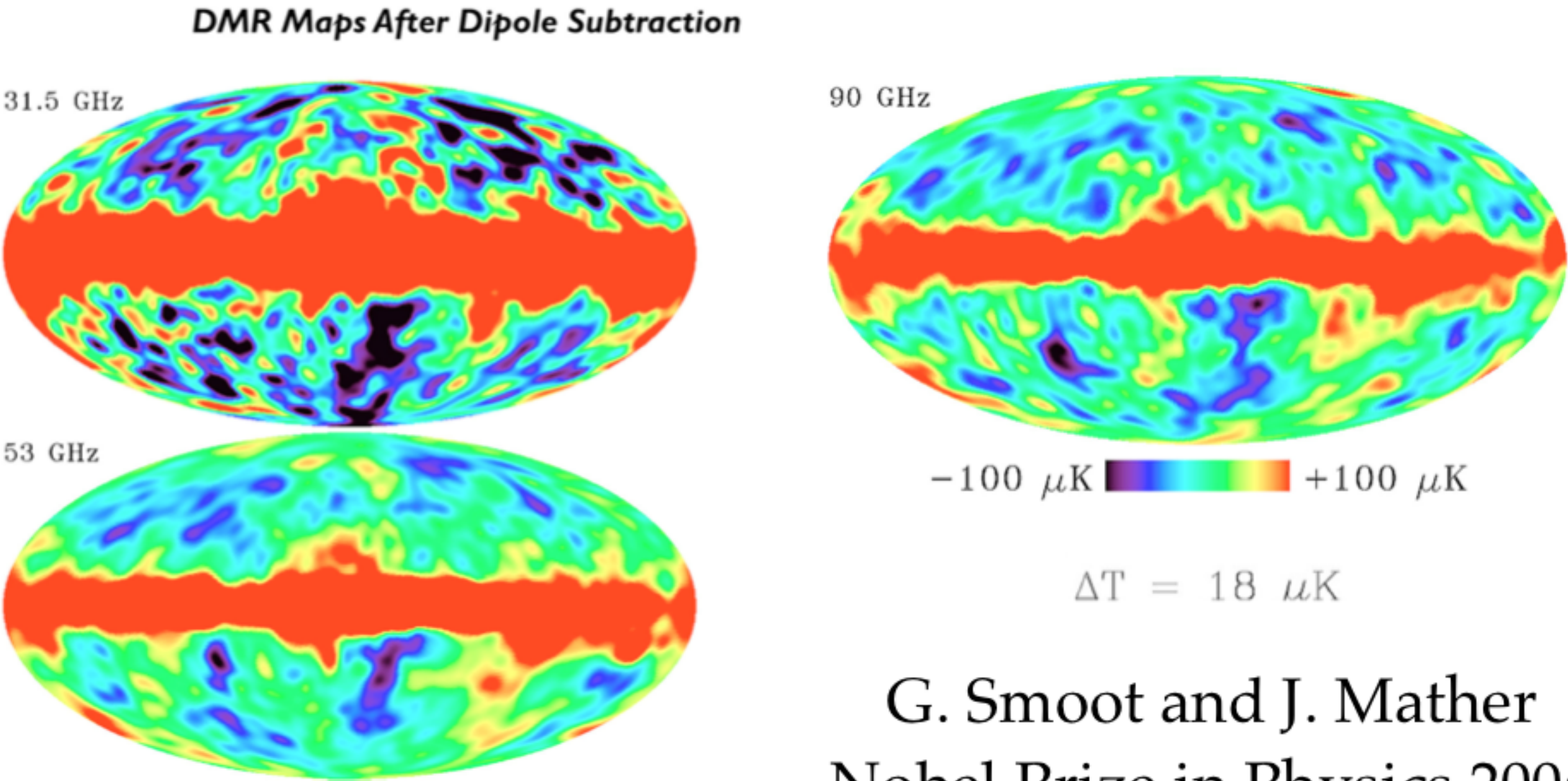
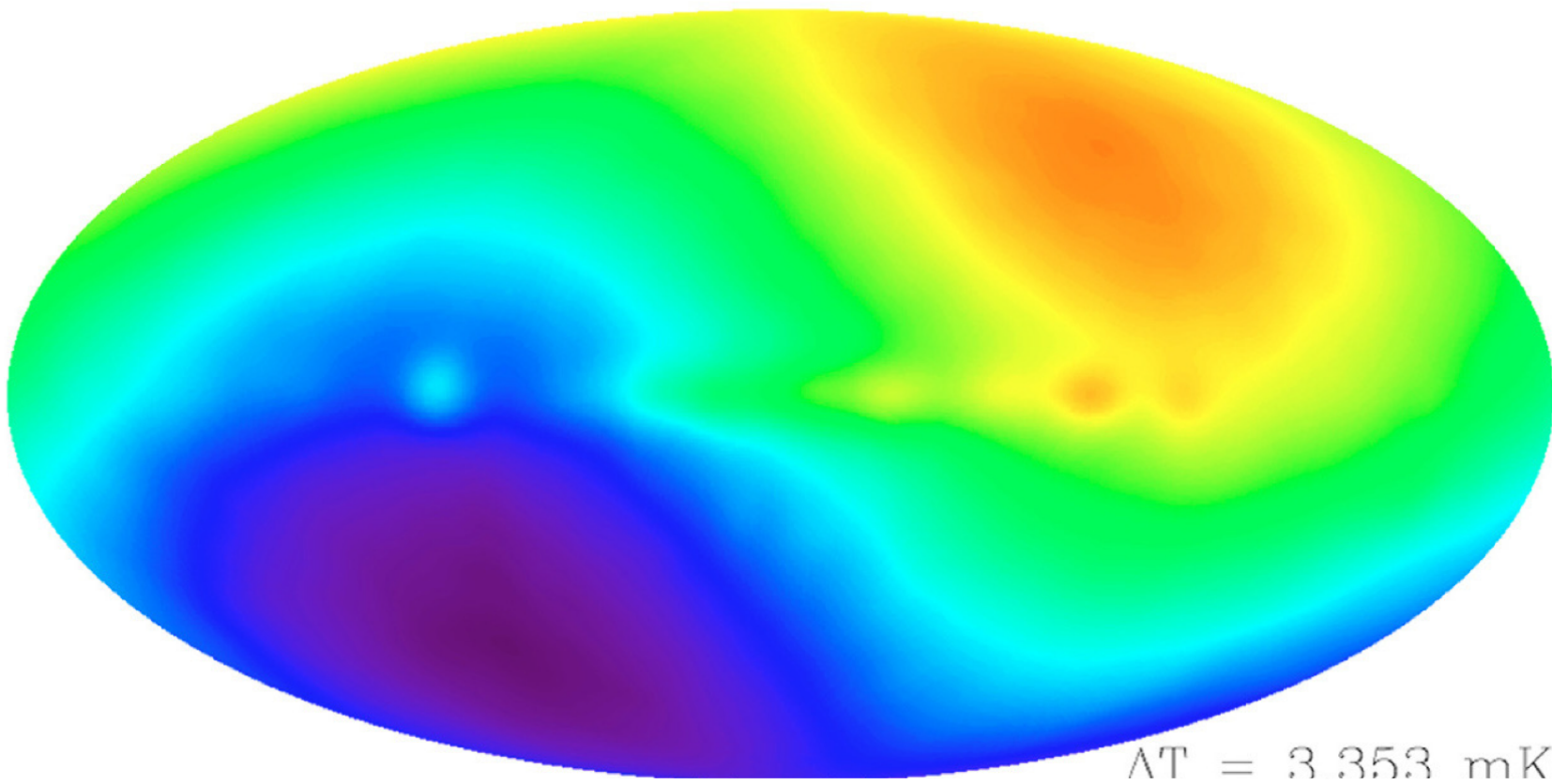
COBE

Instrument	Acronym	Description
Differential Microwave Radiometer	DMR	a microwave instrument that would map variations (or anisotropies) in the CMB
Far-InfraRed Absolute Spectrophotometer	FIRAS	a spectrophotometer used to measure the spectrum of the CMB

+ DIRBE an infrared detector to map dust emission

Anisotropies of the cosmic background radiation:

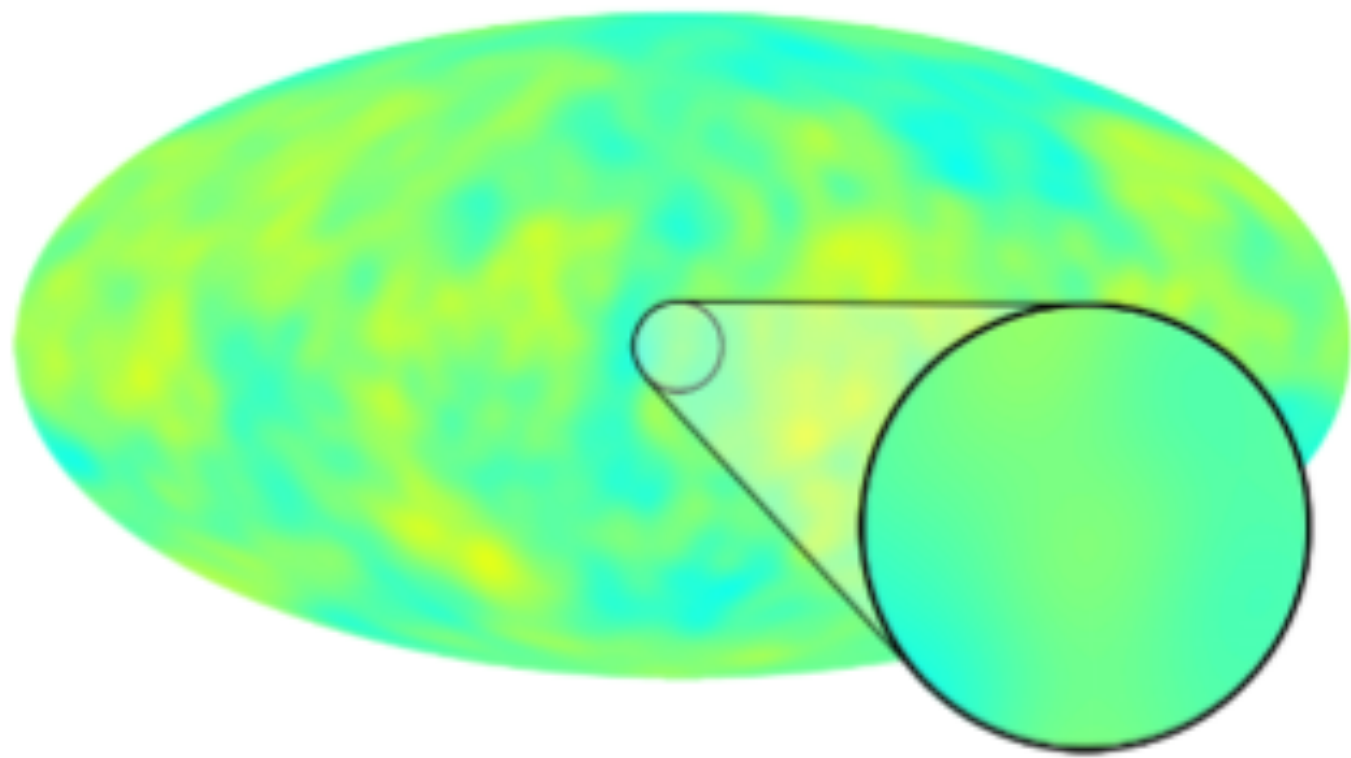
The dipole: The Earth has a peculiar velocity of 600 km/s



G. Smoot and J. Mather
Nobel Prize in Physics 2006

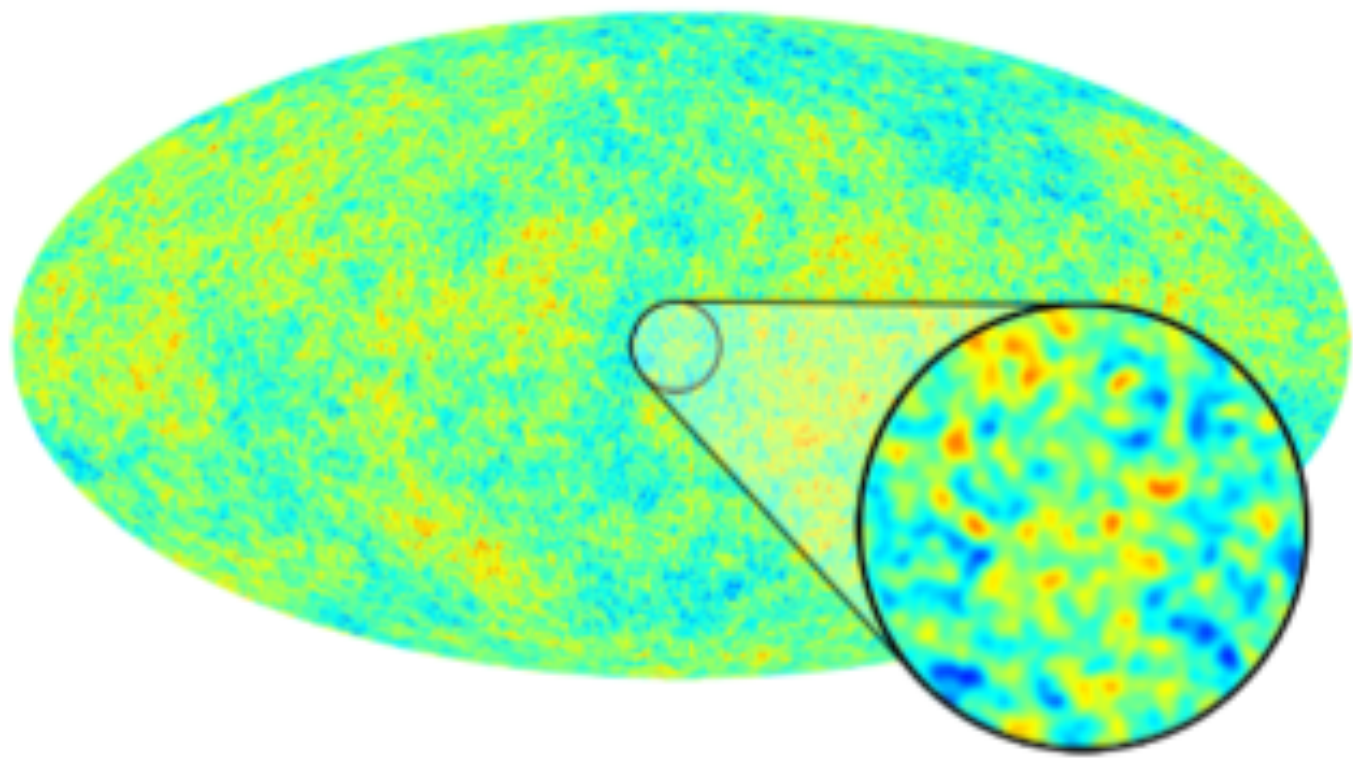
Anisotropies of one part in 100,000!

Other satellites were subsequently launched with instruments more sensitive to CMB fluctuations and with greater angular resolution at different frequencies, which also measure CMB polarization.



COBE

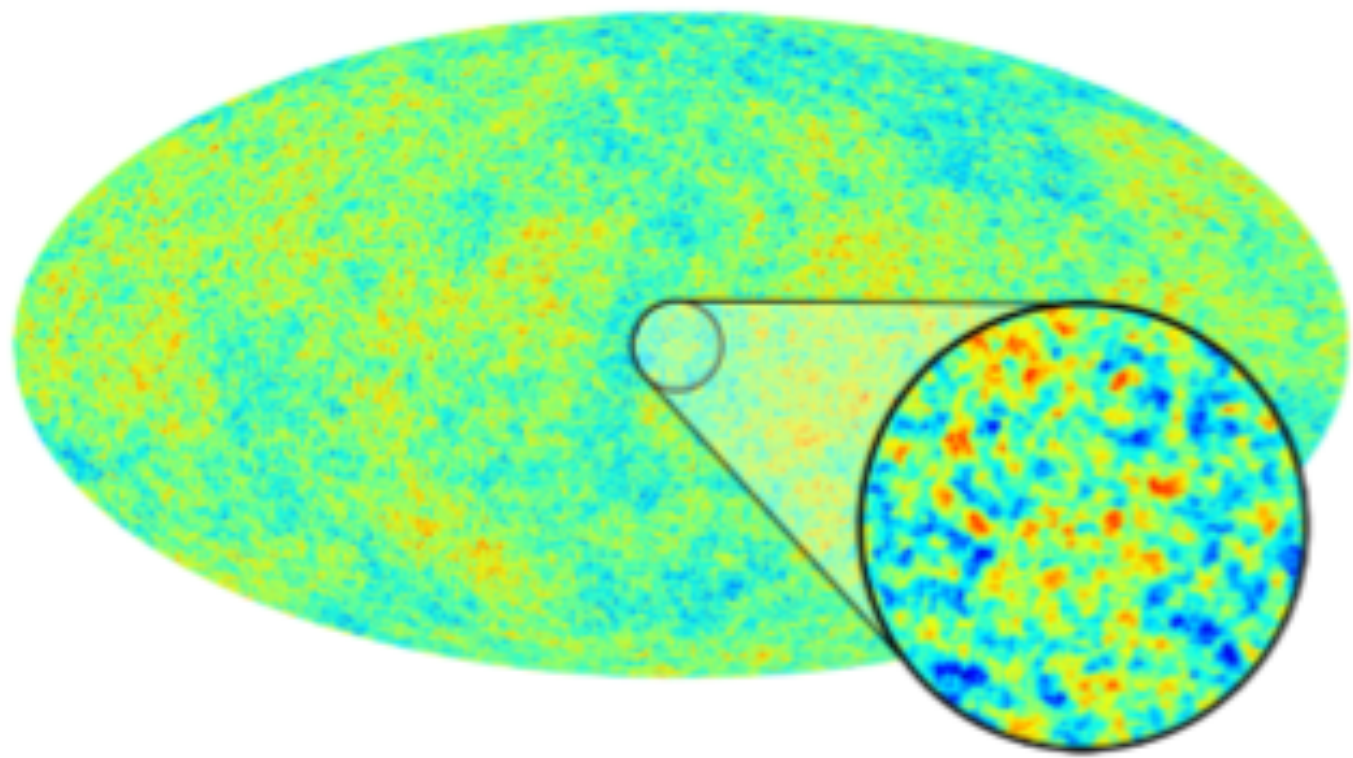
(1989-1992)
Final data 1996



WMAP

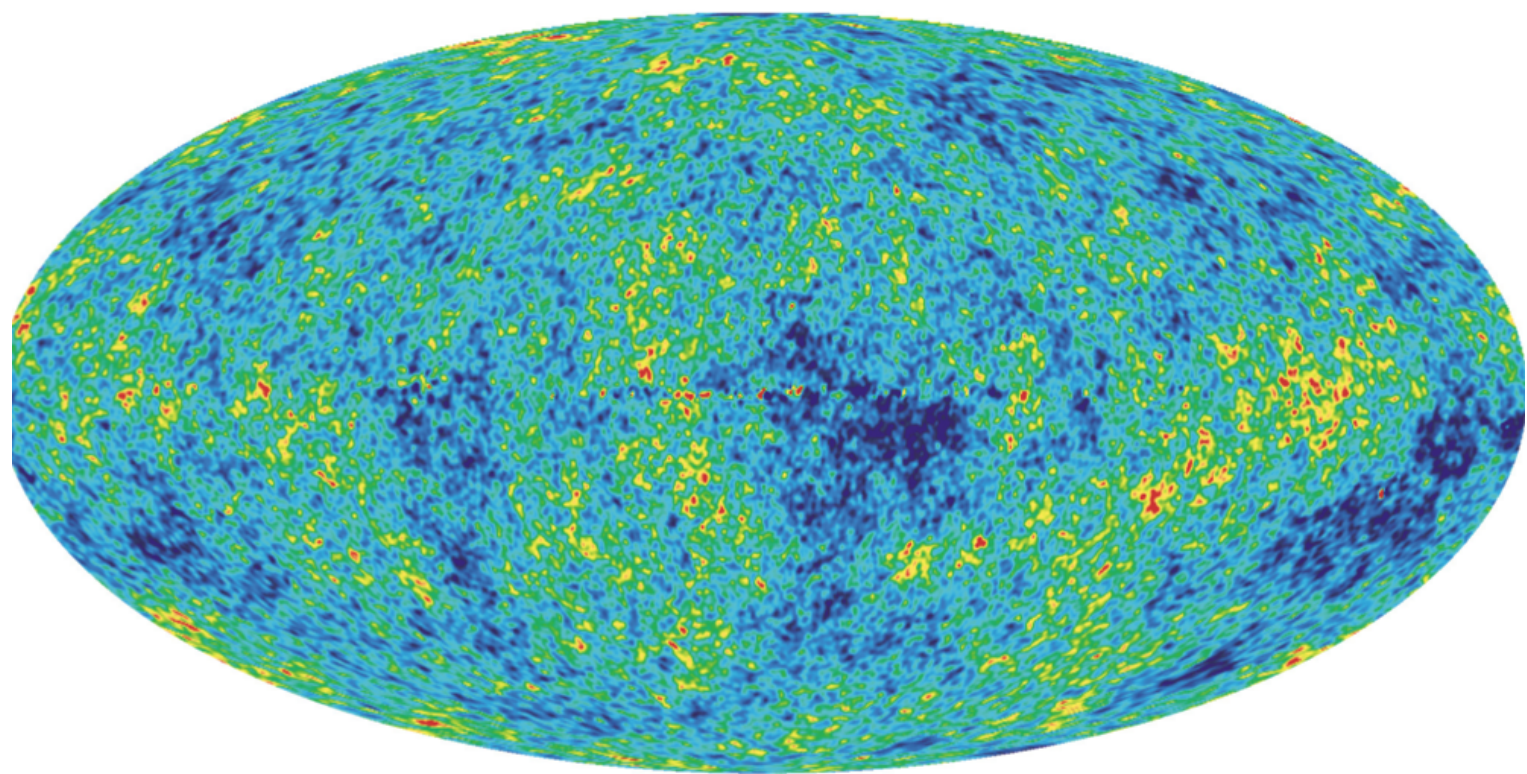
mage credit: Chris North, Cardiff University

(2001-2010)
Final data 2012

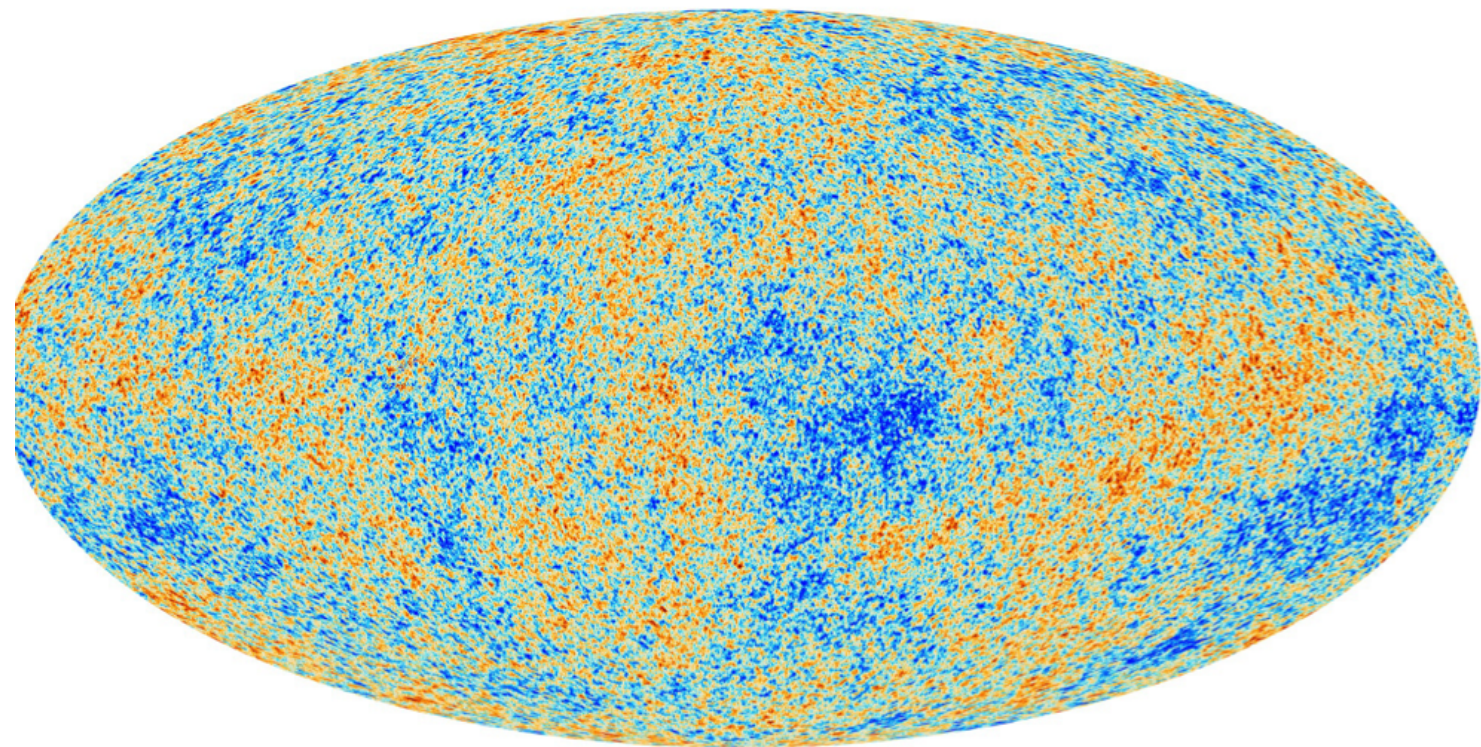


Planck

(2009-2013)
Final data 2018



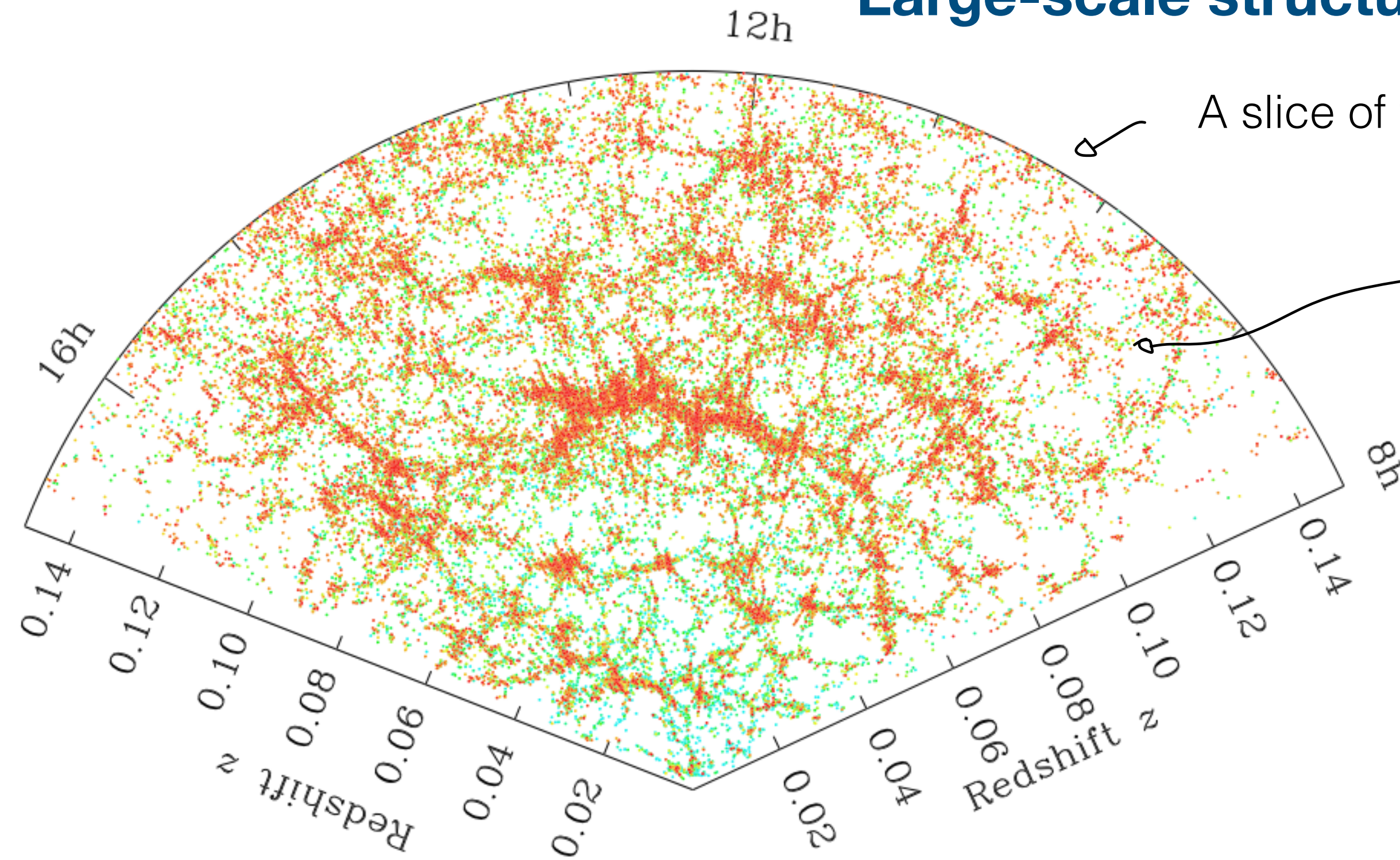
-200 T(μK) +200 WMAP 5-year



-300 T (μK) 300

+ other detectors on balloons and others on the ground with higher angular resolutions

Large-scale structure of the universe



A slice of the galaxy distribution from the Sloan Digital Sky Survey (SDSS)

Each dot represents a galaxy (in red: red galaxies...)

Typical sizes

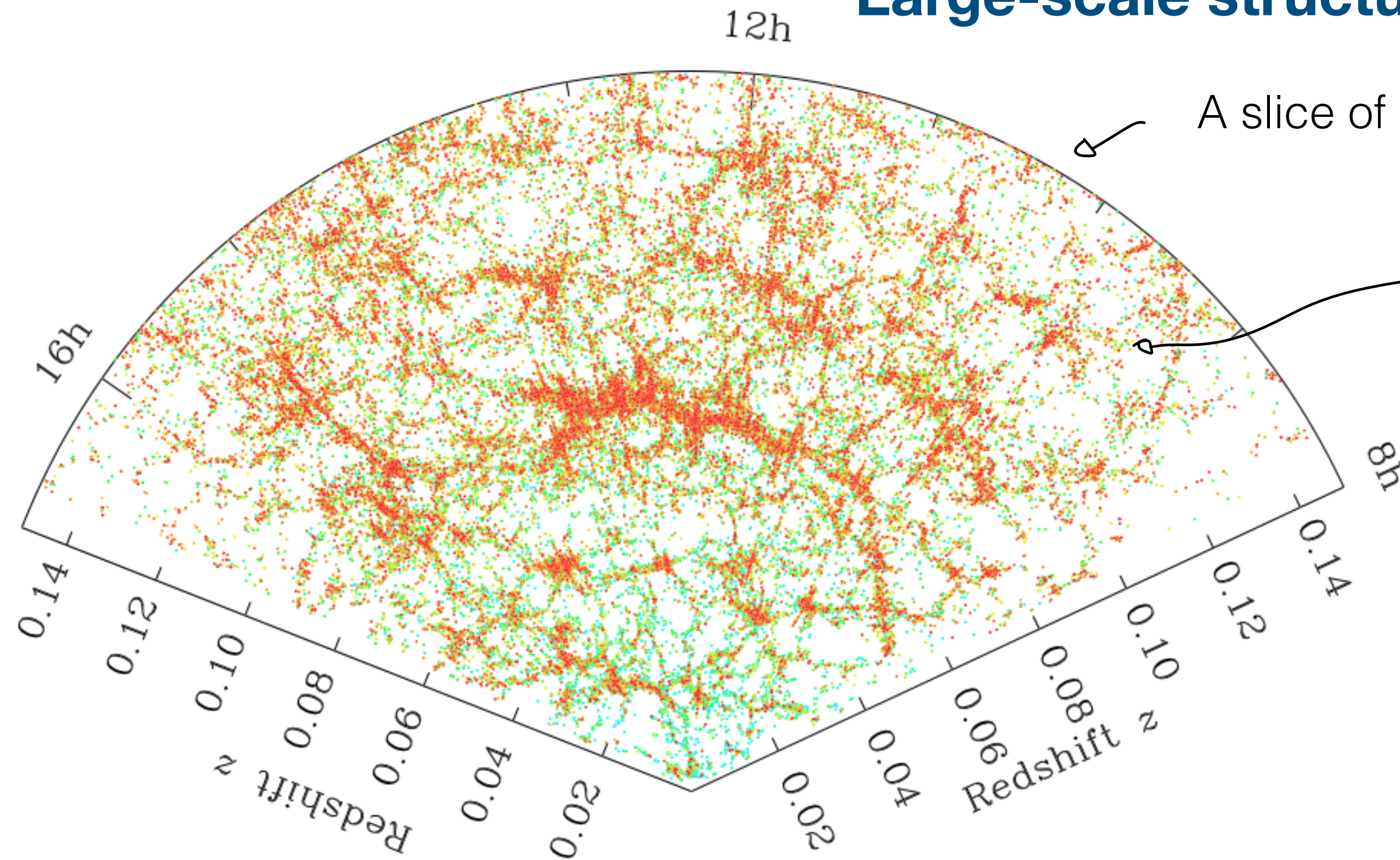
Stars $\sim 10^{-12} - 10^{-5}$ pc

Galaxies $\sim 1 - 100$ kpc, Masses $\sim 10^2 - 10^{11} M_{\odot}$

Cluster de galaxies $\sim 1 - 10$ Mpc; $\supset 10^3$ Galaxies

Super clusters $\gtrsim 10$ Mpc

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Homogeneous background universe + inhomogeneities

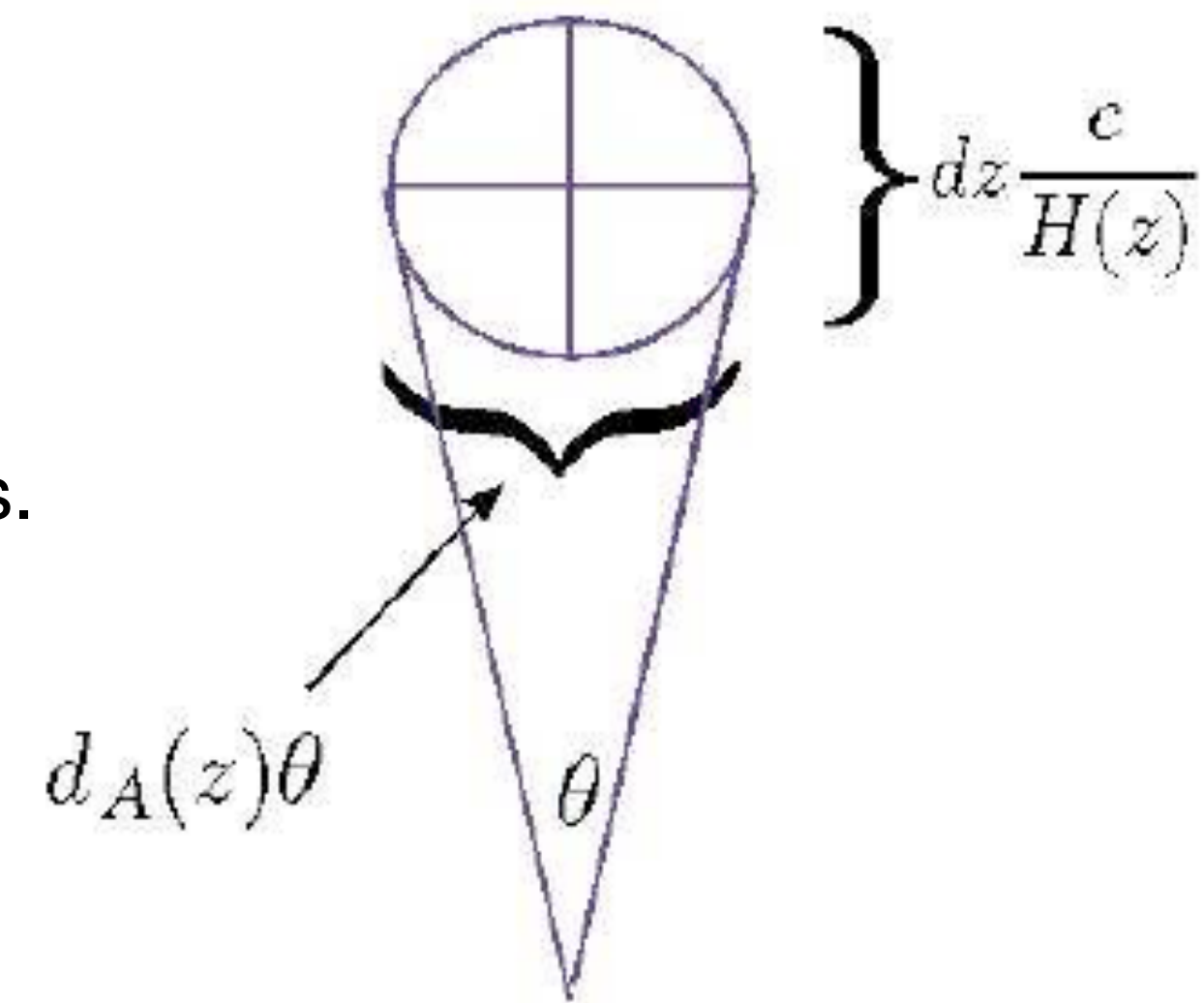
E. g. . $n_g(\mathbf{x})$ = Number density of galaxies una given “position” y $\bar{n}_g$ = Average number density of galaxies.

We characterize the inhomogeneities by:

$\delta_g(\mathbf{x}) = \frac{n_g(\mathbf{x}) - \bar{n}_g}{\bar{n}_g}$ or its Fourier transform $\tilde{\delta}_g(\mathbf{k}) = \int d^3x e^{-i\mathbf{k}\cdot\mathbf{x}} \delta_g(\mathbf{x})$ and their correlations:

$$\langle \delta_g(\mathbf{x}) \delta_g(\mathbf{x}') \rangle \text{ or } \langle \delta_g(\mathbf{k}) \delta_g^*(\mathbf{k}') \rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k} - \mathbf{k}') P_g(\mathbf{k}).$$

Power spectrum

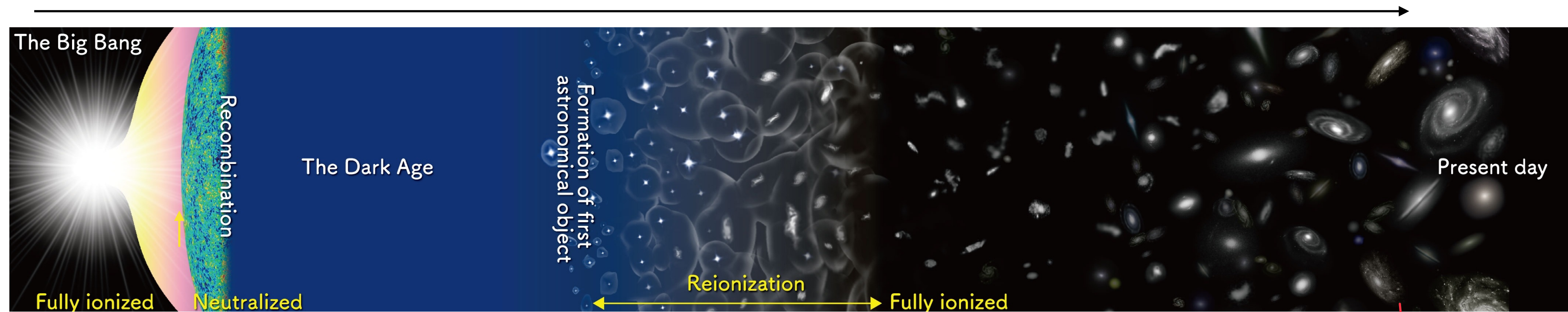


Distance by angular diameter

$$d_A = a(t_1) r_1(z)$$

Large-scale structure of the universe

Evolution of initial perturbations of the energy density with particular properties

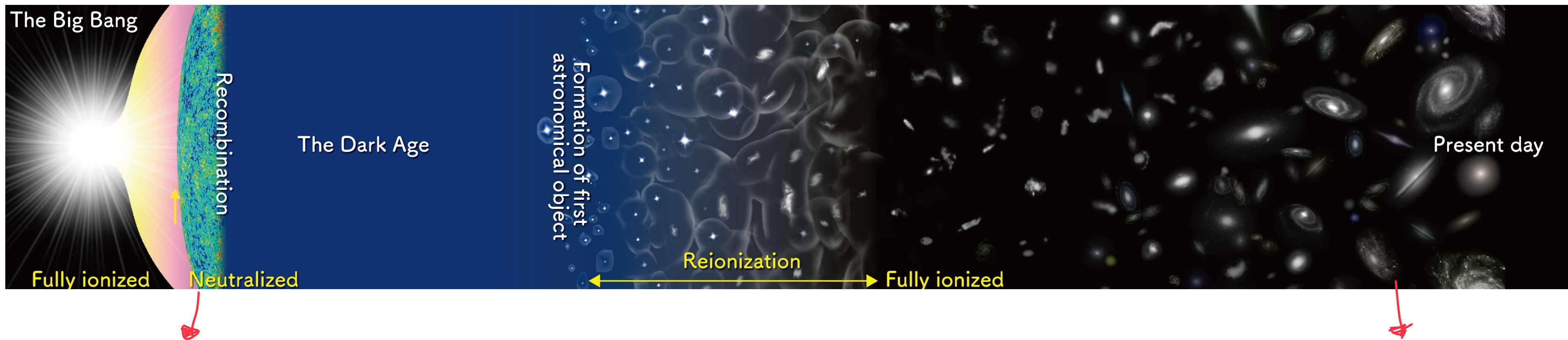


CMB is released - Inhomogeneities $\sim 10^{-5}$

Inhomogeneities $\delta \sim \mathcal{O}(1)$

Large-scale structure of the universe

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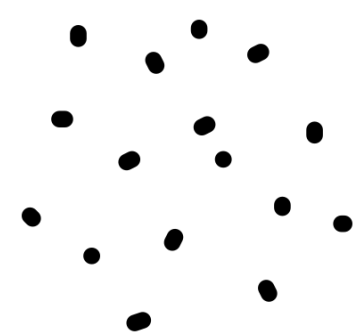


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Inhomogeneities $\delta \sim \mathcal{O}(1)$

Within the Standard Model framework, the inhomogeneities of ordinary matter grow due to its gravitational interaction, but its relative density $\Omega_b \sim 0.02 h^{-2}$ is not sufficient to account for the formation of structures today. If we assume that **cold dark matter (CDM)** exists -> this can be explained

Traditional idea of CDM:



$$N = nV = na^3V_0 = \text{cte} \rightarrow \rho_{\text{DM}} \simeq m n \sim a^{-3}, p_{\text{DM}} \sim 0$$

Some parameters determined by CMB and LSS

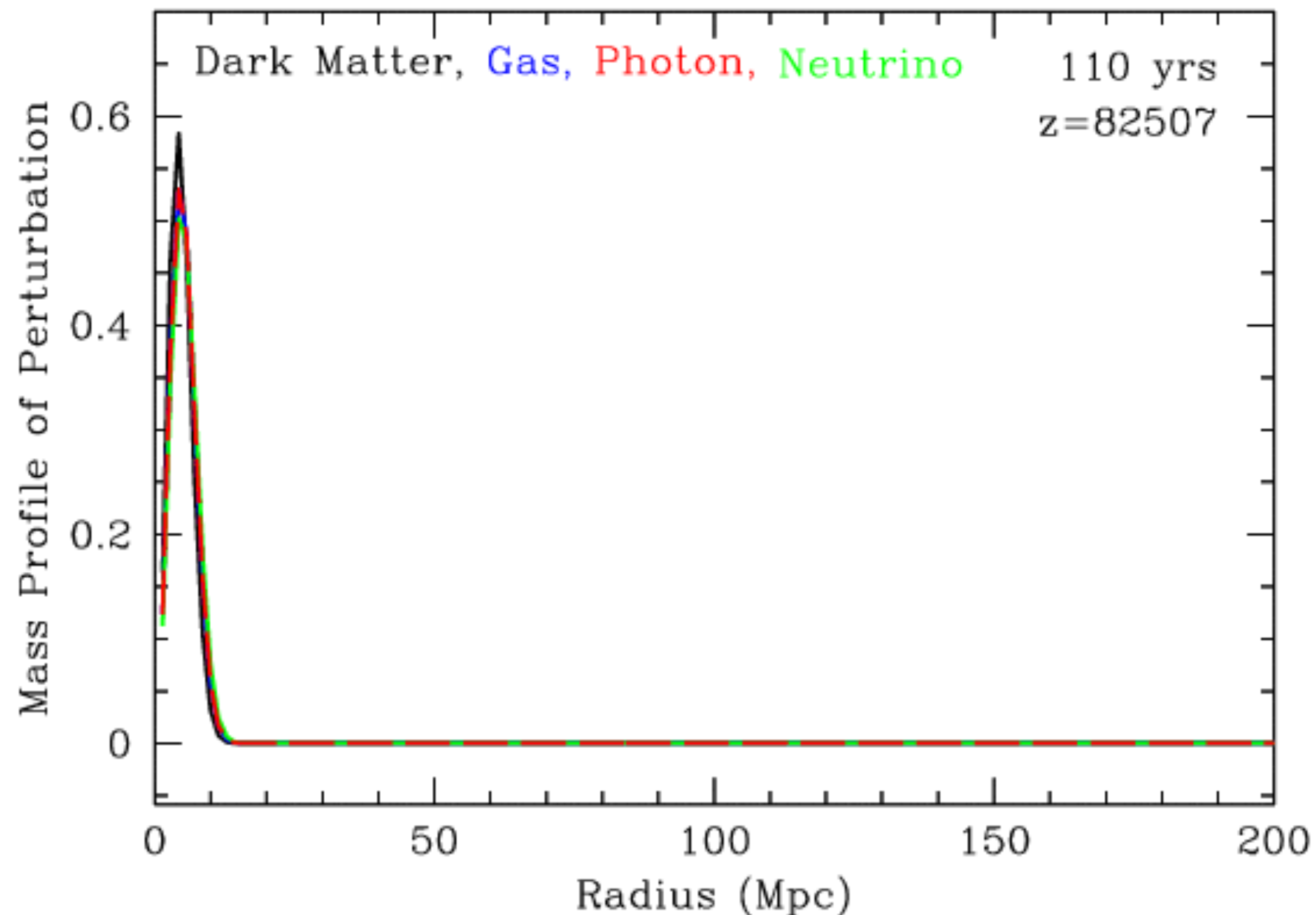
PARAMETRO	II	CMB	II	LSS
h		0.674 ± 0.005		0.677 ± 0.004
$\Omega_b h^2$		0.02237 ± 0.00015		0.02242 ± 0.00014
$\Omega_c h^2$		0.1200 ± 0.0012		0.1193 ± 0.0009
Ω_Λ		0.685 ± 0.007		0.689 ± 0.006

Compatible with BBN! (see <https://pdg.lbl.gov/2024>)

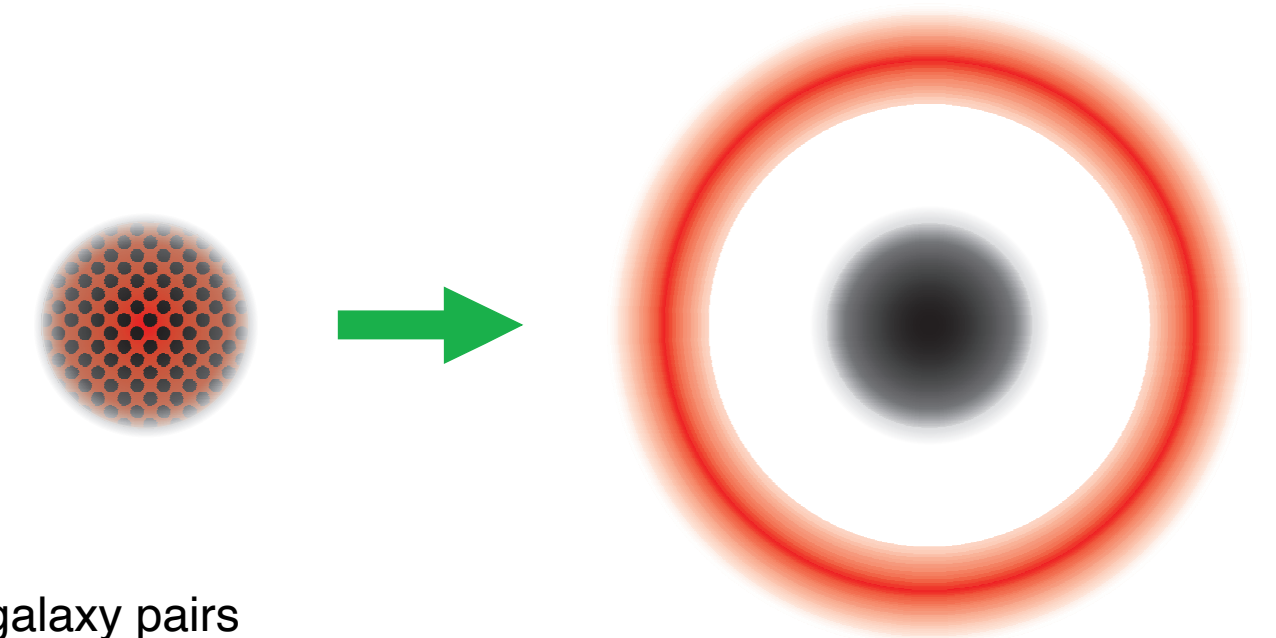
Baryon and DM distributions

- Baryons follow DM after they decoupled from CMB
- Baryon acoustic oscillations (BAO) features

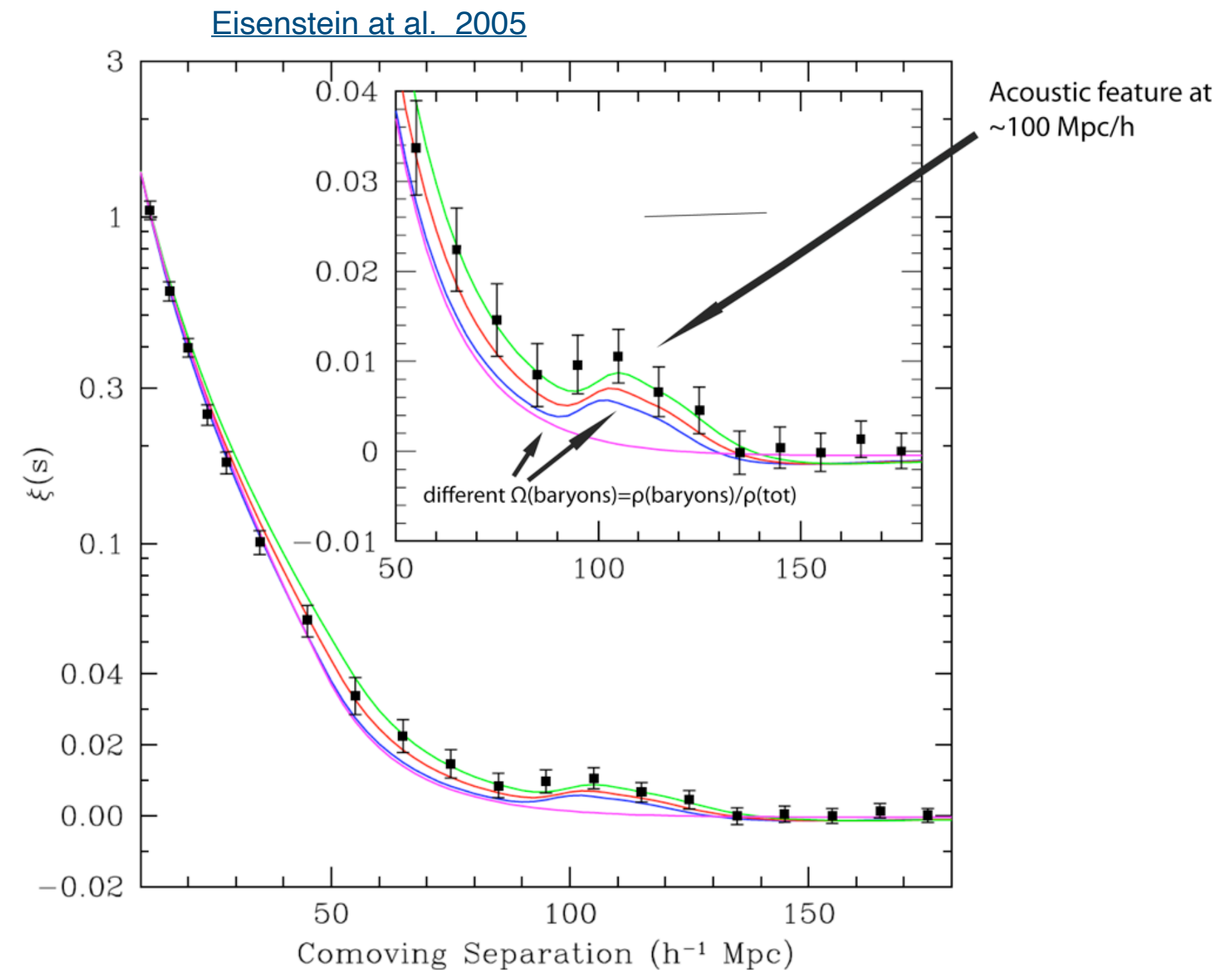
While baryons contribute $\sim 15\%$ of the total matter density, acoustic oscillations give rise to an observable peak in the total matter correlation function at a characteristic distance



Credit: Eisenstein, Seo y White (2007) [here](#)



Correlation of galaxy pairs

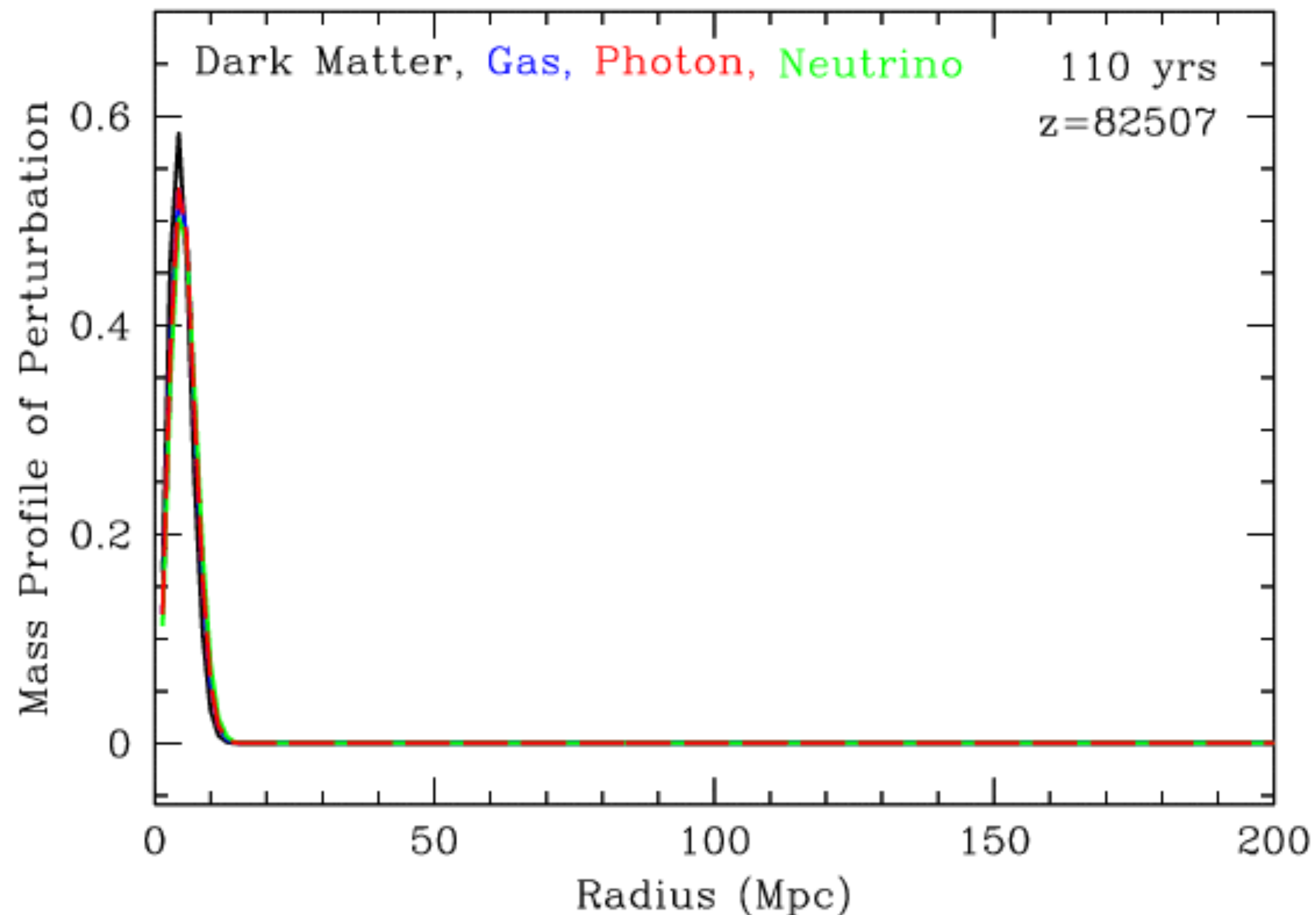


Illustrative video [here](#)

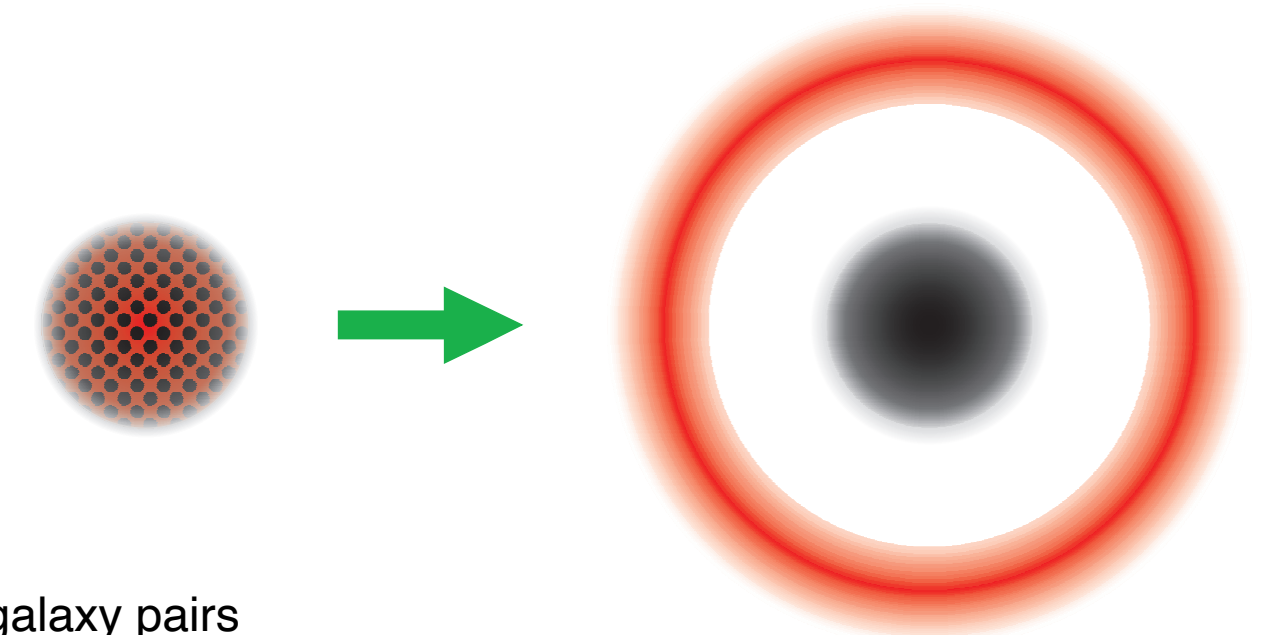
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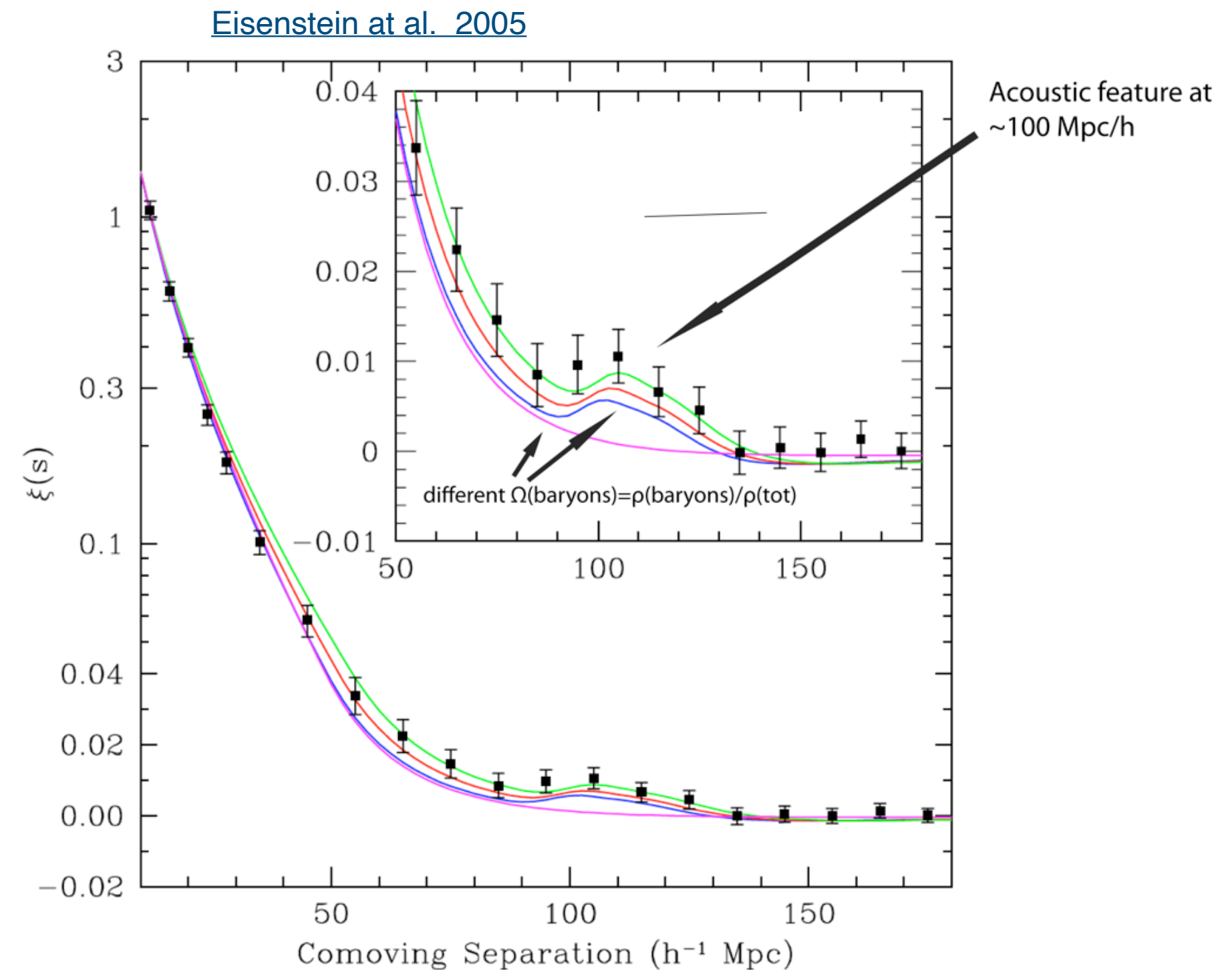
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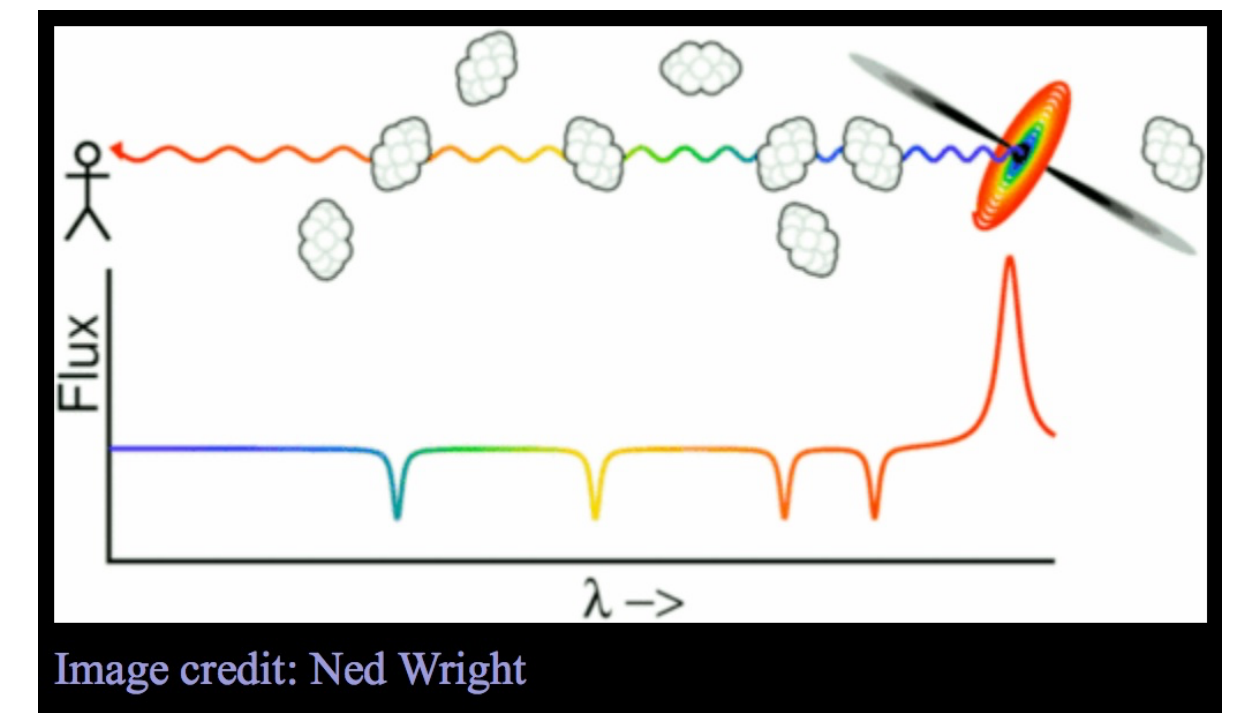
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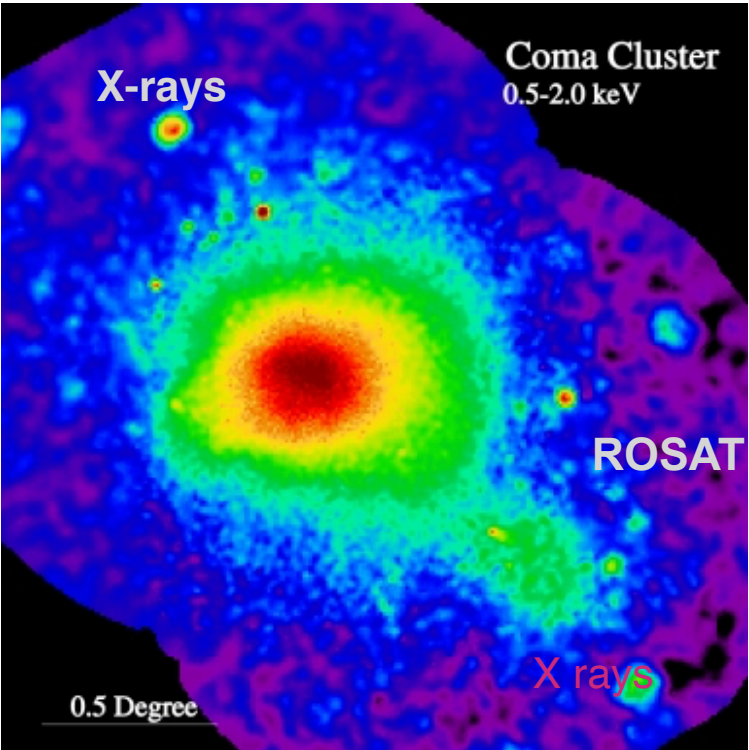
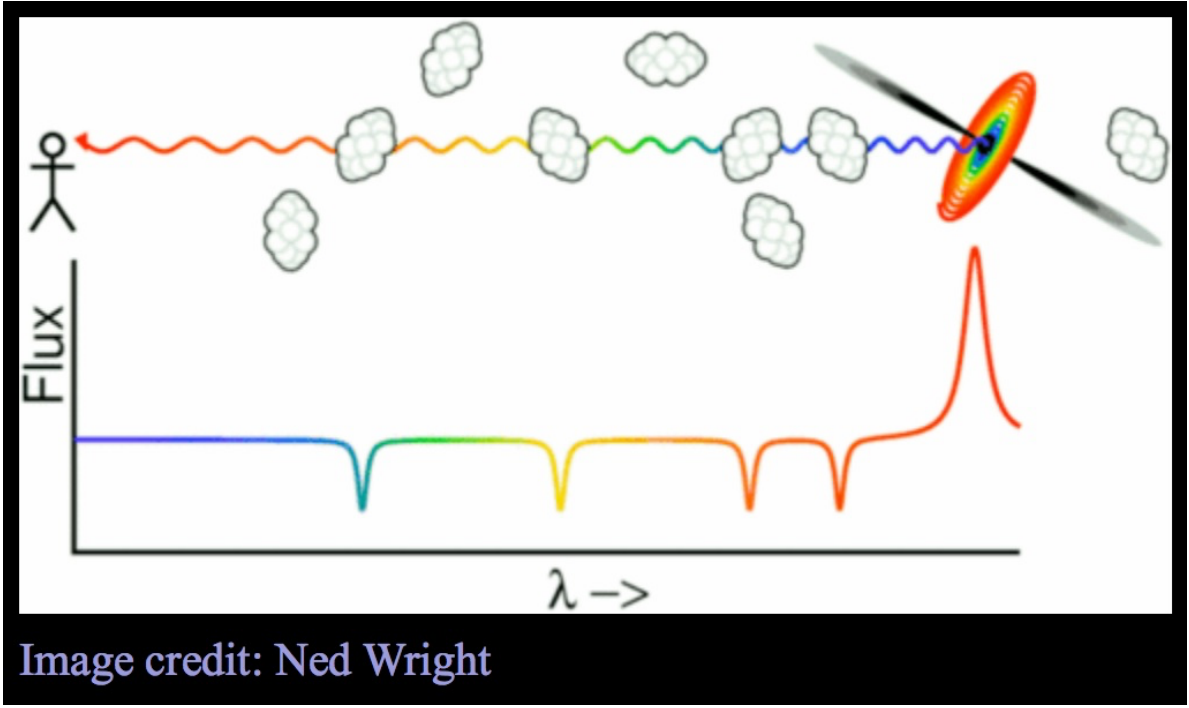
Illustrative video [here](#)

- **Lyman-alfa forest**

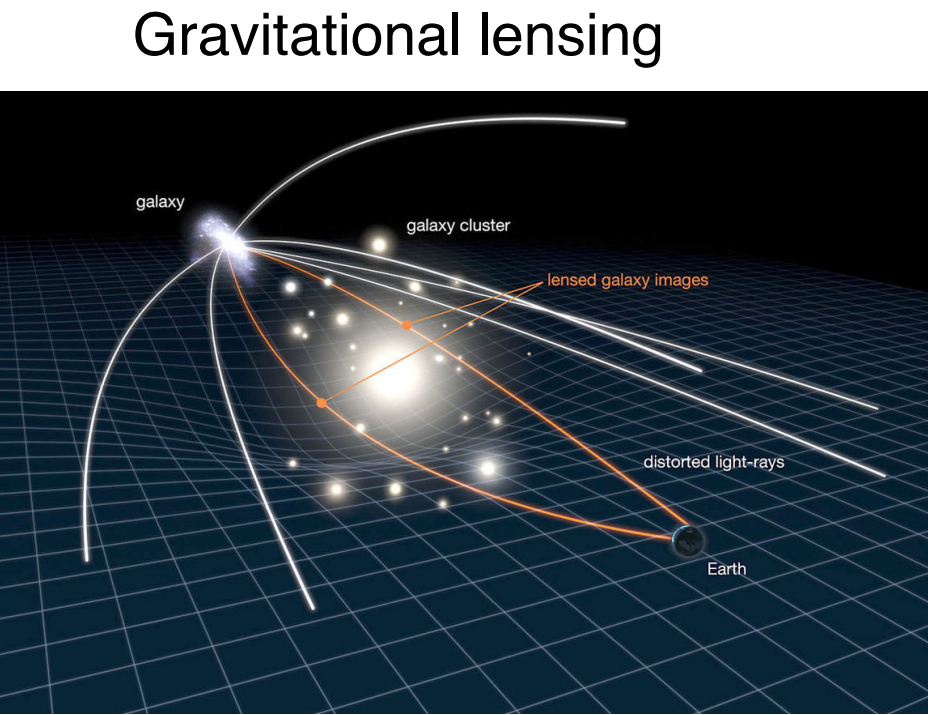
- Absorption lines corresponding to the Lyman-alpha transition of neutral hydrogen in the spectra of far away quasars.
- Characterizes the abundance of Hydrogen in one-dimensional sections
- It is expected that the distribution of Hydrogen and DM are related



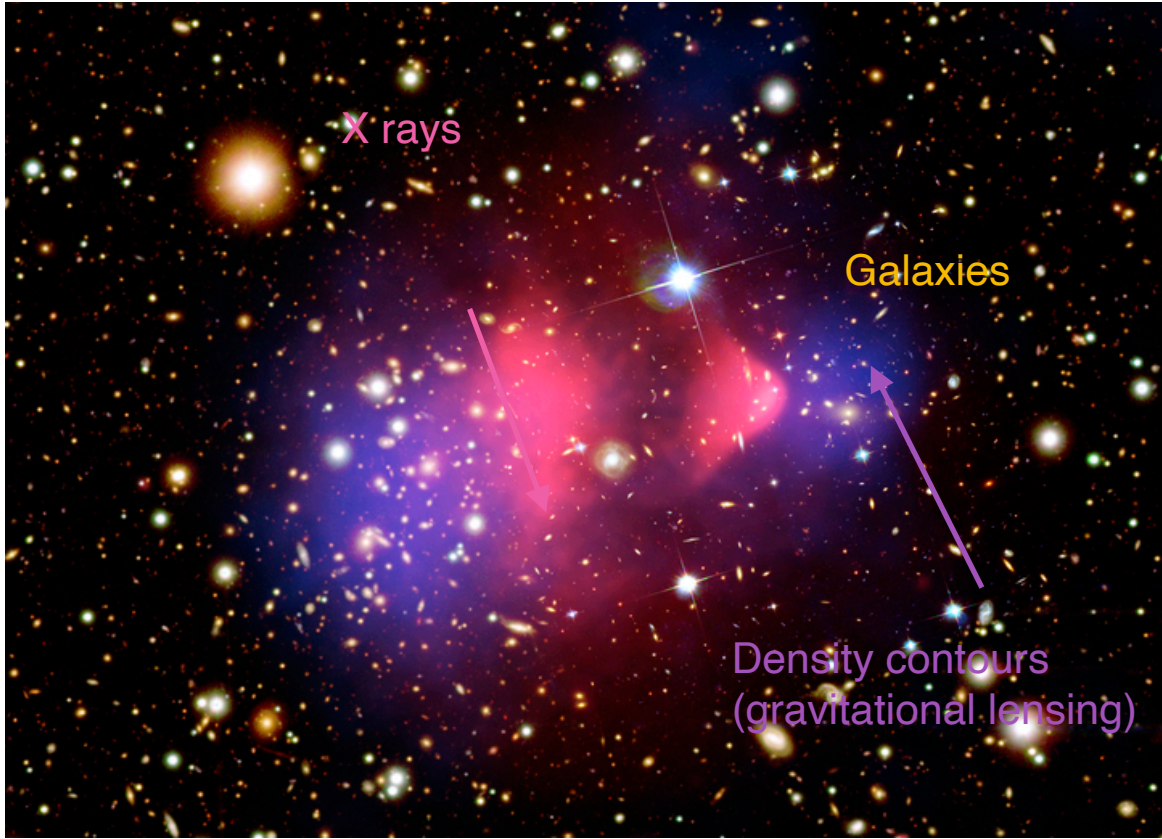
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- **Dynamic and statistical properties of galaxy clusters** (optical, X-rays, gravitational lenses, SZ)



<https://heasarc.gsfc.nasa.gov/docs/rosat/gallery/>

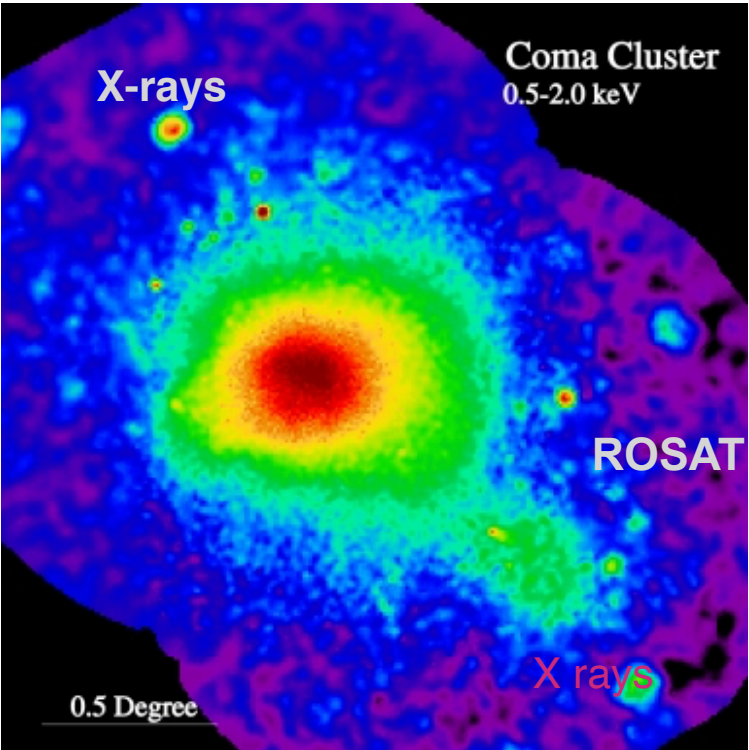
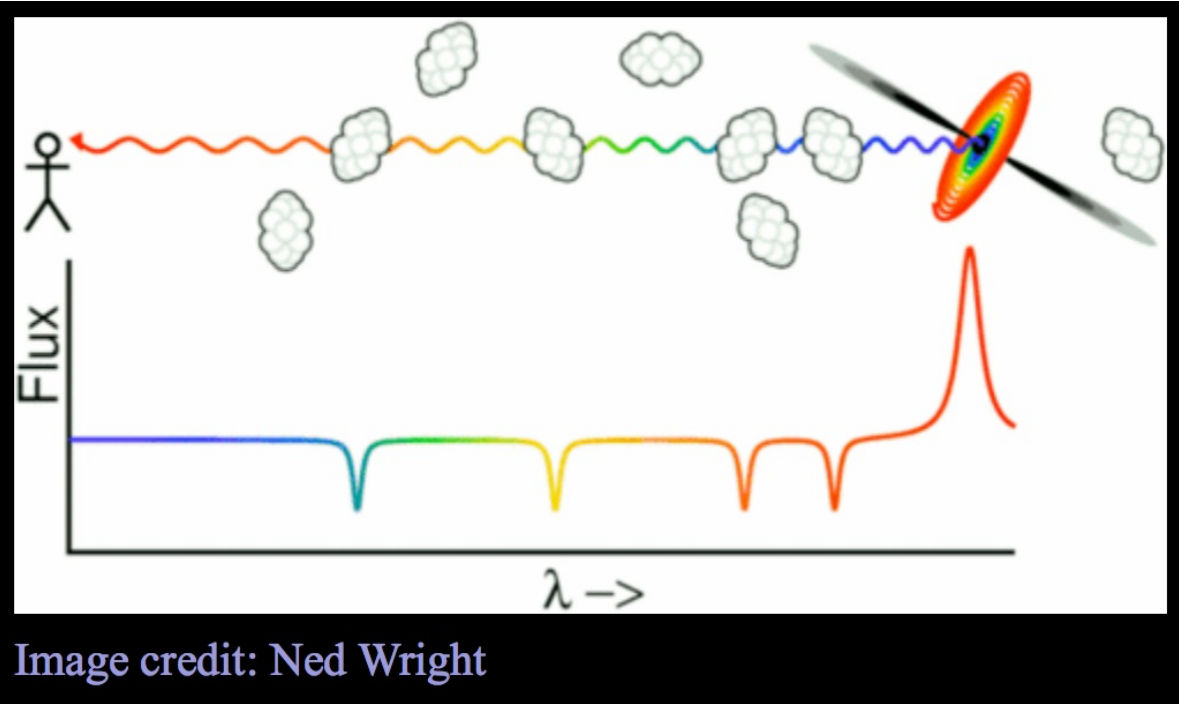


Bullet Cluster

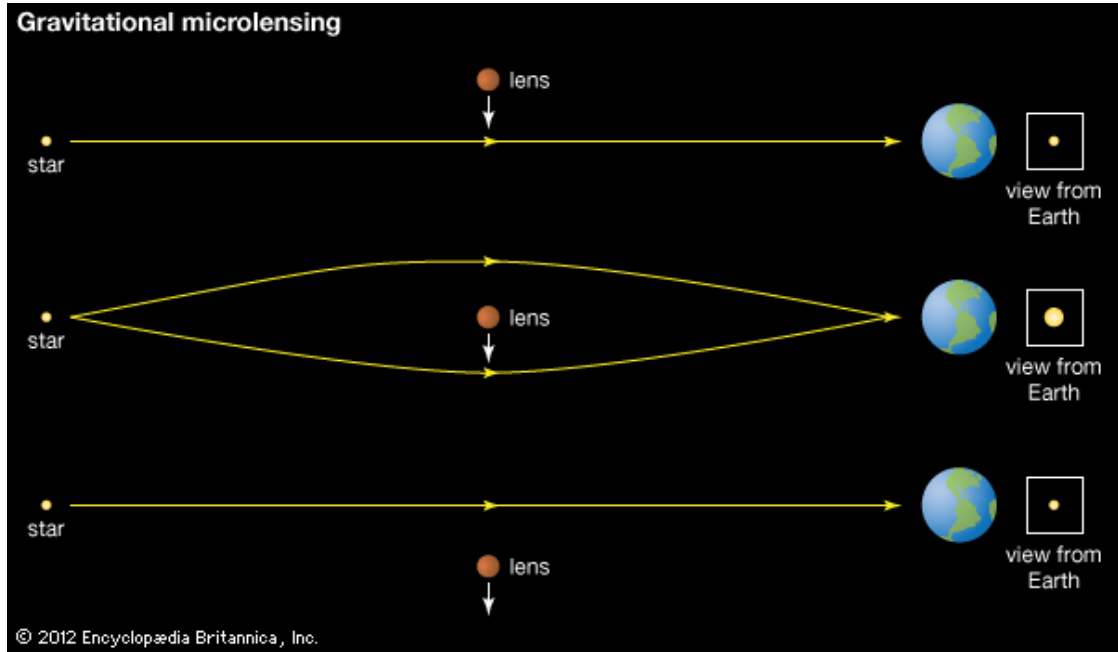
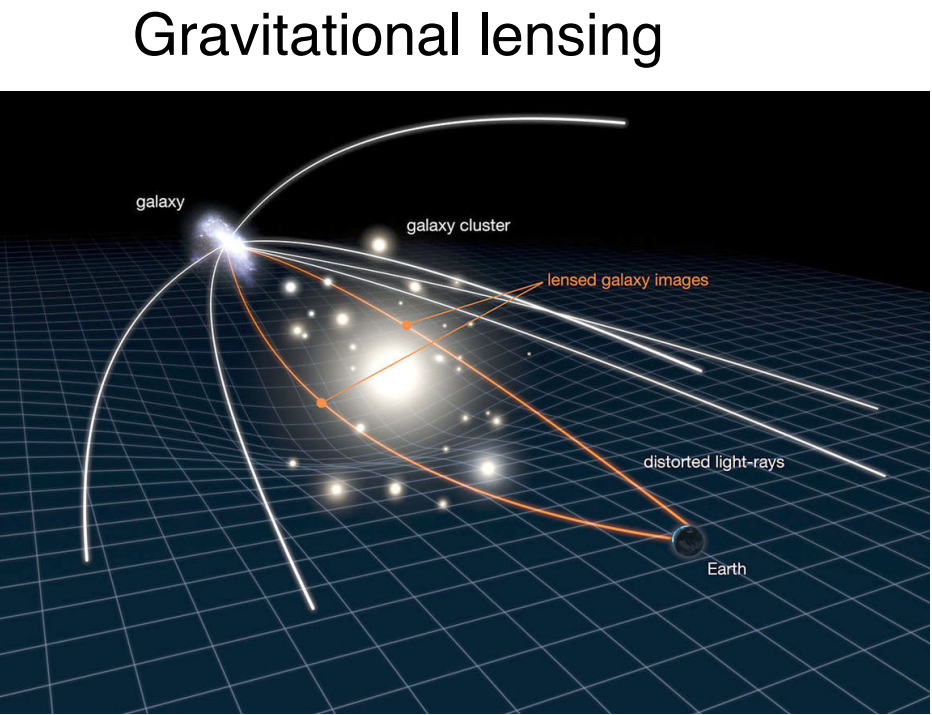


Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

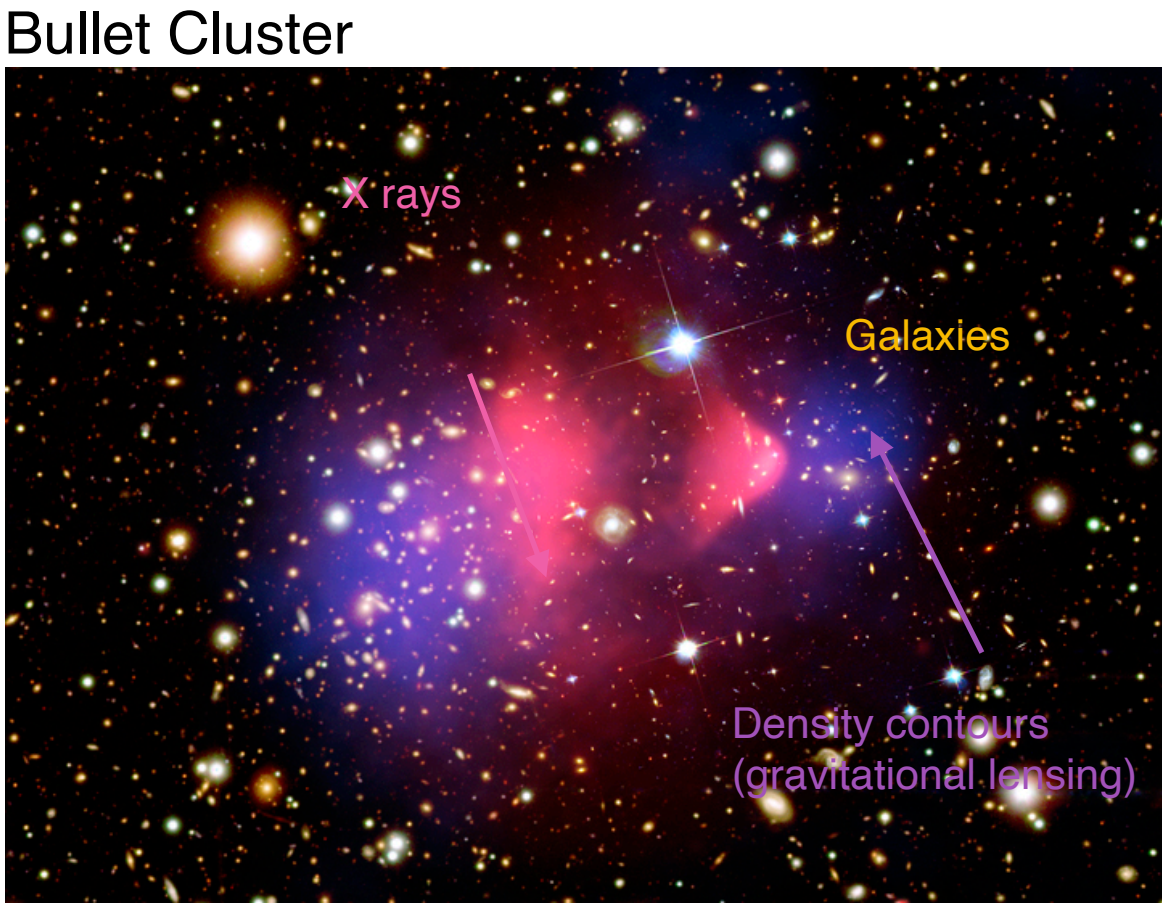
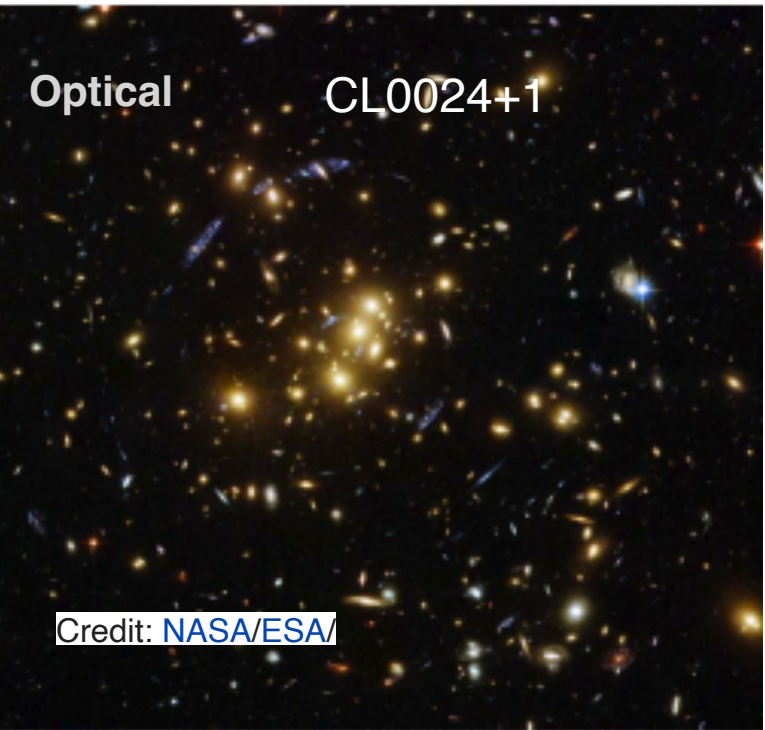
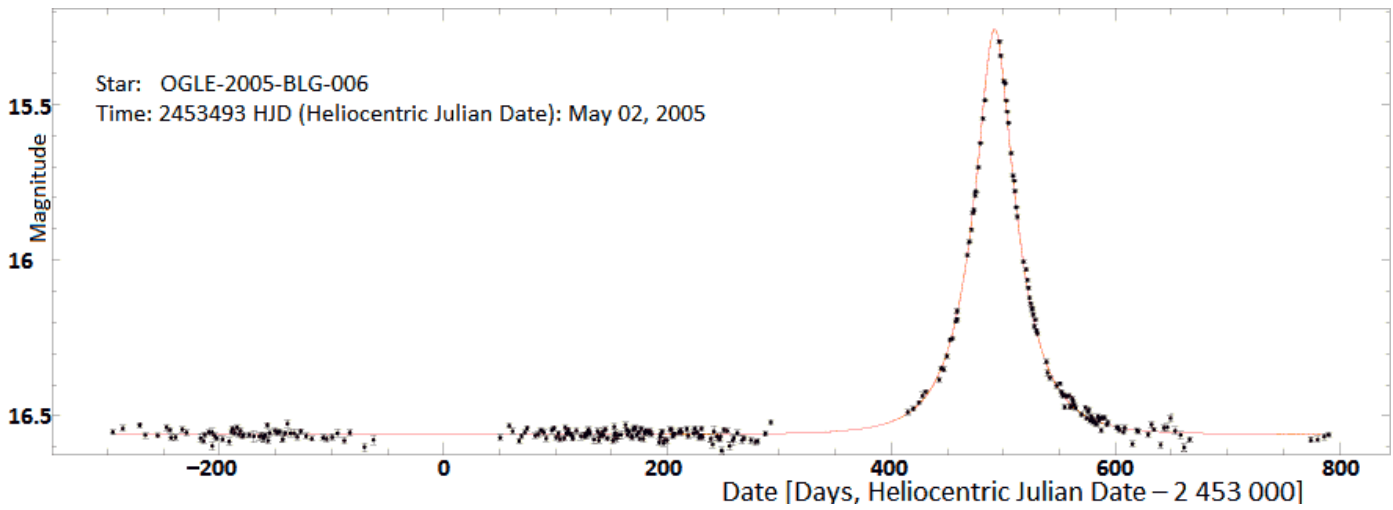
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- **Gravitational lenses:** weak, strong, microlensing, femtolensing → sensitive to the total mass (dark or not dark)



<https://heasarc.gsfc.nasa.gov/docs/rosat/gallery/>

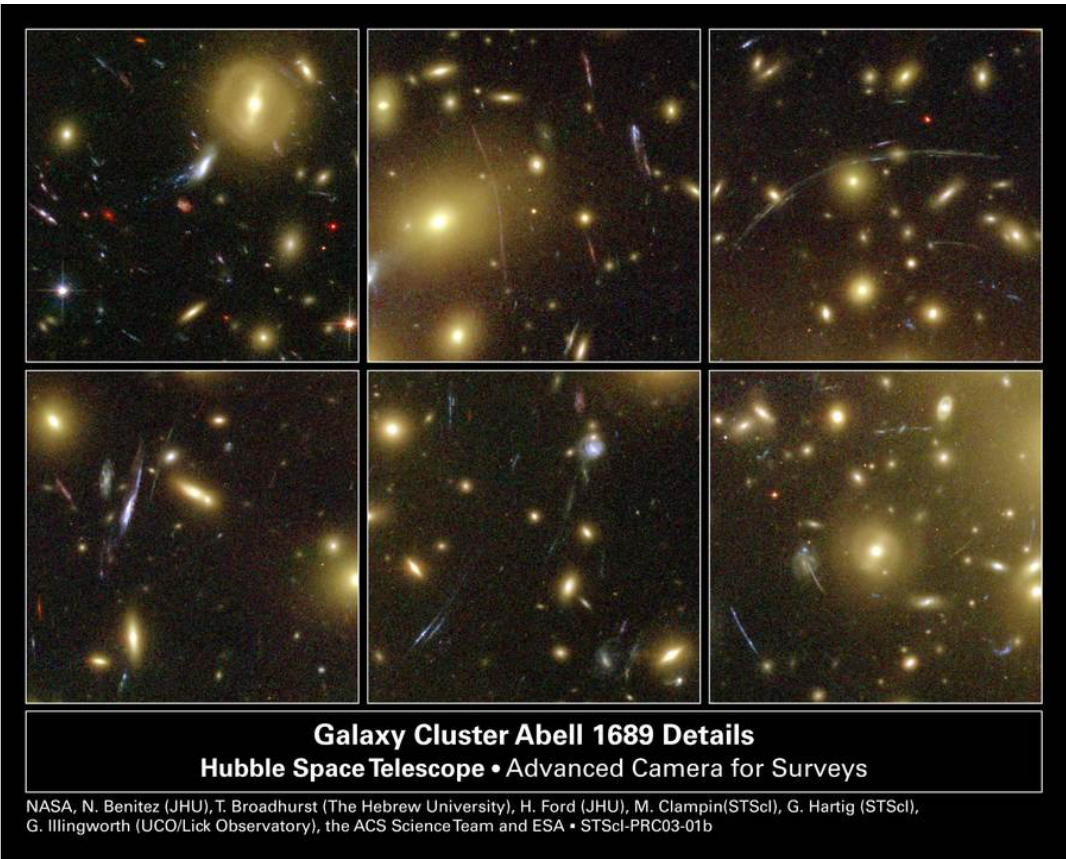


Micro lensing

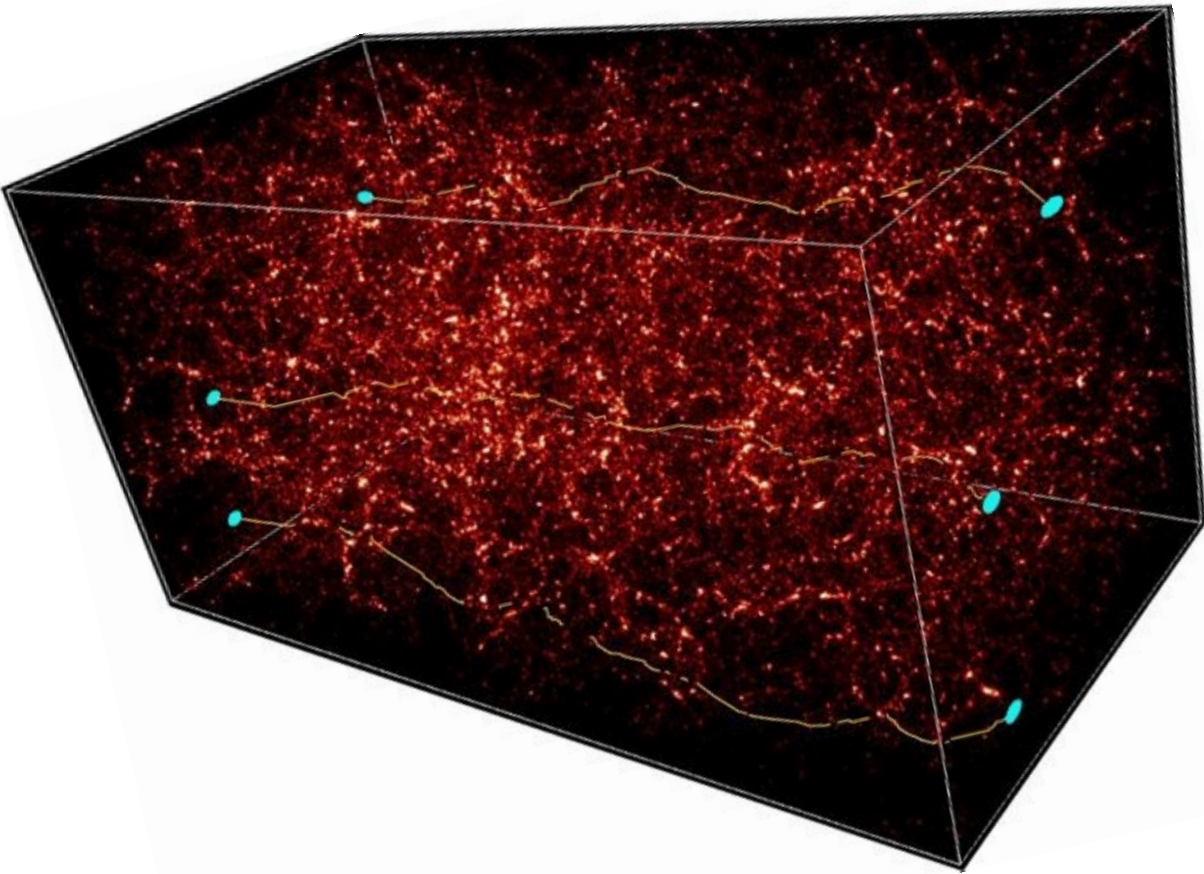


Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Strong lensing



Weak lensing



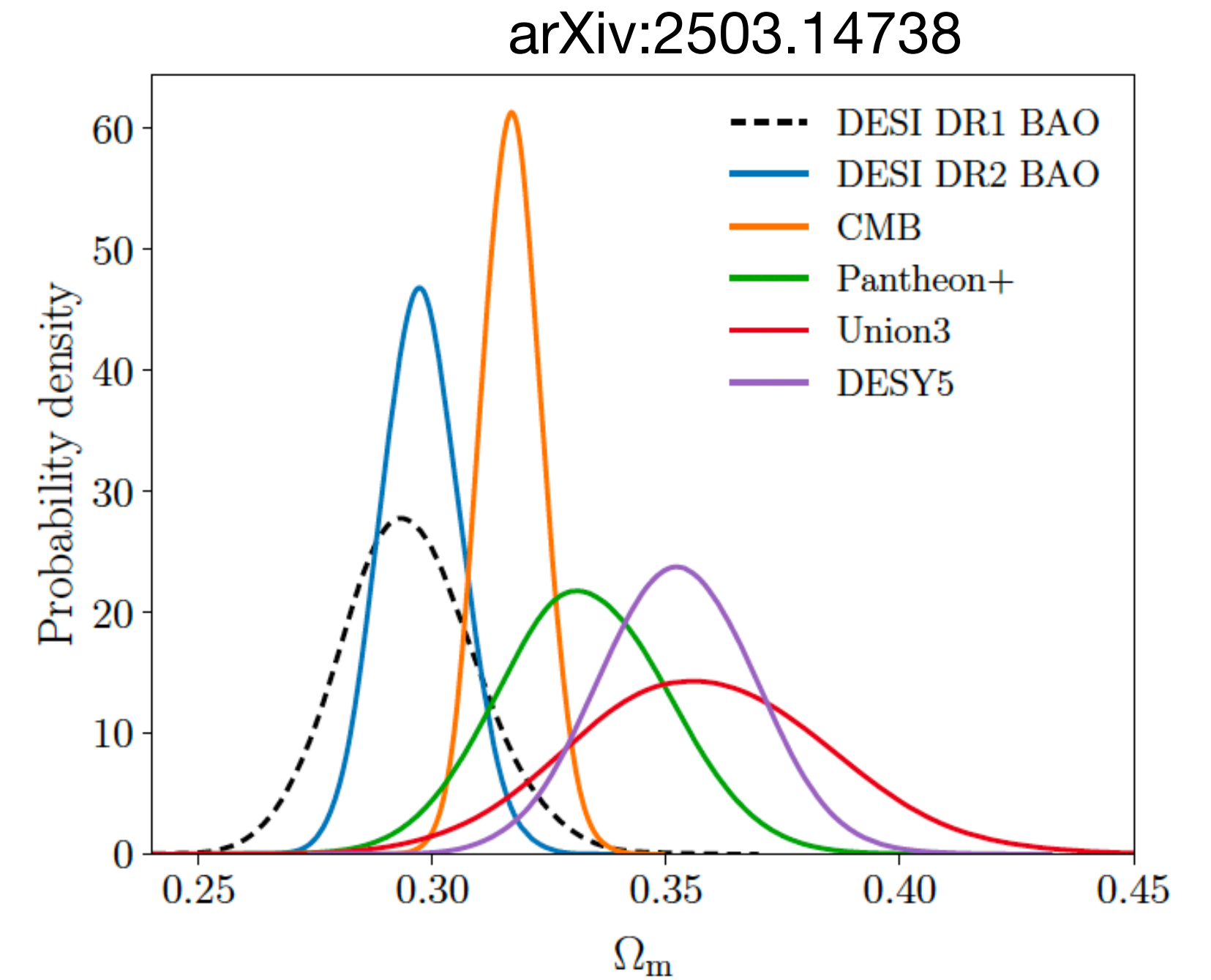
What do we understand about DM? What properties should it have?

- Rotation curves
 - Estimate $\rho_{DM}(r)$: profile of DM halos
 - Analyze statistical properties of the diverse observed curves

What do we understand about DM? What properties should it have?

- Rotation curves
 - Estimate $\rho_{DM}(r)$: profile of DM halos
 - Analyze statistical properties of the diverse observed curves
- Primordial nucleosynthesis (BBN) $\rightarrow 0.021 \leq \Omega_b h^2 \leq 0.024$ (95 CL)
- SNIa & BAO $\rightarrow \Omega_m \sim 0.3$
- CMB and LSS: e.g. by measuring the distribution of galaxies, Hydrogen, and model how such distributions and that of the DM are related
- DM interaction with the SM particles are strongly constrained, DM should be decoupled from the baryon-photon plasma at recombination
- DM is stable on cosmological timescales
- At least at $z \lesssim z_{eq}$, $P_{DM} \sim 0$
- **Adiabatic perturbations:** During RD on large (superhorizon) scales $\frac{\delta \rho_{DM}^{ad}}{\dot{\rho}_{DM}} \simeq \frac{\delta \rho_\gamma}{\dot{\rho}_\gamma}$.

Bound $\frac{P_{iso}(k)}{P_{iso}(k) + P_{ad}(k)} < 0.0038$ (95 % C.L. $k = 0.05/\text{Mpc}$) (Planck 2018)



What do we understand about DM? What properties should it have?

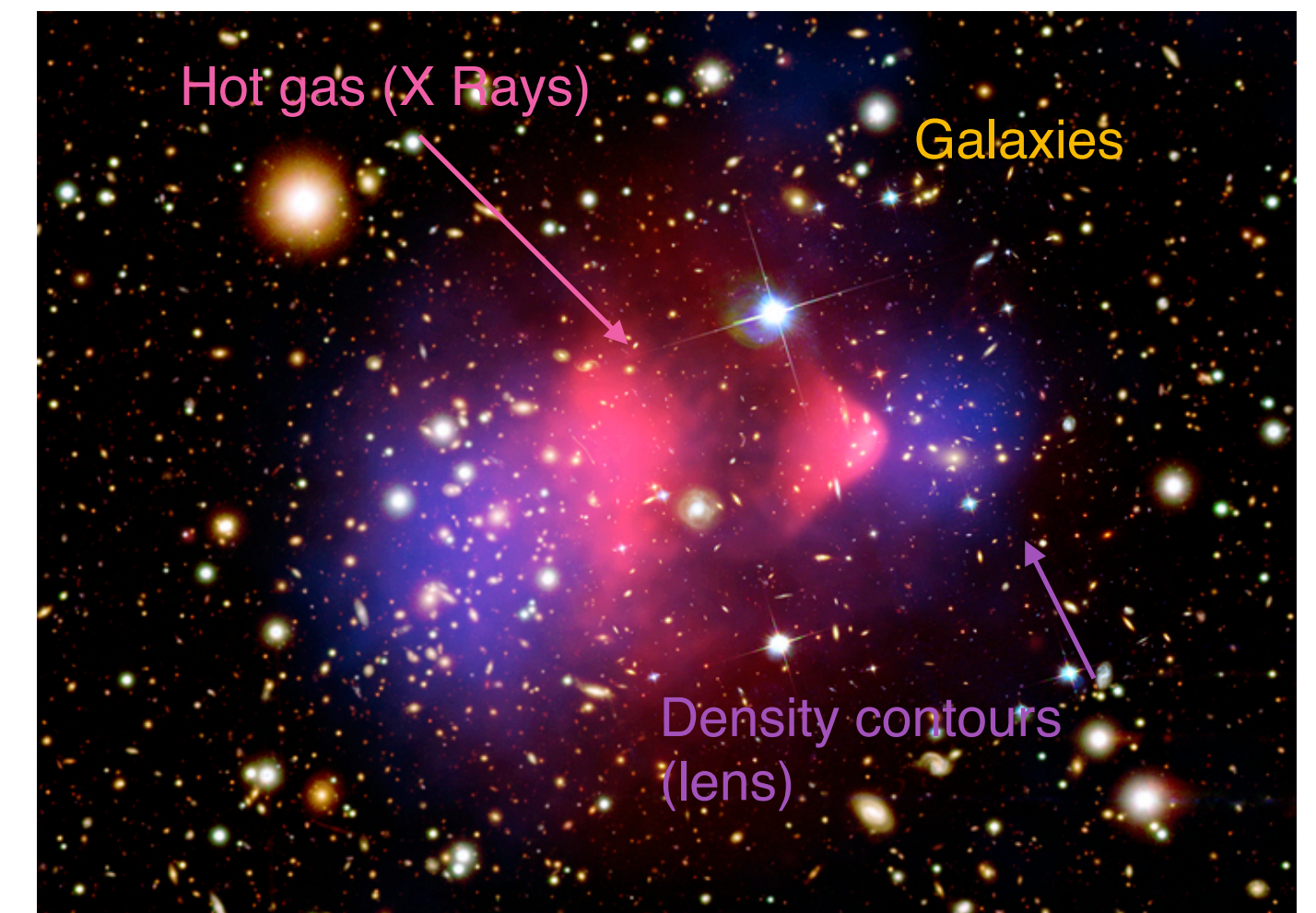
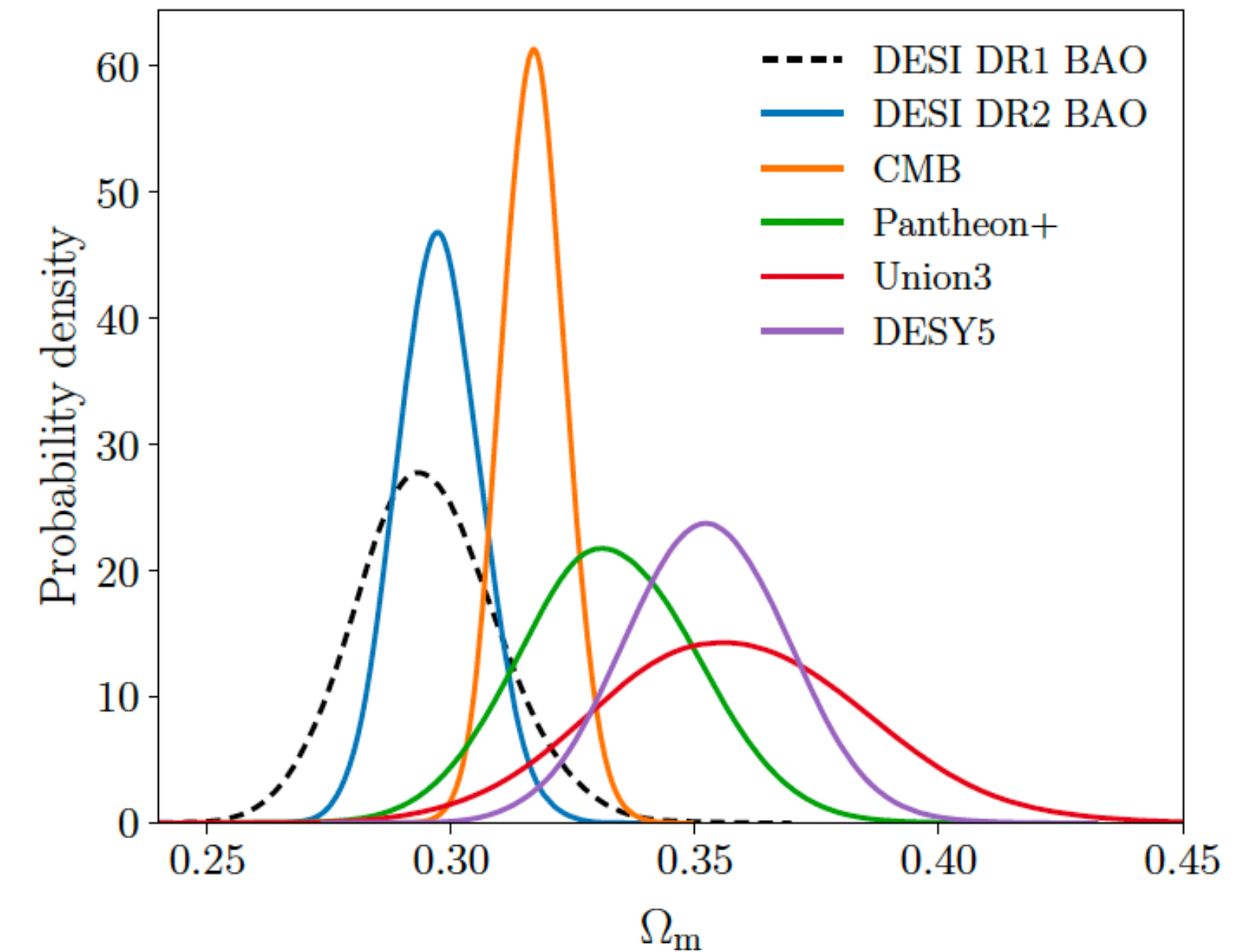
- Rotation curves
 - Estimate $\rho_{DM}(r)$: profile of DM halos
 - Analyze statistical properties of the diverse observed curves
- Primordial nucleosynthesis (BBN) $\rightarrow 0.021 \leq \Omega_b h^2 \leq 0.024$ (95 CL)
- SNIa & BAO $\rightarrow \Omega_m \sim 0.3$
- CMB and LSS: e.g. by measuring the distribution of galaxies, Hydrogen, and model how such distributions and that of the DM are related
- DM interaction with the SM particles are strongly constrained, DM should be decoupled from the baryon-photon plasma at recombination
- DM is stable on cosmological timescales
- At least at $z \lesssim z_{eq}$, $P_{DM} \sim 0$
- **Adiabatic perturbations:** During RD on large (superhorizon) scales $\frac{\delta \rho_{DM}^{ad}}{\dot{\rho}_{DM}} \simeq \frac{\delta \rho_\gamma}{\dot{\rho}_\gamma}$.

Bound $\frac{P_{iso}(k)}{P_{iso}(k) + P_{ad}(k)} < 0.0038$ (95 % C.L. $k = 0.05/\text{Mpc}$) (Planck 2018)

- There are limits to possible self-interactions. For example, the "bullet cluster":

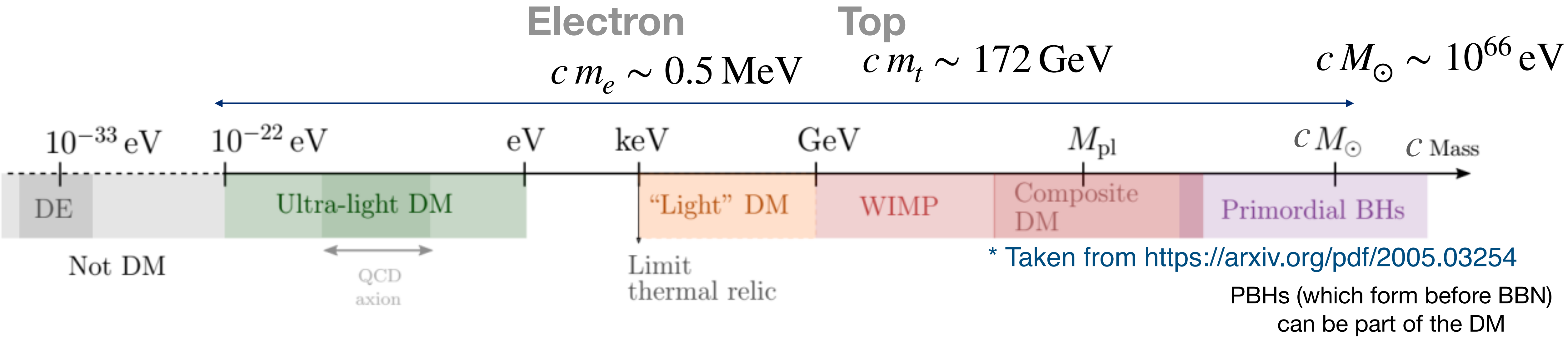
Typically $\frac{\sigma}{m} \lesssim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}}$, (e.g. a typical QCD cross section is $\sim 50 \text{ mb}$)

arXiv:2503.14738

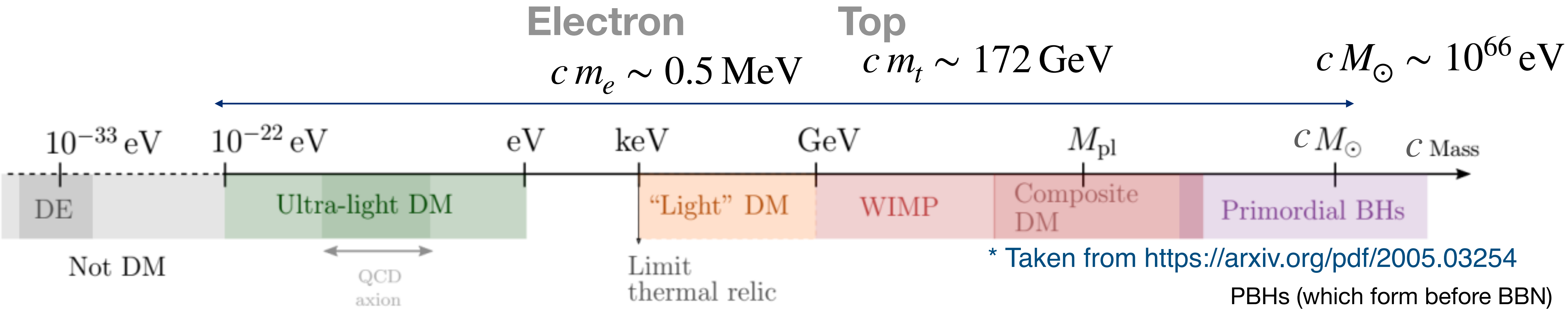


Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Sketch (not to scale) of the huge range of possible DM models that have been conceived *



Sketch (not to scale) of the huge range of possible DM models that have been conceived *

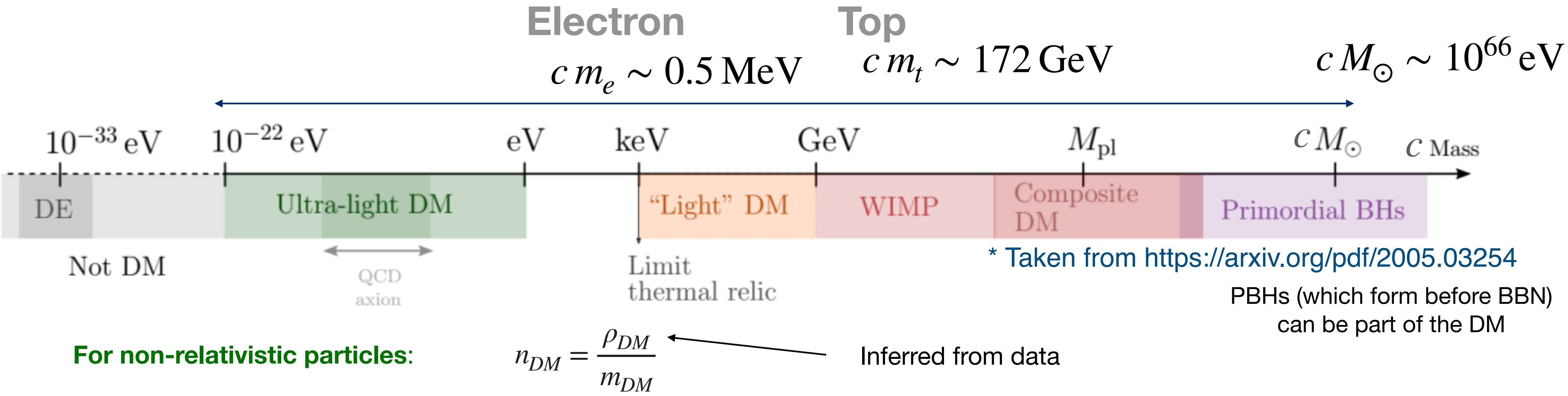


For non-relativistic particles:

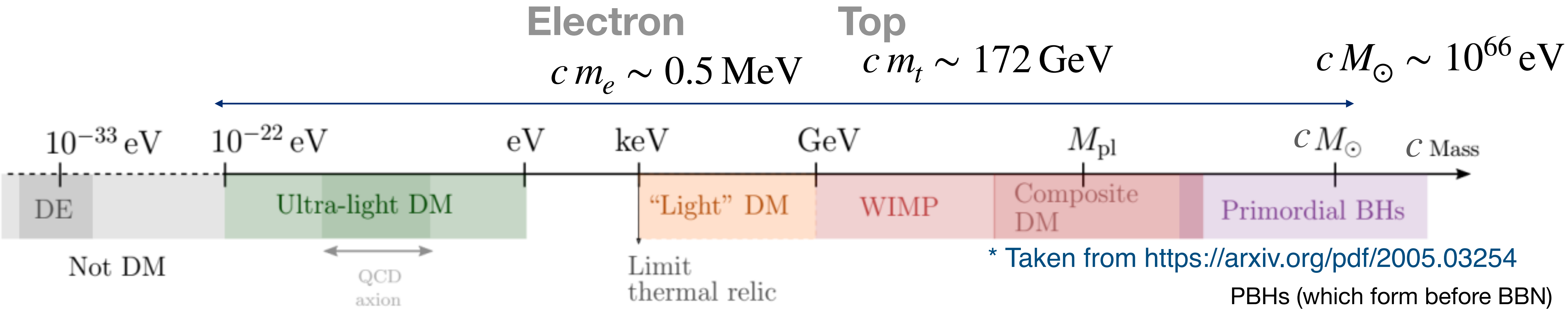
$$n_{DM} = \frac{\rho_{DM}}{m_{DM}}$$

* Taken from <https://arxiv.org/pdf/2005.03254>
PBHs (which form before BBN) can be part of the DM

Sketch (not to scale) of the huge range of possible DM models that have been conceived *



Sketch (not to scale) of the huge range of possible DM models that have been conceived *



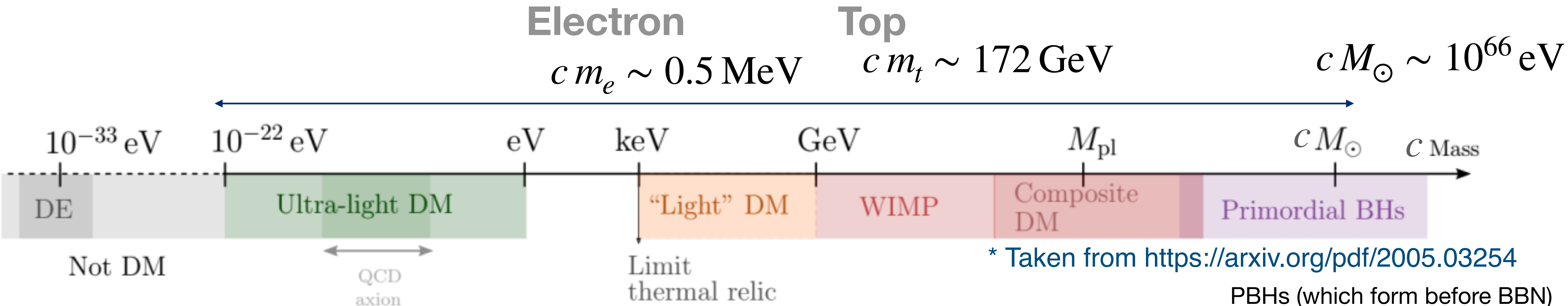
* Taken from <https://arxiv.org/pdf/2005.03254>
PBHs (which form before BBN) can be part of the DM

For non-relativistic particles:

$$n_{DM} = \frac{\rho_{DM}}{m_{DM}}$$

Inferred from data
The smaller m_{DM} , the larger n_{DM}

Sketch (not to scale) of the huge range of possible DM models that have been conceived *



For non-relativistic particles:

Arguments: How small can m_{DM} be?

Bosons

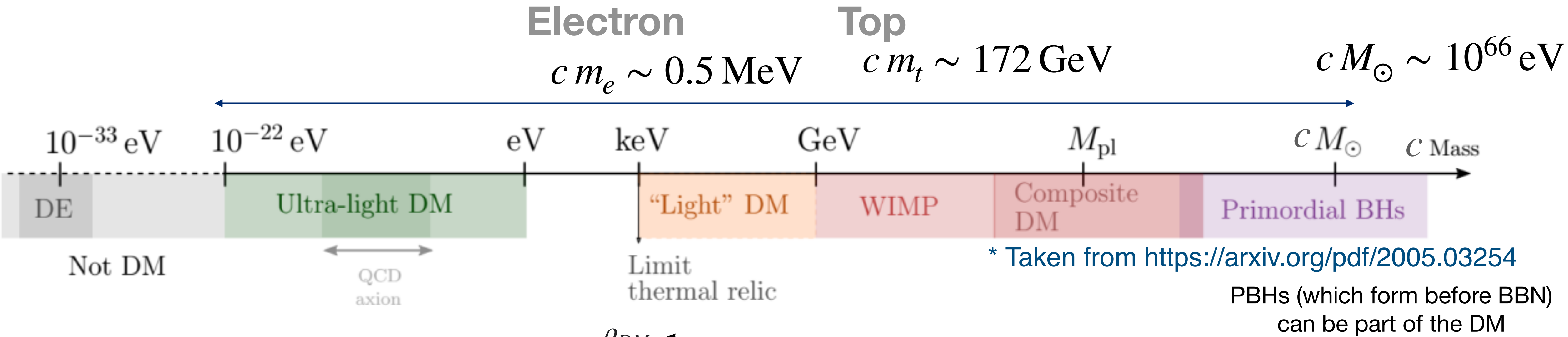
- Reduced de Broglie wavelength: $\lambda_{\text{dB}} = \frac{\hbar}{mv}$
- $$\lambda_{\text{dB}} \simeq 190 \left(\frac{v}{100 \text{ km/s}} \right)^{-1} \left(\frac{cm}{10^{-22} \text{ eV}} \right)^{-1} \text{ pc}$$
- $v \sim 10 \text{ km/s}$ for dwarf galaxies
- $v \sim 100 \text{ km/s}$ for the Milky Way
- Asking that $\lambda_{\text{dB}} \lesssim$ dimensions of the galaxies (1 – 100 kpc), we get $m \gtrsim 10^{-22} \text{ eV}$.

$$n_{DM} = \frac{\rho_{DM}}{m_{DM}}$$

← Inferred from data
← The smaller m_{DM} , the larger n_{DM}

PBHs (which form before BBN) can be part of the DM

Sketch (not to scale) of the huge range of possible DM models that have been conceived *



* Taken from <https://arxiv.org/pdf/2005.03254>
PBHs (which form before BBN) can be part of the DM

For non-relativistic particles:

$$n_{DM} = \frac{\rho_{DM}}{m_{DM}}$$

Inferred from data
The smaller m_{DM} , the larger n_{DM}

Arguments: How small can m_{DM} be?

Bosons

- Reduced de Broglie wavelength: $\lambda_{dB} = \frac{\hbar}{m v}$
- $$\lambda_{dB} \simeq 190 \left(\frac{v}{100 \text{ km/s}} \right)^{-1} \left(\frac{c m}{10^{-22} \text{ eV}} \right)^{-1} \text{ pc}$$
- $v \sim 10$ km/s for dwarf galaxies
- $v \sim 100$ km/s for the Milky Way
- Asking that $\lambda_{dB} \lesssim$ dimensions of the galaxies (1 – 100 kpc), we get $m \gtrsim 10^{-22}$ eV.

Fermions

Exercise: Consider a fermionic DM system decoupled from the plasma, whose initial phase space distribution is $f = (g/h^3) \{ 1 + \exp(\epsilon/k_B T) \}^{-1}$ ($h = 2\pi\hbar$), which gives rise to an object with $f \simeq (\rho/m)(2\pi m^2 \sigma^2)^{-3/2} \exp\{-p^2/(2m^2 \sigma^2)\}$

i) Using the collisionless Boltzmann equation (Liouville equation), which determines the evolution of the distribution function, estimate a bound on m .

ii) Suppose $\rho = \sigma^2/(2\pi G r^2)$ and evaluate the bound to $r = 5$ kpc, $\sigma = 150$ km/s.

Help: See Peacock's book, p. 385. Answers: (i) $m^4 > (\rho/g)(2\pi\hbar/\sigma)$; ii) $m > g^{-1/4} 33$ eV.

Note: For active neutrinos $\sum m_\nu < 0,26$ eV (Planck 2018)

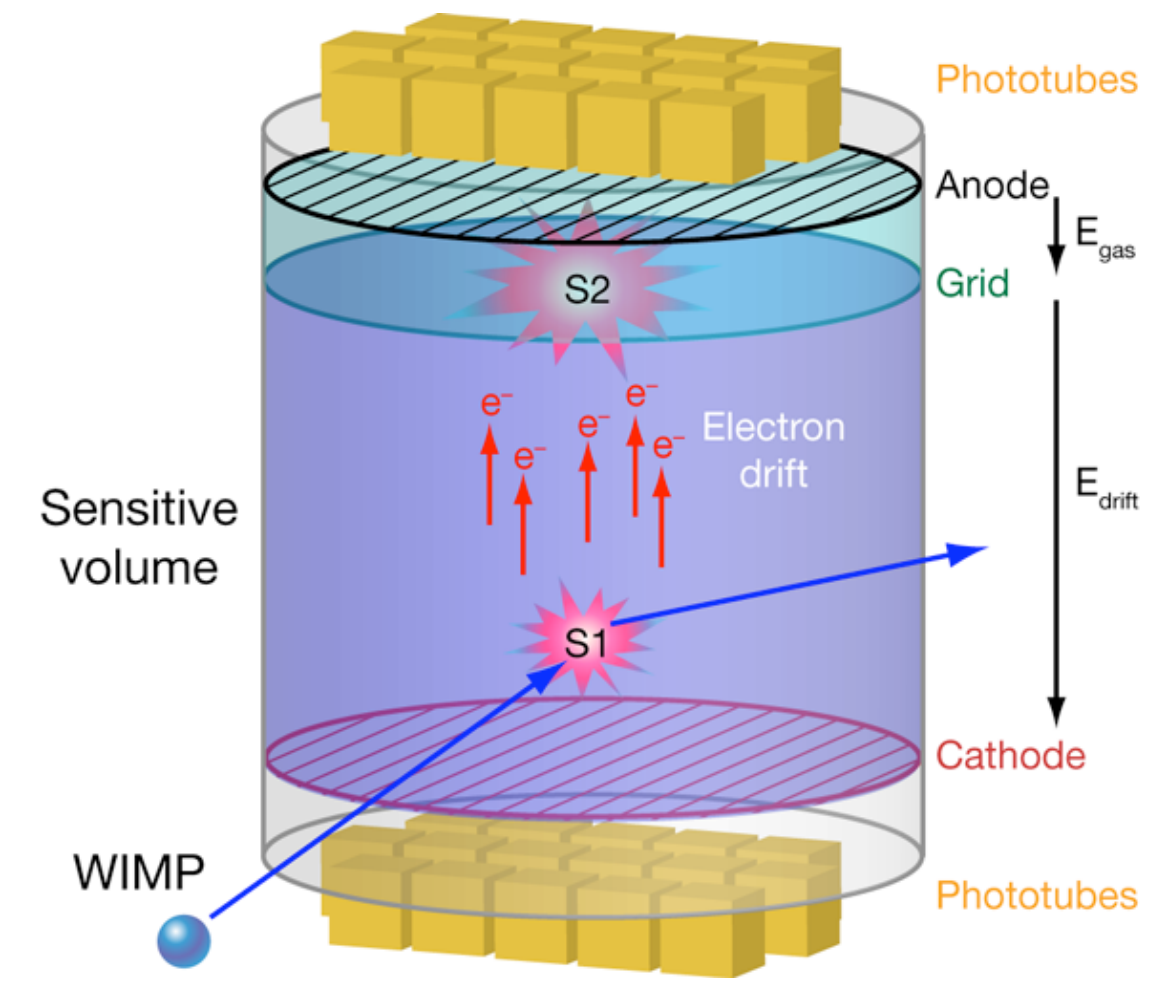
Interactions with SM particles?

Given the model, there are experimental bounds on the probability of DM particle annihilation and interaction cross sections in direct and indirect detection experiments and colliders.

E.g.:

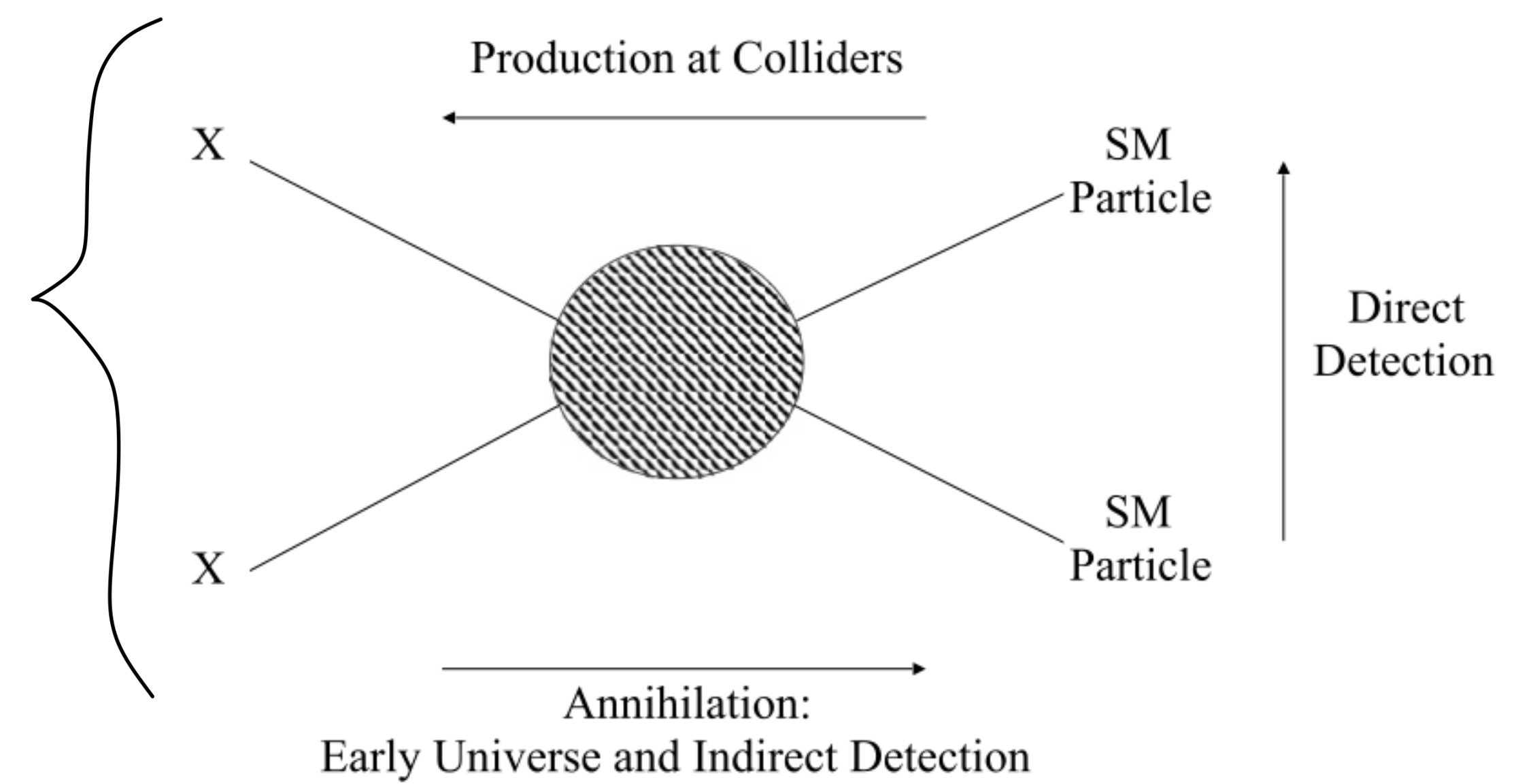
Direct: Xenon

<http://www.xenon1t.org>



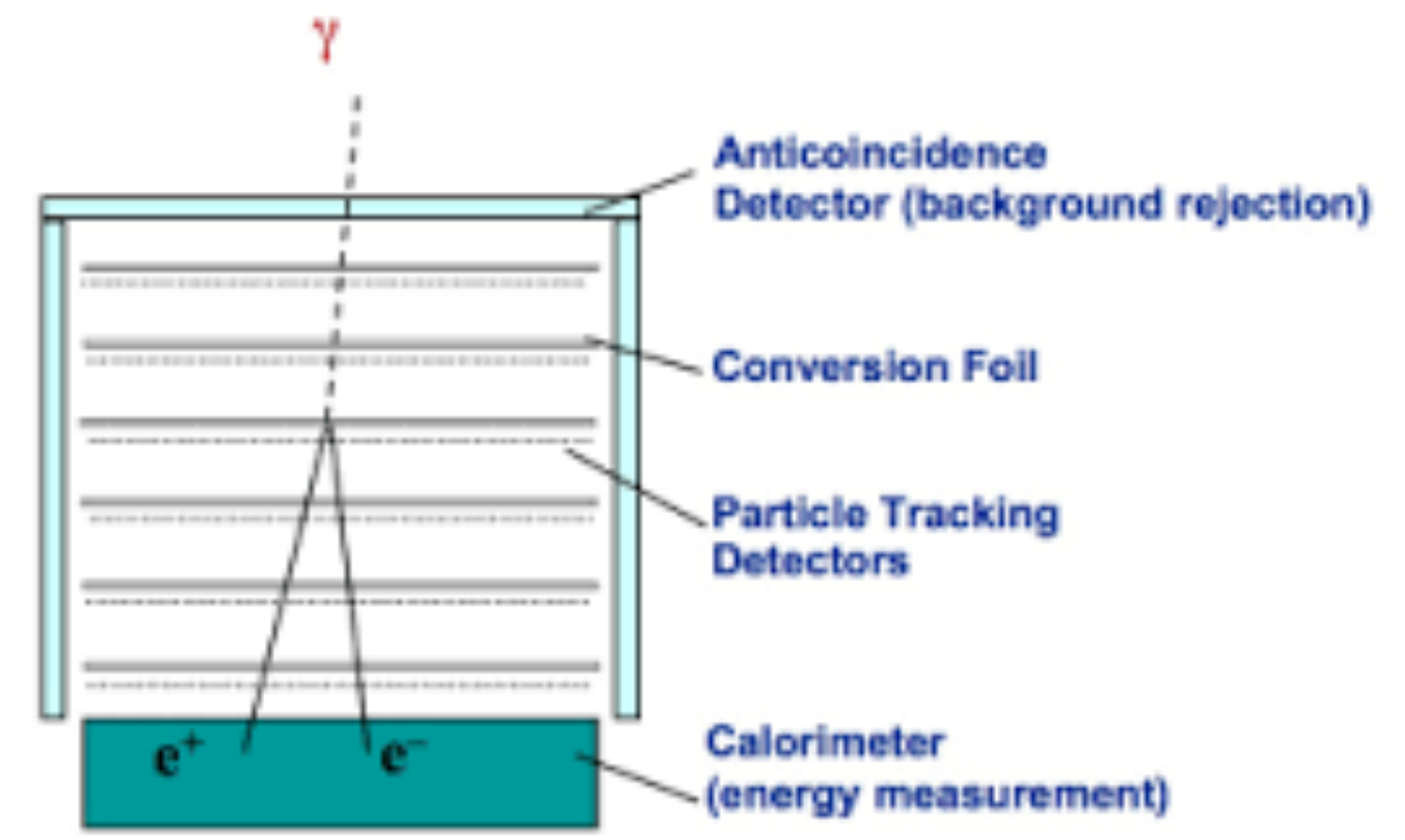
Colliders: LHC

<https://home.cern>



Indirect: FERMI

<https://fermi.gsfc.nasa.gov/science/eteu/dm/>

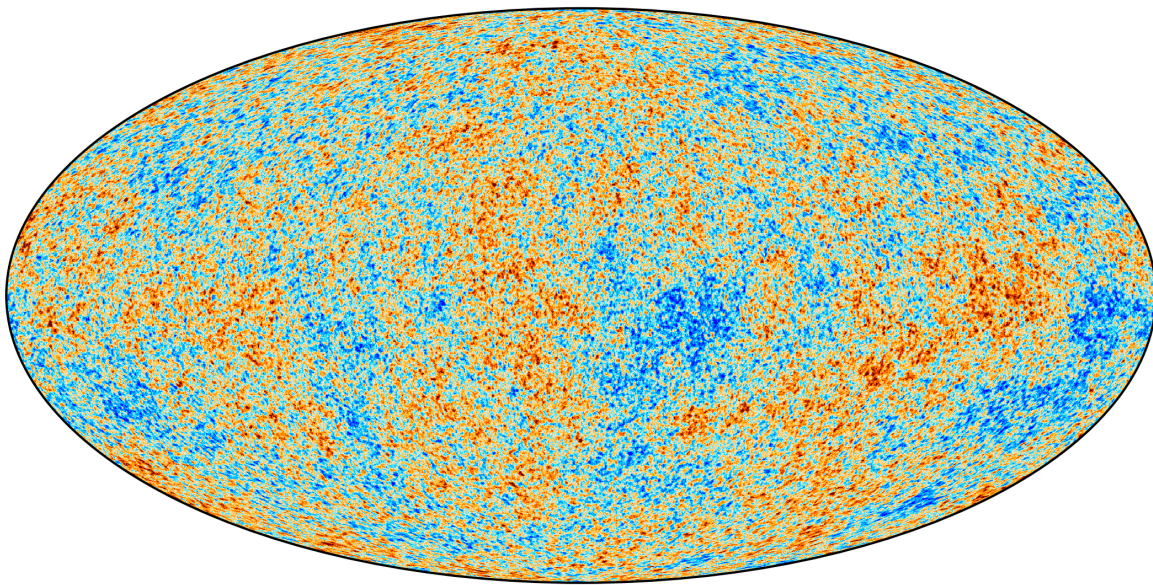


FERMI-LAT

Only the large-scale gravitational interaction of DM has been detected so far and their properties remain largely unknown, despite great effort, both theoretical and experimental, that has been made to identify any direct interactions between the dark sector and luminous matter.

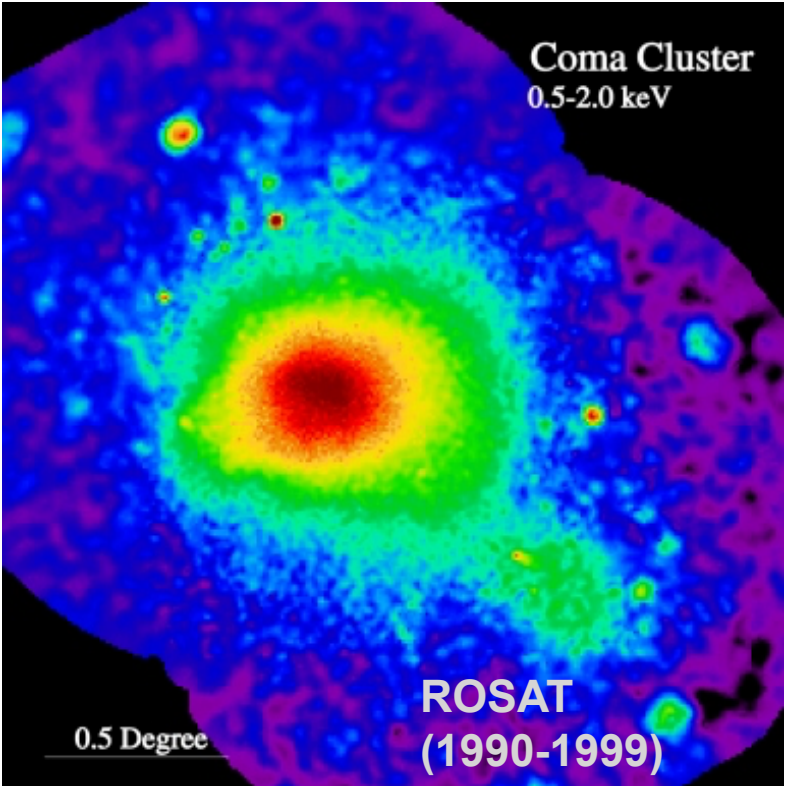
...several observables...

* CMB with polarization



* Galaxy clusters

X rays

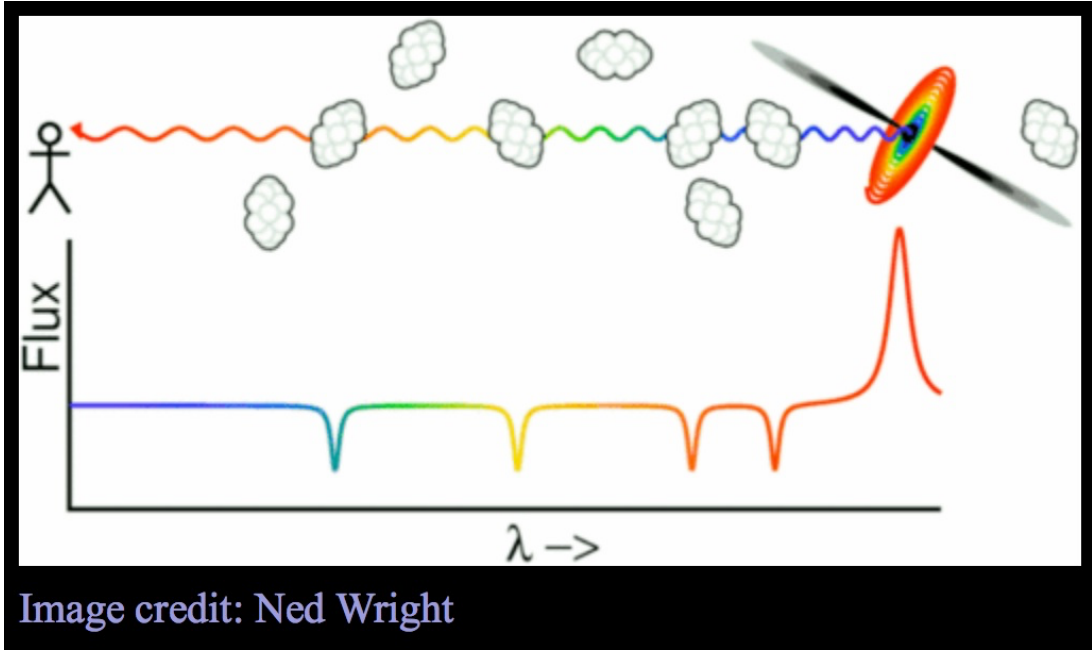


https://heasarc.gsfc.nasa.gov/docs/rosat/gallery/clus_coma.html

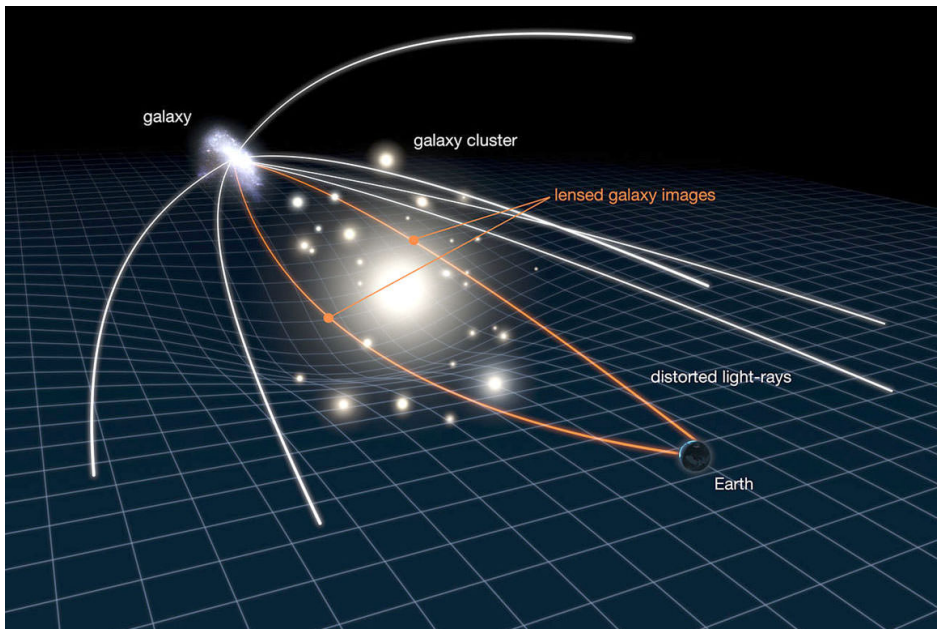
Optic



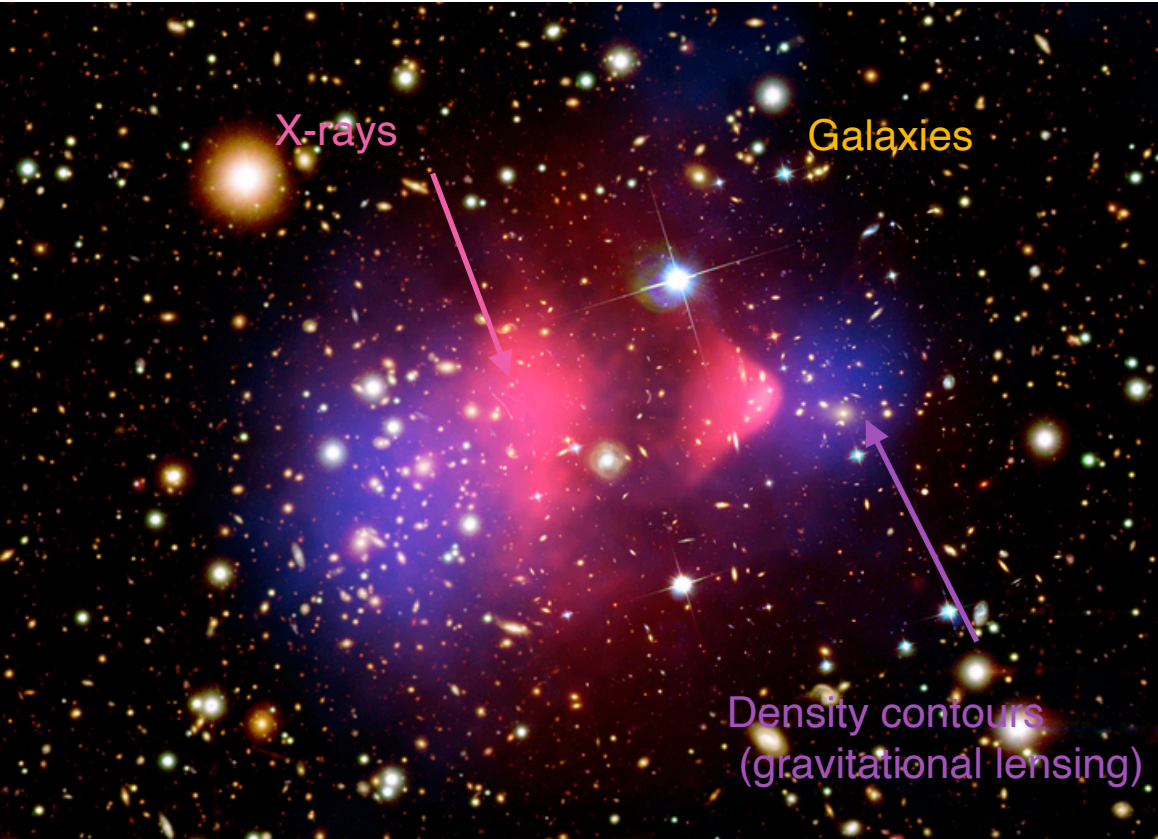
* Lyman- α forest



Gravitational lensing



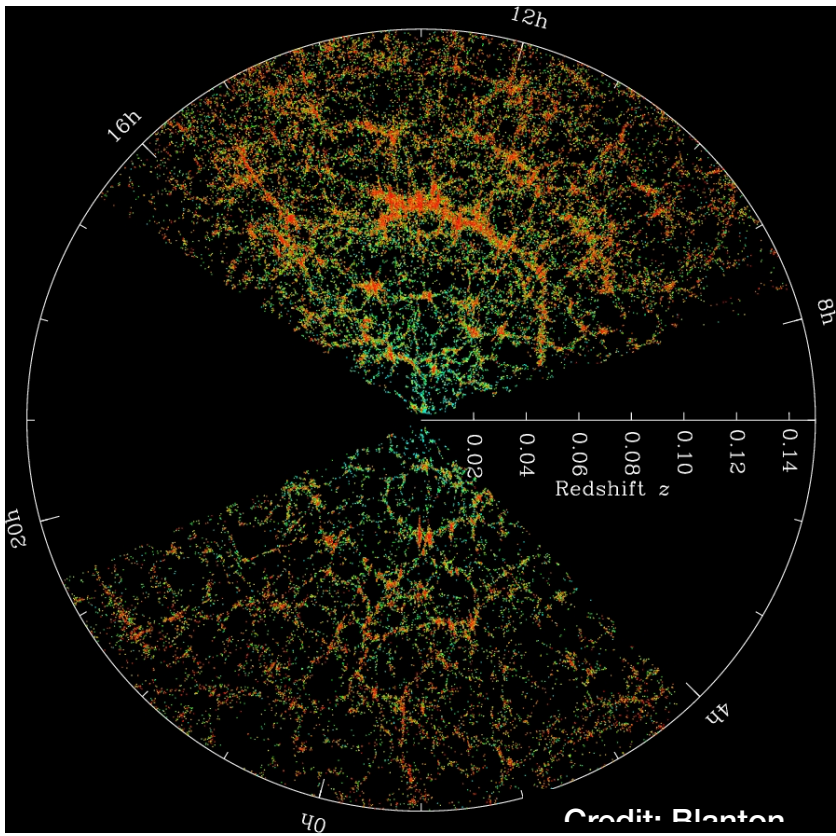
Bullet Cluster



Del Popolo, Int. J. Mod. Phys. D23 (2014)

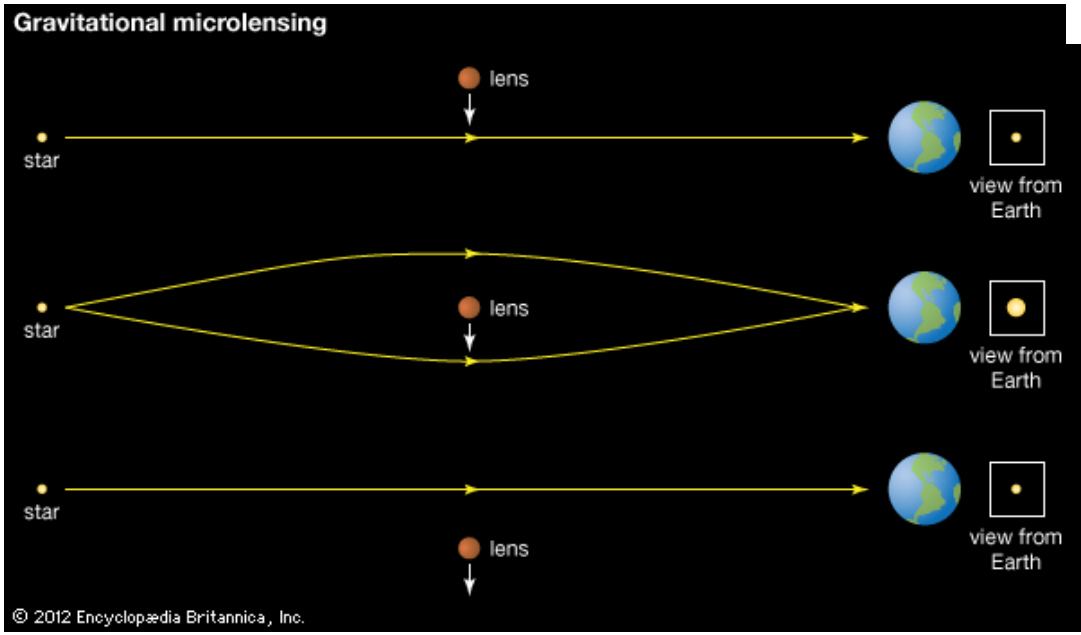
Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI: Magellan/U.Arizona/D.Clowe et al.

* Large scale structure (LSS)

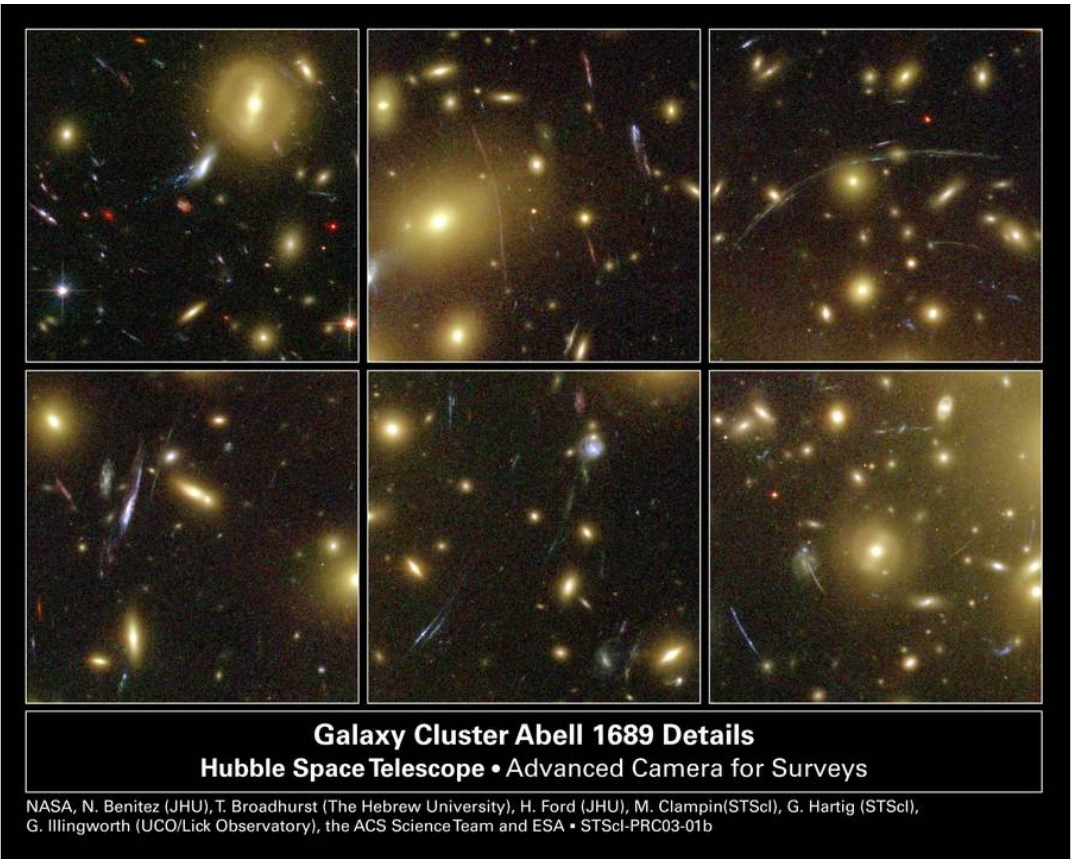


* Gravitational lensing

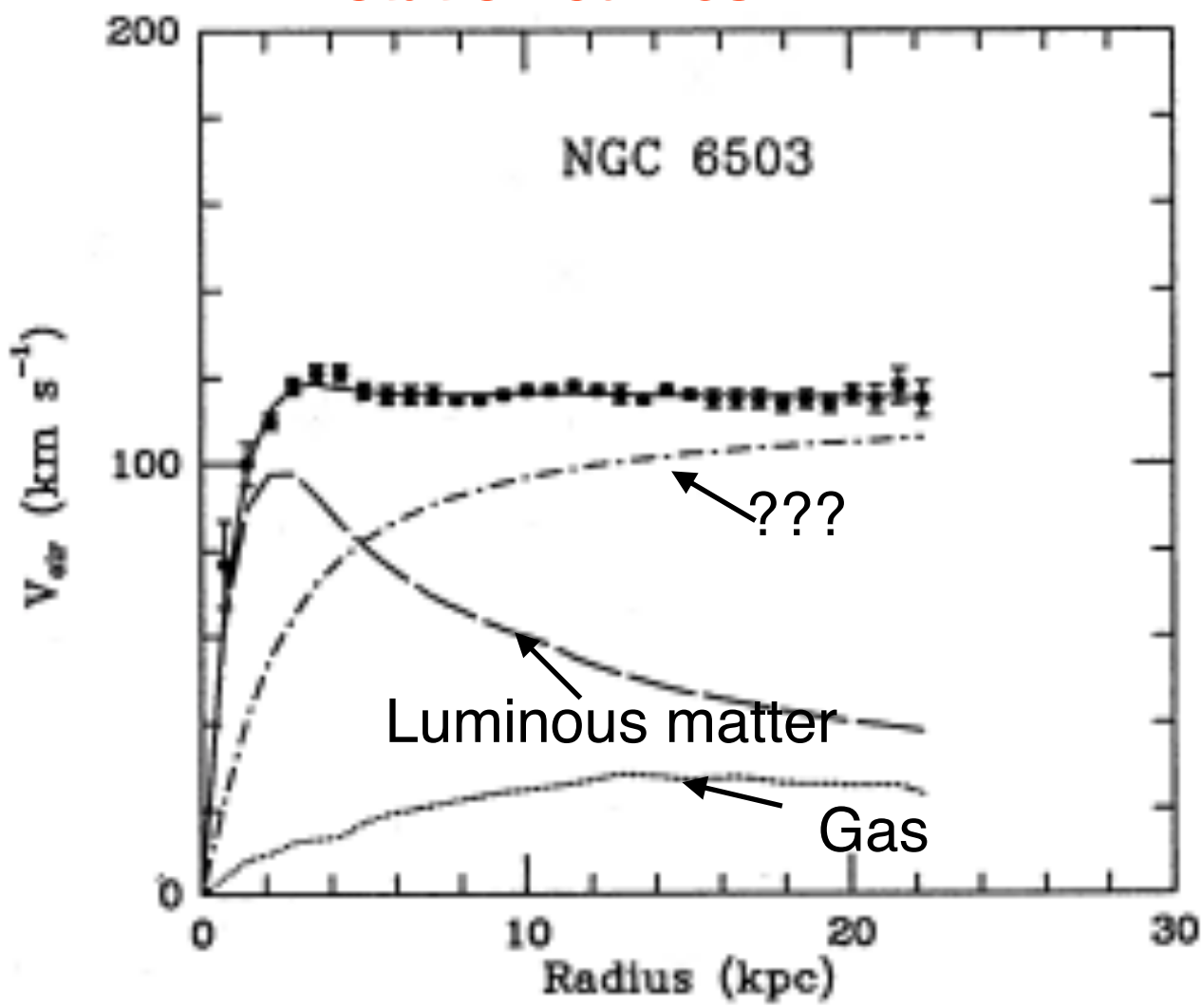
Compact objects



Strong lensing

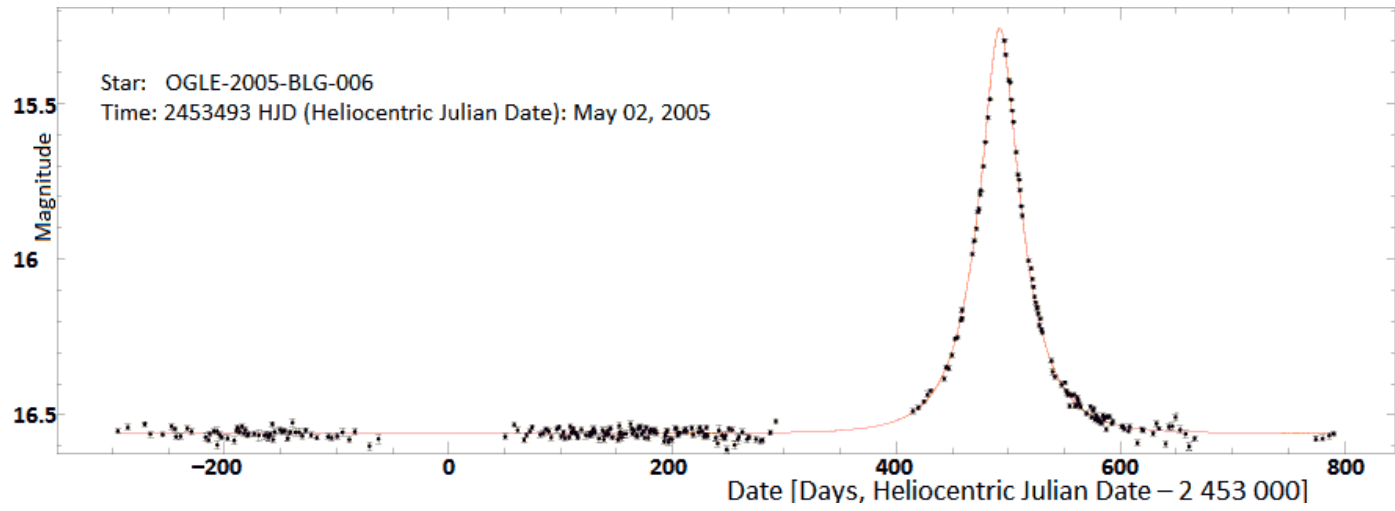


* Rotation curves

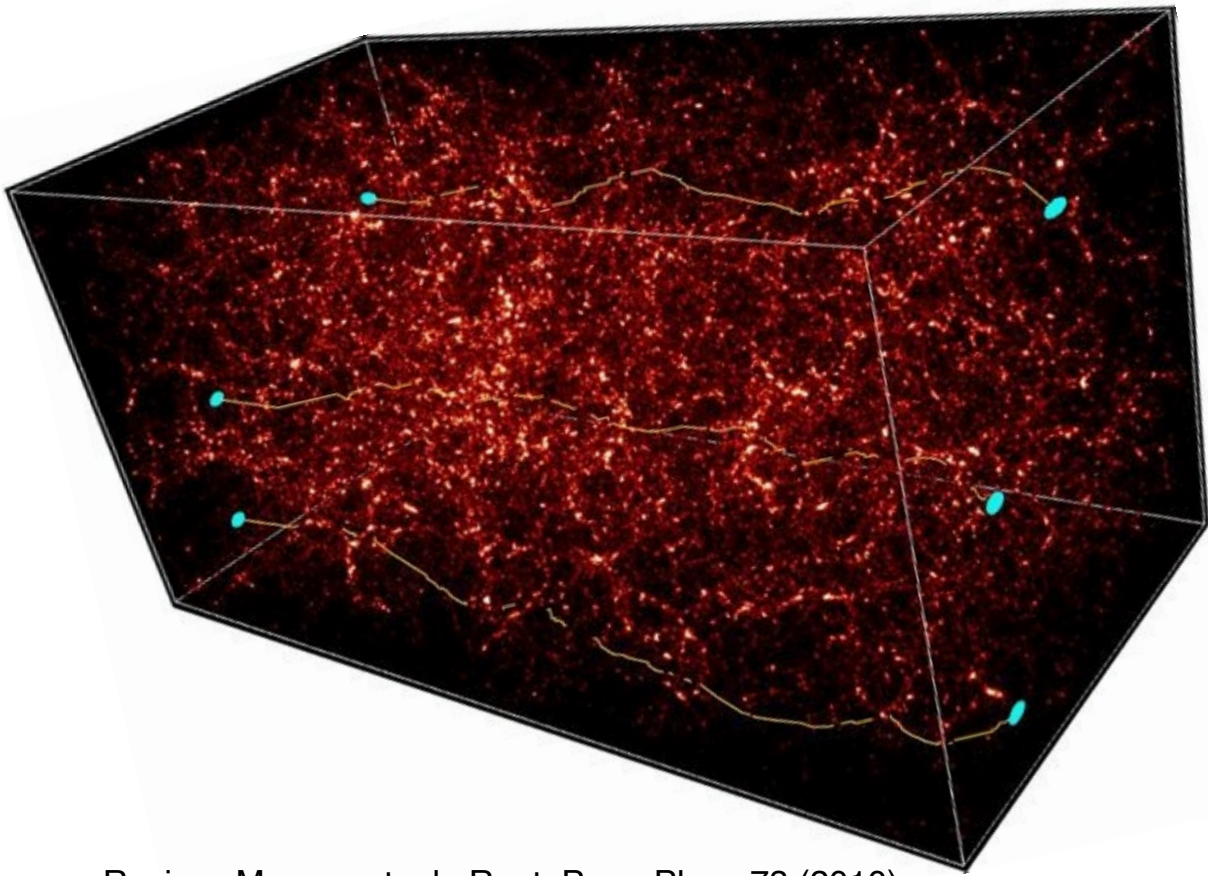


Beegeman et. al., MNRAS 249

Microlensing



Weak lensing



Review: Massey et. al., Rept. Prog. Phys. 73 (2010)

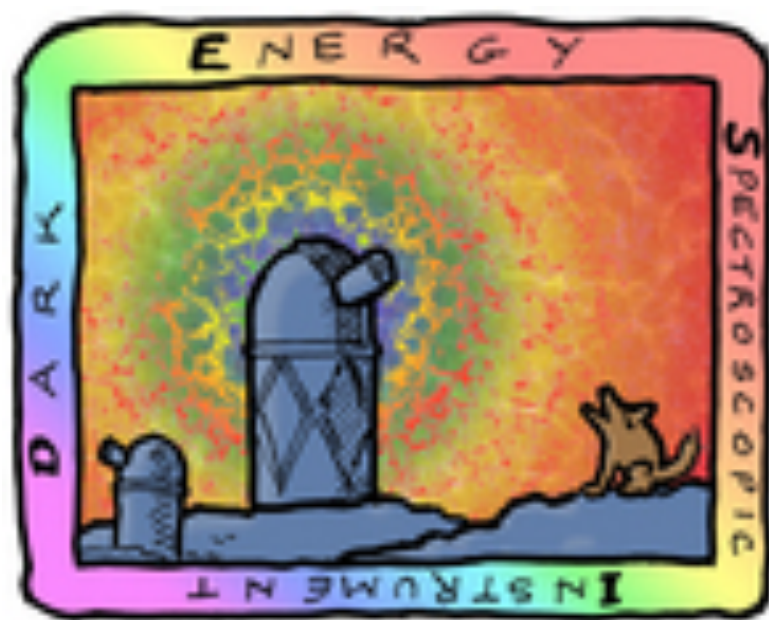


A selection of experiments dedicated to the dark sector taken from PDG 2024

Table 28.1: A selection of major dark-energy experiments, based on Ref. [28]. Abbreviations in the “Data” column refer to optical (Opt) or near-infrared (NIR) imaging (I) or spectroscopy (S). For spectroscopic experiments, the “Spec- z ” column lists the primary redshift range for galaxies (gals), quasars (QSOs), or the Lyman- α forest (Ly α F). Abbreviations in the “Methods” column are weak lensing (WL), clusters (CL), supernovae (SN), baryon acoustic oscillations (BAO), and redshift-space distortions (RSD).

Project	Dates	Area/deg ²	Data	Spec- z Range	Methods
BOSS	2008–2014	10,000	Opt-S	0.3–0.7 (gals) 2–3.5 (Ly α F)	BAO/RSD
KiDS	2011–2019	1350	Opt-I	—	WL/CL
DES	2013–2019	5000	Opt-I	—	WL/CL SN/BAO
eBOSS	2014–2018	7500	Opt-S	0.6–2.0 (gal/QSO) 2–3.5 (Ly α F)	BAO/RSD
SuMIRE	2014–2029	1500	Opt-I		WL/CL
			Opt/NIR-S	0.8–2.4 (gals)	BAO/RSD
DESI	2021–2026	14,000	Opt-S	0–1.7 (gals) 2–3.5 (Ly α F)	BAO/RSD
VRO/LSST	2025–2035	20,000	Opt-I	—	WL/CL SN/BAO
<i>Euclid</i>	2023–2029	15,000	Opt-I		WL/CL
			NIR-S	0.7–2.2 (gals)	BAO/RSD
<i>Roman</i>	2027–2032	2200	NIR-I		WL/CL/SN
			NIR-S	1.0–3.0 (gals)	BAO/RSD

...numerous experiments in the future...for example:

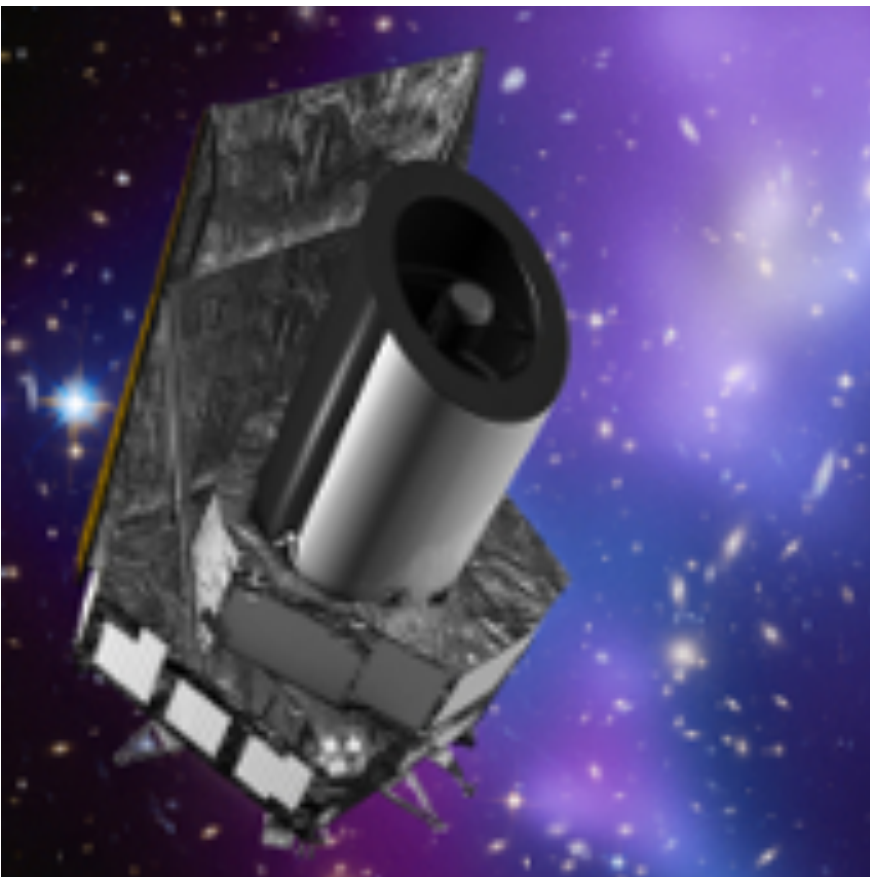


Kitt Peak National Observatory
<http://desi.lbl.gov> (espectrum)

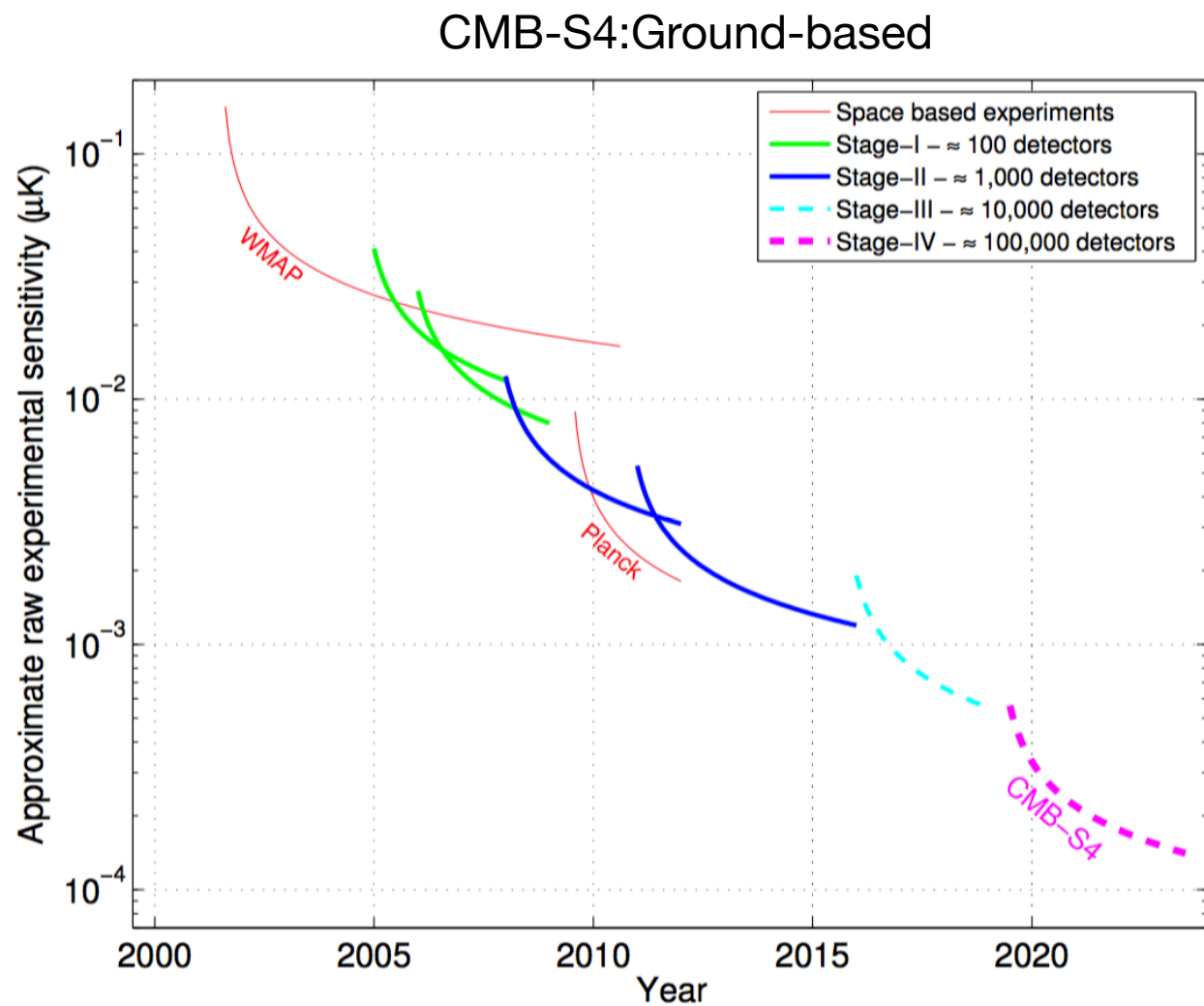


Large Synoptic Survey Telescope (LSST)
Chile
(~2025) <https://www.lsst.org> (image)

An artist view of the Euclid Satellite – © ESA



(Launched 2023) <http://sci.esa.int/euclid/>
(image y spectrum)



<https://cmb-s4.org/> (CMB)



(~ 2028) (CMB)

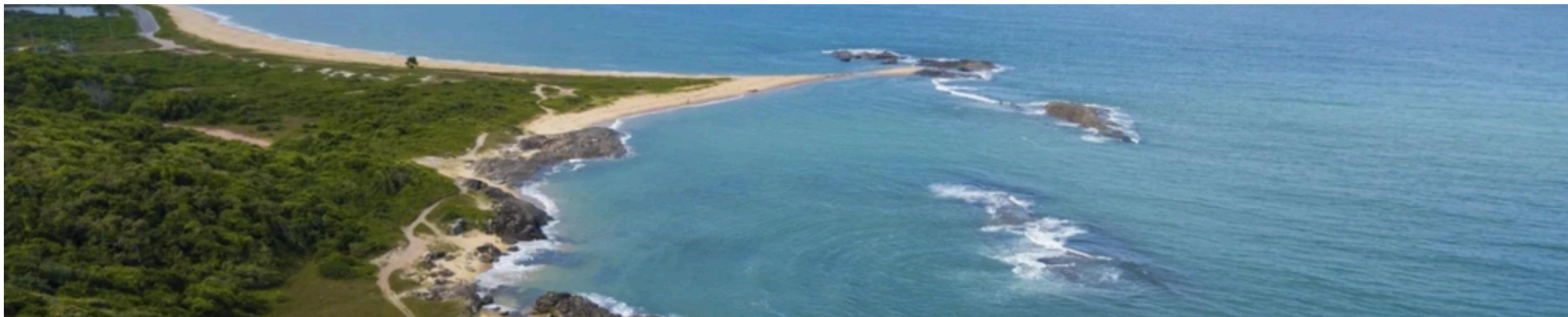


(~ 2027) (image y spectrum)



<https://www.skatelescope.org/>
(21 cm HI, radio)

End of Lecture 1: Thanks for your attention!!



Quantum Summer 2025

Iriri, ES, Brazil. April 07-11, 2025.

Diana López Nacir

