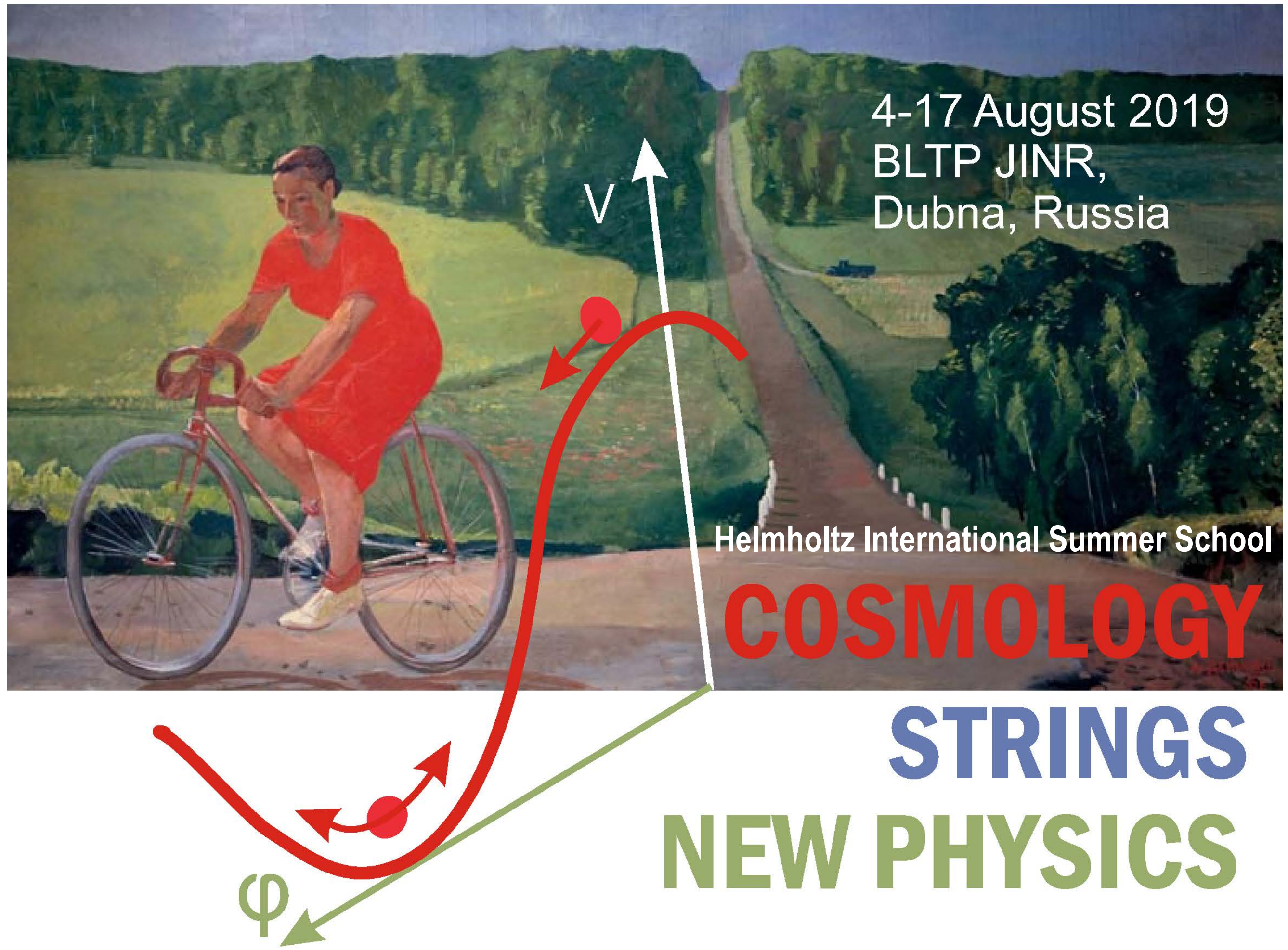
Dubna International Advanced School of Theoretical Physics



Dark Side of the Universe I

Alexander Vikman

06.08.2019

FZU Institute of Physics of the Czech Academy of Sciences

CEICO

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Literature

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- *Ultralight scalars as cosmological dark matter*
  Hui,Ostriker,Tremaine,Witten
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- *Modified Newtonian Dynamics (MOND): Observational Phenomenology and Relativistic Extensions*
  Famaey, McGaugh
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- *Lectures on Dark Matter Physics*
  Mariangela Lisanti
  arXiv:1603.03797

Standard Model of Particle Physics

5%

Standard Model of Particle Physics

5%

Dark Matter

27%

Standard Model of Particle Physics

5%

Dark Matter

Dark Energy

27%

68%

Standard Model of Particle Physics

5%

Dark Matter

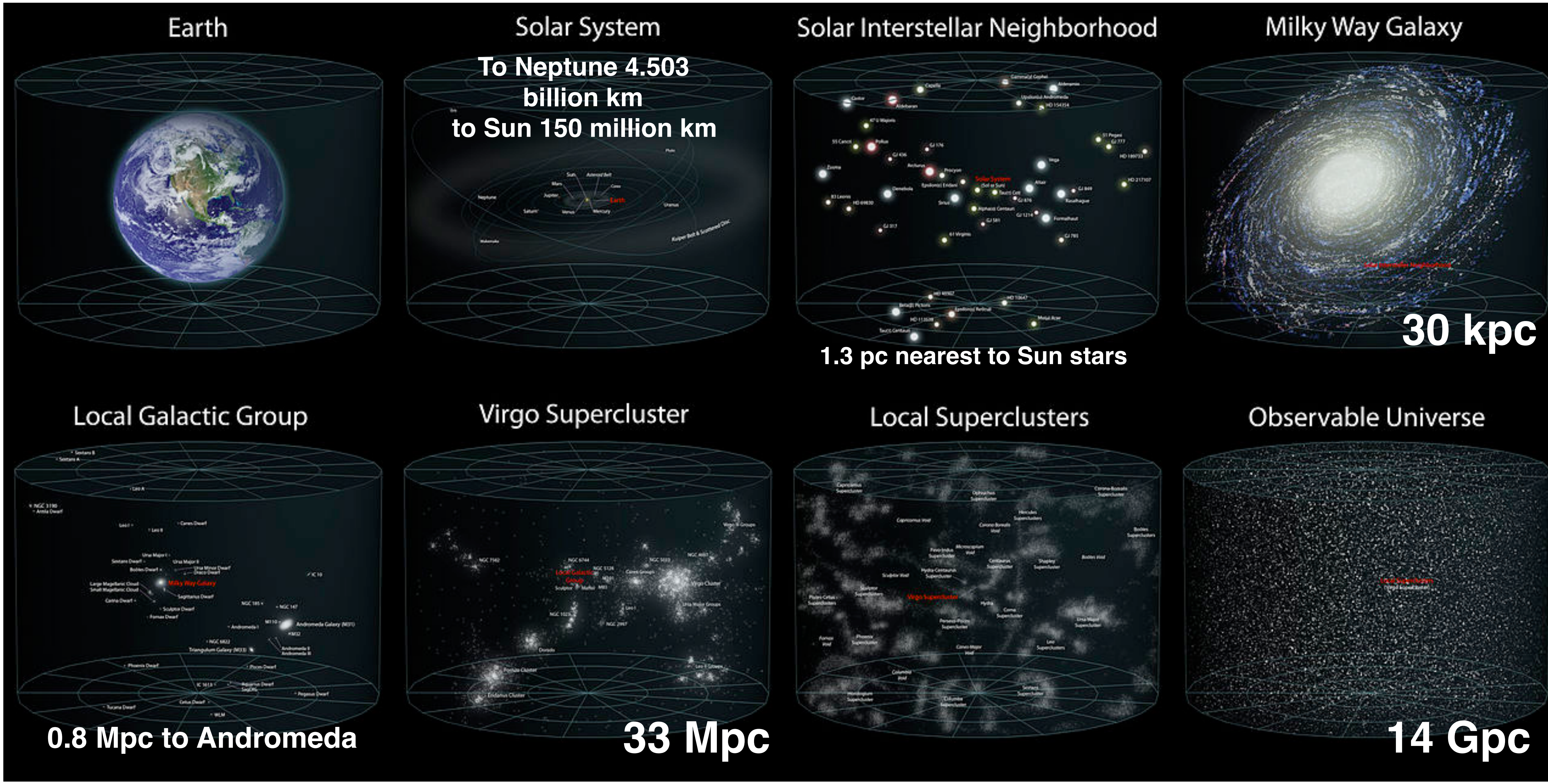
Dark Energy

27%

68%

we feel them through gravity only!

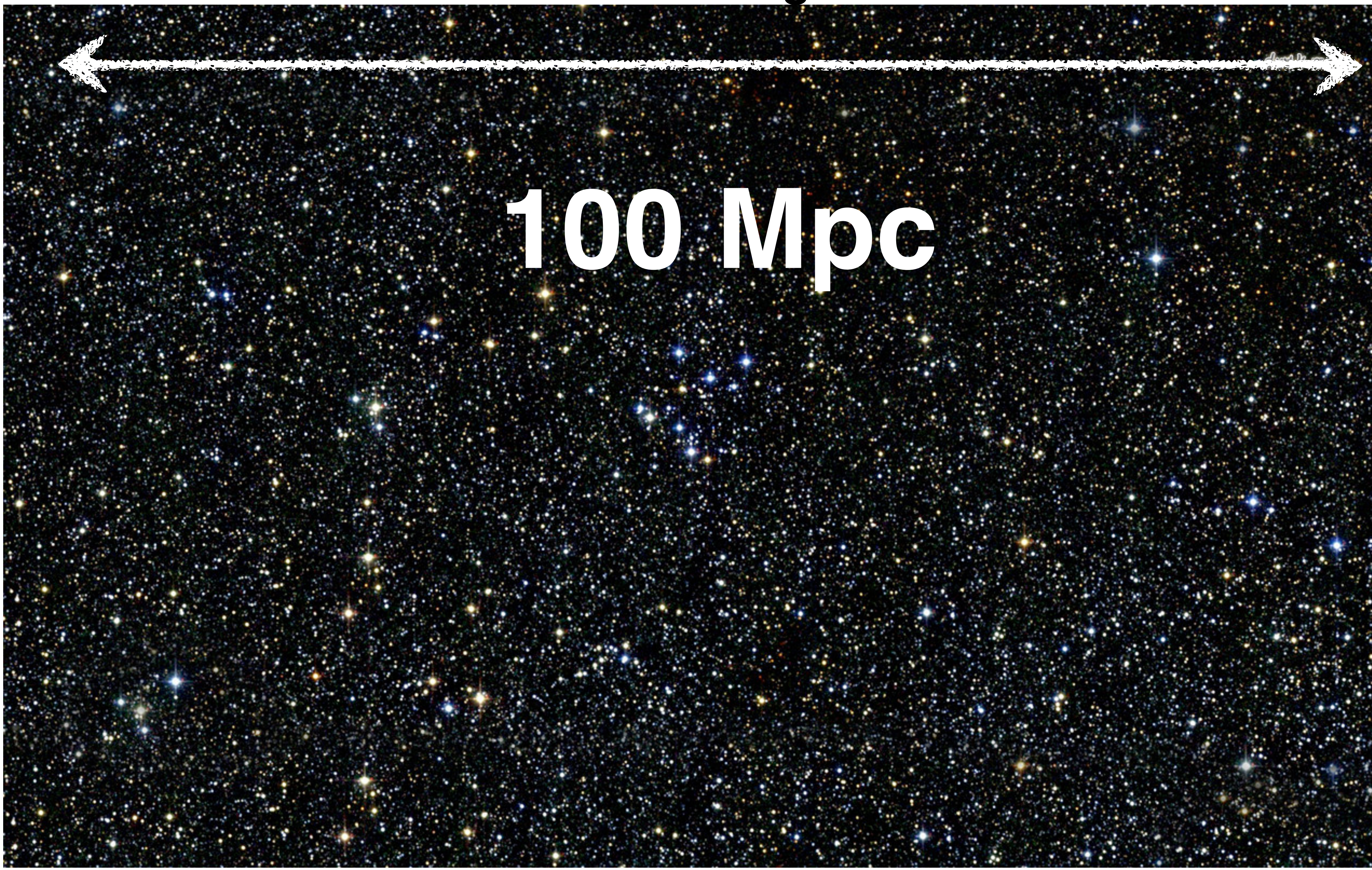
Where are we?



Radius of the observable universe is about 46.5 billion light-years (14 billion pc).

1 pc=parsec is equal to about 3.26 light-years (31 trillion kilometres)

The Universe is practically isotropic and homogeneous on scales larger than



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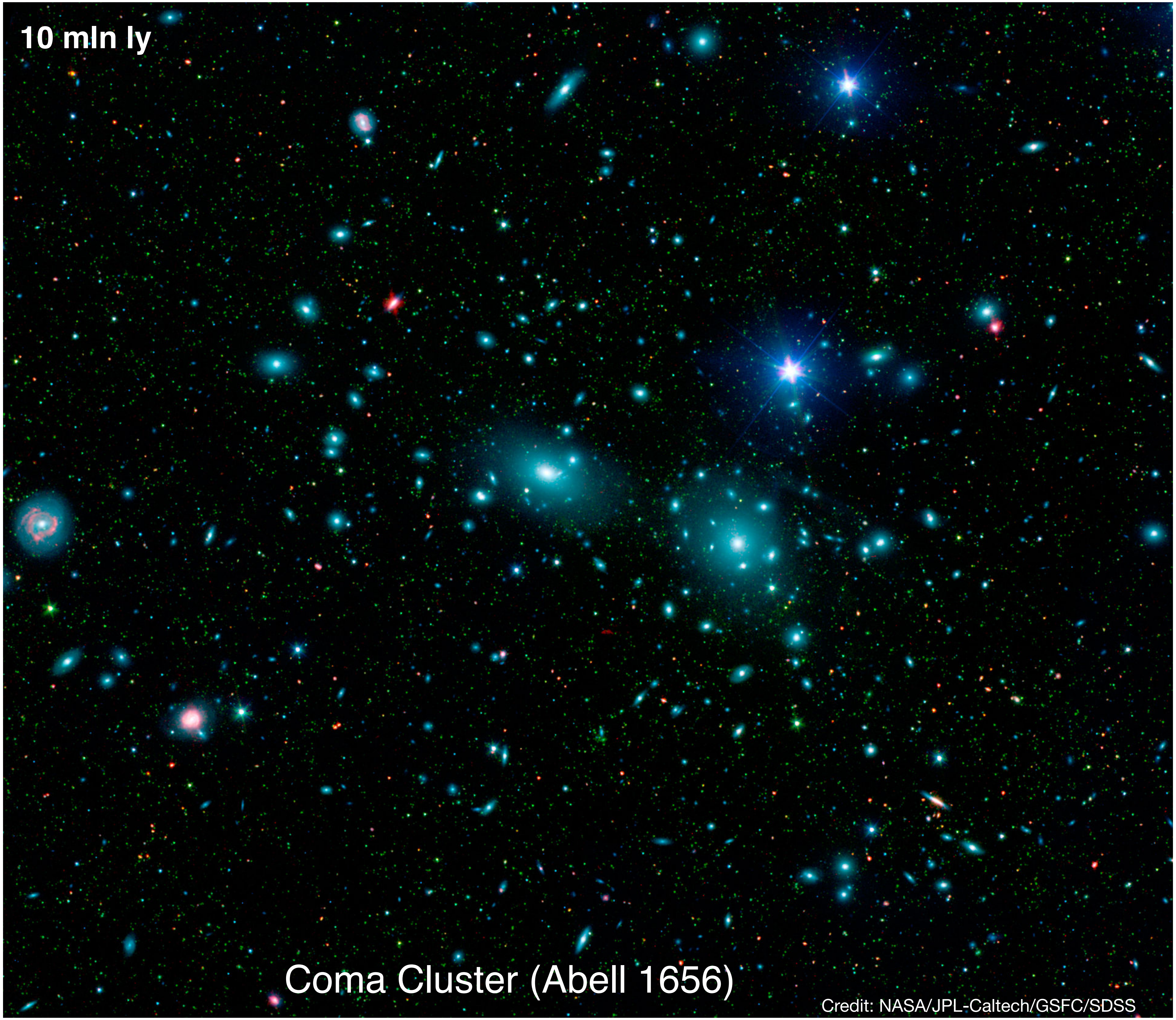
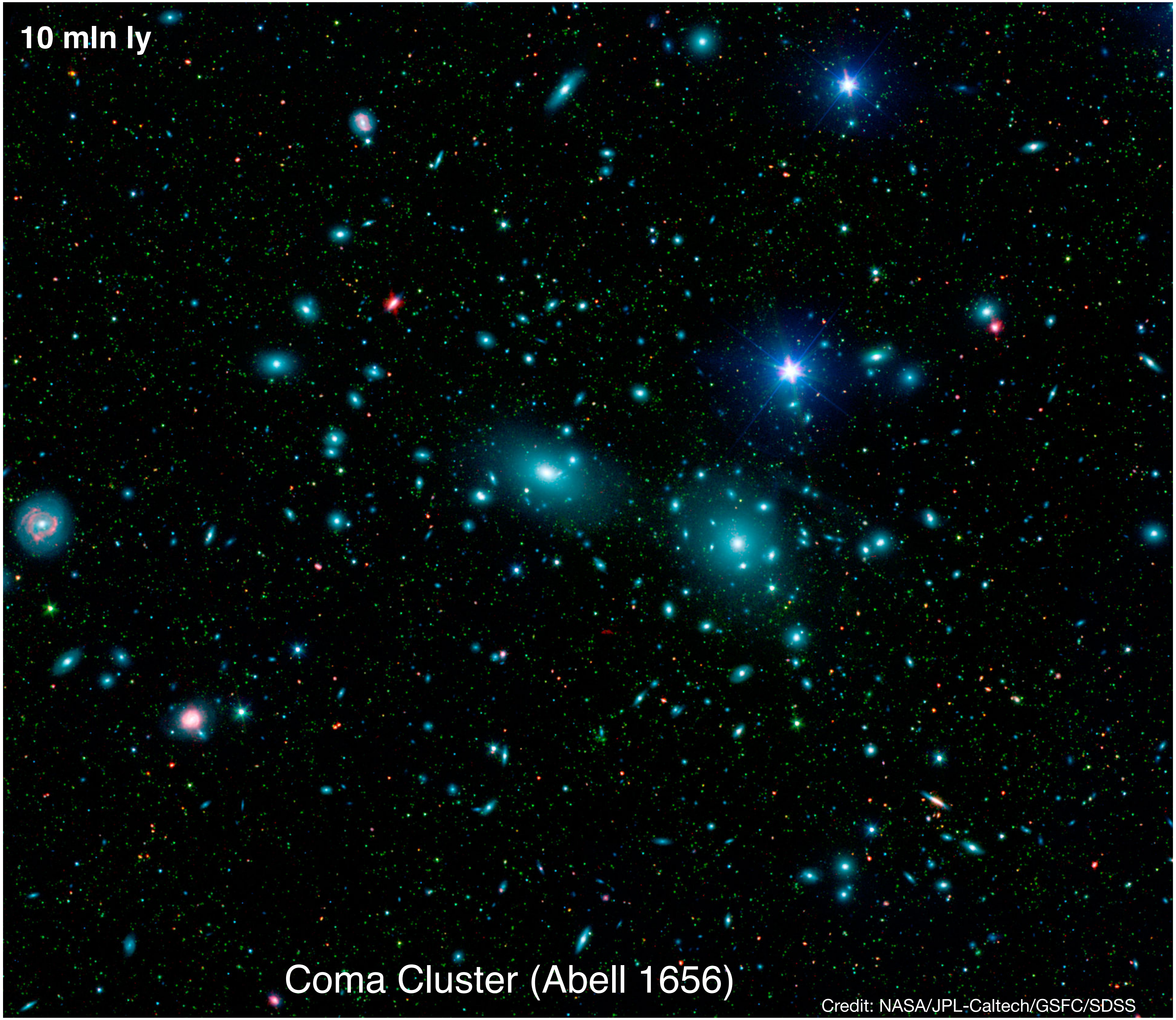

10 mln ly
Coma Cluster (Abell 1656)
Credit: NASA/JPL-Caltech/GSFC/SDSS

Dark Matter on "Small" Scales



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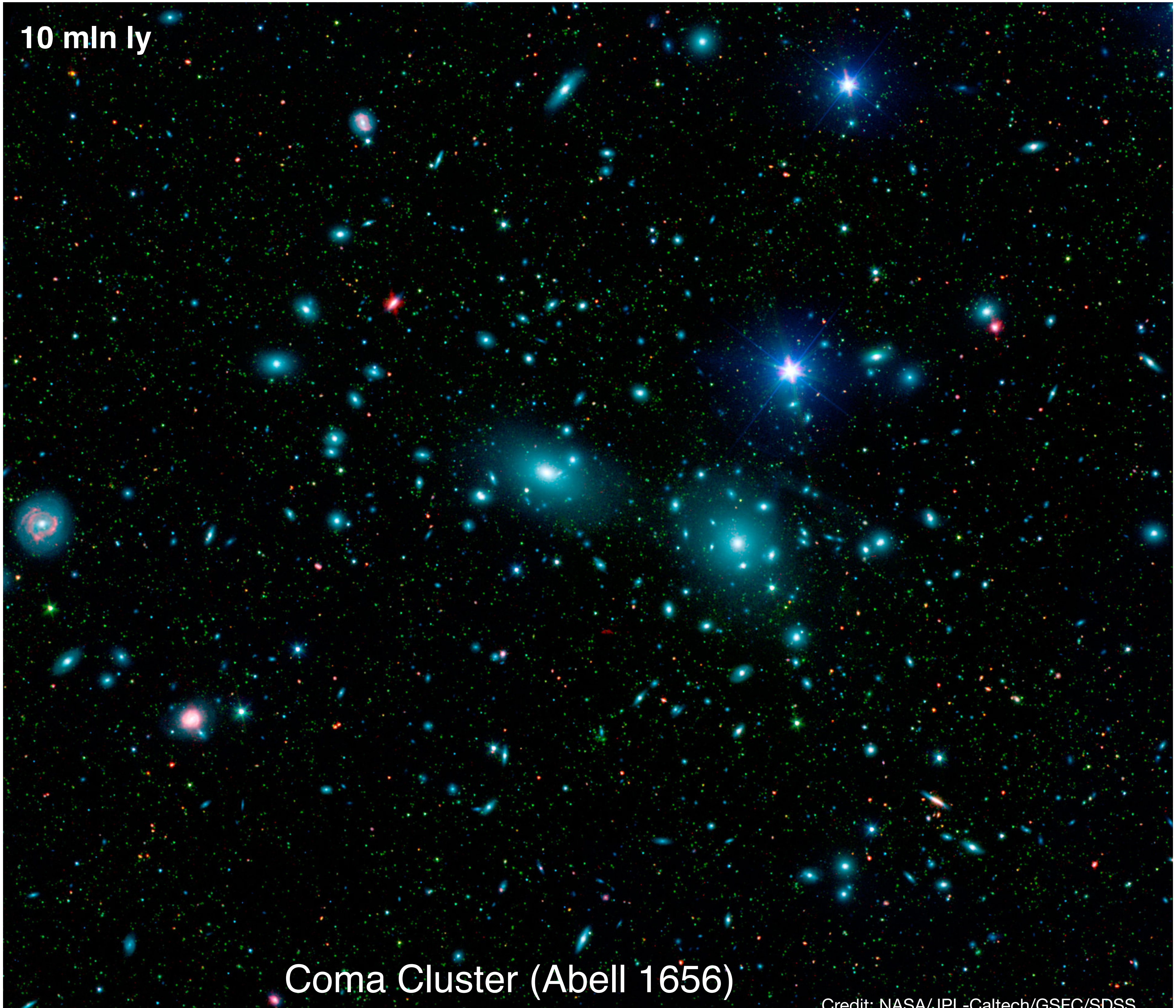

Fritz Zwicky, 1933

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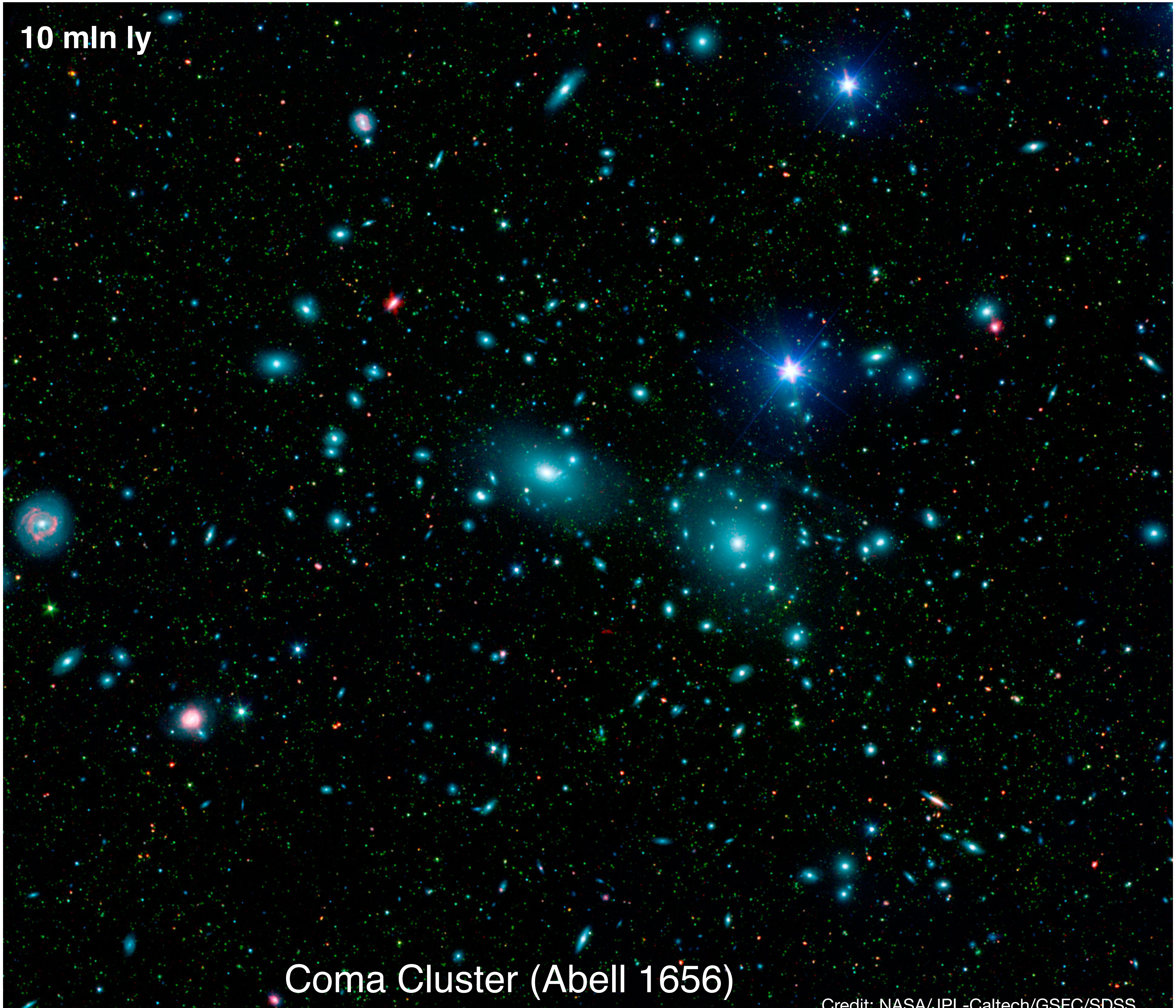
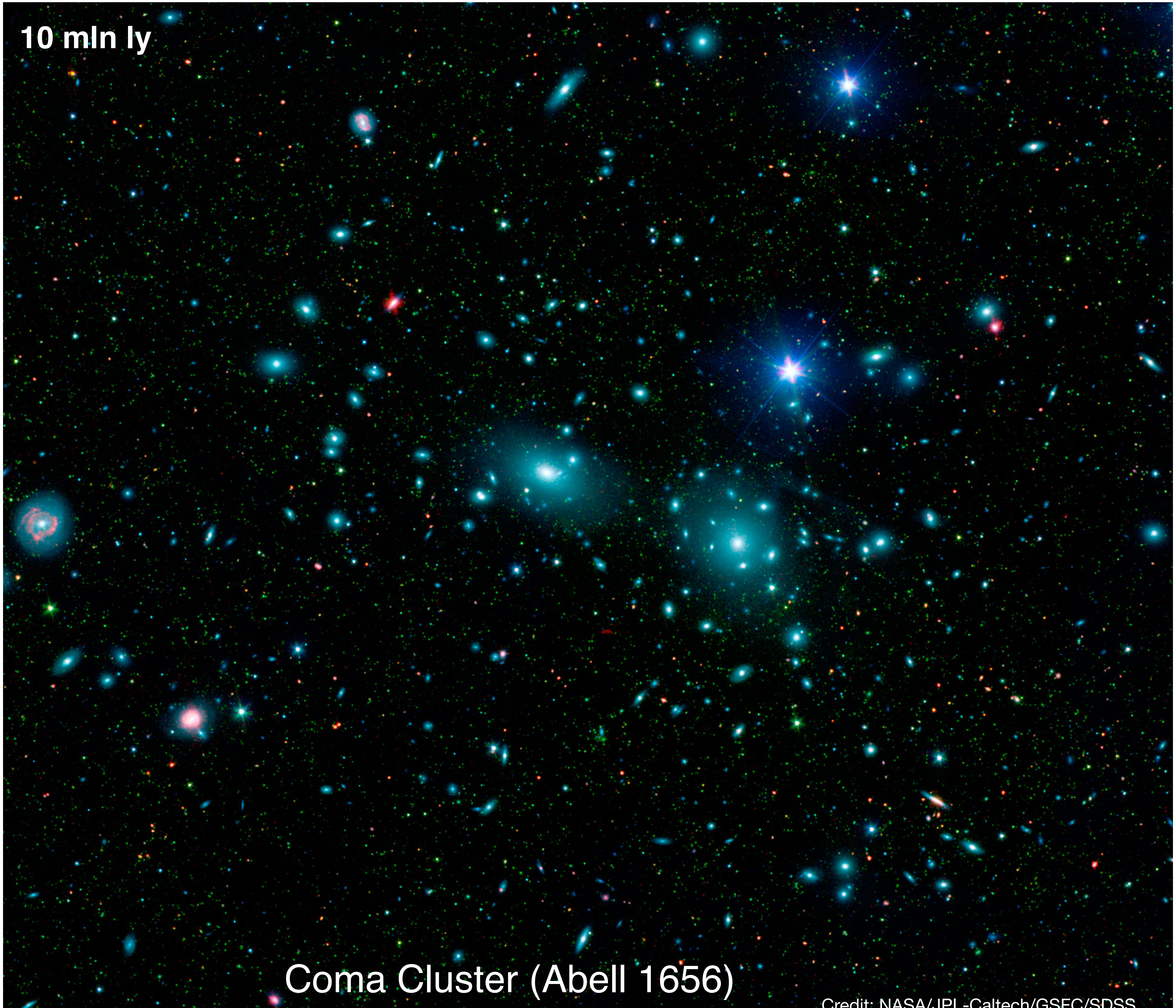


Fritz Zwicky, 1933

$$\bar{U} = -2\bar{T}$$

virial theorem

Dark Matter on "Small" Scales



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$DM_{Zwicki} \simeq 400$ Lum. Matter

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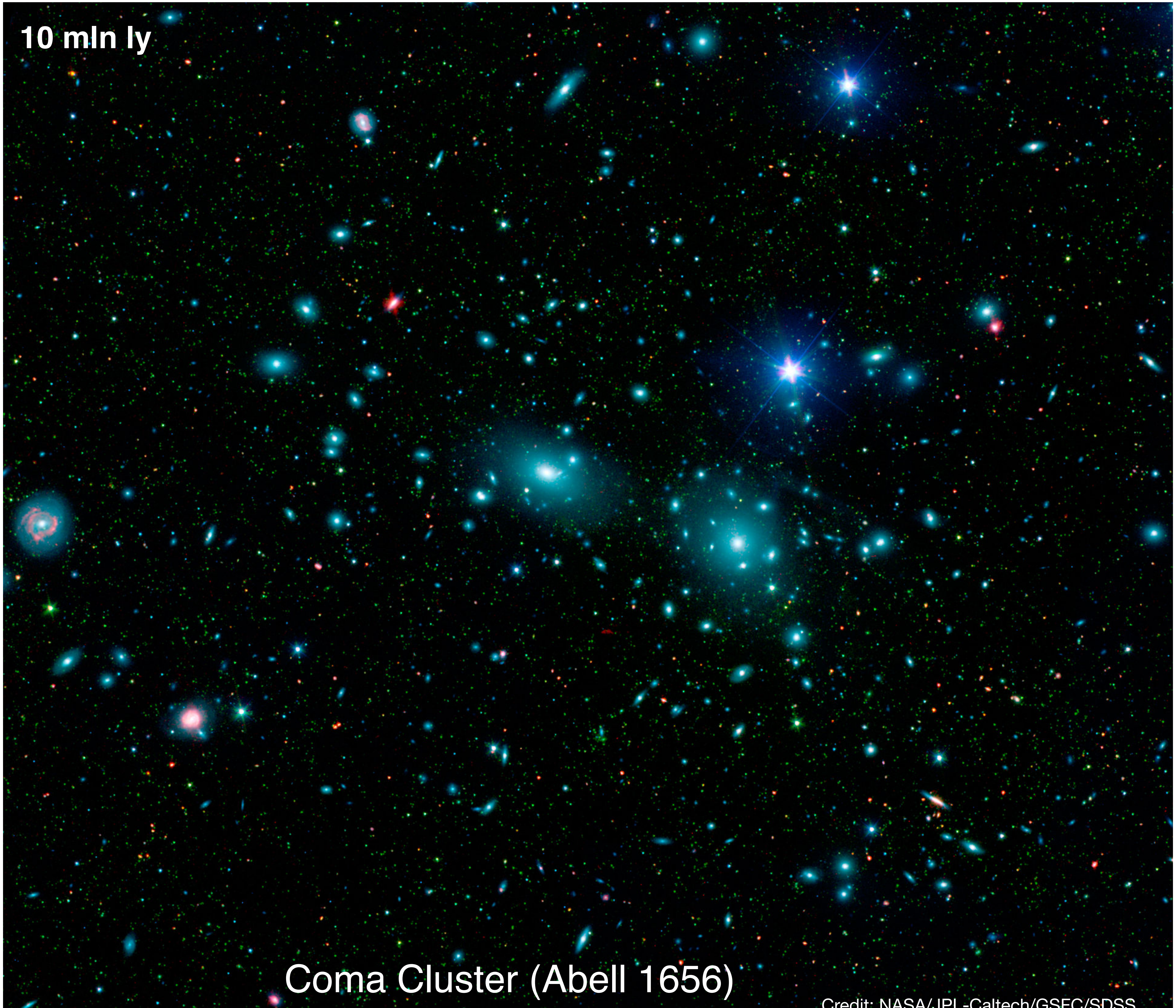

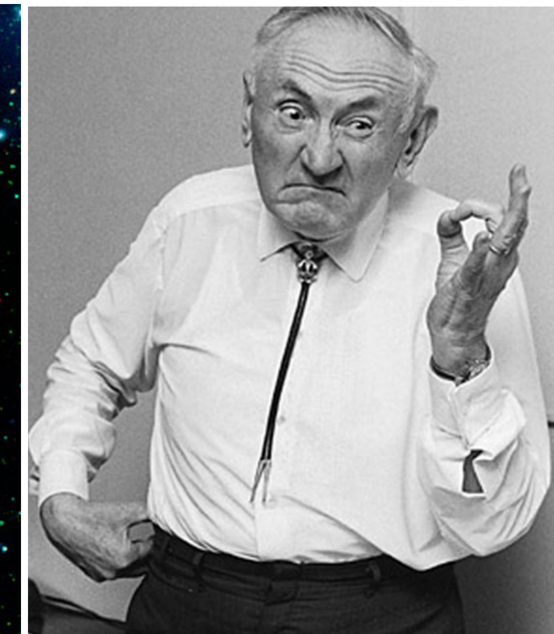

Fritz Zwicky, 1933

$$\bar{U} = -2\bar{T}$$

virial theorem

$DM_{Zwicki} \simeq 400$ Lum. Matter

$DM_{modern} \simeq 10$ Lum. Matter

Dark Matter

on "Small" Scales

Vera Rubin, 1970-80

Dark Matter on "Small" Scales

Galaxy Evolution Explorer image

Vera Rubin, 1970-80

Dark Matter on “Small” Scales

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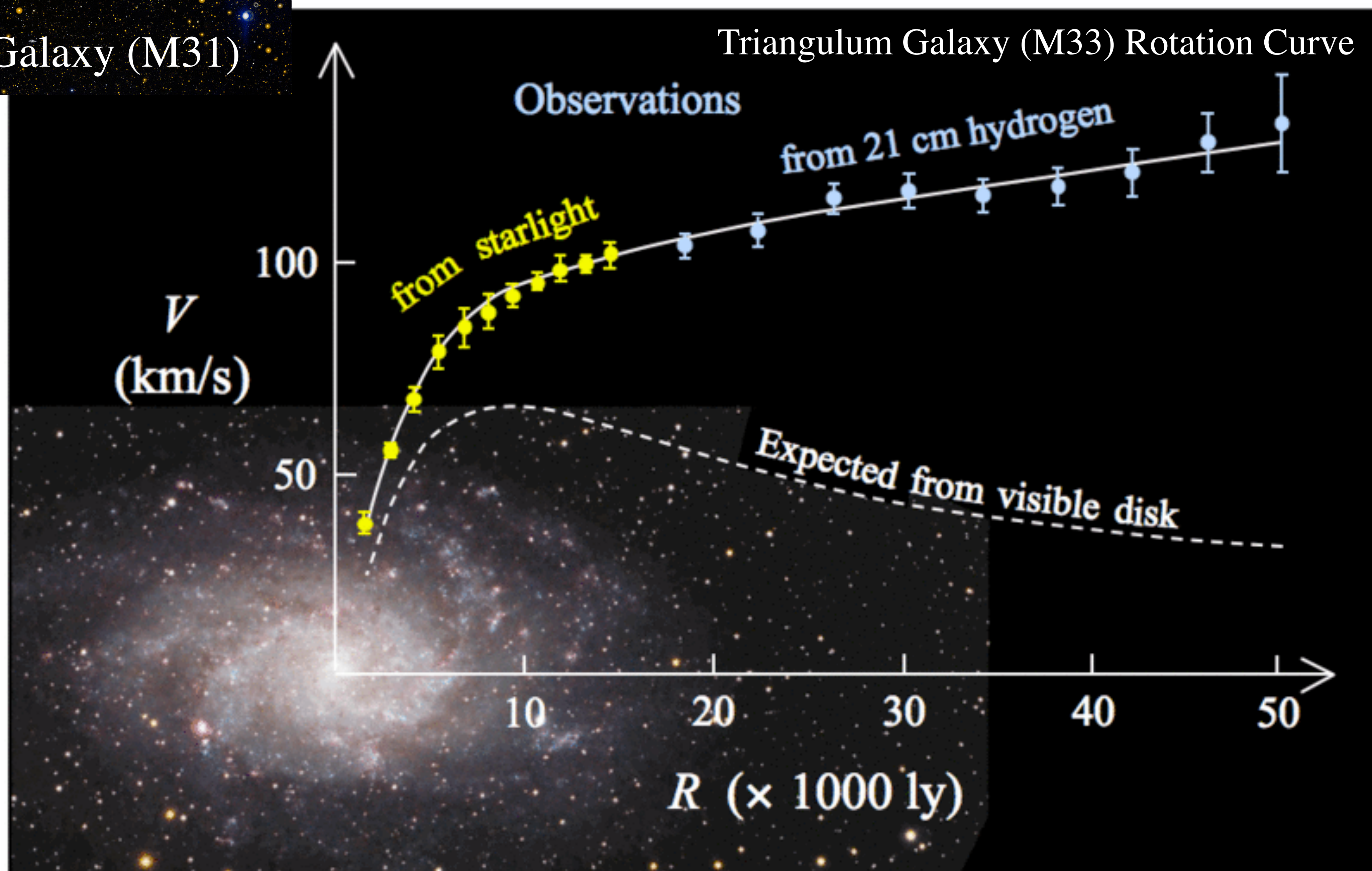

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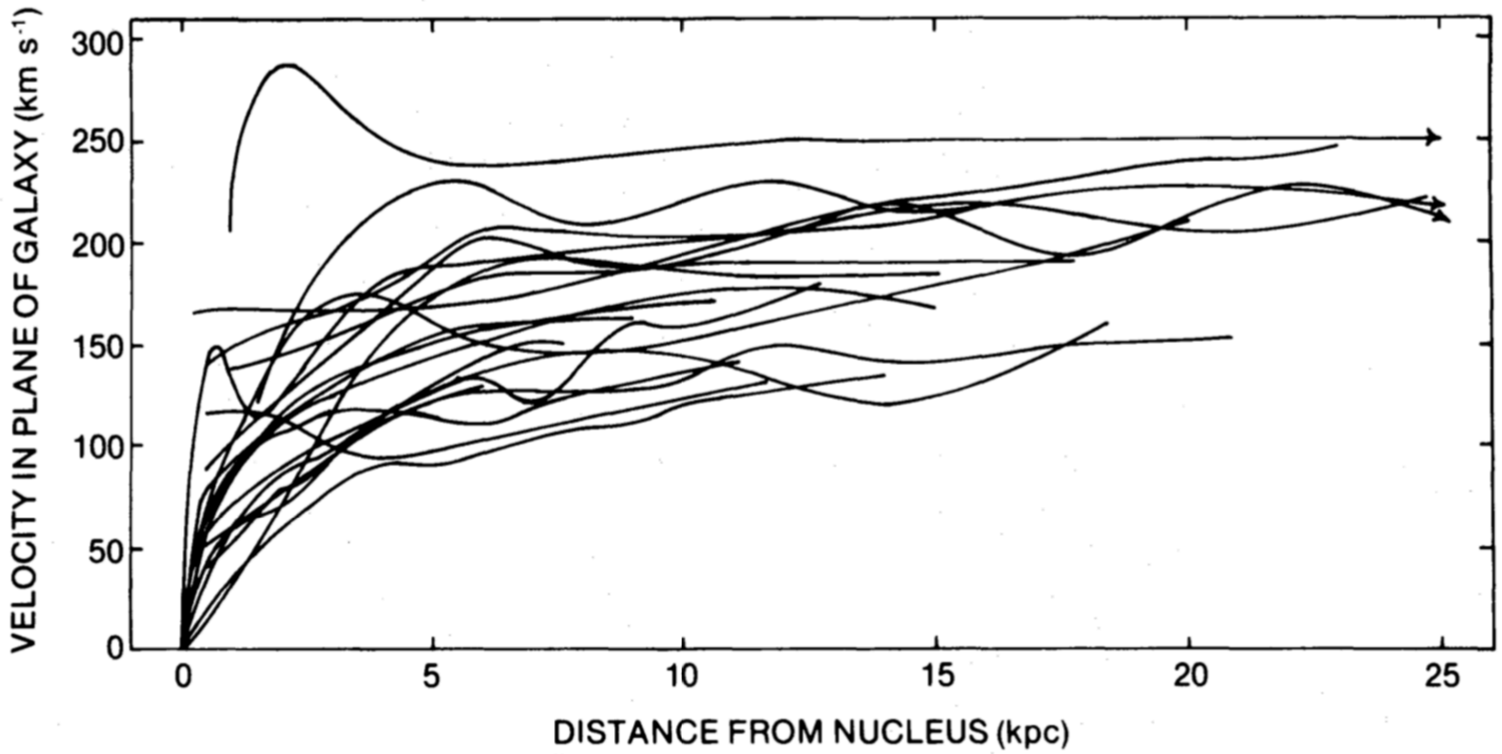

Figure 1: Rotation curves of spiral galaxies as measured in the original Rubin *et al.* paper (1980) Most galaxies show a flattening of the circular velocity at large radial distances.

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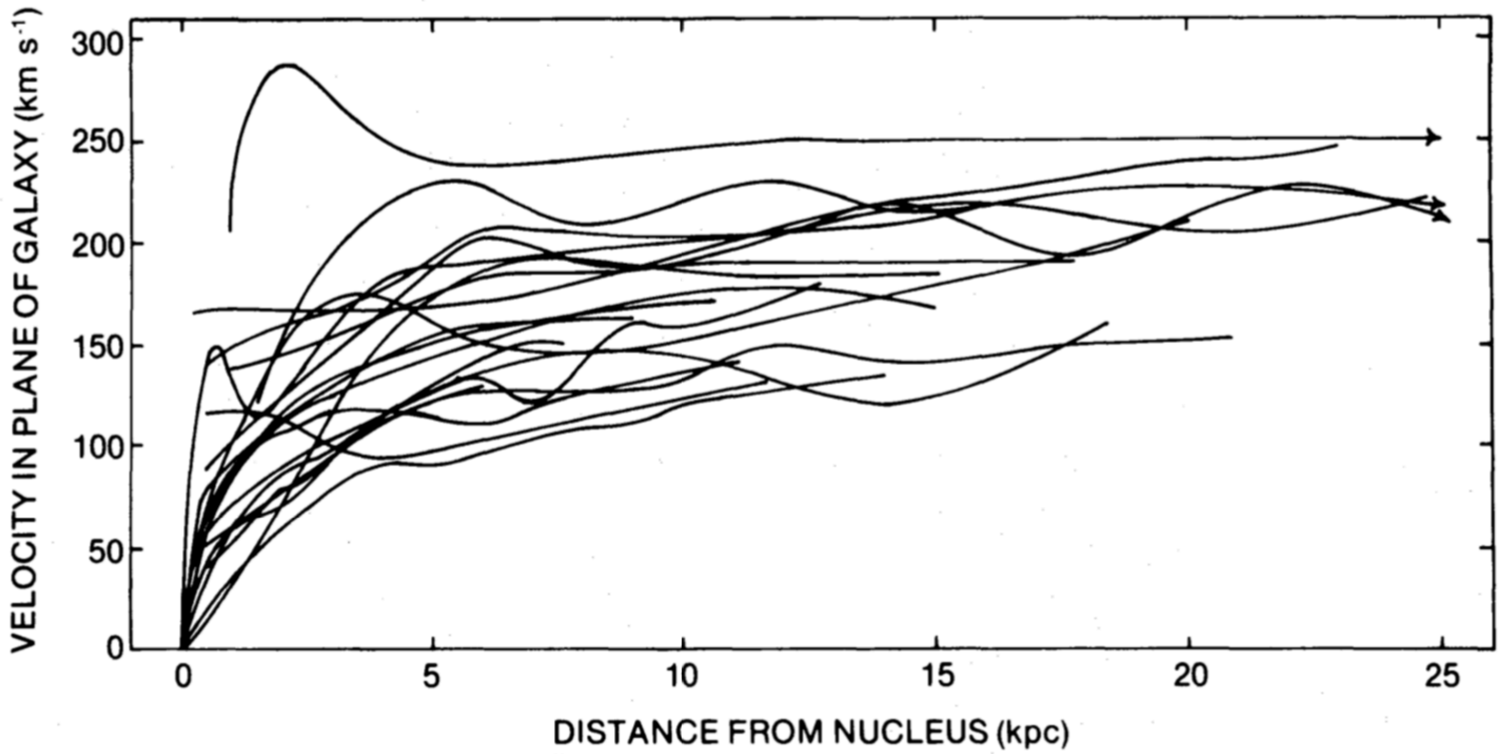

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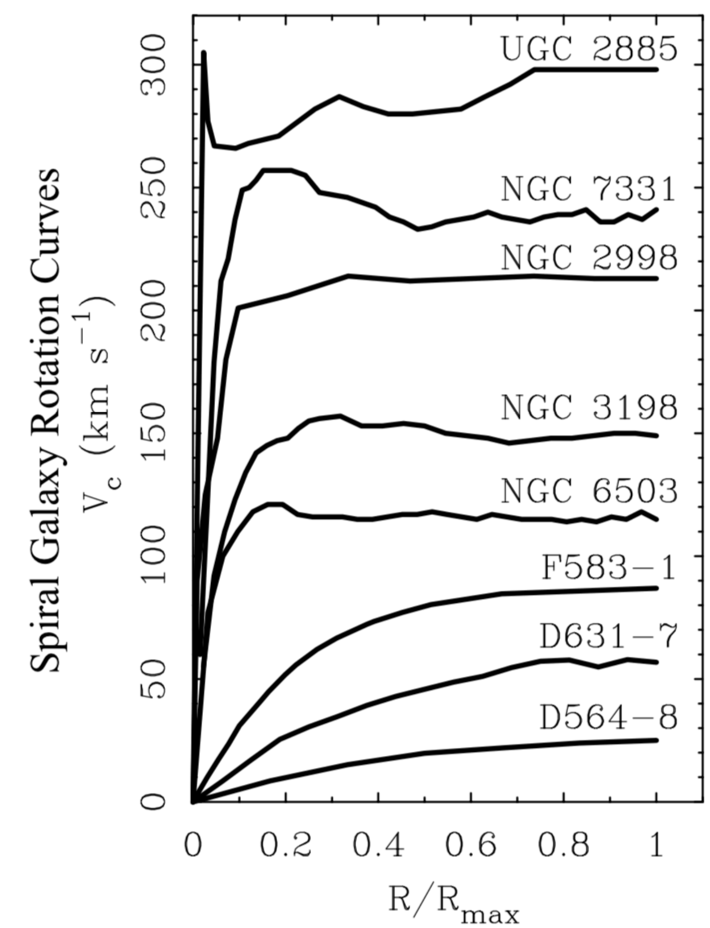
Famaey, McGaugh



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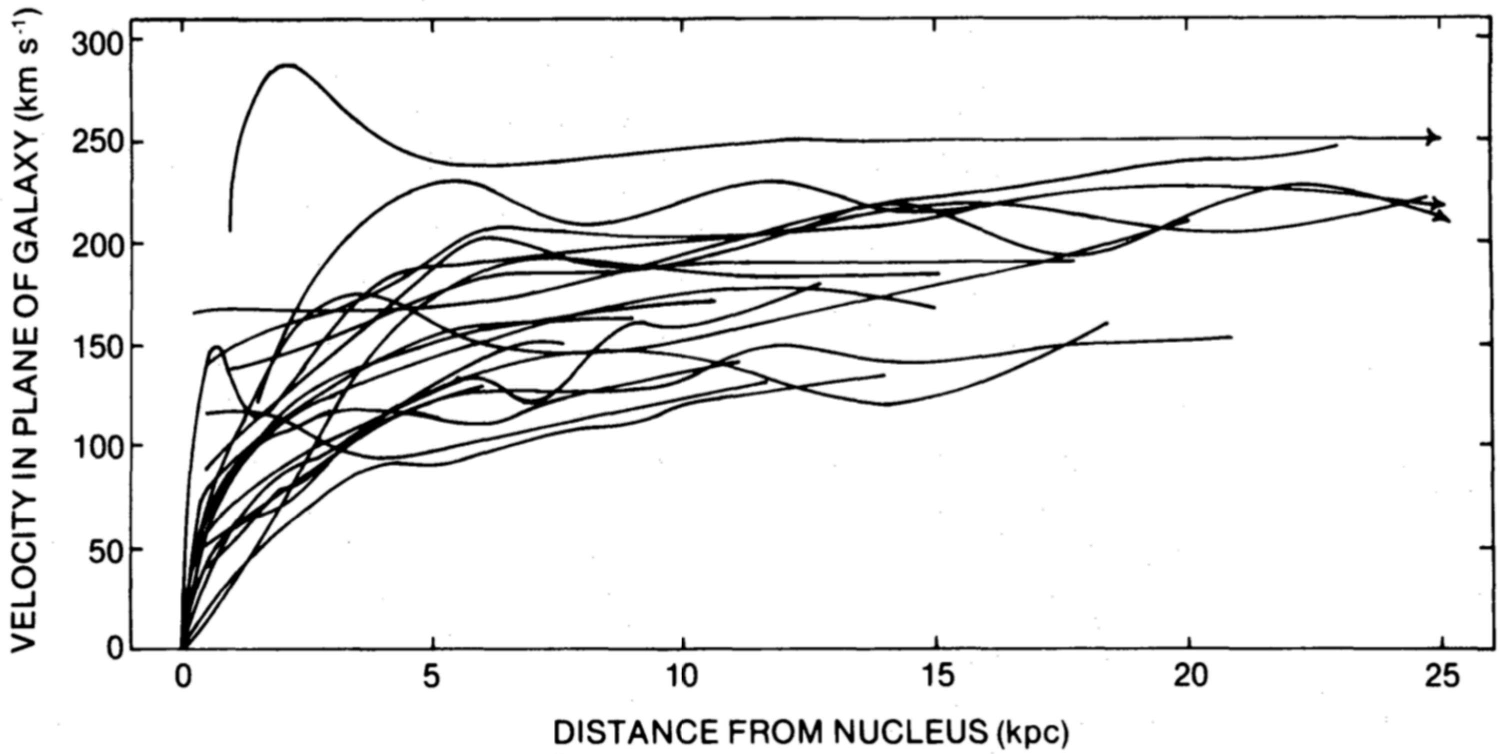

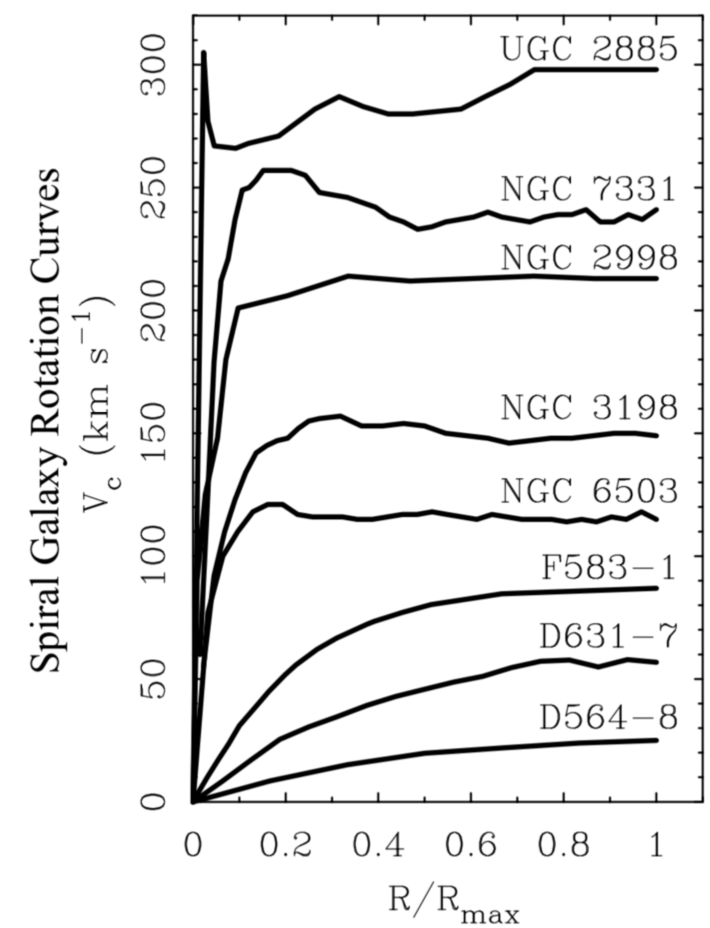

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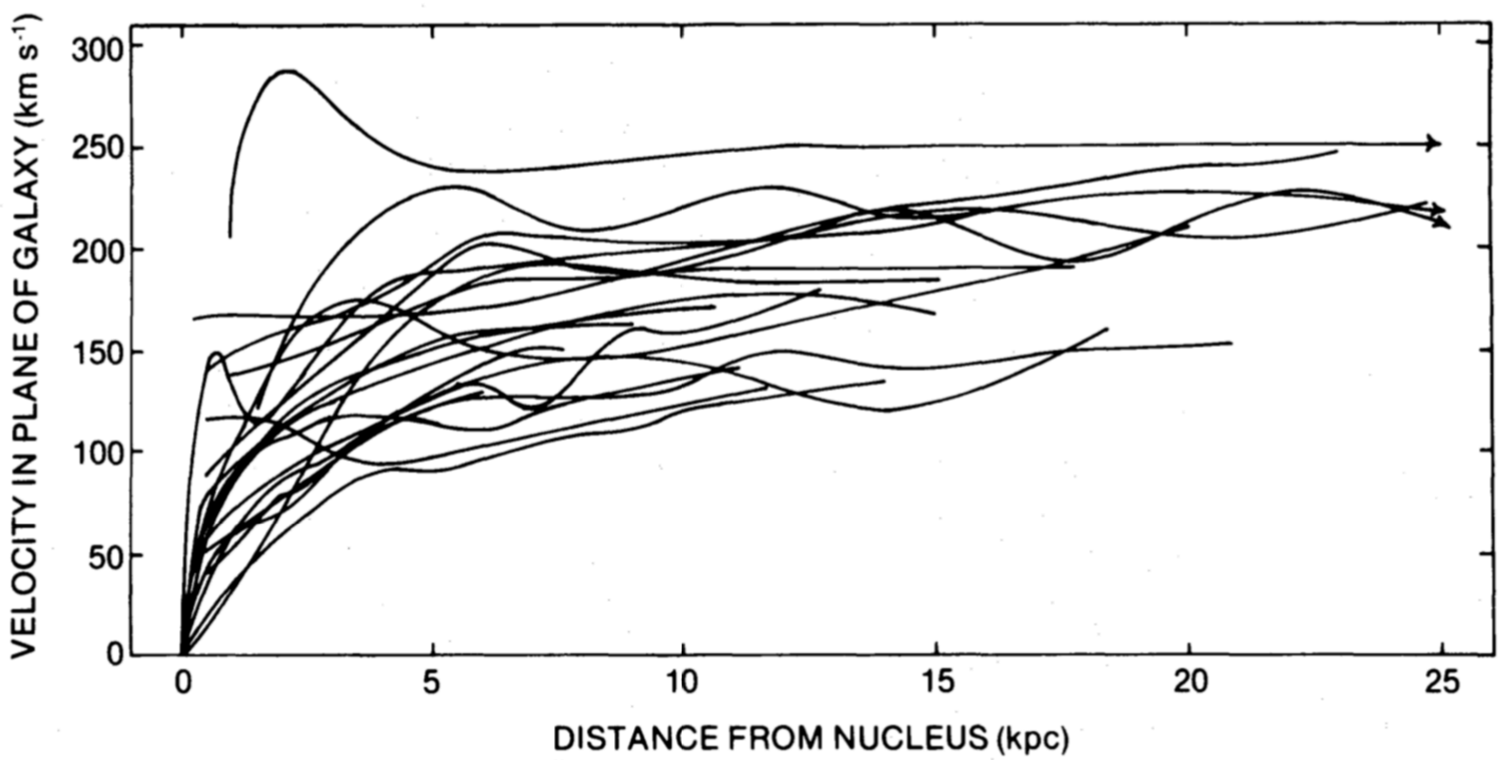

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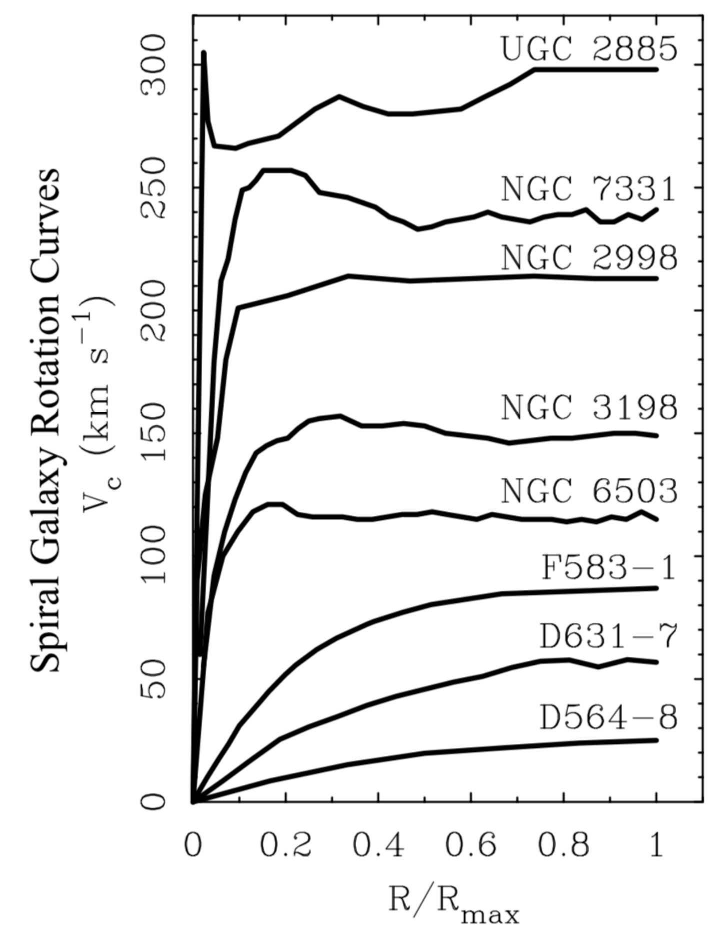

observations $v(r) \simeq const$

$$M = 4\pi \int_0^r dr' \, r'^2 \rho(r') \qquad M \propto r \qquad \rho \propto \frac{1}{r^2}$$

For our Galaxy

$M_{halo} \sim 10^{12} M_{\odot}$ but 10^{11} stars

$\rho_{DM} \sim 0.3\ \text{GeV/cm}^3$

$R_{halo} \sim 100\ \text{kpc}$ but $R_{Earth} \sim 8\ \text{kpc}$

$$\langle v \rangle \sim \sqrt{\frac{G M_{halo}}{R_{halo}}} \sim 200\ \text{km/s}$$

Non-relativistic!

DUST is good enough…

$\rho \propto \frac{1}{r^2}$ **and Maxwell-Boltzmann distribution**

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phase space density for a DM particle $f(\mathbf{x}, \mathbf{v})$

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collision-less Boltzmann equation $$\frac{\partial f}{\partial t} + \dot{\mathbf{x}}\frac{\partial f}{\partial \mathbf{x}} + \dot{\mathbf{v}}\frac{\partial f}{\partial \mathbf{v}} \simeq 0$$

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Jeans Theorem: stationary solution $\quad f\left(I(\mathbf{x}, \mathbf{v})\right) \qquad \frac{d}{dt} I(\mathbf{x}, \mathbf{v}) = 0$

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$E = \frac{1}{2} v^2 + \Phi$ as $I(\mathbf{x}, \mathbf{v})$

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assume $f \propto e^{-E/\sigma^2}$ so that $\rho \propto \int_0^\infty dv v^2 f \propto e^{-\Phi/\sigma^2}$

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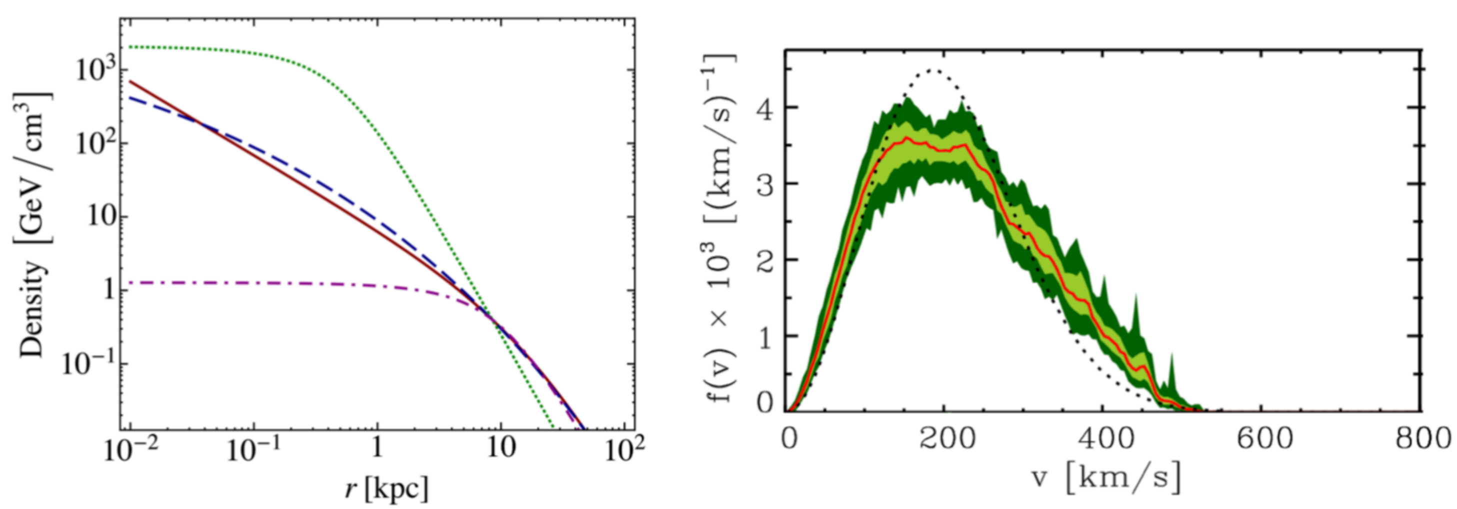
Poisson equation $\Delta \Phi = 4\pi G \rho$ results in $\rho \propto \frac{1}{r^2}$ $f \propto e^{-v^2/\sigma^2}$

DM halo profiles from numerical simulations, Cusp/Core?

Navarro-Frenk-White (NFW) profile: $\rho_{NFW}(r) = \dfrac{\rho_0}{r/r_s\left(1 + r/r_s\right)^2}$ $\quad r_s = 20\,\text{kpc}$

Einasto profile: $\rho_{Ein}(r) = \rho_0 \exp\left(-\dfrac{2}{\gamma}\left[\left(\dfrac{r}{r_s}\right)^{\gamma} - 1\right]\right)$ $\quad \gamma = 0.17$

Burkert profile : $\rho_{Burk}(r) = \dfrac{\rho_0}{\left(1 + r/r_s\right)\left(1 + \left(r/r_s\right)^2\right)}$ $\quad r_s$ core

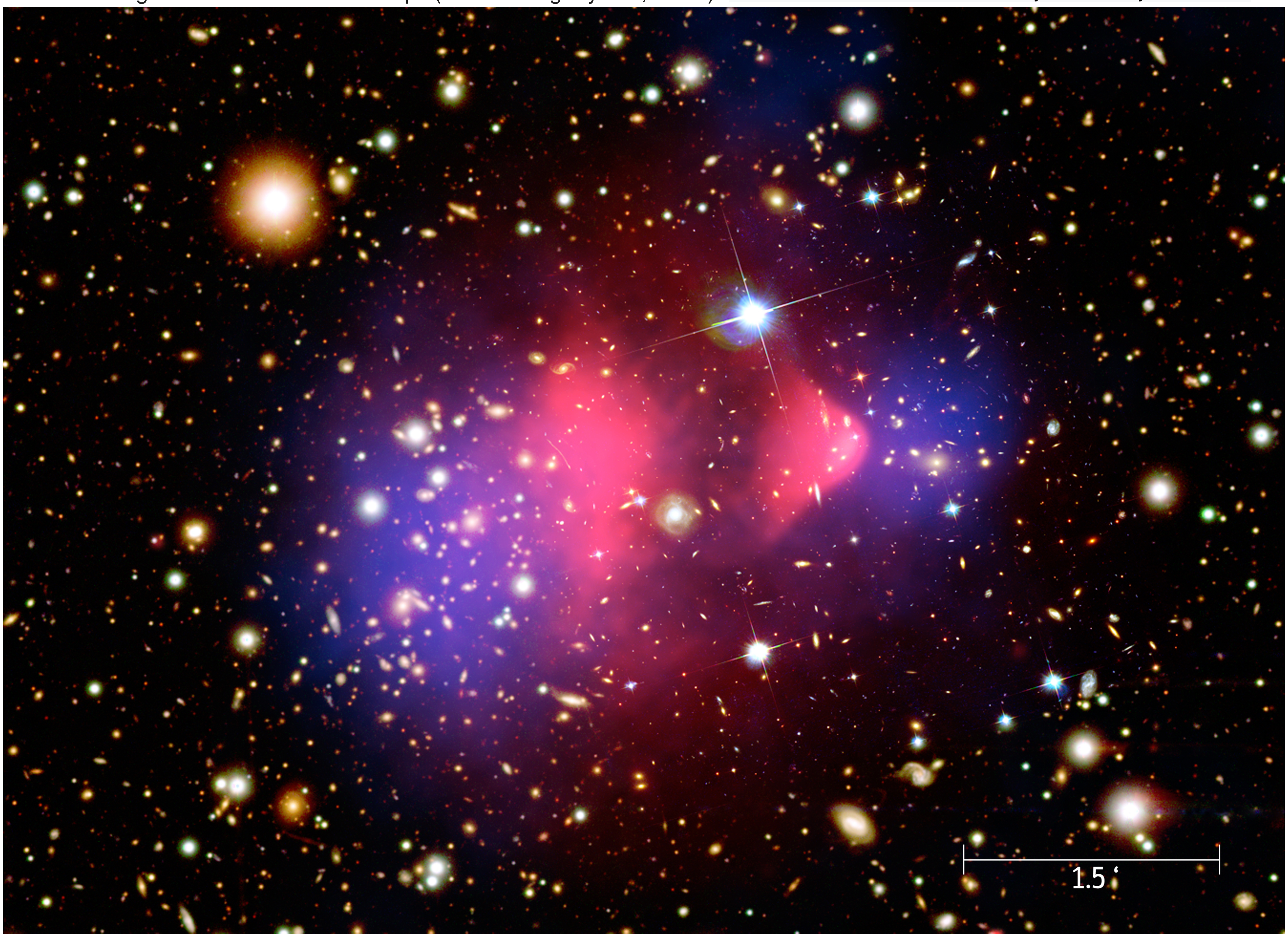


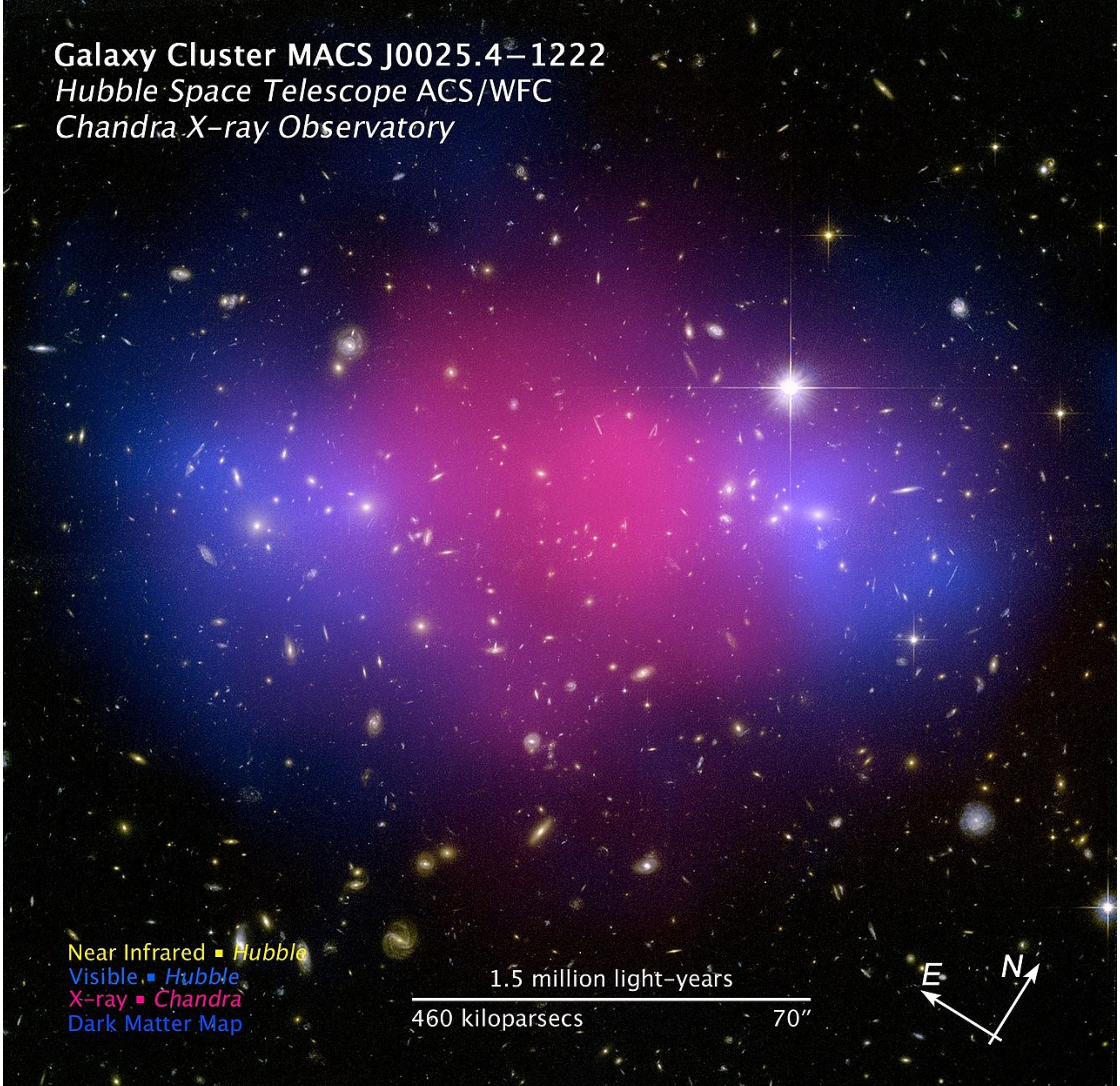
TASI 2015, Lectures on Dark Matter Physics, Lisanti

Figure 2: *(left)* A comparison of the NFW (solid red), Einasto (dashed blue), and Burkert with $r_s = 0.5$ (dotted green) and 10 kpc (dot-dashed purple) profiles. Figure from [32]. *(right)* The expected velocity distribution from the Via Lactea simulation (solid red), with the 68% scatter and the minimum/maximum values shown by the light and dark green shaded regions, respectively. For comparison, the best-fit Maxwell-Boltzmann distribution is shown in dotted black. Figure from [33].

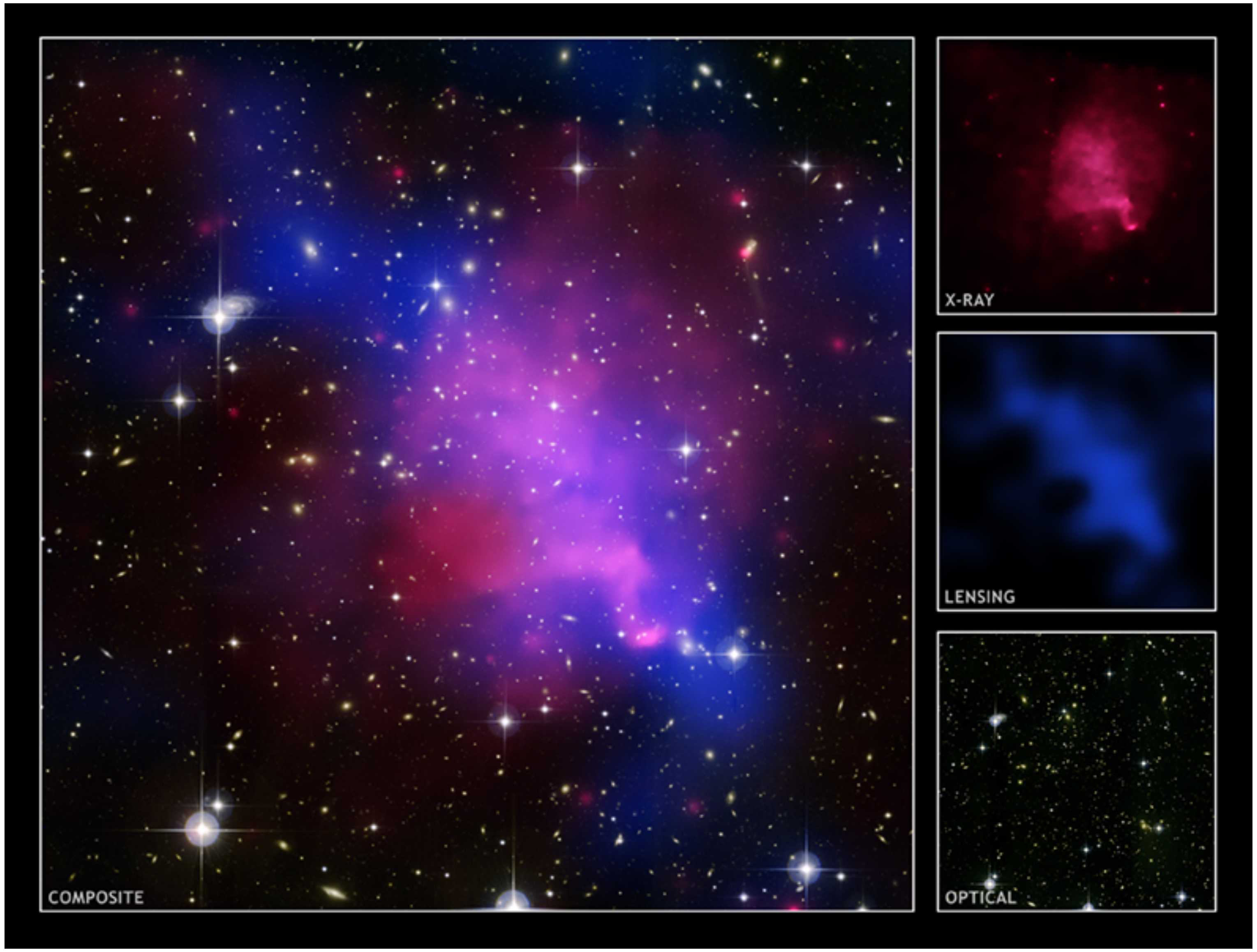
Bullet Cluster: Dark Matter passes by "without" interactions

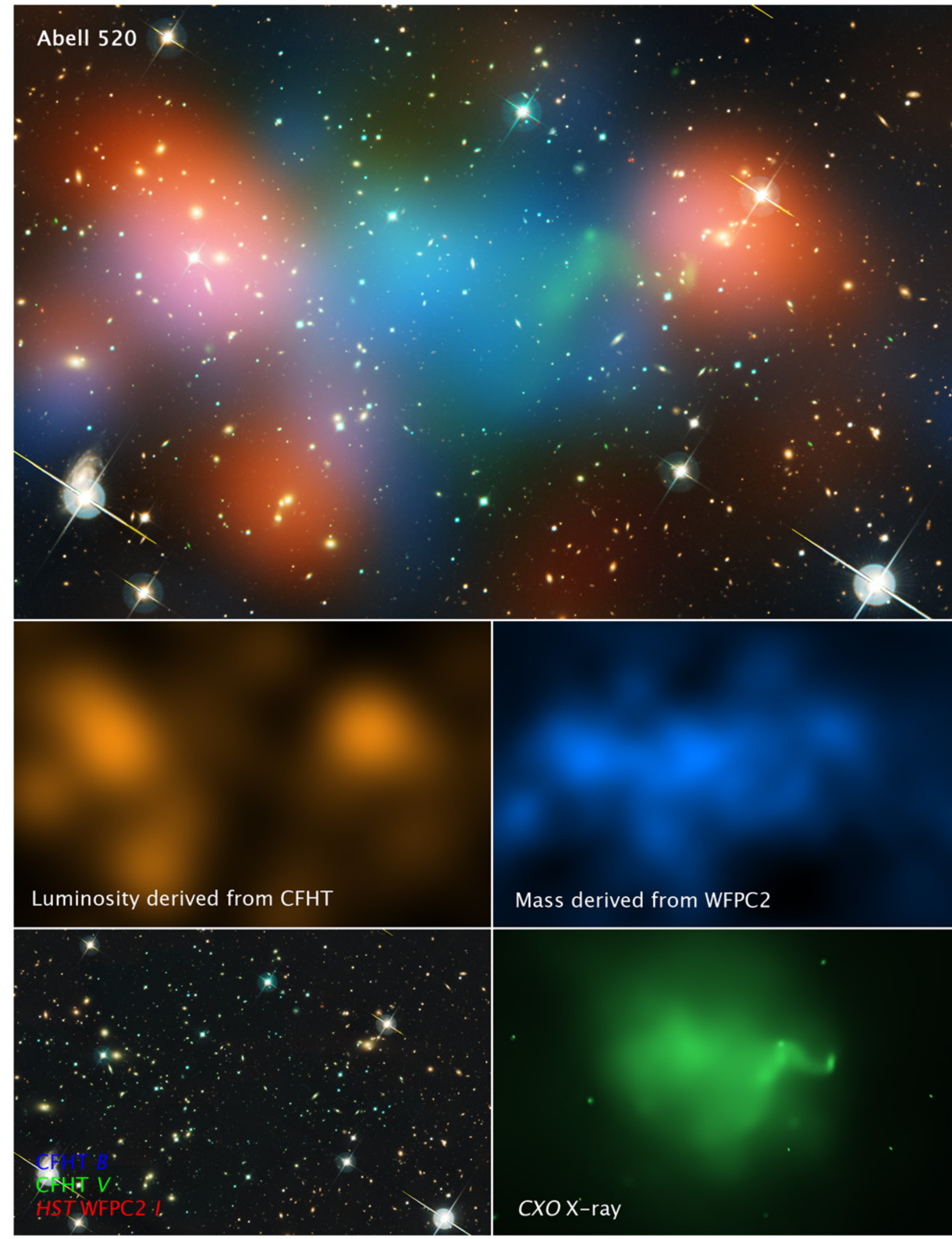
It is at a comoving radial distance of 1.141 Gpc (3.7 billion light-years, z=0.3) NASA/CXC/M. Weiss - Chandra X-Ray Observatory: 1E 0657-56




Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
Near Infrared ▪ Hubble
Visible ▪ Hubble
X-ray ▪ Chandra
Dark Matter Map
1.5 million light-years
460 kiloparsecs
70″
E
N

Abell 520, Train Wreck Cluster





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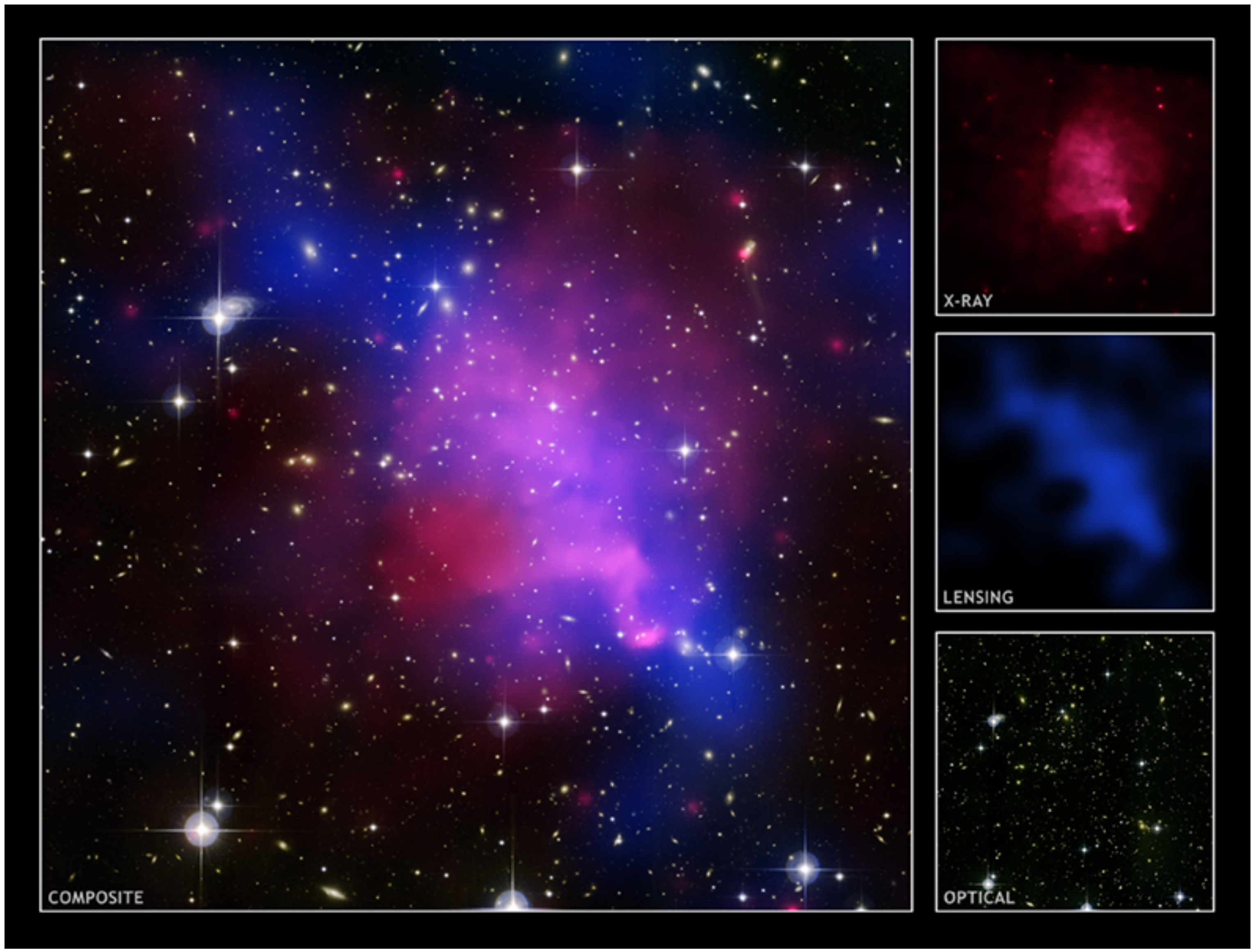

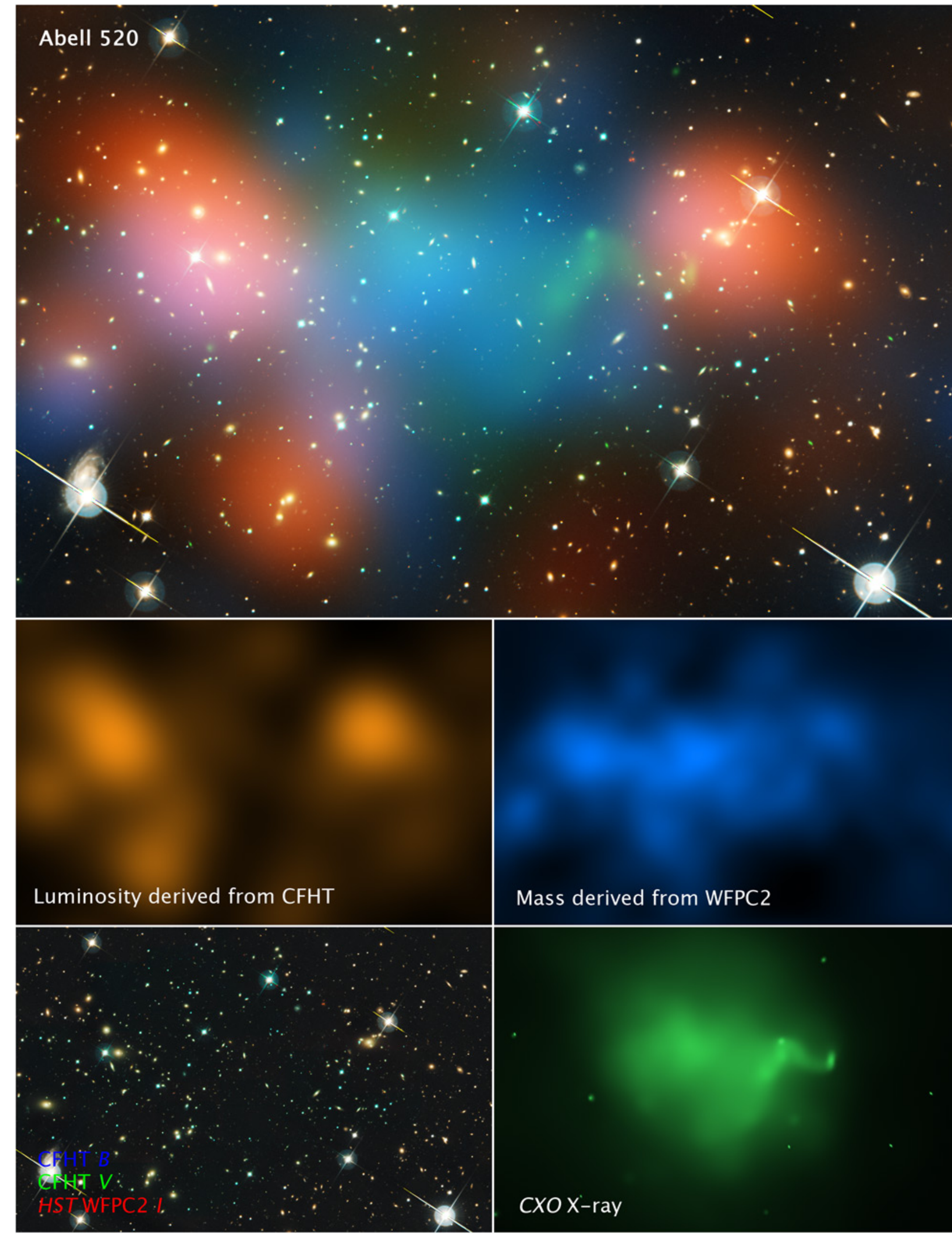

Dark Core?!

But is DM dust-like in Galaxies?

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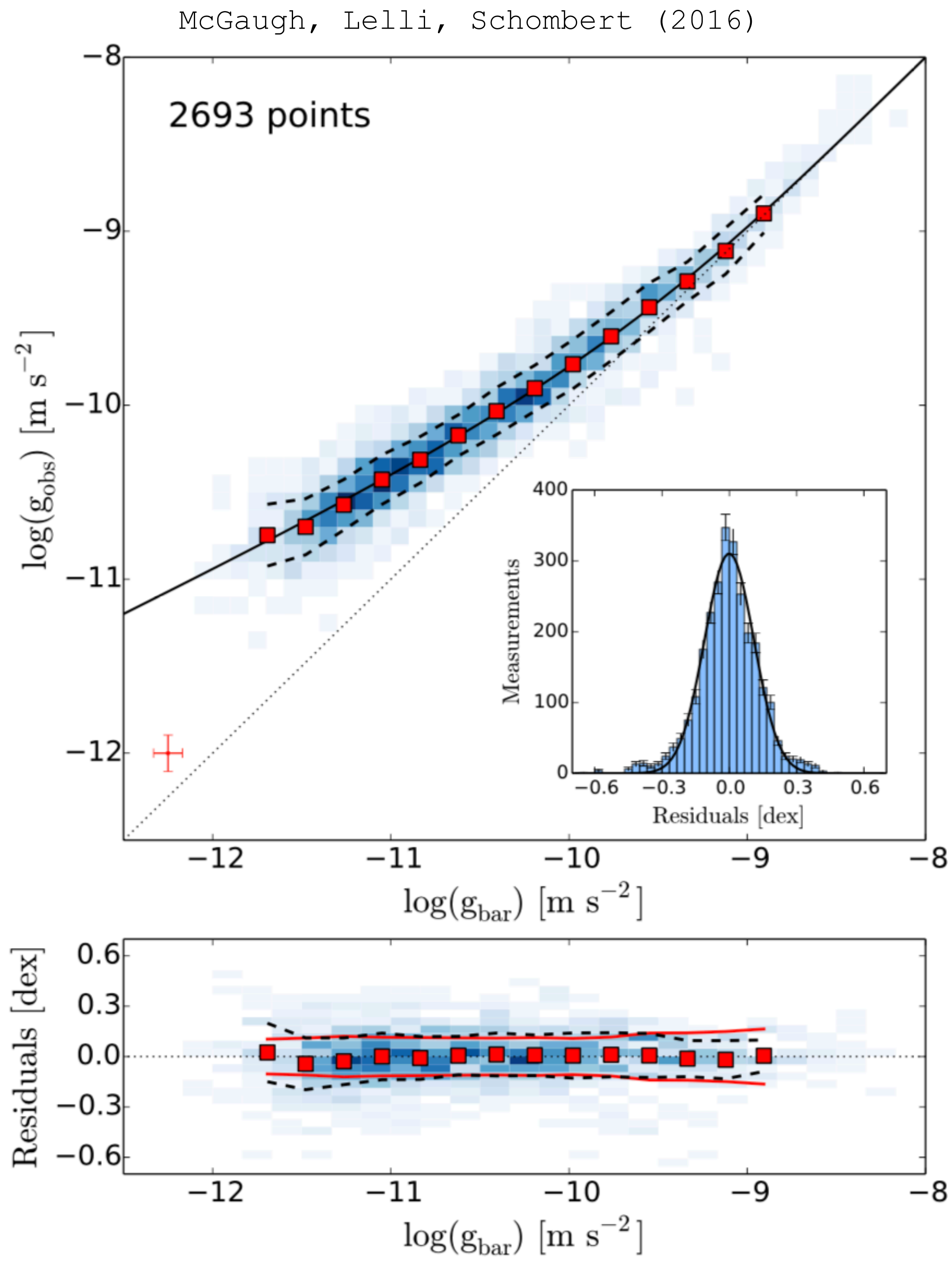
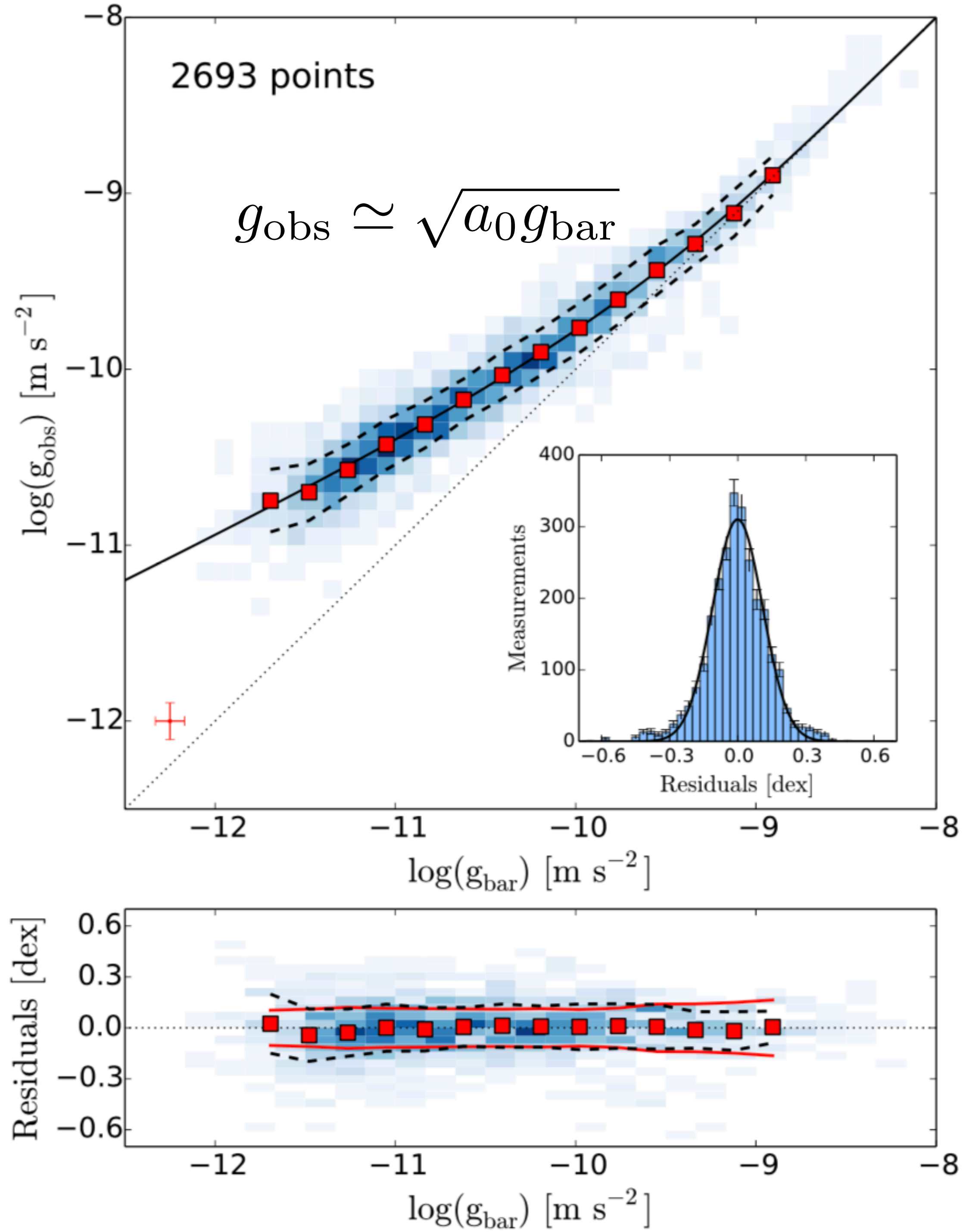


FIG. 3. The centripetal acceleration observed in rotation curves, $g_{obs} = V^2/R$, is plotted against that predicted for the observed distribution of baryons, $g_{bar} = |\partial\Phi_{bar}/\partial R|$ in the upper panel. Nearly 2700 individual data points for 153 SPARC galaxies are shown in grayscale.

But is DM dust-like in Galaxies?

McGaugh, Lelli, Schombert (2016)



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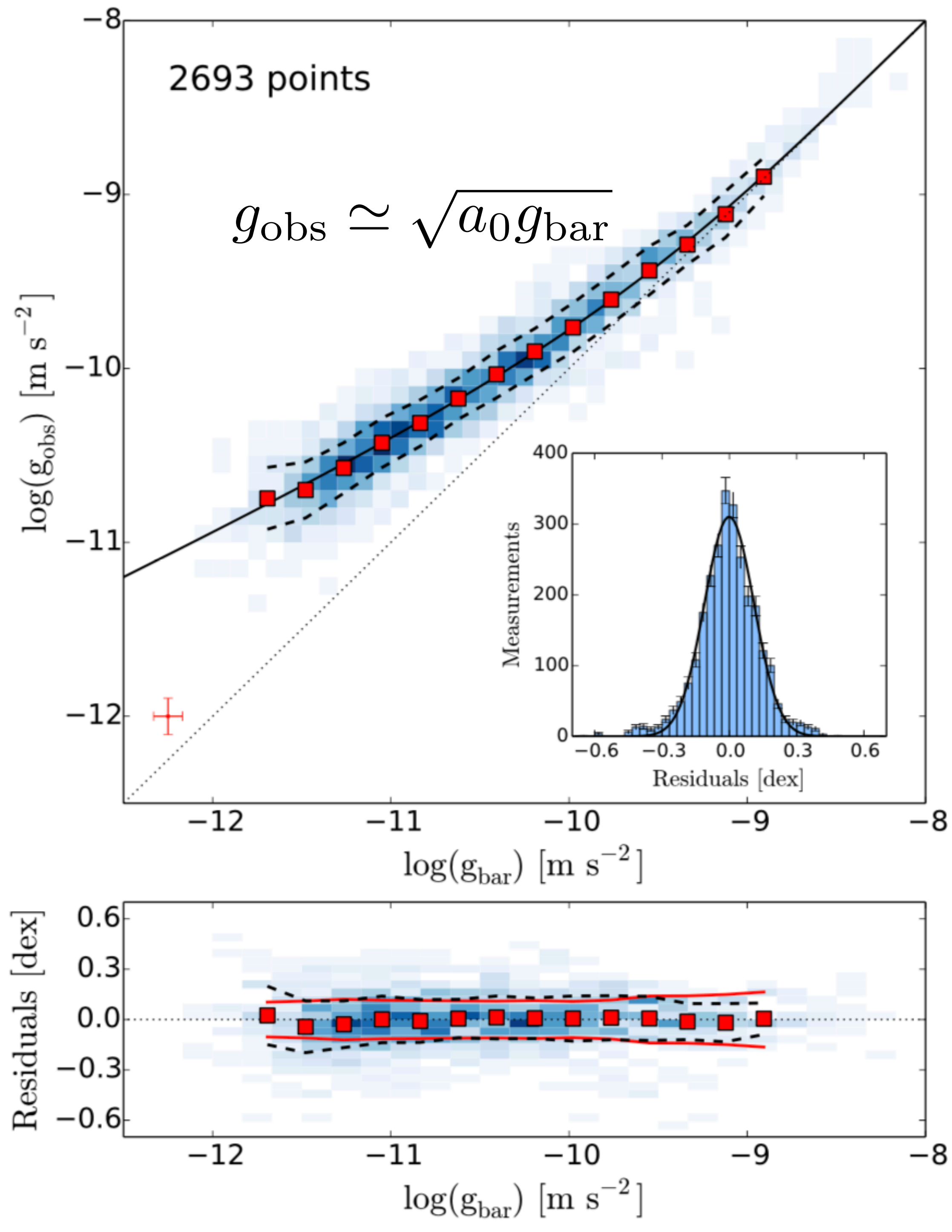

$$a_0 \simeq \frac{1}{6} H_0 \simeq 1.2 \times 10^{-8}\ \mathrm{cm/s^2}$$

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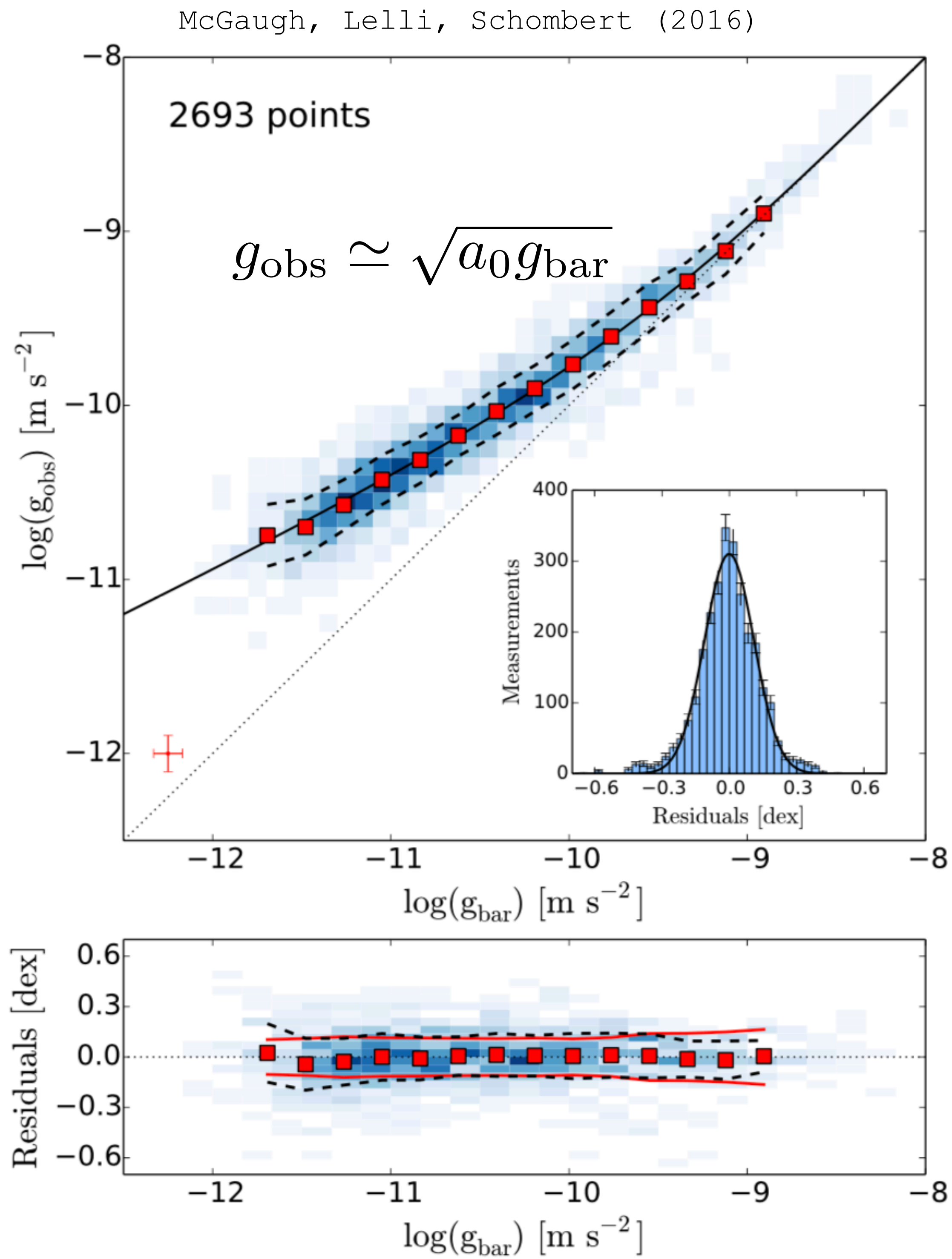

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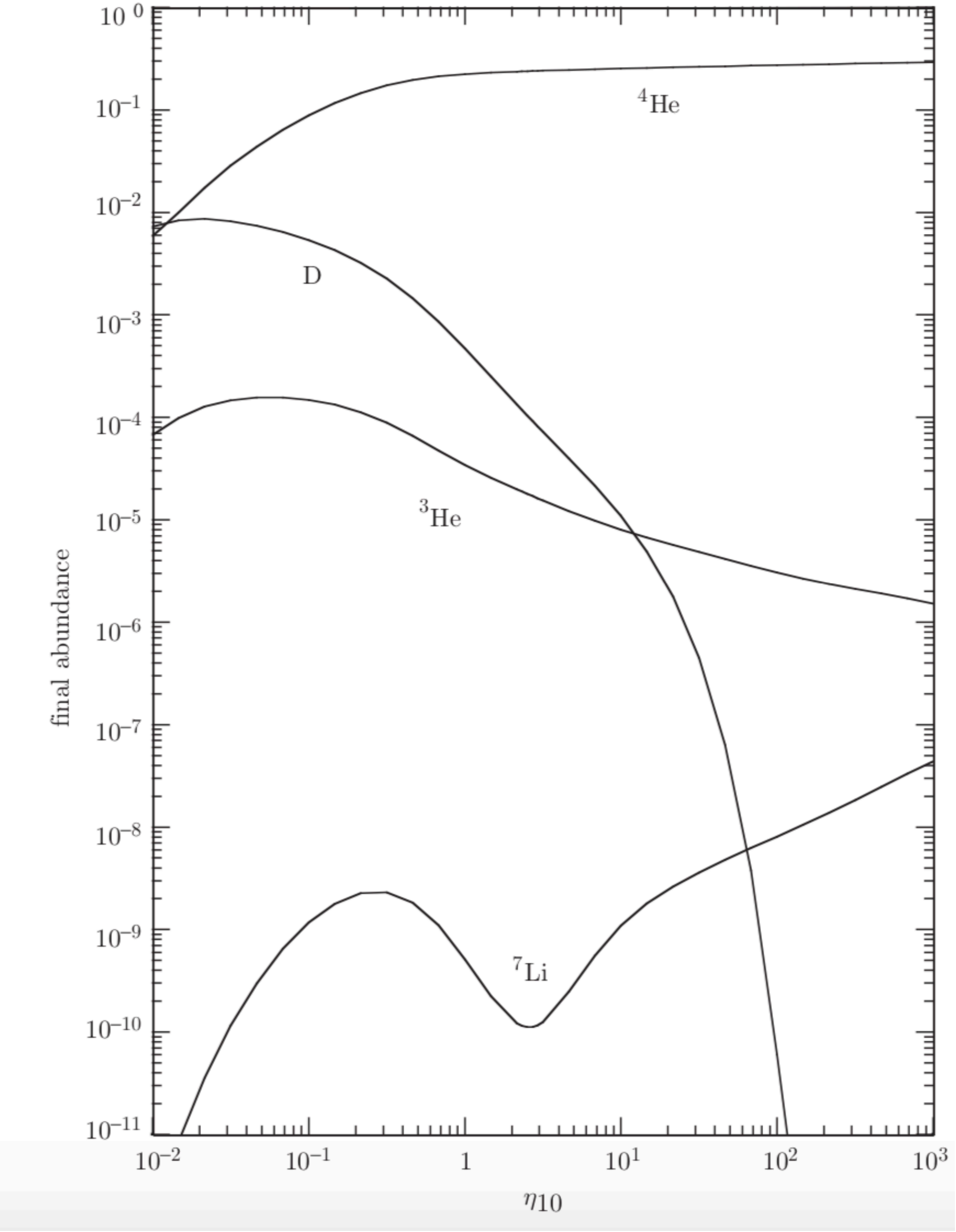
MOND, Milgrom, 1983

BBN



Mukhanov cosmology textbook

$$\eta_{10} \equiv 10^{10} \times \frac{n_N}{n_\gamma}$$

$$\Omega_b h_{75}^2 \simeq 6.53 \times 10^{-3} \eta_{10}$$

For $\eta_{10} > 10$

$$X_D^f \propto \exp\left(-0.1\eta_{10}\right)$$

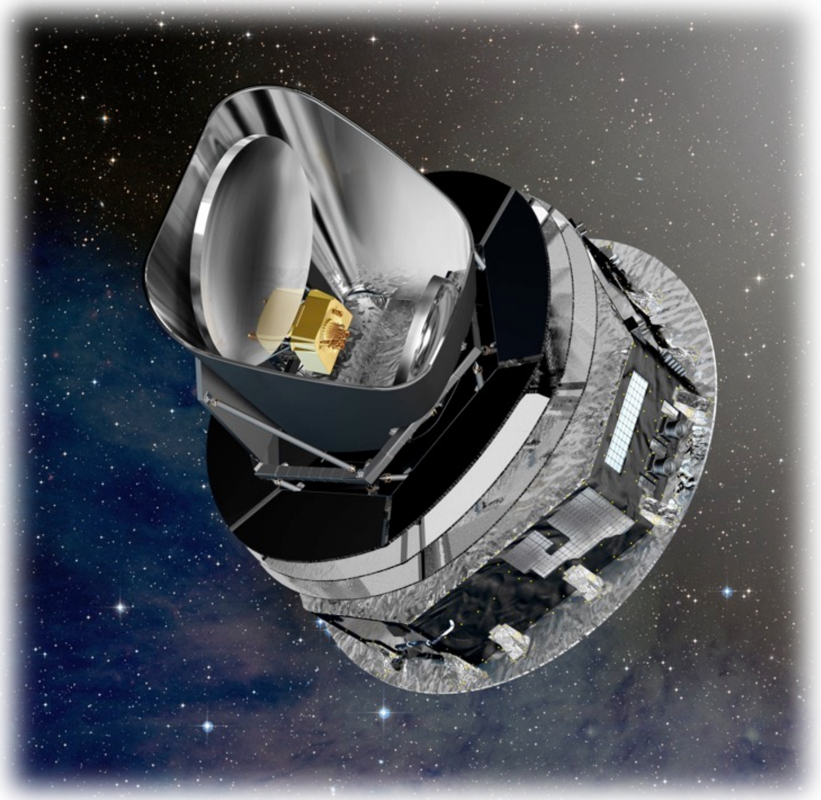
For $\eta_{10} \lesssim 10$

$$X_D^f \simeq 4 \times 10^{-4} \eta_{10}^{-1}$$

observations: $3 < \eta_{10} < 7$

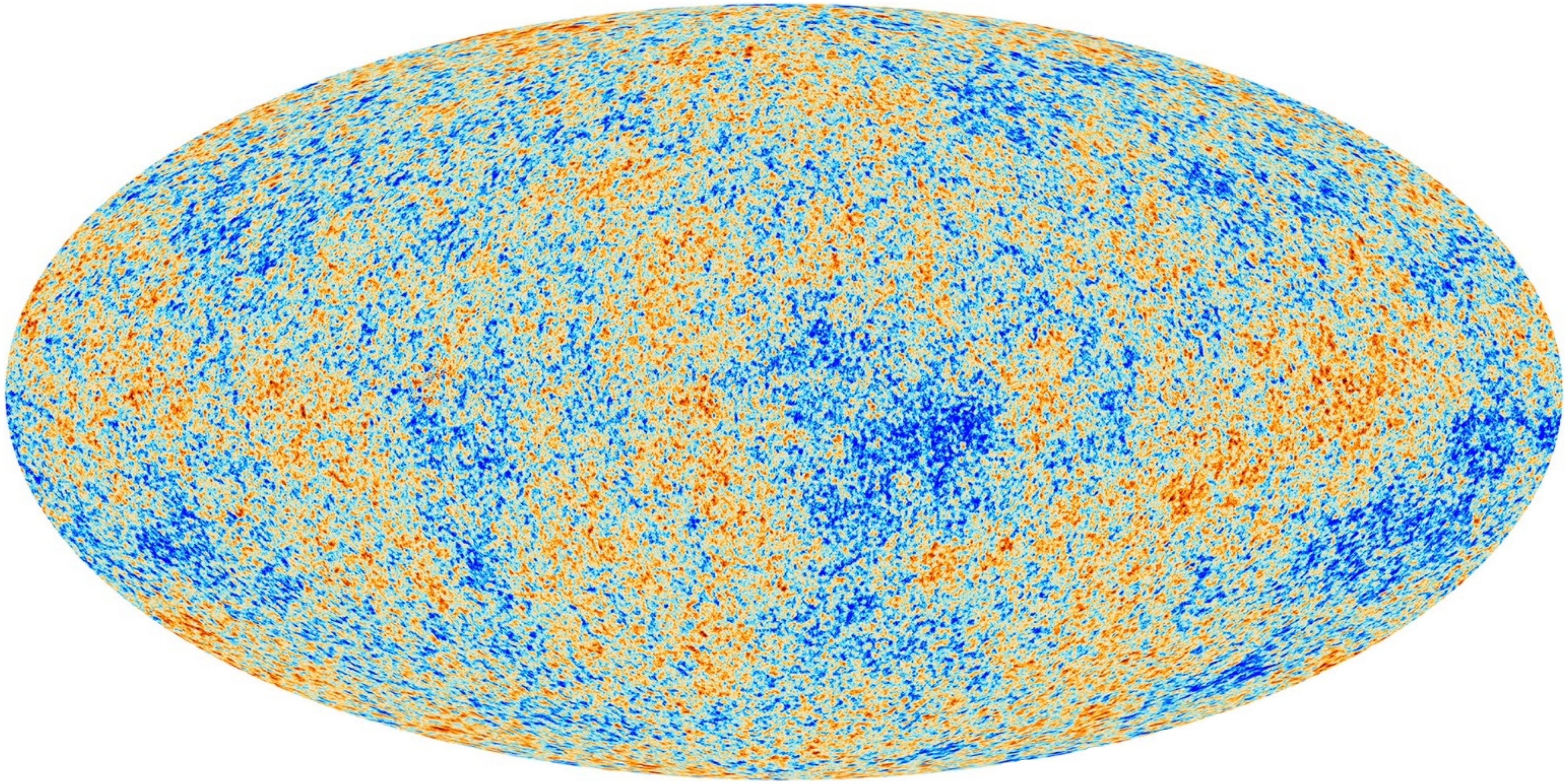
Dark Matter in Cosmology, CMB

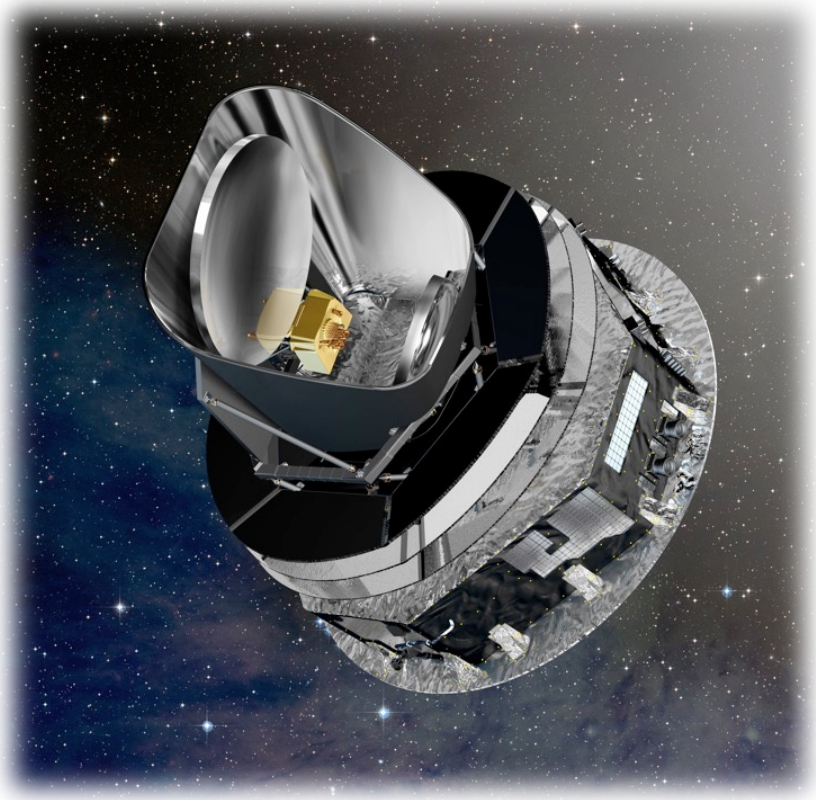
Dark Matter in Cosmology, CMB



PLANCK 2013

Dark Matter in Cosmology, CMB





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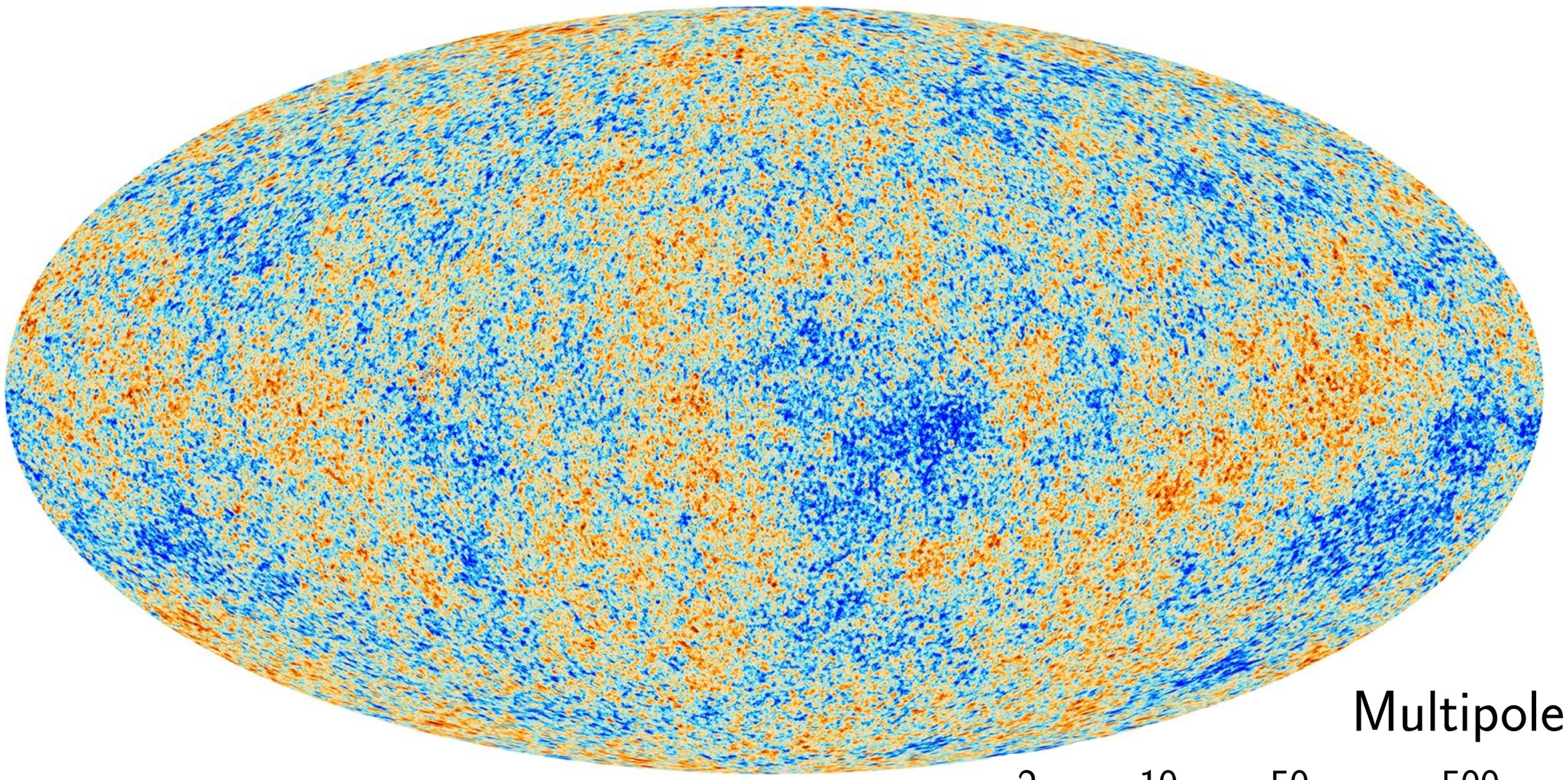

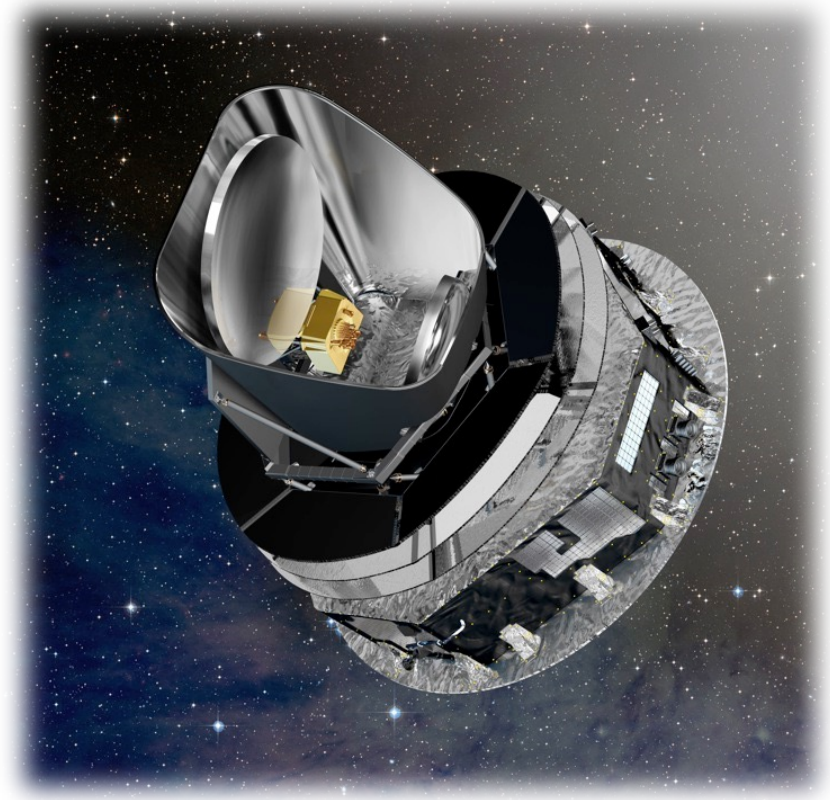

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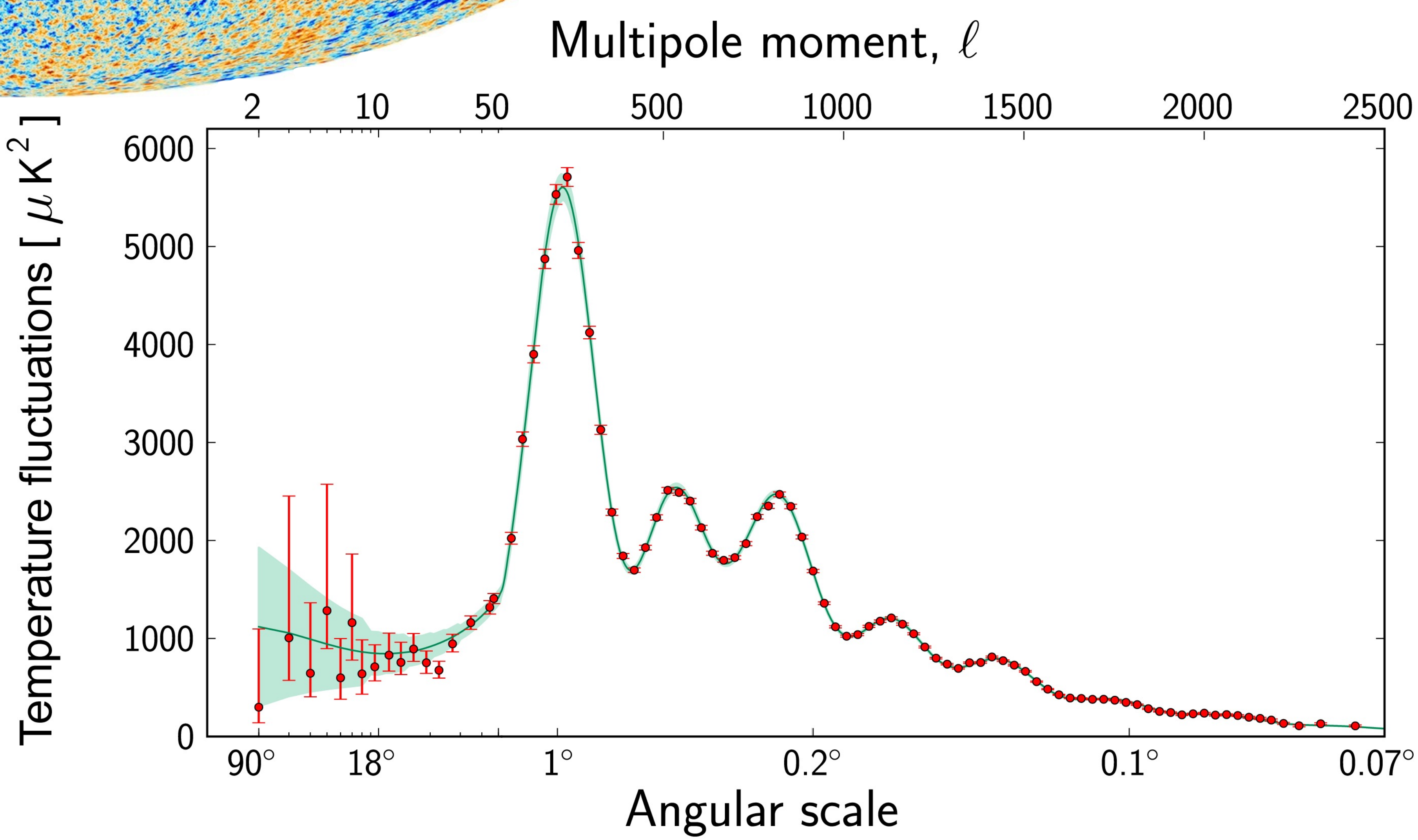


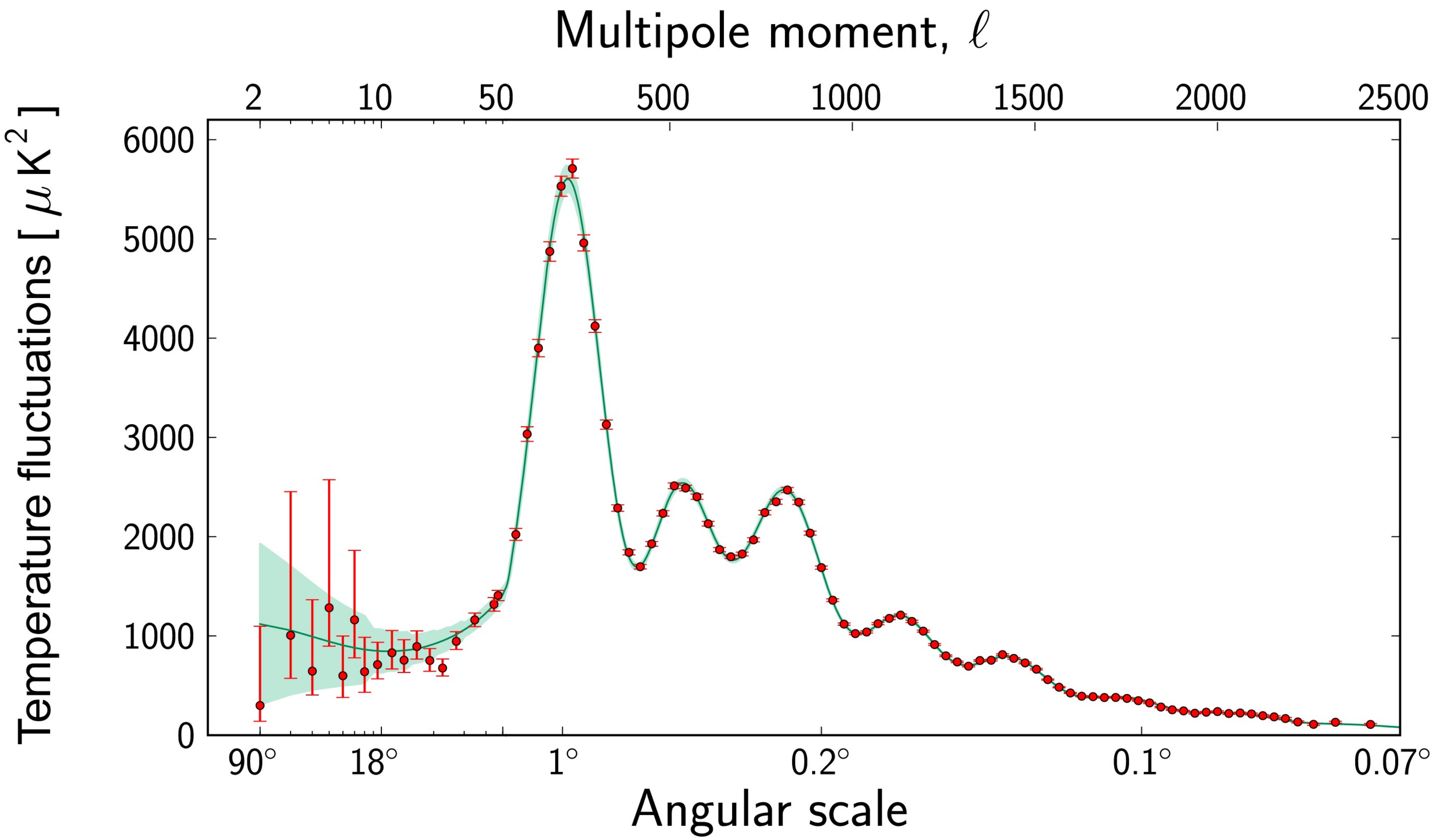
Positions of the peaks $l_n \simeq \pi \varrho^{-1} \left(n - \frac{1}{8} \right)$

$$\varrho \simeq 0.014 \left(1 + 0.13\xi\right)^{-1} \left(\Omega_m h_{75}^{3.1}\right)^{0.16}$$

$$\xi = \frac{1}{3c_s^2} - 1 \simeq 17 \left(\Omega_b h_{75}^2\right)$$

…the height of the first peak together with the existence of the second peak are in themselves convincing evidence of the following key qualitative features of our universe: that the total cold matter density is less than the critical density, that cold dark matter exists and that its density exceeds the baryon density.

Mukhanov cosmology textbook



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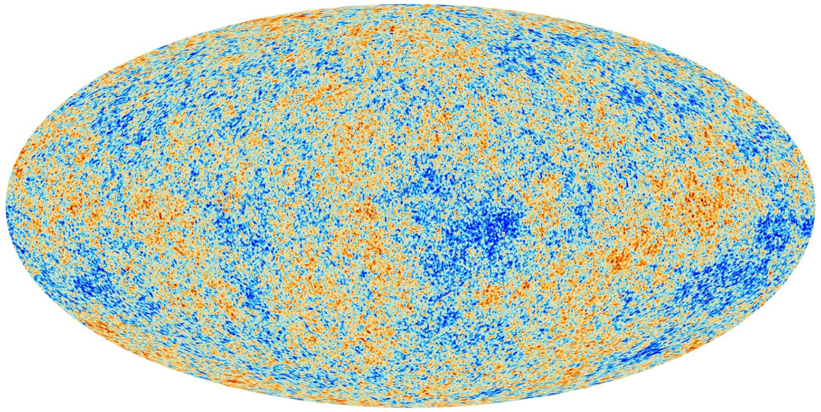
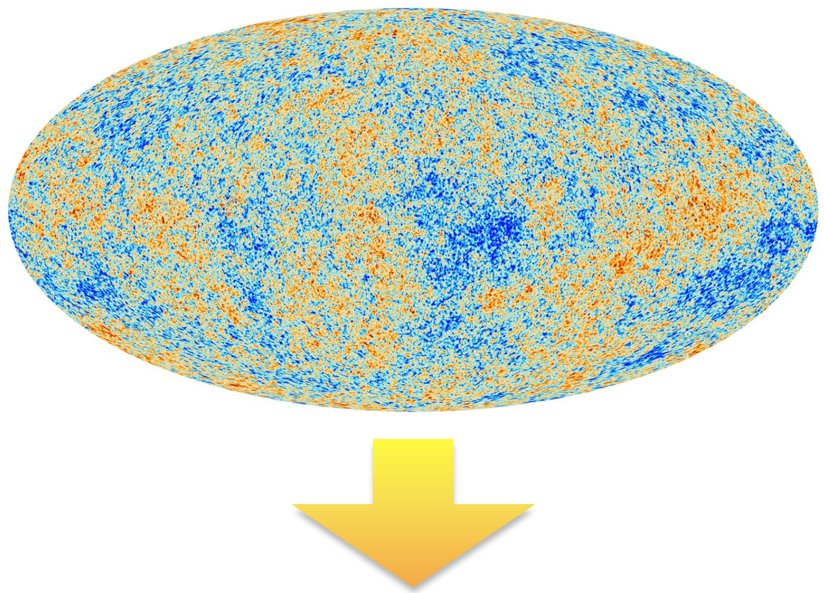
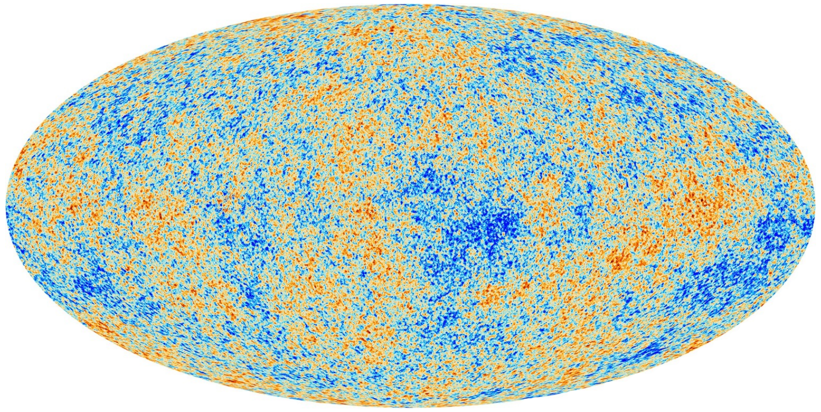


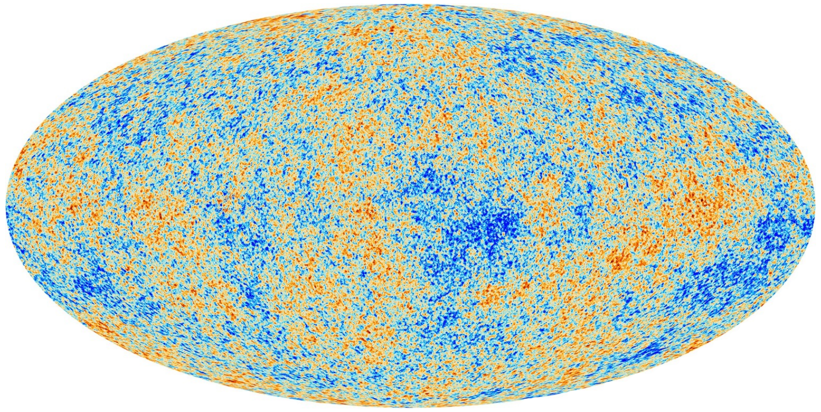


$$T_{\mu\nu}^{\mathrm{DM}} = (\rho + p)\, u_\mu u_\nu - p g_{\mu\nu}$$



$$T_{\mu\nu}^{\rm DM} = (\rho + p)\, u_\mu u_\nu - p g_{\mu\nu}$$

$$w_{\rm DM} = p/\rho$$



$$T_{\mu\nu}^{\rm DM} = (\rho + p)\, u_\mu u_\nu - p g_{\mu\nu}$$

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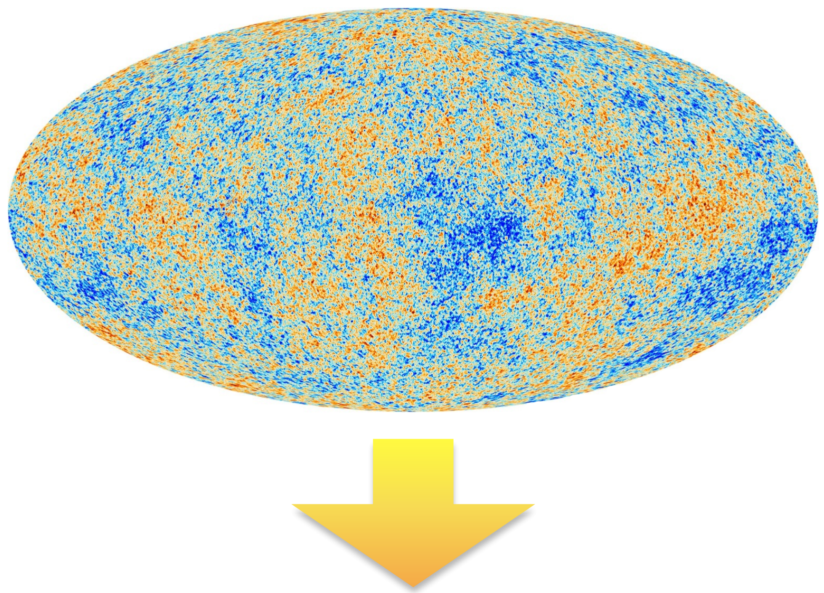
$$-0.000896 < w_{\rm DM} < 0.00238$$

Kopp, Skordis,Thomas,(2016)



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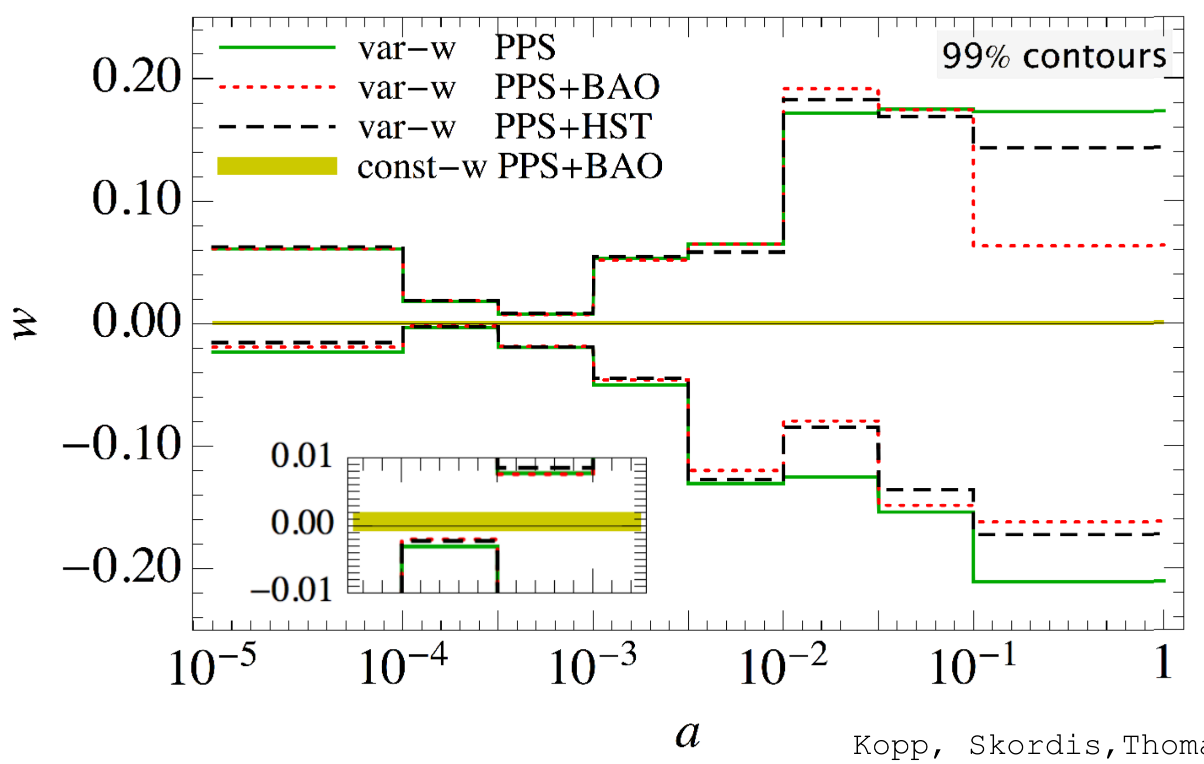
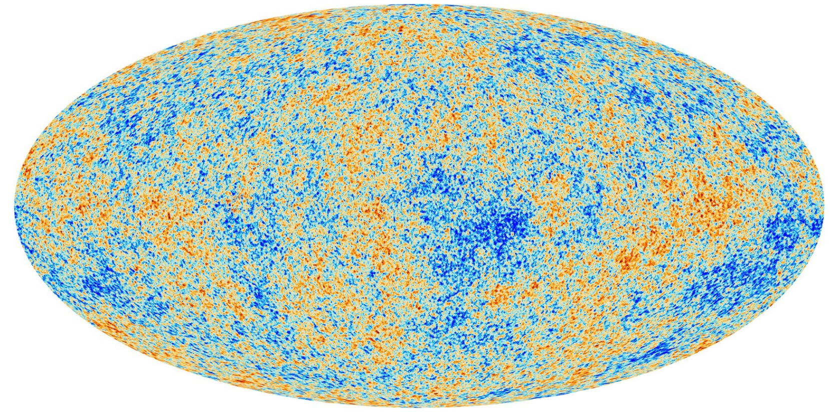
Kopp, Skordis, Thomas, (2016)



Kopp, Skordis, Thomas, Ilic (2018)

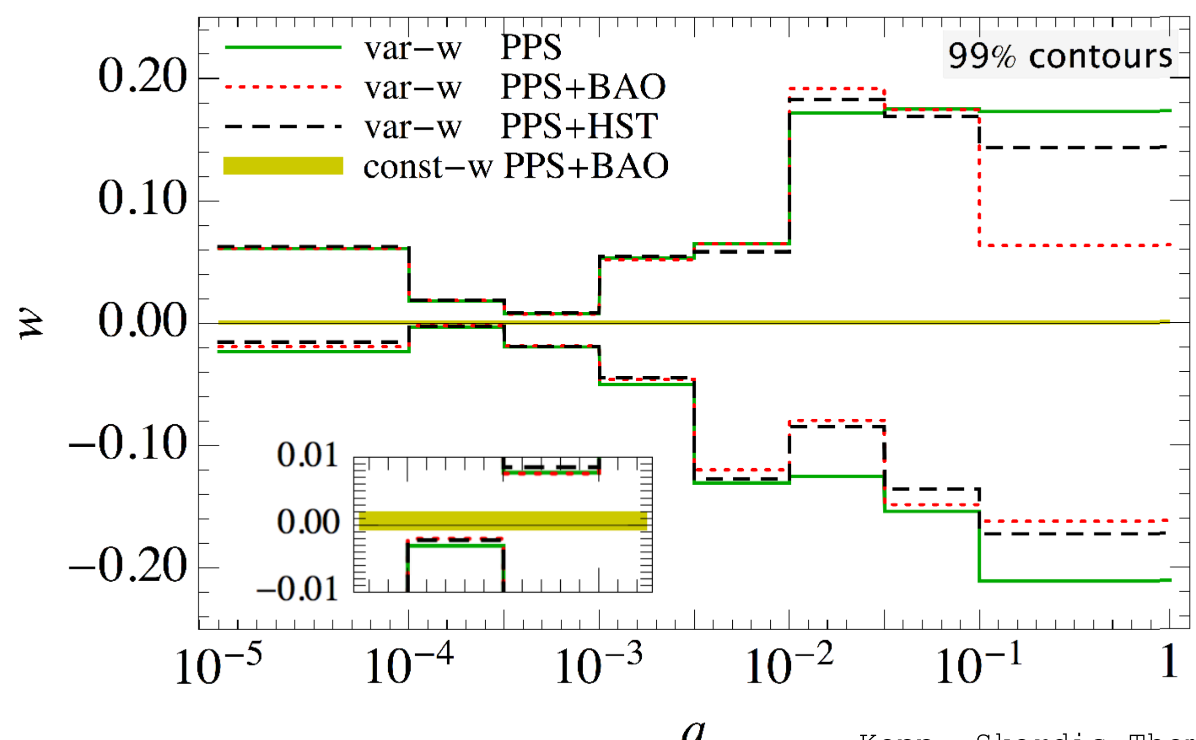


$$T_{\mu\nu}^{\rm DM} = (\rho + p)\, u_\mu u_\nu - p g_{\mu\nu} \quad \Rightarrow \quad T_{\mu\nu}^{\rm DM} \simeq \rho u_\mu u_\nu$$

$$w_{\rm DM} = p/\rho$$

$$-0.000896 < w_{\rm DM} < 0.00238$$

Kopp, Skordis,Thomas,(2016)



Kopp, Skordis,Thomas,Ilic (2018)