Dark Matter

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I. Dark Matter evidences & properties

II. Dark Matter production & candidates

III. Dark Matter in the MW & detection

Bibliography

+ D. Blas notes

An Introduction:

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Some lectures:

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I. Dark Matter evidences & properties

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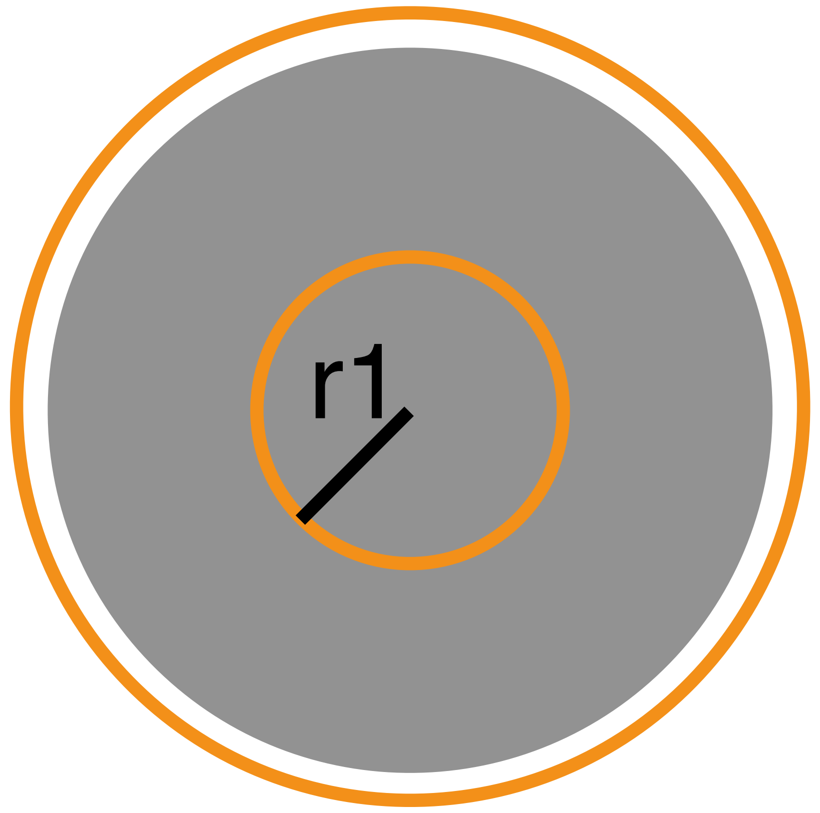
I. Dark Matter evidences

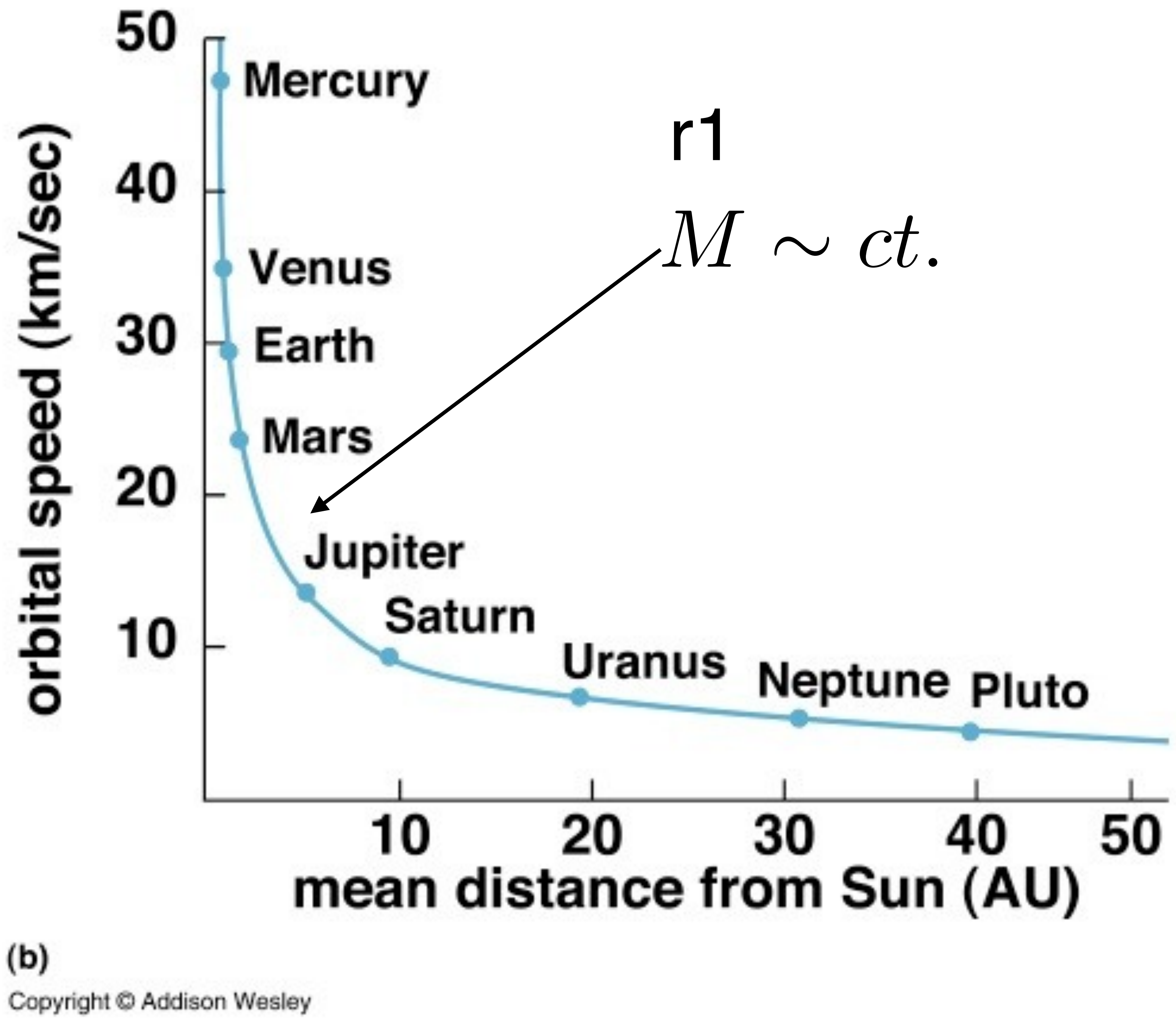
1. Galactic rotation curves

Vera Rubin 1970s

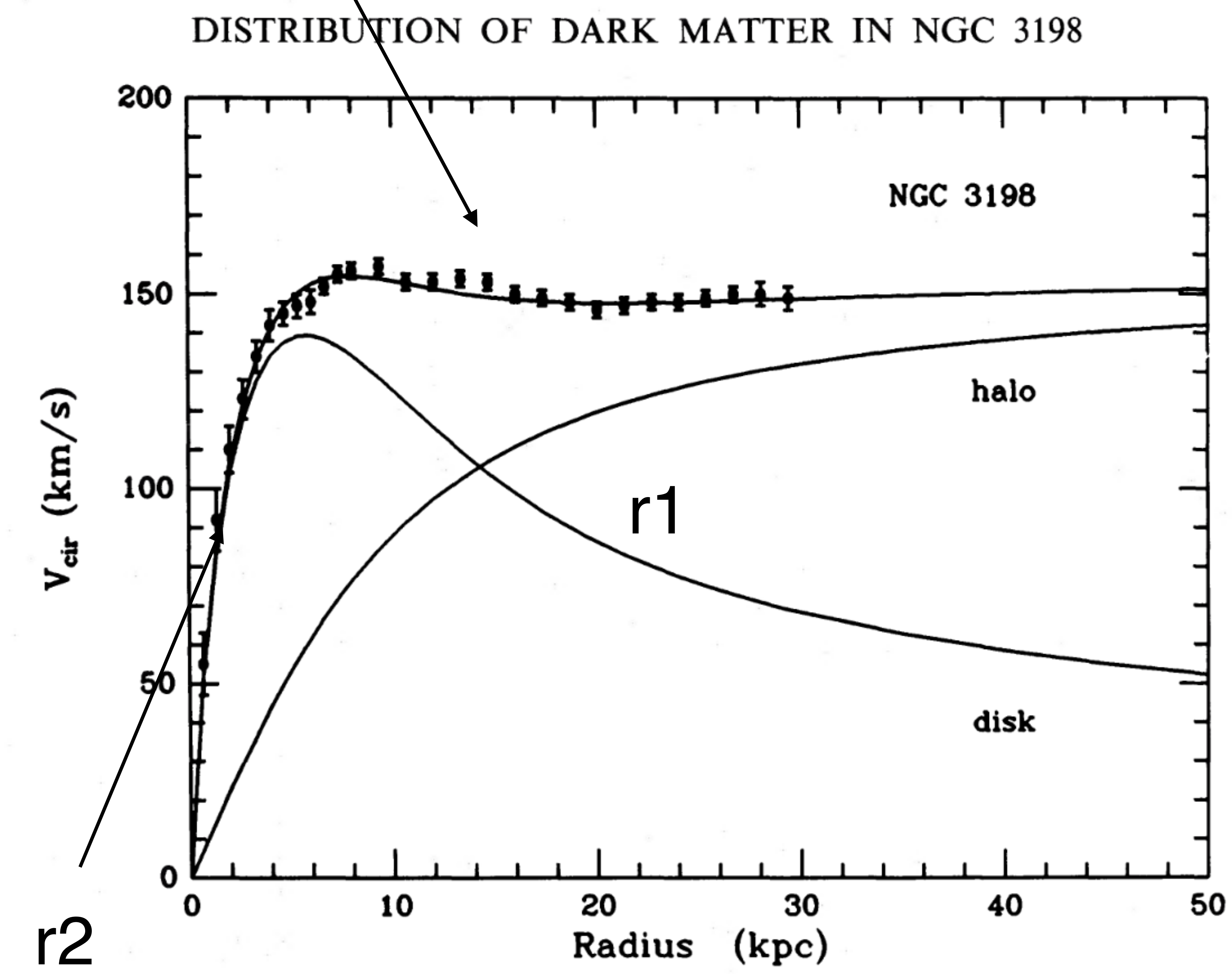
the circular gravitational orbits in a spherical configuration satisfy



$$v^2(r) = \frac{GM(r)}{r}$$

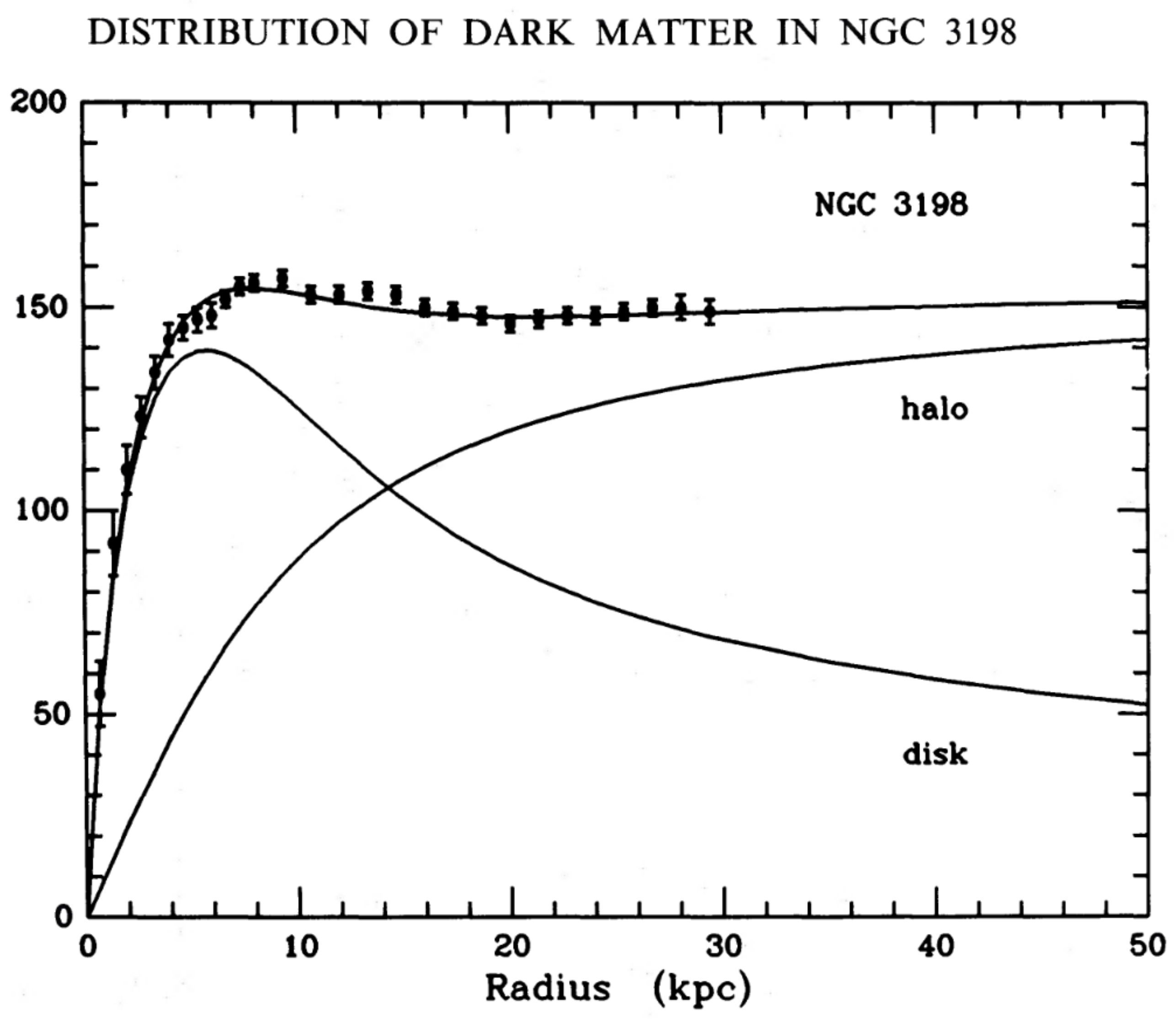


$v \sim ct.$ $M(r) \sim r$



$1\text{pc} \approx 3$ light years

$\rho \sim ct. \rightarrow M(r) \sim \rho r^3 \sim ct. r^3$ $v \sim r$



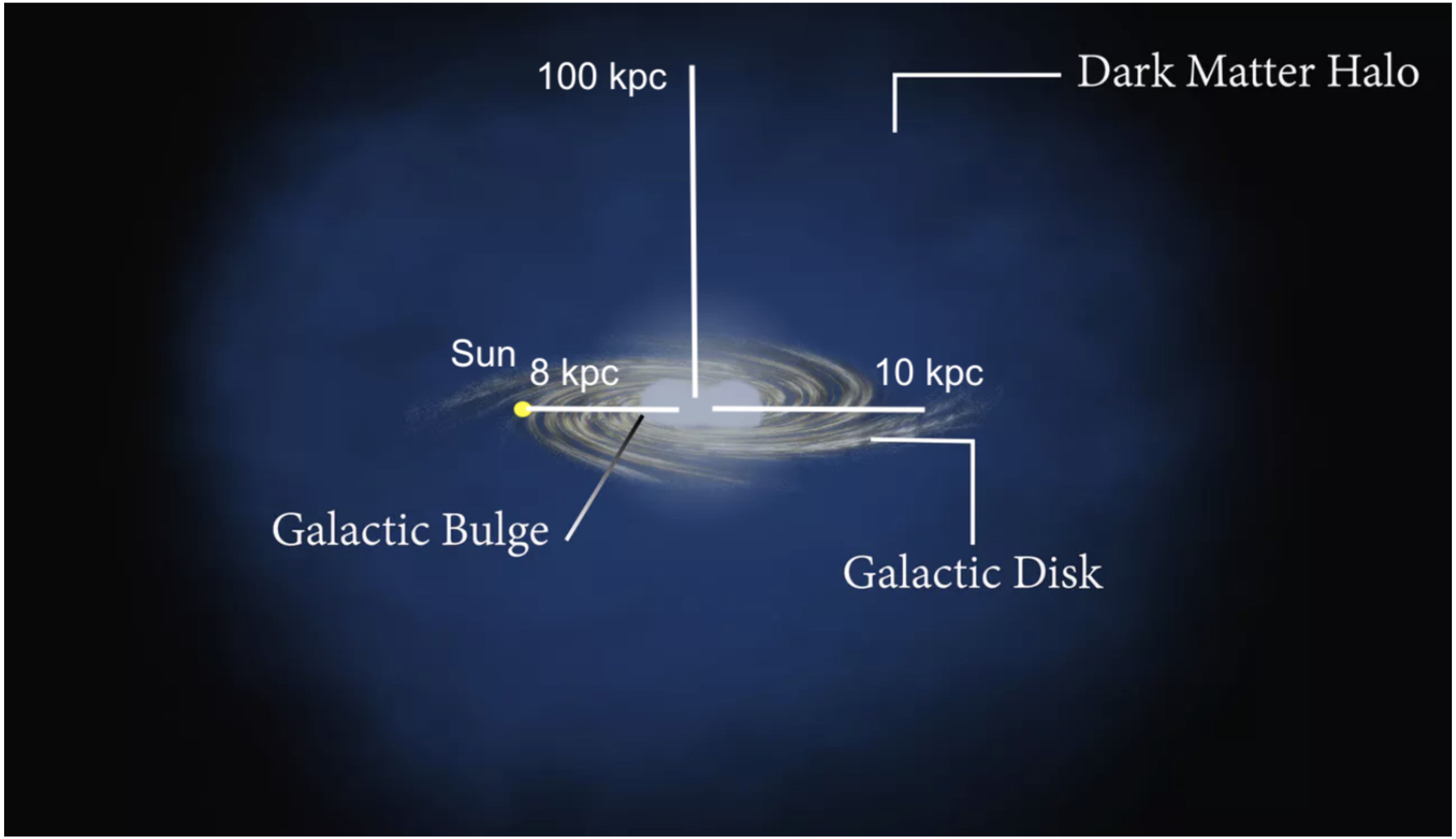
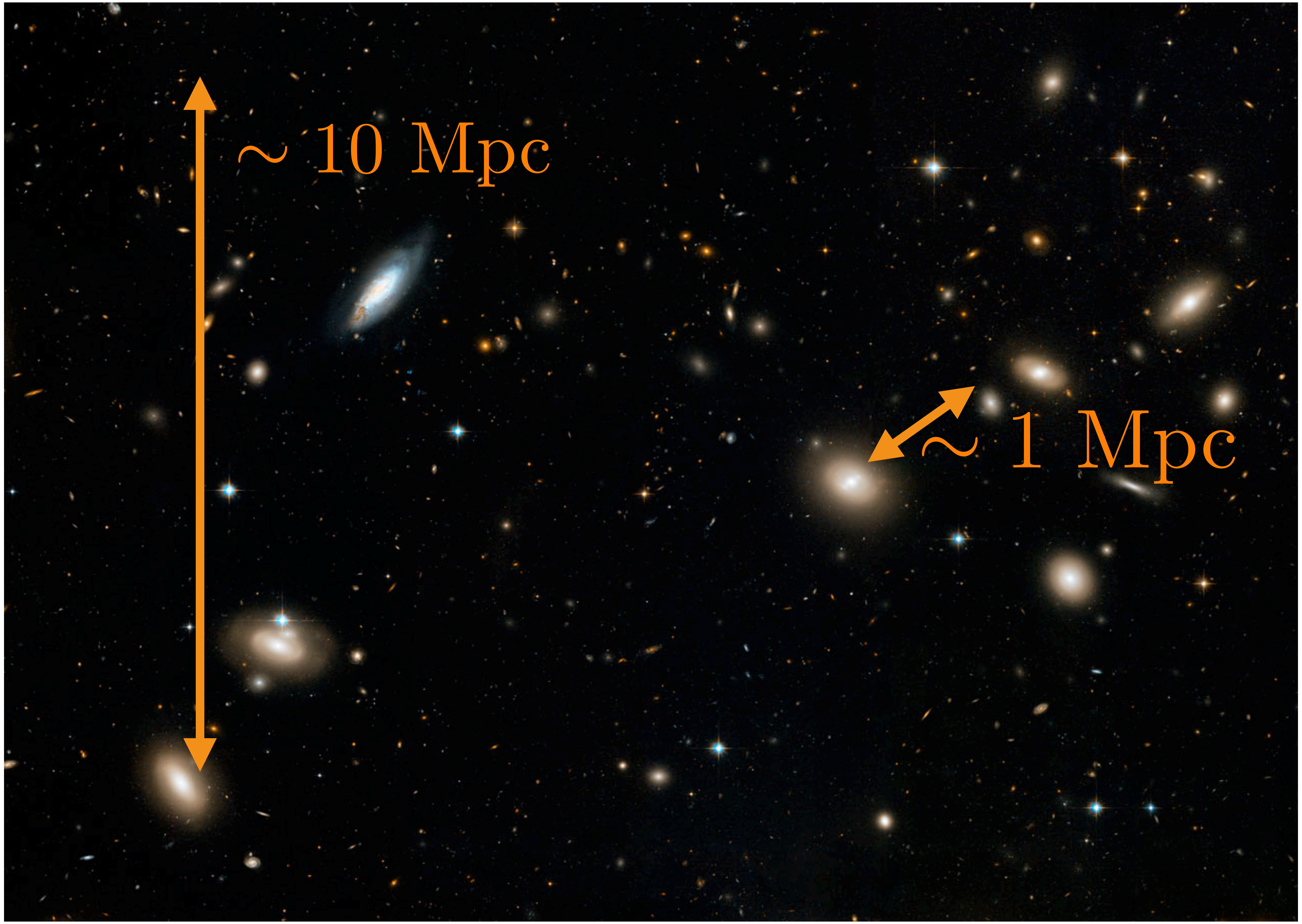


Figure 2: Structure of the Milky Way

I. Dark Matter evidences

2. Dynamics of galaxy clusters



1930s, Zwicky

Coma cluster from HST

Virial theorem: on average

$$2\langle E_K \rangle = -\langle E_V \rangle$$

↓

$$v^2 \sim \phi_N \sim G \sum M_i / r_i$$

Data

$$v^2 \gg \phi_N(\text{visible matter})$$

↓

More mass!

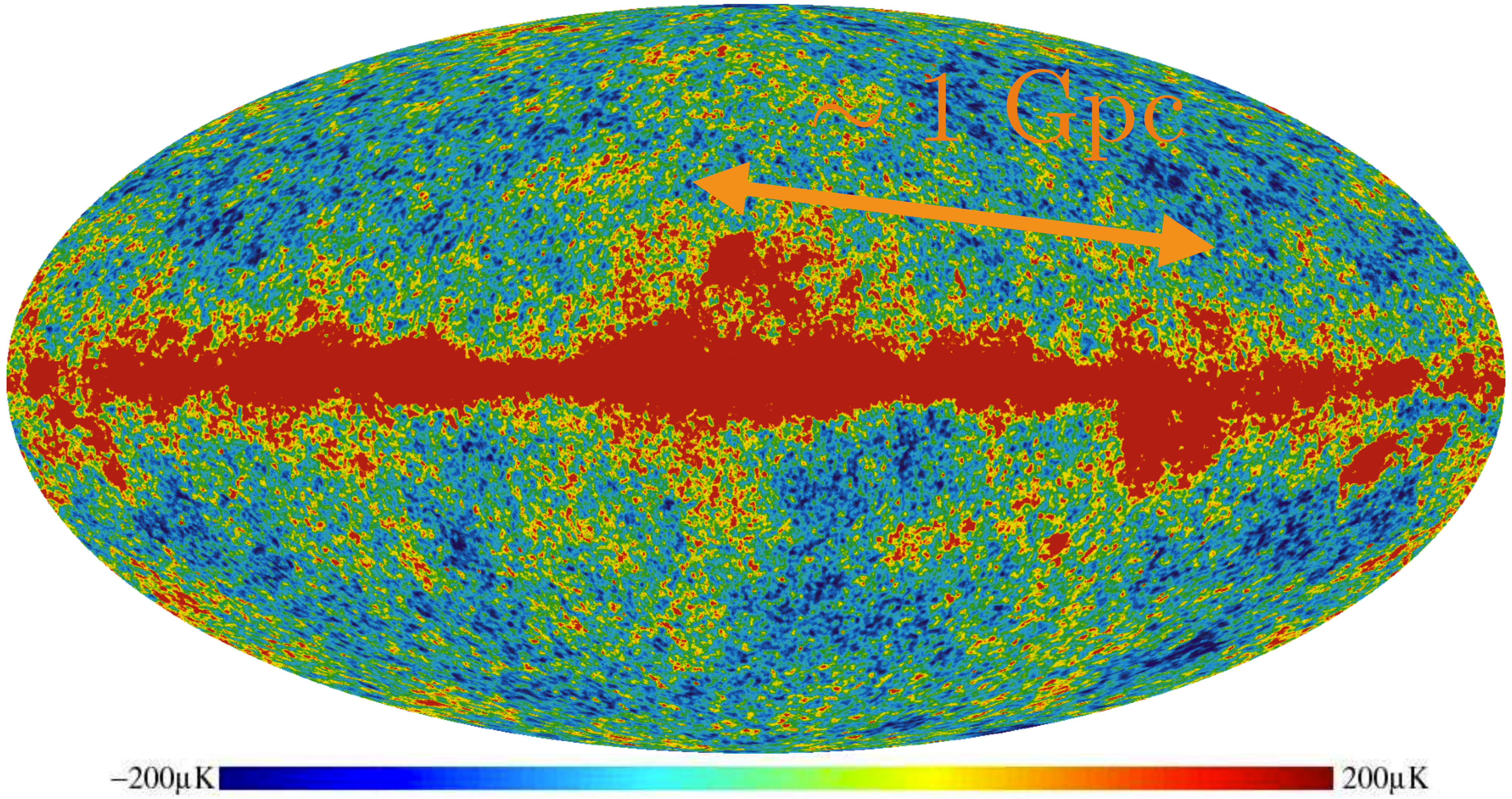
3. Collisions of galaxy clusters

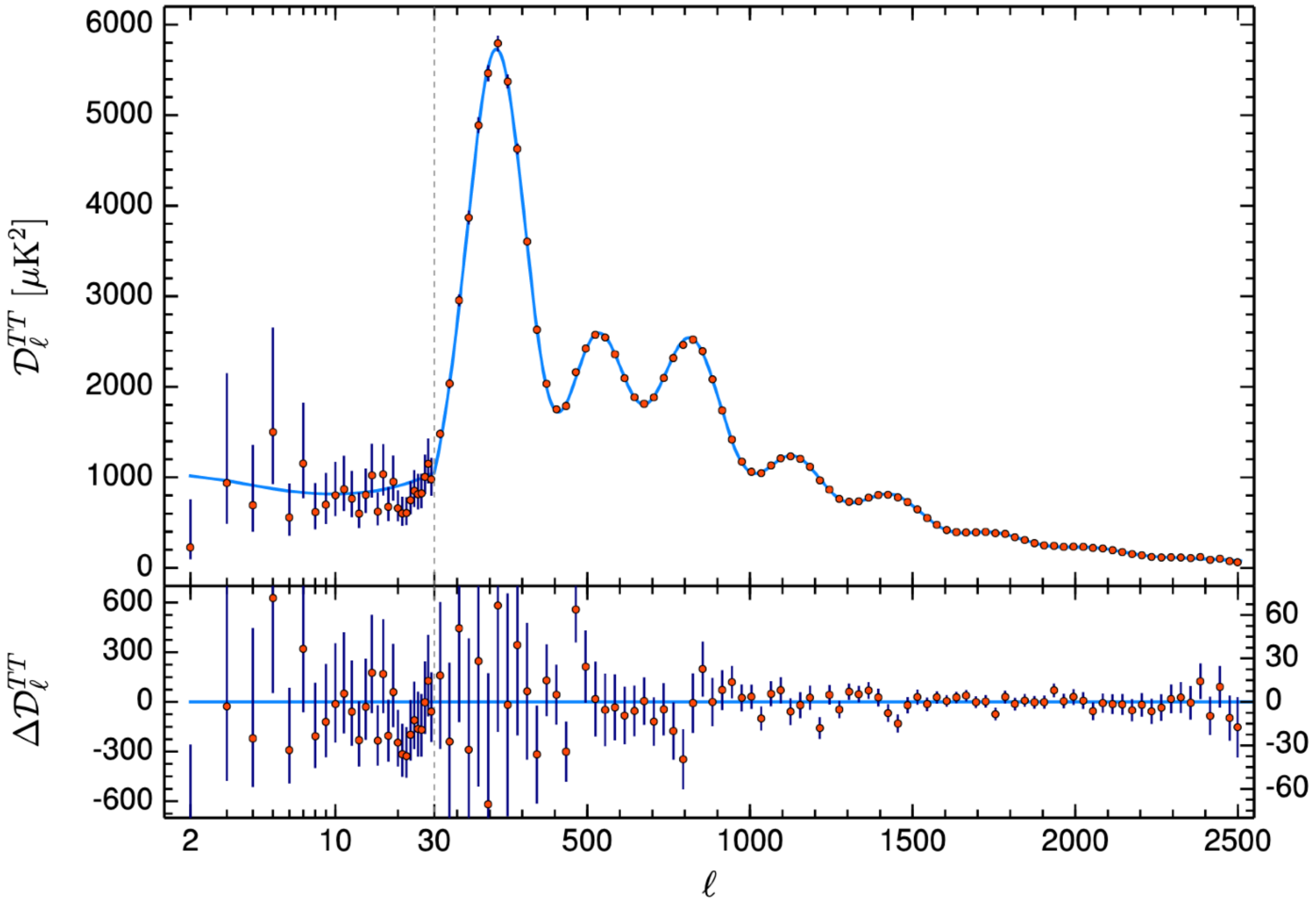
Bullet cluster

3. Collisions of galaxy clusters

Bullet cluster

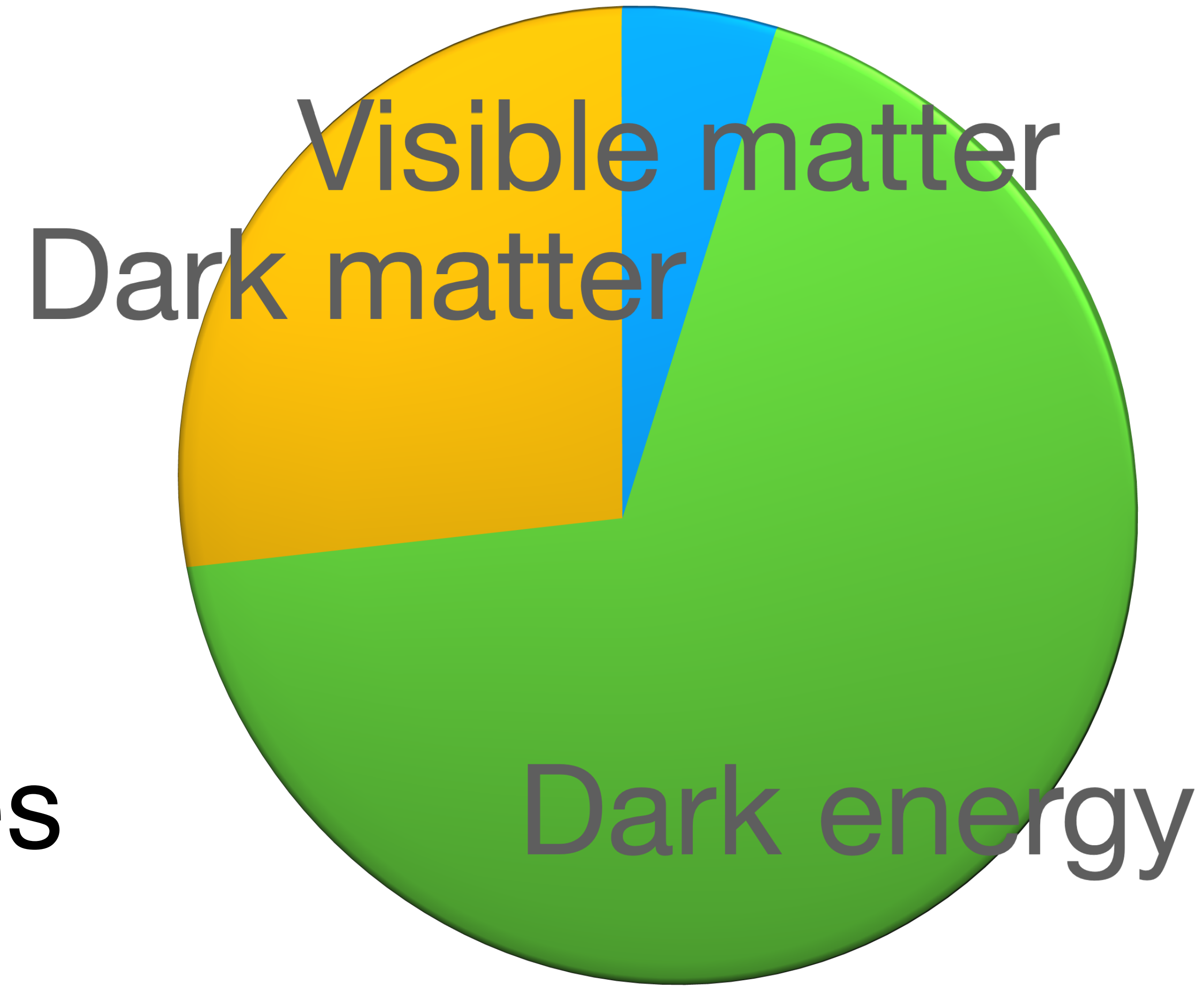
4. Cosmological probes





Angular size of temperature fluctuations

WMAP and Planck satellites



I. Dark Matter evidences

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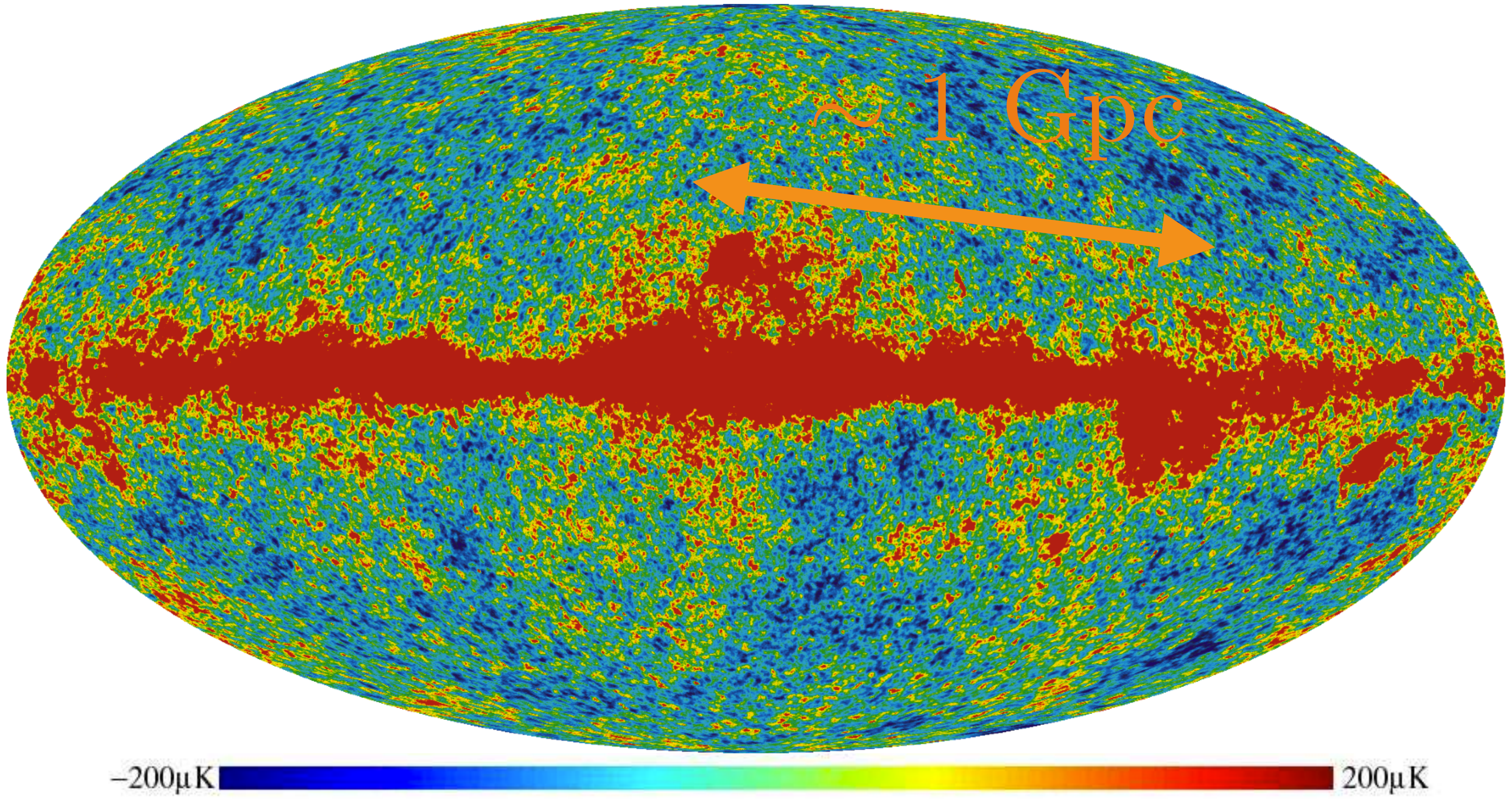

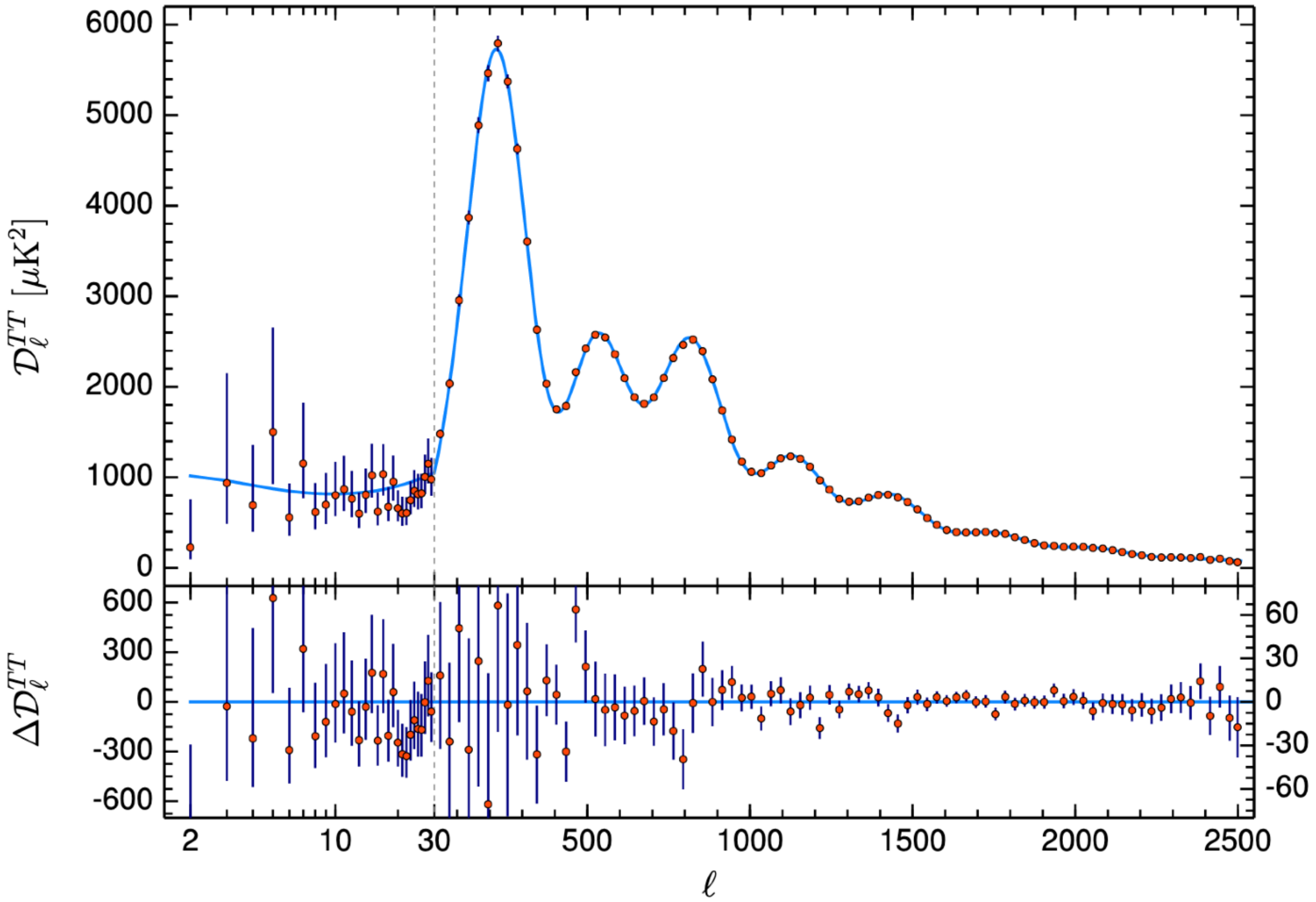

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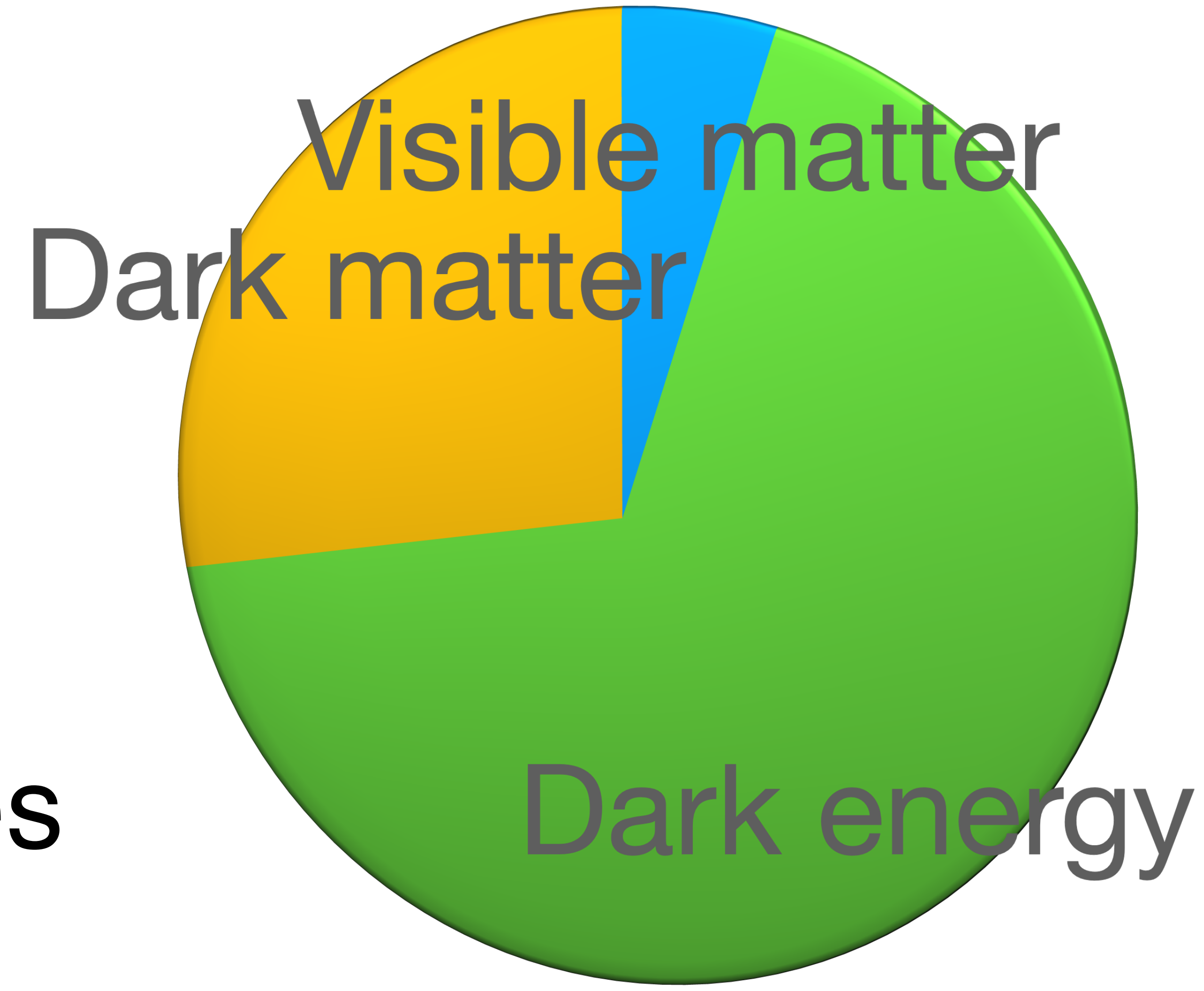
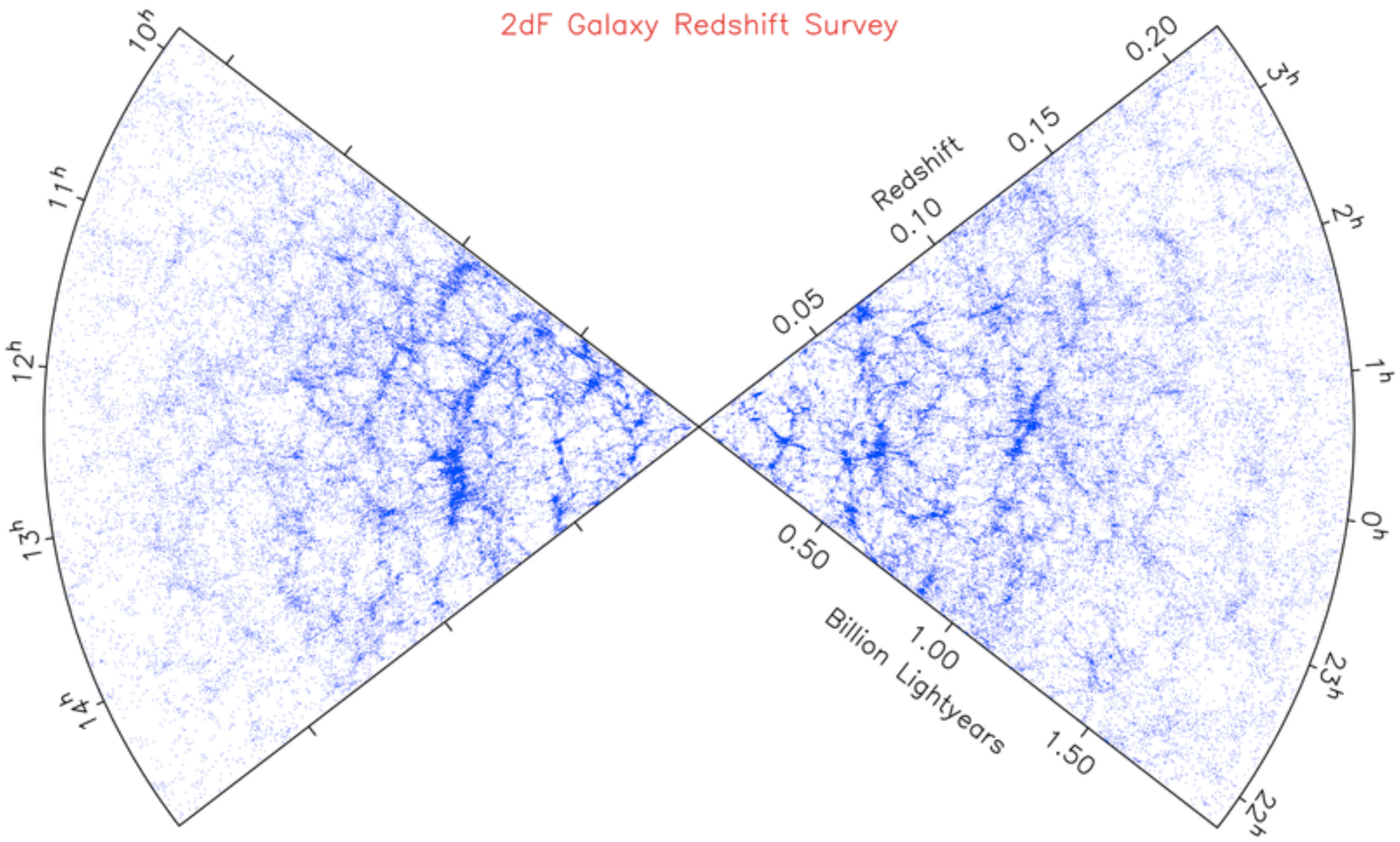


WMAP and Planck satellites

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

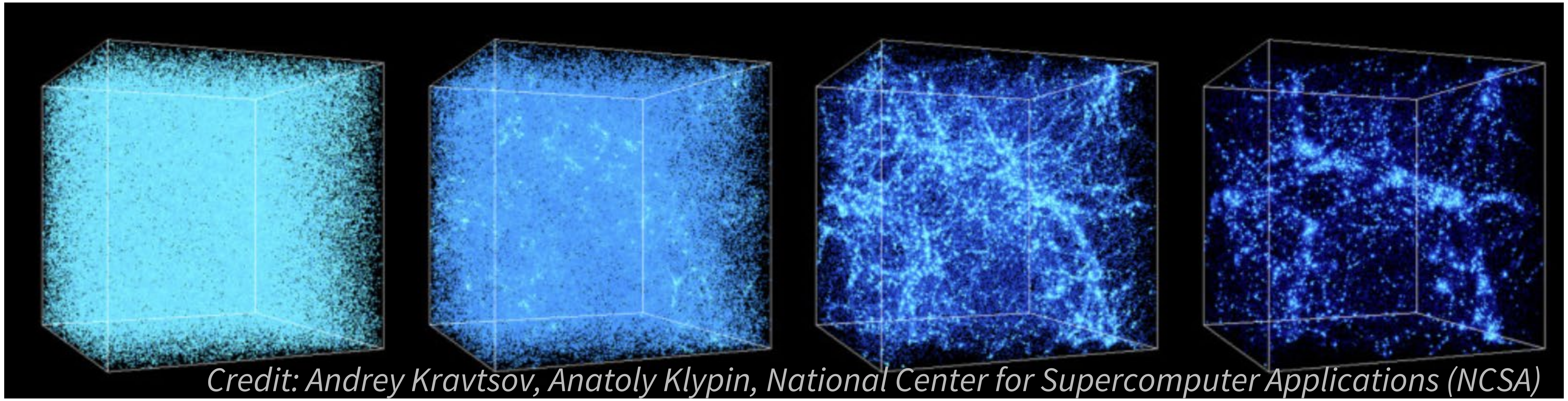


N-body simulations

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.

I. Dark Matter properties

1. Darkness

Small iterations with SM particles

e.g. charge $$q_{DM} \lesssim 10^{-4} \left(\frac{m_{DM}}{\mathrm{TeV}}\right)^{1/2} .$$

2. Coldness

Small kinetic energy:

they need to accumulate in gravitational wells (e.g. galaxies)

$$T \sim E_K \sim mv^2$$

$$v^2 \sim \phi_N$$

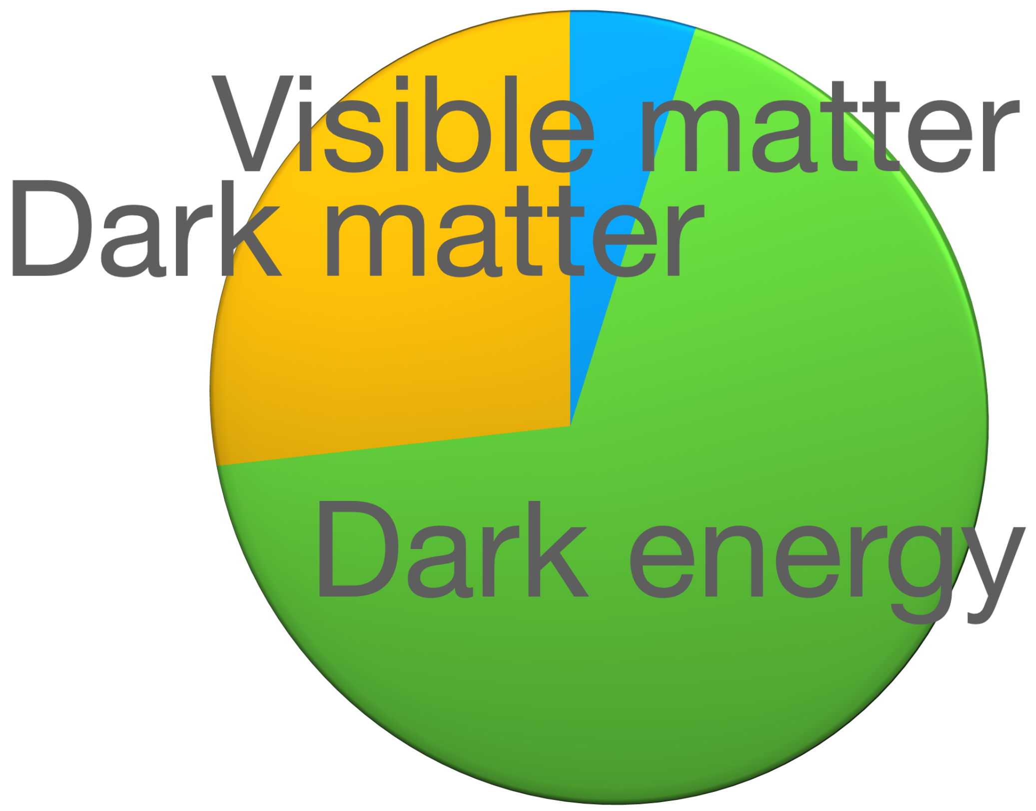
I. Dark Matter properties

3. Stable

We need DM at CMB times (~13 Gyr ago) and at today's galaxies

$$\tau_d^{-1} \times (13 \text{ Gyrs}) \lesssim 1.$$

4. Non-baryonic

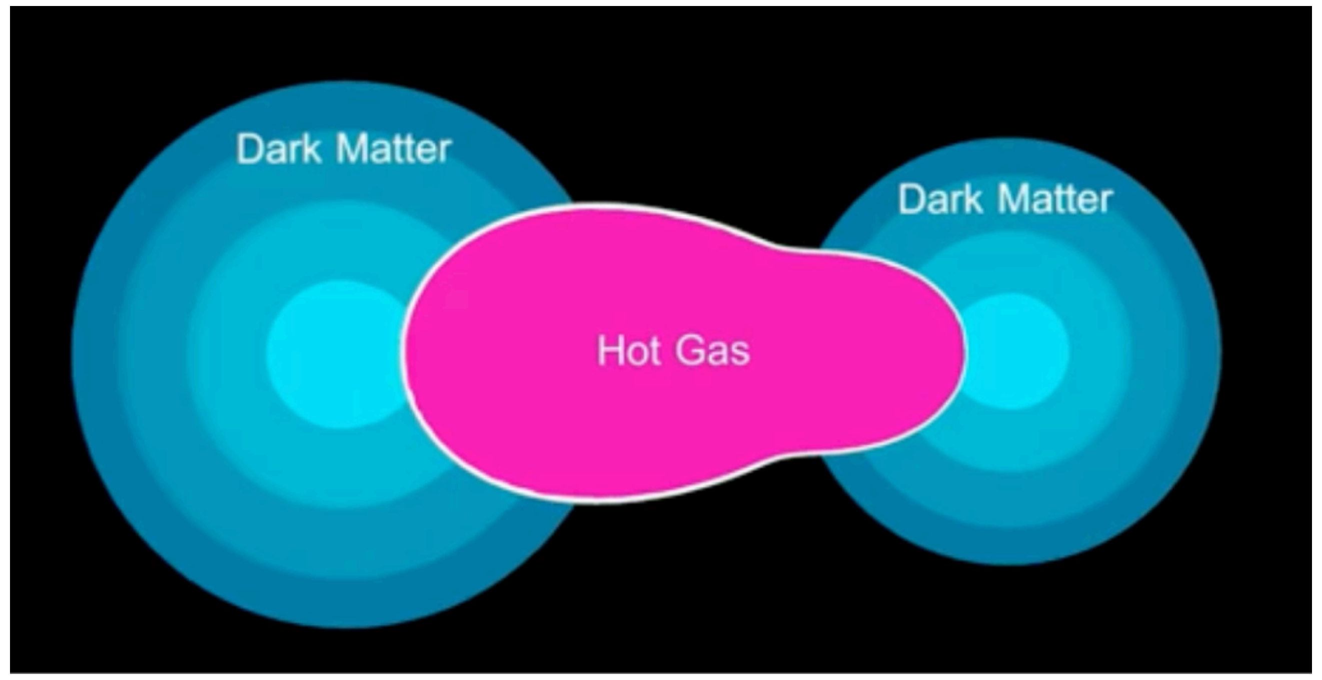


$$\rho_{\rm DM} \sim 5\rho_{SM}$$

5. Collision-less

It shows no self-interaction in galaxy cluster collisions!

$$\sigma/m_{DM} \lesssim 1\,\text{cm}^2/\text{gr}.$$



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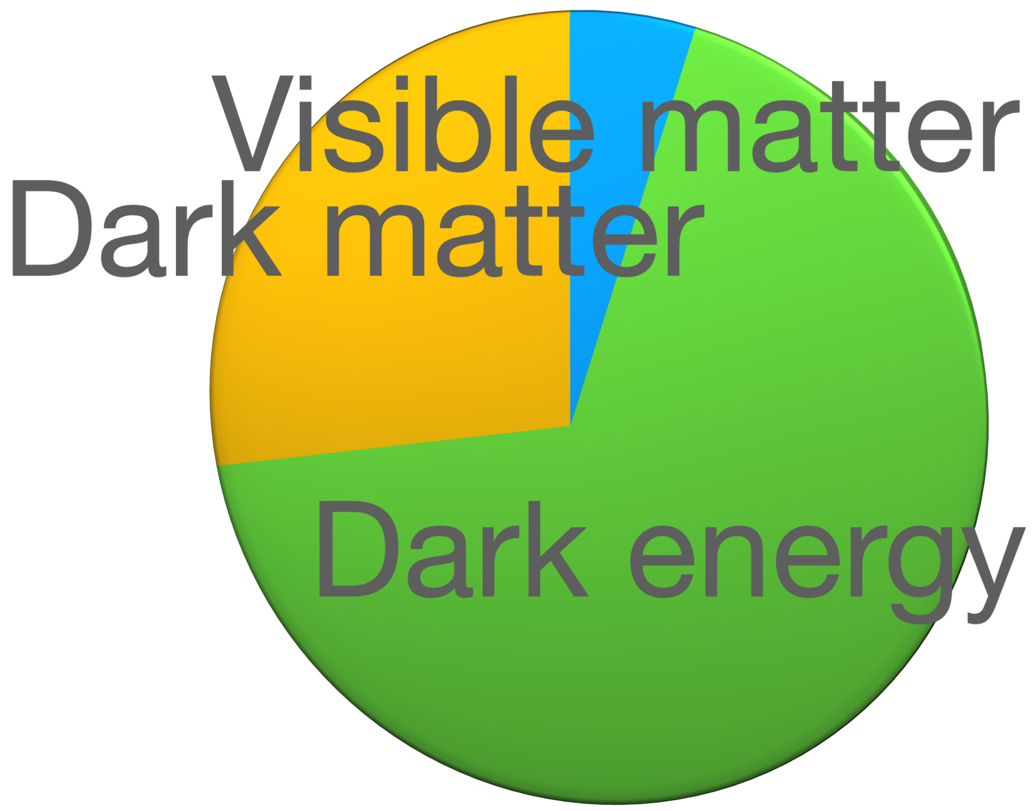

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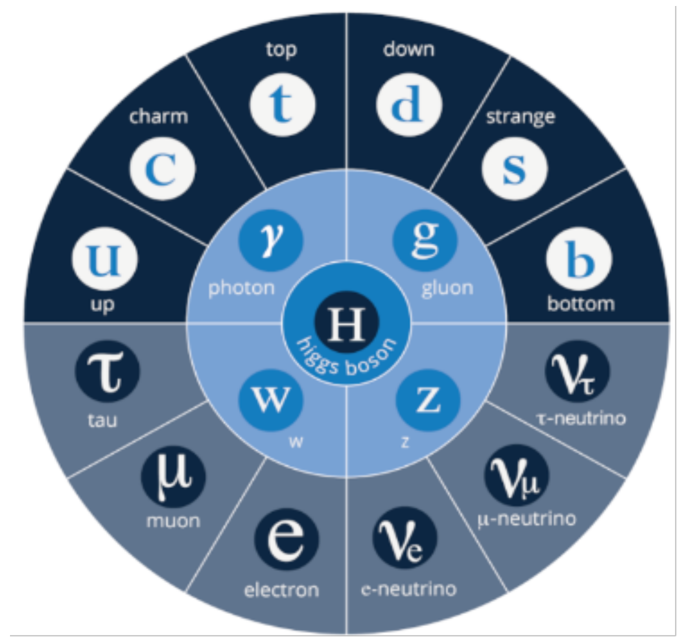

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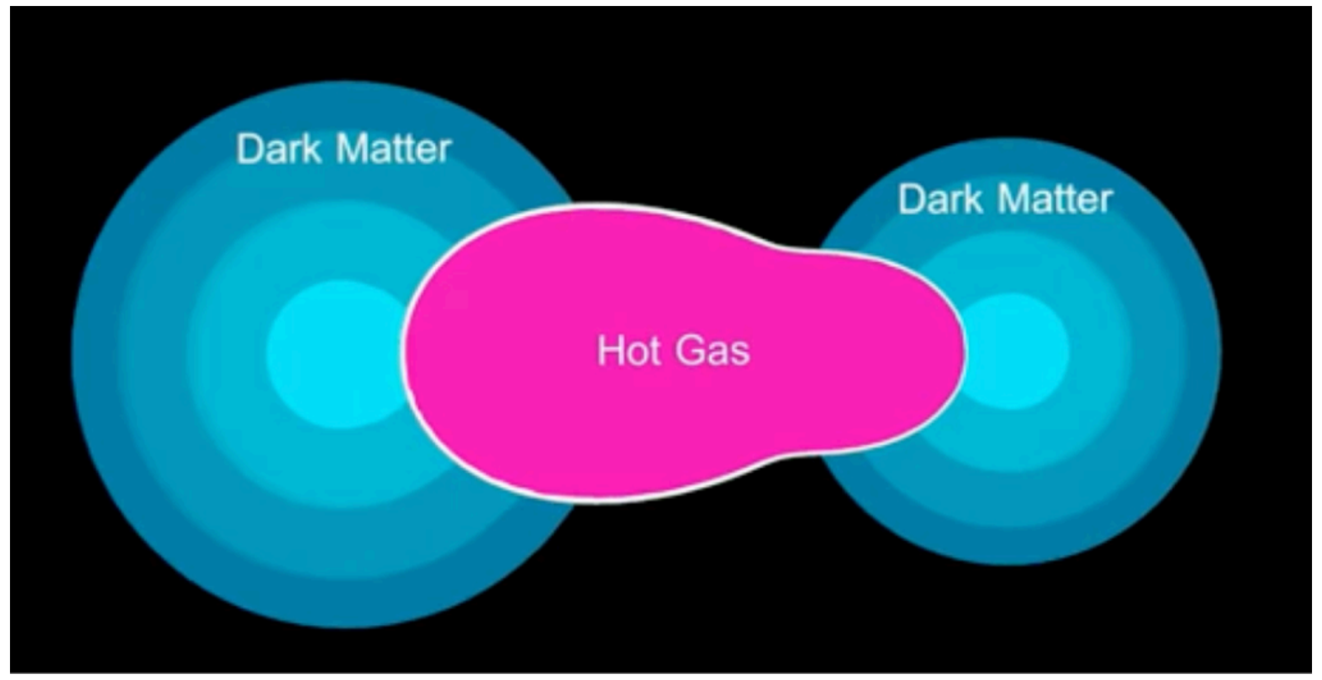

I. Dark Matter properties

Still, the most fundamental properties are unknown

Mass

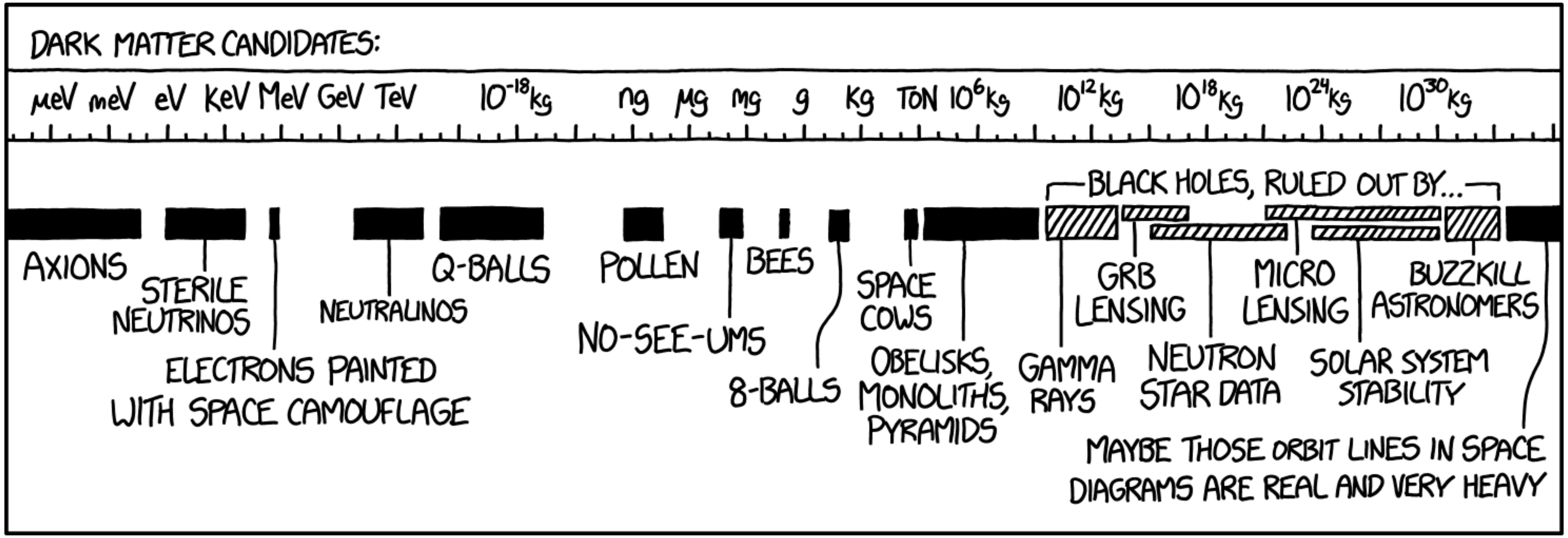

Figure 7: `https://imgs.xkcd.com/comics/dark_matter_candidates.png`

Spin, Interaction properties, unification with SM, connection to SM puzzles…

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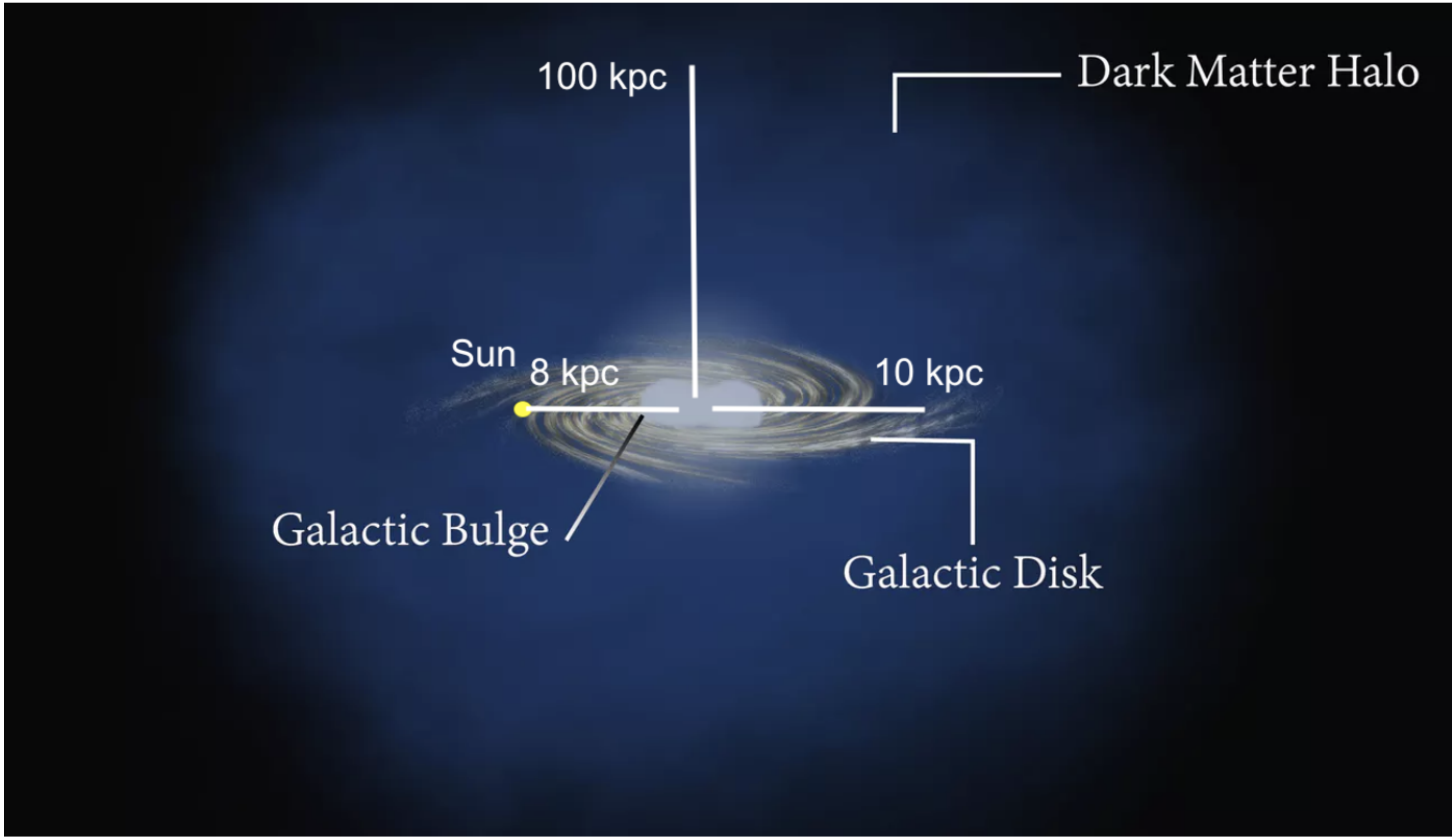


Figure 2: Structure of the Milky Way

Jiao Y., Hammer F., Wang H., Wang J., Amram P., Chemin L., Yang Y., 2023, Astronomy & Astrophysics, 678, A208

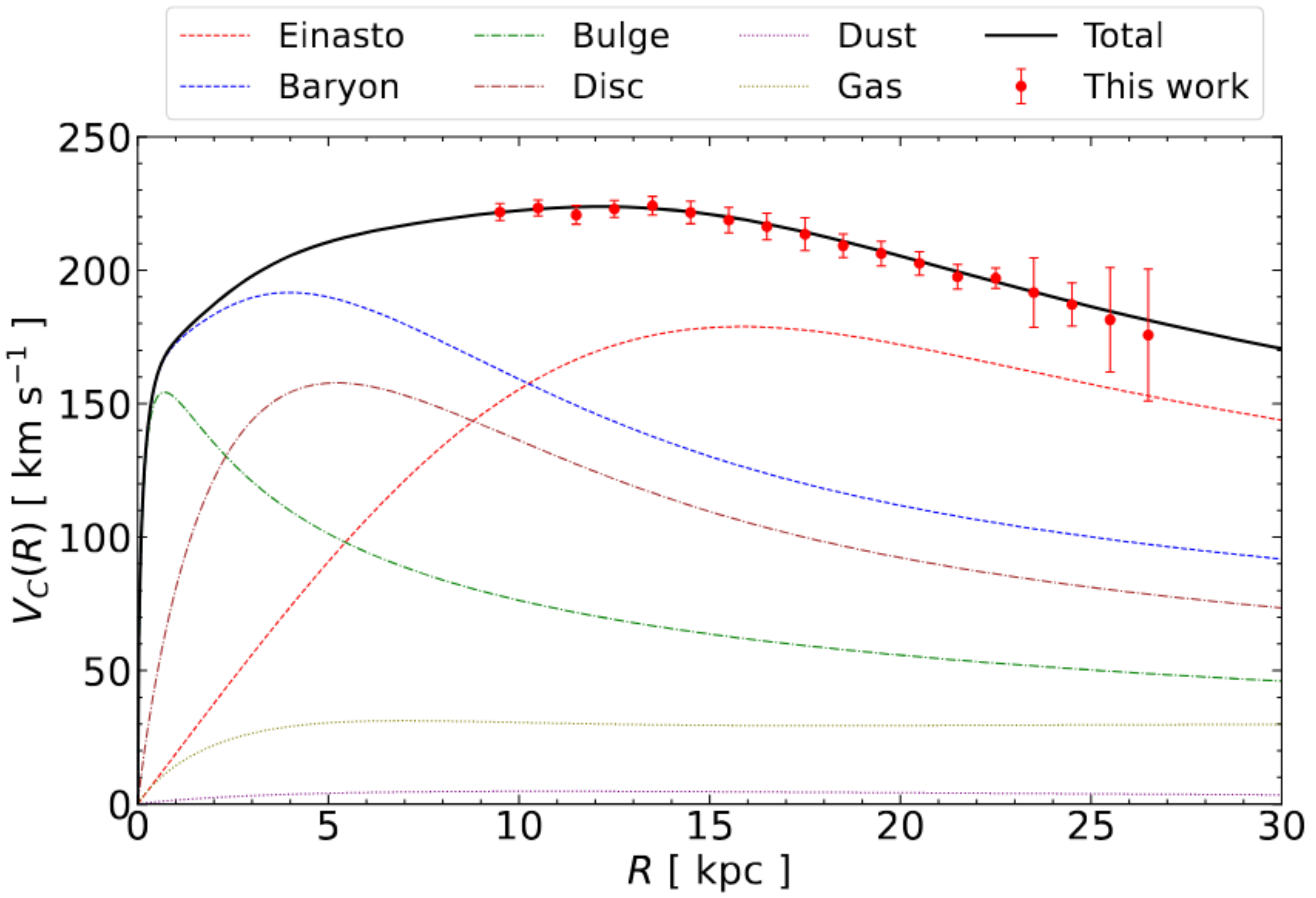


Fig. 5. Circular velocity of the Milky Way. The red data points are the measurements computed in this work; error bars include systematic uncertainties. The black solid line represents the sum of the baryonic and dark matter components: the baryonic model B2 (blue-dashed line), including its decomposition into baryonic components (bulge, disc, gas, and dust) and the best fit of the Einasto dark matter profile (red-dashed line).

Dark Matter distribution

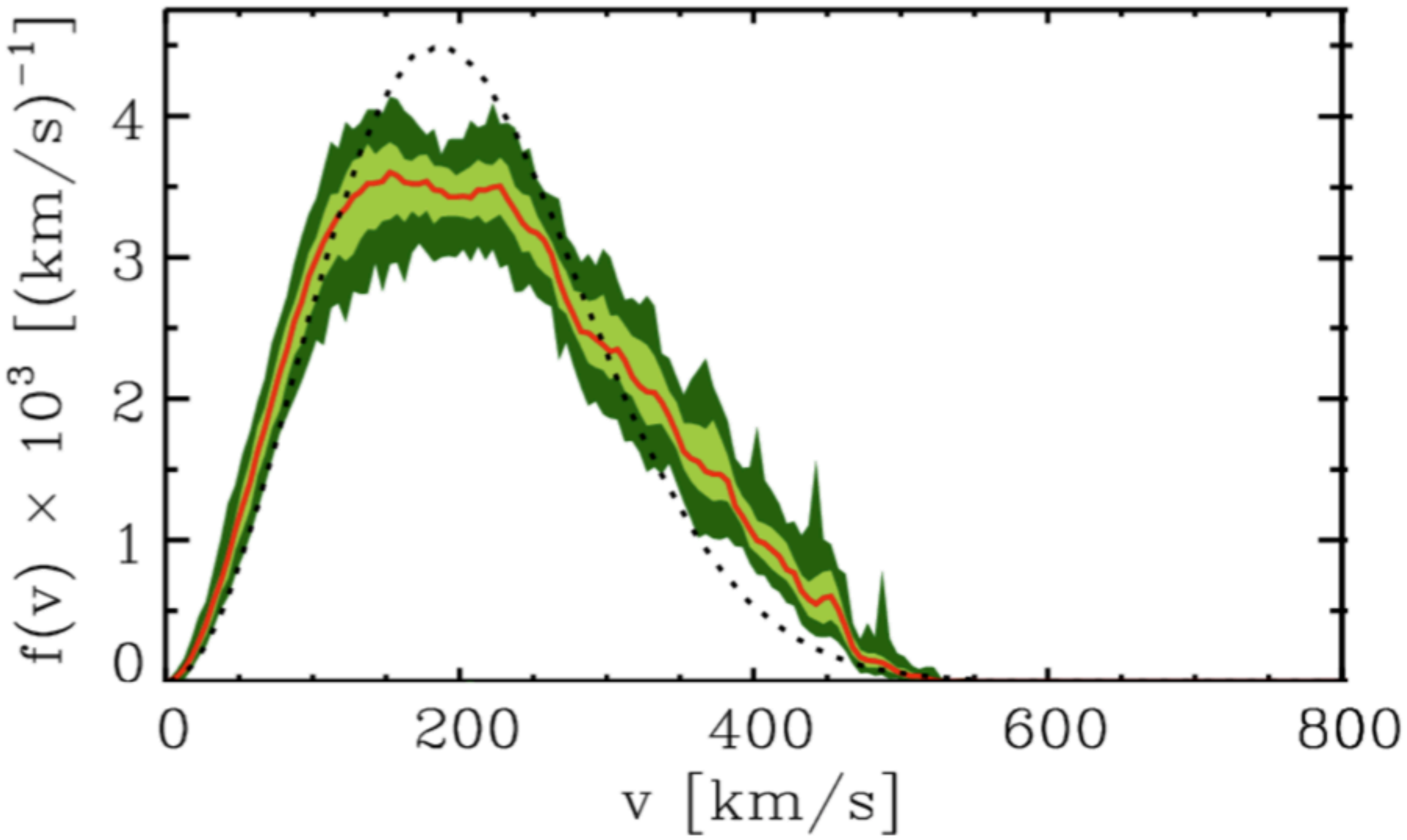
$$\rho_{NFW} = \frac{\rho_0}{r/r_s\left(1+r/r_s\right)^2}$$

$$\rho_{\rm Earth} \sim 0.4\ {\rm GeV/cm^3}$$

$$f(v) = \begin{cases} \frac{1}{N_{esc}}\left(\frac{3}{2\pi\sigma_0^2}\right)^{3/2} e^{-\frac{3}{2}\frac{v^2}{2v_0^2}} & ,v^2 < v_{esc} \\ 0 & ,v > v_{esc} \end{cases}$$

$$v_0 \sim 300\,{\rm km/s}$$

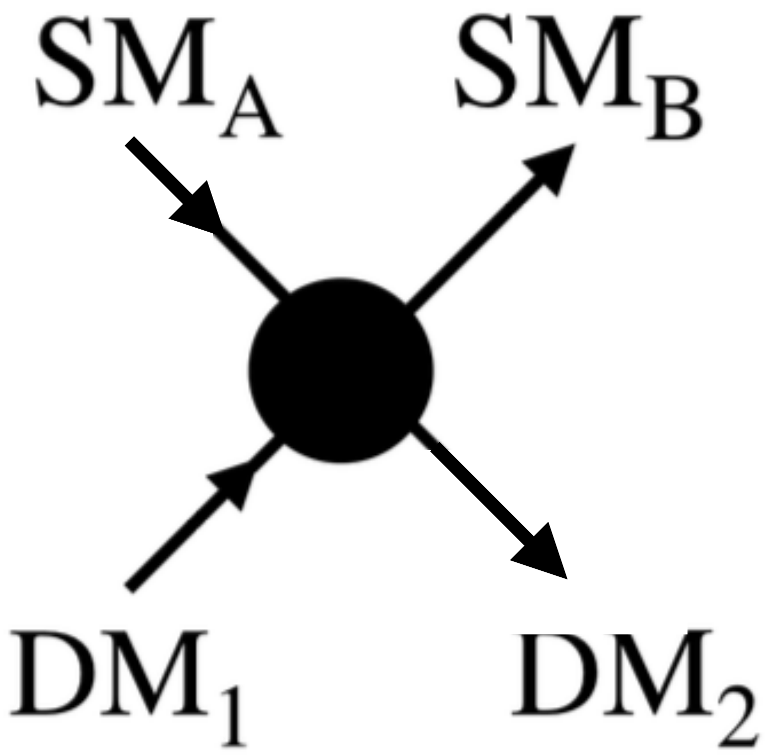
$$v_{esc} \sim 600\,{\rm km/s}$$



Dark Scattering on Earth

$m_{DM} \lesssim \text{GeV}$

$$E_{DM} = \frac{1}{2} m_{DM} v^2 \sim 10^{-6} m_{DM}$$



$$E_R = \frac{1}{2} m_{DM} v^2 \frac{4 m_{DM} m_N}{(m_{DM} + m_N)^2} \frac{1 + \cos\theta}{2}$$

$$\frac{dE_R}{d\cos\theta} = \frac{\mu^2 v^2}{m_N}$$

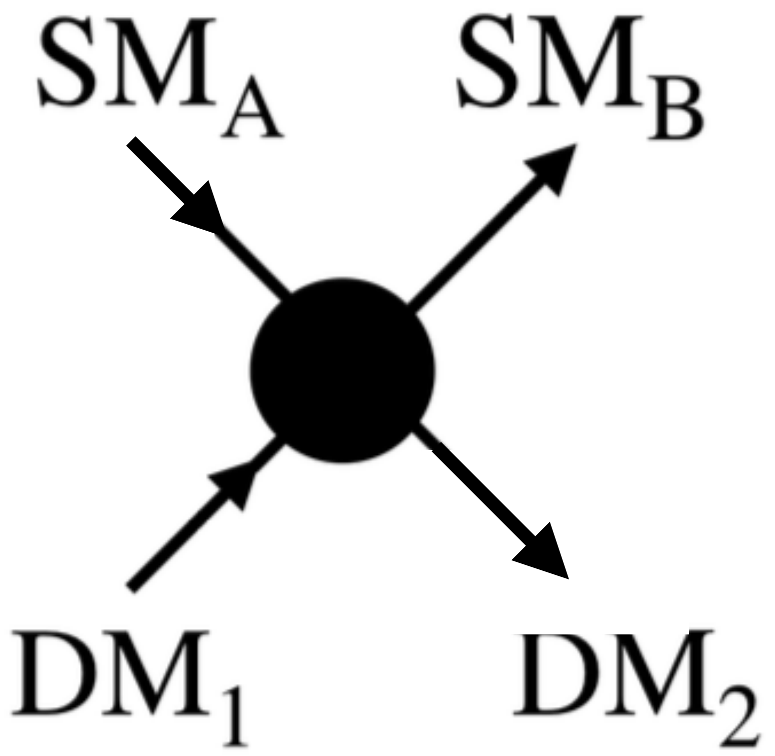
$$E_R^{\max} \sim 10\text{keV} \left(\frac{m_{DM}}{20\text{GeV}}\right)^2 \frac{100\text{GeV}}{m_n}$$

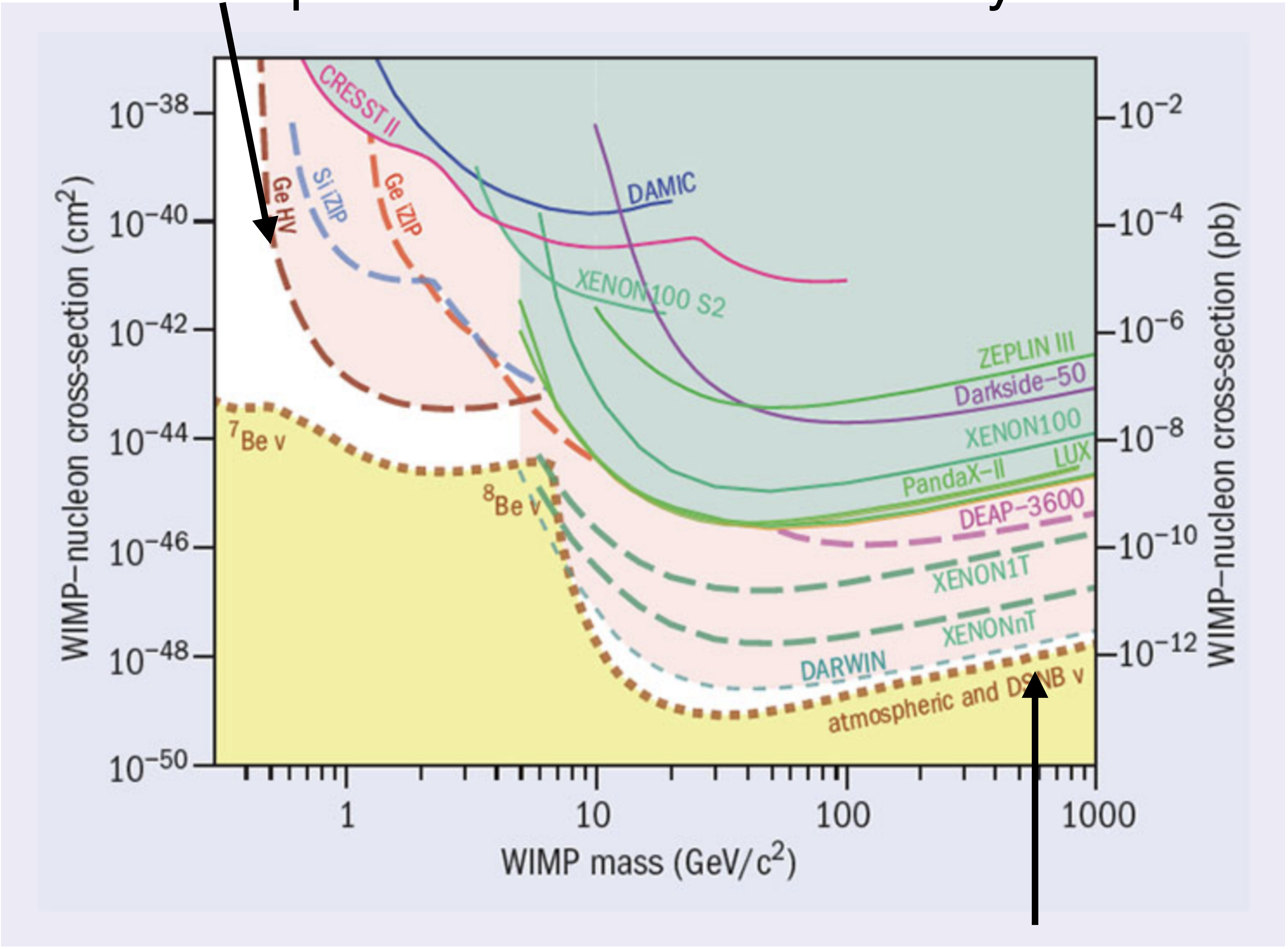
$$\mu^2 \equiv \frac{m_{DM} m_N}{(m_{DM} + m_N)^2}$$

Dark Scattering on Earth

$$E_R^{\max} \sim 10\text{keV} \left(\frac{m_{DM}}{20\text{GeV}}\right)^2 \frac{100\text{GeV}}{m_n}$$

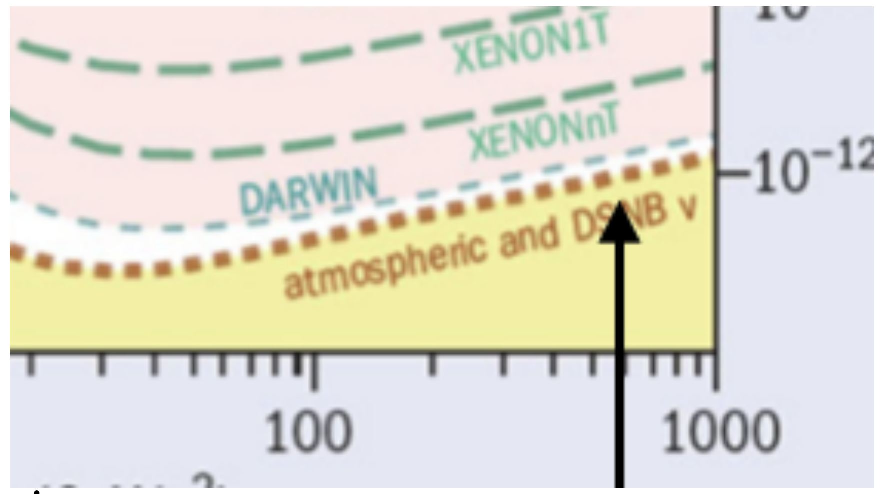
explains the loss of sensitivity at low masses





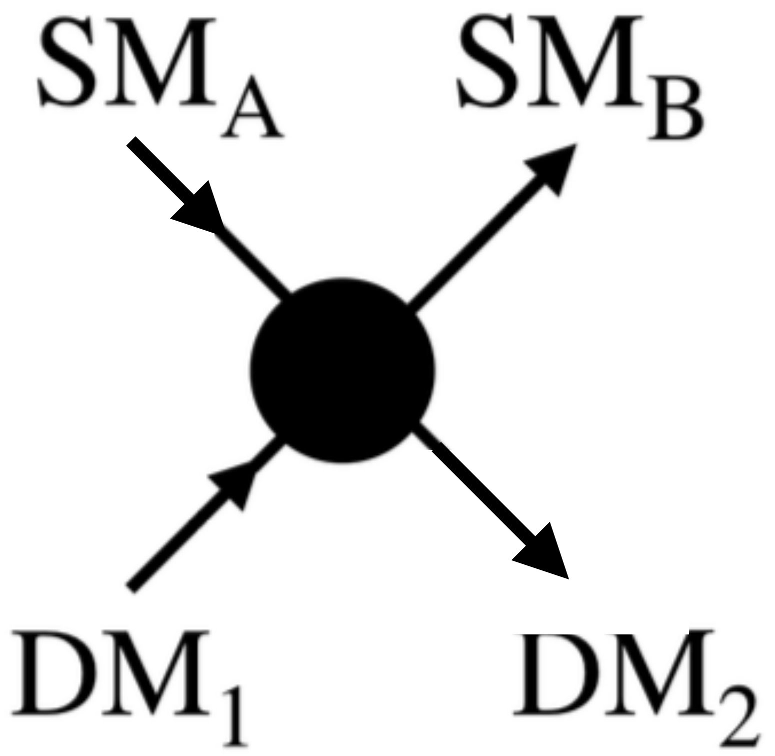
why this? $n \sim \rho / m_{DM}$

Dark Scattering on Earth



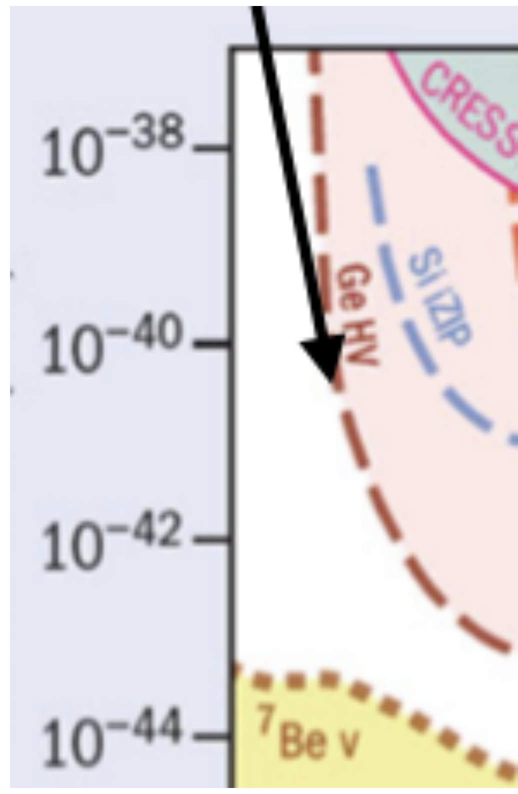
rate of events per recoil energy in a detector
with NT targets of mass mN

$$n \sim \rho / m_{DM}$$



$$\frac{dR}{dE_R} = N_T n_{DM} \left\langle \frac{d\sigma}{dE_R} v \right\rangle . \qquad \frac{dE_R}{d\cos\theta} = \frac{\mu^2 v^2}{m_N}$$

$$\left\langle \frac{d\sigma}{dE_R} v \right\rangle = \int_{v_m}^{v_e} \mathrm{d}^3 v f(v) \frac{d\sigma}{dE_R} v$$



from QM, in the NR limit,

$$\frac{d\sigma}{d\cos\theta} = ct. + O(v) \qquad \int_{v_{\min}}^{v_{\rm esc}} \mathrm{d}^3 v f(v) \frac{d\sigma}{dE_R} v \propto \int_{v_{\min}}^{v_{esc}} \mathrm{d}v v e^{-v^2} \sim e^{-E_R/E_0}$$

WIMP miracle for direct detection

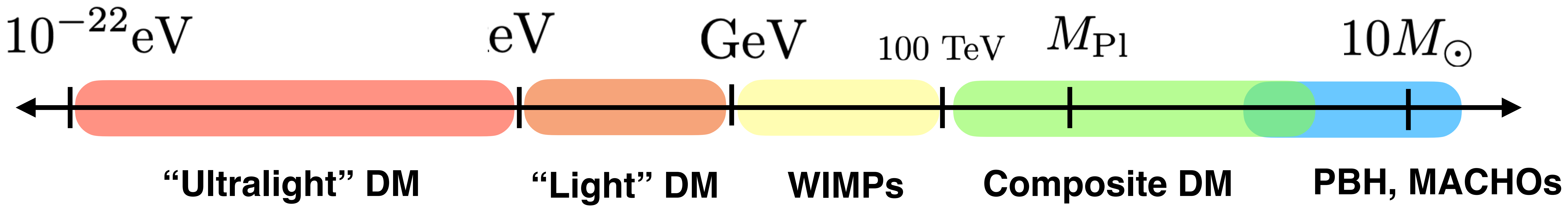
connected to new energy scale

$$\sigma_p \propto \frac{\mu_p^2 g^2}{\pi} \propto \frac{\text{GeV}^2}{\pi(300\text{GeV})^4}$$

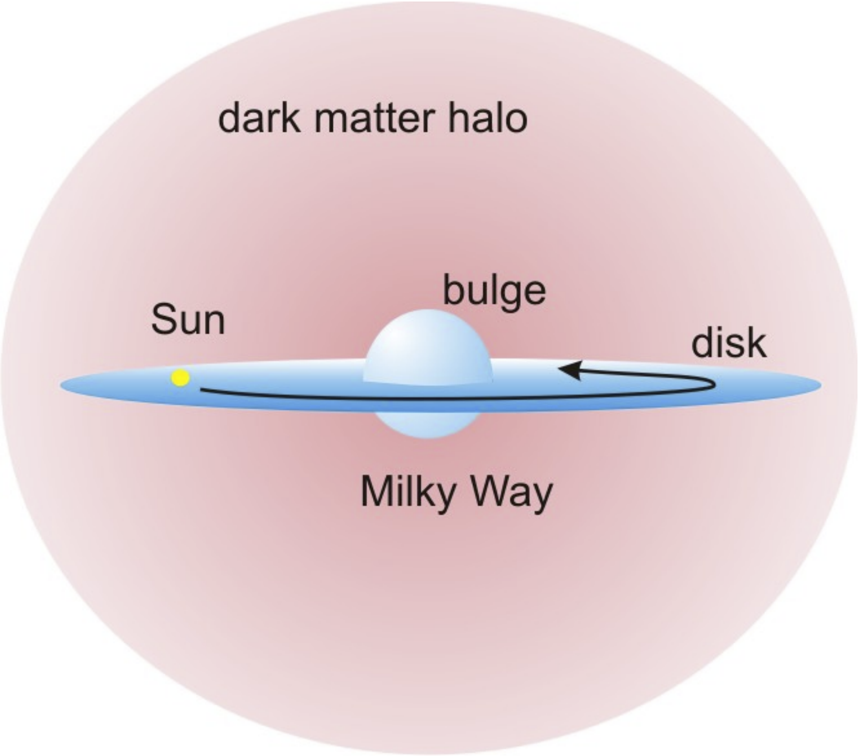
$$N = nv\sigma t N_T \sim 10^{-2} \text{ events } /\text{kg}/ \text{ day}$$

$$N_T \sim kg/(100\text{GeV}) \text{ and } m_{DM} \sim 1\text{GeV}$$

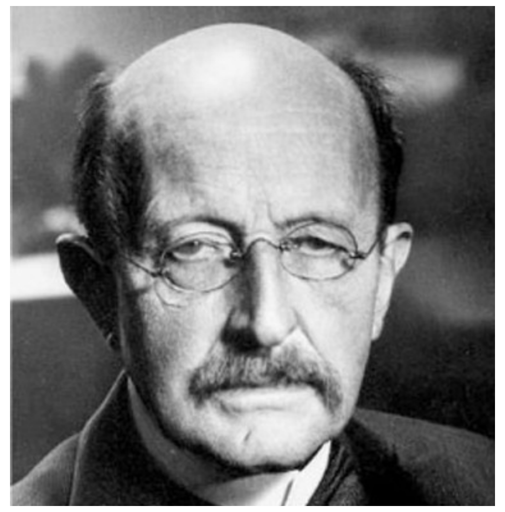
Detecting ultralight dark matter

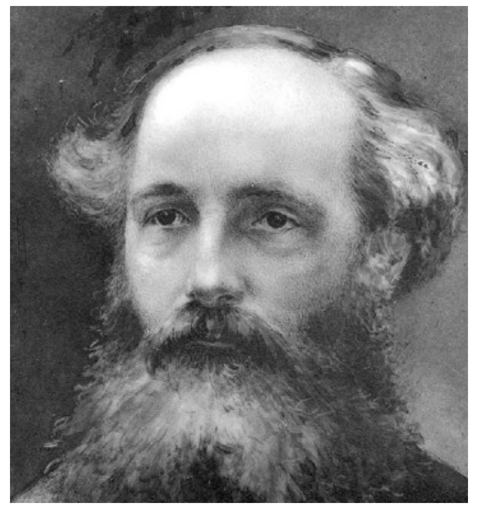


Dark Matter: which state?

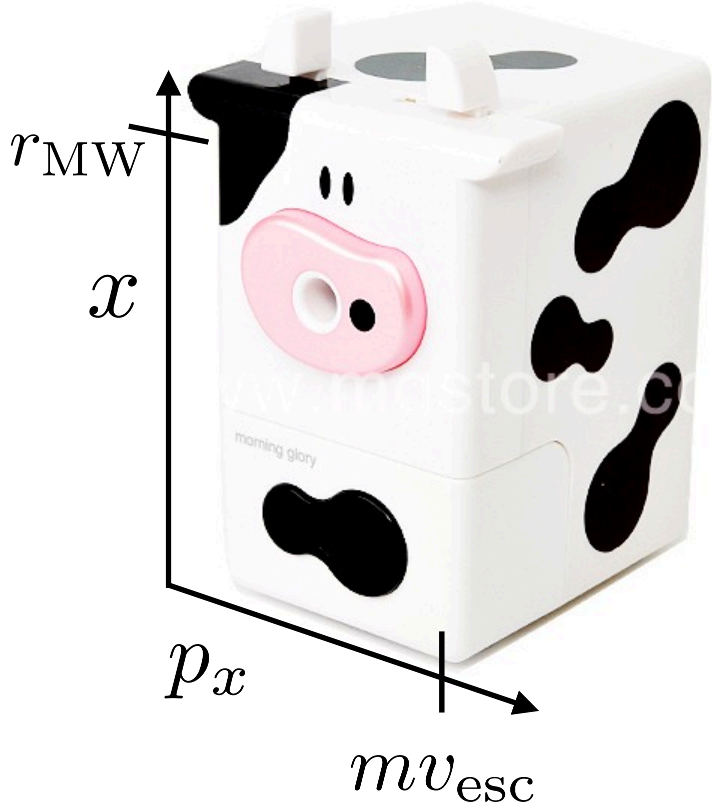


$\hbar\omega$





$F_{\mu\nu}$



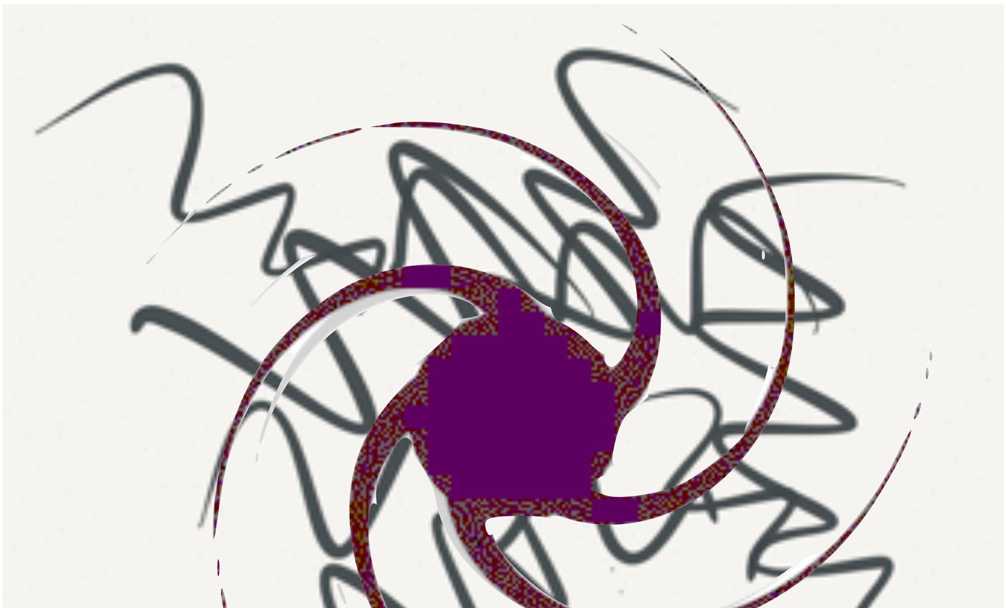
i) escape velocity $\sim 2 \times 10^{-3} c$ ii) size $100\ \mathrm{kpc}$

$$\Delta x \Delta p \gtrsim \hbar \;\rightarrow\; N_s \sim 10^{75} \left(\frac{m}{\mathrm{eV}}\right)^3 \qquad N_p = \frac{M_{MW}}{N_s m} \sim 10^3 \left(\frac{\mathrm{eV}}{m}\right)^4$$

$$m \lesssim 1\,\mathrm{eV} \;\rightarrow\; n^{-1/3} \lesssim \lambda_{\rm dB}$$

For ULDM, field has huge occupation numbers with random phases:

it can be treated as a classical field



$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \;\rightarrow\; \phi_k \sim e^{i(\omega t - kx)}$$

in a virialized halo

Detecting ultralight dark matter

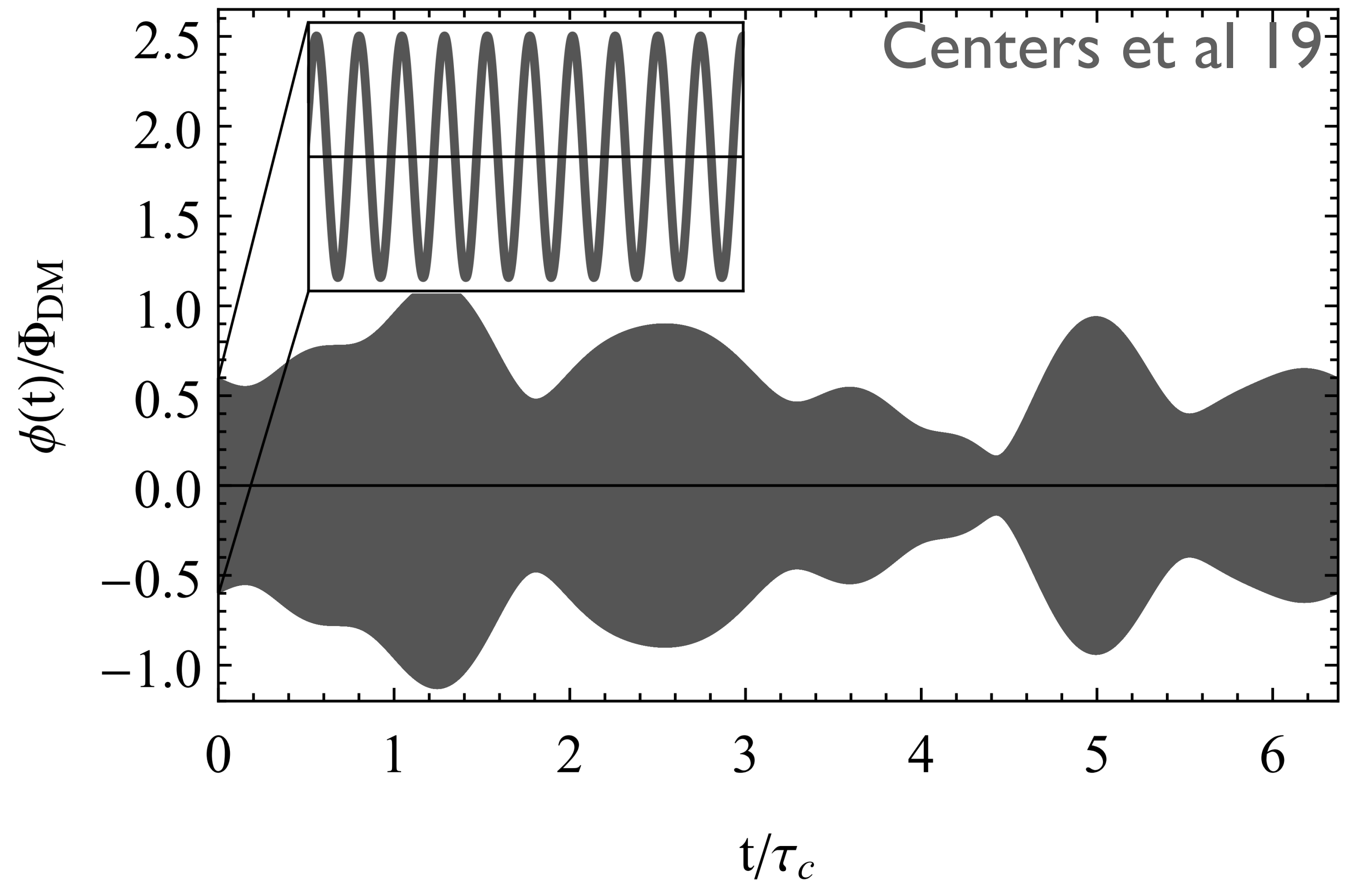
Virialized configuration: collection of waves
with distribution determined by properties from the galaxy

$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3 v \, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$

$(\vec{k} = m\vec{v})$ ϕ_k

$\sigma_0 \sim 10^{-3} c$ in the MW

$$v \sim \sigma_0 \ll 1 \rightarrow \omega_v \approx m(1+v^2) \rightarrow \tau_c \sim 65 \text{ years} \left(\frac{10^{-3}}{V_0}\right)^2 \left(\frac{10^{-18}\mathrm{eV}}{m_\Phi}\right)$$



Detecting ultralight dark matter

ϕ behaves as a classical field. What happens if you coupled to it?

$$\mathcal{L}_{\text{int}} = \frac{\phi}{\sqrt{2}} \left(\frac{d_e}{4\mu_0} F_{\mu\nu} F^{\mu v} - \frac{d_g \beta_3}{2 g_3} G^a_{\mu\nu} G^{a\mu v} - \sum_{i=e,u,d} \left(d_{m_i} + \gamma_{m_i} d_g \right) m_i \bar{\psi}_i \psi_i \right),$$

e.g.

$$\mathcal{L} \supset -\frac{1}{4\mu_0} \left(1 - \frac{d_e \phi}{\sqrt{2}} \right) F_{\mu\nu} F^{\mu\nu} \approx -\frac{1}{4\mu_0 (1 + \frac{d_e \phi}{\sqrt{2}})} F_{\mu\nu} F^{\mu\nu},$$

So, the electric charge is modified. If ϕ oscillates, it will oscillate!

$$\Lambda_3(\phi) = \left(1 + \frac{d_g \phi}{\sqrt{2}} \right) \Lambda_3$$

$$m_e(\phi) = \left(1 + \frac{d_{m_e} \phi}{\sqrt{2}} \right) m_e$$

$$m_i \left(\Lambda_3 \right) (\phi) = \left(1 + \frac{d_{m_i} \phi}{\sqrt{2}} \right) m_i \left(\Lambda_3 \right)$$

no recoil energy, but field effects at low energies!

Detecting ultralight dark matter

https://cajohare.github.io/AxionLimits

$$g_{a\gamma\gamma}\phi F_{\mu\nu}F_{\alpha\beta}\epsilon^{\mu\nu\alpha\beta}$$