Astrophysics and Dark Matter

12th IDPASC School, Granada

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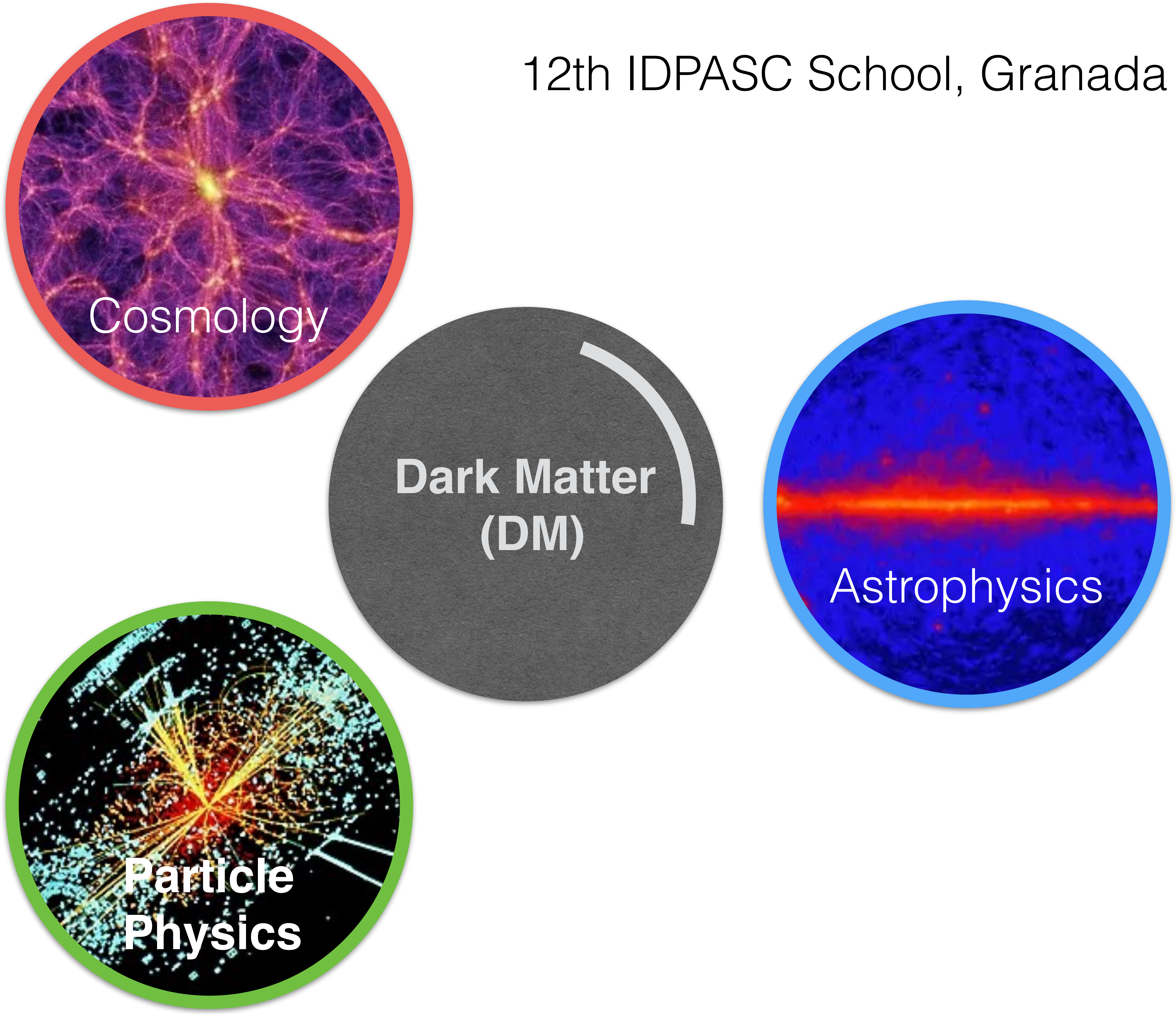


What do the properties of Galaxies tell us about the nature of Dark Matter?

What do astrophysical observations tell us about the nature of Dark Matter?

Lecture 1
Dark Matter evidence, properties, and hints from astrophysics of galaxies

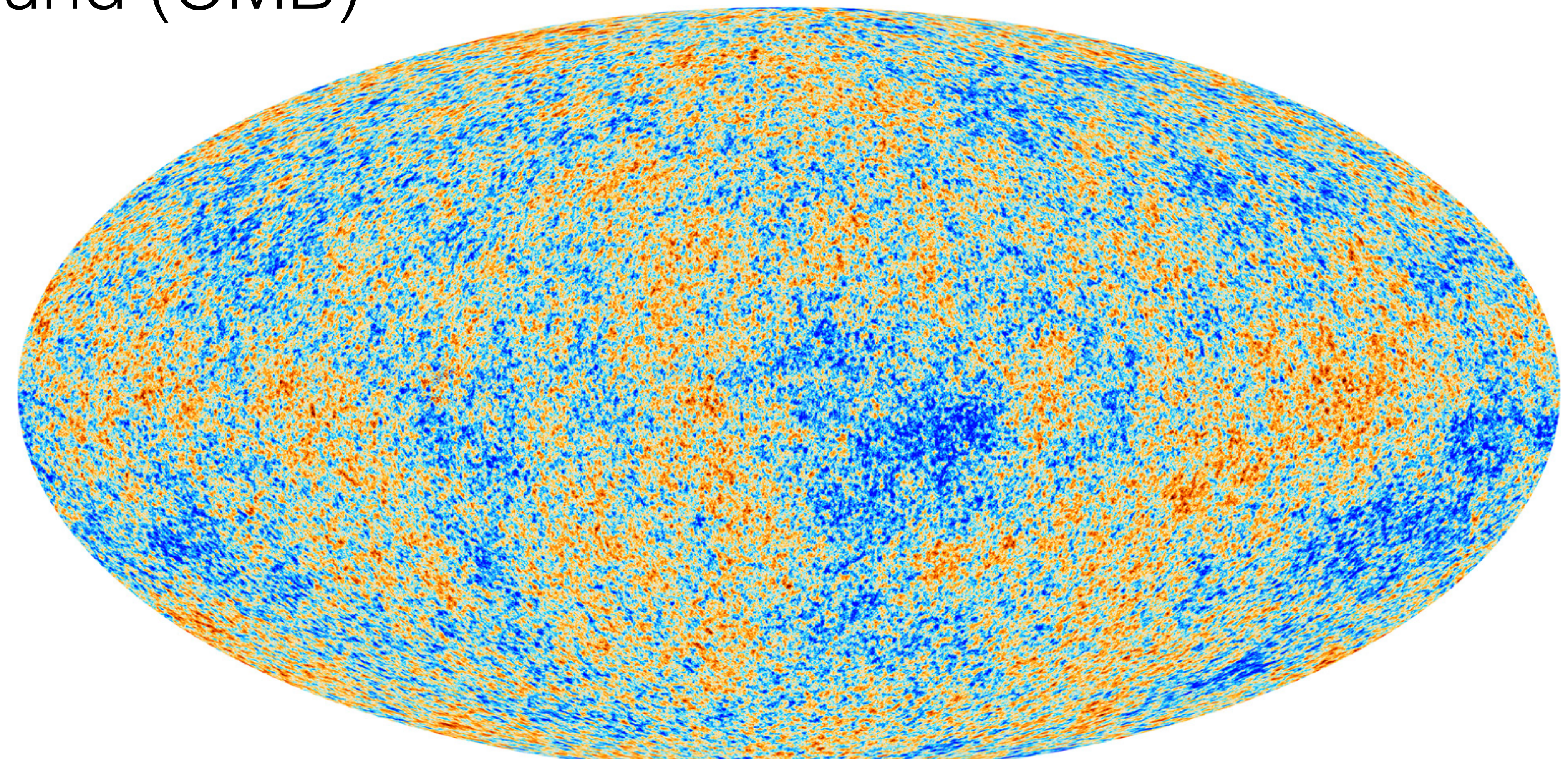
Lecture 2
"Indirect detection" of Dark Matter: formalism and signals

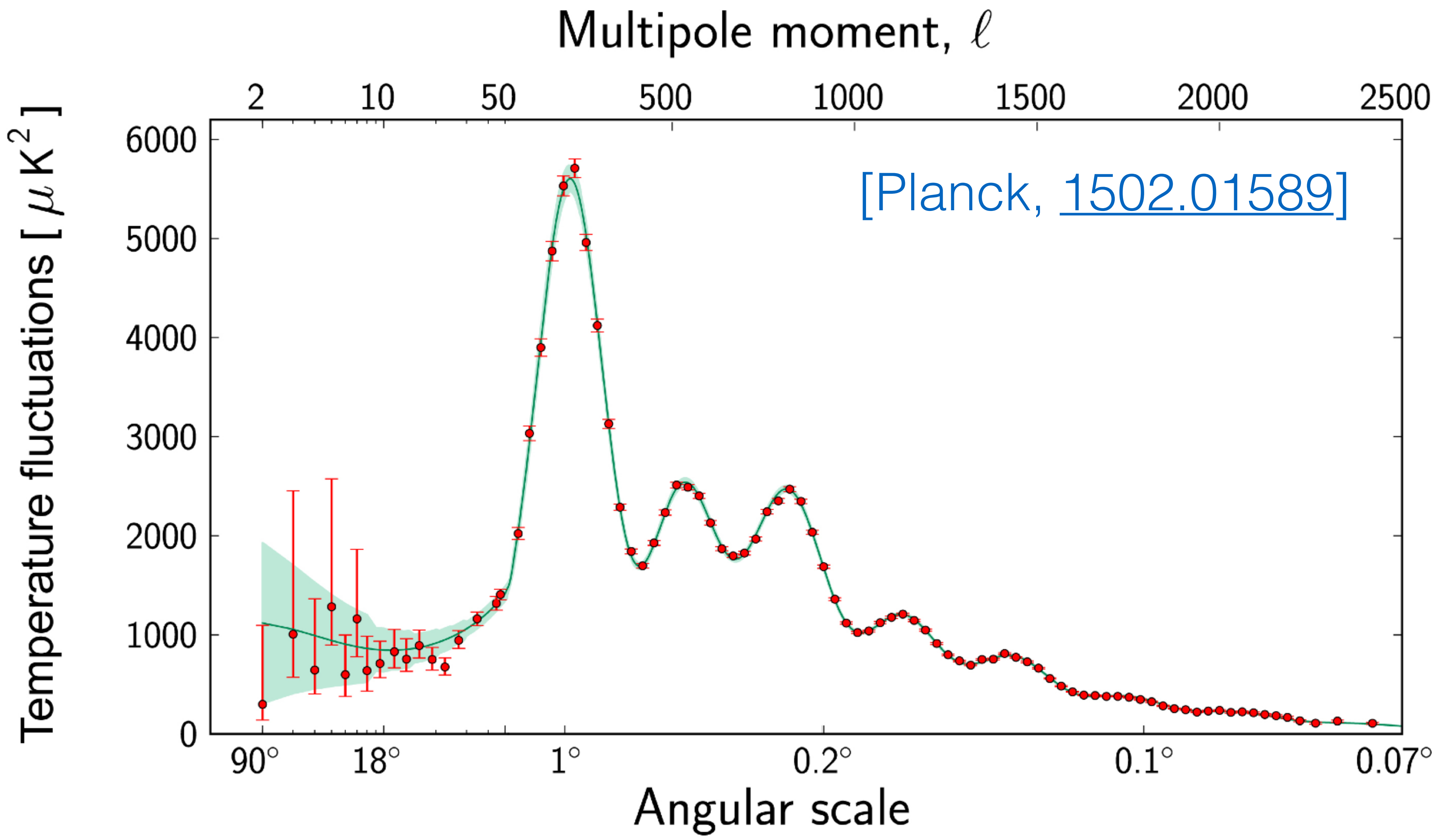
Lecture 3
Constraints and anomalies in indirect searches: gamma rays, cosmic rays, neutrinos, and more…

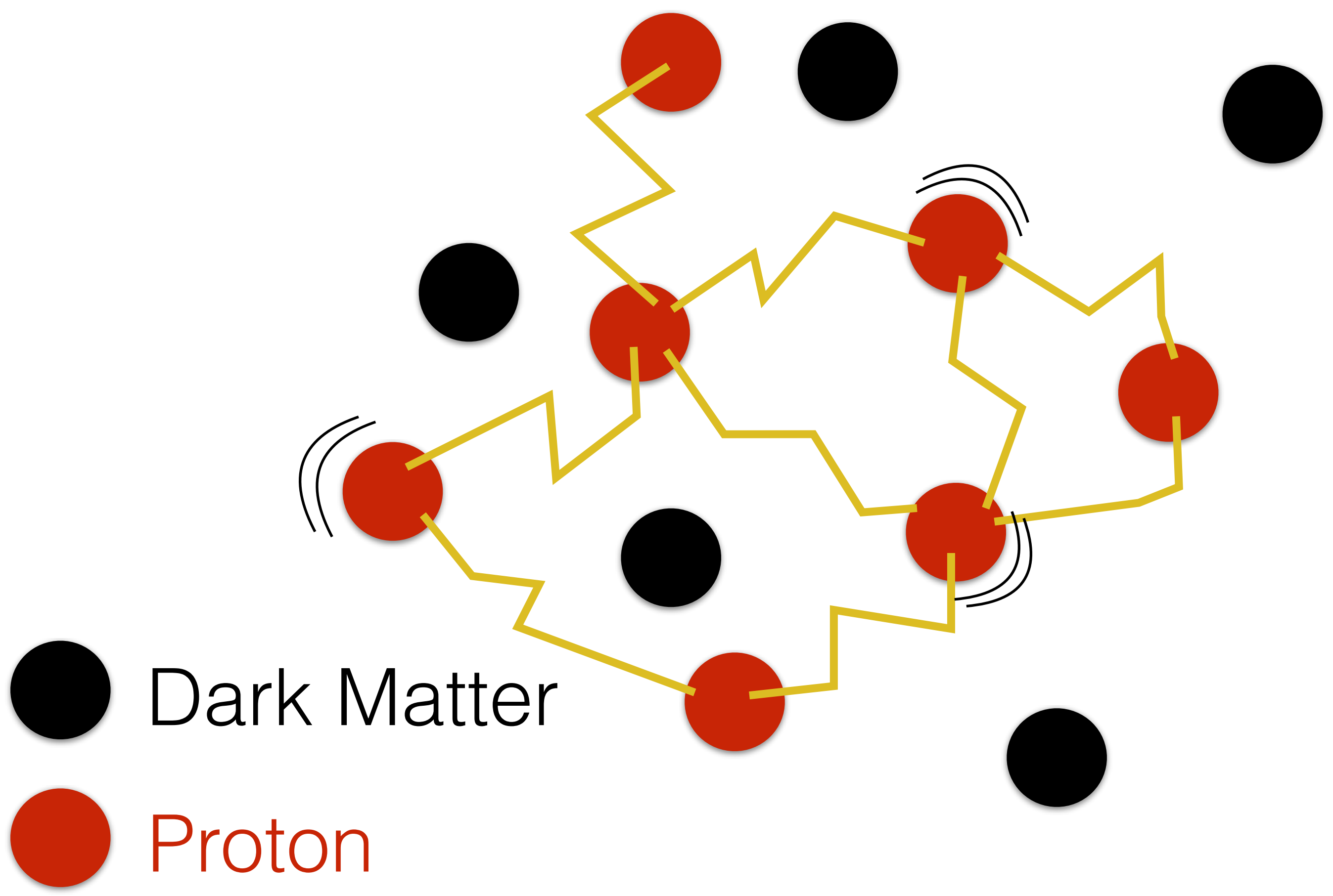
Dark Matter in Cosmology

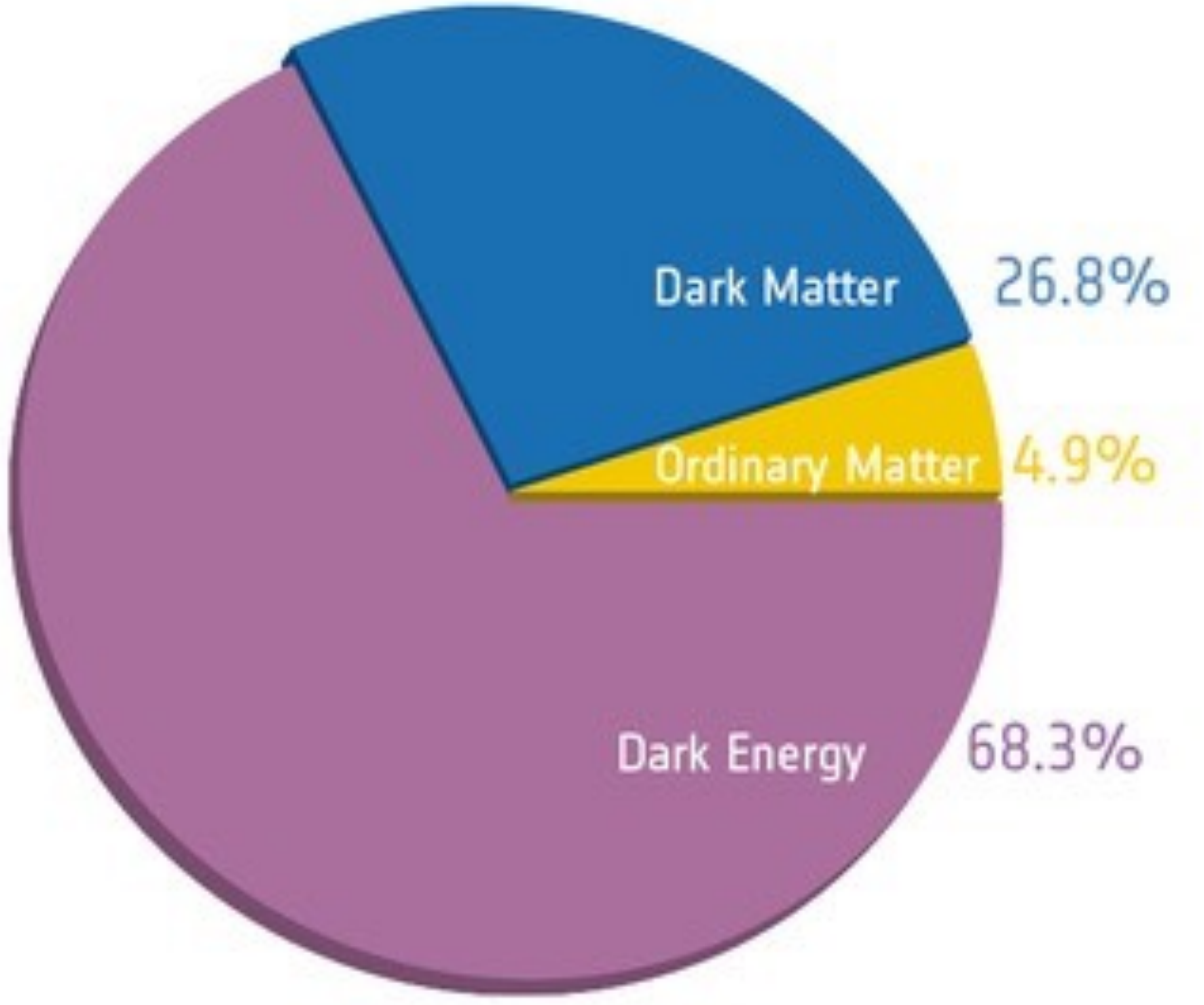
See Cosmology Lecture 3

Cosmic Microwave Background (CMB)









Credit: ESA/Planck Collaboration

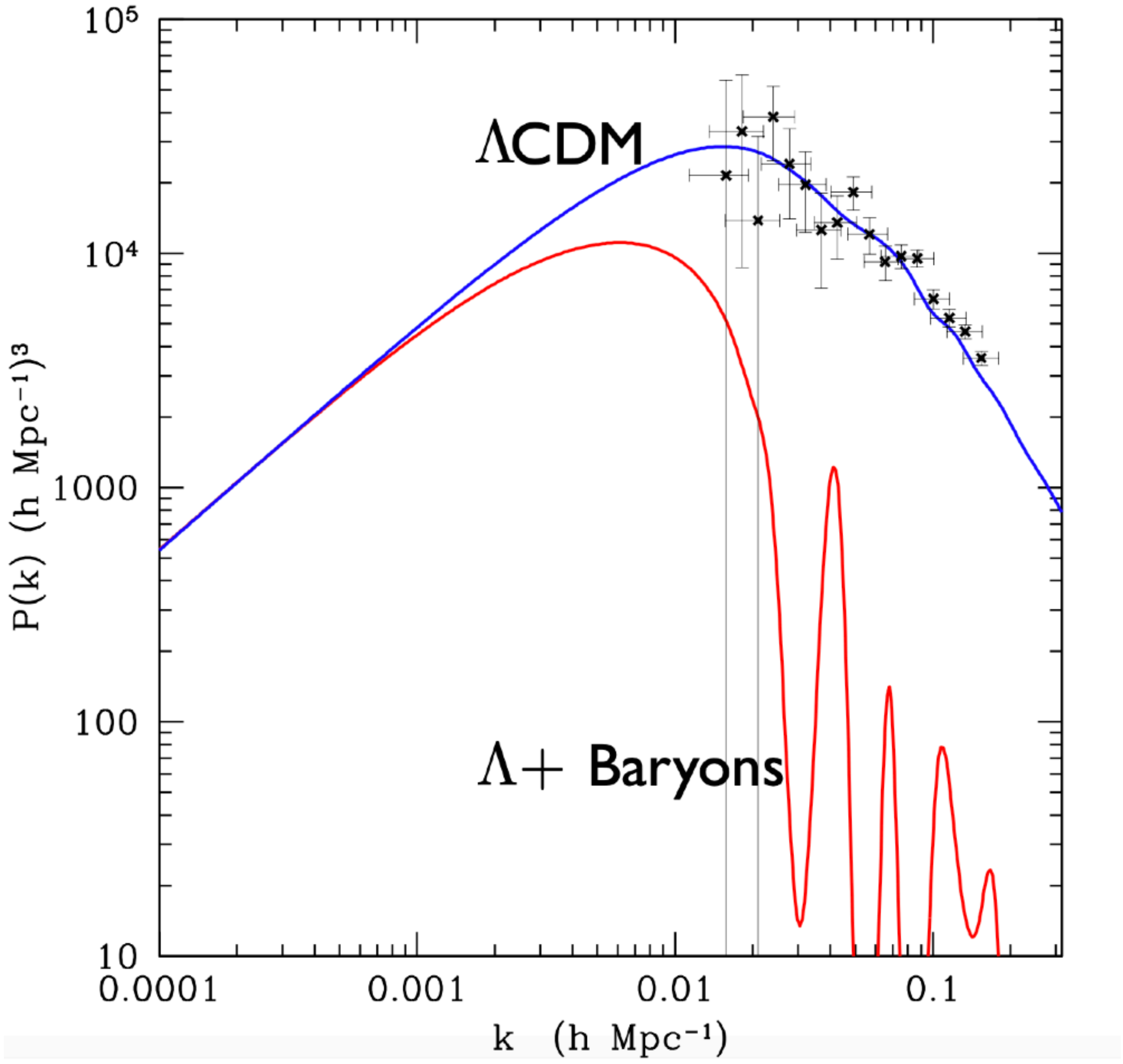
Dark Matter in Cosmology

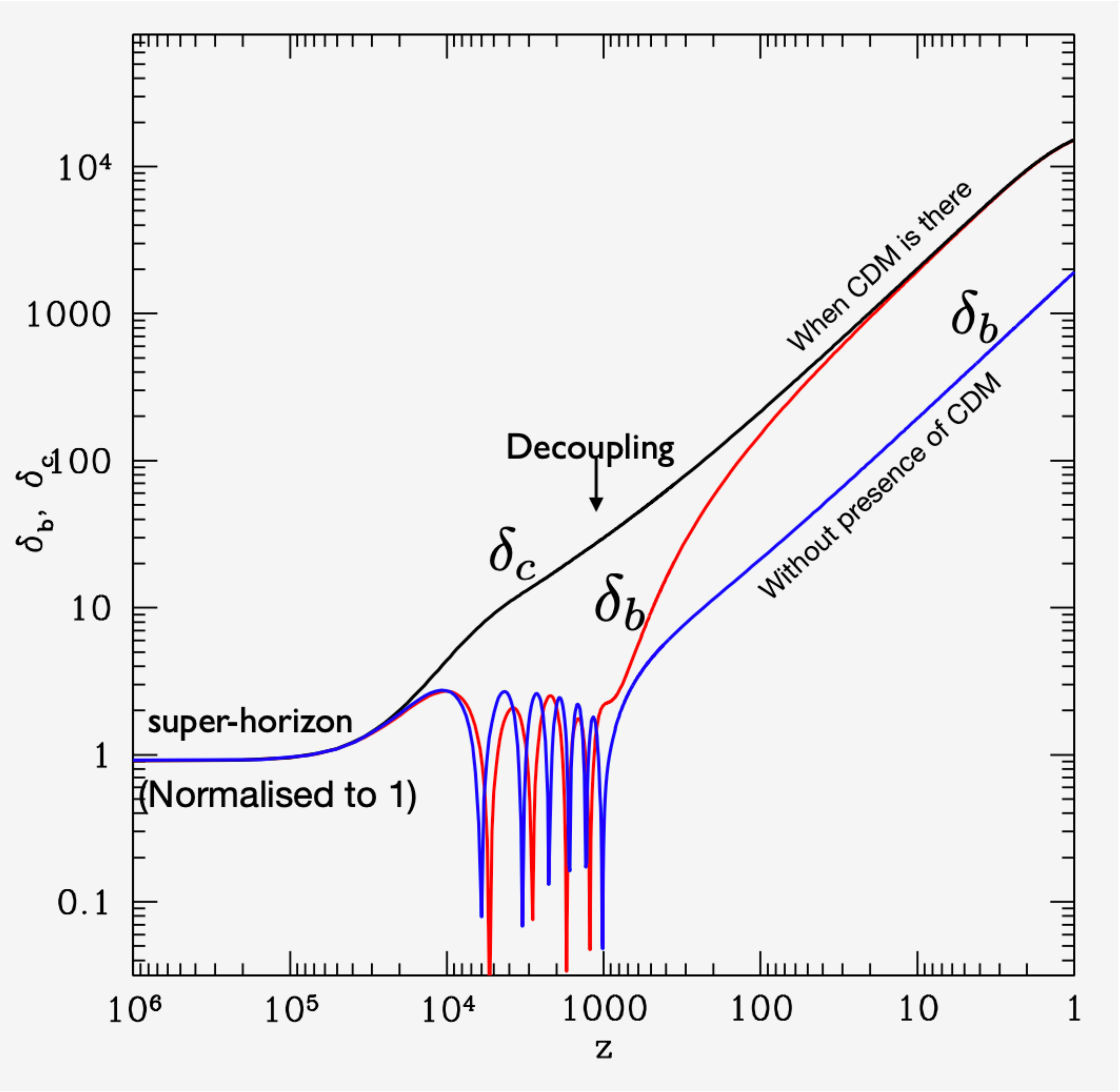
See Cosmology Lecture 3

Dark Matter is essential in forming the large scale structure we see in the Universe today.

Baryons decouple and begin to collapse to form structures only after recombination ($z \sim 1000$), when $c_s^2 = 0 \Rightarrow \lambda_J \ll \lambda_H$.

Dark Matter overdensities collapse earlier and provide the seeds for the formation of baryonic structures!



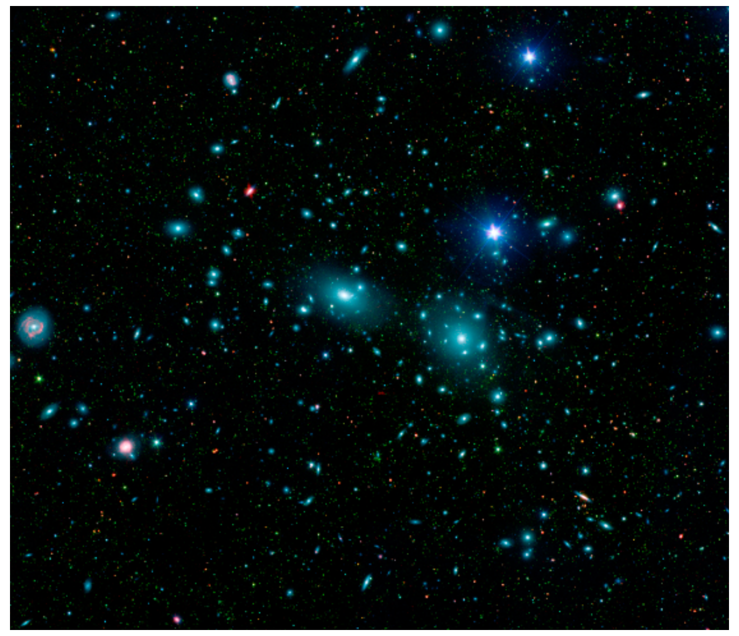


$$\vec{\nabla}^2\Phi = 4\pi G a^2 \bar{\rho}_m \left(\Omega_b\delta_b + \Omega_c\delta_c\right)$$

Dark Matter in Galaxy Clusters

Galaxy Clusters are the largest gravitationally bound structures in the Universe. They are highly Dark Matter dominated, with mass-to-light ratios of $\sim 100\, M_\odot / L_\odot$.

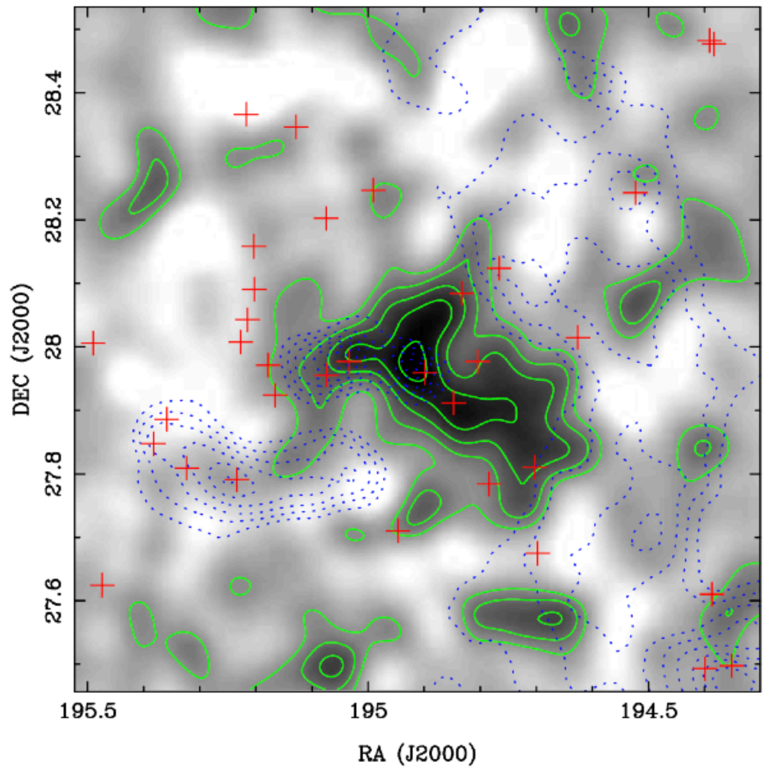
E.g. Coma Cluster



Dynamics - Velocity dispersion of member galaxies can be used to infer the enclosed mass through the Virial Theorem.

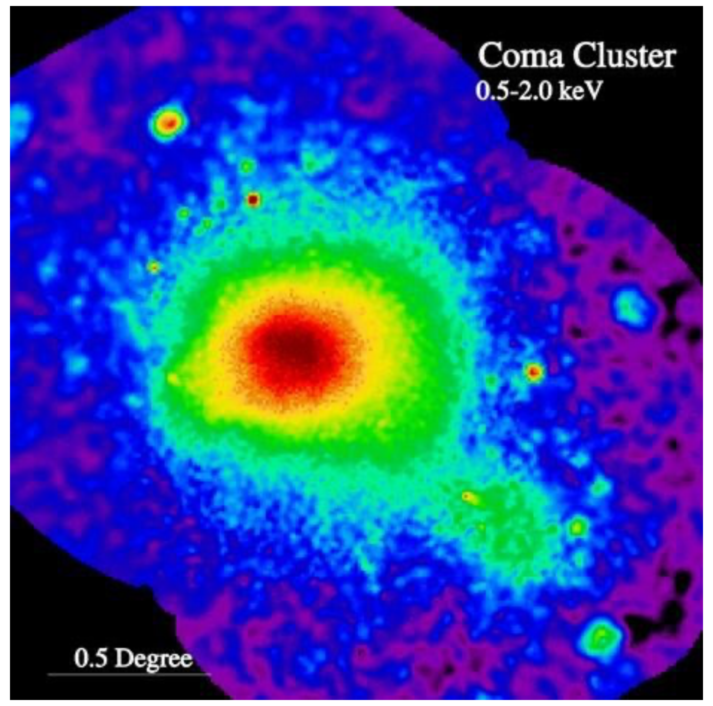
$$\langle T \rangle \approx \frac{1}{2} M_{\rm tot} \sigma_v^2 = -\frac{1}{2} \langle V_{\rm tot} \rangle$$

[0904.0220]



Lensing - Mass in the cluster lenses background galaxies. Projected surface mass density Σ can be inferred from the deflection field $\vec{\hat{\alpha}}$.

$$\vec{\hat{\alpha}}\left(\vec{\xi}\right) = \frac{4G}{c^2} \int \frac{\left(\vec{\xi} - \vec{\xi}'\right) \Sigma \left(\vec{\xi}'\right)}{\left|\vec{\xi} - \vec{\xi}'\right|^2} d^2\xi'$$

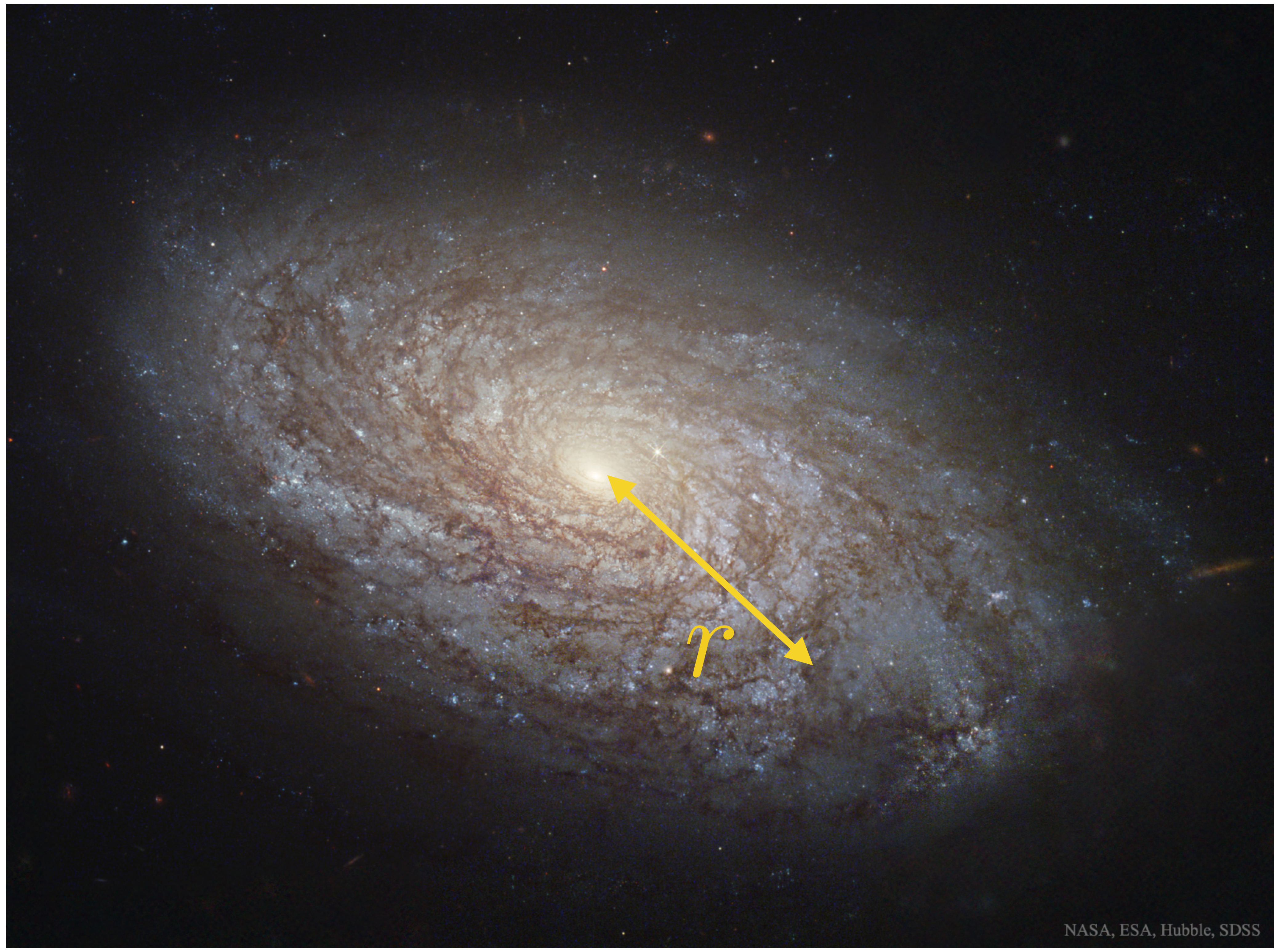


X-ray observations - Assuming hydrostatic equilibrium of hot X-ray gas in the clusters allows us to trace out the mass distribution.

$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{G M_{\rm tot}(<r)}{r^2} = -\frac{1}{\rho_{\rm gas}} \frac{\mathrm{d}P_{\rm gas}}{\mathrm{d}r}$$

Problem 1.1

Dark Matter in Galaxies



NASA, ESA, Hubble, SDSS

DM density at Earth:

$$\rho_\chi \sim 5 \times 10^{-25}\ \mathrm{g/cm^3}$$
$$\sim 0.3\ \mathrm{GeV/cm^3}$$
$$\sim 0.008\ M_\odot/\mathrm{pc}^3$$

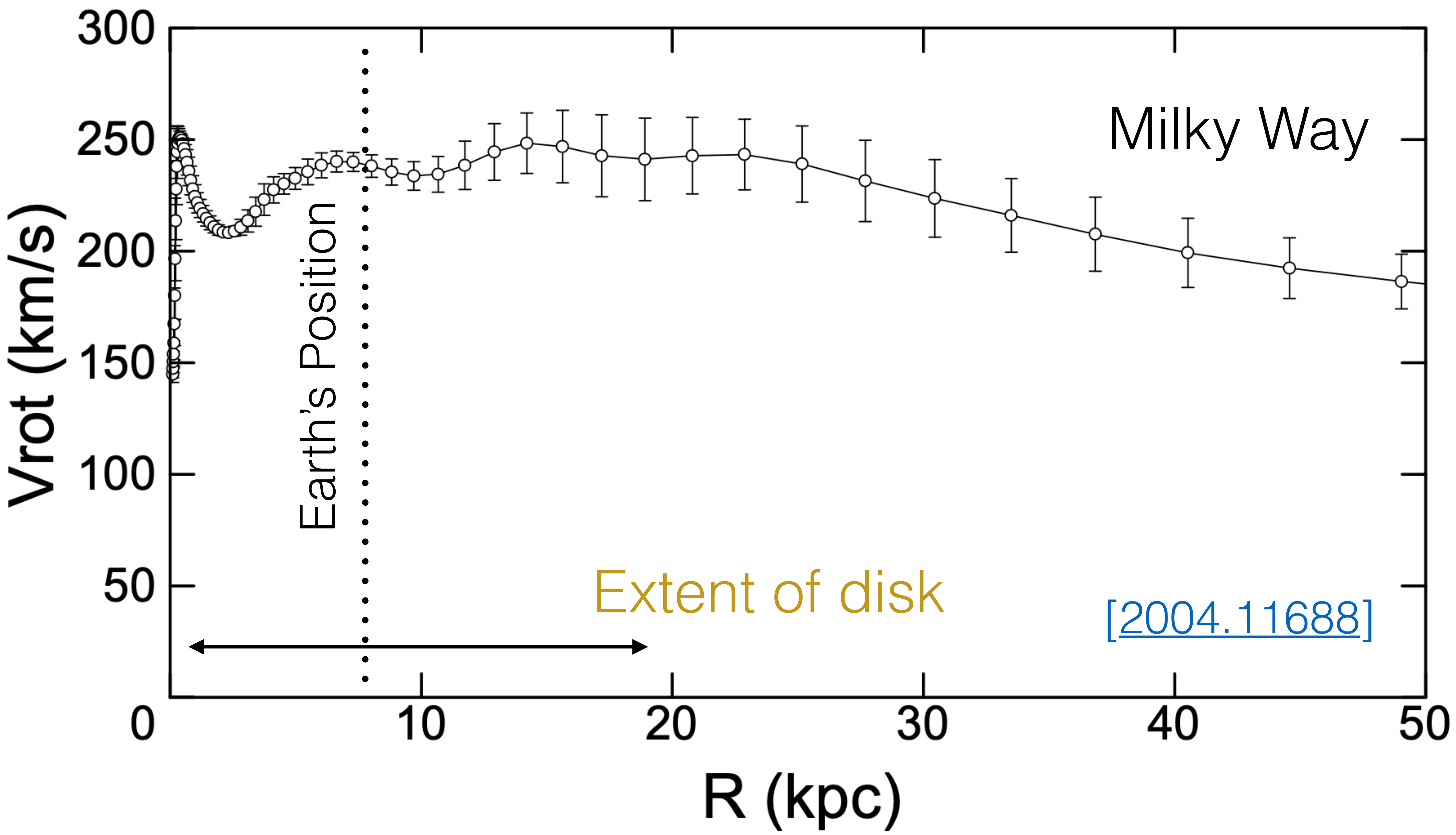
[1404.1938]

Problem 1.2

Rotational velocity $v_{\mathrm{rot}}(r)$ of stars (and gas) in disk galaxies allows us to infer (in principle) the enclosed mass distribution.

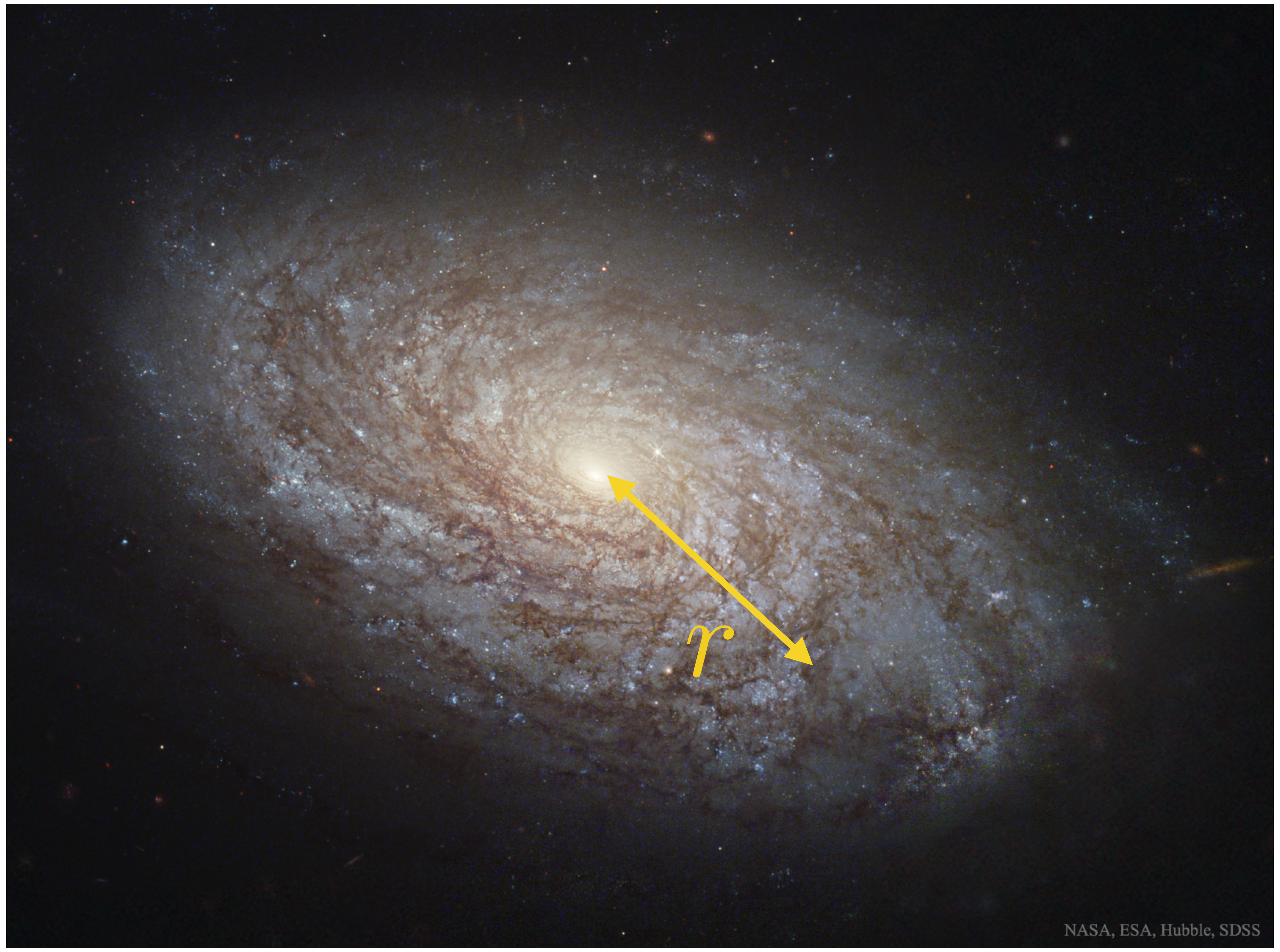
$$v_{\mathrm{rot}}(r) = \sqrt{\frac{GM_{\mathrm{enc}}(r)}{r}}$$

Rotation curve flattens at large radii, which cannot be explained by mass of observed gas and stars (expect Keplerian $v_{\mathrm{rot}}(r) \propto 1/\sqrt{r}$ at large radii).



[2004.11688]

Dark Matter in Galaxies



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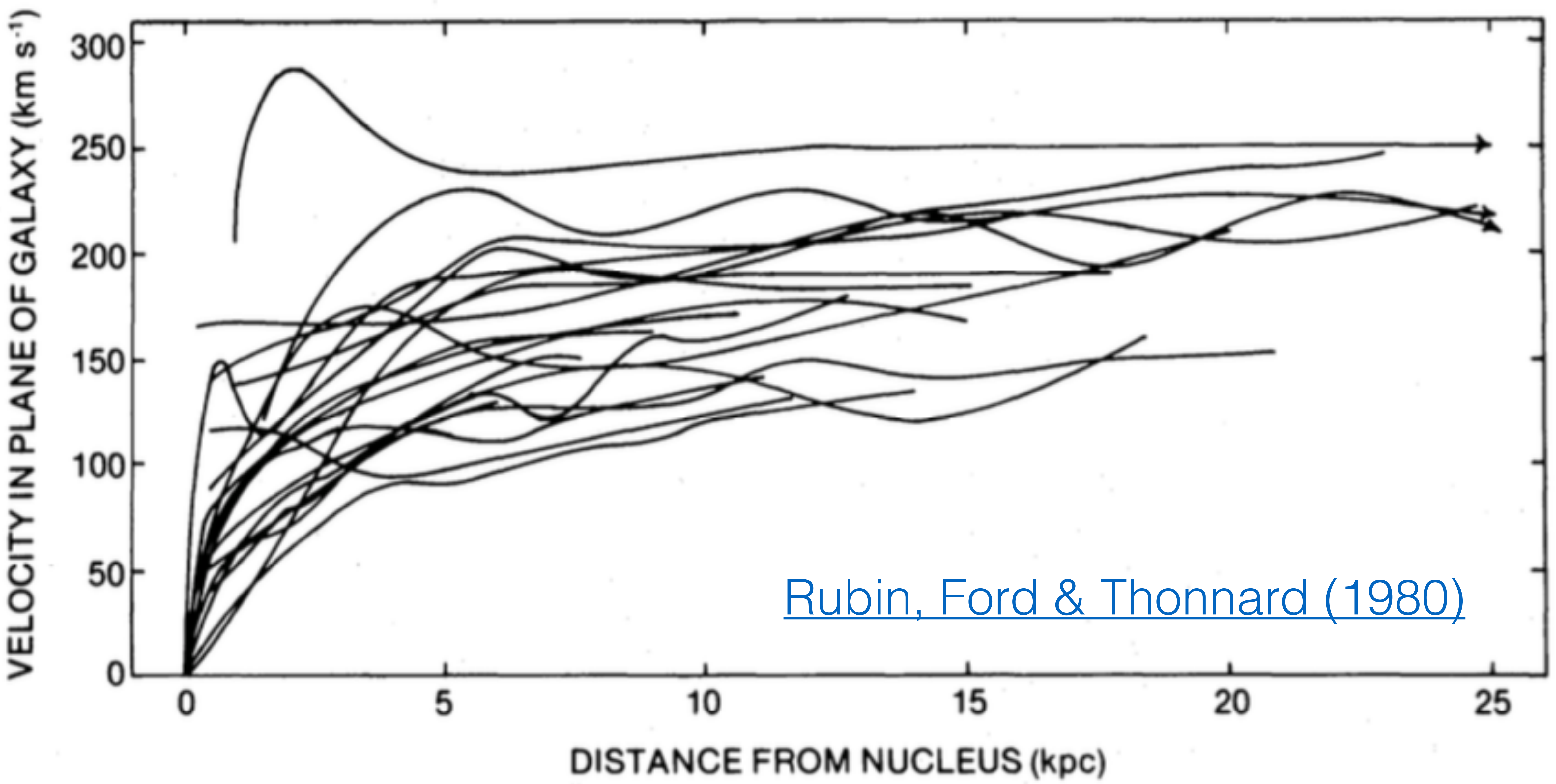

Rubin, Ford & Thonnard (1980)

Problem 1.2

Galaxies in Simulations

Dark matter has become an integral part of the standard cosmological model - the Λ **Cold Dark Matter (ΛCDM)** Model. DM plays a key role in our understanding of how Galaxies form, their properties and distributions.

Cosmological simulations can now produce realistic (and beautiful) Galaxies.

[IllustrisTNG simulation - 2101.12373]

[See also e.g. Auriga Simulations - 1610.01159]

Warning: Galaxy formation is messy and non-linear and still not fully understood (more on this later)

[E.g. 1609.05917 vs 1610.07663]


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icc.dur.ac.uk/Eagle
t_{age} = 0.5 Gyr
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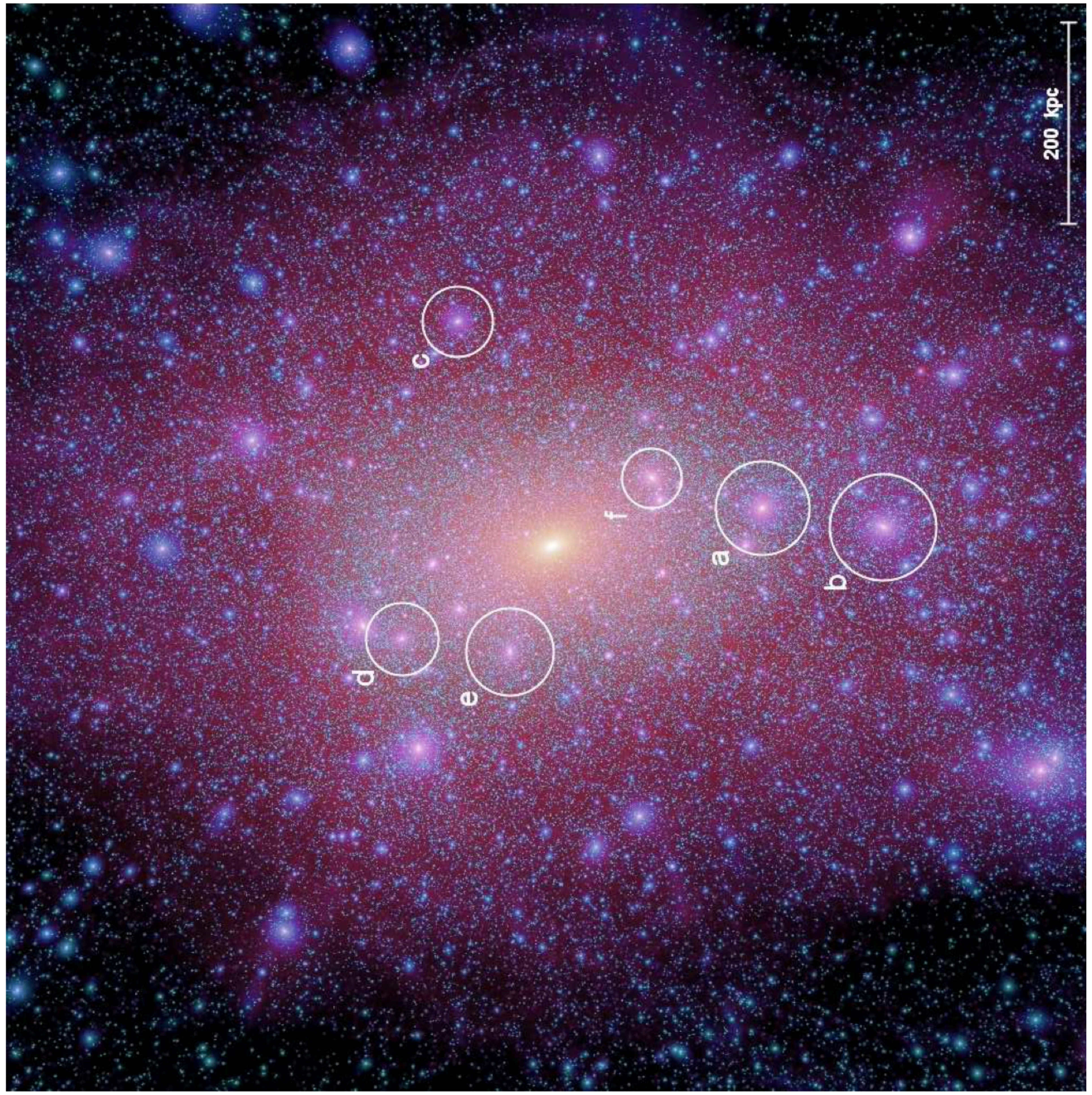
Cosmological and zoom-in simulations point to two crucial aspects of the Dark Matter distribution…

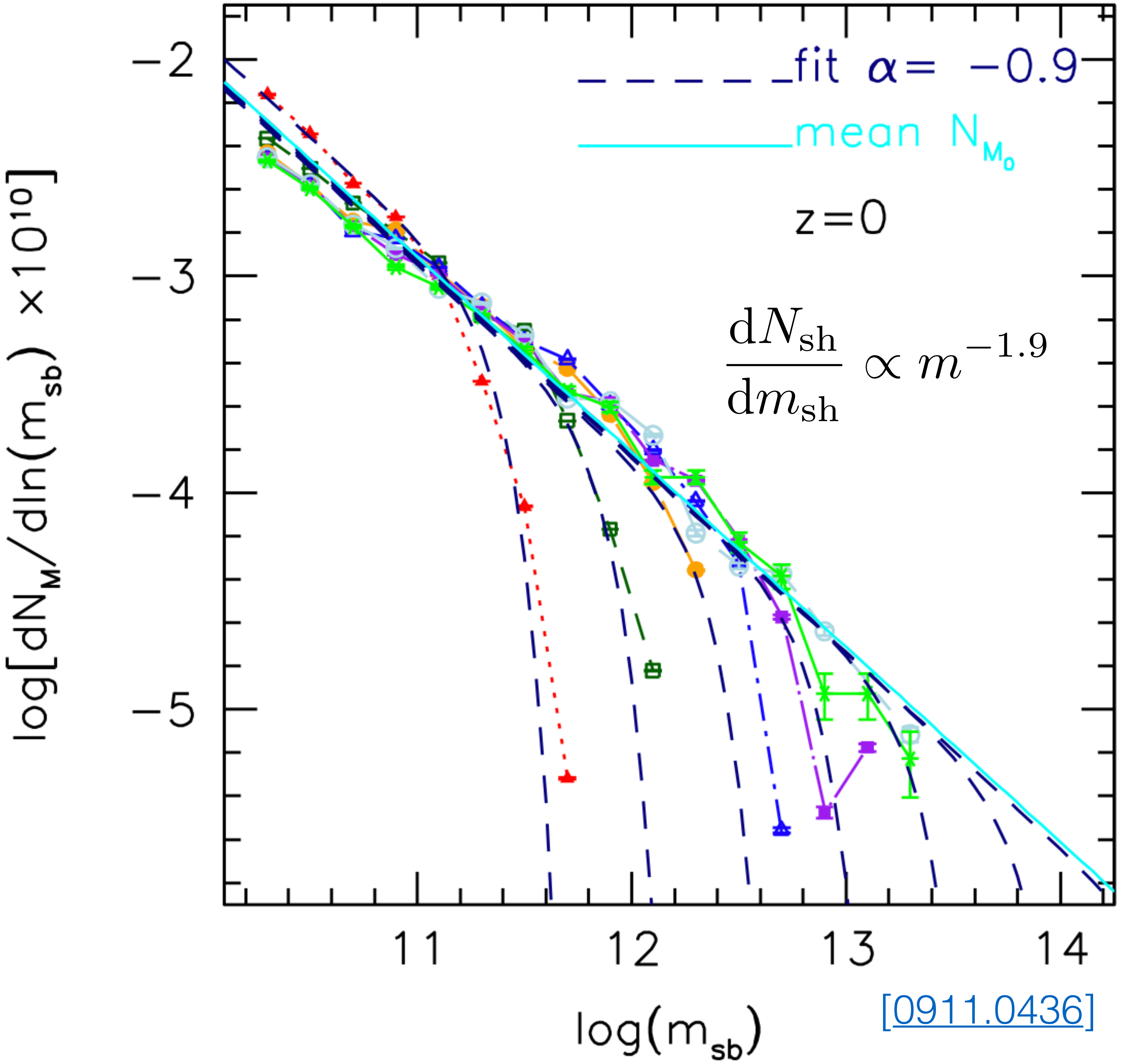
(1) Hierarchical Substructure

[Video on previous slide available here]

Structure formation proceeds ‘bottom-up’: small sub-halos assemble hierarchically to form larger halos.



[Aquarius simulation - 0809.0898]



[0911.0436]

(2) Universal Density Profiles

*More on this shortly.

Density profiles of cold* Dark Matter halos can be well fit over many orders of magnitude by the cuspy "Navarro-Frenk-White" (NFW) profile (1996): [astro-ph/9611107]

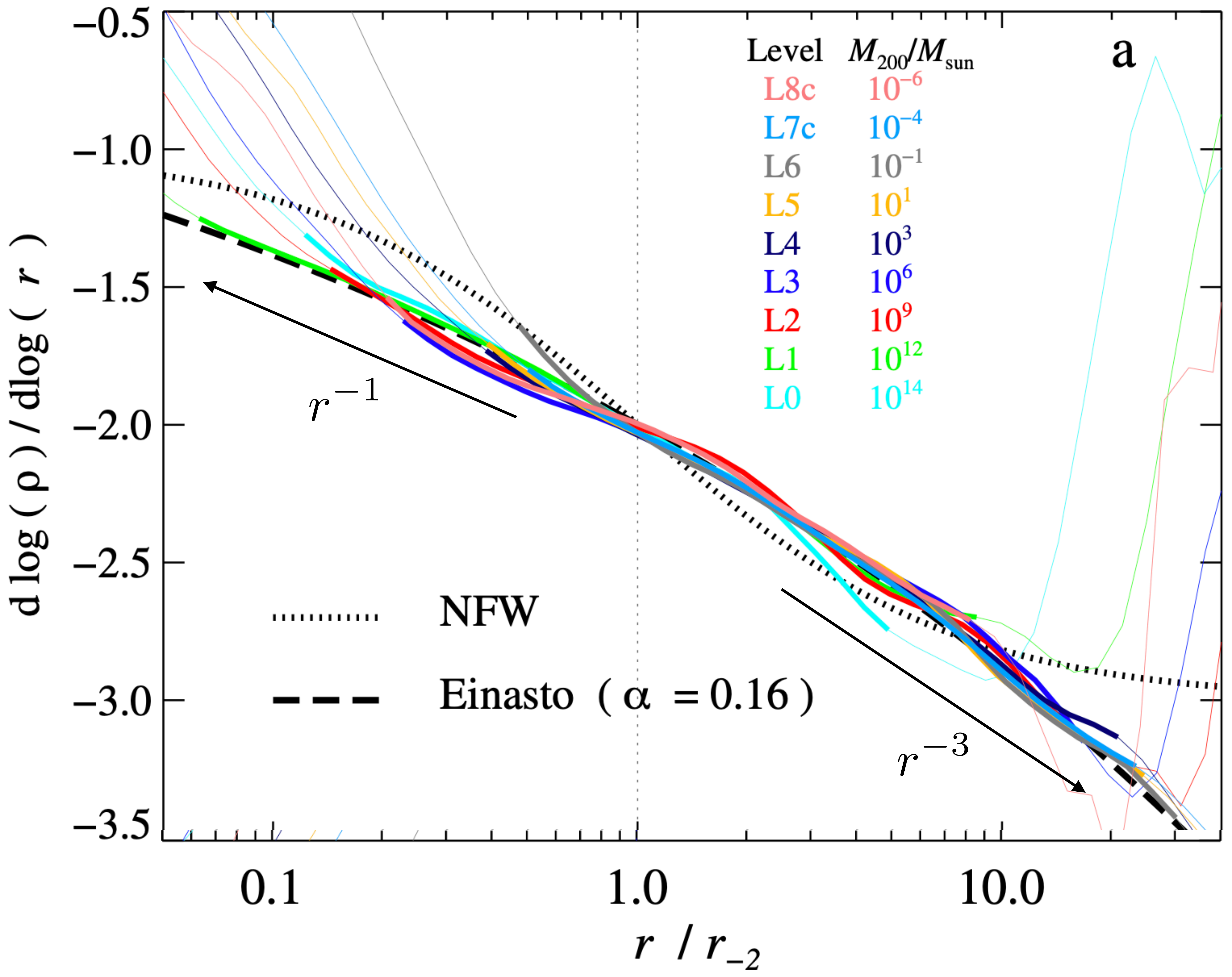
$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

Alternative fitting formulae include the Einasto profile (with $\alpha \approx 0.16$):

$$\rho_{\mathrm{Ein}}(r) = \rho_{-2} \exp\left[-2\alpha^{-1}\left((r/r_{-2})^{\alpha} - 1\right)\right]$$

Mass and concentration of halo ($c = r_s/r_{\max}$) depends on redshift of formation, but density profiles are almost universal.

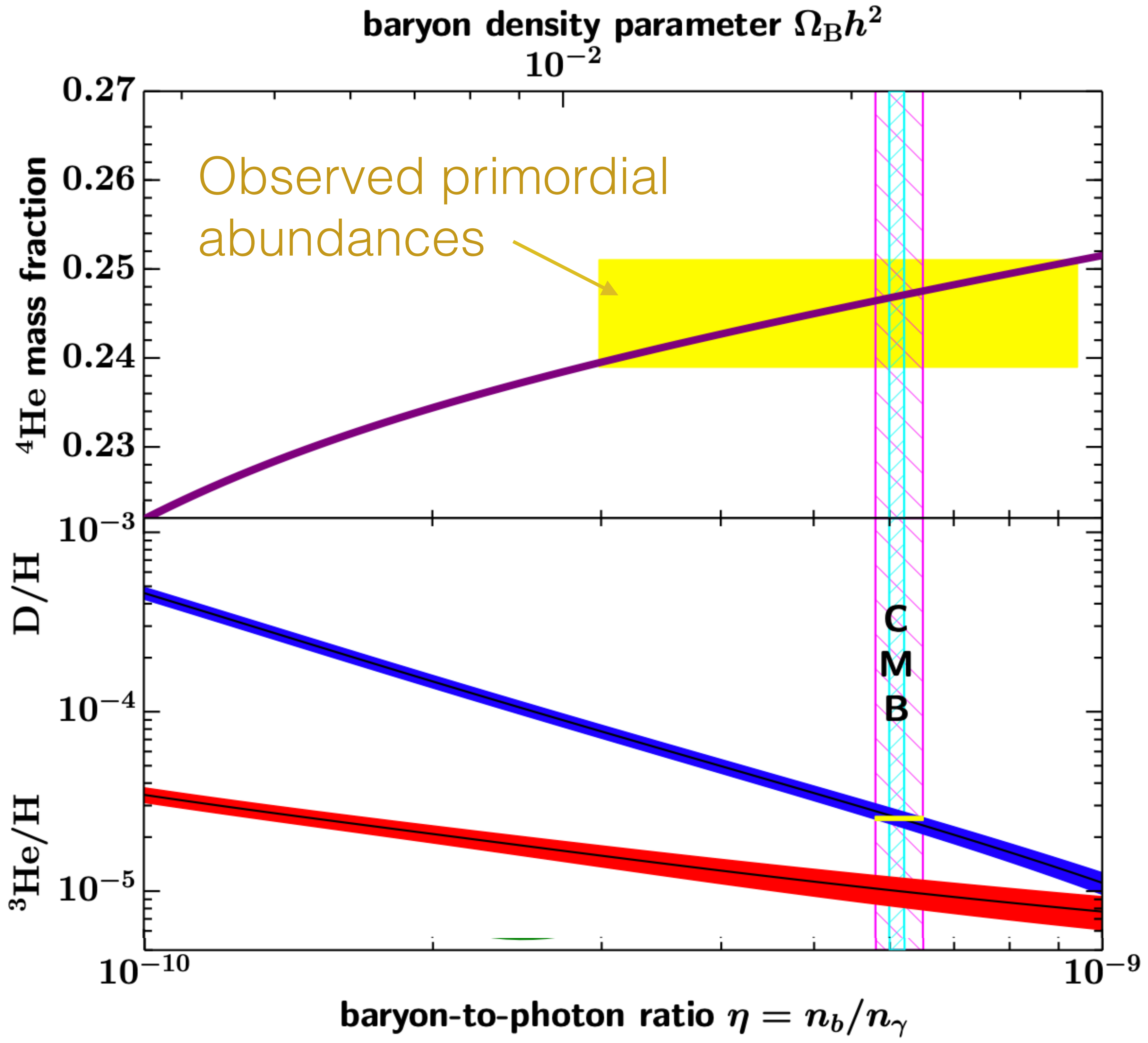
Caveat: inner density profile can be hard to probe due to resolution limitation.



[1911.09720]

Dark Matter properties

Non-baryonic: Dark Matter cannot consist of baryonic matter (protons, neutrons, etc). In particular, it cannot participate in Big Bang Nucleosynthesis (BBN) at $T > 1\,\mathrm{MeV}, t < 3\,\mathrm{mins}$



Dark Matter Shopping List

- Non-baryonic
- 'Neutral'
- 'Cold' (i.e. slow moving)
- Produced in sufficient amounts

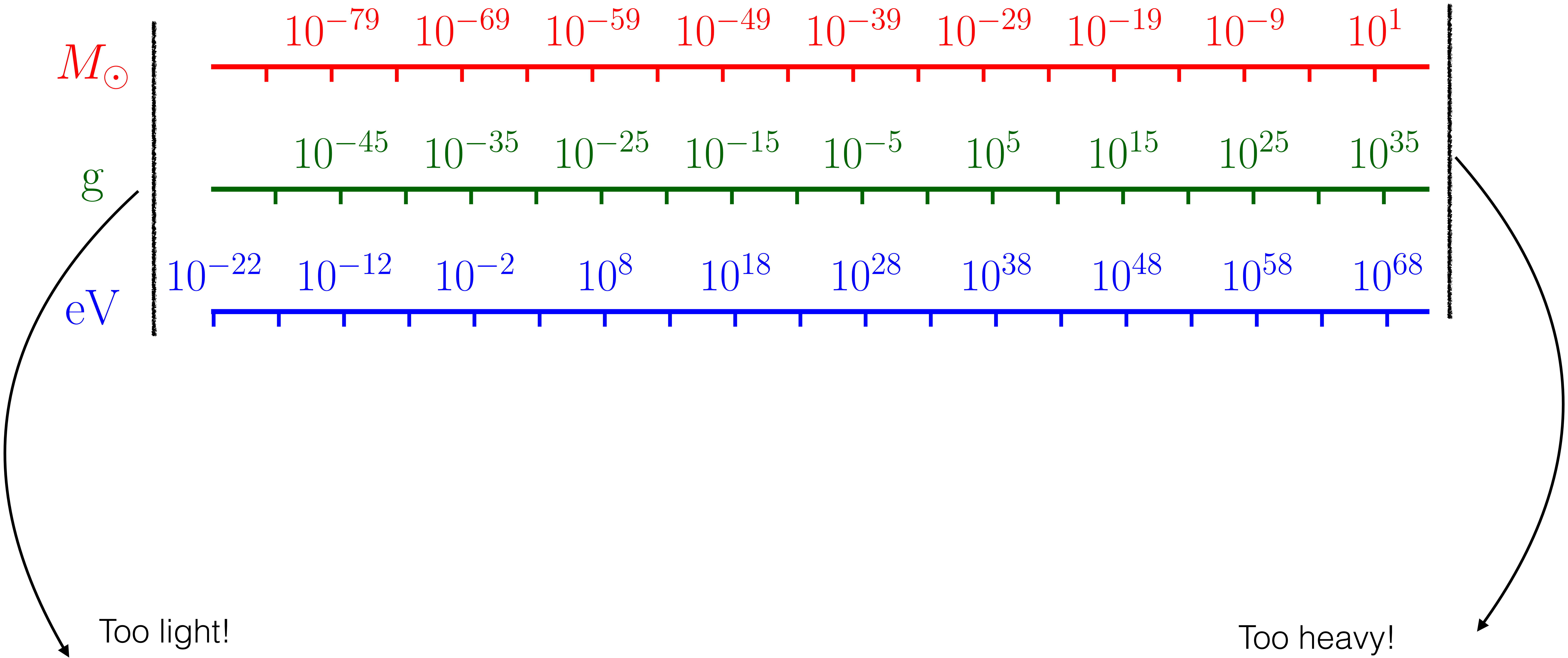
[0711.4996]

Neutral: Dark Matter cannot be charged*, otherwise it would couple to photons, affecting CMB anisotropies. It would also be able to dissipate energy (form visible stars/galaxies?)

*Strictly speaking, the Dark Matter cannot have a large charge-to-mass ratio (it could for example have a *millicharge*, much smaller than the electron charge).

Cold relic: It has to be produced in the correct abundance, with the correct 'temperature' in order to explain the observed distribution of structure in the Universe…

Dark Matter mass range

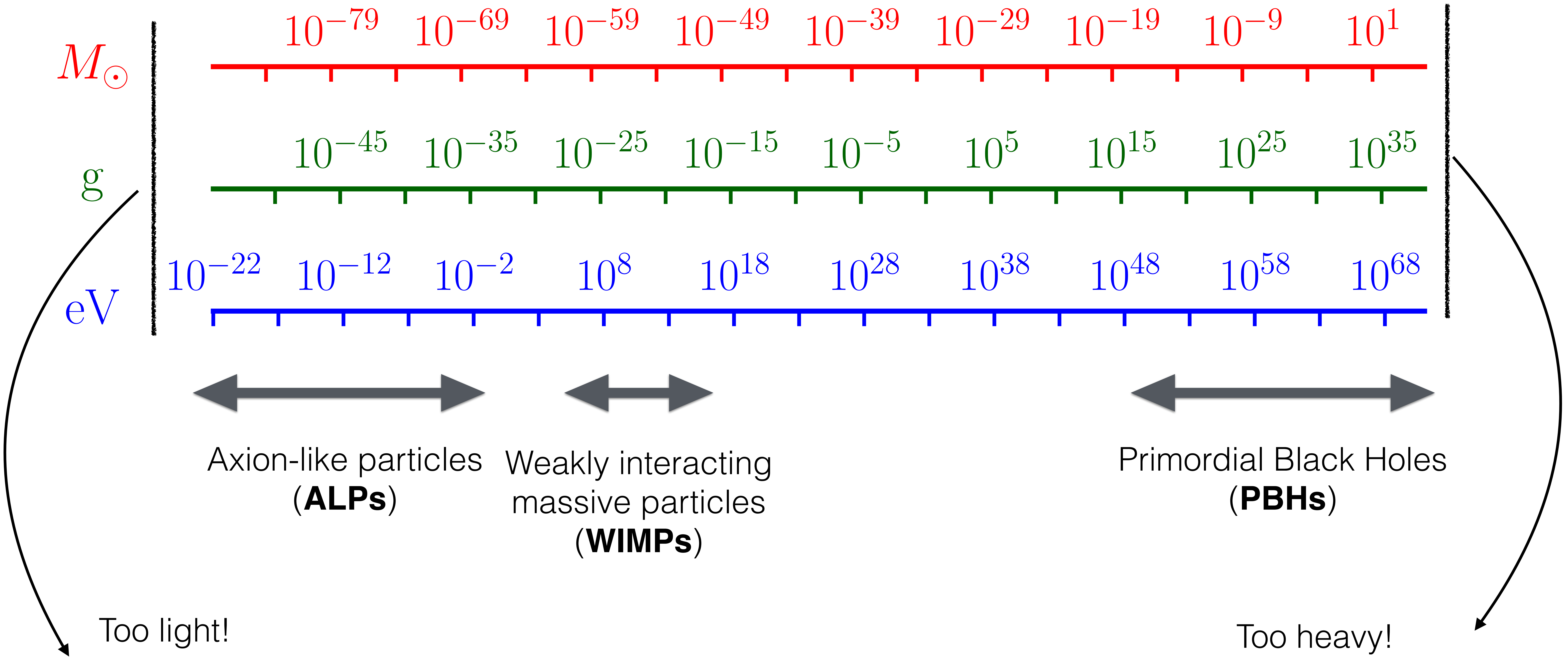


Too light!
Has wave-like properties on
galactic scales!

Too heavy!
DM mass comparable to
galactic masses!

Problem 1.3

Dark Matter mass range



Axion-like particles
(**ALPs**)

Weakly interacting
massive particles
(**WIMPs**)

Primordial Black Holes
(**PBHs**)

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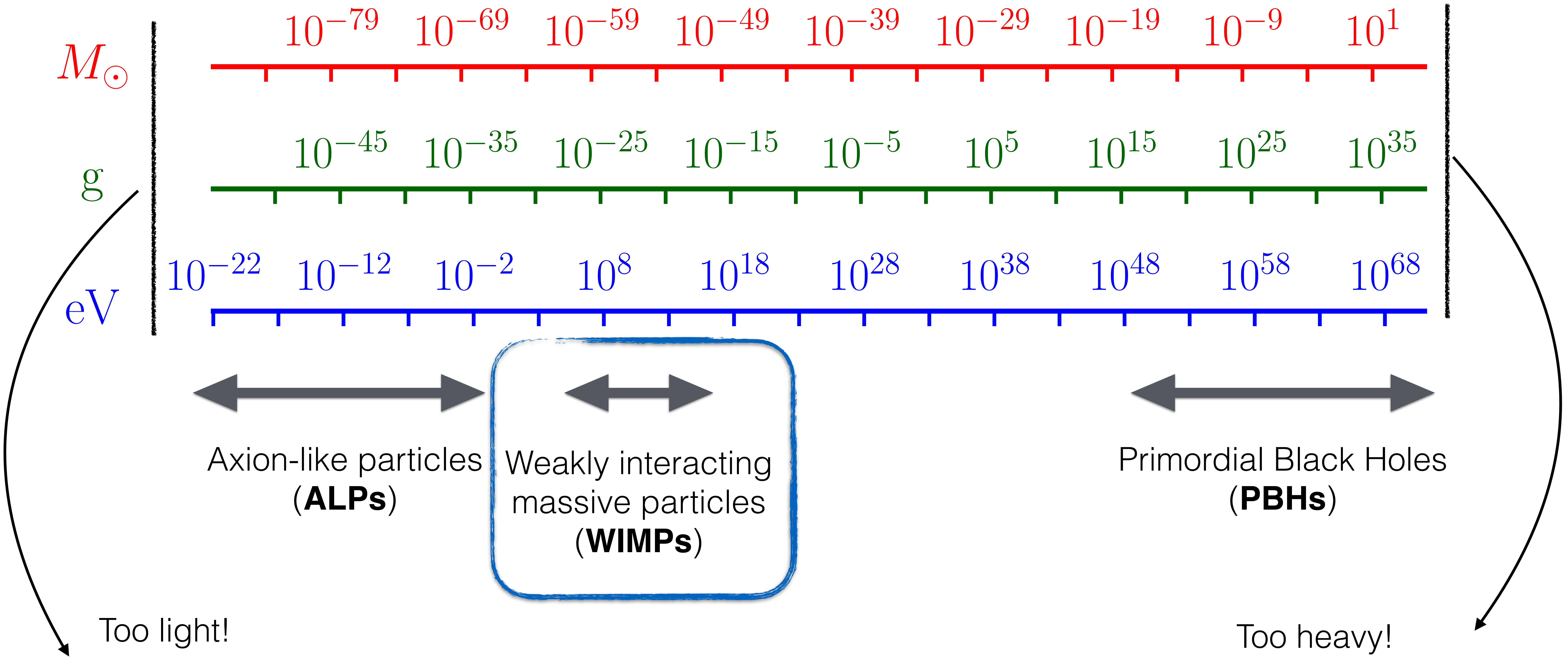
Dark Matter mass range



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Problem 1.3

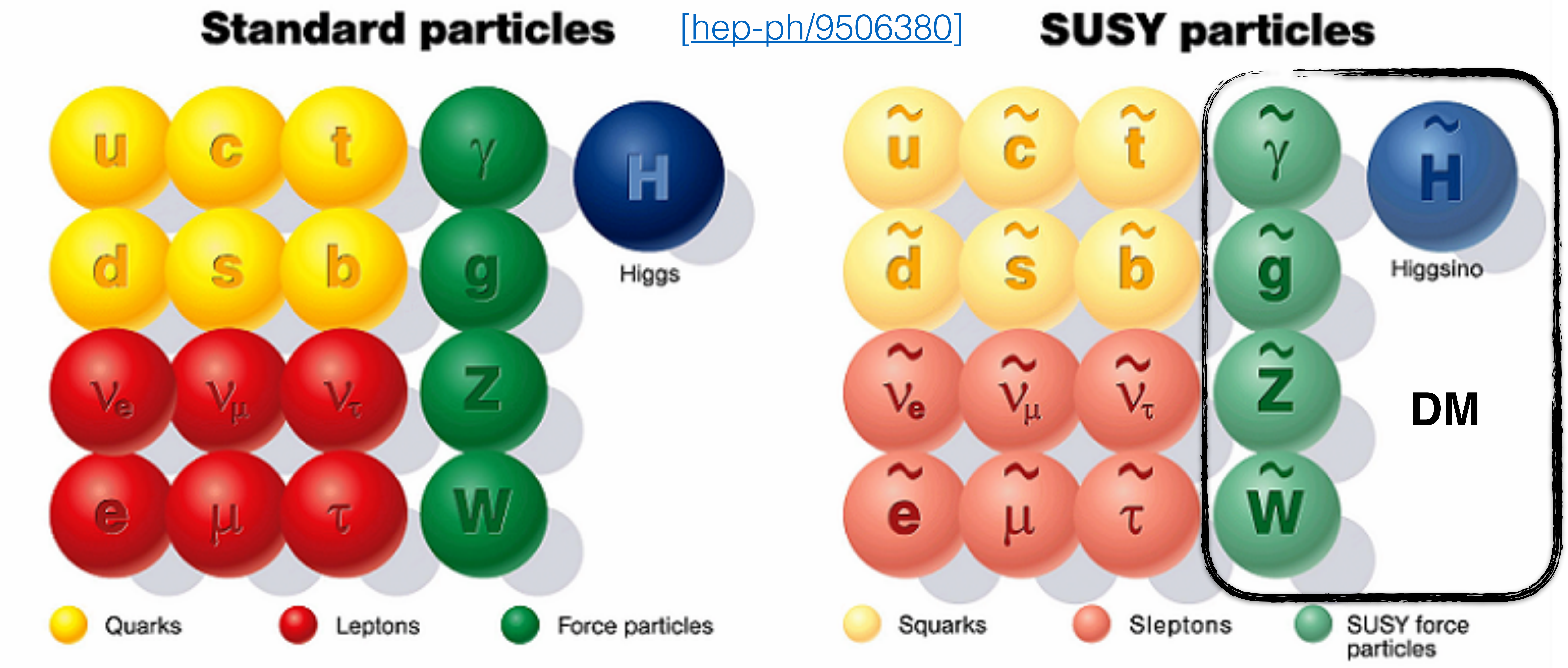
Weakly Interacting Massive Particles

See Standard Model and Beyond Lectures

Weakly Interacting Massive Particles (WIMPs) are a class of particles with couplings comparable to the Standard Model Weak Interactions. Typically in the mass range $1\,\mathrm{GeV} \lesssim m_\chi \lesssim 100\,\mathrm{TeV}$.

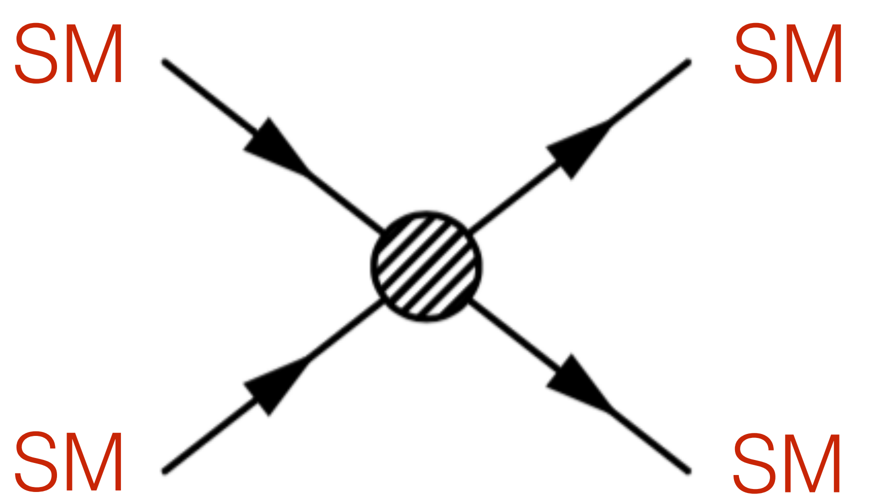
WIMPs generically arise in models of Supersymmetry (SUSY), proposed to solve the Hierarchy Problem in the Standard Model (“why is the Higgs boson so light, when its mass should received receive corrections from loops of heavy particles?”)

In some SUSY models (r-parity conserving), the lightest supersymmetric particle is stable, making it a natural Dark Matter candidate.

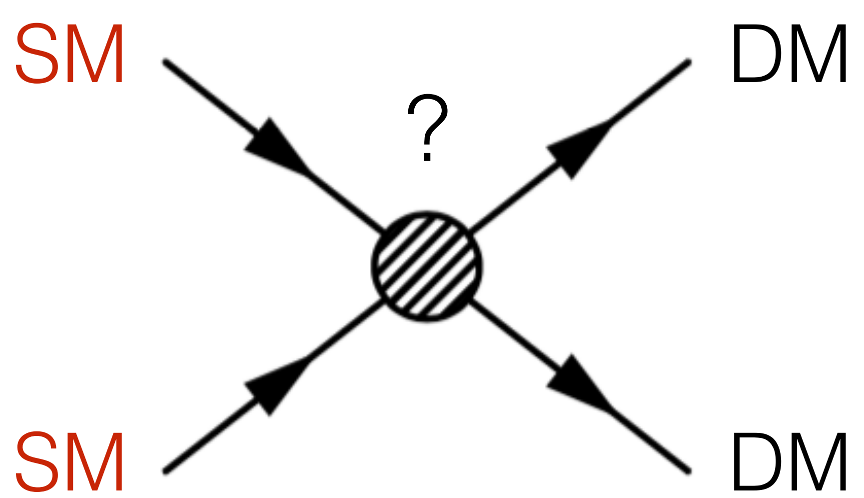


Now, the term WIMP is used to mean a generic MeV-TeV mass particle with weak couplings to the standard model.

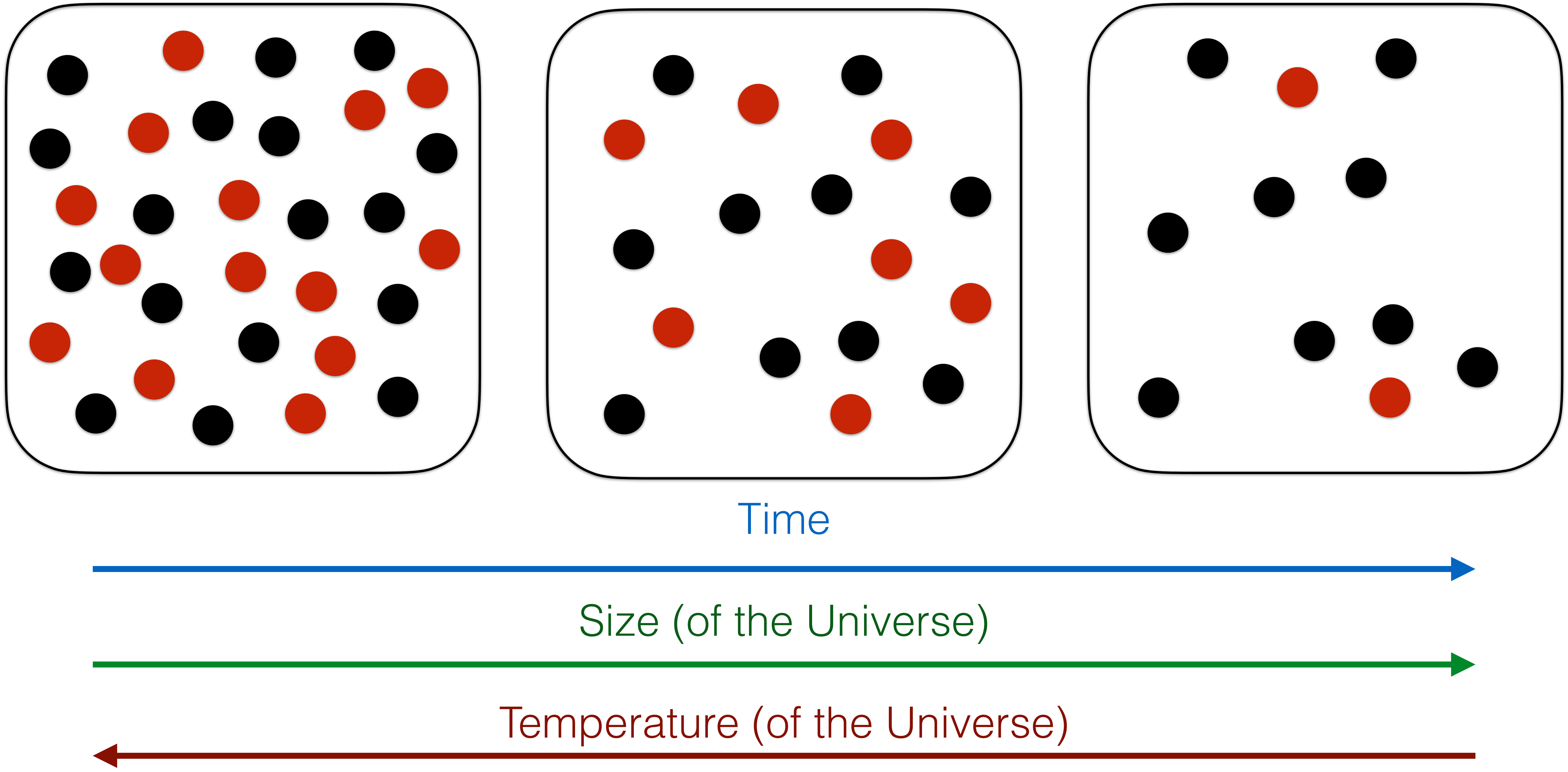
Producing WIMP Dark Matter



$\mathrm{SM} + \mathrm{SM} \leftrightarrow \mathrm{SM} + \mathrm{SM}$



$X + \bar{X} \leftrightarrow \mathrm{SM} + \mathrm{SM}$



Time

Size (of the Universe)

Temperature (of the Universe)

The Boltzmann Equation

See Cosmology Lecture 2

For a species χ initially in thermal equilibrium, their number density n_χ is governed by the Boltzmann Equation:

(Thermally averaged) DM annihilation cross section

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}}v\rangle_{\mathrm{eq}}\left[n_\chi^2 - n_{\chi,eq}^2\right]$$

Dilution due to expansion

Annihilation of DM

Production of DM

Equilibrium number density for fermions is given by:

$$n_{\mathrm{eq}}(T) = \begin{cases} \frac{3}{4}\frac{\zeta(3)}{\pi^2}gT^3 & \text{for } T \gg m_\chi \qquad \text{(relativistic)} \\ g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \qquad \text{(non-relativistic)}\,. \end{cases}$$

If the interaction rate is large compared to Hubble expansion rate, then particles stay in equilibrium with the SM bath. Once interaction rate drops (for example, due to decreasing number density), the number density departs from equilibrium. Similar to neutrino decoupling…

This **Freeze-out** occurs roughly when the annihilation rate per particle equals the Hubble expansion rate:

$$\Gamma \equiv n_\chi\langle\sigma_{\chi\bar{\chi}}v\rangle_{\mathrm{eq}} \sim 1/H$$

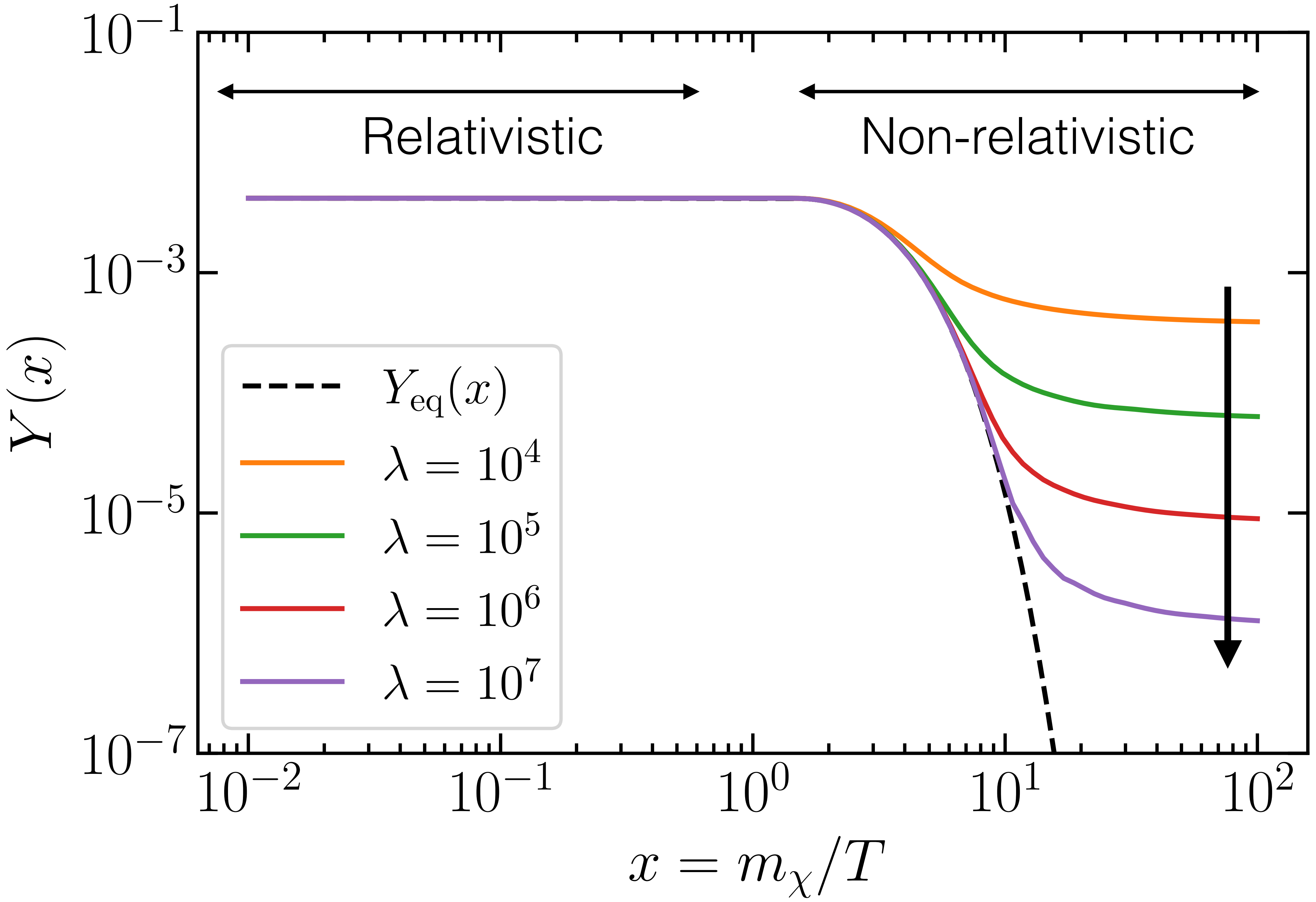
Freeze-out

$s_0 = 2890\ \mathrm{cm}^{-3}$

Convenient to transform Boltzmann Equation in terms of $x = m_\chi/T$, and the entropy density $s = (2\pi^2/45)g_{\star s}(T)T^3$. The equation for the Yield $Y(x) \equiv n/s$ is then:

Ricatti Equation: $$\frac{\mathrm{d}Y}{\mathrm{d}x} = -\frac{\lambda}{x^2}\left[Y^2 - Y_{\mathrm{eq}}^2\right] \qquad \lambda = \frac{2\pi^2}{45} g_{\star s} \frac{m_\chi^3 \langle \sigma v \rangle}{H(T = m_\chi)}$$

At the freeze-out temperature x_f, deviate from equilibrium. Solving numerically, typically find $x_f \sim 5 - 10$.



Increasing $\langle \sigma v \rangle$ (at fixed m_χ)

At late times, $Y \gg Y_{\mathrm{eq}}$, solve to find the present-day yield $Y(x_0) \approx x_f/\lambda$ and the present day DM abundance given by:

$$\boxed{\rho_{\mathrm{DM}} = m_\chi Y(x_0) s_0 \propto \frac{x_f}{\langle \sigma v \rangle}}$$

(where we've used that during radiation domination $a \propto t^{1/2} \Rightarrow H(T) \propto T^2$)

Problem 1.4

Cold vs Hot Dark Matter

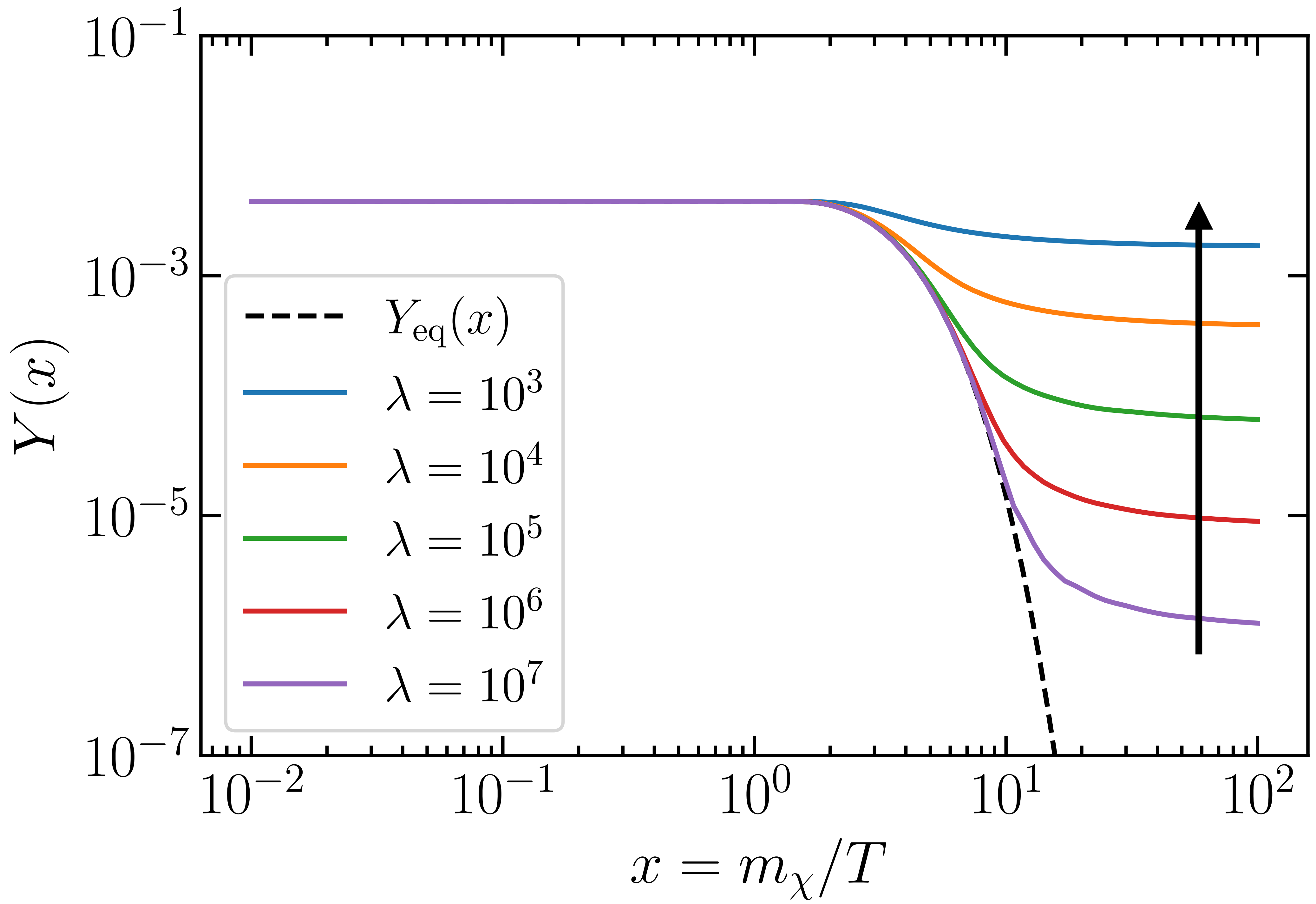
$$\lambda = \frac{2\pi^2}{45} g_{\star s} \frac{m_\chi^3 \langle \sigma v \rangle}{H(T = m_\chi)}$$

$$\rho_{\rm DM} = m_\chi Y(x_0) s_0 \propto \frac{x_f}{\langle \sigma v \rangle}$$

$$\Rightarrow \Omega_{\rm DM} h^2 \approx \frac{3 \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

Fix $\langle \sigma v \rangle$ (to fix the correct relic abundance).

Decreasing m_χ decreases λ, pushing x_f smaller…



Decreasing m_χ (at fixed $\langle \sigma v \rangle$)

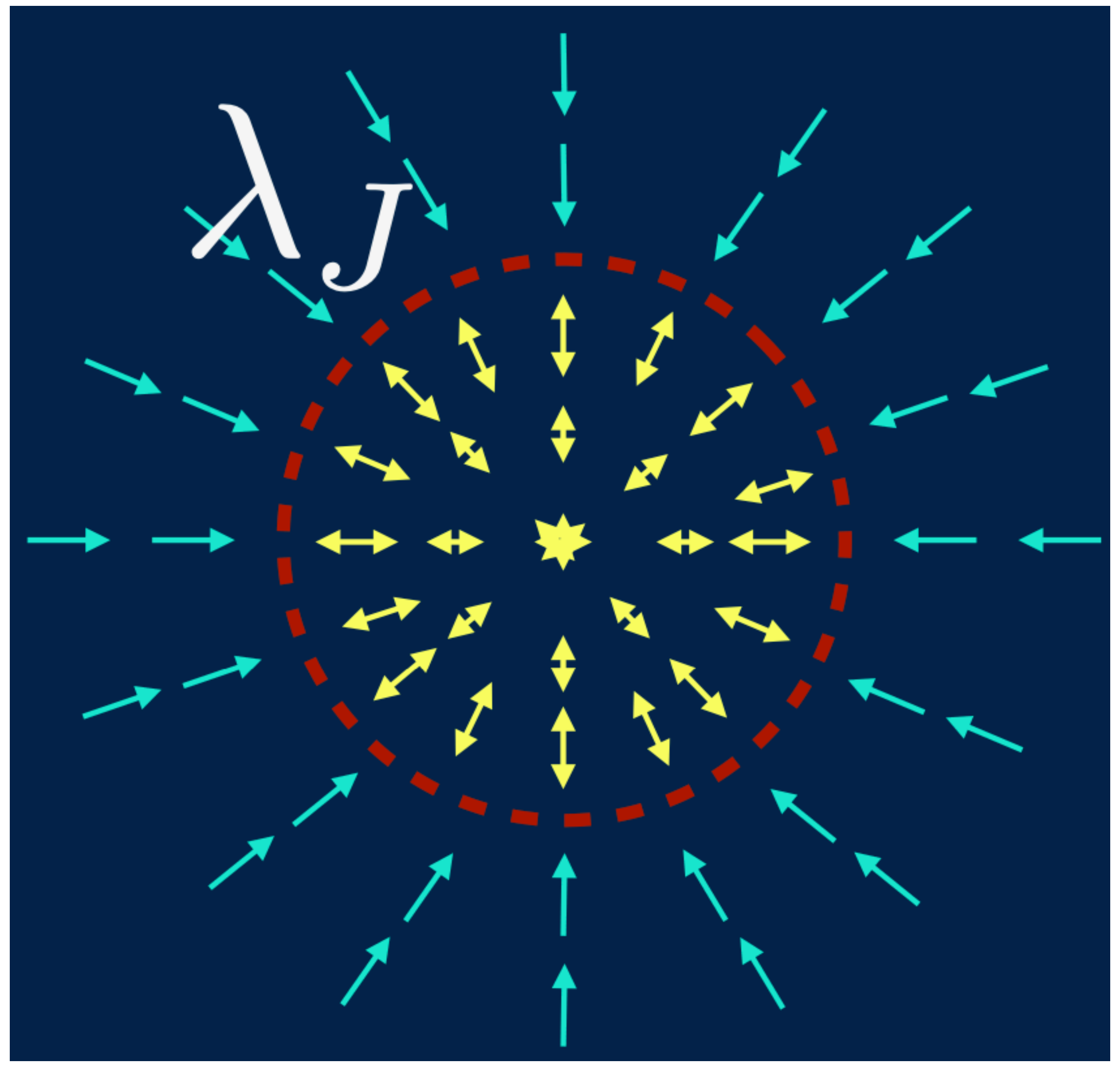
Very light relics $m \lesssim \mathrm{eV}$ decouple and freeze out when they are still relativistic! We call such particles **Hot Dark Matter**. Standard Model Neutrinos are Hot Dark Matter!

In order to explain the observed structure in the Universe, Dark Matter must freeze-out when non-relativistic i.e. it must be **Cold Dark Matter**.

As we will see, Dark Matter which is produced semi-relativistically may also be viable + testable: **Warm Dark Matter**.

Free-streaming

See Cosmology Lecture 3



Jeans equation for the growth of overdensities $\delta \equiv \delta\rho/\bar{\rho}$ in a collisional fluid:

$$\ddot{\delta} + 2H\dot{\delta} + \left(\frac{k^2 c_s^2}{a^2} - 4\pi G\bar{\rho}\right)\delta = 0$$

Expansion Pressure Gravity

For a *collisionless* fluid, such as DM, the role of pressure is played by the velocity dispersion of the fluid, and we can replace $c_s^2 = \sigma^2$.

As in the collisional case,
we can write the Jeans length as

$$\lambda_J(t) = \sqrt{\frac{\pi\sigma(t)^2}{G\bar{\rho}(t)}}$$

→

$\lambda > \lambda_J$: Gravitational Collapse
$\lambda < \lambda_J$: **Free streaming** damping

Physically, we can think of the Jeans length as the scale at which the DM crossing time $t_{\rm cross} \sim \lambda/\sigma$ is comparable to the gravitational collapse timescale $t_{\rm coll} \sim 1/\sqrt{G\bar{\rho}}$. Free-streaming length can be evaluated roughly as $\lambda_{\rm fs} \sim \lambda_J(t_{\rm eq})$, after which point the Jeans length drops rapidly.

Hot Dark Matter freezes out when relativistic, then has a velocity dispersion which is too large at late times. This means that $\lambda_{\rm fs}$ is large: Structure is washed out on small scales!

Problem 1.5

Alternative Production Mechanisms

A wide range of alternative production mechanisms, depending on the DM candidate:

Freeze-out [Kolb & Turner (1990)]
Freeze-in [arXiv:0911.1120]
Asymmetric Dark Matter [arXiv:1305.4939]
Forbidden Dark Matter [arXiv:1505.07107]
Secluded Dark Matter [arXiv:0711.4866]
SIMP Dark Matter [arXiv:1402.5143]
Self-interacting Dark Matter [arXiv:1510.08063]
Misalignment Mechanism [arXiv:1105.2812]
Gravitational production (WIMPzillas!) [hep-ph/9810361]
Hidden sector freeze-out [arXiv:1712.03974]
Early kinematic decoupling [arXiv:1706.07433]
Elastically decoupling relics [arXiv:1706.05381]
Semi-annihilating Dark Matter [arXiv:1611.09360]

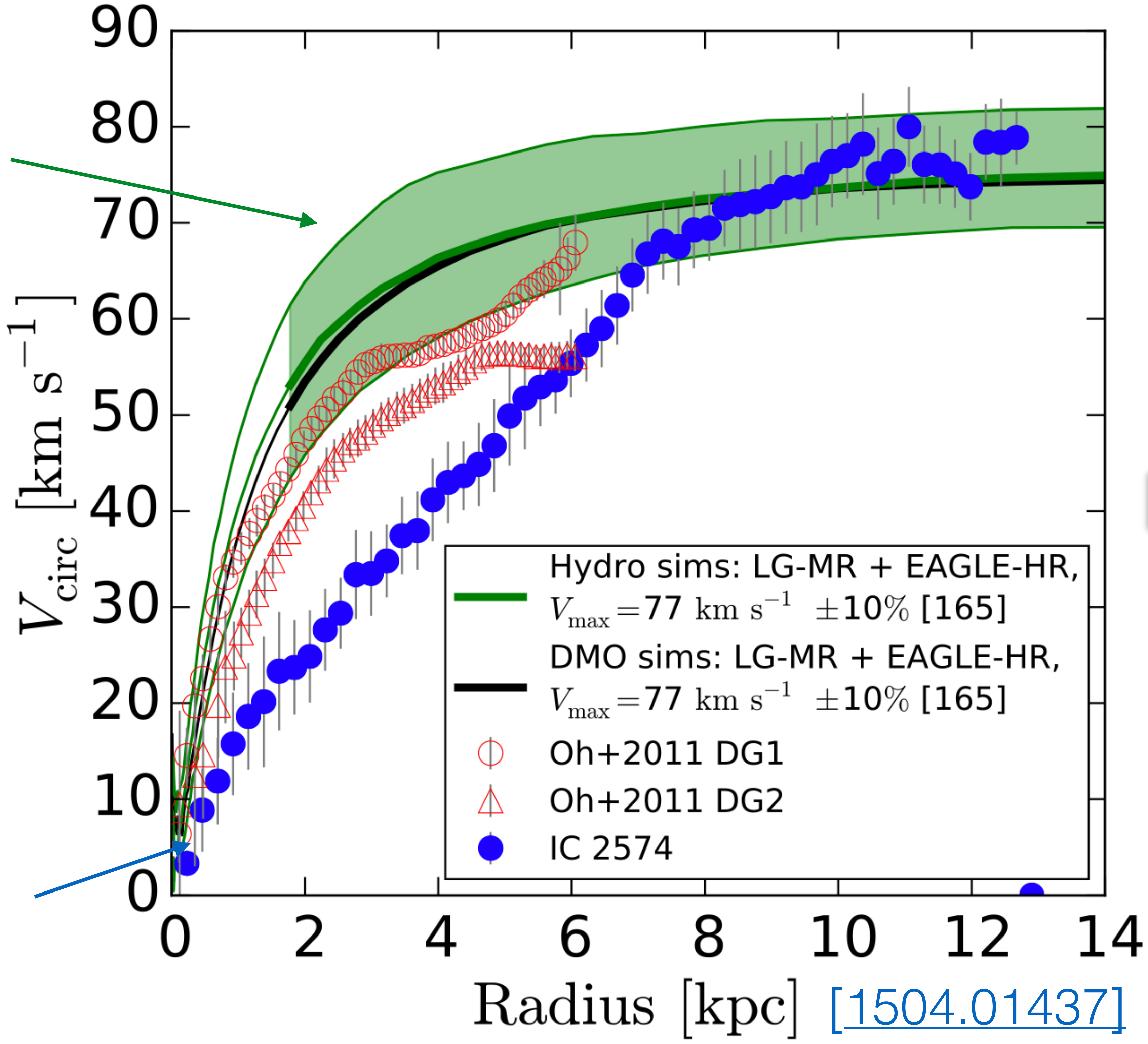
But all of them should satisfy constraints from early Universe, structure formation and astrophysics!

Small-scale problems

Core-vs-cusp problem (Now sometimes called the “diversity of rotation curves’ problem)

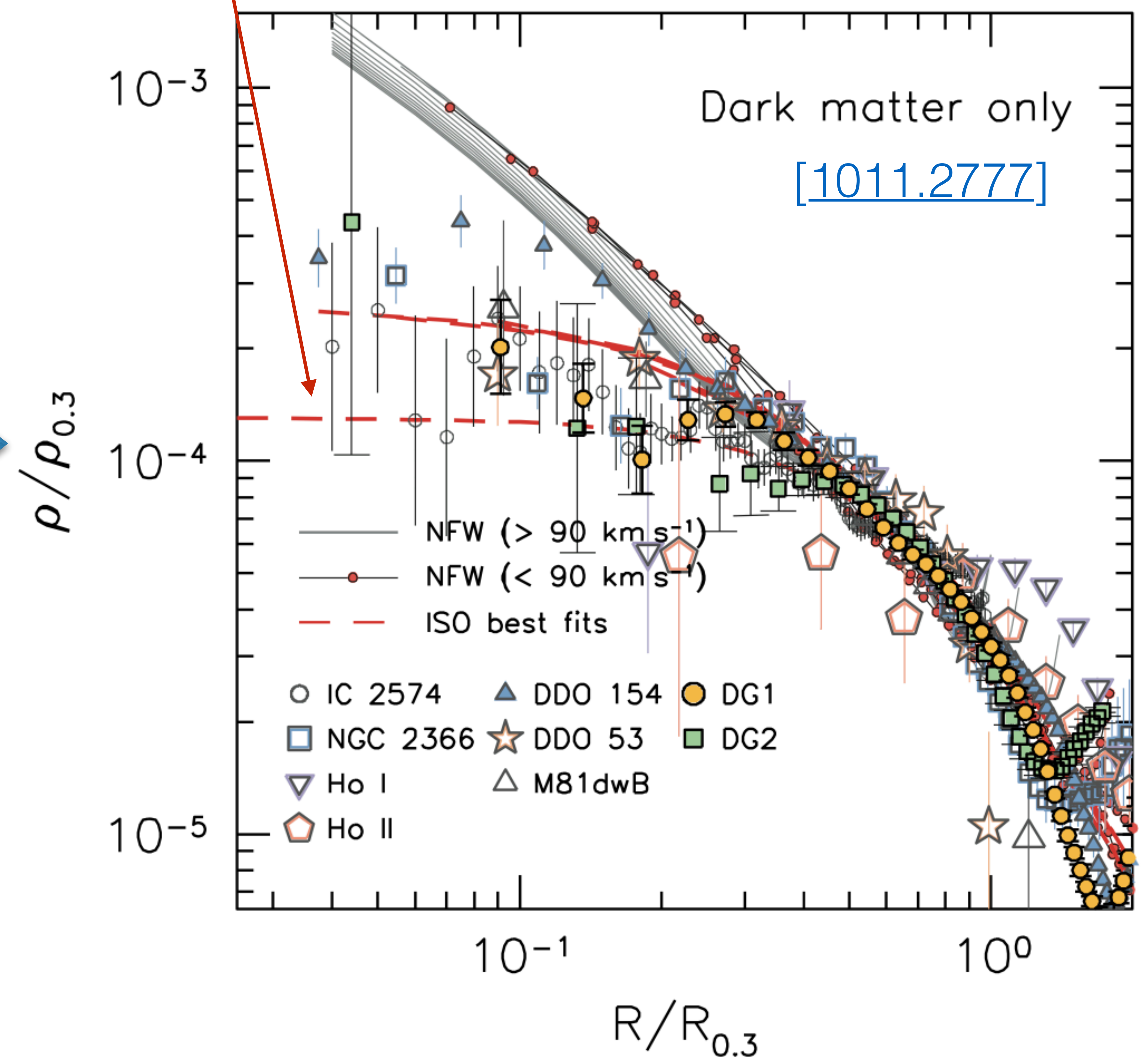
Rotation curve from comparable simulated dwarf galaxies with a ‘cuspy’ DM density profile

Measured rotation curve



[1504.01437]

Suggests some Dwarf Galaxies host ‘cored’ density profiles, rather than ‘cuspy’ NFW profiles!



[1011.2777]

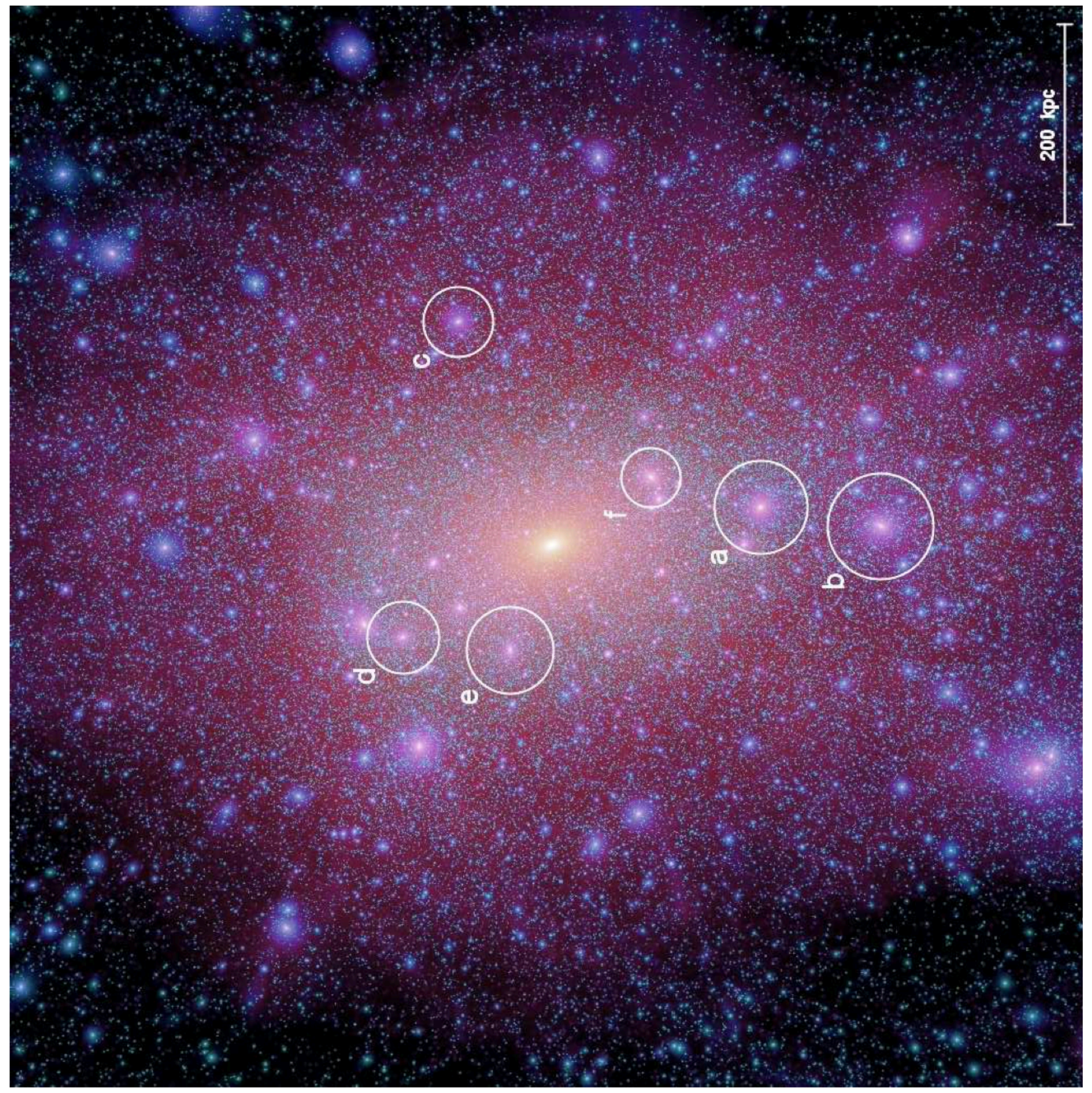
See also “Too big to fail”, “Plane of Satellites”, and others…

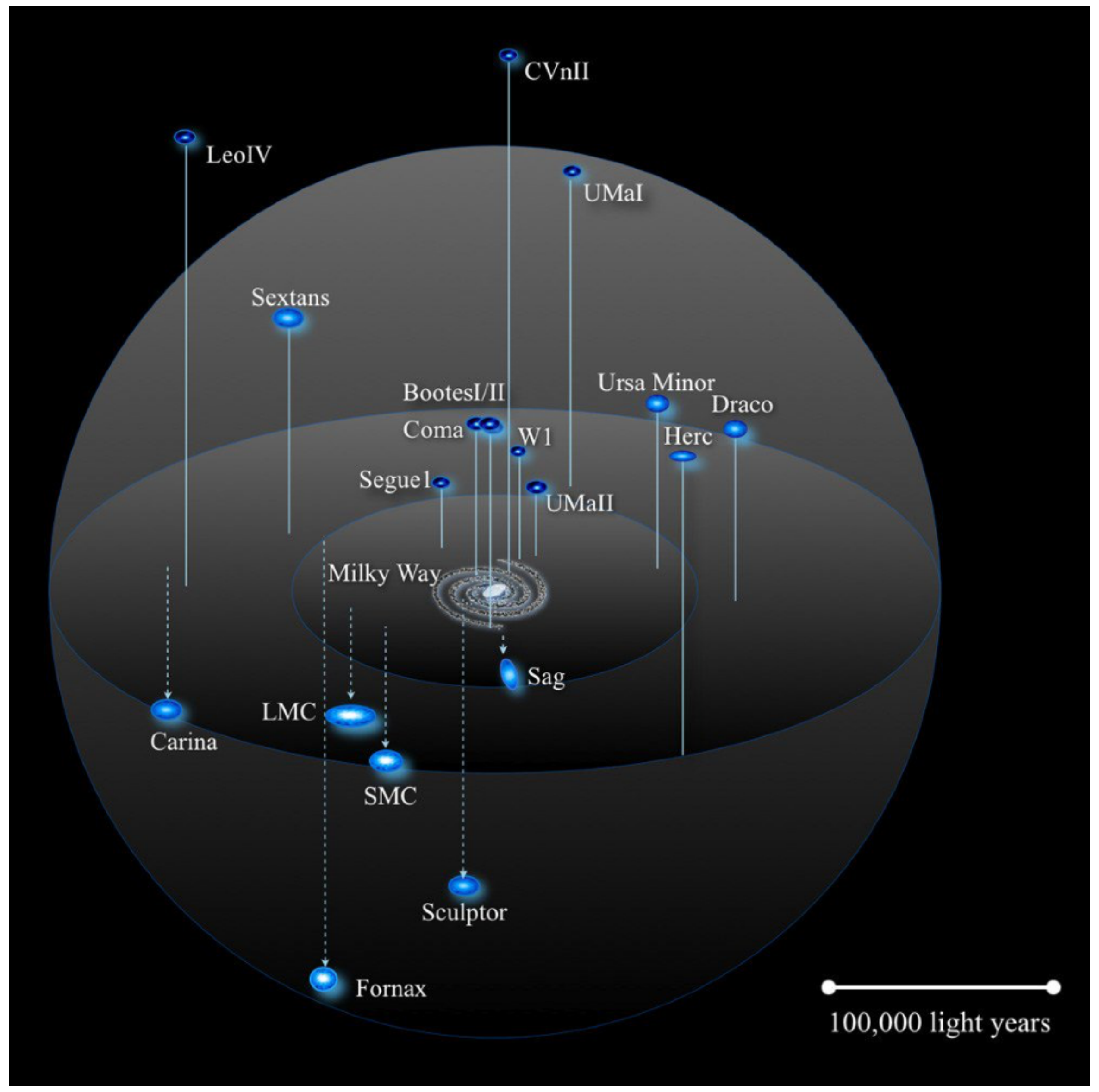
[Sales, Wetzel & Fattahi, 2206.05295]

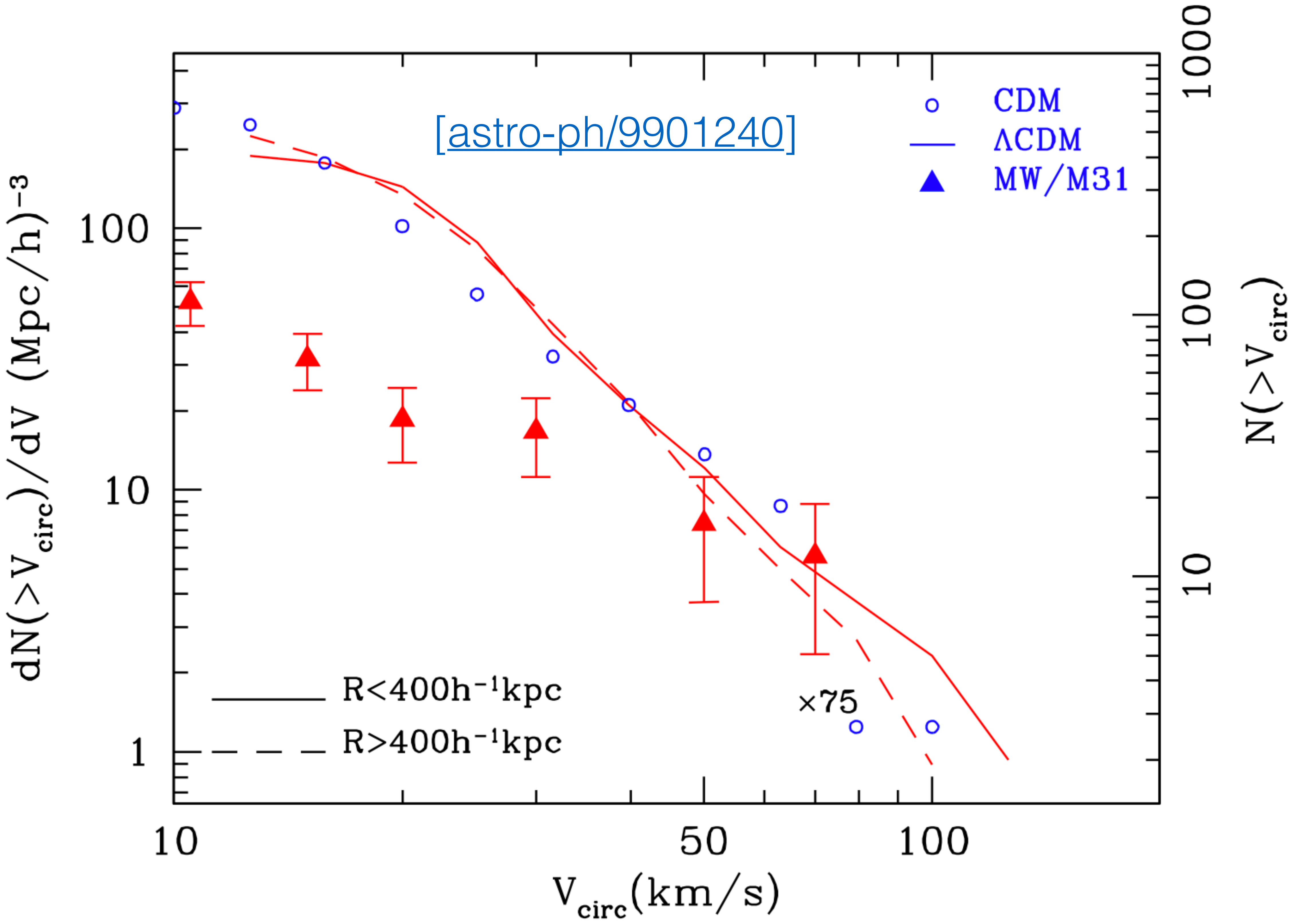
Small-scale problems

Missing Satellites Problem

ΛCDM predicts many more low-mass satellite galaxies of the Milky Way (and Andromeda).
Where is this small-scale structure?







Proxy for dwarf galaxy mass

See also “Too big to fail”, “Plane of Satellites”, and others…

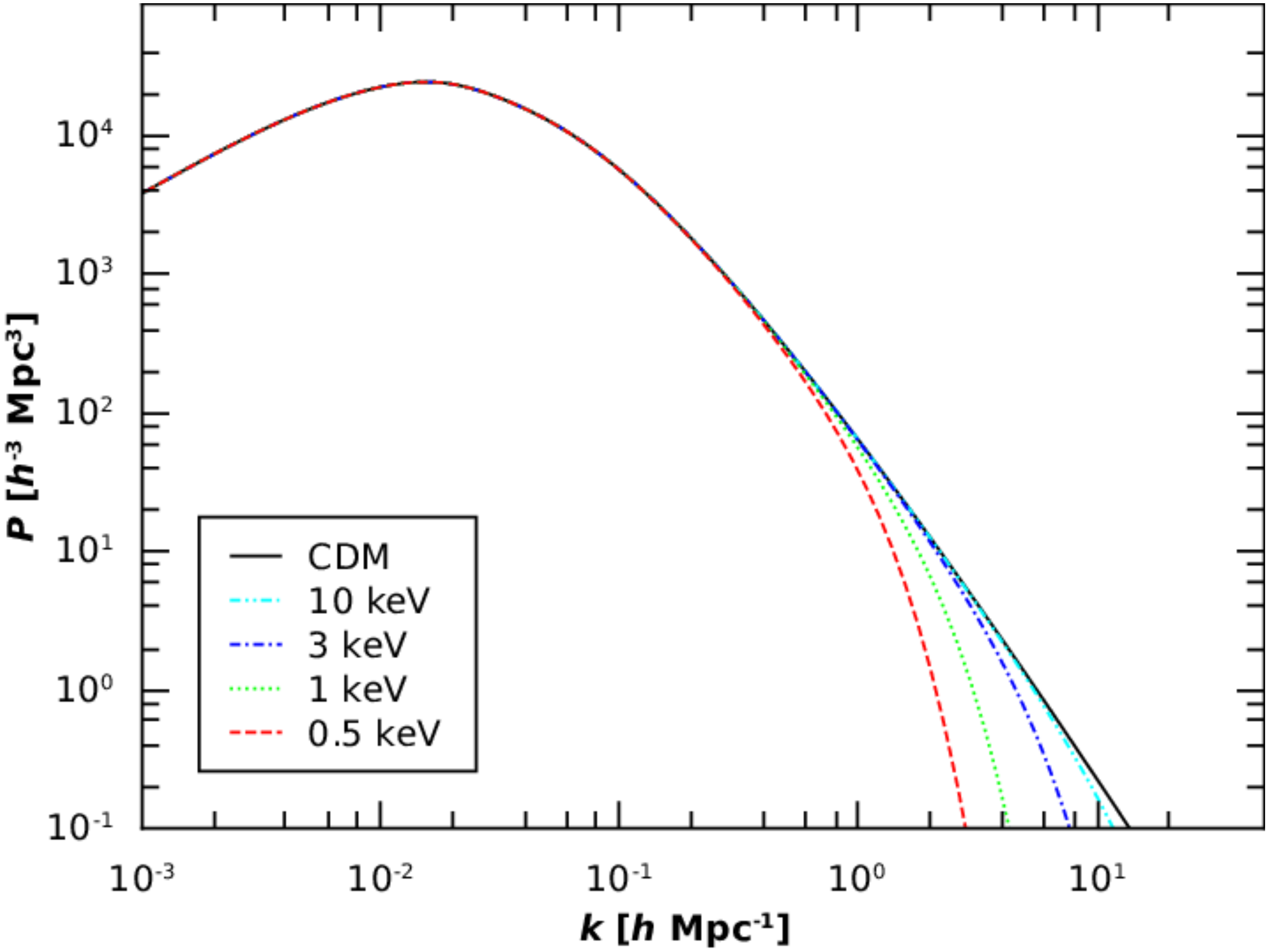
[Sales, Wetzel & Fattahi, 2206.05295]

Warm Dark Matter

One proposal for resolving these ‘small-scale tensions’ is **Warm Dark Matter**, which freezes-out semi-relativistically, washing out structure down to some small scale (but preserving structures on Galaxy scales)

A detailed calculation of the free-streaming damping finds that the comoving lengthscale at which the linear perturbation amplitude drops by a factor of 2 is:

$$R_S \approx 0.47 \left(\frac{\mathrm{keV}}{m_\chi}\right)^{1.15} \mathrm{Mpc}$$

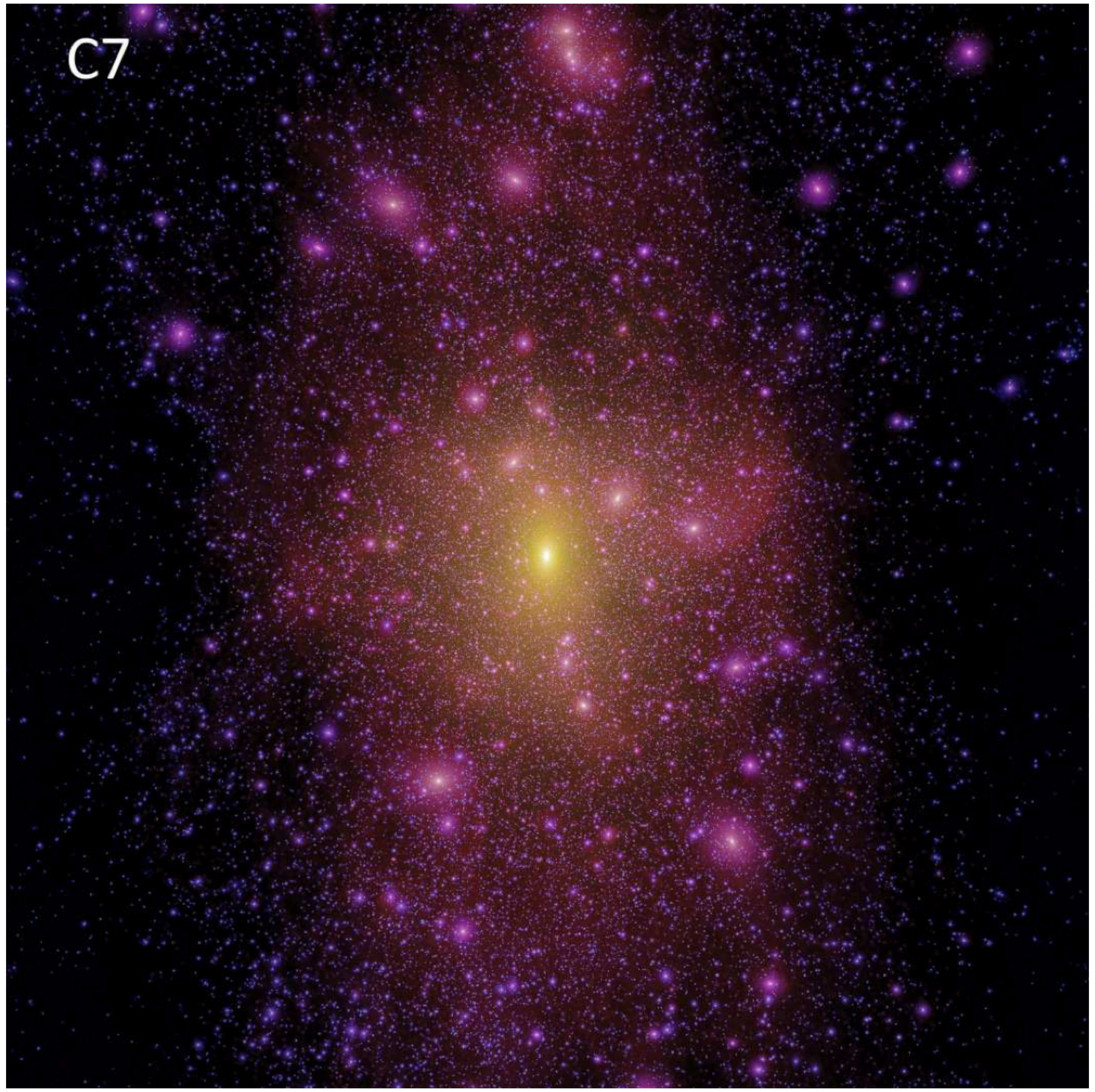


[astro-ph/0010389]

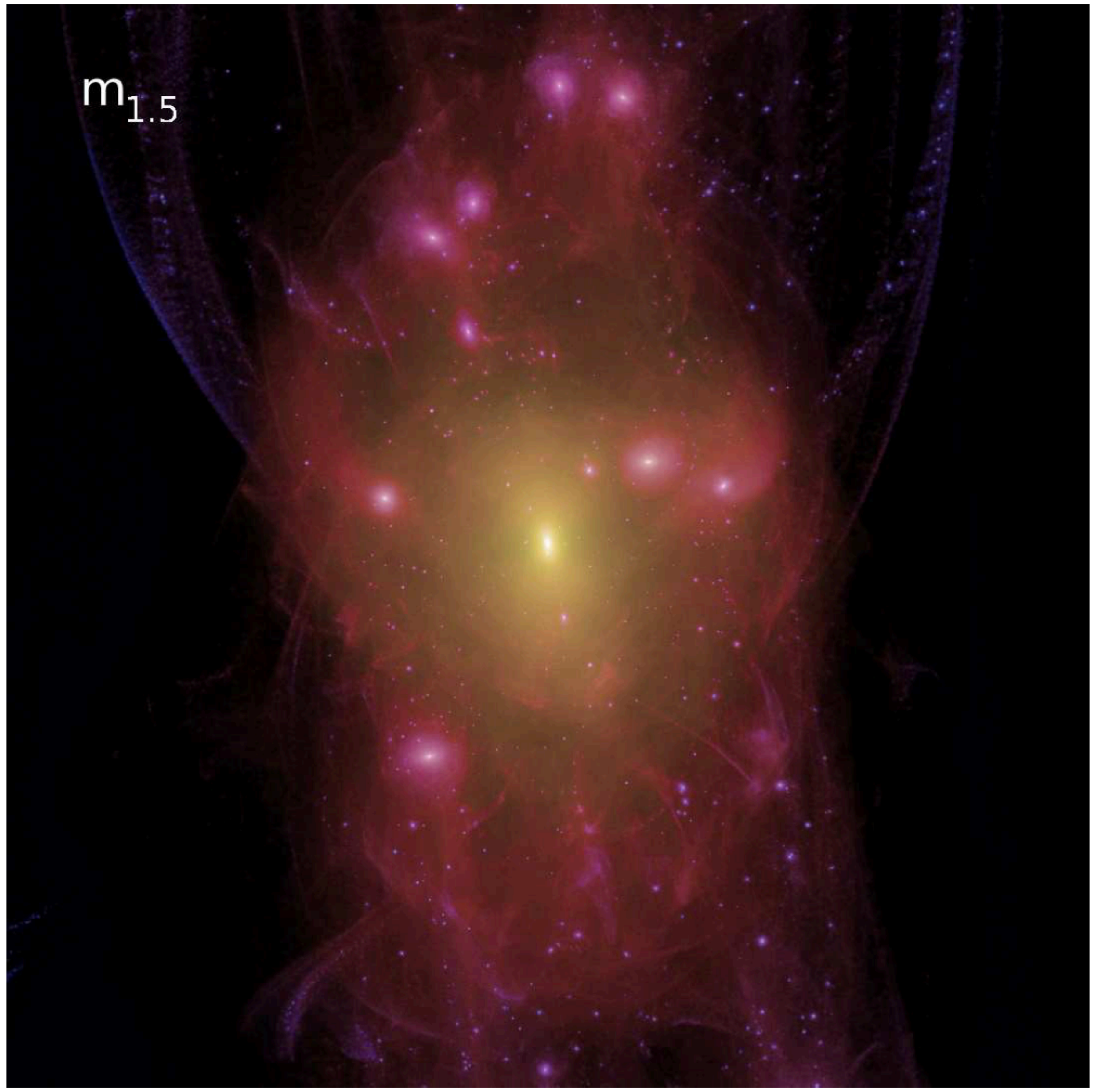
Warm Dark Matter

[1308.1399]

Cold Dark Matter



Warm Dark Matter ($m_\chi = 1.5\,\mathrm{keV}$)



Studying the properties and distribution of Milky Way Satellite galaxies allows us to constrain the Warm DM Mass to $m_{\mathrm{WDM}} \gtrsim 4\,\mathrm{keV}$.

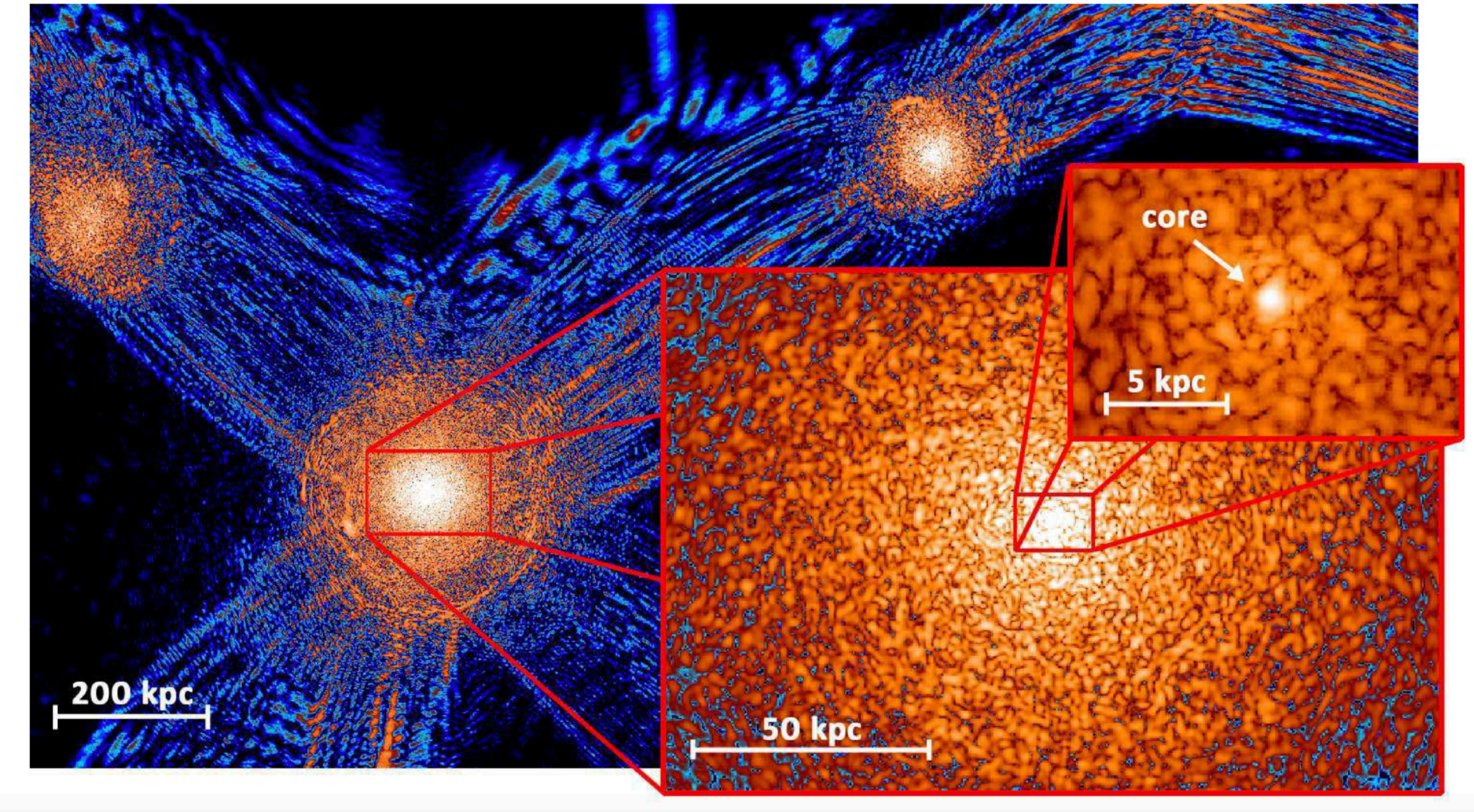
[2011.08865]

Other Dark Matter Models

The small-scale structure of the Universe may also hint towards other models for DM. E.g.

Wave-like Dark Matter

DM is wave-like, and follows the Schrodinger-Poisson Eq.

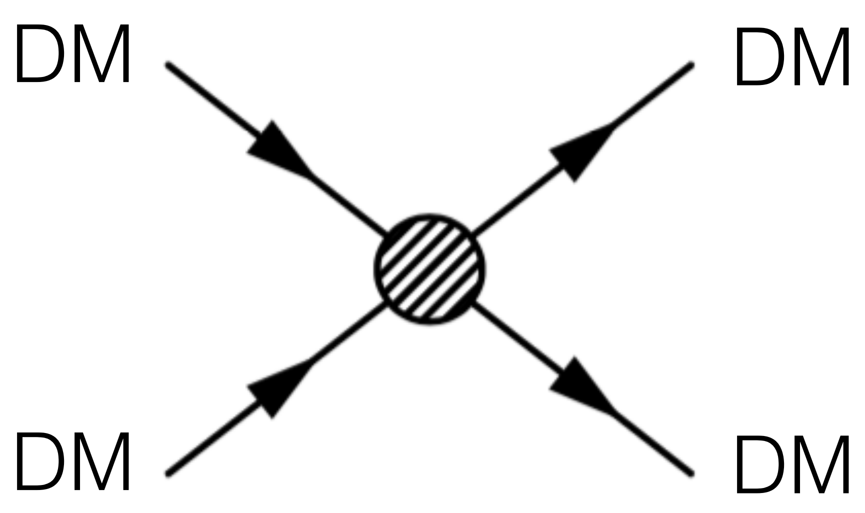


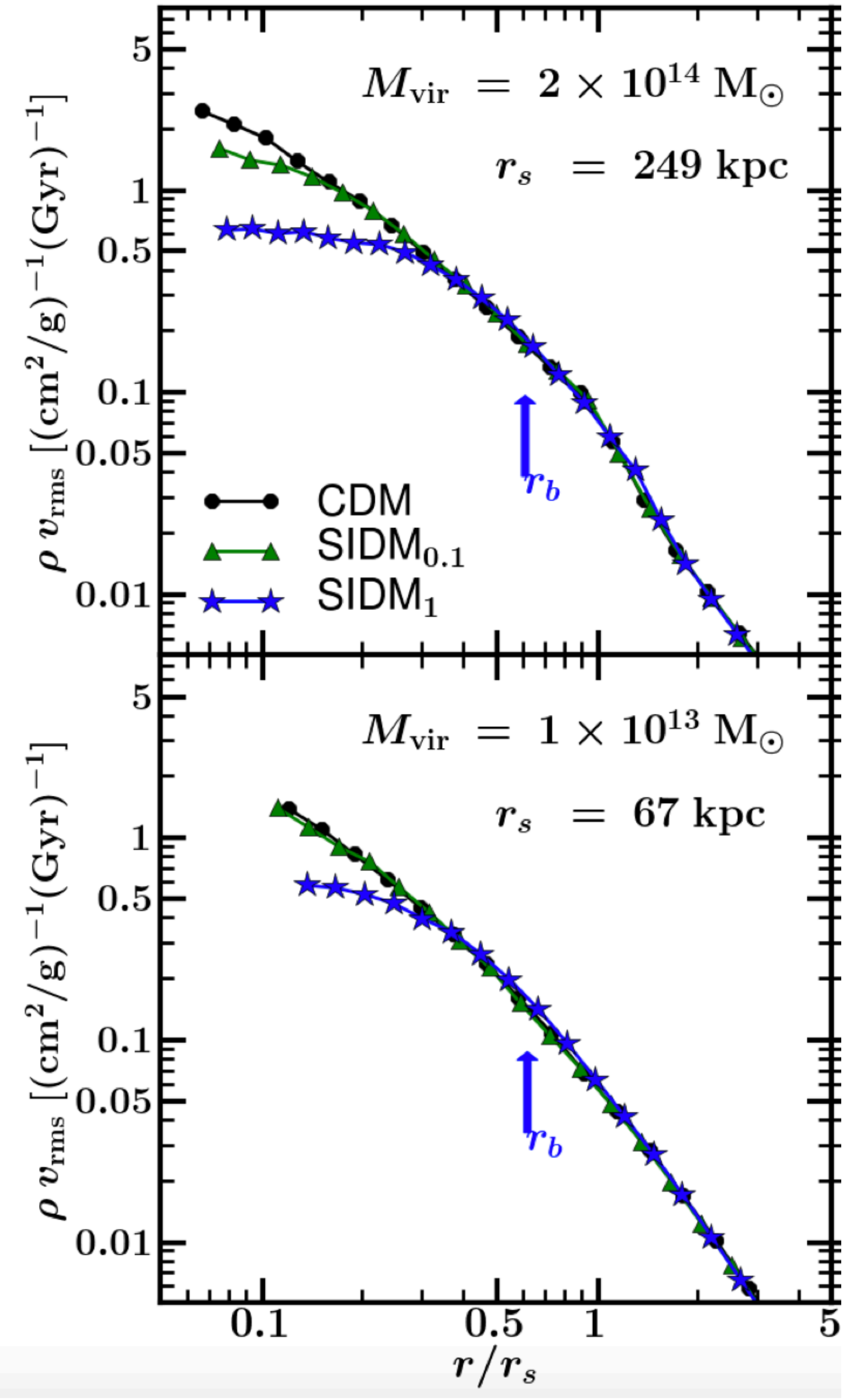
$\lambda_J \propto (1+z)^{1/4} m_\psi^{-1/2}$

[1406.6586]

Self-interacting Dark Matter

DM-self interactions allow energy to be distributed in the halo, flattening the central density.





[1208.3025]

Galaxy formation is complicated!

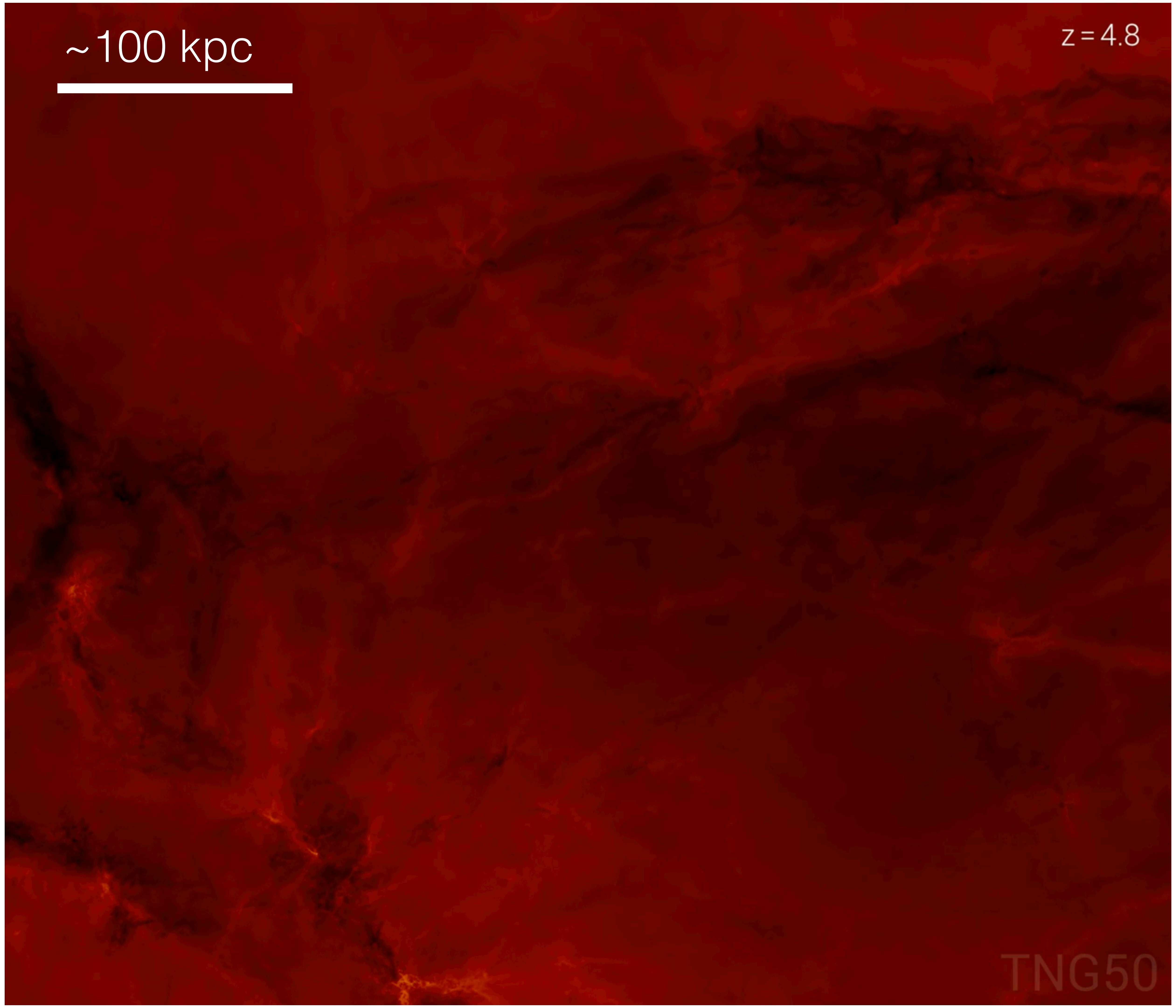
[Full animation available here: https://www.tng-project.org/media/]

Need to model and tune ‘sub-grid physics’ (e.g. star formation, supernova explosions, winds)

Feedback mechanisms (supernovae, reionisation) can drastically affect both the DM density profiles and the threshold for galaxy formation.

If we want to modify the standard model of collisionless cold dark matter, we still have to worry about the complicated baryonic physics!

IllustrisTNG50



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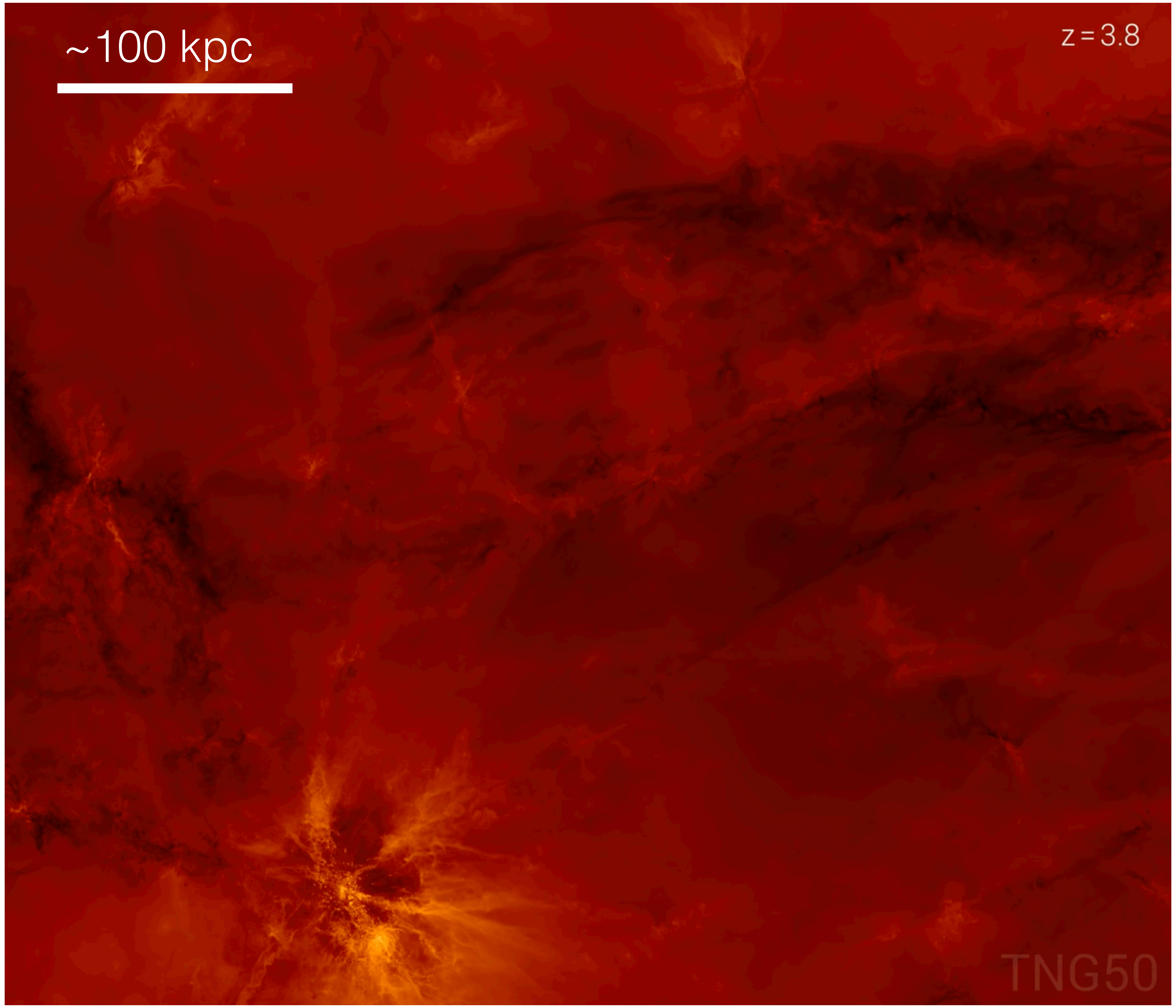

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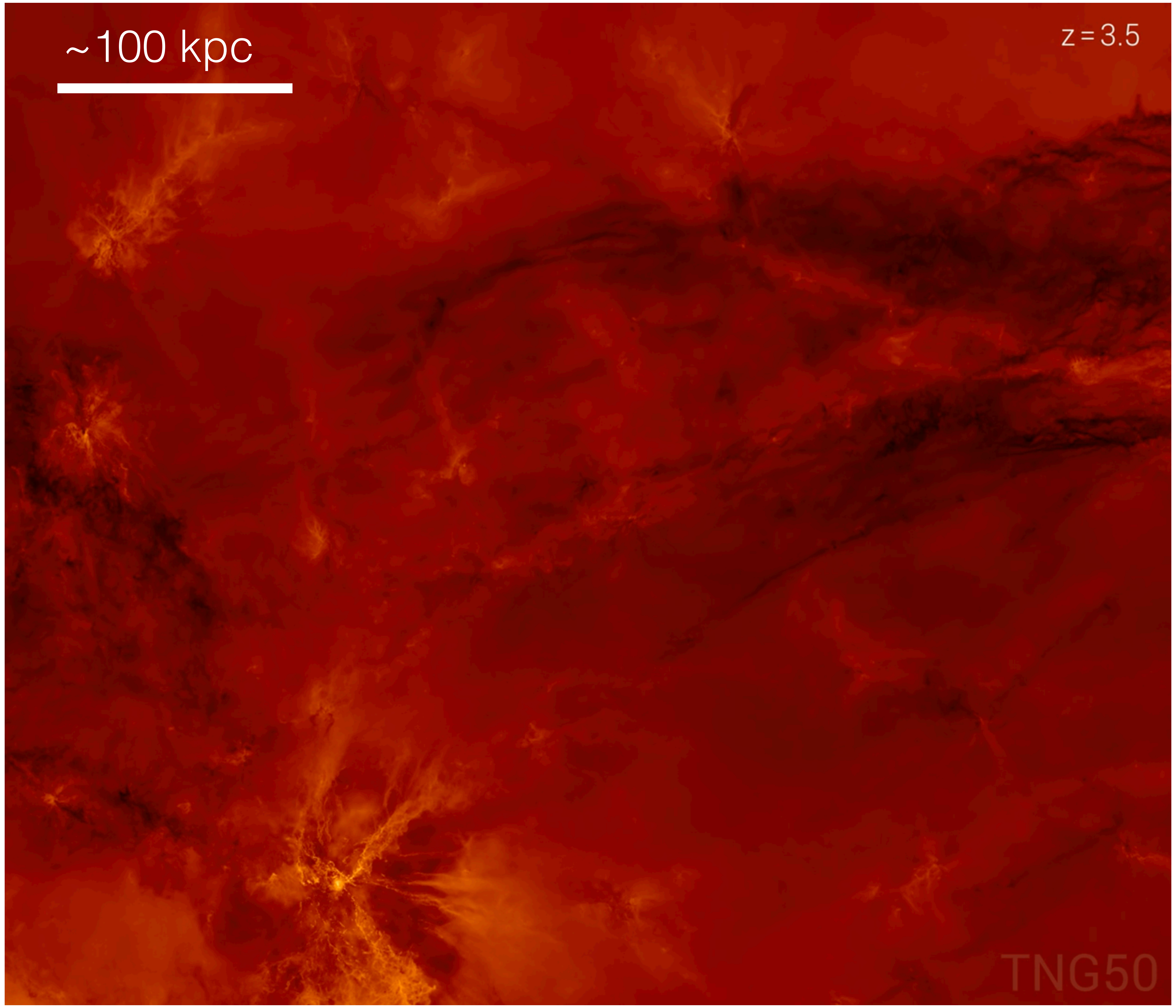

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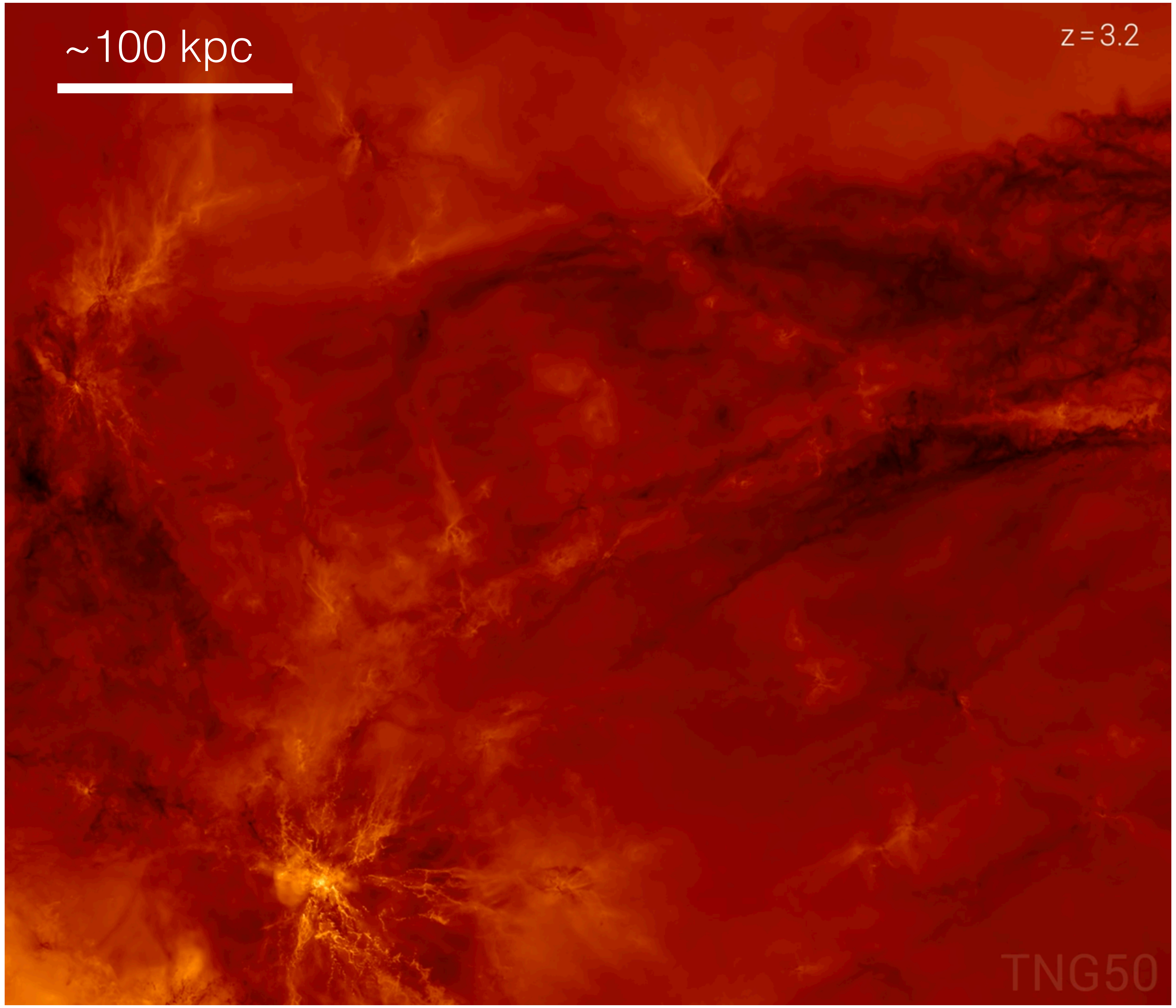

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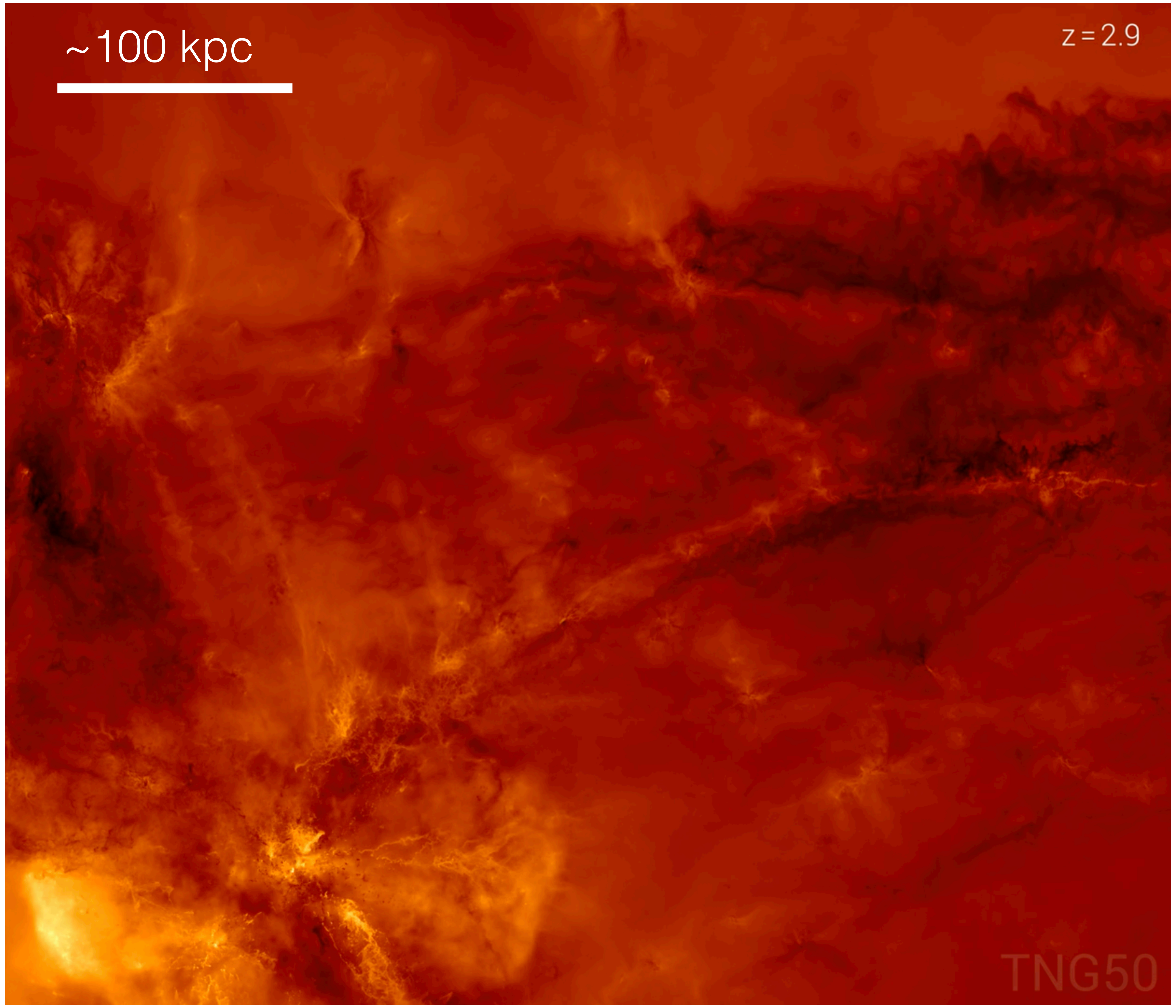

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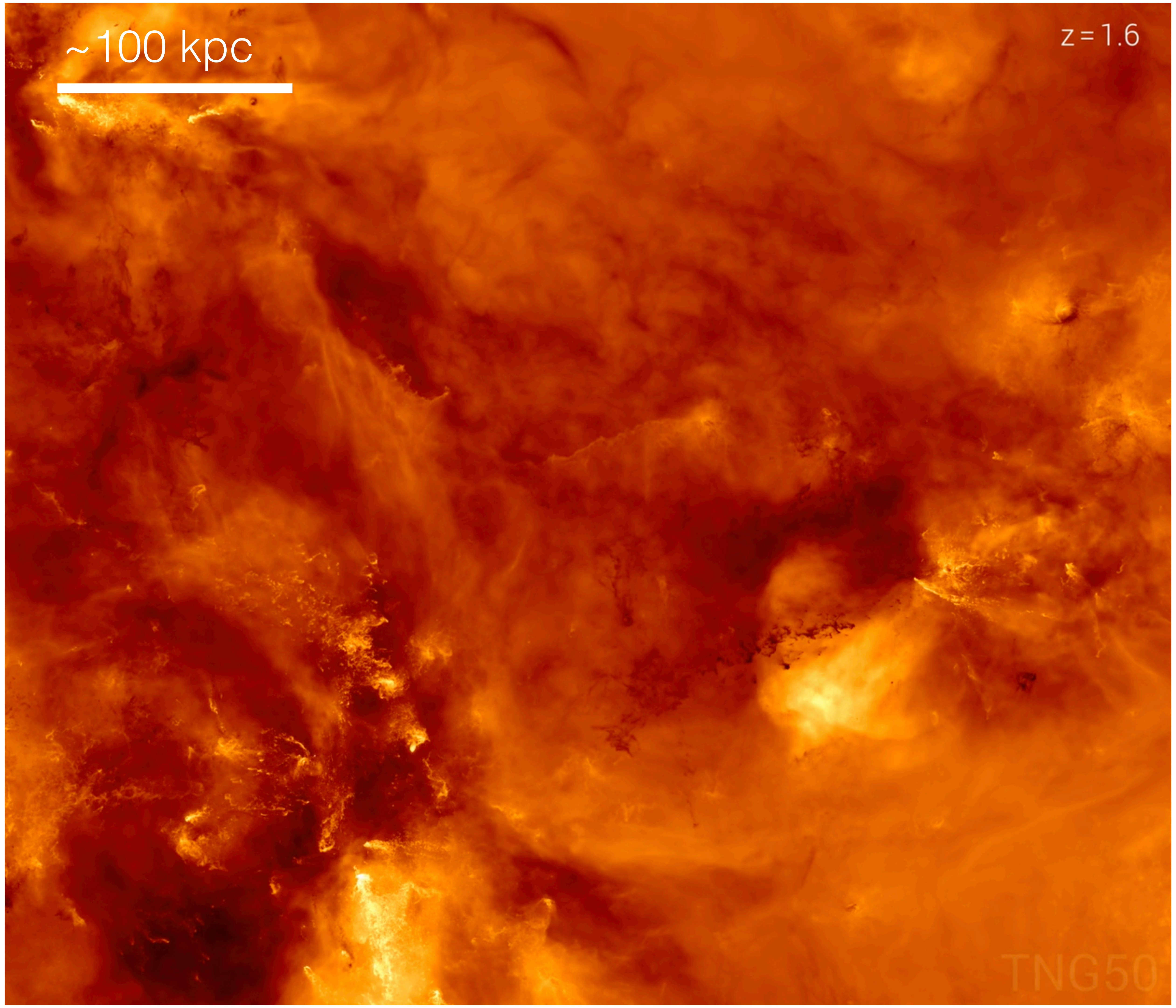
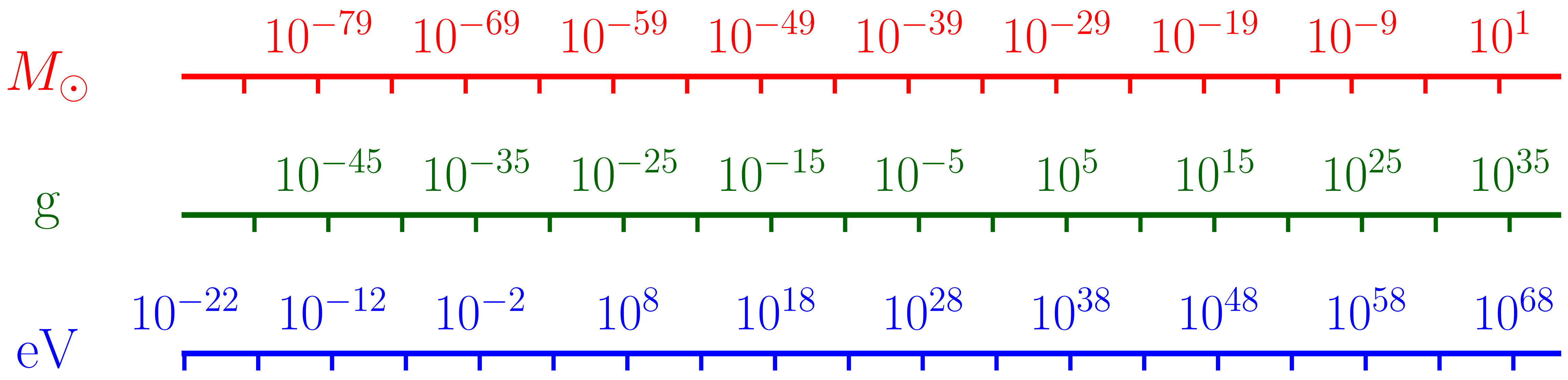
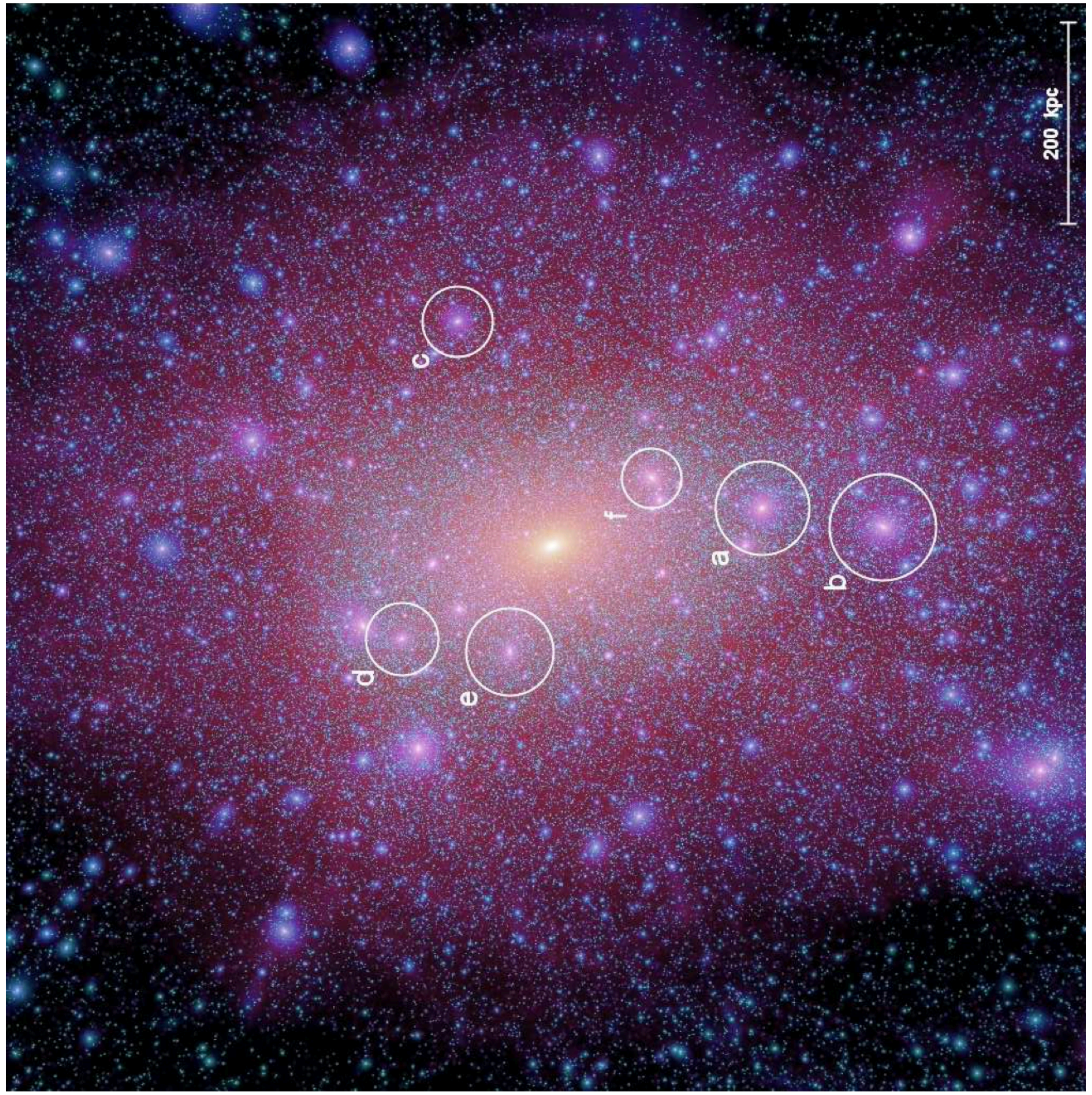


Summary





Evidence for non-baryonic Dark Matter on all scales (cosmological down to galactic).

Dark Matter must be sufficiently **cold** to produce the observed structure in galaxies and galaxy clusters.

Simulations of cold Dark Matter (CDM) make strong predictions about DM halos: (1) hierarchical sub-structure, (2) Universal cuspy density profiles

Observations suggest some **tension** with the standard CDM model on small (sub-galactic) scales. These can provide hints about the nature of Dark Matter!

Next: can we actively search for DM?