Dark Matter
Evidence and model building

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Michigan Cosmology Summer School 2023
June 6th 2023

Image:NASA, ESA, CSA, and STScI

Outline

Lecture 1: evidence and model building

- Evidence for dark matter
- Dark matter model building
  - What we know about DM
  - Pre-requisites for a DM model
- Mass bounds
- Landscape of models
- MOND

Lecture 2: DM models

- DM models
  - Particle DM: WIMPS
  - Macroscopic DM: MACHOS, Primordial BHs
  - Wave DM

Disclaimer

- Impossible to cover the entire topic of DM in ~2 hours (or 2+2 hs)
- Biased review of the DM field
- Focus on giving a general review of the main features of the topic and a closer look to the main models nowadays
- Field that is changing rapidly, so my apologies for not mentioning your model or reference

Units of mass, energy and momentum = eV
Length = eV^{-1}

BUT sometimes (astro/cosmology)
1parsec (pc) $\sim 3 \times 10^{16}$ m

Natural units$(c = \bar{h} = 1)$

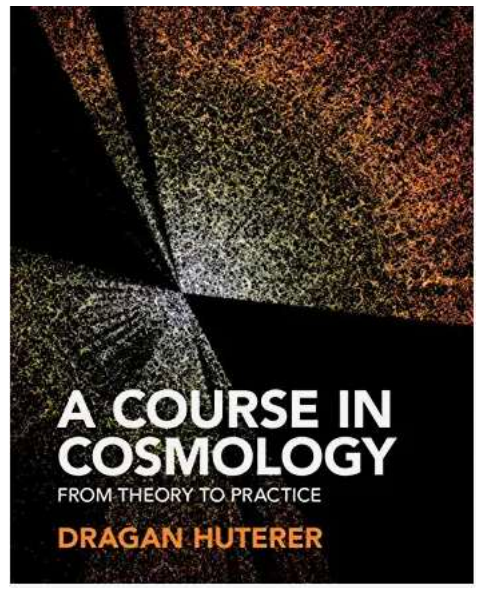
$1\,\mathrm{kg} \to 5 \times 10^{35}\,\mathrm{eV}$

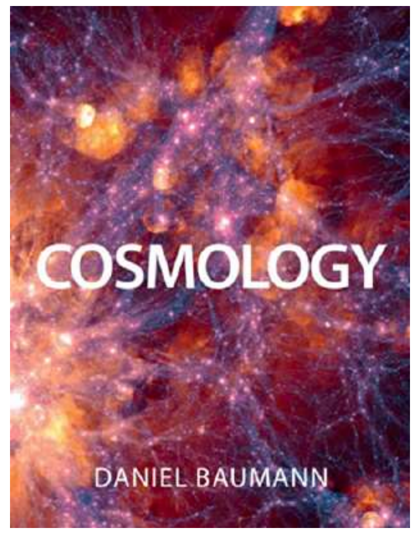
$1\,M_\odot \to \sim 10^{66}\,\mathrm{eV}$

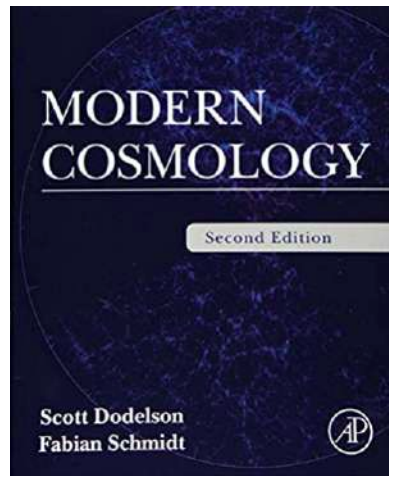
Further reading

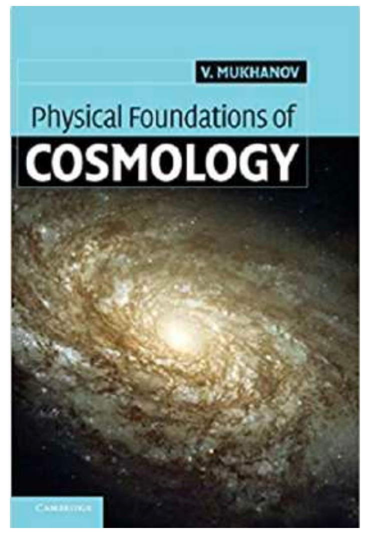
- Dragan Huterer, *A course in cosmology*, Cambridge University Press, 2023
- Daniel Baumann, *Cosmology*, Cambridge University Press, 2022
- Scott Dodelson and Fabian Schmidt, *Modern Cosmology*, Academic Press; 2nd edition, 2020
- Viatcheslav Mukhanov, *Physical Foundations of Cosmology*, Cambridge University Press, 2005

- Reviews!!!









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NASA, ESA, G. Illingworth and D. Magee, K. Whitaker, R. Bouwens , P. Oesch and the Hubble Legacy Field team

We observe billions of galaxies in our universe

Galaxies and gas, are only a small fraction of the gravitational influence in the universe

NASA, ESA, G. Illingworth and D. Magee, K. Whitaker, R. Bouwens , P. Oesch and the Hubble Legacy Field team


These galaxies and gas trace the invisible and underlying gravitational potential (dark matter distribution)
Virgo

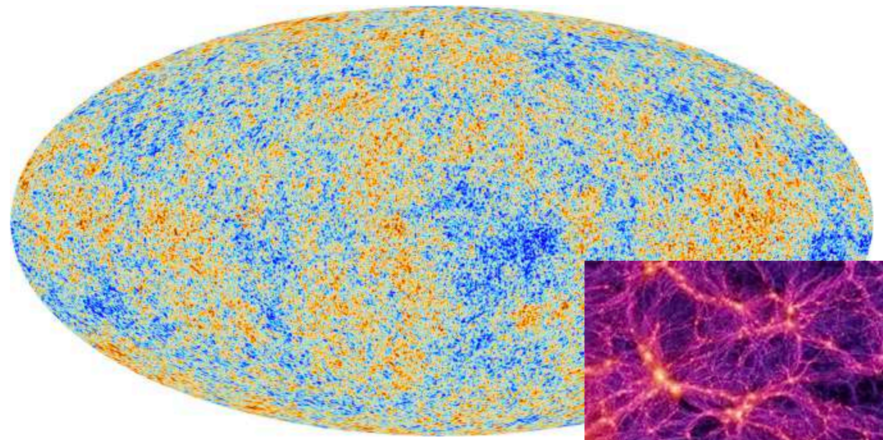
Evidences for dark matter

We can observe its effects in

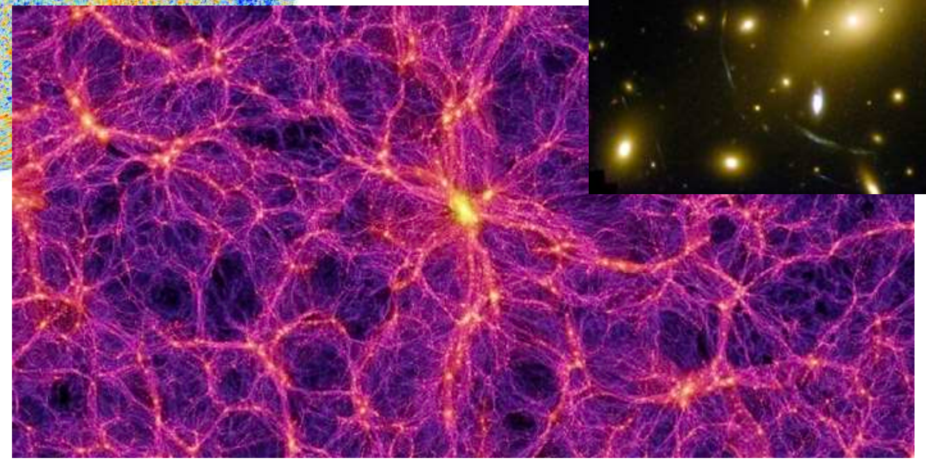
Galaxies

NASA and ESA

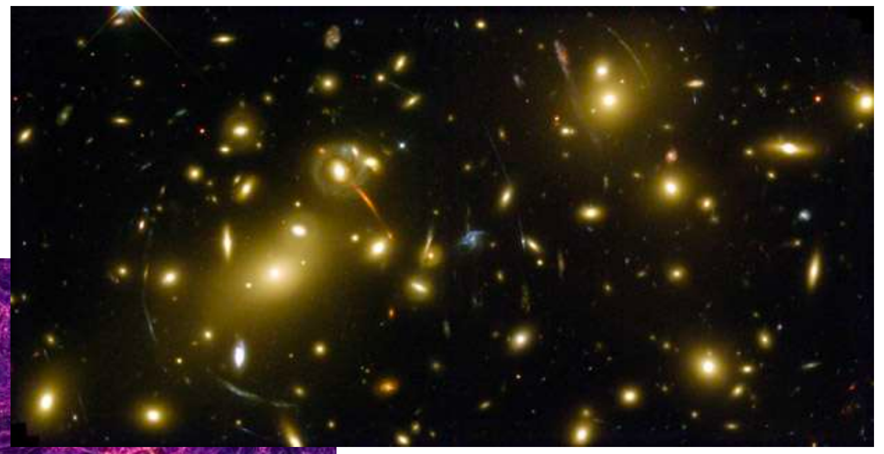
CMB+LSS



ESA and the Planck Collaboration

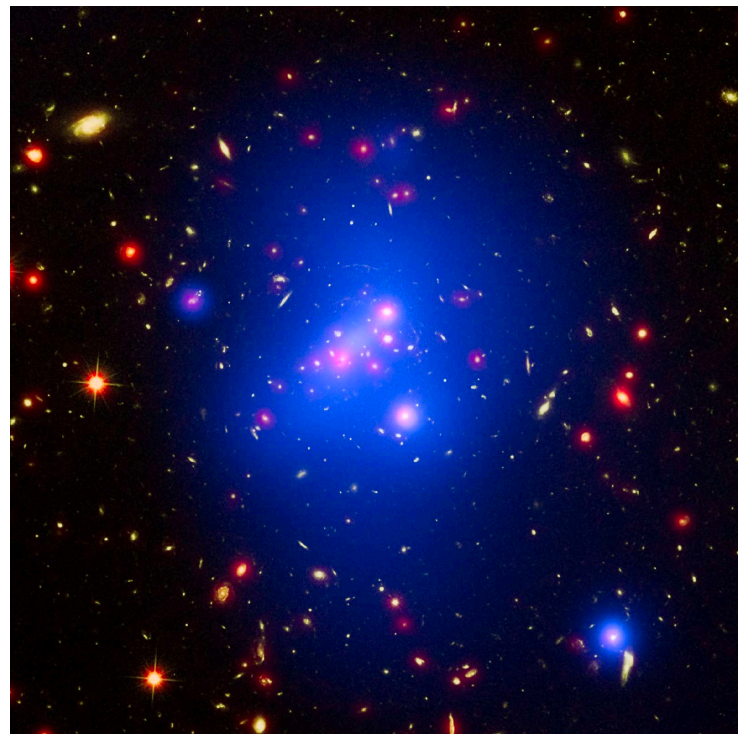


Springel & others / Virgo Consortium



NASA and ESA

Clusters



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Huge amount of evidence
From all scales

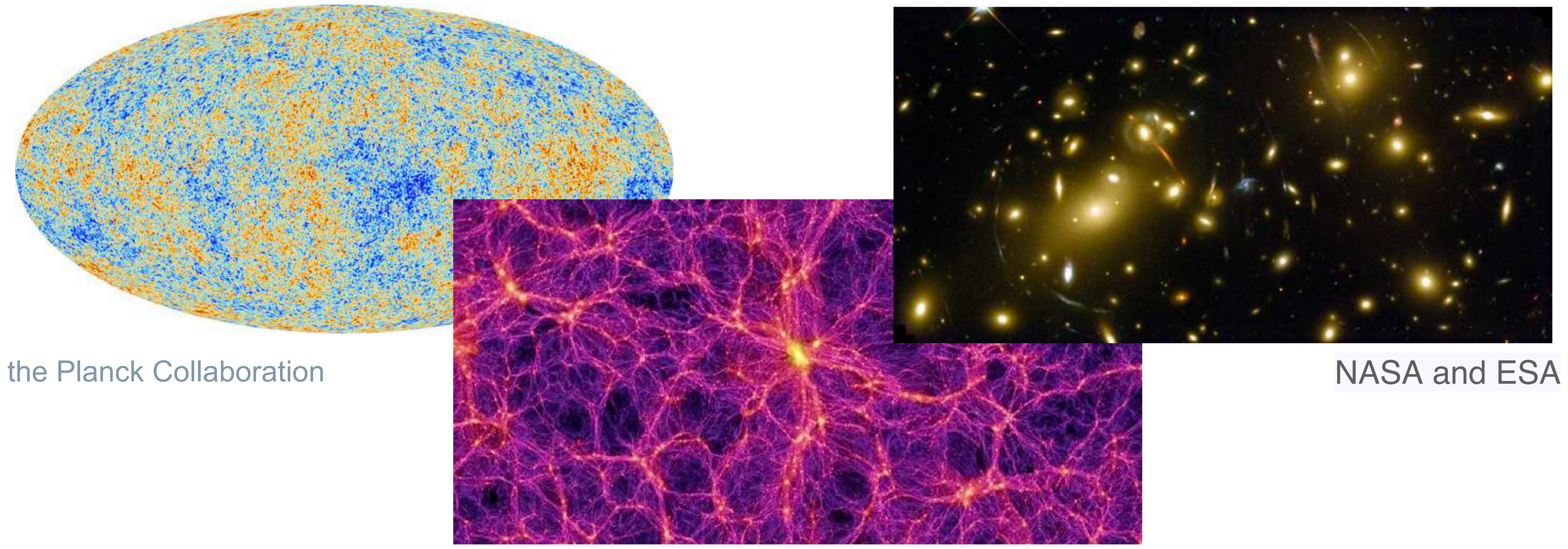
Evidences for ~~dark matter~~ something more in the universe

We can observe its effects in

Galaxies

NASA and ESA

CMB+LSS



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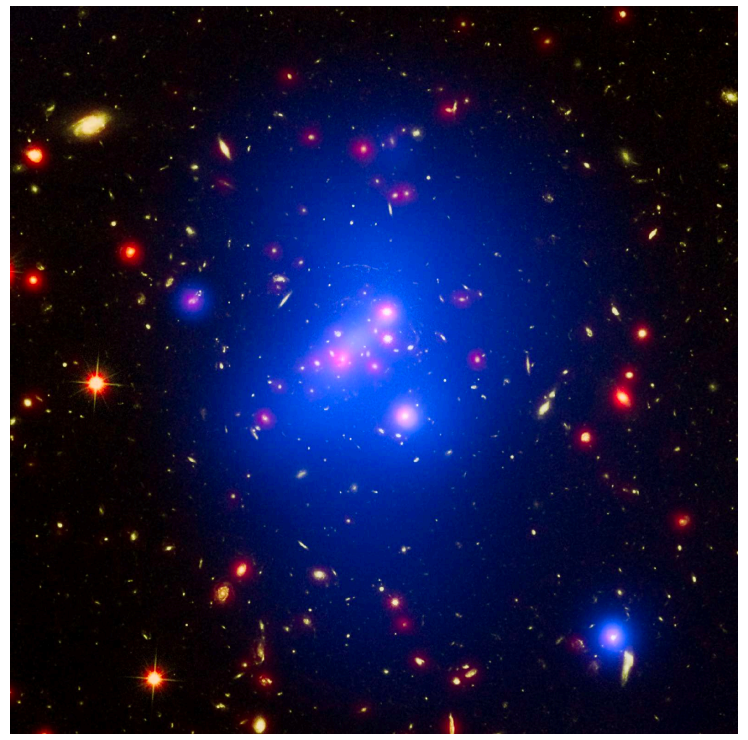
Clusters



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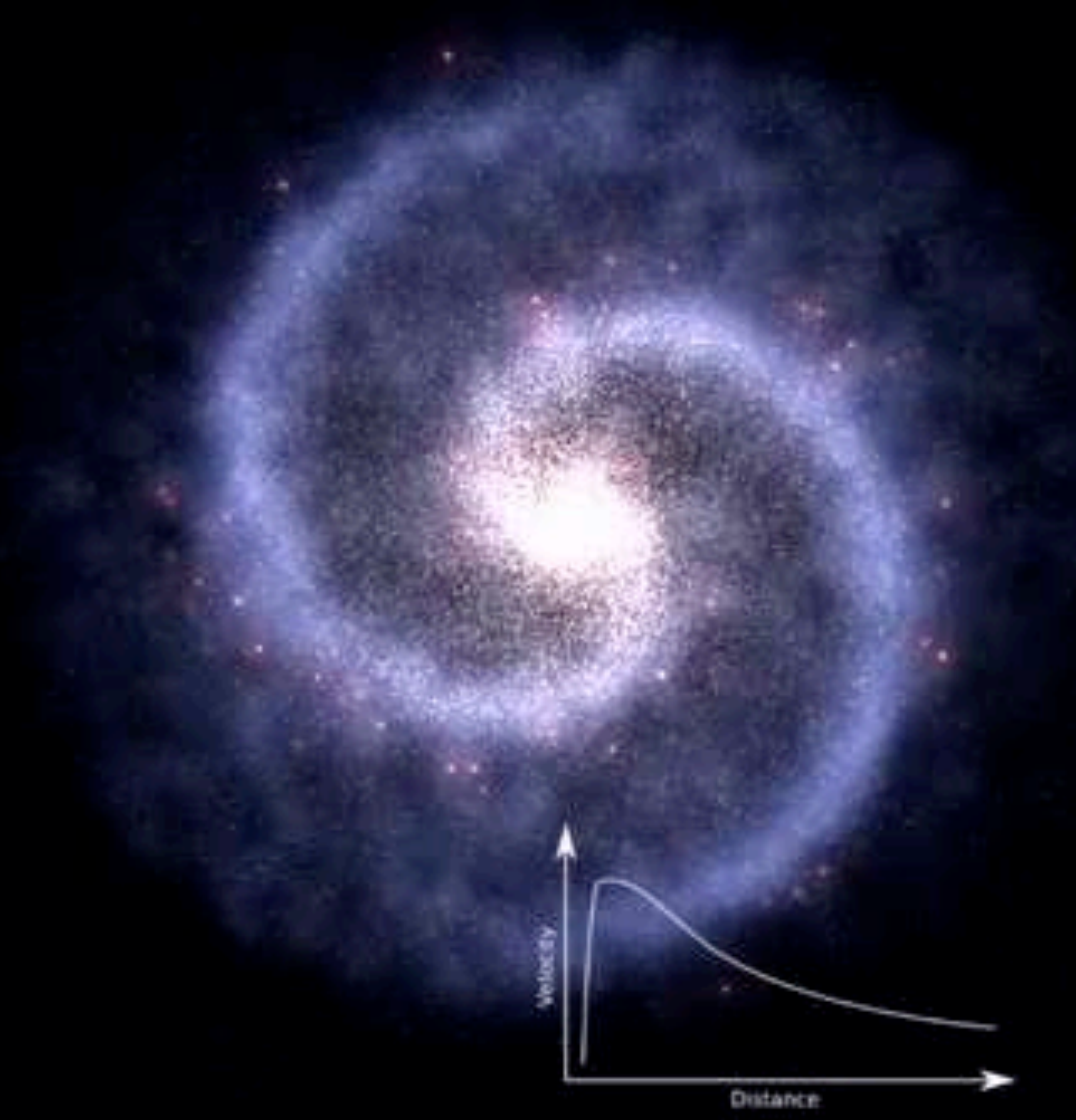
Huge amount of evidence
From all scales

Galaxy rotation curves

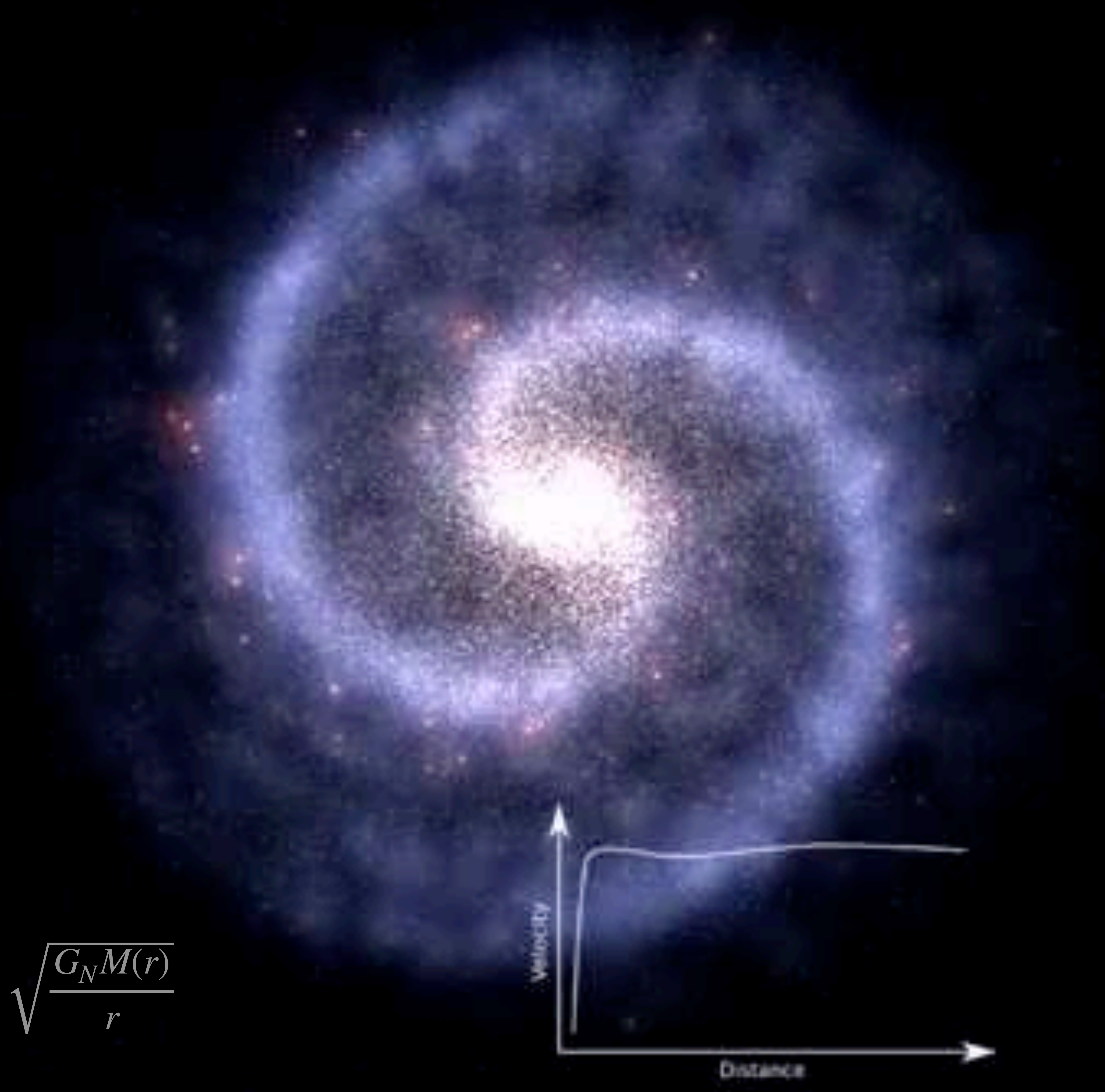
Rubin & Ford; Freeman; …

Stars and hydrogen gas in spiral galaxies move in circular orbits due to gravity

NO dark matter



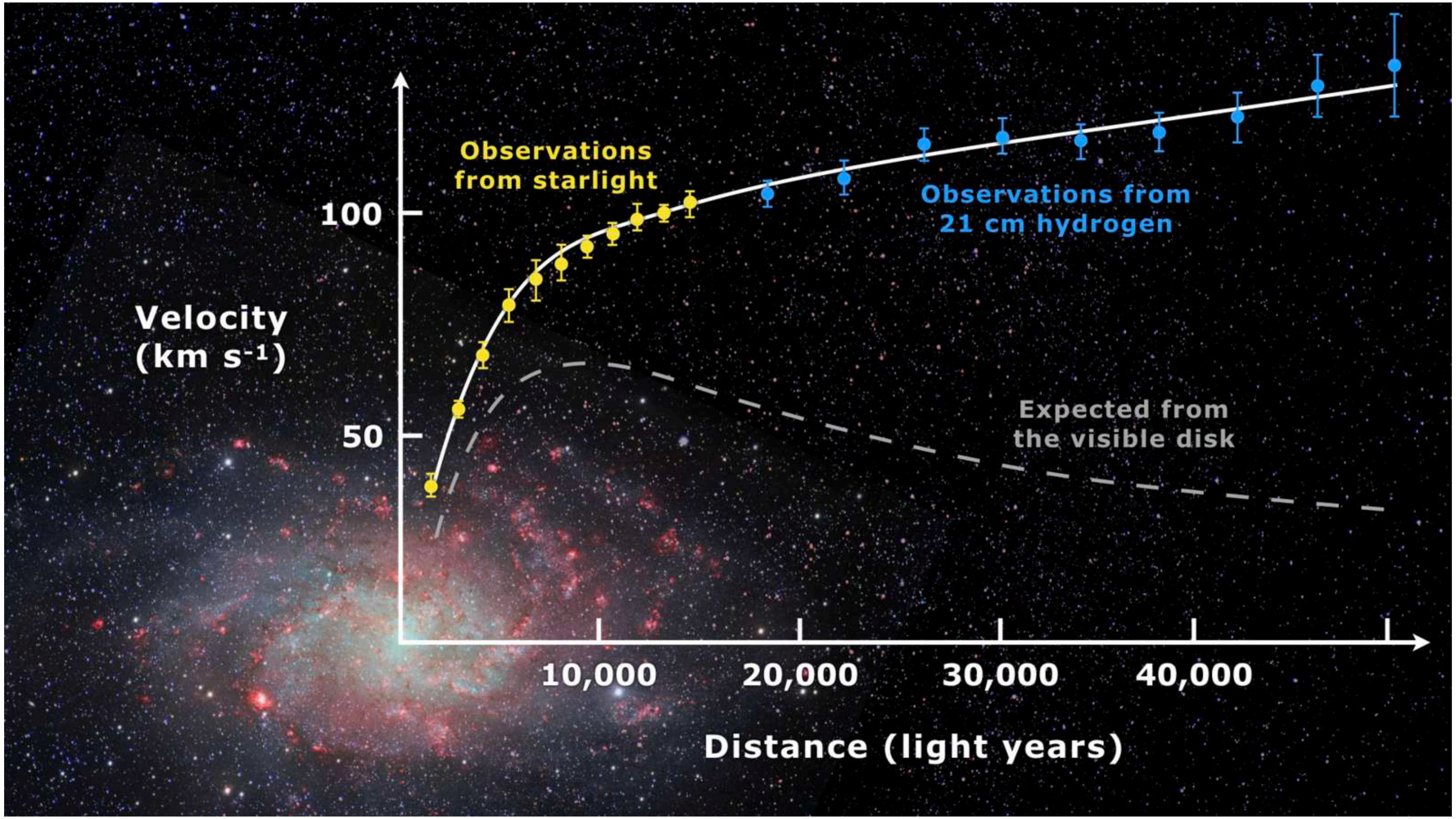
WITH dark matter



$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

Credit: Ingo Berg

Galaxy rotation curves

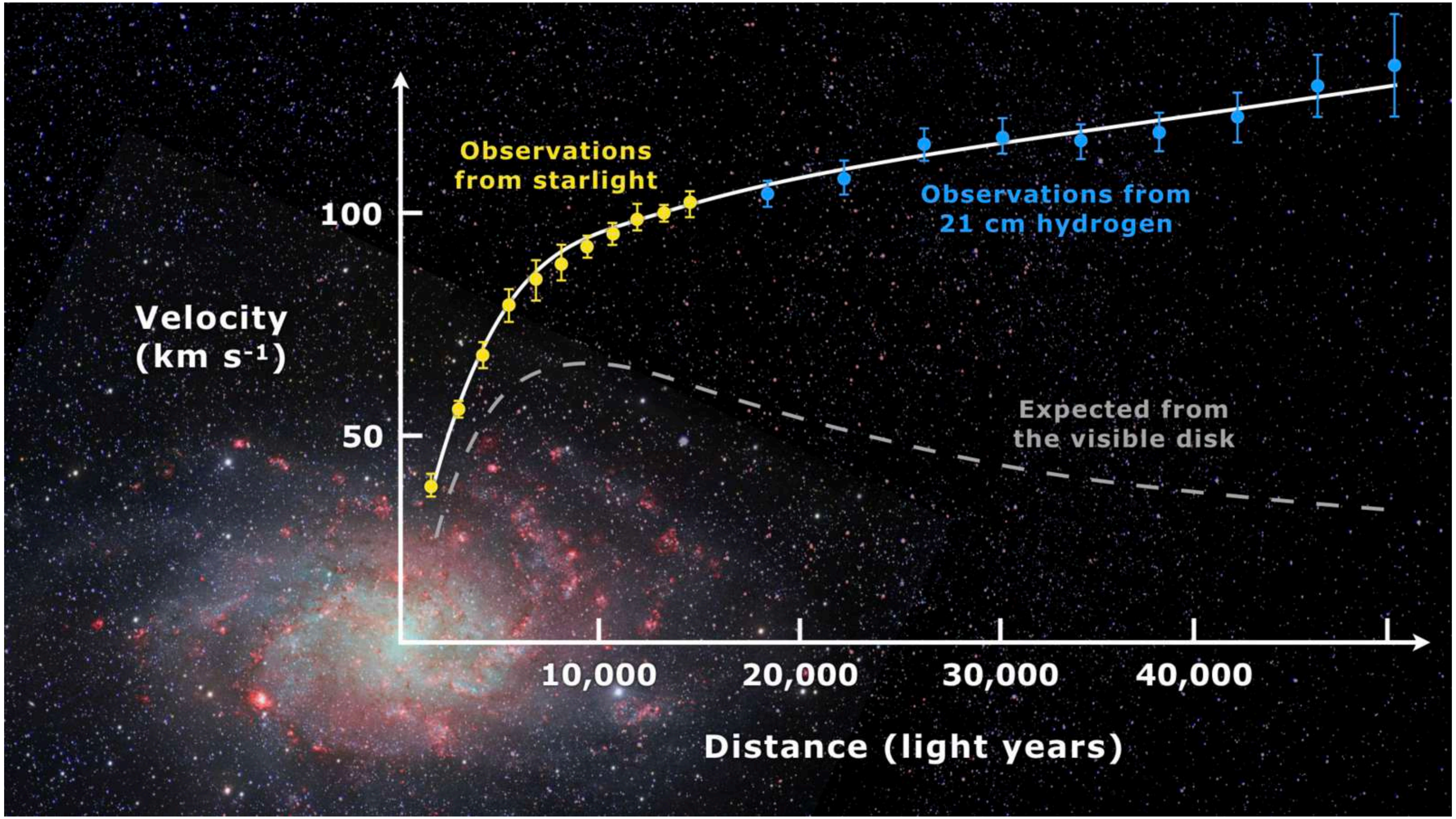


Credit: Mario De Leo

Missing mass

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

Galaxy rotation curves



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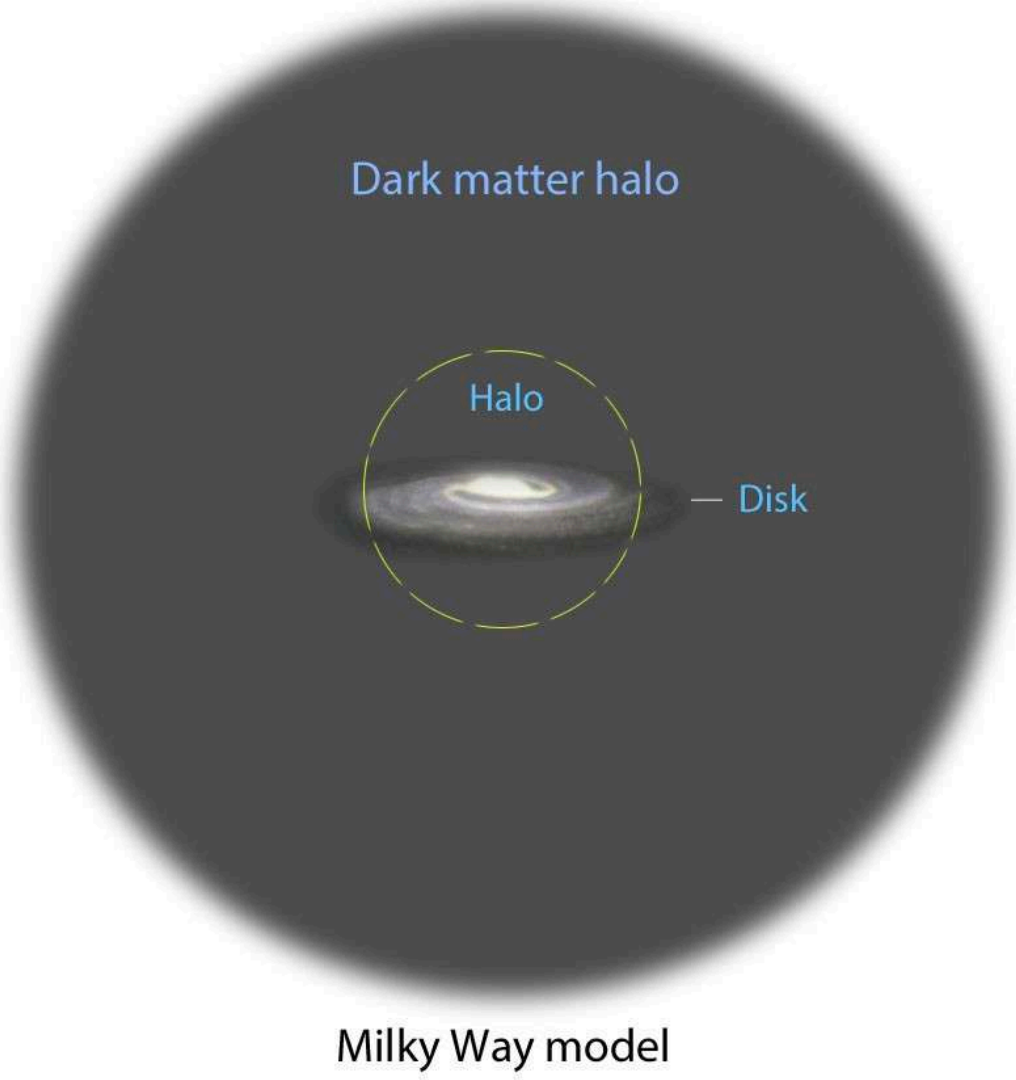
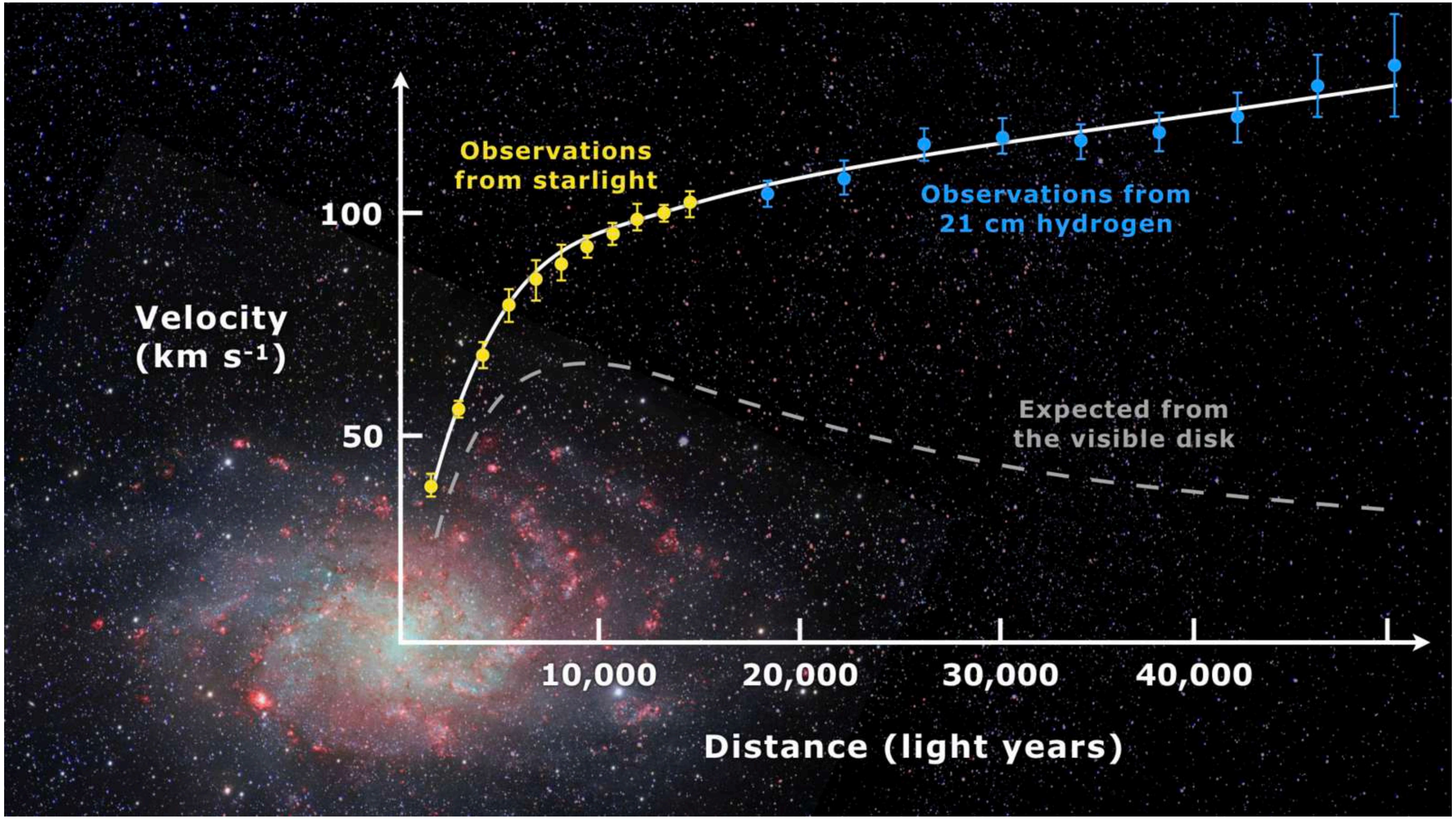
Missing mass



Universidade de Zuricch

Galaxy rotation curves



Credit: Mario De Leo

Missing mass

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

OR this formula is wrong!

Clusters of galaxies

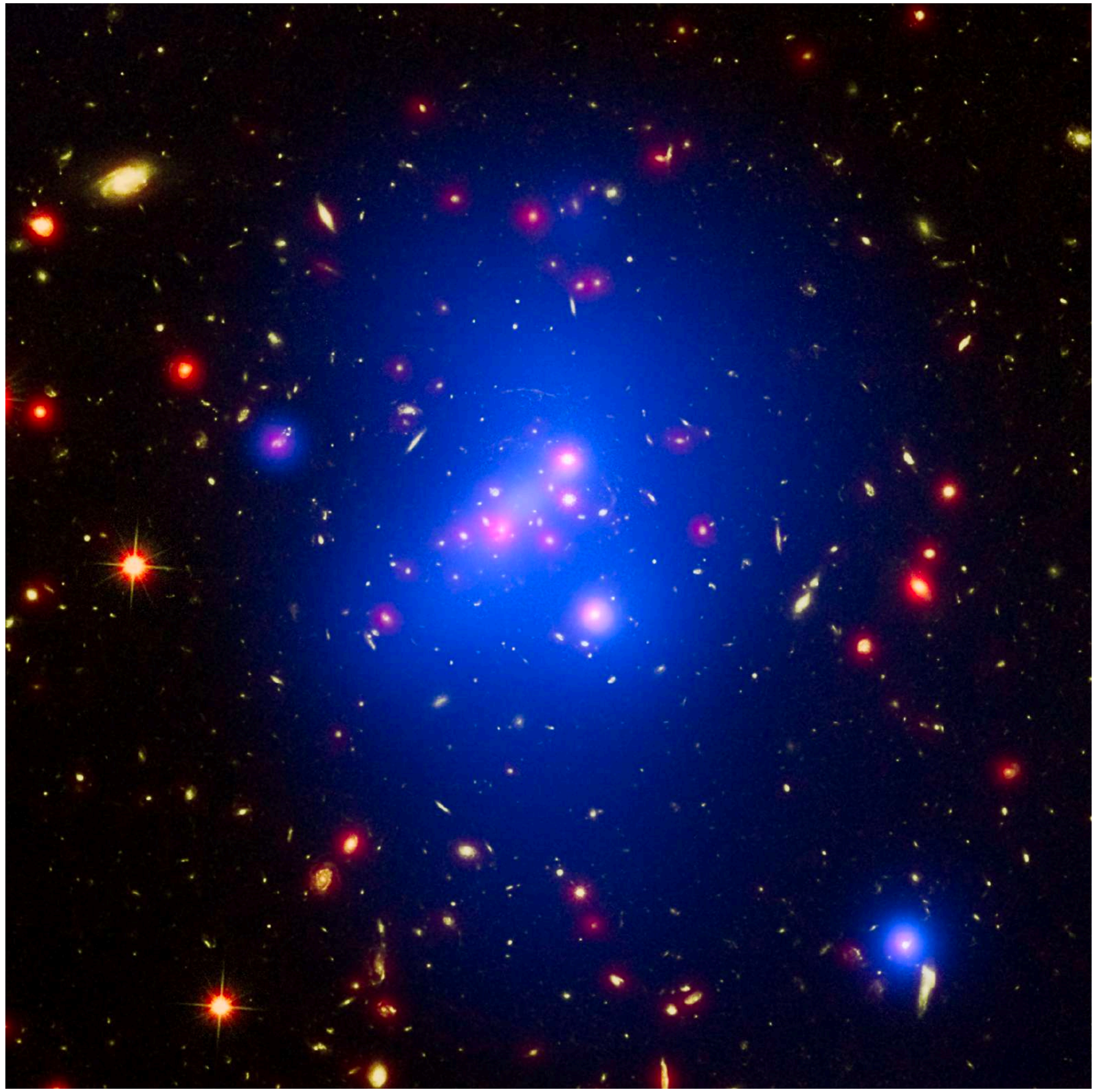
Largest gravitationally bound structures.
Contain 100s/1000s of galaxies and hot x-ray emitting gas

(Zwicky 1933)

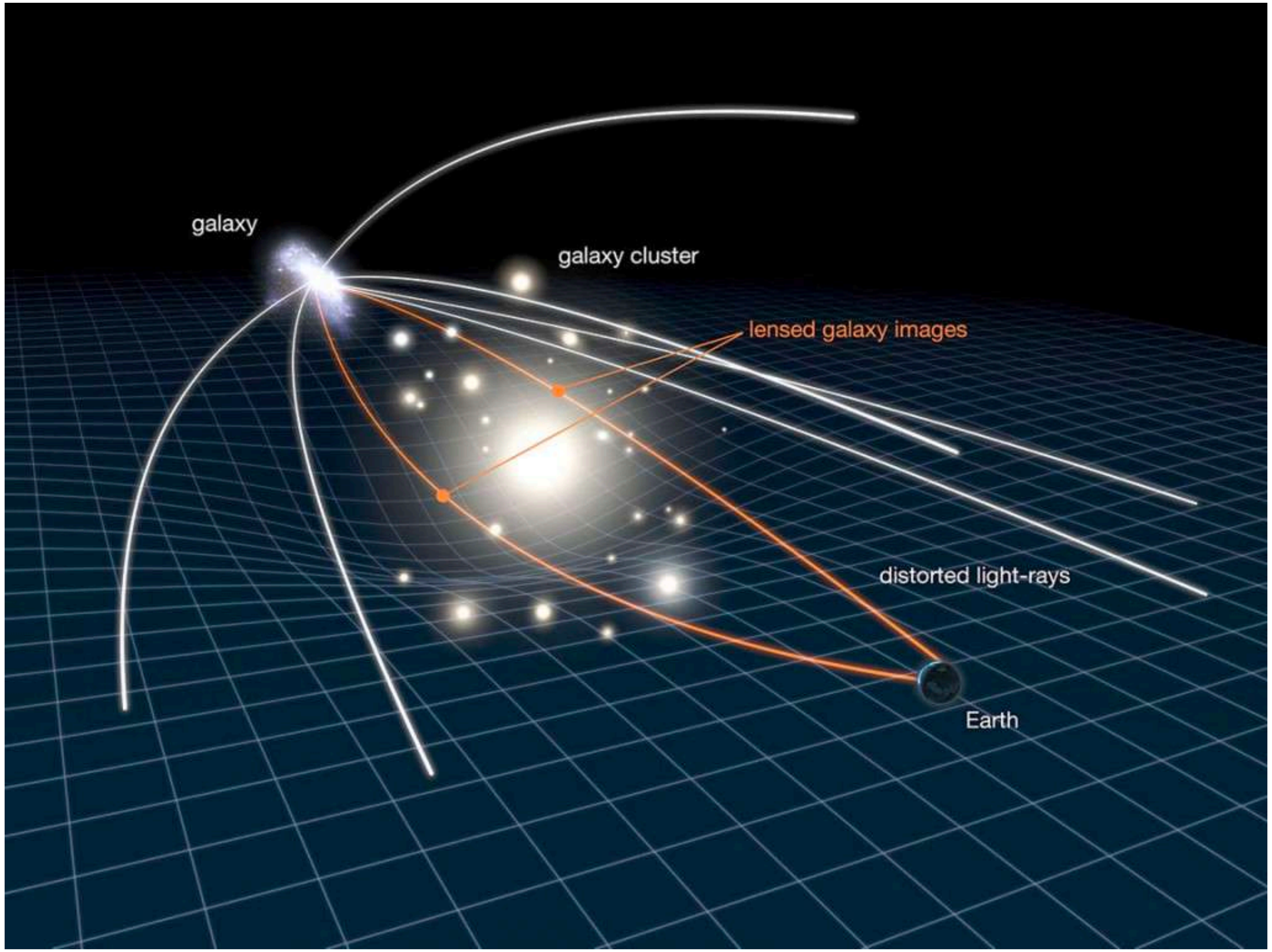
~ 1 %   Galaxies

~ 10 %   Gas

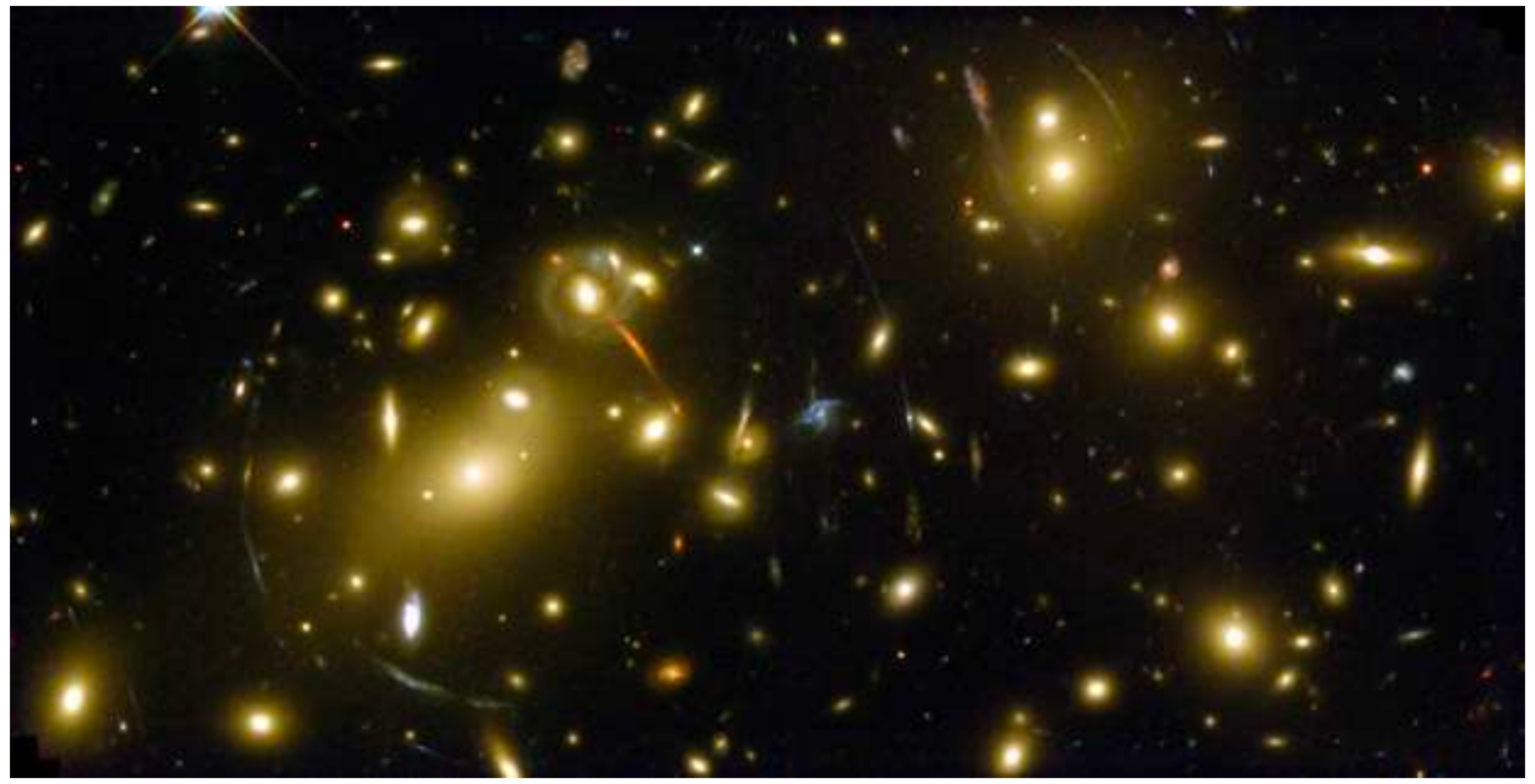
~ 90 %   Dark matter



Gravitational lensing



mage: NASA/ESA



NASA and ESA

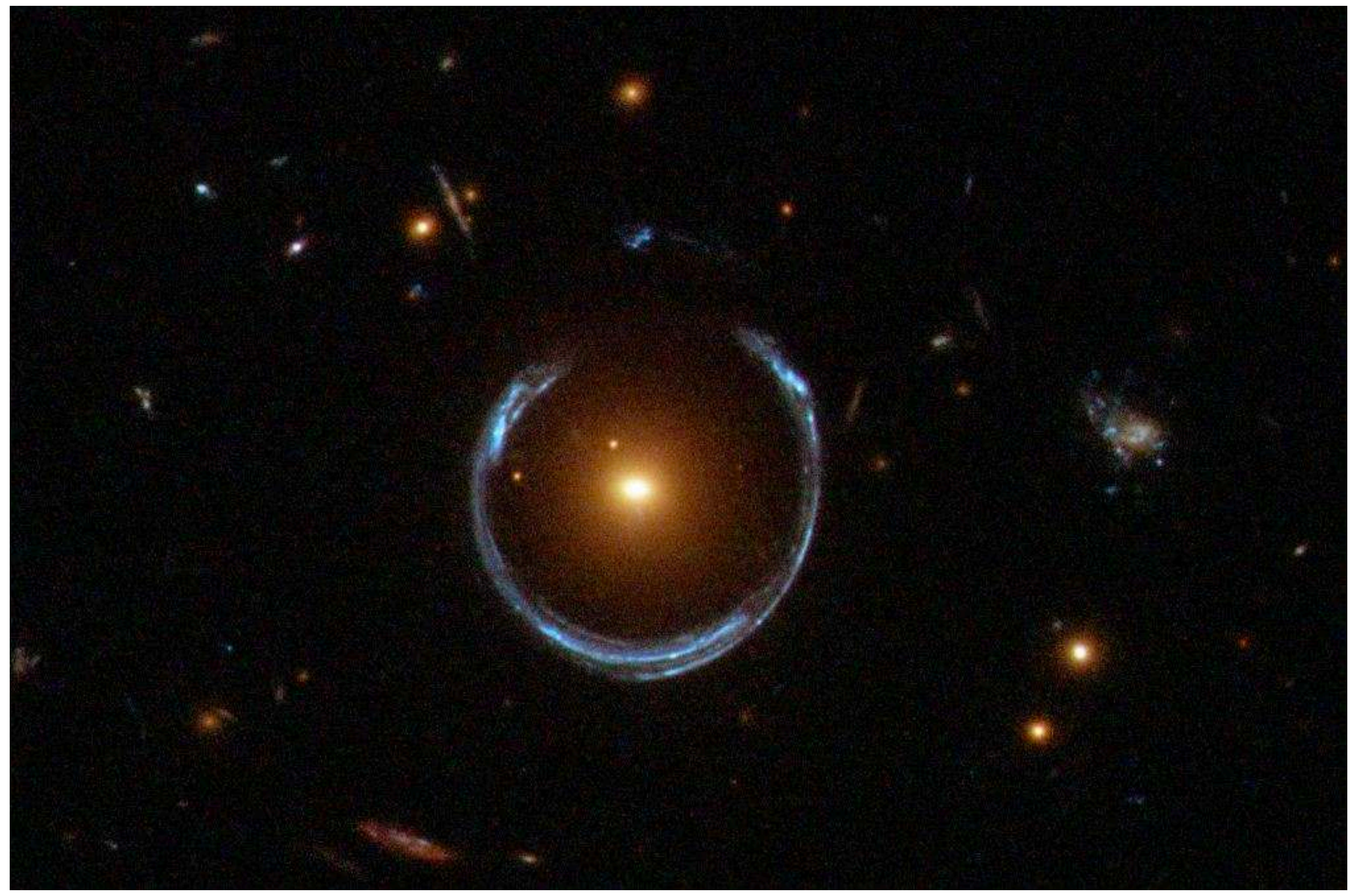
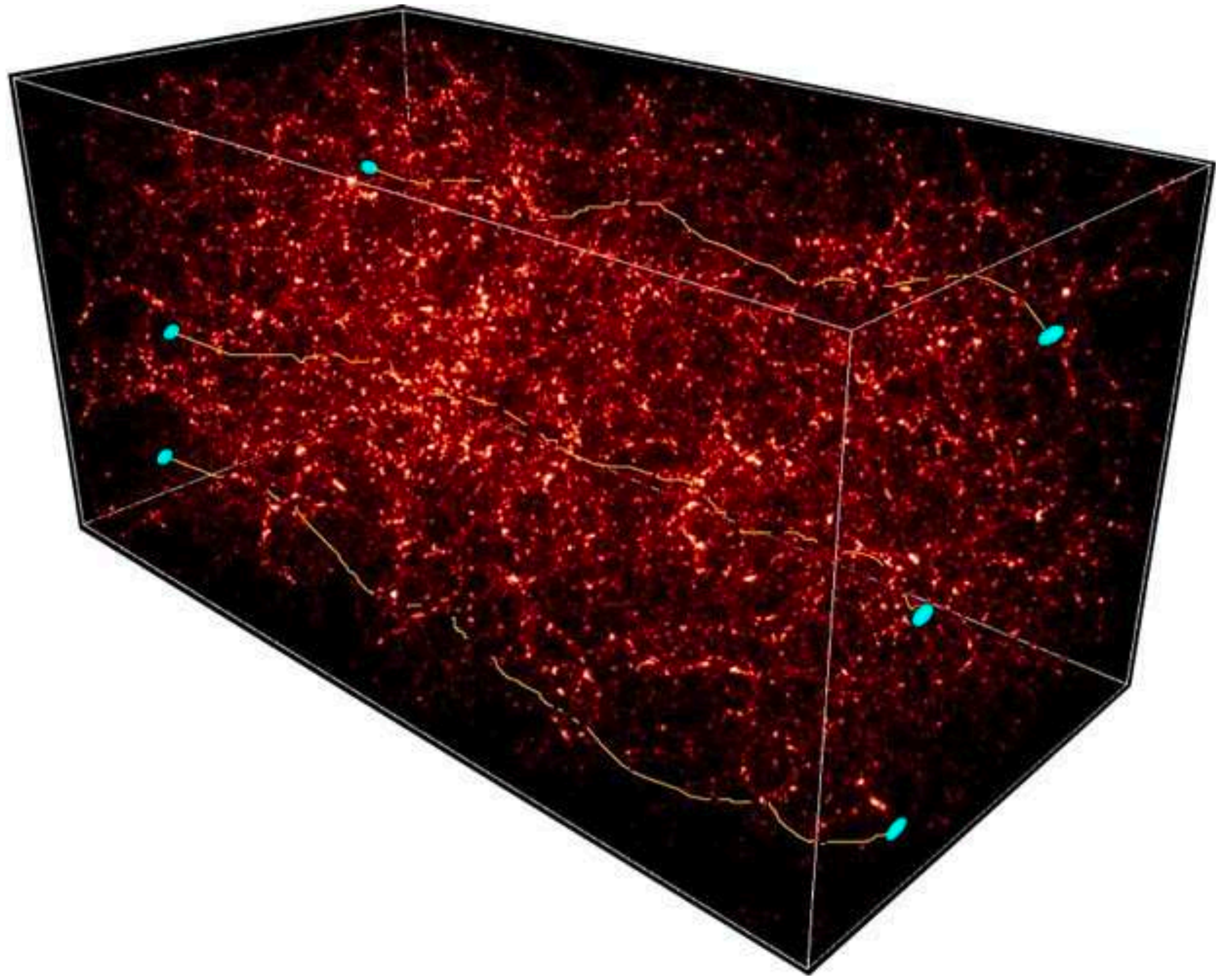


Image: © ESA/Hubble/NASA)

Gravitational lensing

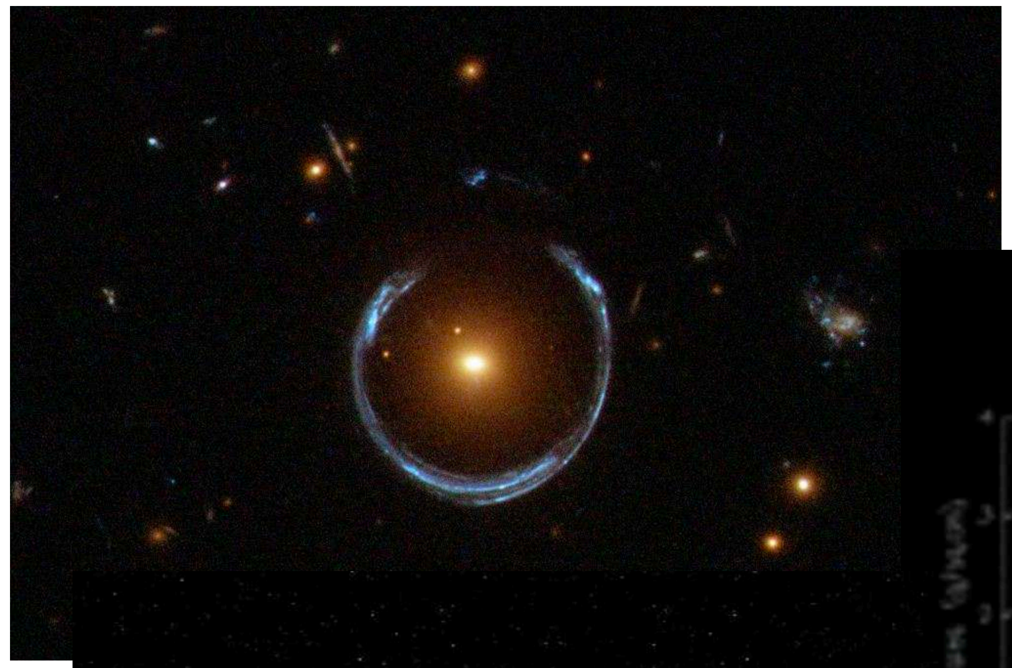
Weak lensing



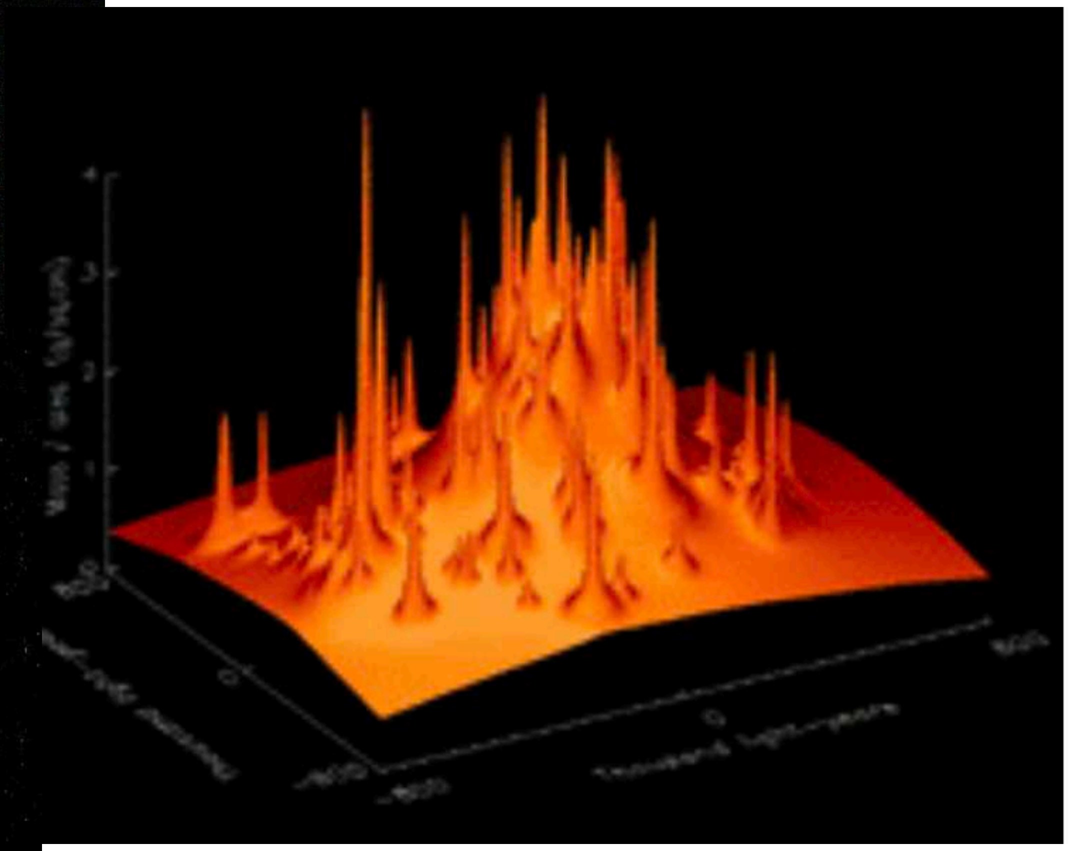
- Background image is perturbed by matter in its path
- Statistical signal
- Total mass on large scales

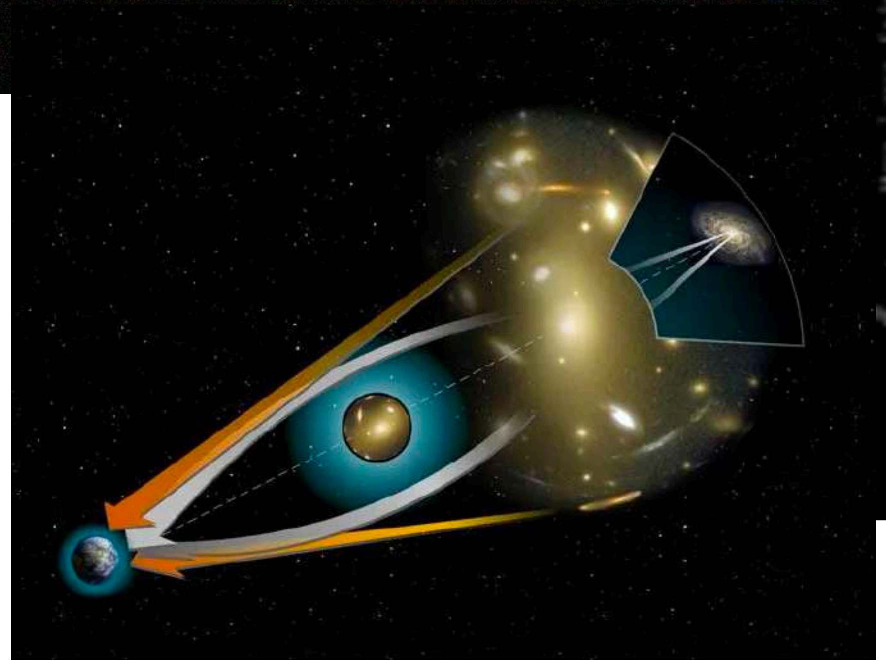
Strong lensing

Image: © ESA/Hubble/NASA)



Tyson, Kochanski & Dell'Antonio

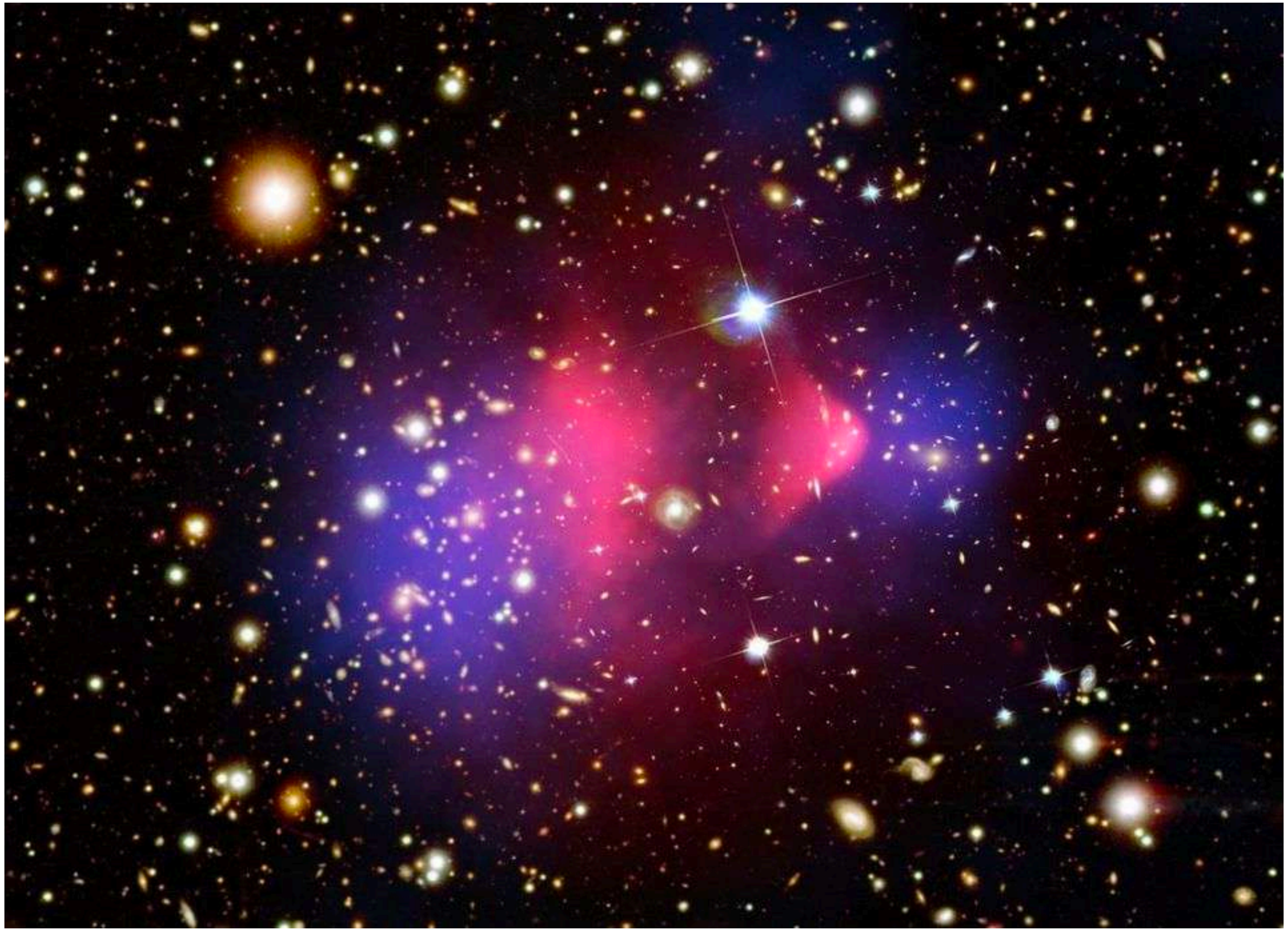




NASA / STSCI

- Reconstruct the gravitational potential (total enclosed mass) of the lens
- Total mass on small scales

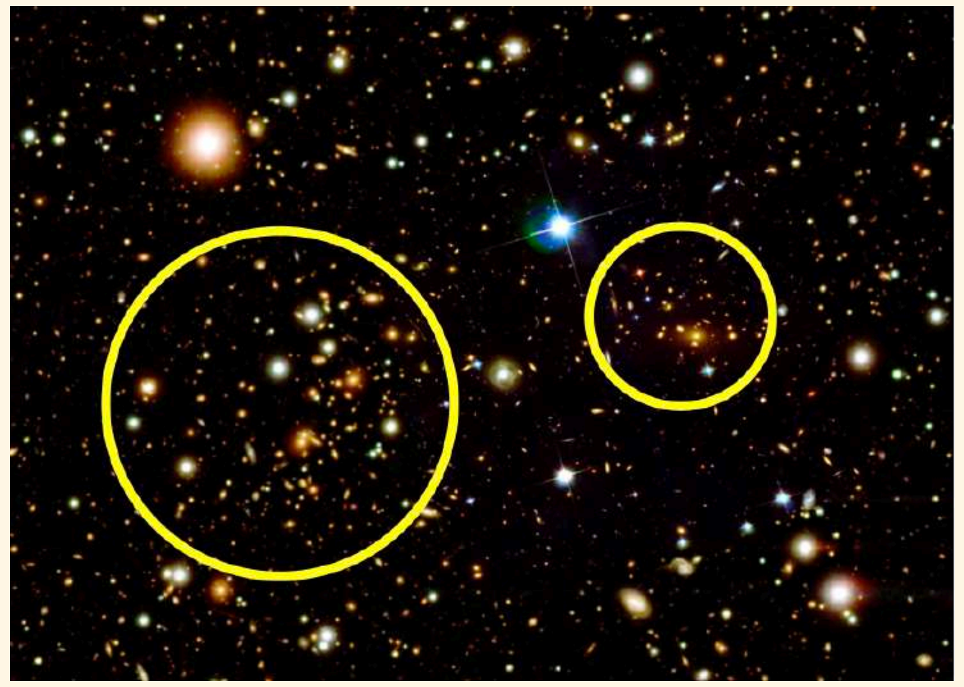
Clusters/lensing



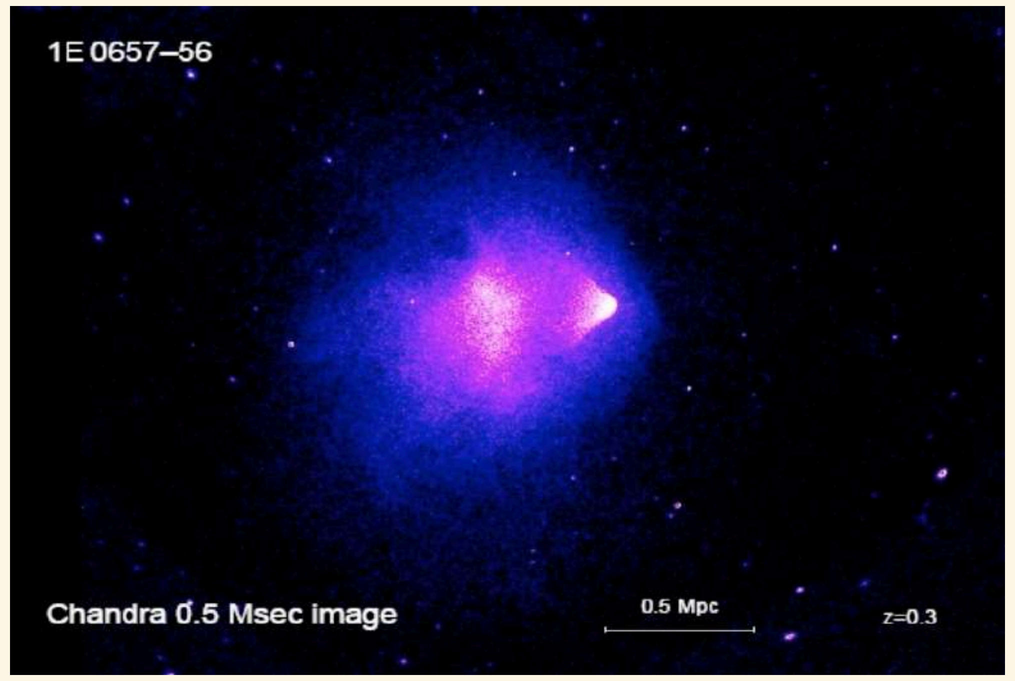
Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

Bullet cluster

Optical

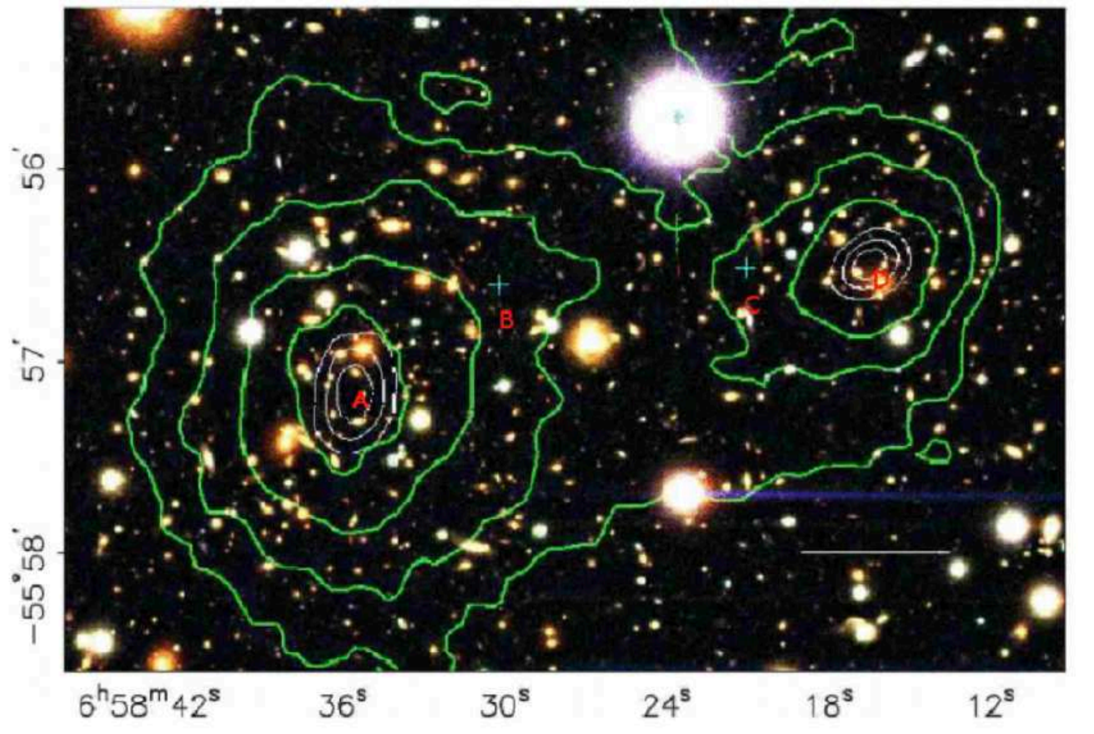


X-ray



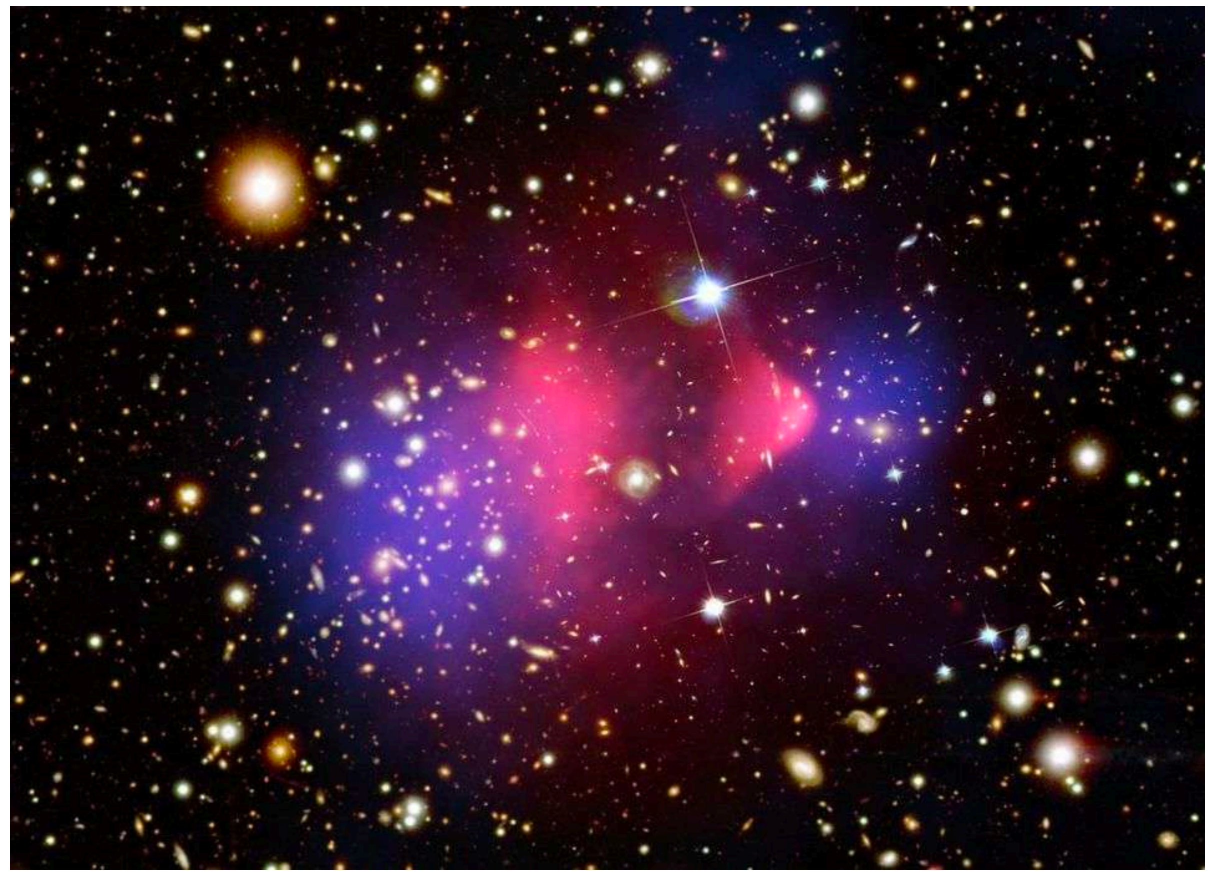
Baryons

Lensing
(Mass contour)



Gravitational potential

Combined



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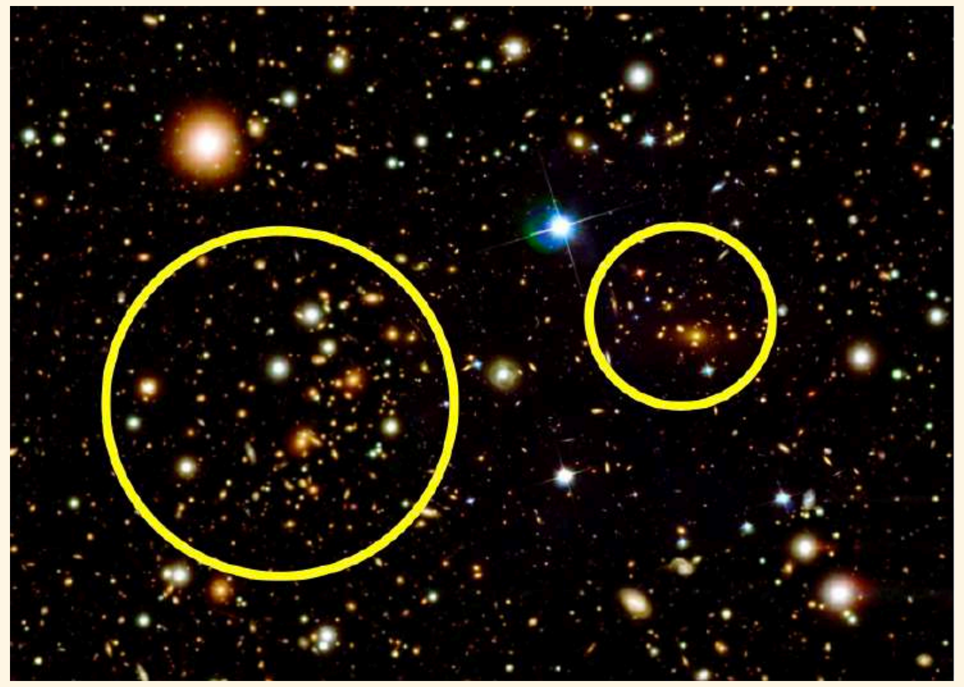
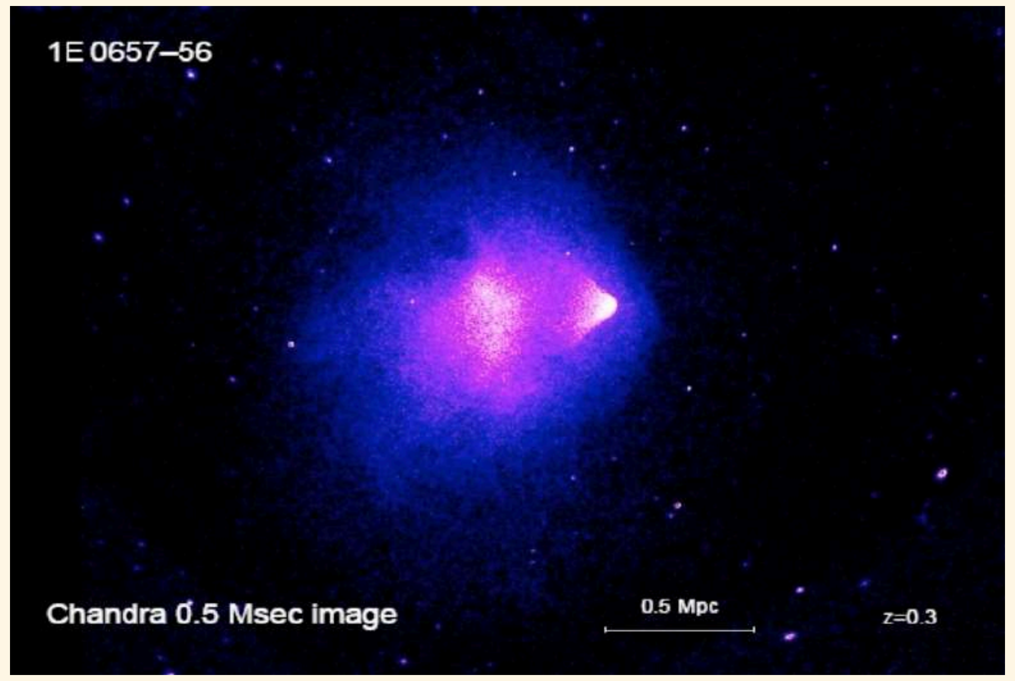


X-ray



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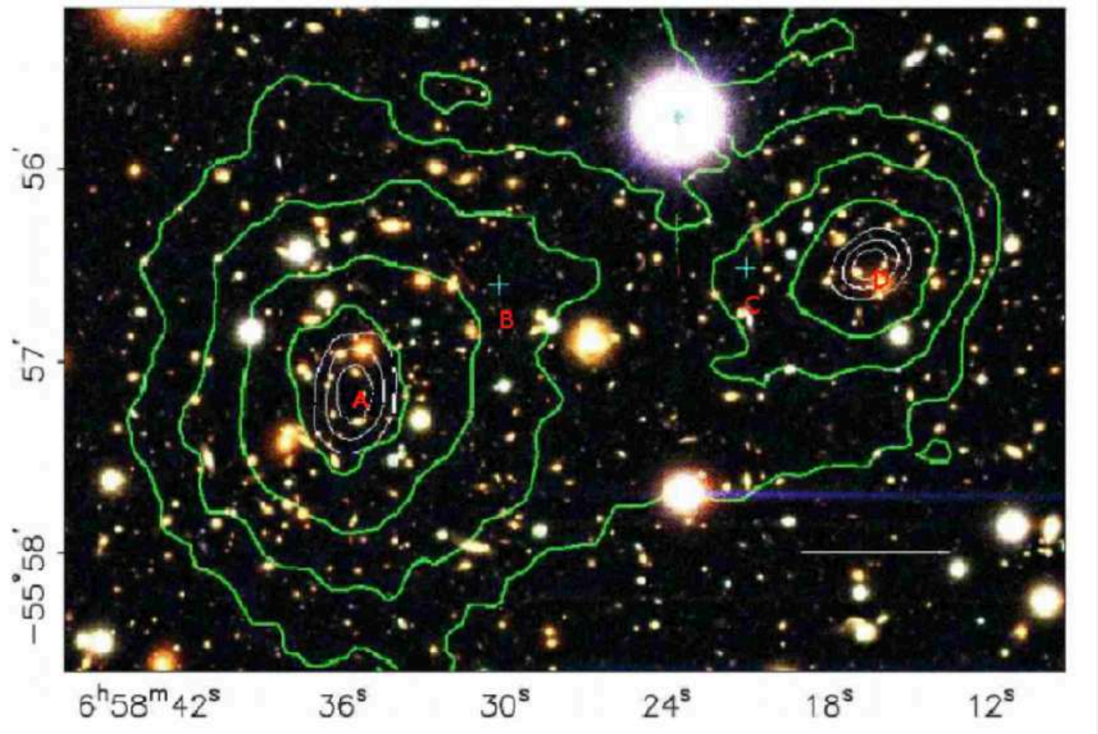
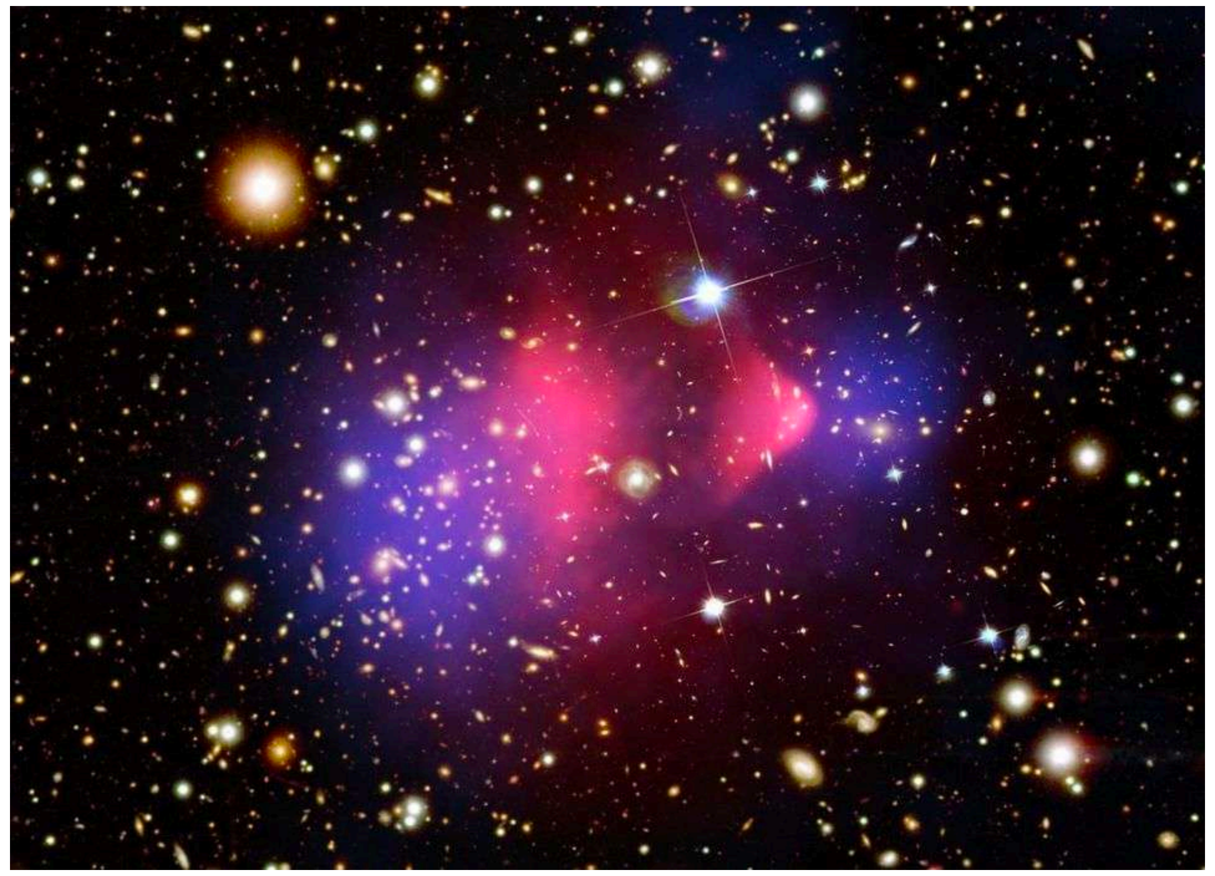


Gravitational potential

Combined



Dark matter

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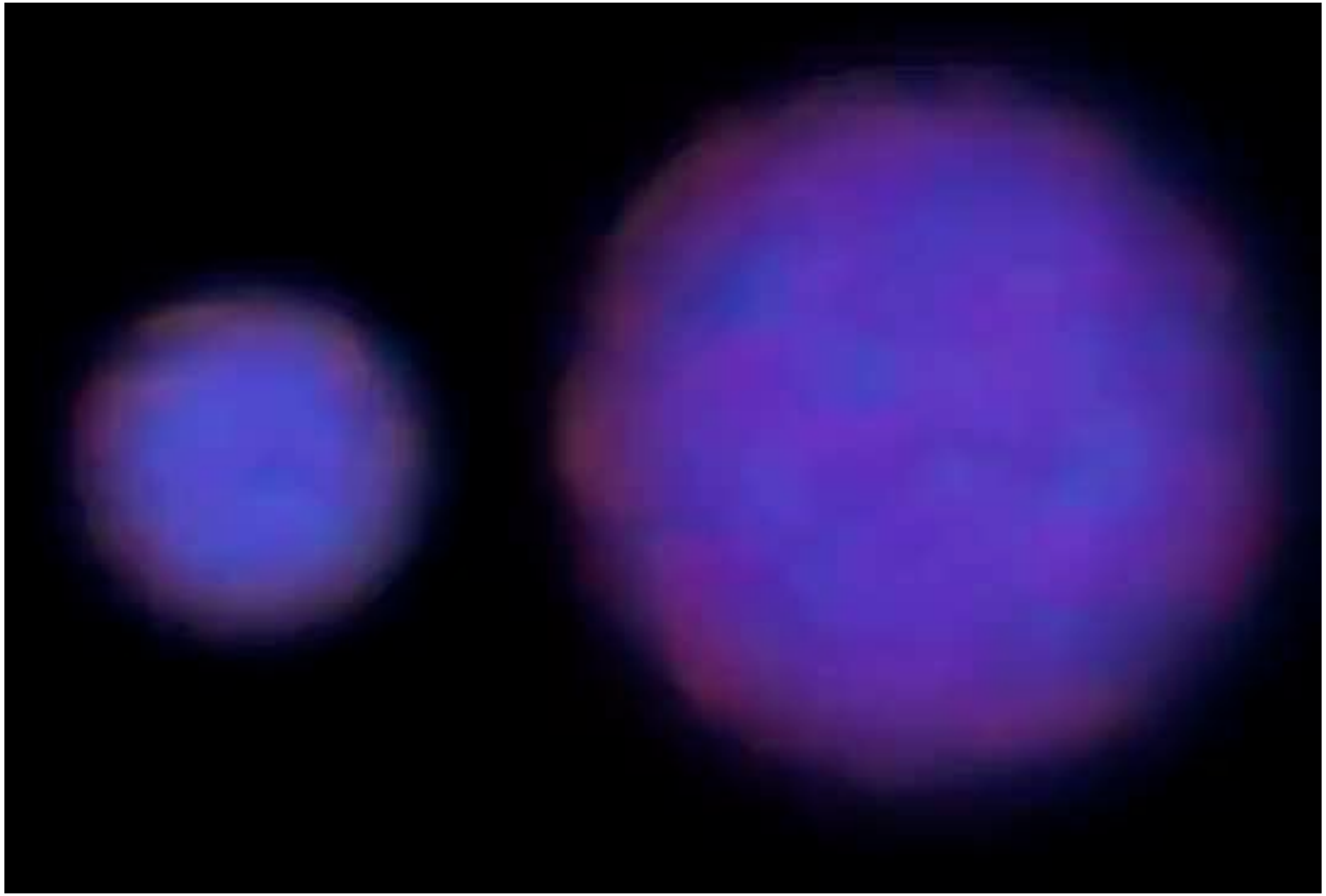
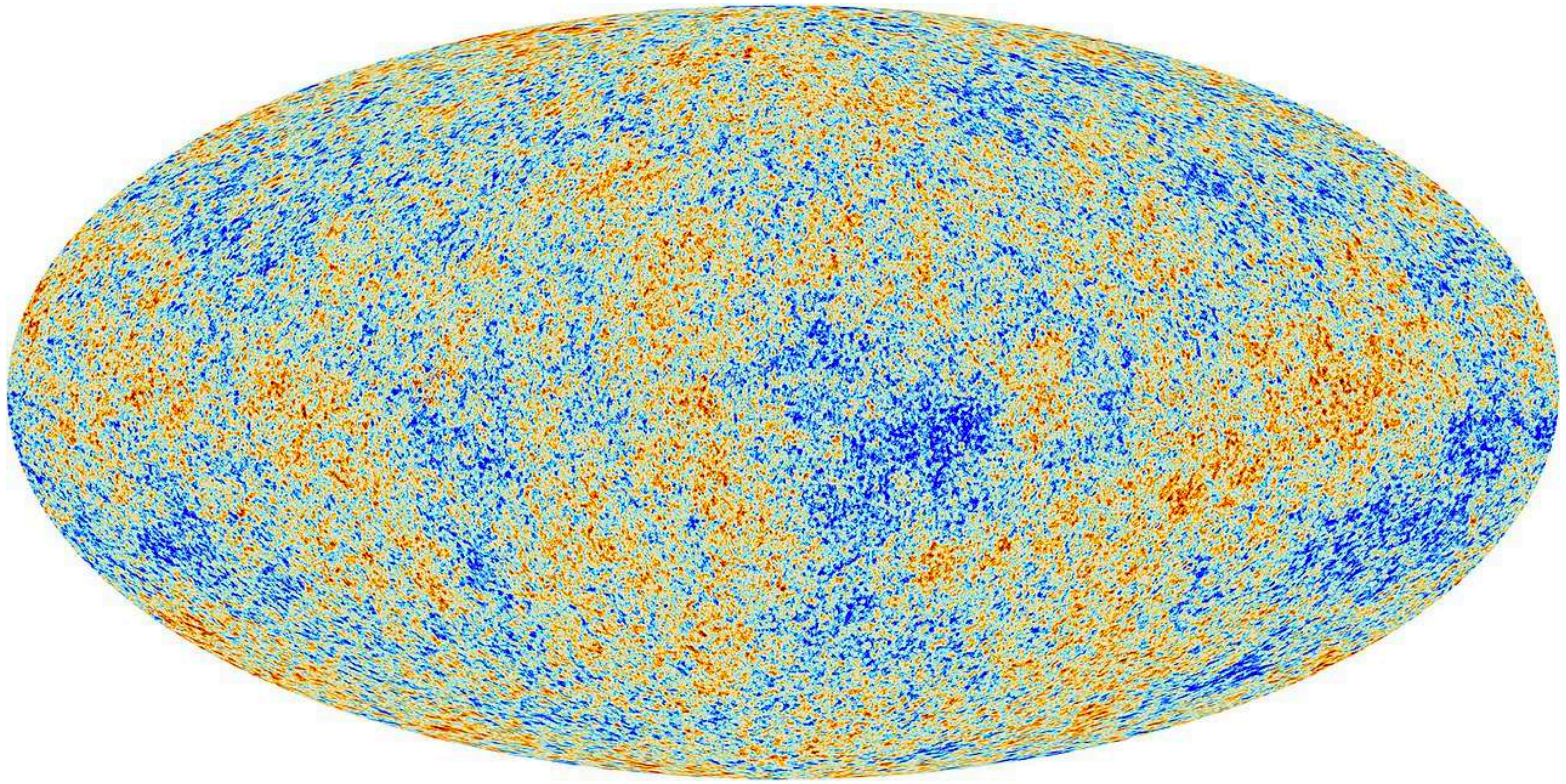
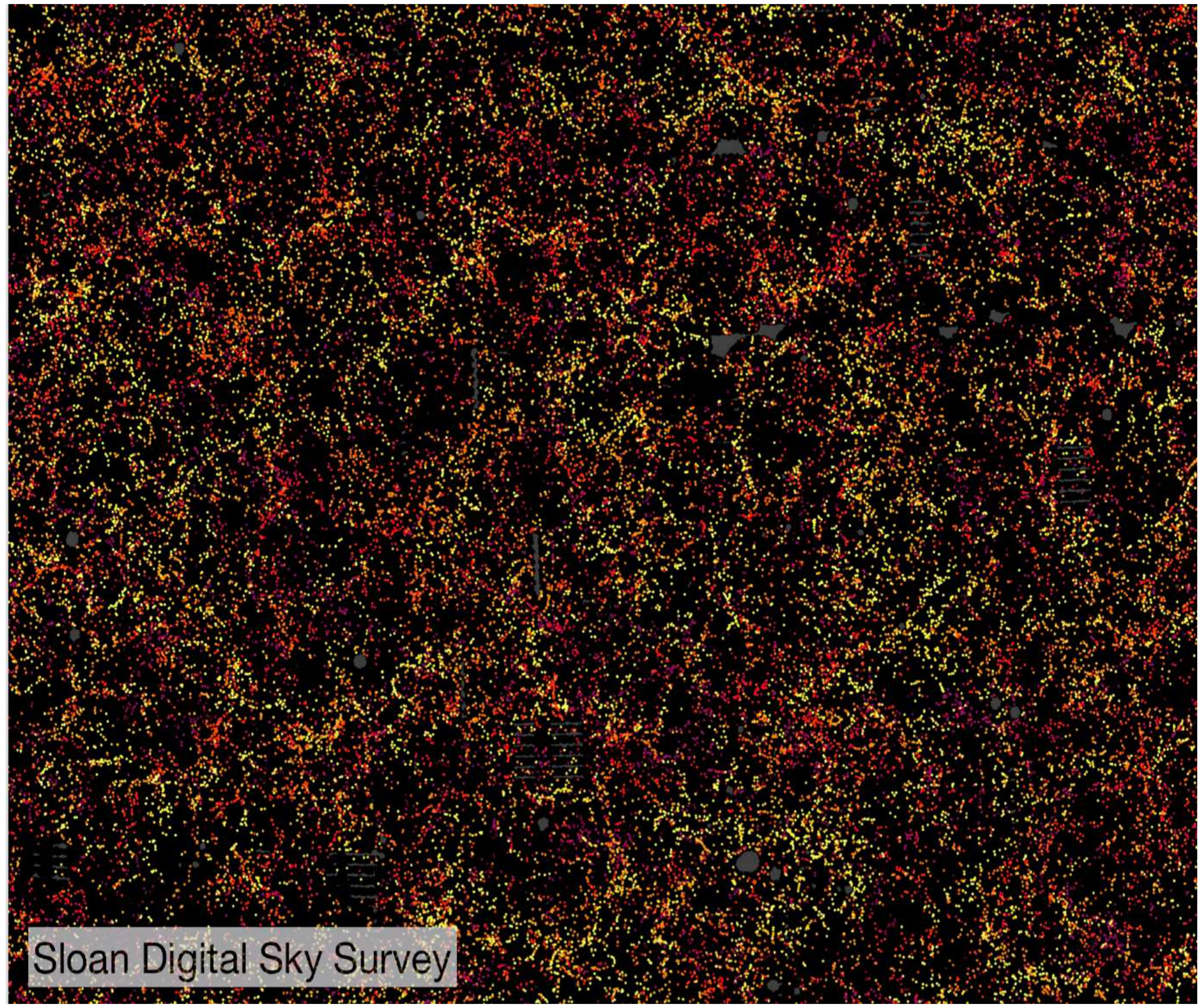
Bullet cluster



Credit: NASA/CXC/M.Weiss

Large scale structure





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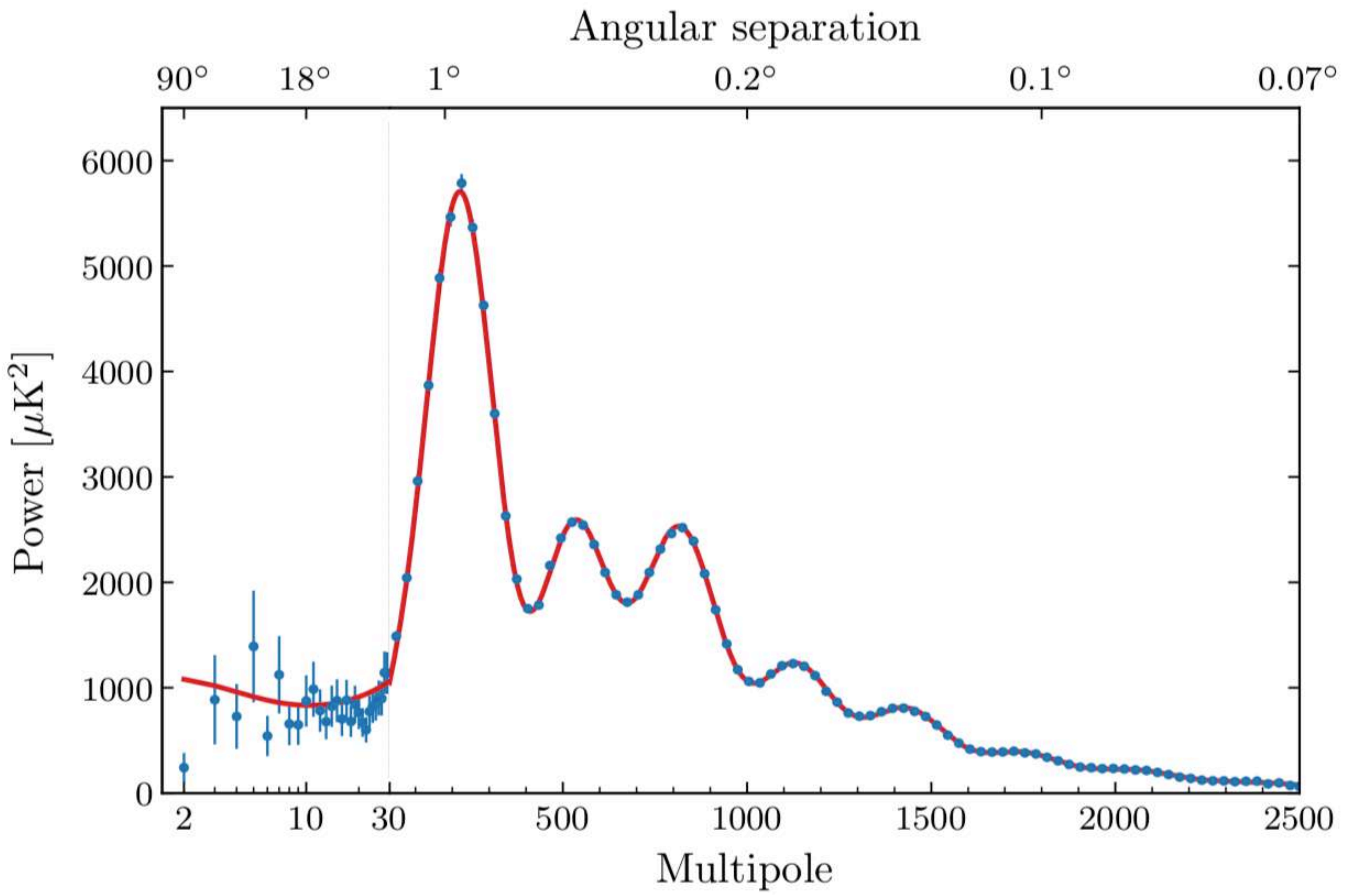
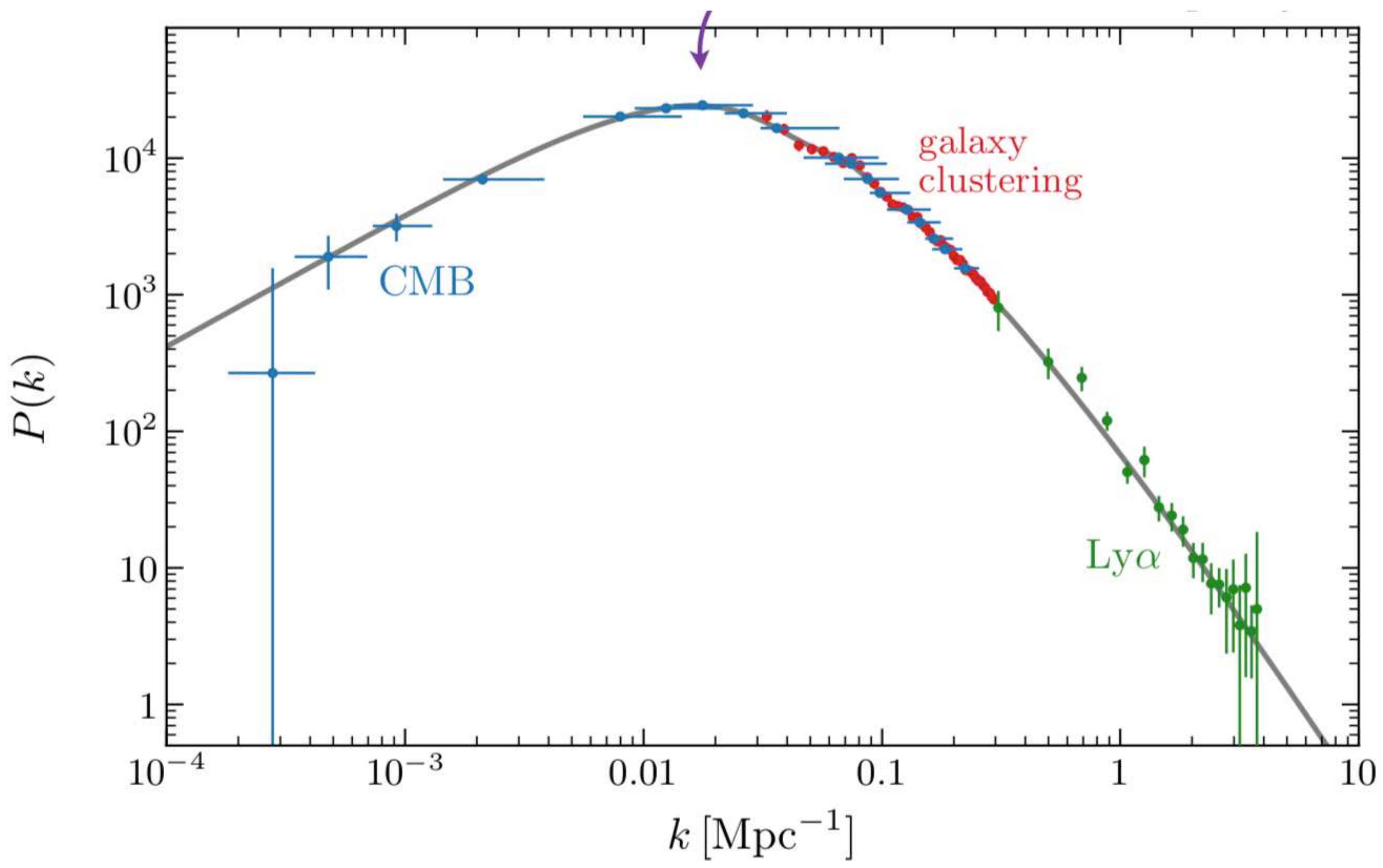
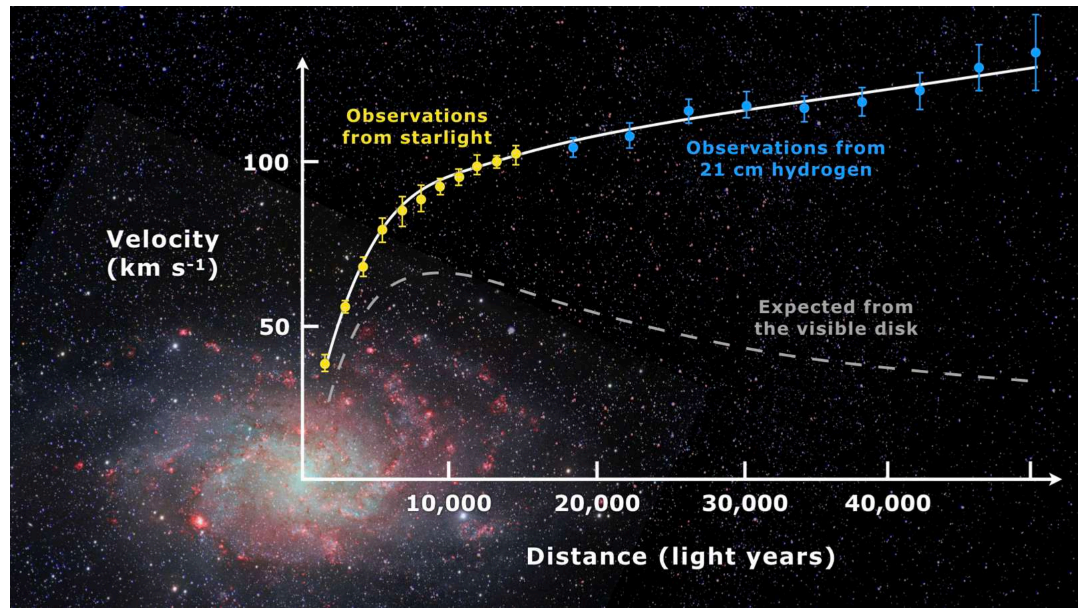




$$\Omega_m = 0.308 \pm 0.012$$ *(Planck 2018)*

Evidences for dark matter - properties

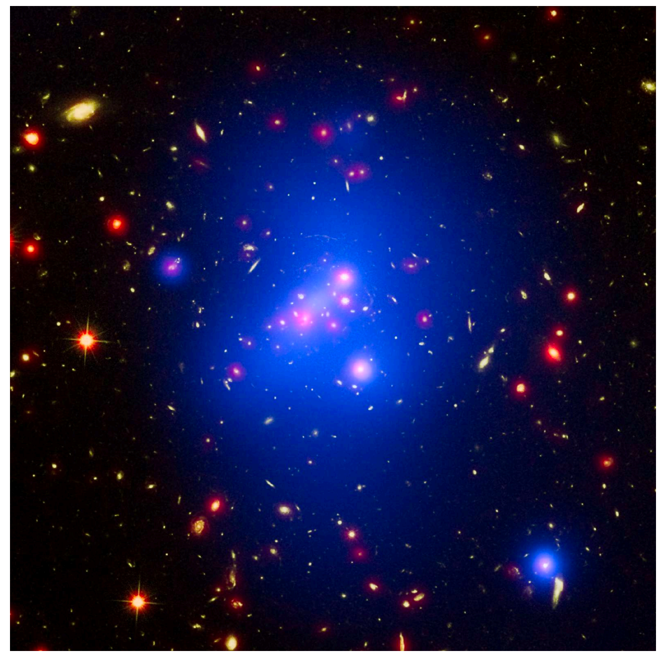
Galaxy rotation curves



Credit: Mario De Leo

- Mass fraction
- Distribution

Clusters



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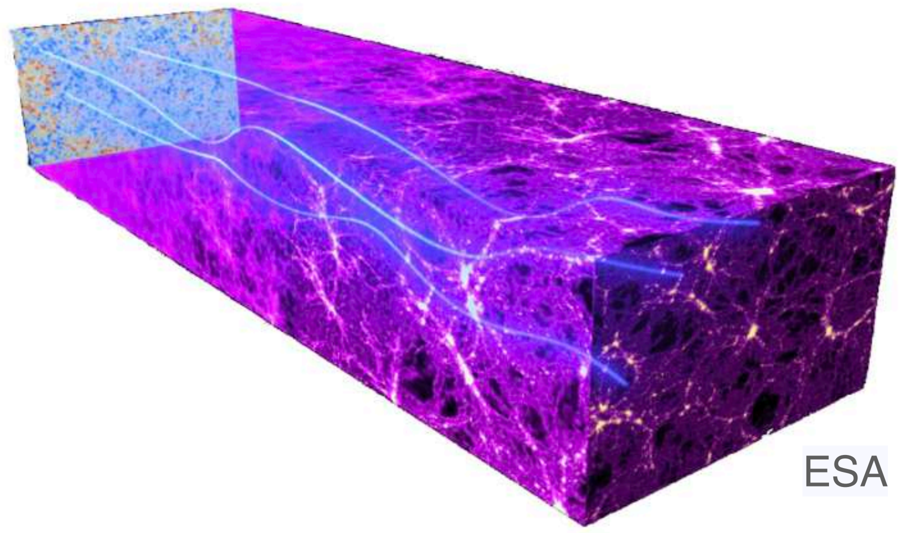
- Mass fraction
- Distribution

Lensing



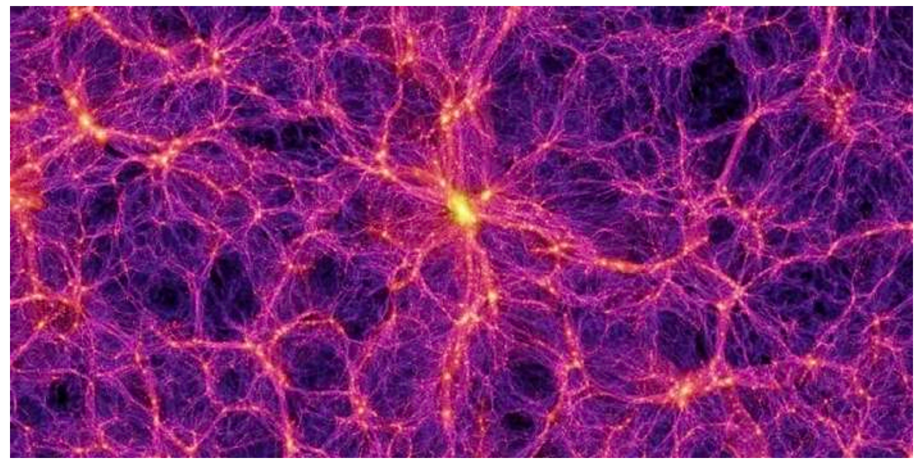
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

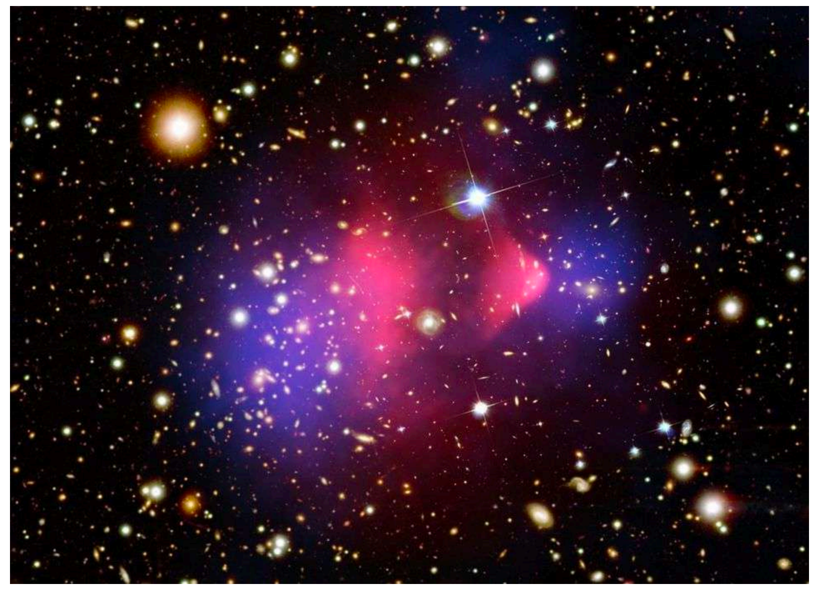
Large Scale Structure



Springel & others / Virgo Consortium

CMB/LSS
- Ratio of DM/collisional matter
- Thermal history

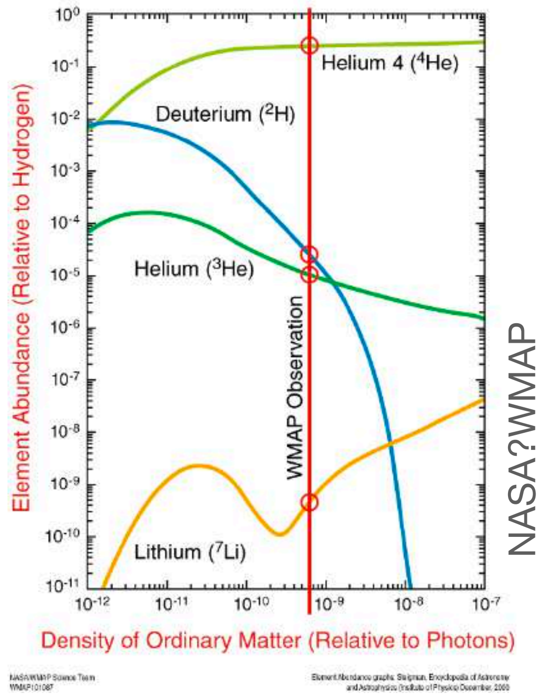
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



NASA?WMAP

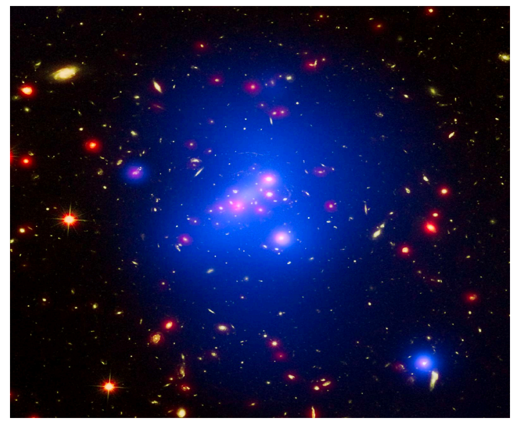
- Amount of baryons

Based on K. Mack

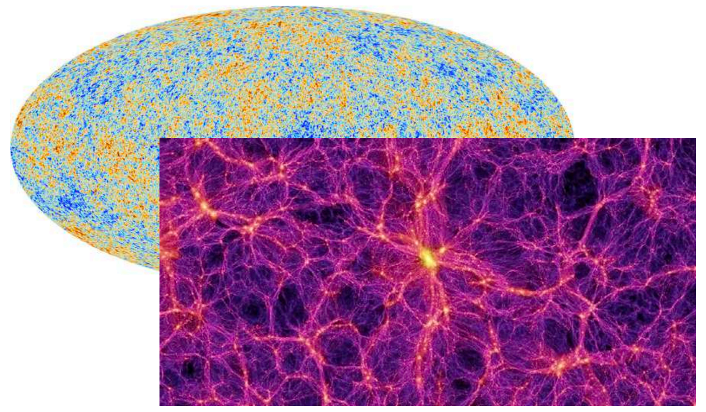
What we know about dark matter

Galaxies

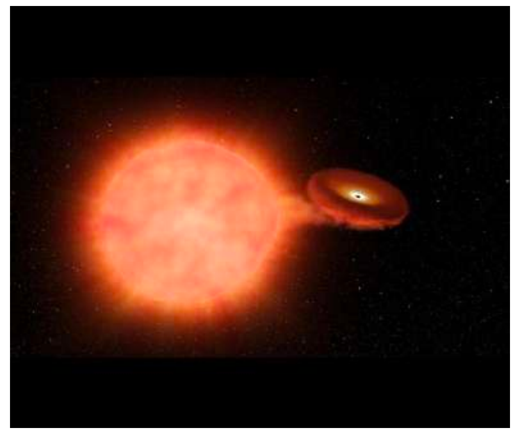
Clusters



Large scales

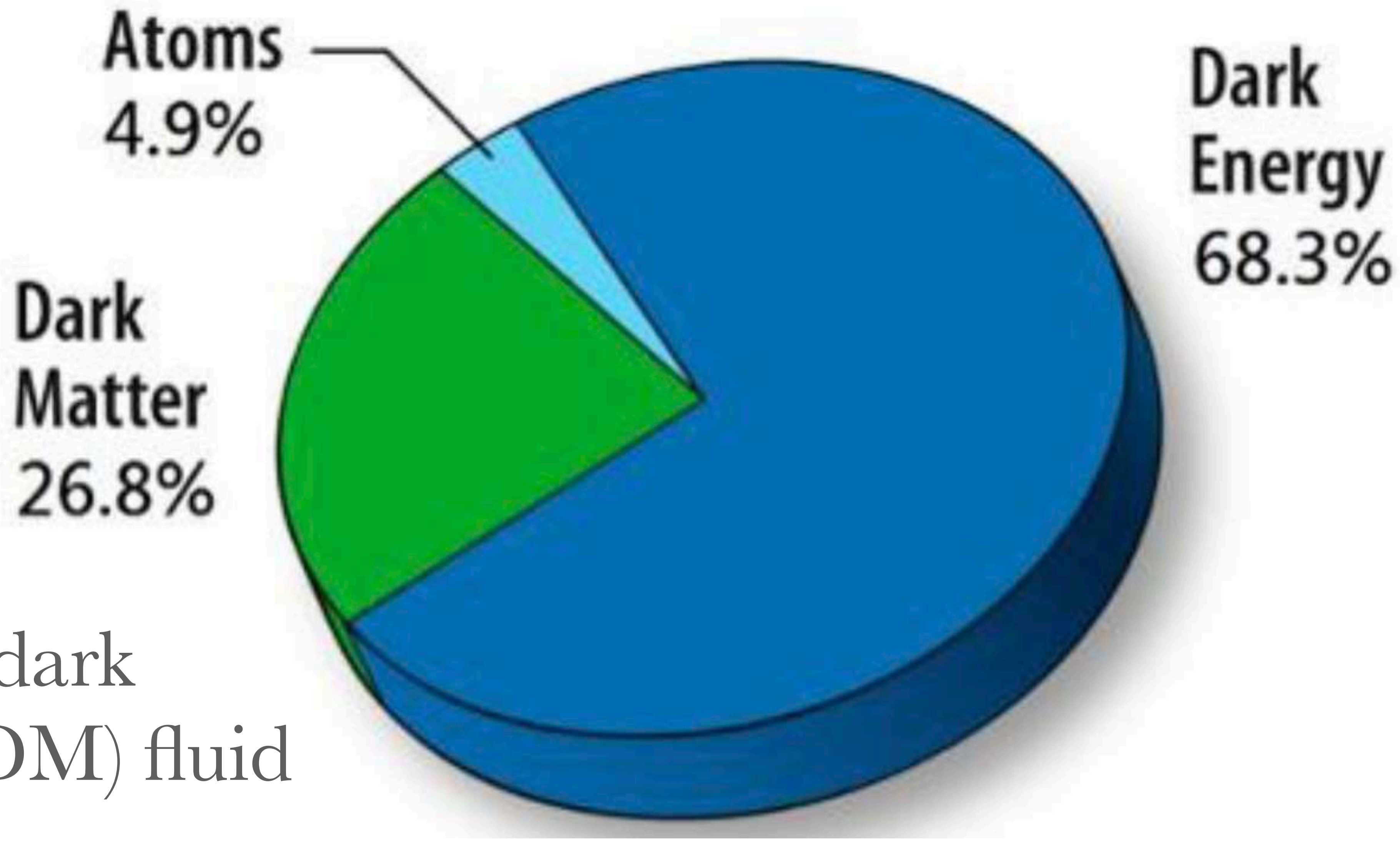


Sn Ia



ΛCDM – the standard cosmological model

Successful description of our universe with 6 free parameters, tested to sub-percent precision.



Λ

DM: cold dark matter (CDM) fluid

Planck 2018

$$\Omega_b = 0.0484 \pm 0.0003$$
$$\Omega_m = 0.308 \pm 0.012$$

Cold dark matter

- Cold: moves much slower than c
- Presureless: gravitational attractive, clusters
- Dark (transparent): no/weakly electromagnetic interaction
- Collisionless: no/weakly self-interaction or interaction with baryons
- Abundance: amount of dark matter today known

CDM on large scales described by a ***perfect fluid***:

Backg.: ρ, P

$w = P/\rho$

with $P = 0 \Rightarrow w = 0$

$\Rightarrow \rho \propto a^{-3}$

Pert.: δ, θ

with $c_s \sim 0$

Cold dark matter

- Cold: moves much slower than c

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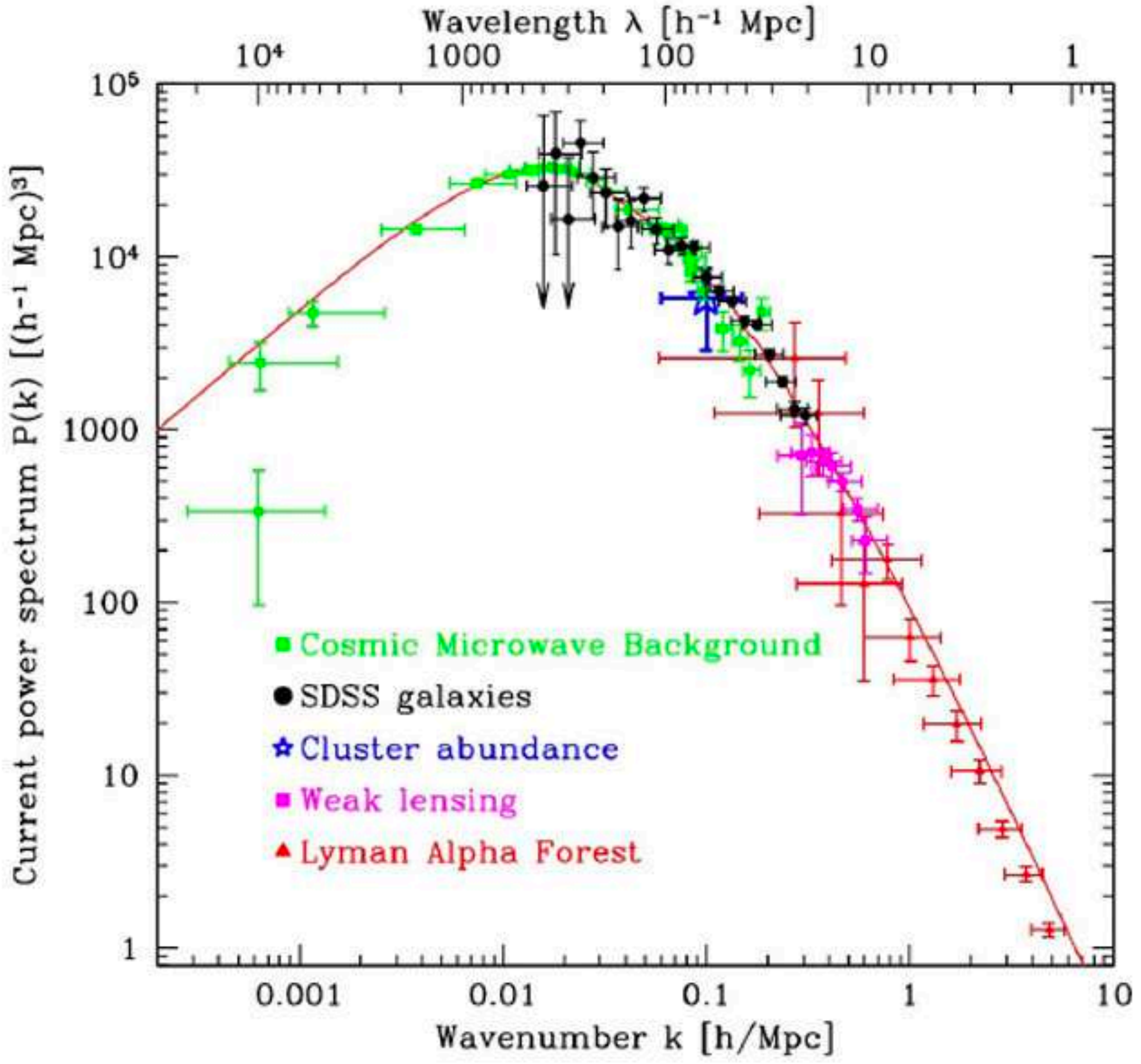


Many observational probes for $k \sim 10^{-3} - 10\,\mathrm{Mpc}^{-1}$

range of redshift $z < 3 - 4$

Incredible agreement to CDM!

What we know about dark matter

What we learned from observations

Properties:

What we know about dark matter

What we learned from observations

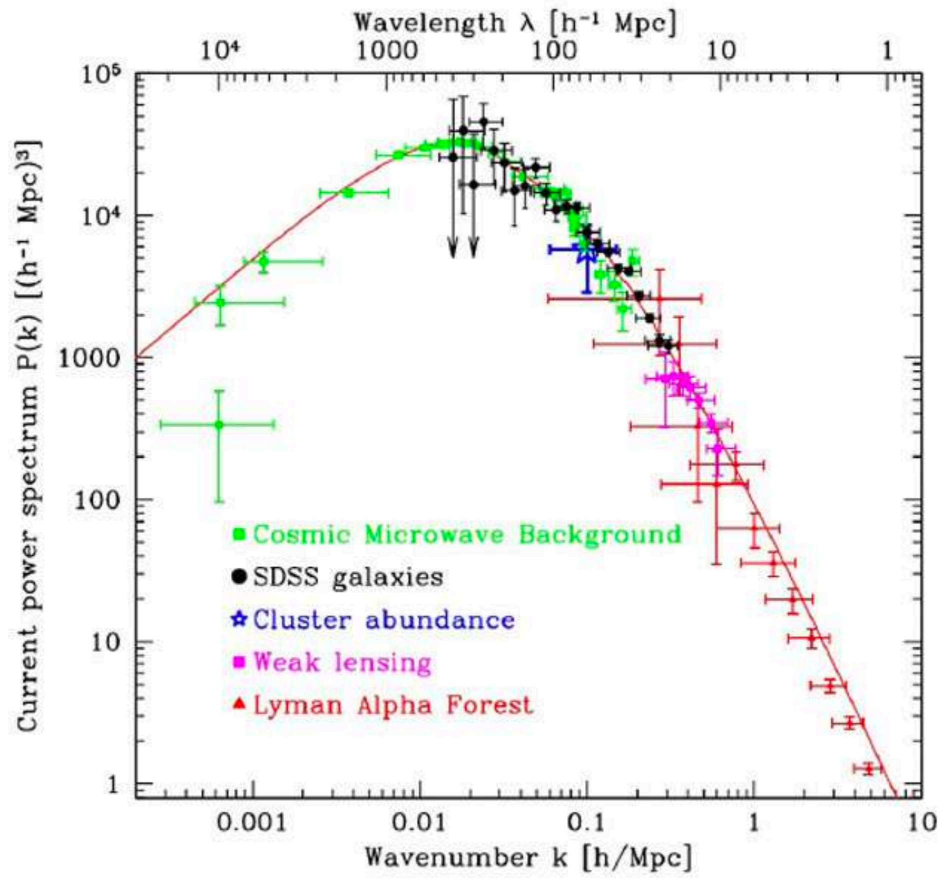
Properties:

- Cold
- Presureless

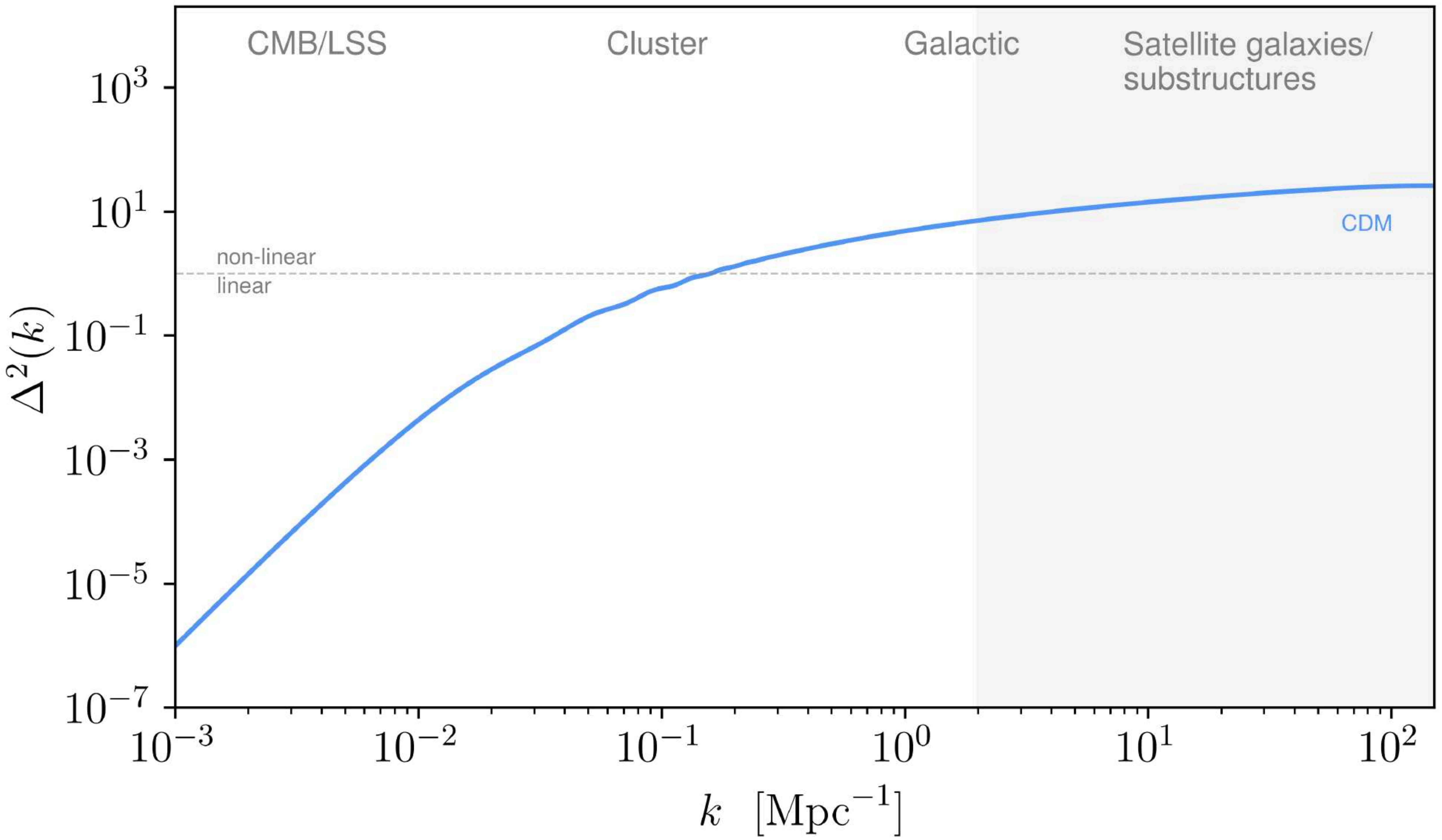
What we know about dark matter

Properties:

From LSS:



Measure PS well until scales
$k \sim 10 - 20\,\mathrm{Mpc}^{-1}$



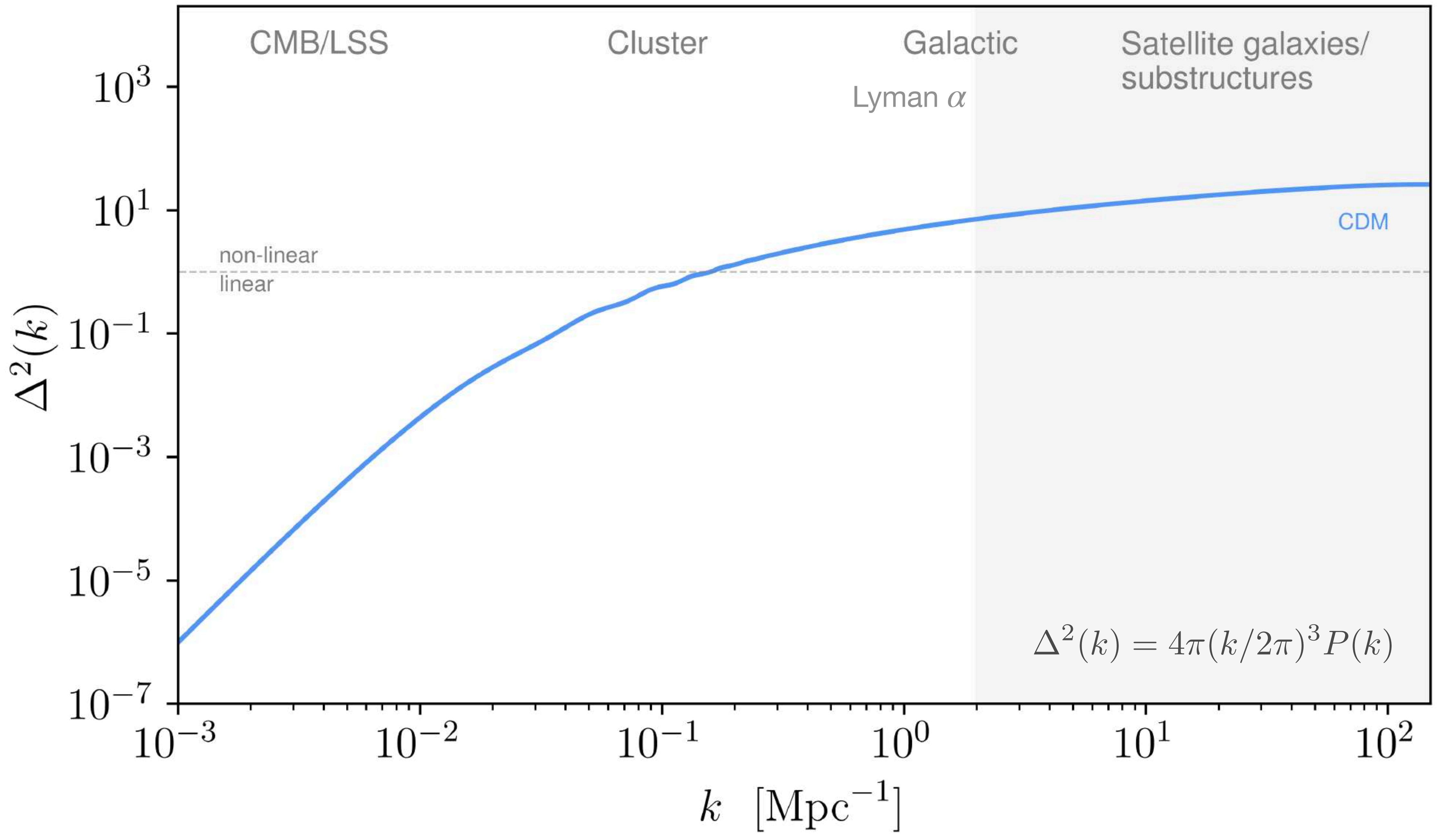
Dimensionless power spectrum

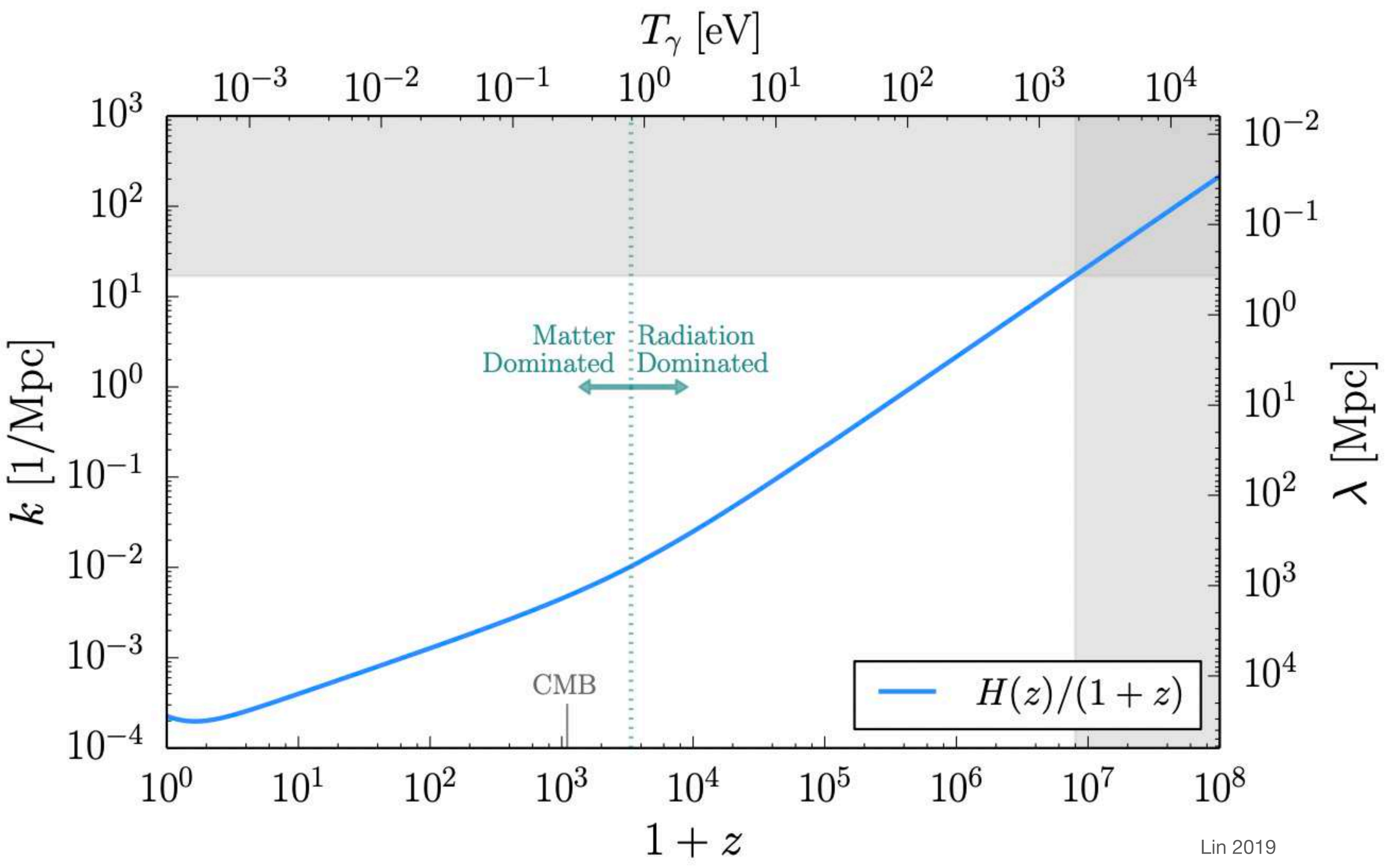
$$\Delta^2(k) = 4\pi(k/2\pi)^3 P(k)$$

What we *know* about dark matter

Properties:

$$T_\gamma = T_{\gamma,0}(1+z)$$





CDM pert. ($c_s = 0$) inside Hubble radius:

$$\delta \propto \begin{cases} \log a & \text{rad. domination} \\ a & \text{matter domination} \end{cases}$$

Perturbation modes enter the Hubble radius $\lambda_{phys} = a/k = H^{-1}$

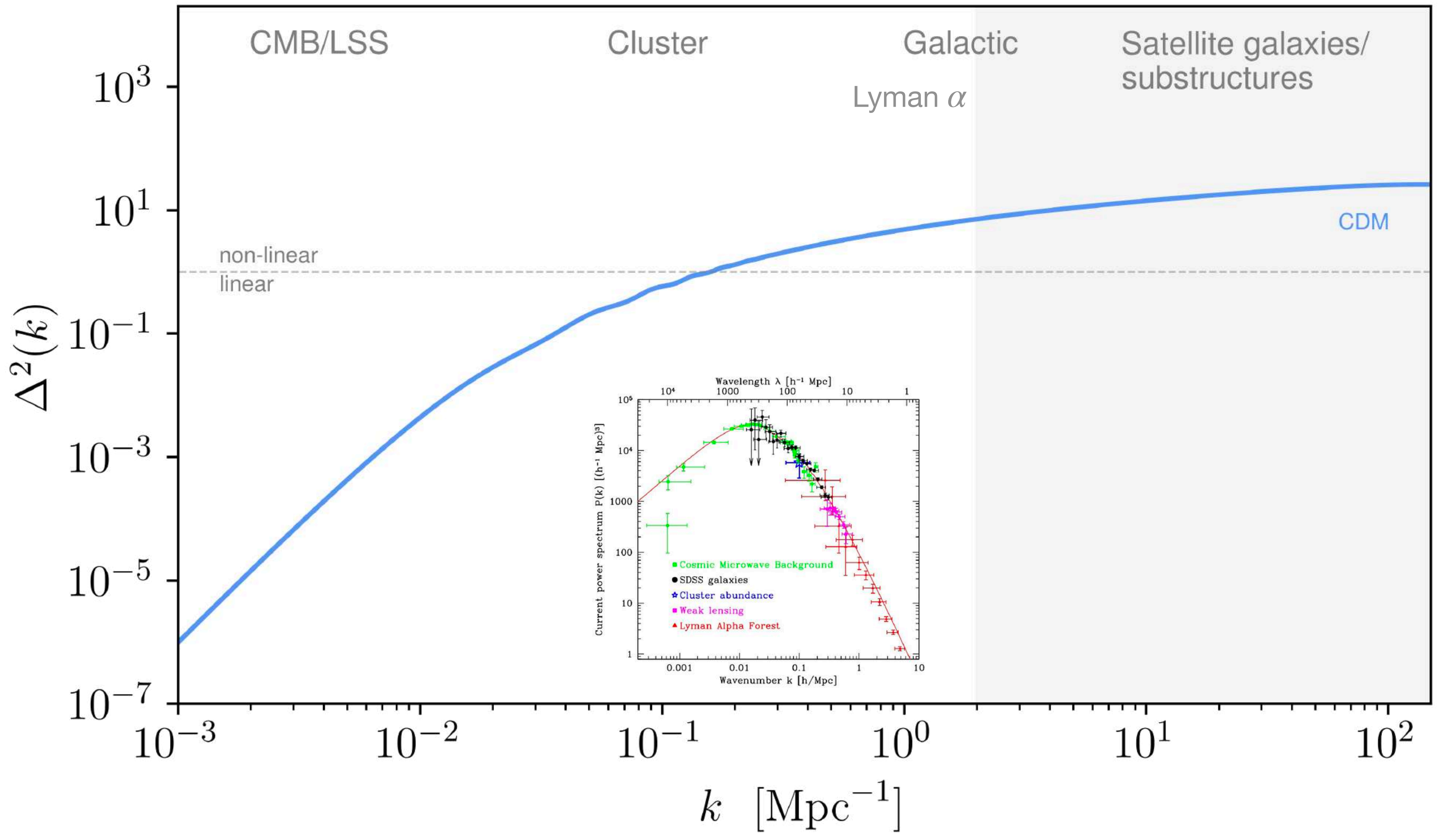
$$k = aH = H/(1+z)$$

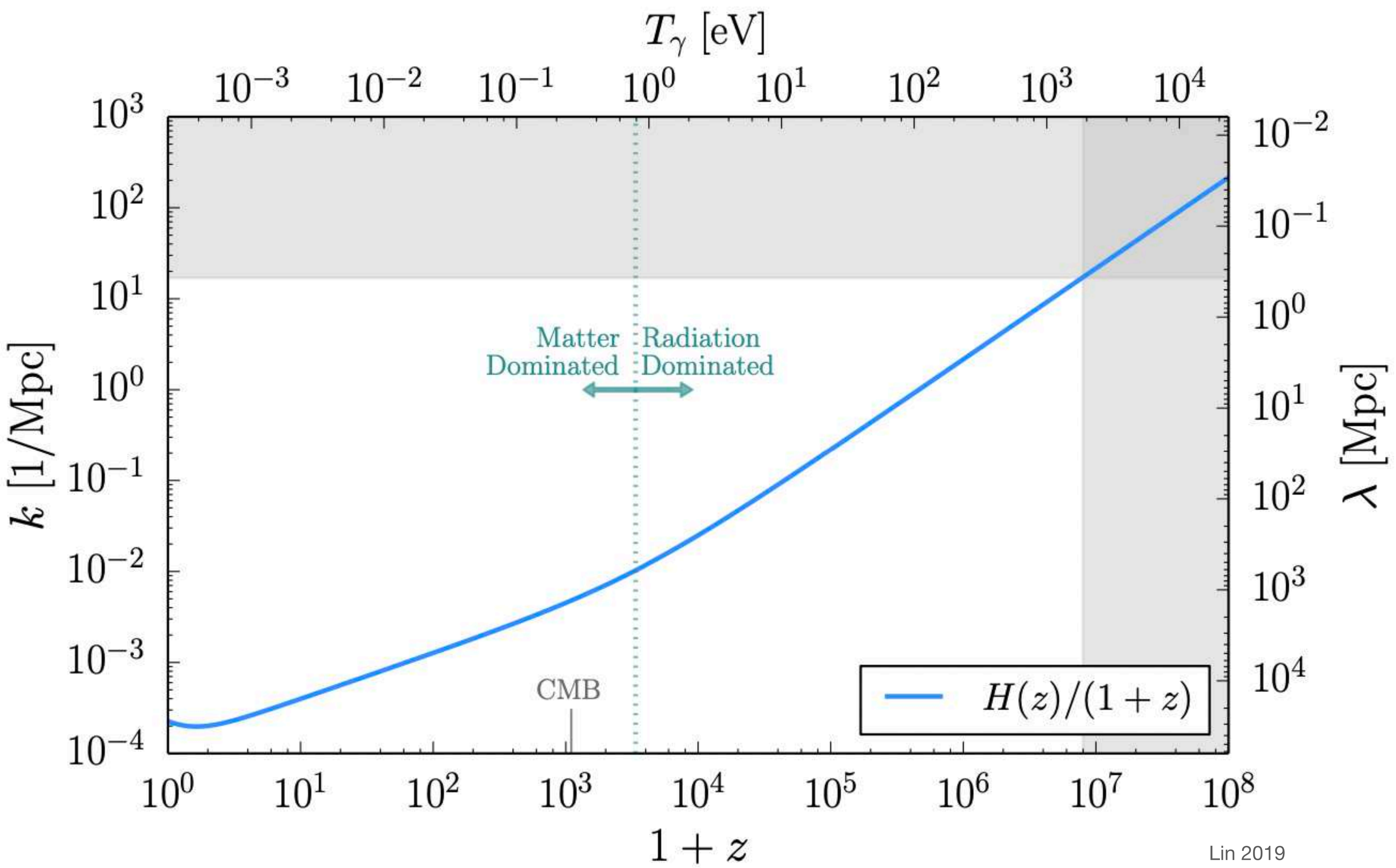
After this, the density pert. of CDM start to evolve, **grow** - contribute to the PS

What we know about dark matter

Properties:

$$T_\gamma = T_{\gamma,0}(1+z)$$





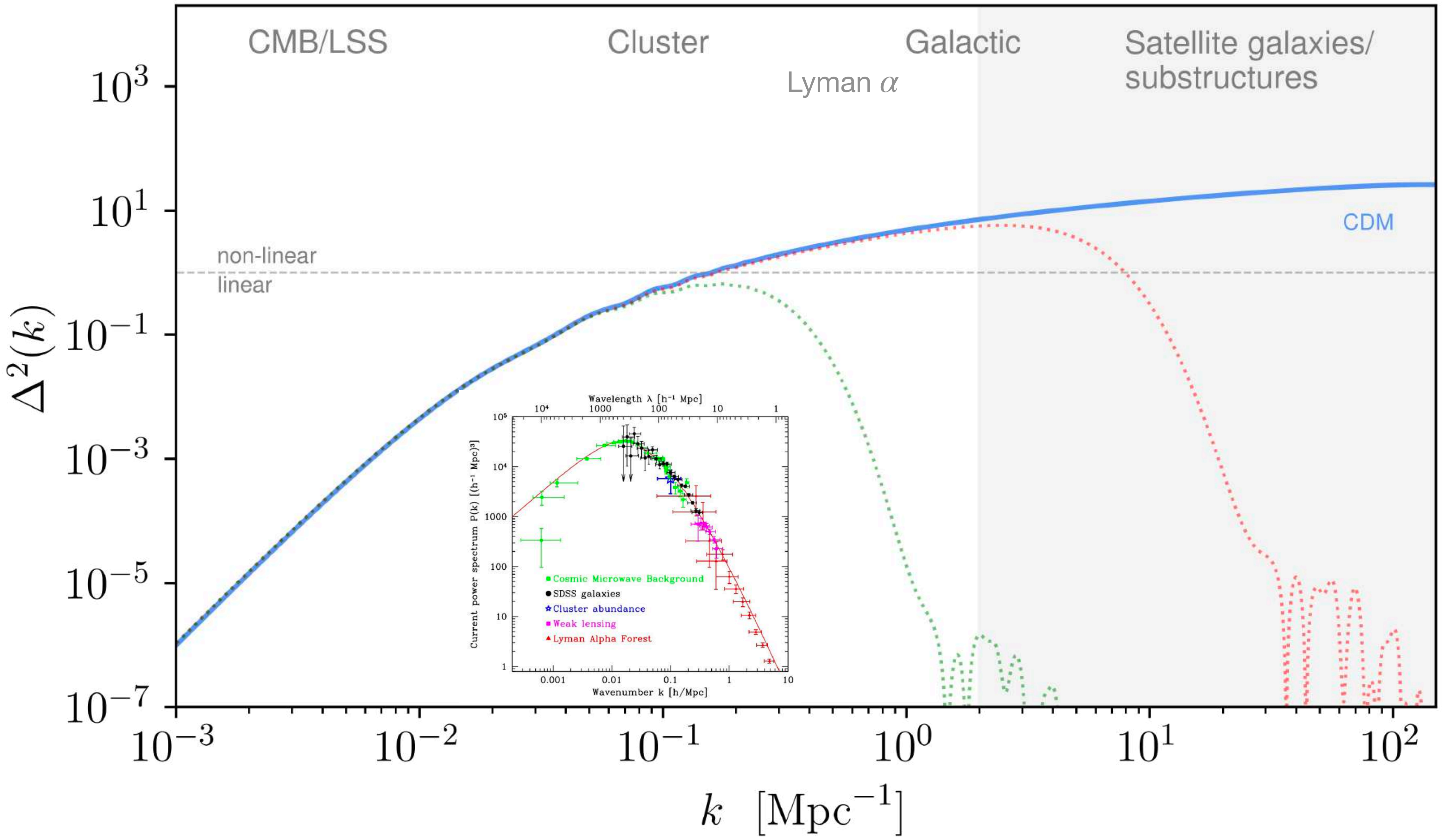
Perturbation modes enter the Hubble radius $\lambda_{phys} = a/k = H^{-1}$

$$k = aH = H/(1+z)$$

So we can describe the observations, all the modes in the white region ($< 10\,\text{Mpc}^{-1}$) are inside the Hubble radius and contribute to the PS, and are very precisely described by CDM $\Rightarrow$ cold and pressureless

What we know about dark matter

Properties:



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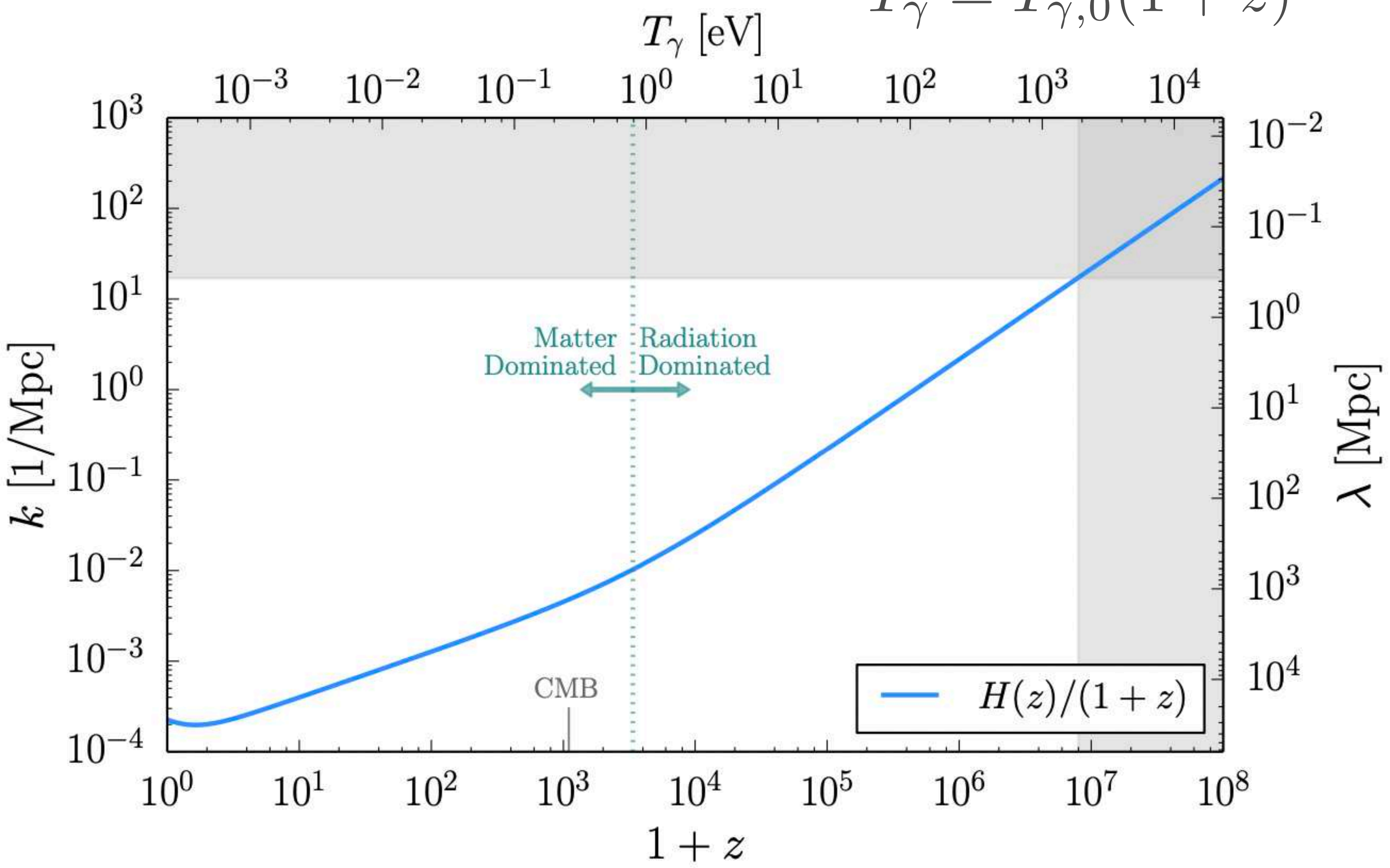

Lin 2019

If DM relativistic (or hot) when $z < 10^7$, this mode is inside R_H, so it will contribute to the PS - since relativ. pert. DO NOT cluster, we would have a **suppression in the power spectrum** for $k < 10 - 20\,\mathrm{Mpc}^{-1}$ - *not in agreement with observations!*

$\Rightarrow$ DM has to be non-relativistic before $z = 10^7$

If **DM in thermal equilibrium** with the photon-mat plasma ($T_{dm} = T_\gamma$)

$\Rightarrow m_{dm} > \mathrm{keV}$

WDM bound

What we know about dark matter

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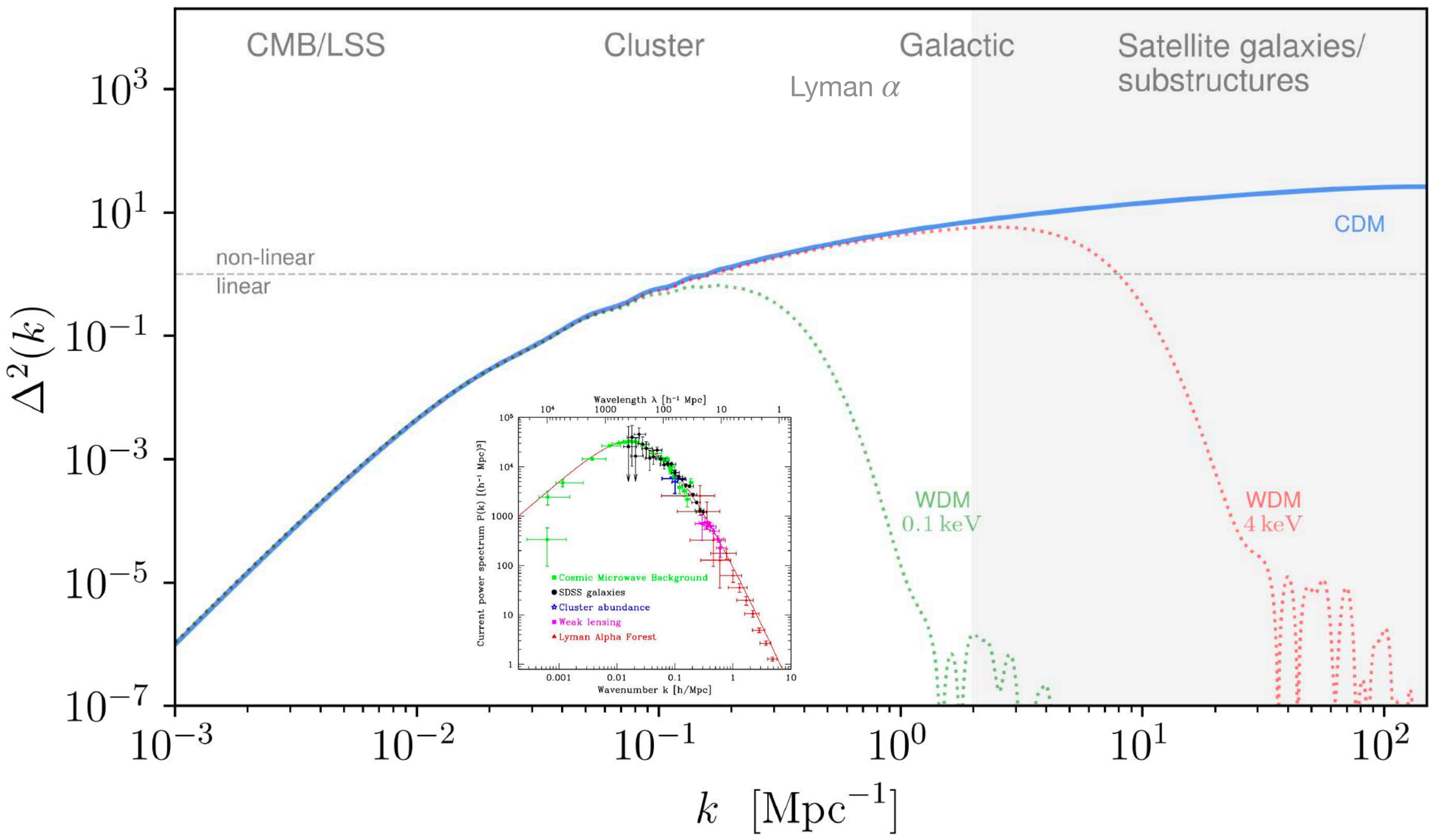

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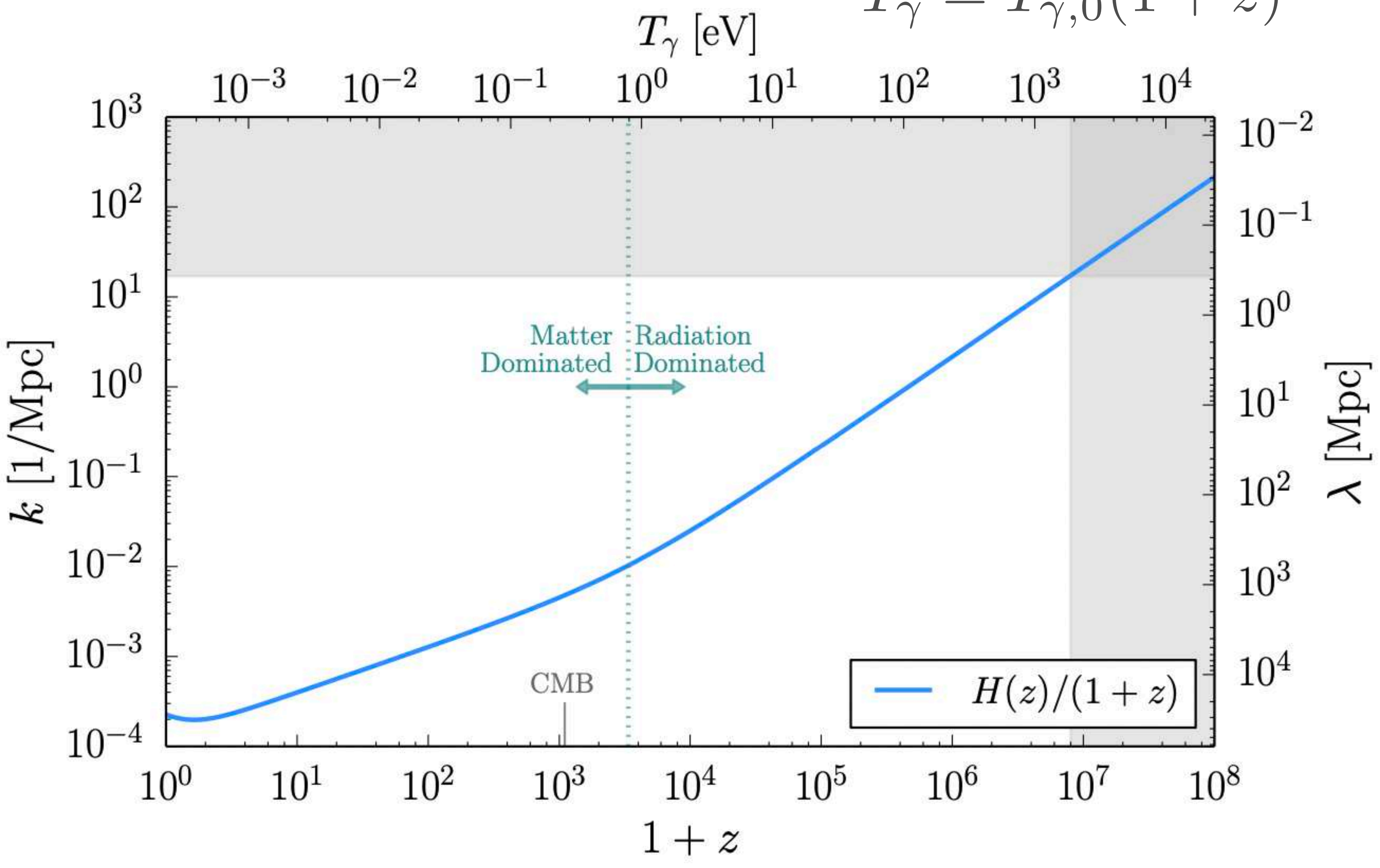

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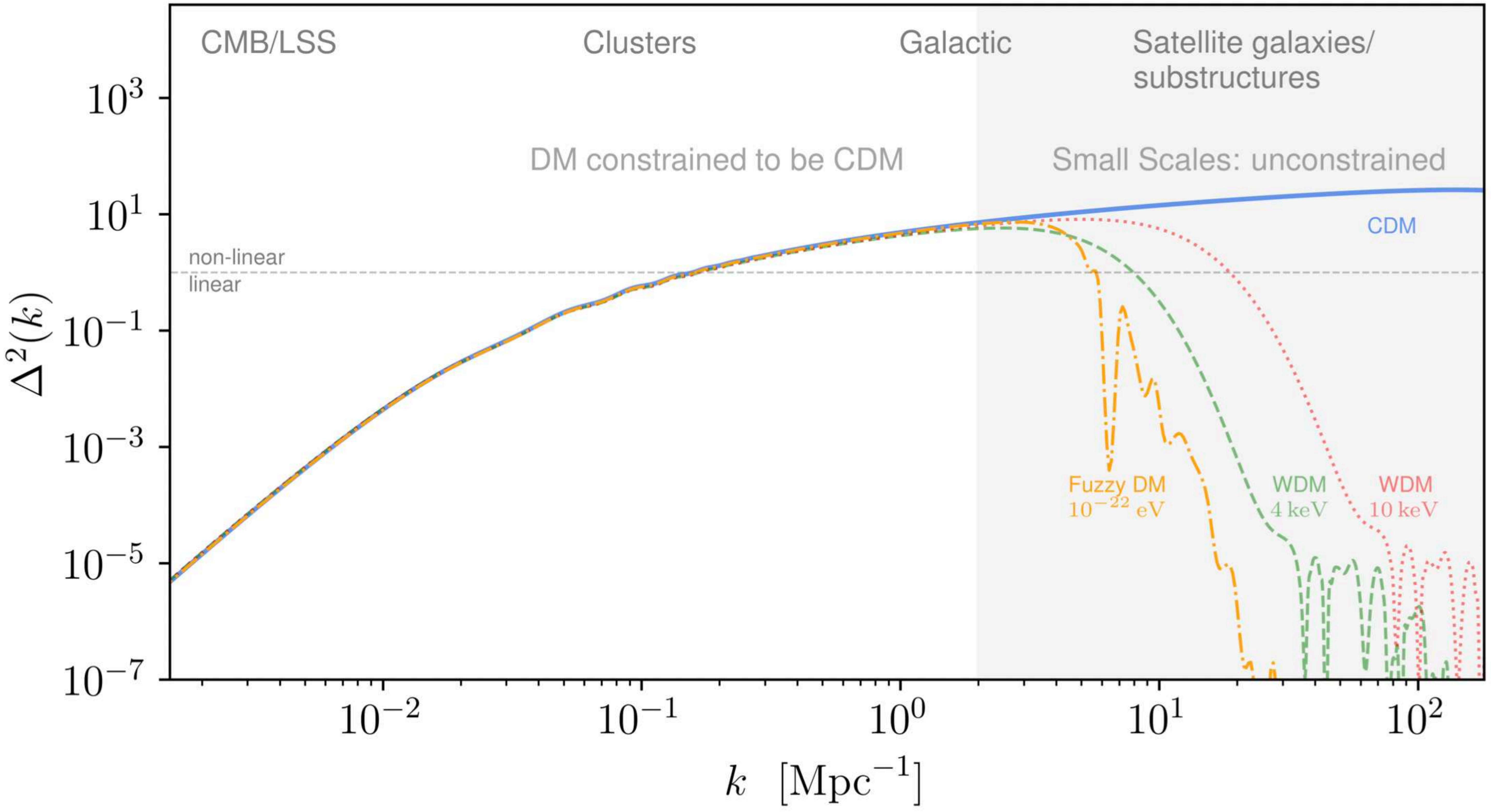
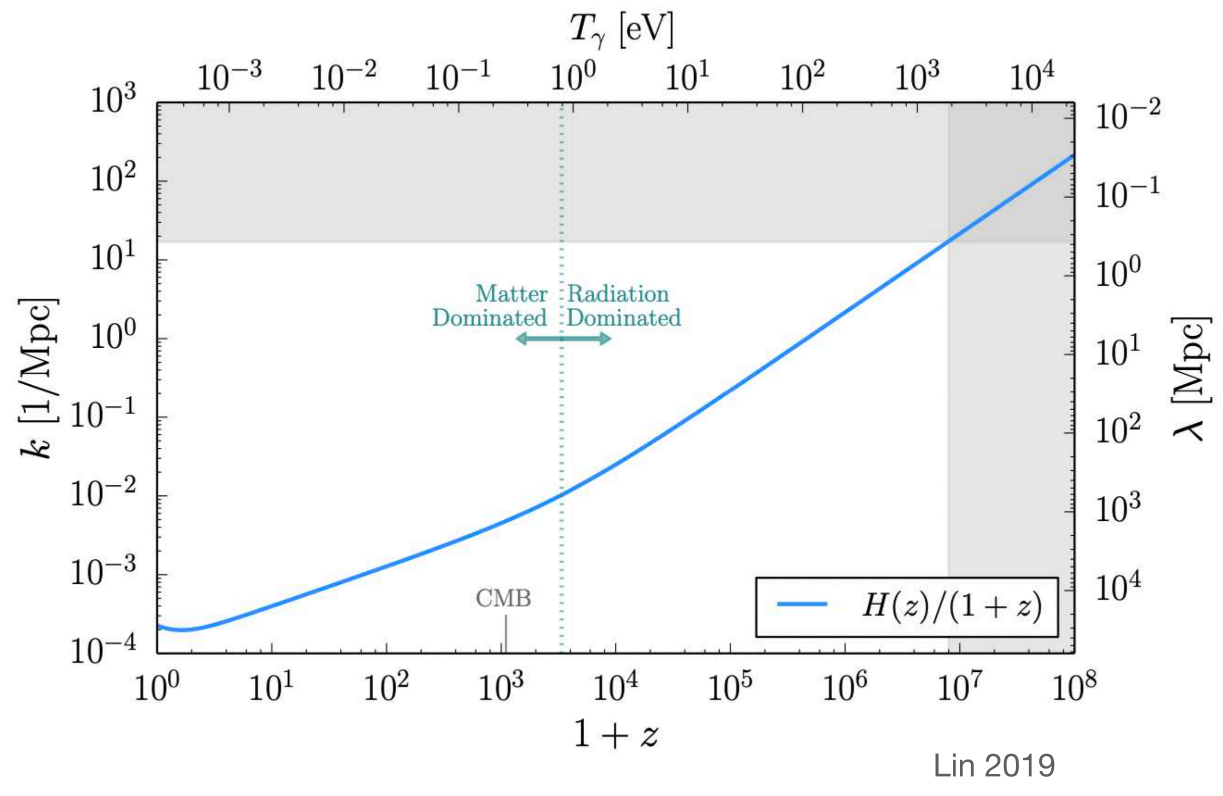




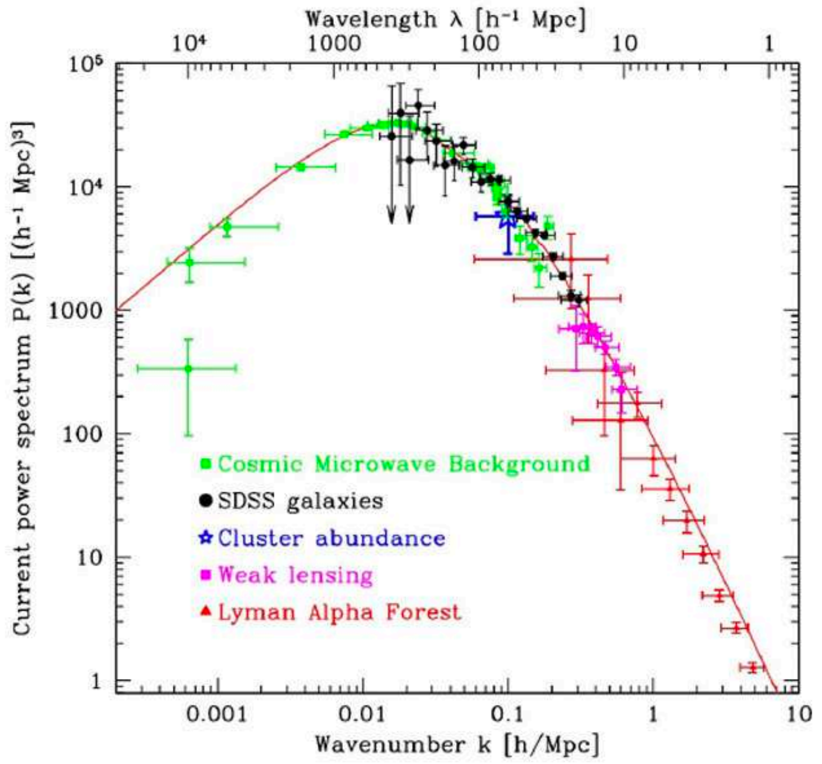
Deviations from CDM in the highlighted region are allowed, since highly unconstrained!

What we know about dark matter

What we learned from observations

Properties:

- Cold
- Presureless



What we know about dark matter

Properties:

- Cold
- Presureless
- Dark (transparent): DM does not interact electromagnetically

What we know about dark matter

- Dark (transparent/neutral): DM does not interact electromagnetically

Obviously: If DM interacted electromagnetically, interacted with photons, it would scatter light and thus not be dark

↘ *DM charge* $\epsilon\, e$

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Change the abundance of light elements

*What we **know** about dark matter*

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↘ *DM charge* ϵe

If DM had a *charge*:
- Suppression of the power spectrum

What we know about dark matter

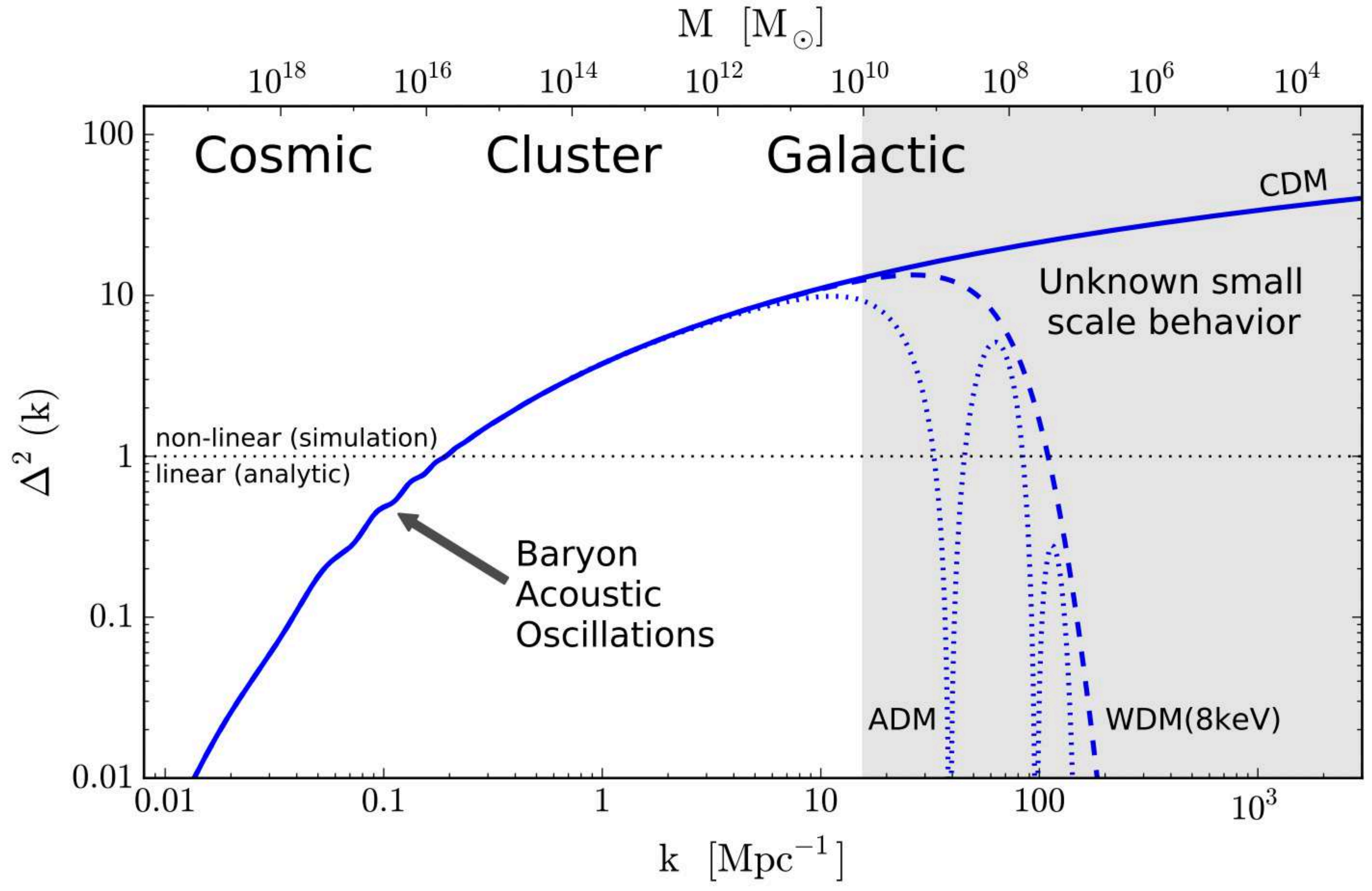
- Dark (transparent/neutral): DM does not interact electromagnetically

If DM had a *charge* $\epsilon\, e$:

- Suppression of the power spectrum

Charged DM particles interact with the Standard Model via a small coupling through the photon

If the DM is coupled with the baryon-photon plasma during *recombination*, the DM density fluctuations can be washed out due to the radiation pressure and the photon diffusion (Silk damping). The BAO structure will also be directly altered through the coupling.



Ex: ADM - atomic dark matter

Ref.: Kaplan et al 2009, Cyr-Racine et al 2012

→ Interactions of DM with SM particles at early times would **suppress** the power spectrum, since the radiation pressure of the baryons and photons would prevent DM density perturbations from growing

What we know about dark matter

- Dark (transparent/neutral): DM does not interact electromagnetically

If DM had a *charge* ϵe :

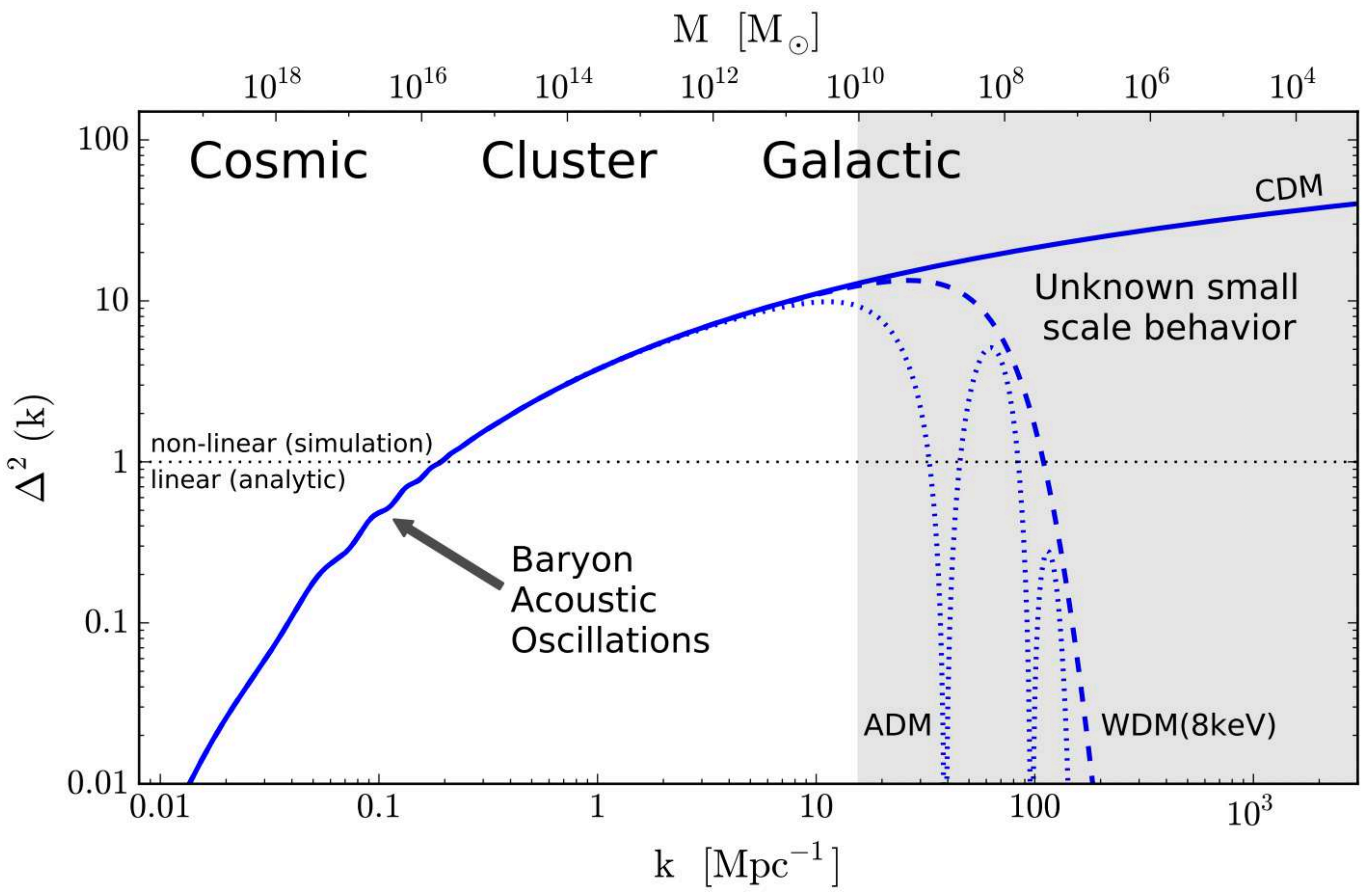
- Bound @ recombination

DM be completely decoupled from the baryon-photon plasma at recombination

$$\epsilon < 3.5 \times 10^{-7} (m_{dm}/1\,\text{GeV})^{0.58} \text{ for } m_{dm} > 1 \text{ GeV}$$
$$\epsilon < 4.0 \times 10^{-7} (m_{dm}/1\,\text{GeV})^{0.58} \text{ for } m_{dm} < 1\,\text{GeV}$$

* similar bounds from direct detection

DM has neutral or charge < mili-charge!



Ex: ADM - atomic dark matter

Interactions

1) DM interacts gravitationally - evidence for its existence

2) It **cannot** or have a small ***electromagnetic*** interaction

DM has neutral or charge < mili-charge!

	Gravitation	Electromagnetic	Weak	Strong
Acts on	particles with mass and energy	particles with charge	quarks and leptons (decay)	quarks
Exchange particle	graviton (not yet observed)	photon, γ	W^+, W^- and Z^0	gluons, g, and mesons
Exchange particle mass	massless	massless	$M_{W^\pm} = 80\,\mathrm{GeVc^{-2}}$, $M_Z = 91\,\mathrm{GeVc^{-2}}$	gluons are massless
Relative strength	negligible, predicted about 10^{-41}	$\frac{1}{137}$	10^{-6}	1
Range	∞ decreasing $\propto \frac{1}{r^2}$	∞ decreasing $\propto \frac{1}{r^2}$	10^{-18} decreasing $\propto \frac{1}{r}$	10^{-15} increasing $\propto r$

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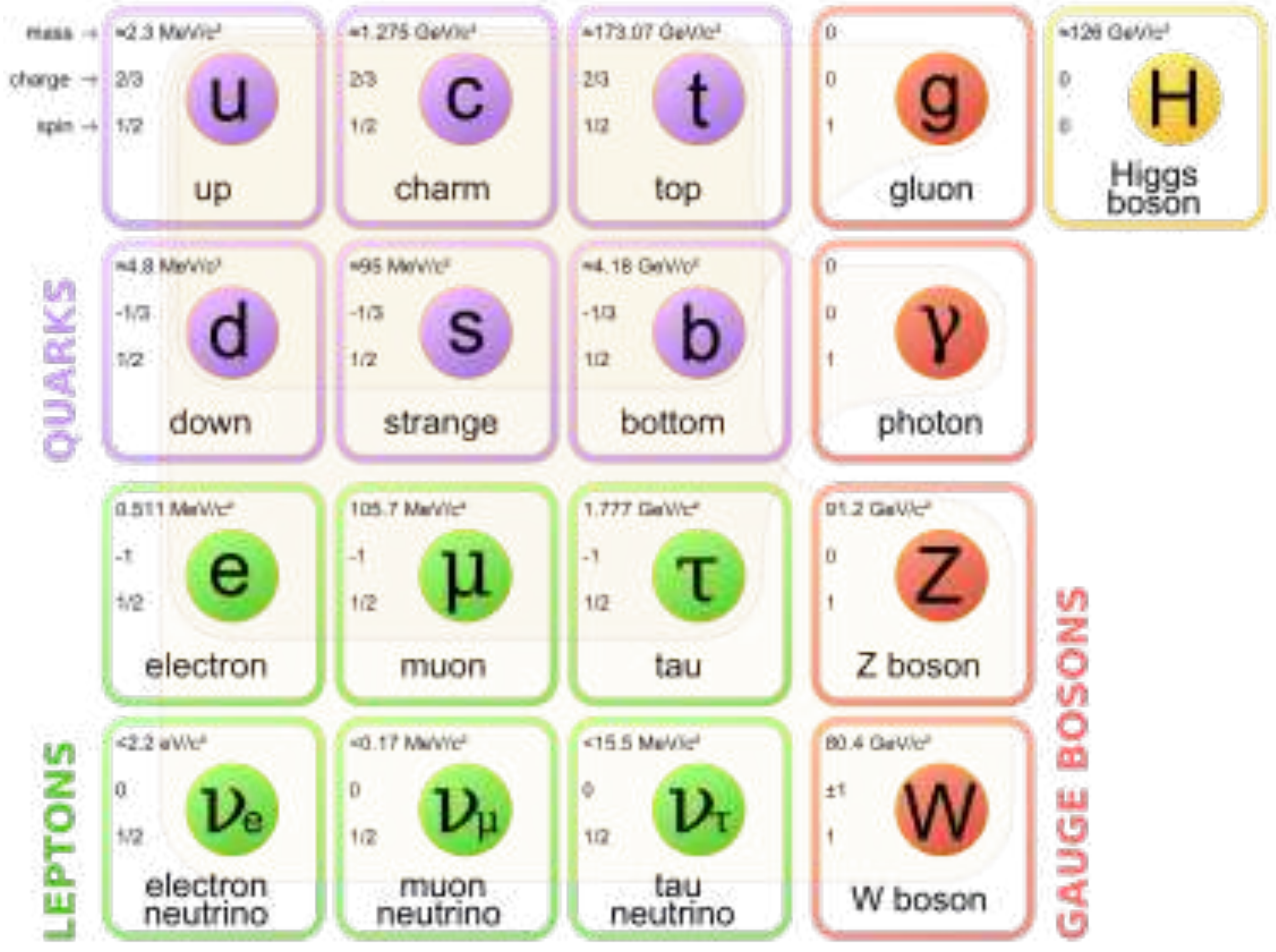
What about the **weak** and **strong forces**?

<u>Strong force</u>

The elementary particles of the DM that interact with the strong force are the quarks, interacting via gluons

And quarks also have electric charge!! This means that they also interact electromagnetically.

If DM interacted through the strong force: this would change the abundance of light elements.



Interactions

1) DM interacts gravitationally - evidence for its existence

2) It cannot or have a small electromagnetic interaction

3) It cannot interact via the strong force

4) Weak force - DM *can* interact through the **weak force**

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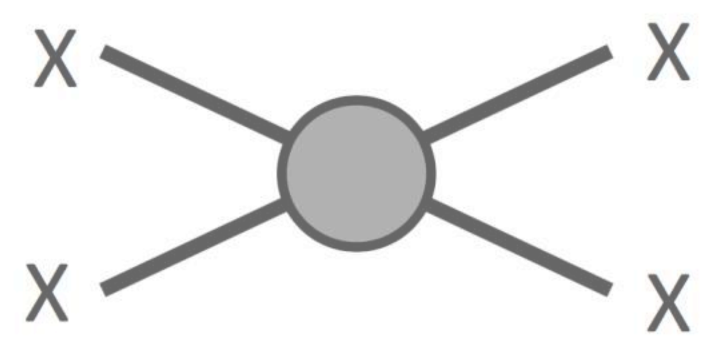
What we know about dark matter



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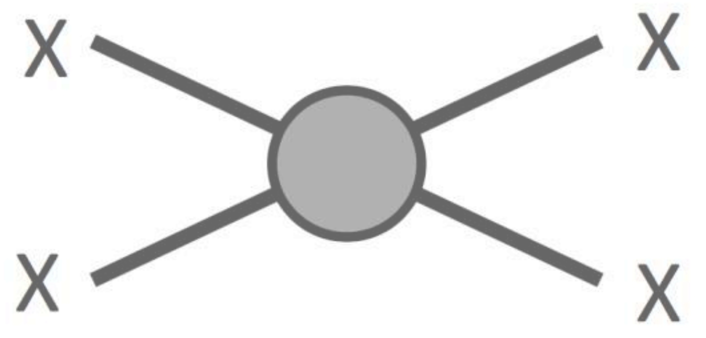
Self-interaction

Can DM interact with itself?

If dark-matter particles have a non-trivial probability of interacting there are implications for the distribution of DM: self-interaction allows ***energy and momentum to flow*** from one part of the dark matter halo to another beyond what is enabled by gravity.

Self-interacting can lead to changes in:
- Distribution of DM in the halo
- Halo shape
- Hierarchical assembly of structure on non-linear scales
- Matter power spectrum
- …

*What we **know** about dark matter*



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<u>Self-interaction</u>

How we quote bounds in the self-interaction?

Most of the discussion of SIDM was framed in the context of **velocity-independent** “hard-sphere" scattering where the outgoing momentum direction is random in the center-of-mass frame.

DM–DM cross section per unit DM particle mass

$$\sigma/m_{dm}$$

How to compute?

For a DM particle moving at velocity v_0 through a background of stationary DM particles with a number density n, the rate at which that particle scatters with background particles is:

$$R = \sigma n v_0 = \frac{\sigma}{m_{dm}} \rho v_0$$

→

The total probability particle to scatter

$$Prob = 1 - \exp\left(-\frac{\sigma}{m_{dm}} \int v_0 \rho dt\right)$$

What we know about dark matter

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Self-interaction

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- …

Can be tested with:

- Mergers in groups and clusters
- Strong gravitational lensing in clusters
- Stellar streams in the Milky Way
- X-ray and weak lensing observations of clusters, groups and large ellipticals
- Dwarf galaxies
- Rotation curves of spiral galaxies
- LSS

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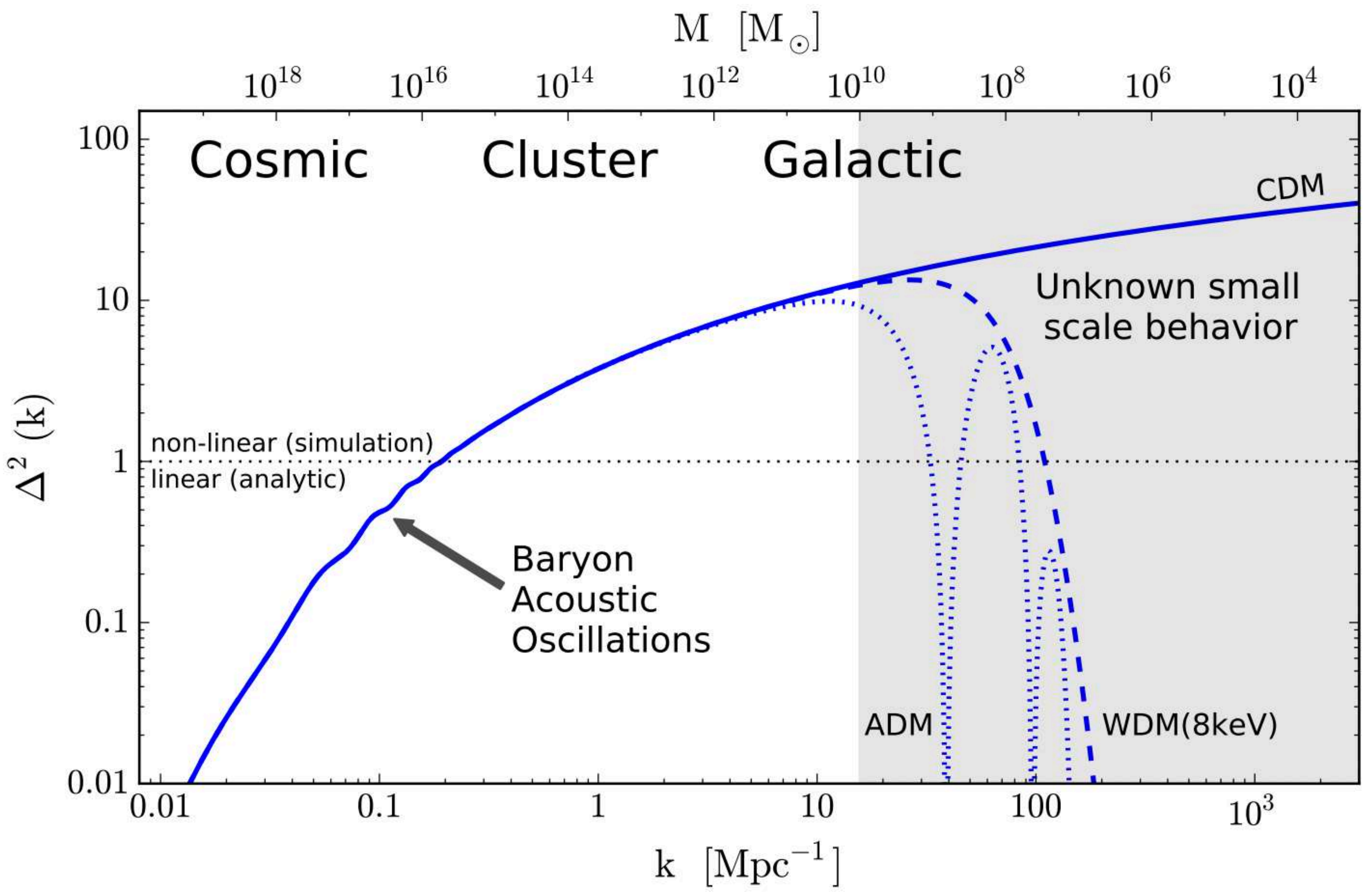

Ex: ADM - atomic dark matter

Presence of a "dark radiation" bath interacting withe the dark matter would delay growth of density perturbations and lead to the presence of "dark acoustic oscillations"

What we know about dark matter

- Collisionless: no/weakly self-interaction; non-interacting

Self-interaction

Self-interacting can lead to changes in:
- Distribution of DM in the halo
- Halo shape
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- Rotation curves of spiral galaxies
- LSS

Current bounds: $\sigma/m_{dm} < 0.13\,\mathrm{cm}^2/\mathrm{g}\,,\ \ \sigma/m_{dm} < 0.35\,\mathrm{cm}^2/\mathrm{g}$ Vel. independent

From: measured core densities from strong lensing

Ref.: Adhikari et al. 2022

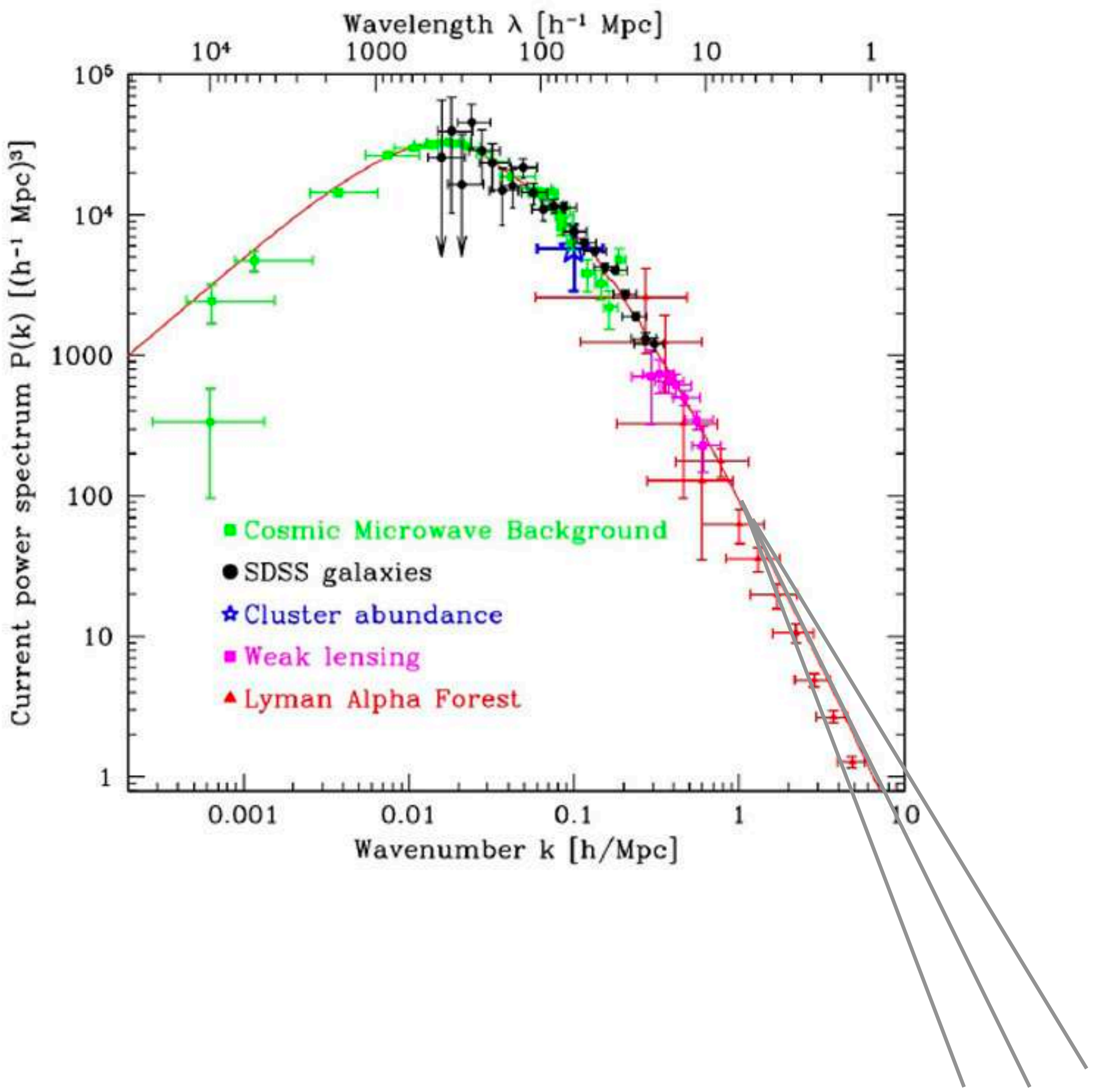
What we know about dark matter

Properties:

- Cold
- Presureless
- Dark (transparent): DM does not interact electromagnetically
- Collisionless: no/weakly self-interaction; non-interacting

What we don't know about dark matter

- ~~Cold~~ → How cold it is? — WDM $m \sim \text{keV}$
- ~~Pressureless~~ → Cluster on all scales?
- ~~Dark~~ → Non-gravitational interaction? — Milicharged DM
- ~~Collisionless~~ → How small sefl-interaction? — SIDM



CDM on large scales

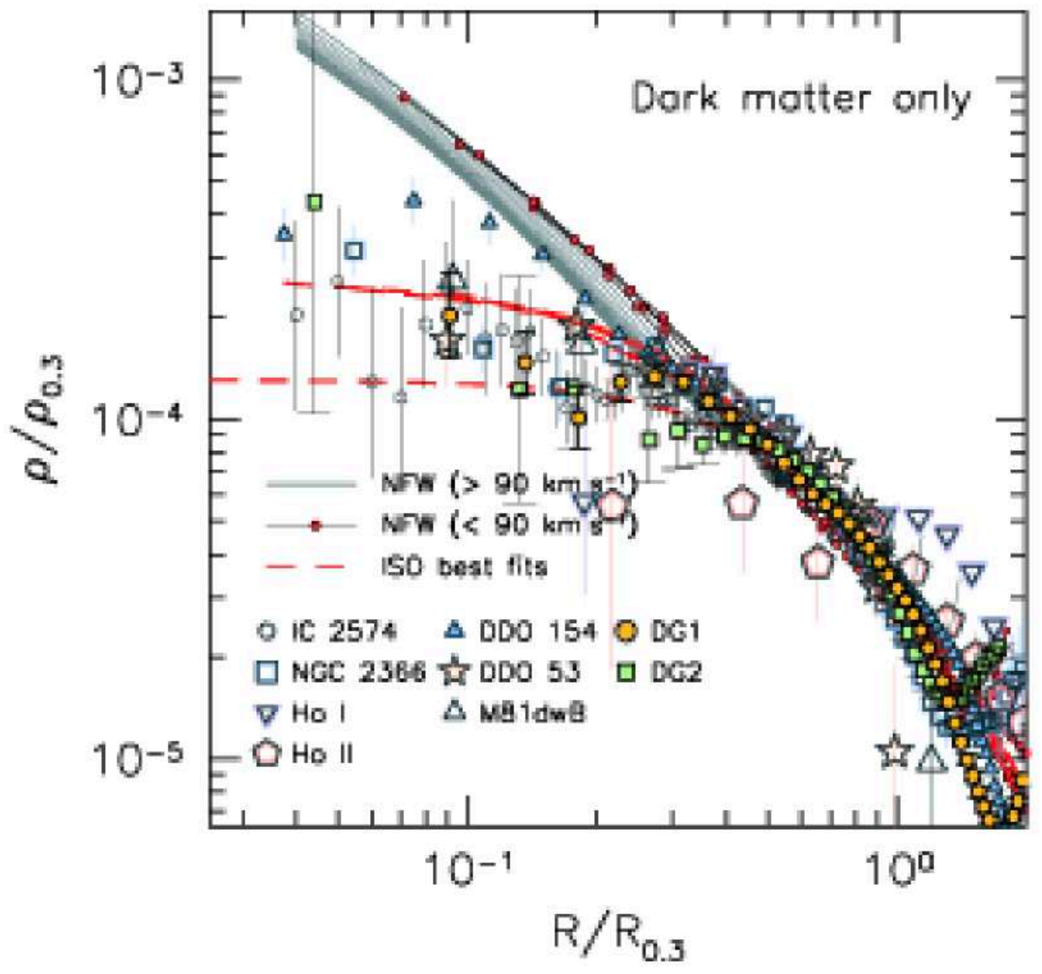
Small scale behavior: still weakly constrained and small scale challenges

Small scale curiosities: cusp-core, missing satellites, BTFR, …

Small scale challenges

Cusp-core

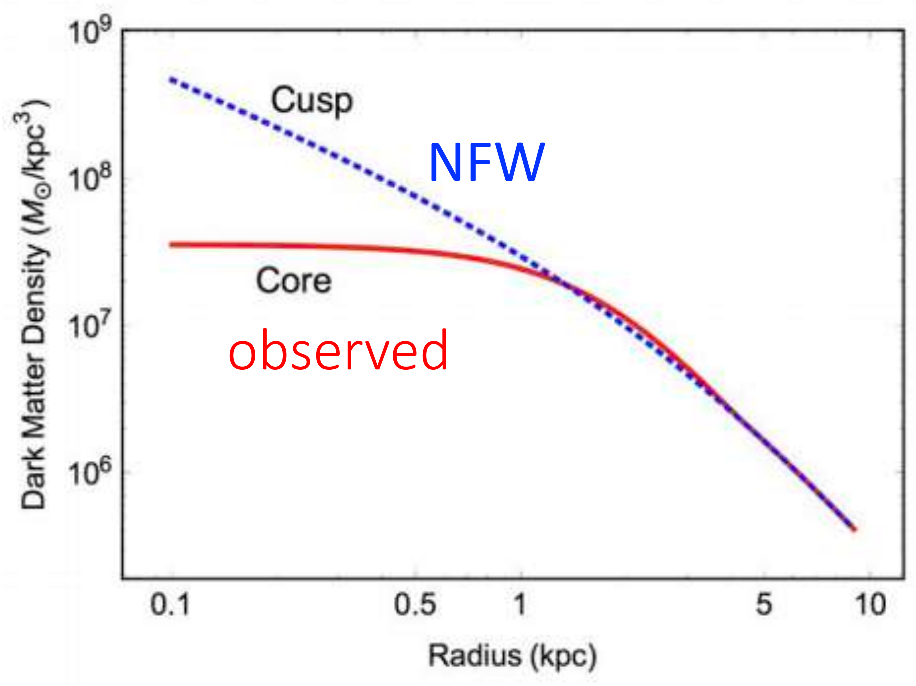
Density

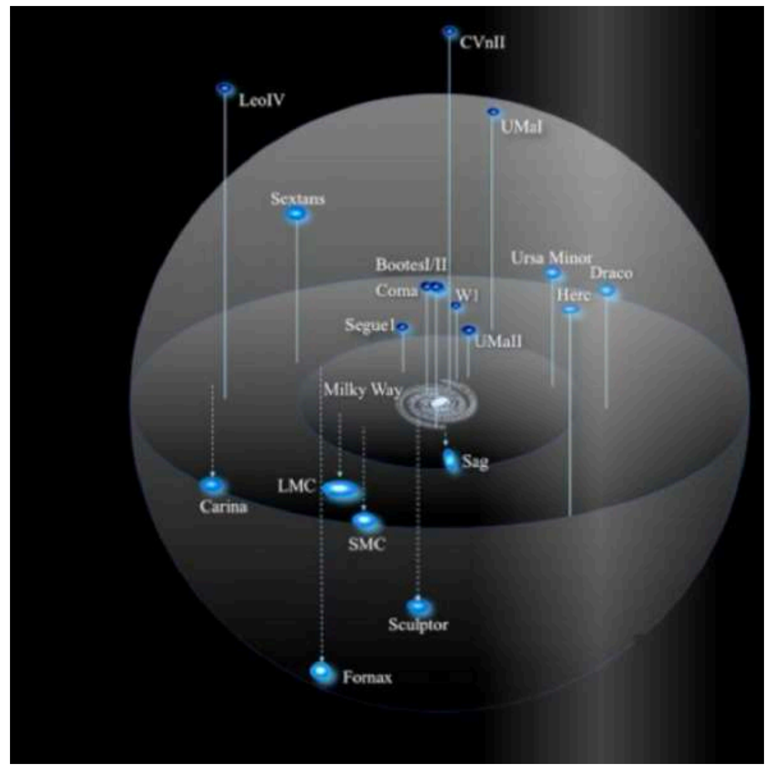


Radius

THINGS (HI Near Galaxy Survey)/LITTLE THINGS

CDM -
NFW profile





Bullock, Baylon-Kolchin

Missing satellites

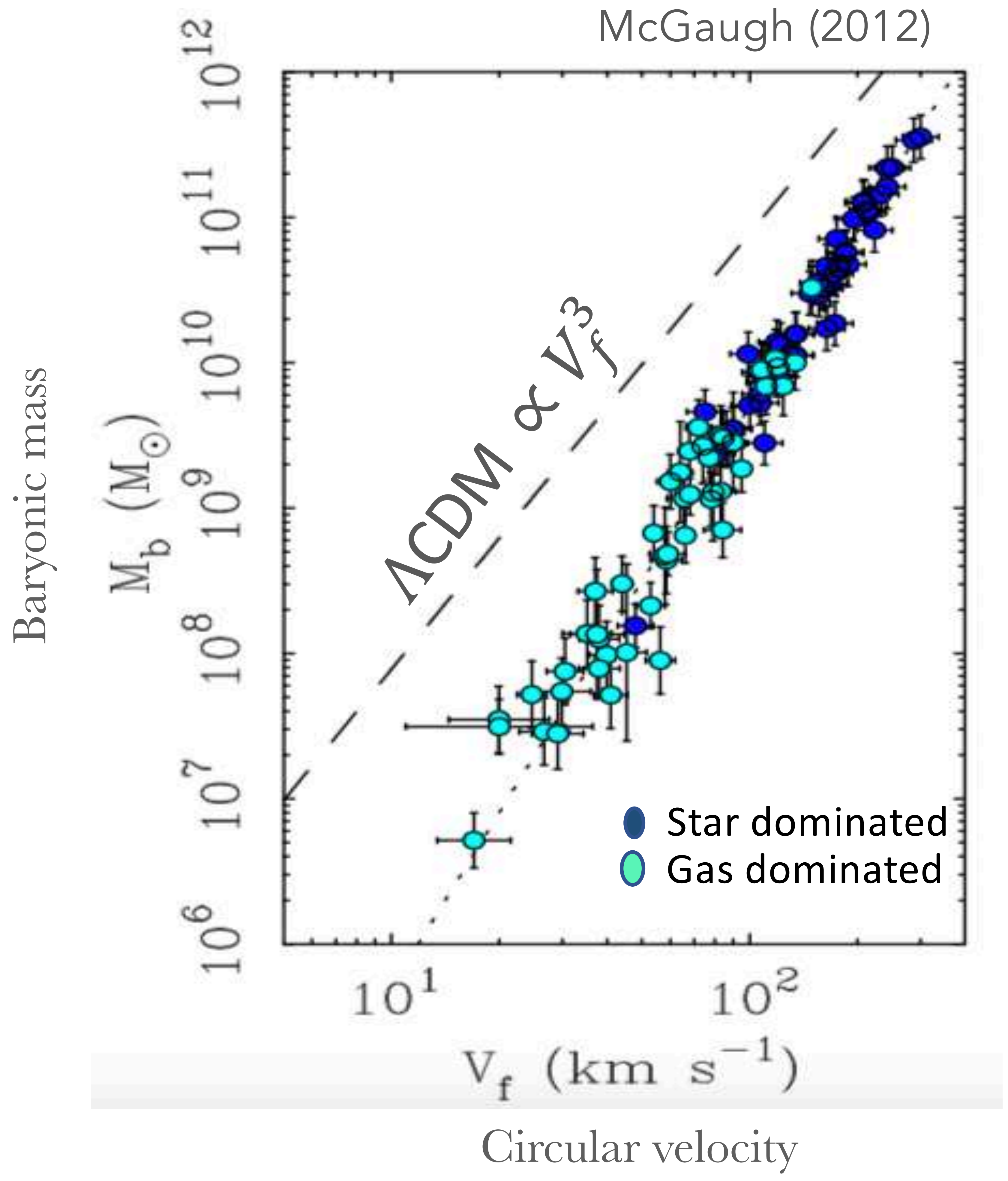
Incompatibility between the # of satellites predicted by simulations using LCDM and the # of observed satellites

Regularity/diversity of rotation curves

Regularity and diversity of rotation curves

- Baryonic Tully-Fisher relation (BTFR)

Remarkably tight scaling relations between dynamical and baryonic properties.



Other scaling relations:

- ✓TRF
- ✓RAR - Radial acceleration relation
- ✓…

$$a_0 \simeq \frac{1}{6} H_0 \simeq 1.2 \times 10^{-8} \text{ cm/s}^2 = 2.7 \times 10^{-34} \text{ eV}\,.$$

Dark matter- Large scales: CDM

Small scales:

• Feedback: Within ΛCDM

- Star formation
- Stellar evolution
- Sn rates
- BH and AGN feedback
- Stellar feedback
- …

Questions:

- Can it solve all these?
- $\neq$ simulations, $\neq$ parametrizations
- Enough feedback?
- Explains tight scaling relation?

• MOND:

Modified Newtonian Dynamics

Empirical relation

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Curiosity: Baryons drive the dynamics!

Works extremely well for: (1) rotation curves; (2) scaling relations

BUT: ~~MOND without DM~~

Problems explaining large scales

• Modify dark matter:

DM with different properties on small scales

- SIDM (Self-interacting DM)

Solve cusp-core and missing satellites

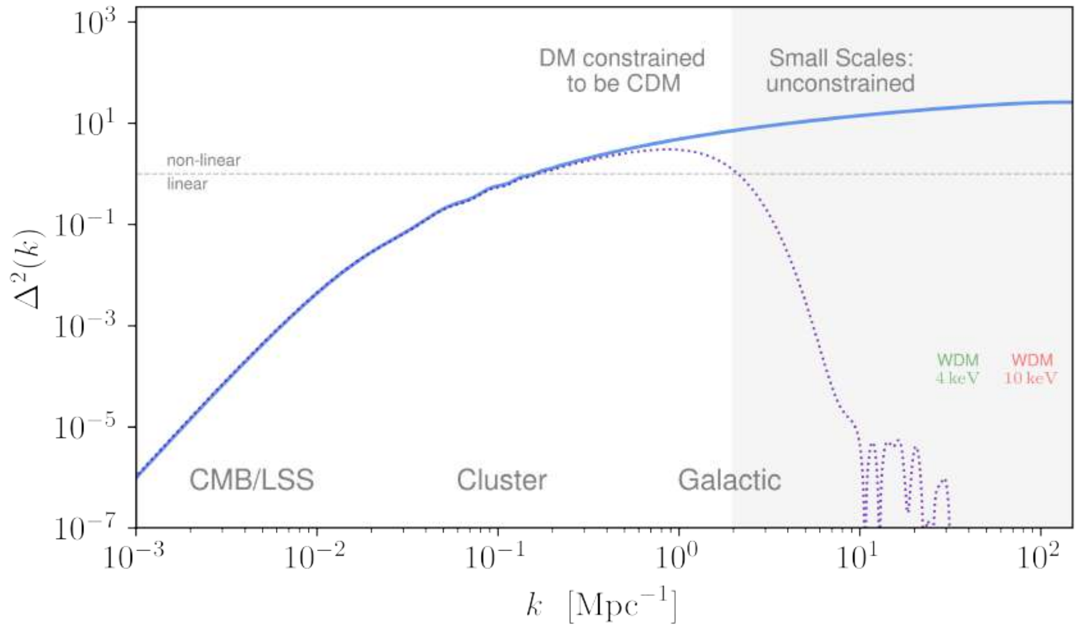
- WDM (Warm DM)

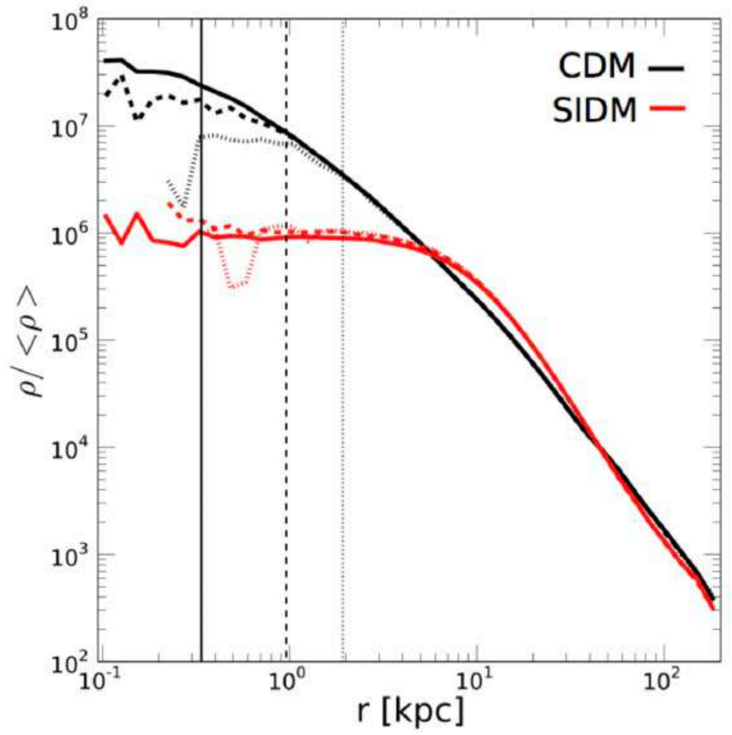
Solve missing satellites

What we know about dark matter

- ~~Cold~~ → How cold it is? WDM (missing sat.)
- ~~Pressureless~~ → Cluster on all scales?
- ~~Dark~~ → Non-gravitational interaction? Milicharged DM
- ~~Collisionless~~ → How small sefl-interaction? SIDM (changes the profile in galaxies - cored; missing sat.)

Solve SSP: $\sigma/m_{dm} \sim 1\,\mathrm{cm}^2\mathrm{g}$





Adhikari et al. 2022

CDM on large scales!

Small scale behavior: still weakly constrained and small scale challenges

Small scale curiosities: cusp-core, missing satellites, BTFR, …

But what is dark matter?
What is its nature/microphysics?

How can we build a model of DM?

What we know about dark matter

- Cold or warm

Thermal candidate: $m_{dm} \geq \mathrm{keV}$

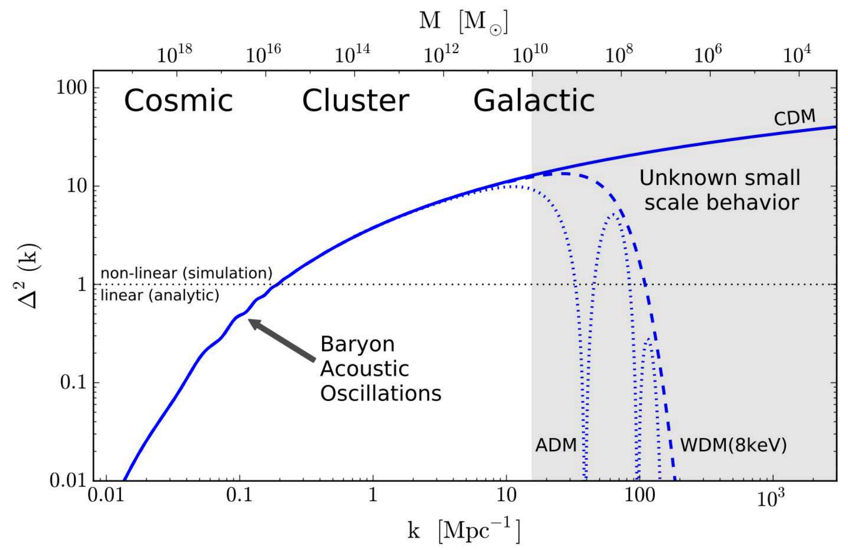
Or produced cold by a non-thermal mechanism

- Small pressure

Reproduce large and small scale distribution!

Clusters like pressure-less fluid on large scales $k \lesssim 10\,\mathrm{Mpc}^{-1}$

Clustering on scales smaller than $k \gtrsim 10\,\mathrm{Mpc}^{-1}$ highly unconstrained



- Dark

Can have a small electromagnetic interaction: **milicharge**

- Collisionless

Non-interacting or weakly interacting

Can have a self interaction. Bounds: $\sigma/m_{dm} < 0.13\,\mathrm{cm}^2/\mathrm{g}\,,\;\; \sigma/m_{dm} < 0.35\,\mathrm{cm}^2/\mathrm{g}$

Can interact via the ***weak force***

Model building:

Pre-requisites for a dark matter candidate

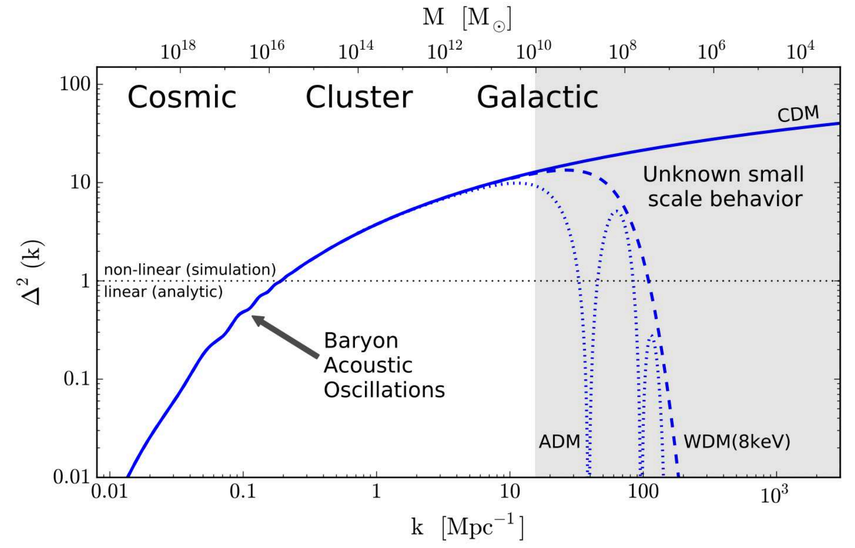
- Cold or warm — Thermal candidate: $m_{dm} \geq \mathrm{keV}$ — Or produced cold by a non-thermal mechanism

  Has to be non-relativistic at BBN

- Reproduce large and small scale distribution

  Clusters like pressure-less fluid on large scales $k \lesssim 10\,\mathrm{Mpc}^{-1}$

  Clustering on scales smaller than $k \gtrsim 10\,\mathrm{Mpc}^{-1}$ highly unconstrained



- Non-interacting or weakly interacting — (~~Dark, colissionless~~)

  Can have a small electromagnetic interaction. Bound < **milicharge**

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  Can interact via the ***weak force***

- Abundance — $\Omega_m = 0.308 \pm 0.012$ (*Planck 2018*)

- Stable — **If** it is a particle, it has to be stable with lifetime of DM should be much greater than the age of the universe

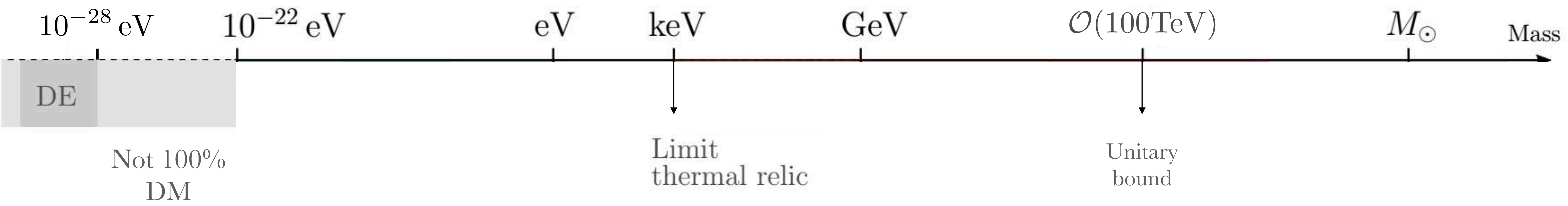
Model building:
Pre-requisites for a dark matter candidate

From observations, we know that any candidate to be the dark matter has to have the following properties:

- Behave like CDM on large scales *(small deviations possible)*
- DM cannot be relativistic during BBN, $m_{\rm dm} > keV$.
  - Production: if thermally produced $m_{\rm dm} > keV$, otherwise, it has to be produced non-thermally
- Abundance today: $\Omega_m = 0.308 \pm 0.012$ (*Planck 2018*)
- Reproduce the small scales distribution of our universe (still *highly unconstrained*)
- **If** it is a particle: it has to be stable with lifetime of DM should be much greater than the age of the universe
- Interacts gravitationally! It cannot interact electromagnetically (and with the strong force), but it can interact with the weak force weakly.

Mass scale of dark matter

Observations from both LSS and local, can put model-independent bounds on DM parameters, like mass and spin.



* not in scale

Observations:

LSS
- LSS
    - Recombination
- BBN

Intermediary
- Galaxy clusters

Small scale structure
- Galaxy properties: namely galaxy densities must reach of order GeV cm−3, their velocity dispersions are of order 100 km s−1, and their sizes are of order kpc.
- Star clusters

- electron mass 0.511 MeV

Natural units ($c = 1$)

$1\,\text{kg} \to \sim 5 \times 10^{35}\,\text{eV}$

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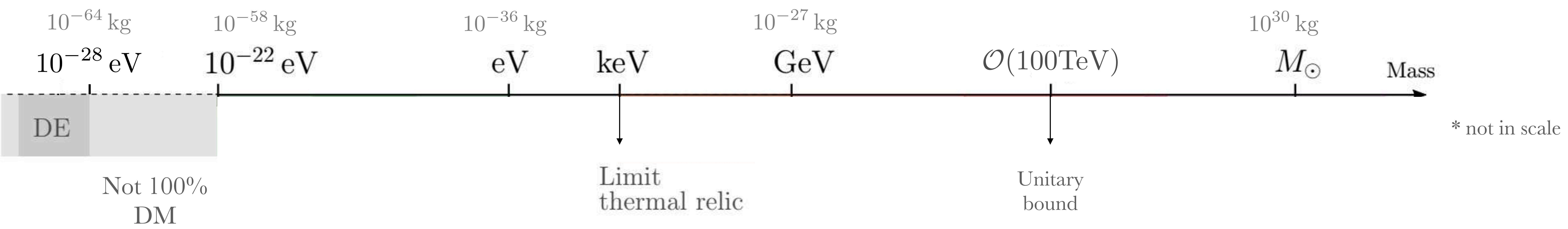

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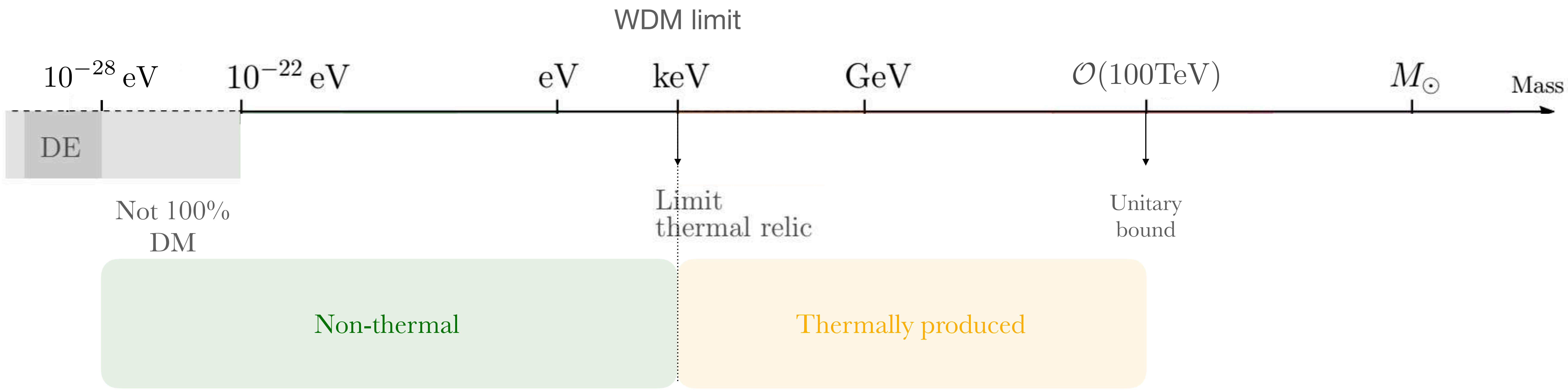

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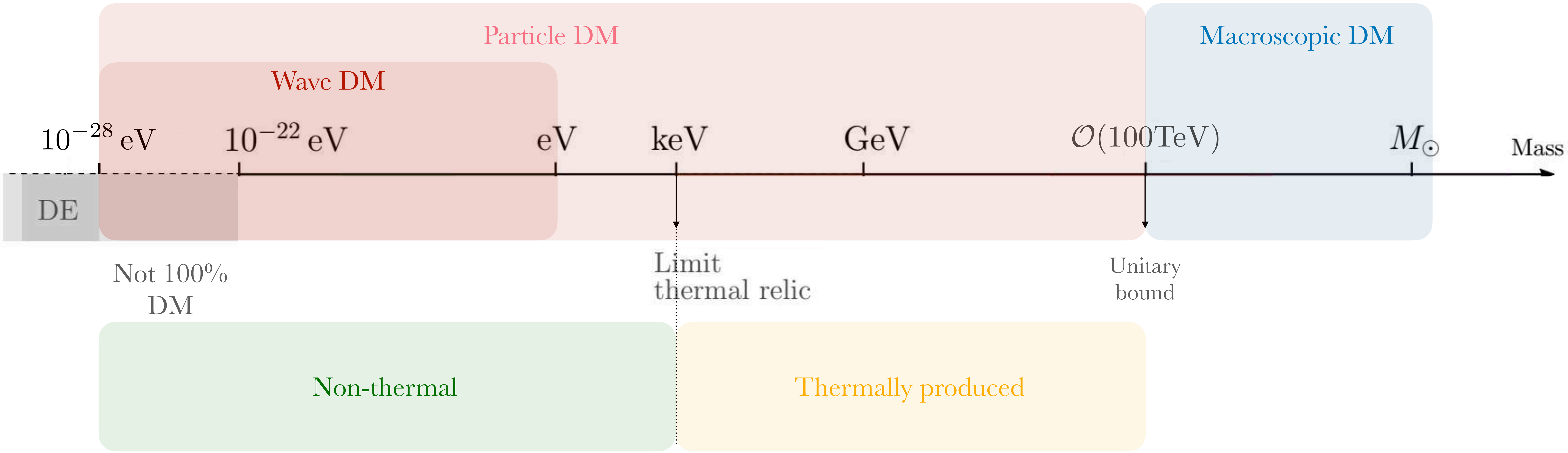

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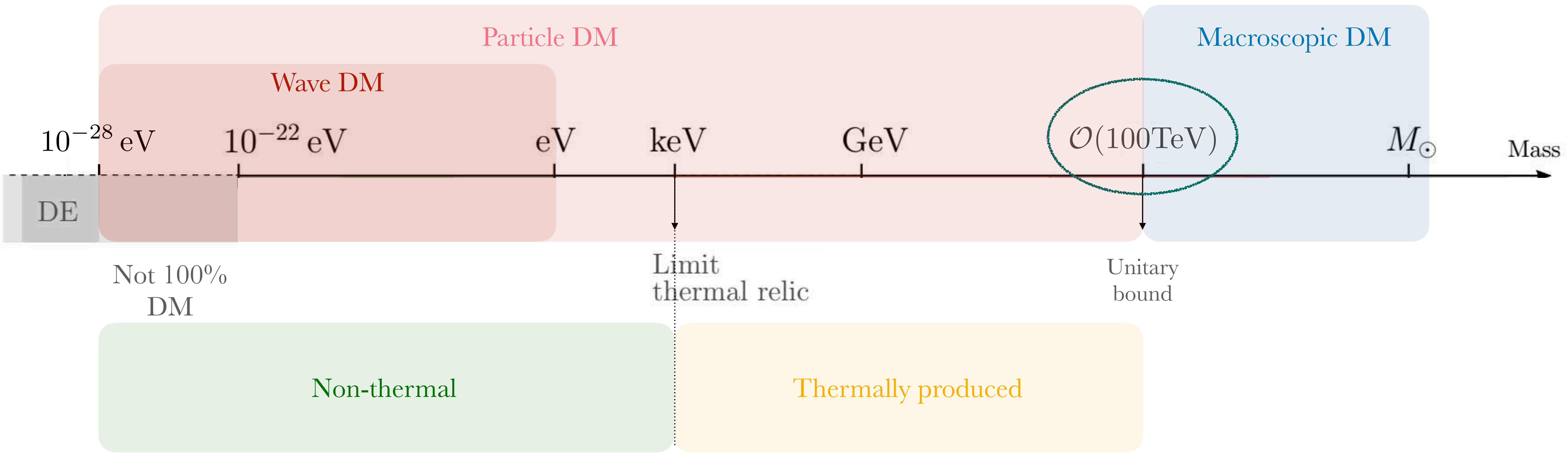
Mass scale of dark matter



Natural units ($c = 1$)

$1\,\mathrm{kg} \to \sim 5 \times 10^{35}\,\mathrm{eV}$

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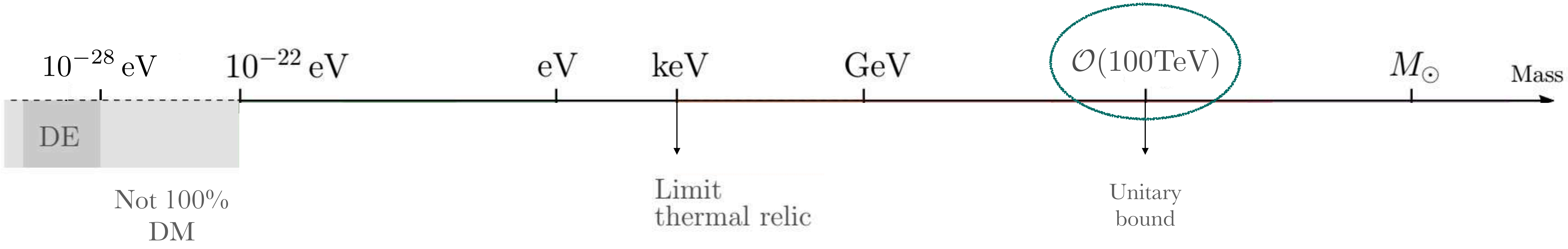
Mass scale of dark matter



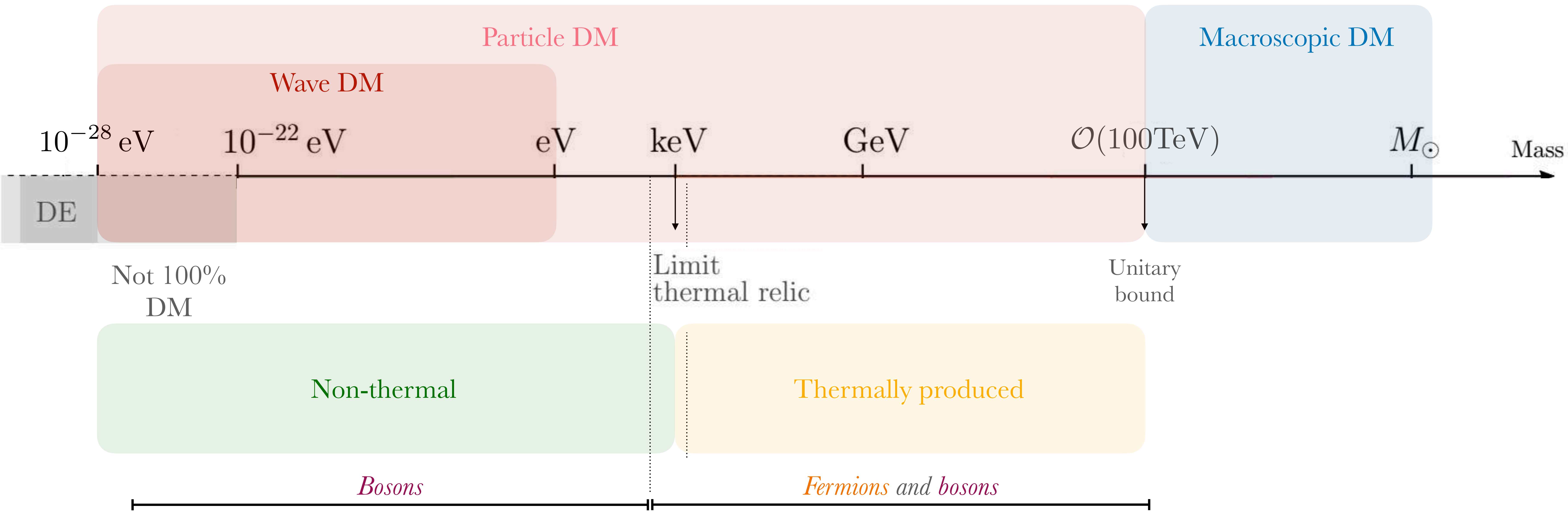
- <u>Maximum mass for **particle** DM</u>

Thermal DM more massive than ~ 100 TeV suffers from what is known as the unitarity bound or an overclosure problem

Natural units ($c = 1$)
$1\,\text{kg} \to \sim 5 \times 10^{35}\,\text{eV}$
$1\,M_\odot \to \sim 10^{66}\,\text{eV}$

Mass scale of dark matter

- <u>Tremaine-Gunn bound</u>: bound for fermionic DM



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Mass scale of dark matter

*From LSS we can put bound on the **spin** of DM*

- Tremaine-Gunn bound: bound for fermionic DM

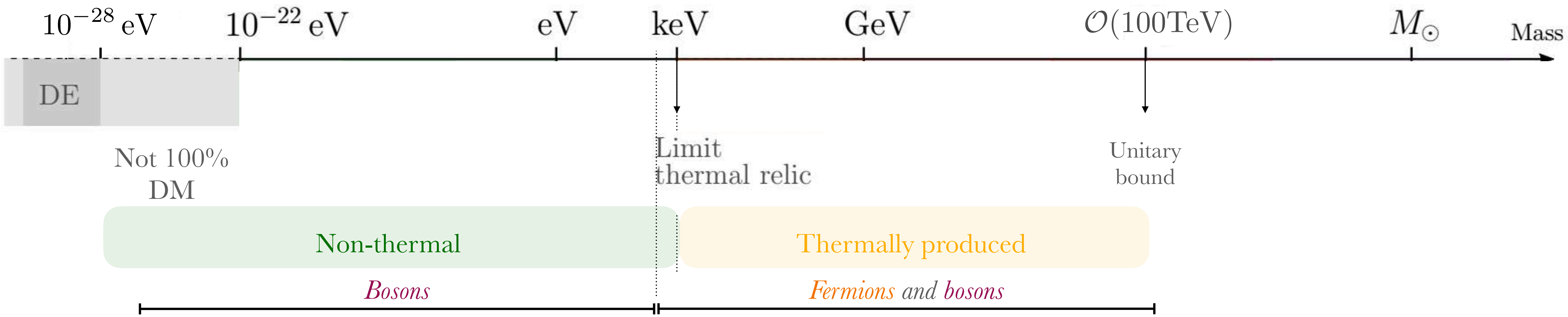
Since the gravitational potential of a galaxy can be inferred from data, this sets an upper bound on the possible velocity of DM particles in the halo. Combining this argument with the Pauli exclusion principle leads to a maximum density of DM.

For fermionic DM, the phase space density $f(x,p)$ is bounded from above due to Pauli's exclusion principle $f(x,p) < g$

# of spin and flavour states

Reminder: the phase space distribution function $f(x,p)$ describes the occupancy number in phase space for a given particle in kinetic equilibrium, and distinguishes between fermions and bosons

Reminder: the **Pauli exclusion principle** states that two or more identical particles with half-integer spins (i.e. fermions) cannot occupy the same quantum state within a quantum system simultaneously.



Mass scale of dark matter

*From LSS we can put bound on the **spin** of DM*

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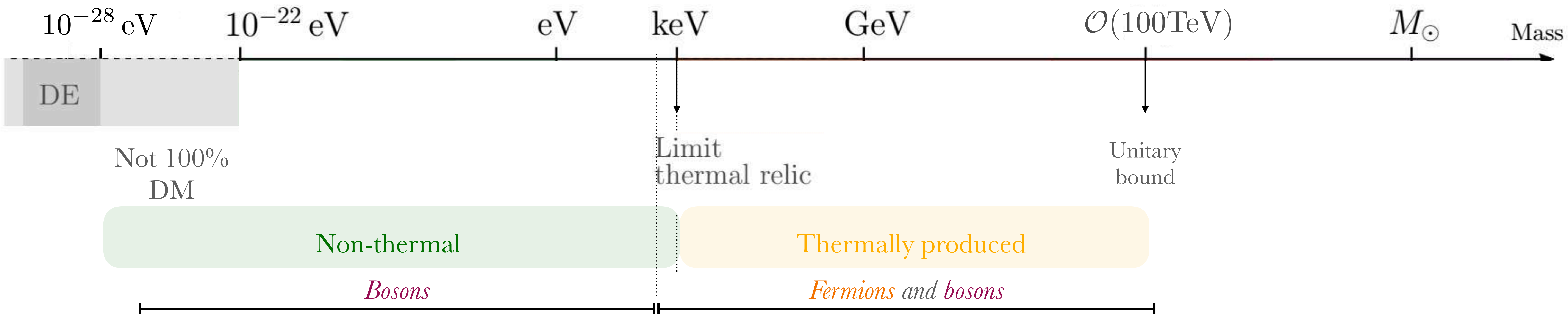
# of spin and flavour states

The local DM number density is given by: $$n(\mathbf{x}) = \int \frac{d^3\mathbf{p}}{(2\pi)^3} f(\mathbf{x},\mathbf{p}) \lesssim g\, p_{max}^3 \sim g\, m_{dm} v_{esc}$$

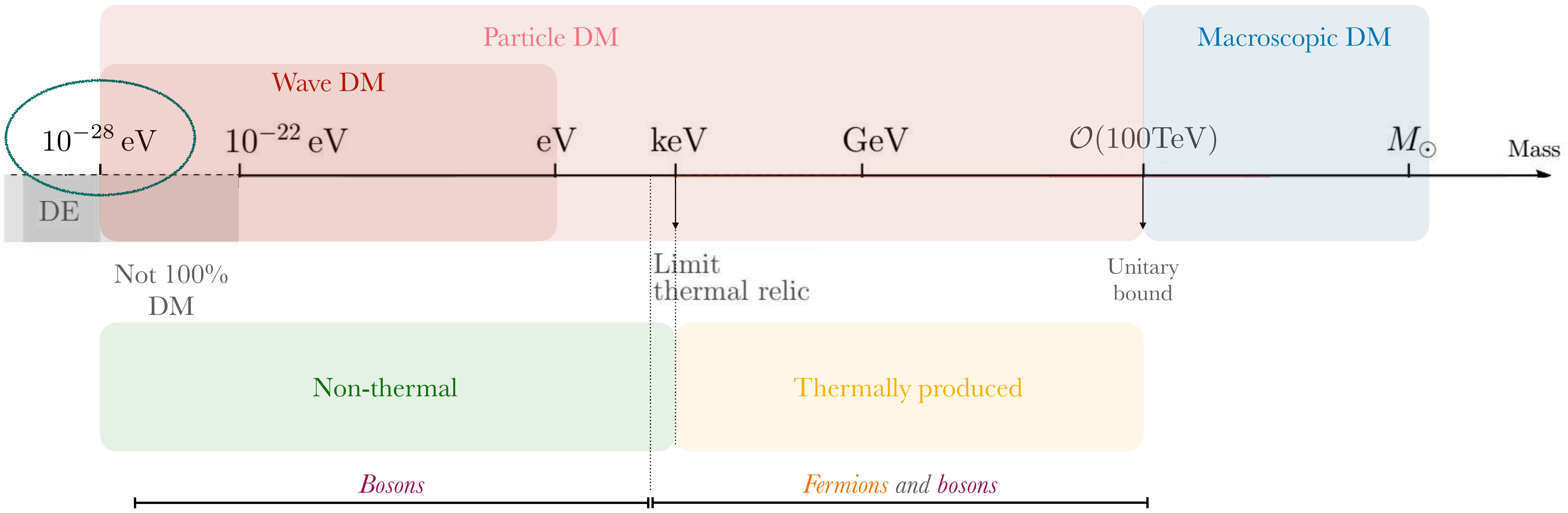
Using a dwarf galaxy, like Fornax, one can find $m_{dm} > 70\,\mathrm{eV}$

Stronger bounds from Lyα. Depend on thermal history of DM!

A fermion DM candidate must have $m_{dm} > \mathcal{O}(10 - 100\,\mathrm{eV})$ *to be consistent with obs. of galaxies*



Mass scale of dark matter



Natural units $(c = 1)$

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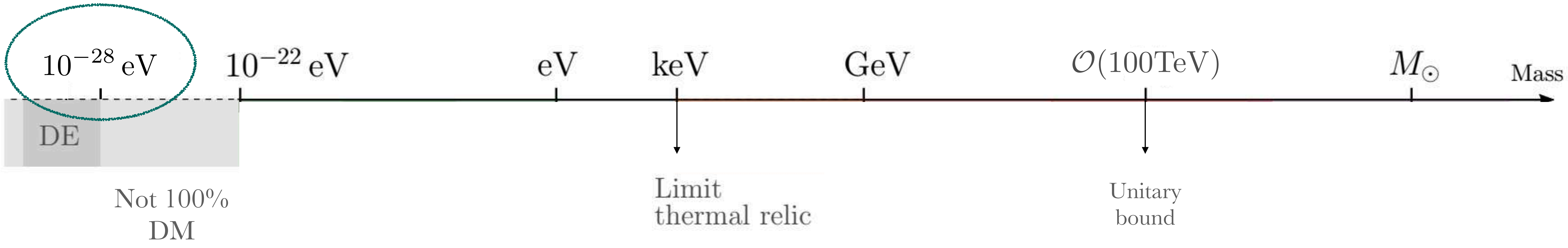
Mass scale of dark matter



- Lower limit

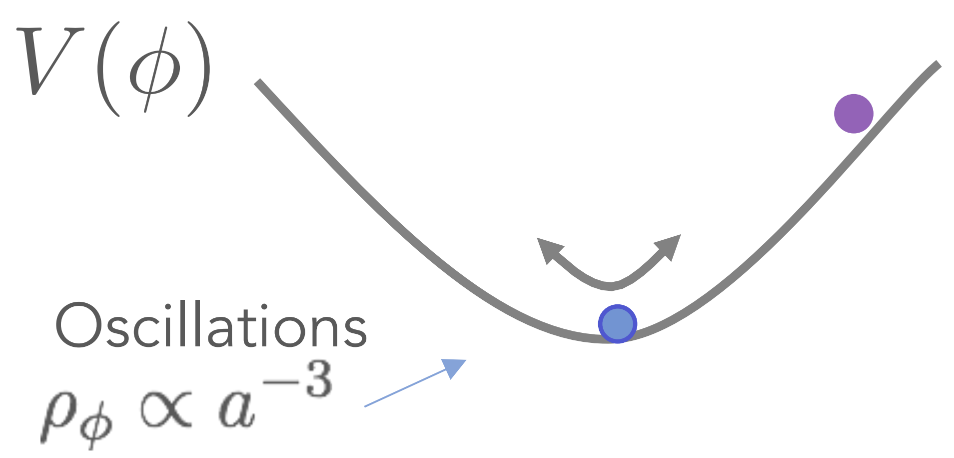
This candidate is described by **bosons**. If for example we consider a ***spin 0*** particle, described by a **scalar field**.

Natural units ($c = 1$)
$1\,\text{kg} \to \sim 5 \times 10^{35}\,\text{eV}$
$1\,M_\odot \to \sim 10^{66}\,\text{eV}$

Cosmological evolution

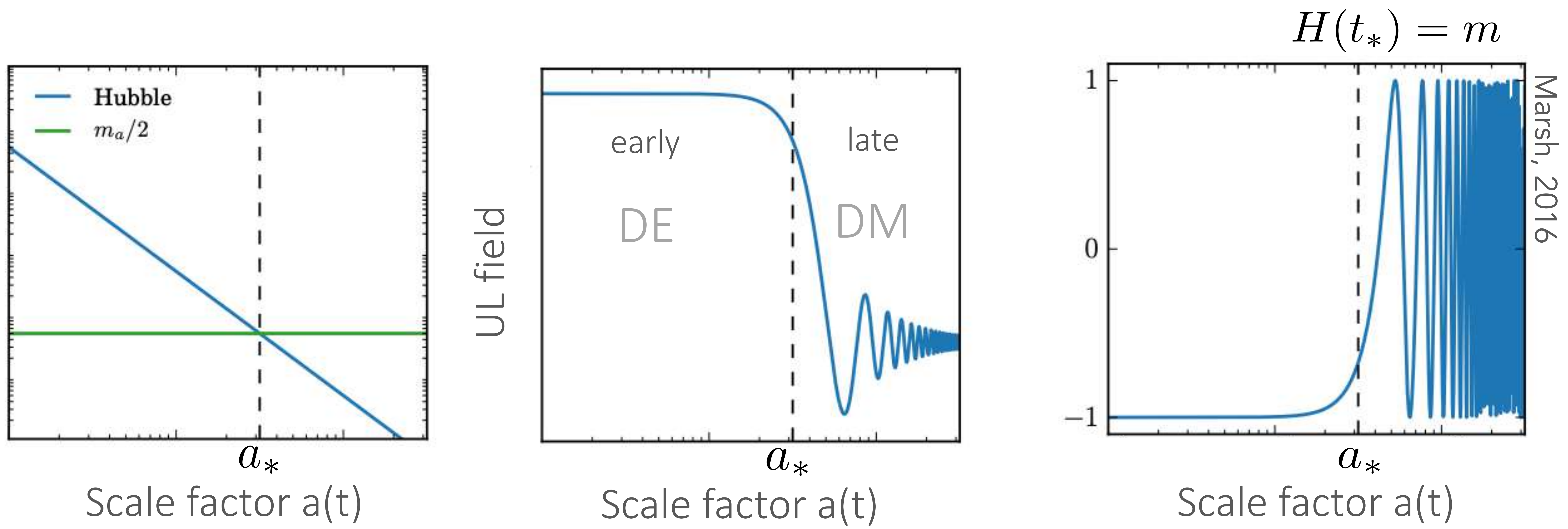
$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

FDM



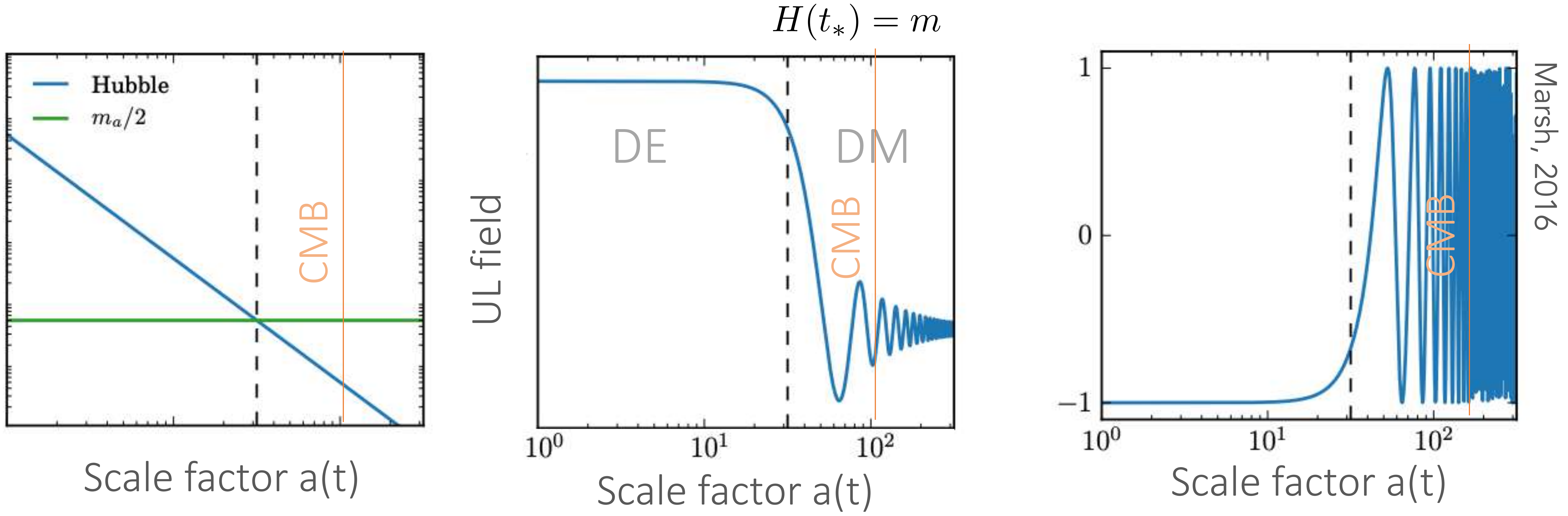
$$\begin{cases} H \gg m \implies \phi_{\text{early}} = \phi(t_i) \longrightarrow \omega = -1 & \text{DE} \\ H \ll m \implies \phi_{\text{late}} \propto e^{imt} \longrightarrow \langle\omega\rangle = 0 & \text{DM} \end{cases}$$

Ex. : $V(\phi) = m^2\phi^2$



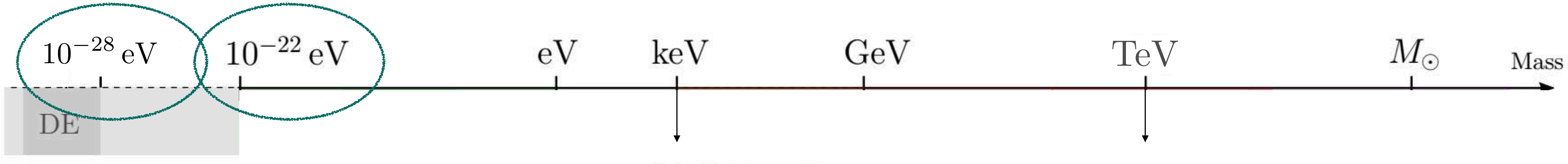
Cosmological evolution

In order to behave like DM: start oscillating before matter-radiation equality



$$m > 10^{-28}\,\mathrm{eV} \sim H(a_{\mathrm{eq}})$$

Mass scale of dark matter

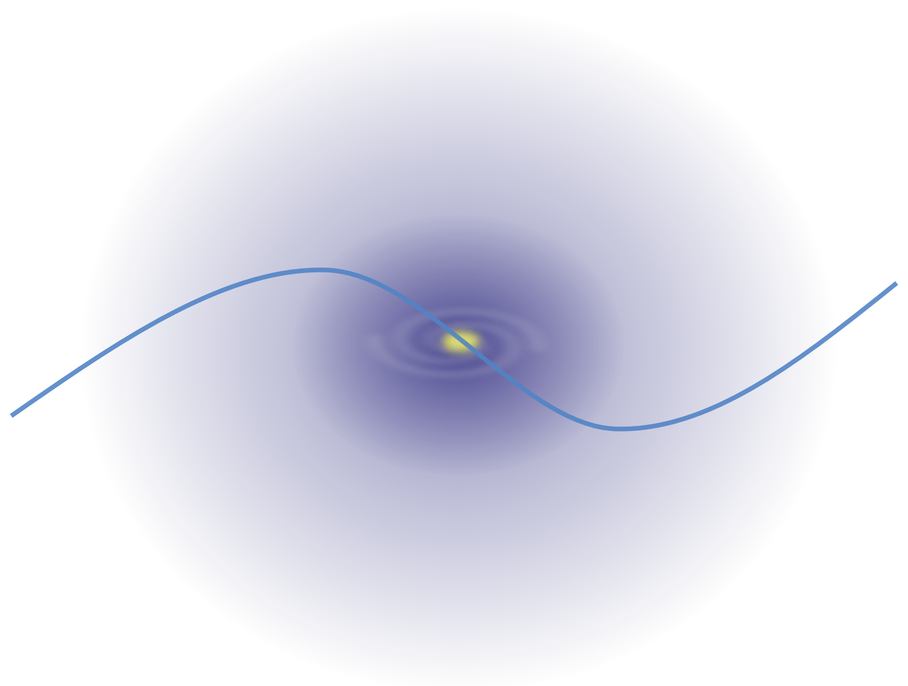


- Lower limit

Galaxies

- $\lambda_{\rm dB}$ must be smaller than the halo

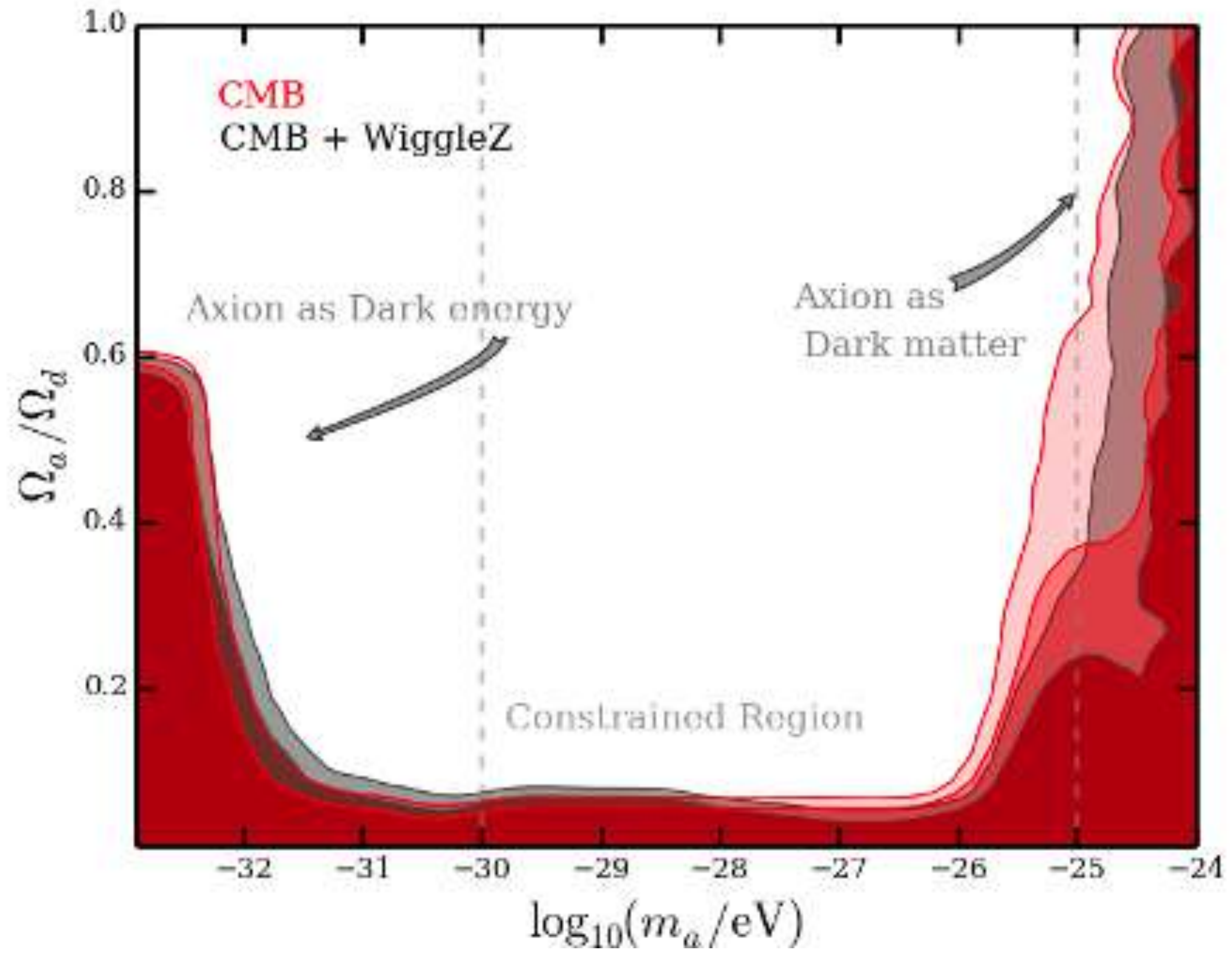
$$\lambda_{\rm dB} < R_{\rm halo}$$



Assume $R_{\rm halo} \sim 1\,{\rm kpc} \Rightarrow m \sim 10^{-22}\,{\rm eV}$

CMB/LSS

Hlozek et al, (2015, 2018)

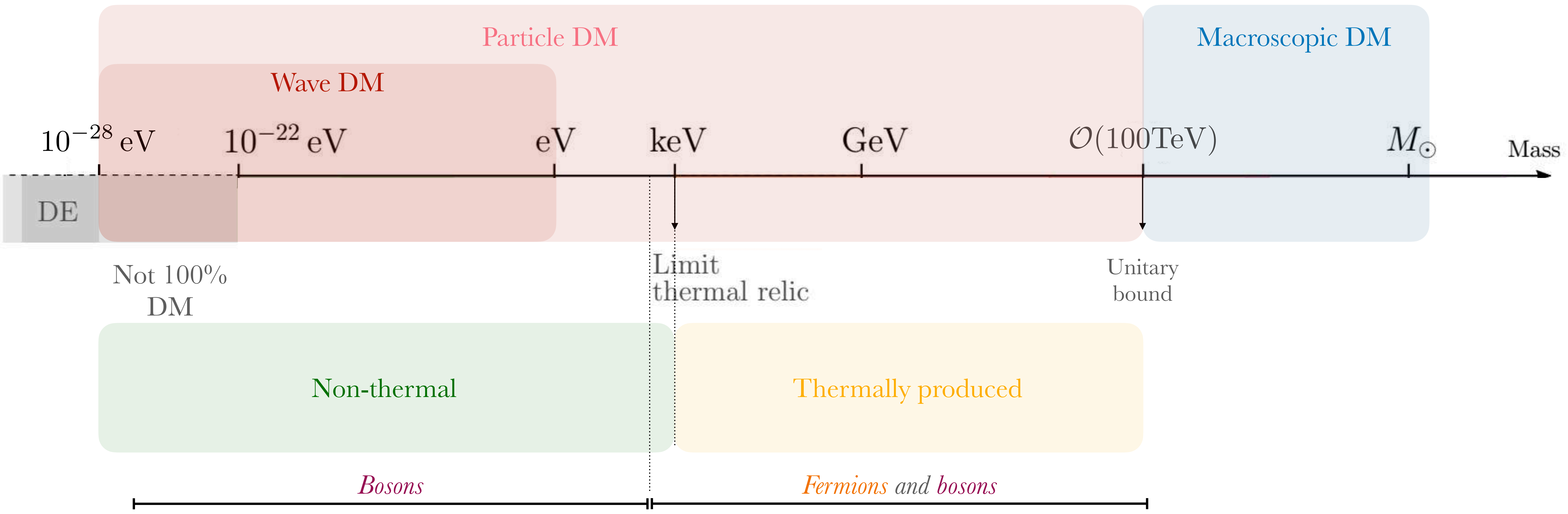


$m \gtrsim 10^{-24}\,{\rm eV}$

for 100% of DM

More tomorrow (Lecture 2)!!

Mass scale of dark matter



Natural units ($c = 1$)

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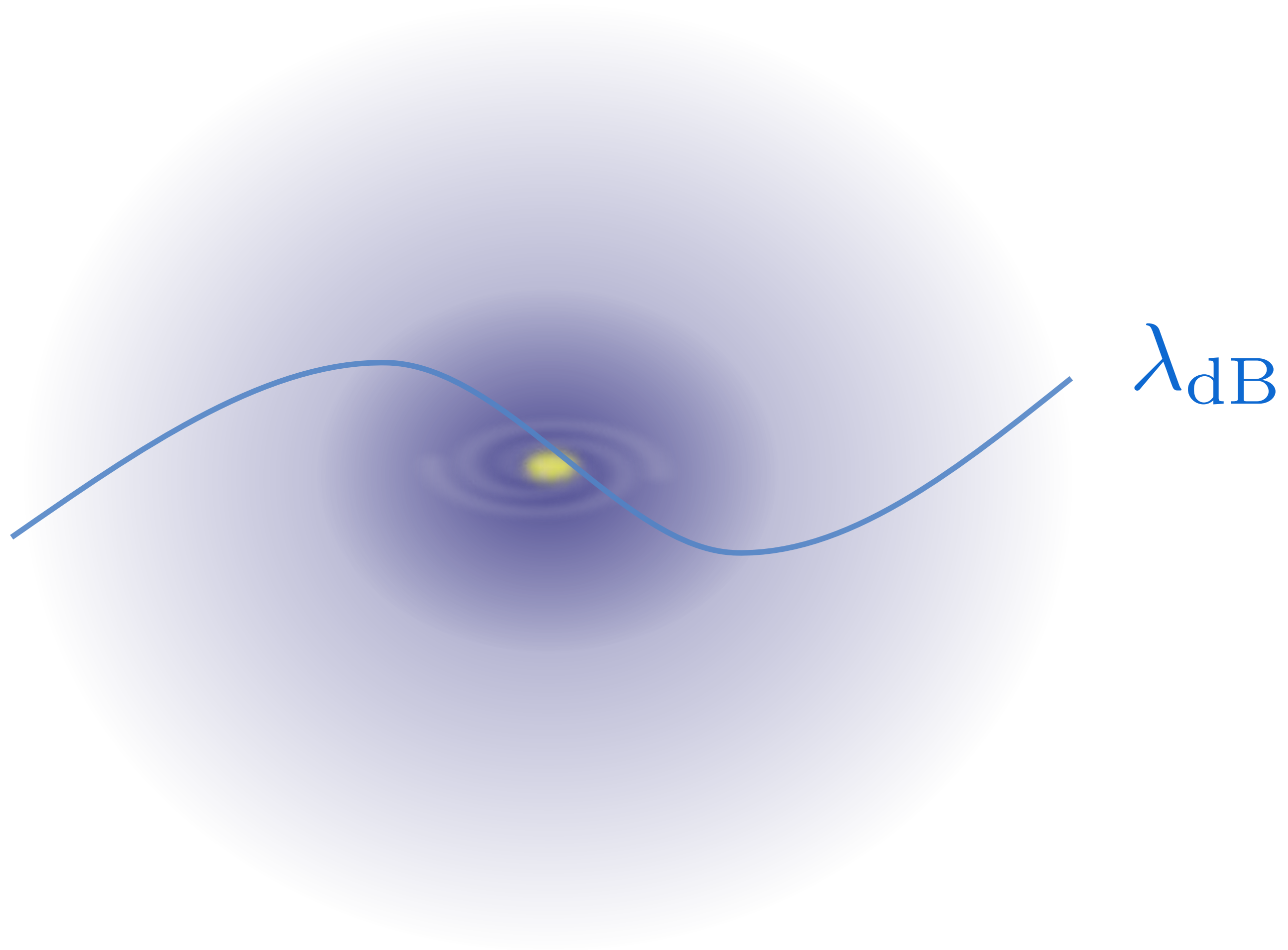
How light is ultra-light? Wave DM

Behave as wave on galactic scales:

- $\lambda_{\rm dB}$ must be smaller than the halo

$$\lambda_{\rm dB} < R_{\rm halo}$$

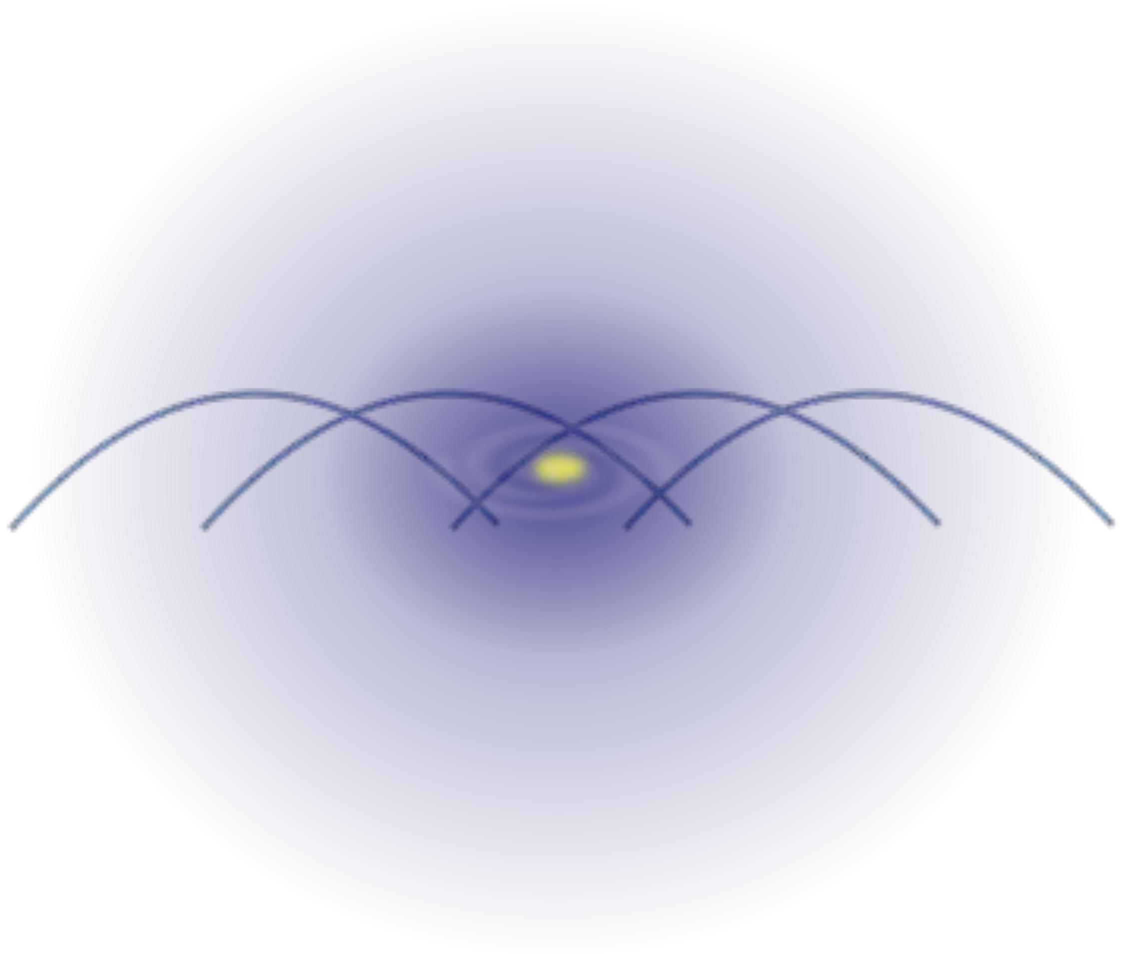
$$\implies \quad m \gtrsim 10^{-25}\,\mathrm{eV}$$



- $\lambda_{\rm dB}$ overlap to be of halo size

$$\lambda_b \sim \frac{1}{mv} \geq d \sim \left(\frac{m}{\rho_{vir}}\right)^{\frac{1}{3}}$$

$$\implies \quad m \leq 2\mathrm{eV}$$



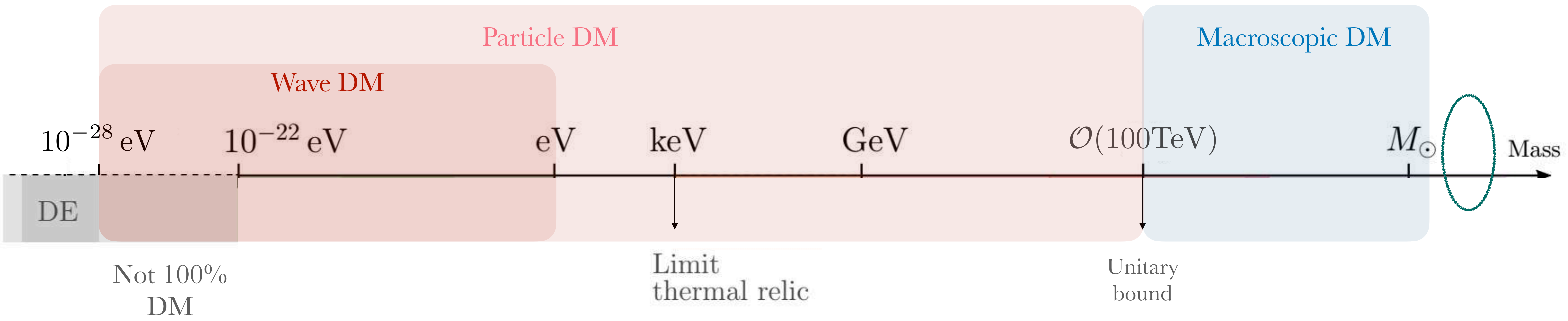
$10^{-60}\,\mathrm{kg}$ $\qquad$ $10^{-35}\,\mathrm{kg}$

$$\boxed{10^{-25}\,\mathrm{eV} \lesssim m \lesssim \mathrm{eV}}$$

$$\lambda_{dB}^{ULDM} \sim \mathrm{pc} - \mathrm{kpc}$$

"Ultra-light dark matter", **EF**, 2020.

Mass scale of dark matter



- <u>Maximum mass for DM?</u>

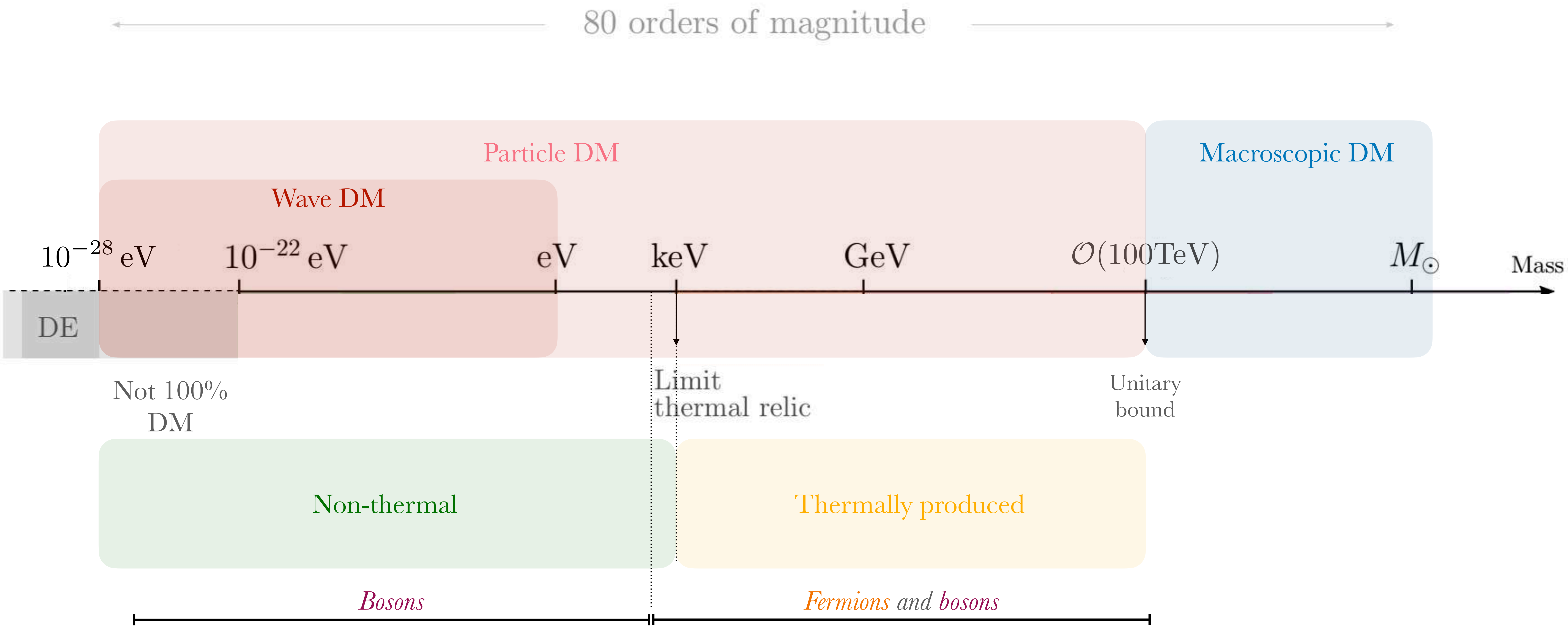
From stability against tidal disruption of structures immersed in DM halos, such as galactic disks and globular clusters, and of individual small galaxies

Constrain an individual, point-like DM constituent, assuming it makes up 100% of the DM: $m \lesssim 5\, M_\odot$

Use star cluster or halo binaries

Mass scale of dark matter

⇒ We can use observations of LSS and galaxies to put bounds in the "particle" physics properties, like mass and spin, of the DM candidate



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Mass scale of dark matter

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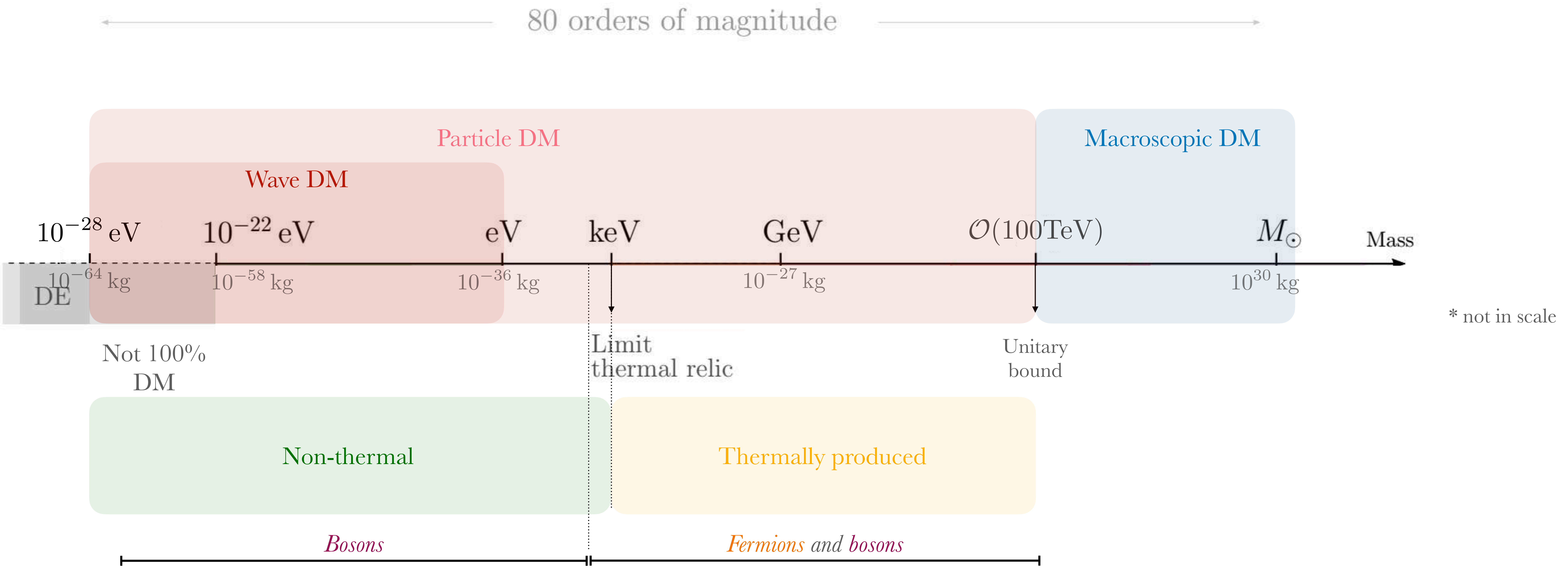

There are ways to evade some of these bounds!

Natural units ($c = 1$)
$1\,\text{kg} \to \sim 5 \times 10^{35}\,\text{eV}$
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Given these properties, what are the possibilities for a DM candidate?

Landscape of dark matter models

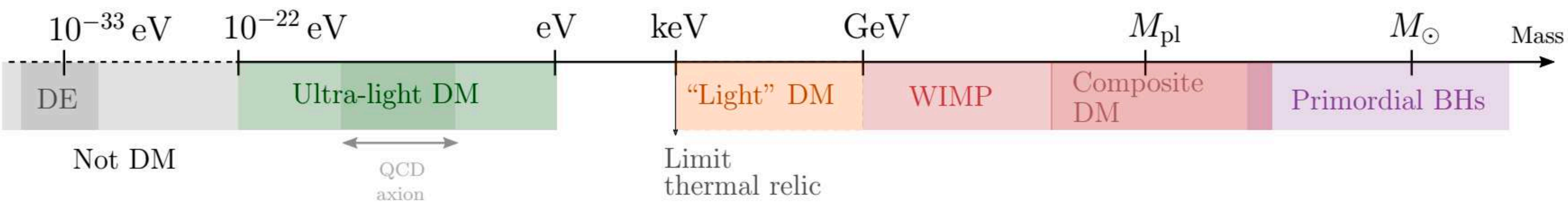
Landscape of dark matter models

- What is DM? What is the nature of DM?

State of the "art"

Mass scale of DM

80 orders of magnitude



Landscape of dark matter models

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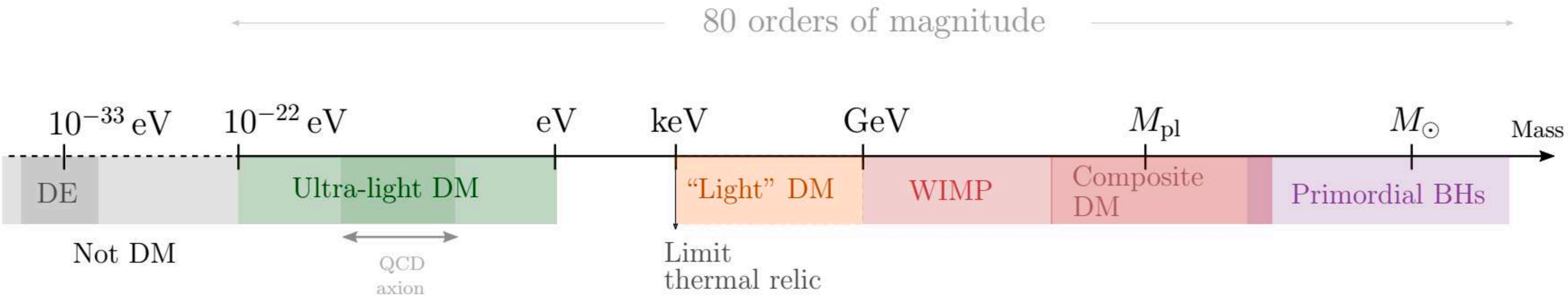
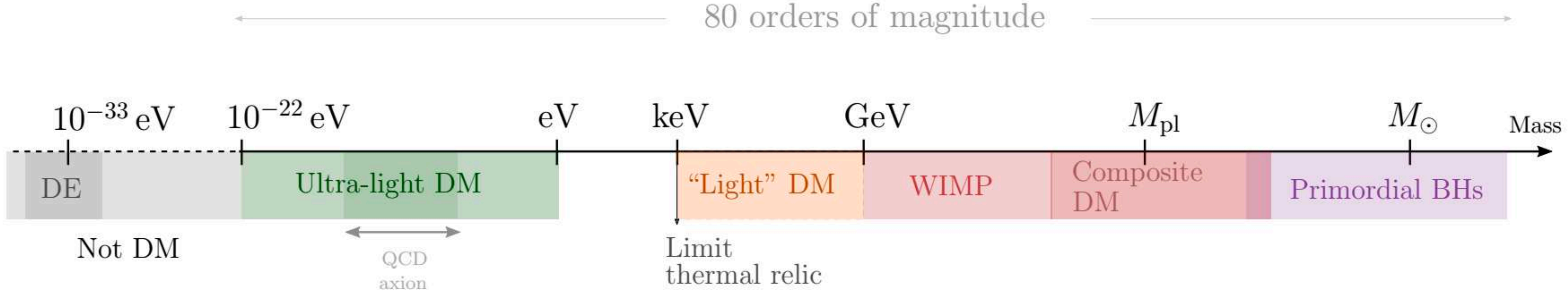


Next lecture

- DM models
  - Particle DM: WIMPS
  - Macroscopic DM: PBHs
  - Wave DM: axions/ALPs

Mass scale of DM



MOND

Milgrom, 1983.

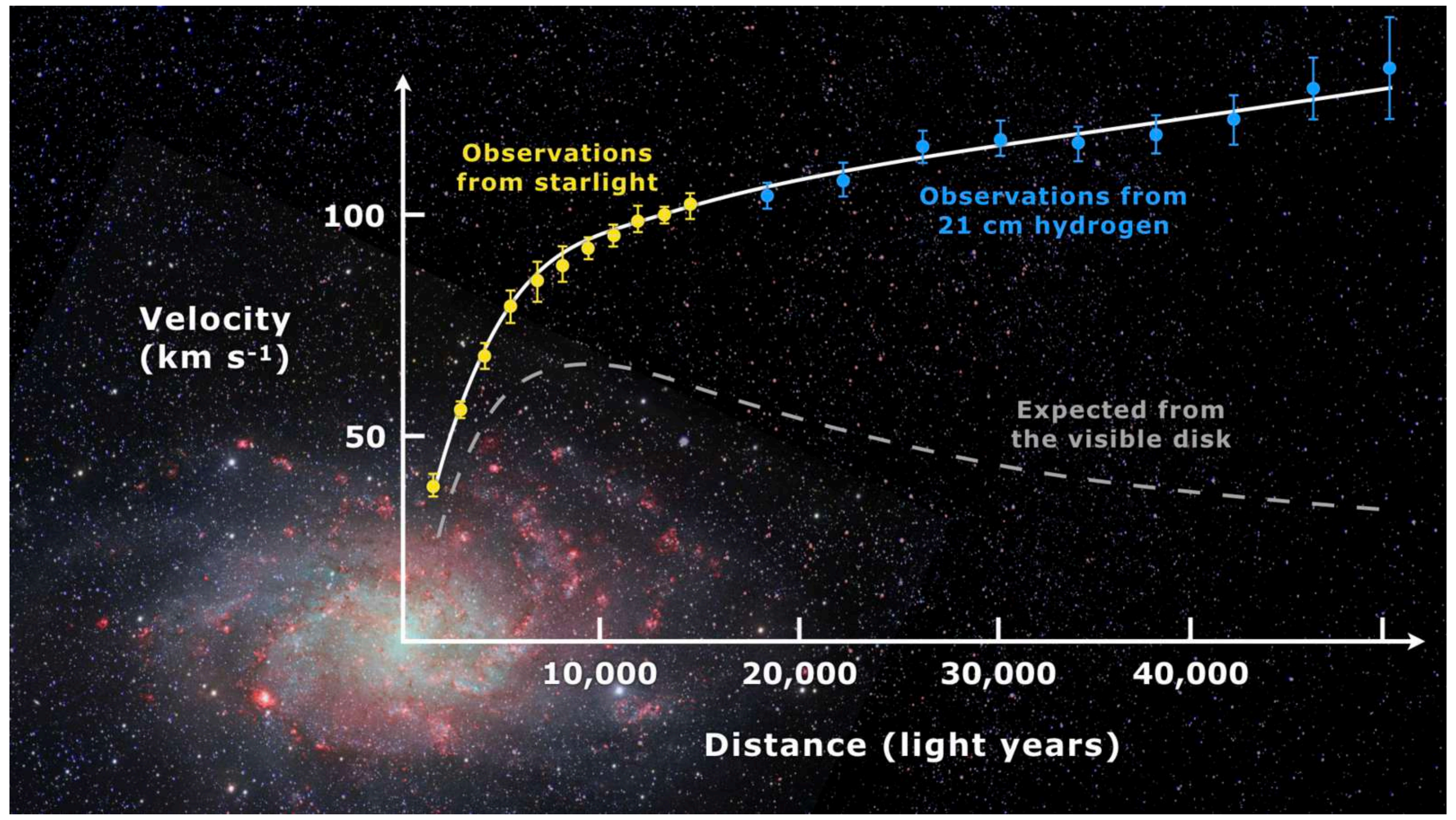
Modified Newtonian Dynamics

Empirical relation

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

$$a_N^b = \frac{G_N M_b}{r^2}$$

$$a_0 \simeq 1.2 \times 10^{-8}\,\mathrm{cm/s^2}$$



~~Missing mass~~

~~$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$~~

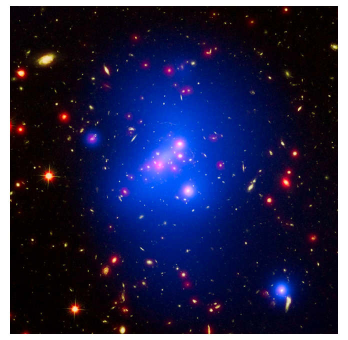
Curiosity: Baryons lead the dynamics!

Works really well to: (1) Fit galaxy rotation curves; (2) Explain the scaling relations

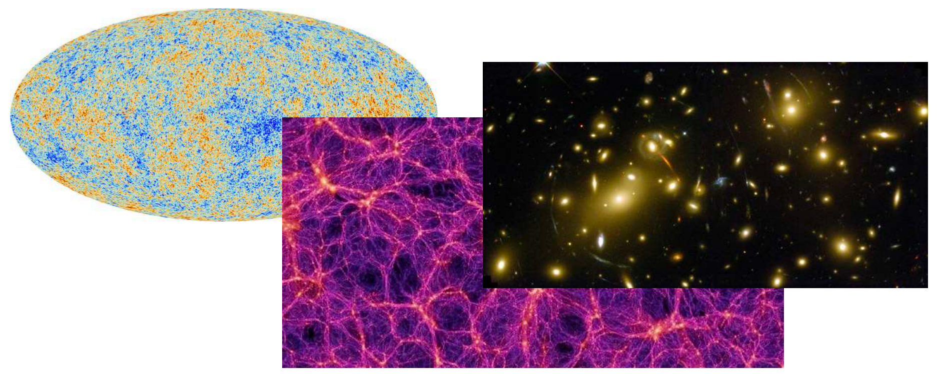
BUT: Modified theory of gravity

Milgrom, 1983.

~~MOND without DM~~



Clusters



Large scales

Relativistic extension: TeVeS, (BIMOND)

2020: "*A new relativistic theory for Modified Newtonian Dynamics*", C. Skordis, T. Zlosnik ⟶ Agreement with CMB