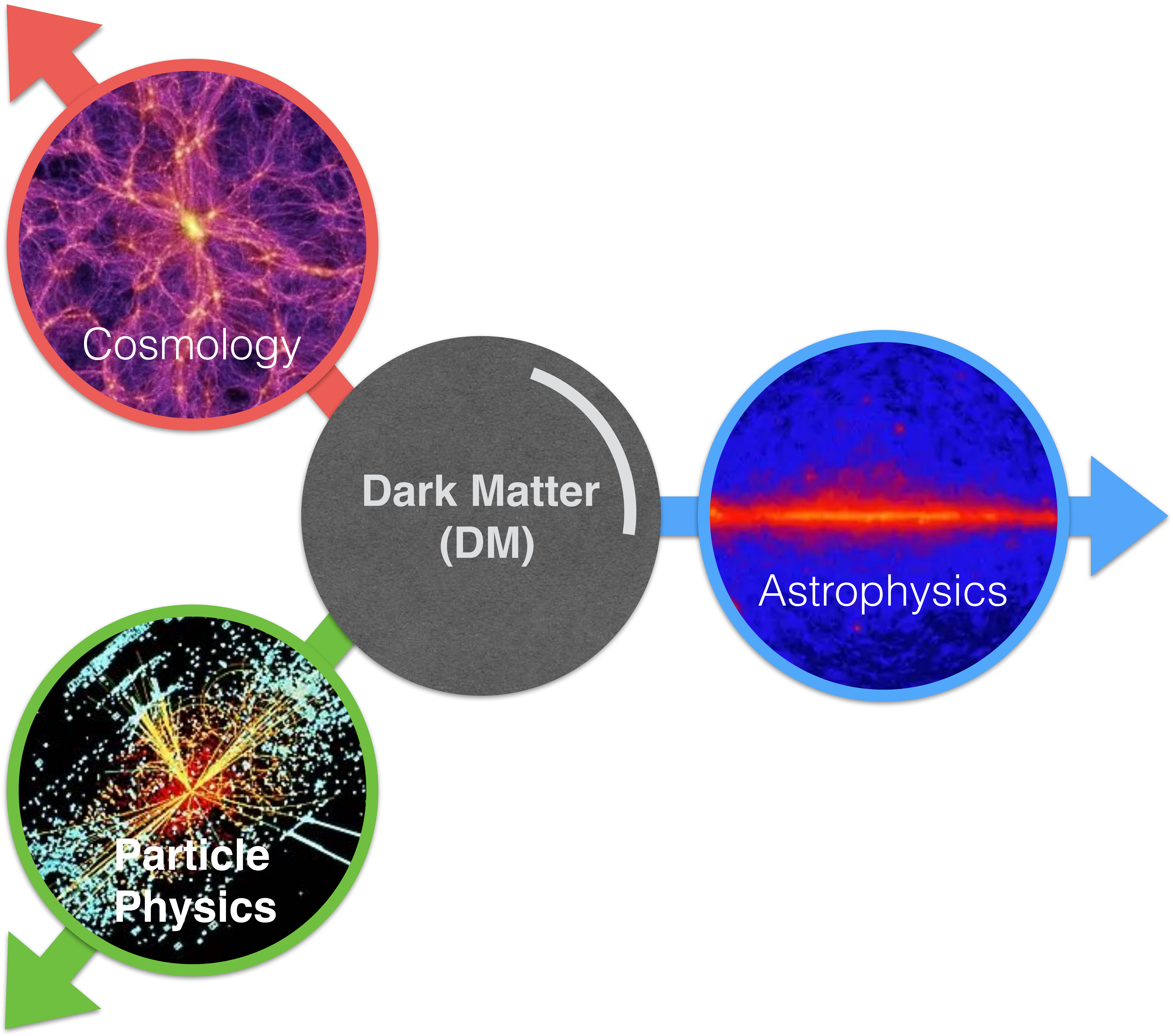


New Directions in the Search for Dark Matter

Bradley J Kavanagh [he/him]
Instituto de Fisica de Cantabria (CSIC-UC)
kavanagh@ifca.unican.es

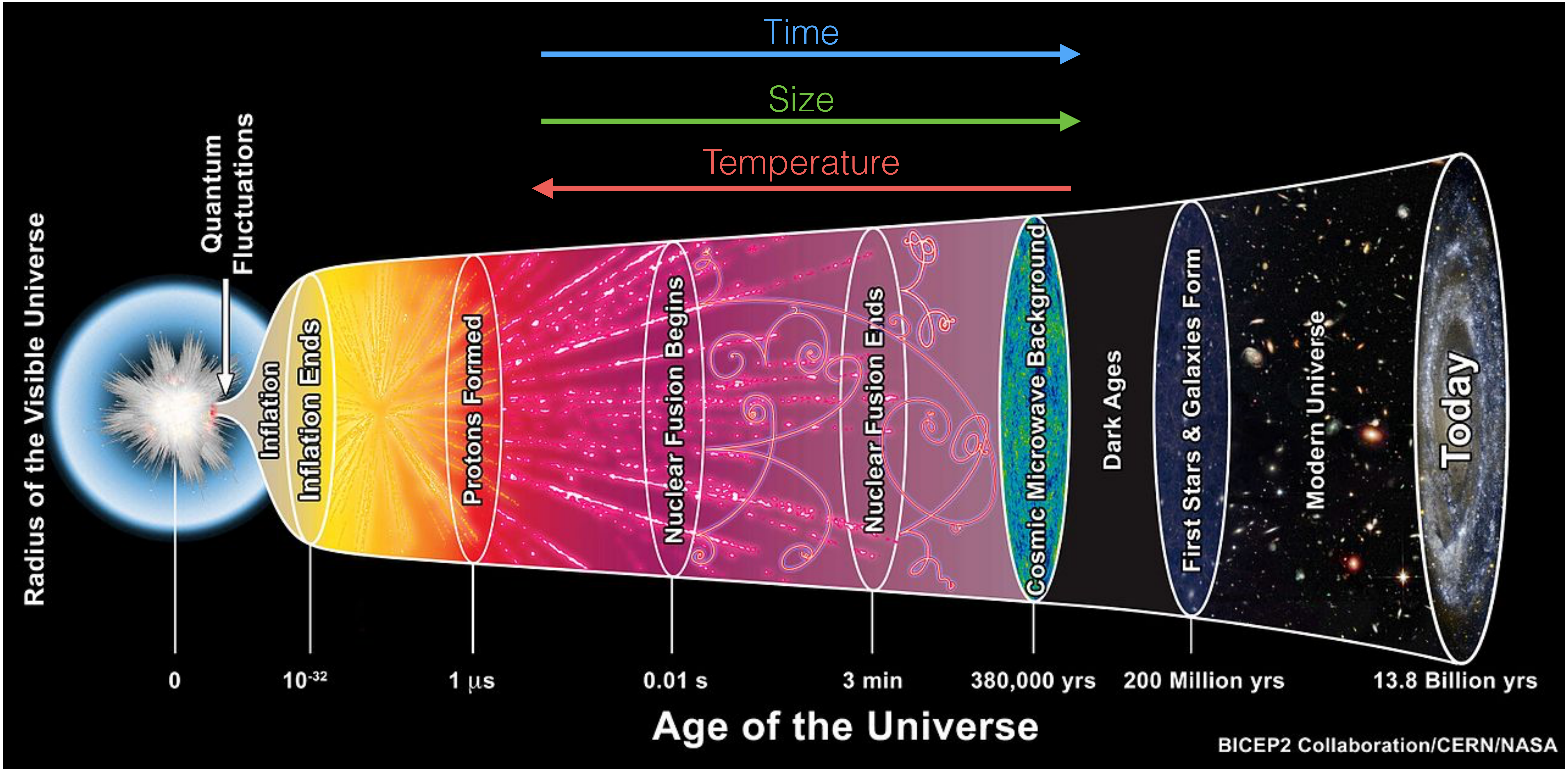
ICMAB Seminar, 18th March 2024

What is the evidence for Dark Matter?

What is it? What are its properties?

How can we uncover its identity?

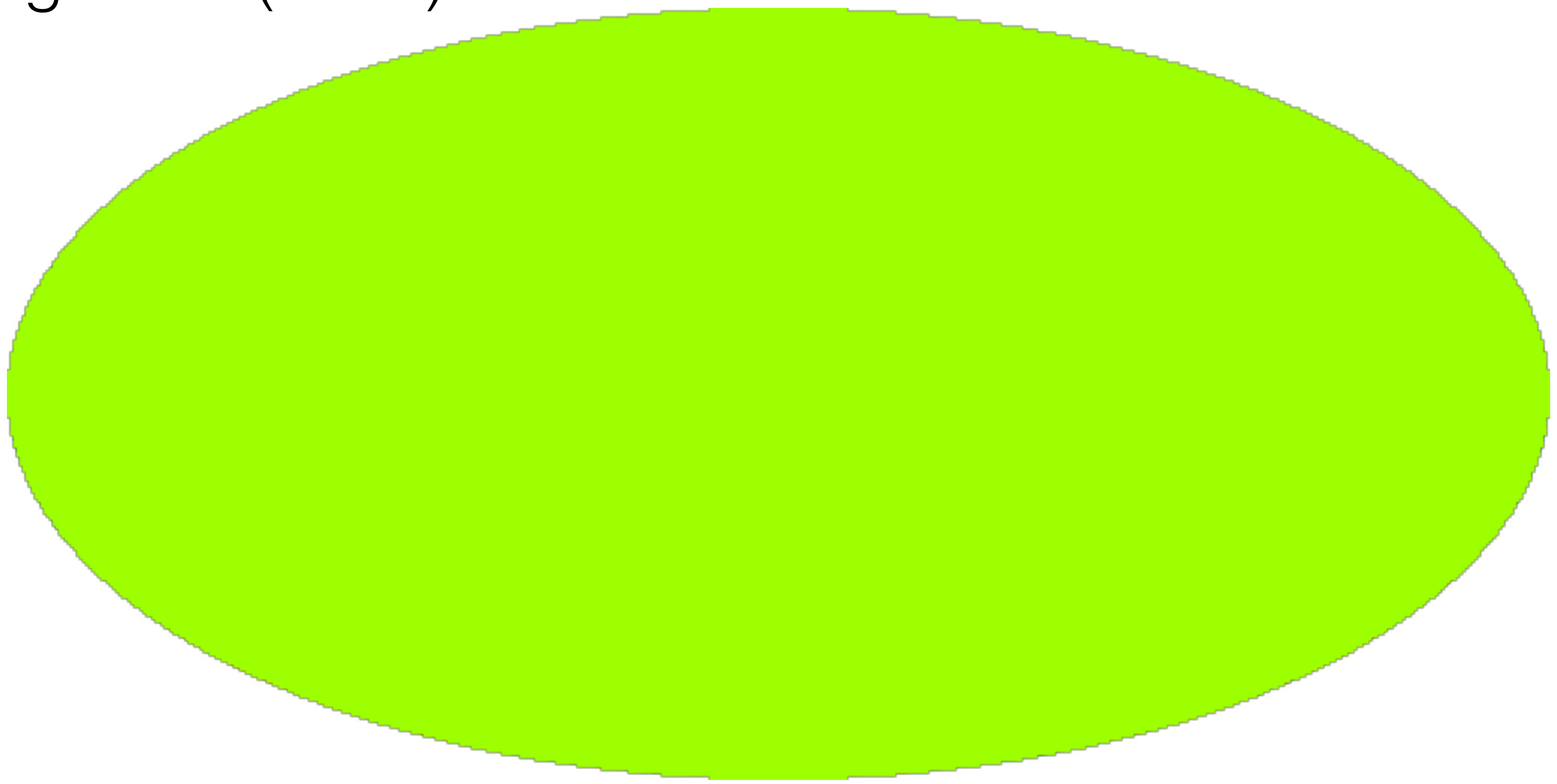
Everything, Everywhere, All at Once



Dark Matter in Cosmology

Cosmic Microwave
Background (CMB)

$$T_{\mathrm{CMB}} = 2.73\,\mathrm{K}$$



Dark Matter in Cosmology

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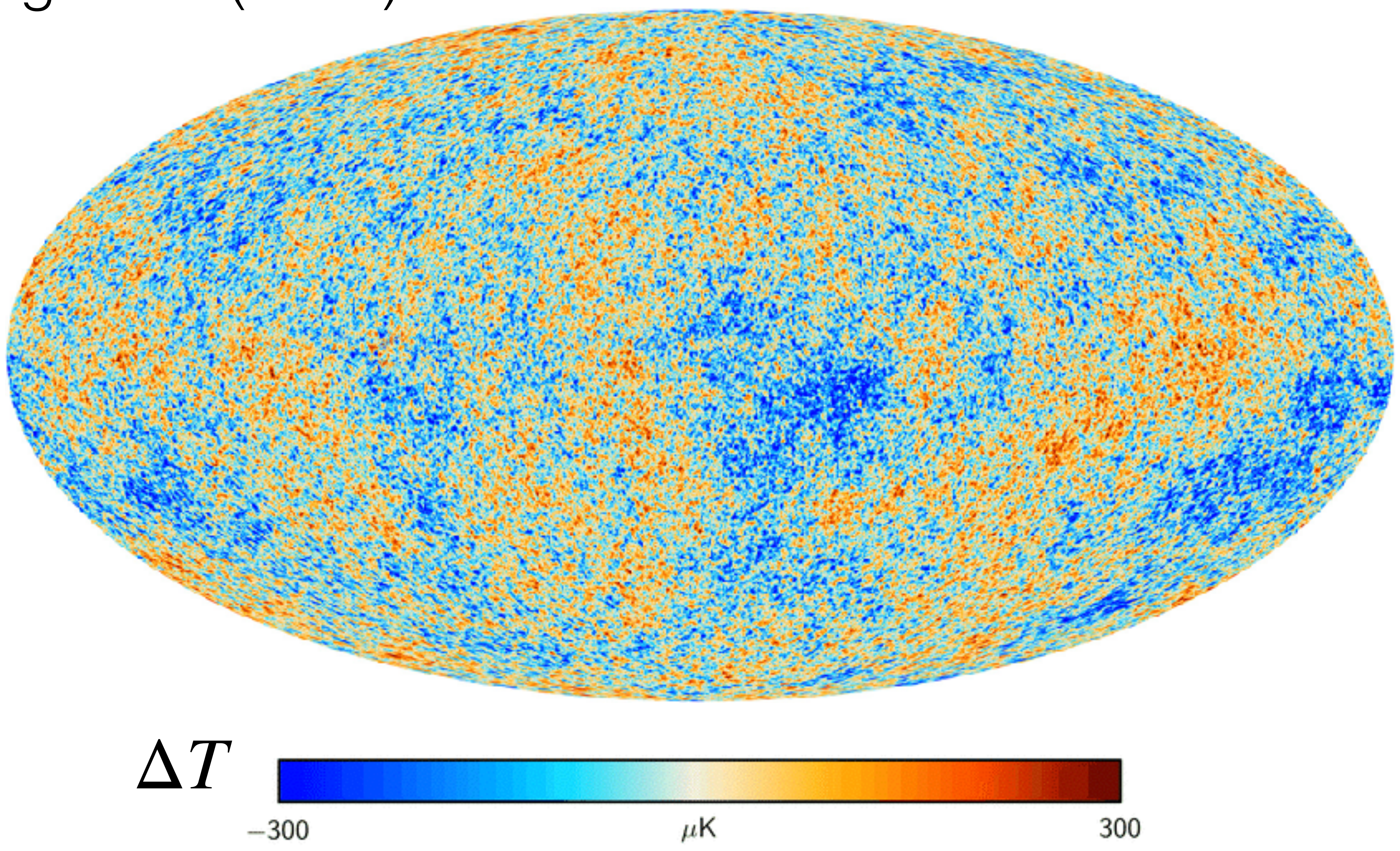

Dark Matter in Cosmology

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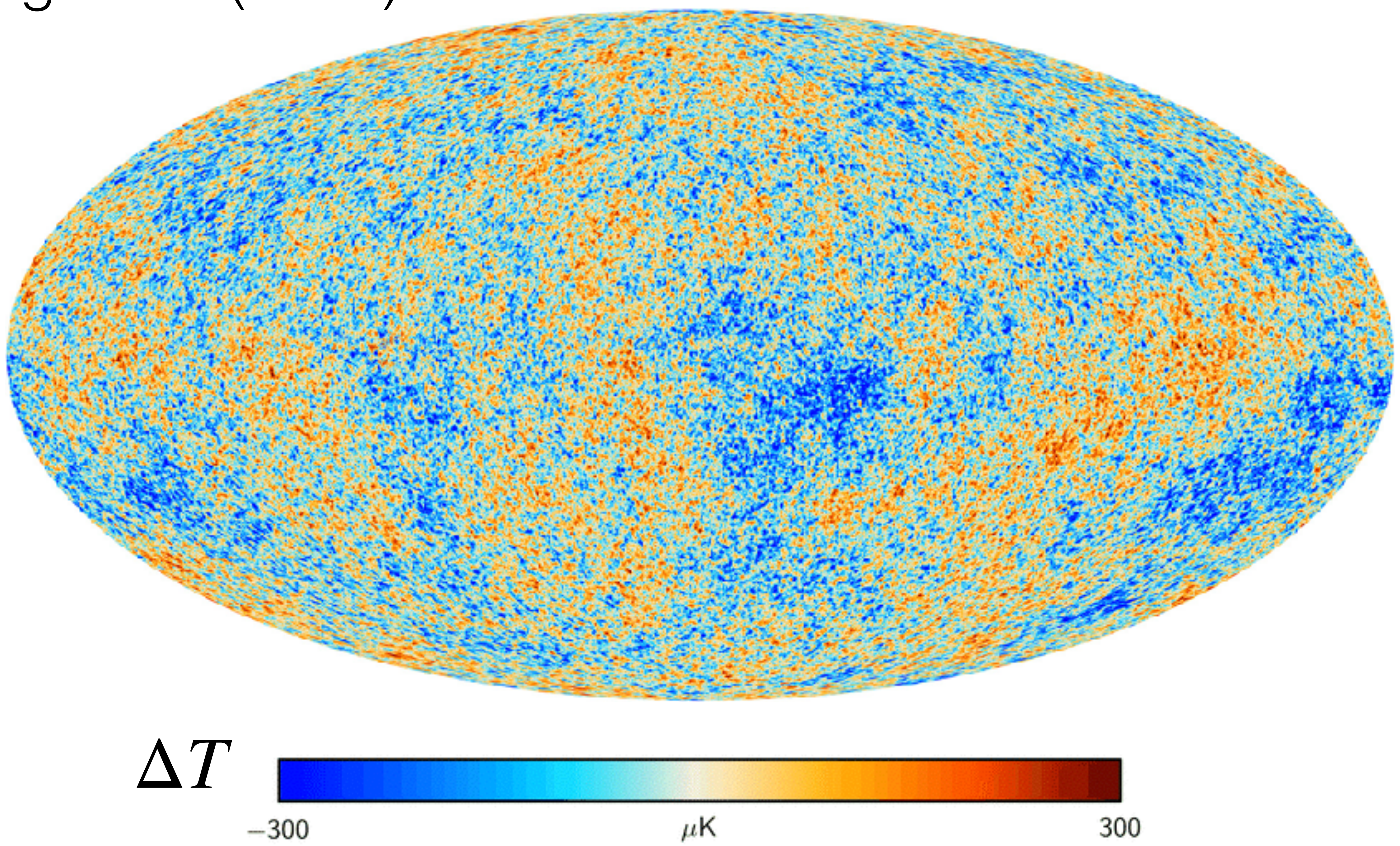
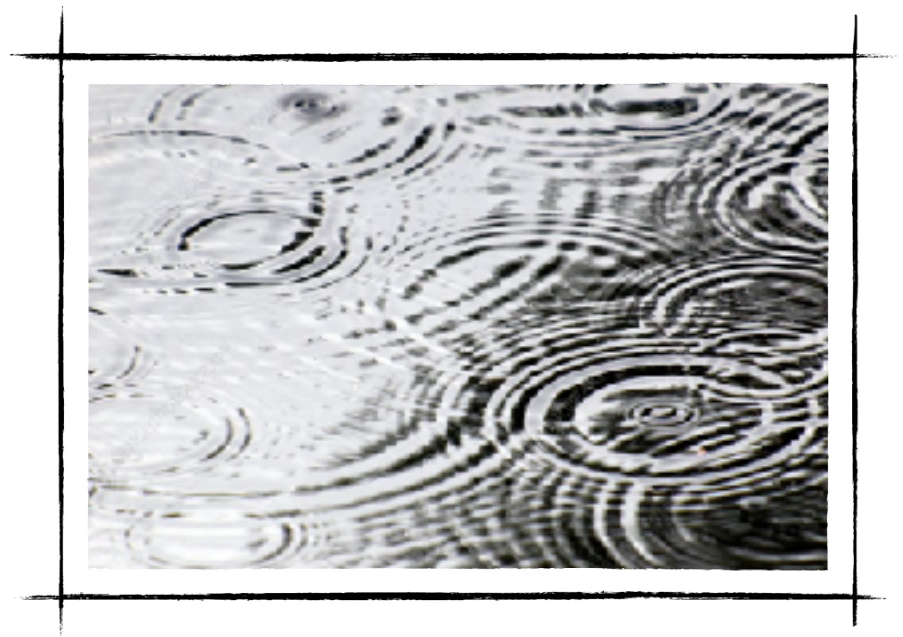
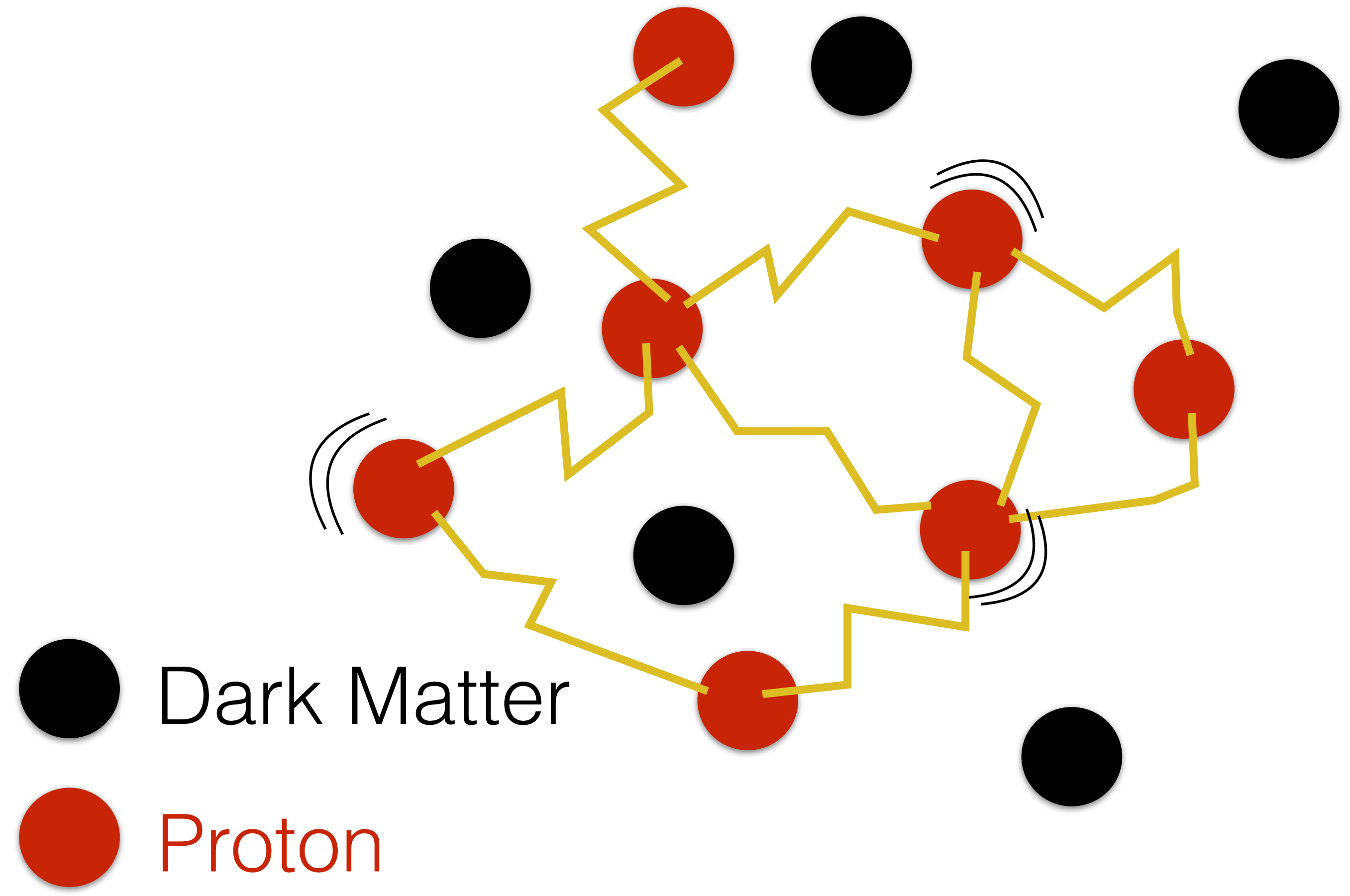


ΔT

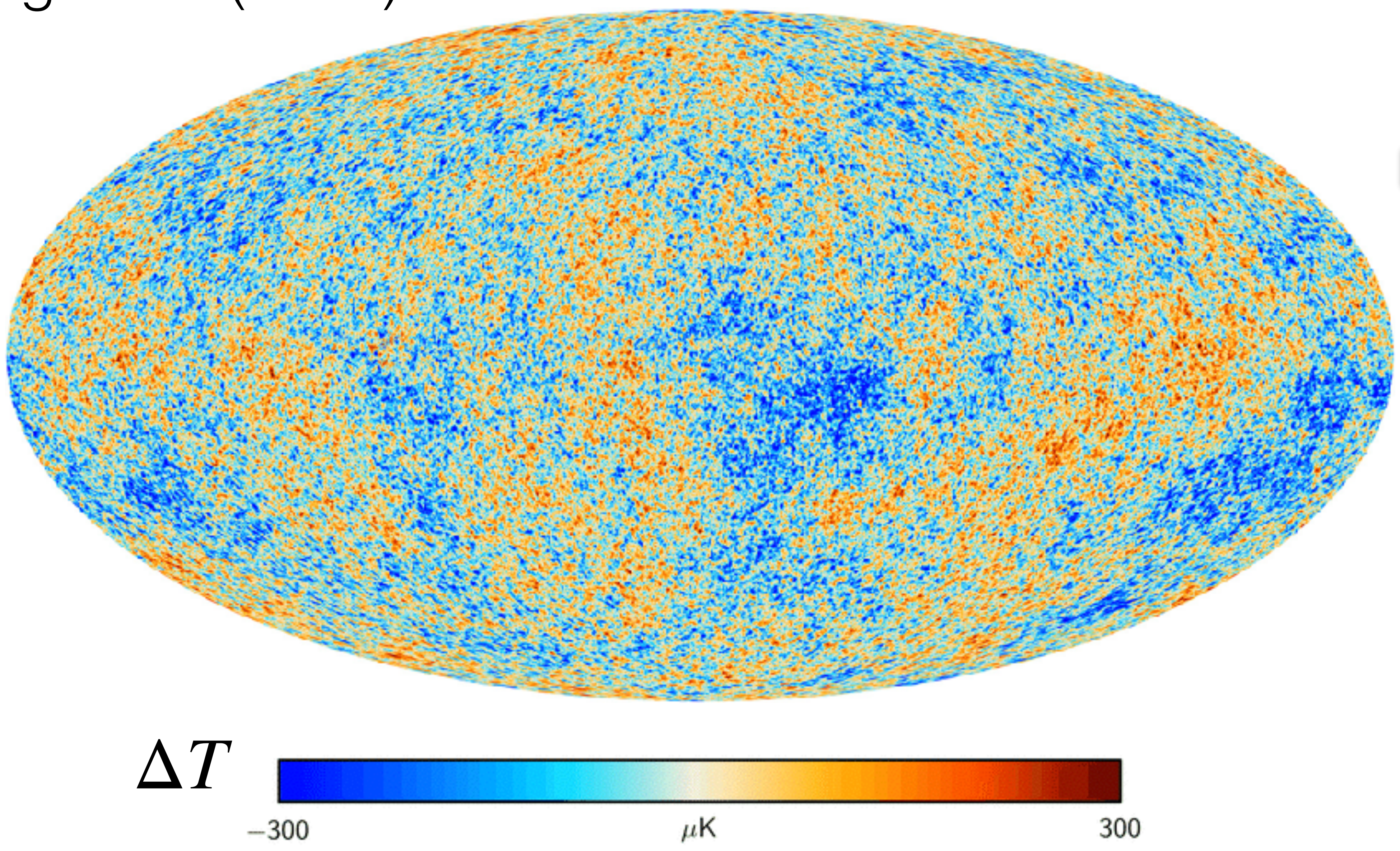


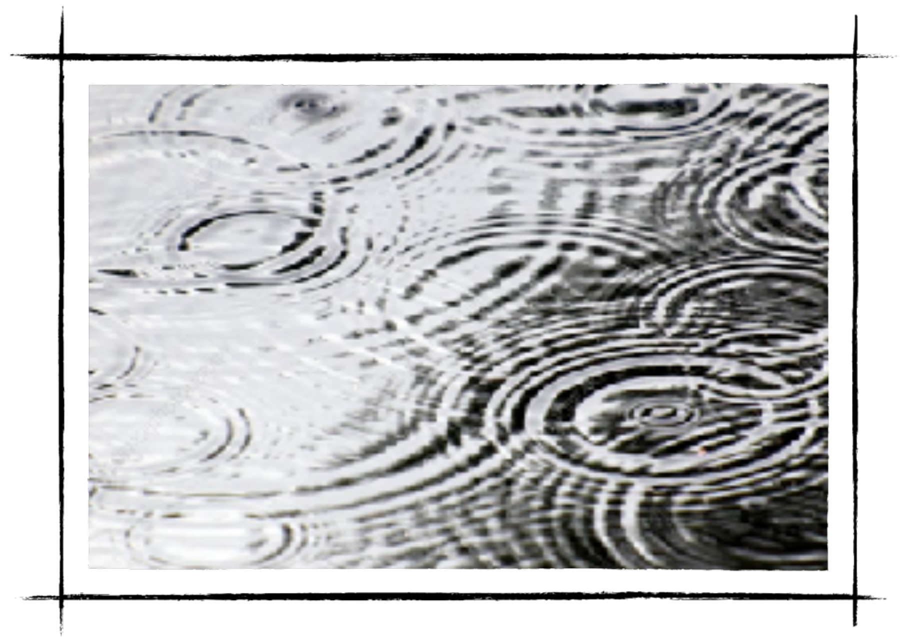


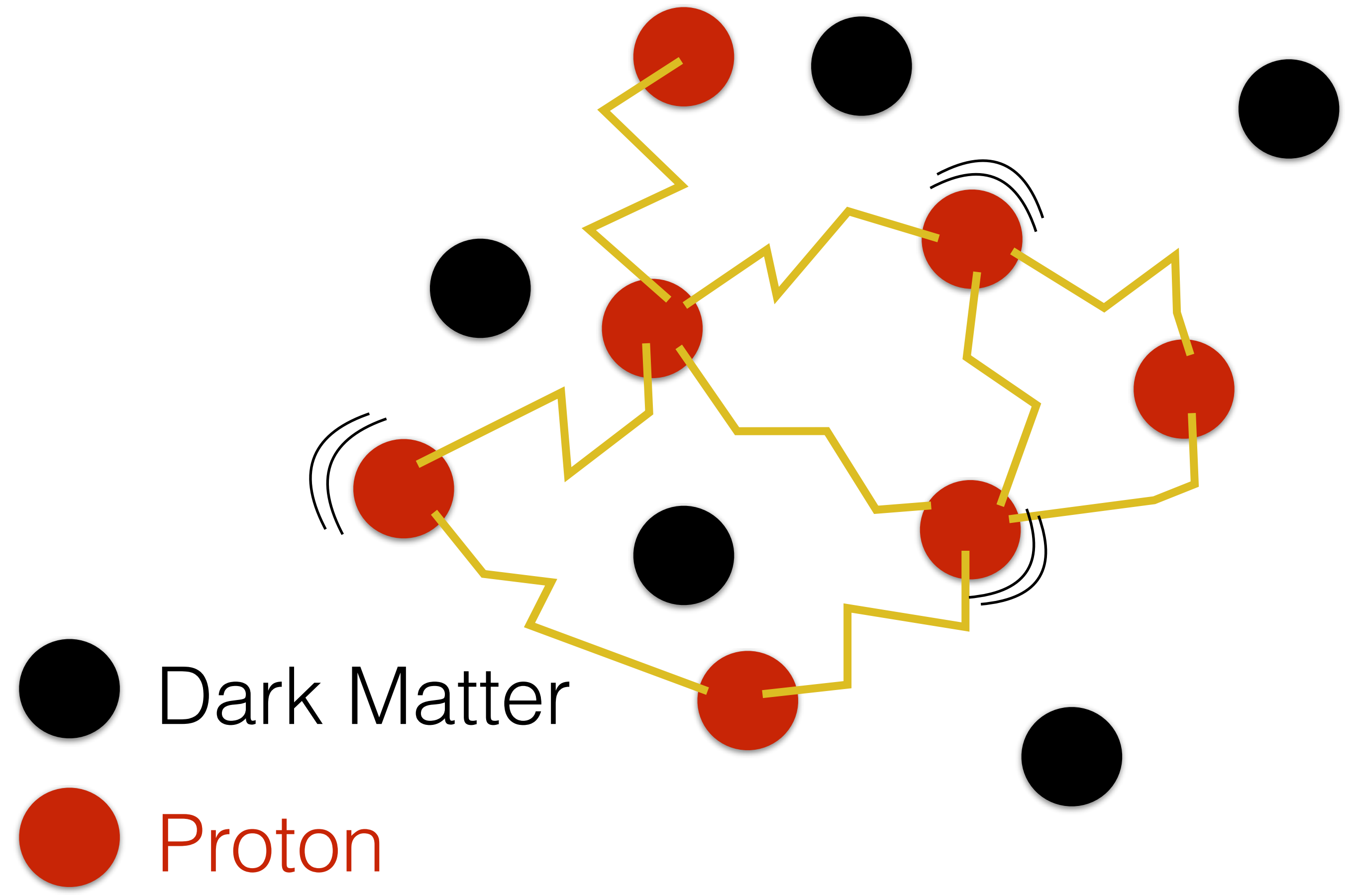
Dark Matter in Cosmology

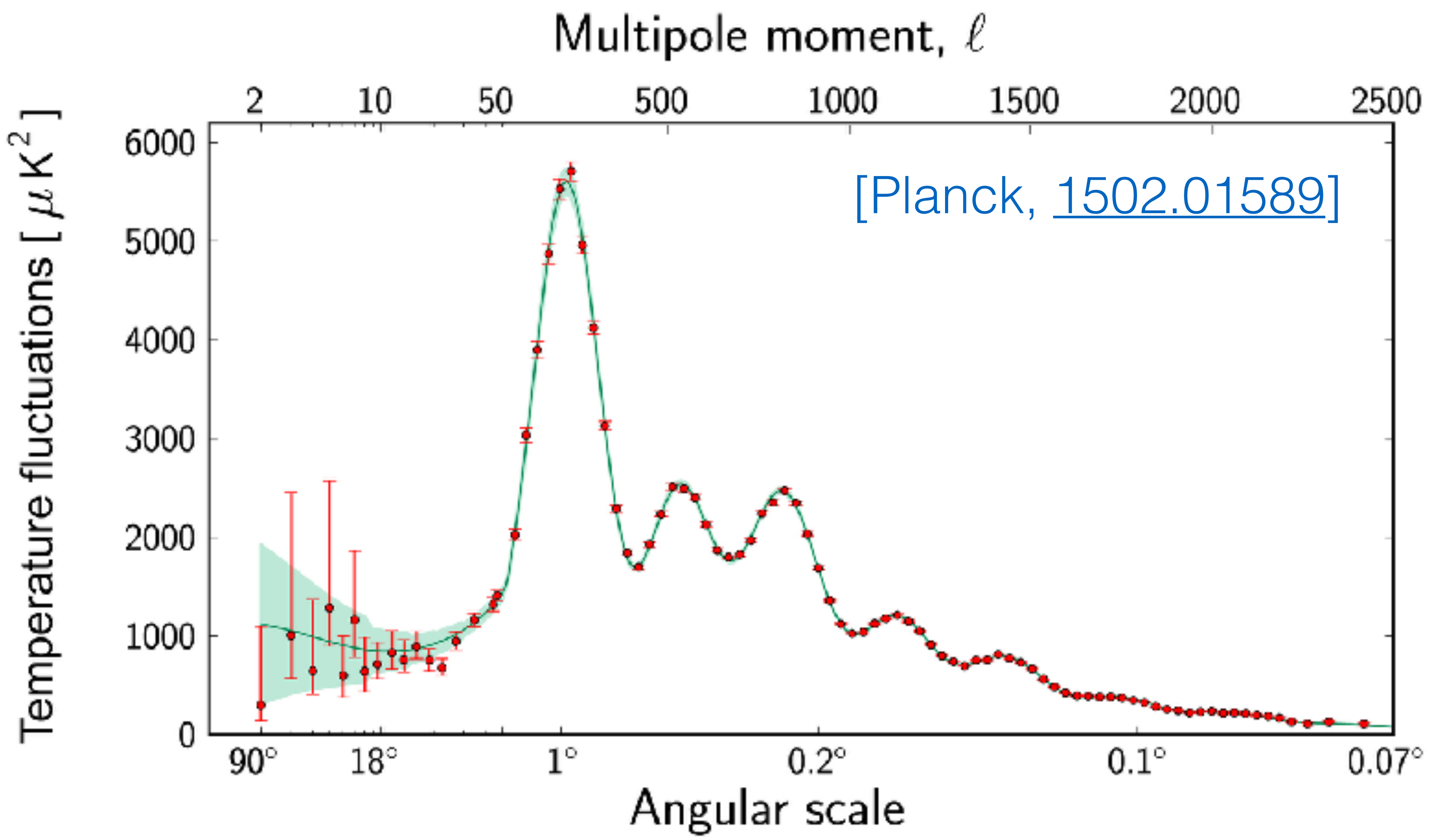
Cosmic Microwave Background (CMB)

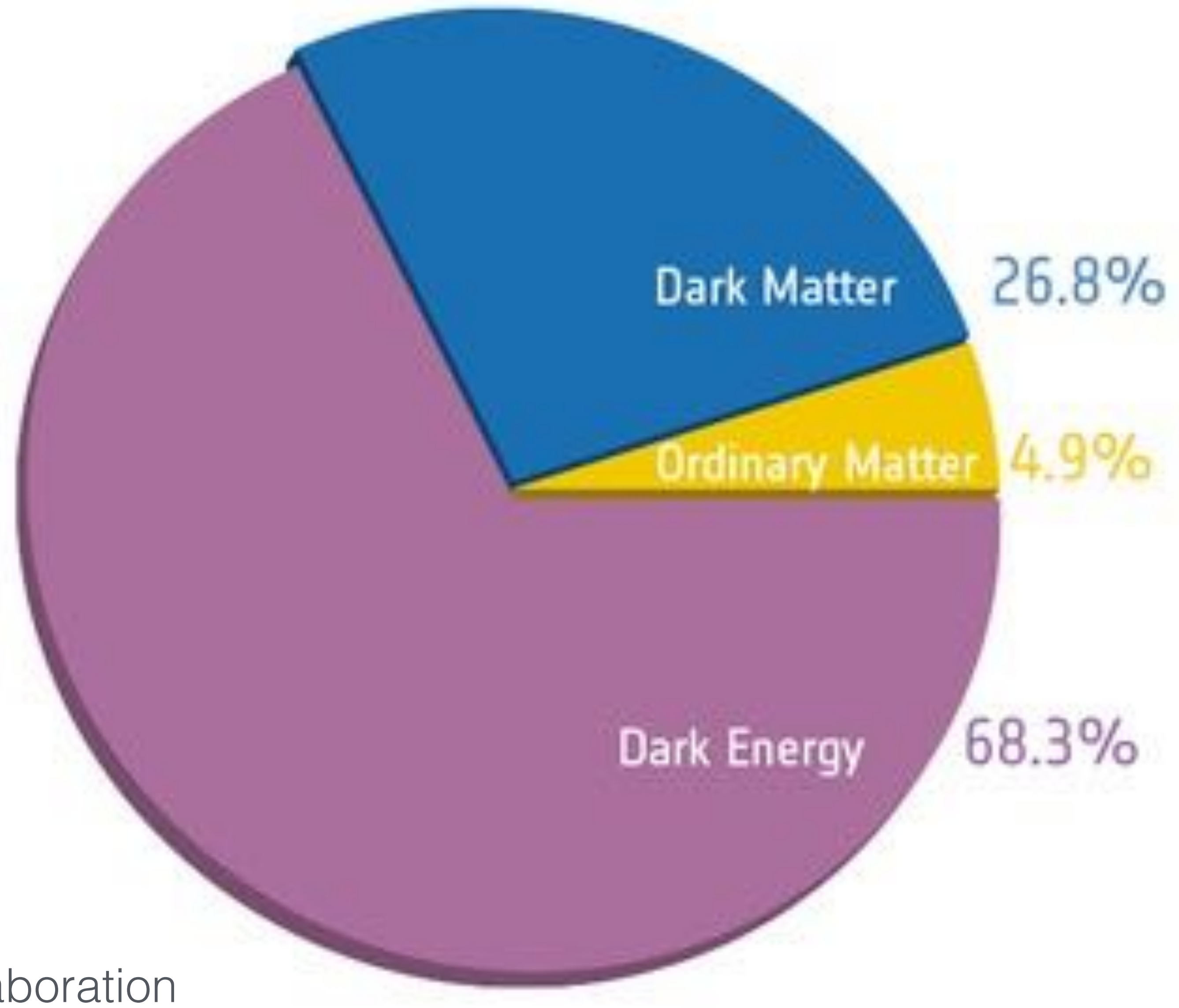
$$T_{\rm CMB} = 2.73\,{\rm K}$$





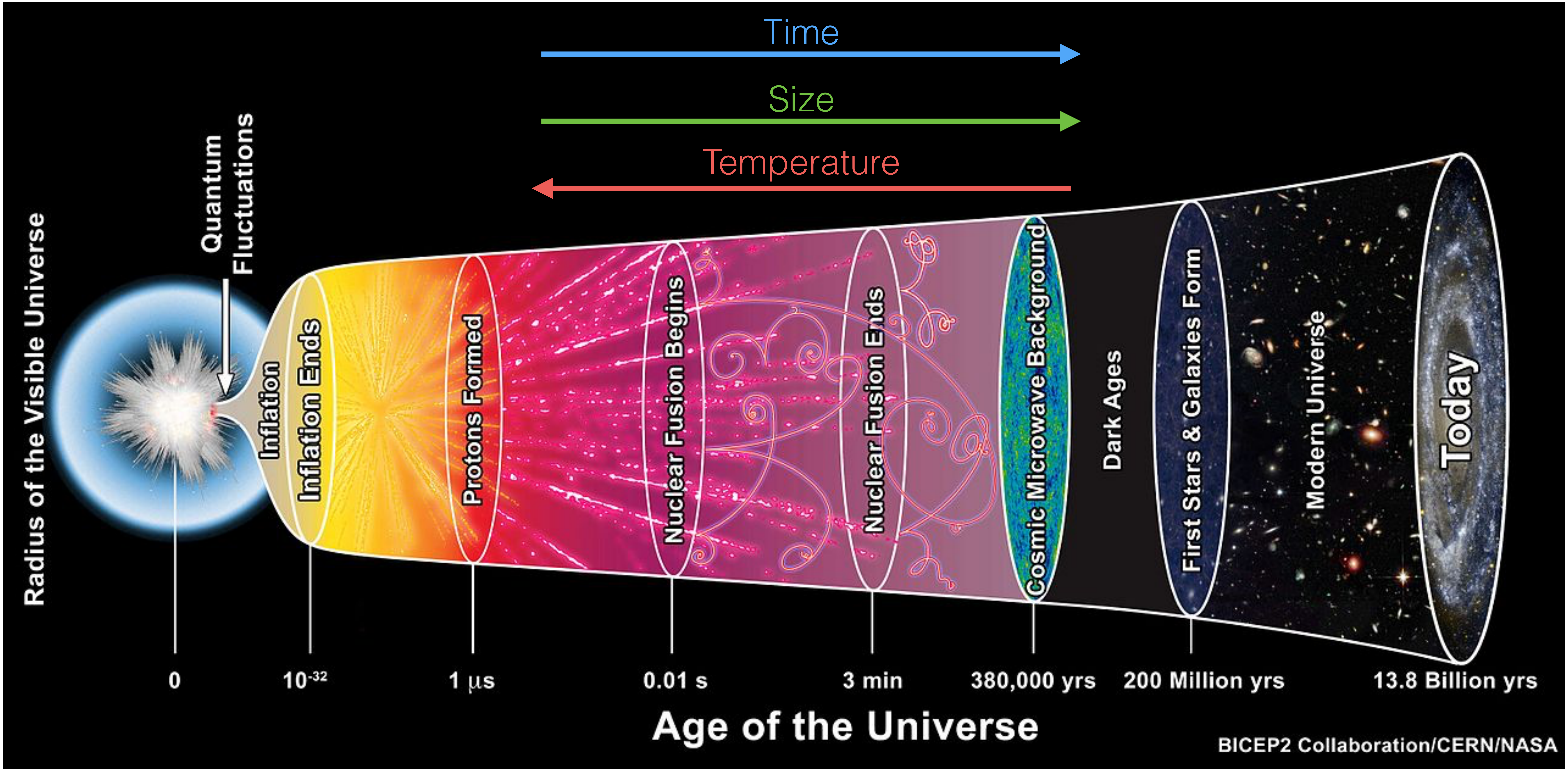






Credit: ESA/Planck Collaboration

Everything, Everywhere, All at Once

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Redshift = 10.11
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Durham University
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t_{age} = 1.7 Gyr
Redshift = 3.73
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Galaxies in Simulations

[Video on previous slide available here]

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.

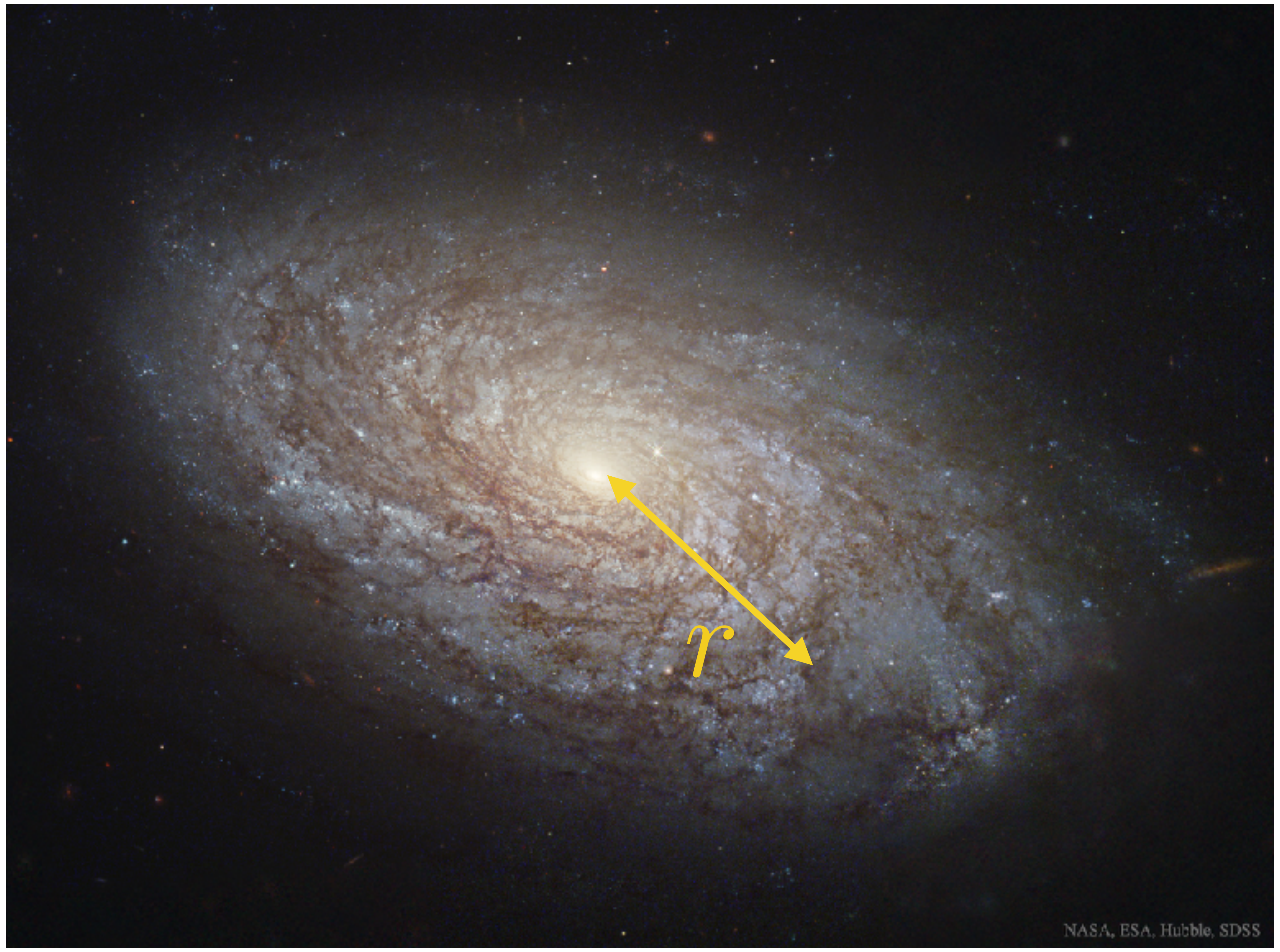
[IllustrisTNG simulation - 2101.12373]

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

Warning: Galaxy formation is messy and non-linear and still not fully understood

[E.g. 1609.05917 vs 1610.07663]

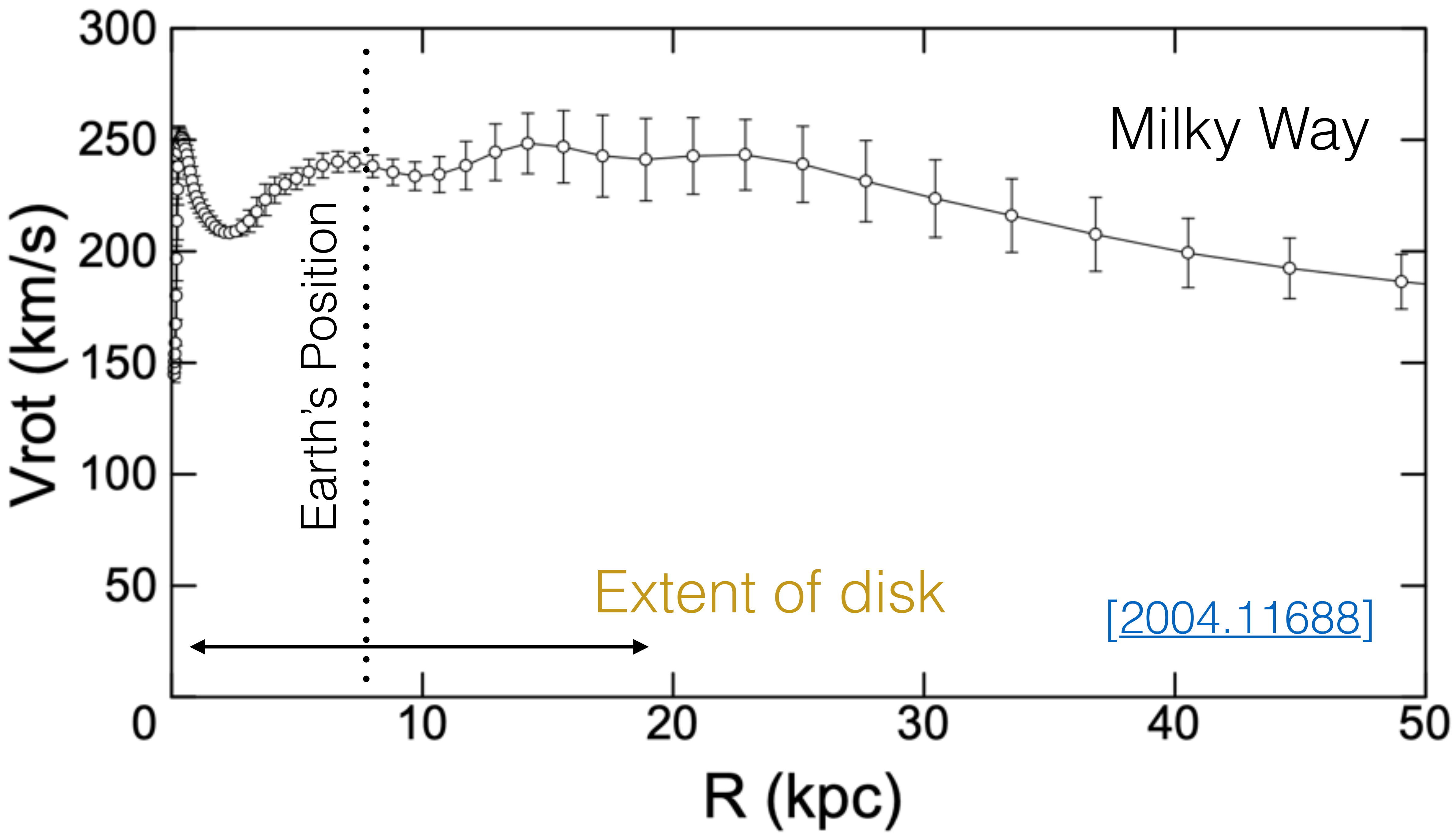
Dark Matter in Galaxies



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

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

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

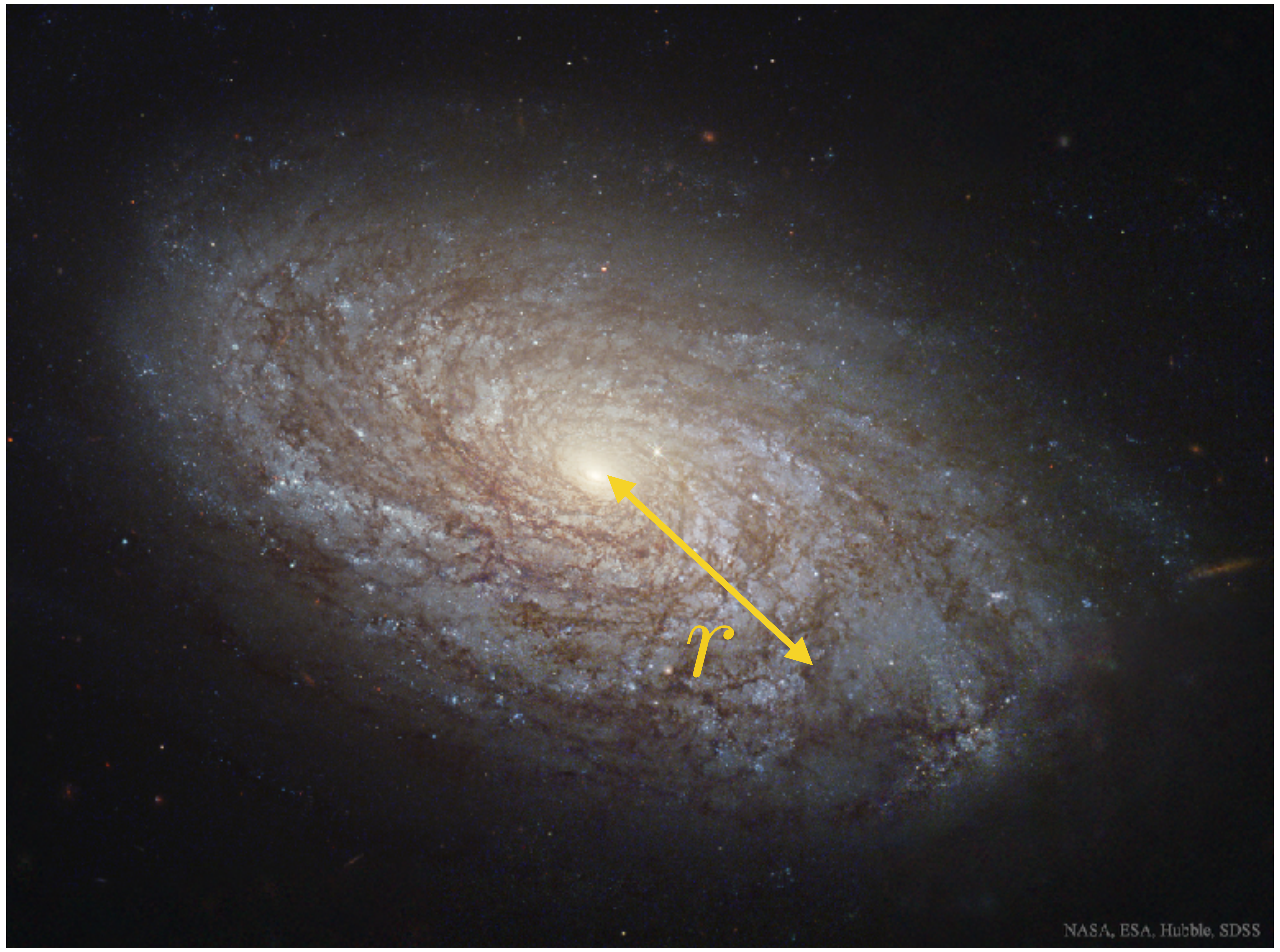


DM density at Earth:

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

[1404.1938]

Dark Matter in Galaxies



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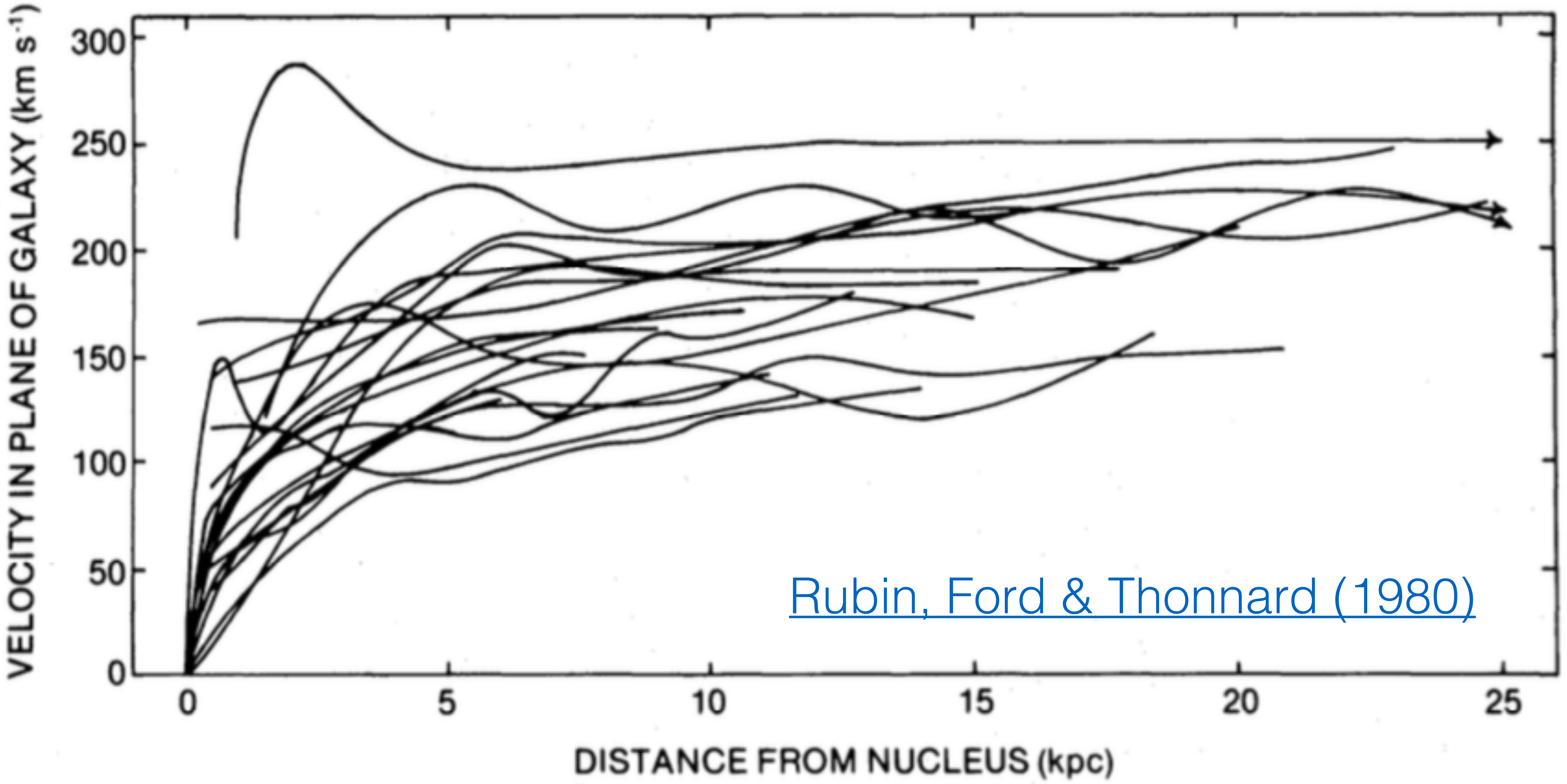
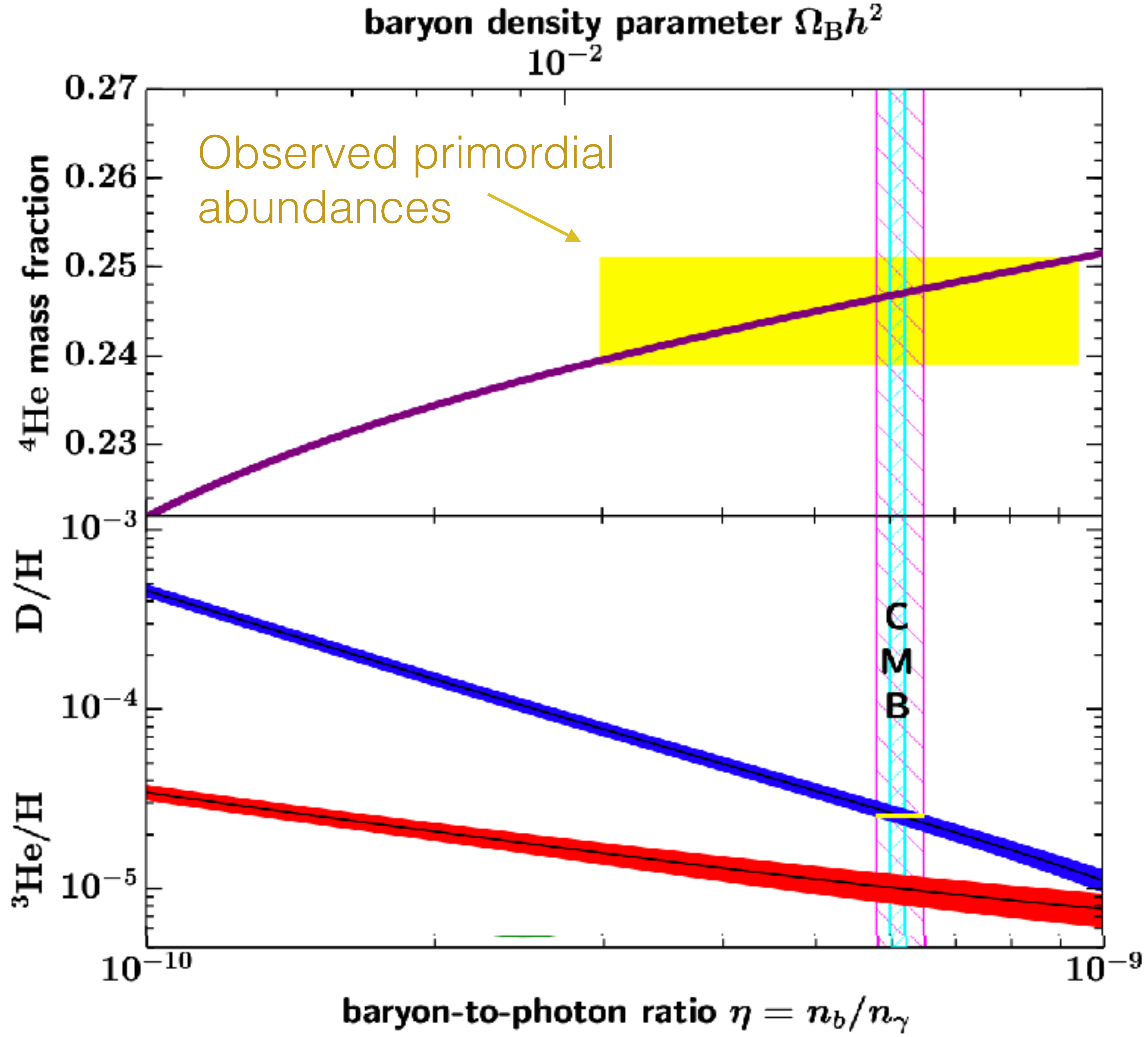


Rubin, Ford & Thonnard (1980)

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

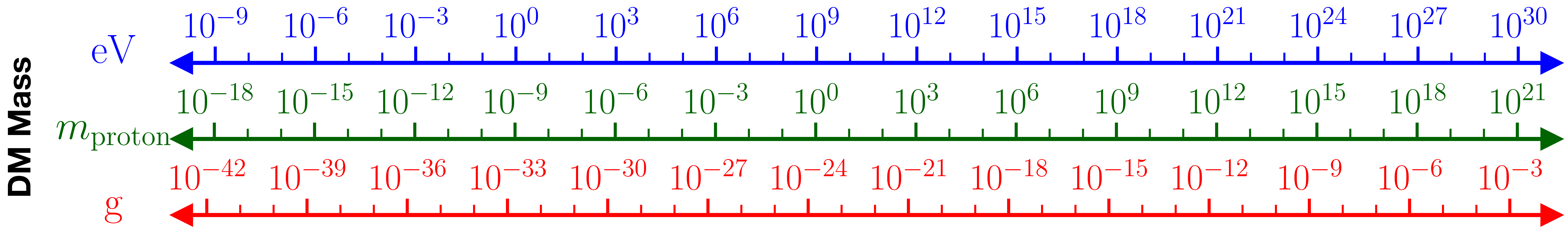
[0711.4996]

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…

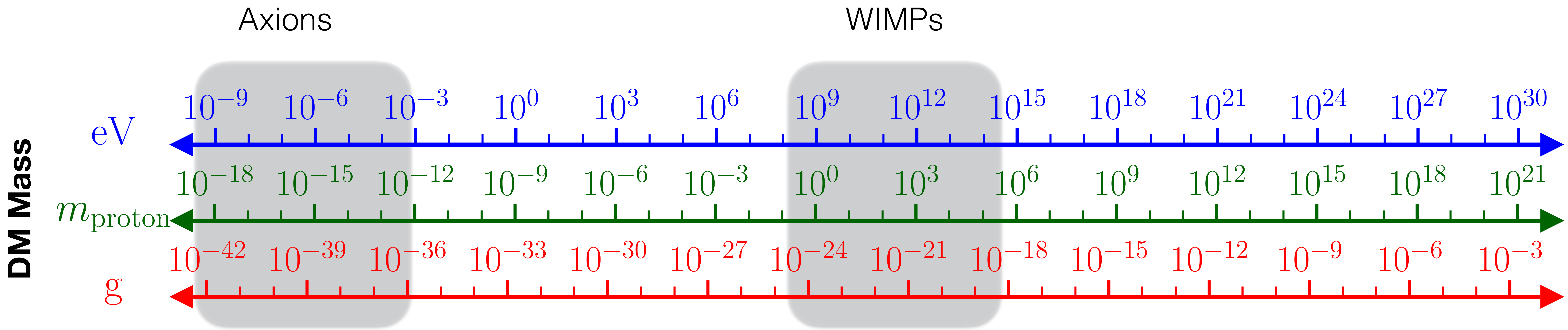
Dark Matter Mass Range



Very light DM ($\lesssim 10^{-22}\,\mathrm{eV}$)
has wave-like properties on
astrophysical scales,
spoiling galactic structure

Very heavy DM ($\gtrsim 10^{3}\,M_{\odot}$)
is ‘discrete’ on astrophysical
scales, spoiling galactic
structure

Dark Matter Mass Range



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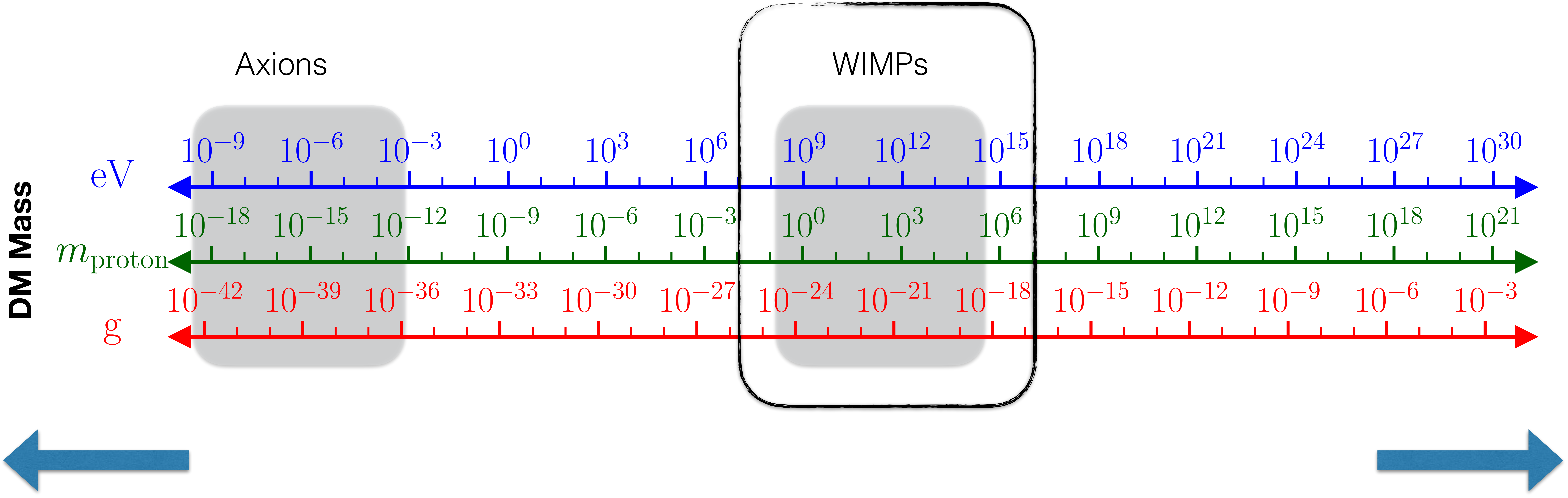
Dark Matter Mass Range



Very light DM ($\lesssim 10^{-22}\,\mathrm{eV}$) has wave-like properties on astrophysical scales, spoiling galactic structure

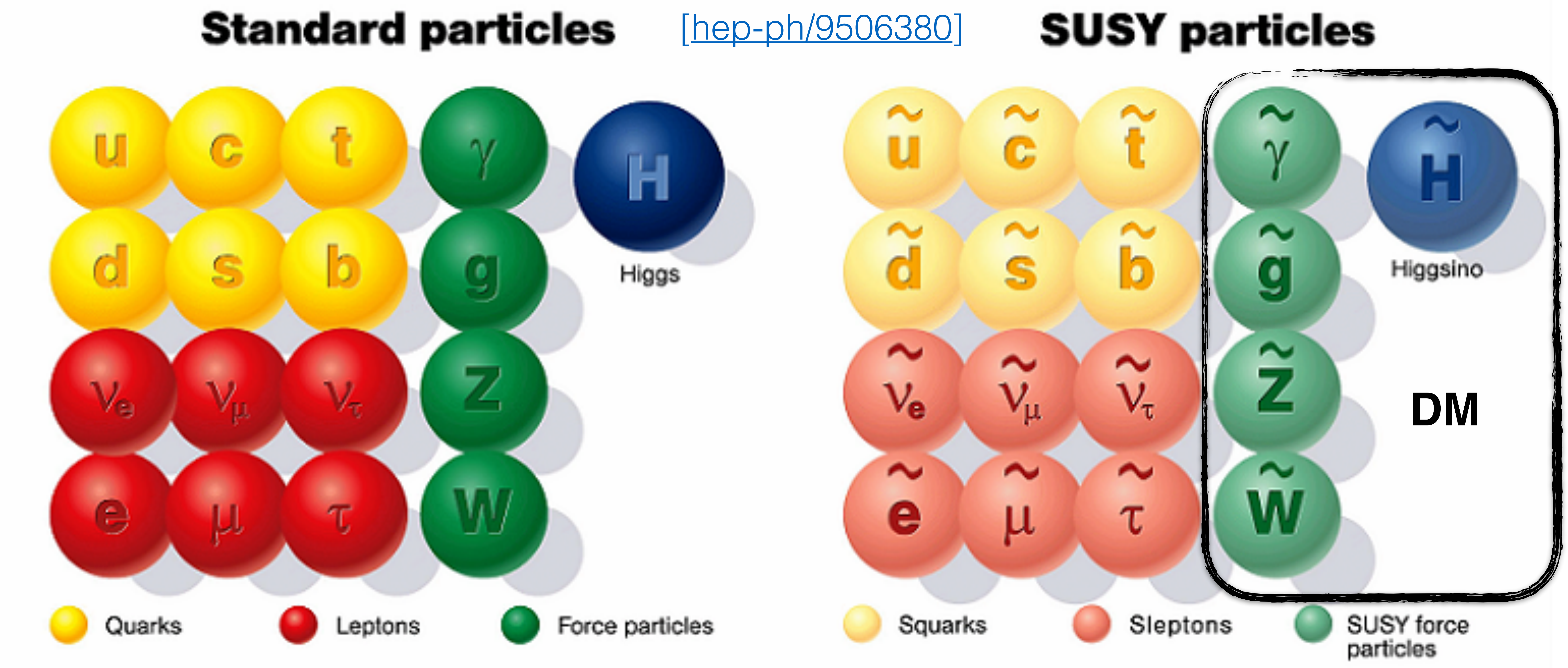
Very heavy DM ($\gtrsim 10^{3}\,M_{\odot}$) is ‘discrete’ on astrophysical scales, spoiling galactic structure

Weakly Interacting Massive Particles

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

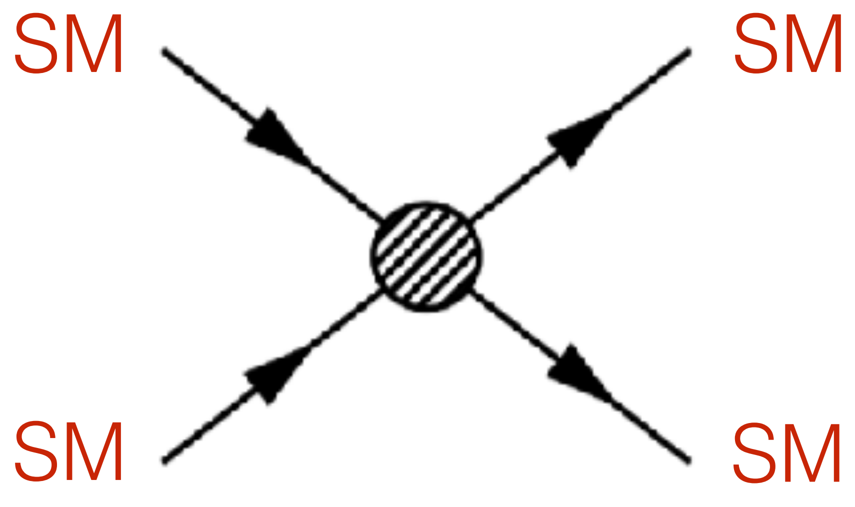
WIMPs generically arise in models of **Supersymmetry (SUSY)**, proposed to solve the Hierarchy Problem in the Standard Model ("why is the Higgs boson so light, when its mass should received receive corrections from loops of heavy particles?")

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

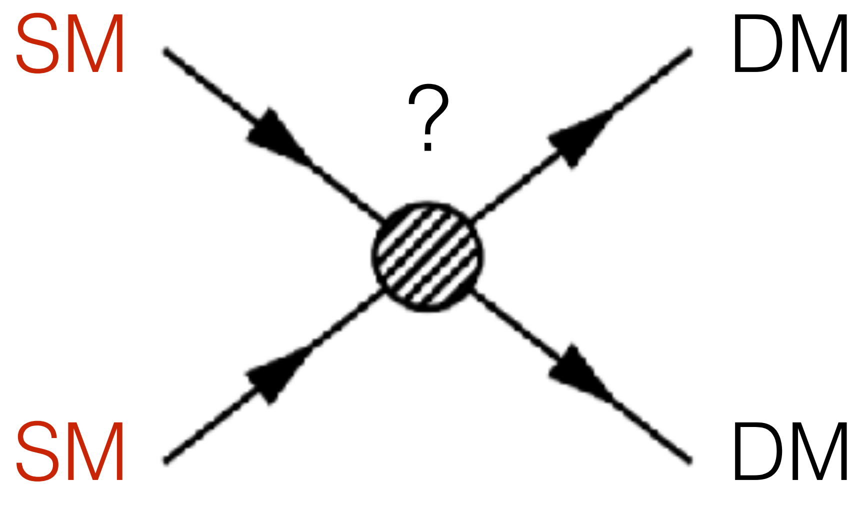


Now, the term WIMP is used to mean a generic MeV-TeV mass particle with weak couplings to the standard model.

Producing WIMP Dark Matter



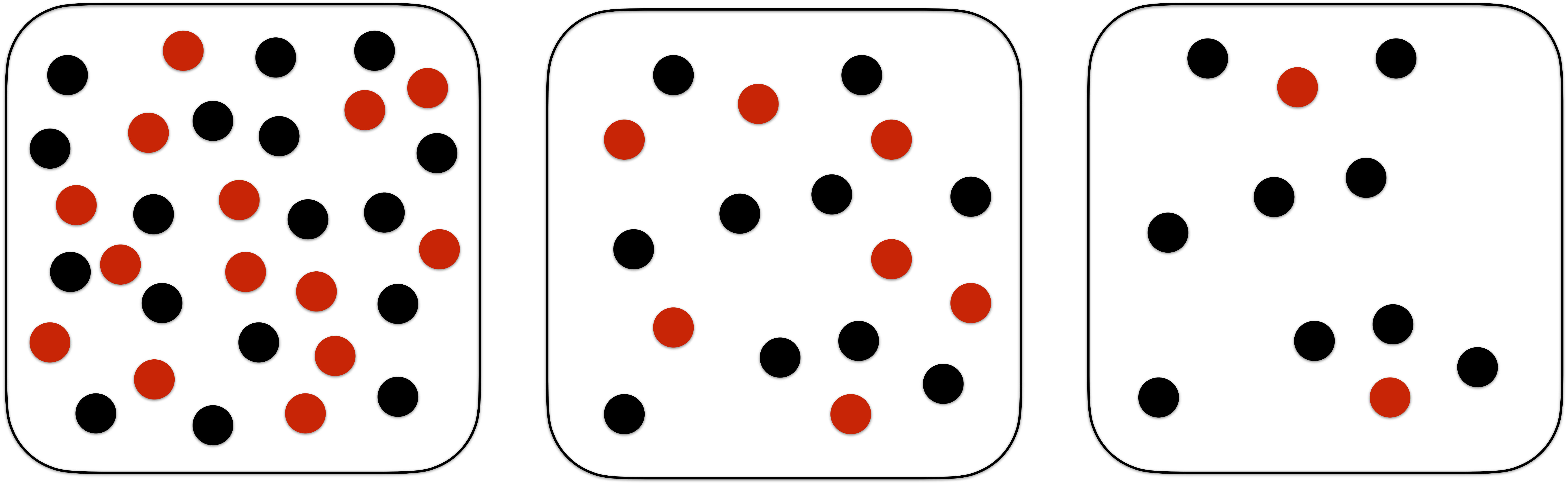
$$\mathrm{SM} + \mathrm{SM} \leftrightarrow \mathrm{SM} + \mathrm{SM}$$



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

"Freeze-out"

- Dark Matter
- Standard Model



Time

Size (of the Universe)

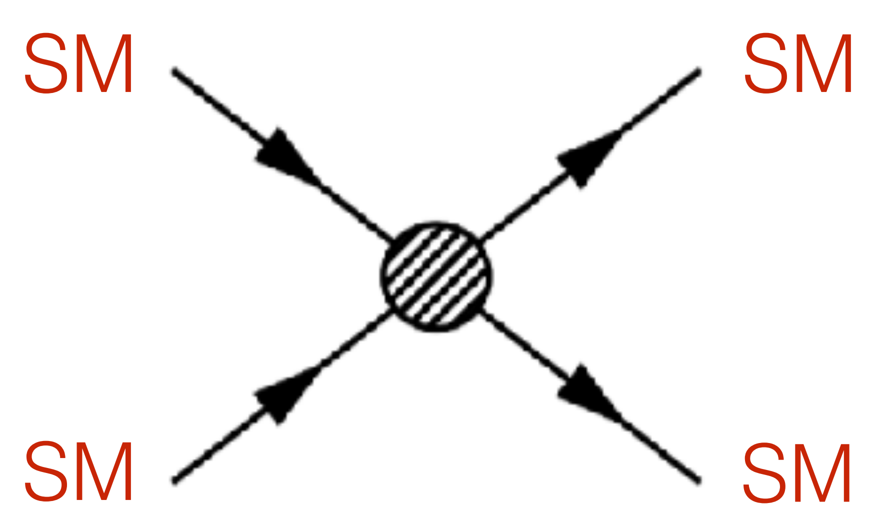
Temperature (of the Universe)

Producing WIMP Dark Matter

“Freeze-in”

● Dark Matter

● Standard Model



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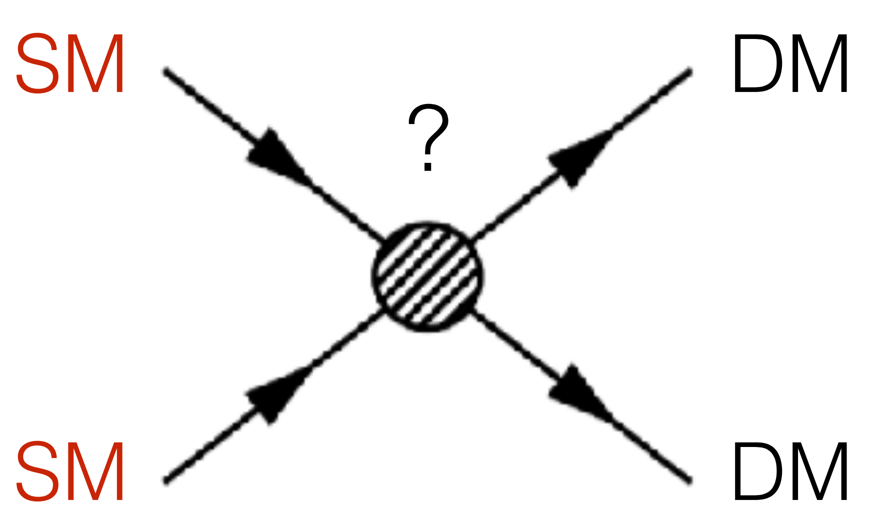

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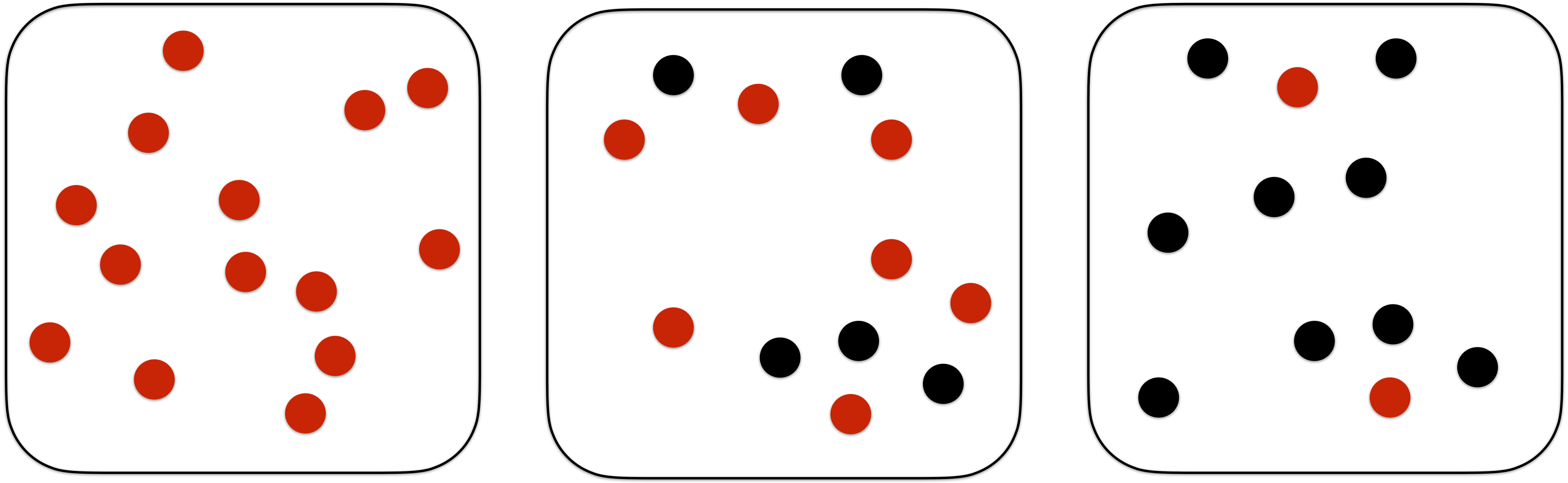


Time →

Size (of the Universe) →

← Temperature (of the Universe)

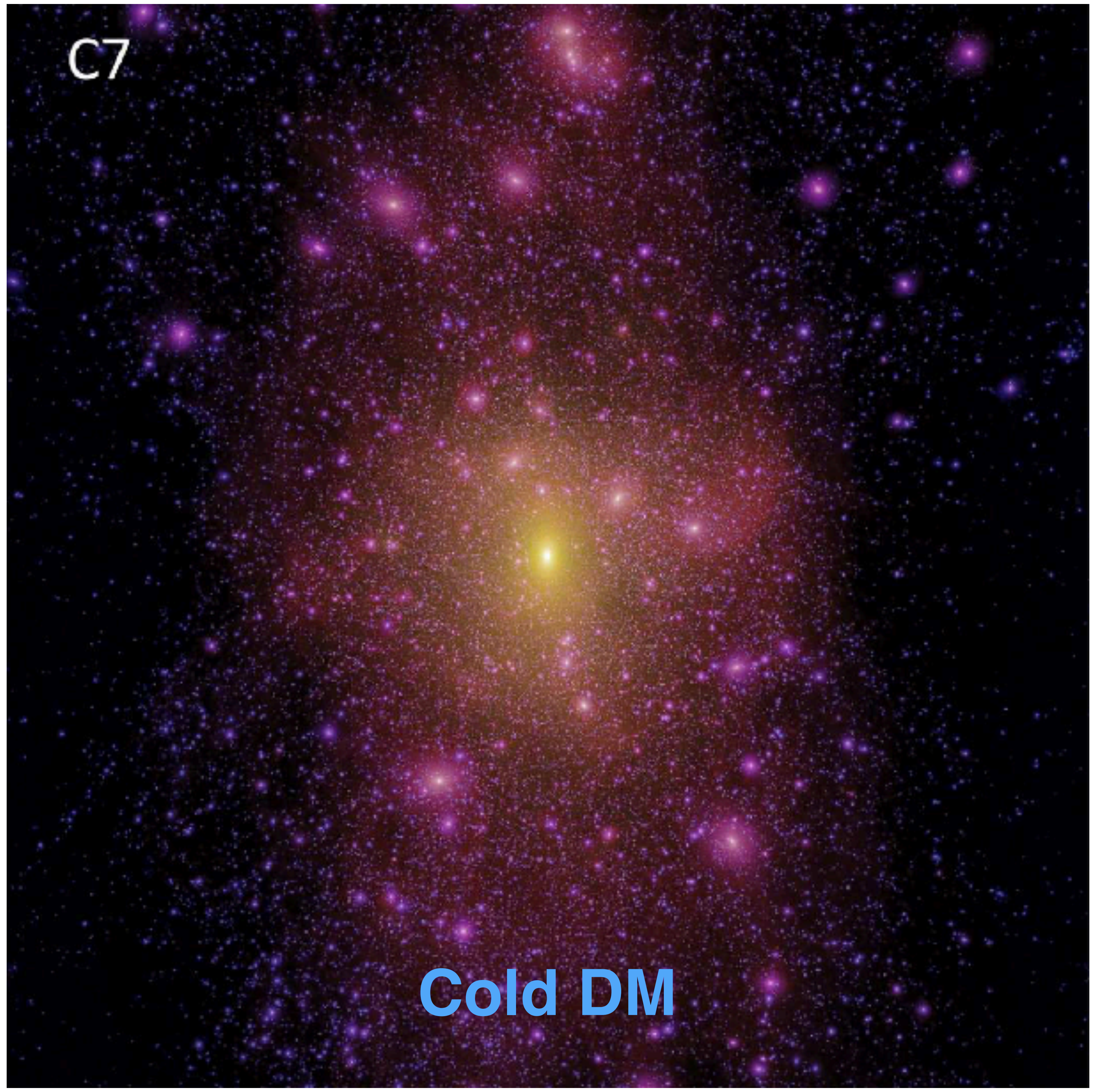
Cold vs Hot Dark Matter

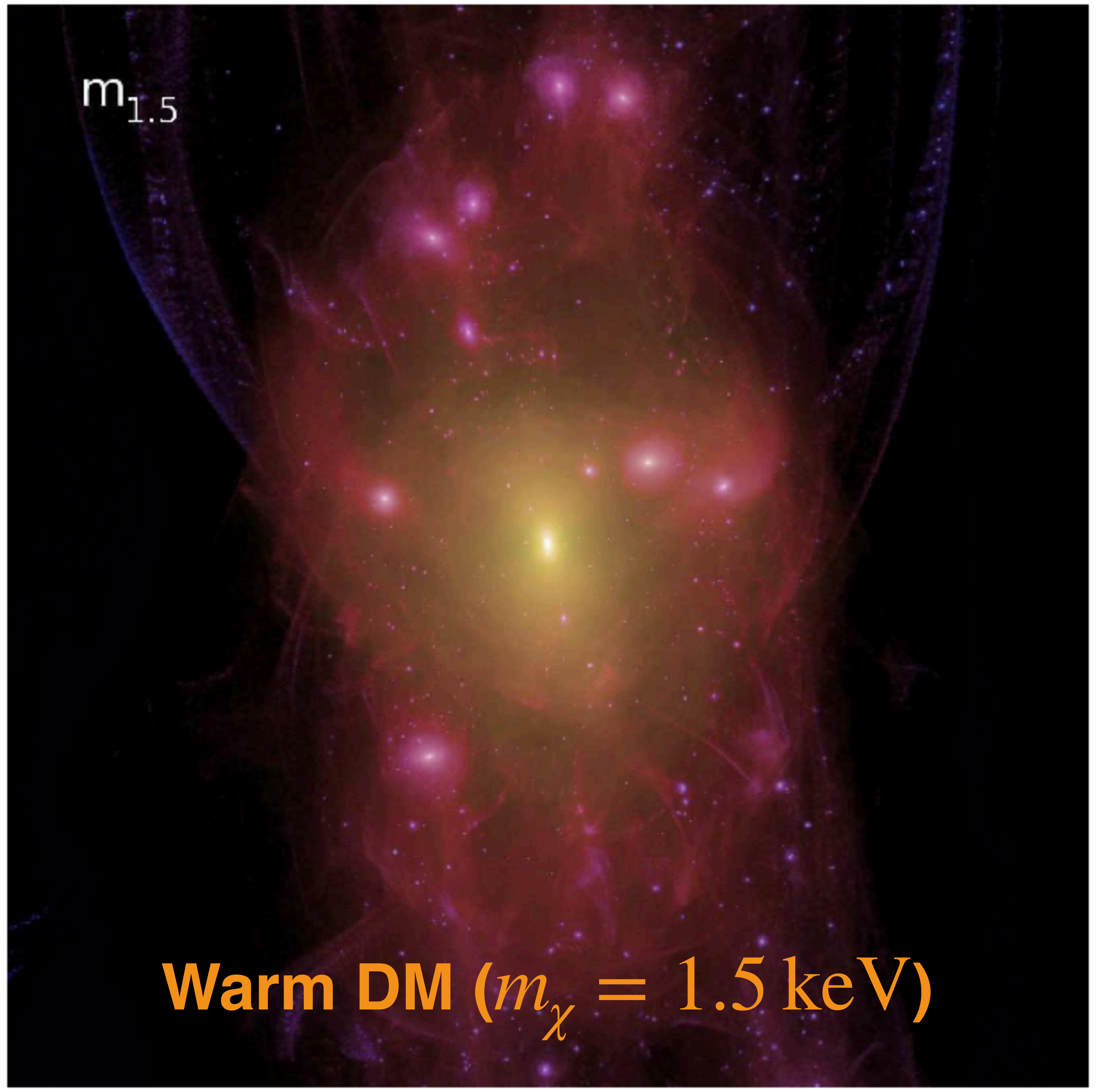
[1308.1399]

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!

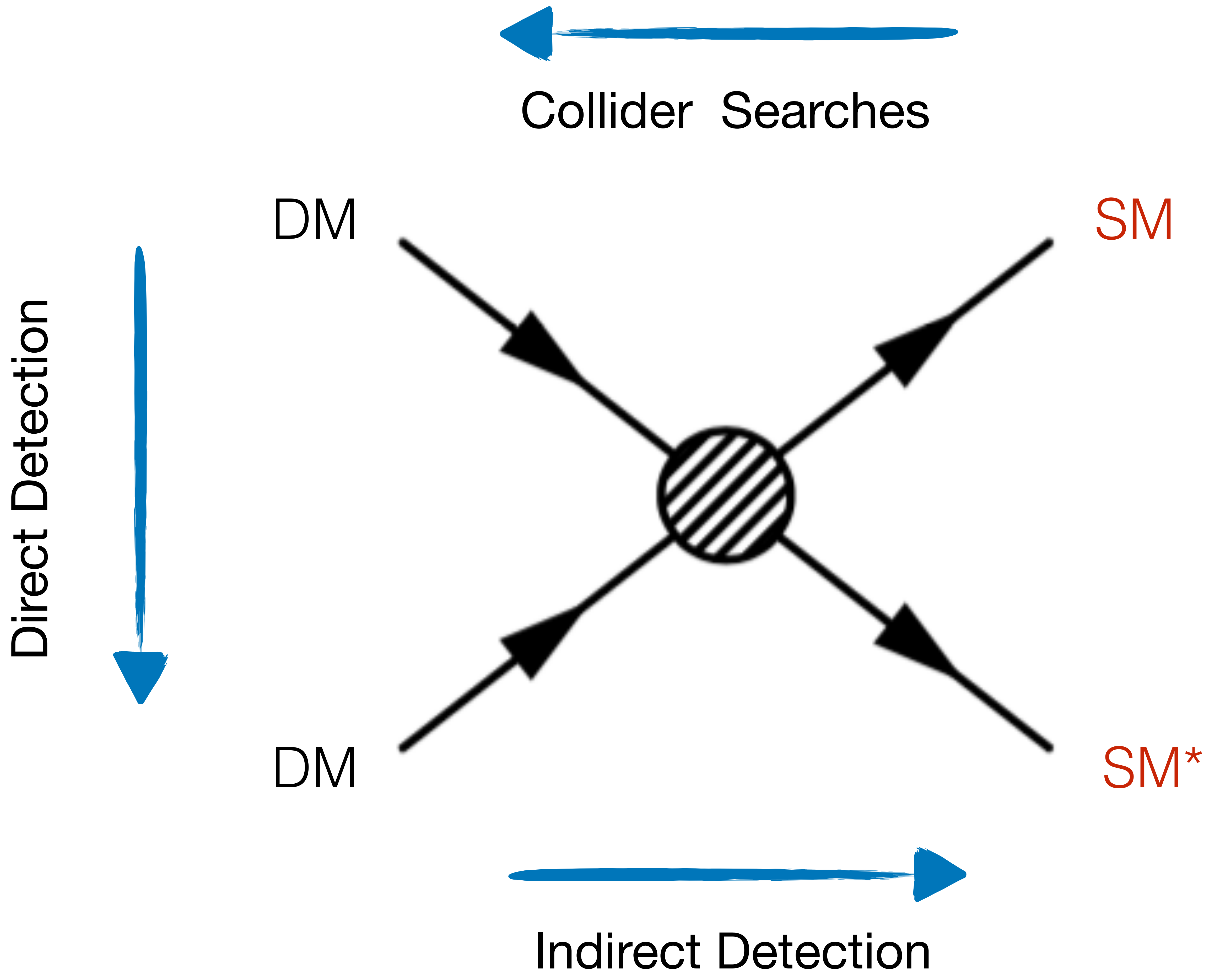
In order to explain the observed structure in the Universe, Dark Matter must freeze-out when non-relativistic i.e. it must be **Cold Dark Matter**.

Dark Matter which is produced semi-relativistically may also be viable + testable: **Warm Dark Matter**.



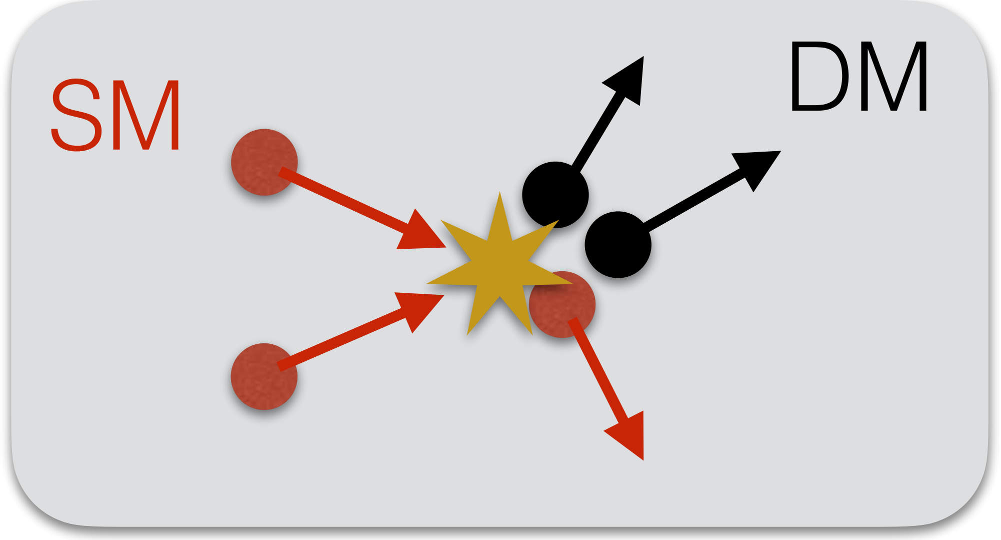


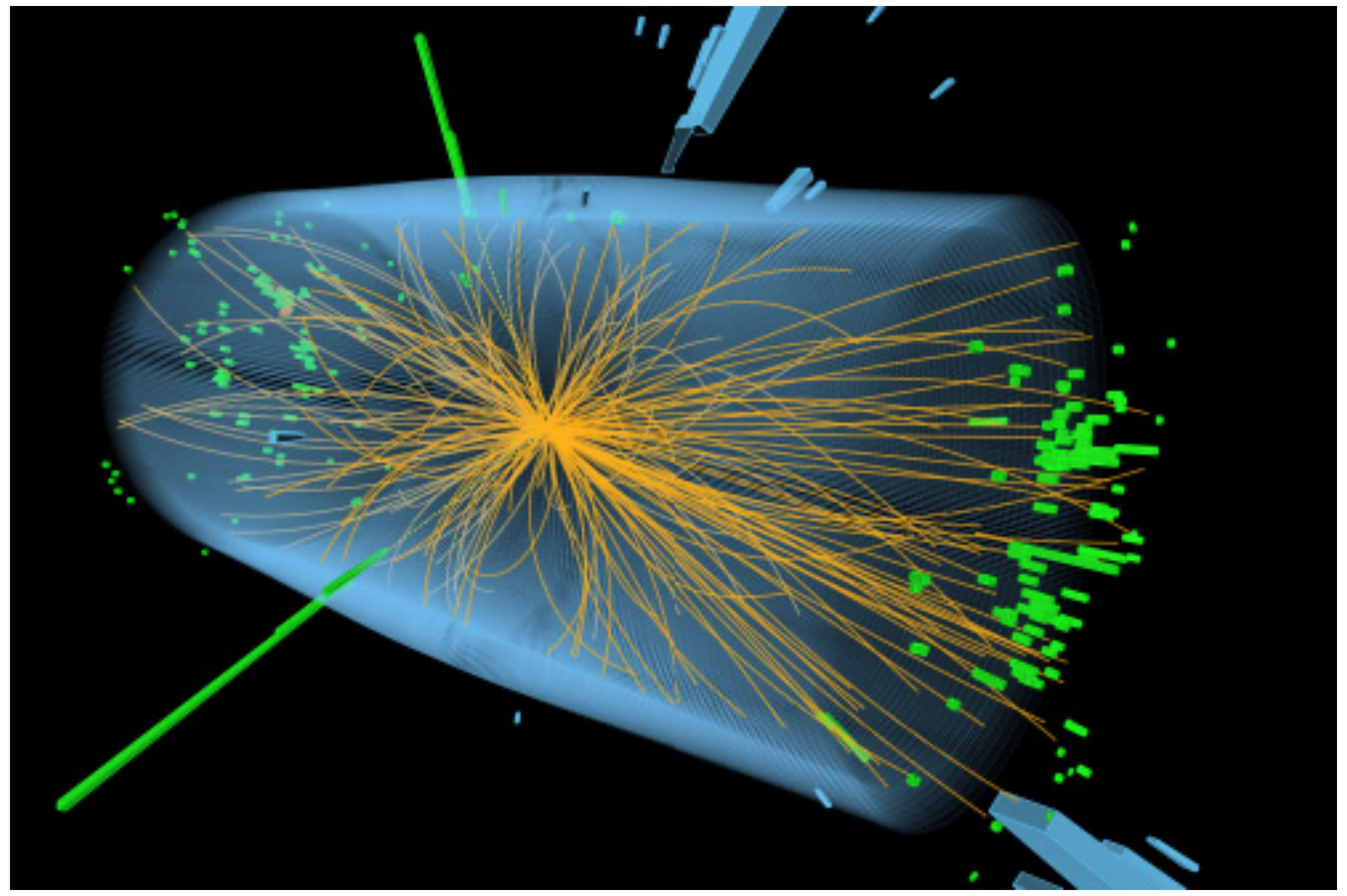
Detection of WIMPs



*Standard Model
(quarks, electrons, photons etc)

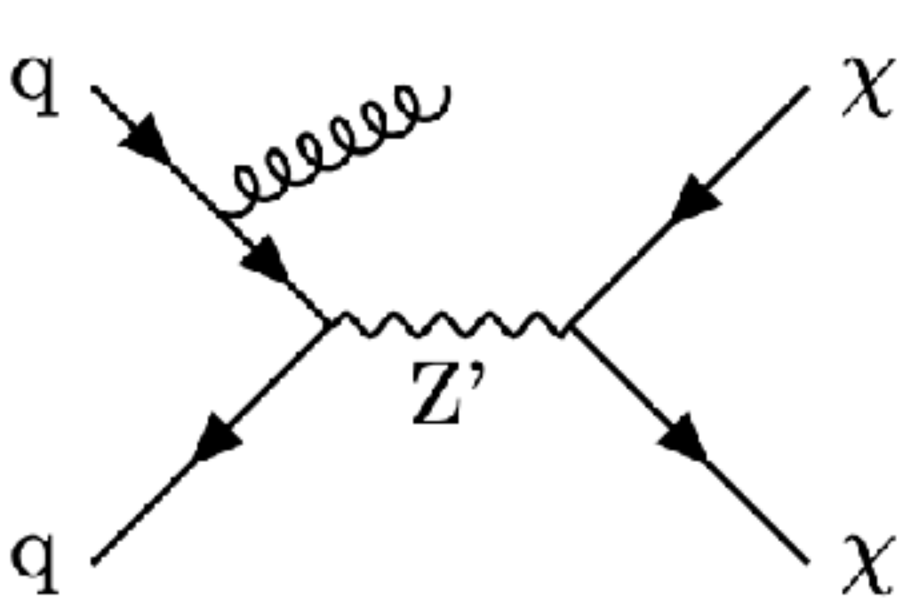
Collider Searches for WIMPs



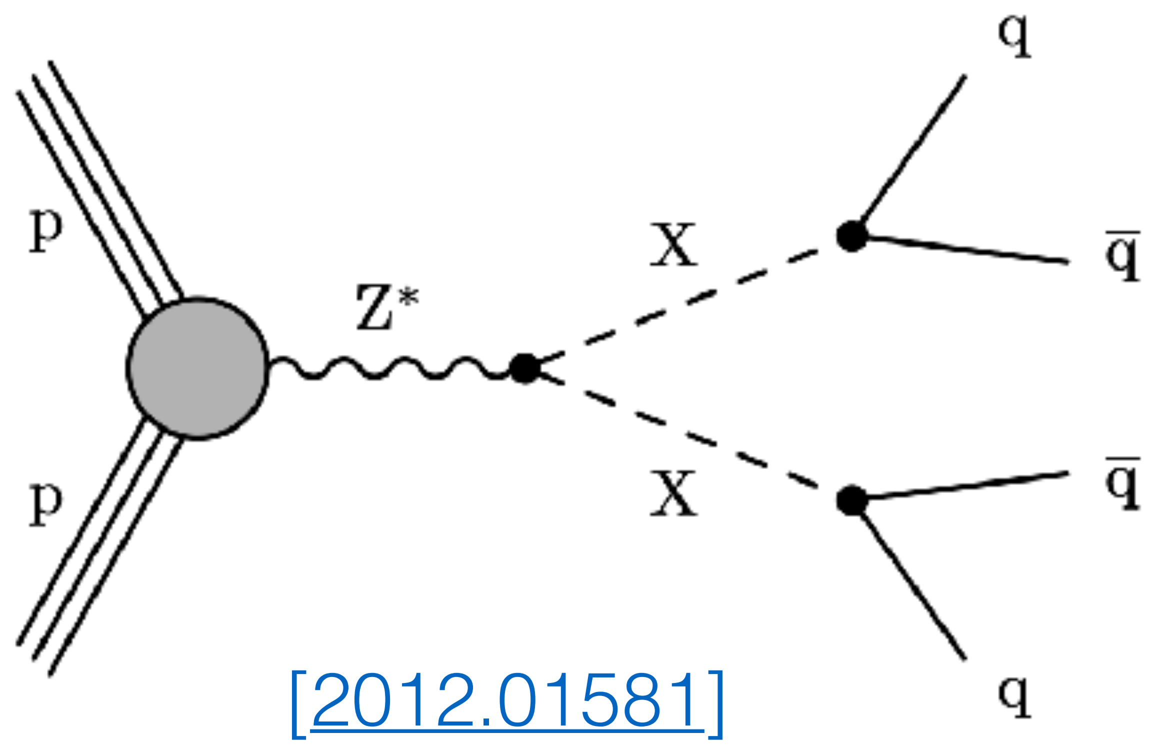


[Credit: CMS/CERN]

A trend towards more complicated signatures:

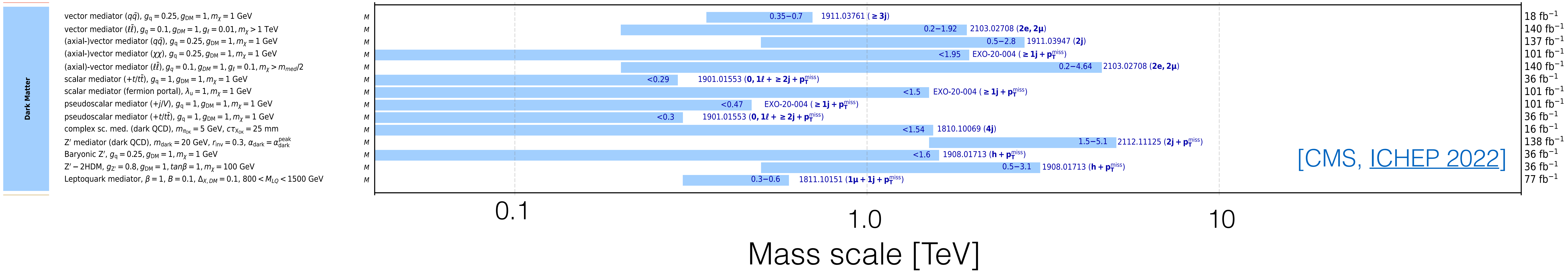


[2107.13021]



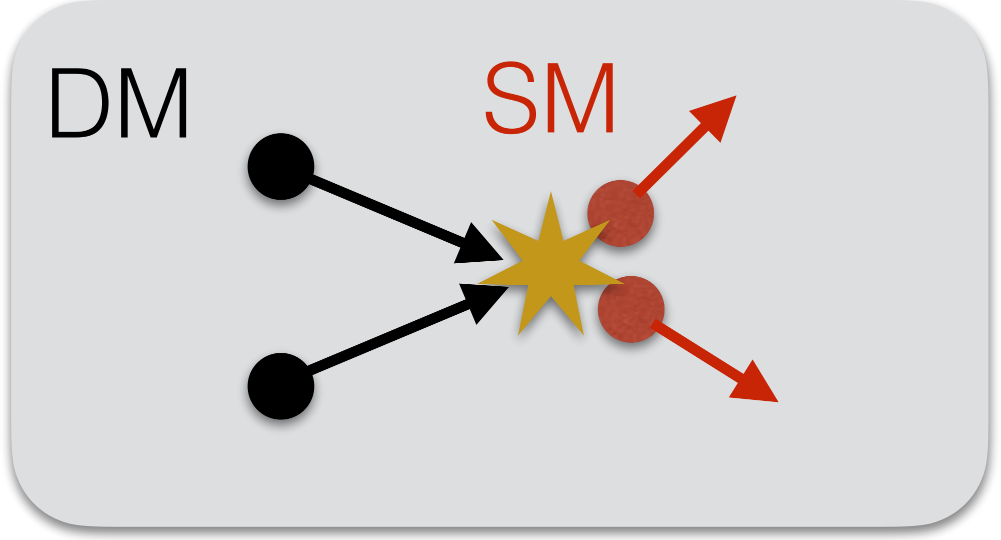
[2012.01581]

Summary of CMS constraints on the mass scale of new mediator particles coupling to DM:

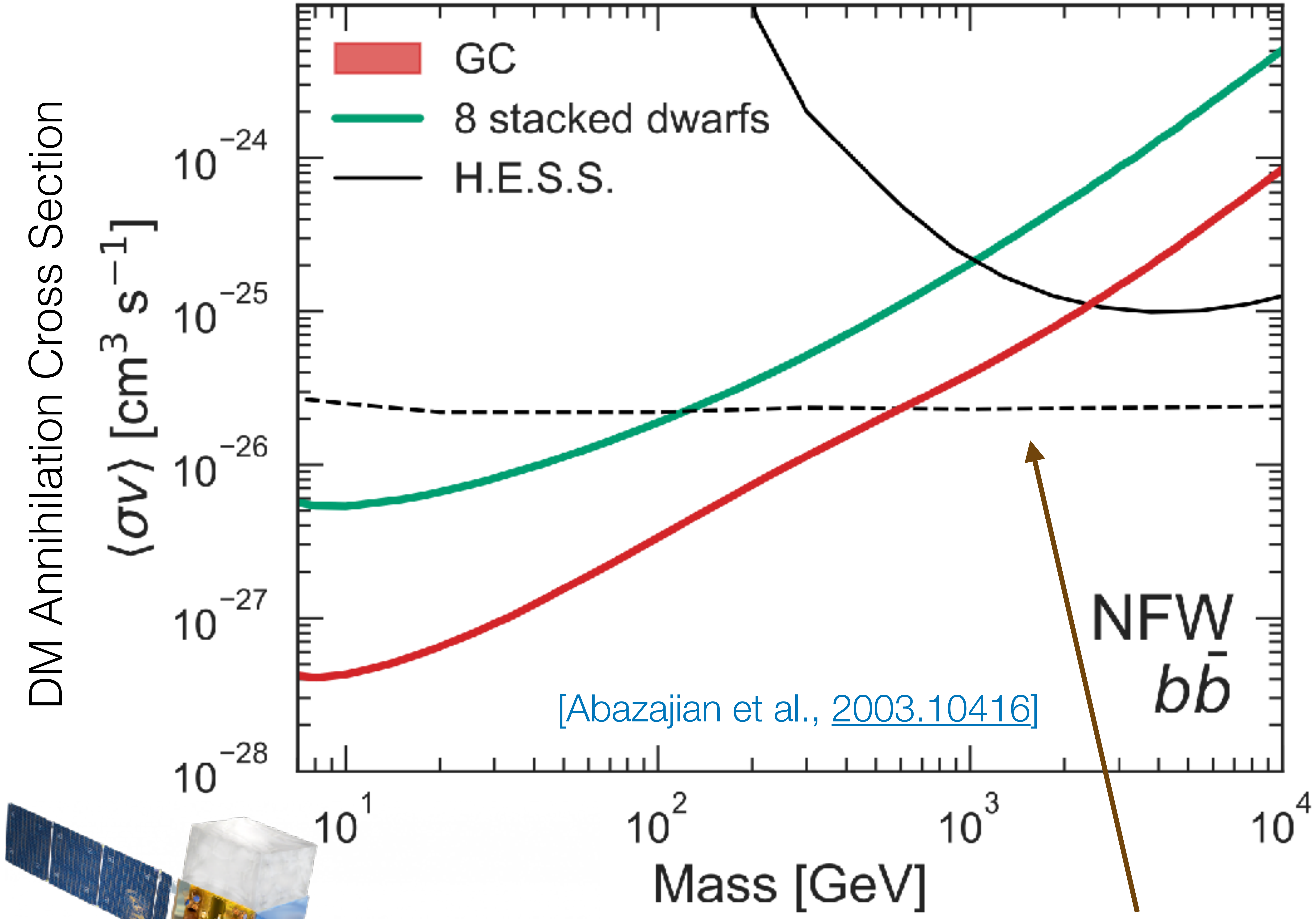


LHC Run-3 (2022 - 2025) and High Luminosity LHC (2029+) will bring more data, but extending to a wider range of masses is challenging…

Indirect Detection of WIMPs

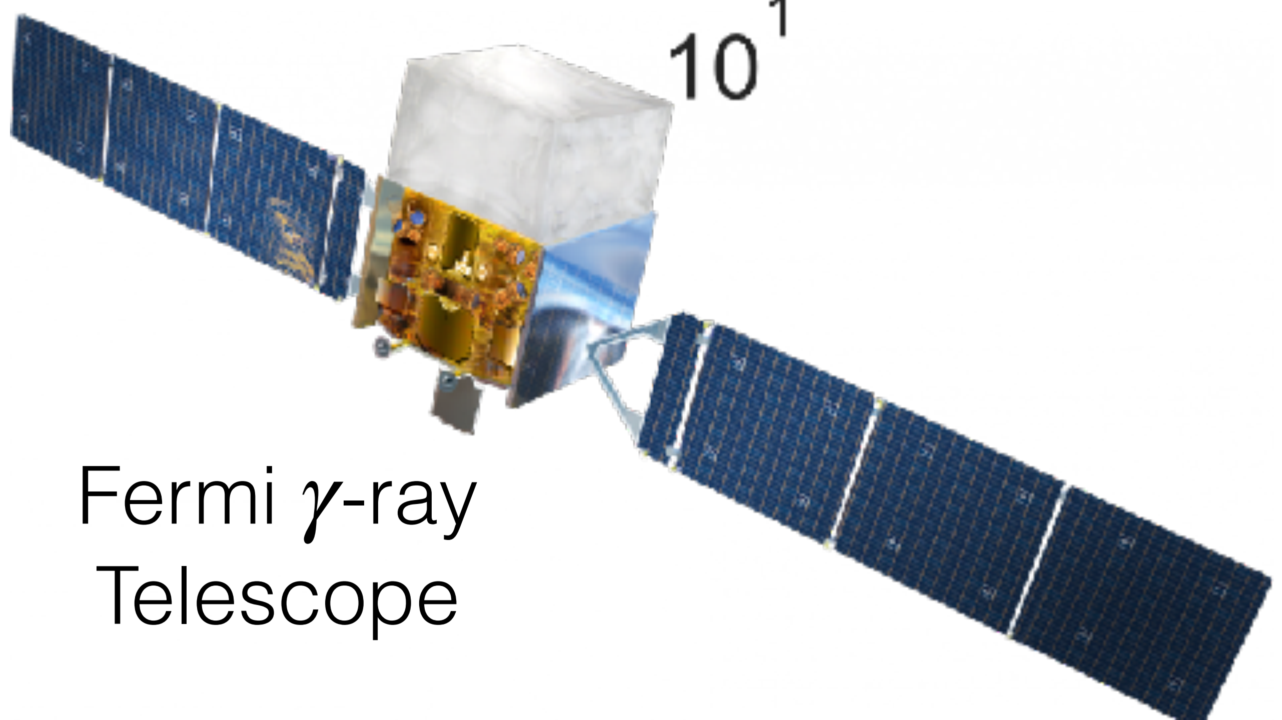


Look for signals of Dark Matter annihilation in regions of large DM density!

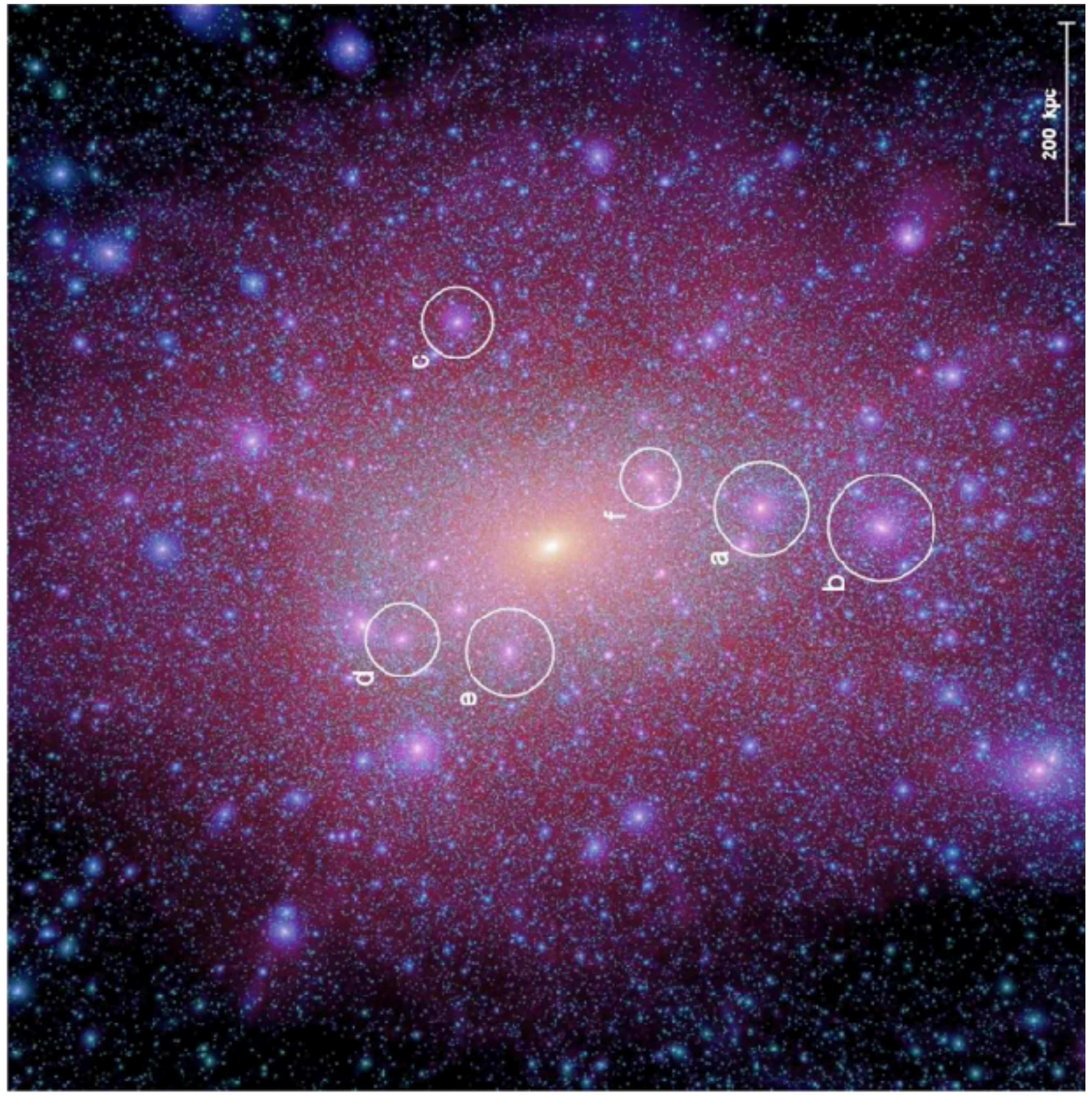


[Abazajian et al., 2003.10416]

Cross section required to produce the correct abundance of DM in the early Universe

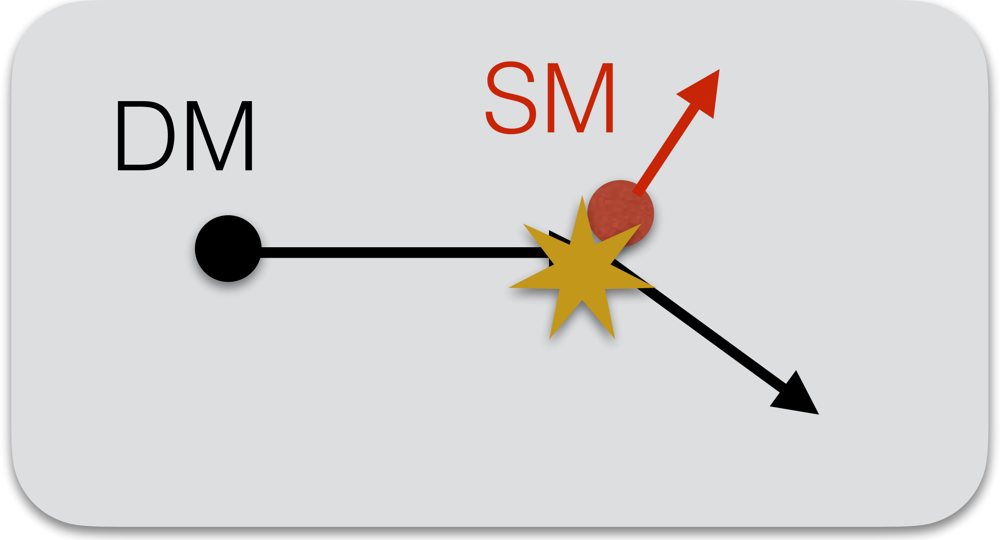


Fermi γ-ray Telescope

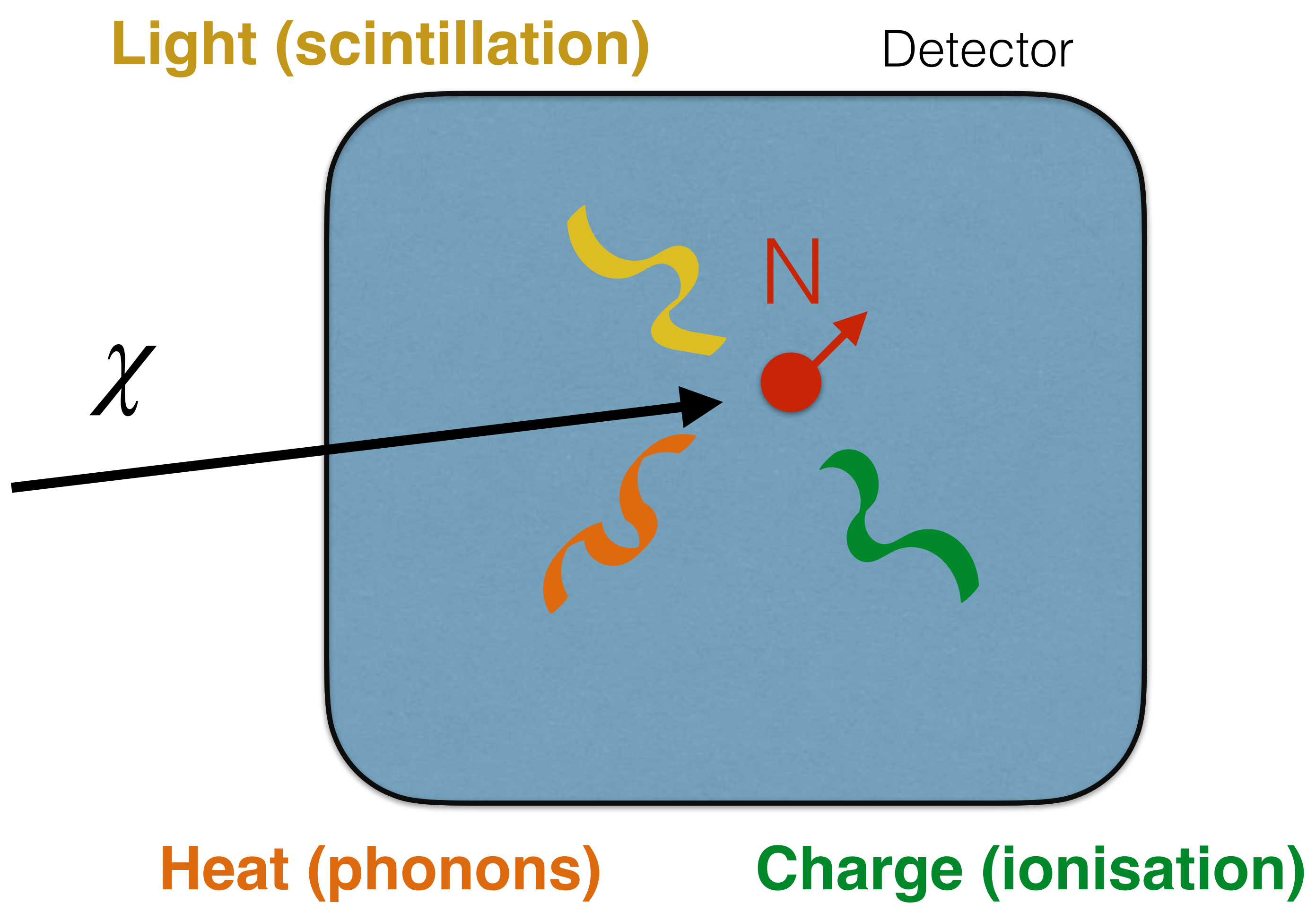


[Aquarius - Springel et al., 0809.0898]

Direct detection of WIMPs on Earth

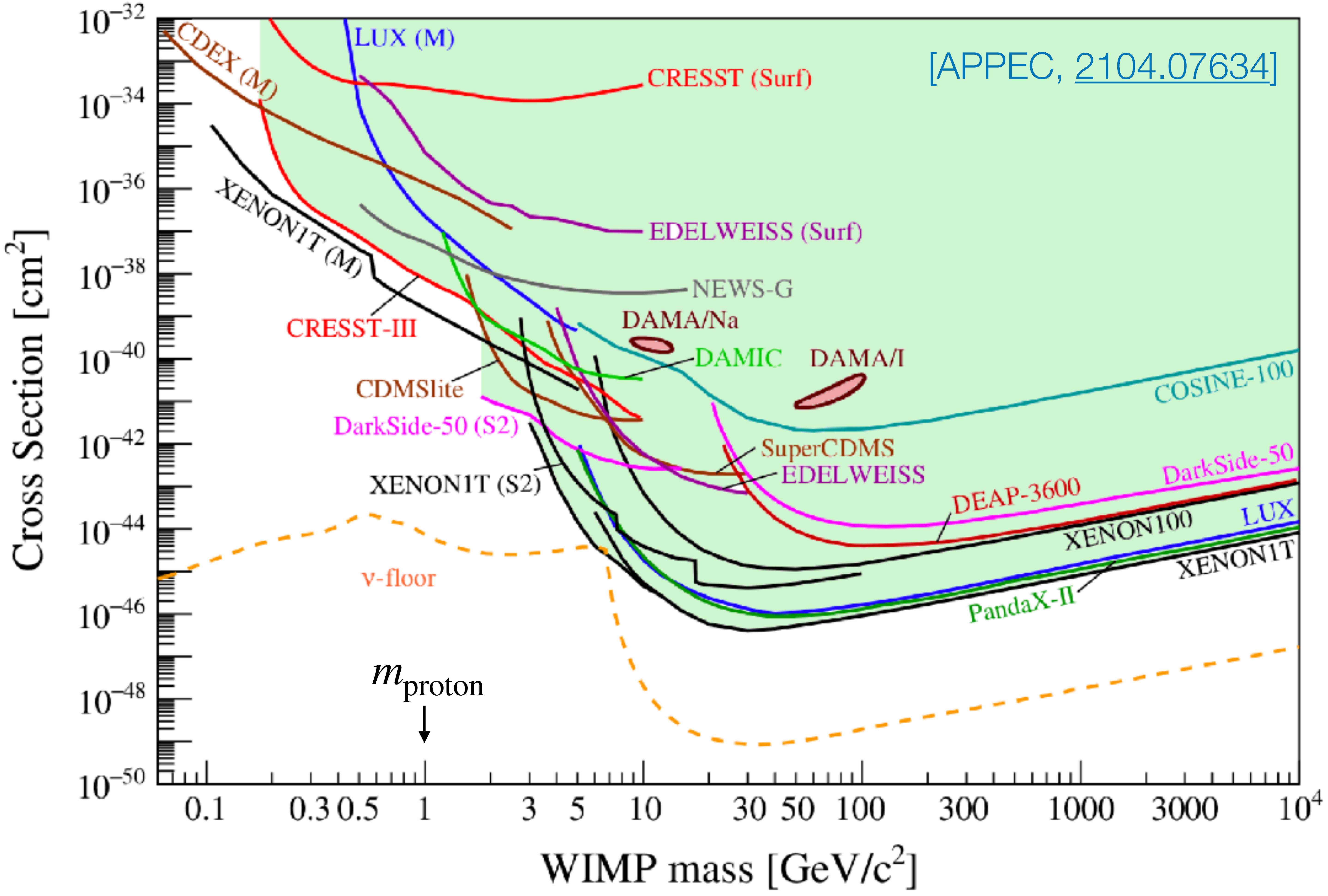


For WIMPs with GeV-scale masses, expect detectable nuclear recoils of energy O(keV)

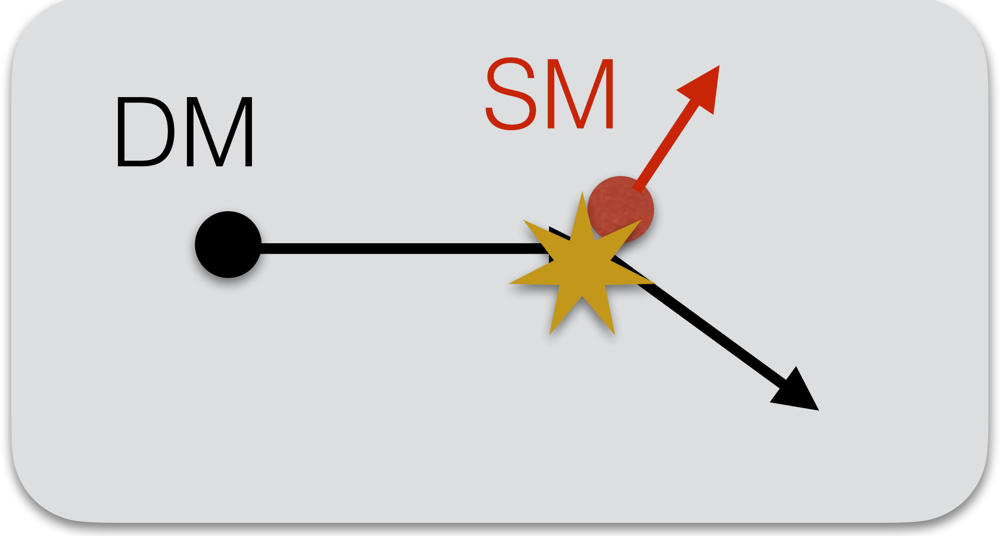


For sensible models, expect signal rates on the order of <1 event per kg per keV per day

No convincing signal yet!

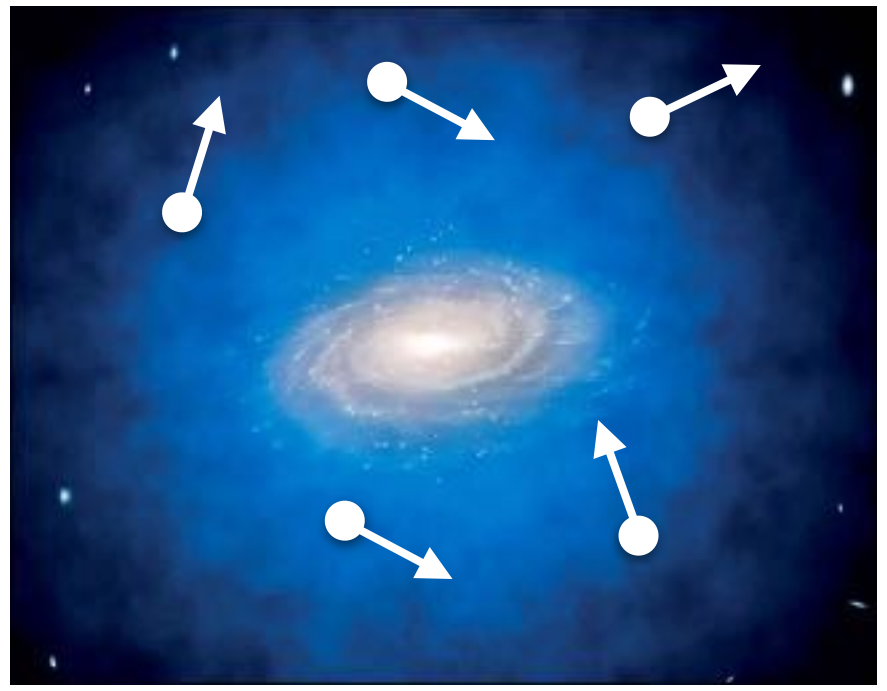


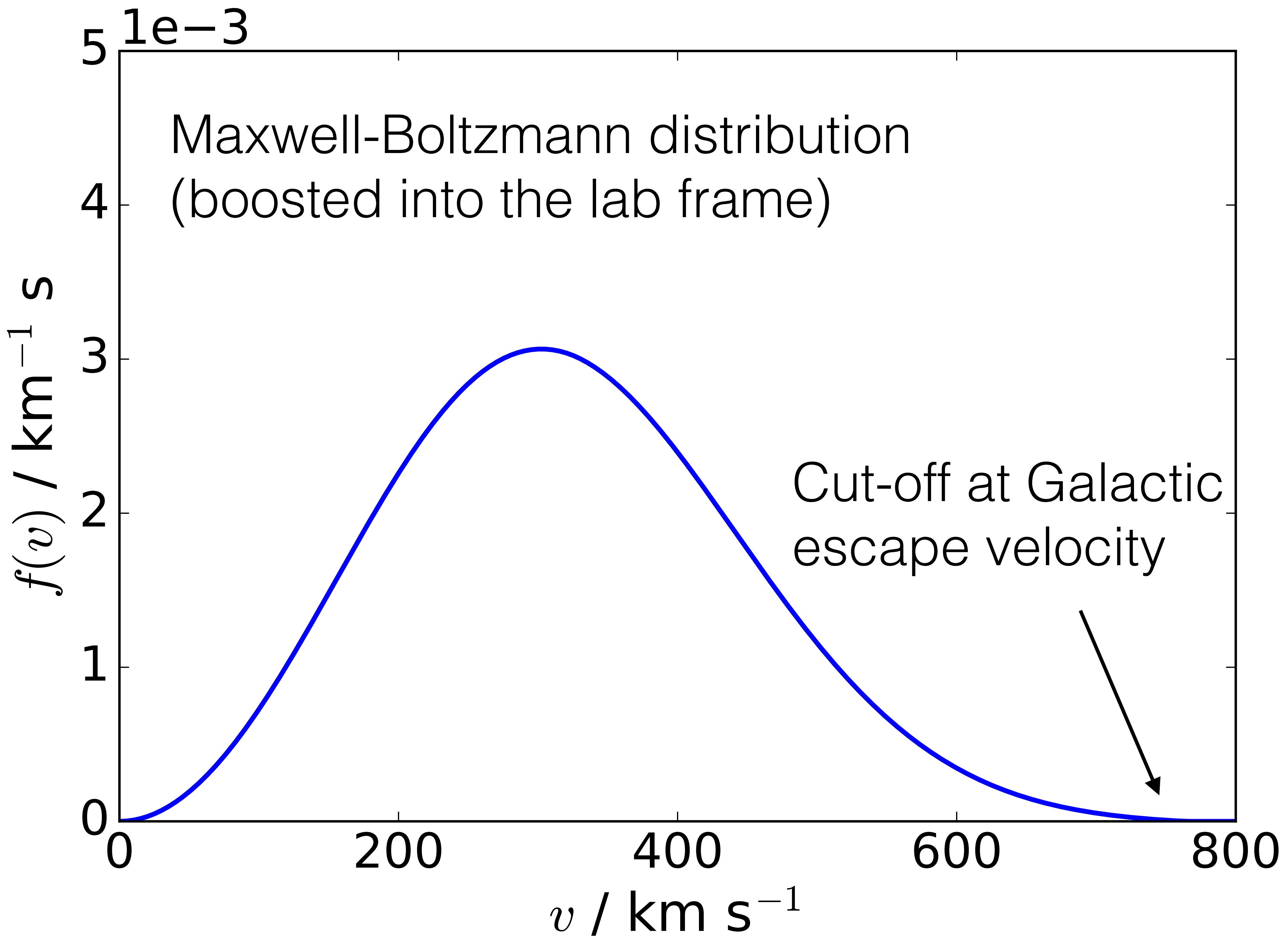
Low-mass WIMP Challenge

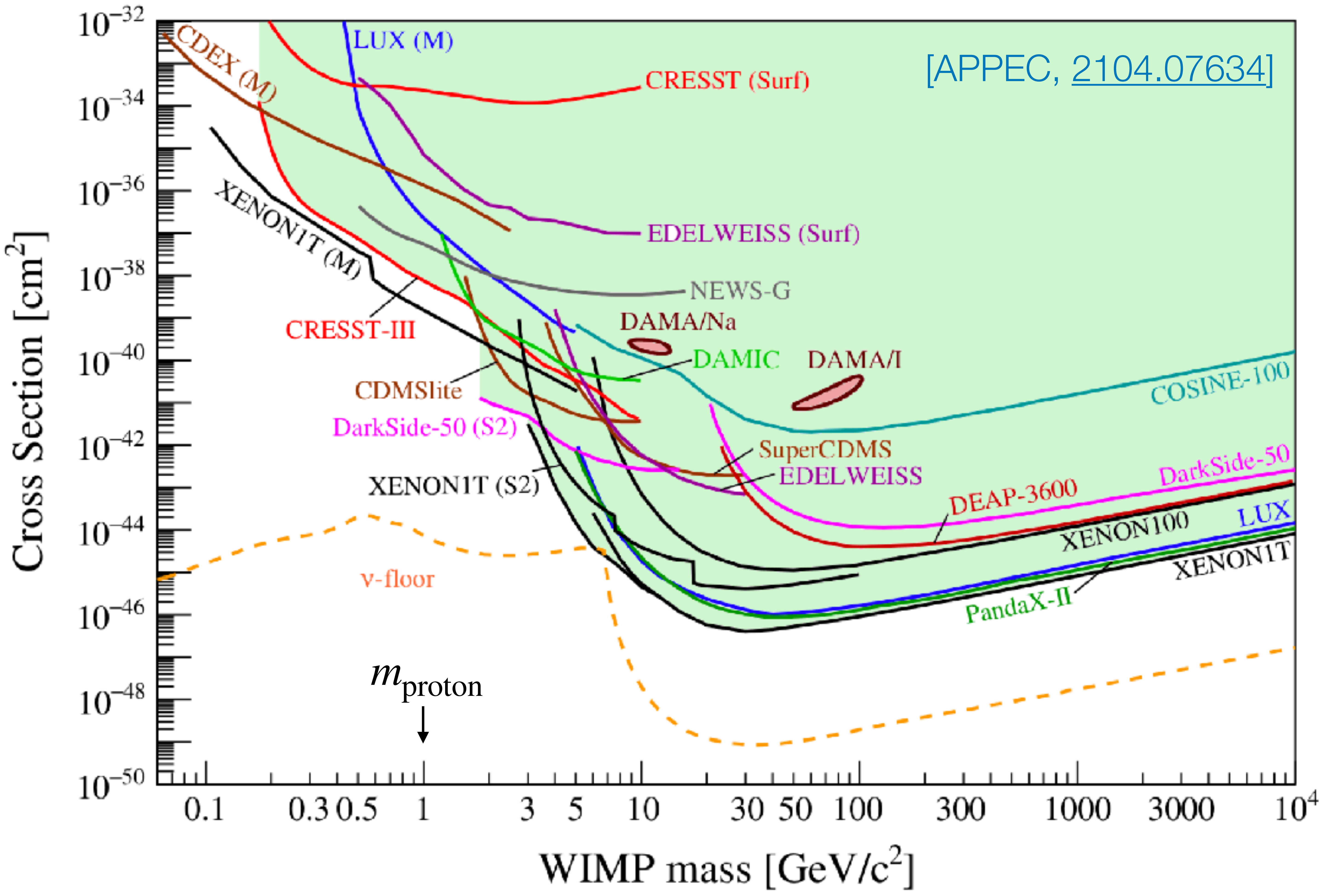


Low-mass WIMPs do not typically have enough kinetic energy to excite detectable nuclear recoils!

$$\langle v_\chi \rangle \sim 300\,\mathrm{km/s}$$
$$\sim 10^{-3}\,c$$

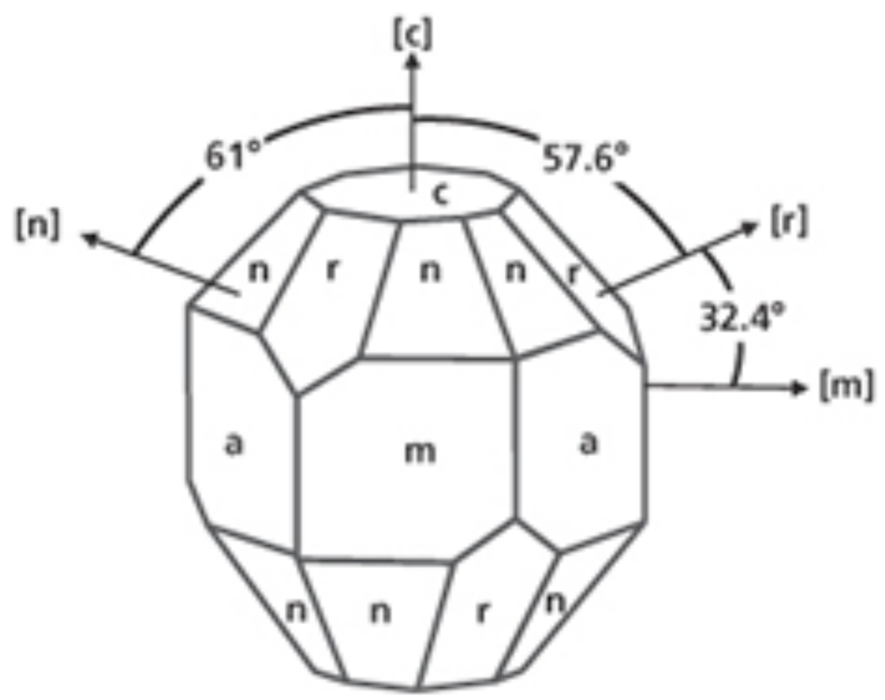






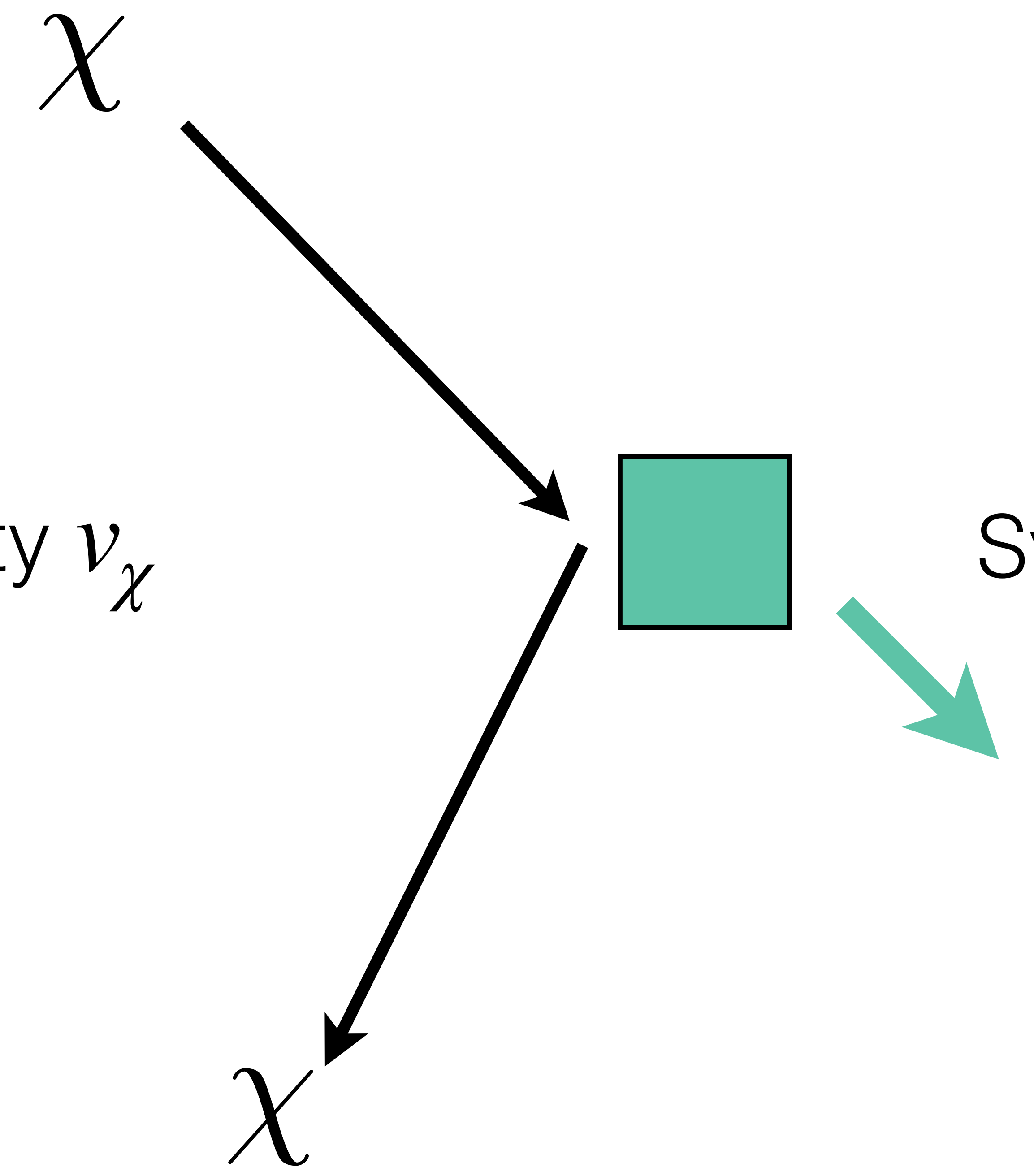
New Directions for Dark Matter

Low-threshold phonon detectors



Black Holes and Gravitational Waves

Direct Detection of Dark Matter



DM with mass m_χ and initial velocity v_χ scatters with a system

System carries away an energy ω and a momentum q

From conservation of energy and momentum, the maximum amount of energy that can be transferred is

$$\omega_{\max} = qv_\chi - \frac{q^2}{2m_\chi}$$

Up to a maximum momentum transfer of $q_{\max} = 2m_\chi v_\chi$

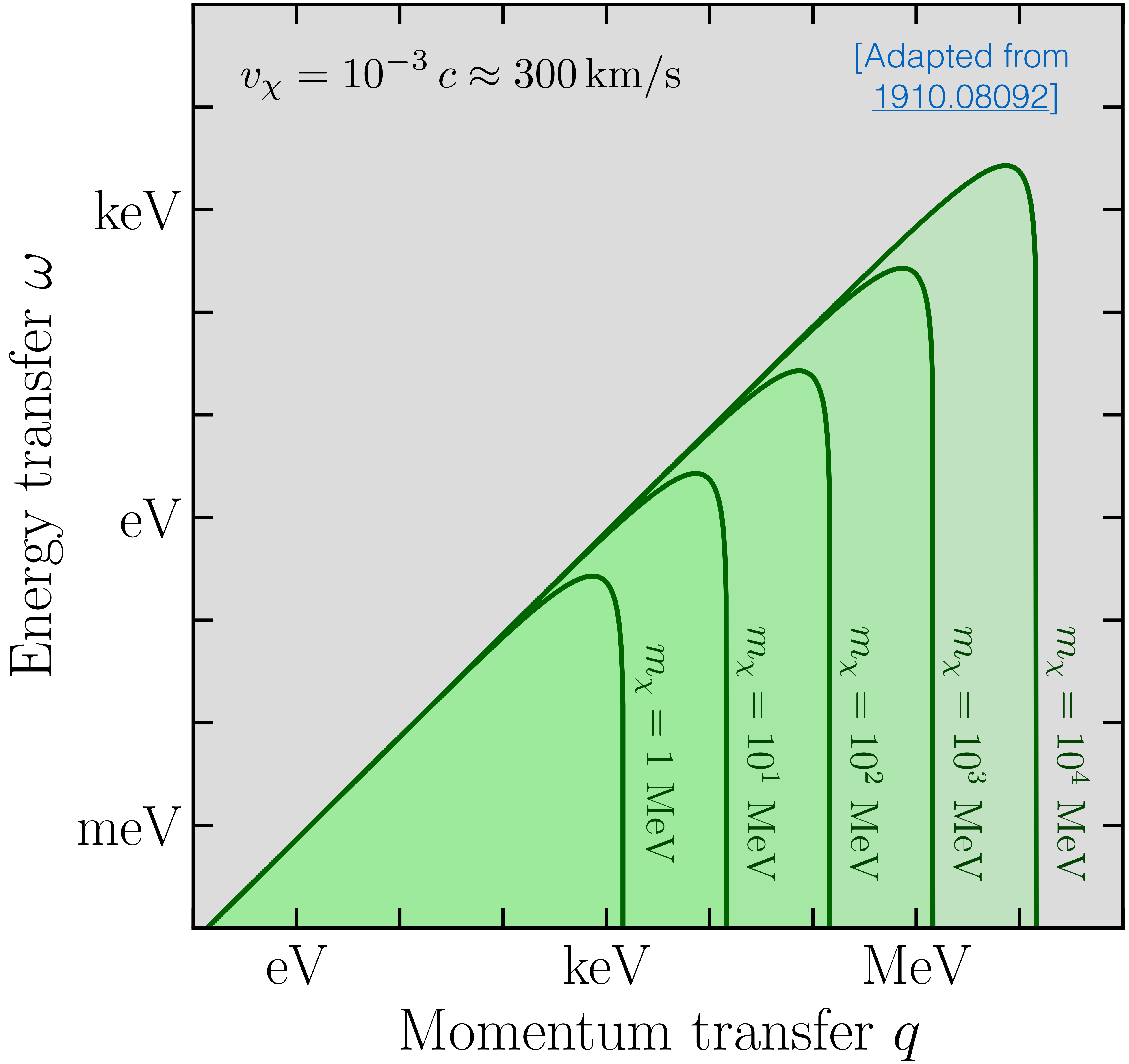
Scattering Kinematics

Allowed range of (ω, q) set by kinematics (green regions):

$$\omega \leq q v_\chi - q^2/2m_\chi$$

Consider:

- **Nuclear recoils** - can probe energies down to eV, but realistically can only measure recoil energies down to ~keV → $m_\chi \gtrsim \mathrm{GeV}$
- **Electron ionisation** - possible for $\omega > \Delta \sim \mathrm{eV} \to m_\chi \gtrsim \mathrm{MeV}$
- **Phonon interactions** - possible for sufficiently small q, with $\omega_{\rm ph} \sim \mathcal{O}(10\mathrm{s})\,\mathrm{meV} \to m_\chi \sim \mathrm{keV} - 50\,\mathrm{MeV}$



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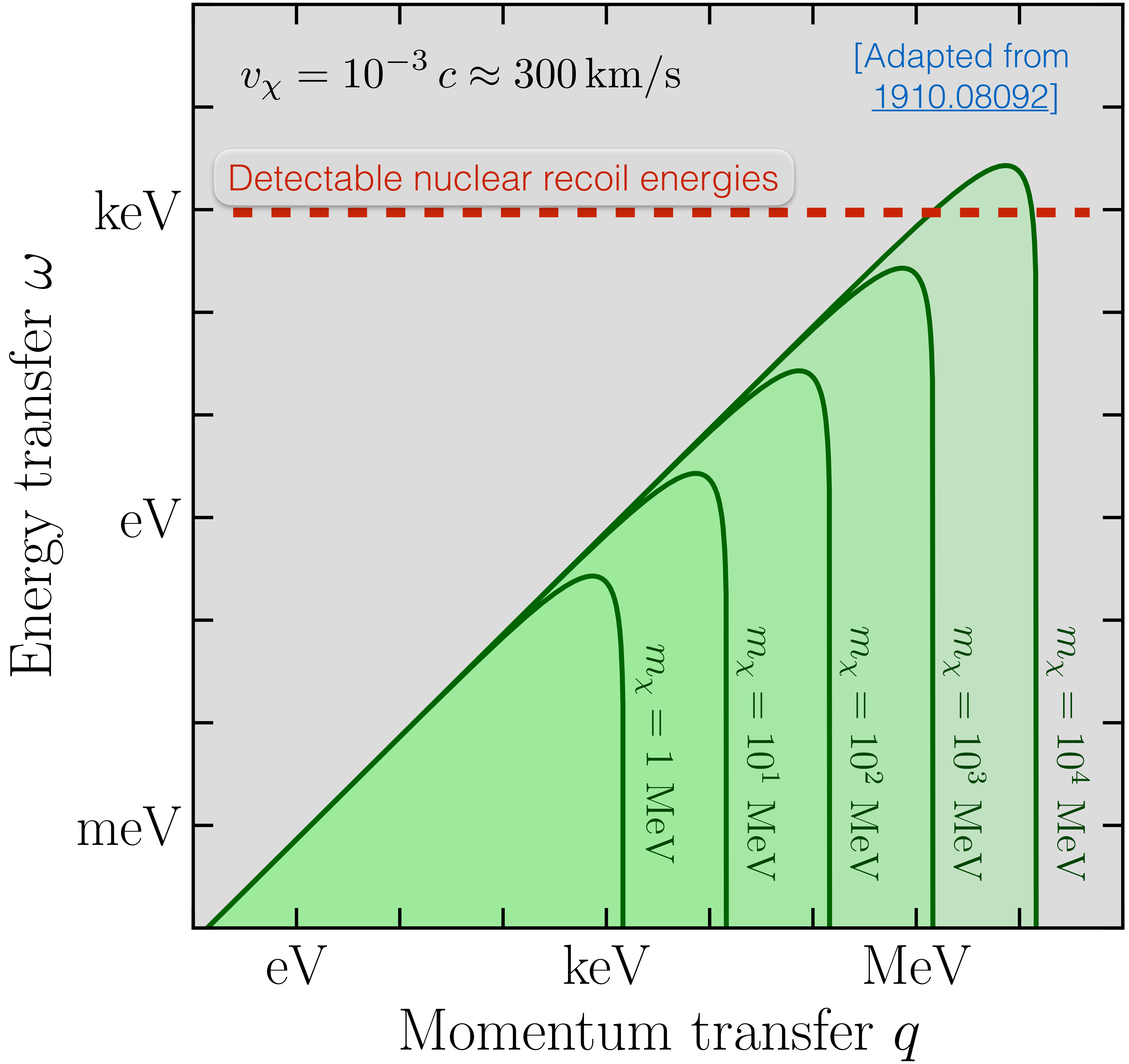

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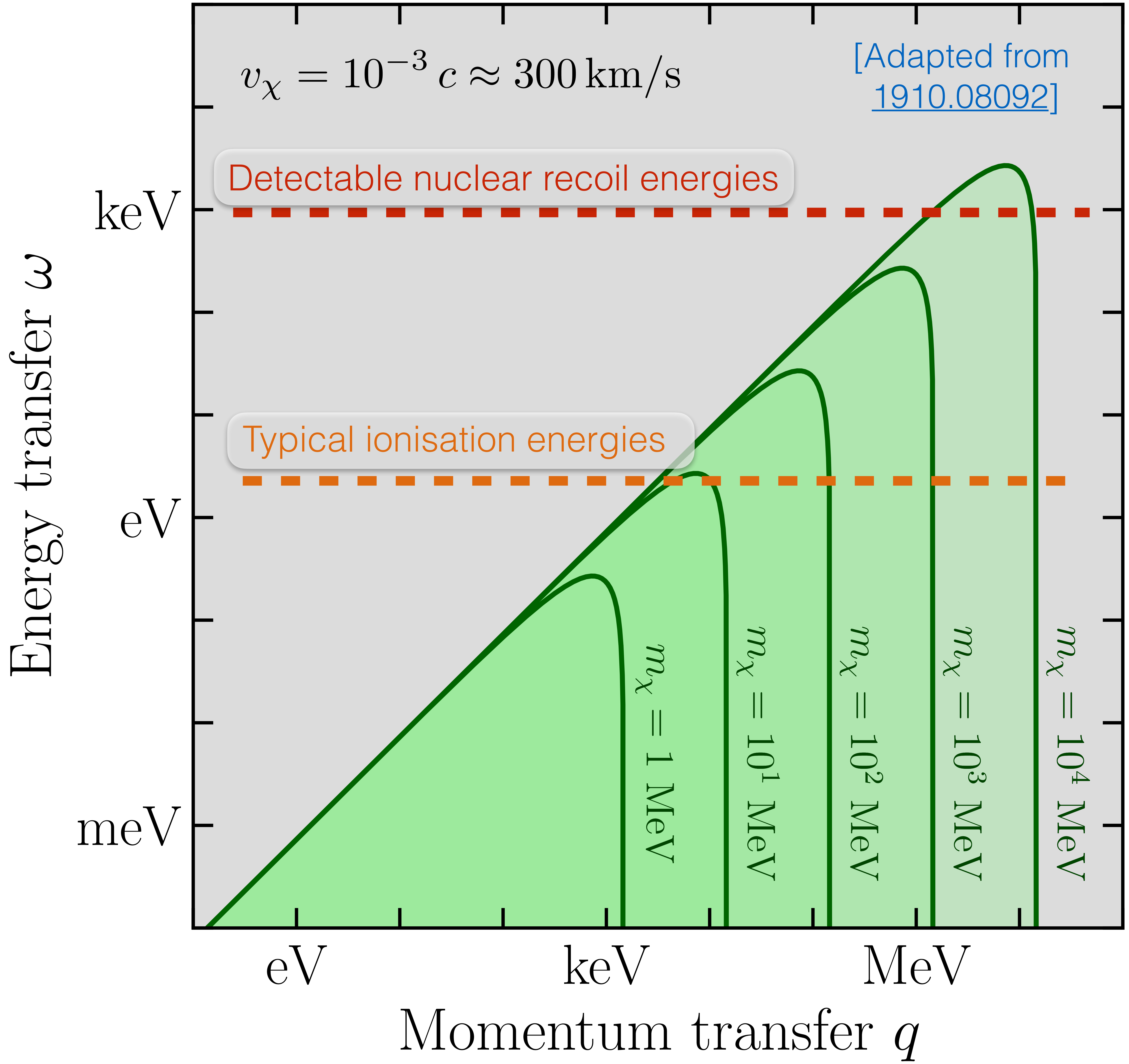
- **Phonon interactions** - possible for sufficiently small q, with $\omega_{\mathrm{ph}} \sim \mathcal{O}(10\mathrm{s})\,\mathrm{meV} \rightarrow m_\chi \sim \mathrm{keV} - 50\,\mathrm{MeV}$



Scattering Kinematics

Allowed range of (ω, q) set by kinematics (green regions):

$$\omega \leq q v_\chi - q^2/2m_\chi$$

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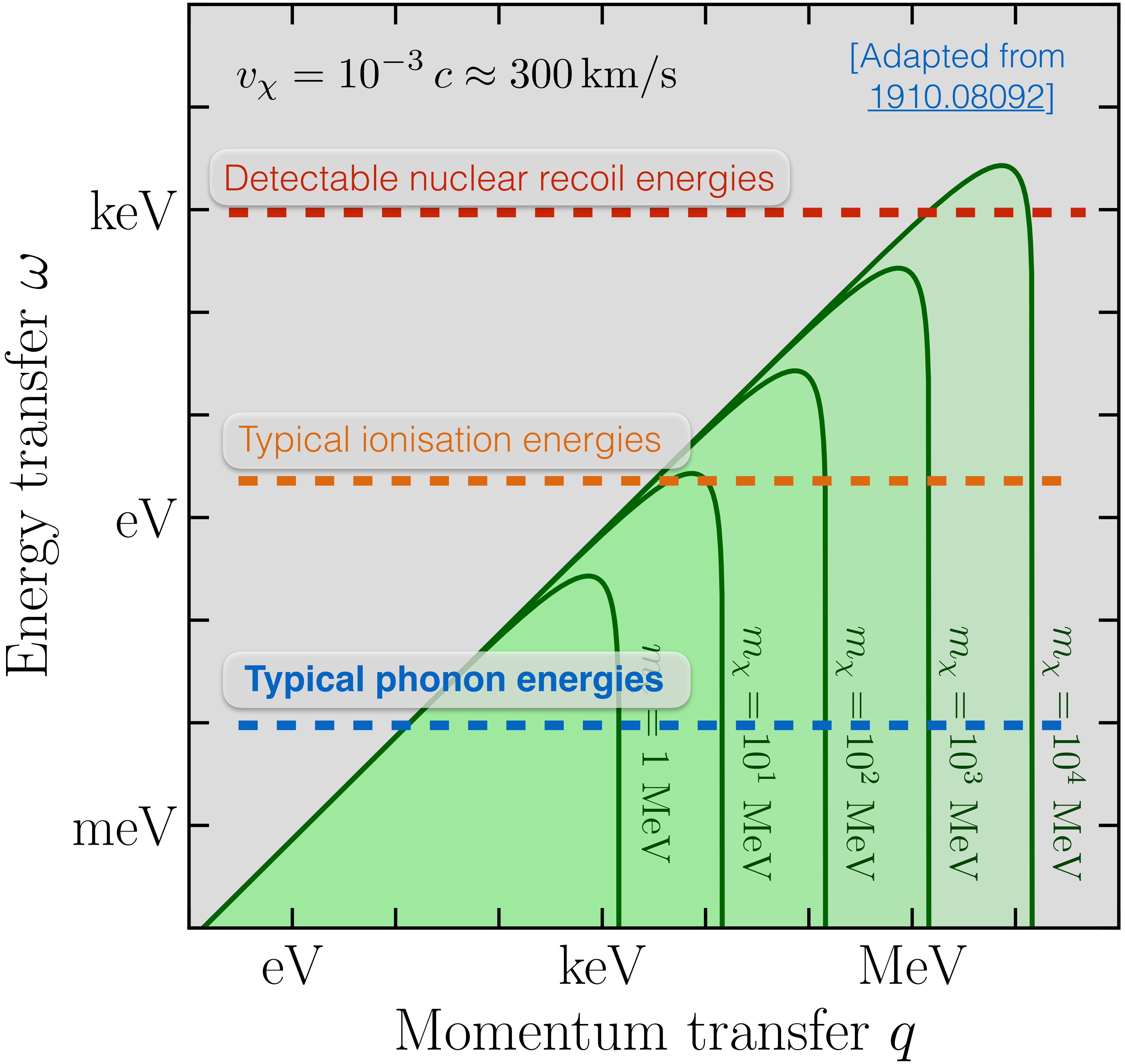

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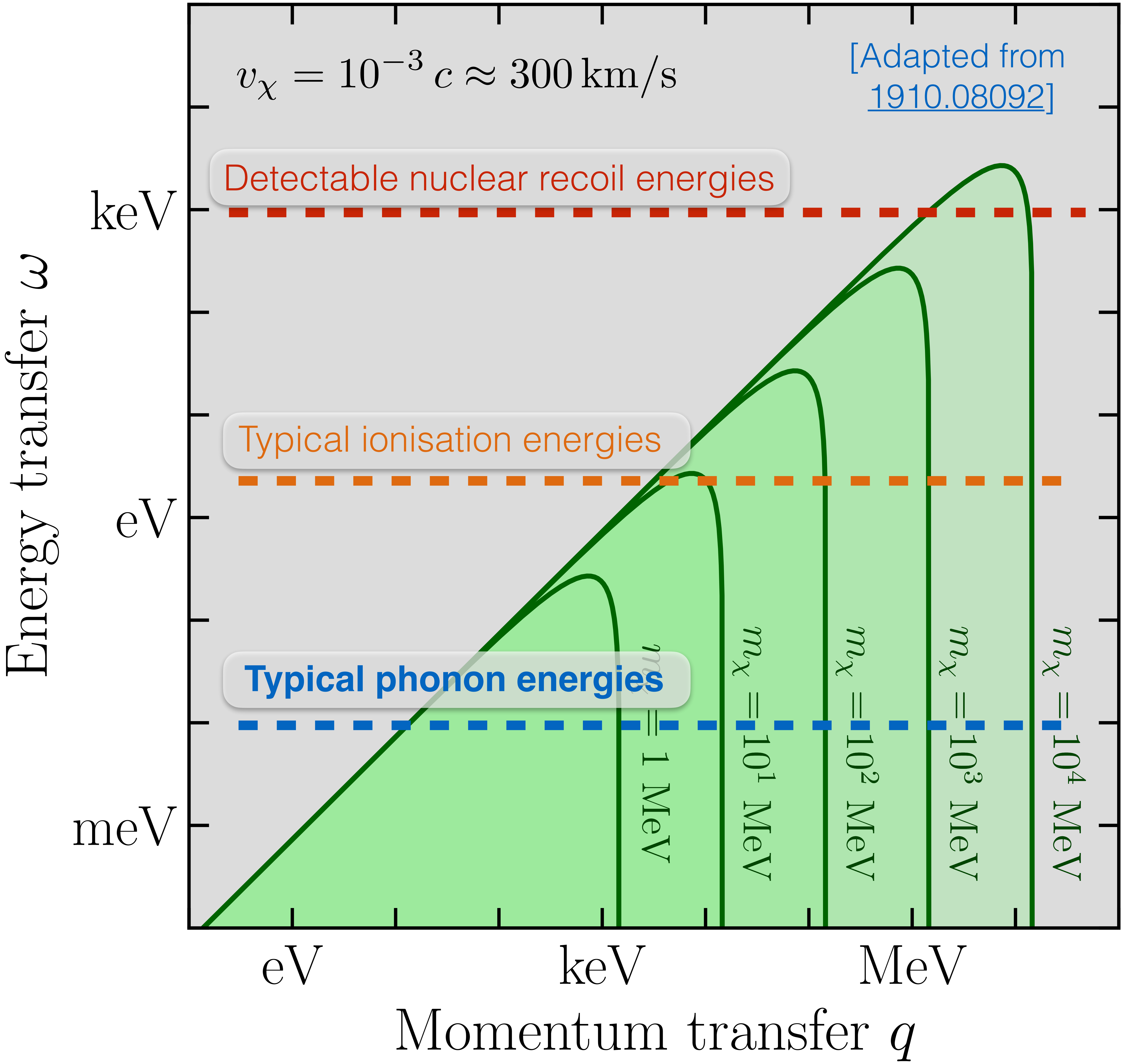
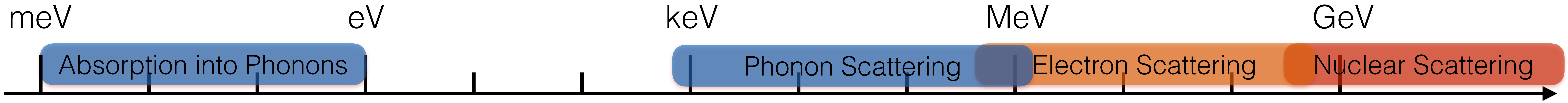
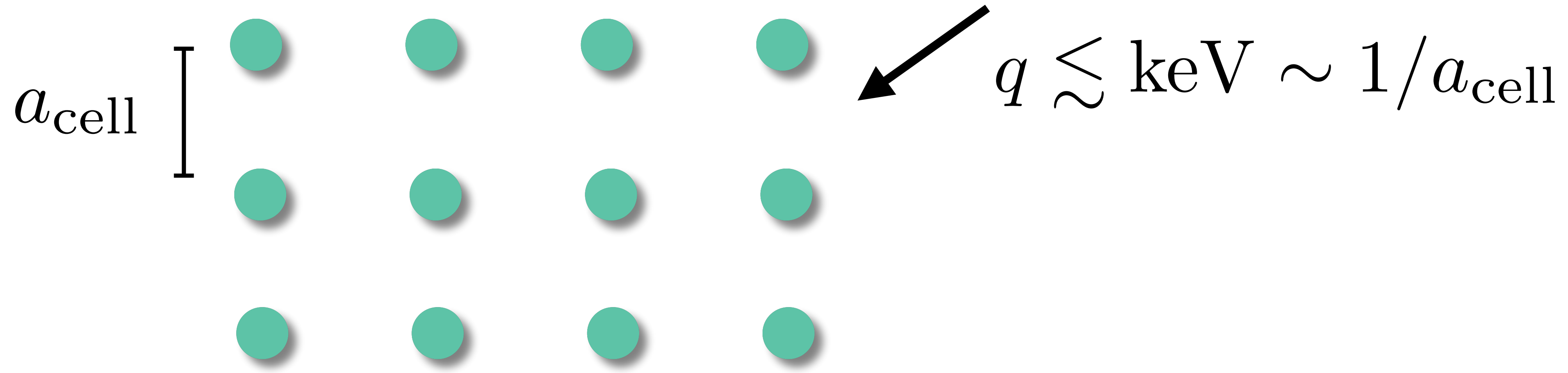


DM mass ranges:

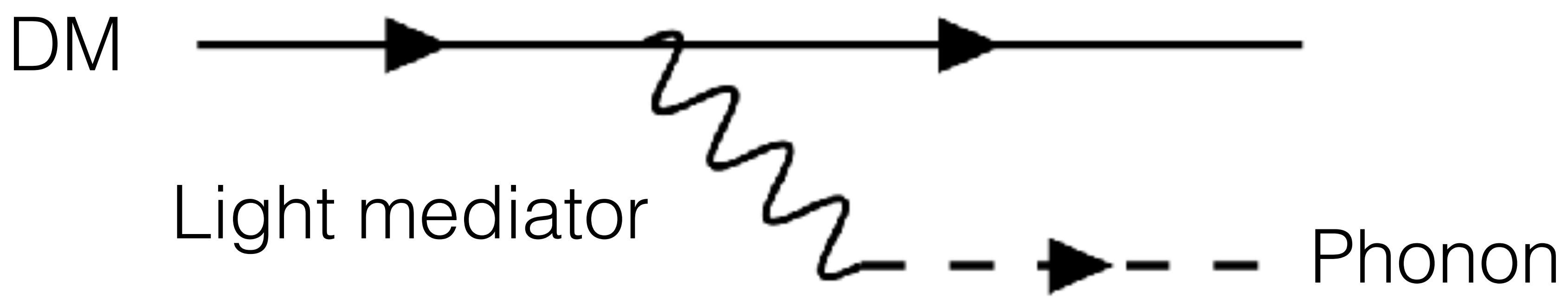


DM-Phonon Scattering



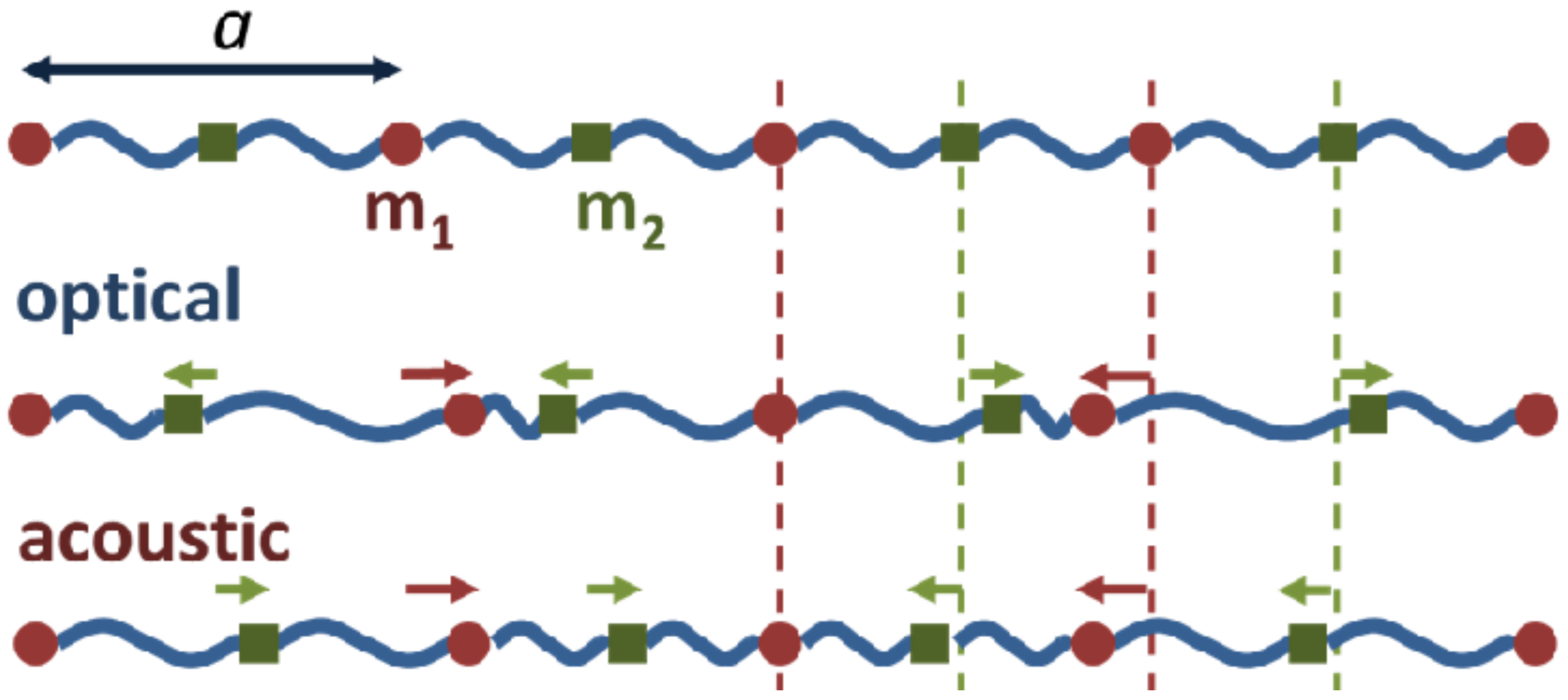
For sufficiently light DM, $m_\chi < 1\,{\rm MeV} \Rightarrow q < {\rm keV}$

DM interaction may not be ‘point-like’. Can scattering collectively with the whole crystal lattice (i.e. it can excite phonons)



If DM couples **differently** to positively and negatively charged ions, then scattering is more likely to excite **optical phonons** in polar materials.

e.g. ‘millicharged’ DM



If DM couples **similarly** to all ions/nuclei, then scattering is more likely to excite **acoustic phonons**.

e.g. hadrophilic scalar mediator

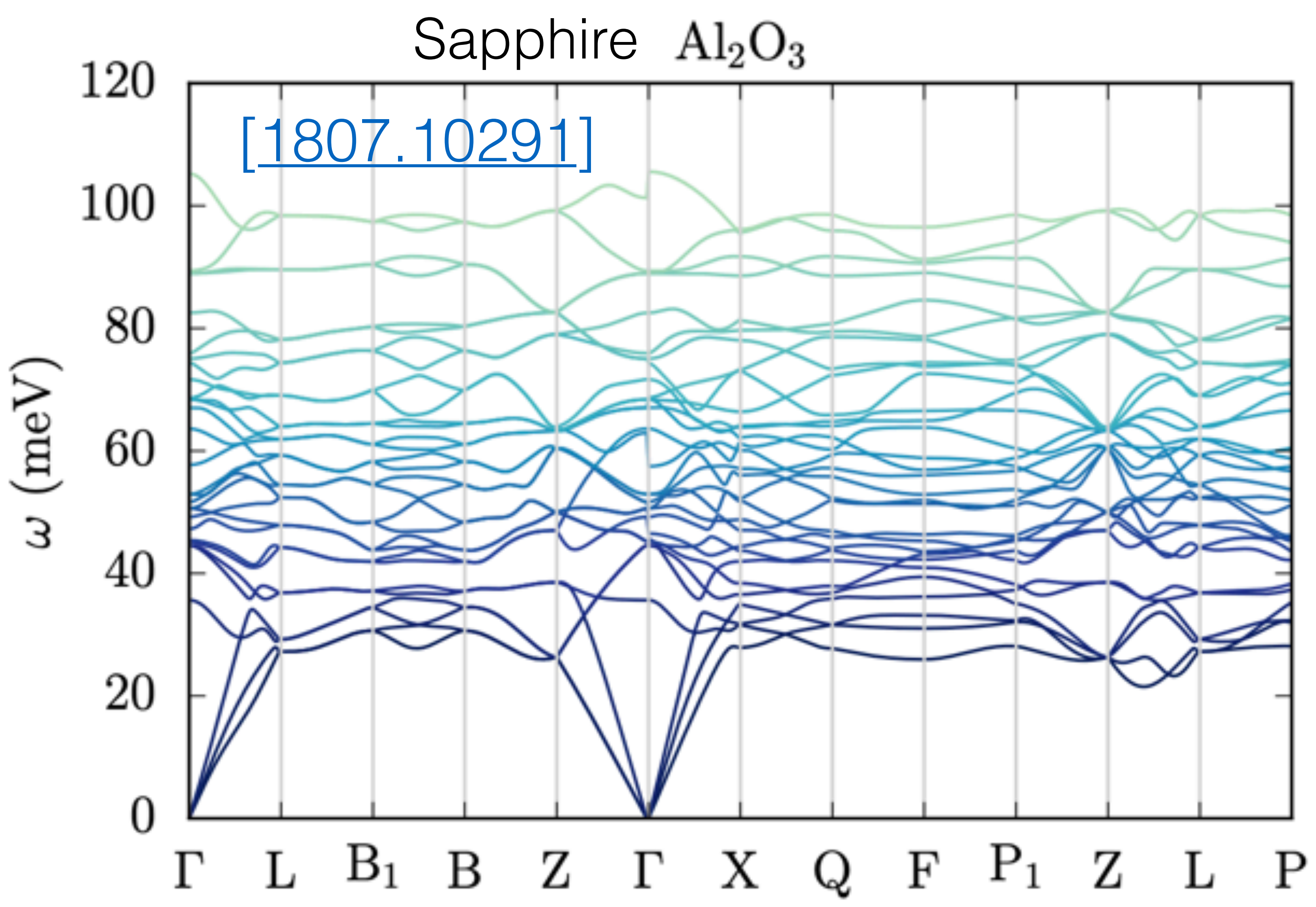
[DM phonon scattering theory - 1712.06598,1905.05575]

[DM-phonon scattering in superfluid Helium - 2005.08824]

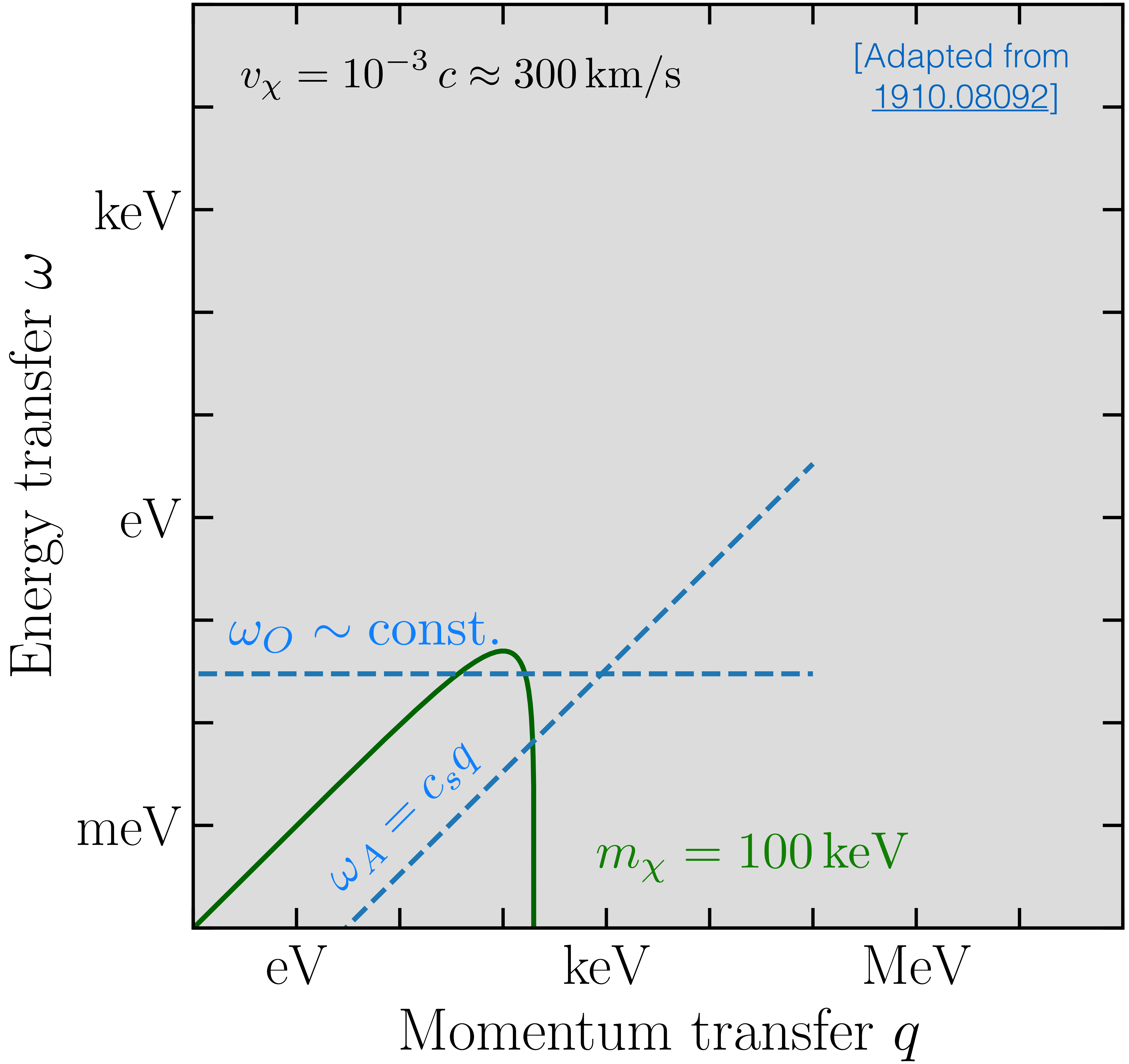
Optical vs acoustic phonons

Allowed range of (ω, q) set by kinematics (green regions):

$$\omega \leq q v_\chi - q^2/2m_\chi$$



For a given DM mass and velocity, gapped optical phonons typically allow for a larger energy deposit (just by looking at kinematics).



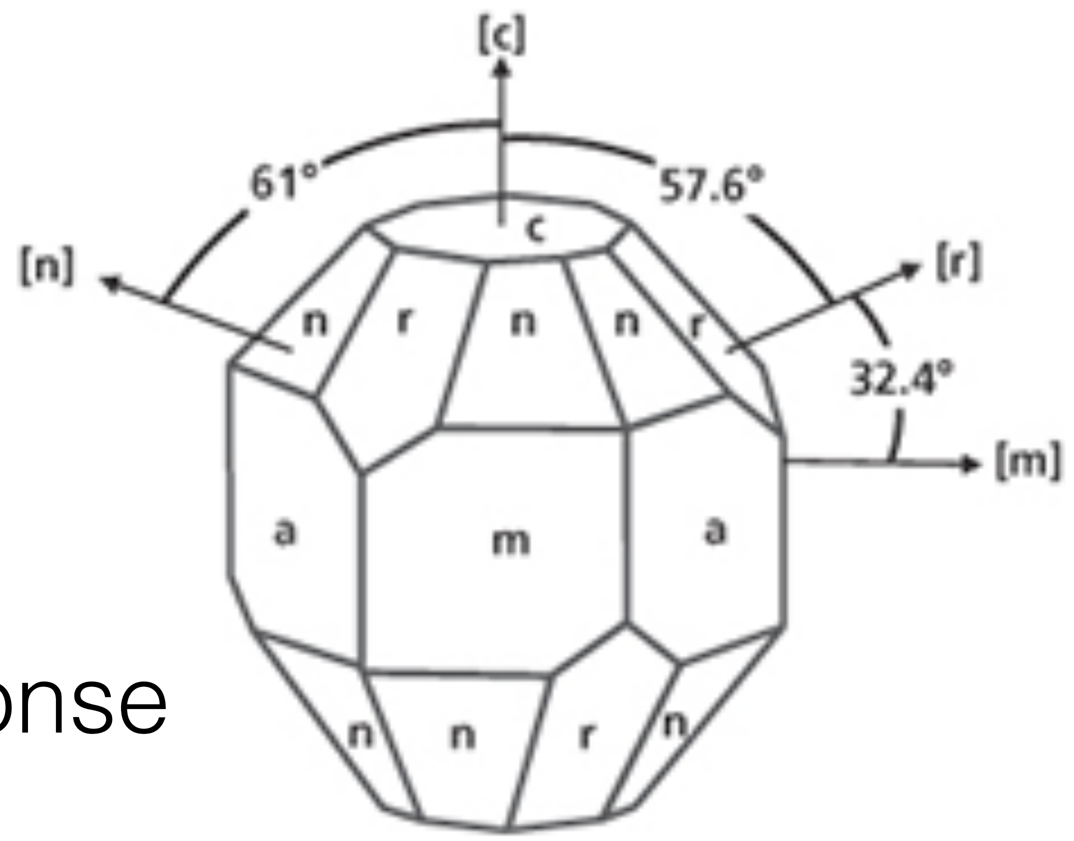
Time-dependent DM Signal

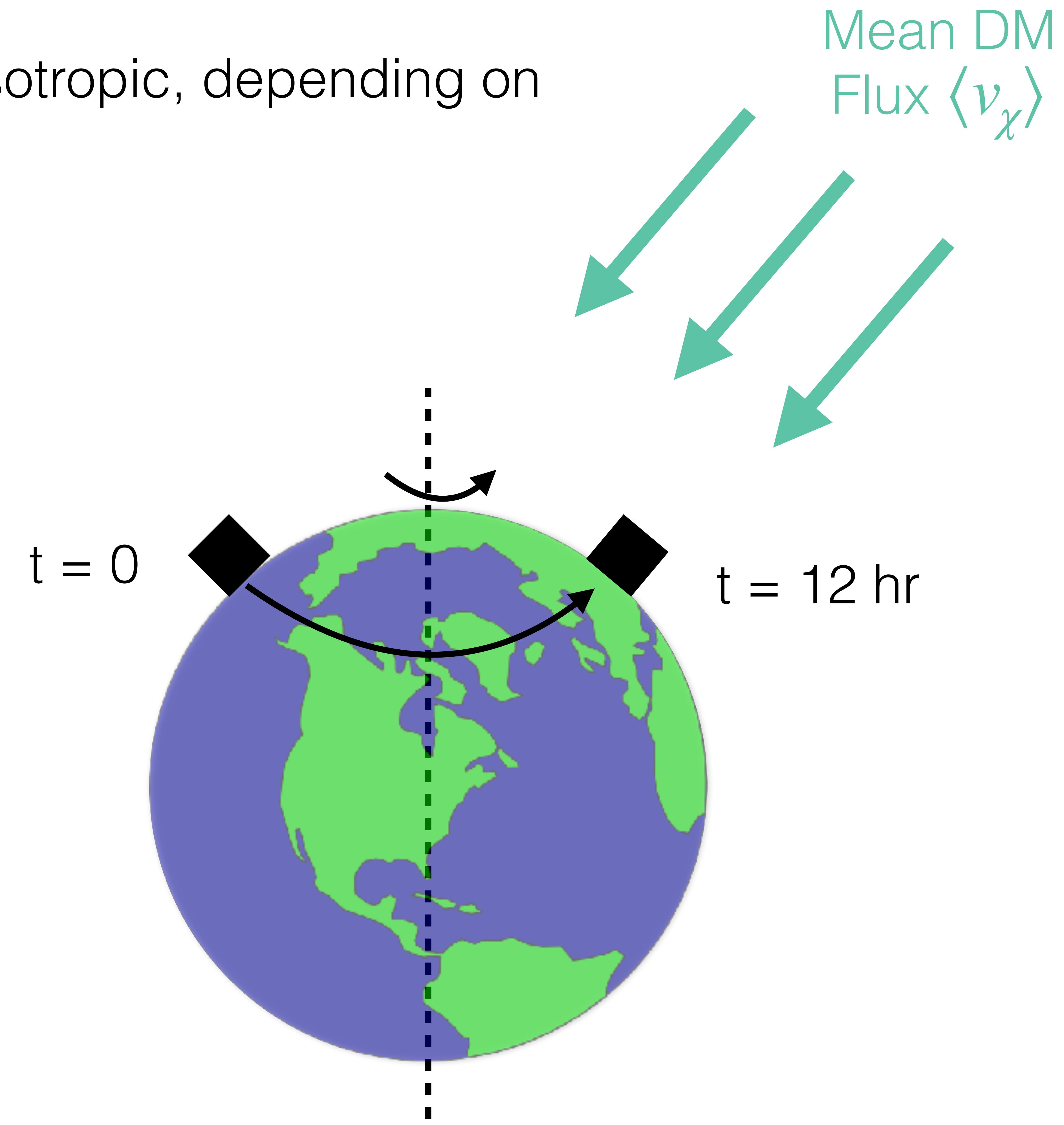
DM flux comes from a preferred direction, meaning that if the phonon response is anisotropic, a characteristic **time-dependent signal** can arise.

Consider Sapphire as an example. The phonon response is anisotropic, depending on orientation with respect to the optical axis ("*c*-axis"):

$\mathbf{k} \parallel c$-axis:
Ordinary response

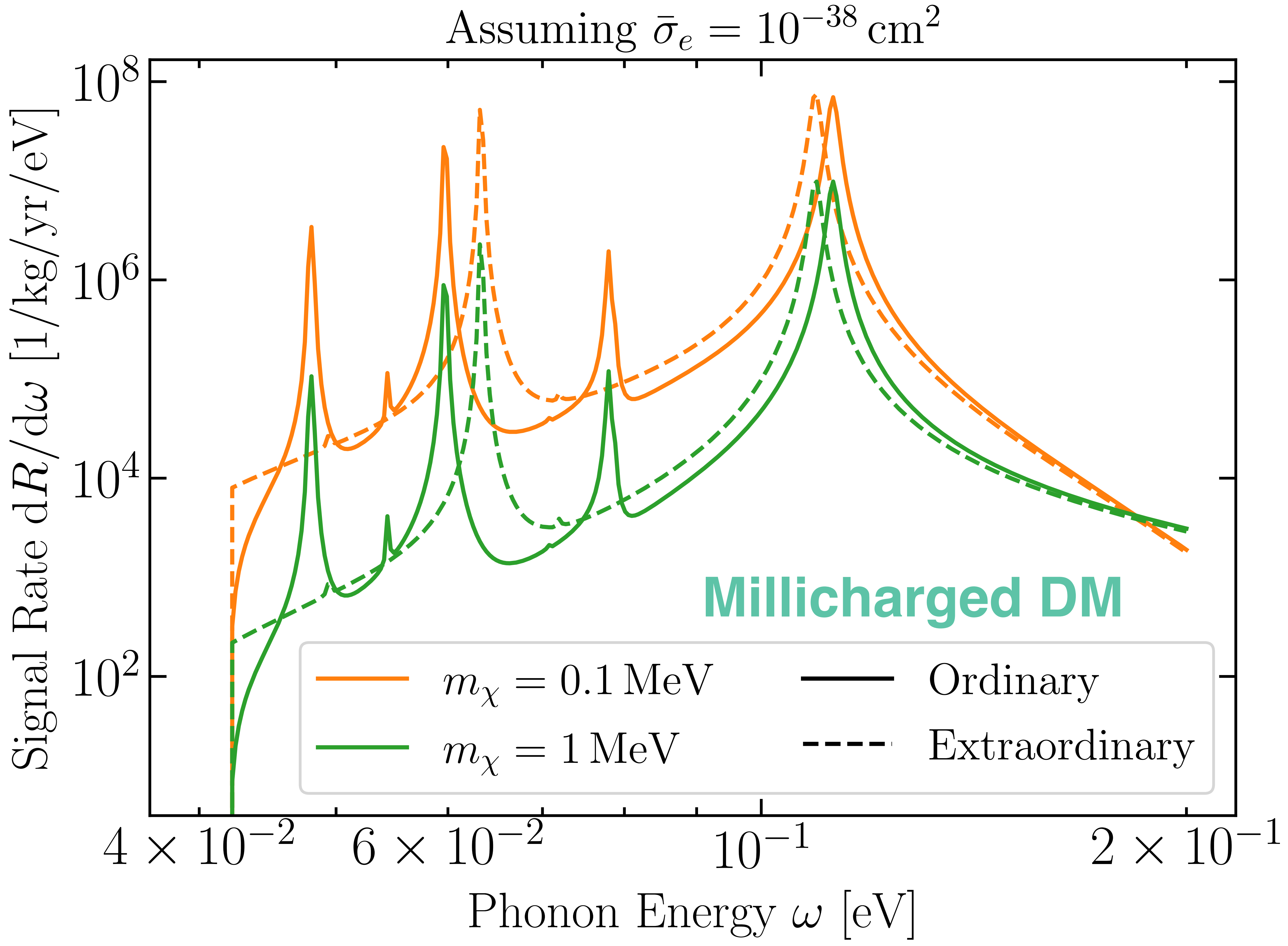
$\mathbf{k} \perp c$-axis:
Extraordinary response

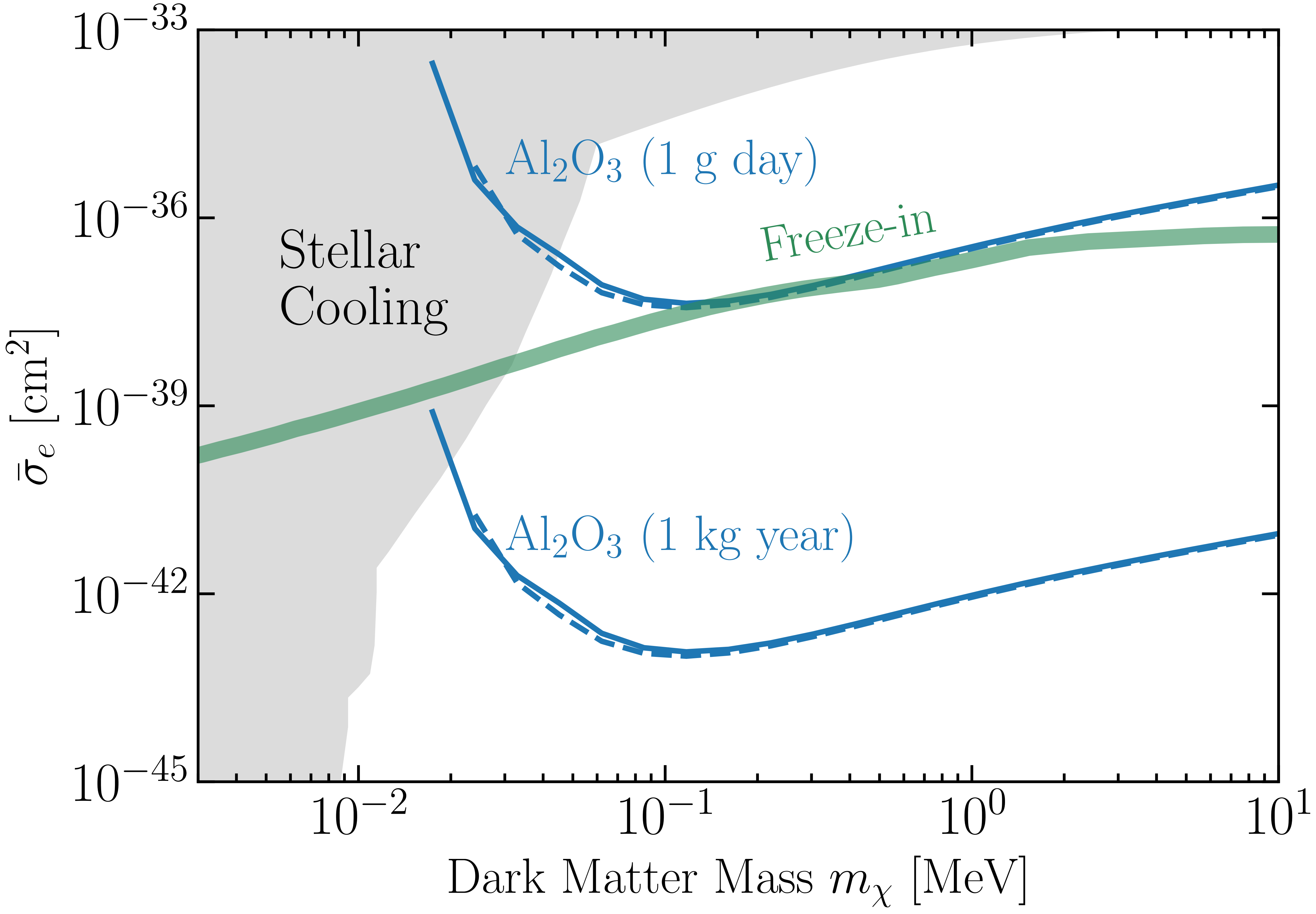




DM-Phonon Scattering Rates

Look for anisotropic, polar materials as good targets.
Some estimates of the DM-phonon scattering rate have been calculated for **Sapphire**.



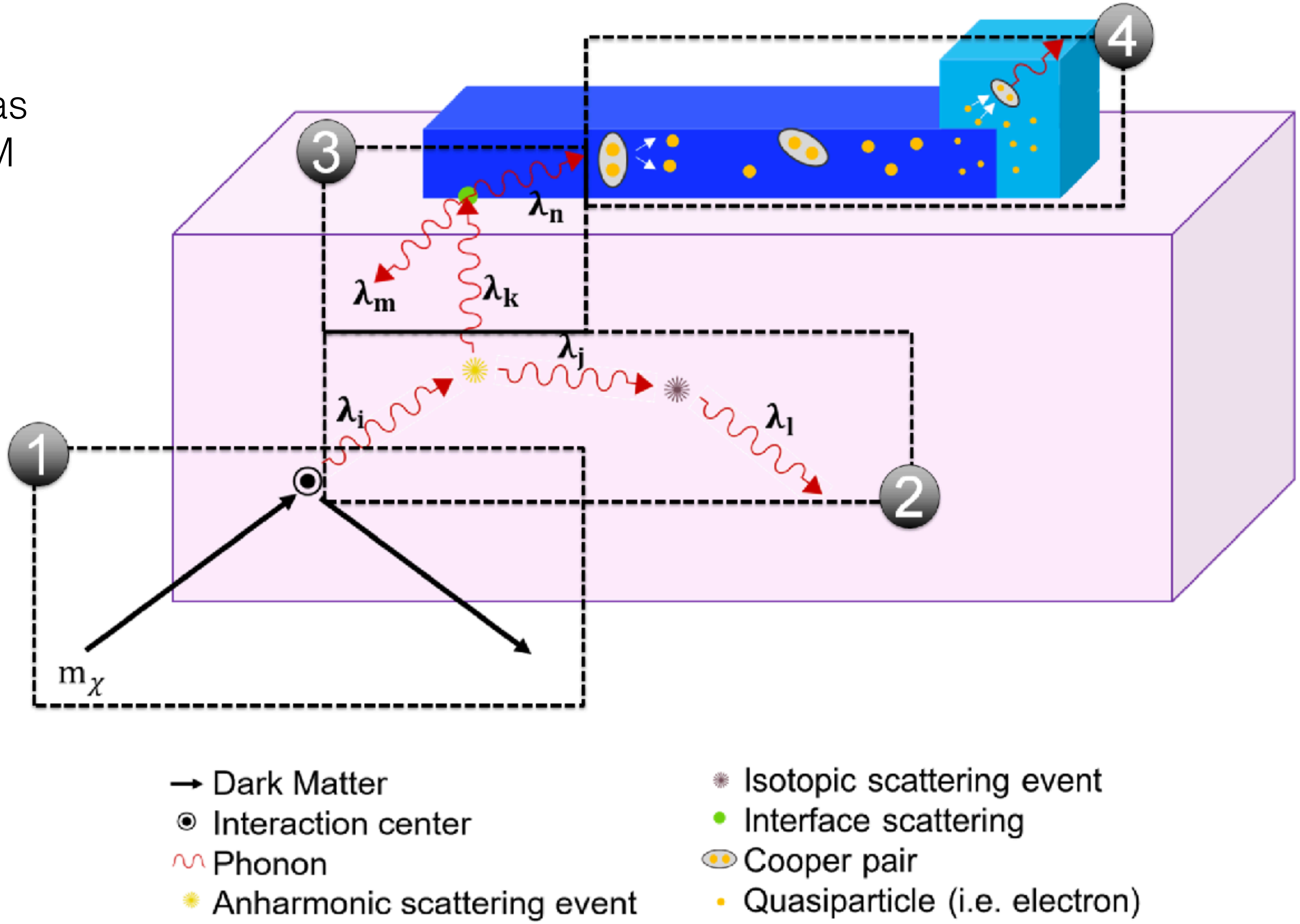


But a **full survey** of Dark Matter models and target materials has not yet been completed.

Quantum Sensors for Dark Matter

Quasi-particle Trap Assisted Transition Edge Sensor (QET)

Working with researchers at ICMAB, as well as in INMA (Zaragoza), IMB-CNM (Zaragoza) and IFCA (Santander) towards a ‘real’ detector!



Conceptual design stage:

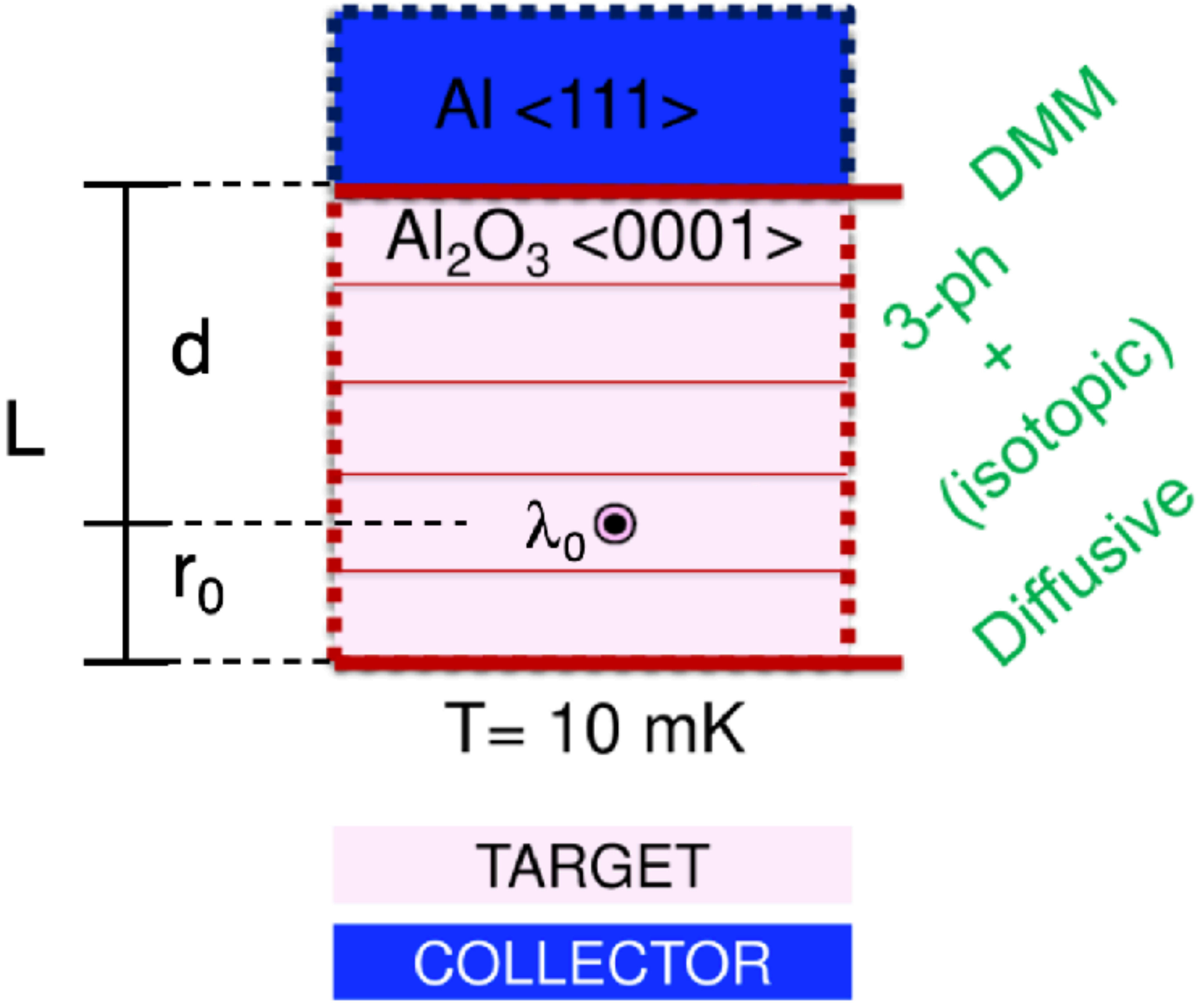
Estimate of DM interaction rates in different targets

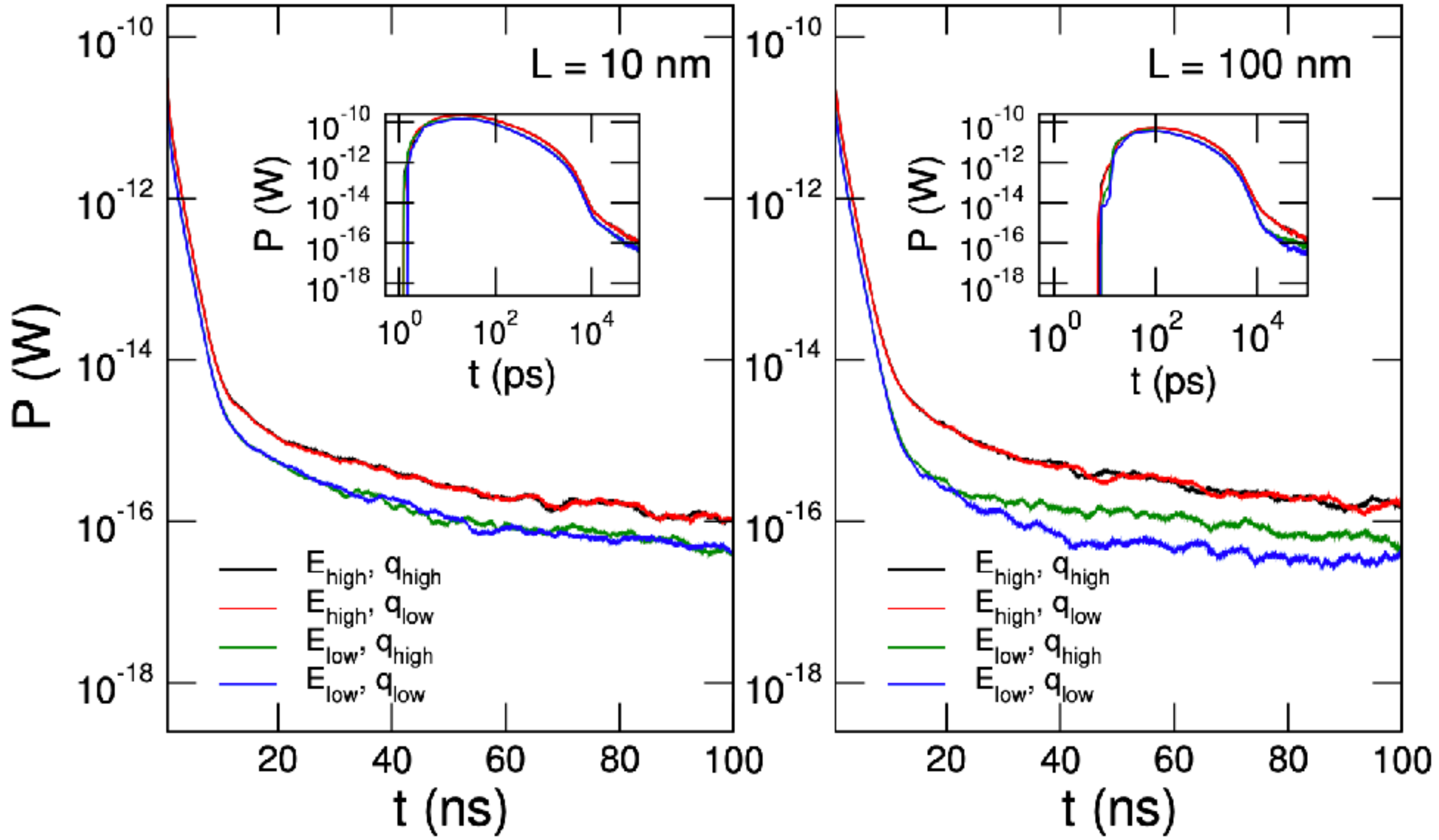
Determine best target, required target mass and possible sensor configuration

[2311.11930]

Phonon Propagation

$$\frac{\partial n_i^d}{\partial t} + \mathbf{v}_i \cdot \nabla_r n_i^d + \frac{\partial n_i^0}{\partial T} \mathbf{v}_i \cdot \nabla_r T_{\mathrm{ref}} = \left. \frac{\partial n_i}{\partial t} \right|_{\mathrm{collision}}$$





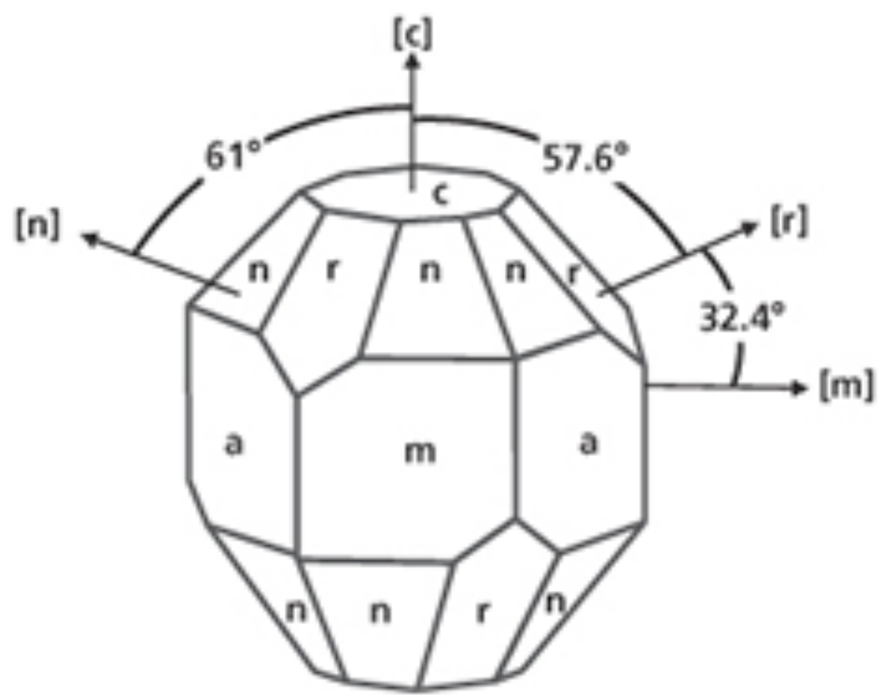
Detectability limits of current transition edge sensors (TES) is $\sim 10^{-16}\,\mathrm{W}$

With Martí Raya-Moreno,
Lourdes Fàbrega & Riccardo Rurali [2311.11930]

New Directions for Dark Matter

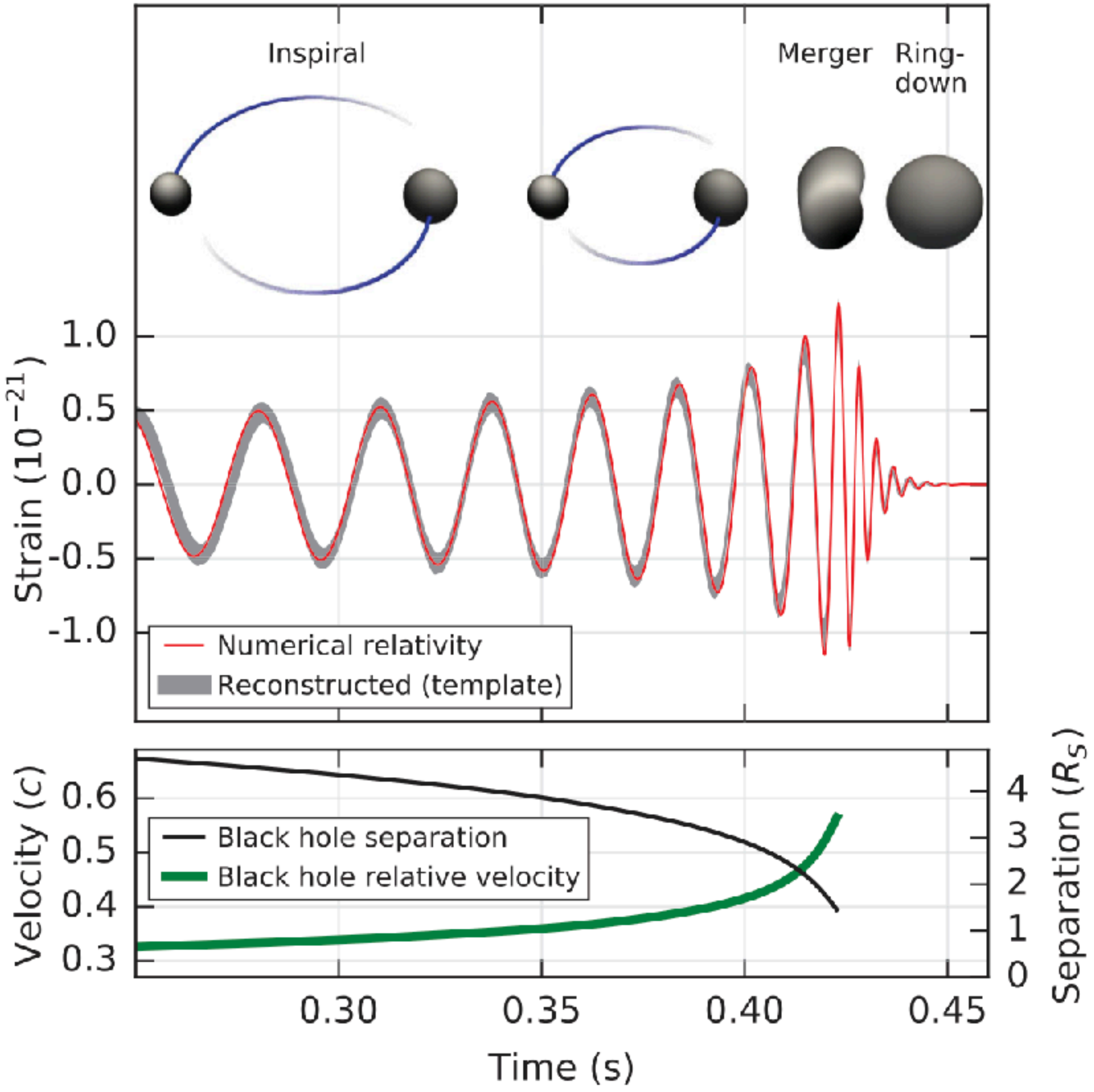
Low-threshold phonon detectors

Black Holes and Gravitational Waves



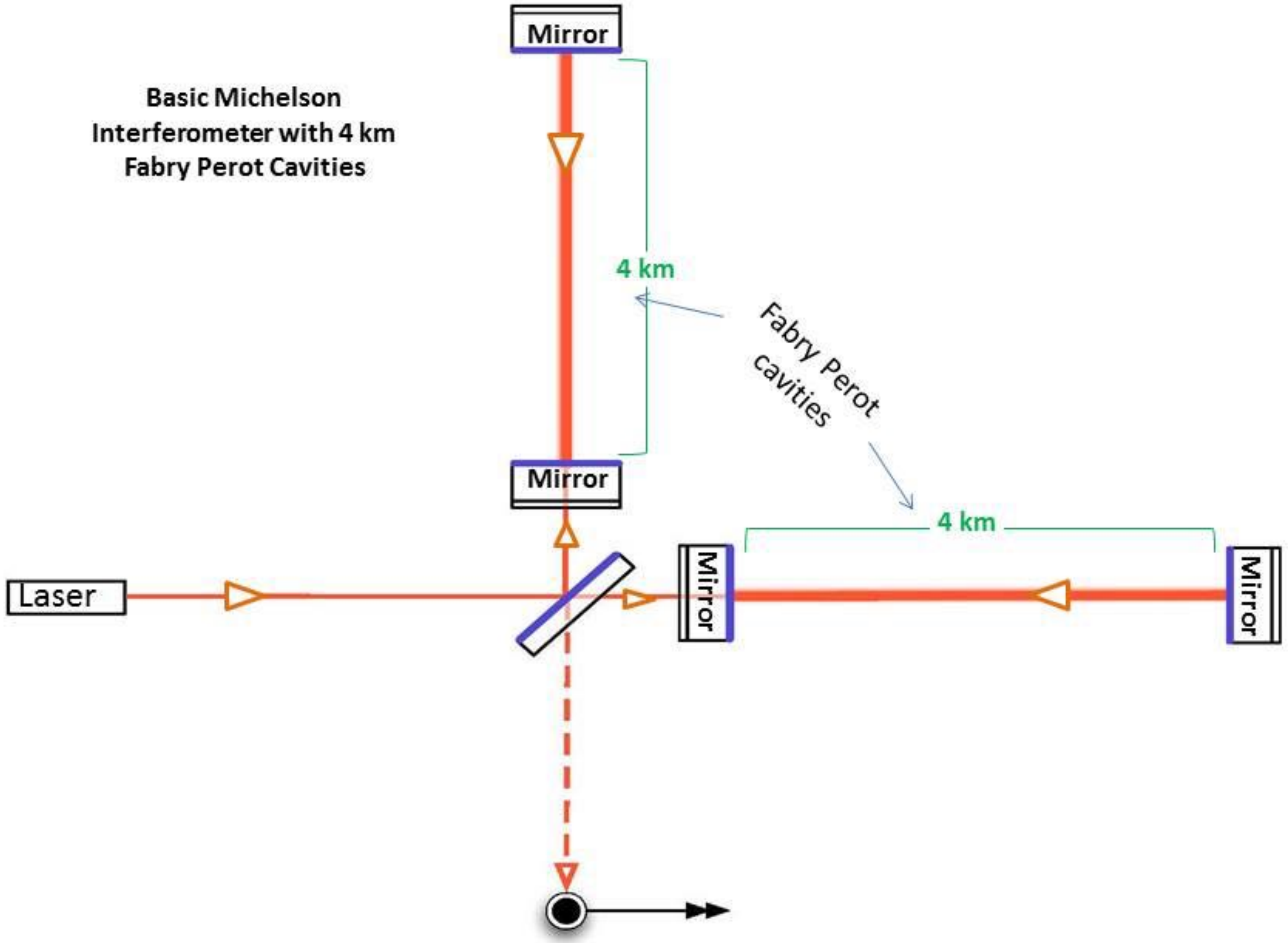
Gravitational Waves (GW)

An ~equal mass inspiral: GW150914



[LIGO/Virgo, arXiv:1602.03837]

www.ligo.caltech.edu/page/ligos-ifo



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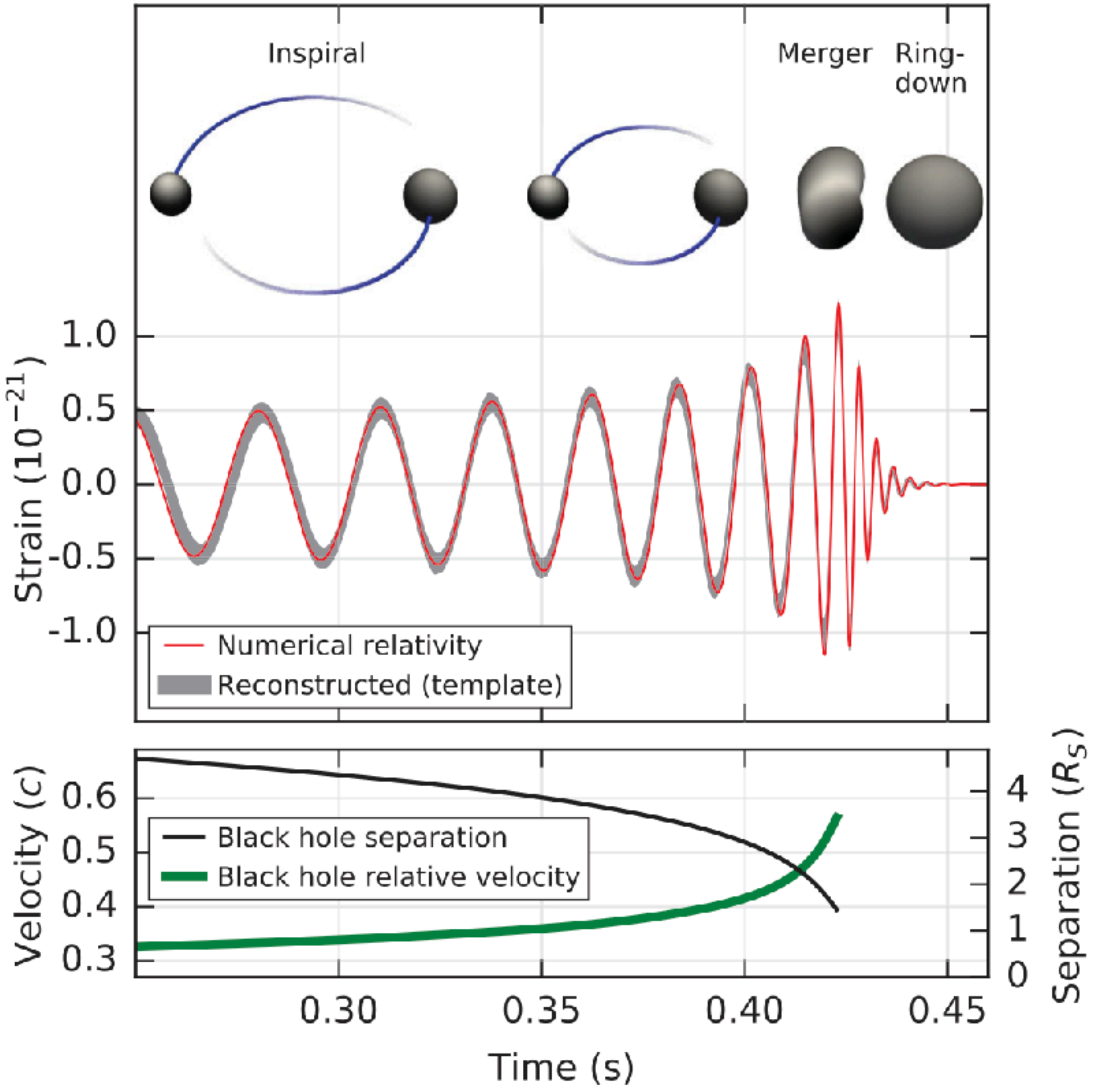
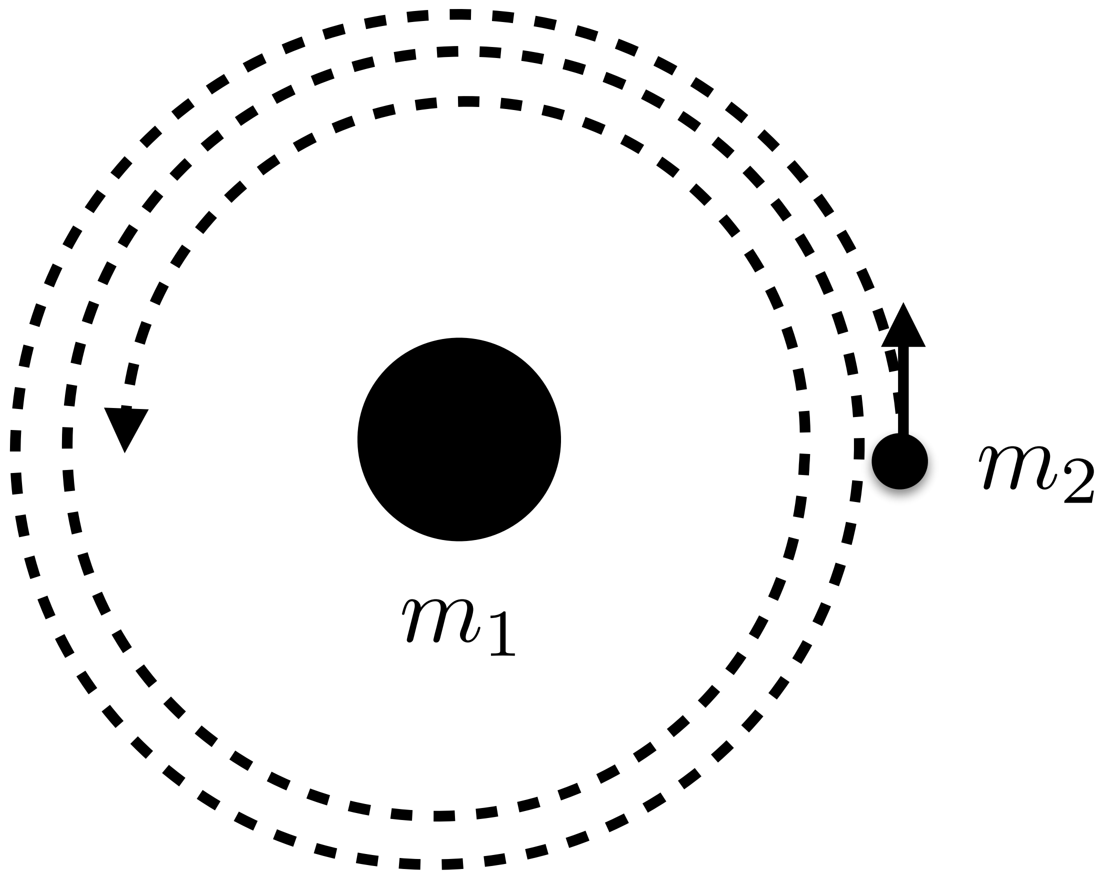


[LIGO/Virgo, arXiv:1602.03837]

Intermediate and extreme mass ratio inspirals:



$m_2/m_1 \ll 1$

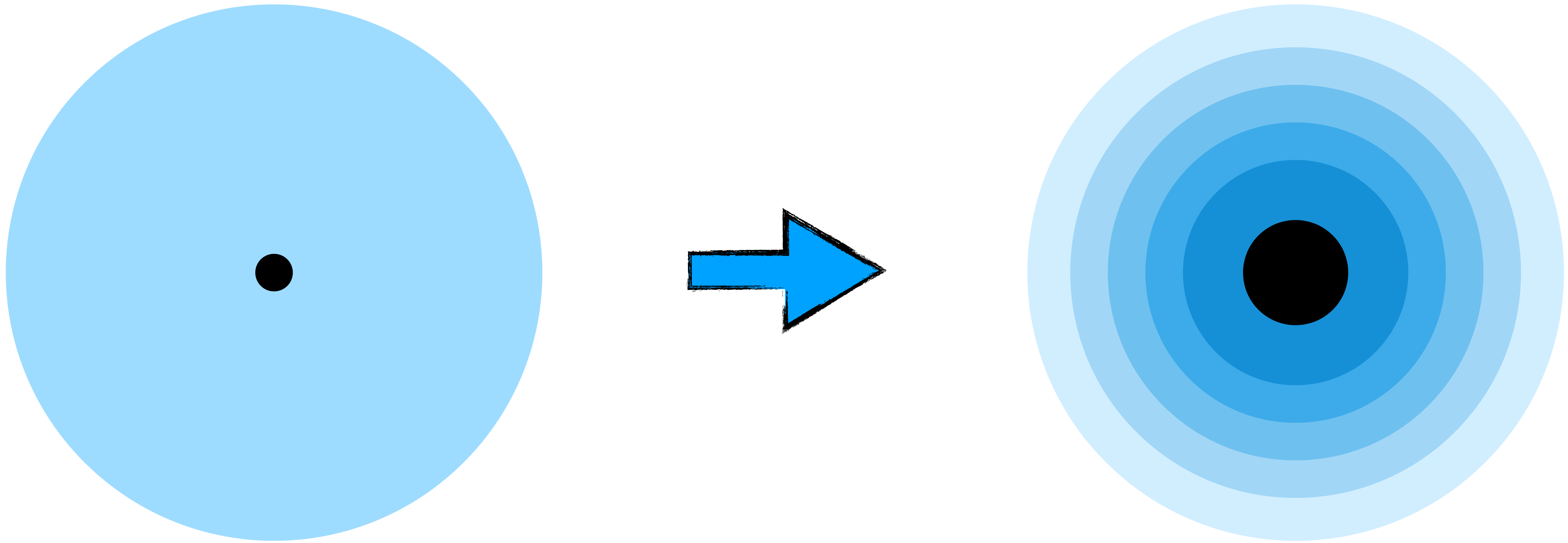
Binary may be observed during *millions of orbits*

Evolution of the GW signal can be used to **trace the dynamical influence of the environment** around the larger black hole

Can be used to probe of Dark Matter overdensities **almost independently of Dark Matter mass** and particle physics properties

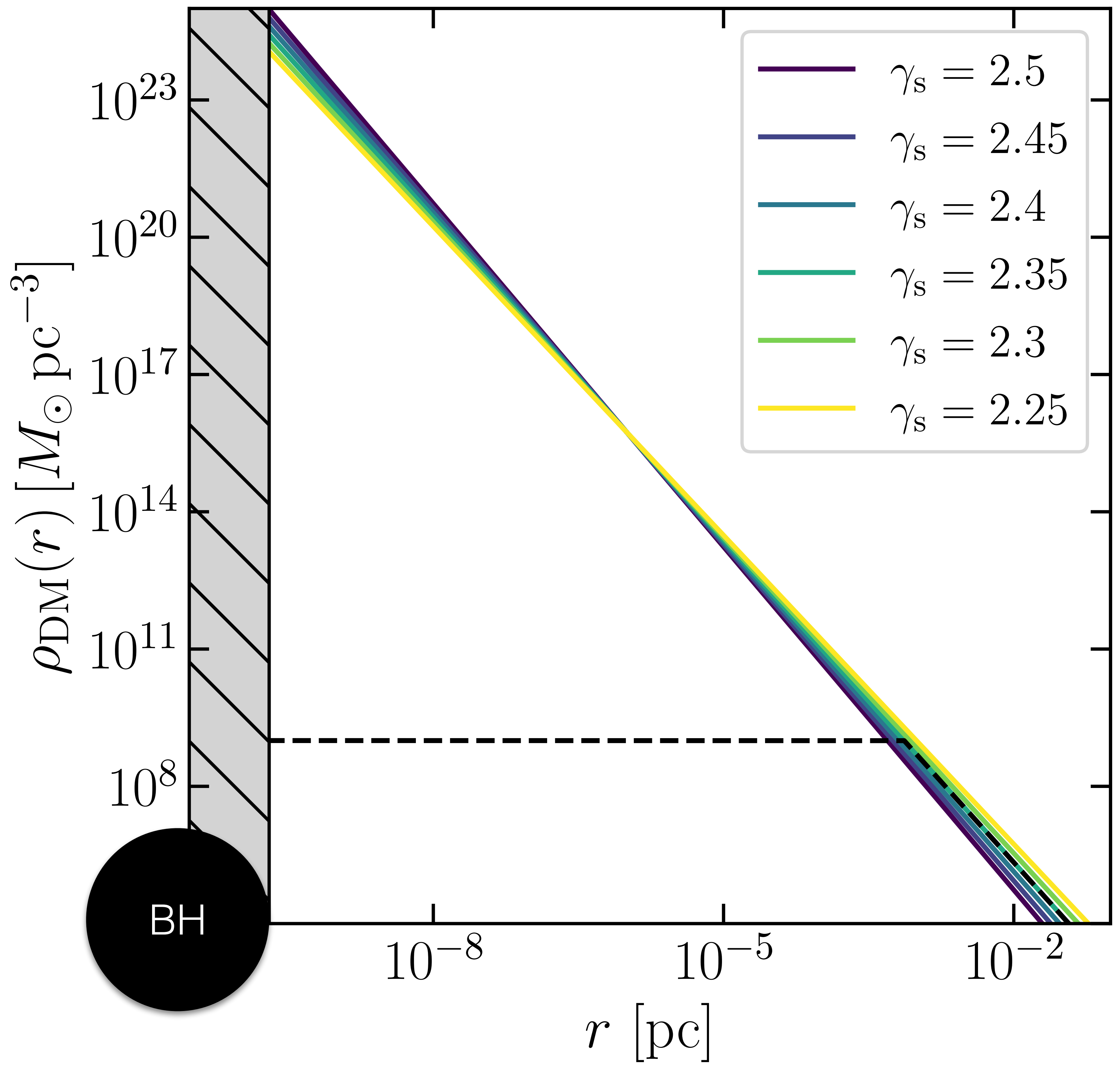
Dark Matter Spikes

'**Spikes**' or '**dresses**' of cold, particle-like DM may form around BHs, e.g. From the slow ('adiabatic') growth of a BH at the centre of a DM halo



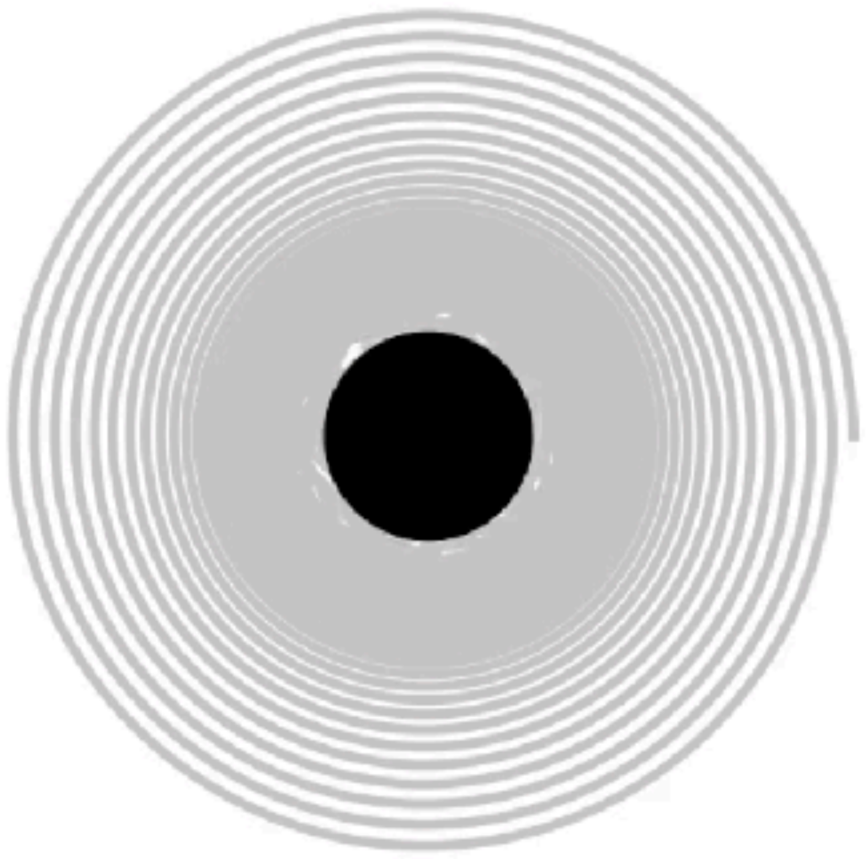
[astro-ph/9906391, astro-ph/0509565, 1305.2619, Bertschinger (1985), astro-ph/0608642, 1901.08528, …]

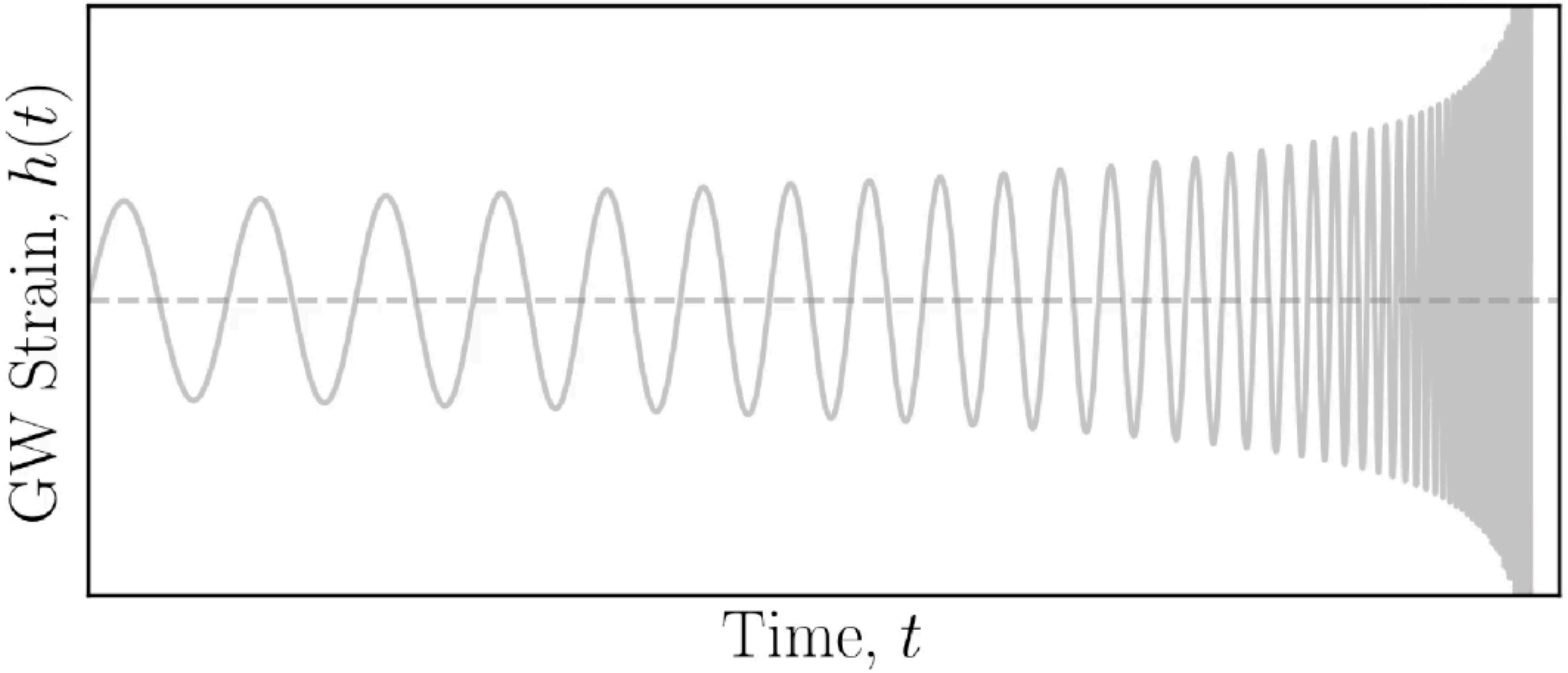
$$\rho_{\rm DM} = \rho_6 \left(\frac{10^{-6}\,{\rm pc}}{r}\right)^{\gamma_{\rm sp}}$$



$$\rho_{\rm DM,\,local} \sim 10^{-2}\, M_\odot/{\rm pc}^3$$

Gravitational Wave Dephasing





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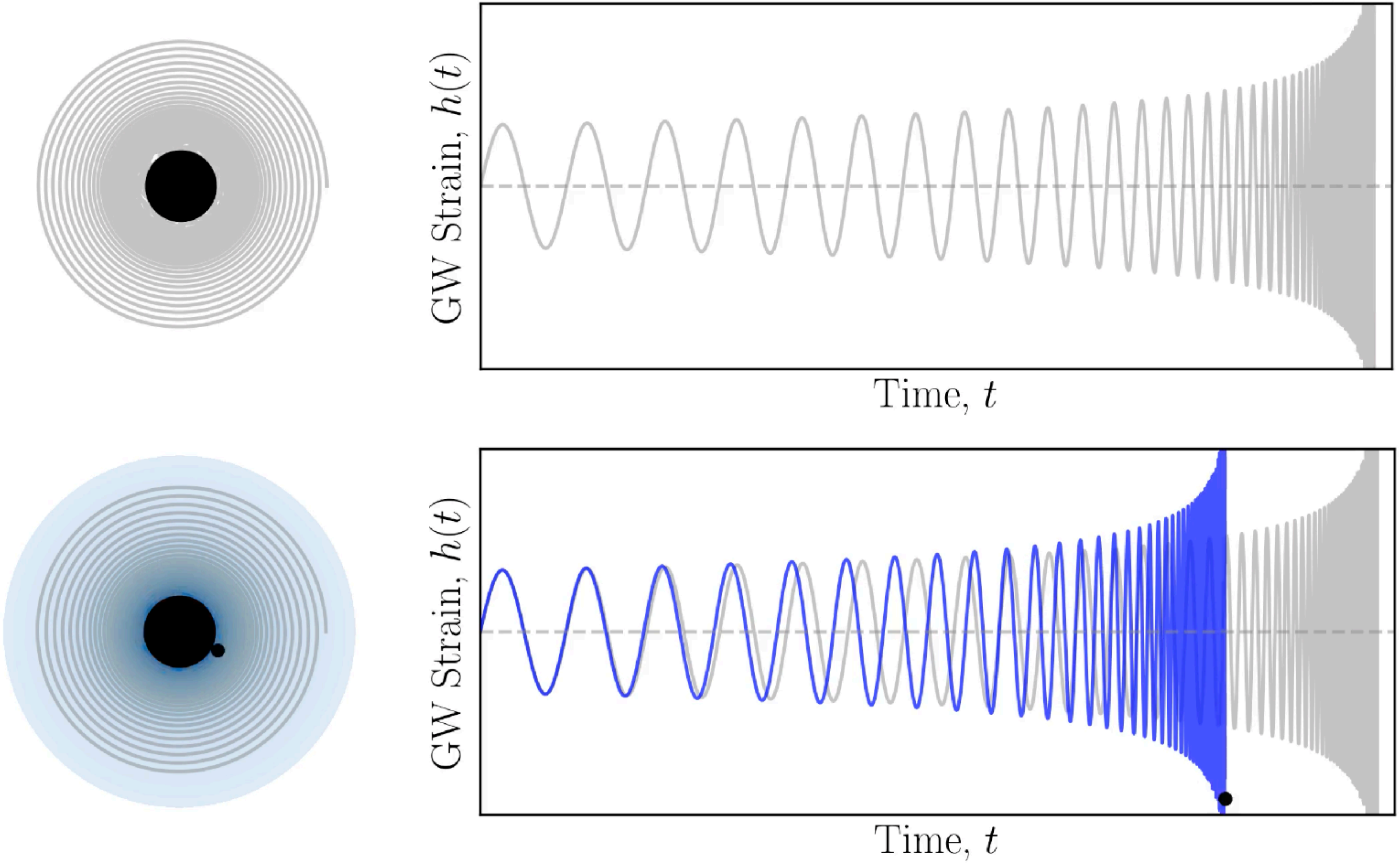

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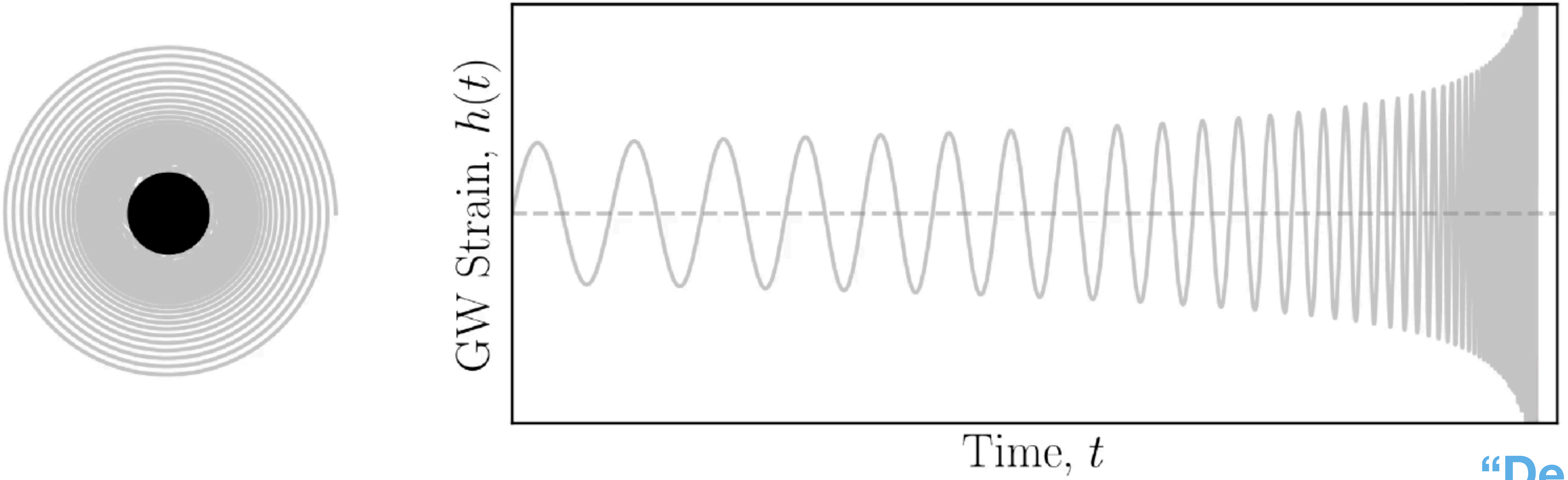
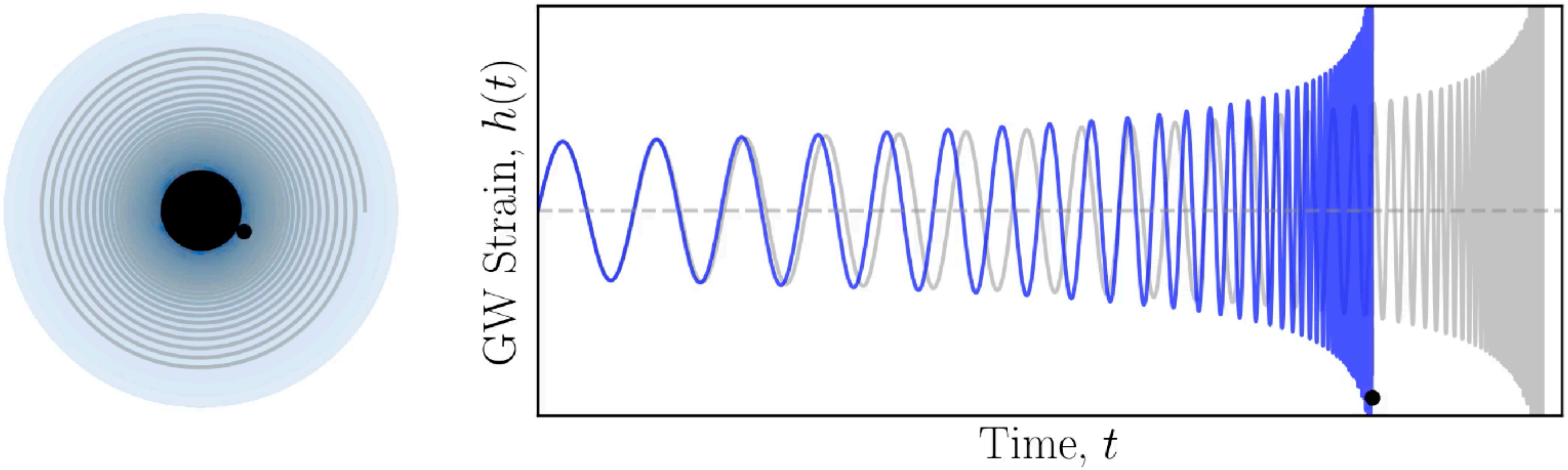
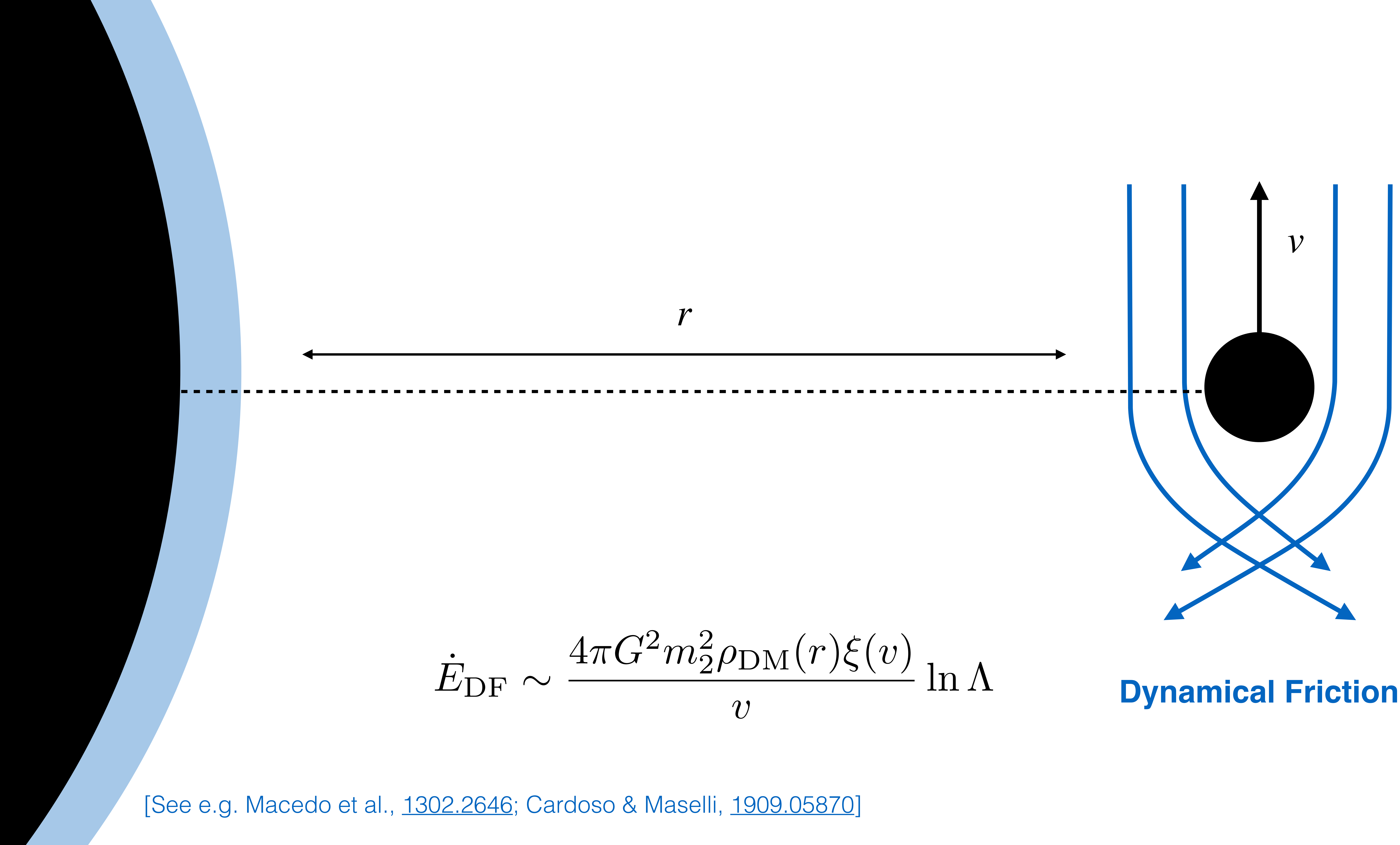


“Dephasing”





$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r)\xi(v)}{v} \ln\Lambda$$

Dynamical Friction

[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]

Co-evolution of the Binary and Spike

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

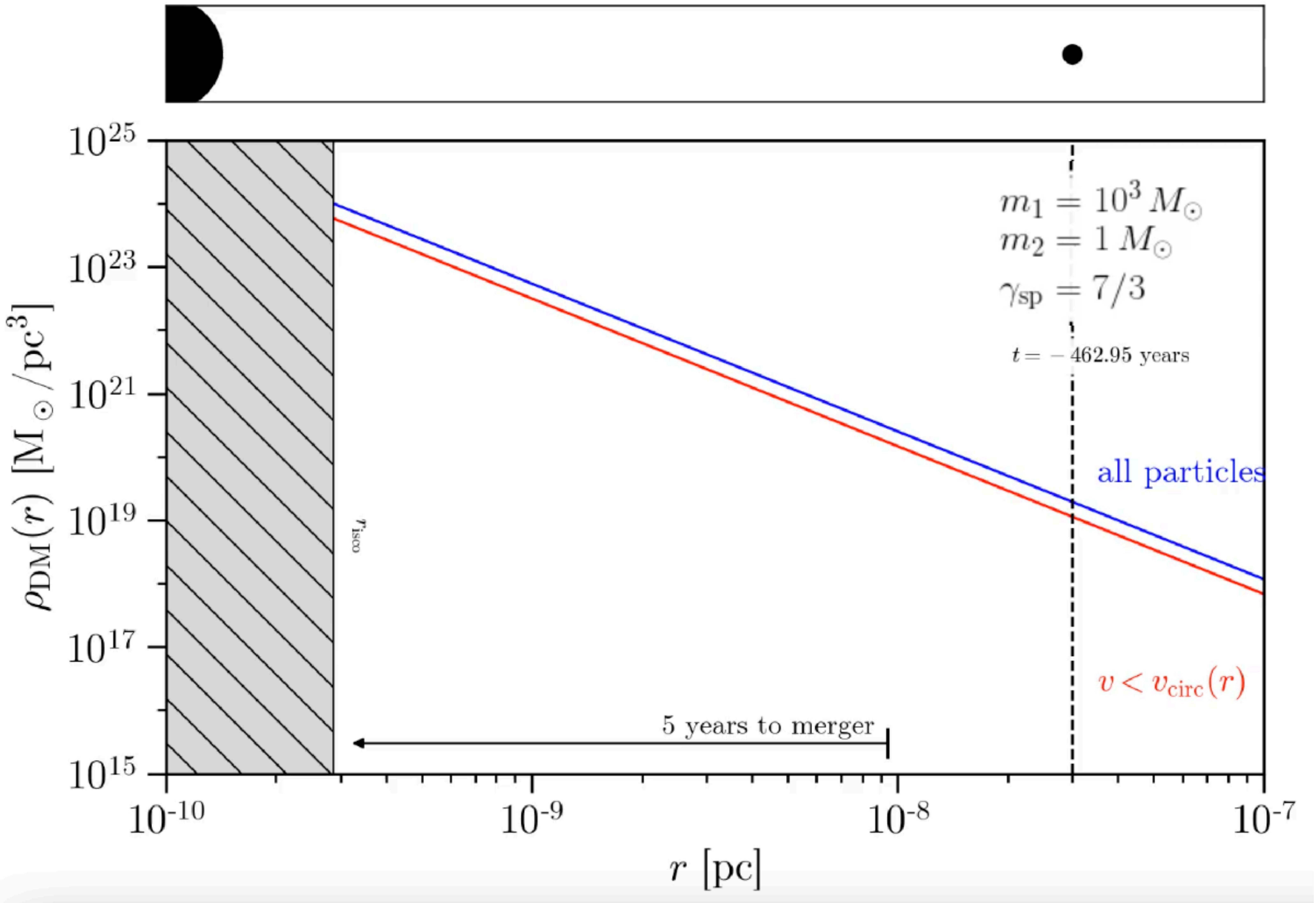
Newtonian motion of the binary, taking into account:

- GW emission
- Dynamical Friction
- DM Halo Feedback

$$-\dot{E}_{\rm orb} = \dot{E}_{\rm GW} + \dot{E}_{\rm DF}$$

Formalism recently extended to eccentric orbits, including accretion [2402.13053, 2402.13762]

$$r(t) \to h(t)$$



[Movies: tinyurl.com/GW4DM]

[Code: github.com/bradkav/HaloFeedback]

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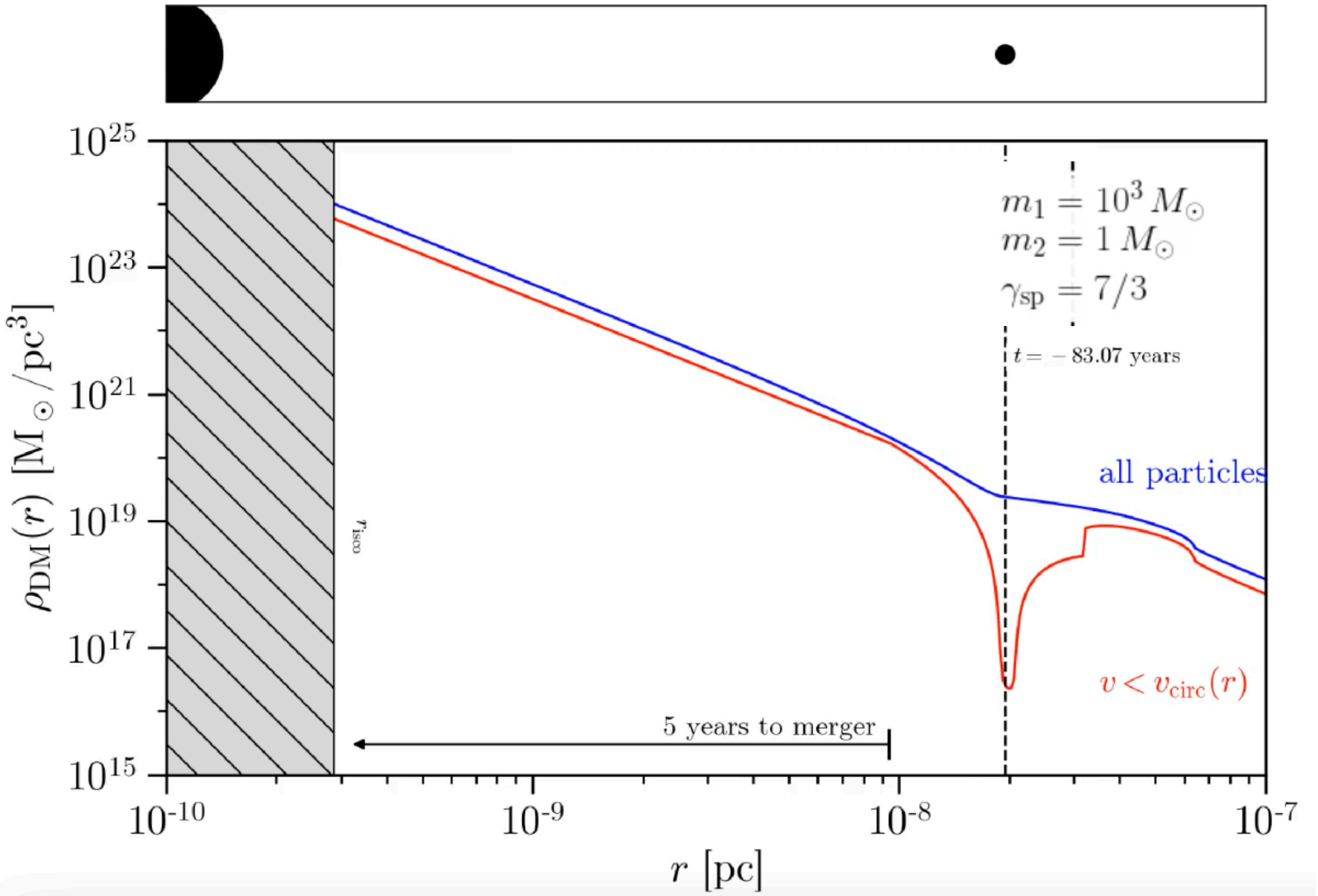

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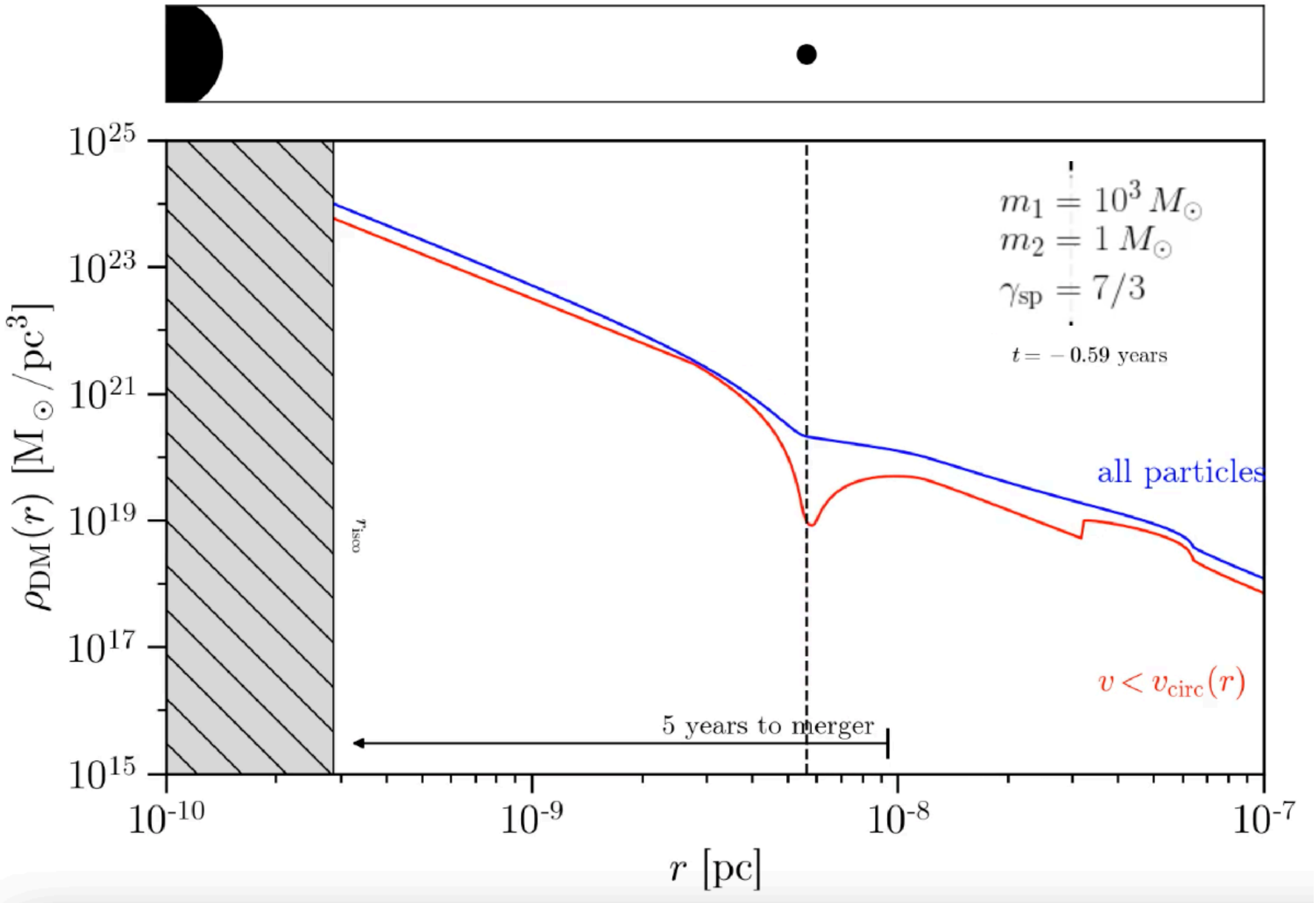

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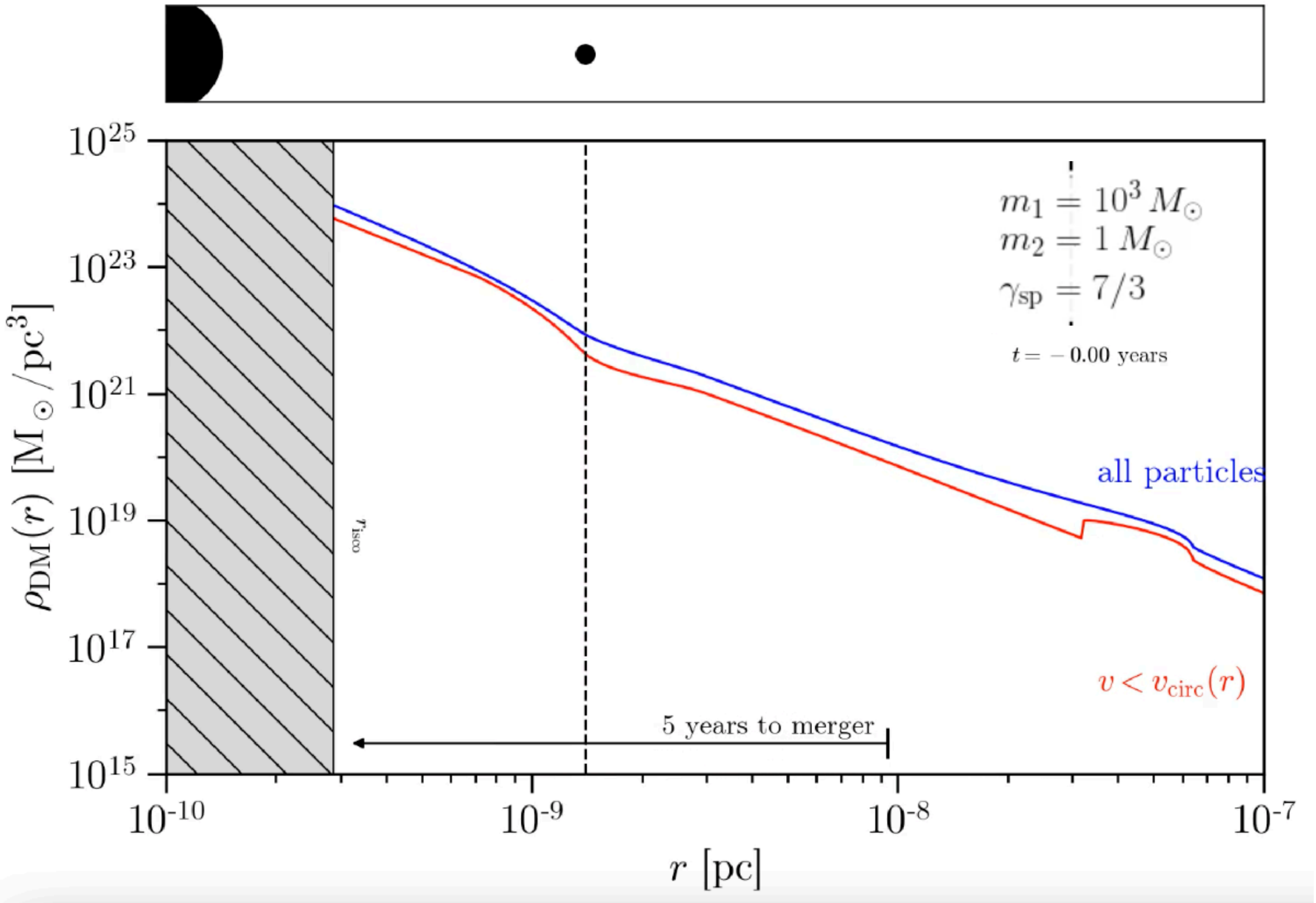

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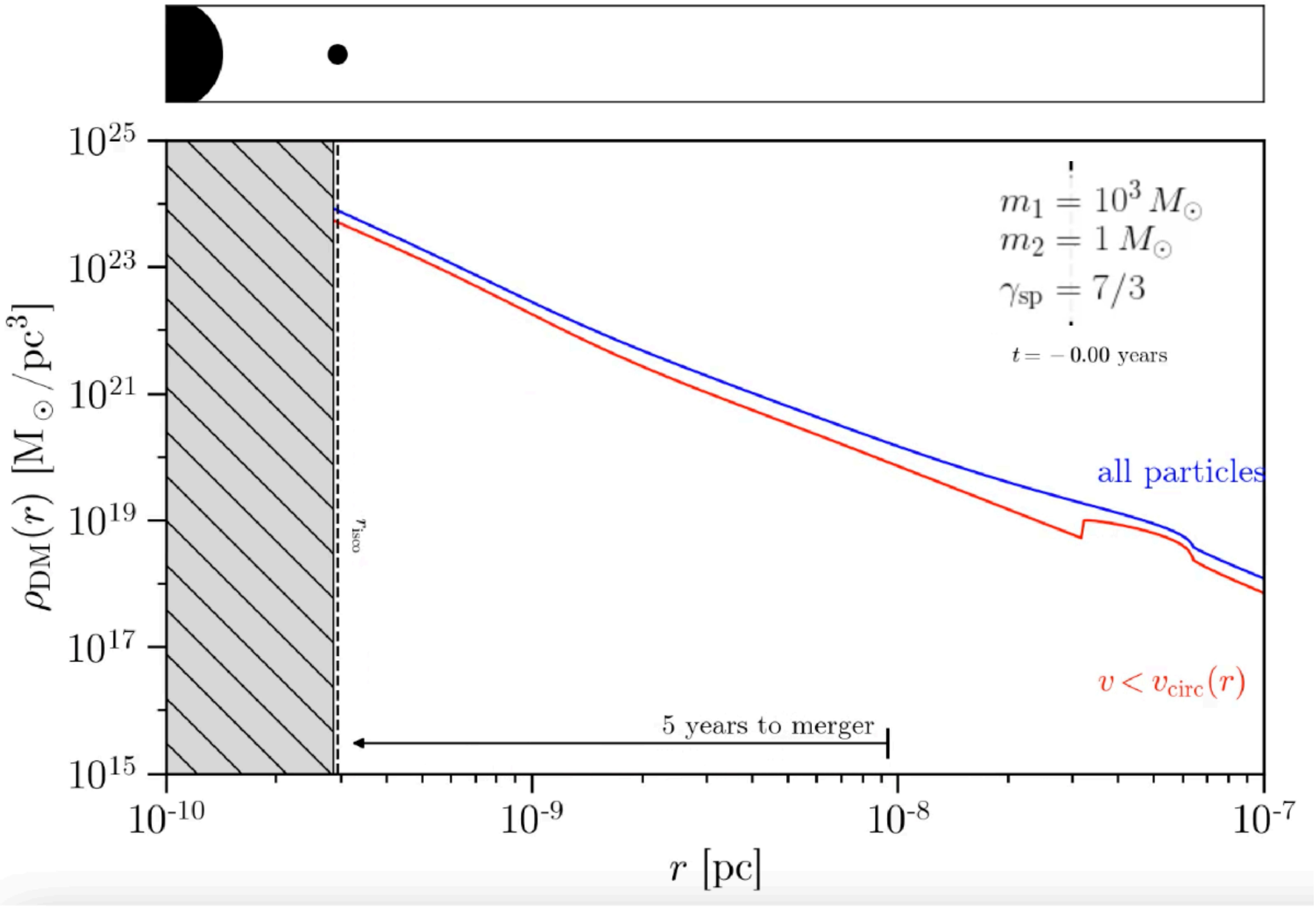

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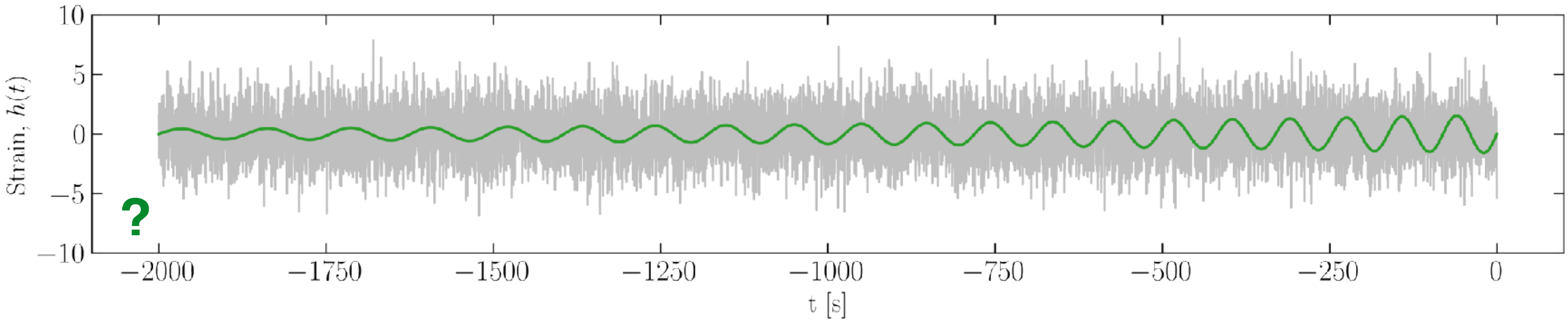
[Code: github.com/bradkav/HaloFeedback]

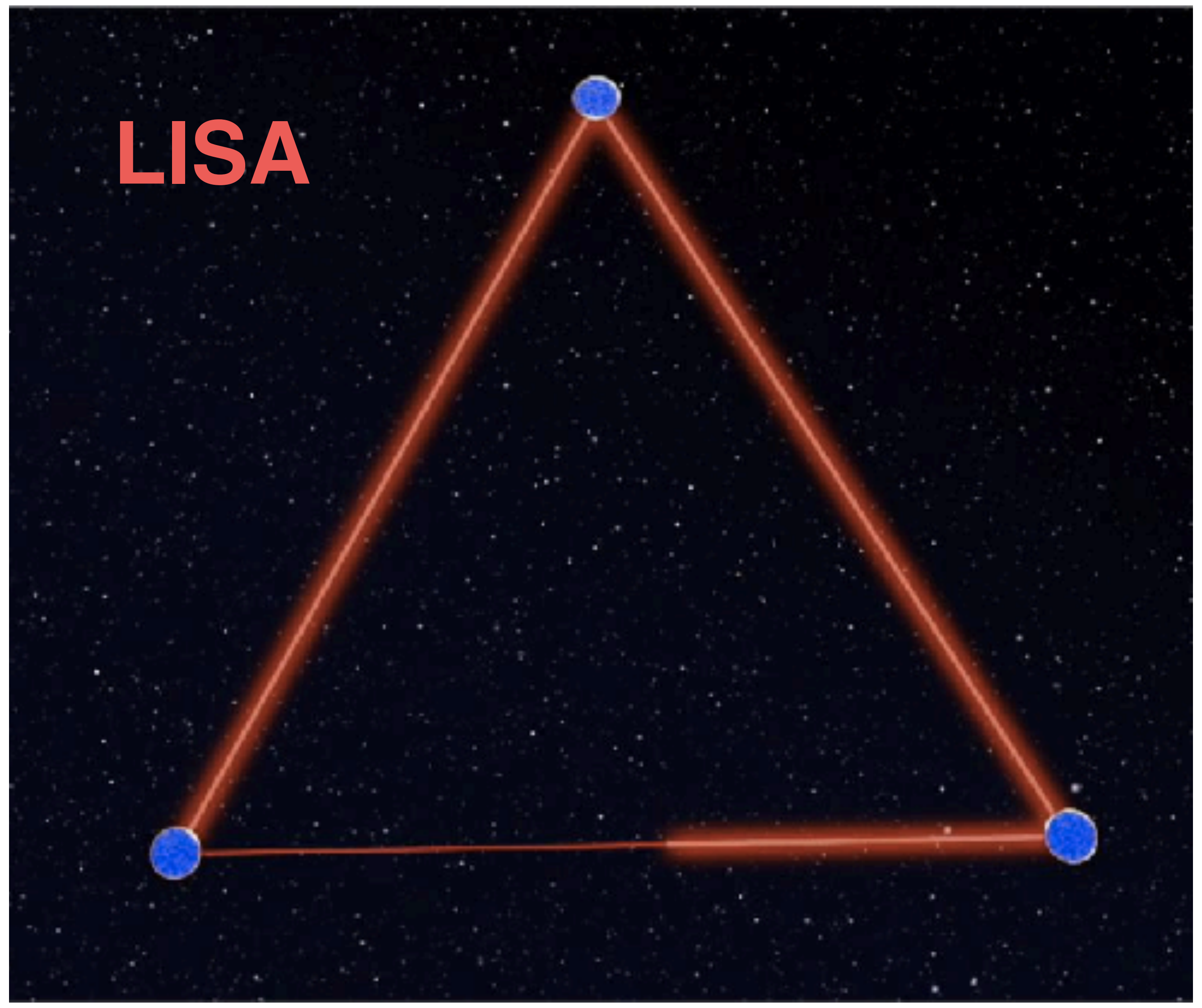
Can we measure this effect?

[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]
[Code available online: https://github.com/adam-coogan/pydd]



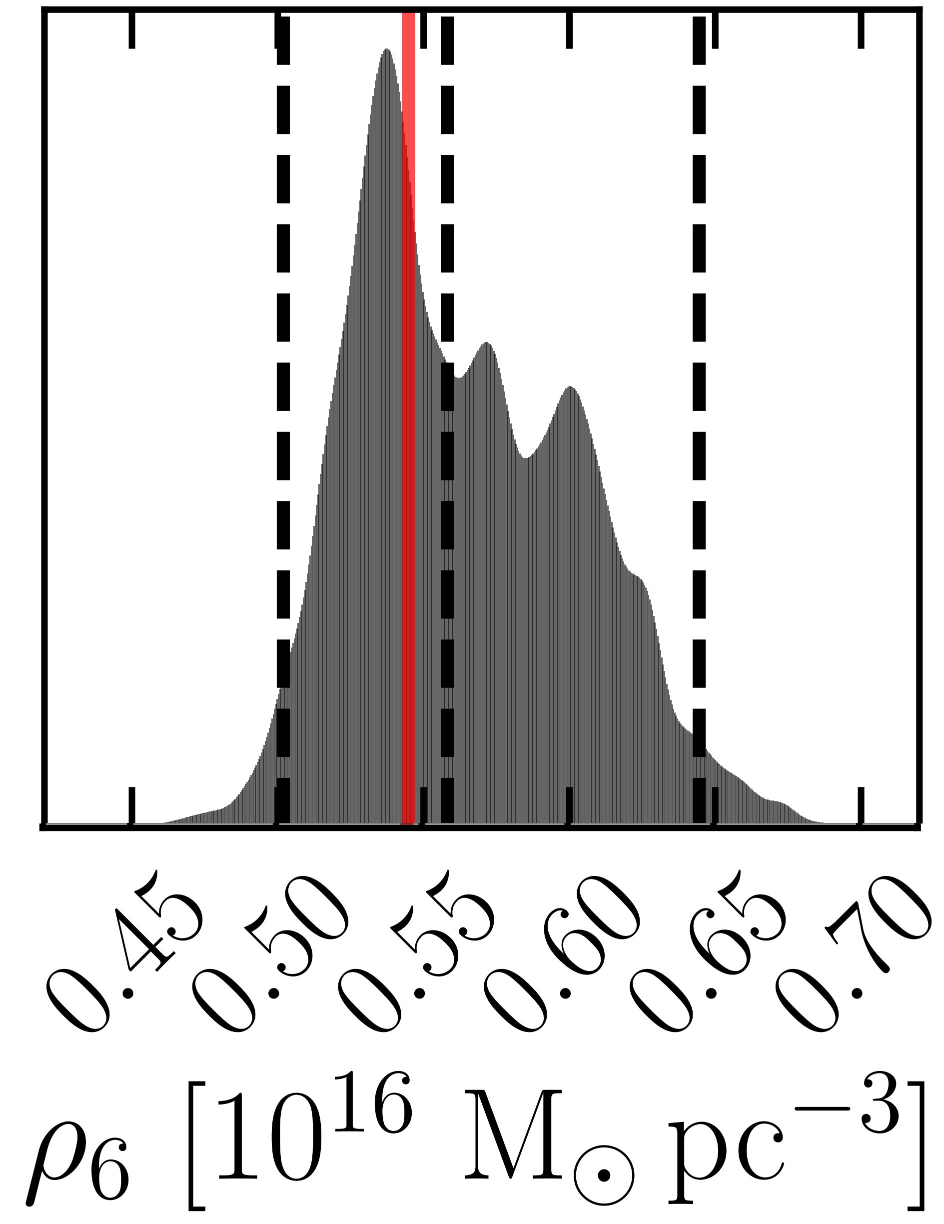
$$m_1 = 10^3\, M_\odot$$
$$m_2 = 1\, M_\odot$$

$$f_{\mathrm{GW}} \sim \mathrm{mHz} - \mathrm{Hz}$$



Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s)
[1907.06482]

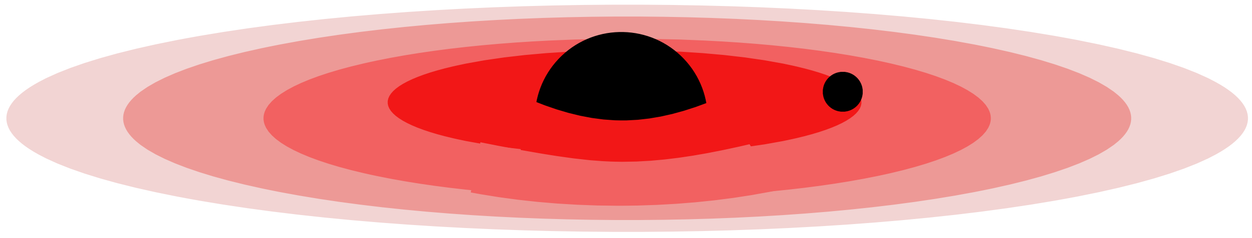
$\rho_6\ [10^{16}\ \mathrm{M_\odot\,pc^{-3}}] = 0.56^{+0.09}_{-0.06}$



Environmental Confusion

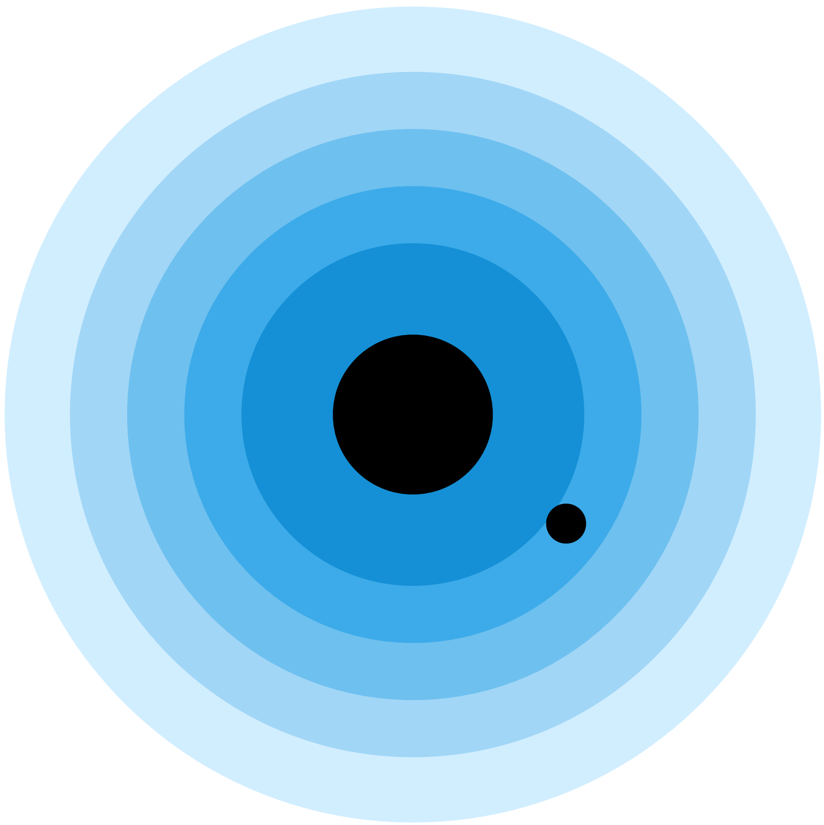
[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**, Spieksma, Tomaselli, 2211.01362, Nature Astronomy]

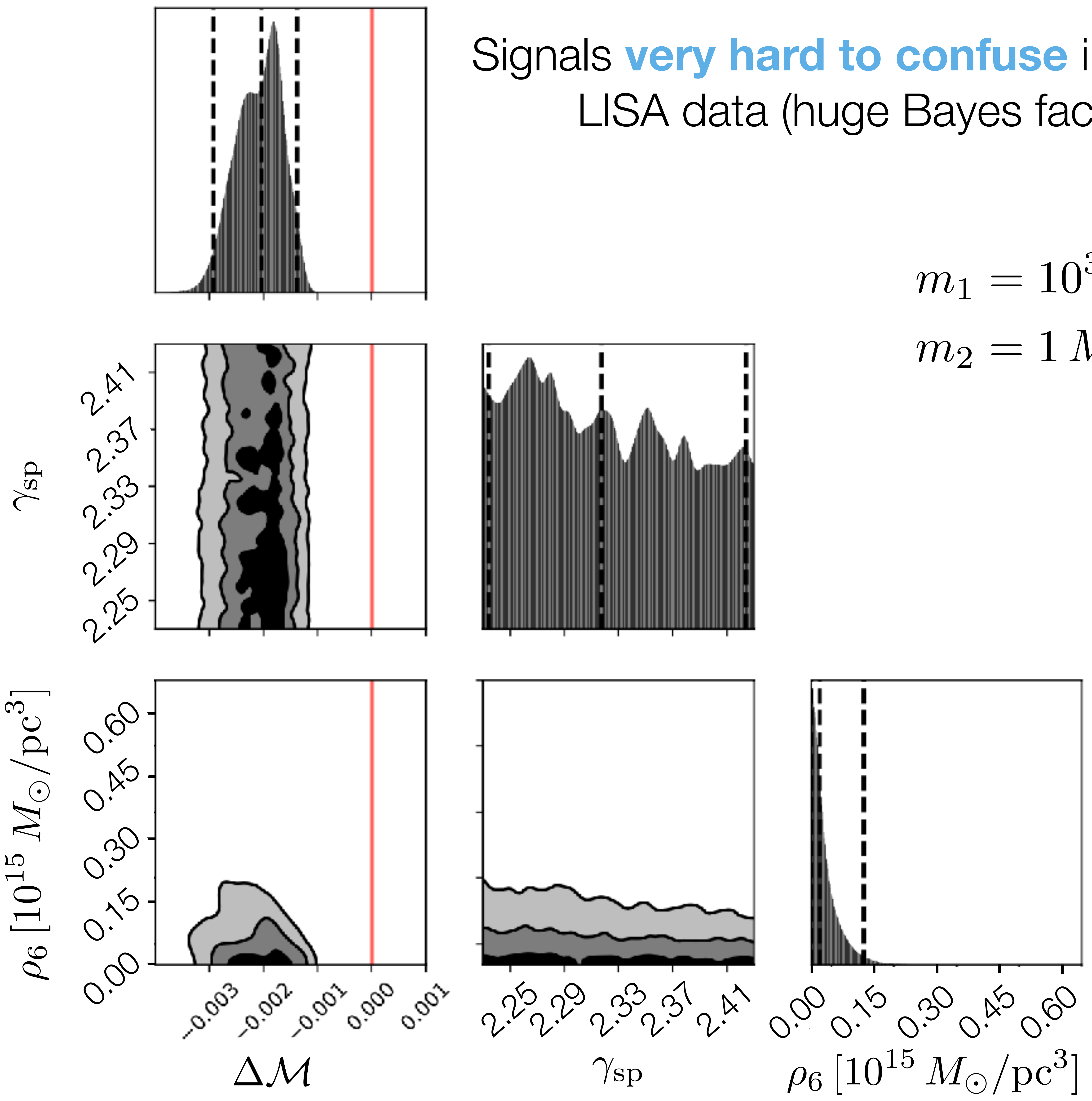
Generate waveform assuming:



$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1/2}$$

Fit signal assuming:



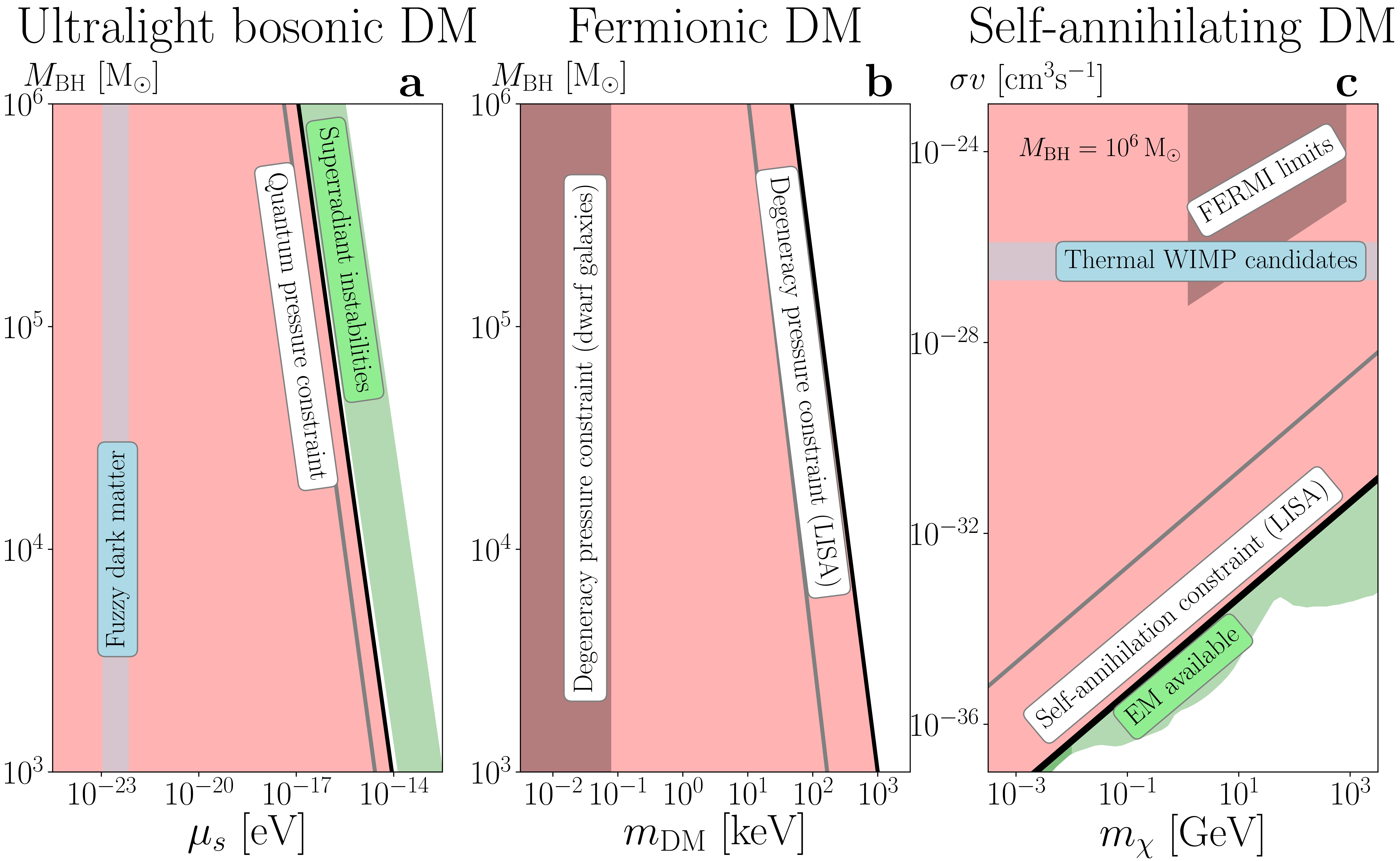


Signals **very hard to confuse** in 1 year of LISA data (huge Bayes factors!)

$$m_1 = 10^3\,M_\odot$$
$$m_2 = 1\,M_\odot$$

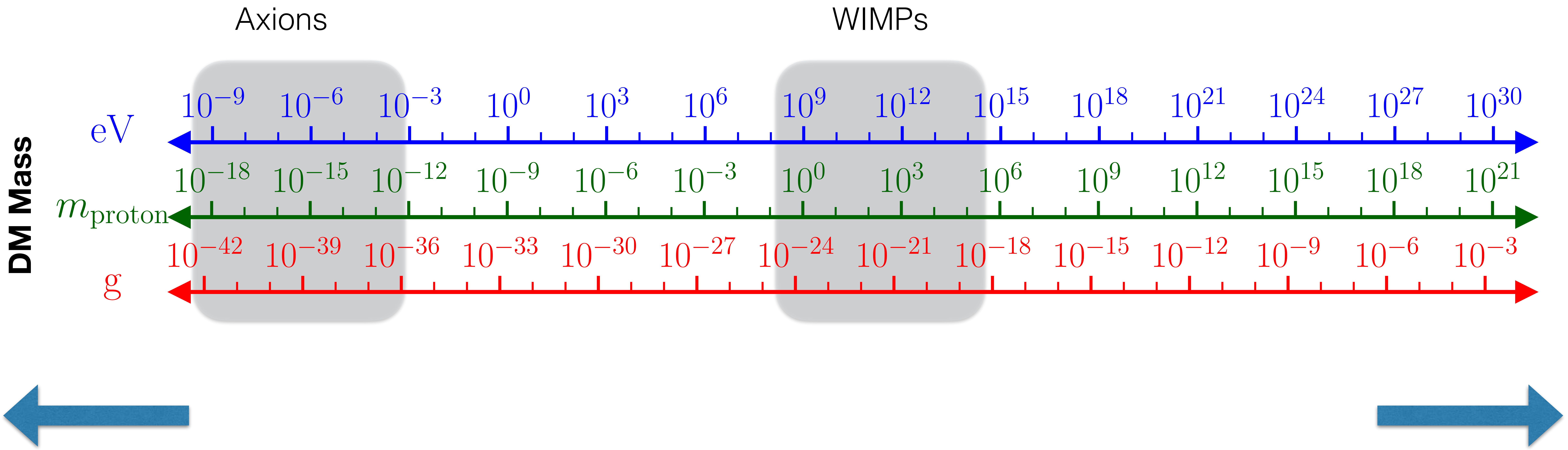
Nature of Dark Matter

Red regions would be ruled out by observation of a DM spike! [1906.11845]



[See also Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

Dark Matter Mass Range



Very light DM ($\lesssim 10^{-22}\,\mathrm{eV}$) has wave-like properties on astrophysical scales, spoiling galactic structure

Very heavy DM ($\gtrsim 10^{3}\, M_{\odot}$) is 'discrete' on astrophysical scales, spoiling galactic structure

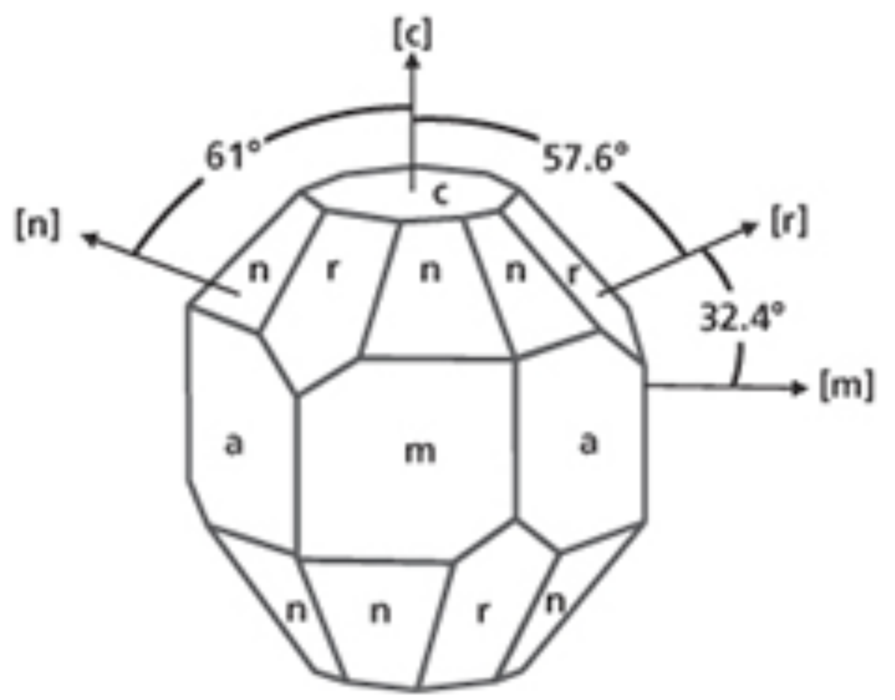
New Directions in the search for DM

Cosmological and astrophysical evidence for Dark Matter is overwhelming

Low-threshold phonon detectors

Black Holes and Gravitational Waves

No convincing detection of DM particles, or DM on small scales, has been made



The search for DM is diversifying!

"…the new guiding principle should be '**no stone left unturned**'…"

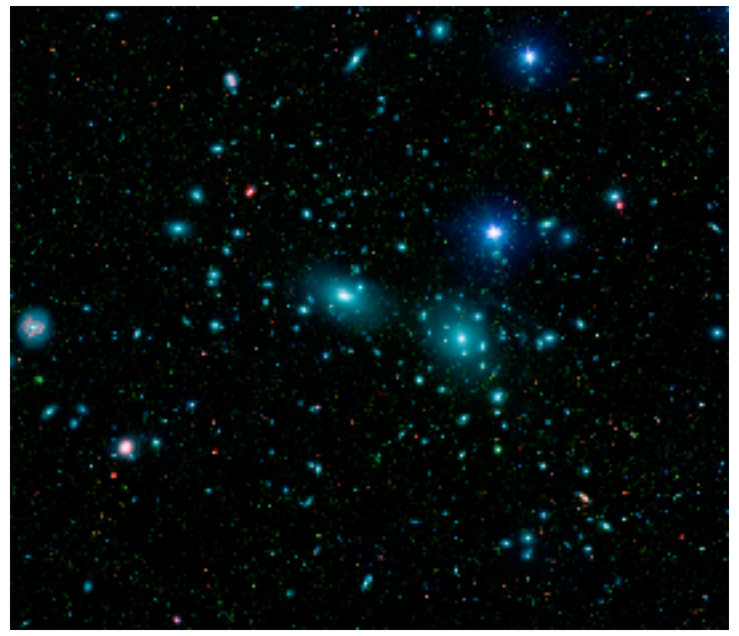
[Bertone & Tait, Nature, 562, 51–56 (2018), 1810.01668]

Backup Slides

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 $\sim 100\, M_\odot / L_\odot$.

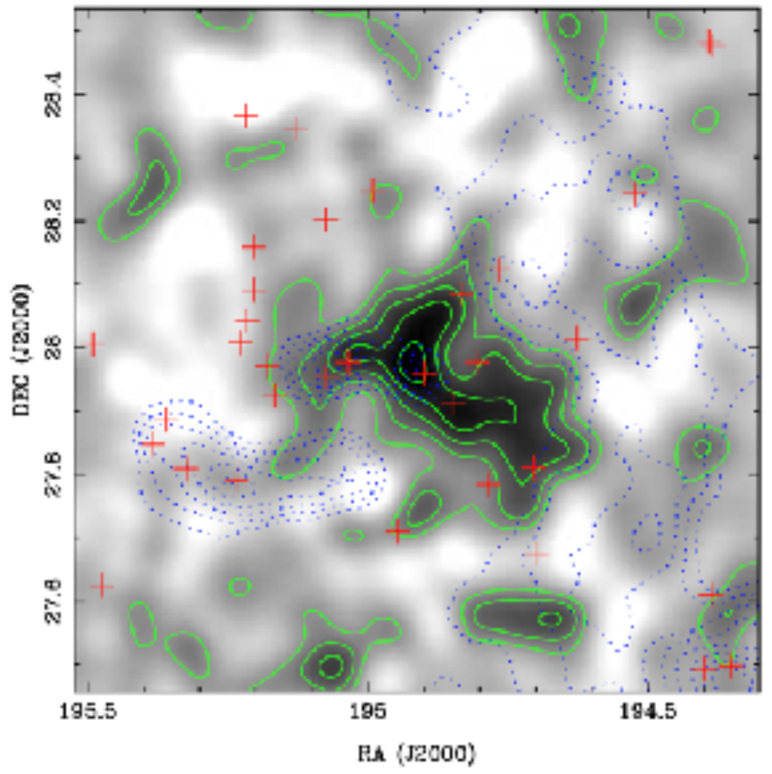
E.g. Coma Cluster



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

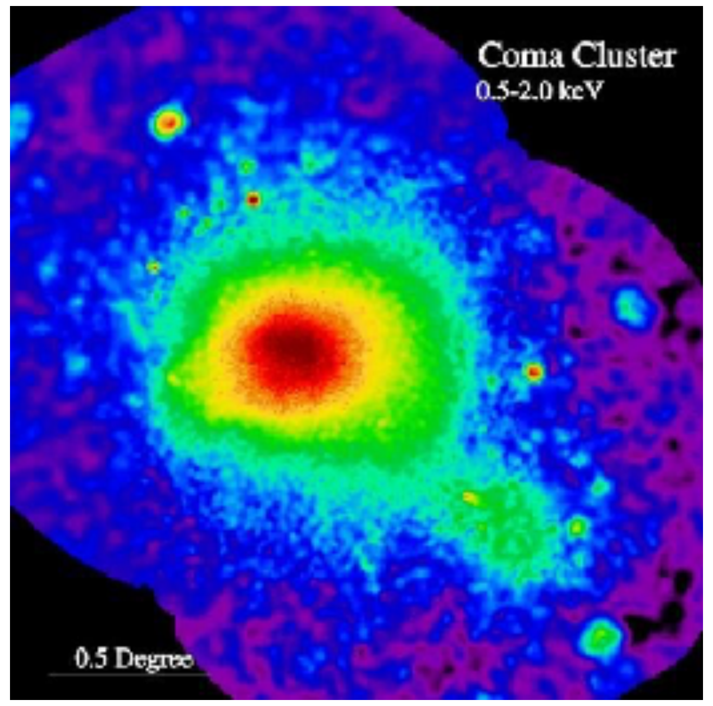
$$\langle T \rangle \approx \frac{1}{2} M_{\rm tot} \sigma_v^2 = -\frac{1}{2} \langle V_{\rm tot} \rangle$$

[0904.0220]



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

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



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

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

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]

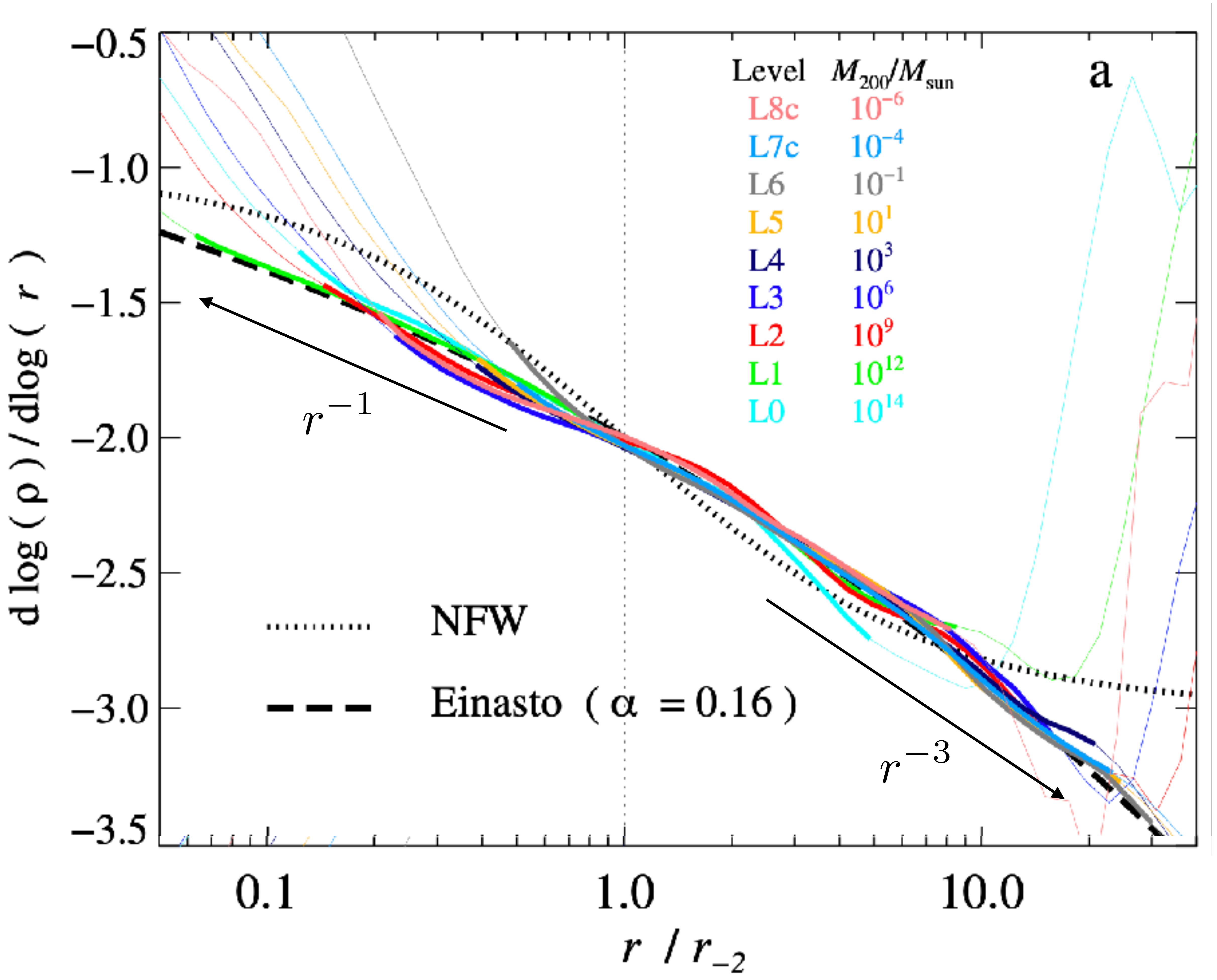
$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

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

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

Mass and concentration of halo ($c = r_s/r_{\rm max}$) 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]

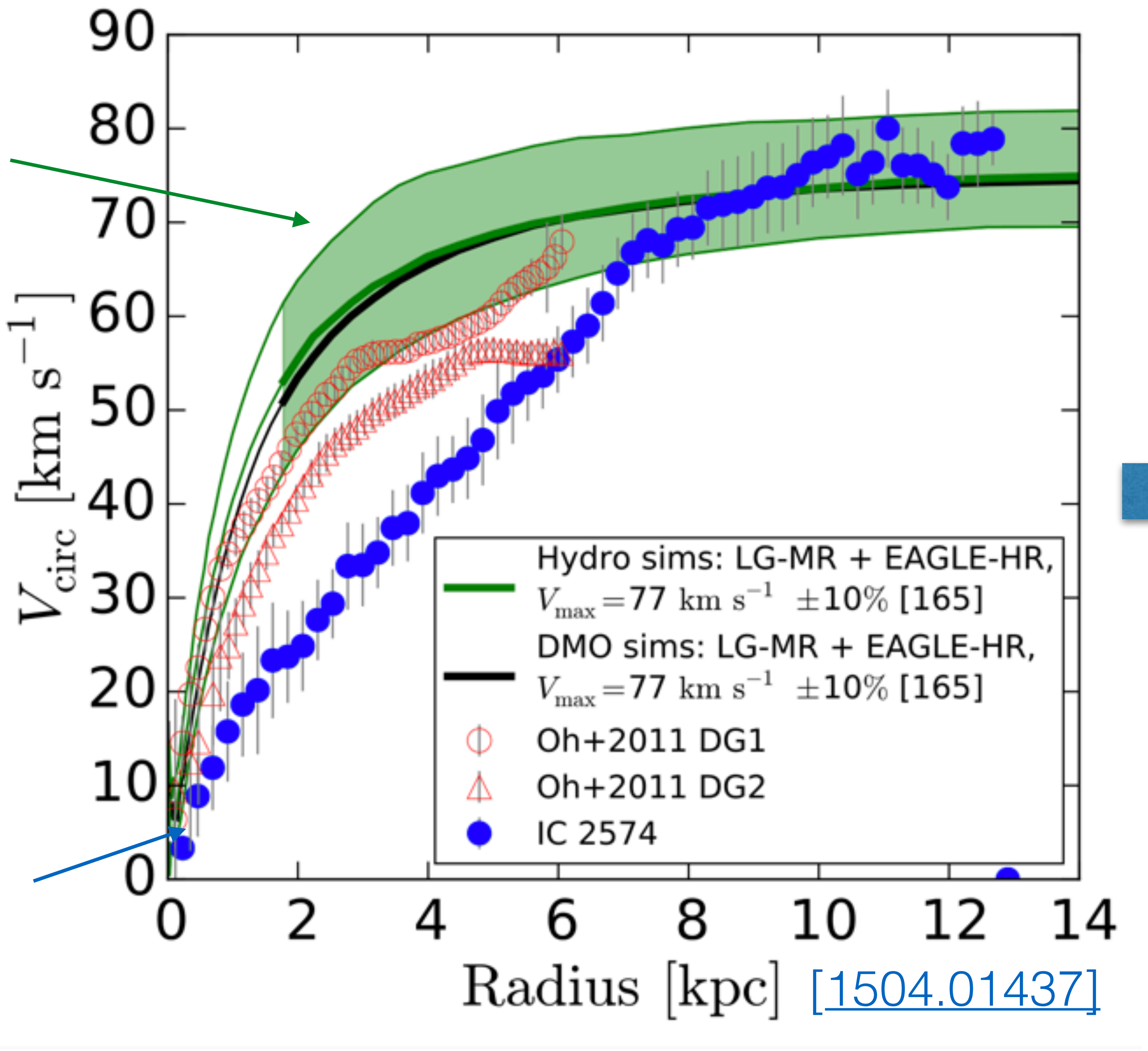
Small-scale problems

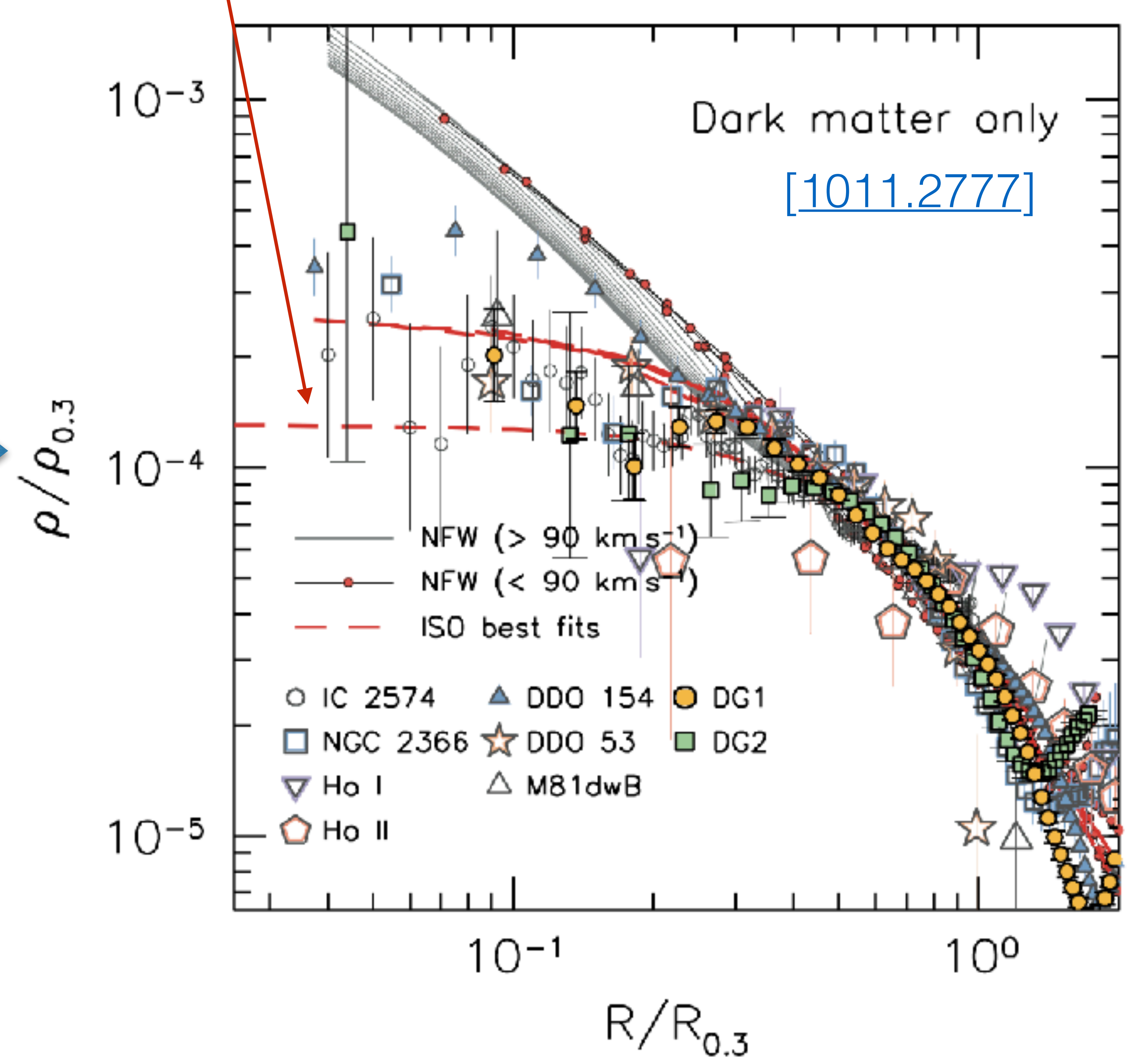
Core-vs-cusp problem (Now sometimes called the “diversity of rotation curves’ problem)

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

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

Measured rotation curve

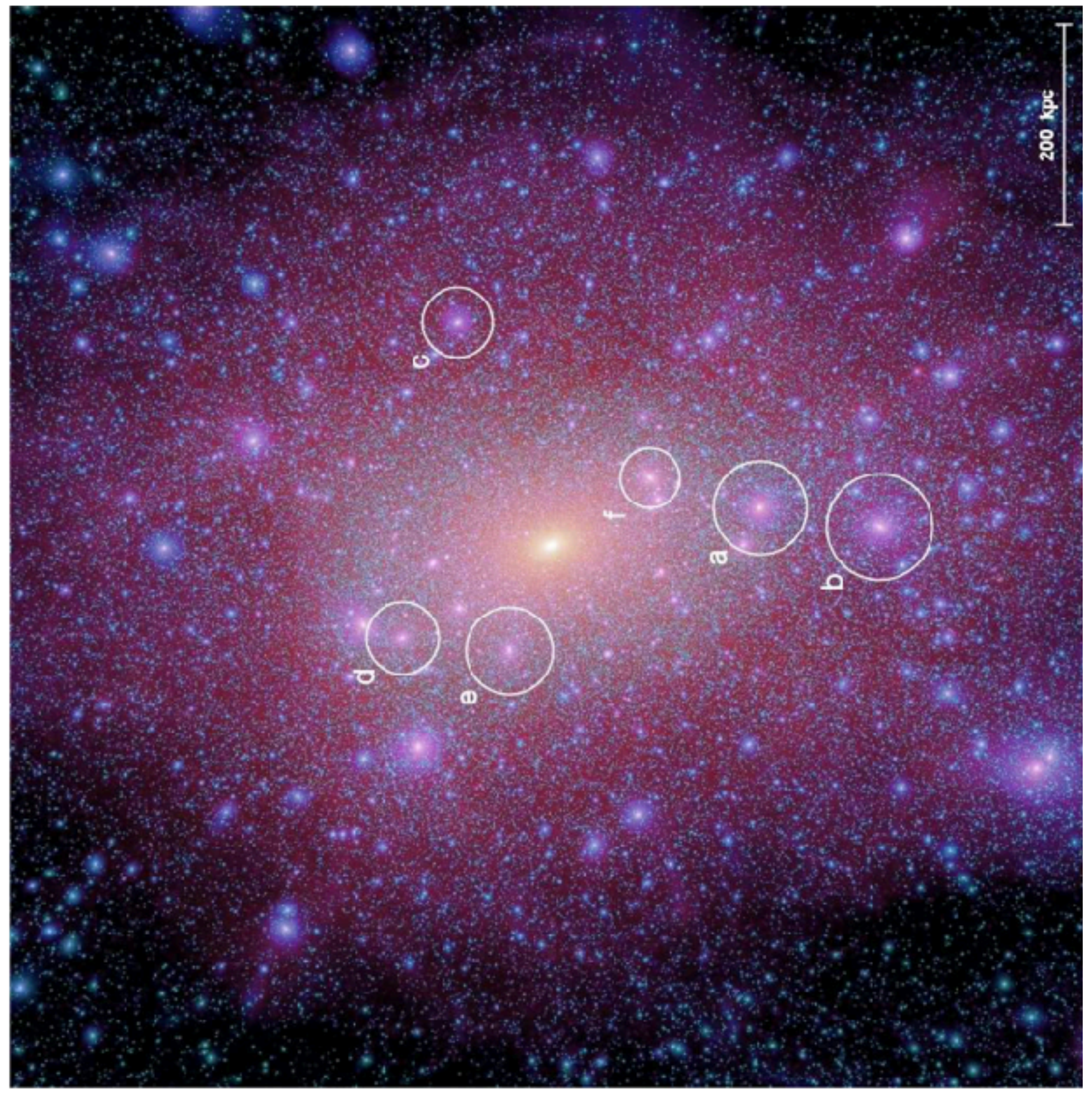


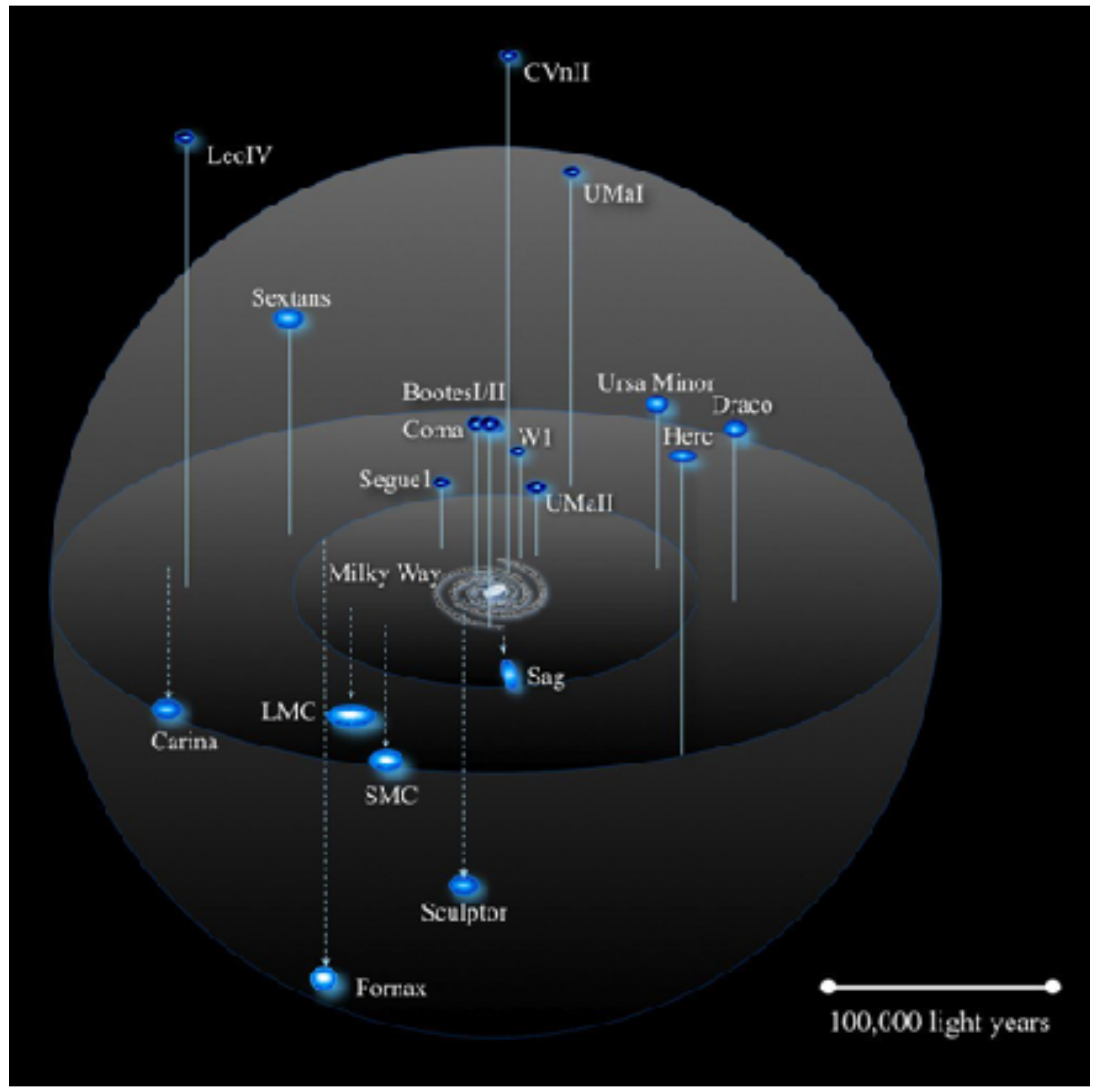


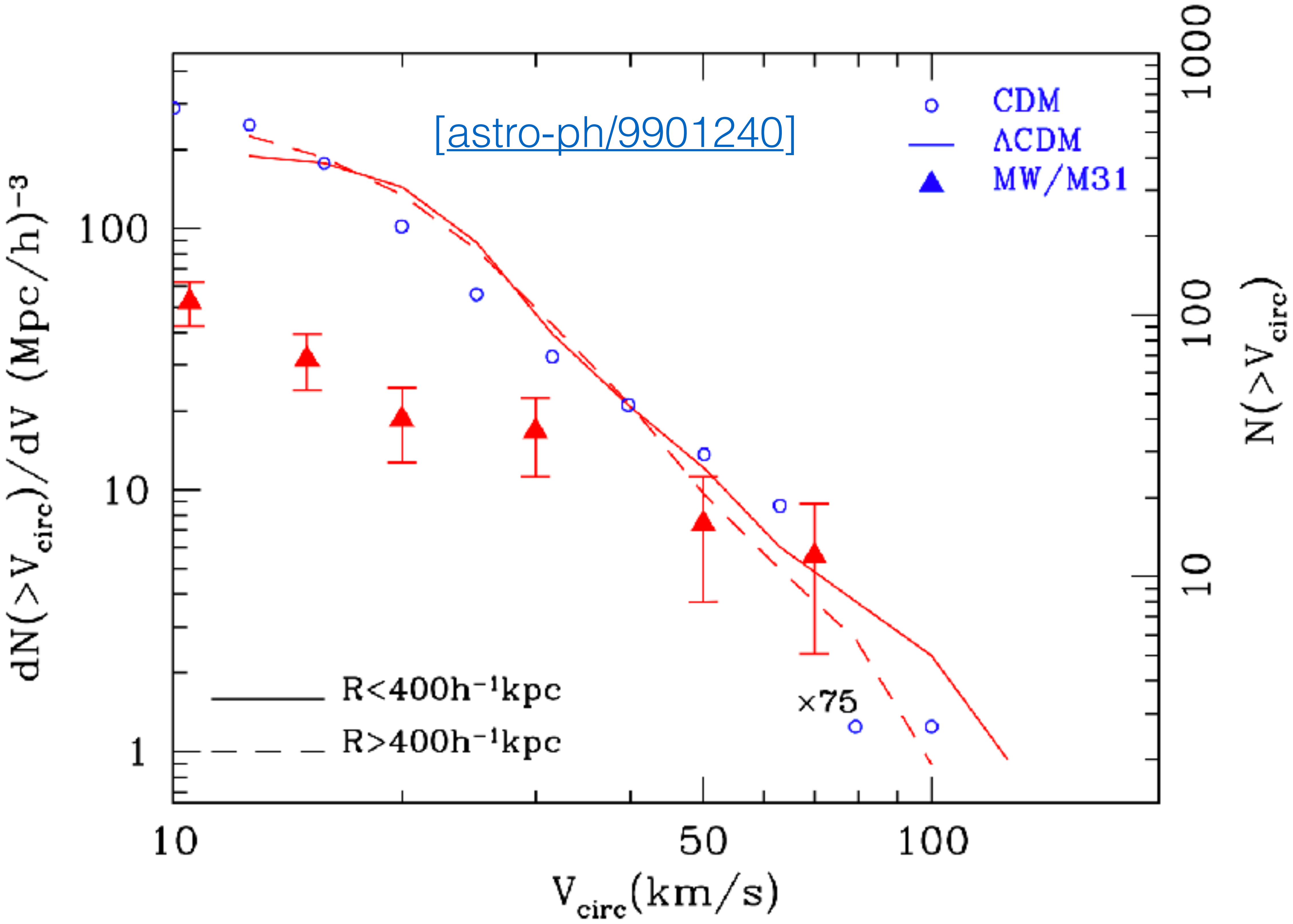
See also “Too big to fail”, “Plane of Satellites”, and others… [Sales, Wetzel & Fattahi, 2206.05295]

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…

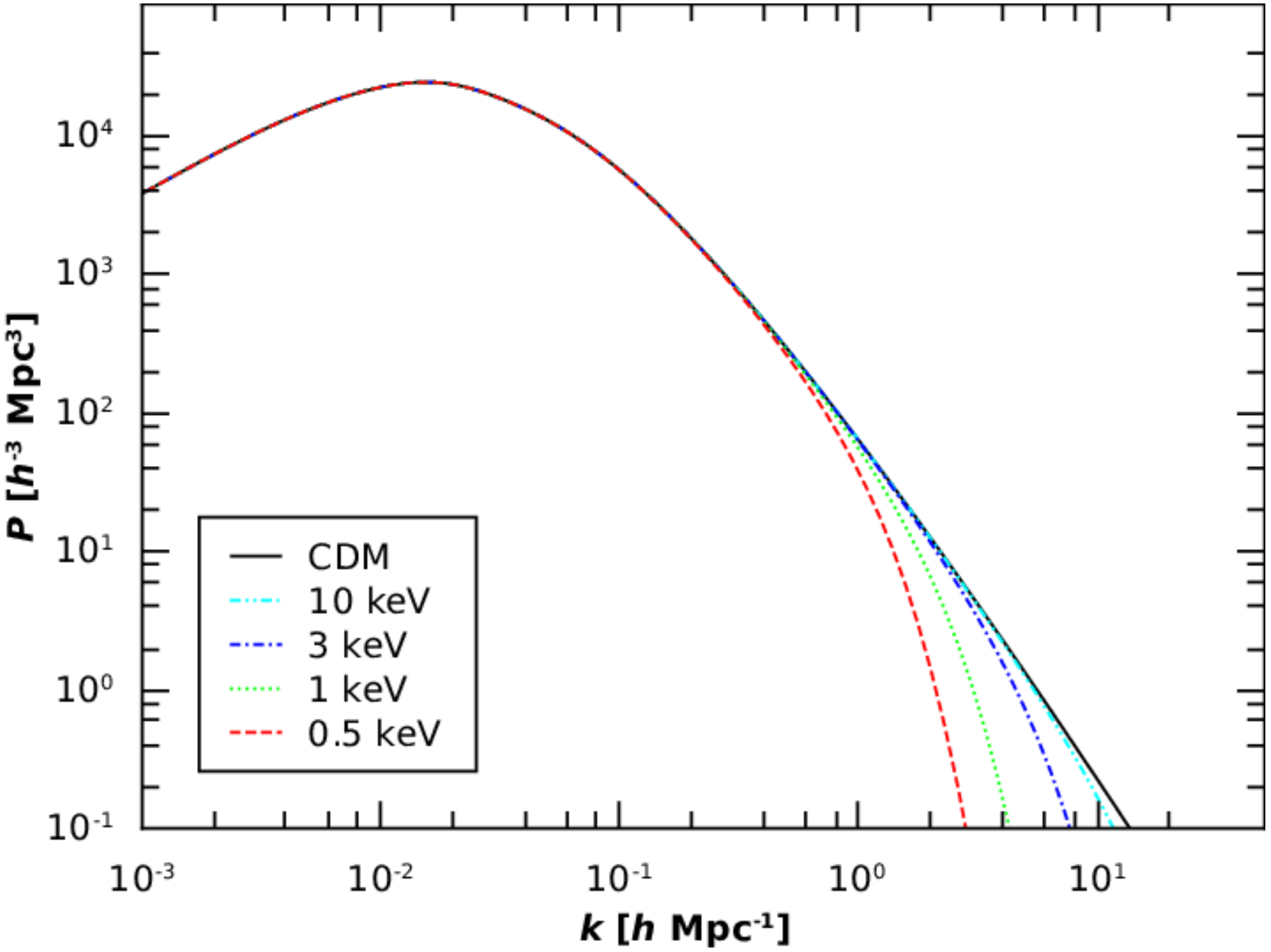
[Sales, Wetzel & Fattahi, 2206.05295]

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:

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

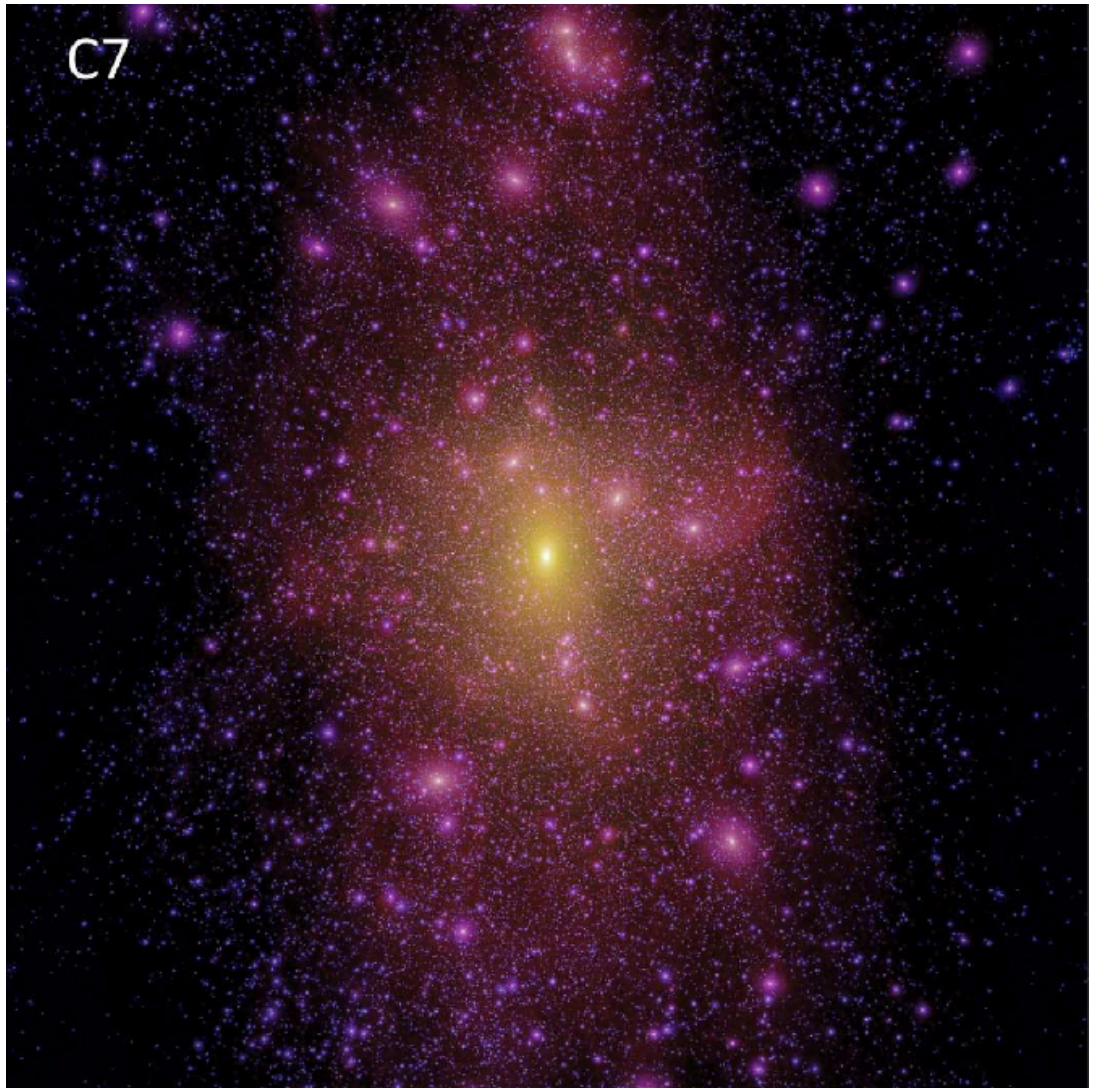


[astro-ph/0010389]

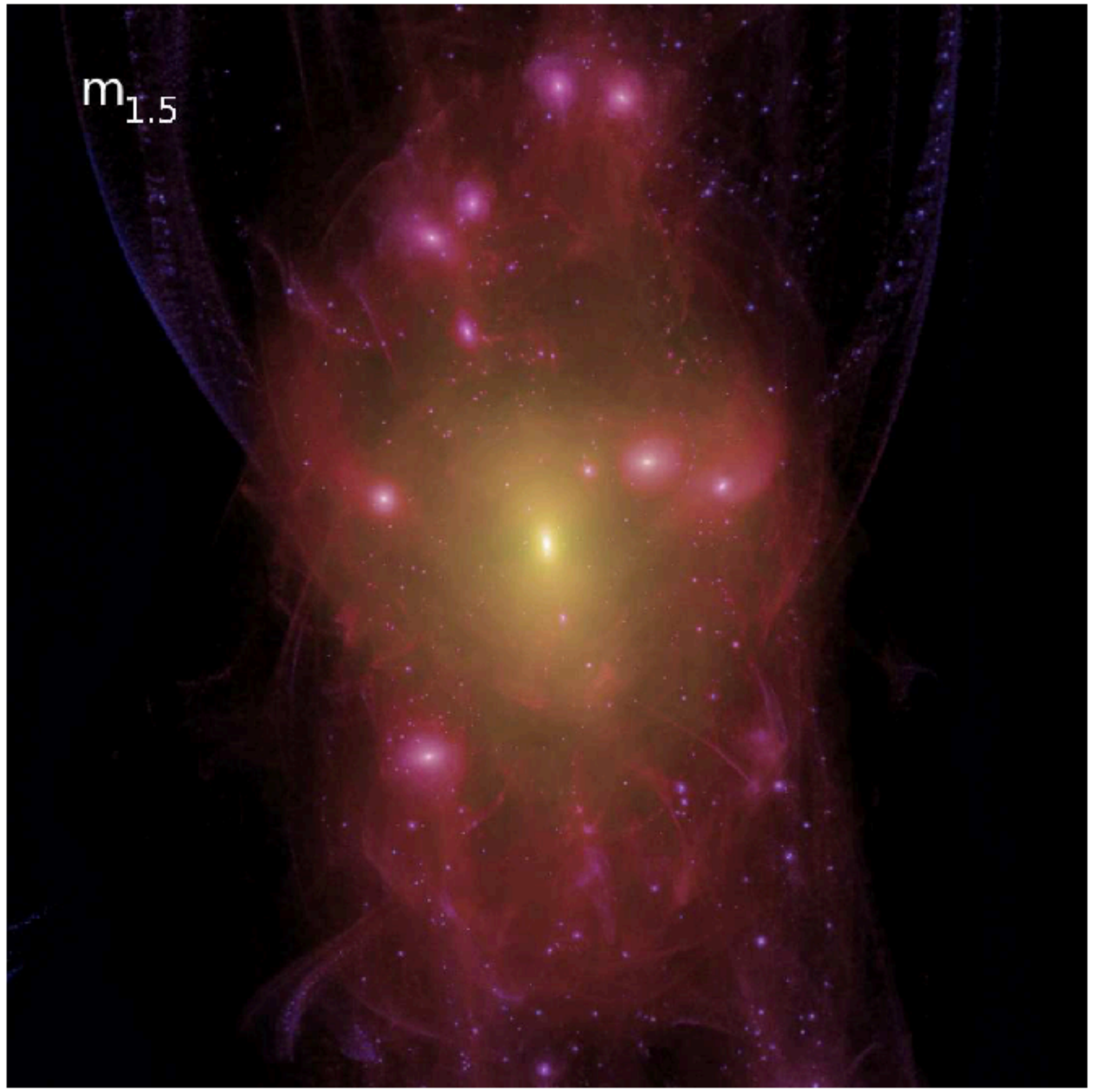
Warm Dark Matter

[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 $m_{\mathrm{WDM}} \gtrsim 4\,\mathrm{keV}$.

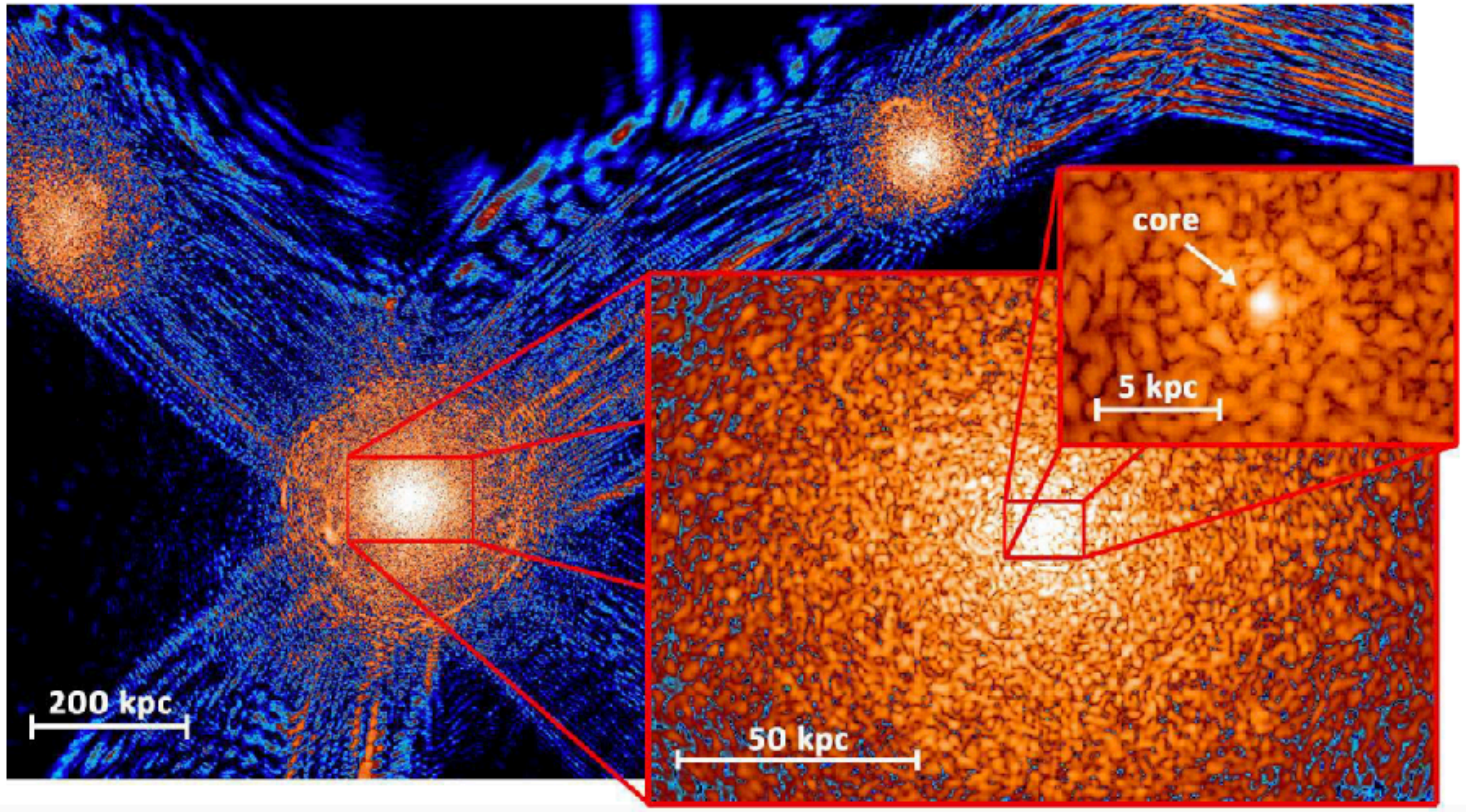
[2011.08865]

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.

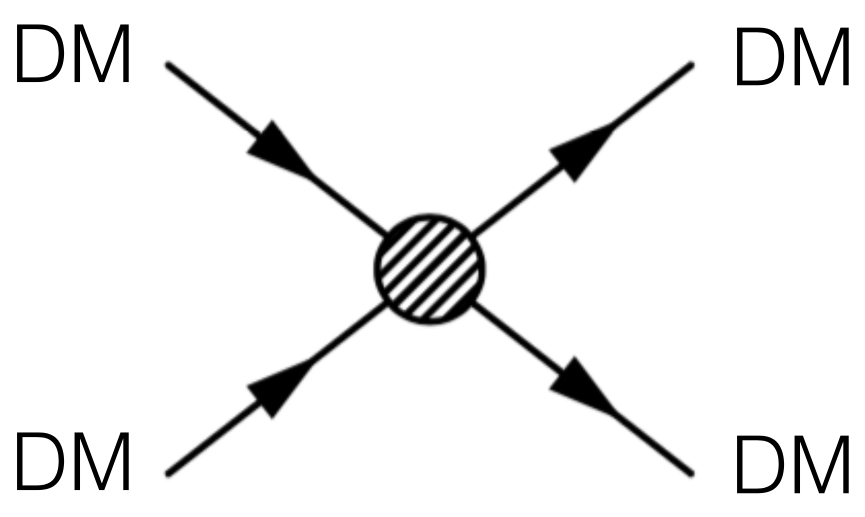


$$\lambda_J \propto (1+z)^{1/4} m_\psi^{-1/2}$$

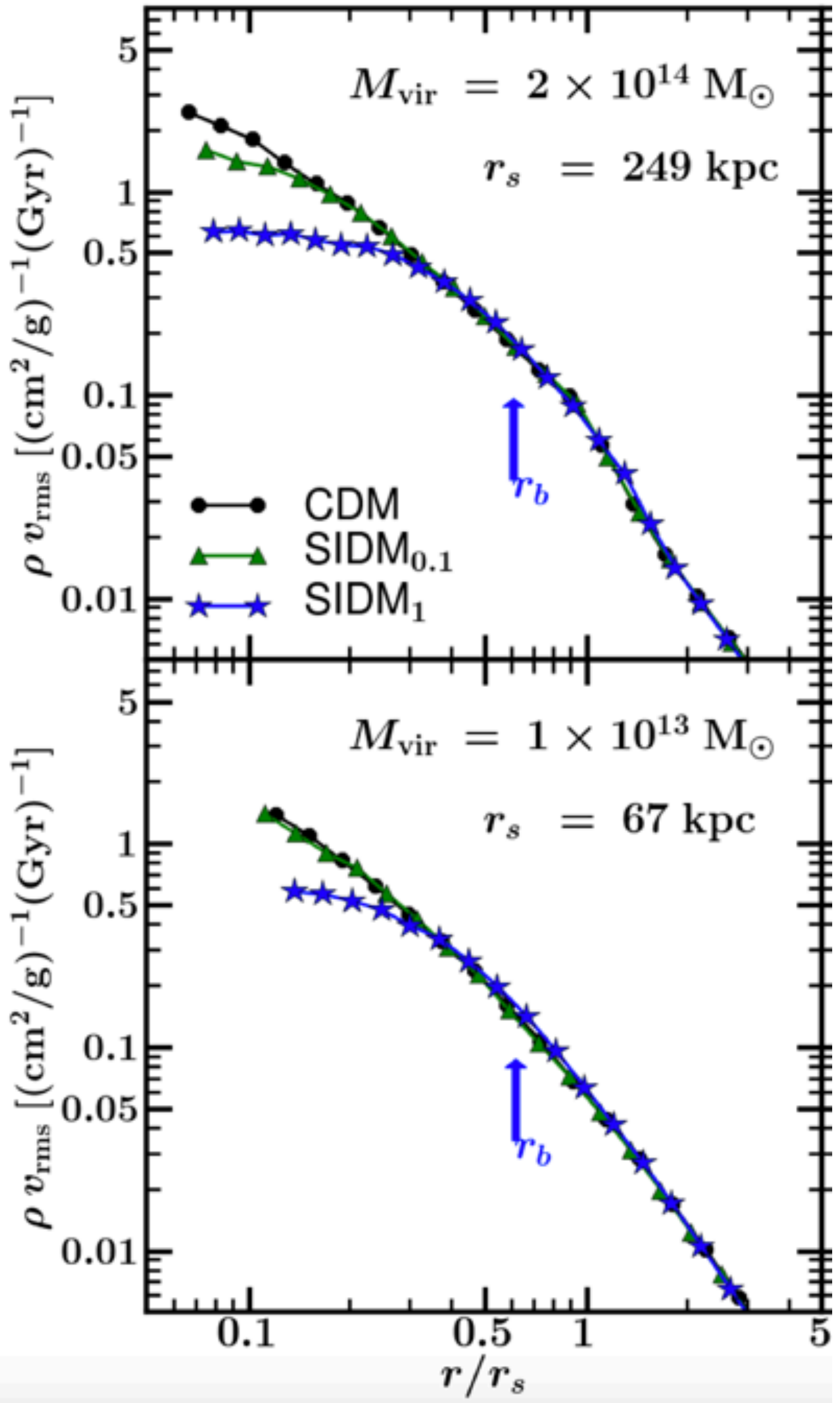
[1406.6586]

Self-interacting Dark Matter

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



[1208.3025]



The Boltzmann Equation

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

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

Dilution due to expansion

Annihilation of DM

Production of DM

Equilibrium number density for fermions is given by:

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

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:

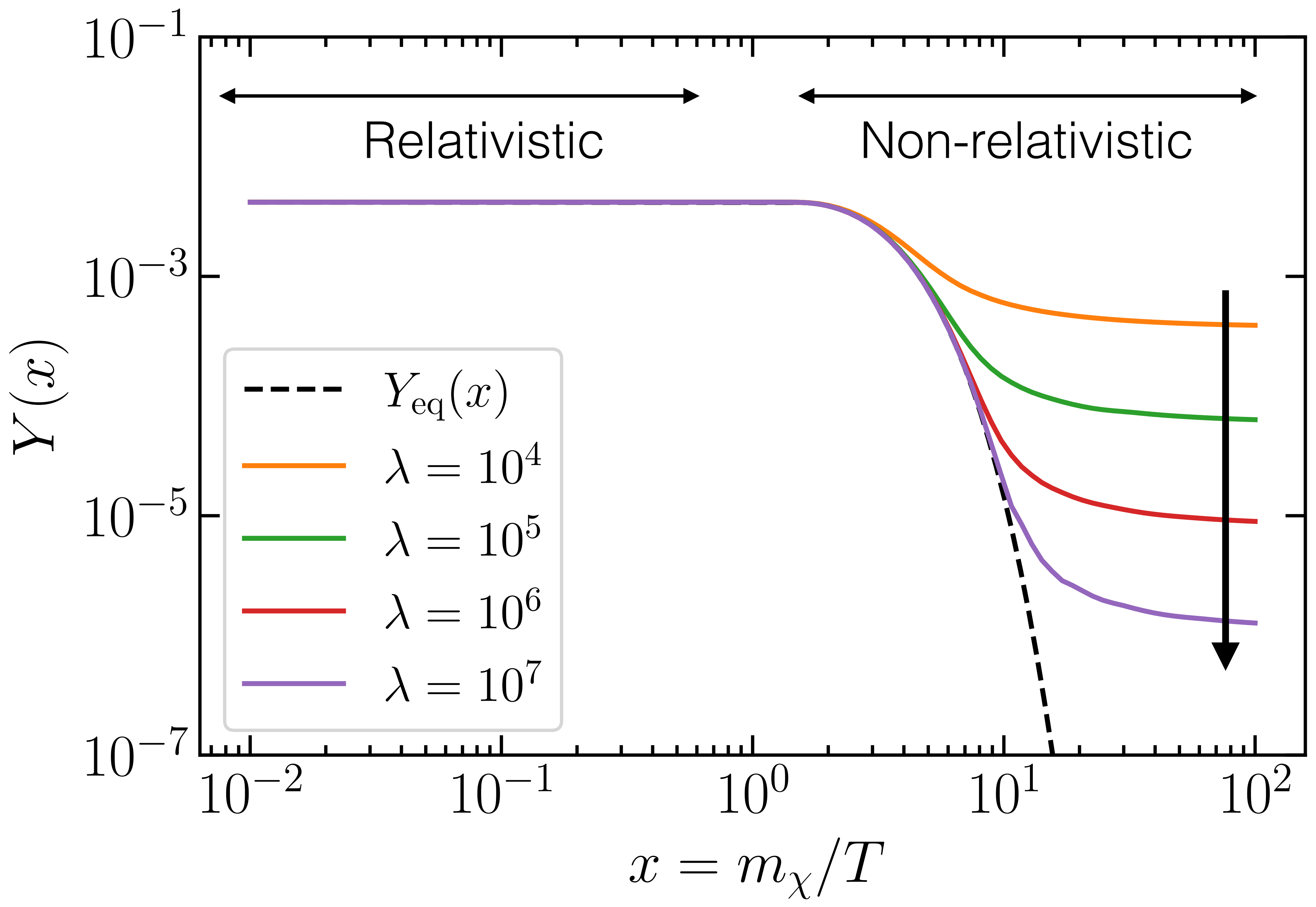
$$\Gamma \equiv n_\chi\langle\sigma_{\chi\bar{\chi}}v\rangle_{\rm eq} \sim 1/H$$

Freeze-out

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 $a \propto t^{1/2} \Rightarrow H(T) \propto T^2$)

Cold vs Hot Dark Matter

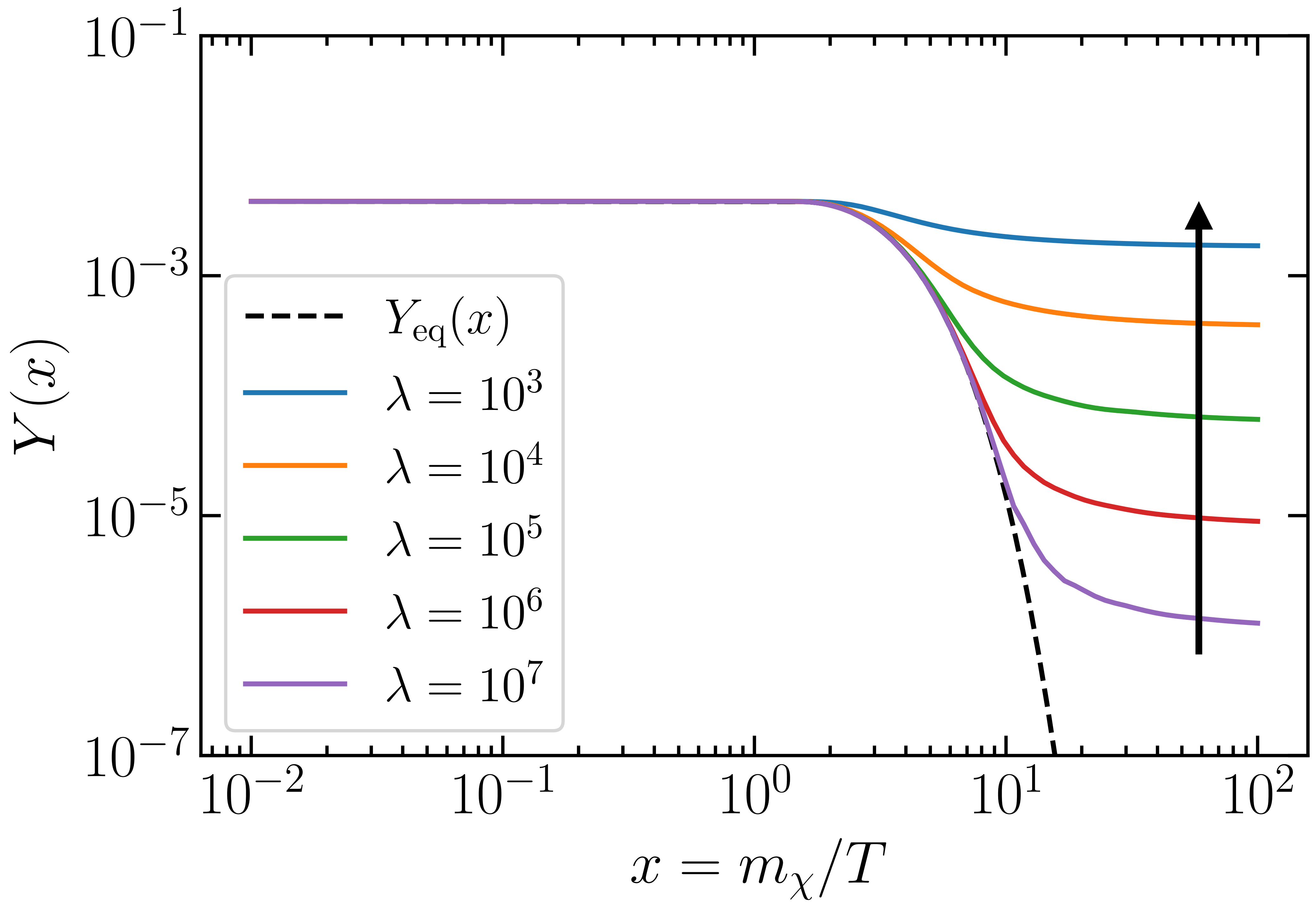
$$\lambda = \frac{2\pi^2}{45} g_{\star s} \frac{m_\chi^3 \langle \sigma v \rangle}{H(T = m_\chi)}$$

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

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

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 $\langle \sigma v \rangle$)

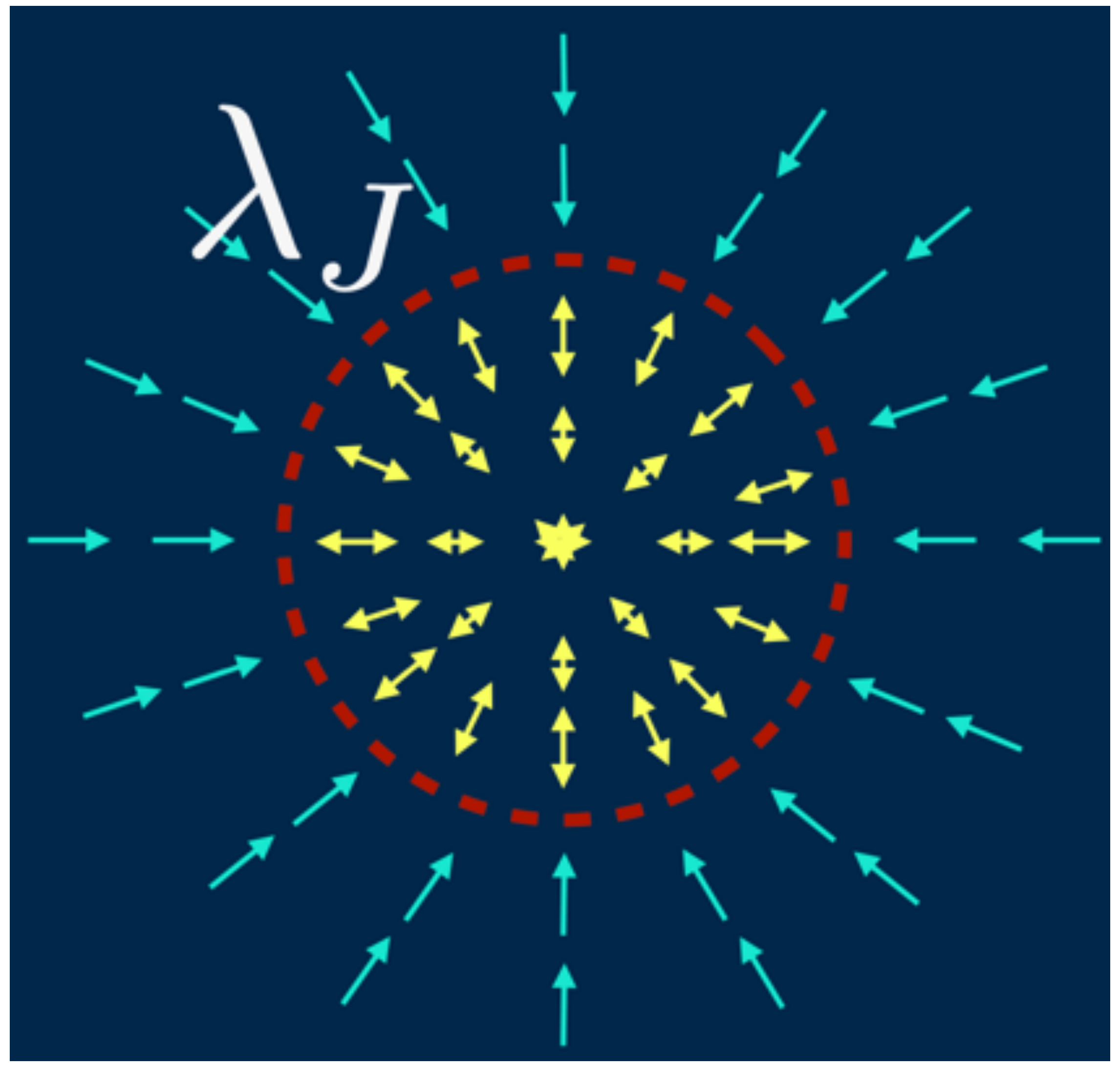
Very light relics $m \lesssim \mathrm{eV}$ decouple and freeze out when they are still relativistic! We call such particles **Hot Dark Matter**. Standard Model Neutrinos are Hot Dark Matter!

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

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!

Alternative Production Mechanisms

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

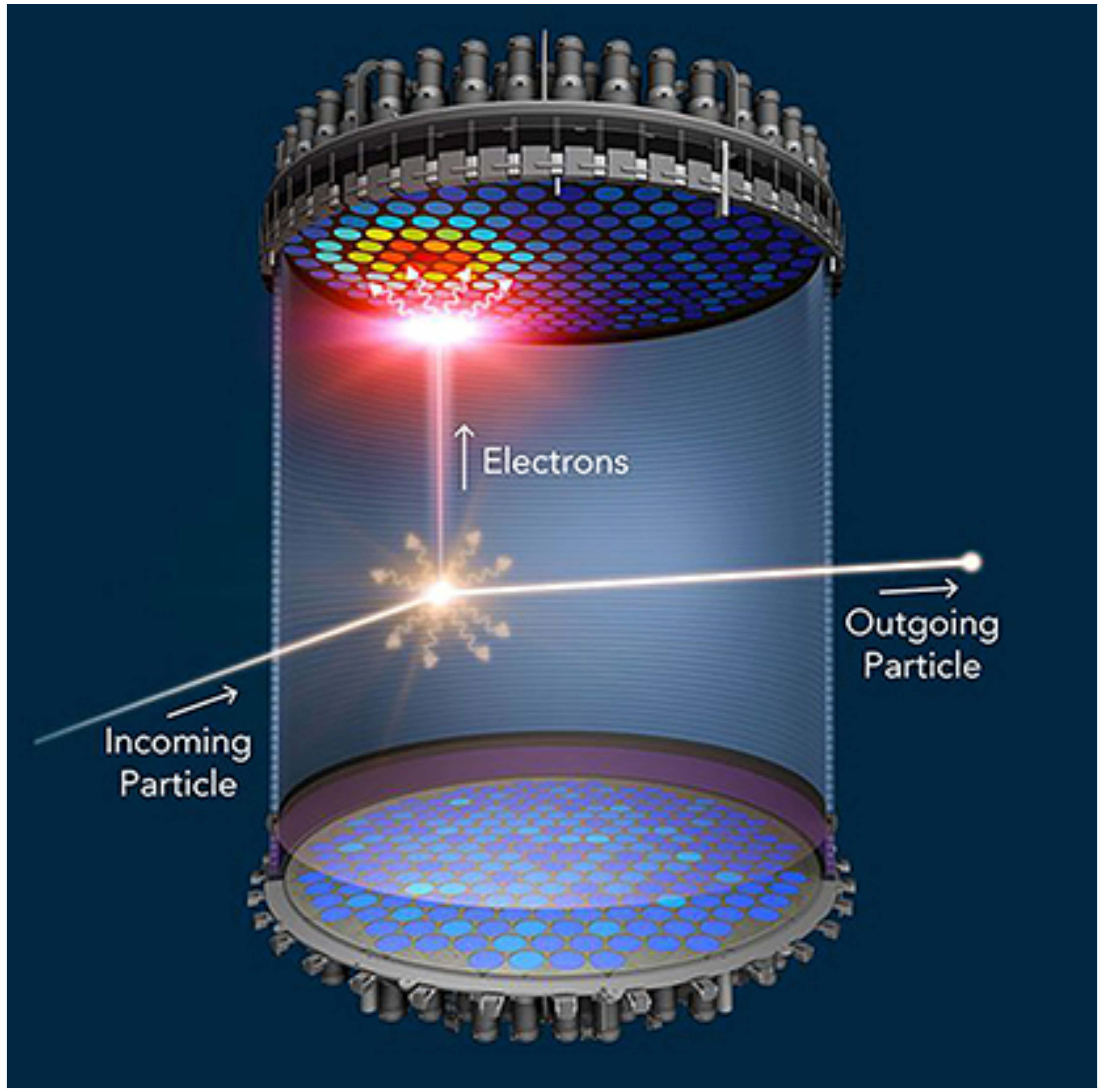
Freeze-out [Kolb & Turner (1990)]
Freeze-in [arXiv:0911.1120]
Asymmetric Dark Matter [arXiv:1305.4939]
Forbidden Dark Matter [arXiv:1505.07107]
Secluded Dark Matter [arXiv:0711.4866]
SIMP Dark Matter [arXiv:1402.5143]
Self-interacting Dark Matter [arXiv:1510.08063]
Misalignment Mechanism [arXiv:1105.2812]
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]

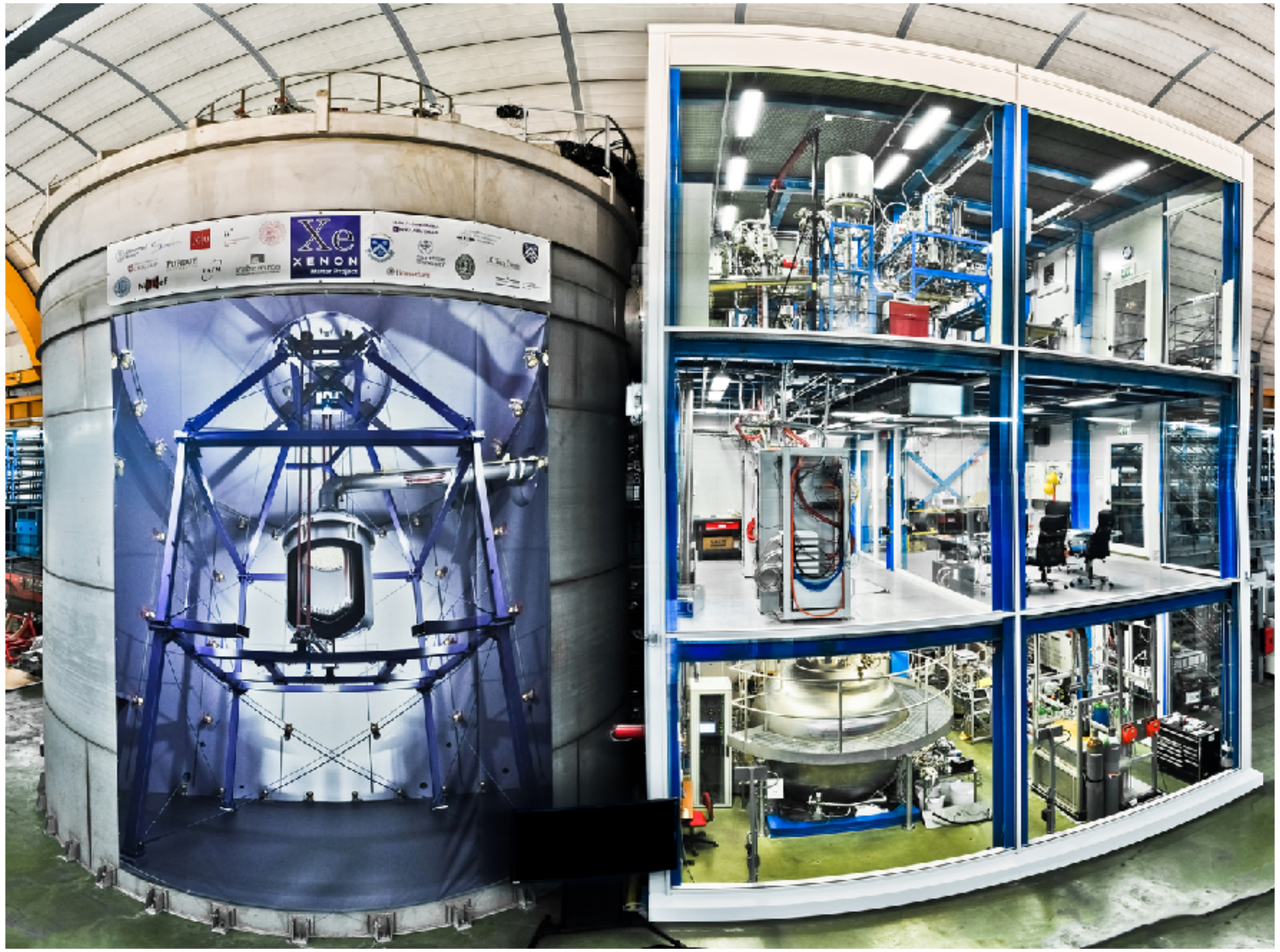
But all of them should satisfy constraints from early Universe, structure formation and astrophysics!

Example: Xenon Experiment

[2402.10446]

XenonNT experiment operated at the Gran Sasso National Laboratory (Italy)



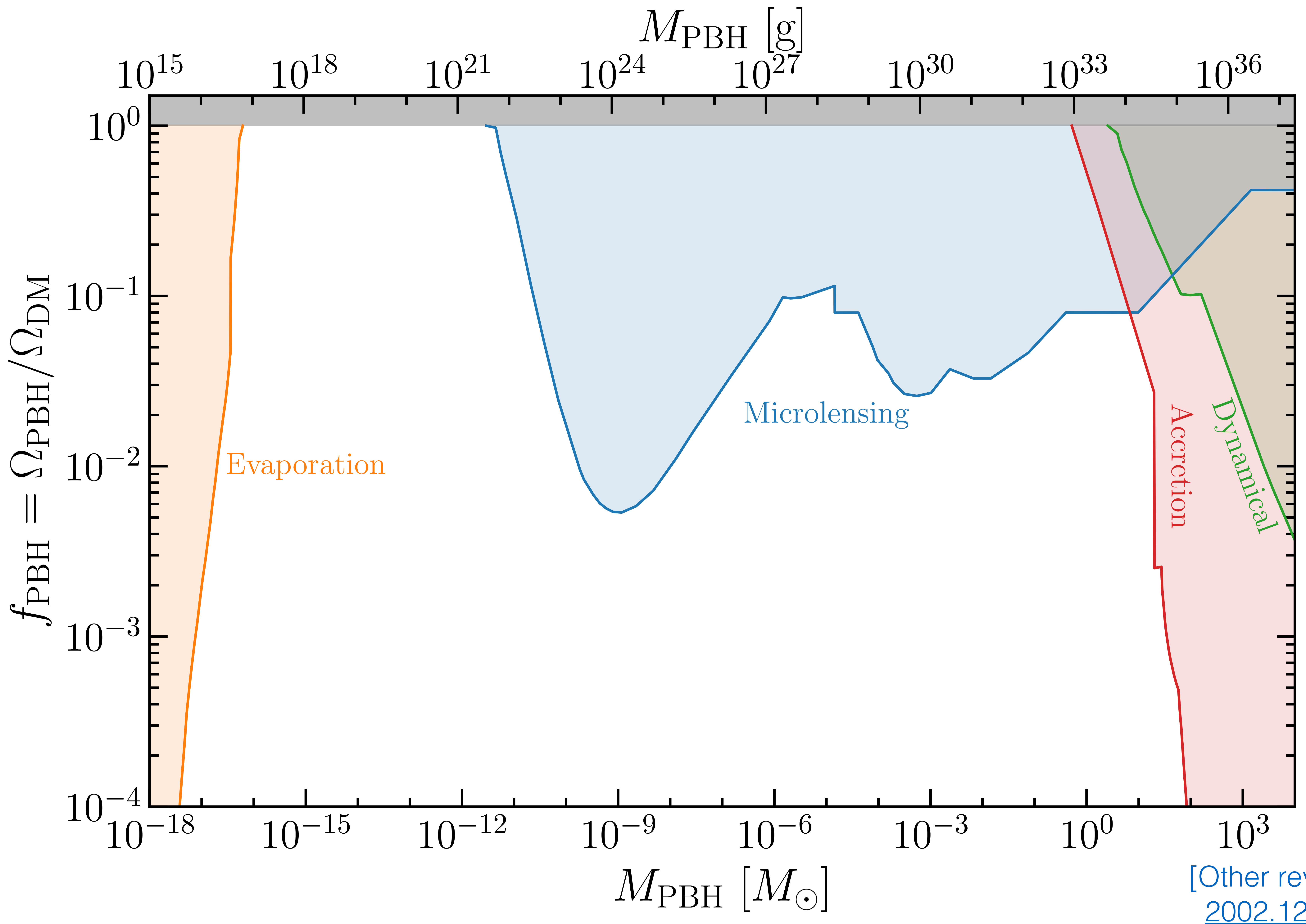


Credit: XENON Collaboration

PBH Parameter Space

[Green & **BJK**, 2007.10722]

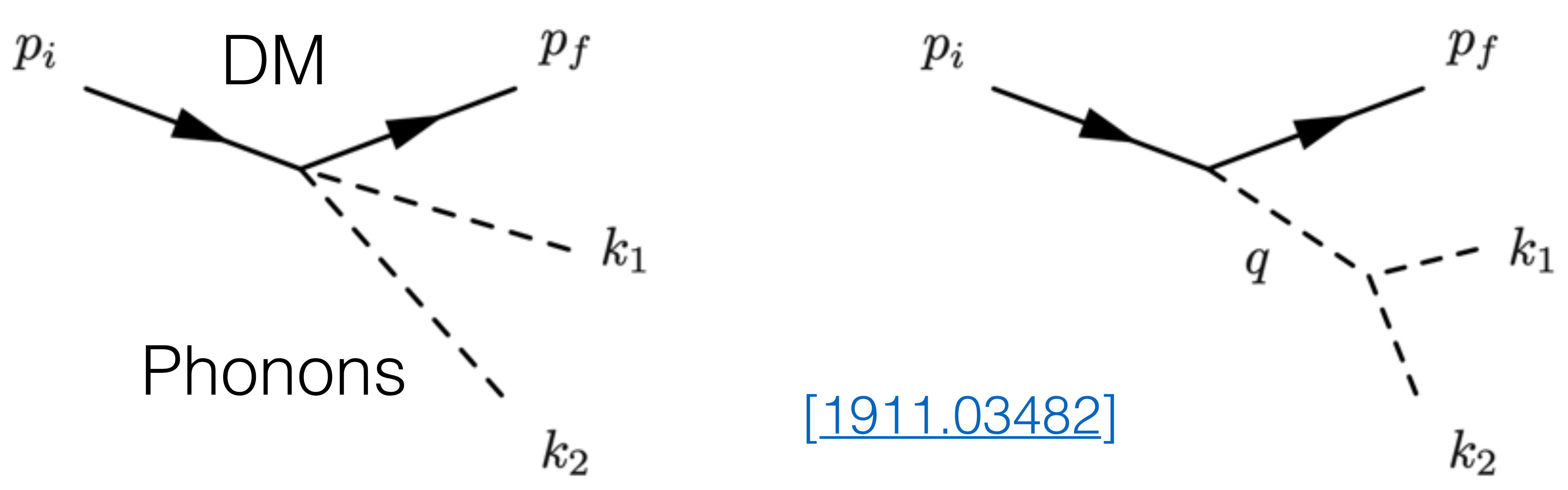
[Code online: github.com/bradkav/PBHbounds]

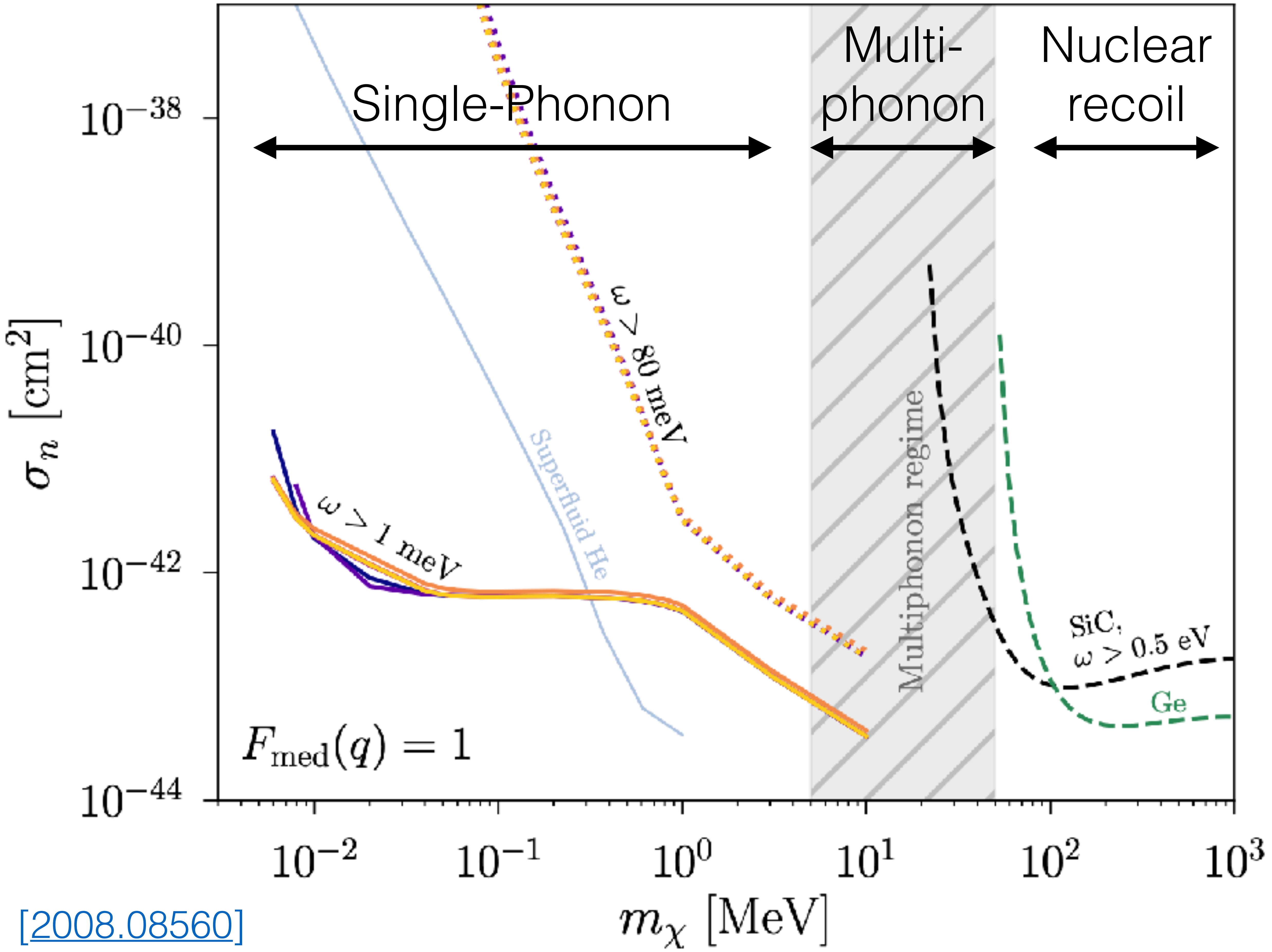


[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Multi-phonon Scattering

Each additional phonon comes with an extra factor of $q/\sqrt{m_N\omega}$ in the matrix element





[2008.08560]

Heavier DM leads to larger q, so multi-phonon scattering may become relevant masses $\gtrsim$ few MeV

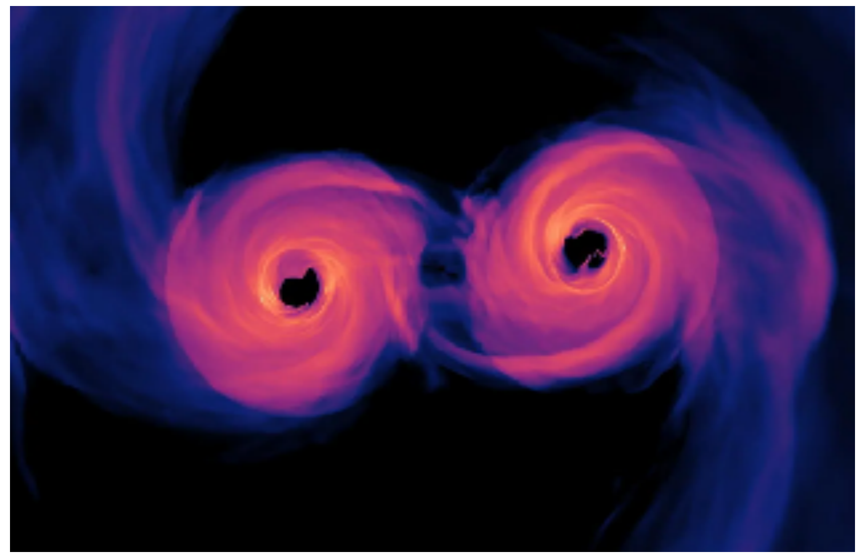
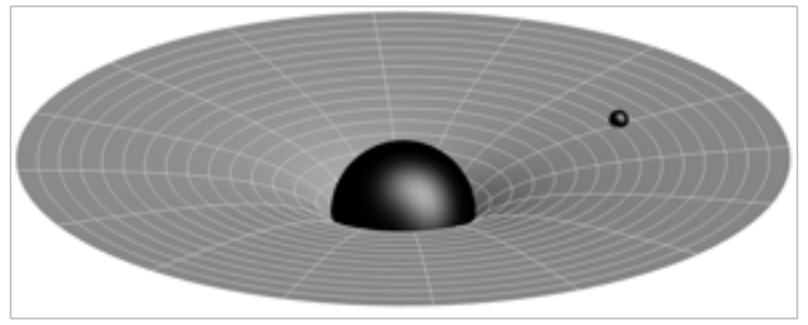
[1608.01994, 1910.08092, 1911.03482]

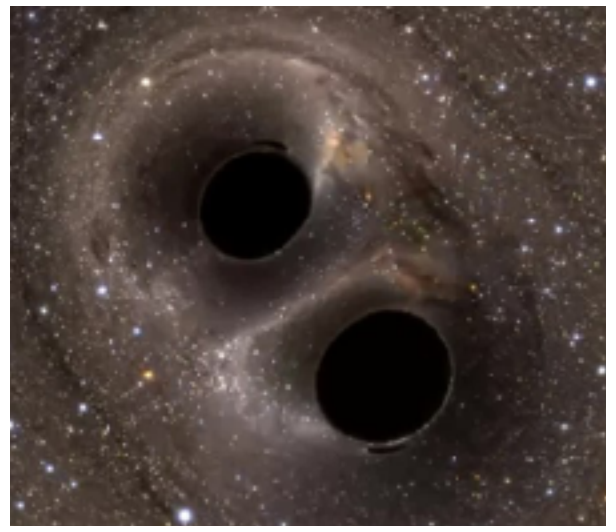
The Gravitational Wave Spectrum

$$c = \lambda_{\mathrm{GW}} \cdot f_{\mathrm{GW}}$$

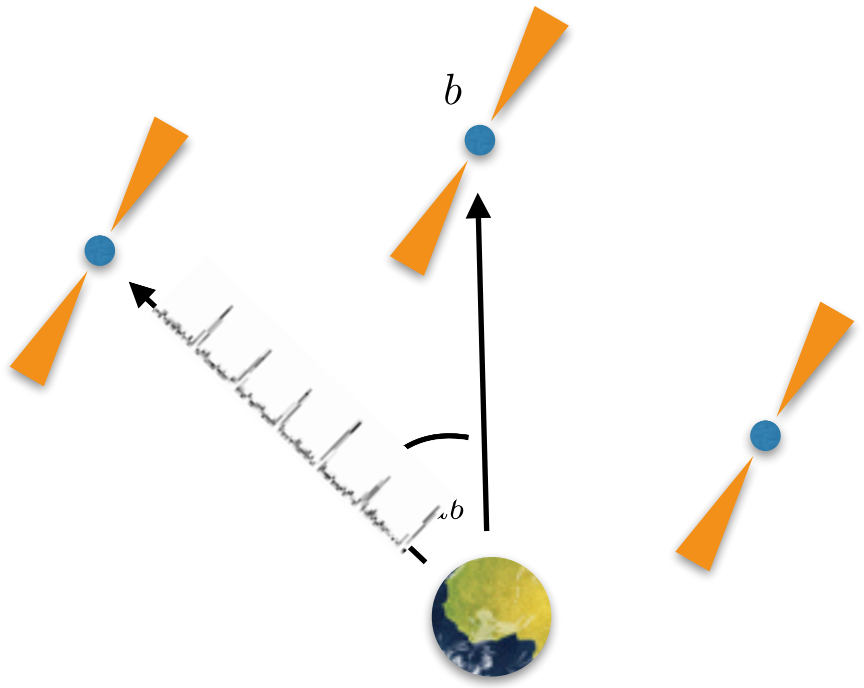
	nHz	μHz	mHz	Hz	kHz
f_{GW}	nHz	μHz	mHz	Hz	kHz
λ_{GW}	10^{13} km ~ pc	10^{11} km	10^{8} km	10^{5} km	100 km
T_{GW}	30 years	10 days	15 minutes	1 second	1 ms

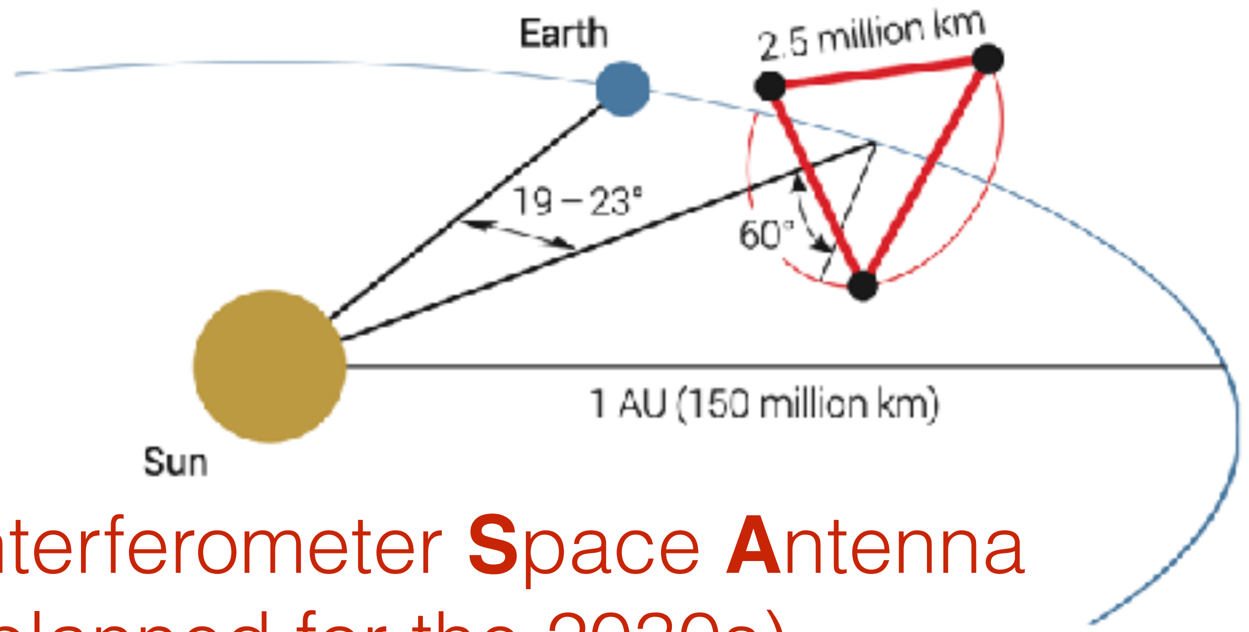
SOURCES



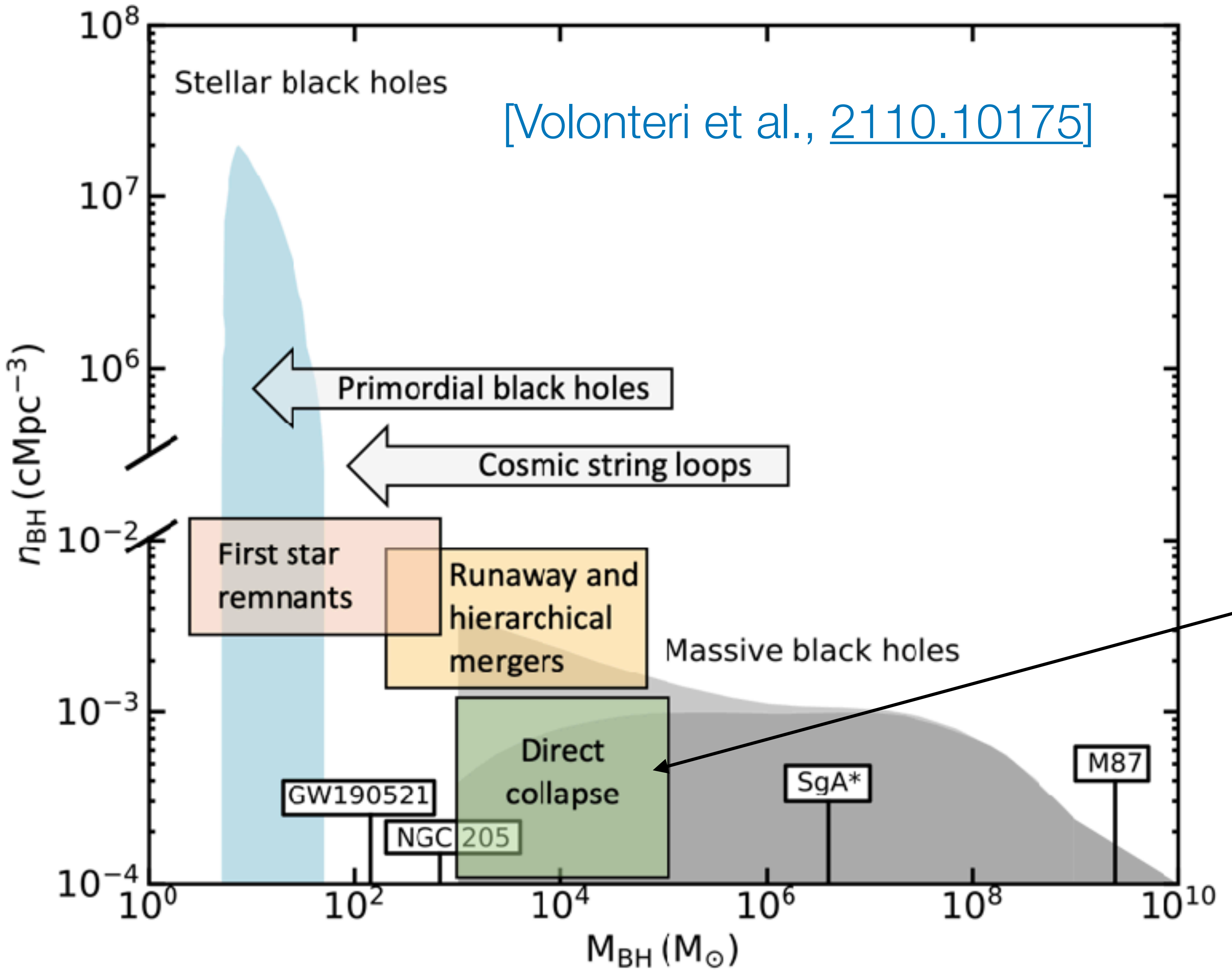
DETECTORS?



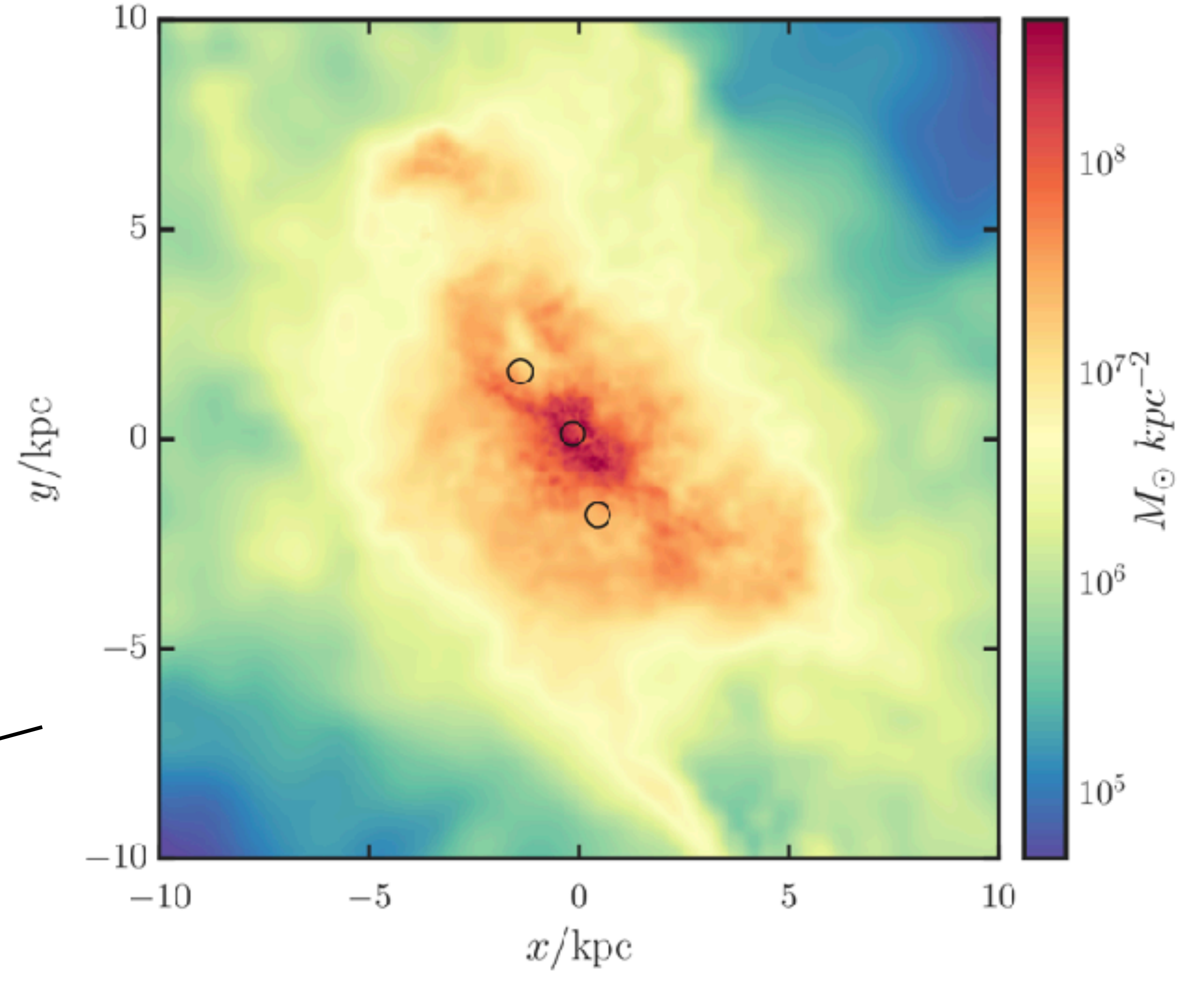


Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s)
[1907.06482]

BH and Spike Formation



[Dunn et al., 1803.01007]



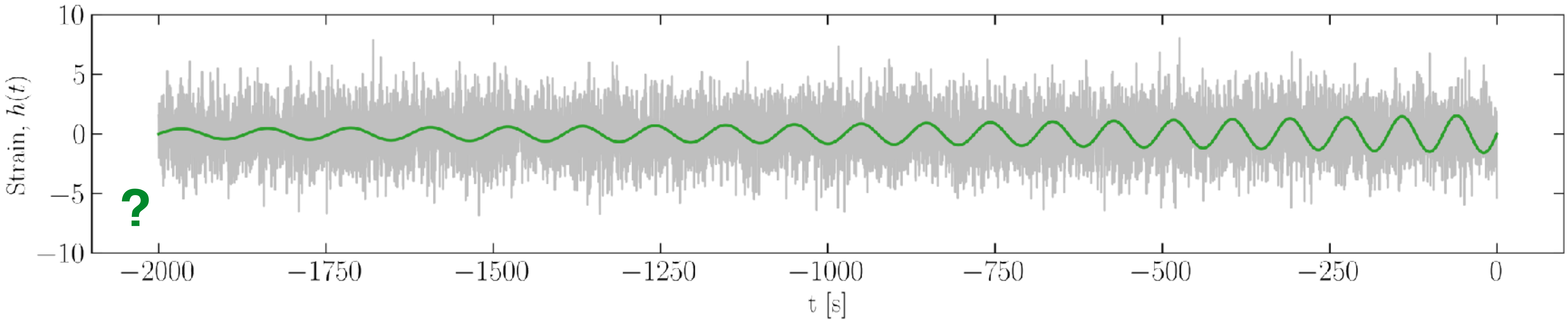
Use semi-analytic galaxy formation models to study the properties of Direct Collapse Black Holes and the halos they form in.

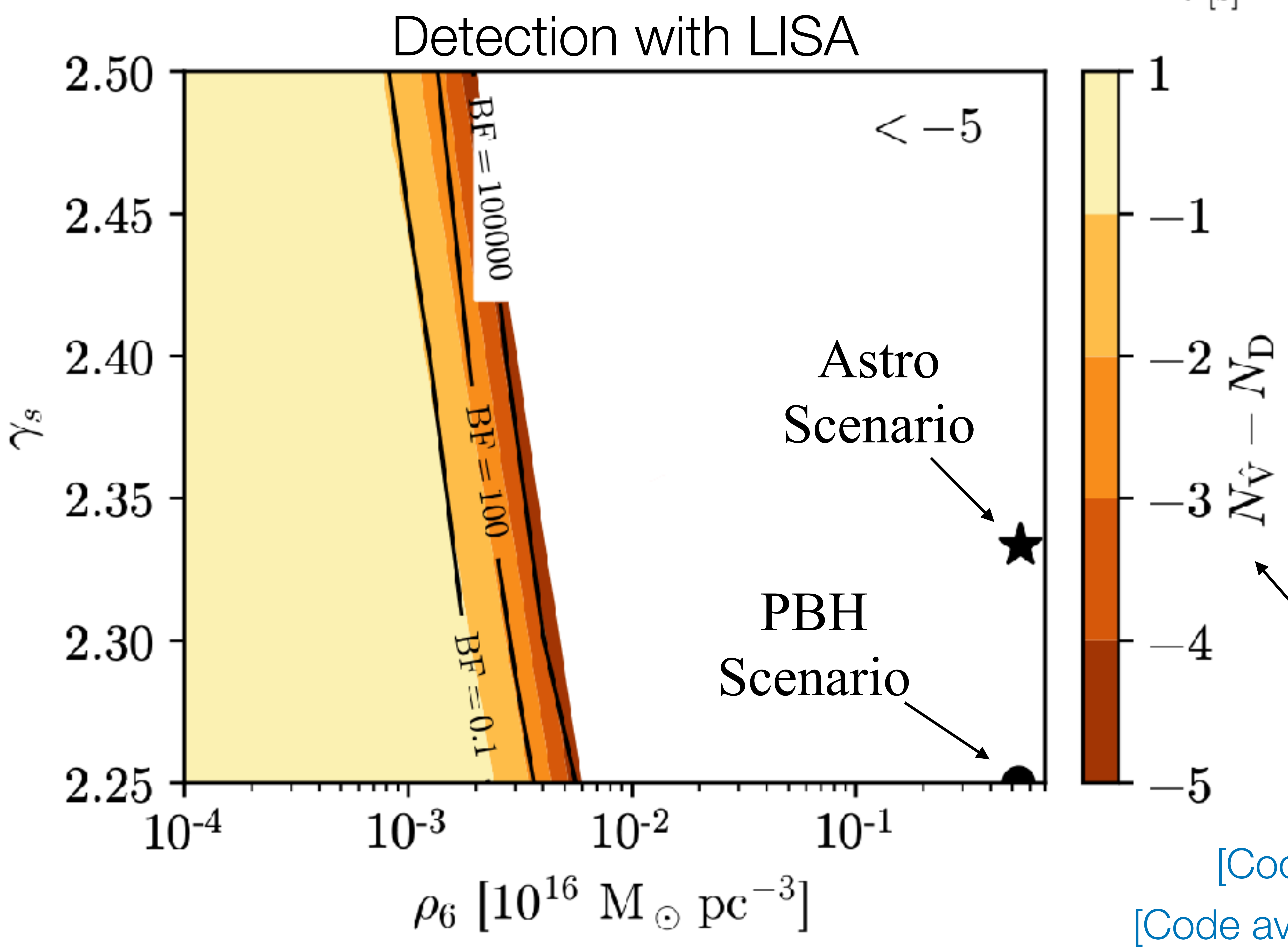
Preliminary results suggest that large densities are possible but do these systems survive, and are they common?

$$\rho_6 \gtrsim 10^{16}\, M_\odot\, \mathrm{pc}^{-3}$$

[Work in progress with Abram Perez, Pratika Dayal, and others]

Discoverability





Compare **Bayes factor (BF)** for the vacuum case (V) and the DM dressed case (D)

$$\boldsymbol{\theta}_\mathrm{V} = \{\mathcal{M}\}$$

vs.

$$\boldsymbol{\theta}_\mathrm{D} = \{\gamma_\mathrm{sp}, \rho_6, \mathcal{M}, \log_{10} q\}$$

Number of GW cycles of dephasing

[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]

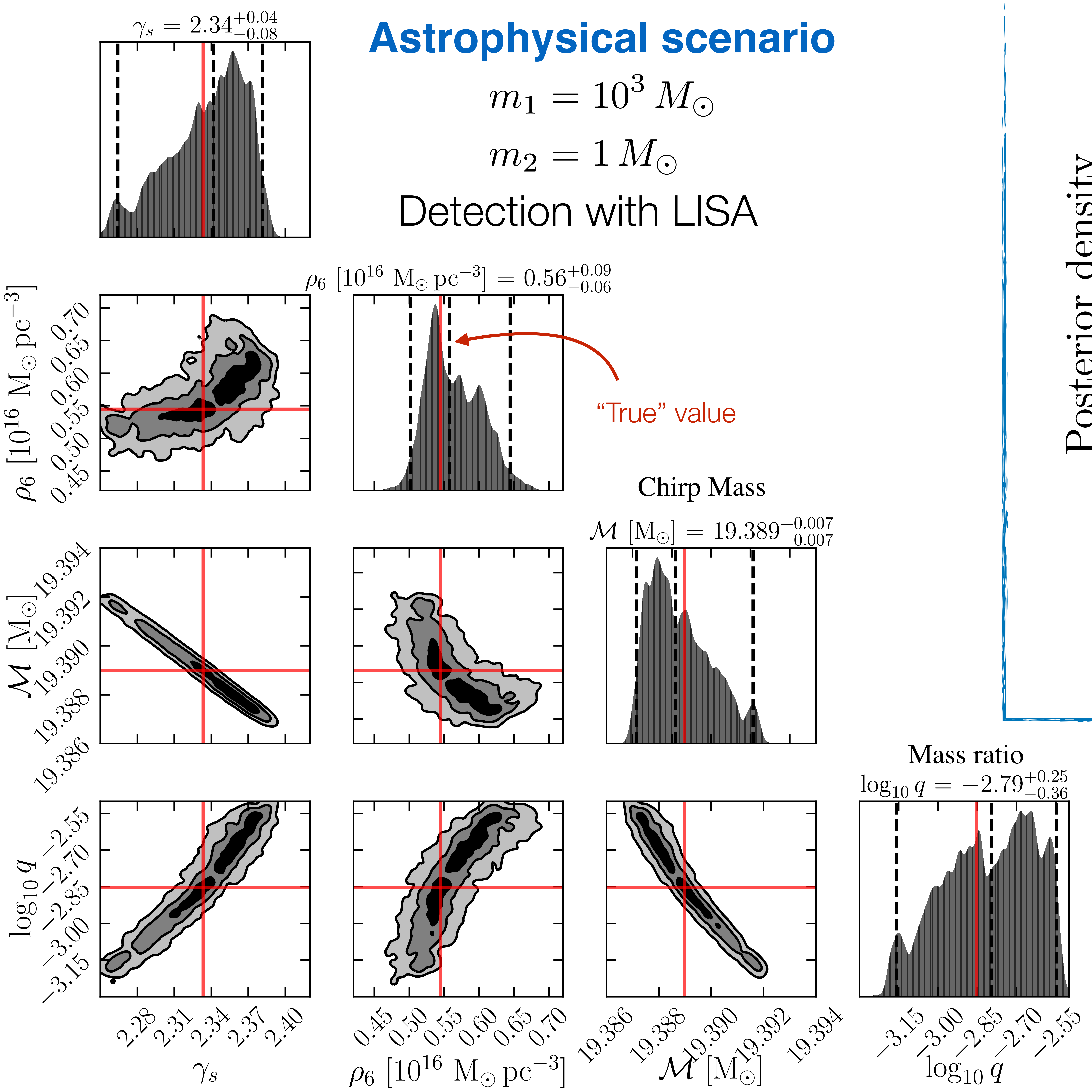
[Code available online: https://github.com/adam-coogan/pydd]

Measurability

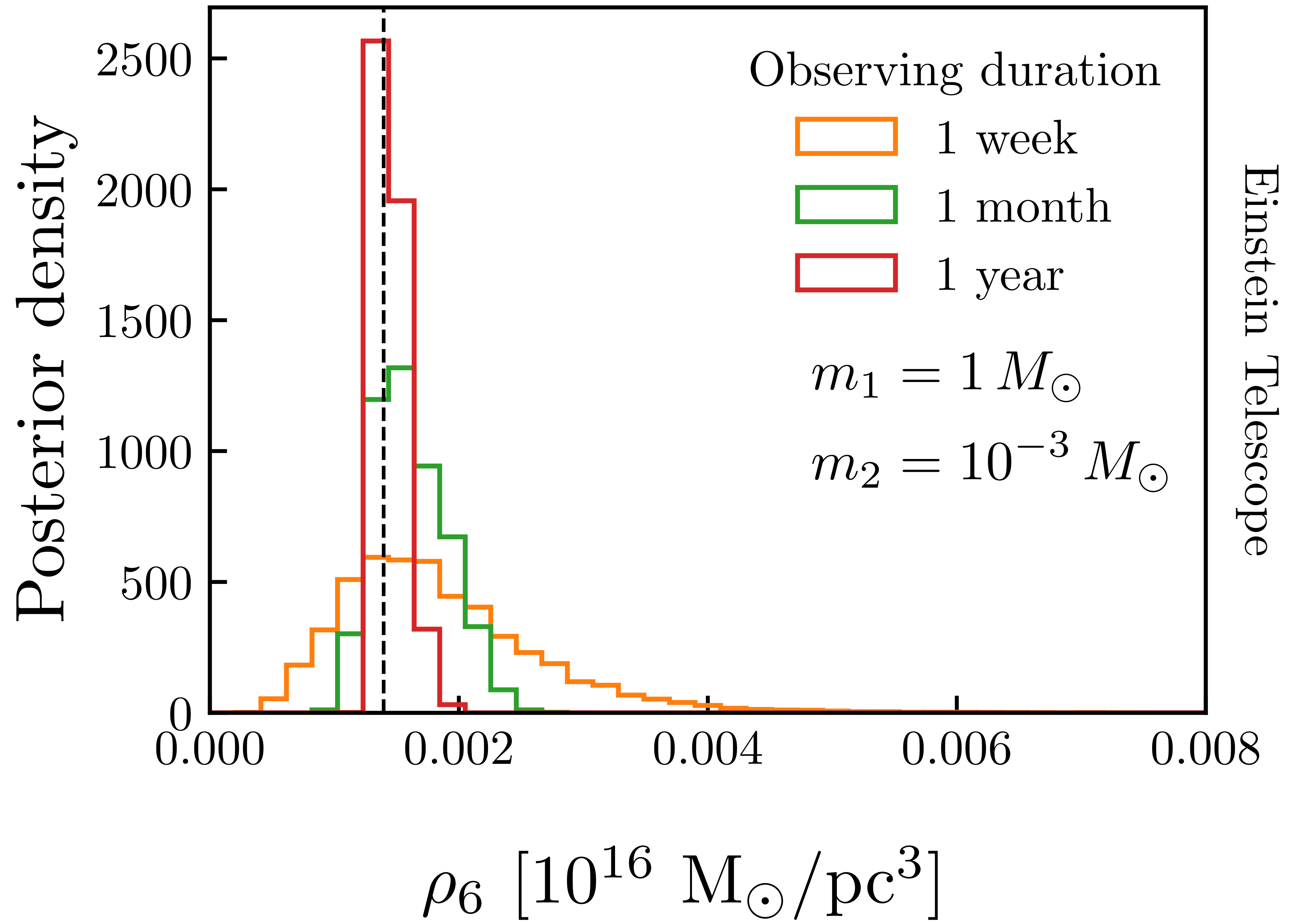
Astrophysical scenario

$$m_1 = 10^3\, M_\odot$$
$$m_2 = 1\, M_\odot$$

Detection with LISA



PBH scenario



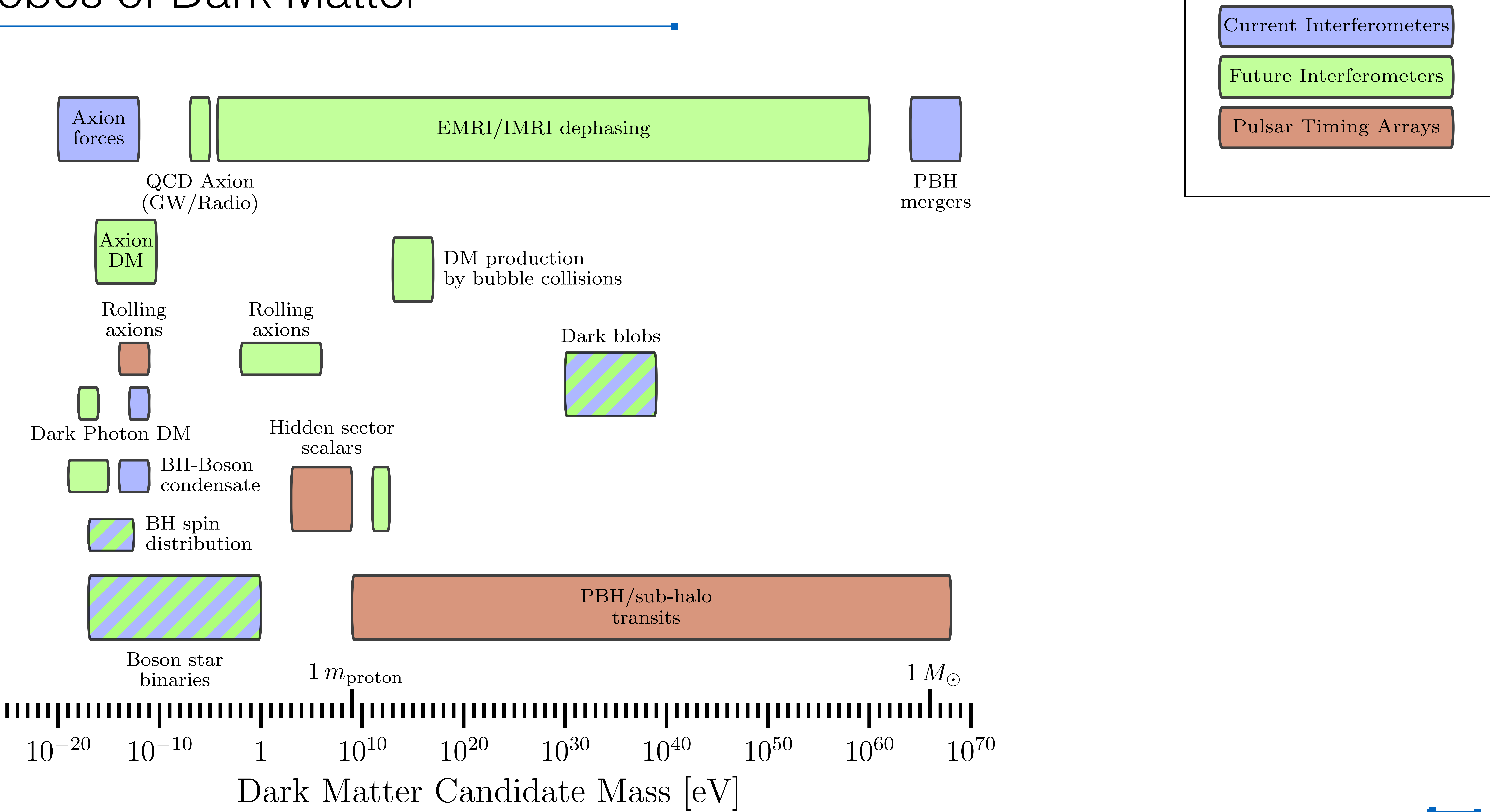
Detection with Einstein Telescope

[Cole, Coogan, **BJK**, Bertone, 2207.07576]

[Coogan, Bertone, Gaggero, **BJK** & Nichols, 2108.04154]

[Code: github.com/adam-coogan/pydd]

GW Probes of Dark Matter



[Bertone, Croon, et al (including **BJK**), 1907.10610]