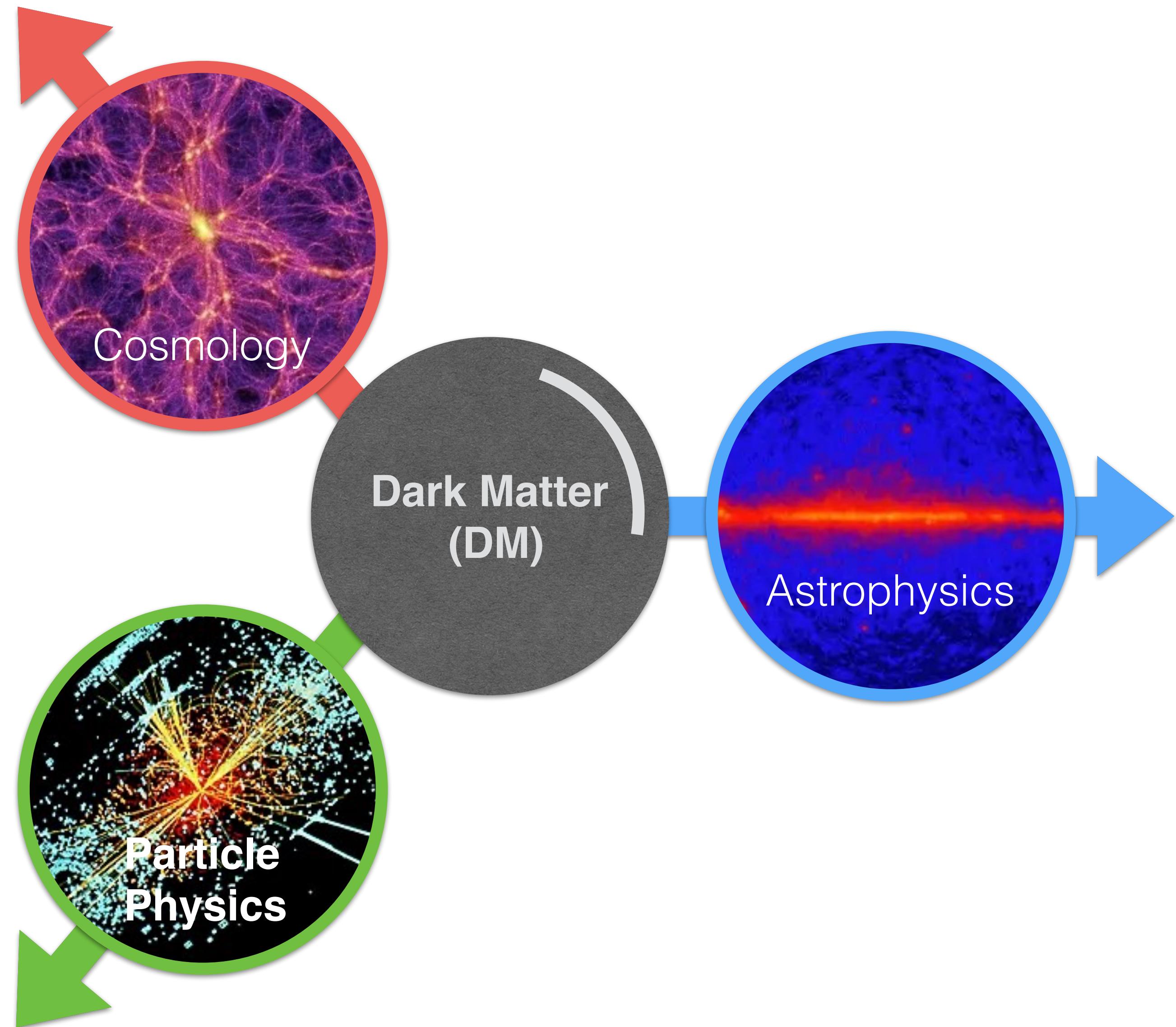


# New Directions in the Search for Dark Matter



Bradley J Kavanagh [he/him]

Instituto de Fisica de Cantabria (CSIC-UC)

[kavanagh@ifca.unican.es](mailto:kavanagh@ifca.unican.es)

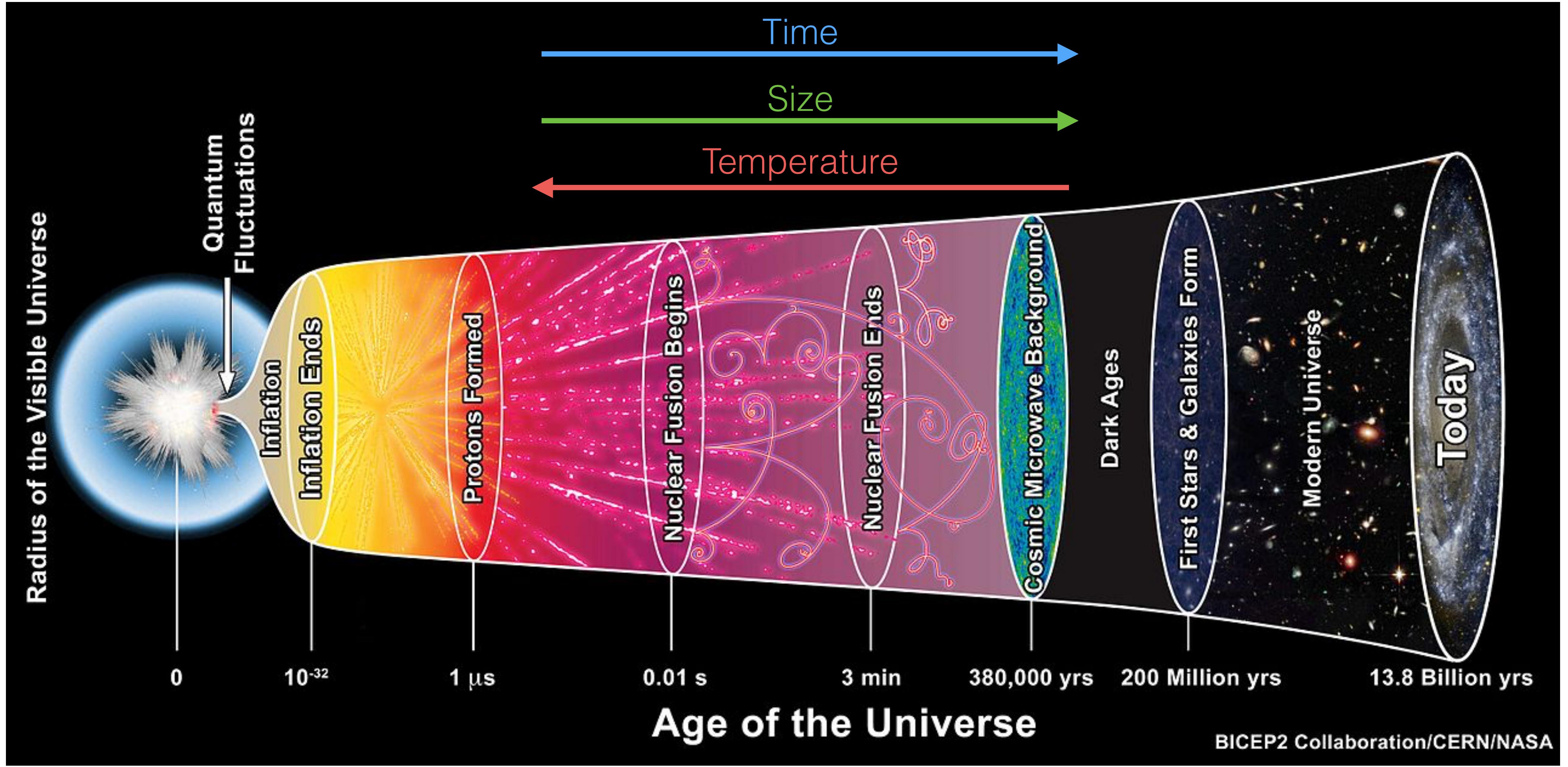
ICMAB Seminar, 18th March 2024

*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



Age of the Universe

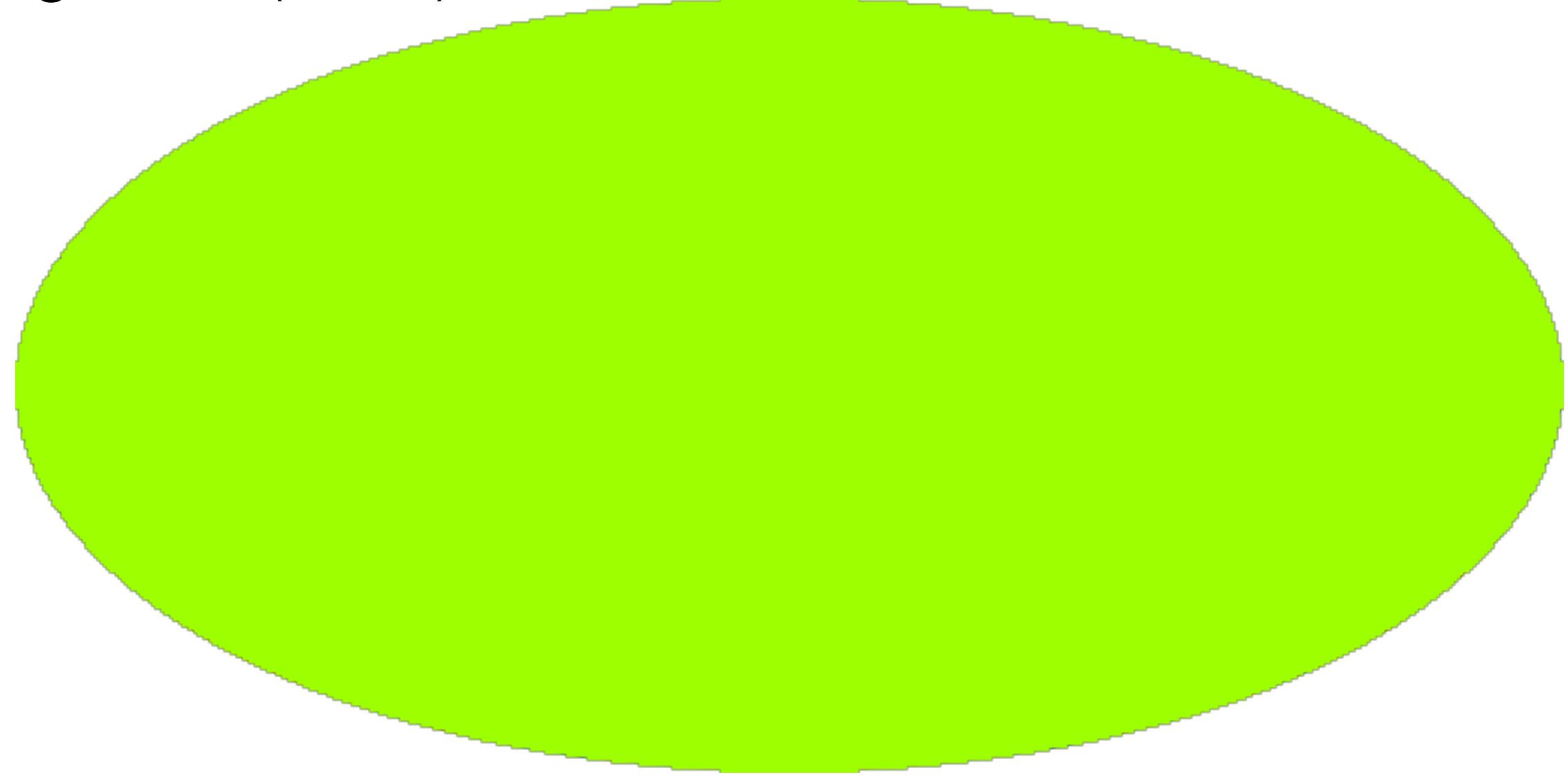
BICEP2 Collaboration/CERN/NASA

# Dark Matter in Cosmology

---

Cosmic Microwave  
Background (CMB)

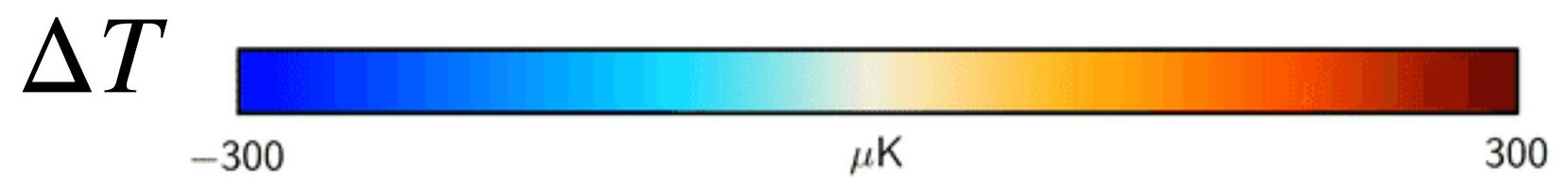
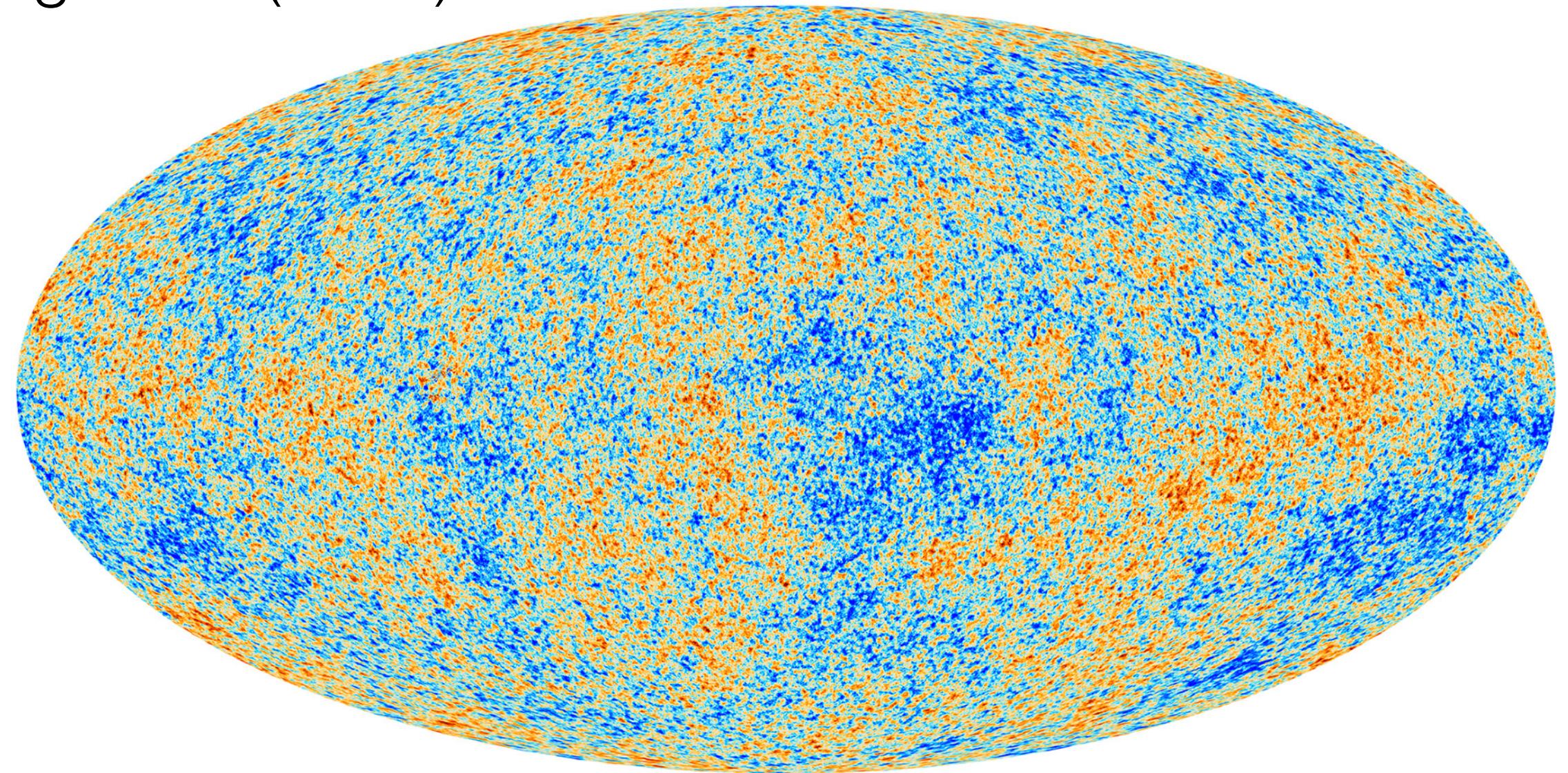
$$T_{\text{CMB}} = 2.73 \text{ K}$$



# Dark Matter in Cosmology

Cosmic Microwave  
Background (CMB)

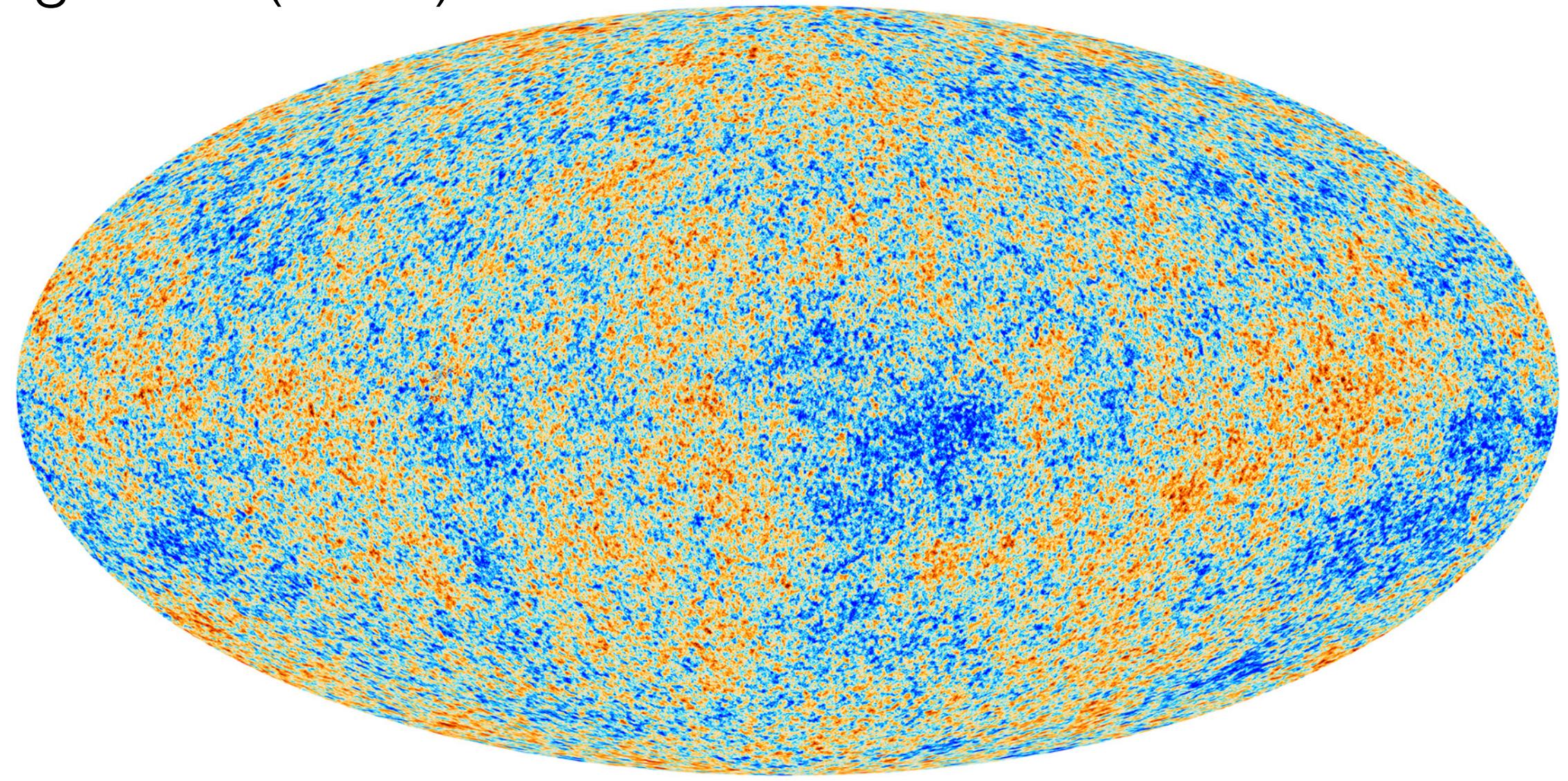
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# Dark Matter in Cosmology

# Cosmic Microwave Background (CMB)

$$T_{\text{CMB}} = 2.73 \text{ K}$$

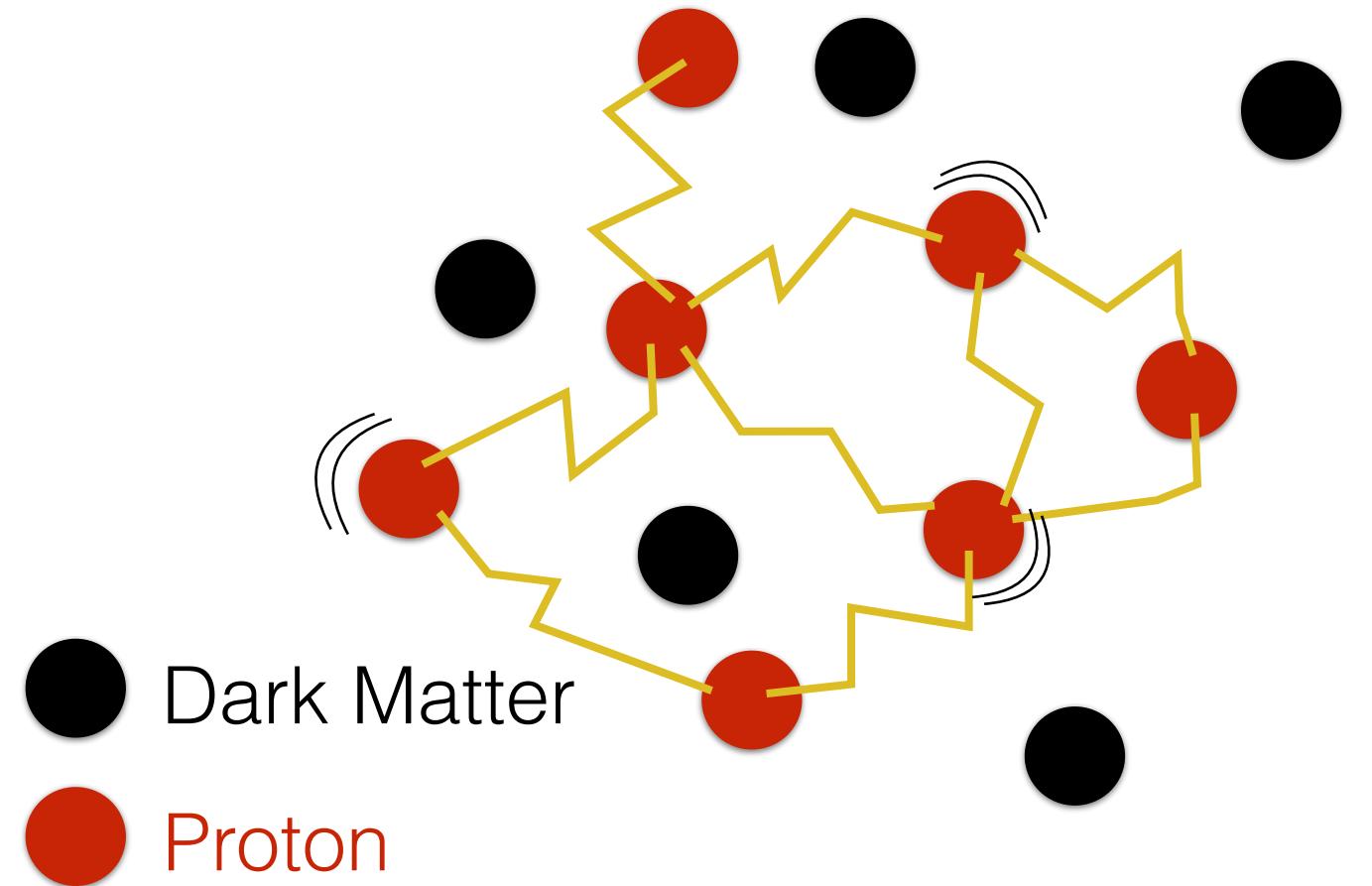
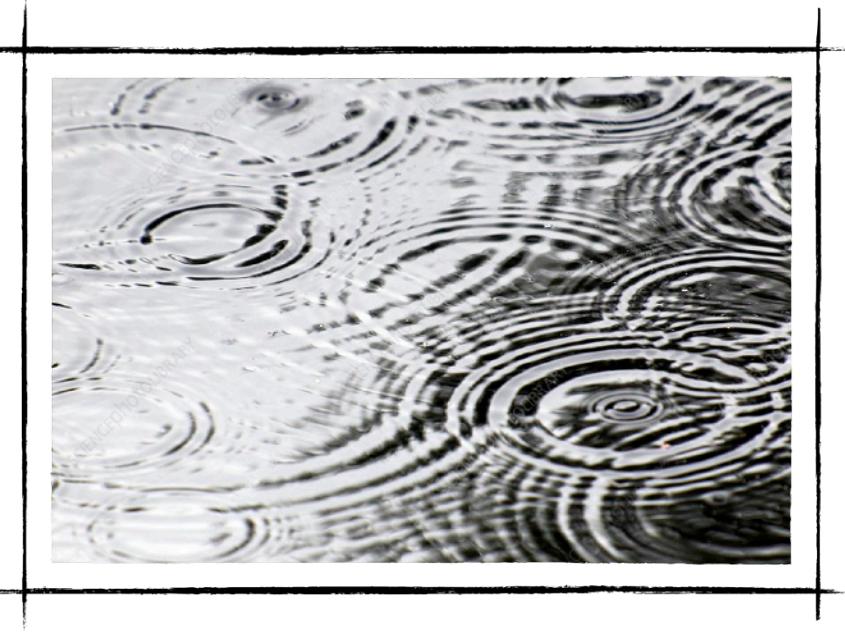


$$\Delta T$$

-300

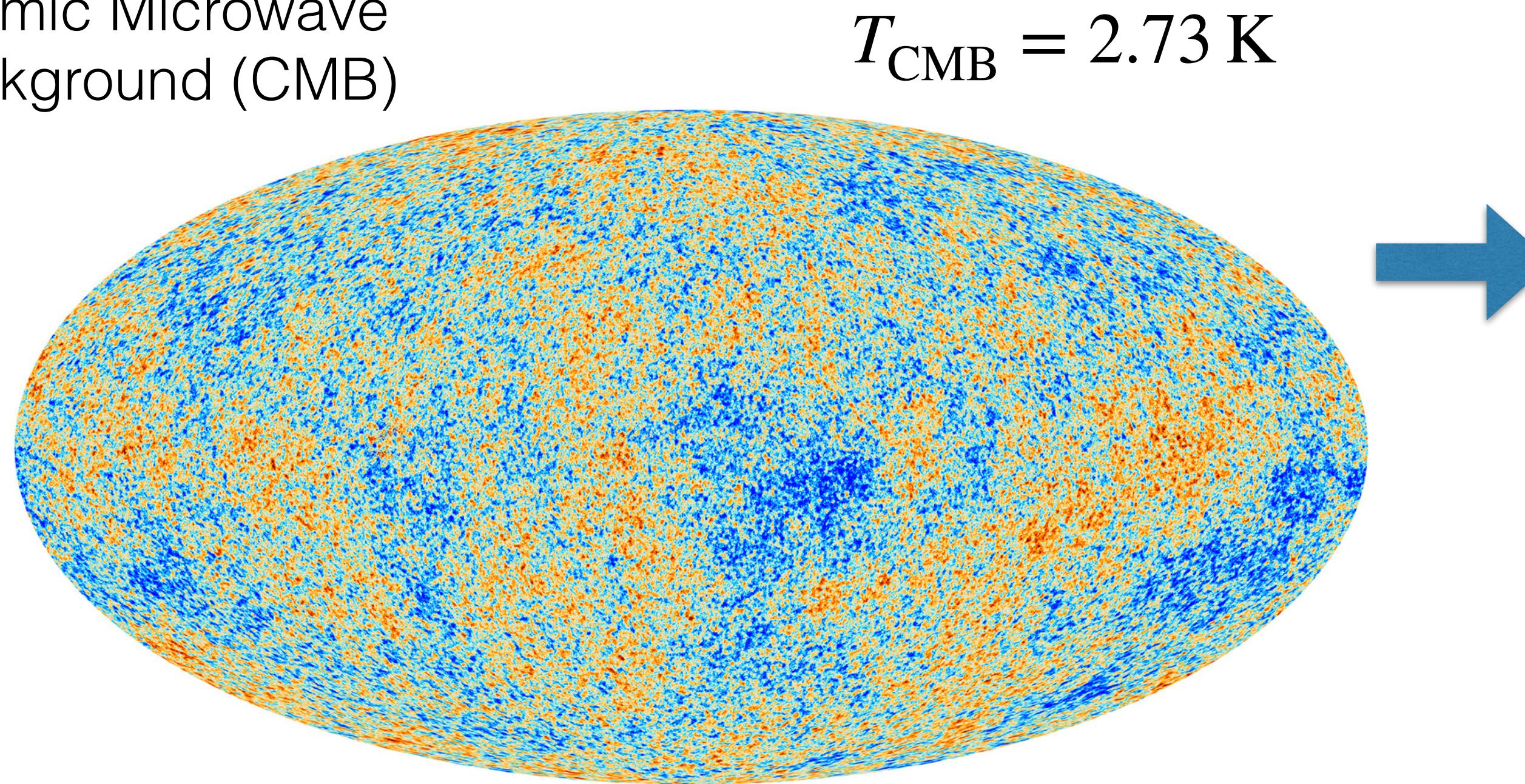
μK

300

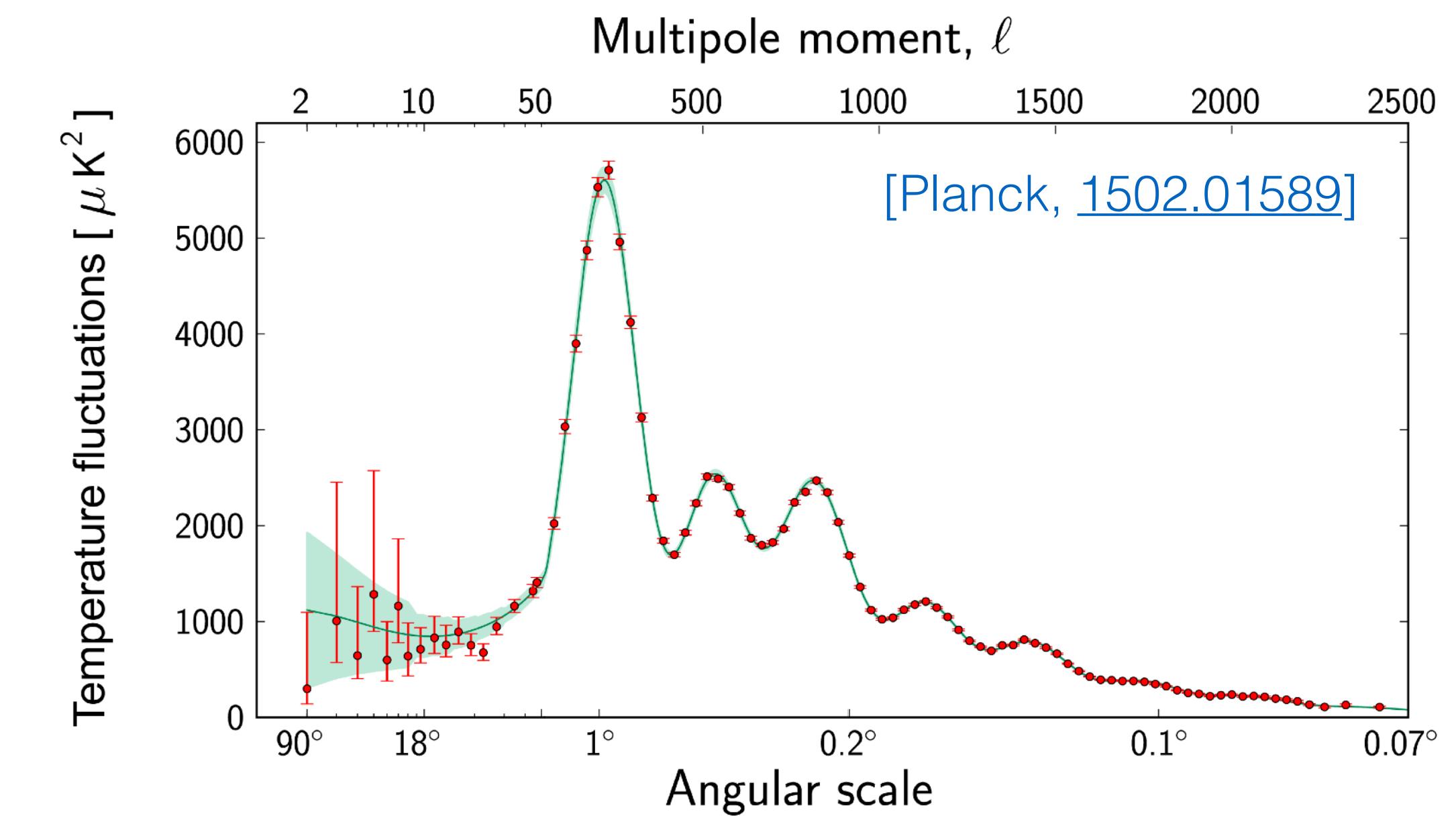
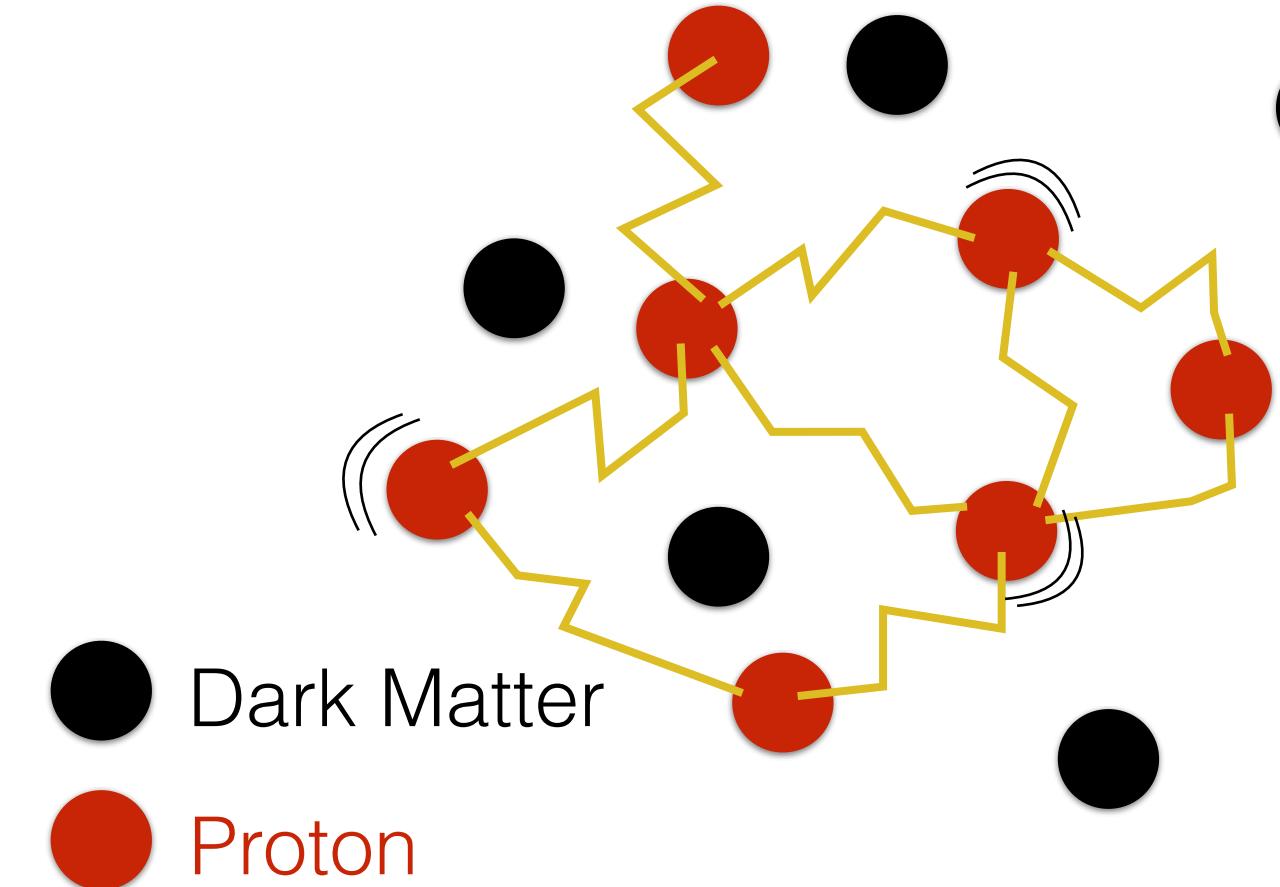
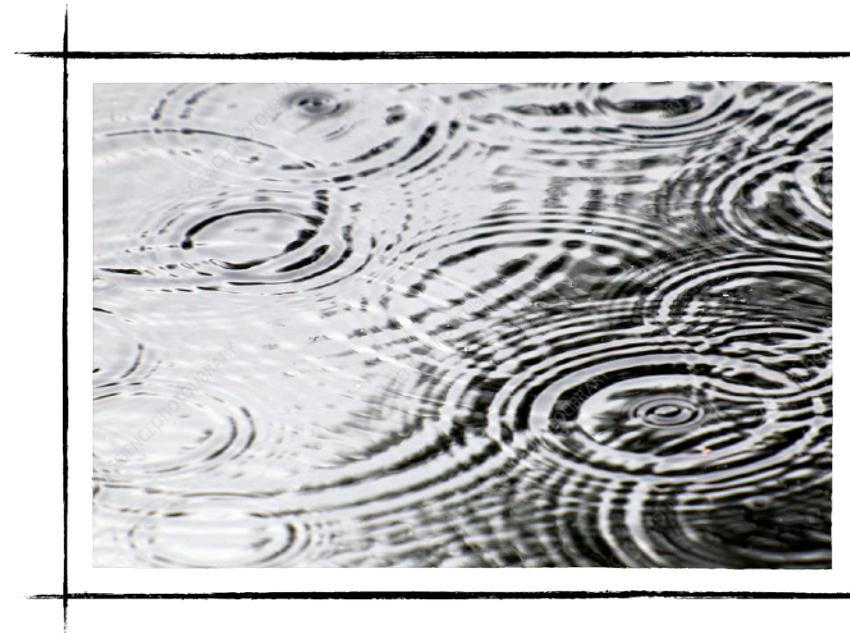
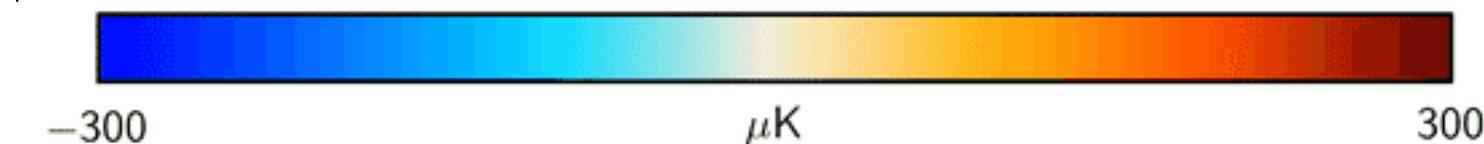


# Dark Matter in Cosmology

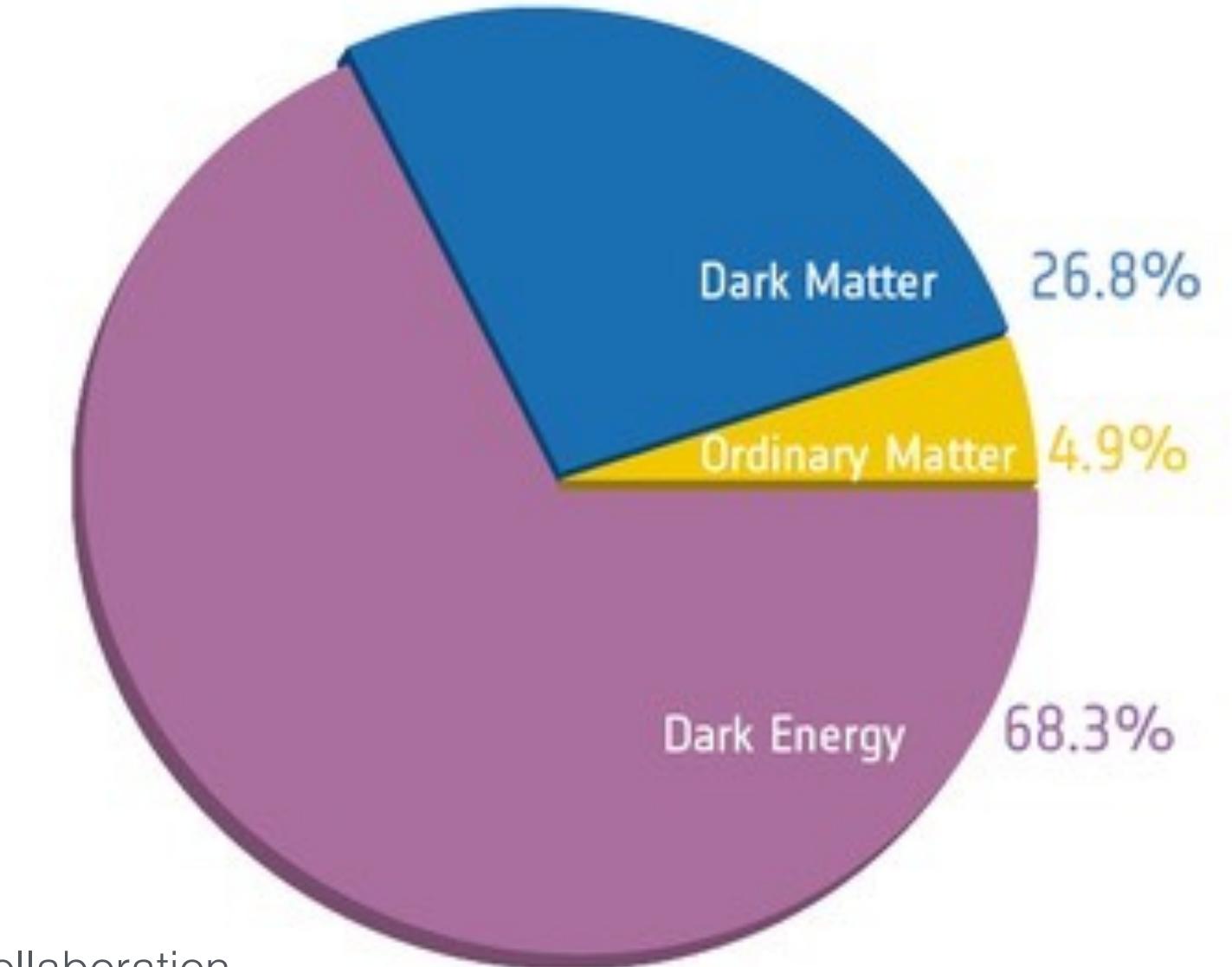
Cosmic Microwave  
Background (CMB)



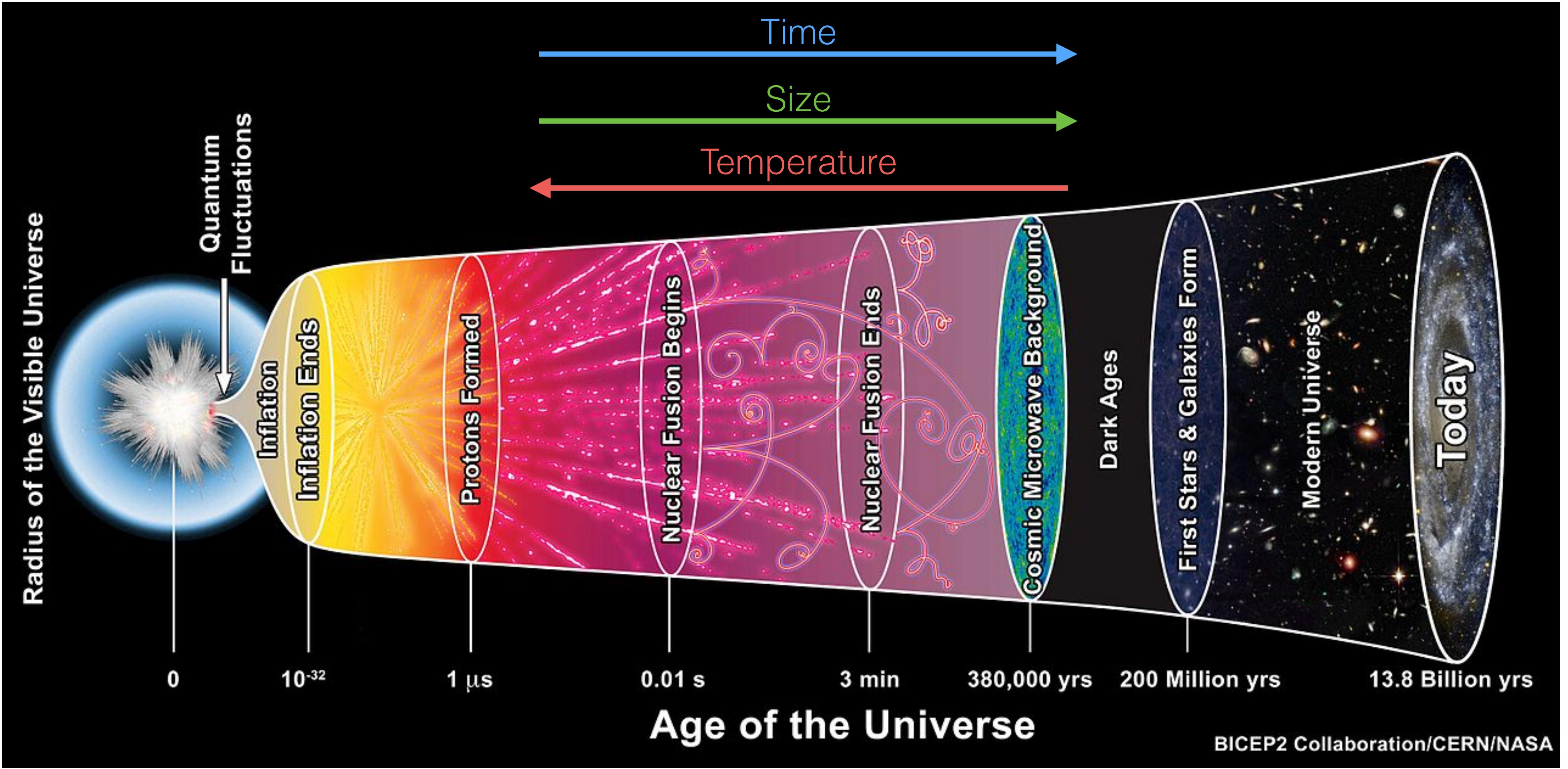
$\Delta T$



Credit: ESA/Planck Collaboration



# Everything, Everywhere, All at Once





Durham  
University

Universiteit Leiden

THE EAGLE SIMULATION  
[icc.dur.ac.uk/Eagle](http://icc.dur.ac.uk/Eagle)

$t_{\text{age}} = 0.5 \text{ Gyr}$

Redshift = 10.11



Universiteit Leiden



Durham  
University

THE EAGLE SIMULATION  
[icc.dur.ac.uk/Eagle](http://icc.dur.ac.uk/Eagle)

$t_{\text{age}} = 1.1 \text{ Gyr}$

**Redshift = 5.24**



Durham  
University

Universiteit Leiden

THE EAGLE SIMULATION  
[icc.dur.ac.uk/Eagle](http://icc.dur.ac.uk/Eagle)

$t_{\text{age}} = 1.7 \text{ Gyr}$

Redshift = 3.73

[www.smcalpine.com](http://www.smcalpine.com)

# Galaxies in Simulations

[Video on previous slide available [here](#)]

Dark matter has become an integral part of the standard cosmological model - the  **$\Lambda$  Cold Dark Matter ( $\Lambda$ CDM)** 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.



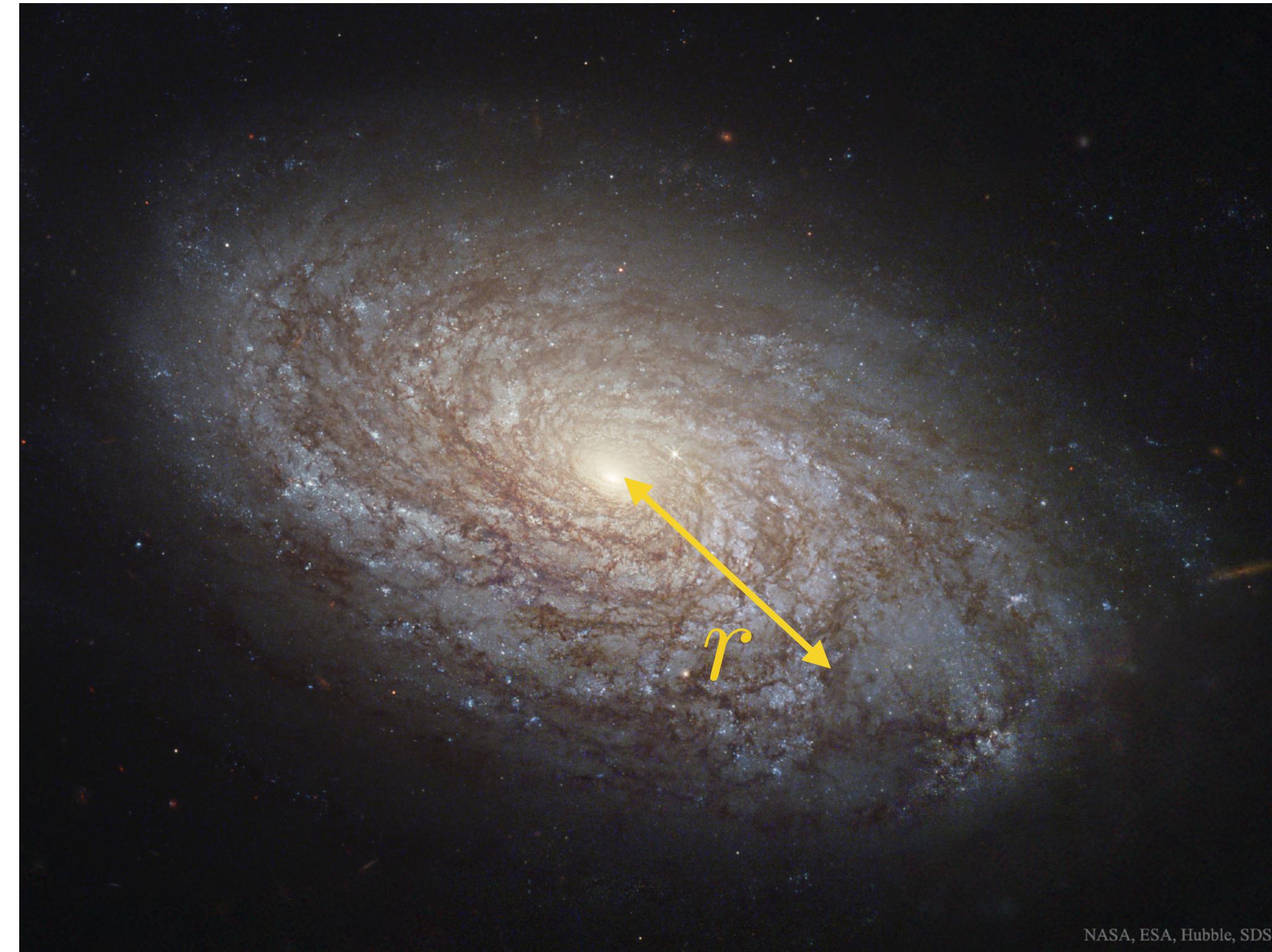
[IllustrisTNG simulation - [2101.12373](#)]

[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



NASA, ESA, Hubble, SDSS

DM density at Earth:

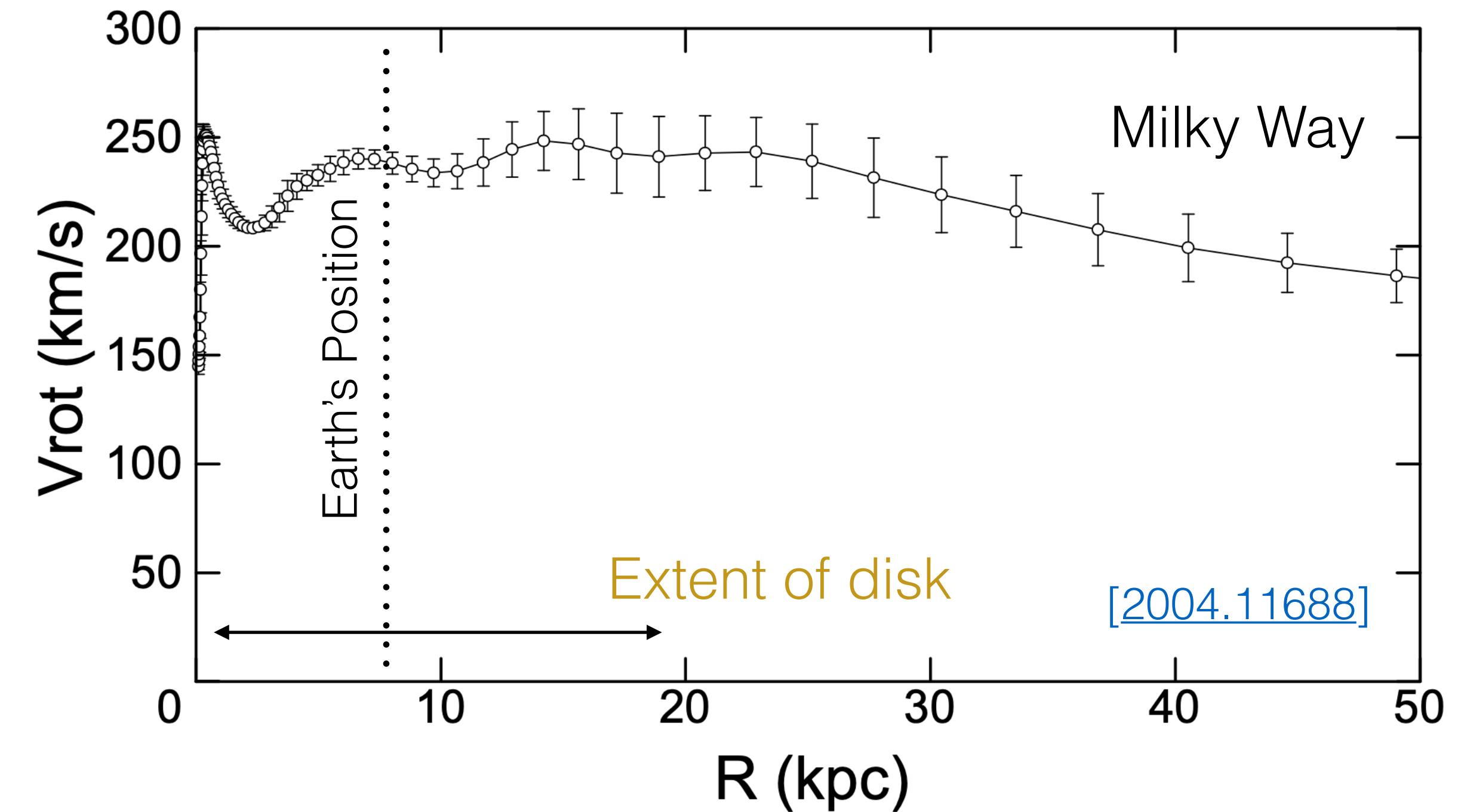
$$\begin{aligned}\rho_\chi &\sim 5 \times 10^{-25} \text{ g/cm}^3 \\ &\sim 0.3 \text{ GeV/cm}^3 \\ &\sim 0.008 M_\odot/\text{pc}^3\end{aligned}$$

[\[1404.1938\]](#)

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

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

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



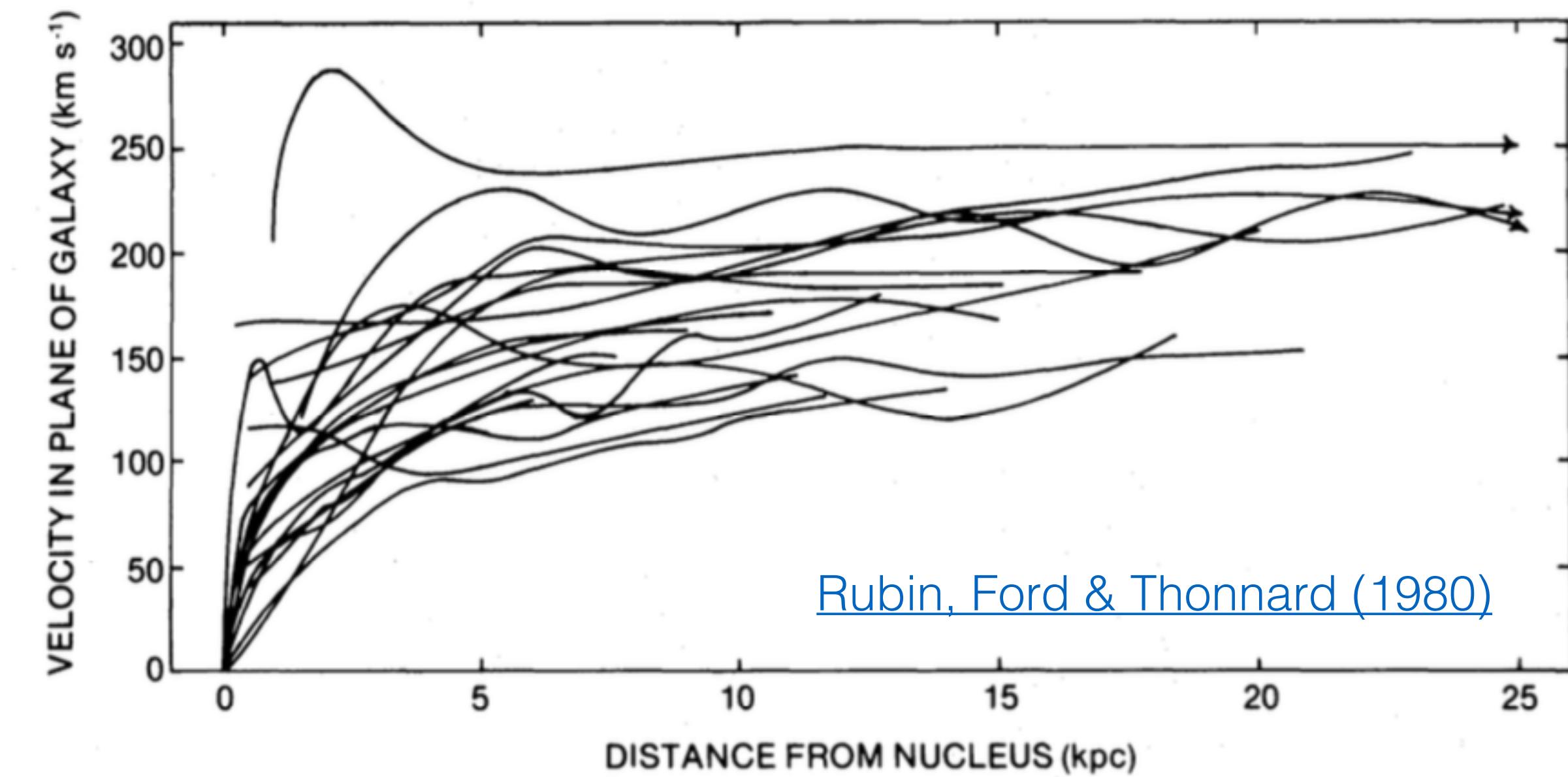
# Dark Matter in Galaxies



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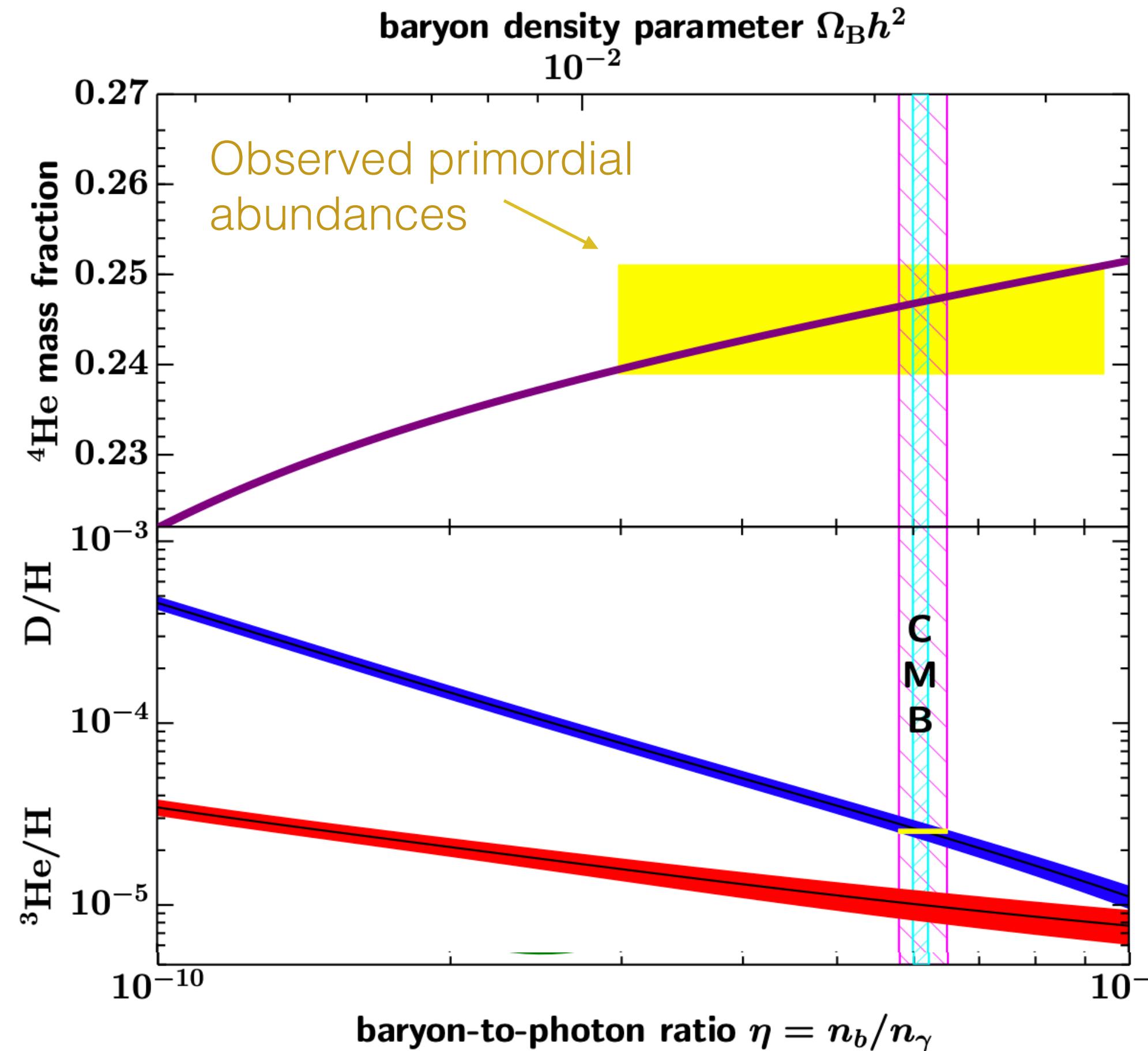
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Rotation curve flattens at large radii, which cannot be explained by mass of observed gas and stars (expect Keplerian  $v_{\text{rot}}(r) \propto 1/\sqrt{r}$  at large radii).



# 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  $T > 1 \text{ MeV}$ ,  $t < 3 \text{ mins}$



## Dark Matter Shopping List

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

[0711.4996]

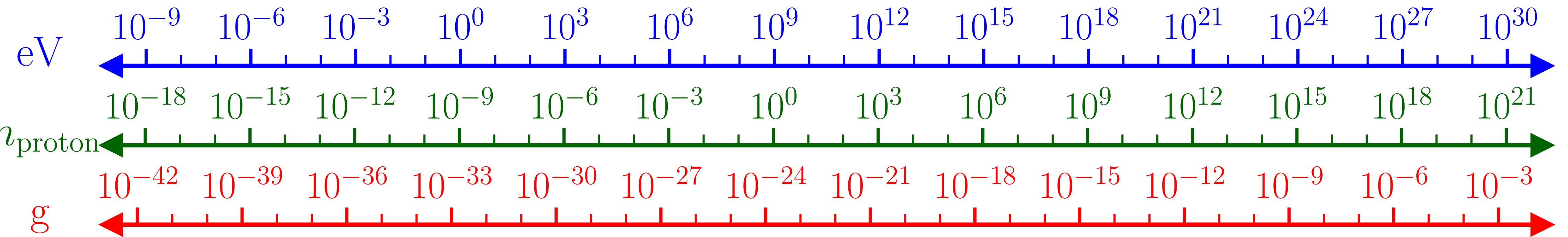
**Neutral:** Dark Matter cannot be charged\*, otherwise it would couple to photons, affecting CMB anisotropies. It would also be able to dissipate energy (from visible stars/galaxies?)

\*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

DM Mass

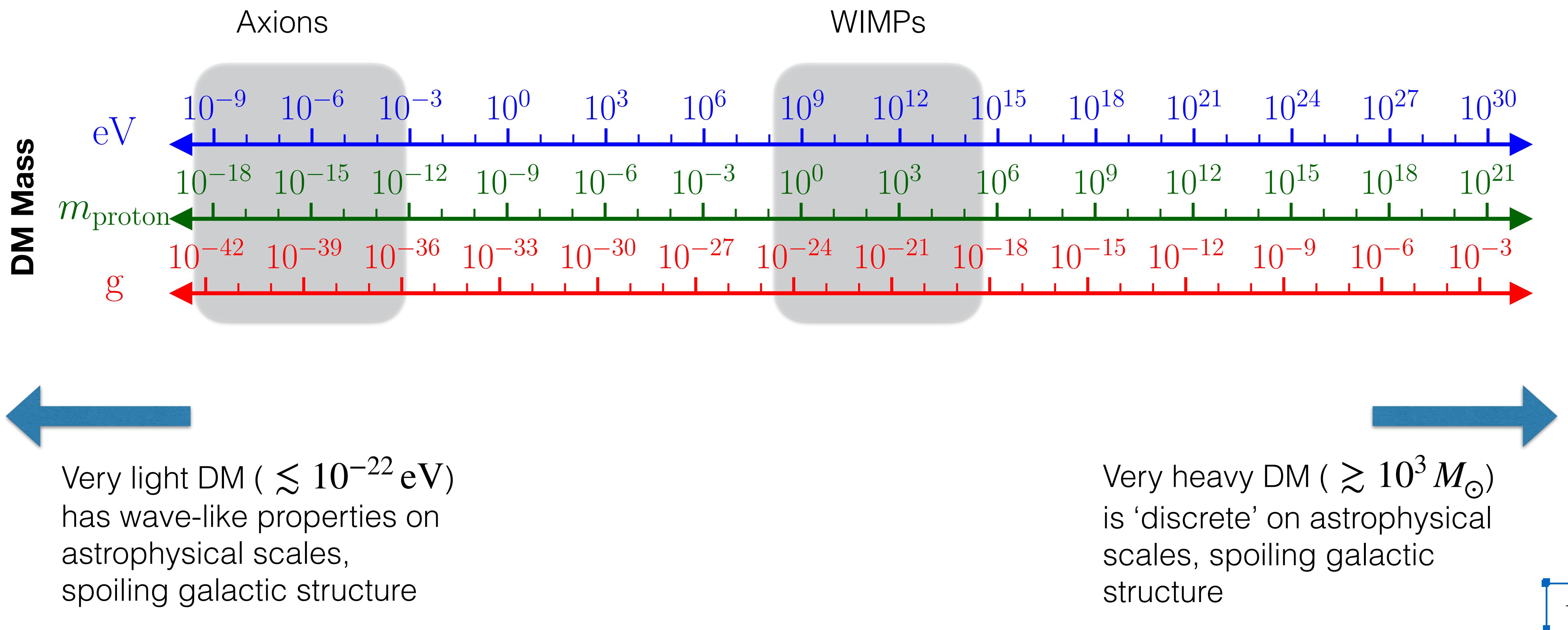


Very light DM ( $\lesssim 10^{-22} \text{ eV}$ )  
has wave-like properties on  
astrophysical scales,  
spoiling galactic structure

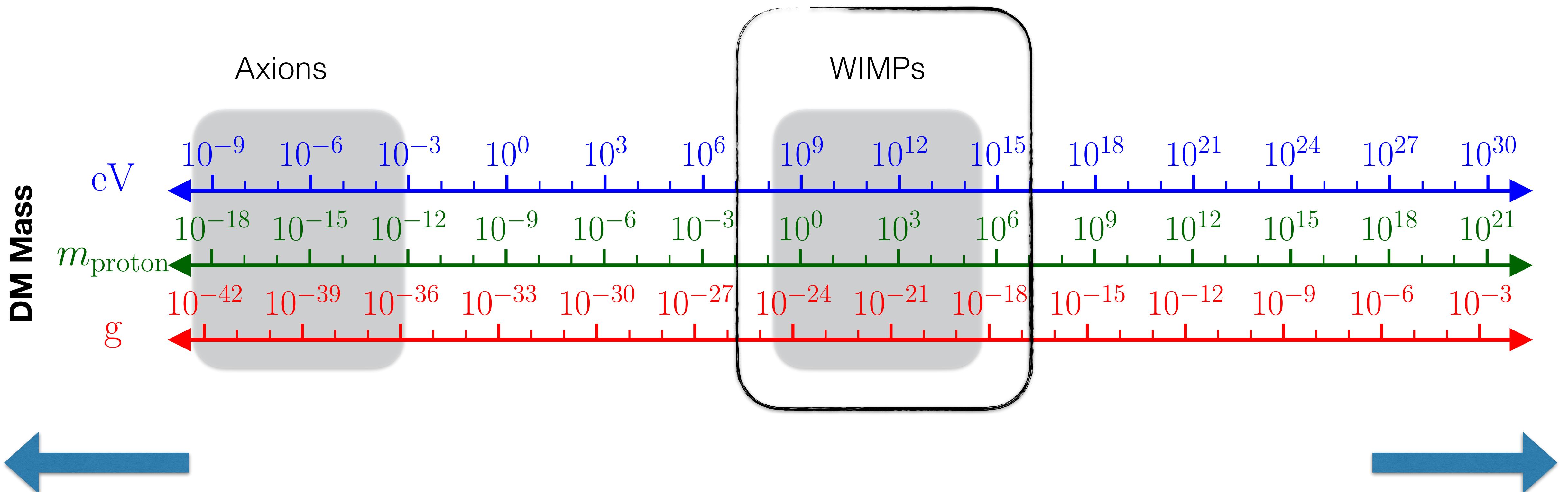


Very heavy DM ( $\gtrsim 10^3 M_{\odot}$ )  
is 'discrete' on astrophysical  
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structure

# Dark Matter Mass Range



# Dark Matter Mass Range



Very light DM ( $\lesssim 10^{-22}$  eV)  
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astrophysical scales,  
spoiling galactic structure

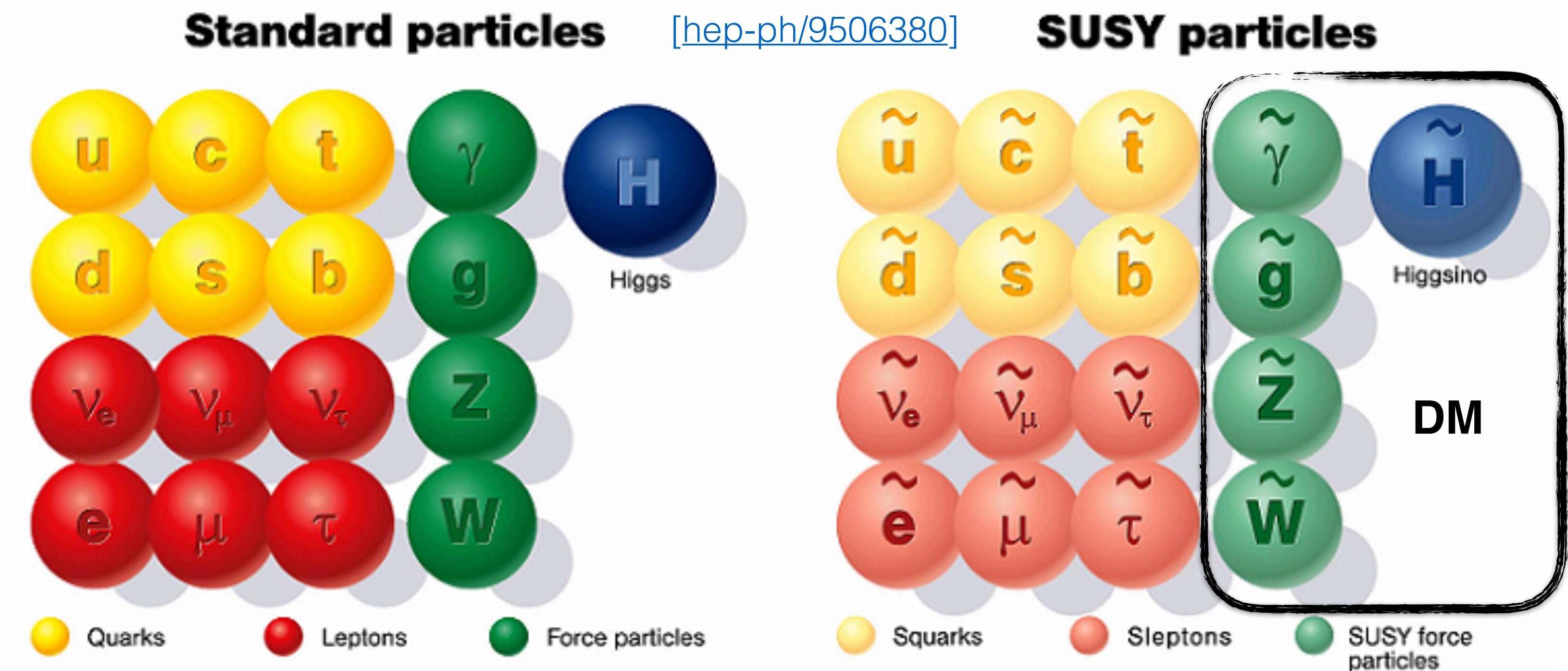
Very heavy DM ( $\gtrsim 10^3 M_{\odot}$ )  
is 'discrete' on astrophysical  
scales, spoiling galactic  
structure

# 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  $1 \text{ GeV} \lesssim m_\chi \lesssim 100 \text{ TeV}$ .

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 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.

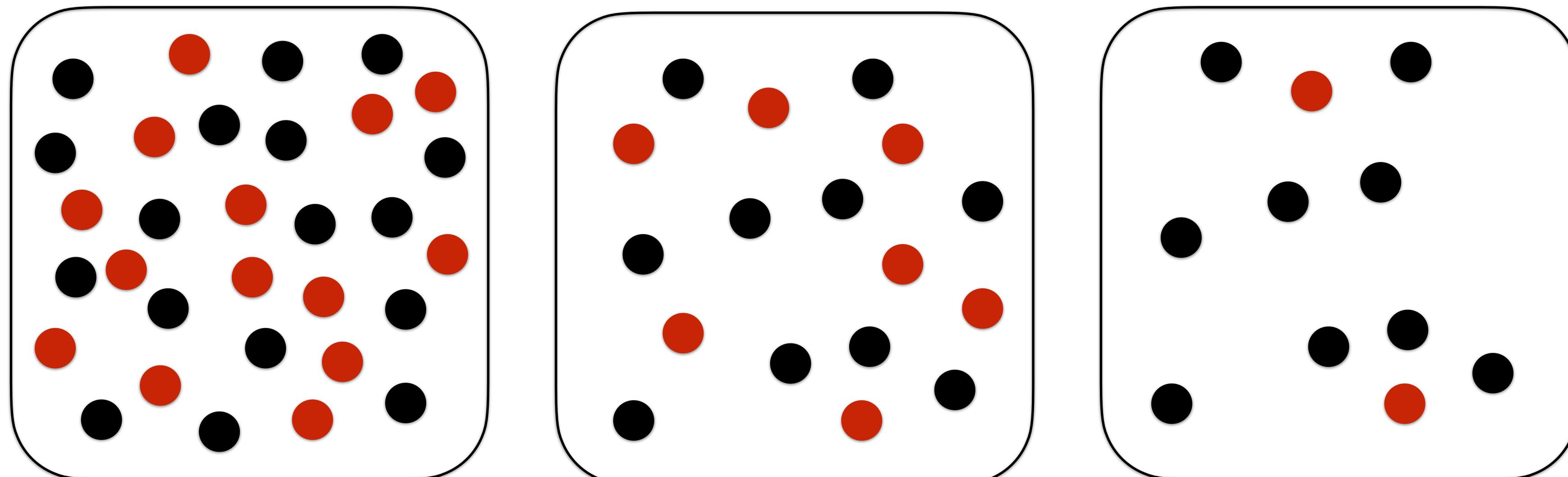
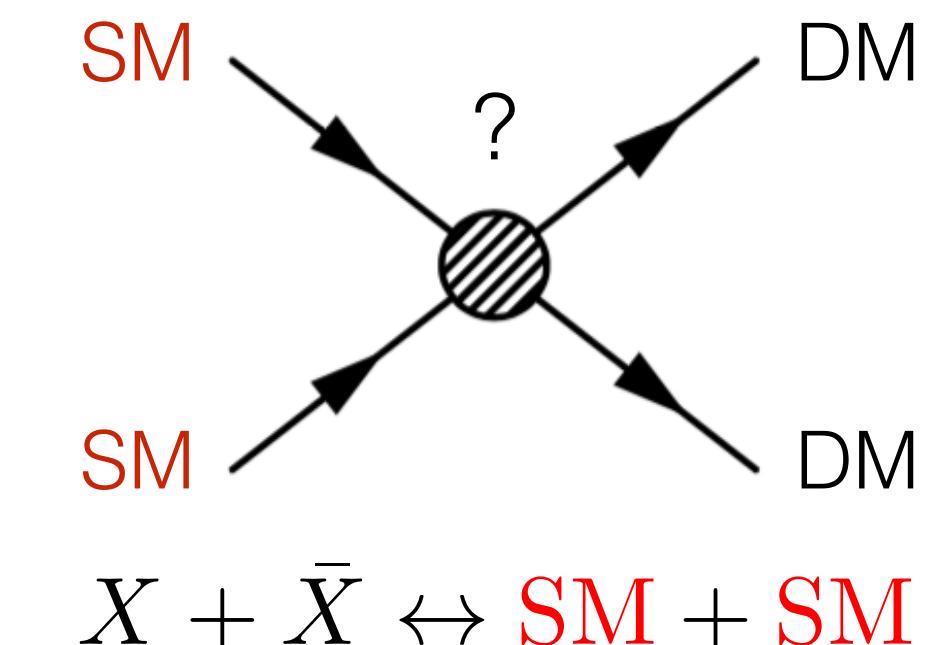
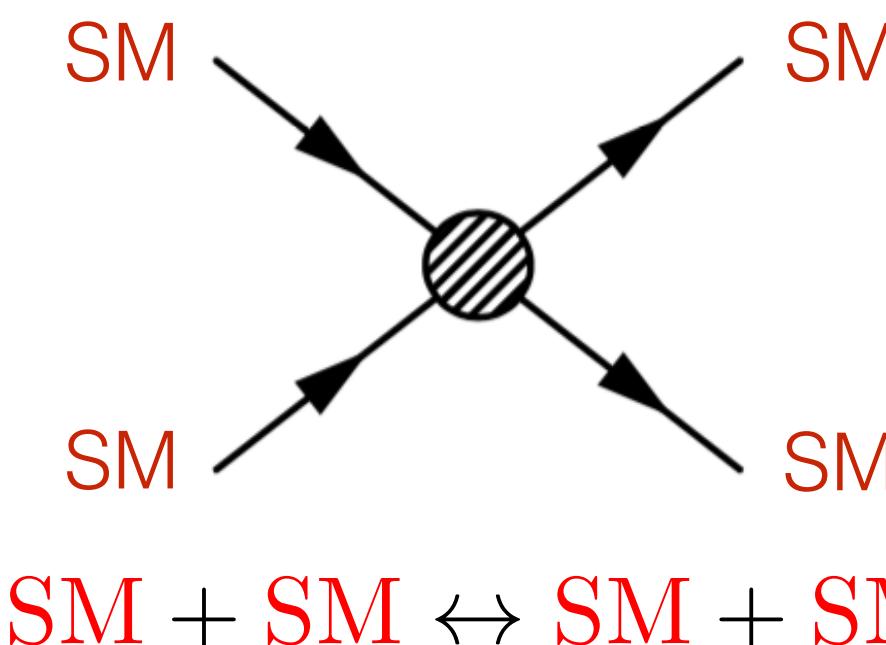


Now, the term WIMP is used to mean a generic MeV-TeV mass particle with weak couplings to the standard model.

# Producing WIMP Dark Matter

“Freeze-out”

- Dark Matter
- Standard Model



Time

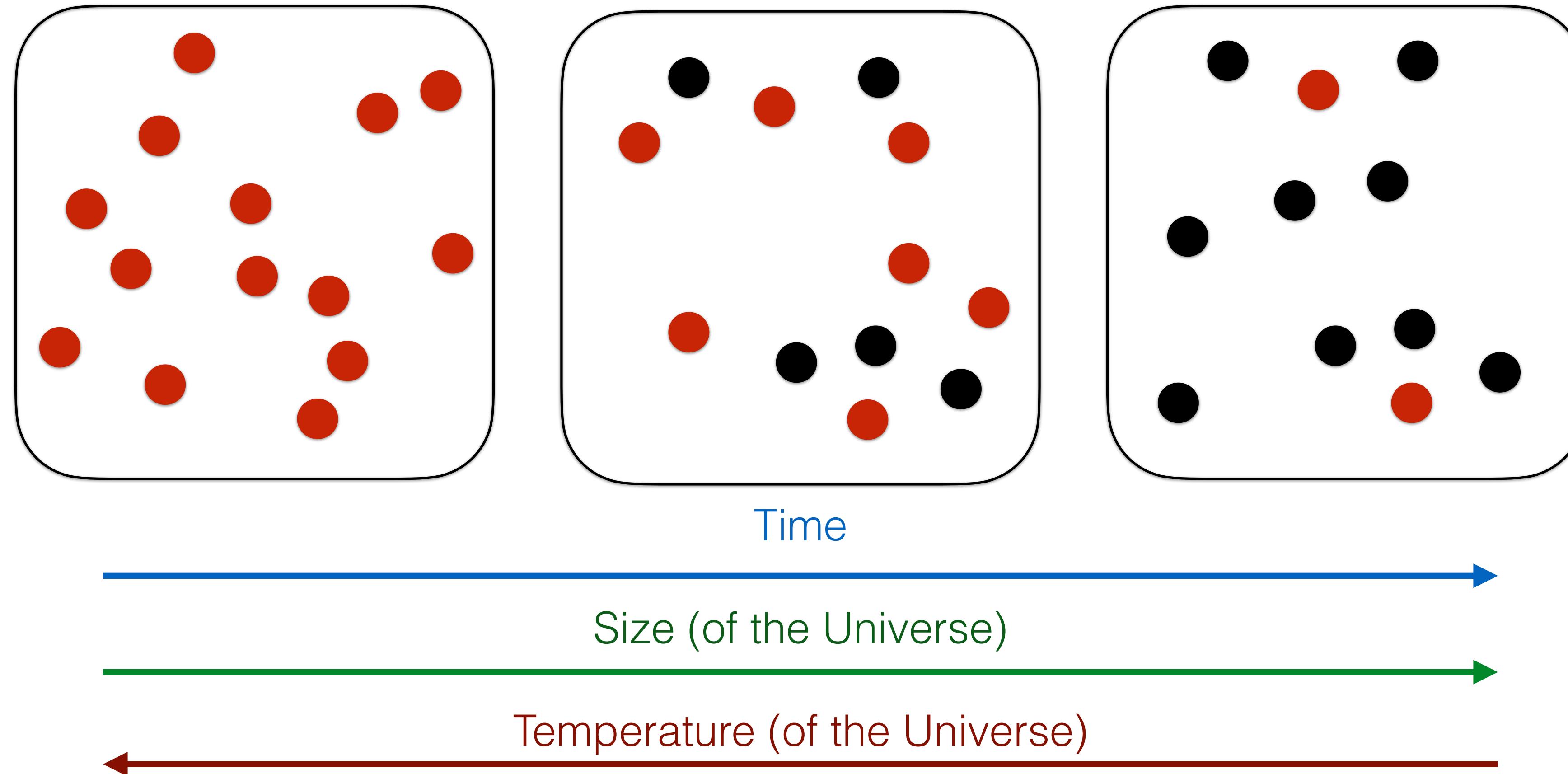
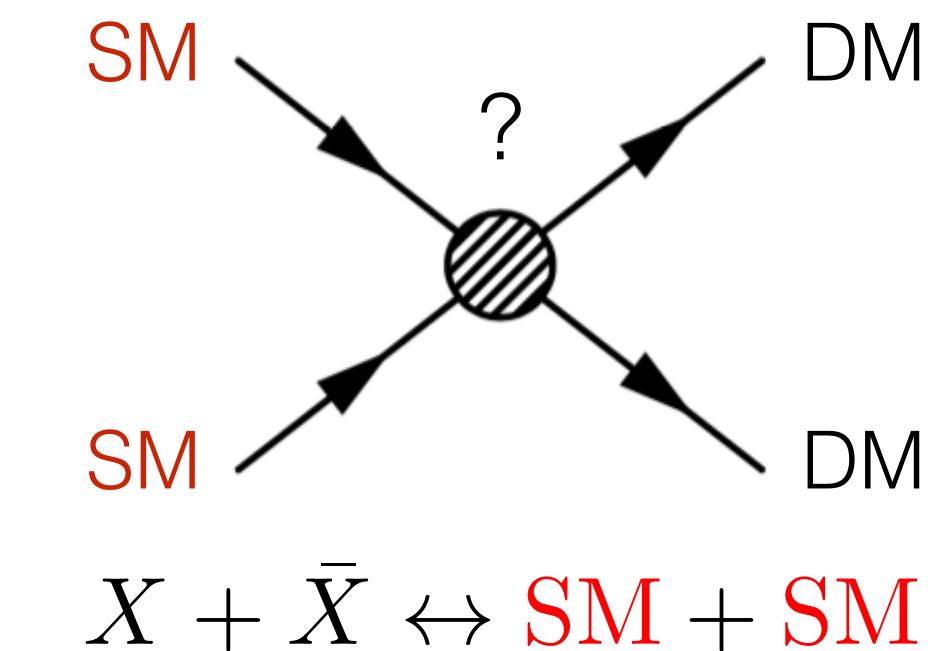
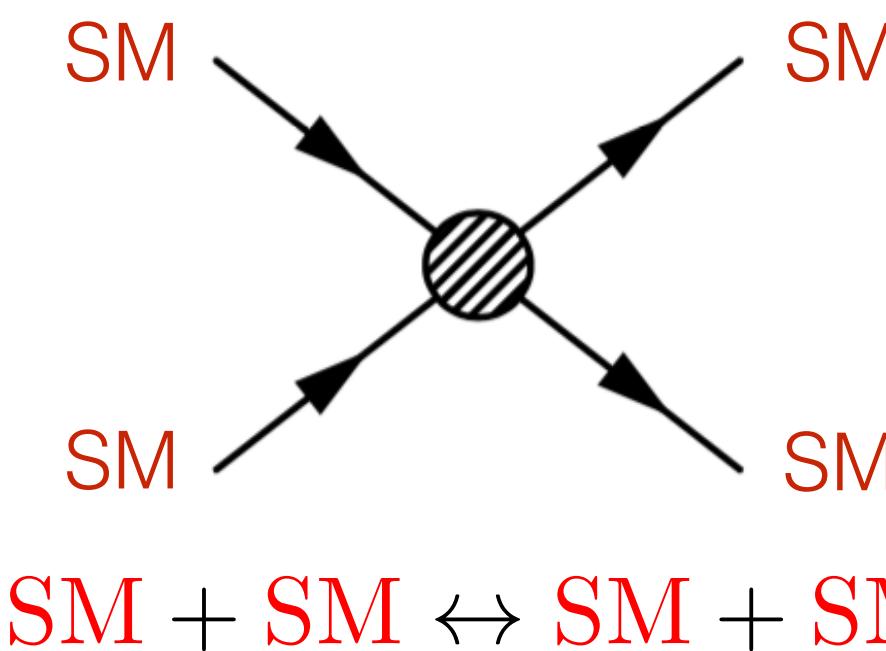
Size (of the Universe)

Temperature (of the Universe)

# Producing WIMP Dark Matter

“Freeze-in”

- Dark Matter
- Standard Model



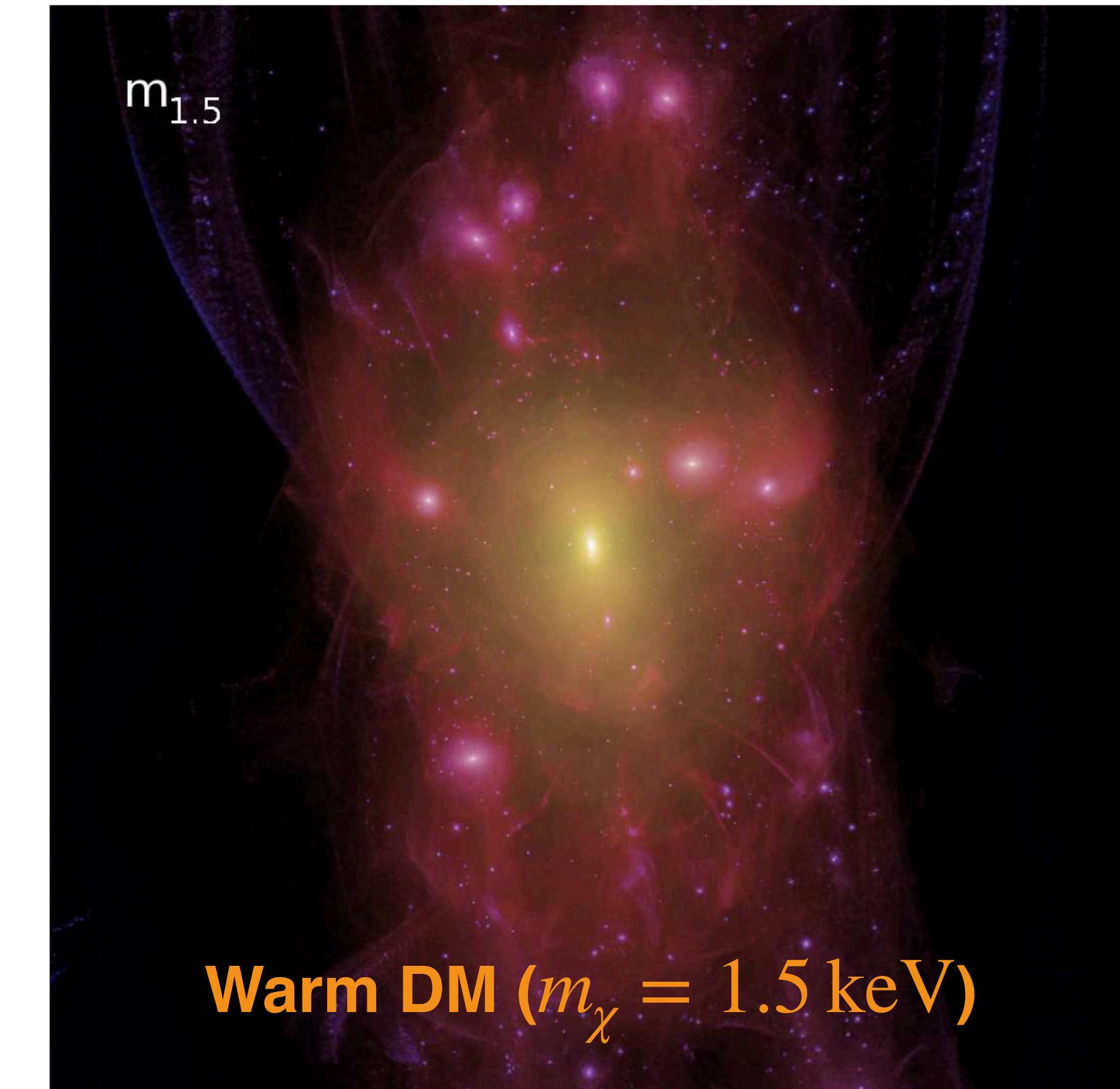
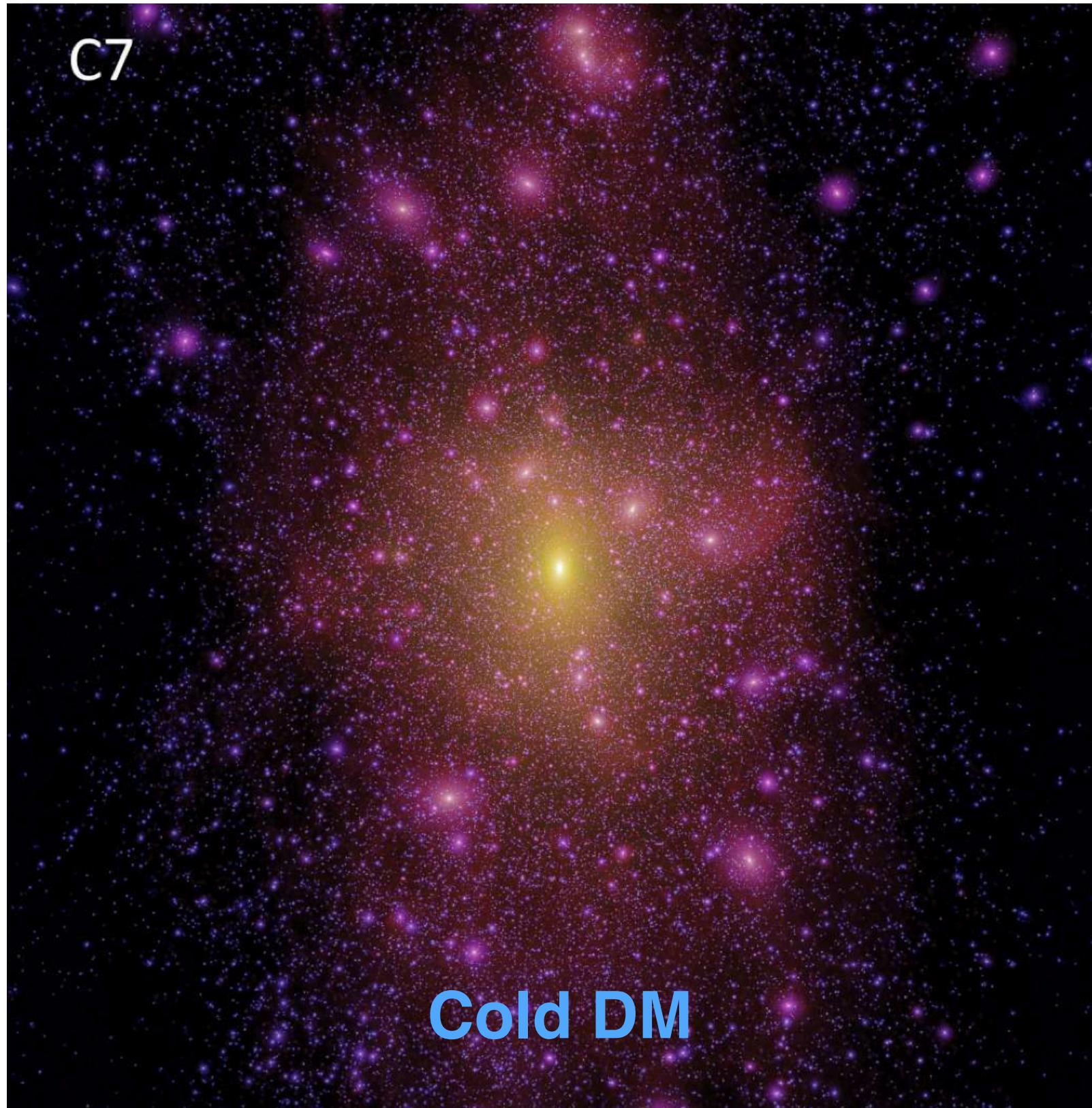
# Cold vs Hot Dark Matter

[1308.1399]

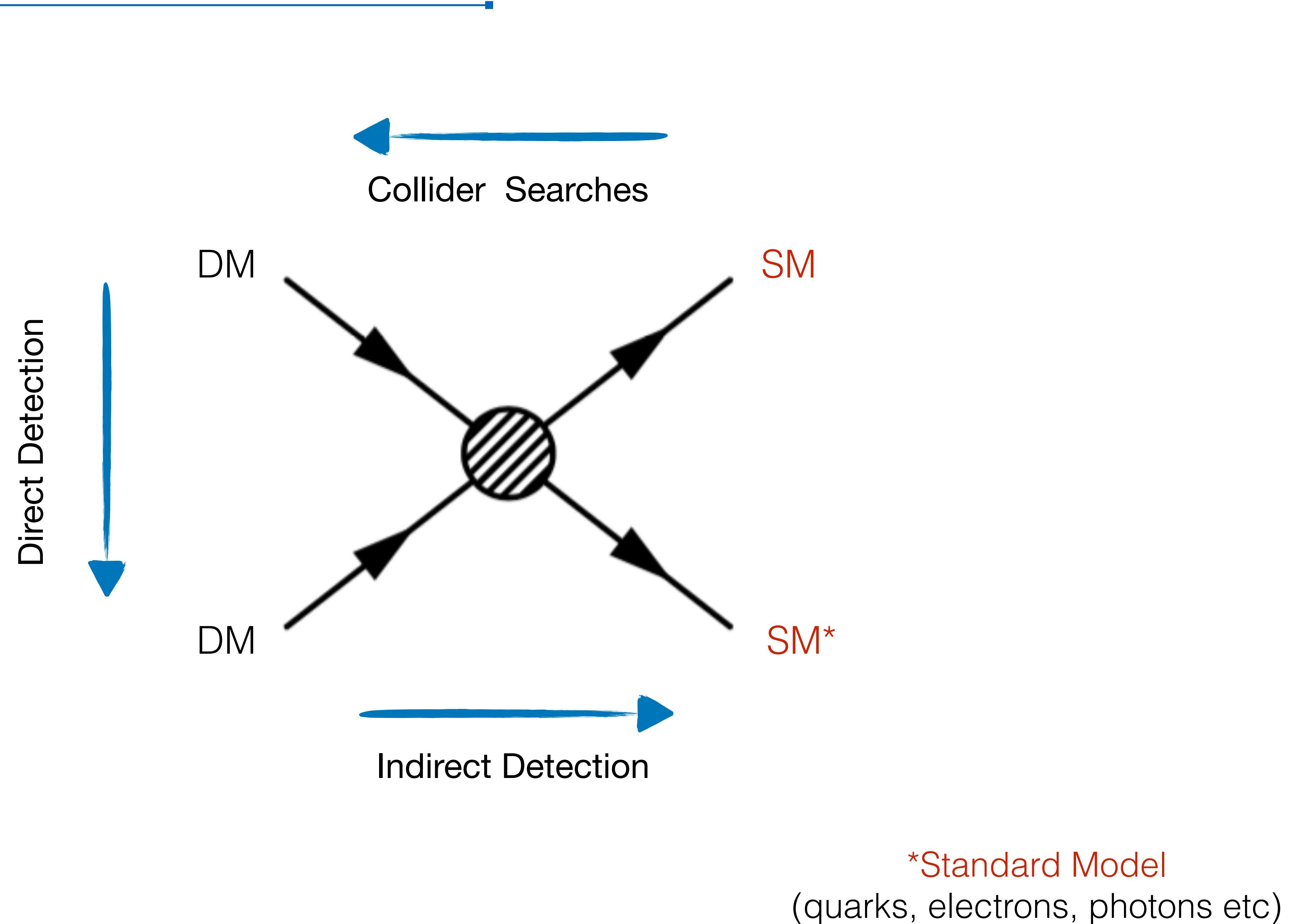
Very light relics  $m \lesssim \text{eV}$  decouple and freeze out when they are still relativistic! We call such particles **Hot Dark Matter**. Standard Model Neutrinos are Hot Dark Matter!

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**.

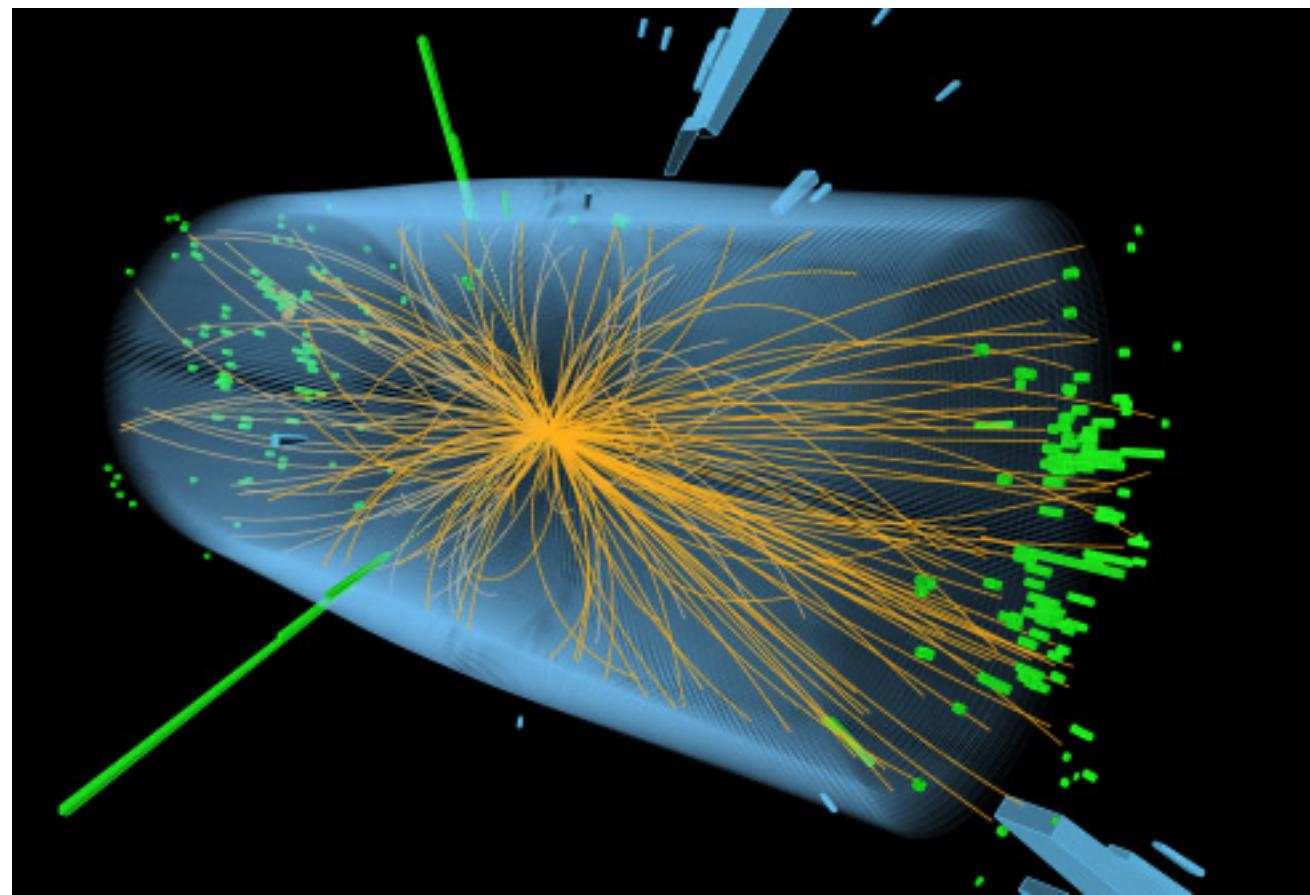


# Detection of WIMPs

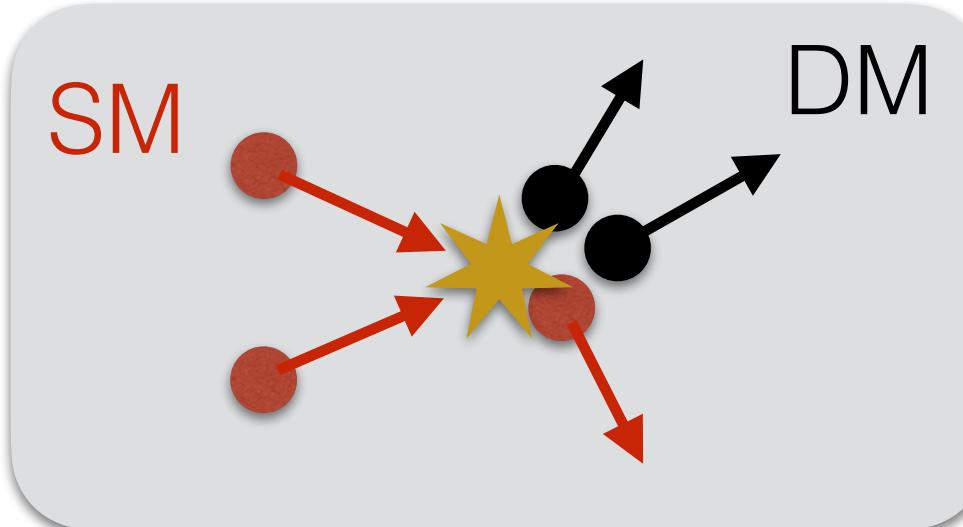
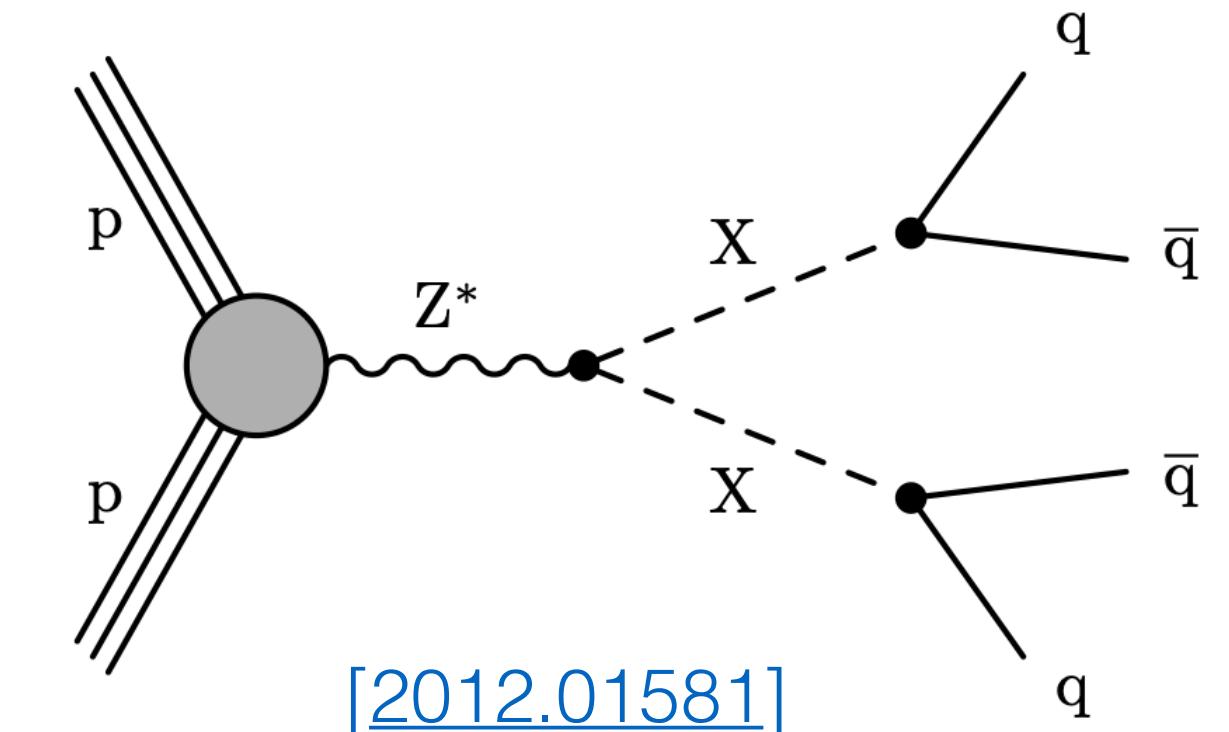
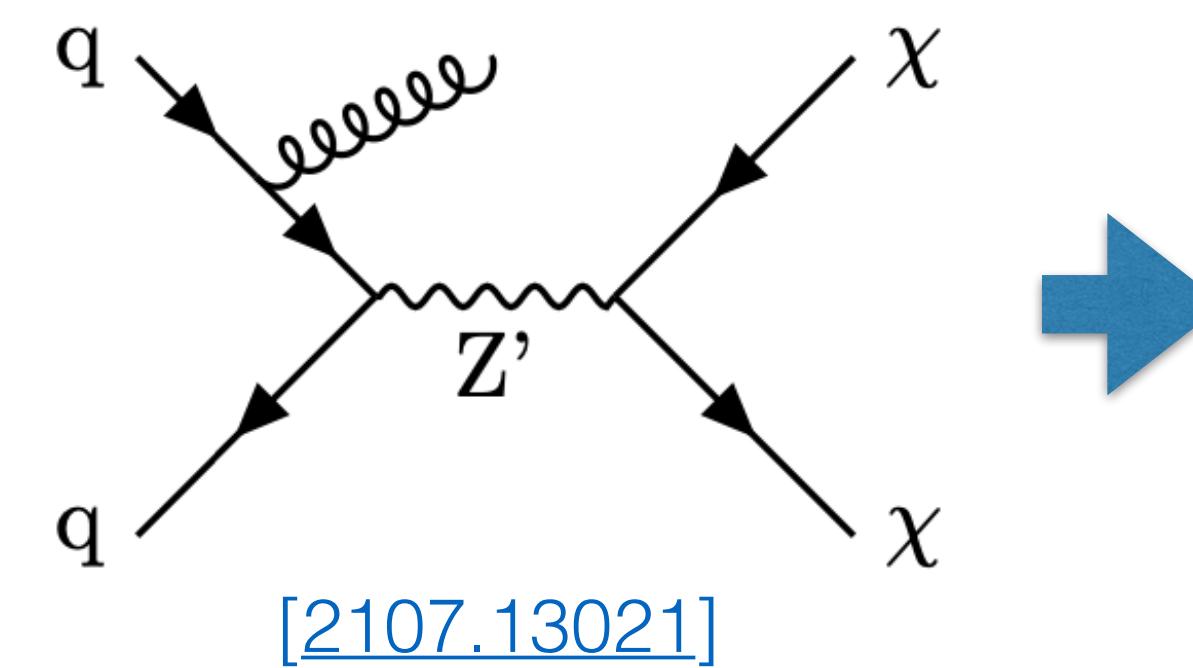


# Collider Searches for WIMPs

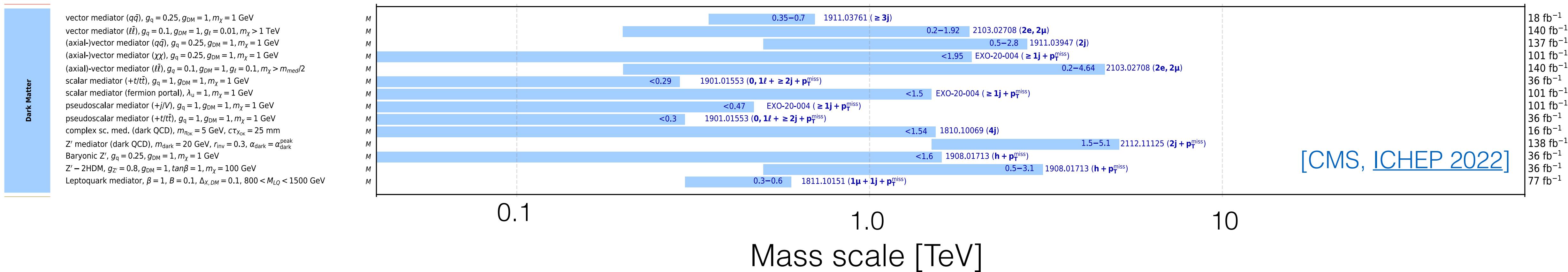
[Credit: CMS/CERN]



A trend towards more complicated signatures:

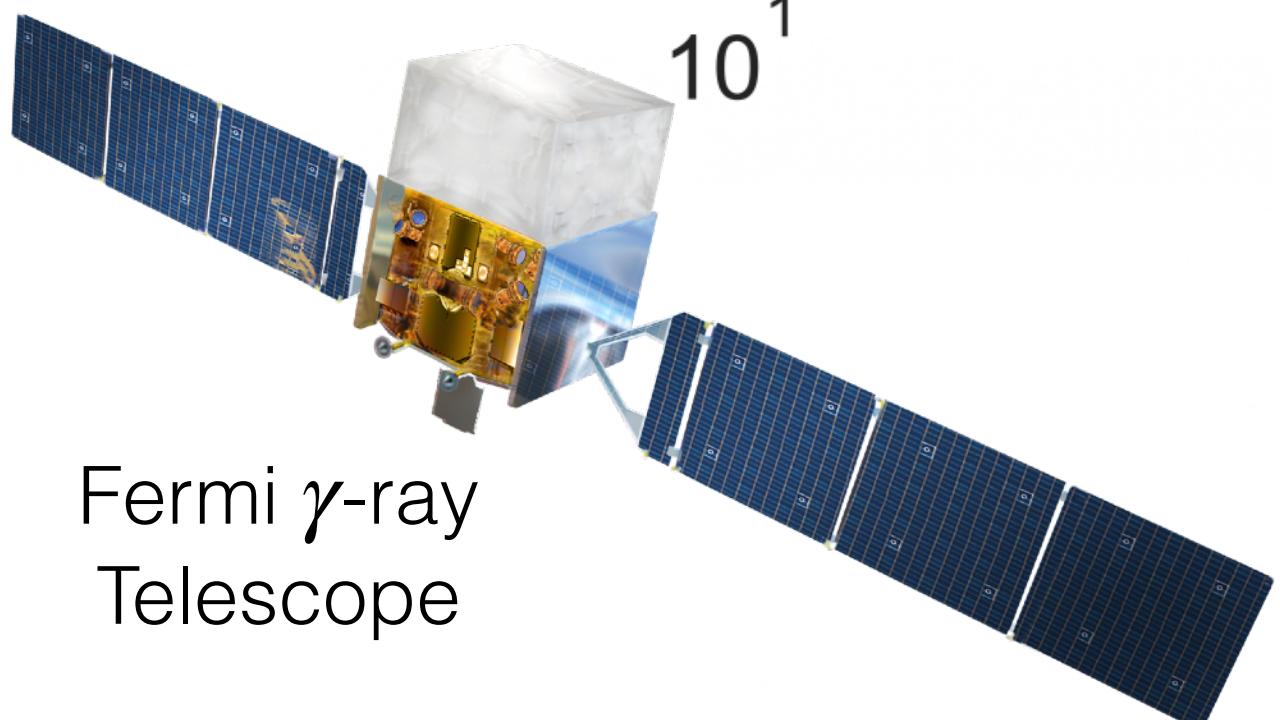


Summary of CMS constraints on the mass scale of new mediator particles coupling to DM:

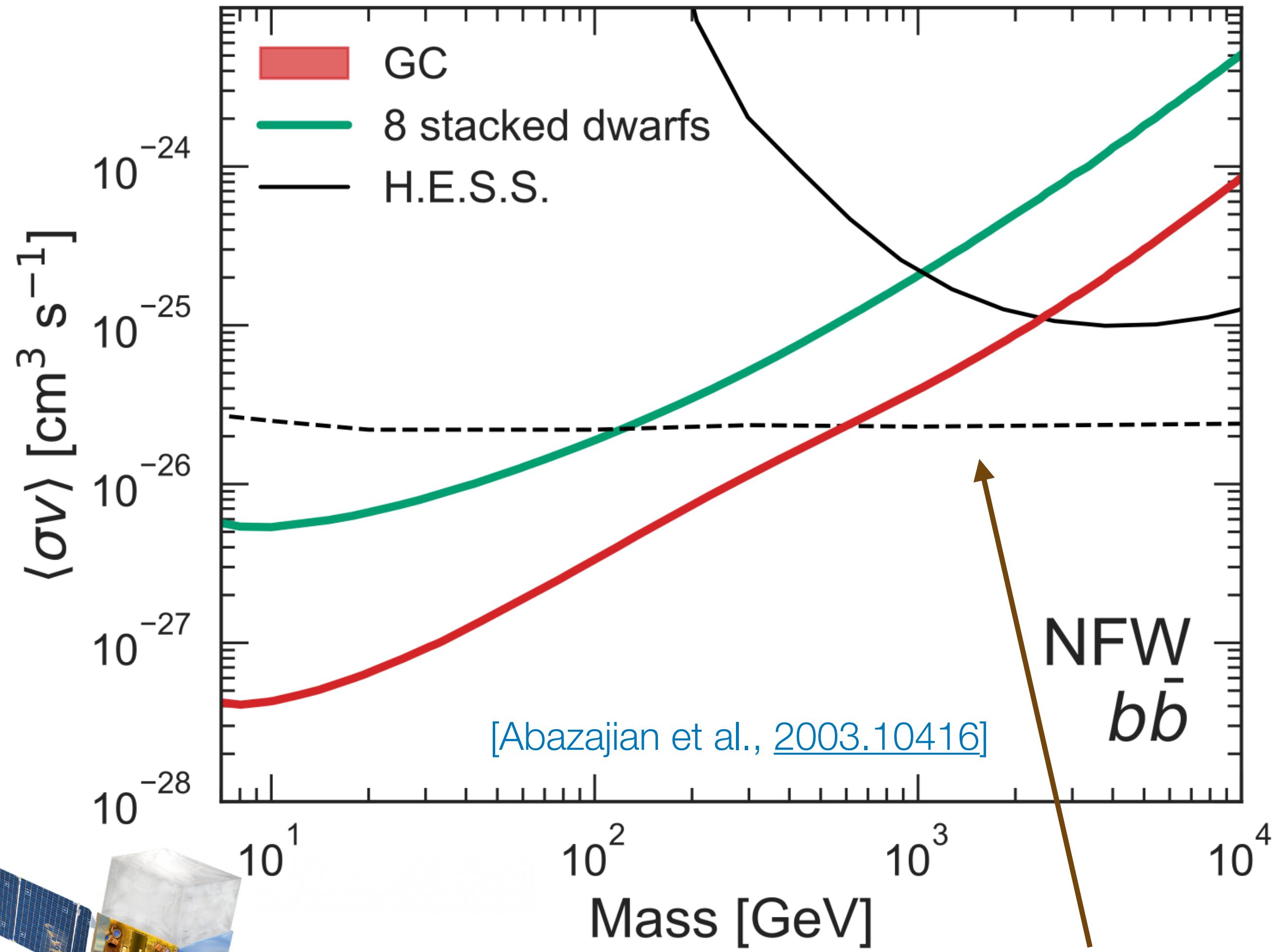


LHC Run-3 (2022 - 2025) and High Luminosity LHC (2029+) will bring more data, but extending to a wider range of masses is challenging...

# Indirect Detection of WIMPs

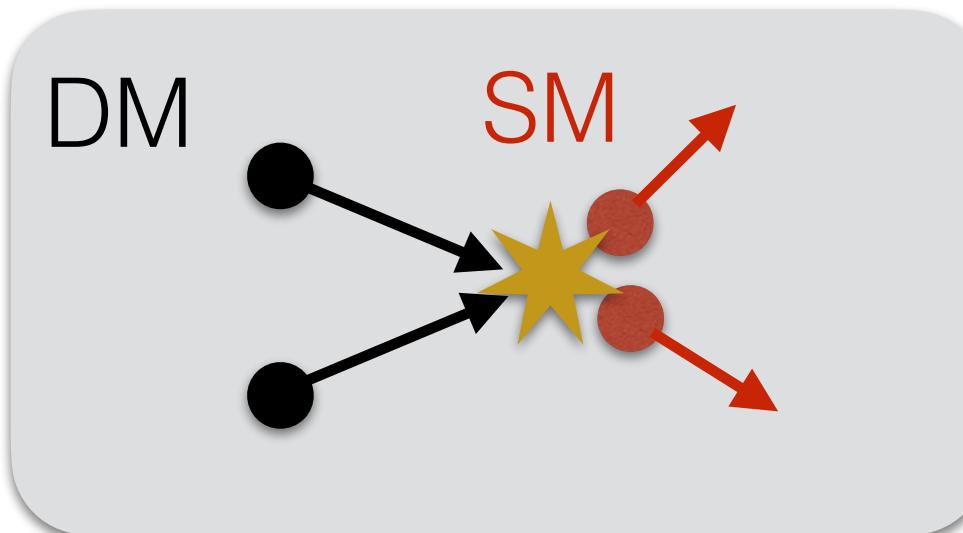


DM Annihilation Cross Section

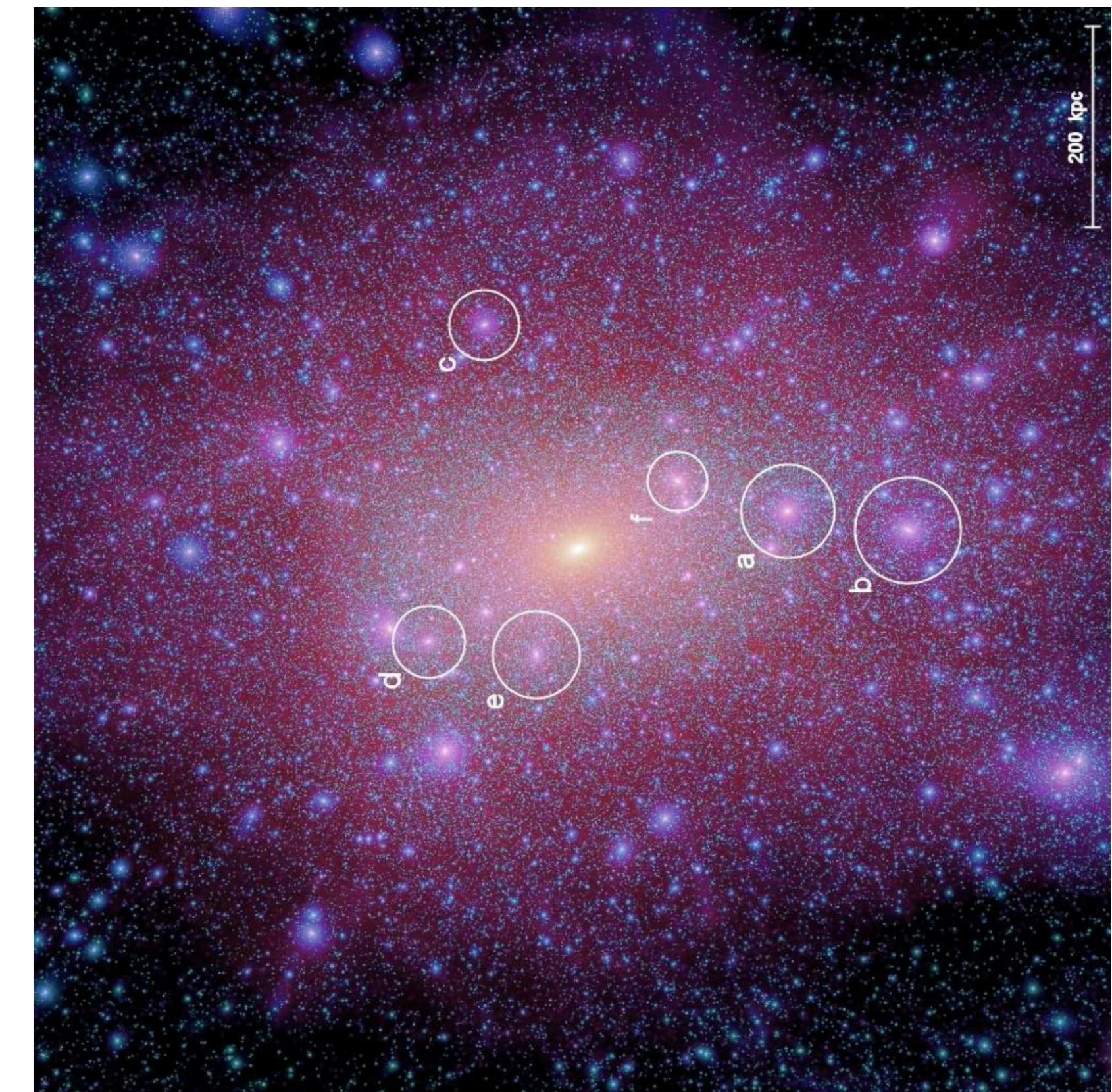


Fermi  $\gamma$ -ray  
Telescope

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



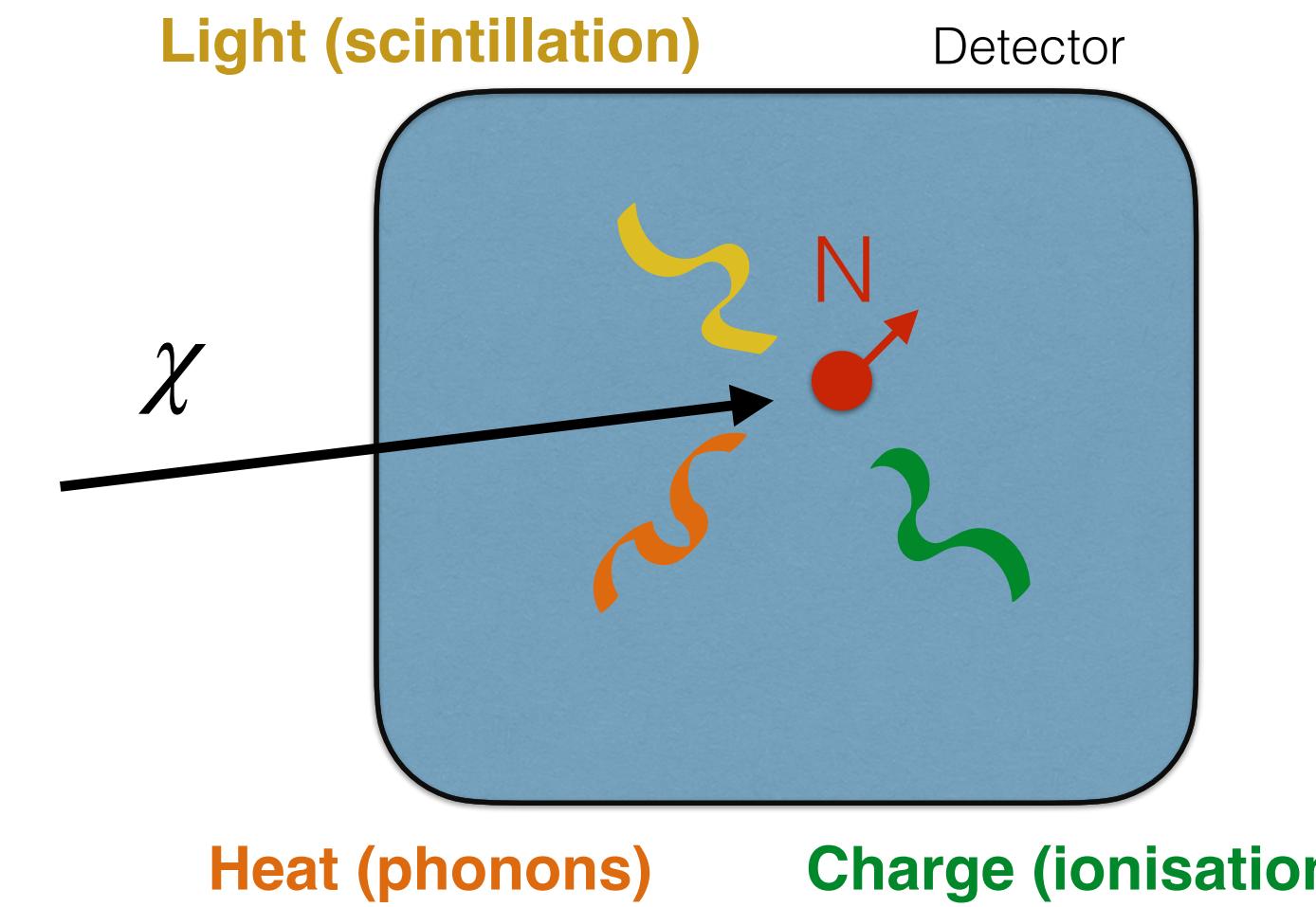
Look for signals of Dark Matter annihilation in regions of large DM density!



[Aquarius - Springel et al., 0809.0898]

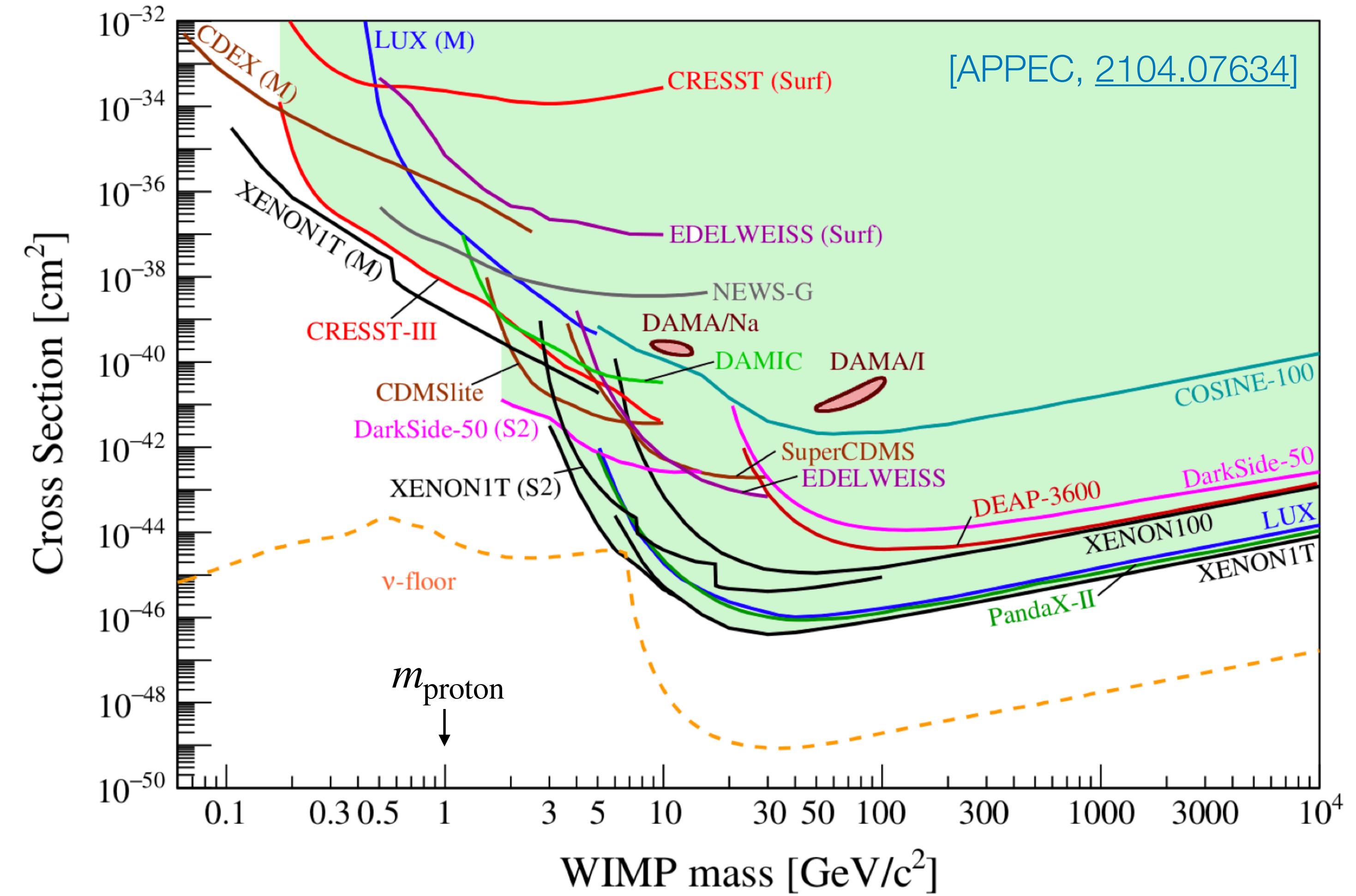
# Direct detection of WIMPs on Earth

For WIMPs with GeV-scale masses,  
expect detectable nuclear recoils of  
energy  $O(\text{keV})$



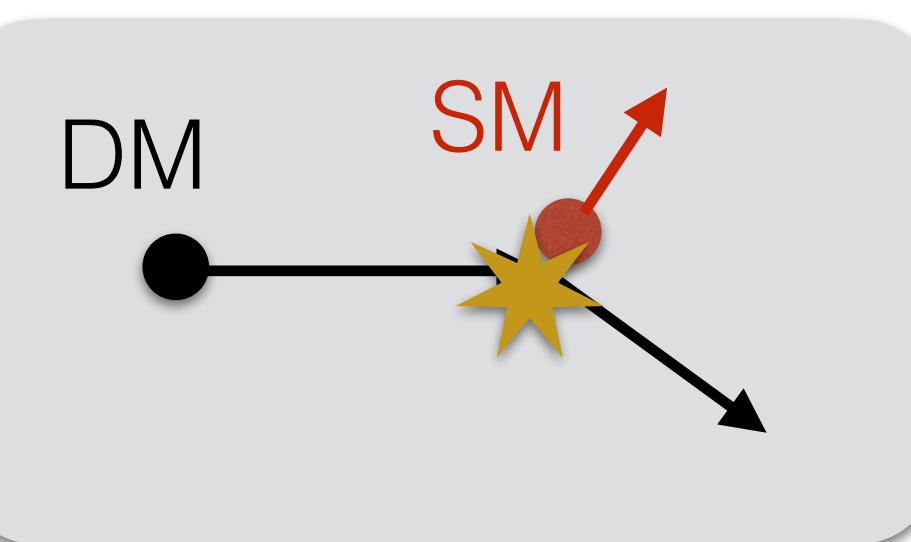
For sensible models, expect signal  
rates on the order of <1 event per  
kg per keV per day

No convincing signal yet!

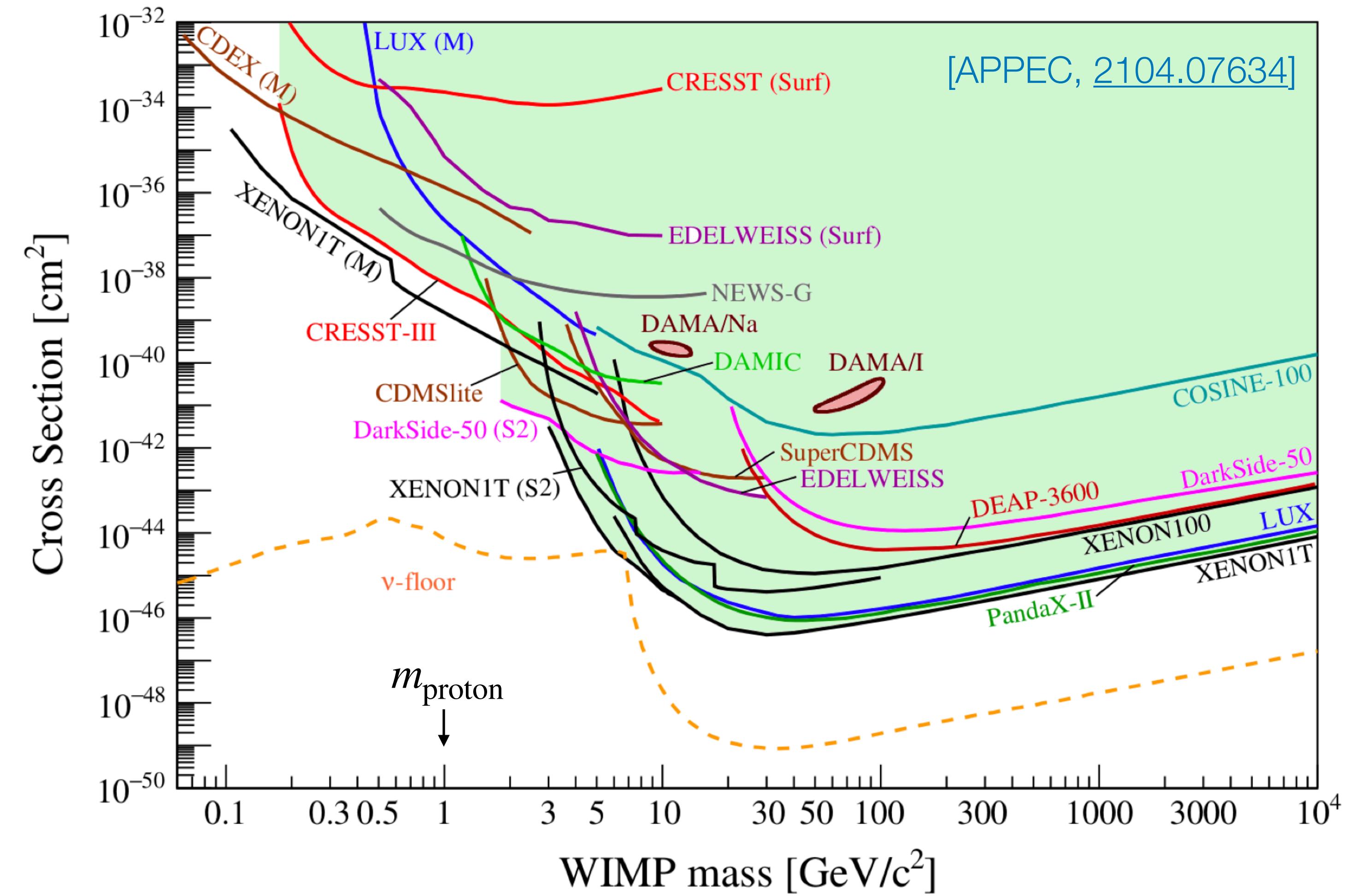
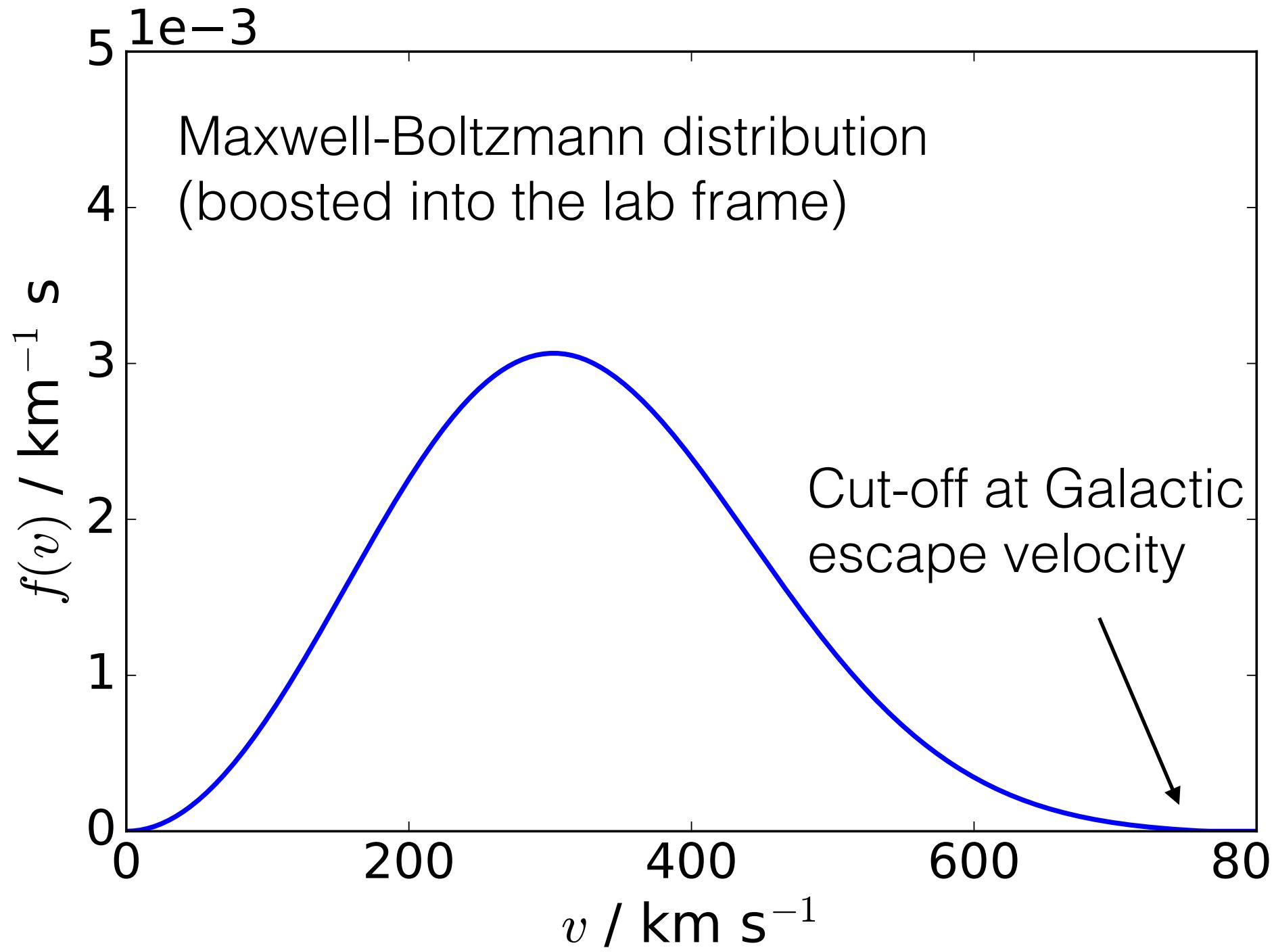
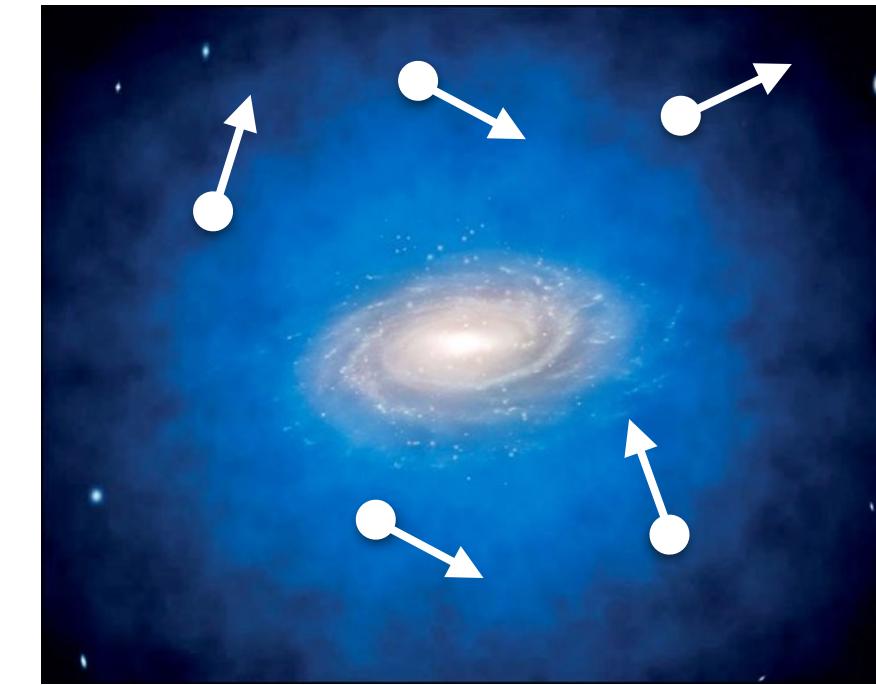


# Low-mass WIMP Challenge

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

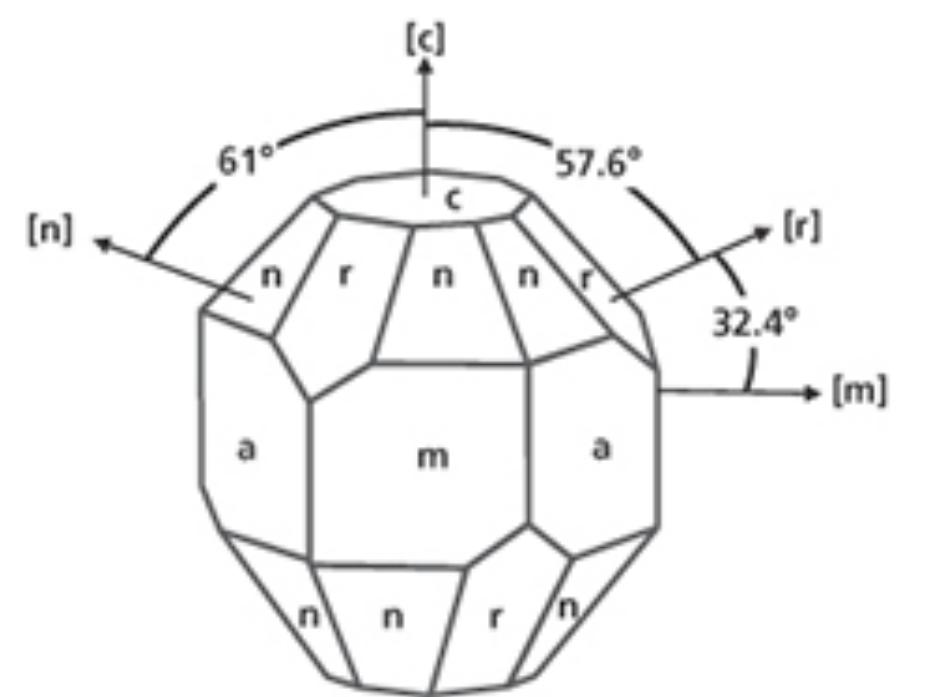


$$\langle v_\chi \rangle \sim 300 \text{ km/s}$$
$$\sim 10^{-3} c$$



# New Directions for Dark Matter

Low-threshold  
phonon detectors

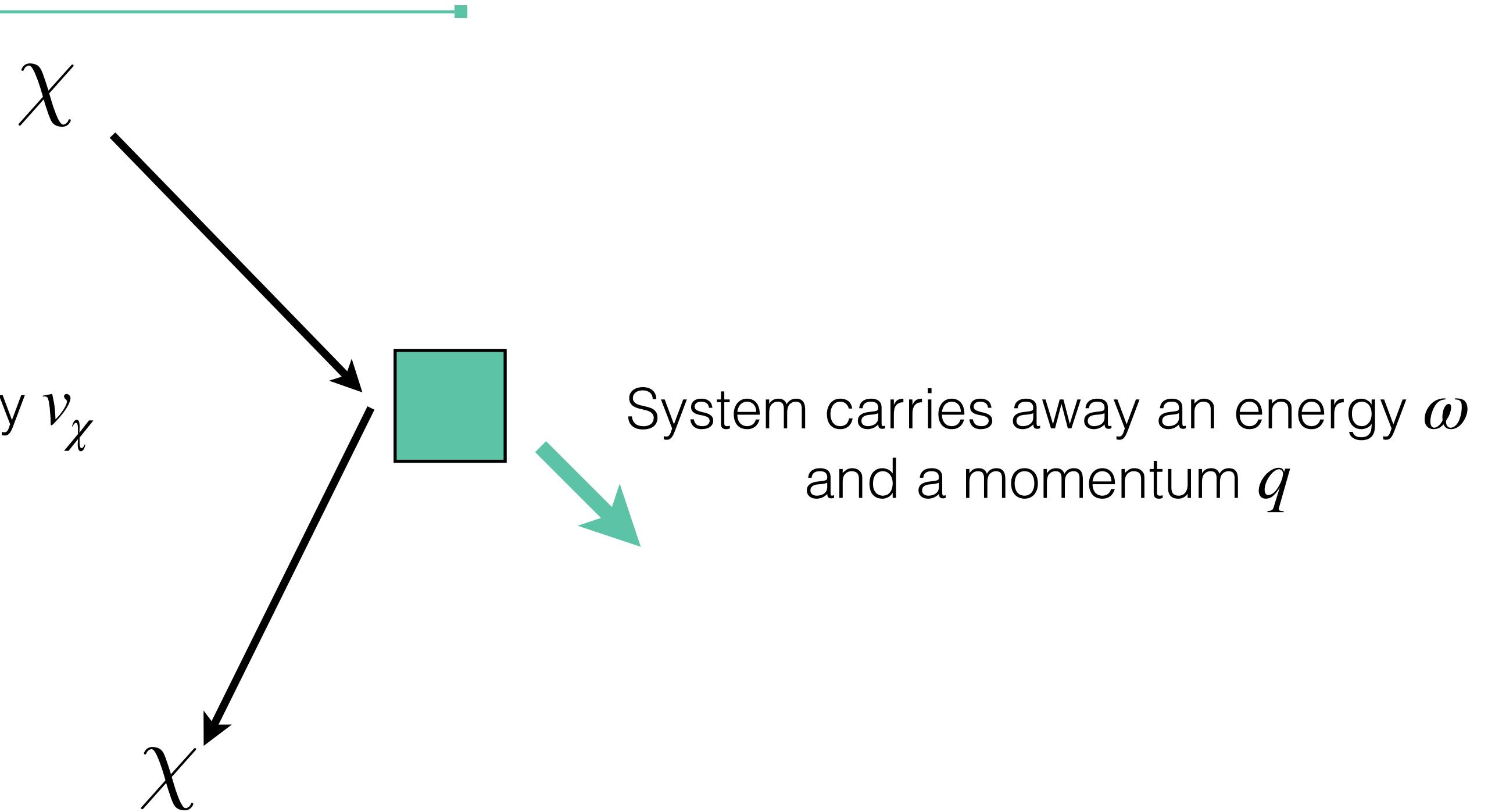


Black Holes and  
Gravitational Waves



# Direct Detection of Dark Matter

DM with mass  $m_\chi$  and initial velocity  $v_\chi$  scatters with a system



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

$$q_{\max} = 2m_\chi v_\chi$$

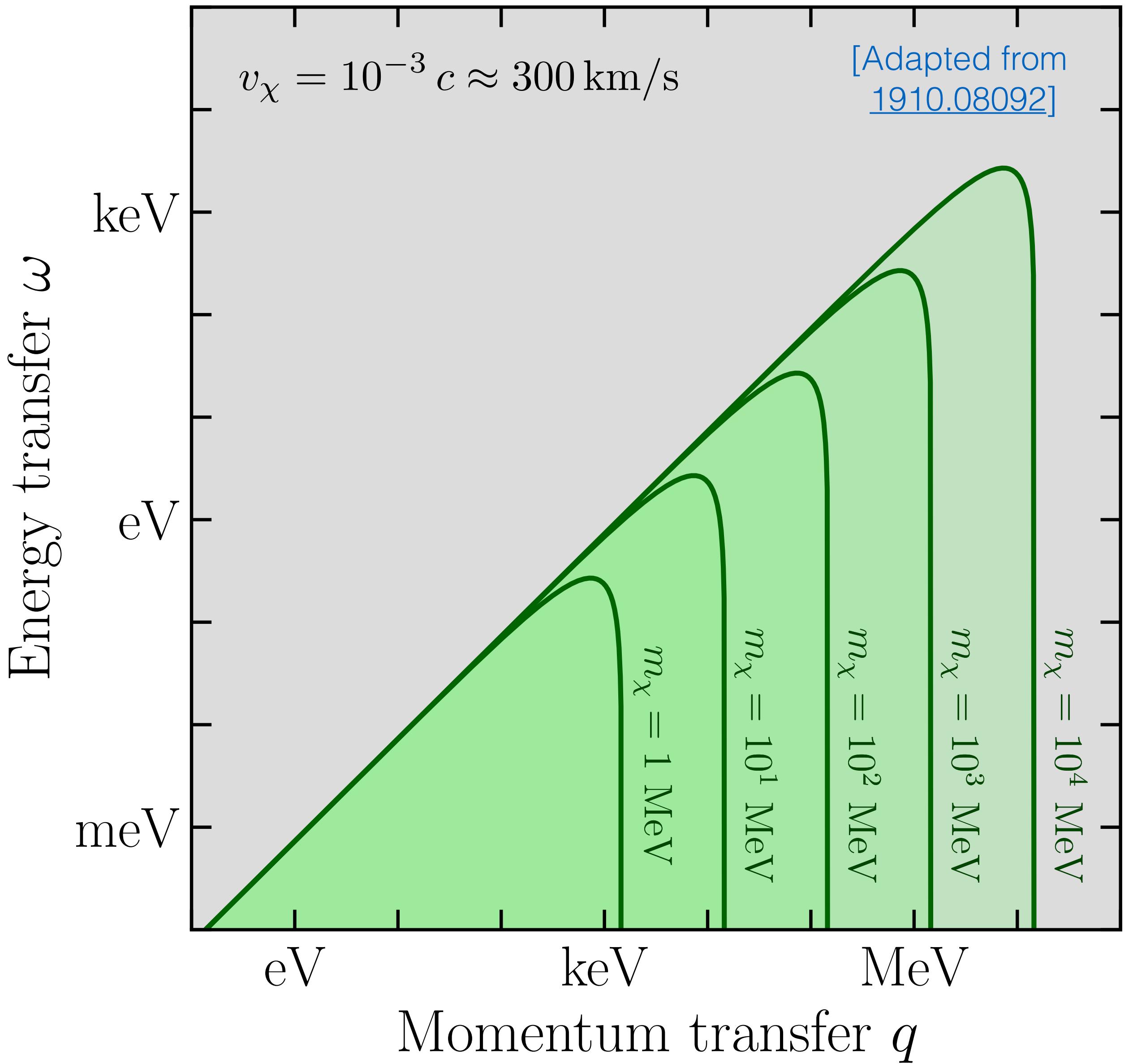
# Scattering Kinematics

Allowed range of  $(\omega, q)$  set by kinematics (green regions):

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

Consider:

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



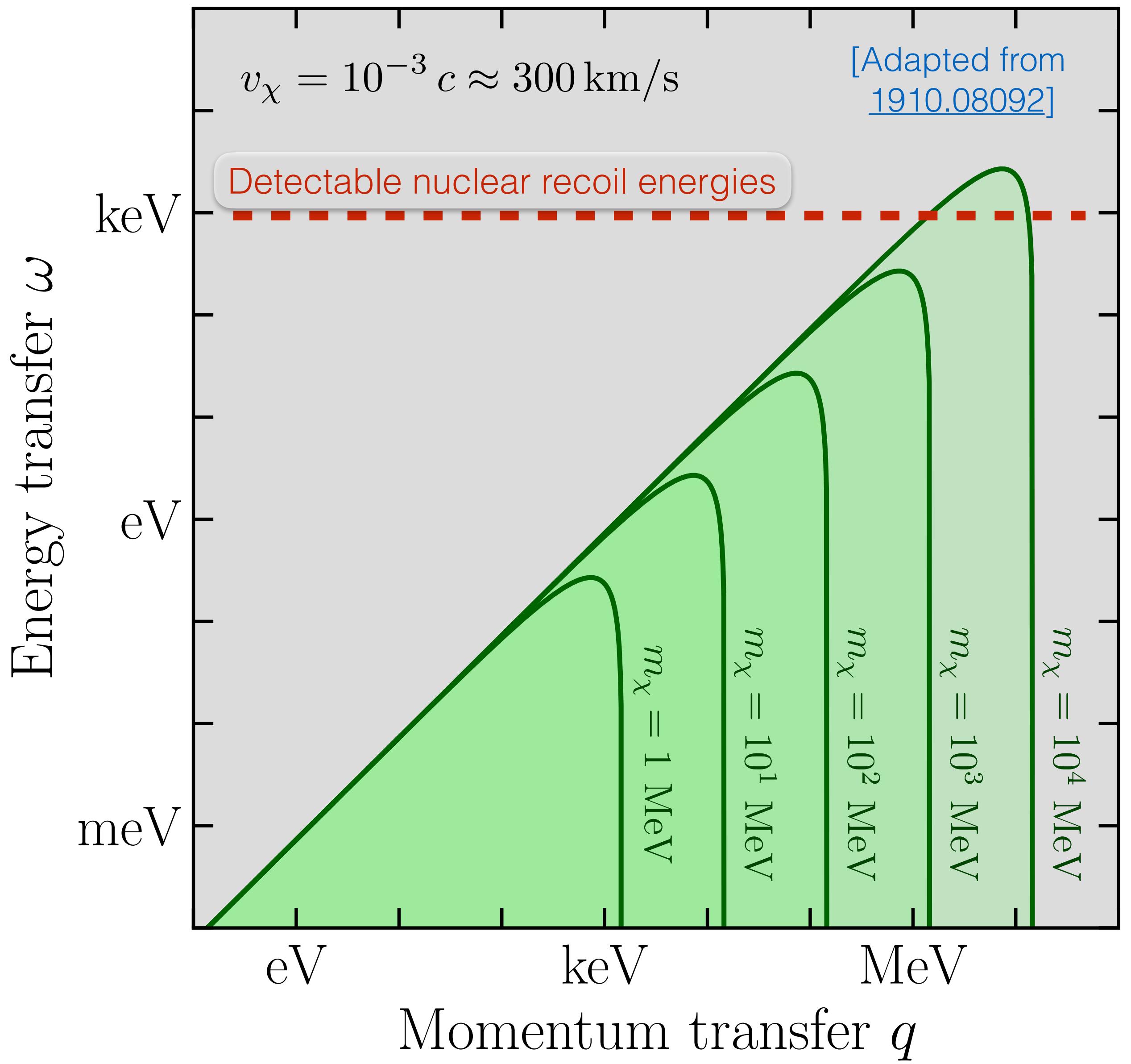
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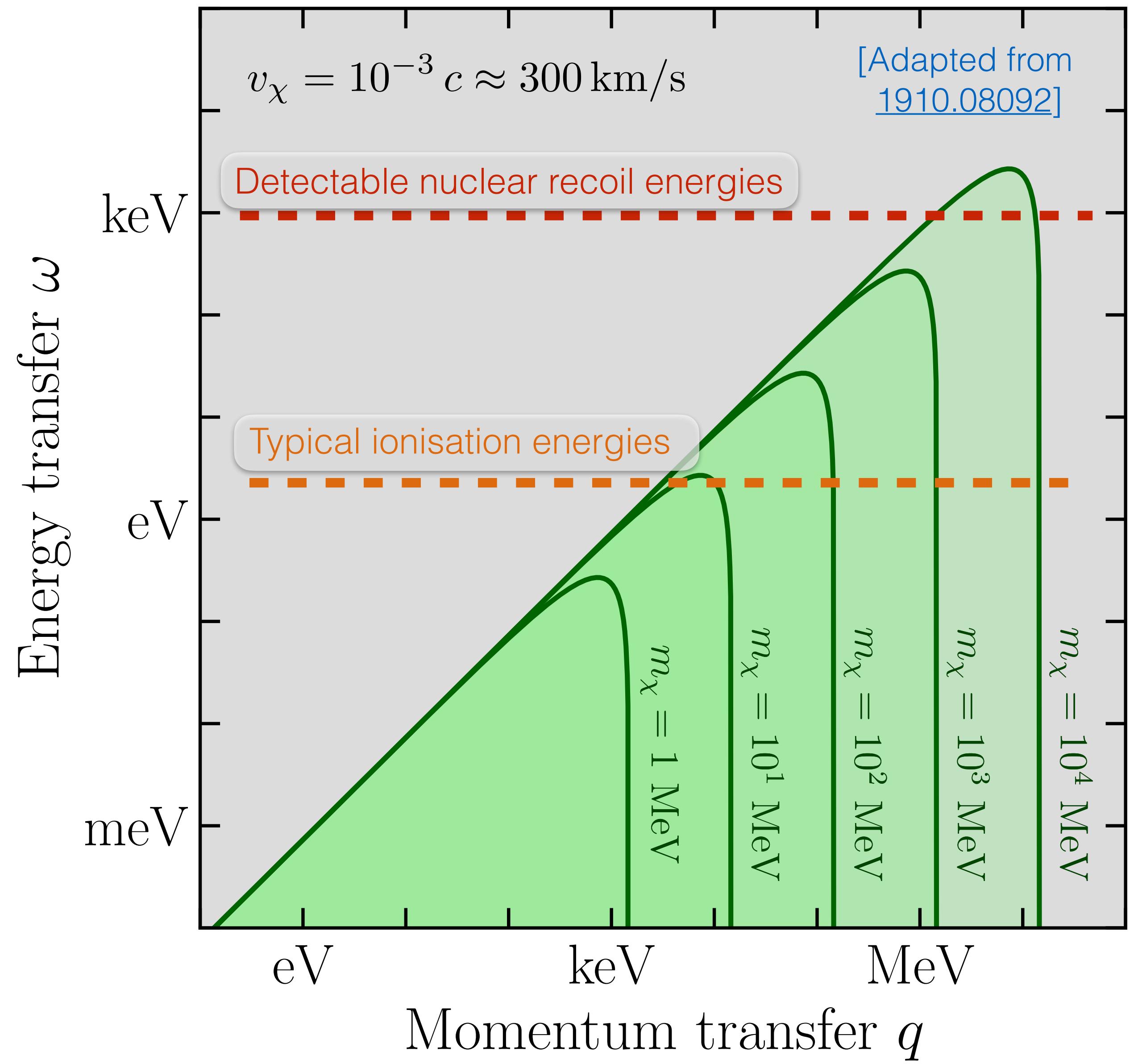
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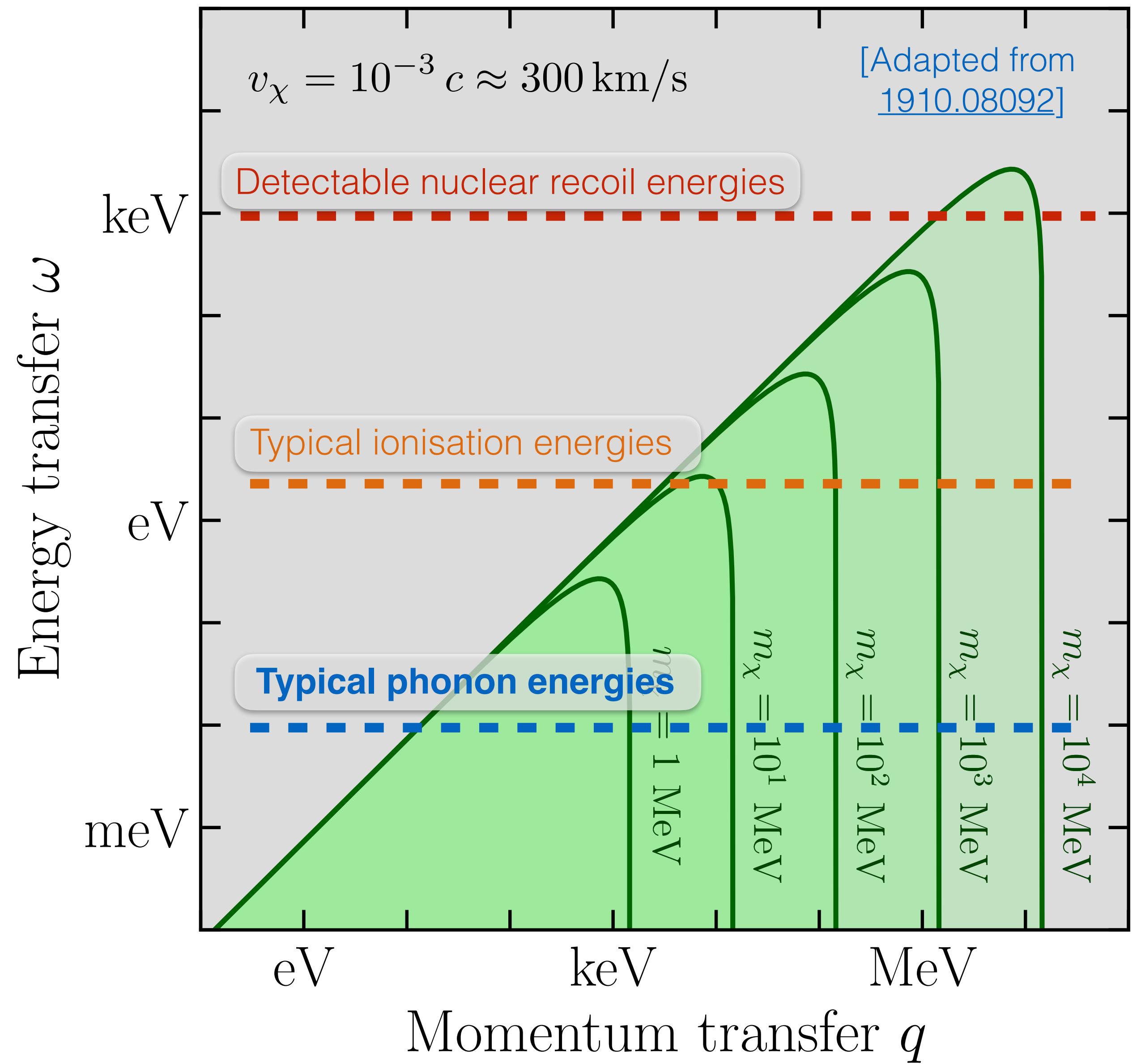
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**DM mass ranges:**

meV

eV

keV

MeV

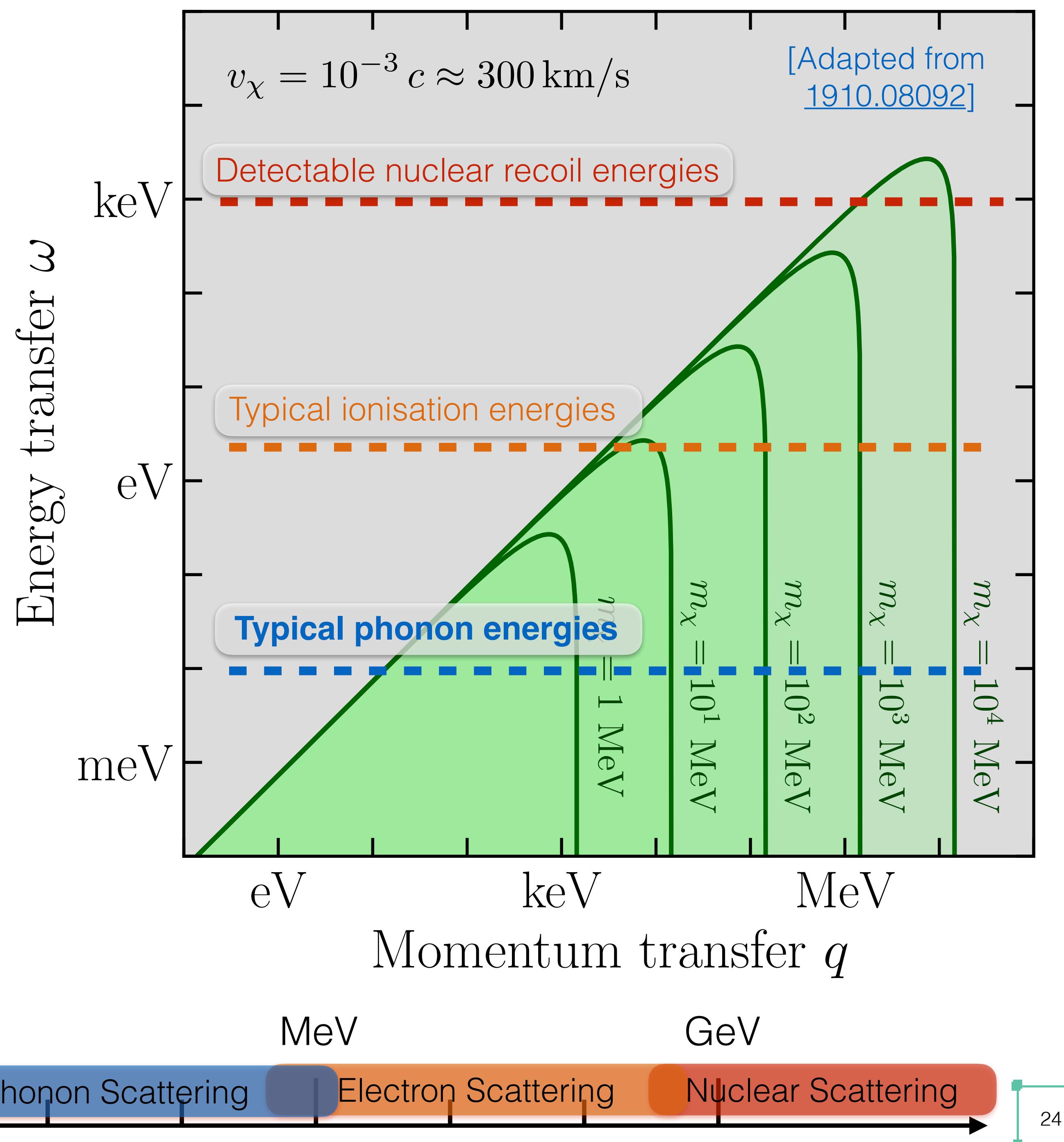
GeV

Absorption into Phonons

Phonon Scattering

Electron Scattering

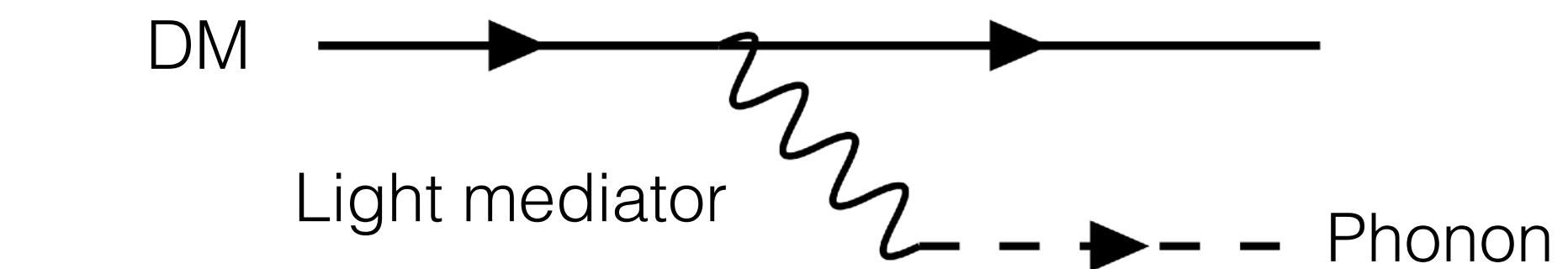
Nuclear Scattering



# DM-Phonon Scattering

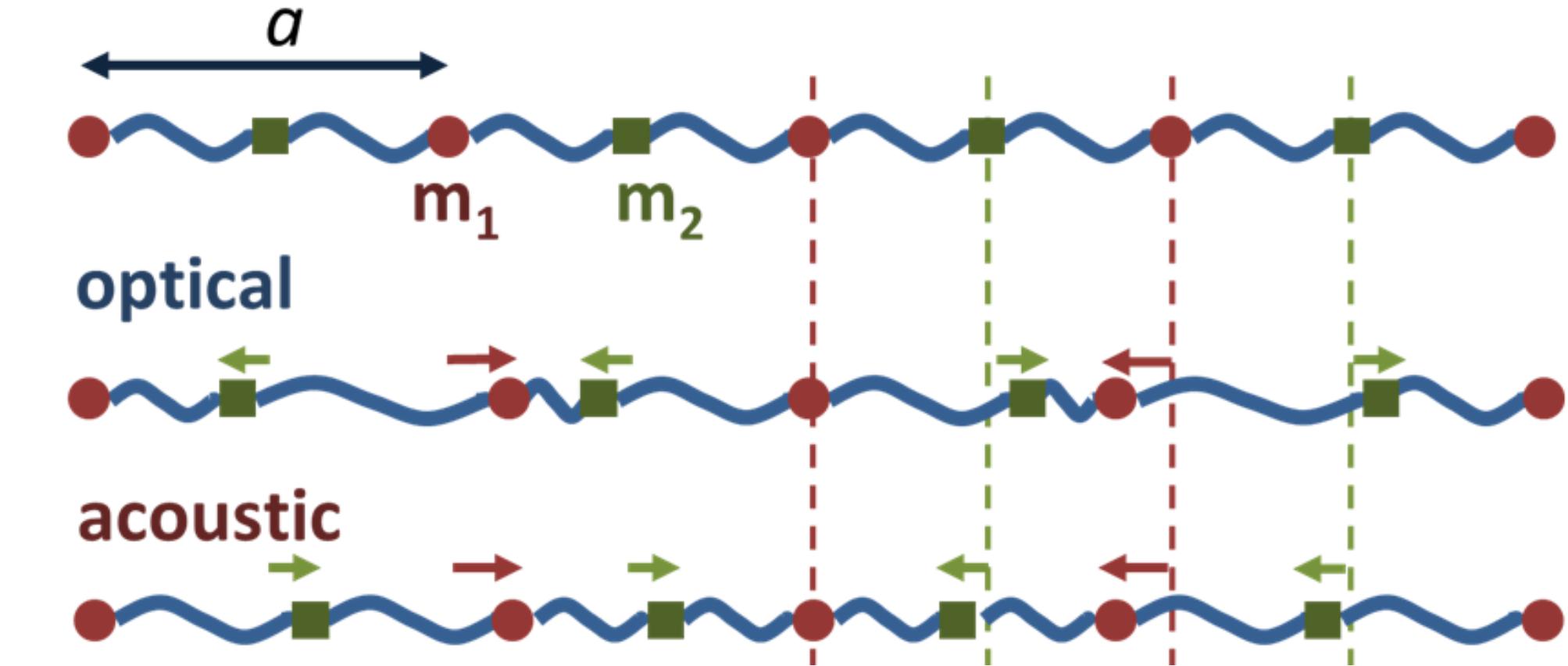
For sufficiently light DM,  $m_\chi < 1 \text{ MeV} \Rightarrow q < \text{keV}$

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**.

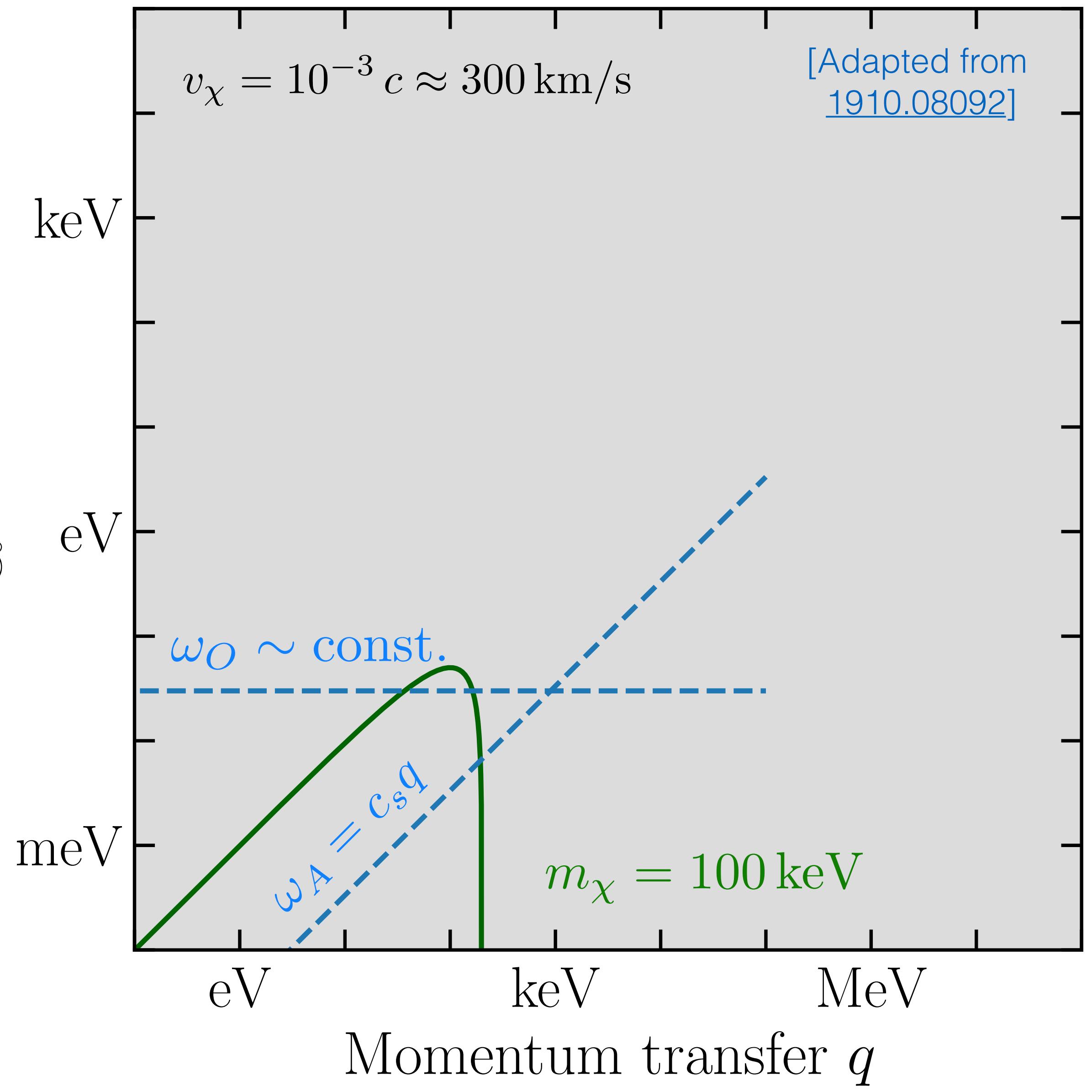
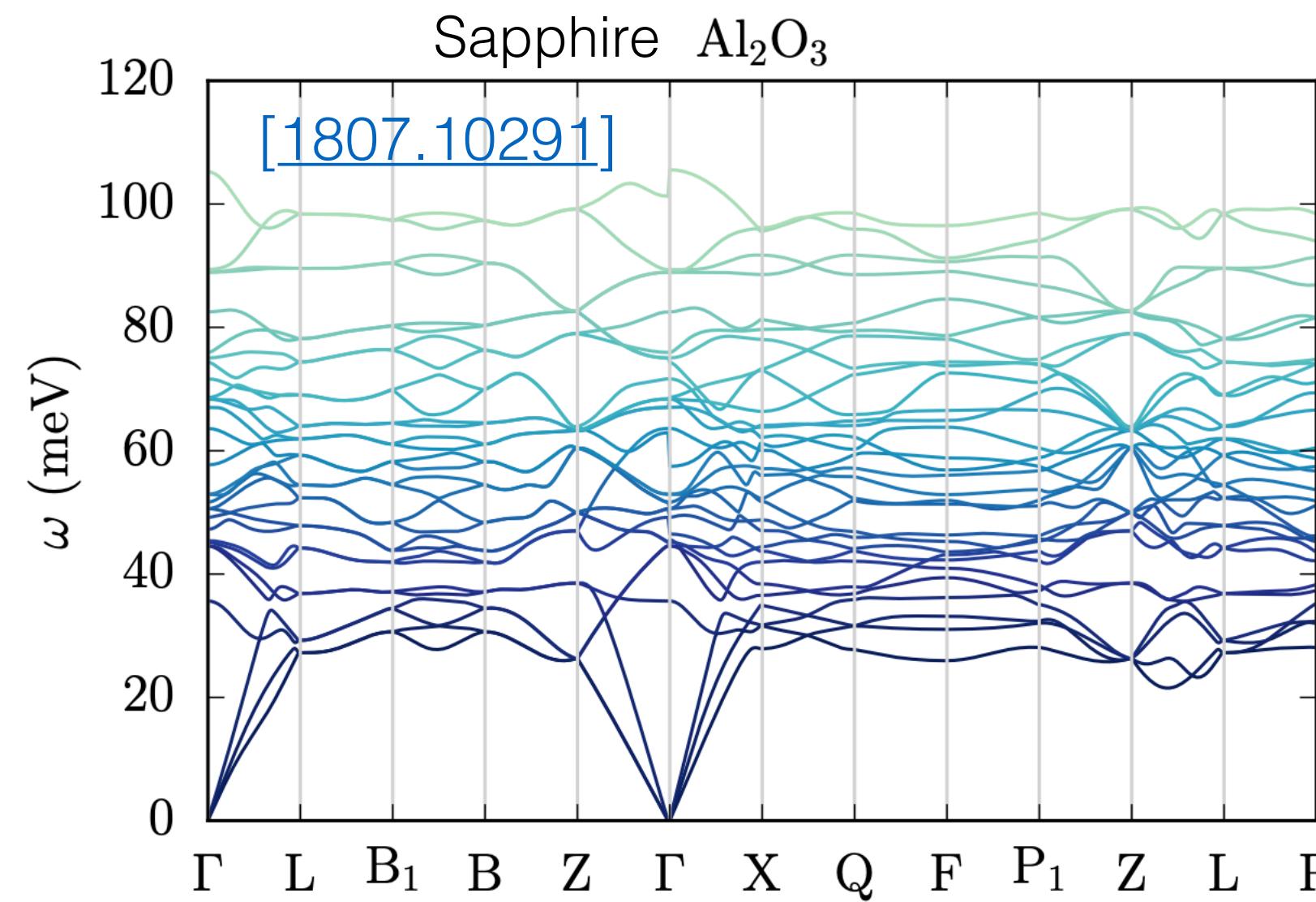
e.g. hadrophilic scalar mediator

[DM phonon scattering theory - [1712.06598, 1905.05575](#)]  
[DM-phonon scattering in superfluid Helium - [2005.08824](#)]

# Optical vs acoustic phonons

Allowed range of  $(\omega, q)$  set by kinematics (green regions):

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



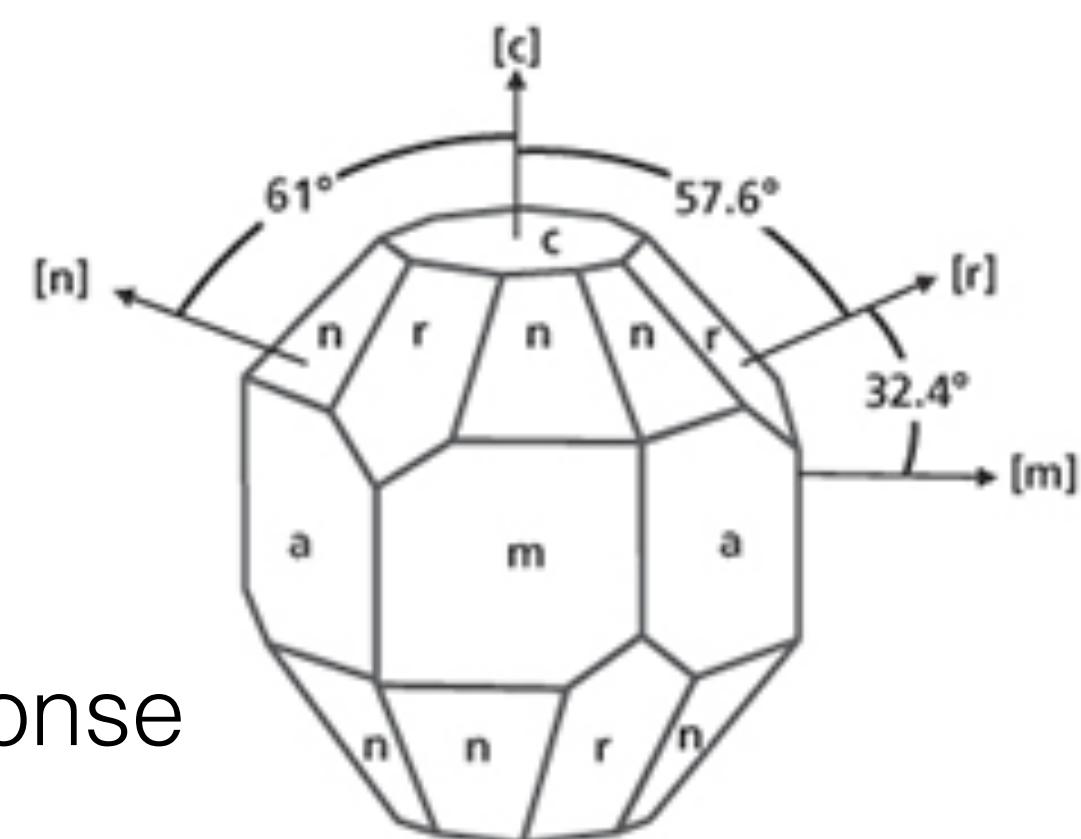
For a given DM mass and velocity, gapped optical phonons typically allow for a larger energy deposit (just by looking at kinematics).

# Time-dependent DM Signal

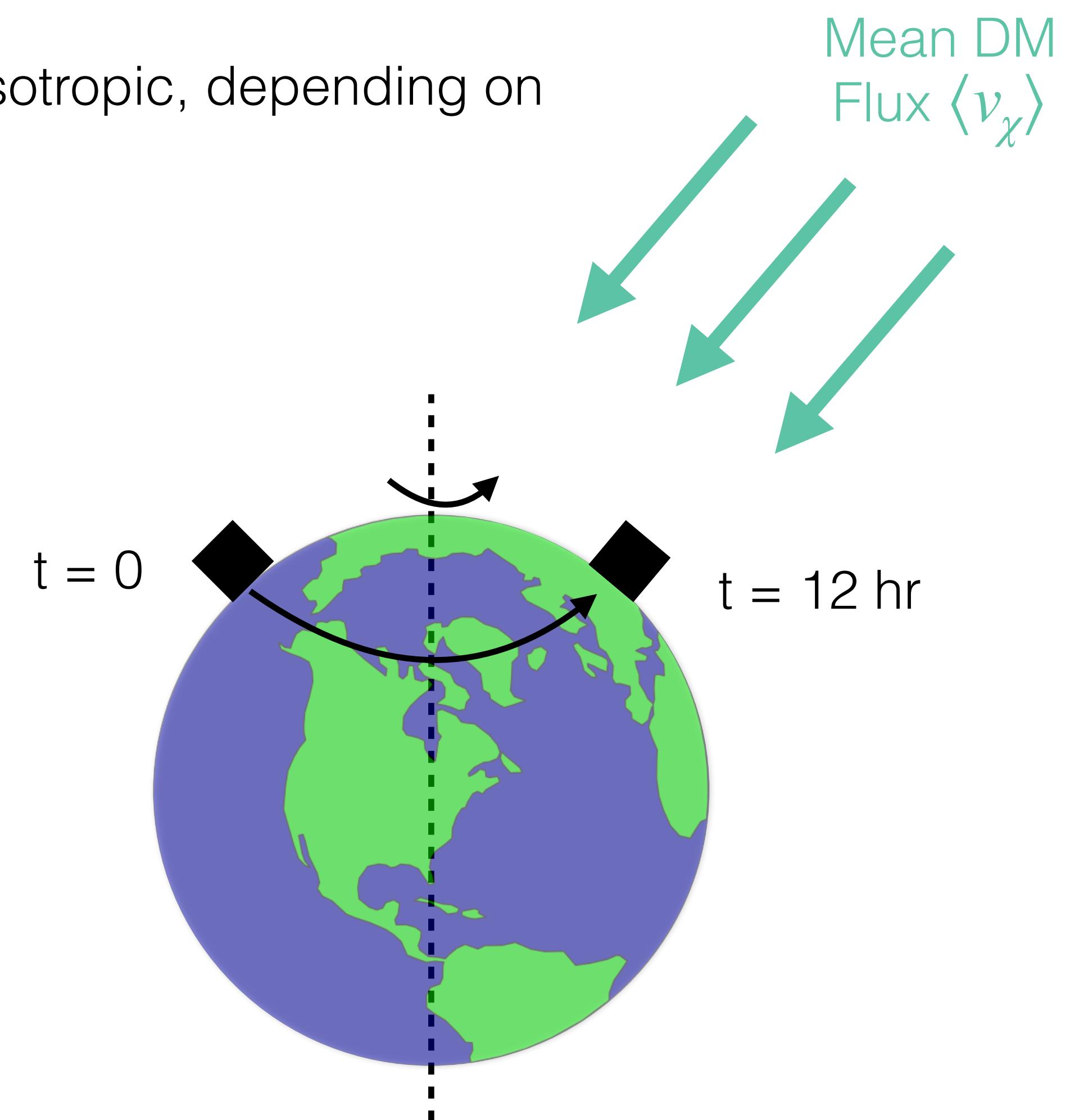
DM flux comes from a preferred direction, meaning that if the phonon response is anisotropic, a characteristic **time-dependent signal** can arise.

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

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

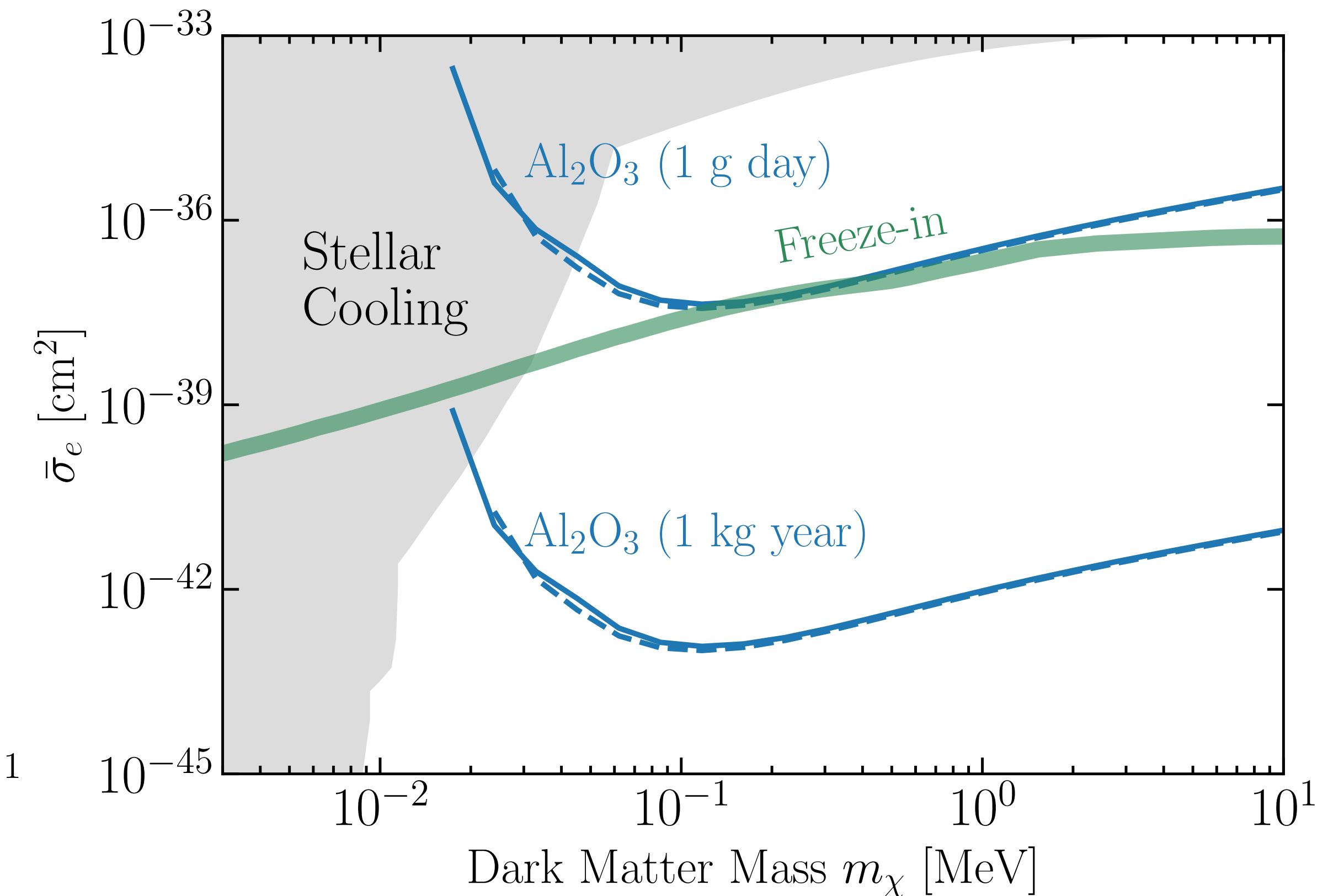
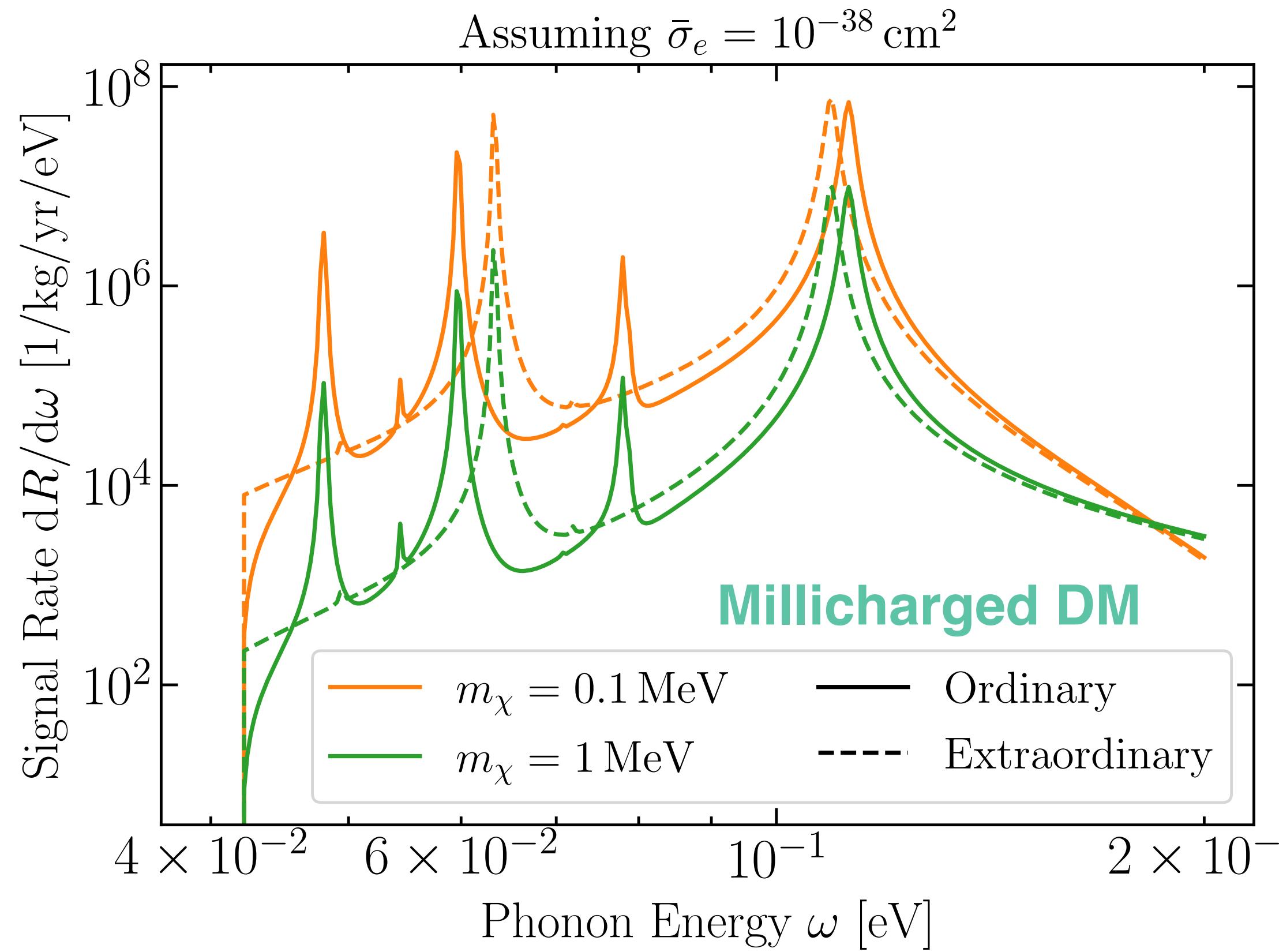


$\mathbf{k} \perp c\text{-axis}$ :  
Extraordinary response



# 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

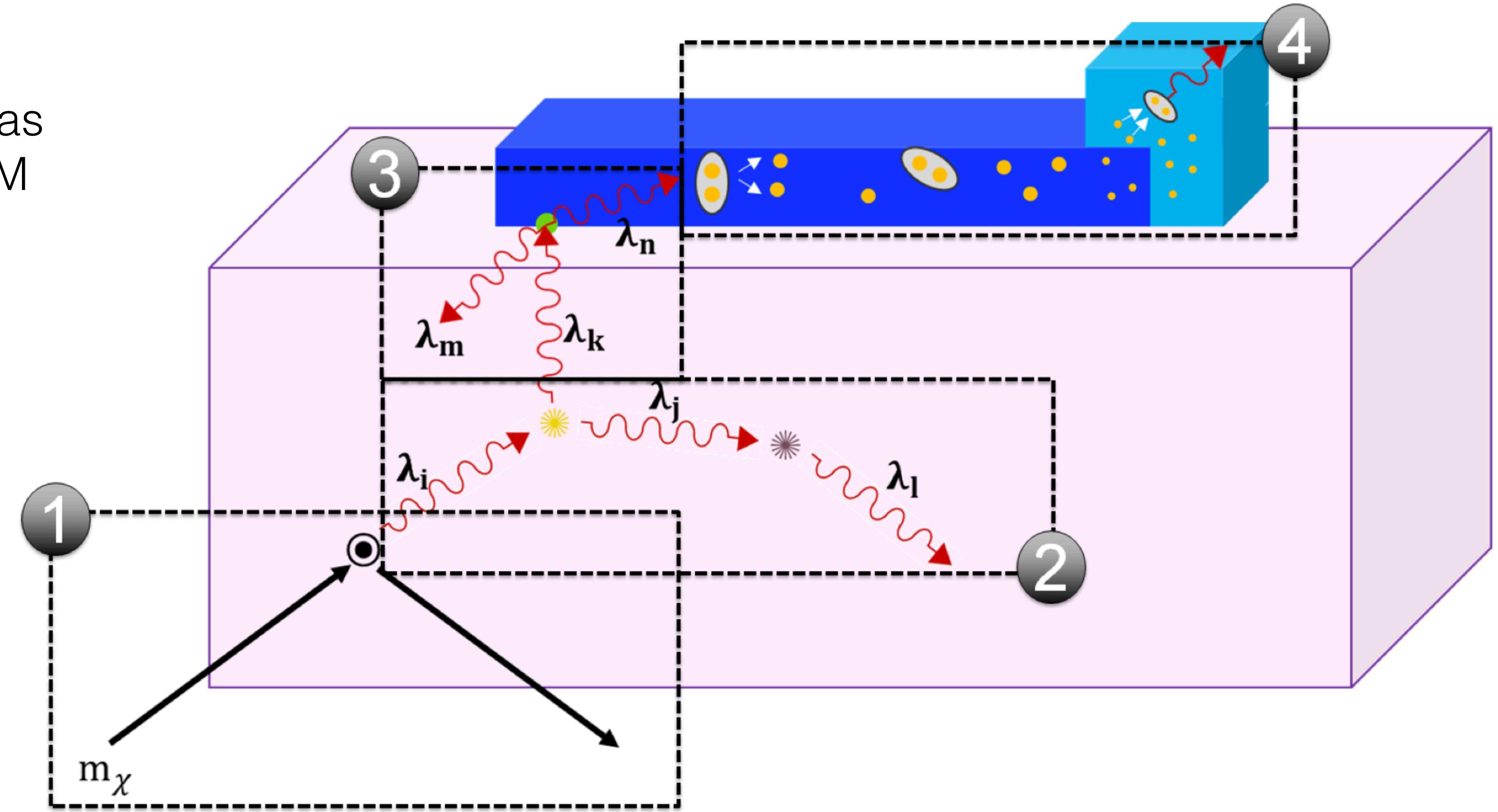
## Quasi-particle Trap Assisted Transition Edge Sensor (QET)

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

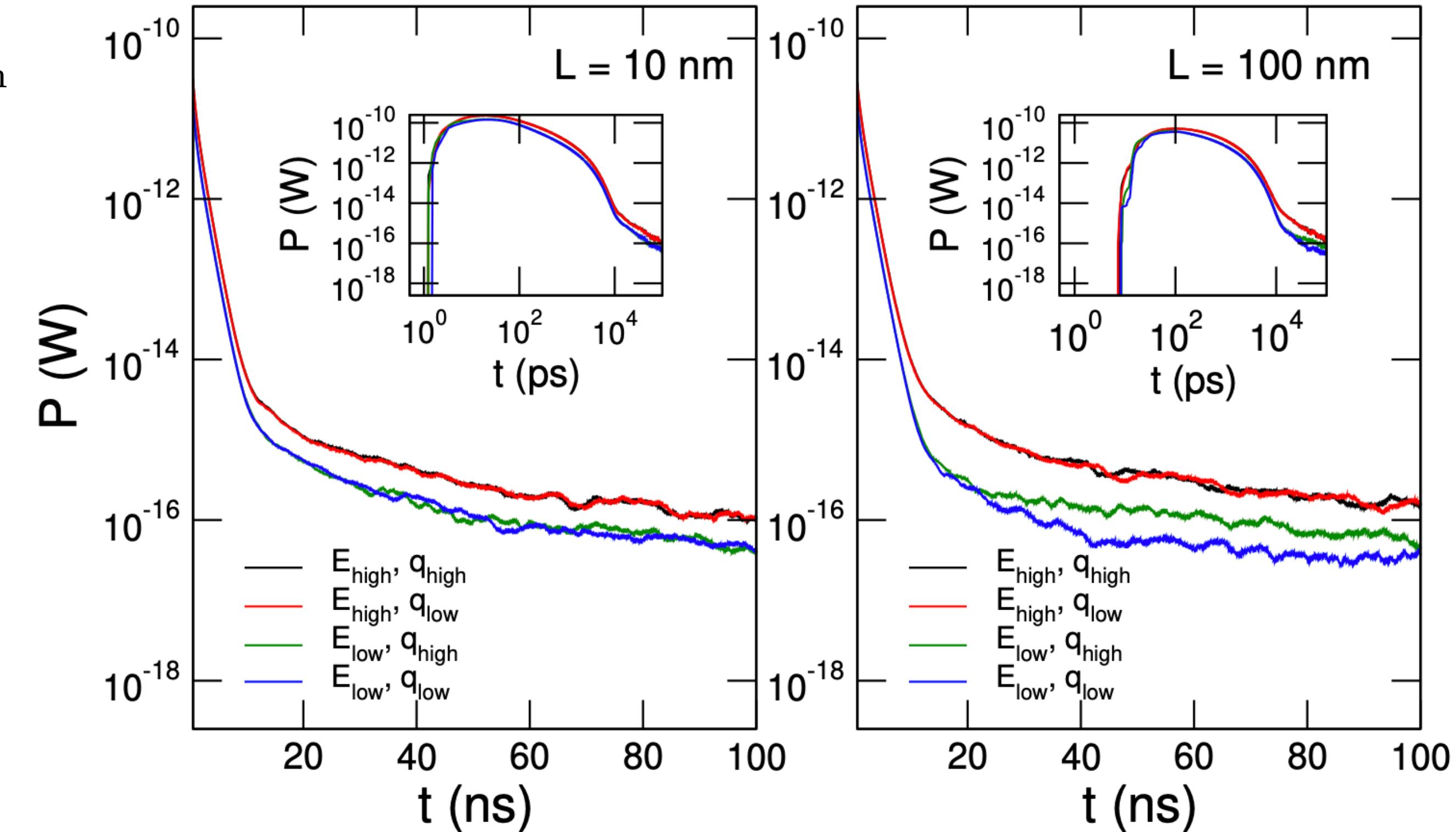
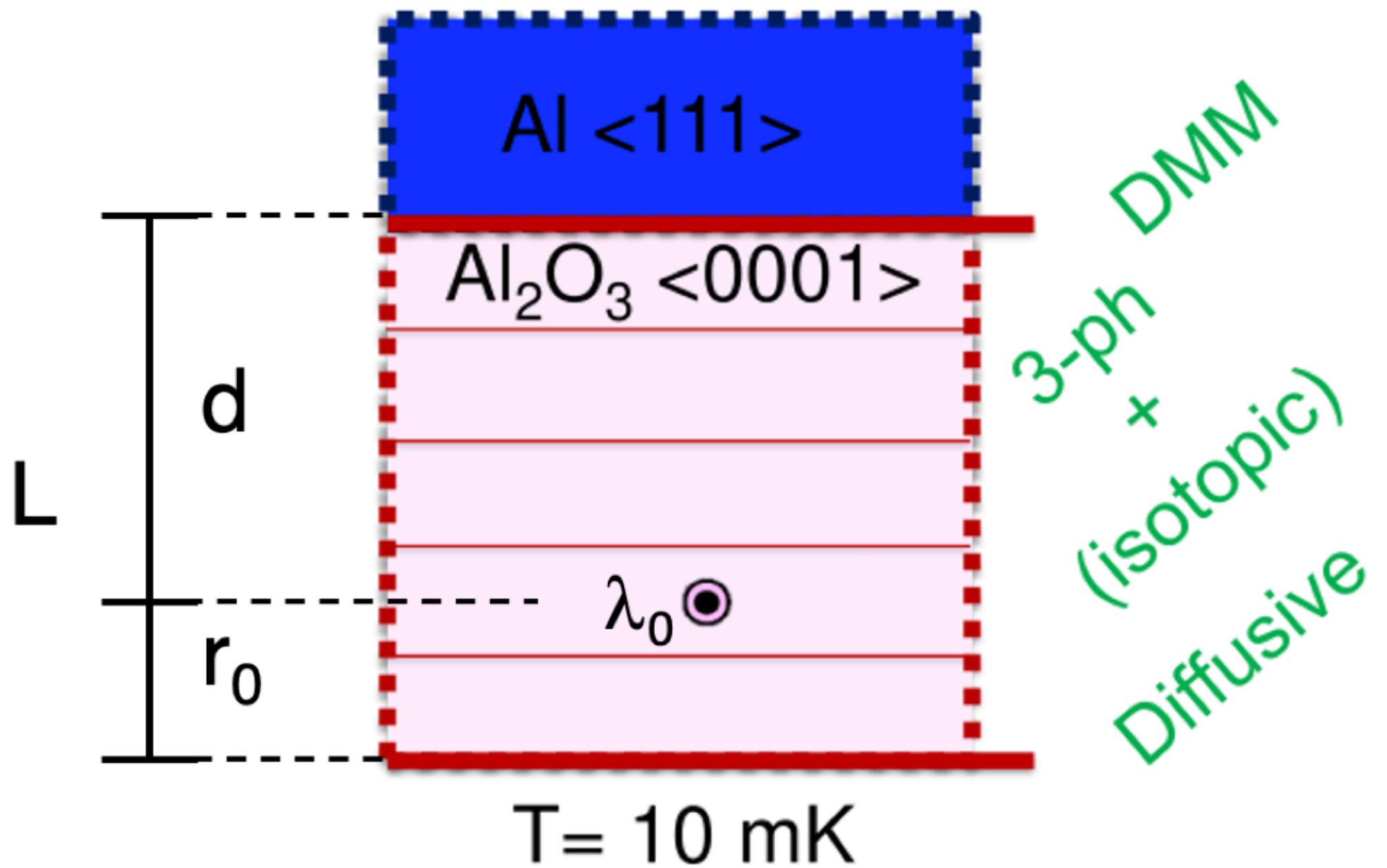


- Dark Matter
- Interaction center
- ~~ Phonon
- ★ Anharmonic scattering event

- Isotopic scattering event
- Interface scattering
- Cooper pair
- Quasiparticle (i.e. electron)

# Phonon Propagation

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



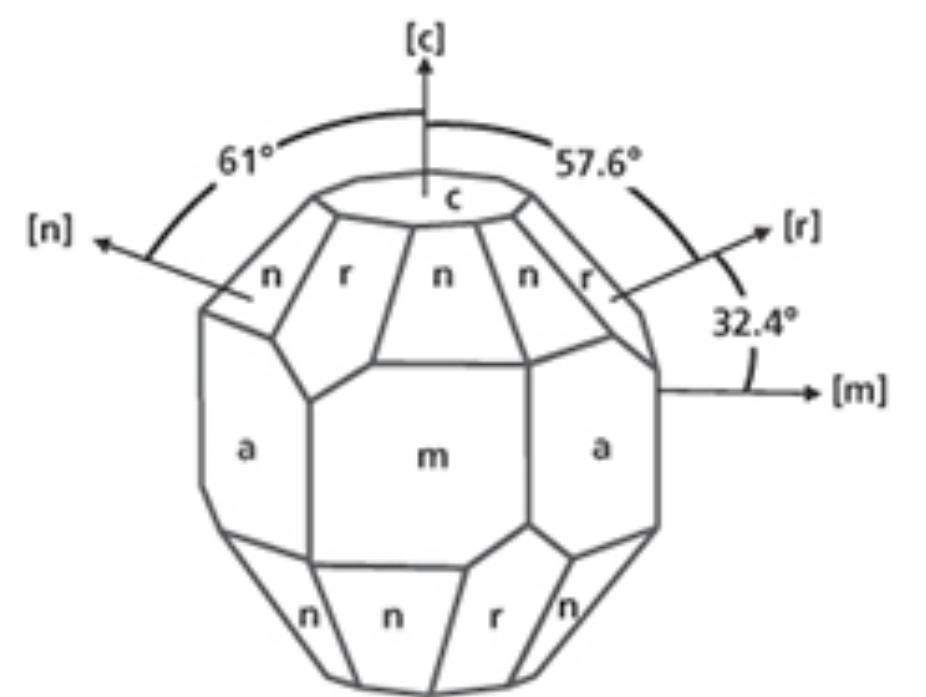
TARGET

COLLECTOR

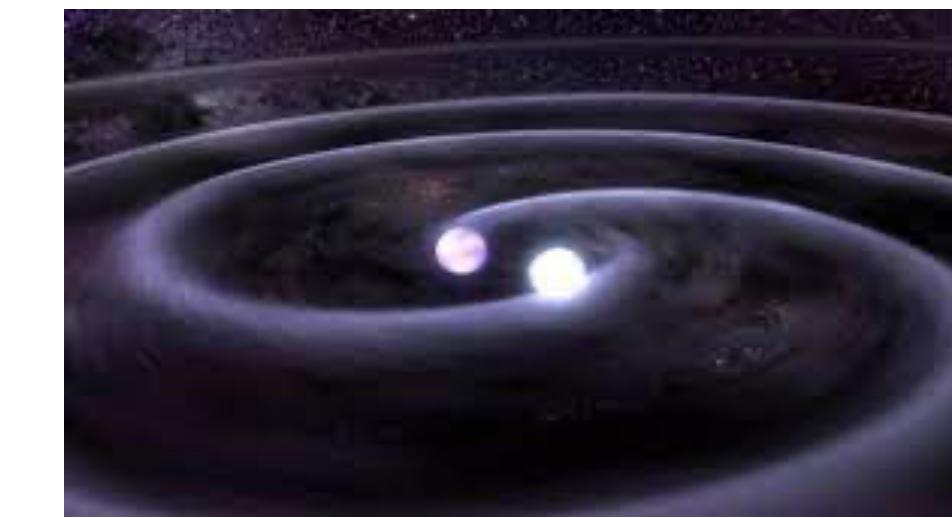
Detectability limits of current transition edge sensors (TES) is  $\sim 10^{-16} \text{ W}$

# New Directions for Dark Matter

Low-threshold  
phonon detectors

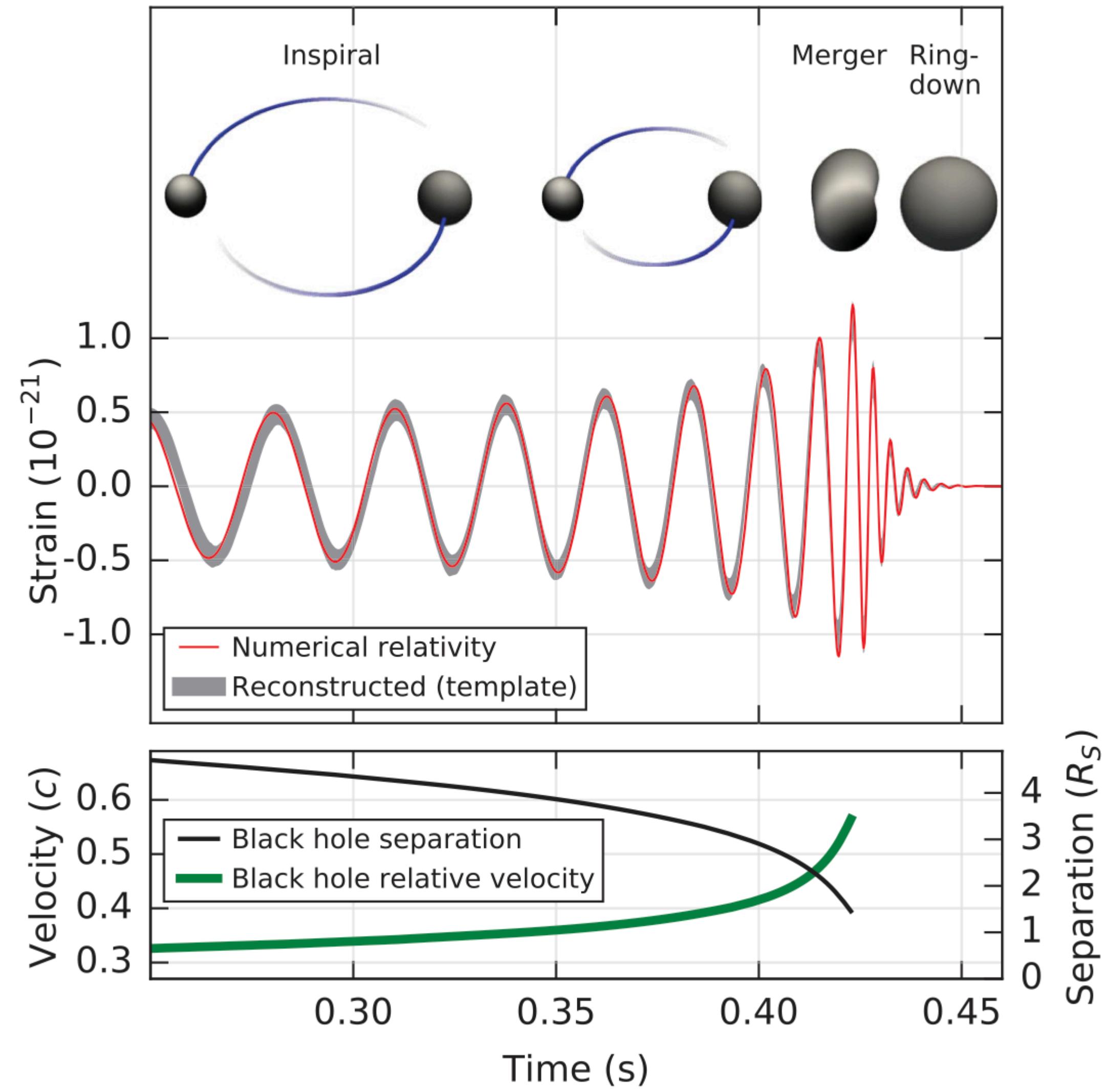


Black Holes and  
Gravitational Waves

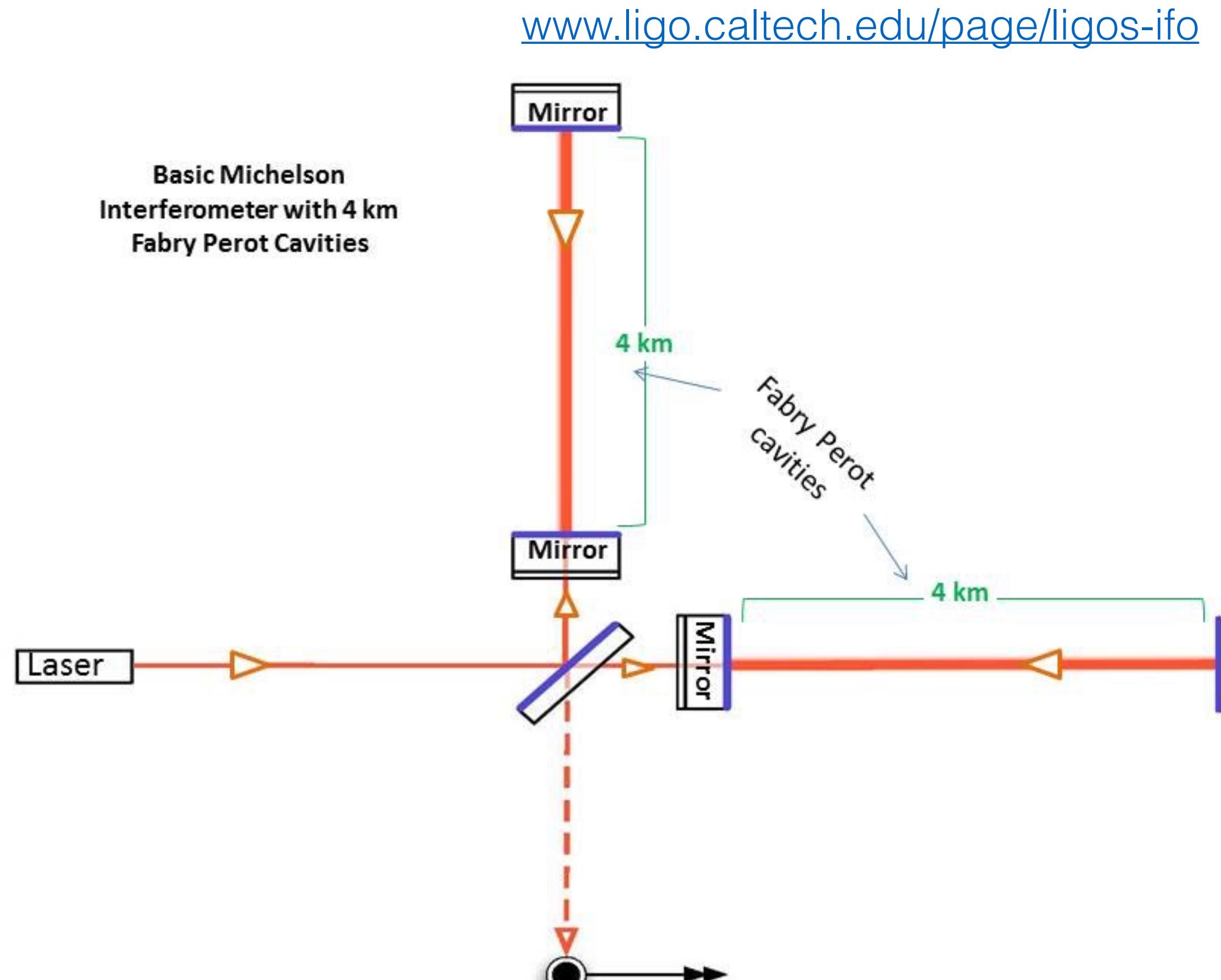


# Gravitational Waves (GW)

An ~equal mass inspiral: GW150914

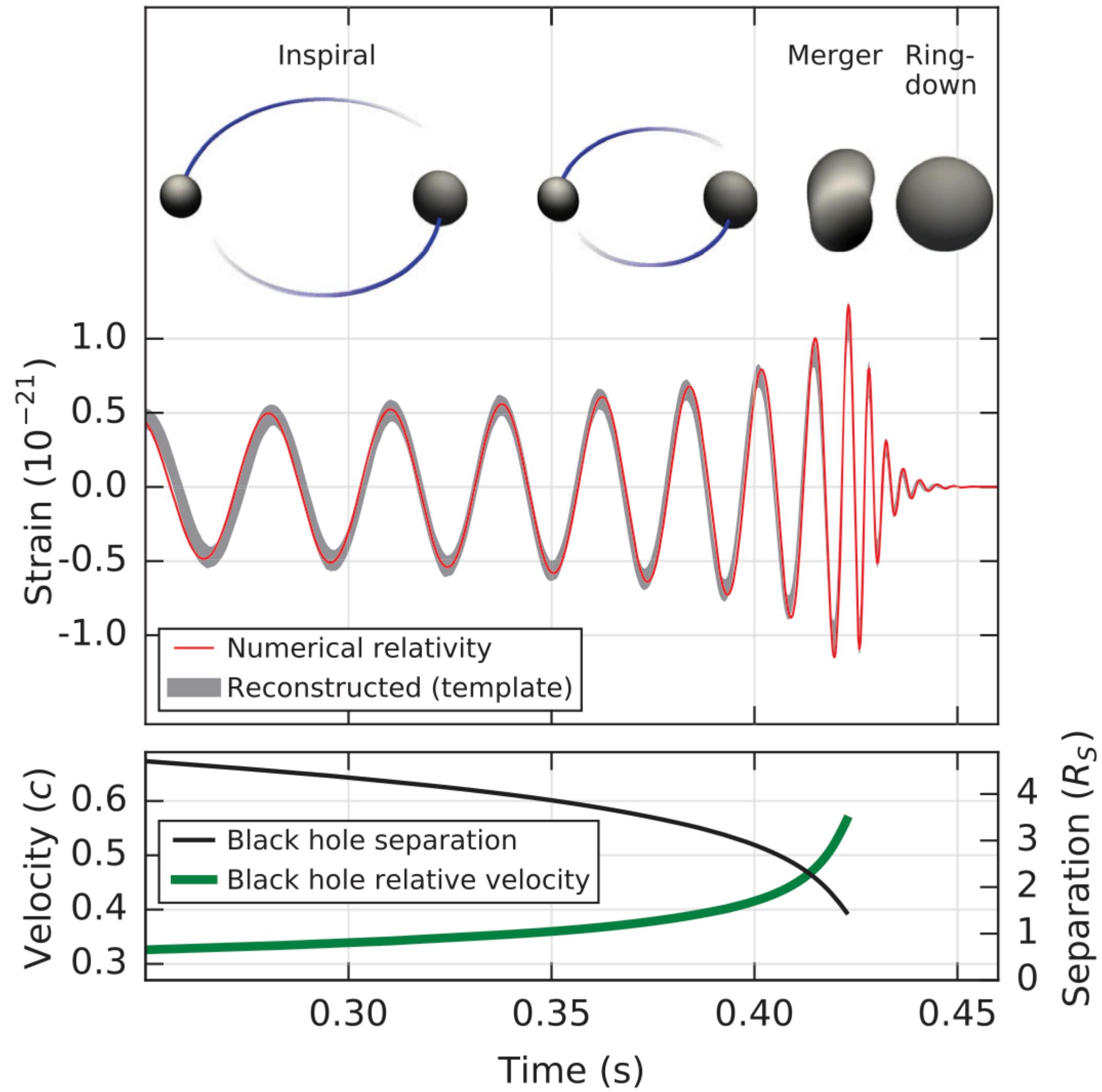


[LIGO/Virgo, arXiv:1602.03837]



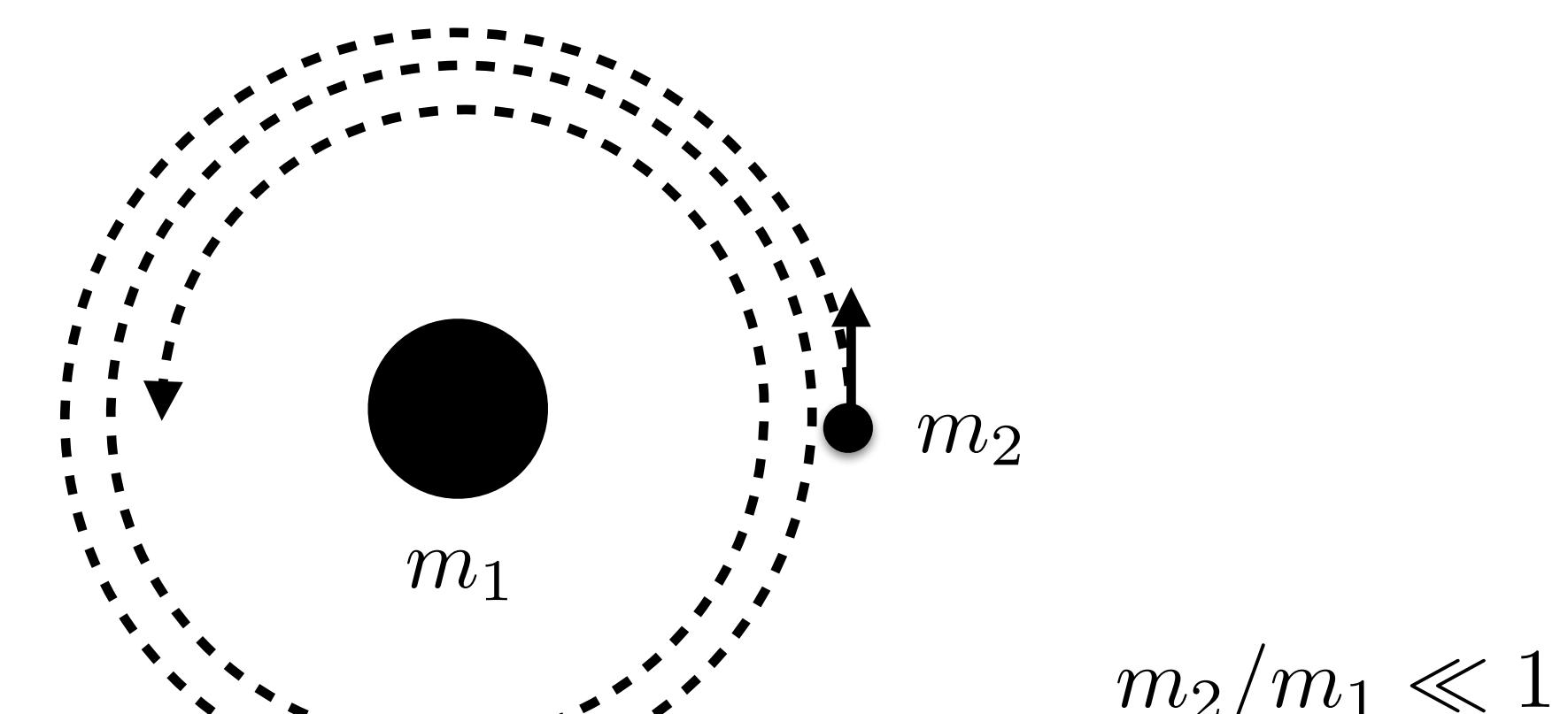
# Gravitational Waves (GW)

An ~equal mass inspiral: GW150914



[LIGO/Virgo, arXiv:1602.03837]

Intermediate and extreme mass ratio inspirals:



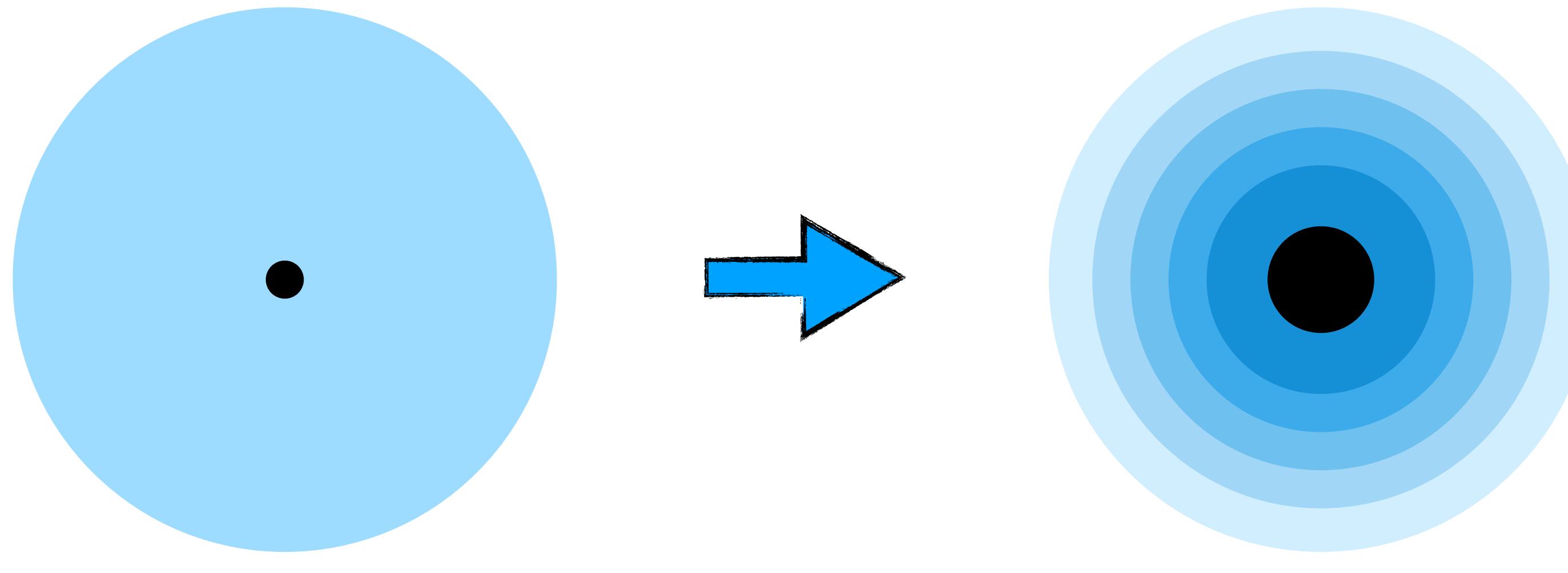
Binary may be observed during *millions of orbits*

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

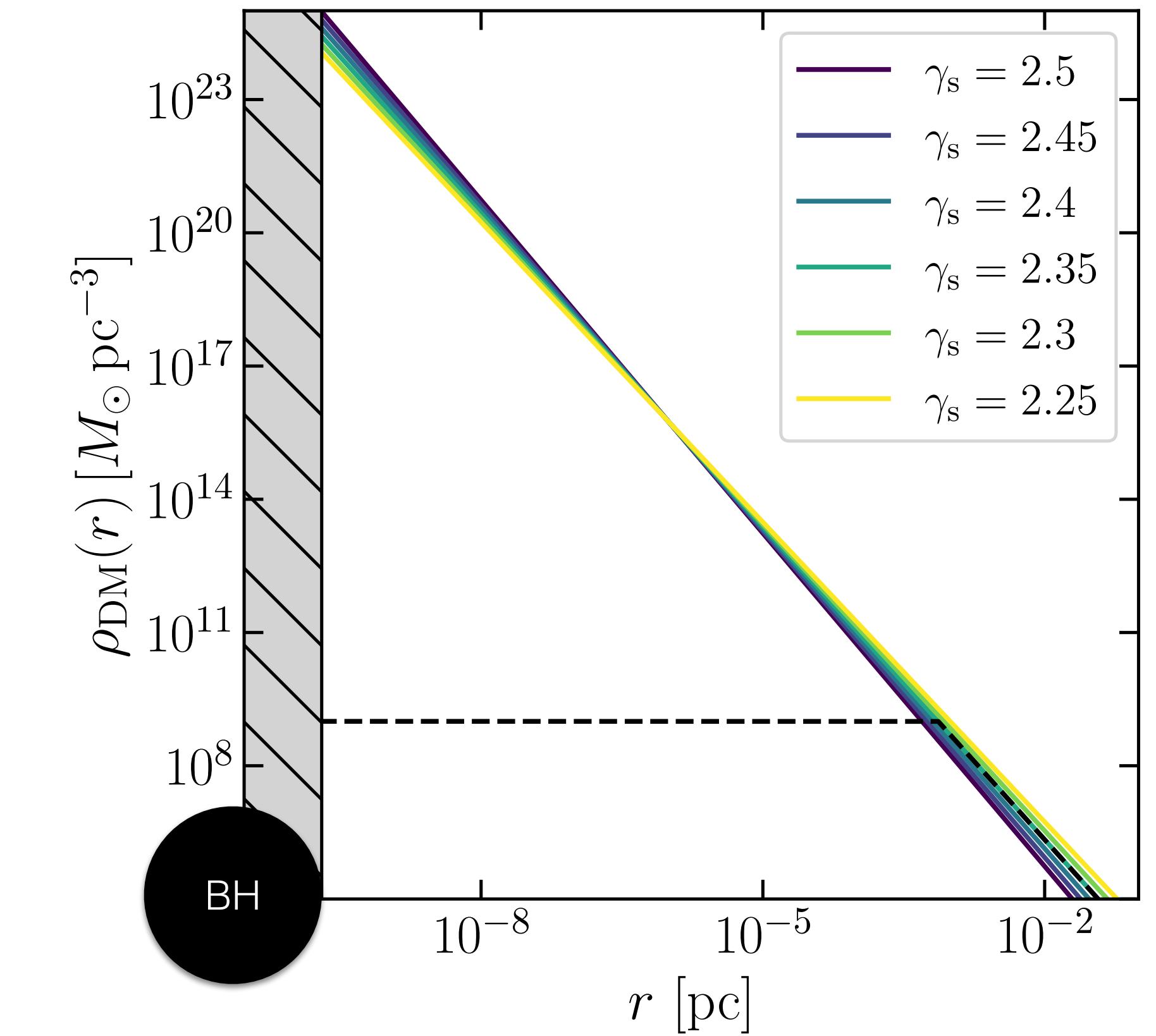
# Dark Matter Spikes

'**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



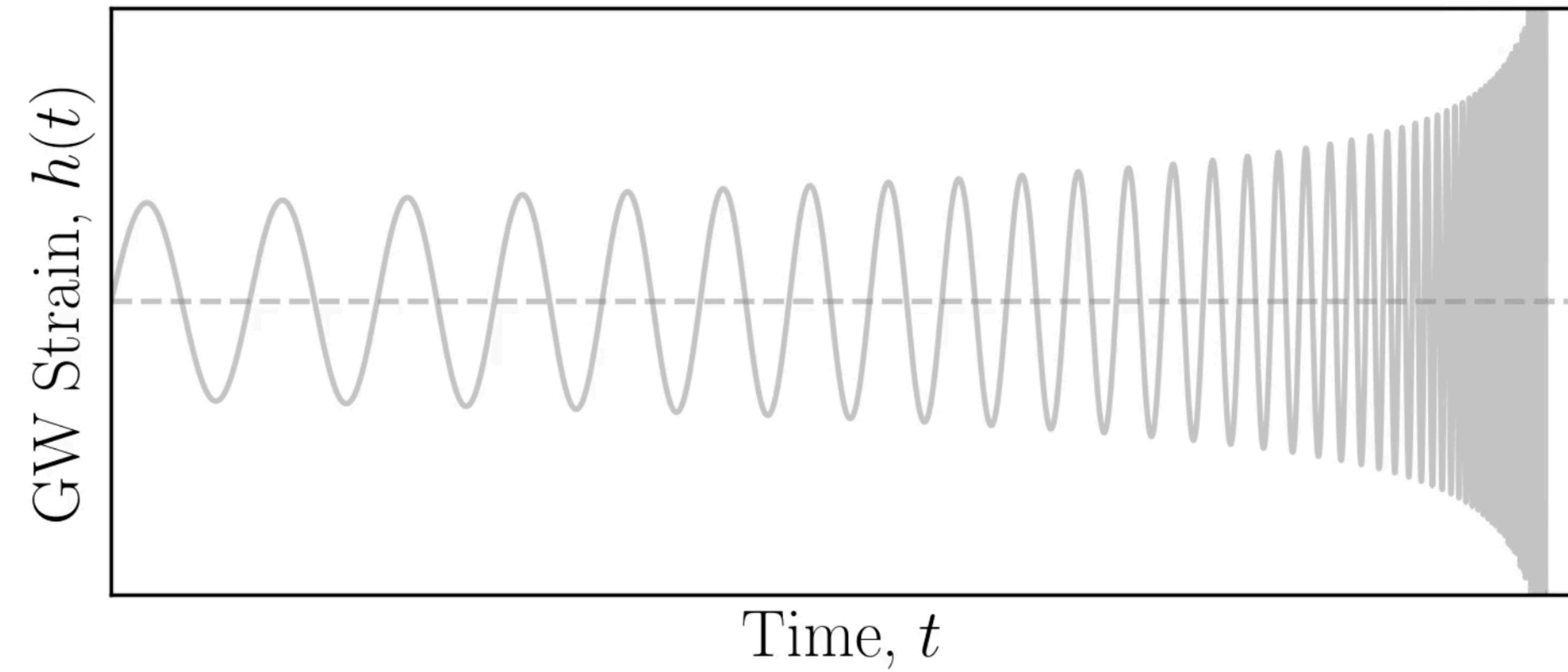
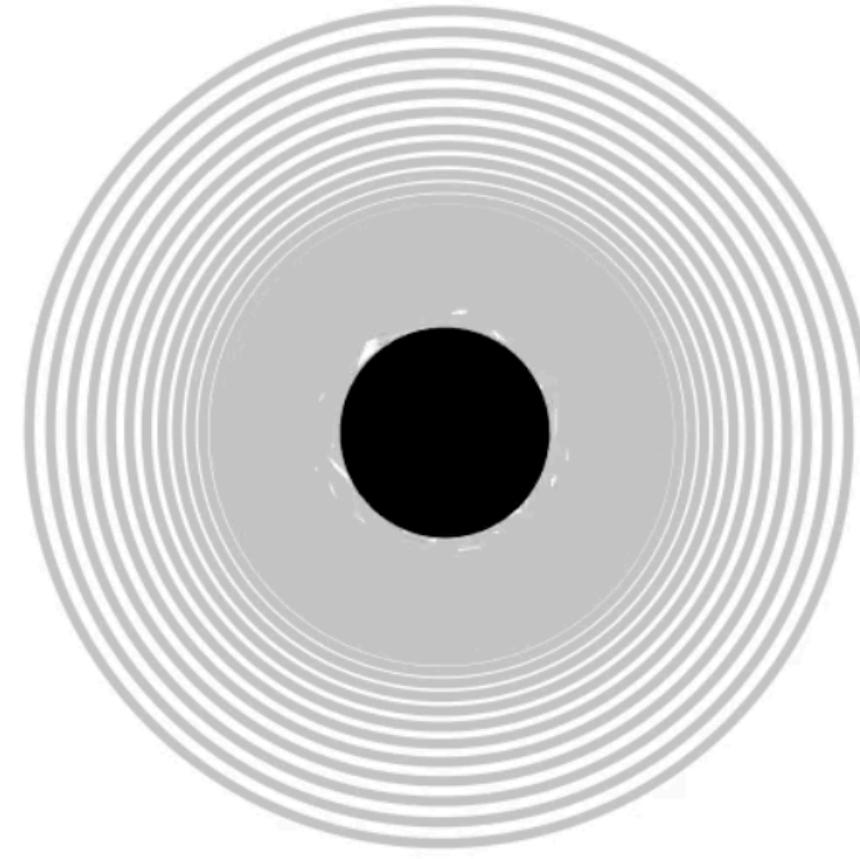
[[astro-ph/9906391](#), [astro-ph/0509565](#),  
[1305.2619](#), [Bertschinger \(1985\)](#), [astro-ph/0608642](#), [1901.08528](#), ...]

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

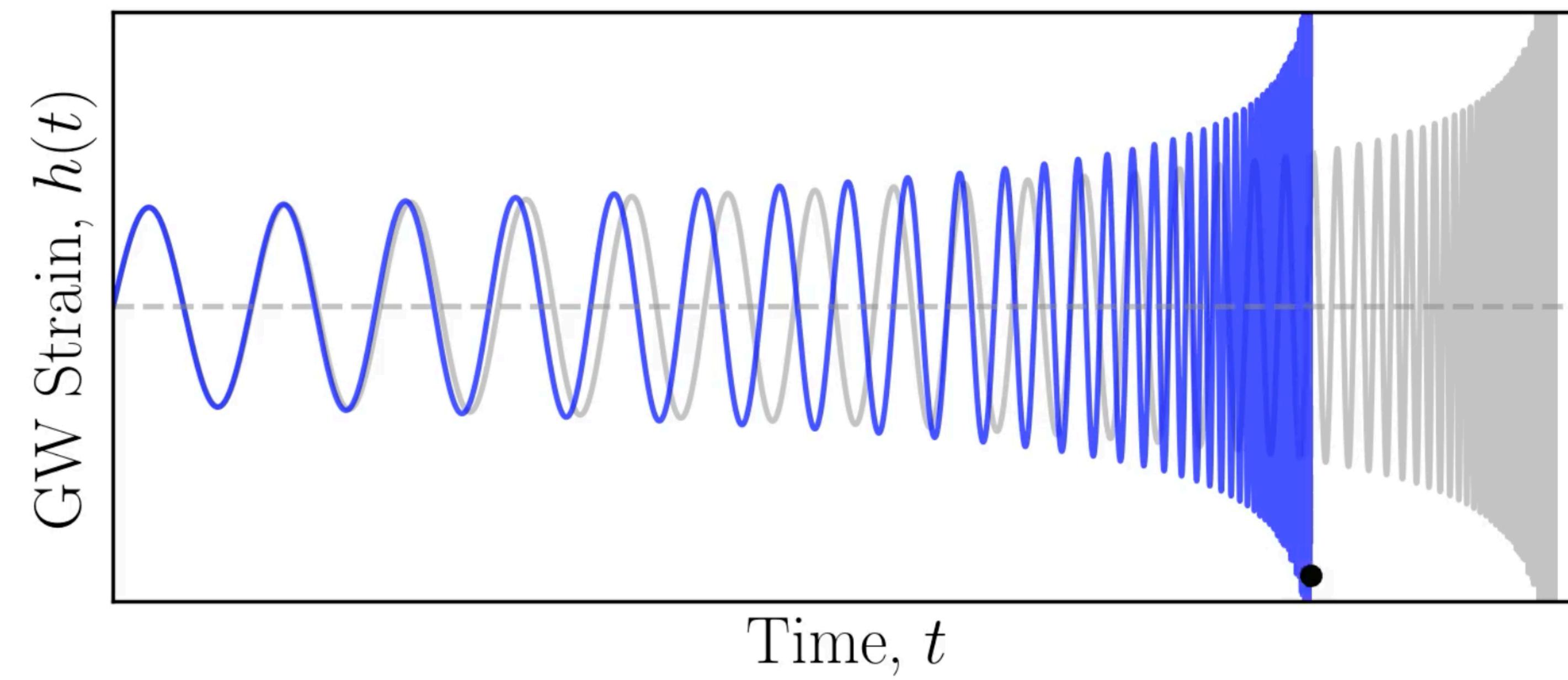
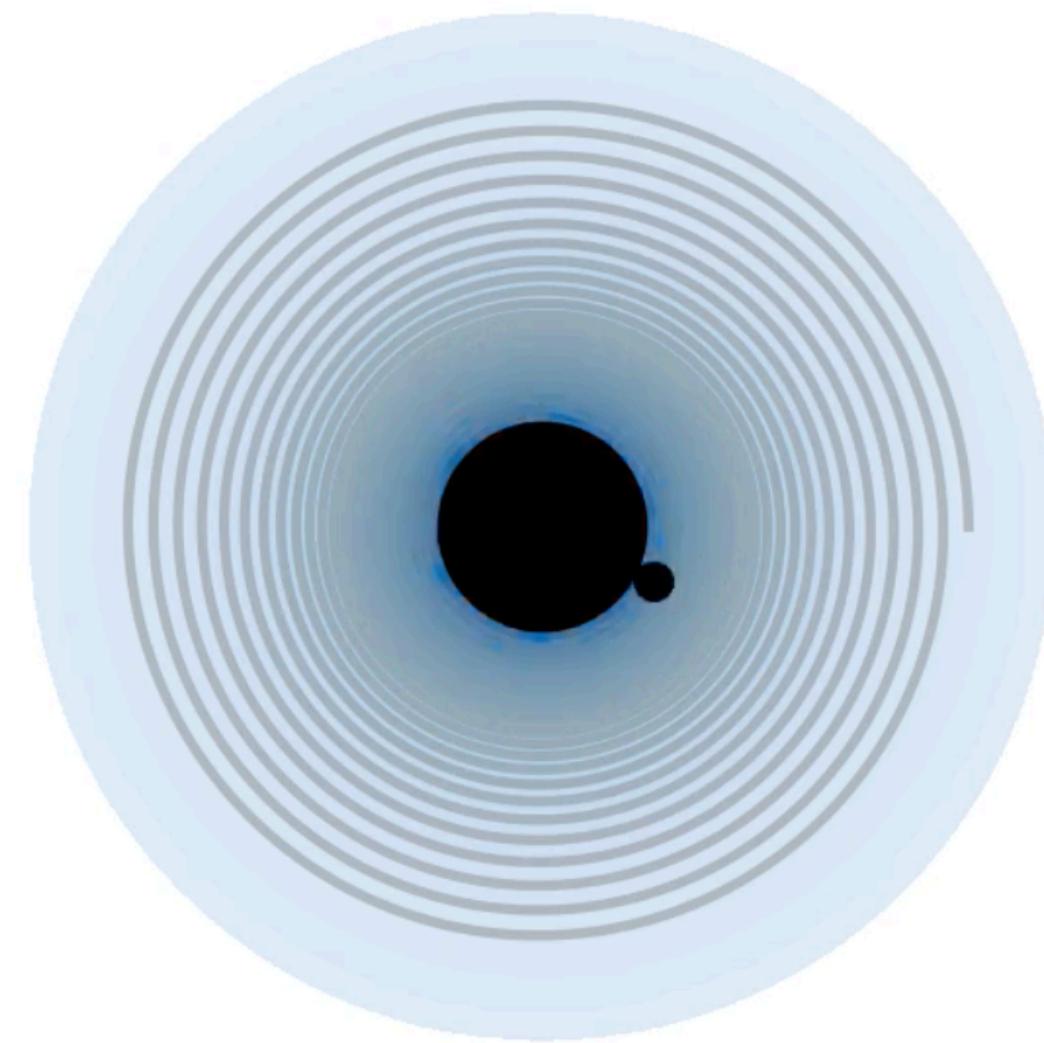
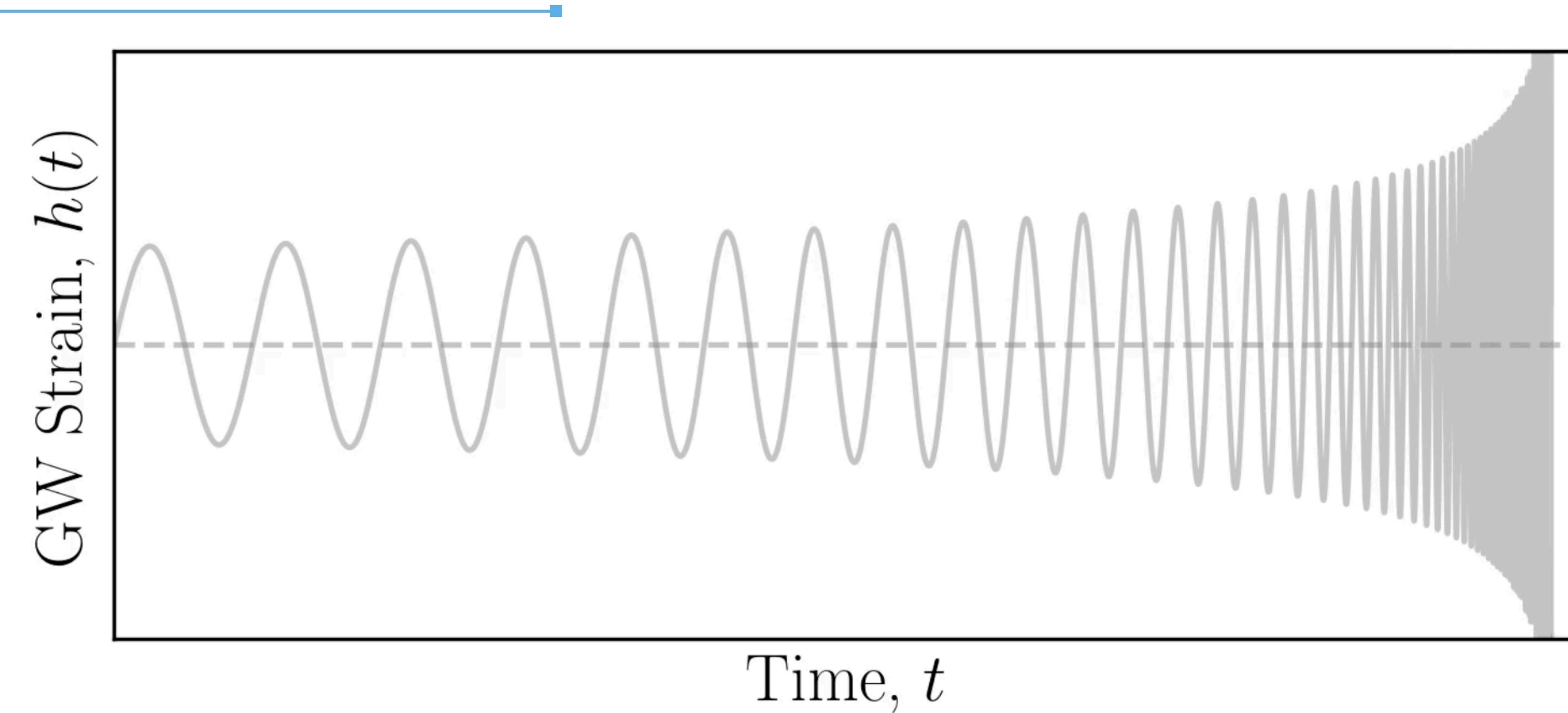
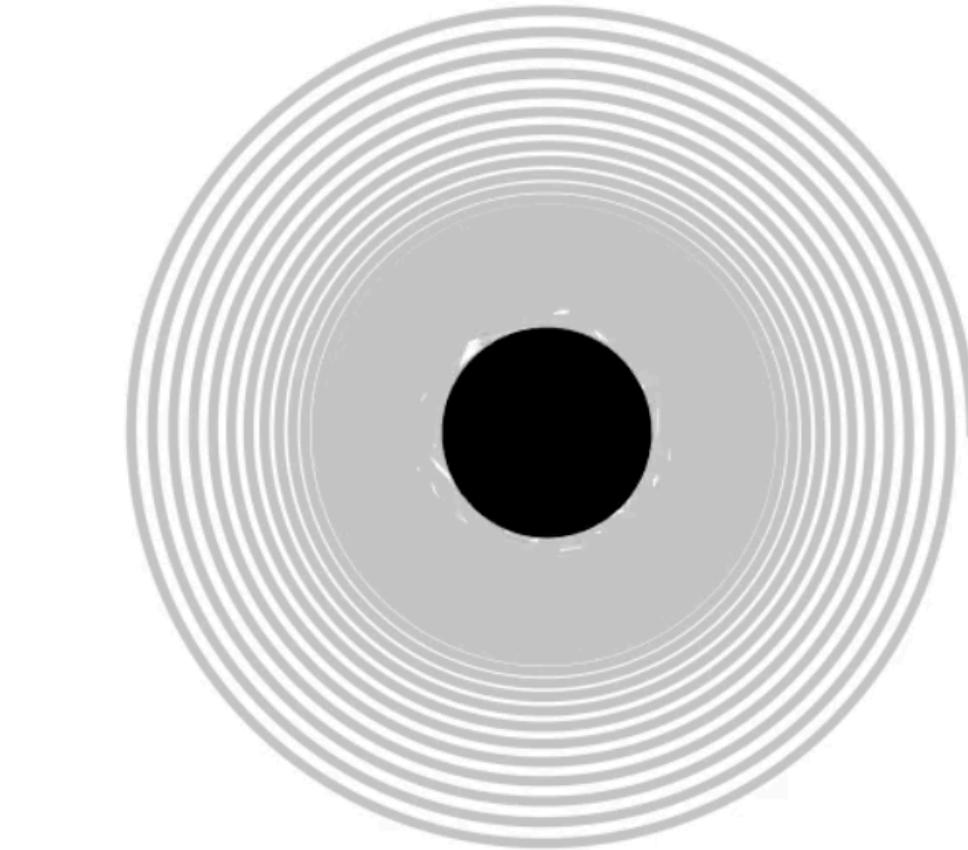


$$\rho_{\text{DM, local}} \sim 10^{-2} M_{\odot} / \text{pc}^3$$

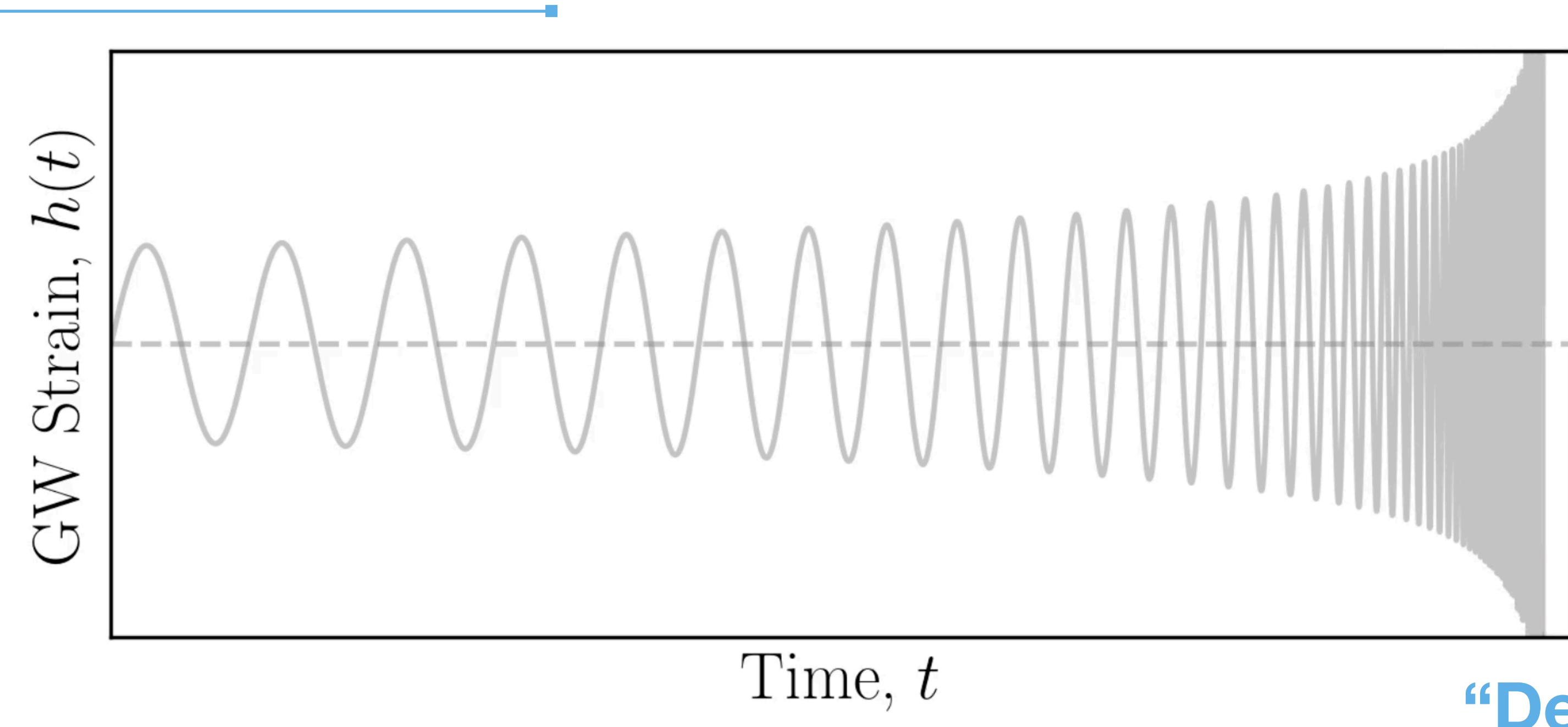
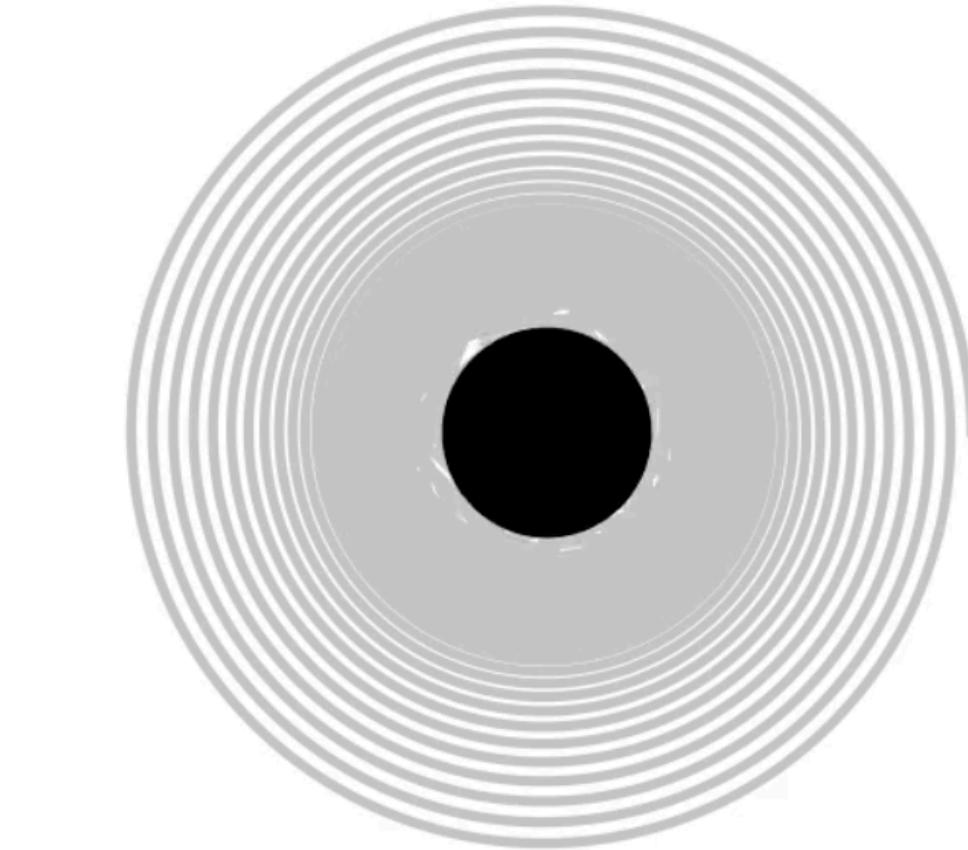
# Gravitational Wave Dephasing



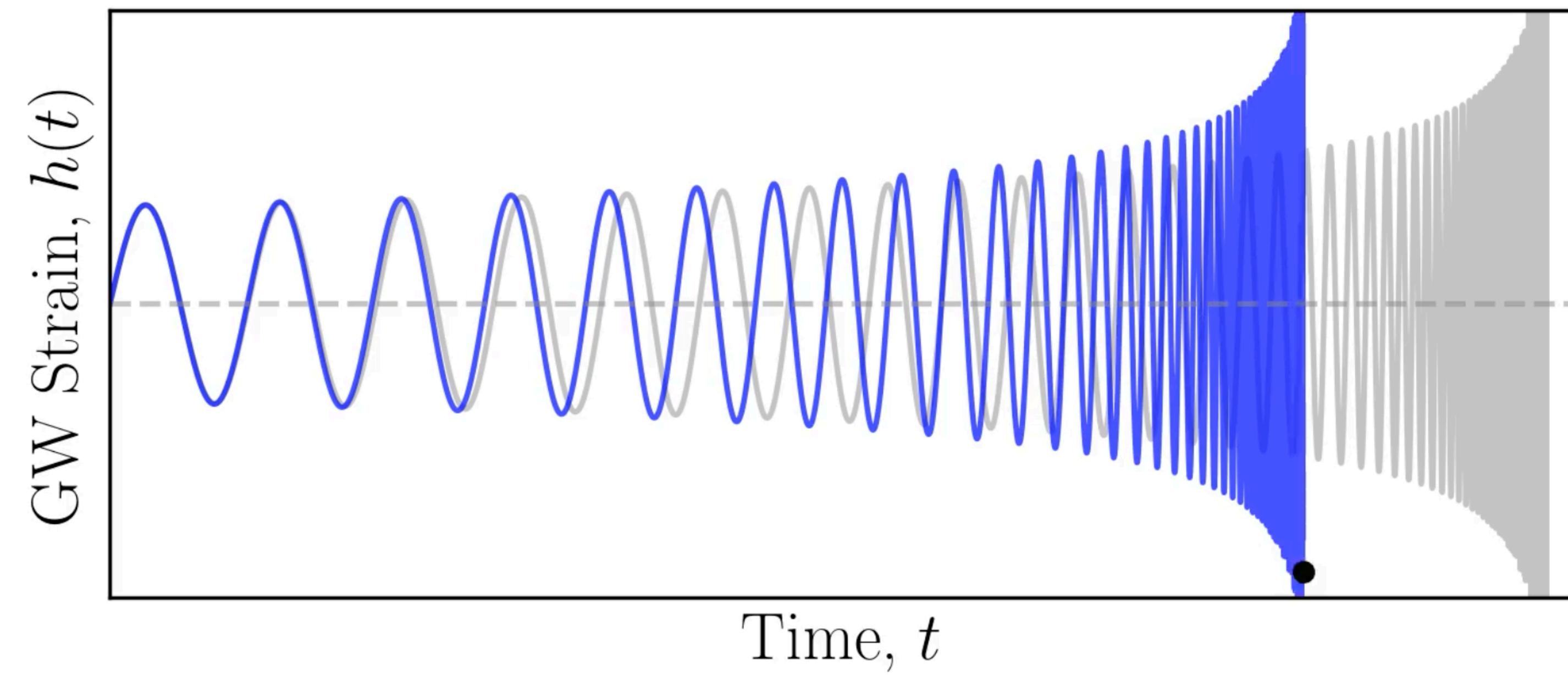
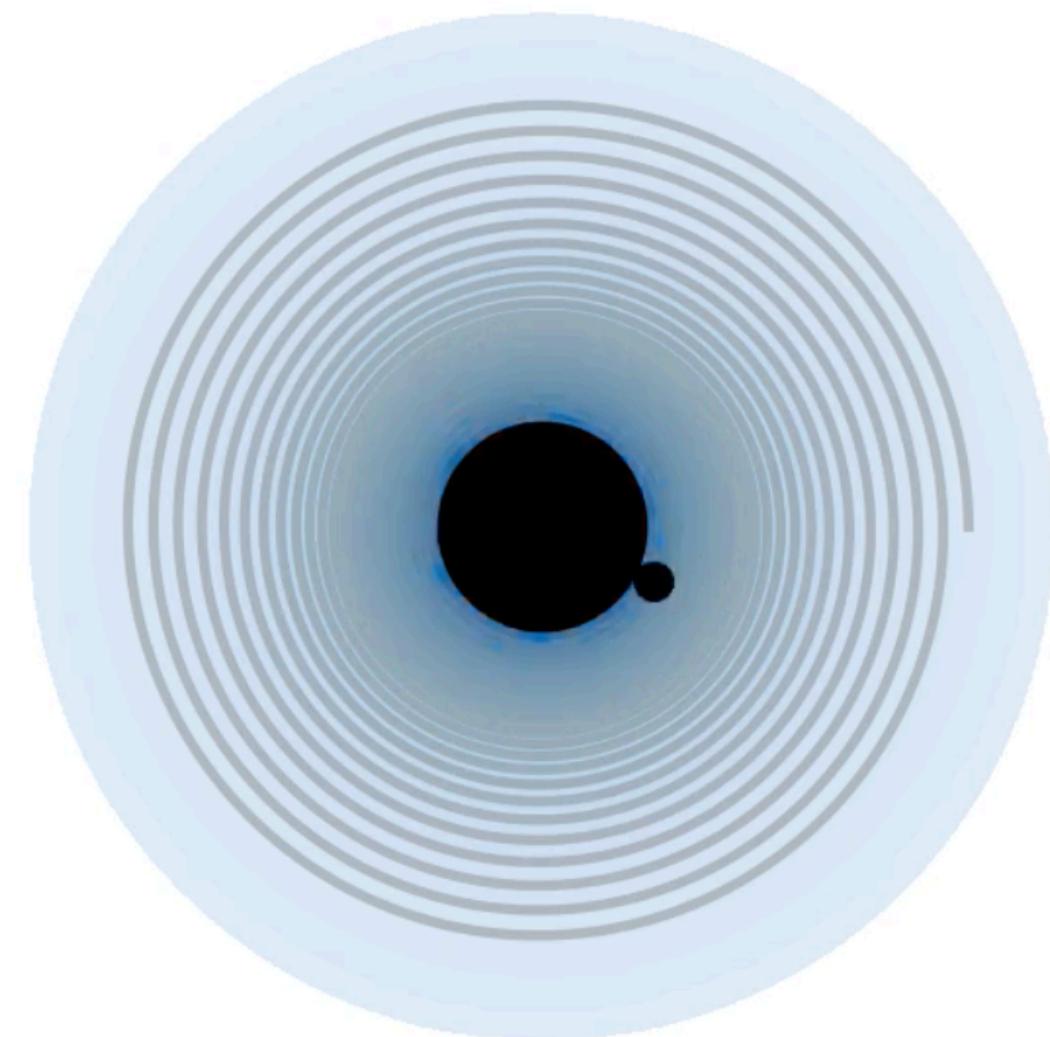
# Gravitational Wave Dephasing



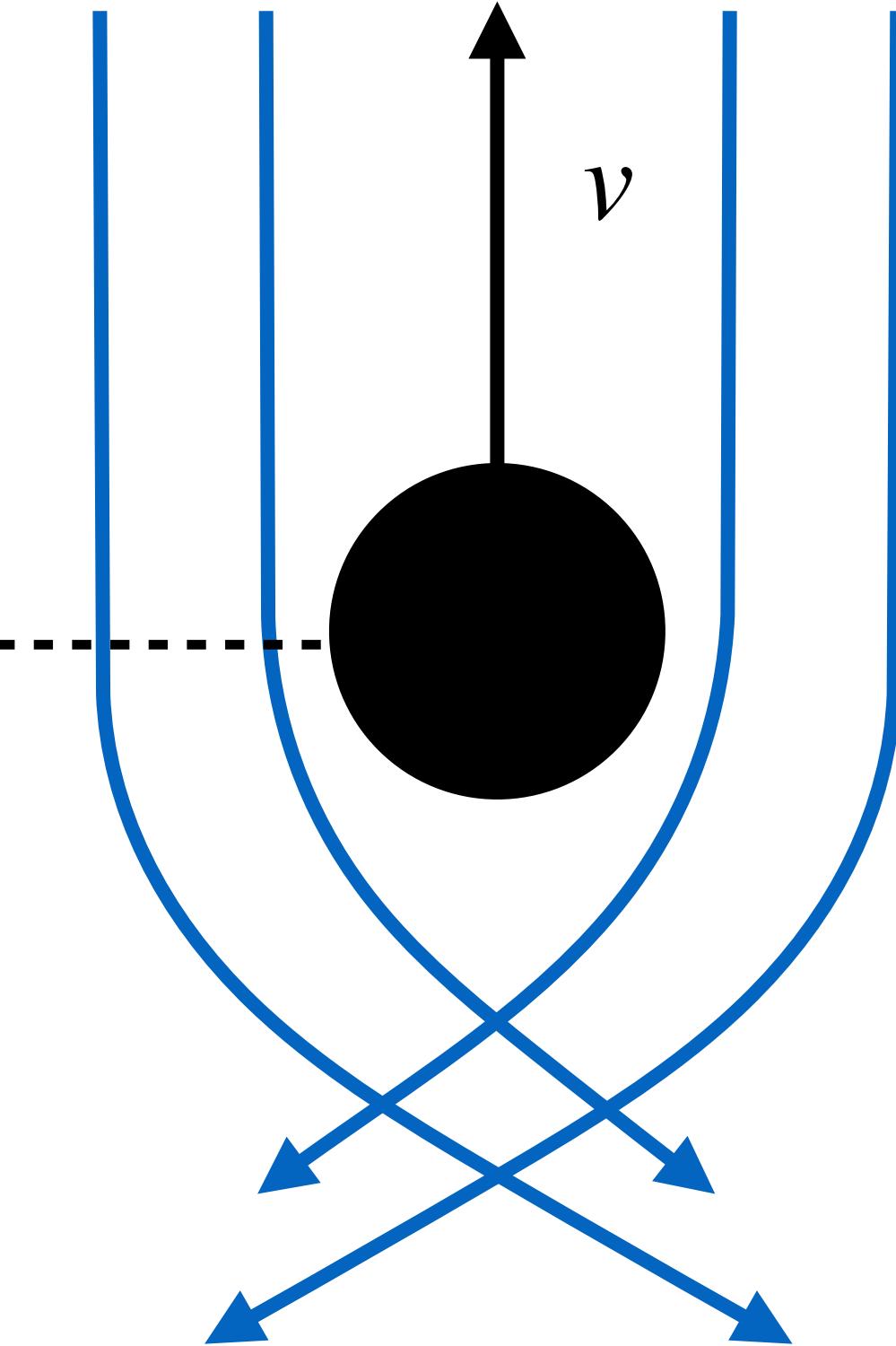
# Gravitational Wave Dephasing



**“Dephasing”**



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



**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:

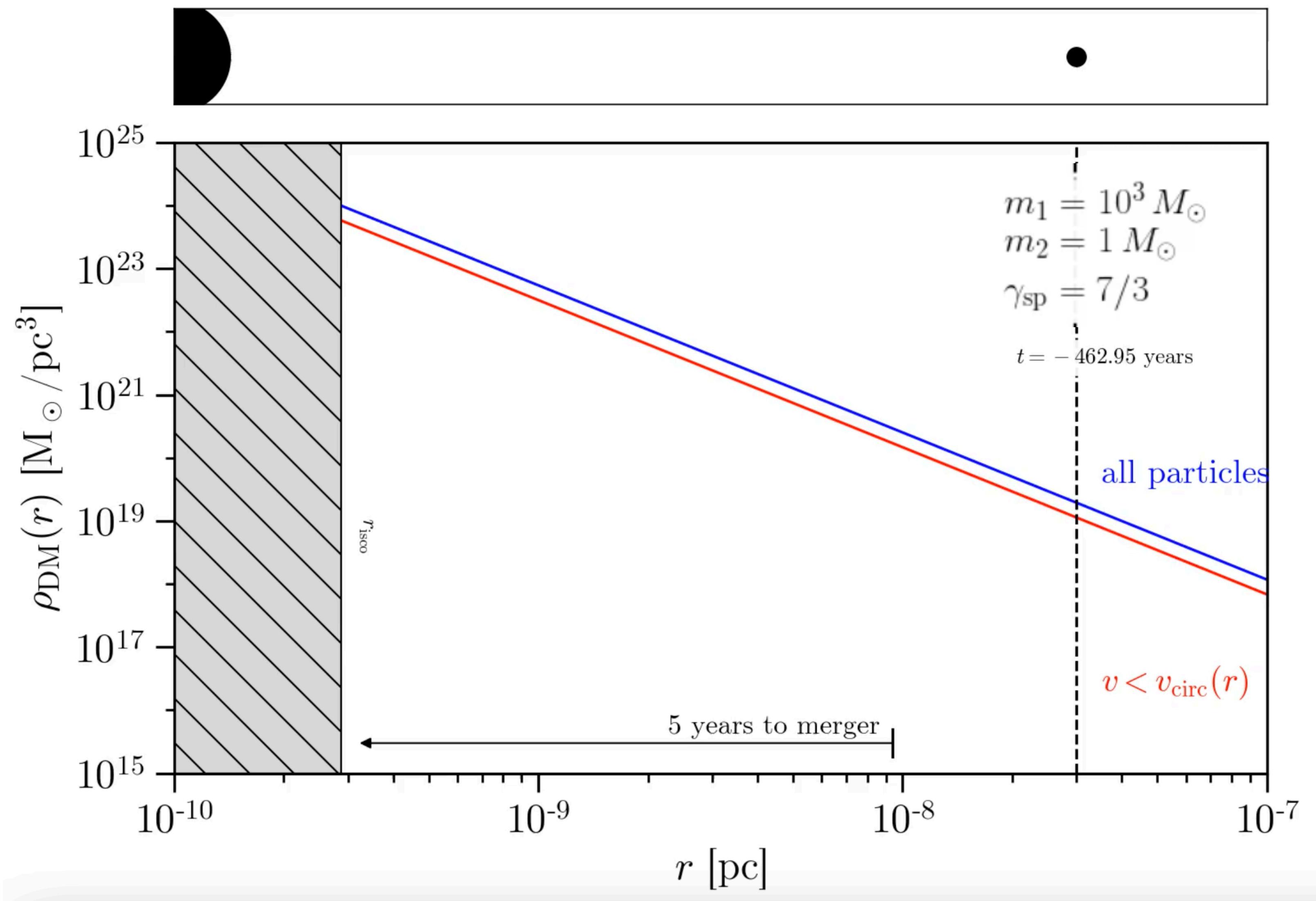
- GW emission
- Dynamical Friction
- DM Halo Feedback

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

Formalism recently extended to eccentric orbits, including accretion

[\[2402.13053\]](#), [\[2402.13762\]](#)

$$r(t) \rightarrow h(t)$$



[Movies: [tinyurl.com/GW4DM](#)]

[Code: [github.com/bradkav/HaloFeedback](#)]

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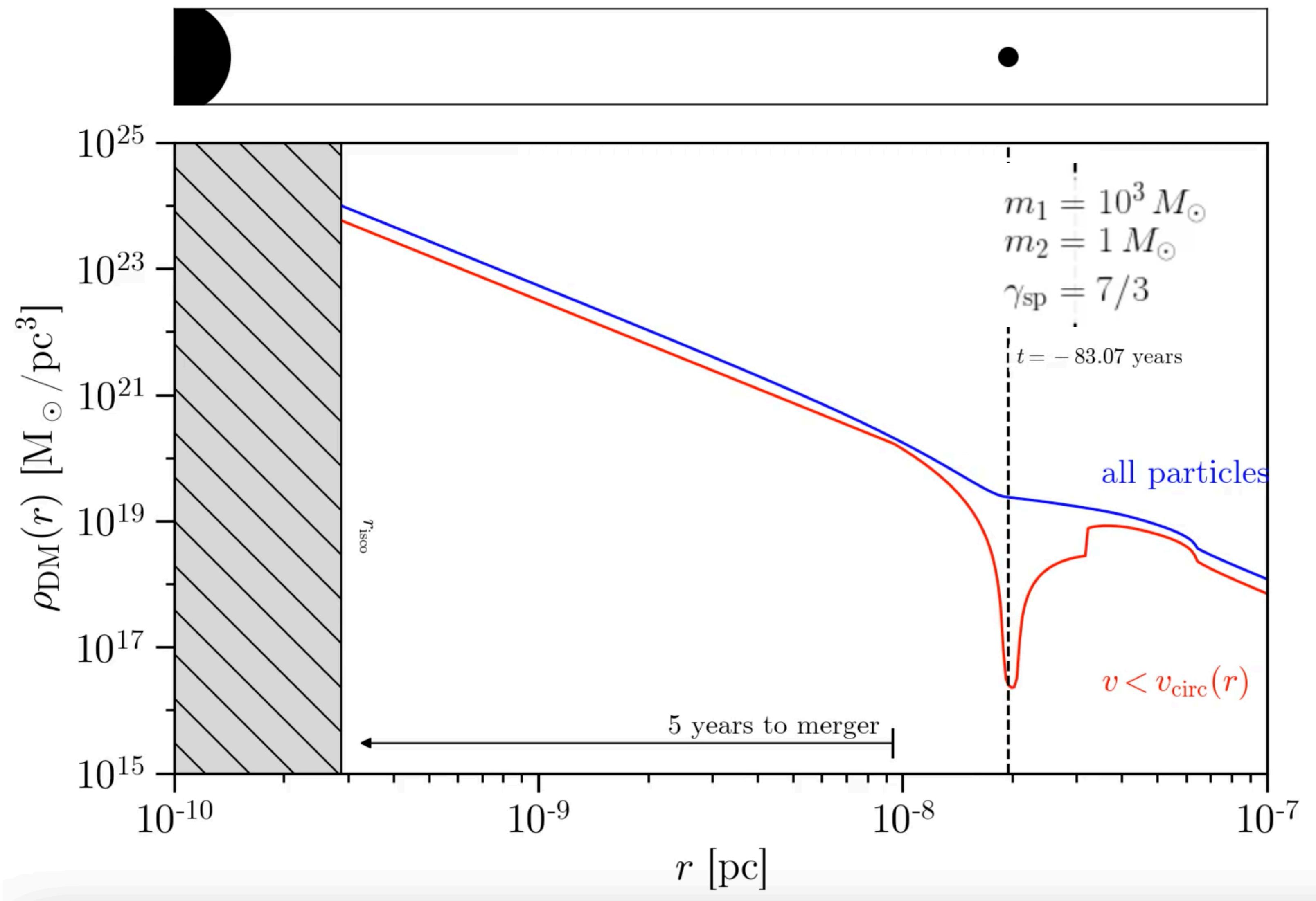
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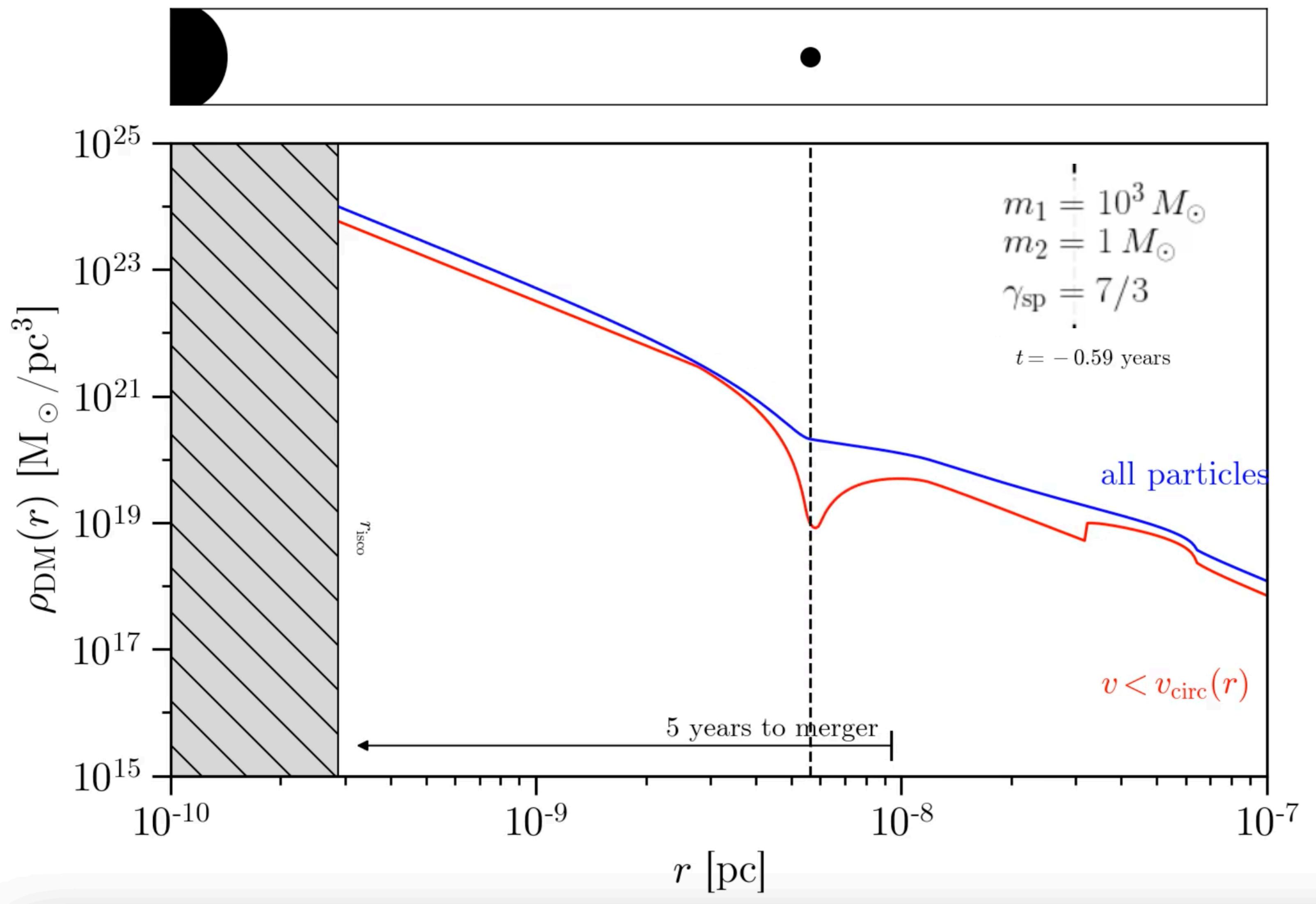
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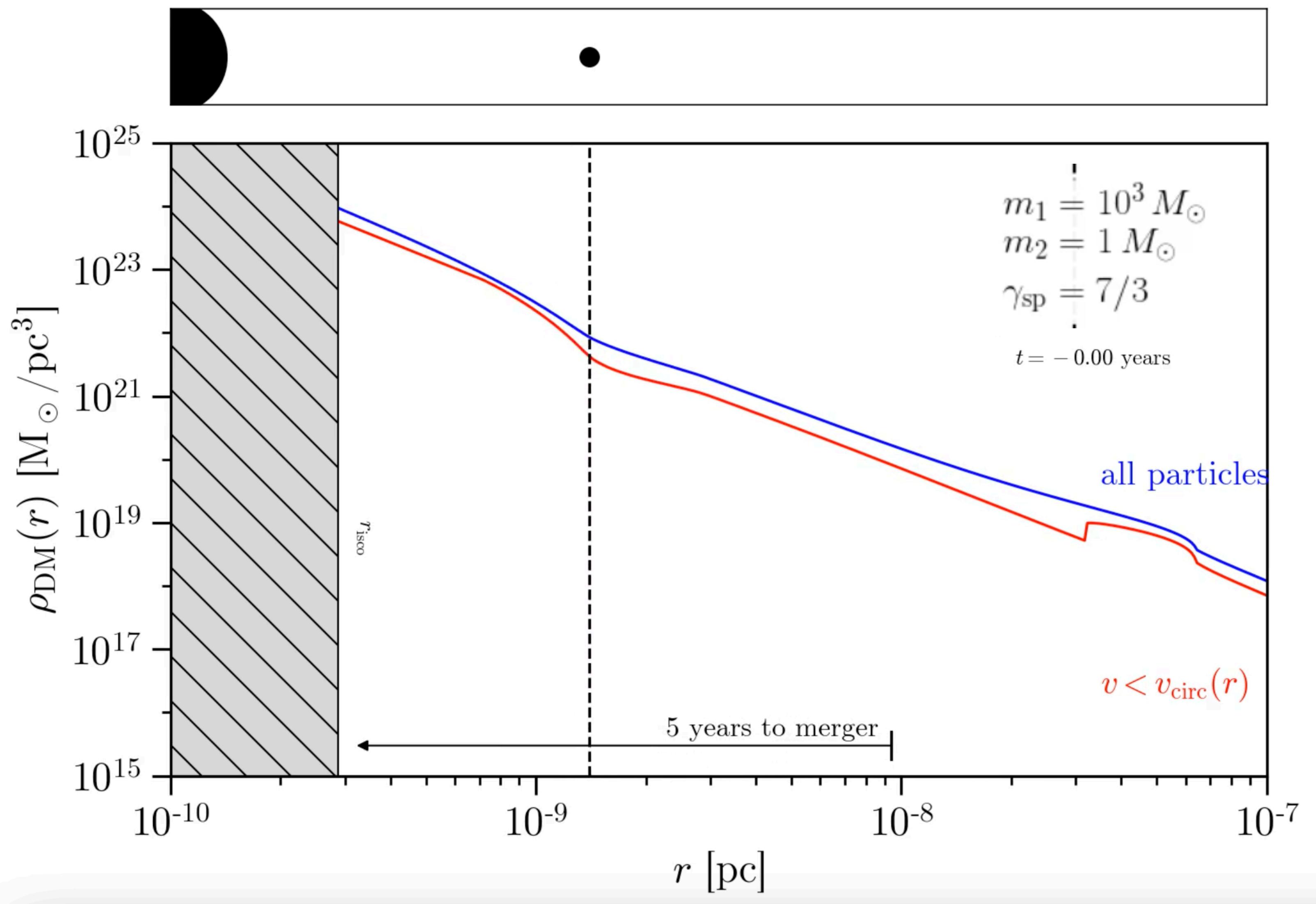
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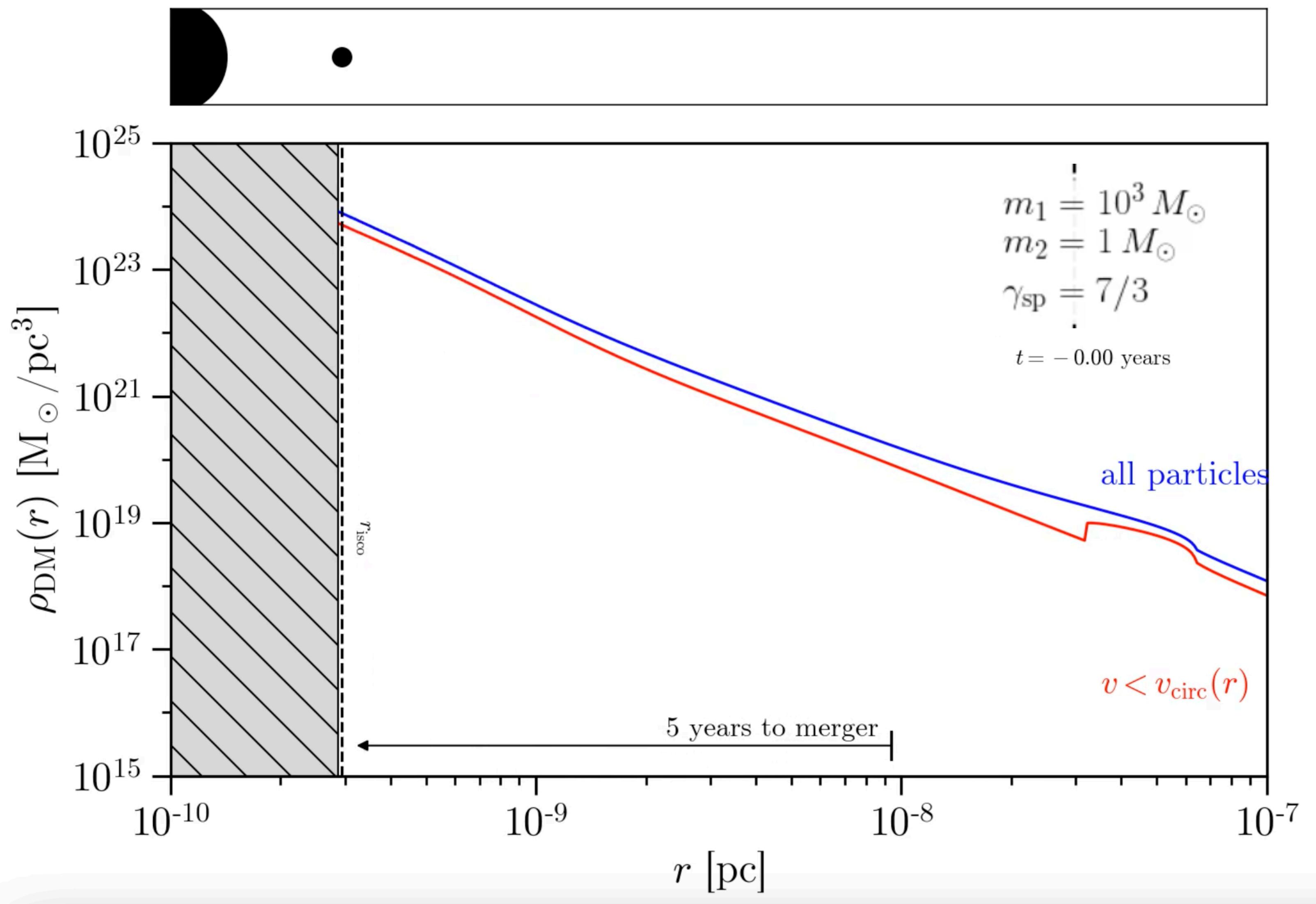
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Formalism recently extended to eccentric orbits, including accretion

[2402.13053, 2402.13762]

$$r(t) \rightarrow h(t)$$



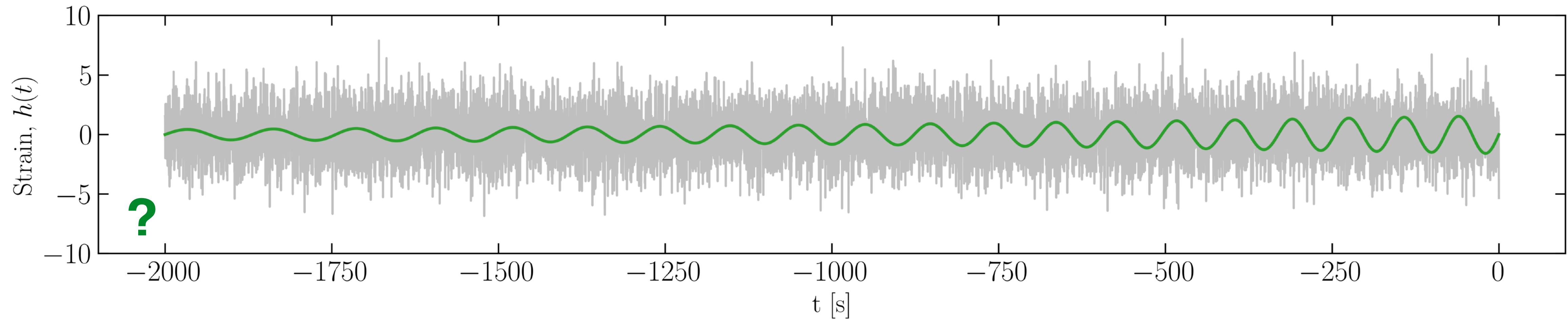
[Movies: [tinyurl.com/GW4DM](http://tinyurl.com/GW4DM)]

[Code: [github.com/bradkav/HaloFeedback](https://github.com/bradkav/HaloFeedback)]

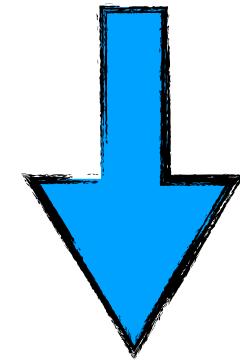
# Can we measure this effect?

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

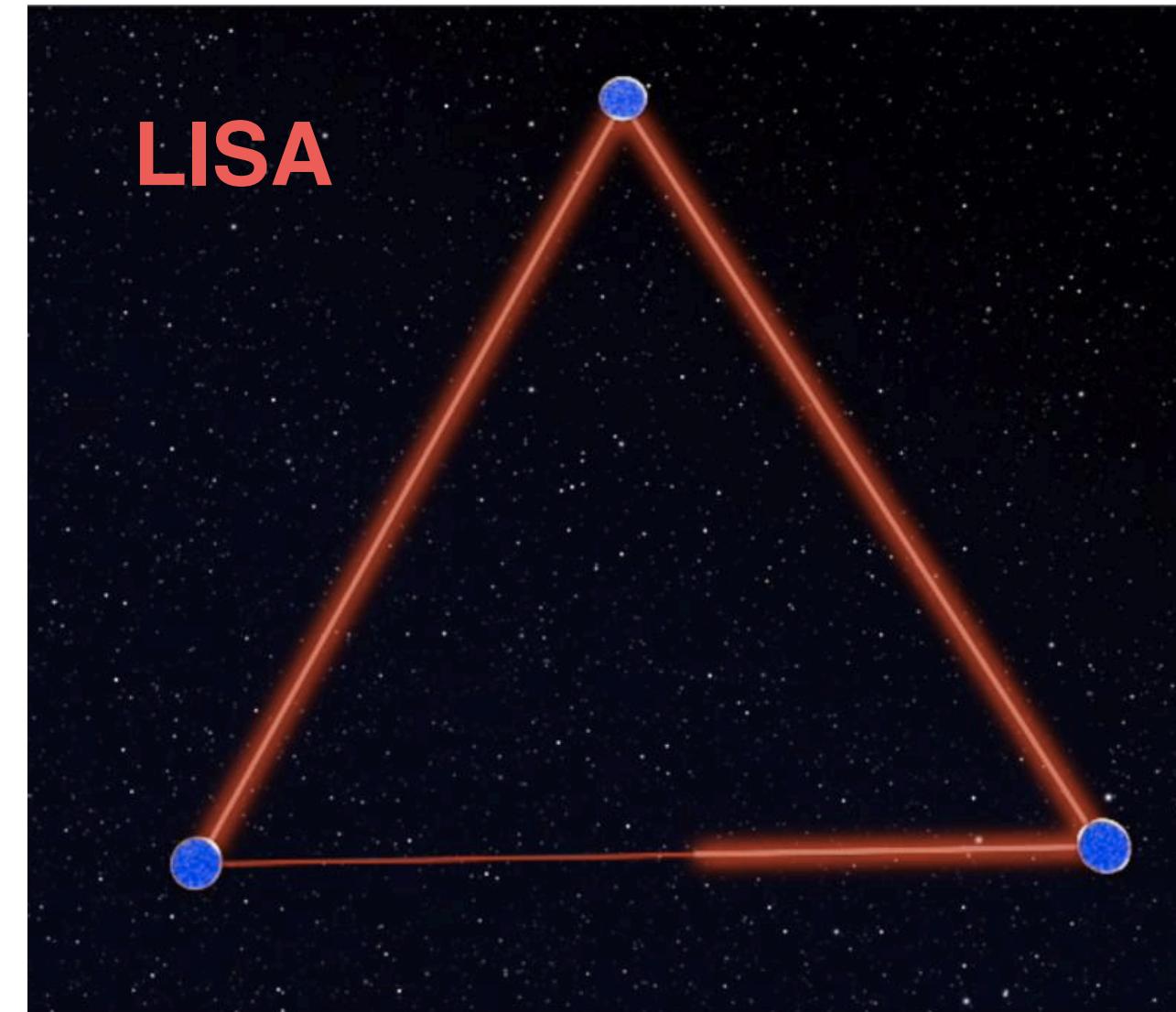
[Code available online: <https://github.com/adam-coogan/pydd>]



$$m_1 = 10^3 M_{\odot}$$
$$m_2 = 1 M_{\odot}$$



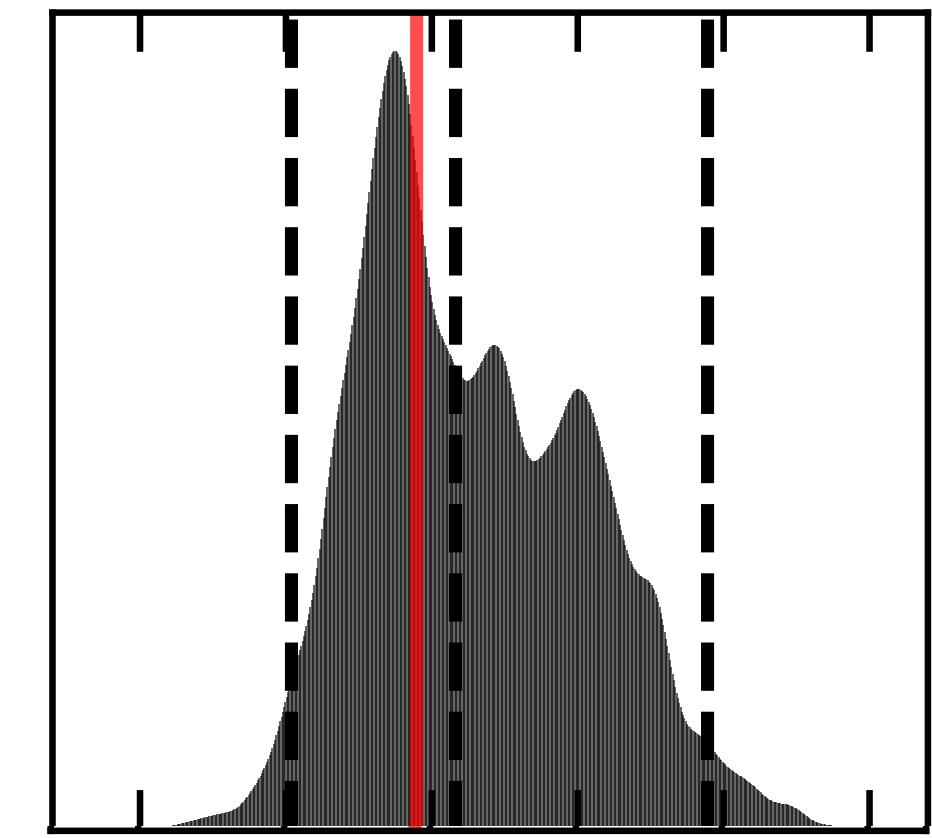
$$f_{\text{GW}} \sim \text{mHz} - \text{Hz}$$



Laser Interferometer Space Antenna  
(planned for the 2030s)

[1907.06482]

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

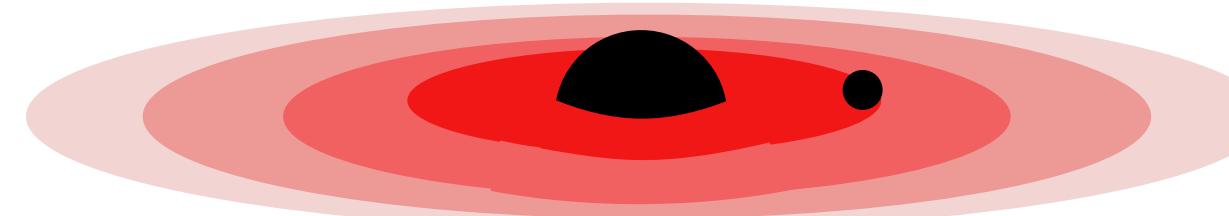


$$\rho_6 [10^{16} M_{\odot} \text{ pc}^{-3}]$$

# Environmental Confusion

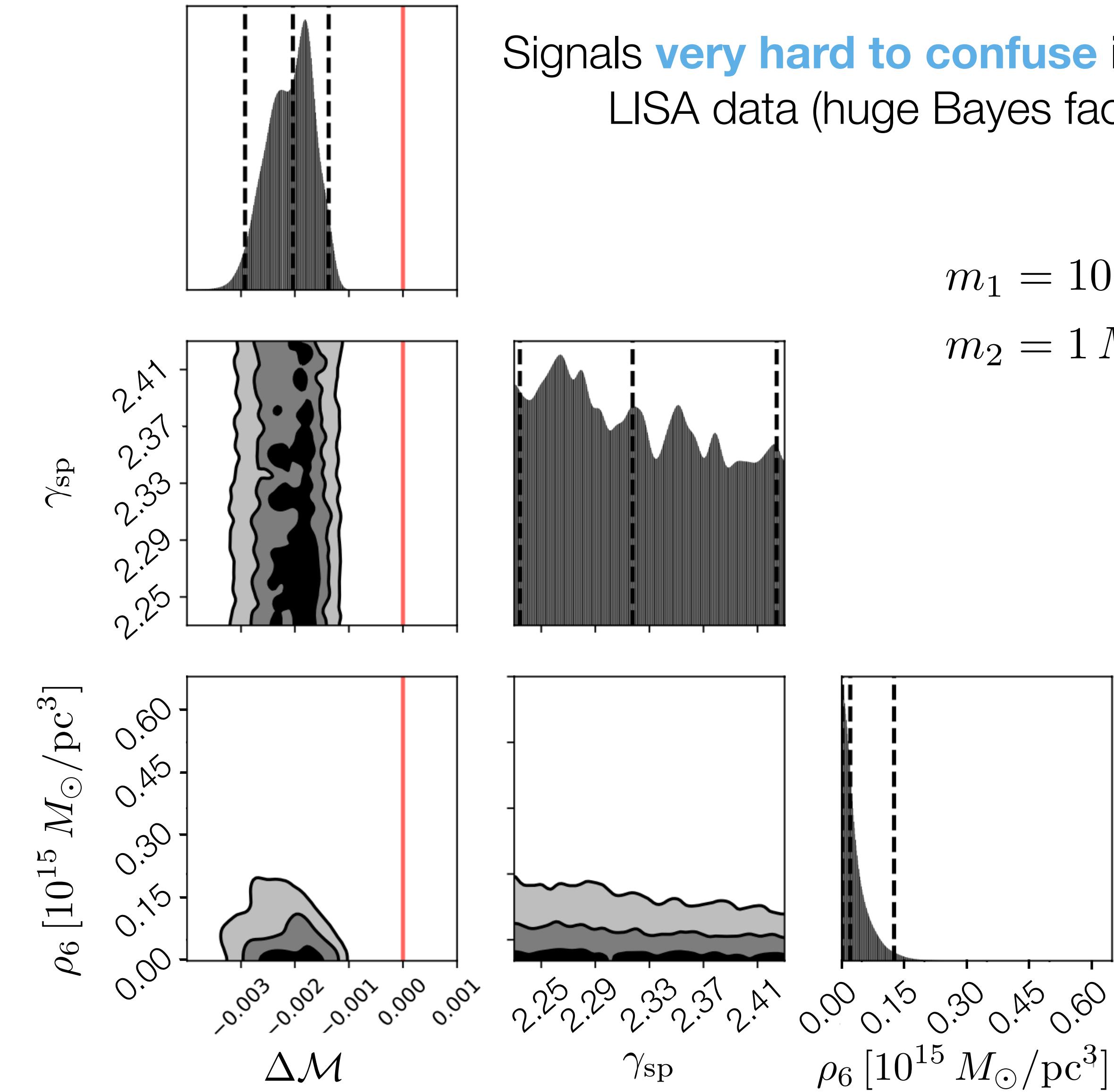
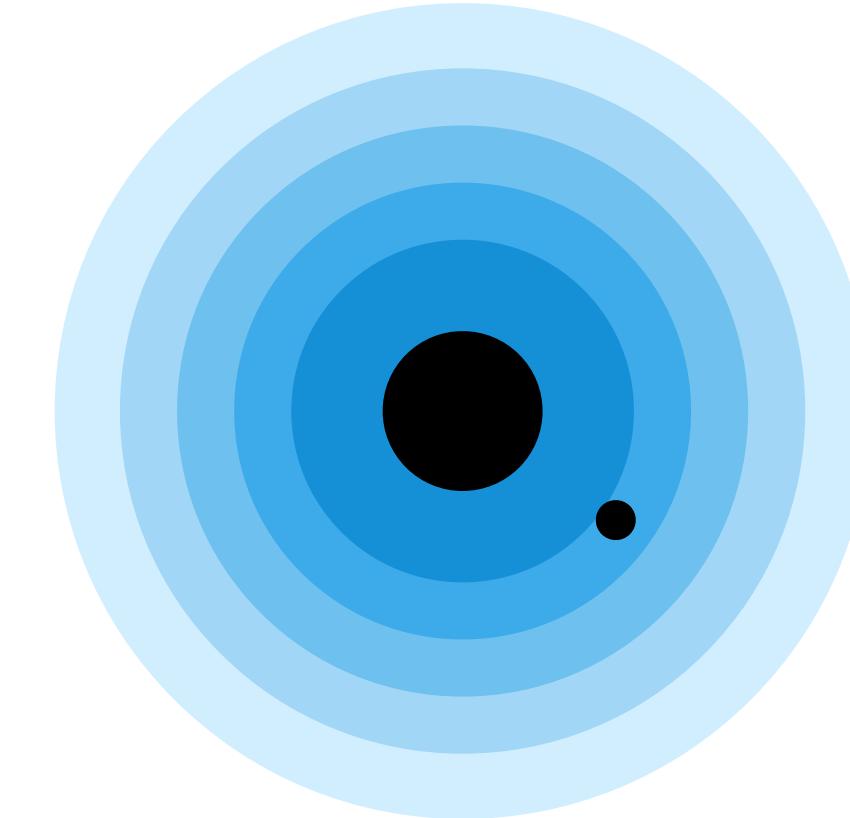
[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**,  
Spieksma, Tomaselli, [2211.01362](#), Nature Astronomy]

Generate waveform  
assuming:



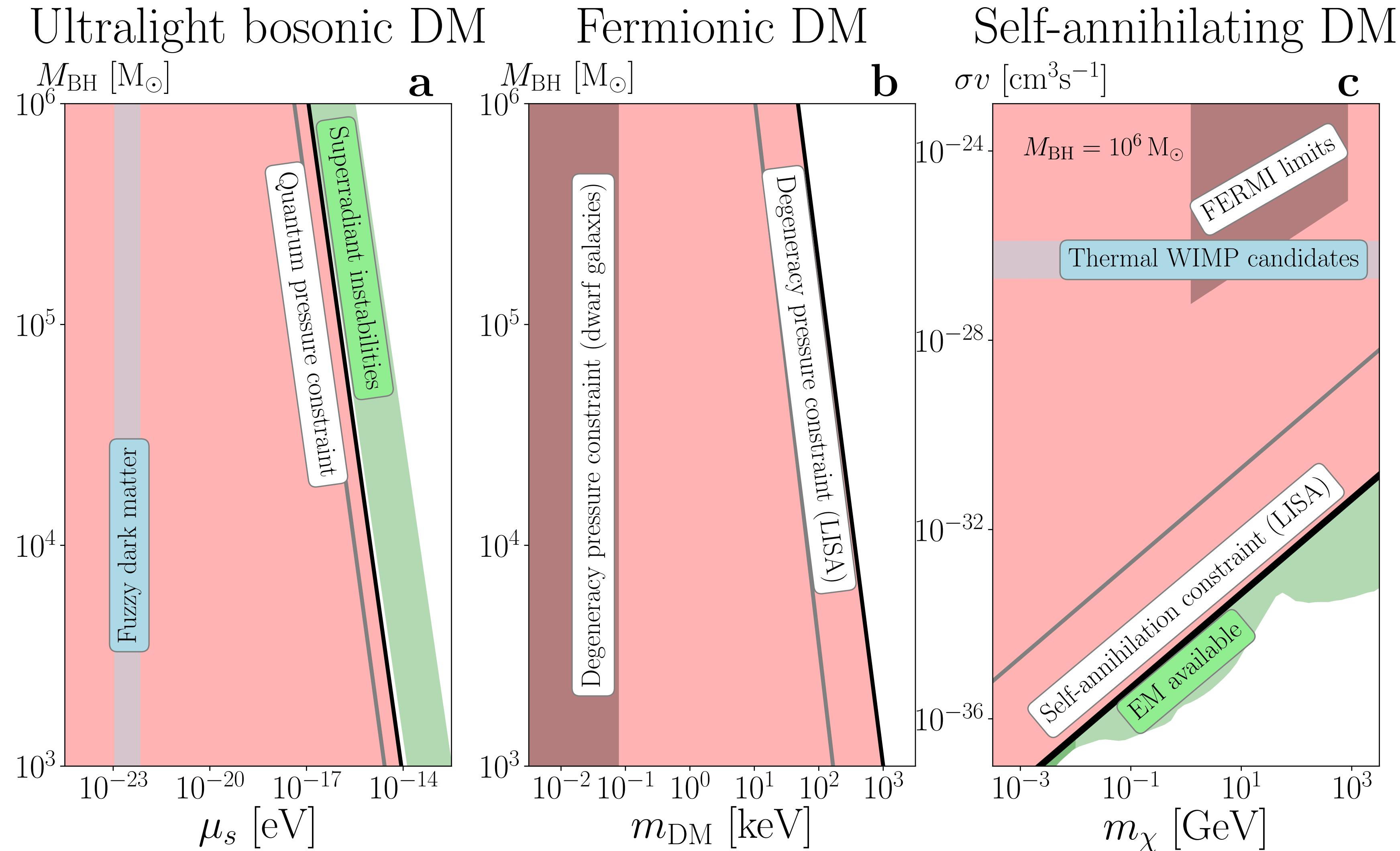
$$\Sigma(r) = \Sigma_0 \left( \frac{r}{r_0} \right)^{-1/2}$$

Fit signal assuming:



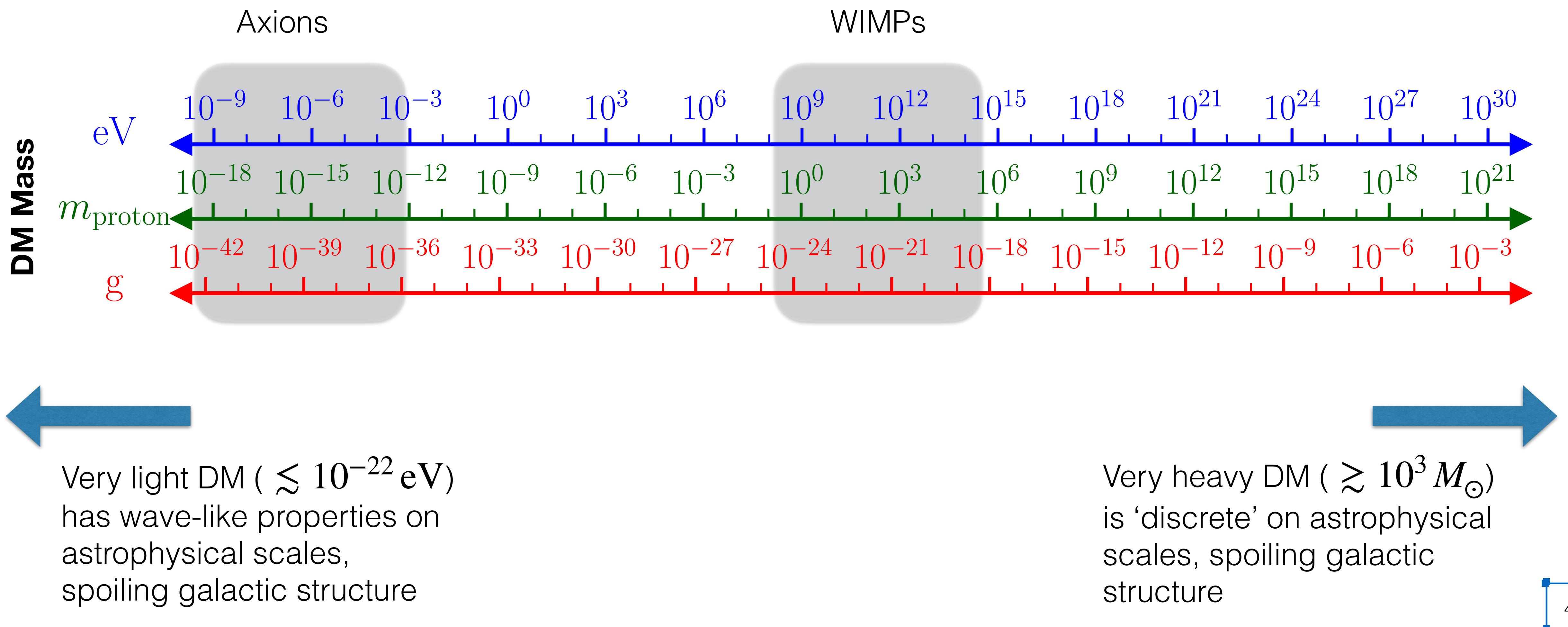
# Nature of Dark Matter

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



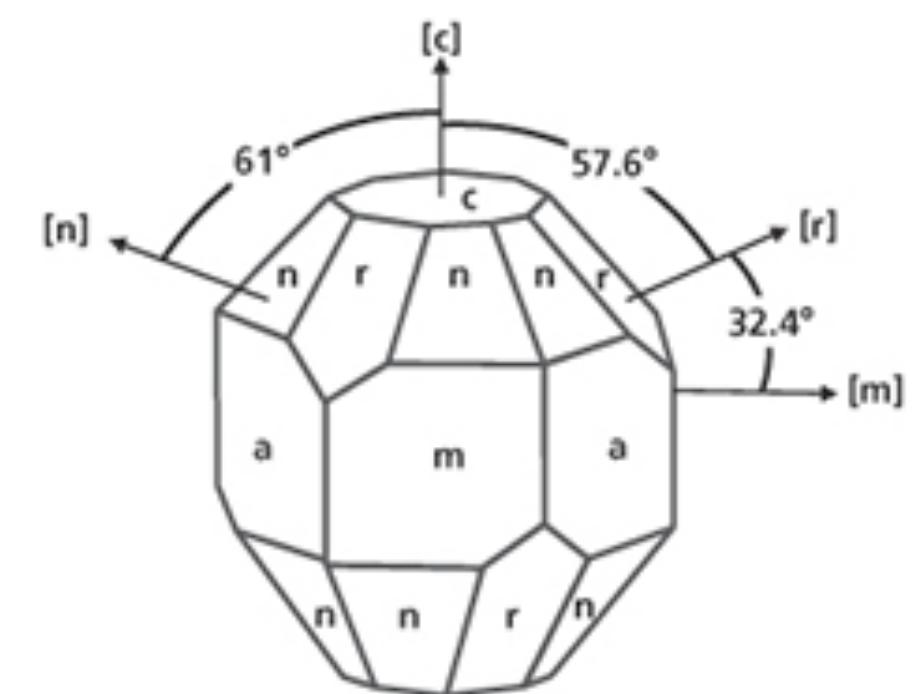
[See also Bertone, Coogan, Gaggero, **BJK** & Weniger, [1905.01238](#)]

# Dark Matter Mass Range



# New Directions in the search for DM

## Low-threshold phonon detectors



Cosmological and astrophysical evidence for Dark Matter is overwhelming

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

The search for DM is diversifying!

## Black Holes and Gravitational Waves



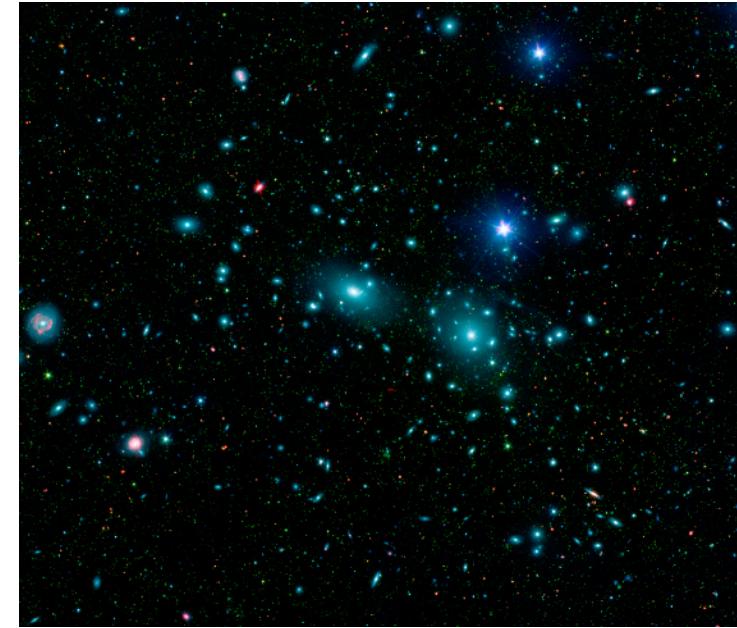
“...the new guiding principle should be ‘**no stone left unturned**’...”

[Bertone & Tait, Nature, 562, 51–56 (2018), [1810.01668](https://doi.org/10.1038/nature25791)]

## Backup Slides

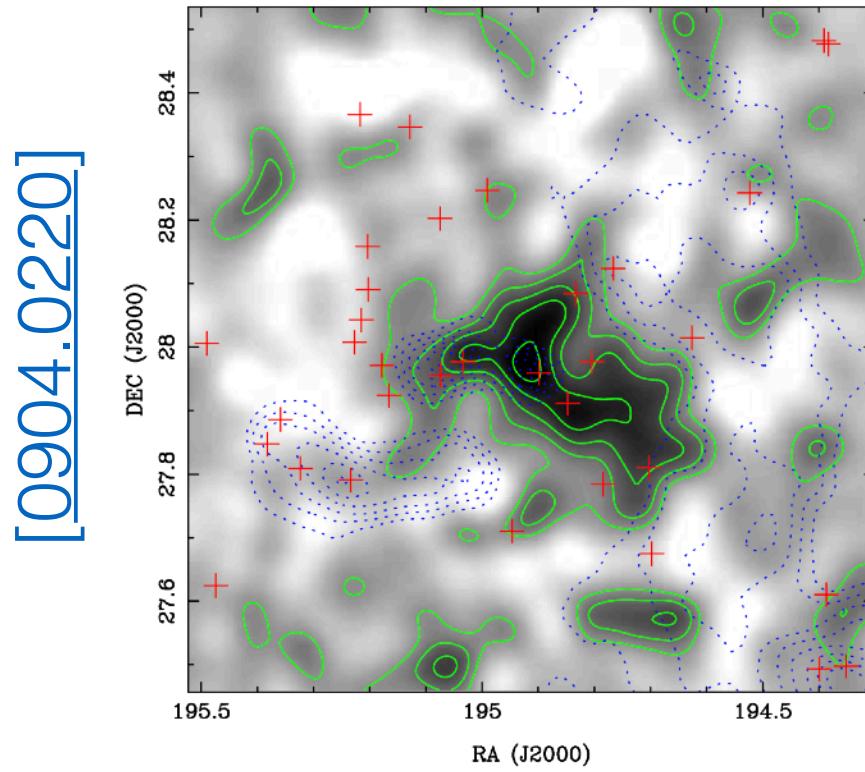
# Dark Matter in Galaxy Clusters

E.g. Coma Cluster



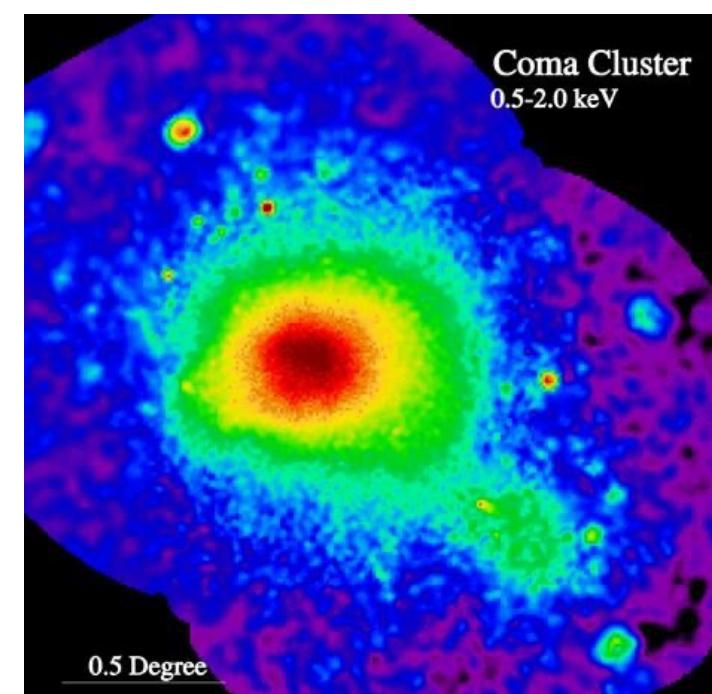
**Dynamics** - Velocity dispersion of member galaxies can be used to infer the enclosed mass through the Virial Theorem.

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



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

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



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

$$\frac{d\Phi}{dr} = \frac{GM_{\text{tot}}(< r)}{r^2} = -\frac{1}{\rho_{\text{gas}}} \frac{dP_{\text{gas}}}{dr}$$

# Universal Density Profiles

\*More on this shortly.

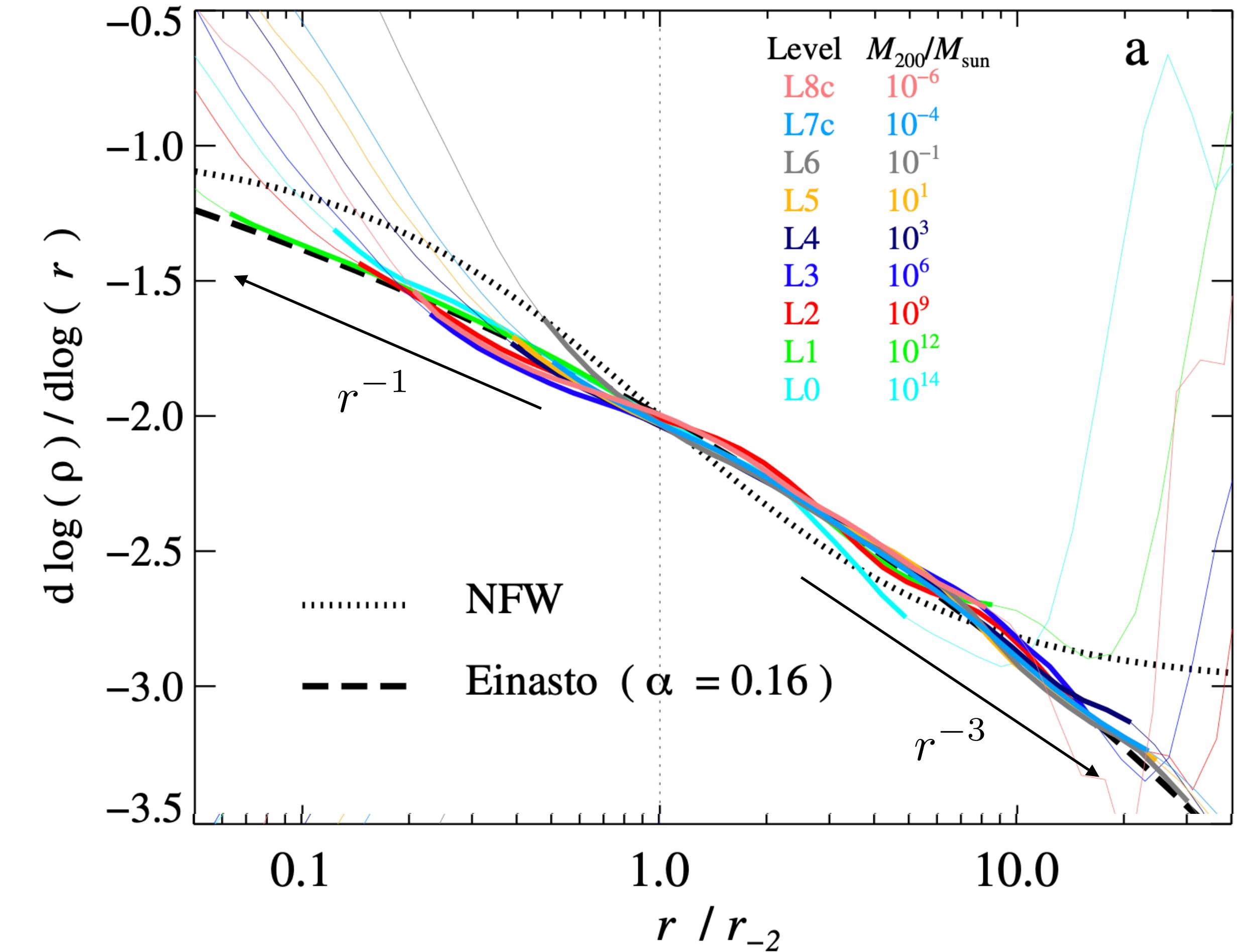
Density profiles of cold\* Dark Matter halos can be well fit over many orders of magnitude by the cuspy “Navarro-Frenk-White” (NFW) profile (1996): [\[astro-ph/9611107\]](https://arxiv.org/abs/astro-ph/9611107)

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

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

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

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



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

[1911.09720]

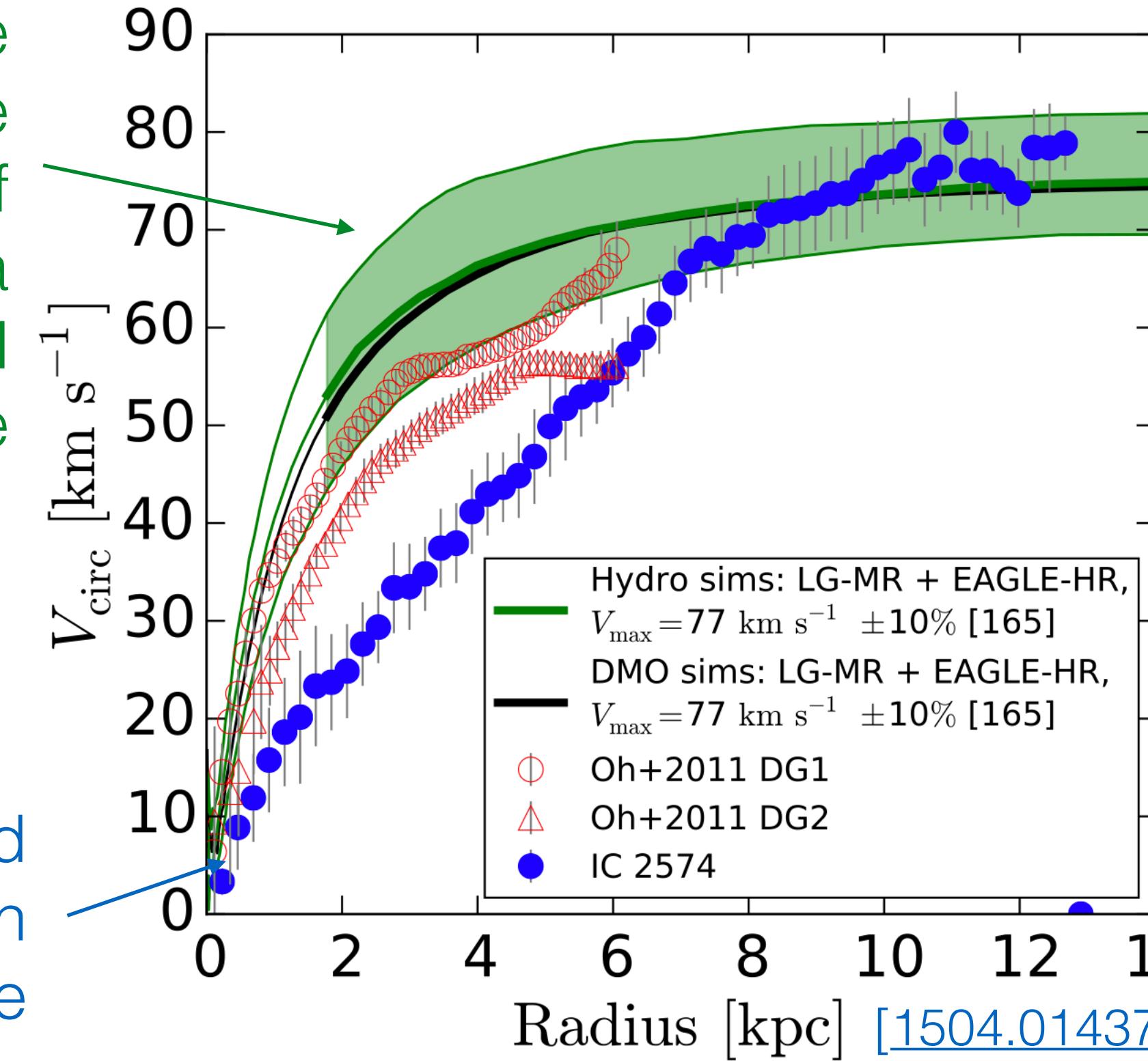
# Small-scale problems

## Core-vs-cusp problem

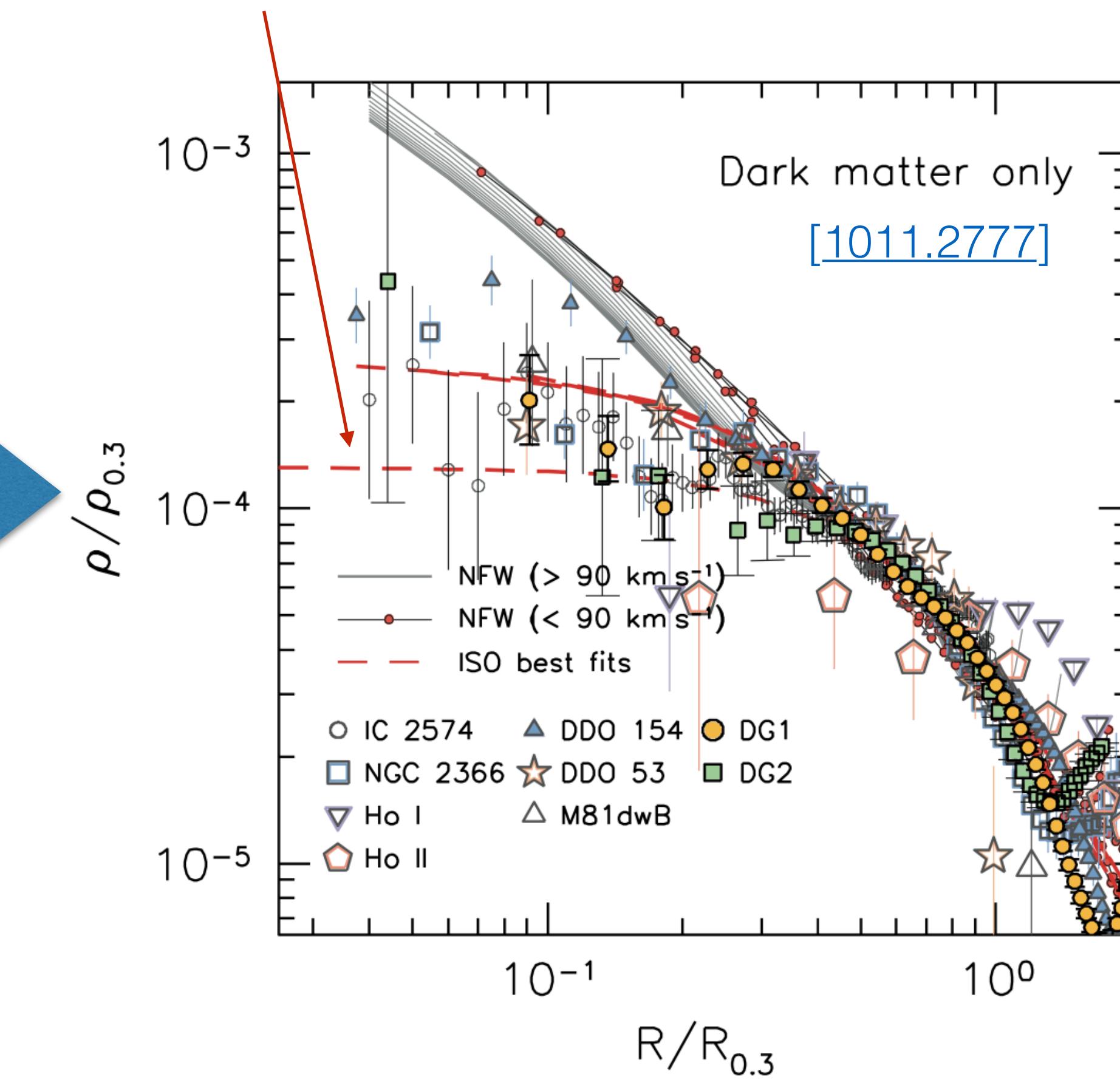
(Now sometimes called the “diversity of rotation curves’ problem)

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



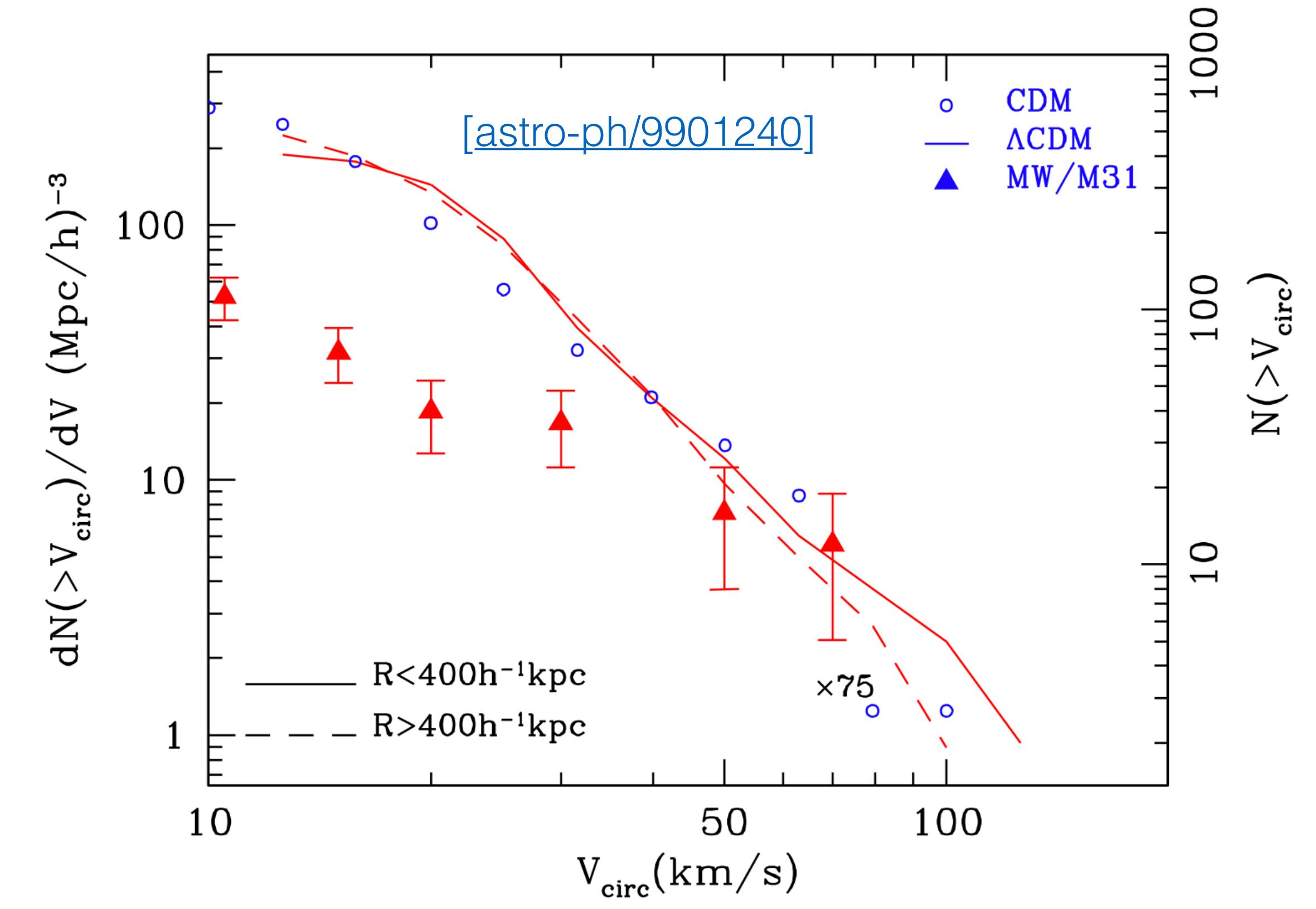
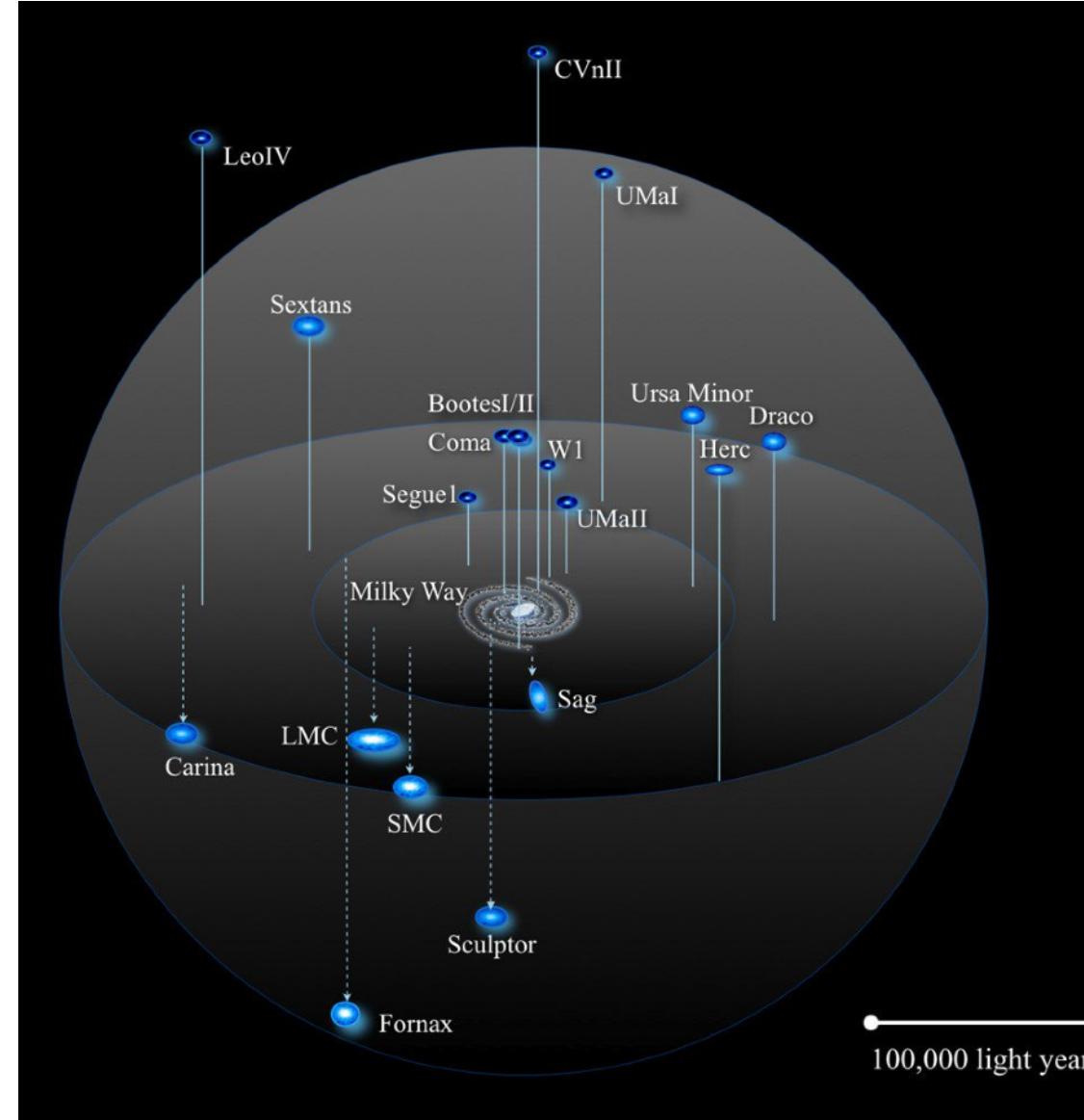
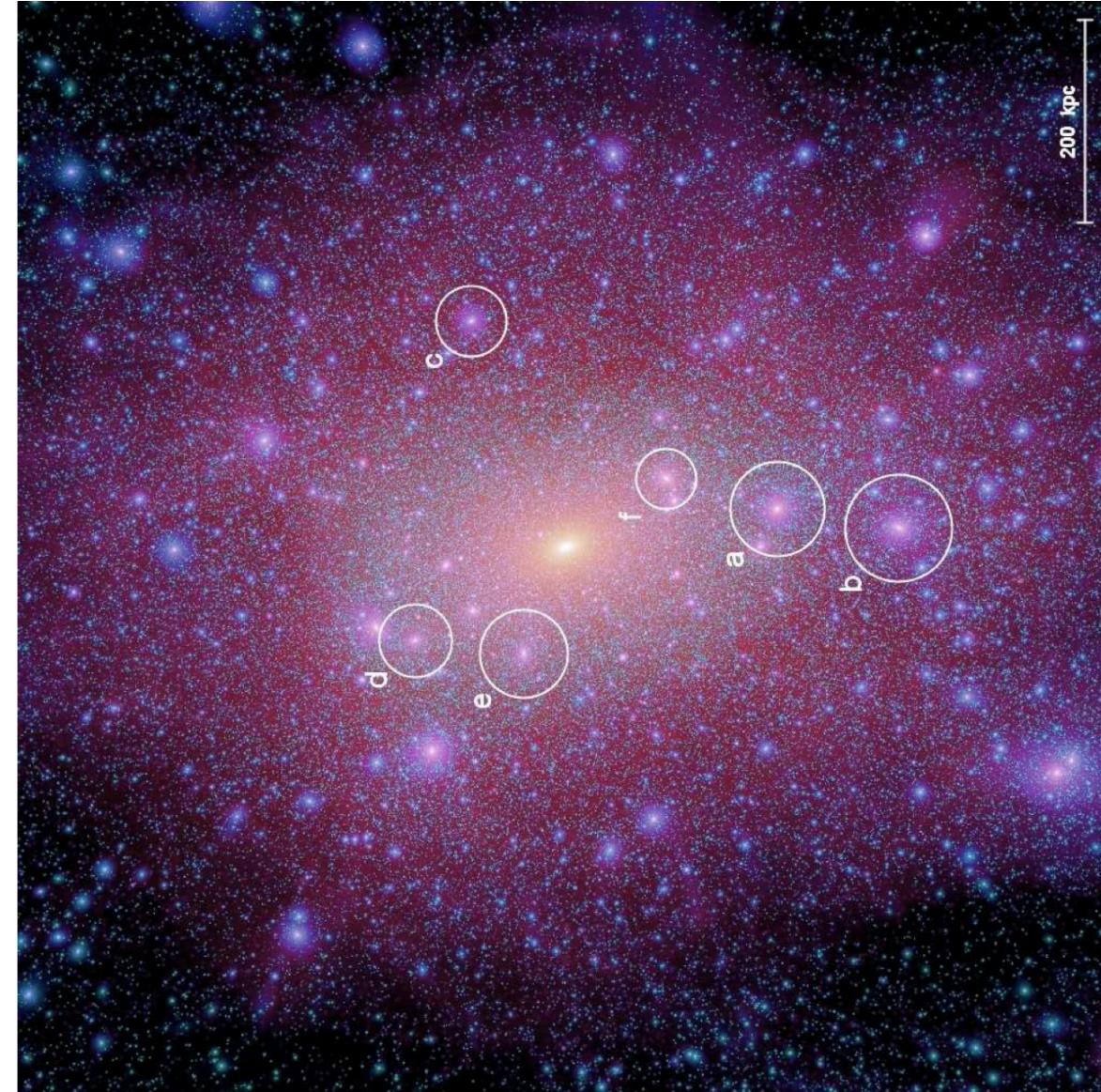
See also “Too big to fail”, “Plane of Satellites”, and others...

[Sales, Wetzel & Fattahi, 2206.05295]

# Small-scale problems

## Missing Satellites Problem

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



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

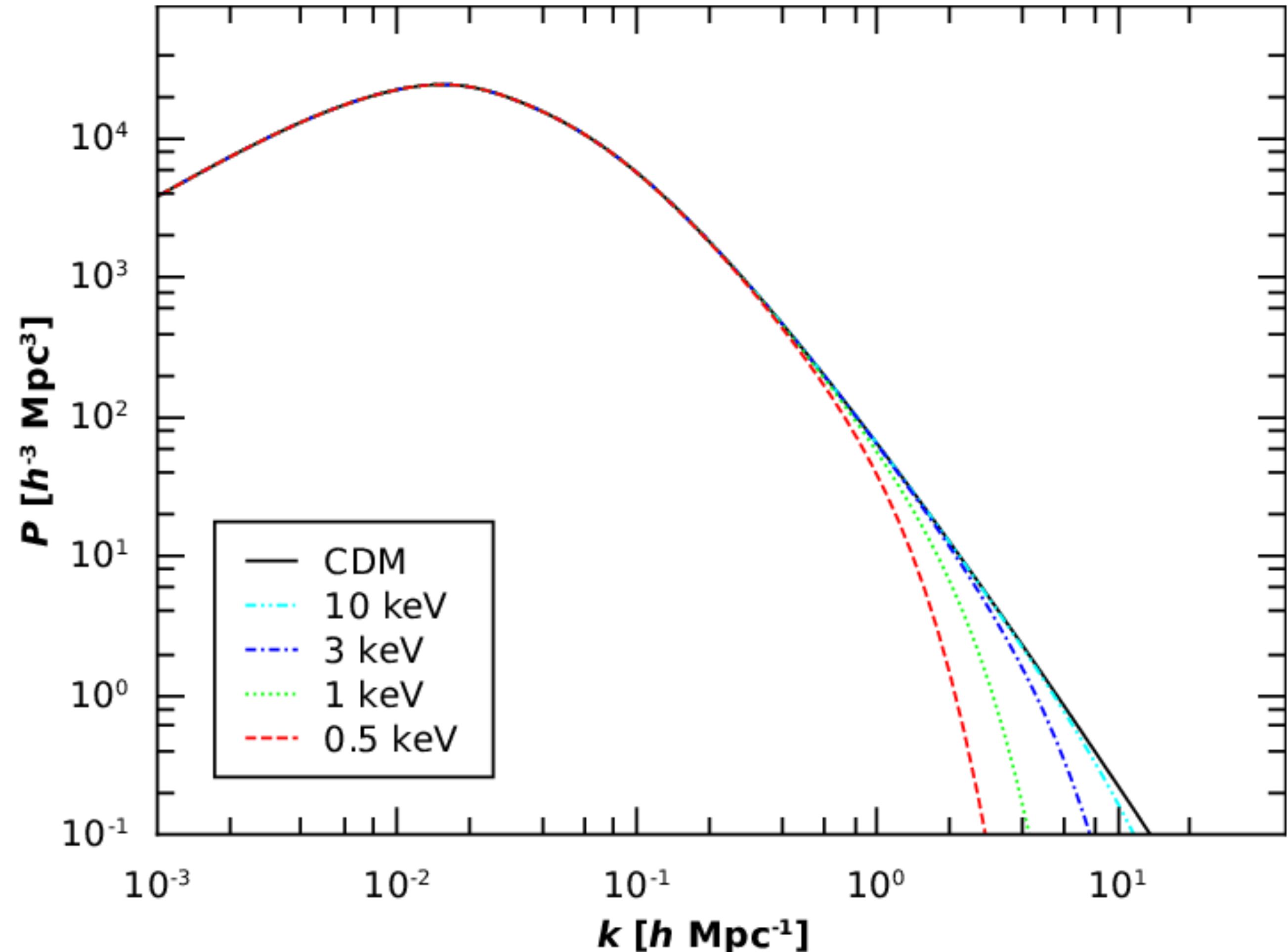
[Sales, Wetzel & Fattahi, 2206.05295]

# 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:

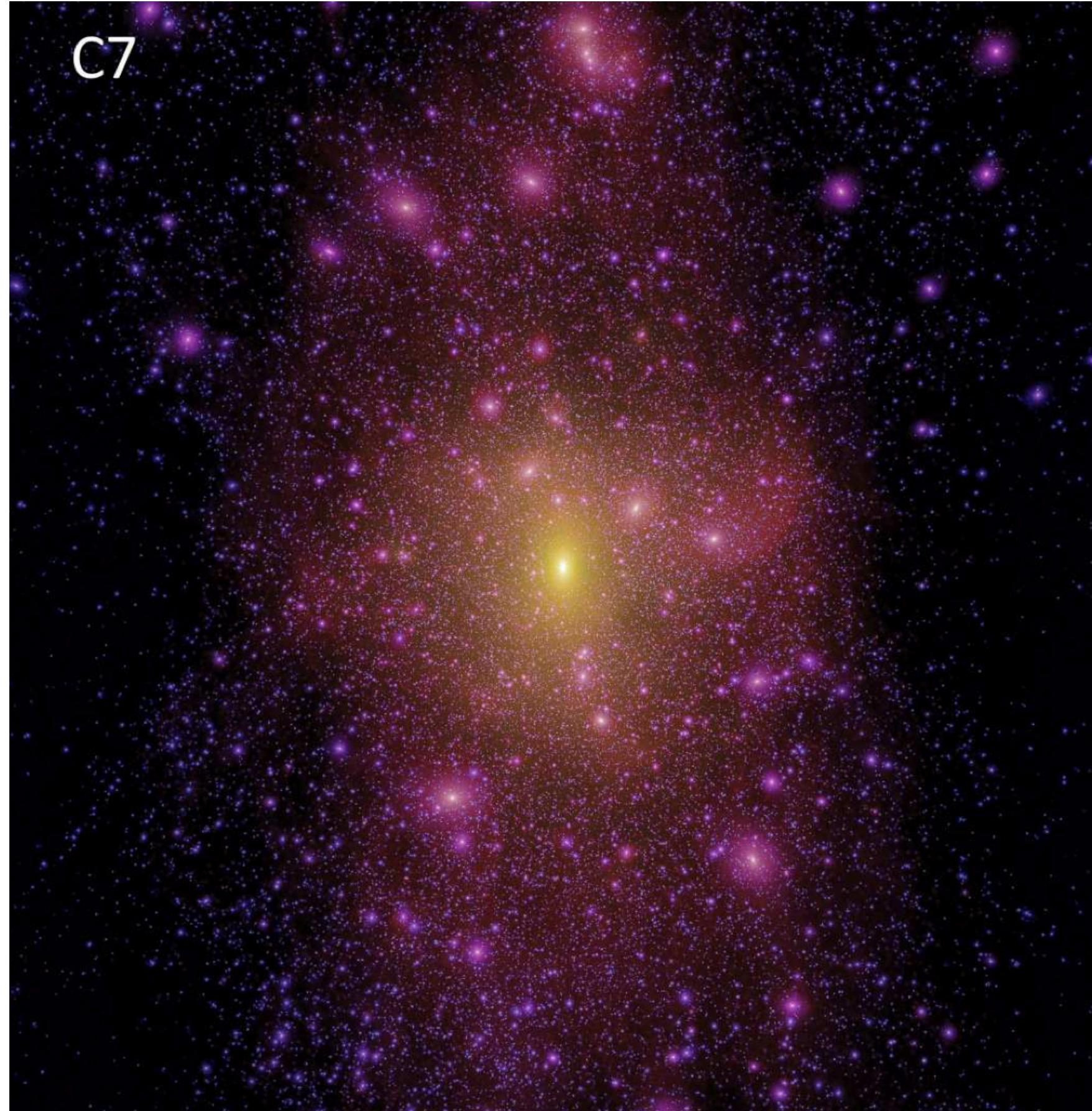
$$R_S \approx 0.47 \left( \frac{\text{keV}}{m_\chi} \right)^{1.15} \text{Mpc}$$



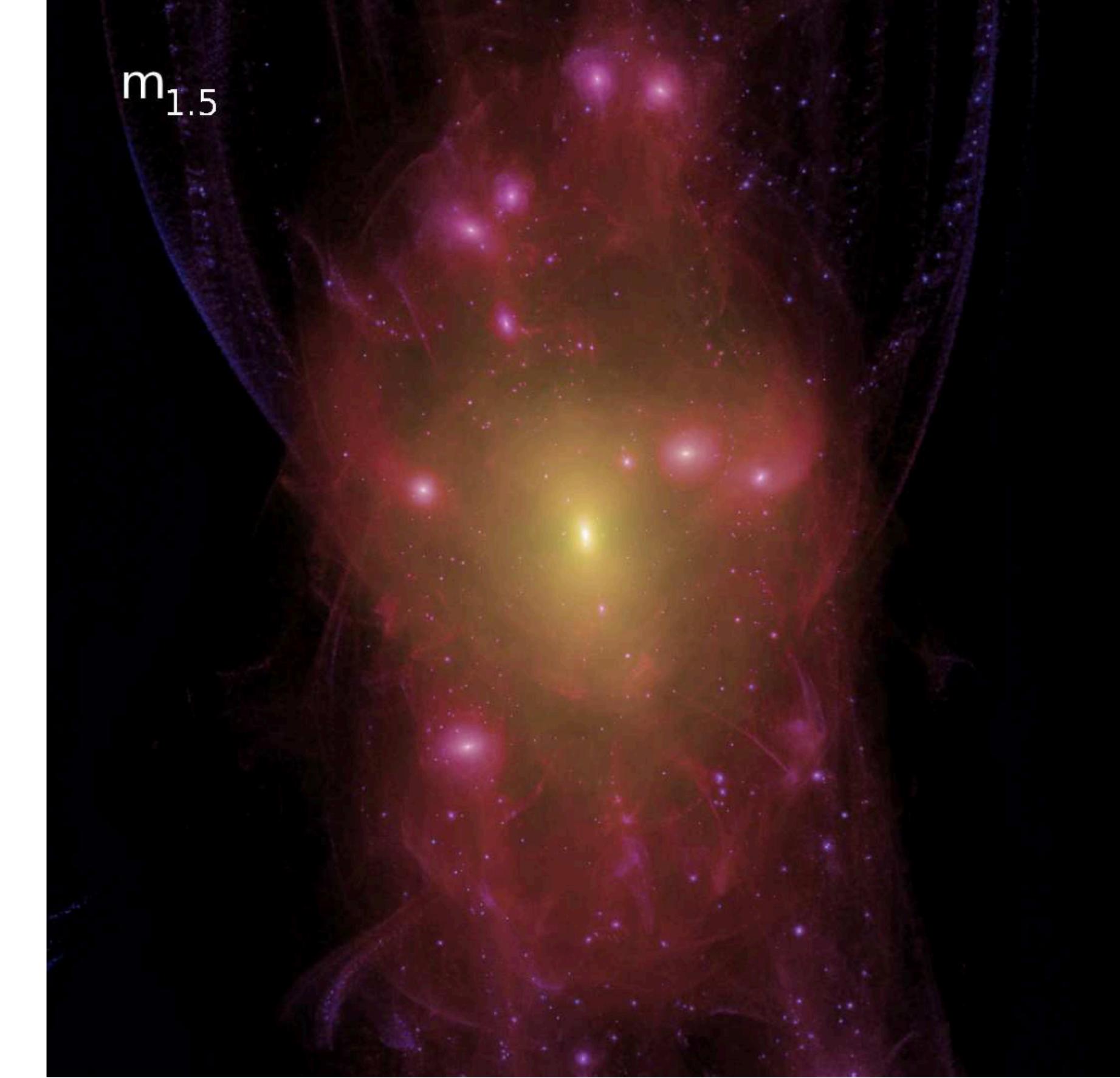
# Warm Dark Matter

[1308.1399]

Cold Dark Matter



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



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

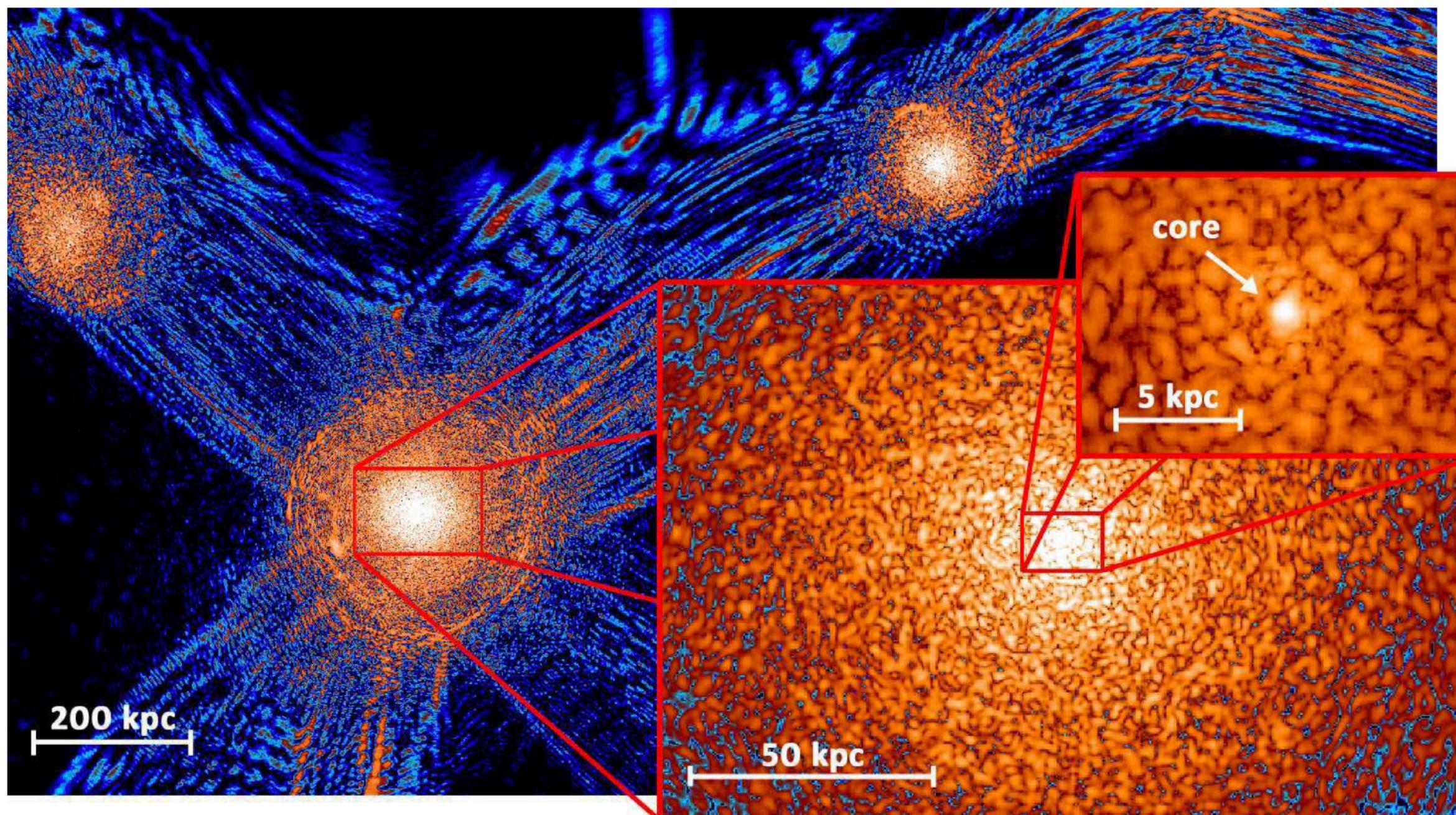
[2011.08865]

# 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.

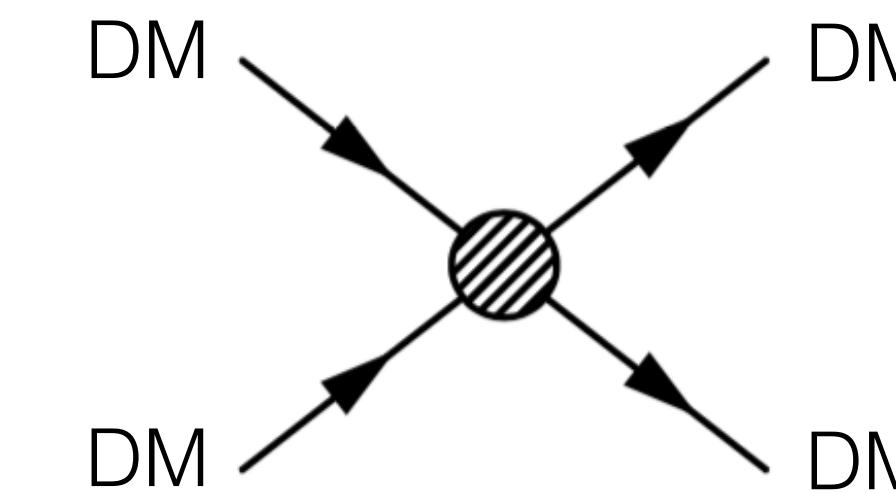


$$\lambda_J \propto (1+z)^{1/4} m_\psi^{-1/2}$$

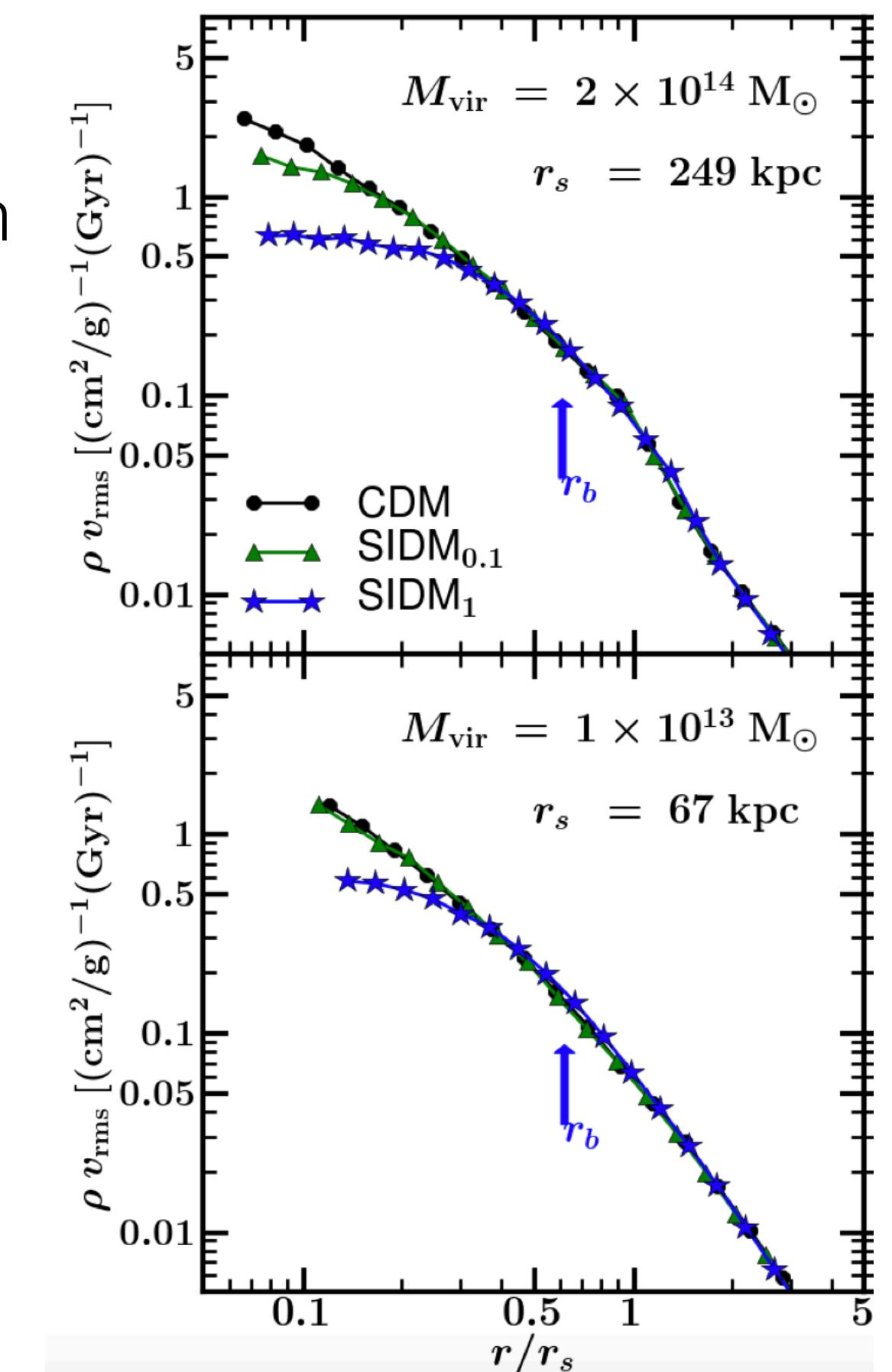
[1406.6586]

## 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  $\chi$  initially in thermal equilibrium, their number density  $n_\chi$  is governed by the Boltzmann Equation:

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

Dilution due to expansion

Annihilation of DM

Production of DM

(Thermally averaged)  
DM annihilation cross  
section

Equilibrium number density for fermions is given by:

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

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:

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

# Freeze-out

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

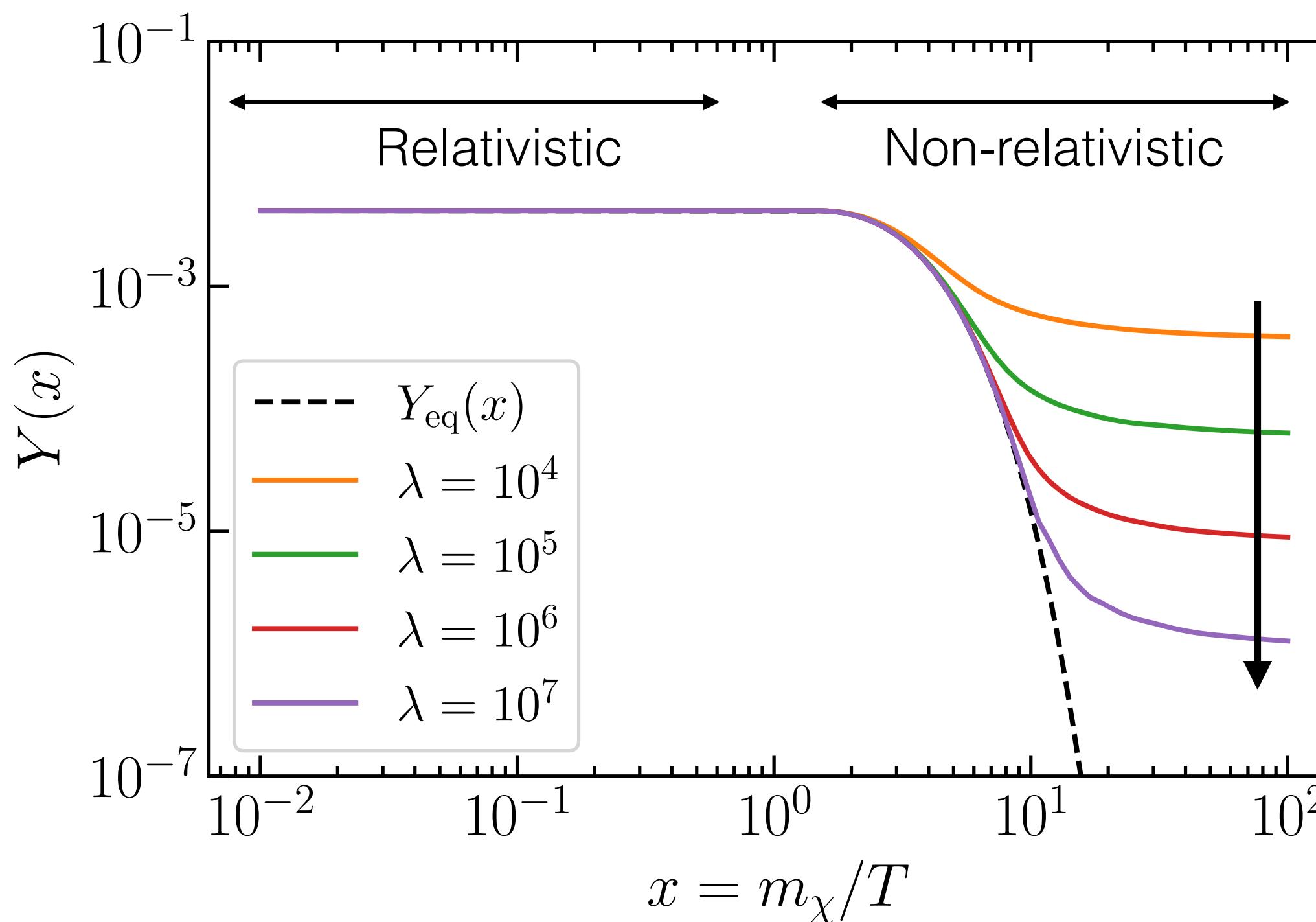
Convenient to transform Boltzmann Equation in terms of  $x = m_X/T$ , and the entropy density  $s = (2\pi^2/45)g_{\star s}(T)T^3$ . The equation for the Yield  $Y(x) \equiv n/s$  is then:

Riccati Equation:

$$\frac{dY}{dx} = -\frac{\lambda}{x^2} [Y^2 - Y_{\text{eq}}^2]$$

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

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



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

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

Increasing  $\langle \sigma v \rangle$   
(at fixed  $m_\chi$ )

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

# Cold vs Hot Dark Matter

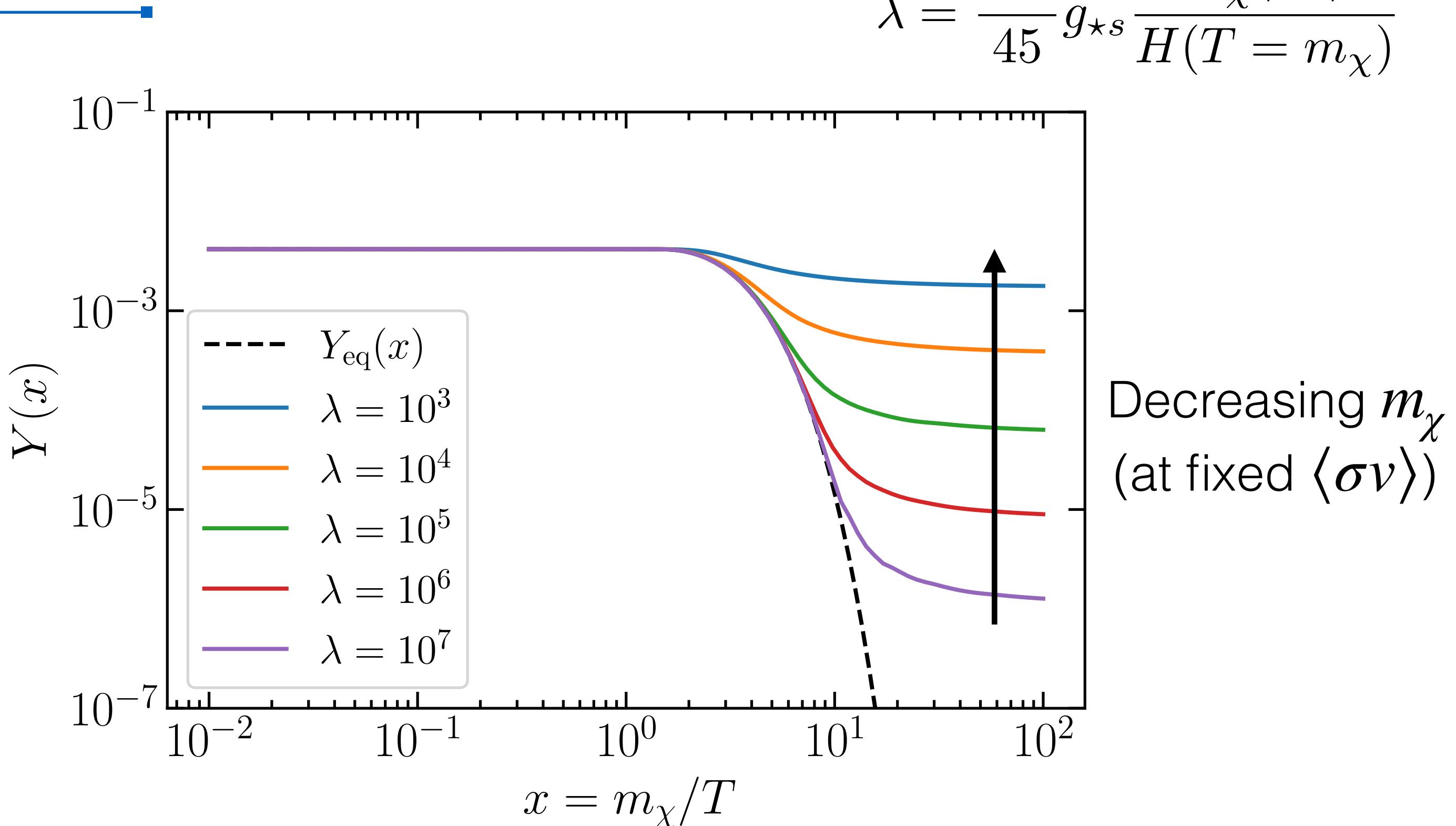
$$\lambda = \frac{2\pi^2}{45} g_{*s} \frac{m_\chi^3 \langle \sigma v \rangle}{H(T = m_\chi)}$$

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

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

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

Decreasing  $m_\chi$  decreases  $\lambda$ , pushing  $x_f$  smaller...



Very light relics  $m \lesssim \text{eV}$  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  $c_s^2 = \sigma^2$ .

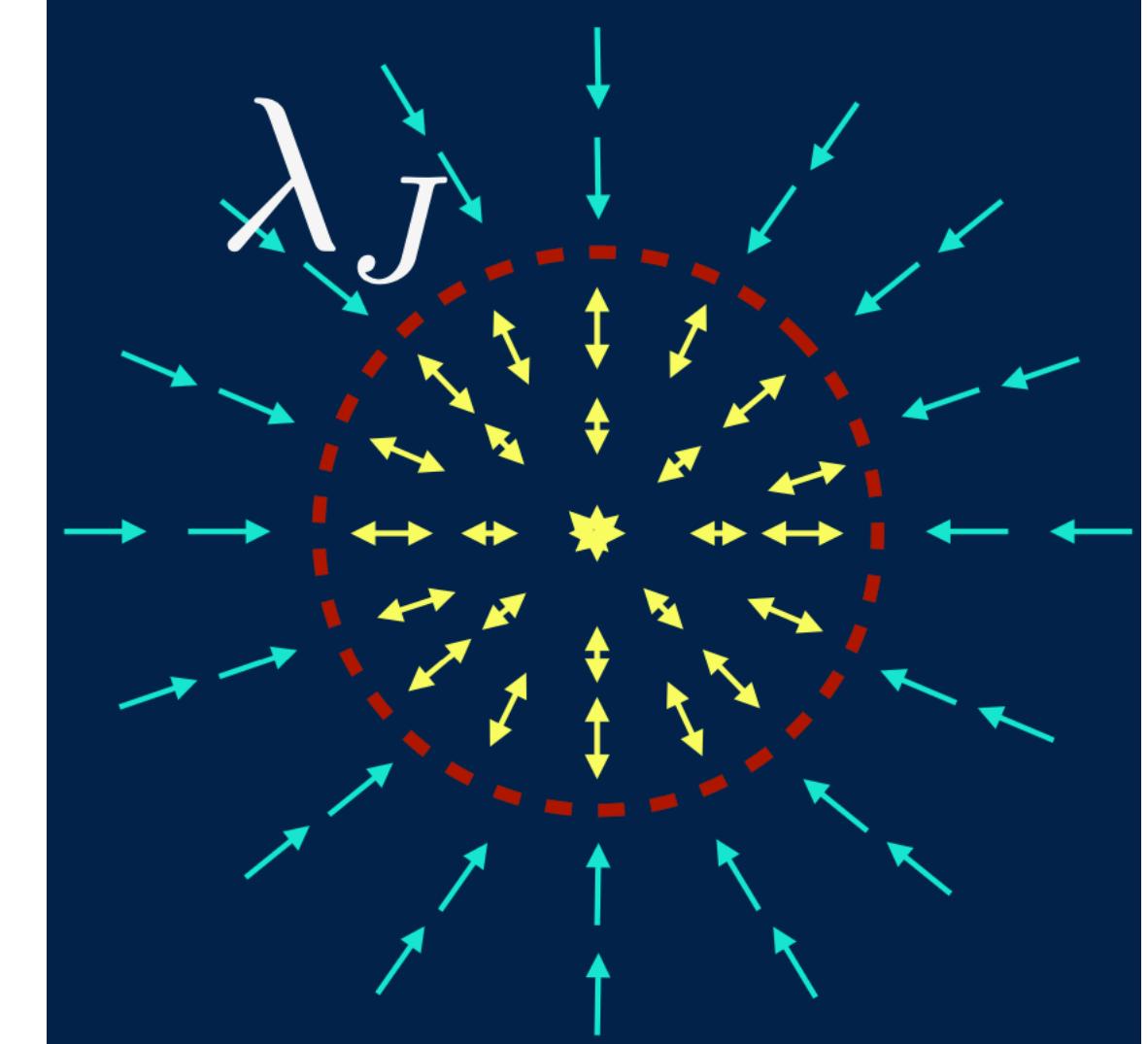
As in the collisional case,  
we can write the Jeans length as

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

$\lambda > \lambda_J$  : 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  $t_{\text{cross}} \sim \lambda/\sigma$  is comparable to the gravitational collapse timescale  $t_{\text{coll}} \sim 1/\sqrt{G\bar{\rho}}$ . Free-streaming length can be evaluated roughly as  $\lambda_{\text{fs}} \sim \lambda_J(t_{\text{eq}})$ , 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  $\lambda_{\text{fs}}$  is large: Structure is washed out on small scales!



# Alternative Production Mechanisms

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

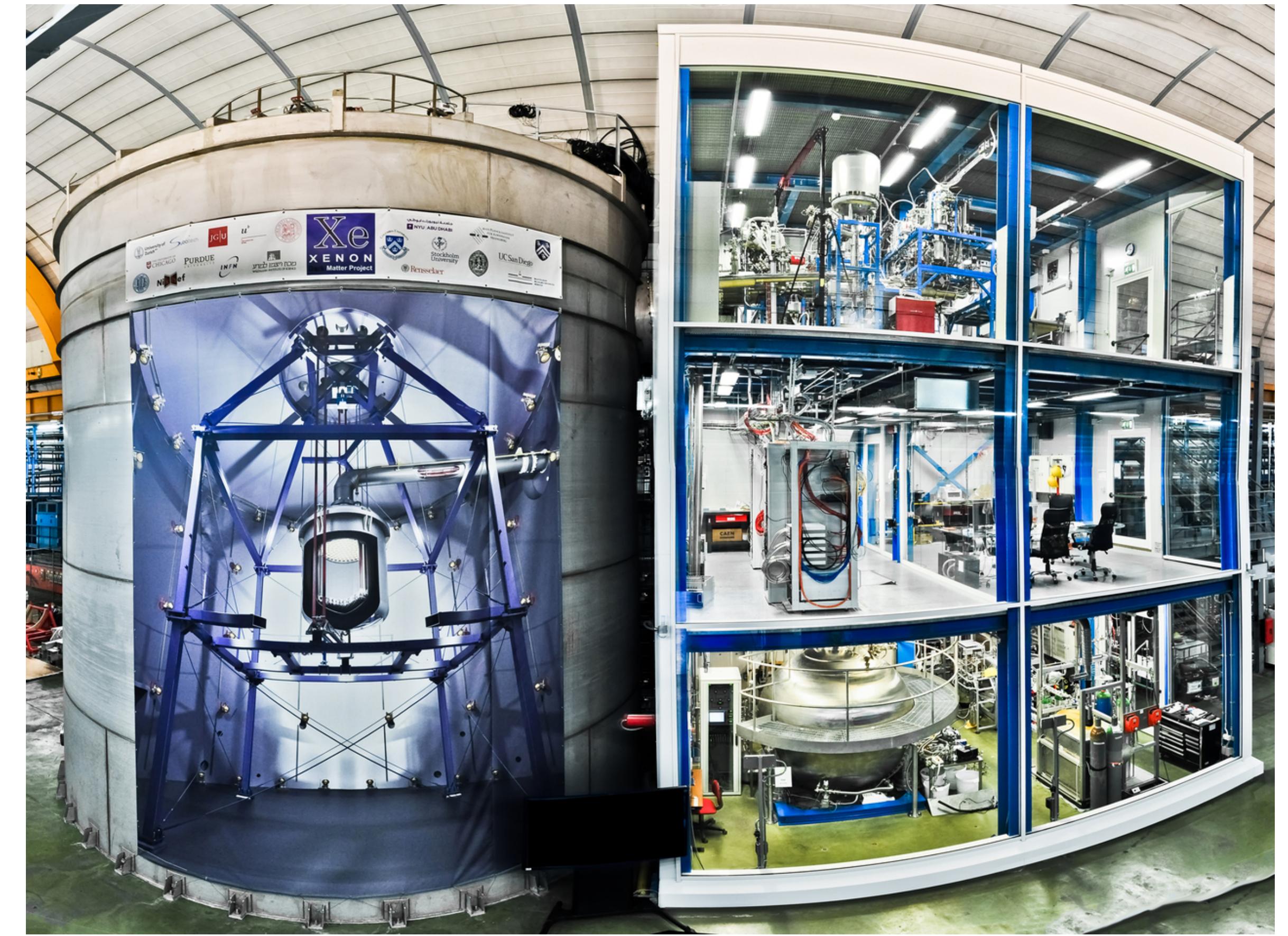
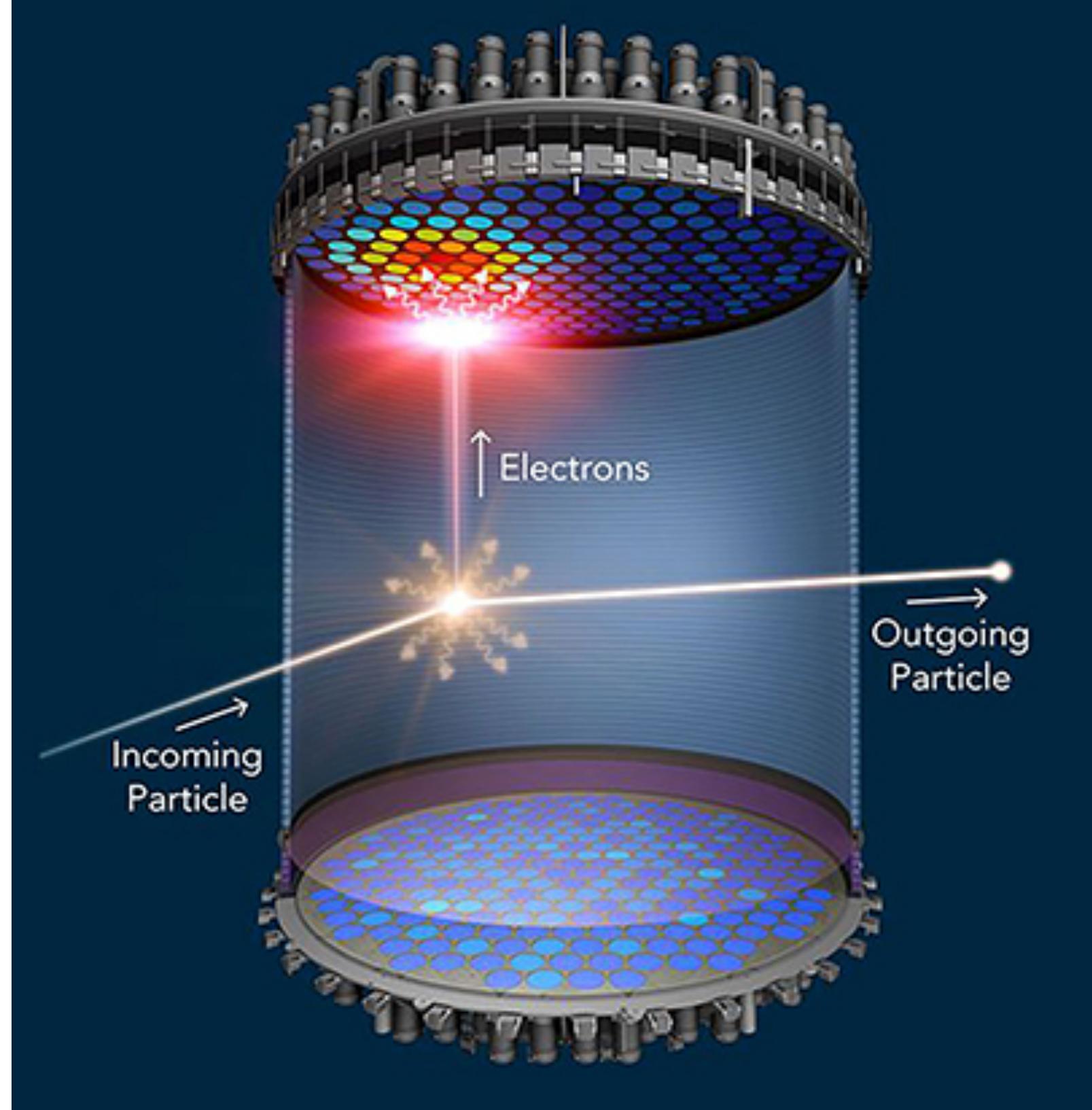
- Freeze-out [[Kolb & Turner \(1990\)](#)]
- Freeze-in [[arXiv:0911.1120](#)]
- Asymmetric Dark Matter [[arXiv:1305.4939](#)]
- Forbidden Dark Matter [[arXiv:1505.07107](#)]
- Secluded Dark Matter [[arXiv:0711.4866](#)]
- SIMP Dark Matter [[arXiv:1402.5143](#)]
- Self-interacting Dark Matter [[arXiv:1510.08063](#)]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

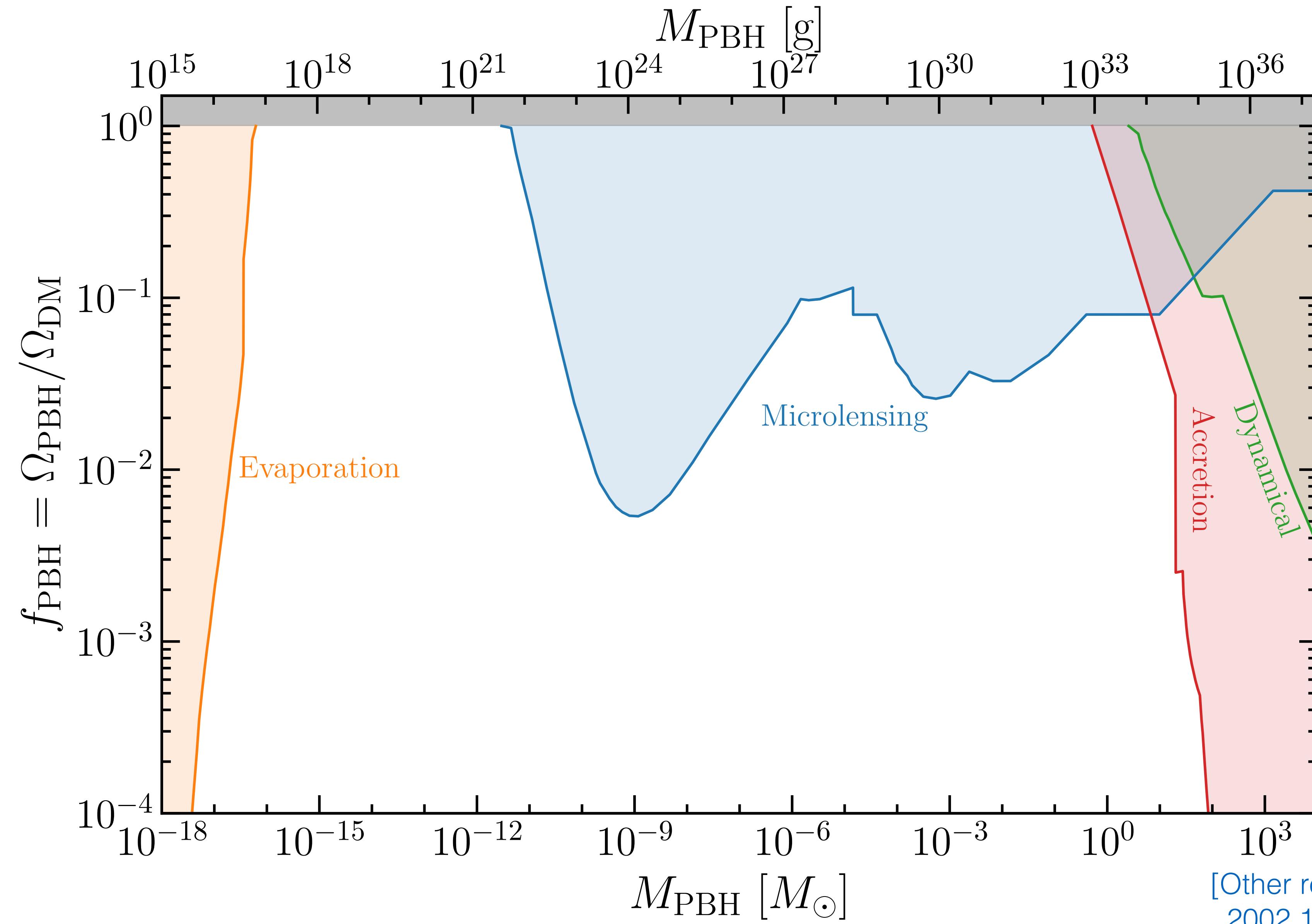


Credit: XENON Collaboration

# PBH Parameter Space

[Green & BJK, 2007.10722]

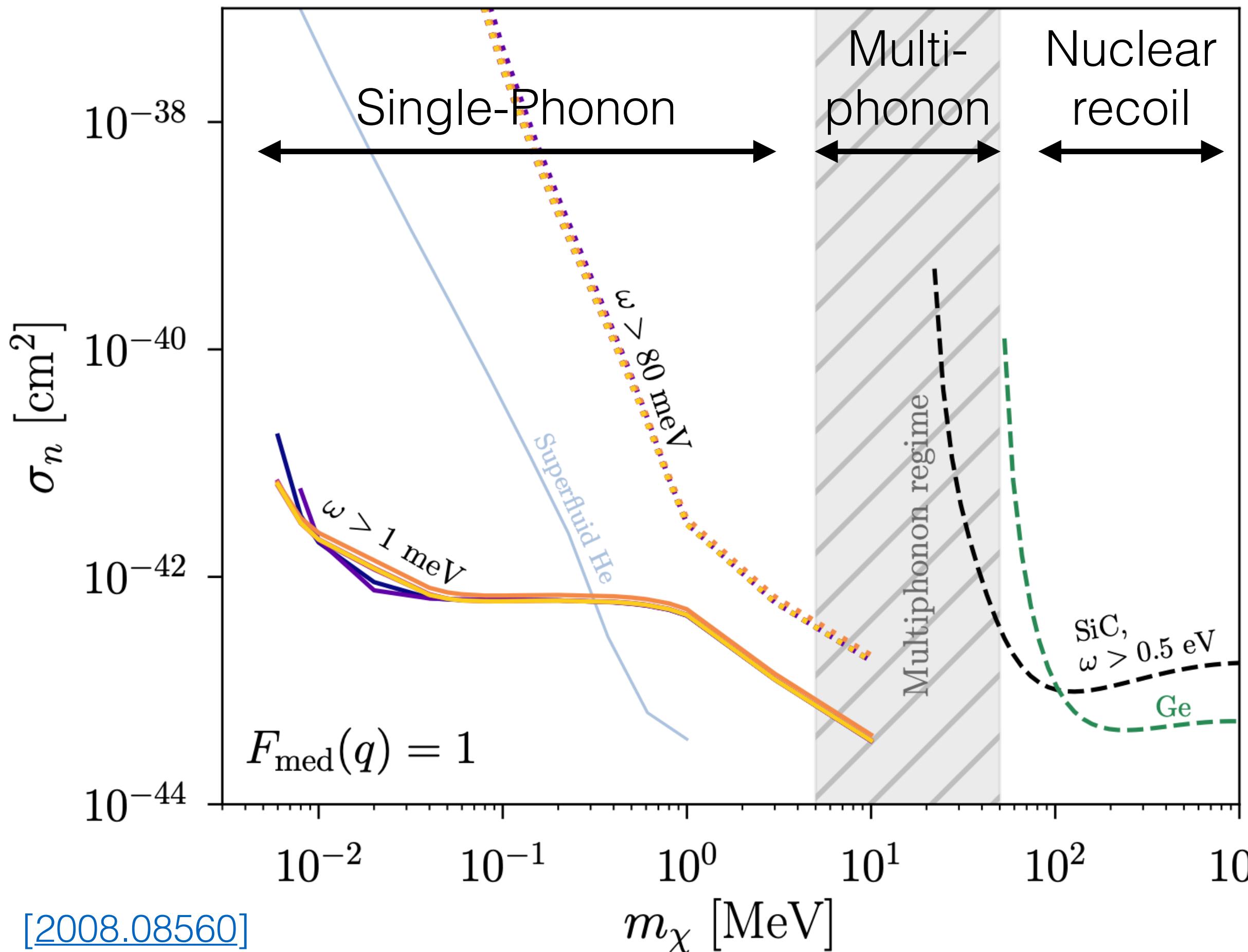
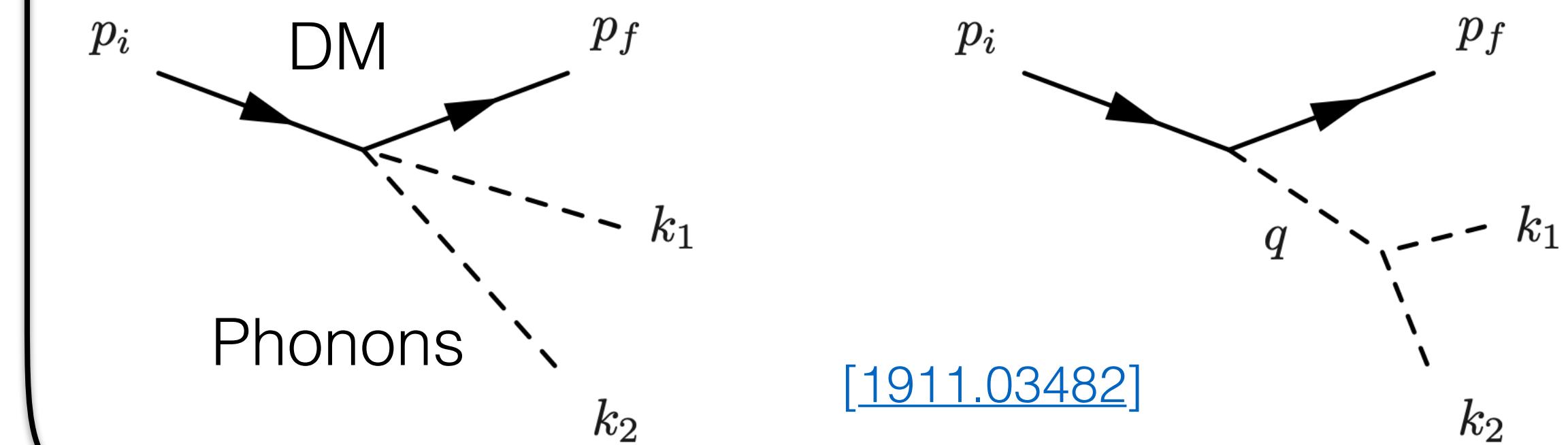
[Code online: [github.com/bradkav/PBHbounds](https://github.com/bradkav/PBHbounds)]



[Other reviews: [1801.05235](https://arxiv.org/abs/1801.05235),  
[2002.12778](https://arxiv.org/abs/2002.12778), [2006.02838](https://arxiv.org/abs/0606.02838)]

# Multi-phonon Scattering

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

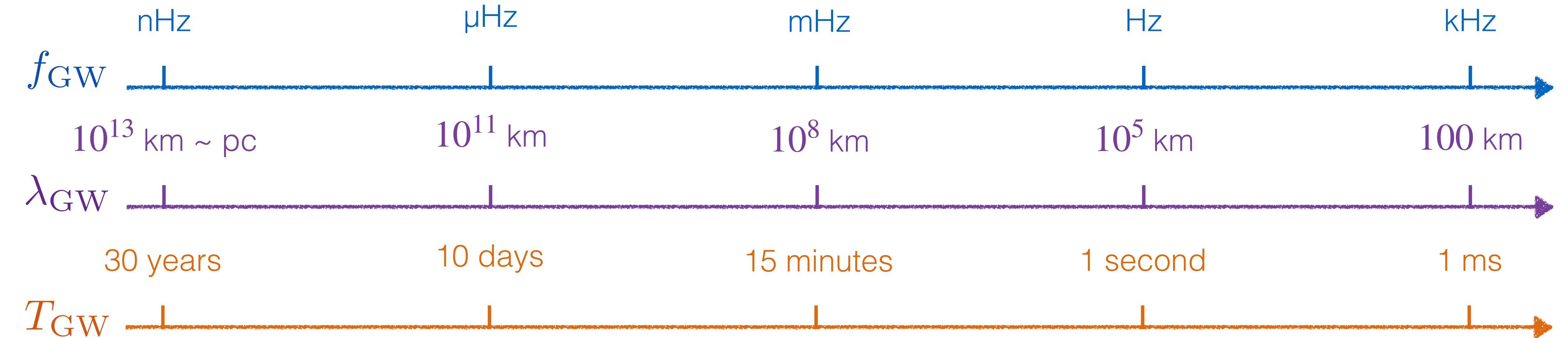


Heavier DM leads to larger  $q$ , so multi-phonon scattering may become relevant masses  $\gtrsim$  few MeV

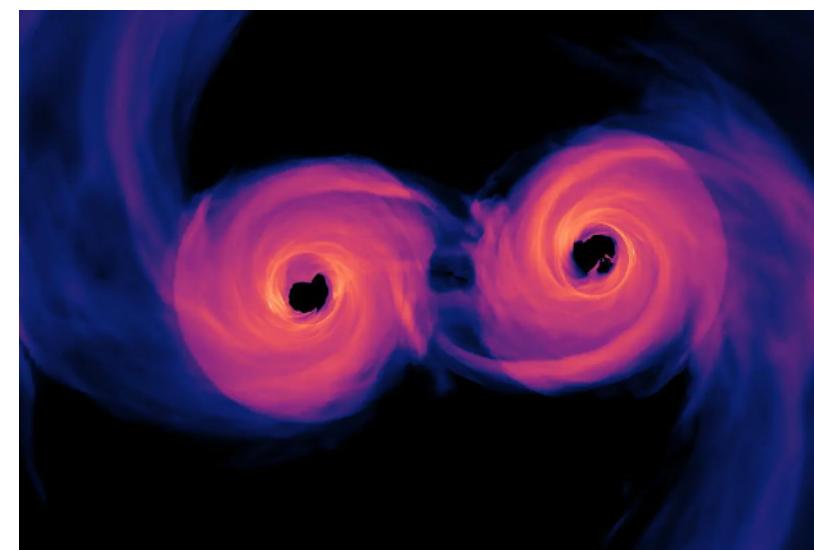
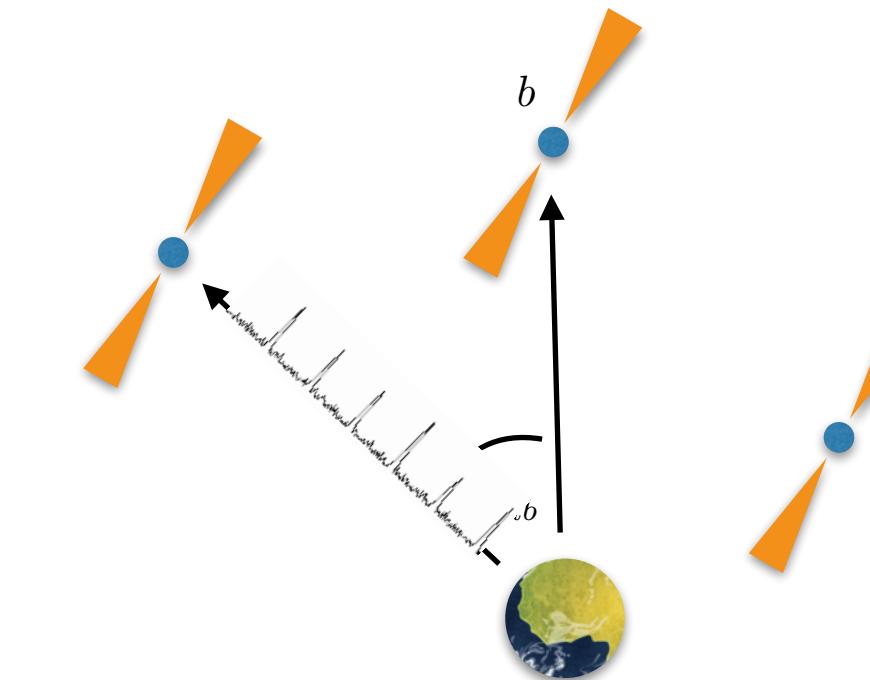
[1608.01994, 1910.08092, 1911.03482]

# The Gravitational Wave Spectrum

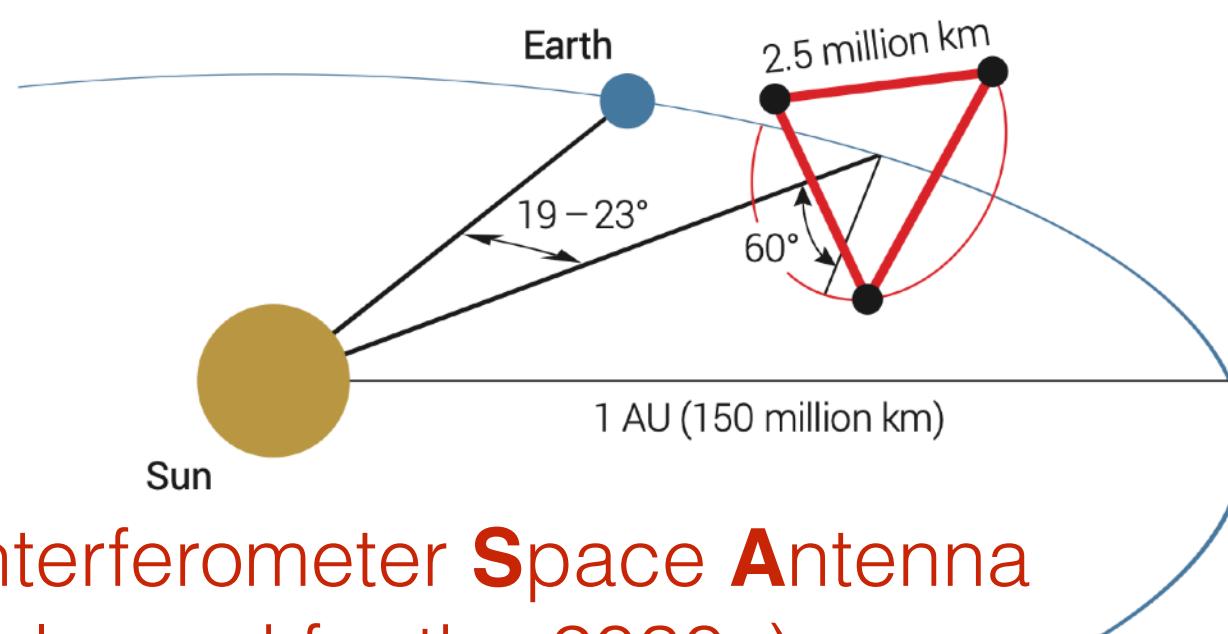
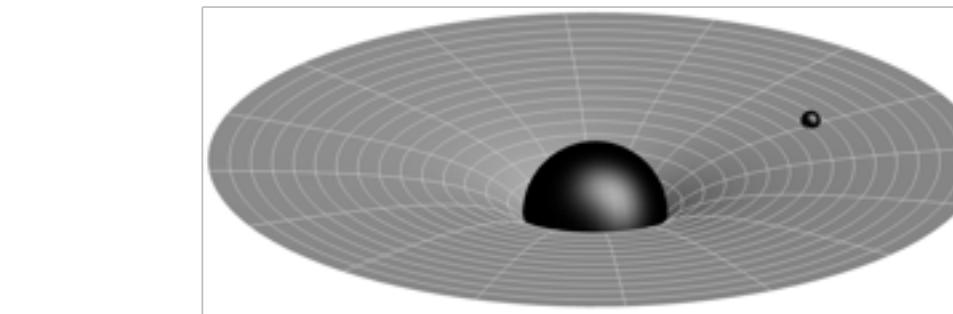
$$c = \lambda_{\text{GW}} \cdot f_{\text{GW}}$$



DETECTORS?

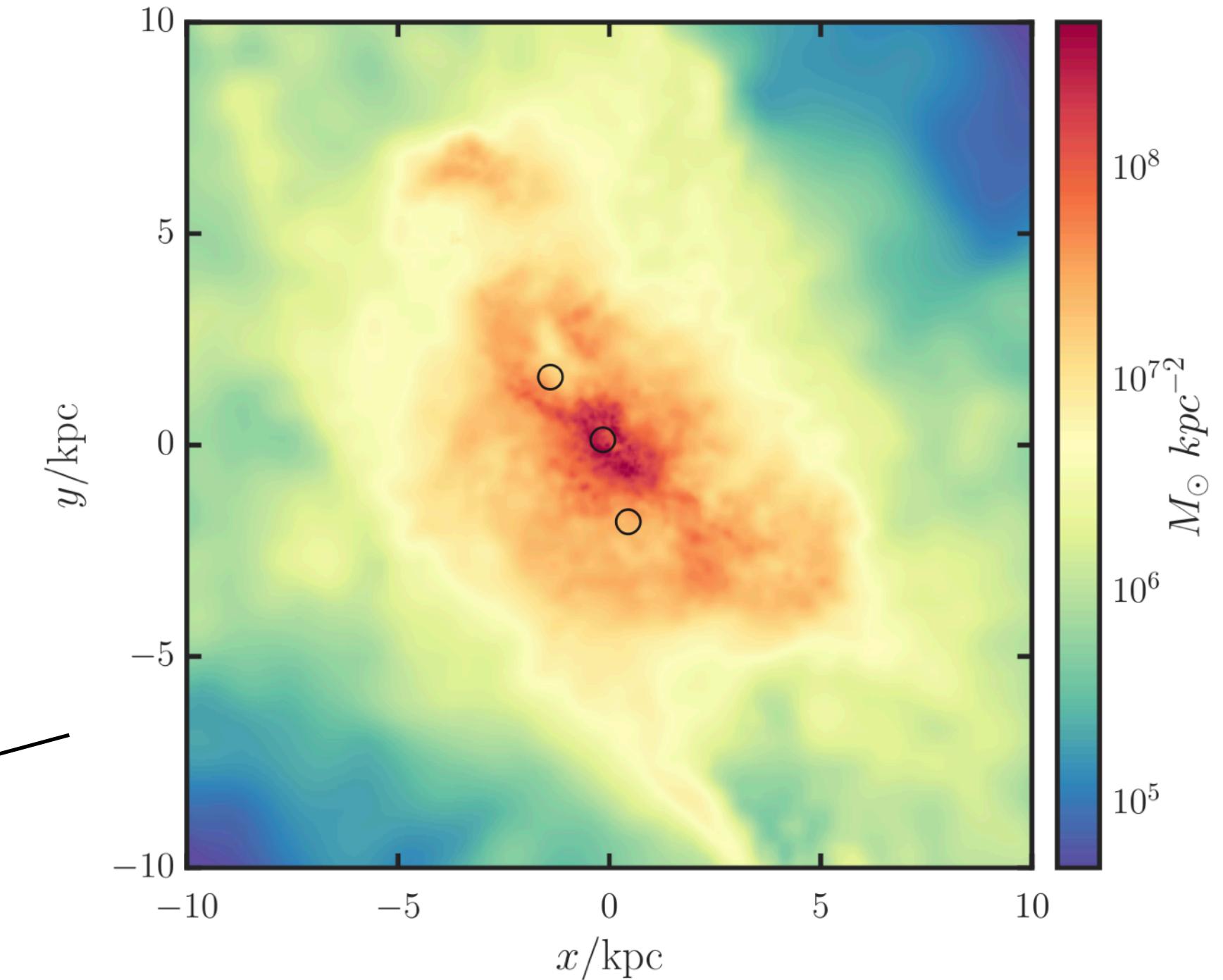
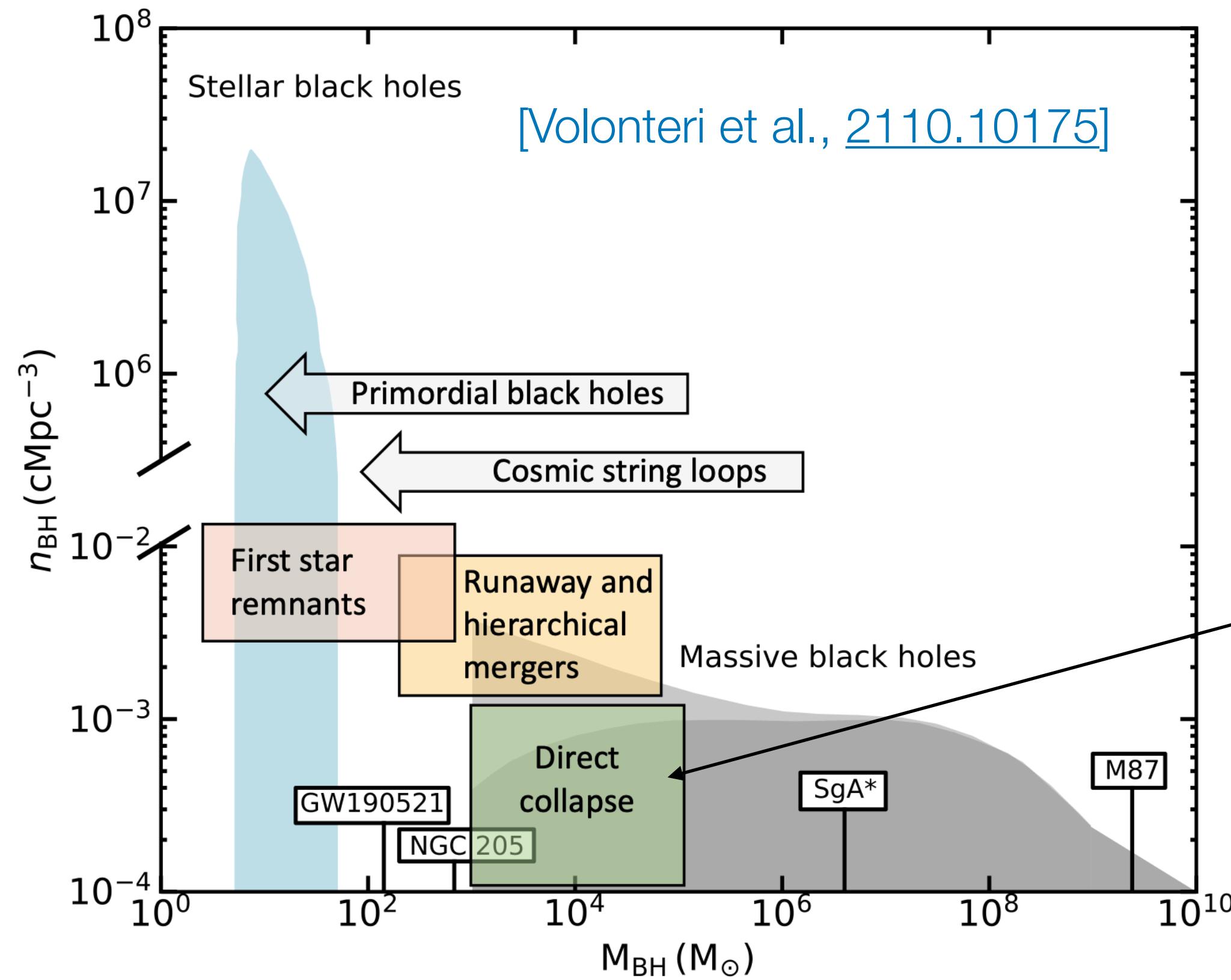


Laser Interferometer Space Antenna  
(planned for the 2030s)  
[\[1907.06482\]](https://arxiv.org/abs/1907.06482)



# BH and Spike Formation

[Dunn et al., 1803.01007]



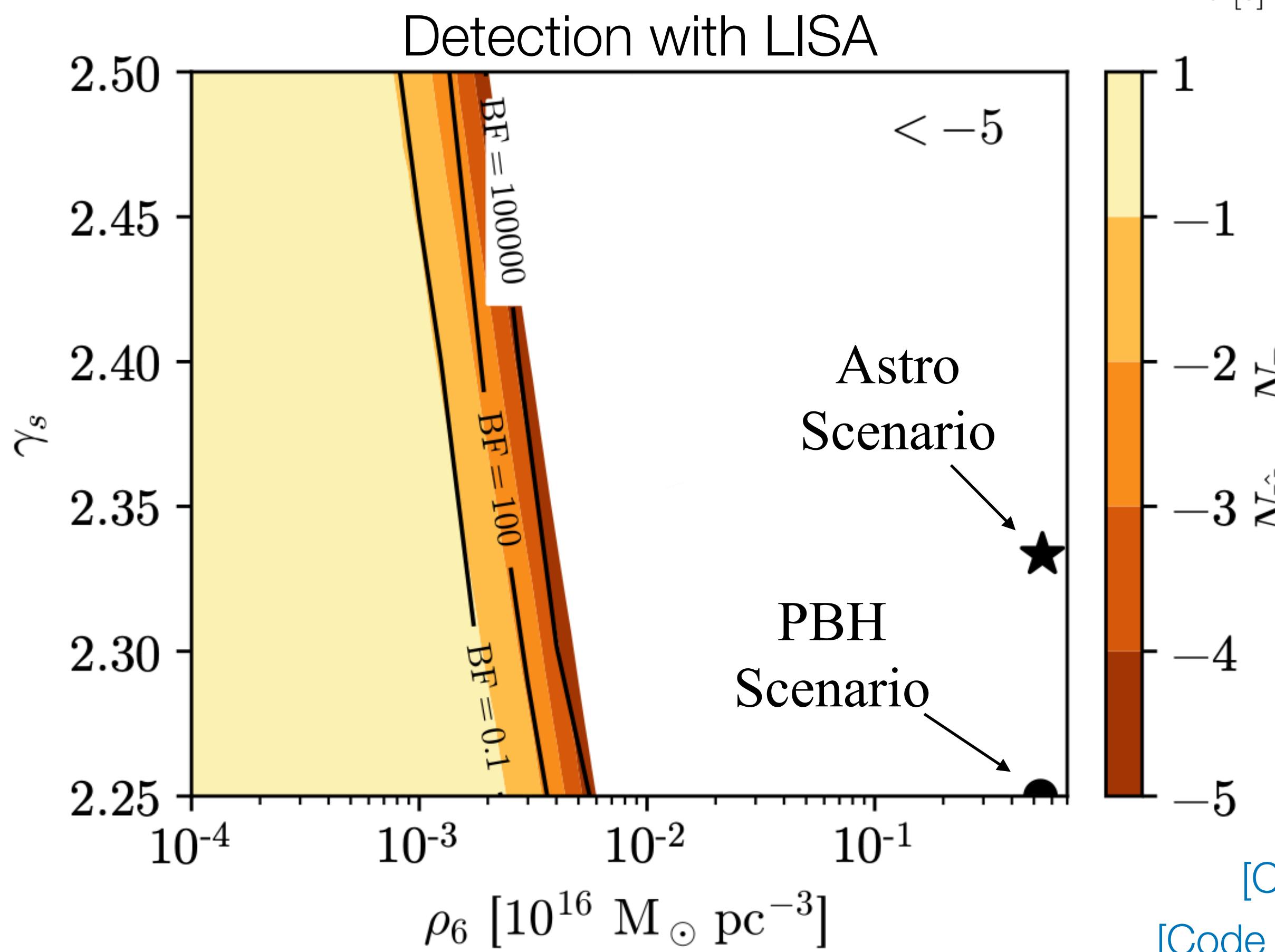
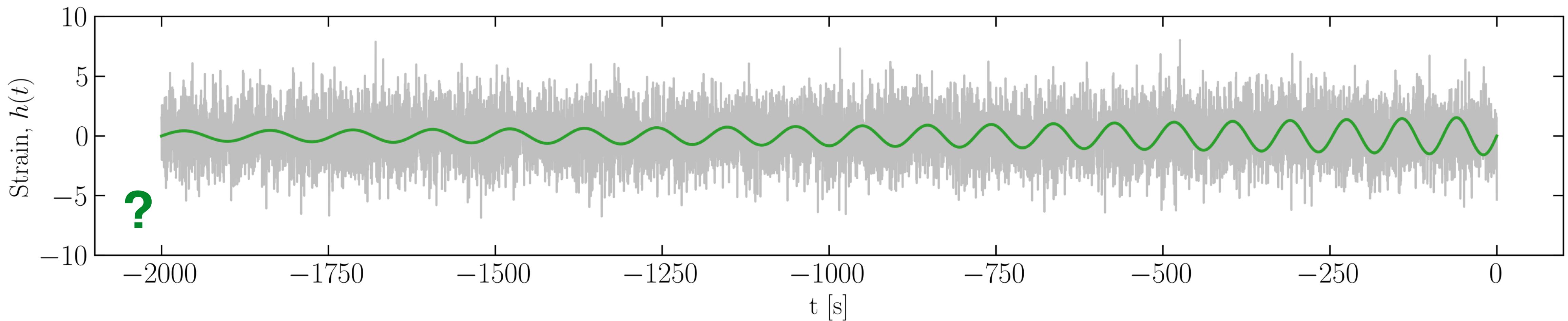
Use semi-analytic galaxy formation models to study the properties of Direct Collapse Black Holes and the halos they form in.

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

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

[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)

$$\theta_V = \{\mathcal{M}\}$$

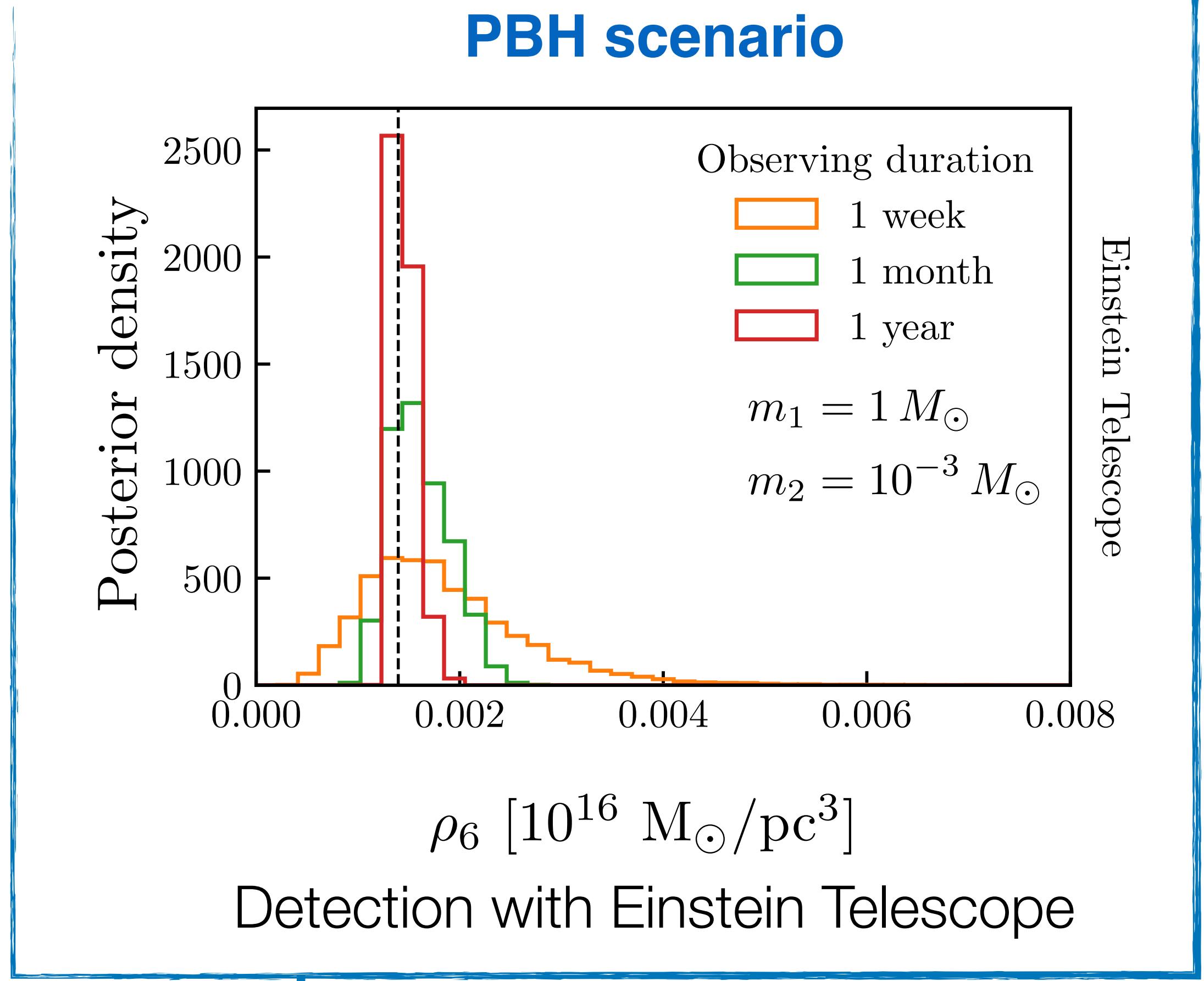
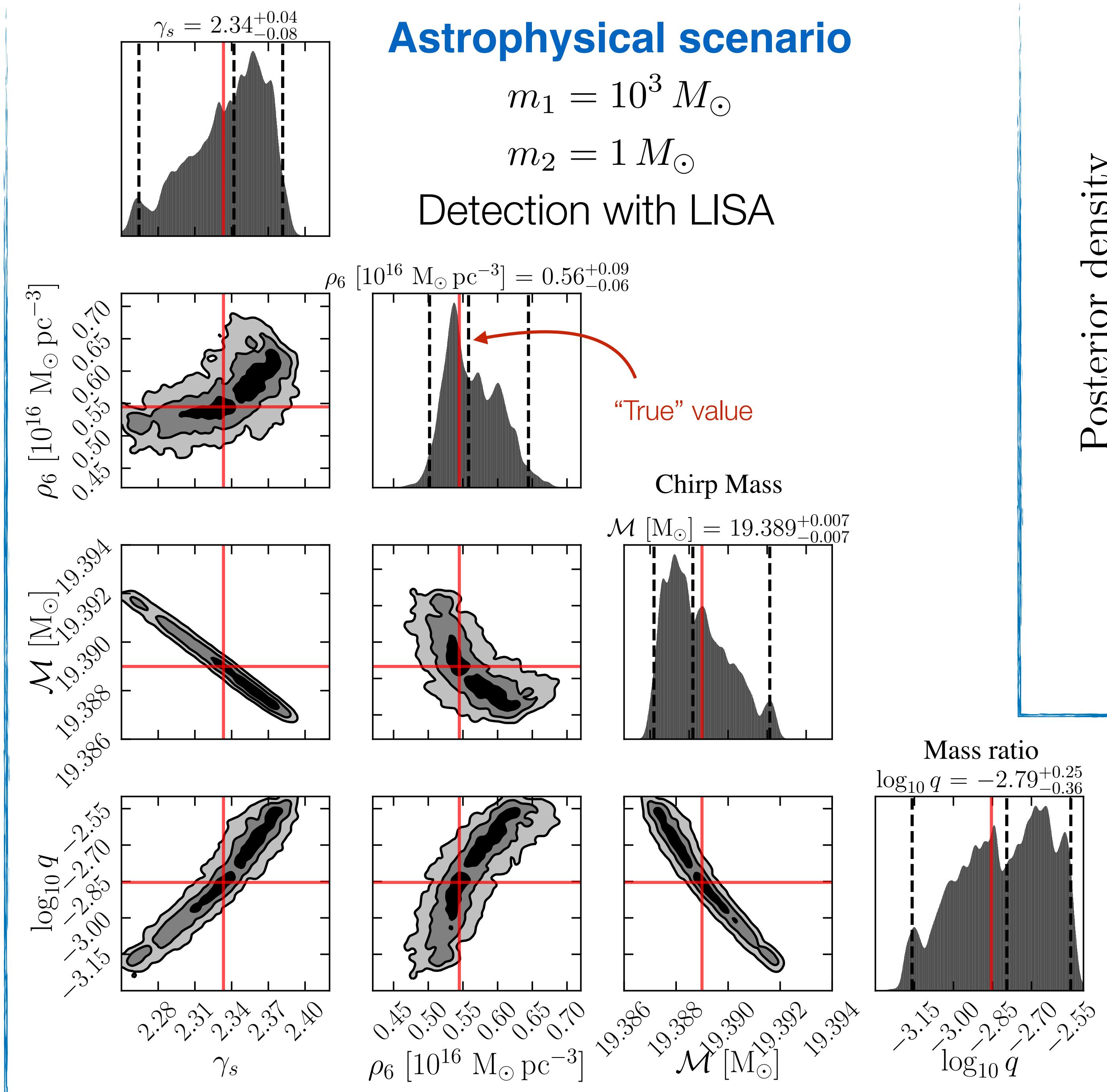
vs.

$$\theta_D = \{\gamma_{\text{sp}}, \rho_6, \mathcal{M}, \log_{10} q\}$$

Number of GW cycles of dephasing

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

# Measurability



[Cole, Coogan, **BJK**, Bertone, [2207.07576](#)]

[Coogan, Bertone, Gaggero, **BJK** & Nichols, [2108.04154](#)]

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

# GW Probes of Dark Matter

