Dark Matter on all scales

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

IFIC Colloquium, 23rd January 2025

- *What is the evidence for Dark Matter?*
- *What is it? What are its properties?*
- *How can we uncover its identity?*

iFCA

DE LO MÁS PEQUEÑO A LO MÁS GRANDE

Instituto de Física de Cantabria CSIC UC

Dark Matt

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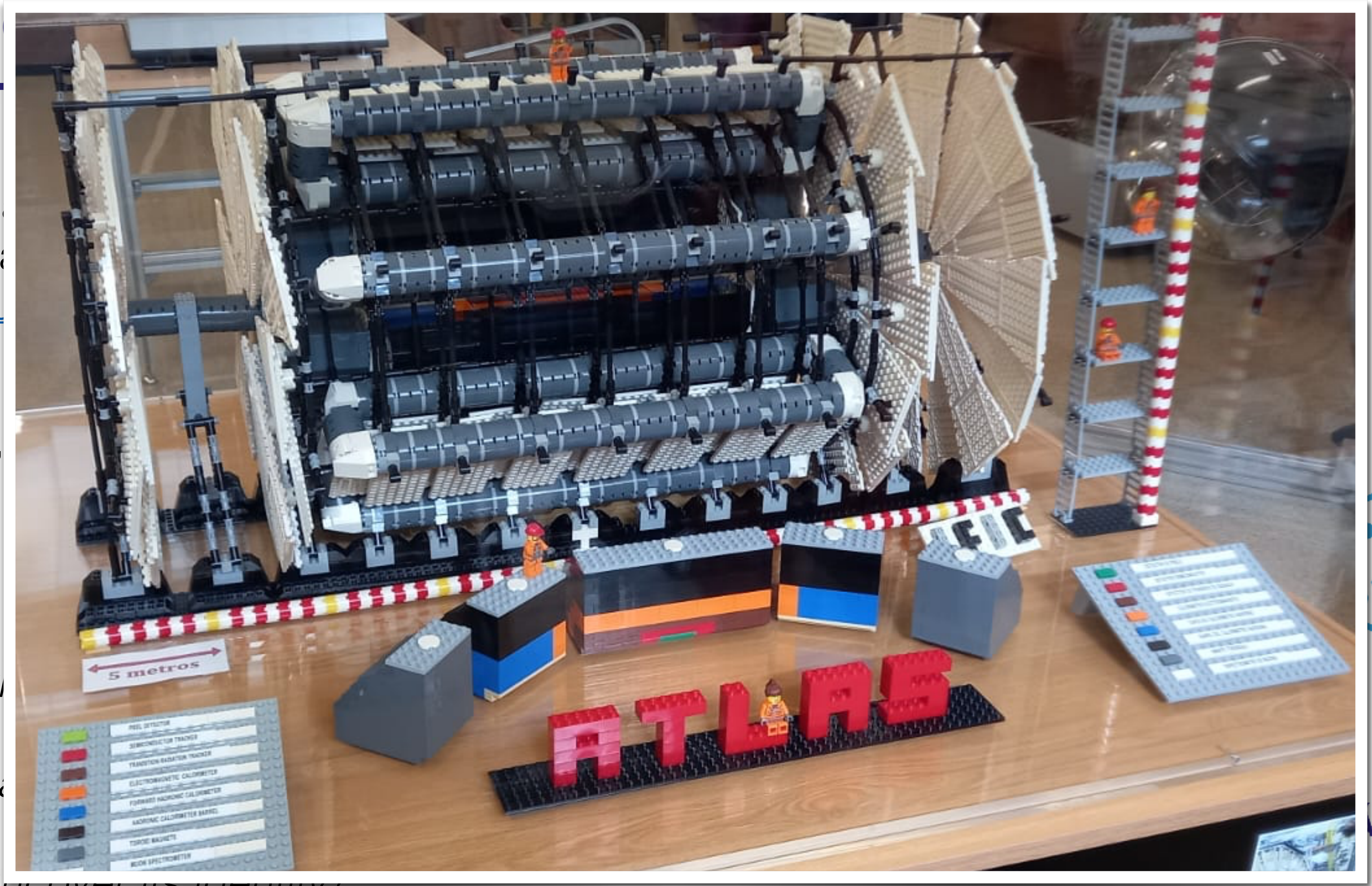
IFIC Colloquium,



- *What is the ev*
- *What is it? Wh*
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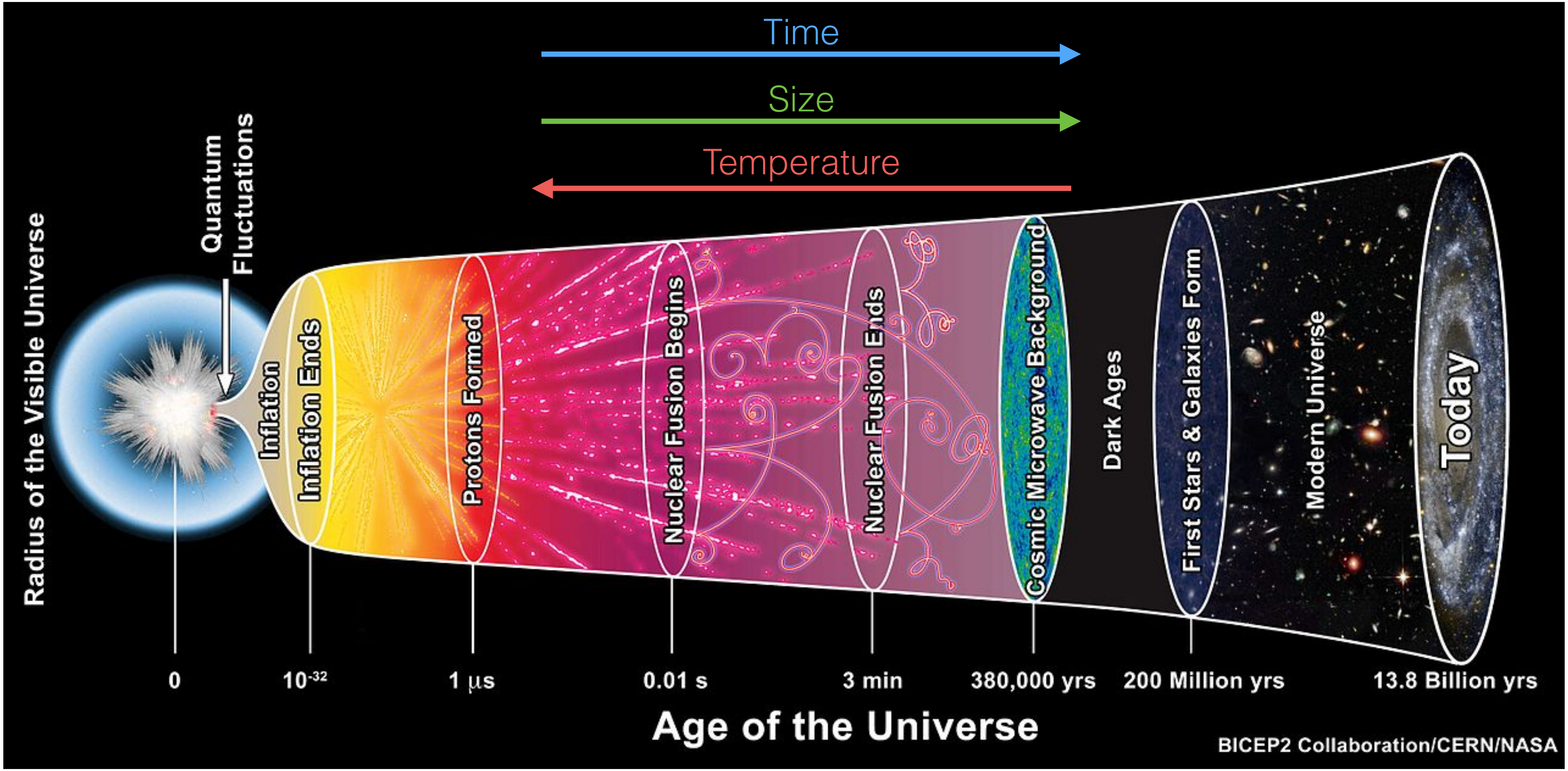
DE LO MÁS PEQUEÑO A LO MÁS GRANDE

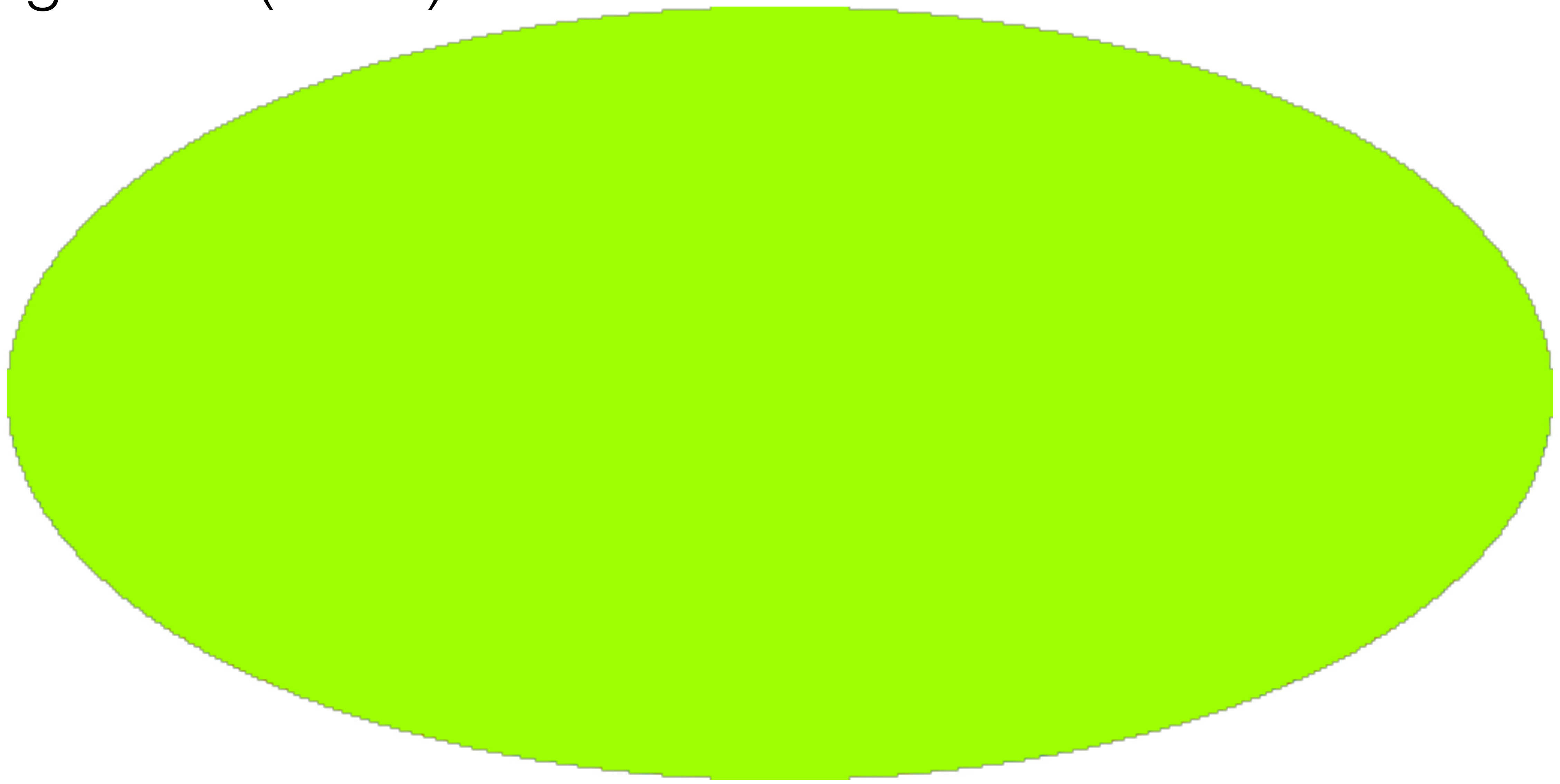
Everything, Everywhere, All at Once



Dark Matter in Cosmology

Cosmic Microwave
Background (CMB)

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



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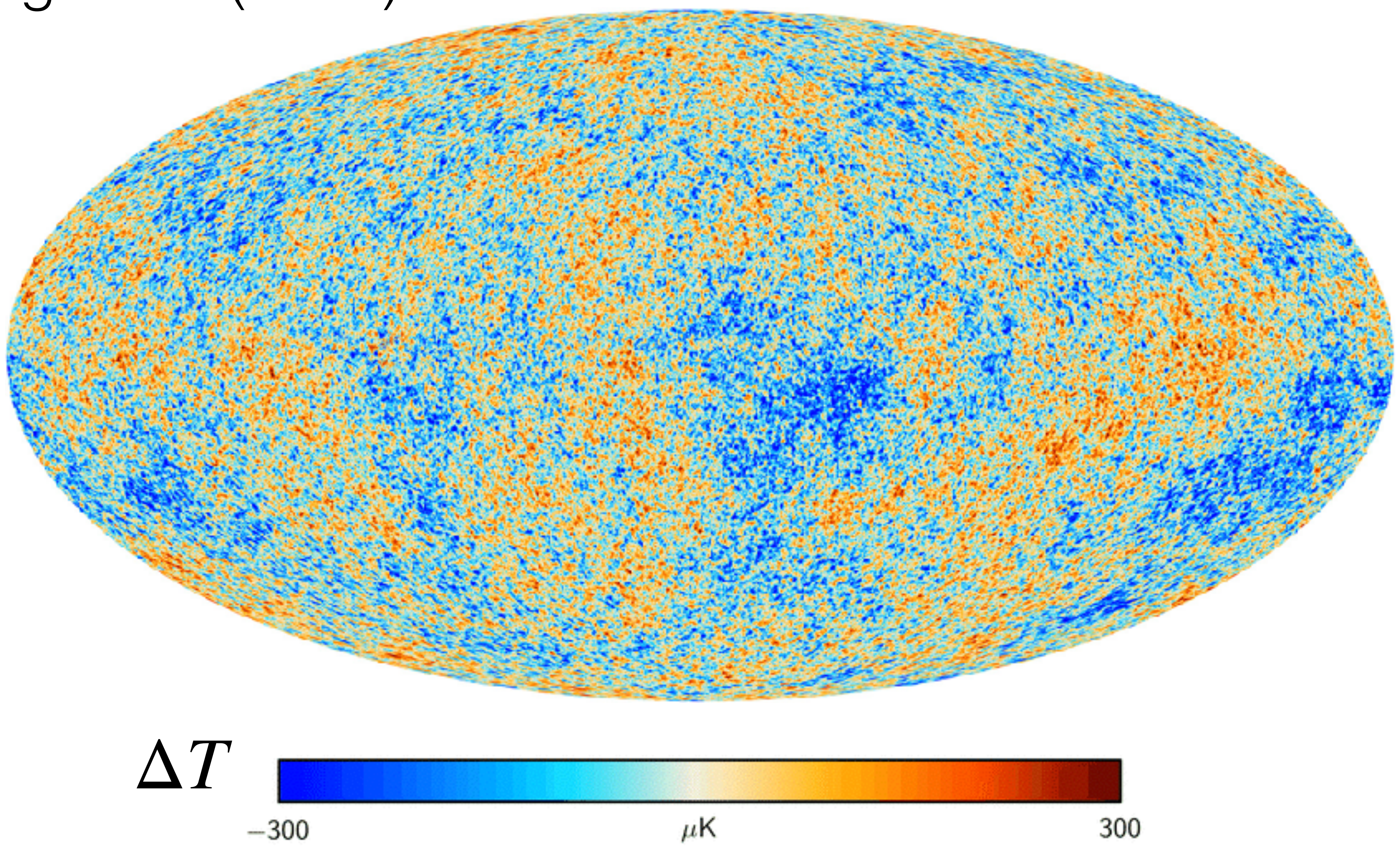

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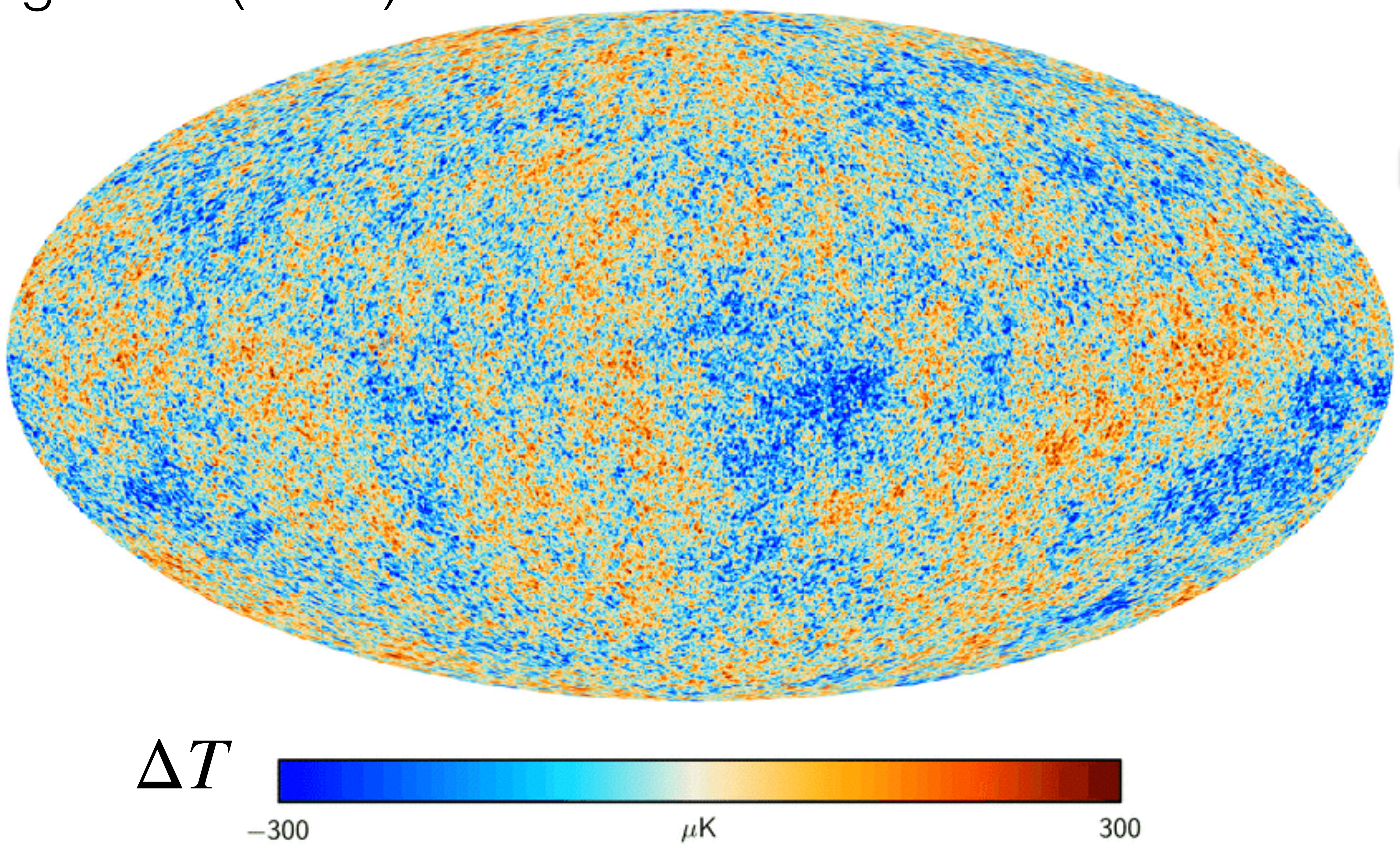

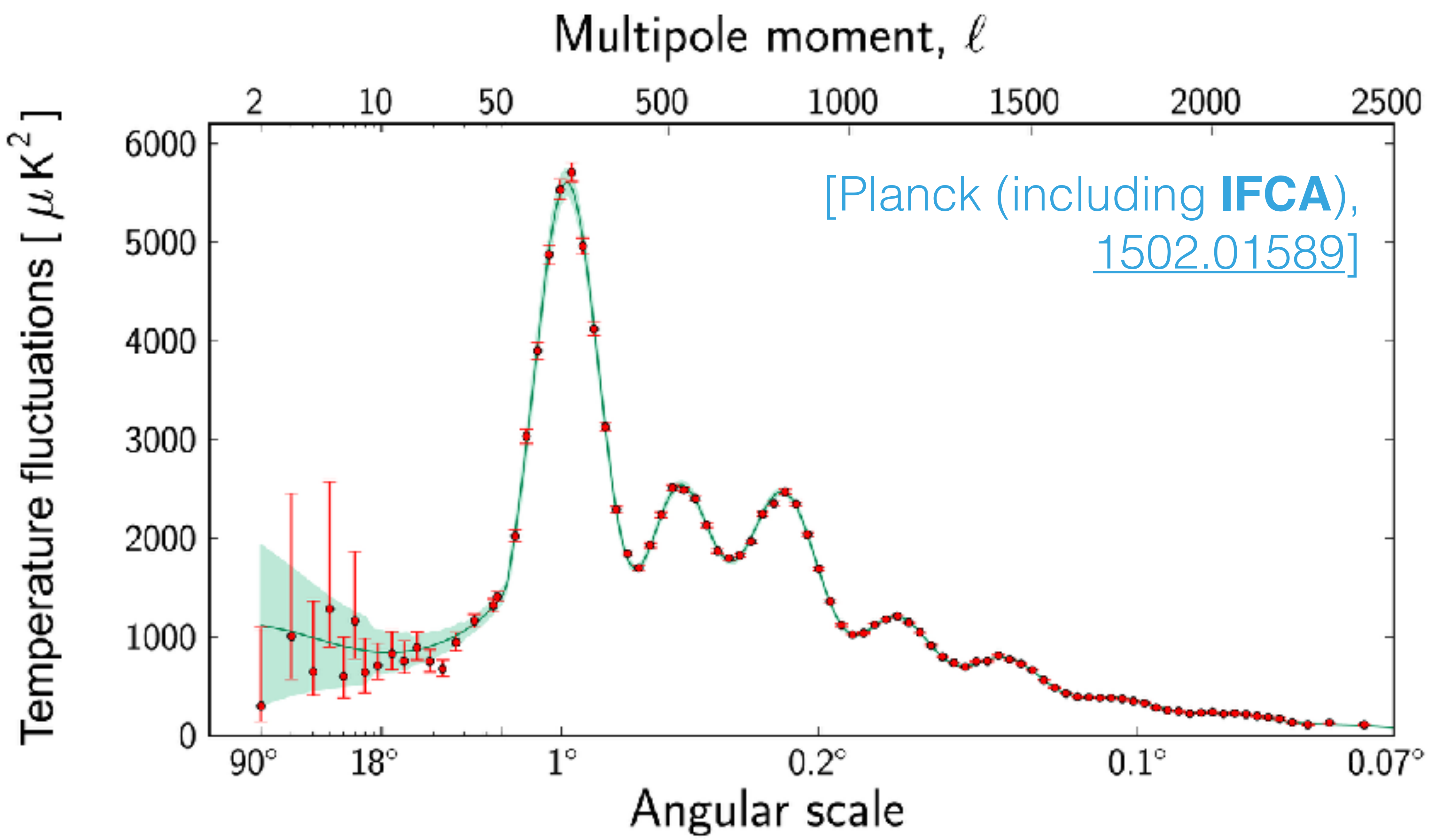

[Planck (including **IFCA**), 1502.01589]

Dark Matter in Cosmology

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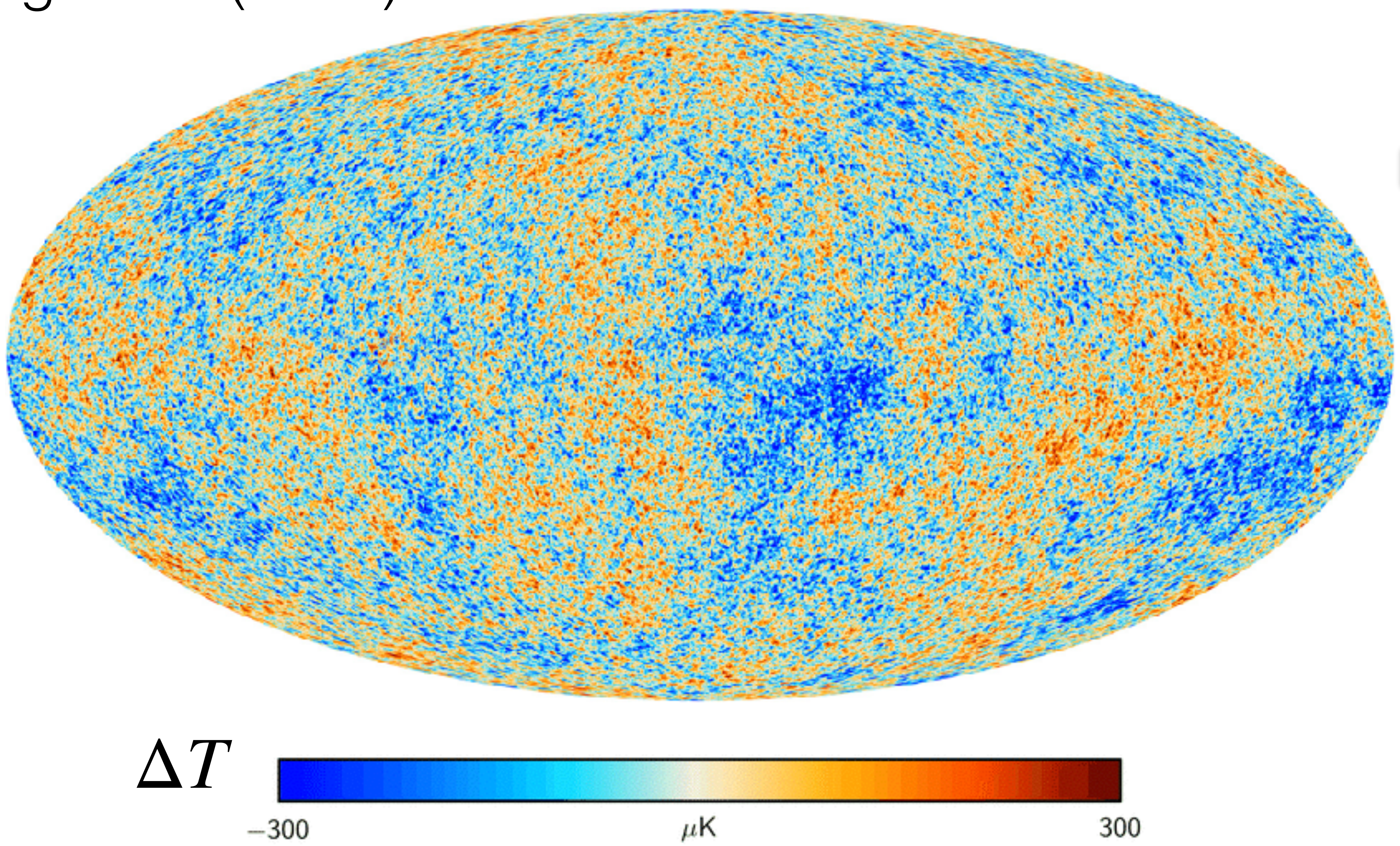
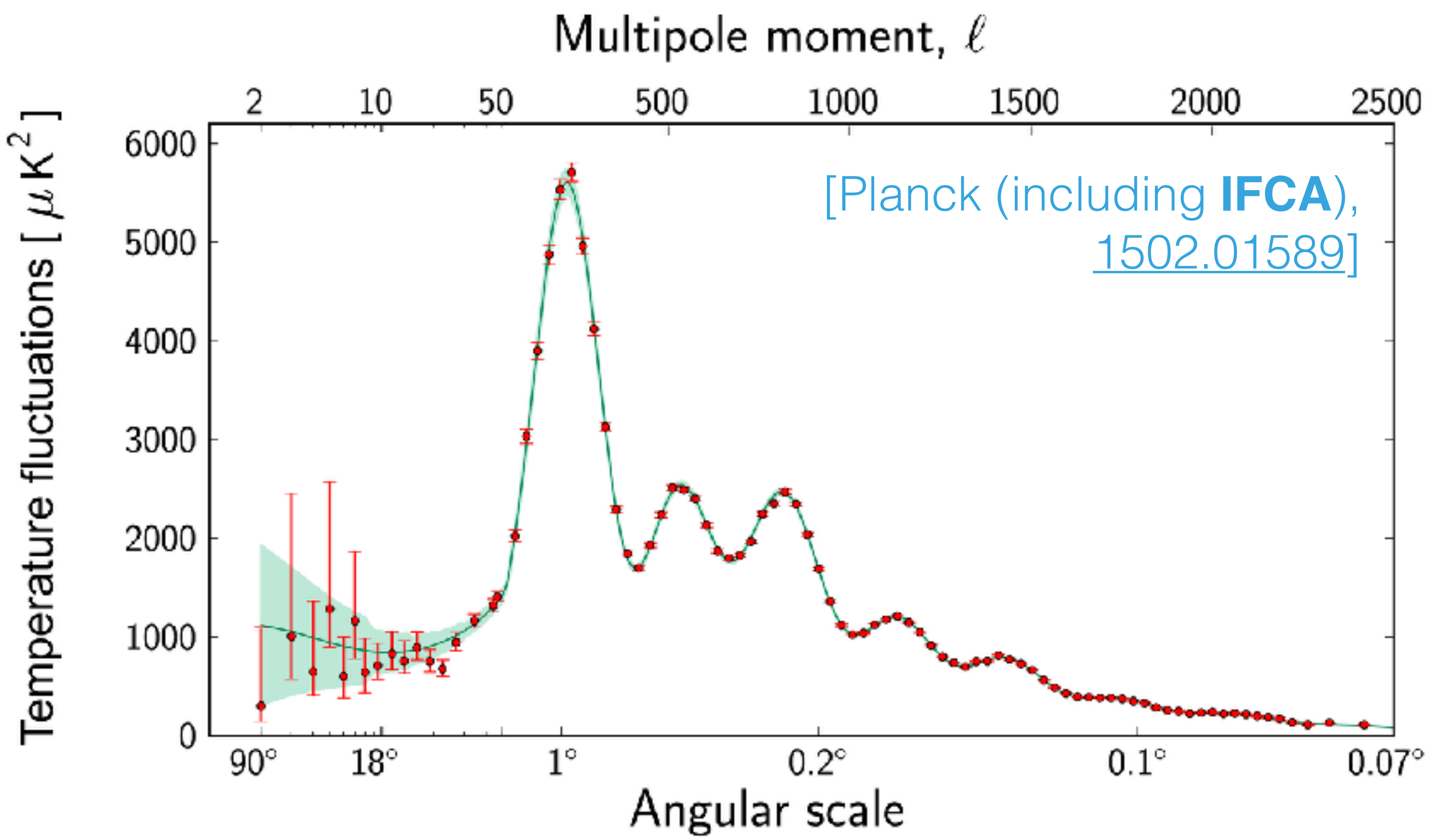
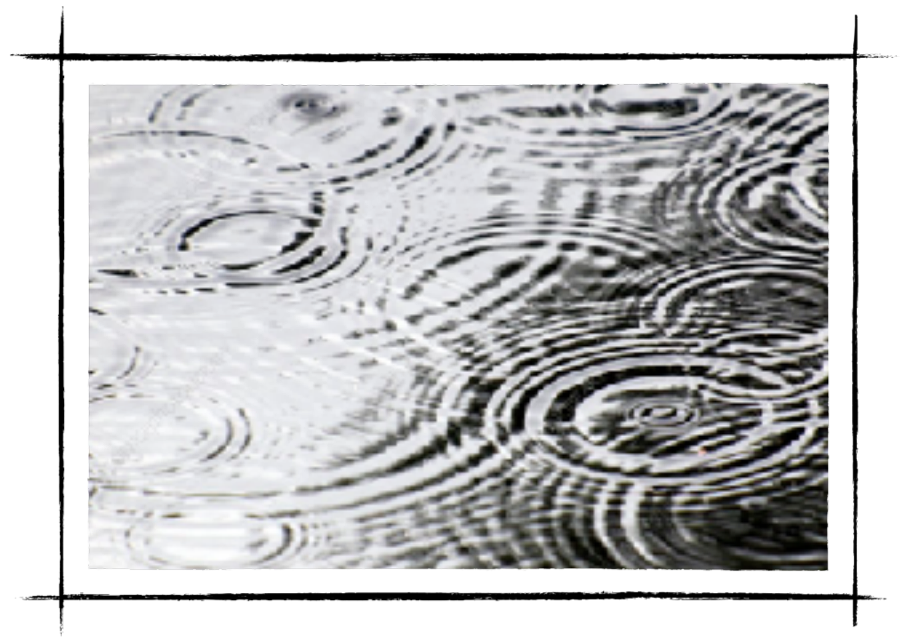
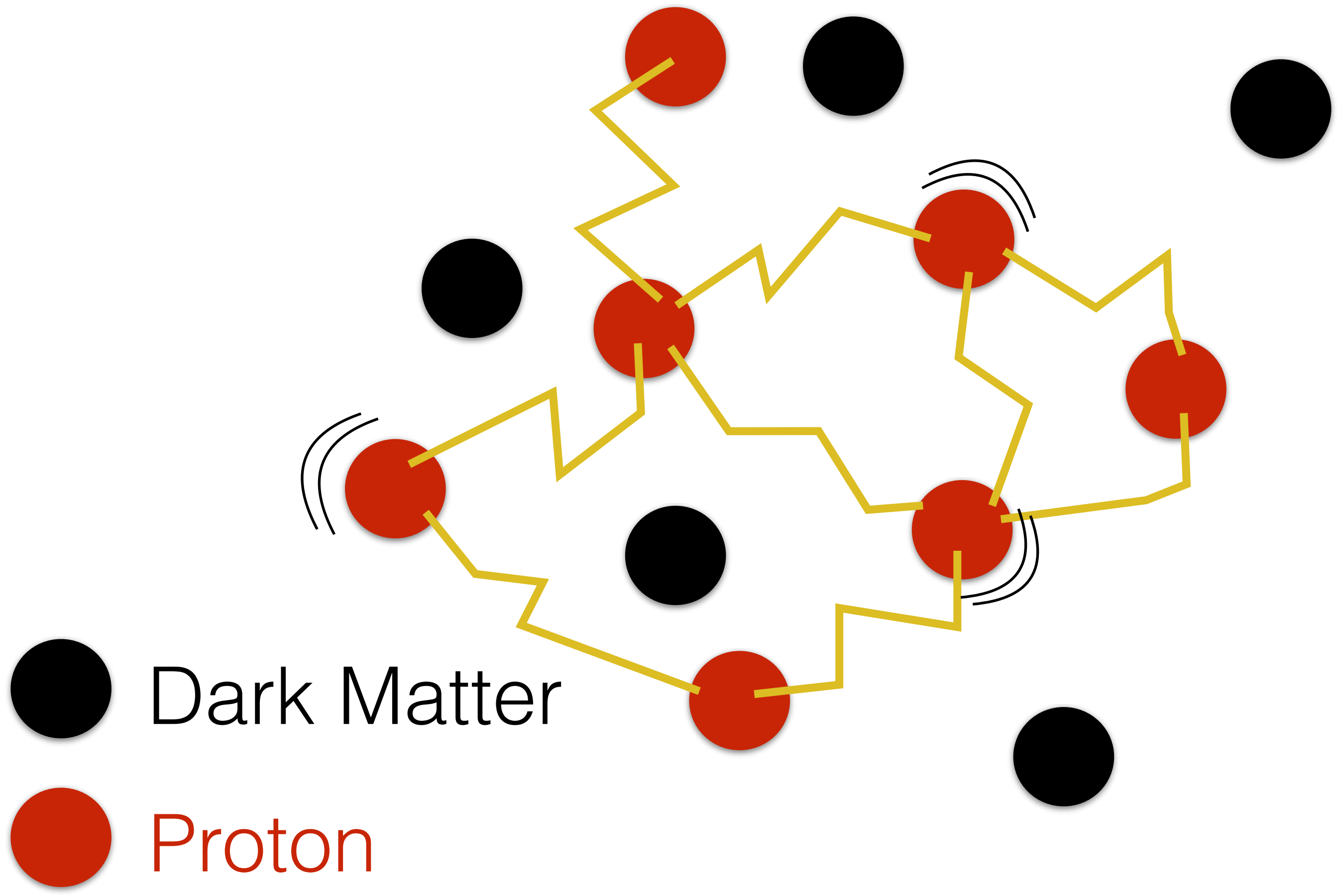




[Planck (including **IFCA**), 1502.01589]





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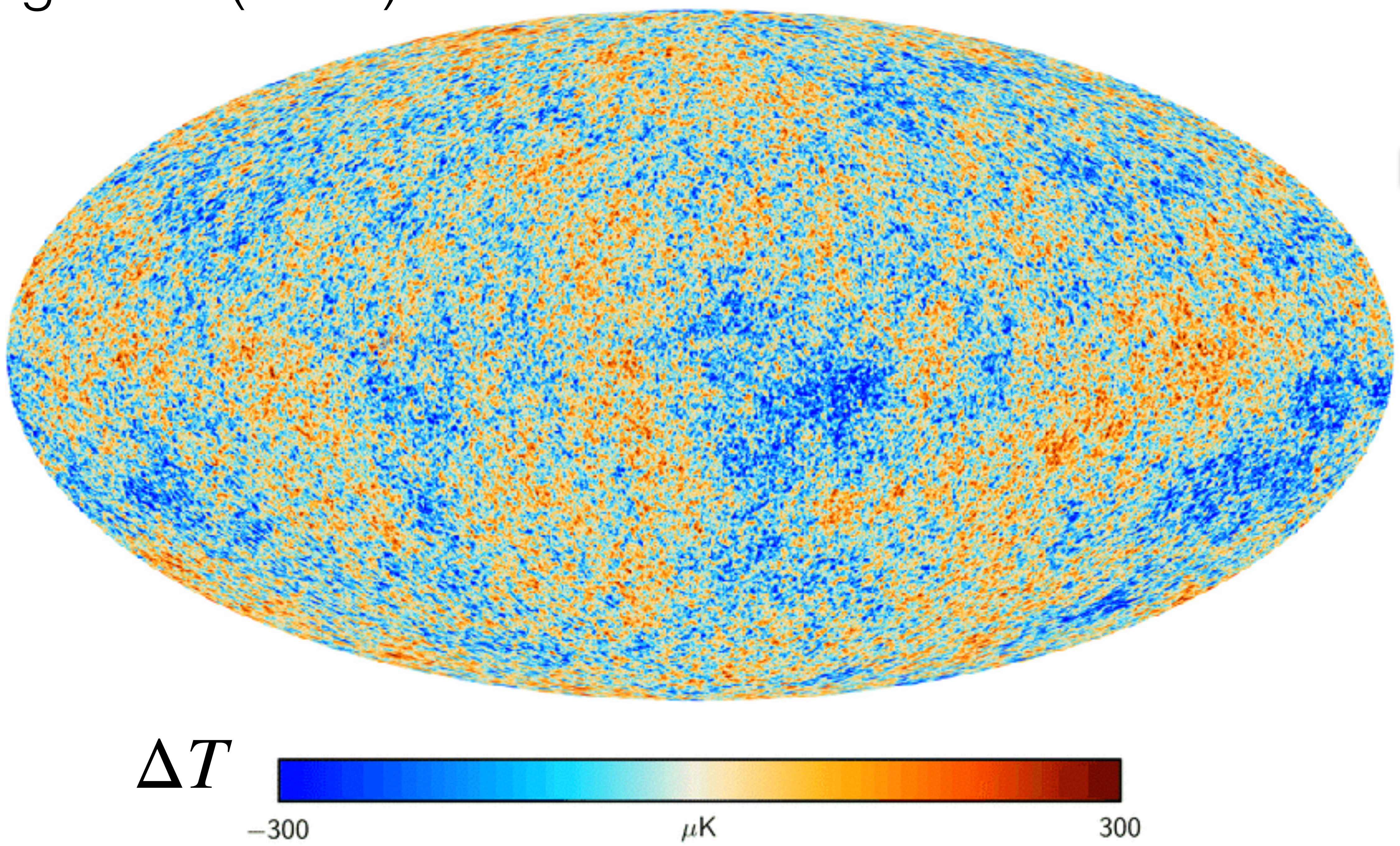
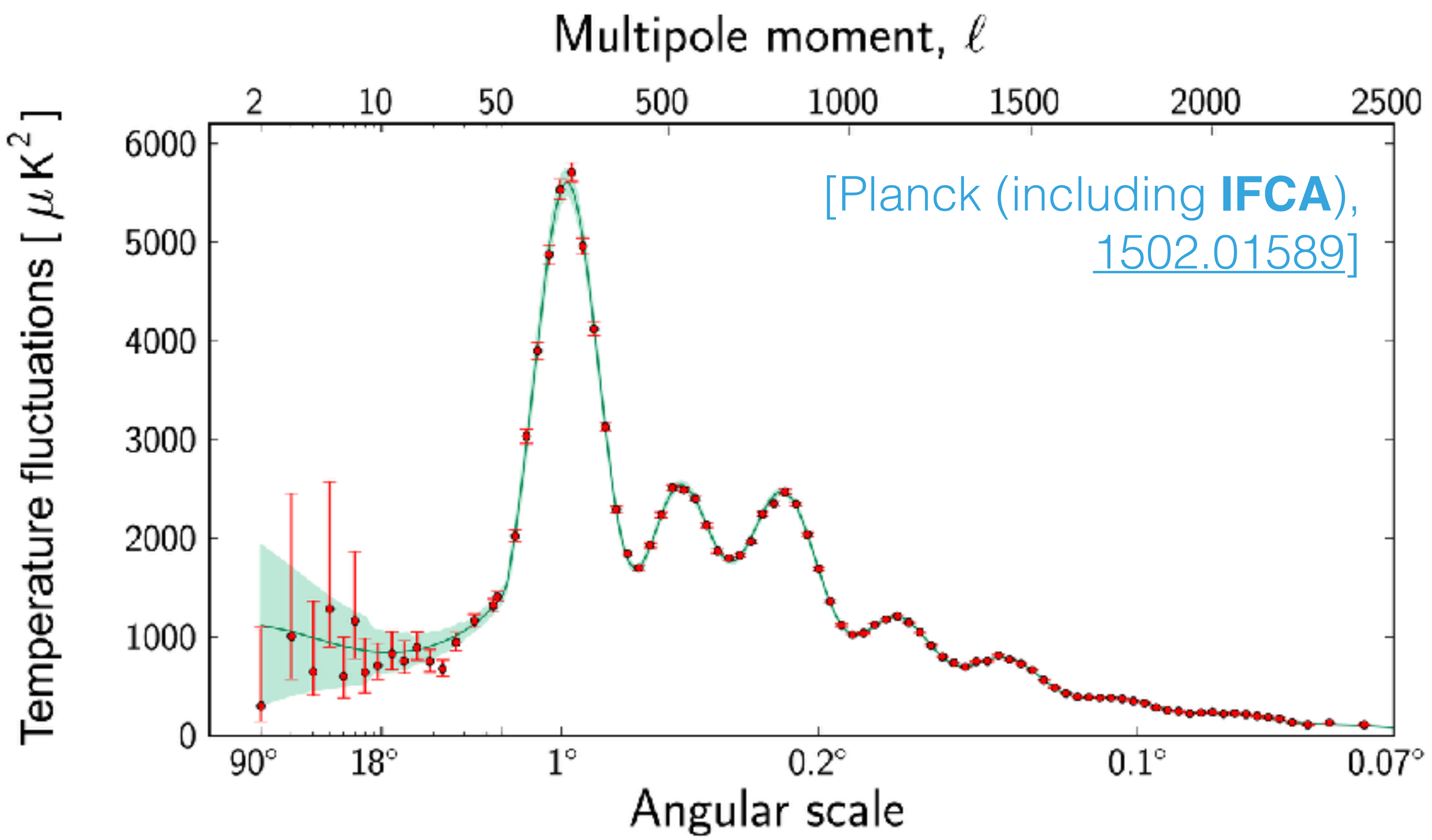
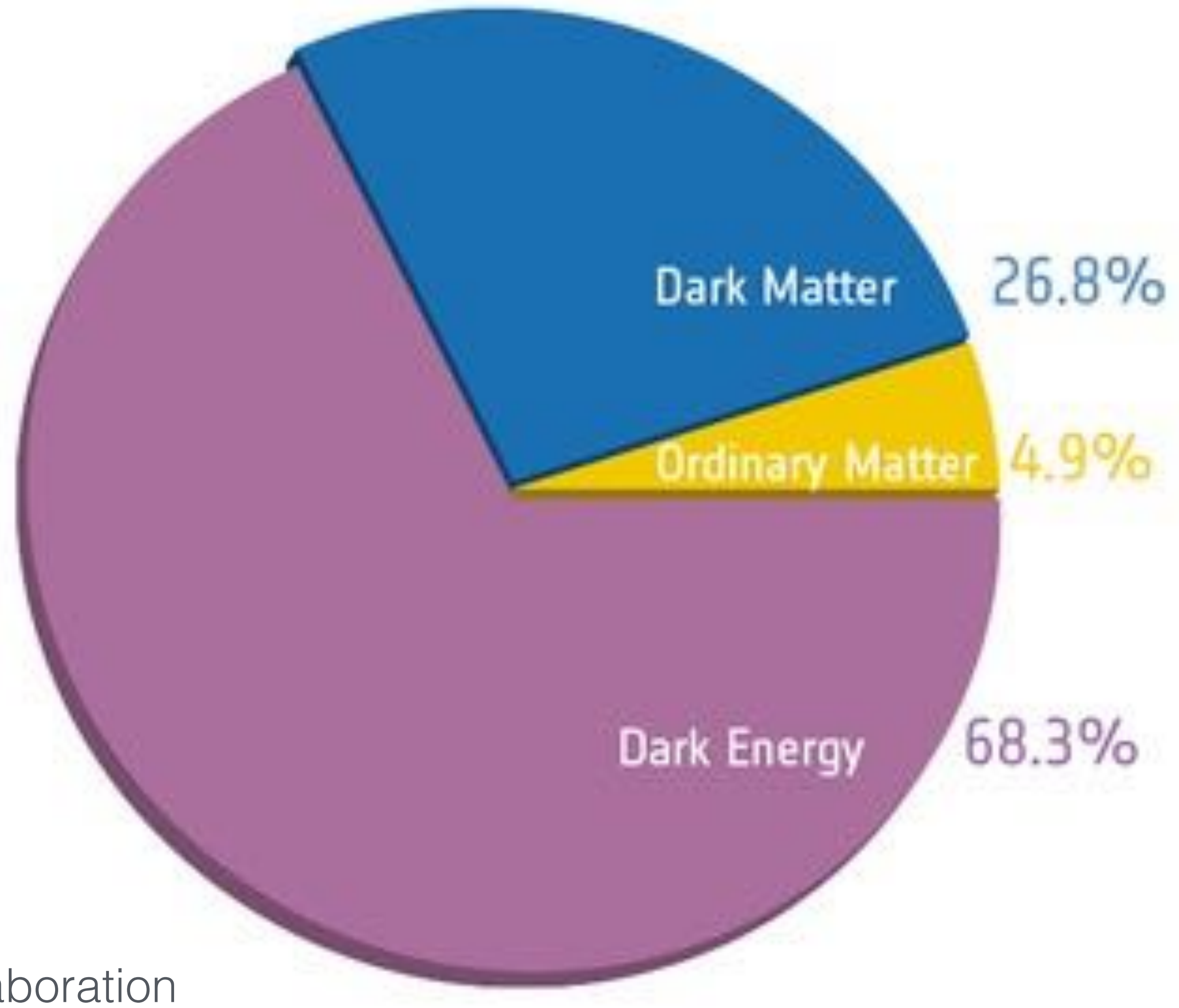
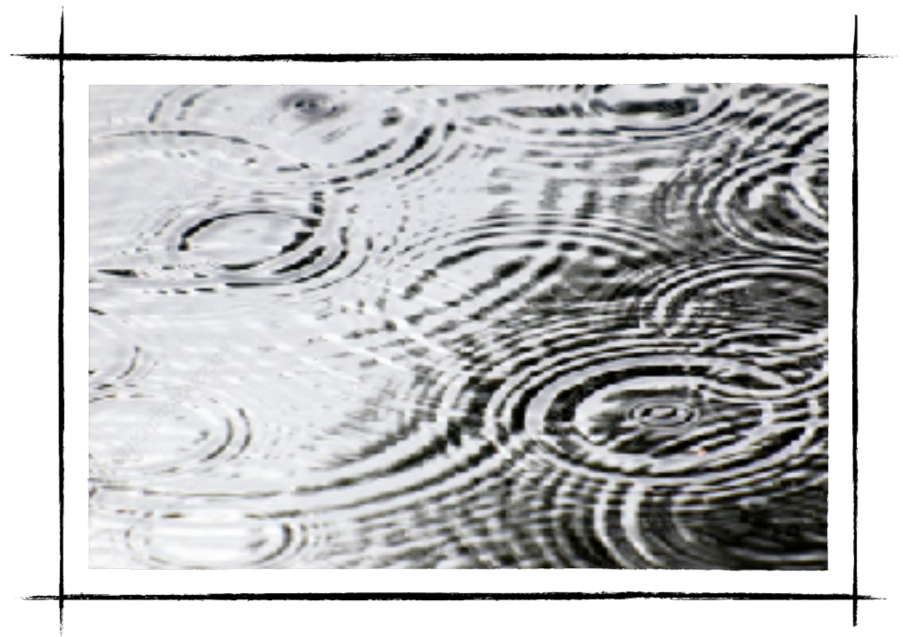
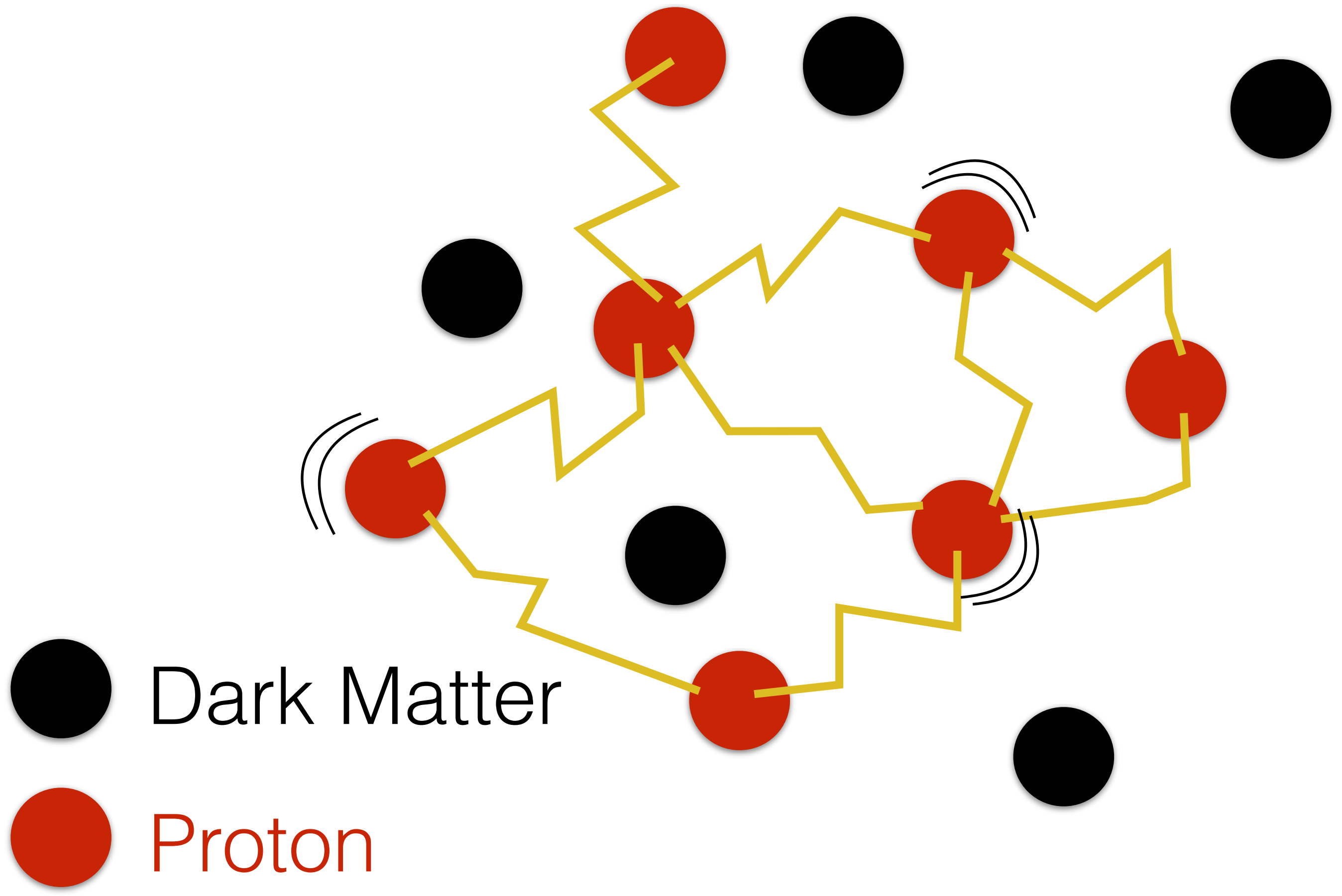




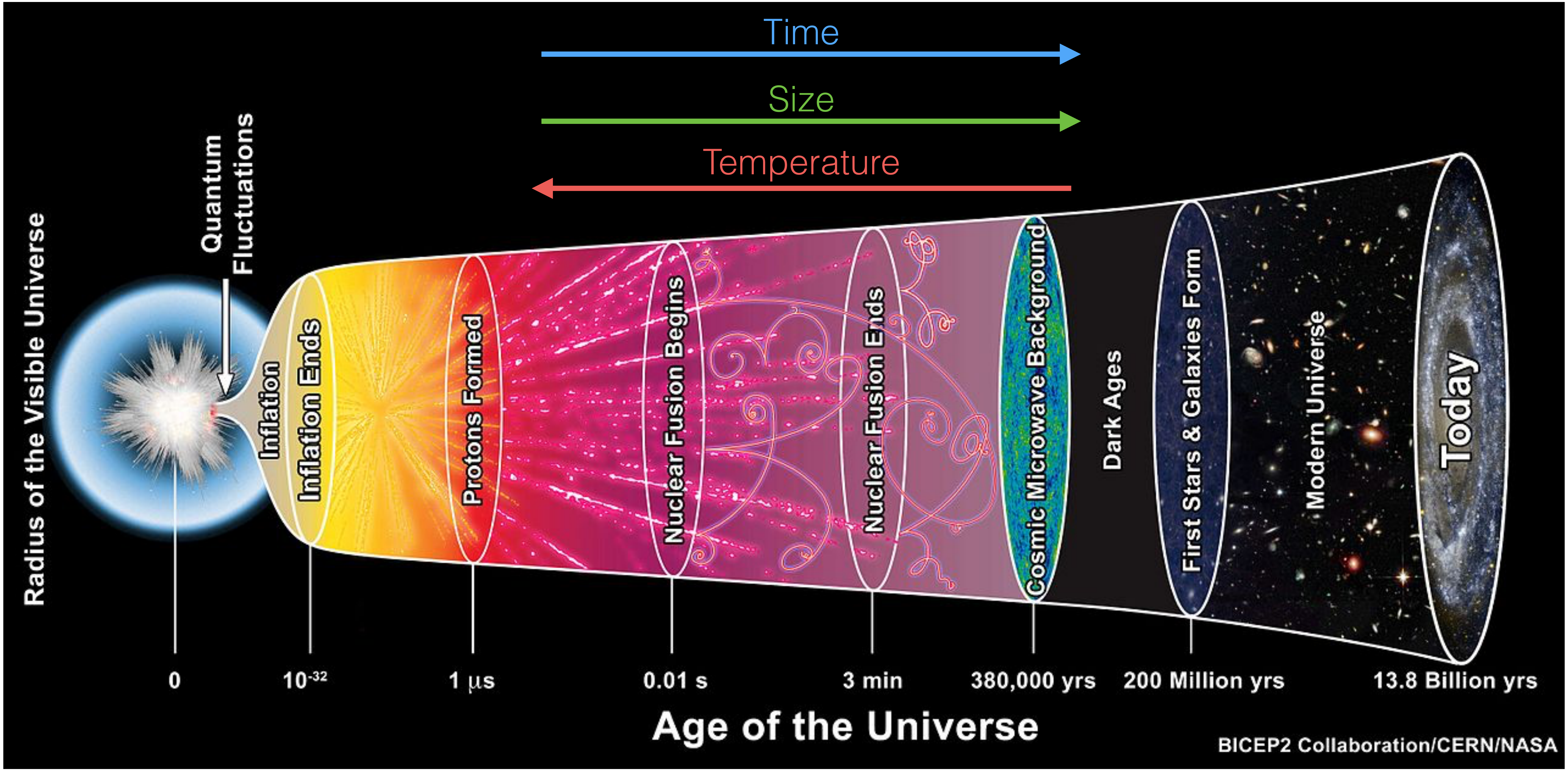






Credit: ESA/Planck Collaboration

Everything, Everywhere, All at Once



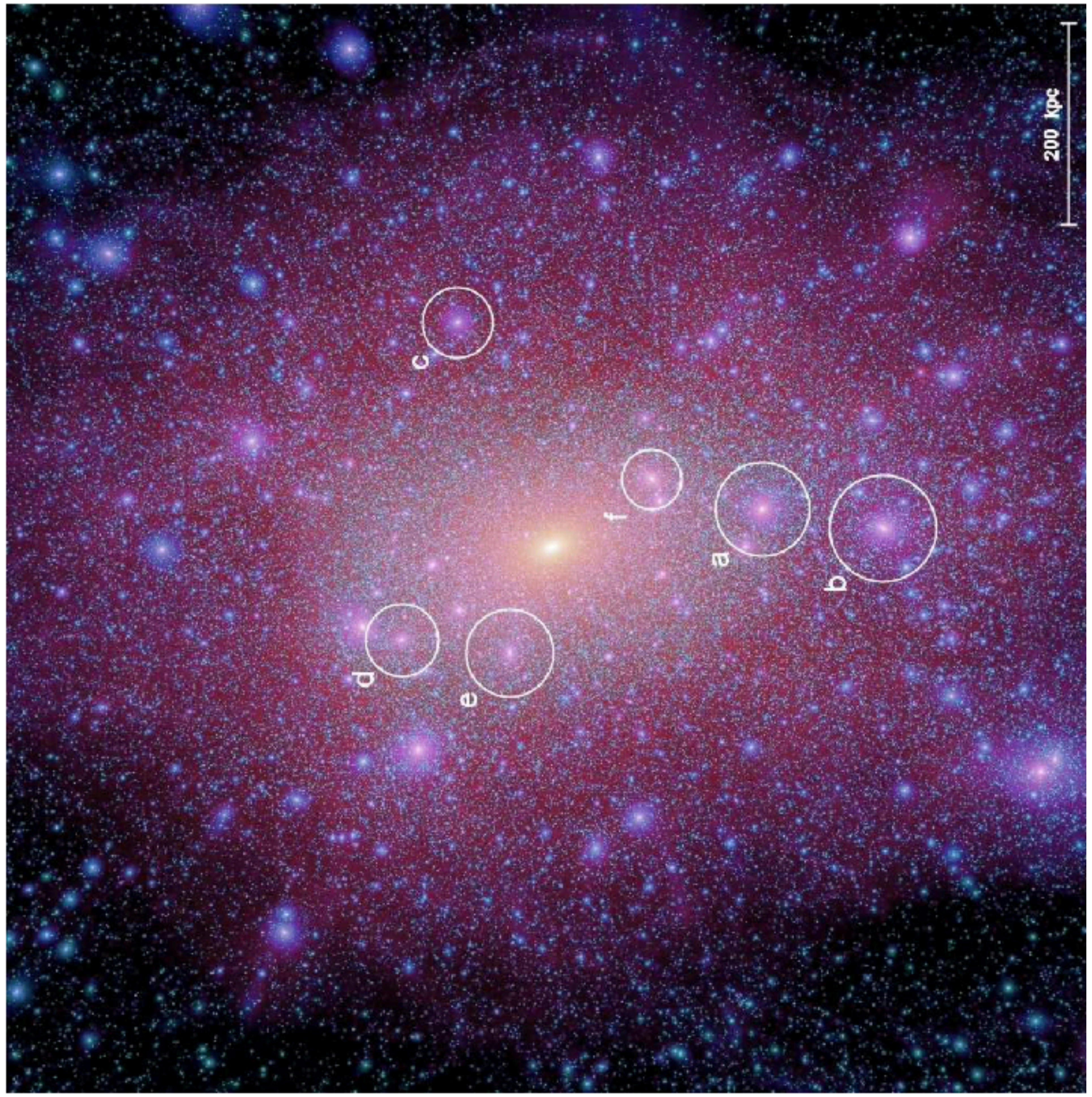

Universiteit Leiden
Durham
University
The EAGLE simulation
icc.dur.ac.uk/Eagle
t_{age} = 0.5 Gyr
Redshift = 10.11
www.smcalpine.com

Universiteit Leiden
Durham University
THE EAGLE SIMULATION
icc.dur.ac.uk/Eagle
t_{age} = 1.1 Gyr
Redshift = 5.24
www.smcalpine.com

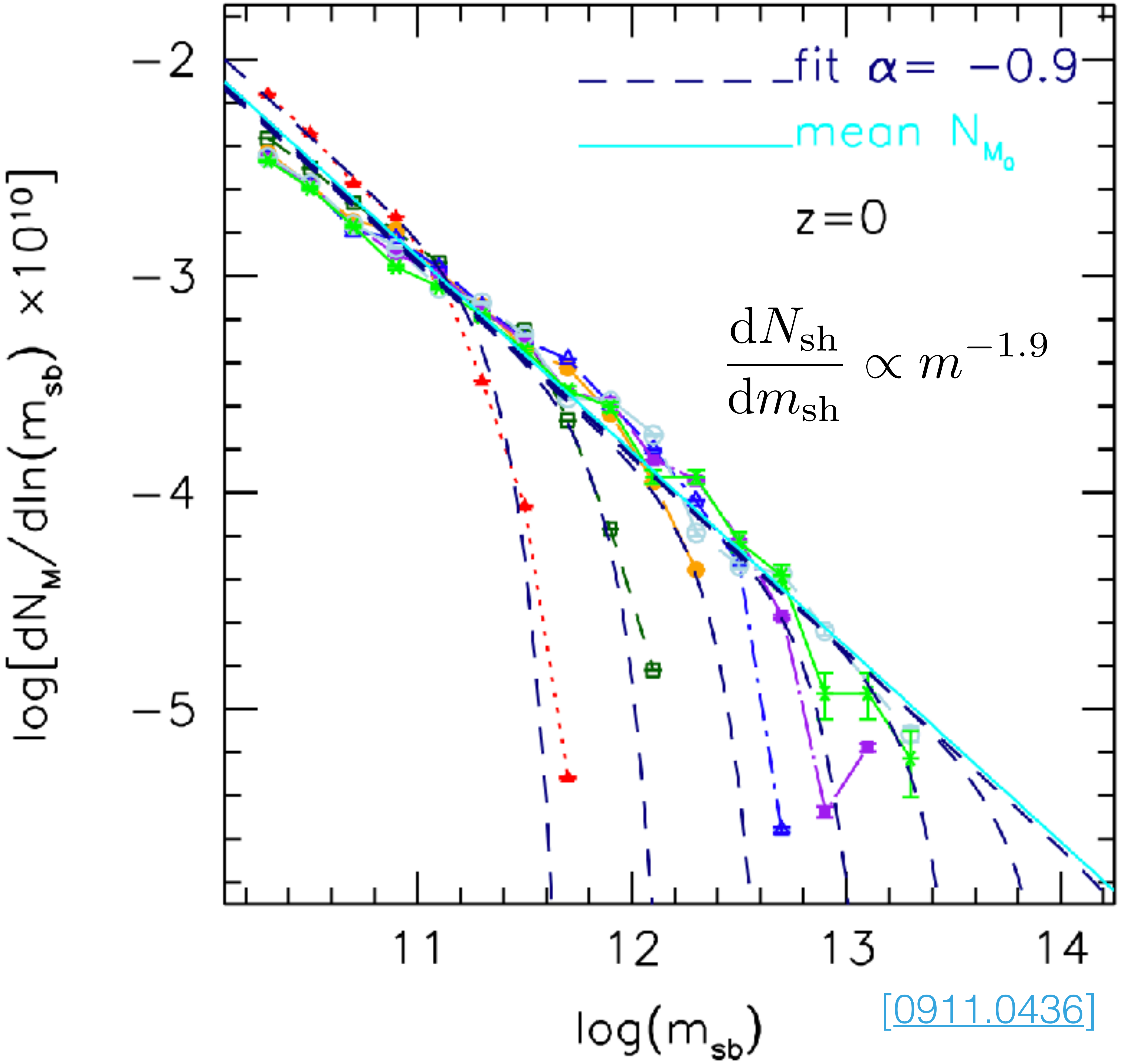

Universiteit Leiden
Durham University
THE EAGLE SIMULATION
icc.dur.ac.uk/Eagle
t_{age} = 1.7 Gyr
Redshift = 3.73
www.smcalpine.com

Hierarchical Substructure

Structure formation proceeds **'bottom-up'**: small sub-halos assemble hierarchically to form larger halos, which host galaxy clusters, galaxies and dwarf galaxies!



[Aquarius simulation - 0809.0898]



[0911.0436]

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.

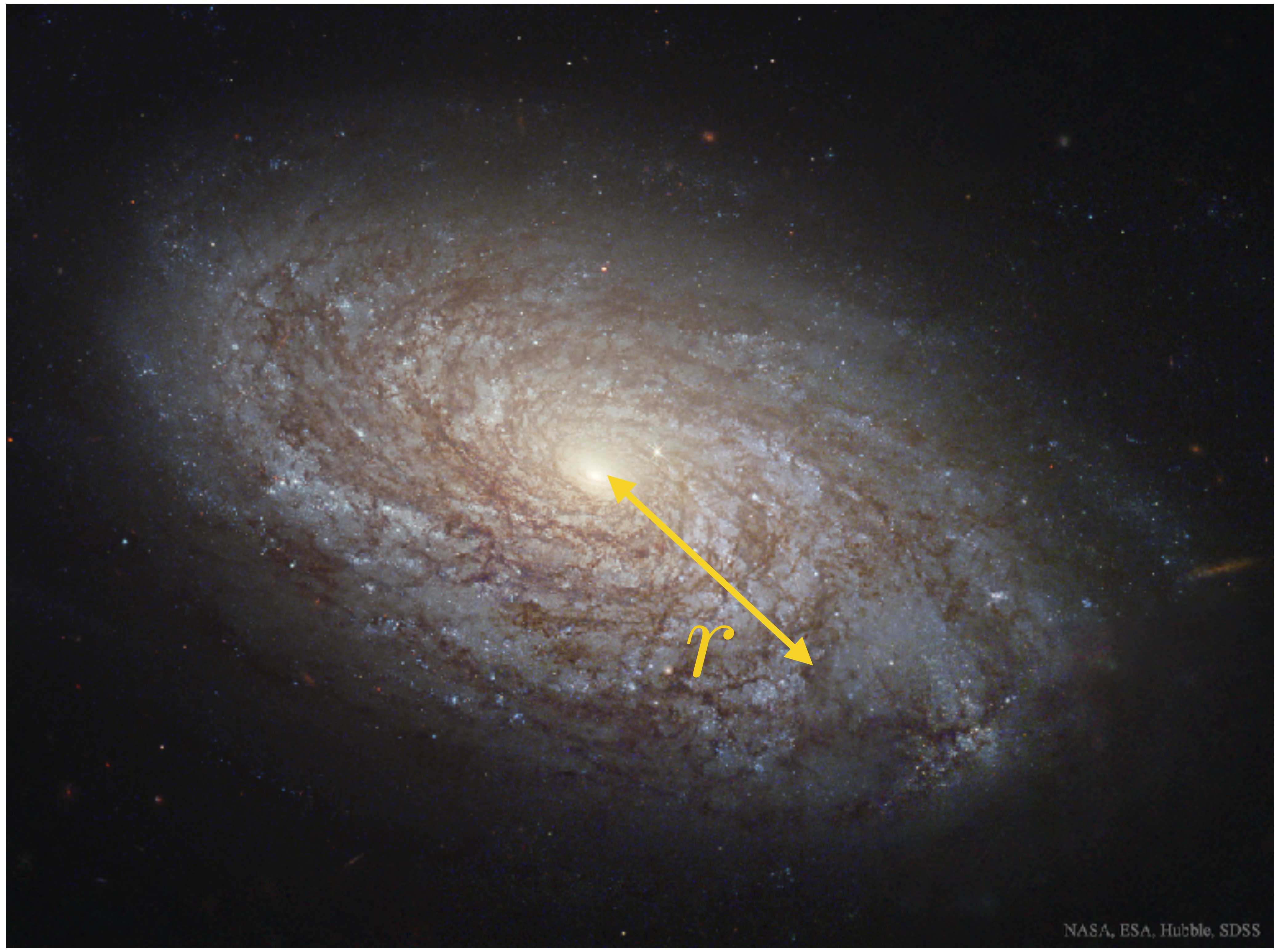
[IllustrisTNG simulation - 2101.12373]

[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]

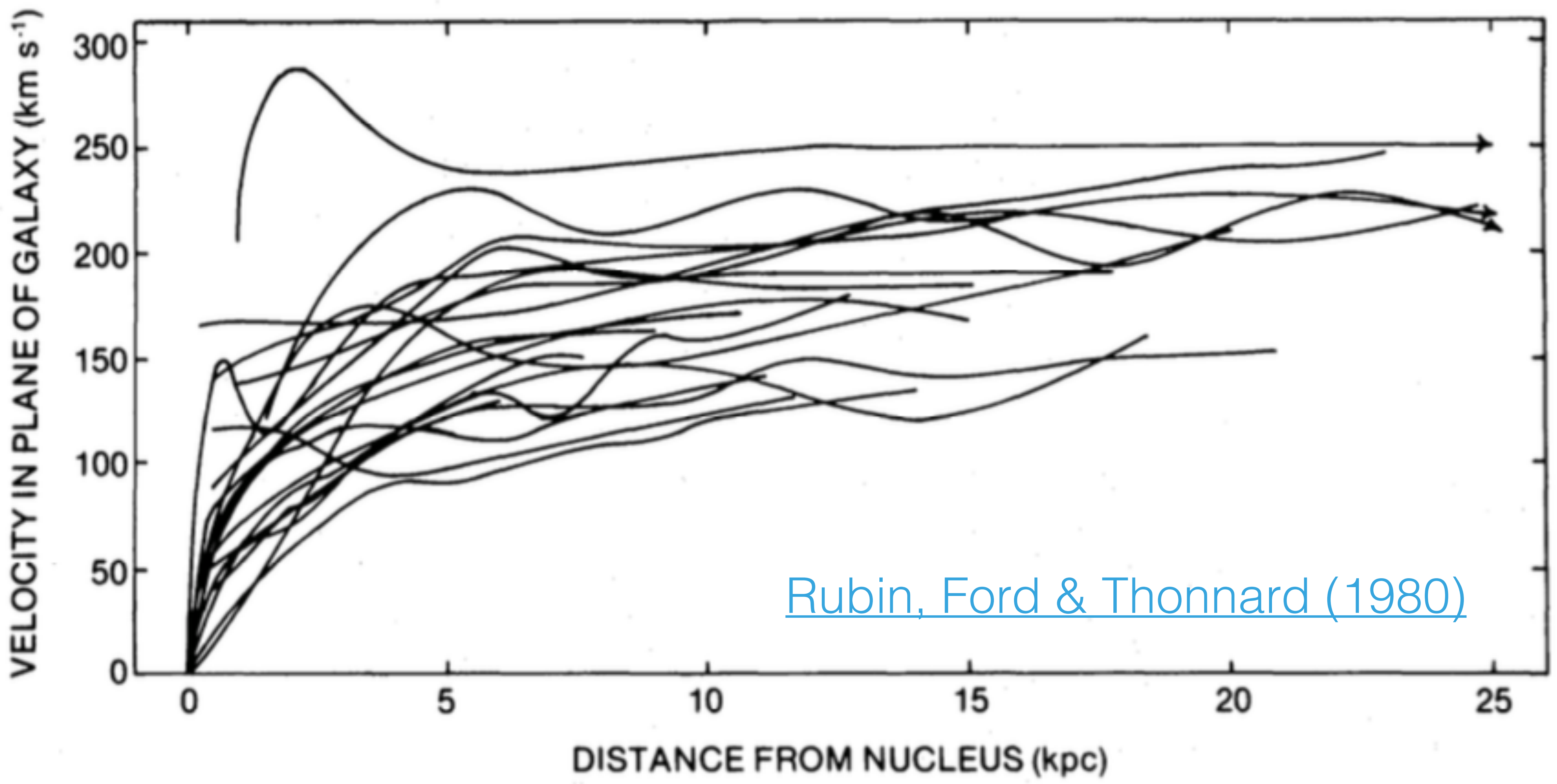
Dark Matter in Galaxies



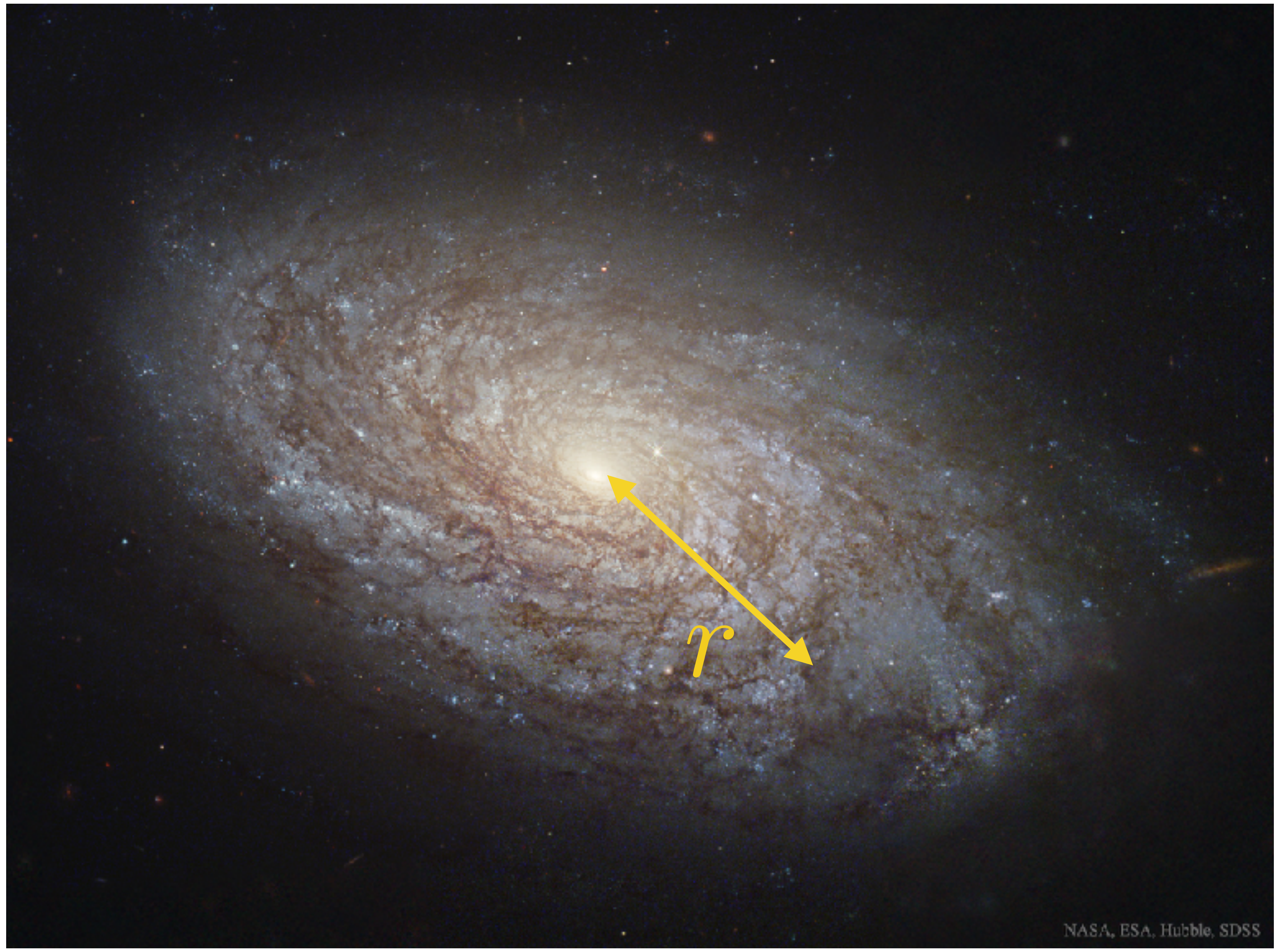
Rotational velocity $v_{rot}(r)$ of stars (and gas) in disk galaxies allows us to infer (in principle) the enclosed mass distribution.

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

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



Dark Matter in Galaxies



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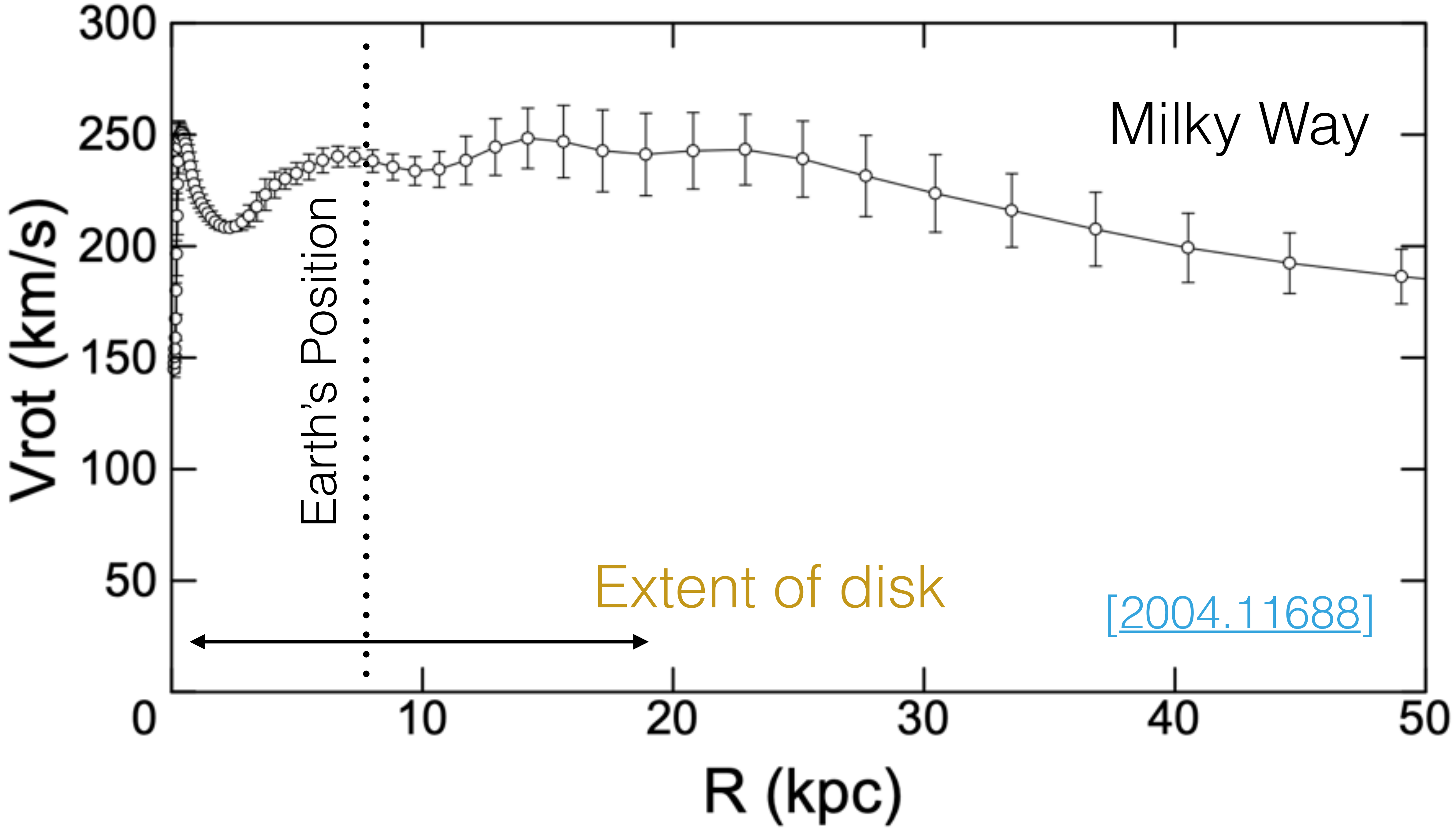


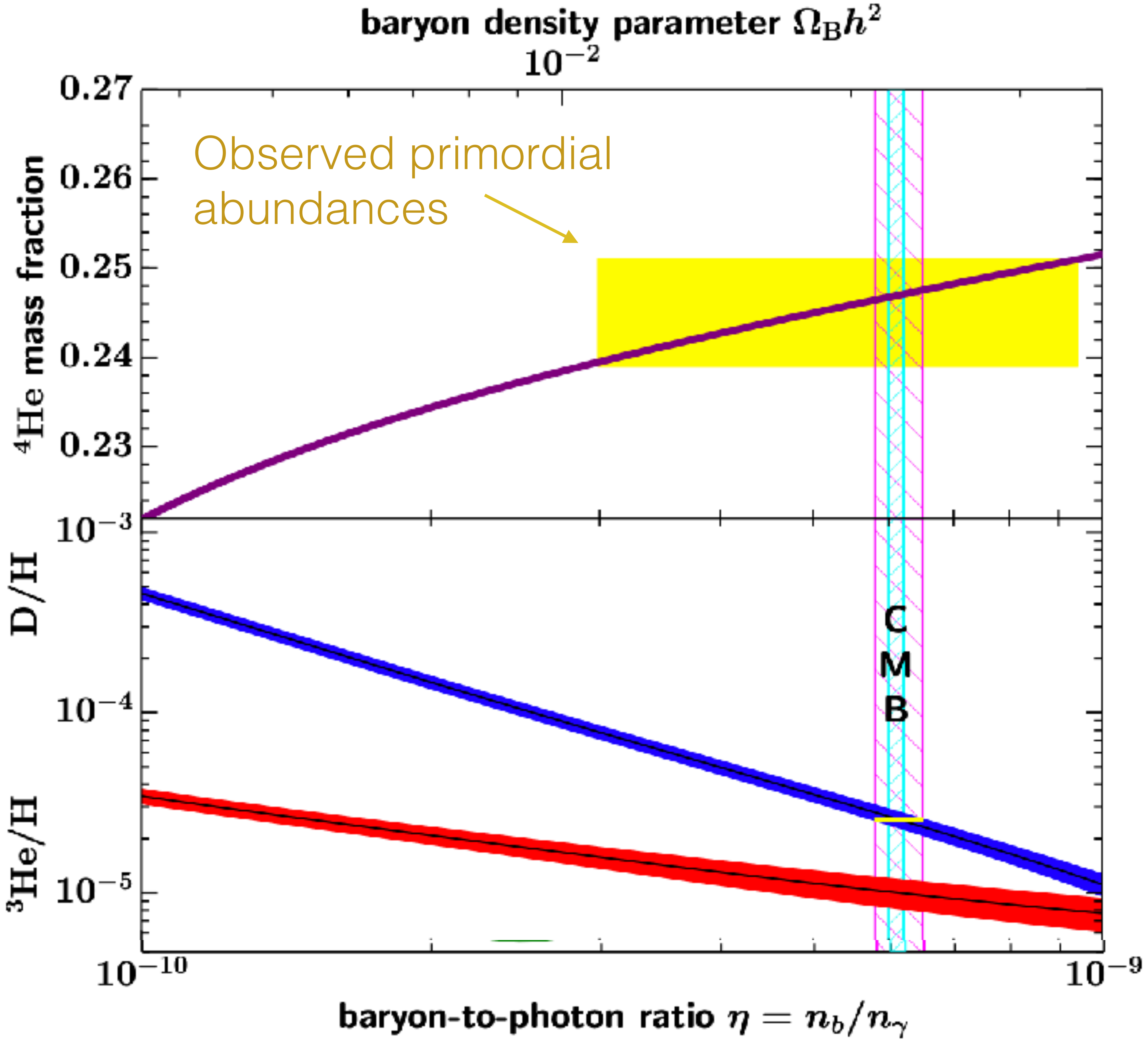
DM density at Earth:

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

[1404.1938]

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

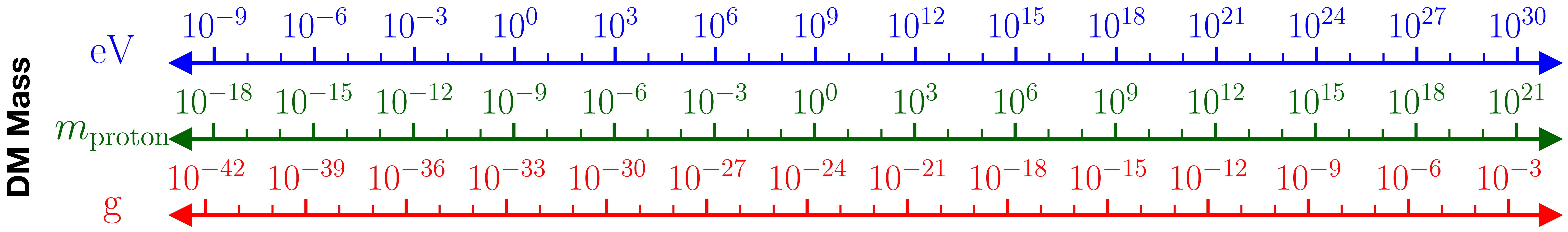
[0711.4996]

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



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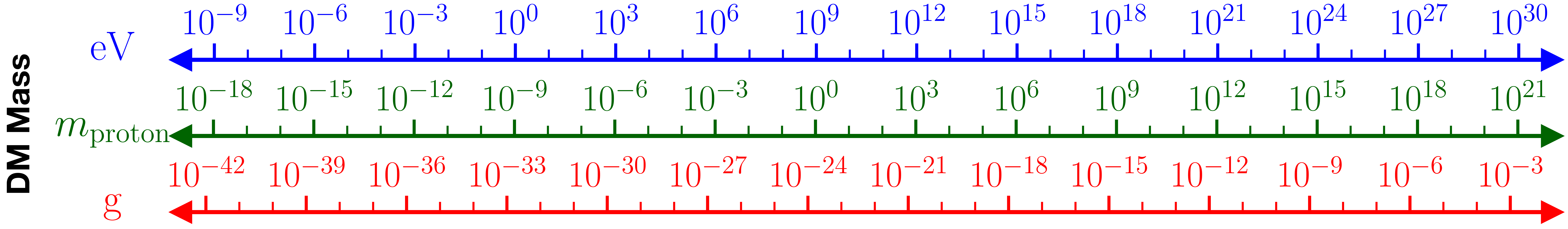
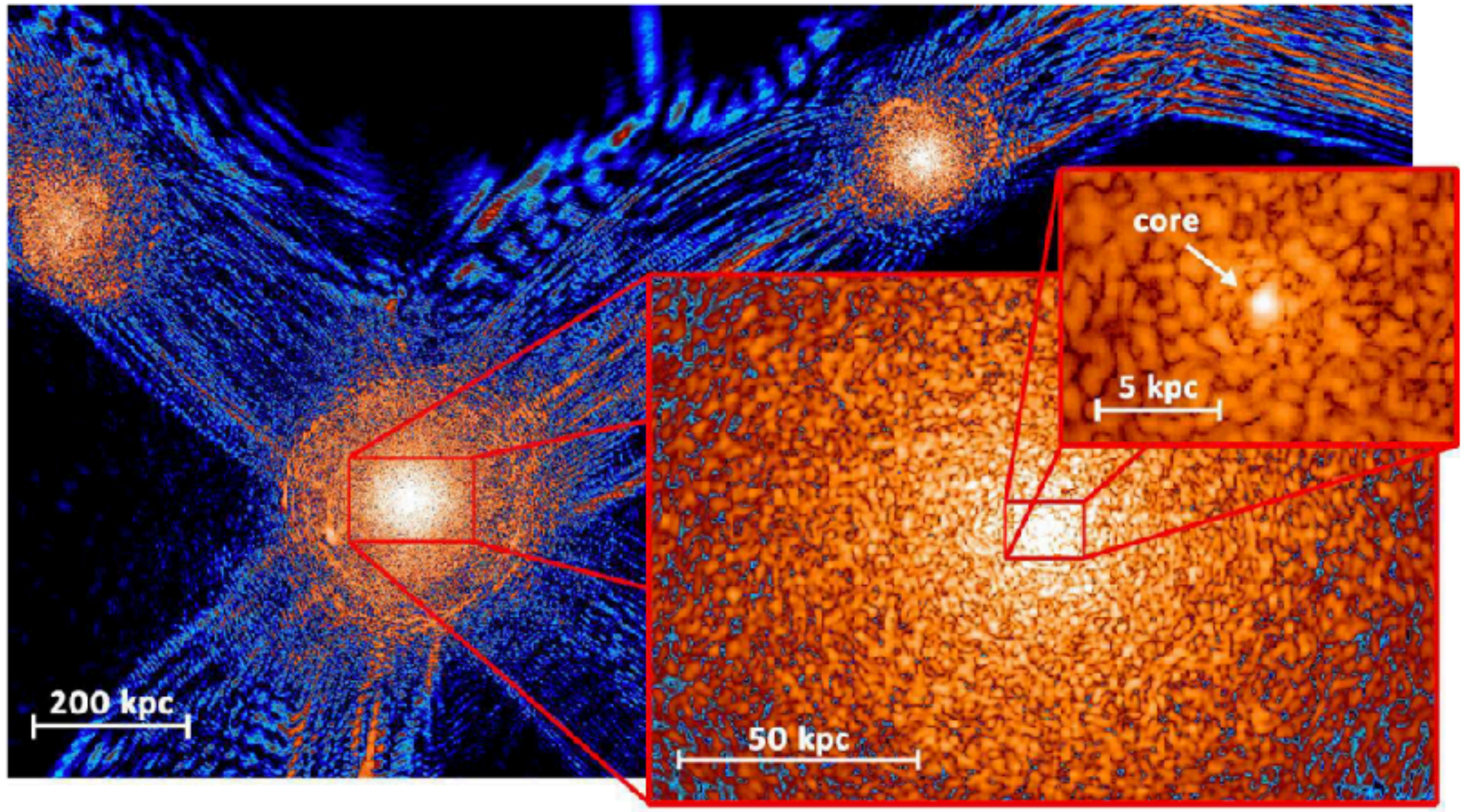
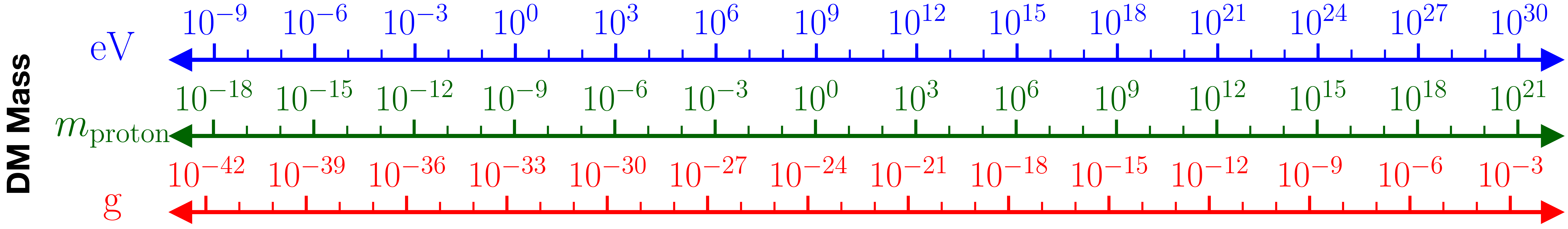


Very light DM ($\lesssim 10^{-22}\,\mathrm{eV}$)
has wave-like properties on
astrophysical scales,
spoiling galactic structure



[Schive et al (2014), 1406.6586]

Dark Matter Mass Range

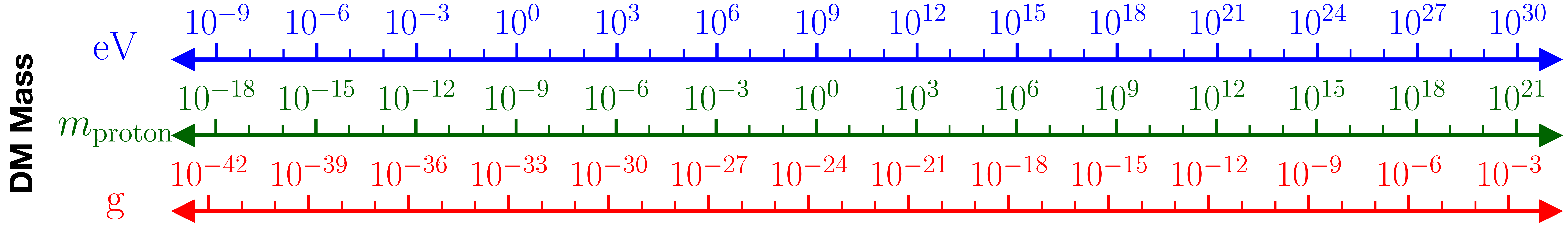


Very light DM ($\lesssim 10^{-22}\,\mathrm{eV}$) has wave-like properties on astrophysical scales, spoiling galactic structure

DM lighter than ~1 keV must be bosonic (fermions cannot be packed to high enough densities in galaxies)

[Tremaine & Gunn (1979)]

Dark Matter Mass Range



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

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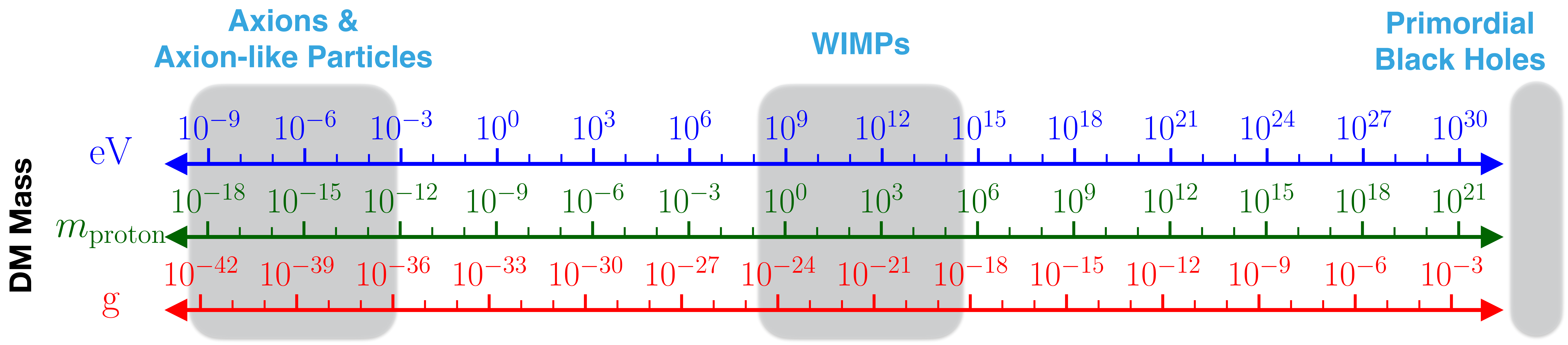

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[Tremaine & Gunn (1979)]

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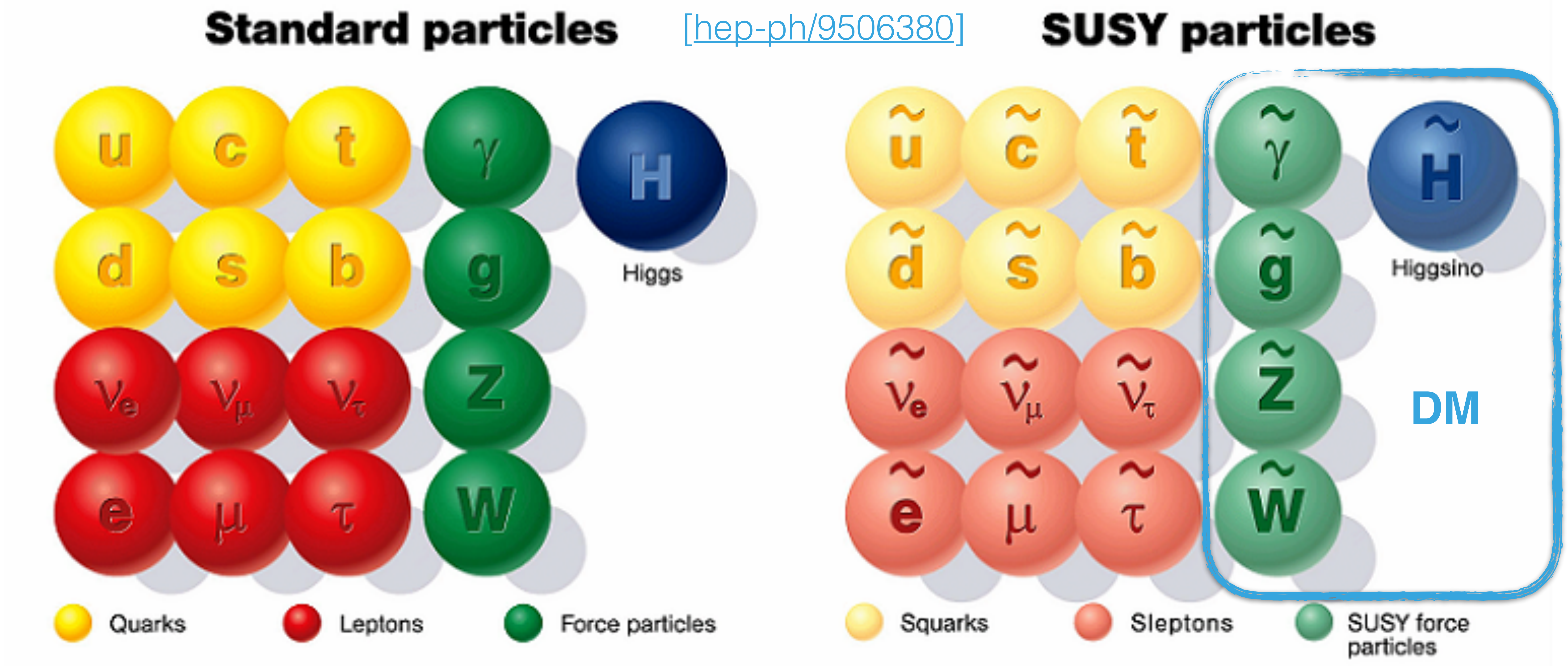
Weakly Interacting Massive Particles

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.

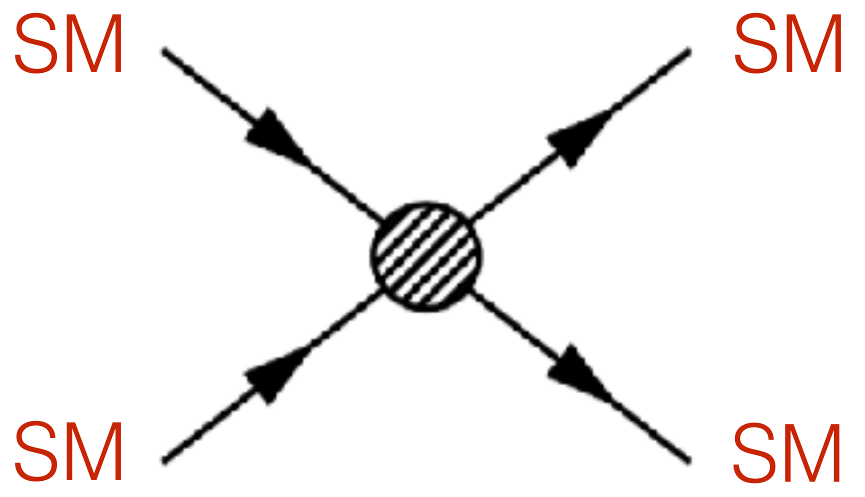


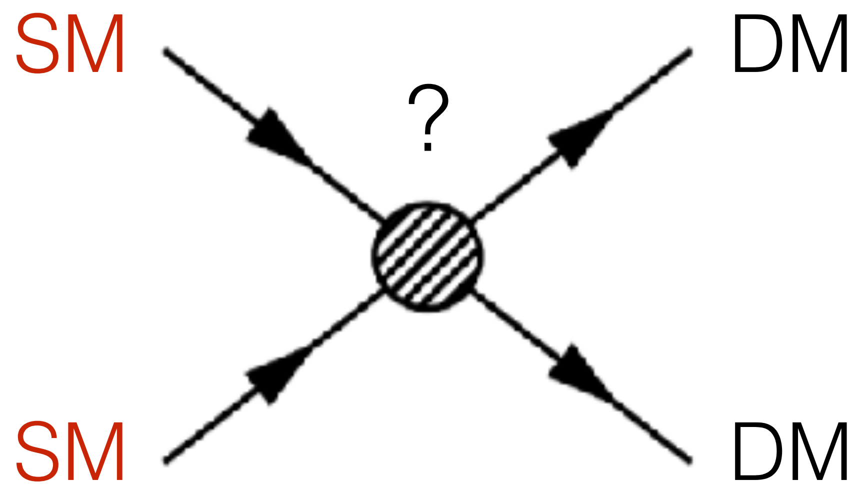
Now, the term WIMP is used to mean a generic MeV-TeV mass particle with weak couplings to the standard model.

Producing WIMP Dark Matter

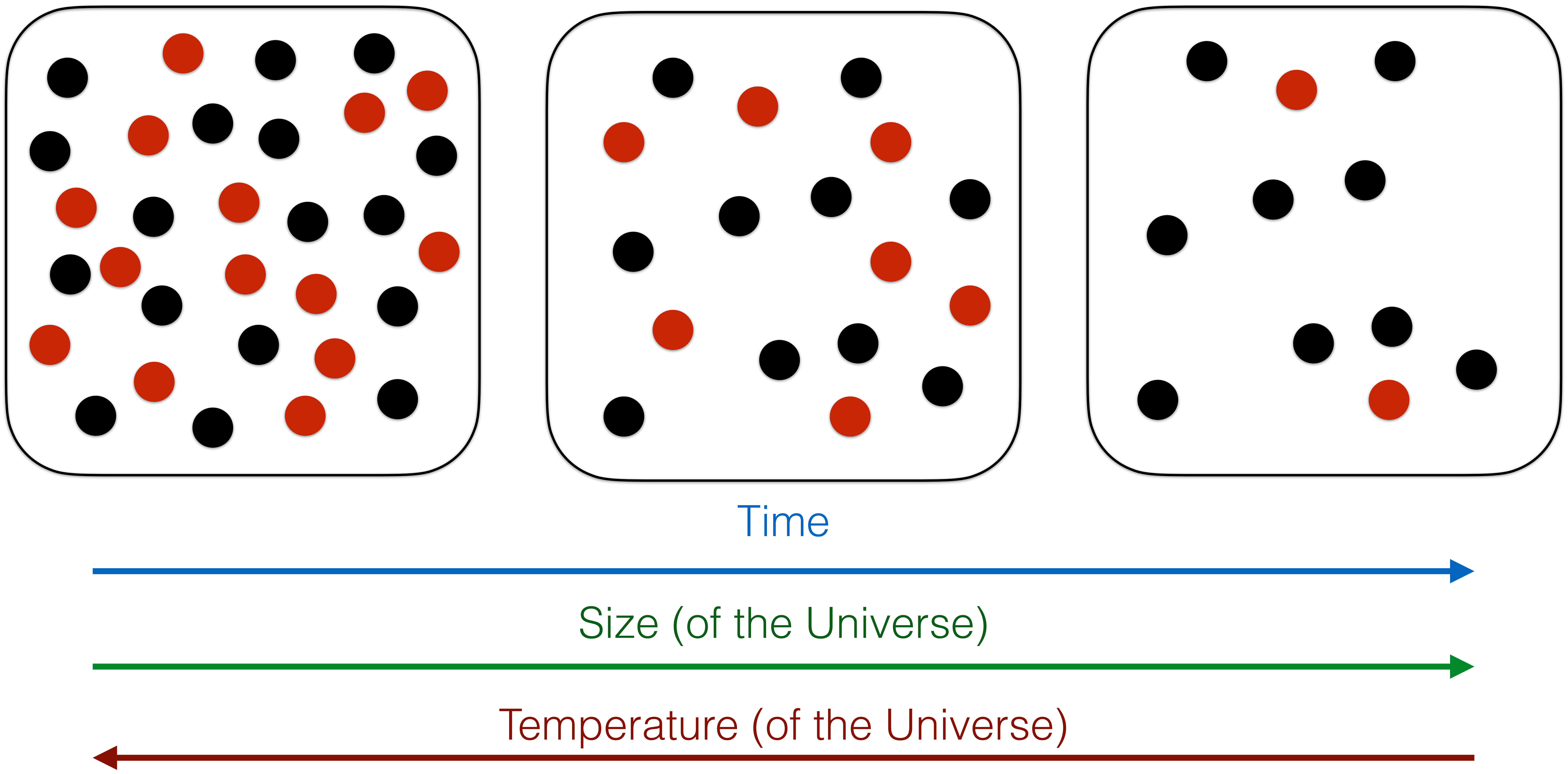
"Freeze-out"

- Dark Matter
- Standard Model





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



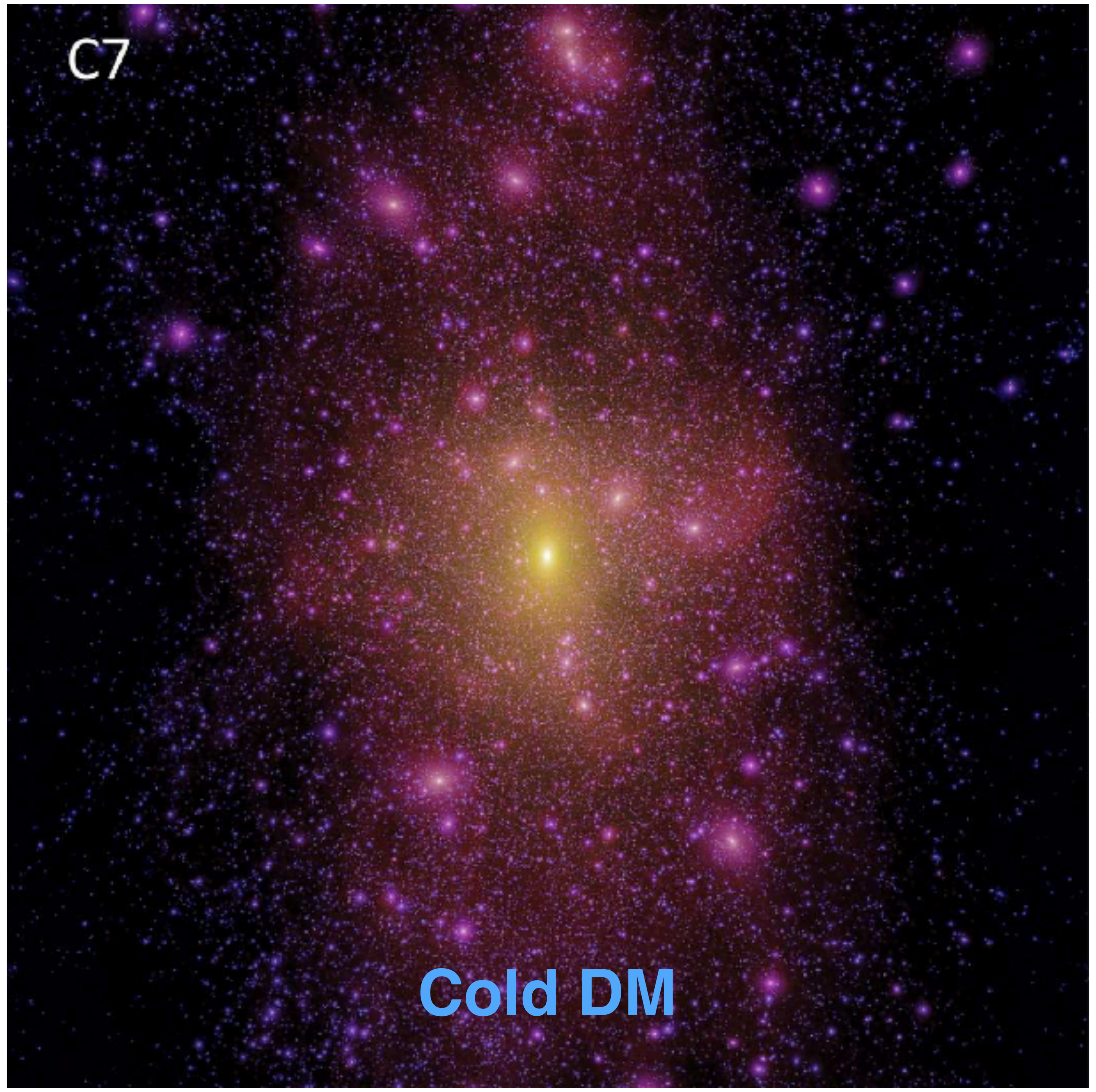
Cold vs Hot Dark Matter

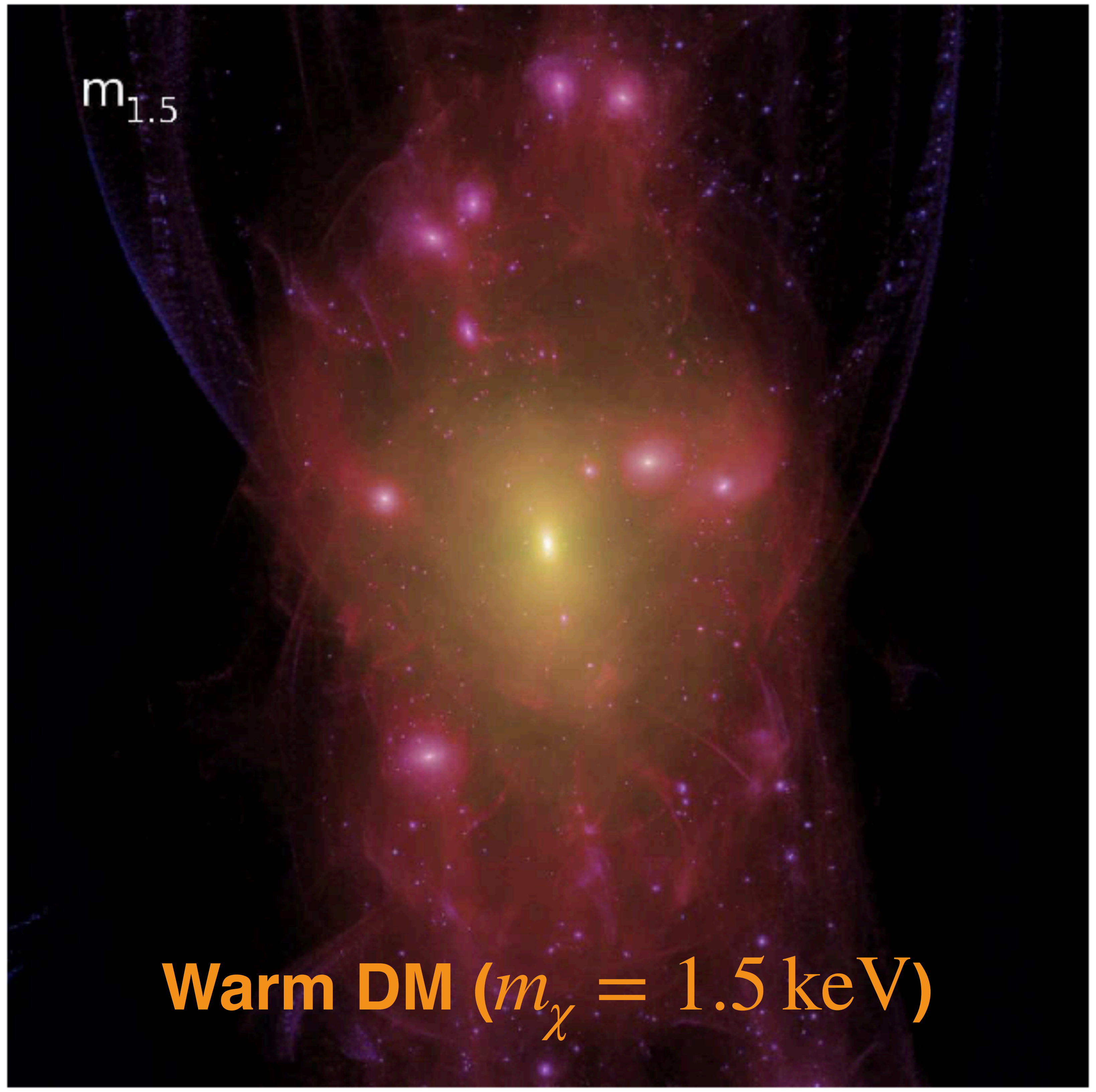
[1308.1399]

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 ($m \sim \mathrm{keV}$) may also be viable + testable: **Warm Dark Matter**.

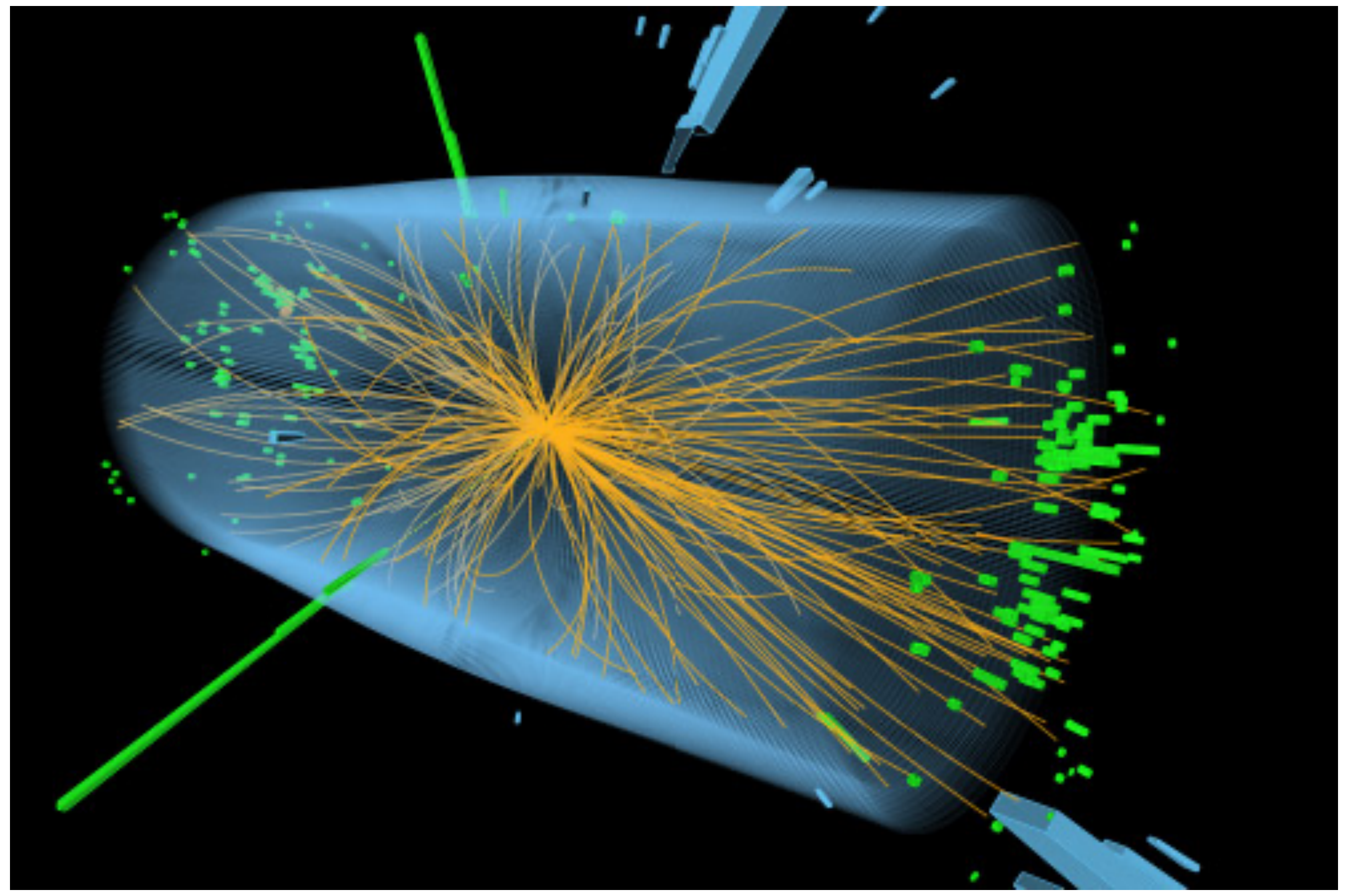


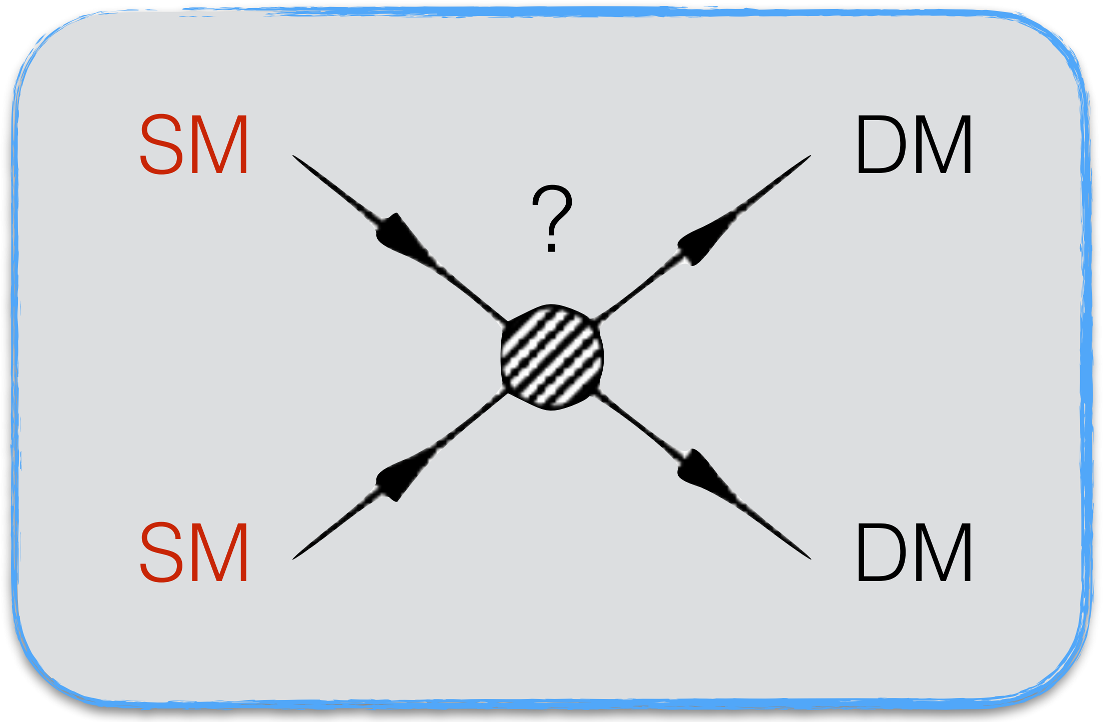


Collider Searches for WIMPs

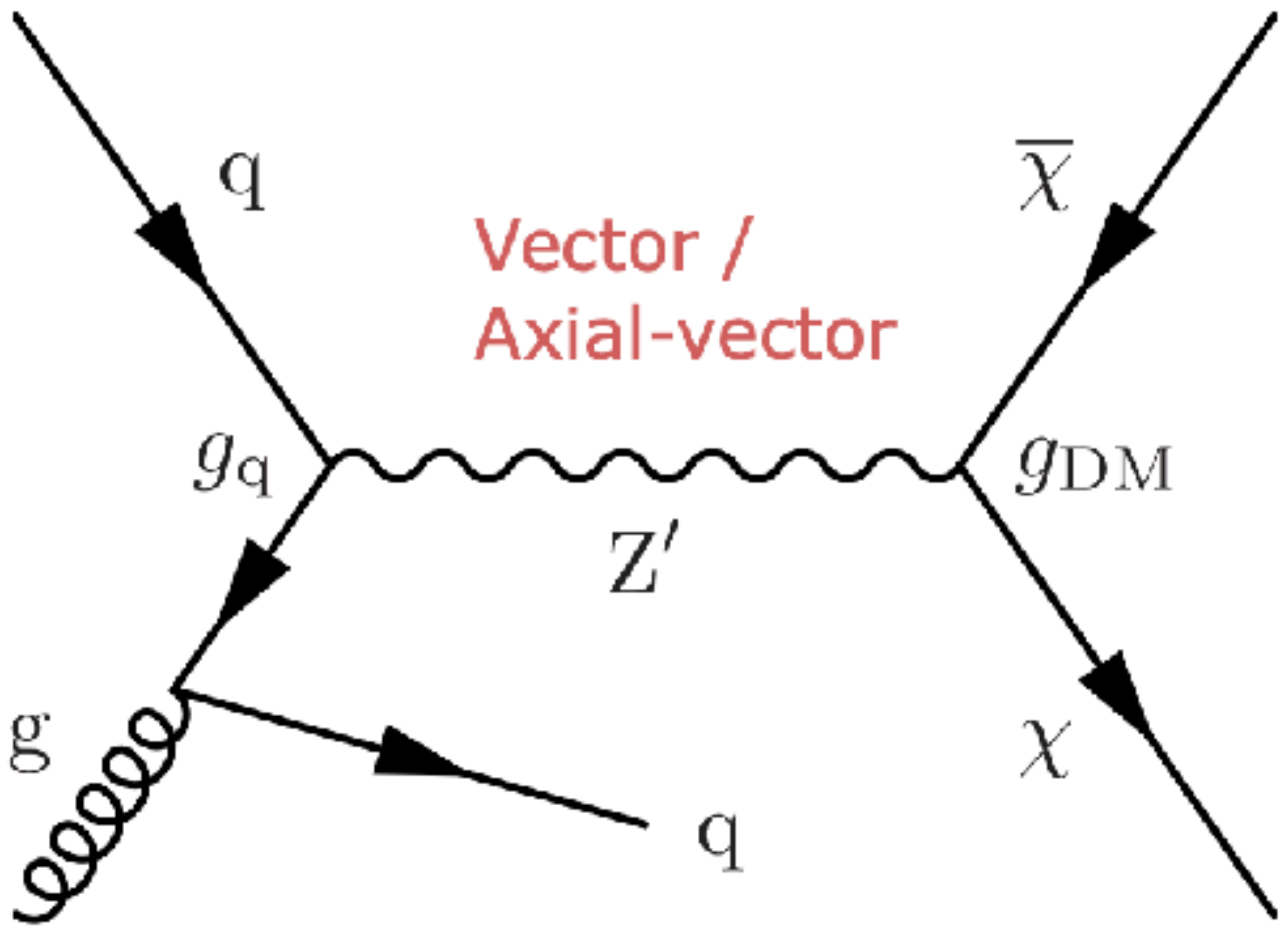
The same interactions which produce DM early in the Universe can be used to search for DM in colliders (e.g. proton-proton collisions):

[Credit: CMS/CERN]

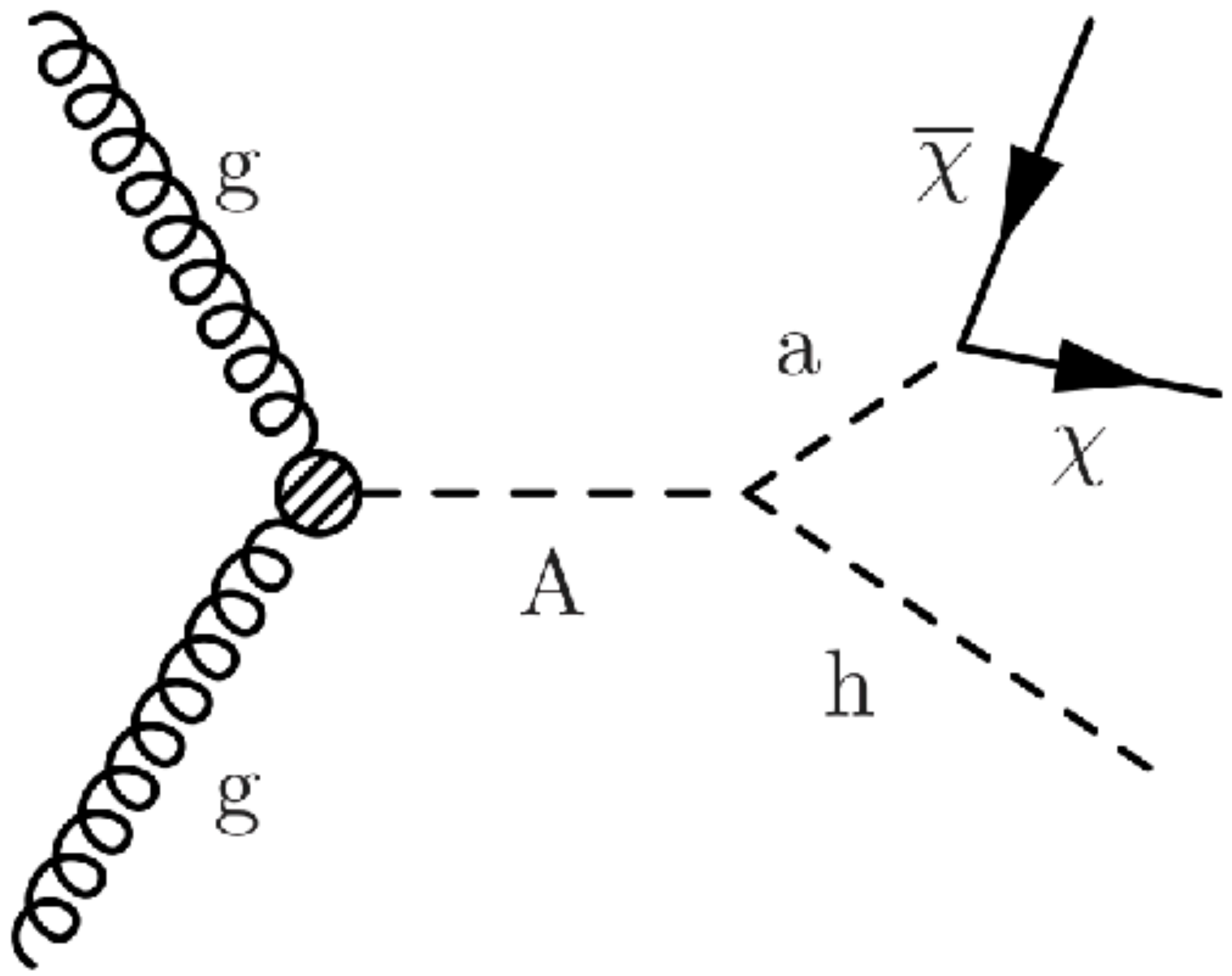




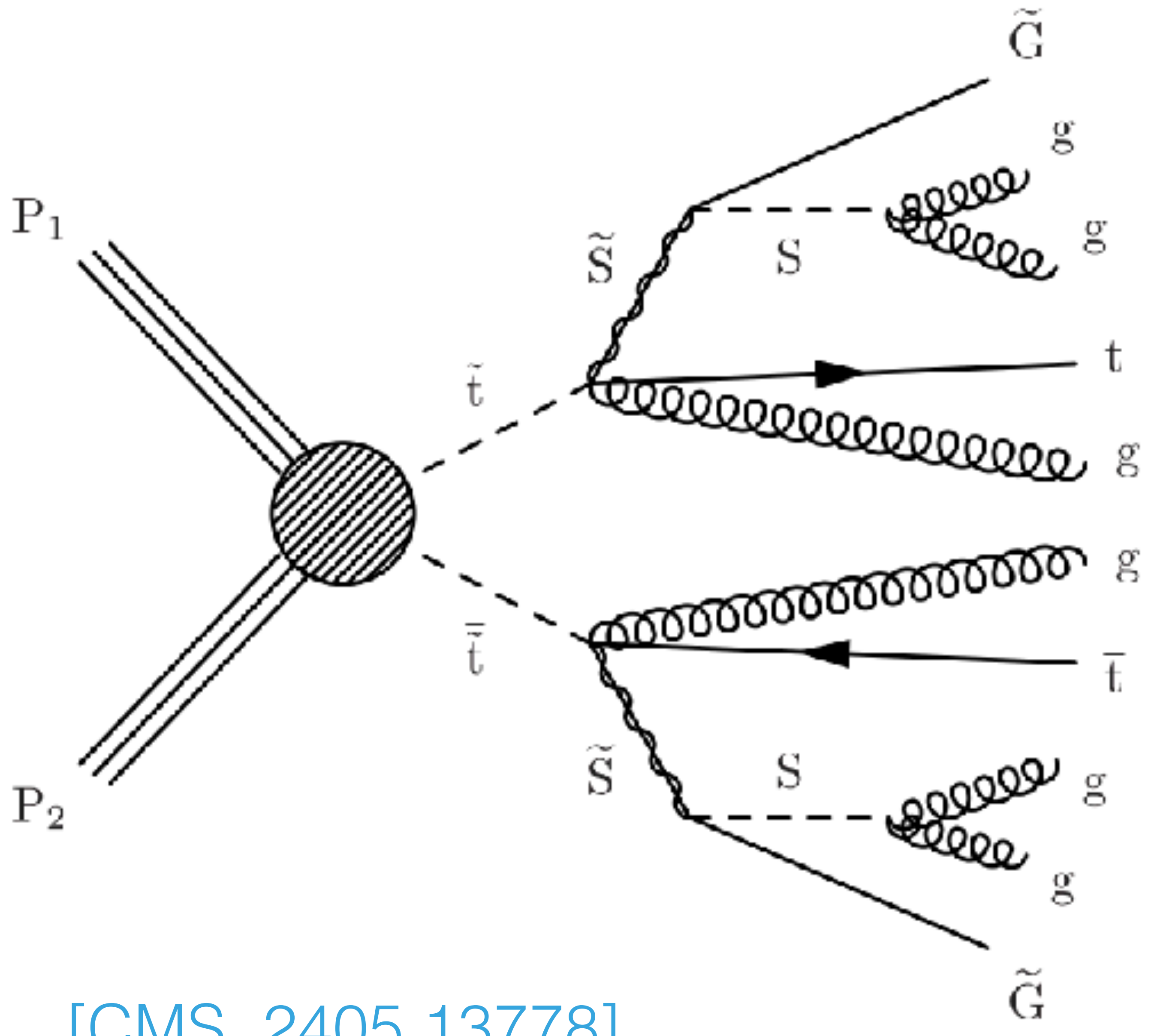
Spin-1 Portal



2HDM+a



Stealth SUSY

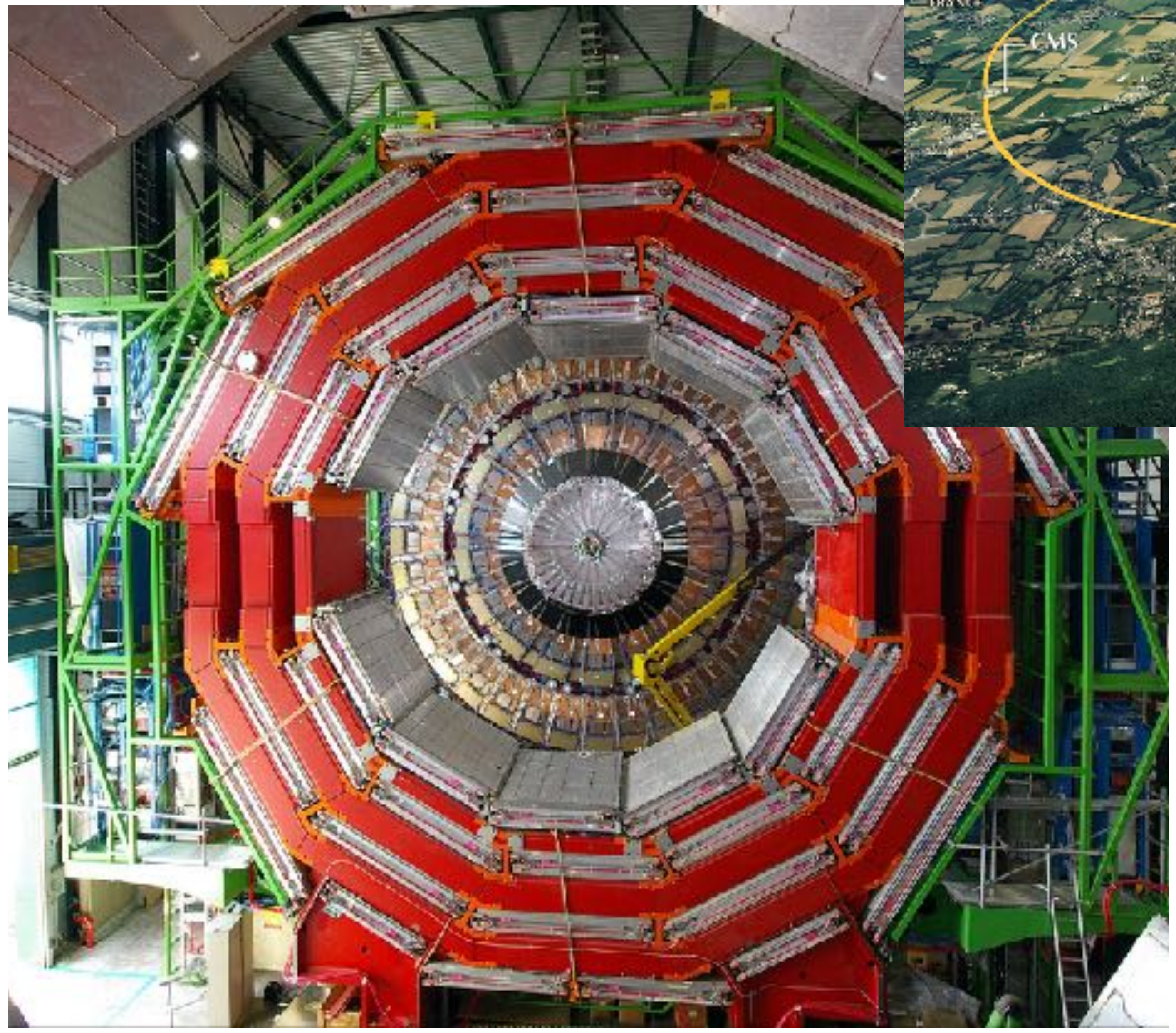


[CMS, 2405.13778]

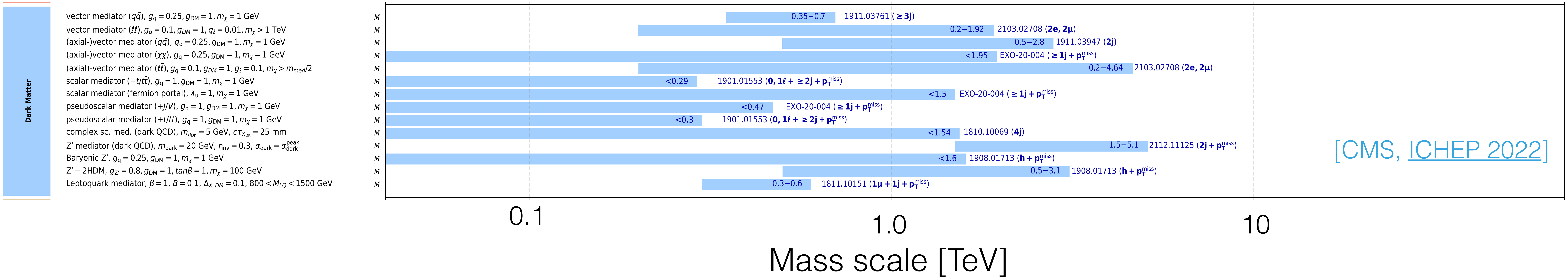
DM at Colliders: CMS at LHC

IFCA participates in the **Compact Muon Solenoid (CMS)** experiment at the Large Hadron Collider (LHC):

- **Run I-II (completed):** involved in search for DM candidates with associated SM particle production - e.g. mono-Higgs, Dark Higgs, top quark-associated
- **Run III (2022 - 2024):** extend to search for long lived Dark mediators from DM decay
- **HL-LHC (2027+):** preparing for high luminosity → precision measurements (esp. Higgs and top) to search for deviations due to New Physics.



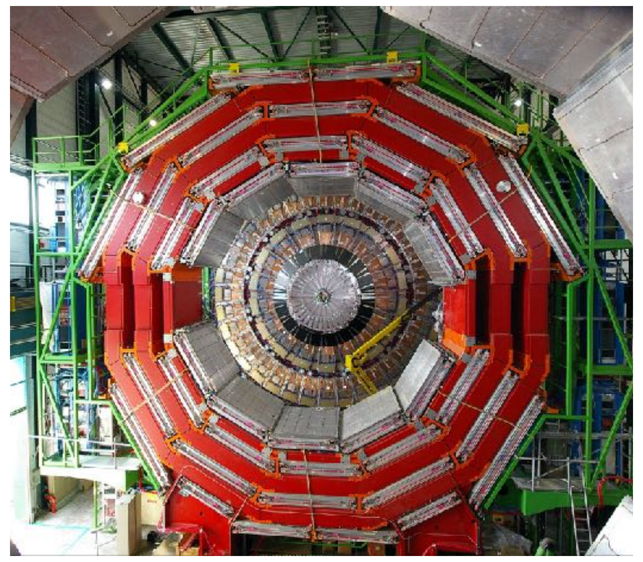
Summary of CMS constraints on the mass scale of new mediator particles coupling to DM:

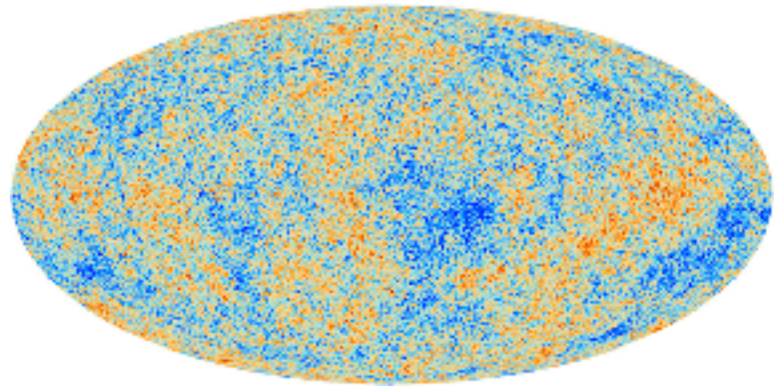


[CMS, ICHEP 2022]

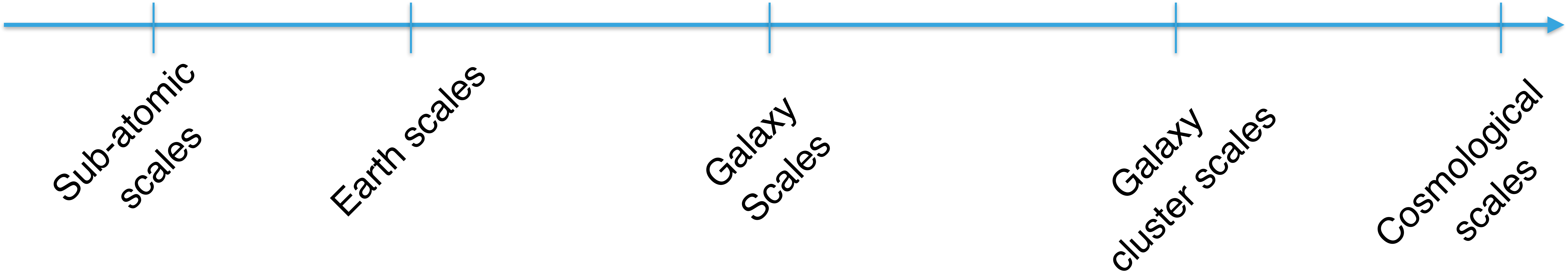
Dark Matter on all scales

CMS

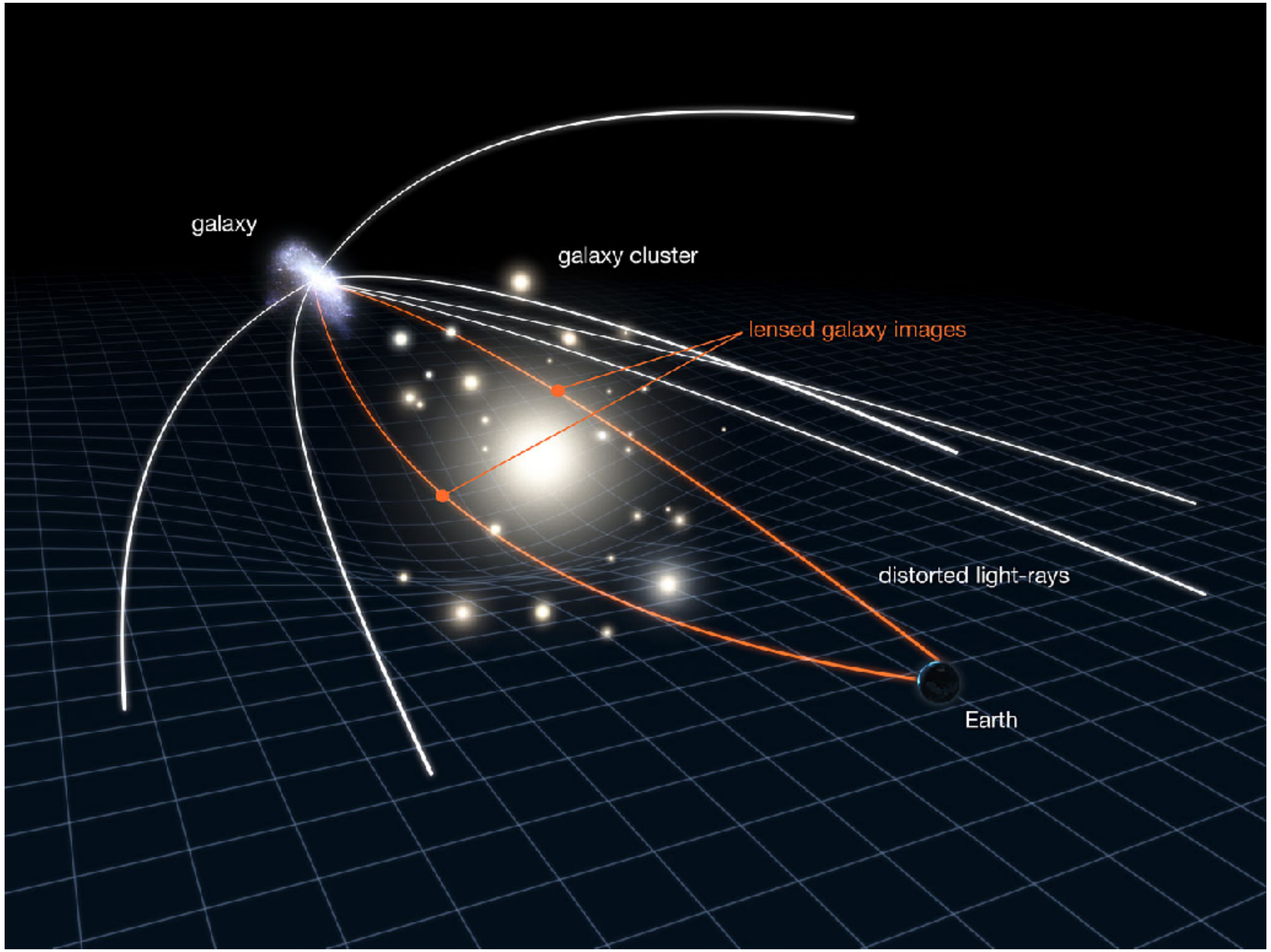




CMB



Gravitational Lensing



[Credit: NASA, ESA & L. Calçada]

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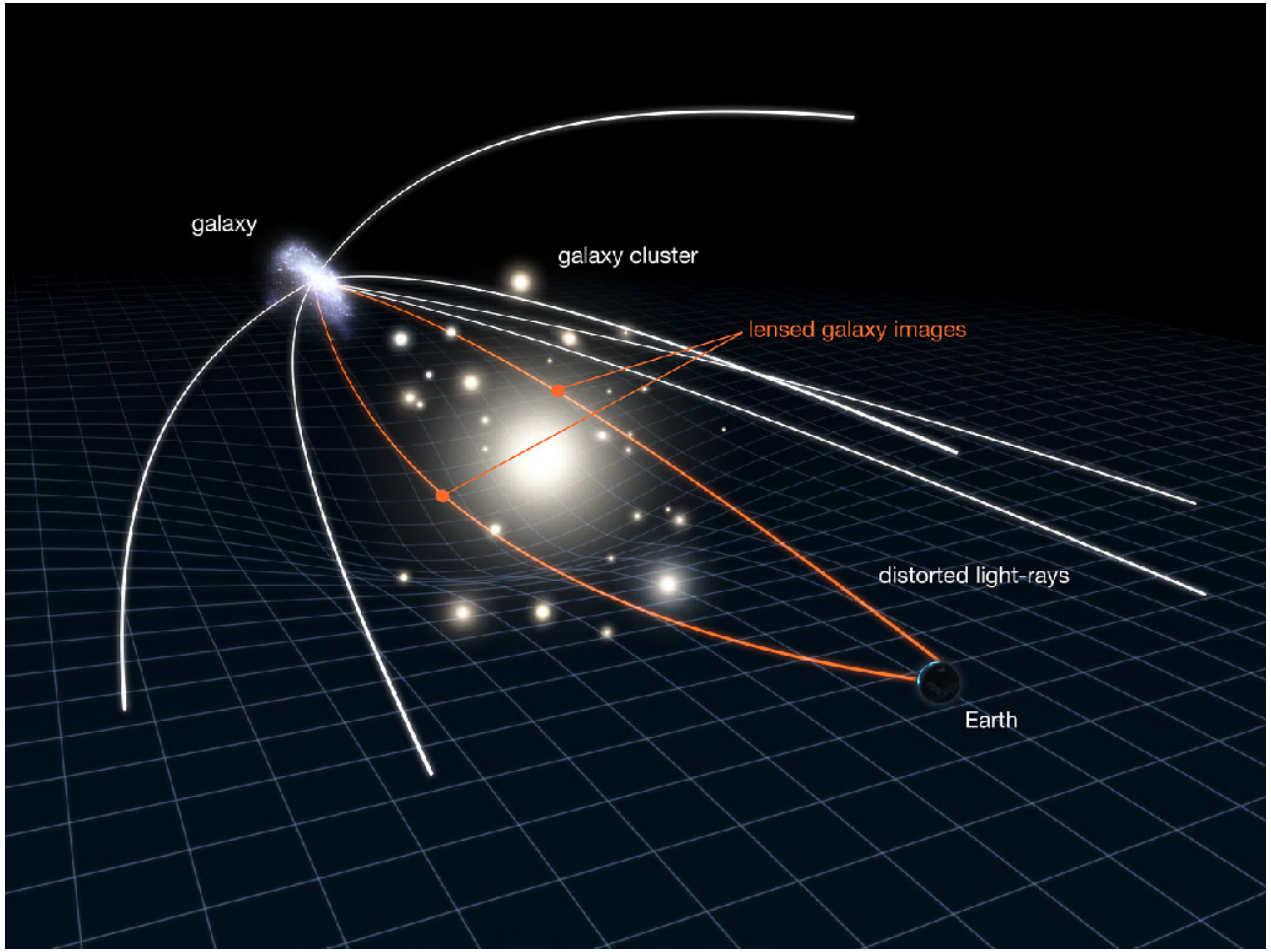
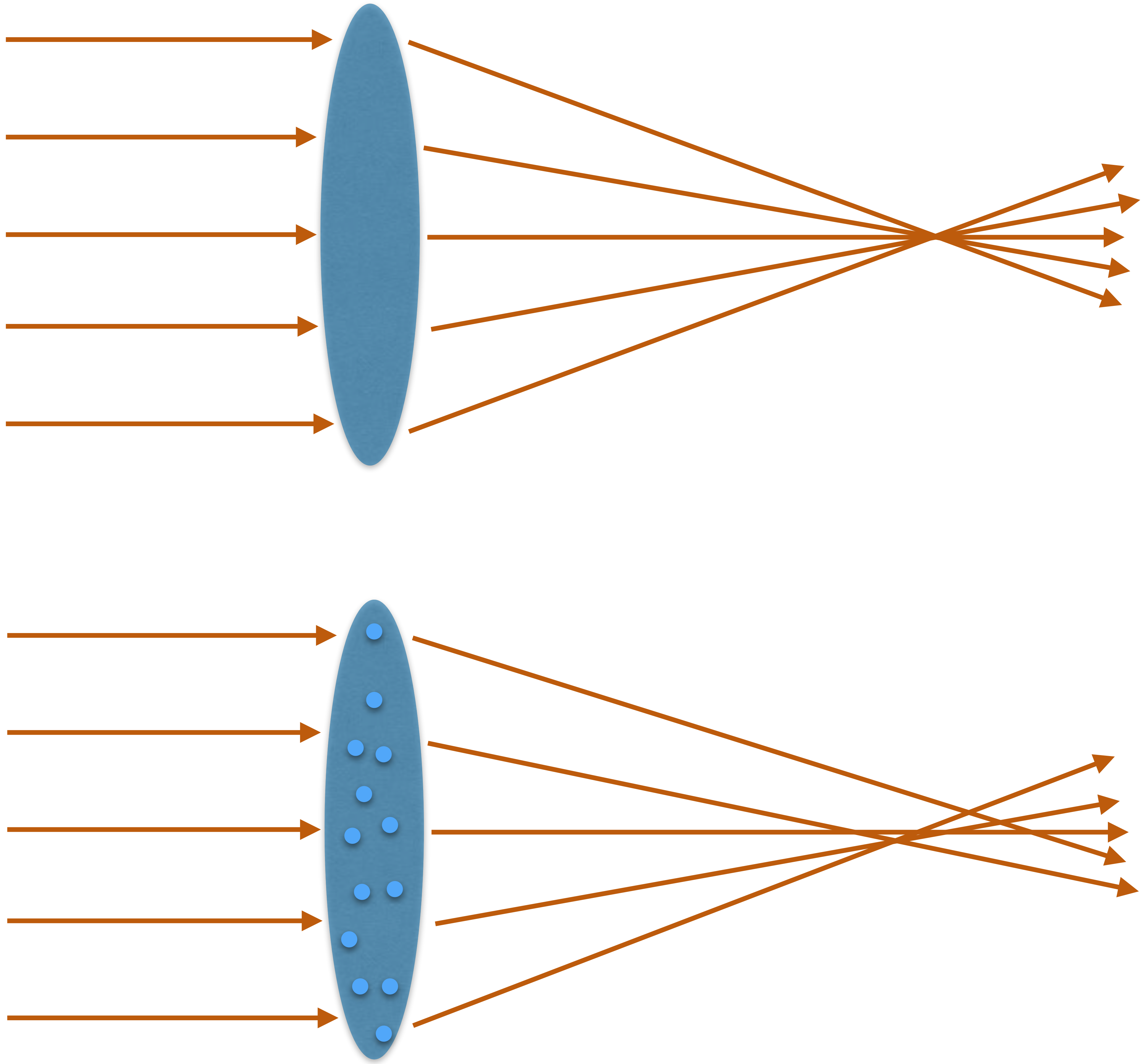


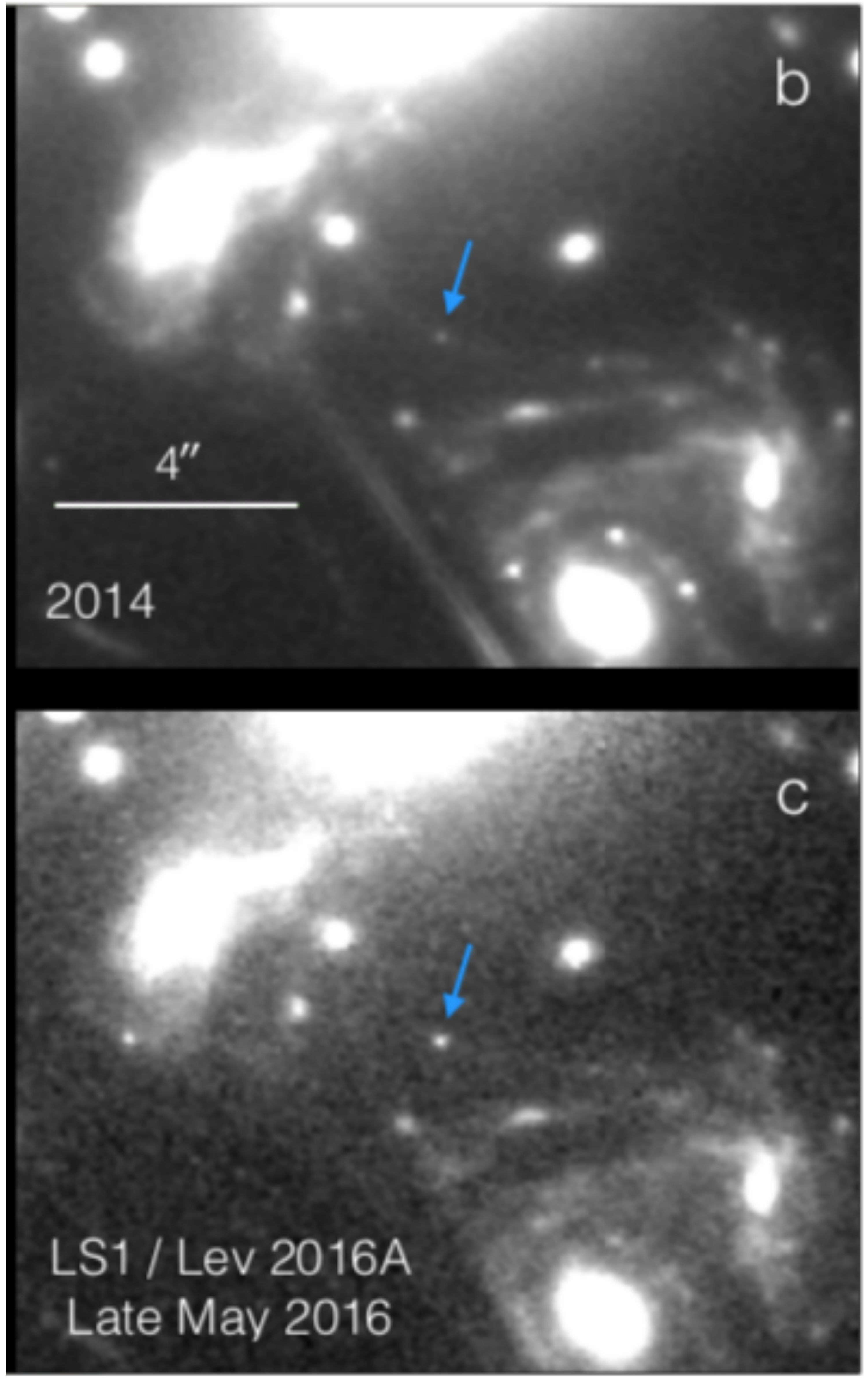
[Credit: NASA, ESA & L. Calçada]

A smooth lens and a lens with structure do not produce the same maximum magnification



[See e.g. Palencia, Diego, BJK & Martinez, 2307.09505]

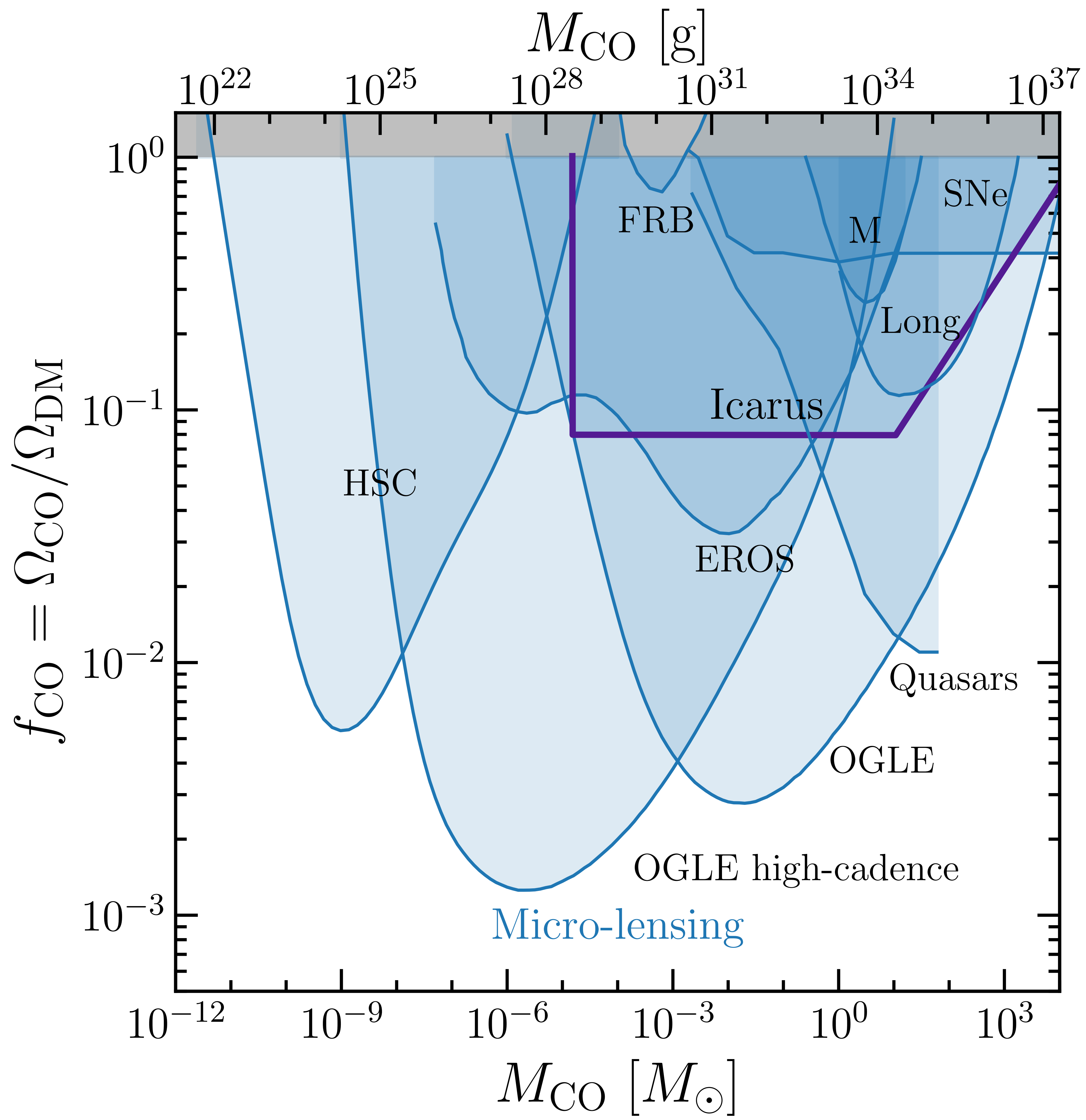
Primordial Black Holes (PBHs) as DM



[Kelly et al., 1706.10279; Diego et al., 1706.10281]

Icarus, a star at z ~ 1.49 observed by Hubble Space Telescope. Lensed and magnified by >2000x by intervening galaxy cluster (MACS J1149).

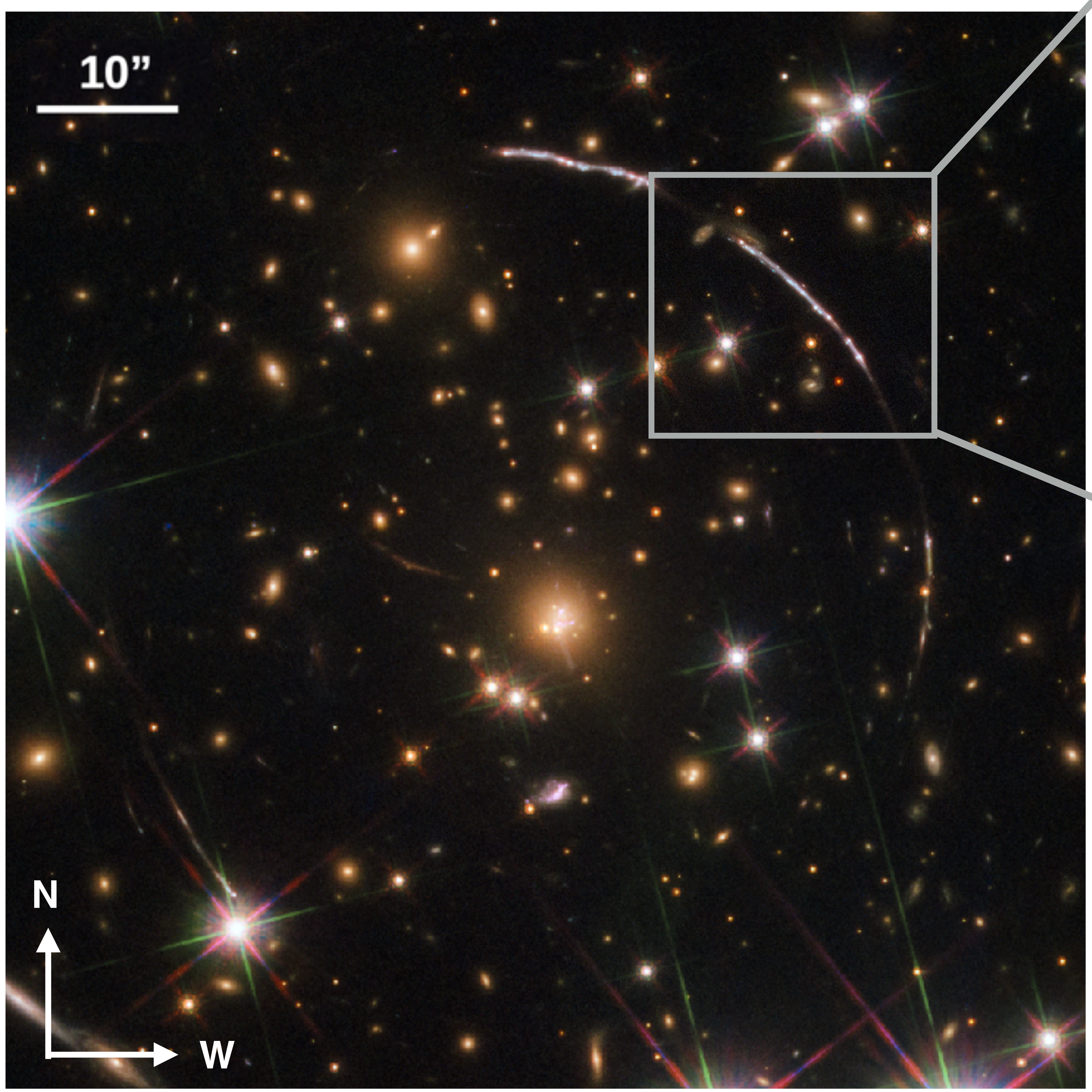
Compact objects (COs) such as **Primordial Black Holes (PBHs)** in the lens would reduce the total magnification → constraint!



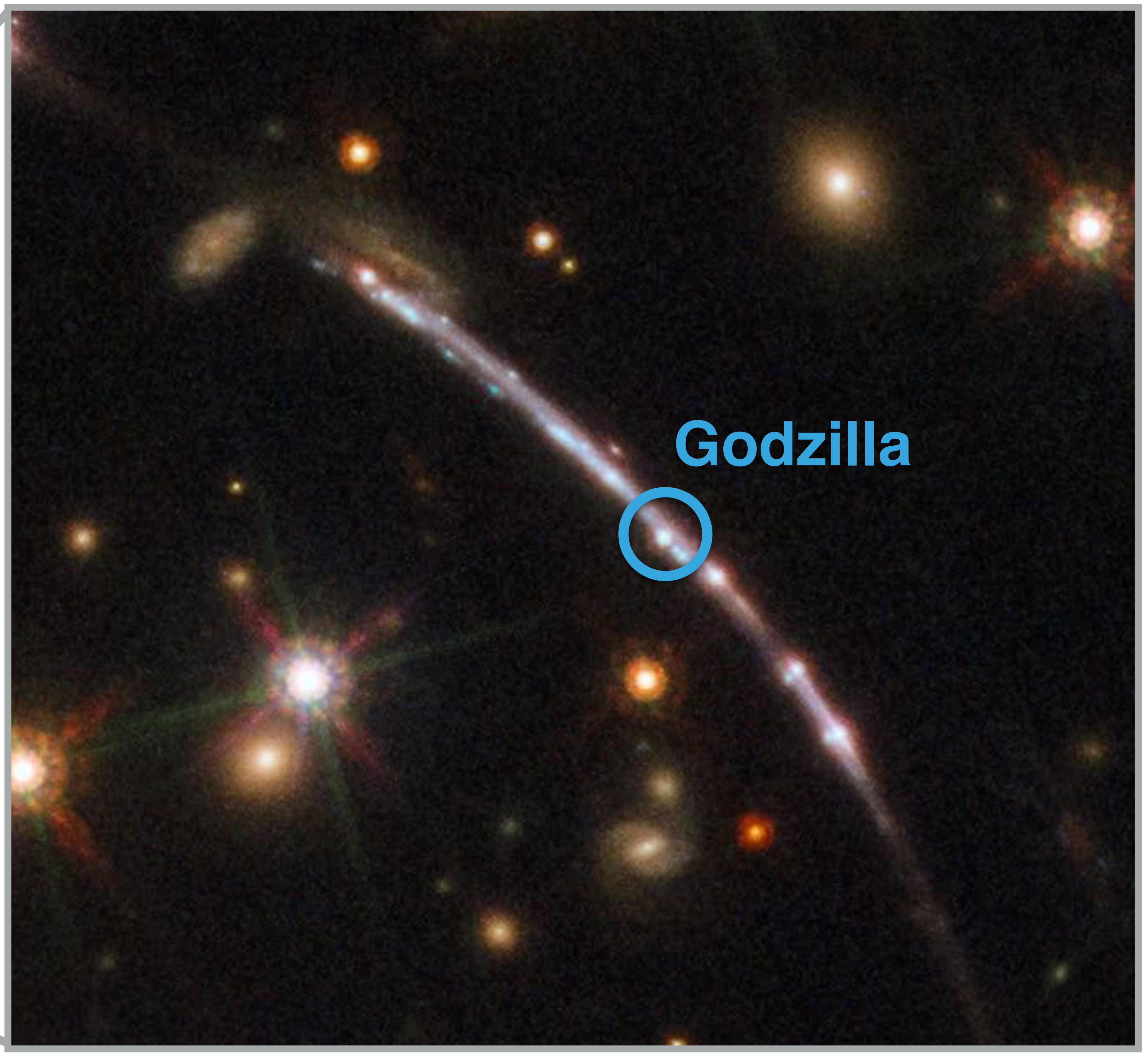
[See e.g. Green & **BJK**, arXiv:2007.10722 for a review of PBHs]

Crushing substructure with Godzilla

[Diego et al. (including **BJK**), 2203.08158]



Galaxy cluster PSZ1 G311.65-18.48
($z = 0.443$)



Giant Sunburst arc ($z = 2.37$)

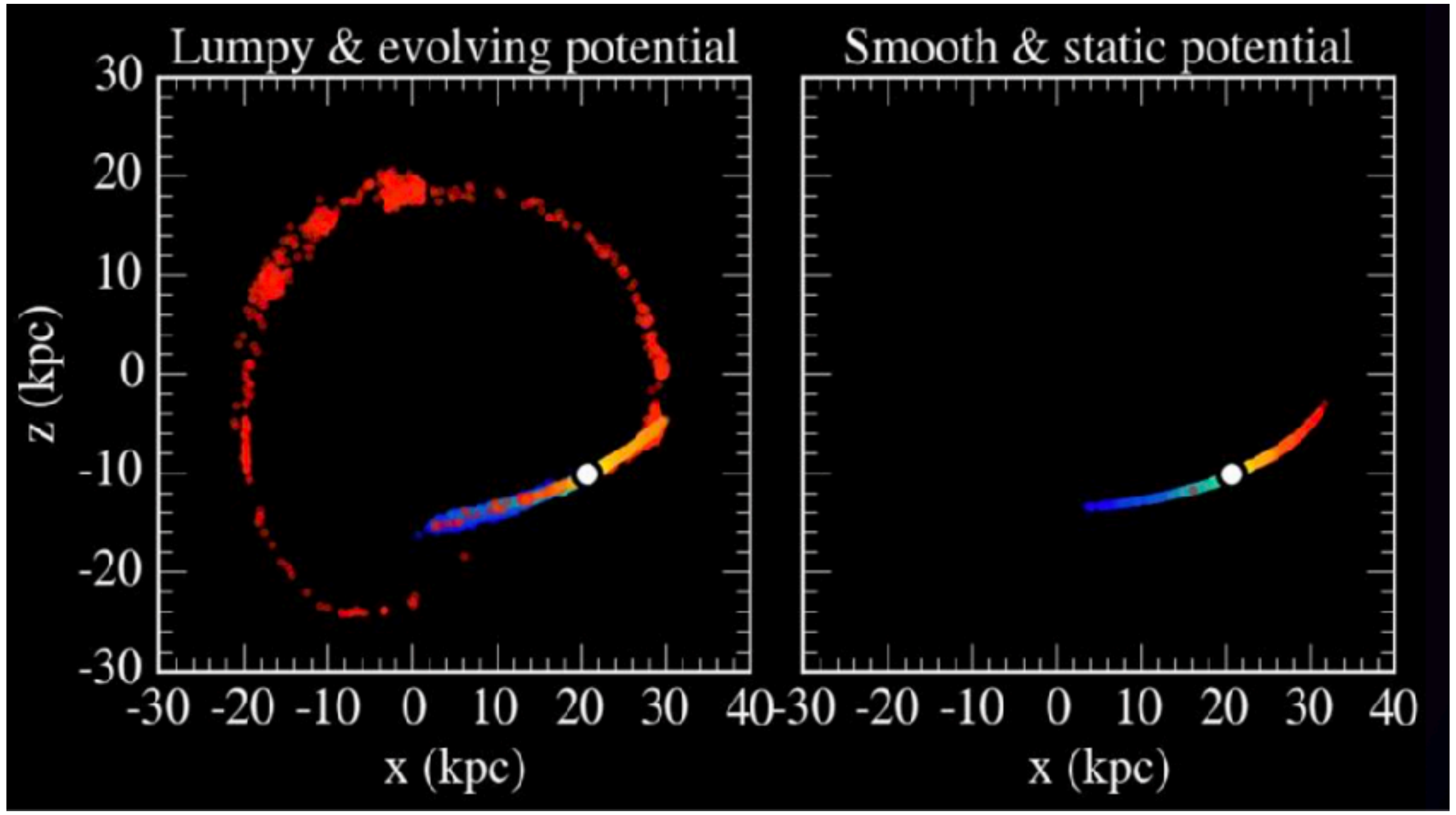
This image appears to be an extremely bright luminous blue variable (LBV) star, nicknamed **Godzilla**.

Extreme magnification ($\mu > 1000$) may be explained by a DM halo with mass $\sim 10^8\, M_\odot$ along the line of sight (suggests $m_{\rm DM} \gtrsim 4\,{\rm keV}$?)

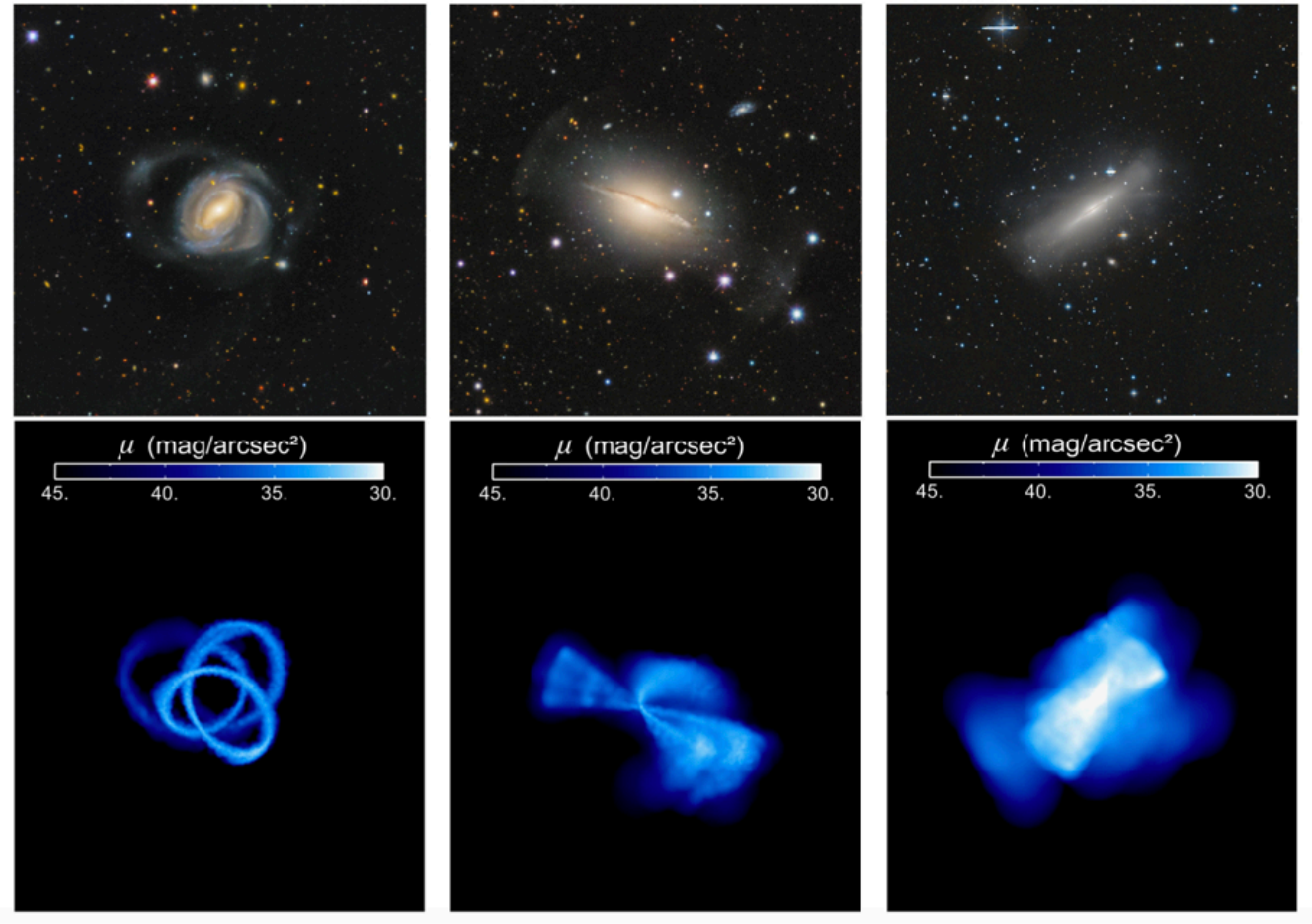
Satellites and Stellar Streams

Counting the number of satellite ("dwarf") galaxies also allows us to constrain the amount of DM substructure and therefore the nature of DM.

Some satellite galaxies are disrupted by the tidal field of the host galaxy, leading to the formation of **stellar streams.**



[Pearson et al. (2017)]



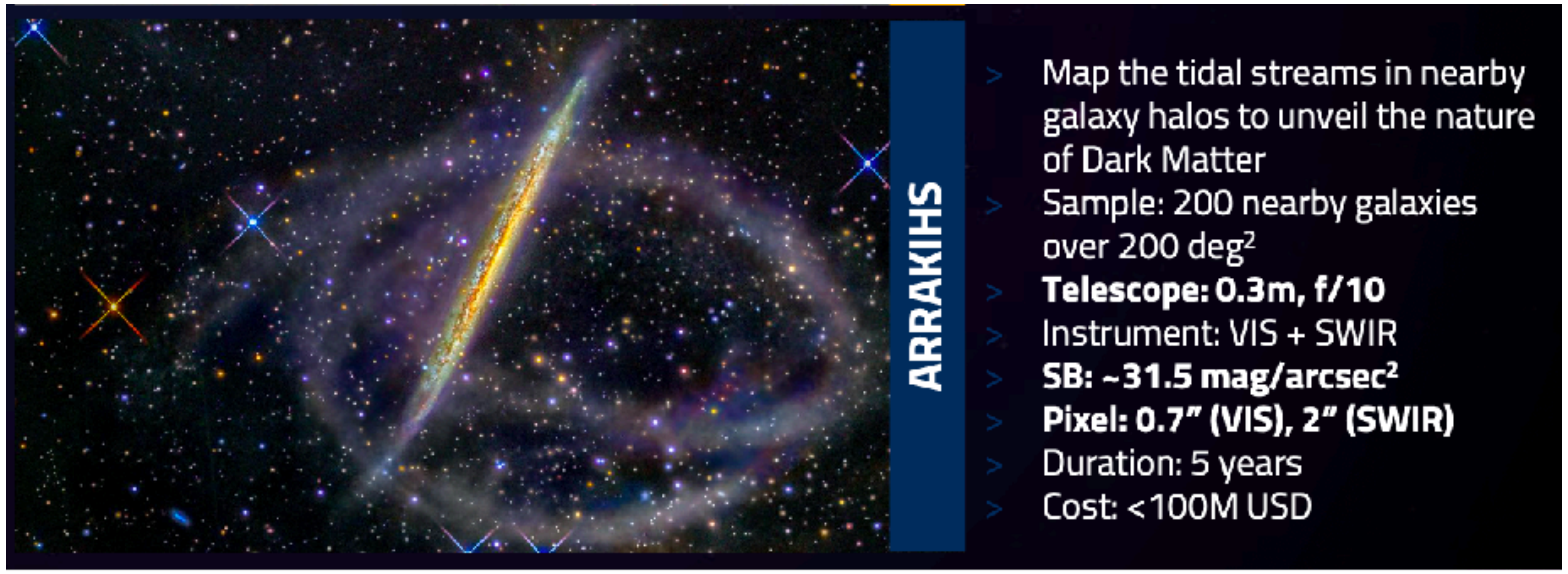
[Stellar Stream Legacy Survey, Martinez-Delgado et al., 2104.06071]

Stellar streams probe the gravitational potential of the host galaxy.

This allows us to map out the density in the DM halo and test for the **presence of substructure** (e.g. DM sub-halos).

[See e.g. Walder et al., 2402.13314]

ARRAKIHS



Analysis of Resolved Remnants of Accreted galaxies as a Key Instrument for Halo Surveys

Aim to perform the definitive survey of nearby Milky Way-like galaxies down to low surface brightnesses. Study the statistics and shapes of satellite galaxies and stellar streams to probe the nature of DM.

iSIM300
(2 visible, 2 near IR bands)

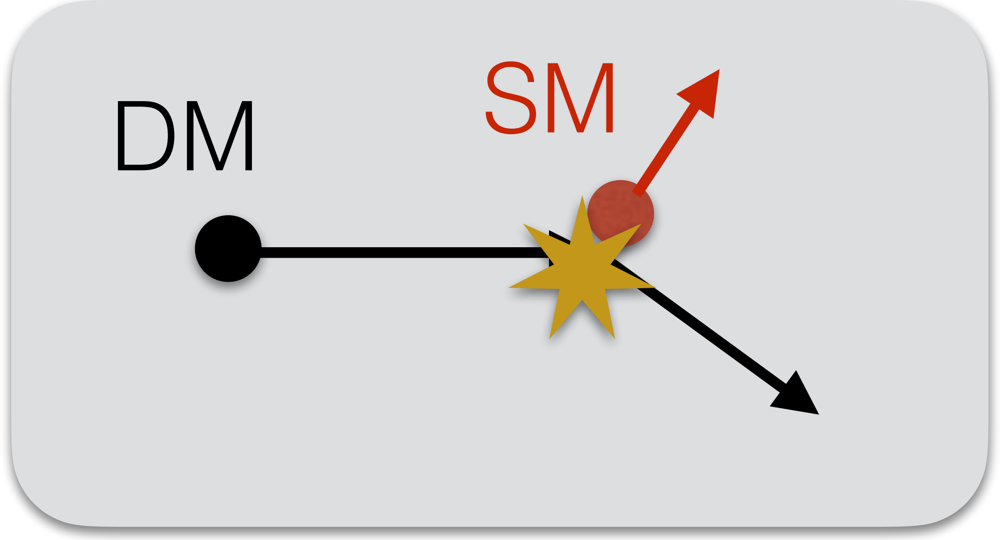
First Fast ("F-class") mission of ESA's Science Programme **led by Spain (specifically IFCA).**

Selected in November 2022, passing to Phase B of mission preparation in May 2024, with **launch into Low Earth Orbit planned for 2030.**

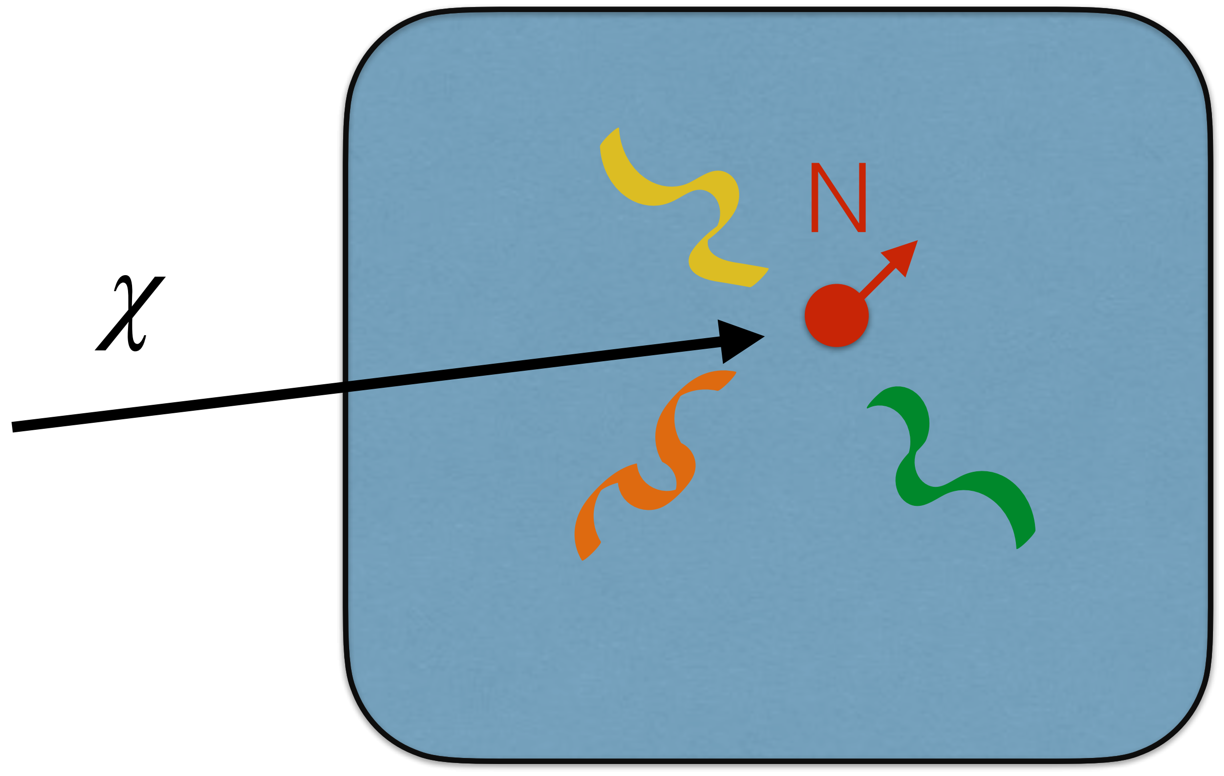
ARRAKIHS

[Includes content from slides by Rafael Guzman]

Direct detection of WIMPs on Earth

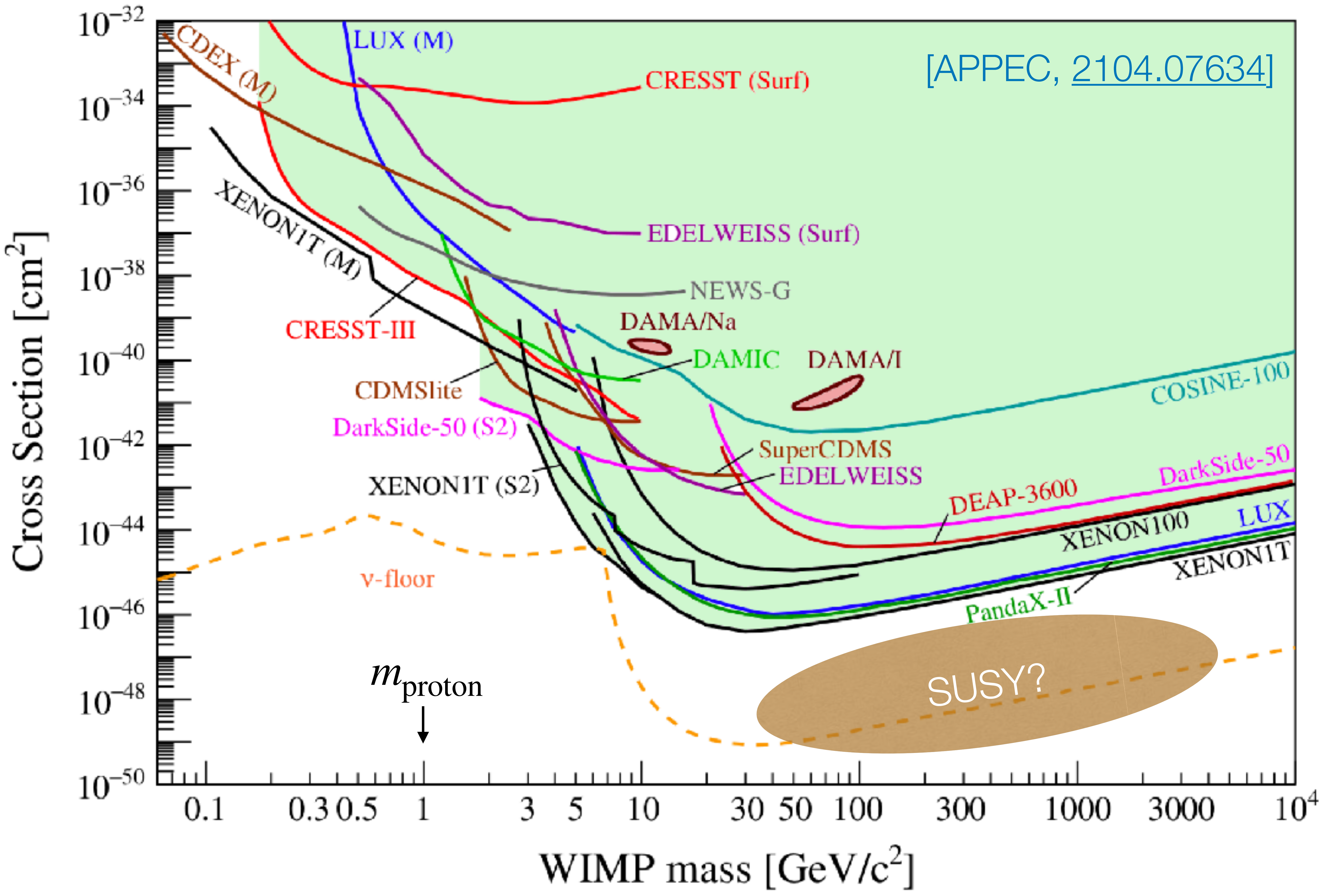


For WIMPs with GeV-scale masses, expect detectable elastic nuclear recoils of energy O(keV)



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

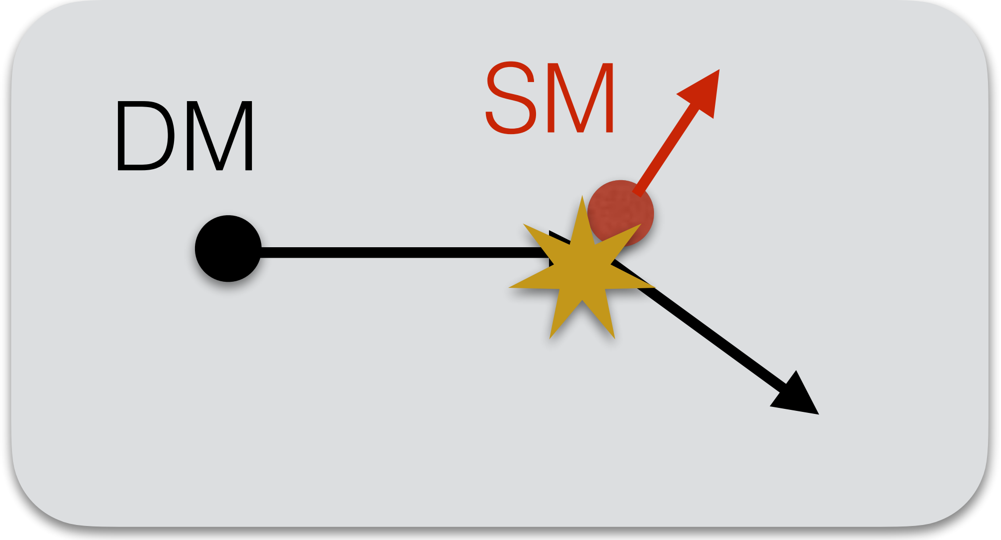
No convincing signal yet!



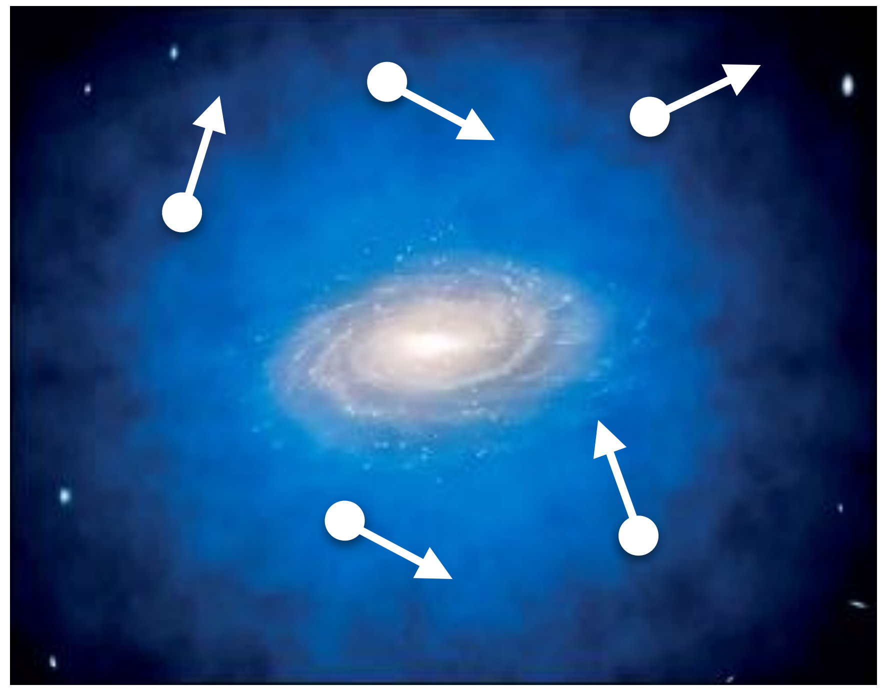
Low-mass WIMP Challenge

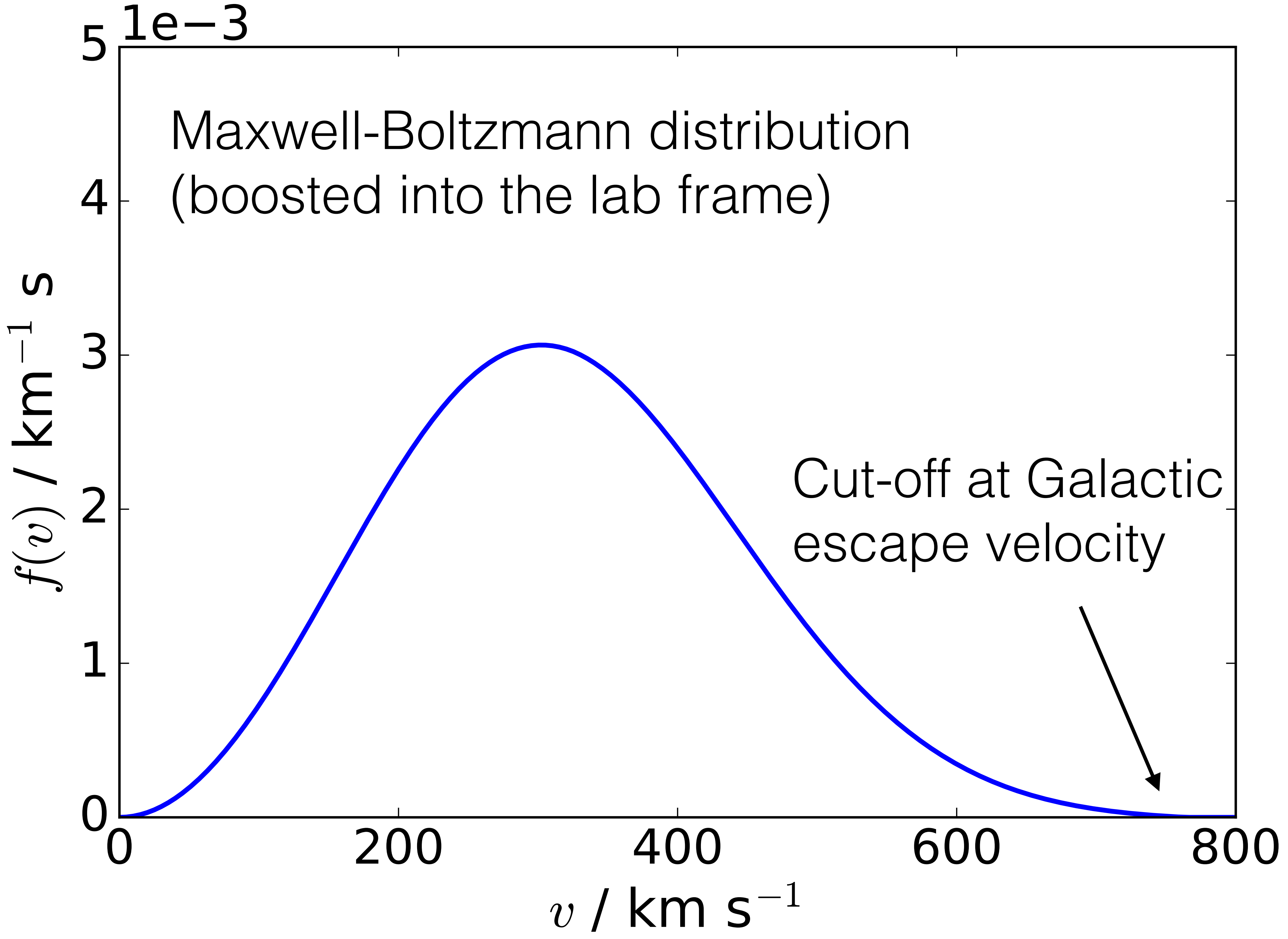
Low-mass WIMPs do not typically have enough kinetic energy to excite detectable elastic nuclear recoils!

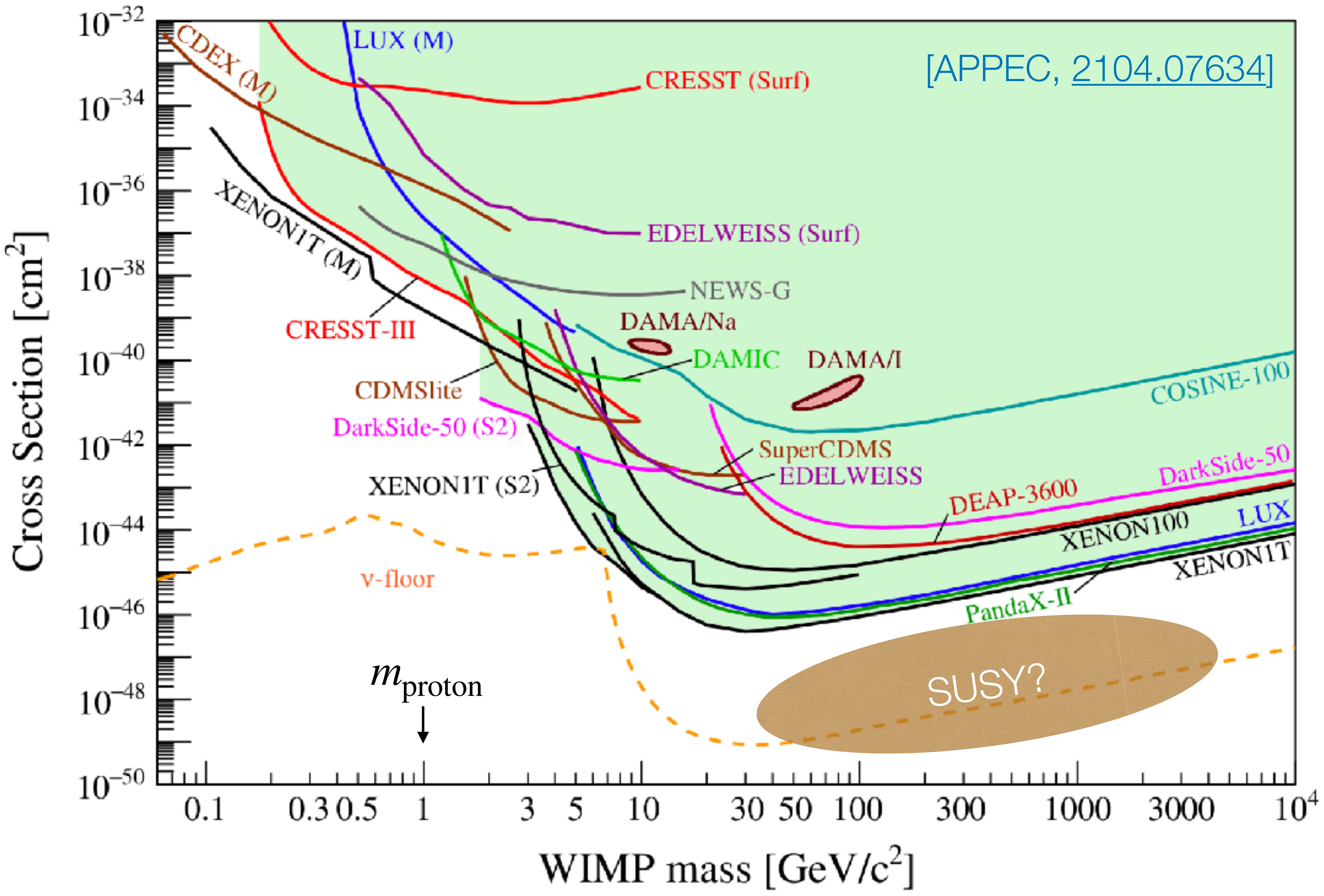
$$E_{\text{deposit}} \leq q v_\chi - q^2/2m_\chi$$



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







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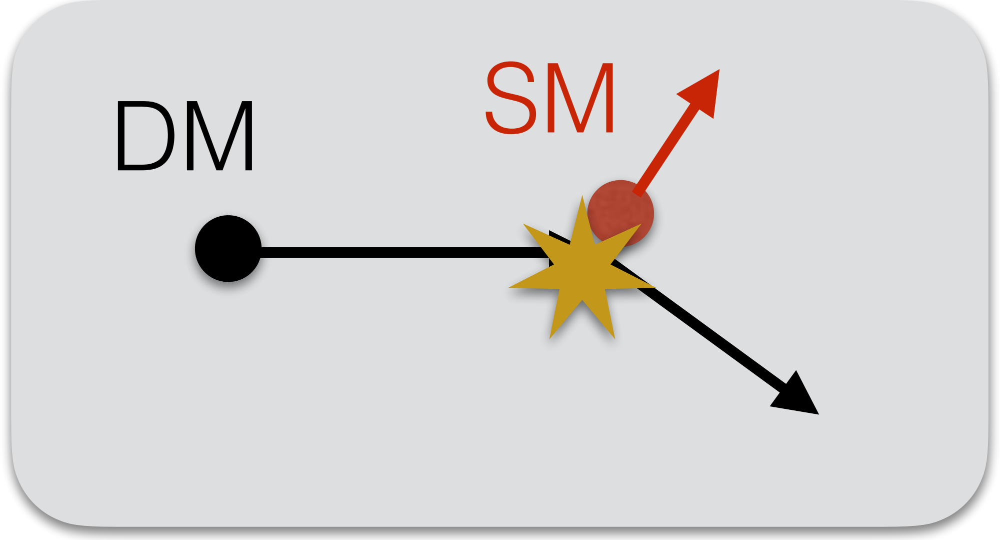

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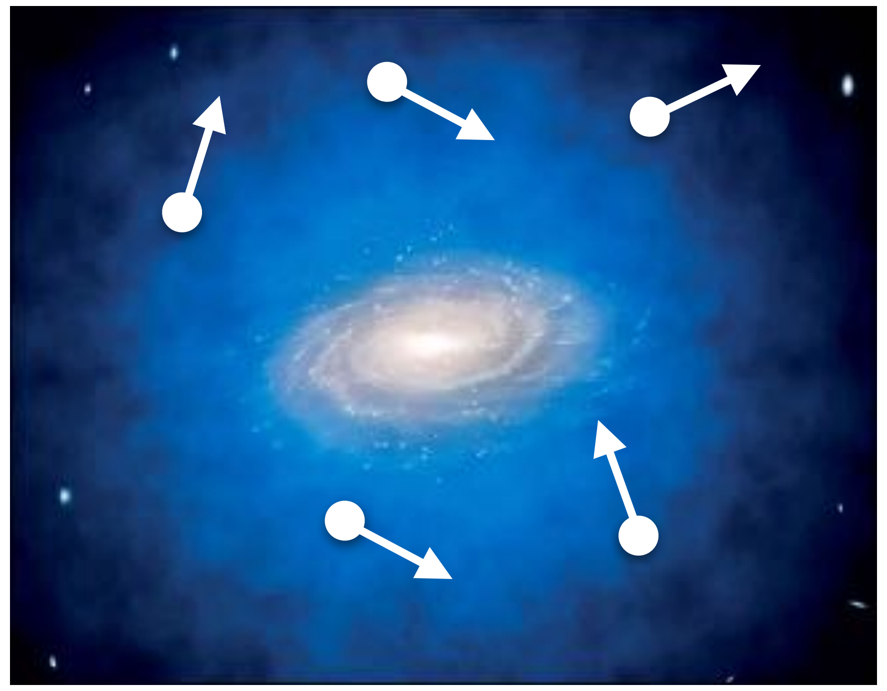
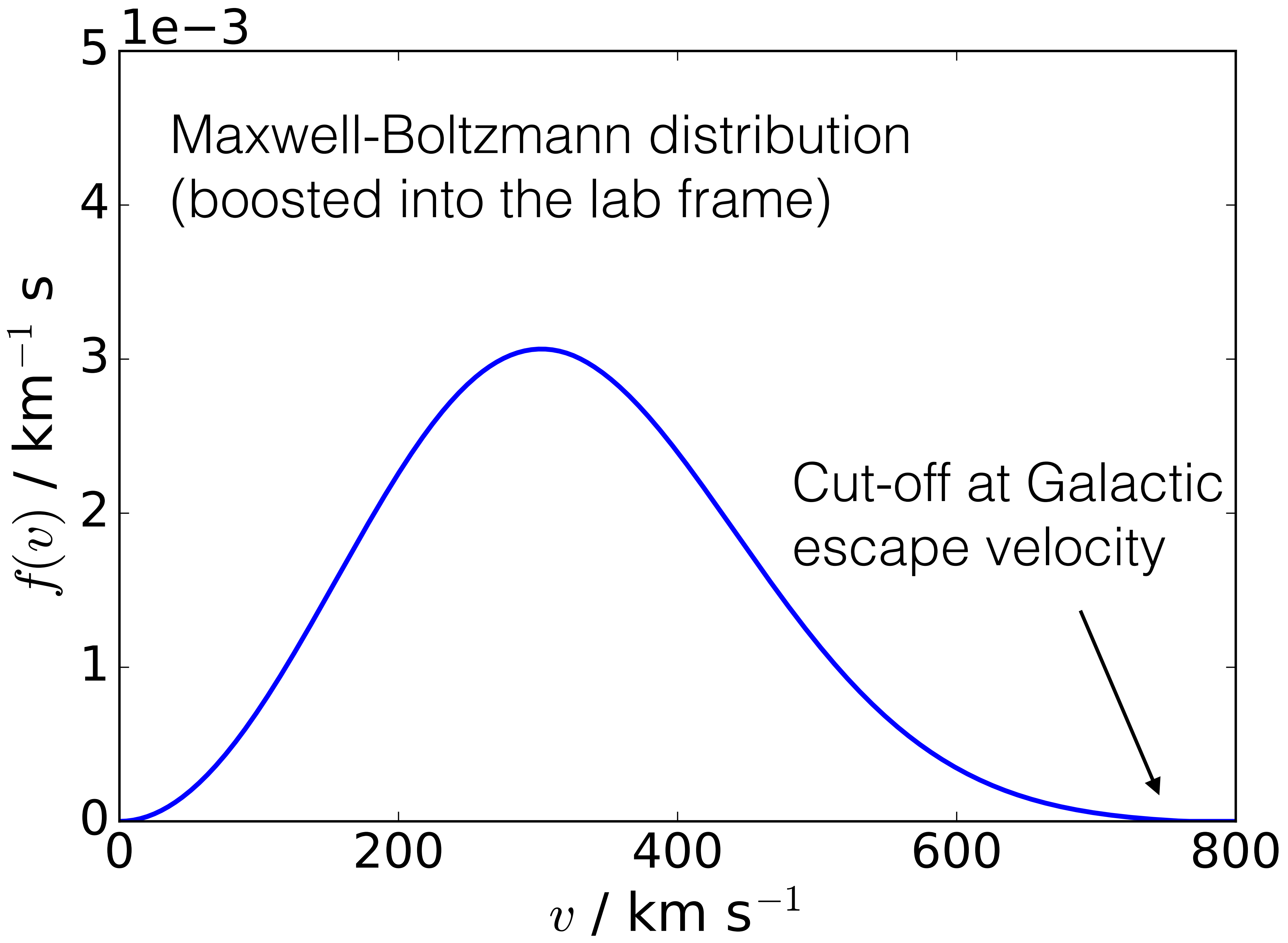
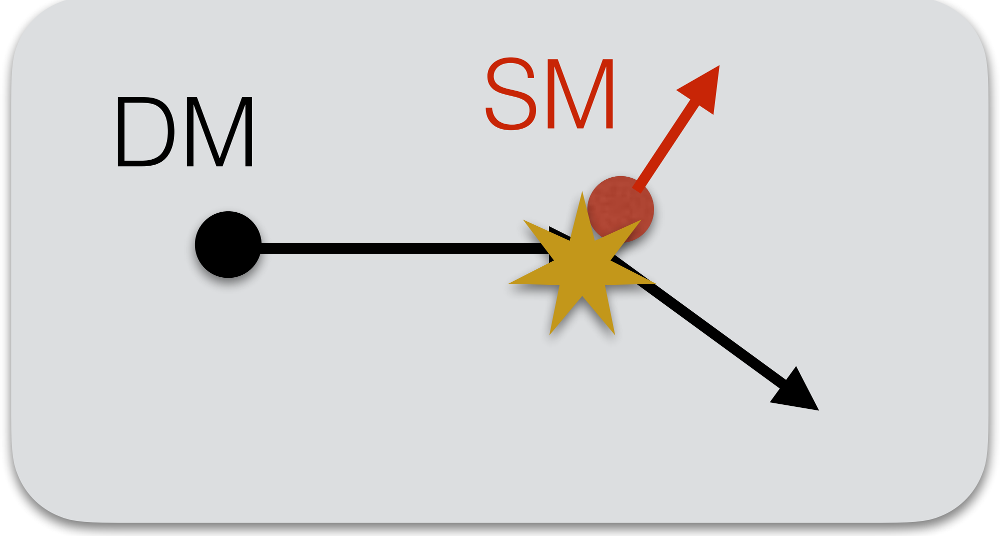




Consider:

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

Low-mass WIMP Challenge



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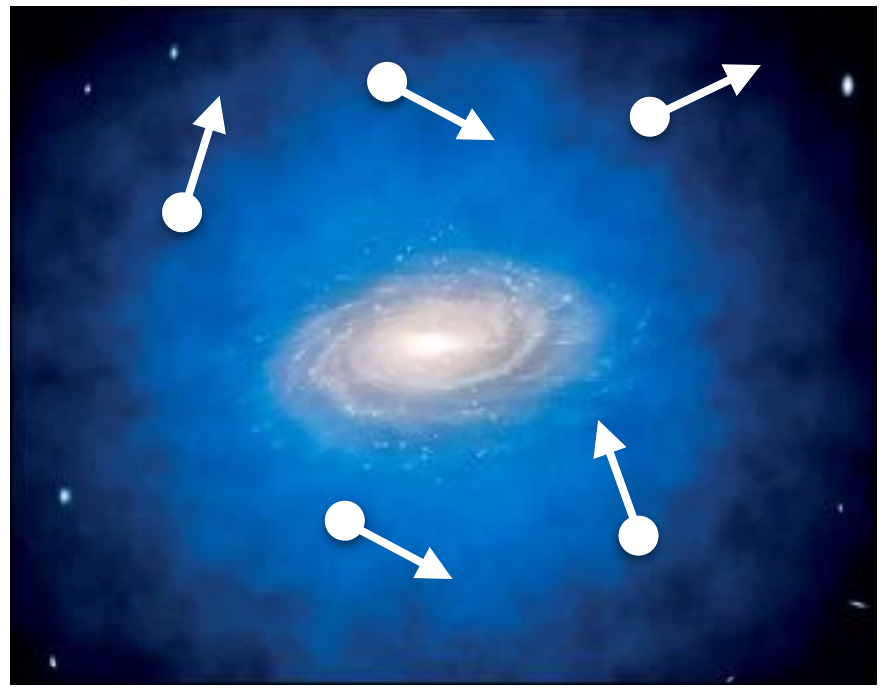

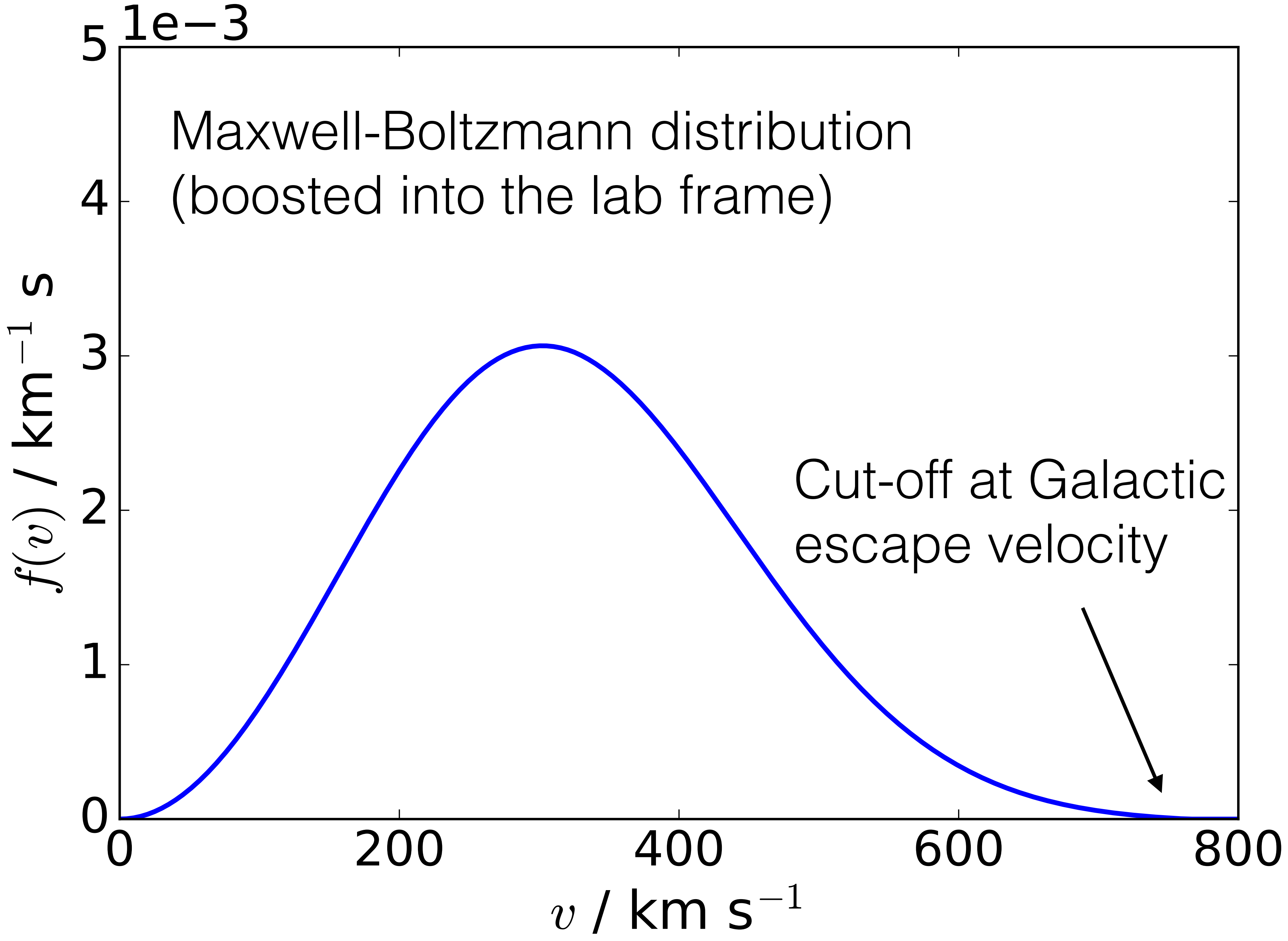

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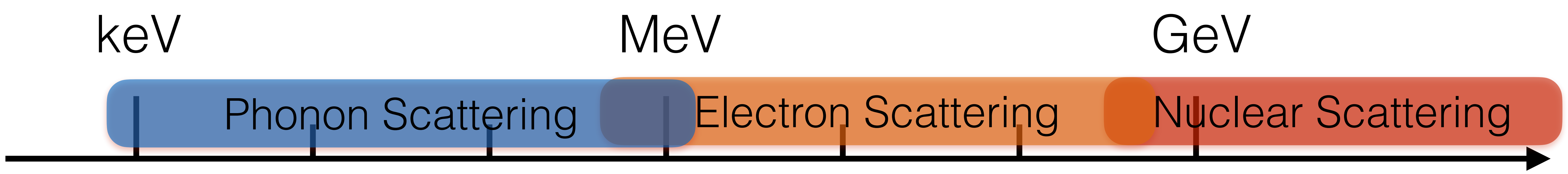
DM mass ranges:



DAMIC-M **(Dark Matter in CCDs at Modane)**

Charge Coupled Devices (CCDs) - pixellated ionisation detectors to look for DM-electron interactions. **Skipper** readout allows multiple non-destructive readout of a single pixel, leading to single-electron resolution!

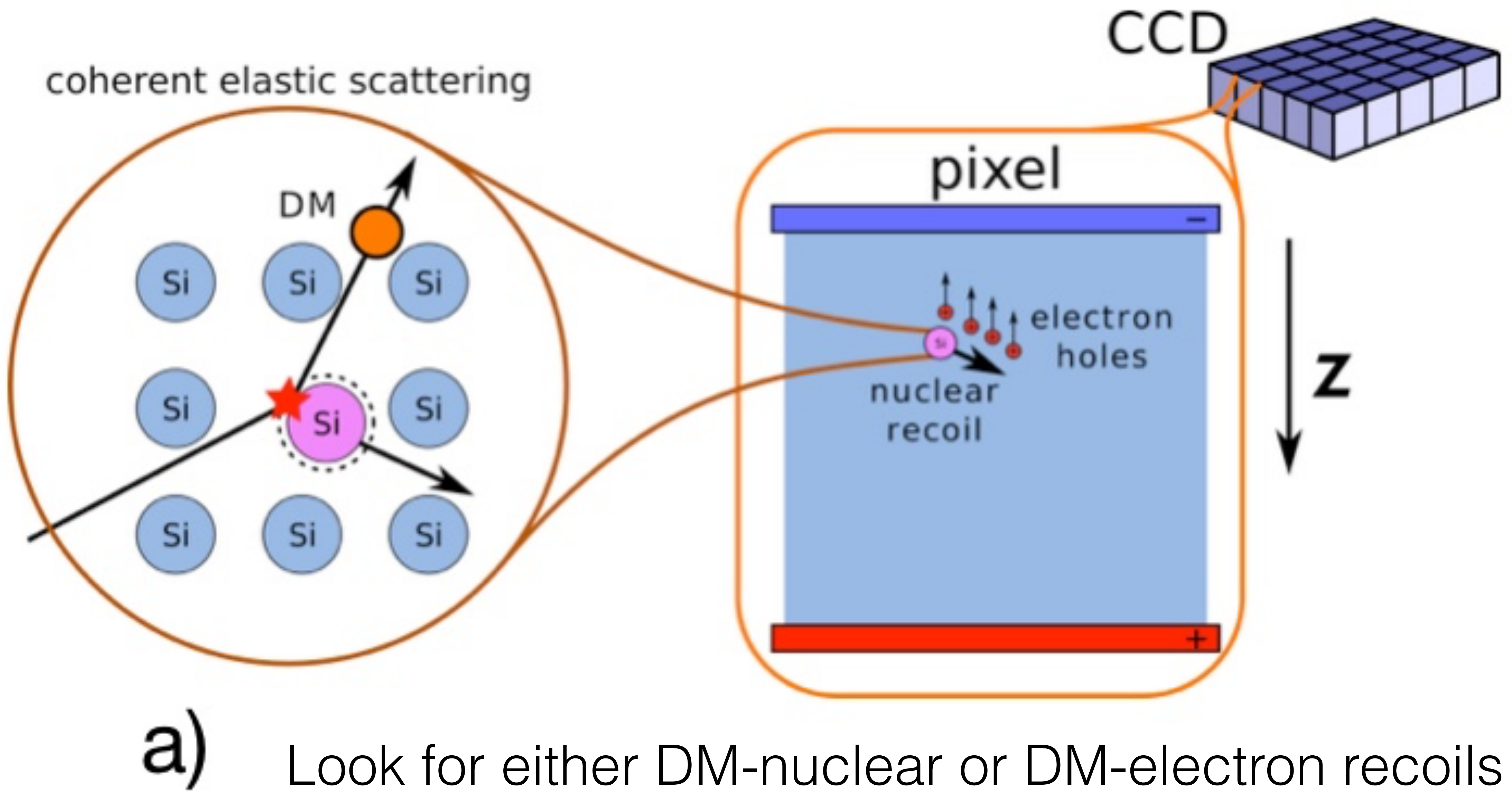
- **Low Background Chamber (LBC):** a prototype for DAMIC-M with two skipper CCDs to test electronics, backgrounds and do initial science

- **DAMIC-M**: full kg-scale CCD detector (~100 CCD modules). Modules currently being tested. Installation to be begin March/April 2025 in Modane, and science data-taking to start Fall 2025.

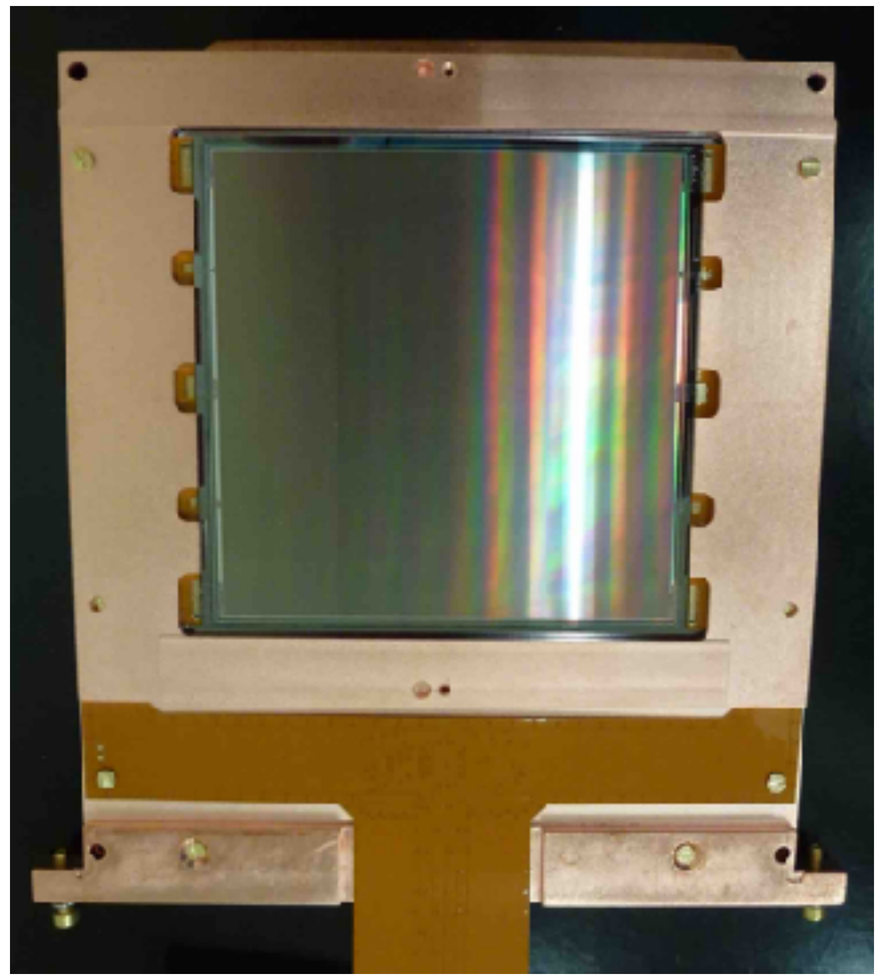
- **Oscura:** 4 year DOE R&D project to develop a 10kg detector

[DAMIC-M Collaboration, 2210.12070, 2407.17872]
[Oscura Collaboration, 2202.10518]

[arXiv:2007.15622]



Look for either DM-nuclear or DM-electron recoils

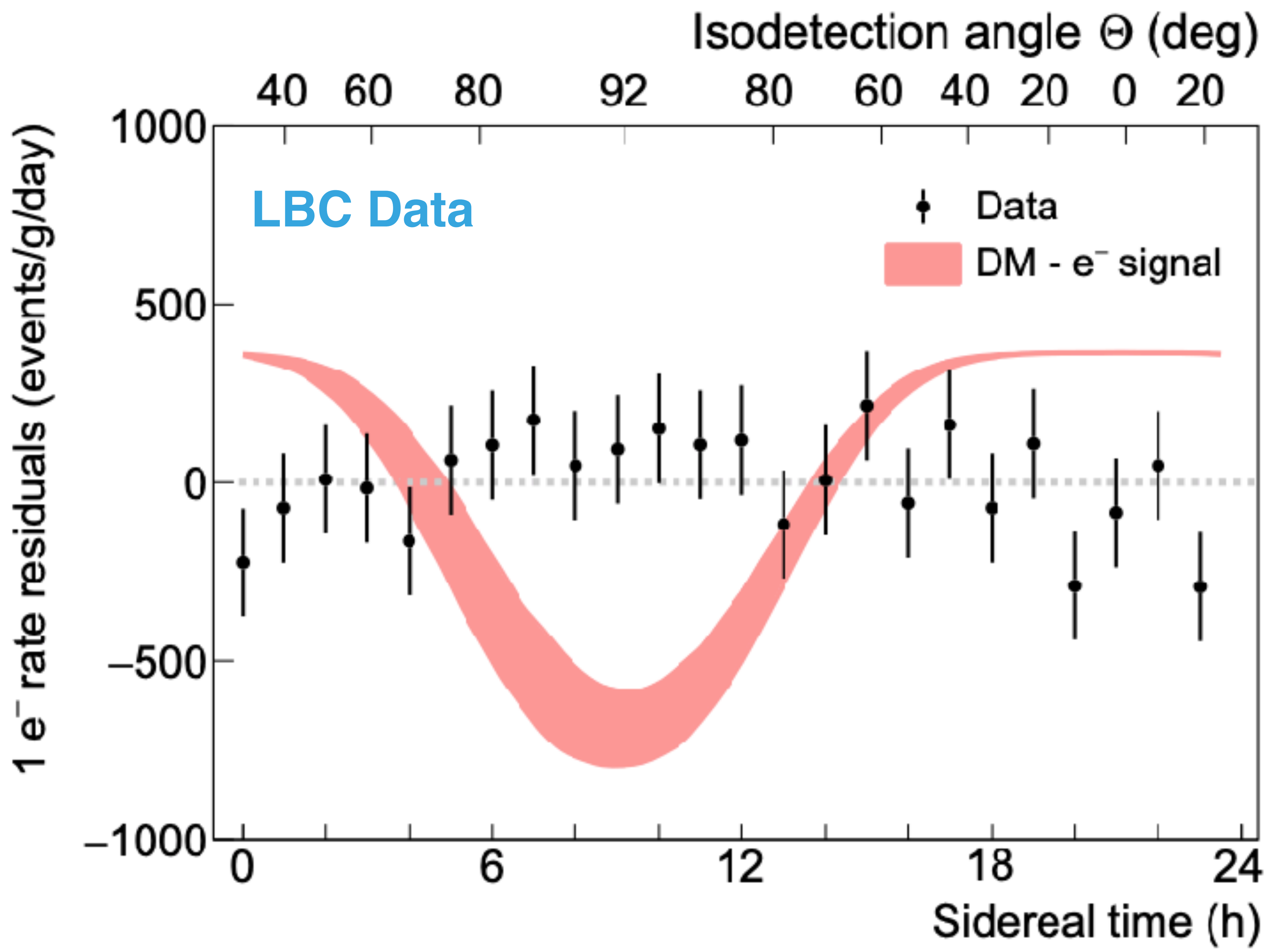


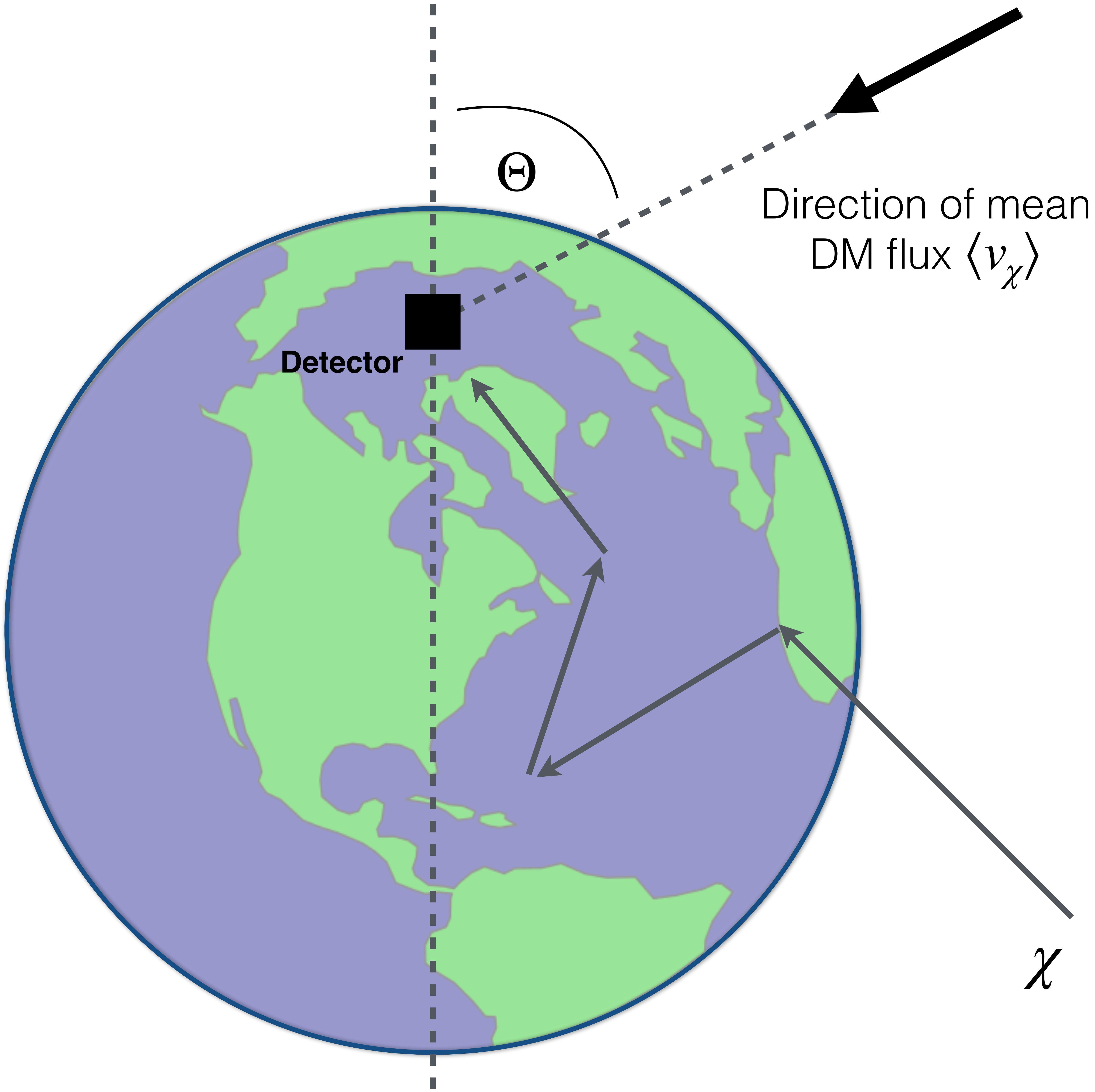
Earth-Scattering

If scattering cross-section is large enough, DM velocity distribution $f(\mathbf{v})$ may be affected by DM interactions in the Earth

At certain times of day, the Earth may act as a shield and at other times, it may act as a reflector!

→ **Daily Modulation** of the DM Scattering Rate!





[See e.g. **BJK** et al., 1611.05453;
Emken & Kouvaris, 1706.02249; BJK, 1712.04901;

Earth-Scattering

[DAMIC-M Collaboration (including **BJK**), 2307.07251]

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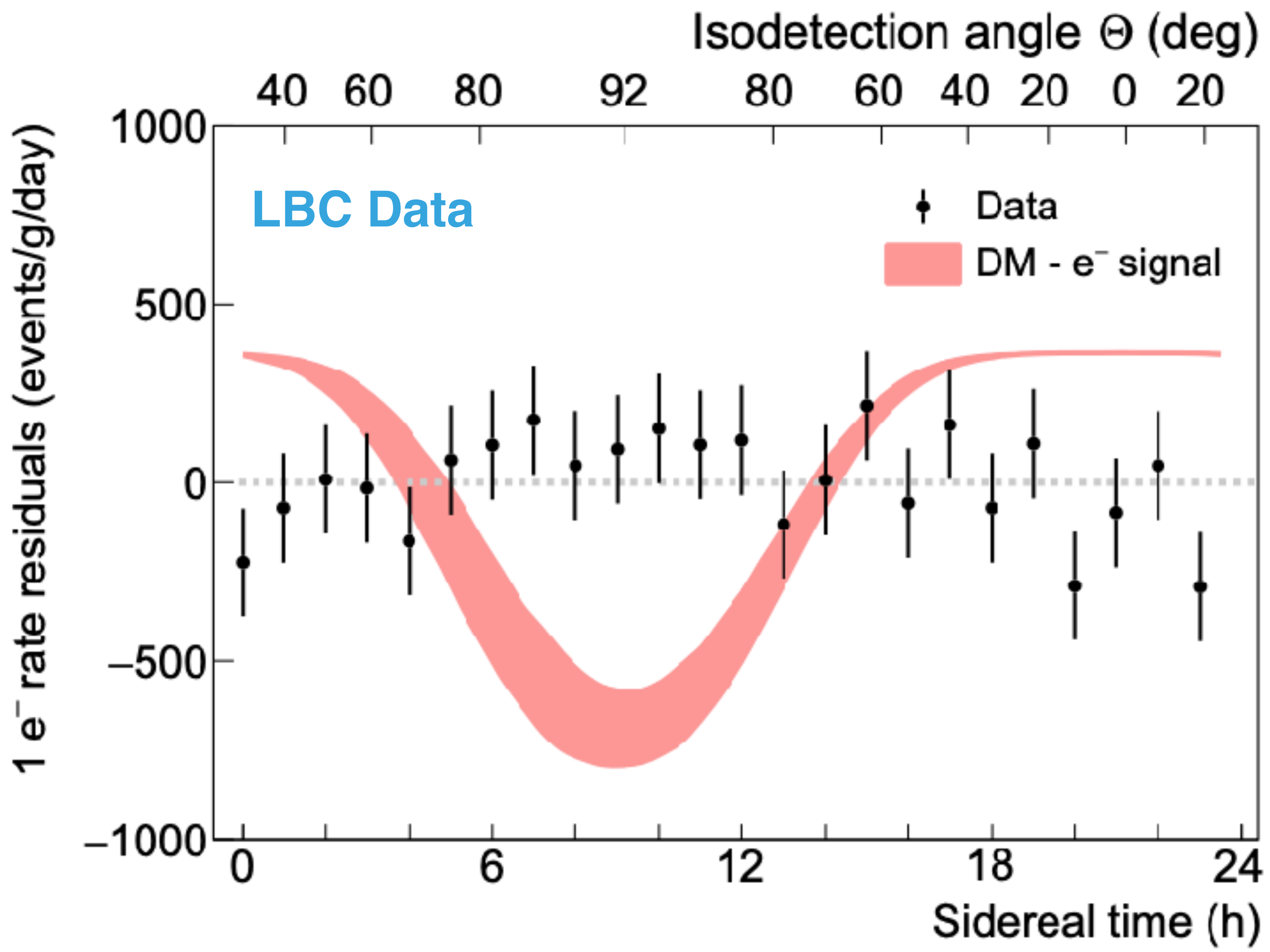
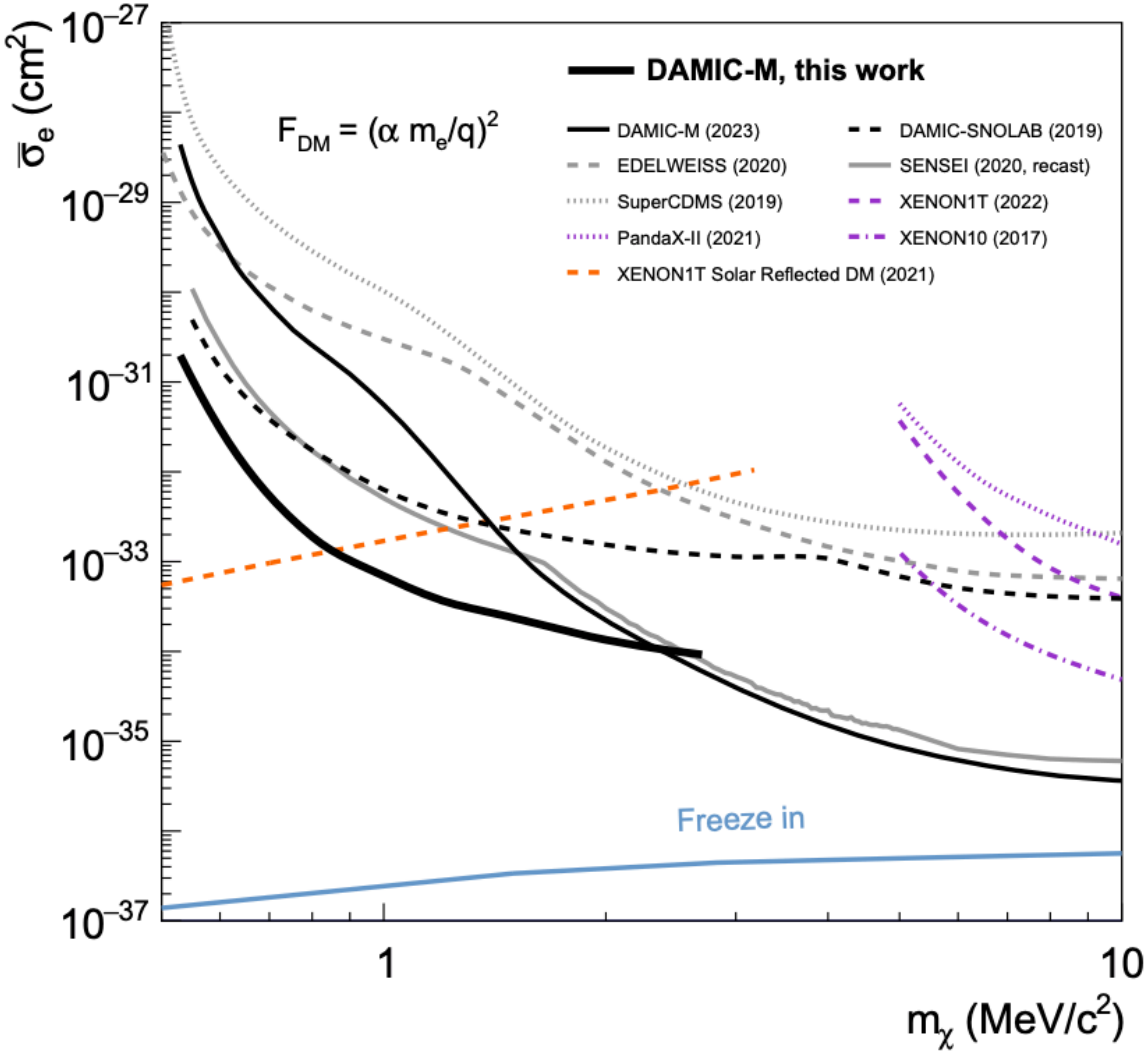
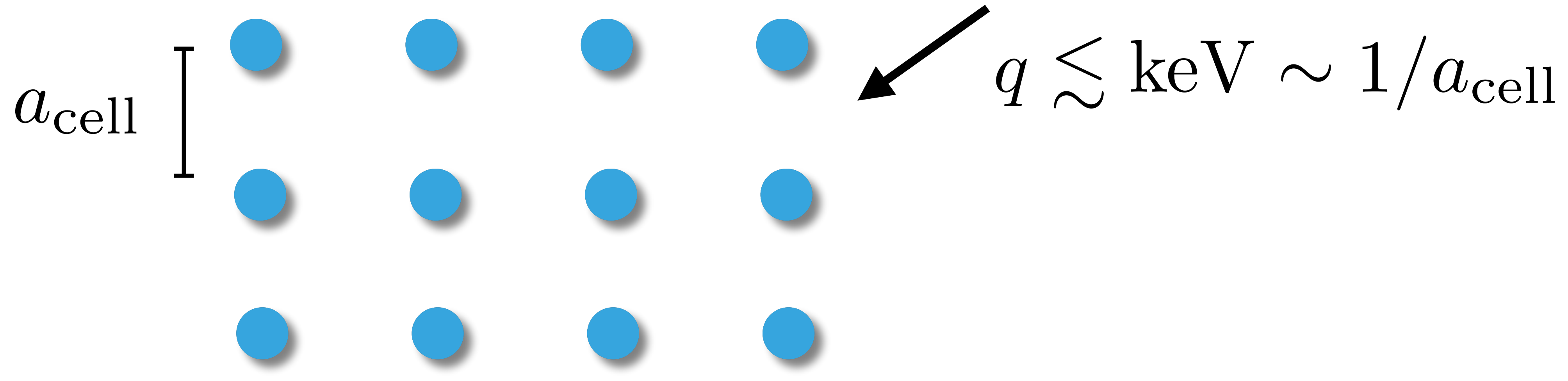




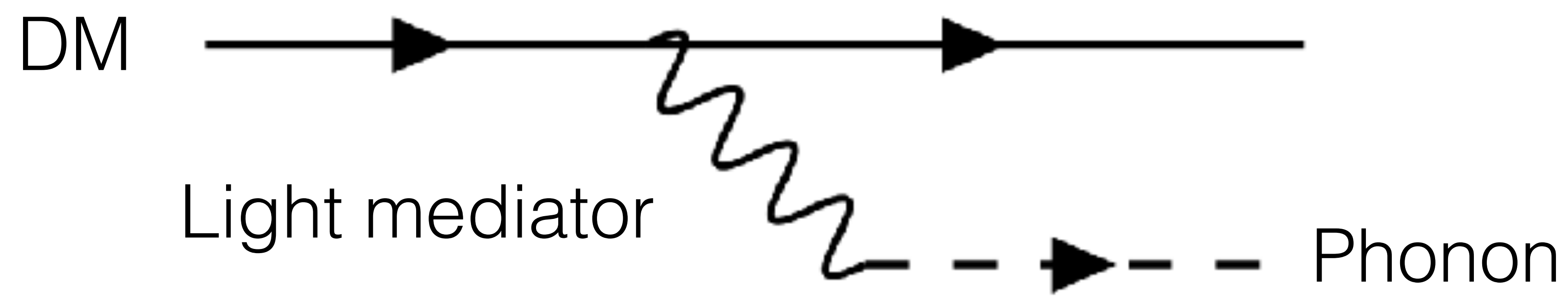
Analysis of new LBC Data (~1 kg-day) underway!

DM-Phonon Scattering



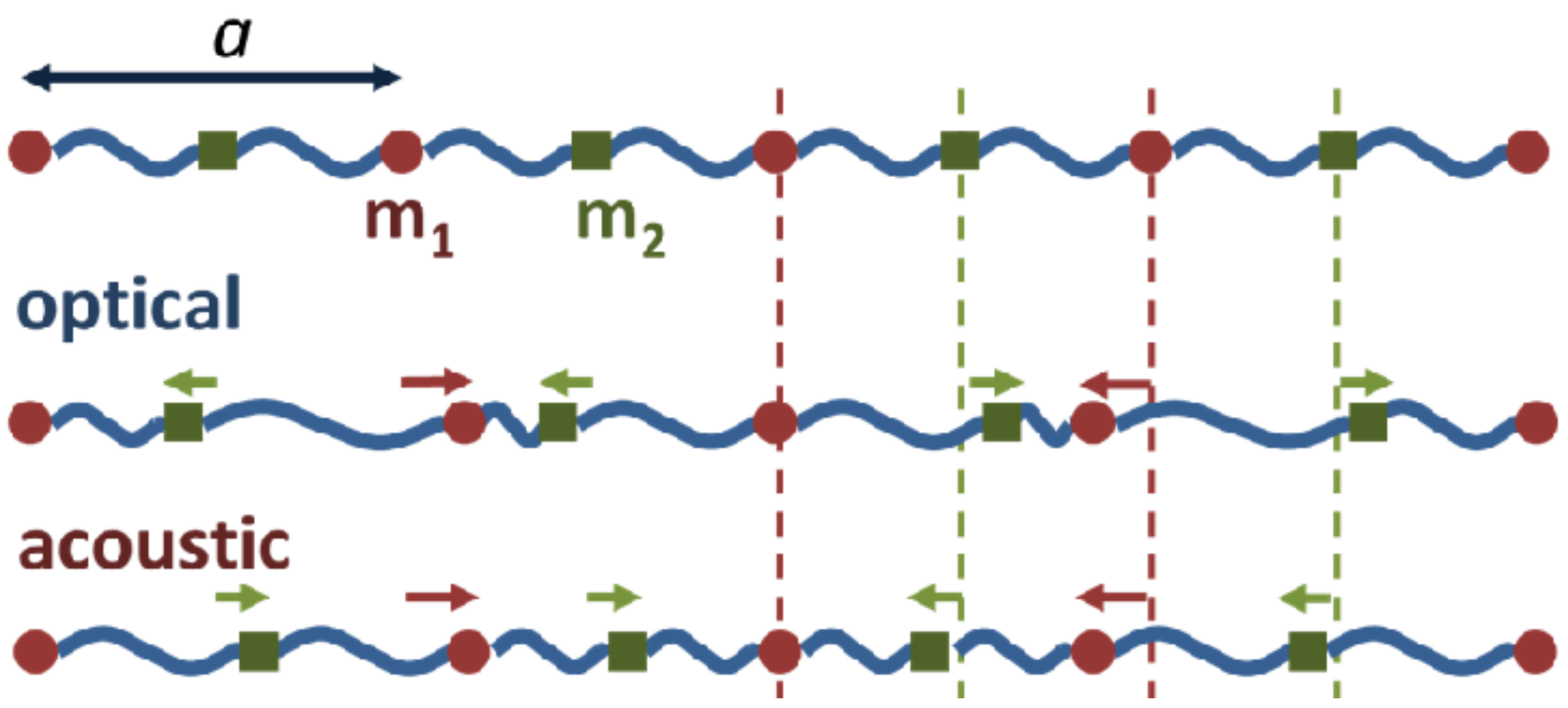
For sufficiently light DM, $m_\chi < 1\,\text{MeV} \Rightarrow q < \text{keV}$

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]

Quantum Sensors for Dark Matter

IFCA is involved in R&D efforts to develop a phonon detector for DM.

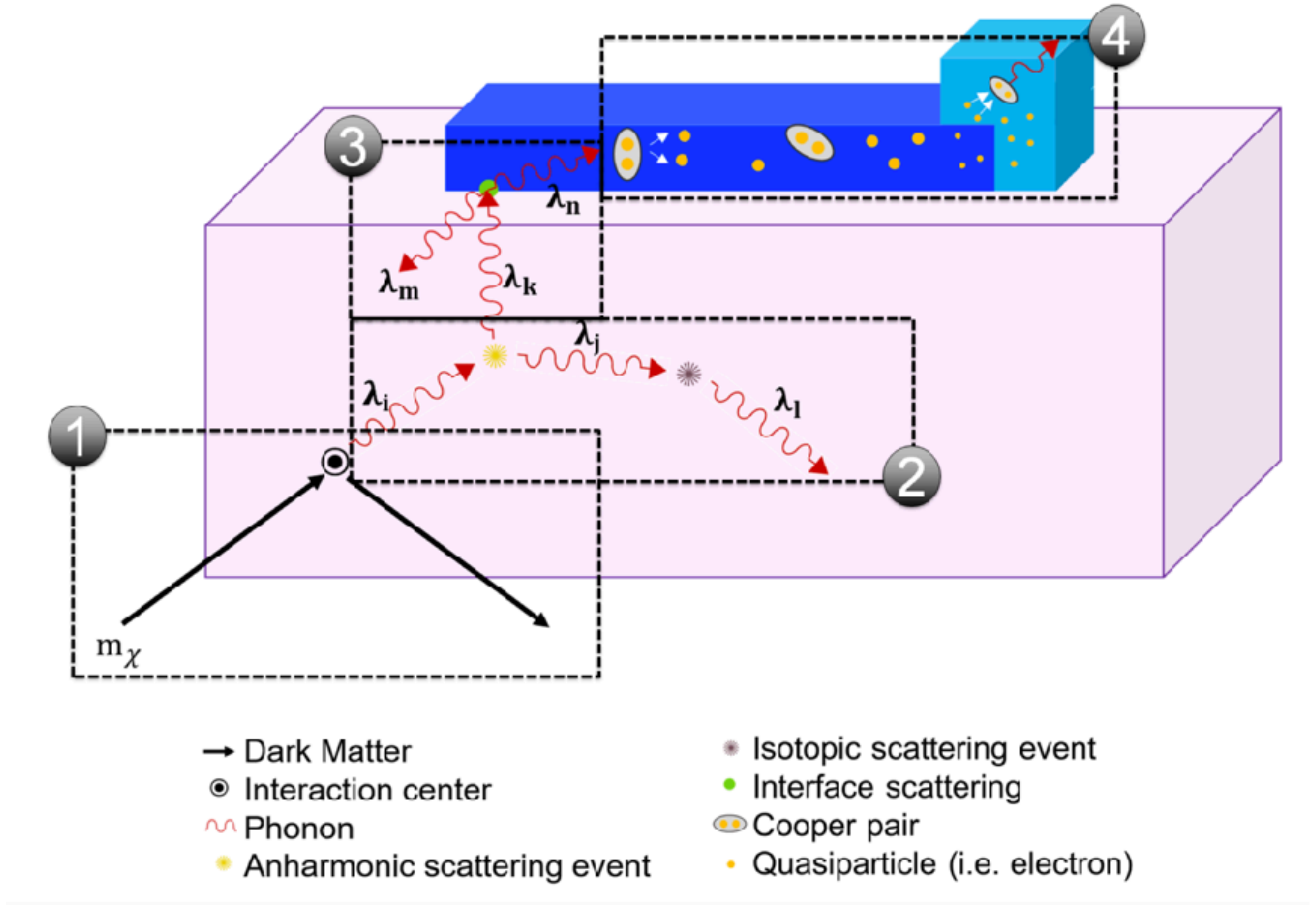
Conceptual design stage:

Estimate of DM interaction rates in different targets

Determine best target, required target mass and possible sensor configuration

Simultaneously developing superconducting TES sensor for readout.

Quasi-particle Trap Assisted Transition Edge Sensor (QET)



[Raya-Moreno, **BJK**, Fàbrega & Rurali, 2311.11930]

Part of the CSIC Interdisciplinary Thematic Platform (PTI) on Quantum Technologies (with IFCA, ICMAB, IMB and INMA). Would extend **sensitivity down to ~keV masses.**

Canfranc Axion Detection Experiment

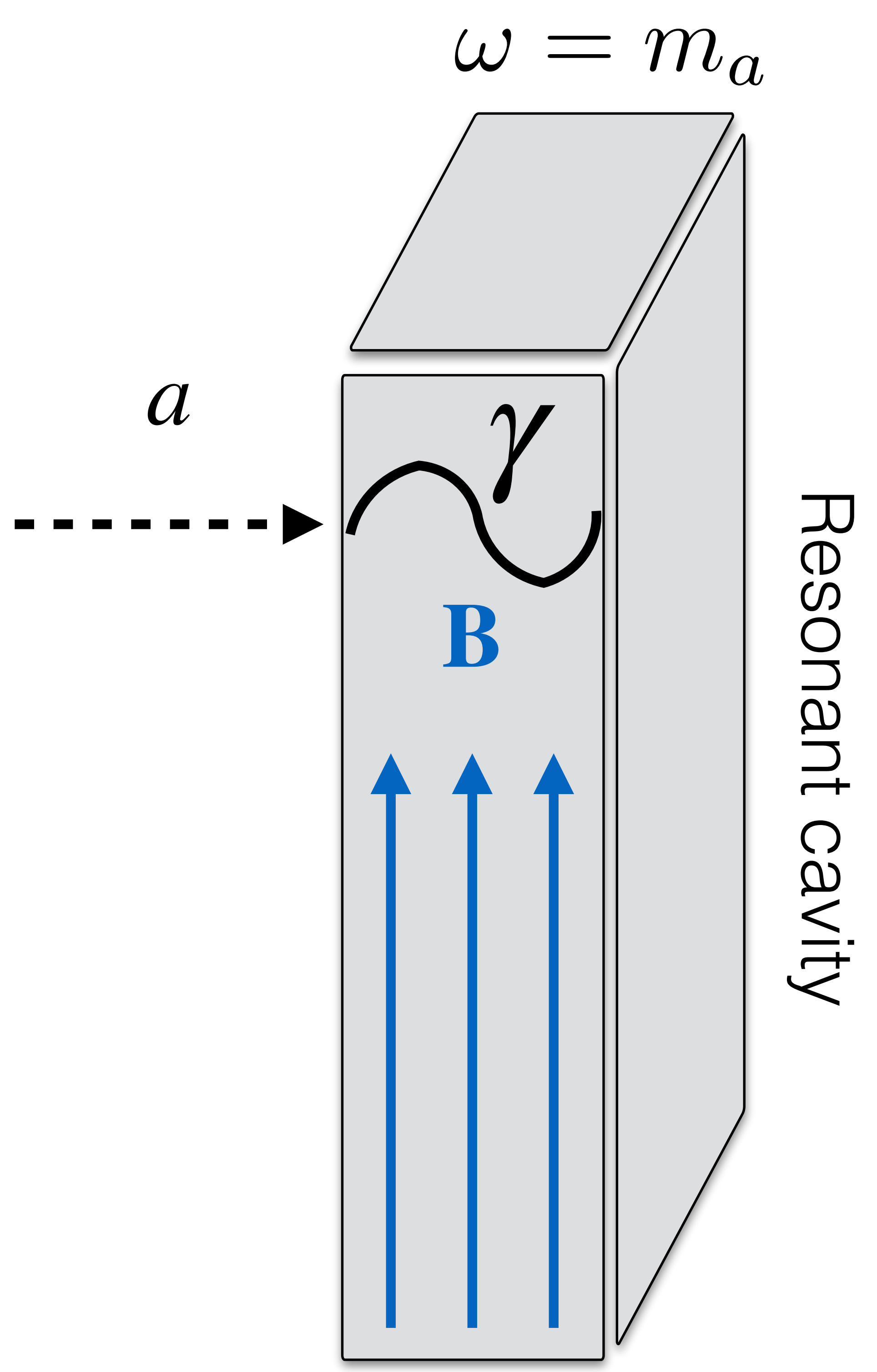
Below ~keV masses, DM must be bosonic e.g. Axions and Axion-like particles. In a strong magnetic field, these can be converted into photons!

The **Canfranc Axion Detection Experiment (CADEx)** will make use of Kinetic Inductance Detectors (KIDs) originally developed for CMB polarisation measurements to search for axion-photon conversion in the unexplored mass range 330-460 μeV ($f \in [86, 111]\,\mathrm{GHz}$)

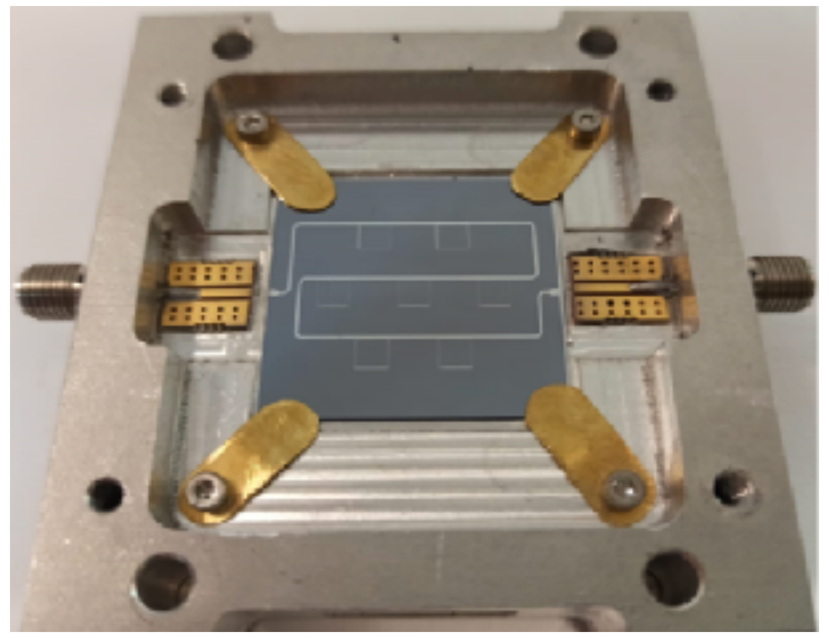
A **pathfinder phase** in a mK dilution cryostat will be operated at IFCA, with IFCA is playing a key role in instrumentation and science analysis.

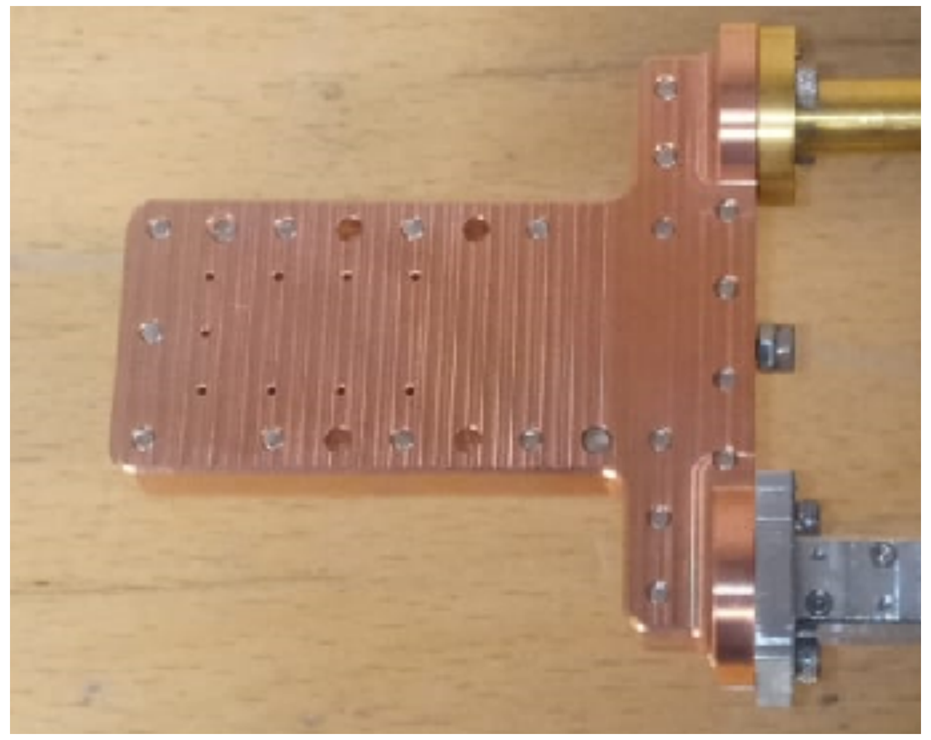
Full experiment is planned for operation at Canfranc Underground Lab (LSC).

[CADEx Collaboration (including **BJK**), 2206.02980]



KIDs





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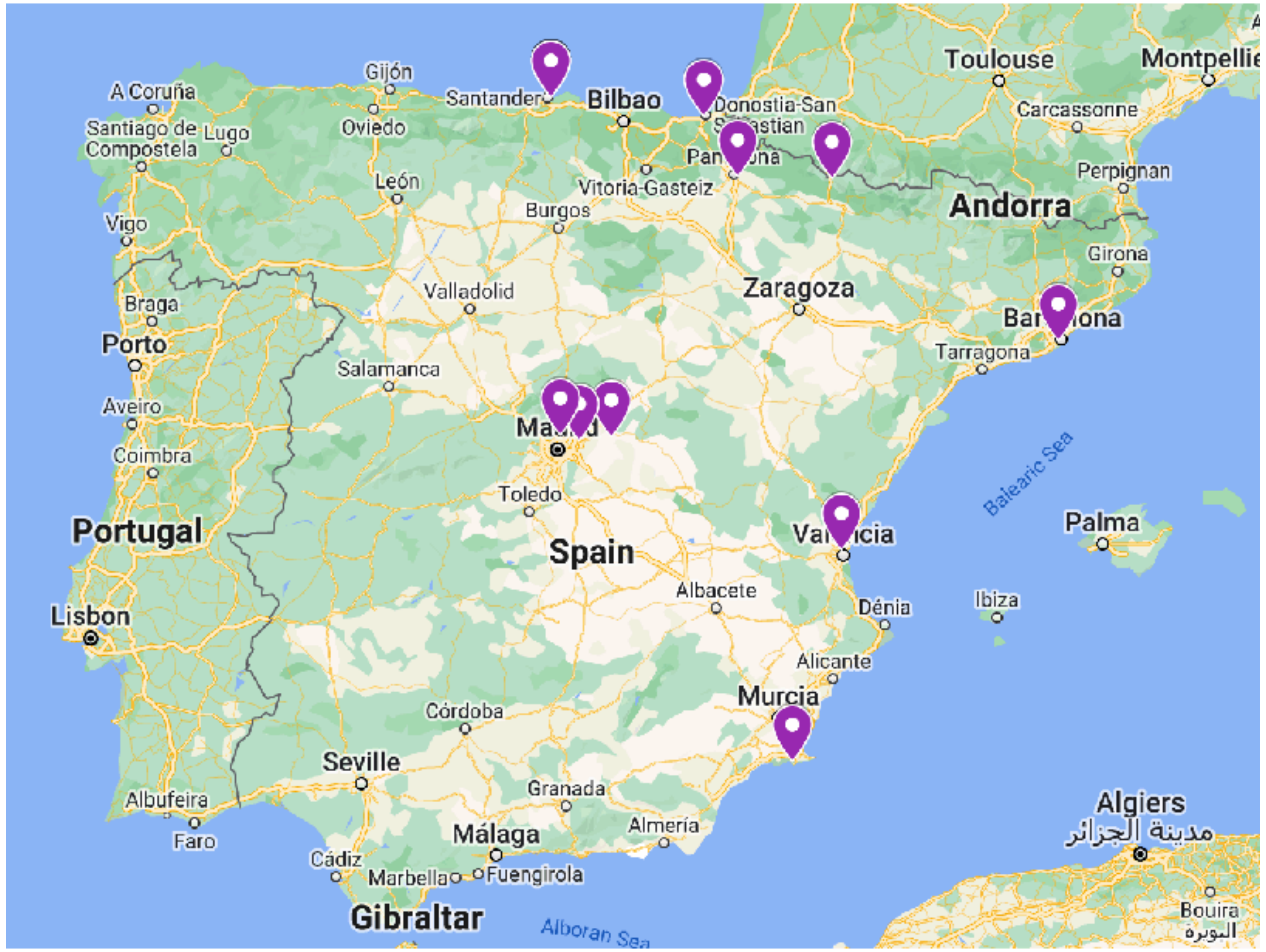
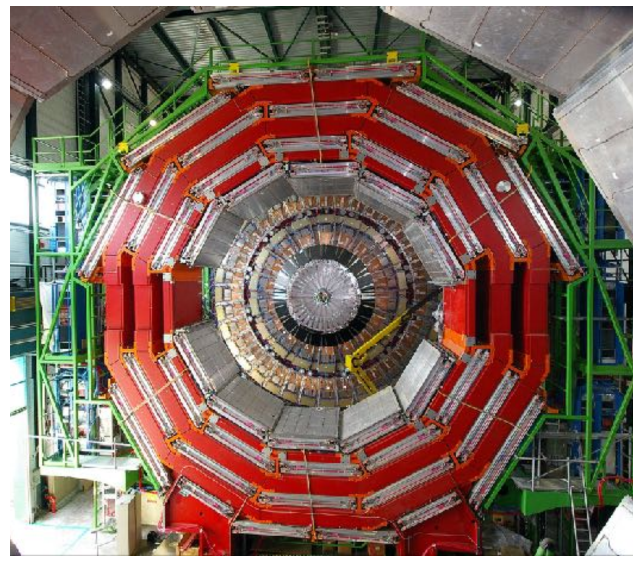
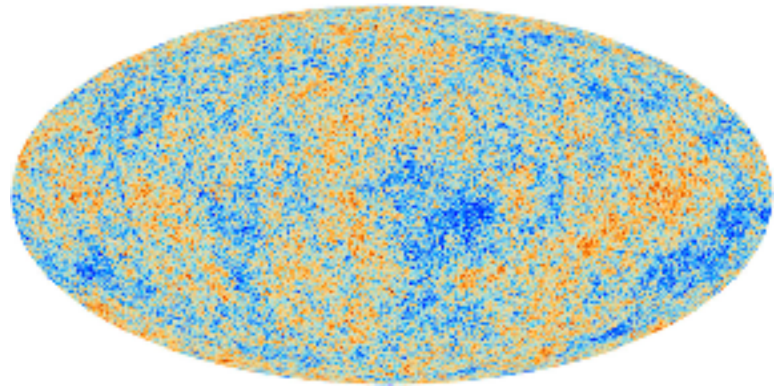


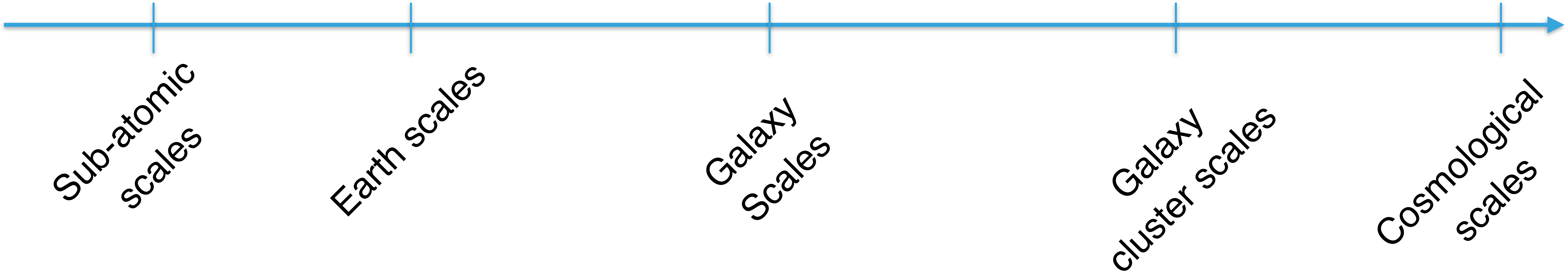
Dark Matter on all scales

CMS





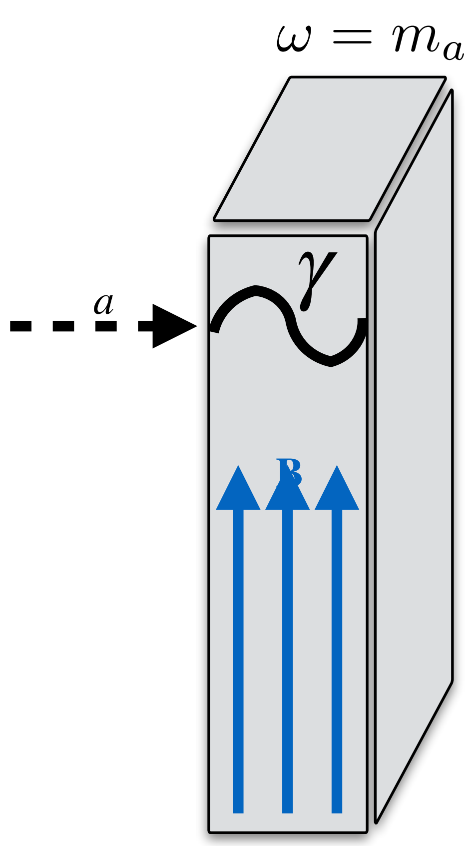
CMB



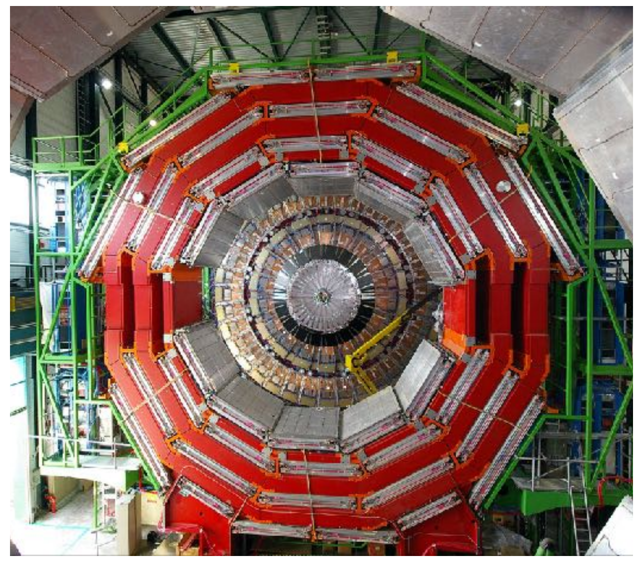
Dark Matter on all scales

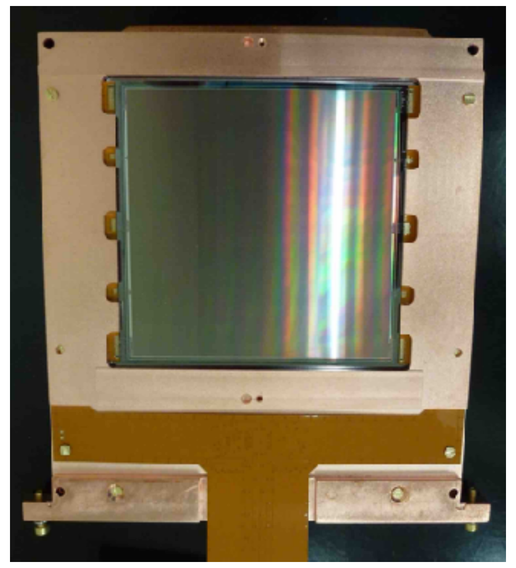
Instituto de Física de Cantabria

CMS

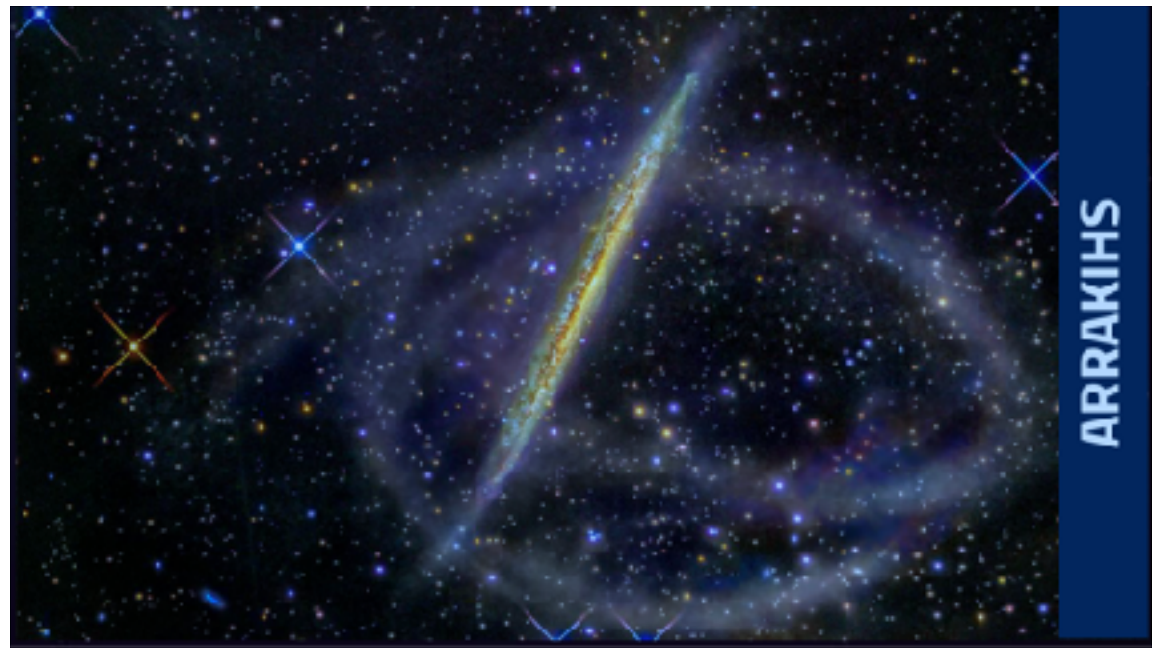


CADEx

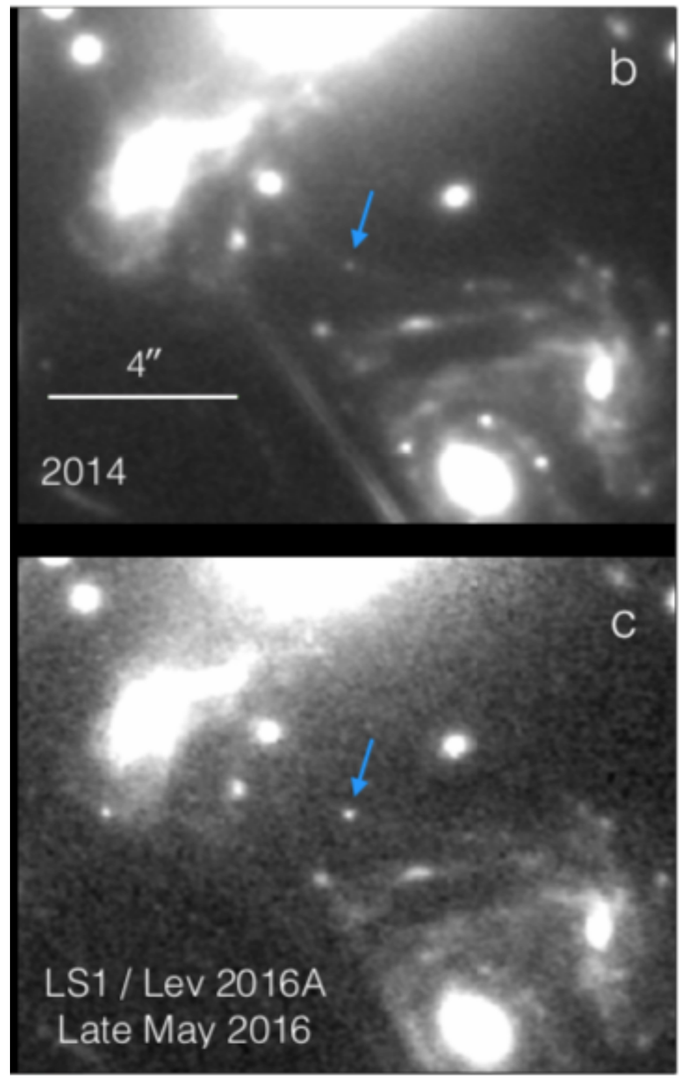




DAMIC-M

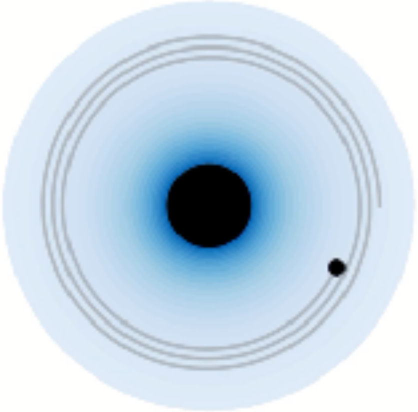


ARRAKIHS

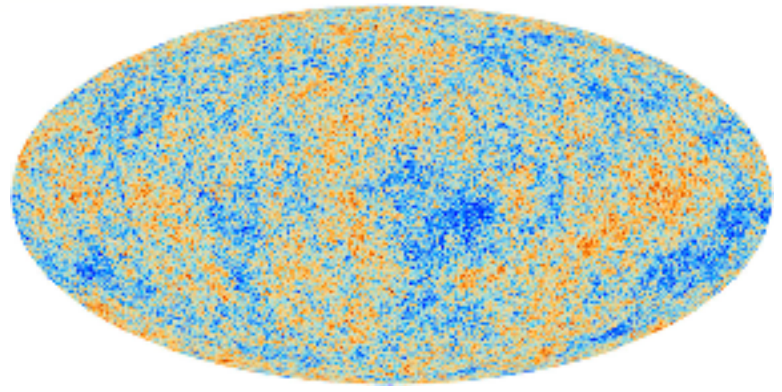


Lensing & PBHs

Line intensity mapping (LIM)*



Gravitational Waves (GWs)*



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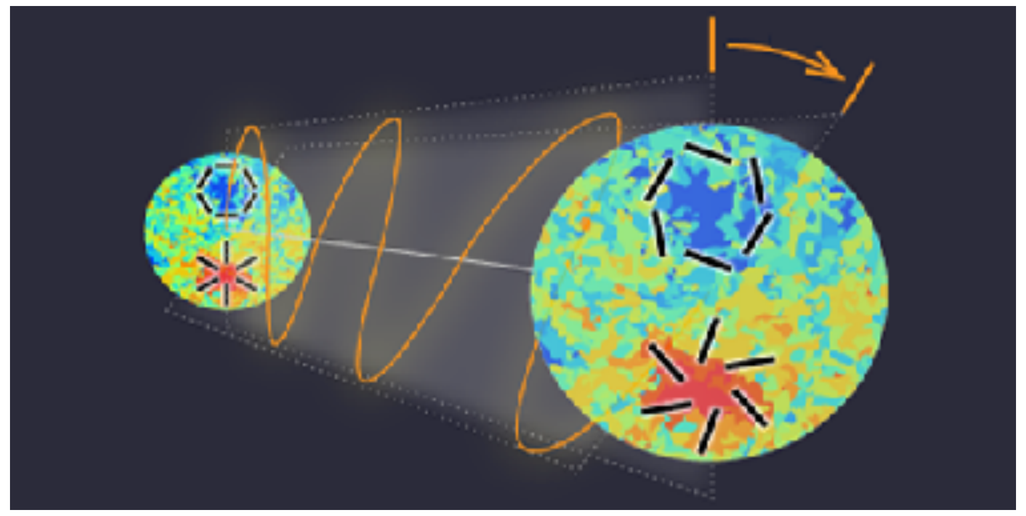

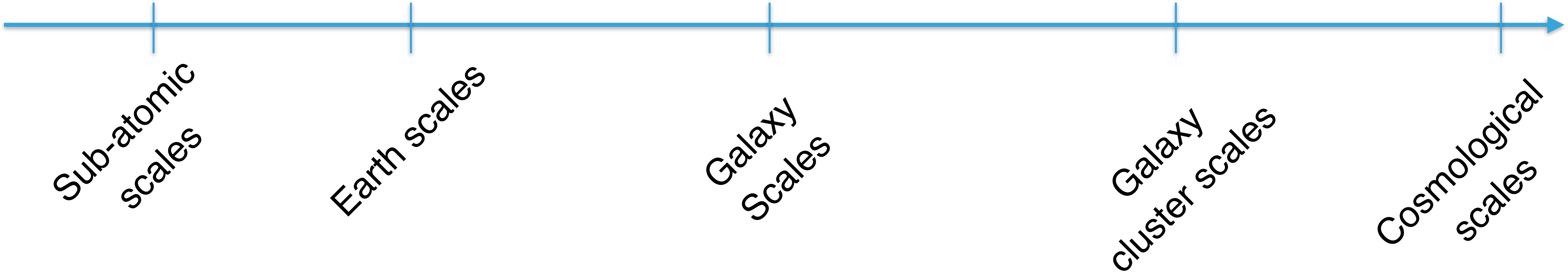

“Dark Collaboration” at IFCA

The **Dark Collaboration** is an informal ‘working group’ with the goal of coordinating Dark Matter research at IFCA, and developing new research lines in this direction.

Formed in May 2020, it now consists of >30 active members: PhDs, Postdocs and Staff from IFCA and ‘nearby’ institutes (UPV/EHU, IFT-Madrid).

A number of joint activities between Cosmology and Particle Physics groups:

- **Teaching:** Joint supervision of Master and PhD students, as well as contributions to the Master program “Master in Particle Physics and Physics of the Cosmos”
- Organisation of **DM conferences** in Santander in 2016, 2018, 2021, 2023. Dark Matter 2025 planned for June 2025.

DARK MATTER 2025

FROM THE SMALLEST TO THE LARGEST SCALES

2 - 6 June 2025

Abstract submission now open,
registration to open early 2025

Instituto de Física de Cantabria

Webpage: indico.ifca.es/e/DM2025

Info: dm_santander@ifca.unican.es

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iFCA
Instituto de Física de Cantabria

Thank you!

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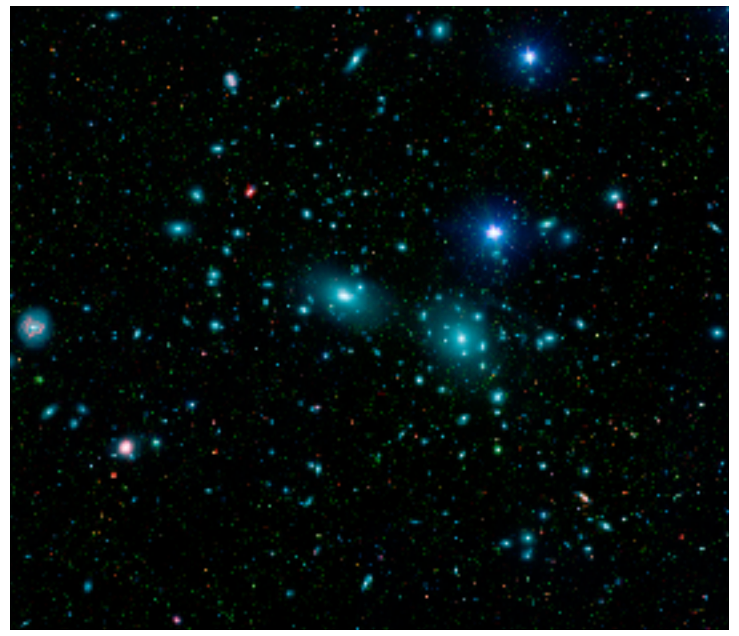
Backup Slides

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

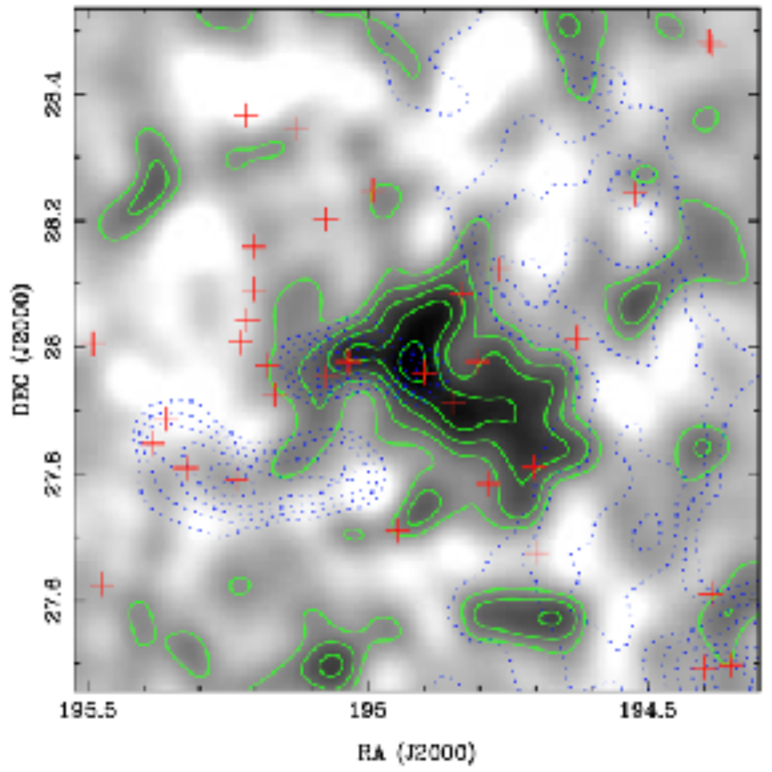
E.g. Coma Cluster



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

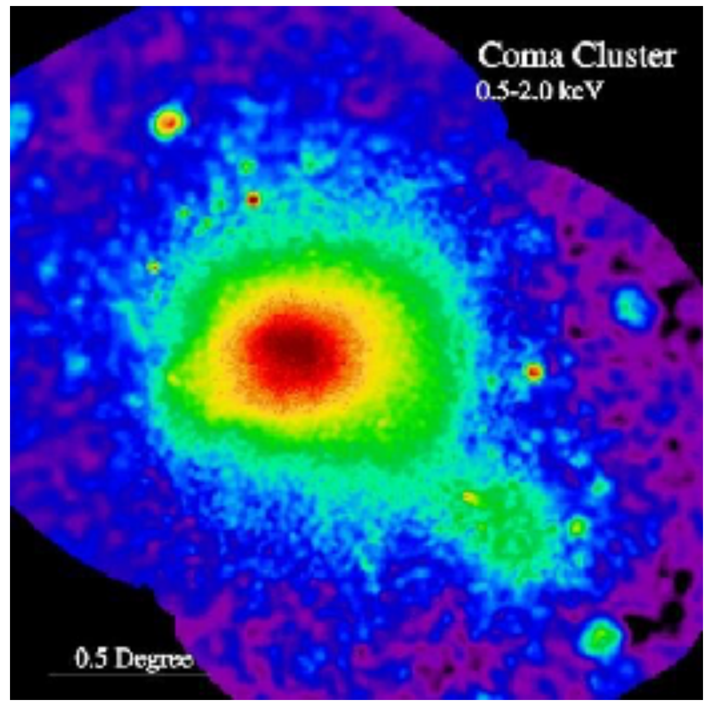
$$\langle T \rangle \approx \frac{1}{2} M_{\rm tot} \sigma_v^2 = -\frac{1}{2} \langle V_{\rm tot} \rangle$$

[0904.0220]



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

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



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]

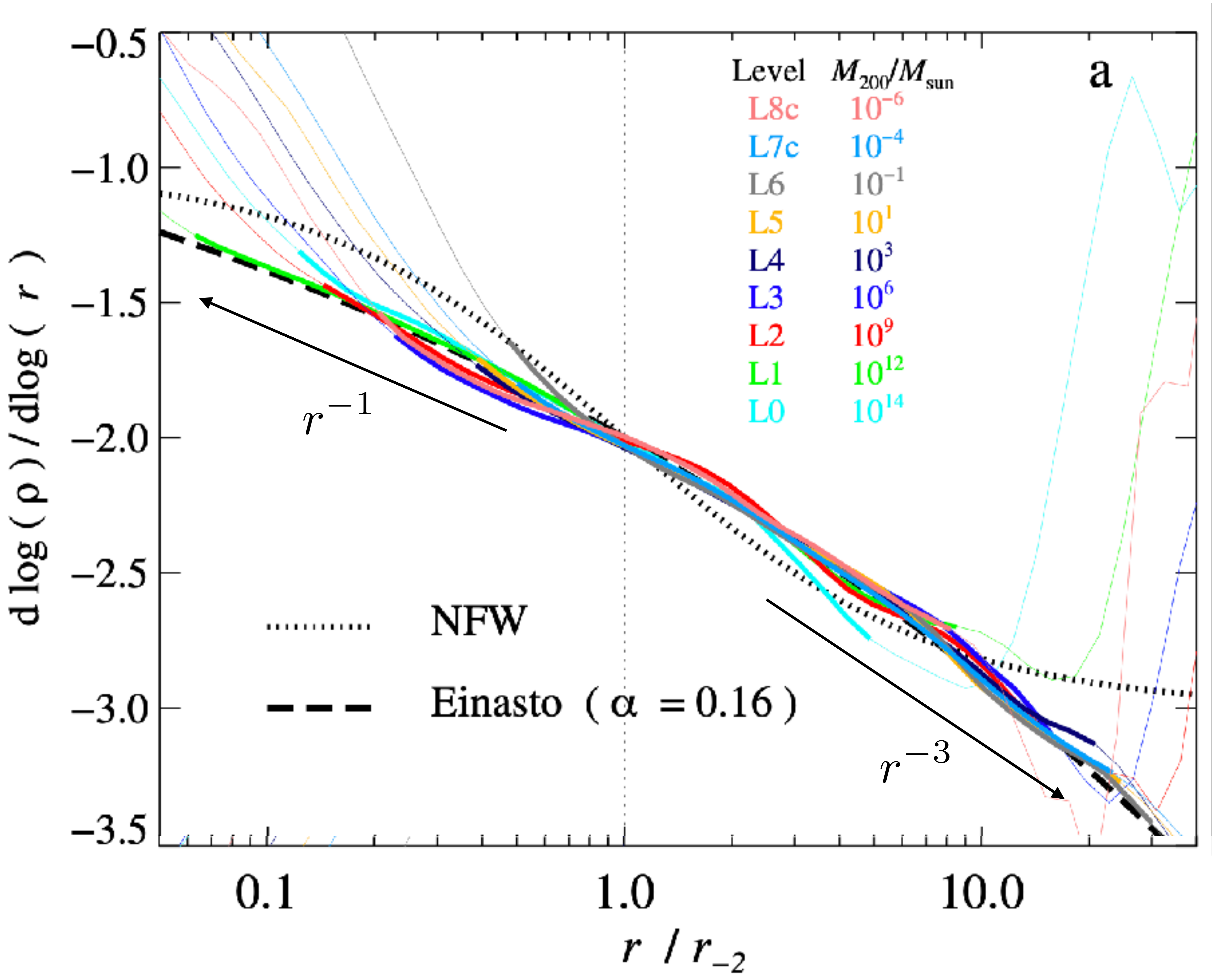
$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

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.



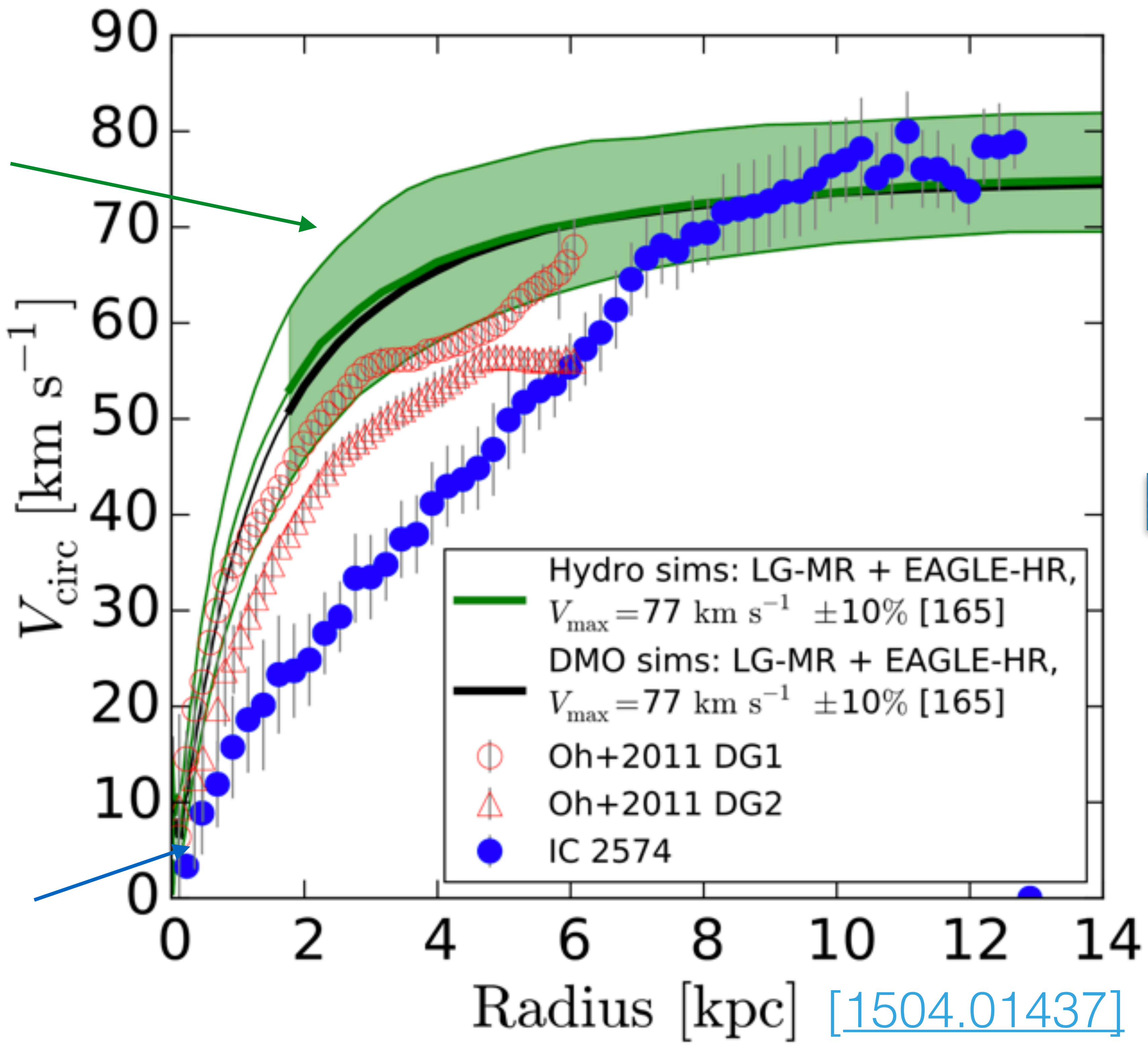
[1911.09720]

Small-scale problems

Core-vs-cusp problem (Now sometimes called the "diversity of rotation curves' problem)

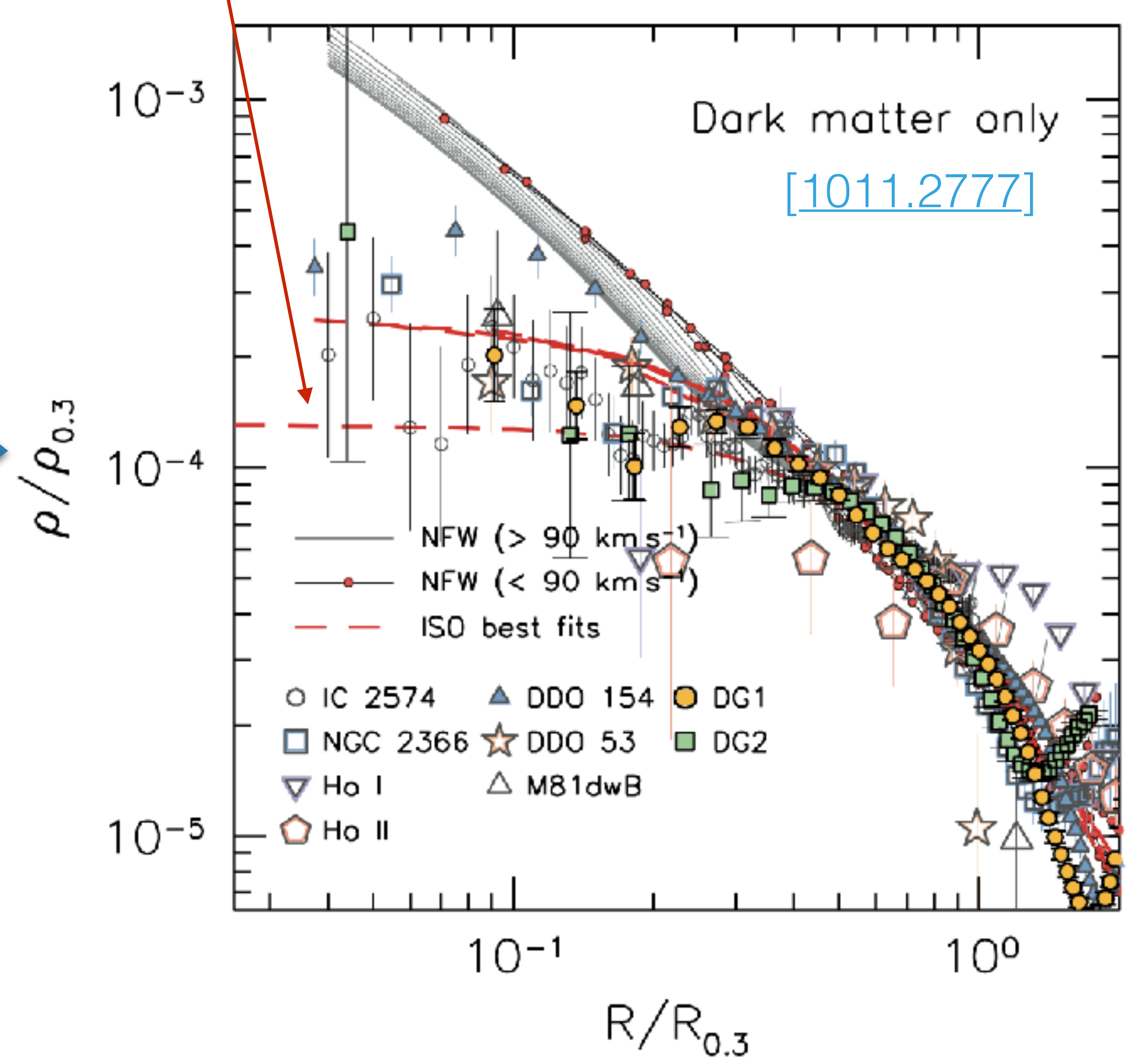
Rotation curve from comparable simulated dwarf galaxies with a 'cuspy' DM density profile

Measured rotation curve



[1504.01437]

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



[1011.2777]

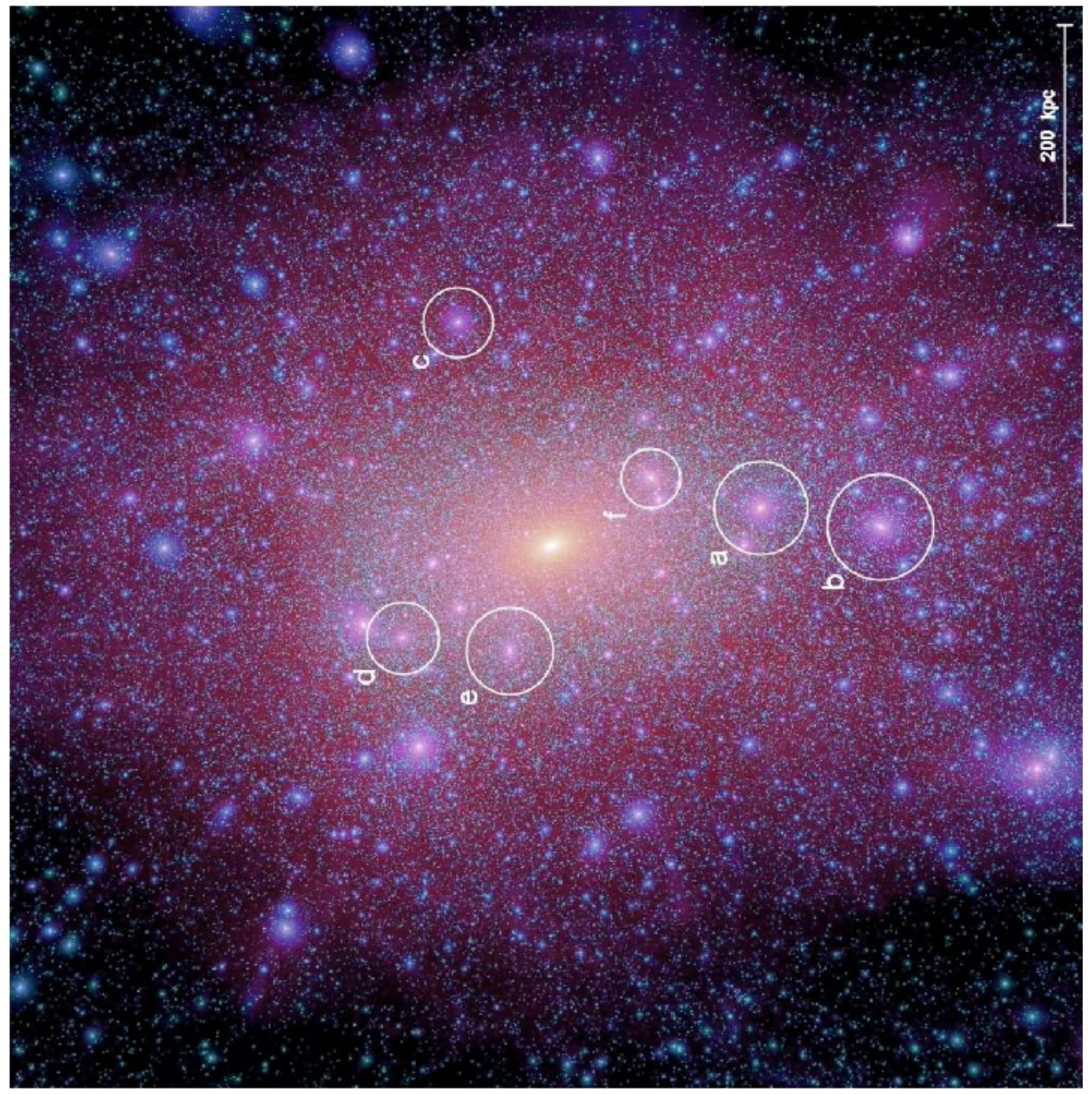
See also "Too big to fail", "Plane of Satellites", and others…

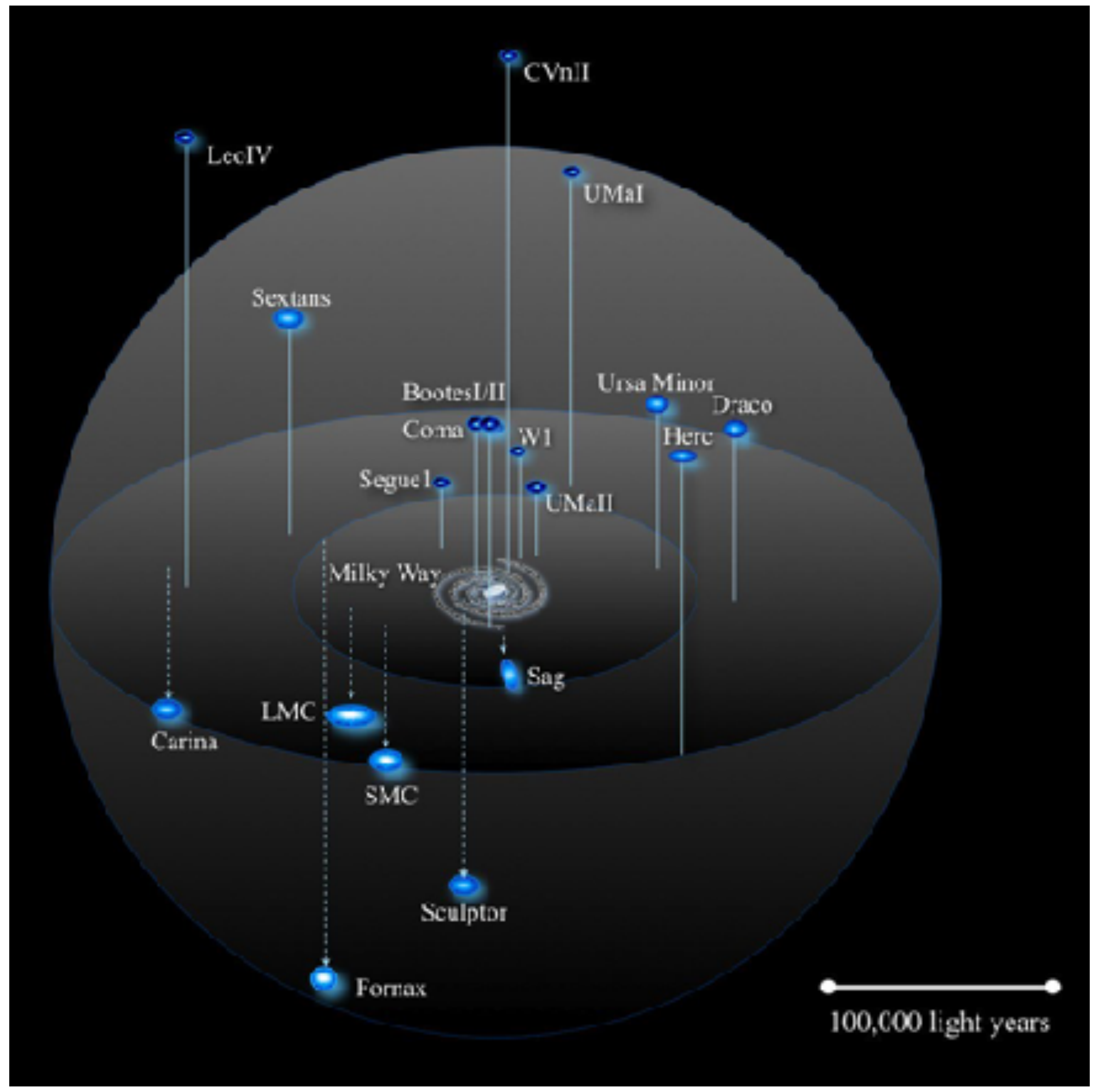
[Sales, Wetzel & Fattahi, 2206.05295]

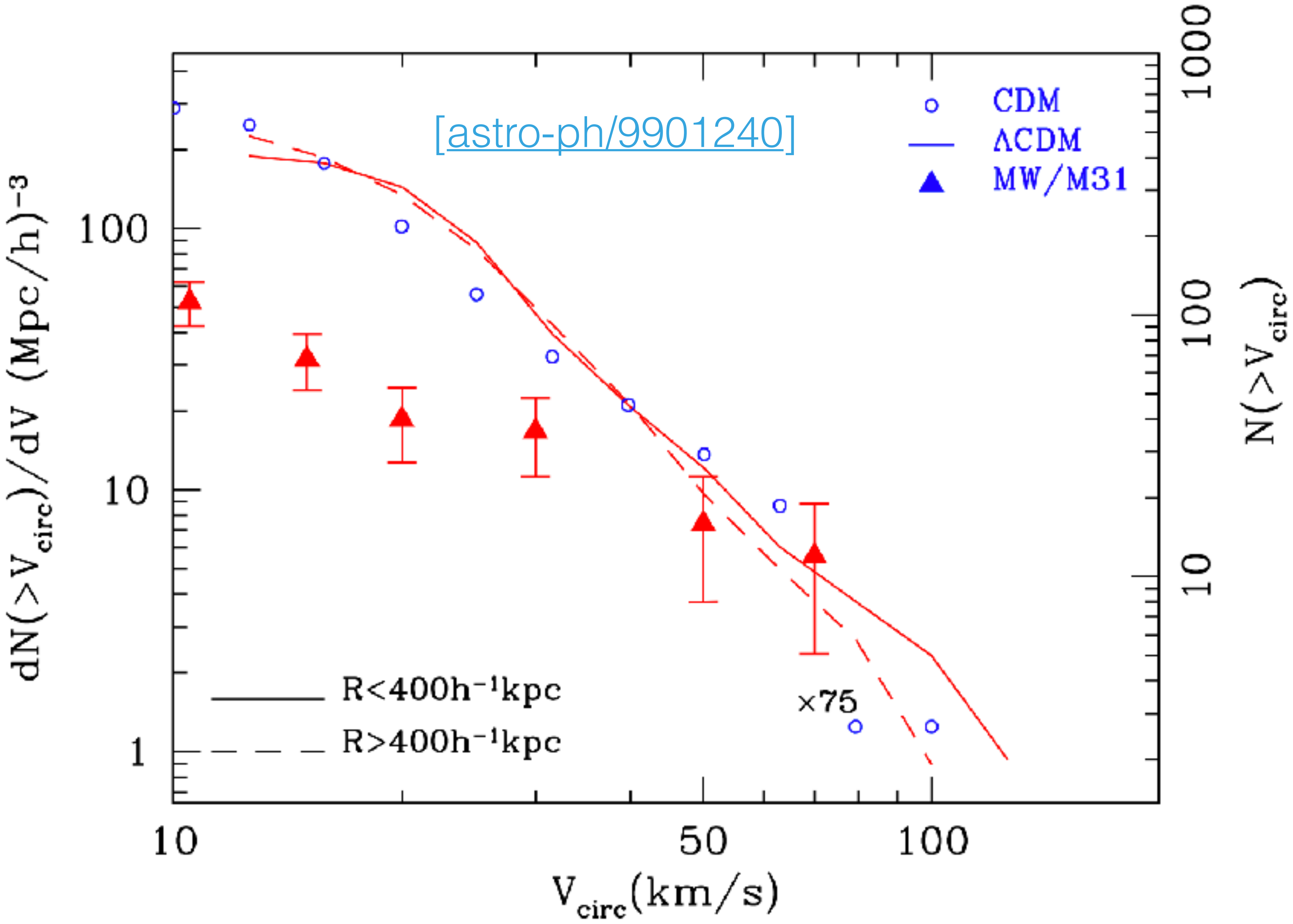
Small-scale problems

Missing Satellites Problem

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







Proxy for dwarf galaxy mass

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

[Sales, Wetzel & Fattahi, 2206.05295]

Galaxy formation is complicated!

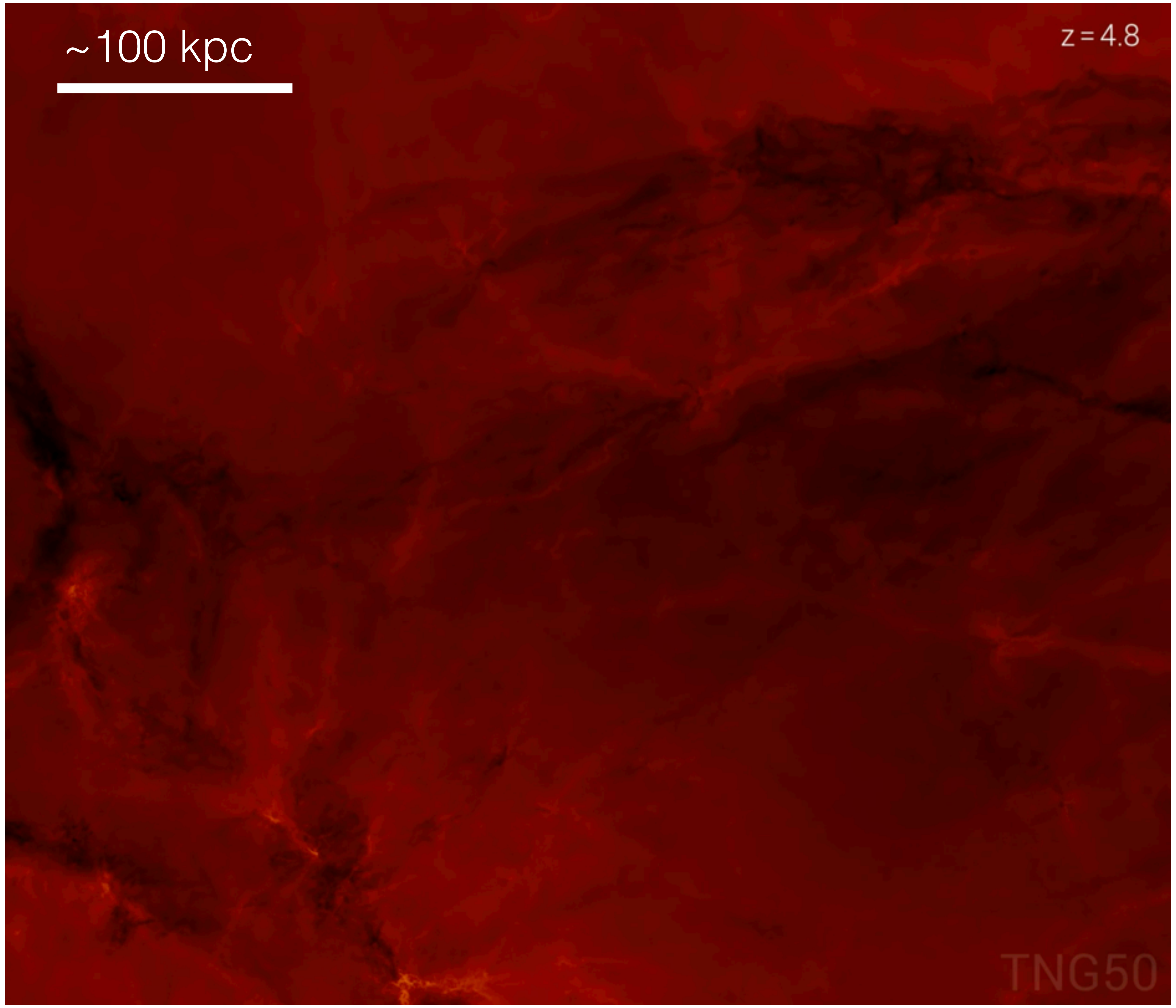
[Full animation available here: https://www.tng-project.org/media/]

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

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

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

IllustrisTNG50



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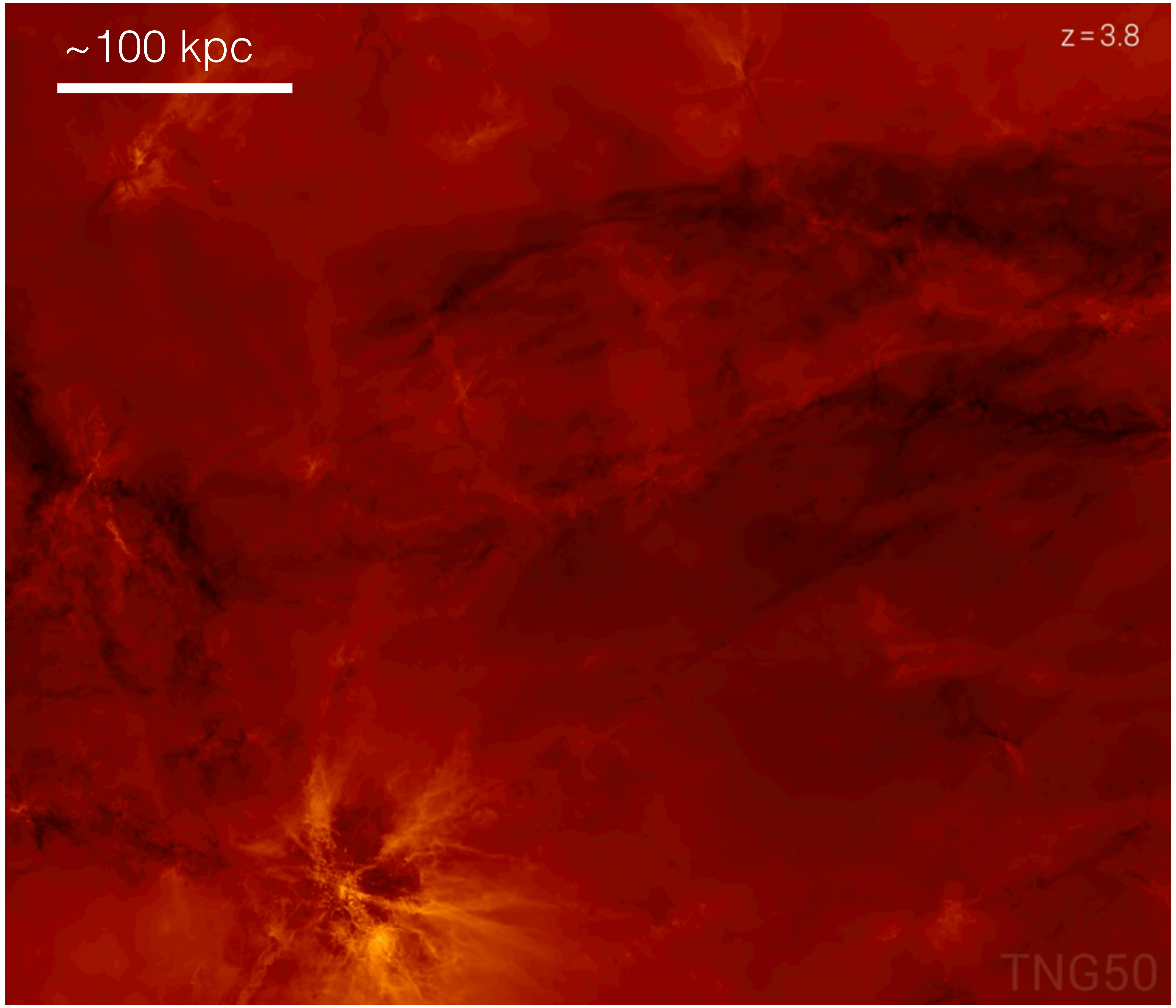

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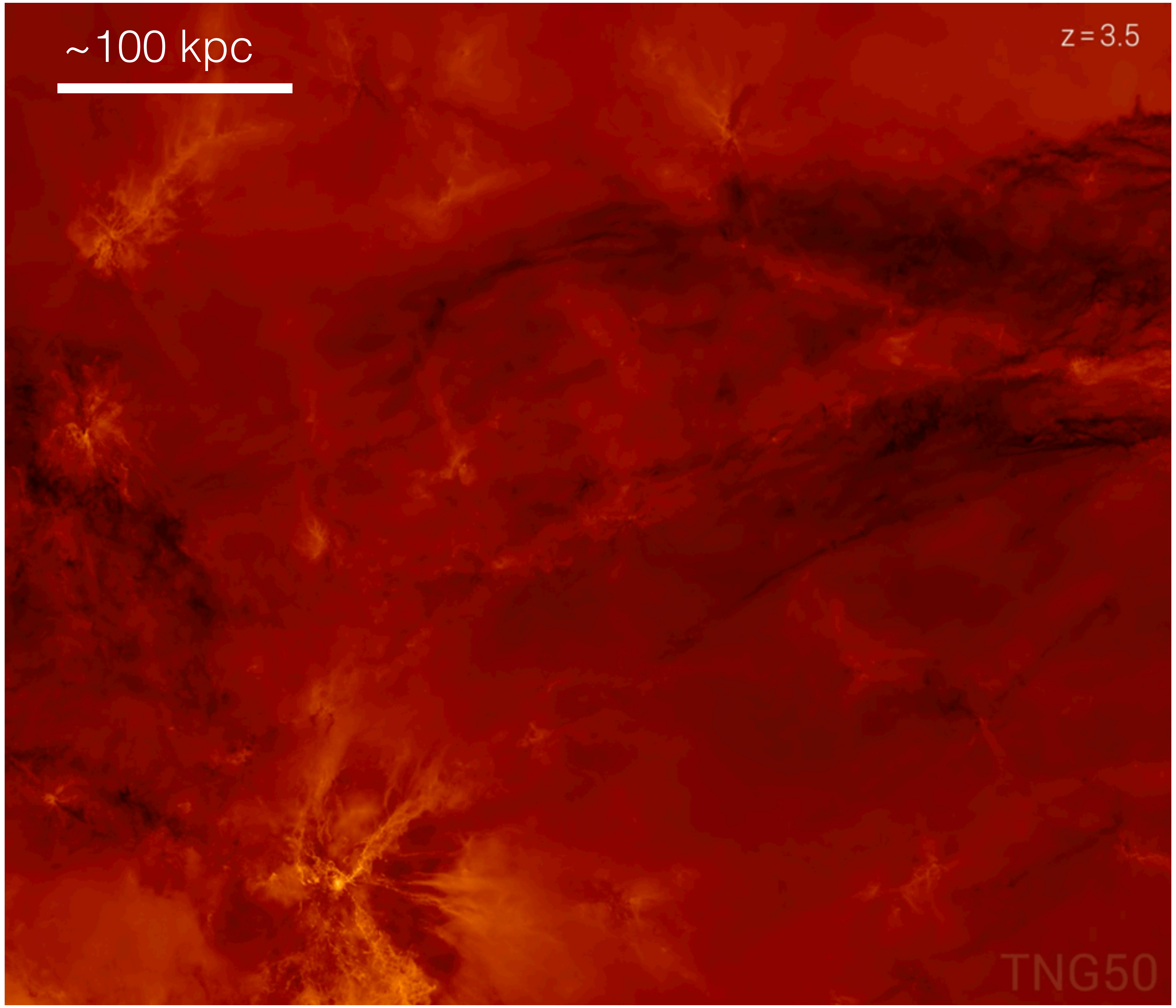

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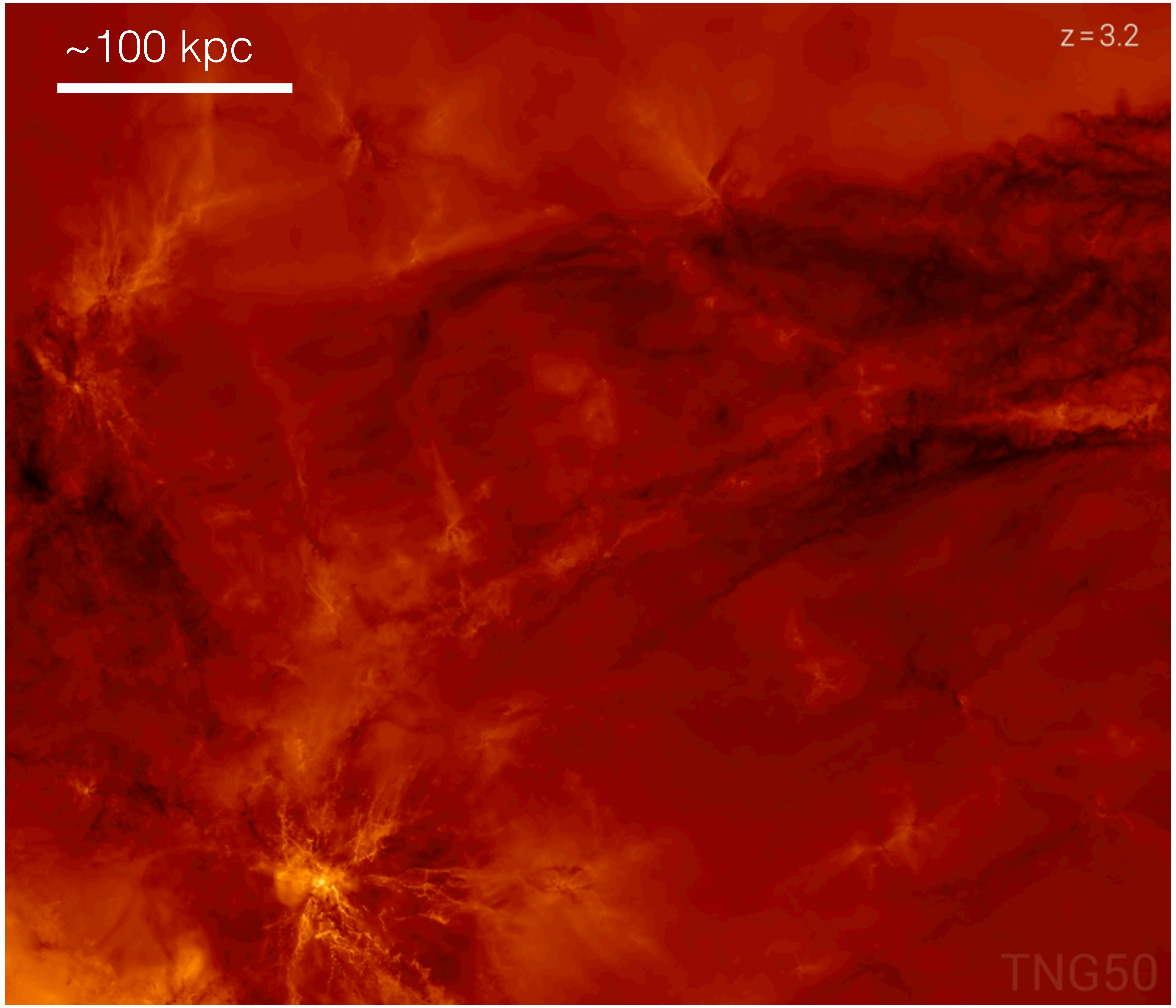

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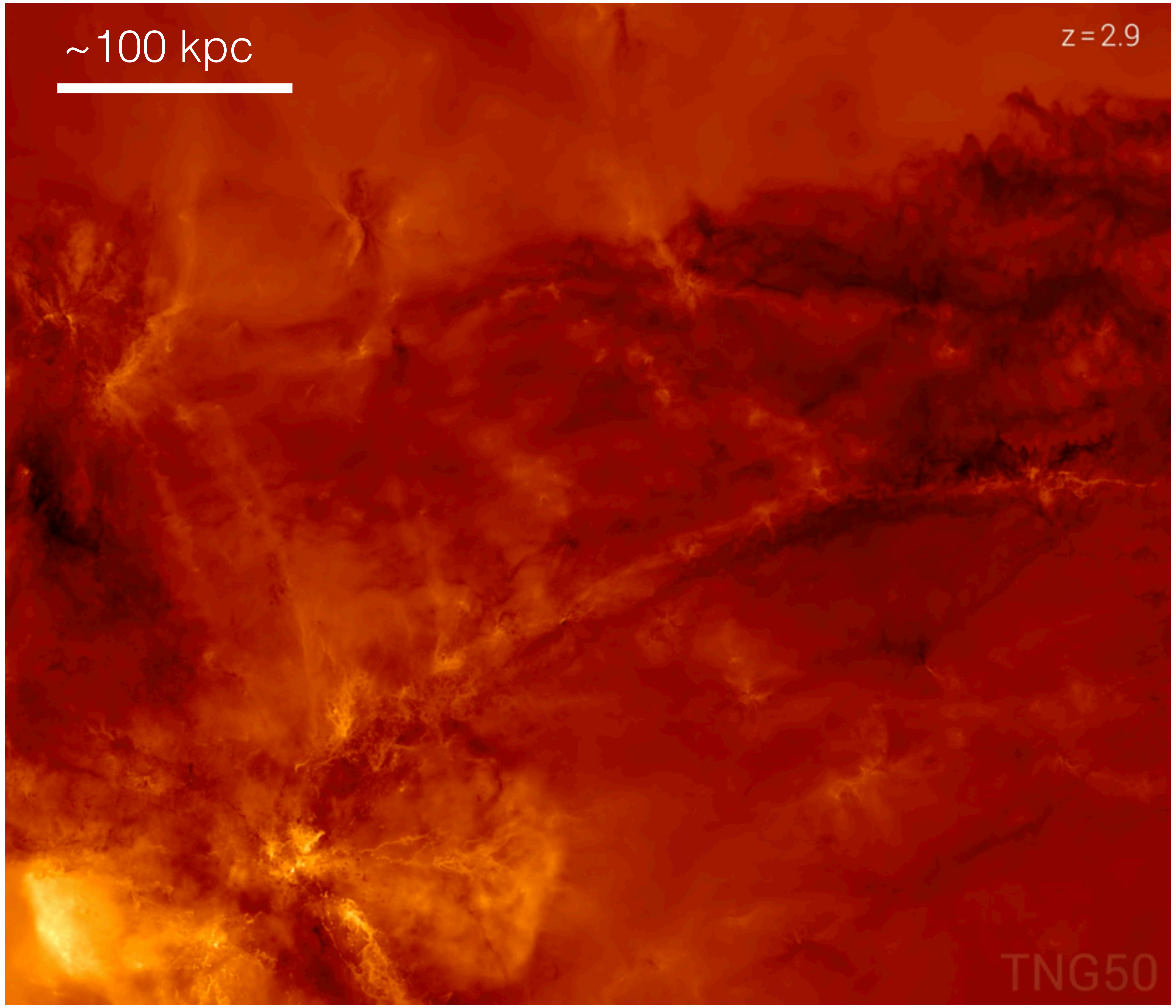

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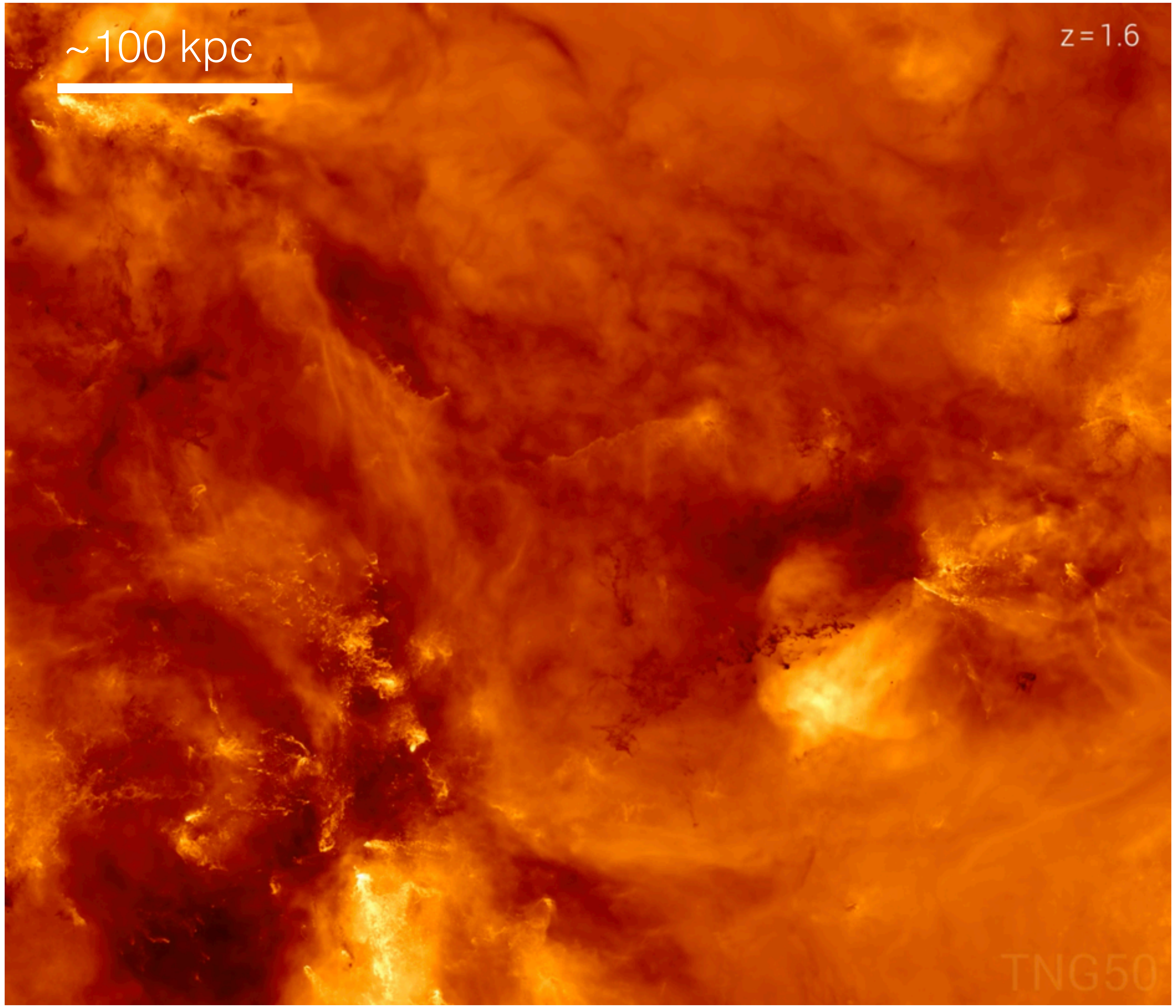
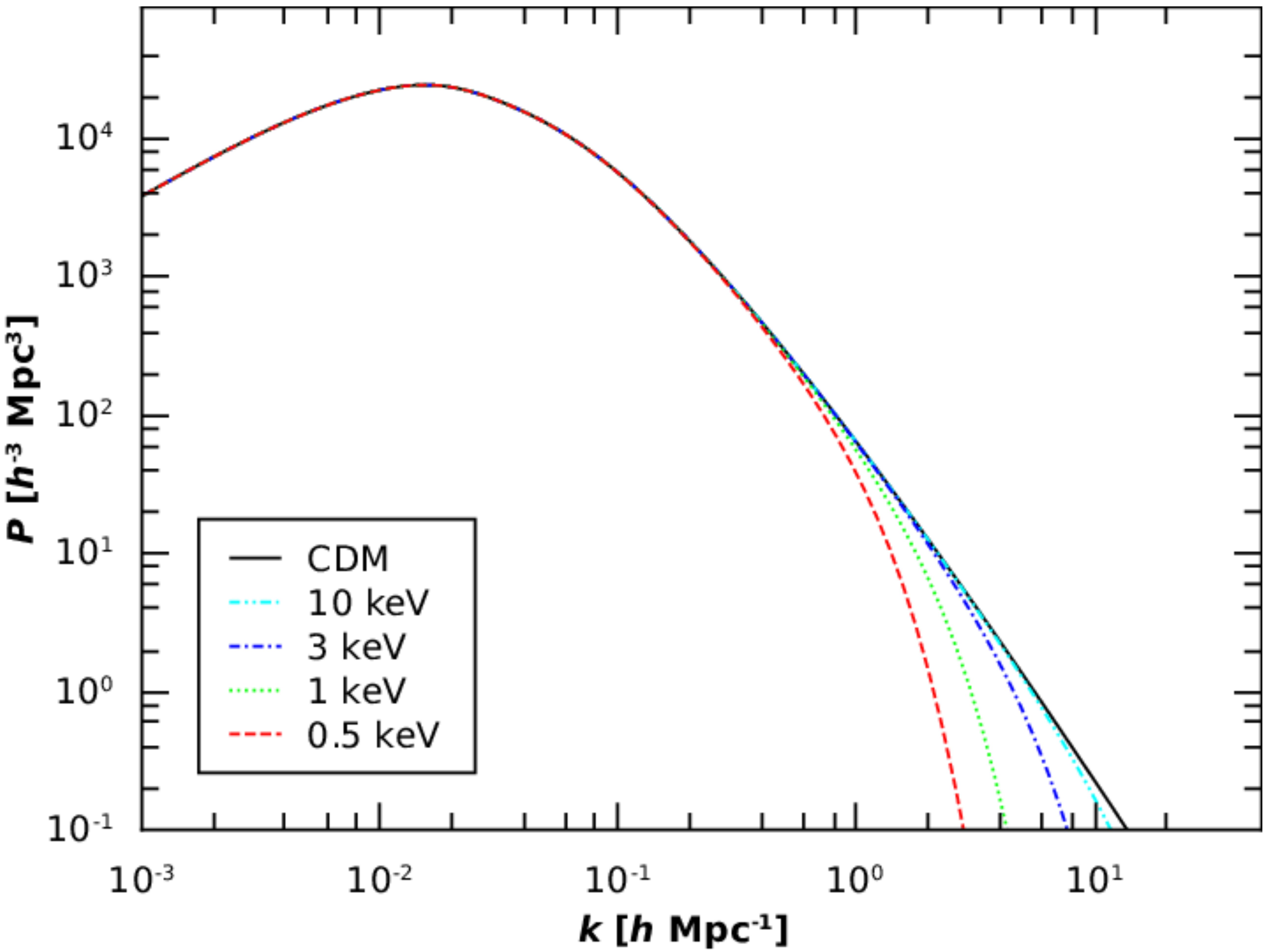


Warm Dark Matter

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:

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



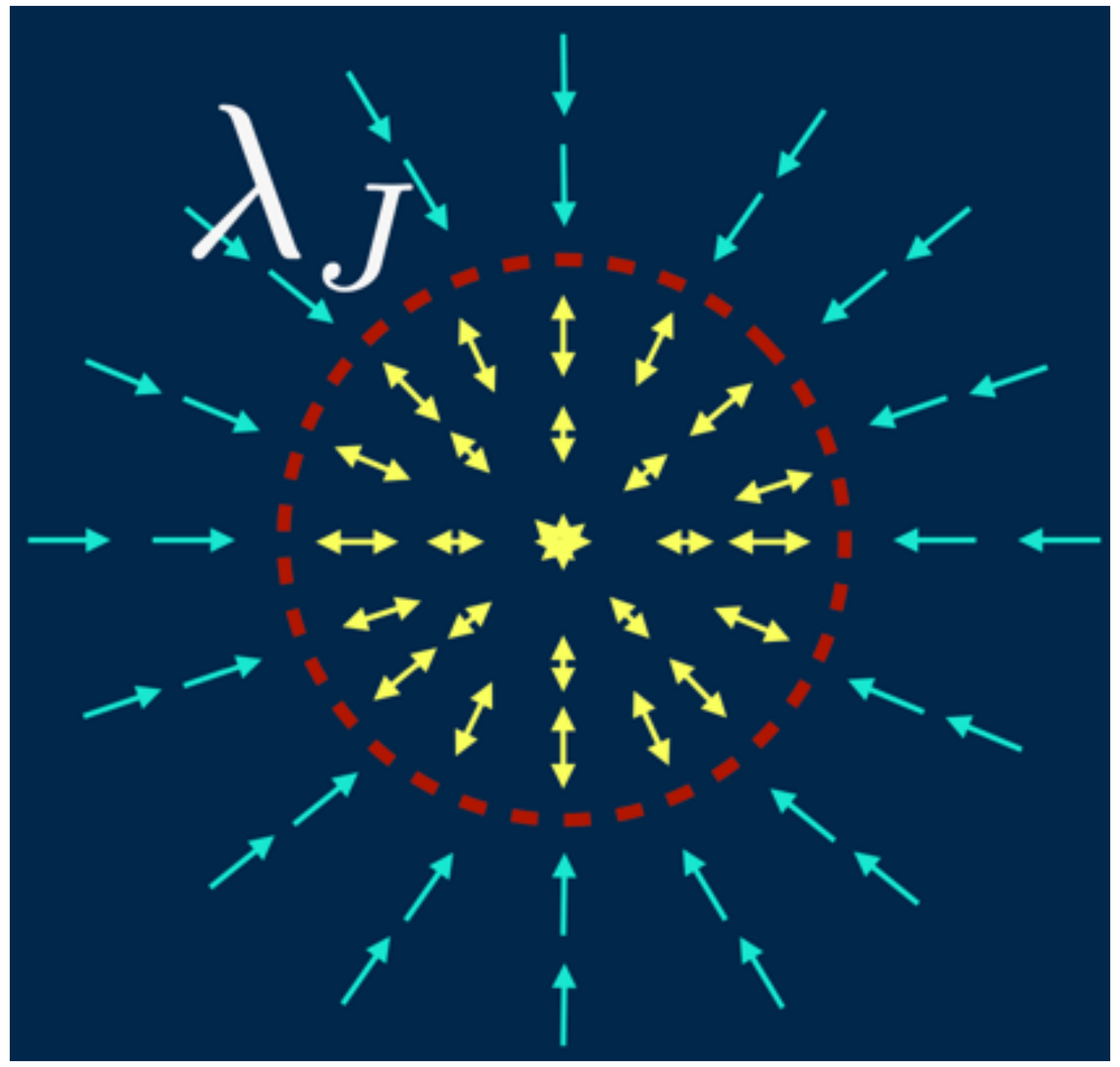
[astro-ph/0010389]

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

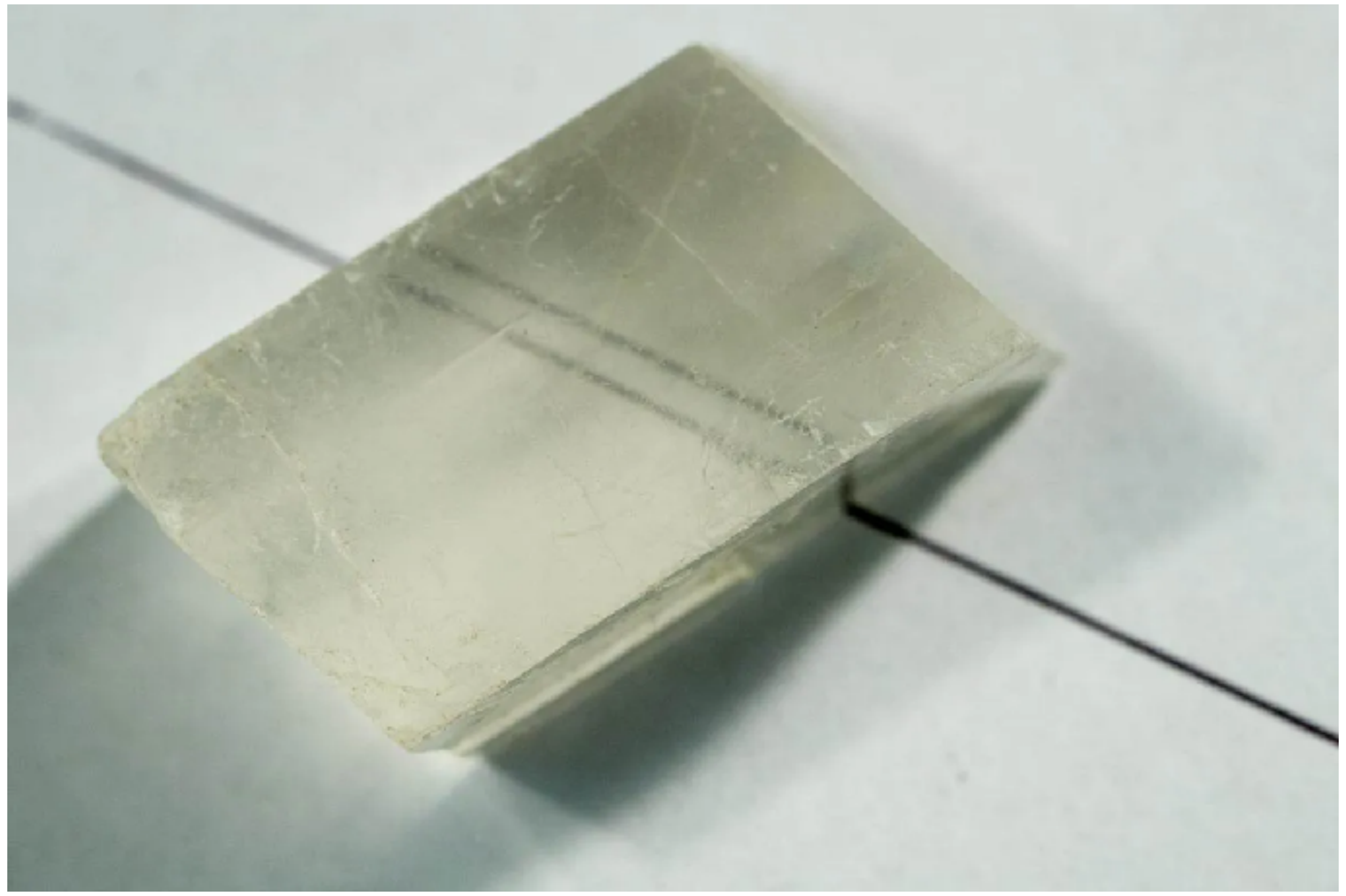
Physically, we can think of the Jeans length as the scale at which the DM crossing time $t_{\rm cross} \sim \lambda/\sigma$ is comparable to the gravitational collapse timescale $t_{\rm coll} \sim 1/\sqrt{G\bar{\rho}}$. Free-streaming length can be evaluated roughly as $\lambda_{\rm fs} \sim \lambda_J(t_{\rm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

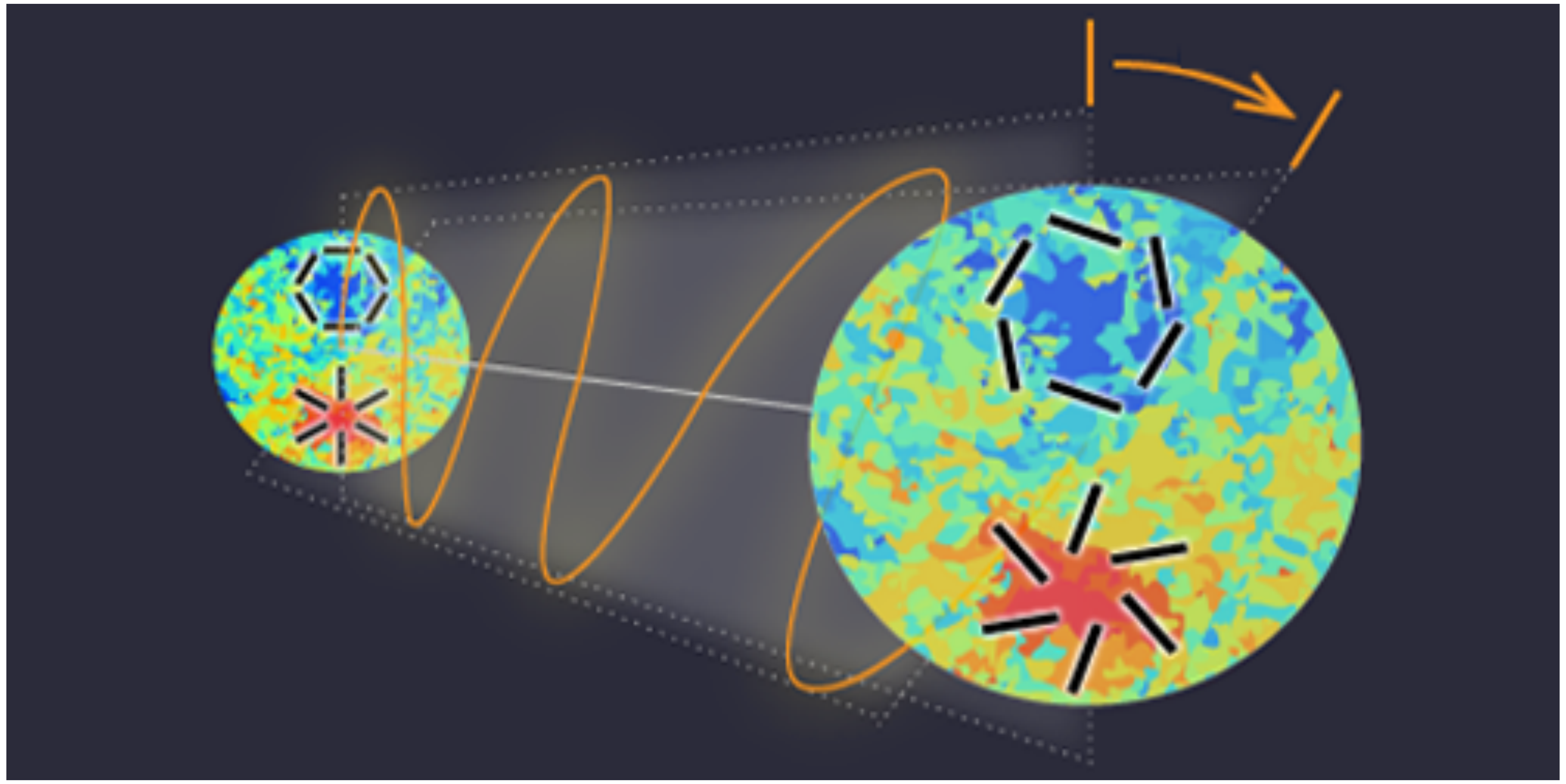
Hot Dark Matter freezes out when relativistic, then has a velocity dispersion which is too large at late times. This means that $\lambda_{\rm fs}$ is large: Structure is washed out on small scales!

CMB and Polarization

The analysis of CMB data continues to provide promising hints about Dark Matter.

For example, ultralight "axion-like" particles (ALPS, $m < 10^{-25}\,\mathrm{eV}$) may affect the polarization of CMB photons as they travel through the Universe to us: **Cosmic Birefringence.**





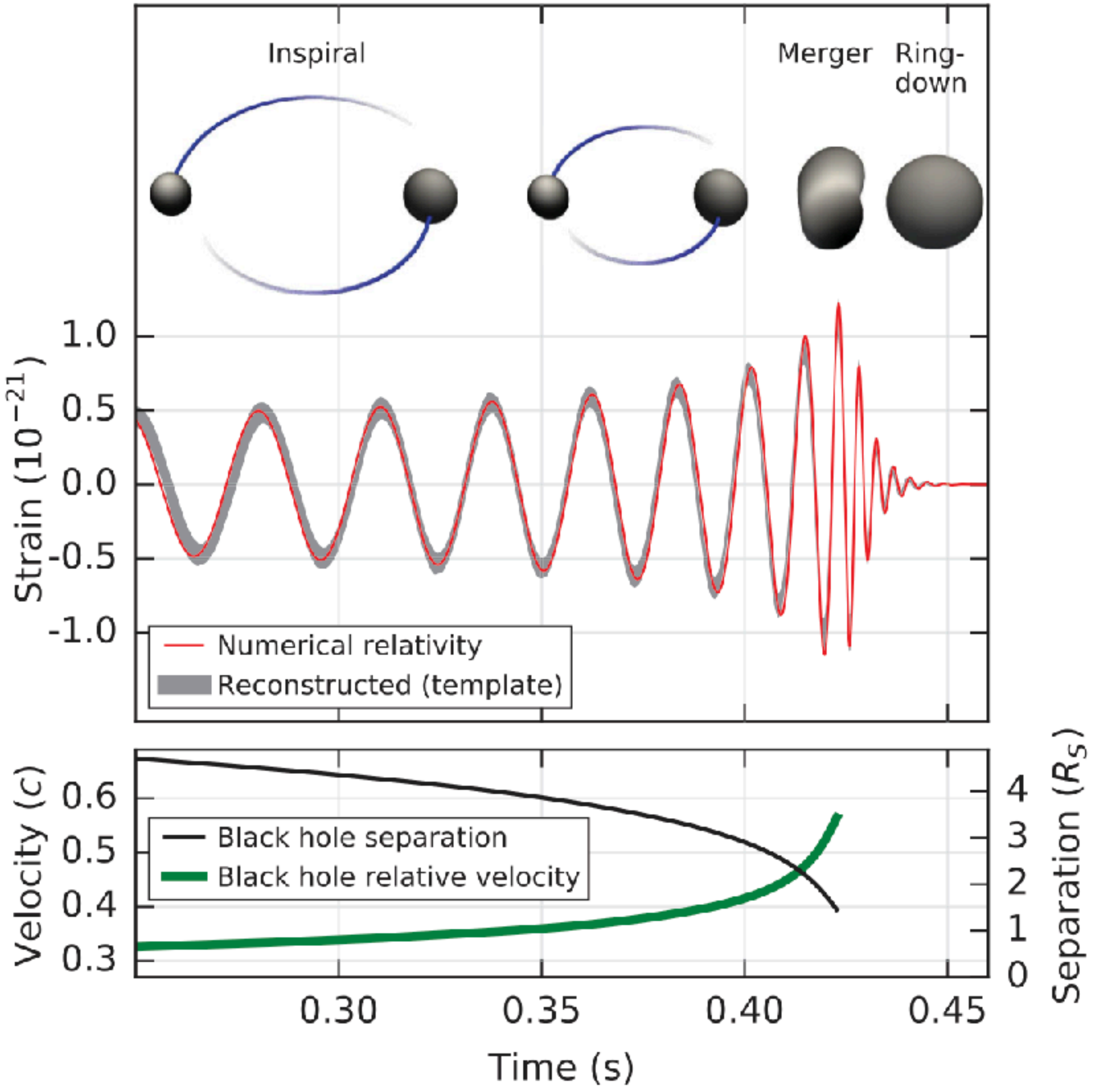
Credit: Y. Minami/KEK

The IFCA Cosmology Group recently found **evidence for a weak cosmic birefringence effect** (~0.35 degrees). Future work required to understand whether the effect is real and to interpret in terms of new light particles.

[E.g. P. Diego-Palazuelos et al., arXiv:2201.07682]

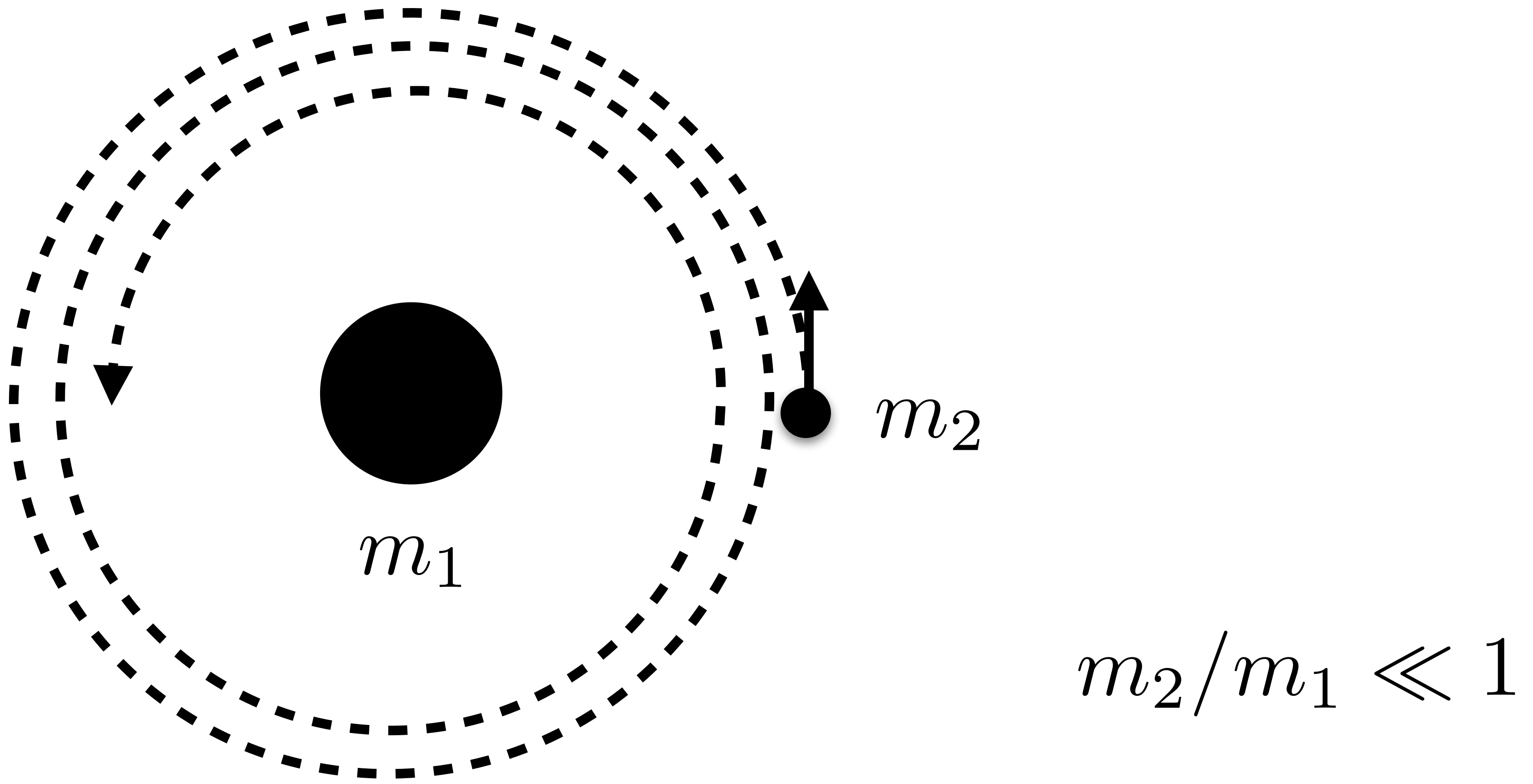
Gravitational Waves (GW)

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

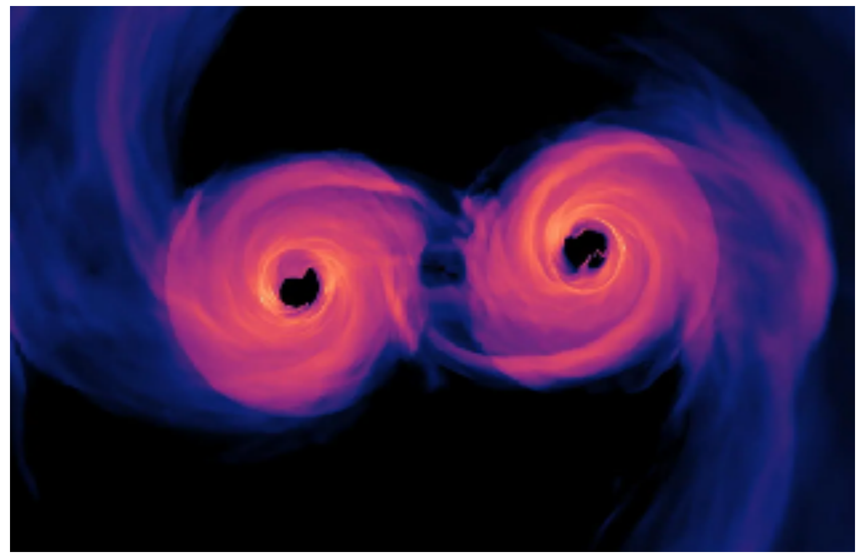
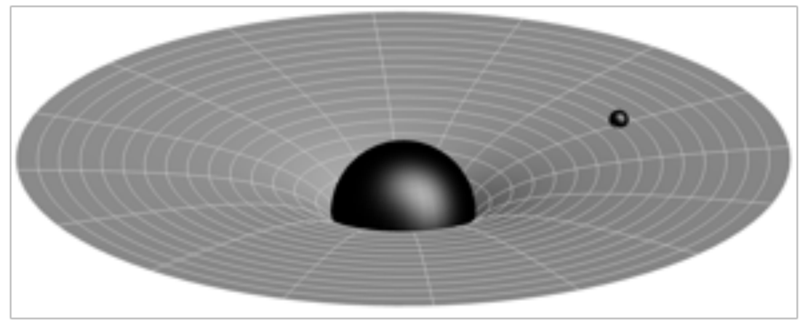
Can be used to probe of Dark Matter overdensities **almost independently of Dark Matter mass** and particle physics properties

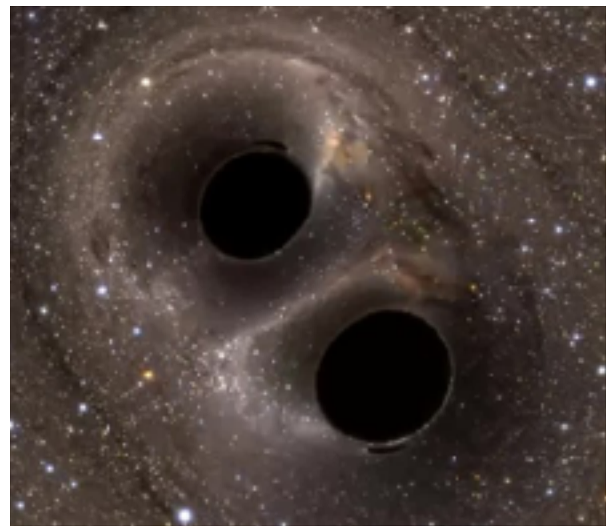
The Gravitational Wave Spectrum

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

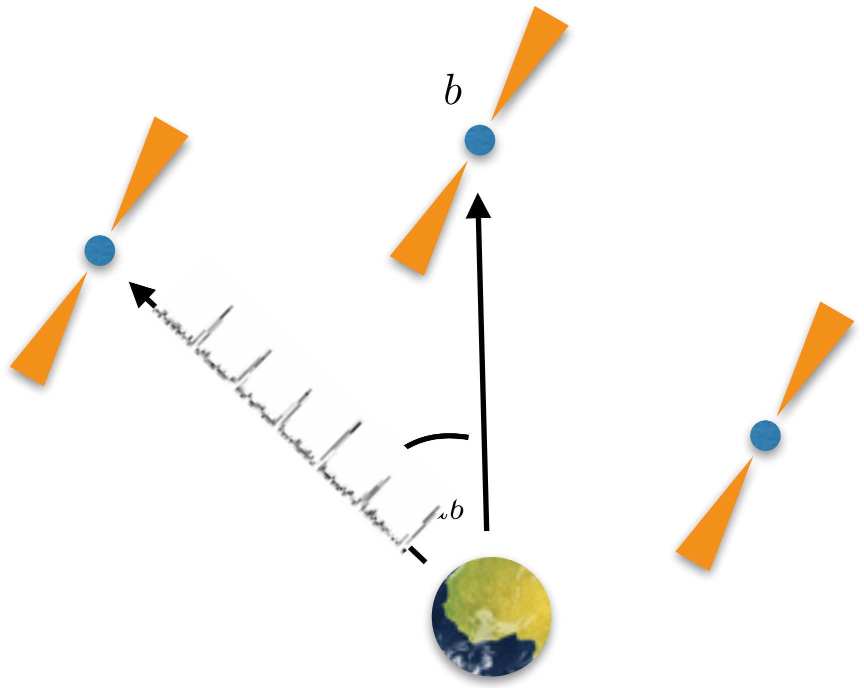
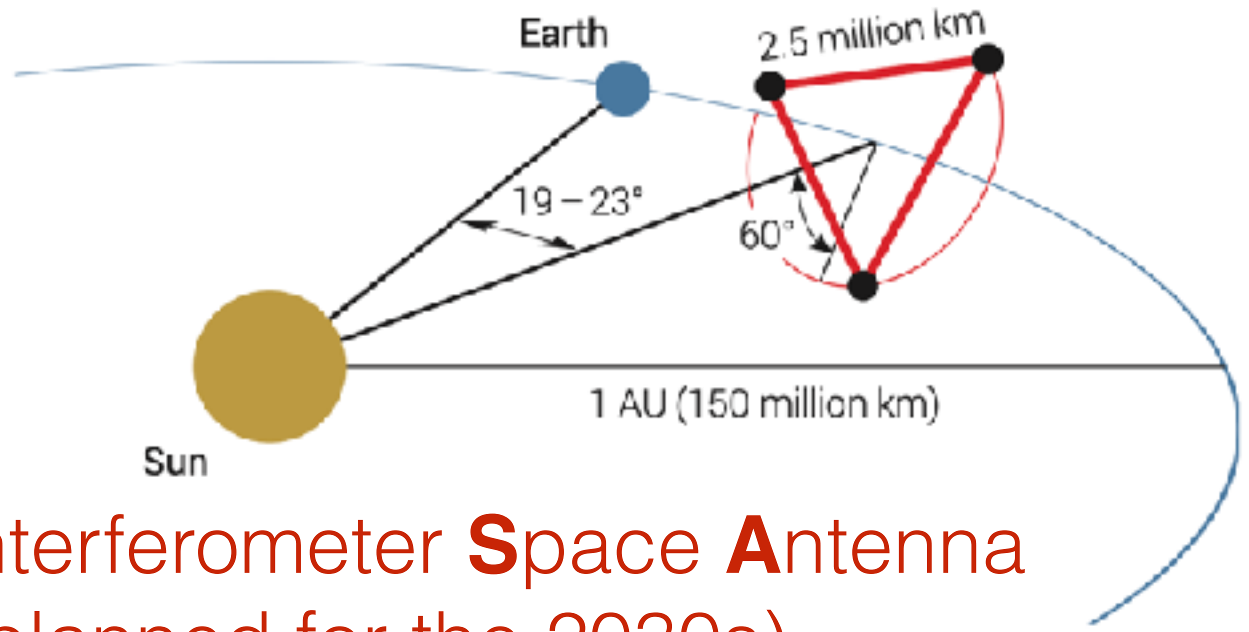
	nHz	μHz	mHz	Hz	kHz
f_{GW}					
	10^{13} km ~ pc	10^{11} km	10^{8} km	10^{5} km	100 km
λ_{GW}					
	30 years	10 days	15 minutes	1 second	1 ms
T_{GW}					

SOURCES

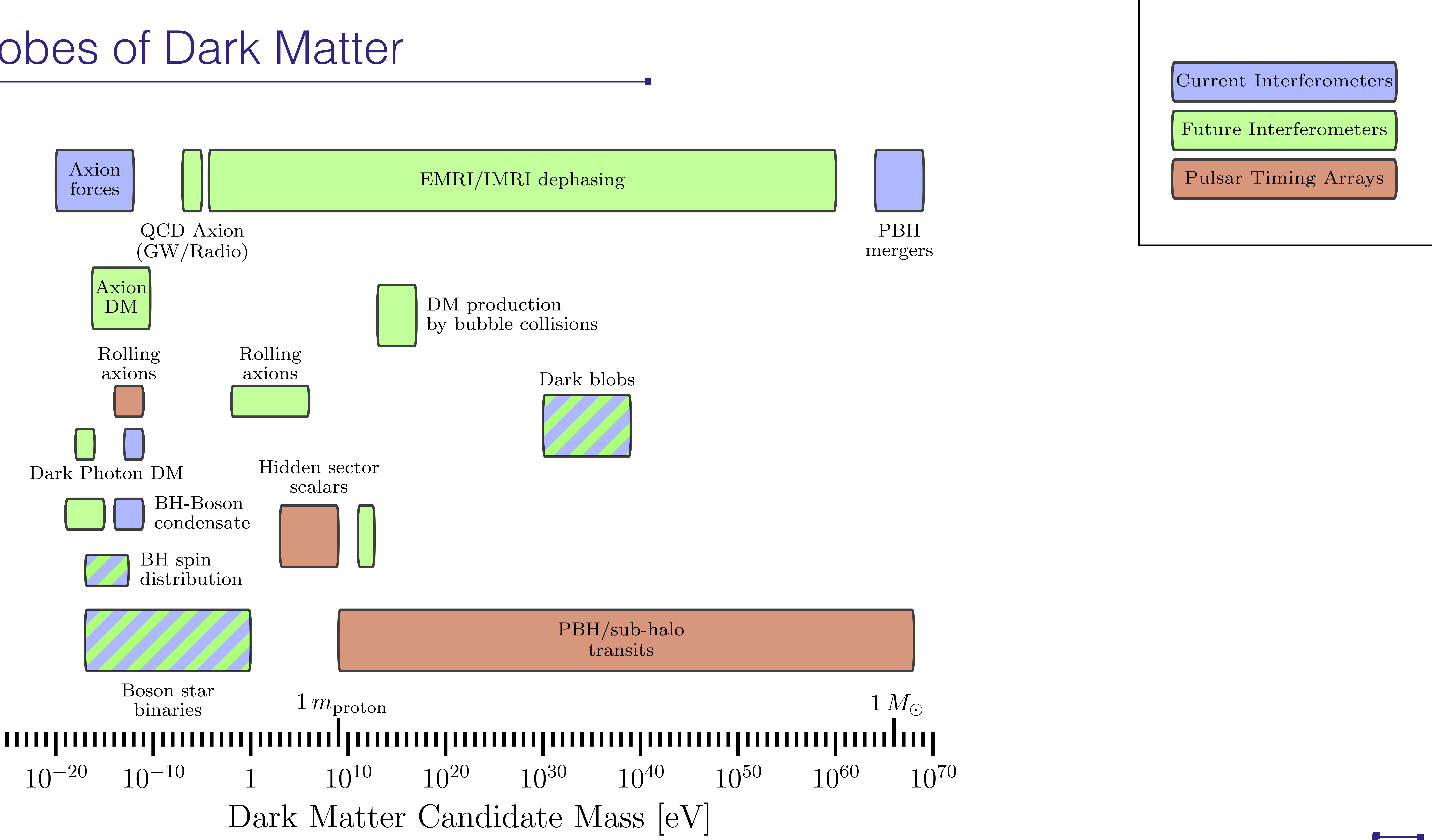


DETECTORS?

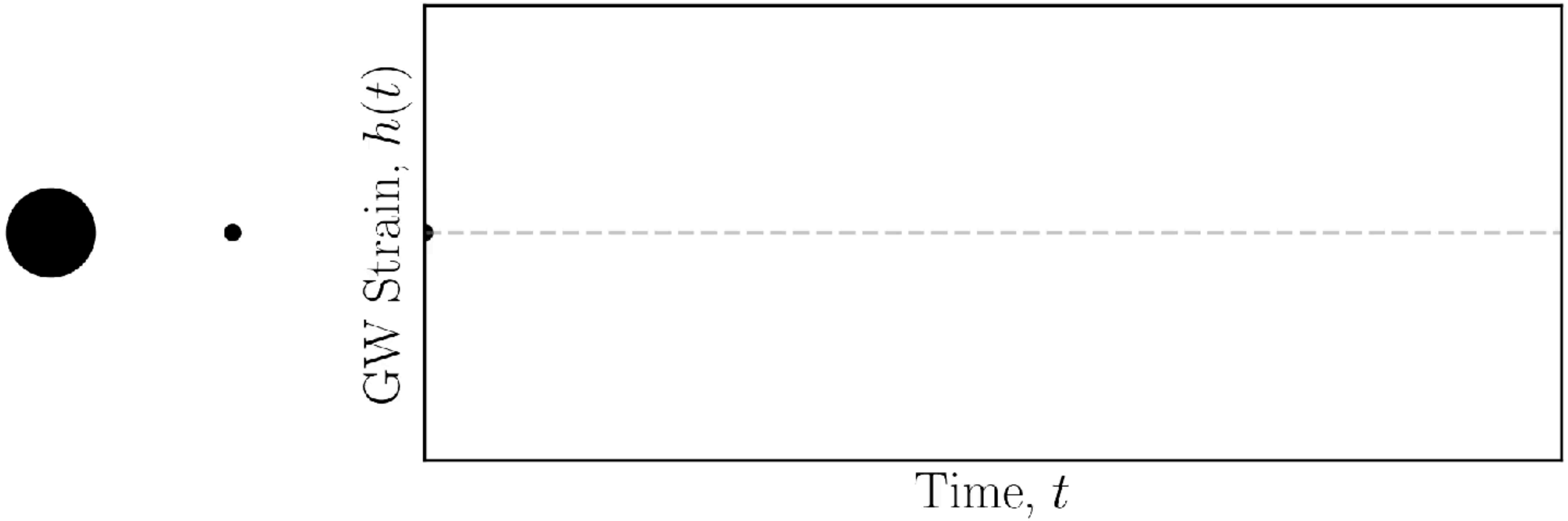



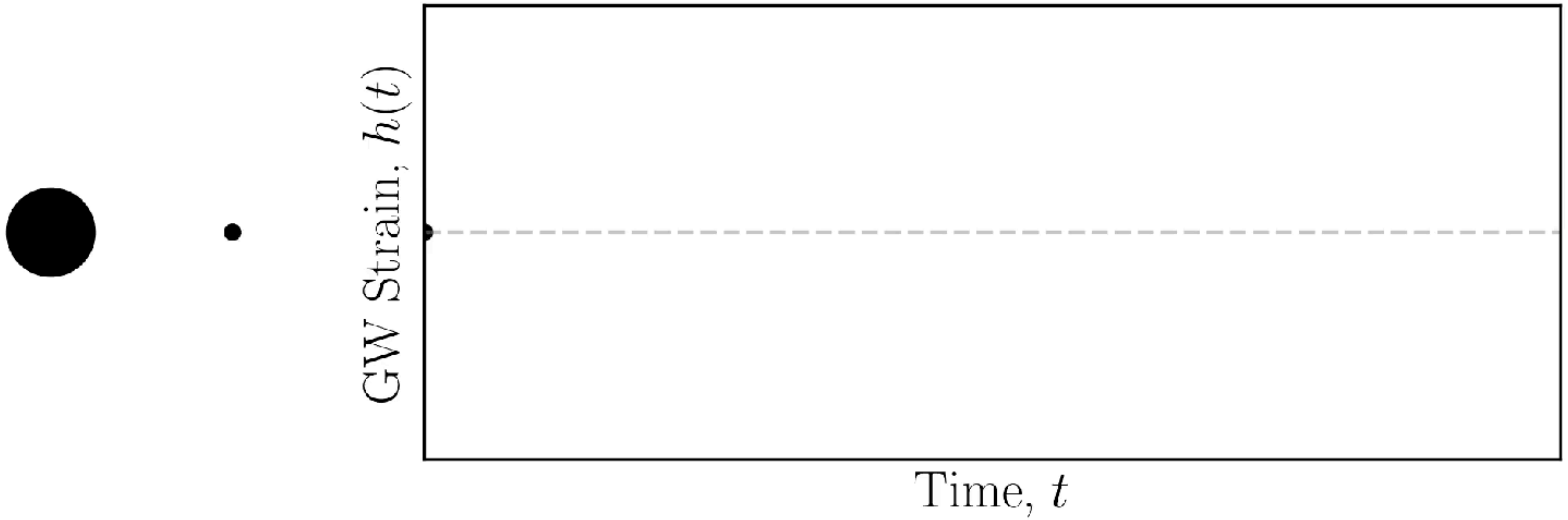
Laser **I**nterferometer **S**pace **A**ntenna
(planned for the 2030s)
[1907.06482]

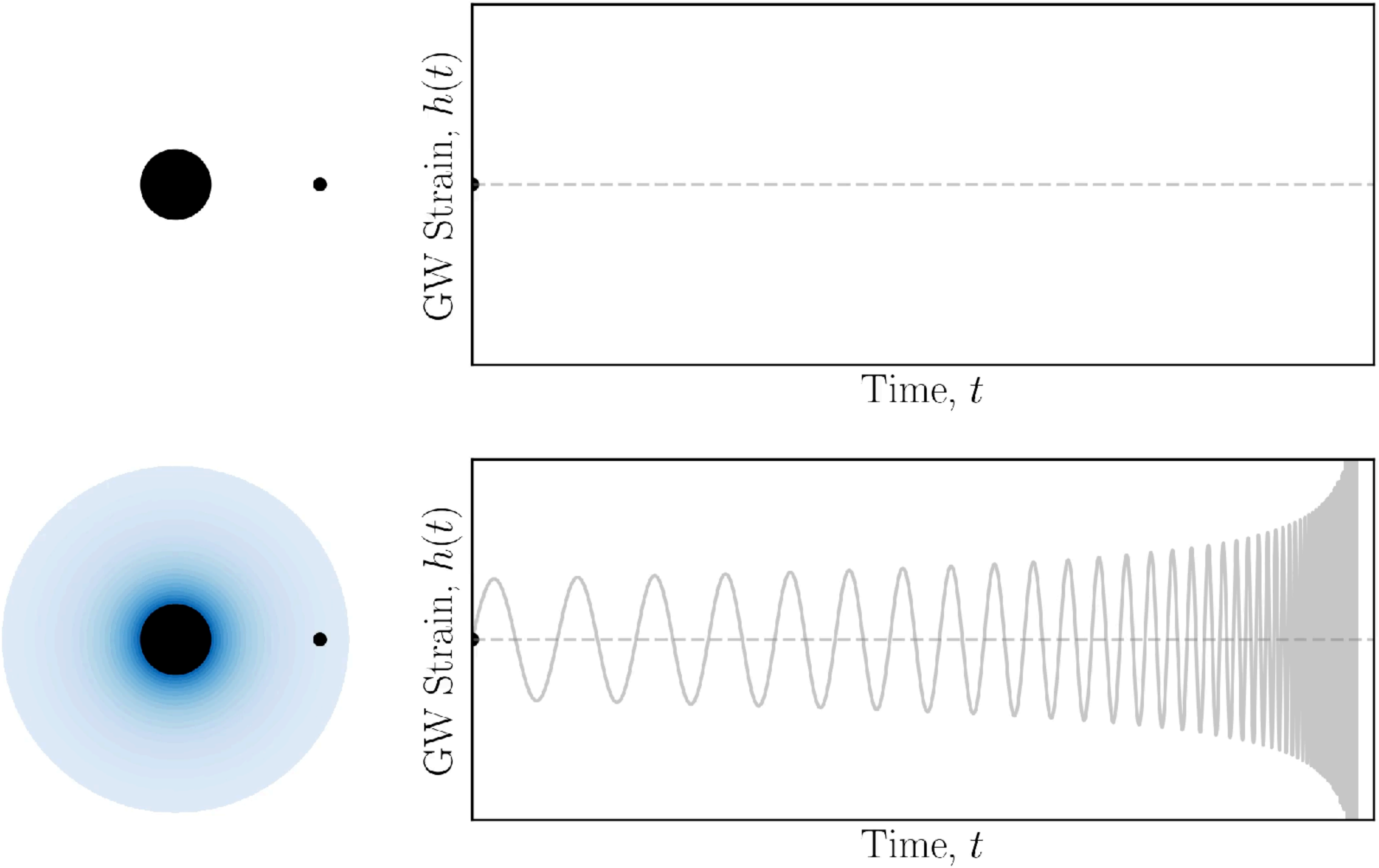
GW Probes of Dark Matter



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


GW Strain, $h(t)$
Time, t


GW Strain, $h(t)$
Time, t


GW Strain, $h(t)$
Time, t
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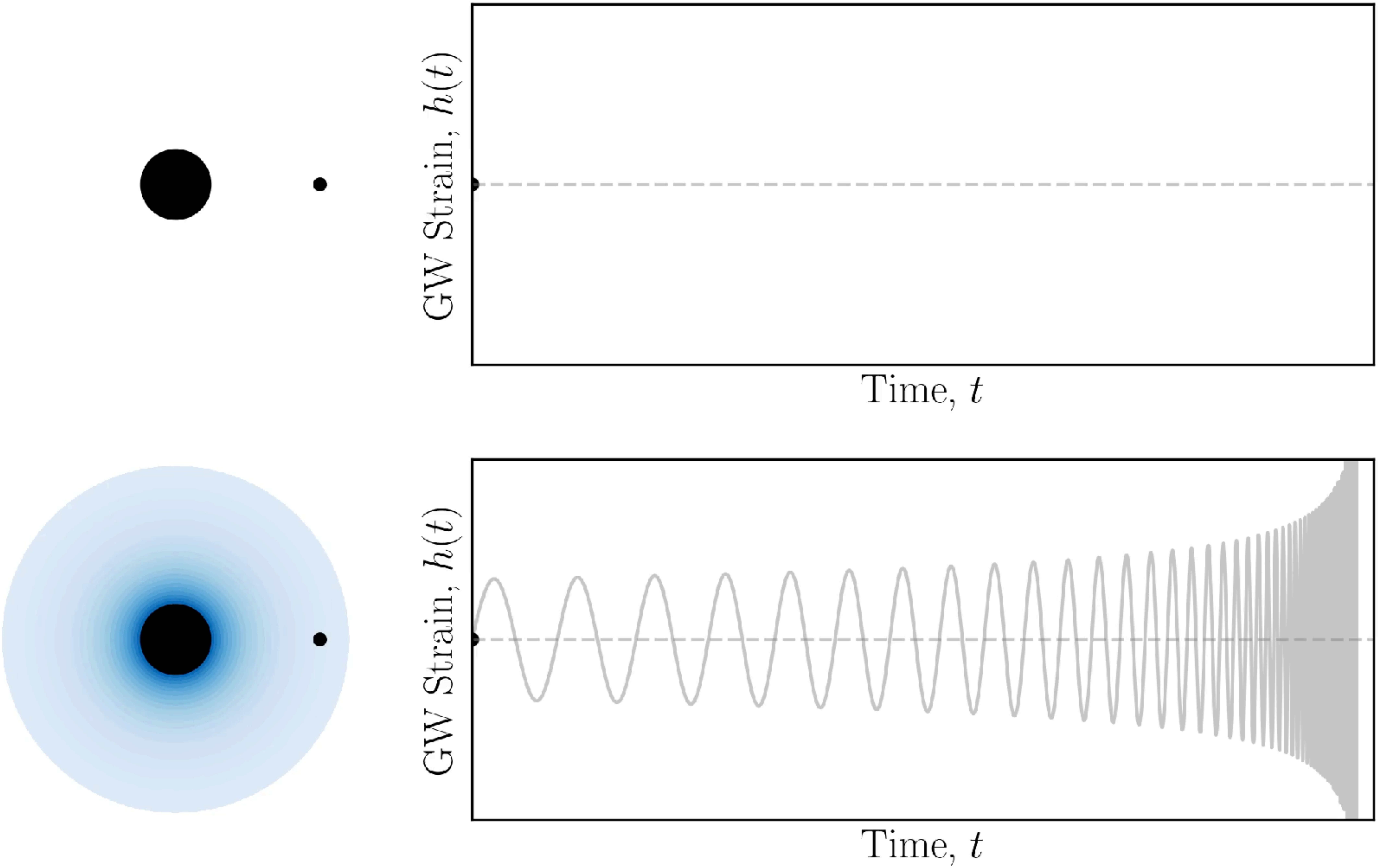
Time, t


GW Strain, $h(t)$
Time, t
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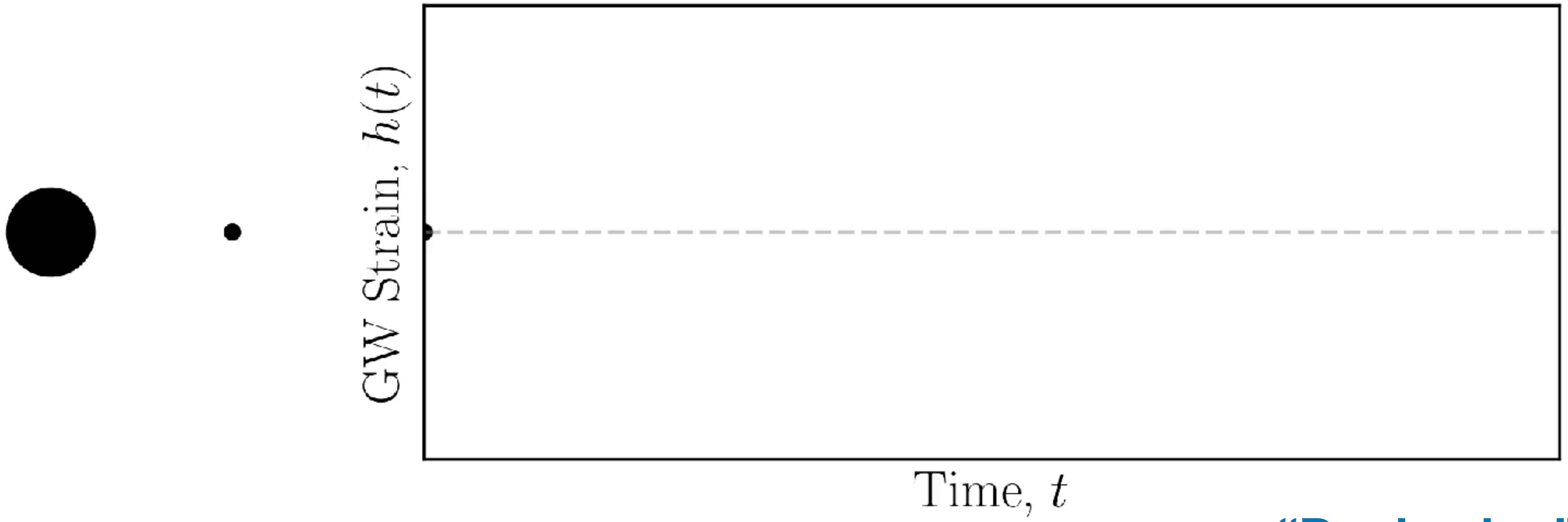
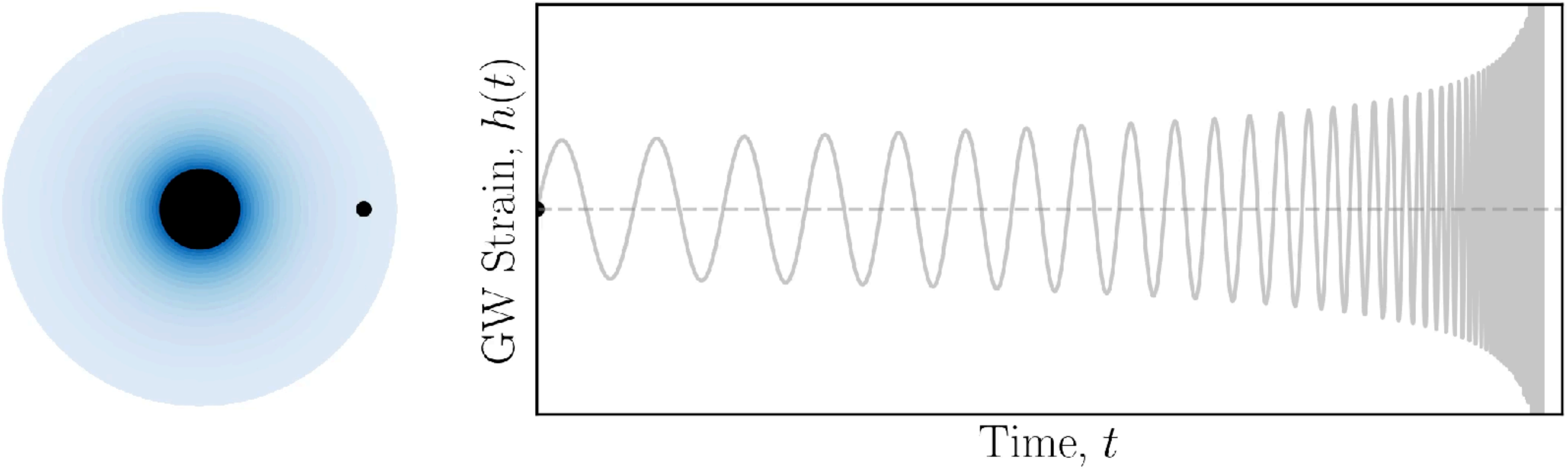
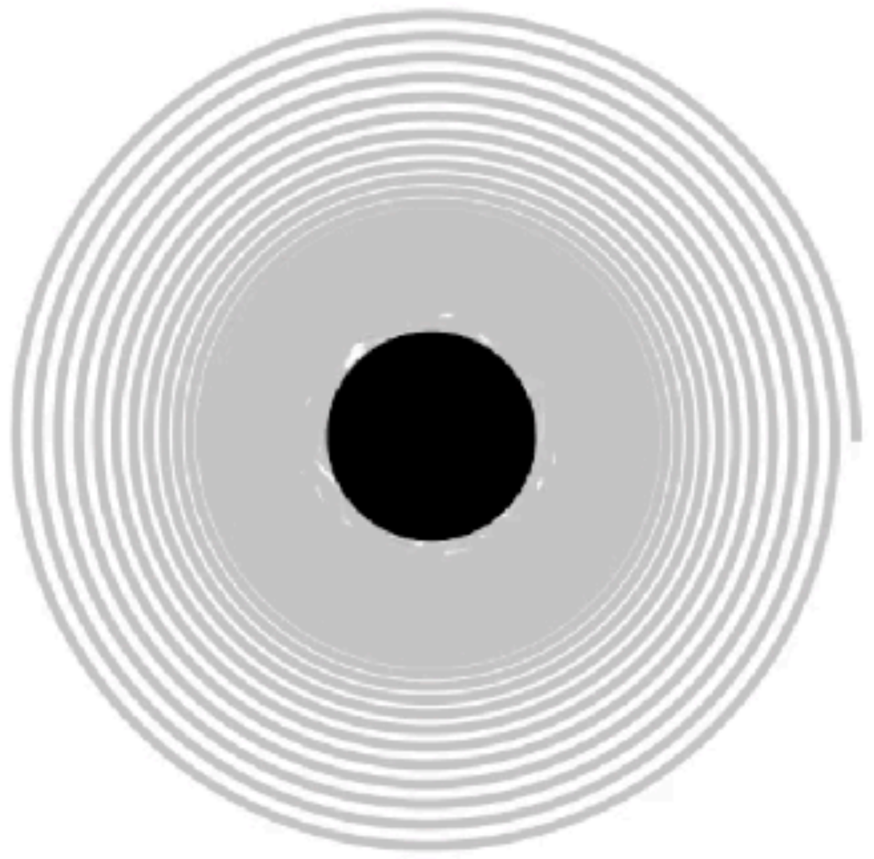
Time, t

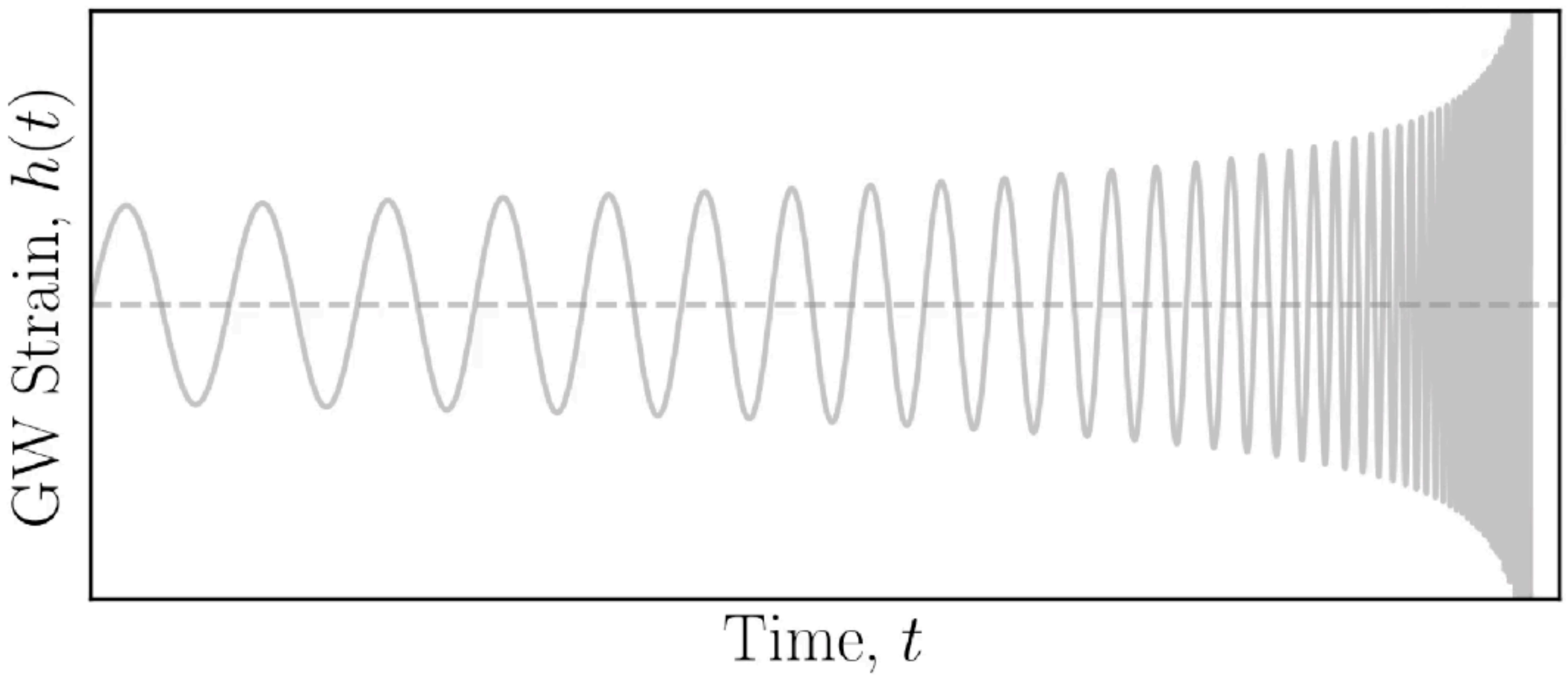


“Dephasing”

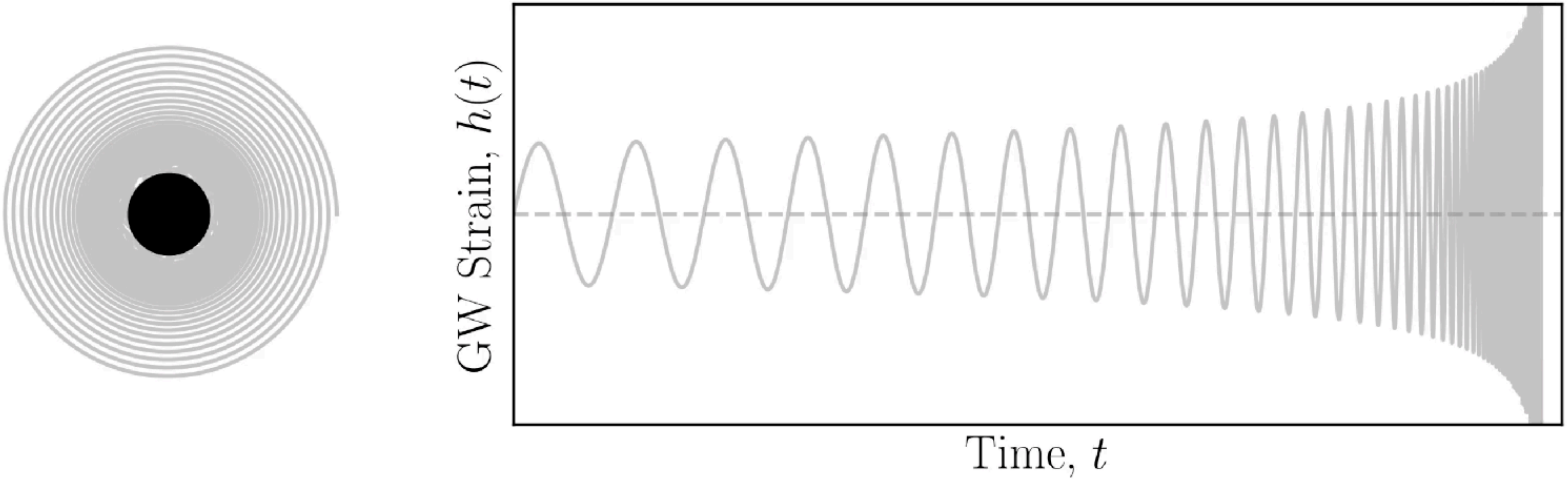


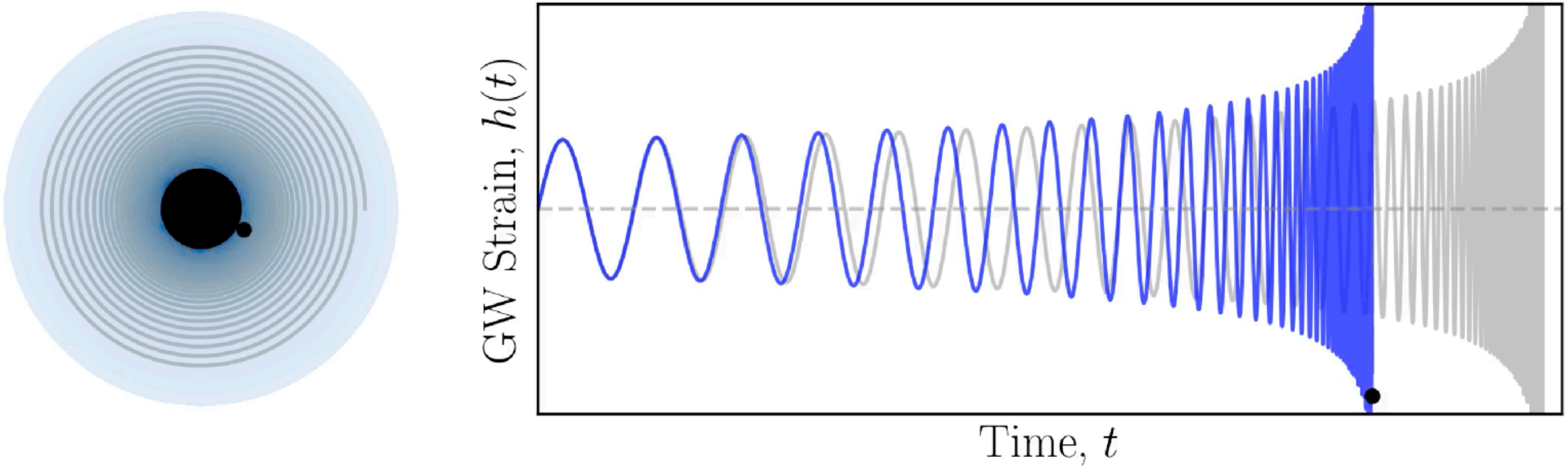
Gravitational Wave Dephasing



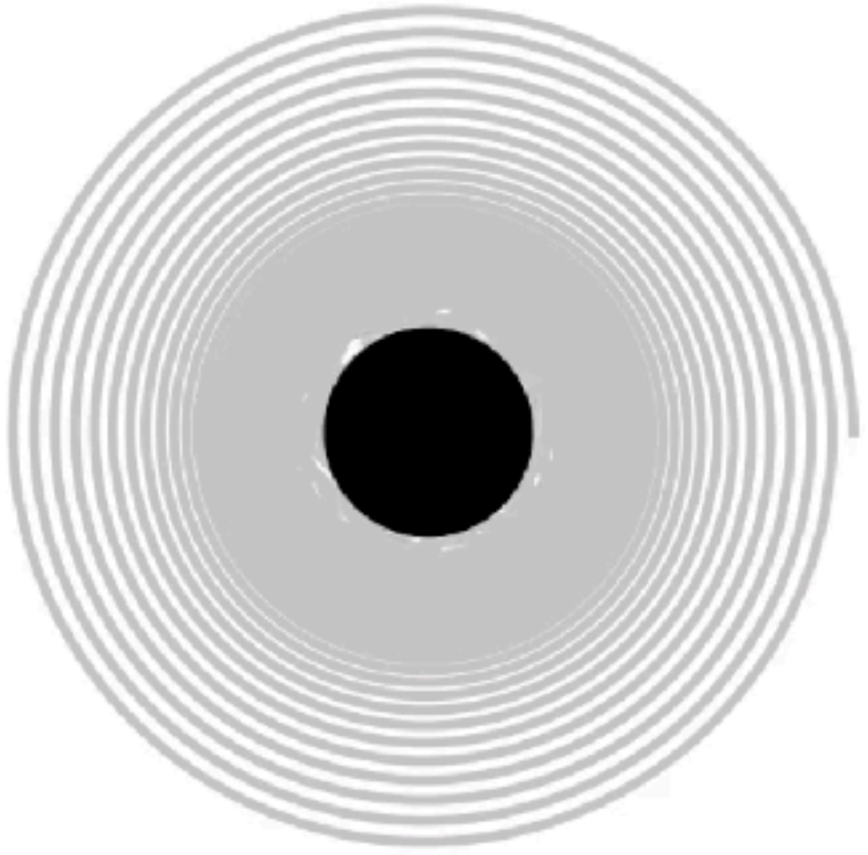


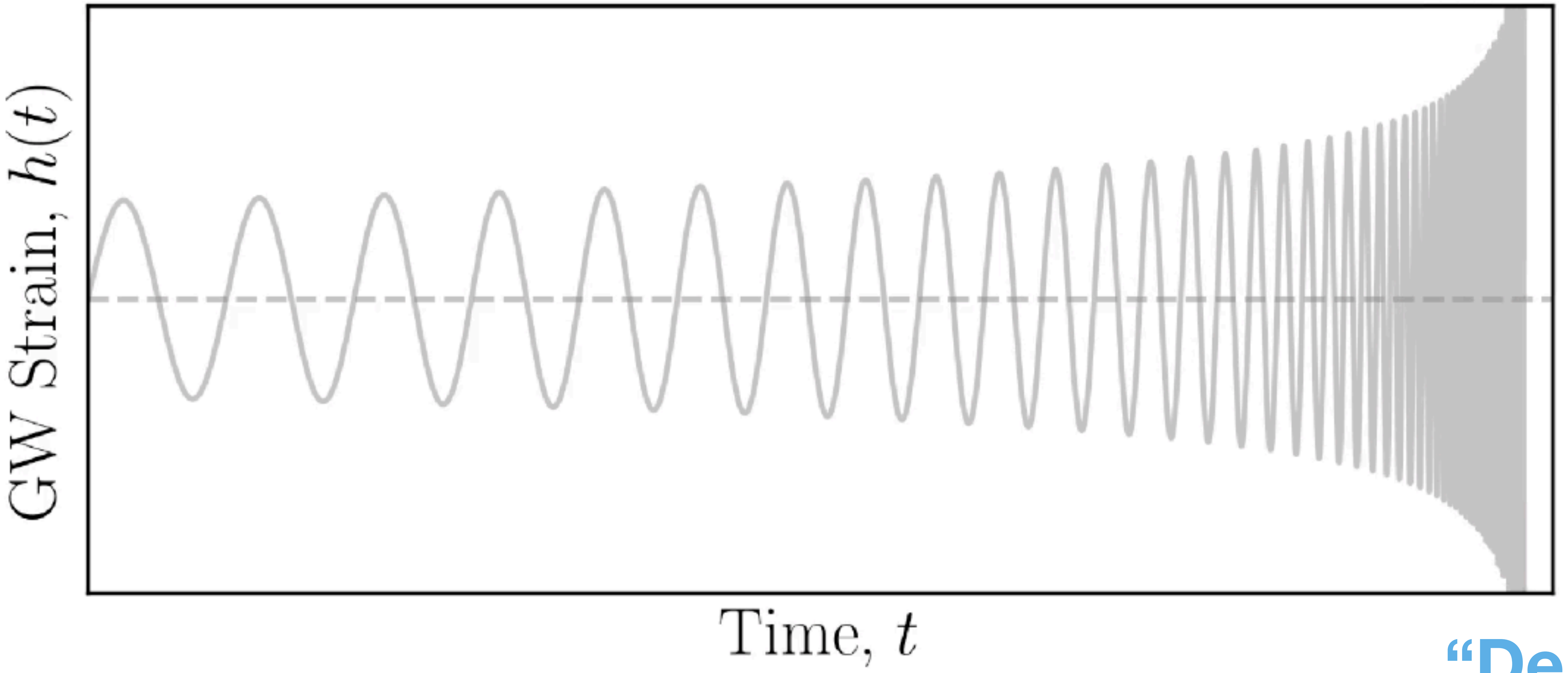
Gravitational Wave Dephasing

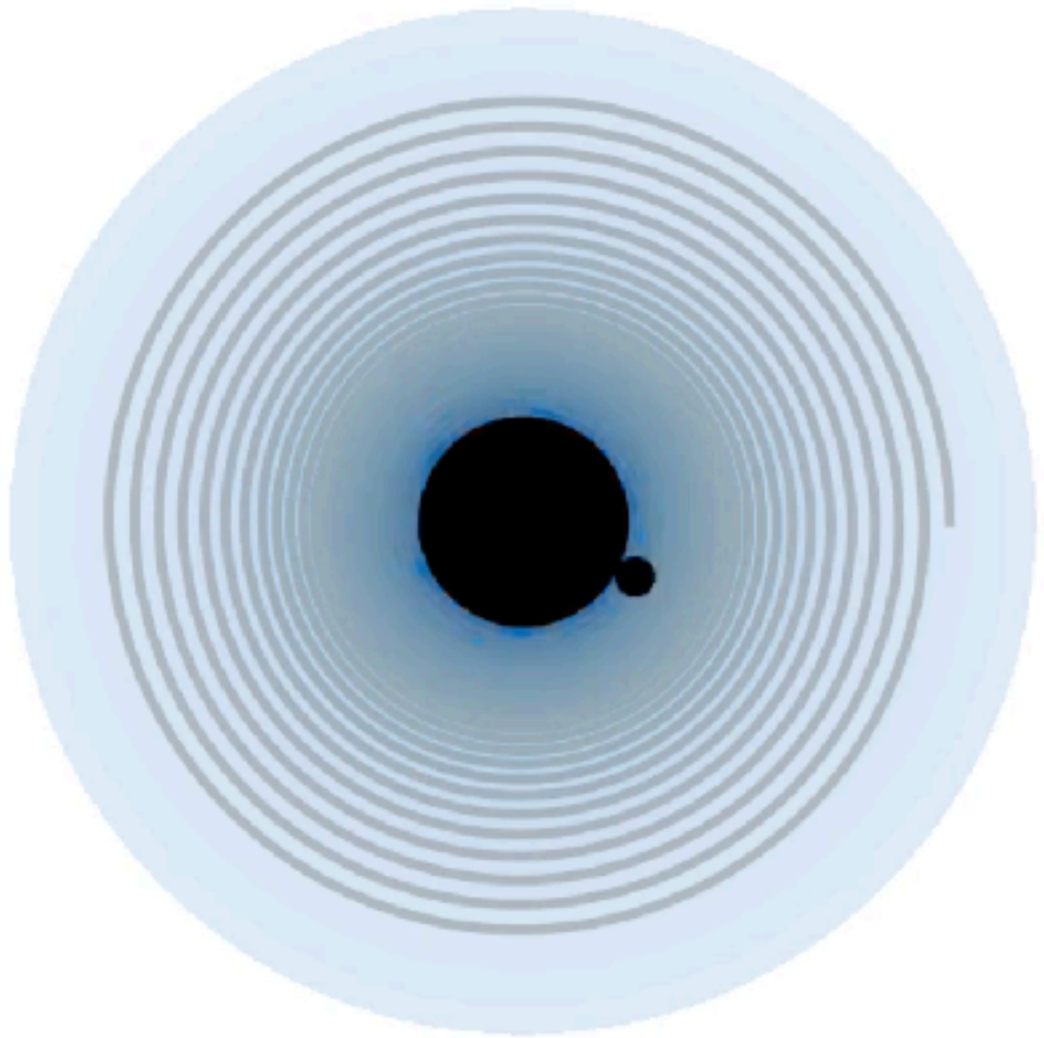


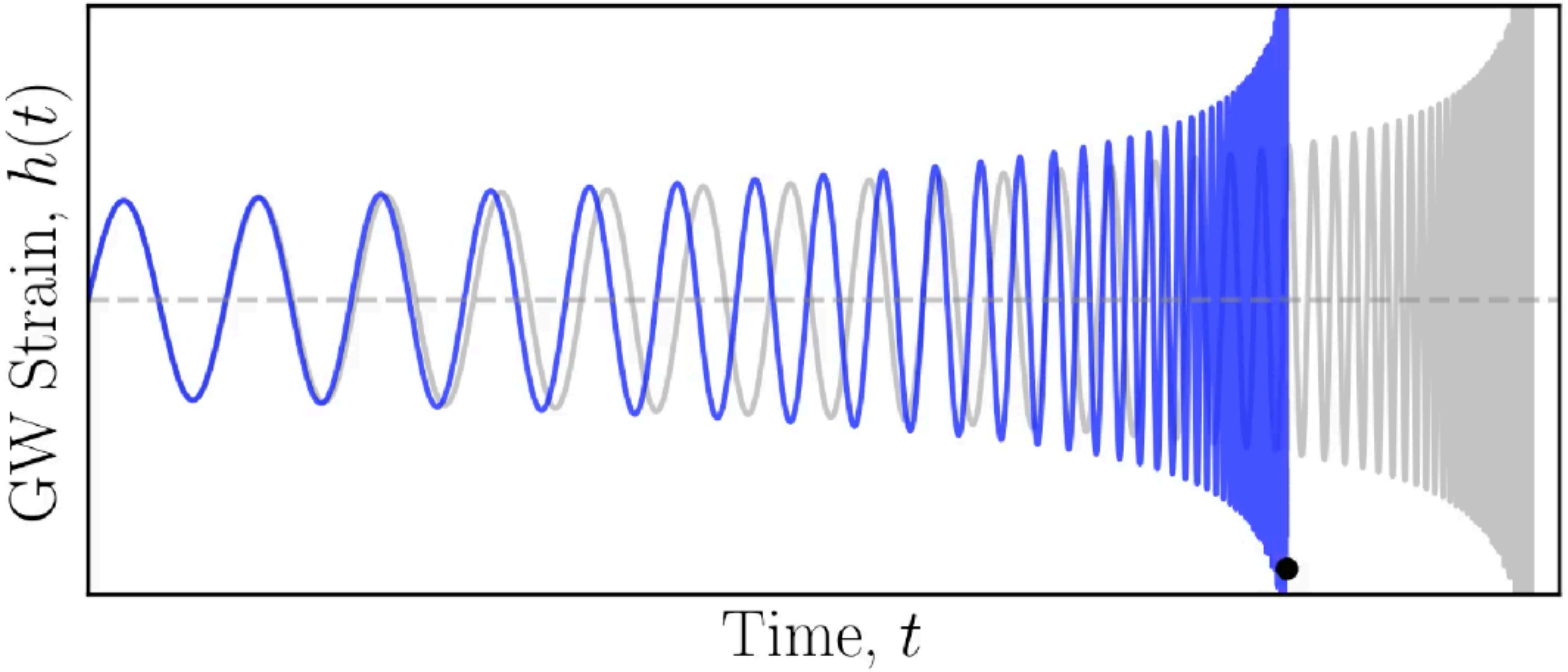


Gravitational Wave Dephasing







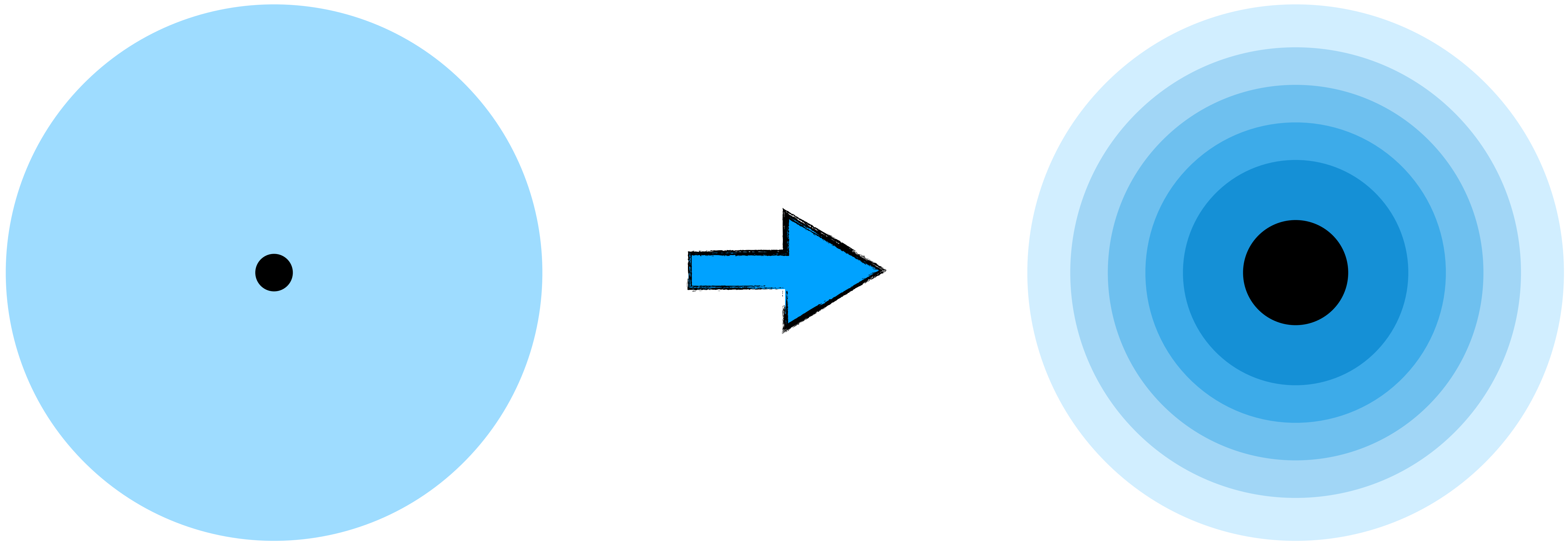


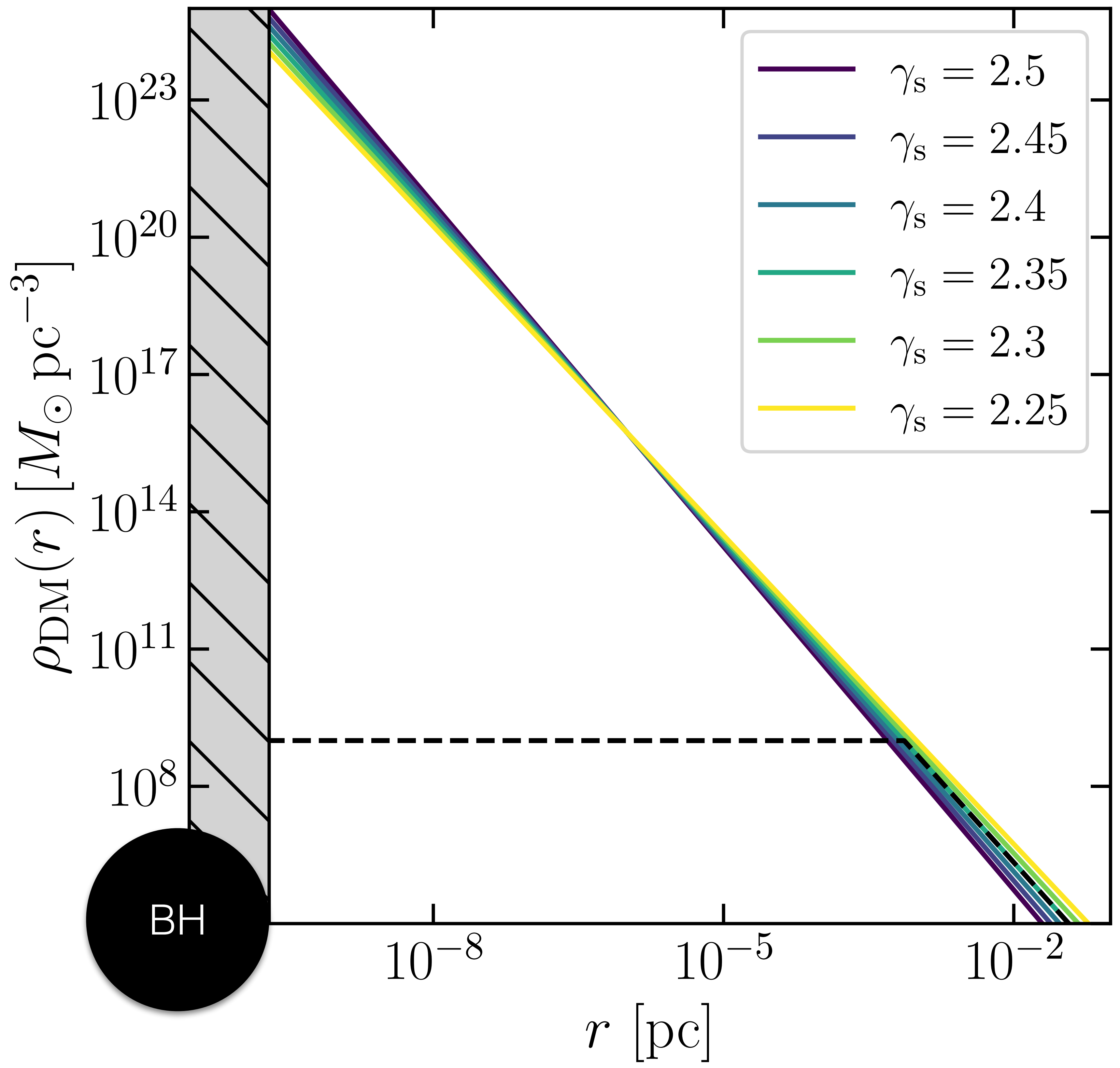
"Dephasing"

Dark Matter Spikes

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

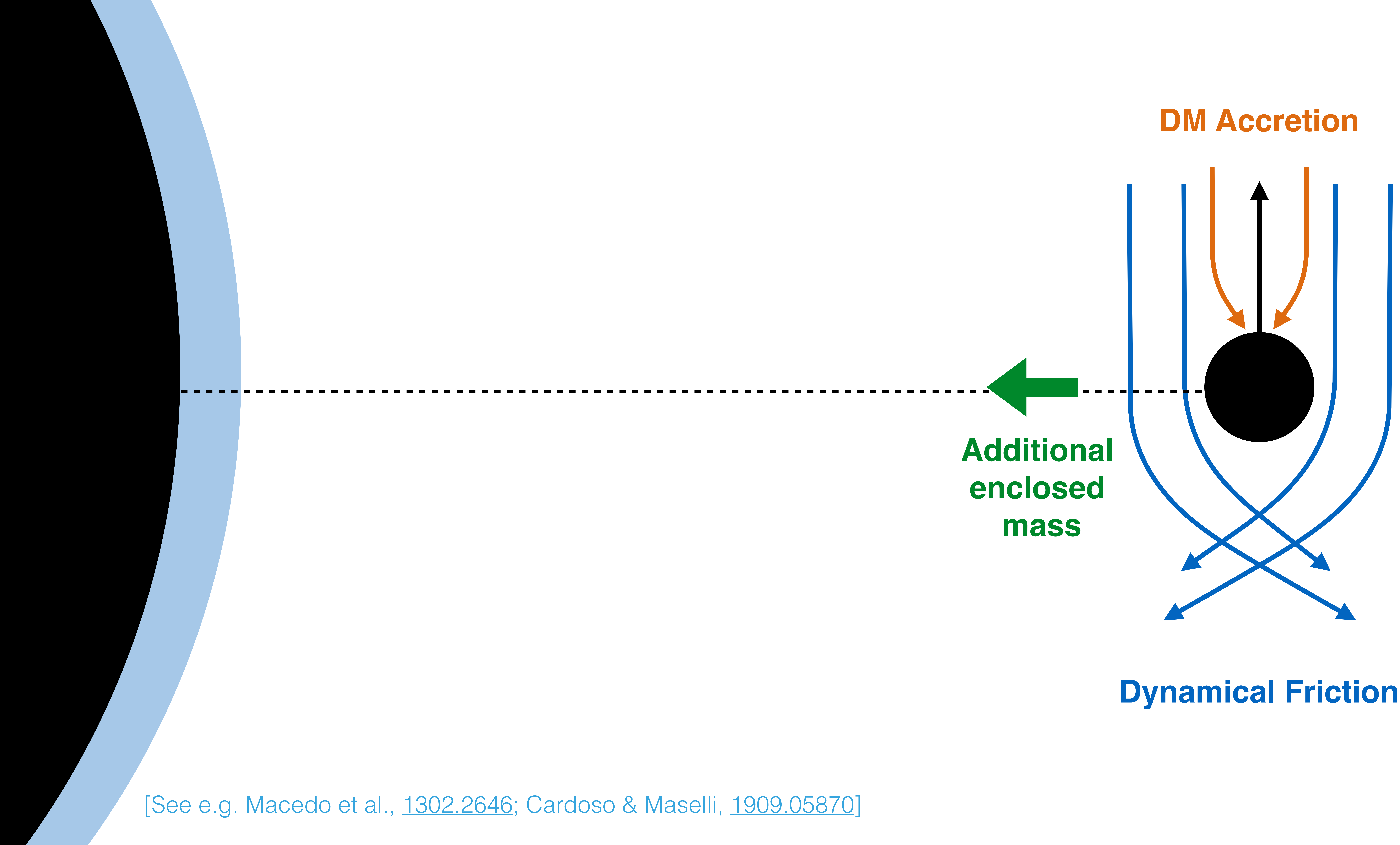
'**Spikes**' or '**dresses**' of cold, particle-like DM may form around BHs, e.g. From the slow ('adiabatic') growth of a BH at the centre of a DM halo



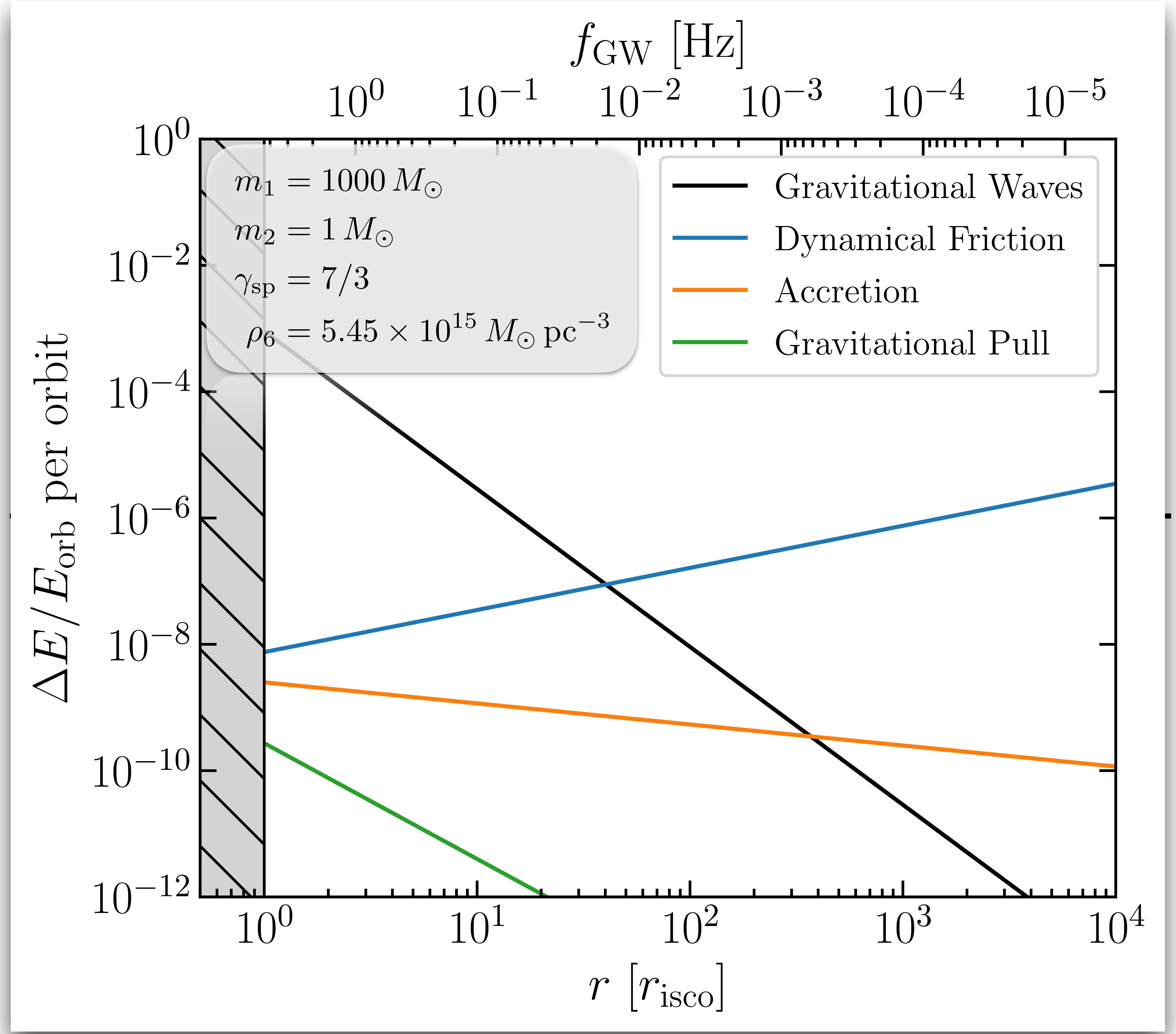


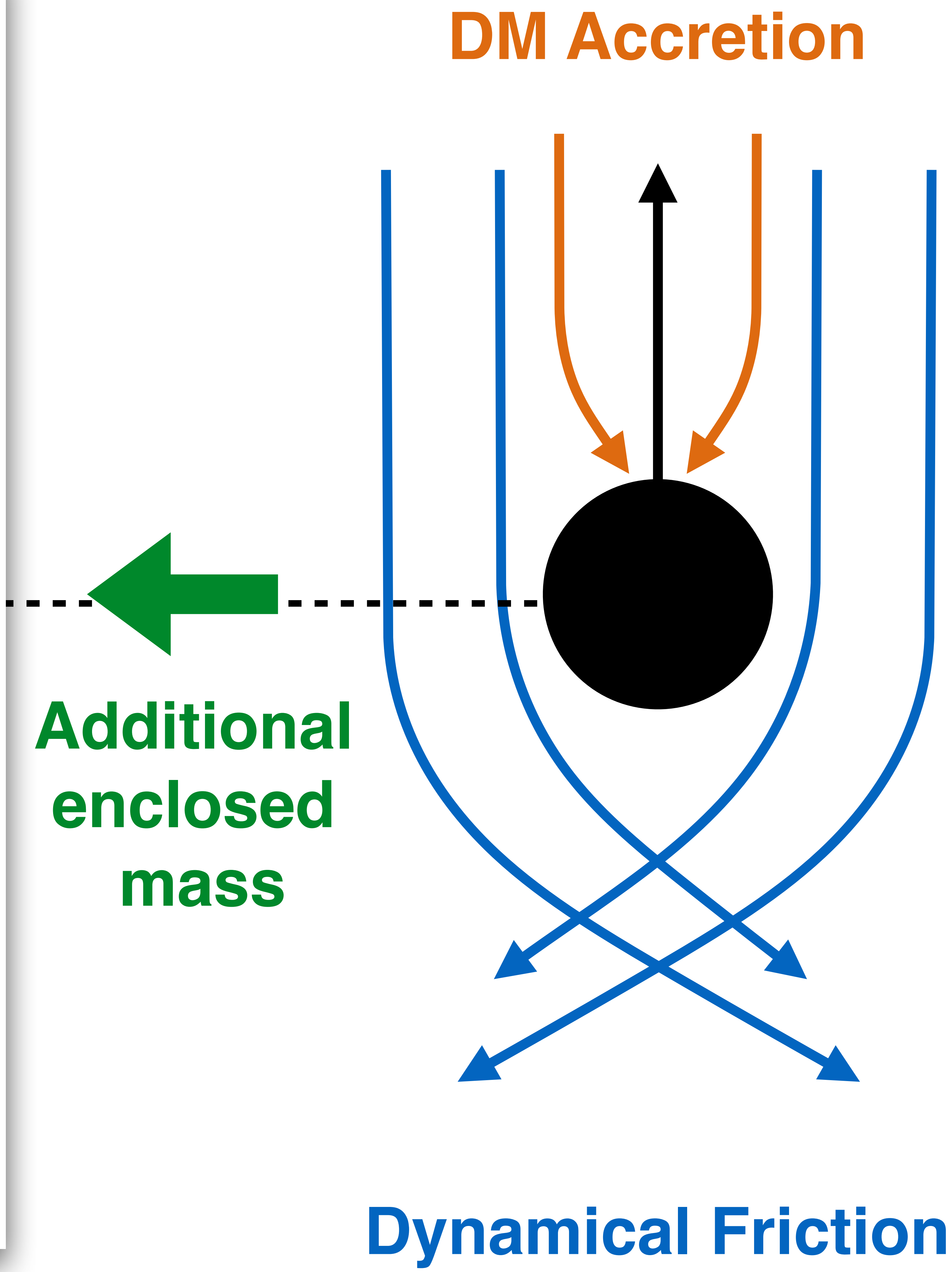
[astro-ph/9906391, astro-ph/0509565, 1305.2619, Bertschinger (1985), astro-ph/0608642, 1901.08528, …]

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

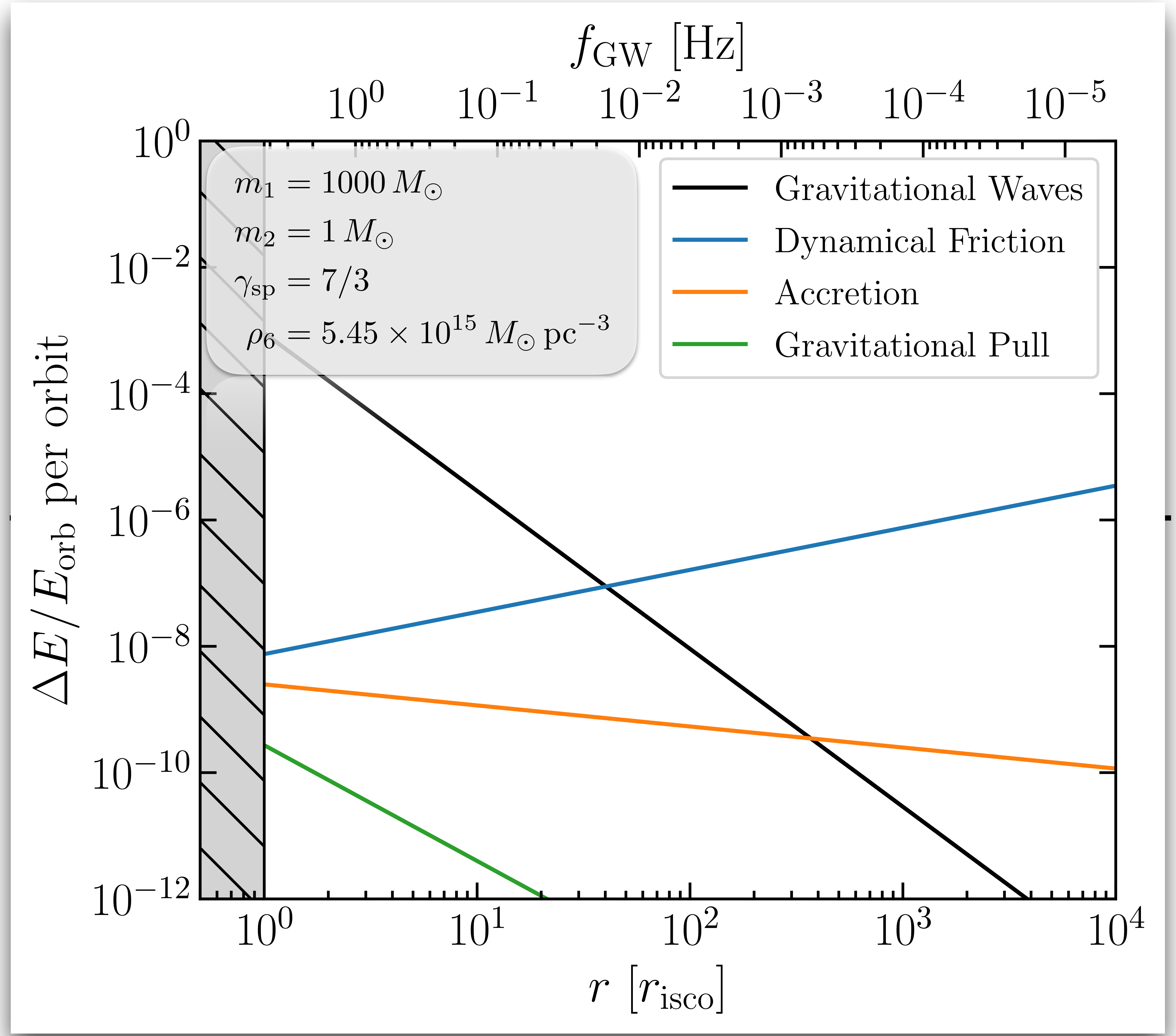


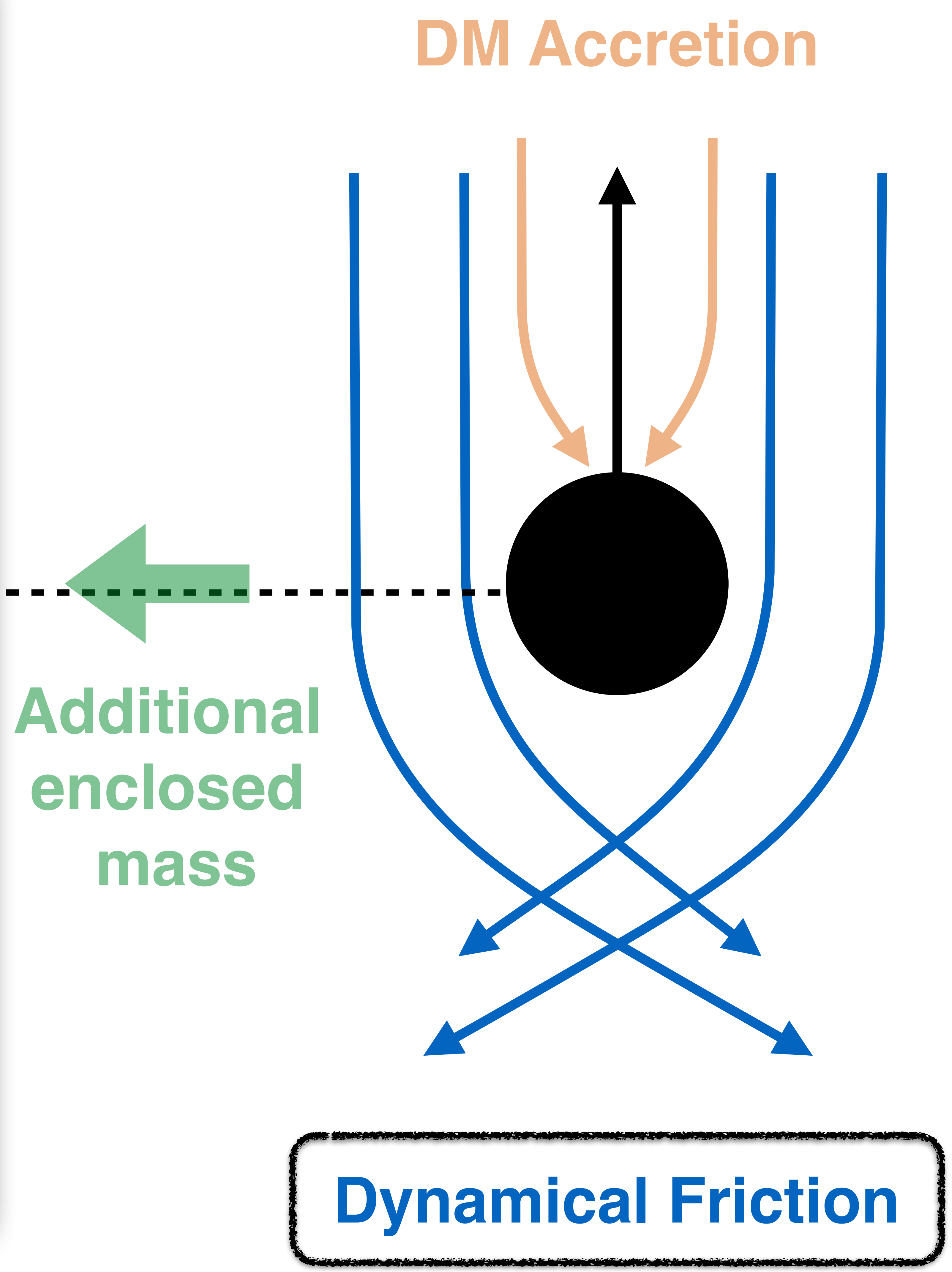
[See e.g. Macedo et al., 1302.2646; Cardoso & Maselli, 1909.05870]





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



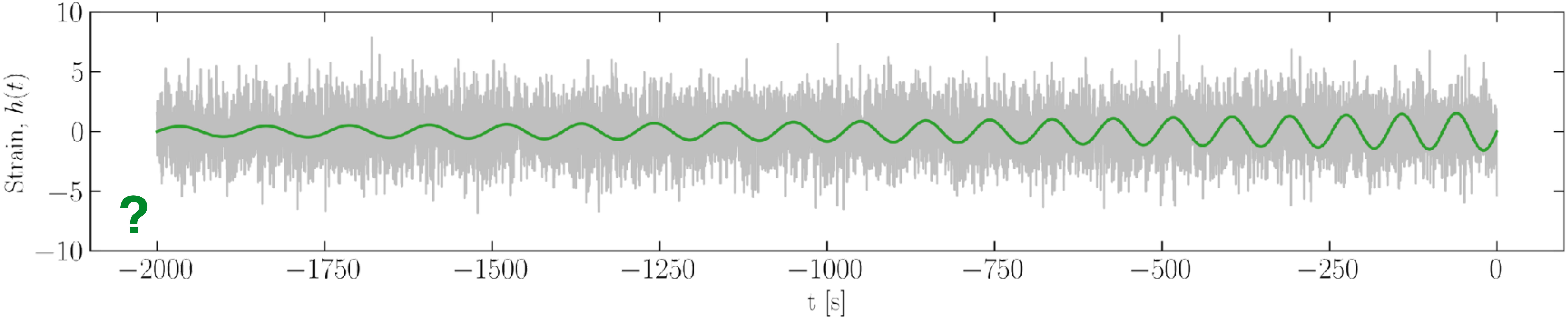


$$\dot{E}_{\rm DF} \sim \frac{4\pi G^2 m_2^2 \rho_{\rm DM}(r)\xi(v)}{v} \ln\Lambda$$

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

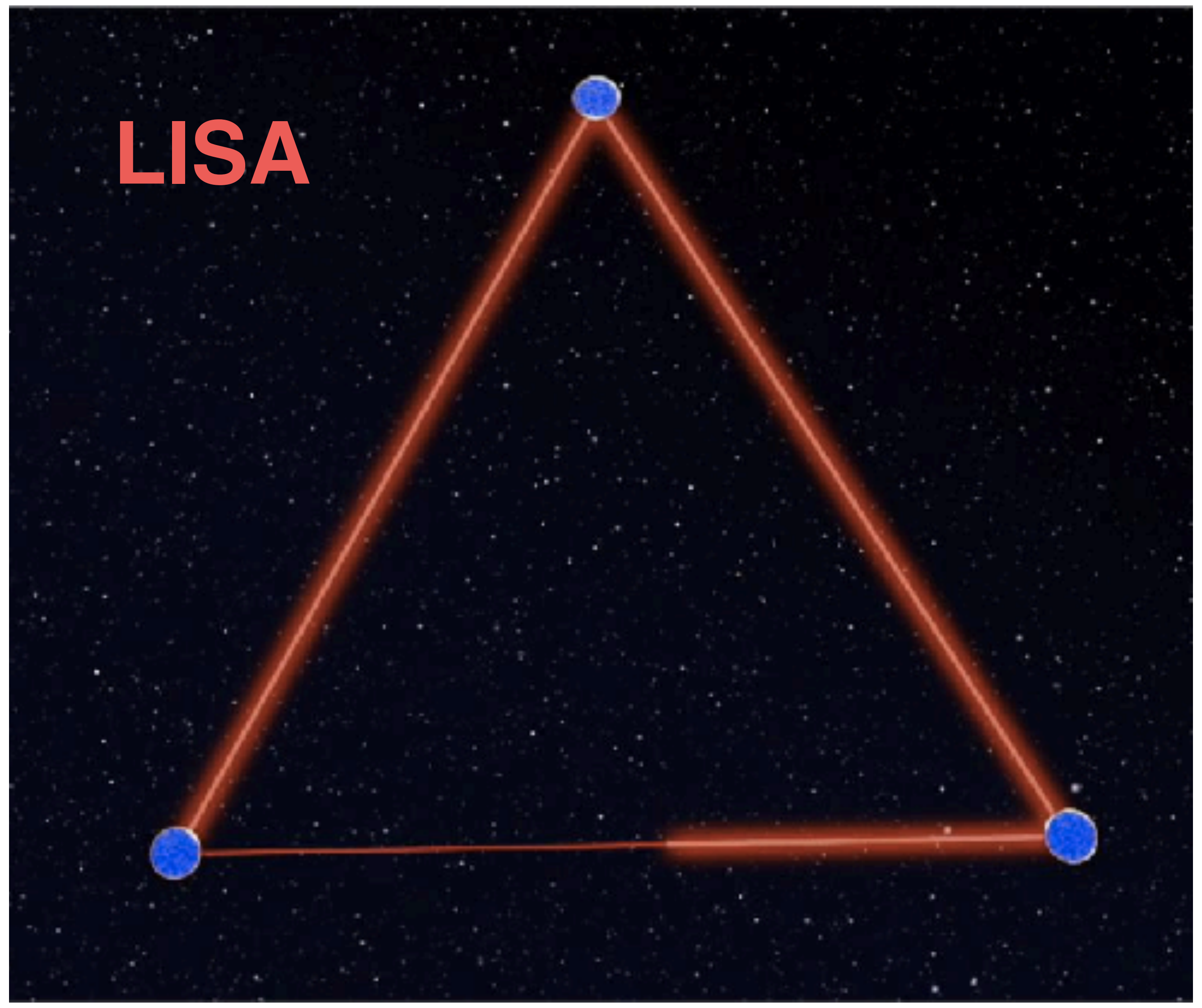
Can we measure this effect?

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



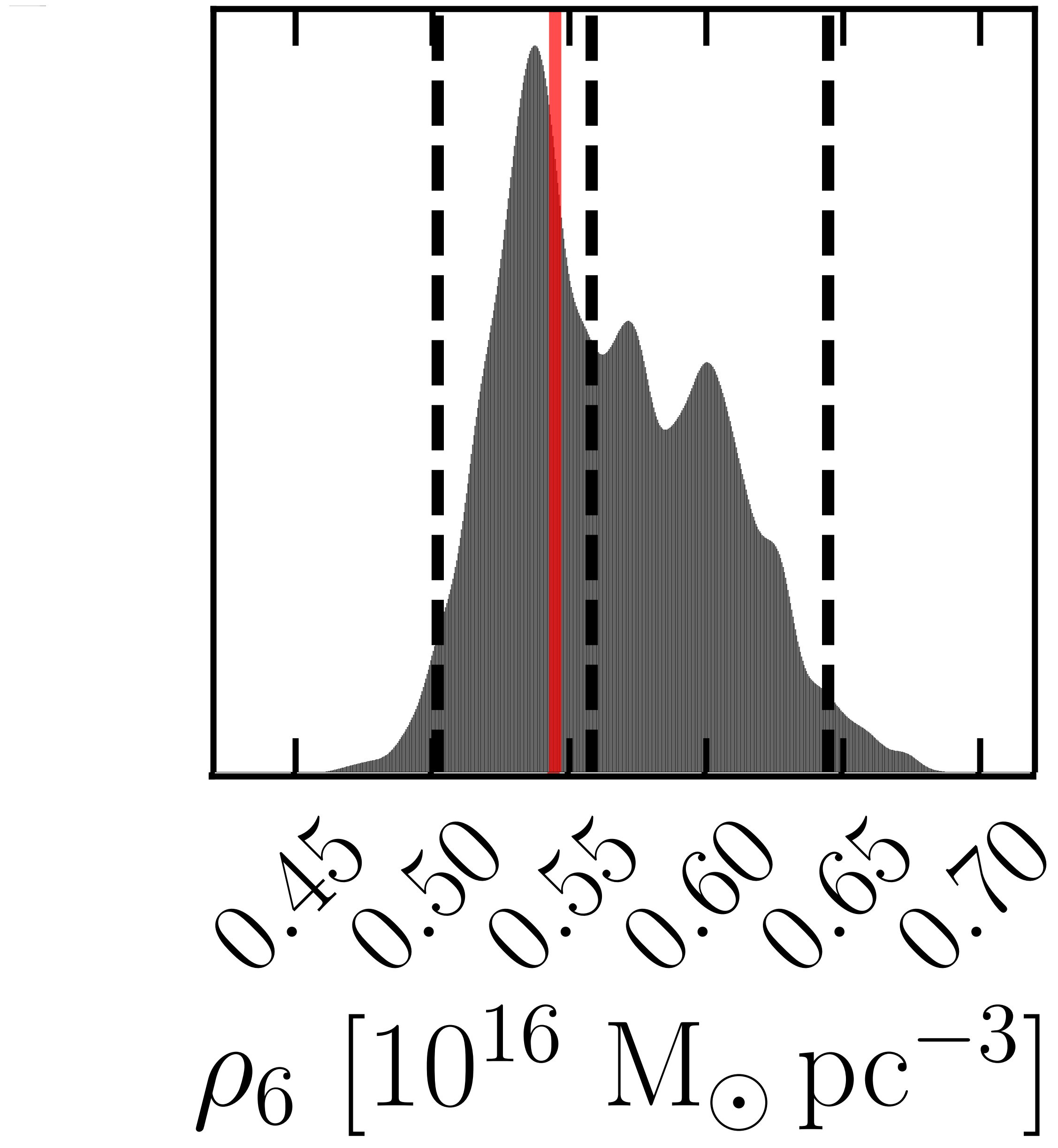
$$m_1 = 10^3\, M_\odot$$
$$m_2 = 1\, M_\odot$$

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



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

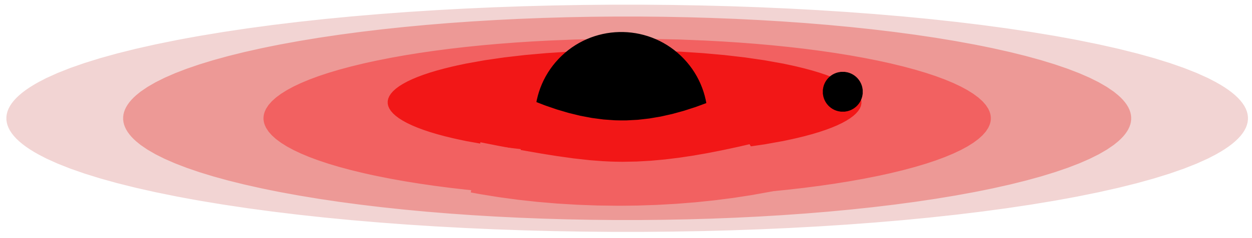
$$\rho_6\ [10^{16}\ \mathrm{M_\odot\,pc^{-3}}] = 0.56^{+0.09}_{-0.06}$$



Environmental Confusion

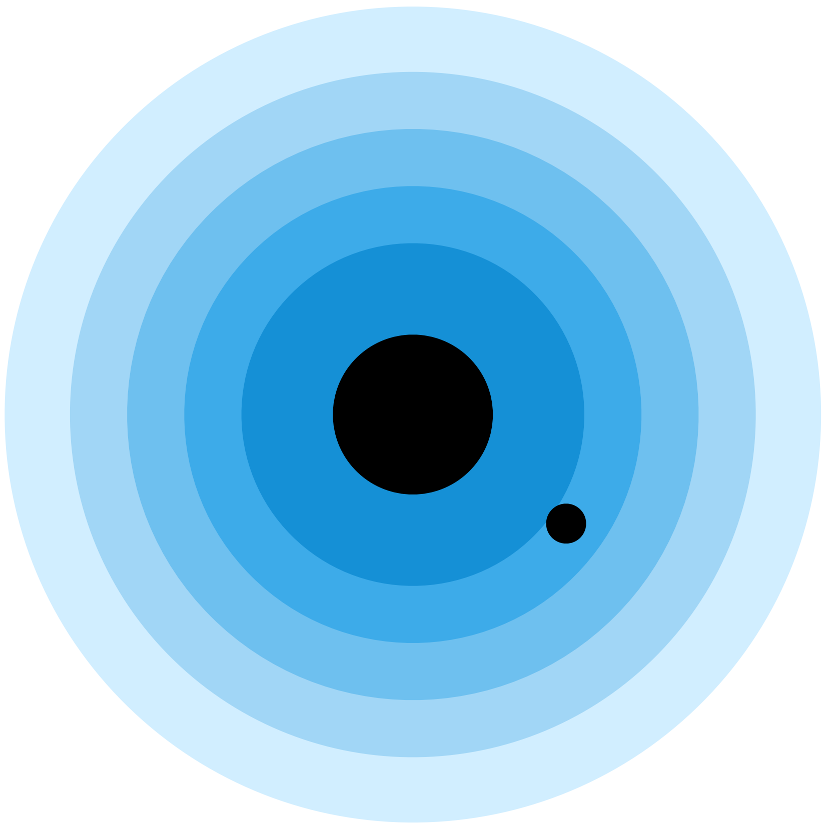
[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**, Spieksma, Tomaselli, 2211.01362, Nature Astronomy]

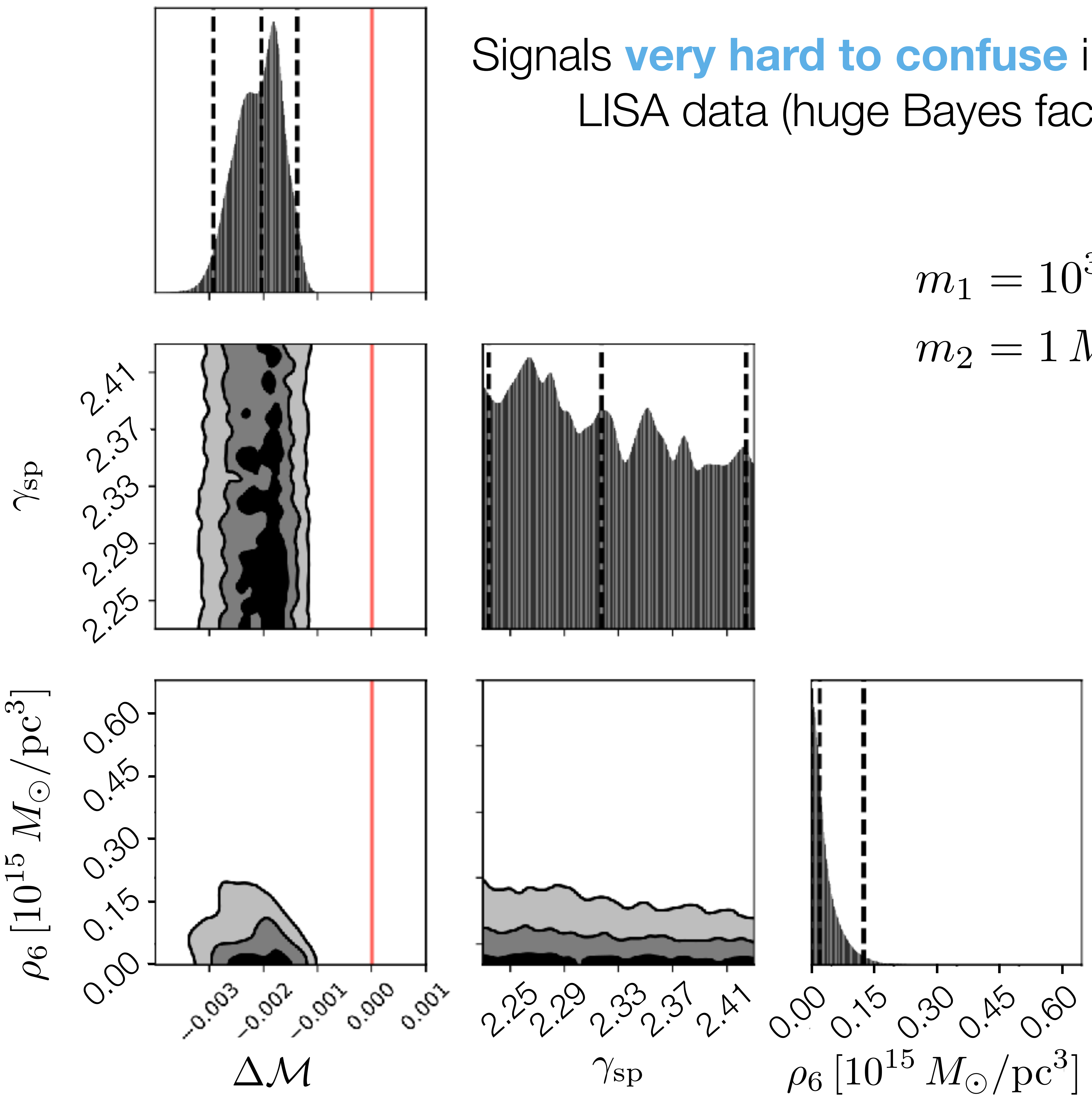
Generate waveform assuming:



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

Fit signal assuming:





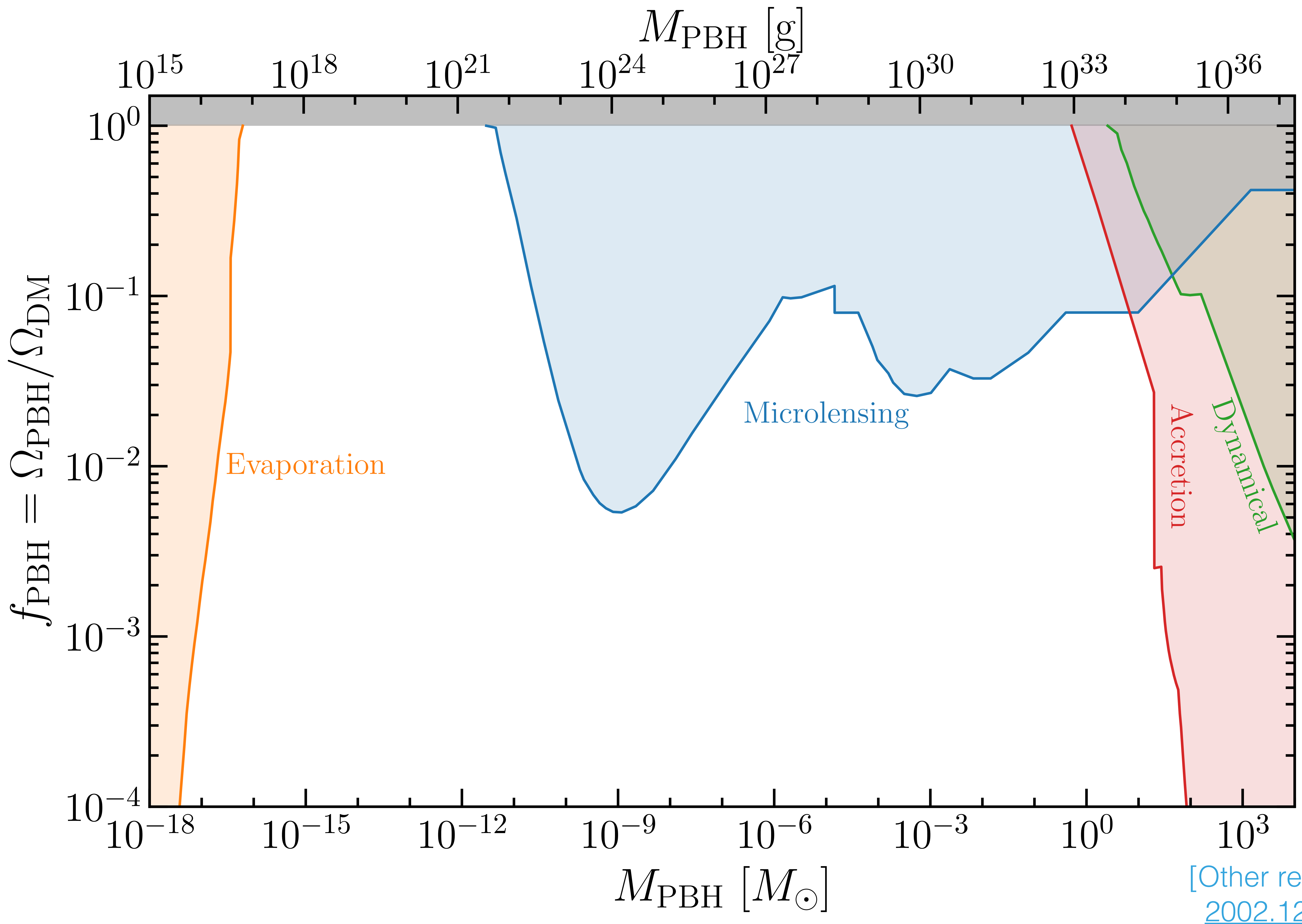
Signals **very hard to confuse** in 1 year of LISA data (huge Bayes factors!)

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

PBH Parameter Space

[Green & **BJK**, 2007.10722]

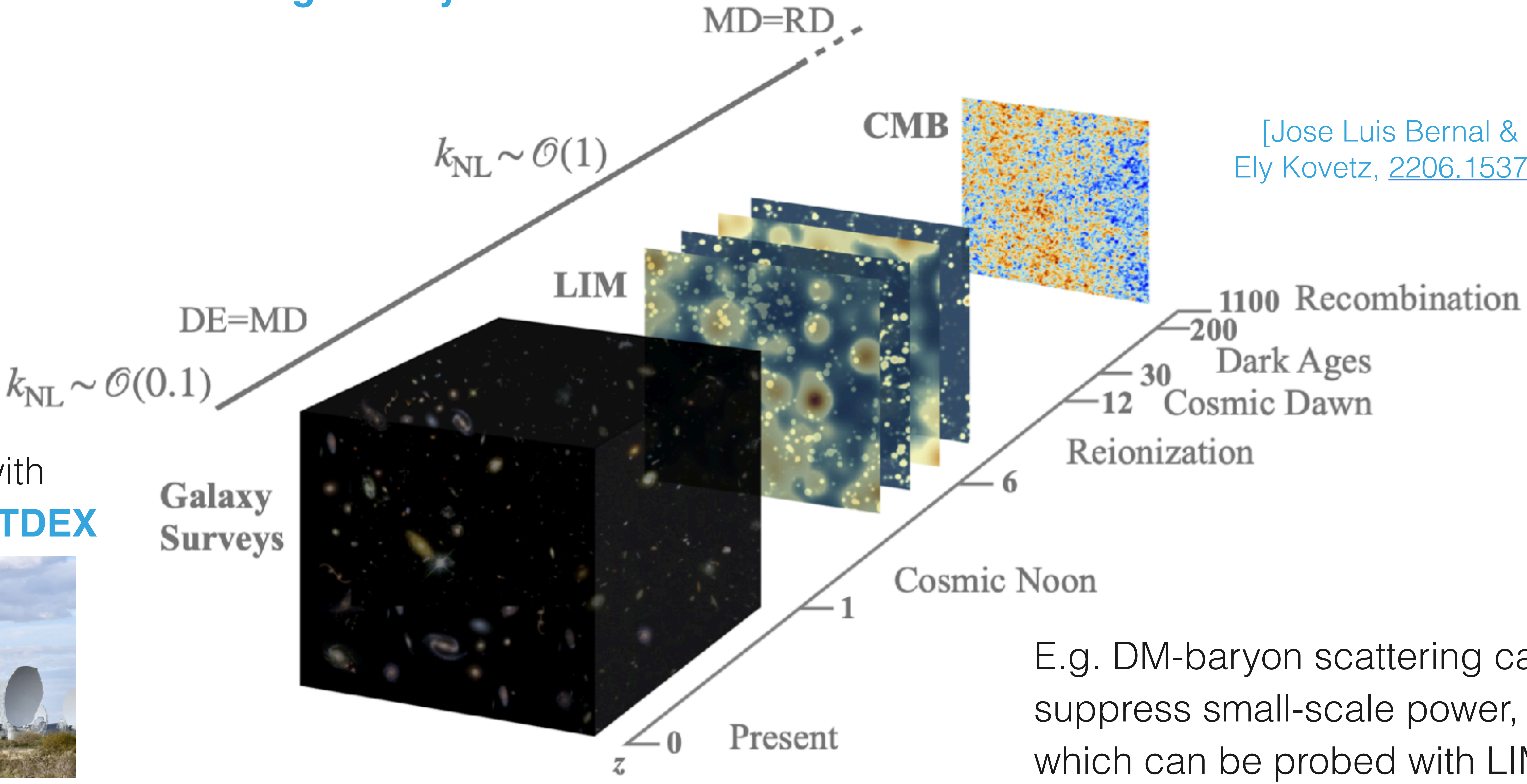
[Code online: github.com/bradkav/PBHbounds]



[Other reviews: 1801.05235, 2002.12778, 2006.02838]

Line Intensity Mapping (LIM)

Growing expertise in **Line Intensity Mapping (LIM):** mapping out the intensity of emission lines (microwave to optical) across large portions of the sky. Fluctuations in intensity can provide information about **small-scale matter clustering at early times.**



[Jose Luis Bernal & Ely Kovetz, 2206.15377]

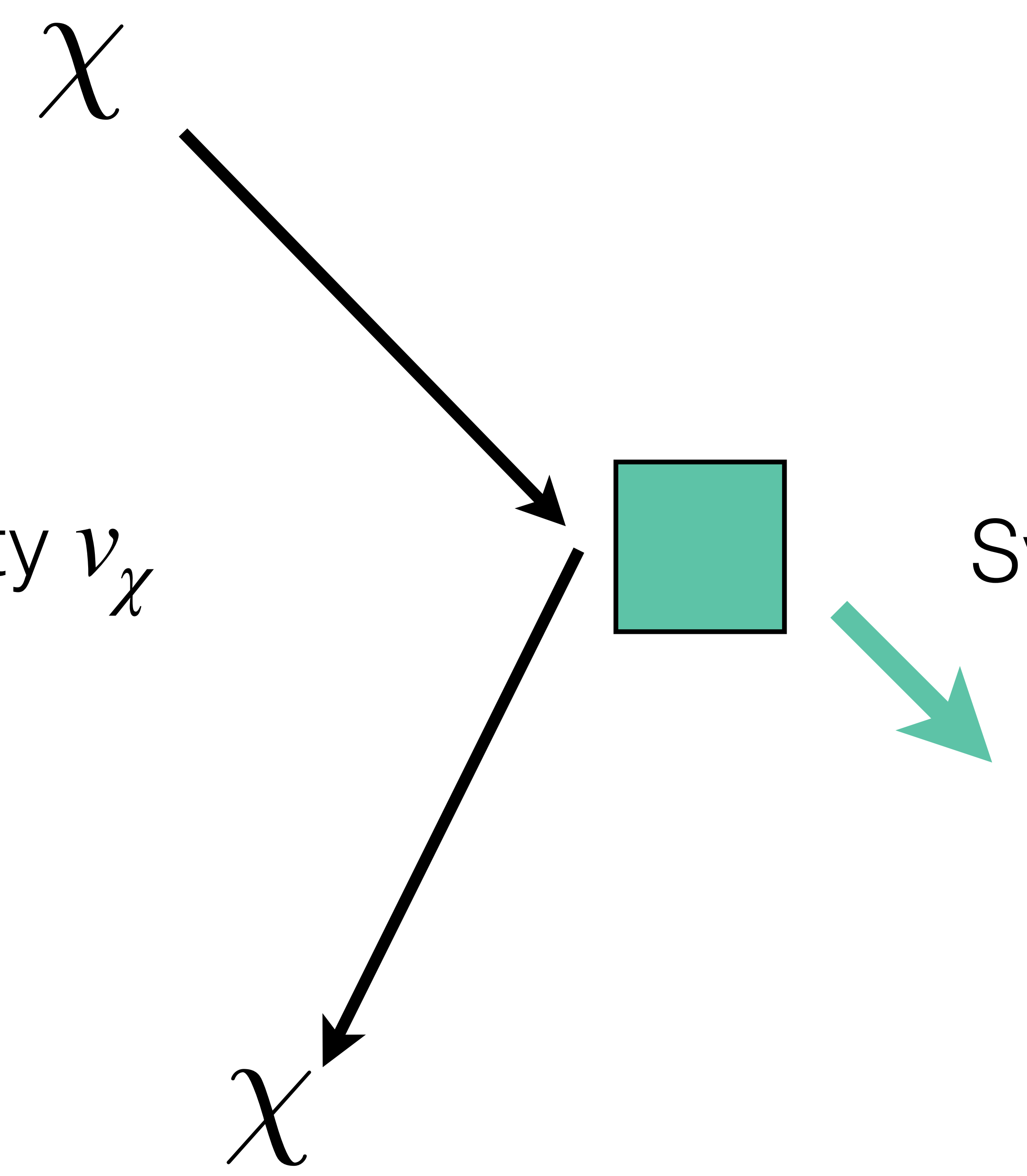
IFCA is involved with **MeerKAT** and **HETDEX**

E.g. DM-baryon scattering can suppress small-scale power, which can be probed with LIM

[Short et al., arXiv:2203.16524]

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

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

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

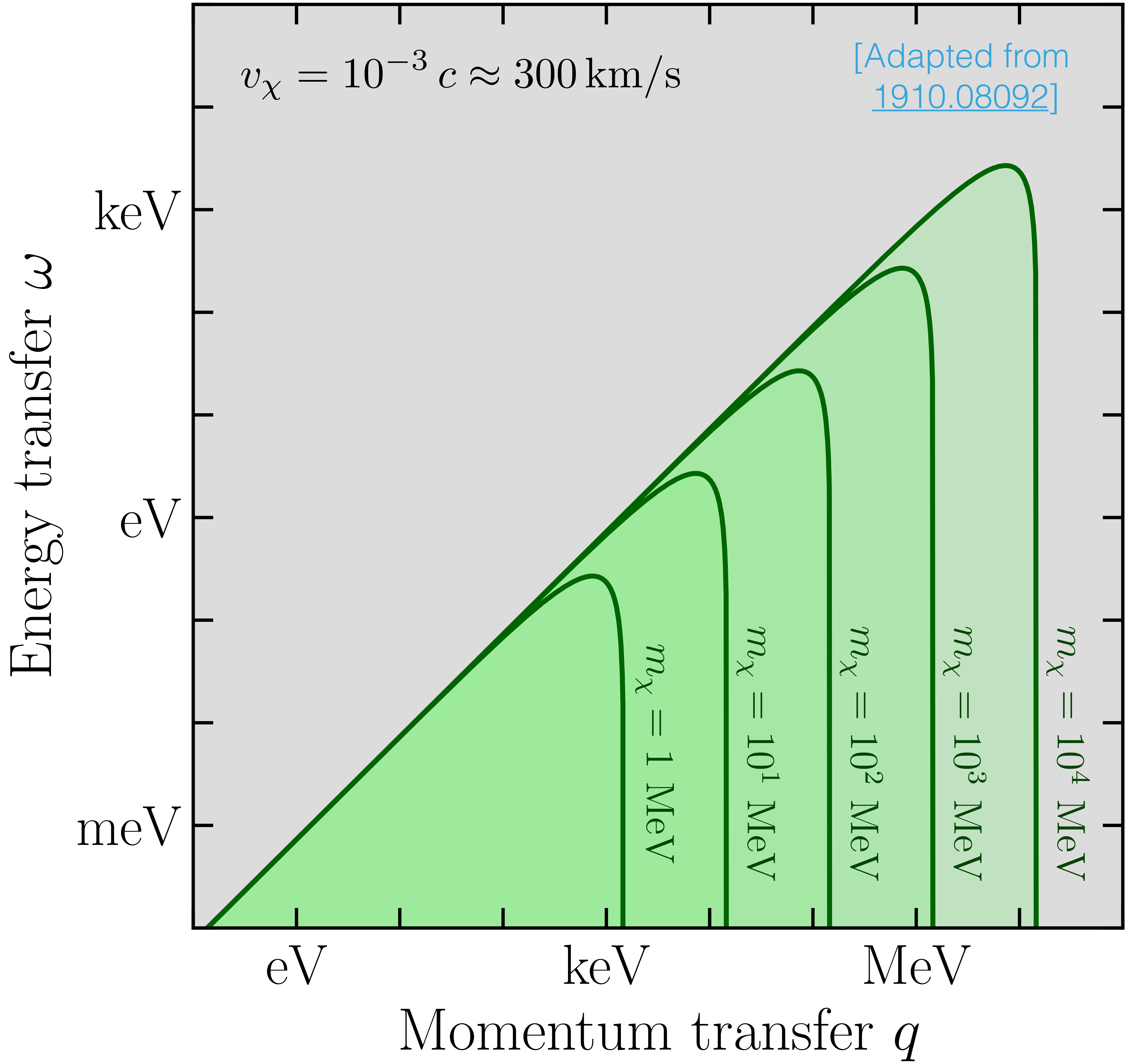
Scattering Kinematics

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



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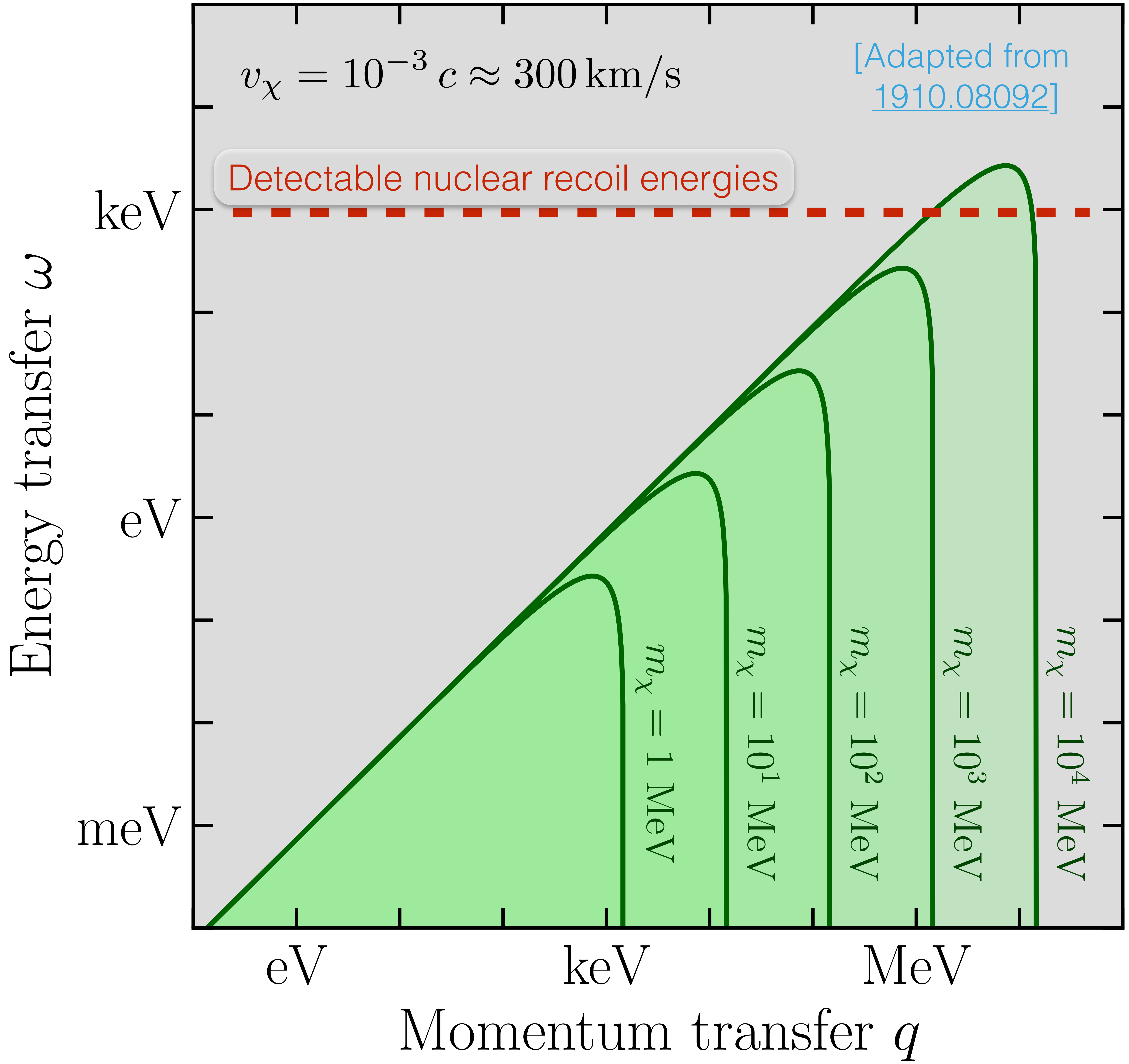

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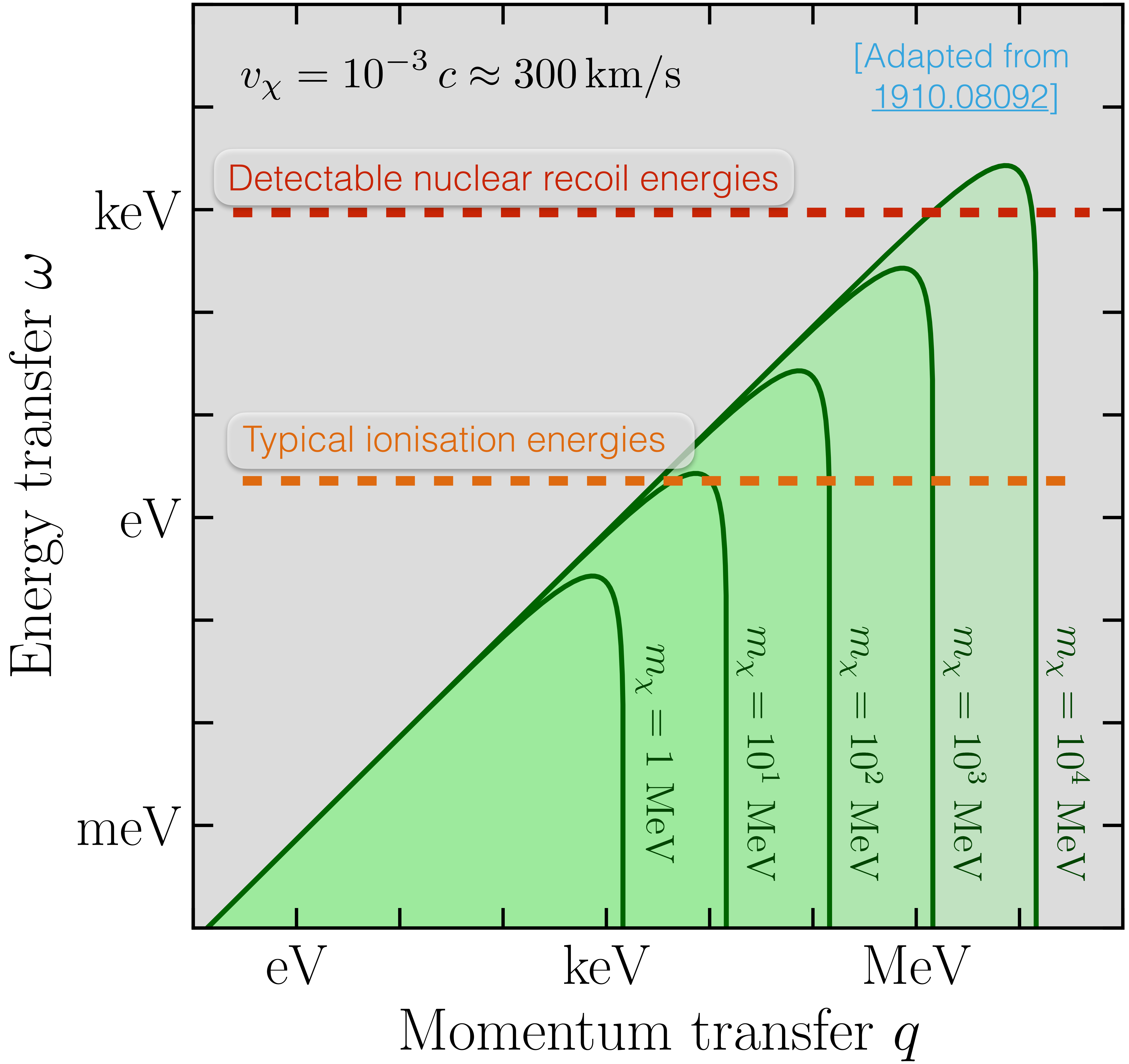

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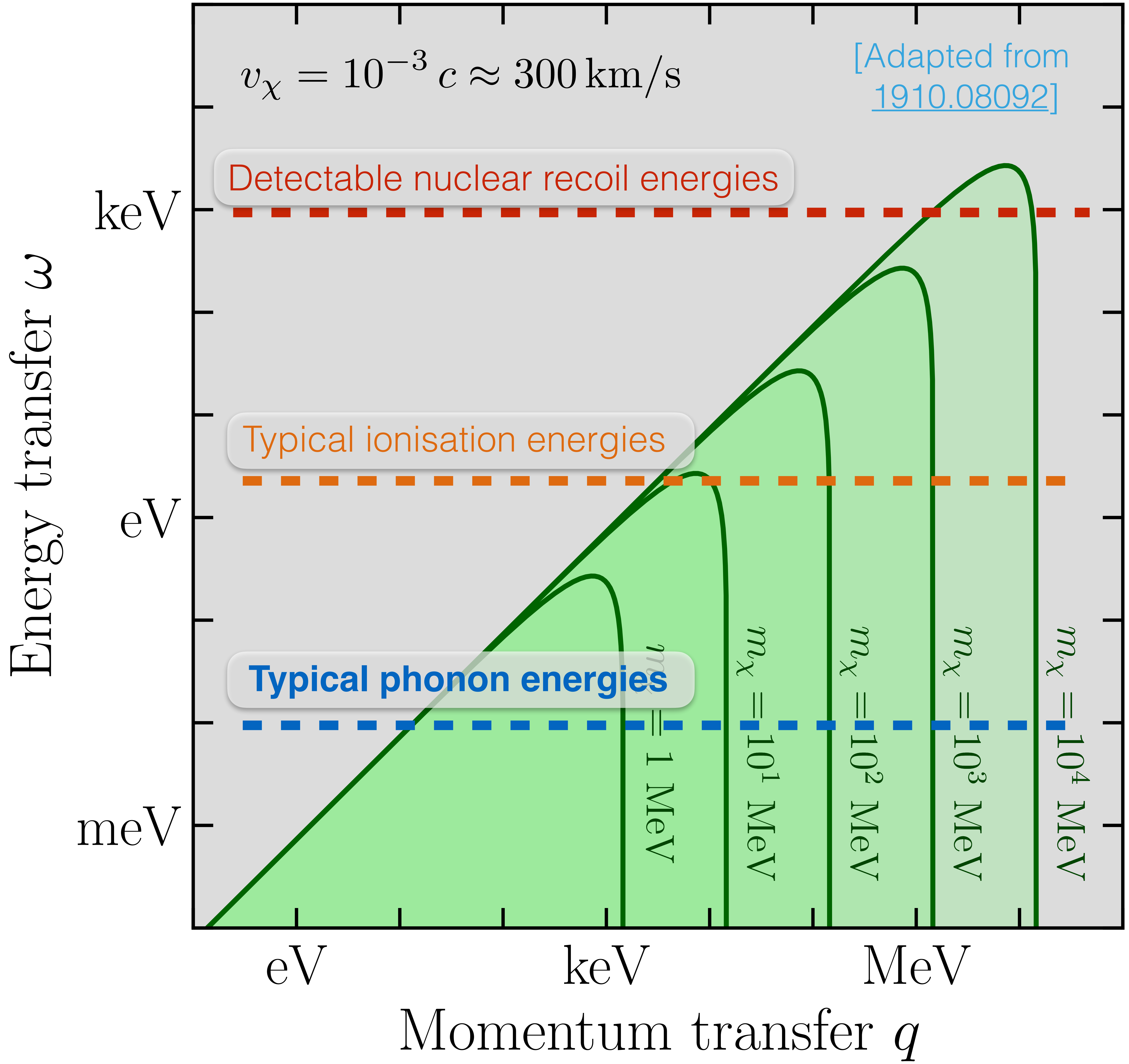

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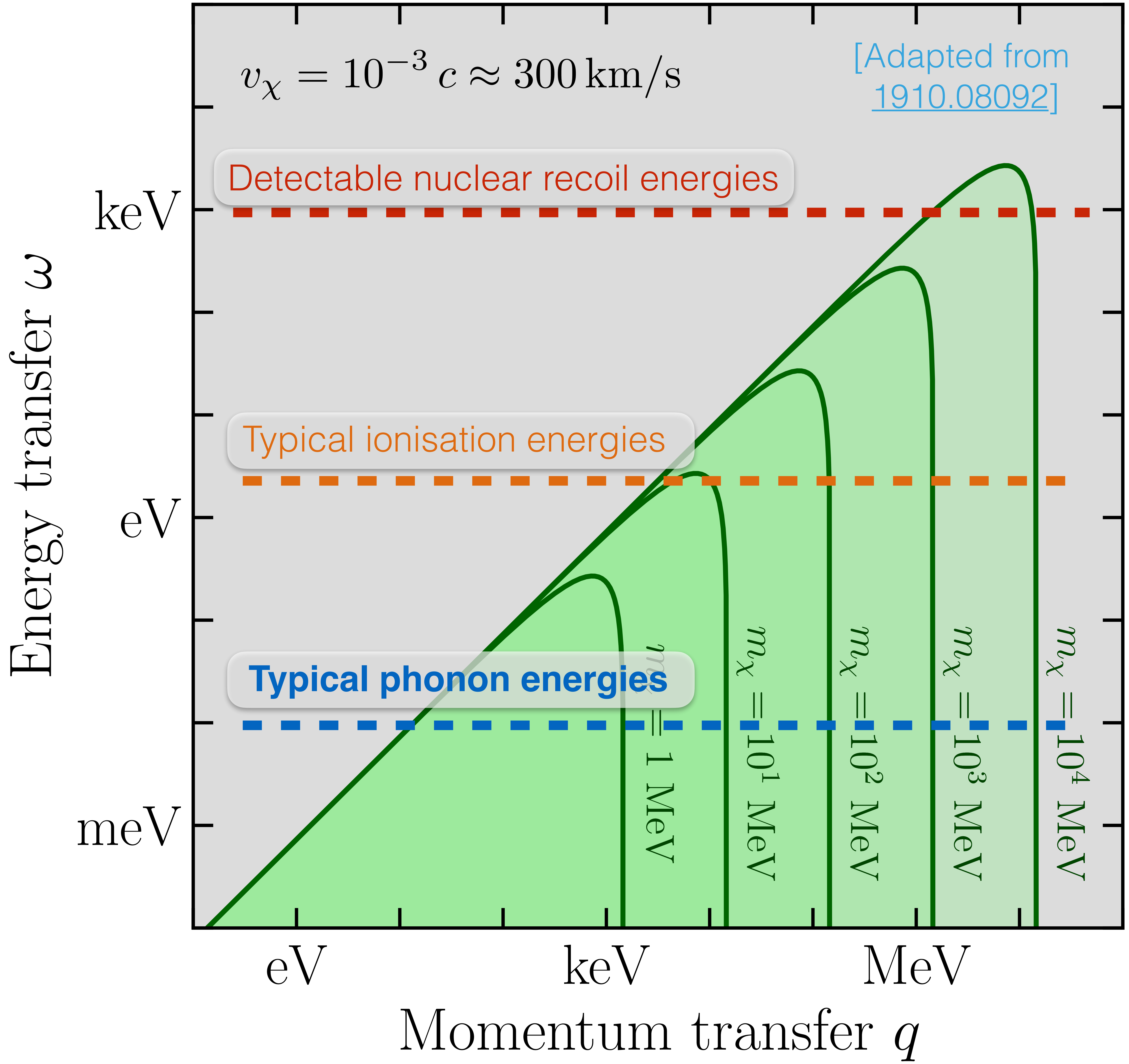
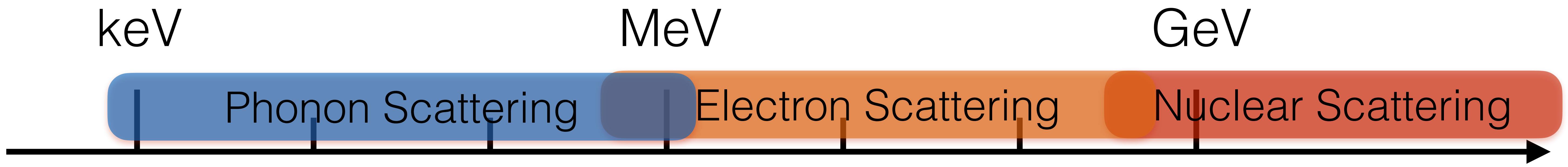


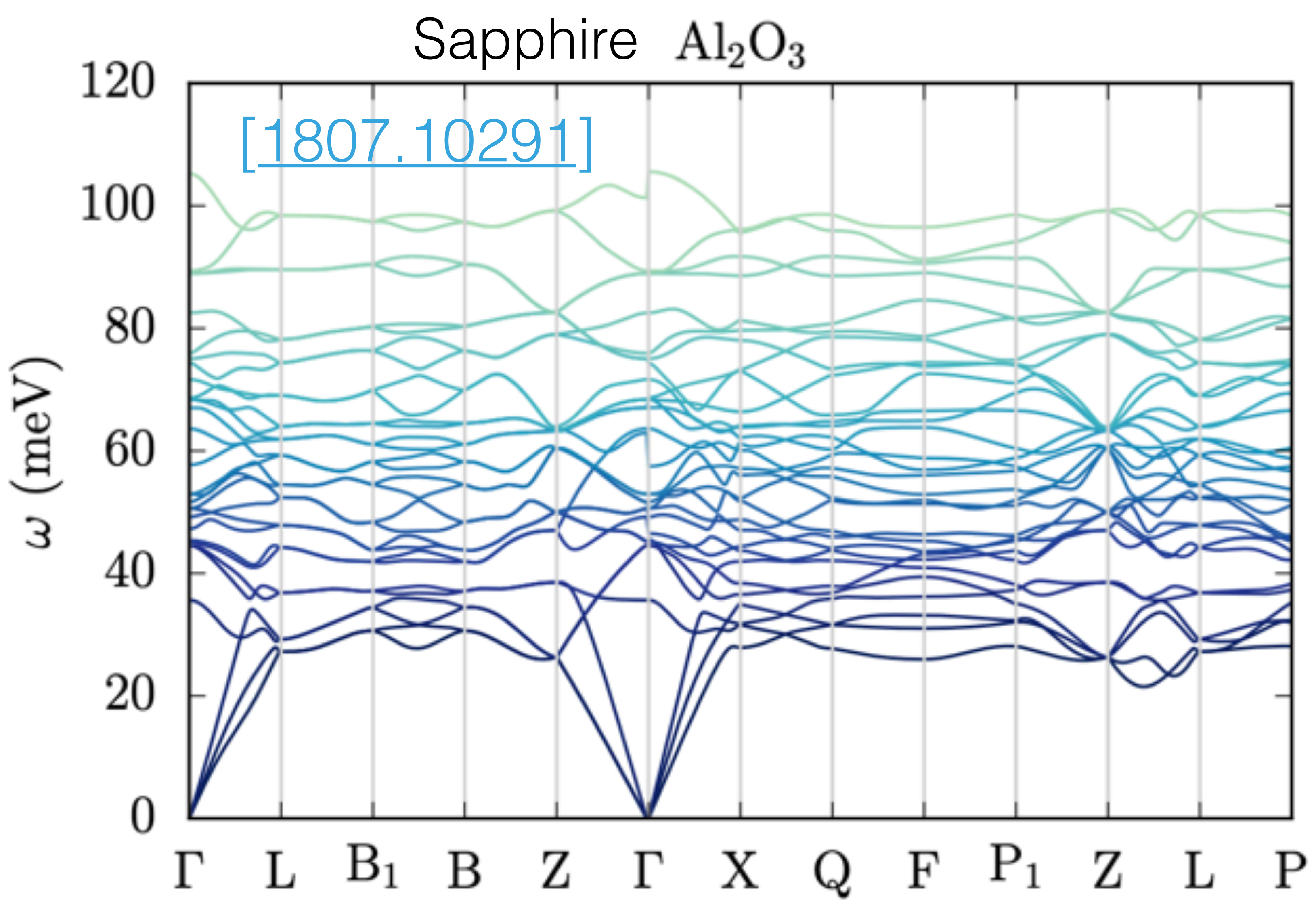
DM mass ranges:



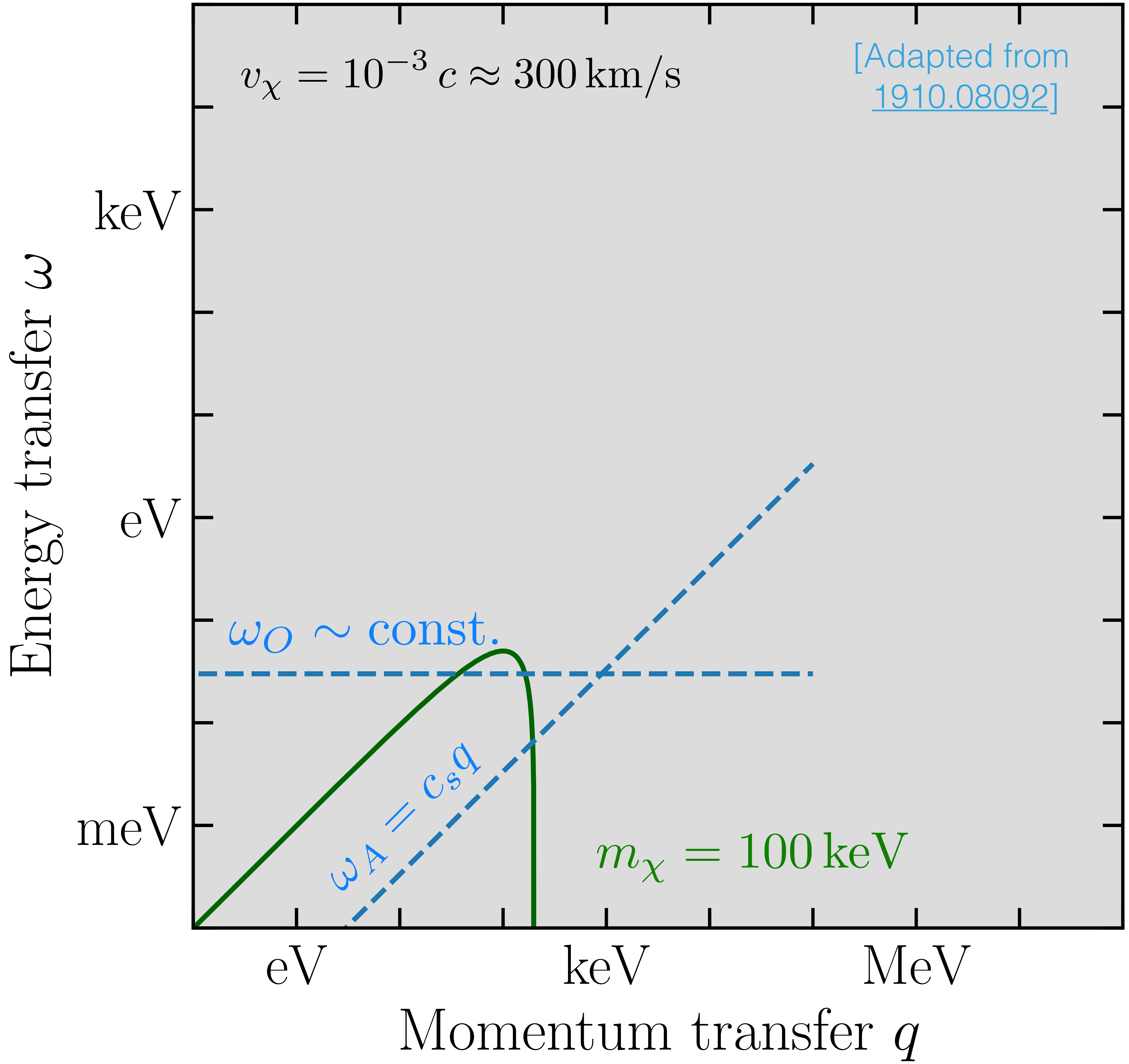
Optical vs acoustic phonons

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).



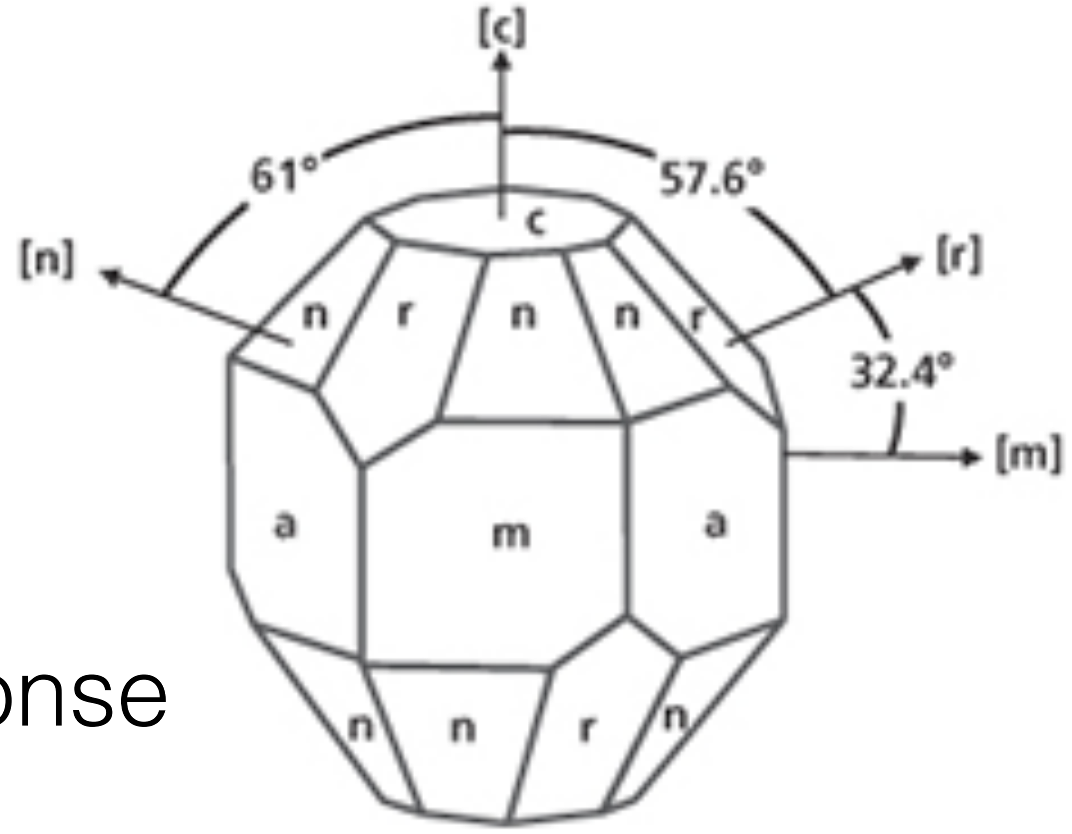
Time-dependent DM Signal

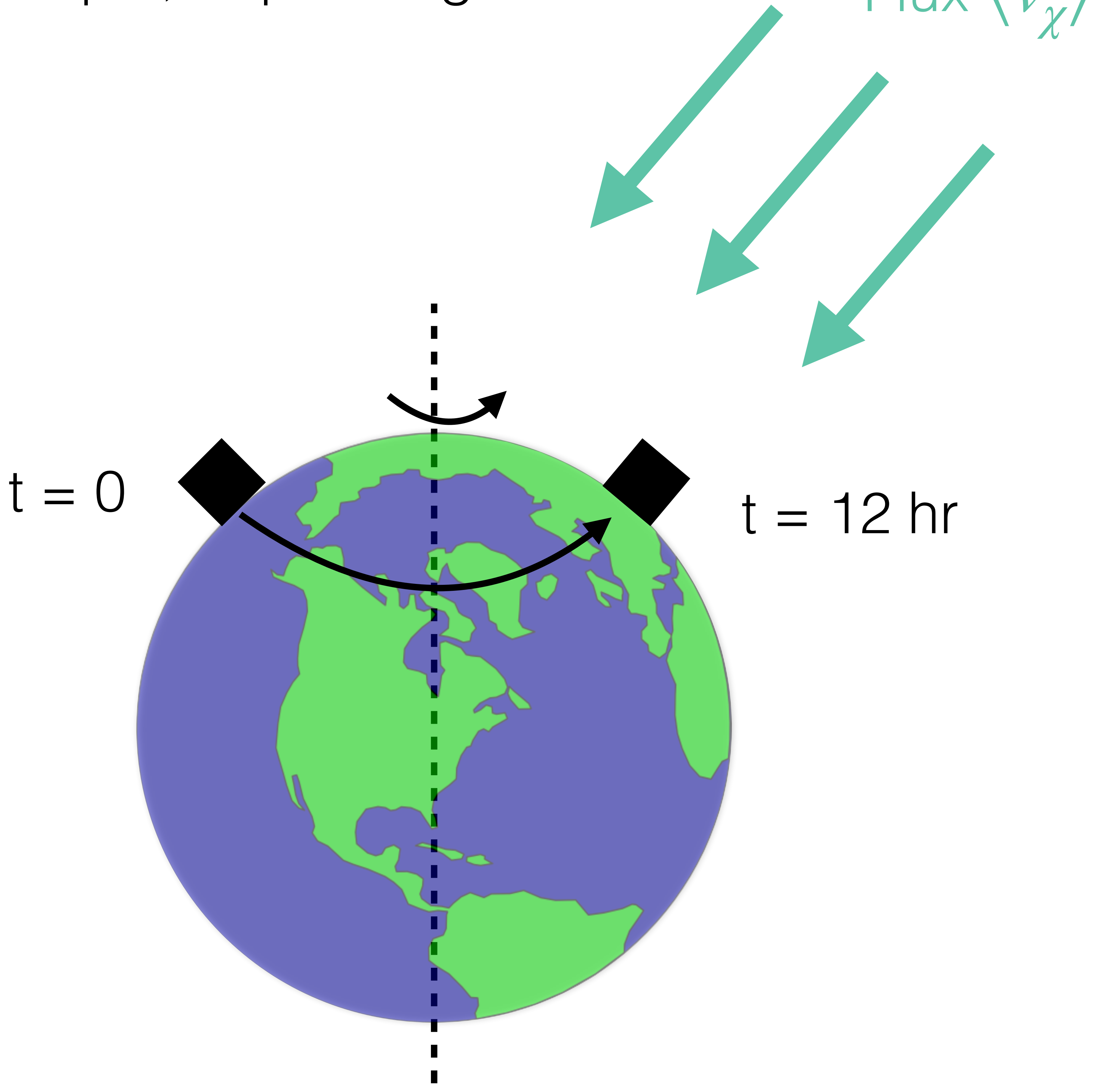
DM flux comes from a preferred direction, meaning that if the phonon response is anisotropic, a characteristic **time-dependent signal** can arise.

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

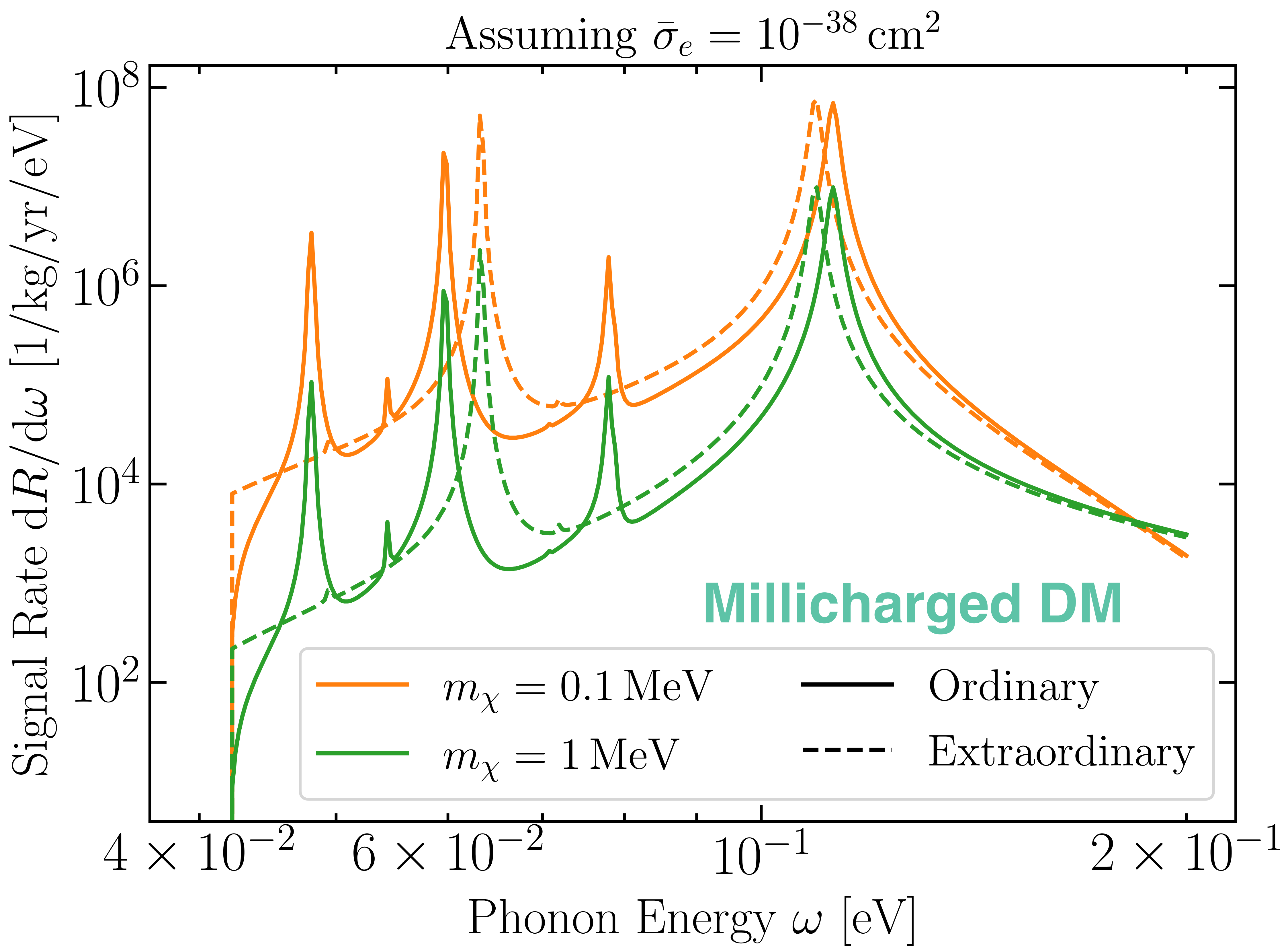
$\mathbf{k} \perp c$-axis:
Extraordinary response

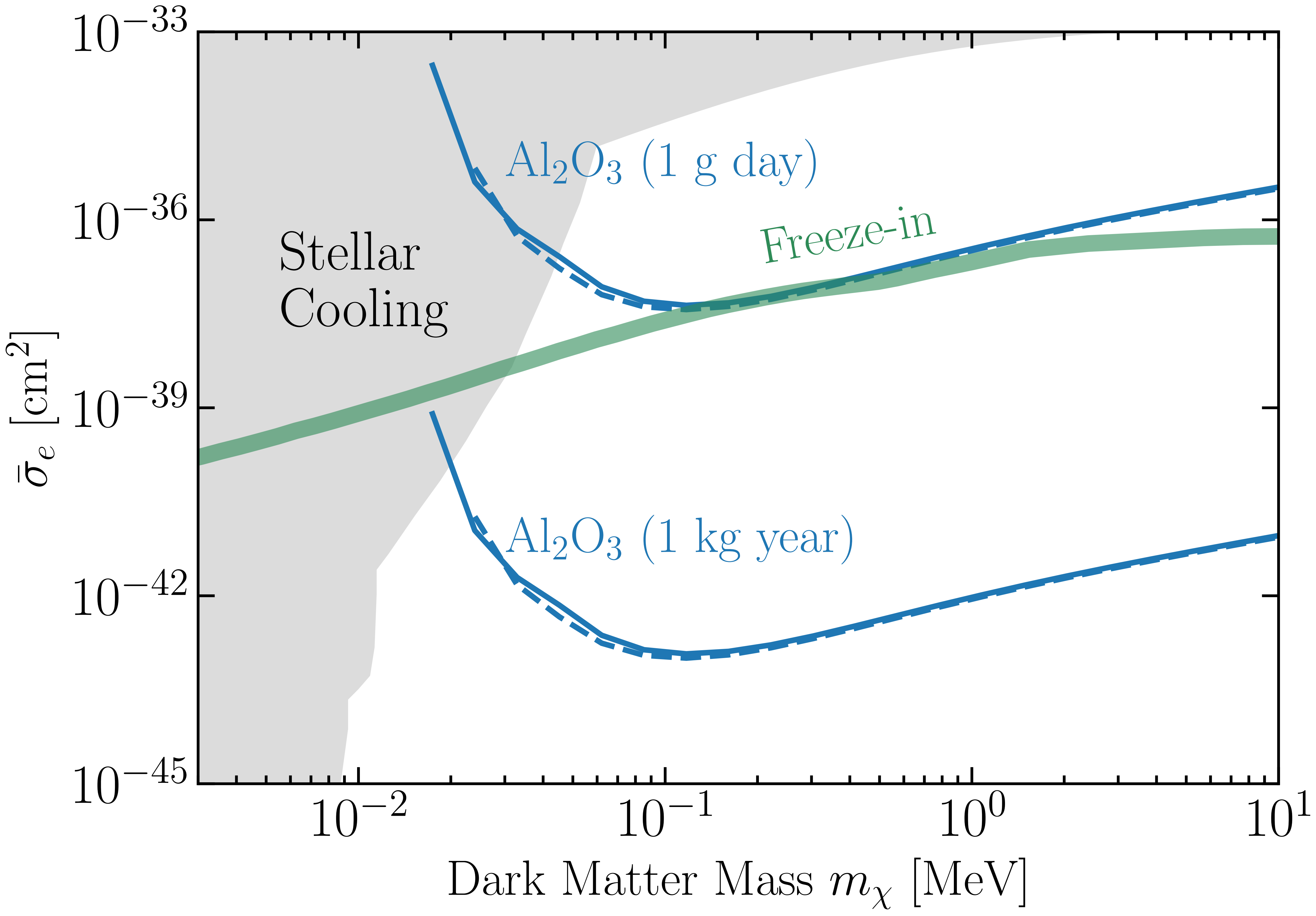




DM-Phonon Scattering Rates

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

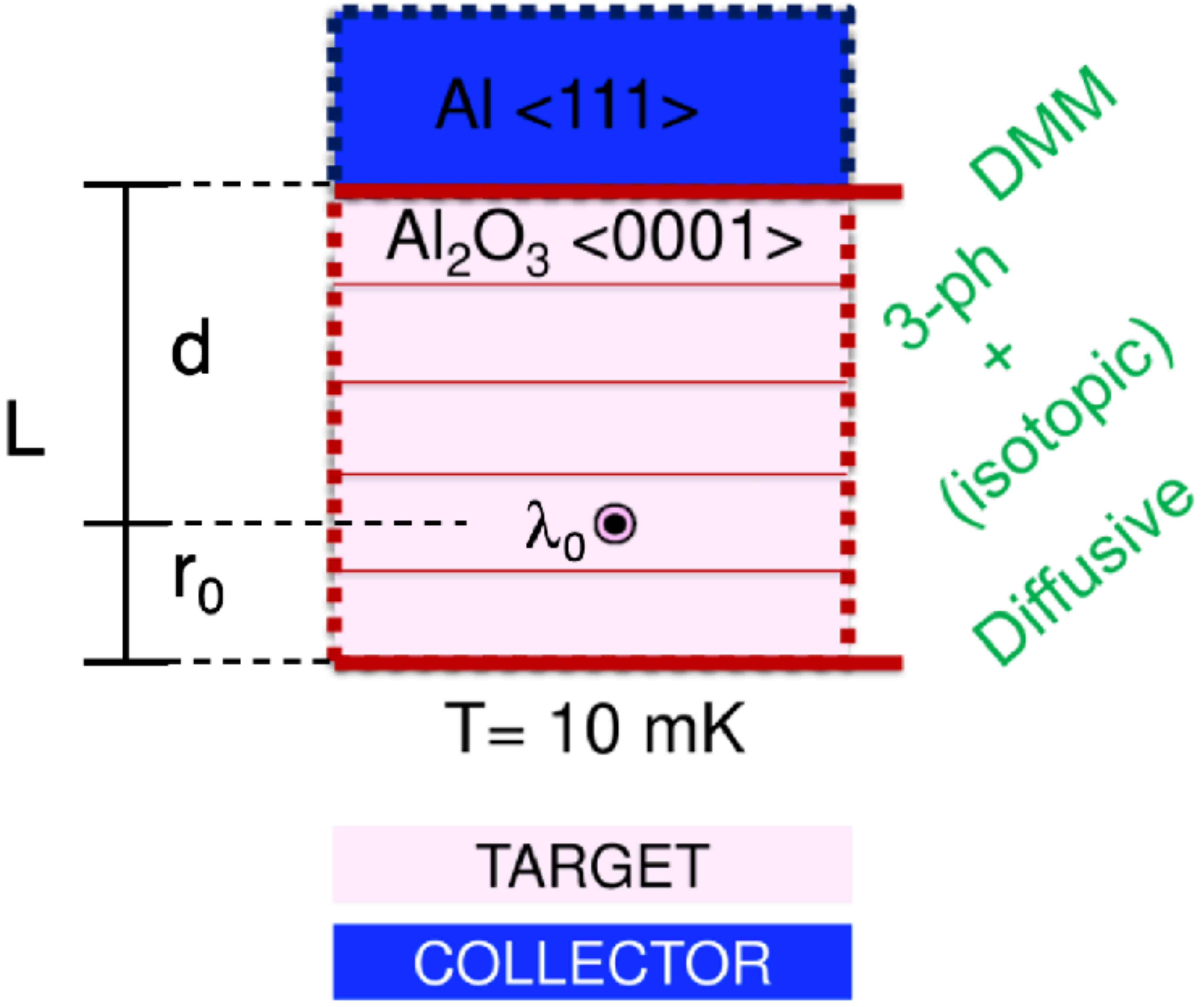


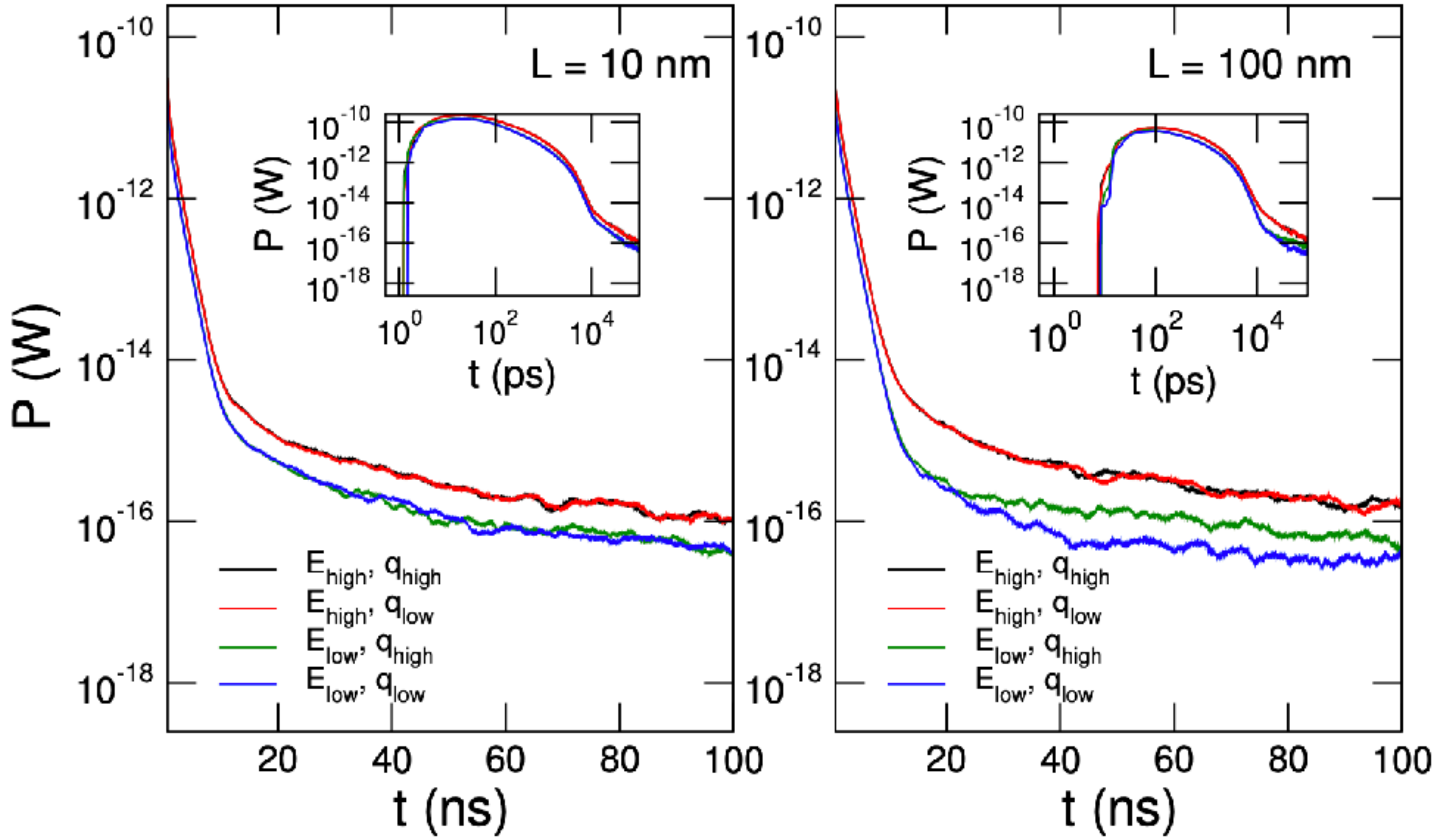


But a **full survey** of Dark Matter models and target materials has not yet been completed.

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]

Kinetic Inductance Detectors (KIDs)

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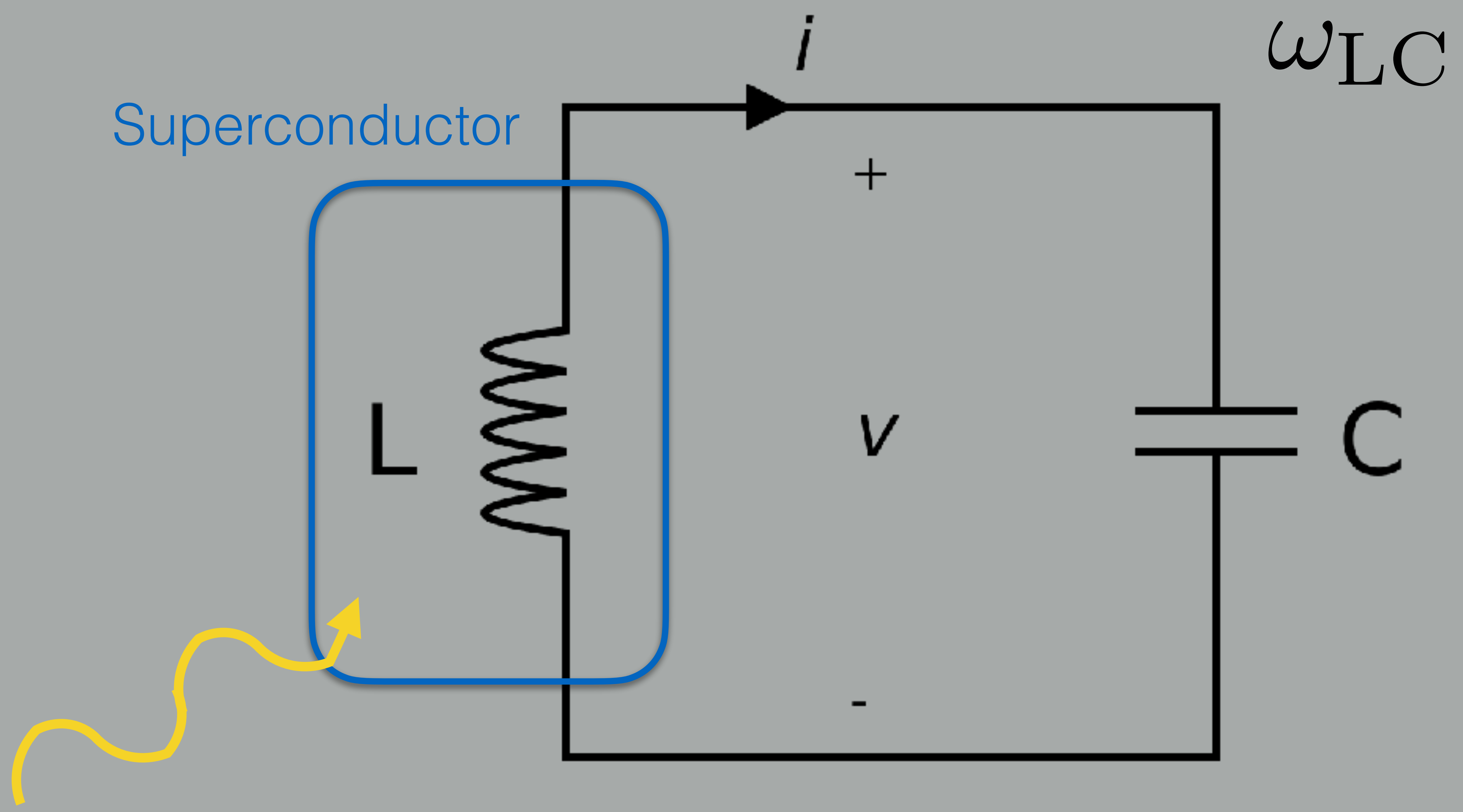
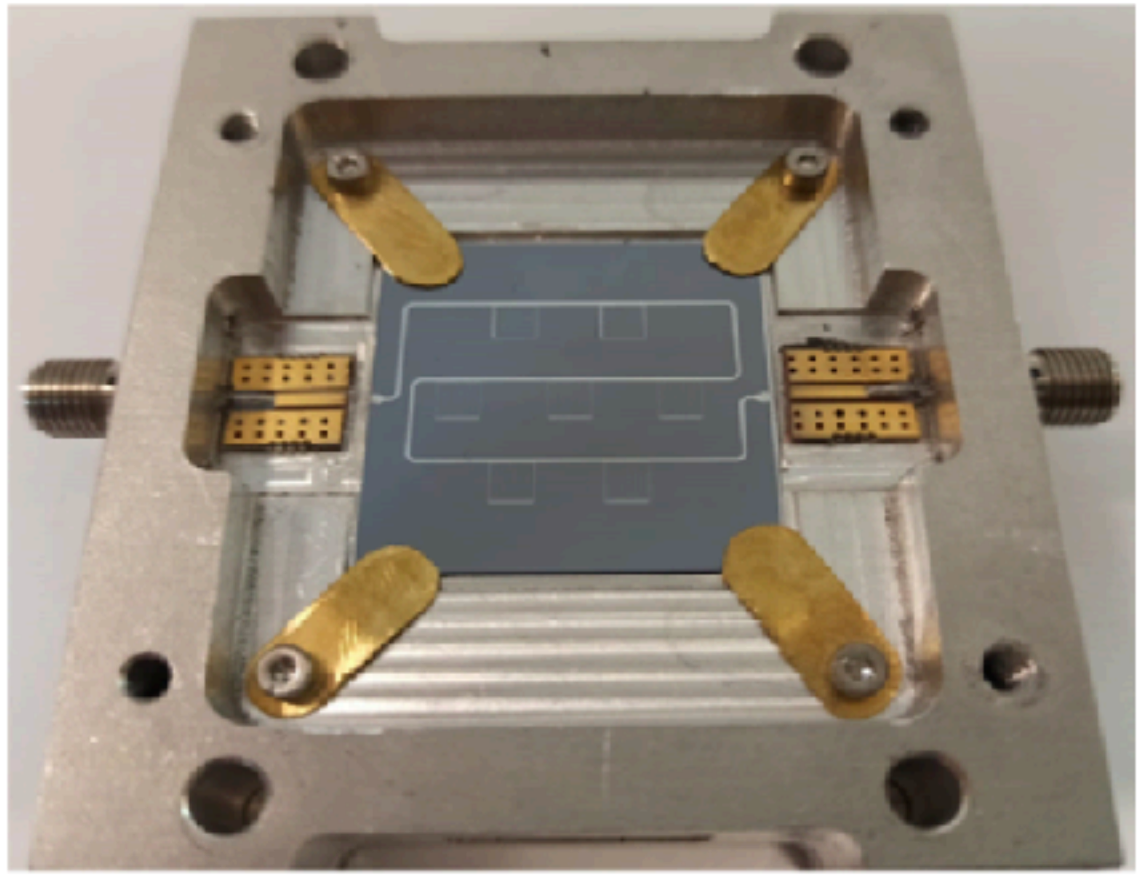


Photon absorbed by superconductor reduces kinetic inductance,
altering the resonant frequency of the LC circuit



Kinetic Inductance Detectors (KIDs)