# Dark Matter models


## Celine Boehm
## Usyd


Courtesy Millie McDonald, Whisky Bay in Wilsons Promontory, 45 frames, each a stack of 4x 6s exposures at ISO 800

The problem(s)

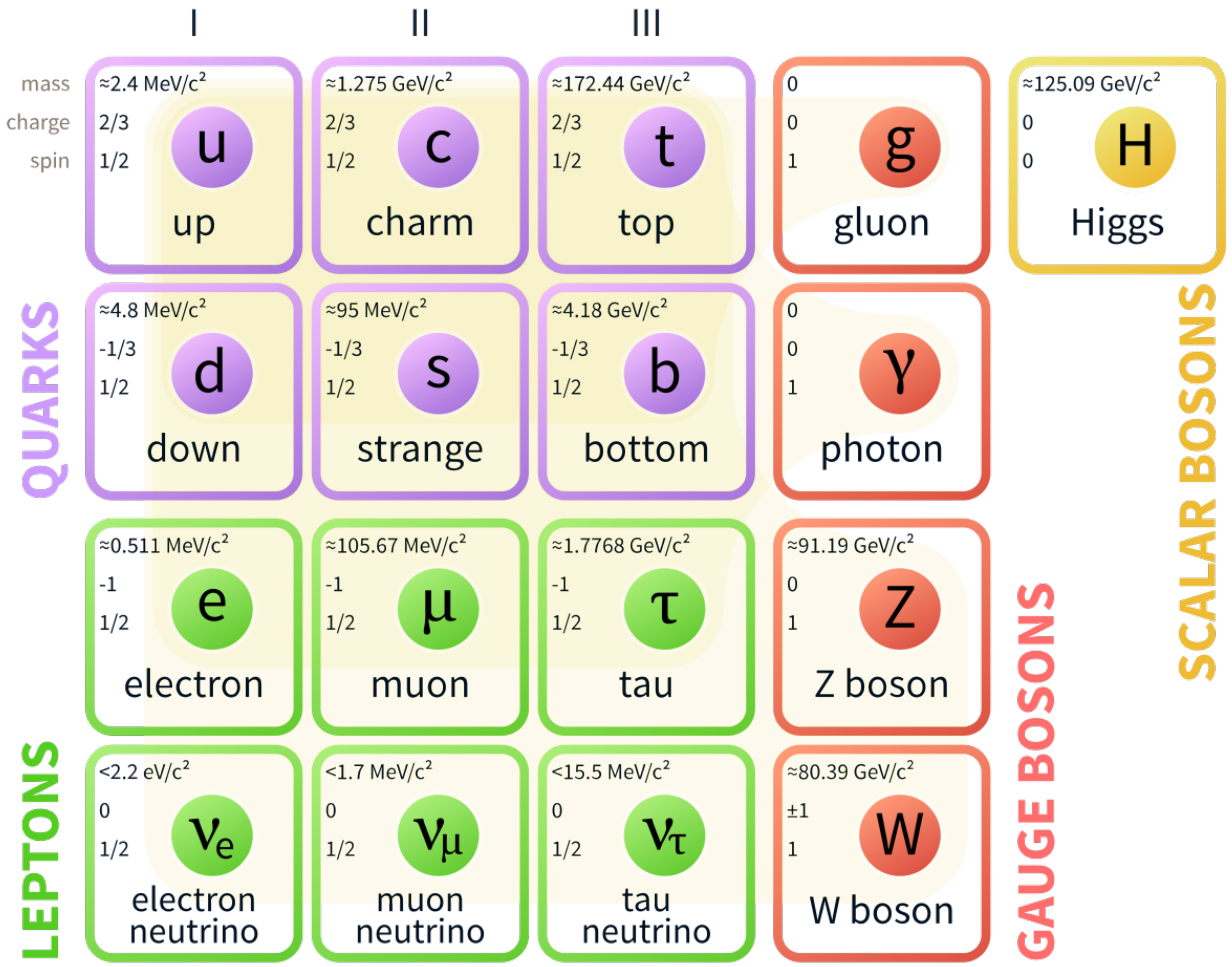
Modifying gravity solution

Missing mass solution

- Neutrinos, MACHOs, PBHs
- WIMPs

# The SM framework seems valid

*All the matter that Particle Physicists know on Earth*



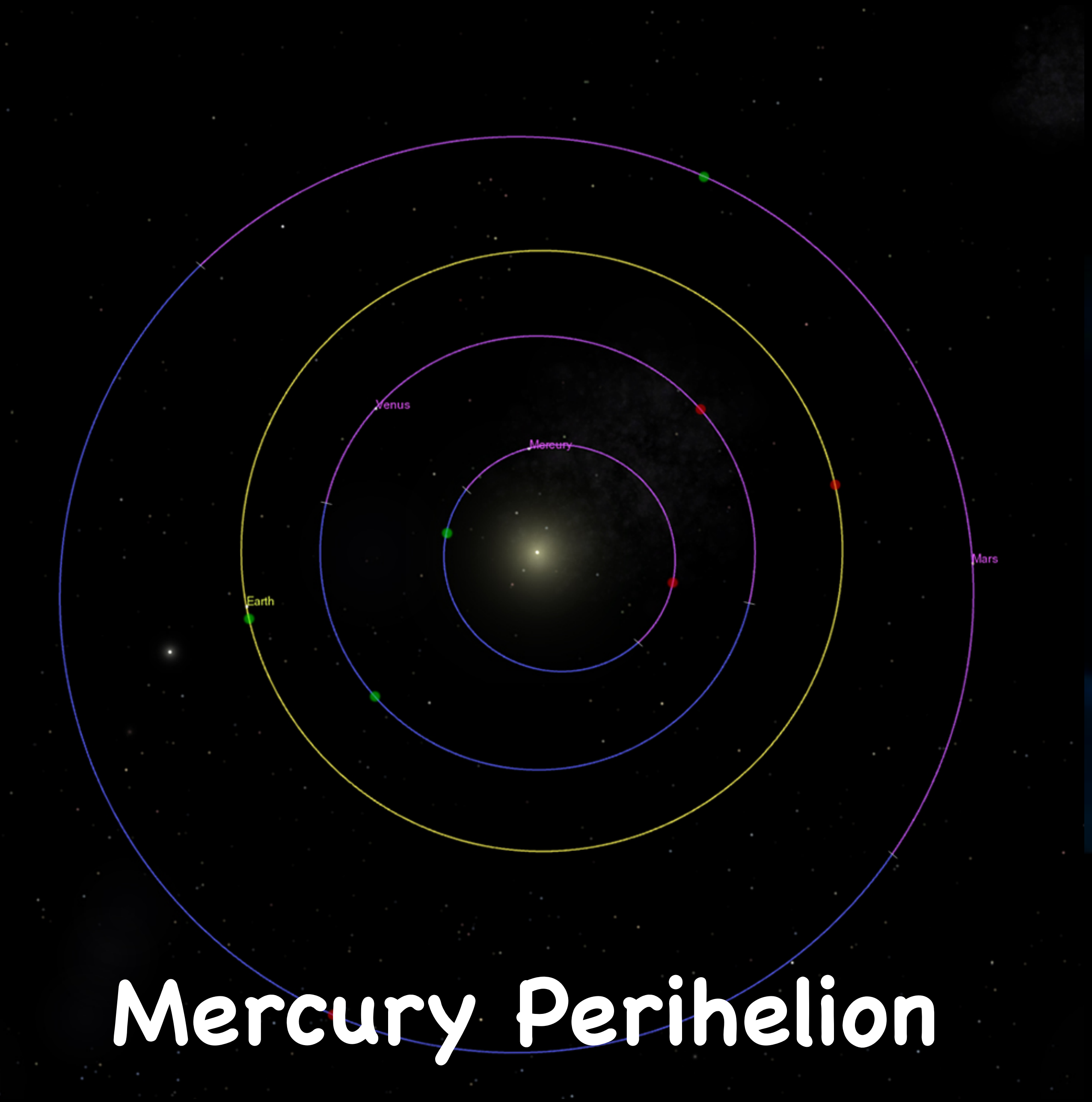

*Interactions*

**Strong force** **Weak force** **Electromagnetism**

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

**This model perfectly describes everything we see on Earth**

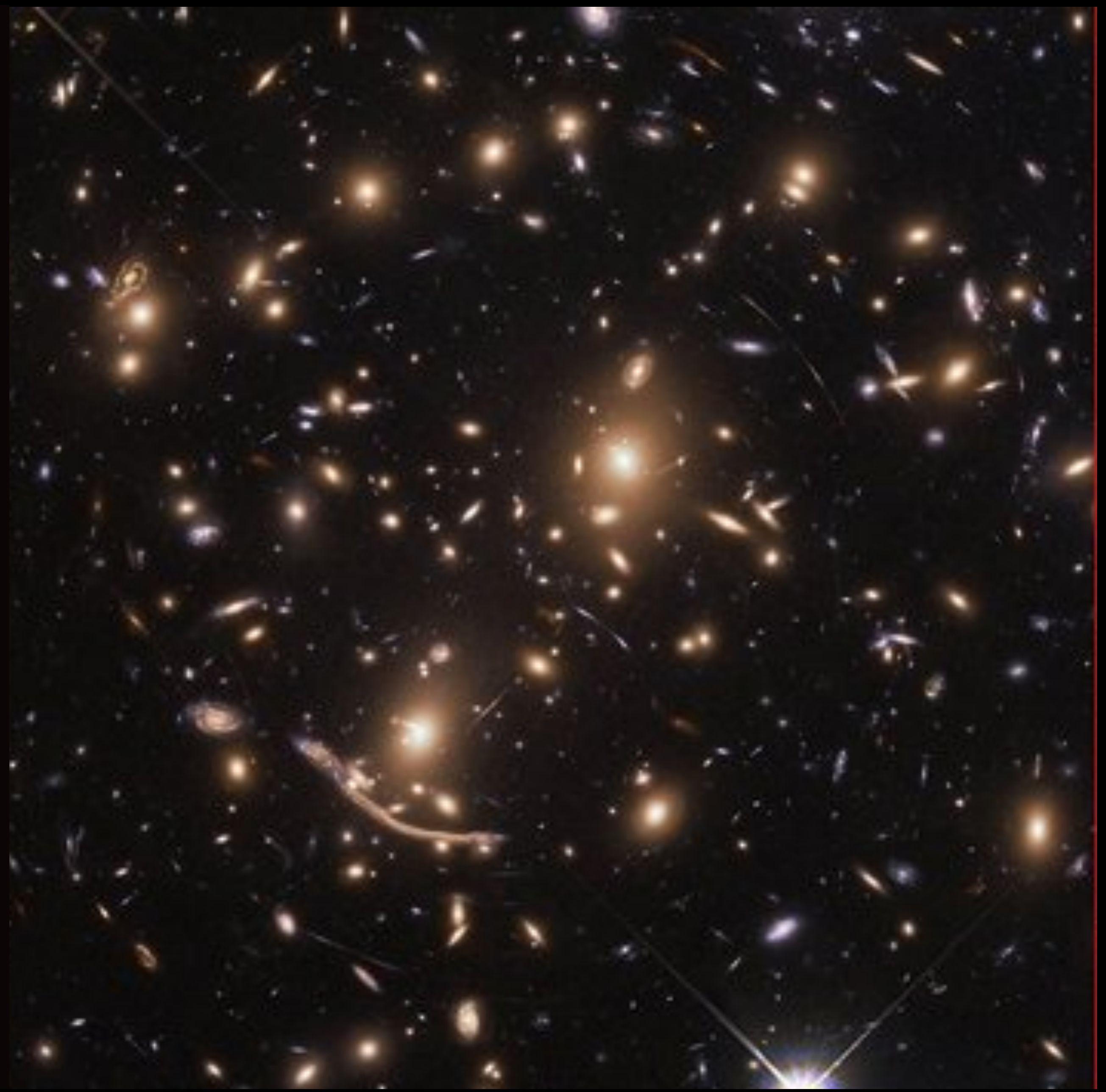
# General Relativity seems valid so far




Mercury Perihelion

Gravitational waves

BH horizon

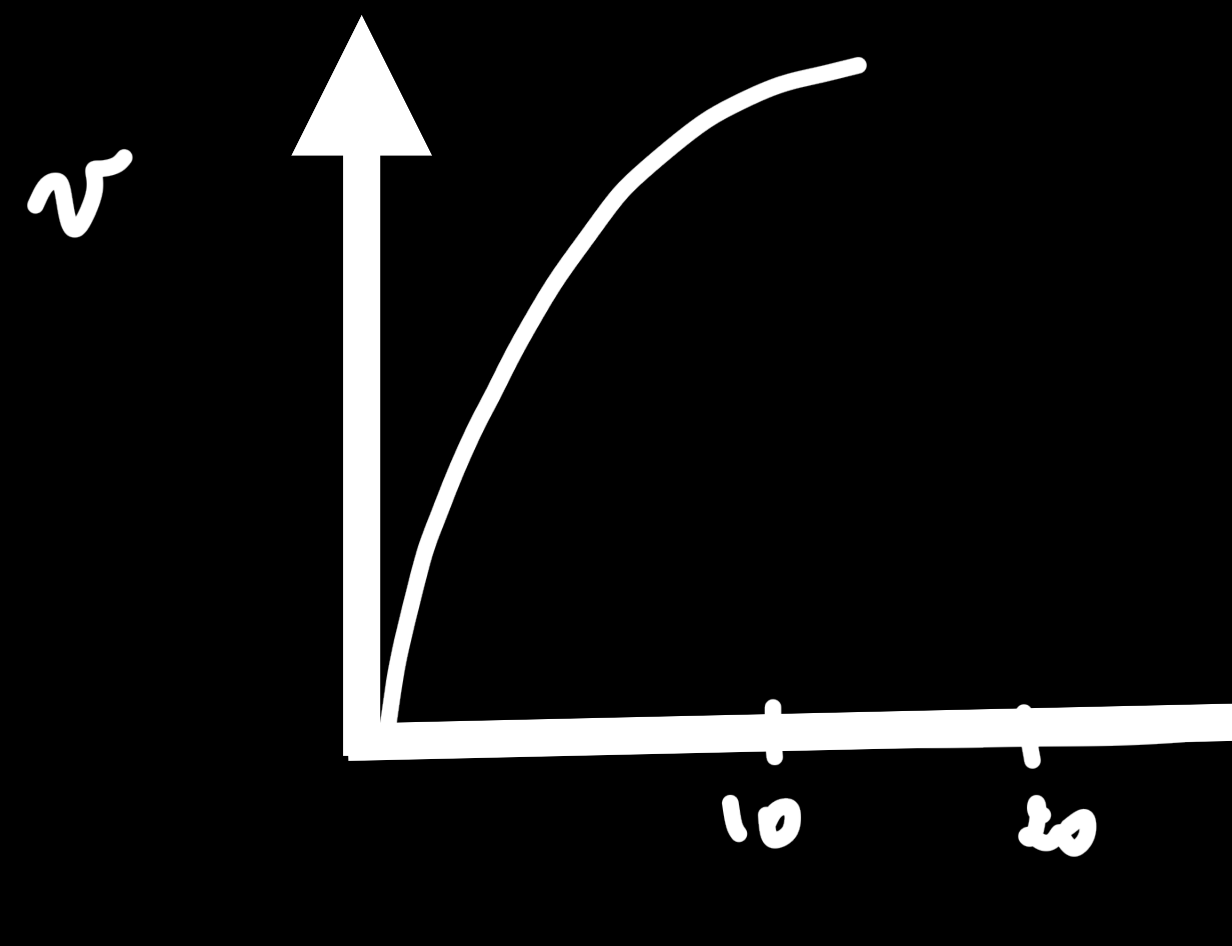


Einstein rings

**But there are severe issues**

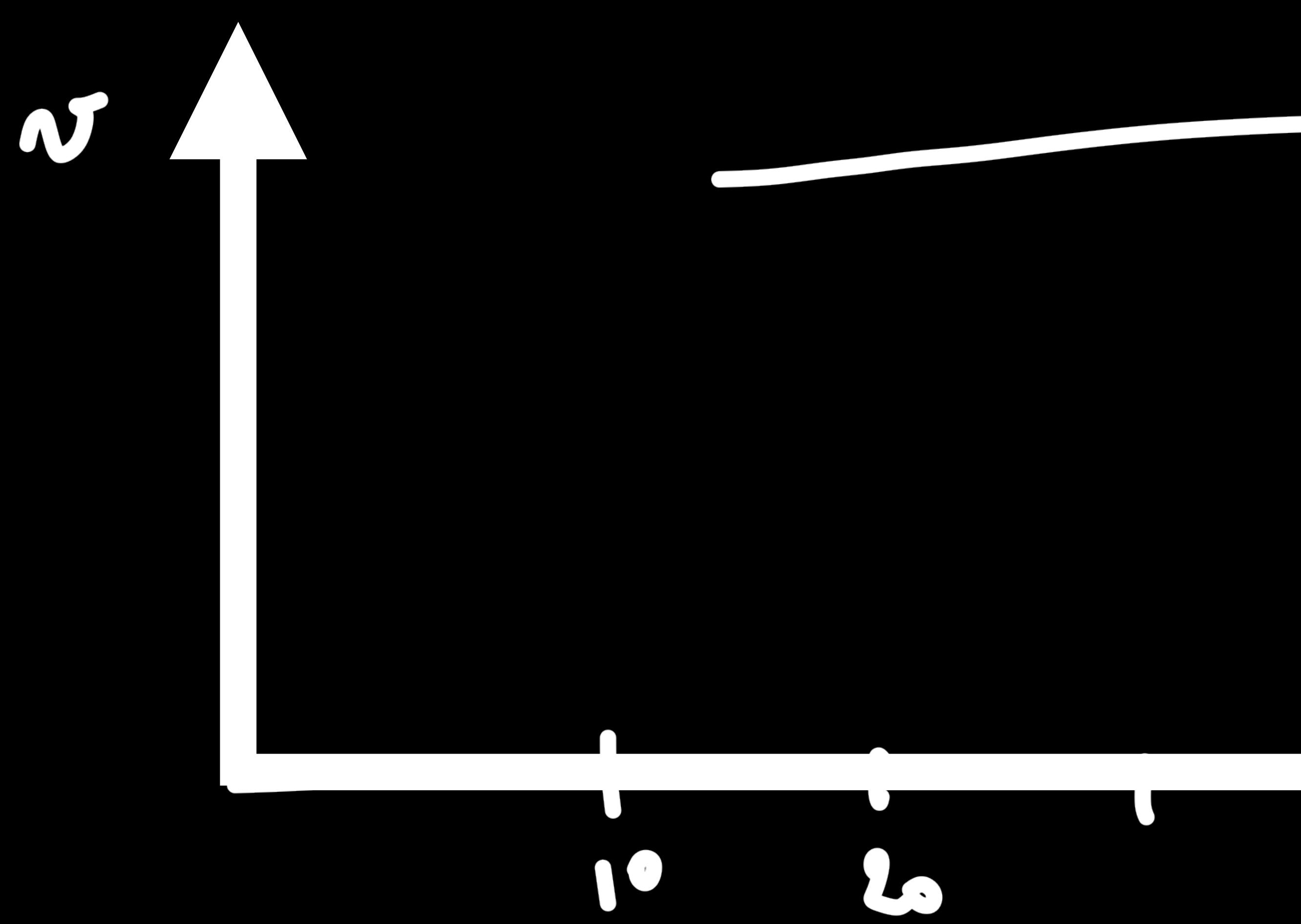
# Issue #1


## Stars rotate in galaxies



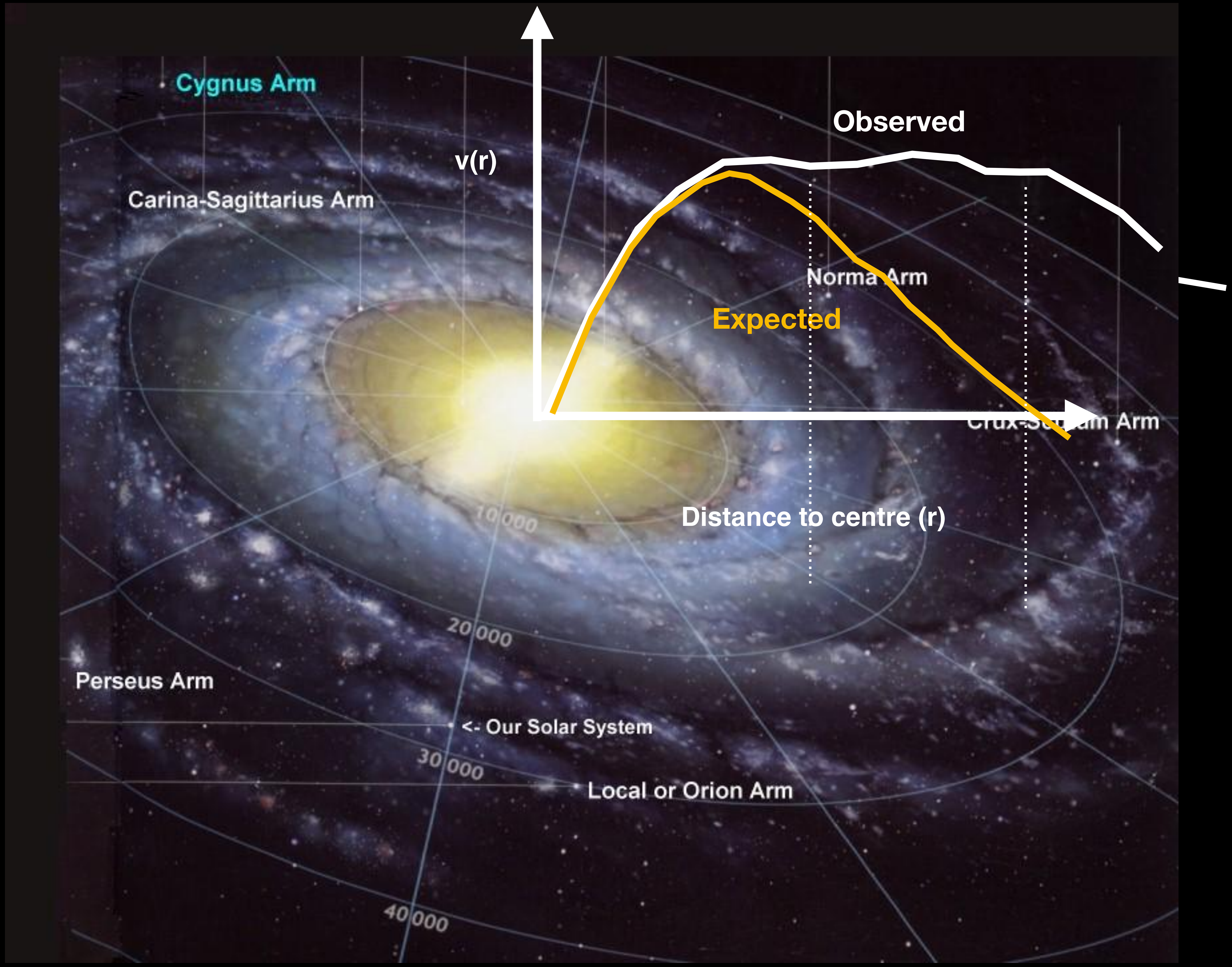

Vera Rubin

## Neutral Hydrogen gas too




Albert Bosma

# Rotation curves of galaxies




No dissipation but ordinary matter does dissipate

Issue #2

# Strong lensing in galaxy clusters

Missing mass

Issue #3

# Evolution of the Universe


## How to form cosmological structures from rapid expansion?

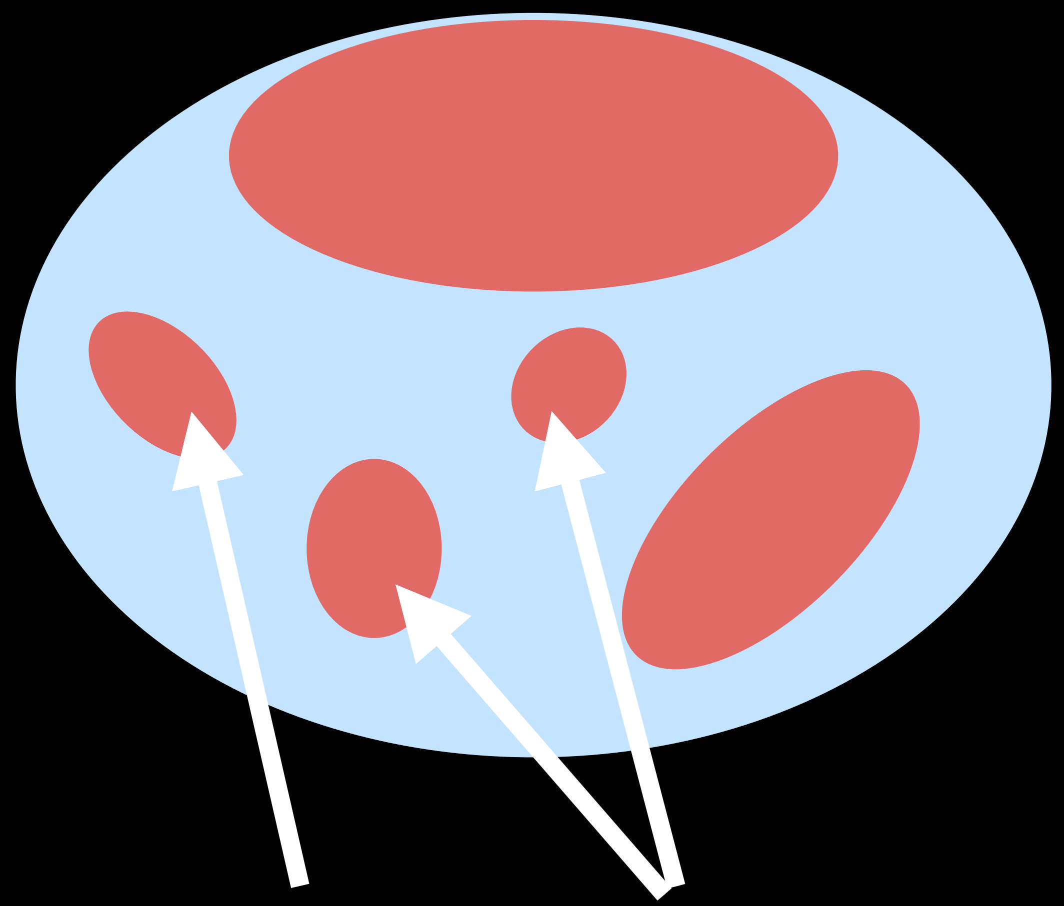
Ordinary matter is bound by BBN to be < 5% of the content of the Universe but we need more mass to start the genesis of galaxies

# Initial conditions for structure formation

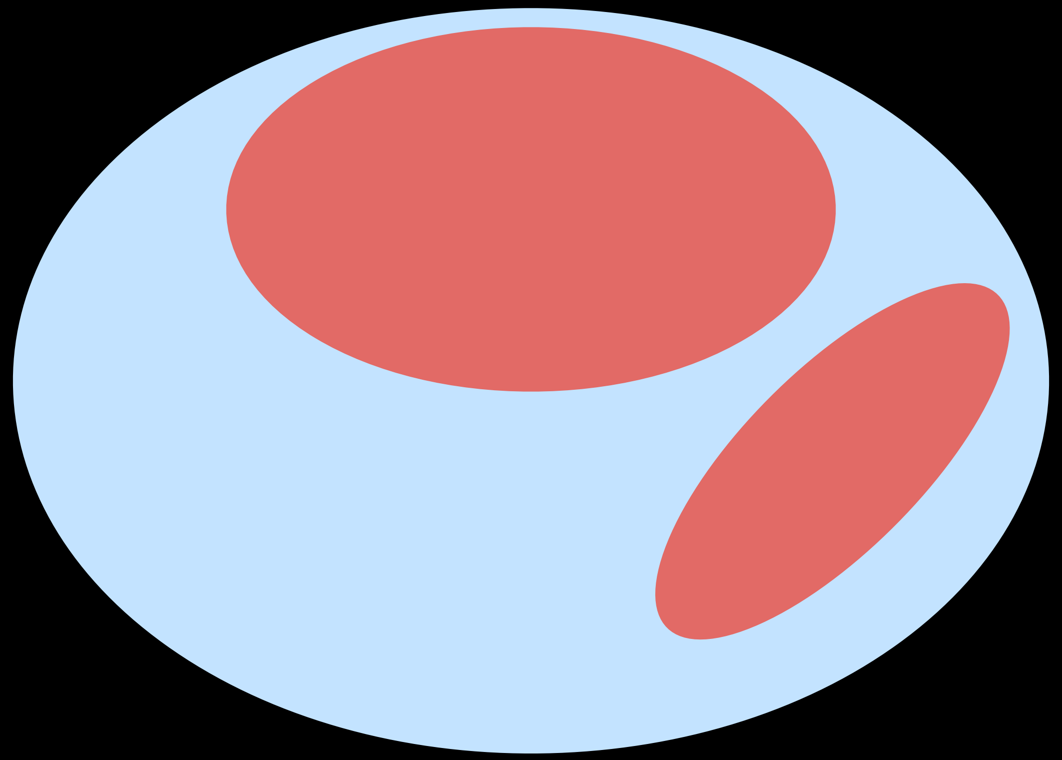
J. Peebles

The gravitational instability of the Universe

1967APJ...147..859P
1970ApJ...162..815P



Needed for galaxy formation



letters to nature

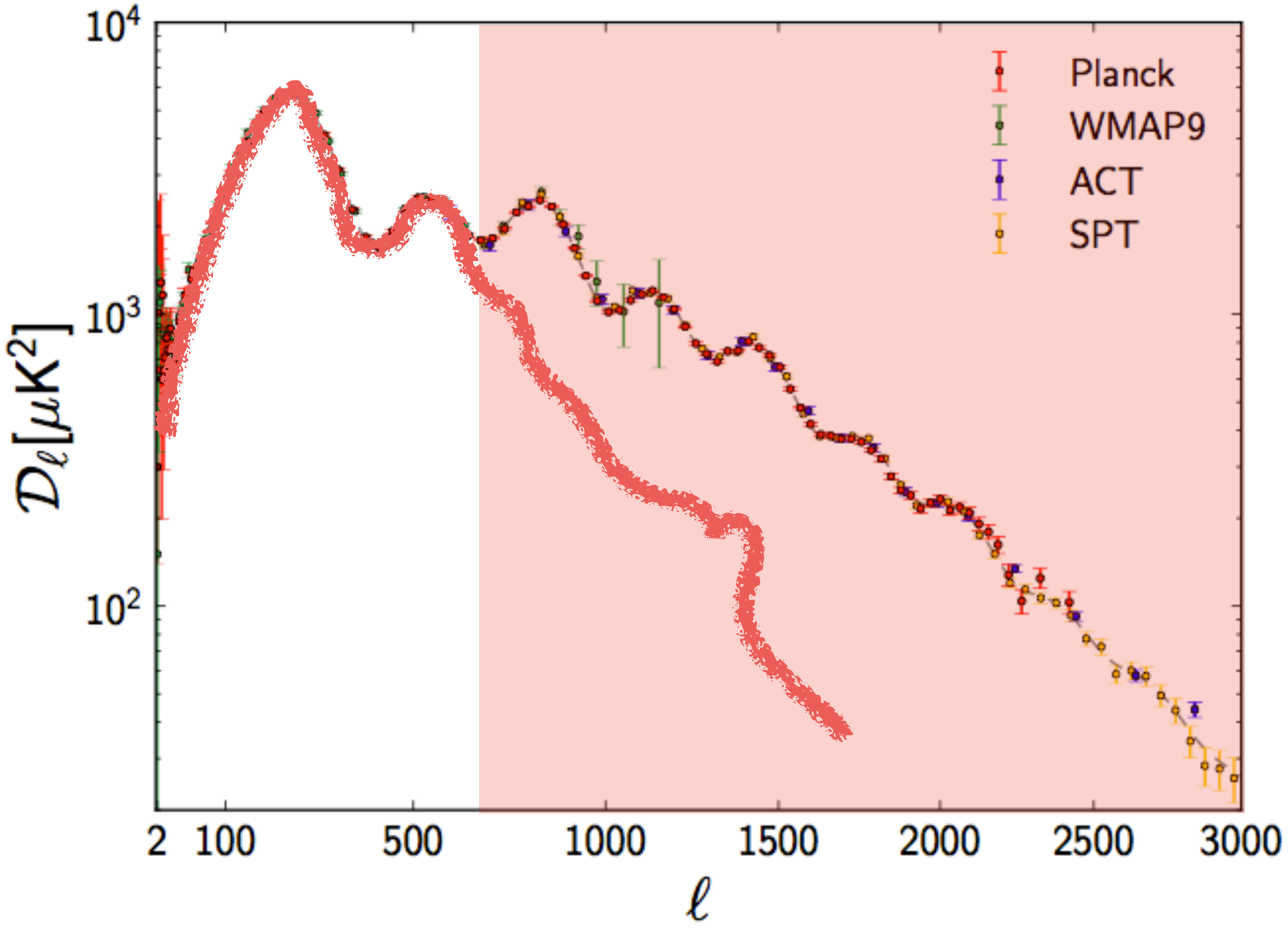
*Nature* **215**, 1155 - 1156 (09 September 1967); doi:10.1038/2151155a0

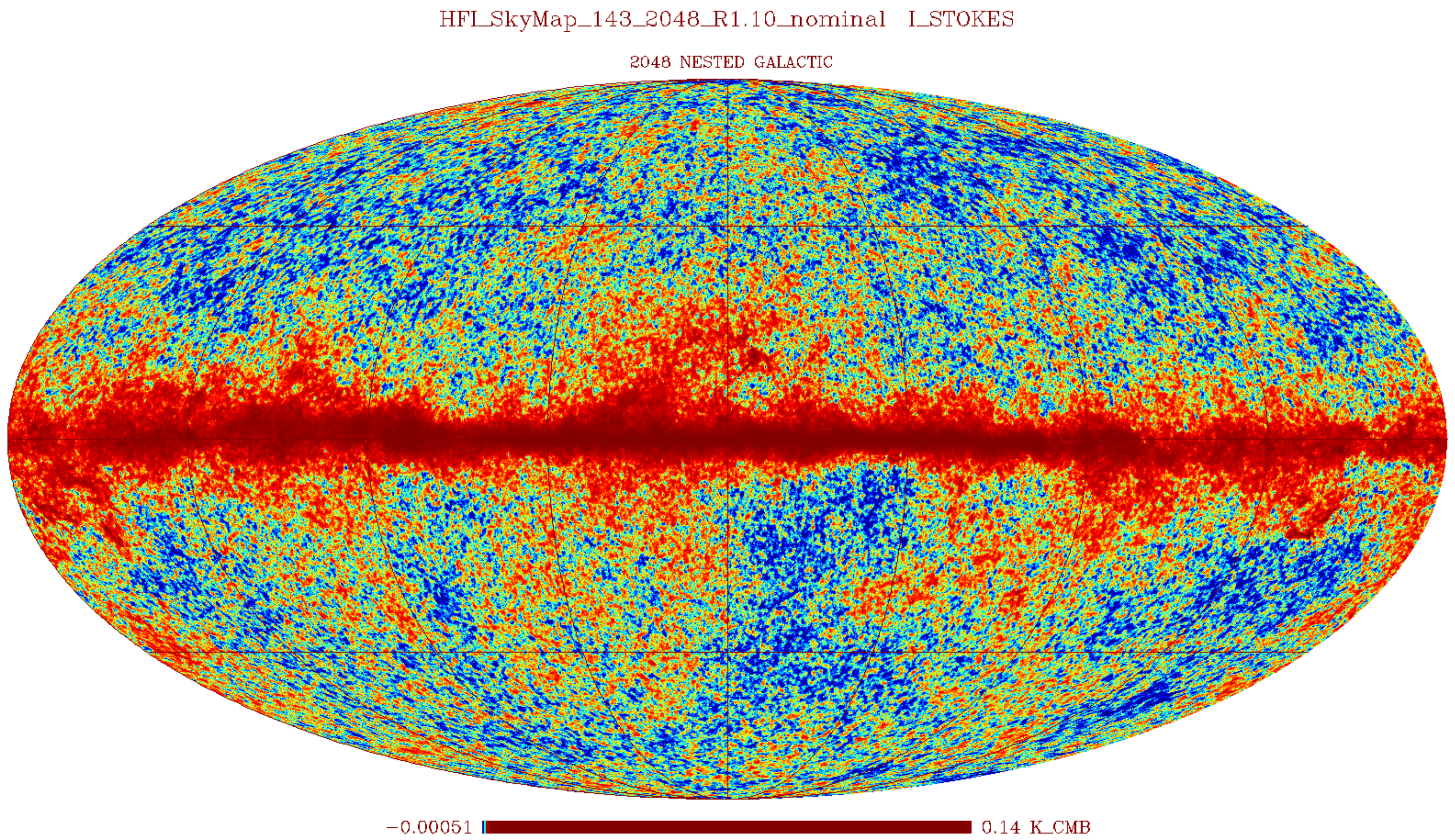
## Fluctuations in the Primordial Fireball

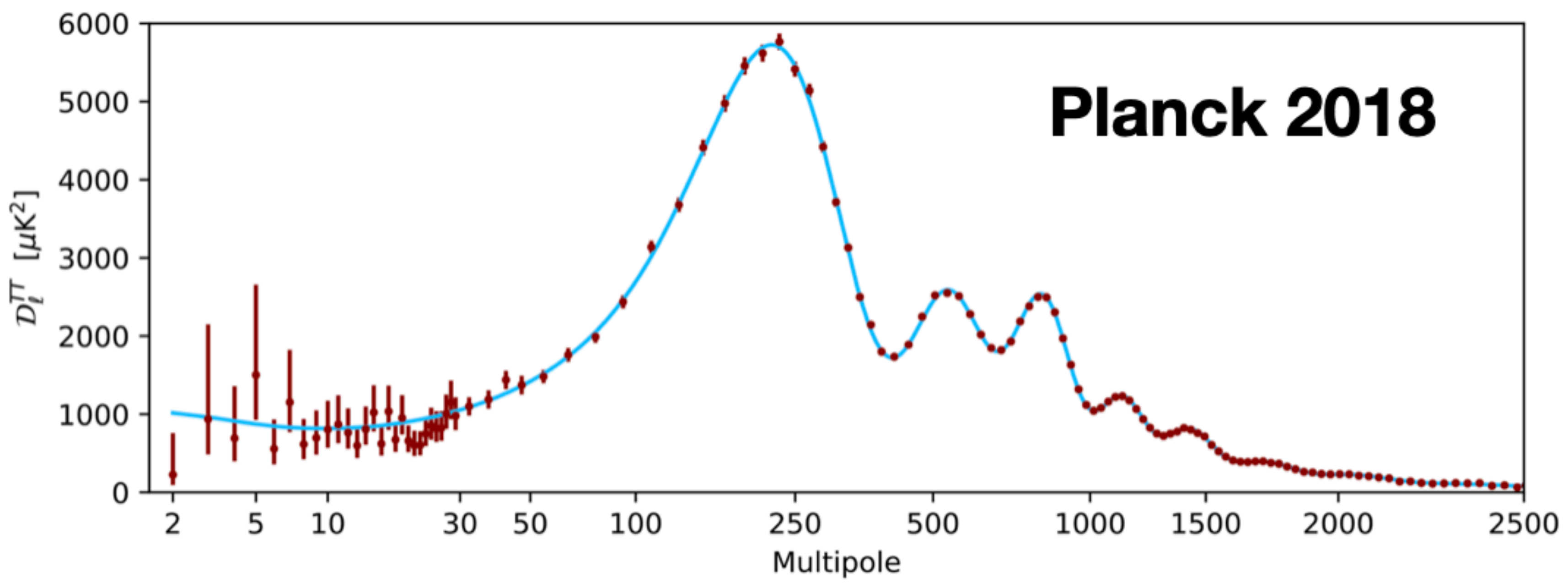
JOSEPH SILK

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature $T_D$ of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible ?

# Initial conditions for structure formation

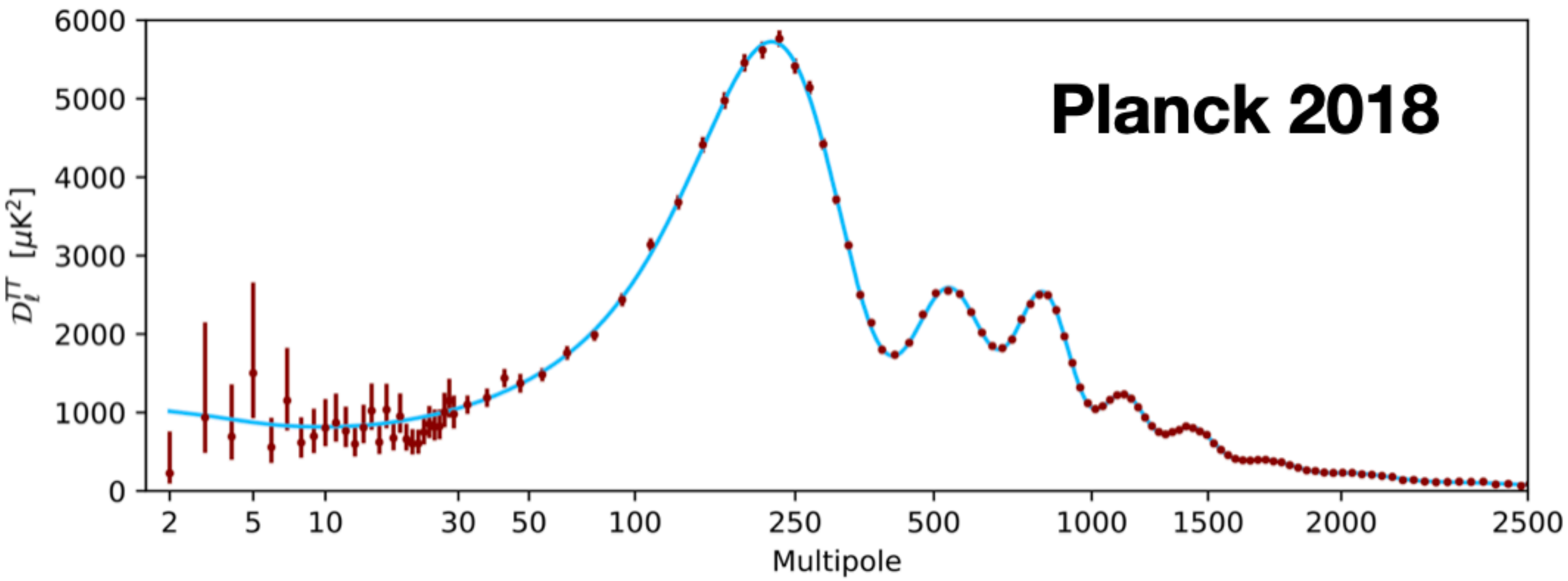



$$
\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_b)\ , \\
\dot{\theta}_{DM} &= k^2\psi - \mathcal{H}\theta_{DM}\ ,
\end{aligned}
$$

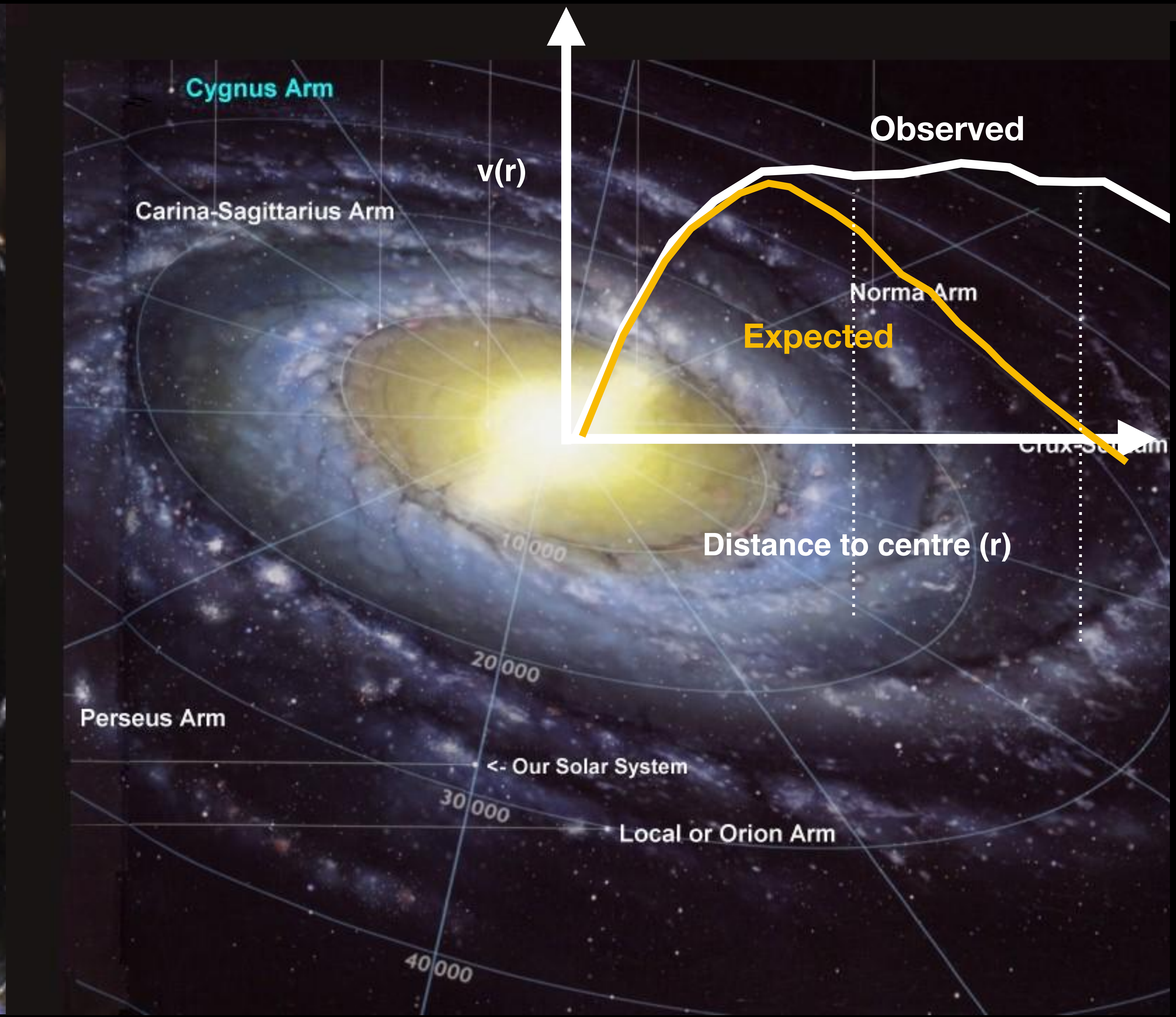
# Initial conditions for structure formation




| Parameter | Plik best fit |
|---|---|
| $\Omega_b h^2$ . . . . . . . . . . . . . . | 0.022383 |
| $\Omega_c h^2$ . . . . . . . . . . . . . . | 0.12011 |
| $100\theta_{MC}$ . . . . . . . . . . . . | 1.040909 |
| $\tau$ . . . . . . . . . . . . . . . . . | 0.0543 |
| $\ln(10^{10}A_s)$ . . . . . . . . . | 3.0448 |
| $n_s$ . . . . . . . . . . . . . . . . | 0.96605 |
| $\Omega_m h^2$ . . . . . . . . . . . . | 0.14314 |
| $H_0$ [ km s$^{-1}$Mpc$^{-1}$] . . . | 67.32 |
| $\Omega_m$ . . . . . . . . . . . . . . | 0.3158 |
| Age [Gyr] . . . . . . . . . | 13.7971 |
| $\sigma_8$ . . . . . . . . . . . . . . . . | 0.8120 |
| $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . . | 0.8331 |
| $z_{re}$ . . . . . . . . . . . . . . . . | 7.68 |
| $100\theta_*$ . . . . . . . . . . . . | 1.041085 |
| $r_{drag}$ [Mpc] . . . . . . . . . . | 147.049 |

# The 3 main issues

Missing mass




Missing mass
lack of dissipation


Lack of dissipation
Missing mass
Over long time scales

The physics that we know cannot explain the formation of the objects that we know

We are on for a major paradigm shift

# Solutions?

| | Deeper gravitational potential | Fighting Dissipation |
|---|---|---|
| Modifying gravity | ✓ (Acceleration) | Hard :( |
| Adding mass/particles | ✓ | ✓ |

Others... It is all about the initial conditions, i.e. the CMB!!!

# The modified gravity route

# Modifying Gravity

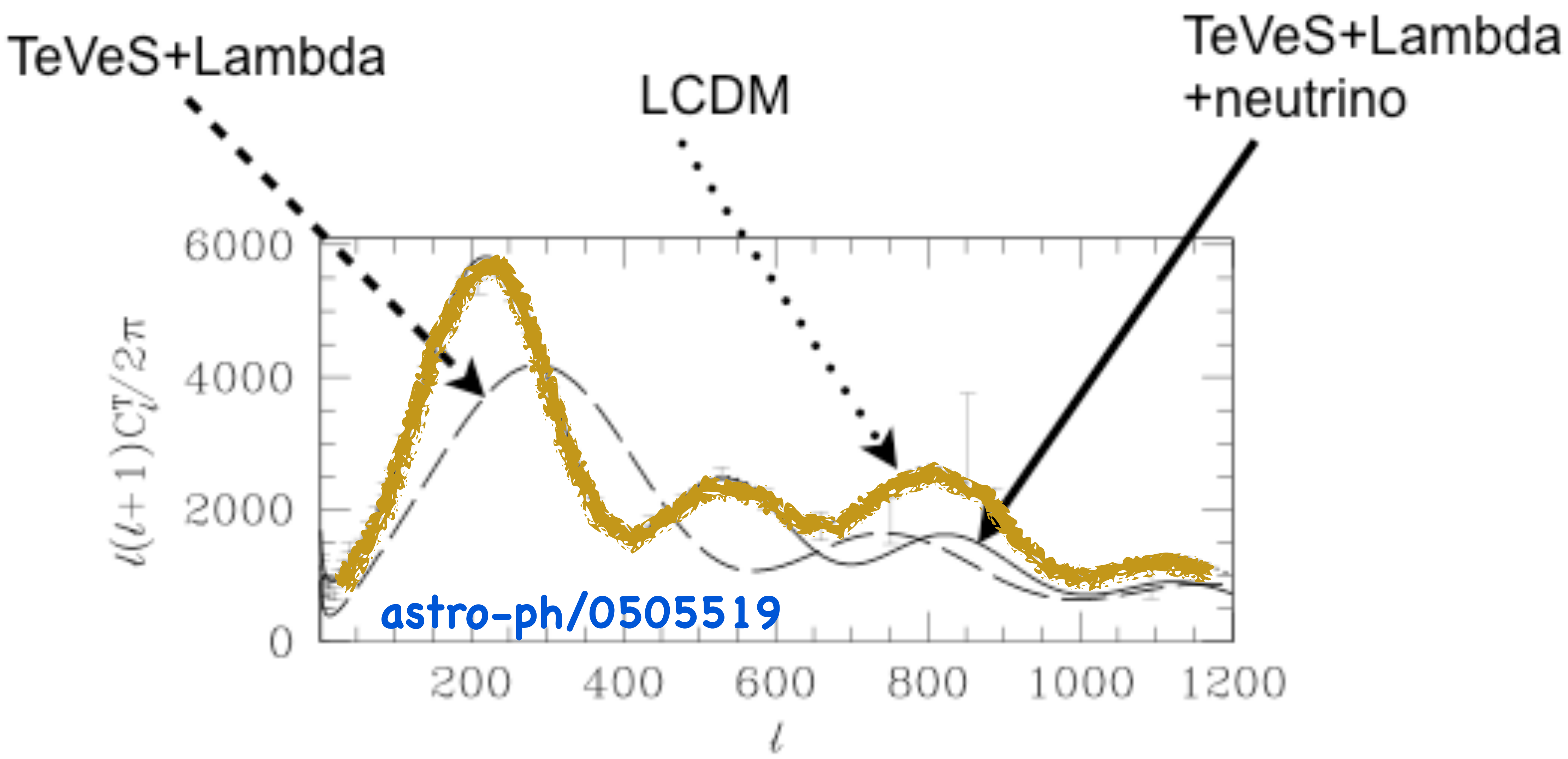
## GR′ + SU(3)XSU(2)XU(1)

$$\mu\left(\frac{|\vec{a}|}{a_0}\right)\vec{a} = -\nabla\Phi$$

empirical

$\mu(x) = 1$ if $x > 1$ $\mu(x) \simeq x$ if $x < 1$

TEVES: astro-ph/0403694




arXiv:2007.00082v3 [astro-ph.CO] 14 Oct 2021

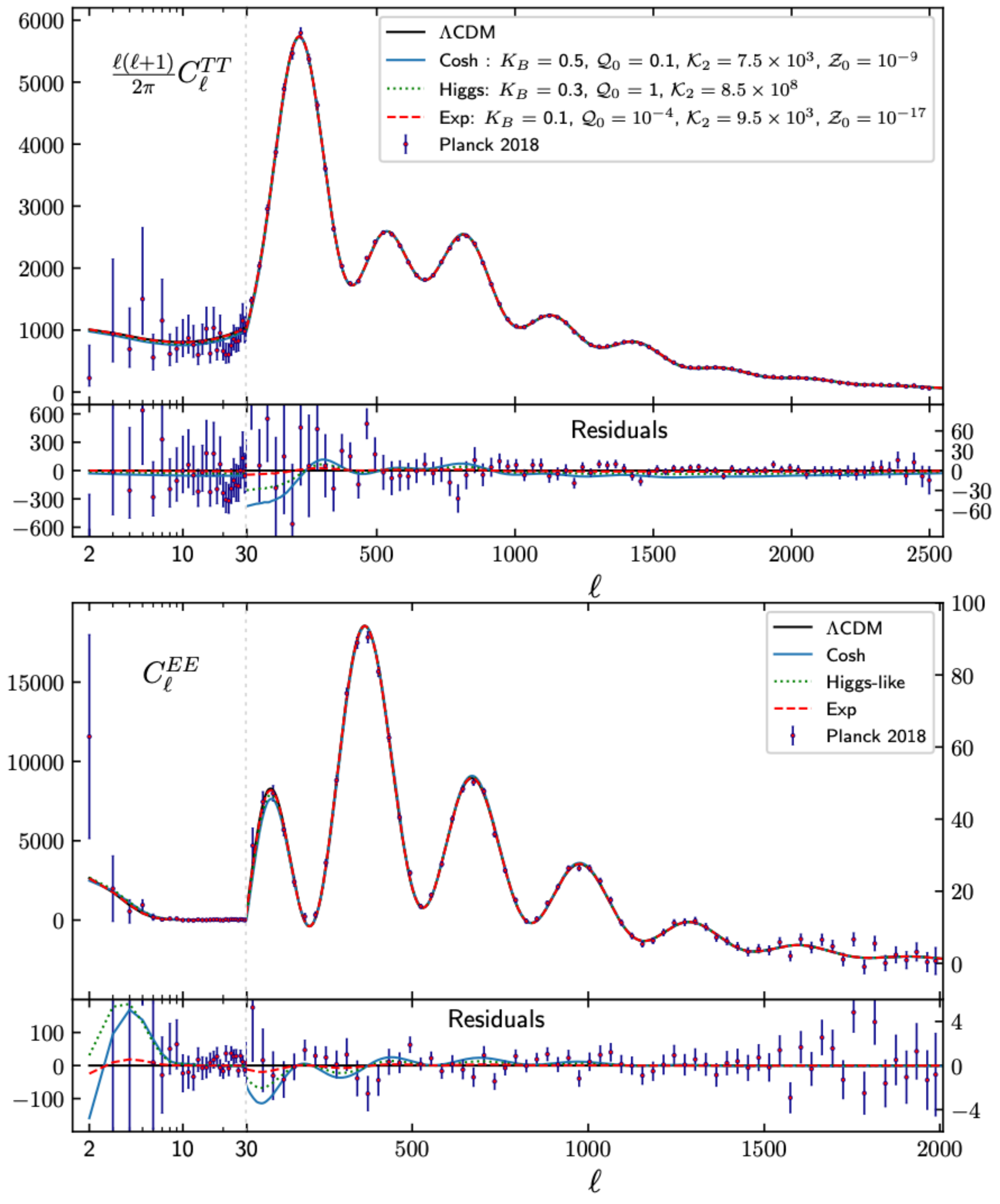
**New Relativistic Theory for Modified Newtonian Dynamics**


Constantinos Skordis* and Tom Złośnik†

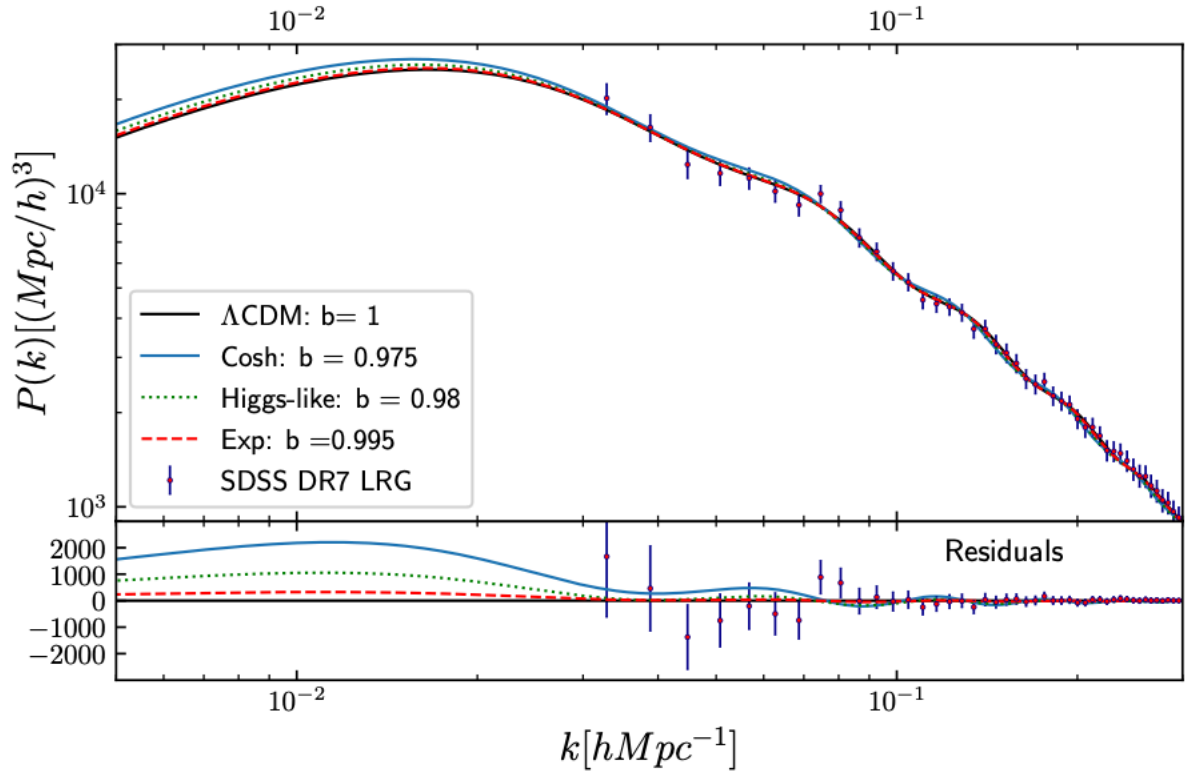
*CEICO, Institute of Physics (FZU) of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21, Prague, Czech Republic*



We propose a relativistic gravitational theory leading to modified Newtonian dynamics, a paradigm that explains the observed universal galactic acceleration scale and related phenomenology. We discuss phenomenological requirements leading to its construction and demonstrate its agreement with the observed cosmic microwave background and matter power spectra on linear cosmological scales. We show that its action expanded to second order is free of ghost instabilities and discuss its possible embedding in a more fundamental theory.


For a point source of mass $M$, the MOND-to-Newton transition occurs at $r_M \sim \sqrt{(G_N M/a_0)}$. A MOND force $\sim \sqrt{G_N M a_0}/r$ lends its way trivially to a Newtonian force $G_N M/r^2$ as $r \ll r_M$ but in the inner Solar System this is



# Modifying Gravity

https://arxiv.org/pdf/2007.00082.pdf

$$S = \int d^4x \Big\{ -\frac{1}{2}\bar{\nabla}_\mu h \bar{\nabla}_\nu h^{\mu\nu} + \frac{1}{4}\bar{\nabla}_\rho h \bar{\nabla}^\rho h + \frac{1}{2}\bar{\nabla}_\mu h^{\mu\rho}\bar{\nabla}_\nu h^\nu{}_\rho - \frac{1}{4}\bar{\nabla}^\rho h^{\mu\nu}\bar{\nabla}_\rho h_{\mu\nu} K_B |\dot{\vec{A}} - \frac{1}{2}\vec{\nabla} h^{00}|^2 - 2K_B \vec{\nabla}_{[i}A_{j]}\vec{\nabla}^{[i}A^{j]}$$
$$+ (2 - K_B)\left[2(\dot{\vec{A}} - \frac{1}{2}\vec{\nabla}h^{00})\cdot(\vec{\nabla}\varphi + \mathcal{Q}_0\vec{A}) - (1+\lambda_s)|\vec{\nabla}\varphi + \mathcal{Q}_0\vec{A}|^2\right] + 2\mathcal{K}_2\left|\dot{\varphi} + \frac{1}{2}\mathcal{Q}_0 h^{00}\right|^2 + \frac{1}{\tilde{M}_p^2}T_{\mu\nu}h^{\mu\nu}\Big\} \quad (13)$$

In preparation

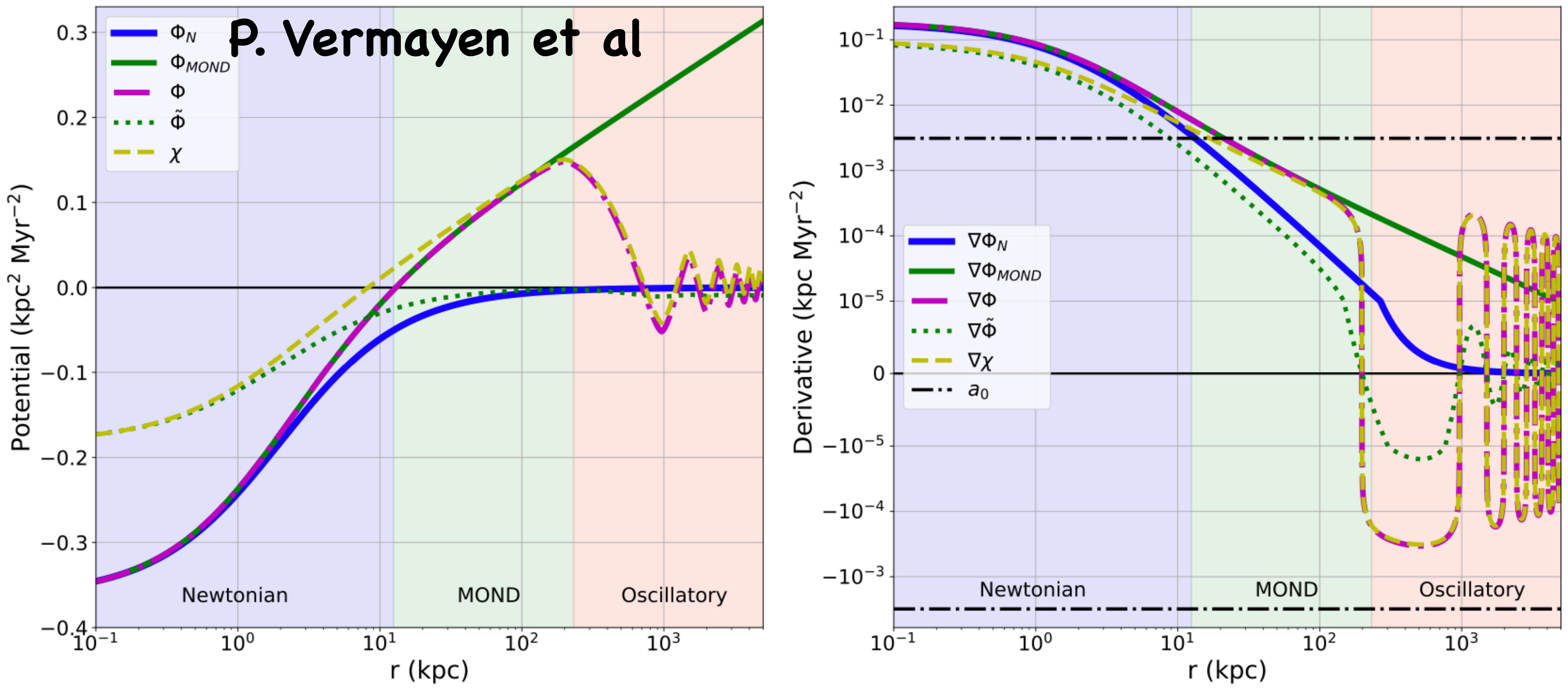
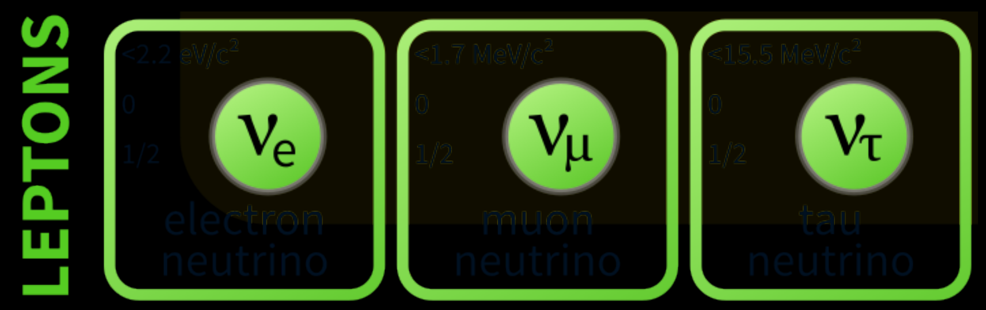


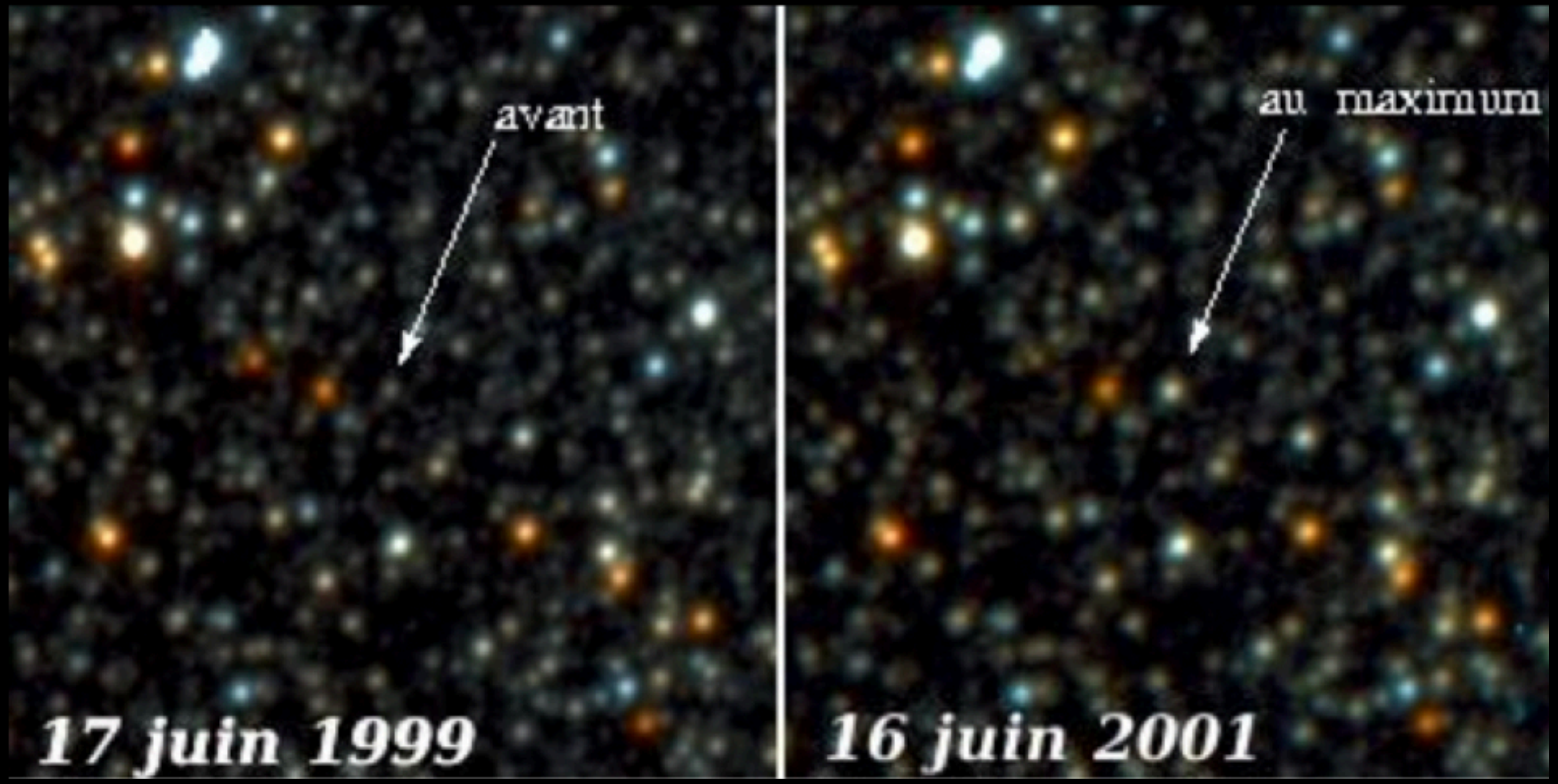

**Figure 2.** Solution of the field equations (left) and their gradients (right) for the Hernquist density profile and the fiducial model parameters with $(\lambda_s, \mu) = (1, 1\ \text{Mpc}^{-1})$. The blue, green and red regions delineate the Newtonian, MOND and Oscillatory regions respectively. The yellow and green dashed lines are the auxiliary fields $\tilde{\Phi}$ and $\chi$ and the pink dotted-dashed line is the metric perturbation which is responsible for defining the trajectories of free falling particles. We have included the Newtonian (blue) and classical MOND (green) solutions for comparison. The break in the blue curve at $\nabla\Phi = 10^{-5}$ is not physical, but related to the symlog scaling that we use for the vertical axis of the right panel.

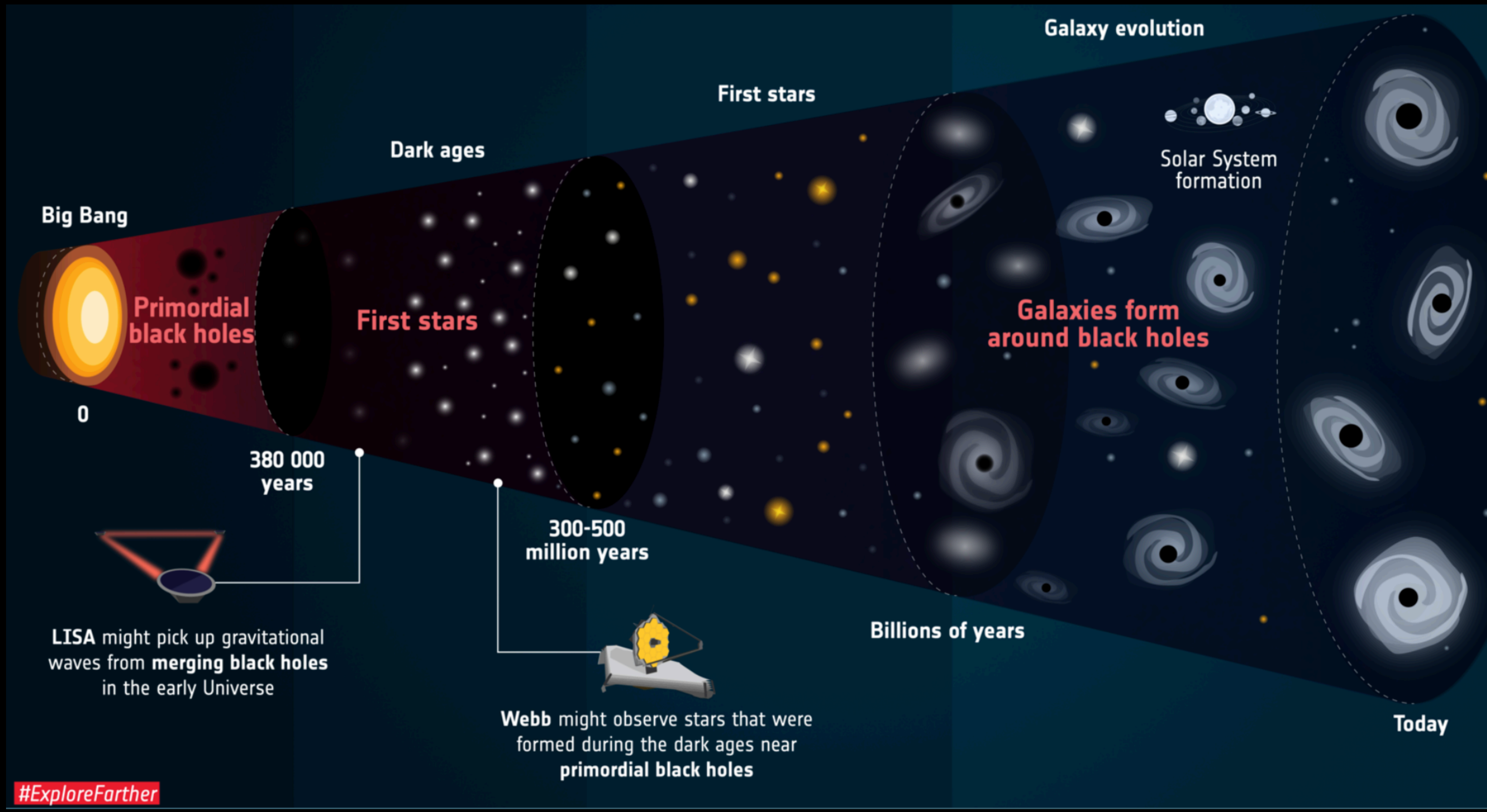
# The “missing mass” route

# "Standard Model" solutions




## MACHOs

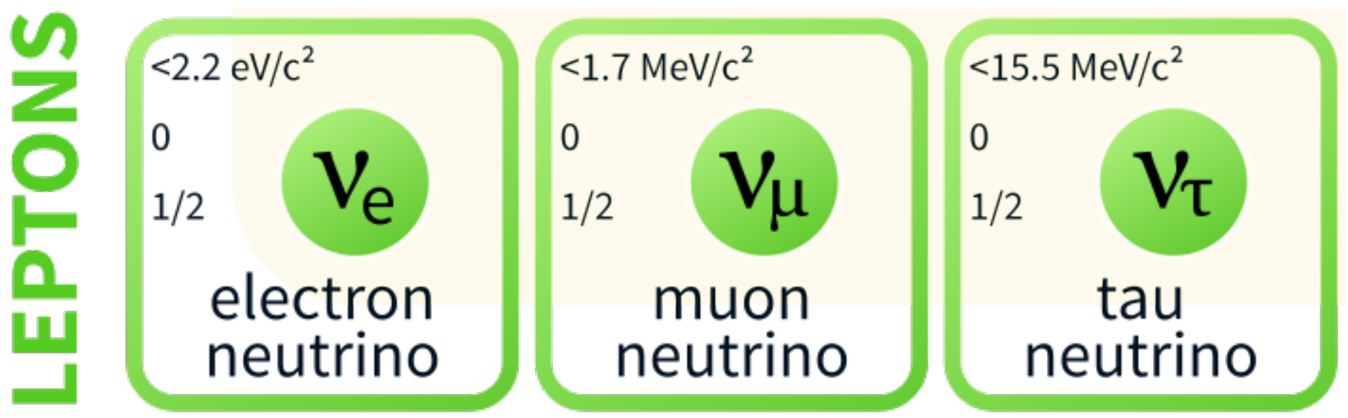



# Or ?

# Let us go through these options

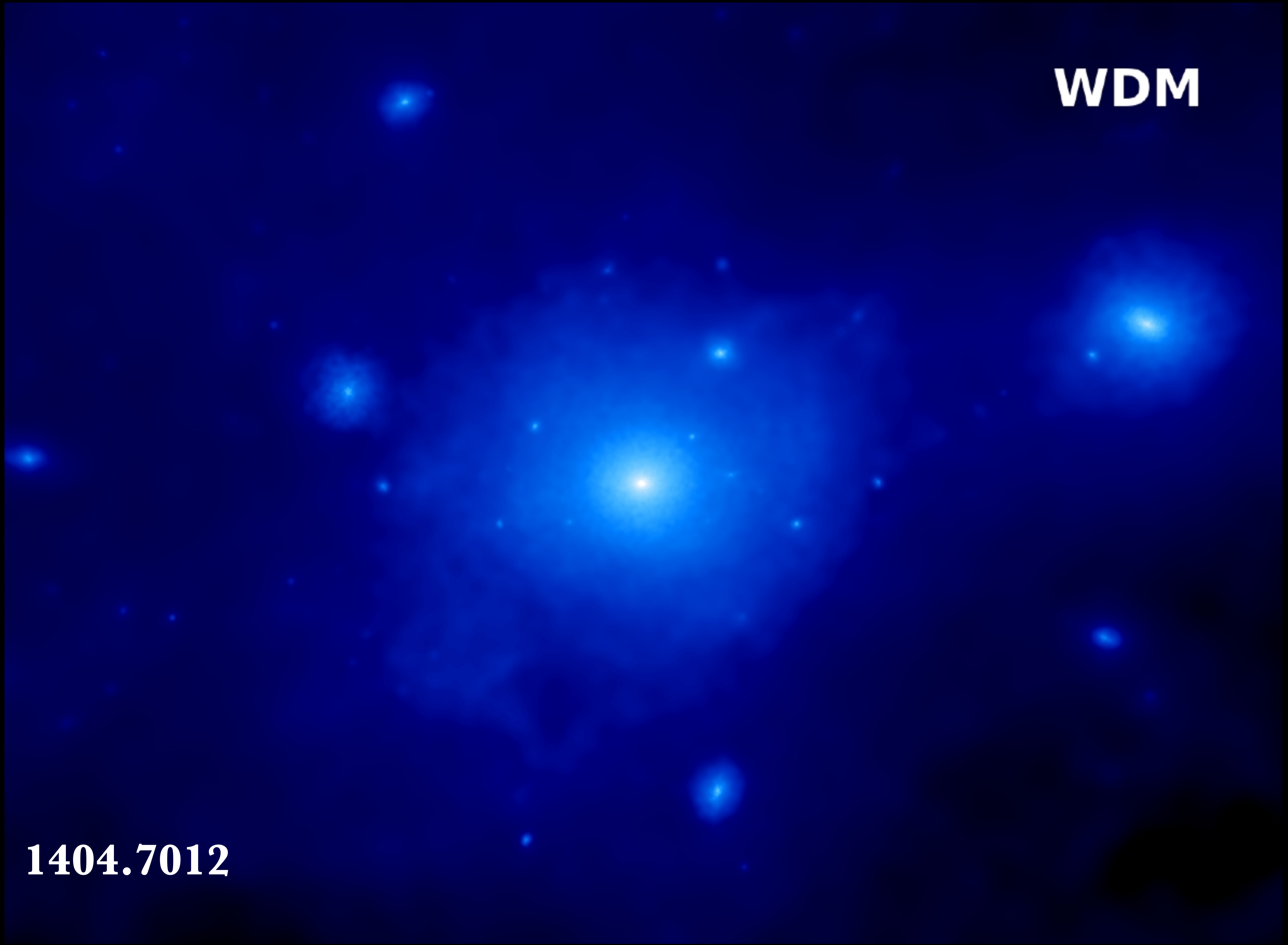
# Neutrinos






They would need to have a mass > keV to form as many galaxies as we have observed

# keV neutrinos = Warm dark matter




1988ApJ...332....1S

Bond & Szalay 1983  Bardeen et al. 1986

**Halo Formation in Warm Dark Matter Models**

Paul Bode and Jeremiah P. Ostriker
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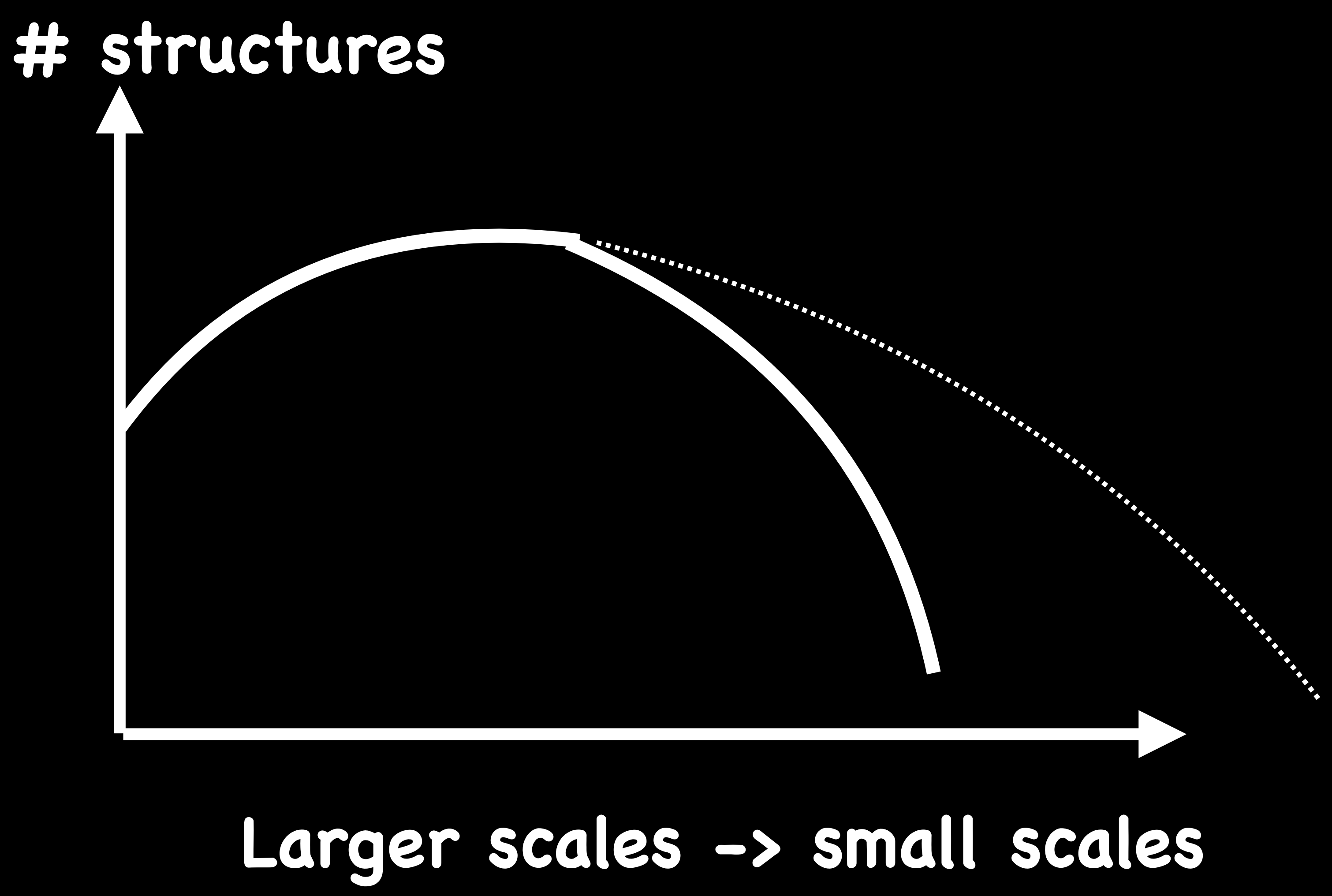
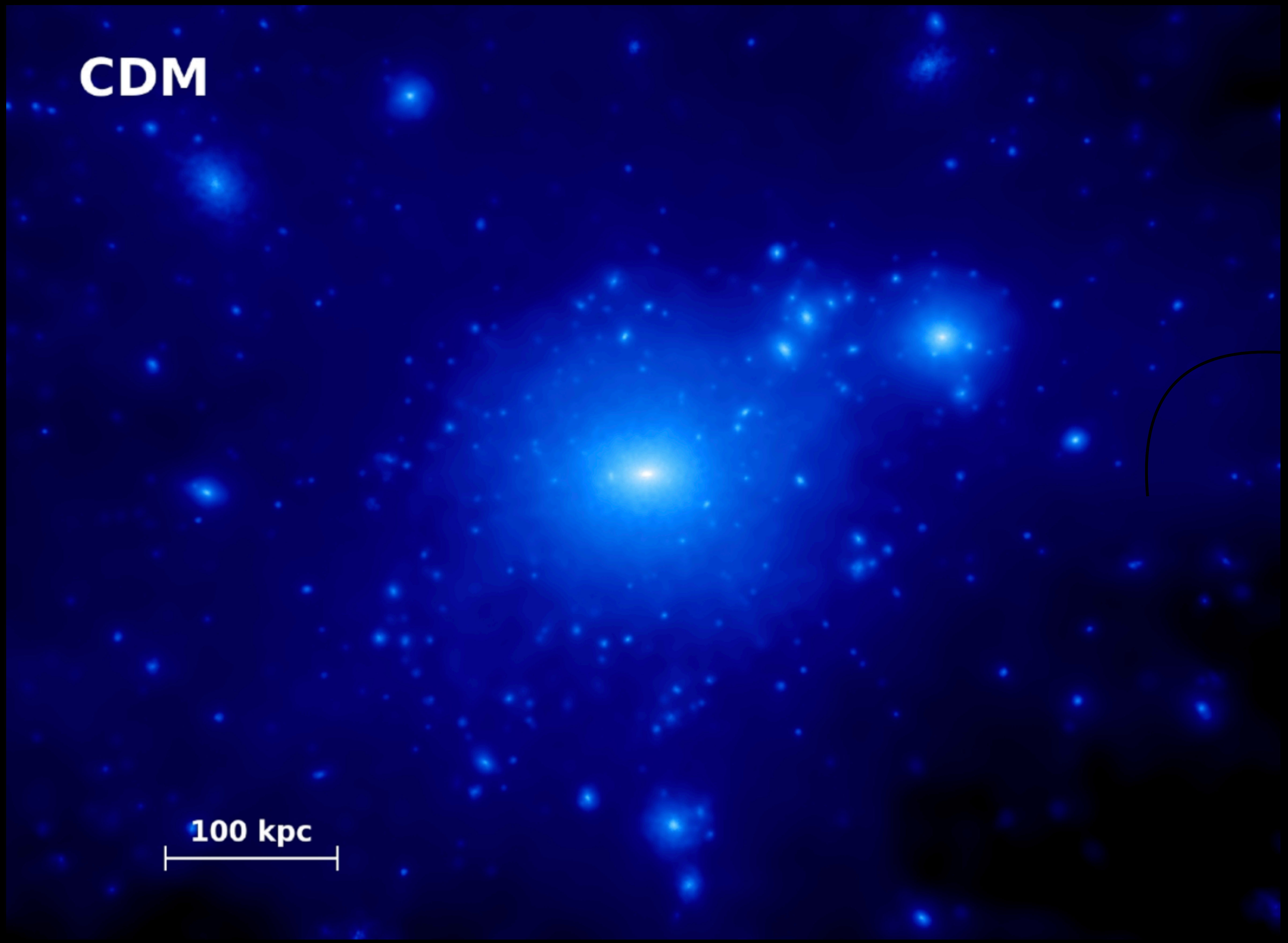
*DAMTP, Centre for Mathematical Sciences, Wilberforce Road, CB3 0WA Cambridge, UK*

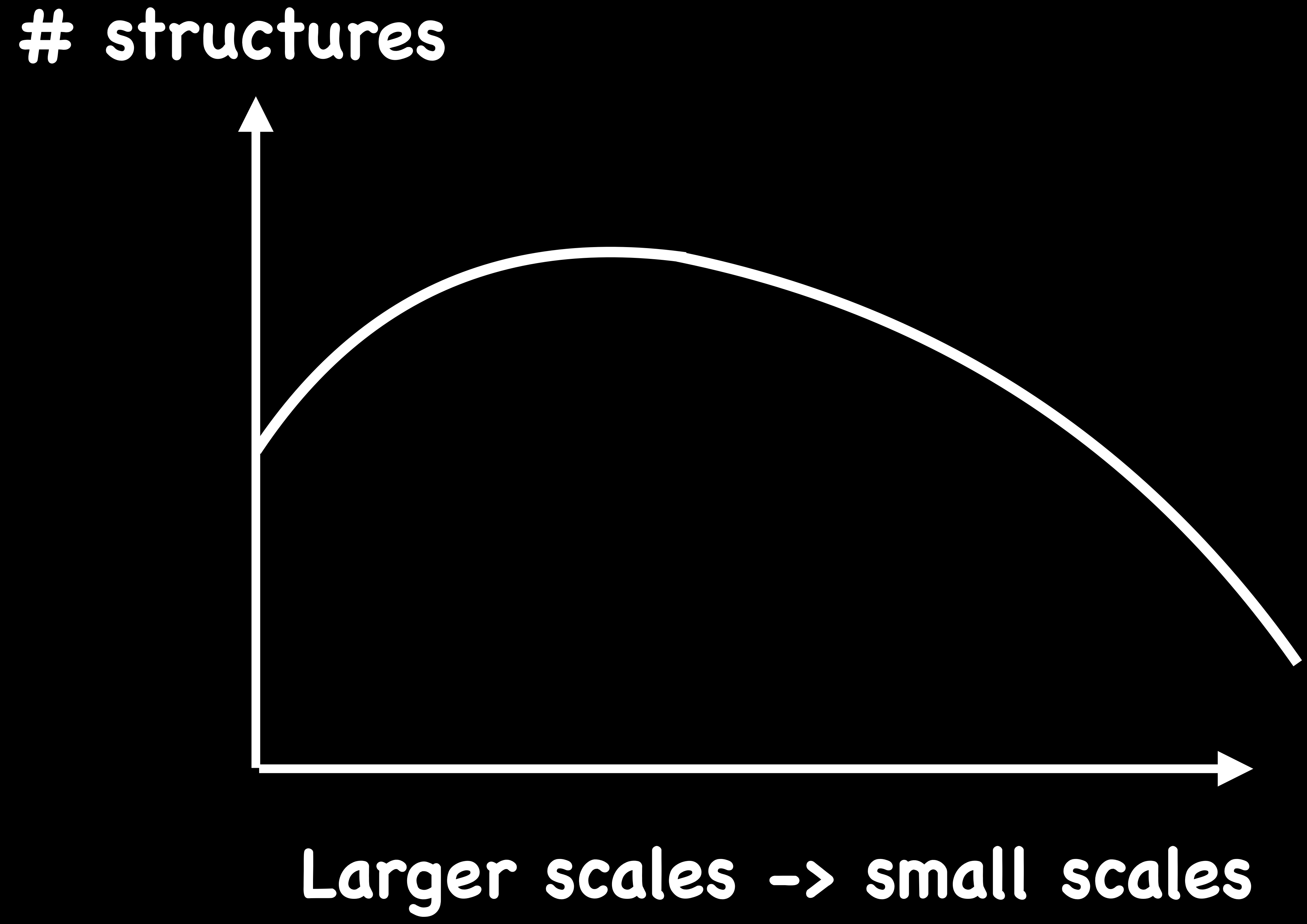
*Received 2000 October 26; accepted 2001 March 26*




$$R_s \approx 0.31\left(\frac{\Omega_X}{0.3}\right)^{0.15}\left(\frac{h}{0.65}\right)^{1.3}\left(\frac{\text{keV}}{m_X}\right)^{1.15} h^{-1}\ \text{Mpc}\,.$$

# Heavy dark matter = Cold Dark Matter



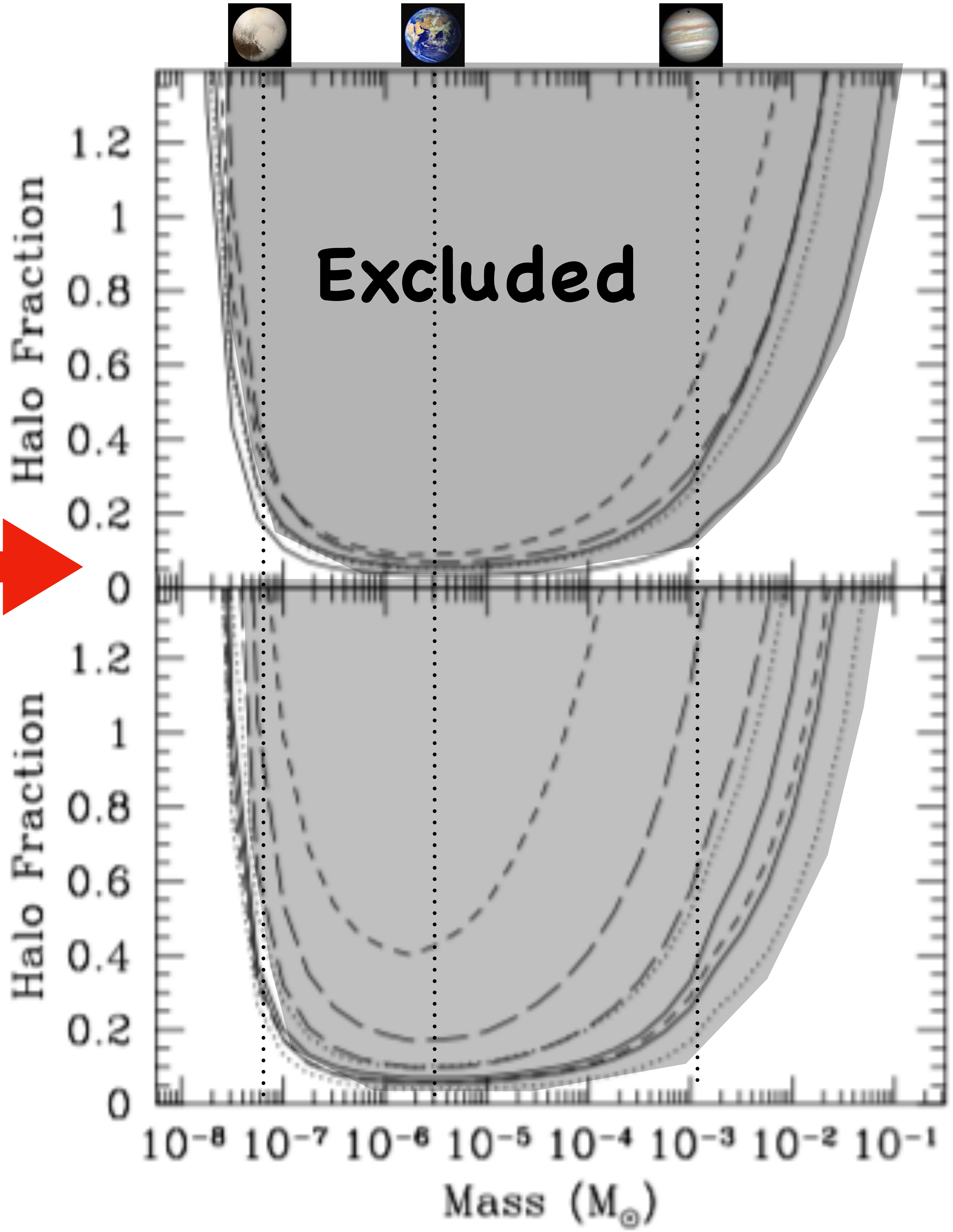




1404.7012

# MACHOs

EROS & MACHO experiments

Tiny fraction of our
MW halo allowed but …

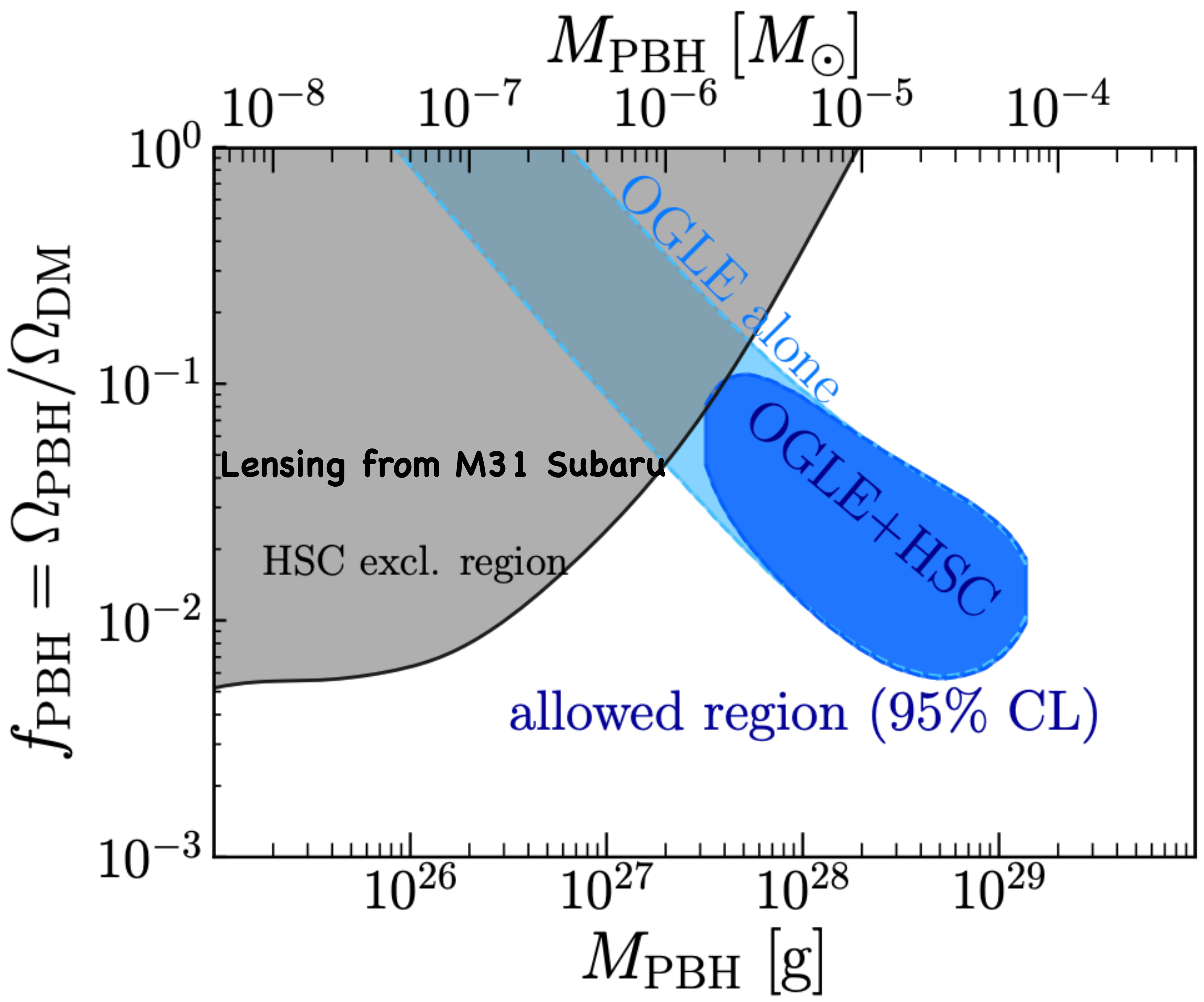


# Primordial Black Holes

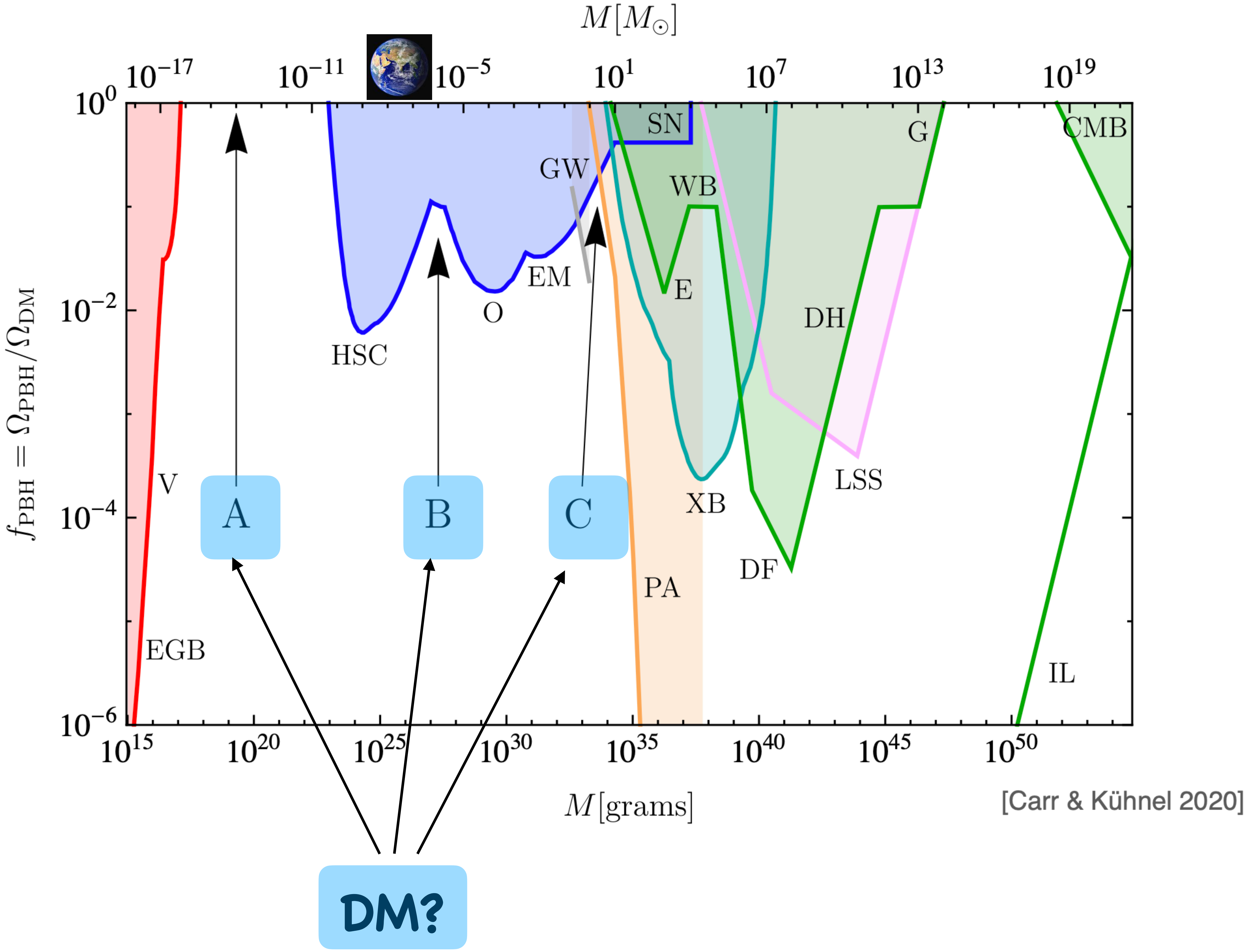
(See Kuhnel's talk at DSU2022 + papers)

OGLE detected events (0.1-0.3 days light curve timescale)

18/58 events consistent with 2-5 Msol PBH

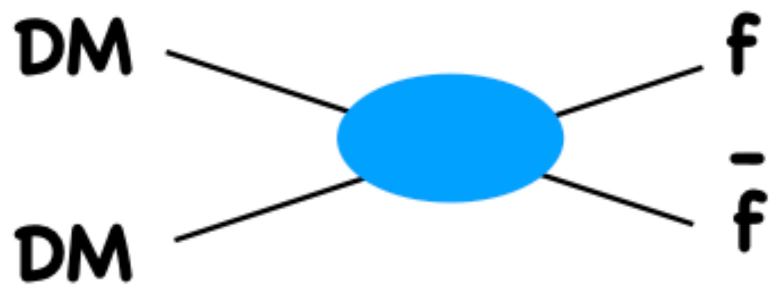



[Niikura *et al.* 2019]




[Carr & Kühnel 2020]

# Massive weakly interacting particles



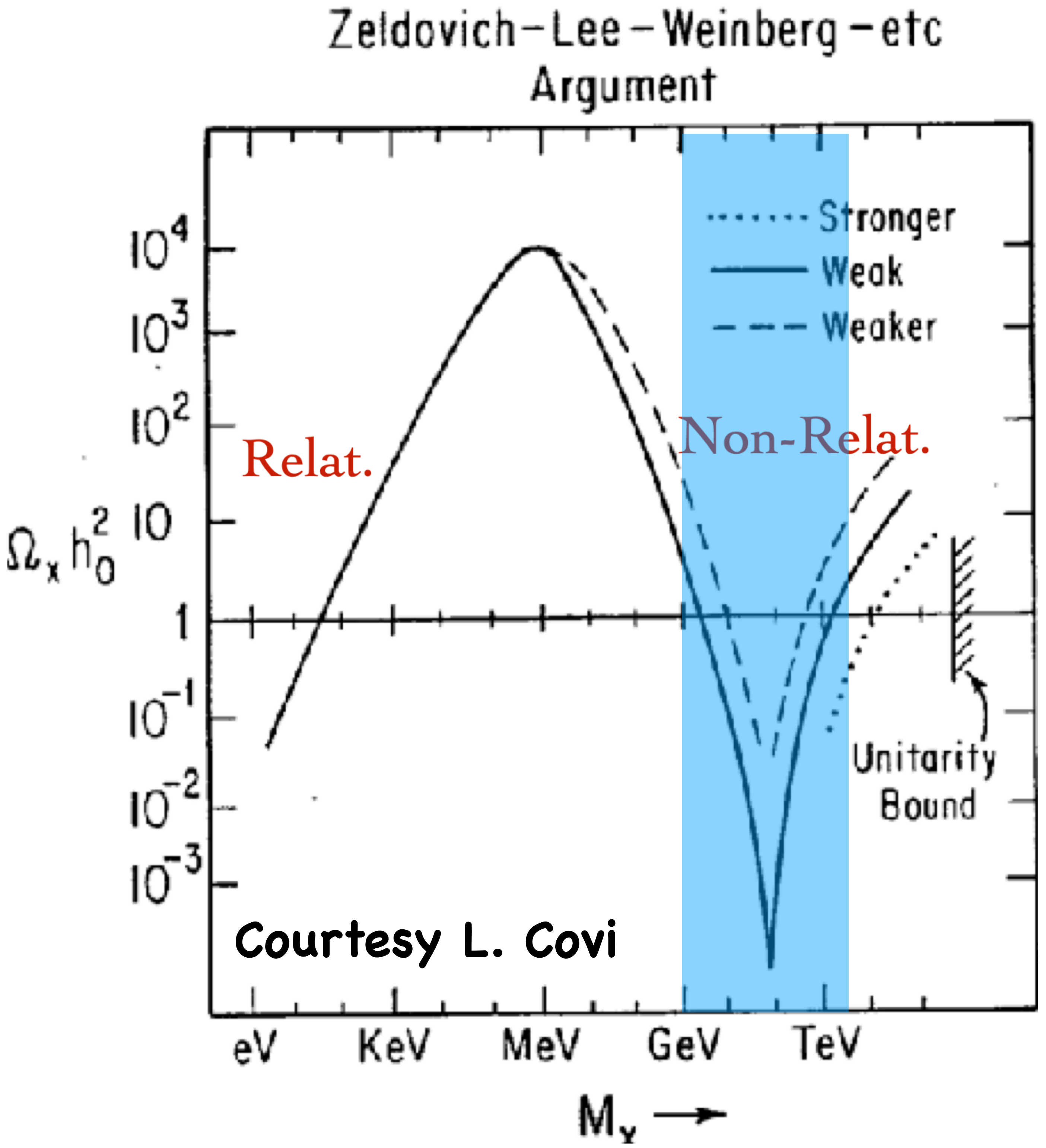

**Collisionless (to avoid dissipation) but annihilation**

Thermal DM

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2) \quad \Rightarrow \quad \Omega h^2 \simeq \frac{3\times 10^{-27} cm^3/s}{\langle \sigma v \rangle}$$

Planck 2018

**Hut, Lee&Weinberg 77**




Add some hypothesis about the DM nature (heavy neutrino)

$$\sigma v \propto \frac{m_{DM}^2}{m_W^4}$$

Impose that this cross section explains the relic density

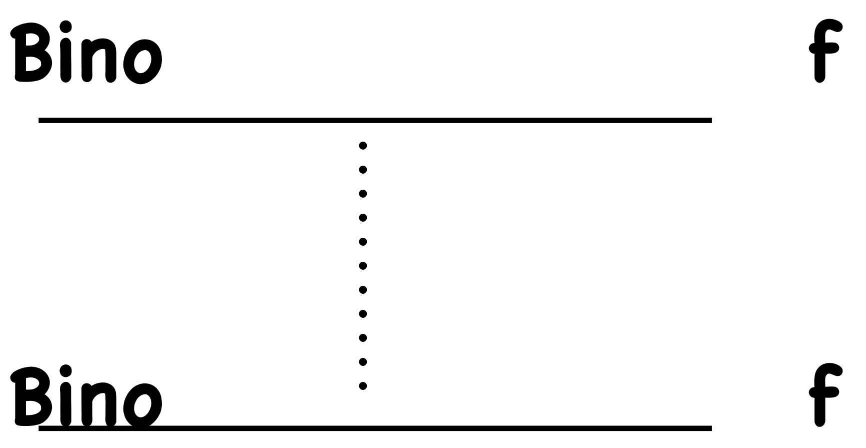
$$\sigma v \propto \frac{m_{DM}^2}{m_W^4} \simeq 3 - 10 \times 10^{-26}\ cm^3/s$$

# “Old” prediction

Dark matter is supposedly collisionless but it does annihilate and therefore must be heavier than a proton

# Supersymmetric WIMPS

https://arxiv.org/pdf/hep-ph/9810360.pdf

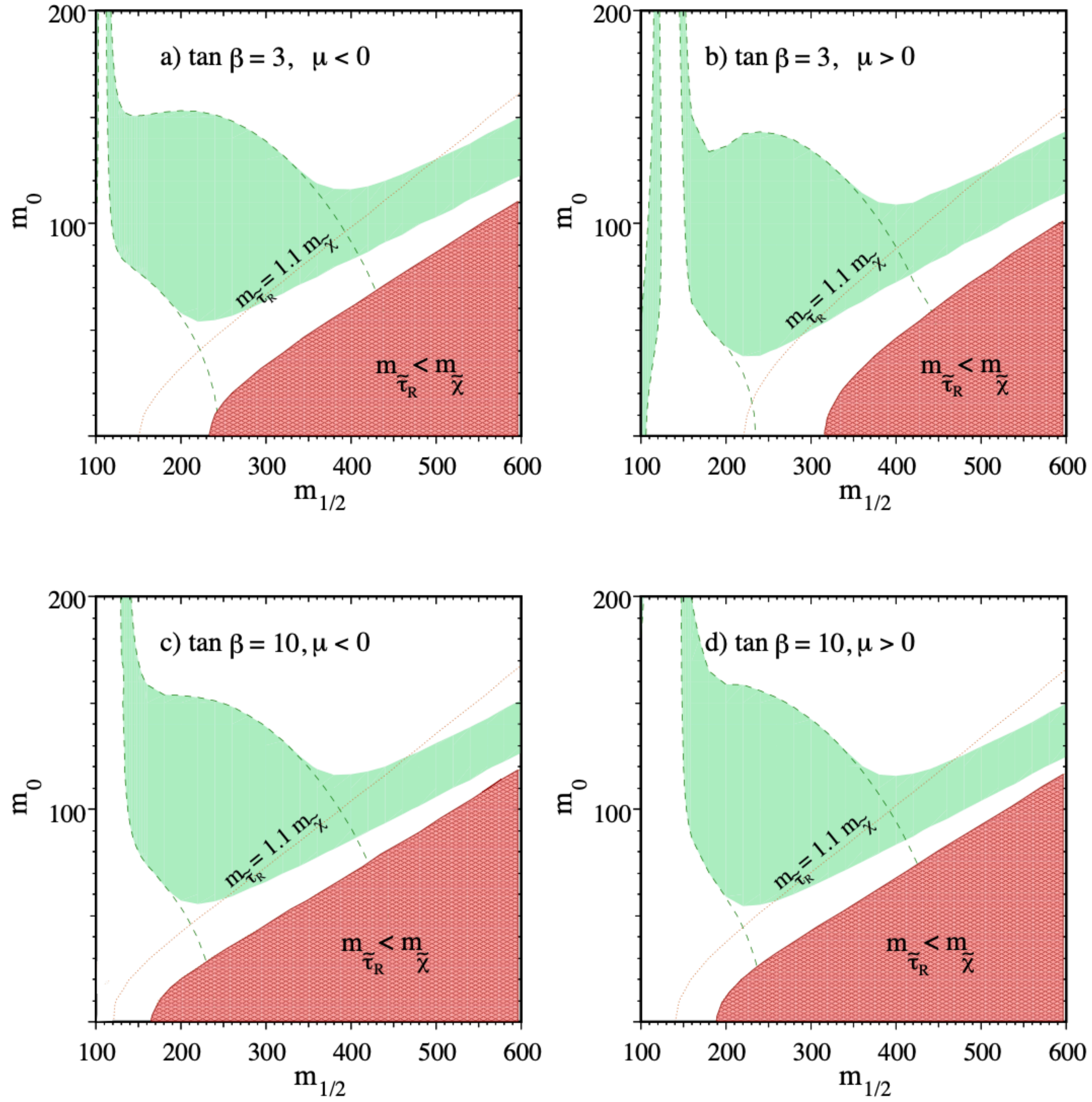



$$\langle \sigma v \rangle = \left(1 - \frac{m_f^2}{m_{\widetilde{B}}^2}\right)^{1/2} \frac{g_1^4}{128\pi} \left[ (Y_L^2 + Y_R^2)^2 \left(\frac{m_f^2}{\Delta_f^2}\right) + (Y_L^4 + Y_R^4)\left(\frac{4m_{\widetilde{B}}^2}{\Delta_f^2}\right)(1 + \ldots)\, x \right]$$

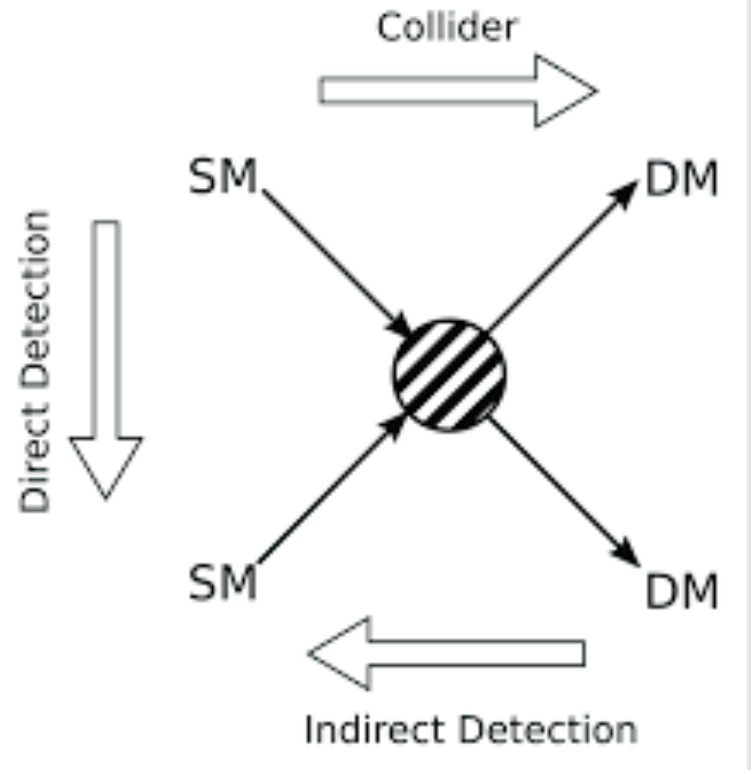
Table 1: Initial and Final States for Coannihilation: $\{i, j = \tau, e, \mu\}$

| Initial State | Final States |
|---|---|
| $\widetilde{\ell}_R^i \widetilde{\ell}_R^{i*}$ | $\gamma\gamma,\ ZZ,\ \gamma Z,\ W^+W^-,\ hh,\ \ell^i\bar{\ell}^i$ |
| $\widetilde{\ell}_R^i \widetilde{\ell}_R^j$ | $\ell^i \ell^j$ |
| $\widetilde{\ell}_R^i \widetilde{\ell}_R^{j*},\ i \neq j$ | $\ell^i \bar{\ell}^j$ |
| $\widetilde{\ell}_R^i \widetilde{\chi}$ | $\ell^i\gamma, \ell^i Z, \ell^i h$ |

Neutralino-stau co-annihilation



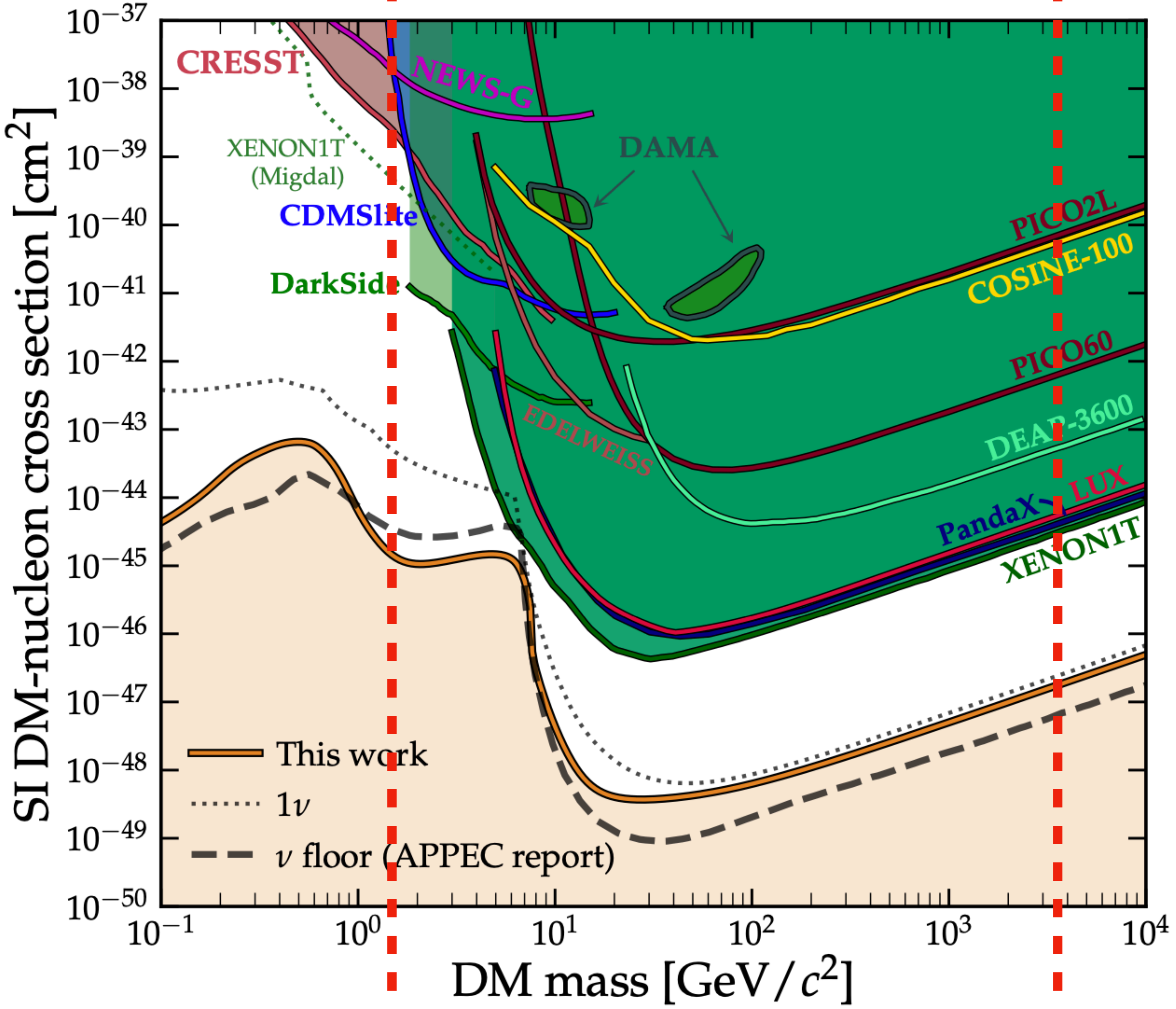

**Neutralino mass >> GeV and within the reach of LHC (or just at the limit)**




Annihilations

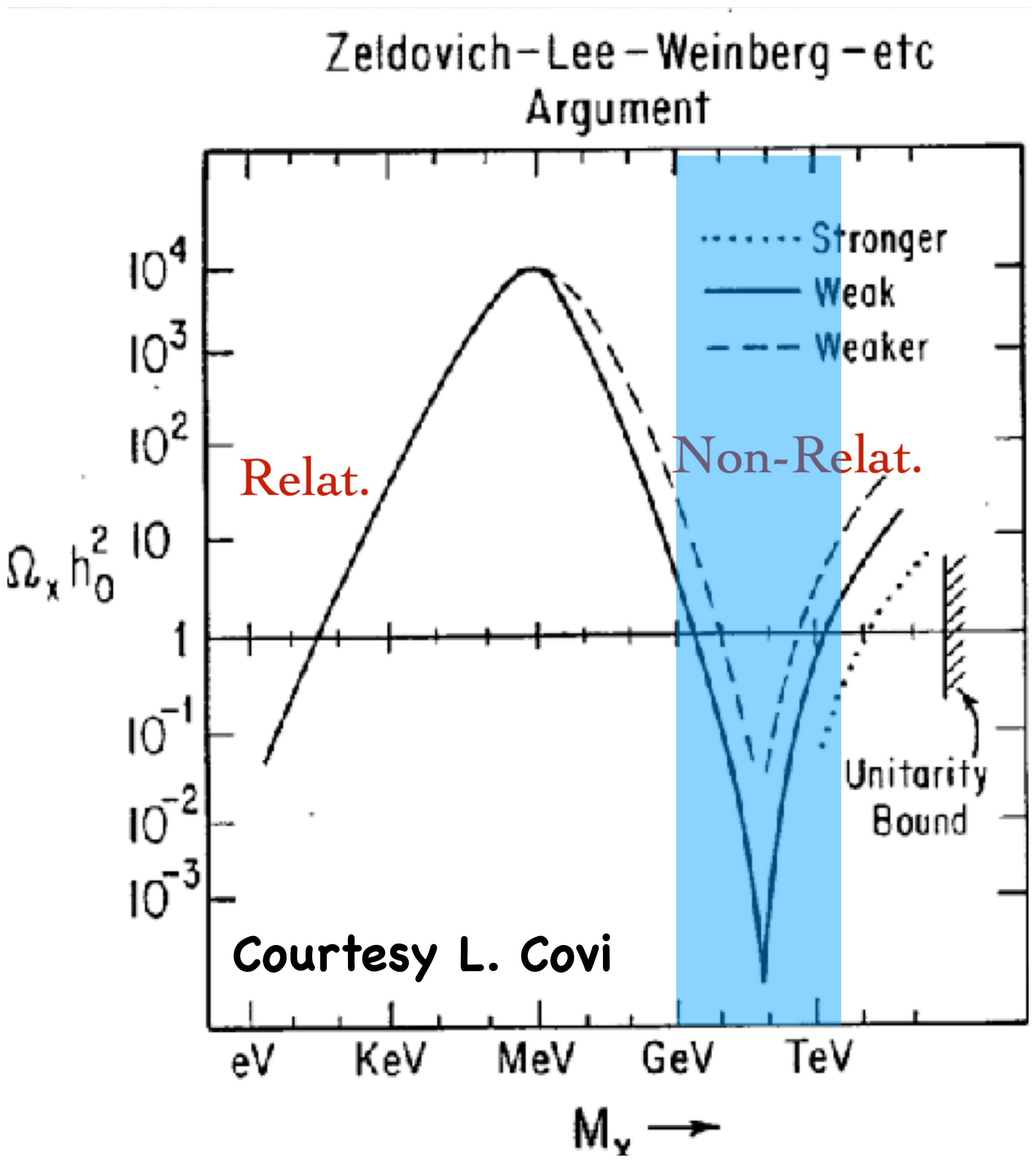
# Direct detection constraints

arXiv:2109.03116



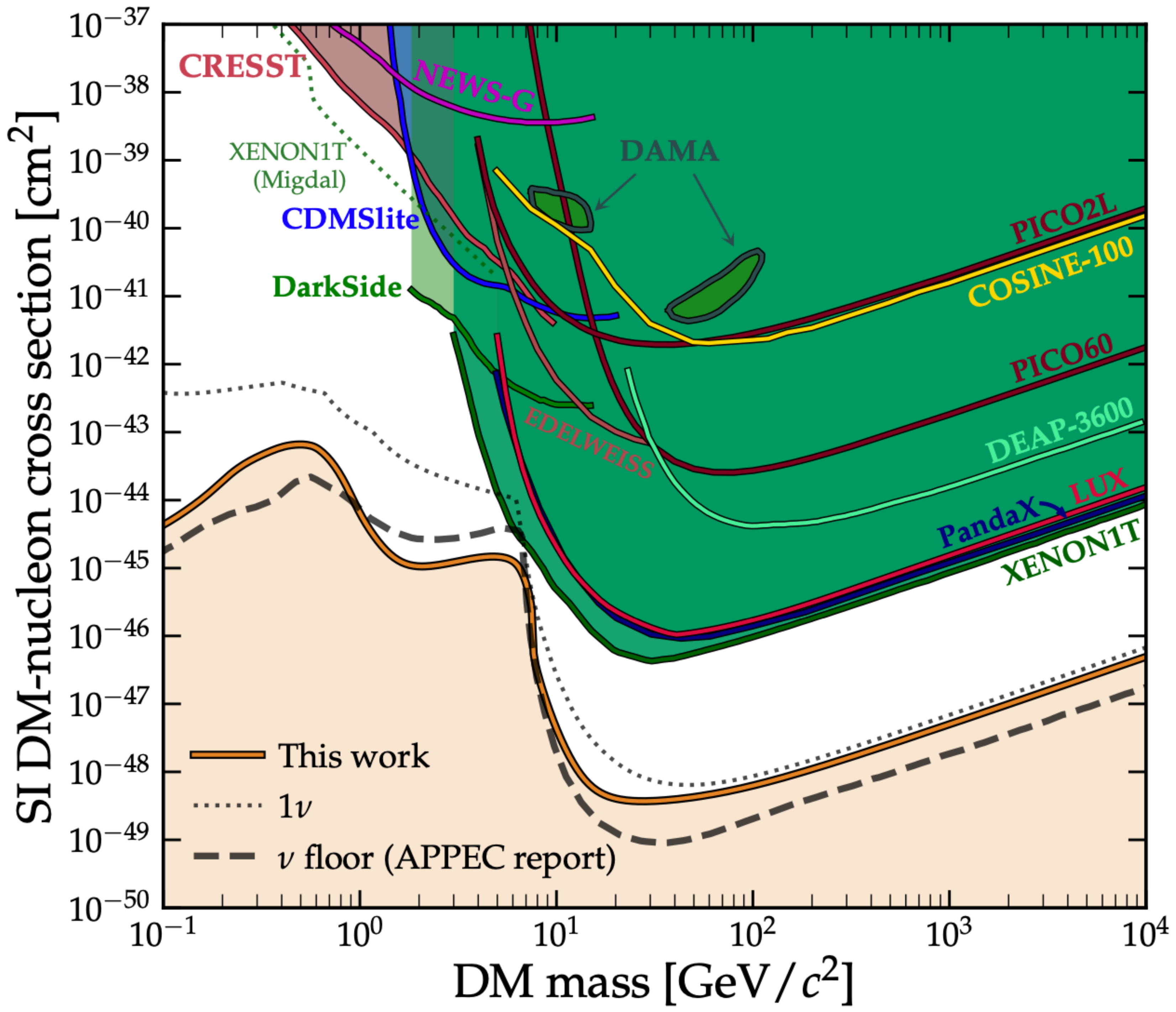

# Hold on...

## Collisionless but annihilations



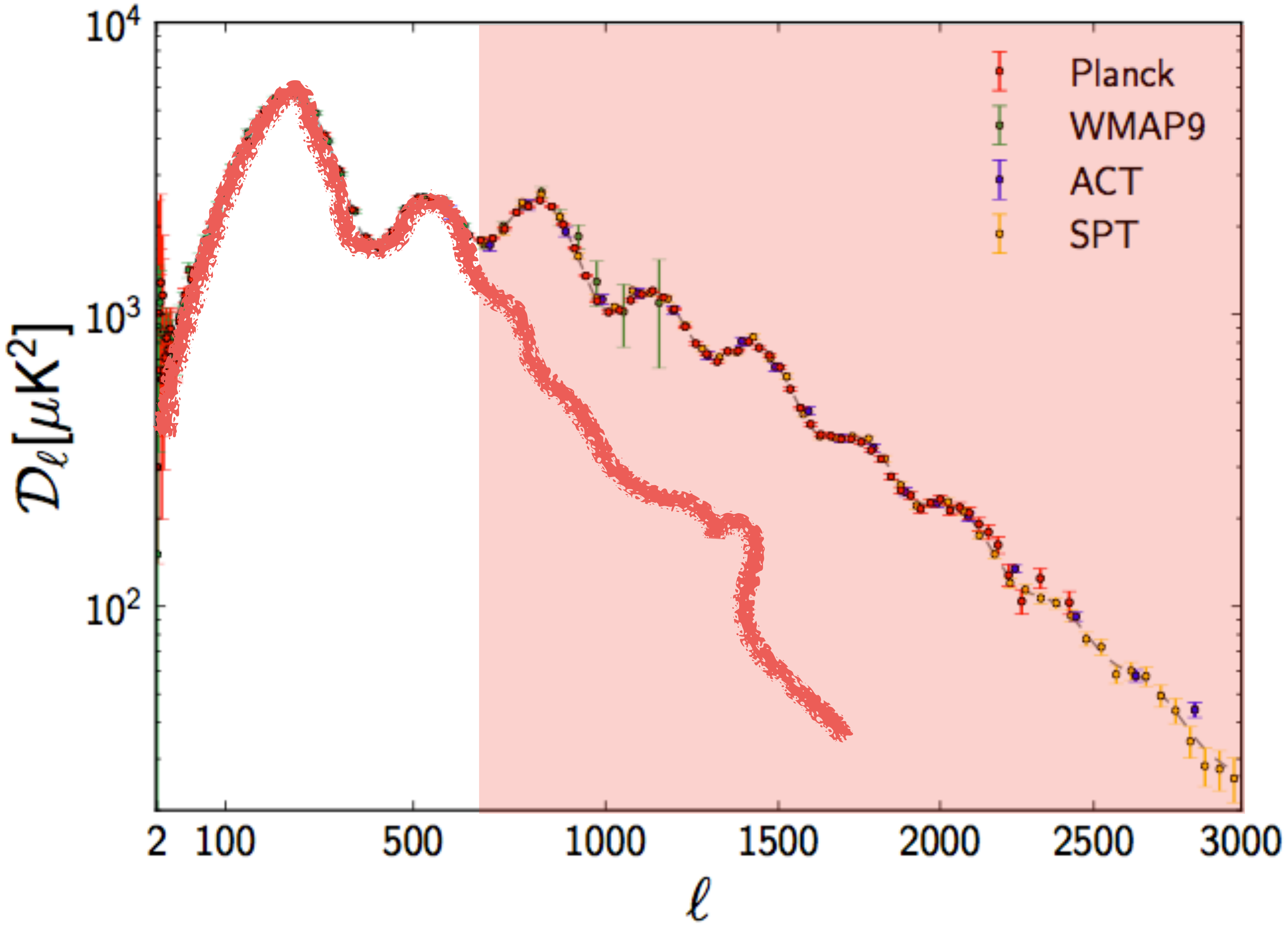

## DM is heavy

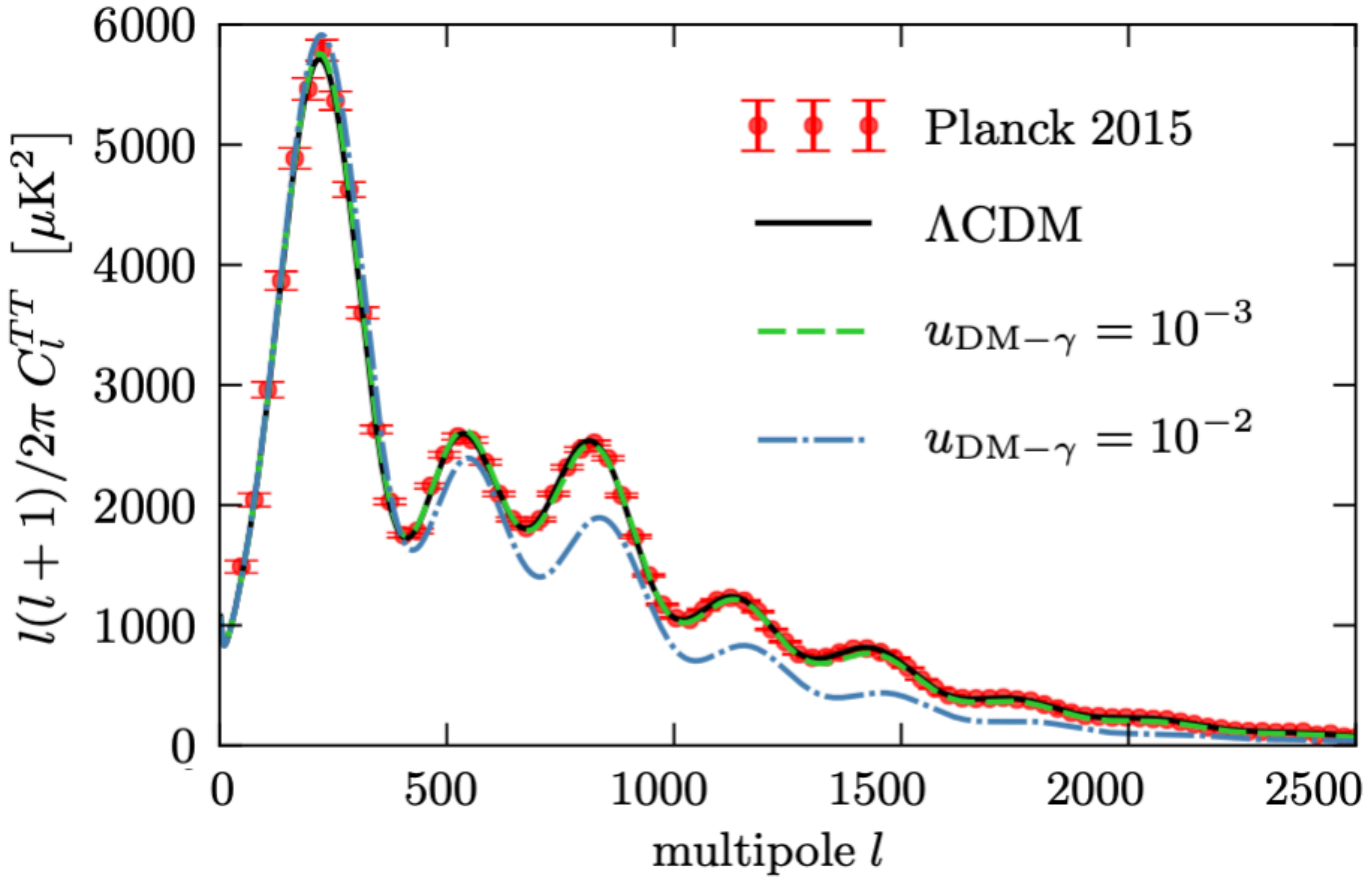
## Scattering with nuclei

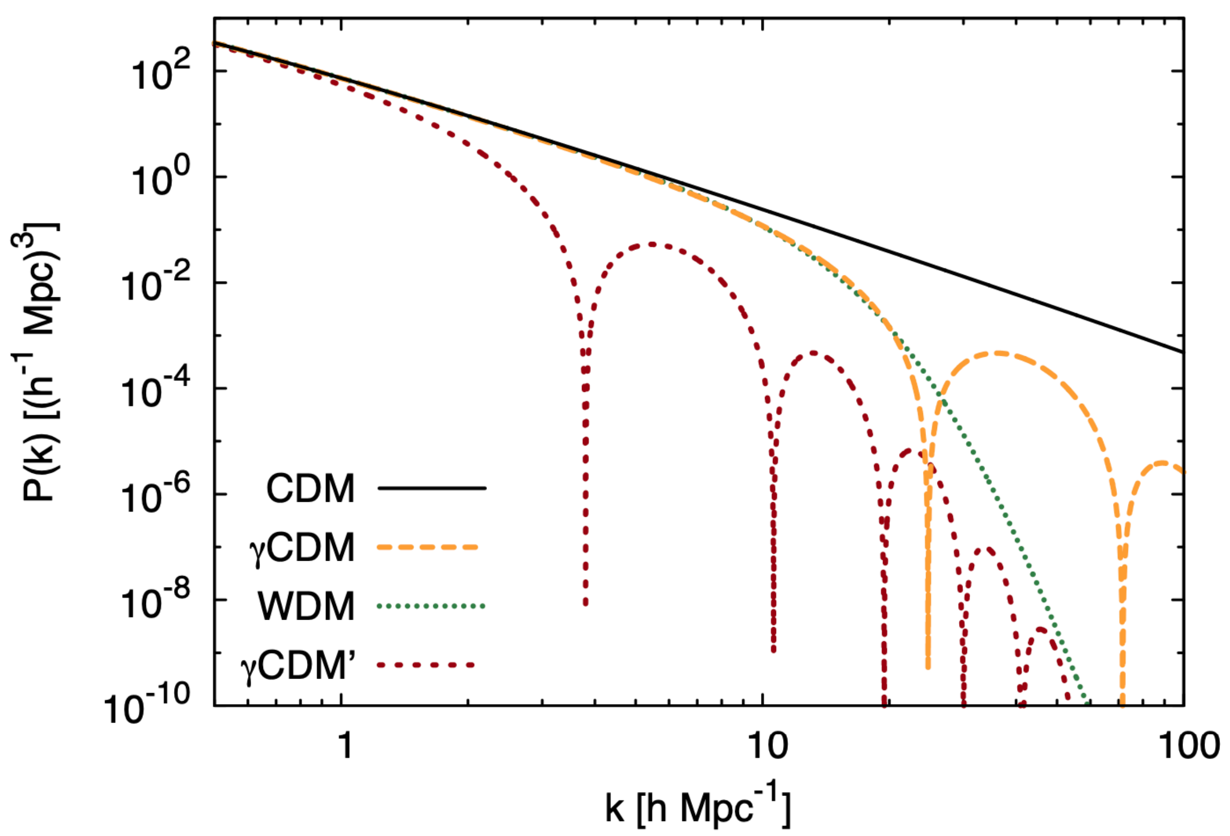



## So DM can scatter off SM particles???

# What does cosmology have to say?

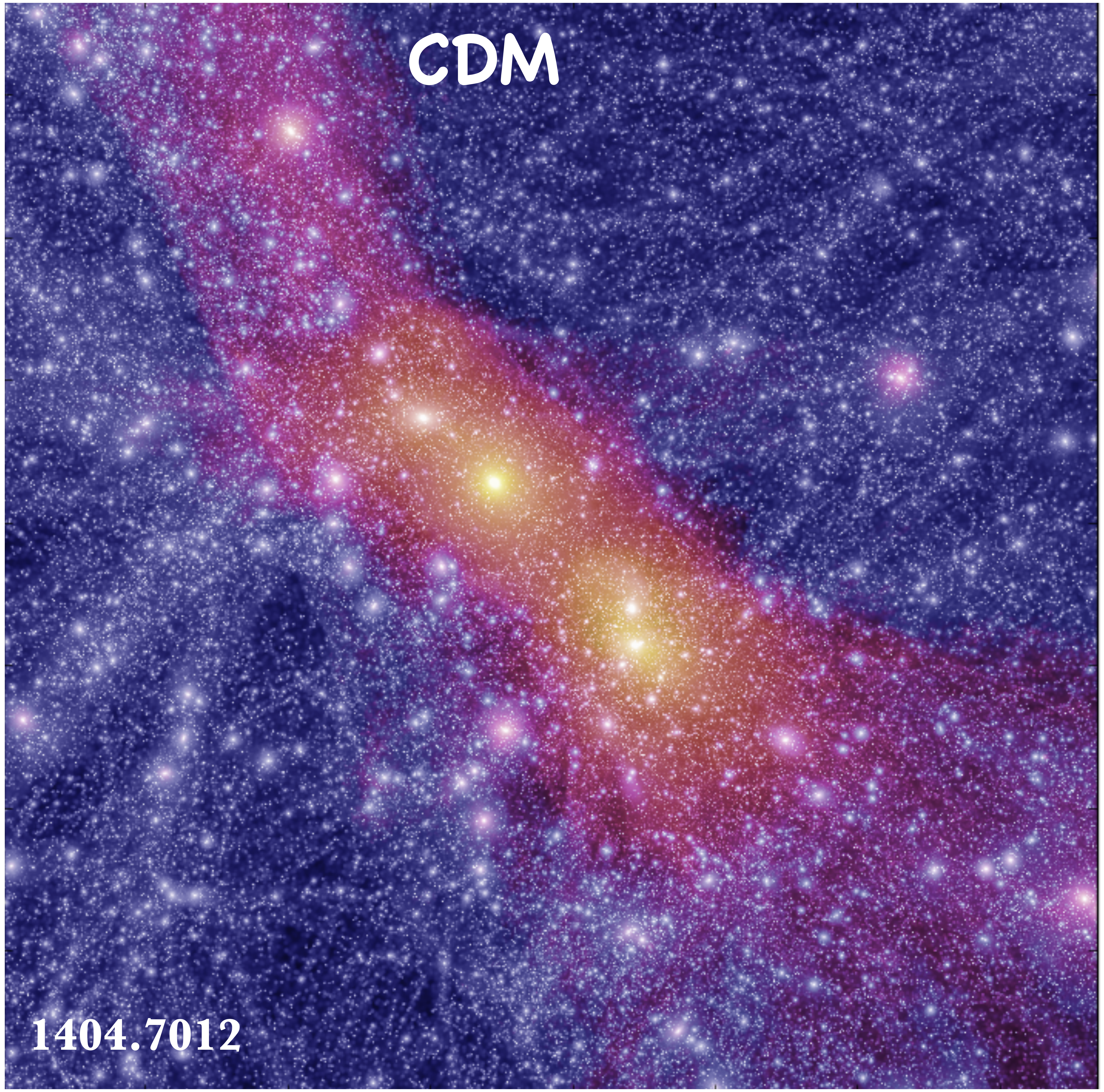


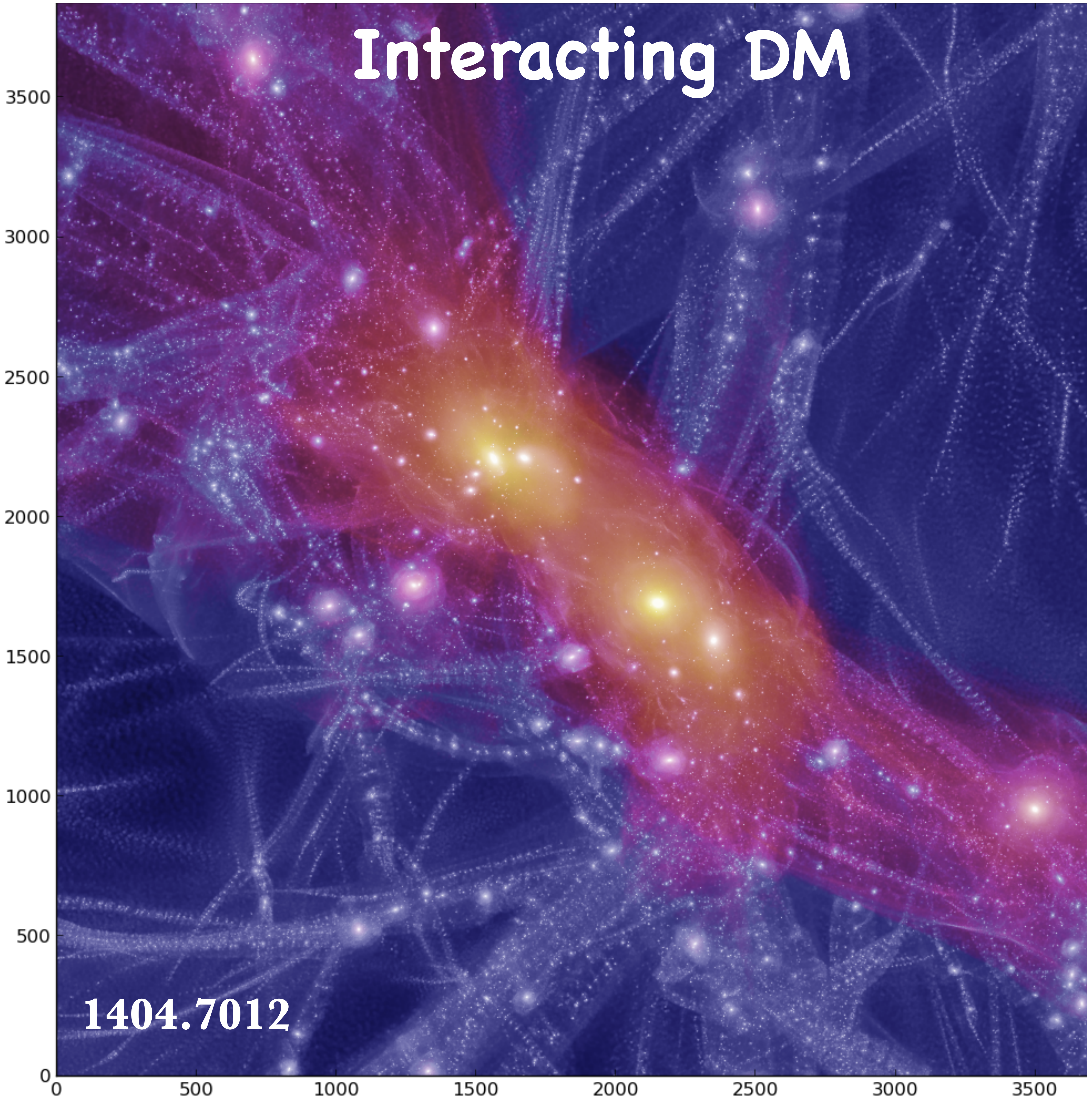




We should assume that DM can scatter off SM and let the particle physics and cosmology data guide us

# DM -SM interactions & large scales

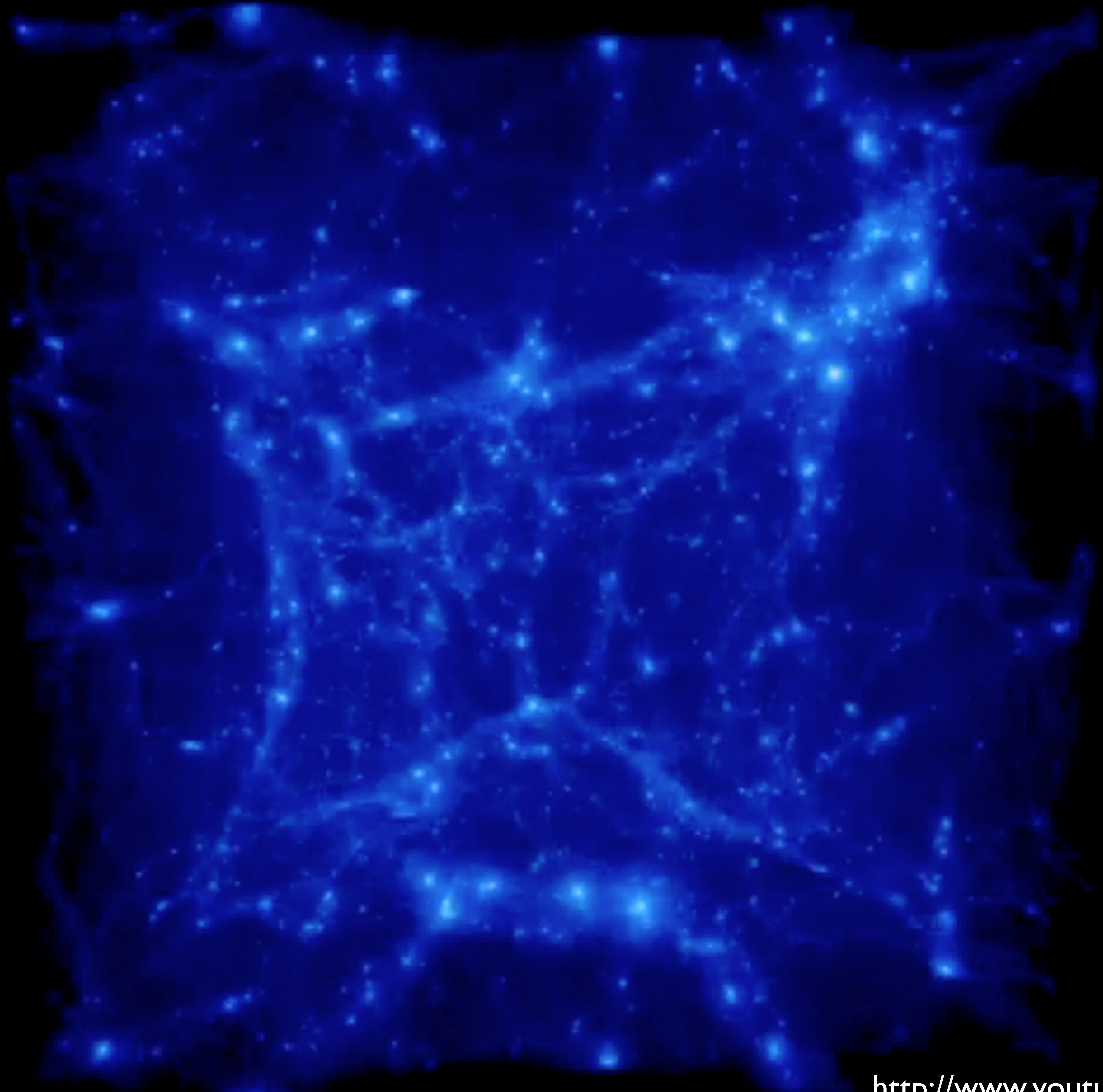



DM-SM 1404.7012

LSST, EUCLID will be essential!

1404.7012



http://www.youtube.com/watch?v=YhJHN6z_0ek

# Newish prediction

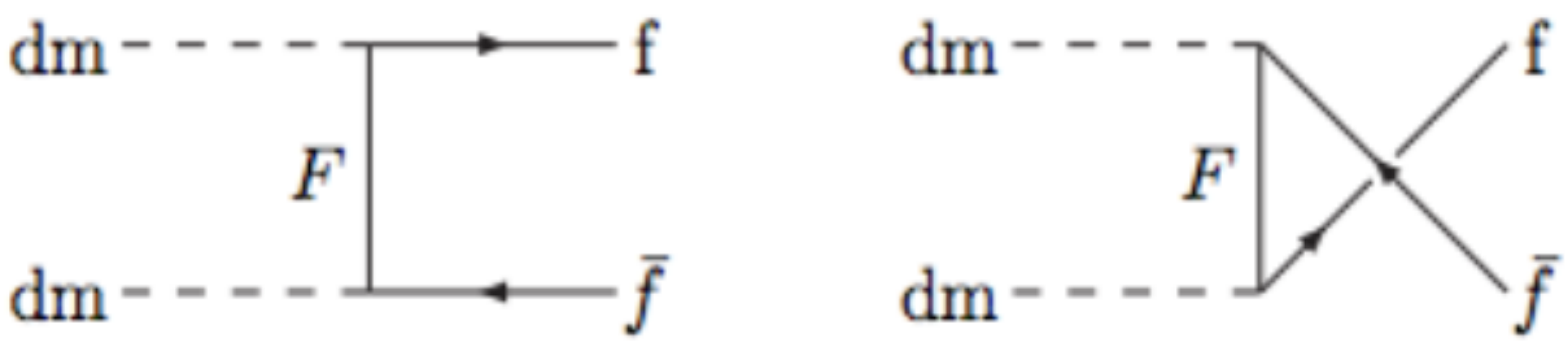
Dark matter can be collisional (not too much though)
It can annihilate and therefore
must be heavier than a proton

# Can dark matter be lighter than a proton?

hep-ph/0305261

$$\Omega h^2 \simeq \frac{3\times 10^{-27} cm^3/s}{\langle \sigma v \rangle} \quad + \quad \sigma v \propto \frac{m_{DM}^2}{m_W^4} \quad \Rightarrow \quad \text{GeV DM}$$

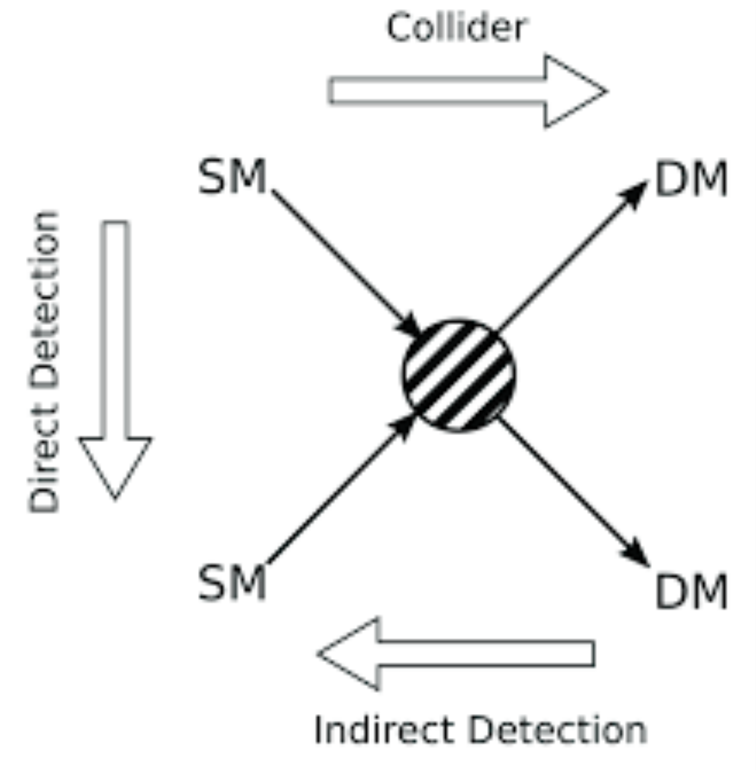
**Take a scalar instead of a fermion and assume new interactions**




$$\sigma v \propto \frac{1}{m_F^4} \left( (C_l^2 + C_r^2)\ m_f + 2 C_l\ C_r\ m_F \right)^2 \Rightarrow \sigma v \propto \frac{C_l^2 C_r^2}{m_F^2}$$

**Imposing a specific value for sigma doesn't constrain mdm so DM can be light and it is ok!**

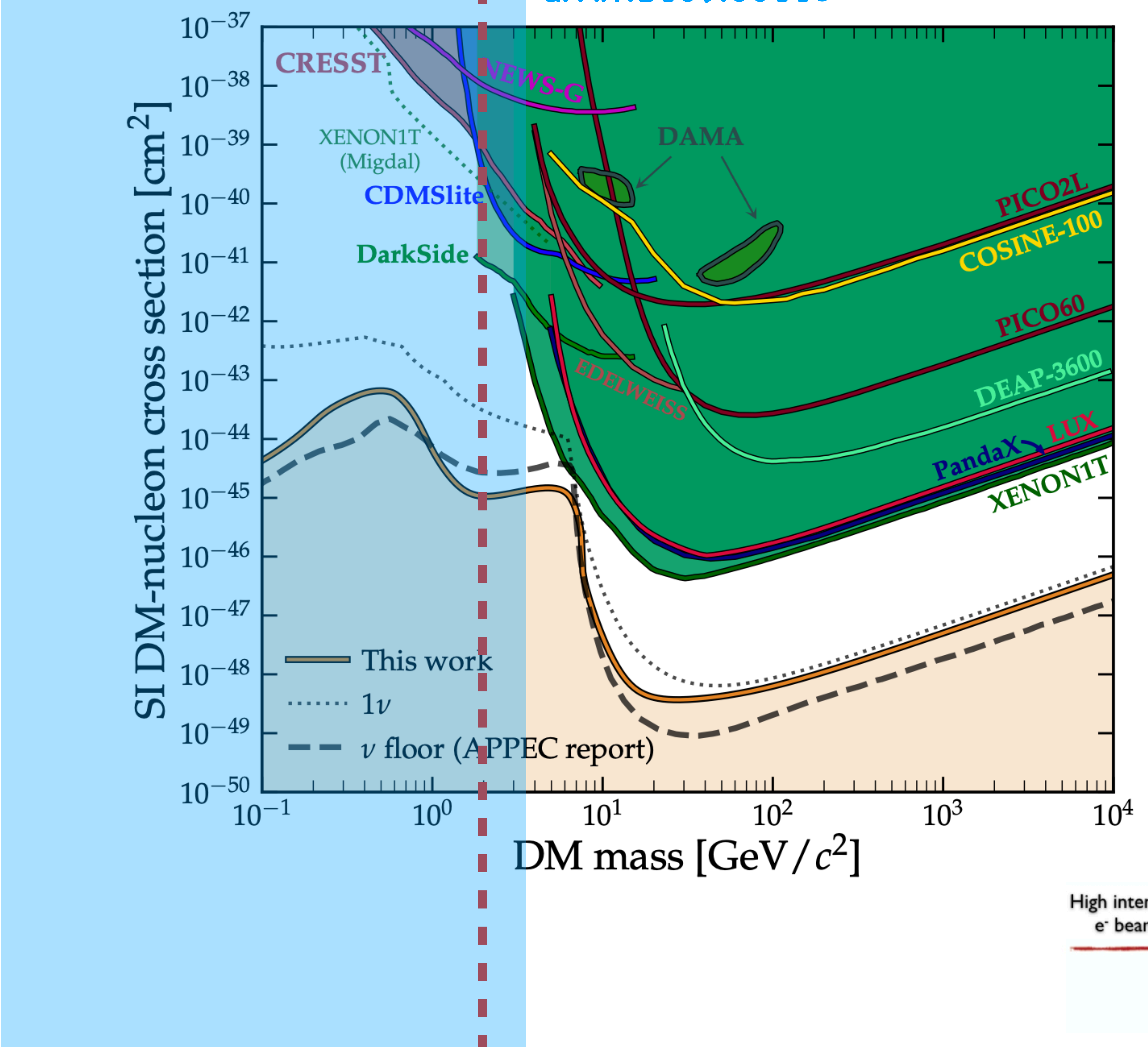
Also found by Feng&kumar (0803.4196)

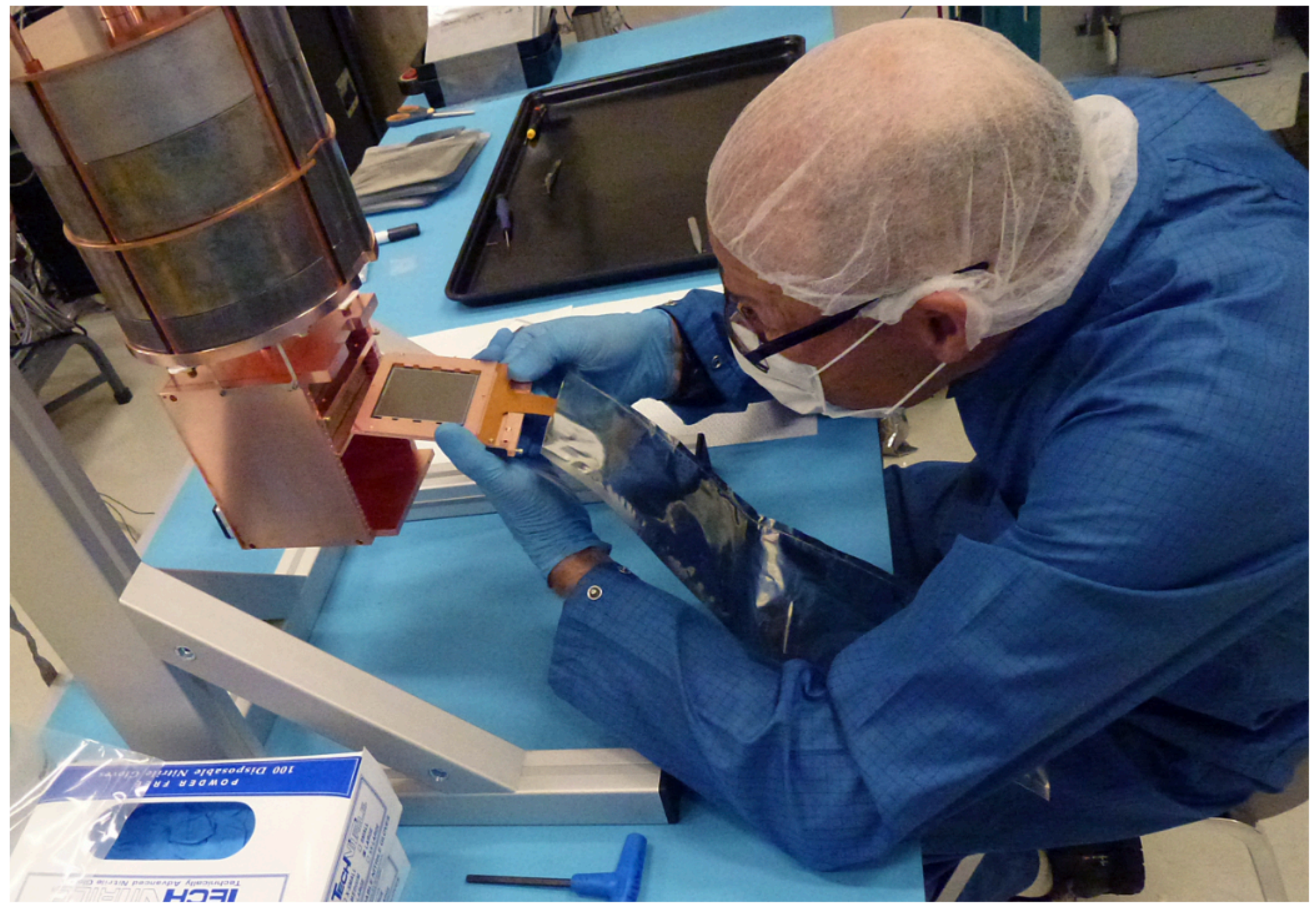



Annihilations

# Direct detection constraints

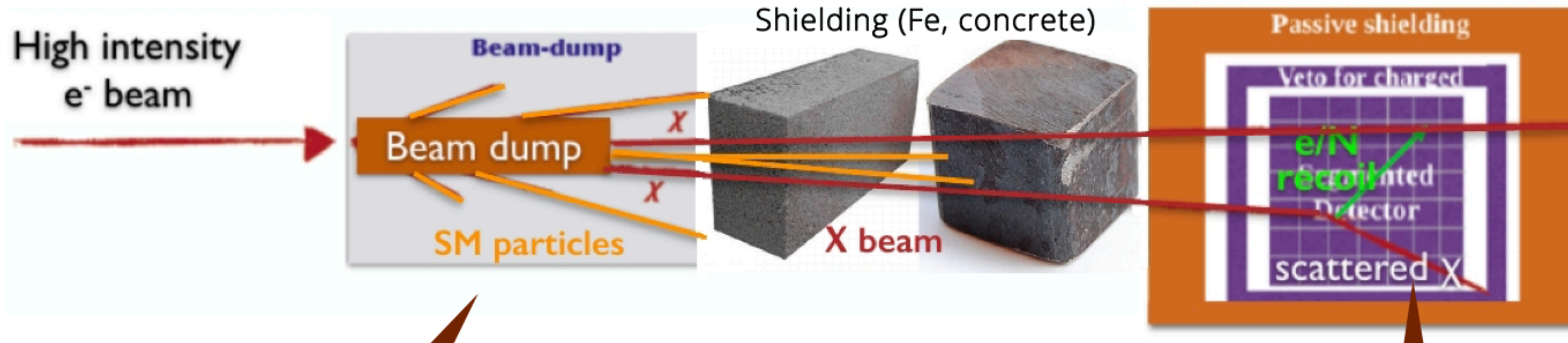
arXiv:2109.03116



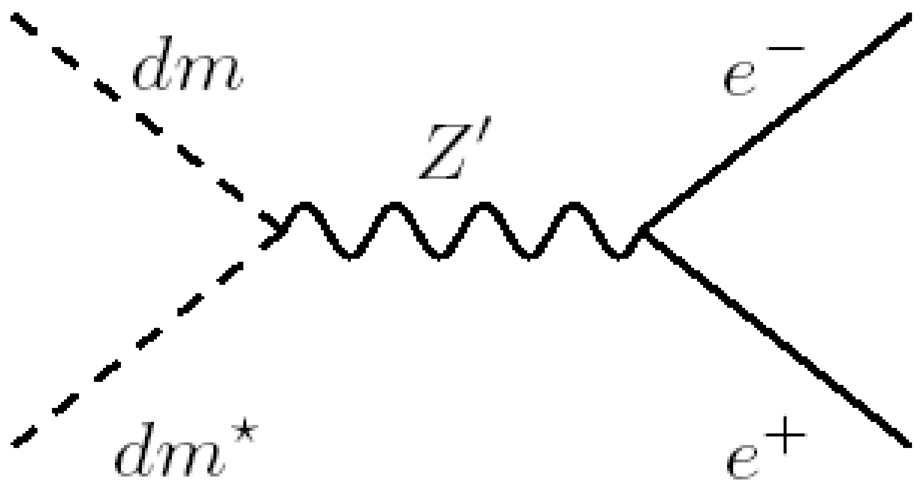



**DAMIC installation at SNOLAB**

A packaged CCD being inserted in the copper box. Above the box is a lead cylinder shielding the CCDs from radiogenic backgrounds. DAMIC is taking data at SNOLAB with 7 CCDs for a total mass of 40 g.



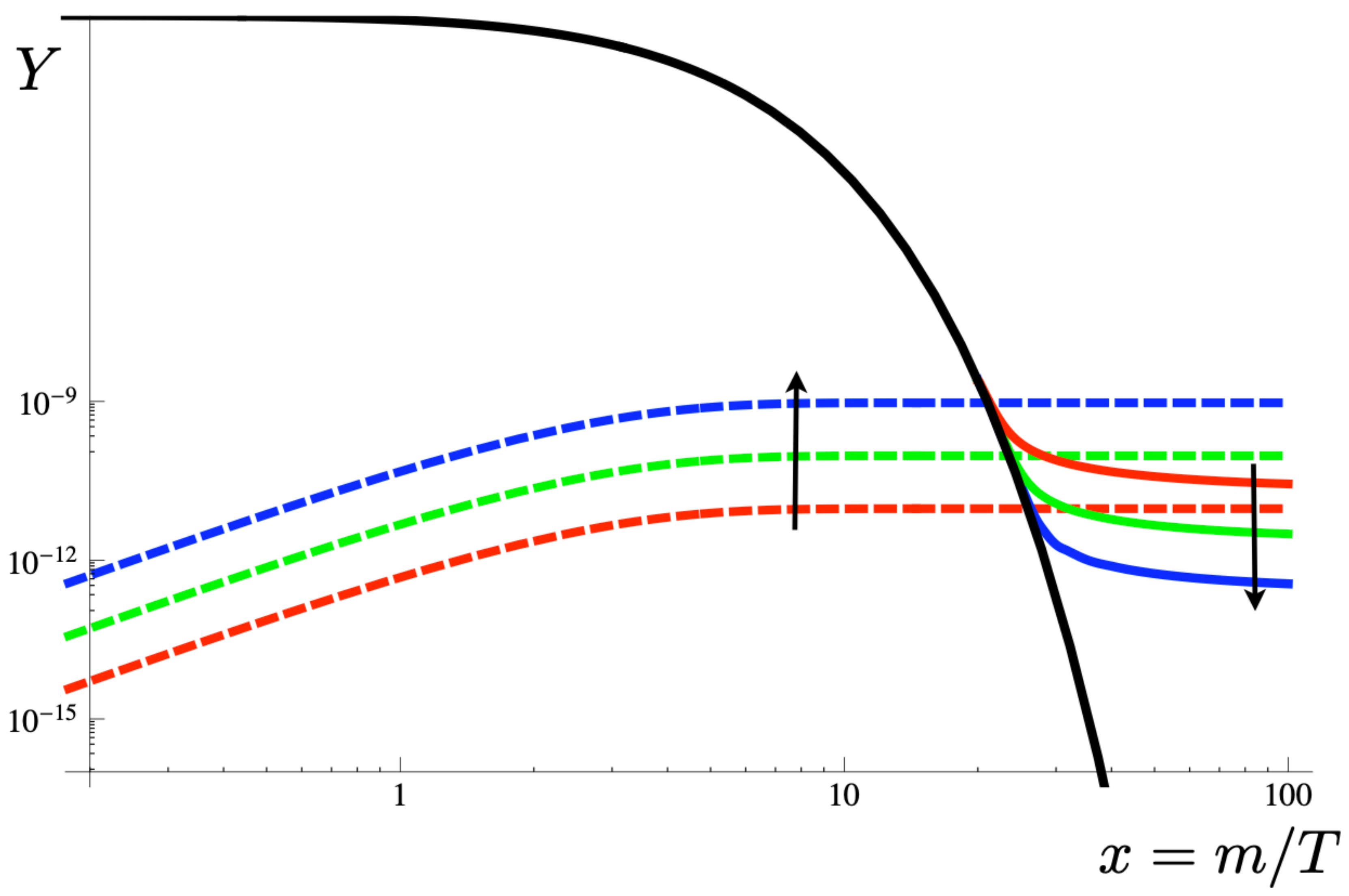
# Light Dark Matter & Light mediators

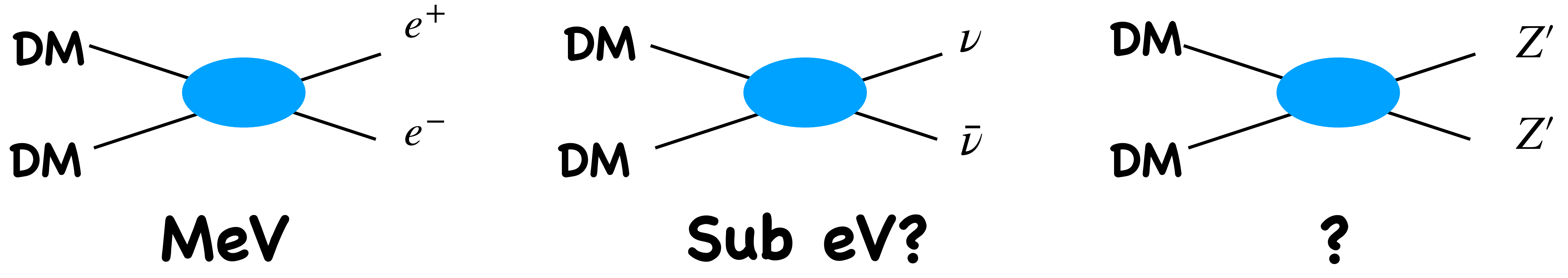



$$\sigma v \propto v^2 \, \frac{m_{\rm DM}^2}{m_{Z'}^4} \, g_{\rm DM}^2 \, g_e^2$$

DM can be light if the mediator is light

0911.1120



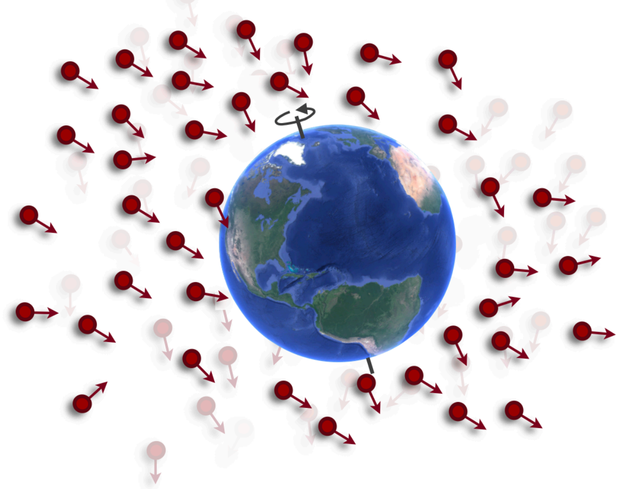




Should there be annihilations at all?

Asymmetric DM, Freeze-in, non thermal DM

# Even lighter DM? Revisiting axions

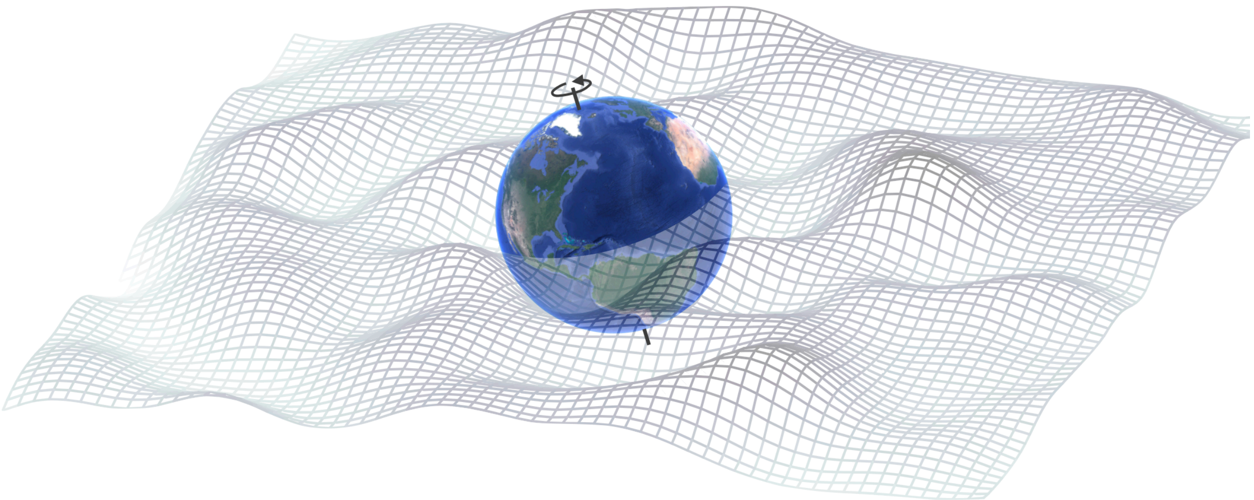
**Particle-like**



Number density $n_\chi = \rho / m_\chi$

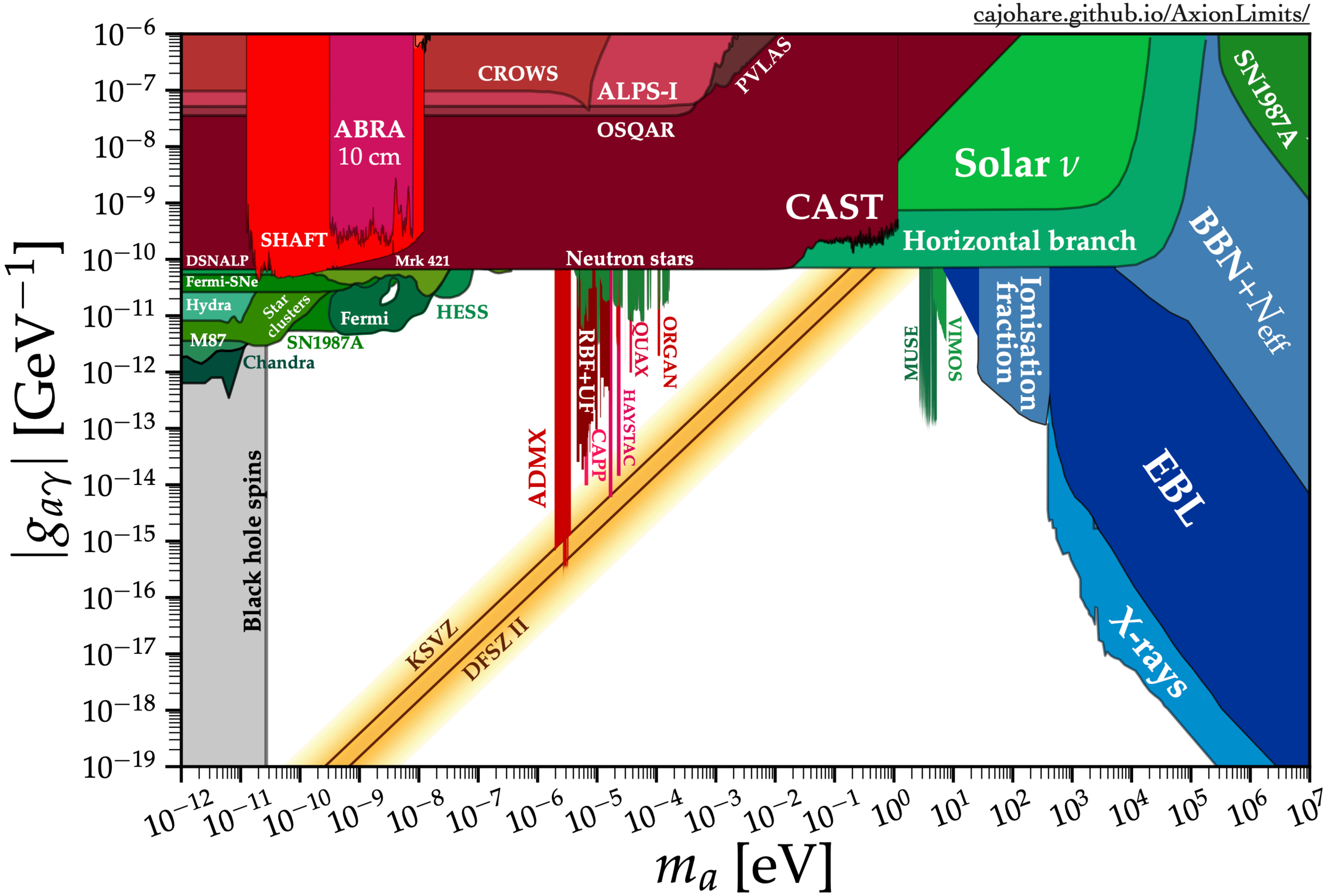
Flux $\Phi = v n_\chi$

**Wave-like**



Amplitude $A = \frac{\sqrt{2\rho}}{m_\chi}$

Frequency $\omega = m_\chi + \frac{1}{2} m_\chi v^2$




**News from sub-GeV FI(N)Ps**

Feebly Interacting (Non)Particle

J. Jaeckel*

# Conclusion

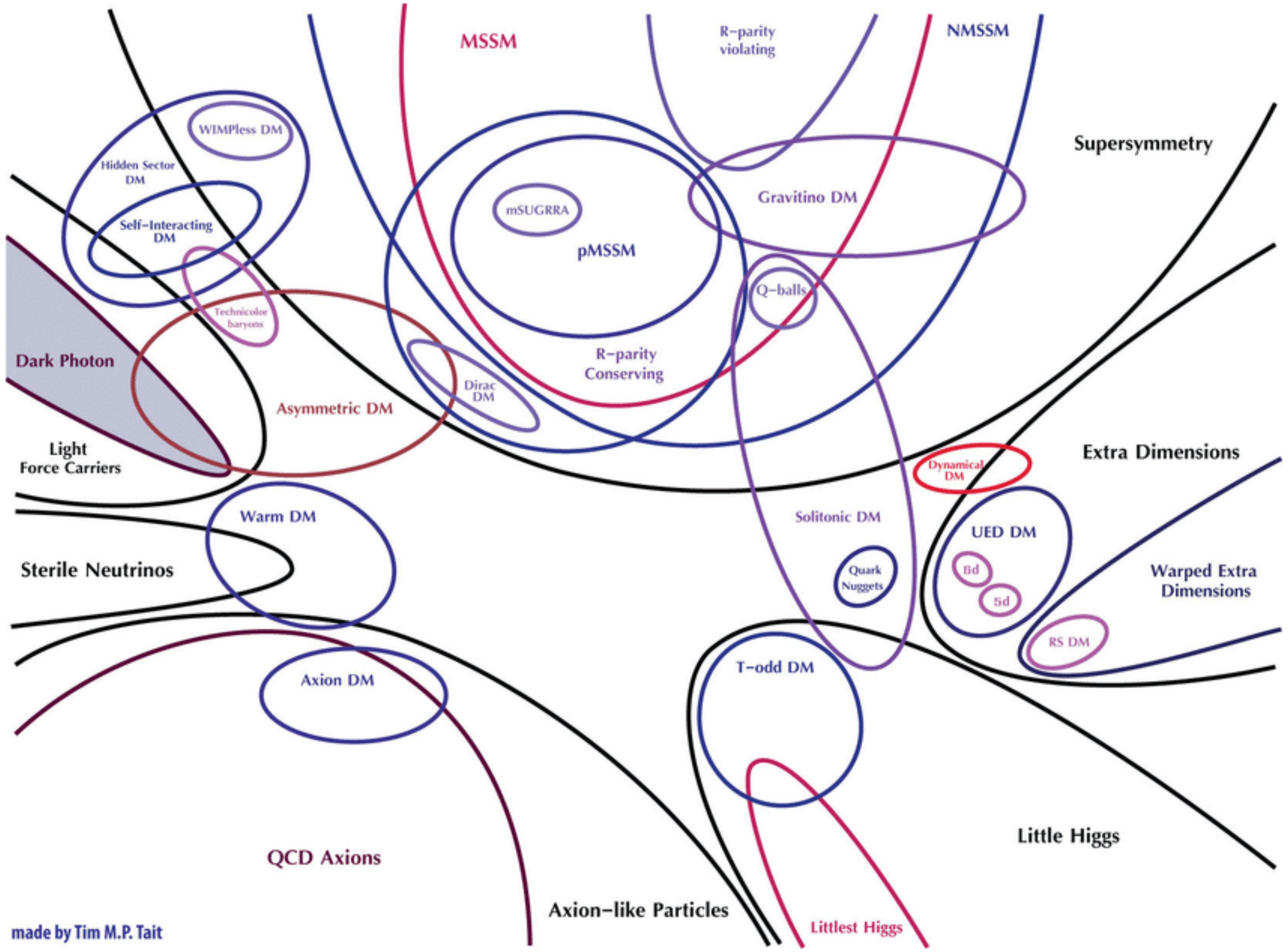
- The physics that we know — formulated in a "standard" way — does not explain the number and properties of cosmological structures that we observe

- Solutions involve

  - new particles which could be light / heavy but with small (if any) interactions with SM particles
  - modifying gravity
  - wave-like components

- Cosmological survey will bring important information if we don't detect the dark matter on Earth but the main thing is

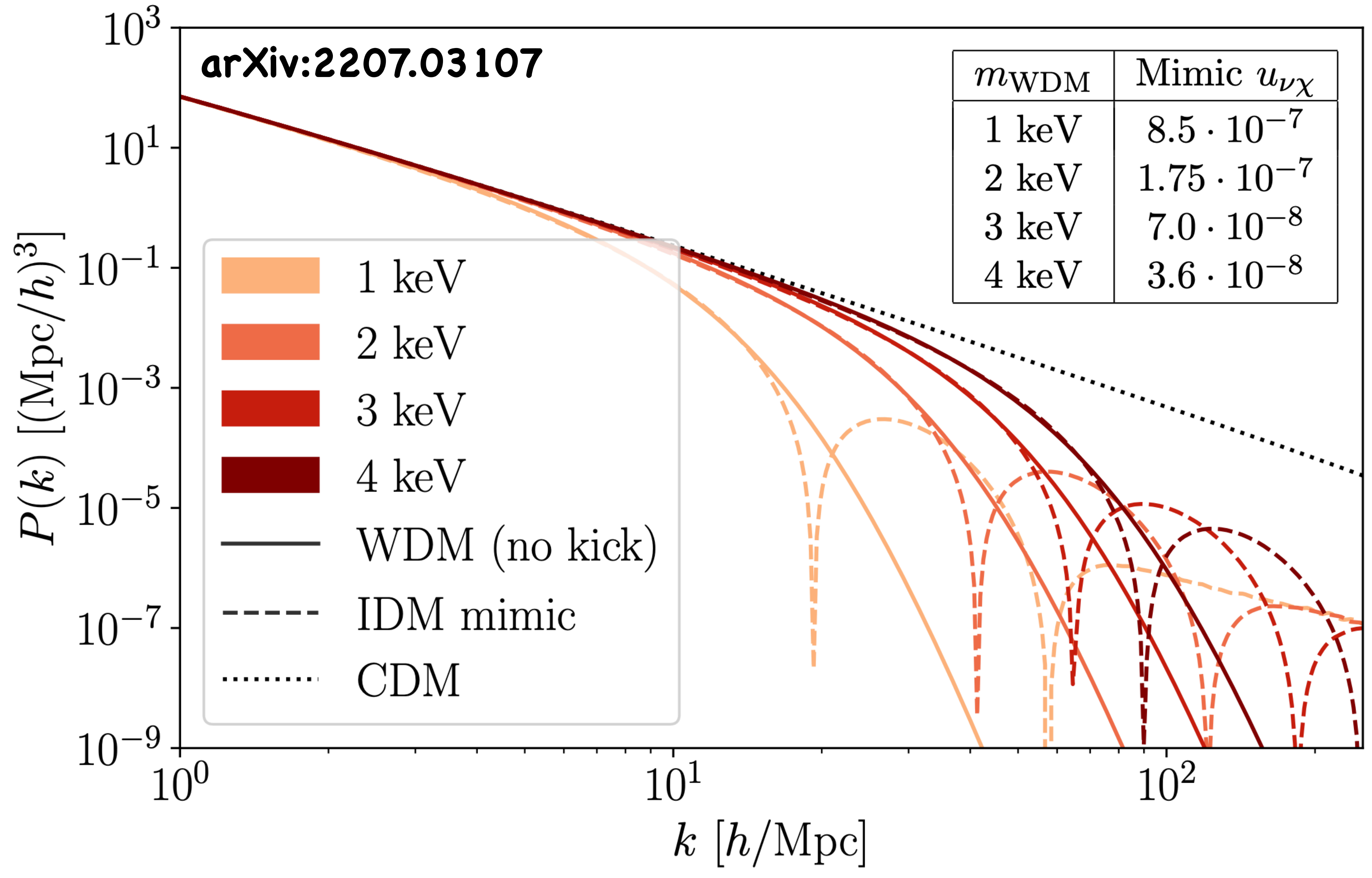
**We need new ideas!**

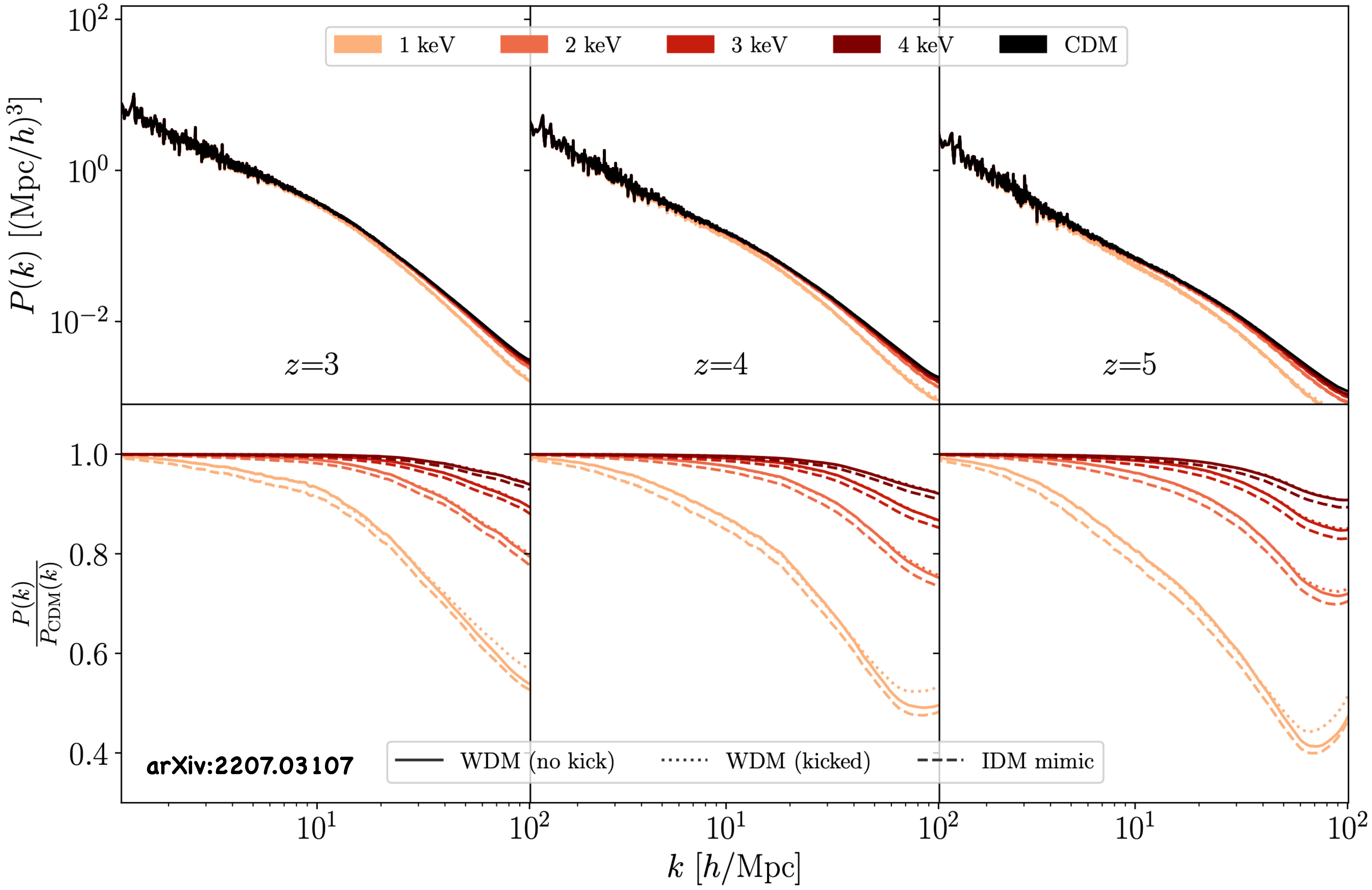




https://phys.org/news/2018-10-era-quest-dark.html

# How to probe Dark Matter models?

**arXiv:2207.03107 in agreement with astro-ph/0309652**



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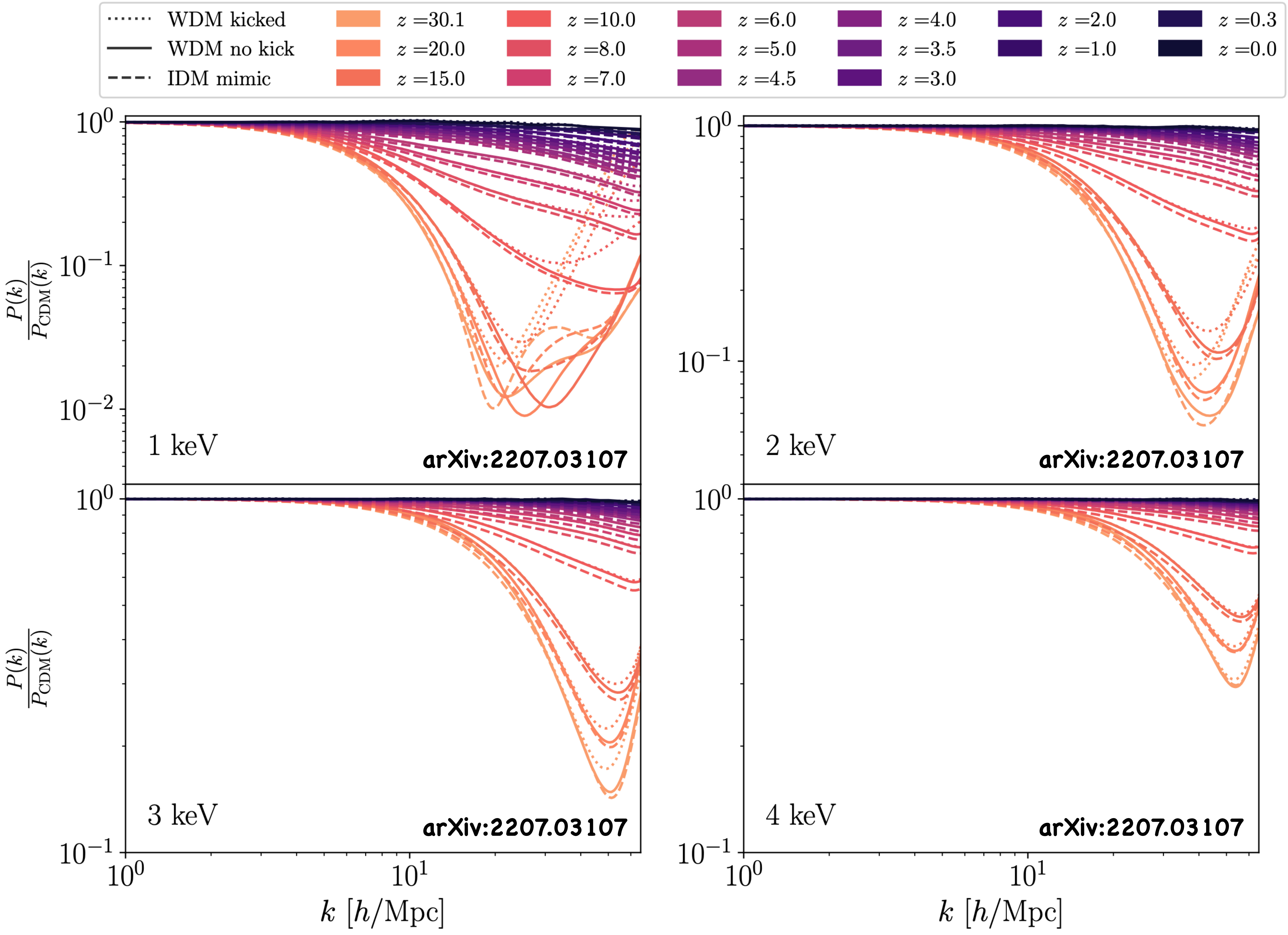


# How to probe Dark Matter interactions?

arXiv:2207.14126

## Gravitational-wave event rates as a new probe for dark matter microphysics

Markus R. Mosbech,[1,*] Alexander C. Jenkins,[2,†] Sownak Bose,[3,‡]
Celine Boehm,[1,§] Mairi Sakellariadou,[4,¶] and Yvonne Y. Y. Wong[5,**]

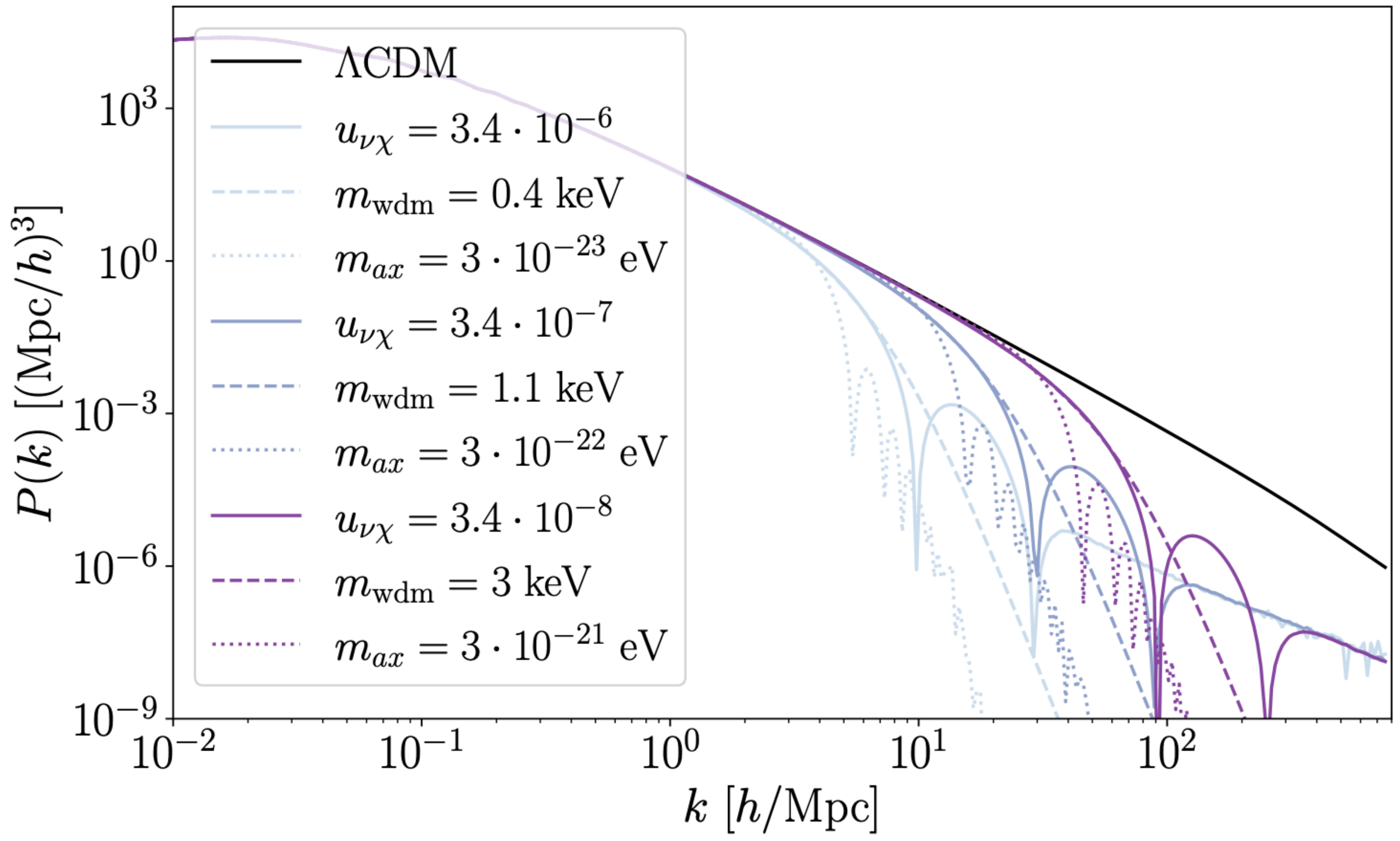
[1] *School of Physics, The University of Sydney, Camperdown NSW 2006, Australia*
*ARC Centre of Excellence for Dark Matter Particle Physics*
*Sydney Consortium for Particle Physics and Cosmology*
[2] *Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom*
[3] *Institute for Computational Cosmology, Department of Physics,*
*Durham University, Durham DH1 3LE, United Kingdom*
[4] *Theoretical Particle Physics and Cosmology Group, Physics Department,*
*King's College London, University of London, Strand, London WC2R 2LS, United Kingdom*
[5] *School of Physics, The University of New South Wales, Sydney NSW 2052, Australia,*
*Sydney Consortium for Particle Physics and Cosmology*

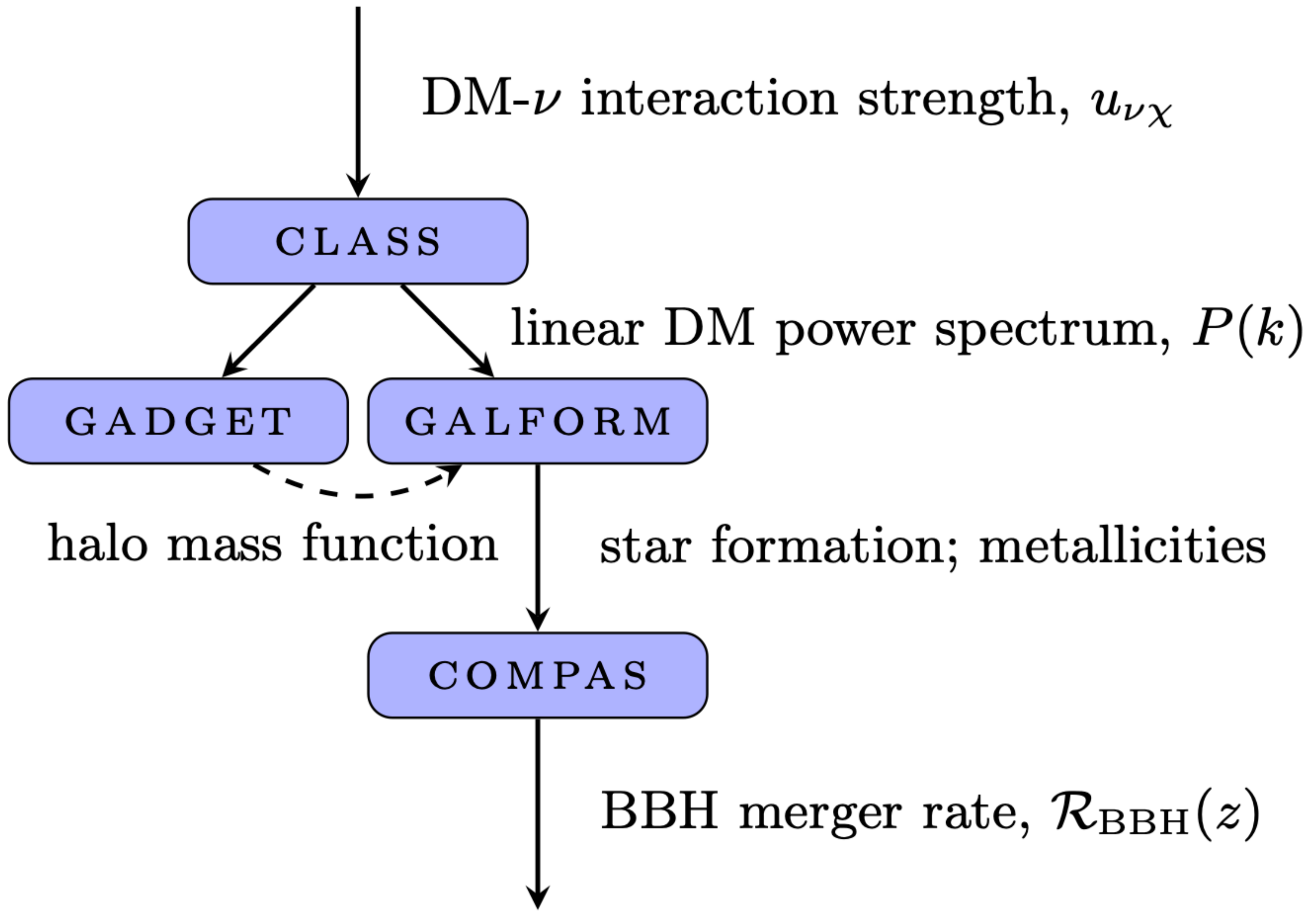
(Dated: 3 August 2022)

We show that gravitational waves have the potential to unravel the microphysical properties of dark matter due to the dependence of the binary black hole merger rate on cosmic structure formation, which is itself highly dependent on the dark matter scenario. In particular, we demonstrate that suppression of small-scale structure—such as that caused by interacting, warm, or fuzzy dark matter—leads to a significant reduction in the rate of binary black hole mergers at redshifts $z \gtrsim 5$. This shows that future gravitational-wave observations will provide a new probe of the $\Lambda$CDM cosmological model.

# How to probe Dark Matter interactions?

arXiv:2207.14126




The BBH merger rate is thus essentially a delayed tracer of star formation, whose normalisation depends on the efficiency with which massive binary stars are converted into BBHs. This efficiency is mostly determined by the stellar metallicity.

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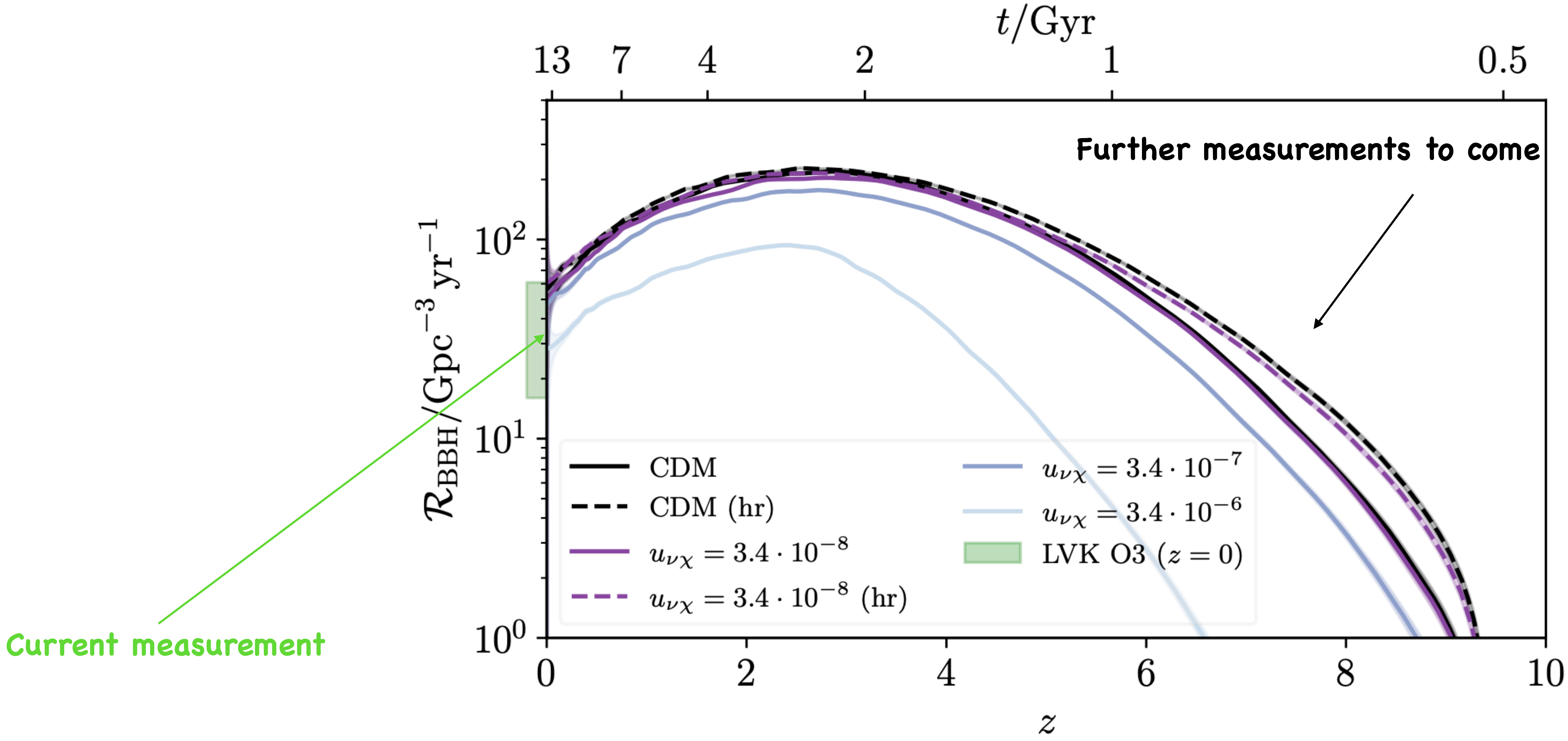
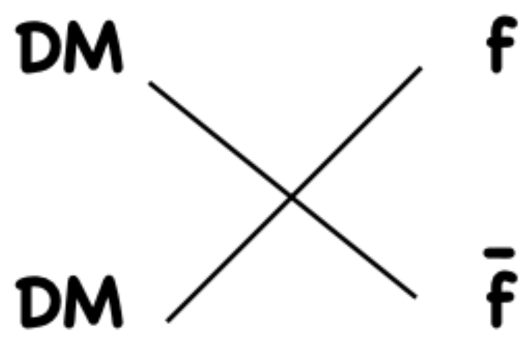


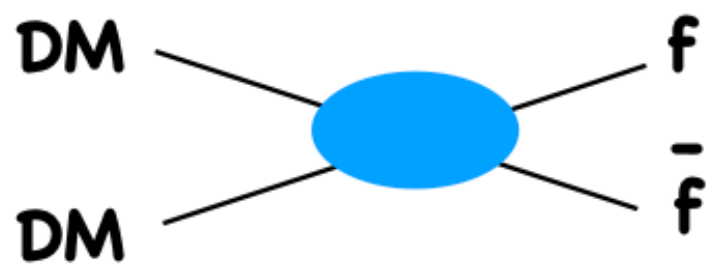

LCDM almost excluded (!!!) so next measurements will be critical!


Universiteit Leiden
Durham University
THE EAGLE SIMULATION
icc.dur.ac.uk/Eagle
$t_{age}$ = 13.8 Gyr
Redshift = 0.00
www.smcalpine.com

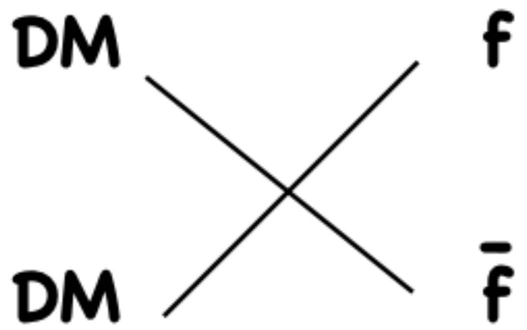
# Important evolution

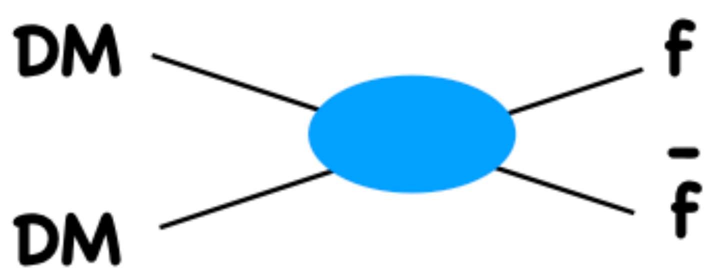
No collision but annihilation



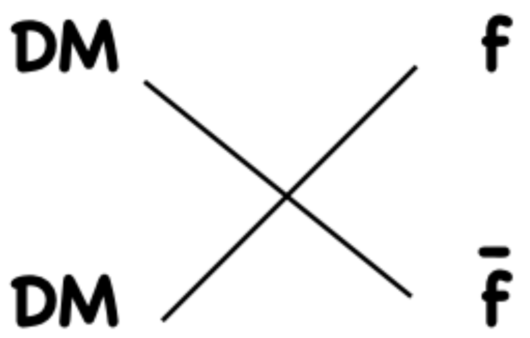



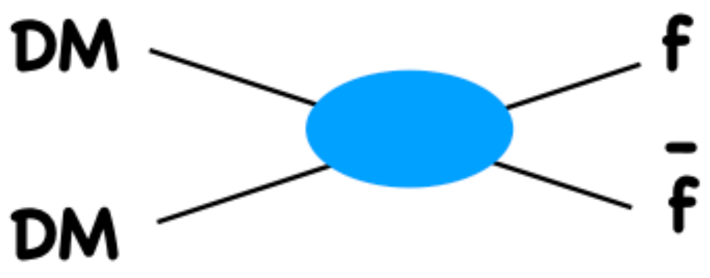

Collision and annihilation




No collision, no annihilation




Asymmetric DM

FIMPs DM

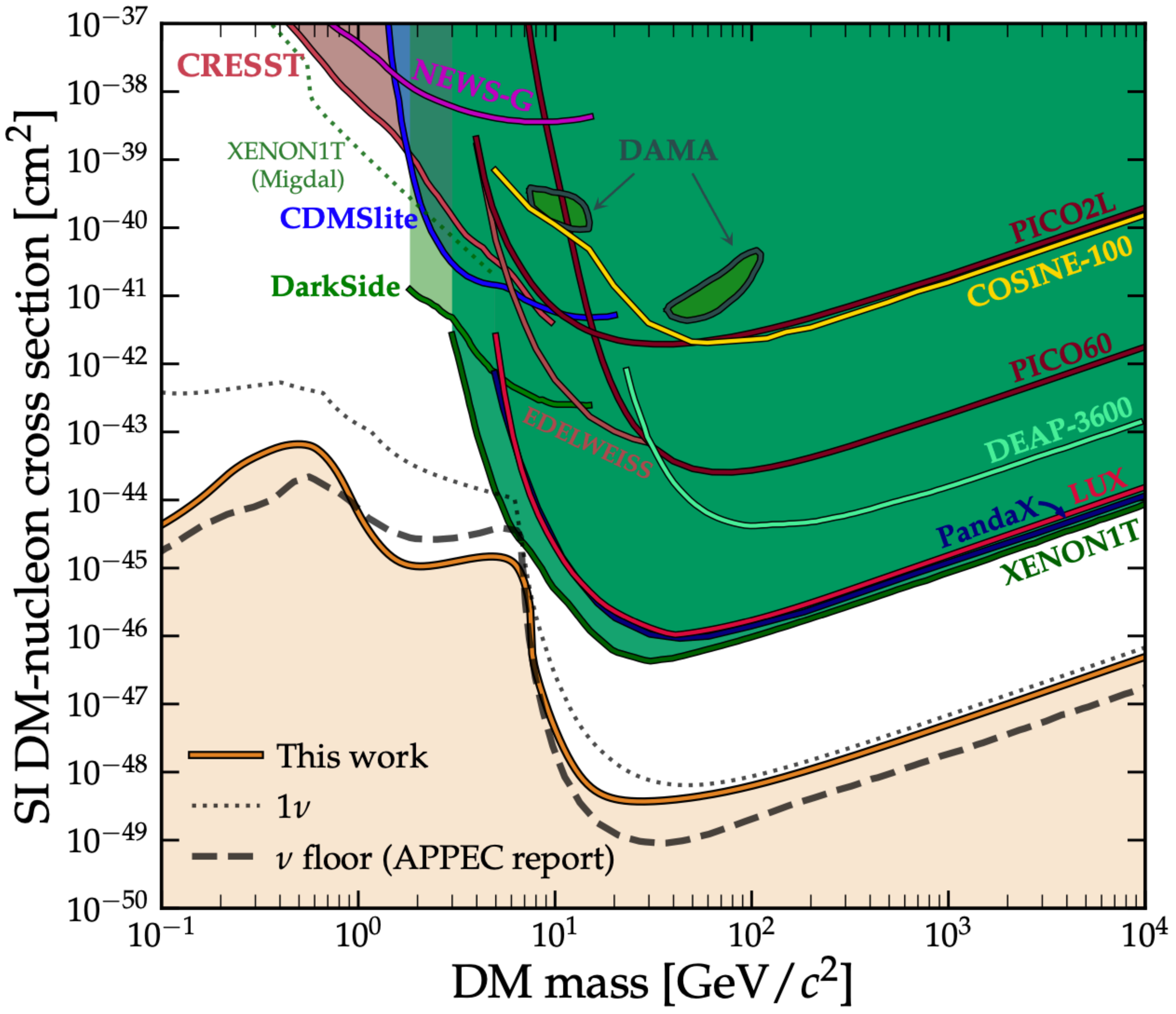
Decay DM

No collision, annihilation into new stuff

DM mass range

# "Dark Matter"

arXiv:2109.03116



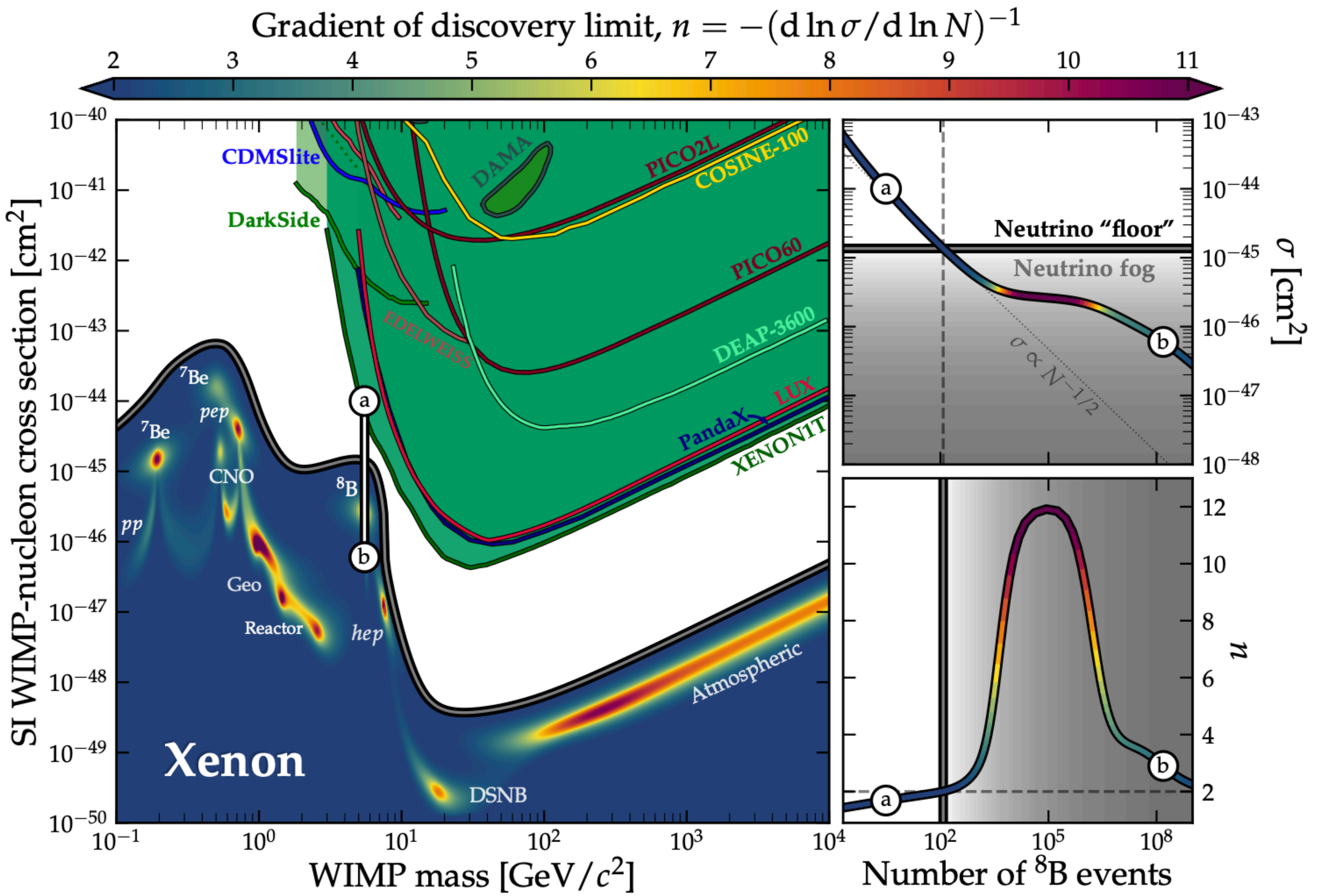
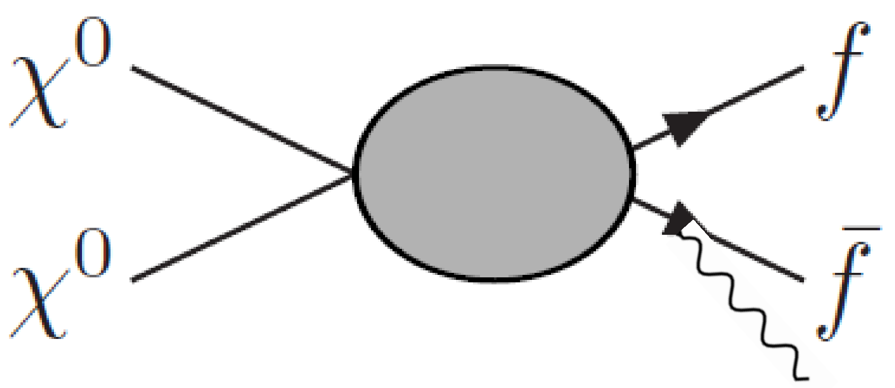




FIG. 2. A graphical description of the technique we adopt to map the neutrino fog and plot its boundary. In the main panel we show the spin-independent DM parameter space, colouring the section below the neutrino floor by the value of $n$, defined as the index with which a discovery limit scales with the number of background events, i.e. $\sigma \propto N^{-1/n}$. The neutrino fog is defined to be the regime for which $n > 2$, with the neutrino floor being the cross section for a given mass where this transition occurs. The top right panel shows the evolution of $\sigma$ with $N$ at $m_\chi = 5.5$ GeV between the two cross sections labelled "a" and "b" on the main panel. The lower right panel shows the value $n$, found from derivative of the curve in the top right panel.

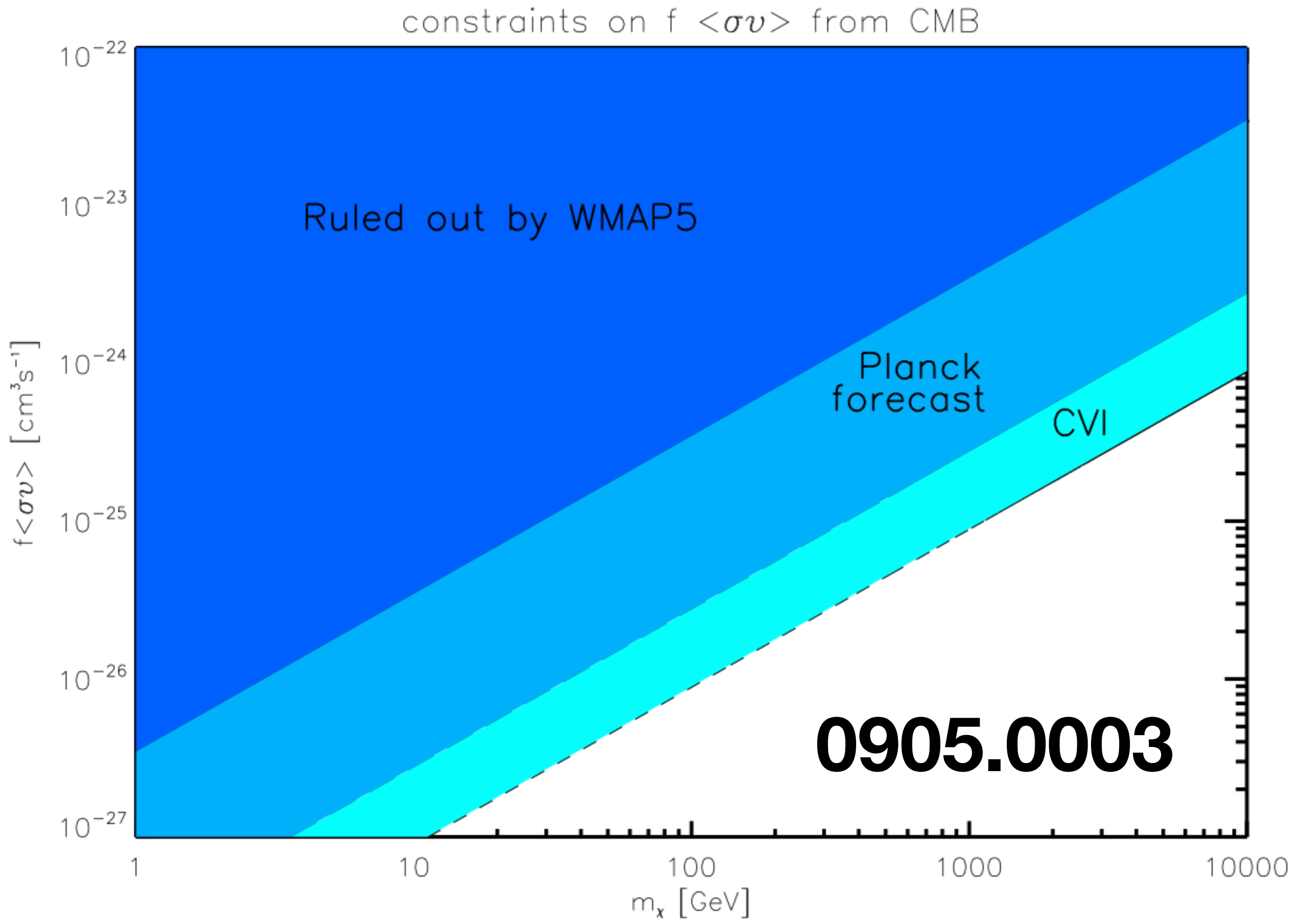
**As weakly interacting as neutrinos, if not even worse?**

# Astrophysical implications of light dark matter




Gamma-ray emission

S-wave must be suppressed
P-wave ok



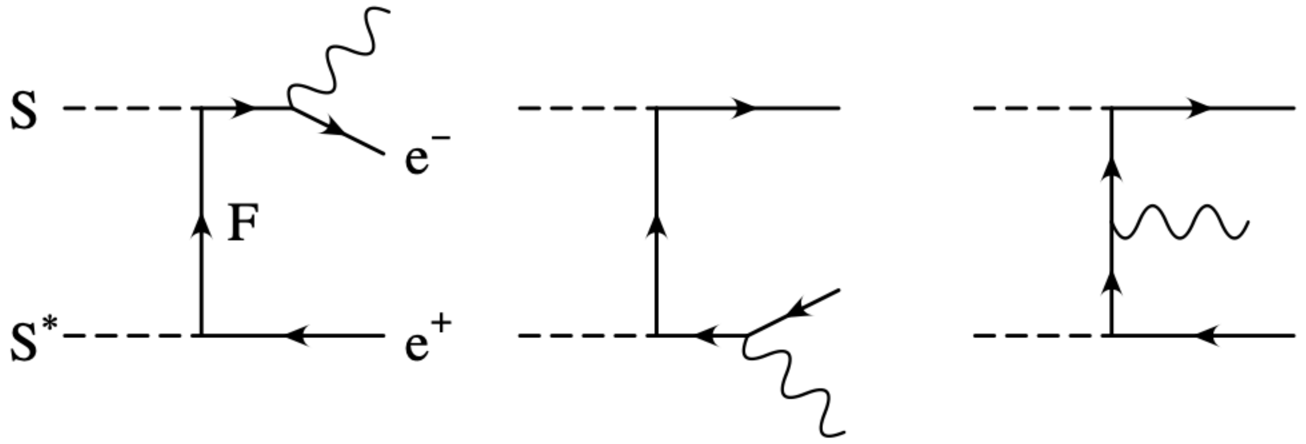

See also by Boudaud et al (1810.01680)
+ X-ray: 2007.11493 (Cirelli et al) — strong constraints m > 20 MeV
+ CMB study in the context of the 511 keV line in 1301.0819

Beacom, Bell & Bertone (0409403)
Using e+e- ann into muons

$$\frac{d\sigma_{\rm Br}}{dE} = \sigma_{\rm tot} \times \frac{\alpha}{\pi}\frac{1}{E}\left[\ln\left(\frac{s'}{m_e^2}\right) - 1\right]\left[1 + \left(\frac{s'}{s}\right)^2\right],$$

mdm < 20 MeV

Boehm&Uwer (0606058)




$$\frac{d\sigma_\gamma}{dx_\gamma} \approx \sigma_0 \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left\{\left(1+\frac{s'^2}{s^2}\right)\ln\left(\frac{s'}{m_e{}^2}\right) - 2\frac{s'}{s}\right\},$$

mdm < 30 MeV

# Constraints on vector-like fermions

arXiv:2010.02954

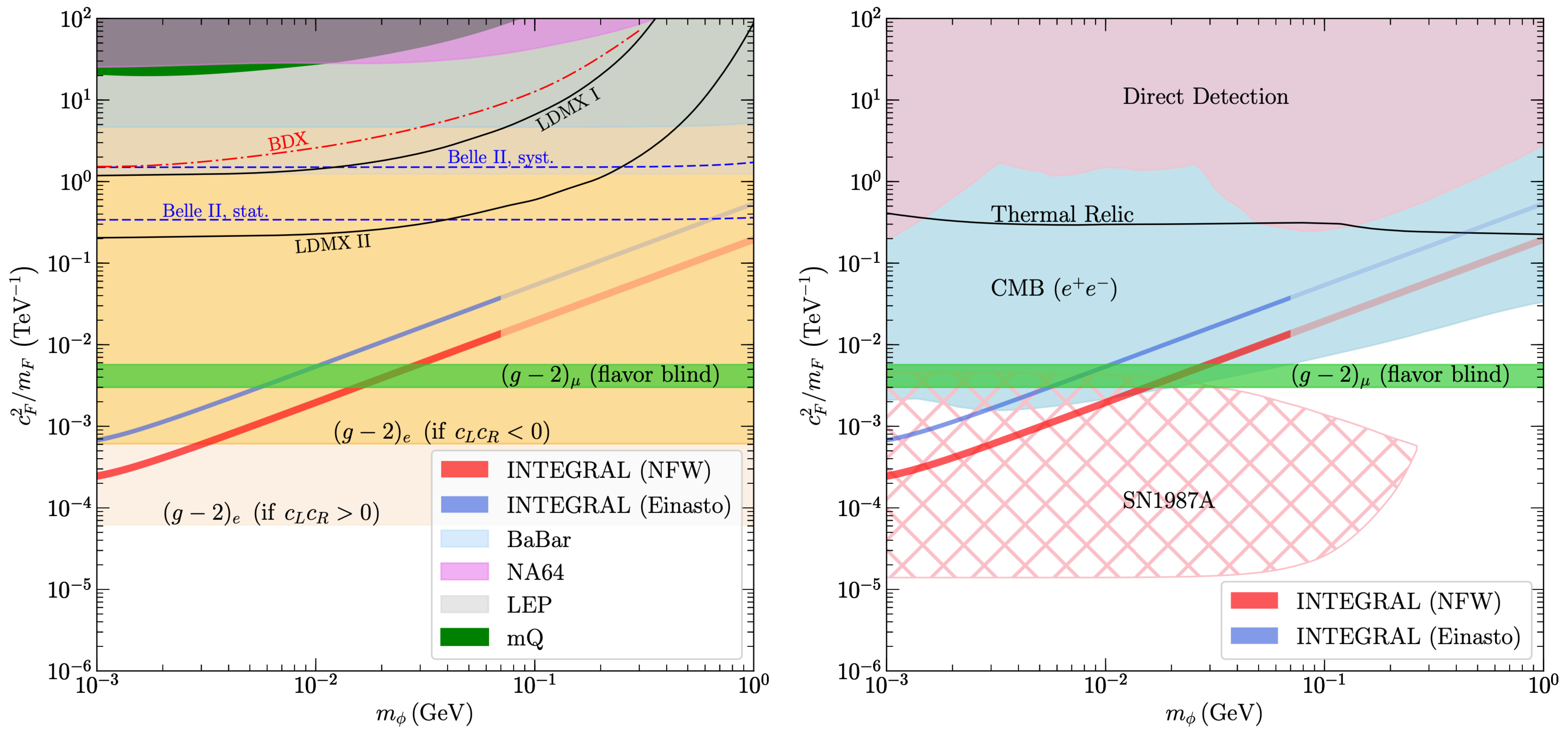



FIG. 6. Bounds on the inverse of effective UV-scale $\Lambda_F^{-1} = c_F^2/m_F$ in the $F$-mediated model from laboratory experiments (left panel) and from astrophysical observations including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are shown as thin blue and red bands; for $m_\phi \geq 70\,\text{MeV}$ the DM interpretation is disfavored as indicated by a lighter shading. The green horizontal band where $(g-2)_\mu$ is explained carries the assumption $c_F^\mu = c_F^e$.

# Constraints on dark gauge bosons

arXiv:2010.02954

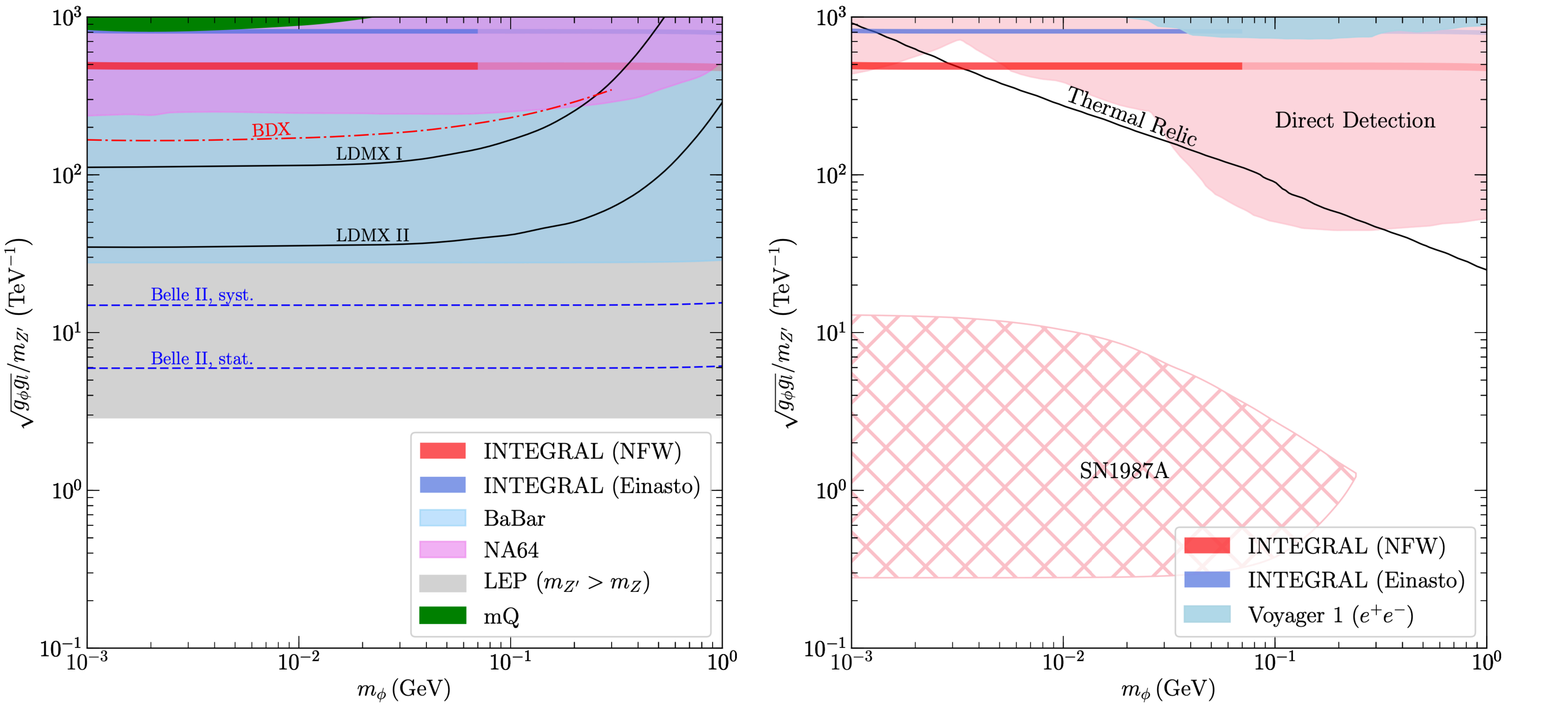
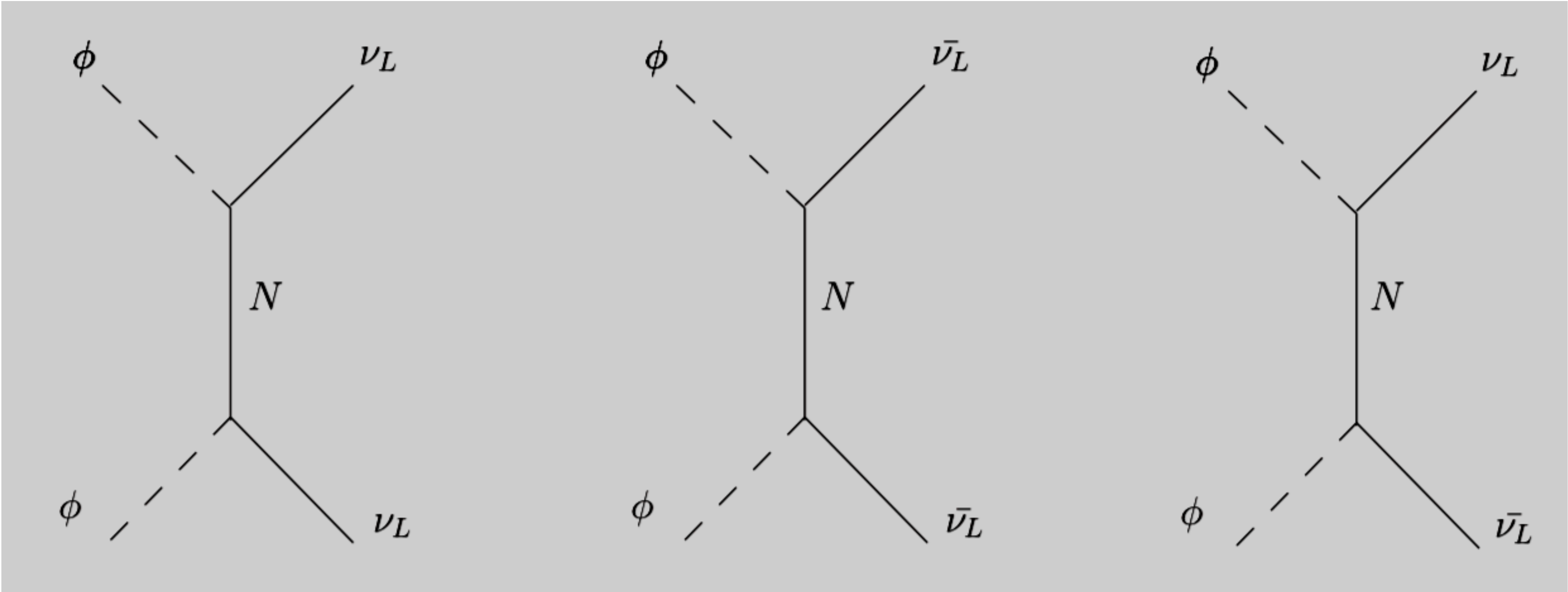


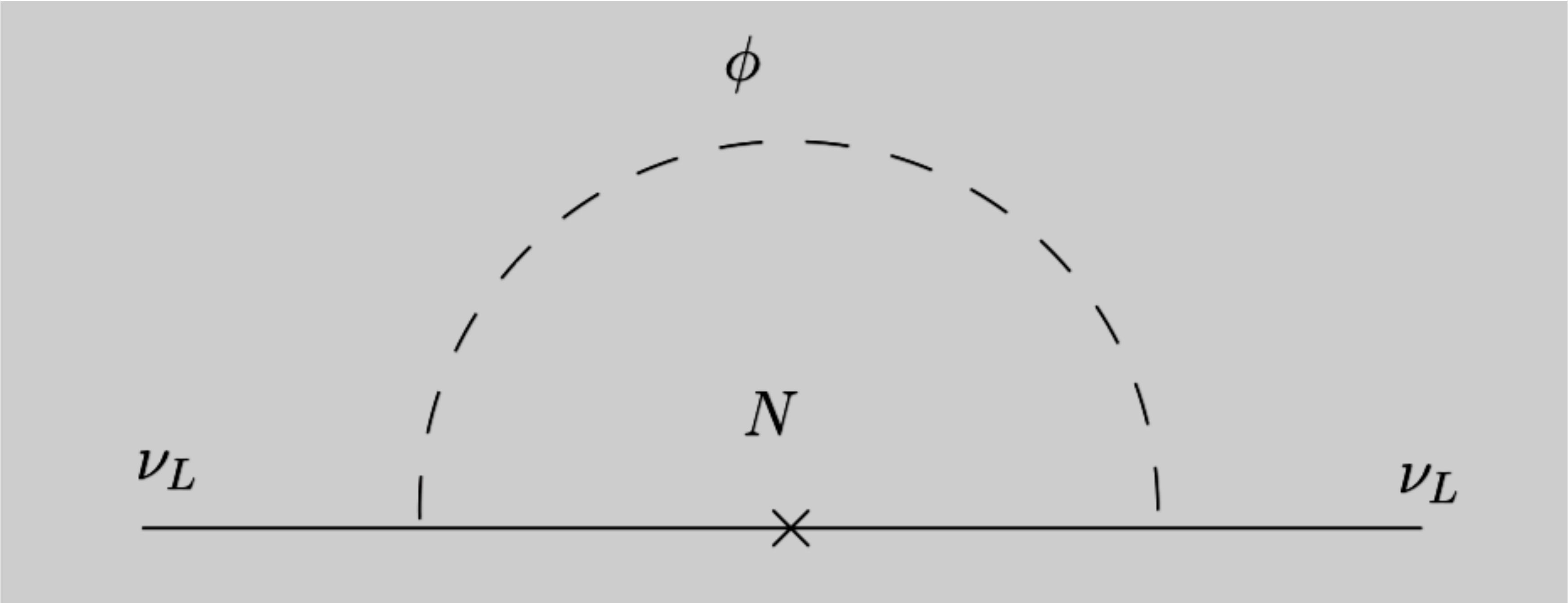

FIG. 7. Bounds on the inverse of effective UV scale $\Lambda_{Z'}^{-1} = \sqrt{g_\phi g_l}/m_{Z'}$ for the $Z'$ model from laboratory tests (left panel) and from cosmological and astrophysical probes including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are shown as thin blue and red bands; for $m_\phi \geq 70\,\text{MeV}$ the DM interpretation is disfavored as indicated by a lighter shading. LEP bound only applies for $m_{Z'}$ above the EW scale, below which (18) applies instead. We do not show a band for $(g-2)_\mu$, which would need an assumption on $g_\phi/g_l$, since it is already excluded elsewhere (see main text and Fig. 2).

# Astrophysical implications of light dark matter

hep-ph/0612228

Annihilations into neutrinos




$$m_{\nu_L} \simeq \sqrt{\frac{\langle \sigma v_r \rangle}{128\,\pi^3}}\, m_N^2 (1 + m_\phi^2/m_N^2)\, \ln\left(\frac{\Lambda^2}{m_N^2}\right).$$

**Basic model can give rise to neutrino masses in the eV range but UV completion is hard!**

See e.g. work by Yasaman Farzan (e.g. 1009.0829 and 1208.2732) + Arhrib et al (1512.08796)

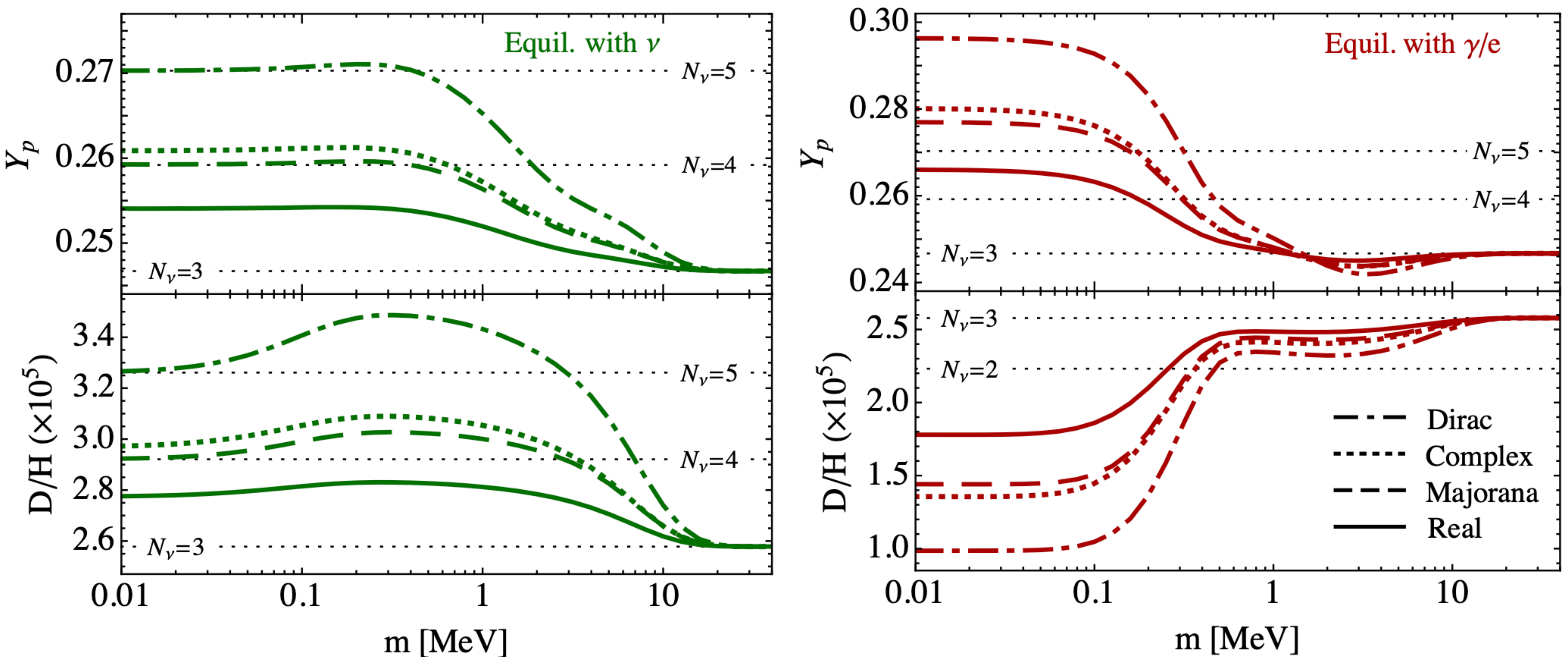
# Cosmological implications of light dark matter

1207.0497 1303.6270

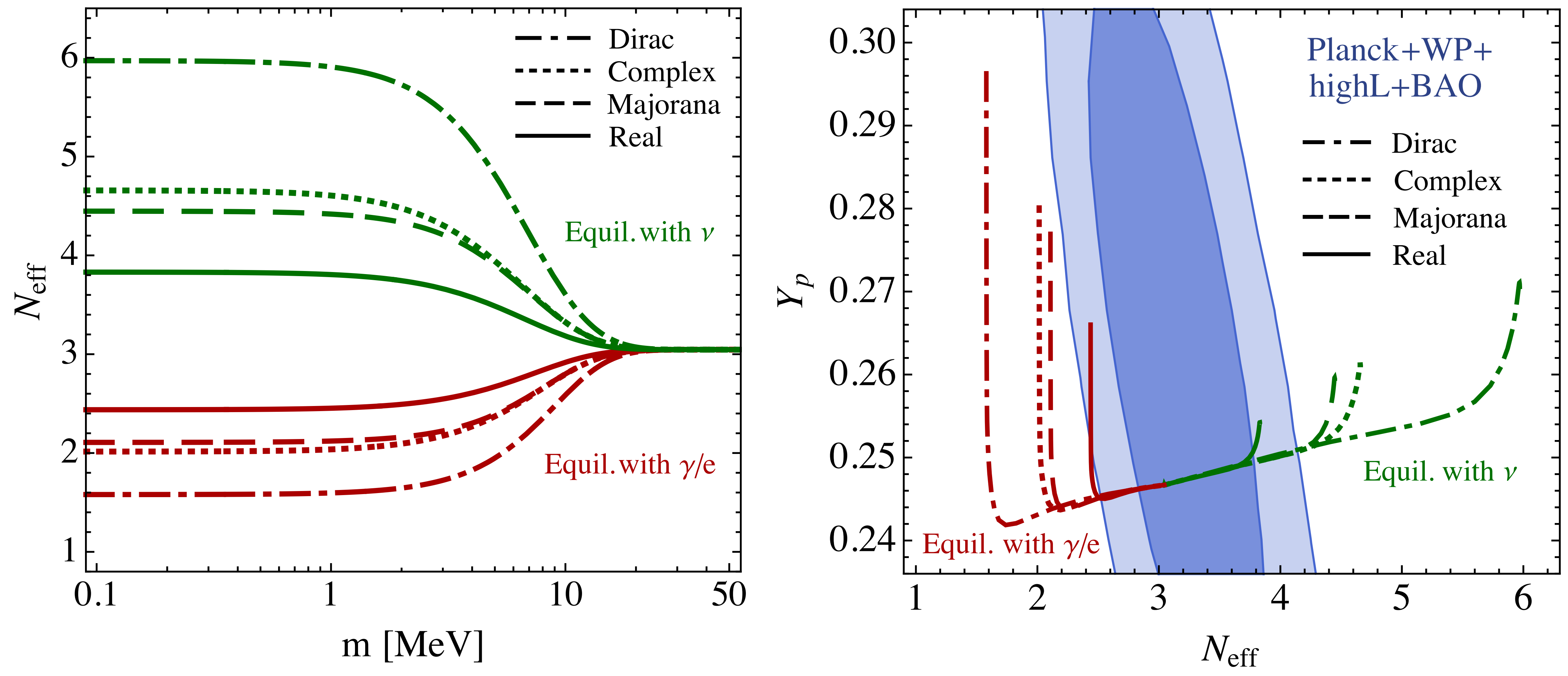
Raffelt & Serpico astro-ph/0403417

M < 10 MeV but [4,10] MeV exciting for 511 keV

## Helium/D abundance



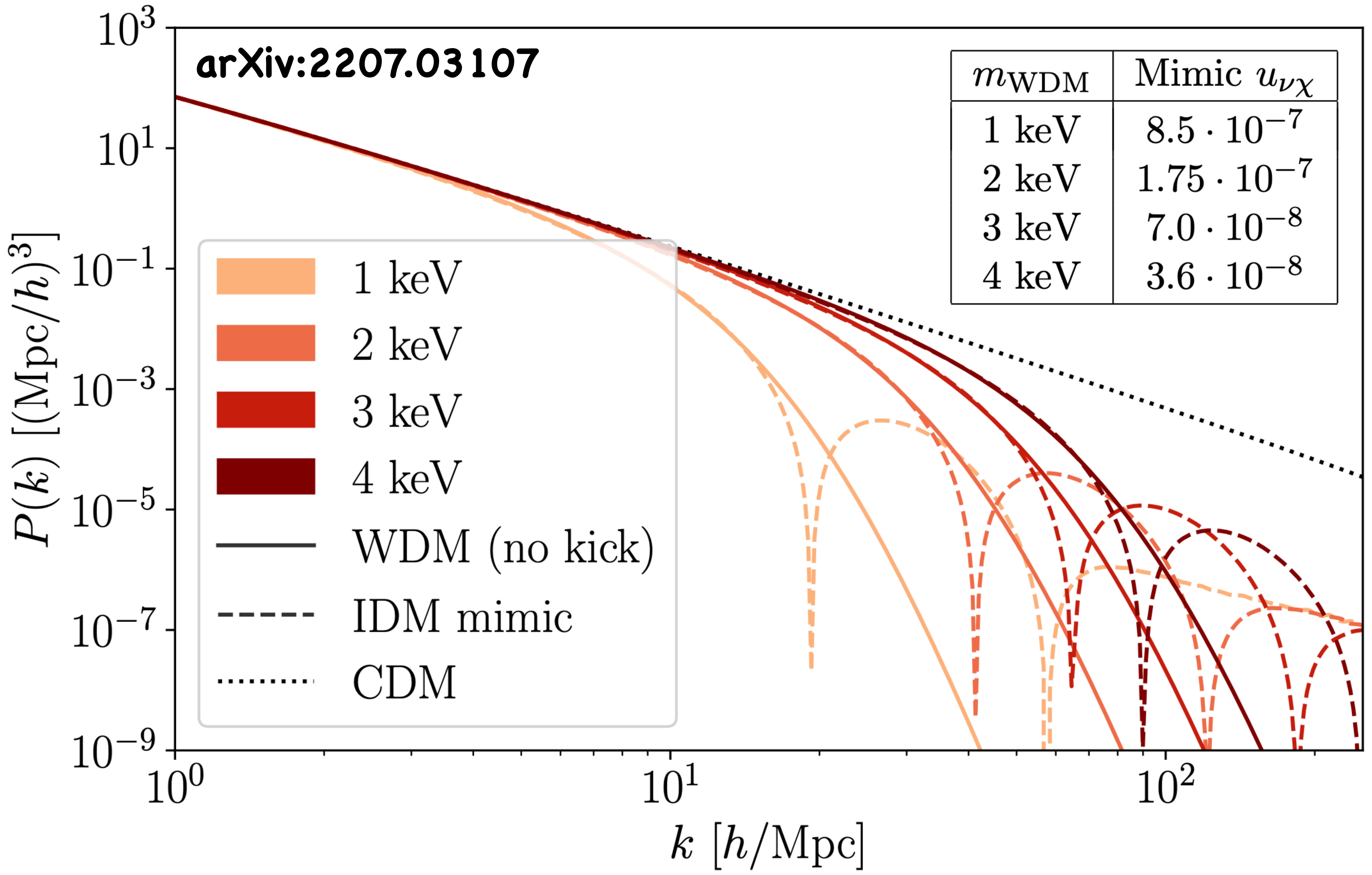

## Neff

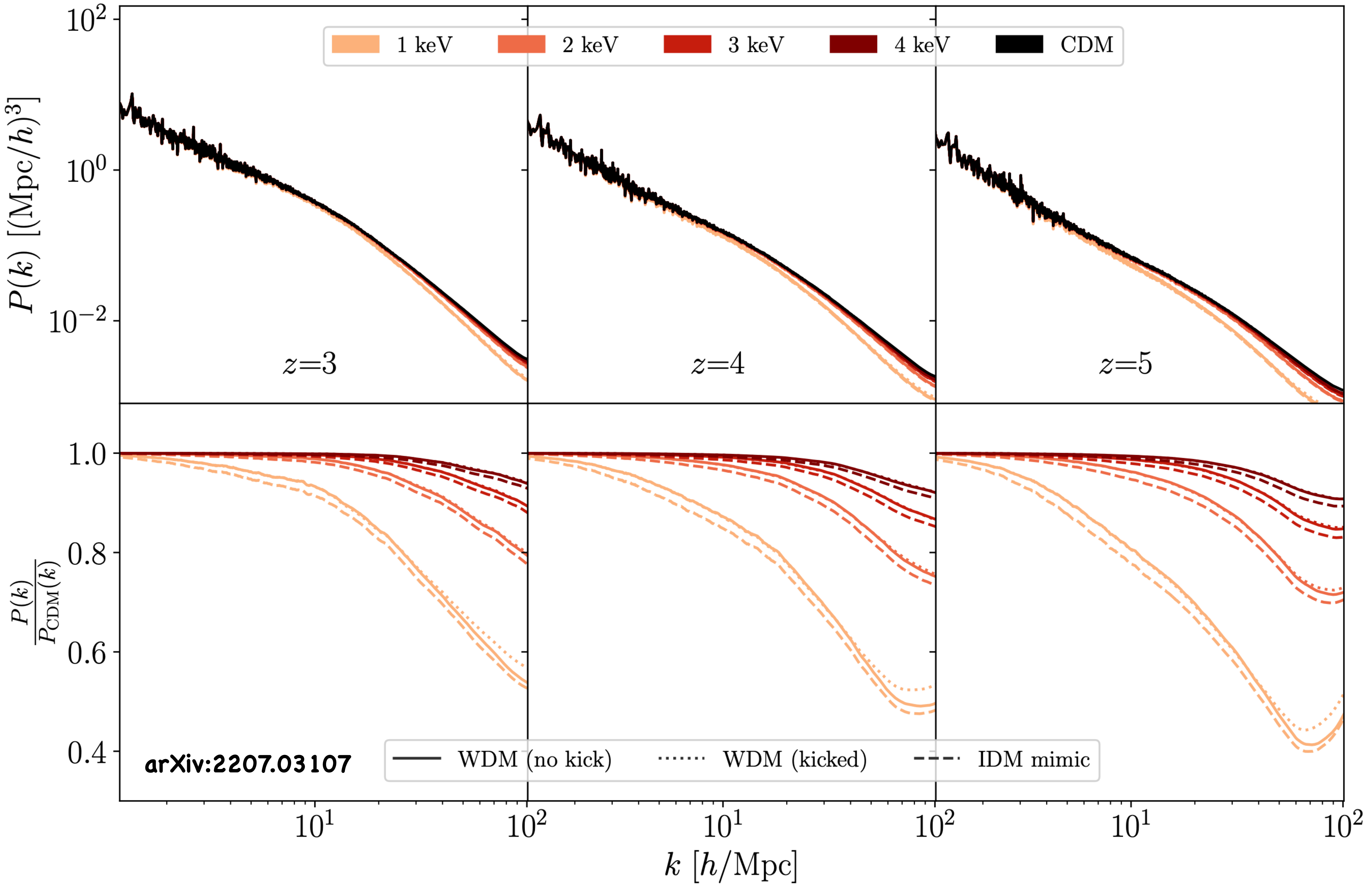



M < 10-20 MeV

# How to probe Dark Matter interactions?

**arXiv:2207.03107 in agreement with astro-ph/0309652**



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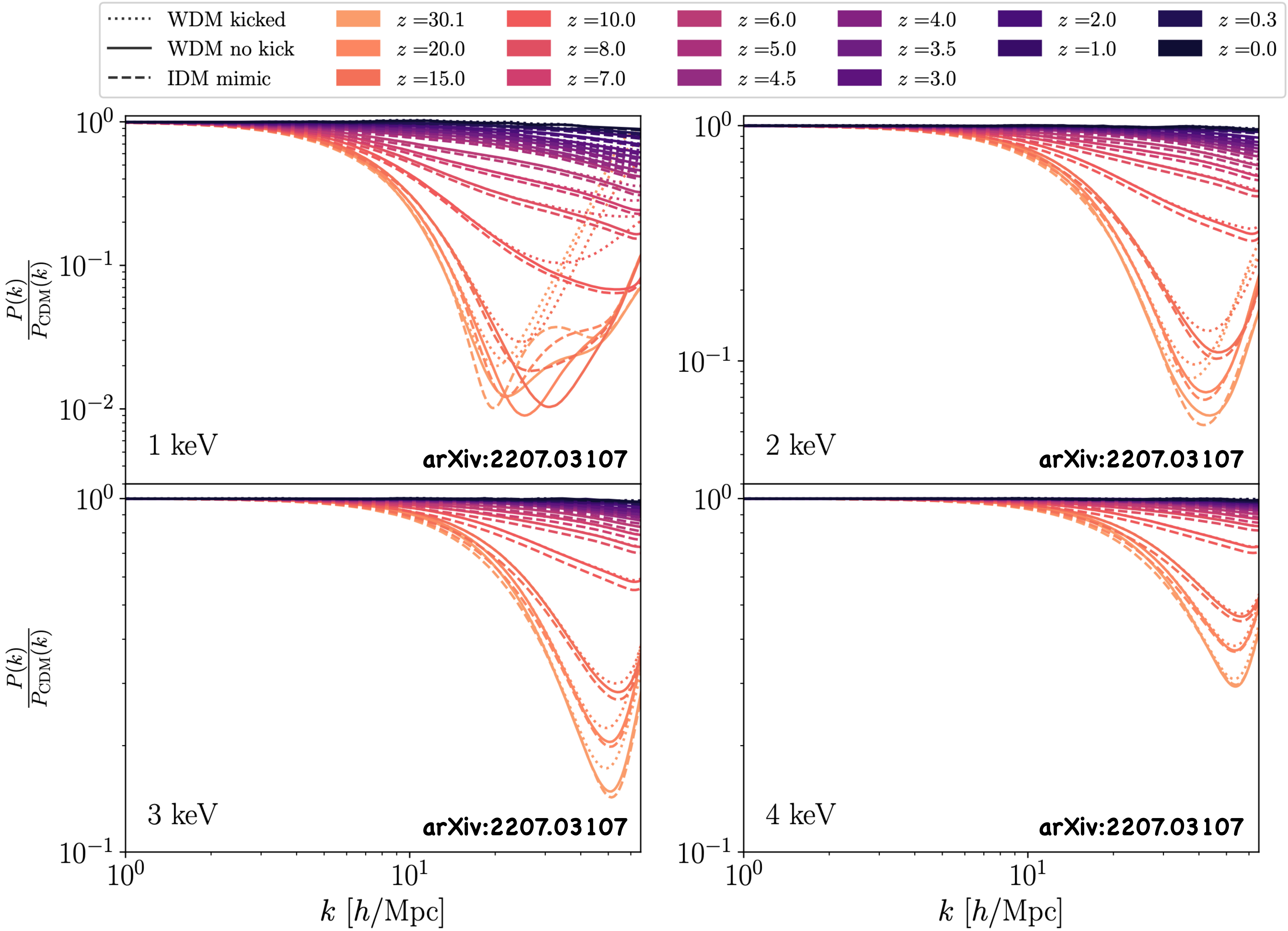

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Markus R. Mosbech,[1,*] Alexander C. Jenkins,[2,†] Sownak Bose,[3,‡]
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[2] *Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom*
[3] *Institute for Computational Cosmology, Department of Physics,*
*Durham University, Durham DH1 3LE, United Kingdom*
[4] *Theoretical Particle Physics and Cosmology Group, Physics Department,*
*King's College London, University of London, Strand, London WC2R 2LS, United Kingdom*
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(Dated: 3 August 2022)

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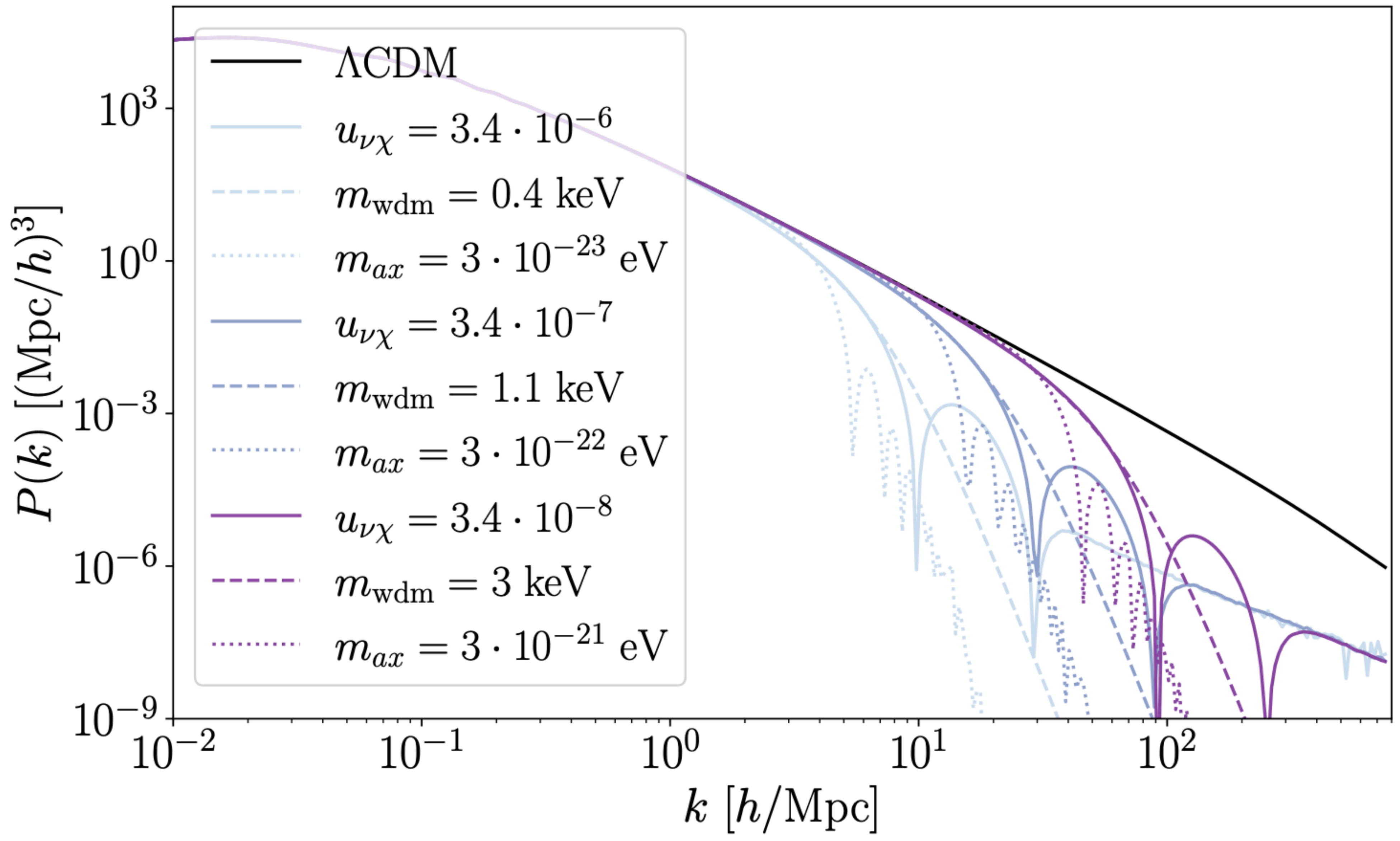
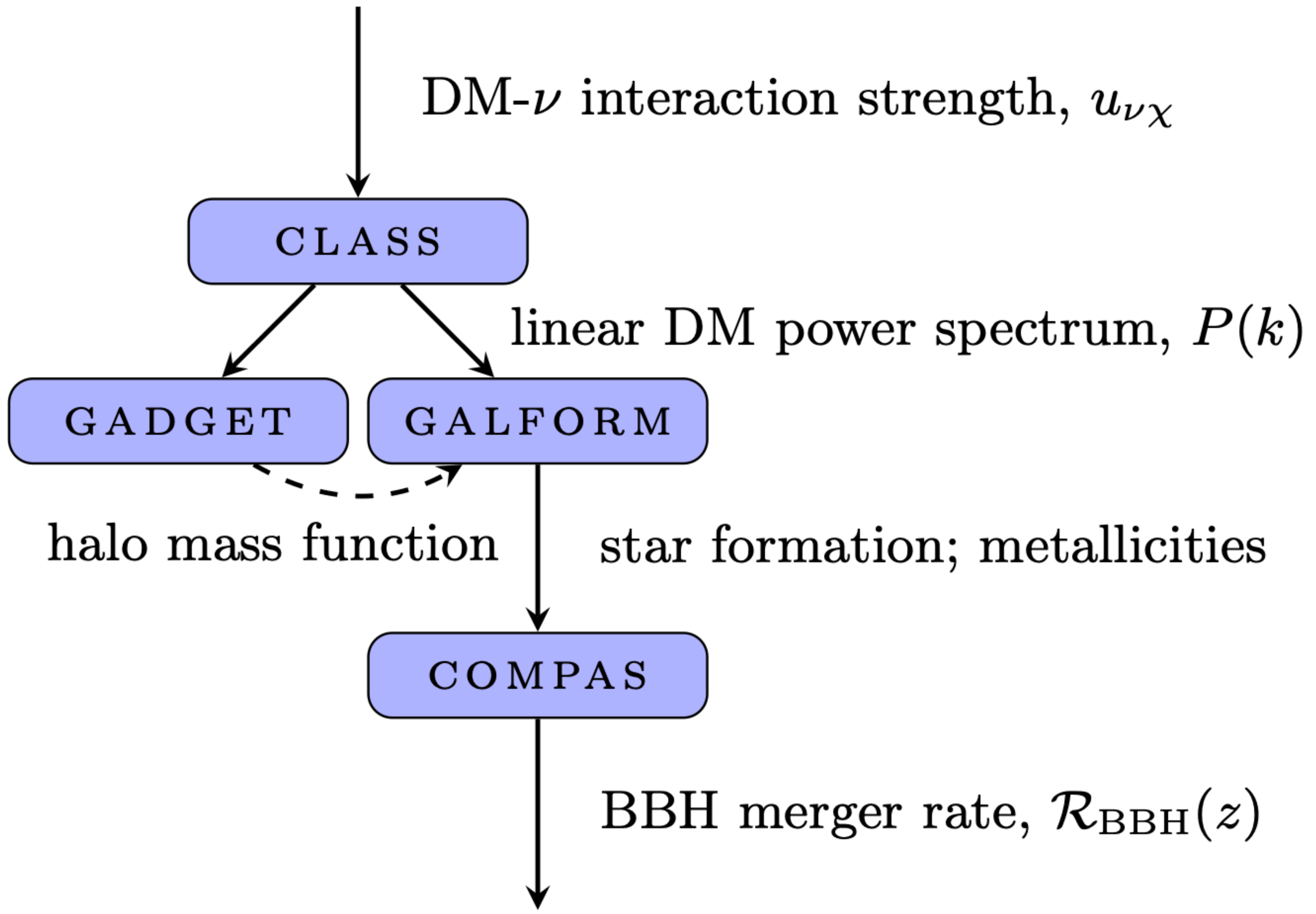
arXiv:2207.14126

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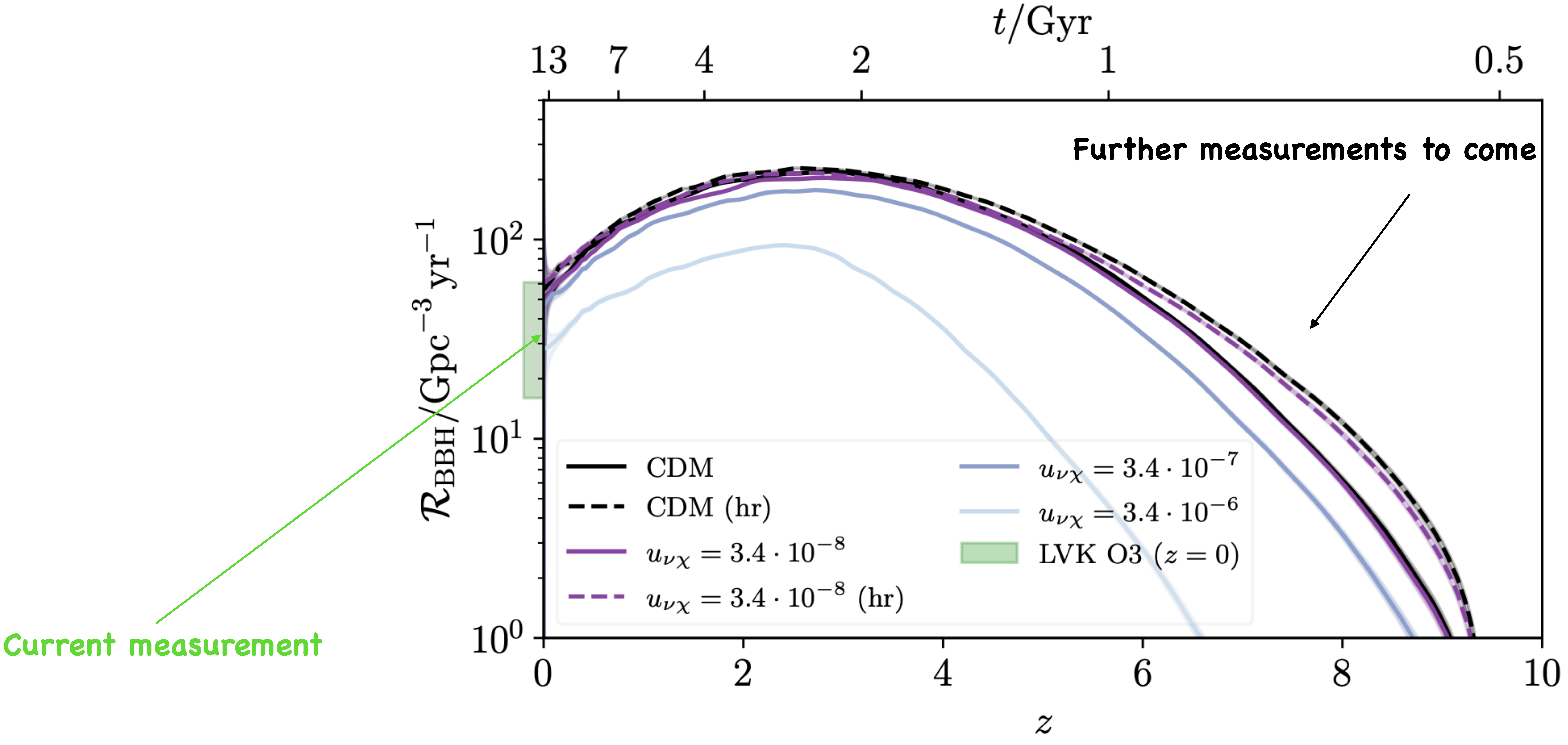
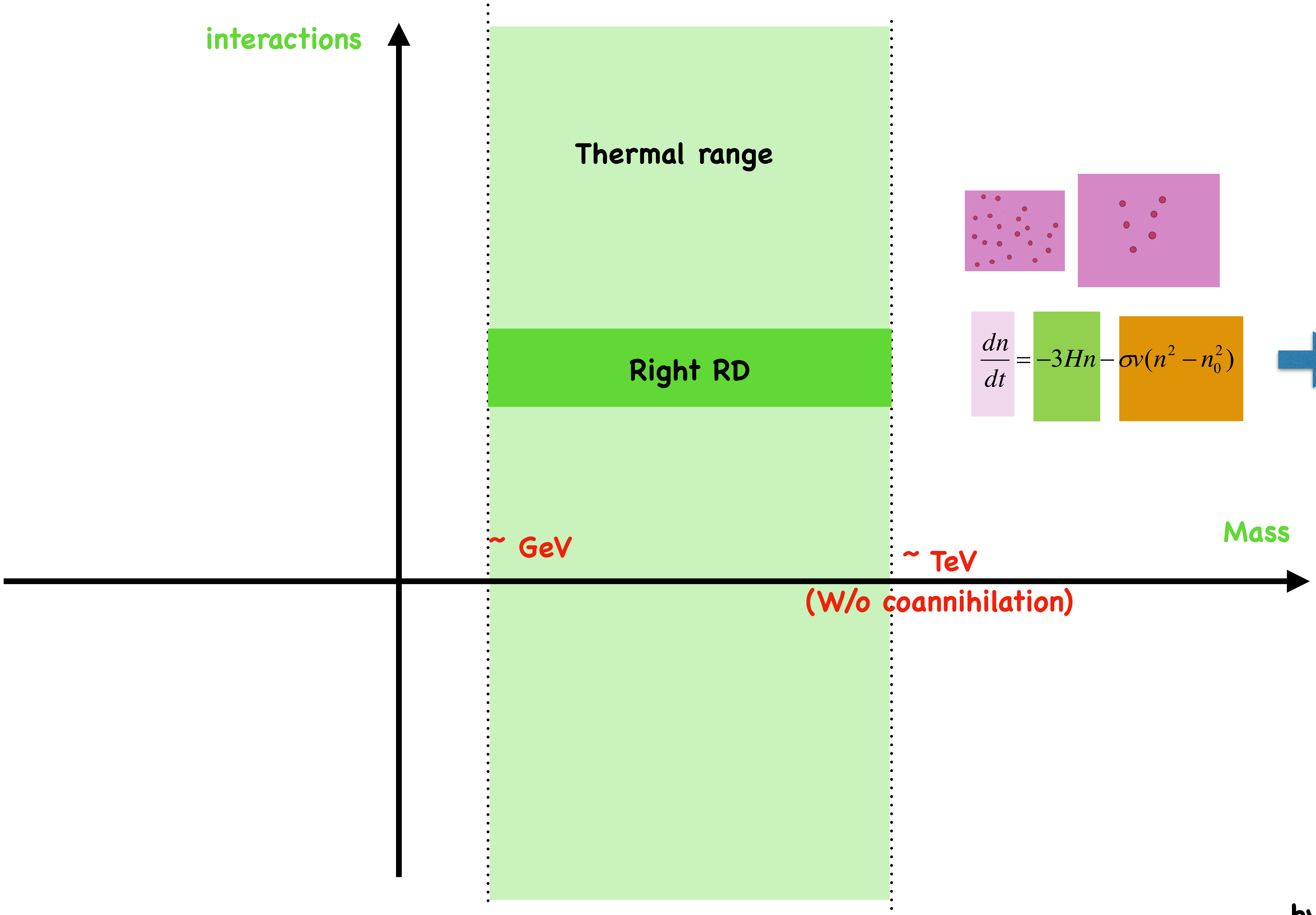



LCDM almost excluded (!!!) so next measurements will be critical!

# Thermal massive weakly interacting particles




$$\frac{dn}{dt} = -3Hn - \sigma v (n^2 - n_0^2)$$

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

| Parameter | Plik best fit |
|---|---|
| $\Omega_b h^2$ | 0.022383 |
| $\Omega_c h^2$ | 0.12011 |
| $100\theta_{MC}$ | 1.040909 |
| $\tau$ | 0.0543 |
| $\ln(10^{10} A_s)$ | 3.0448 |
| $n_s$ | 0.96605 |
| $\Omega_m h^2$ | 0.14314 |
| $H_0$ [ km s$^{-1}$Mpc$^{-1}$] | 67.32 |
| $\Omega_m$ | 0.3158 |
| Age [Gyr] | 13.7971 |
| $\sigma_8$ | 0.8120 |
| $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ | 0.8331 |
| $z_{re}$ | 7.68 |
| $100\theta_*$ | 1.041085 |
| $r_{drag}$ [Mpc] | 147.049 |

$$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

Range of interactions is given by experimental value & error bars

# Predicting fluctuations

**without DM interactions**

$$\dot{\theta}_b = k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma)$$

$$\dot{\theta}_\gamma = k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_b)\ ,$$

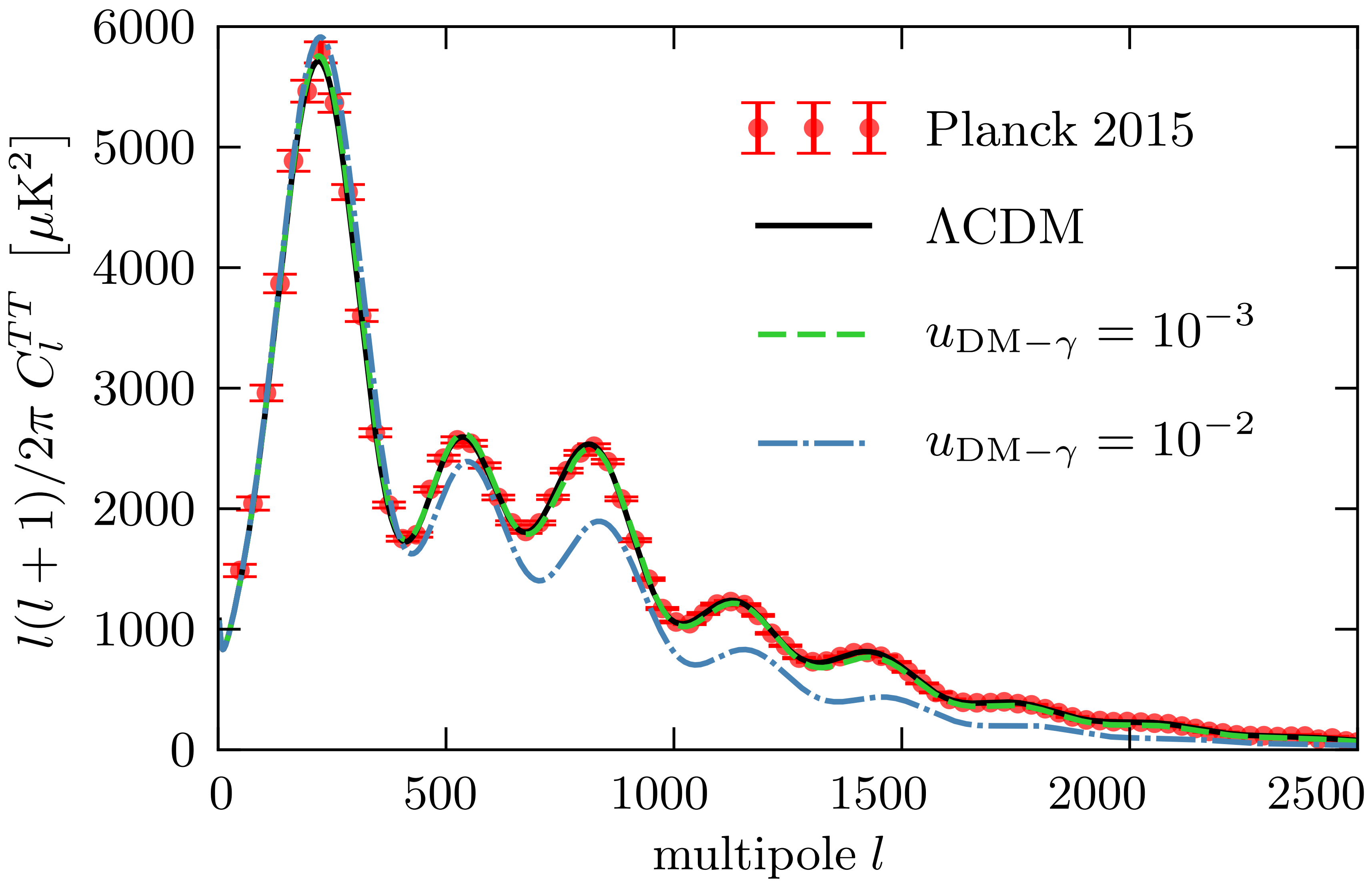
$$\dot{\theta}_{DM} = k^2\psi - \mathcal{H}\theta_{DM}\ ,$$

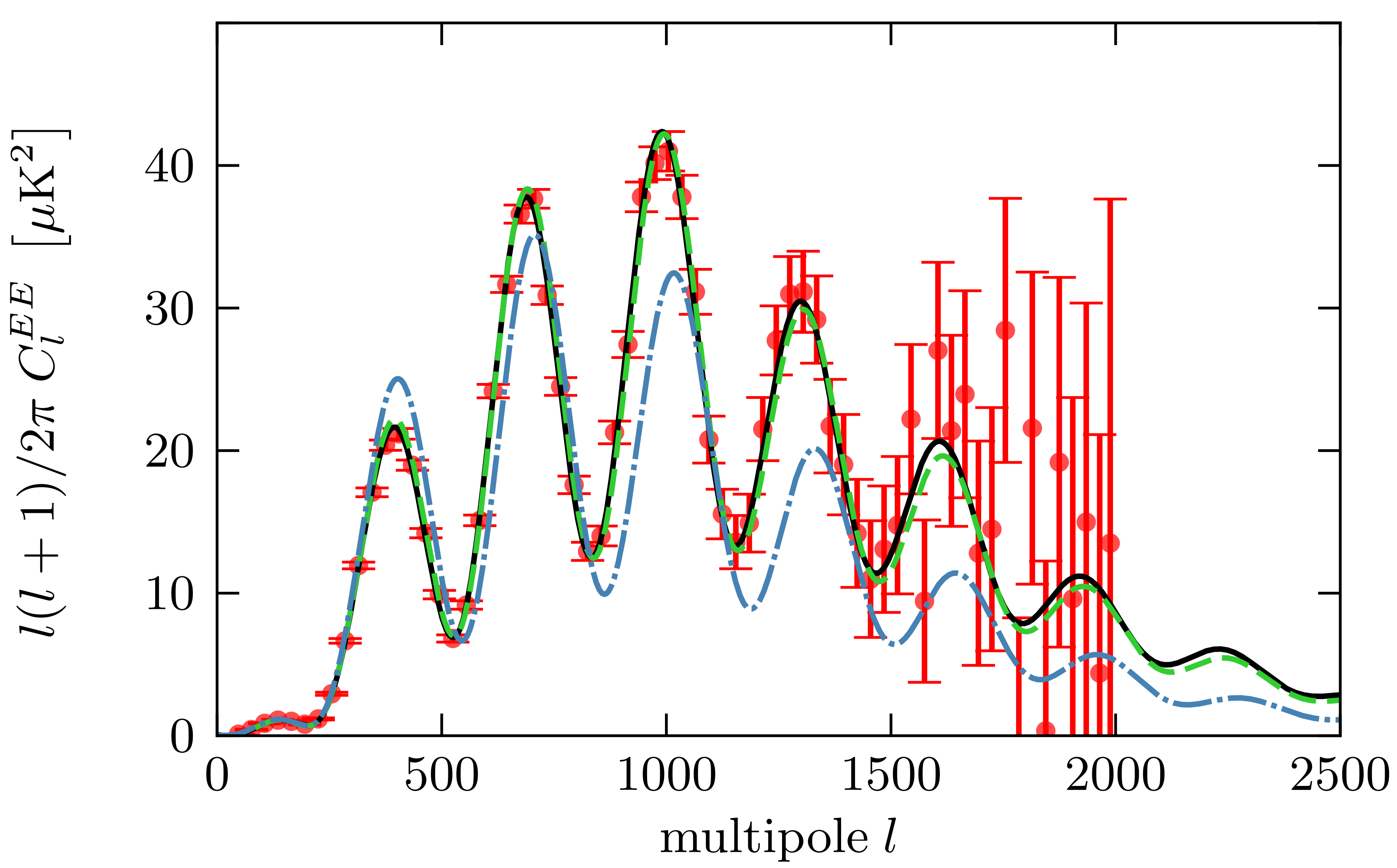
**with DM interactions**

$$\dot{\theta}_b = k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma)$$

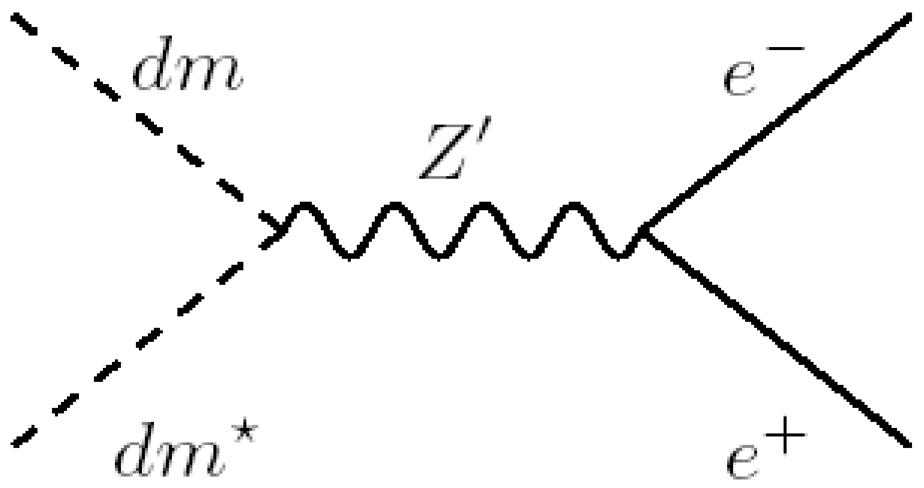
$$\dot{\theta}_\gamma = k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_b) - \dot{\mu}(\theta_\gamma - \theta_{DM})\ ,$$

$$\dot{\theta}_{DM} = k^2\psi - \mathcal{H}\theta_{DM} - S^{-1}\dot{\mu}(\theta_{DM} - \theta_\gamma)\ .$$



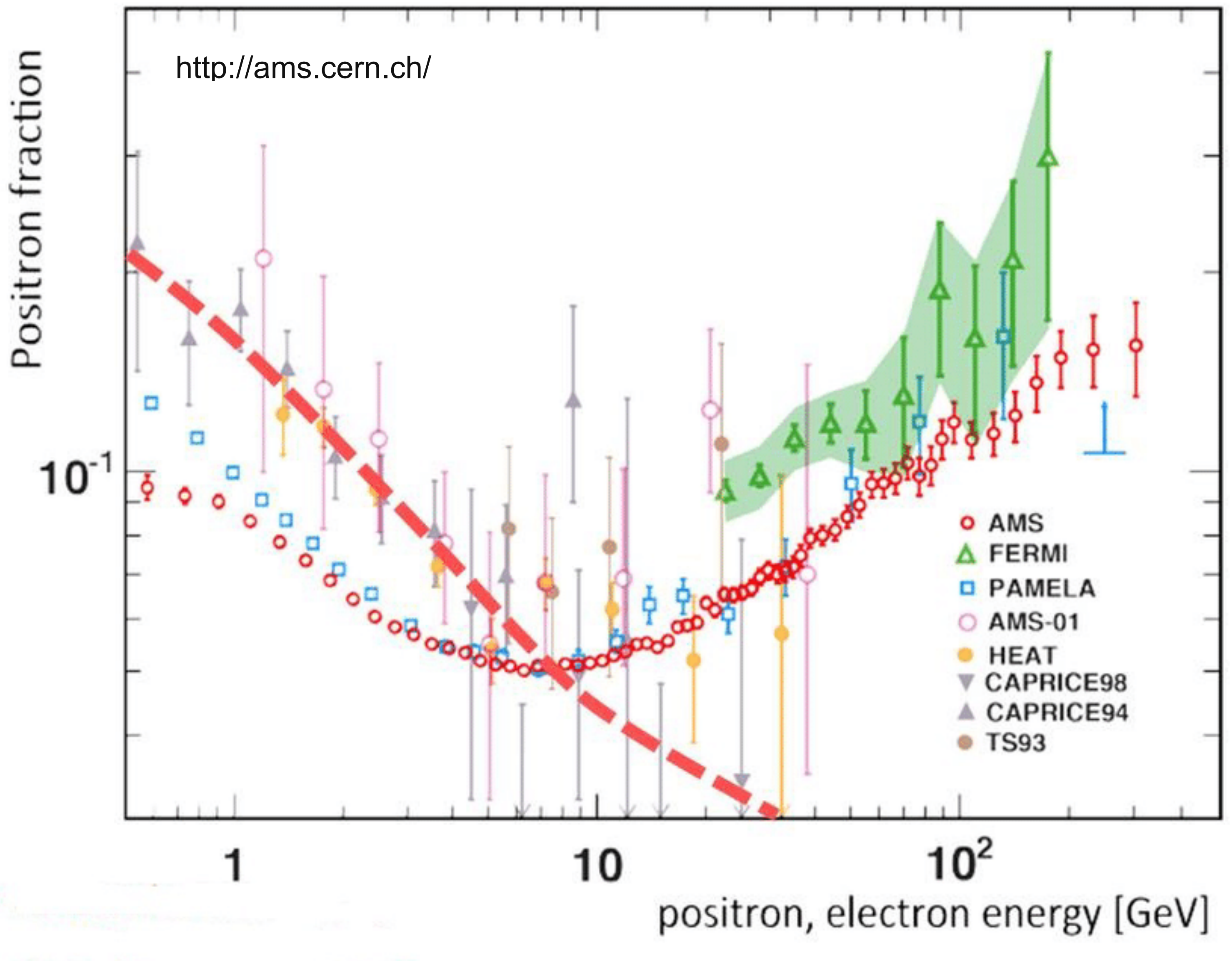



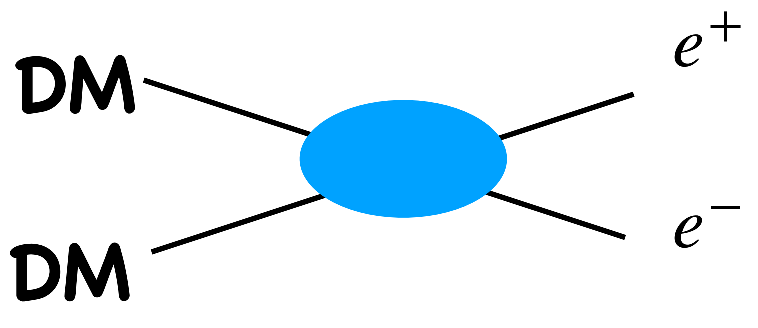
# Light Dark Matter & Light mediators



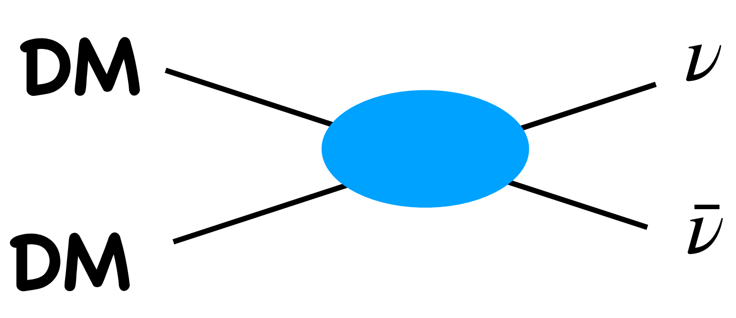

$$\sigma v \propto v^2 \, \frac{m_{\rm DM}^2}{m_{Z'}^4} \, g_{\rm DM}^2 \, g_e^2$$

DM can be light if the mediator is light

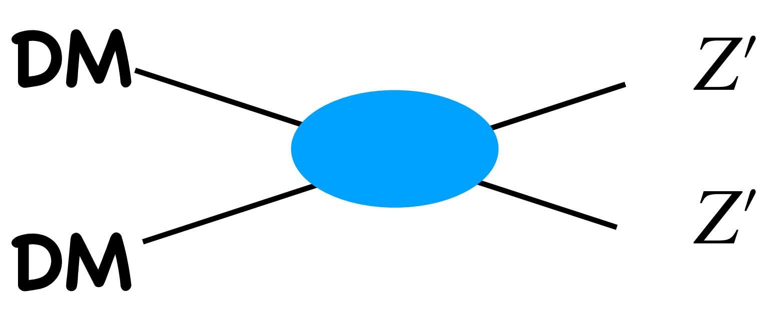



MeV




Sub eV?



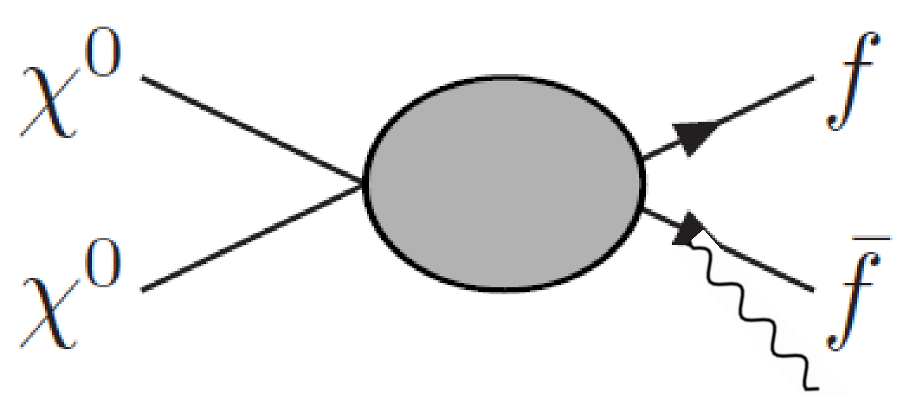

?

Should there be annihilations at all?

Asymmetric DM, Freeze-in, non thermal DM

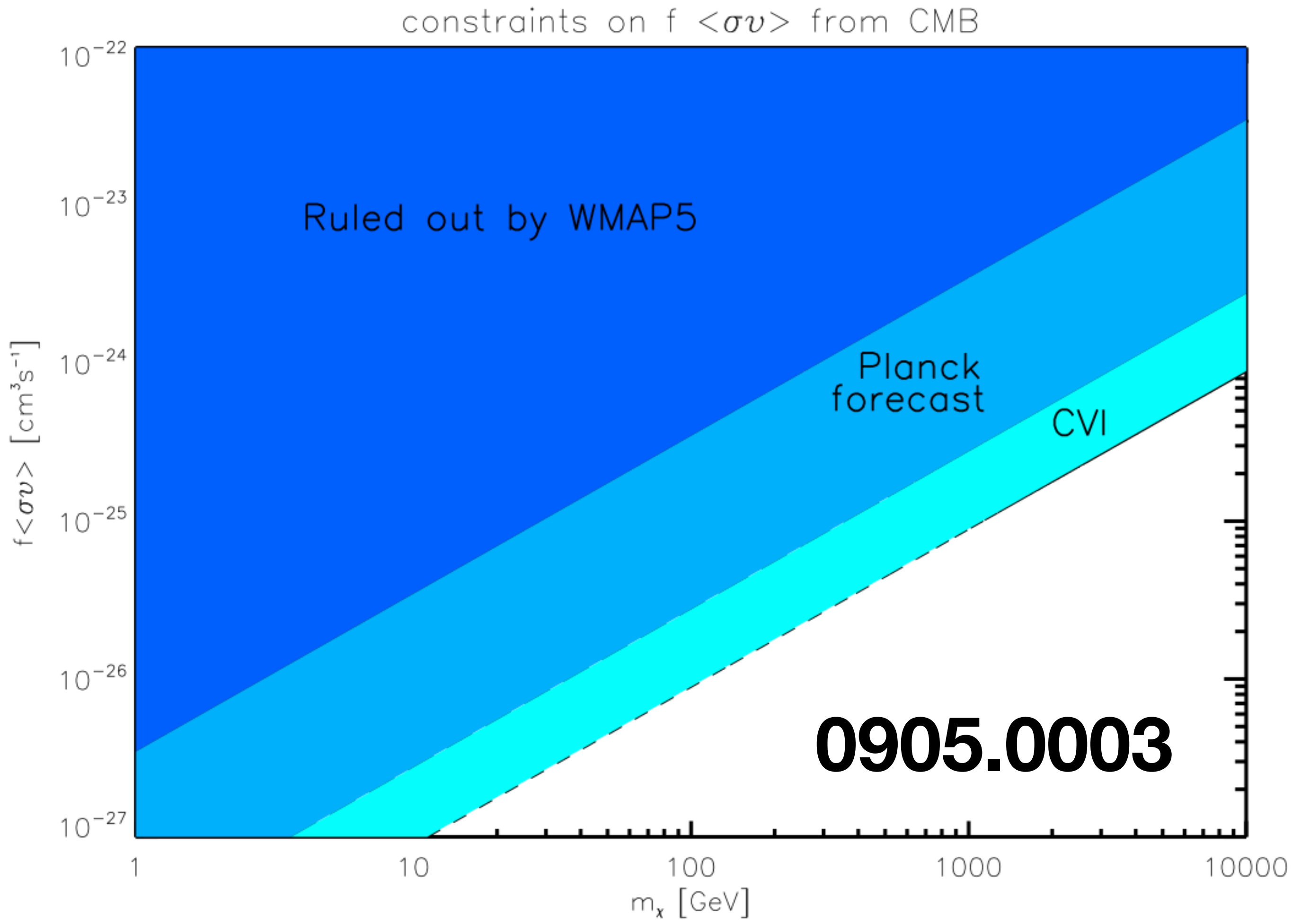
https://arxiv.org/pdf/0911.1120.pdf

# Astrophysical implications of light dark matter




Gamma-ray emission

S-wave must be suppressed
P-wave ok



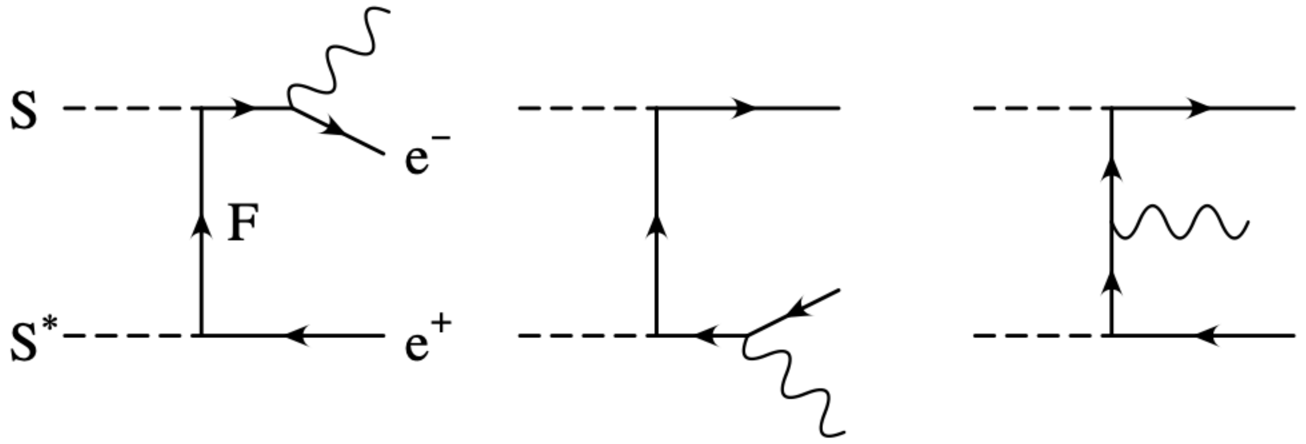

See also by Boudaud et al (1810.01680)
+ X-ray: 2007.11493 (Cirelli et al) — strong constraints m > 20 MeV
+ CMB study in the context of the 511 keV line in 1301.0819

Beacom, Bell & Bertone (0409403)
Using e+e- ann into muons

$$\frac{d\sigma_{\rm Br}}{dE} = \sigma_{\rm tot} \times \frac{\alpha}{\pi}\frac{1}{E}\left[\ln\left(\frac{s'}{m_e^2}\right) - 1\right]\left[1 + \left(\frac{s'}{s}\right)^2\right],$$

mdm < 20 MeV

Boehm&Uwer (0606058)




$$\frac{d\sigma_\gamma}{dx_\gamma} \approx \sigma_0 \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left\{\left(1+\frac{s'^2}{s^2}\right)\ln\left(\frac{s'}{m_e{}^2}\right) - 2\frac{s'}{s}\right\},$$

mdm < 30 MeV