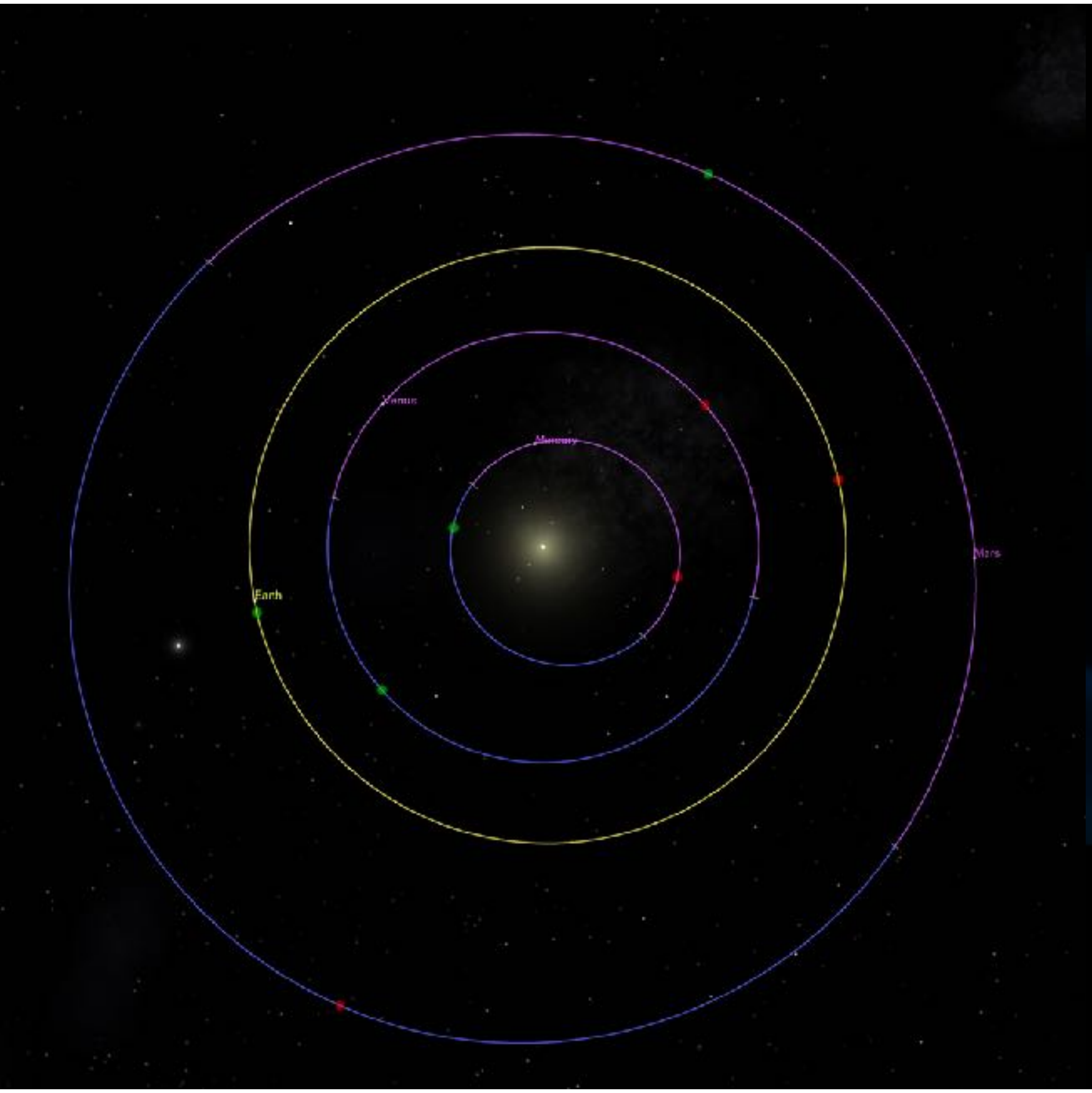
Light dark matter
Implications for structure formation

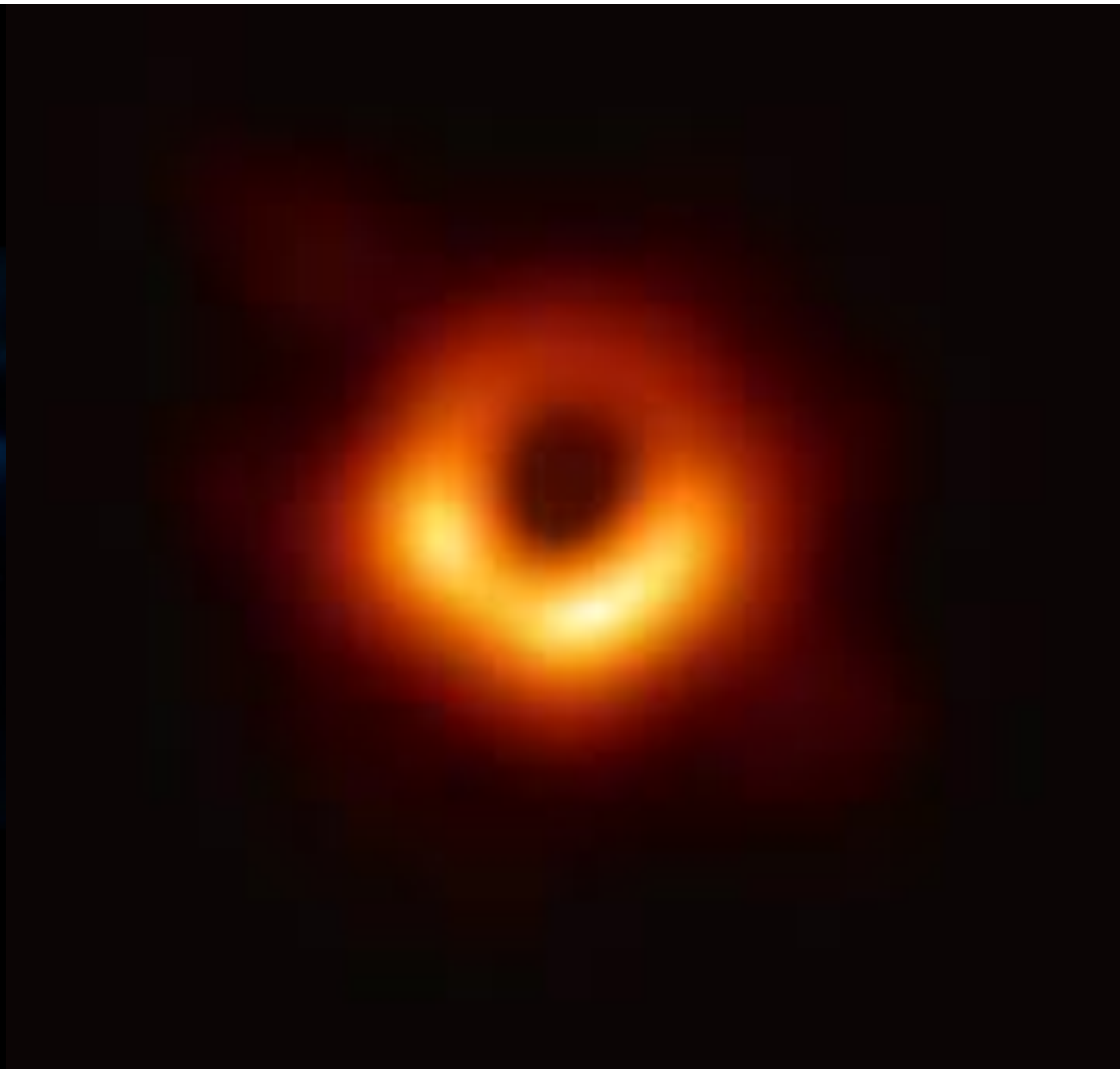
Celine Boehm

Nanjing, December 2022

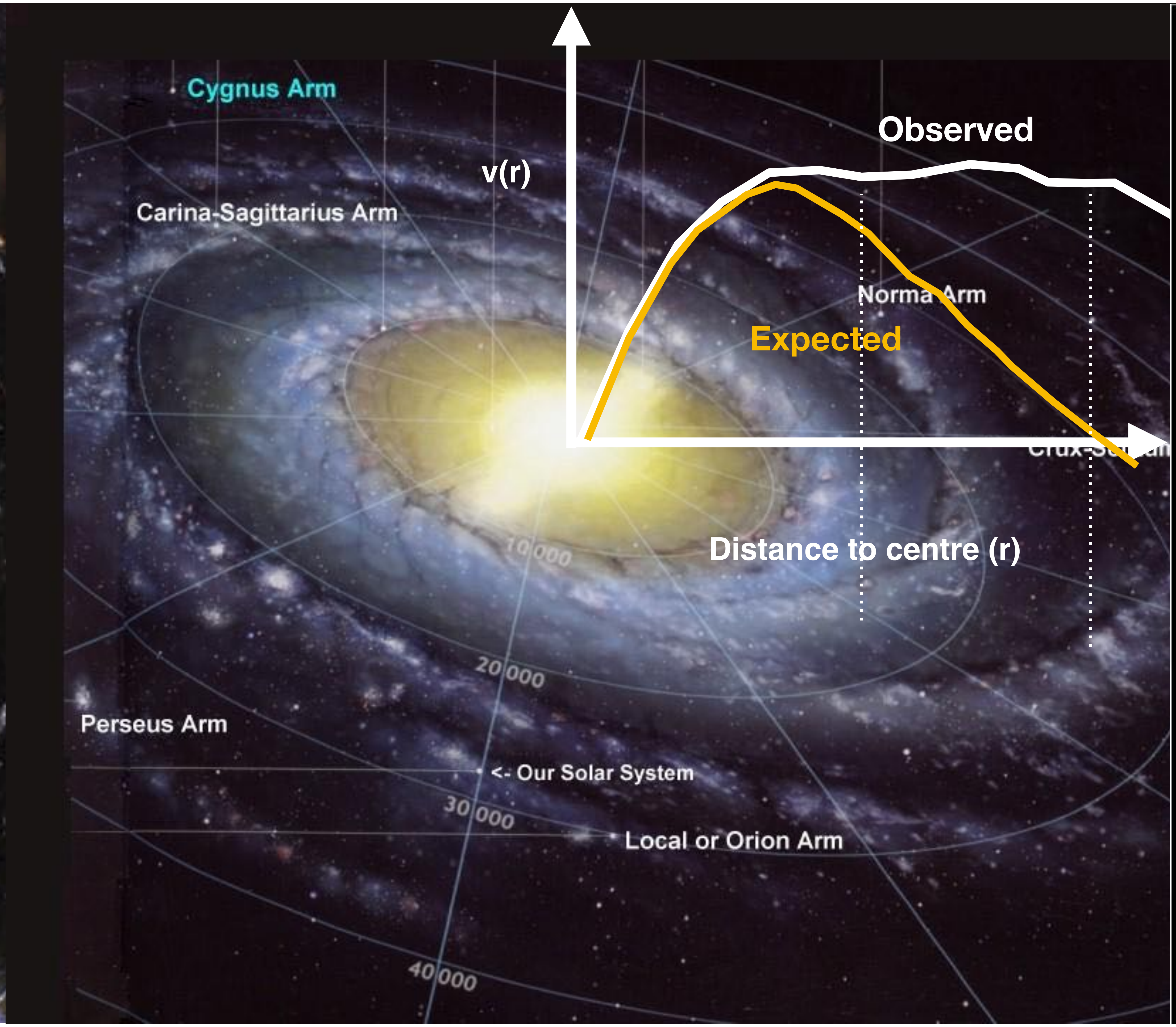
Courtesy Millie McDonald, Whisky Bay in Wilsons Promontory, 45 frames, each a stack of 4x 6s exposures at ISO 800

General Relativity is triumphant



And yet, in its current form, it is insufficient



The good news: It is always the same thing that is missing

The bad news: It is not clear what it is but it does mimic extra (invisible) mass

How to make sense of these observations?

"Dark Matter"

GR + SU(3)XSU(2)XU(1)X ?

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

+ ? (A new form of matter)

"Modified GR"

GR' + SU(3)XSU(2)XU(1)

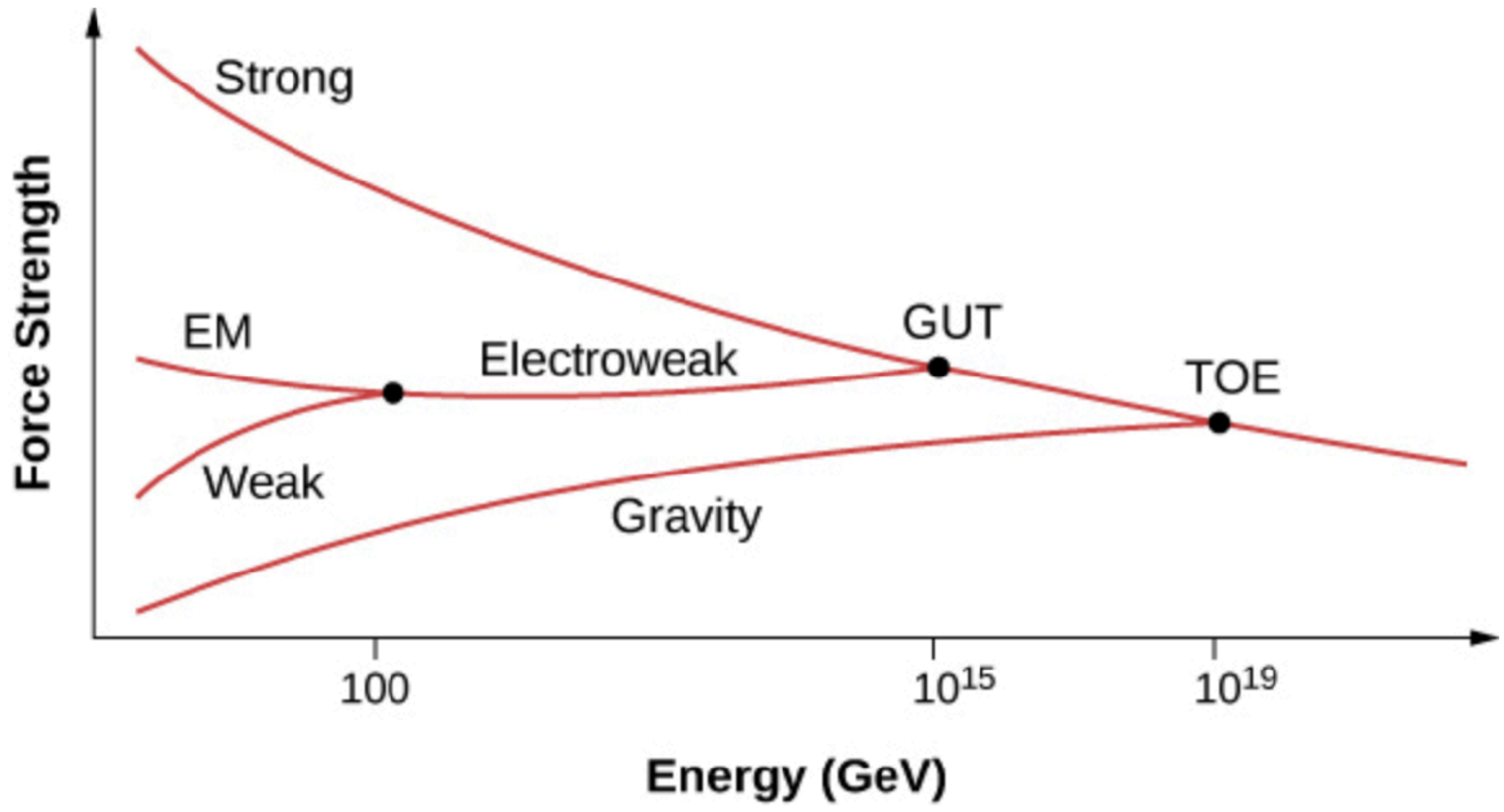
$$\mu\left(\frac{|\vec{a}|}{a_0}\right)\vec{a} = -\nabla\Phi$$

$$\mu(x) = 1 \text{ if } x > 1 \qquad \mu(x) \simeq x \text{ if } x < 1$$

GR somewhat scale-dependent

Or PBH, cosmic strings, MACHOs?, etc

But we might also need a deeper change



Grand unification of forces at high energies.

Norris-2016-Dawes-Review-Aboriginal-Astronomy.pdf

Our place in the Universe

Galaxies within galaxies

LMC and SMC are galaxies within the Milky Way and many more

1. A small recap of 2 options (GR' vs DM)
2. Focus on DM
3. sub-GeV DM

The modified gravity route

“Modified GR”

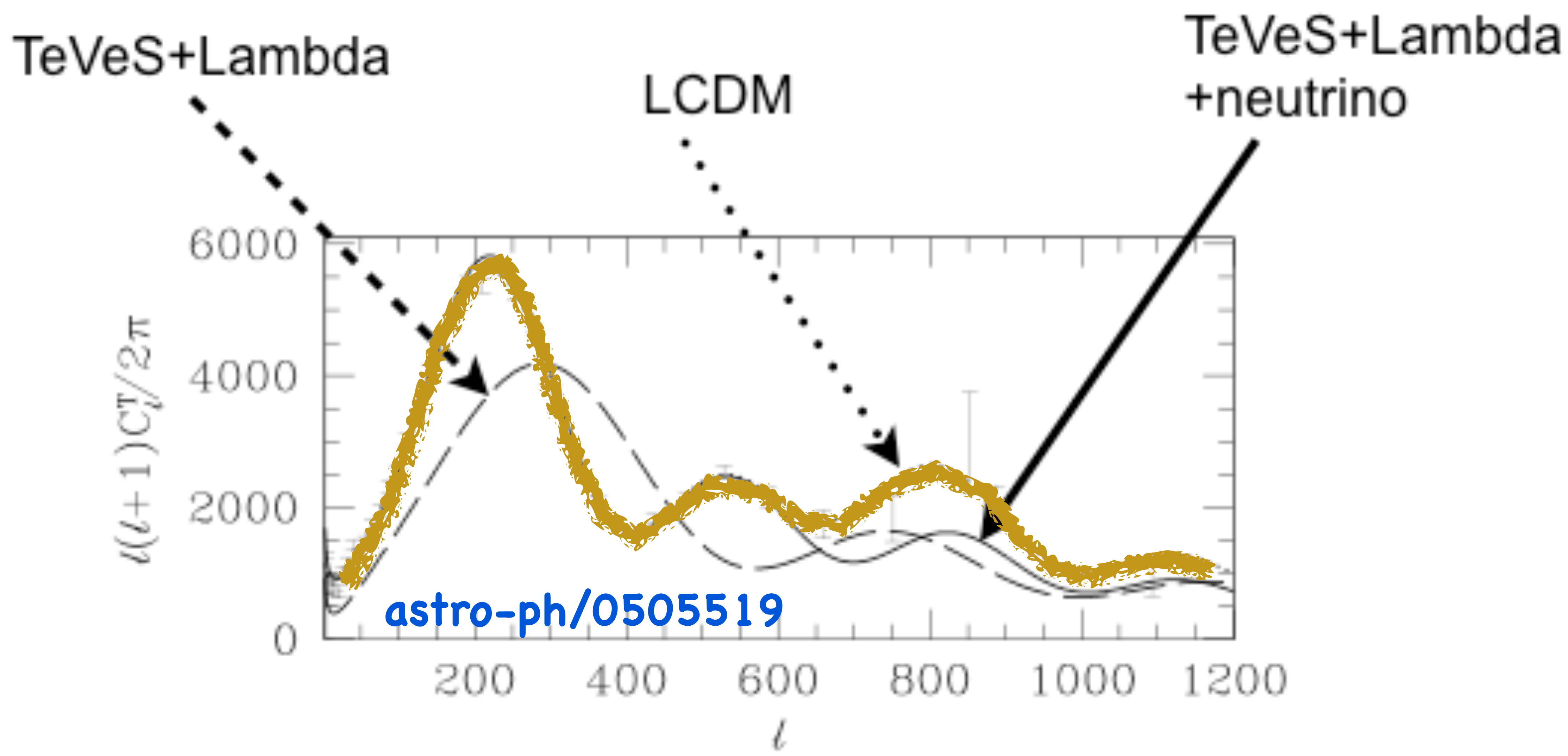
GR′ + SU(3)XSU(2)XU(1)

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

empirical

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

TEVES: astro-ph/0403694

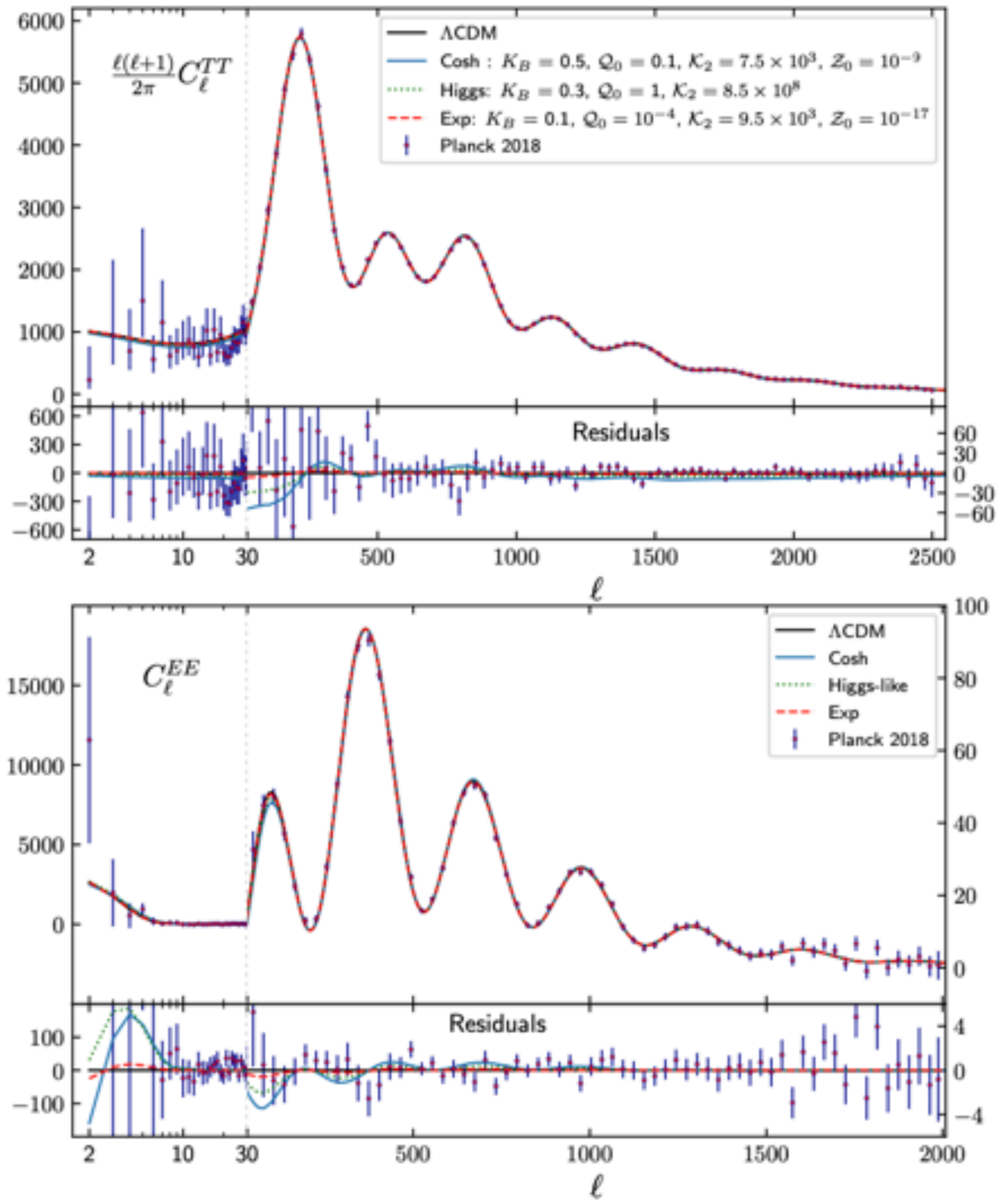


arXiv:2007.00082v3 [astro-ph.CO] 14 Oct 2021

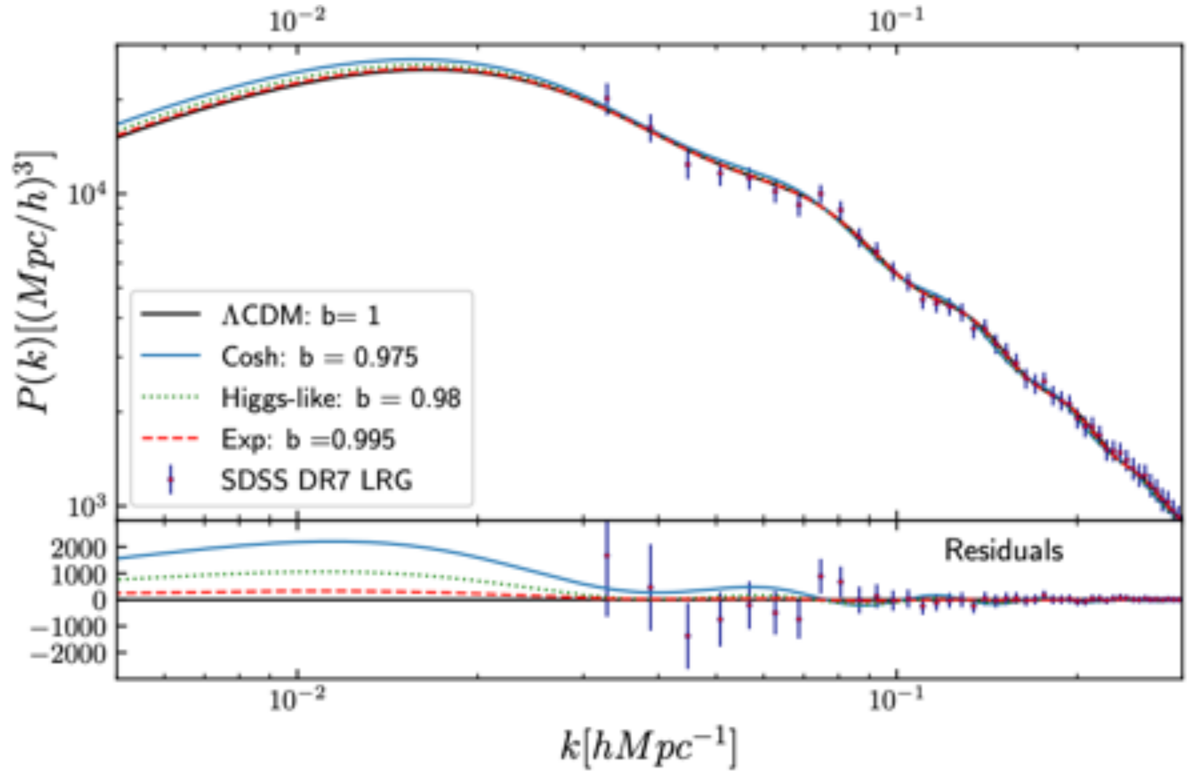
New Relativistic Theory for Modified Newtonian Dynamics

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.



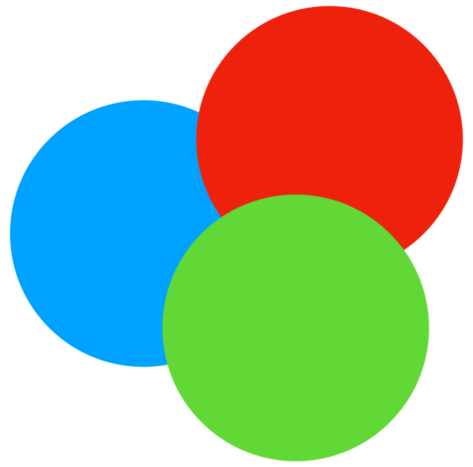
For a point source of mass M, the MOND-to-Newton transition occurs at $r_M \sim \sqrt{(G_N M/a_0)}$. A MOND force $\sim \sqrt{C_N M a_0}/r$ lends its way trivially to a Newtonian force $G_N M/r^2$ as $r \ll r_M$ but in the inner Solar System this is



The Particle Physics route

Dark Matter as ordinary matter

GR + SU(3)XSU(2)XU(1)



$$Q = T_3 + \frac{1}{2} Y_{\mathrm{W}} \, .$$

+ −

Would be glue to protons

Would be ok

Would be visible

+ needs to be long-lived (from BBN to us now)

Dark Matter as ordinary matter

Is it a neutrino?

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720
(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

1980 - Zel'dovich et al develop Hot Dark Matter (HDM) theory

1983

CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

SIMON D. M. WHITE,[1,2] CARLOS S. FRENK,[1] AND MARC DAVIS[1,3]
University of California, Berkeley
Received 1983 June 17; accepted 1983 July 1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.

The formation of galaxies from massive neutrinos

Show affiliations

Davis, M.; Lecar, M.; Pryor, C.; Witten, E.

Scenarios are described that, by including an unstable tau-neutrino, facilitated galaxy formation. Although the unstable particle is chosen to be the tau-neutrino, it is noted that another particle (perhaps not a neutrino at all) with similar mass, lifetime, and decoupling time would serve as well. Without the massive, unstable particle, however, the lighter neutrinos by themselves seem to make galaxy formation on scales less than or equal to 10 to the 12th solar masses almost impossible.

Publication:	Astrophysical Journal, Part 1, vol. 250, Nov. 15, 1981, p. 423-431.
Pub Date:	November 1981
DOI:	10.1086/159390
Bibcode:	1981ApJ...250..423D
Keywords:	Big Bang Cosmology; Galactic Evolution; Neutrinos; Particle Mass; Black Holes (Astronomy); Nuclear Fusion; Perturbation Theory; Universe; Astrophysics

Is Dark Matter a neutrino?

1980 - Zel'dovich et al develop Hot Dark Matter (HDM) theory

1983 - White, Frenk, Davis: numerical simulations rule out HDM

CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

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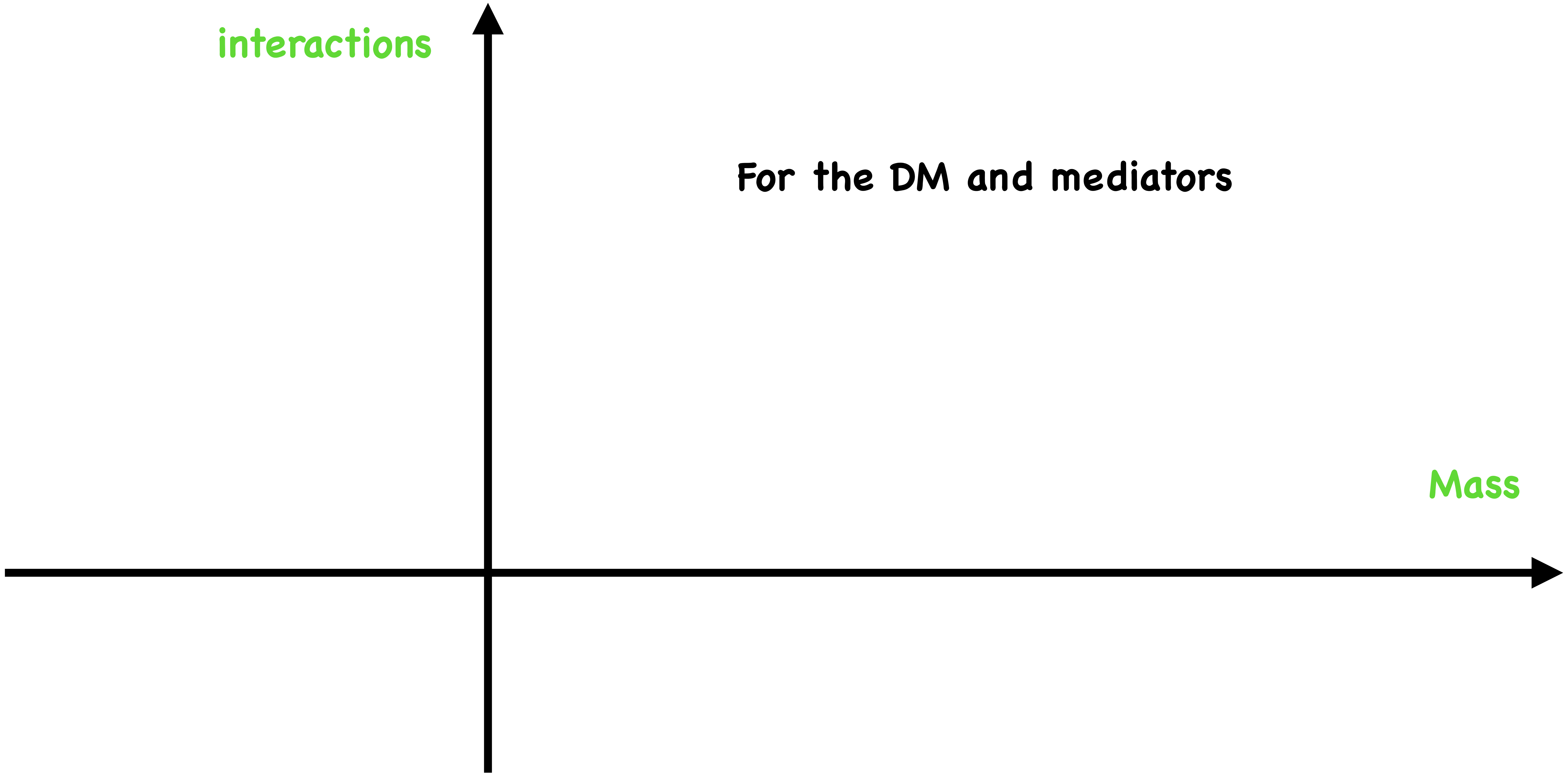
We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.

No! (Or at least very unlikely)

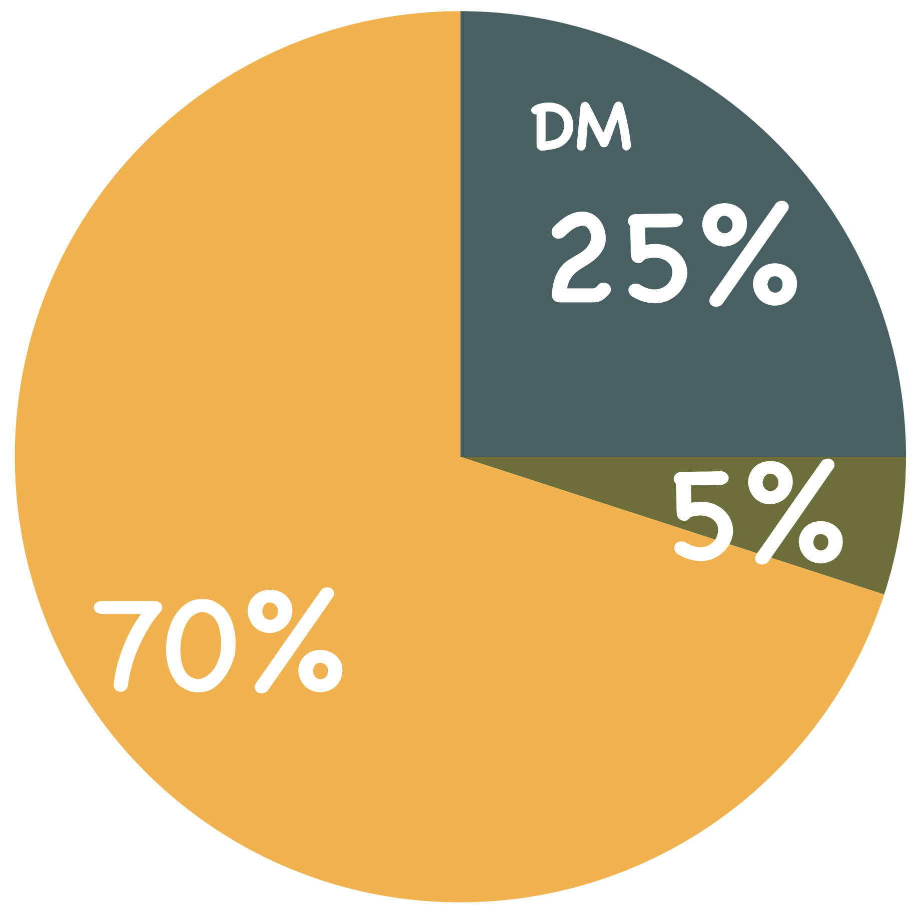
How to characterise Dark Matter?

GR + SU(3)XSU(2)XU(1) X ??



Mass, spin, Quantum numbers, interactions...

"Dark Matter"



Also Hut 1977

VOLUME 39 — 25 JULY 1977 — NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

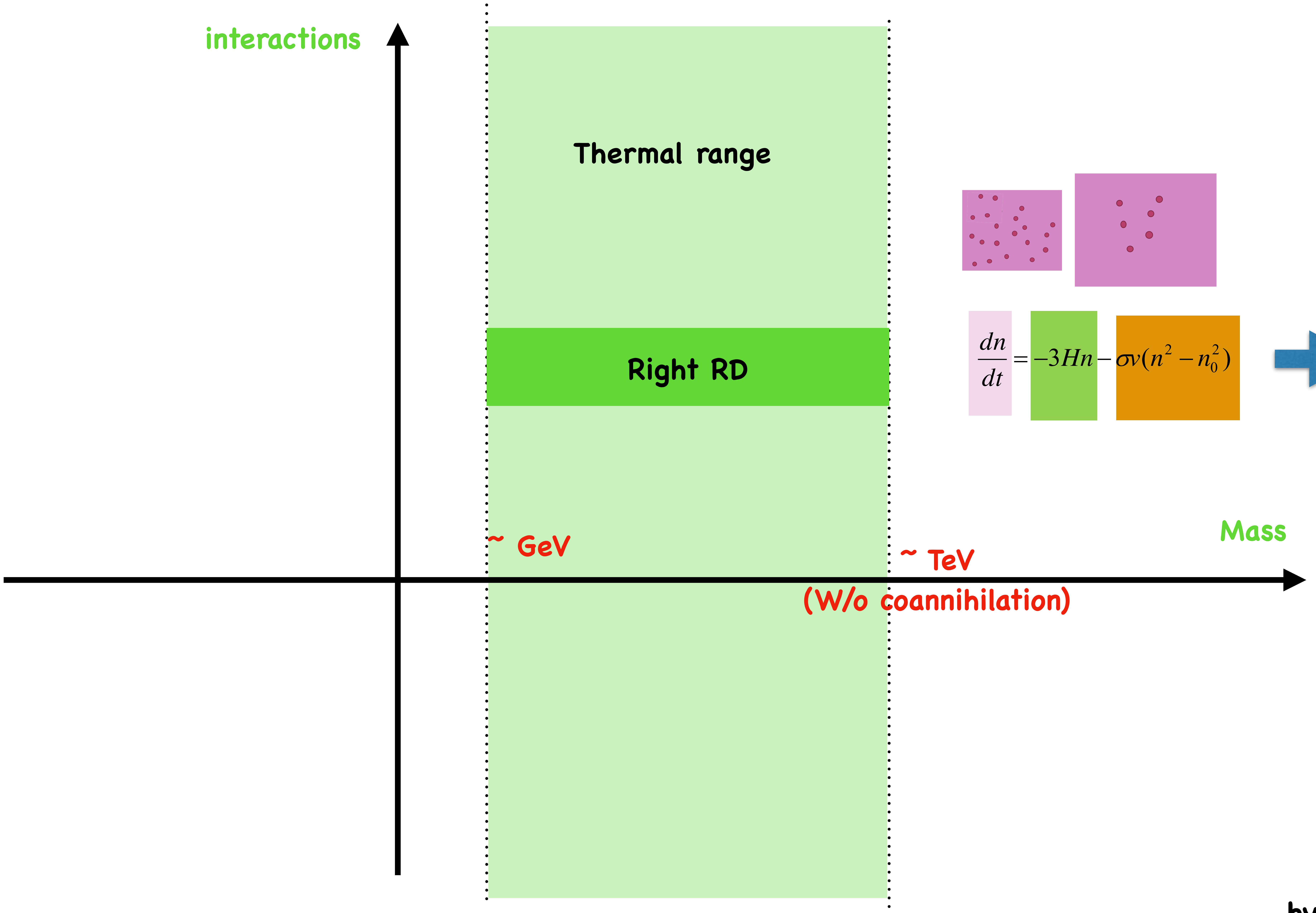
Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

$$m_\nu < 2\mathrm{eV} \;\; or \;\; \mathrm{m}_\nu > 2\mathrm{GeV}$$

Dark Matter mass range (historically)

Dark Matter mass range (historically)



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

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

Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	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
Ω_m	0.3158
Age [Gyr]	13.7971
σ_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

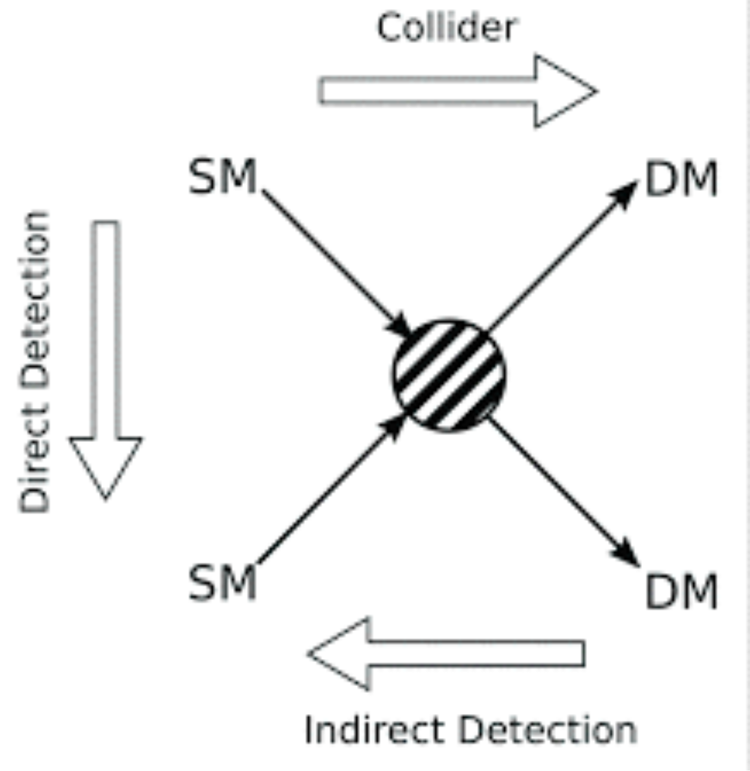
$$\boxed{\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}$$

Range of interactions is given by experimental value & error bars

Assuming thermal particles,
It seems DM must have weak-strength annihilations...

What about the elastic scattering?

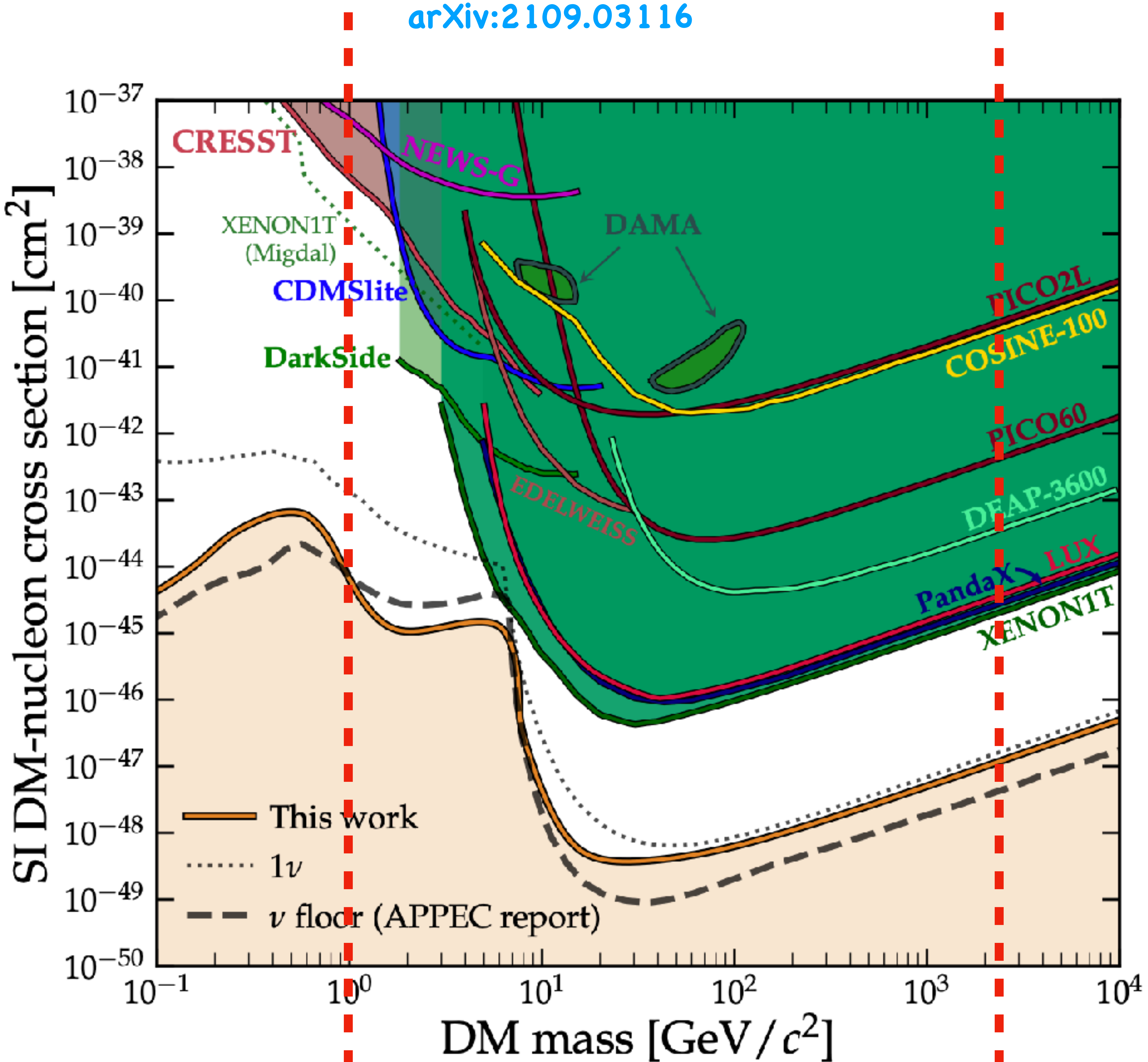
Assuming NO interaction



Annihilations

Dark Matter scattering with nucleon

arXiv:2109.03116



(Back in 2000s) The main question

Cosmology	Particle Physics	Cosmology
$\sigma = 0$	$\sigma_{ann} \sim \sigma_{weak}$	$\sigma_{SIDM} \sim \sigma_T$
	DM-SM	

What is the effect of DM-SM interactions on cosmological structures?

Towards MeV-GeV thermal DM (or lighter!)

Effect of collisions in cosmology

letters to nature

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

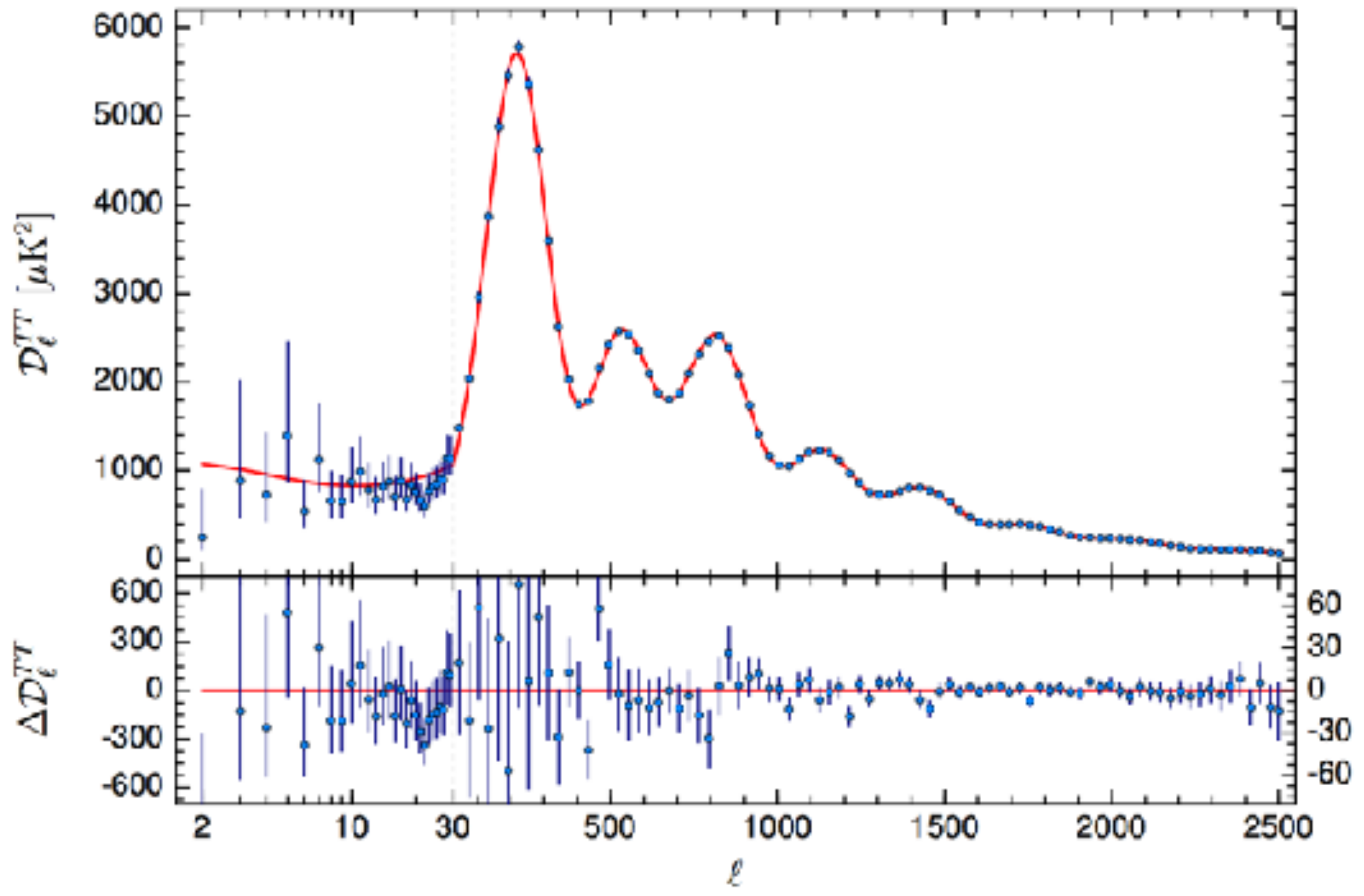
Fluctuations in the Primordial Fireball

JOSEPH SILK

Harvard College Observatory, Cambridge, Massachusetts.

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 ?

Planck Collaboration: The *Planck* mission



Silk damping

The photon fluctuations are erased

but so are baryonic fluctuations!

And the rest can also be erased due to free-streaming

Effect of collisions in cosmology

Silk damping revisited

$$l_{Silk}^2 \simeq \frac{2\pi^2}{3} \int^{t_{dec(b-\gamma)}} \frac{c^2\,\rho_\gamma}{\rho_{tot}\ a^2\ \Gamma_\gamma} \left(1+\Theta_\gamma\right)\ dt$$

Boehm-Schaeffer 2000, 2004 using Weinberg 1971 & Chapman, Cowling 1970

Generalising the Silk damping

$$l_{cd}^2 \simeq \frac{2\pi^2}{3} \sum_i \int^{t_{dec(DM-i)}} \frac{v_i^2\,\rho_i}{\rho_{tot}\ a^2\ \Gamma_i} \left(1+\Theta_i\right)\ dt$$

And the free-streaming

$$l_{fs}^2 \ \propto \int_{t_{dec(DM)}}^{t_0} \frac{v}{a(t)}\, dt$$

Maximising the collisional damping

$$l^2_{DM-\gamma} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\gamma)}} \frac{c^2 \rho_\gamma}{\rho_{tot}\ a^2\ \Gamma_\gamma}\ dt$$

~ **Silk damping**

$$l^2_{DM-\nu} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\nu)}} \frac{c^2 \rho_\nu}{\rho_{tot}\ a^2\ \Gamma_\nu}\ dt$$

New and new regime **(Like b-nu interactions by Misner 1966)**

$$l^2_{DM-b} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-b)}} \frac{v^2 \rho_b}{\rho_{tot}\ a^2\ \Gamma_b}\ dt$$

Inefficient unless dark Coulomb interactions

$$l^2_{DM-DM} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-DM)}} \frac{v^2 \rho_{DM}}{\rho_{tot}\ a^2\ \Gamma_{DM}}\ dt$$

Self-Interacting

DM-neutrino collisional damping

$$l^2_{DM-\nu} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\nu)}} \frac{c^2 \rho_\nu}{\rho_{tot}\, a^2\, \Gamma_\nu}\, dt \quad \text{with} \quad \Gamma_\nu \equiv \sum_i \Gamma_{dec(\nu-i)}$$

	SM	BSM
Collisional damping	$\Gamma_{\nu-e} > \Gamma_{\nu-DM}$ $\Gamma_\nu > \Gamma_{DM-\nu}$	$\Gamma_{\nu-DM} > \Gamma_{\nu-e}$ $\Gamma_\nu > \Gamma_{DM-\nu}$
Mixed damping	$\Gamma_{\nu-e} > \Gamma_{\nu-DM}$ $\Gamma_{DM-\nu} > \Gamma_\nu$	$\Gamma_{\nu-DM} > \Gamma_{\nu-e}$ $\Gamma_{DM-\nu} > \Gamma_\nu$

$$l^2_{DM-\nu} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\nu)}} \frac{c^2 \rho_\nu}{\rho_{tot}\, a^2\, H}\, dt$$

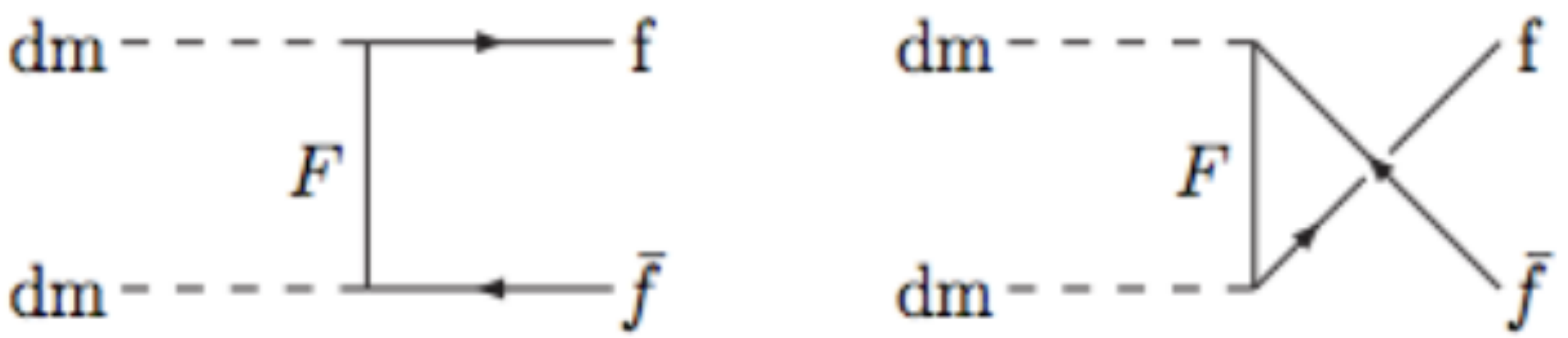
DM stays coupled to free-streaming neutrinos (i.e. < MeV): the lighter the DM, the more efficient

Can the annihilation cross section be independent of the dark matter mass?

Evading the Lee-Weinberg limit

hep-ph/0305261

Assuming thermal DM, the main requirement is to find a cross section that is not dependent on mdm



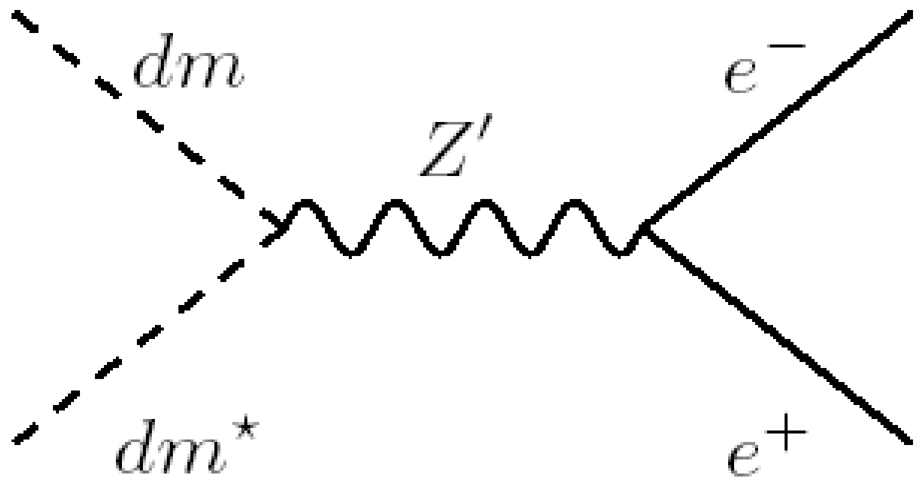
$$\sigma v \propto \frac{1}{m_F^4} \left(\left(C_l^2 + C_r^2 \right) \, m_f + 2 C_l \, C_r \, m_F \right)^2$$

The cross section is independent of the DM mass so the DM can be light!

Also found by Feng&kumar (0803.4196)

Evading the Lee-Weinberg limit

Boehm & Fayet hep-ph/0305261



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

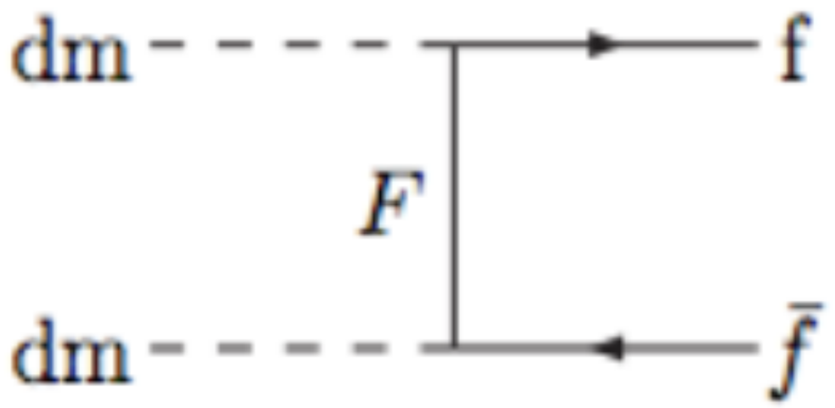
P-wave (but D-wave can be important too)

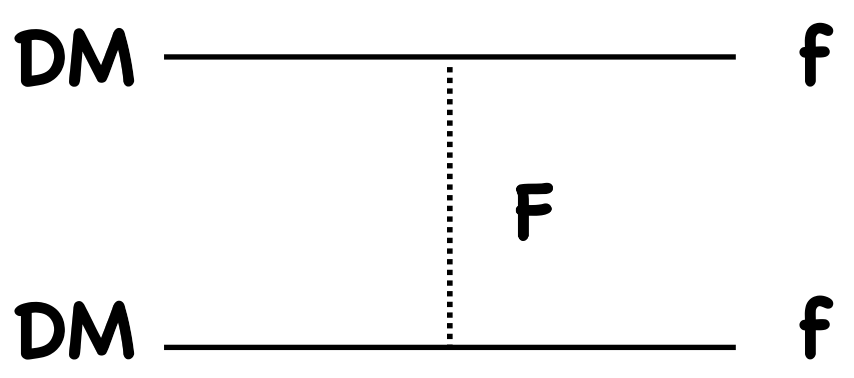
Depends on the DM mass but the cross section can have the right value if mdm = mZ'

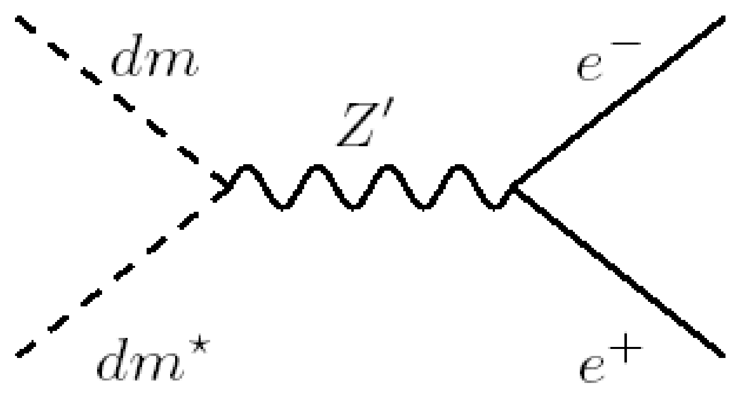
==> viable solution for light DM provided that the dark mediator/dark photon is light

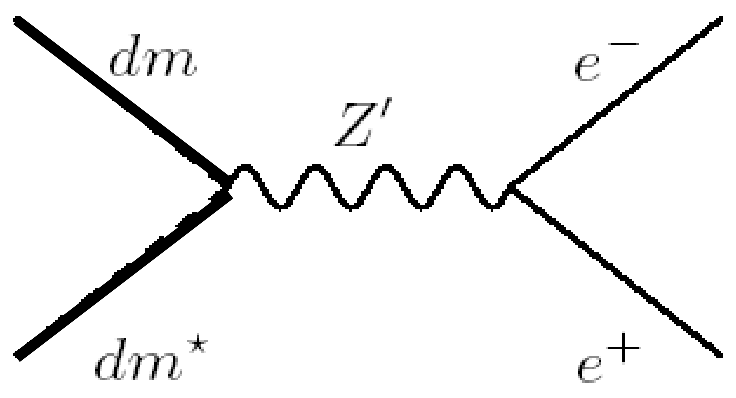
Dark Photons/Z' were used afterwards in a different context: Pamela anomaly, DAMA, Ultra Light DM etc

MeV-GeV range DM : which mediators?









NMSSM-like: light scalar and pseudo scalar (Higgs-like) mediators

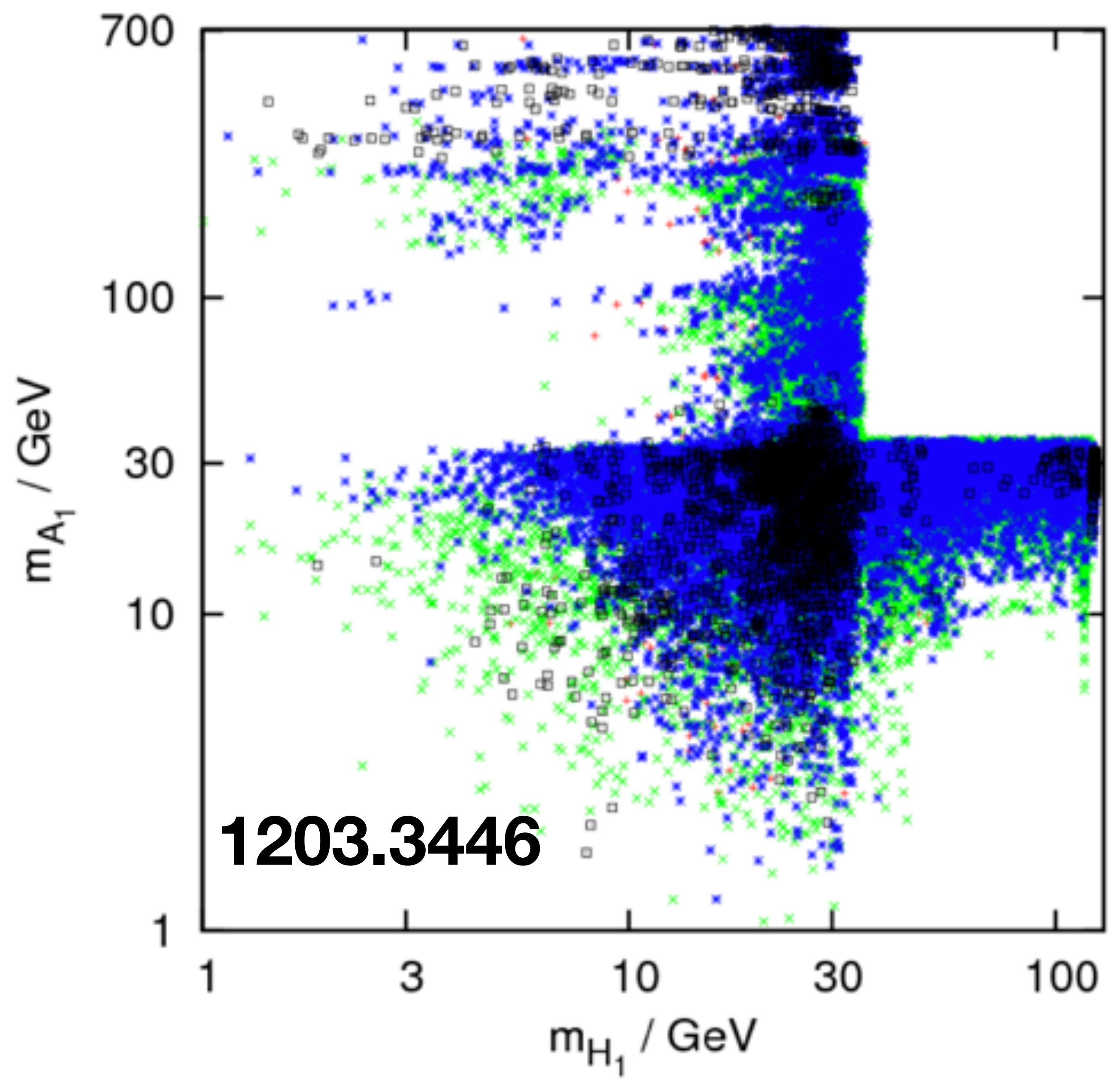


FIG. 2: Masses of the Higgs scalars H_1, H_2 and pseudoscalar A_1. Red points are ruled out either by HiggsBounds constraints or the ATLAS 1fb^{-1} jets and missing E_T SUSY search. Green points have no Higgs with a mass in 122 – 128 GeV, blue points have a Higgs (H_1 and/or H_2) within this mass range, and black points have such a Higgs with $R_{gg\gamma\gamma} > 0.4$.

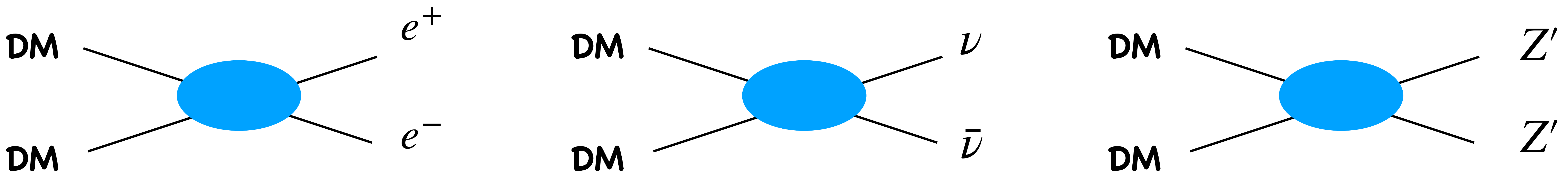
Axions?

Spin 3/2?

See Natalia Toro's talk

Burst of alternative models/thinking

DM can be lighter than a proton but how low can it be?



MeV Sub eV? Depends on the dark sector

Should there be annihilations at all?

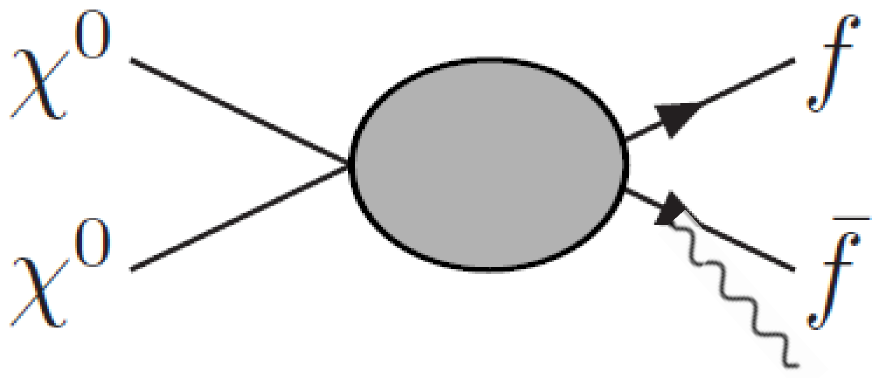
Asymmetric DM, Freeze-in, non thermal DM

Can annihilating Dark Matter be lighter than a few GeVs?

C. Boehm[1], T. A. Enßlin[2], J. Silk[1]
[1] *Denys Wilkinson Laboratory, Astrophysics Department, OX1 3RH Oxford, England UK;*
[2] *Max-Planck-Institut für Astrophysik Karl-Schwarzschild-Str. 1, Postfach 13 17, 85741 Garching*
(Dated: 22 August 2002)

We estimate the gamma ray fluxes from the residual annihilations of Dark Matter particles having a mass $m_{dm} \in [\mathrm{MeV}, O(\mathrm{GeV})]$ and compare them to observations. We find that particles lighter than $O(100\,\mathrm{MeV})$ are excluded unless their cross section is S-wave suppressed.

astro-ph/0208458



Annihilation for RD needs to be p-wave!

Dark Matter haloes

	α	β	γ	r_s	$F(\theta)$			$\Phi/(\langle\sigma v_r\rangle_{26}\, m_{\mathrm{GeV}}^{-2})$
				kpc	1°	10°	45°	$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
NFW	1	3	1	25	0.077	0.62	1.7	$5.9\ 10^{-6}$
KRA	2	3	0.2	11	$1.7 \cdot 10^{-4}$	0.014	0.15	$7.5\ 10^{-8}$
ISO	2	2	0	4	$1.2 \cdot 10^{-4}$	0.011	0.08	$1.8\ 10^{-7}$
BE	1	3	0.3	4	$1.2 \cdot 10^{-4}$	0.004	0.01	$4.1\ 10^{-6}$

TABLE I: Angular function $F(\theta)$ and central γ-ray flux $\Phi(< 1.5^\circ)$ for different galactic DM profiles, $R_{\mathrm{sol}} = 8.5\,\mathrm{kpc}$ and ρ_0 chosen so that $\rho(R_{\mathrm{sol}}) = 0.3\,\mathrm{GeV/c^2\,cm^{-3}}$ [23].

	α	β	γ	r_s	D	ρ_0	$\Phi_{cl}/(\langle\sigma v_r\rangle_{26} m_{\mathrm{GeV}}^{-2})$
				kpc	Mpc	$\mathrm{GeV/c^2\,cm^3}$	$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
C-NFW	1	3	1	$0.25/h$	$70/h$	$0.090h^2$	$5.3\,10^{-10}h^3$
C-β-pr.	2	2.25	0	$0.2/h$	$70/h$	$0.13h^2$	$8.8\,10^{-10}\,h^3$
V-NFW	1	3	1	0.56	15	0.012	$2.4\,10^{-9}$
V-β-pr.	2	1.41	0	0.015	15	0.76	$3.0\,10^{-9}$

TABLE II: Expected fluxes from the Coma (C) and Virgo (V) cluster for different DM profiles [24]. For the β-profile of Virgo, only the flux within 1 Mpc is given. $h = 0.7$.

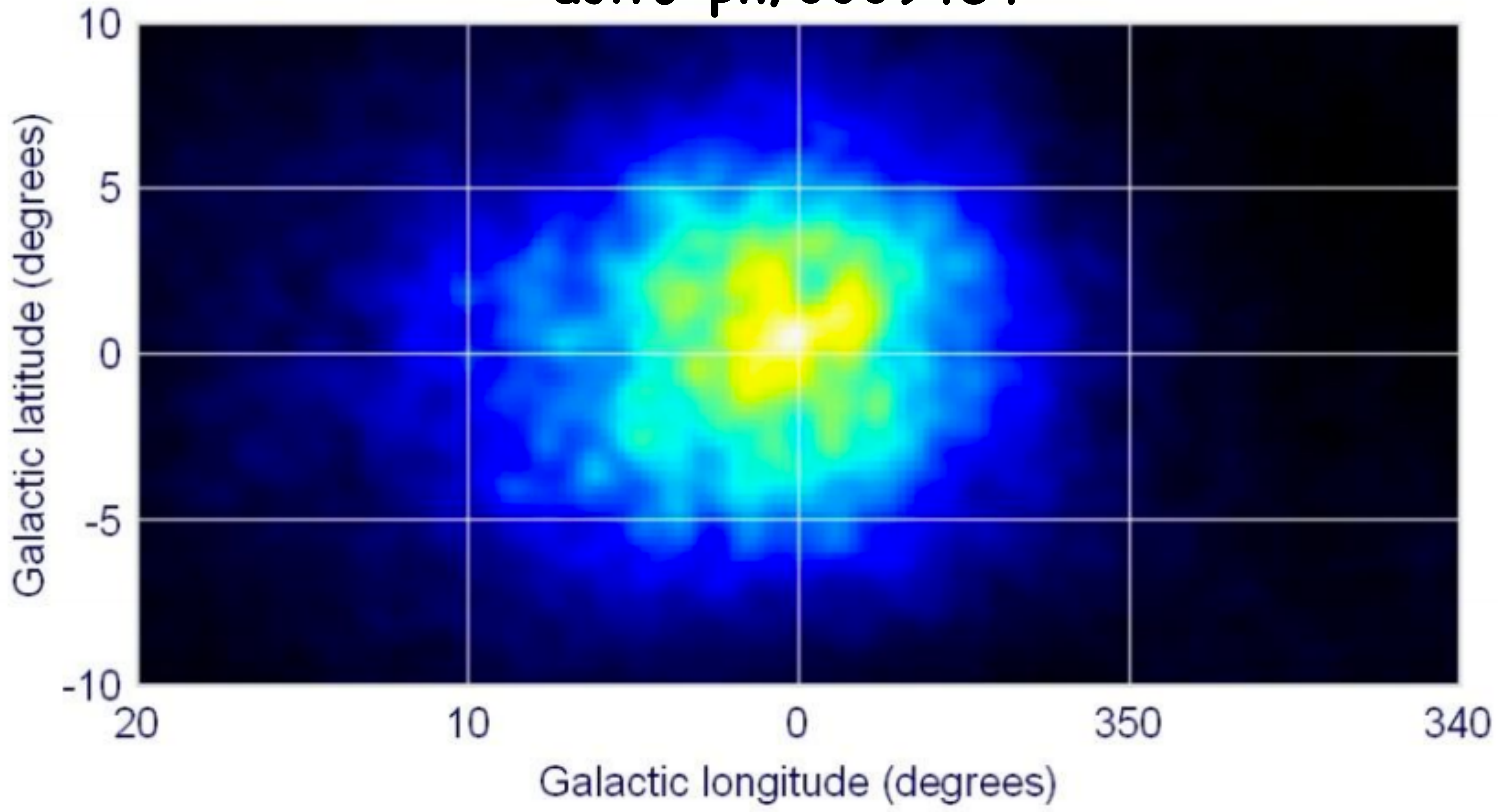
Astrophysical implications of light dark matter

$\mathrm{DM\ DM} \to \mathrm{e^+ e^-}$ Positronium formation $\to \gamma\gamma$ 511 keV (para)

$\gamma\gamma\gamma$ continuum (ortho)

511 keV line

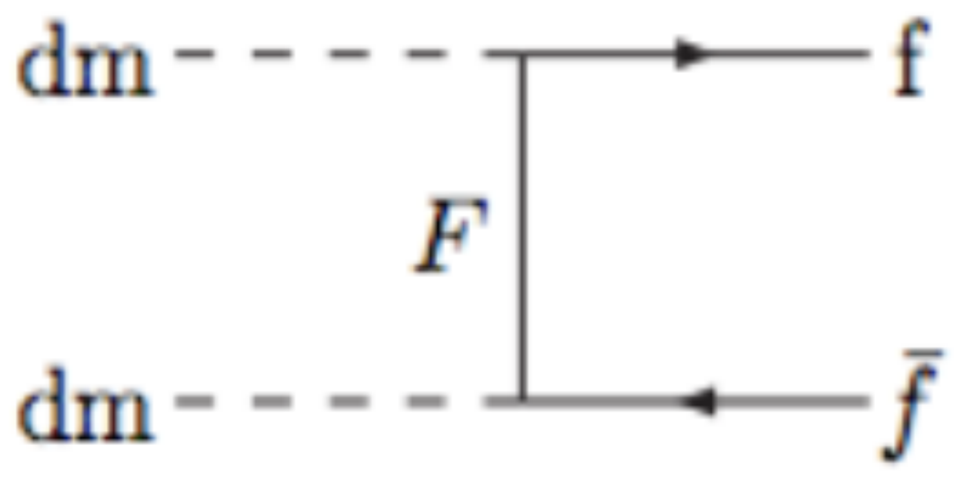
astro-ph/0309484

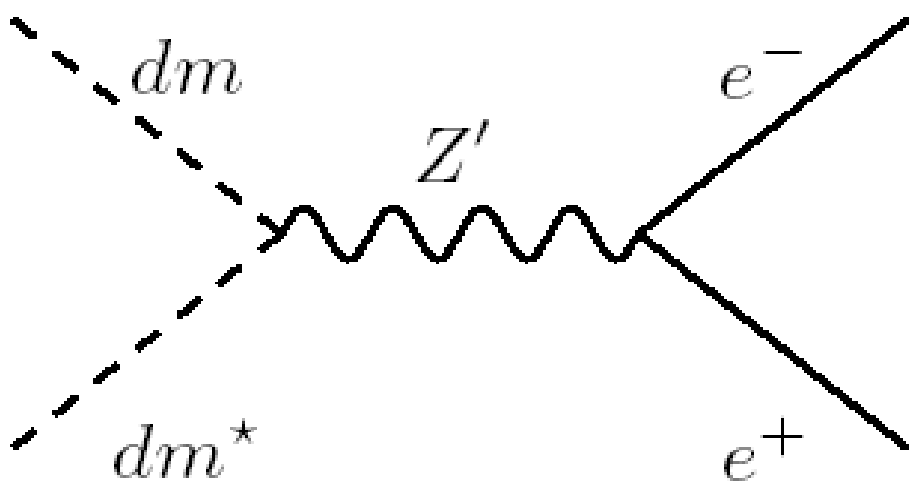


Morphology of 511 keV line in agreement with DM distribution astro-ph/0309686

Astrophysical implications of light dark matter

astro-ph/0507142





Can explain the observed 511 keV morphology
But cannot explain the relic abundance

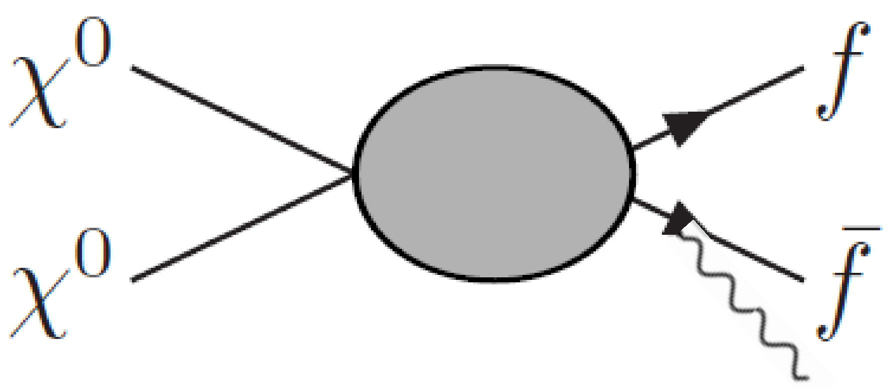
Cannot explain the 511 keV morphology
But can explain the relic abundance

Could explain the observed flux (with scalar dark matter)

$$\frac{m_F}{100\ \mathrm{GeV}} \simeq 6 \times 10^3\ \frac{c_l\, c_r}{m_{\mathrm{MeV}}}$$

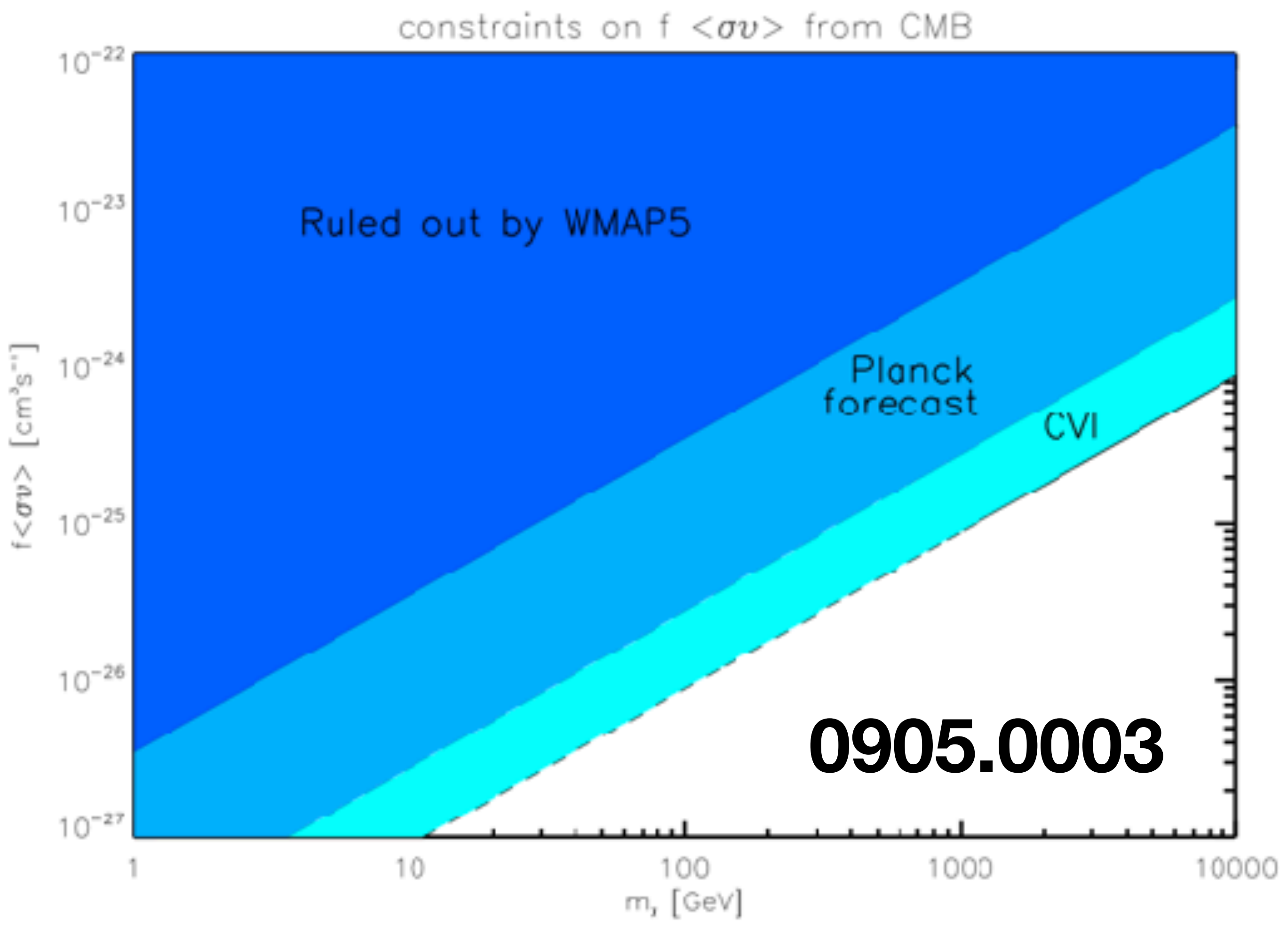
Not the right channel

Astrophysical implications of light dark matter



Gamma-ray emission

S-wave must be suppressed
P-wave ok



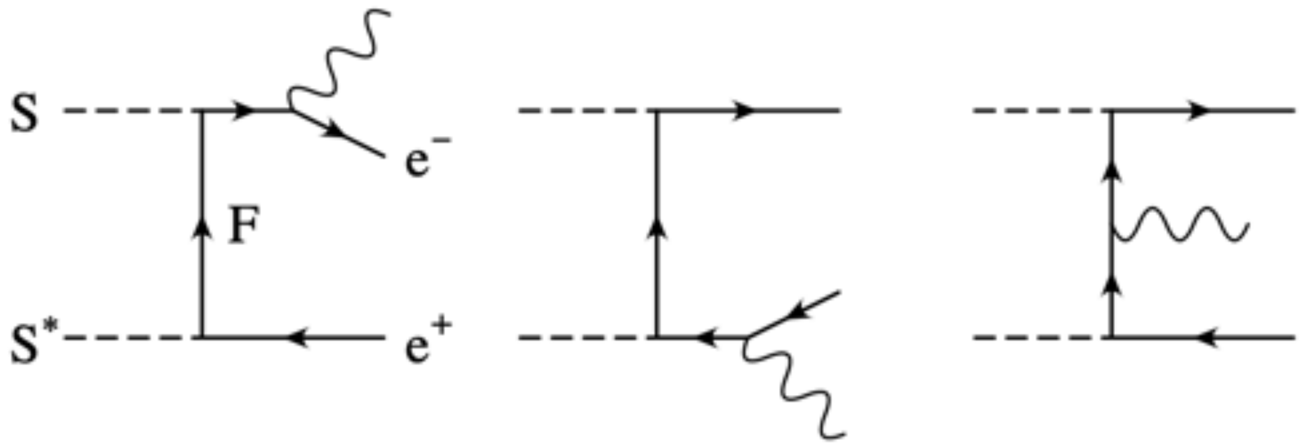
See also by Boudaud et al (1810.01680)
+ X-ray: 2007.11493 (Cirelli et al) — strong constraints m > 20 MeV
+ CMB study in the context of the 511 keV line in 1301.0819

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

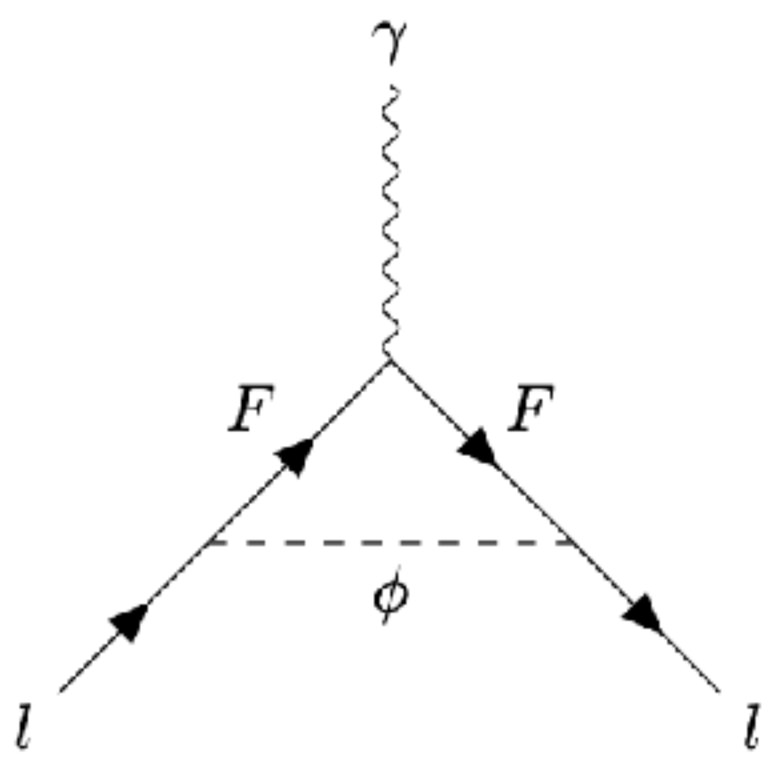
Boehm&Uwer (0606058)

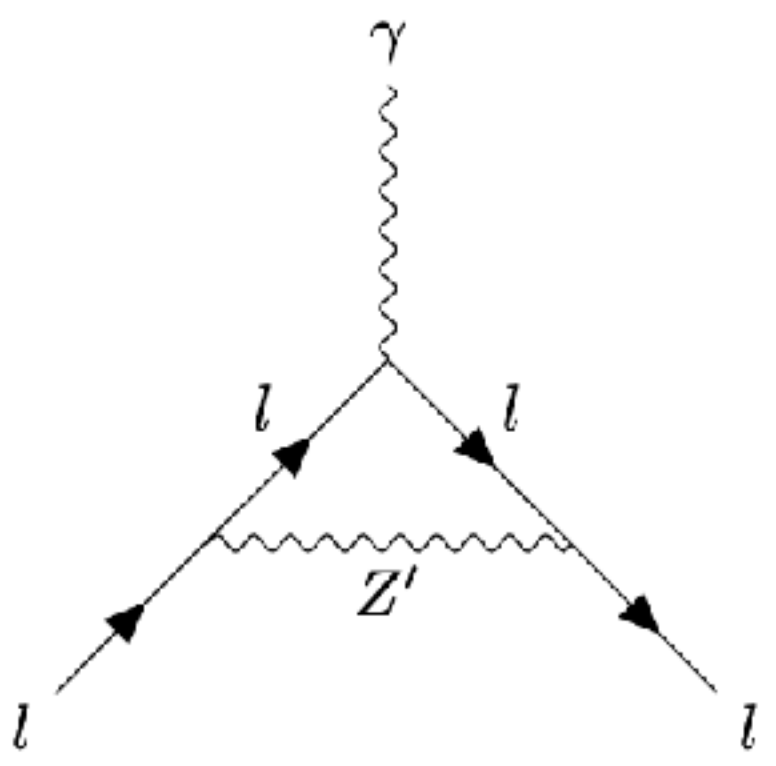


$$\frac{d\sigma_\gamma}{dx_\gamma} \approx \sigma_0 \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left\{\left(1 + \frac{s'^2}{s^2}\right)\ln\left(\frac{s'}{m_e{}^2}\right) - 2\frac{s'}{s}\right\},$$

mdm < 30 MeV

g-2 constraints of light dark matter





hep-ph/0305261 :
electron g-2 sets more severe constraints on this model

hep-ph/0405240 hep-ph/0408213 arXiv:0708.2768

hep-ph/0408213

More evidence in favour of Light Dark Matter particles?

Celine Boehm, Yago Ascasibar

In a previous work, it was found that the Light Dark Matter (LDM) scenario could be a possible explanation to the 511 keV emission line detected at the centre of our galaxy. Here, we show that hints of this scenario may also have been discovered in particle physics experiments. This could explain the discrepancy between the measurement of the fine structure constant and the value written in the CODATA. Finally, our results indicate that some of the LDM features could be tested in accelerators. Their discovery might favour N=2 supersymmetry.

	F_e	Z'
a_e	$\frac{c_l c_r}{16\pi^2} \frac{m_e}{m_{F_e}}$	$\frac{z_e^2}{12\pi^2} \frac{m_e^2}{m_{Z'}^2}$
=	$5.10^{-12} \sqrt{f} \left(\frac{m_{\rm dm}}{\rm MeV}\right)$	$10^{-11} \left(\frac{z_e}{7\,10^{-5}}\right)^2 \left(\frac{m_{Z'}}{\rm MeV}\right)^{-2}$

To be compared with ae ~10^-13
DM unlikely to explain the 511 keV line

Constraints on vector-like fermions

arXiv:2010.02954

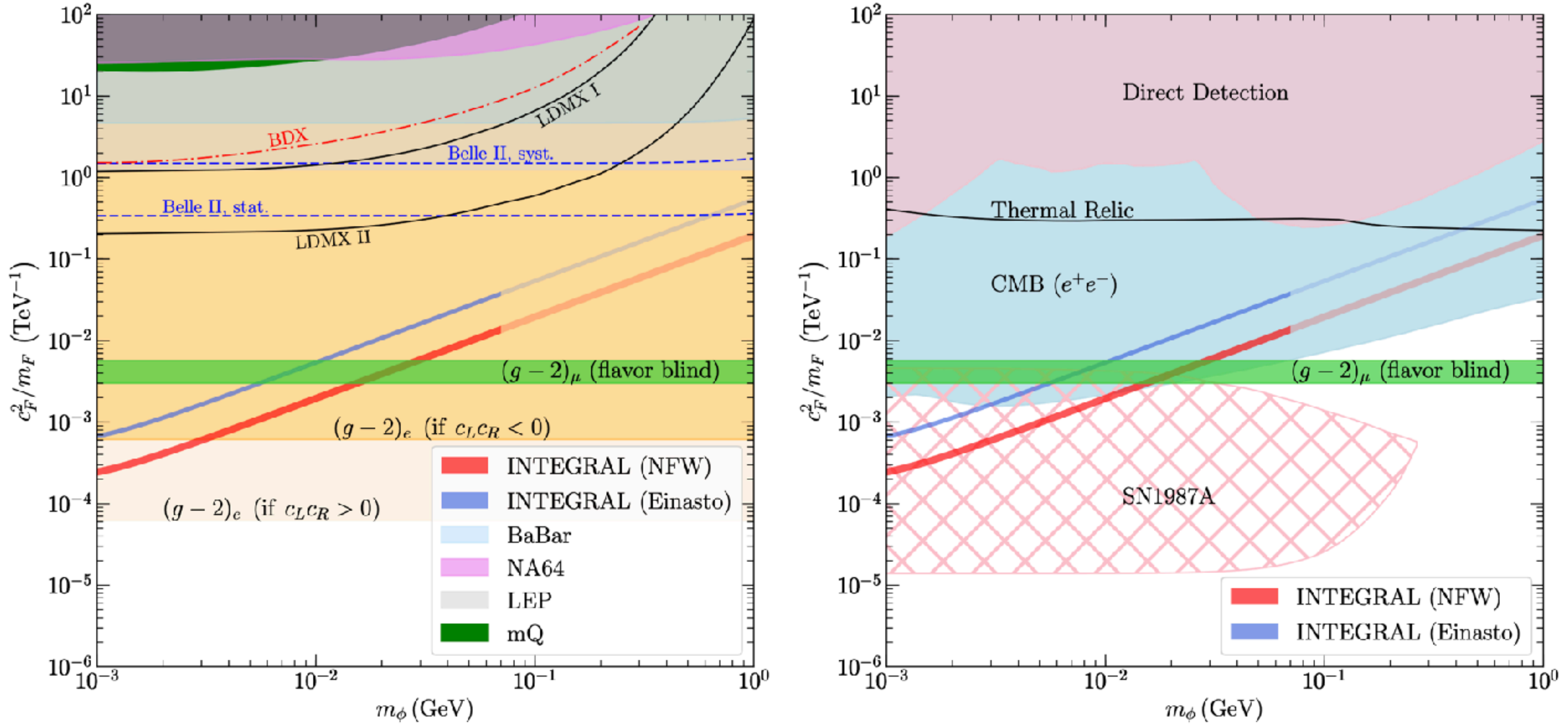


FIG. 6. Bounds on the inverse of effective UV-scale $\Lambda_F^{-1} = c_F^2/m_F$ in the F-mediated model from laboratory experiments (left panel) and from astrophysical observations including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are shown as thin blue 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

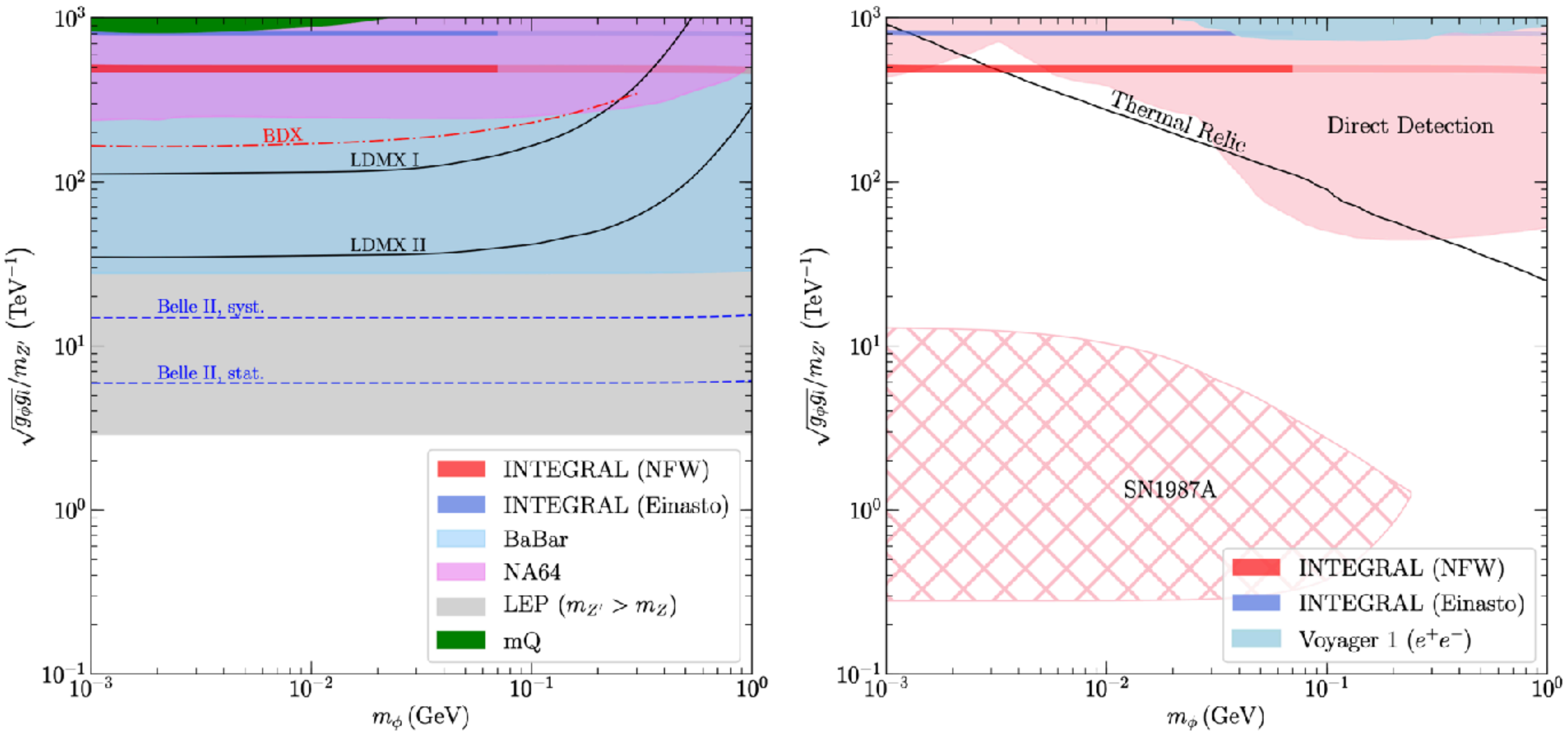
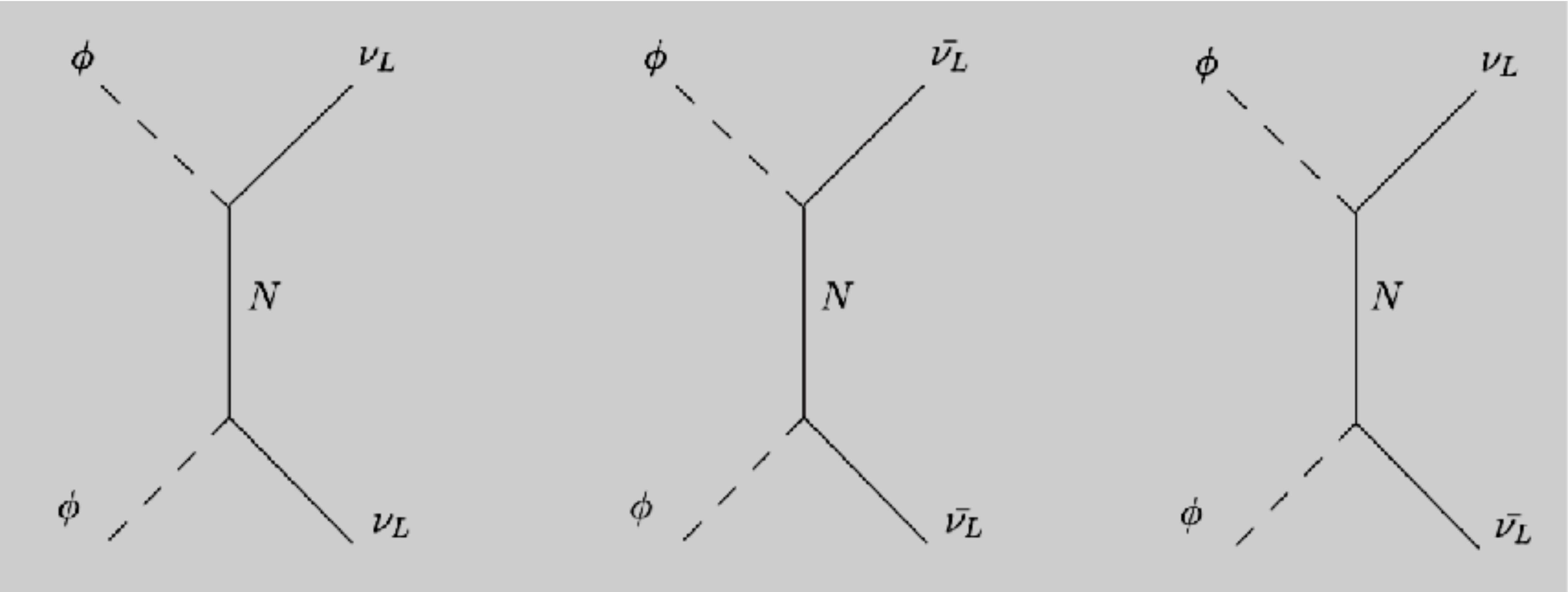


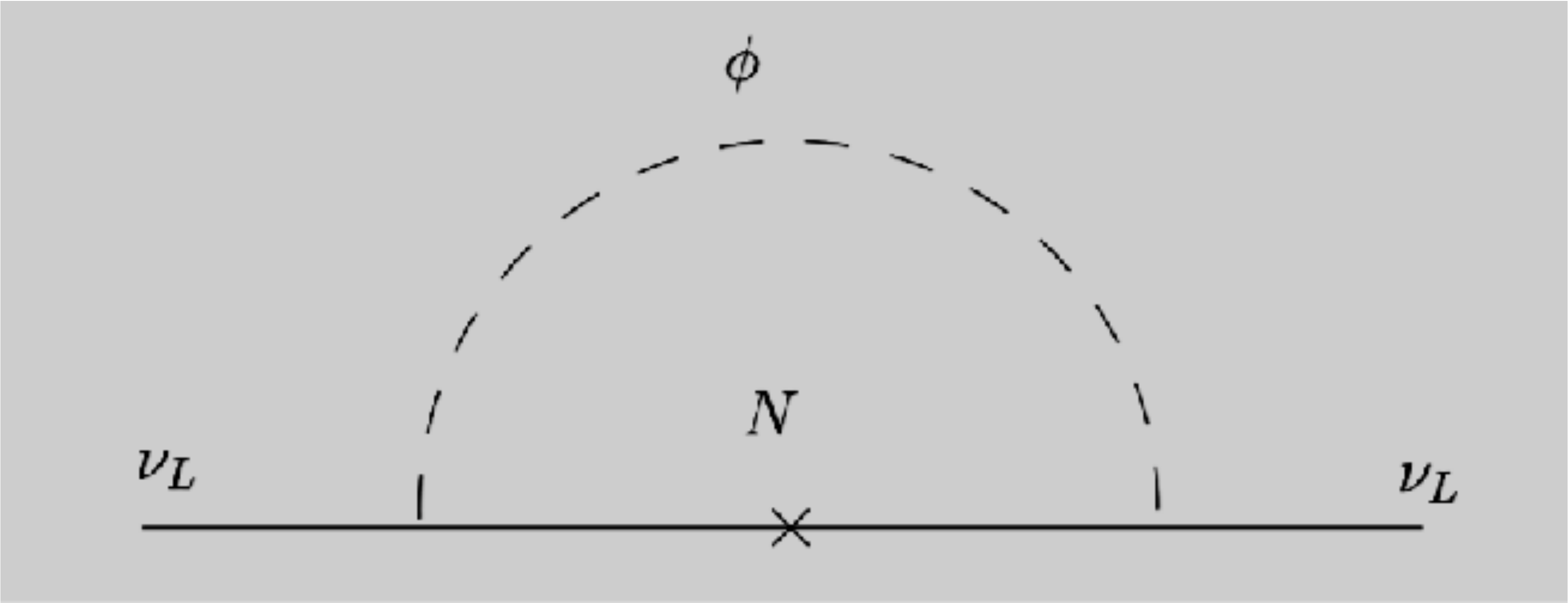
FIG. 7. Bounds on the inverse of effective UV scale $\Lambda_{Z'}^{-1} = \sqrt{g_\phi g_l}/m_{Z'}$ for the Z' model from laboratory tests (left panel) and from cosmological and astrophysical probes including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are shown as thin blue and red bands; for $m_\phi \geq 70\,\mathrm{MeV}$ 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_ϕ/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

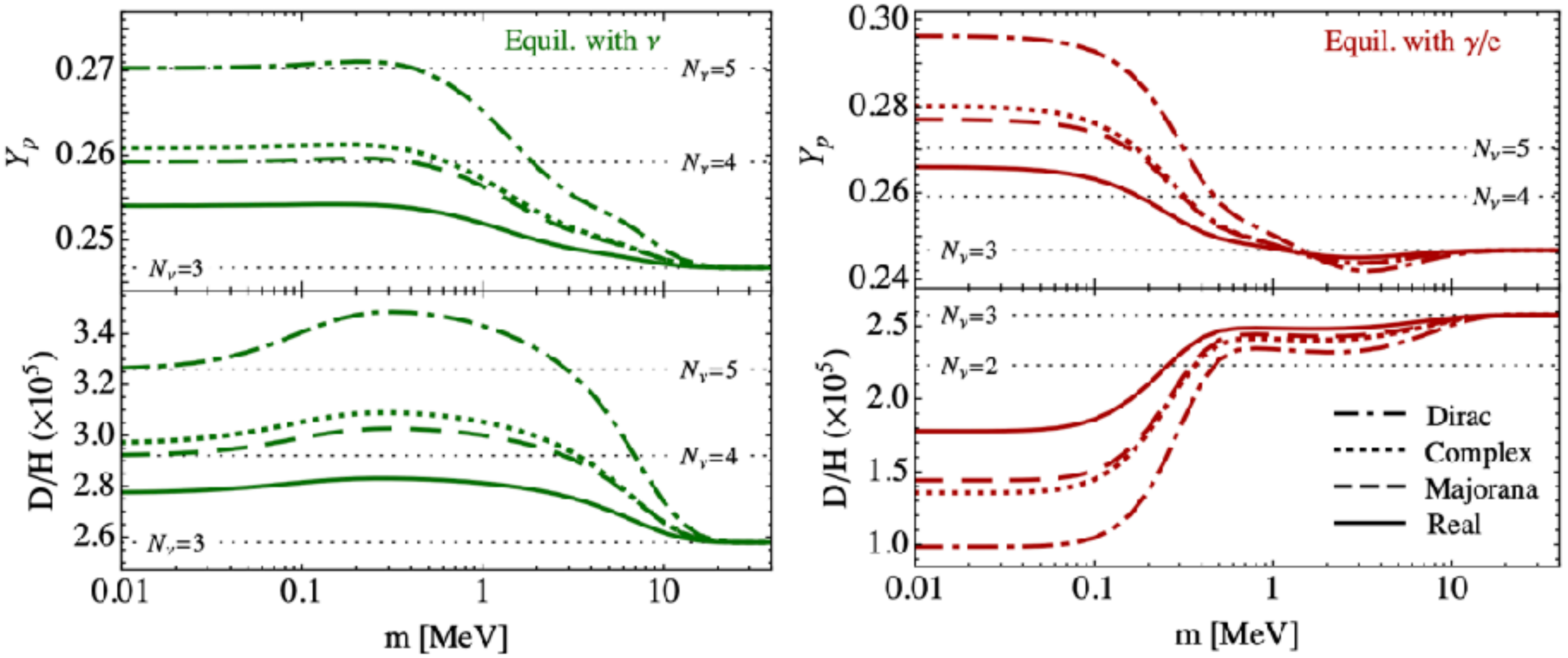
1207.0497 1303.6270

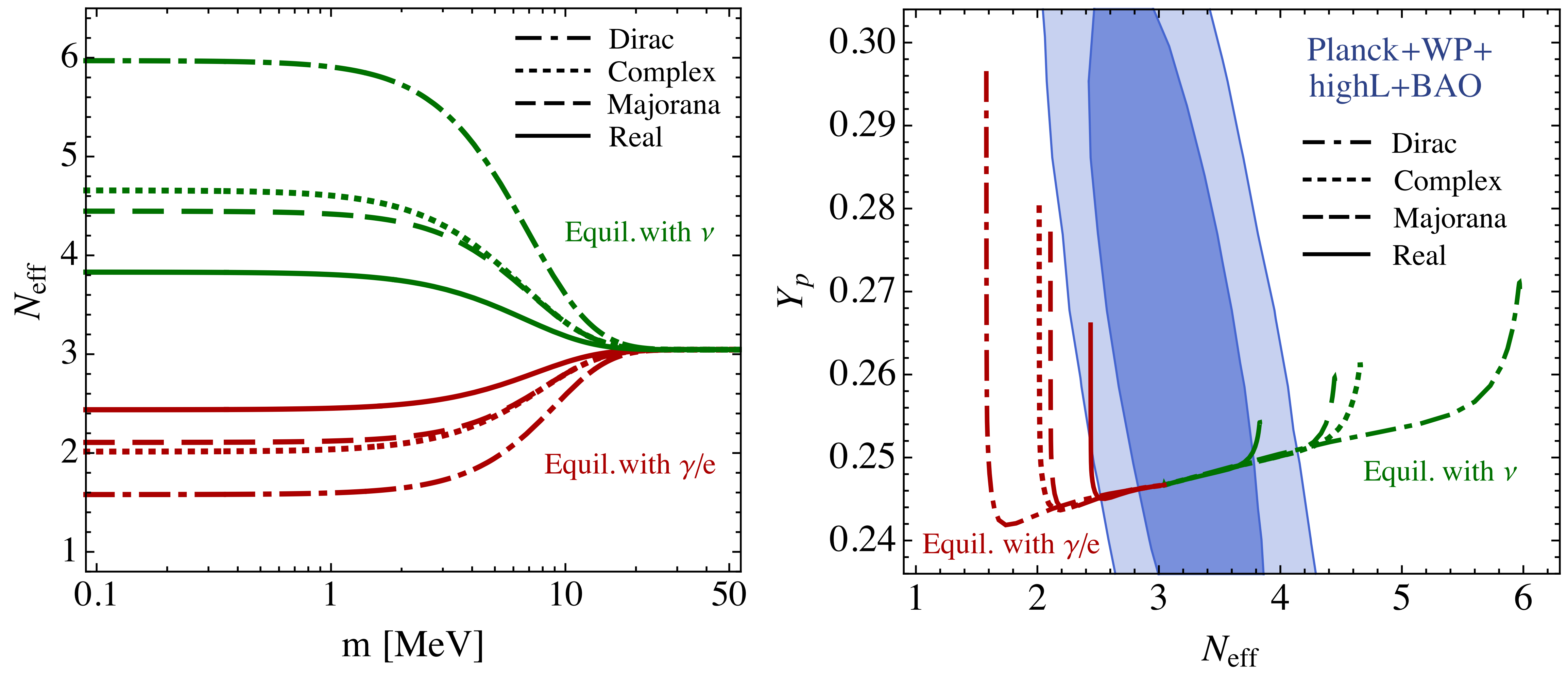
Raffelt & Serpico astro-ph/0403417

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

Helium/D abundance

Neff





M < 10-20 MeV

Overly simplified summary of (Astro) constraints

Indirect detection: mdm < 30 MeV (for the 511 keV line)
P-wave annihilations or s-wave suppressed
But see talk by Francesca!

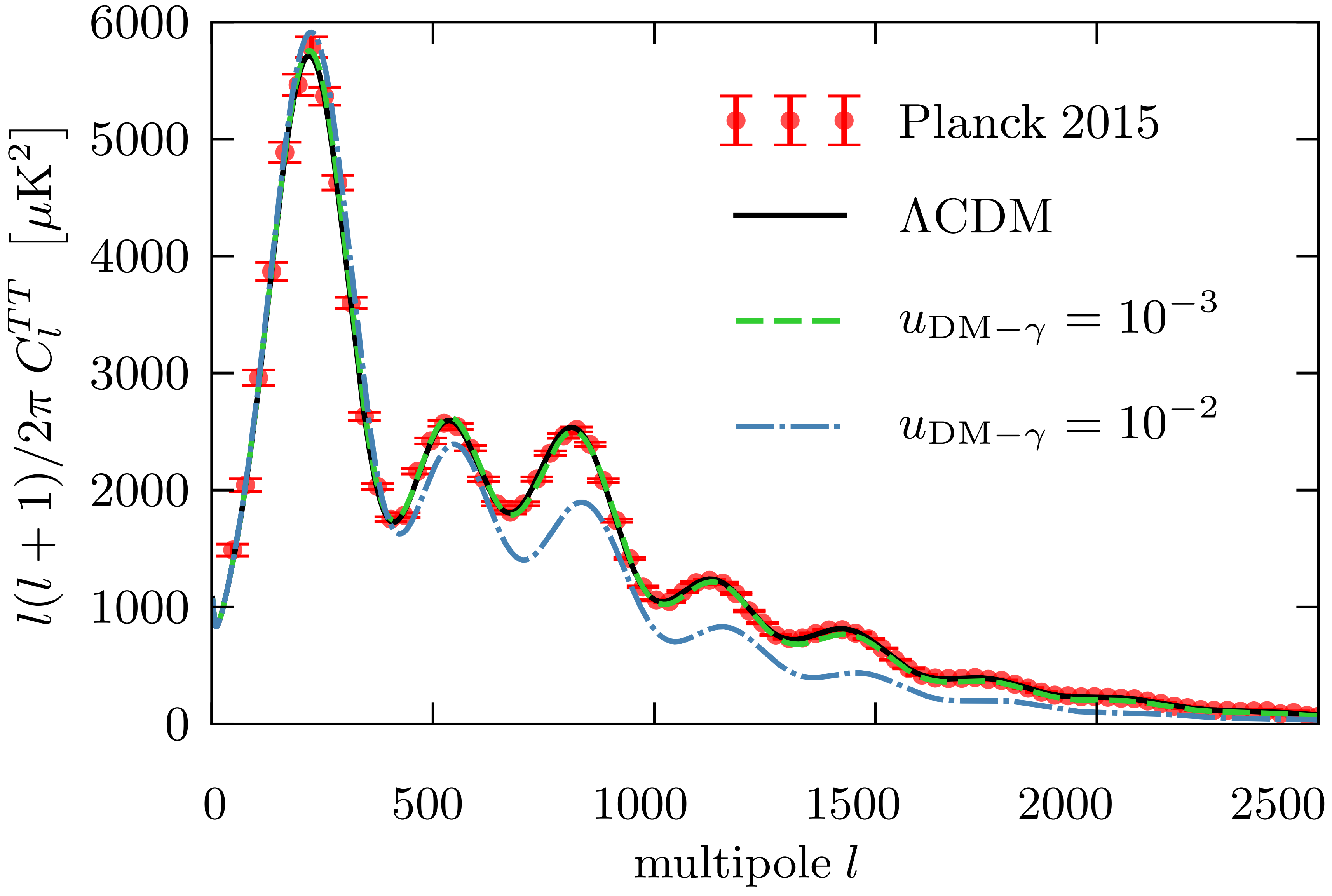
CMB / Primordial abundance: mdm < 10 MeV

Also

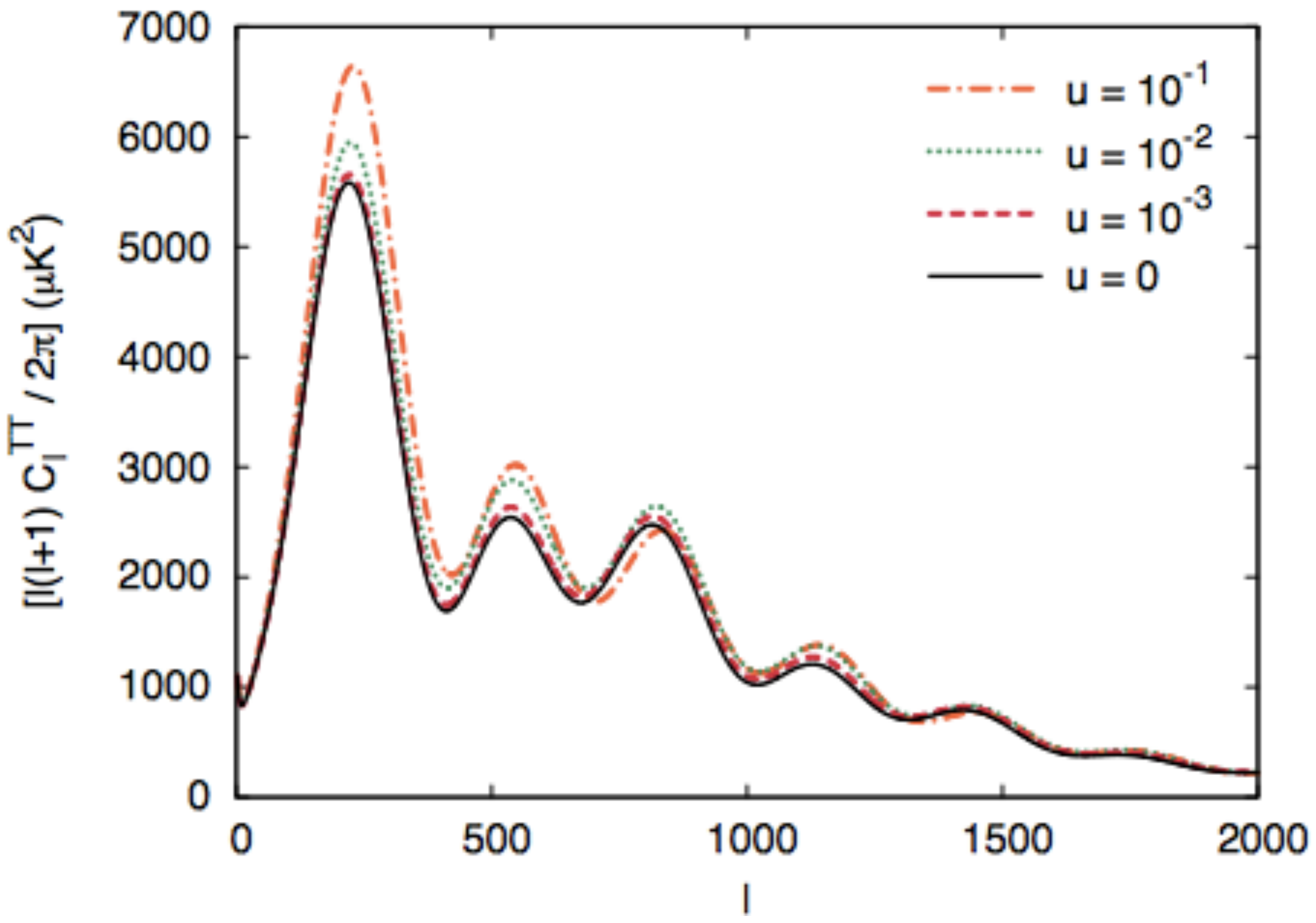
Electron g-2 (muon less stringent) mdm < 30 MeV
and in fact likely kills many "Astro" models

Cosmological implications of light dark matter

DM-photon interactions



DM-neutrino interactions



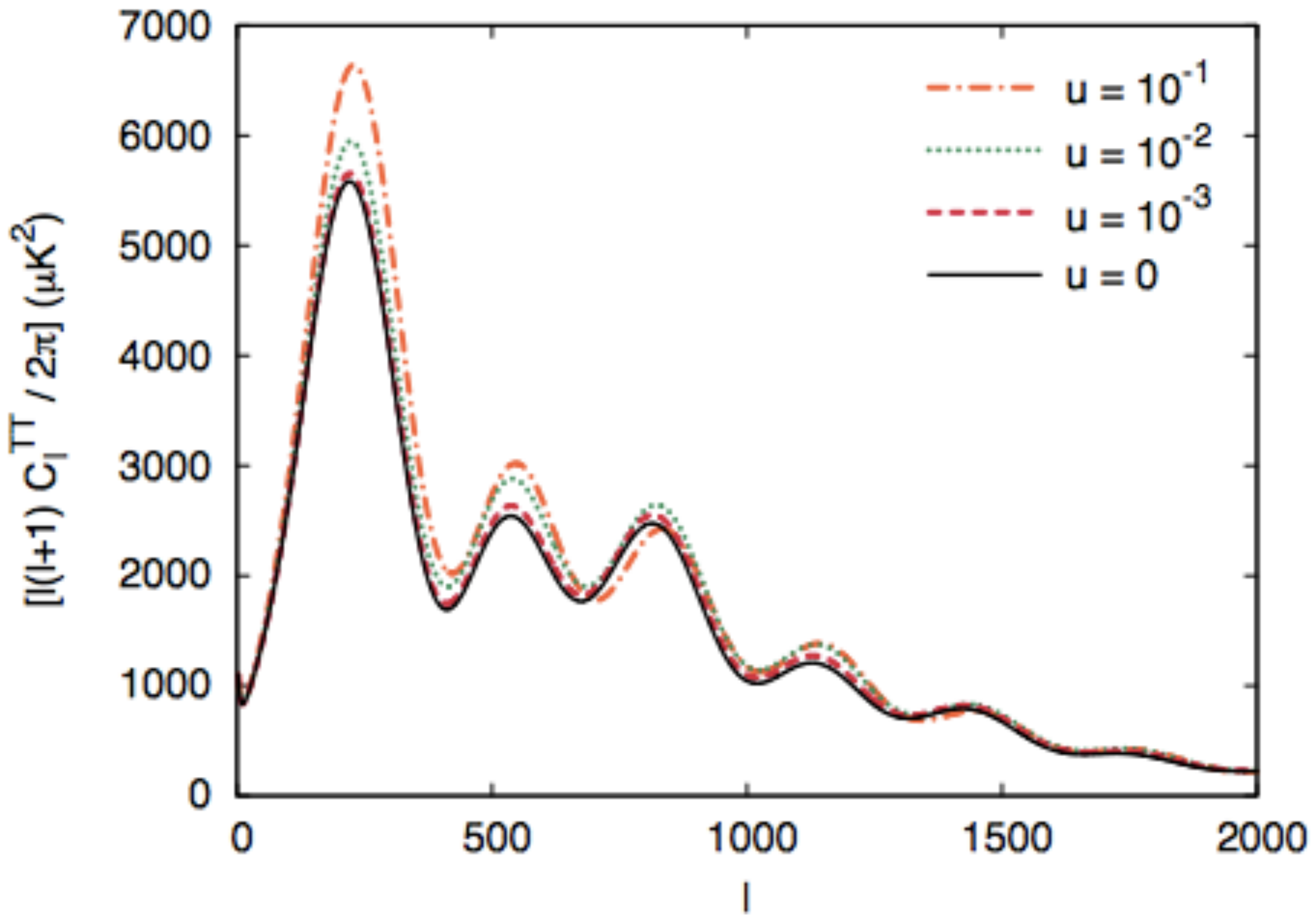
1401.7597

DM-b interactions

SIDM

Impact on cosmological parameters

DM-neutrino interactions



1401.7597

ΛCDM + u	+ $N_{\rm eff}$	+ $N_{\rm eff}$ + Σm_ν
Parameter	Planck TT + lowTEB + R16	Planck TT + lowTEB + R16
$\Omega_b h^2$	$0.02278^{+0.00026}_{-0.00025}$	0.02278 ± 0.00027
$\Omega_c h^2$	$0.1238^{+0.0037}_{-0.0038}$	$0.1240^{+0.0035}_{-0.0045}$
τ	$0.099^{+0.019}_{-0.021}$	$0.100^{+0.023}_{-0.021}$
n_s	$0.9898^{+0.0088}_{-0.0094}$	$0.990^{+0.009}_{-0.010}$
$ln(10^{10}A_s)$	$3.143^{+0.041}_{-0.039}$	$3.145^{+0.054}_{-0.037}$
$H_0[\mathrm{Km\,s^{-1}\,Mpc^{-1}}]$	$72.1^{+1.5}_{-1.7}$	$71.9^{+1.6}_{-1.8}$
σ_8	$0.850^{+0.024}_{-0.018}$	$0.846^{+0.030}_{-0.025}$
u	< -4.0	< -4.0
$N_{\rm eff}$	3.54 ± 0.20	$3.56^{+0.19}_{-0.26}$
$\Sigma m_\nu[eV]$	0.06	< 0.87

1710.02559

Dark matter-neutrino interactions

With neutrino mass hierarchy

2011.04206

	Planck TTTEEE	Planck + Lensing	Planck + BAO	Planck + Lensing + BAO
$100\,\omega_b$	$2.24^{+0.03}_{-0.04}$	$2.24^{+0.03}_{-0.03}$	$2.25^{+0.03}_{-0.03}$	$2.24^{+0.03}_{-0.03}$
ω_{DM}	$0.120^{+0.003}_{-0.003}$	$0.120^{+0.004}_{-0.001}$	$0.120^{+0.002}_{-0.003}$	$0.119^{+0.002}_{-0.002}$
$100\,\theta_s$	$1.0420^{+0.0009}_{-0.0005}$	$1.0419^{+0.0010}_{-0.0005}$	$1.0419^{+0.0011}_{-0.0004}$	$1.0419^{+0.0010}_{-0.0004}$
$\ln 10^{10} A_s$	$3.05^{+0.03}_{-0.04}$	$3.04^{+0.04}_{-0.02}$	$3.03^{+0.05}_{-0.02}$	$3.05^{+0.03}_{-0.03}$
n_s	$0.963^{+0.009}_{-0.012}$	$0.965^{+0.006}_{-0.014}$	$0.966^{+0.008}_{-0.009}$	$0.967^{+0.007}_{-0.010}$
τ_{reio}	$0.055^{+0.016}_{-0.016}$	$0.0528^{+0.019}_{-0.012}$	$0.048^{+0.026}_{-0.006}$	$0.057^{+0.017}_{-0.014}$
u_χ	$3.97 \cdot 10^{-4}$	$3.83 \cdot 10^{-4}$	$3.83 \cdot 10^{-4}$	$3.34 \cdot 10^{-4}$
$\sum m_\nu$ [eV]	0.33	0.26	0.15	0.14
H_0 [km/s/Mpc]	$67.2^{+1.2}_{-3.3}$	$67.3^{+0.9}_{-2.9}$	$67.5^{+1.2}_{-0.9}$	$67.6^{+1.0}_{-1.0}$
σ_8	$0.80^{+0.01}_{-0.09}$	$0.79^{+0.03}_{-0.06}$	$0.80^{+0.02}_{-0.07}$	$0.81^{+0.01}_{-0.06}$

Table 3. Best fit values with 95% confidence limits for the case of varying neutrino mass, except for u_χ and $\sum m_\nu$, where 95% CL upper limits are shown.

$$\frac{\sigma_0}{\sigma_{Th}} \left(\frac{m_\chi}{100\text{GeV}}\right)^{-1} \leq 3.34 \cdot 10^{-4}$$

$$\sigma < 2\ 10^{-33} \left(\frac{m_{DM}}{MeV}\right)\ cm^2$$

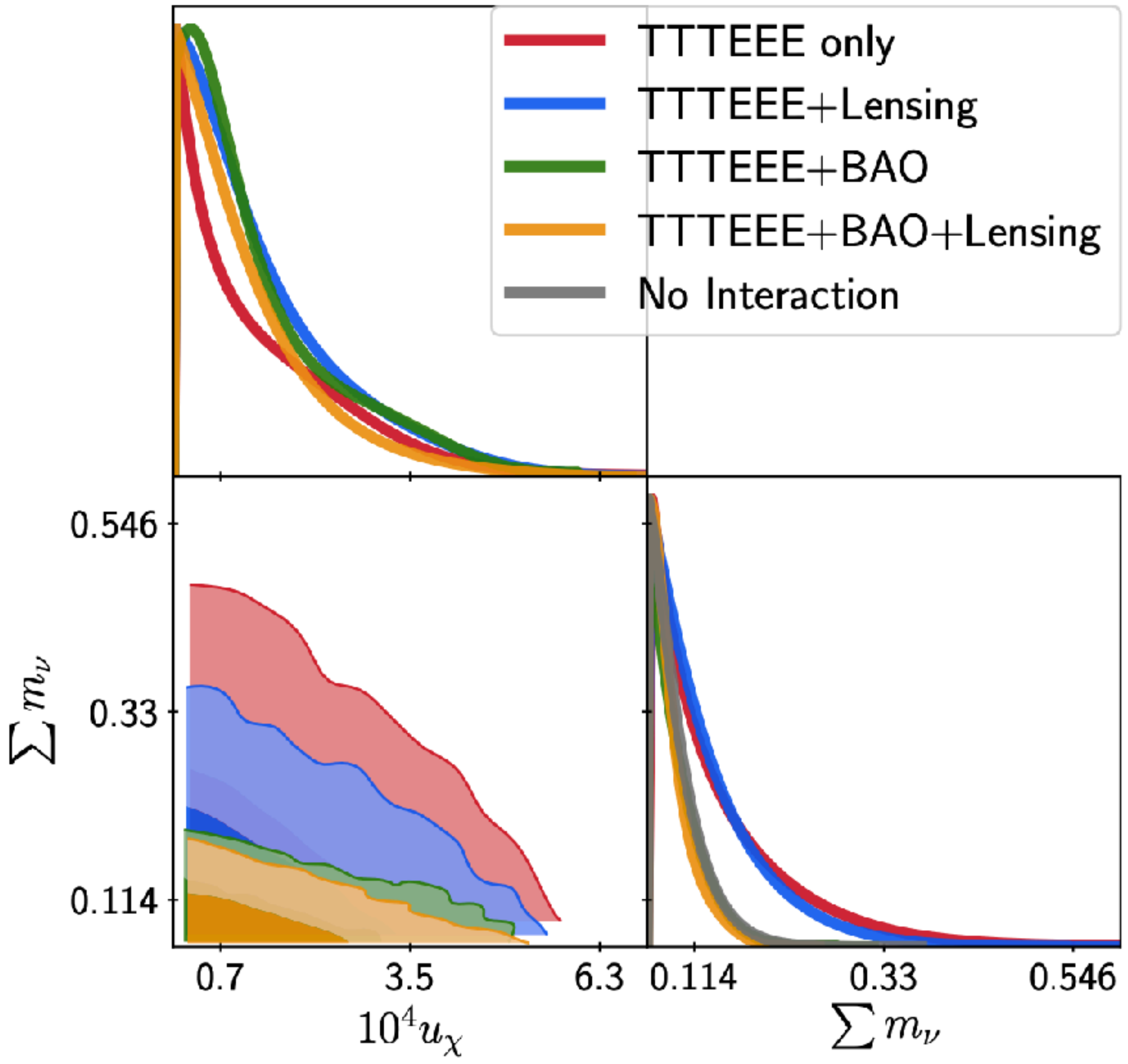
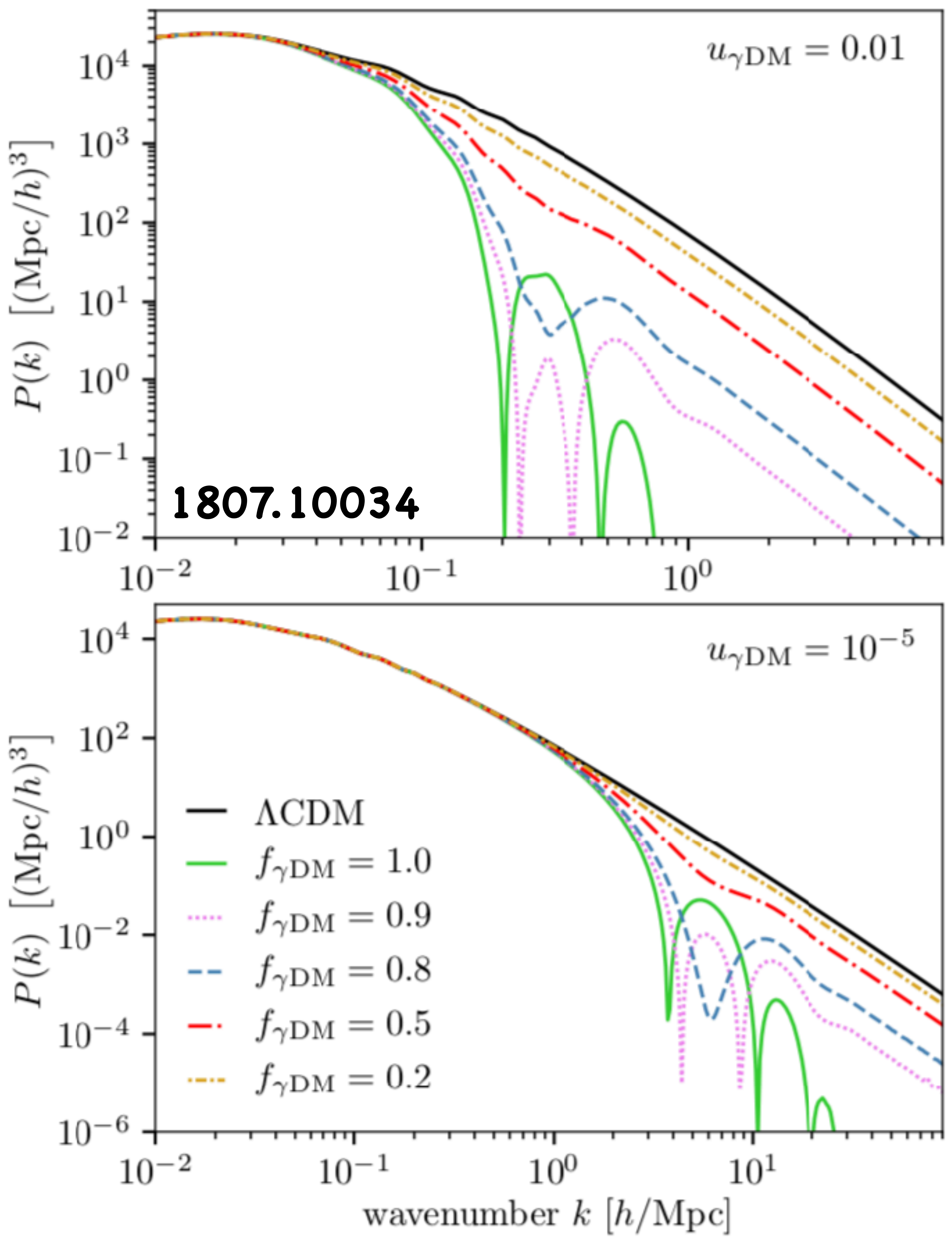
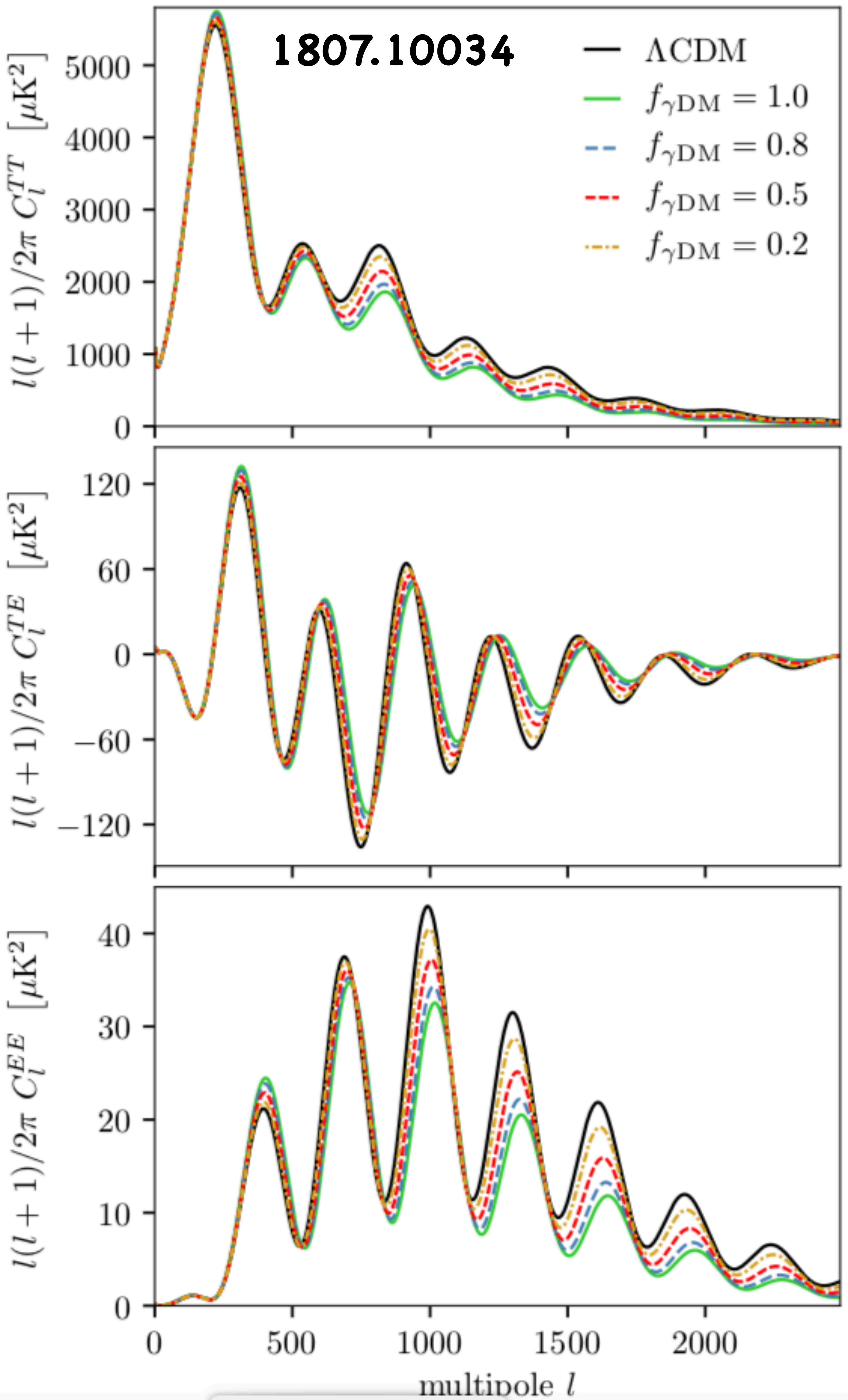


Figure 3. One-dimensional posterior probability distributions for u_χ and $\sum m_\nu$ for different combination of datasets and two-dimensional 68% and 95% CL allowed regions in the (u_χ,$\sum m_\nu$) plane. The 'Non-Interacting' posterior uses all the three datasets, that is, Planck CMB TTTEEE+ Planck CMB Lensing + BAO.

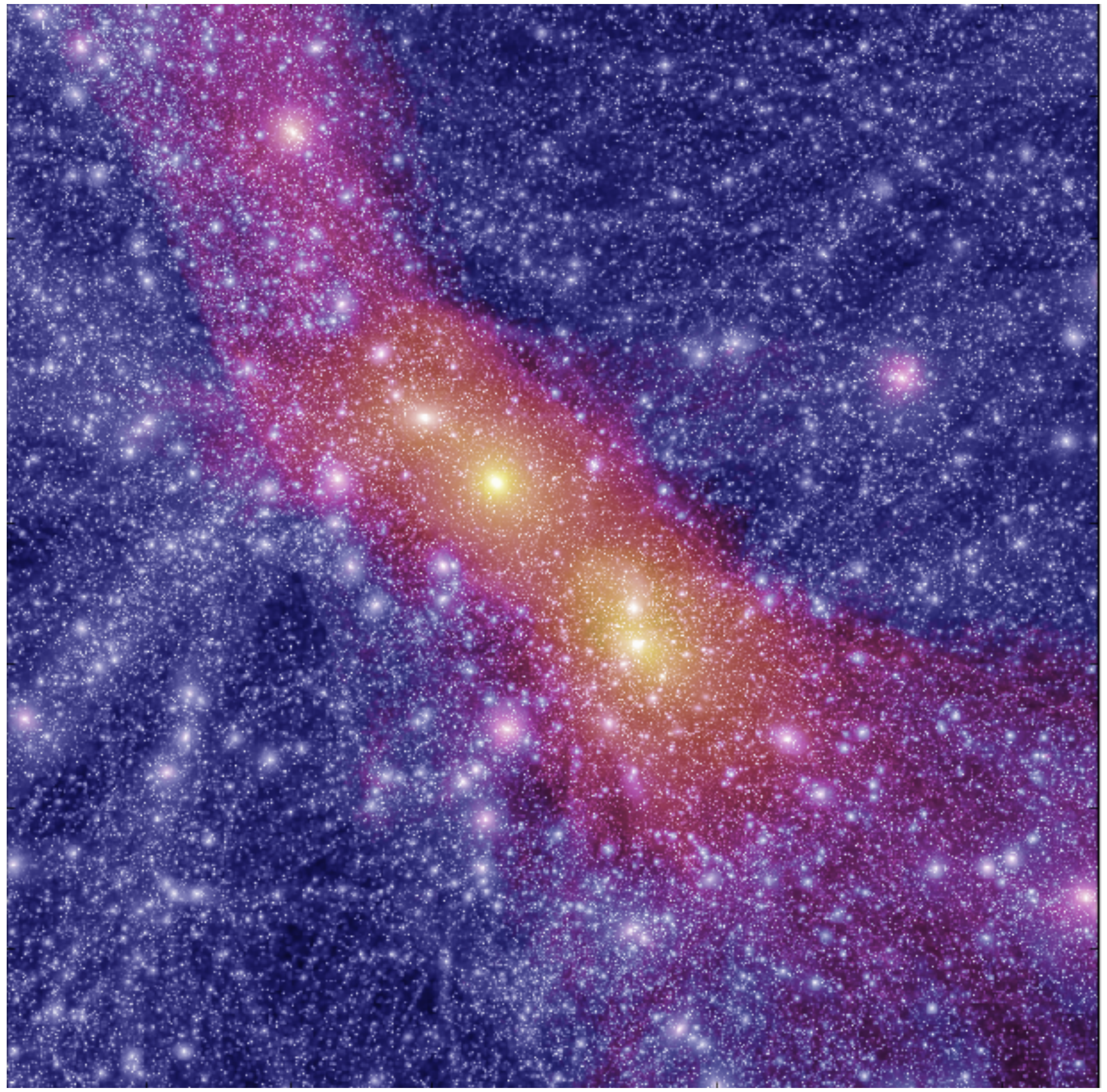
Mixed Scenarios

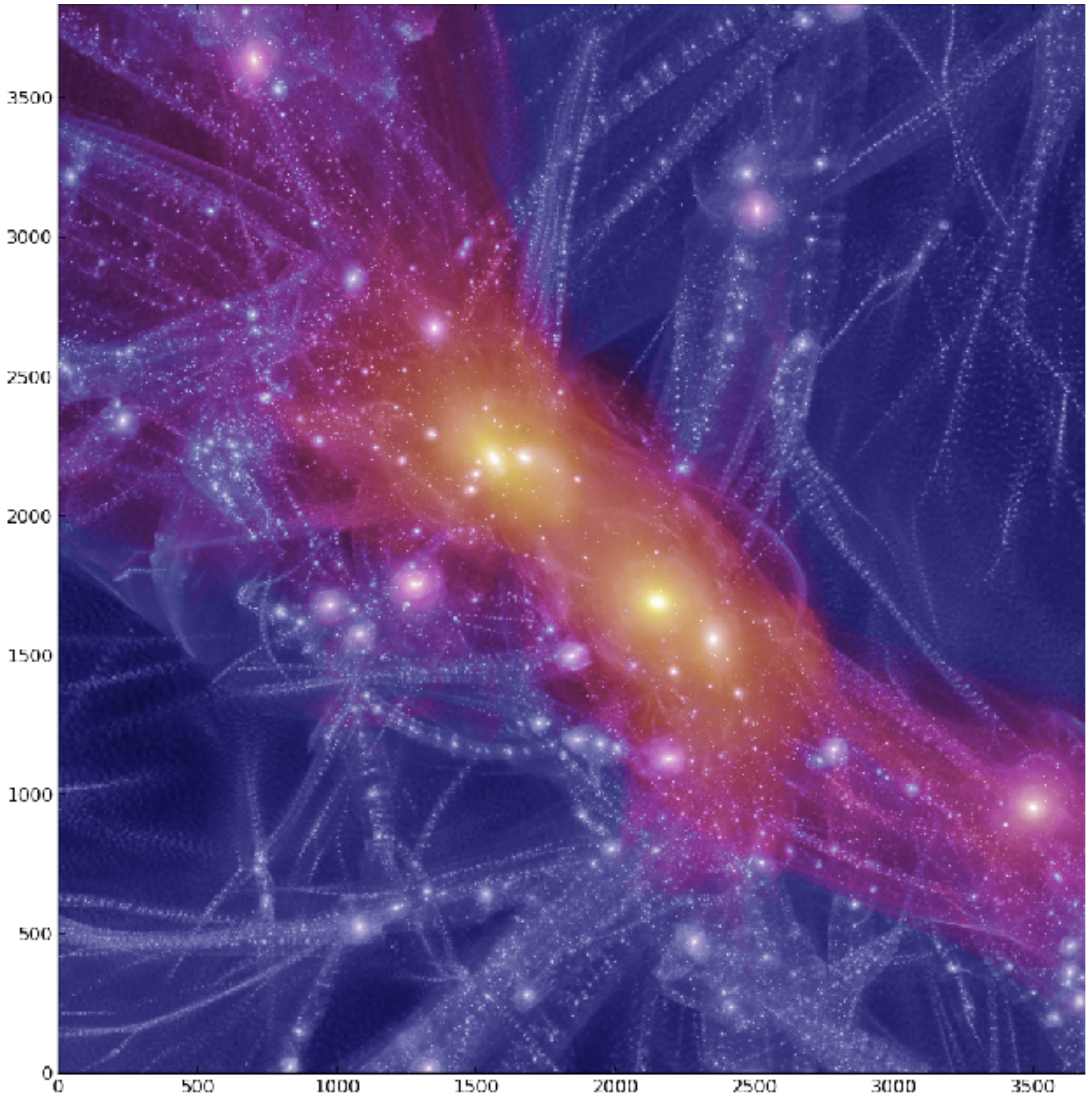




Dark Matter interactions & large scales

CDM | **IDM**



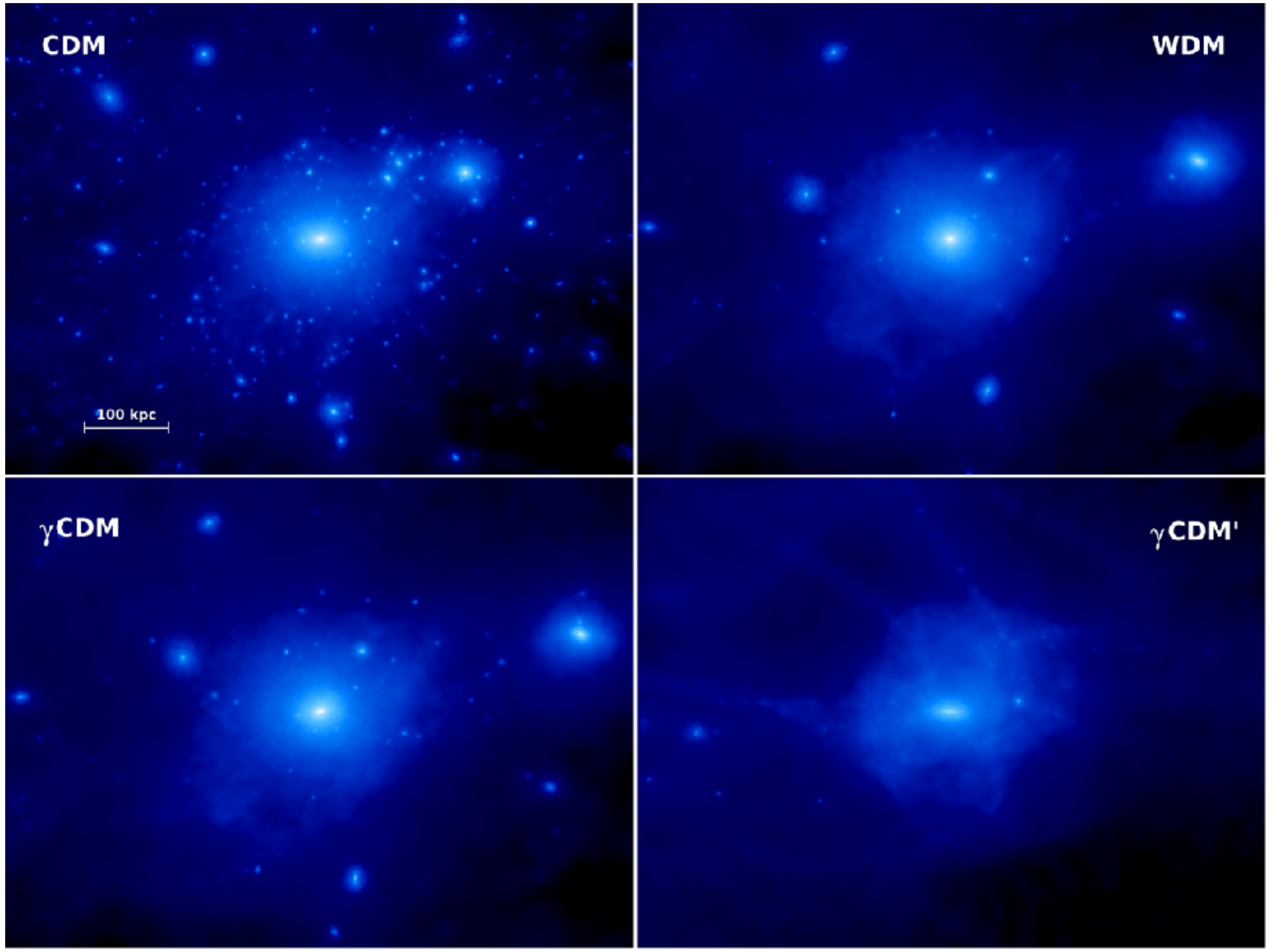


DM-SM [1404.7012]

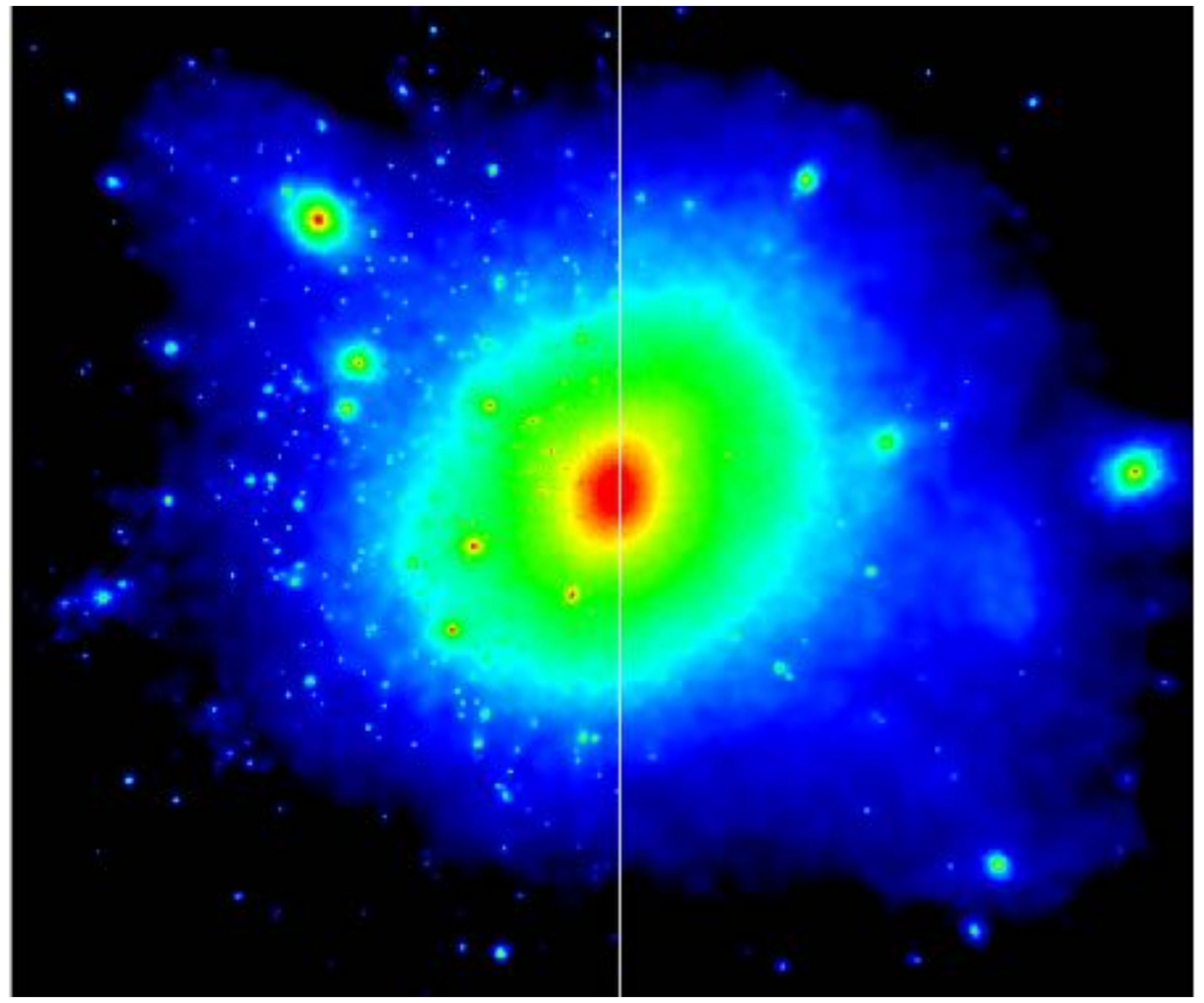
LSST, EUCLID will be essential!

The Milky Way in IDM scenarios

Less satellites

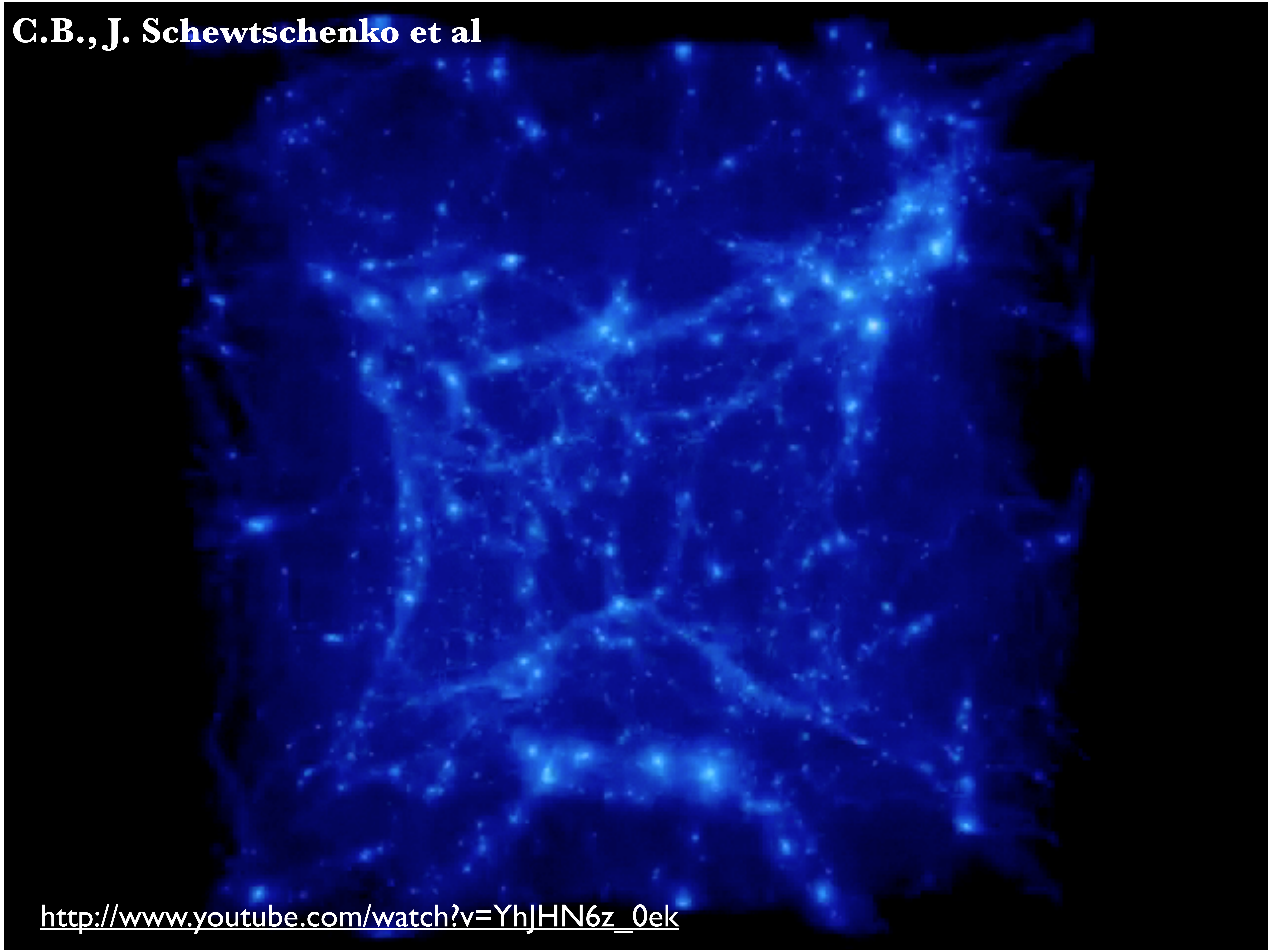


$$u_i = \frac{\sigma_{DM-i}}{\sigma_T}\left(\frac{m_{\mathrm{DM}}}{100\mathrm{GeV}}\right)^{-1}.$$



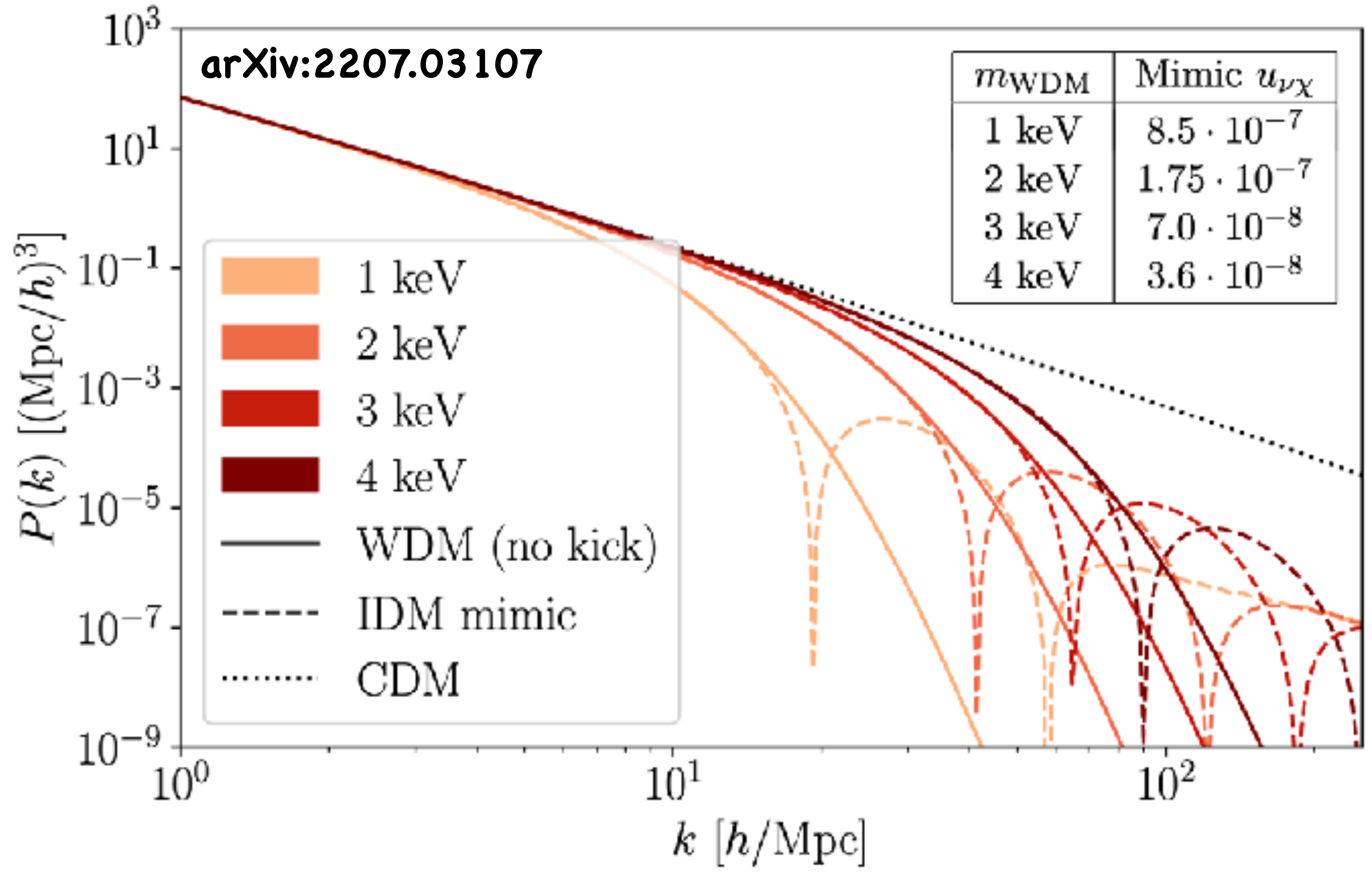
$$\sigma v \lesssim 10^{-36}\ \mathrm{cm}^2\ \left(\frac{\mathrm{m_{DM}}}{\mathrm{MeV}}\right)$$

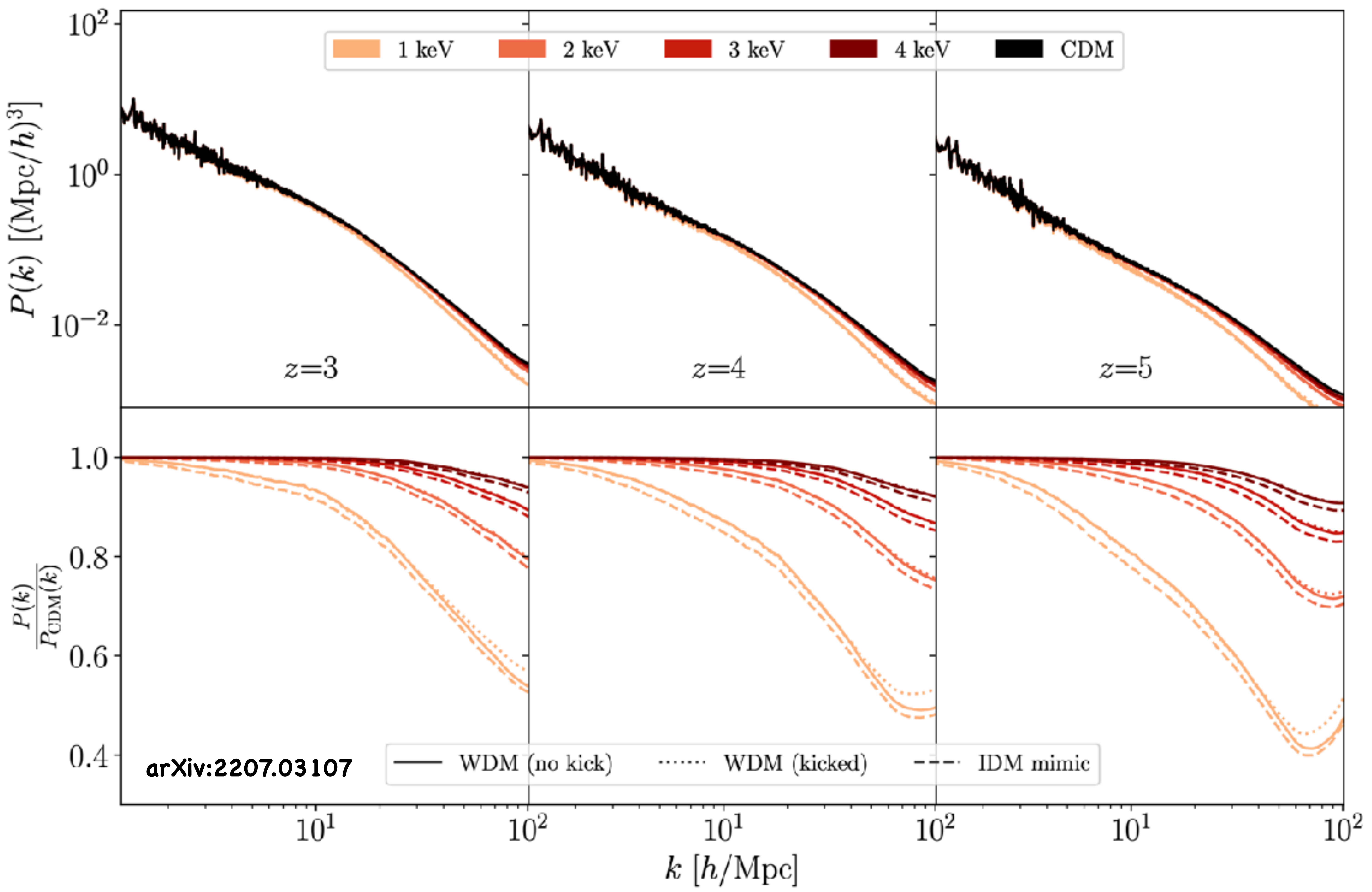
The Milky Way for interacting DM



How to probe Dark Matter interactions?

arXiv:2207.03107 in agreement with astro-ph/0309652





How to probe Dark Matter interactions?

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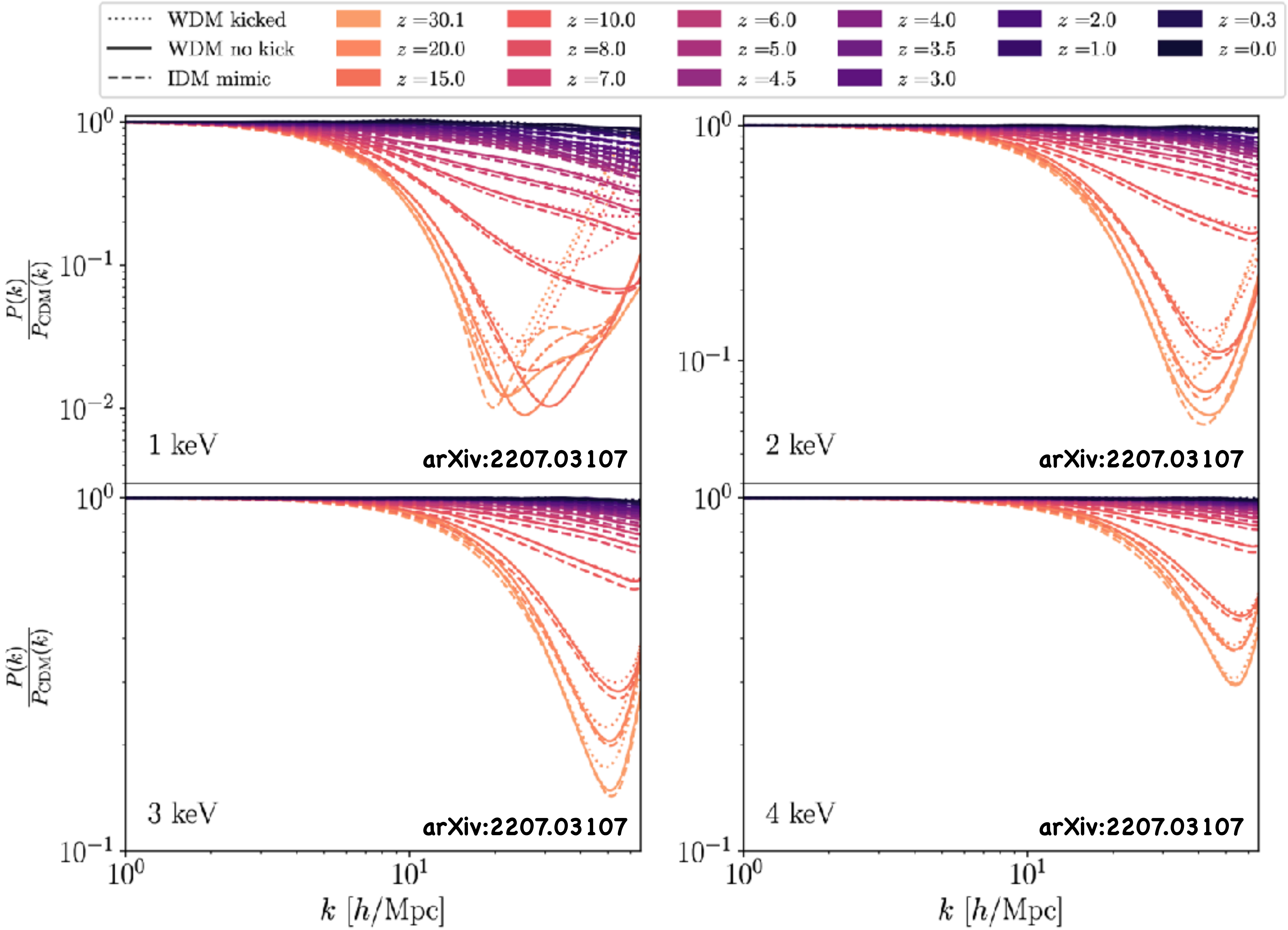

How to probe Dark Matter interactions?

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,**]

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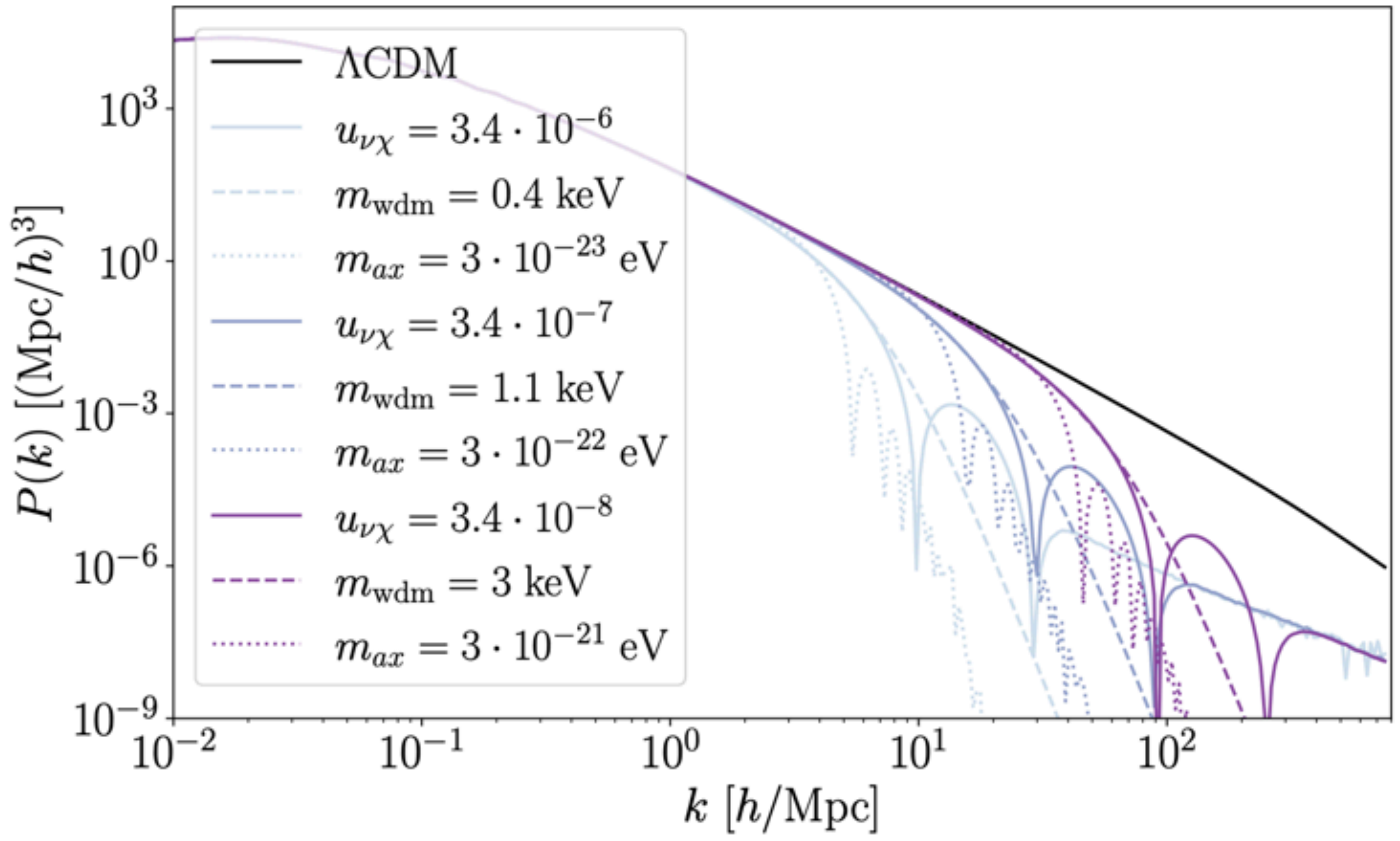
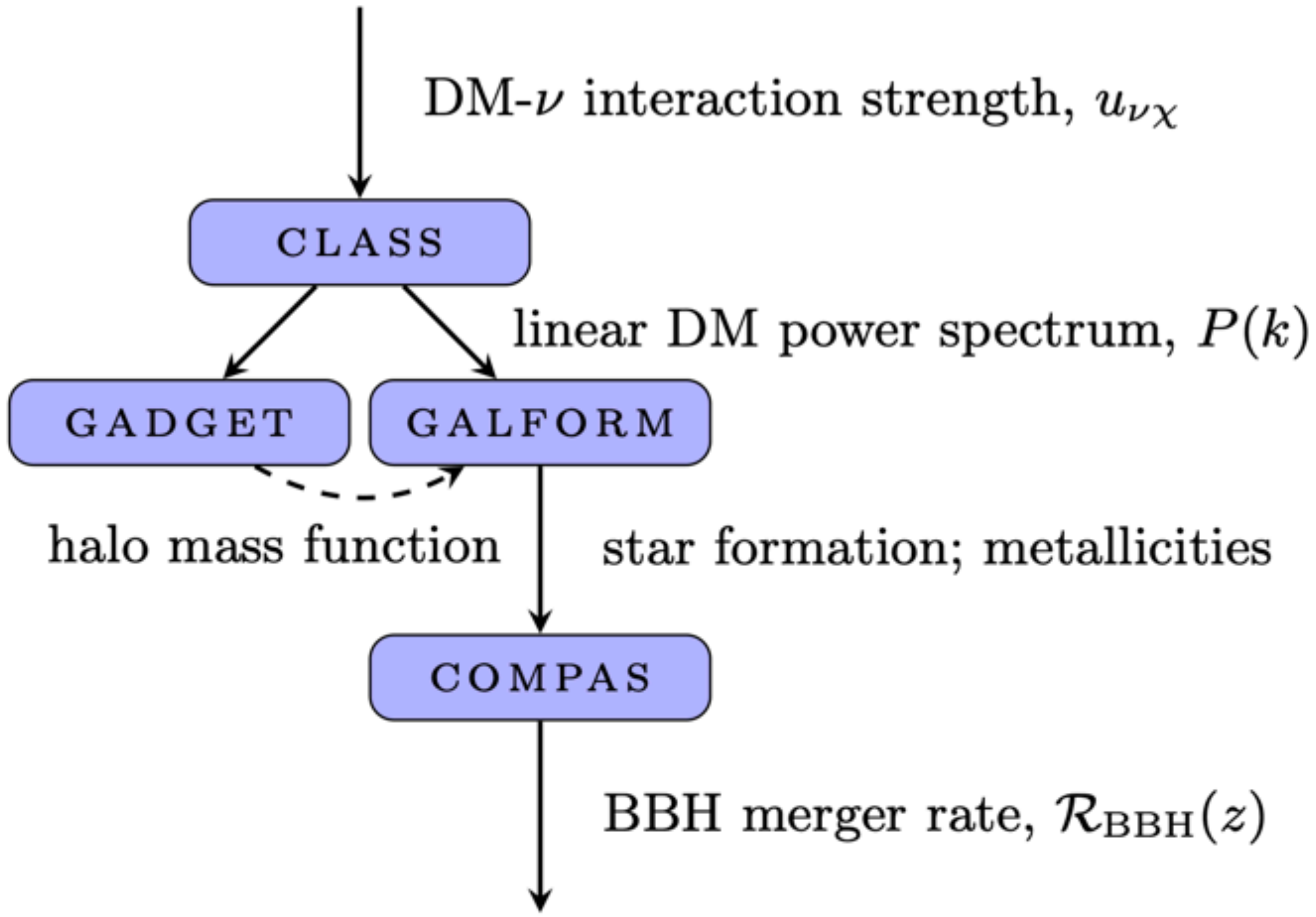
Sydney Consortium for Particle Physics and Cosmology
(Dated: 3 August 2022)

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 ΛCDM cosmological model.

How to probe Dark Matter interactions?

arXiv:2207.14126



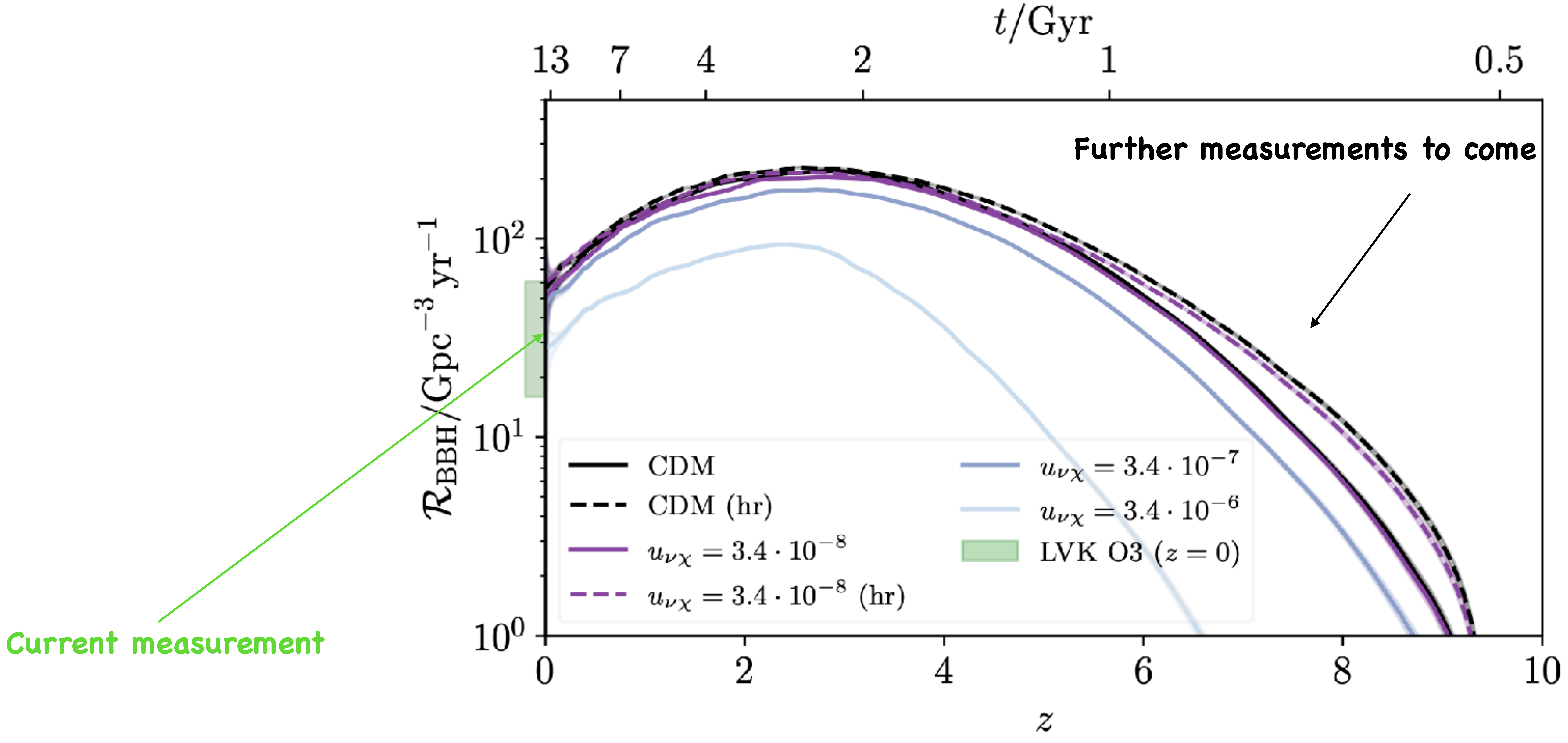


The BBH merger rate is thus essentially a delayed tracer of star formation, whose normalisation depends on the efficiency with which massive binary stars are converted into BBHs. This efficiency is mostly determined by the stellar metallicity.

We use a compas dataset of 20 million evolved binaries (resulting in ≈ 0.7 million BBHs) presented in [104], which is publicly available at [105]. This gives us the BBH formation efficiency as a function of initial mass and metallicity, as well as the delay time between star formation and BBH merger. By combining this with a model for the star formation rate density and metallicity distribution as functions of redshift, we can use the compas "cosmic integration" module [106] to average over the synthetic population and obtain the cosmic BBH merger rate
(i.e., the fraction of the stellar mass that is in elements heavier than helium).

How to probe Dark Matter interactions?

arXiv:2207.14126



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

Conclusion

- MeV-GeV range alive(?) but constrained?
- Was never properly investigated but things are changing
- Its fate relies on that of the mediators
- Cosmology is another powerful tool to constrain this mass range
- The DM-neutrinos interactions are the most promising in my opinion
- The Gravitational wave & higher redshift (SKA) tests will be critical