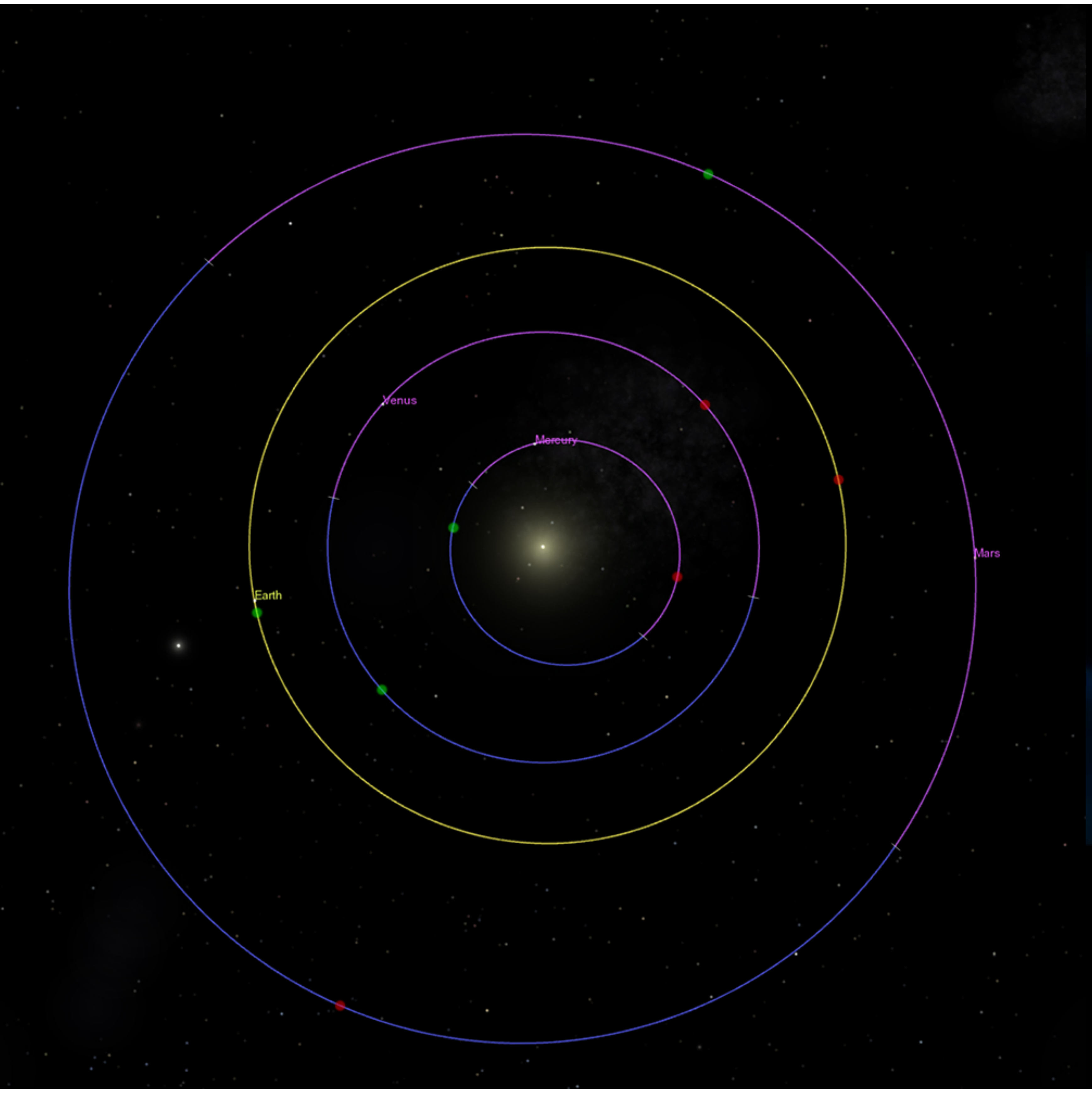
Light Dark Matter interactions:
From Large-Scale down to laboratory experiments

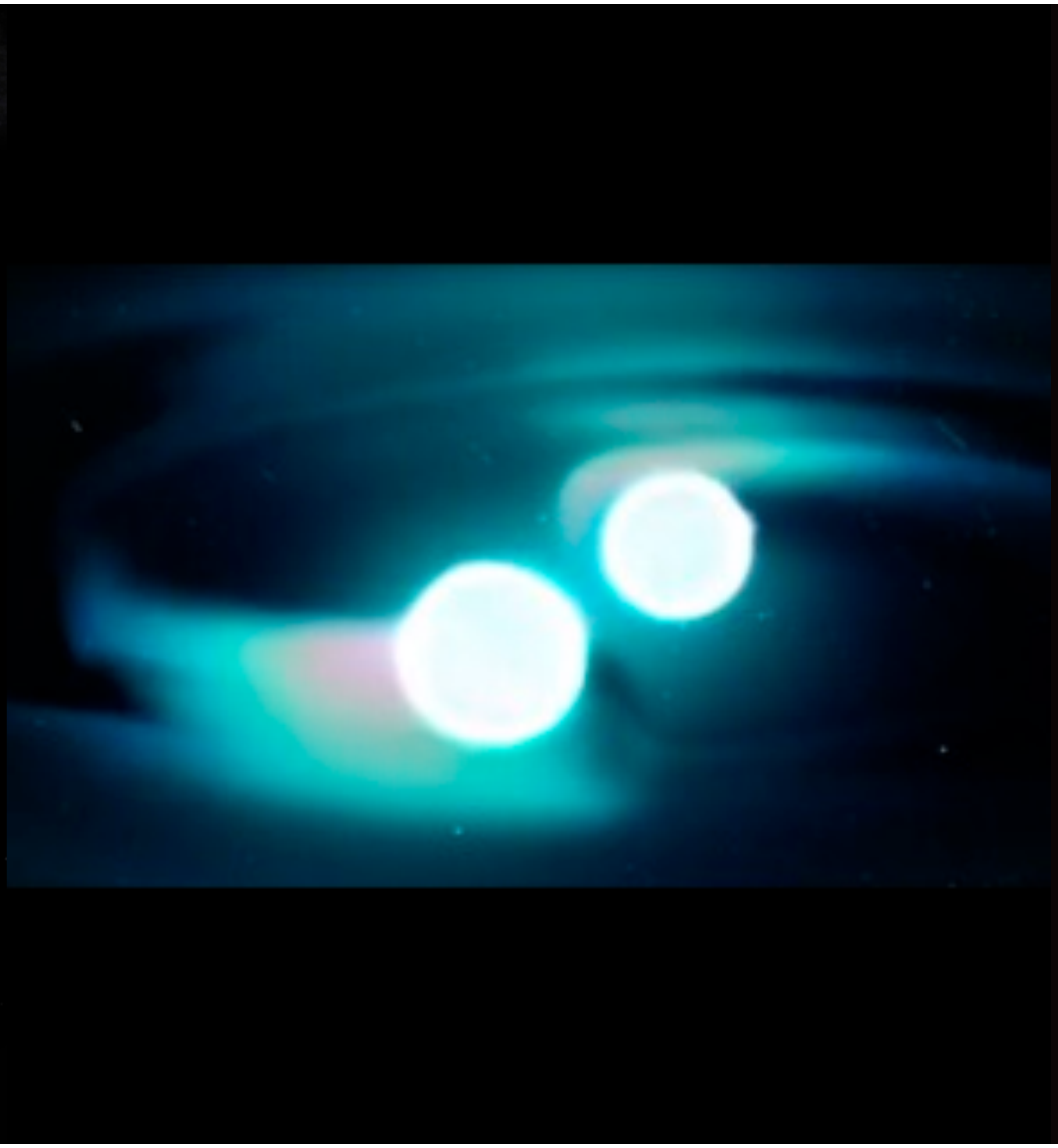
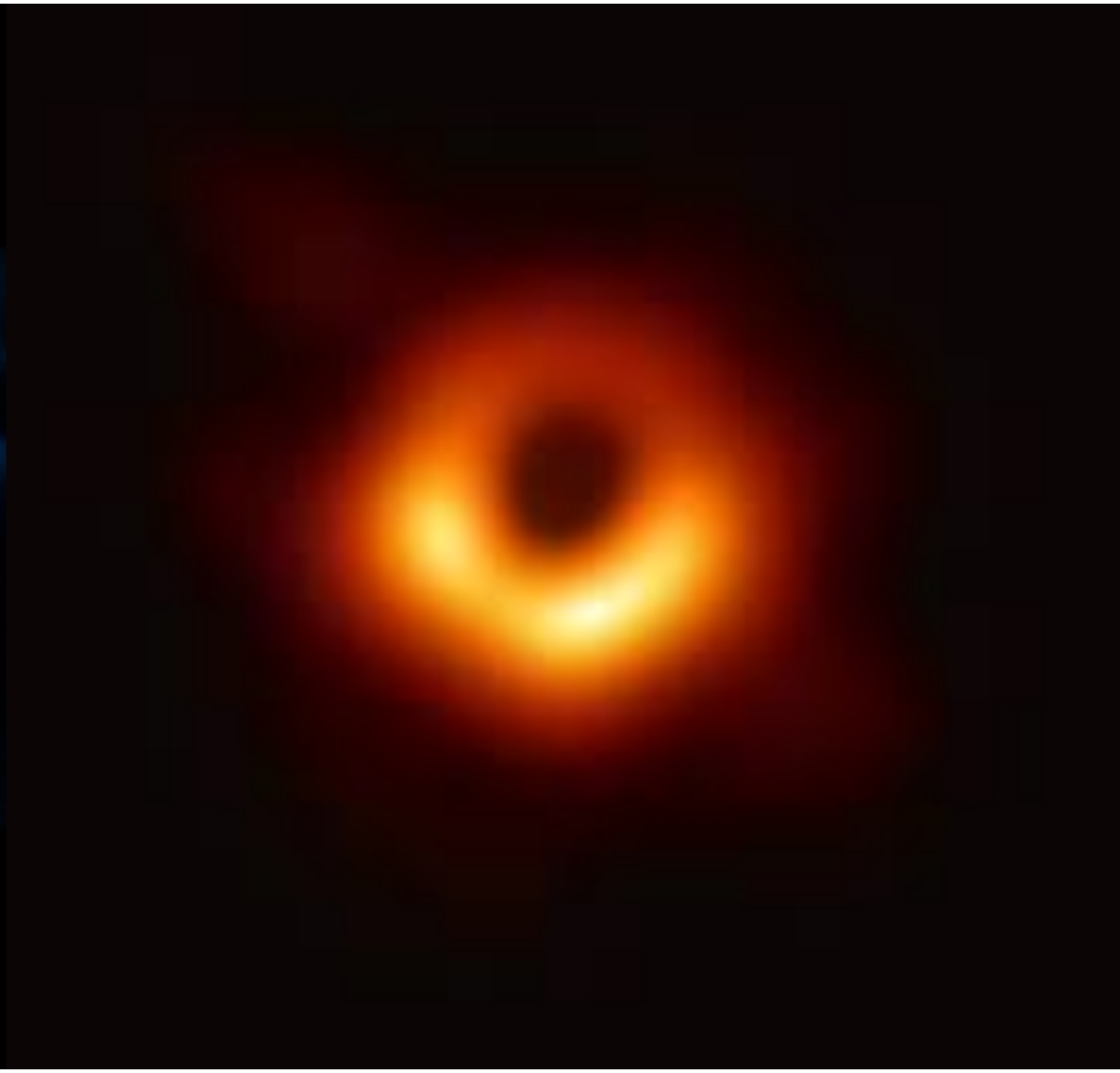
Celine Boehm

LDW, December 2021

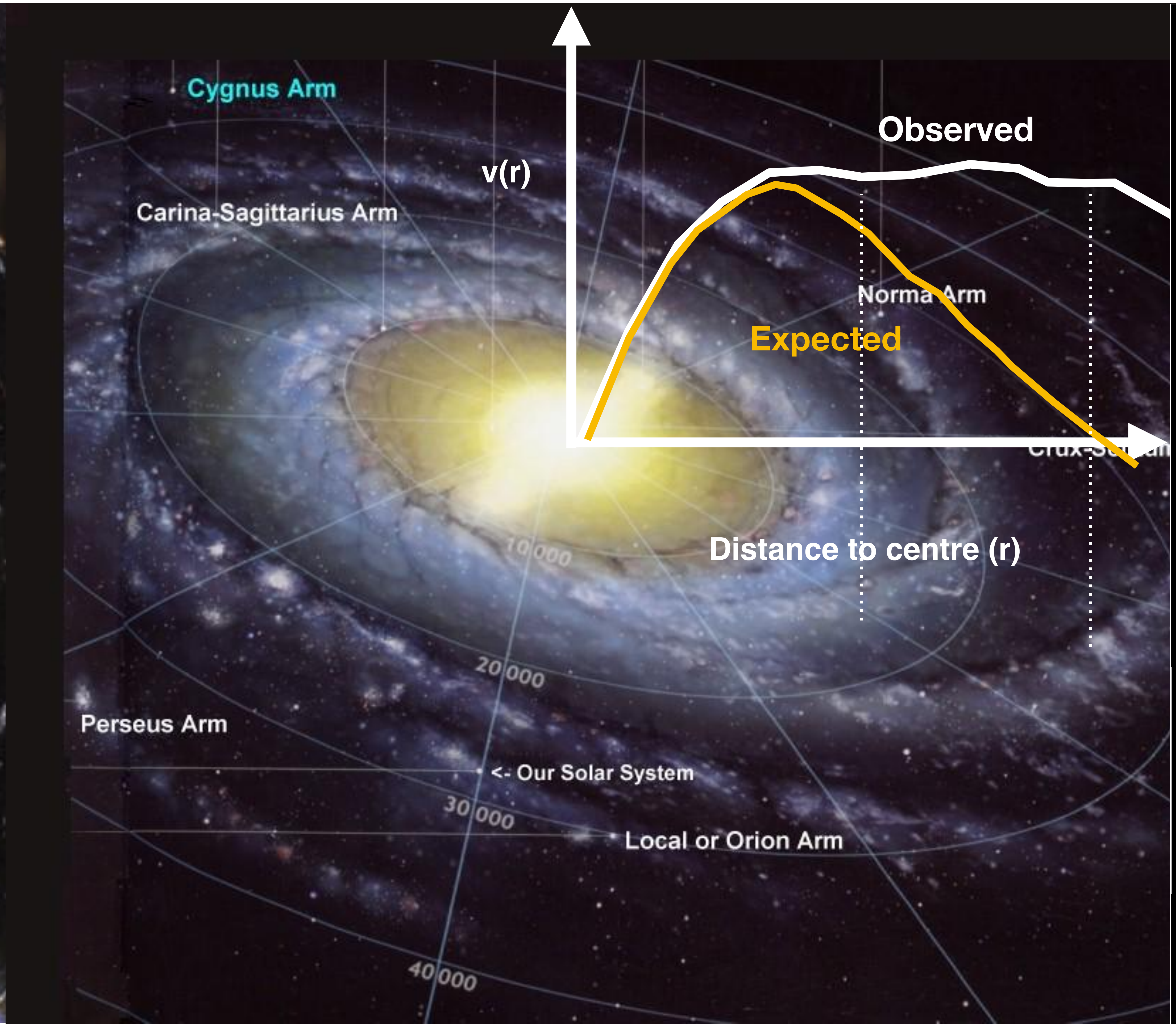
Photo courtesy Millie McDonald

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

Two popular solutions

"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

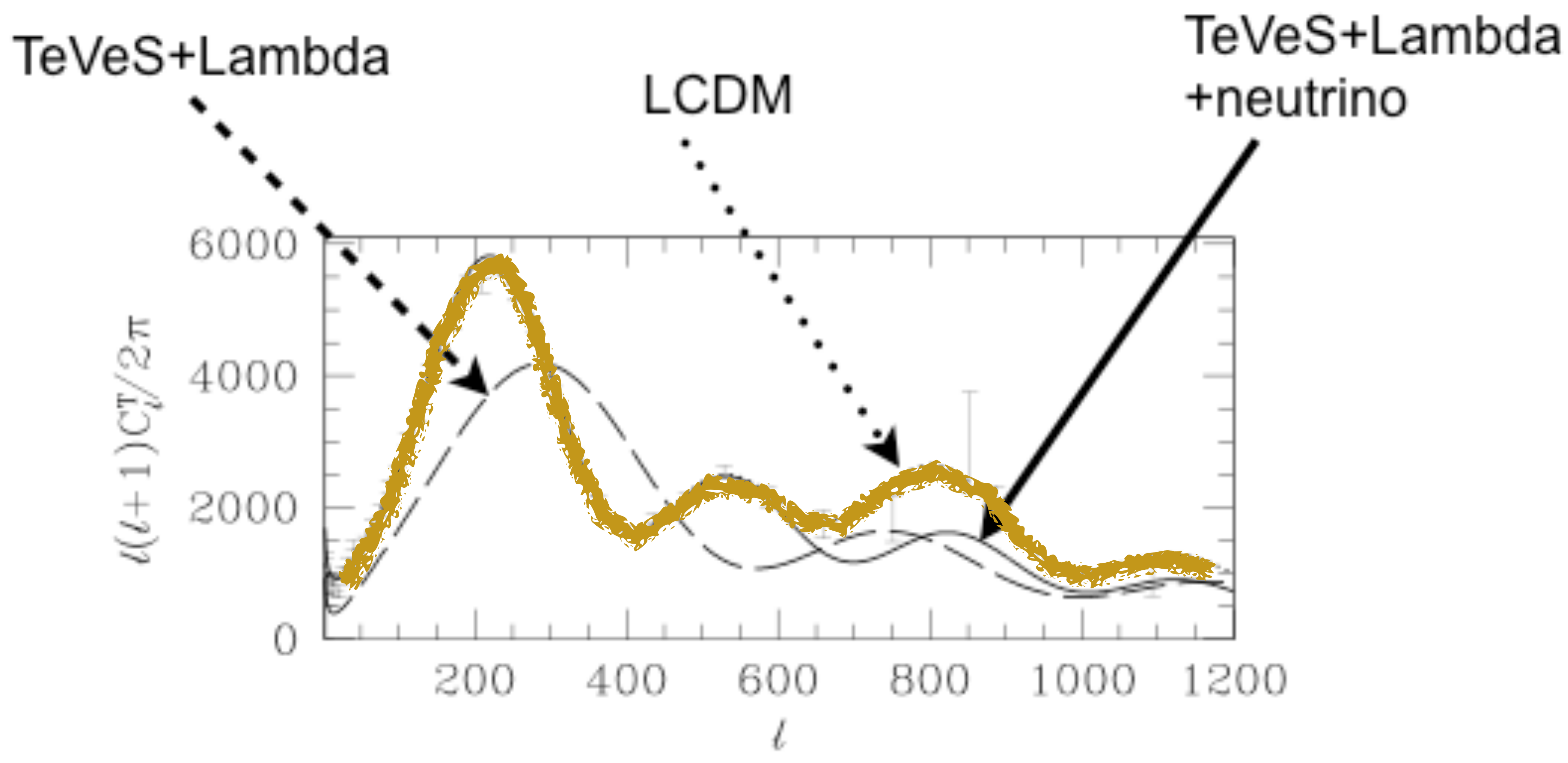
“Modified GR”

GR′ + SU(3)XSU(2)XU(1)

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

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

TEVES: astro-ph/0403694



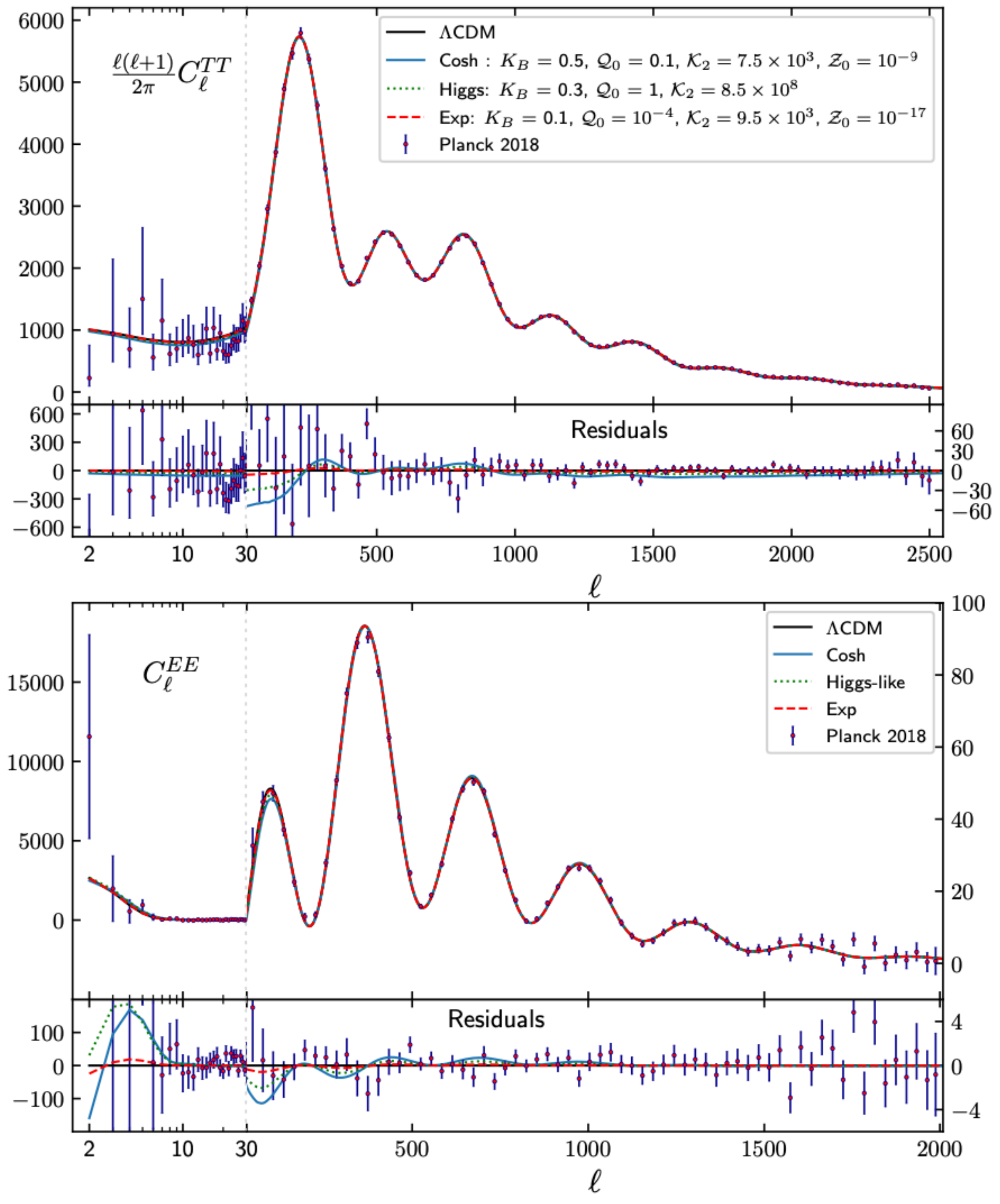
astro-ph/0505519

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

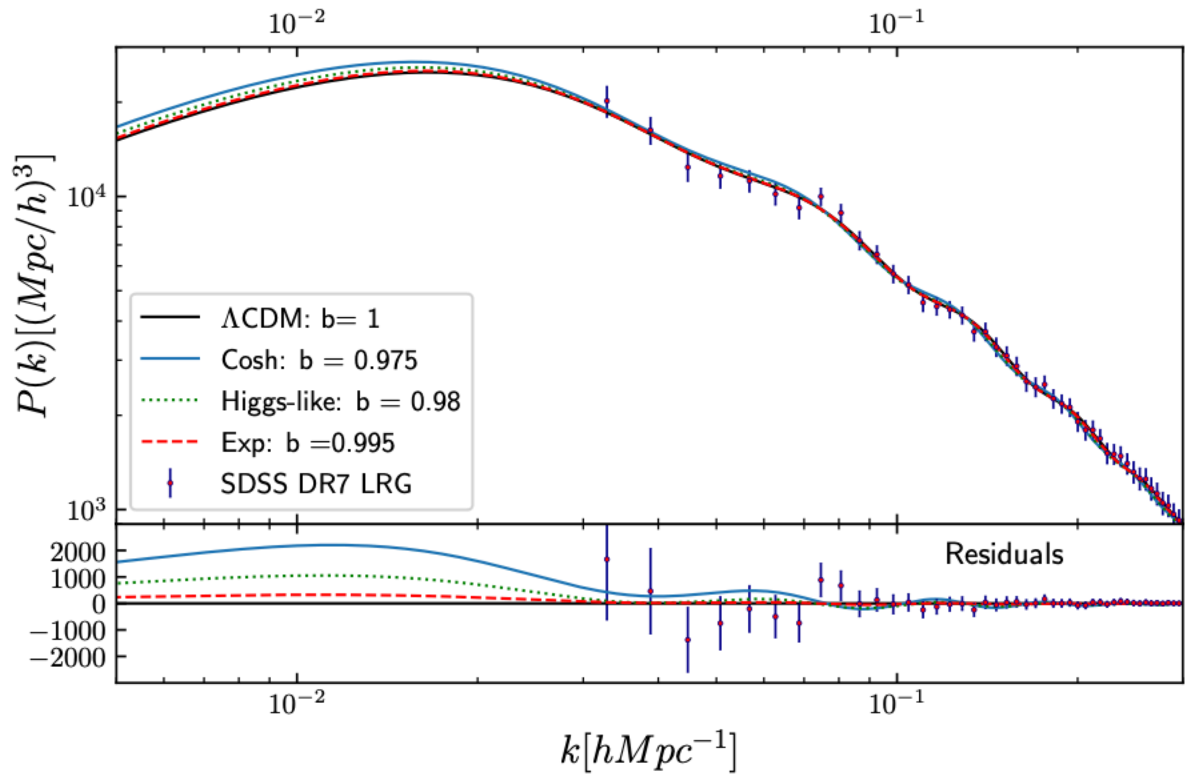
New Relativistic Theory for Modified Newtonian Dynamics

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



Zachary S. C. Picker,
University of Sydney

Thakurta solution- Kodama time

arXiv: 2008.10743

$$ds^2 = \left(1 - \frac{2m(r,t)}{r}\right) dt^2 + \frac{dr^2}{1 - 2m(r,t)/r} + r^2 \left\{d\theta^2 + \sin^2\theta \, d\phi^2\right\}$$

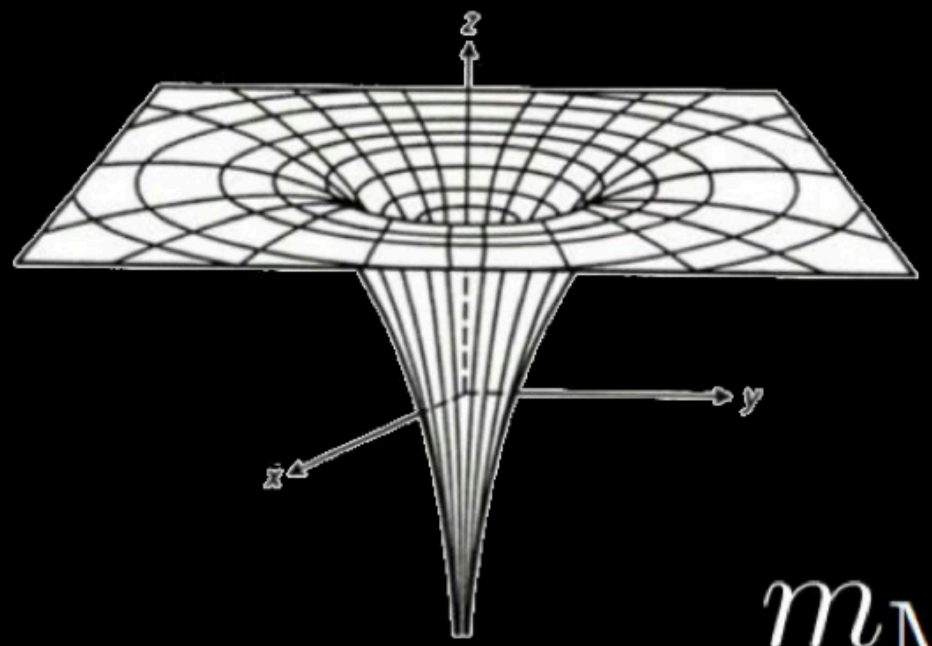
$$m_{\rm MS} = ma(t) + \frac{H^2 R^3}{2Gf(R)}$$

(30-100) M⊙ mass PBHs could be all the DM

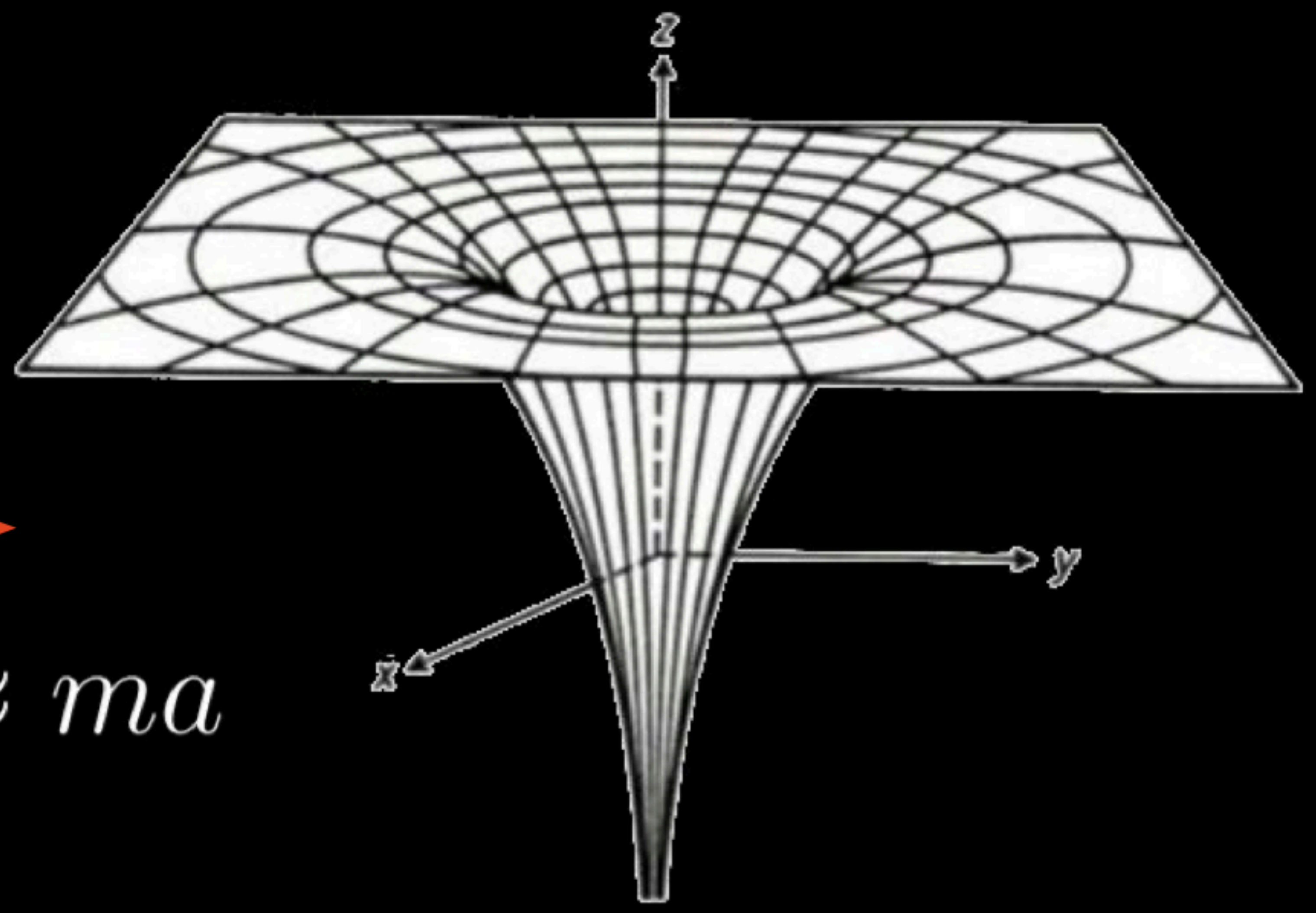
Zachary S. C. Picker,
University of Sydney

One simple example: The Thakurta metric, with a growing effective horizon

$$ds^2 = a^2 ds^2_{schw.}$$



$$m_{\rm Misner-Sharp} \approx ma$$



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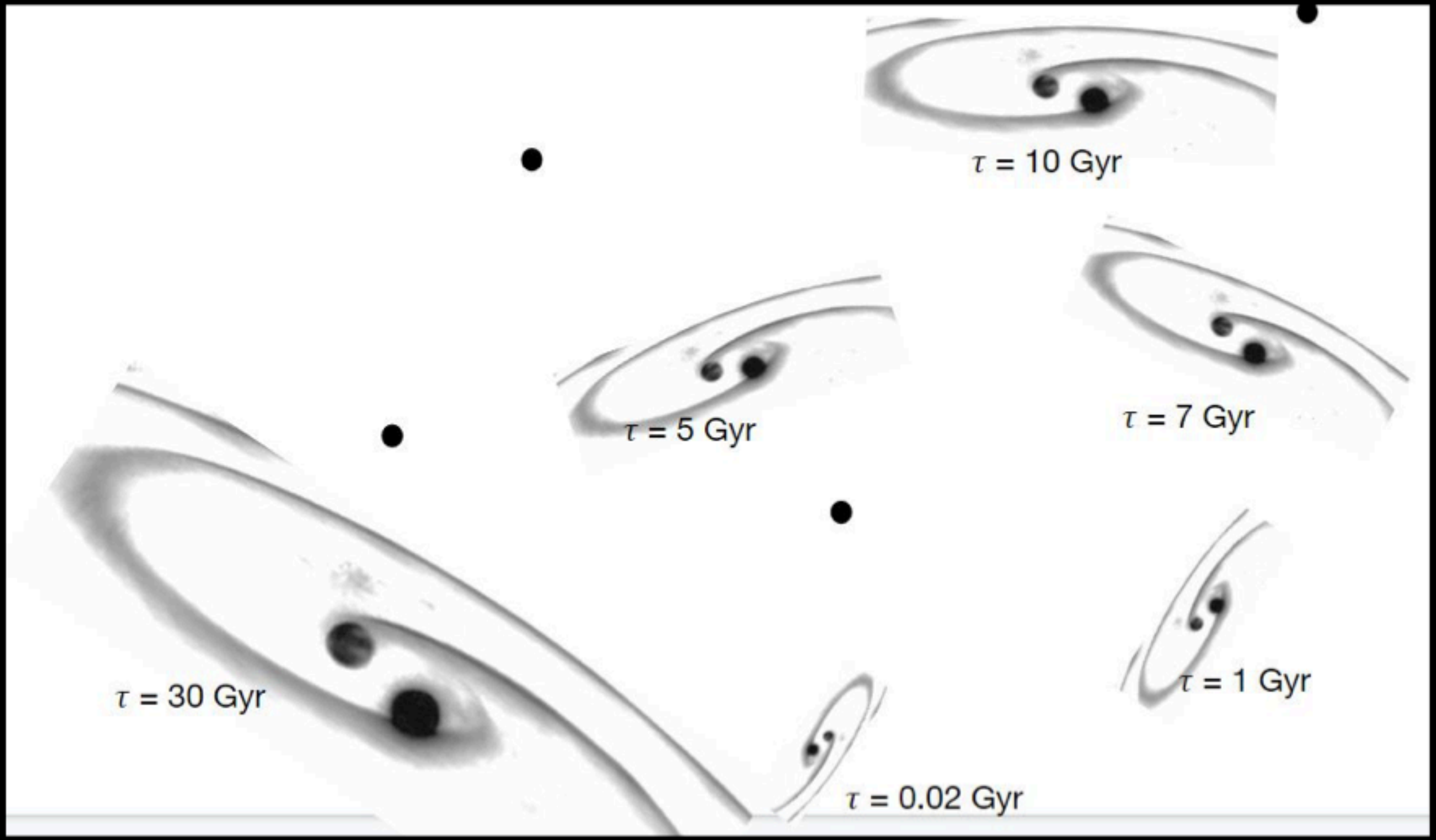
University of Sydney

Big change #1:
Thakurta black holes do not form binaries easily

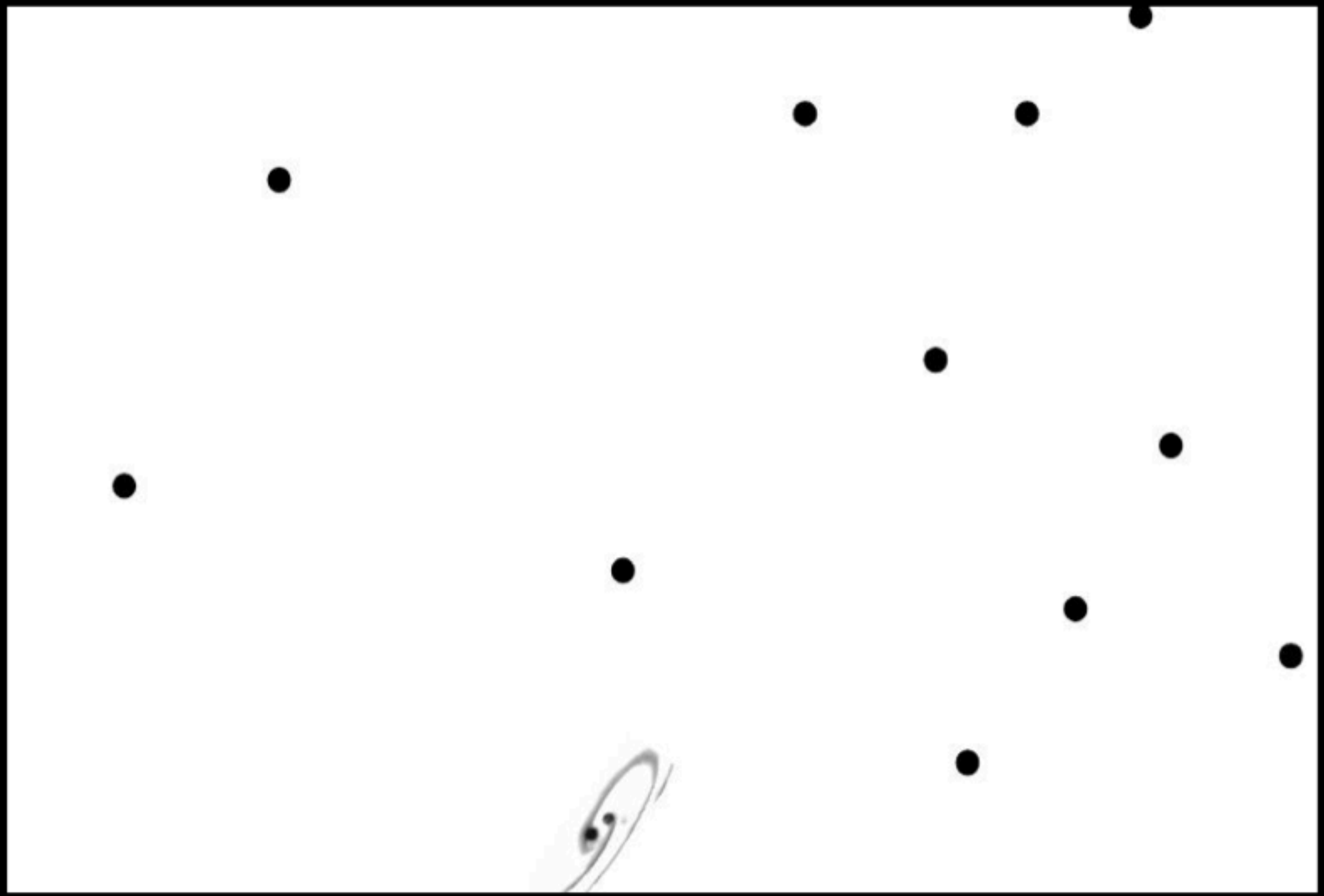
At matter radiation equality:

Schwarzschild black holes



Many of these coalesce today

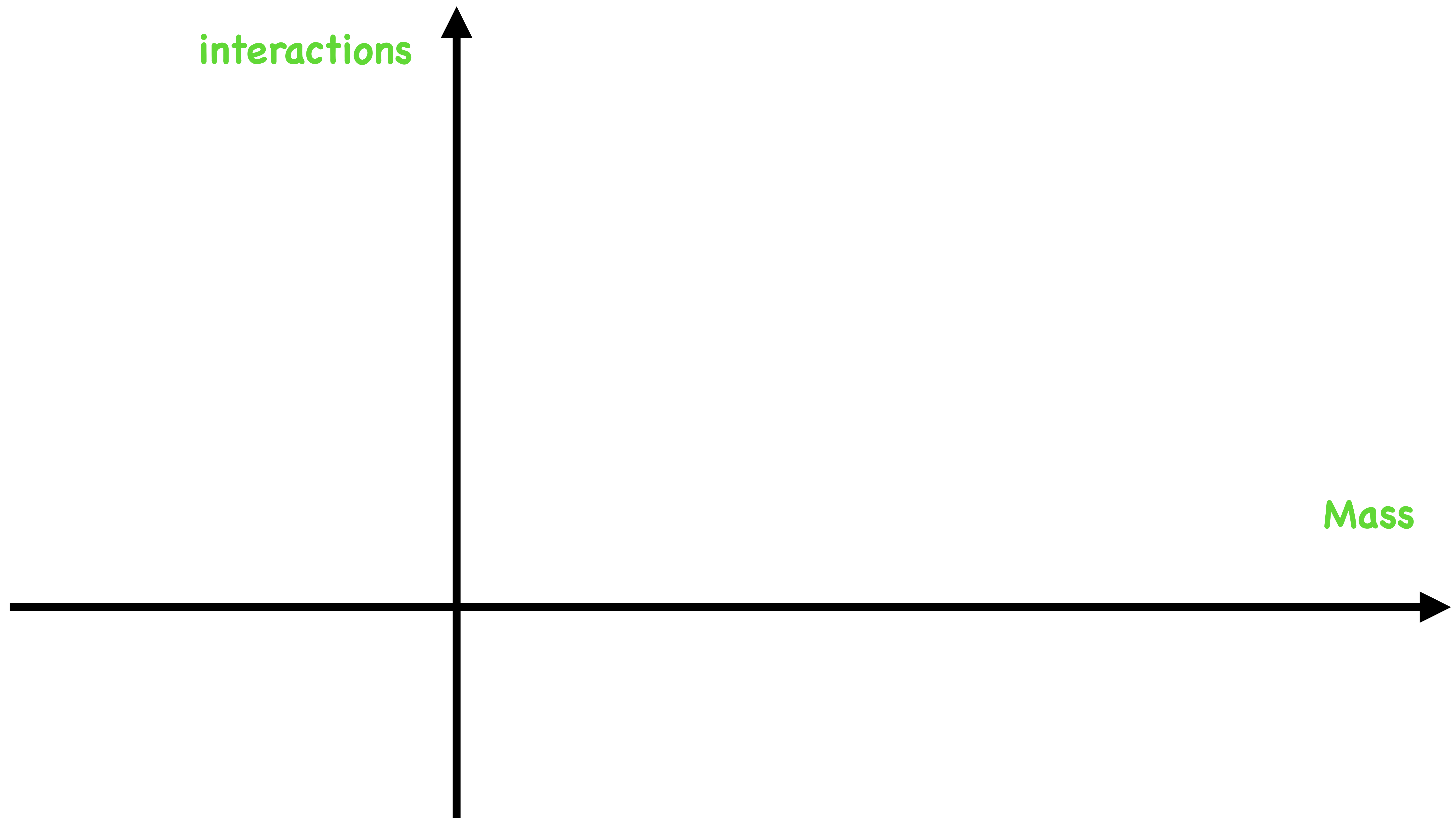
Thakurta black holes



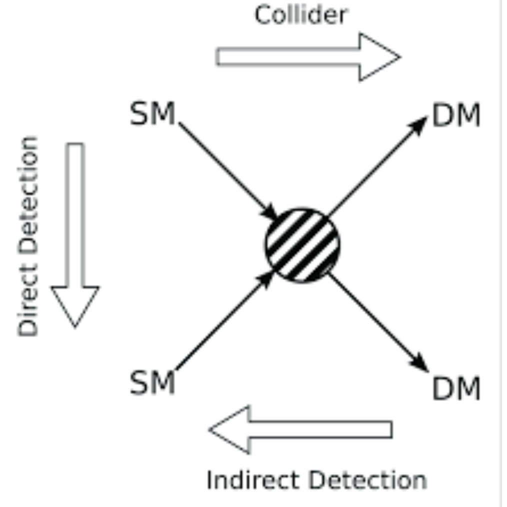
$\tau_{max} \sim 100$ sec (!)

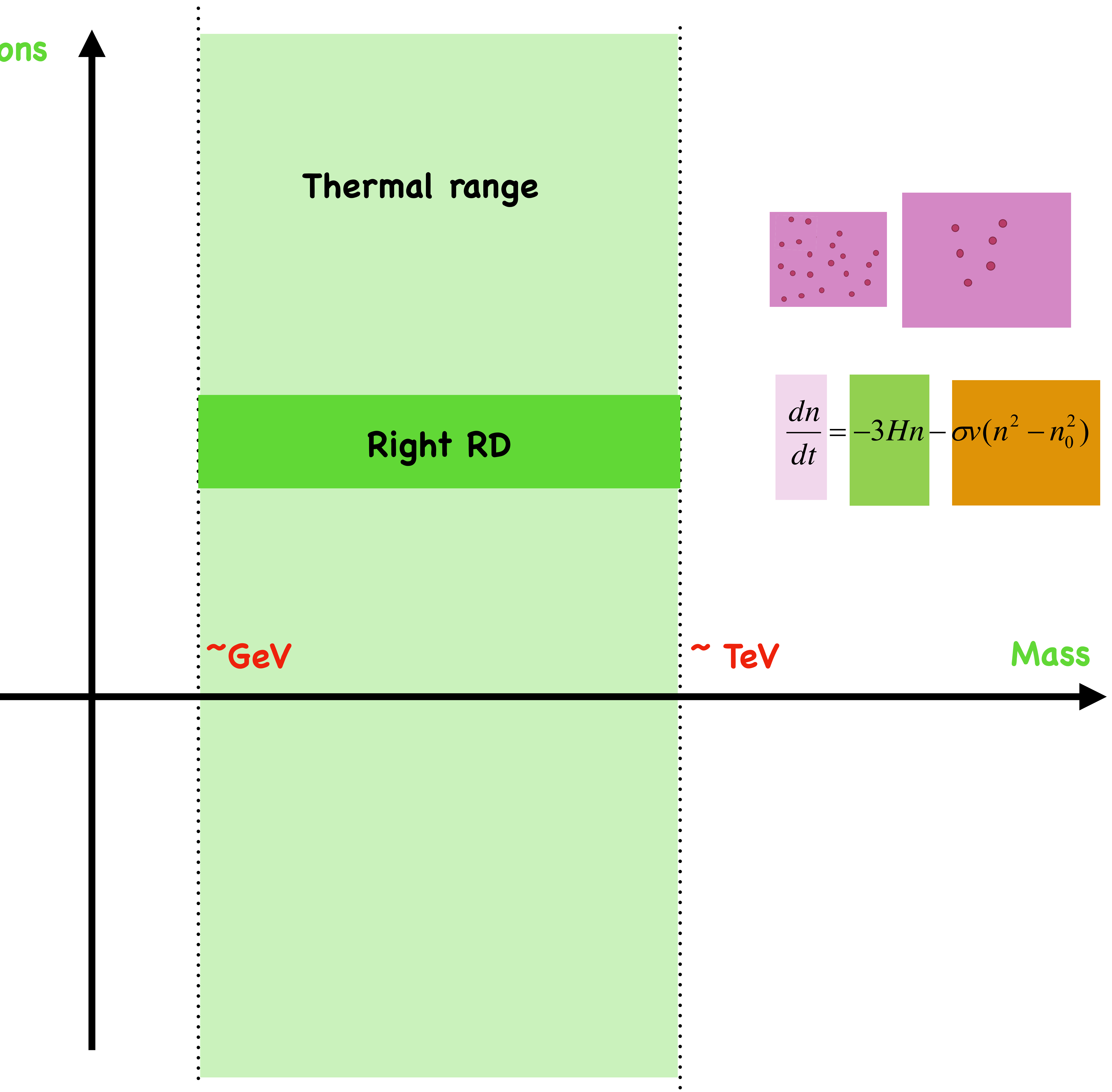
How to characterise Dark Matter?

Find the quantum numbers…



How to characterise Dark Matter?





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

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

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

arXiv:1107.1614

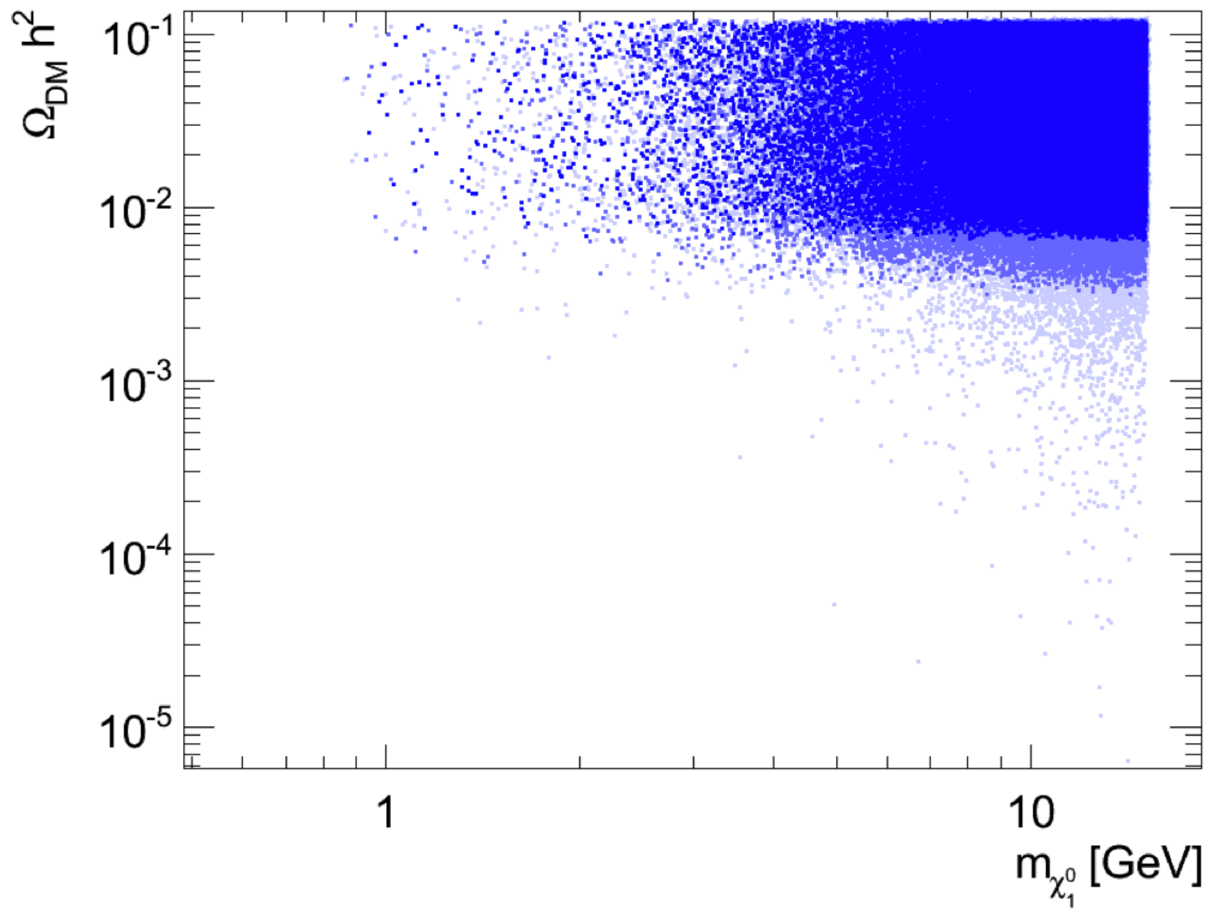
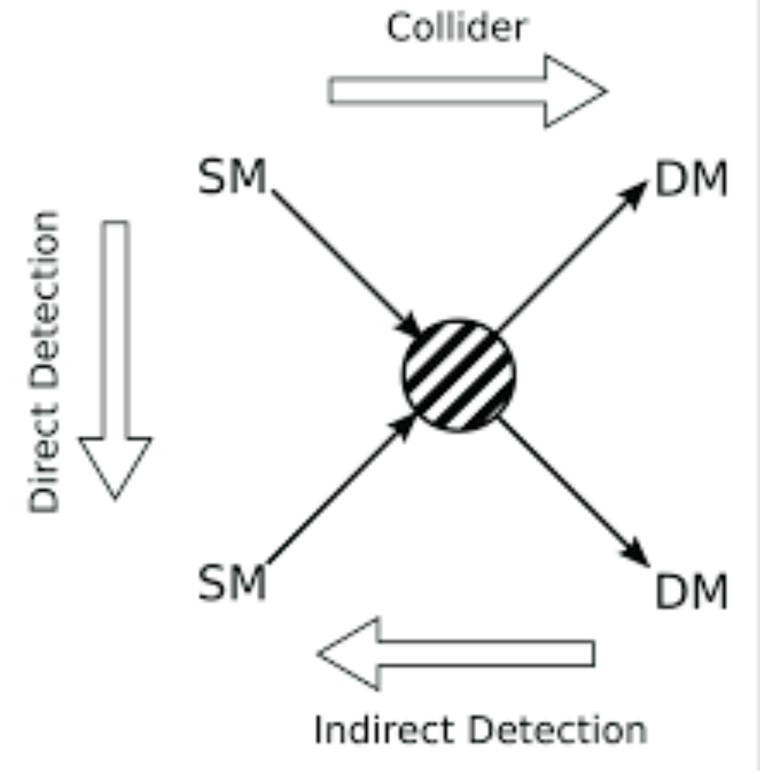


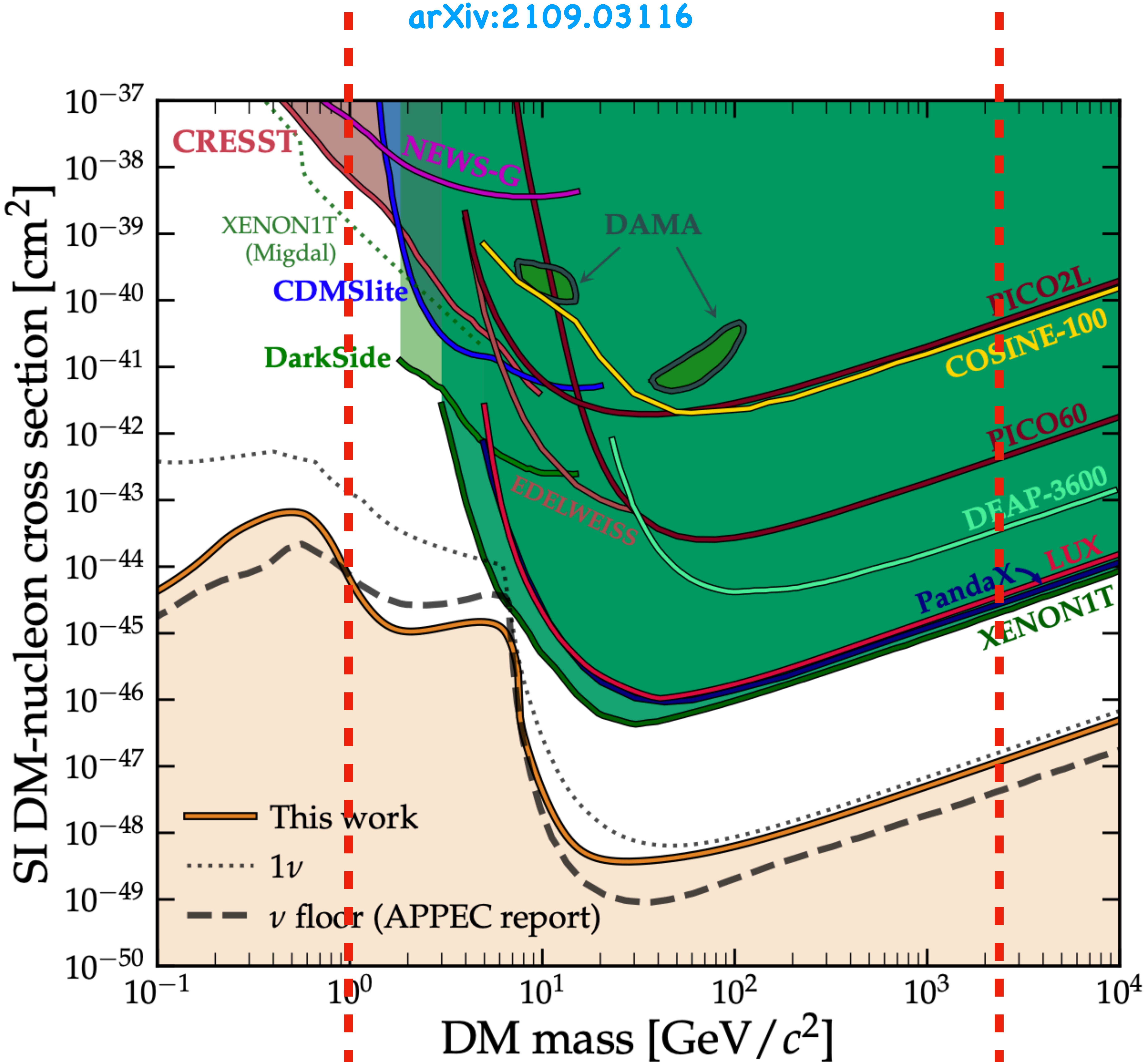
FIG. 1: Relic density of light NMSSM neutralinos, the darker the dot the larger the likelihood.

How to characterise Dark Matter?

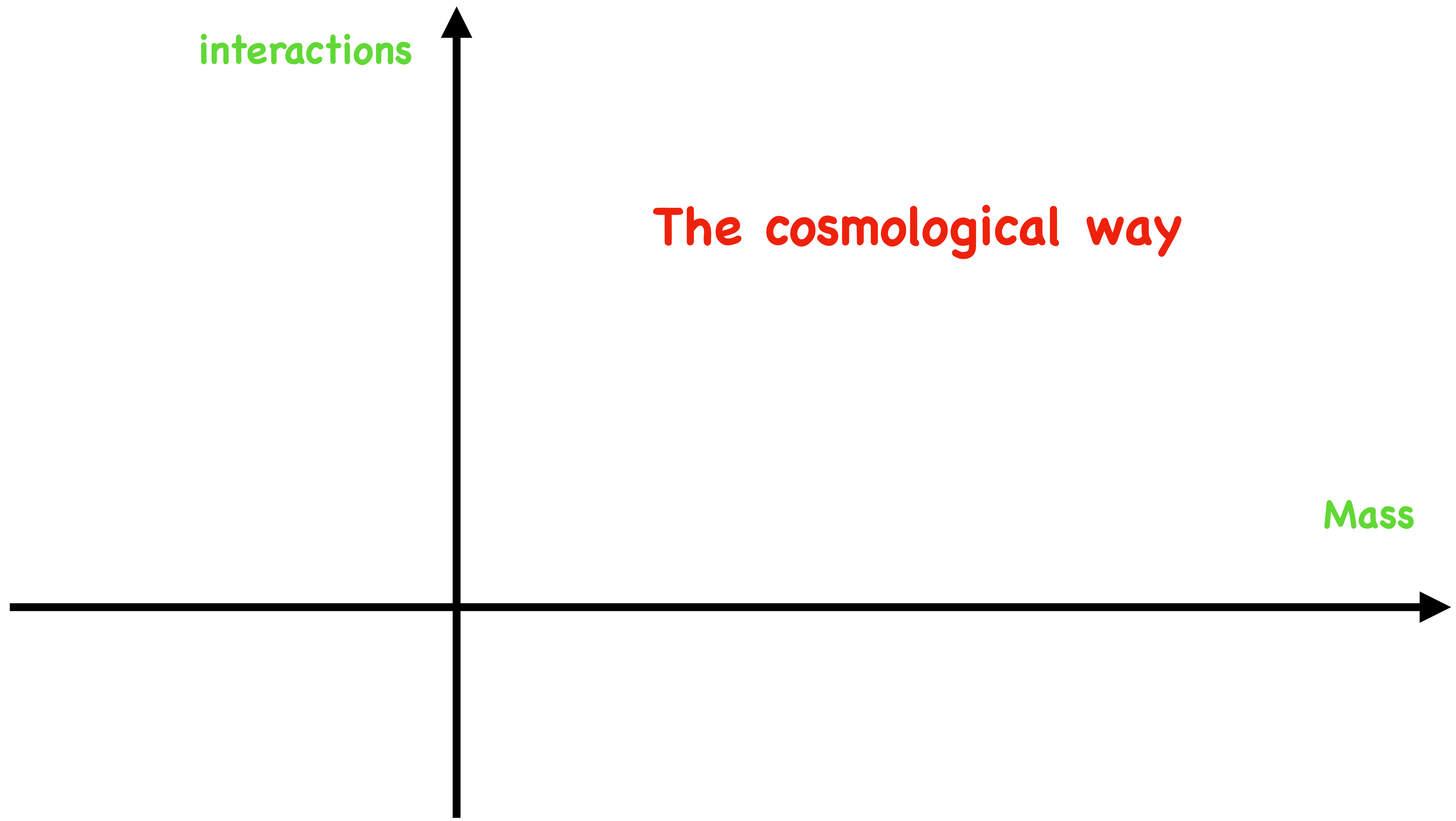


Annihilations

arXiv:2109.03116



How to characterise Dark Matter?



How to characterise Dark Matter?

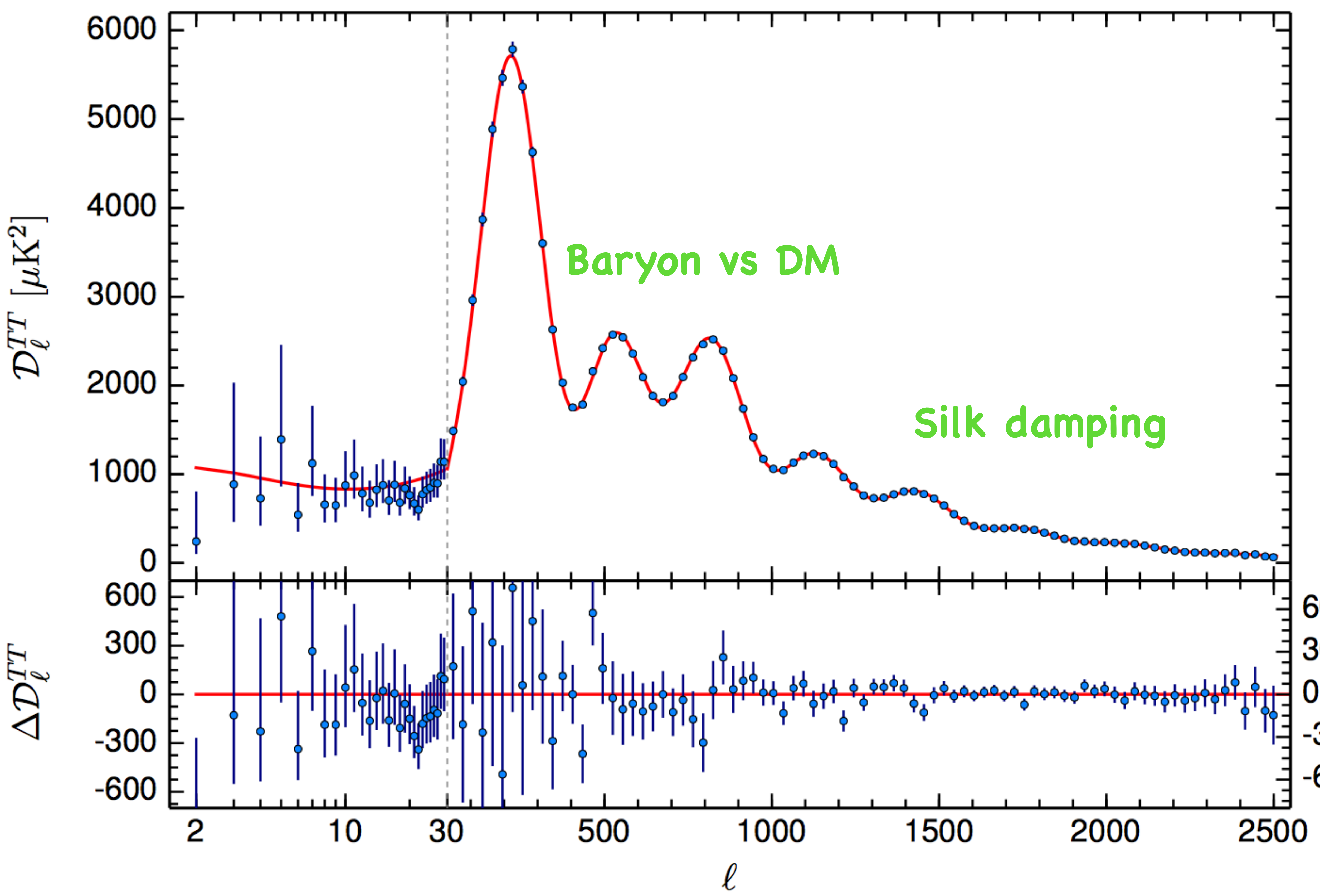
Apparently very small couplings to ordinary matter. Does dark matter dissipate at all?

LCDM

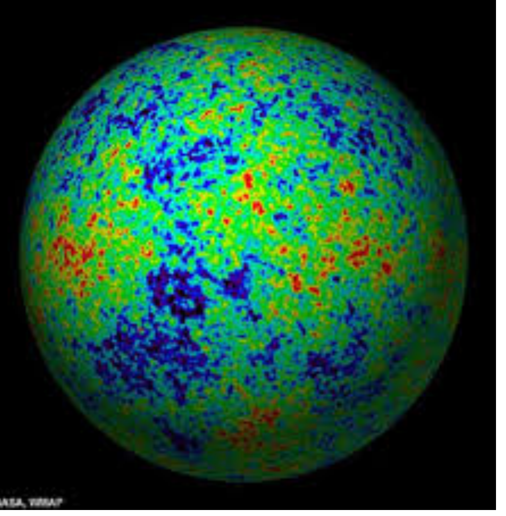
Cold DM = no interaction in simulations gives the observed CMB

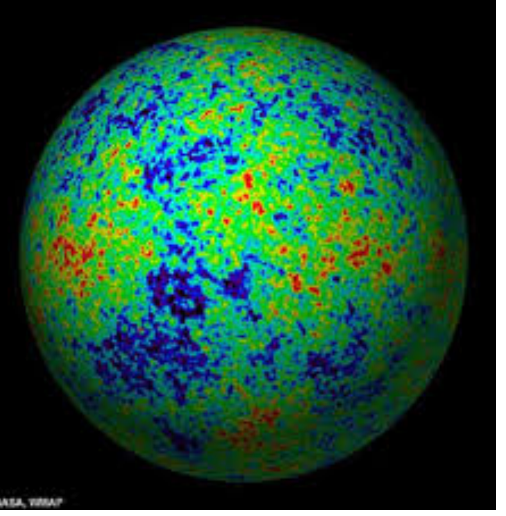
So what would happen if interactions?

Planck Collaboration: The *Planck* mission

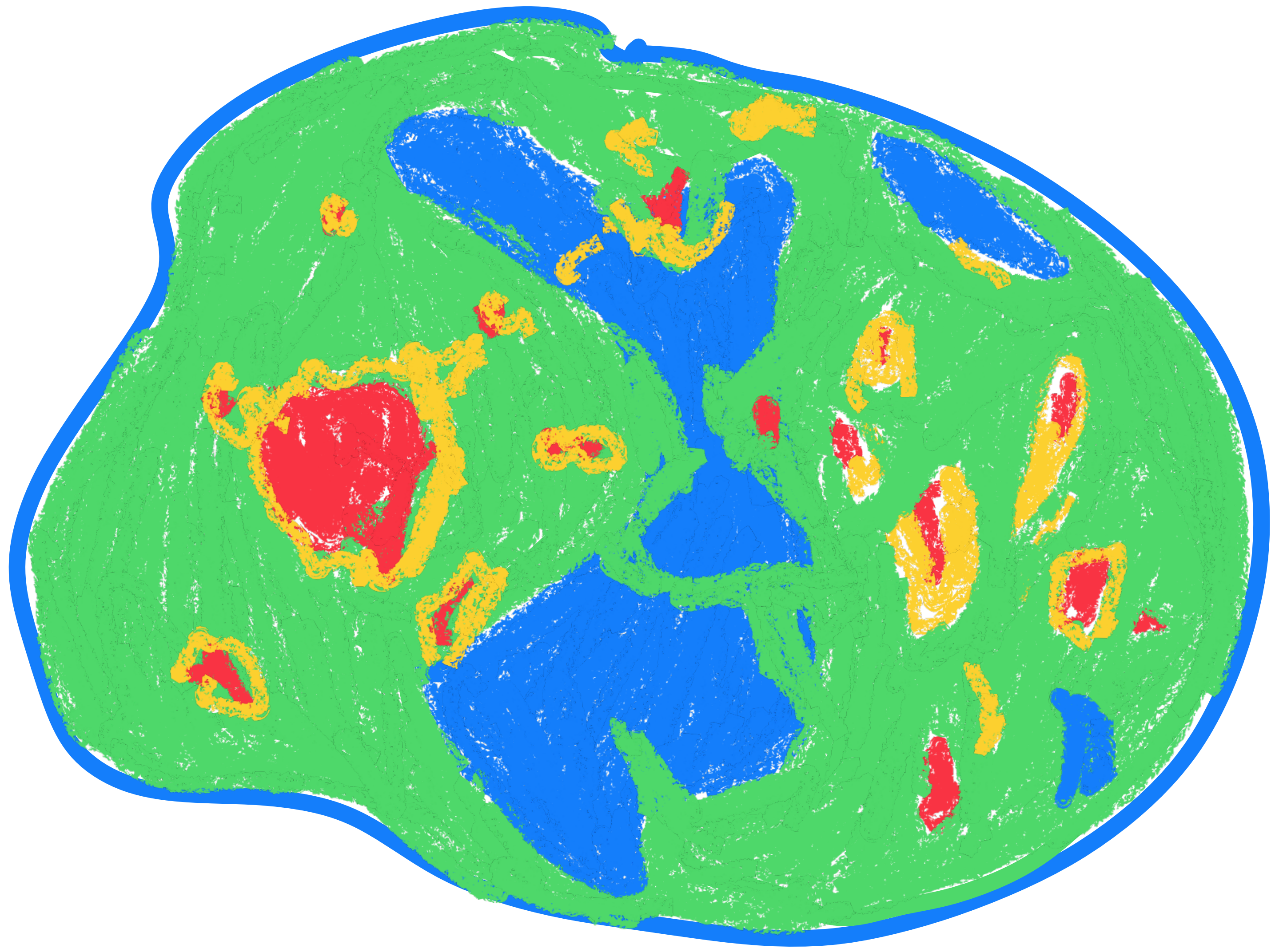


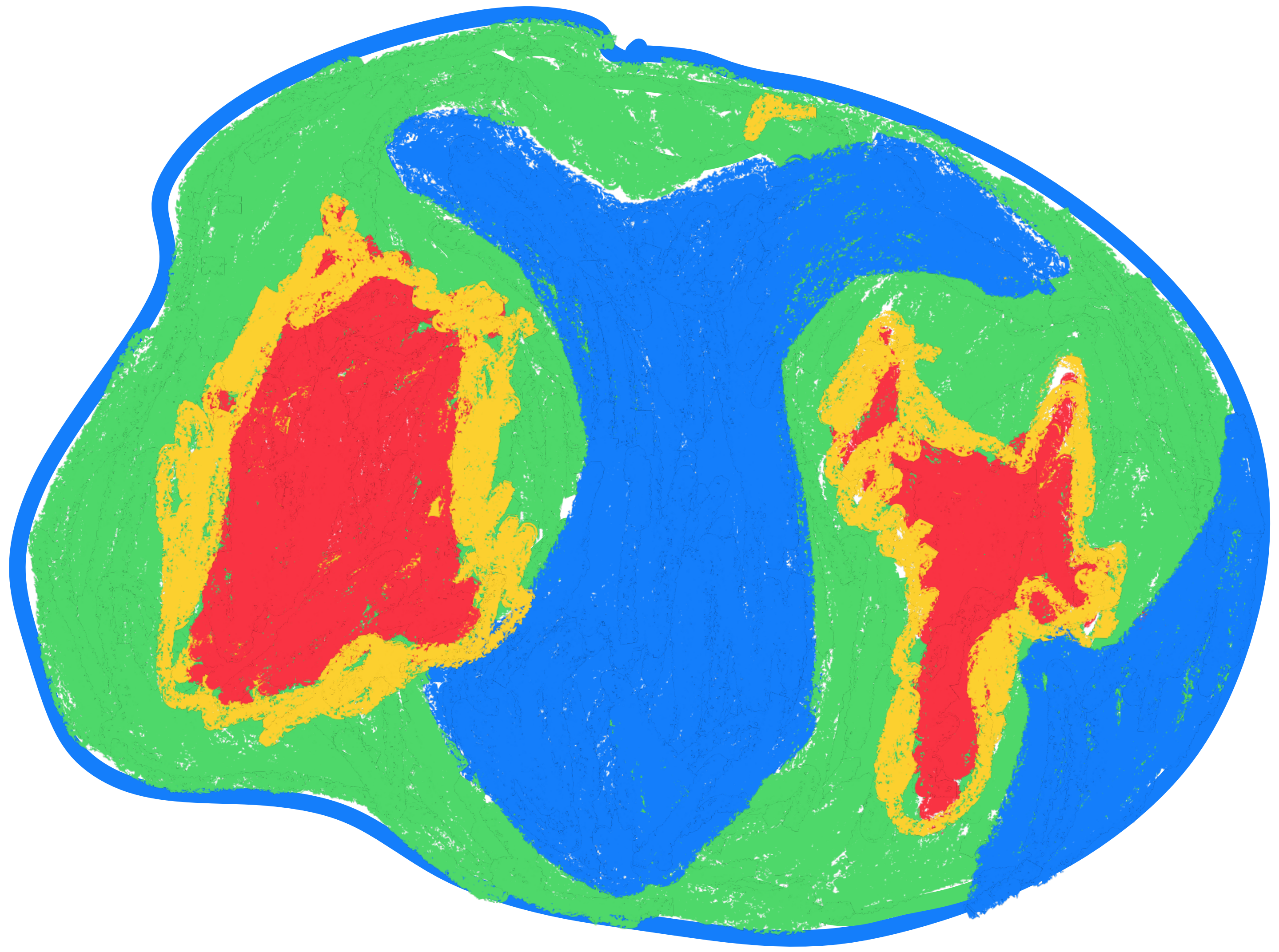
Silk damping

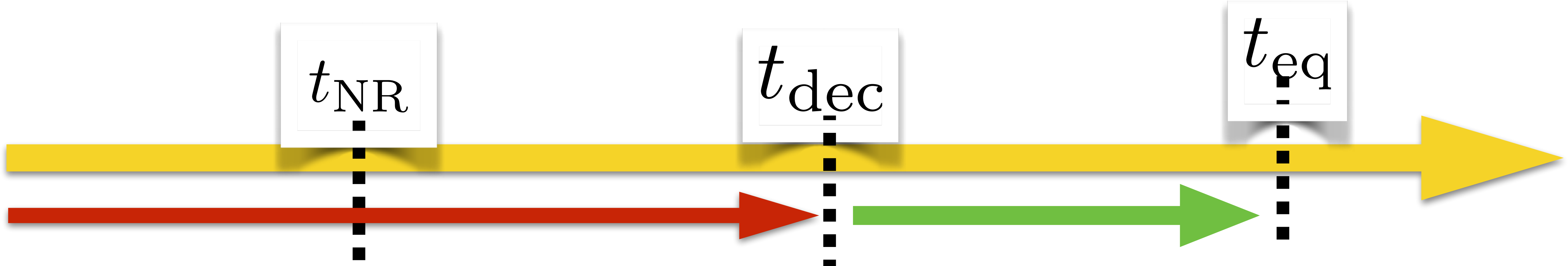




Generalising the Silk damping to DM collisional damping

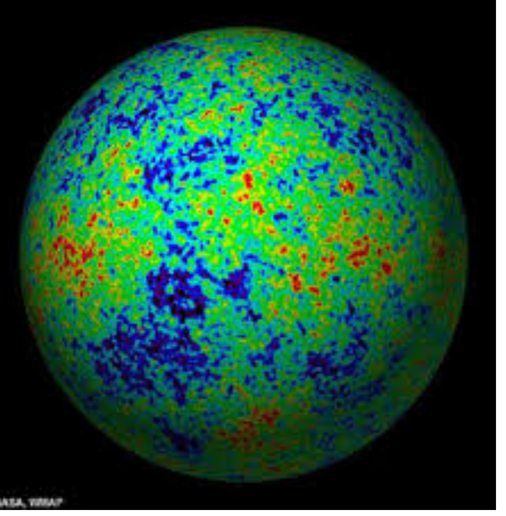




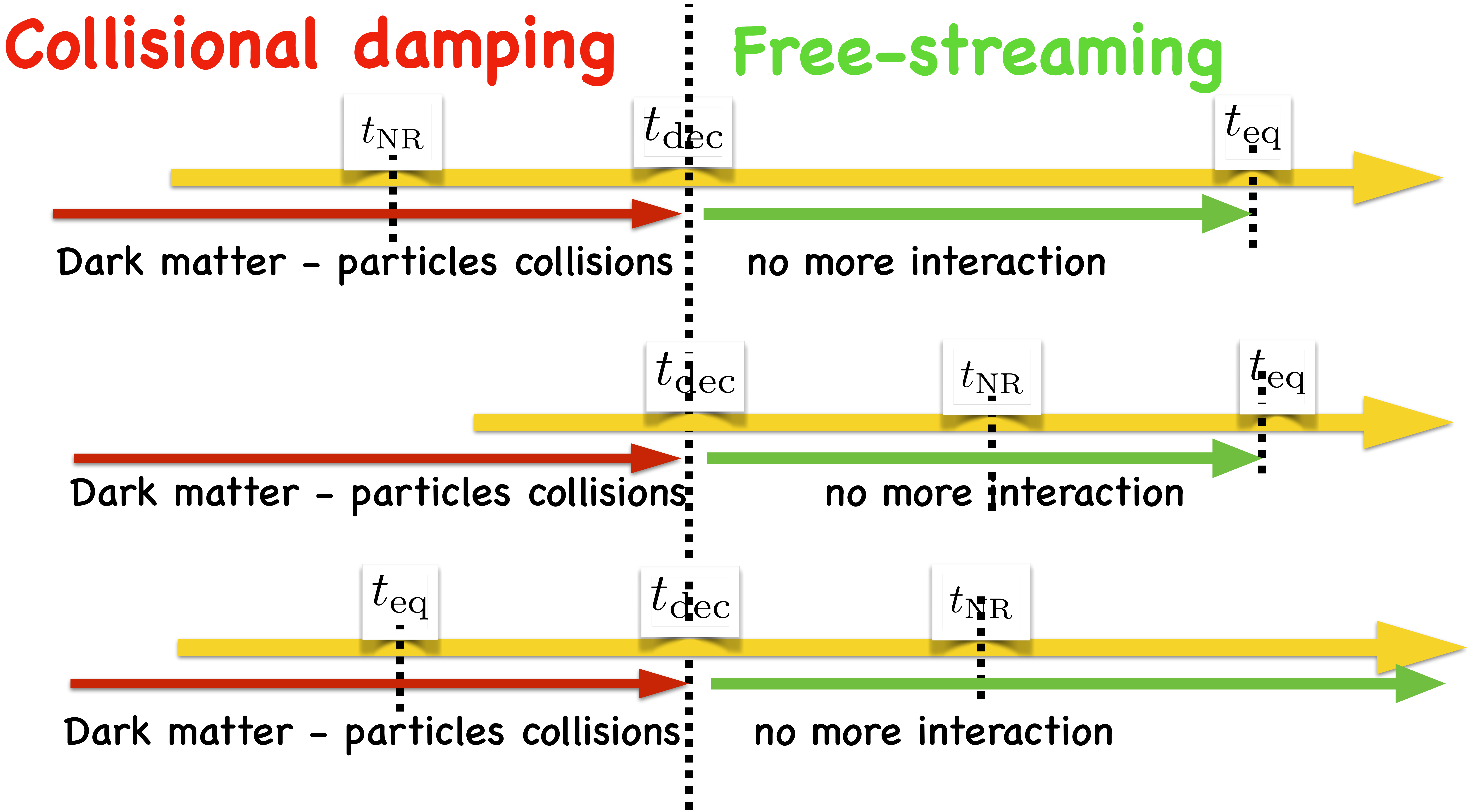


Dark matter - particles collisions | no more interaction

Collisional damping | **Free-streaming**

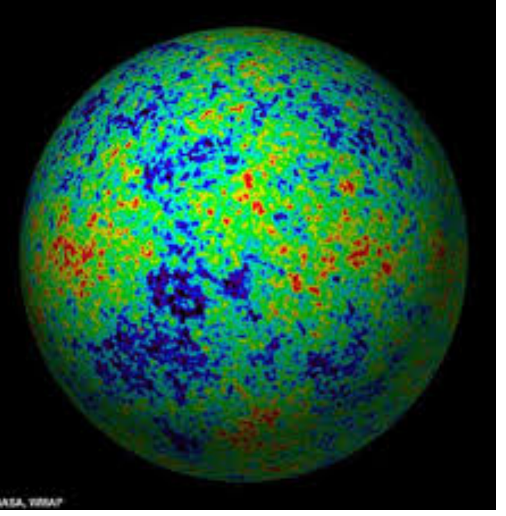


Generalising the Silk damping

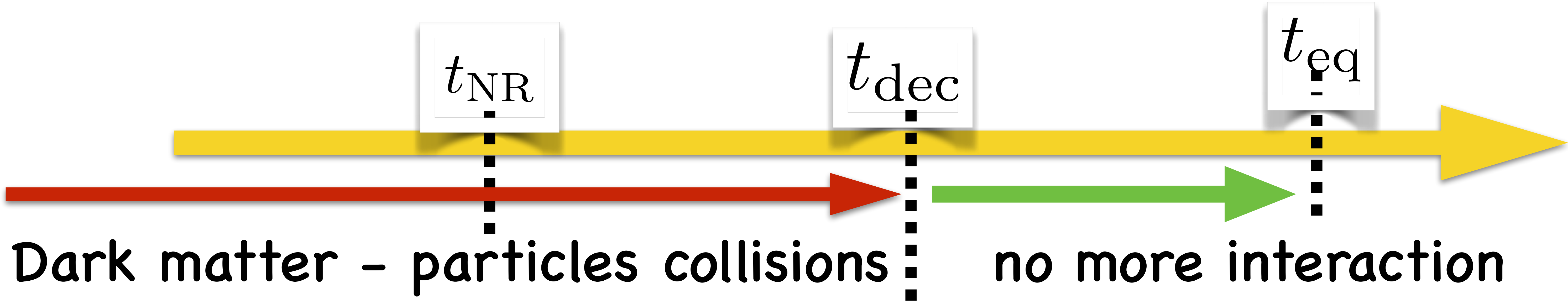


In total 6 combinations… so only 6 generic calculations

(



Generalising the Silk damping



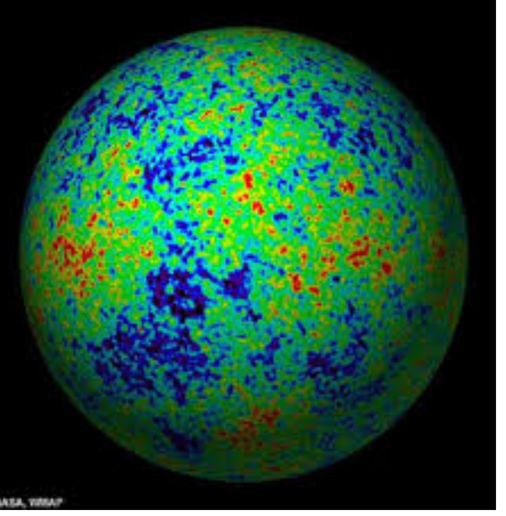
$t_{\mathrm{NR}} \longrightarrow m_{DM}$

$t_{\mathrm{dec}} \longrightarrow \Gamma_{dec}$

$t_{\mathrm{eq}} \longrightarrow t_{eq} \longrightarrow$ Corresponds to H @ equality matter-radiation

$\downarrow$

Can be translated into an interaction rate



Generalising the Silk damping

$$t_{\mathrm{NR}} \longrightarrow m_{DM}$$

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$$\downarrow$$

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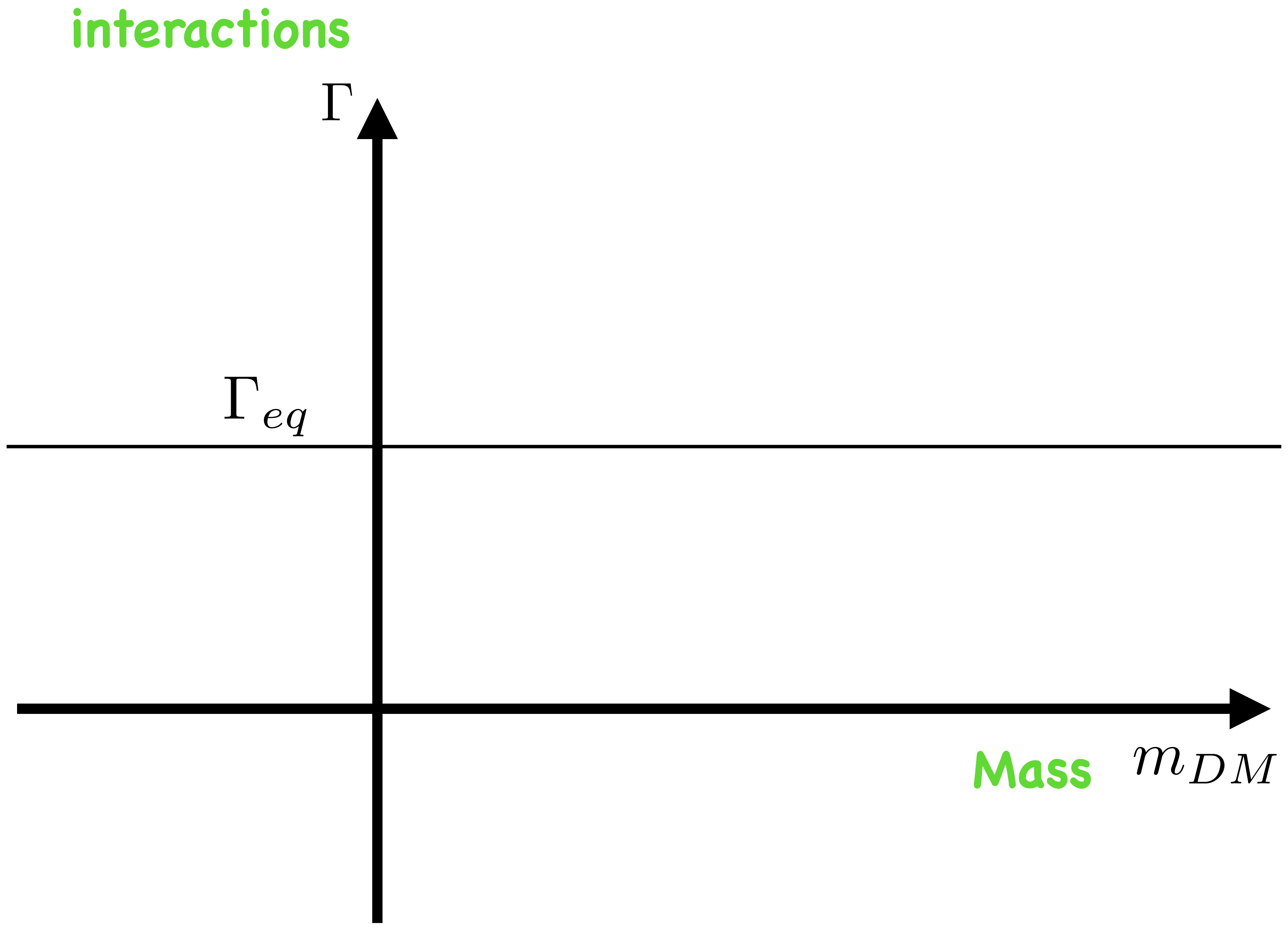

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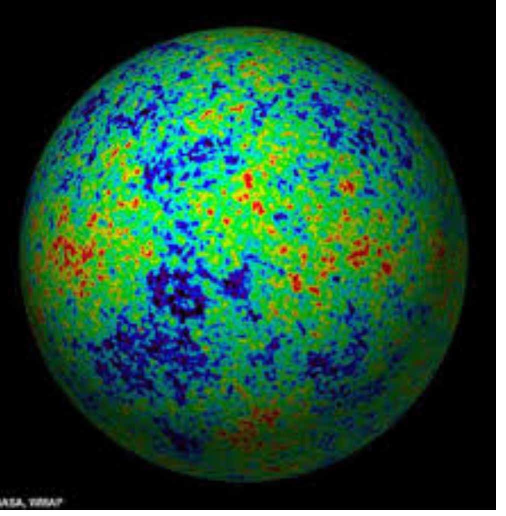
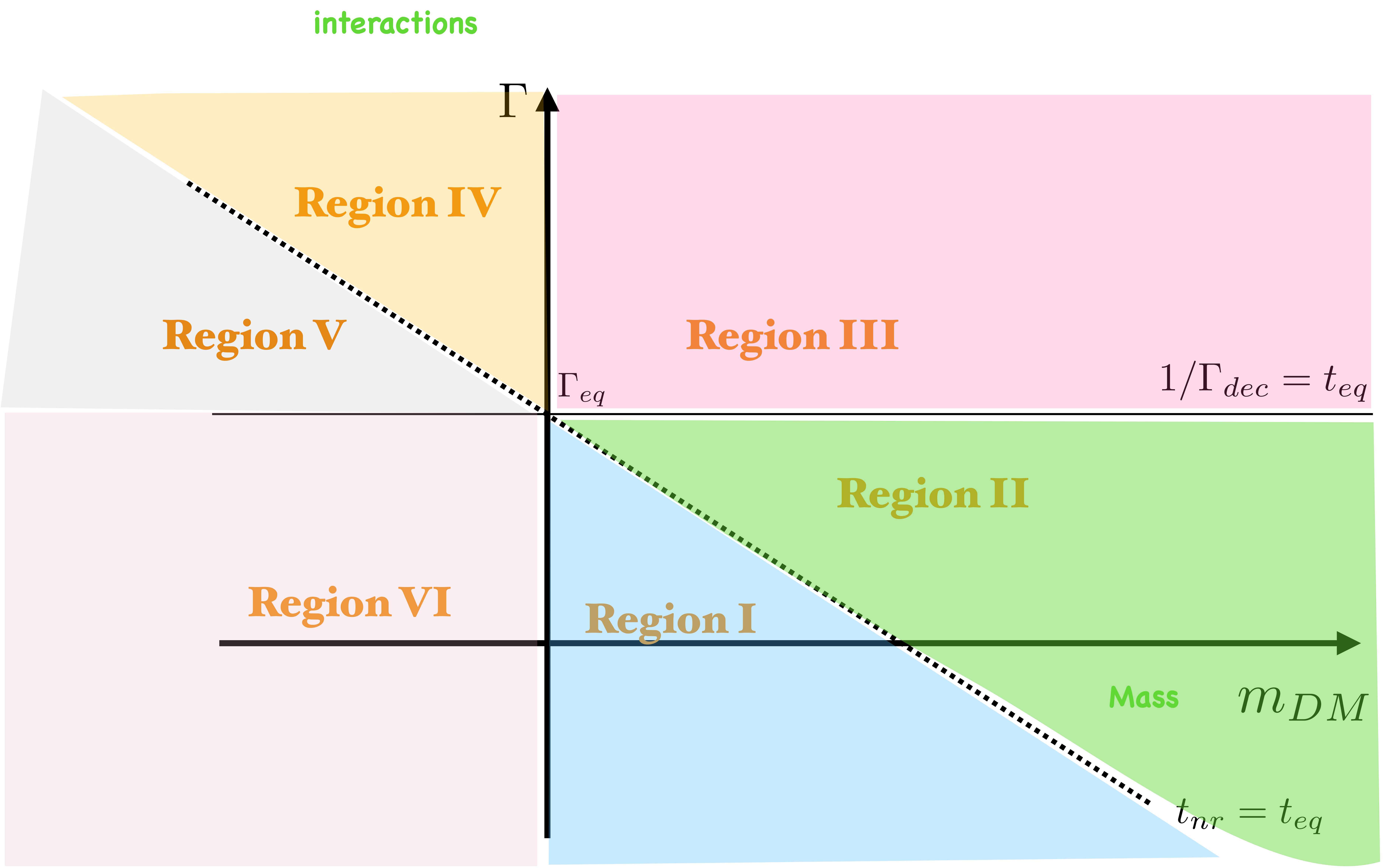
Free-streaming scale

(astro-ph/0012504, astro-ph/0410591)





Free-streaming scale

(astro-ph/0012504, astro-ph/0410591)

depends on mass

$$l_{\rm fs} = \int_{t_{\rm dec}}^{t_0} \frac{v(t)}{a(t)}\, dt$$

depends on interactions

depends on the history of the Universe

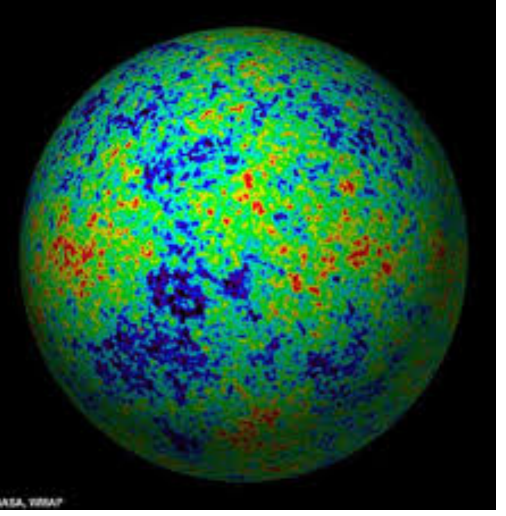
Applications to different dark matter scenarios

$$\int_{t_{dec}}^{t_{nr}} \frac{c}{a(t)} dt + \int_{t_{nr}}^{t_0} \frac{v(t)}{a(t)} dt \quad \text{if} \quad \mathrm{t_{dec}} < \mathrm{t_{nr}}$$

$$\int_{t_{dec}}^{t_0} \frac{v(t)}{a(t)} dt \quad \text{if} \quad \mathrm{t_{dec}} > \mathrm{t_{nr}}$$

Decoupling, the non-relativistic

non-relativistic, then decoupling



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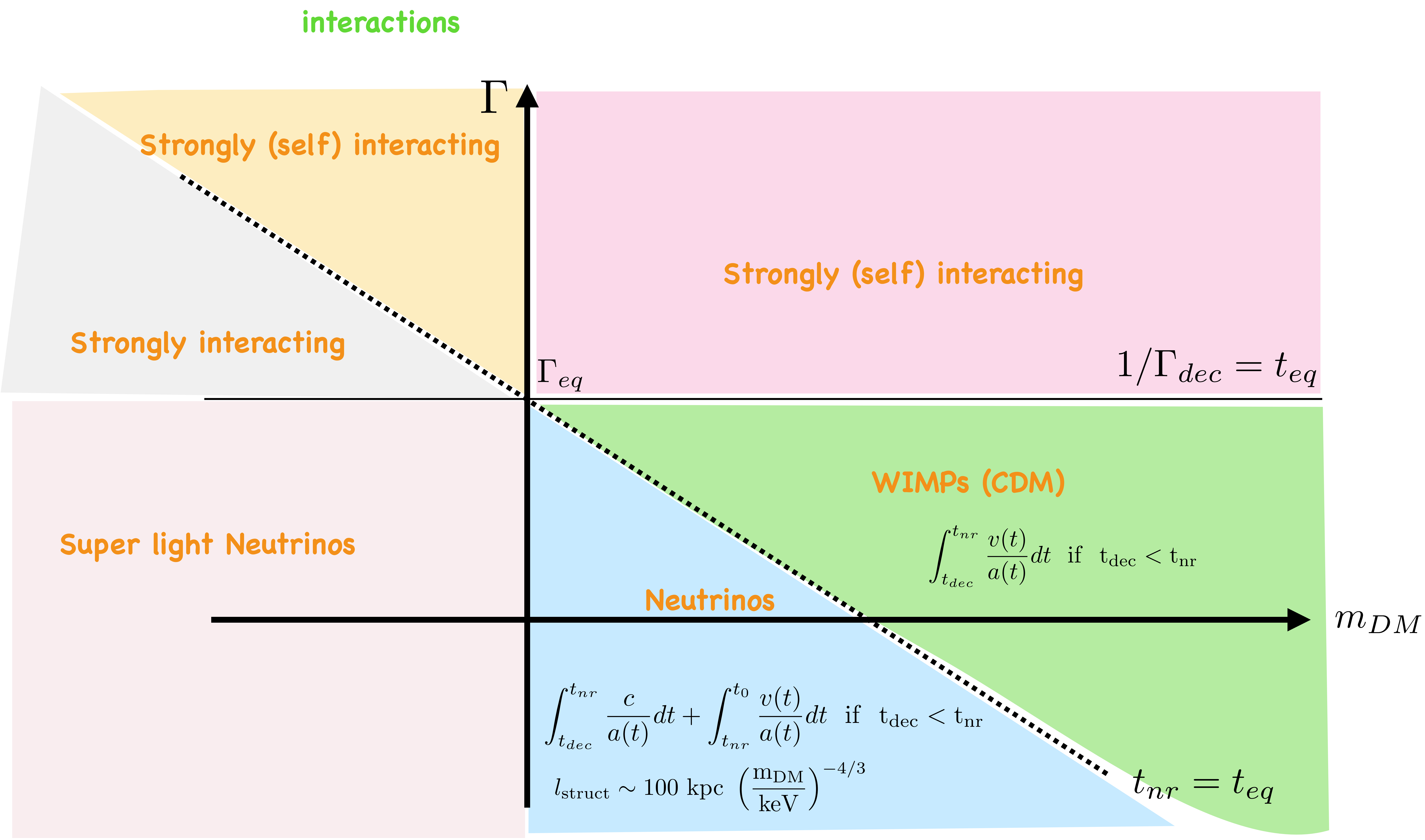
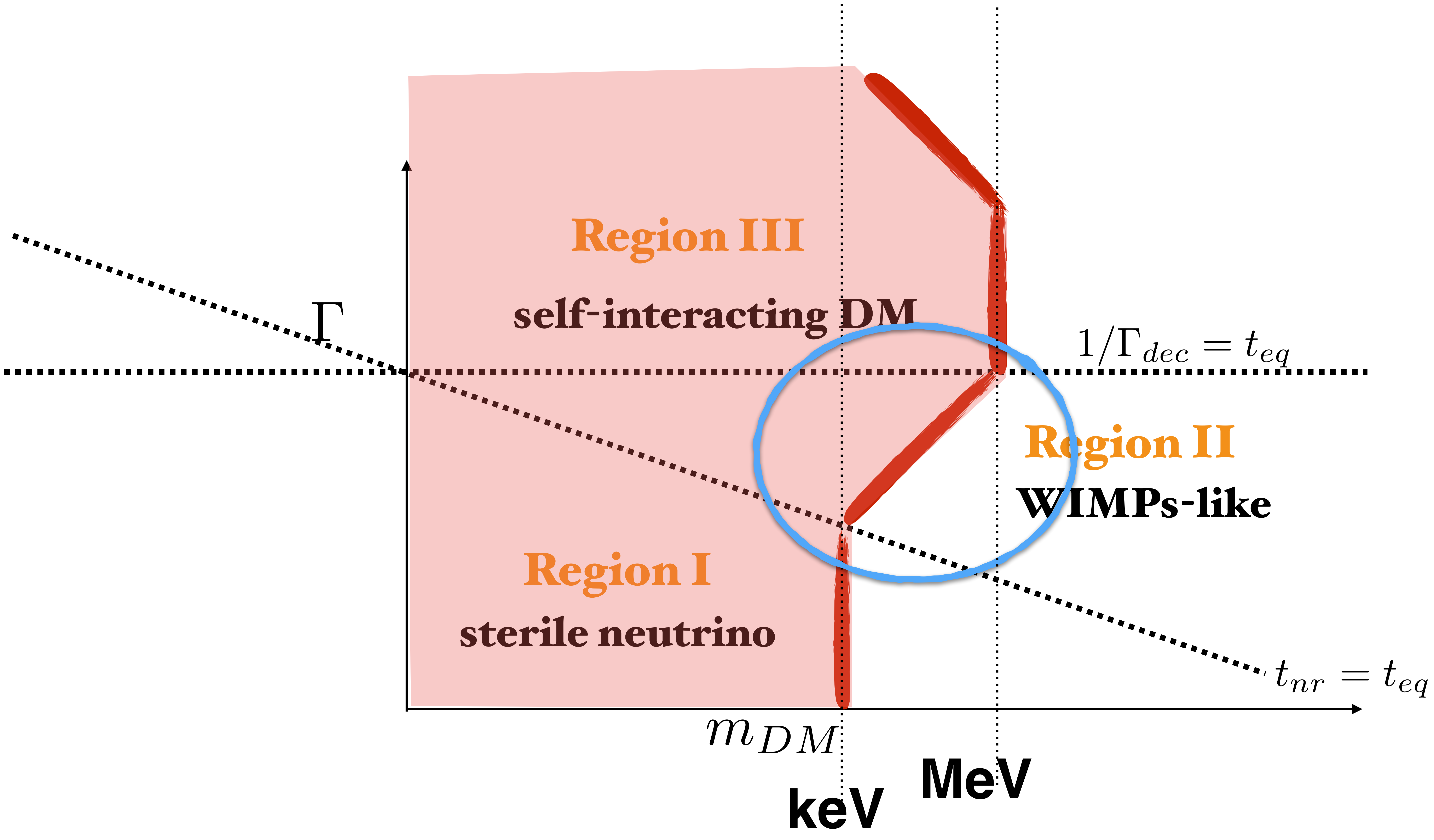


Free-streaming constraints

(astro-ph/0012504, astro-ph/0410591)



MeV (WIMP) DM can suffer from large free-streaming effect!

Collisional damping constraints

(astro-ph/0012504, astro-ph/0410591)

last until DM stop interacting

efficient if DM is coupled to a relativistic species

$$\boxed{l_{id}^2 = \frac{2\pi^2}{3}\int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\rho a^2 \Gamma_i}(1+\Theta_i)\ \frac{dt}{t}}$$

efficient if DM is coupled to interacting species

$$\eta = \sum_i \frac{\rho_i\, v_i^2}{3\,\Gamma_i}$$

Collisional damping constraints

astro-ph/0410591

DM-Photons

$$l^2_{dm-\gamma} \propto \int^{t_{dec(dm-\gamma)}} \frac{\rho_\gamma\, v_\gamma^2}{\rho\!\!\!/\, a^2\, \Gamma_\gamma} dt$$

DM-Neutrinos

$$l^2_{dm-\nu} \propto \int^{t_{dec(dm-\nu)}} \frac{\rho_\nu\, v_\nu^2}{\rho\!\!\!/\, a^2\, \Gamma_\nu} dt$$

DM-Baryons

$$l^2_{dm-b} \propto \int^{t_{dec(dm-b)}} \frac{\rho_b\, v_b^2}{\rho\!\!\!/\, a^2\, \Gamma_b} dt$$

DM-DM

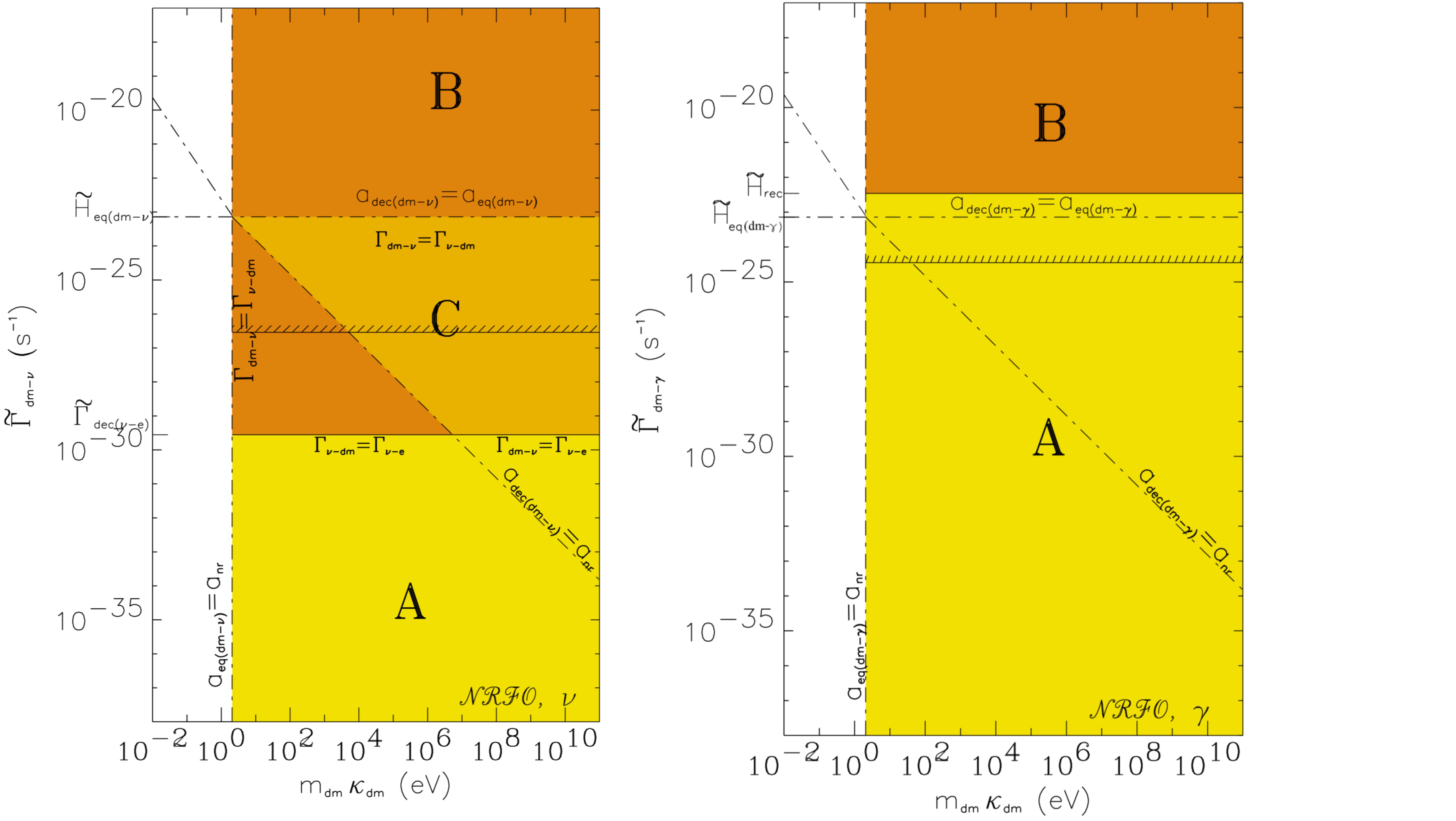
$$l^2_{dm-dm} \propto \int^{t_{dec(dm-dm)}} \frac{\rho_{dm}\, v_{dm}^2}{\rho\!\!\!/\, a^2\, \Gamma_{dm}} dt$$

Same effect requires

$$\sigma_{dm-dm} \simeq \sigma_{dm-b} > \sigma_{dm-\gamma} > \sigma_{dm-\nu}$$

Collisional damping constraints

astro-ph/0410591



Predicting fluctuations

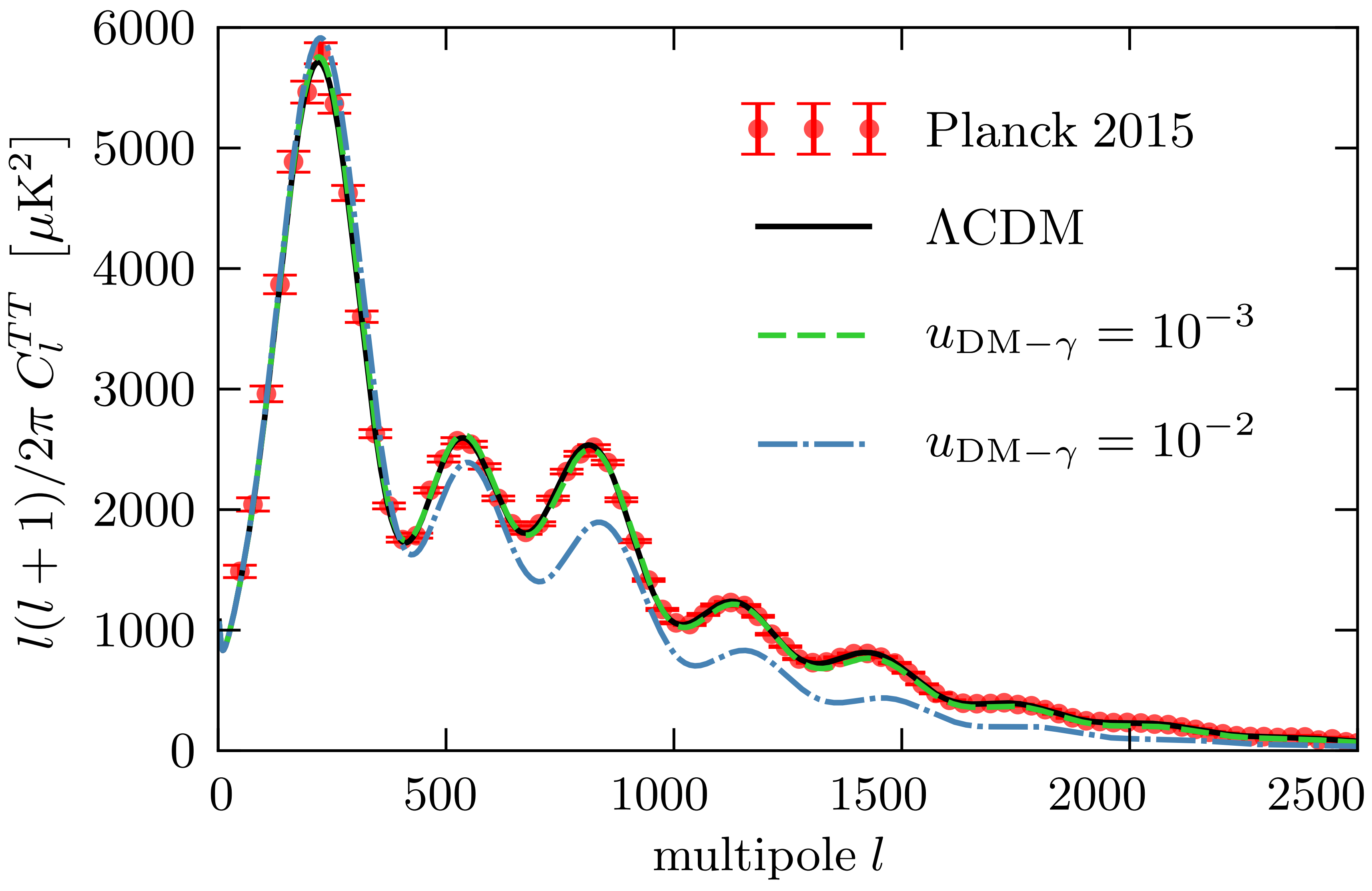
astro-ph/0112522

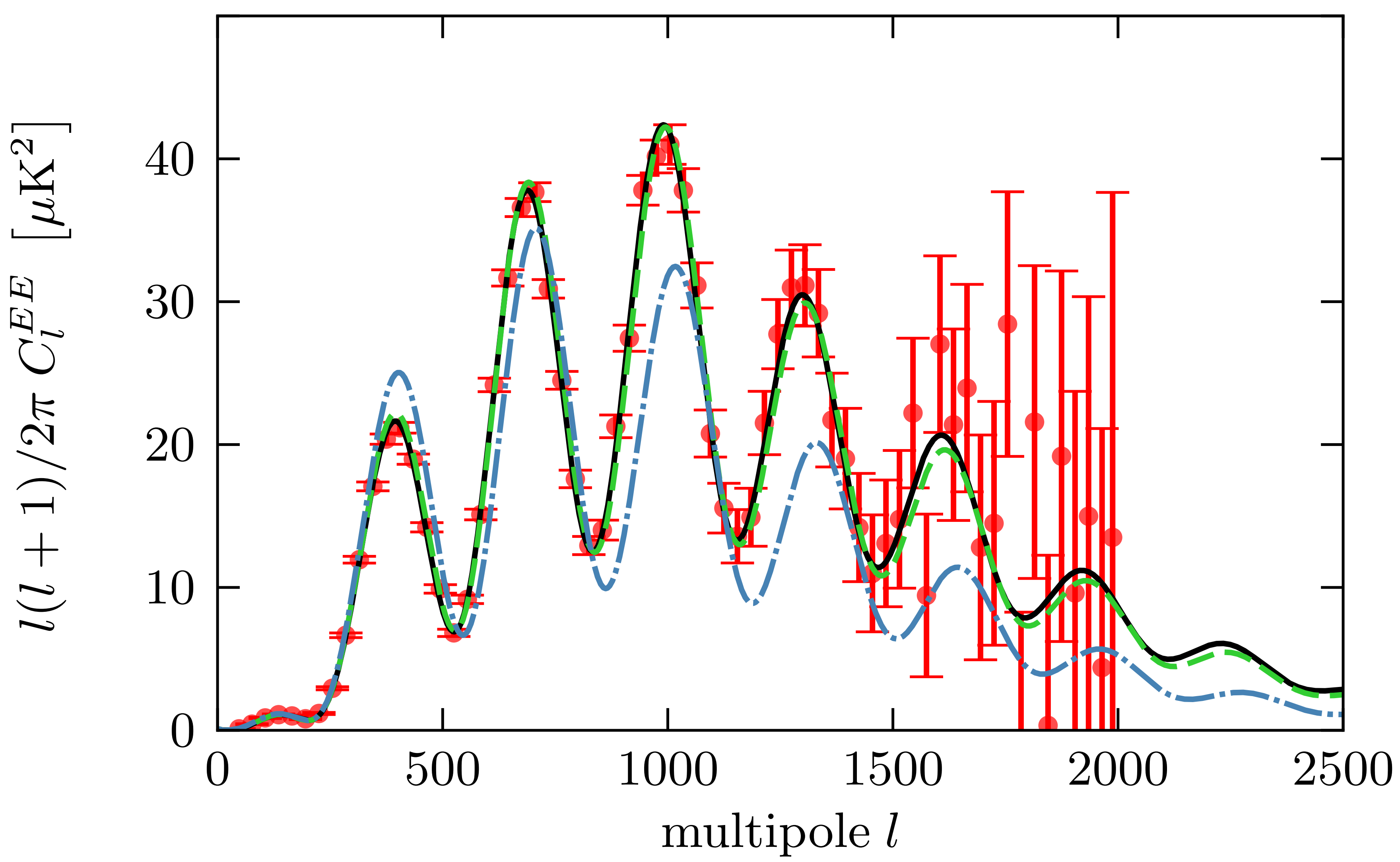
without DM interactions

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

with DM interactions

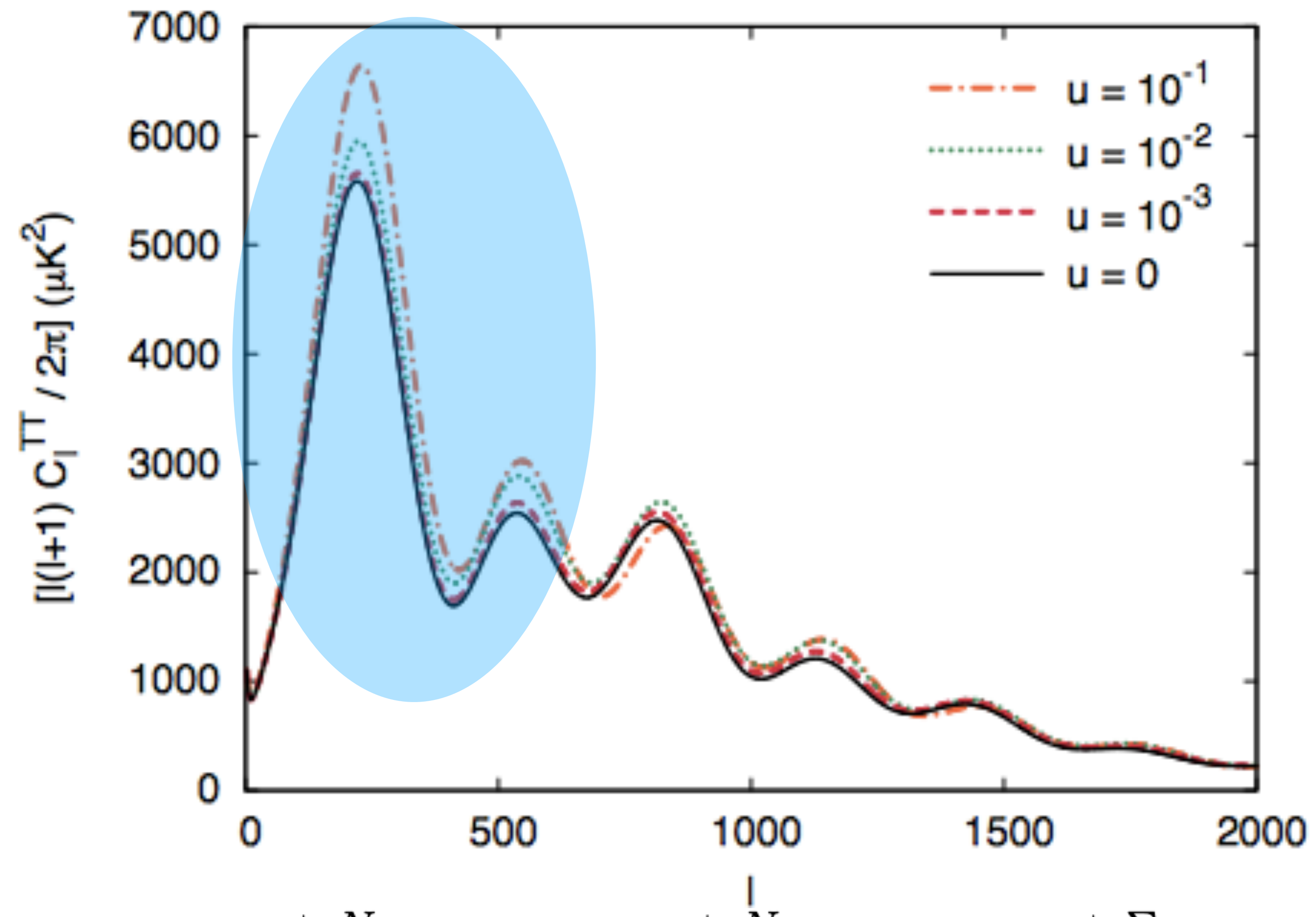
$$\begin{aligned}\dot\theta_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma)\\ \dot\theta_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right)\\ &\quad - \dot\kappa(\theta_\gamma - \theta_b) - \dot\mu(\theta_\gamma - \theta_{DM})\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





Dark matter-neutrino interactions

1401.7597

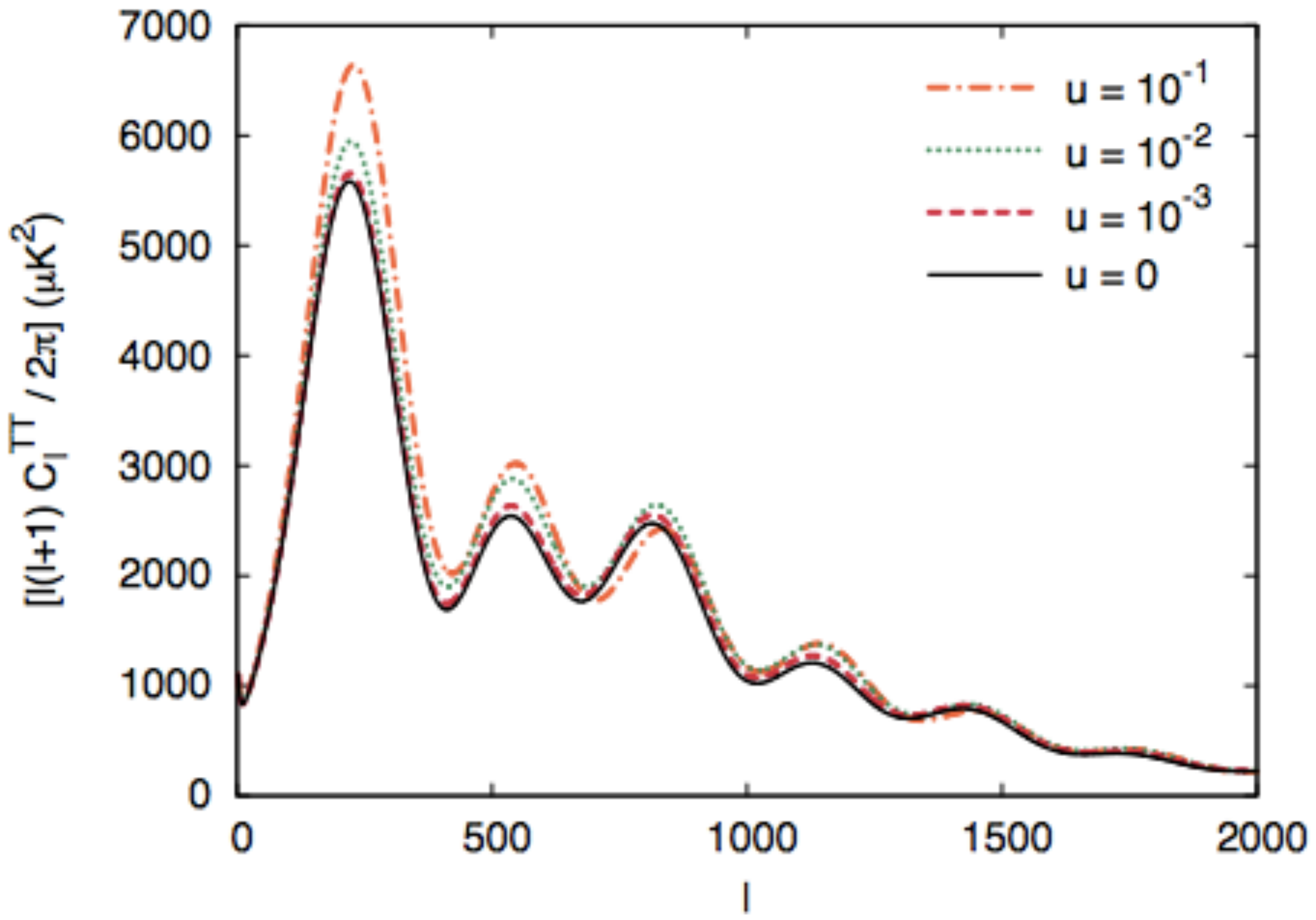


1710.02559

ΛCDM + u Parameter	Planck TTTEEE + lowTEB	Planck TTTEEE + lowTEB + lensing	+ $N_{\rm eff}$ Planck TTTEEE + lowTEB	+ $N_{\rm eff}$ Planck TTTEEE + lowTEB + lensing	+ Σm_ν Planck TTTEEE + lowTEB	+ Σm_ν Planck TTTEEE + lowTEB + lensing	+ $N_{\rm eff}$ + Σm_ν Planck TTTEEE + lowTEB	+ $N_{\rm eff}$ + Σm_ν Planck TTTEEE + lowTEB + lensing
$\Omega_b h^2$	0.02225 ± 0.00017	$0.02225,^{+0.00017}_{-0.00018}$	0.02218 ± 0.00028	$0.02216^{+0.00023}_{-0.00025}$	$0.02219^{+0.00018}_{-0.00017}$	0.02219 ± 0.00018	$0.02212^{+0.00029}_{-0.00031}$	$0.02210^{+0.00025}_{-0.00026}$
$\Omega_c h^2$	$0.1198^{+0.0016}_{-0.0015}$	0.1194 ± 0.0015	$0.1190^{+0.0035}_{-0.0036}$	0.1179 ± 0.0030	0.1200 ± 0.0016	$0.1197^{+0.0015}_{-0.0016}$	$0.1188^{+0.0038}_{-0.0037}$	0.1185 ± 0.0032
τ	$0.080^{+0.016}_{-0.018}$	$0.066^{+0.013}_{-0.015}$	$0.078^{+0.018}_{-0.019}$	$0.065^{+0.011}_{-0.015}$	$0.082^{+0.018}_{-0.017}$	$0.073^{+0.015}_{-0.016}$	$0.080^{+0.019}_{-0.021}$	$0.071^{+0.014}_{-0.016}$
n_s	$0.9639^{+0.0053}_{-0.0052}$	$0.9644^{+0.0056}_{-0.0054}$	0.961 ± 0.011	$0.9603^{+0.0093}_{-0.0095}$	$0.9620^{+0.0060}_{-0.0056}$	$0.9628^{+0.0057}_{-0.0055}$	$0.959^{+0.012}_{-0.013}$	0.959 ± 0.010
$ln(10^{10} A_s)$	$3.093^{+0.032}_{-0.035}$	$3.065^{+0.024}_{-0.027}$	$3.087^{+0.040}_{-0.041}$	$3.059^{+0.024}_{-0.030}$	$3.099^{+0.035}_{-0.033}$	$3.079^{+0.028}_{-0.031}$	$3.092^{+0.041}_{-0.043}$	$3.072^{+0.030}_{-0.034}$
$H_0[{\rm Km\,s^{-1}\,Mpc^{-1}}]$	$67.32^{+0.70}_{-0.71}$	$67.50^{+0.70}_{-0.71}$	$66.8^{+1.8}_{-1.9}$	66.8 ± 1.6	$66.0^{+2.3}_{-1.2}$	$66.1^{+1.9}_{-1.3}$	$65.4^{+2.8}_{-2.5}$	$65.4^{+2.2}_{-2.0}$
σ_8	$0.827^{+0.016}_{-0.015}$	$0.814^{+0.013}_{-0.012}$	0.822 ± 0.023	$0.809^{+0.013}_{-0.014}$	$0.797^{+0.049}_{-0.023}$	$0.789^{+0.036}_{-0.020}$	$0.791^{+0.052}_{-0.050}$	$0.784^{+0.035}_{-0.024}$
u	< -4.1	< -4.1	< -4.0	< -4.0	< -4.1	< -4.2	< -3.9	< -4.3
$N_{\rm eff}$	3.046	3.046	$2.98^{+0.23}_{-0.24}$	2.94 ± 0.20	3.046	3.046	$2.96^{+0.23}_{-0.28}$	$2.95^{+0.20}_{-0.21}$
$\Sigma m_\nu[eV]$	0.06	0.06	0.06	0.06	< 1.9	< 1.5	< 2.0	< 1.6

Impact on cosmological parameters

Ho / sigma8



1401.7597

ΛCDM $+ u$	$+ N_{\rm eff}$	$+ N_{\rm eff} + \Sigma m_\nu$
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.

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

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

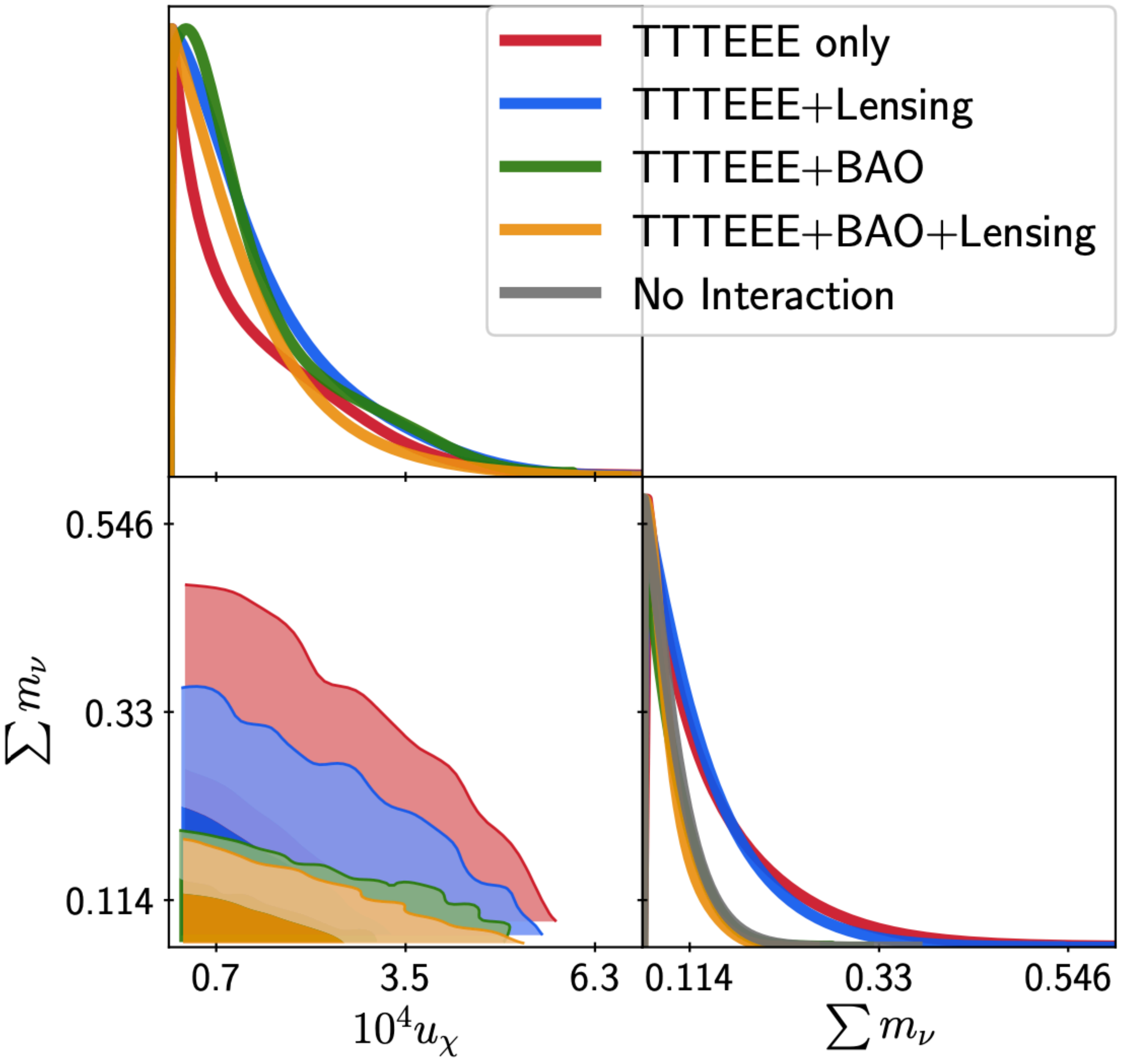


Figure 3. One-dimensional posterior probability distributions for u_χ and $\sum m_\nu$ for different combination of datasets and two-dimensional 68% and 95% CL allowed regions in the (u_χ,$\sum m_\nu$) plane. The 'Non-Interacting' posterior uses all the three datasets, that is, Planck CMB TTTEEE+ Planck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

Mixed damping constraints

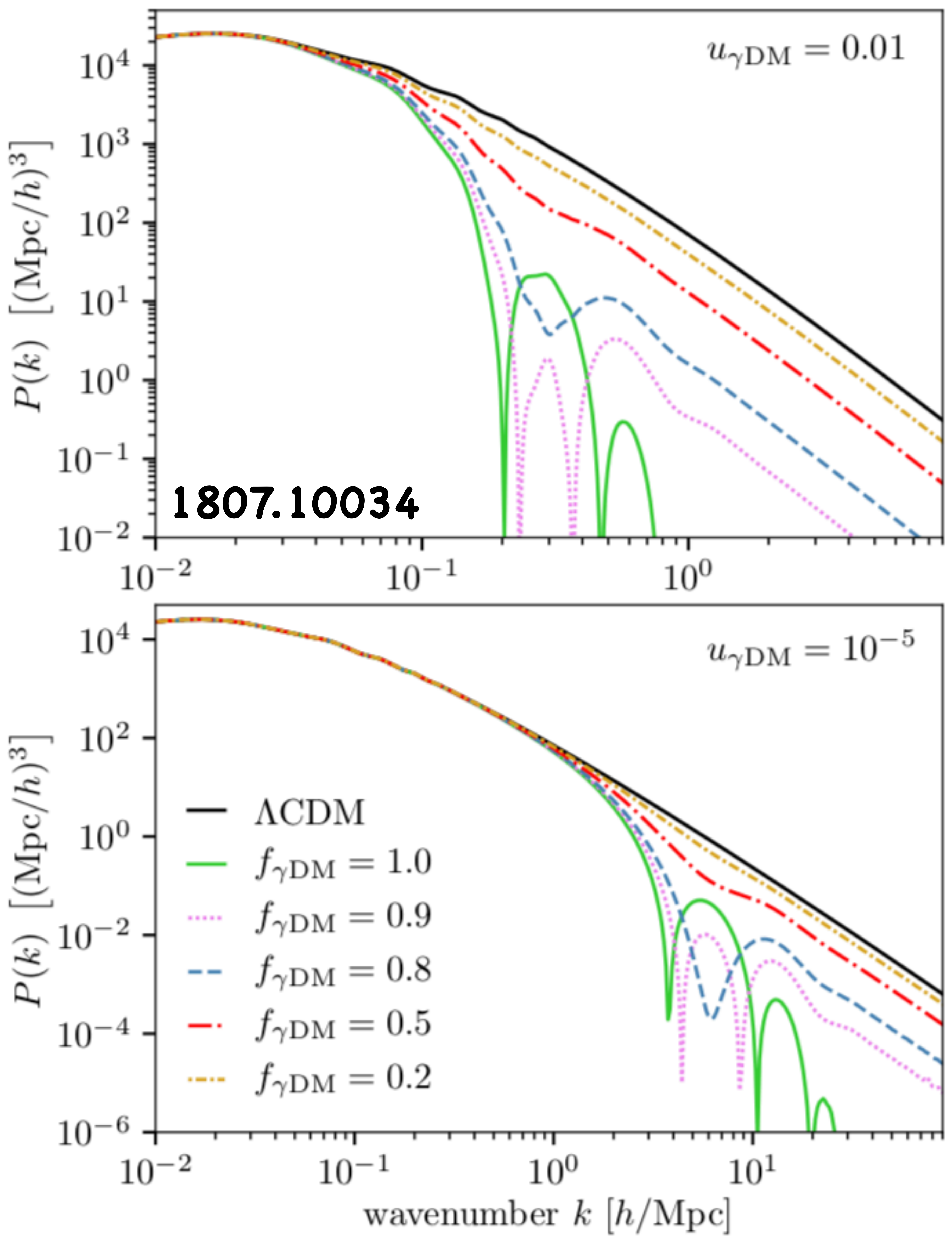
(astro-ph/0012504, astro-ph/0410591)

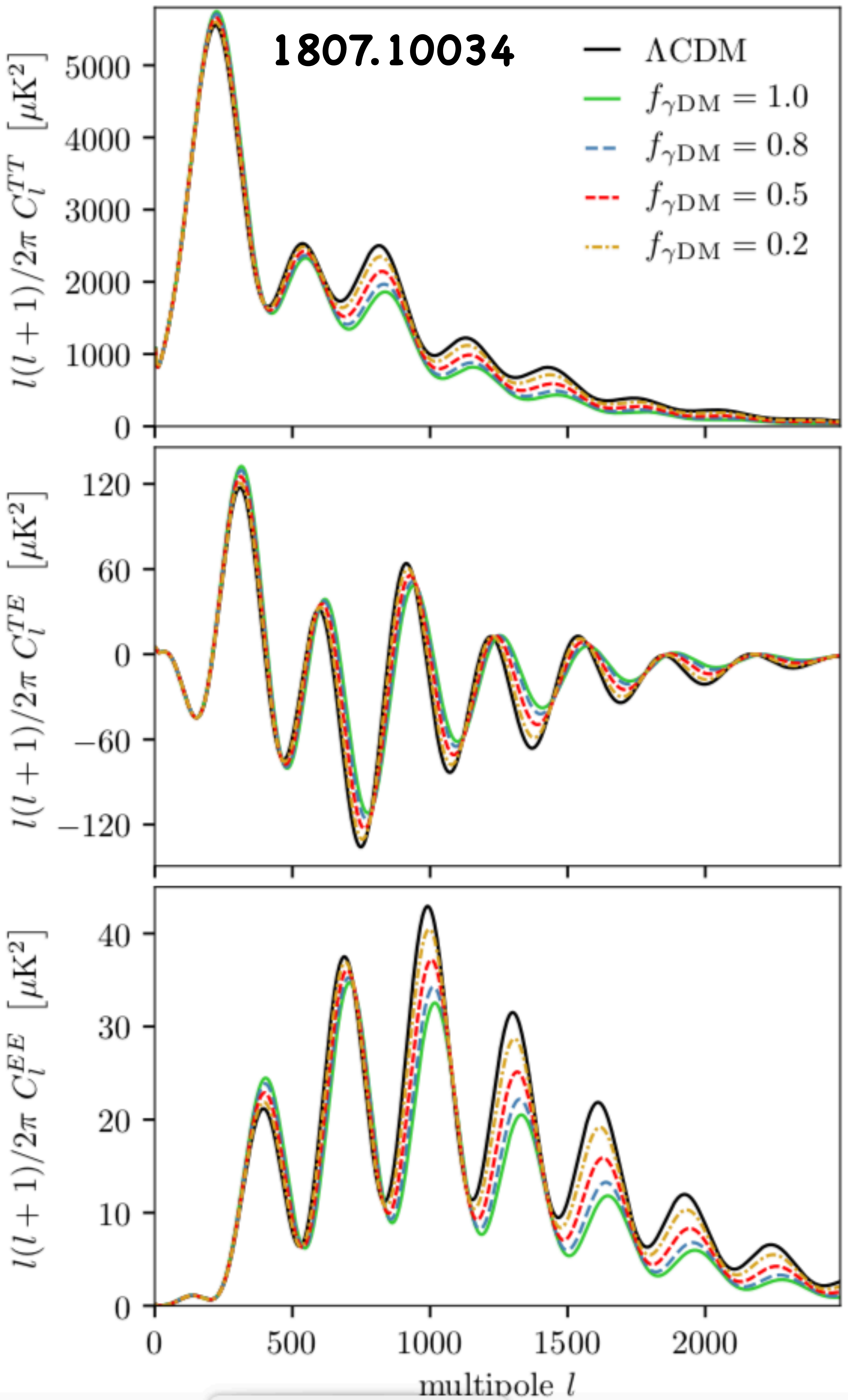
$$l_{id}^2 = \frac{2\pi^2}{3} \int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\rho a^2 \cancelto{H}{\Gamma}_i} (1 + \Theta_i) \frac{dt}{t}$$

DM - neutrino interactions are the most efficient

Most prominent for MeV DM

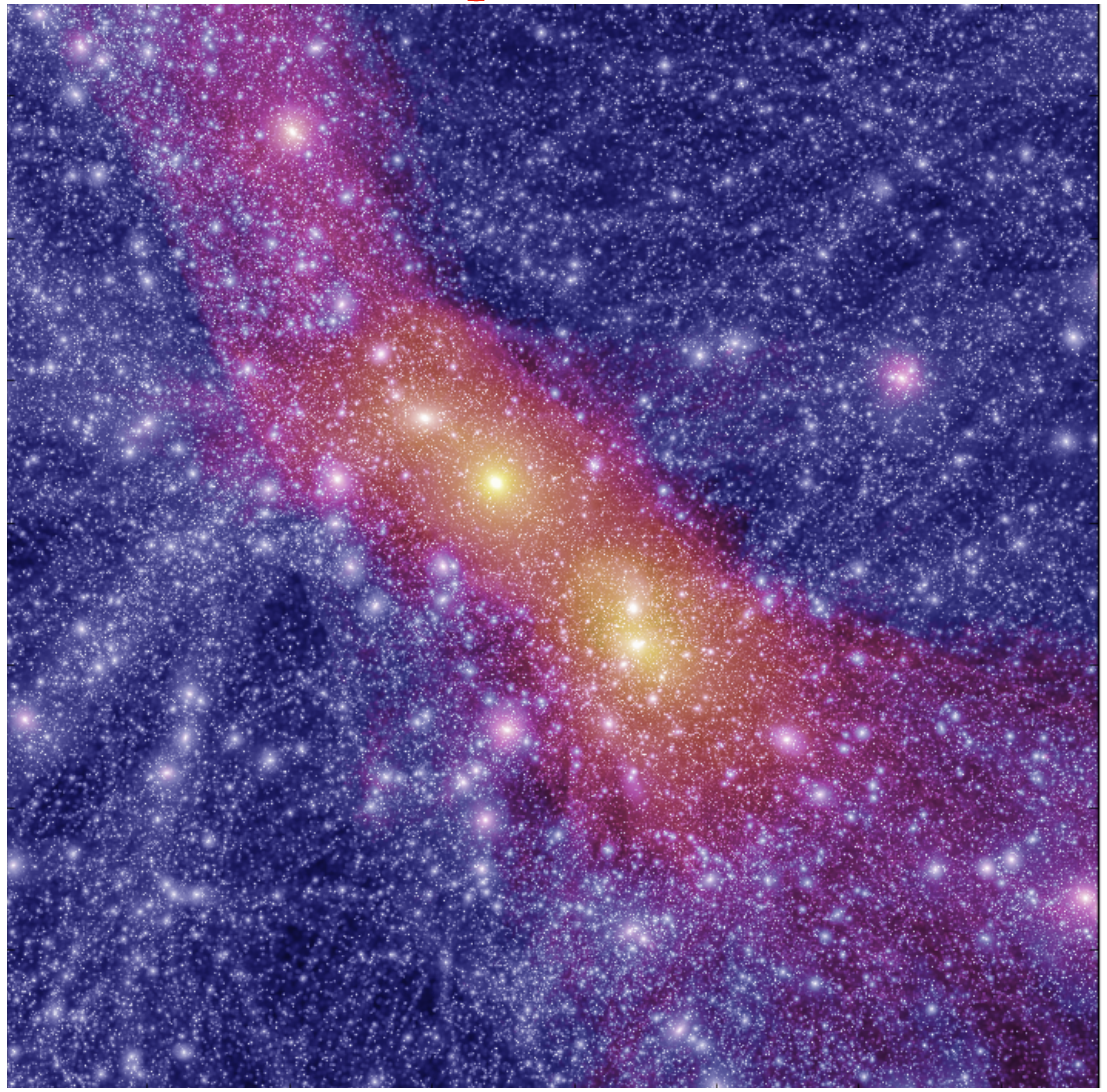
Mixed Scenarios



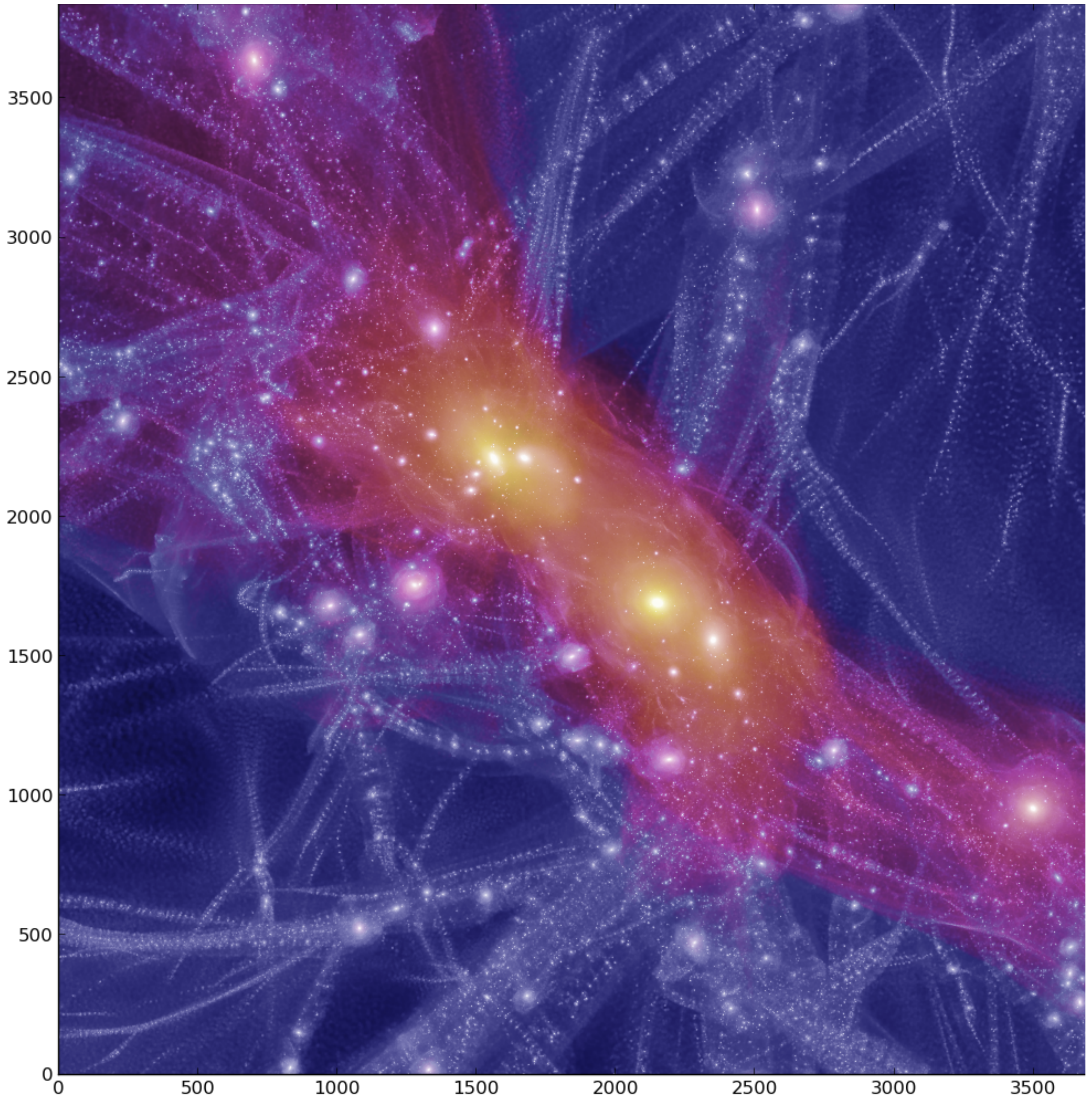


DM -SM interactions & large scales

CDM



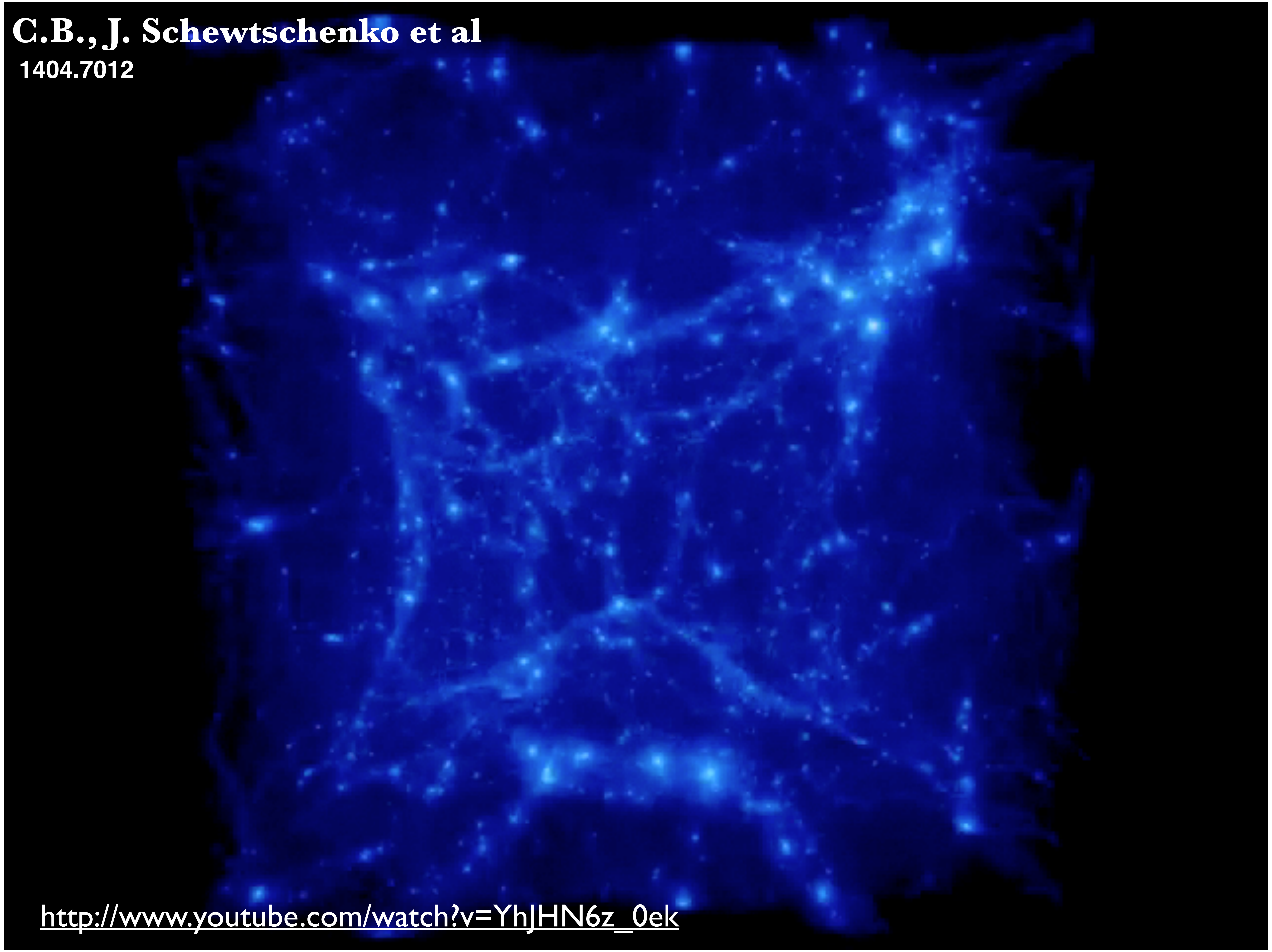
IDM



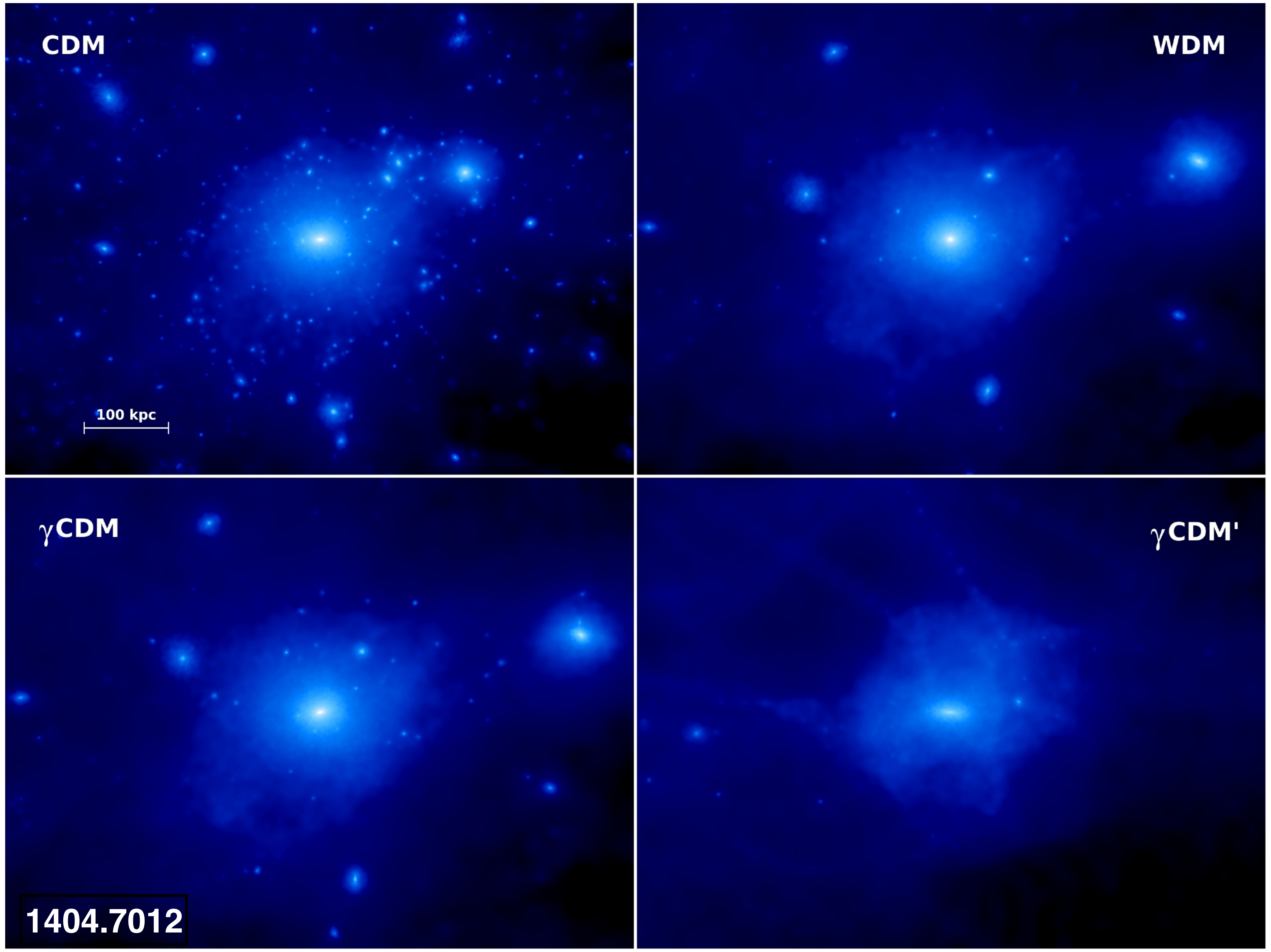
DM-SM [1404.7012](1404.7012)

LSST, EUCLID will be essential!

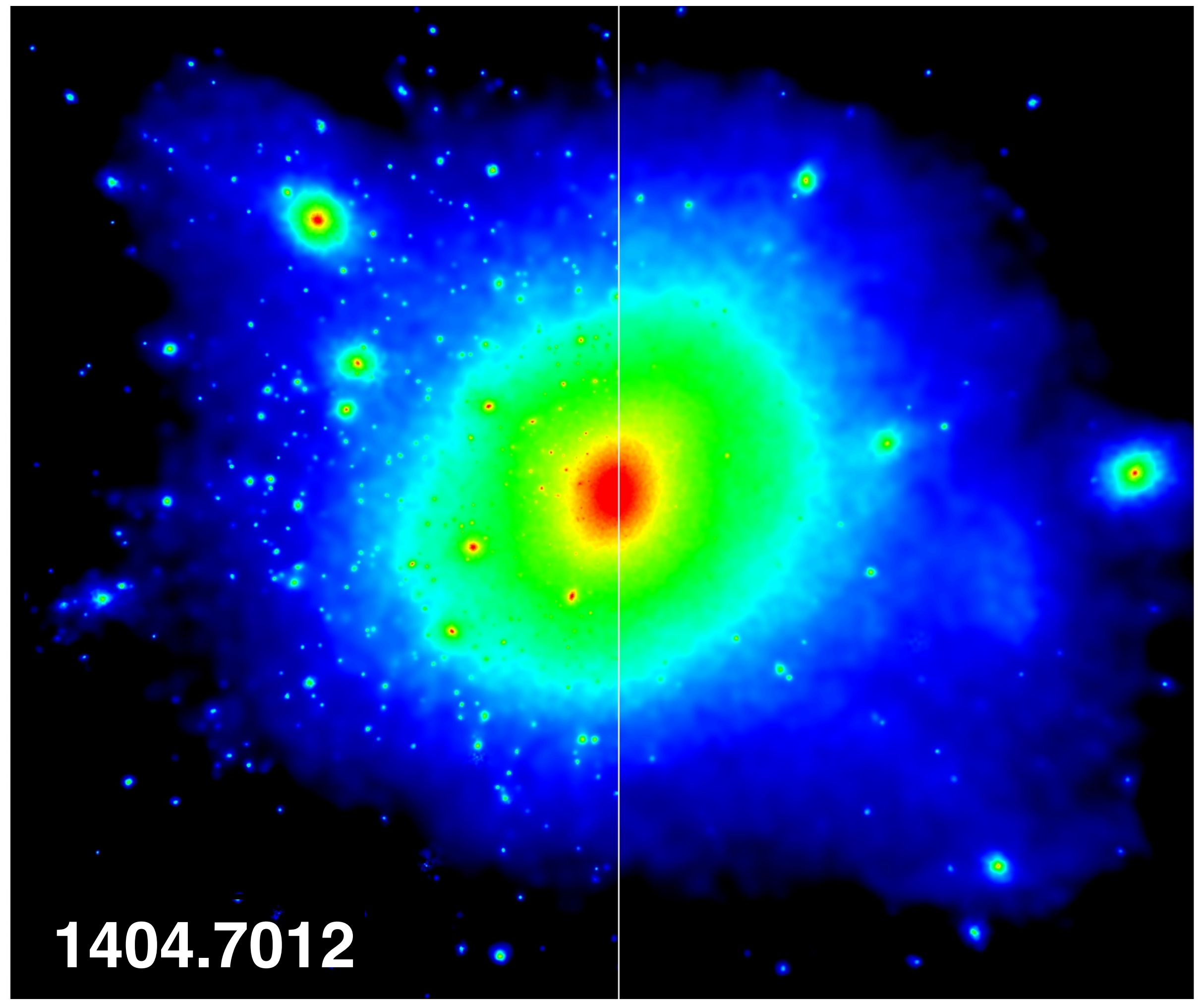
The Milky Way for interacting DM



The Milky Way when DM is interacting



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



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

Going much lower than MeV?

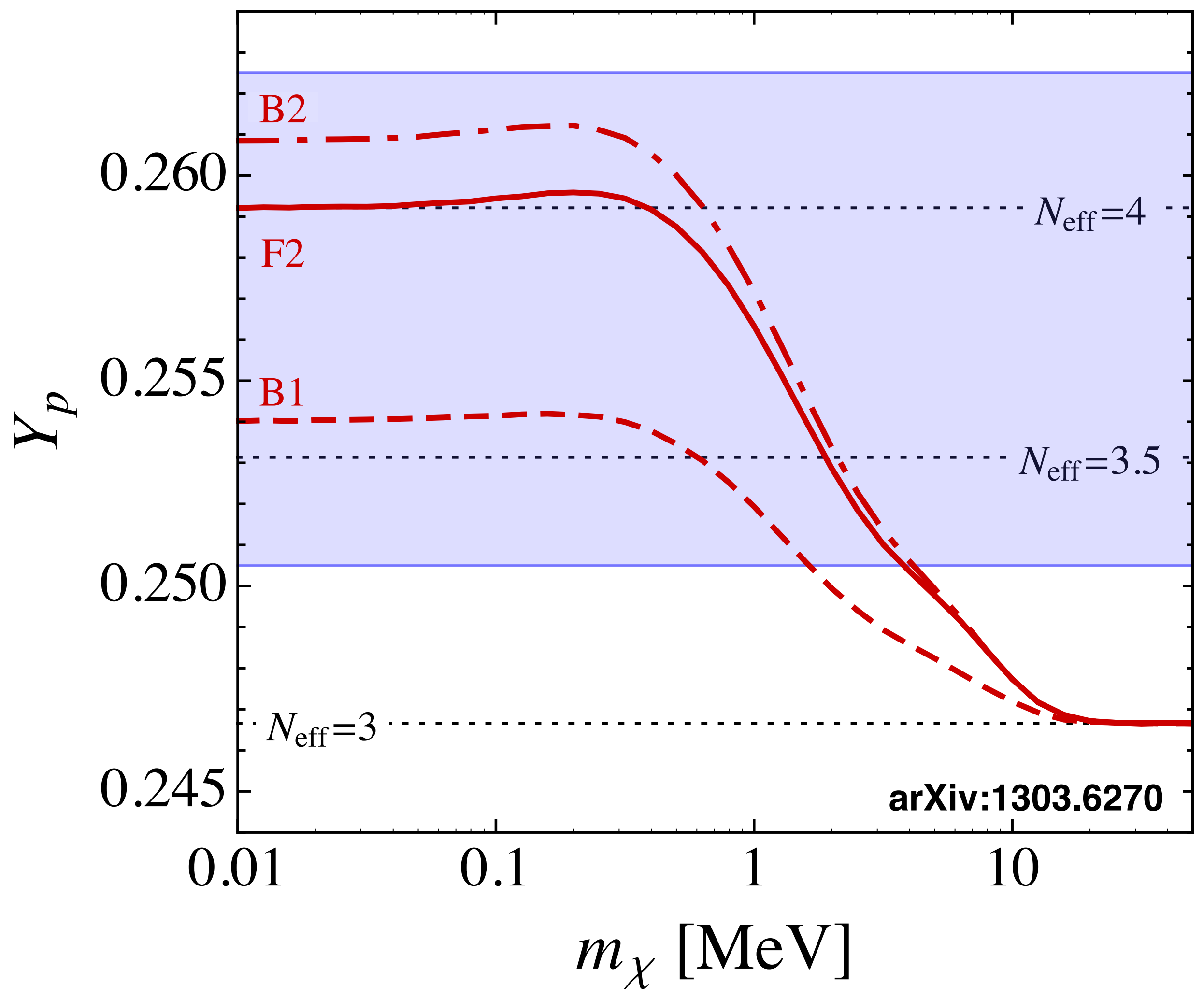
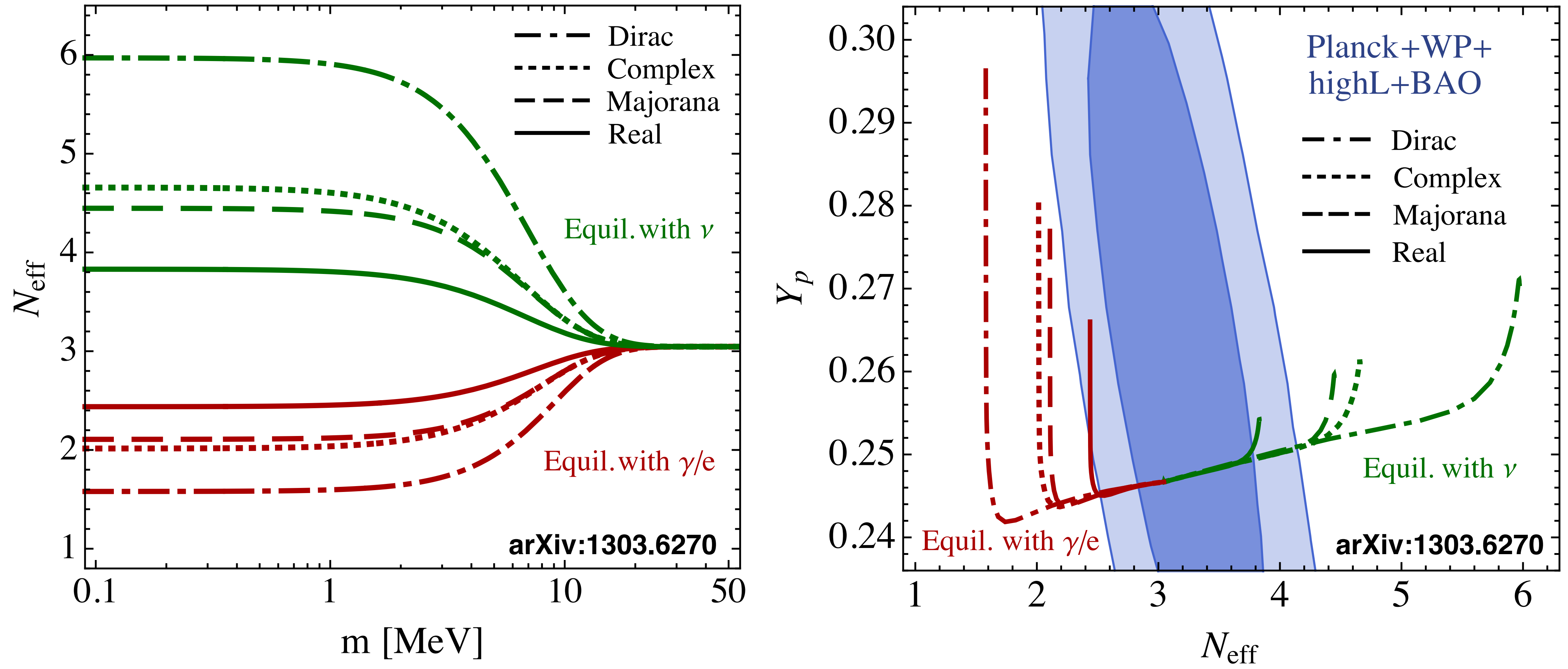


FIG. 2: The red dot-dashed, solid and dashed lines show the predictions for Y_p (upper panel) and D/H (lower panel) for a complex scalar (B2), Majorana fermion (F2) and real scalar (B1) respectively. The blue shaded region indicates the 1σ region for Y_p from [4] (with statistical and systematic errors

Recent inferences of Y_p from observations of metal-poor H II regions have been slightly higher than results from the past decade. For instance, while refs. [44] and [45] found $Y_p = 0.249 \pm 0.009$ and $Y_p = 0.2477 \pm 0.0029$ respectively, more recently, refs. [4], [46], [47] and [48] found $Y_p = 0.2565 \pm 0.0010(\text{stat.}) \pm 0.0050(\text{syst.})$, $Y_p = 0.2561 \pm 0.0108$, $Y_p = 0.2573^{+0.0033}_{-0.0088}$

Impact on CMB

much lower photon temperature (eV) instead of MeV

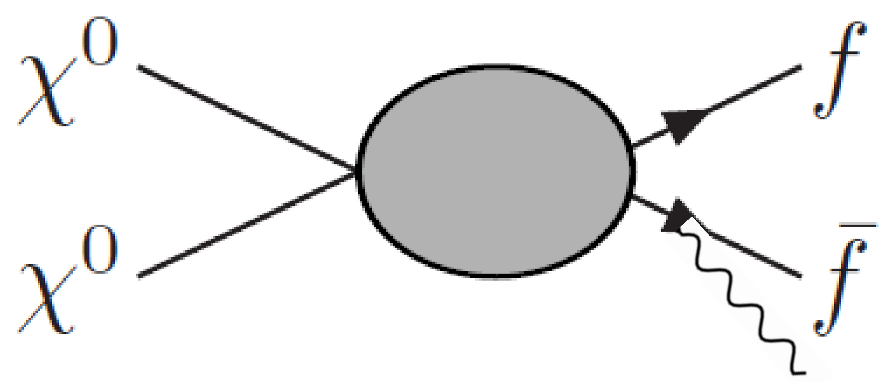


Thermal DM cannot be much lighter than a few MeV

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.



$$\sigma v \propto a + b\, v^2$$

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	$1.7\cdot10^{-4}$	0.014	0.15	$7.5\ 10^{-8}$
ISO	2	2	0	4	$1.2\cdot10^{-4}$	0.011	0.08	$1.8\ 10^{-7}$
BE	1	3	0.3	4	$1.2\cdot10^{-4}$	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	$\mathrm{GeV/c^2\,cm^3}$	$\mathrm{cm^{-2}\,s^{-1}}$
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. $h = 0.7$.

Scalar Dark Matter candidates

C. Bœhm

Denys Wilkinson Laboratory, 1 Keble Road, OX1 3RH, Oxford, England, UK

P. Fayet

Laboratoire de Physique Théorique de l'ENS, 24 rue Lhomond, 75231 Paris Cedex 05, France [1]

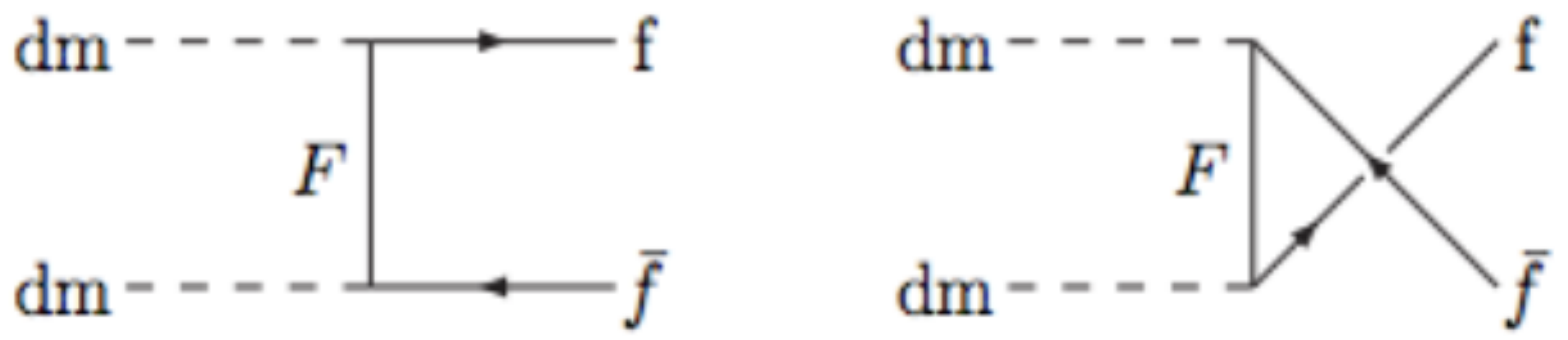
Abstract

We investigate the possibility that Dark Matter could be made of scalar candidates and focus, in particular, on the unusual mass range between a few MeV's and a few GeV's. After showing why the Lee-Weinberg limit (which usually forbids a Dark Matter mass below a few GeV's) does not necessarily apply in the case of scalar particles, we discuss how light candidates ($m_{dm} < O(\text{GeV})$) can satisfy both the gamma ray and relic density constraints. We find two possibilities. Either Dark Matter is coupled to heavy fermions (but if $m_{dm} \lesssim 100$ MeV, an asymmetry between the Dark Matter particle and antiparticle number densities is likely to be required), or Dark Matter is coupled to a new light gauge boson U. The (collisional) damping of light candidates is, in some circumstances, large enough to be mentioned, but in most cases too small to generate a non linear matter power spectrum at the present epoch that differs significantly from the Cold Dark Matter spectrum. On the other hand, heavier scalar Dark Matter particles (*i.e.* with $m_{dm} \gtrsim O(\text{GeV})$) turn out to be much less constrained. We finally discuss a theoretical framework for scalar candidates, inspired from theories with $N = 2$ extended supersymmetry and/or extra space dimensions, in which the Dark Matter stability results from a new discrete (or continuous) symmetry.

Can the cross section be independent of mDM?

hep-ph/0305261

One example



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

Non chiral couplings

$$C_l C_r \neq 0 \quad + \quad m_F >> m_f$$

$$\sigma v \propto \frac{C_l^2 \, C_r^2}{m_F^2} = 3 \; 10^{-26} \; \mathrm{cm}^3/\mathrm{s}$$

The cross section can be independent
of the dark matter mass

And so the correct relic density
Can be achieved for any dark matter mass

Constraints on vector-like fermions

arXiv:2010.02954

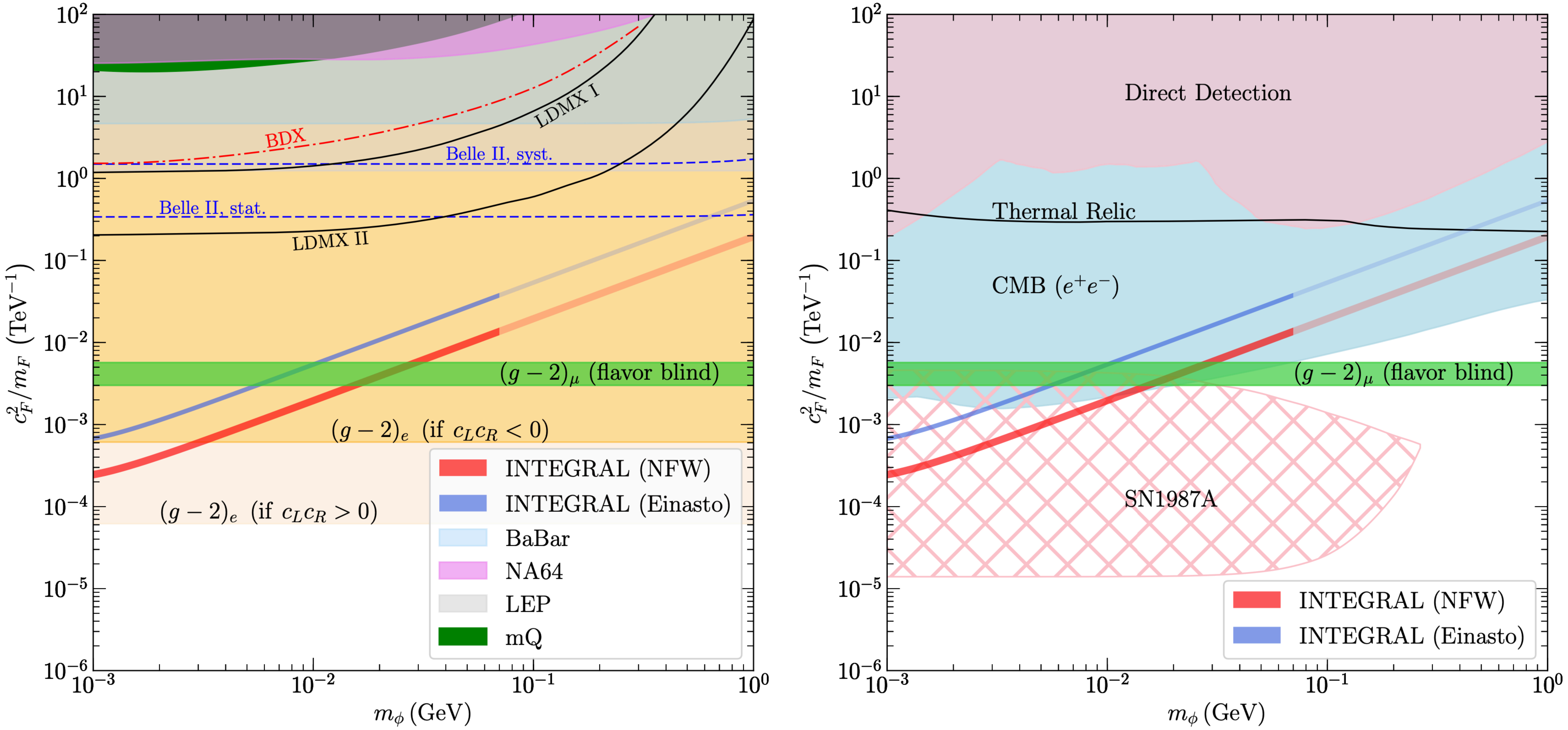
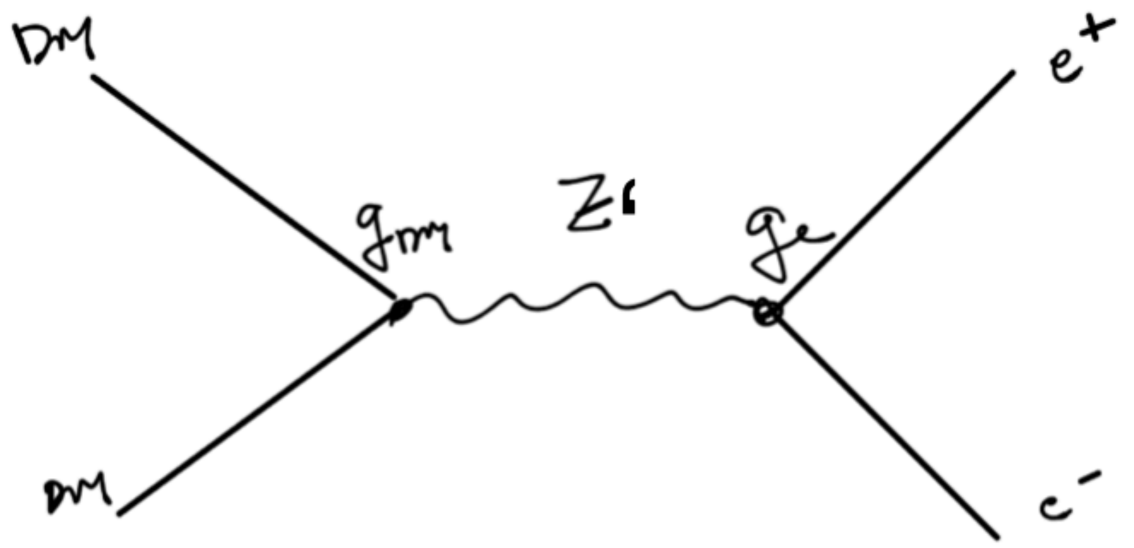


FIG. 6. Bounds on the inverse of effective UV-scale $\Lambda_F^{-1} = c_F^2/m_F$ in the F-mediated model from laboratory experiments (left panel) and from astrophysical observations including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are shown as thin blue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

Can the cross section be independent of mDM?

Dark photon/Z'

hep-ph/0305261
astro-ph/0208458v3



$$\sigma v \propto v^2 \, \frac{m_{\rm DM}^2}{m_{Z'}^4} \, g_{\rm DM}^2 \, g_e^2 \;\; = 3\ 10^{-26}\ {\rm cm}^3/{\rm s}$$

Dark Matter masses smaller than a proton require

$$m_{\rm DM} \simeq m_{Z'}$$

Constraints on dark photons/Z'

arXiv:2010.02954

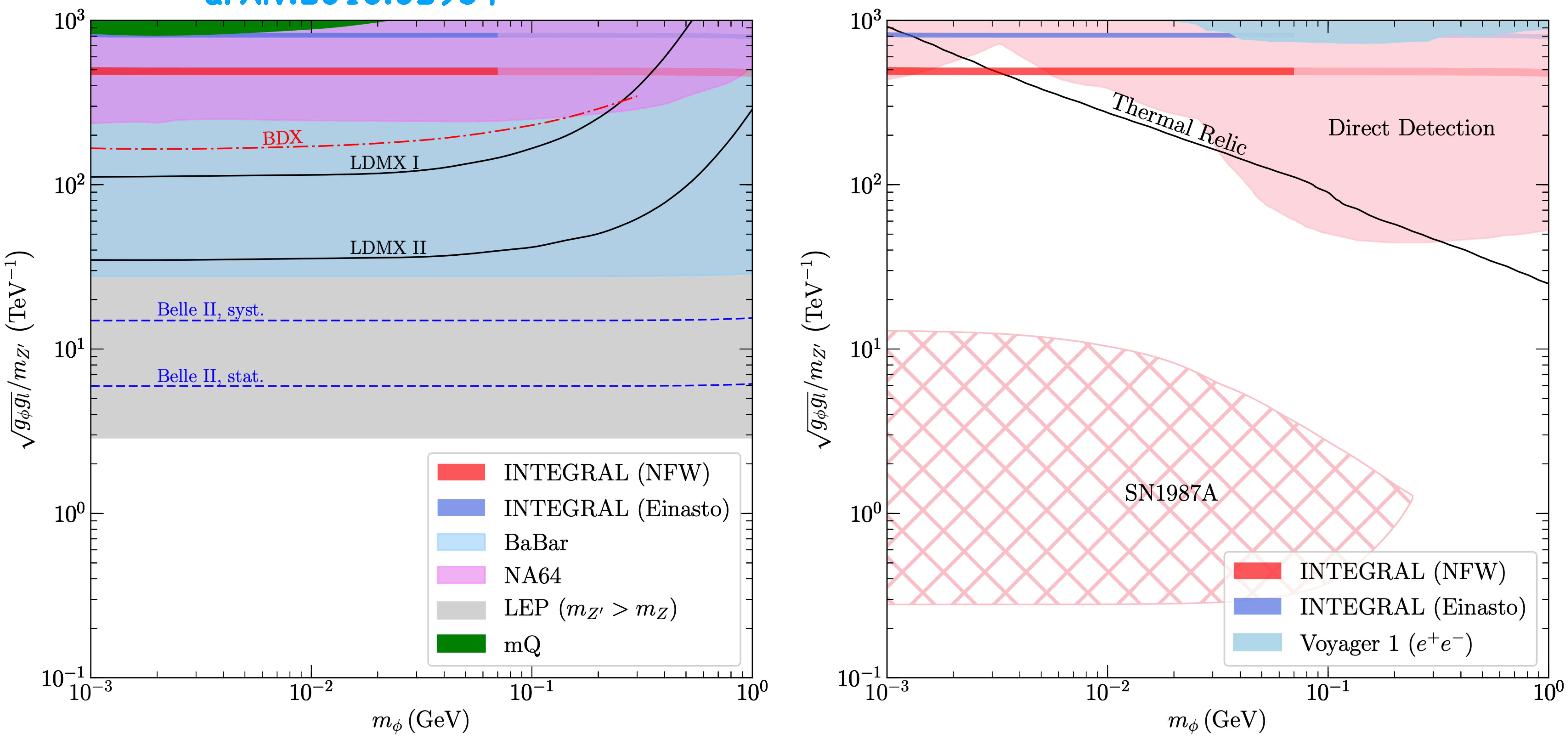


FIG. 7. Bounds on the inverse of effective UV scale $\Lambda_{Z'}^{-1} = \sqrt{g_\phi g_l}/m_{Z'}$ for the Z' model from laboratory tests (left panel) and from cosmological and astrophysical probes including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are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

Conclusion

* LDM very constrained but …
* We have explored a new part of the parameter space
* Unlikely to be the solution to the 511 keV excess
* Which new directions should we take?

Courtesy C. O'Hare