# Dark Matter
# USyd node's perspective

Celine Boehm

University of Sydney & Edinburgh

3rd annual workshop, Adelaide, 29 Nov 2023

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

# Sydney perspective:

**2018:** one dark matter person

**2023:** CB + Ciaran + Theresa + Laura

\+ Ellen + Tarak

\+ Chiara, Sharry, and more

\+ Have already trained 9 PhD students in the field

\+ Hired Ciaran and (60% of) Theresa on centre funds to do Direct Detection and related stuff

\+ Hired Laura *on half my salary* to also do Direct Detection

**USyd has greatly supported efforts on direct detection + other things**

# Sydney perspective:

**Nature of DM**

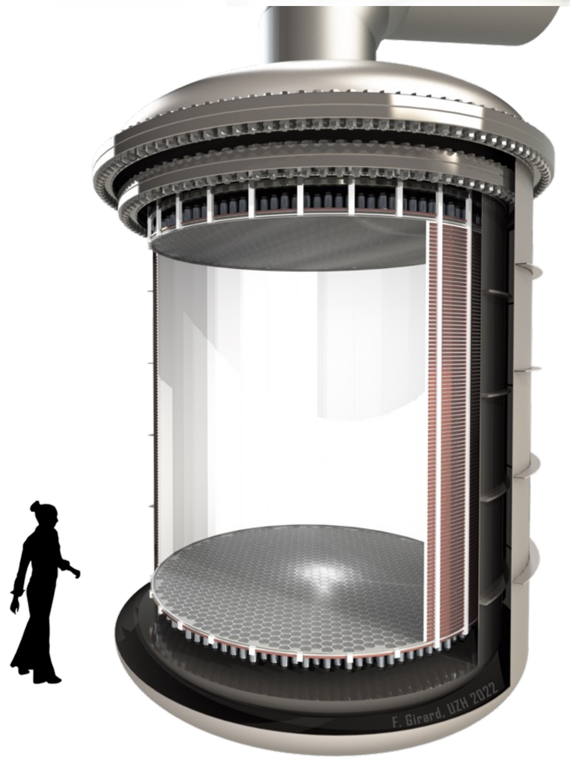
**What is the kind of interactions we are dealing with?**

Sabre LZ/Xenon-nT/Darwin Axions/Light DM Astro & Cosmo

P(k) Dust MG

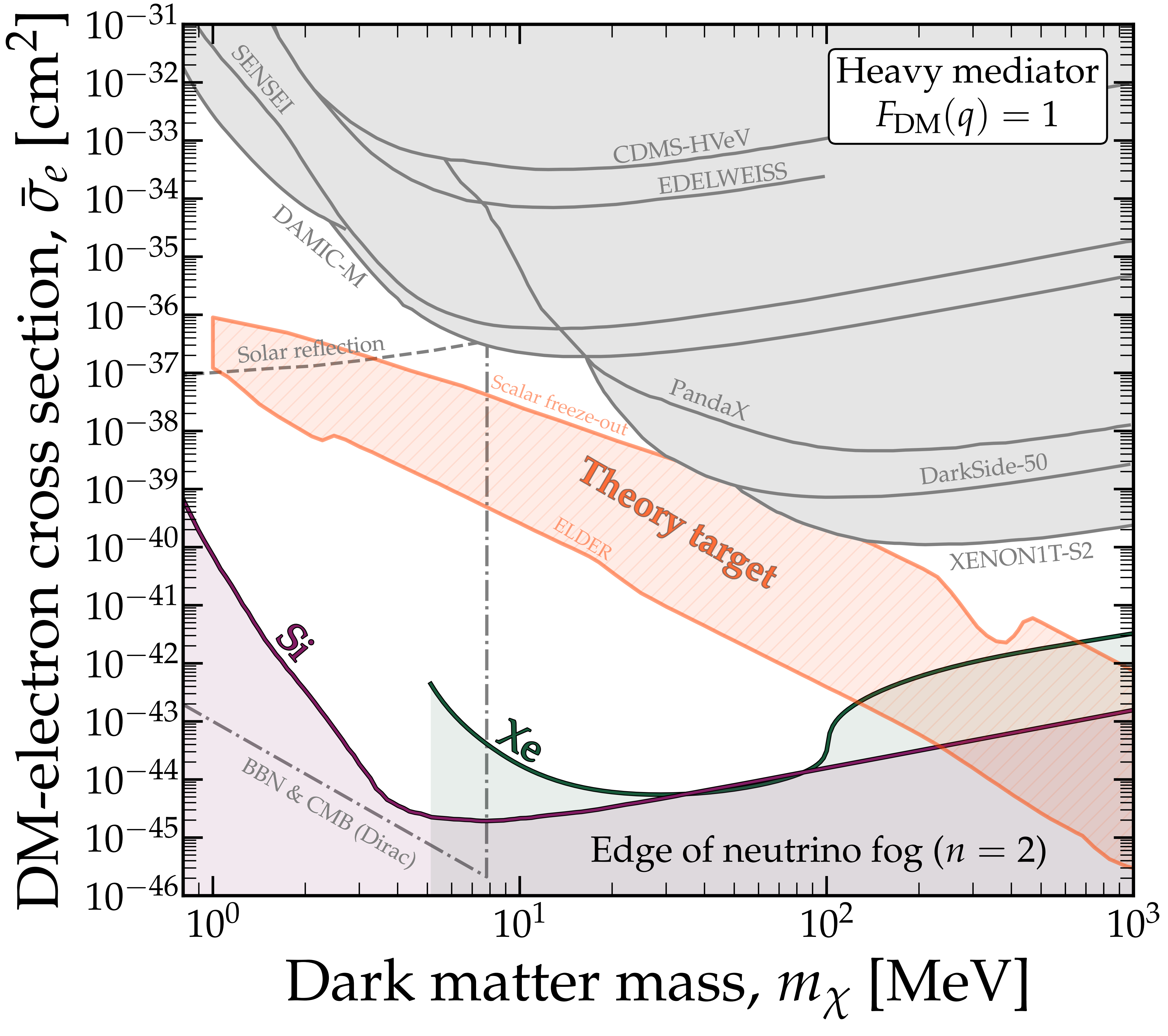
# Direct detection (experimental)

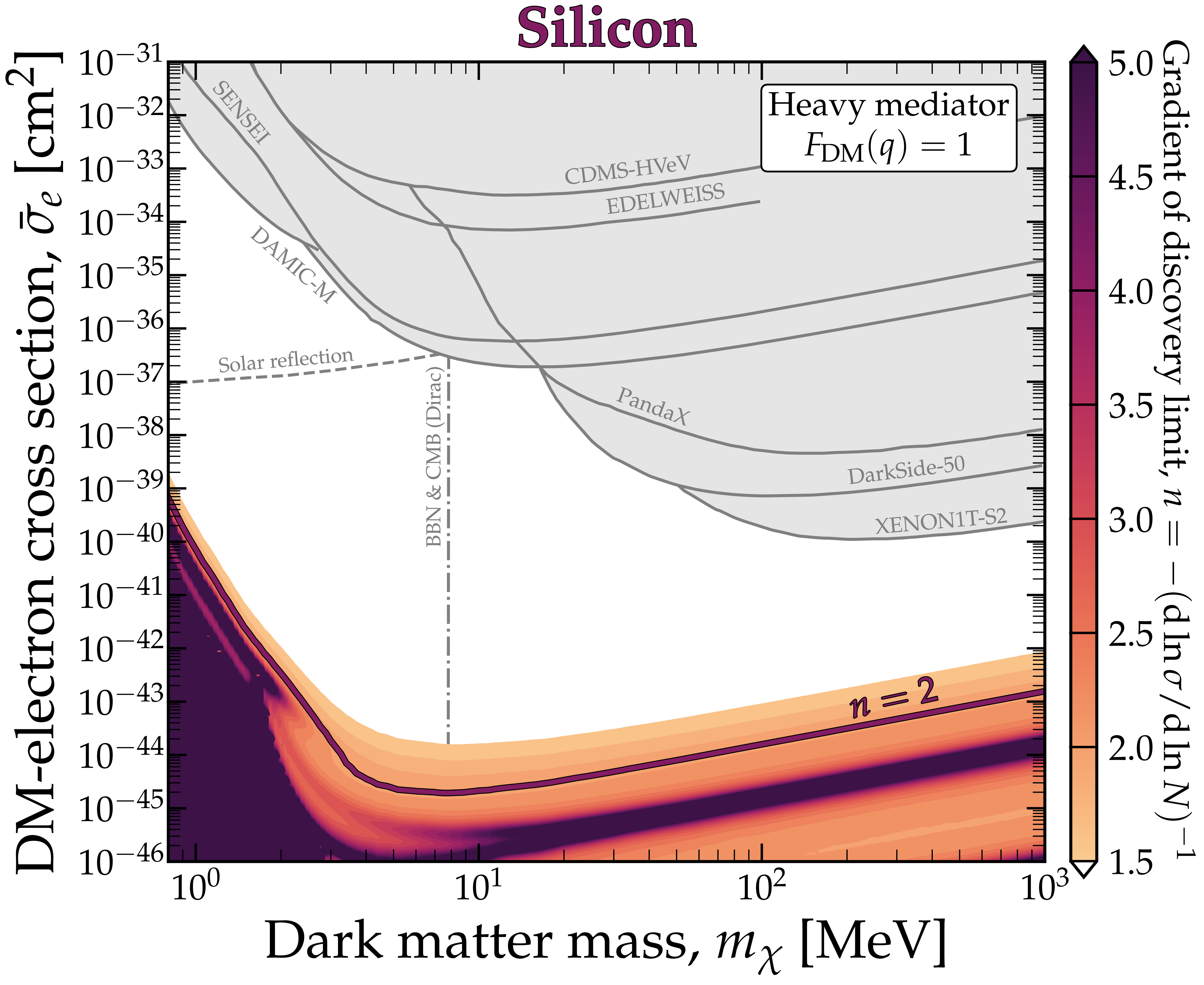
- Team: Theresa & Sharry
- Involved in three experiments:
  - LZ (currently running)
    - Circulation and cryogenics paper
  - SABRE (in preparation)
    - PMT working group
    - Sharry will start on background simulations
  - XLZD (in planning)
    - Simulations work
- Preparing R&D lab space for photosensor characterisation



# Mapping the neutrino fog for dark matter-electron scattering

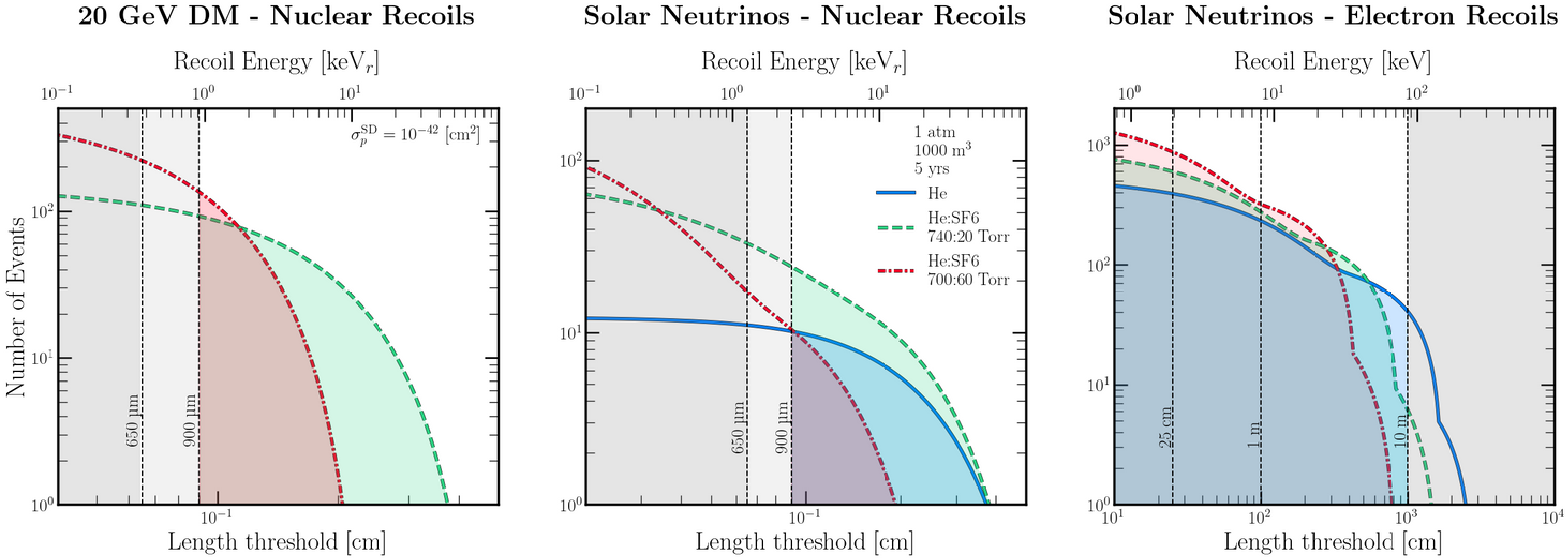
Ben Carew (CDM Vacation Student), Tarak Nath-Maity, Ciaran O'Hare



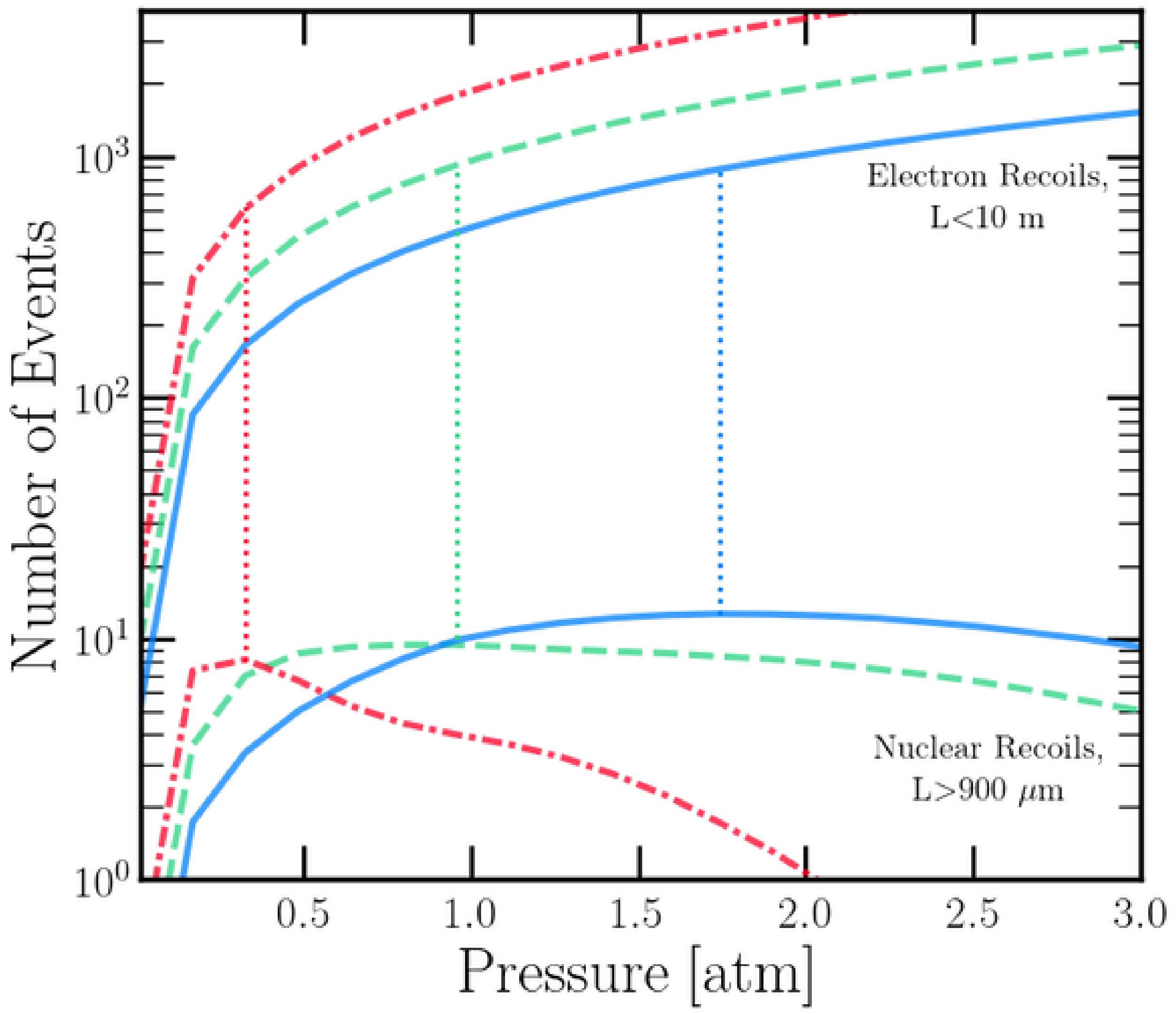


# Chiara

- Working on finding optimal parameters for the CYGNUS experiment
- Nuclear recoils are short, electron recoils are long, as can be seen by plotting number of events for recoils above a certain threshold against the threshold itself



- **An experiment that has optimal sensitivity to low-energy nuclear recoils does not have optimal sensitivity to electron recoils**
- A future analysis will include directionality to predict the optimal orientation of the readout plane

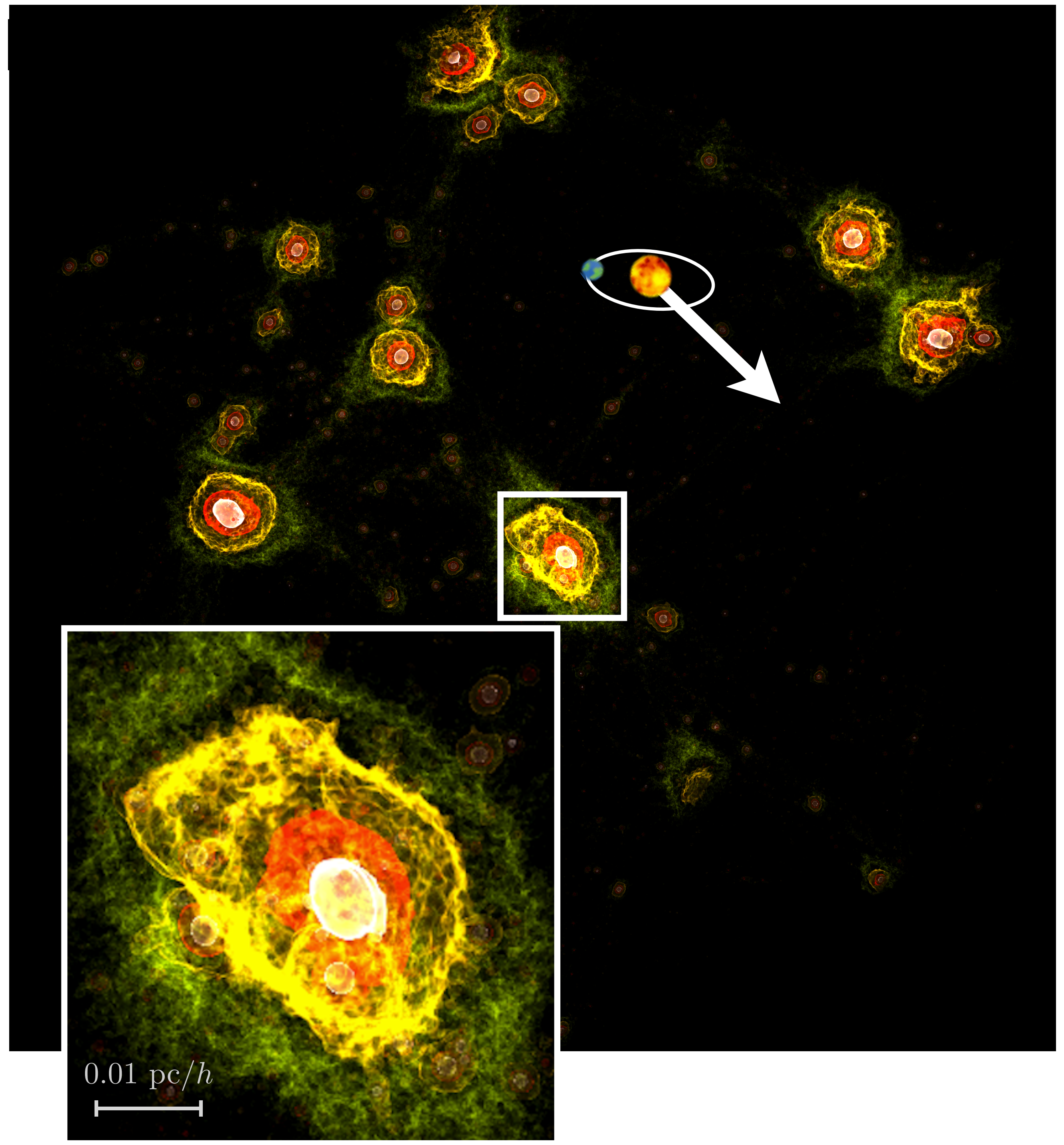


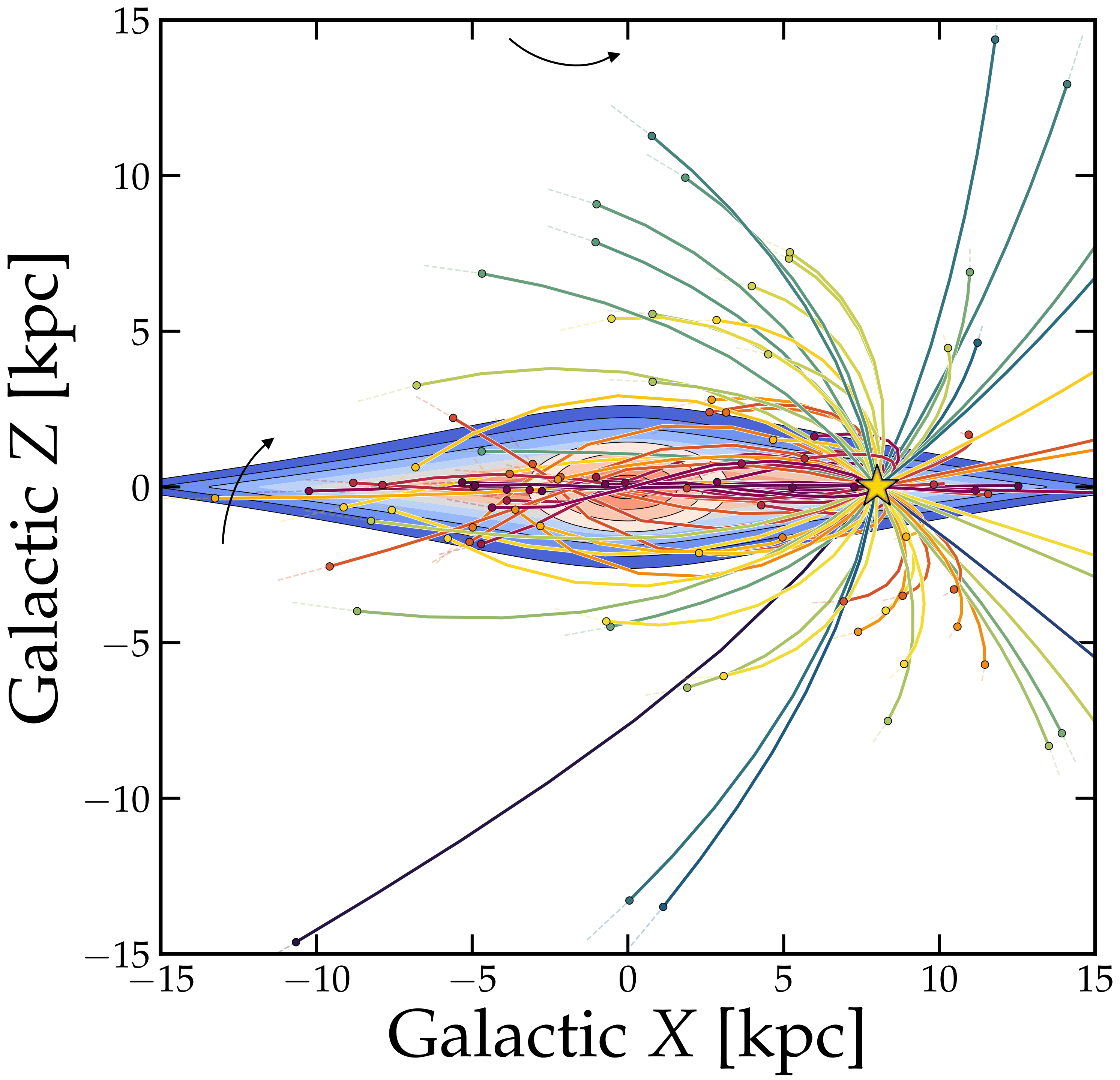
# Predicting the local axion dark matter distribution

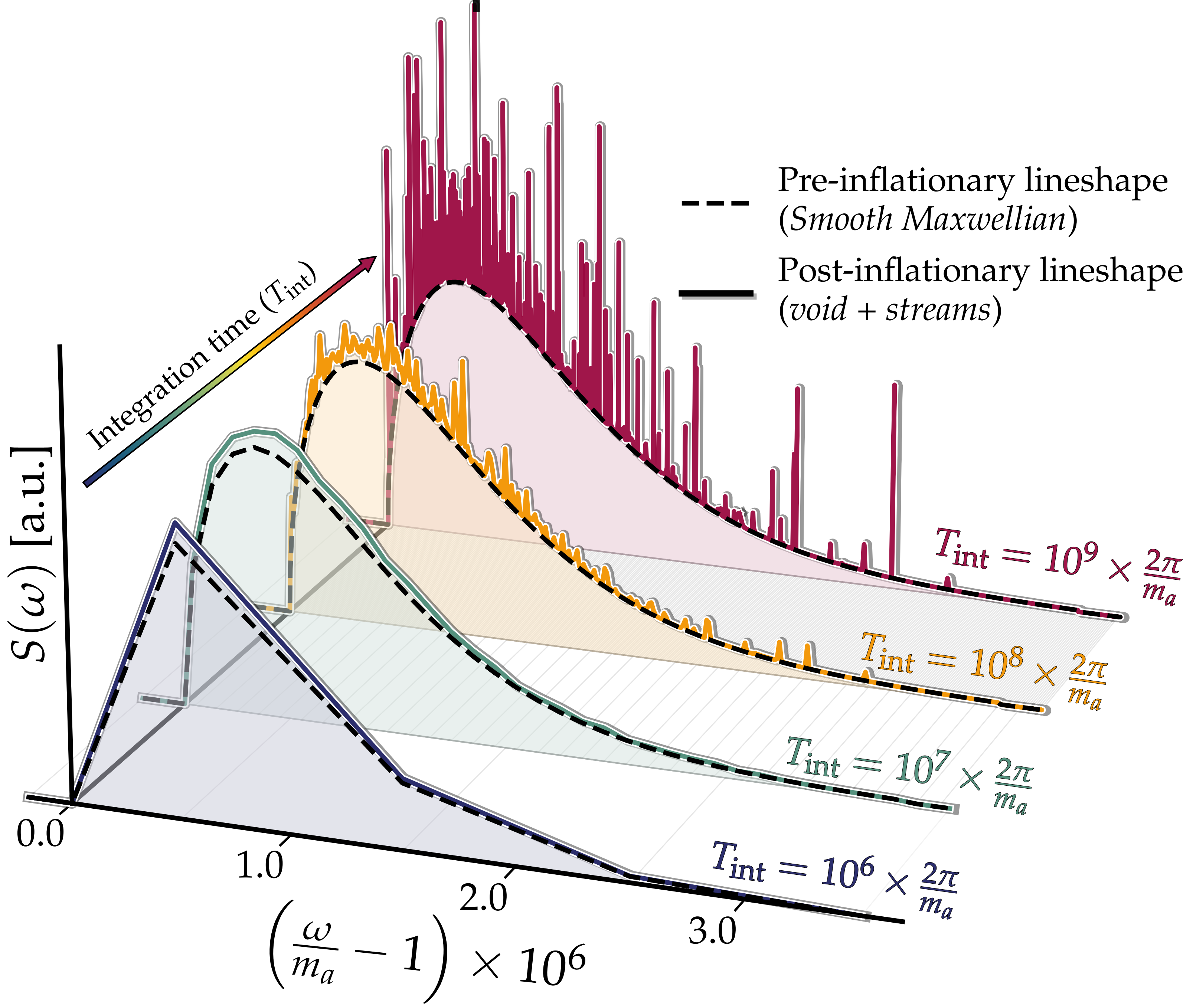
Ciaran O'Hare, Giovanni Pierobon

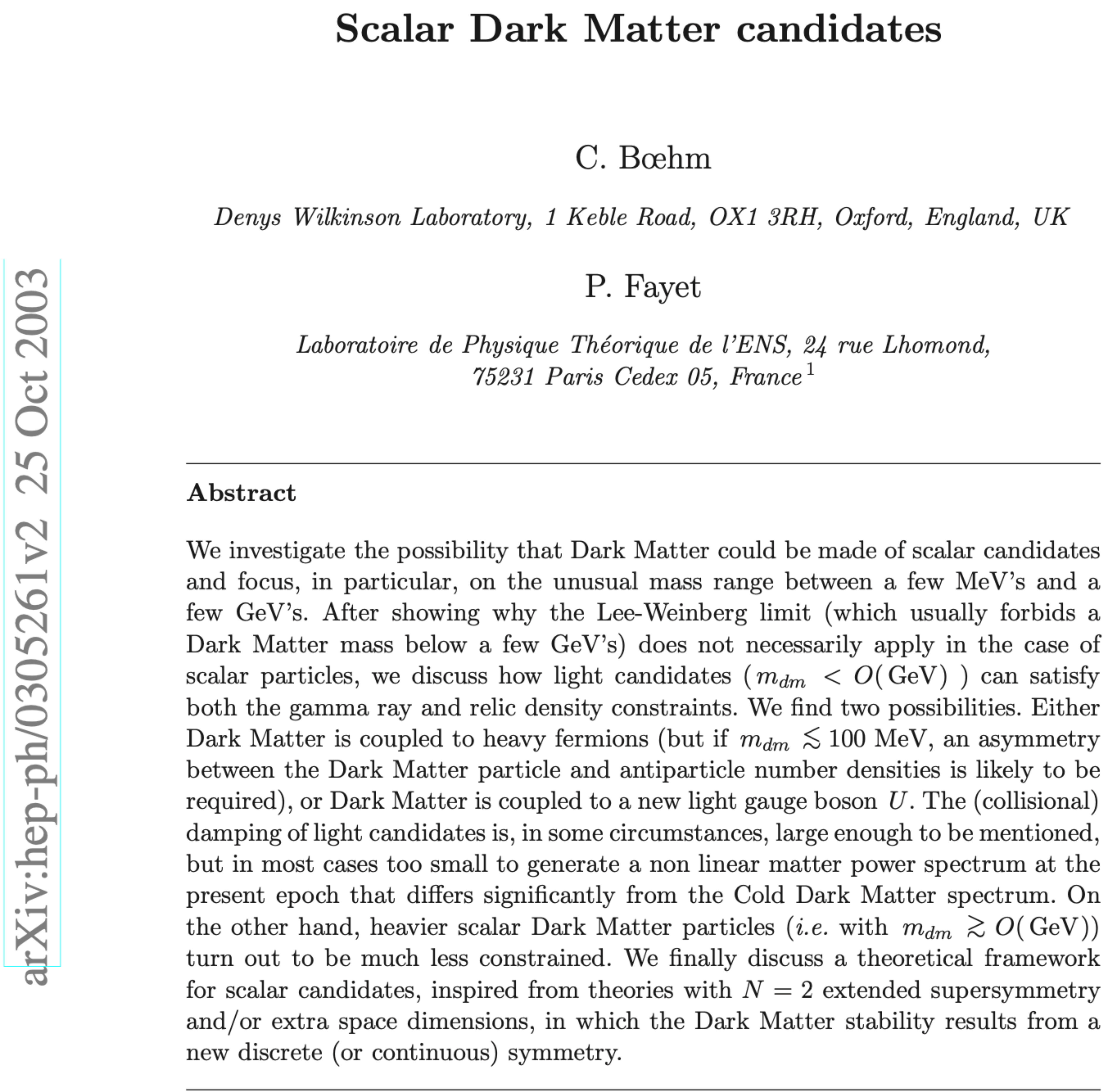
Axions form tightly bound clumps called miniclusters in the early Universe. These were thought to threaten prospects for direct detection. We have performed simulations to show that the DM density in the solar neighbourhood is mostly refilled due to tidal disruption, thereby rescuing prospects for direct detection in haloscopes

N- → Monte- → Experimental









# 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,*
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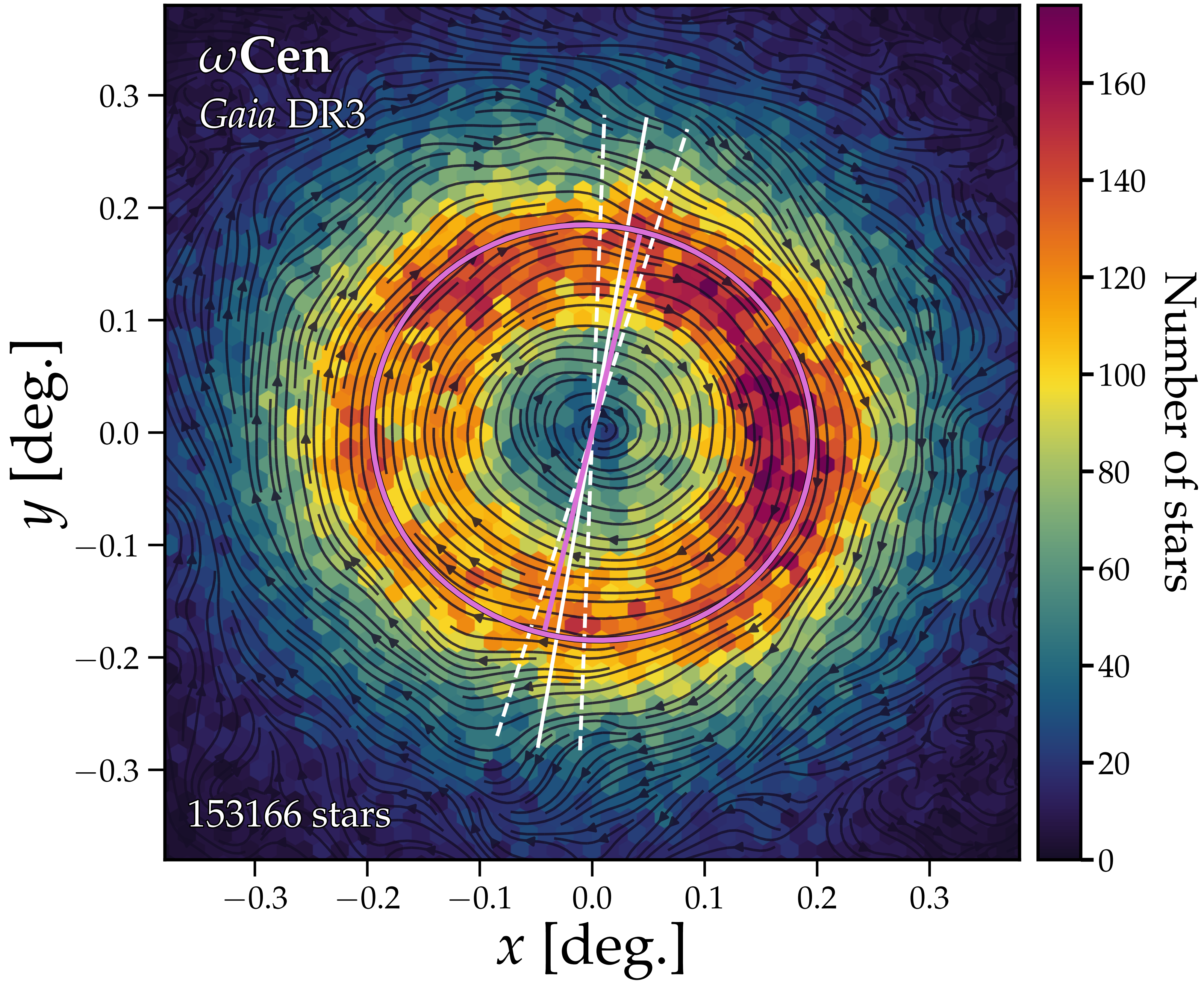
**Abstract**

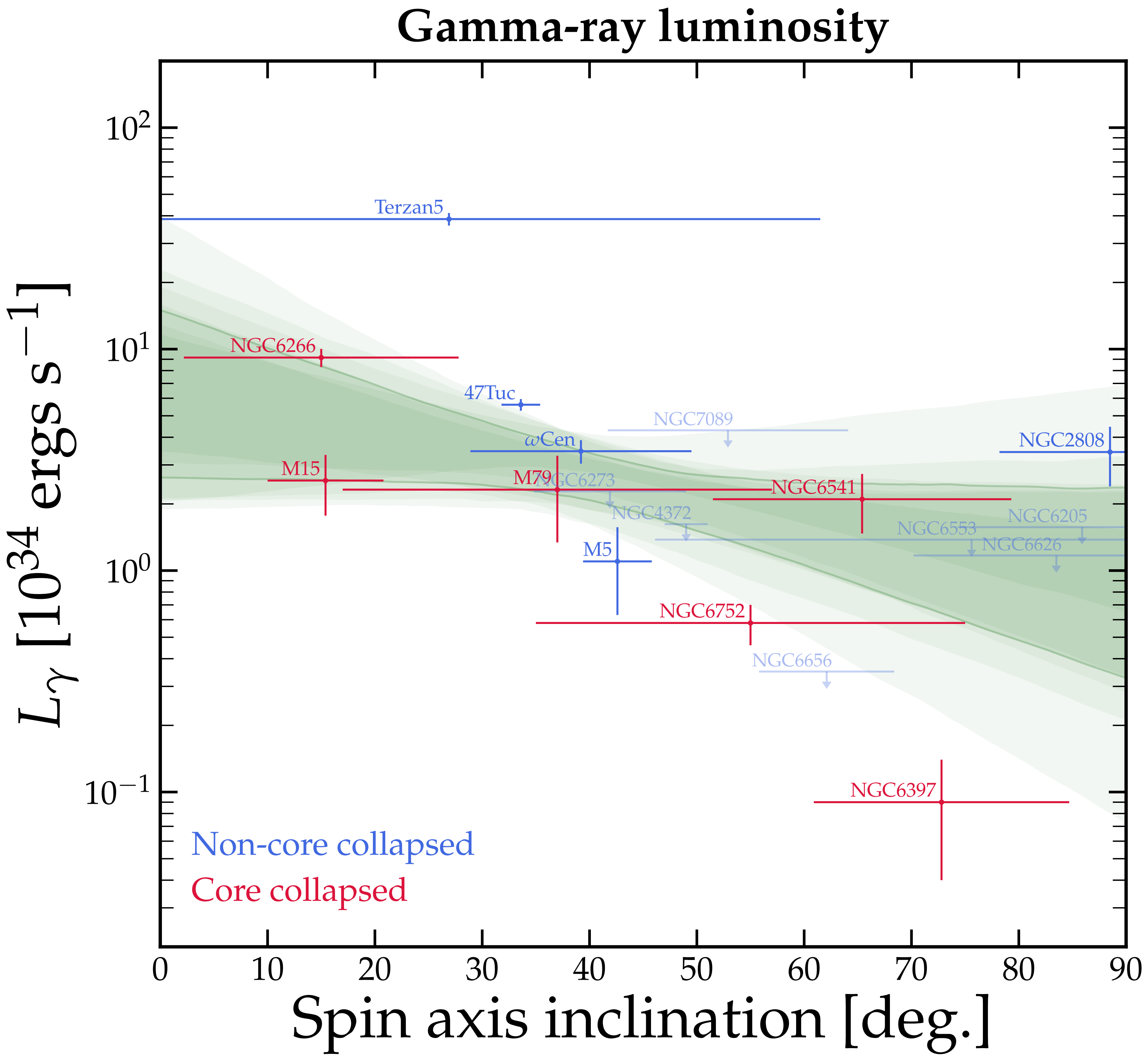
We investigate the possibility that Dark Matter could be made of scalar candidates and focus, in particular, on the unusual mass range between a few MeV's and a few GeV's. After showing why the Lee-Weinberg limit (which usually forbids a Dark Matter mass below a few GeV's) does not necessarily apply 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.

# Spinning globular clusters

Ciaran O'Hare, Alberto Krone-Martins, Celine Boehm, Roland Crocker

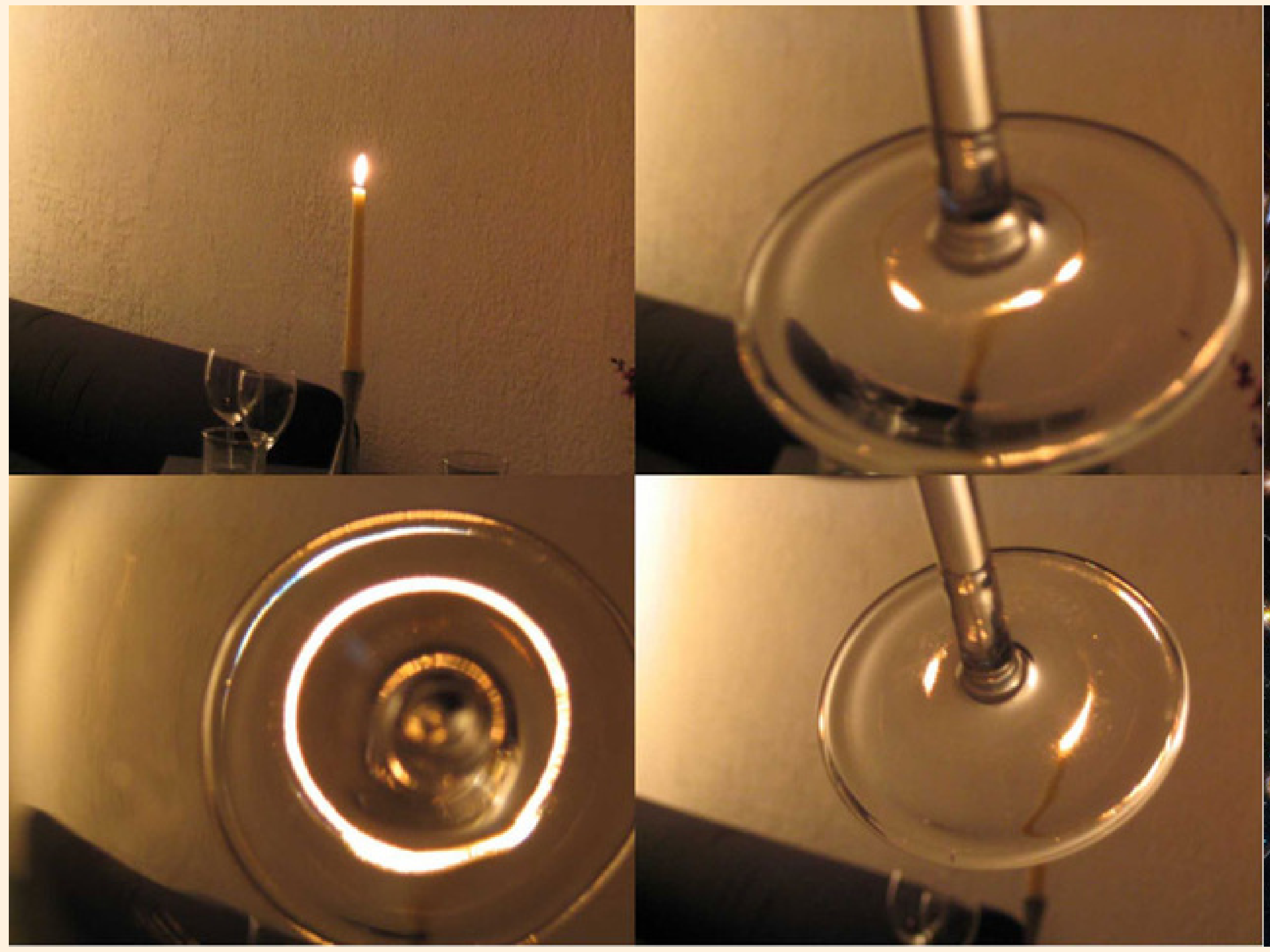
Spinning globular clusters show a puzzling correlation between their gamma-ray emission and their spin axis inclination.

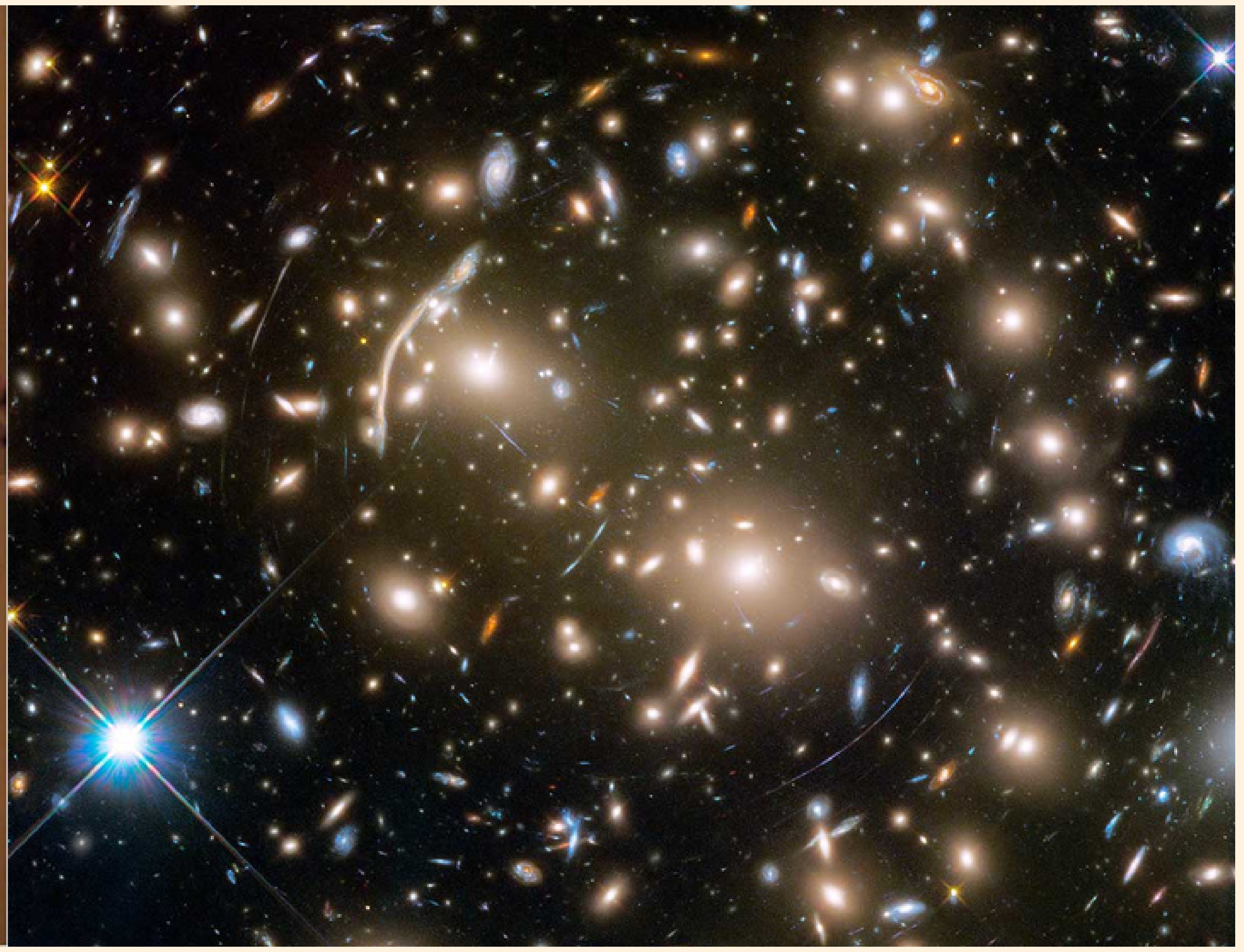




# Ellen Sirks

Postdoc in the Astroparticle
group at USyd



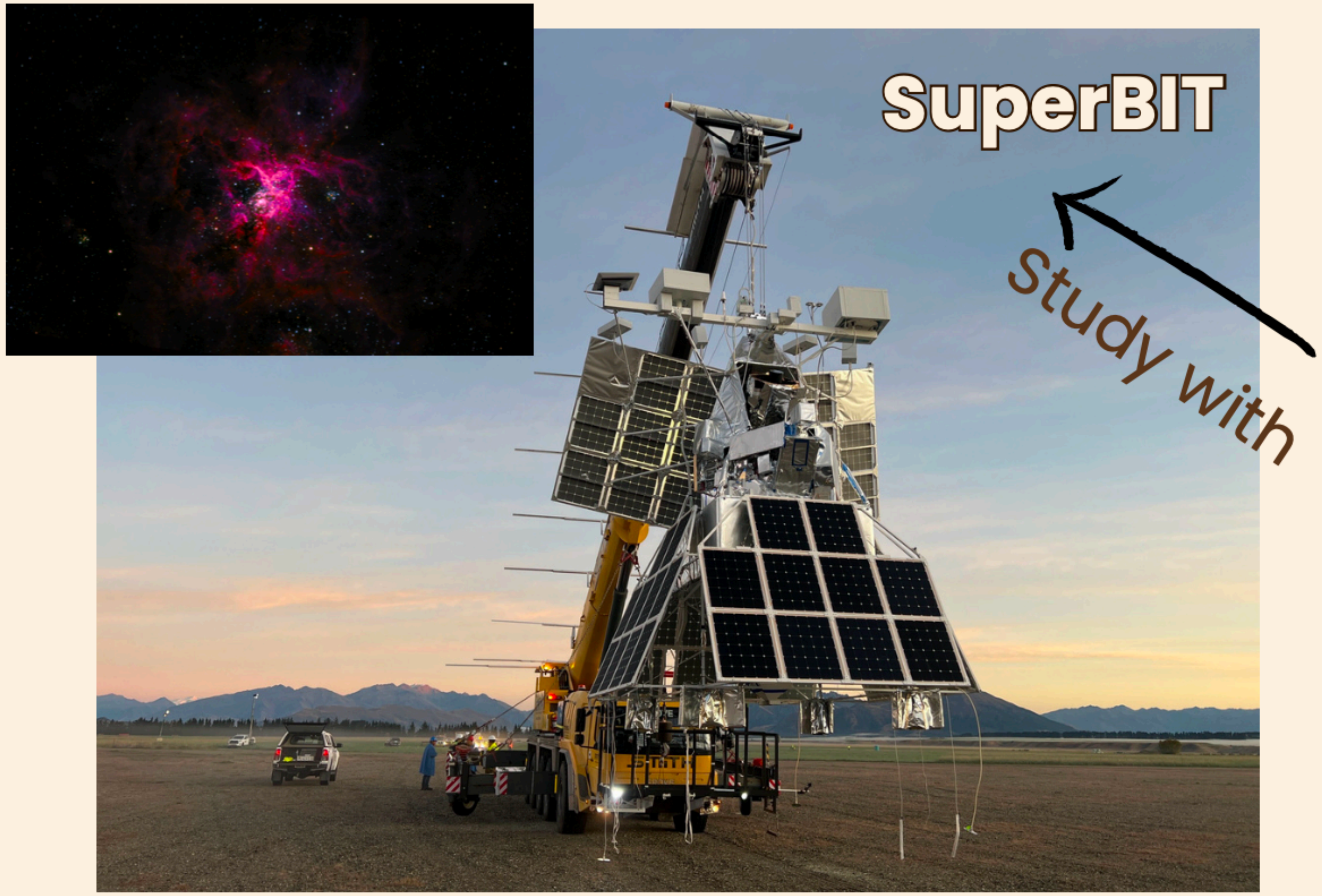


Use **gravitational lensing** to do critical tests of CDM theory

Use **cosmological simulations**
to **devise** observational **tests**

Get high quality data to possibly
**do** these observational **tests**!

# Ellen Sirks



Science flight: 16 April - 25 May, 2023
Currently cleaning the data!
More info in poster session

In the past looked at:

- Increased mass loss of cluster galaxies due to DM self-interactions
- DM-galaxy offsets in merging clusters du to extra drag from DM self-interactions

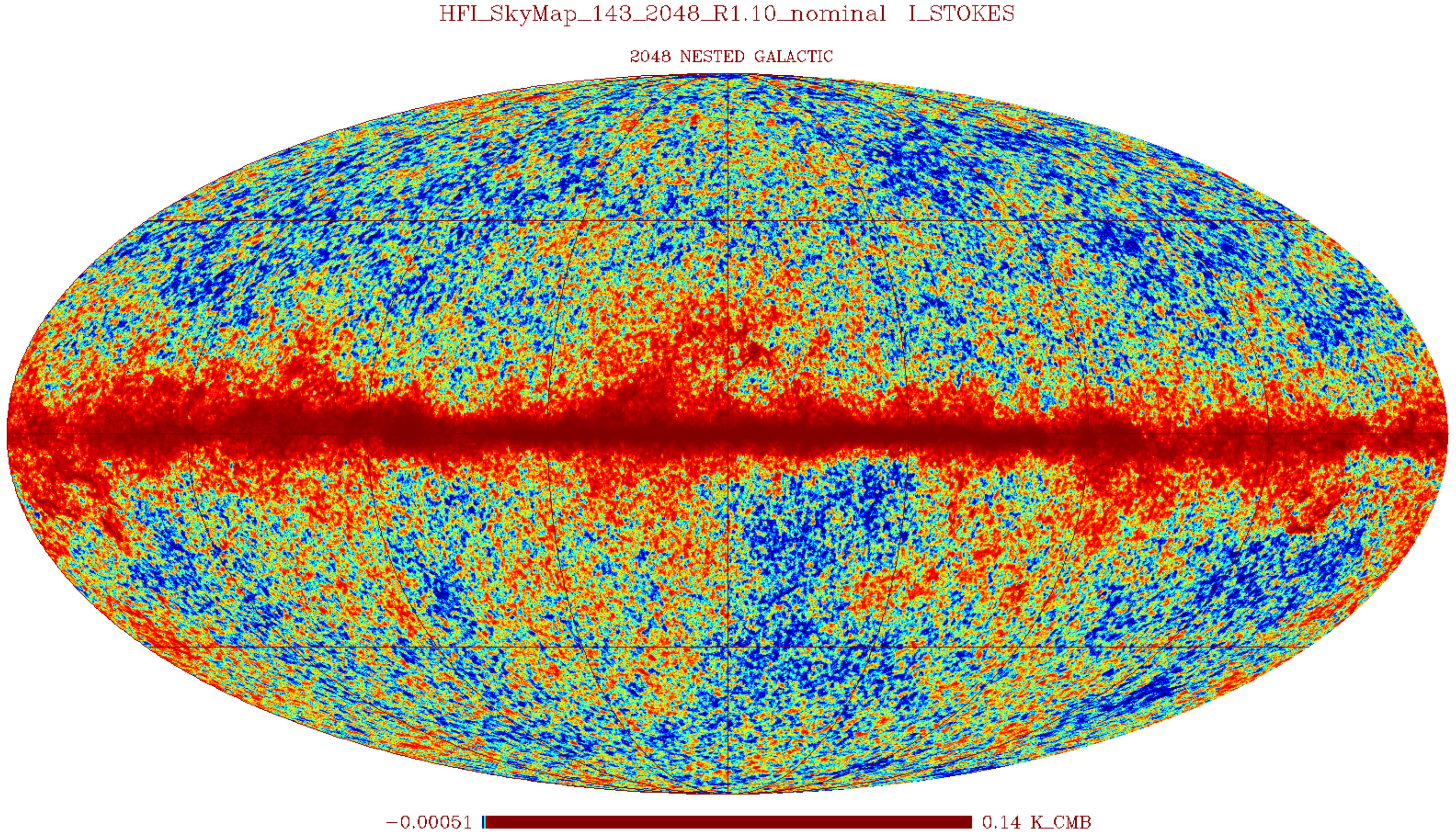
Currently studying/writing simulations with:

- Neutrino-DM interactions
- Baryon(gas)-DM interactions

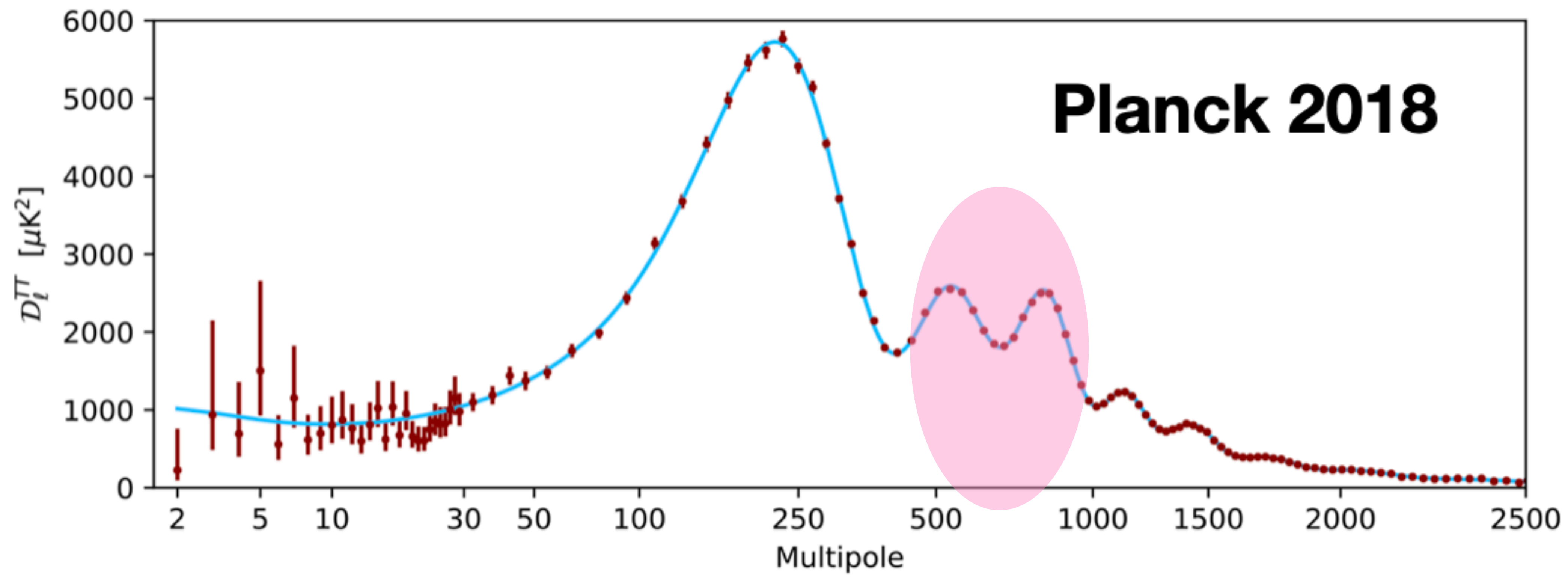
# My obsession

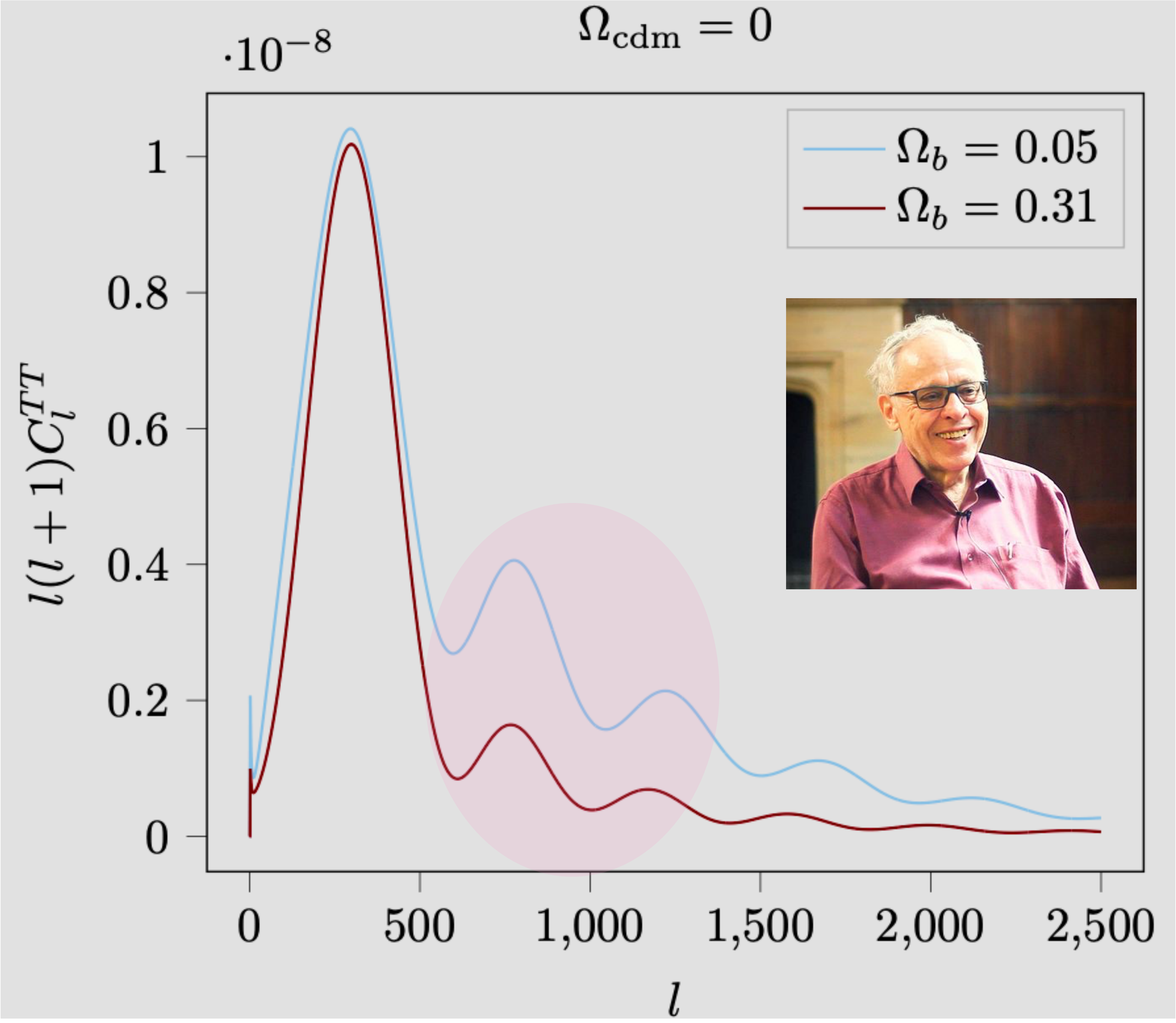
Characterising the dark matter interactions using Astro/Cosmology observations

# CMB & Structure formation

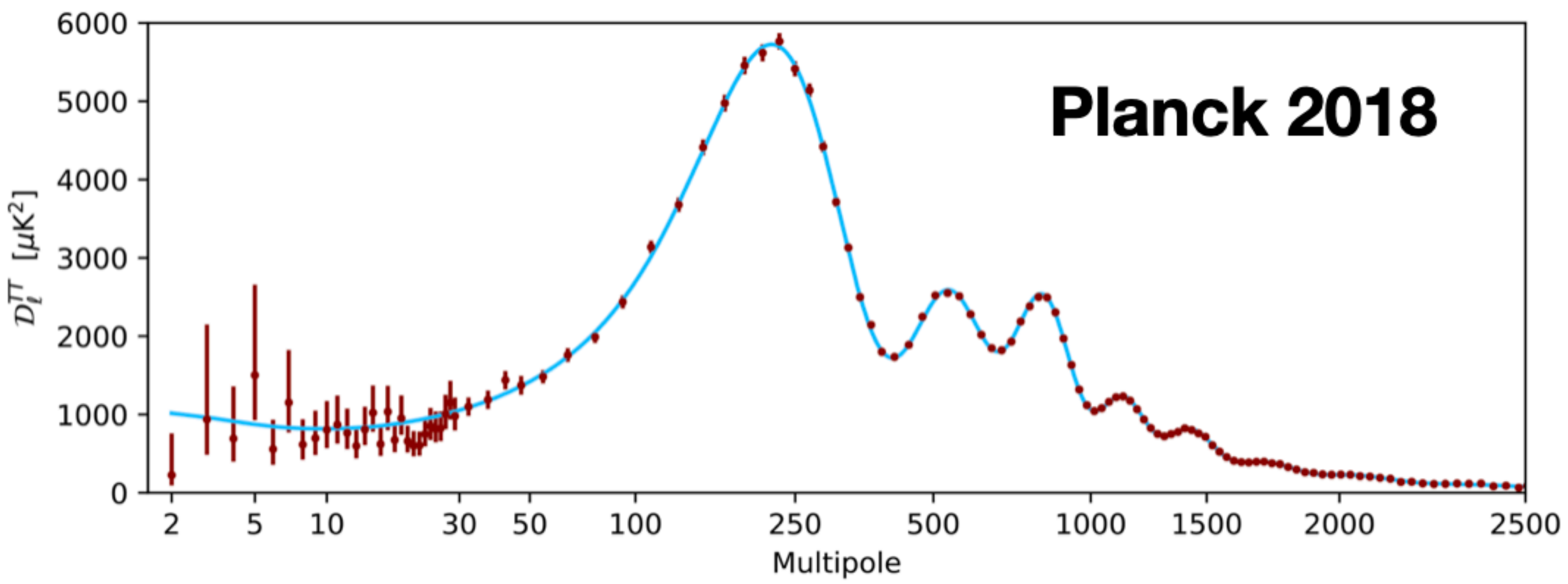


$$
\begin{aligned}
\dot{\theta}_{\rm b} &= k^2\psi - \mathcal{H}\theta_{\rm b} + c_s^2 k^2 \delta_{\rm b} - R^{-1}\dot{\kappa}(\theta_{\rm b} - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_{\rm b})\ ,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





# CMB & Structure formation



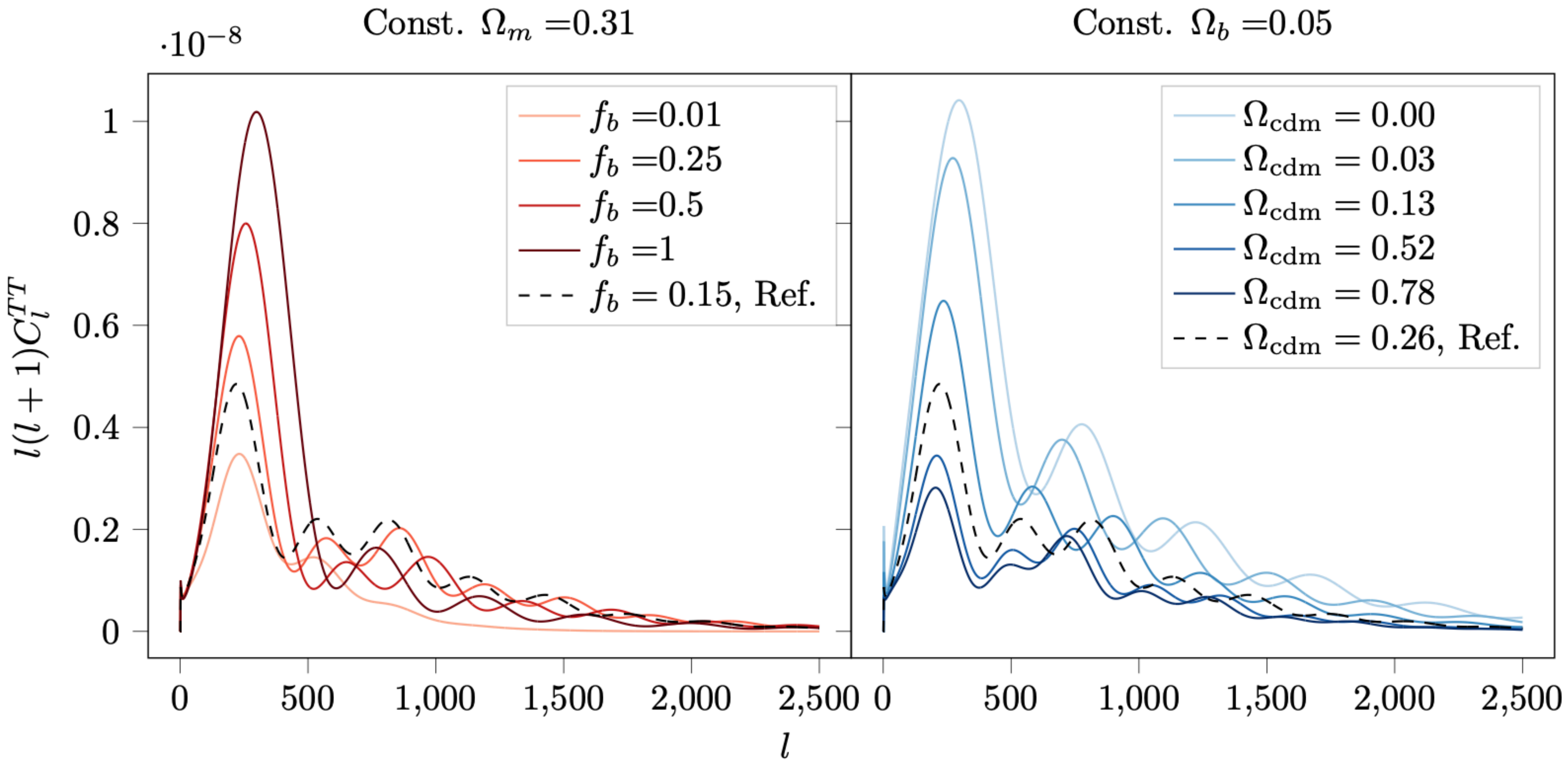
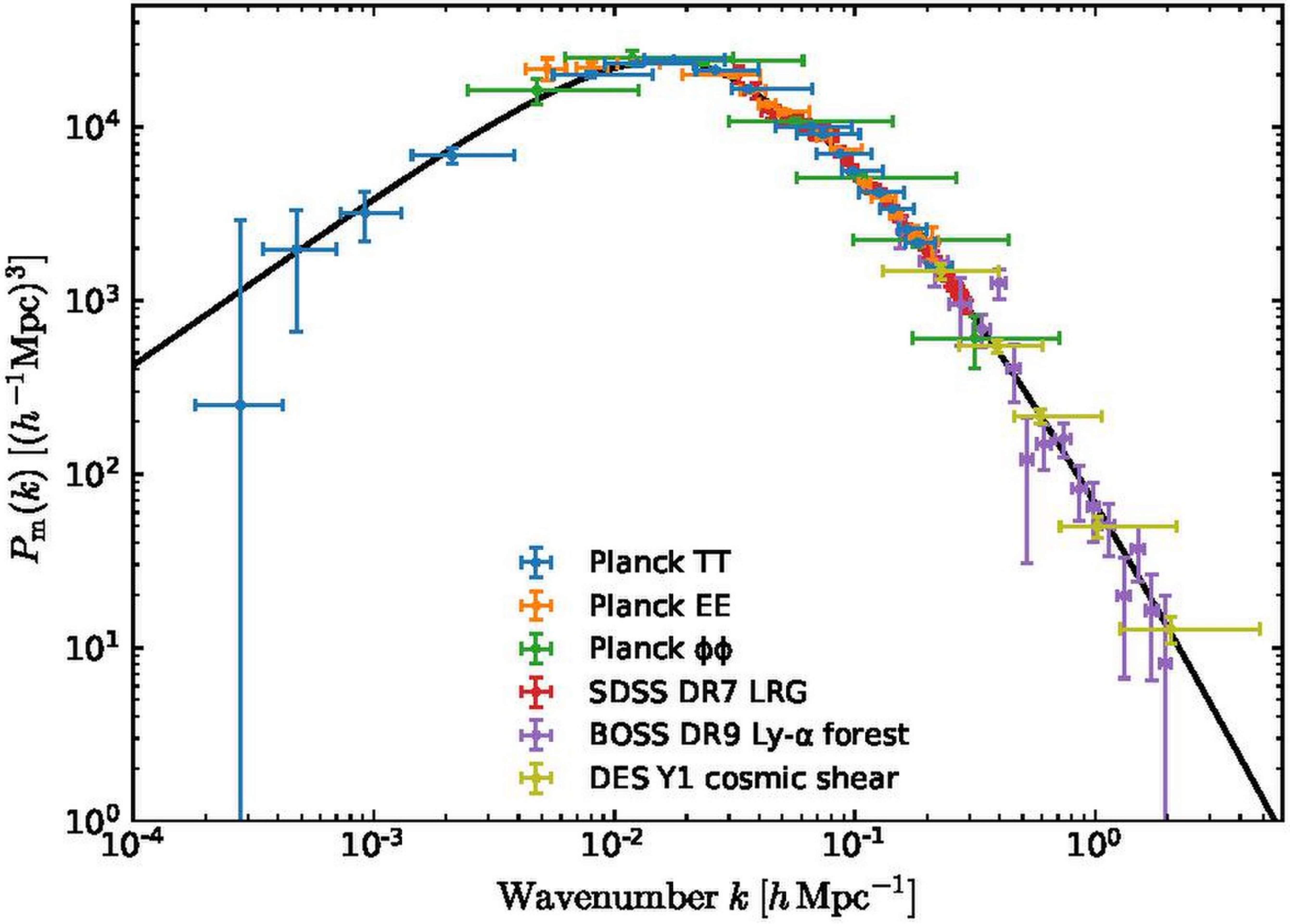


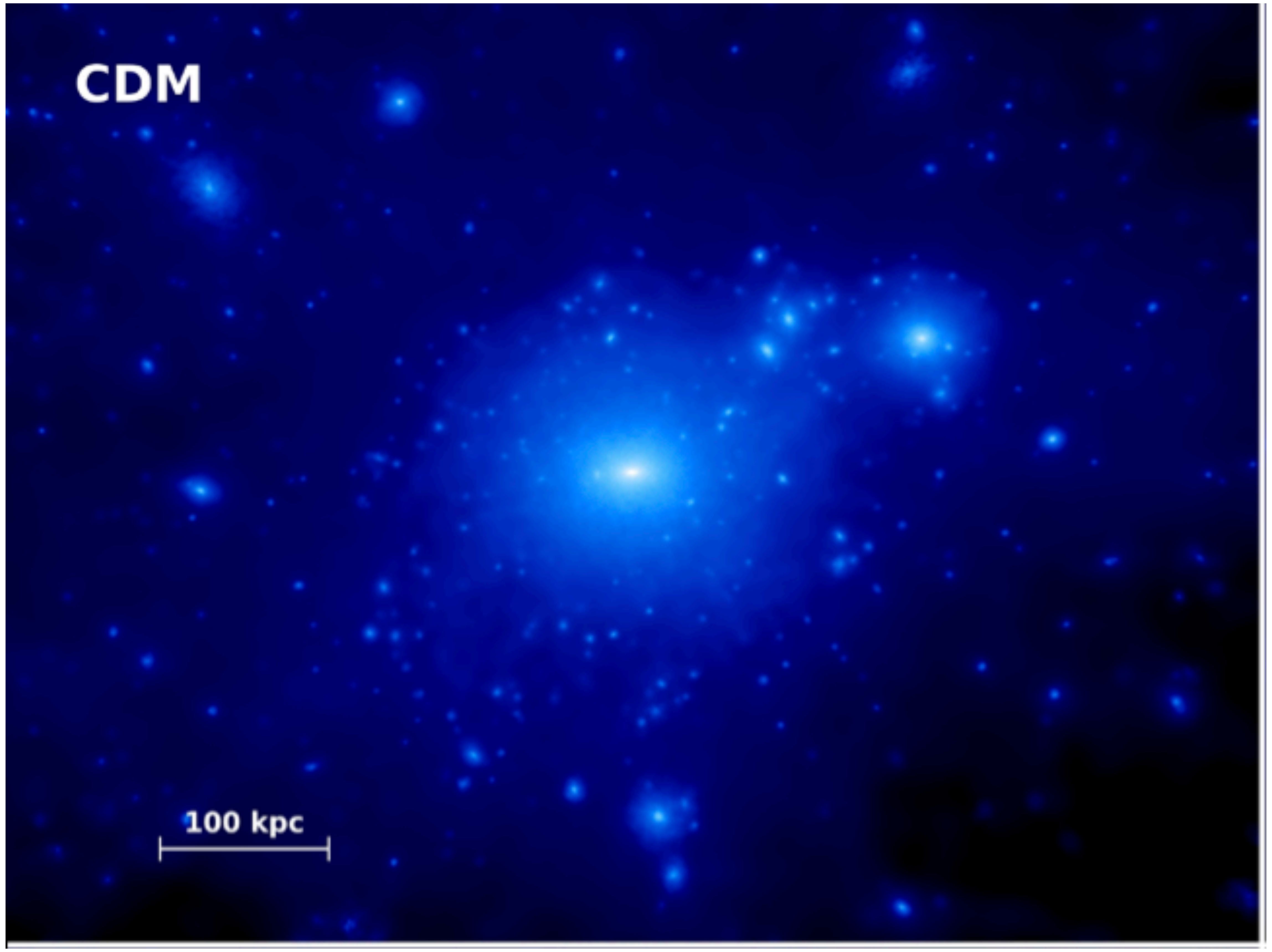
**Figure 1.6:** *The impact on the CMB TT spectrum of changing the baryon fraction while keeping the total matter density constant (left) as well as changing the dark matter density while keeping the baryon density constant (right). In the latter, the Hubble rate today is kept constant, while $\Omega_\Lambda$ varies to maintain flatness. Ref. notes the values inferred from observations [5].*

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

## Dark matter is a form of modification of gravity!

# CMB & Structure formation — LCDM





# Cosmology vs Particle Physics

**Cosmology**
**CMB/LSS**

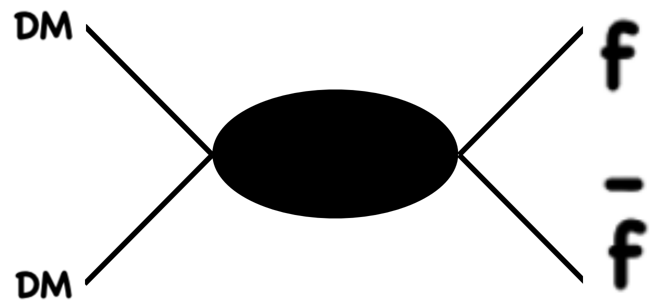
$\sigma = 0$

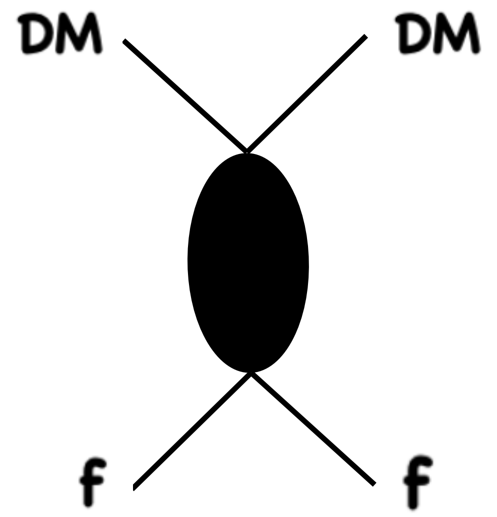
$$\begin{aligned}
\dot{\theta}_{\rm b} &= k^2\psi - \mathcal{H}\theta_{\rm b} + c_s^2 k^2 \delta_{\rm b} - R^{-1}\dot{\kappa}(\theta_{\rm b} - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_{\rm b}) \,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

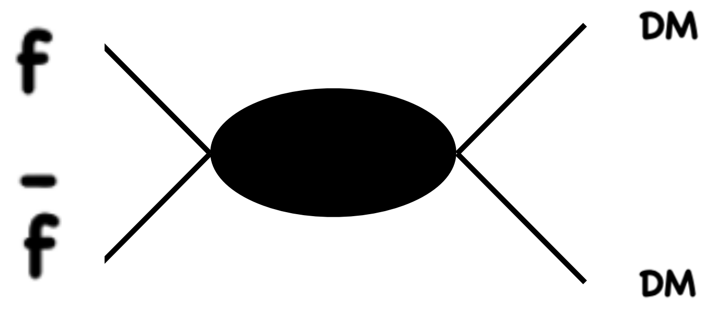
No interaction at all work;
No information about the mass

**Particle Physics**

$\sigma_{ann} \sim \sigma_{weak}$







Consistency check: weak interactions in cosmology should lead to unchanged conclusions…

# Are dark matter interactions compatible with LCDM?

# What kind of interactions?

**DM-photon**

**DM-neutrino**

**DM-baryon**

**DM-DM**
**DM-dark sector**

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

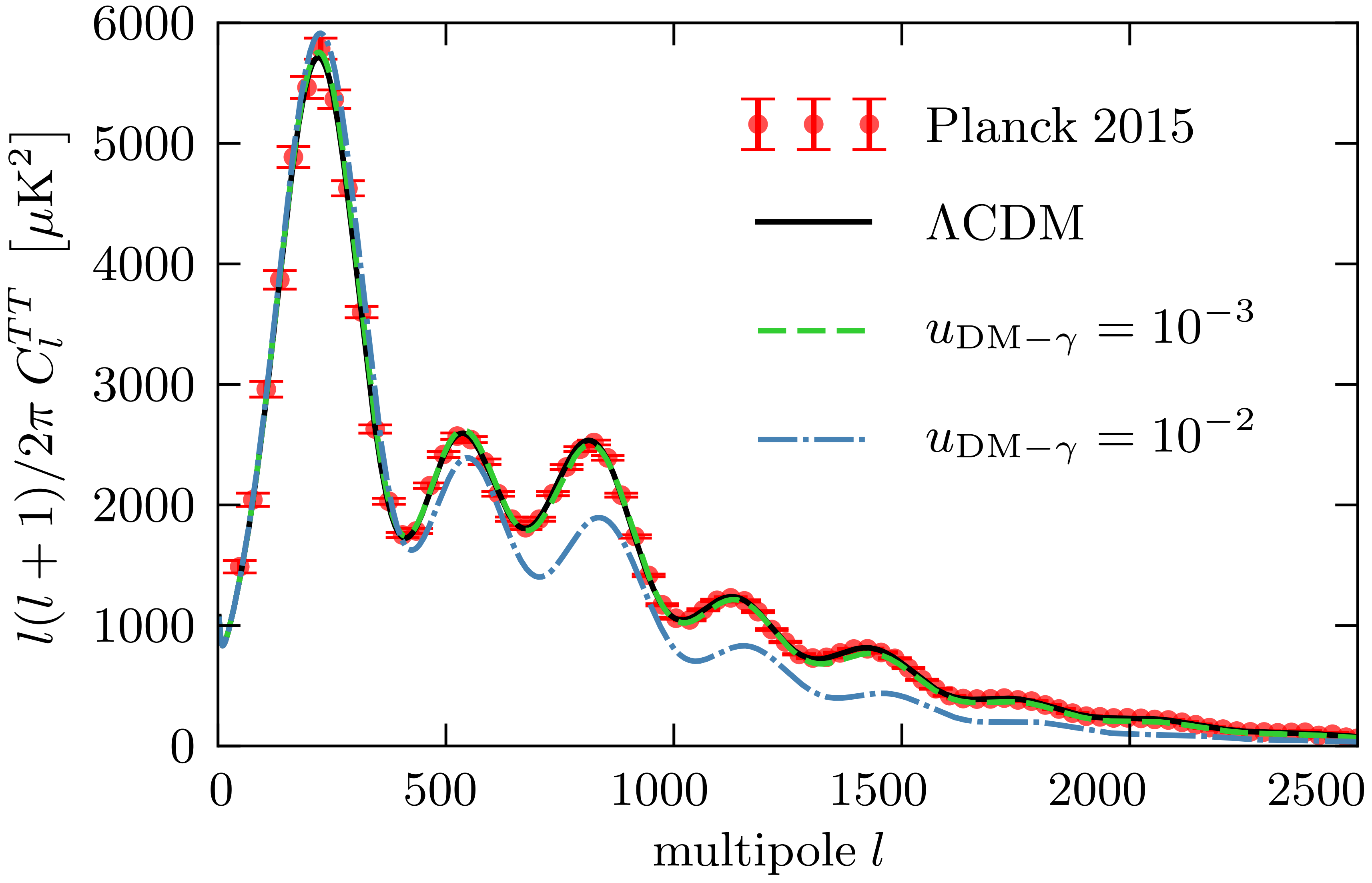
# Photon-dark matter coupling

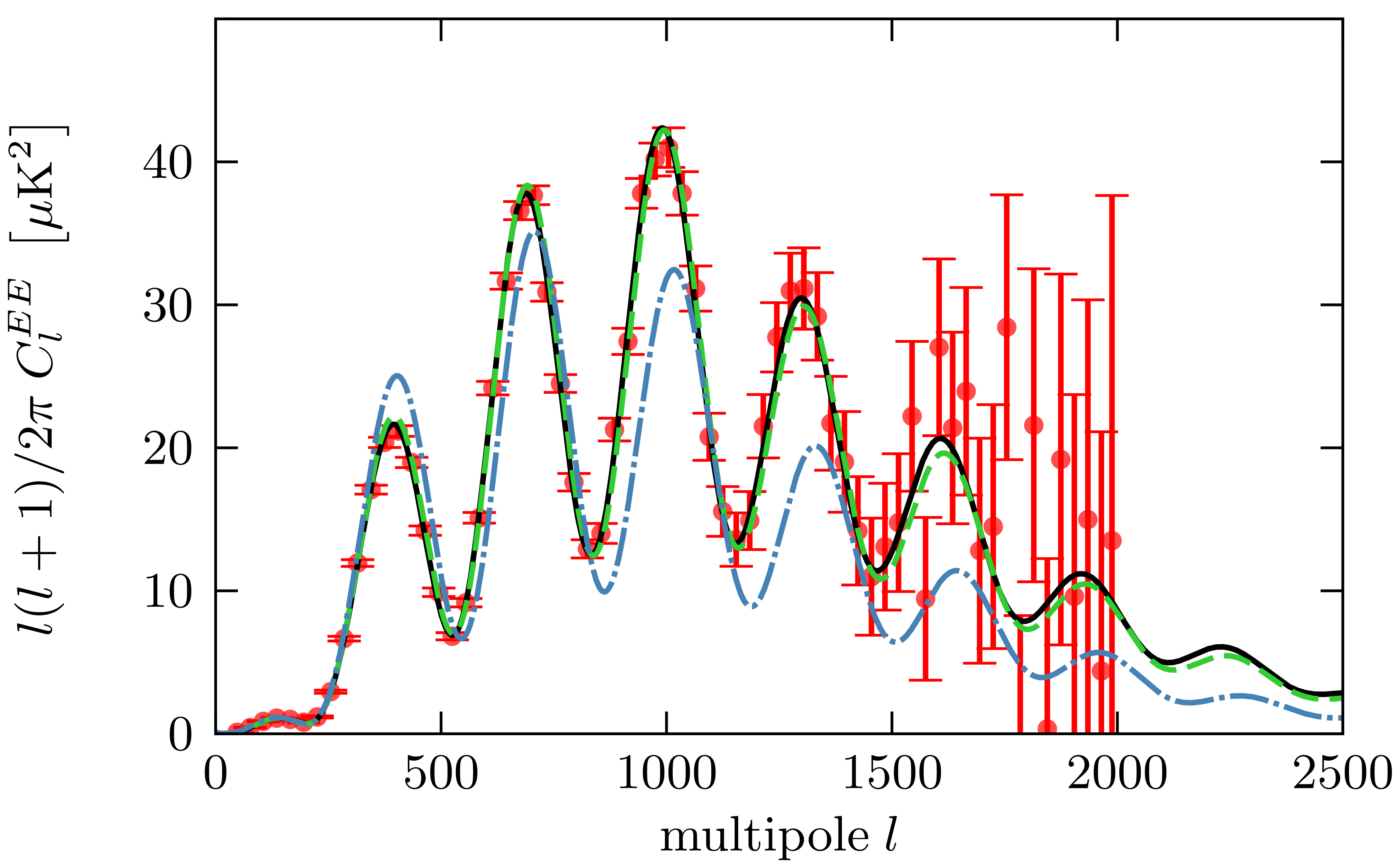
### without DM interactions

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

### with DM interactions

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





### Constant cross section

$\sigma_{\rm DM-\gamma} \leq 8\times 10^{-31}\,(m_{\rm DM}/{\rm GeV})\ {\rm cm}^2$ (68% CL)

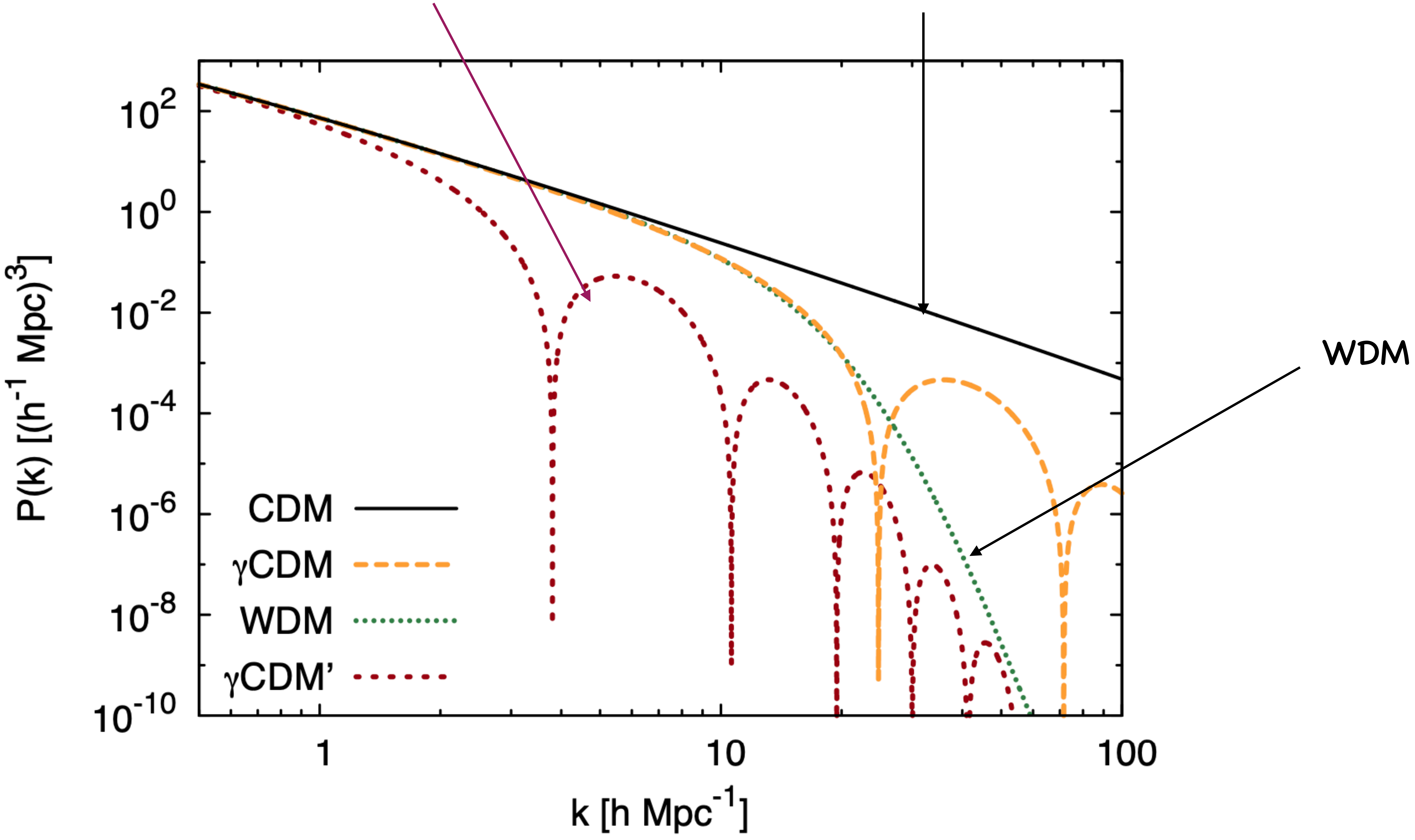
### Temperature dependent cross section

$\sigma_{\rm DM-\gamma} \leq 6\times 10^{-40}\,(m_{\rm DM}/{\rm GeV})\ {\rm cm}^2$

# Photon-dark matter coupling

| | Planck TTTEEE + lowTEB | Planck TTTEEE + lowTEB + lensing | Planck TTTEEE + lowTEB + $N_{\rm eff}$ | Planck TTTEEE + lowTEB + lensing + $N_{\rm eff}$ |
|---|---|---|---|---|
| $\Omega_b h^2$ | $0.02228 \pm 0.00016$ | $0.02228^{+0.00015}_{-0.00017}$ | $0.02221^{+0.00022}_{-0.00026}$ | $0.02218^{+0.00022}_{-0.00024}$ |
| $\Omega_c h^2$ | $0.1201^{+0.0014}_{-0.0016}$ | $0.1197^{+0.0015}_{-0.0014}$ | $0.1192^{+0.0030}_{-0.0032}$ | $0.1182^{+0.0031}_{-0.0028}$ |
| $H_0$ [km/(Mpc s)] | $67.33^{+0.67}_{-0.66}$ | $67.52^{+0.66}_{-0.60}$ | $66.8 \pm 1.6$ | $66.78^{+1.5}_{-1.6}$ |
| $\ln\left(10^{10} A_s\right)$ | $3.097^{+0.038}_{-0.028}$ | $3.069^{+0.021}_{-0.028}$ | $3.087^{+0.035}_{-0.039}$ | $3.06^{+0.026}_{-0.028}$ |
| $n_s$ | $0.964^{+0.0046}_{-0.0048}$ | $0.9646^{+0.0051}_{-0.0047}$ | $0.961^{+0.0096}_{-0.0095}$ | $0.9604^{+0.0091}_{-0.0095}$ |
| $\tau_{reio}$ | $0.08107^{+0.019}_{-0.016}$ | $0.06755^{+0.012}_{-0.014}$ | $0.07734^{+0.016}_{-0.018}$ | $0.06557^{+0.012}_{-0.014}$ |
| $10^{+4}\ u_{\gamma-c}$ | $< 1.579$ | $< 1.490$ | $< 1.623$ | $< 1.359$ |
| $N_{\rm eff}$ | 3.046 | 3.046 | $2.974^{+0.20}_{-0.21}$ | $2.943^{+0.19}_{-0.20}$ |
| $\sigma_8$ | $0.8103^{+0.024}_{-0.018}$ | $0.7982^{+0.022}_{-0.012}$ | $0.8036^{+0.027}_{-0.021}$ | $0.7946^{+0.021}_{-0.016}$ |

# Photon-dark matter coupling



Other DM (with interaction) — dissipation

CDM (no interaction) — observed

WDM

# Lessons from DM-photon interactions

- Interactions = Dissipation (as expected!)
- Not prohibitive though (more surprising…)
- DM-photon cross section = 10^-5 Thomson is compatible with CMB/LSS for a particle of 1 GeV
- DM-photon cross section = 10^-8 Thomson is compatible with CMB/LSS for a particle of 1 MeV

# Neutrino-dark matter coupling

$$\dot{\delta}_{\rm DM} = -\theta_{\rm DM} + 3\dot{\phi}\,,$$

$$\dot{\theta}_{\rm DM} = k^2\psi - \mathcal{H}\,\theta_{\rm DM} - R\,\dot{\kappa}_{\nu{\rm DM}}\,(\theta_{\rm DM} - \theta_{\nu})$$

$$\dot{\delta}_{\nu} = -\frac{4}{3}\theta_{\nu} + 4\dot{\phi}\,,$$

$$\dot{\theta}_{\nu} = k^2\left(\frac{\delta_{\nu}}{4} - \sigma\nu\right) + k^2\psi - \dot{\kappa}_{\nu{\rm DM}}\,(\theta_{\nu} - \theta_{\rm DM})\ ,$$

$$2\dot{\sigma}_{\nu} = \frac{8}{15}\theta_{\nu} - \frac{3}{5}kF_{\nu,3} - \alpha_2\,\dot{\kappa}_{\nu{\rm DM}}\sigma\nu\,,$$

$$\dot{F}_{\nu,l} = \frac{k}{2l+1}\left[lF_{\nu,l-1} - (l+1)F_{\nu,l+1}\right] - \alpha_l\,\dot{\kappa}_{\nu{\rm DM}}F_{\nu,l}\,,$$

$$\dot{F}_{\nu,l_{\max}} = k\left[F_{\nu,l_{\max}-1} - \frac{l_{\max}+1}{k\tau}F_{\nu,l_{\max}}\right] - \alpha_l\,\dot{\kappa}_{\nu{\rm DM}}F_{\nu,l_{\max}}$$

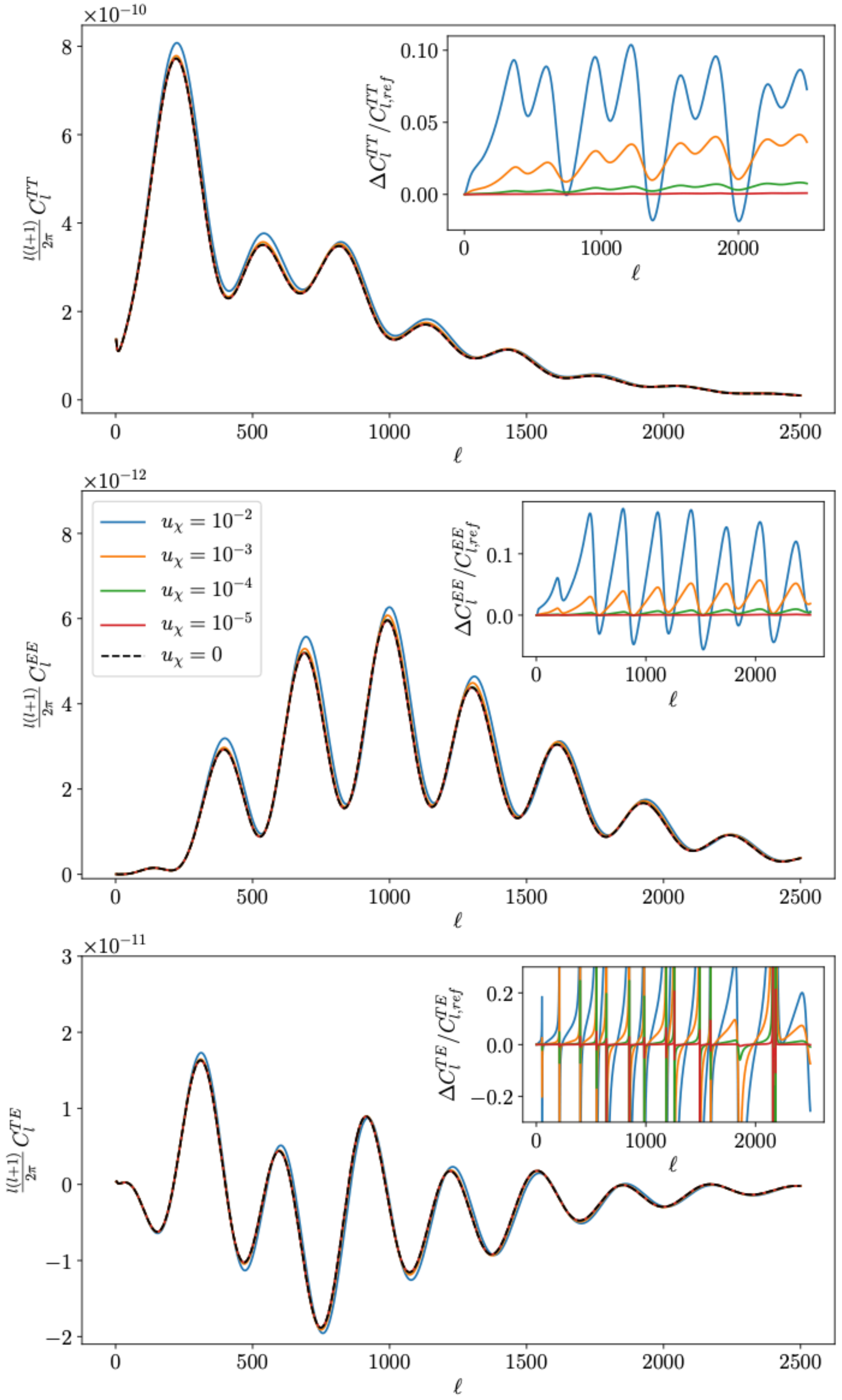


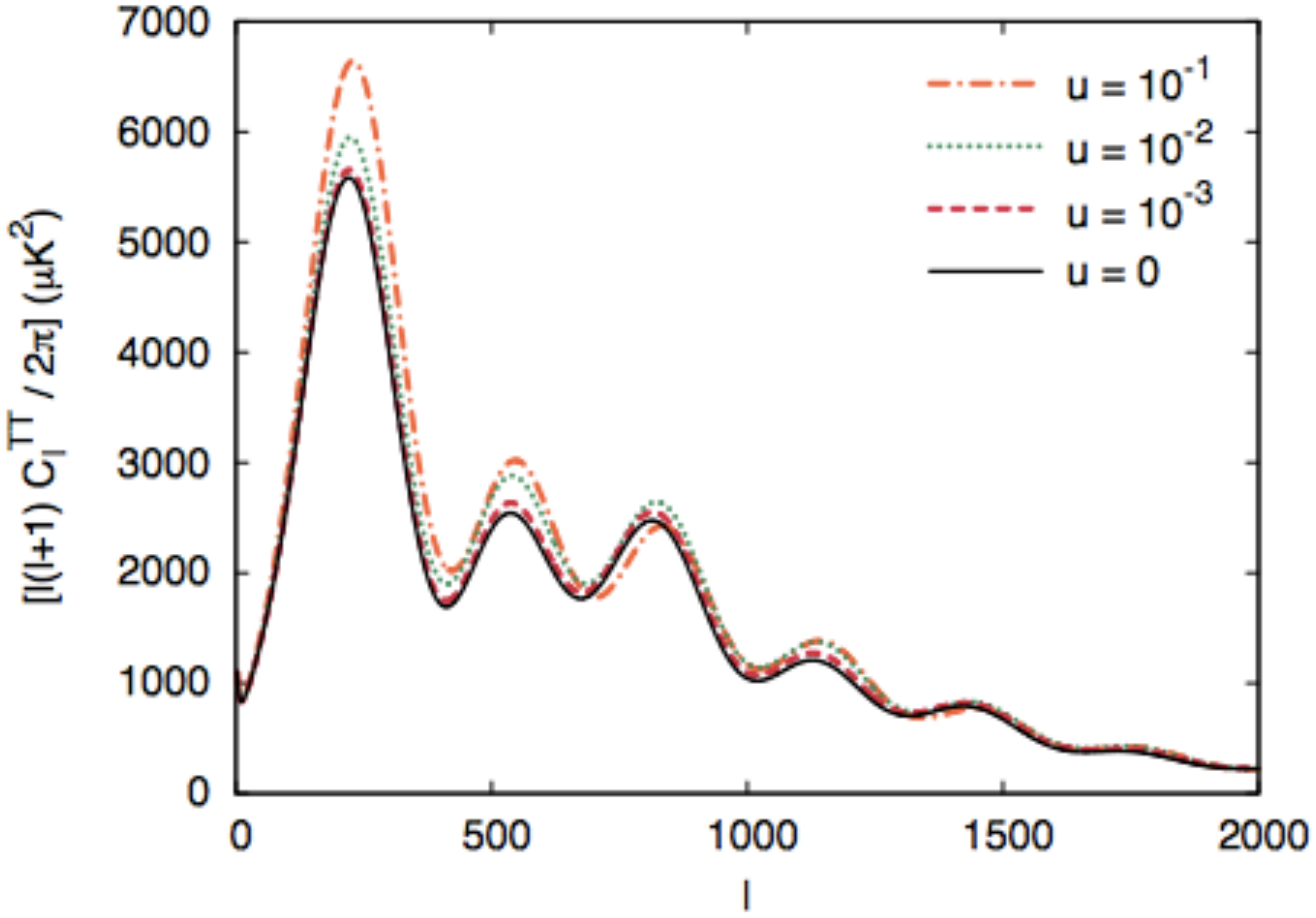
**Figure 2.** CMB TT, EE and TE power spectra for different values of $u_\chi$ in a fiducial cosmology using Planck 2018 parameters [18]. The insert panels show the relative differences compared to the non-interacting case.

**2011.04206**

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

# Neutrino-dark matter coupling

DM-neutrino interactions
Neutrinos are prevented to free-stream



1401.7597

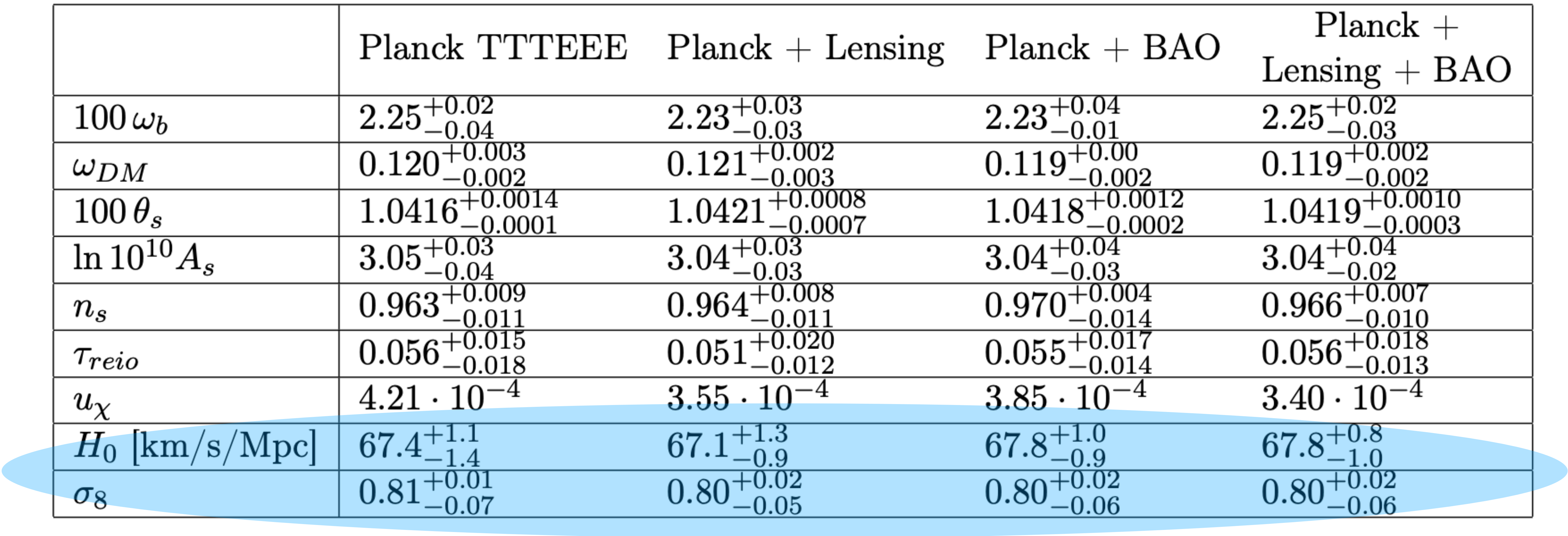
| $\Lambda$CDM + $u$ | + $N_{\rm eff}$ | + $N_{\rm eff}$ + $\Sigma m_\nu$ |
|---|---|---|
| Parameter | Planck TT + lowTEB + R16 | Planck TT + lowTEB + R16 |
| $\Omega_b h^2$ | $0.02278^{+0.00026}_{-0.00025}$ | $0.02278 \pm 0.00027$ |
| $\Omega_c h^2$ | $0.1238^{+0.0037}_{-0.0038}$ | $0.1240^{+0.0035}_{-0.0045}$ |
| $\tau$ | $0.099^{+0.019}_{-0.021}$ | $0.100^{+0.023}_{-0.021}$ |
| $n_s$ | $0.9898^{+0.0088}_{-0.0094}$ | $0.990^{+0.009}_{-0.010}$ |
| $ln(10^{10} A_s)$ | $3.143^{+0.041}_{-0.039}$ | $3.145^{+0.054}_{-0.037}$ |
| $H_0 [{\rm Km\, s^{-1}\, Mpc^{-1}}]$ | $72.1^{+1.5}_{-1.7}$ | $71.9^{+1.6}_{-1.8}$ |
| $\sigma_8$ | $0.850^{+0.024}_{-0.018}$ | $0.846^{+0.030}_{-0.025}$ |
| $u$ | $< -4.0$ | $< -4.0$ |
| $N_{\rm eff}$ | $3.54 \pm 0.20$ | $3.56^{+0.19}_{-0.26}$ |
| $\Sigma m_\nu [eV]$ | 0.06 | $< 0.87$ |

1710.02559

# Dark matter-neutrino interactions

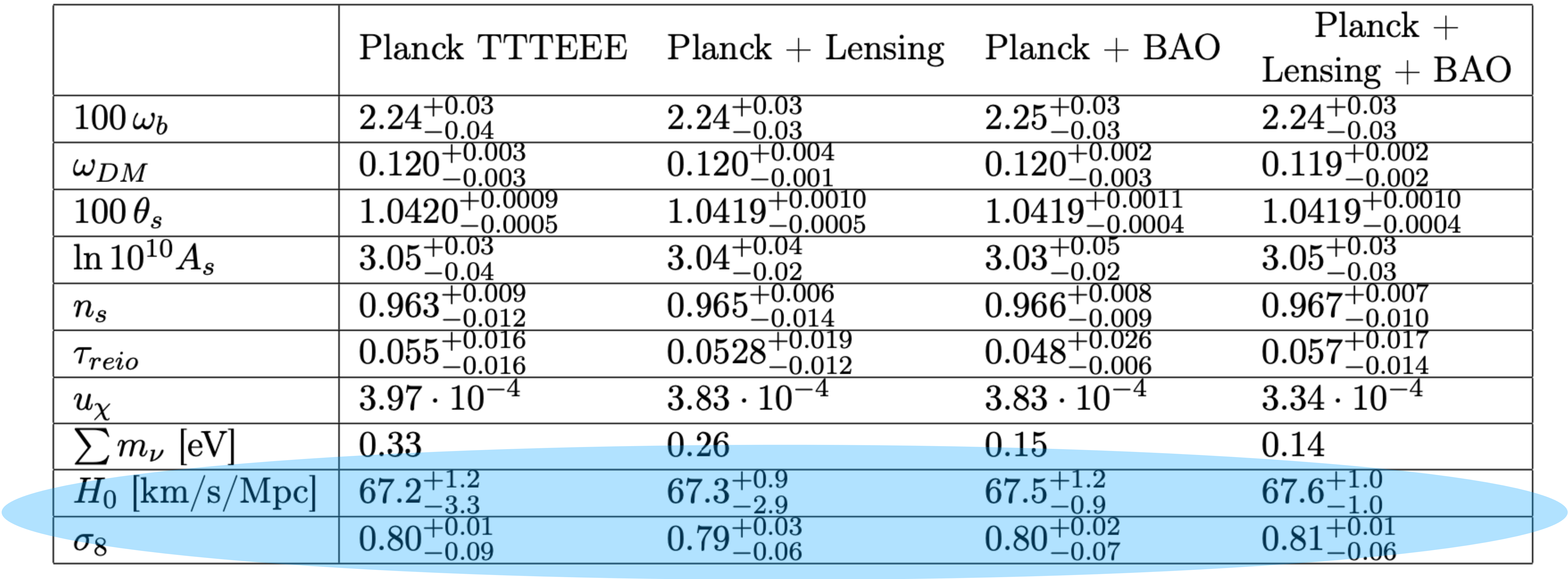
With neutrino mass hierarchy

2011.04206



| | Planck TTTEEE | Planck + Lensing | Planck + BAO | Planck + Lensing + BAO |
|---|---|---|---|---|
| $100\,\omega_b$ | $2.25^{+0.02}_{-0.04}$ | $2.23^{+0.03}_{-0.03}$ | $2.23^{+0.04}_{-0.01}$ | $2.25^{+0.02}_{-0.03}$ |
| $\omega_{DM}$ | $0.120^{+0.003}_{-0.002}$ | $0.121^{+0.002}_{-0.003}$ | $0.119^{+0.00}_{-0.002}$ | $0.119^{+0.002}_{-0.002}$ |
| $100\,\theta_s$ | $1.0416^{+0.0014}_{-0.0001}$ | $1.0421^{+0.0008}_{-0.0007}$ | $1.0418^{+0.0012}_{-0.0002}$ | $1.0419^{+0.0010}_{-0.0003}$ |
| $\ln 10^{10} A_s$ | $3.05^{+0.03}_{-0.04}$ | $3.04^{+0.03}_{-0.03}$ | $3.04^{+0.04}_{-0.03}$ | $3.04^{+0.04}_{-0.02}$ |
| $n_s$ | $0.963^{+0.009}_{-0.011}$ | $0.964^{+0.008}_{-0.011}$ | $0.970^{+0.004}_{-0.014}$ | $0.966^{+0.007}_{-0.010}$ |
| $\tau_{reio}$ | $0.056^{+0.015}_{-0.018}$ | $0.051^{+0.020}_{-0.012}$ | $0.055^{+0.017}_{-0.014}$ | $0.056^{+0.018}_{-0.013}$ |
| $u_\chi$ | $4.21 \cdot 10^{-4}$ | $3.55 \cdot 10^{-4}$ | $3.85 \cdot 10^{-4}$ | $3.40 \cdot 10^{-4}$ |
| $H_0$ [km/s/Mpc] | $67.4^{+1.1}_{-1.4}$ | $67.1^{+1.3}_{-0.9}$ | $67.8^{+1.0}_{-0.9}$ | $67.8^{+0.8}_{-1.0}$ |
| $\sigma_8$ | $0.81^{+0.01}_{-0.07}$ | $0.80^{+0.02}_{-0.05}$ | $0.80^{+0.02}_{-0.06}$ | $0.80^{+0.02}_{-0.06}$ |

**Table 2**. Best fit values with 95% confidence limits for the case of constant neutrino mass, except for $u_\chi$, where only the 95% CL upper limit is shown.



| | Planck TTTEEE | Planck + Lensing | Planck + BAO | Planck + Lensing + BAO |
|---|---|---|---|---|
| $100\,\omega_b$ | $2.24^{+0.03}_{-0.04}$ | $2.24^{+0.03}_{-0.03}$ | $2.25^{+0.03}_{-0.03}$ | $2.24^{+0.03}_{-0.03}$ |
| $\omega_{DM}$ | $0.120^{+0.003}_{-0.003}$ | $0.120^{+0.004}_{-0.001}$ | $0.120^{+0.002}_{-0.003}$ | $0.119^{+0.002}_{-0.002}$ |
| $100\,\theta_s$ | $1.0420^{+0.0009}_{-0.0005}$ | $1.0419^{+0.0010}_{-0.0005}$ | $1.0419^{+0.0011}_{-0.0004}$ | $1.0419^{+0.0010}_{-0.0004}$ |
| $\ln 10^{10} A_s$ | $3.05^{+0.03}_{-0.04}$ | $3.04^{+0.04}_{-0.02}$ | $3.03^{+0.05}_{-0.02}$ | $3.05^{+0.03}_{-0.03}$ |
| $n_s$ | $0.963^{+0.009}_{-0.012}$ | $0.965^{+0.006}_{-0.014}$ | $0.966^{+0.008}_{-0.009}$ | $0.967^{+0.007}_{-0.010}$ |
| $\tau_{reio}$ | $0.055^{+0.016}_{-0.016}$ | $0.0528^{+0.019}_{-0.012}$ | $0.048^{+0.026}_{-0.006}$ | $0.057^{+0.017}_{-0.014}$ |
| $u_\chi$ | $3.97 \cdot 10^{-4}$ | $3.83 \cdot 10^{-4}$ | $3.83 \cdot 10^{-4}$ | $3.34 \cdot 10^{-4}$ |
| $\sum m_\nu$ [eV] | 0.33 | 0.26 | 0.15 | 0.14 |
| $H_0$ [km/s/Mpc] | $67.2^{+1.2}_{-3.3}$ | $67.3^{+0.9}_{-2.9}$ | $67.5^{+1.2}_{-0.9}$ | $67.6^{+1.0}_{-1.0}$ |
| $\sigma_8$ | $0.80^{+0.01}_{-0.09}$ | $0.79^{+0.03}_{-0.06}$ | $0.80^{+0.02}_{-0.07}$ | $0.81^{+0.01}_{-0.06}$ |

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

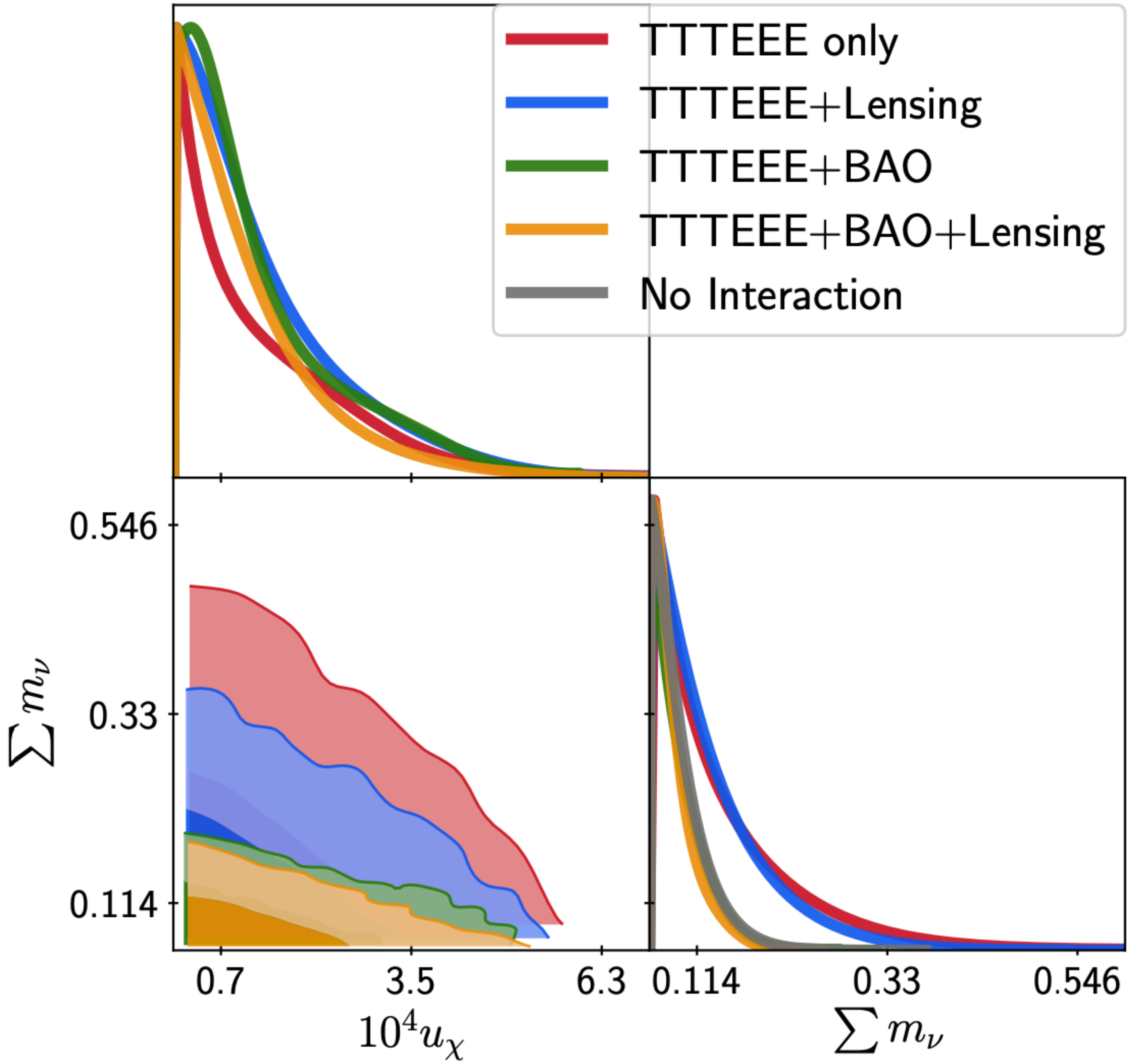
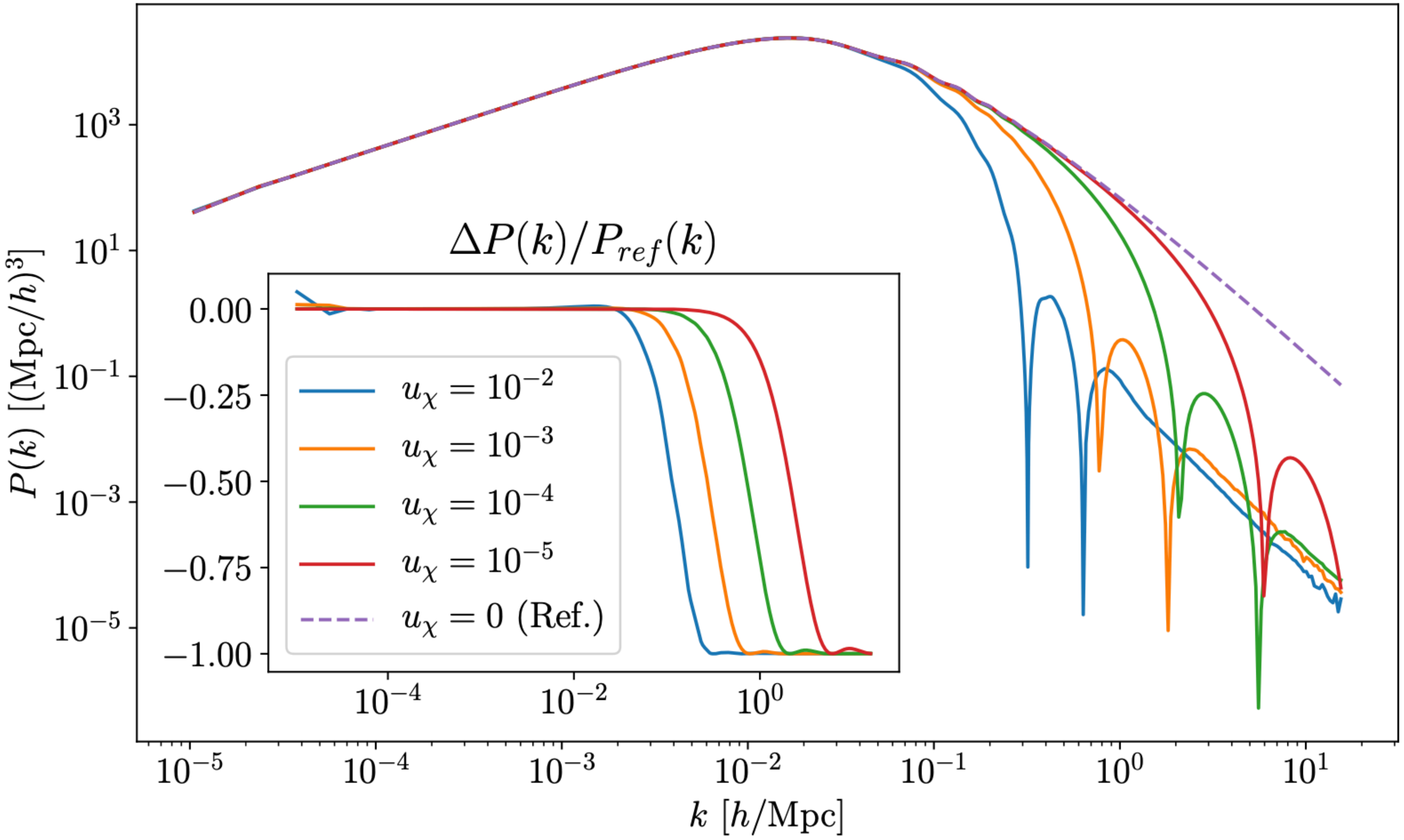


**Figure 3**. One-dimensional posterior probability distributions for $u_\chi$ and $\sum m_\nu$ for different combination of datasets and two-dimensional 68% and 95% CL allowed regions in the $(u_\chi, \sum m_\nu)$ plane. The 'Non-Interacting' posterior uses all the three datasets, that is, Planck CMB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

# Neutrino-dark matter coupling

The full Boltzmann hierarchy for dark matter-massive neutrino interactions

Markus R. Mosbech,[a] Celine Boehm,[a] Steen Hannestad,[b] Olga Mena,[c] Julia Stadler,[d] and Yvonne Y. Y. Wong[e]

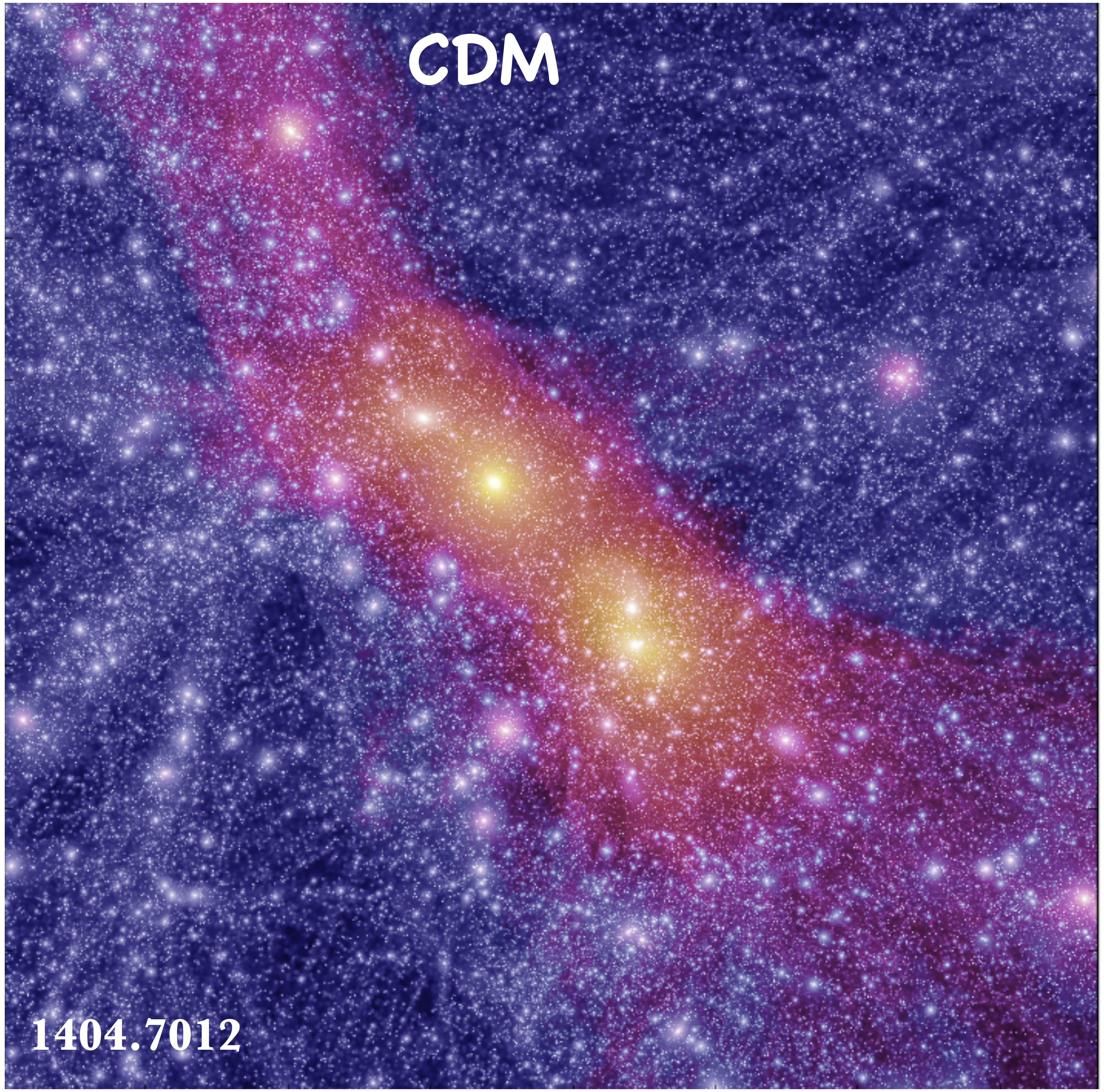


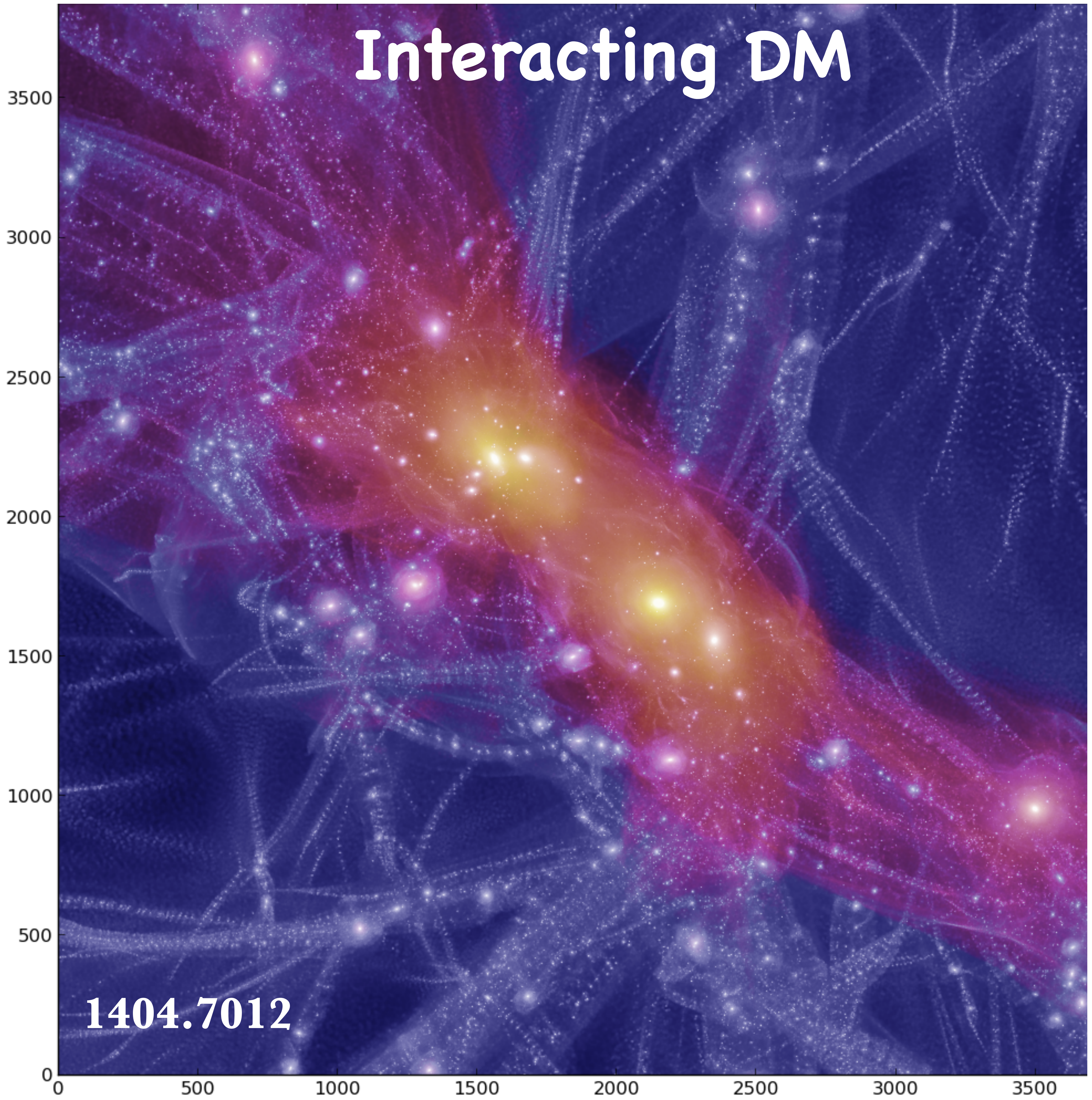
# Lessons from DM-neutrino interactions

- Interactions = not just dissipation - can be more subtle
- DM-neutrino cross section = 10^-8 Thomson is compatible with LSS for a particle of 1 MeV
- They can affect the cosmological parameters (Ho, sigma8) but..
- The lighter DM is the bigger the effect

# Effect of the microscopic nature of dark matter on Large-Scale-Structure formation?

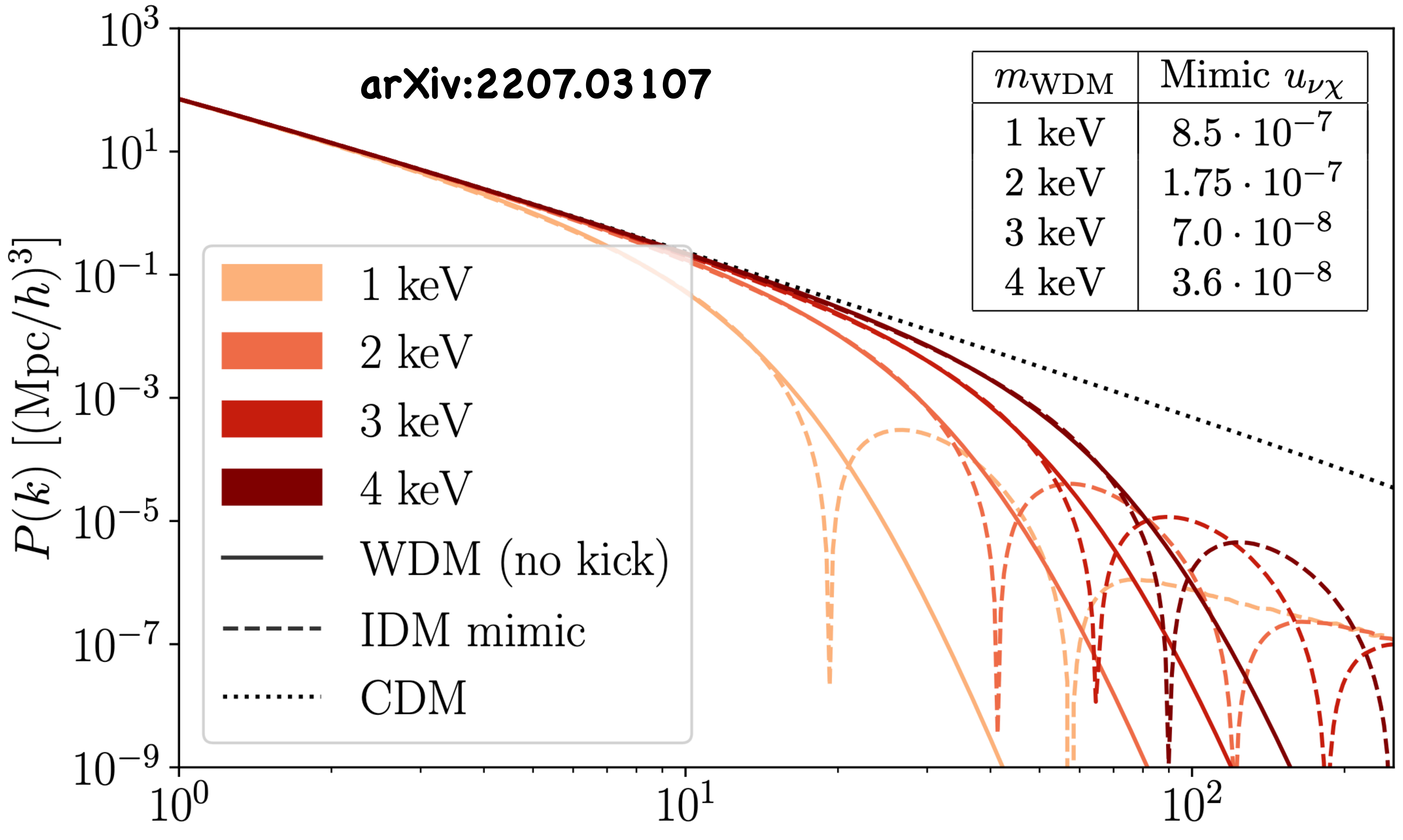
# Dark Matter interactions & structure formation



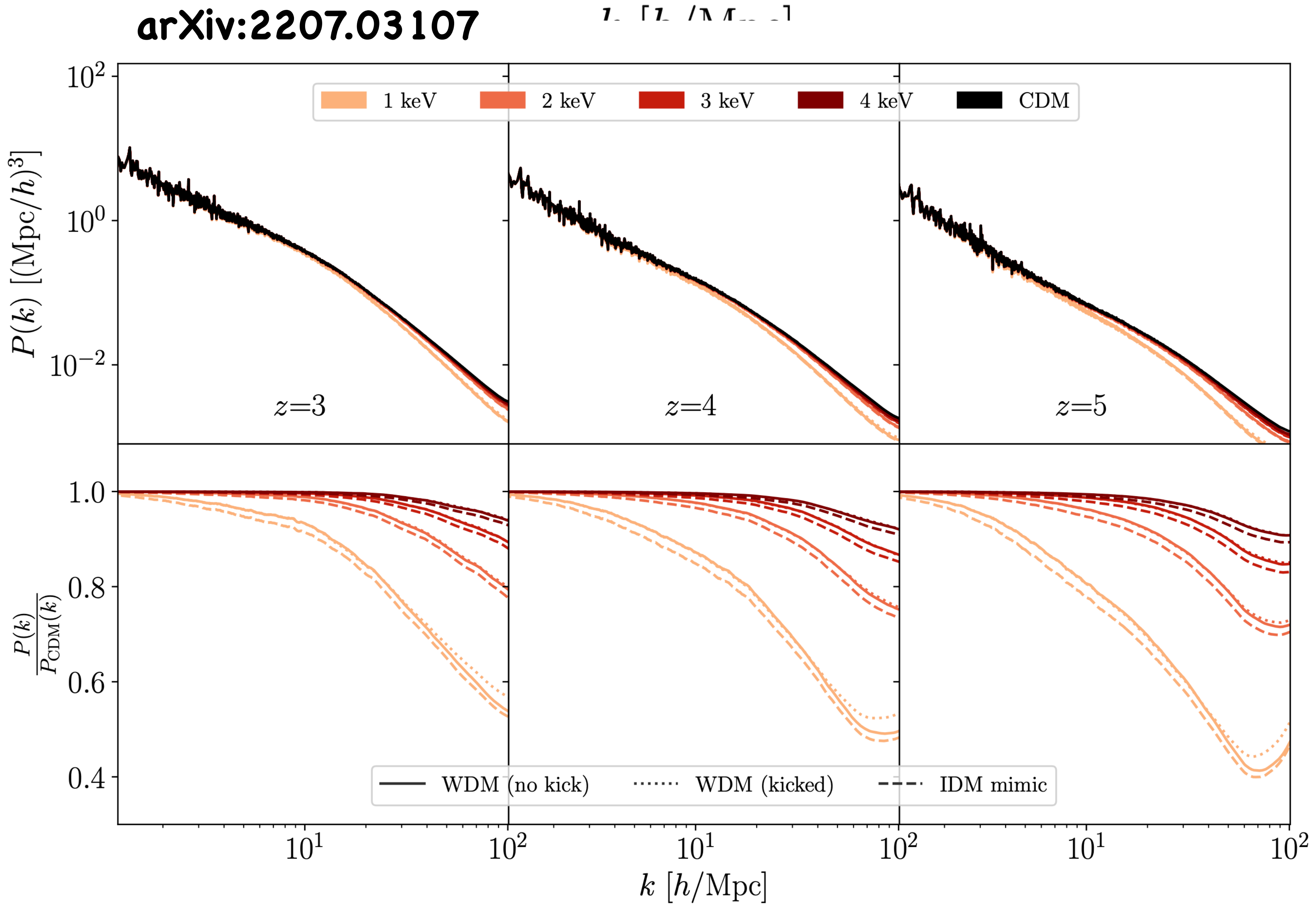


# Unexplored: redshift dependence & Ska

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



| $m_{\mathrm{WDM}}$ | Mimic $u_{\nu\chi}$ |
|---|---|
| 1 keV | $8.5 \cdot 10^{-7}$ |
| 2 keV | $1.75 \cdot 10^{-7}$ |
| 3 keV | $7.0 \cdot 10^{-8}$ |
| 4 keV | $3.6 \cdot 10^{-8}$ |



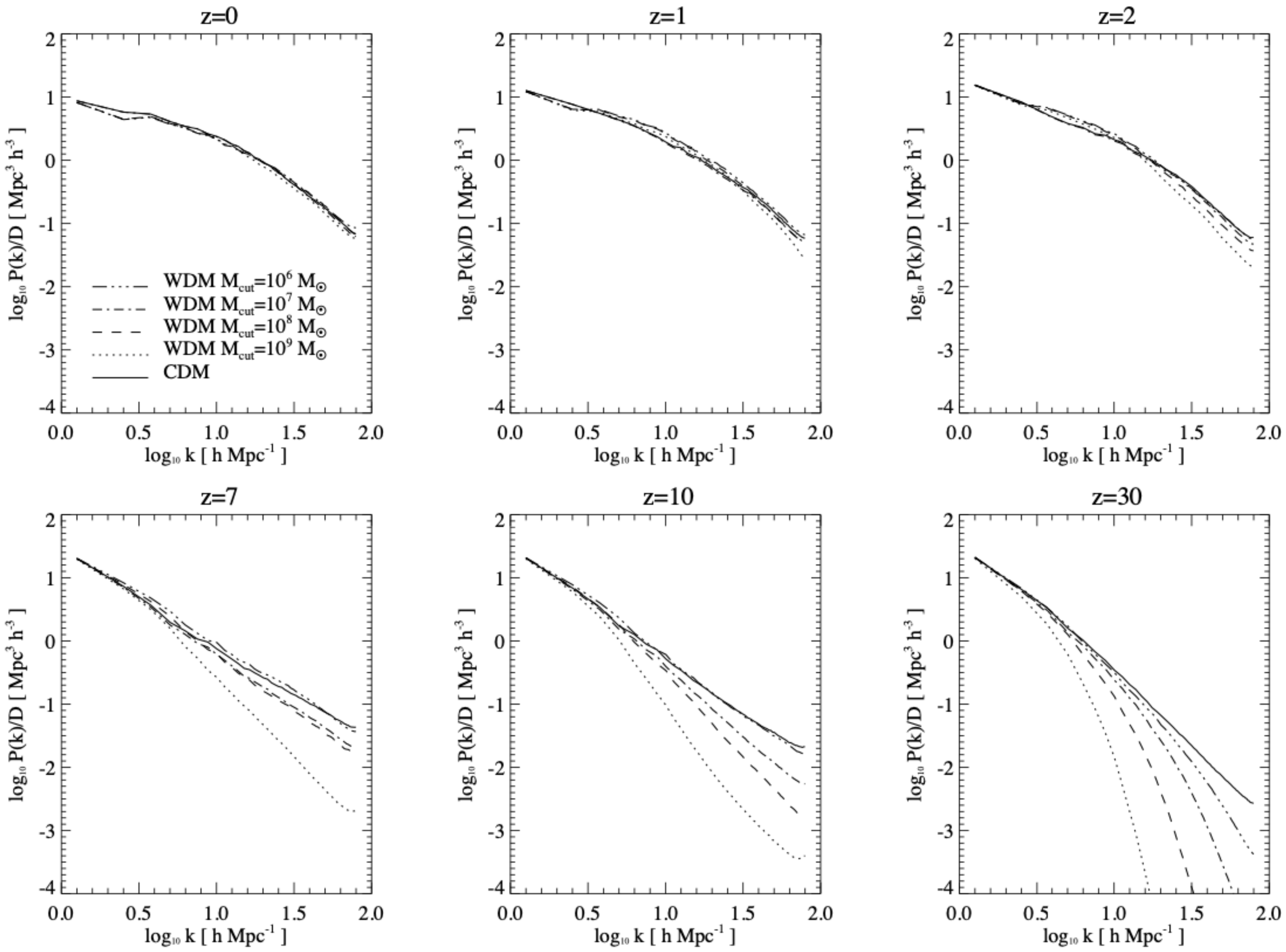
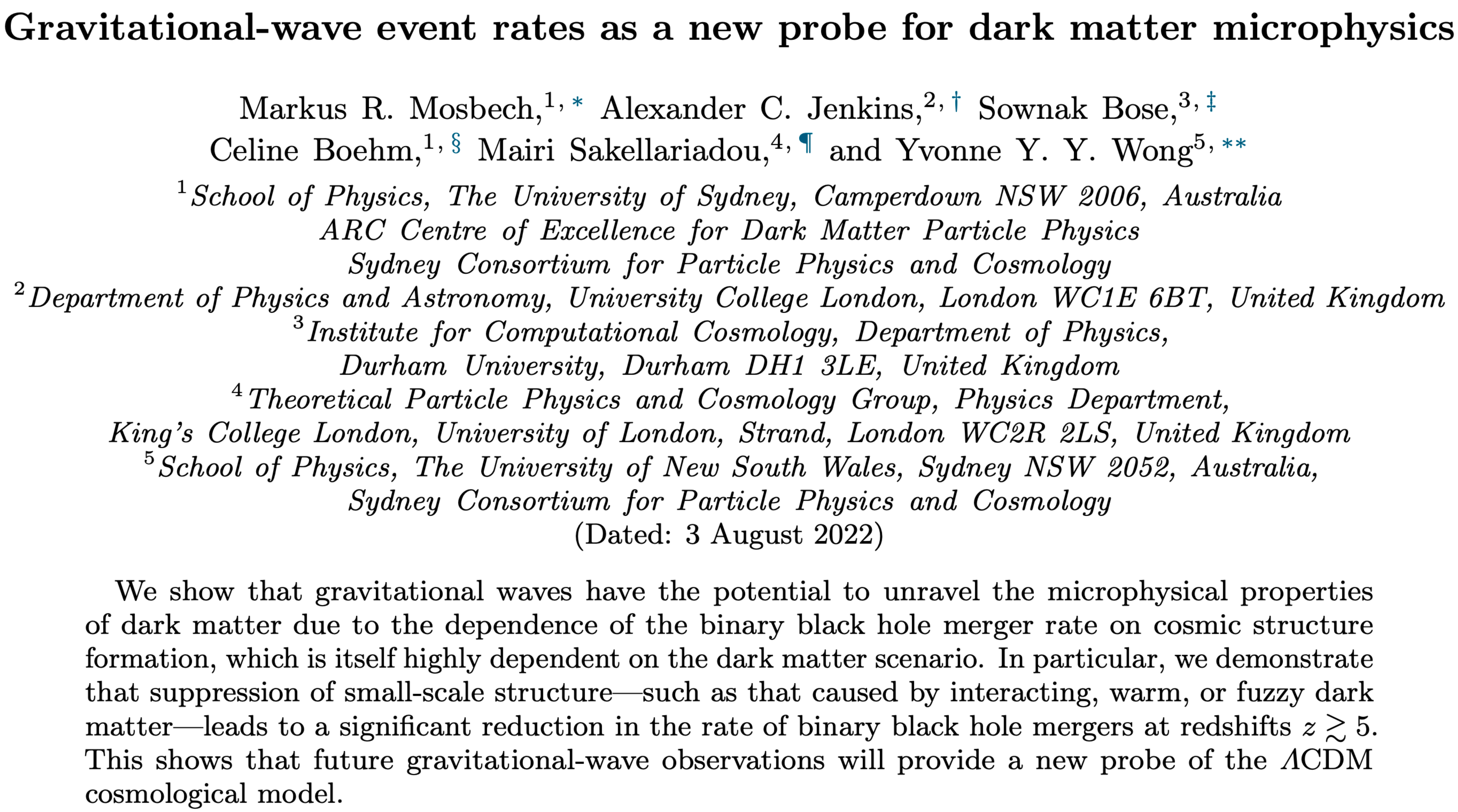


**Figure 1.** Snapshots of the dark matter power spectra measured in simulations of a series of DM models. CDM and 0.6, 1.1, 2 and 3.5 keV heavy warmon WDM corresponding to respectively $10^9$, $10^8$, $10^7$ and $10^6$ $h^{-1}$ $M_\odot$ Lagrangian masses in the free-streaming length are shown. The power spectra have been divided by the linear growth factor to facilitate the comparison between redshifts. Note the exponential cut-off at z= 30 in the spectrum of WDM models and the similarity of the spectra of all five models over the simulated scales at z<2.

# Probing the P(k) with the gravitational waves

arXiv:2207.14126



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

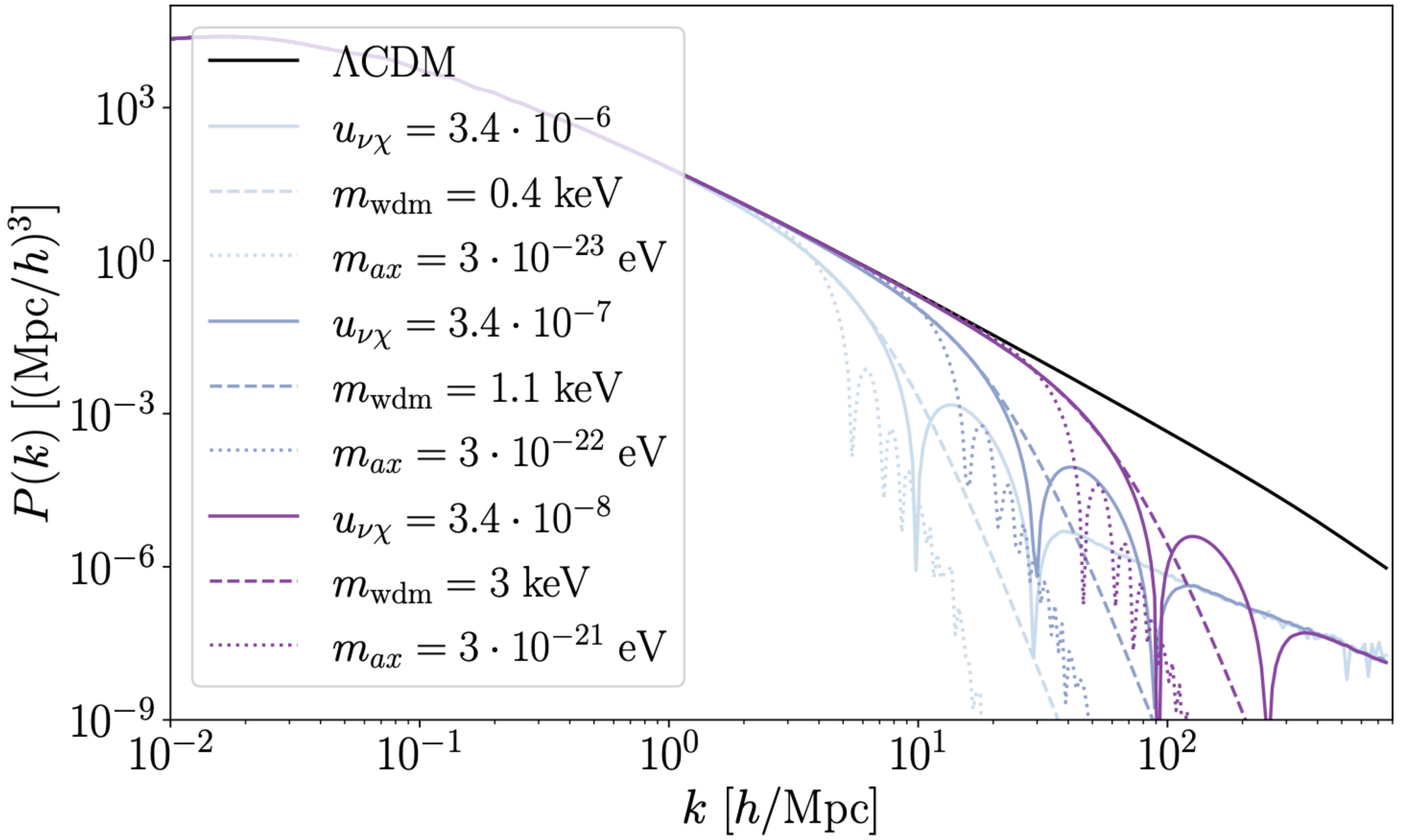
Markus R. Mosbech,[1,*] Alexander C. Jenkins,[2,†] Sownak Bose,[3,‡]
Celine Boehm,[1,§] Mairi Sakellariadou,[4,¶] and Yvonne Y. Y. Wong[5,**]
[1] *School of Physics, The University of Sydney, Camperdown NSW 2006, Australia*
*ARC Centre of Excellence for Dark Matter Particle Physics*
*Sydney Consortium 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*

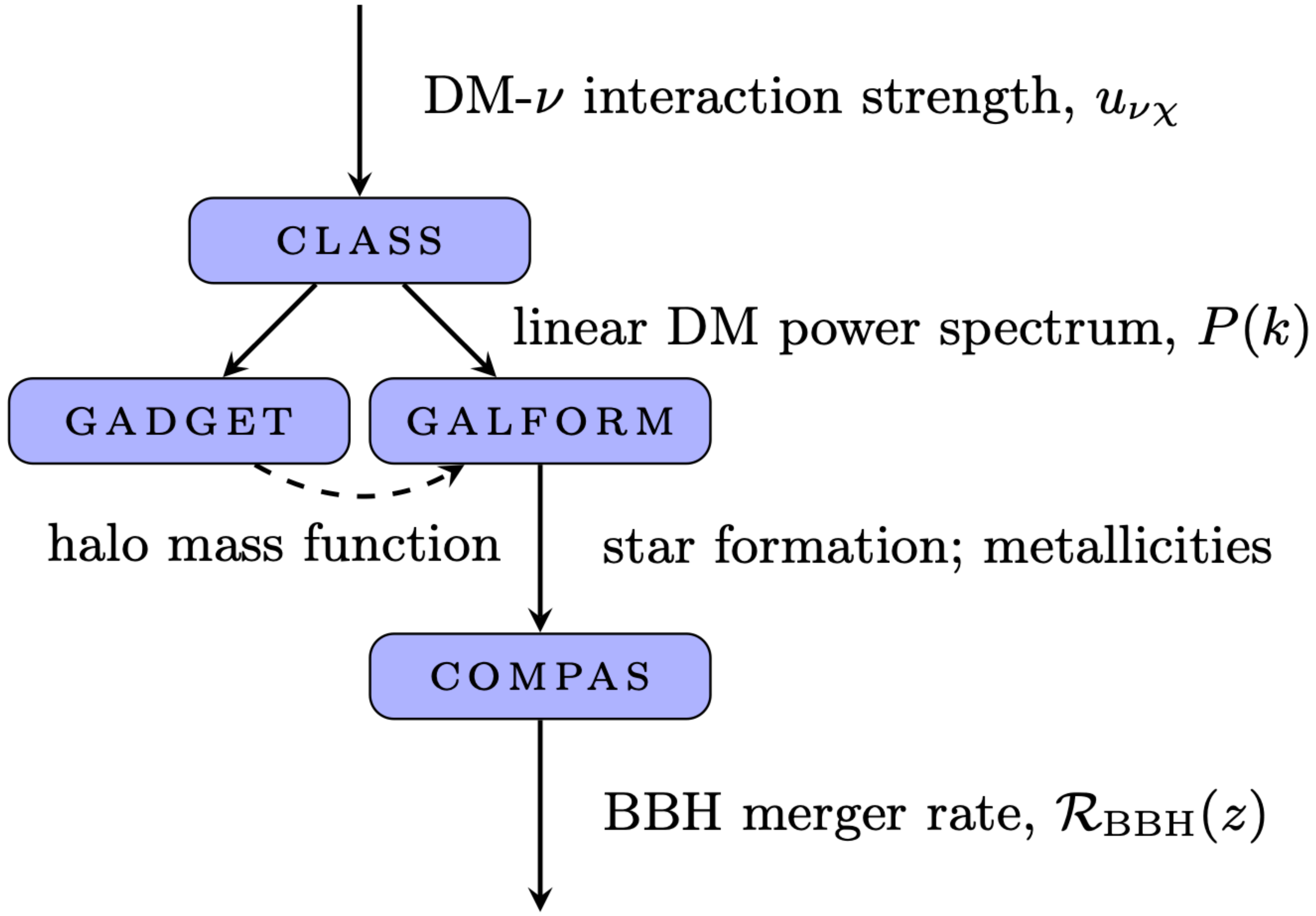
(Dated: 3 August 2022)

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.

# Probing the P(k) with the gravitational waves

arXiv:2207.14126





DM-$\nu$ interaction strength, $u_{\nu\chi}$

CLASS

linear DM power spectrum, $P(k)$

GADGET

GALFORM

halo mass function

star formation; metallicities

COMPAS

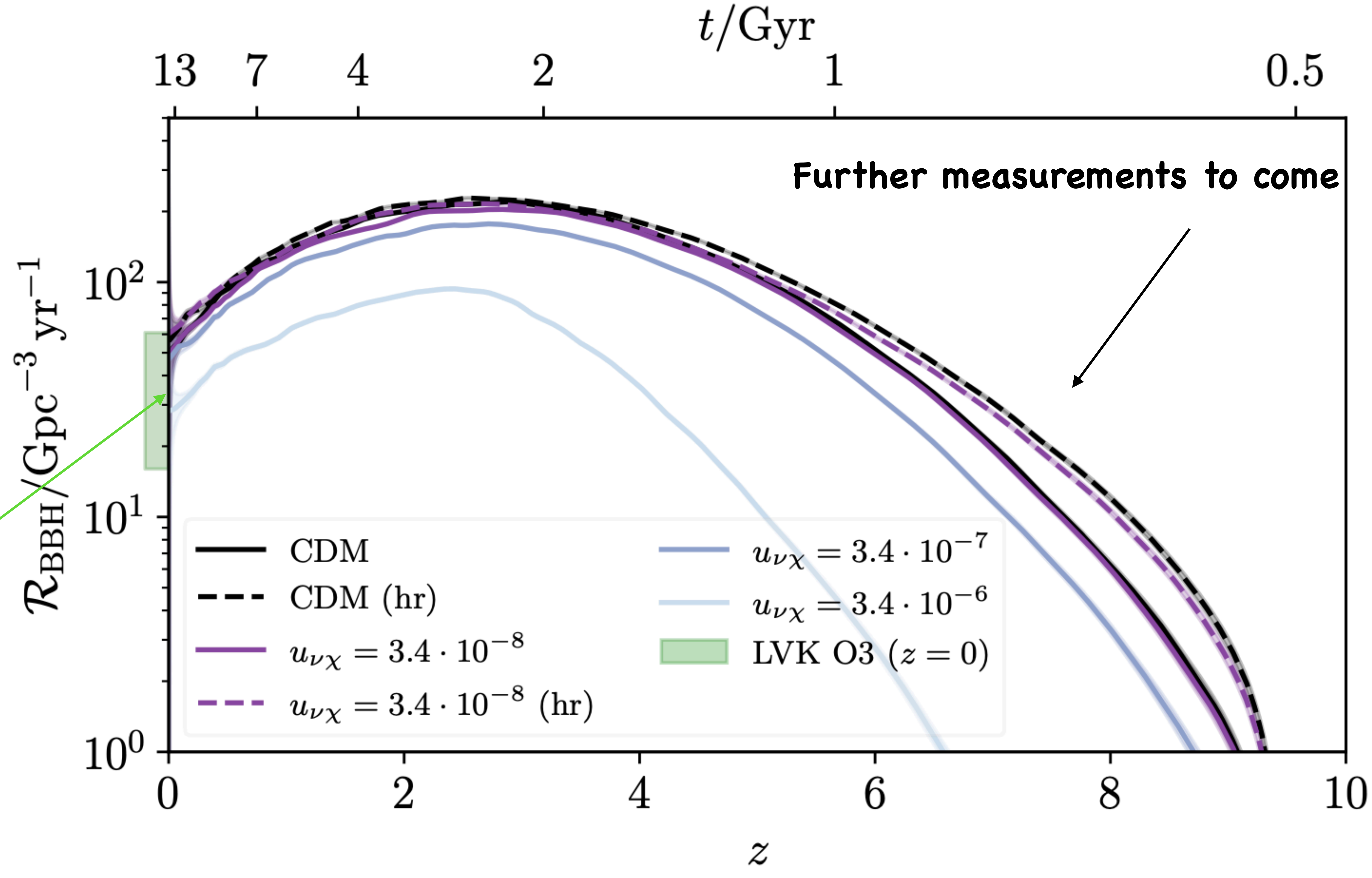
BBH merger rate, $\mathcal{R}_{\rm BBH}(z)$

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).

# Probing the P(k) with the gravitational waves

arXiv:2207.14126



Further measurements to come

Current measurement

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

# Probing the P(k) with weak lensing

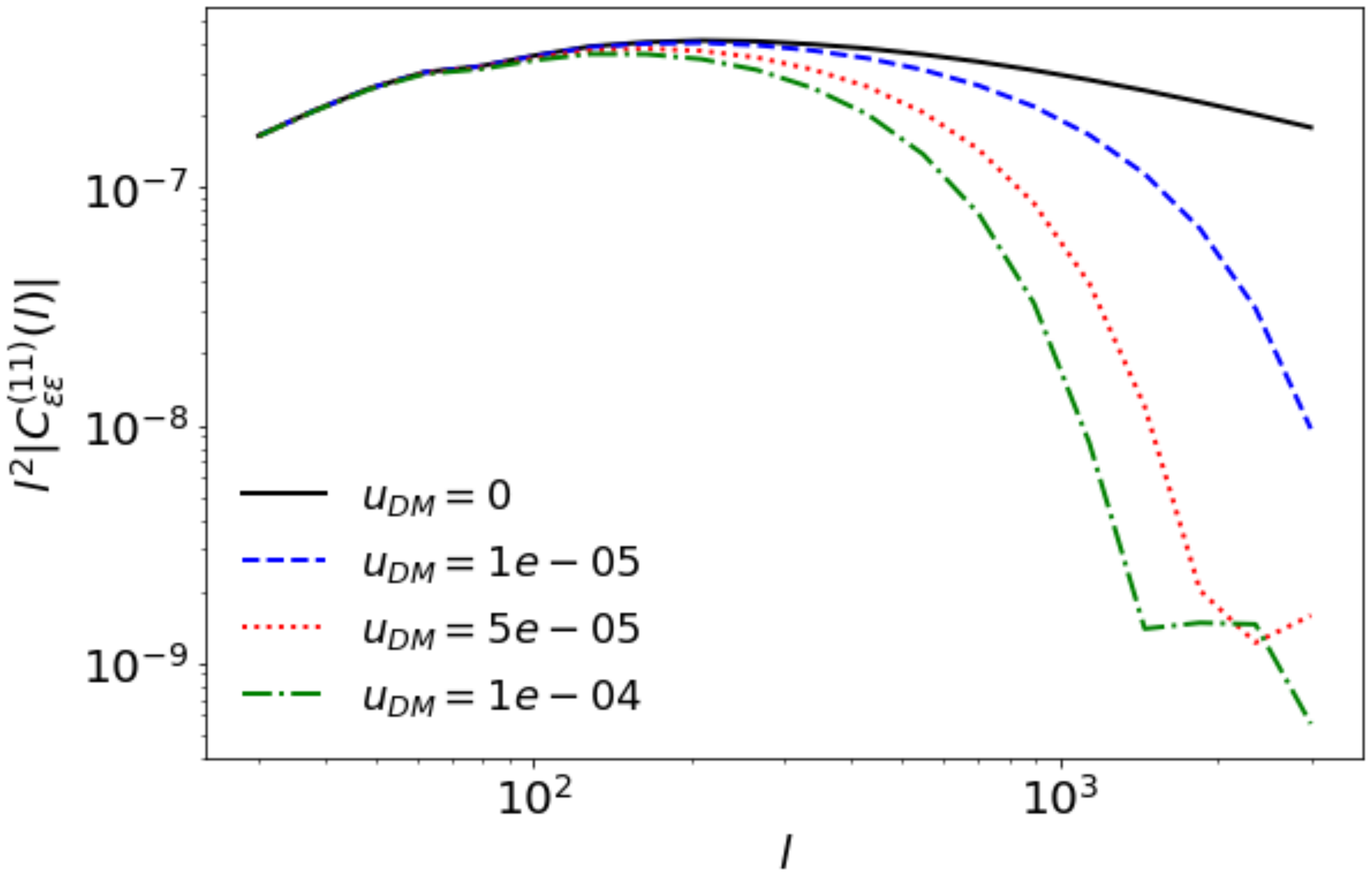
**Ellen Sirks**

**Miguel de Icaza**

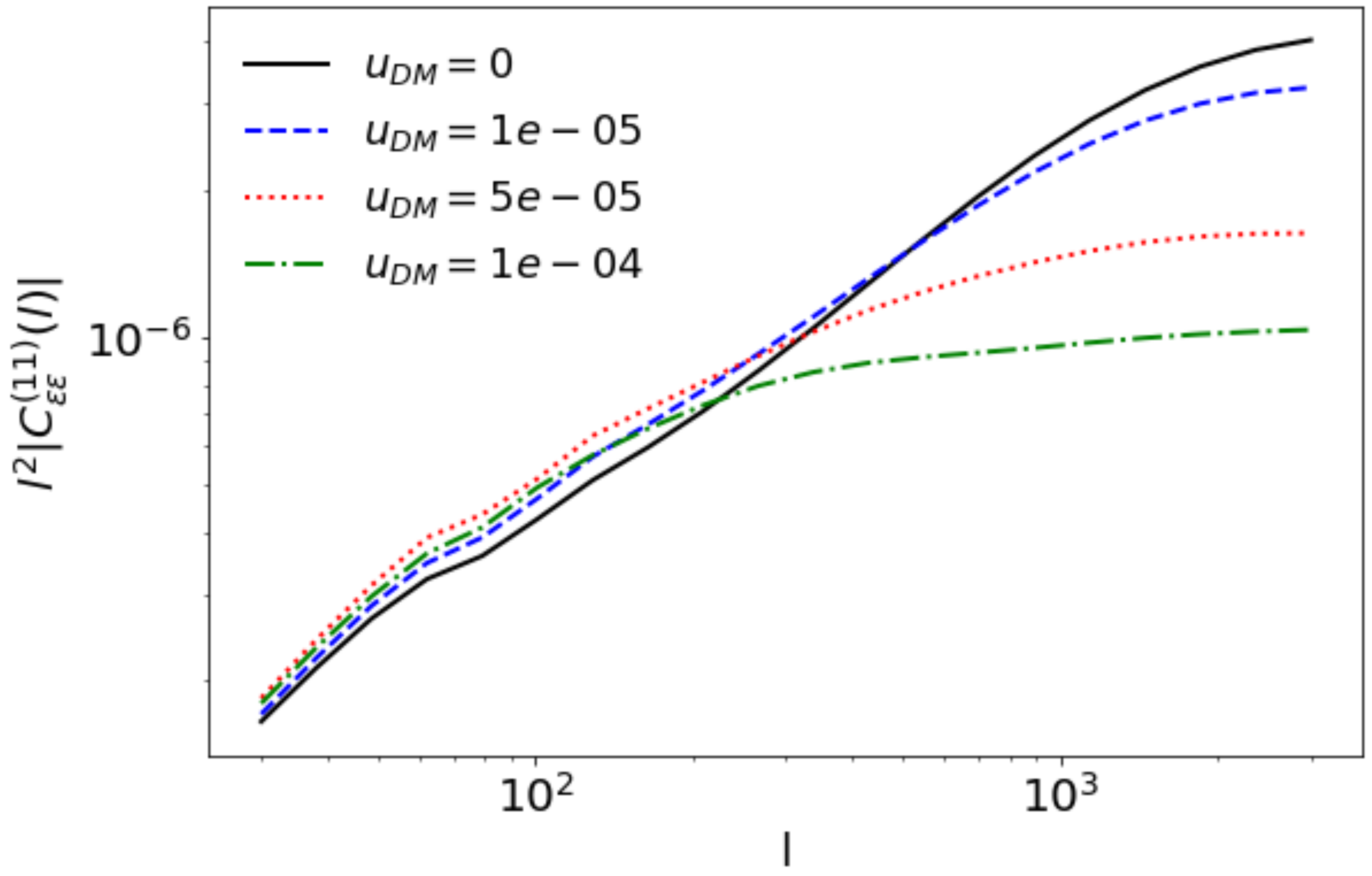
**In preparation**

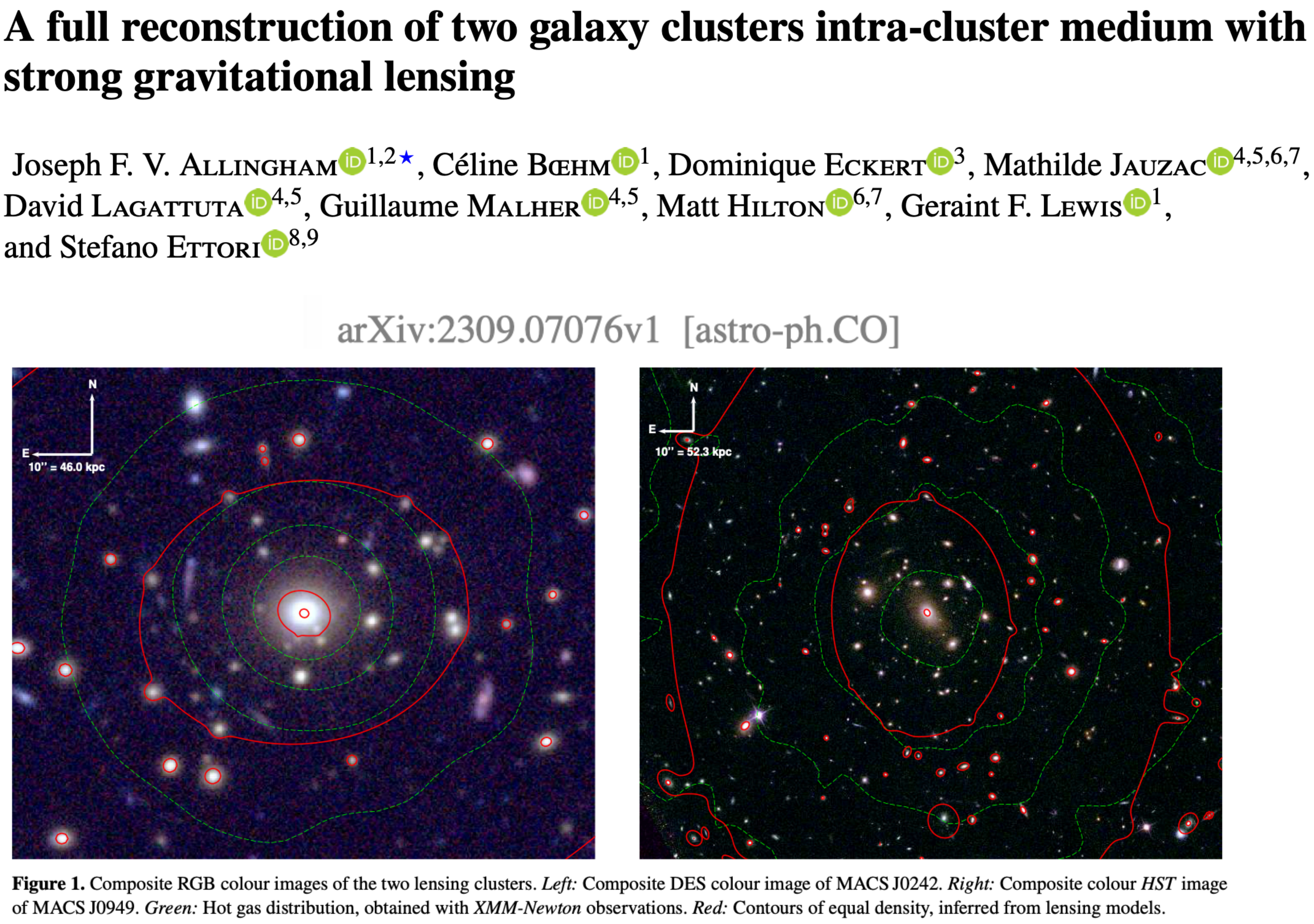
**Following https://arxiv.org/abs/2112.01545**

**Linear**



**Non linear**





# A full reconstruction of two galaxy clusters intra-cluster medium with strong gravitational lensing

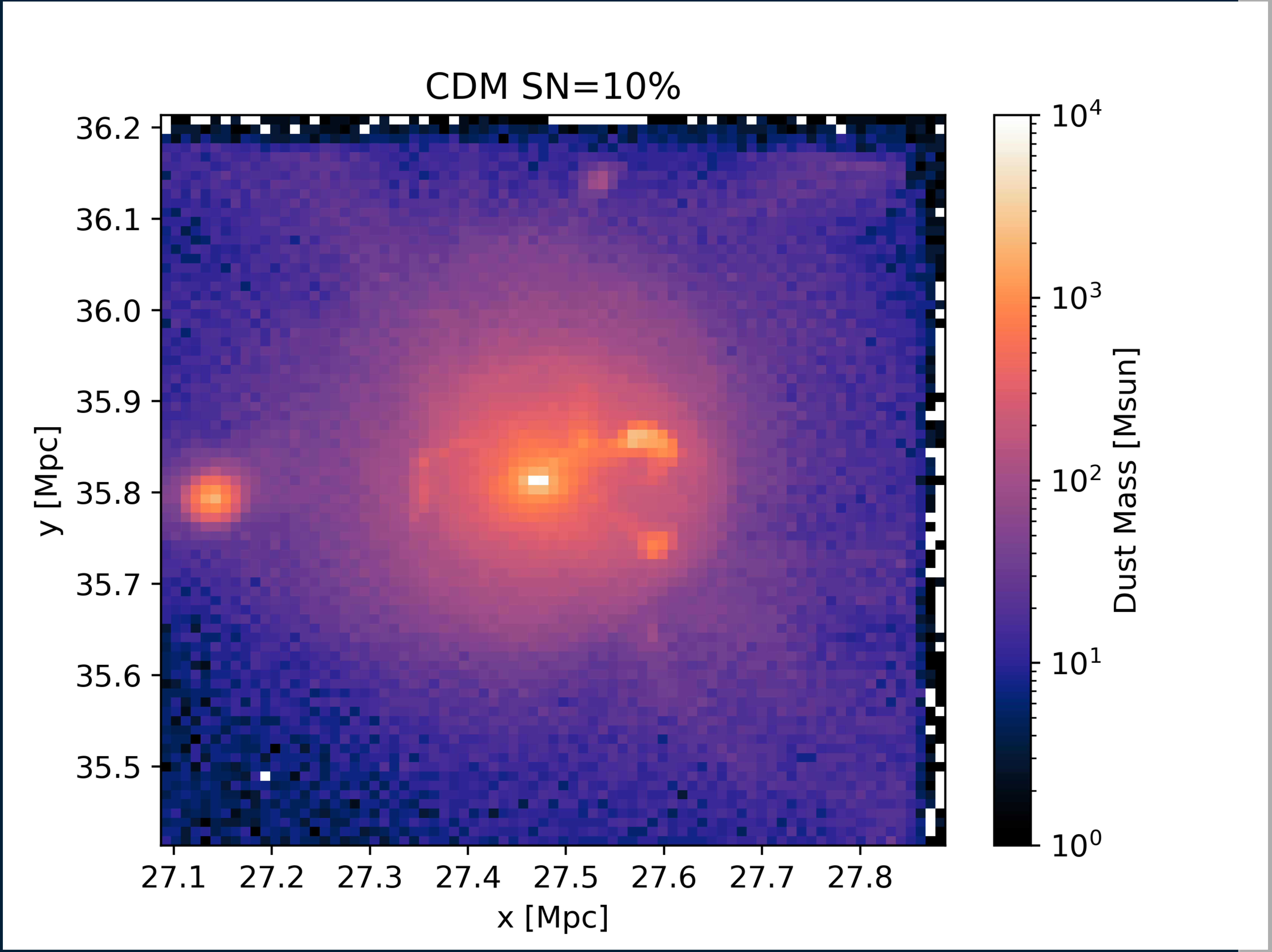
Joseph F. V. Allingham[1,2]★, Céline Bœhm[1], Dominique Eckert[3], Mathilde Jauzac[4,5,6,7],
David Lagattuta[4,5], Guillaume Malher[4,5], Matt Hilton[6,7], Geraint F. Lewis[1],
and Stefano Ettori[8,9]

arXiv:2309.07076v1 [astro-ph.CO]

**Figure 1.** Composite RGB colour images of the two lensing clusters. *Left:* Composite DES colour image of MACS J0242. *Right:* Composite colour *HST* image of MACS J0949. *Green:* Hot gas distribution, obtained with *XMM-Newton* observations. *Red:* Contours of equal density, inferred from lensing models.

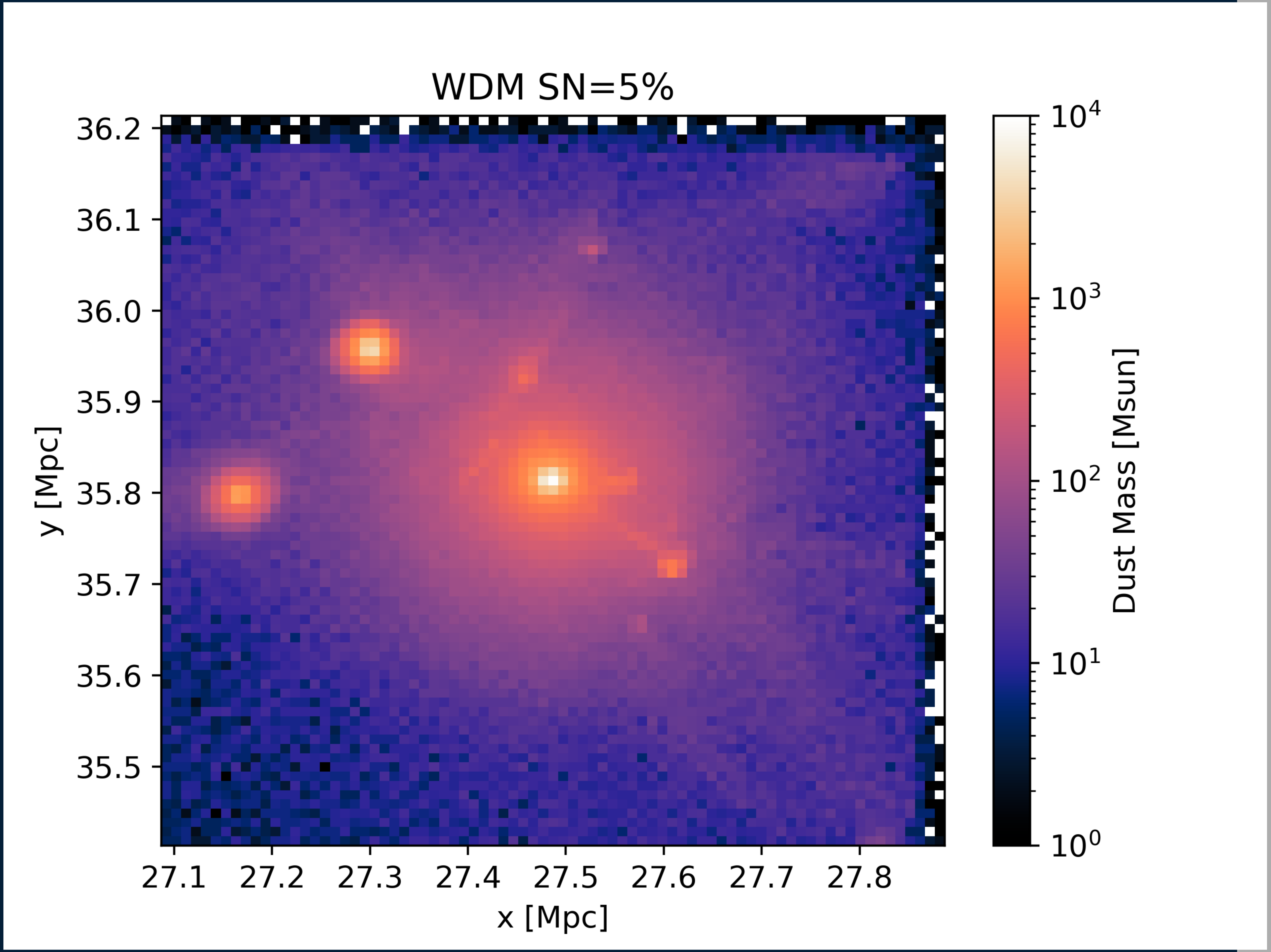
# From Adam with Darren, Robert and Markus

- Histogram dust mass of CDM
- 2 x R_200c

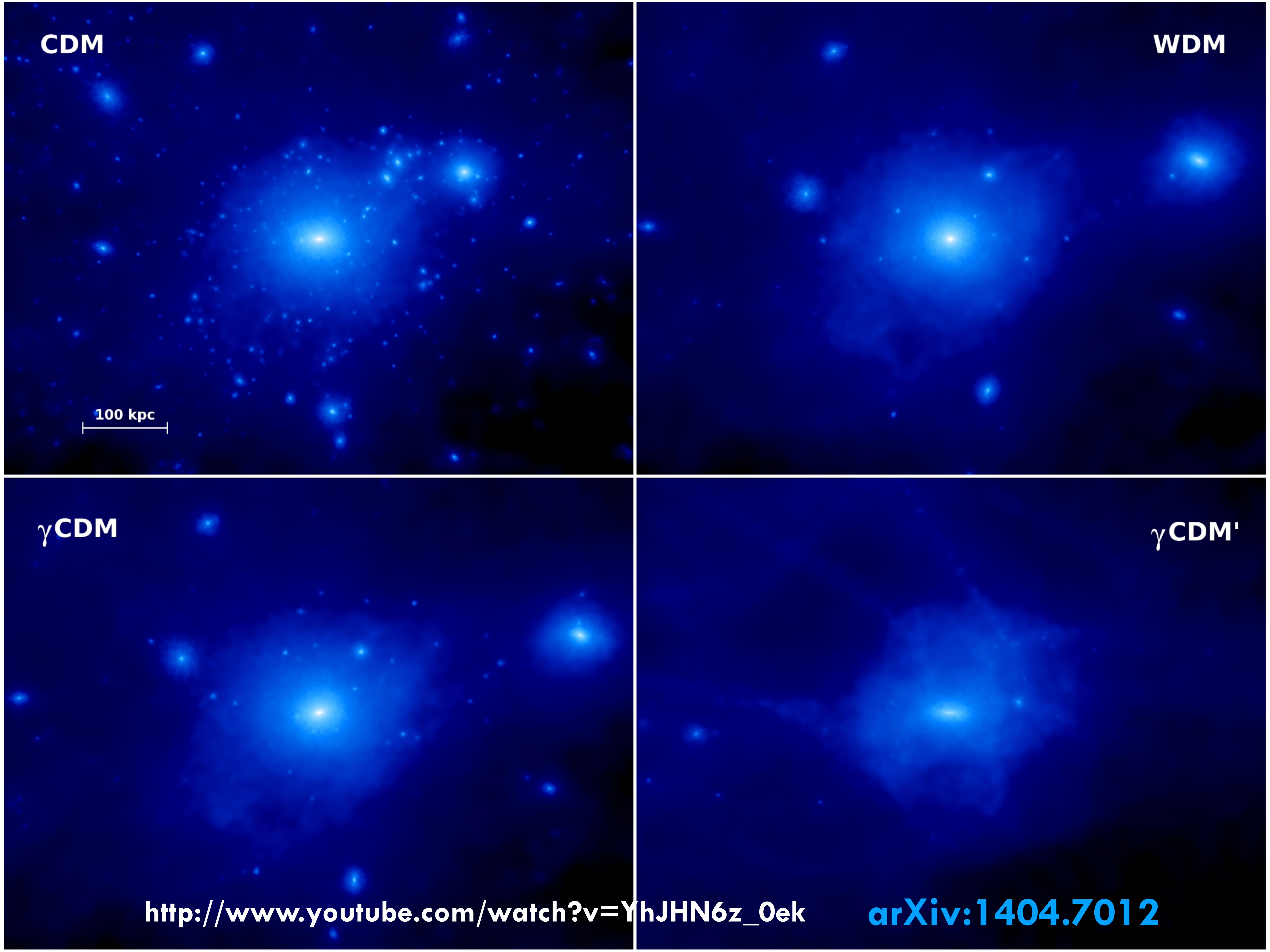


# From Adam  with Darren, Robert and Markus

- Histogram dust mass of WDM
- 2 x R_200c



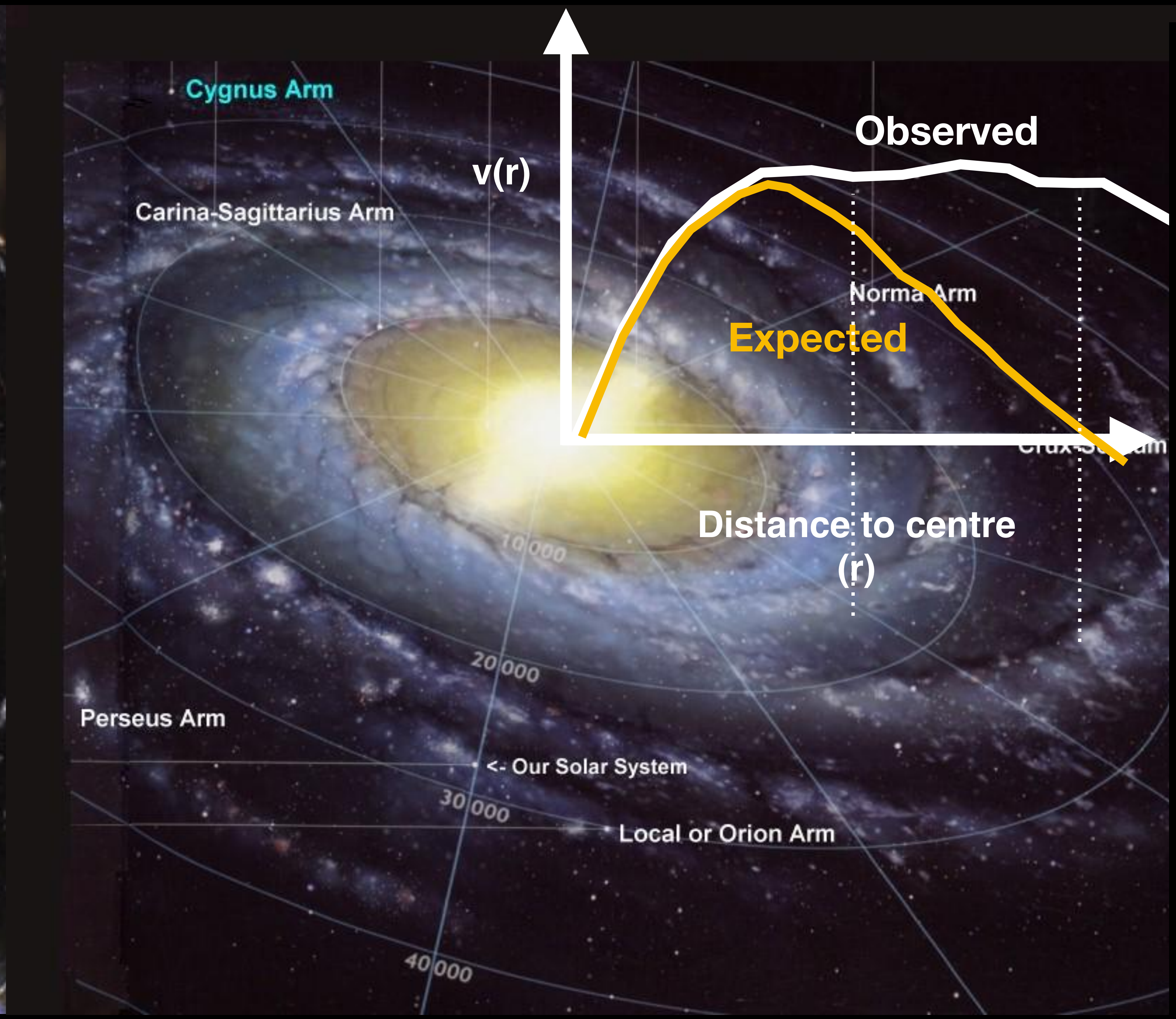
# Dark Matter interactions - Milky Way & lensing



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

arXiv:1404.7012

# Can modified gravity explain:



Story of the Universe

At the beginning of time, space exploded out of nothingness to create the ever-expanding universe we inhabit now. It took billions of years for the story, depicted here, to unfold.
–Breanna Draxler

YOU ARE HERE

ACCELERATING EXPANSION
A little more than 5 billion years ago, dark energy caused the universe to expand increasingly fast.

INFLATION
In less than $10^{-30}$ of a second after the Big Bang, the universe burst open, expanding faster than the speed of light and flinging all the matter and energy in the universe apart in all directions.

BIG BANG
The universe expanded violently from an extremely hot and dense initial state some 13.7 billion years ago.

Celine Boehm

# Modifying Gravity

## MOND

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

empirical

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

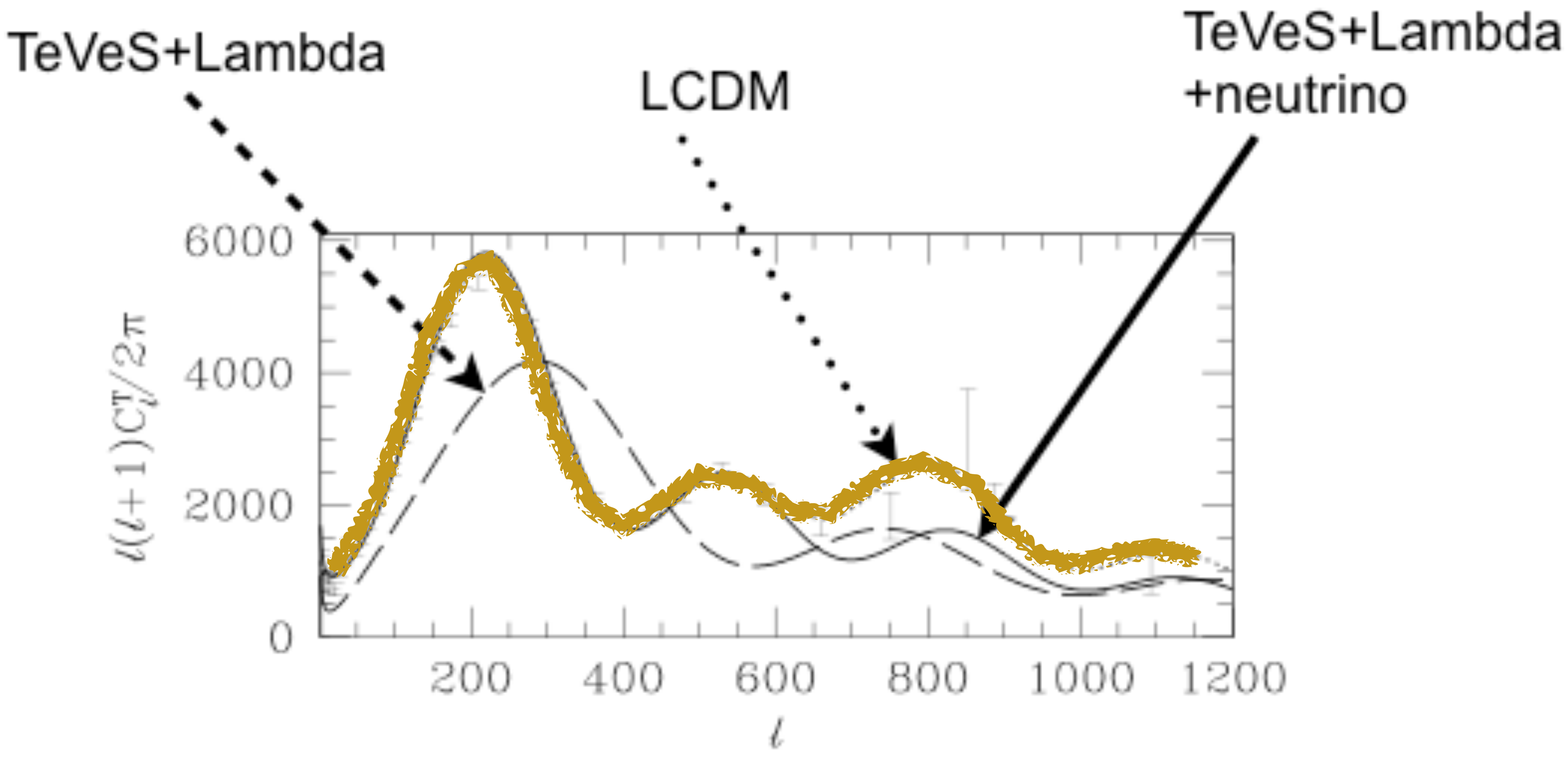
Modification of small acceleration values

(F = ma and F->0 at large radii in Newtonian physics but not in MOND to reproduce DM)

MOND doesn't allow to go back in time
(No notion of redshift)

## Relativistic version (TeVeS)

TeVeS: astro-ph/0403694



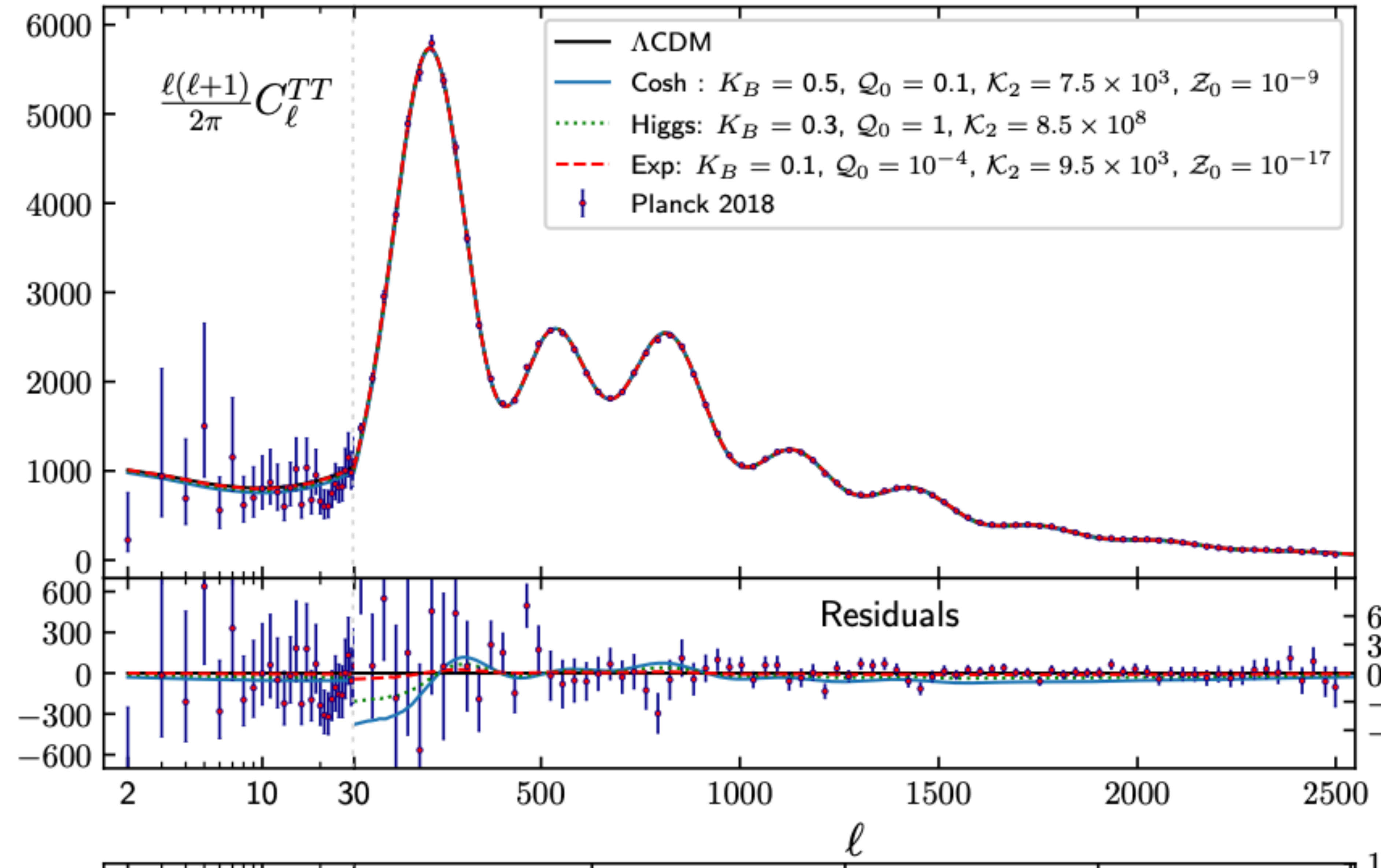
astro-ph/0505519

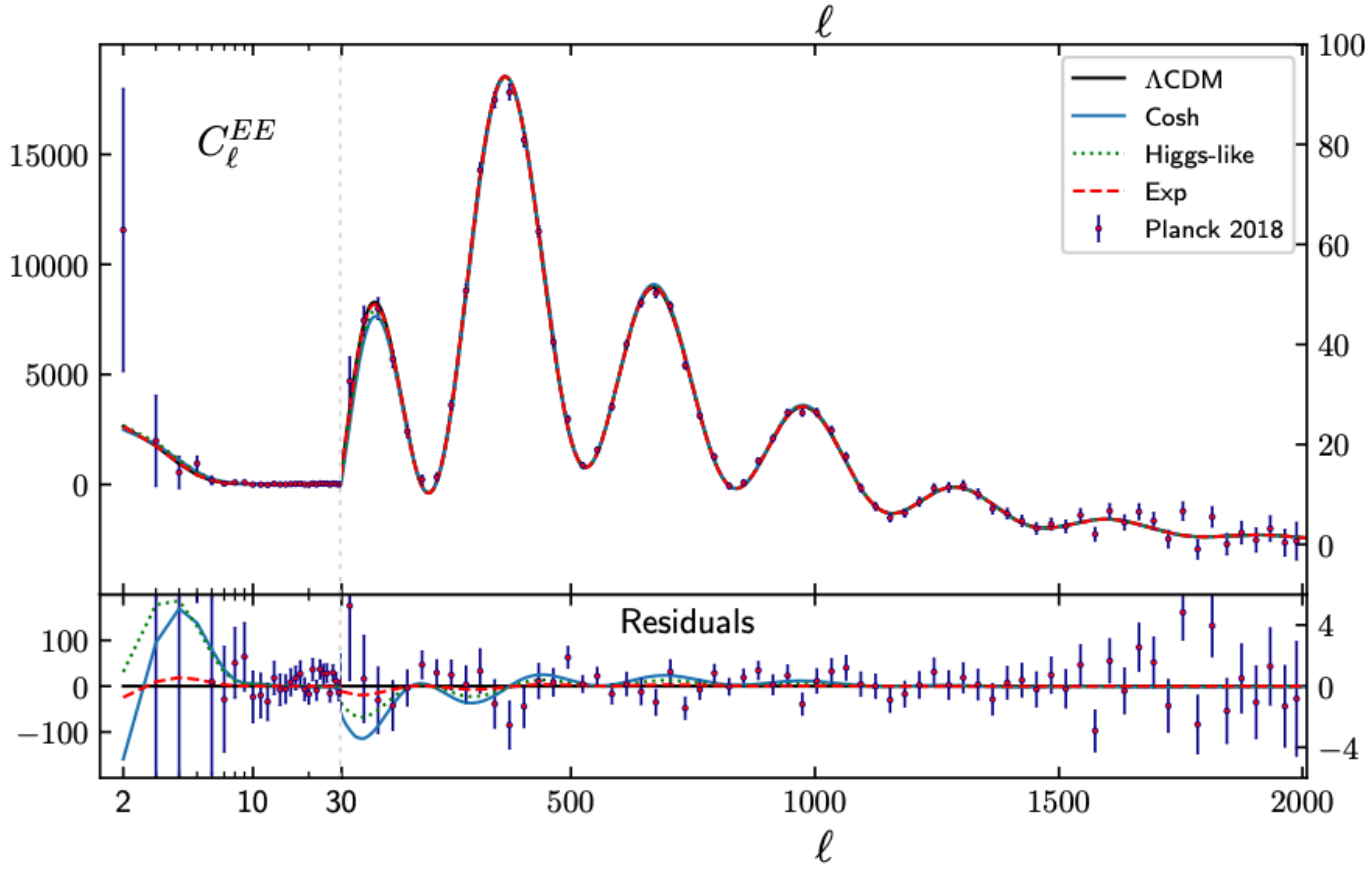
# New Relativistic theory for modified Newtonian dynamics

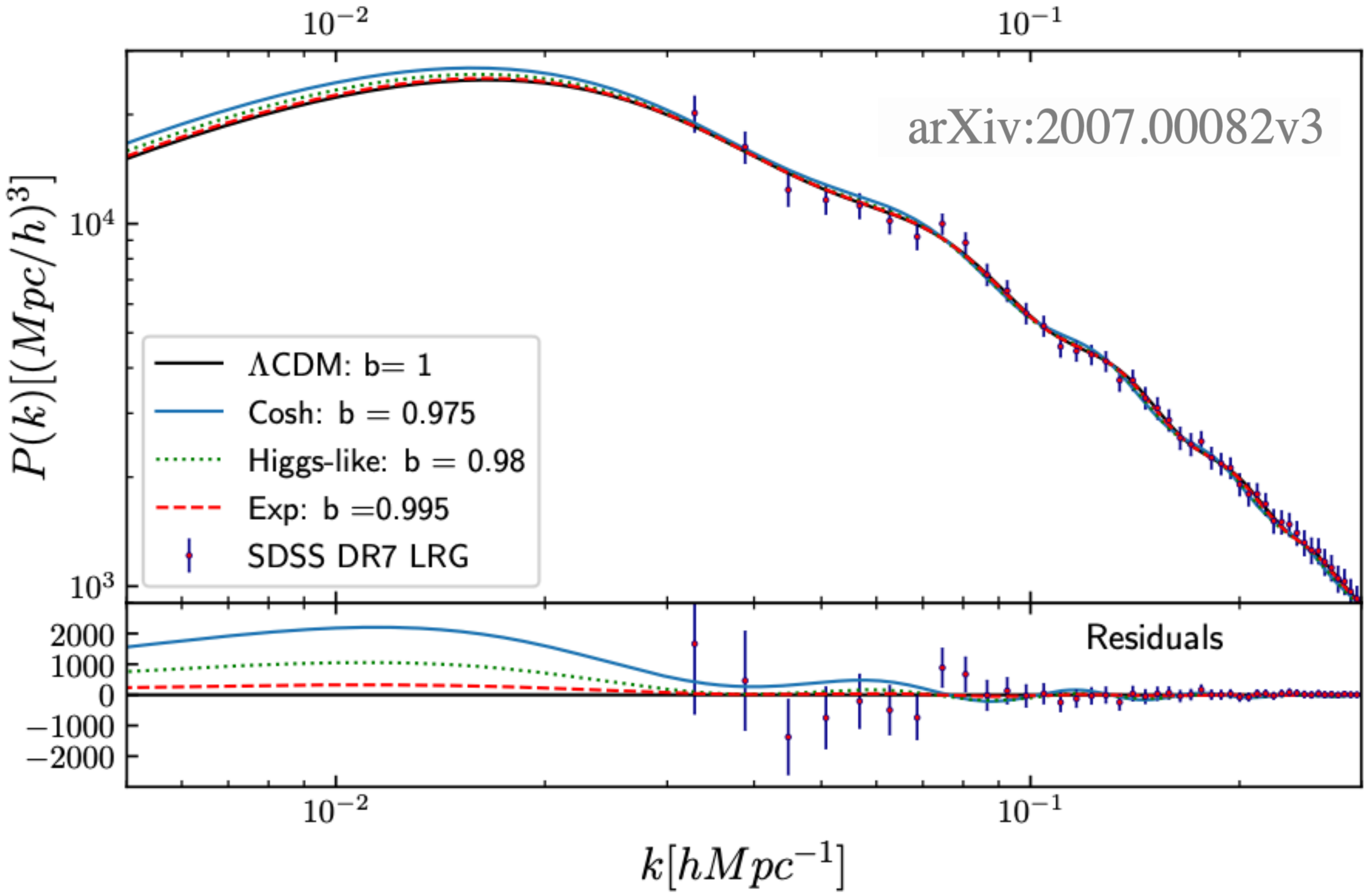
arXiv:2007.00082v3

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.






arXiv:2007.00082v3

# AeST with Peter Vermayen

Follow

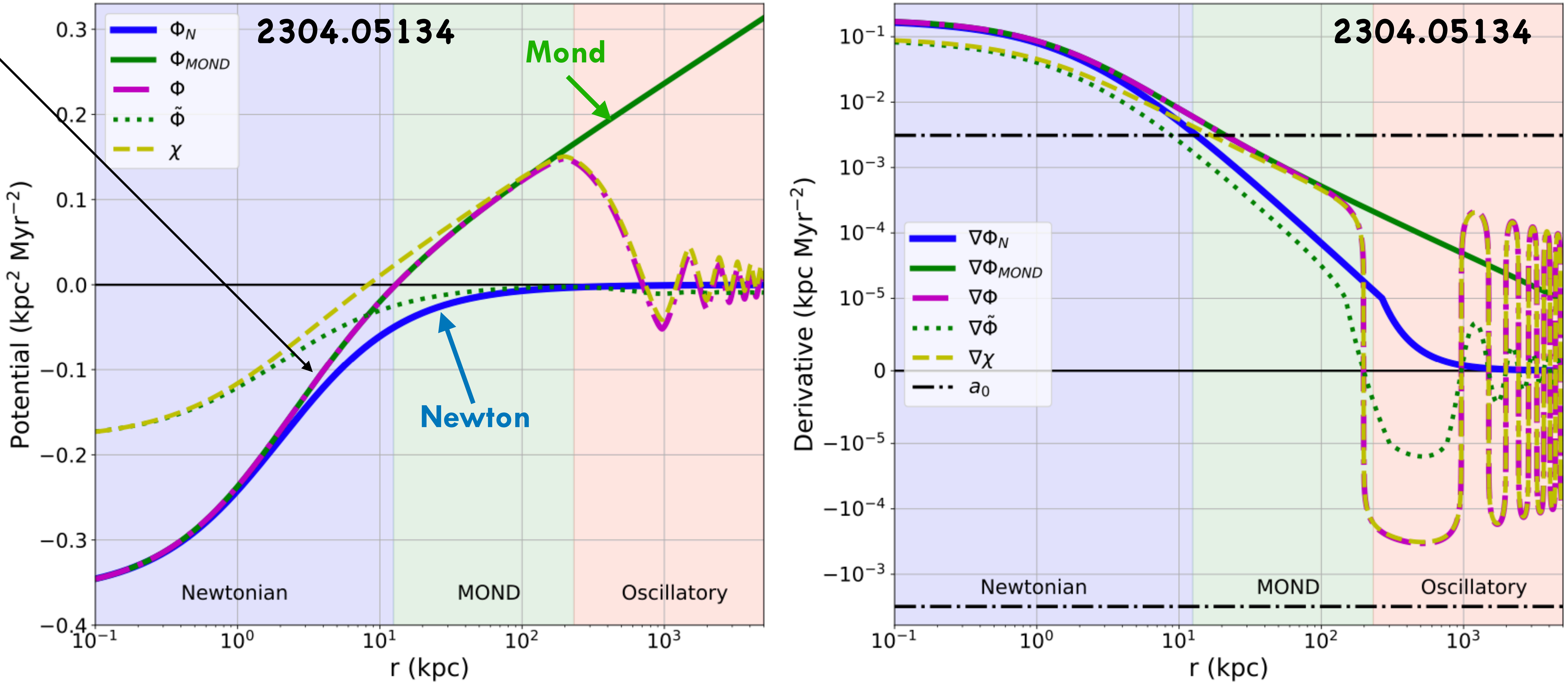
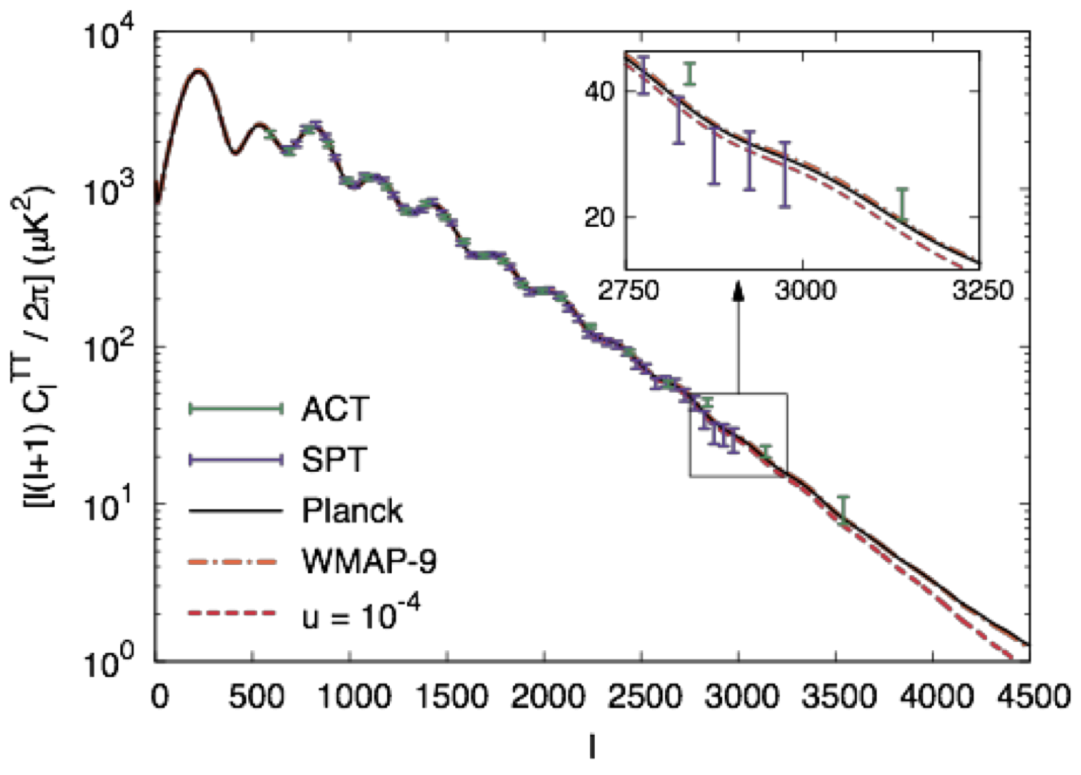
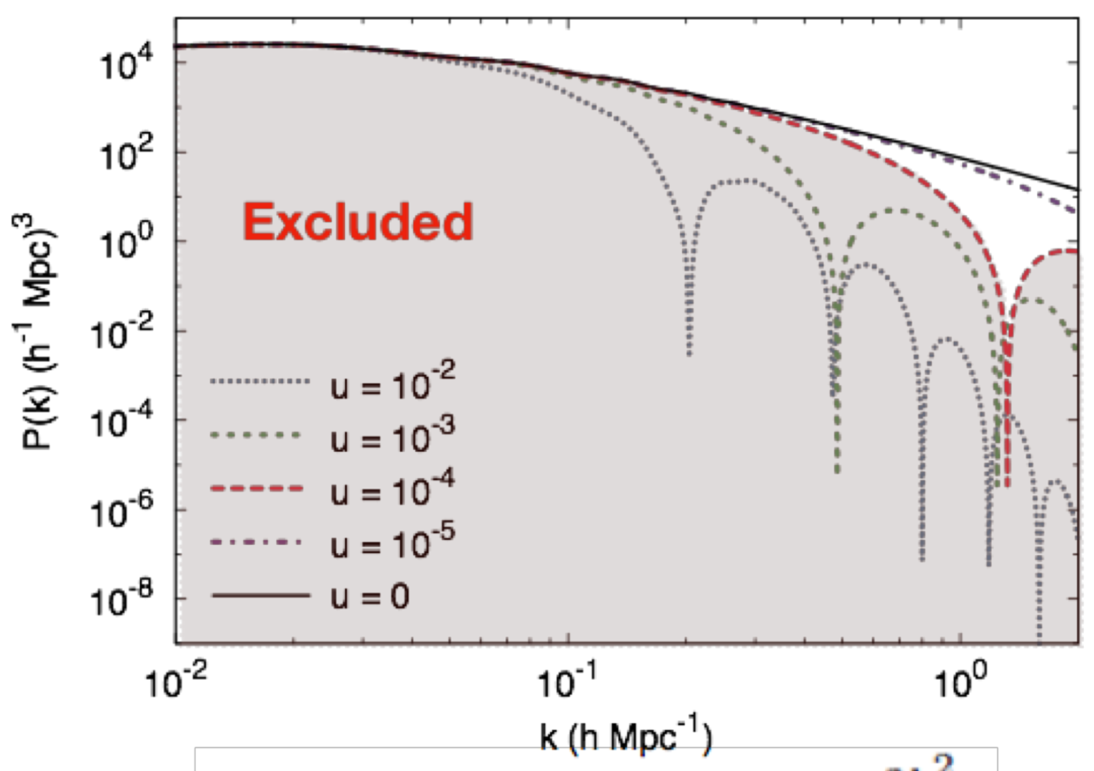


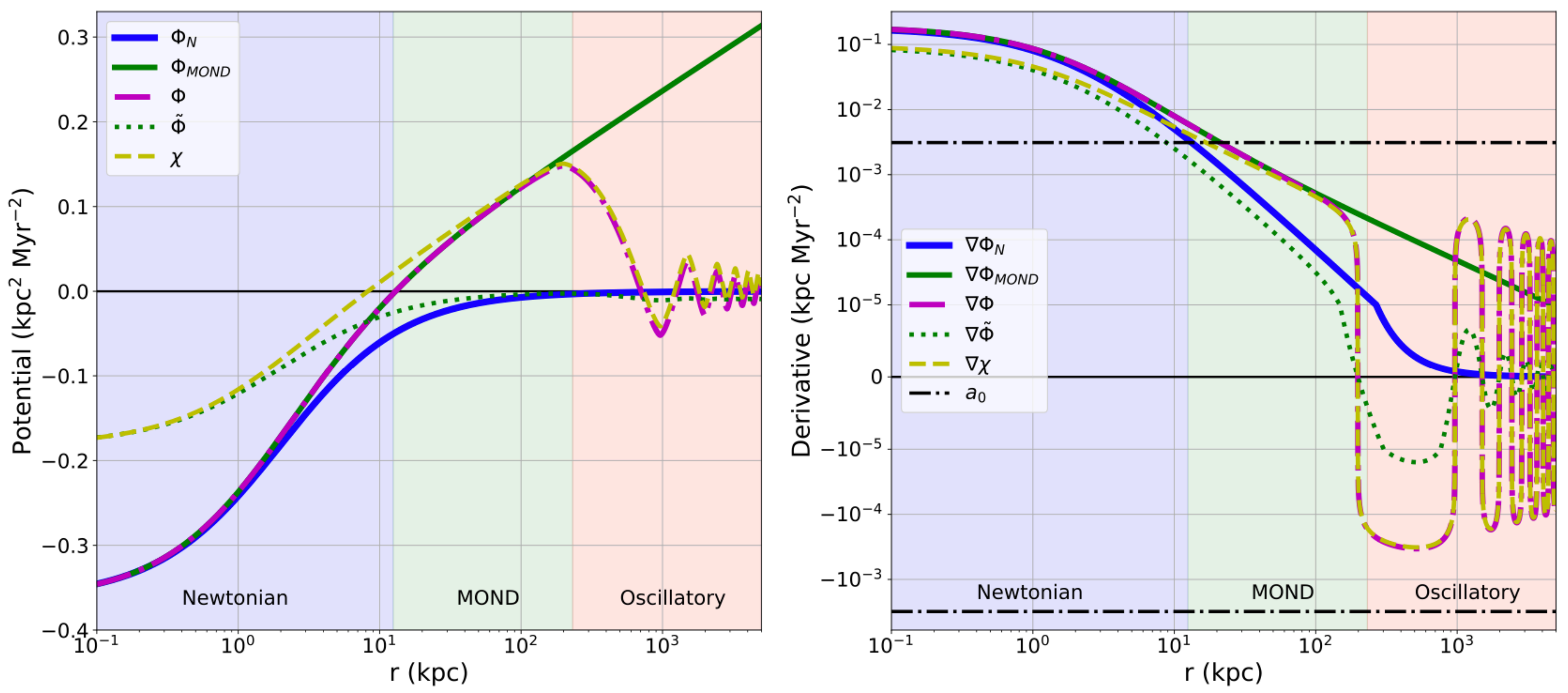
**Figure 2.** Solution of the field equations (left) and their gradients (right) for the Hernquist density profile and the fiducial model parameters with $(\lambda_s, \mu) = (1, 1\ \mathrm{Mpc}^{-1})$. The blue, green and red regions delineate the Newtonian, MOND and Oscillatory regions respectively. 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.

# Conclusion / USyd's contributions





$$\delta_\gamma \sim \delta_k \cos(k\eta/\sqrt{3})e^{-\frac{2k^2\eta}{15\dot{\kappa}}}$$



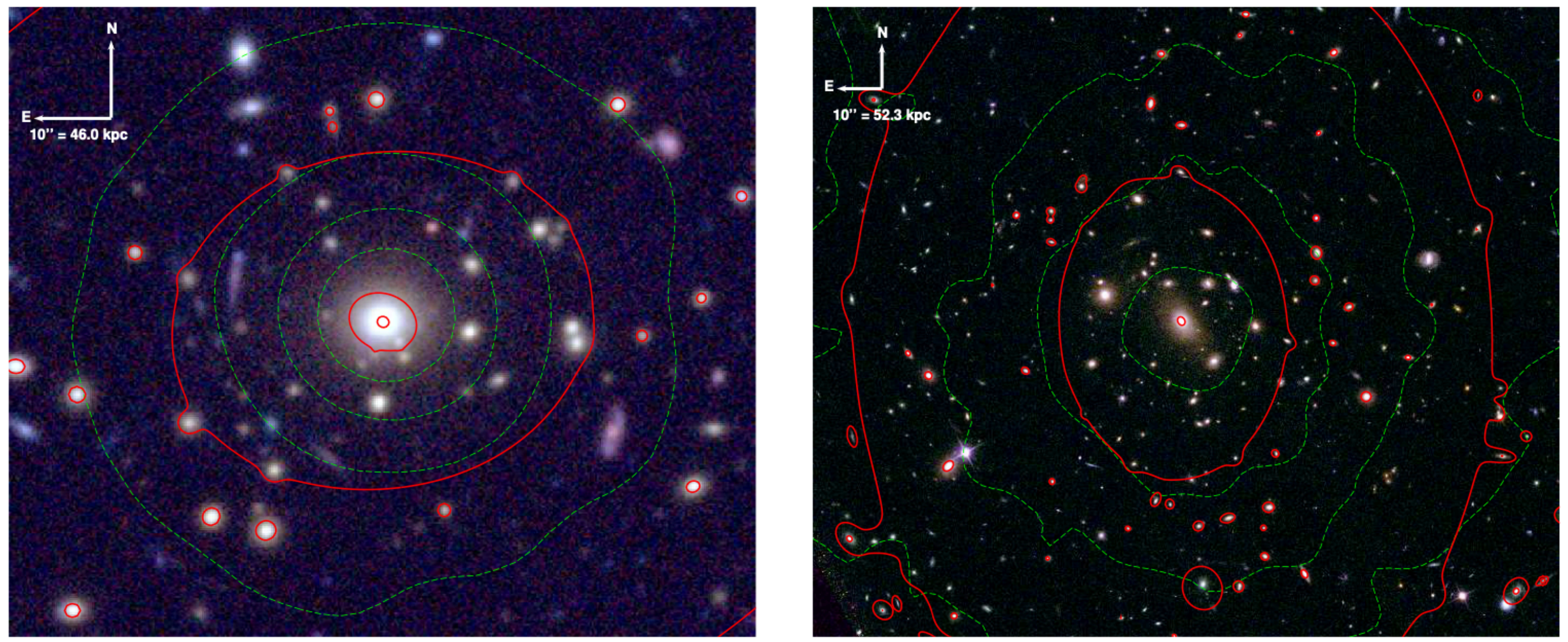
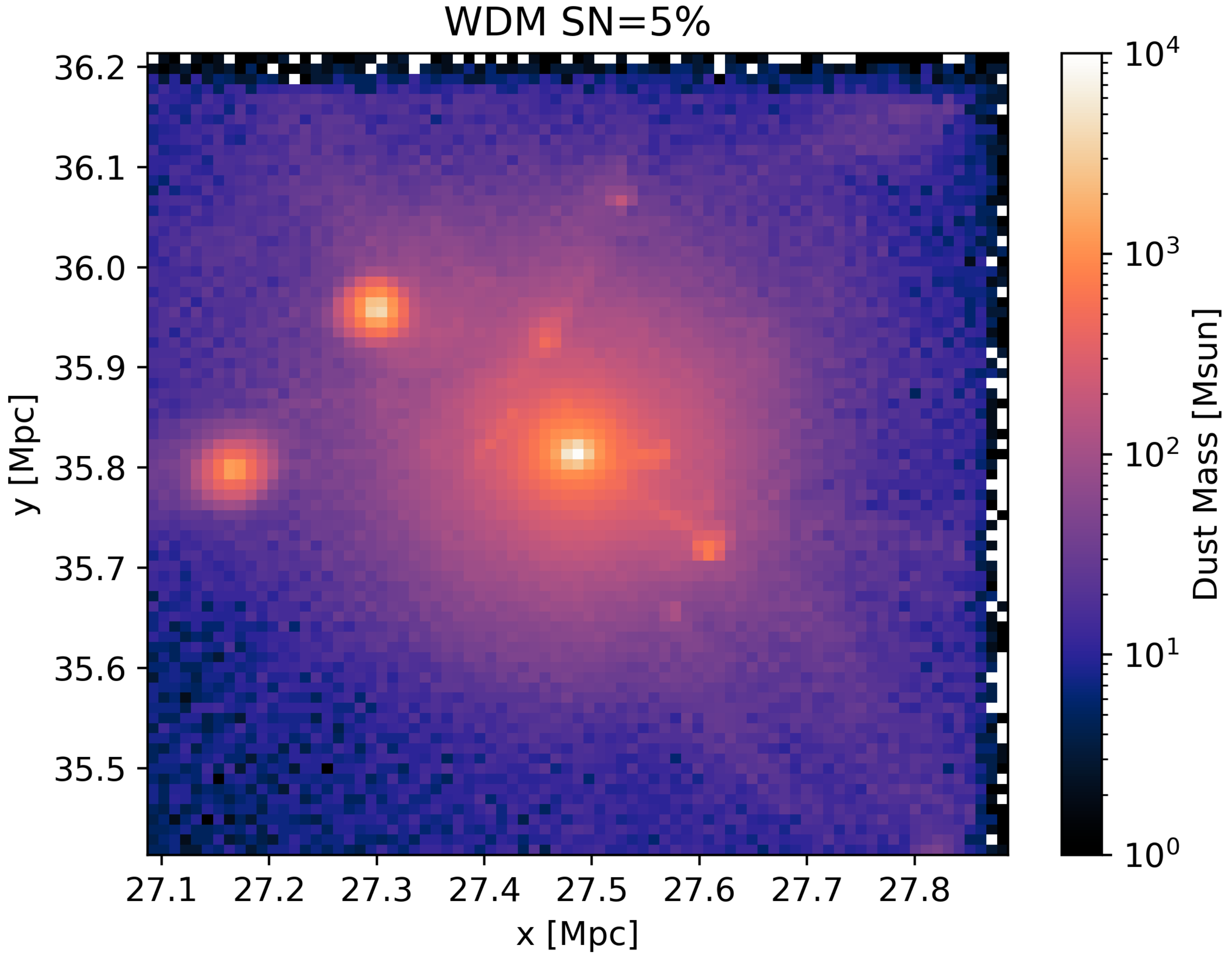
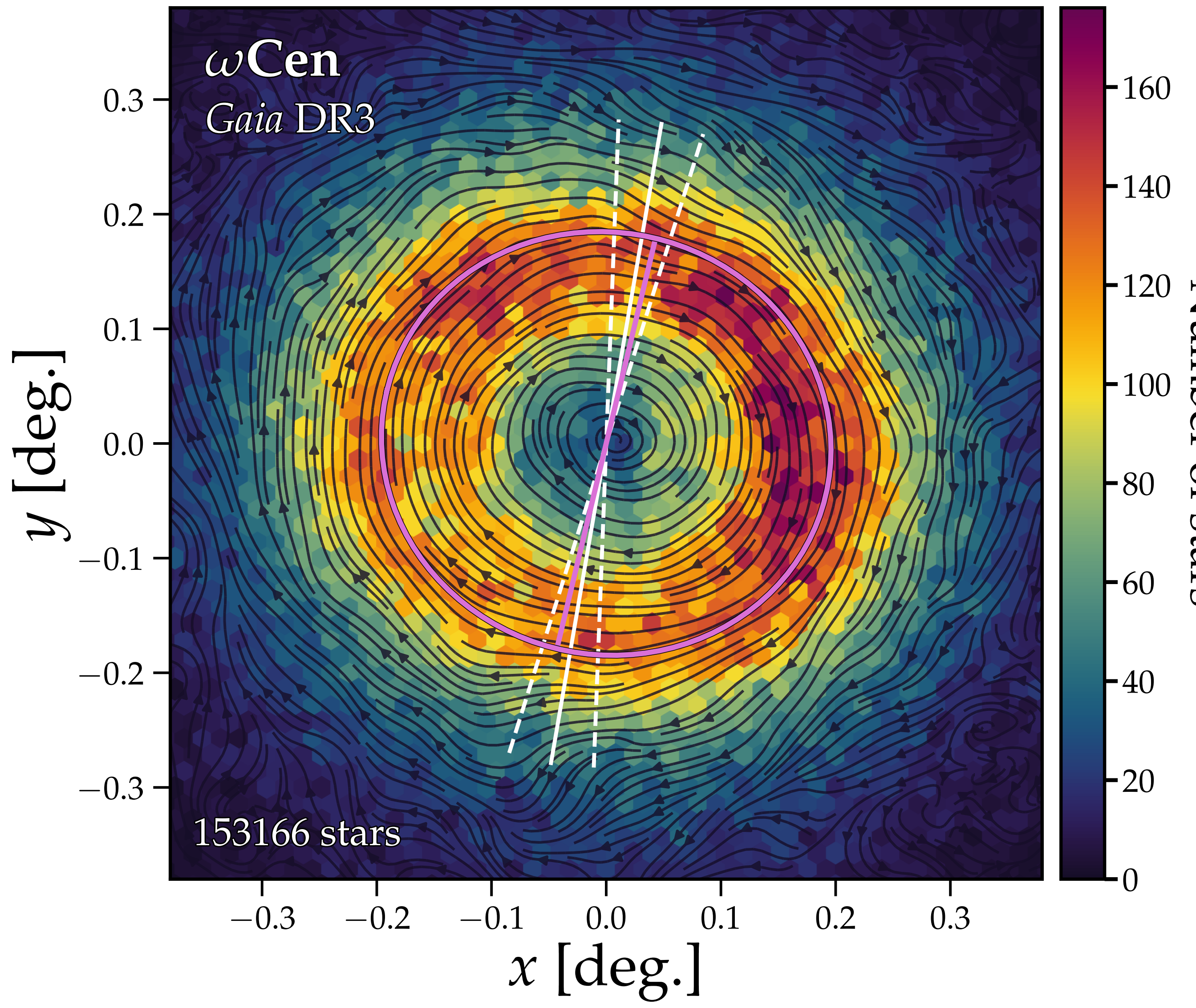


**Figure 1.** Composite RGB colour images of the two lensing clusters. *Left:* Composite DES colour image of MACS J0242. *Right:* Composite colour *HST* image of MACS J0949. *Green:* Hot gas distribution, obtained with *XMM-Newton* observations. *Red:* Contours of equal density, inferred from lensing models.





# Additional slides

# What kind of interactions?

**DM-photon**

**DM-neutrino**

**DM-baryon**

**DM-DM**
**DM-dark sector**

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

# Generalising the Silk damping to dark matter

**baryon-photon** →

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

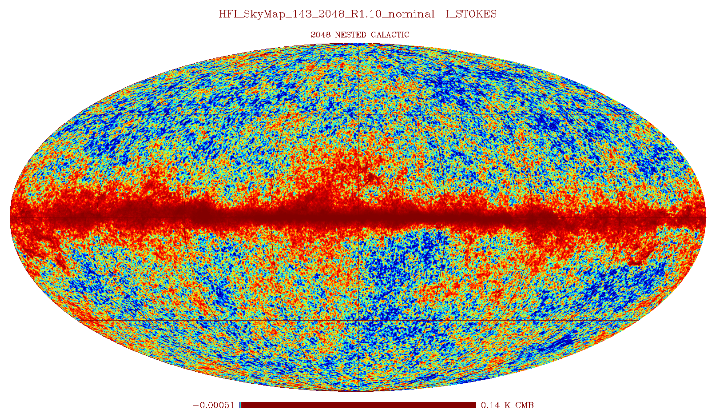
**Intuitively**
**A damping scale**

Last very long

Highest possible energy density

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

Largest possible interactions (except for Coulomb)



CB & Schaeffer 2000, 2004 using Weinberg 1971 & Chapman, Cowling 1970

# Generalising the Silk damping to dark matter

CB & Schaeffer 2000, 2004 using Weinberg 1971 & Chapman, Cowling 1970

**Silk damping revisited**

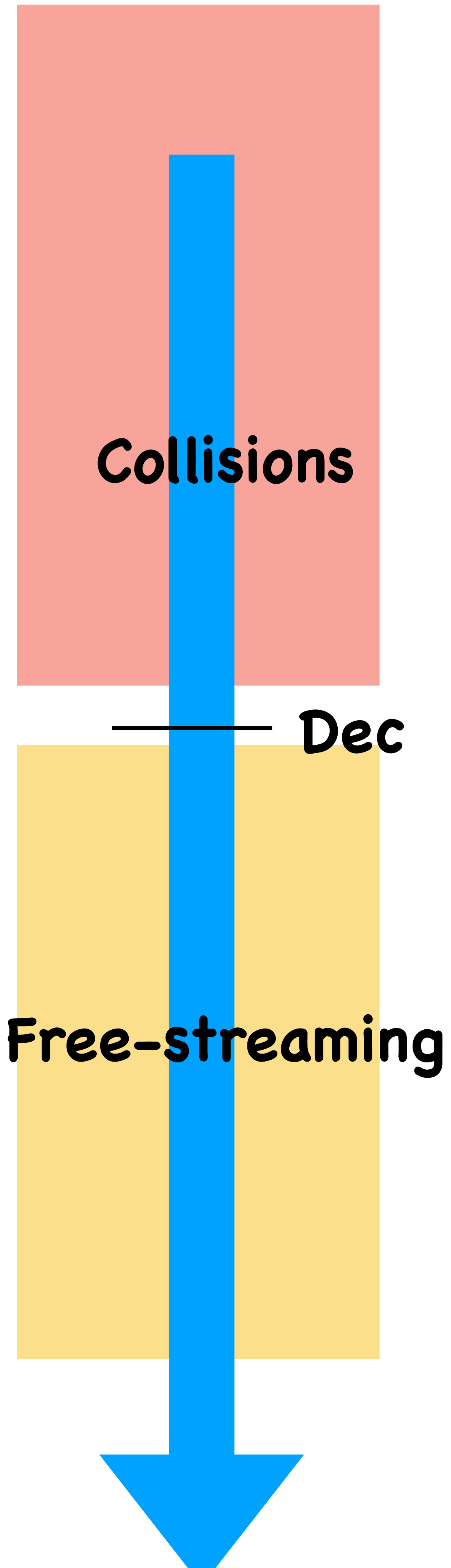
$$l_{Silk}^2 \simeq \frac{2\pi^2}{3} \int^{t_{dec(b-\gamma)}} \frac{c^2 \rho_\gamma}{\rho_{tot}\, a^2\, \Gamma_\gamma} \left(1 + \Theta_\gamma\right) dt$$

**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

astro-ph/0012504, astro-ph/0112522,
astro-ph/0205406, astro-ph/0410591

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

**Large when the dm-photon cross section is large**

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

**New and new regime**

(Like b-nu interactions by Misner 1966
Expected to be large if DM is MeV and
coupled to neutrinos even after they
start free-streaming)

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

**Inefficient unless the cross section is very large (Thomson like)**

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

**Inefficient unless the cross section is very large (dark Coulomb interactions)**

Very suppressed so you can let the DM coupled to these species for a long time

-> dark cooling possible (see Edges)