DM interactions and impact on structure formation

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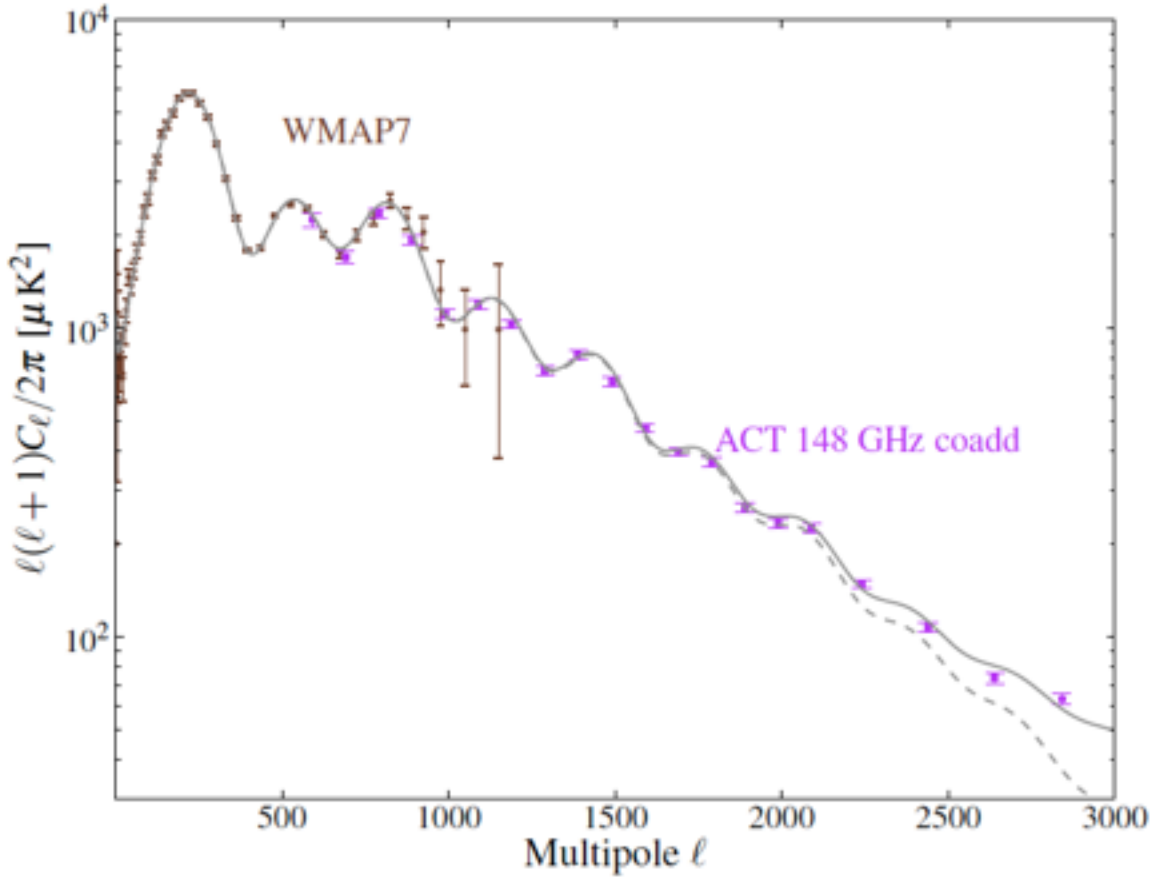
Pascos, Vietnam, 15 July 2016

LCDM is successful but ...

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

No DM mass ;
no DM interaction in the DM equation.
Just a modification of gravity...



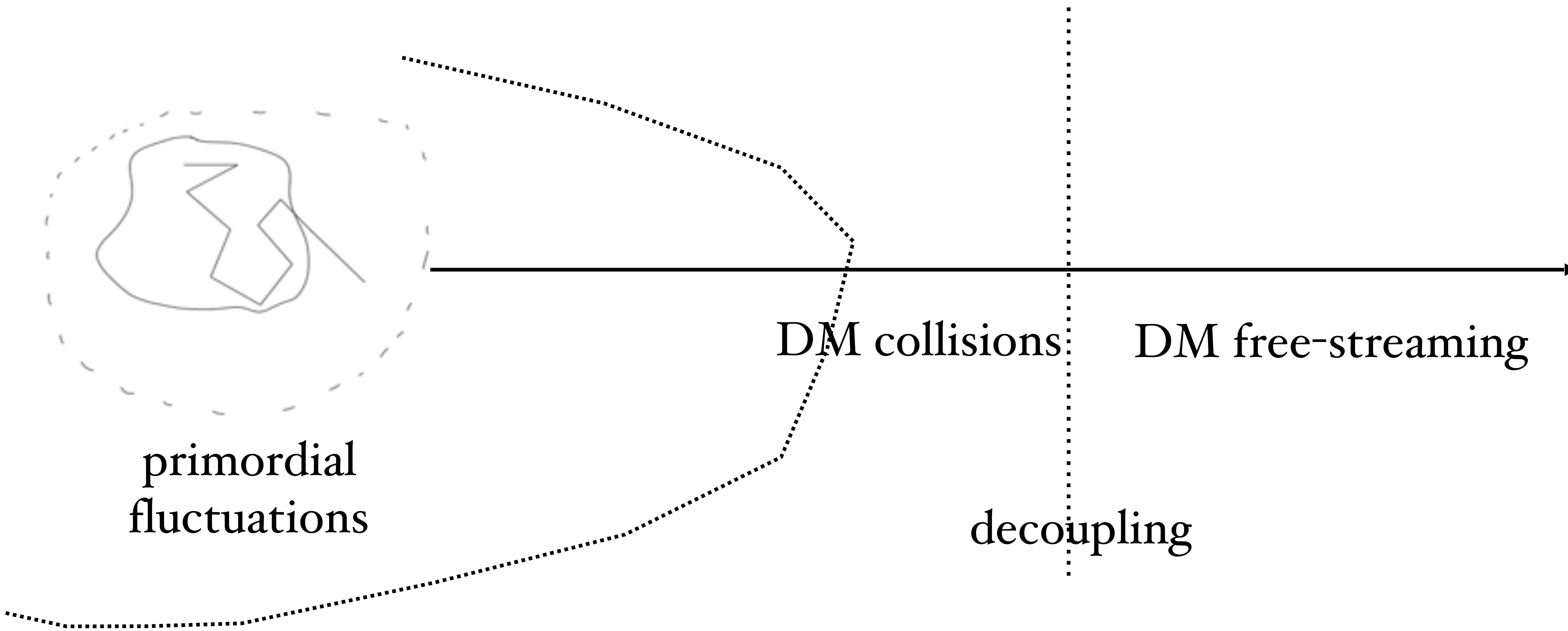
DM interactions are omitted

and yet DM should have interactions!

Cold DM after all (mass and kinetic decoupling at a few MeV in several models)

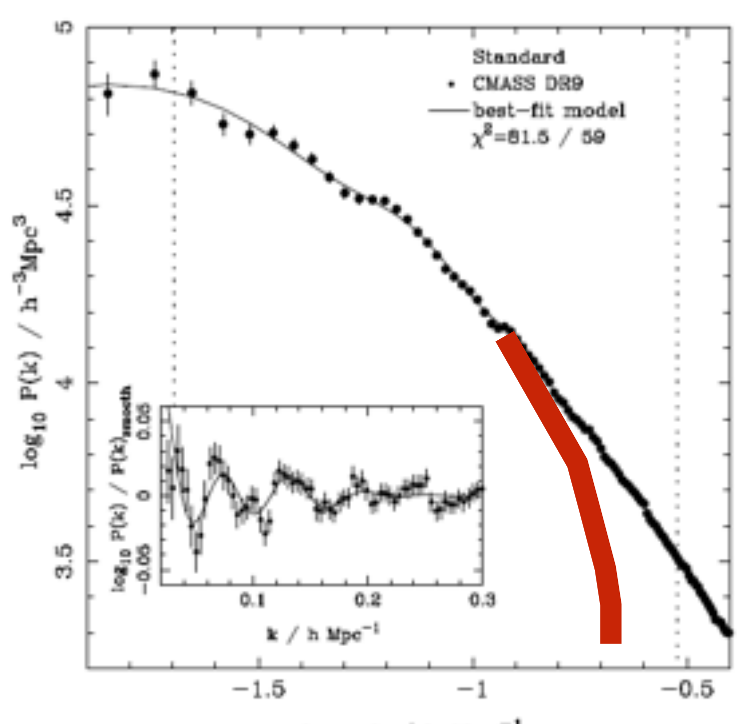
Impact of DM interactions on CMB physics

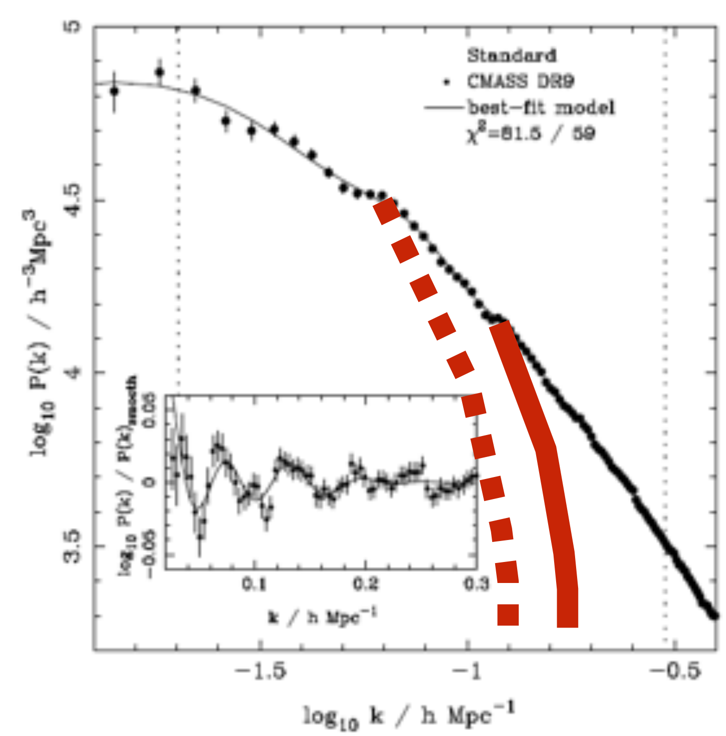
The physics of DM interactions on primordial fluctuations



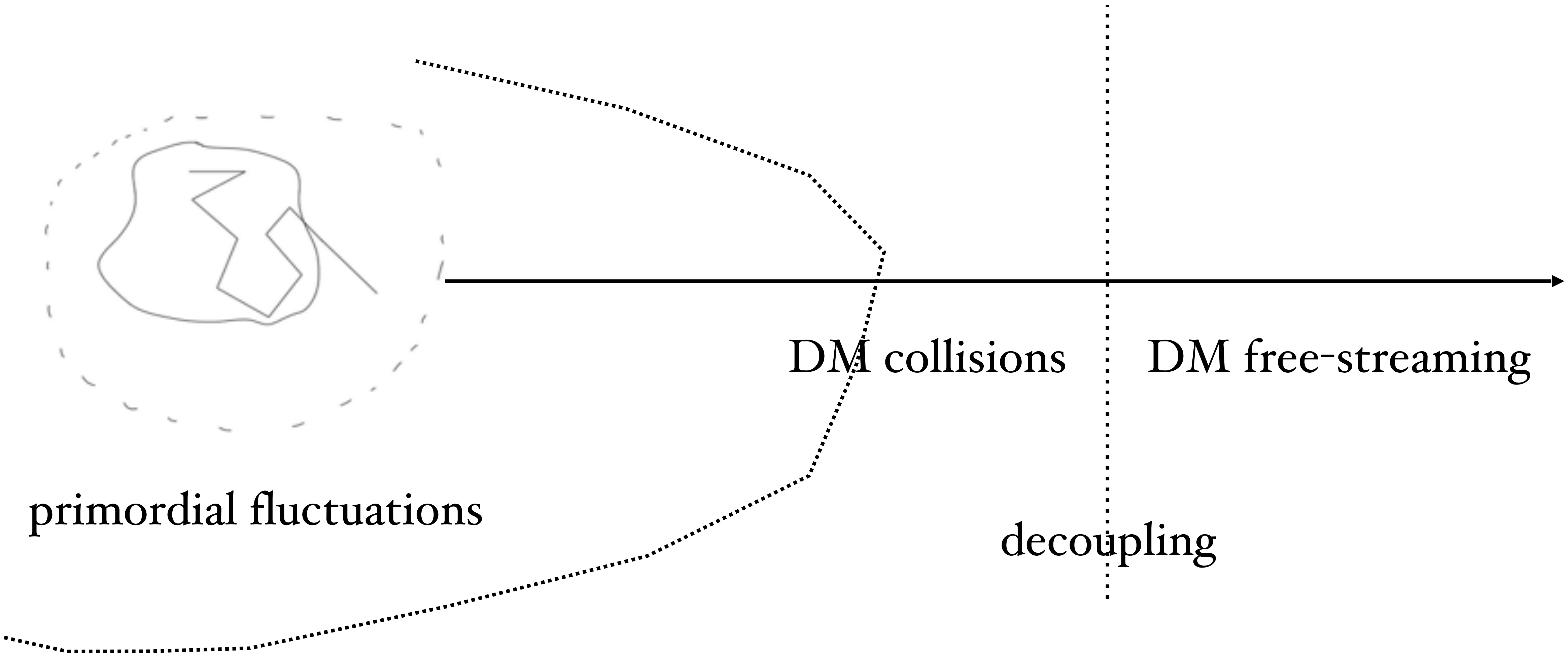
Fluctuations first erased by collisional damping

then free-streaming





The physics of DM interactions on primordial fluctuations



Fluctuations first erased by collisional damping — then free-streaming

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

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

astro-ph/0012504 astro-ph/0410591

The physics of DM interactions on primordial fluctuations

astro-ph/0112522

last until DM stop interacting

efficient if the DM is coupled to a relativistic species

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

efficient if DM is coupled to a species that is also interacting with other fluids

without DM interactions

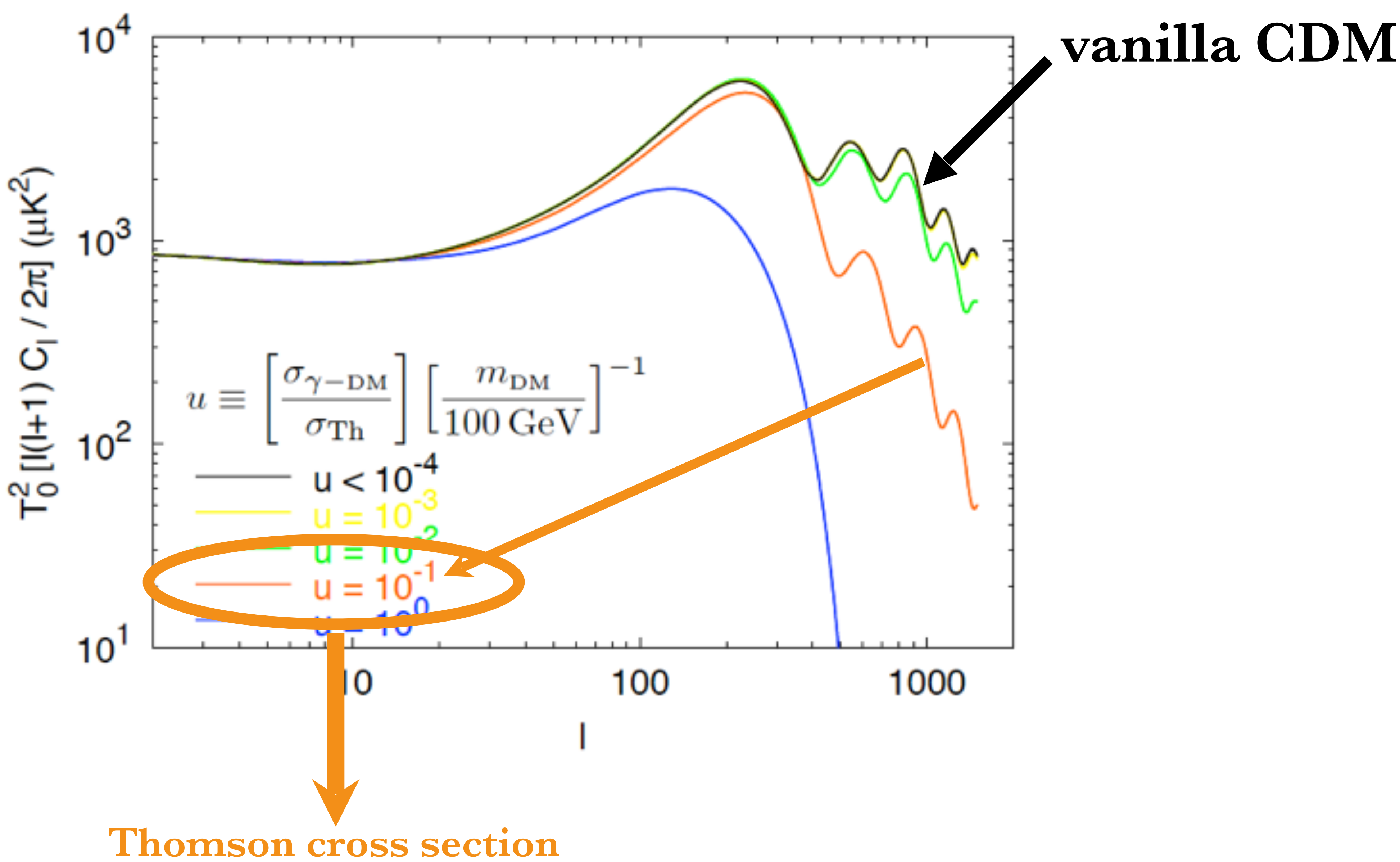
$$\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_b) , \\
\dot{\theta}_{DM} &= k^2\psi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

with DM interactions

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

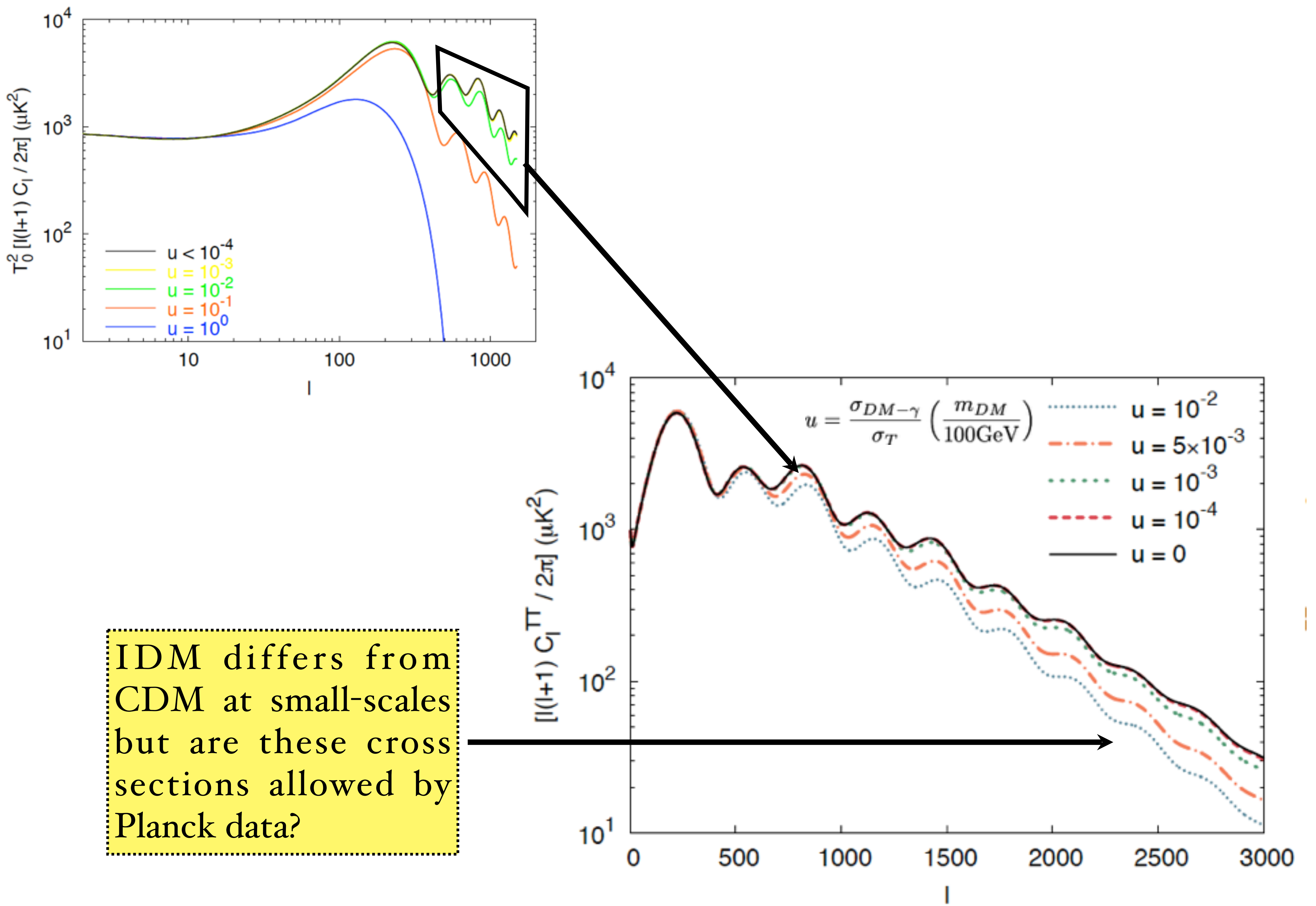
DM-photon interactions astro-ph/0112522

u = ratio of cross section to the DM mass (1 parameter!)



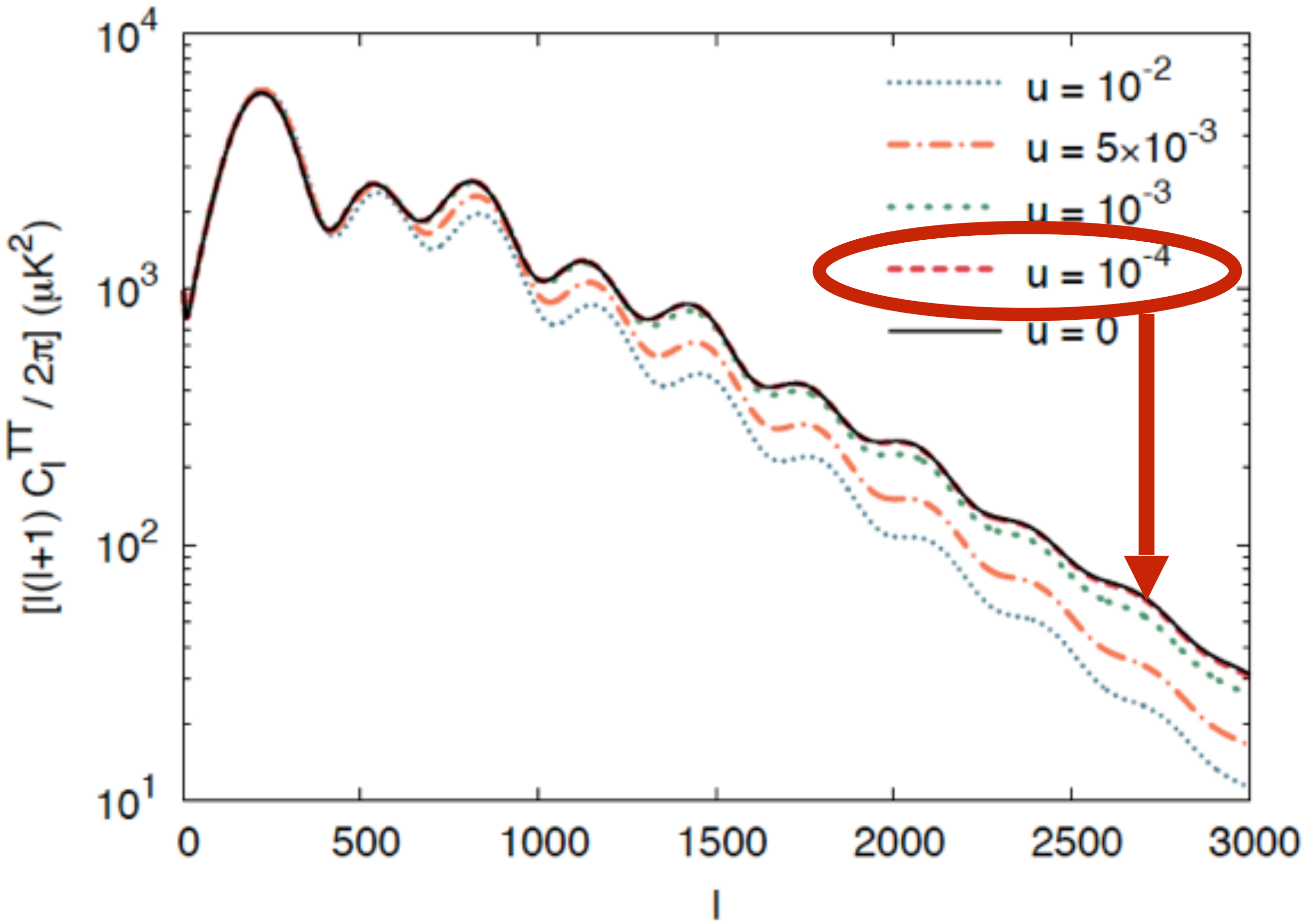
dark matter cannot be a baryon…but CMB does not prevent a coupling to photons

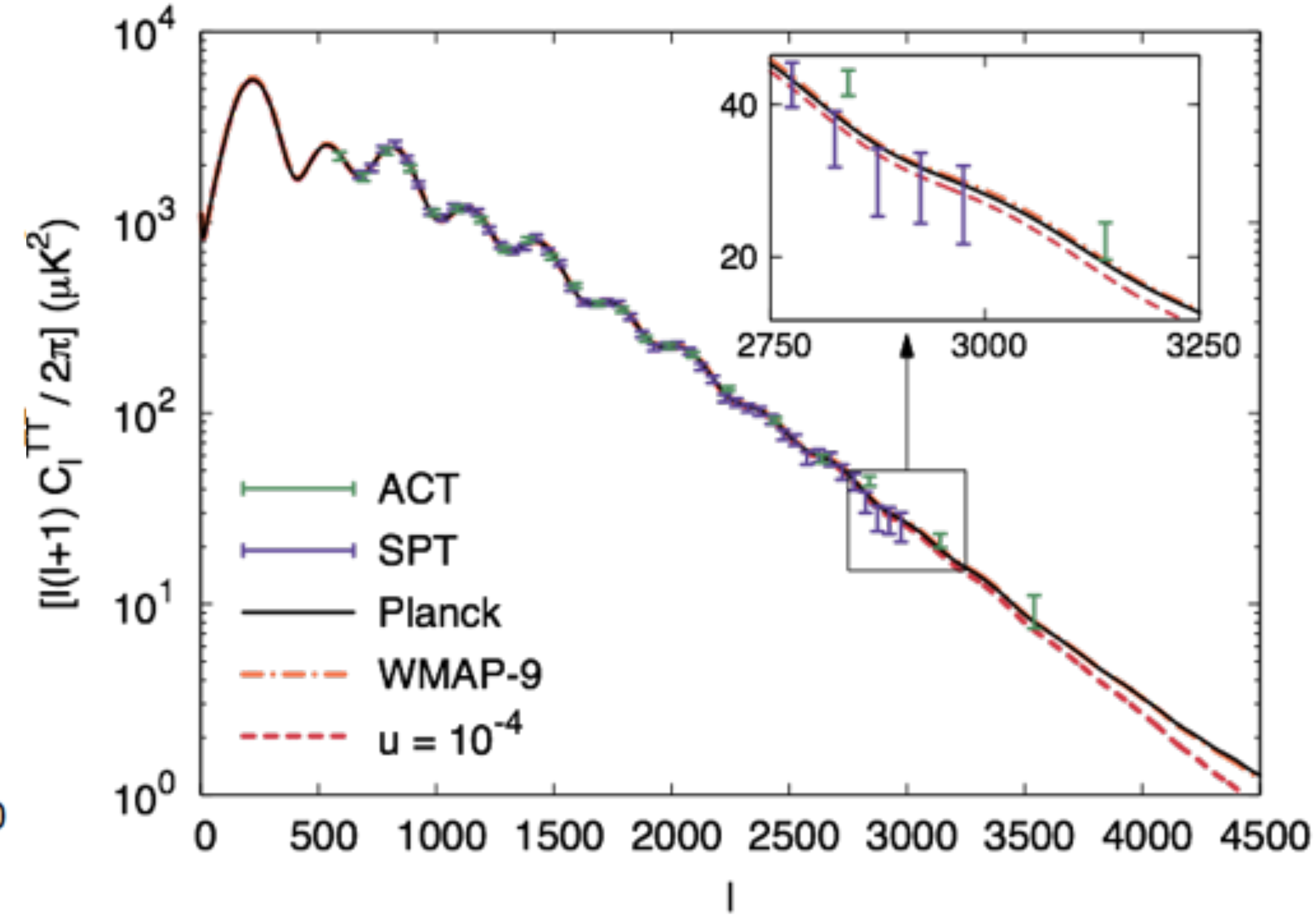
ZOOMING IN (with Class) [arXiv:1309.7588]



IDM differs from CDM at small-scales but are these cross sections allowed by Planck data?

DM-photon interactions [arXiv:1309.7588]



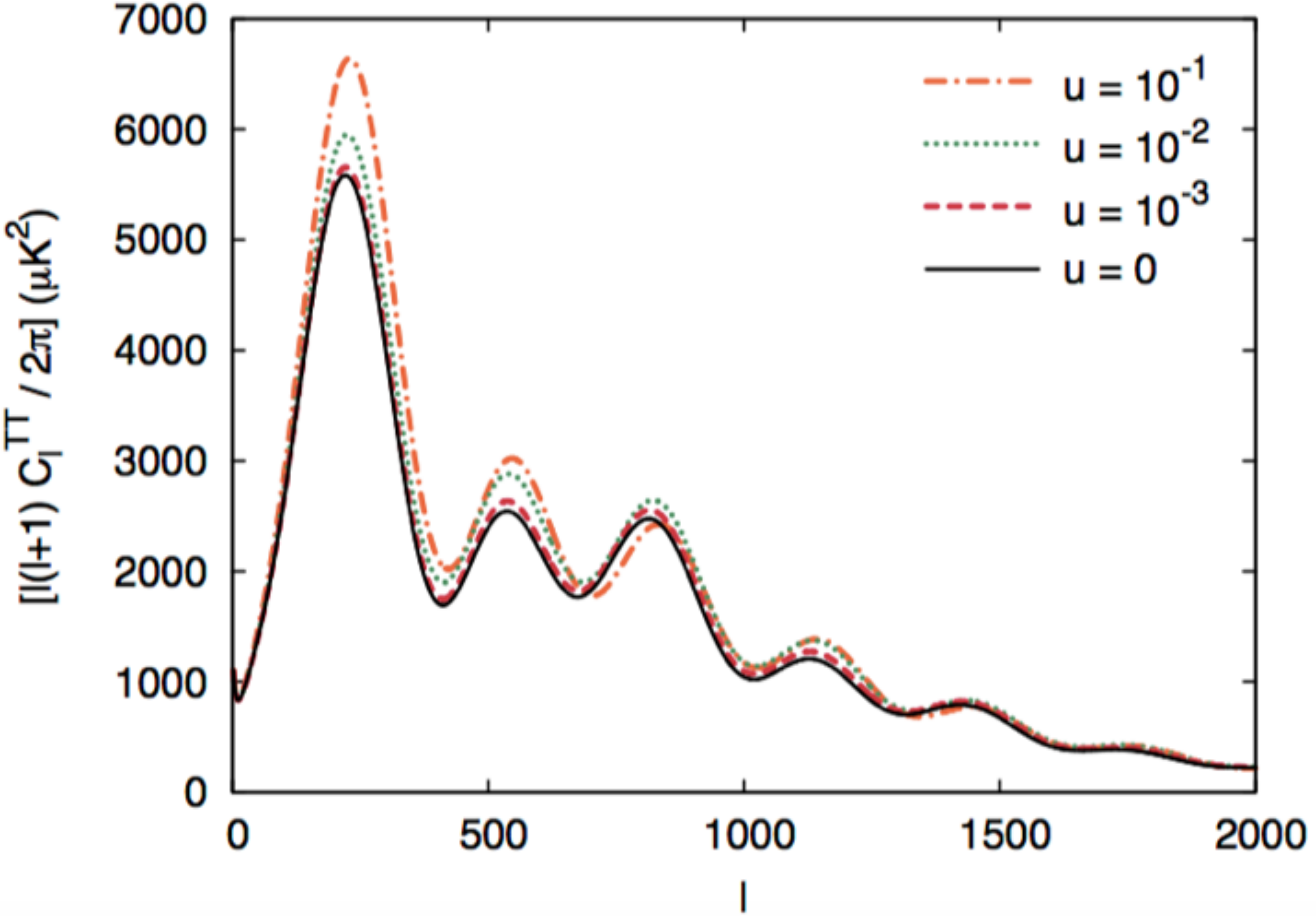


$$\sigma_{DM-\gamma} \lesssim 8\ 10^{-31} \left(\frac{m_{\rm DM}}{\rm GeV}\right)\ {\rm cm}^2$$

CMB can exclude large DM-photon interactions!
This limit is not competitive for heavy DM but it is reliable!

DM-neutrino interactions

R. Wilkinson, CB, J. Lesgourgues arXiv:1401.7597



$$\sigma_{\mathrm{DM}-\nu} \lesssim 3\ 10^{-28}\ \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)\ \mathrm{cm}^2$$

Impact of DM interactions

on cosmological parameters

Impact on cosmological parameters

DM-nu interactions arXiv:1401.7597

CMB alone

	$100\,\Omega_b h^2$	$\Omega_{DM} h^2$	$100\,h$	$10^{+9}\,A_s$	n_s	z_{reio}	N_{eff}	$10^{+2}\,u$	$10^{+13}\,u_0$
No interaction	$2.205^{+0.028}_{-0.028}$	$0.1199^{+0.0027}_{-0.0027}$	$67.3^{+1.2}_{-1.2}$	$2.196^{+0.051}_{-0.060}$	$0.9603^{+0.0073}_{-0.0073}$	$11.1^{+1.1}_{-1.1}$	(3.046)	–	–
	$2.238^{+0.041}_{-0.041}$	$0.1256^{+0.0055}_{-0.0055}$	$70.7^{+3.2}_{-3.2}$	$2.251^{+0.069}_{-0.085}$	$0.977^{+0.016}_{-0.016}$	$11.6^{+1.3}_{-1.3}$	$3.51^{+0.39}_{-0.39}$	–	–
$\sigma_{DM-\nu}$ constant	$2.225^{+0.029}_{-0.033}$	$0.1211^{+0.0027}_{-0.0030}$	$69.5^{+1.2}_{-1.2}$	$2.020^{+0.063}_{-0.065}$	$0.9330^{+0.0104}_{-0.0095}$	$10.8^{+1.1}_{-1.1}$	(3.046)	< 3.99	–
	$2.276^{+0.043}_{-0.048}$	$0.1299^{+0.0059}_{-0.0061}$	$75.0^{+3.4}_{-3.7}$	$2.086^{+0.068}_{-0.089}$	$0.956^{+0.017}_{-0.016}$	$11.6^{+1.2}_{-1.3}$	$3.75^{+0.40}_{-0.43}$	< 3.27	–
$\sigma_{DM-\nu} \propto T^2$	$2.197^{+0.028}_{-0.028}$	$0.1197^{+0.0027}_{-0.0027}$	$67.8^{+1.2}_{-1.2}$	$2.167^{+0.052}_{-0.059}$	$0.9527^{+0.0086}_{-0.0085}$	$10.8^{+1.1}_{-1.1}$	(3.046)	–	< 0.54
	$2.262^{+0.042}_{-0.046}$	$0.1326^{+0.0065}_{-0.0072}$	$75.3^{+3.6}_{-4.0}$	$2.257^{+0.072}_{-0.084}$	$0.981^{+0.017}_{-0.017}$	$11.9^{+1.3}_{-1.4}$	$4.07^{+0.46}_{-0.52}$	–	< 2.56

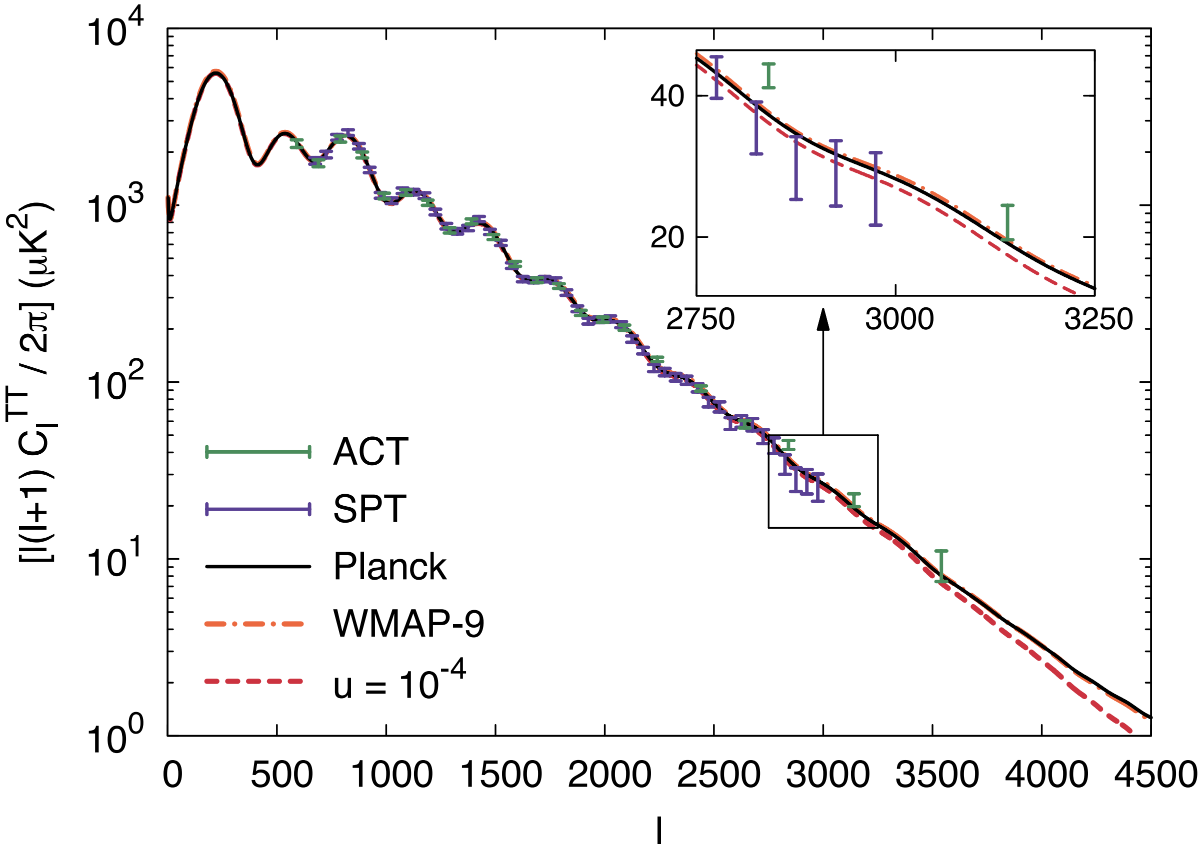
Planck

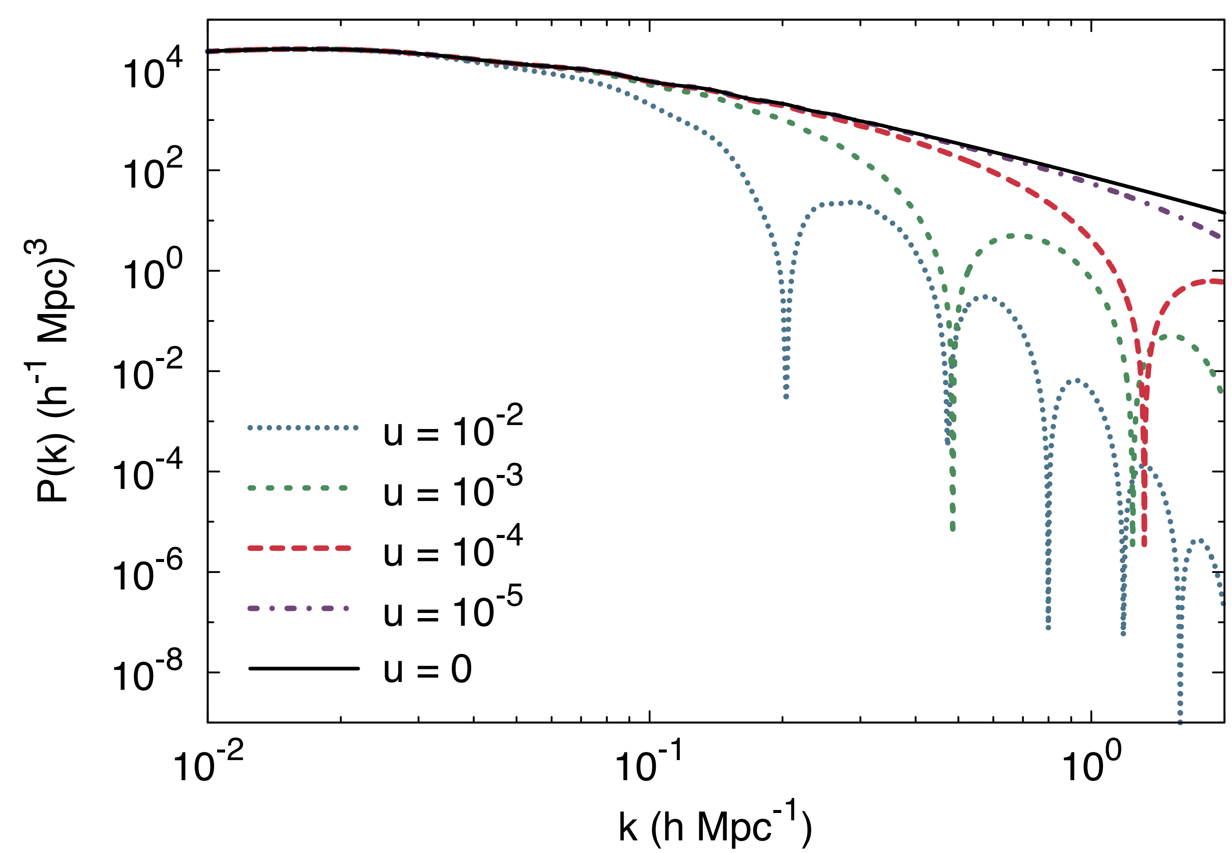
H0 changes because of the additional source of damping!

Could reconcile cepheids and CMB measurements!

Structure formation

The P(k) is different from LCDM
(whatever the interactions)!





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

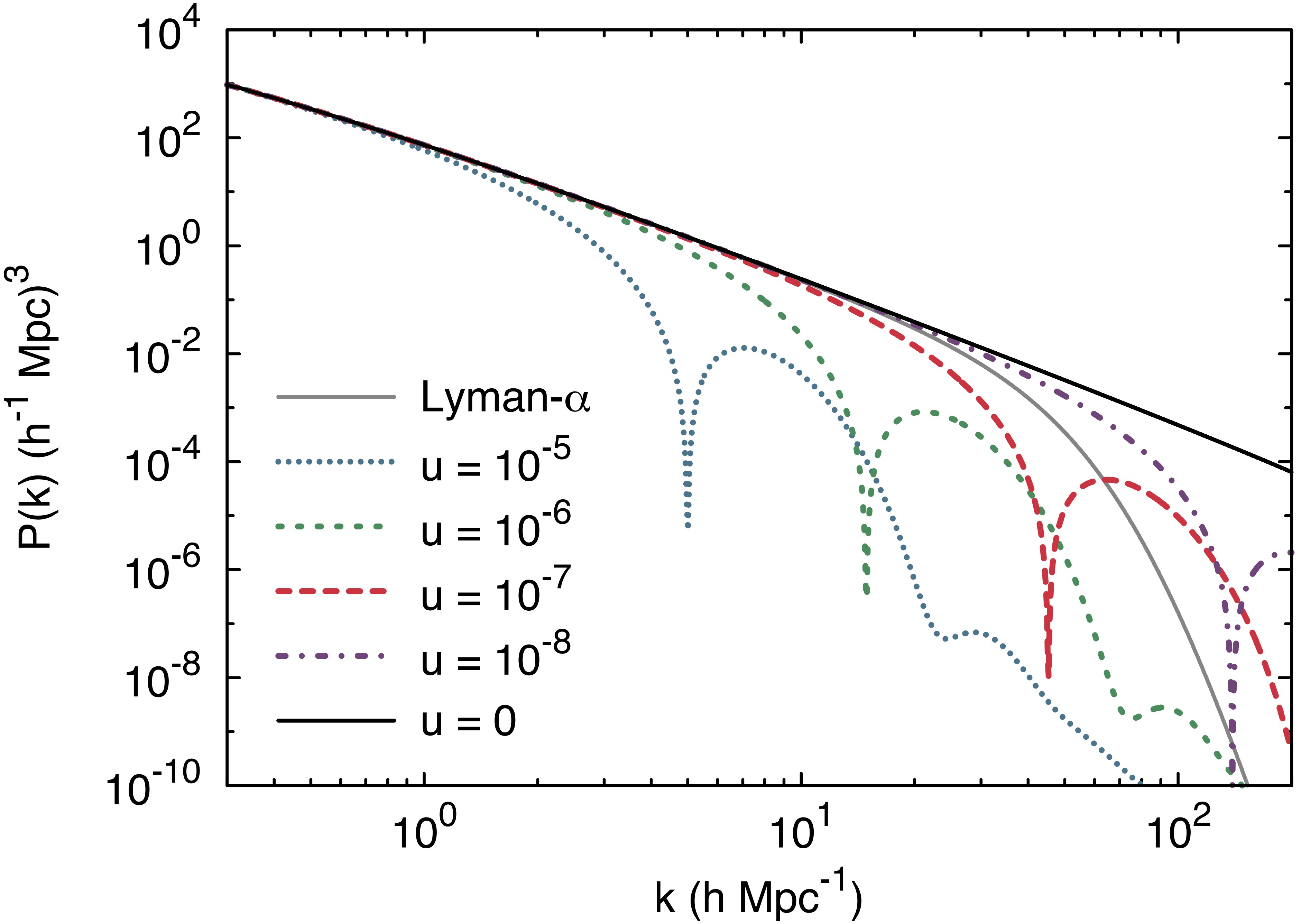
(CB, Riazuelo, S. Hansen, R. Schaeffer : astro-ph/0112522)

R. Wilkinson, J. Lesgourgues, C. Boehm: arXiv:1309.7588

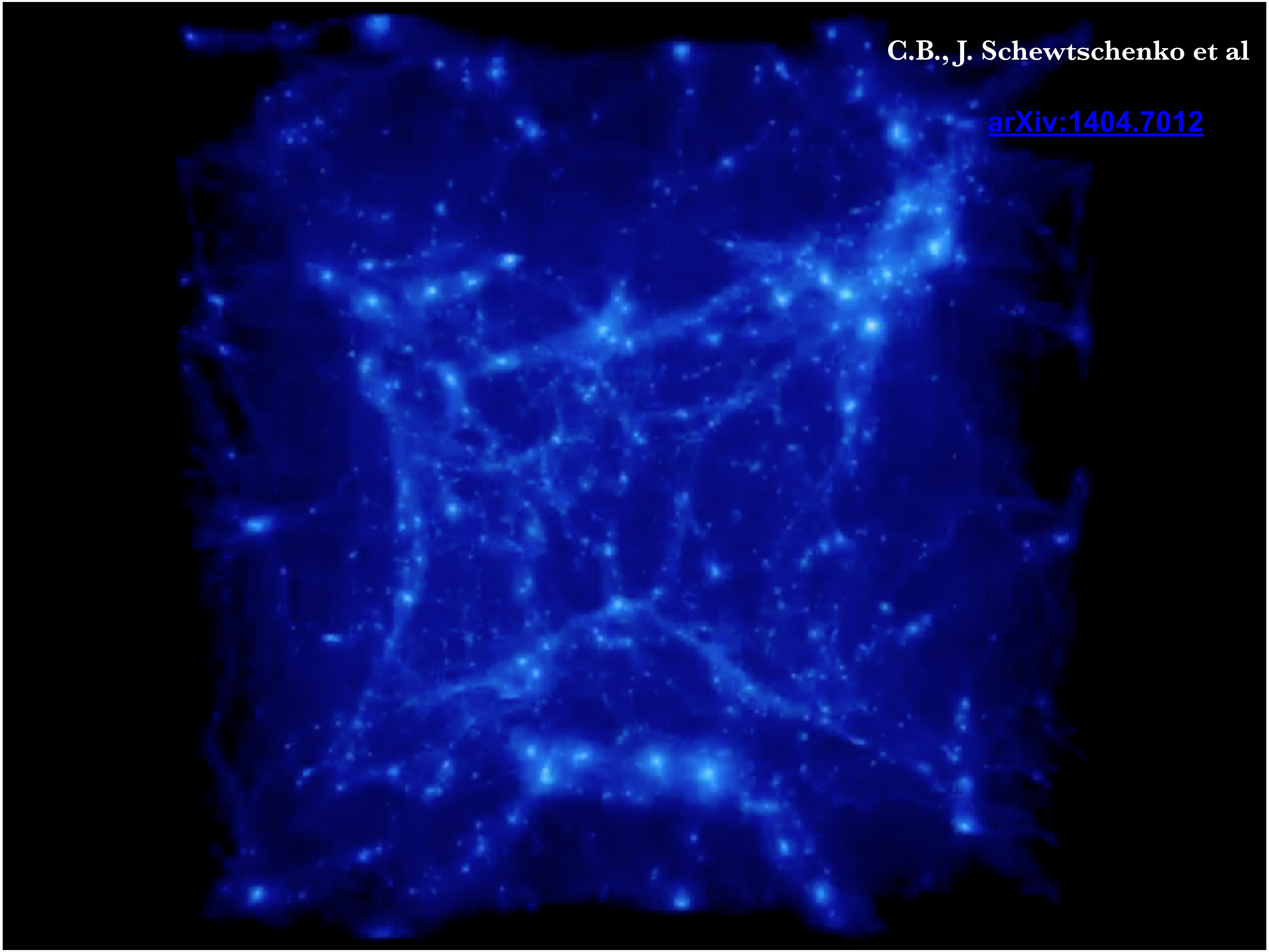
Dark Oscillations

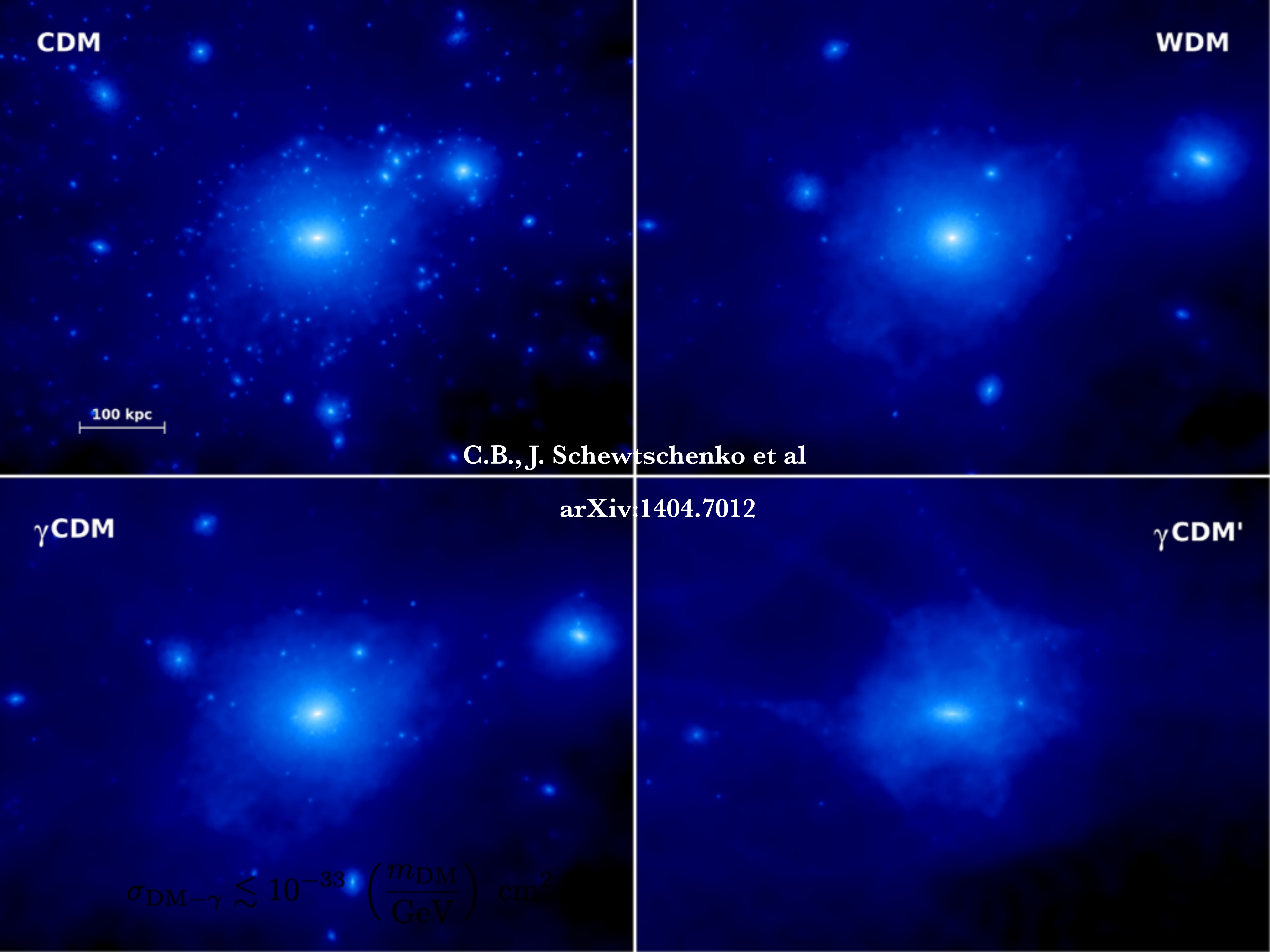
Structure formation is sensitive to DM interactions!

DM-neutrino interactions in the Early Universe



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

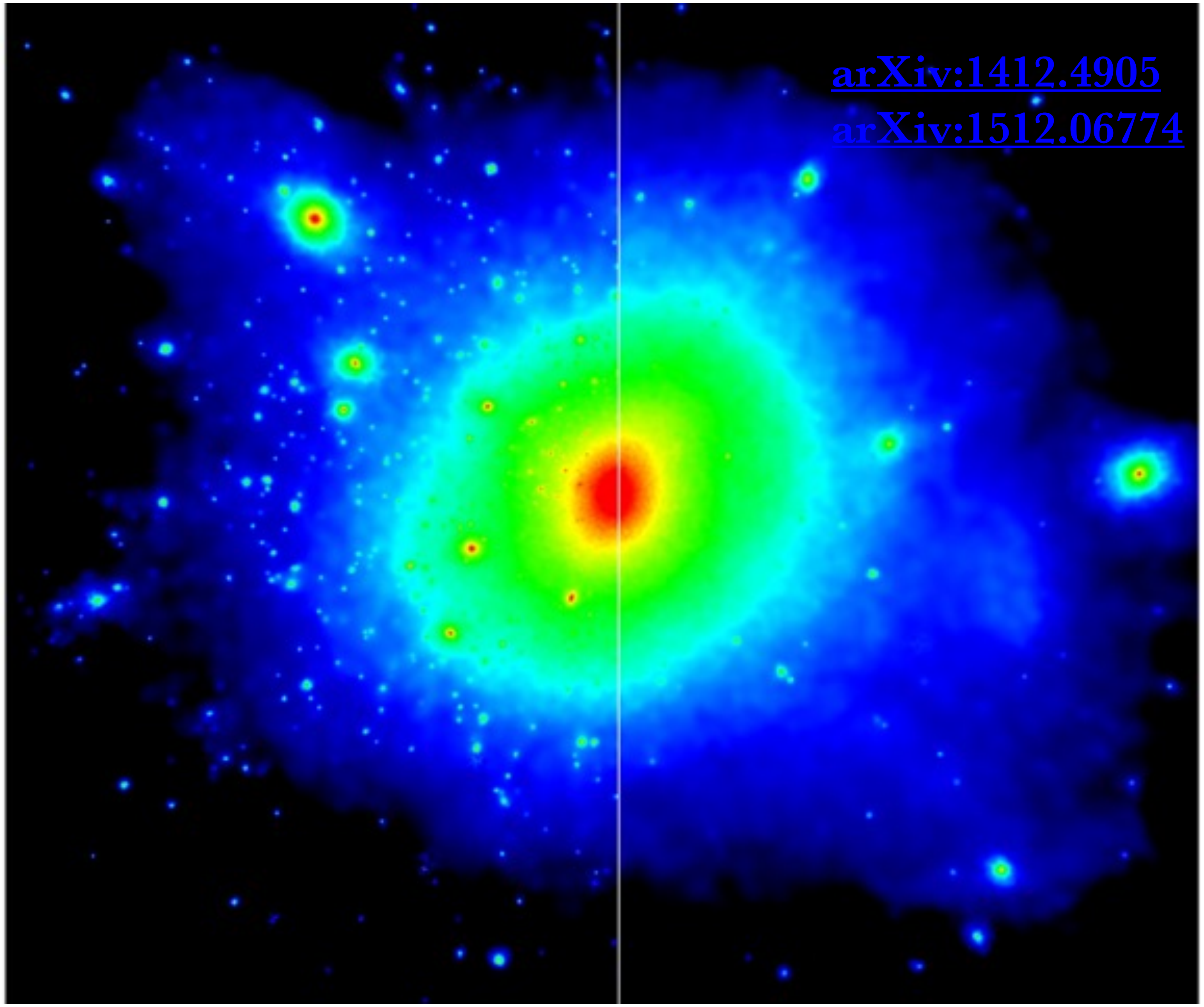




C.B., J. Schewtschenko et al

arXiv:1404.7012

$$\sigma_{\mathrm{DM}-\gamma} \lesssim 10^{-33} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right) \mathrm{cm}^2$$



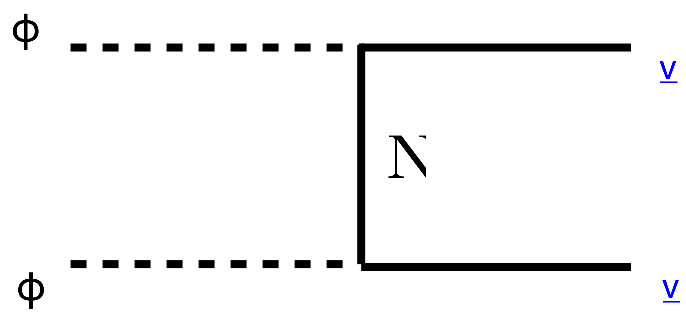
$$\sigma_{\mathrm{DM}-\gamma} \lesssim 10^{-33} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right) \mathrm{cm}^2$$ (same with neutrinos)

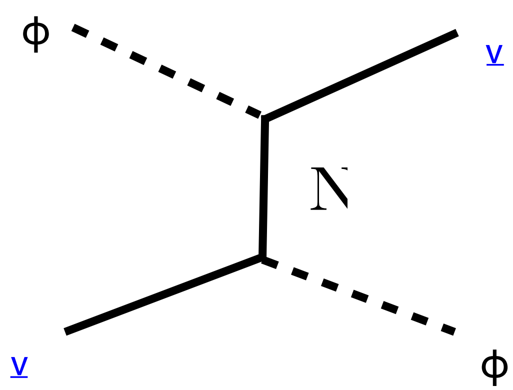
(factor 100 better than CMB)

Structure formation severely constrains such primordial DM interactions!

	$100\,\Omega_b h^2$	$\Omega_{\mathrm{DM}} h^2$	$100\,h$	$10^{+9} A_s$	n_s	z_{reio}	N_{eff}
Lyman-α limit	$2.246^{+0.039}_{-0.042}$	$0.1253^{+0.0053}_{-0.0056}$	$71.5^{+3.0}_{-3.3}$	$2.254^{+0.069}_{-0.082}$	$0.979^{+0.016}_{-0.016}$	$11.7^{+1.2}_{-1.3}$	$3.52^{+0.36}_{-0.40}$

DM-neutrino interactions





hep-ph/0305261

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

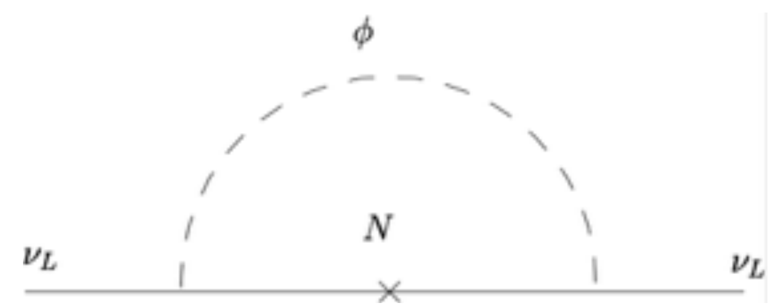
N

Effective theory

(N singlet of SU(2) for example)

hep-ph/0612228

arxiv:1512.08796



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

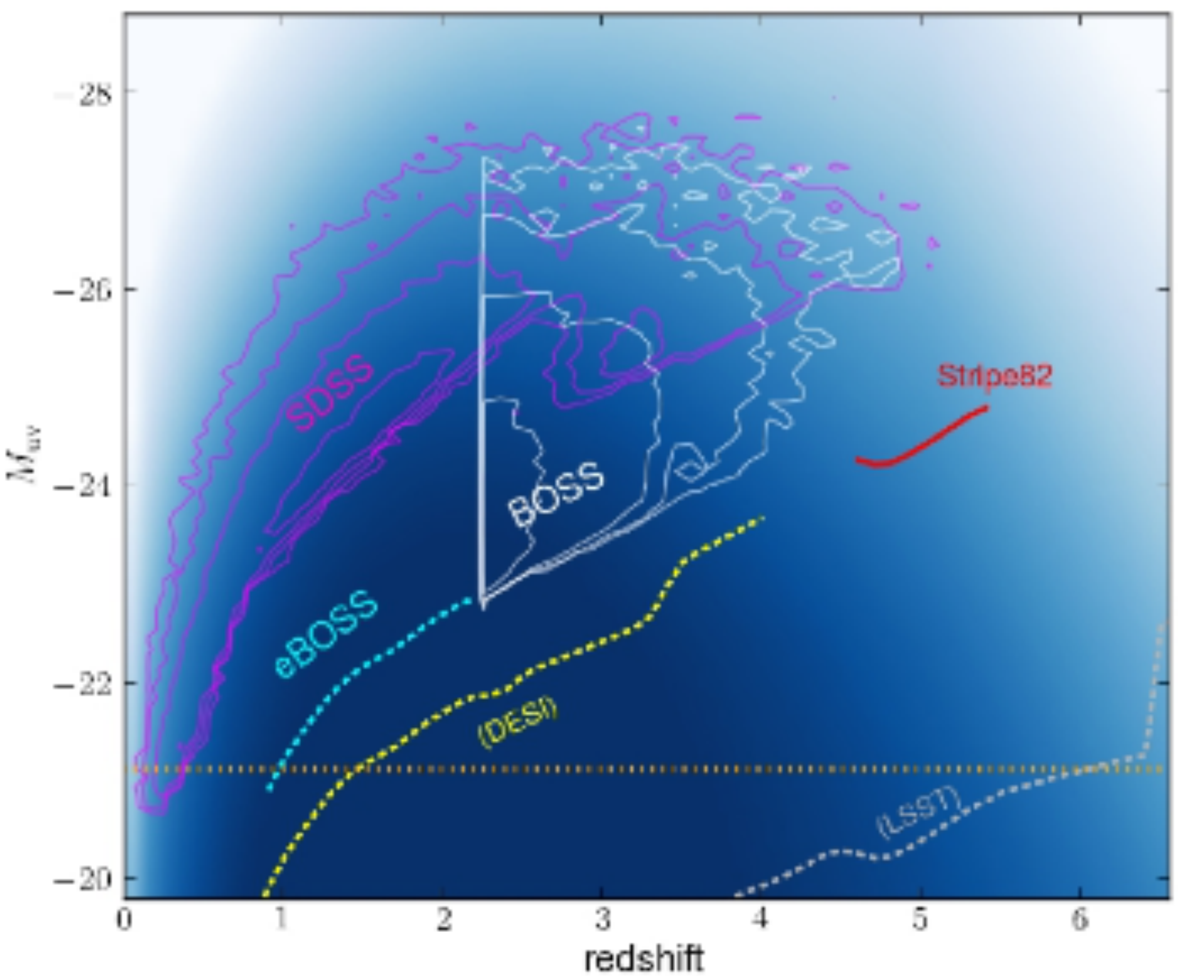
$0.01\ \mathrm{eV} < m_\nu < 1\ \mathrm{eV}$

With MeV DM (mN=mDM)

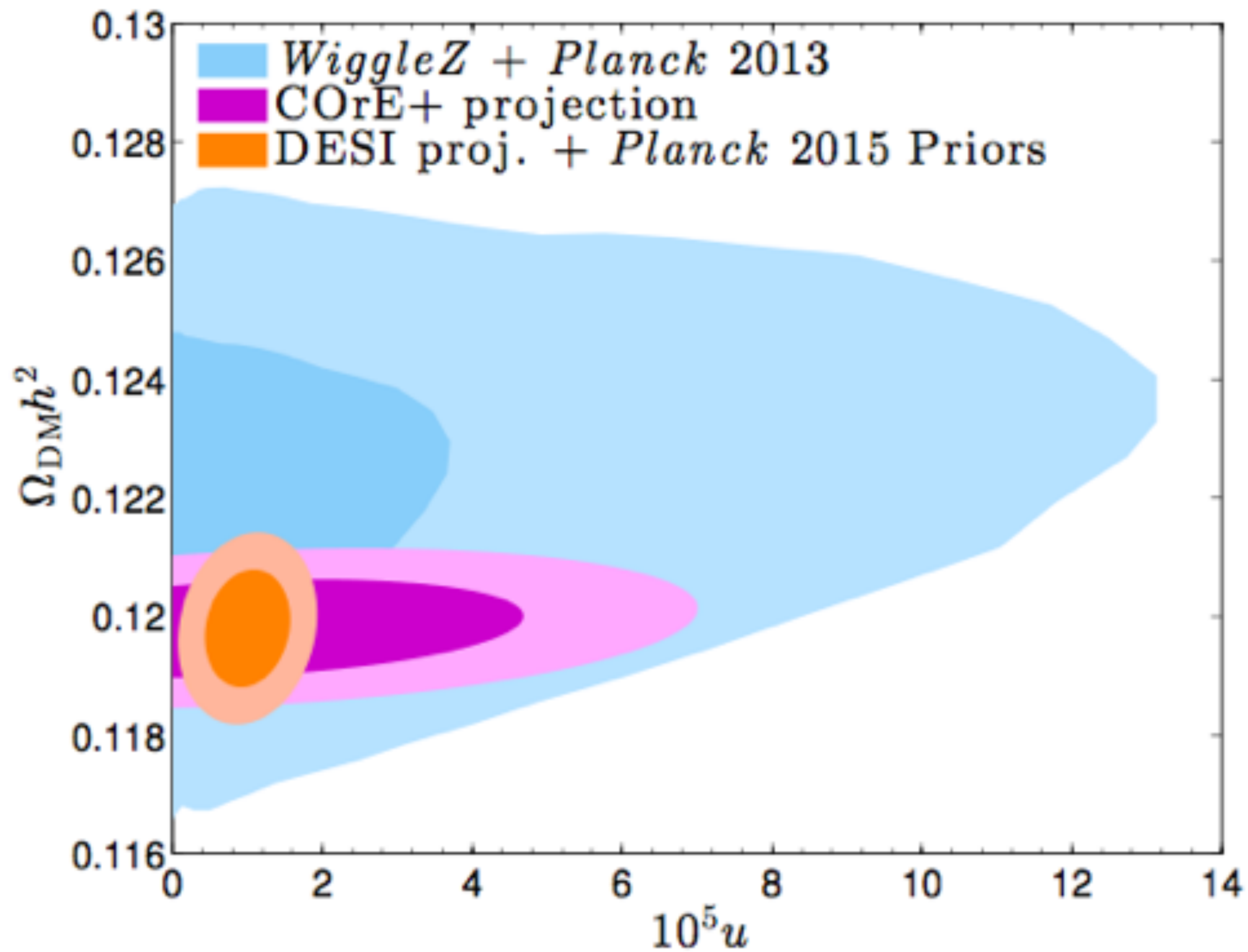
The future for data-driven analysis

DESI and LSST will set strong bounds (stronger than CMB)

arXiv:1505.06735



Courtesy JP Kneib



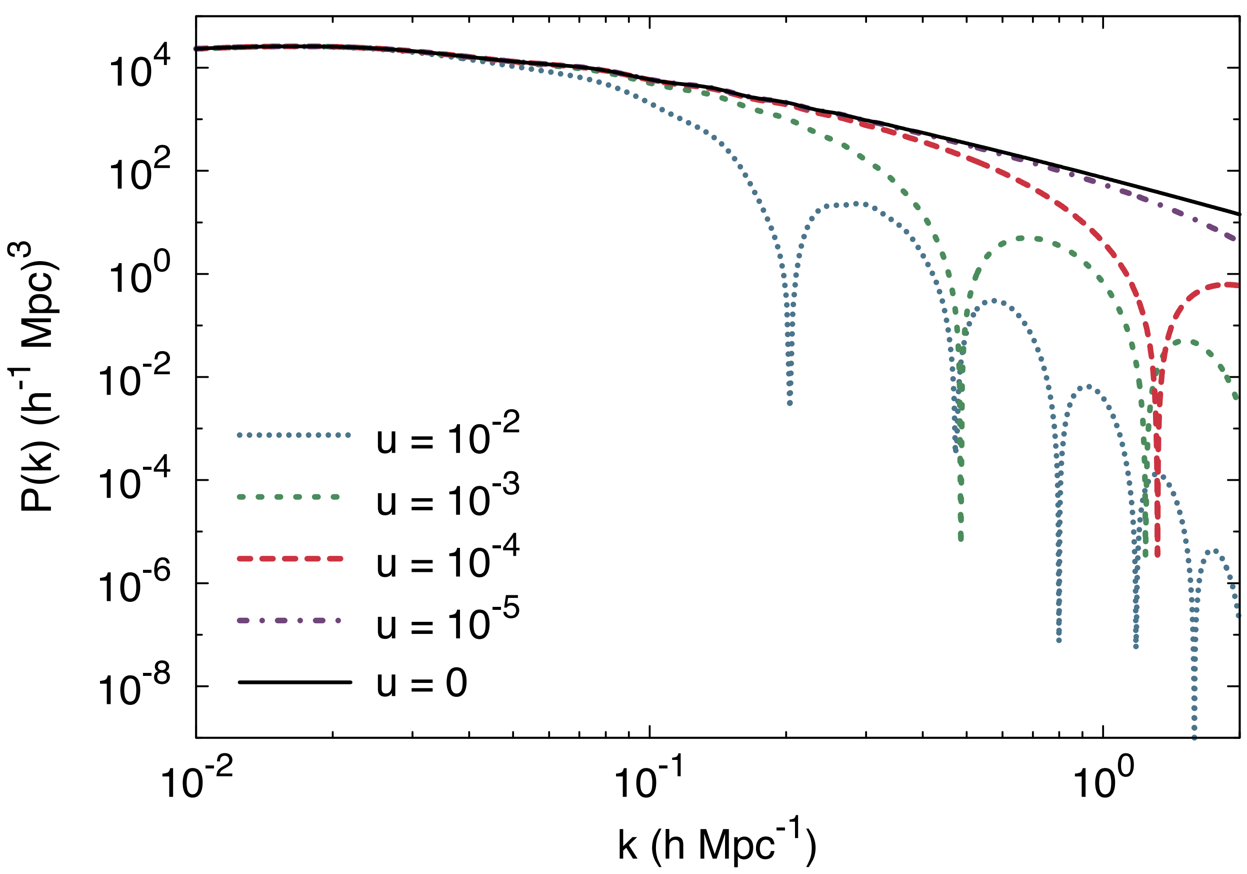
With DESI we gain a factor 10 for the DM-photon interactions

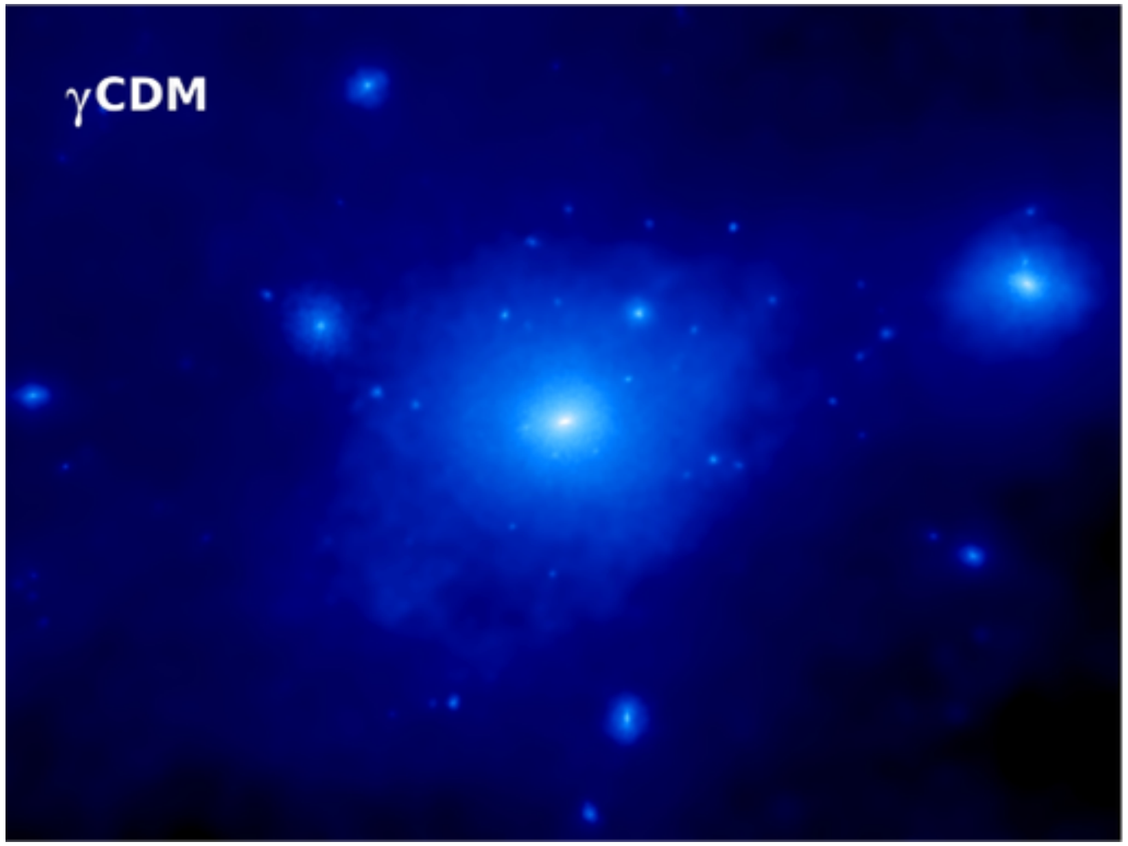
What will LSST bring?

DM indirect detection searches

arXiv:1602.07282

Extragalactic gamma-ray signal: damping + annihilations





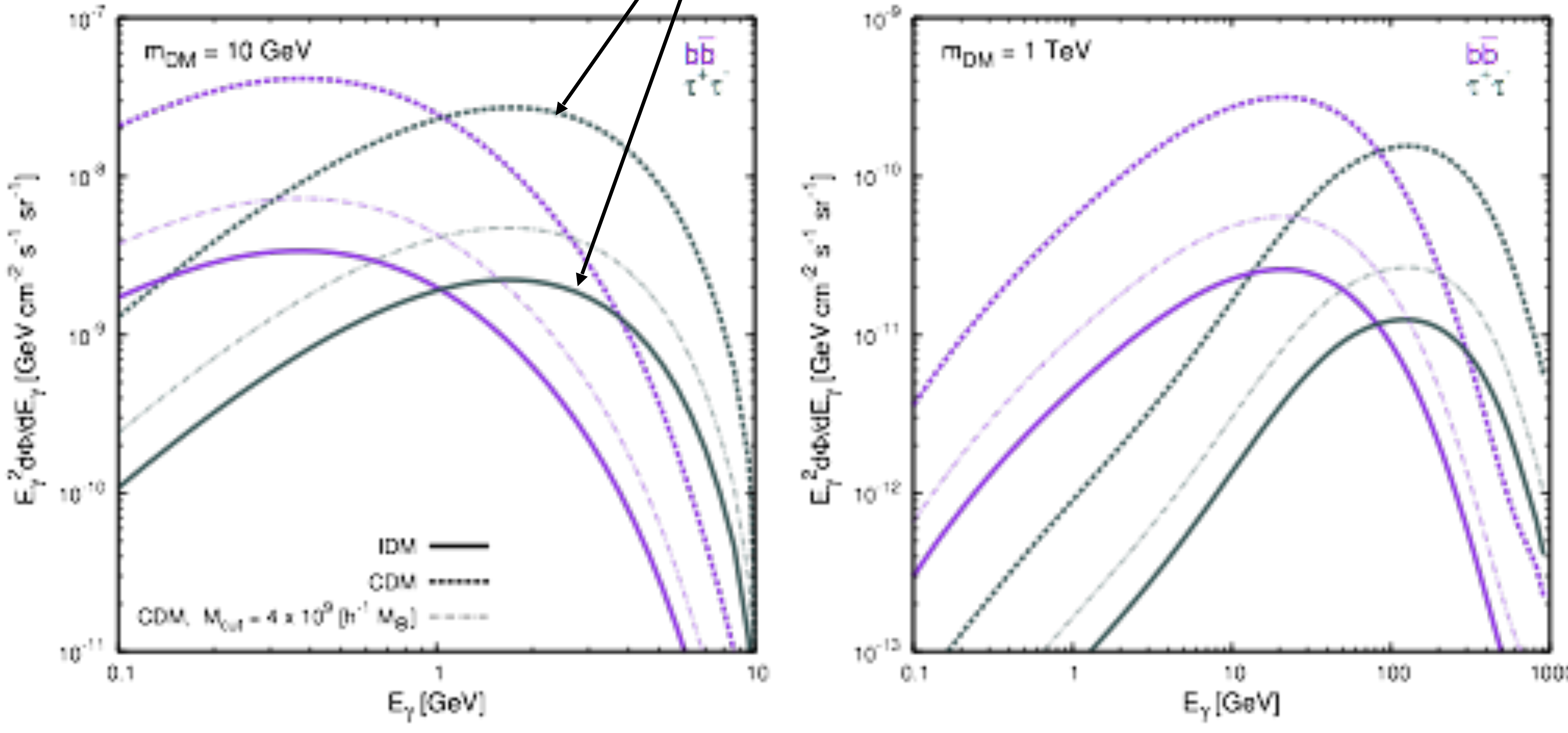
Issues about extrapolations of P(k) at small scales

DM indirect detection searches

arXiv:1602.07282

Extragalactic gamma-ray signal: damping + annihilations

wo/with damping



Same signal as in LCDM but suppressed
so one could mistaken the damping effect with a smaller annihilation cross section

Conclusion

Cosmology can probe the DM microphysics

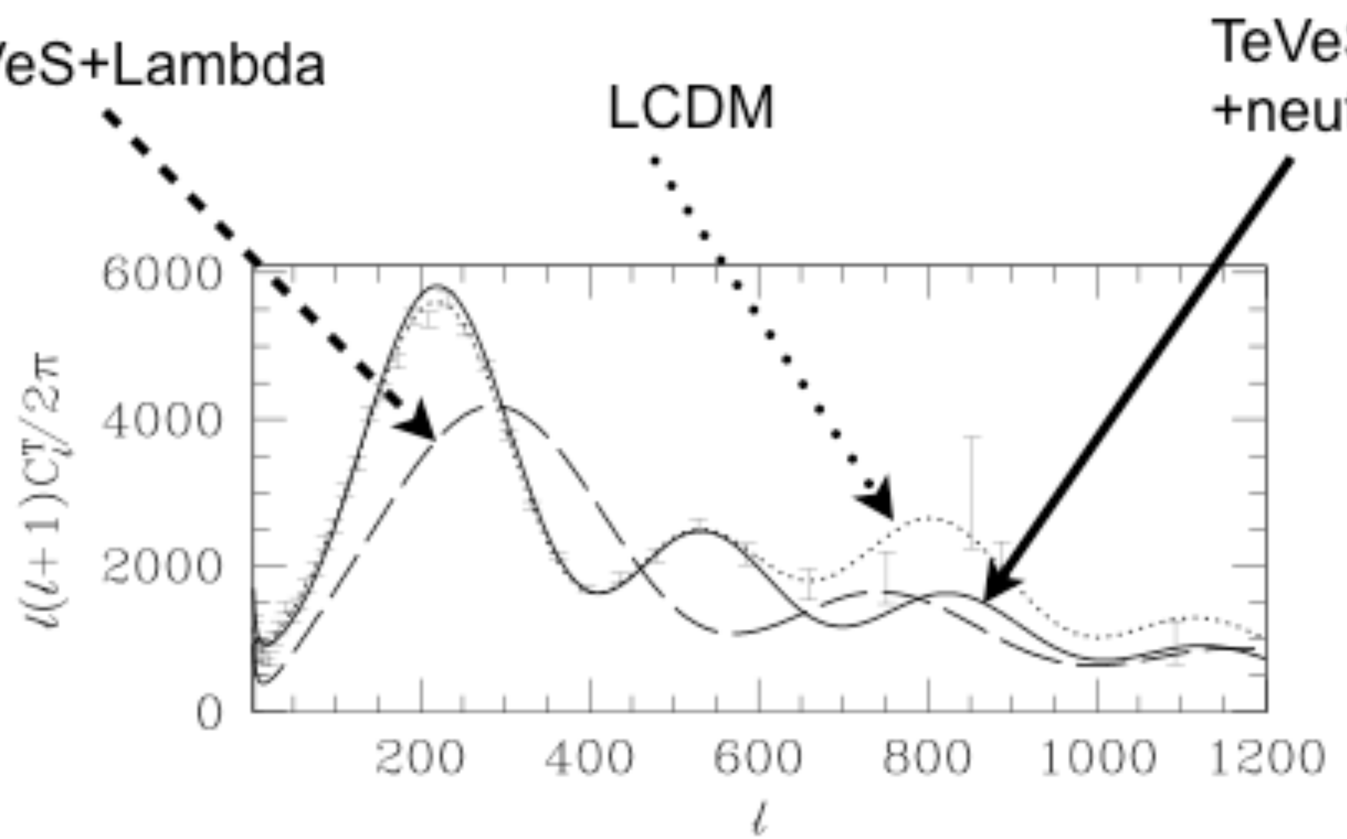
- CMB observations alone constrain primordial DM interactions
- CMB observations do not exclude DM interactions though
- N-body simulations of LSS beat CMB constraints but they are more uncertain
- If "H_0 discrepancies" persists, it may be that DM has interactions

DM without DM particles

Mond/Bekenstein

Bekenstein astro-ph/0403694

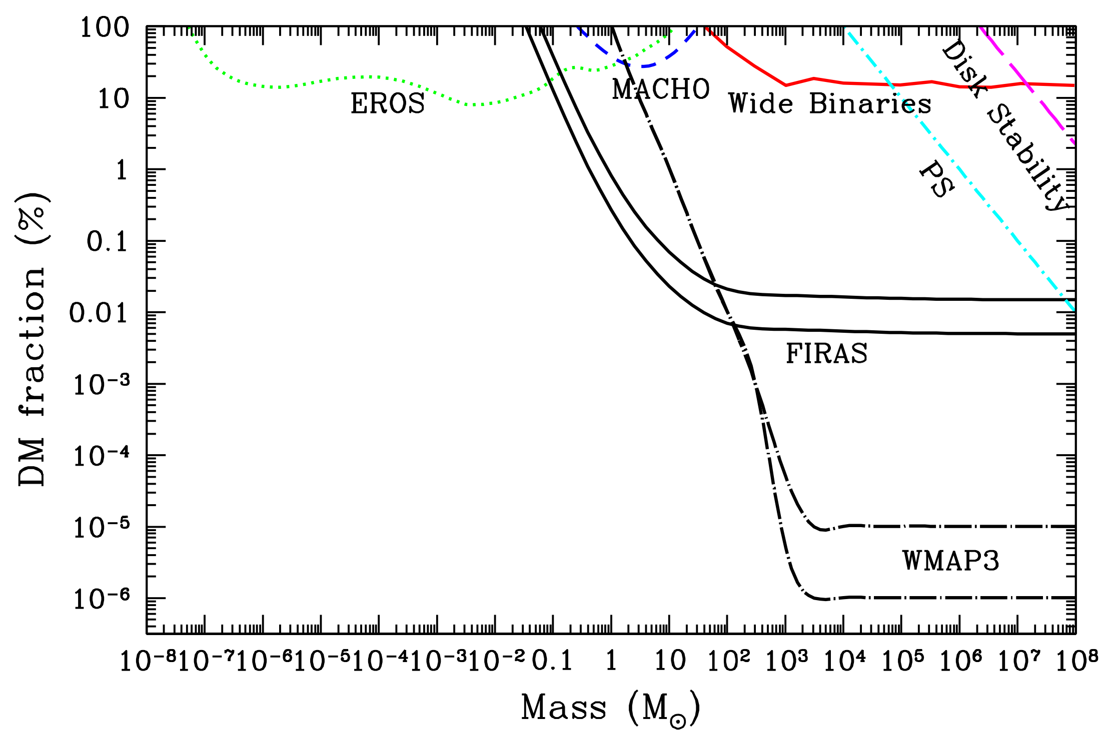
C. Skordis, D. Mota, P. Ferreira, C.Boehm : astro-ph/0505519



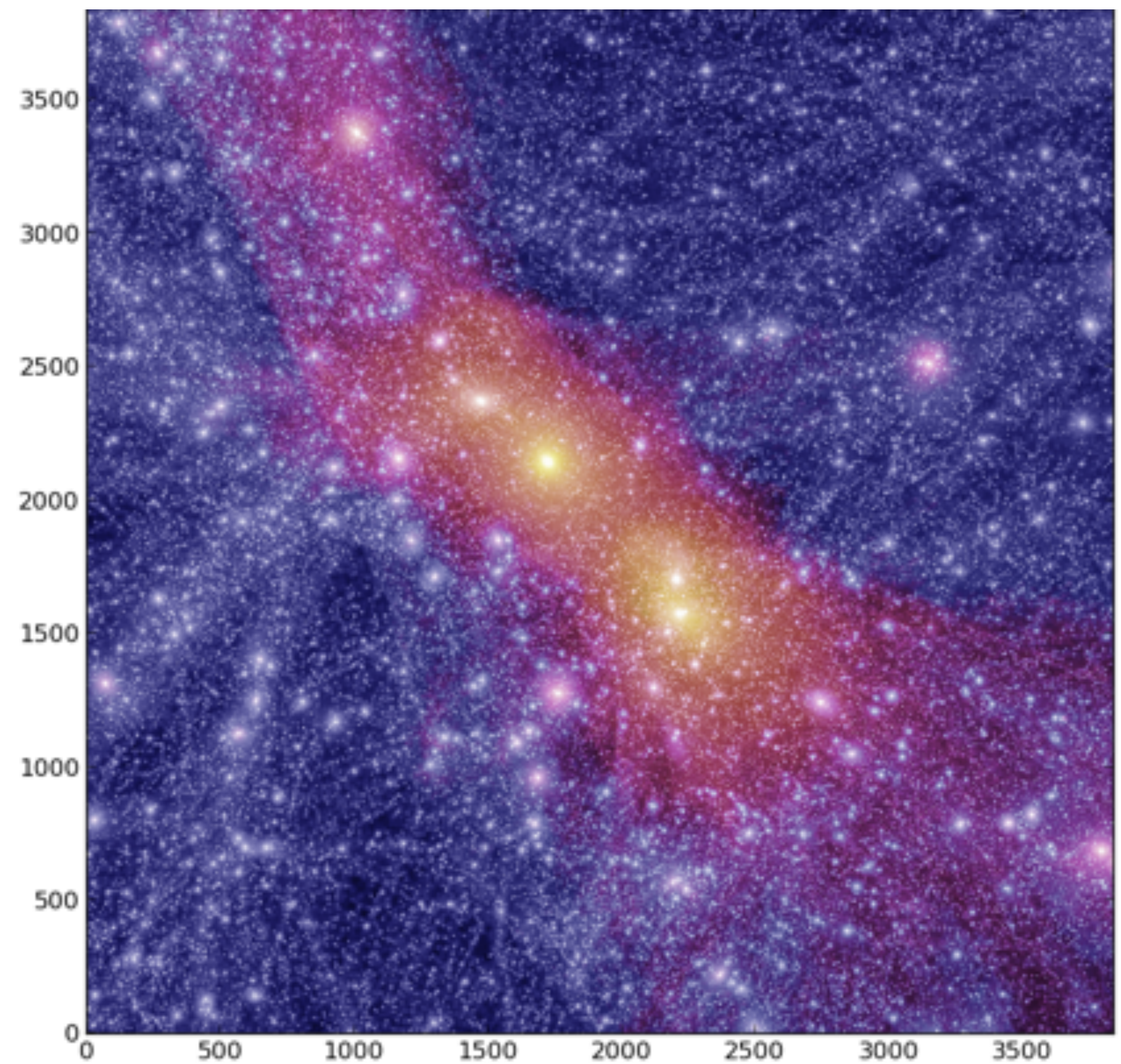
Impossible to explain Planck 2015!

Black Holes

0709.0524v1

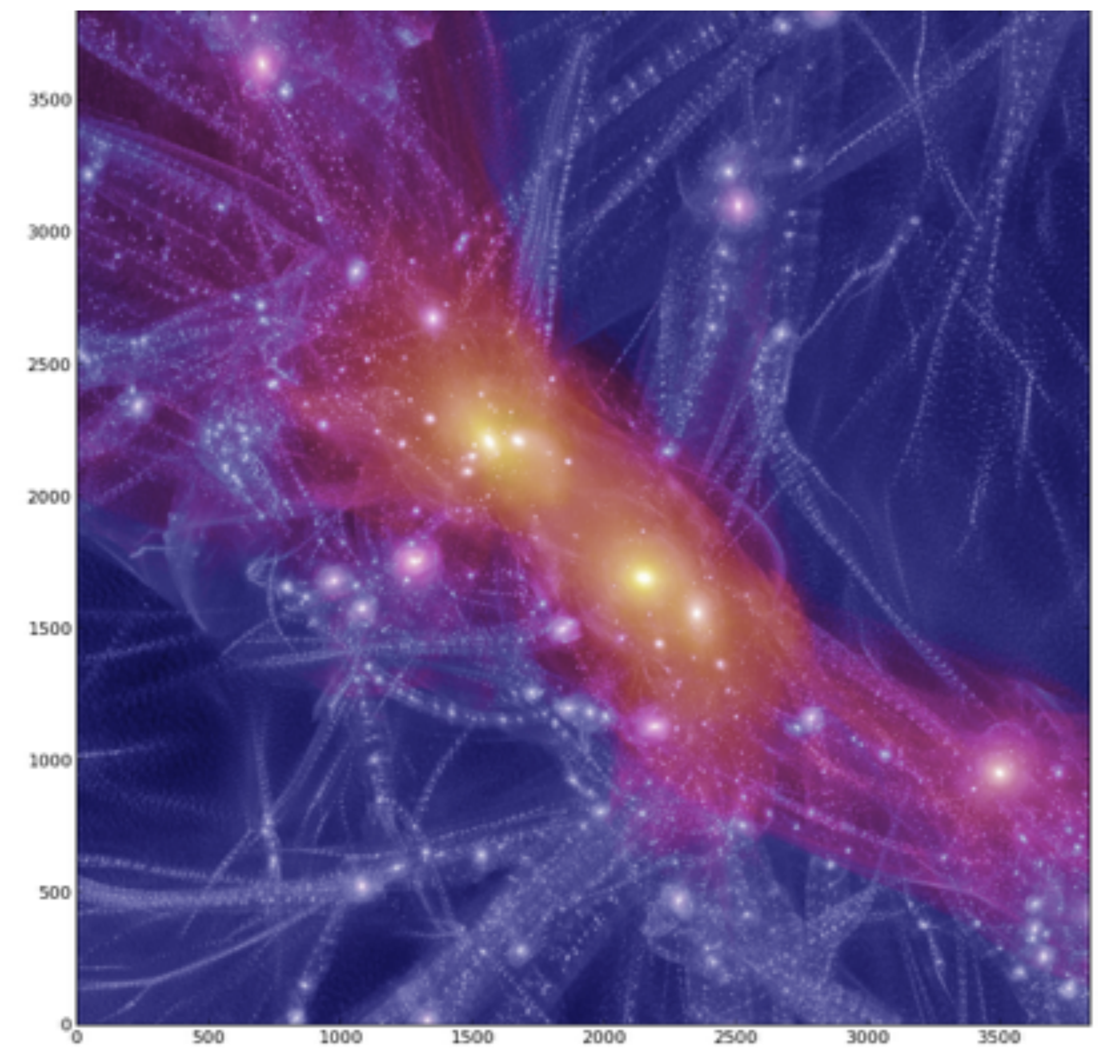


a fraction of PBH is possible but one still needs a collisionless fluid.



LSS in the Universe are modified too!

arXiv:1404.7012

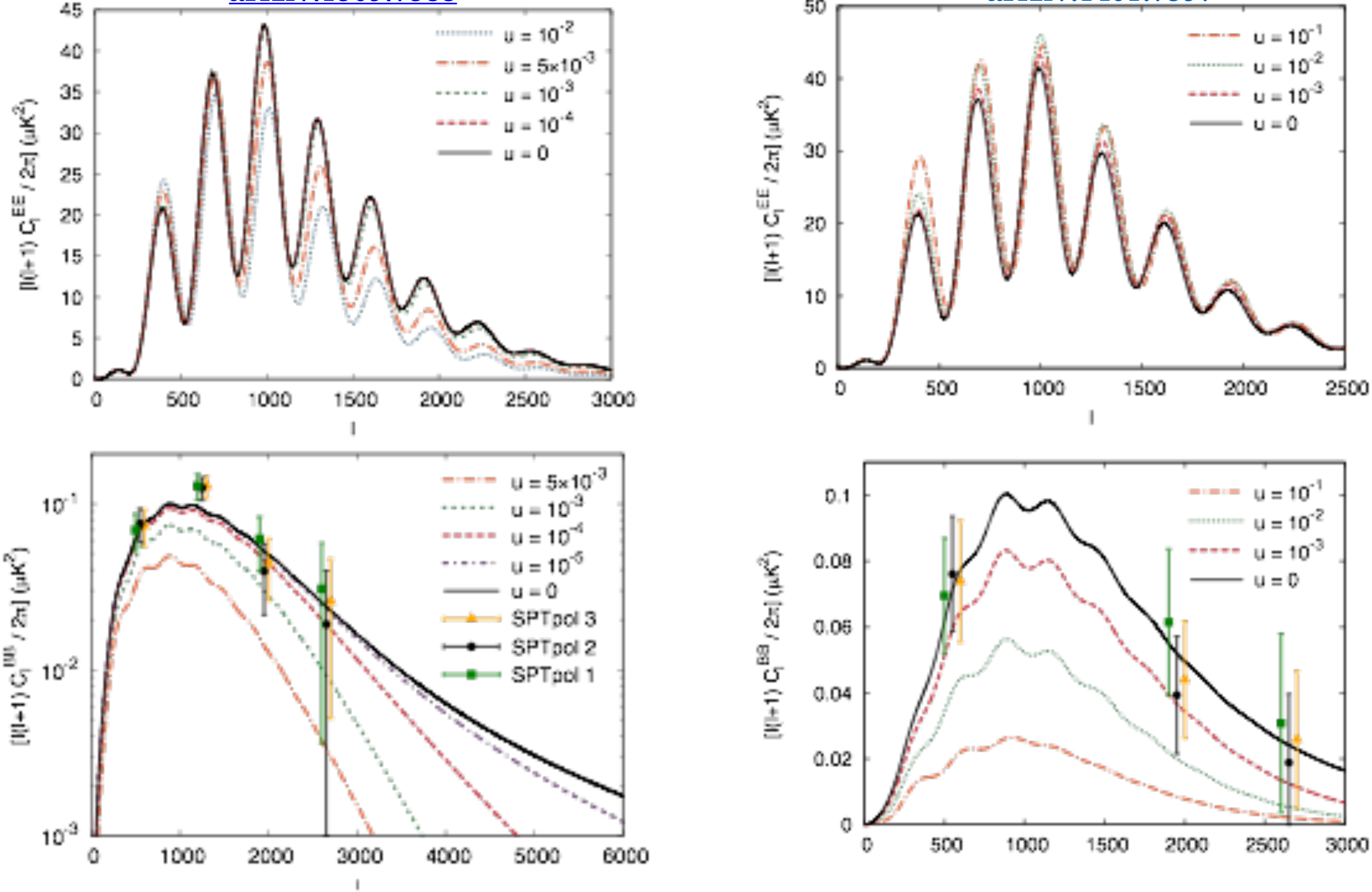


lengths 100/h Mpc and 300/h Mpc
10243 particles

EE & BB spectra

arXiv:1309.7588

arXiv:1401.7597



Photons

Neutrinos

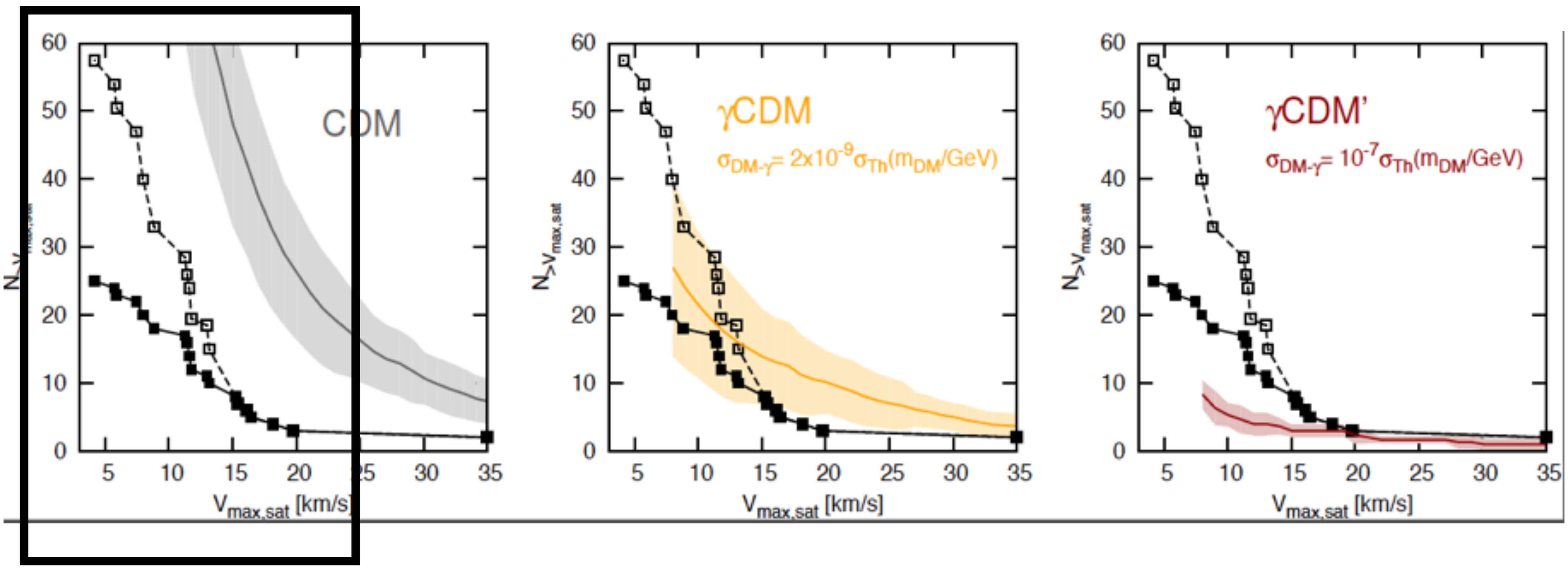
Numbers of MW satellite galaxies

arXiv:1404.7012

CDM prediction is well above observation

Interacting DM agrees with observation

Too many interactions



small satellites

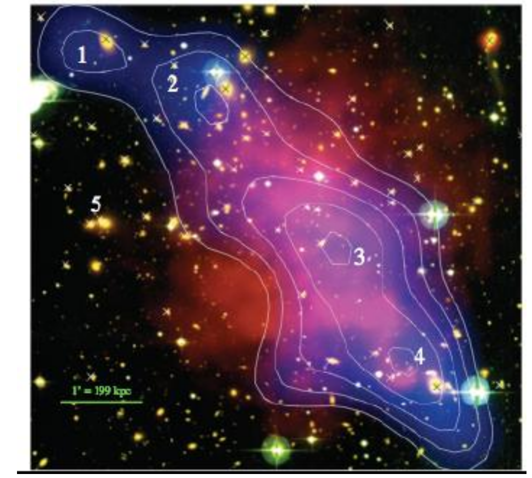
Solve the MW satellite problem!

Sterilise the MW!

$$\sigma \simeq 10^{-33} \left(\frac{m_{DM}}{\mathrm{GeV}}\right) \mathrm{cm}^2 \qquad \sigma \simeq 10^{-31} \left(\frac{m_{DM}}{\mathrm{GeV}}\right) \mathrm{cm}^2$$

self - interacting DM

Galaxies are correlated with DM

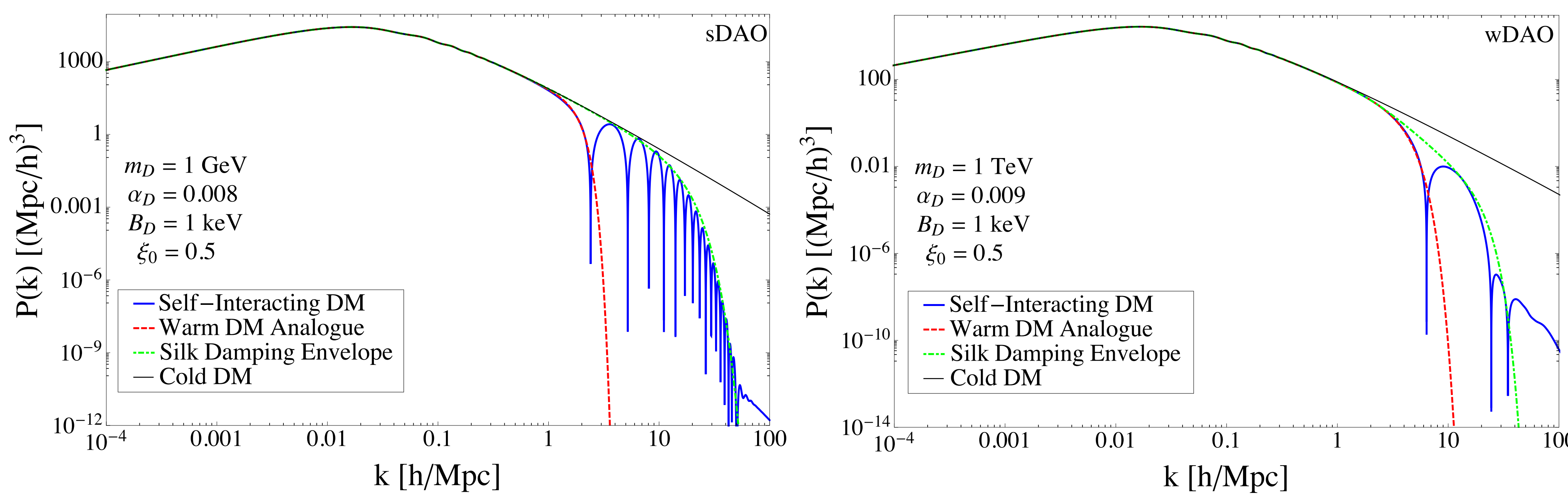


Cosmic wreck train

Galaxies are not correlated with DM

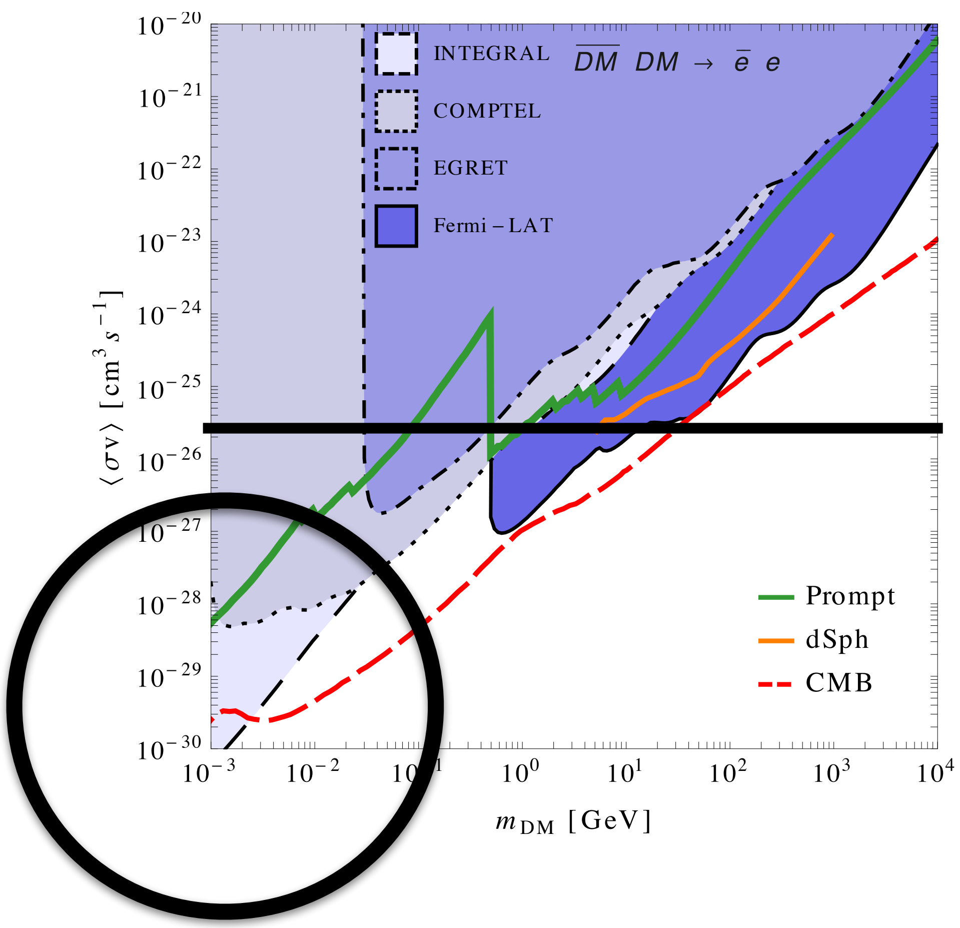
$$l_{id}^2 = \frac{2\pi^2}{3}\int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\not\rho a^2 \Gamma_i}\left(1+\Theta_i\right)\frac{dt}{t}$$

Thomson-like cross section: dark Coulomb or similar needed!



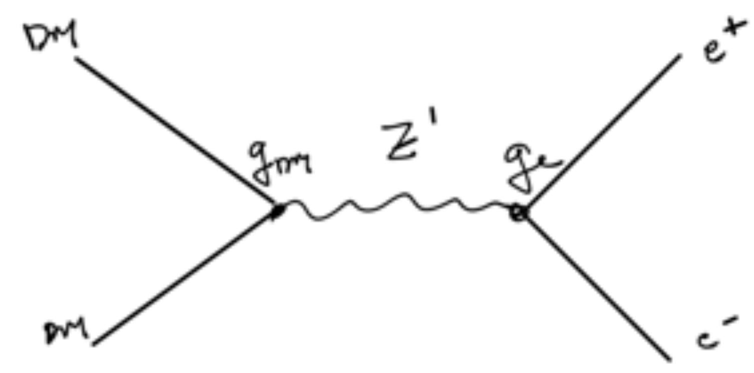
1405.2075

Light DM?



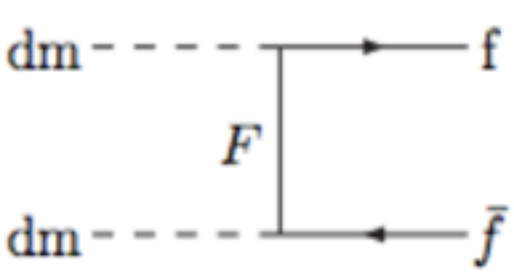
astro-ph/0208458

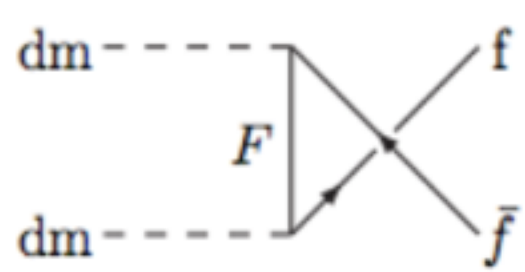
p-wave annihilations still allowed



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

hep-ph/0305261





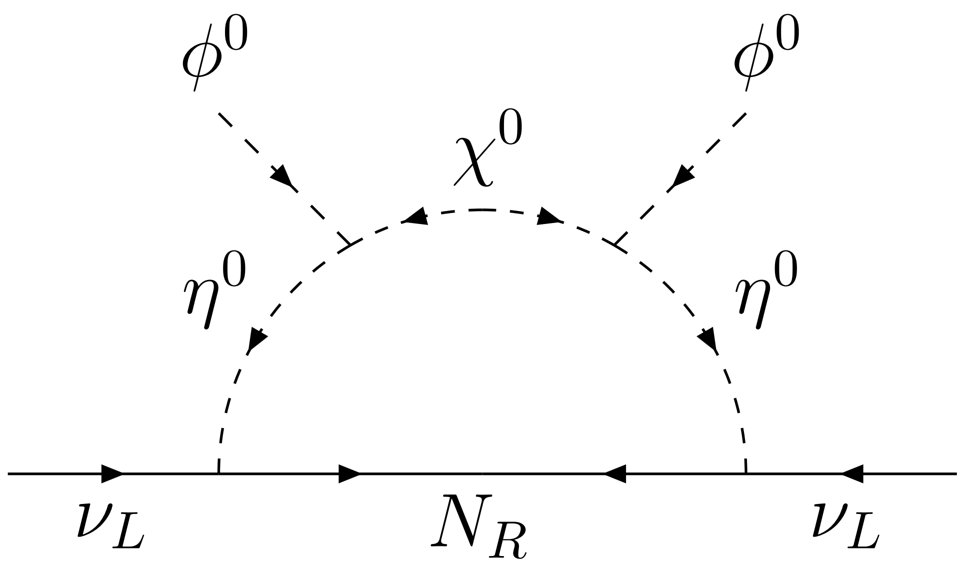
$$\sigma v \propto \frac{1}{m_F^4}\ \left(\left(C_l^2 + C_r^2\right)\ m_f + 2 C_l\ C_r\ m_F\right)^2$$

keV-MeV is possible depending on mediator
but indirect detection constraints are important

arxiv:1512.08796

Abdesslam Arhrib

Ernest Ma[3] and Tzu-Chiang Yuan



1 scalar doublet (η^+, η^0) + mixing between chi, eta!

3 singlet Majorana fermions (N)

As is well known $h \to \gamma\gamma$ is fully dominated by $W^\pm$ loop with some subleading contribution from top quark loop which interferes destructively with the $W^\pm$ loop. As alluded earlier, $h \to \gamma\gamma$ receives additional contribution from charged Higgs $\eta^\pm$ in this model [46].