Dark Matter interactions vs LSS data & cosmology

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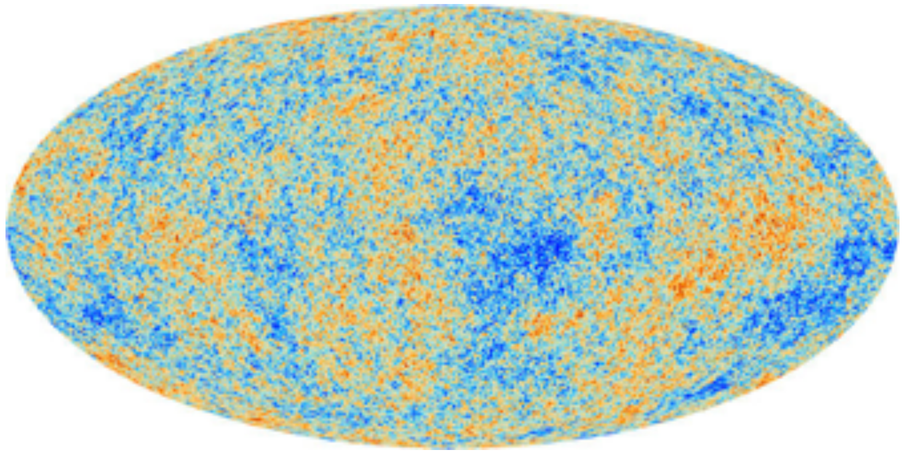
credit arXiv:1404.7012

IPPP, Durham

LAPTH, Annecy

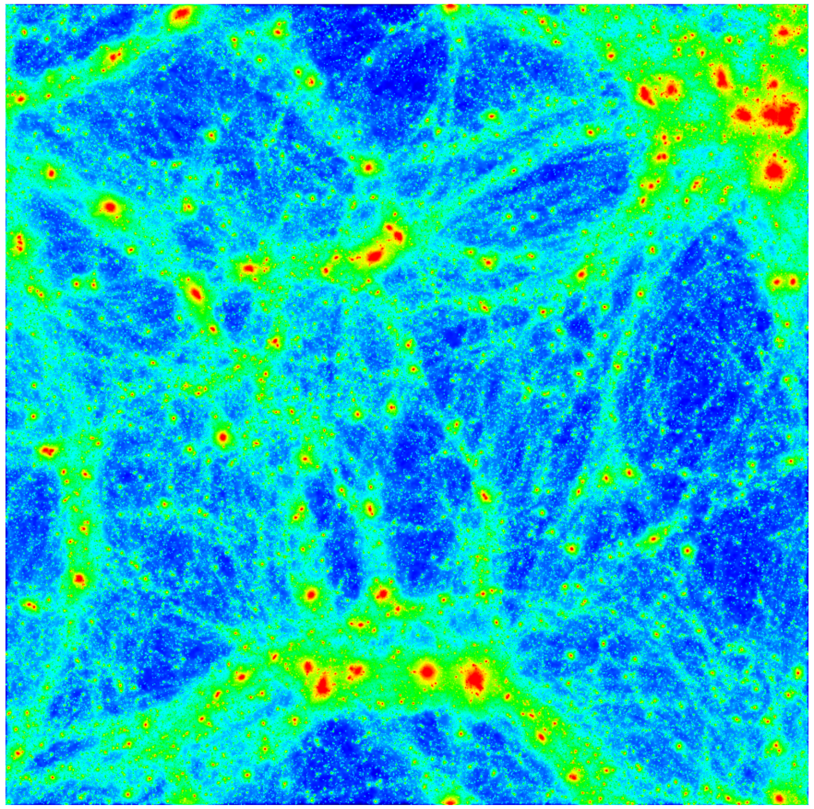
Heidelberg, 06 July 2015

Modern Cosmology has unraveled the distribution of matter in the past universe



Z~1100

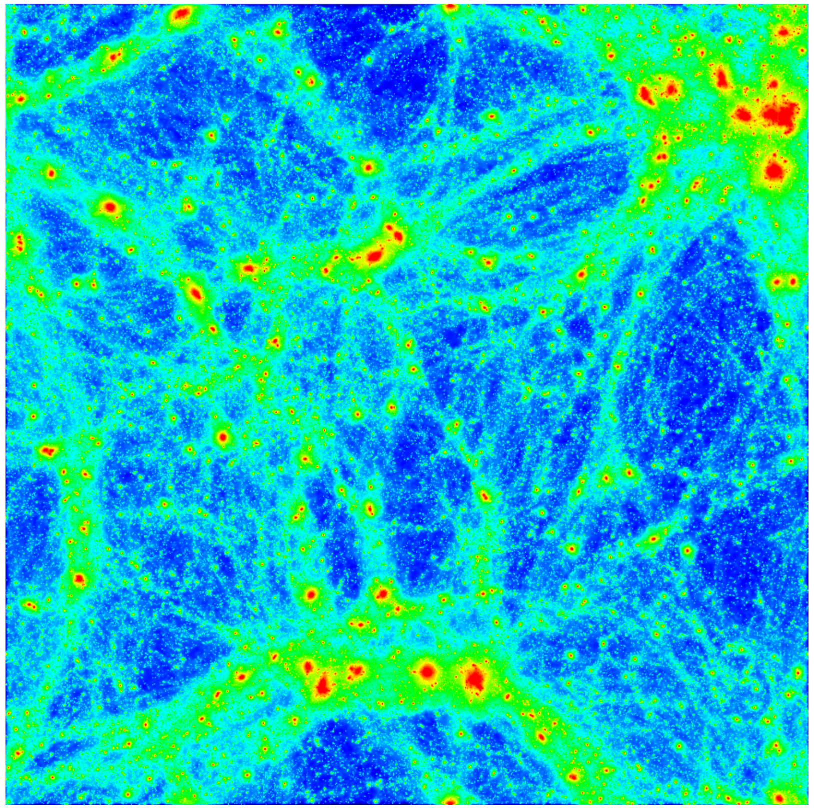
$z \langle 0.2$



Measurement of the matter distribution at large scale

consistent with the notion of primordial fluctuations

Modern Cosmology has unraveled a new type of matter



There is more matter than what we see (Dark Matter)

new matter = invisible so weakly interacting particles(?)
massive enough particles to cluster

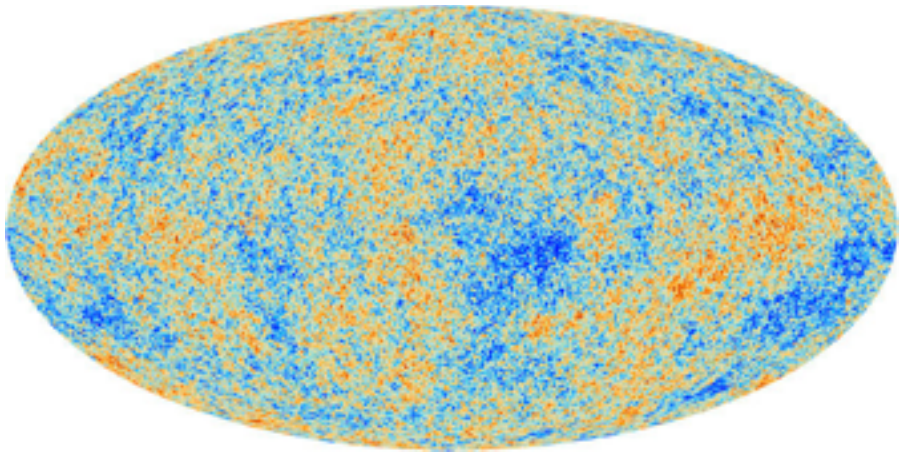
(Cold DM = CDM)

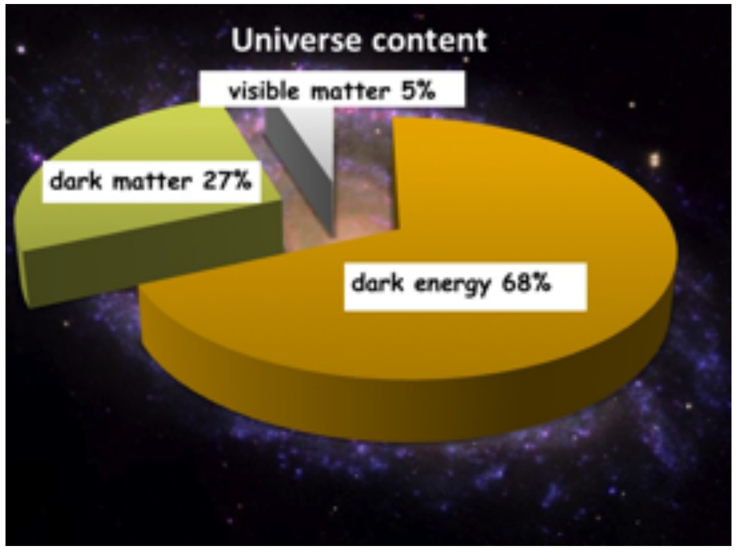
How weak is weak?

Lessons from CMB

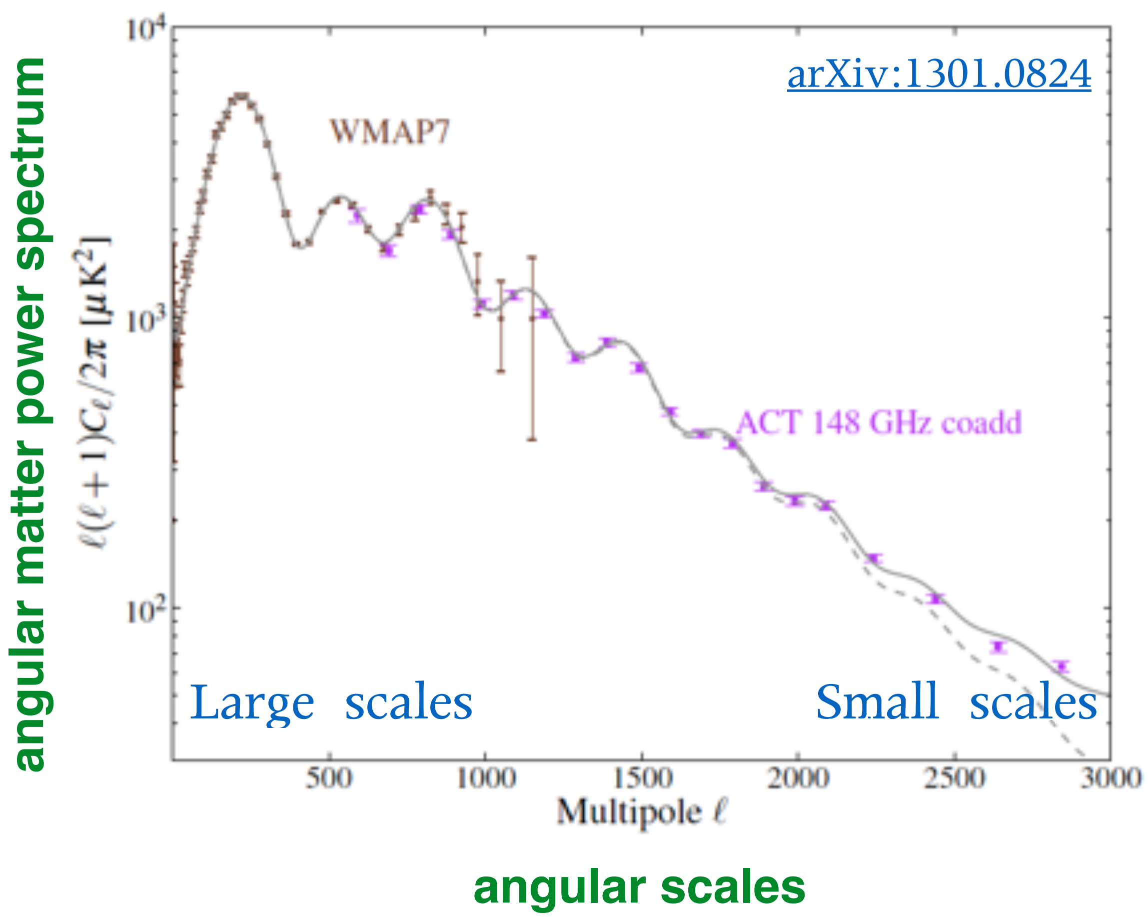
Fluctuations in the matter energy density is at the origin of galaxies

courtesy Planck

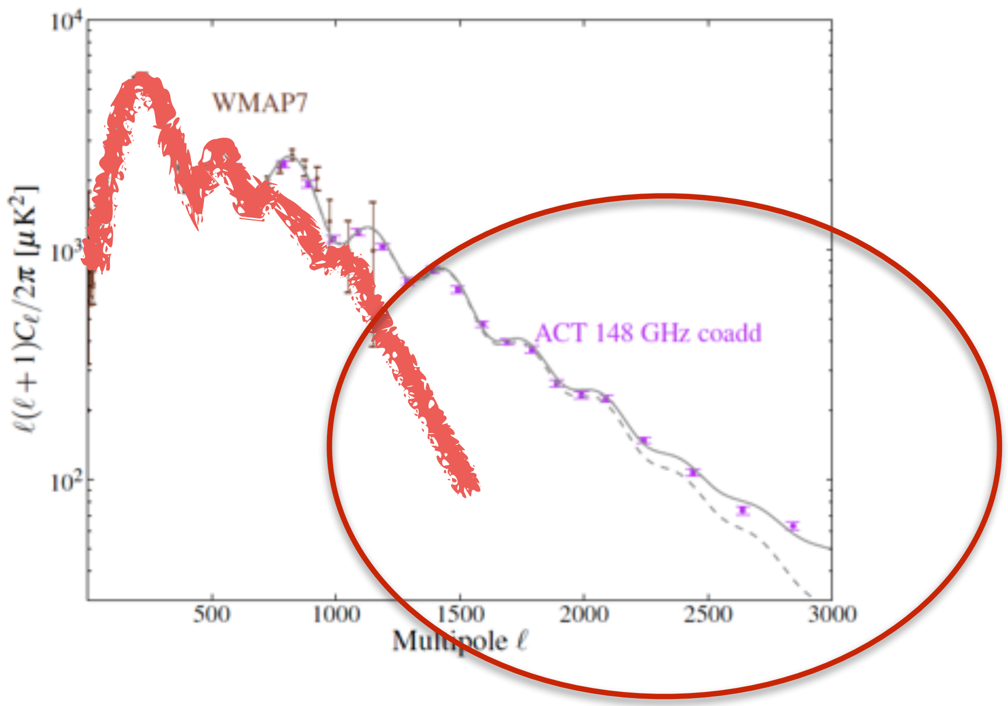




$$\frac{\delta T}{T} = \frac{\delta \rho}{\rho}$$



CMB without DM?



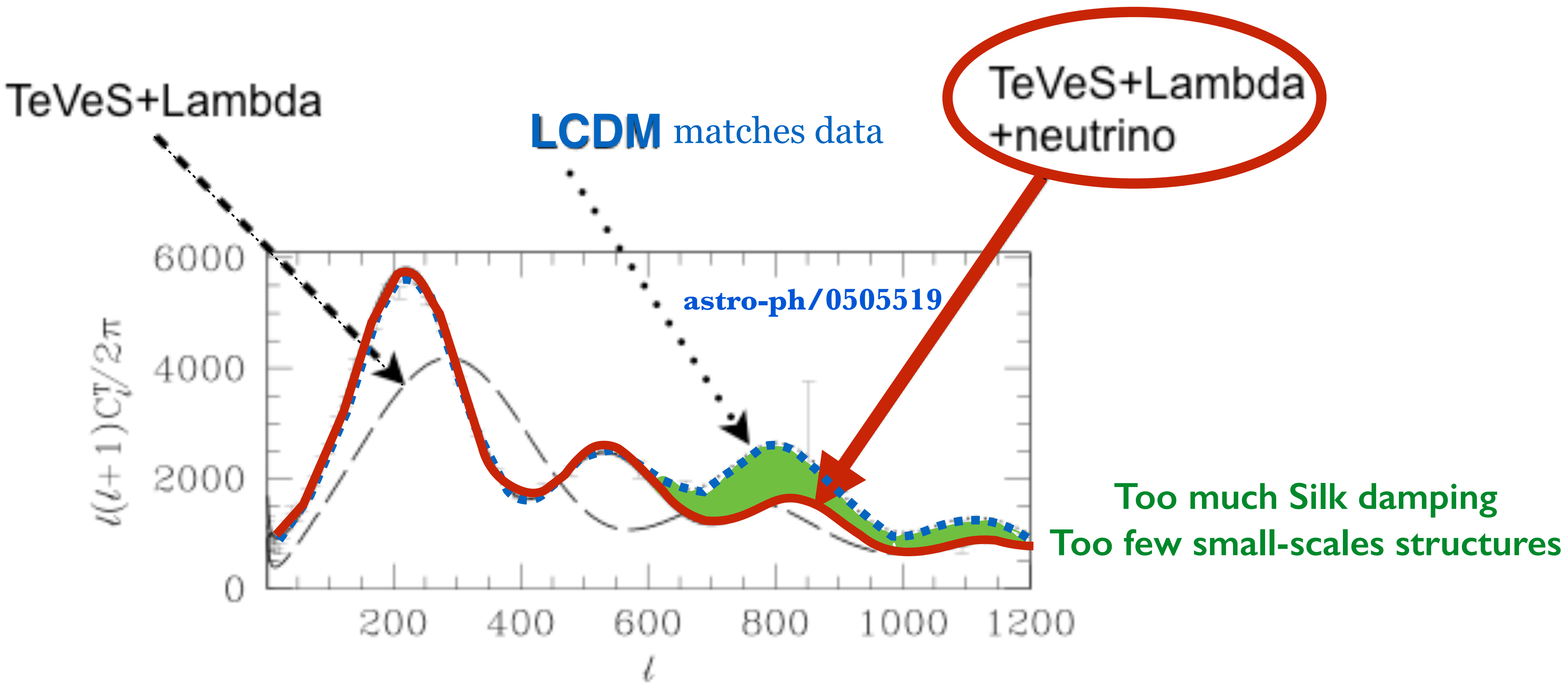
Silk damping

we need a new form of matter!

A Universe without DM is not a good Universe

TeVeS (relativistic MOND, only baryons; no DM)

Bekenstein astro-ph/0403694

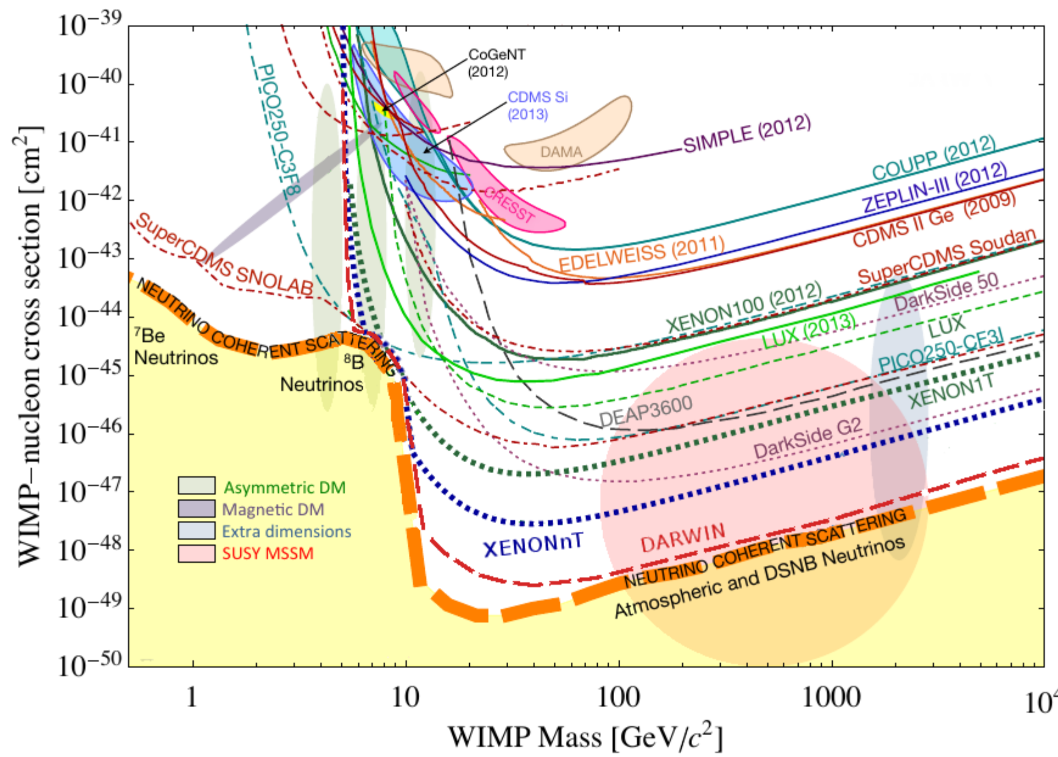


Suppression at small scales unavoidable

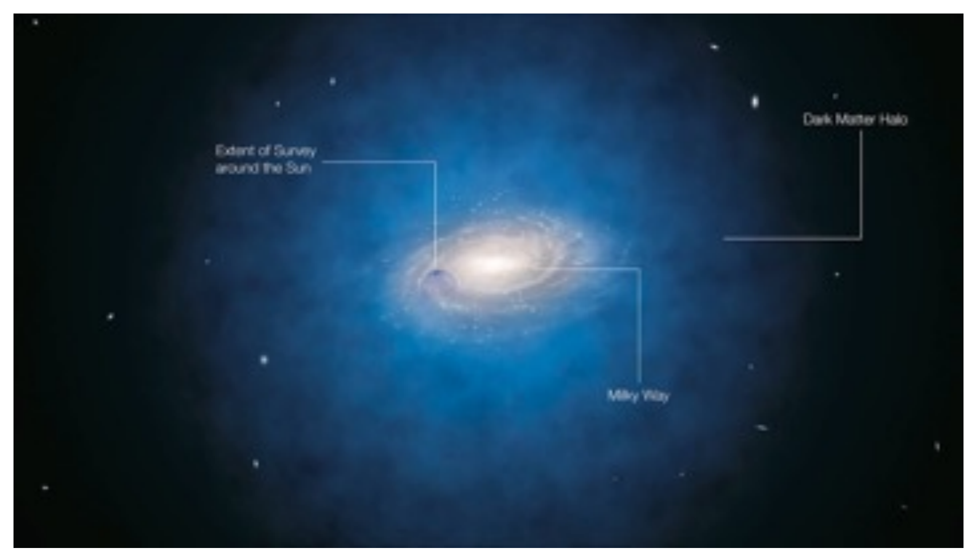
We need Dark Matter!
We need a new type of matter!

3 main strategies to discover DM particles

Direct detection



Indirect detection



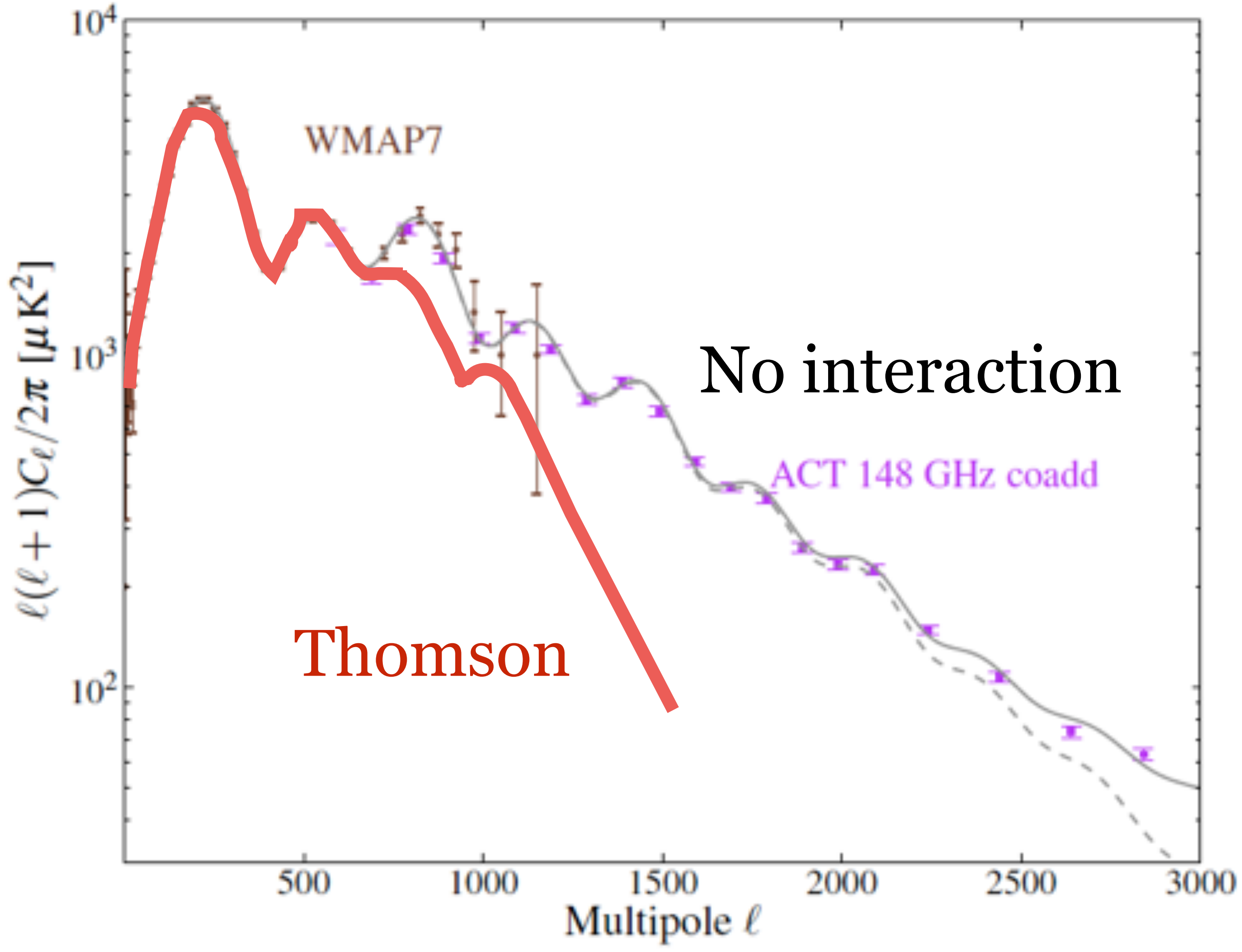
LHC

Or …

you can try to exploit galaxy surveys

starting point: doubt everything you know!

Is dark matter really weakly interacting? (current paradigm)

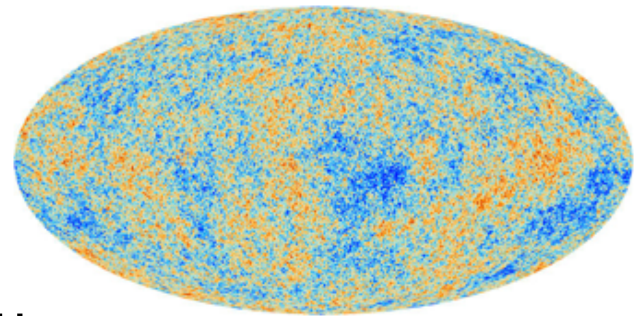


We know the 2 extremes cases but what would happen if DM had weak but non negligible interactions?

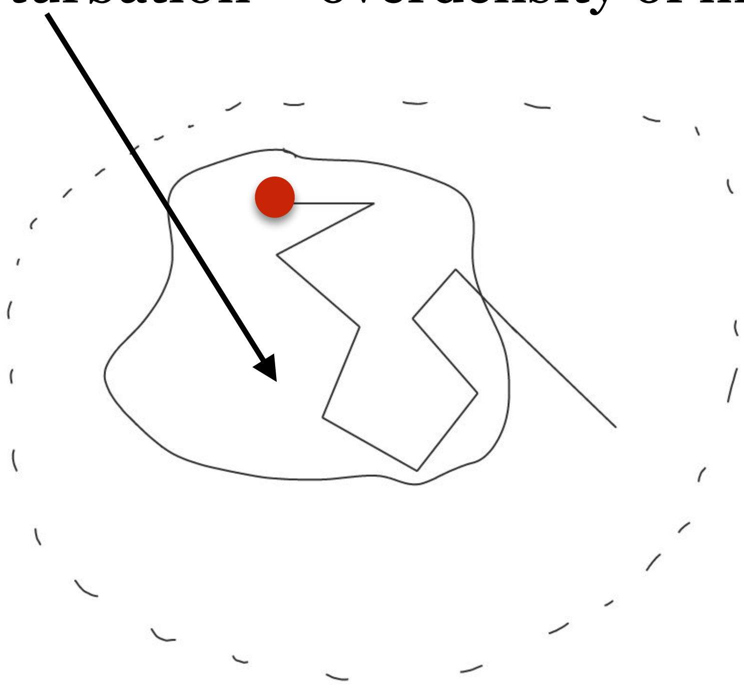
We need a formalism which include the 2 cases

Notion of *collisional damping*

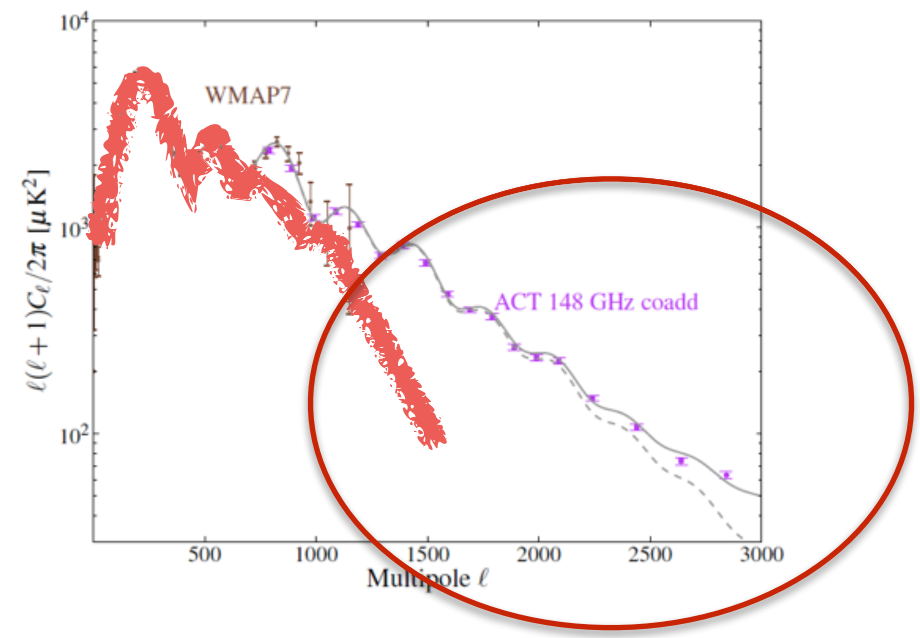
(**astro-ph/0012504**, **astro-ph/0112522**, **hep-ph/0305261**, **astro-ph/0309652**, **astro-ph/0410591**)



Perturbation = overdensity of matter



Diffusion DM-SM
the effect should be large depending
on the cross section



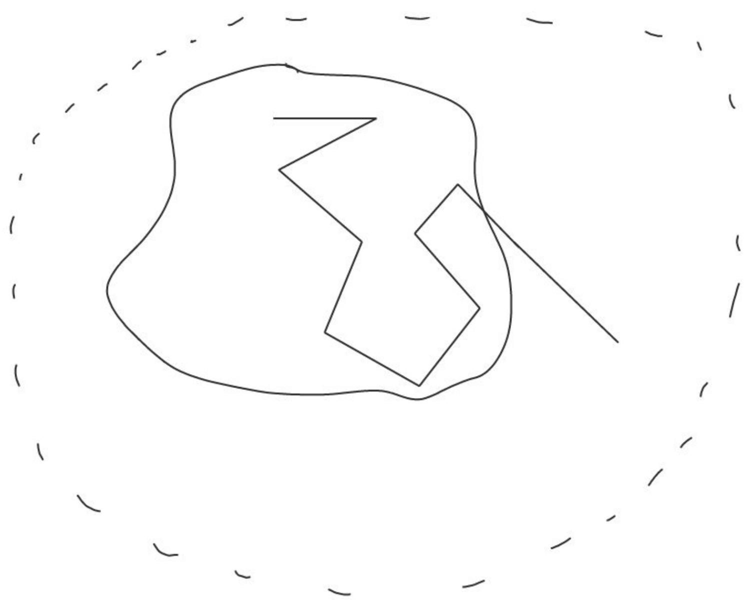
Silk damping
suppression of small size perturbations

Generalisation of Silk damping

1) Dark Matter instead of baryons
2) any SM particle instead of photons only

Notion of *collisional damping*

(astro-ph/0012504, astro-ph/0112522, hep-ph/0305261, astro-ph/0309652, astro-ph/0410591)



Mean free-path

$$\lambda = \frac{v}{\sigma v_r n}$$

$$\lambda = \frac{v}{\Gamma}$$

$$\mathrm{E\ per\ length\ per\ s} \propto \rho \mathrm{v} \lambda = \frac{\rho \mathrm{v}^2}{\Gamma}$$

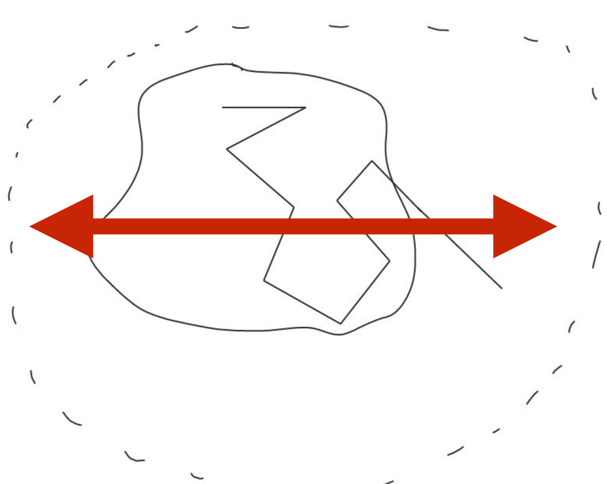
whether the species that is interacting with DM
is relativistic or not

whether DM has interactions or not?

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

astro-ph/0012504 **astro-ph/0410591**

damping scale



whether the species that is interacting with DM
is collisional or not

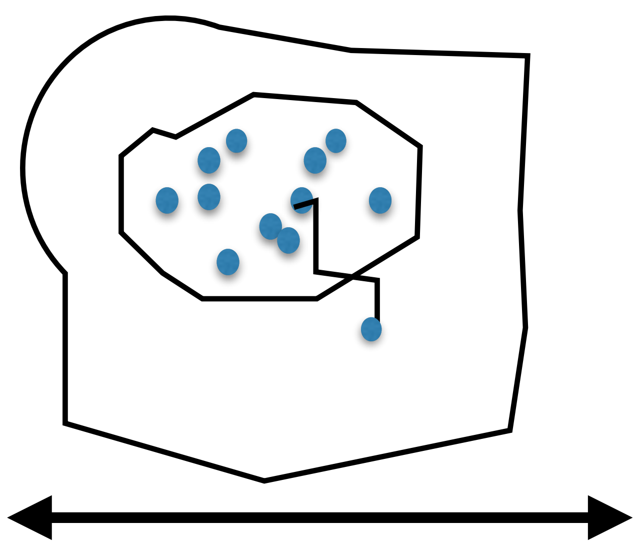
No interaction, no effect! **Work for baryon-photon!**

Generalising the Silk damping to DM

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

DM interacts   DM decouples   DM free-stream   photons decouple from baryons

kinetic theory $\boxed{\text{collisional damping!}}$



collisional damping length

$$l_{cd}^2 = \pi^2 \int^{t_{dec(dm)}} \frac{\cancel{\zeta} + \frac{4}{3}\eta + \cancel{\chi T}\,\frac{\rho_m^2}{4\,\not\rho\,\rho_r}}{\not\rho\, a^2}\, dt$$

$$\eta = \sum_i \frac{\rho_i\, v_i^2}{3\,\Gamma_i} \longrightarrow \boxed{\Gamma_i = \sum_j \Gamma_{ij} \qquad \Gamma_{ij} = \langle \overline{\sigma v} \rangle_{ij}\, n_j}$$

$$l_{cd}^2 = l_{sd}^2 + \sum_{i \neq dm} l_{id}^2 \qquad \boxed{l_{id}^2 \sim \frac{2\pi^2}{3}\frac{\rho_i v_i^2 t}{\not\rho a^2 \Gamma_i}\,(1+\Theta_i)\,|_{dec(dm-i)}}$$

- photons
- neutrinos

give the largest effect

(large energy density, relativistic with an interaction rate fixed at least by the electrons -- if not the DM)

Collisional damping in modern Cosmology

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

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

Translation in terms of Cosmological perturbations

without DM interactions

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

$$\dot{\kappa} = a\sigma_{Th} n_e$$

with DM interactions

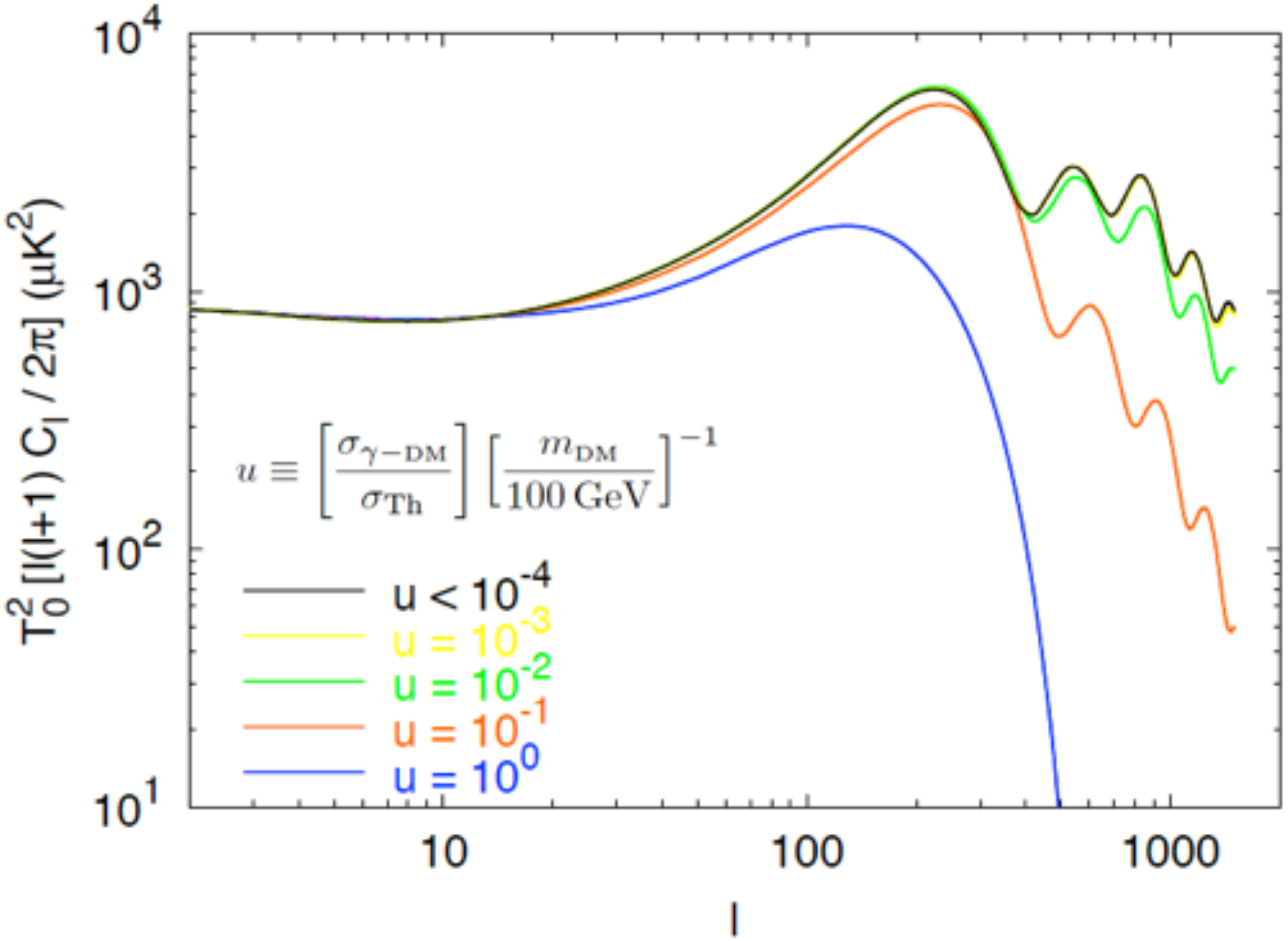
$$\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) \\
&\quad - \dot{\kappa}(\theta_\gamma - \theta_b) - \dot{\mu}(\theta_\gamma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

$$\dot{\mu} \equiv a\sigma_{\gamma-DM} n_{DM} \qquad S \equiv \frac{3}{4}\frac{\rho_{DM}}{\rho_\gamma}$$

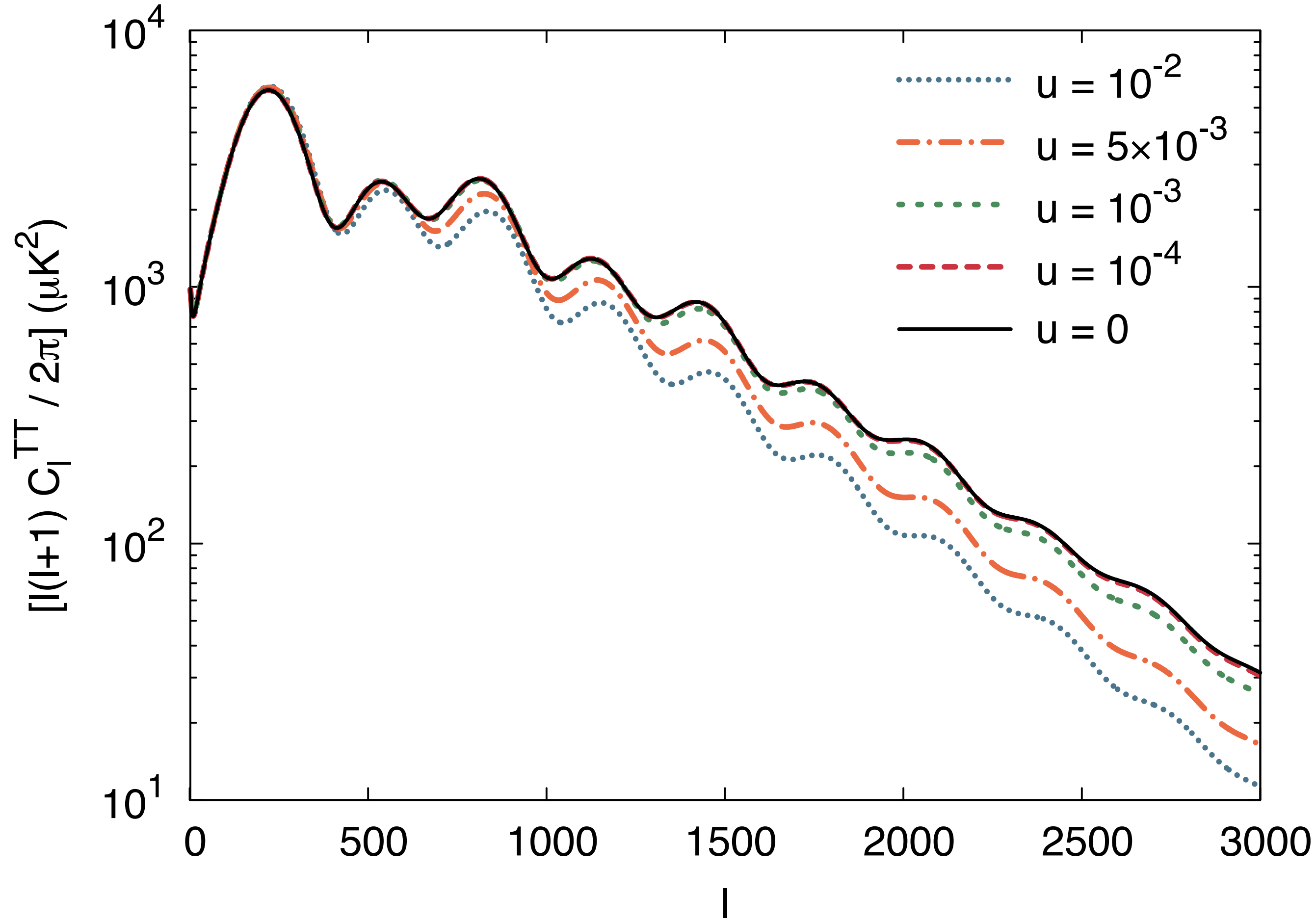
What would the CMB look like if DM interacts?

DM-photon interactions (but DM-neutrinos are similar)

C.B&Riazuelo et al: astro-ph/0112522



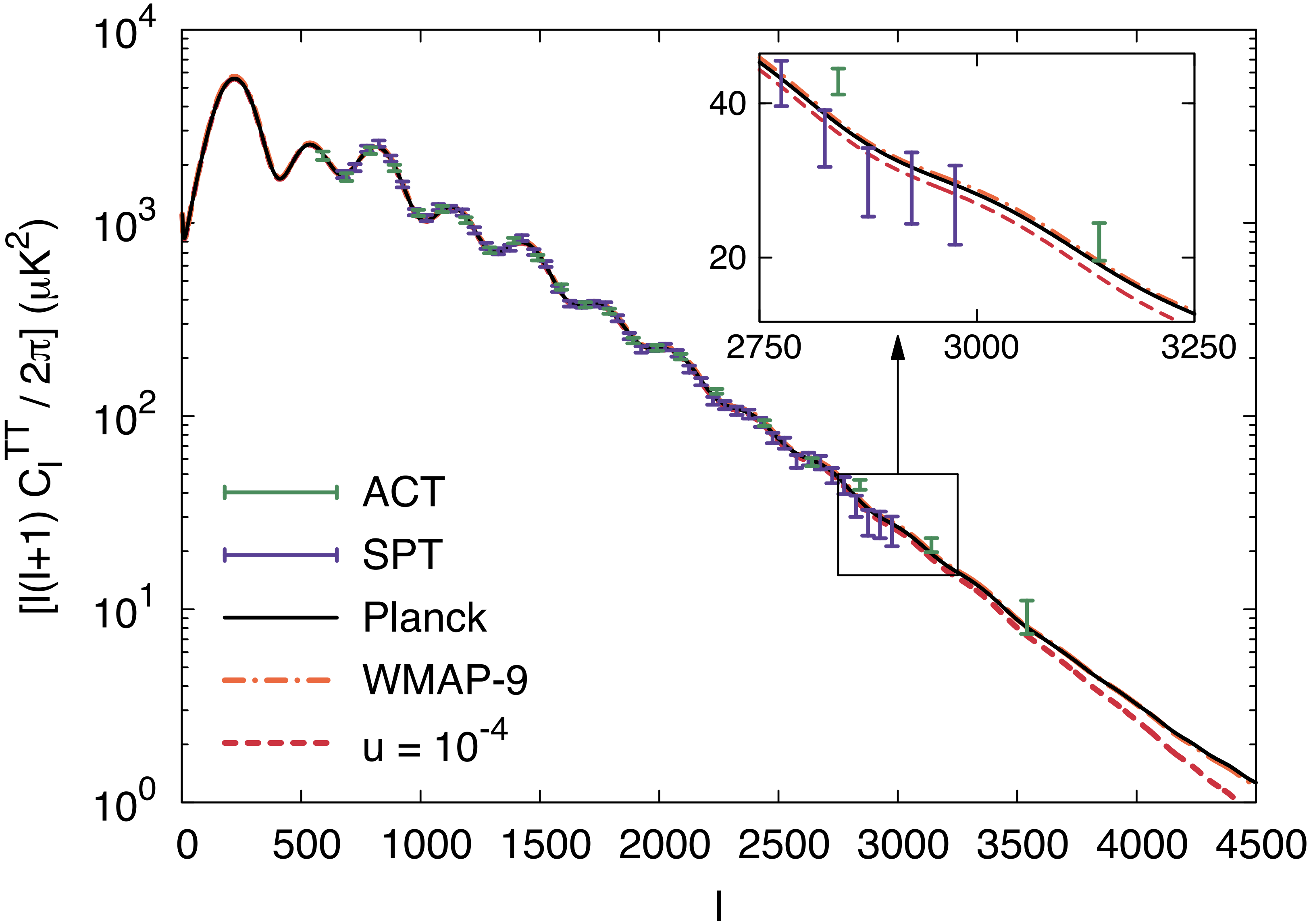
R. Wilkinson, CB et al : arXiv:1309.7588

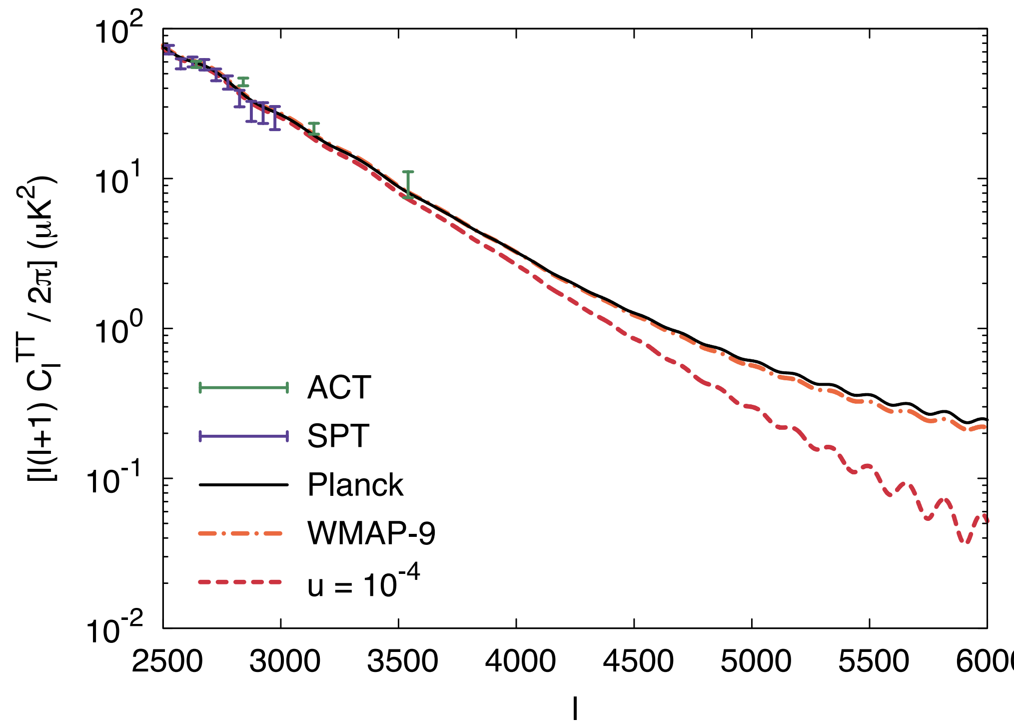


$u = 1$ Thomson interactions dark matter is even more interacting than a baryon!

$u = 10^{-4} \Rightarrow \sigma \sim 6\ 10^{-31}\left(\frac{m_{DM}}{\rm GeV}\right)\ {\rm cm}^2$ dark matter is not a baryon:
Can you tell it is coupled to photons?

Comparison with Planck data





$$\boxed{(\sigma v)_{\gamma-\mathrm{DM}} < 6\ 10^{-31}\ \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)\ \mathrm{cm}^2}$$

The CMB can be used to probe the WIMPs paradigm!

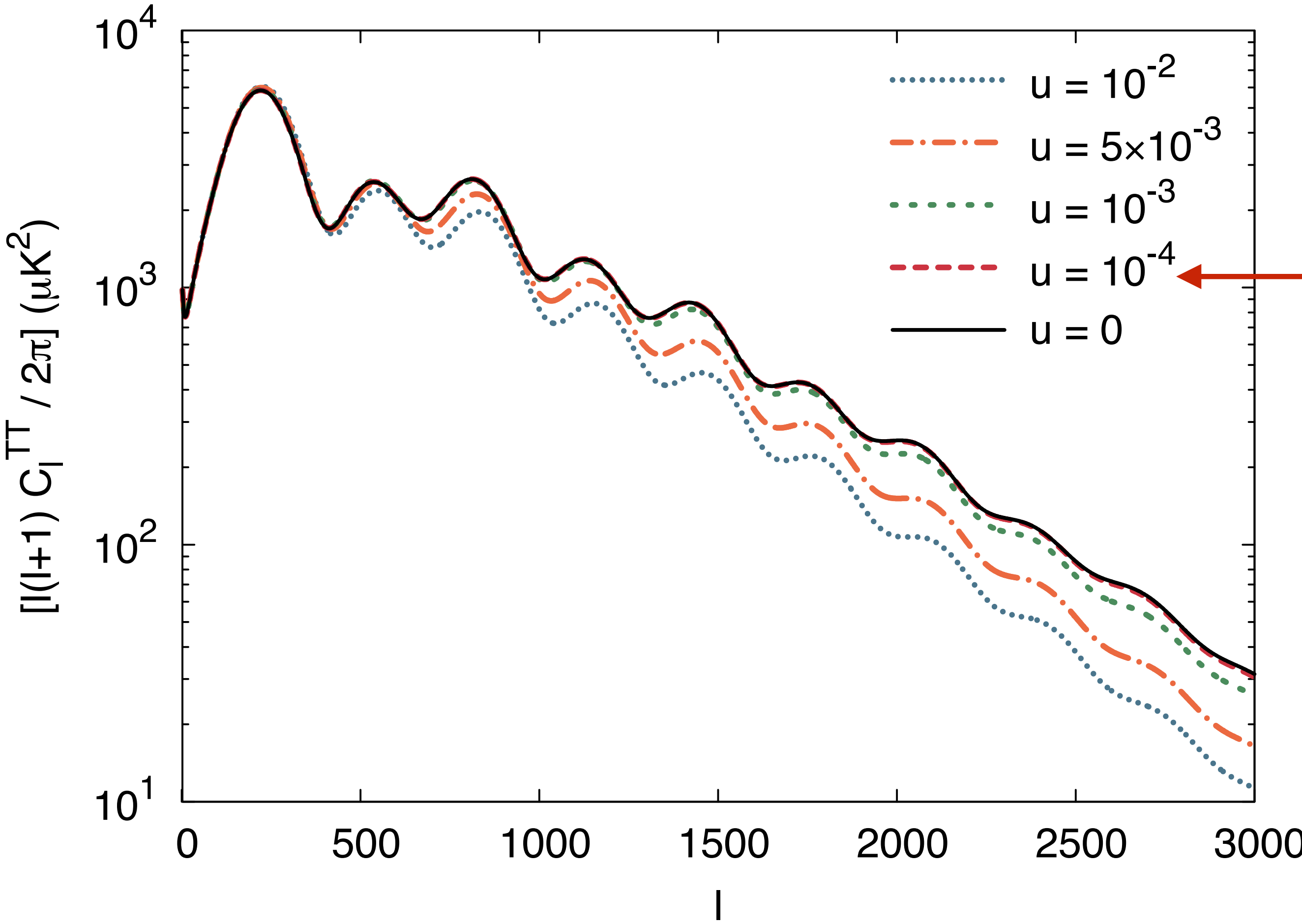
Compatibility with Planck data

	$100\,\Omega_b h^2$	$\Omega_{DM} h^2$	$100\,h$	$10^{+9}\,A_s$	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 alone

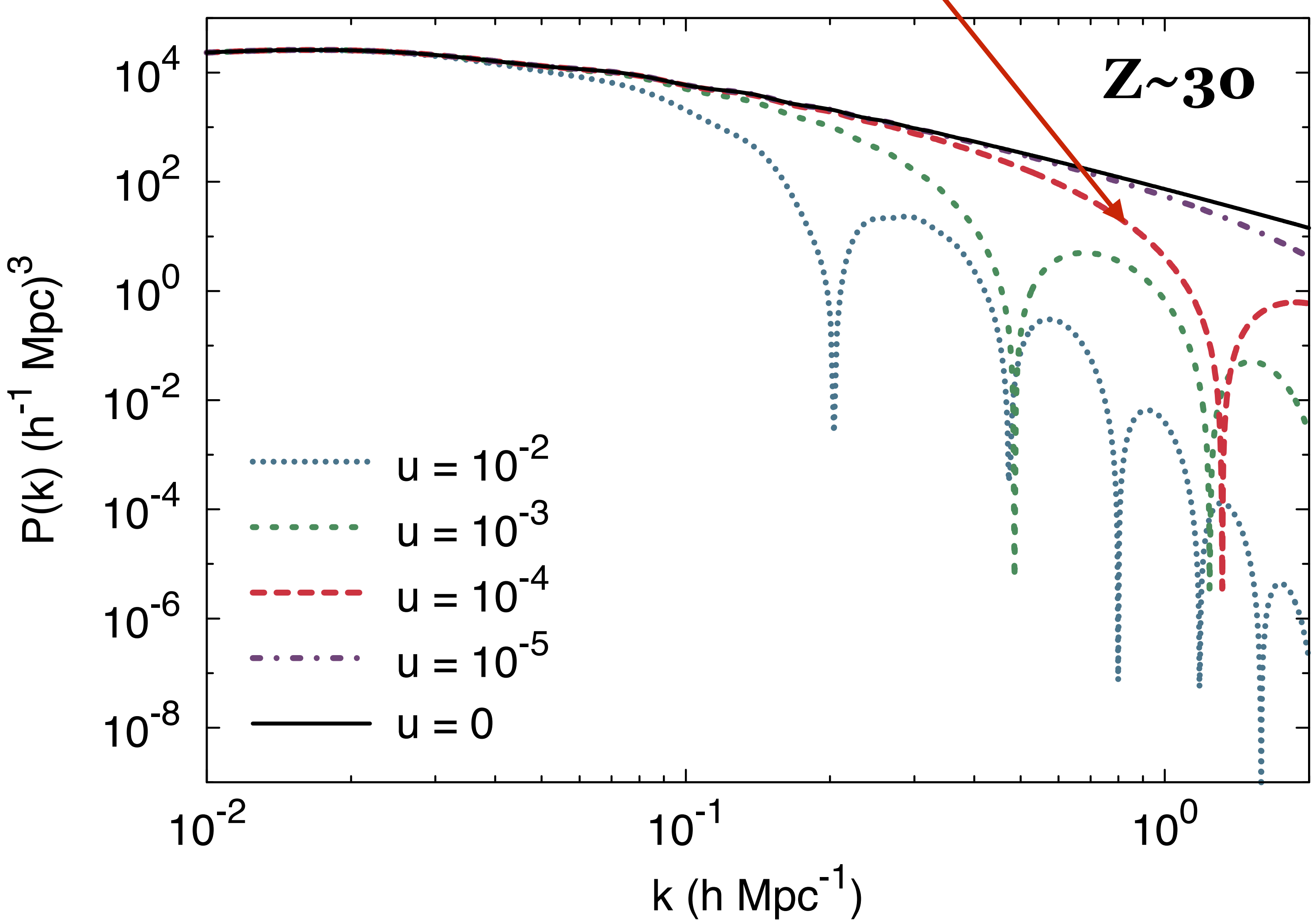
Neff is important!

H0 changes to change the horizon

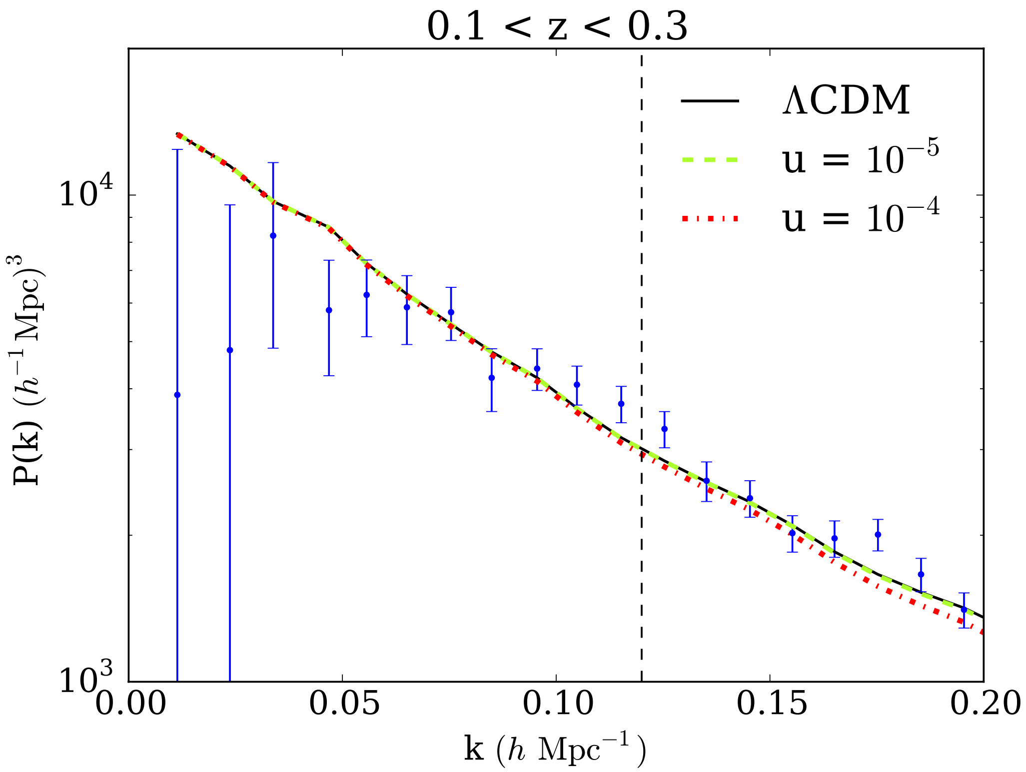


barely visible (CDM like for CMB)

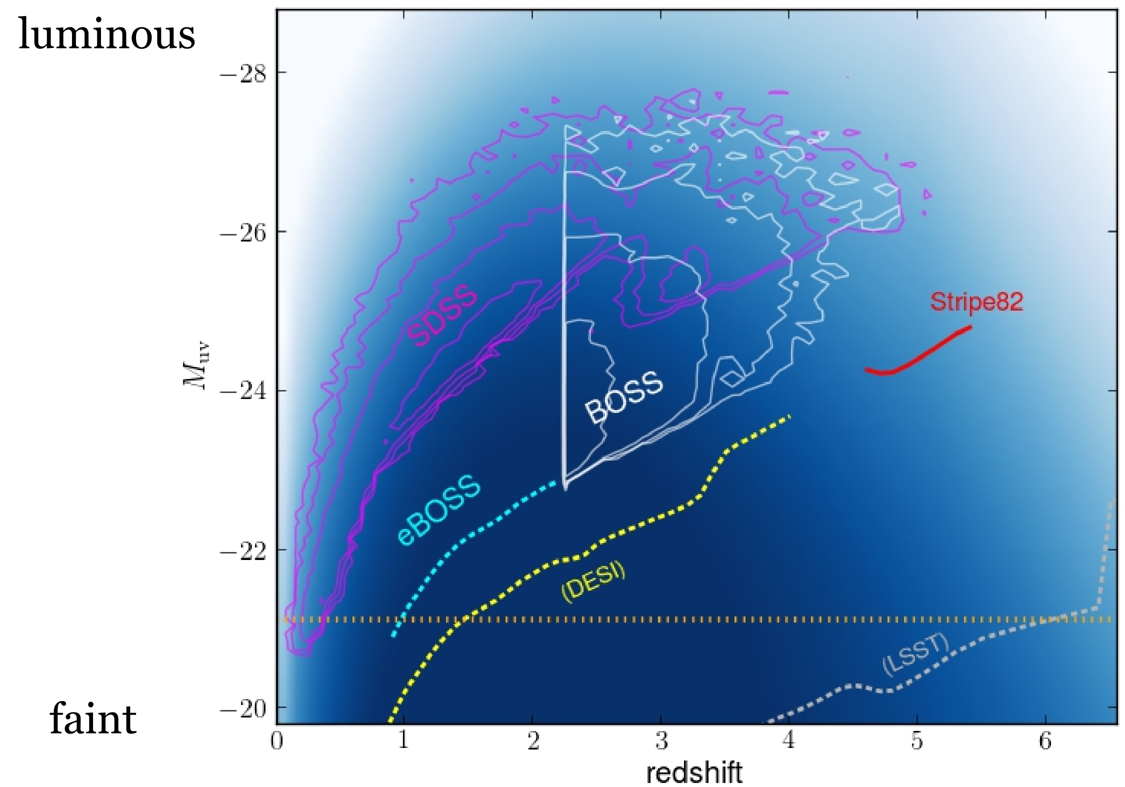
Visible pattern; not CDM for LSS!



LSS can probe tiny differences in P(k)

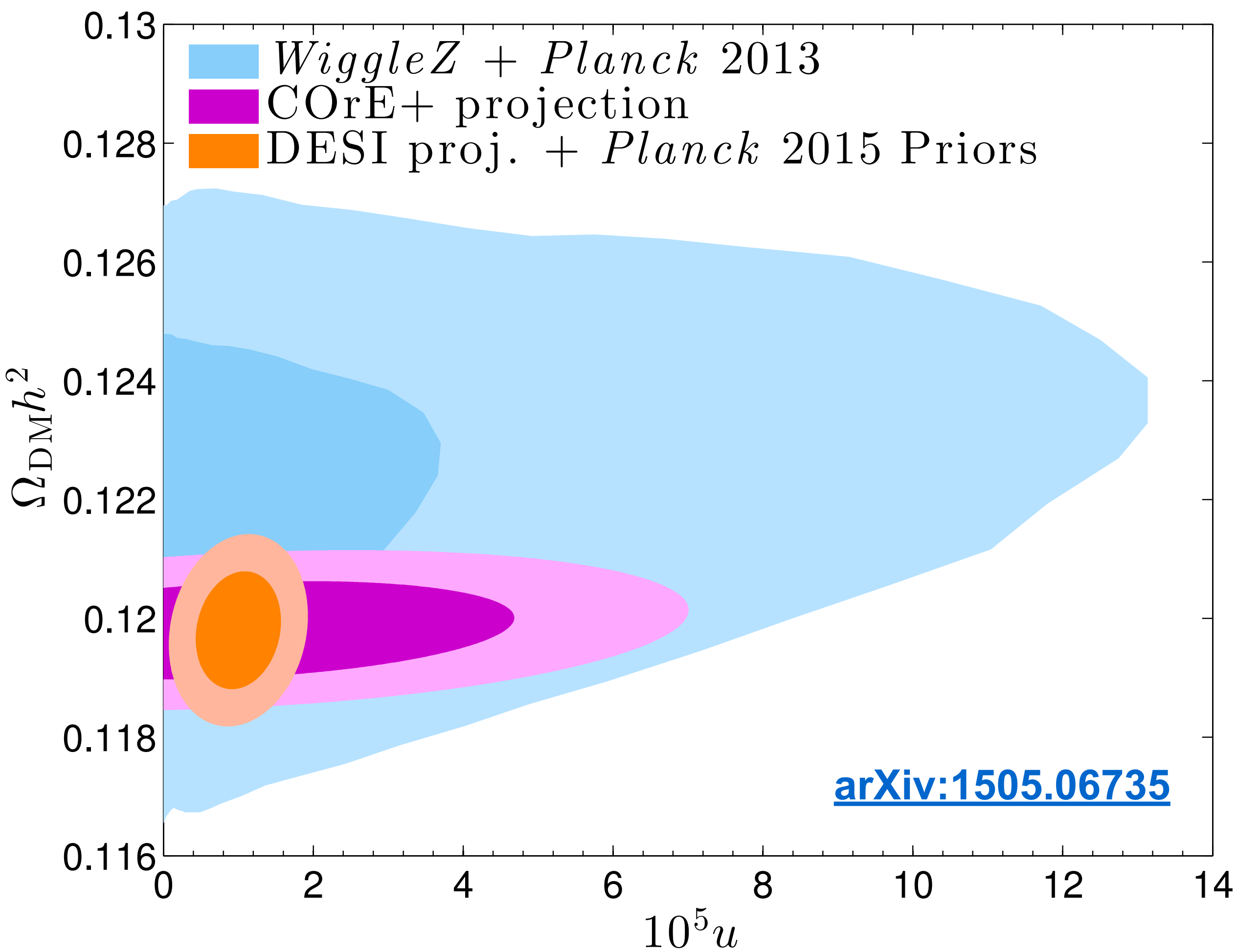


future surveys: DESI, LSST, ...



Courtesy JP Kneib

$$M - M^\star = -2.5 \log\left(\frac{L}{L^\star}\right)$$



How weakly interacting DM is?

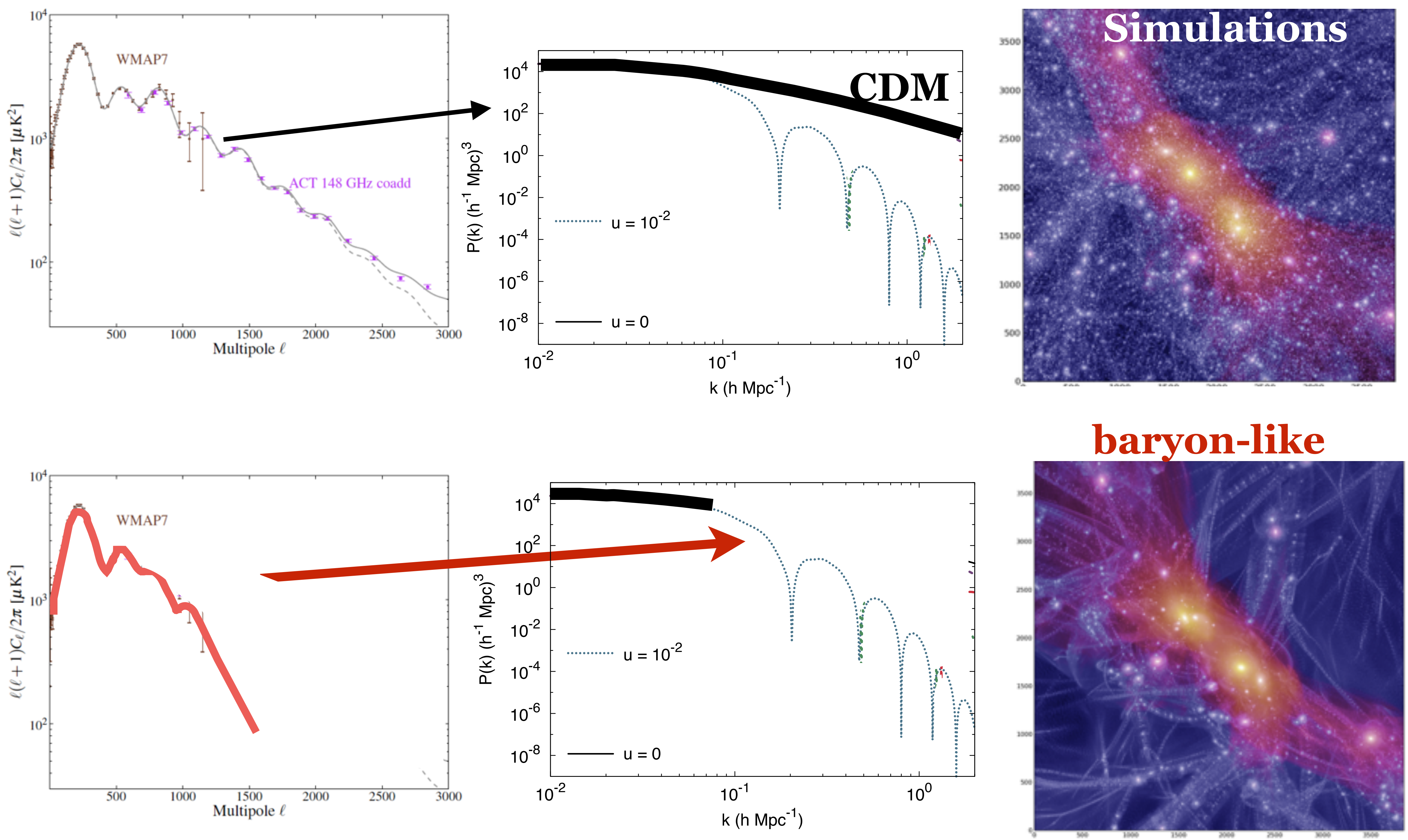
CMB alone & current LSS data (no simulation, linear P(k))

$$\sigma_{DM-\nu,\gamma} \lesssim 10^{-30} \ \frac{m_{DM}}{\rm GeV} \ {\rm cm}^2$$

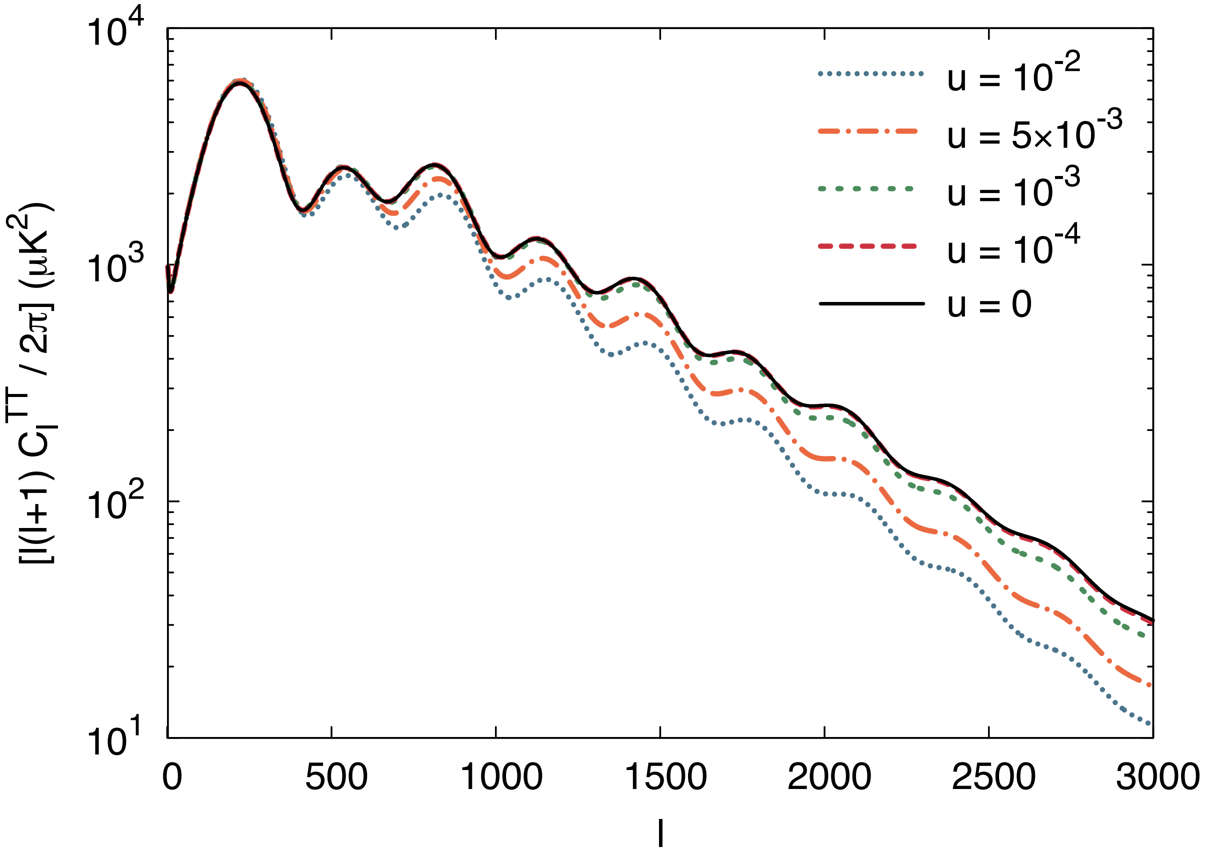
DESI can make us win a factor 10.

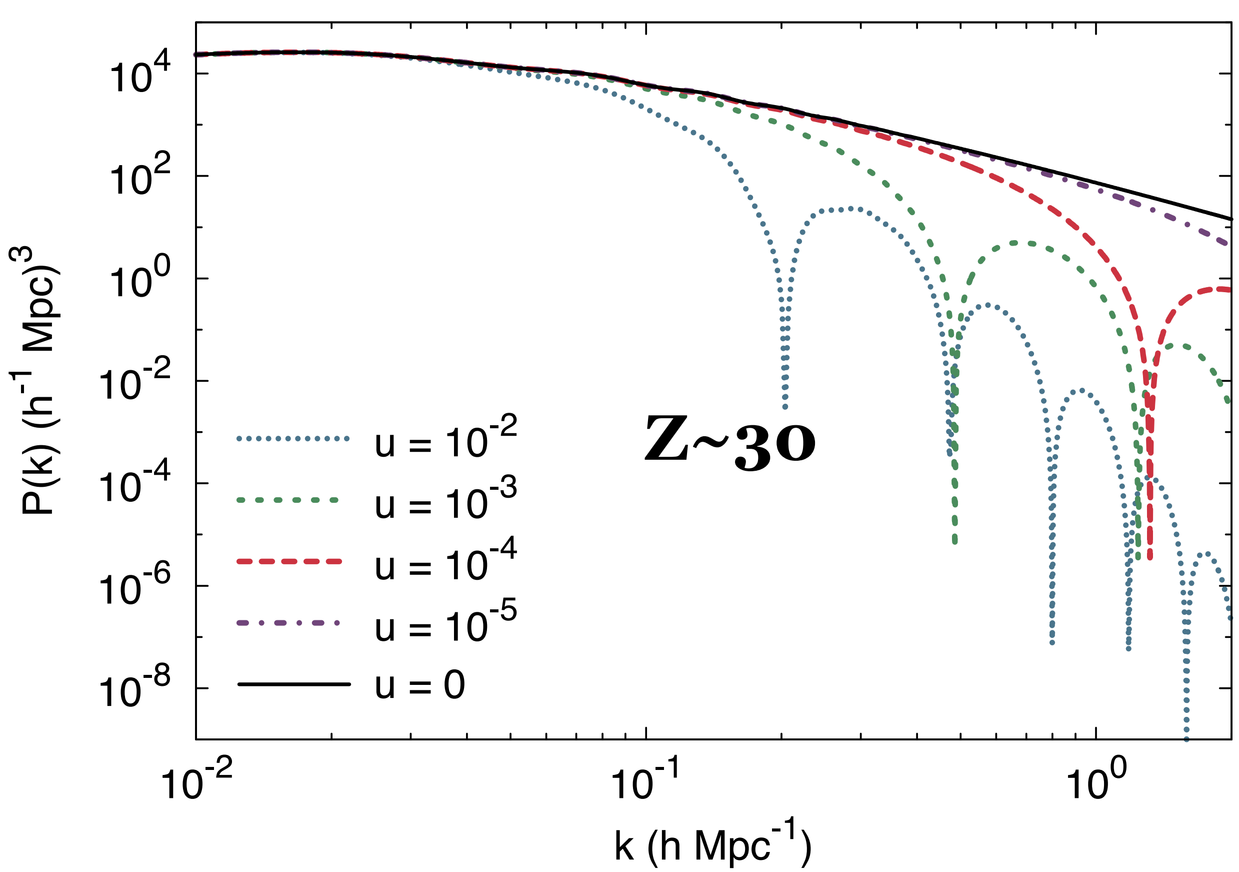
But constraints get better when investigating very small scales!

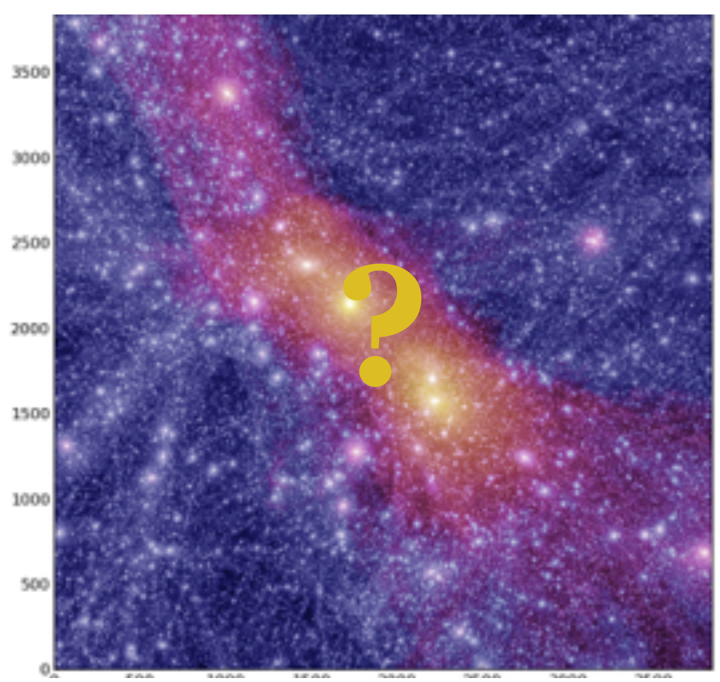
What would the Universe look like if DM interacted?



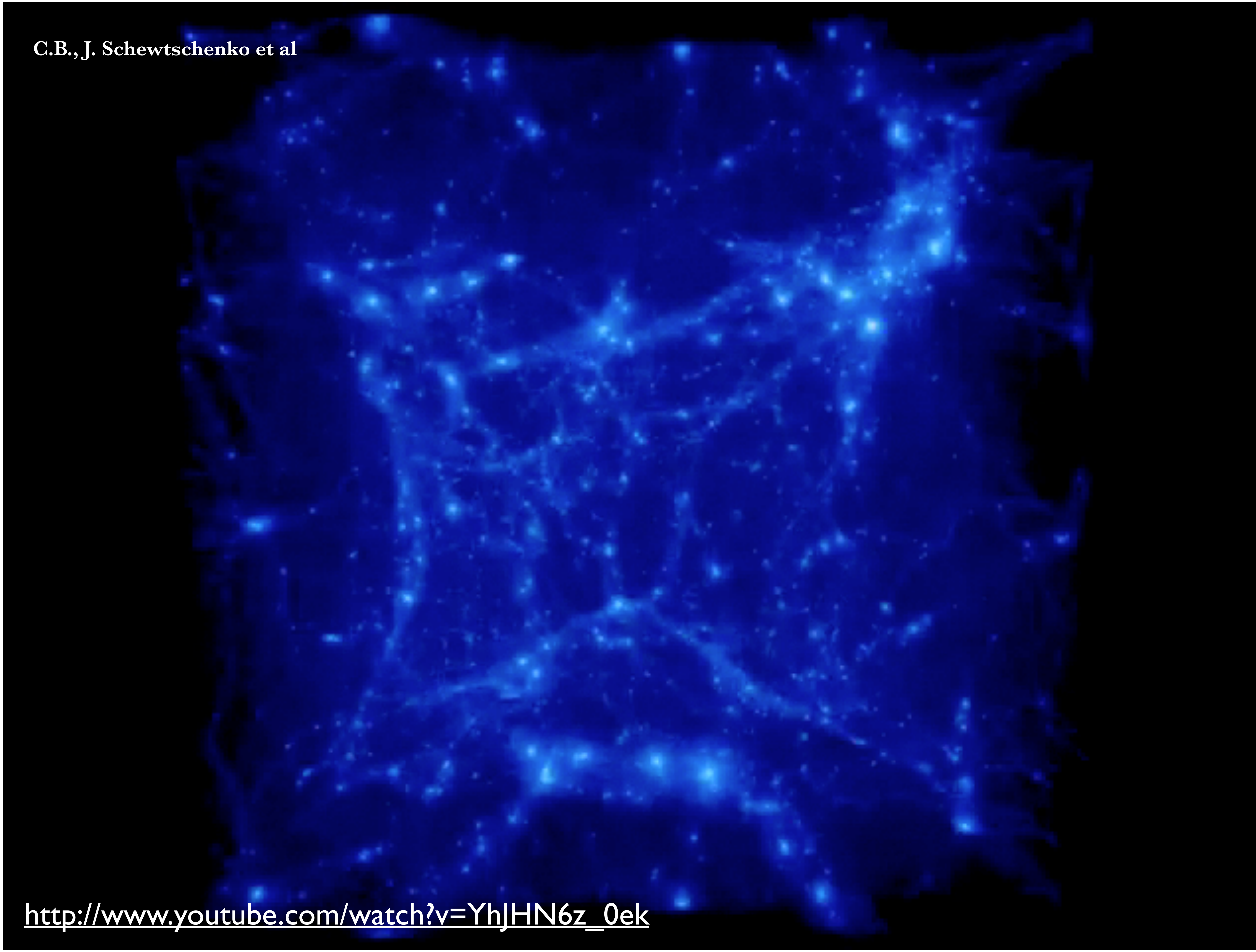
The weakly interacting massive particle paradigm makes sense!


$u = 10^{-2}$
$u = 5\times10^{-3}$
$u = 10^{-3}$
$u = 10^{-4}$
$u = 0$
$[l(l+1)\,C_l^{TT} / 2\pi]$ (μK^2)
l
0
500
1000
1500
2000
2500
3000
10^1
10^2
10^3
10^4

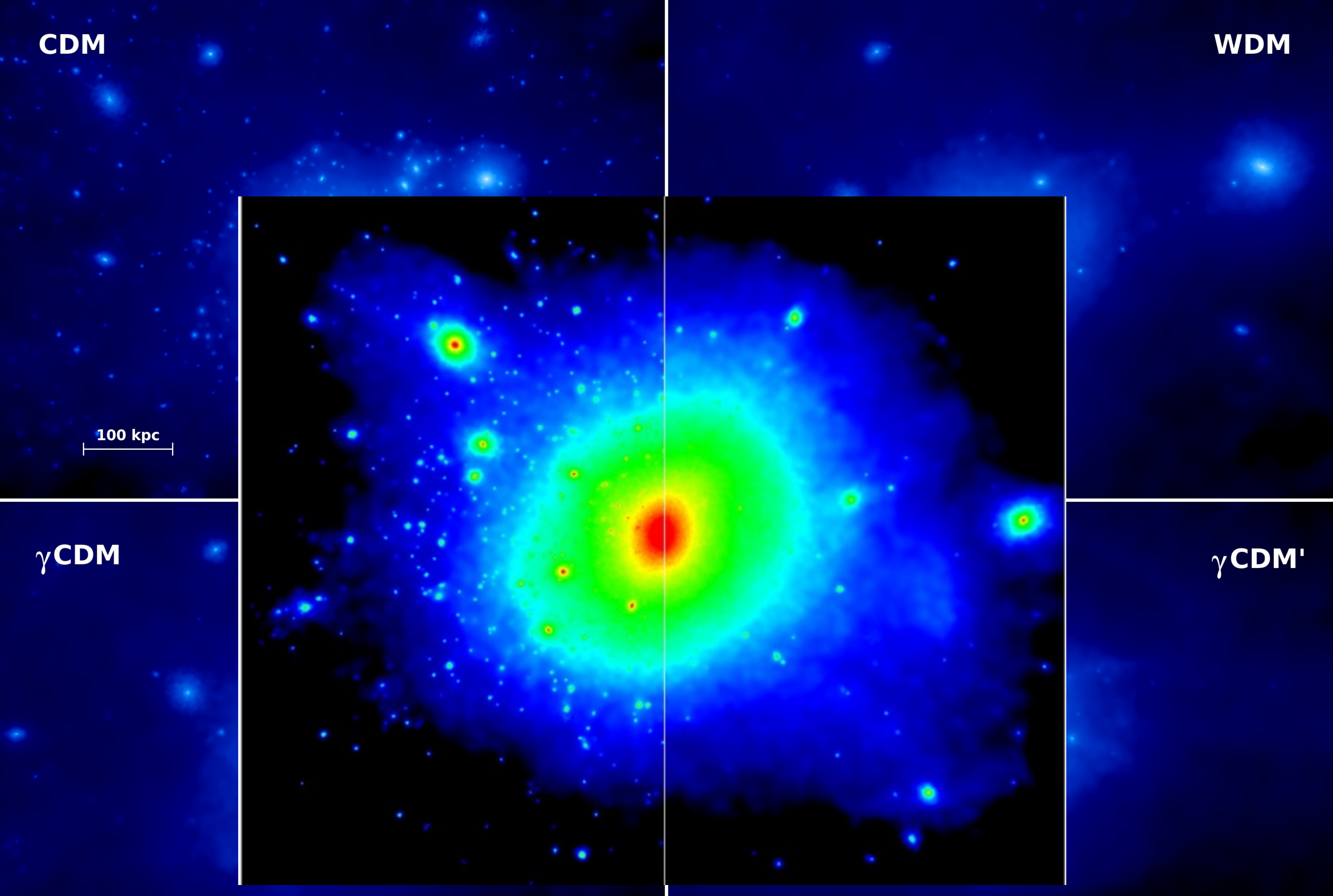

Z~30
$u = 10^{-2}$
$u = 10^{-3}$
$u = 10^{-4}$
$u = 10^{-5}$
$u = 0$
P(k) (h^{-1} Mpc)^3
k (h Mpc^{-1})
10^{-2}
10^{-1}
10^{0}
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}


?

C.B., J. Schewtschenko et al



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



Also $\sigma_{\mathrm{DM}-\nu} \lesssim 10^{-33}\,(m_{\mathrm{DM}}/\mathrm{GeV})\ \mathrm{cm}^2$

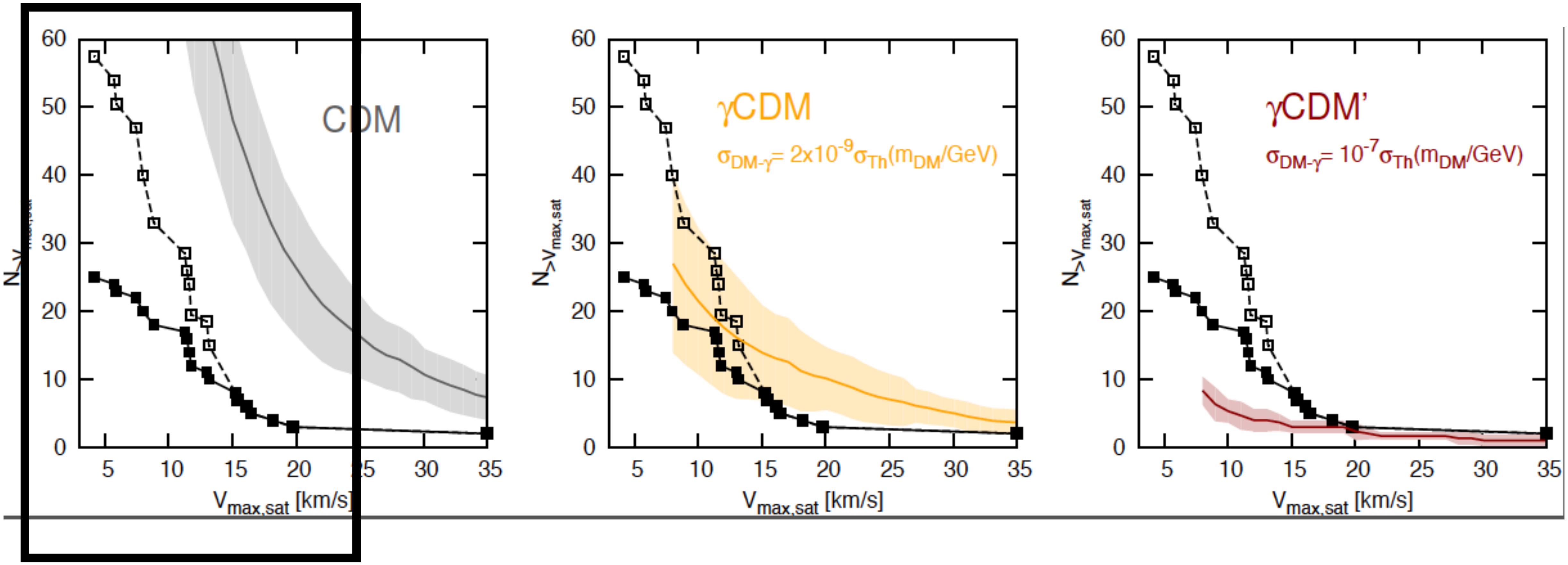
Numbers of satellite galaxies in the Milky Way

arXiv:1404.7012

CDM prediction is well above observation

Interacting DM agrees with observation

Too many interactions

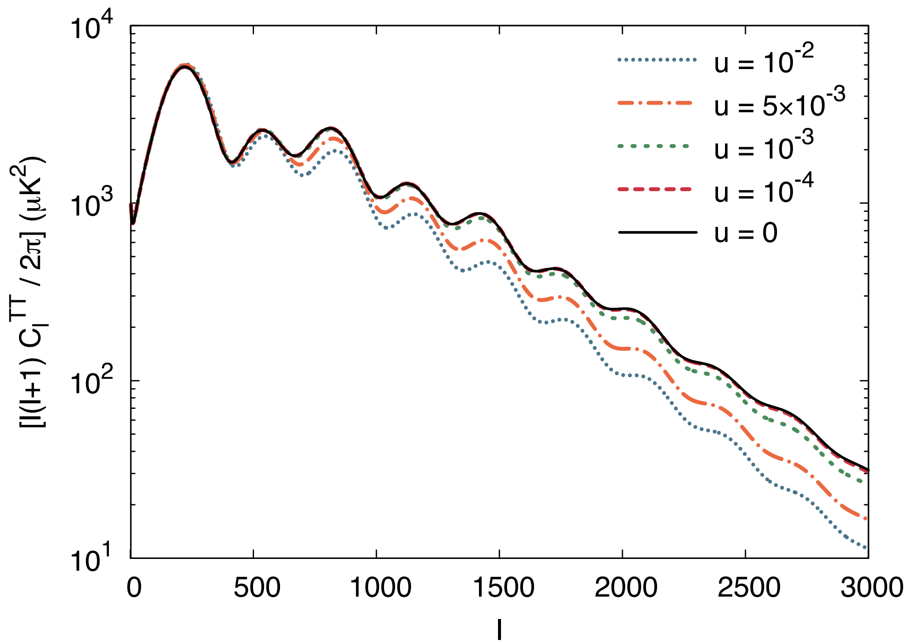


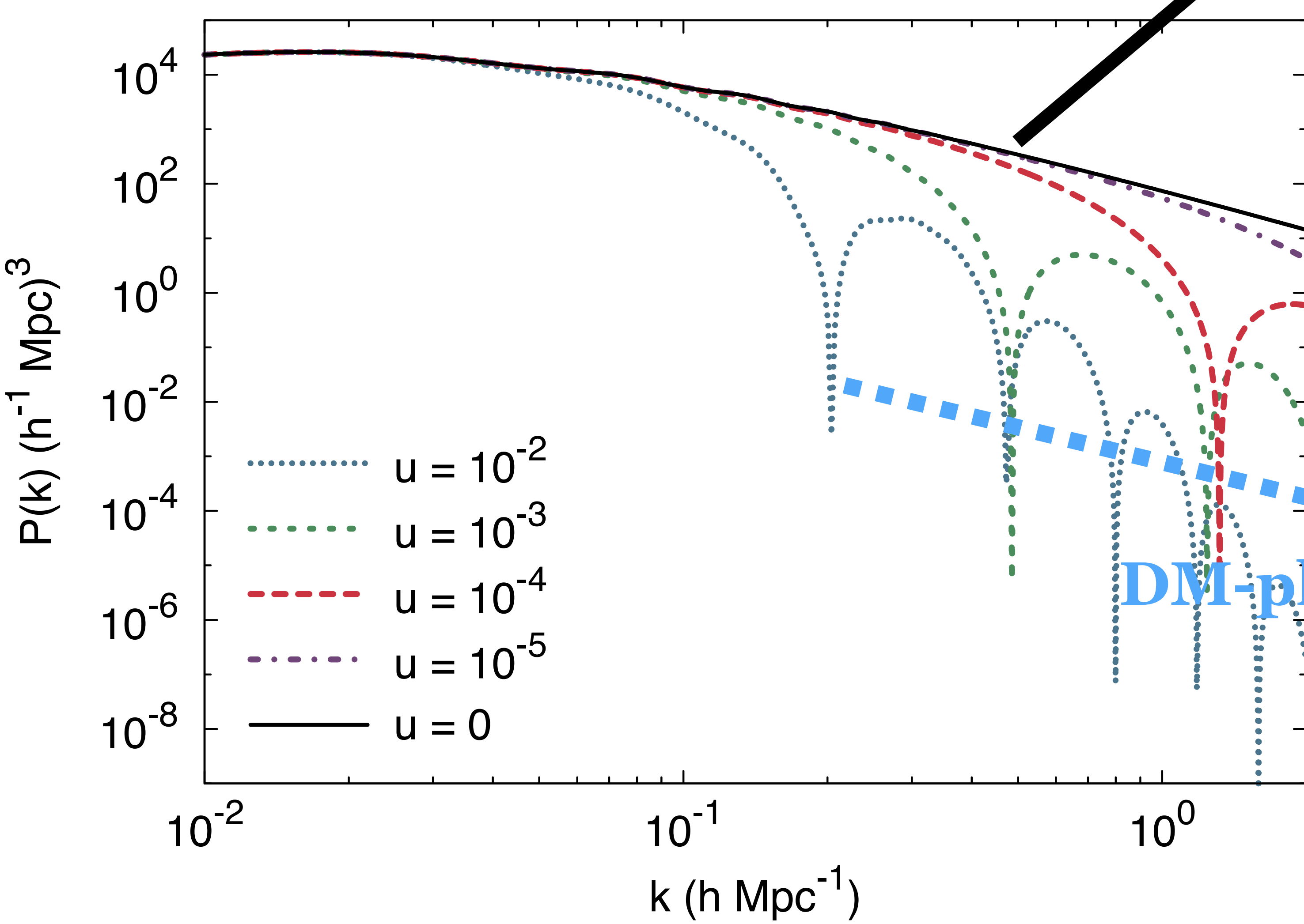
small satellites

Solve the MW satellite problem!

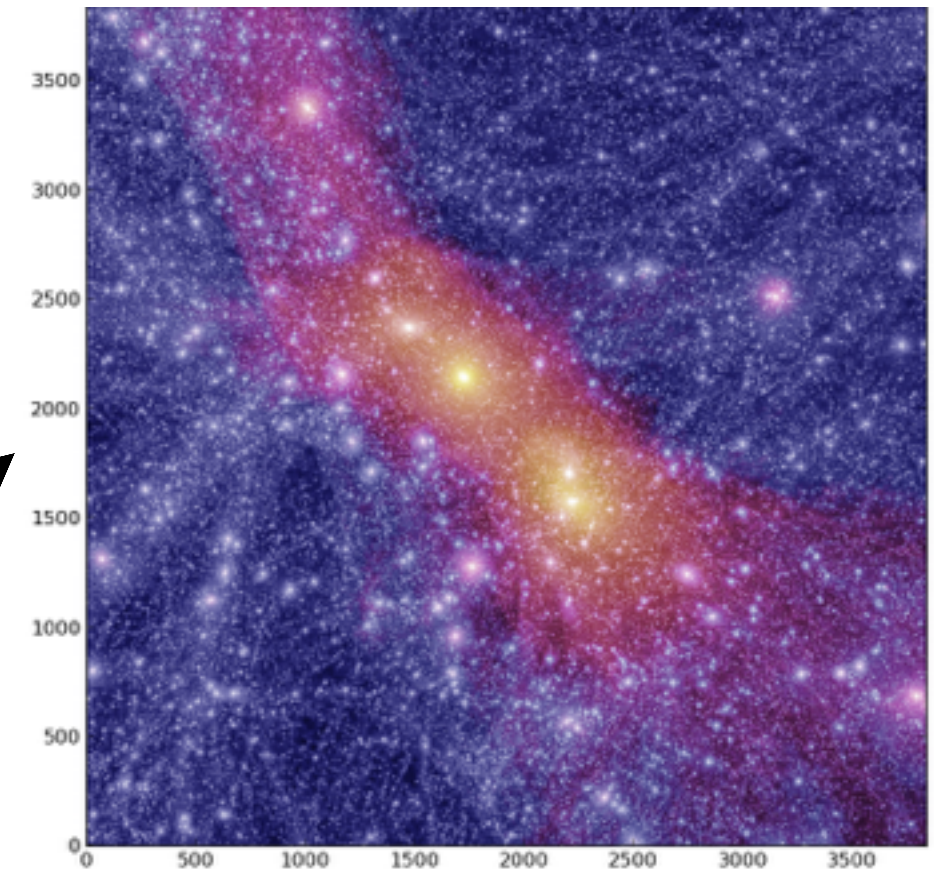
Sterilise the MW!

The Universe shaped by interacting DM

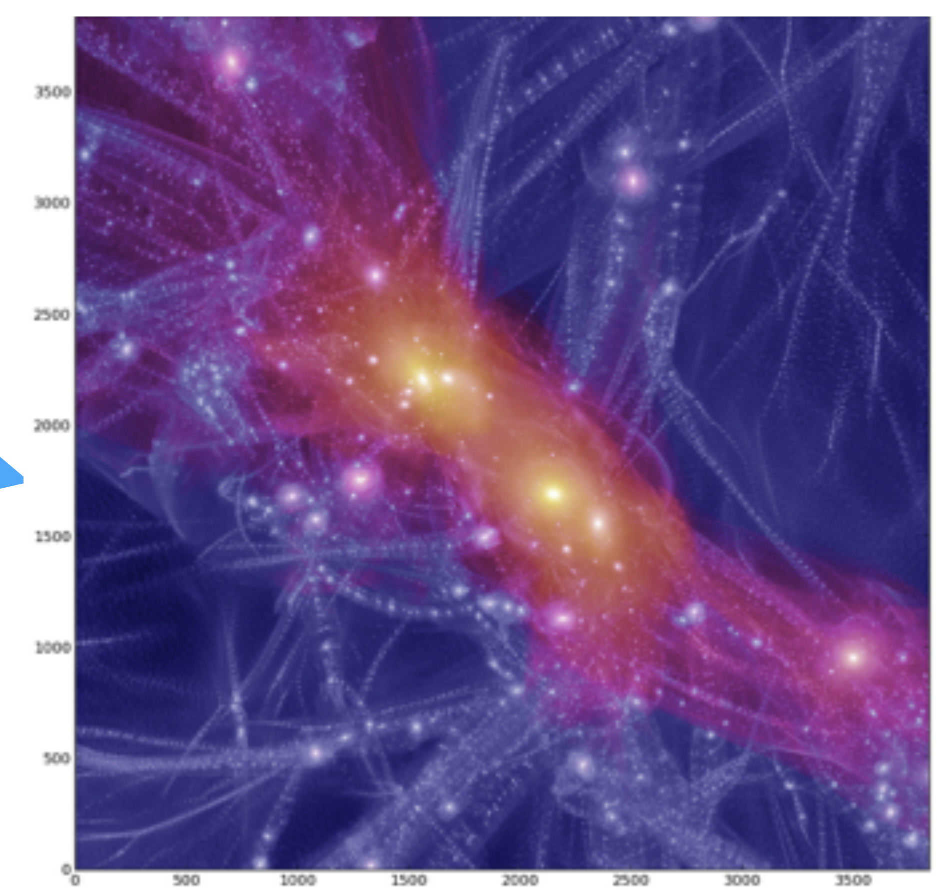




LCDM



DM-photon



How weakly interacting DM is?

CMB alone & current LSS data (no simulation, linear P(k))

$$\sigma_{DM-\nu,\gamma} \lesssim 10^{-30} \, \frac{m_{DM}}{\mathrm{GeV}} \, \mathrm{cm}^2$$

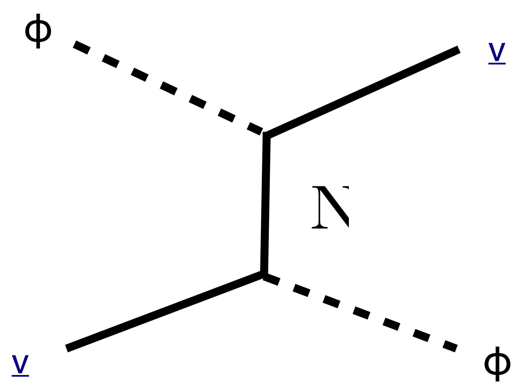
LSS data in the non-linear regime (the smallest scales observed but depend on simus):

$$\sigma_{DM-\nu,\gamma} \lesssim 10^{-33} \, \frac{m_{DM}}{\mathrm{GeV}} \, \mathrm{cm}^2$$

Same strength as "SM weak interactions" if MeV DM!

Potential link with neutrino physics

C.Boehm, Y. Farzan, S. Palomares-Ruiz,T. Hambye, S. Pascoli hep-ph/0612228

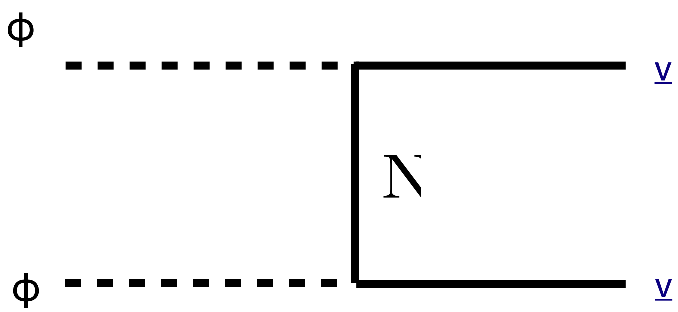


$$\sigma_{DM-\nu} \simeq 4 \times 10^{-36} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}} \right) \mathrm{cm}^2$$

$$\sigma_{DM-\nu} \simeq \frac{g^4}{4\pi m_{DM}^2}$$

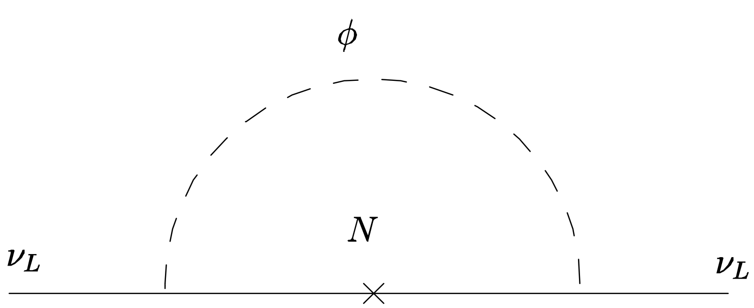
$$\simeq 3 \times 10^{-33} \left(\frac{g}{0.1}\right)^4 \left(\frac{m_{DM}}{\mathrm{GeV}}\right)^{-2} \mathrm{cm}^2$$

MeV DM requires couplings of about 3 10^-3



Effective theory

(N singlet of SU(2) for example)

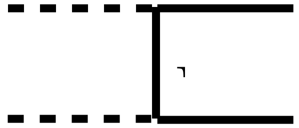


$$m_{\nu_L} \simeq \sqrt{\frac{\langle \sigma v_r \rangle}{128\,\pi^3}}\, m_N^2 (1 + m_\phi^2/m_N^2)\, \ln\left(\frac{\Lambda^2}{m_N^2}\right)$$

With **MeV DM** ($m_N = m_{DM}$) one obtains

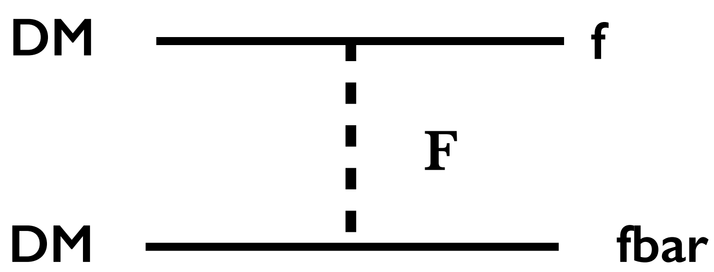
$$0.01\ \mathrm{eV} < m_\nu < 1\ \mathrm{eV}$$

$$\boxed{\sigma_{DM-\nu} \simeq 1.2\ 10^{-36} \left(\frac{m_N}{MeV}\right)^2 \left(\frac{\langle \sigma v \rangle}{3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}\right) \left(\frac{m_{DM}}{MeV}\right)^{-2} \mathrm{cm}^2}$$

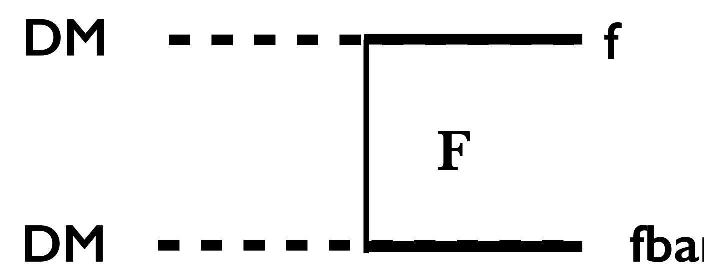


Light thermal DM?

$$\Omega_{DM}h^2 \propto \frac{10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\sigma v}$$



Majorana DM



scalar DM

$$\sigma v \propto \frac{\left(2c_l c_r\ \mathrm{m_{DM}} + (\mathrm{c_l^2} + \mathrm{c_r^2})\ \mathrm{m_f}\right)^2}{(m_F^2 - \mathrm{m_{DM}^2} - \mathrm{m_f}^2)^2}$$

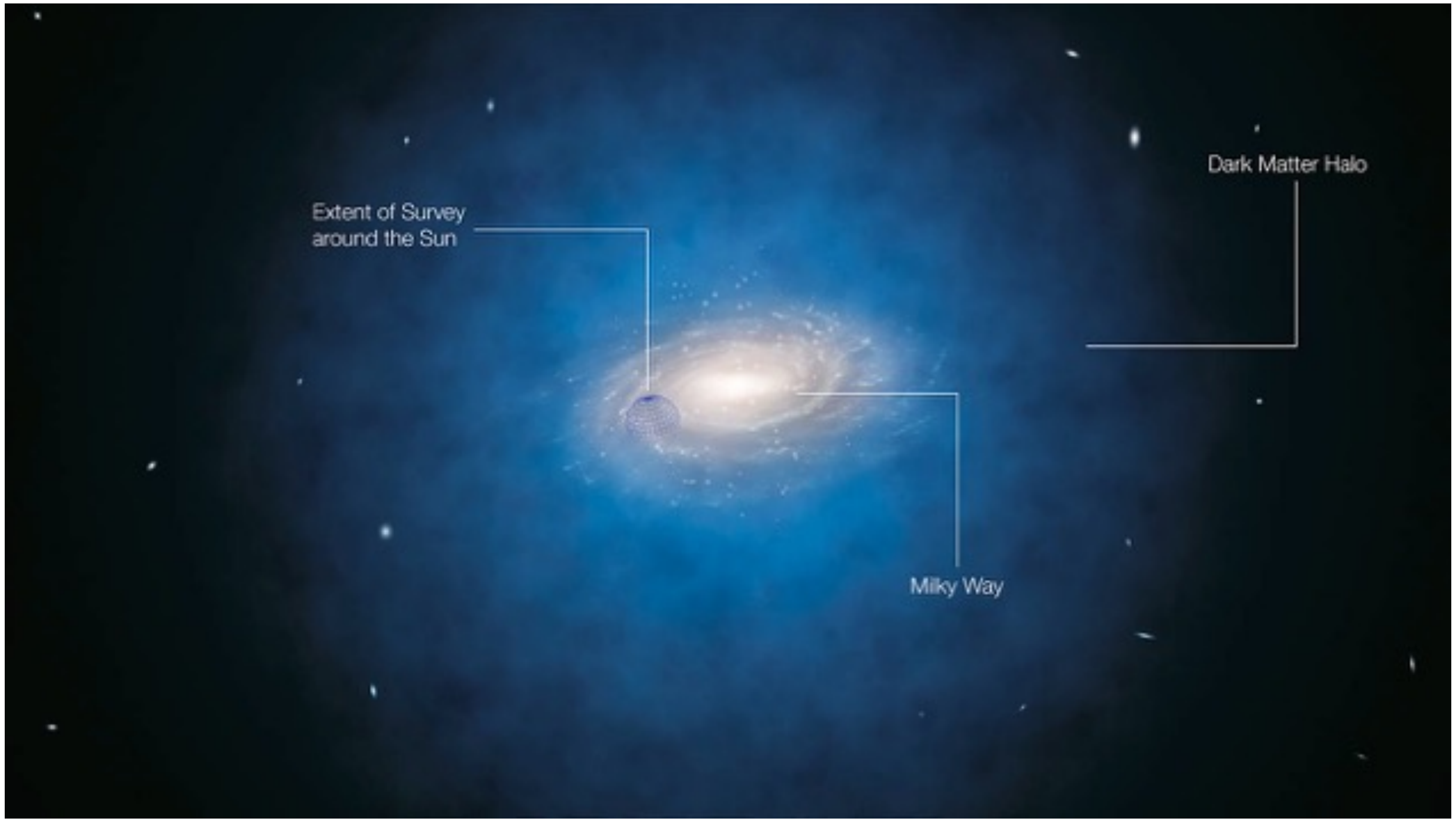
$$\sigma v \propto \frac{\left(2c_l c_r m_F + (c_l^2 + c_r^2)\ \cancel{m_f}\right)^2}{(m_F^2 - \mathrm{m_{DM}^2} - \mathrm{m_f}^2)^2}$$

$$\boxed{\sigma v \propto couplings \times \frac{m_{\mathrm{DM}}^2}{m_F^4} \propto couplings \times 10^{-22}\mathrm{cm}^3/\mathrm{s} \times \left(\frac{\mathrm{m_{DM}}}{100\mathrm{GeV}}\right)^2 \times \left(\frac{\mathrm{m_F}}{100\mathrm{GeV}}\right)^{-4}}$$

Fermionic DM scenario depends on both DM and mediator masses.
Scalar DM scenario depends only on the mediator mass

DM can be light if the mediator is also light and couplings are small!

Indirect detection



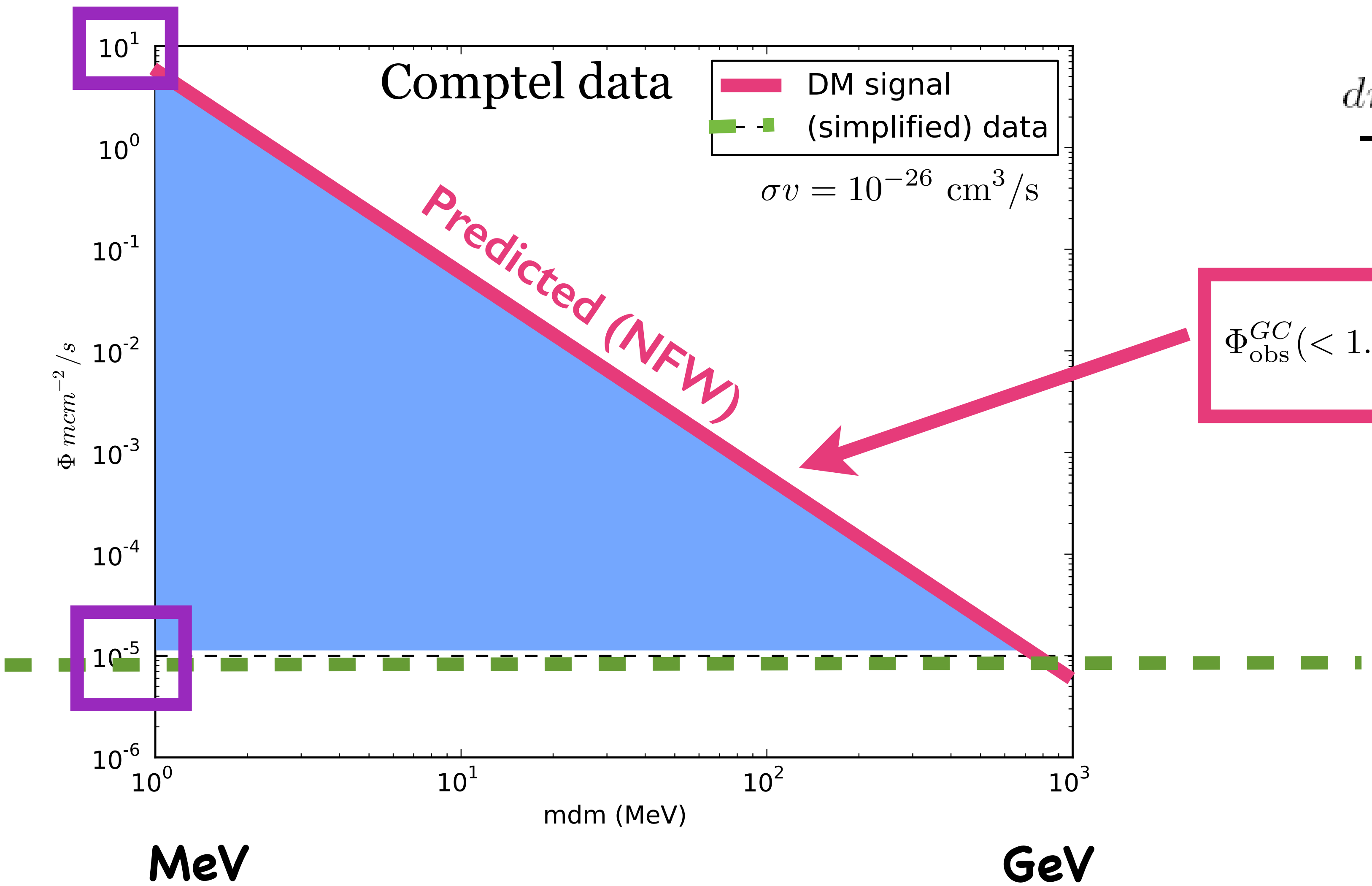
annihilations DM DM —> SM SM + photons

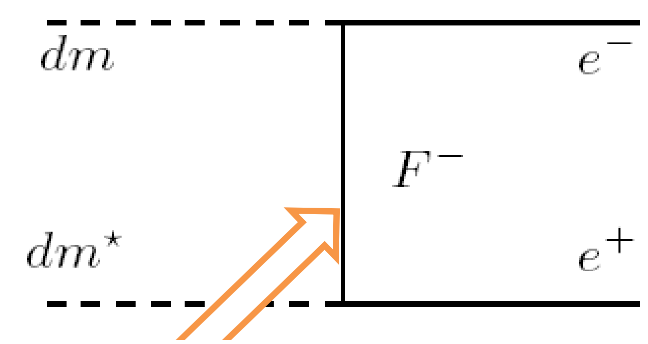
Only depends on the DM profile

$$\frac{d\phi}{dE} = \frac{1}{8\,\pi}\left(\frac{\sigma v}{m_\chi^2}\right) \underbrace{\sum_i \mathrm{BR_i}\,\frac{\mathrm{dN_i}}{\mathrm{dE}}}_{=1}\,\xi^2 \boxed{\int \mathrm{dl}\ \rho_\chi^2(\mathrm{l})} \Rightarrow \Phi_{\mathrm{prompt}} \propto \frac{\sigma v}{\mathrm{m_{DM}}^2}\int dl\ \rho^2(l)$$

Gamma rays constrain the light mass range

astro-ph/0208458 & hep-ph/030526





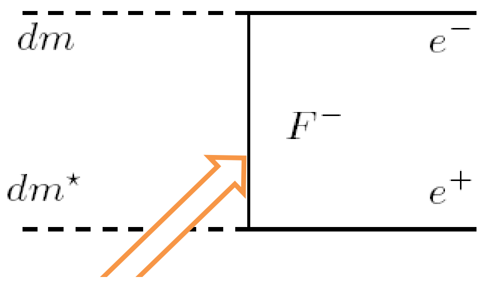
$$\Phi^{GC}_{\rm obs}(< 1.5^\circ) \sim\ 5.9\ \left(\frac{m_{\rm DM}}{\rm MeV}\right)^{-2} \left(\frac{\sigma v}{10^{-26}\ {\rm cm}^3/{\rm s}}\right)\ {\rm cm}^{-2}\ {\rm s}^{-1}$$

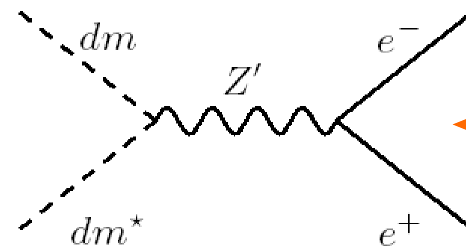
LIGHT (thermal) DM needs p-wave annihilations or neutral final states

Light (MeV - 10 GeV) DM

astro-ph/0208458

too many gamma-rays
unless it is suppressed





correct abundance
small indirect detection signal

Are light annihilating Dark Matter particles possible?

astro-ph/0208458

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*

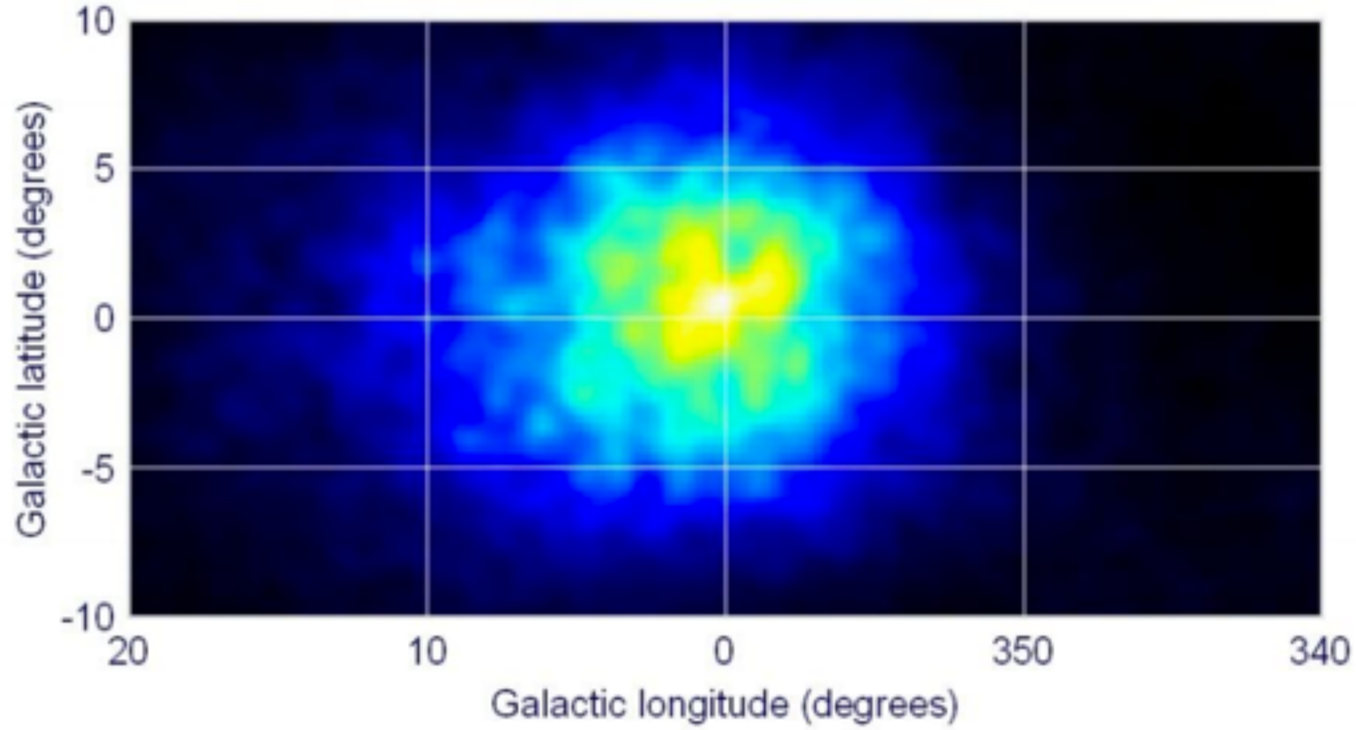
(Dated: 22 August 2002)

We investigate the status of light Dark Matter (DM) particles from their residual annihilation and discuss the range of the DM mass and total annihilation cross section compatible with gamma-rays experiment data. We find that particles as light as a few 10 MeV or up to $\sim$ 10 GeV could perhaps represent an interesting alternative to the standard picture of very massive WIMPs.

So in principle no reason to neglect the low mass range!

Related signals: the 511 keV line

astro-ph/0309686

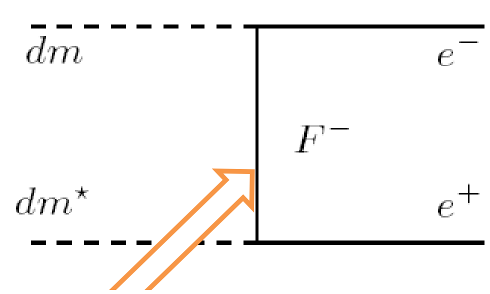


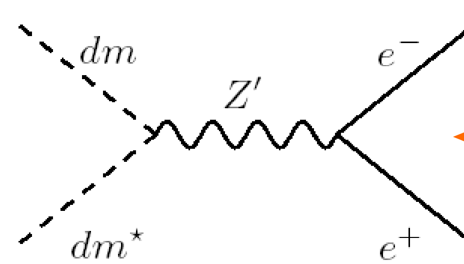
511 keV

DM DM -> e- e+

If DM has a mass of a few MeV it may explain the 511 keV line

signal at LHC?





very constrained now
and not necessarily a good fit

Light (MeV - 10 GeV) DM

astro-ph/0208458

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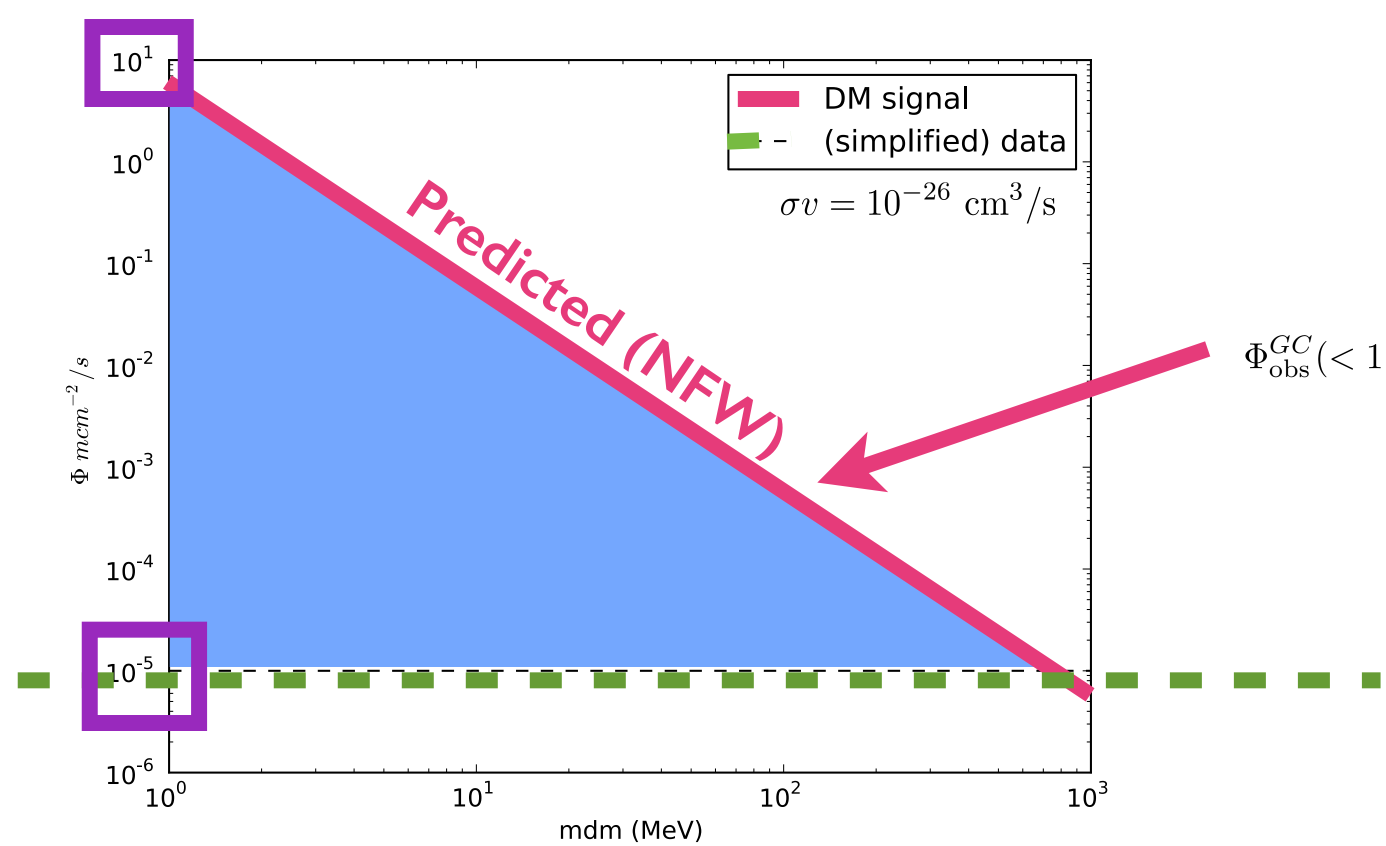
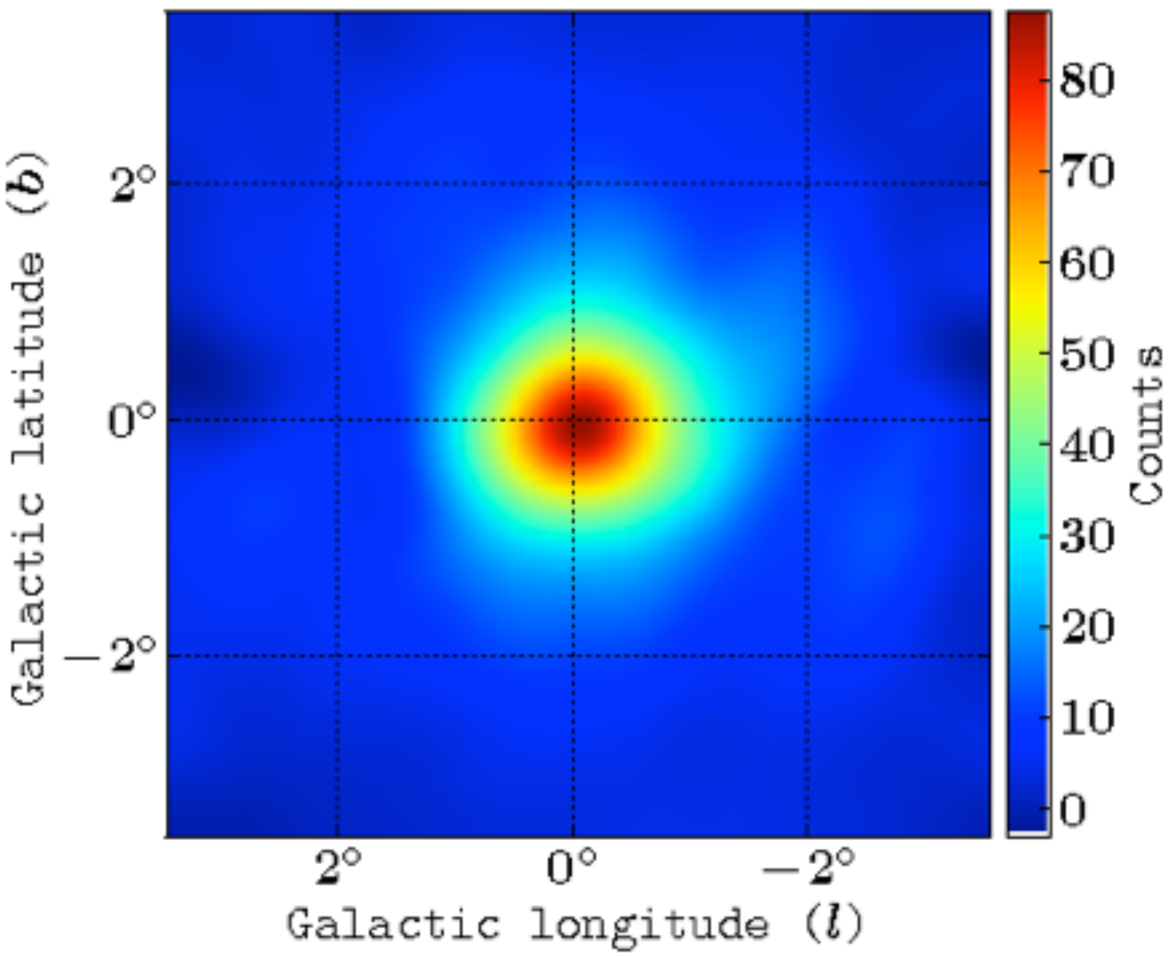


$$\Phi^{GC}_{\rm obs}(<1.5^\circ) \sim\ 5.9\ \left(\frac{m_{\rm DM}}{\rm MeV}\right)^{-2}\ \left(\frac{\sigma v}{10^{-26}\ \rm cm^3/s}\right)\ \rm cm^{-2}\ s^{-1}$$

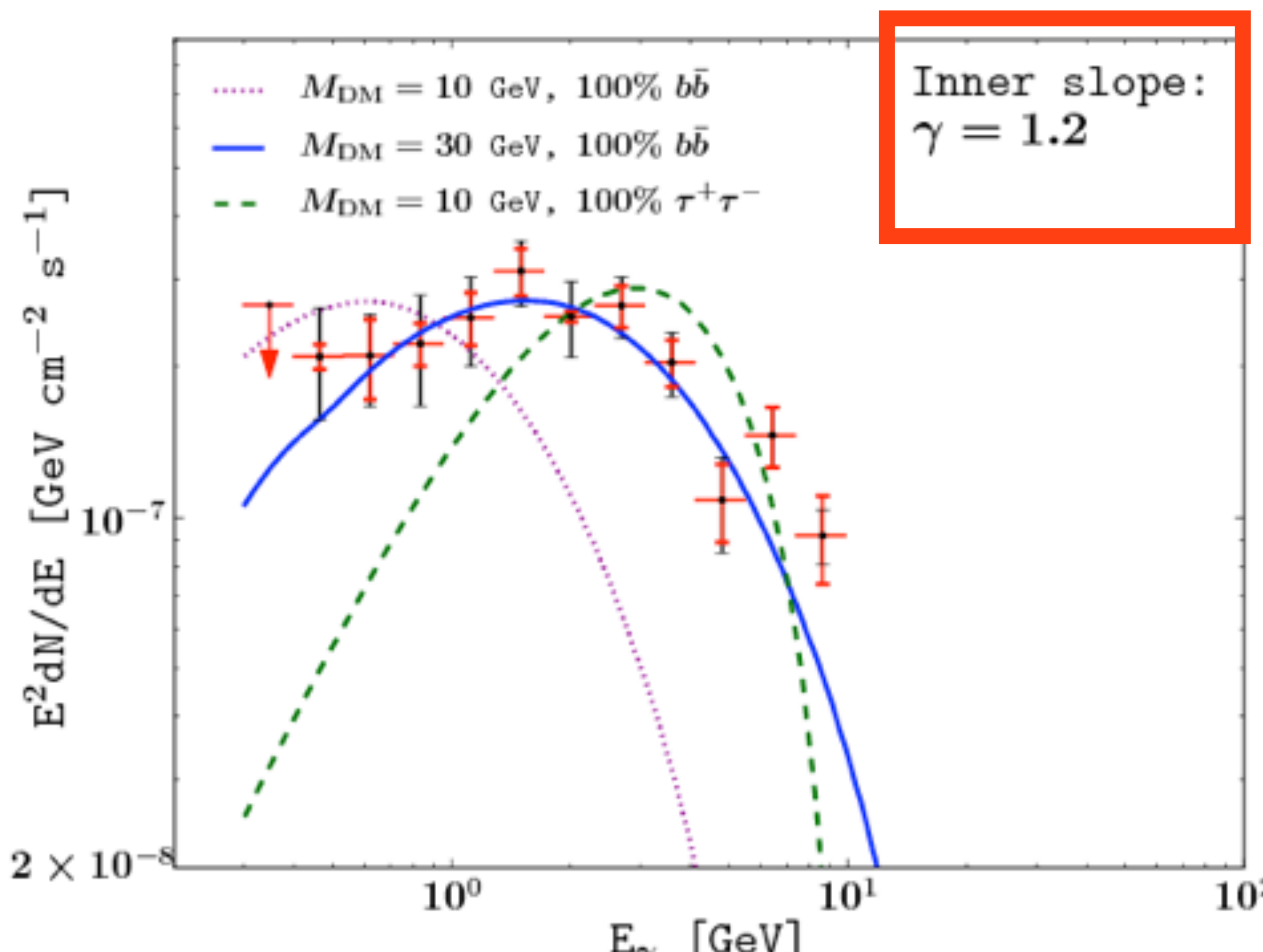
observations (rough guide!)

Me Ge

Related signals: the gamma-ray excess



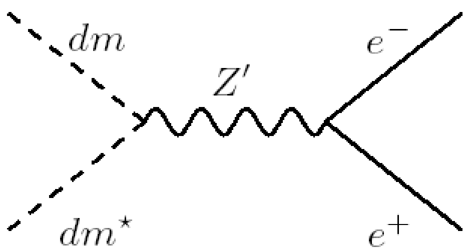
10-30 GeV DM annihilating mostly into b-quarks or muons can fit the FERMI-LAT data...

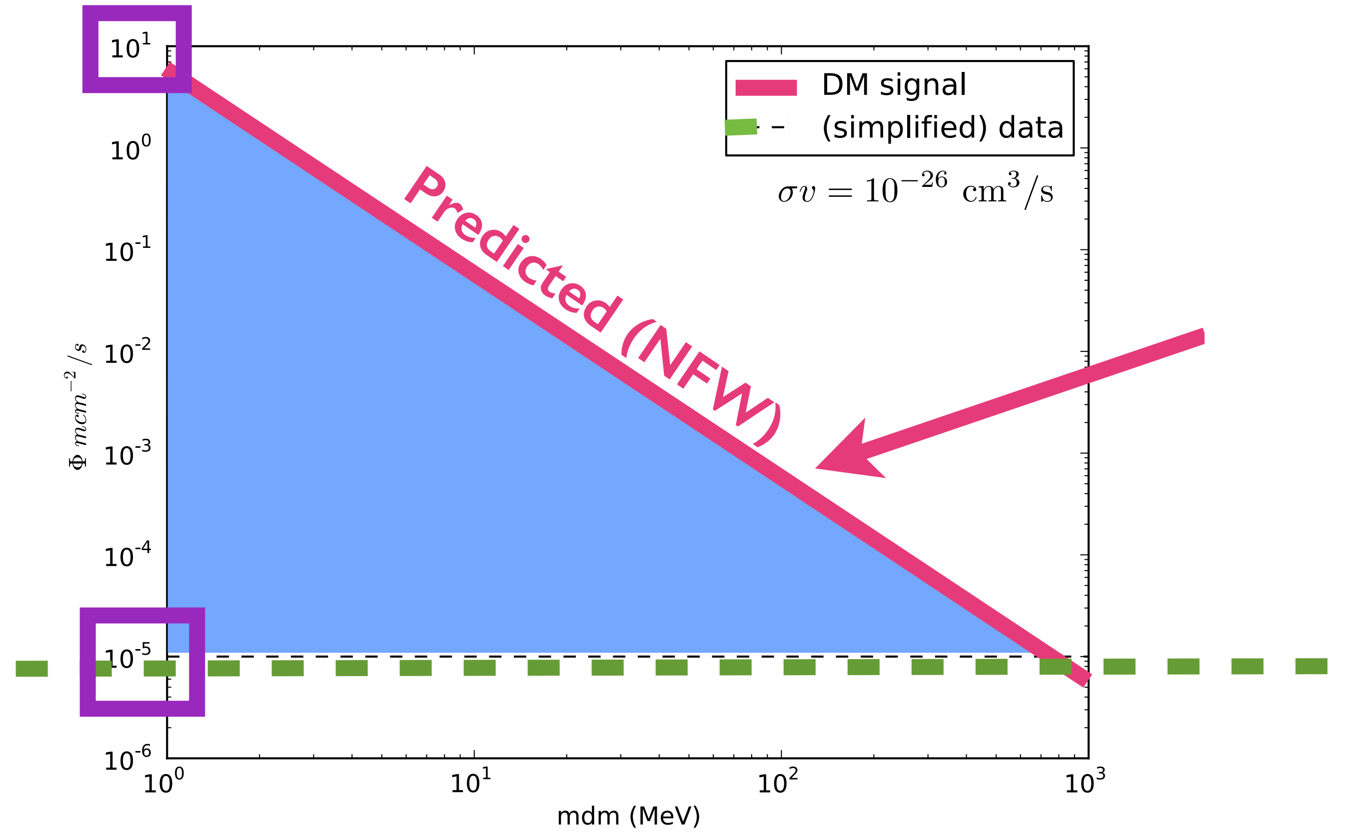


Fermi collaboration 2009
Hooper&Goodenough 2009
D. Hooper and T. Linden: arXiv: 1110.0006
C. Gordon & O. Macias: arXiv:1306.5725

Light (MeV - 10 GeV) DM

astro-ph/0208458





MeV GeV

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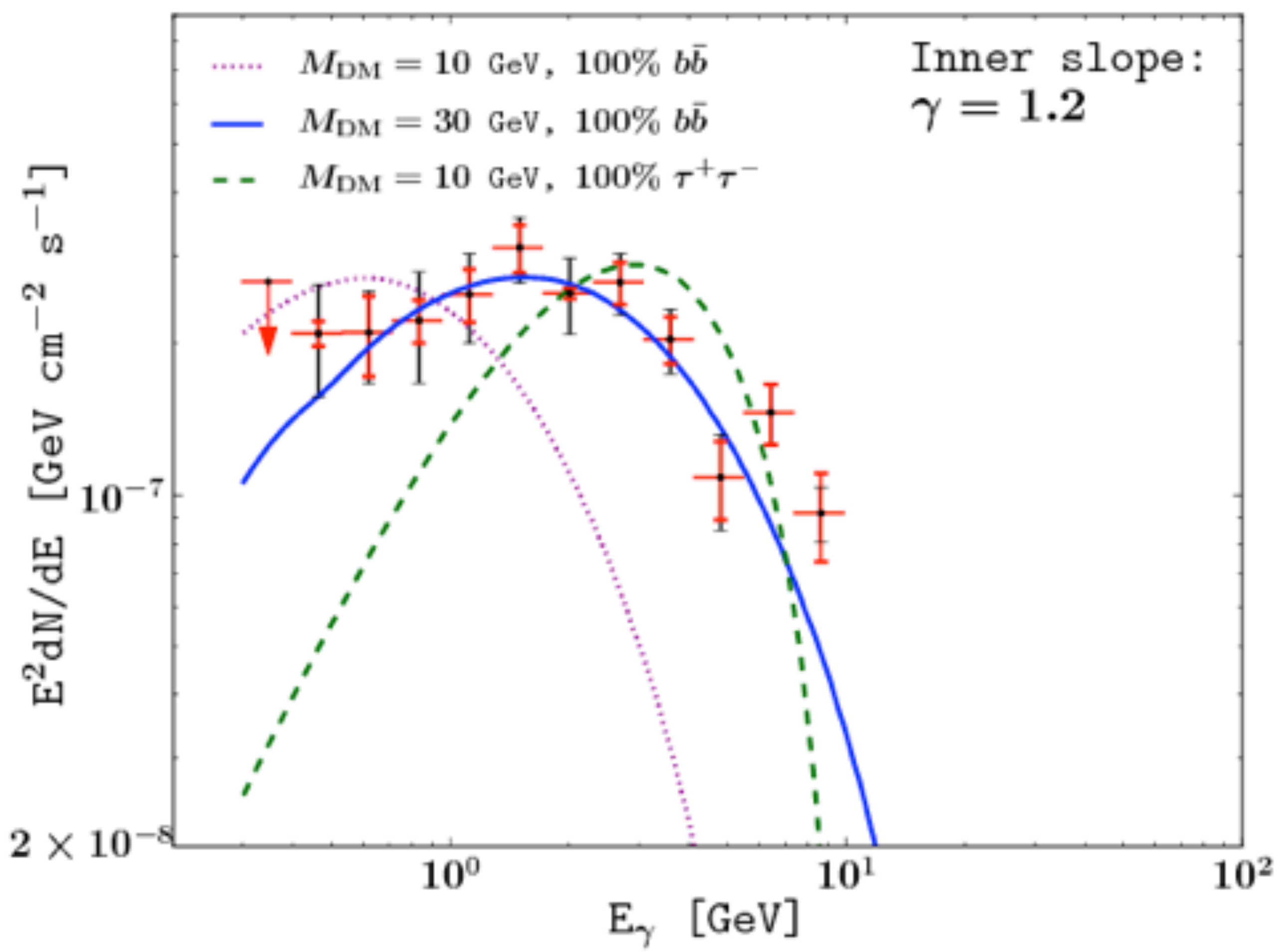
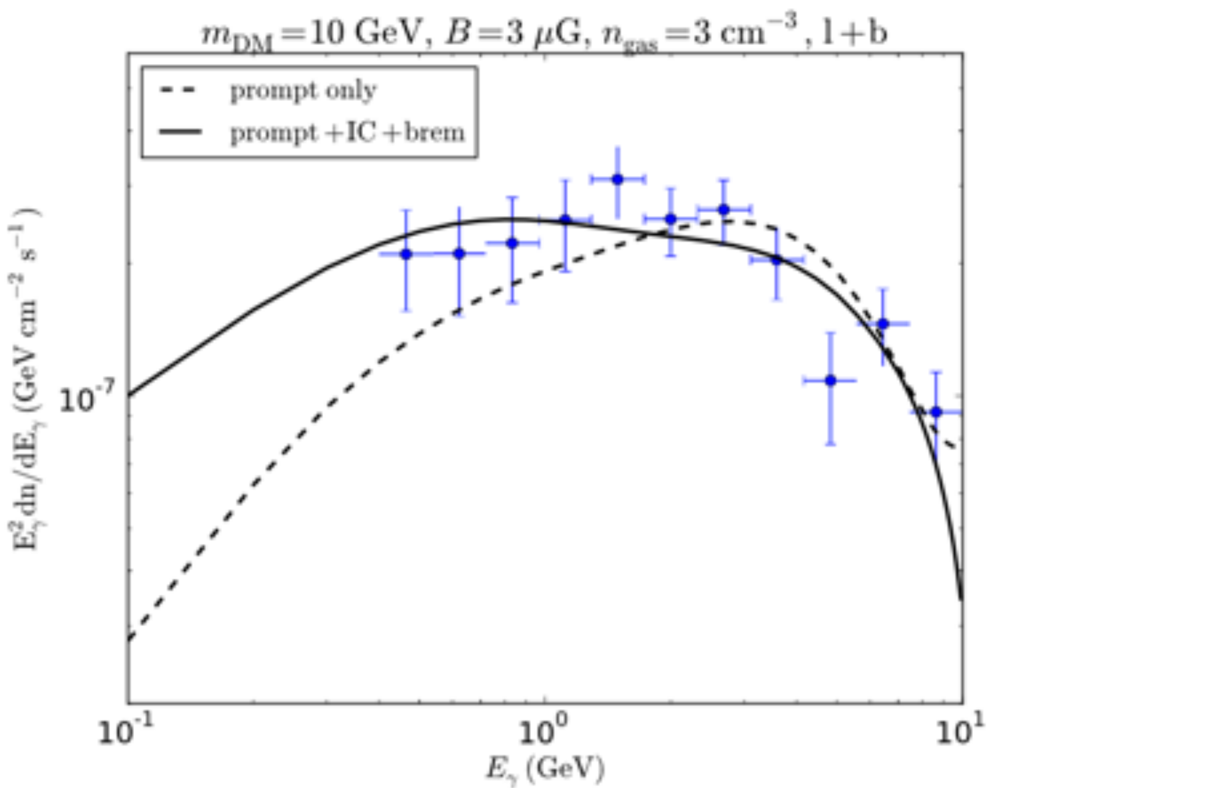
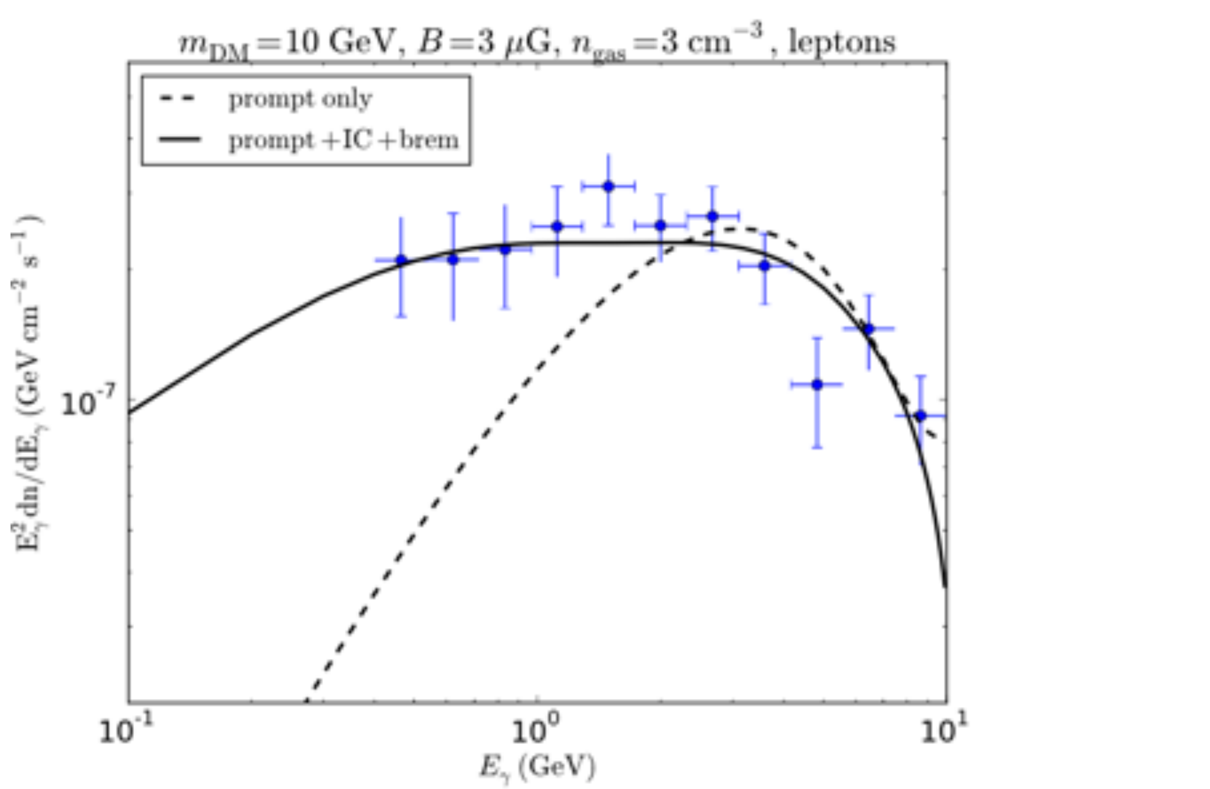
Related signals: the gamma-ray excess

But propagation of cosmic ray cannot be neglected







Conclusion

We can probe DM microphysics using

Direct detection
Indirect detection
LHC (particle physics experiments)

But now also: Large scale surveys

(probing LCDM will be essential if no discovery in lab experiments!)