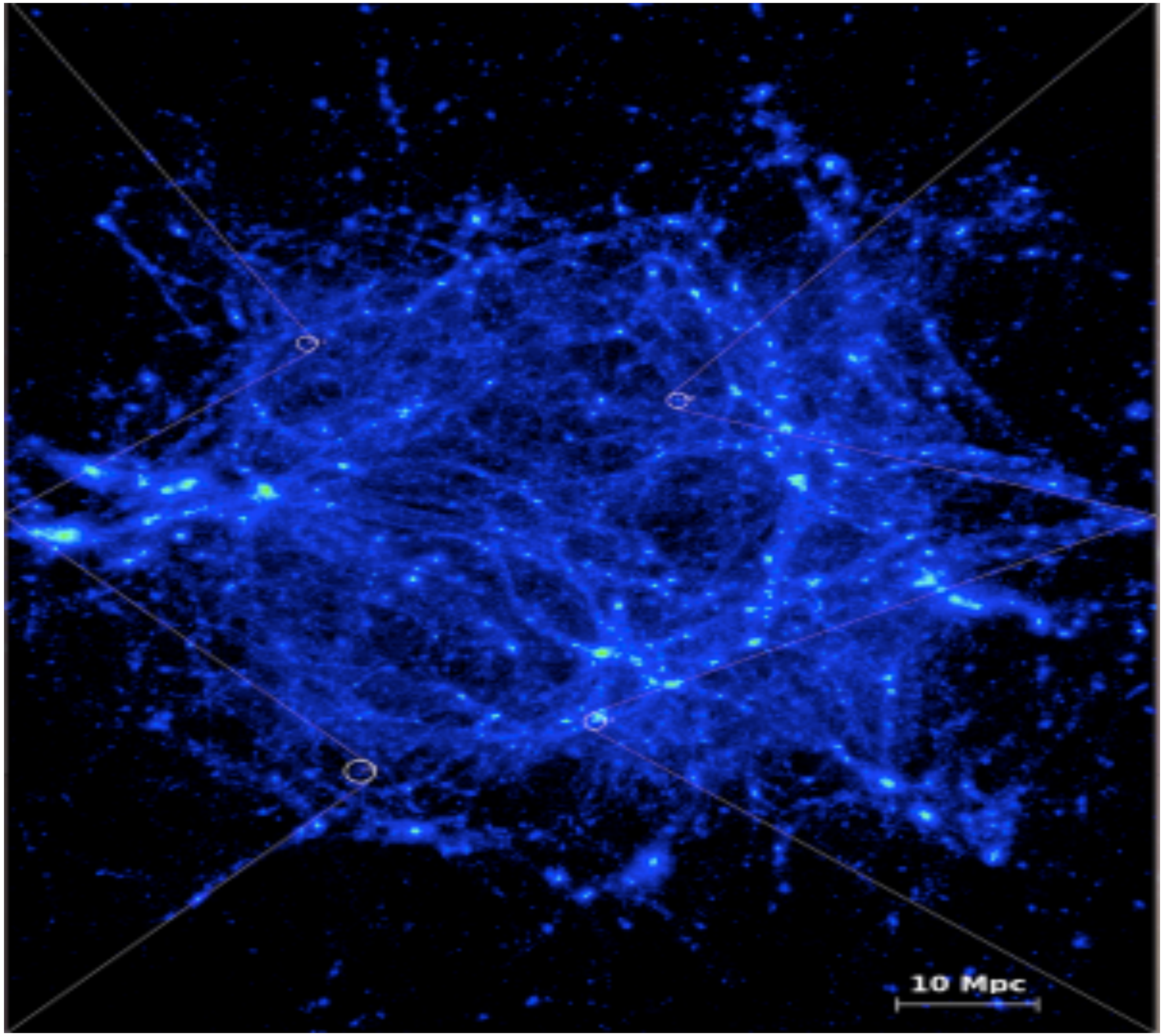
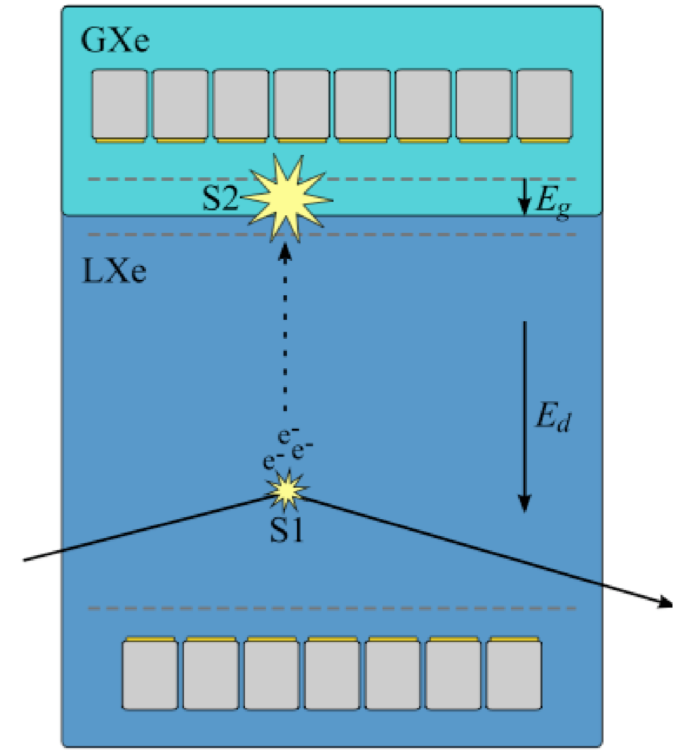
Recent progress in Dark Matter



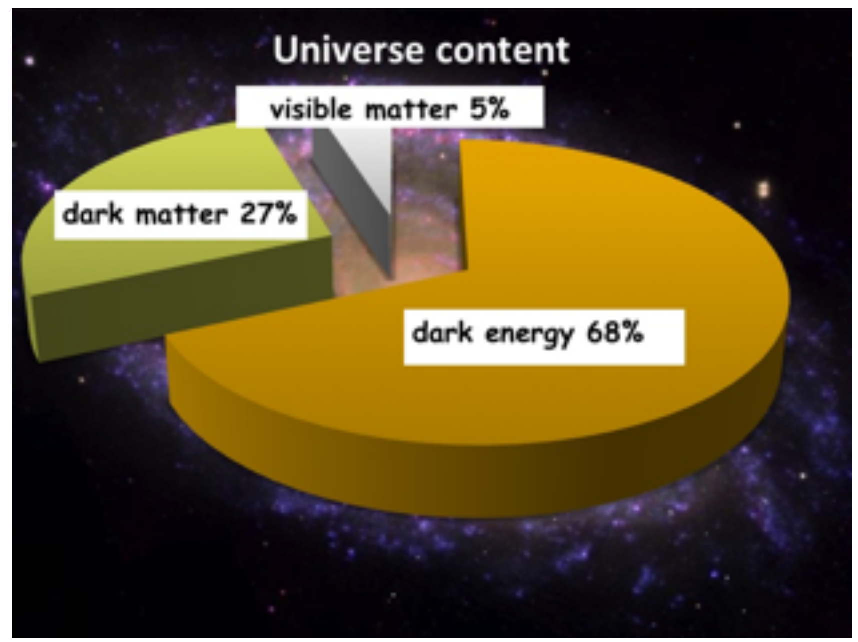
Céline Boehm

IPPP, Durham   LAPTH, Annecy

NCTS, Hsinchu, 11 Dec 2015

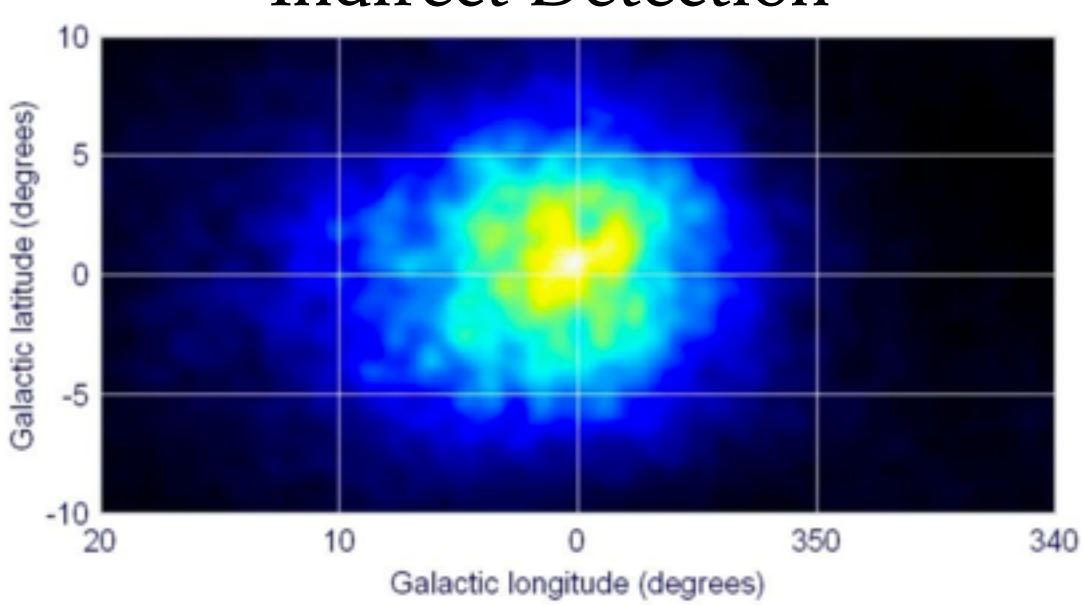


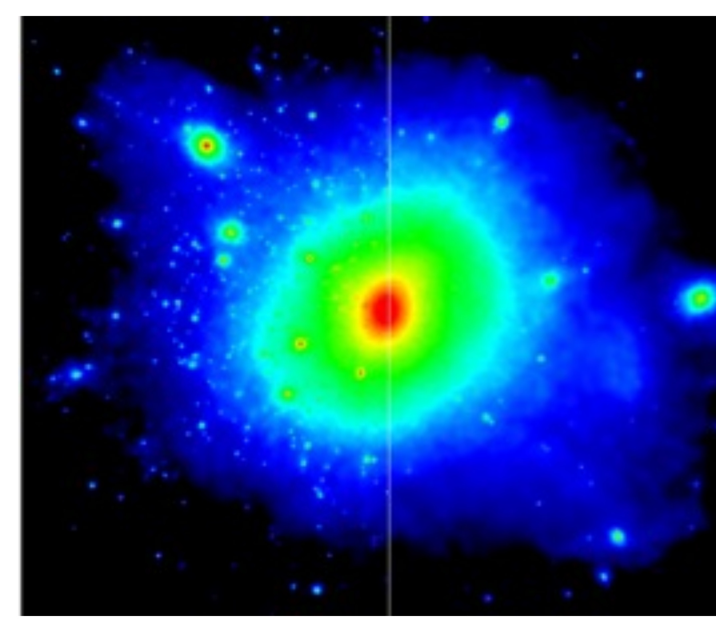
Direct Detection



Cosmology

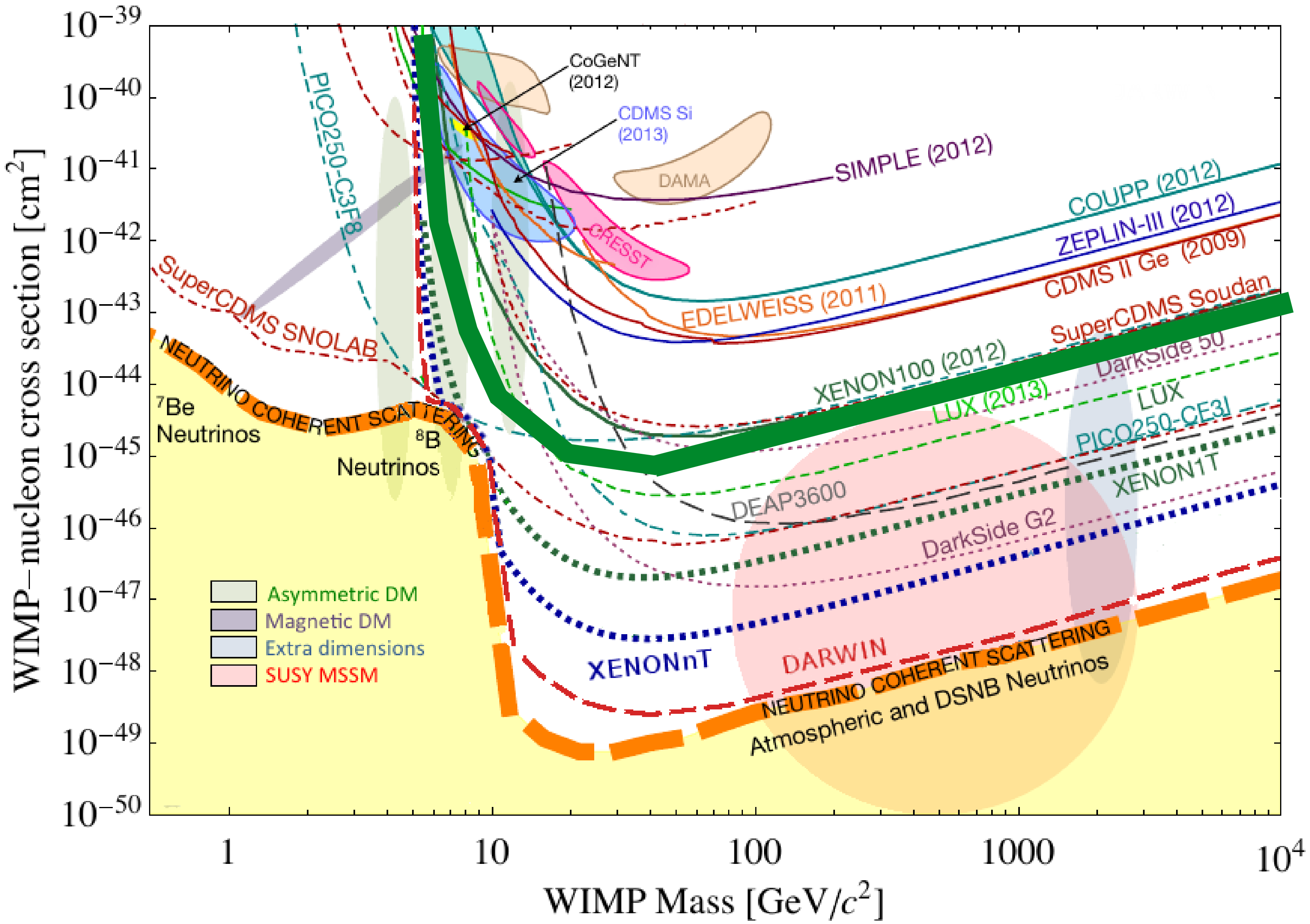
Indirect Detection

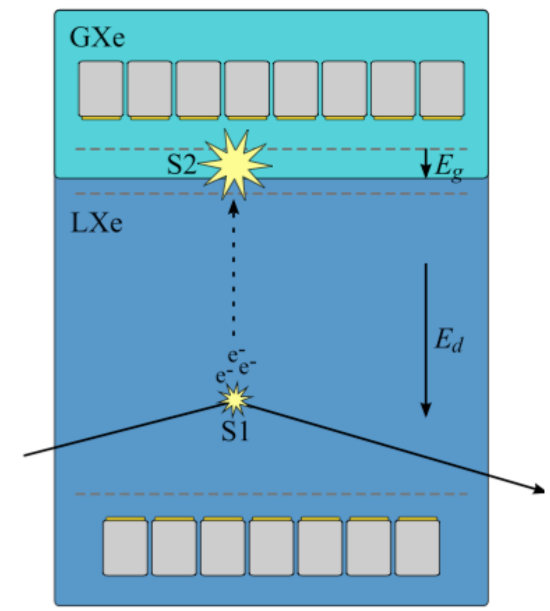


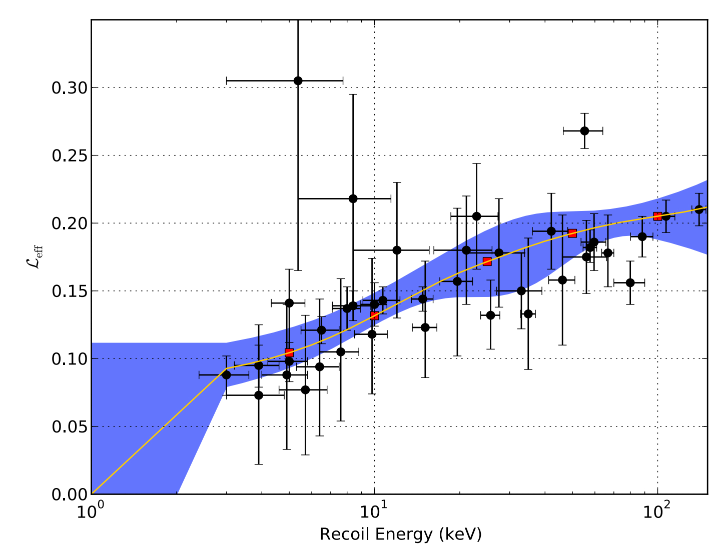


Direct detection

A. Direct detection





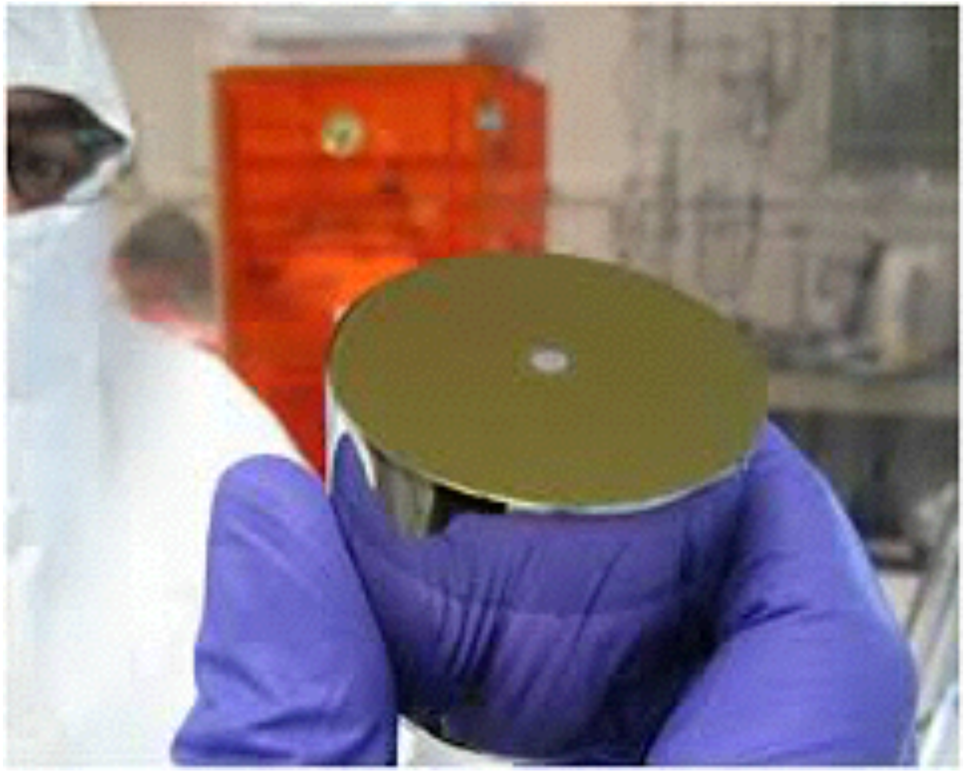


1) Tremendous progress in 15 years!
2) But anomalies
3) Neutrino floor

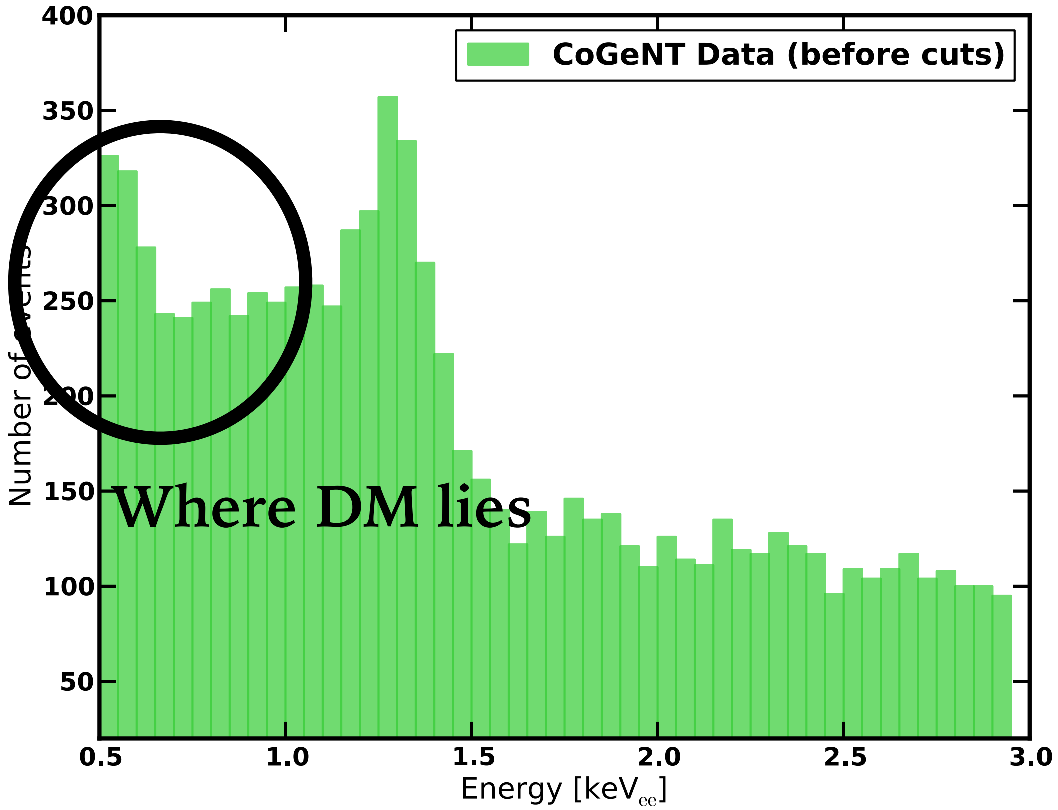
A. Direct detection

status of anomalies?   (CRESST, CoGeNT, DAMA)

CoGeNT



collect ionisation charge



Claim of an excess at low energy

Hopes for Light Dark Matter

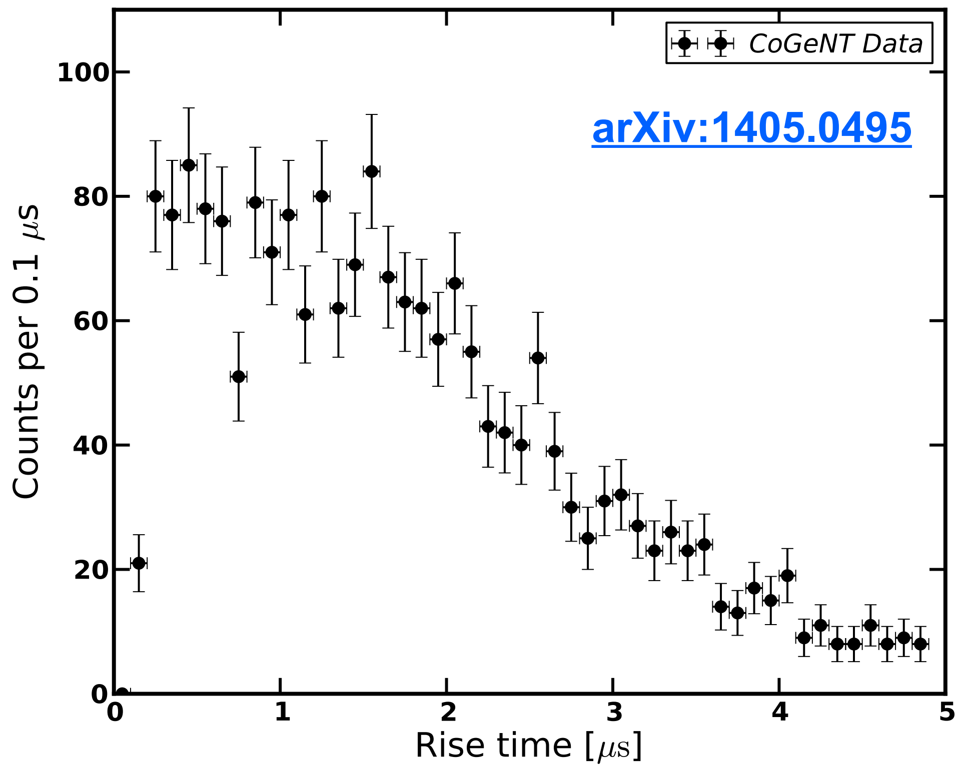
The CoGeNT detector collects signal+background

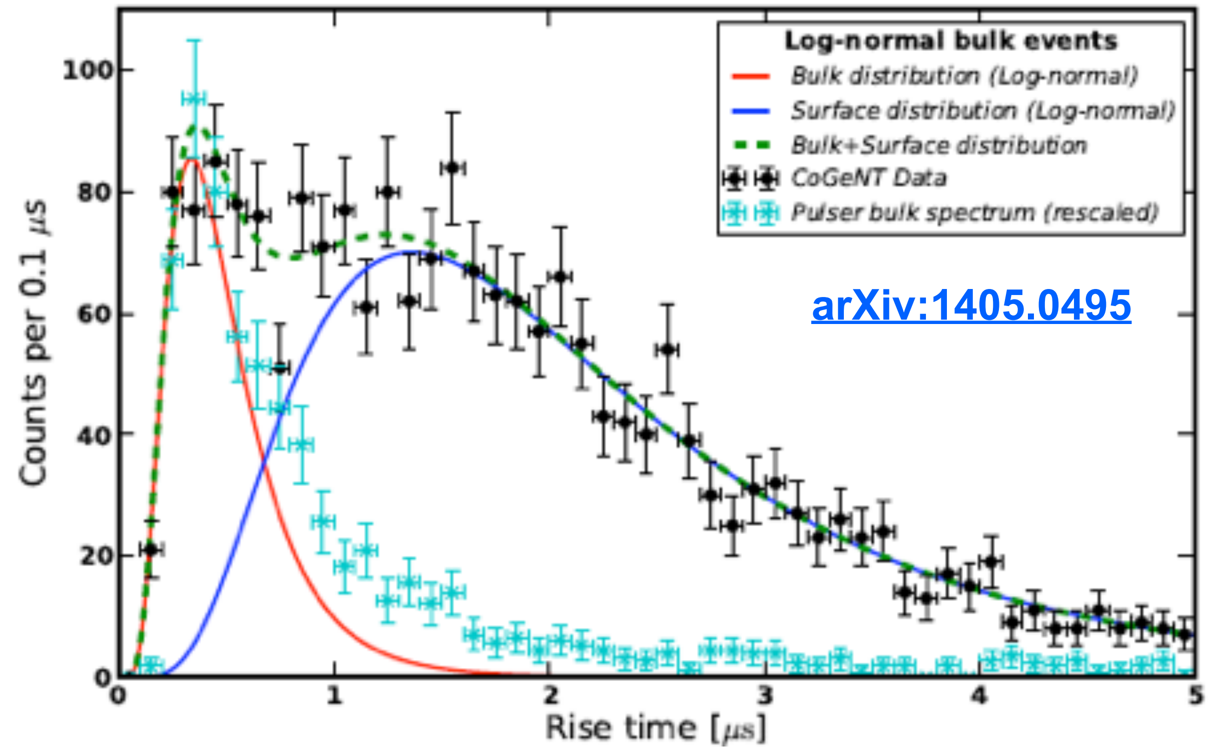
There is no way to distinguish between DM and neutrons

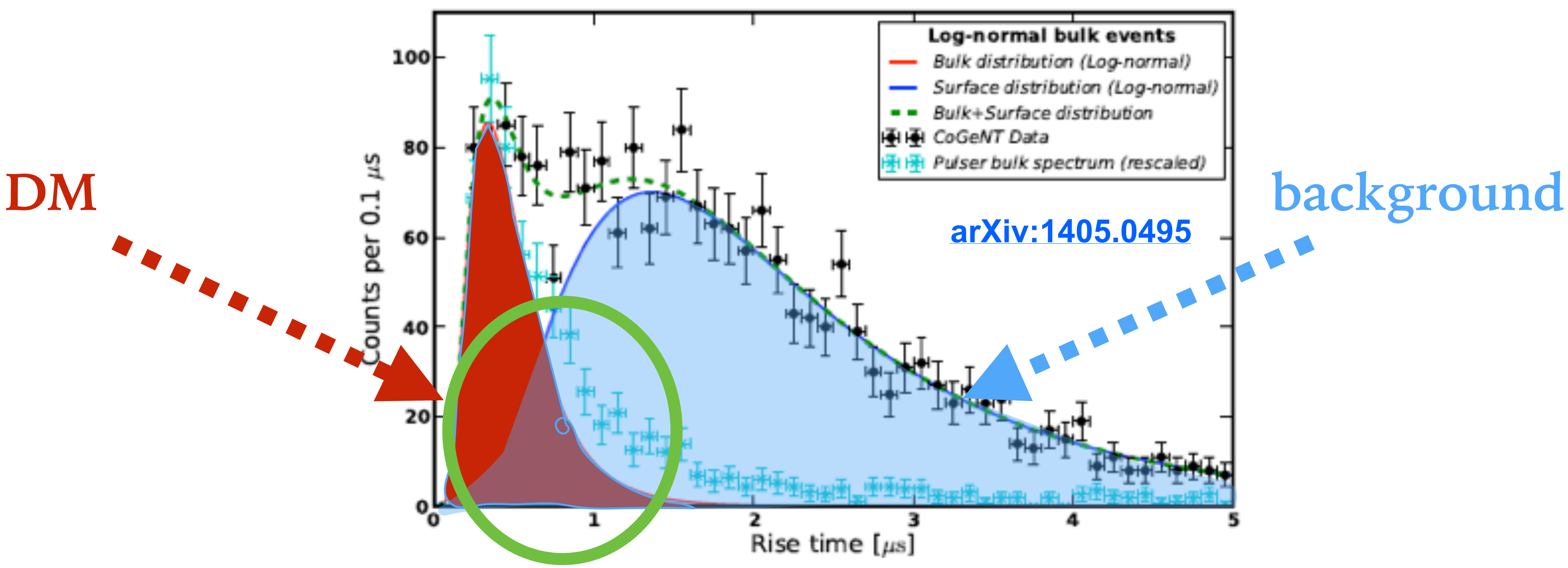
A. Direct detection

CoGeNT

To discriminate CoGeNT uses the rise time of events

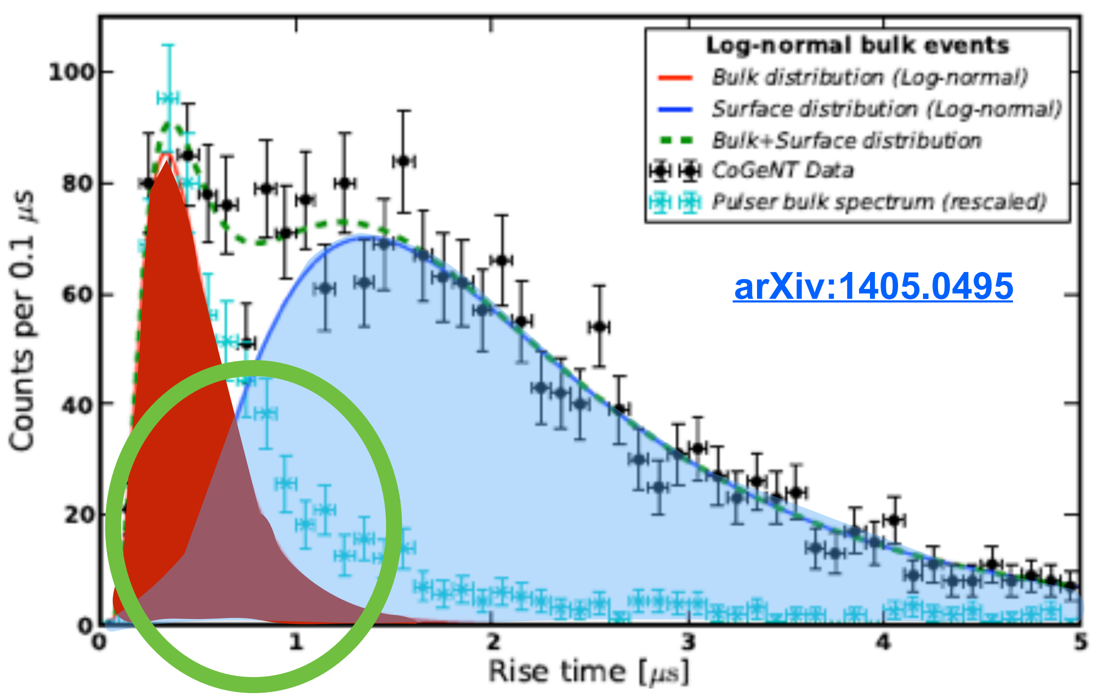






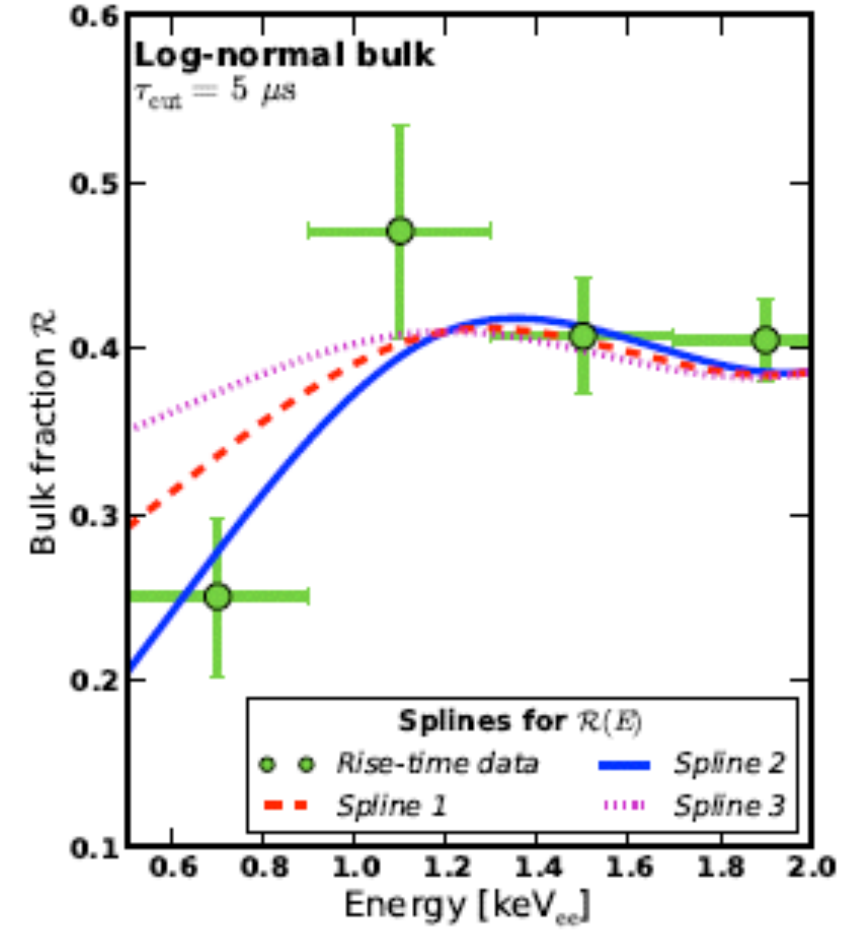
A. Direct detection

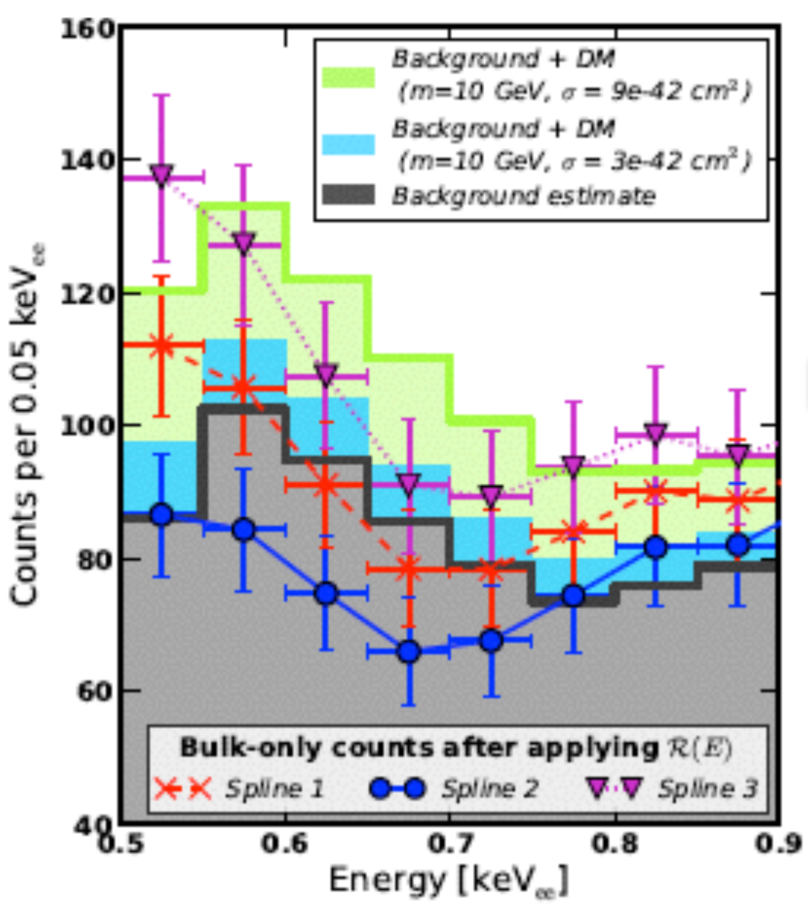
CoGeNT

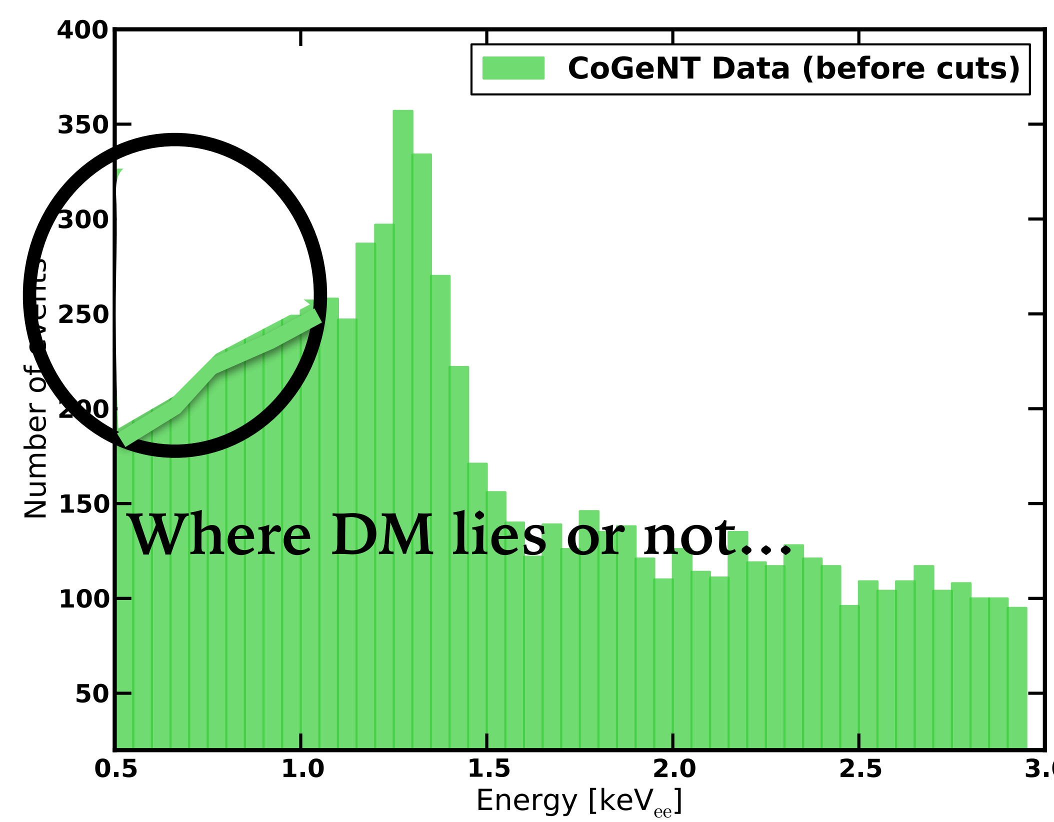


“signal (DM)”/“background”

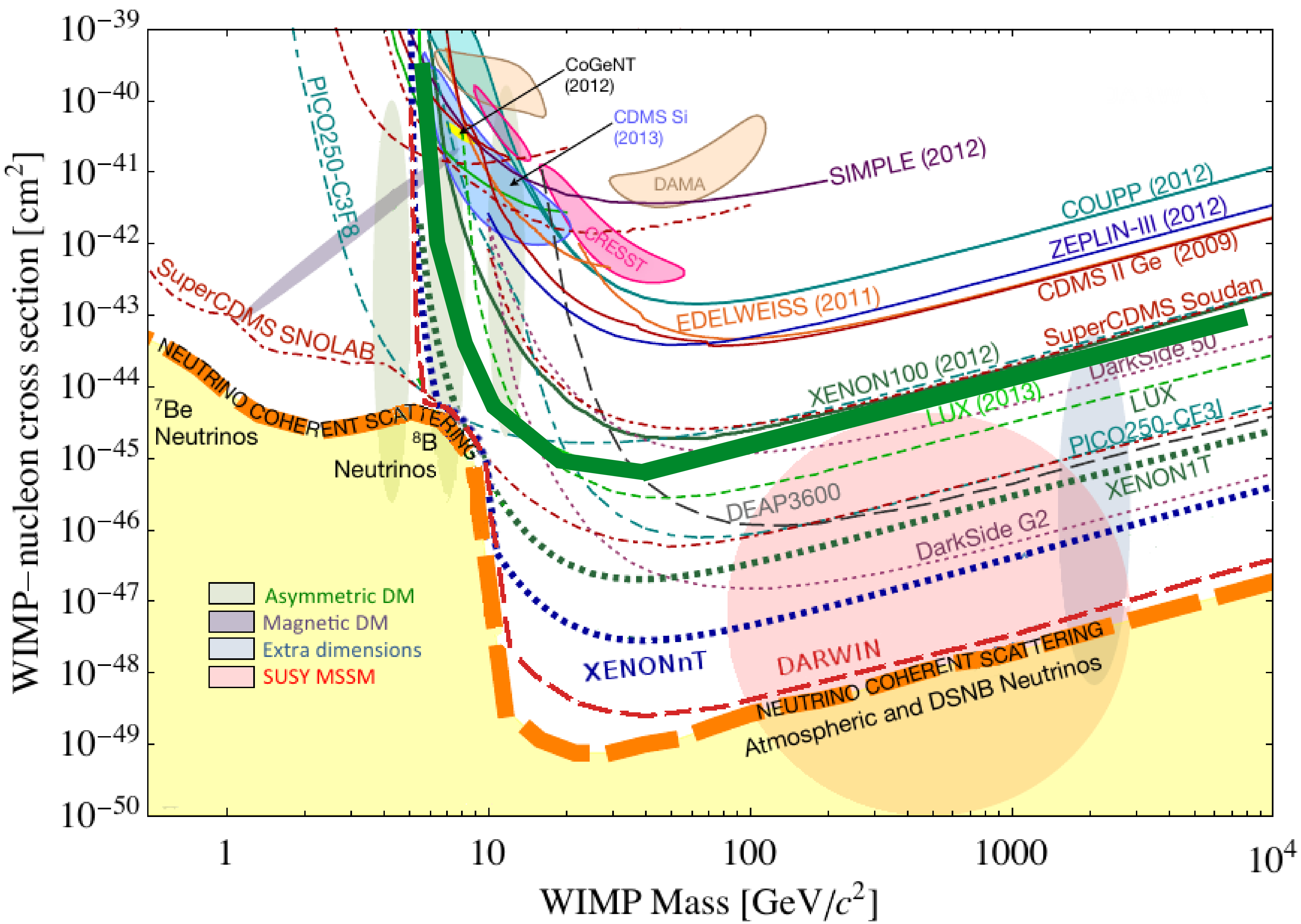
Bulk fraction
per energy
only data points







A. Direct detection

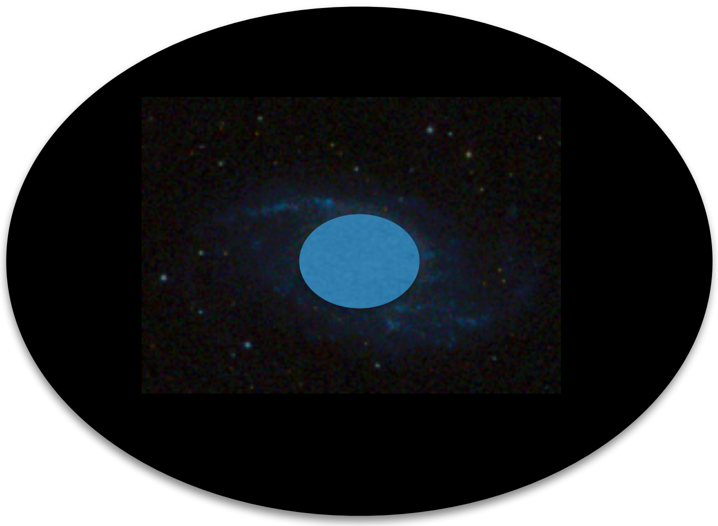


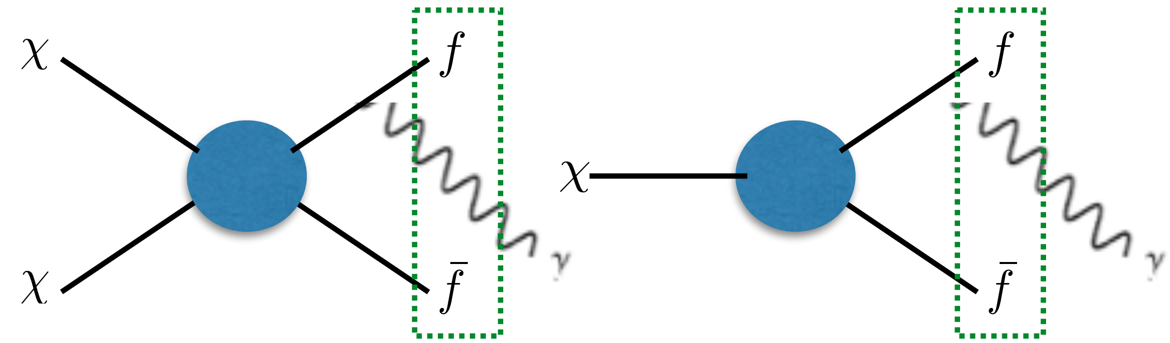
1) super CDMS will probe small masses (just below 1 GeV)
2) Still some room before we reach the neutrino floor
3) But soon we will be doing neutrino physics!

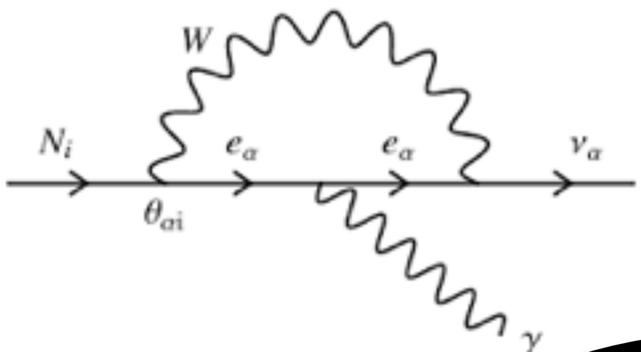
Indirect detection

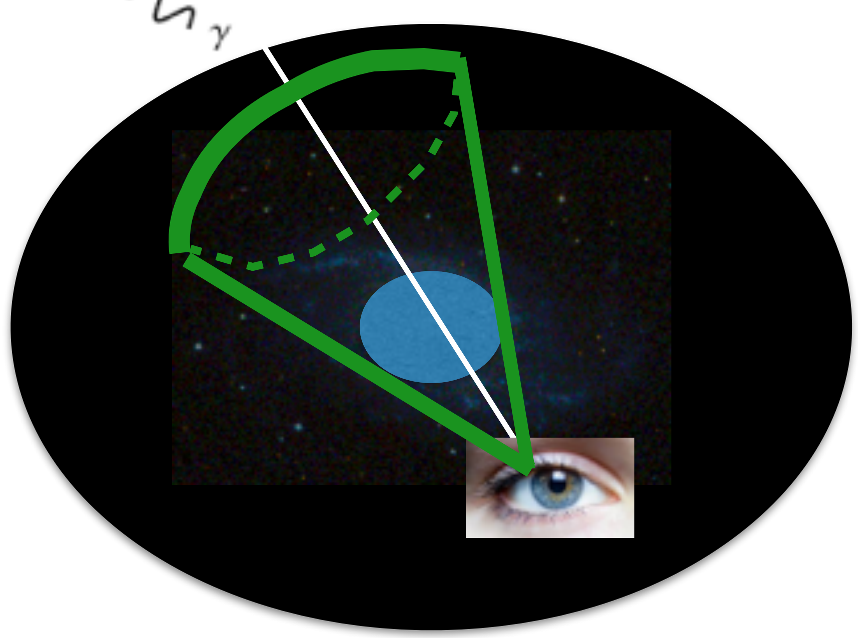
B. Indirect detection

Silk & Srednicki 1984
Silk, Olive & Srednicki 1985









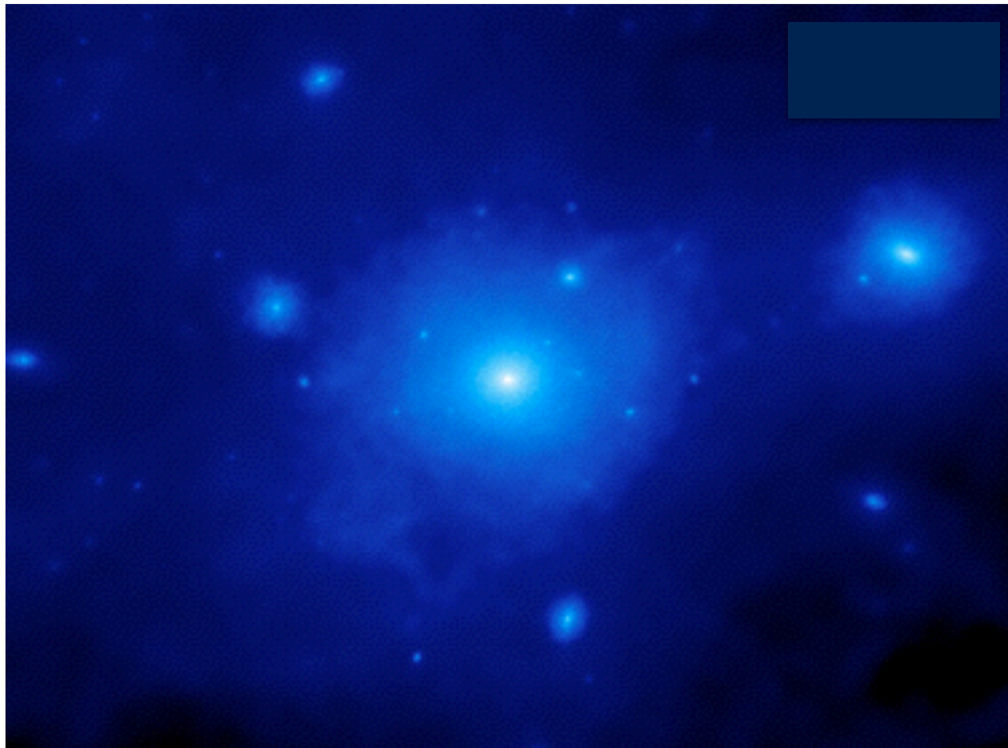
Integral over the l.o.s of
the interaction rate times DM number density

$$\frac{d\phi}{dE} = \frac{1}{8\pi}\left(\frac{\sigma v}{m_\chi}\right)^2 \sum_i \mathrm{BR_i}\,\frac{\mathrm{dN_i}}{\mathrm{dE}}\,\xi^2 \int \mathrm{dl}\,\rho_\chi^2(\mathrm{l})$$

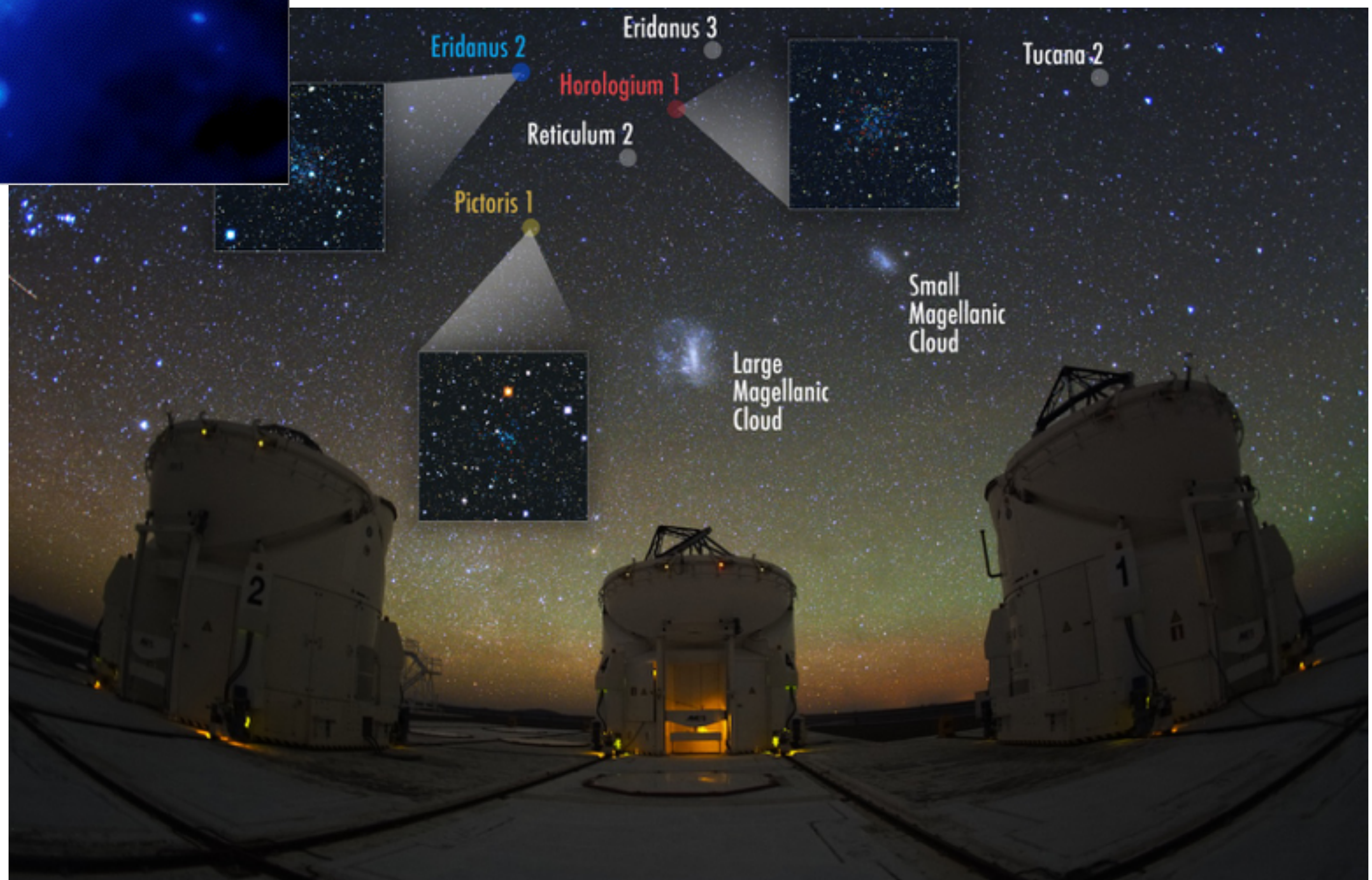
$$\boxed{\phi_X \simeq g_X\,\sigma v\left(\frac{\rho_0}{m_{dm}}\right)^2\left(\frac{r_s}{d}\right)^2\left[d\,\zeta\,\arctan\left(\frac{\sqrt{r_s^2-d^2\zeta^2}}{d\,\zeta}\right)\right]_{-\delta}^{+\delta}}$$

The GC is very messy!

Prompt gamma-ray emission in dwarf Spheroidal galaxies



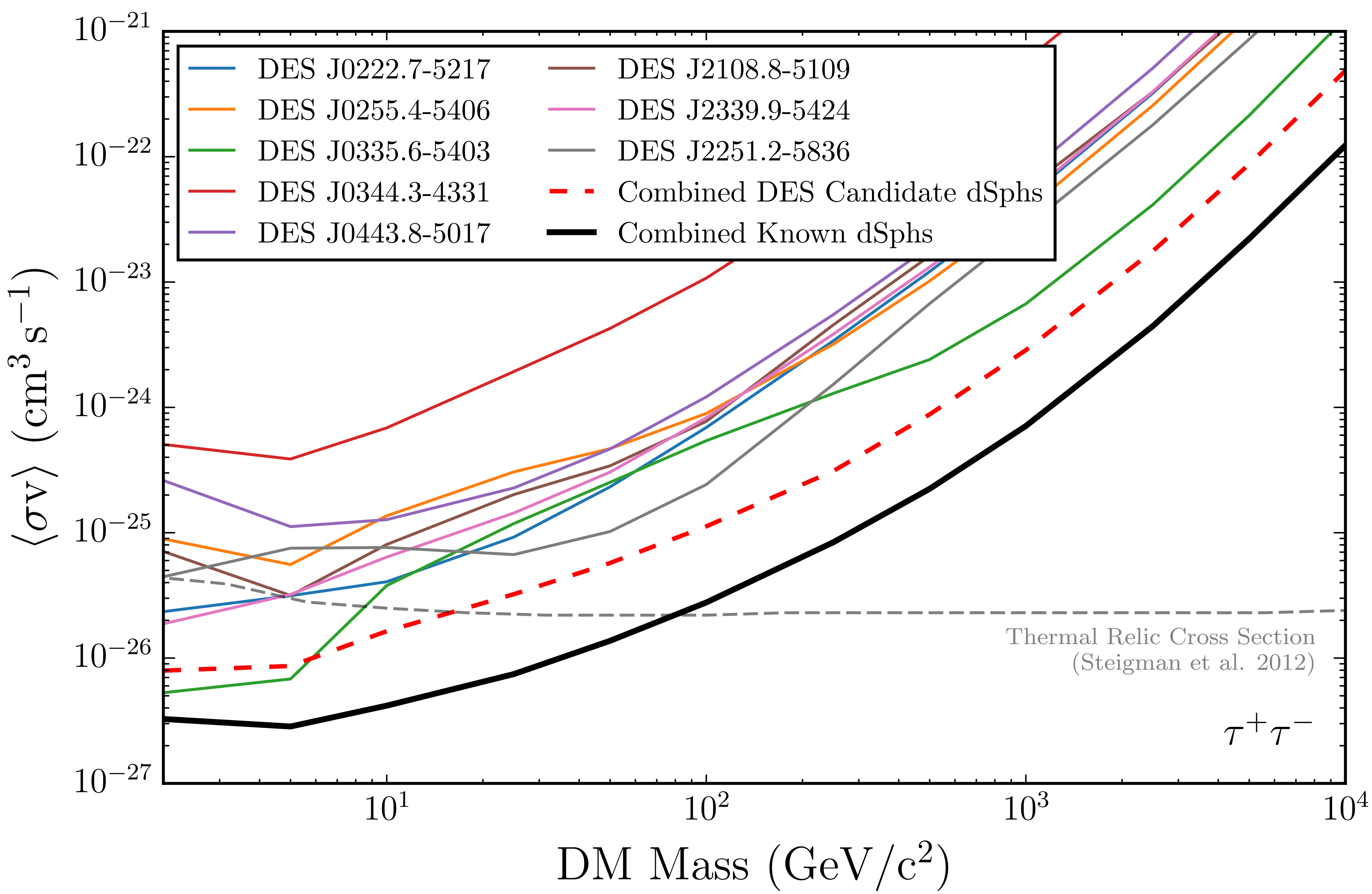
dSphs are faint objects presumably because they are DM dominated



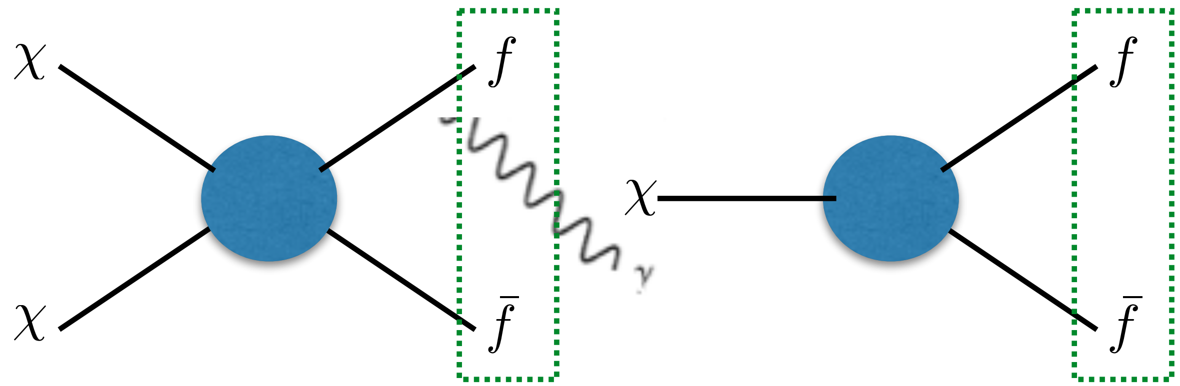
Prompt gamma-ray emission in Dwarf Spheroidal galaxies

DES + FERMI-LAT

s-wave thermal DM is excluded up to ~[20,100] GeV

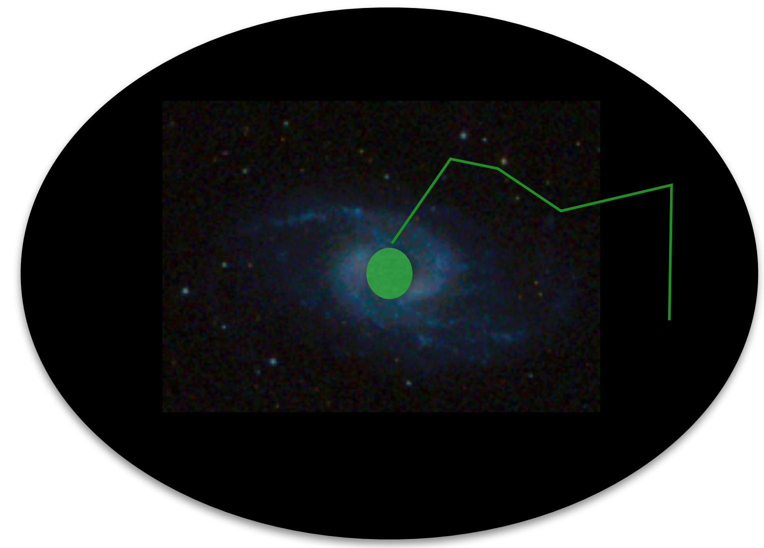


B. Indirect detection   Propagation of cosmic rays



electrons, positrons are produced eventually
(protons, antiprotons, deuterons etc)

$$f^- \Rightarrow e^-$$

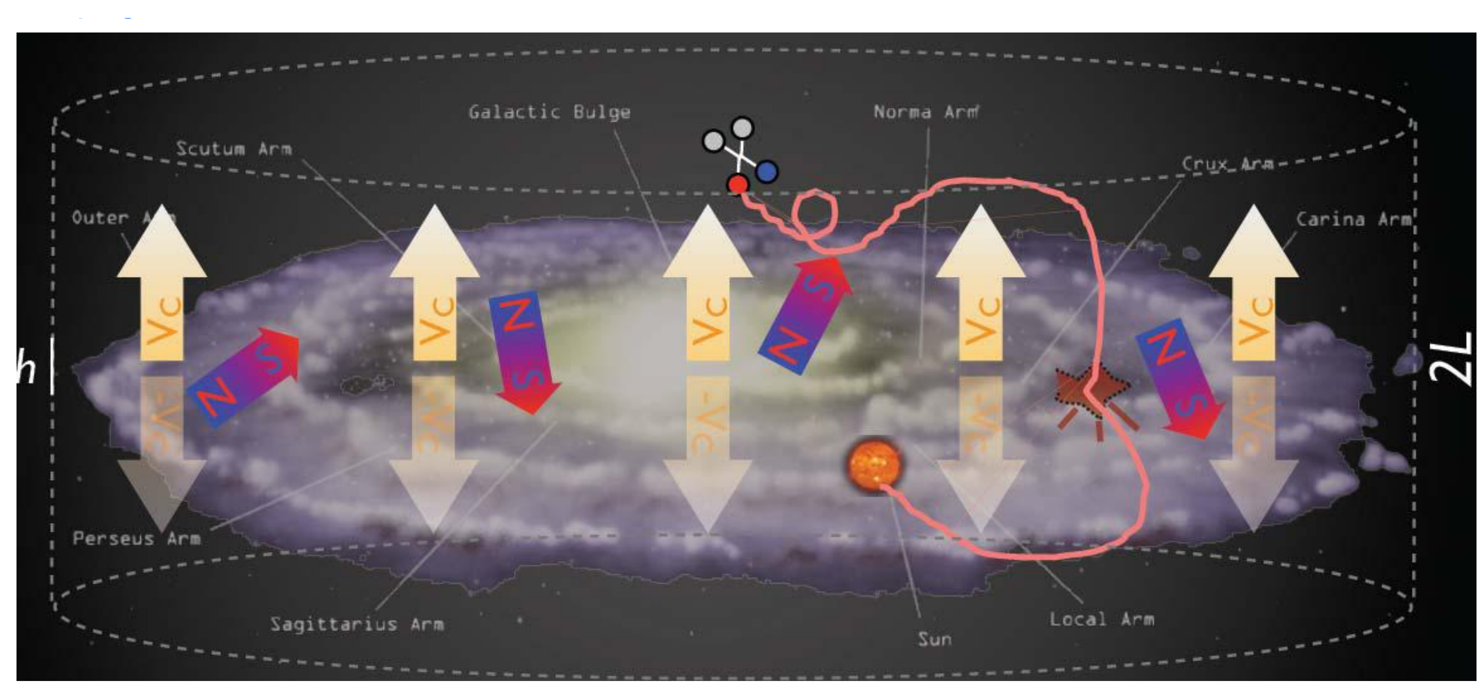


They can diffuse (B field)

They can lose energy
(Bremsstrahlung, IC, Coulomb…)

(They can also be accelerated)

courtesy P. Salati



B. Indirect detection   Propagation of cosmic rays

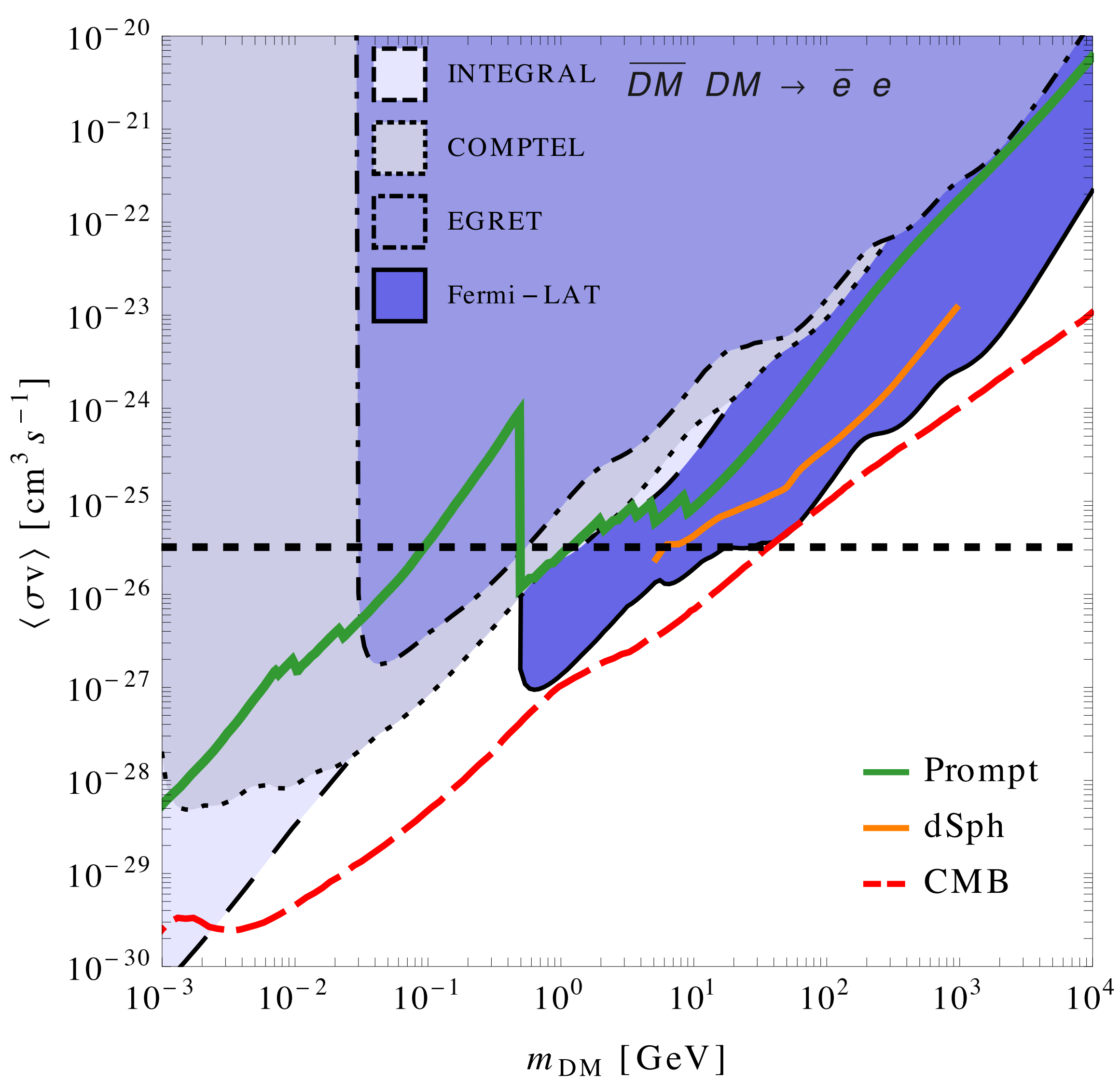
losses   source

$$\partial_t N(r,E) = K(E)\,\nabla^2 N(r,E) + \partial_E \big(b(E) N(r,E)\big) + Q(r,E)$$

$$\boxed{K(E) = K_0 \frac{d_B^{2/3}}{B_\mu^{1/3}} \left(\frac{E}{\{E_0 \equiv 1\ \mathrm{GeV}\}}\right)^{1/3}}$$

diffusion coefficient
(fitting astrophysical sources)

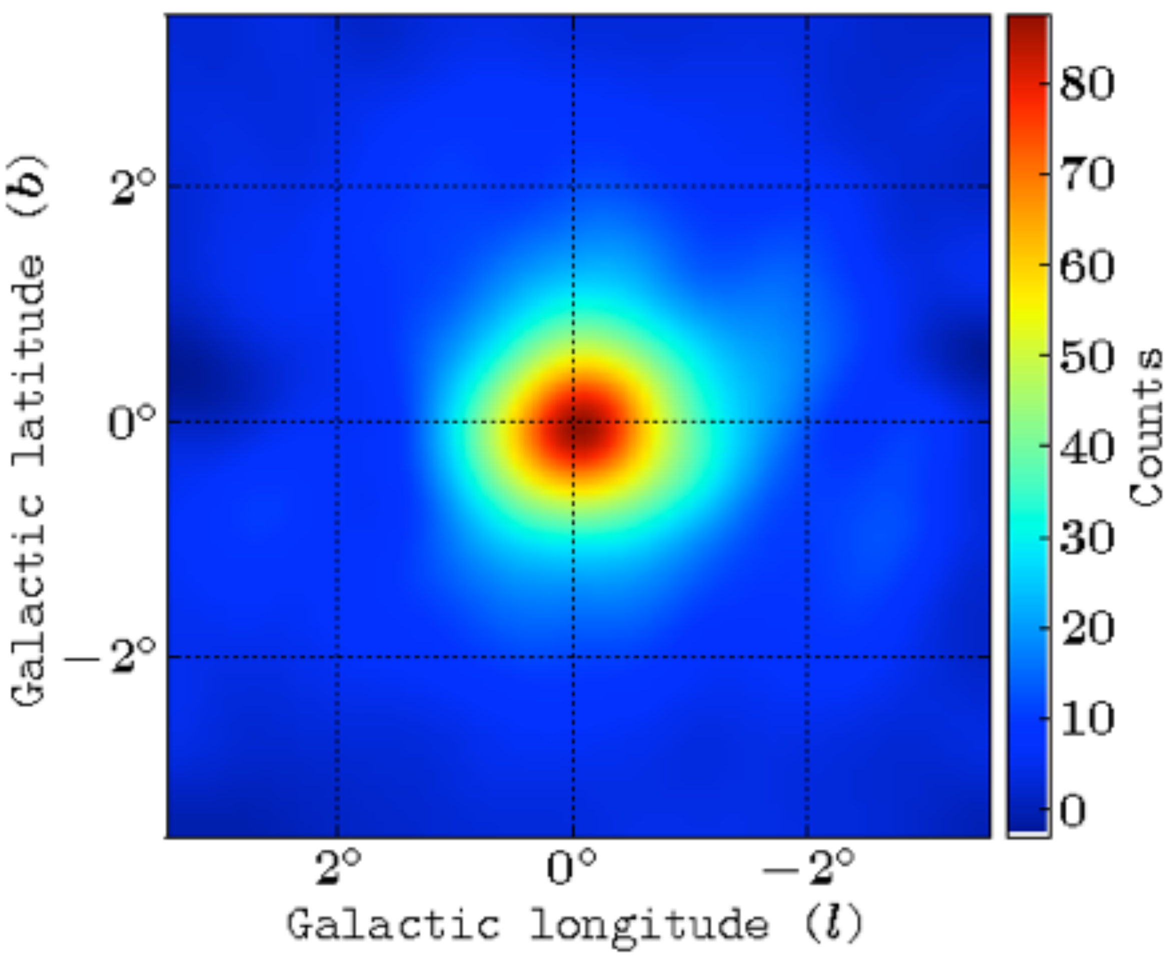
After propagation they can emit photons (same processes as for losses)

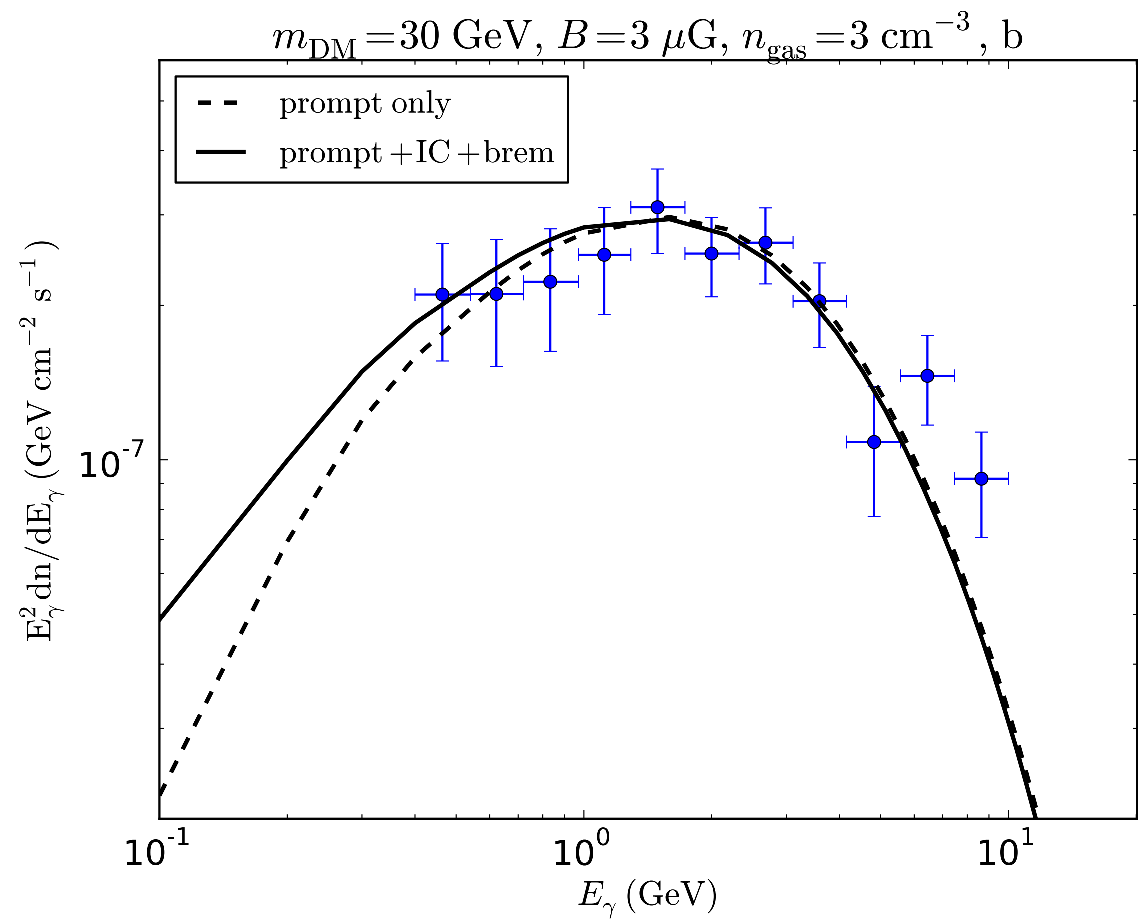


Jubb, AV, CB
in preparation

B. Indirect detection Propagation of cosmic rays

Light DM and the GeV excess

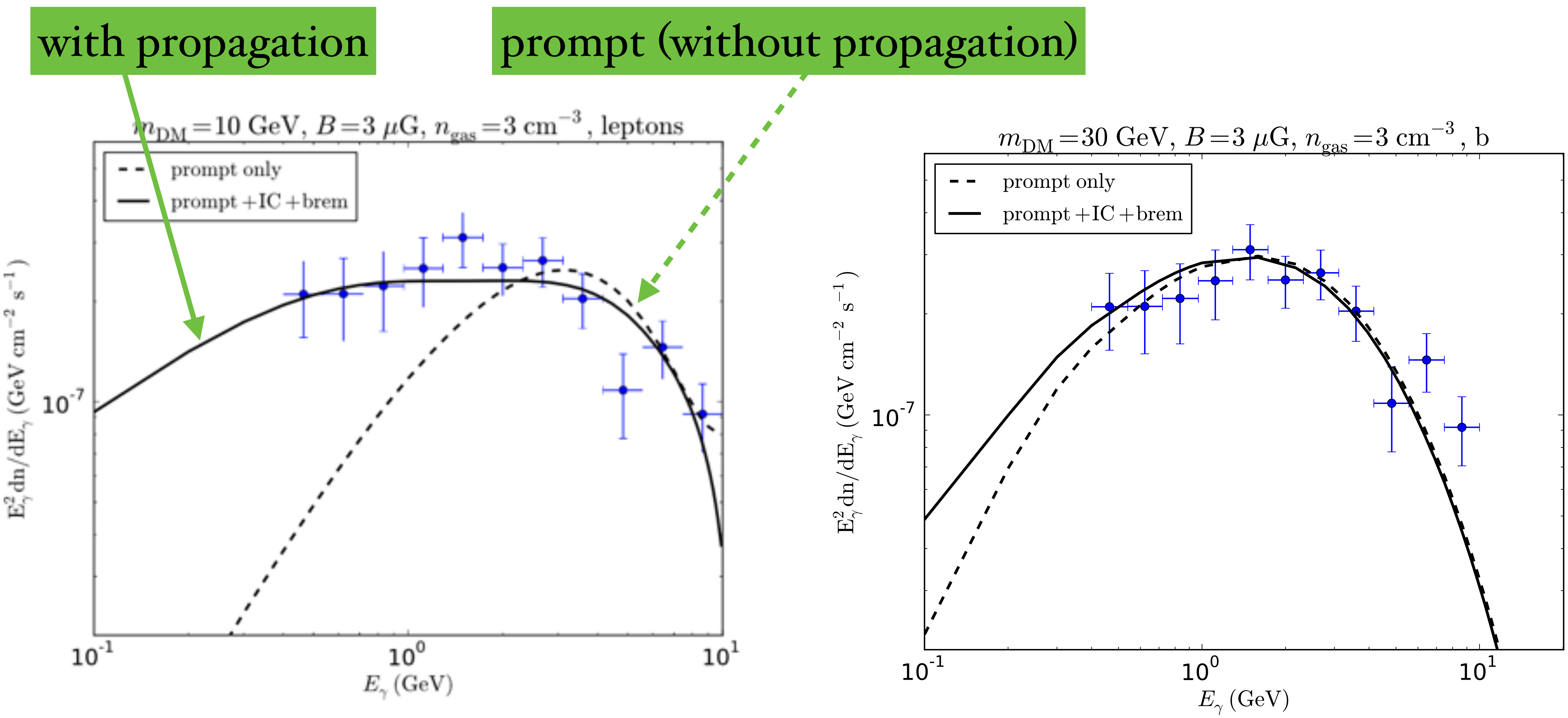




Goodenough&Hooper, 2009
Fermi collaboration 2009
D. Hooper and T. Linden: arXiv: 1110.0006
C. Gordon & O. Macias: arXiv:1306.5725

B. Indirect detection   Propagation of cosmic rays

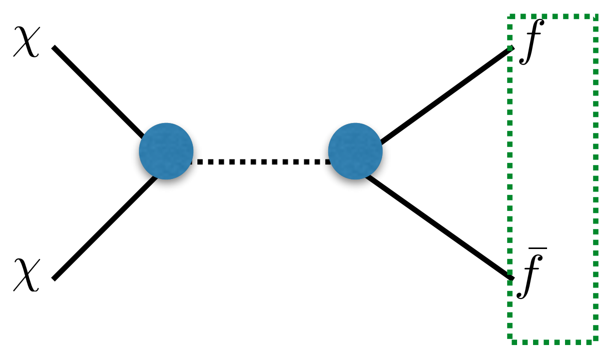
Light DM and the GeV excess

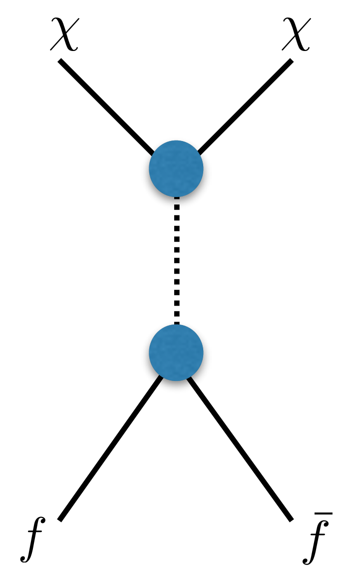


Existence of an anomaly but propagation is important for leptons
but analysis need to take also into account secondaries (including for astro sources)

Direct + Indirect detection

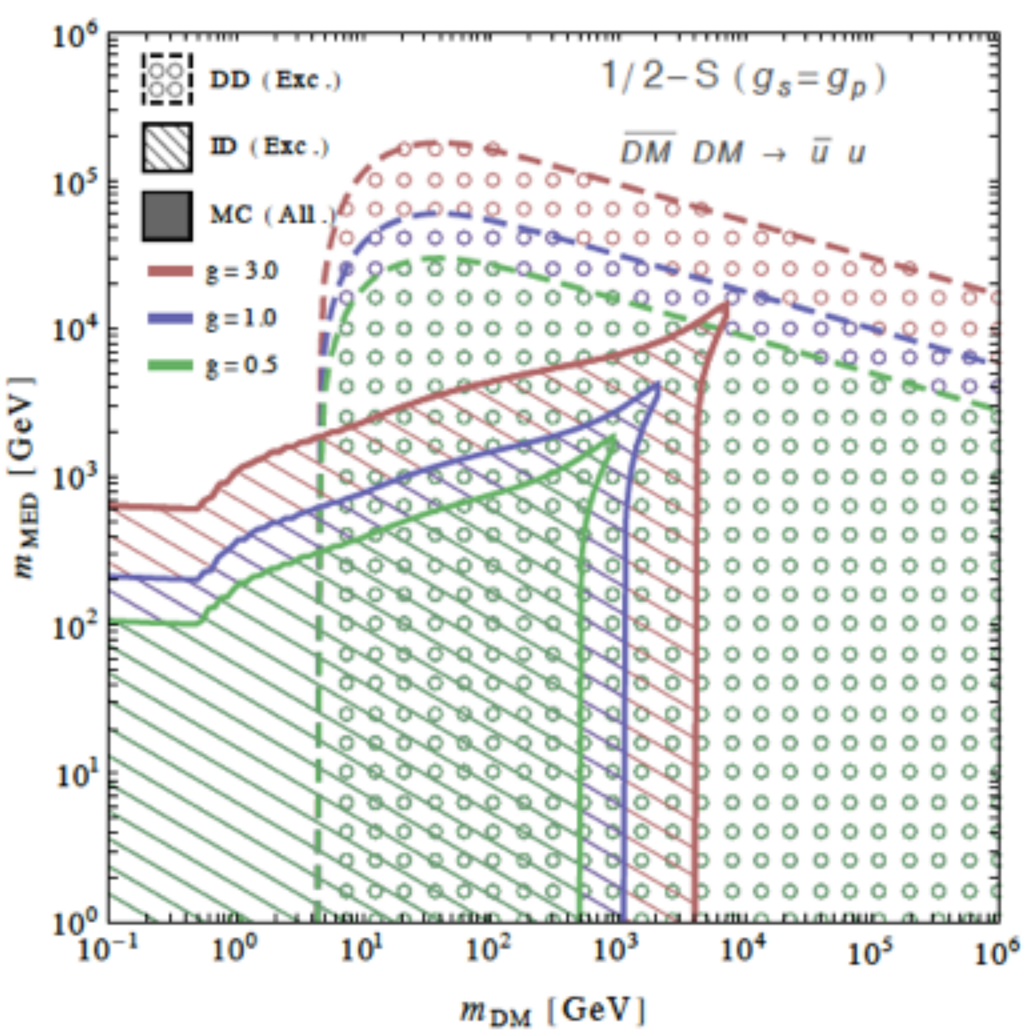
C. Direct + Indirect detection





assuming the same coupling g

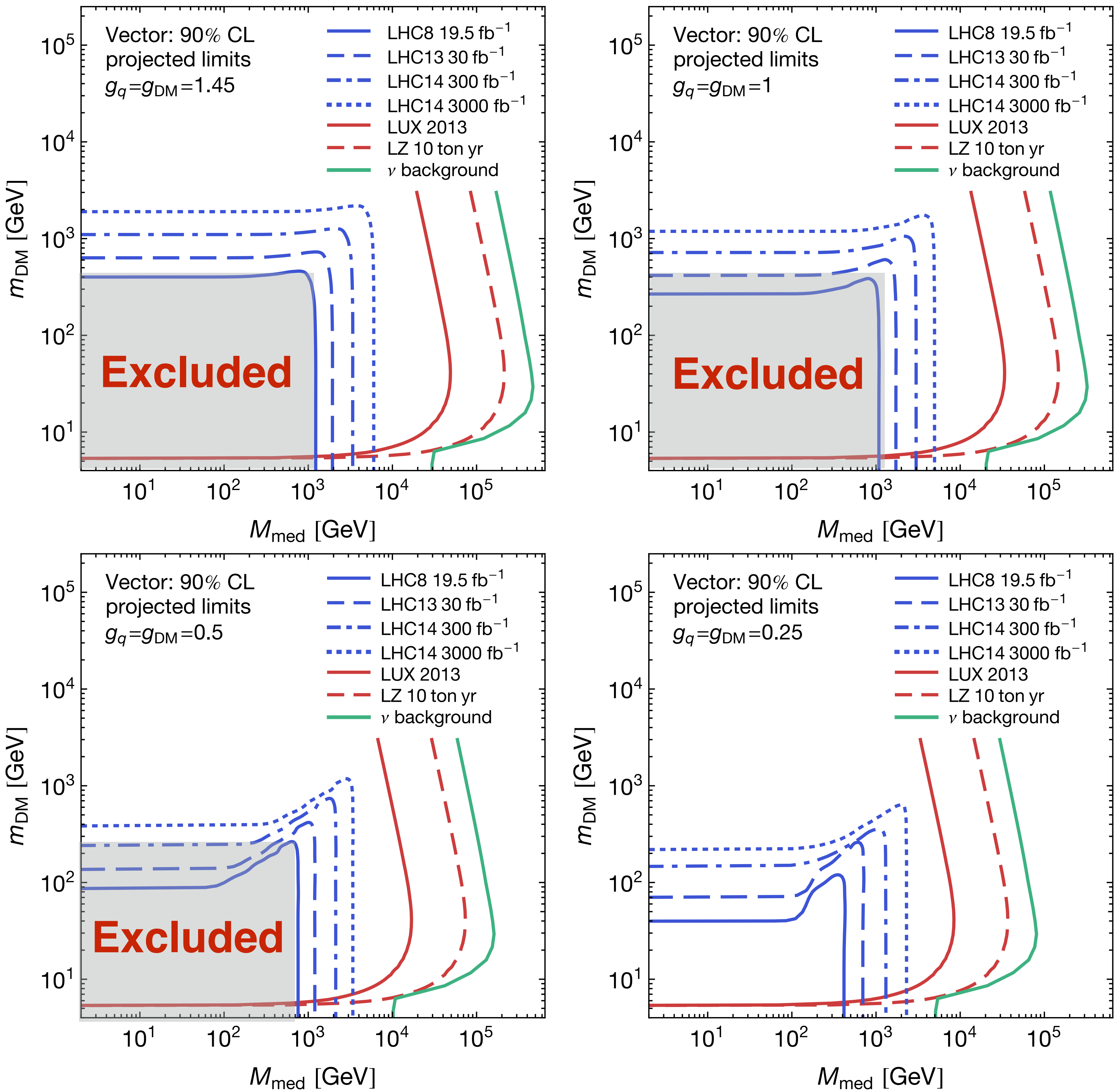
Jubb, A. Vincent, CB in preparation



Small couplings (g<0.5) are needed.

For large couplings a very large fraction of the parameter space is totally ruled out.

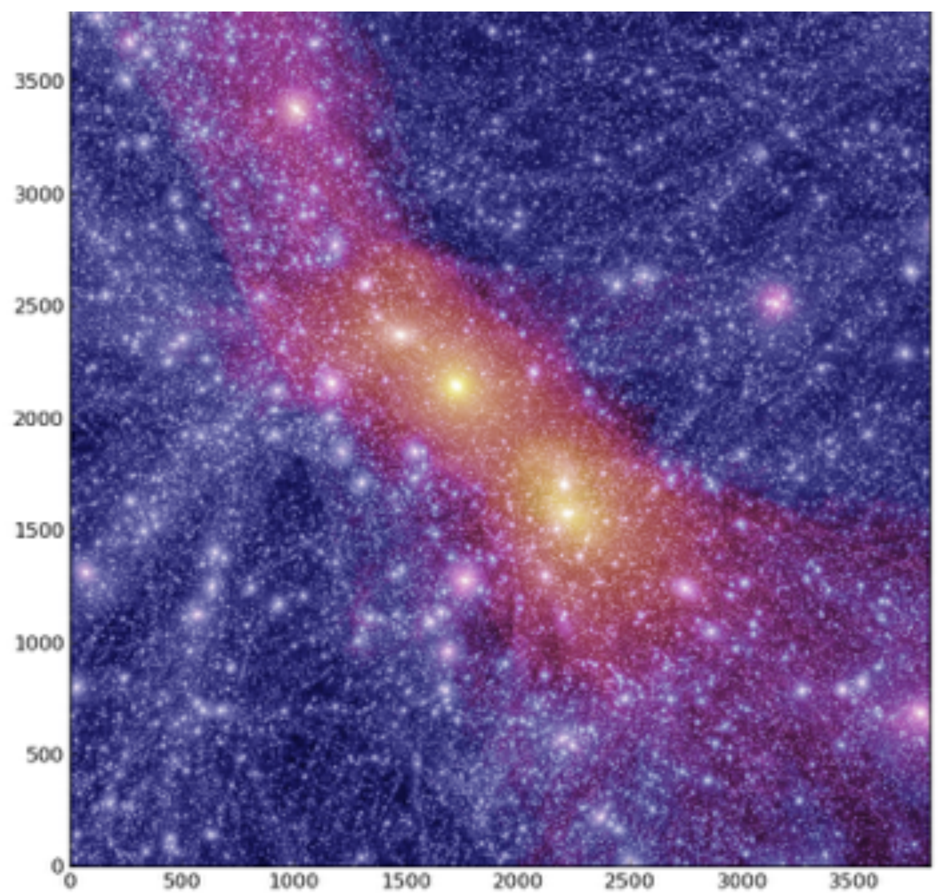
LHC vs DD 1409.4075



Cosmology

D. Cosmology

Cold Dark Matter seems to describe well our Universe



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

Weakly Interacting Massive Particle

Invisible **Clustered**

Is it true at all scales?

(astro-ph/0012504, astro-ph/0112522, astro-ph/0410591)

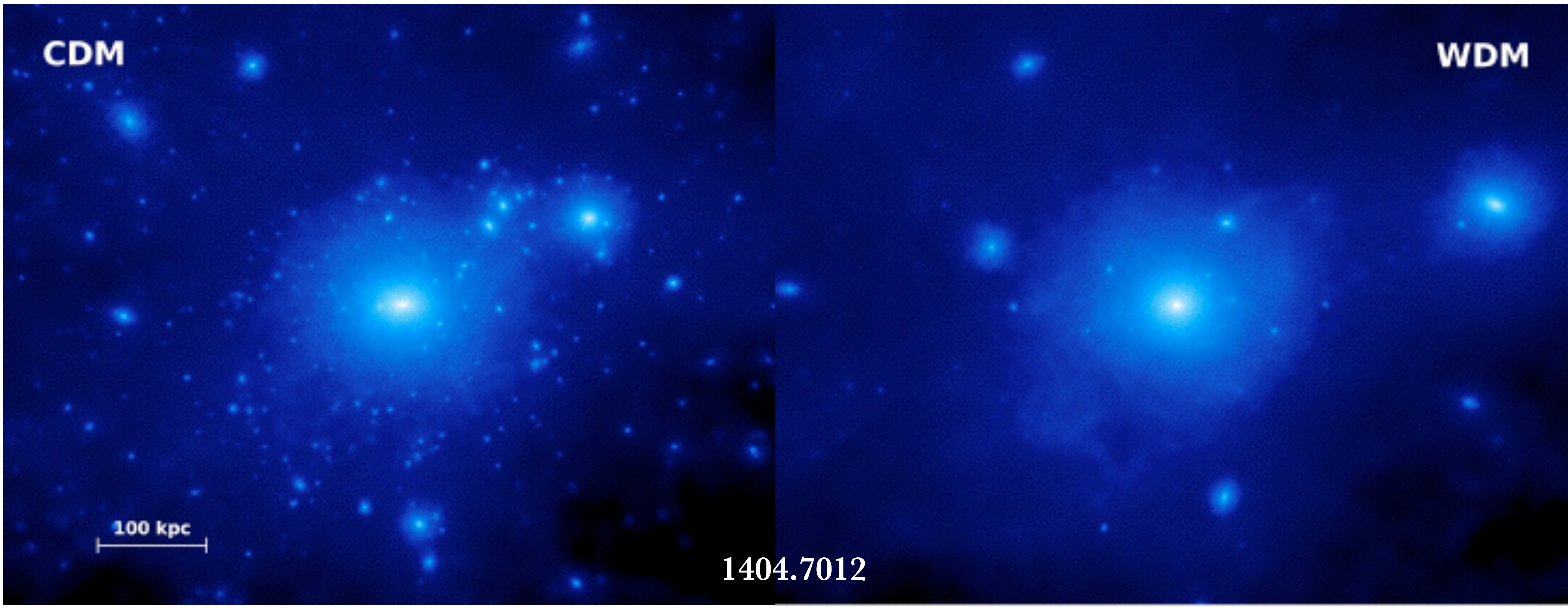
Galaxies properties can give away the DM properties and probe WIMPs!

D. Cosmology

Weakly Interacting Massive Particle

Invisible **Clustered**

Heavy WIMPs Particle of a 3 keV



This picture is valid if DM is collisionless but …

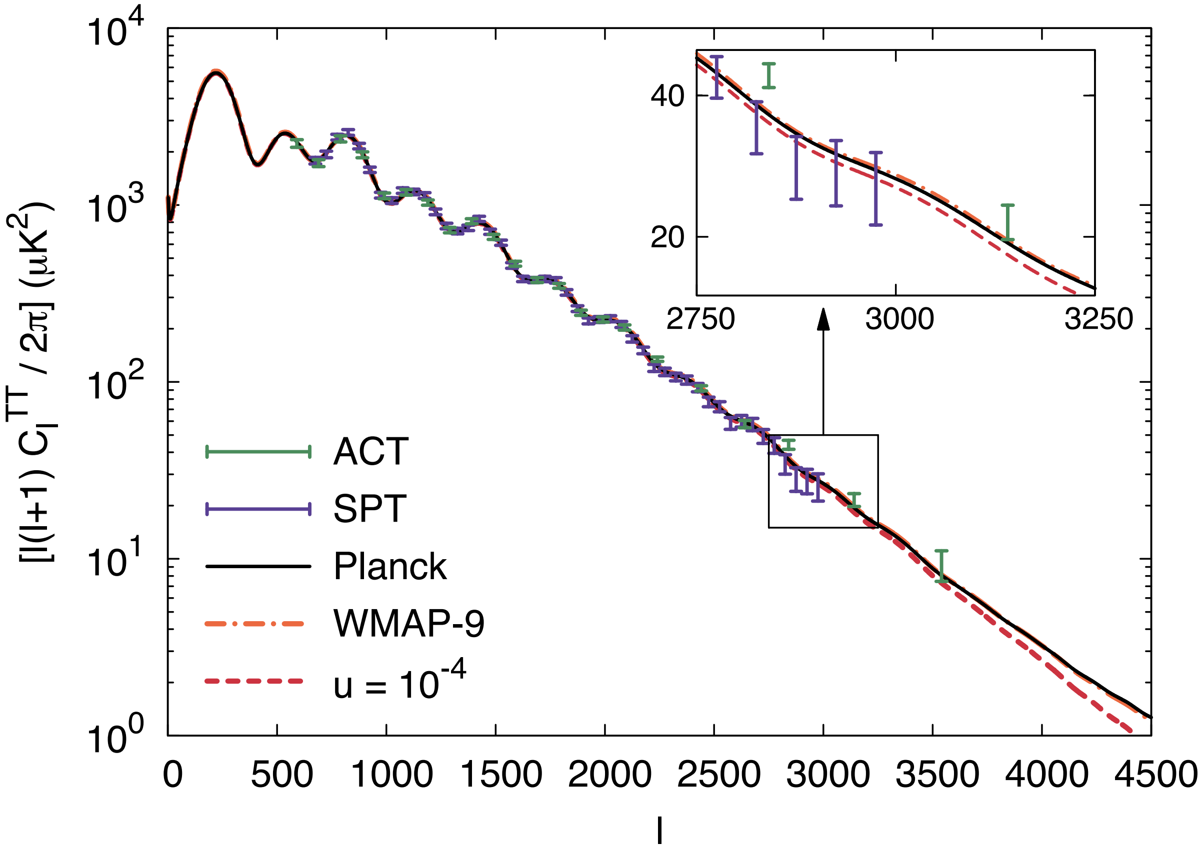
D. Cosmology

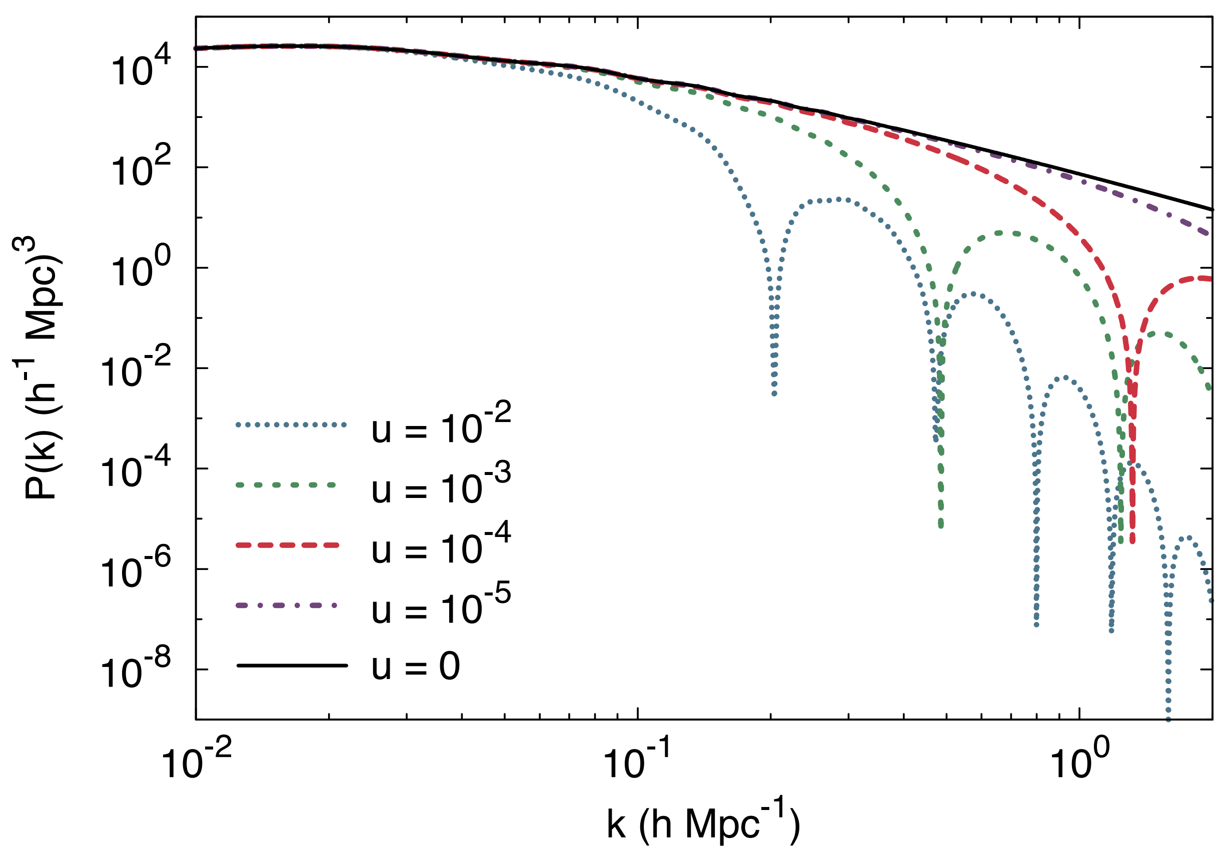
Weakly Interacting Massive Particle

Invisible

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

$$\dot{\theta}_{DM} = k^2\psi - \mathcal{H}\theta_{DM} - S^{-1}\dot{\mu}(\theta_{DM} - \theta_\gamma) .$$





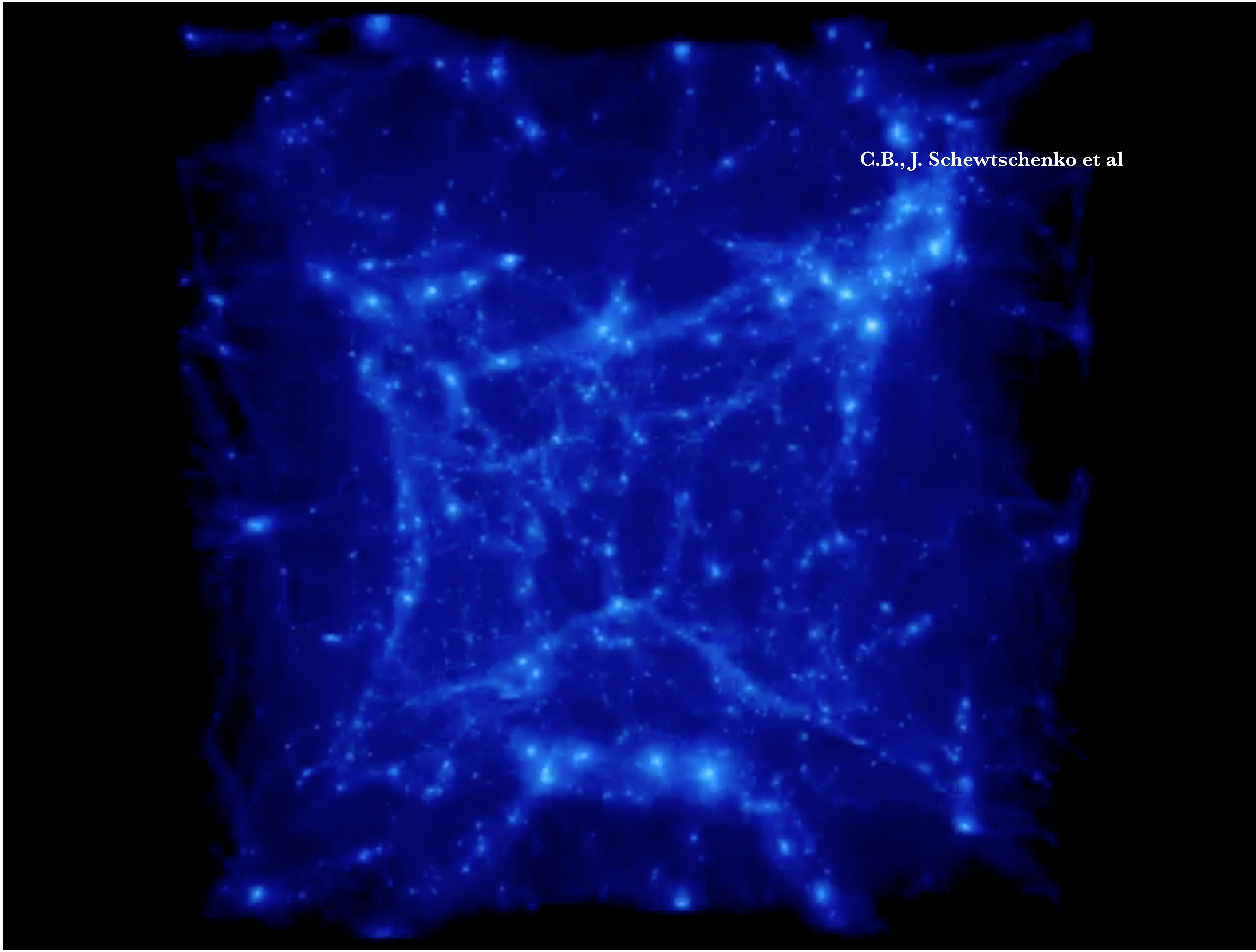
(CB, Riazuelo, S. Hansen, R. Schaeffer : astro-ph/0112522)

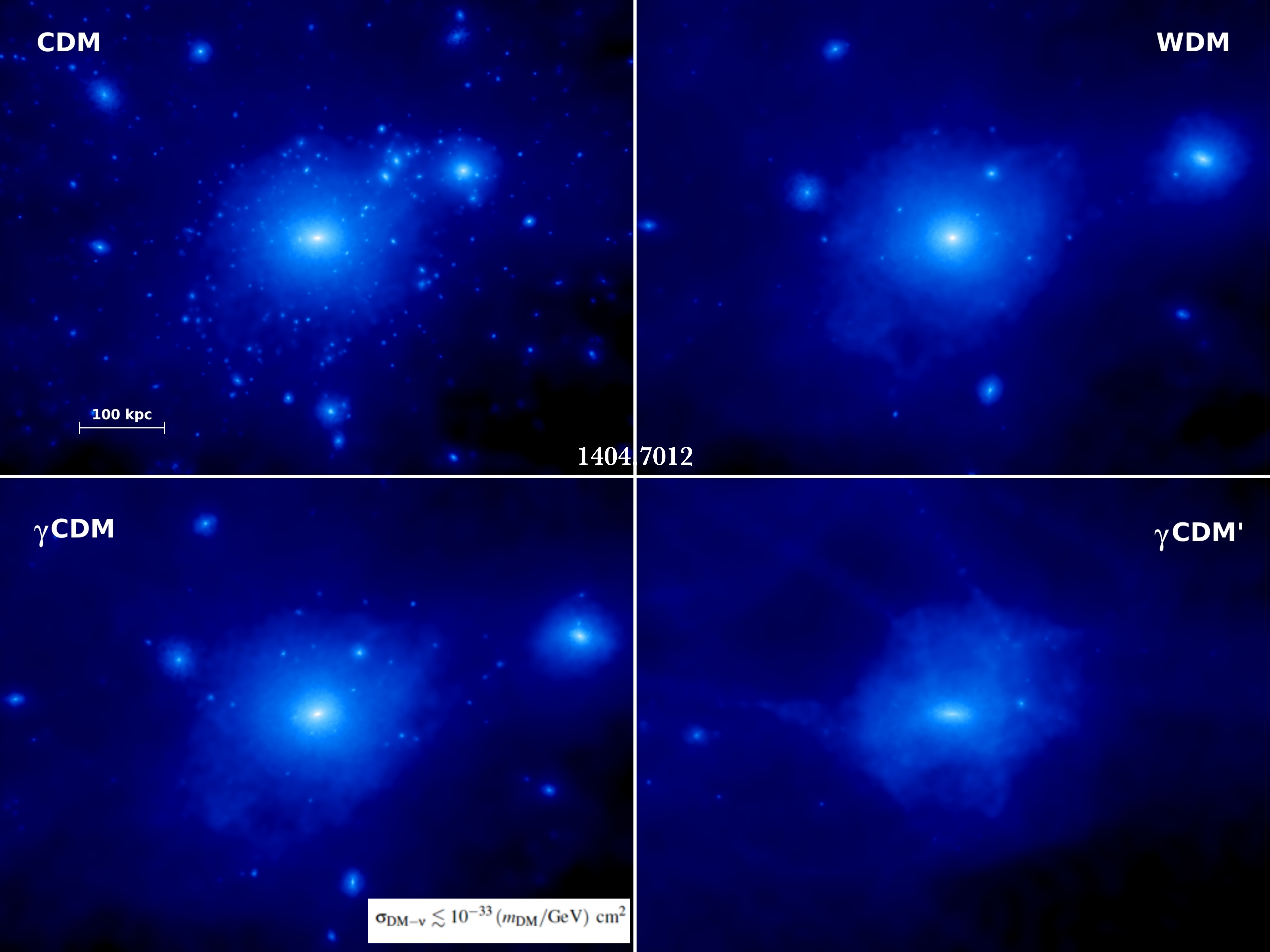
R. Wilkinson, J. Lesgourgues, C. Boehm: arXiv:1309.7588

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

Dark Oscillations

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

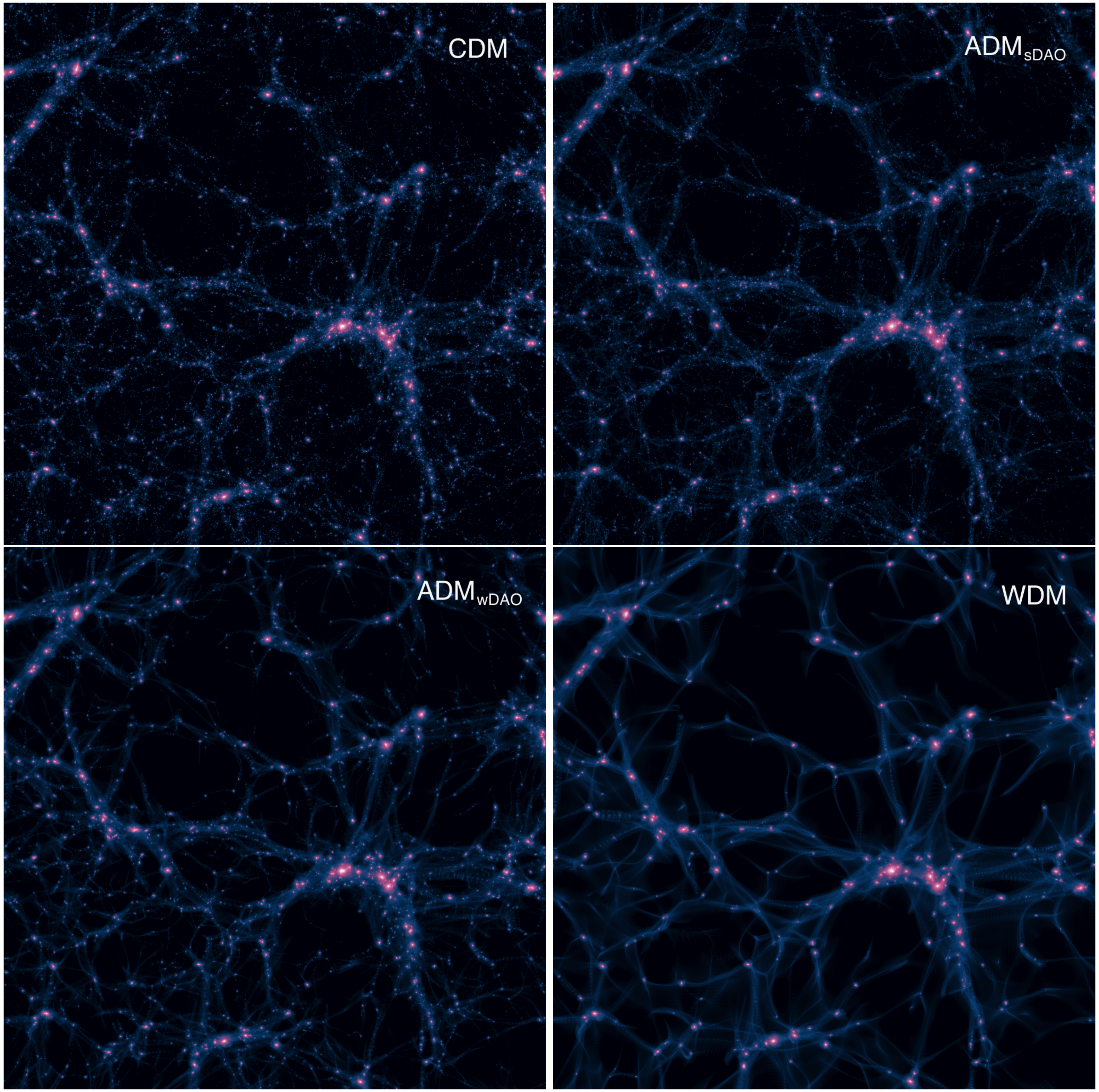



CDM
WDM
100 kpc
1404.7012
γCDM
γCDM'
$\sigma_{DM-\nu} \lesssim 10^{-33}\,(m_{DM}/\text{GeV})\ \text{cm}^2$

D. Cosmology

Self - interacting DM

1405.2075



D. Cosmology

Decaying DM 1406.0527

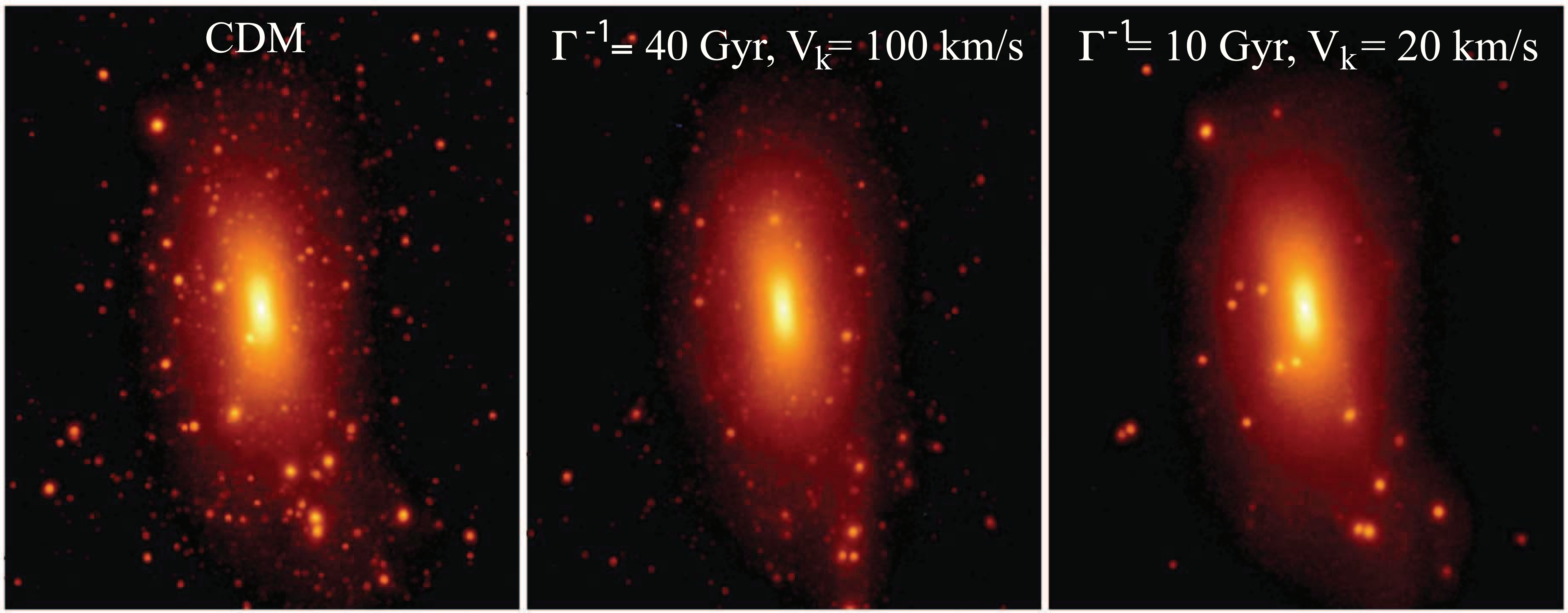
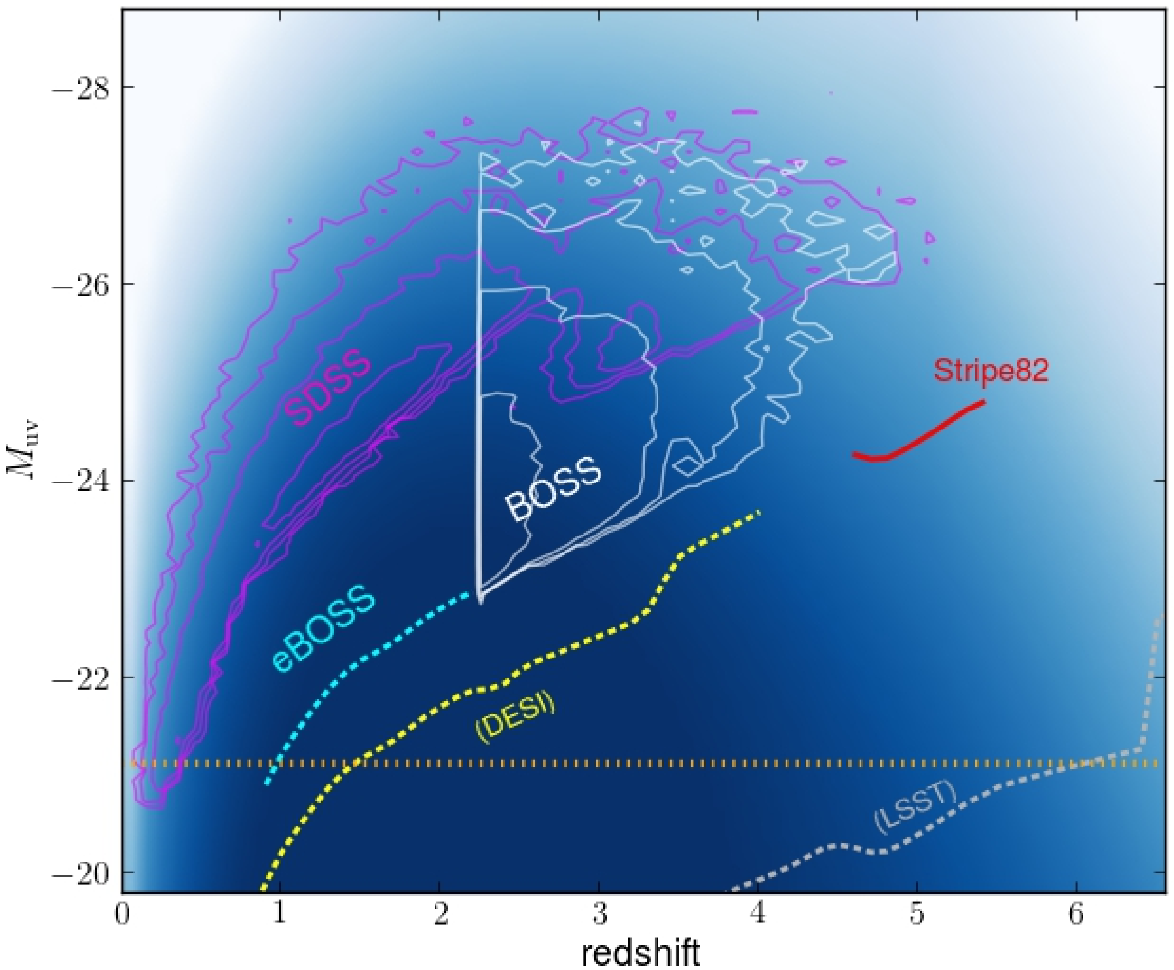


Figure 2. Small-scale structure in a Milky Way mass halo (Z12) in CDM (left) and DDM models with Γ^{-1} = 40 Gyr and V_k = 100 km/s (middle) and Γ^{-1} = 10 Gyr and V_k = 20 km/s (right) within 260 kpc of the halo centers at $z = 0$. The color scheme indicates the line-of-sight projected square of the density in order to emphasize the dense structures such as the host halo interiors and the associated subhalos. The DDM halos have slightly more diffuse central regions. The abundance and structure of subhalos are altered significantly compared to CDM in both of the DDM simulations presented.

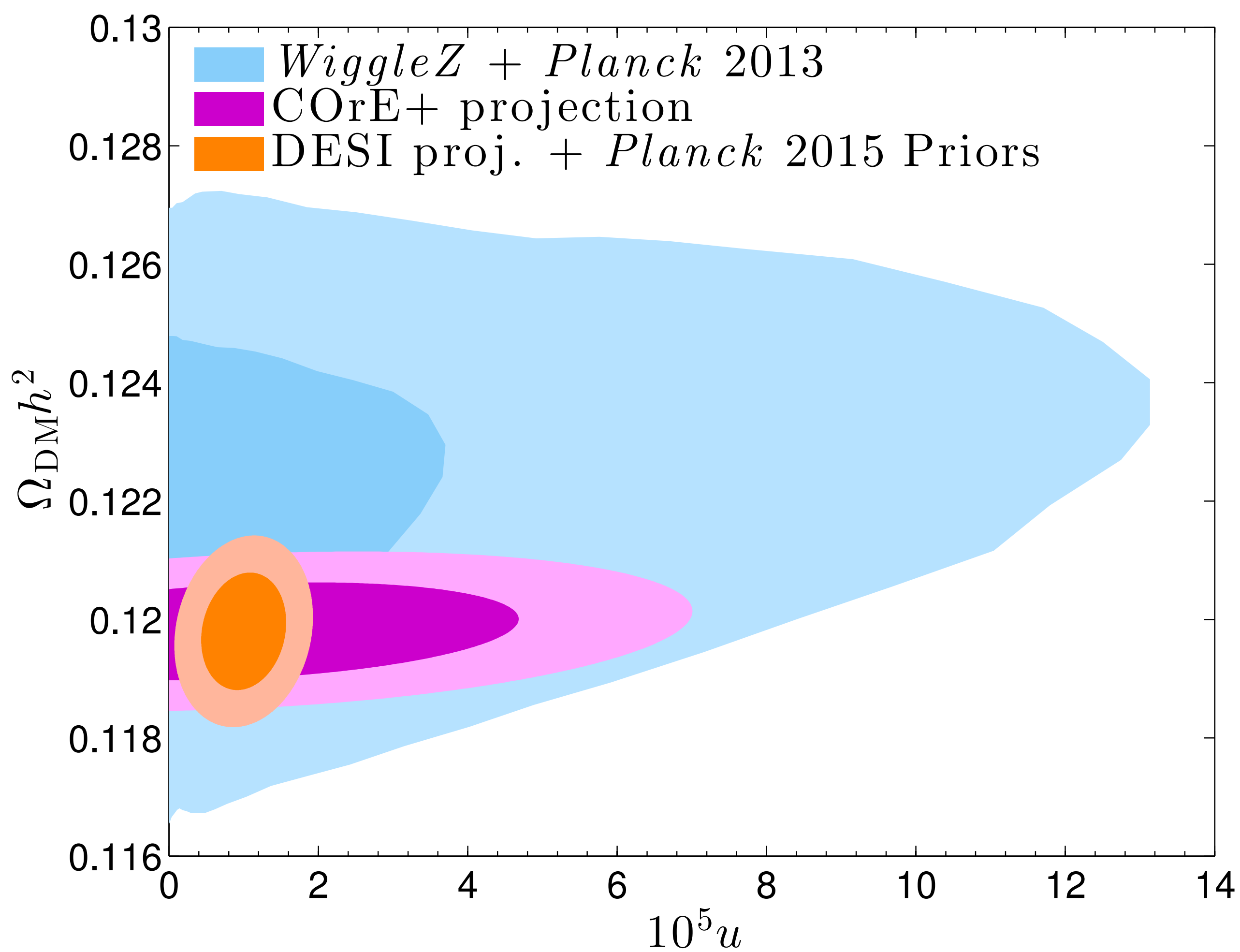
The future

D. Cosmology



Courtesy JP Kneib

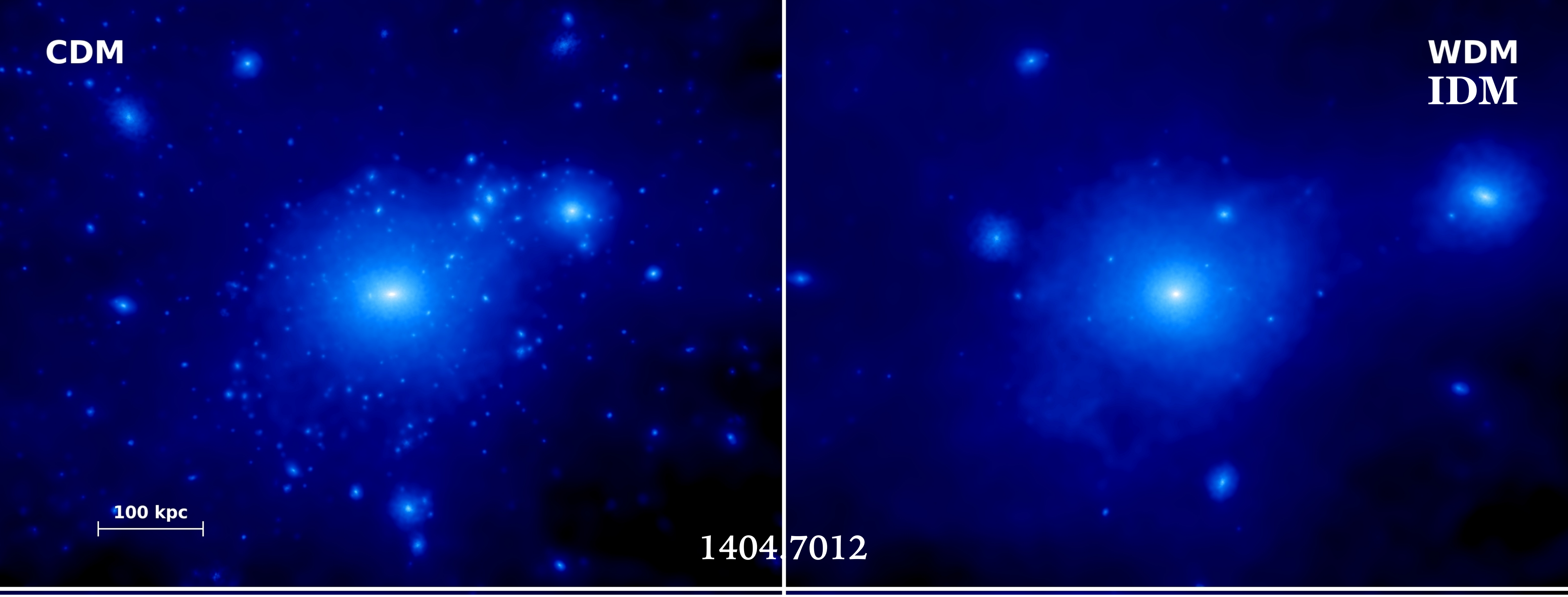
1505.06735

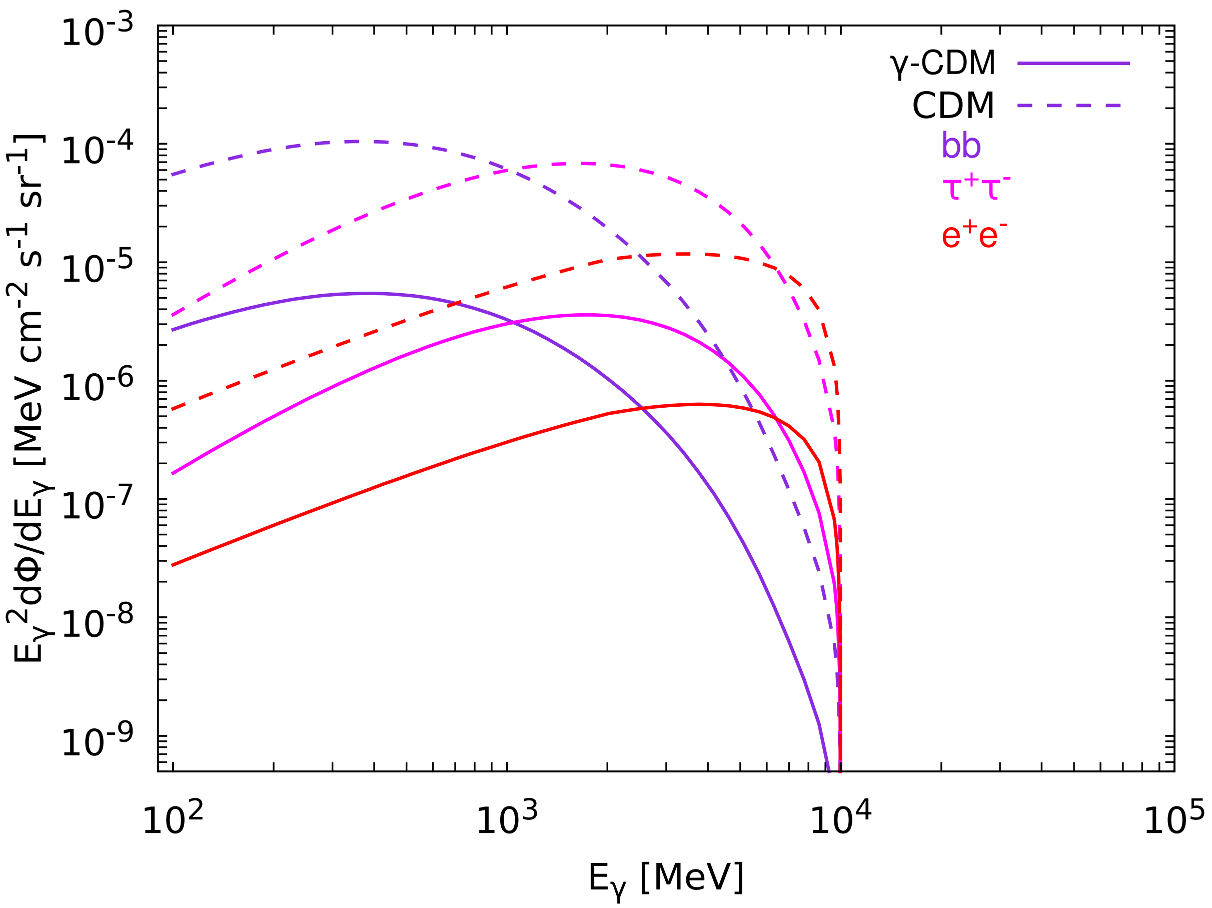


With DESI we gain a factor 10

Future LSS experiments can set strong bounds

It will be amazing to see what LSST brings …





There is the danger to misinterpret signals from DM annihilating particles as originating from a weaker annihilation cross section

Conclusion

We have not find the DM but we know it is there!

If it is a particle, it is well hidden (small couplings)

If small couplings, we may not even find it at LHC!

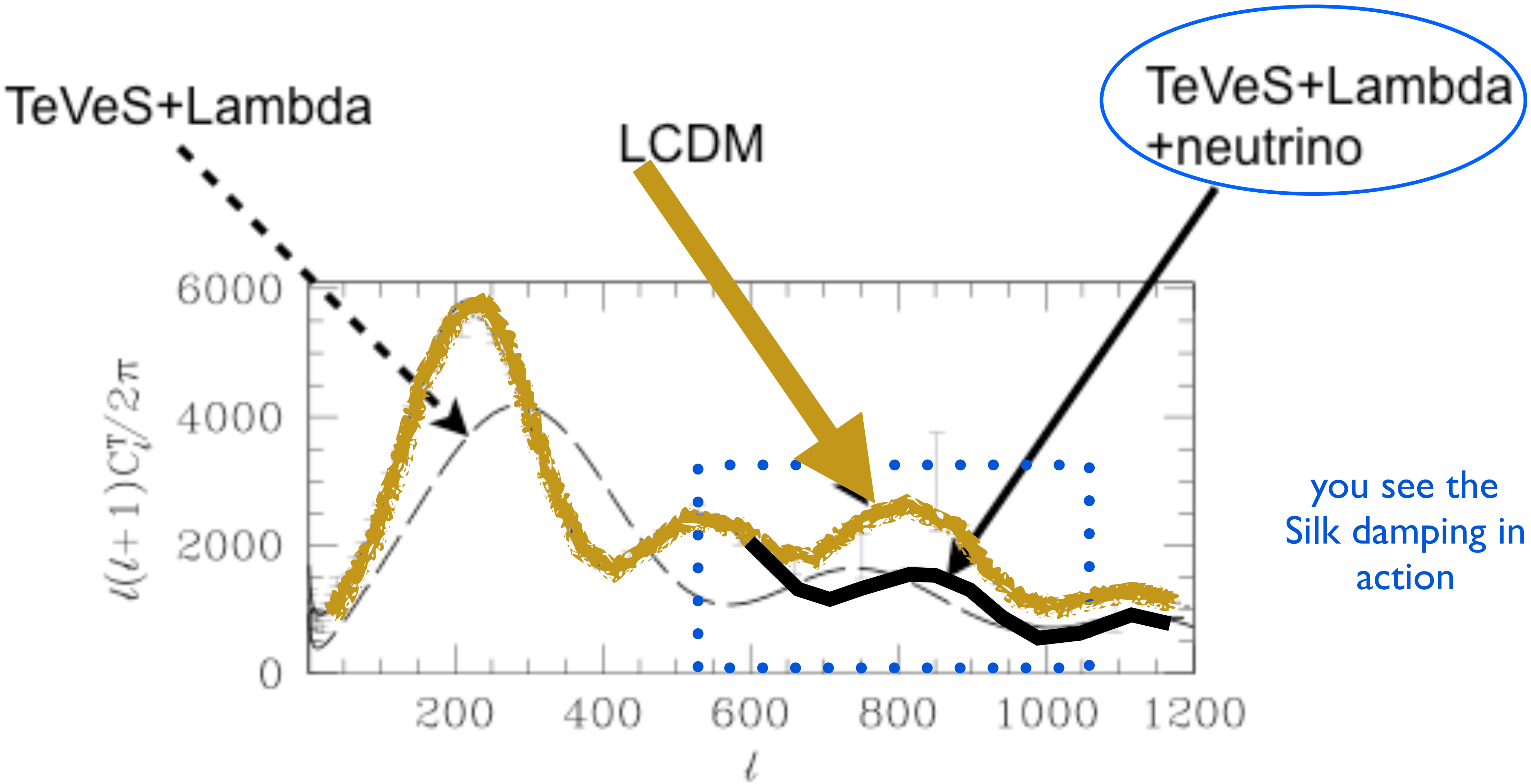
But large-scale-structures may tell us something important

Let the data speak without making too many assumptions!

One possible theory : TeVeS (baryons only)

Bekenstein [astro-ph/0403694]()

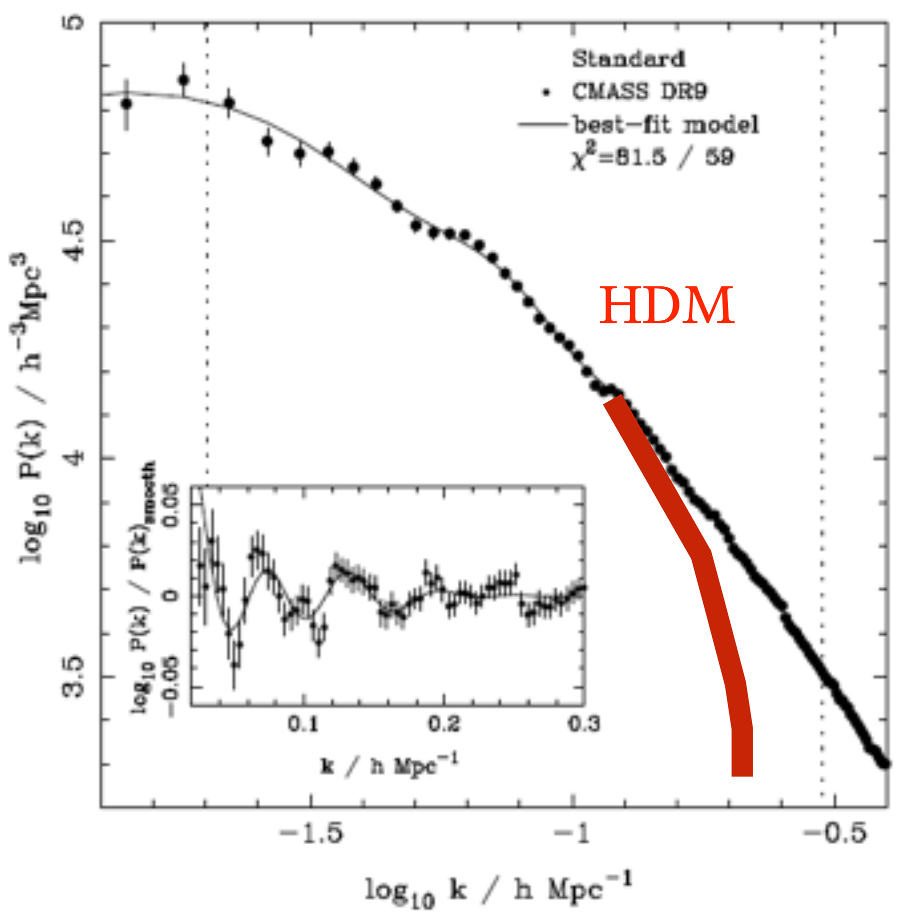
Silk damping unavoidable   C. Skordis, D. Mota, P. Ferreira, C.Boehm : astro-ph/0505519

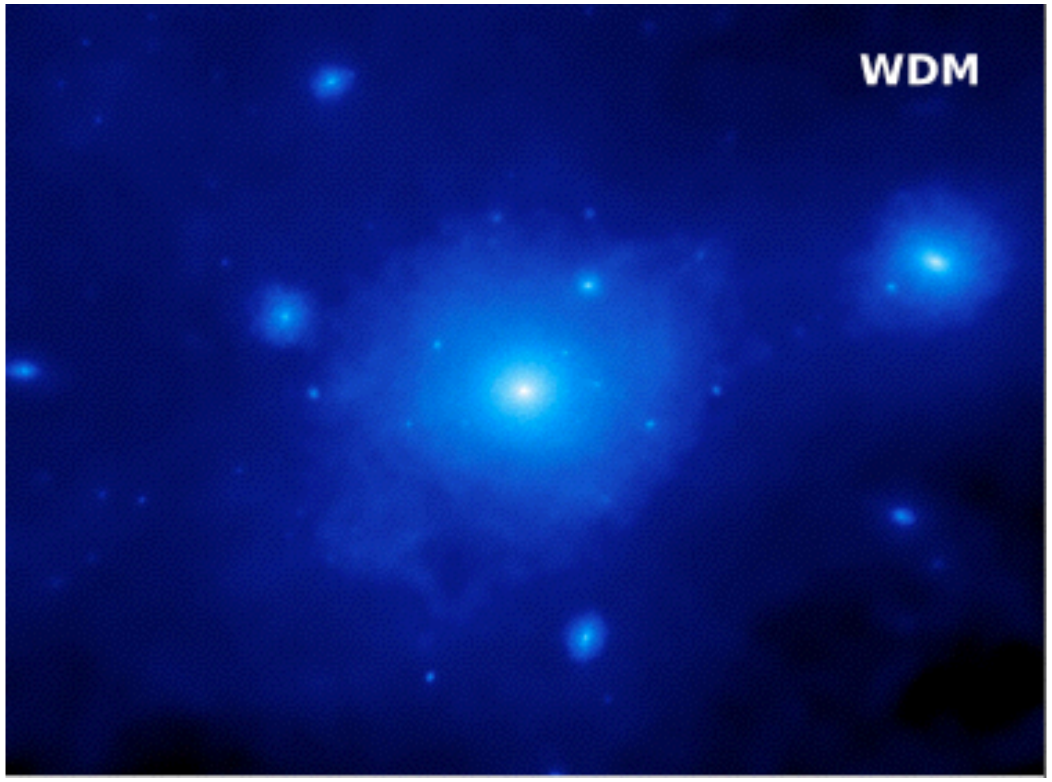


you see the Silk damping in action

Main problem: how to reproduce the 7-8 peaks seen by Planck & ACT?

D. Cosmology





Light particles and no interaction

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

No interaction, tdec = "0"time; $\boxed{\int_{\cancel{t_{\rm dec}}\ 0}^{t_{nr}} dt\ldots} + \boxed{\int_{t_{\rm nr}}^{t_0} dt\ldots}$

astro-ph/0012504

$$\boxed{l_{\rm struct} \sim 100\ {\rm kpc}\ \left(\frac{\rm m_{DM}}{\rm keV}\right)^{\boxed{-4/3}}}$$

D. Cosmology

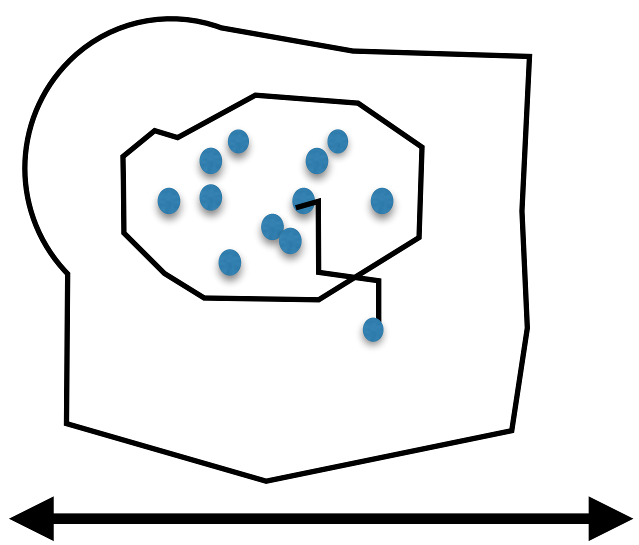
What happens when there are interactions?

(astro-ph/0012504, astro-ph/0112522, astro-ph/0410591)

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

Free-streaming gets delayed

But there is also collisional damping



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

Generalisation of Silk damping to the DM

D. Cosmology

Collisional damping in modern Cosmology

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

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

Translation in terms of Cosmological perturbations

without DM

with DM

astro-ph/0112522

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

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

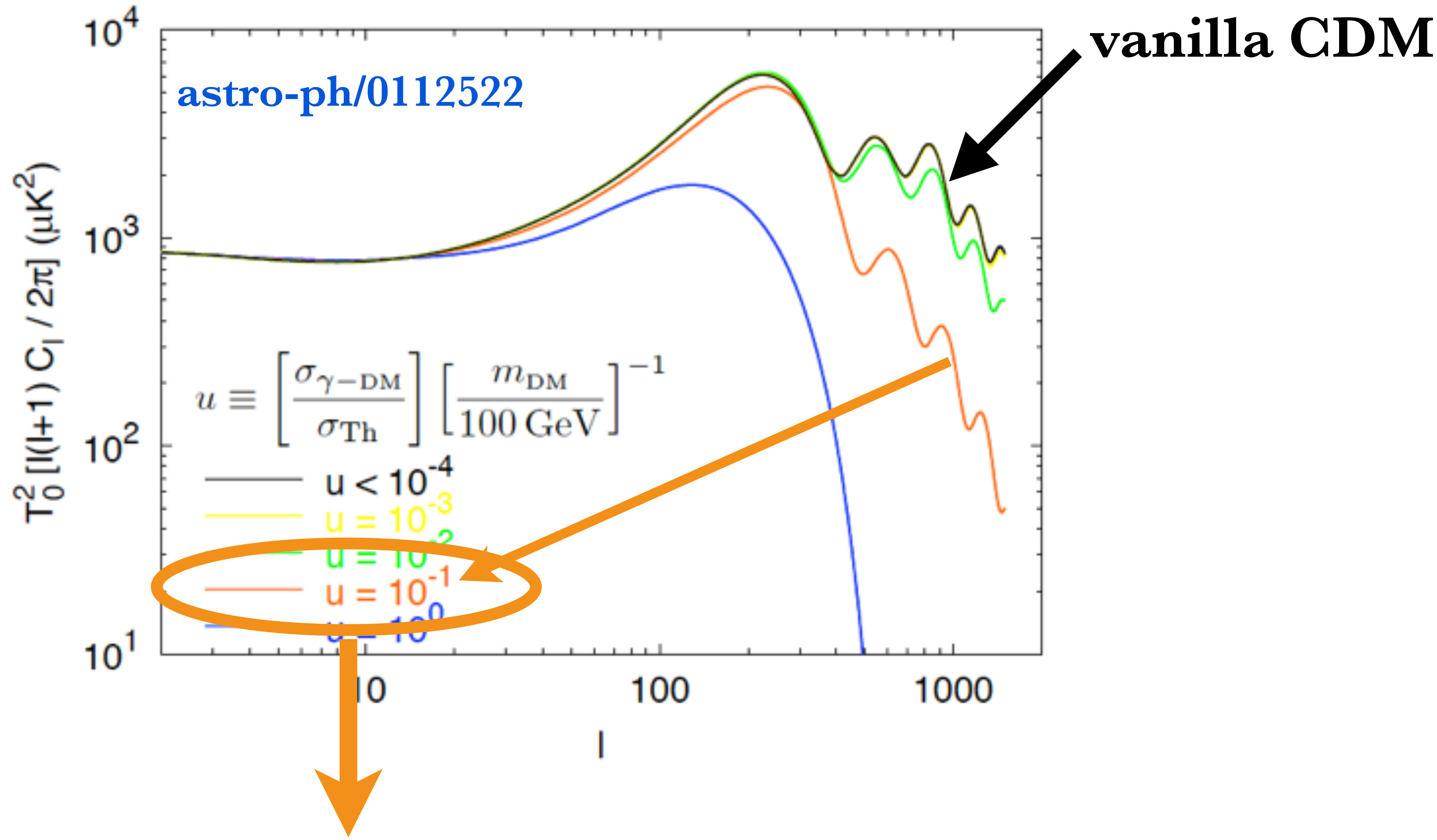
$$\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) \\
&\quad - \dot{\kappa}(\theta_\gamma - \theta_b) - \dot{\mu}(\theta_\gamma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

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

D. Cosmology

DM-photon interactions

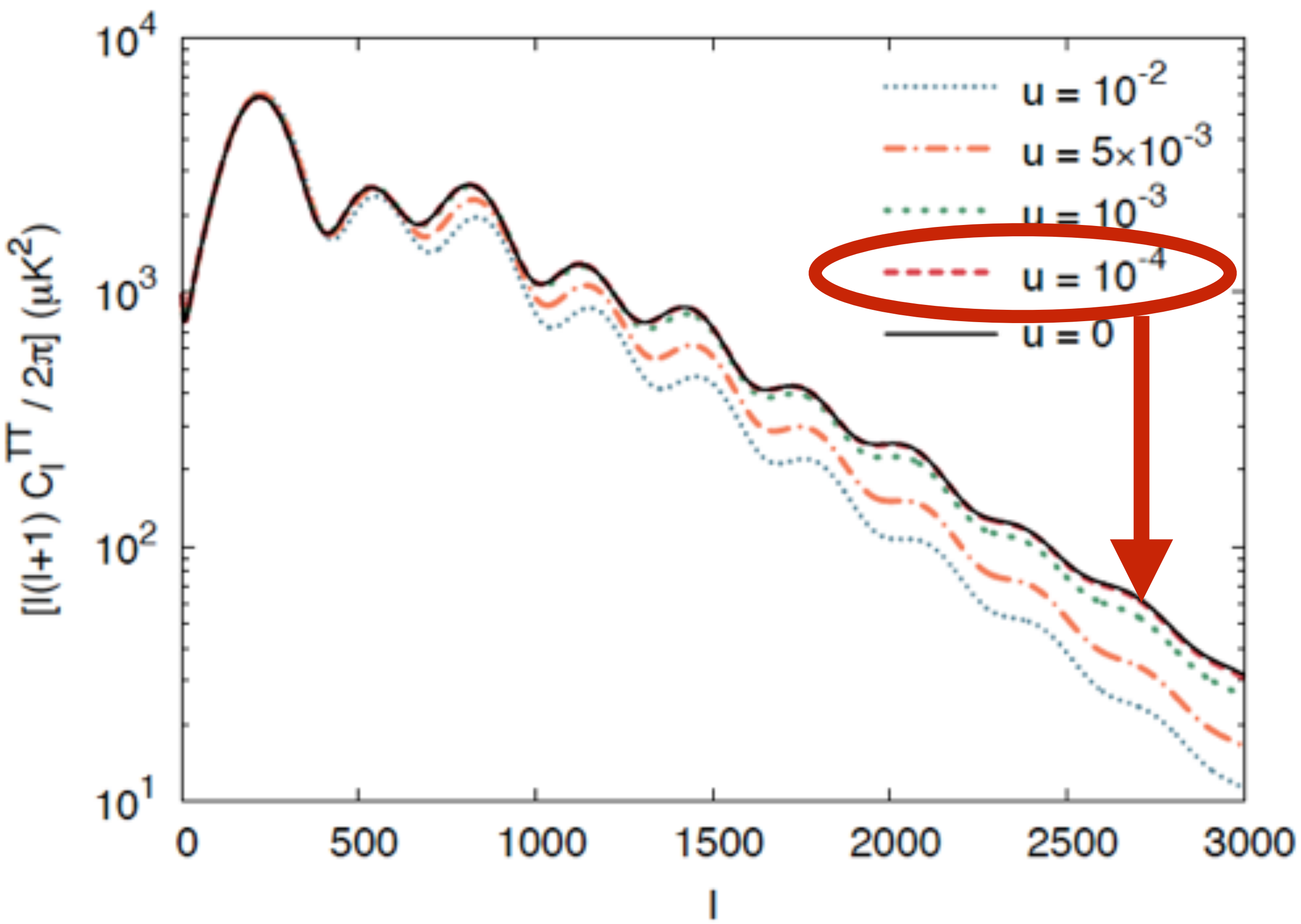
1 parameter (the ratio of cross section to the DM mass)

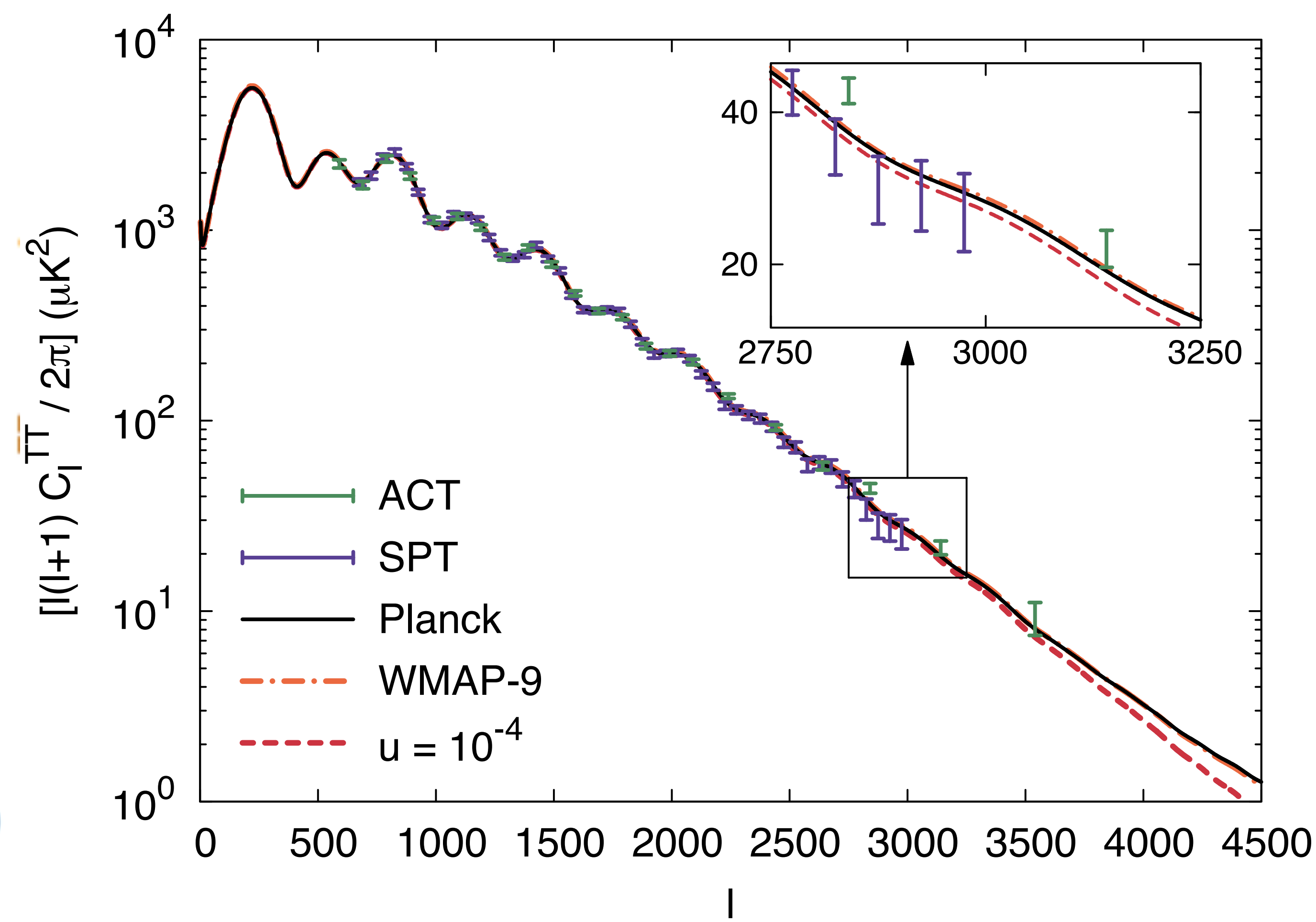


Thomson cross section;
dark matter would be a baryon… it is excluded!

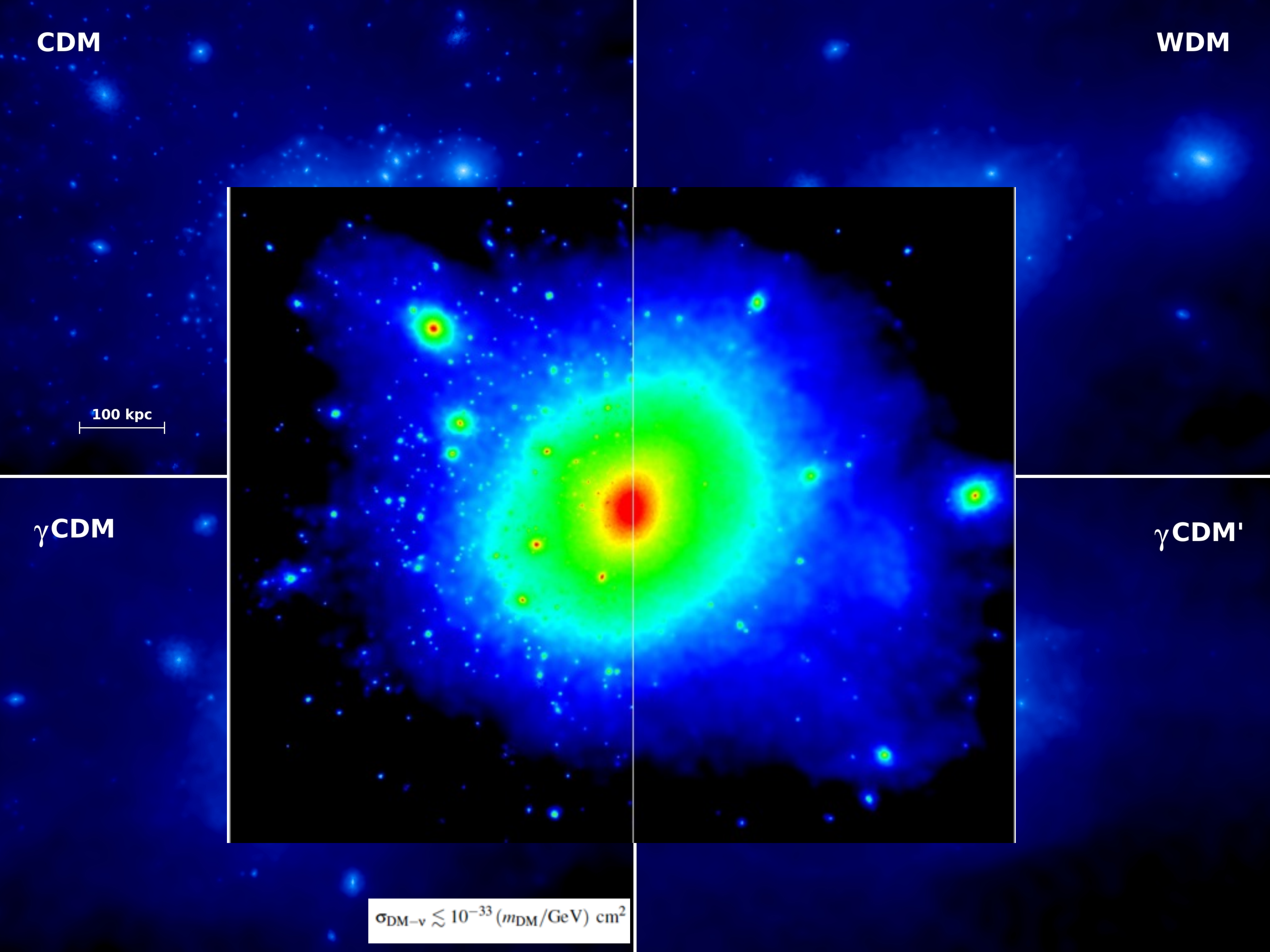
Deviations to LCDM

R. Wilkinson, J. Lesgourgues, CB: arXiv:1309.7588

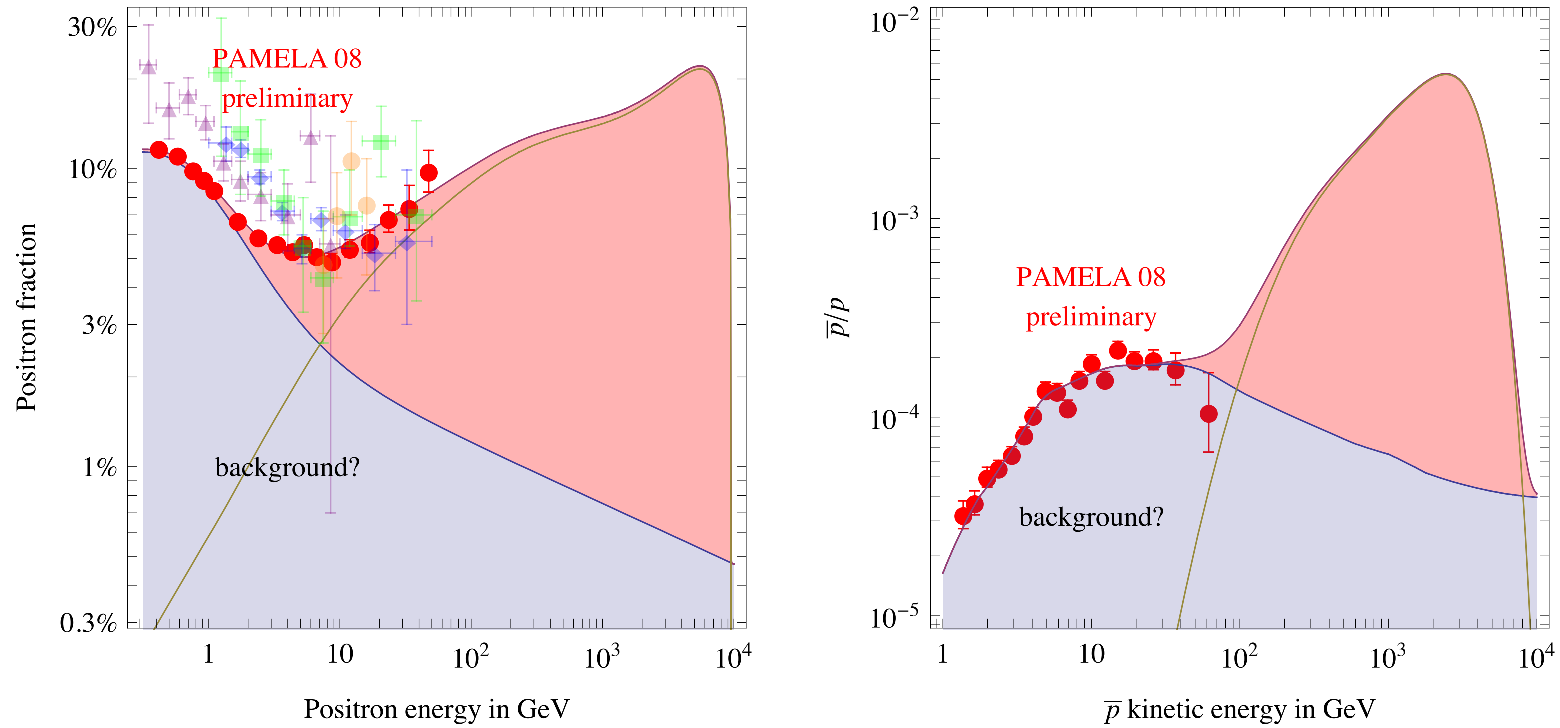




	$100\,\Omega_b h^2$	$\Omega_{DM} h^2$	$100\,h$	$10^{+9}\,A_s$	n_s	z_{reio}	N_{eff}	$10^{+2}\,u$	$10^{+13}\,u_0$
No interaction	$2.205^{+0.028}_{-0.028}$	$0.1199^{+0.0027}_{-0.0027}$	$67.3^{+1.2}_{-1.2}$	$2.196^{+0.051}_{-0.060}$	$0.9603^{+0.0073}_{-0.0073}$	$11.1^{+1.1}_{-1.1}$	(3.046)	–	–
	$2.238^{+0.041}_{-0.041}$	$0.1256^{+0.0055}_{-0.0055}$	$70.7^{+3.2}_{-3.2}$	$2.251^{+0.069}_{-0.085}$	$0.977^{+0.016}_{-0.016}$	$11.6^{+1.3}_{-1.3}$	$3.51^{+0.39}_{-0.39}$	–	–
$\sigma_{DM-\nu}$ 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	–


CDM
WDM
100 kpc
γCDM
γCDM'
$\sigma_{DM-\nu} \lesssim 10^{-33} \, (m_{DM}/\text{GeV}) \text{ cm}^2$

Precision Astrophysics



arXiv:1208.5009 (see also arXiv:1401.6212)

Wino-like candidates give very large cross sections