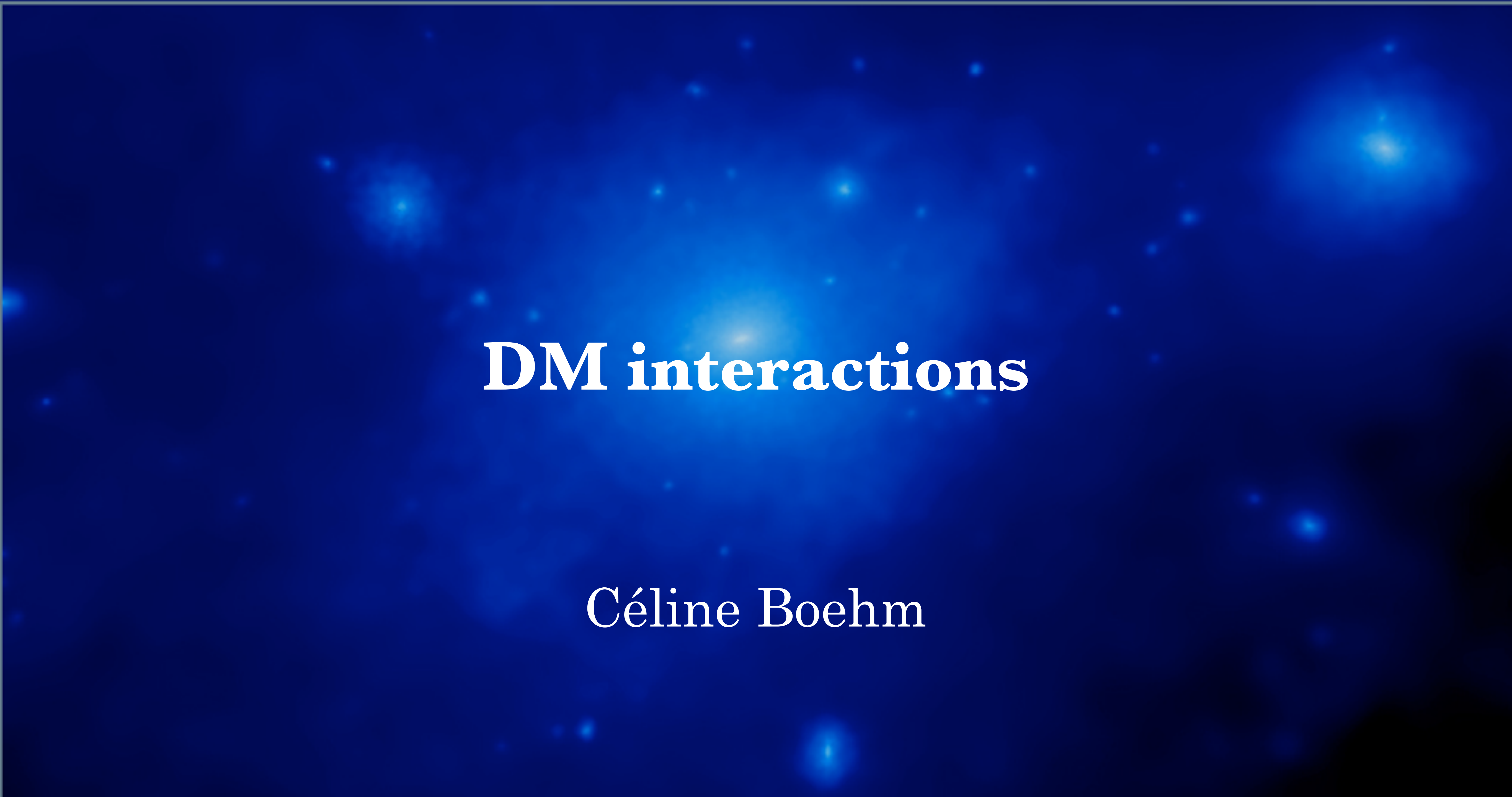


DM interactions

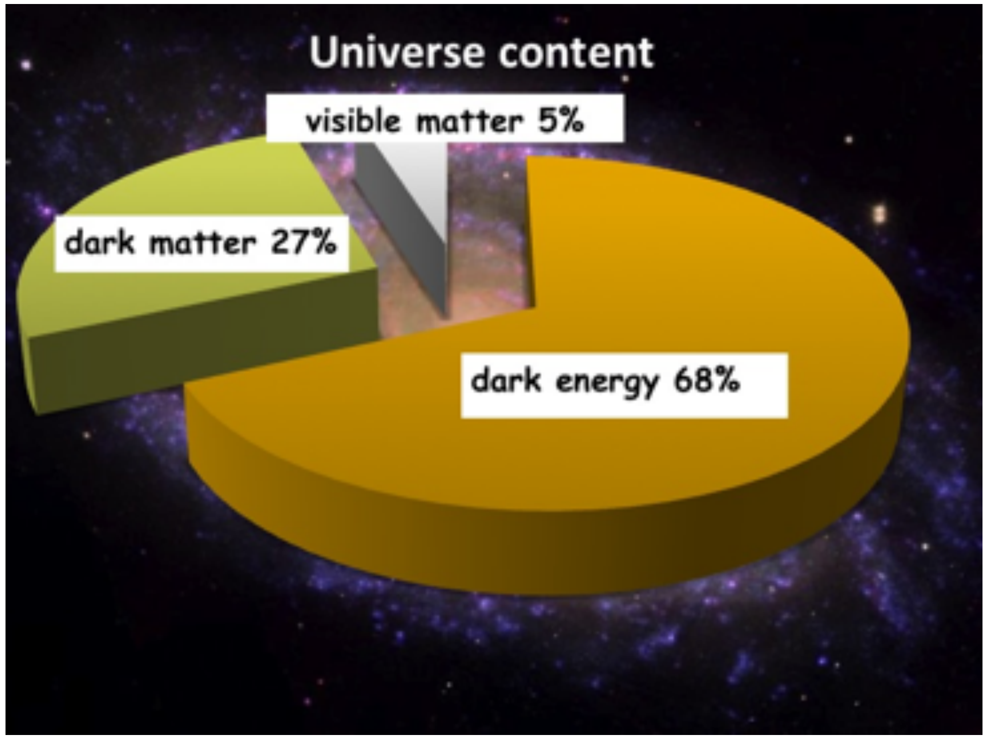
Céline Boehm

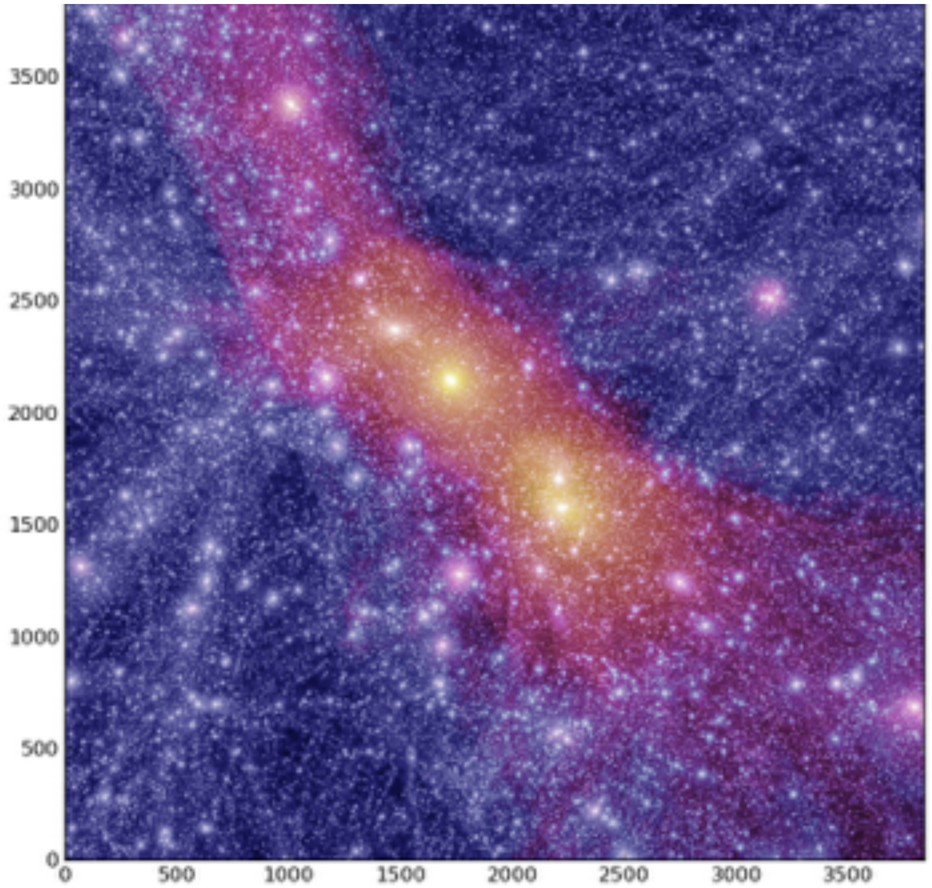
IPPP, Durham

LAPTH, Annecy

Corfu, 16 Septembre 2015

Dark Matter is a key element to structure formation





It is supposed to be a collisionless fluid $\Rightarrow$ never sensitive to the DM interactions….

That is not quite true!

One can constrain the DM microphysics using cosmology!

A particle solution to the DM problem?

Weakly Interacting Massive Particle

Invisible **Clustered**

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

which DM mass?
which DM cross section?

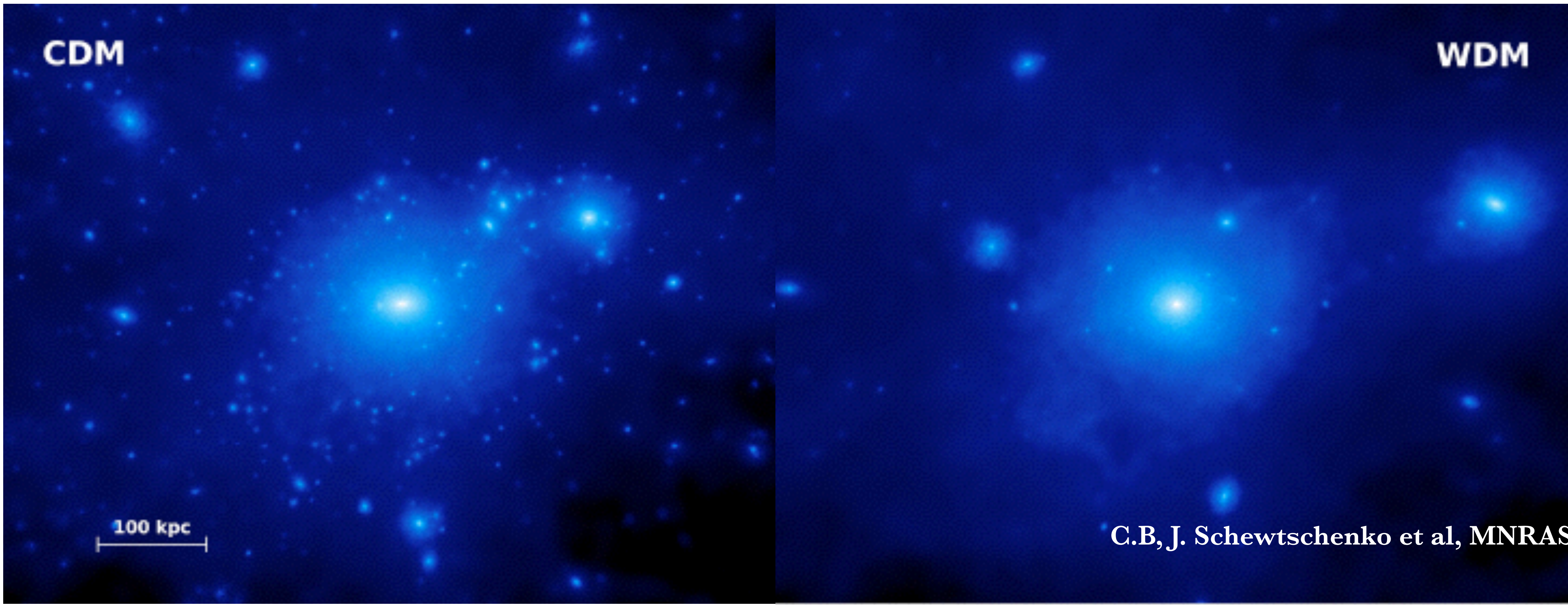
The CDM microphysics is absent from the equations!

(we do not include them!)

Which mass?

Heavy WIMPs

Particle of a 3 keV

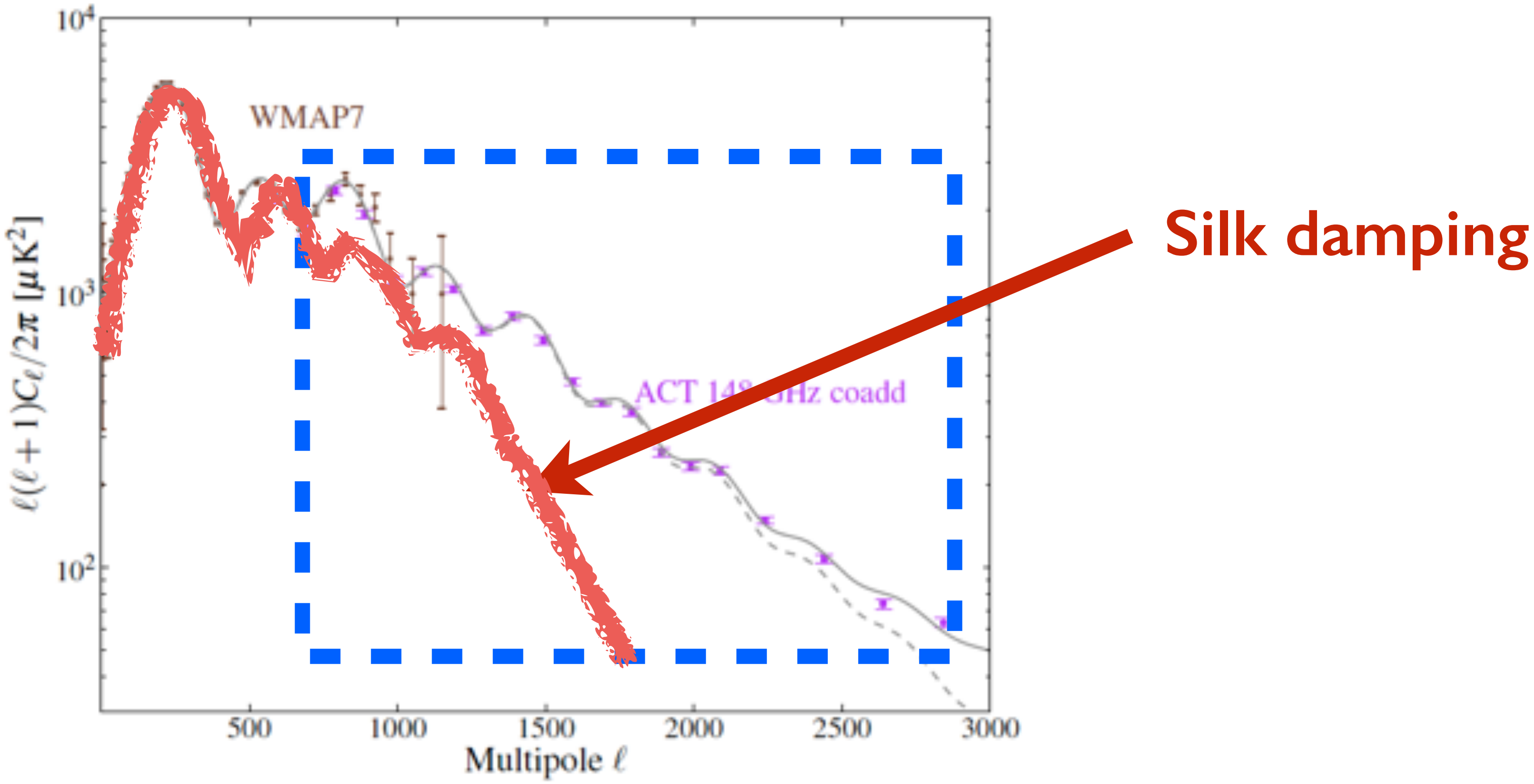


Observations agree better in the case of WDM but it is not the end of the story

This picture is valid if DM is collisionless but …

How weakly interacting?

We already have a partial answer



"WIMPs" : no electromagnetic interaction based on the SM.

But how invisible the DM really needs to be?

Let us introduce $dm - \gamma$ interactions

Collisional (Silk) damping in modern Cosmology

astro-ph/0112522

without DM interactions

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

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

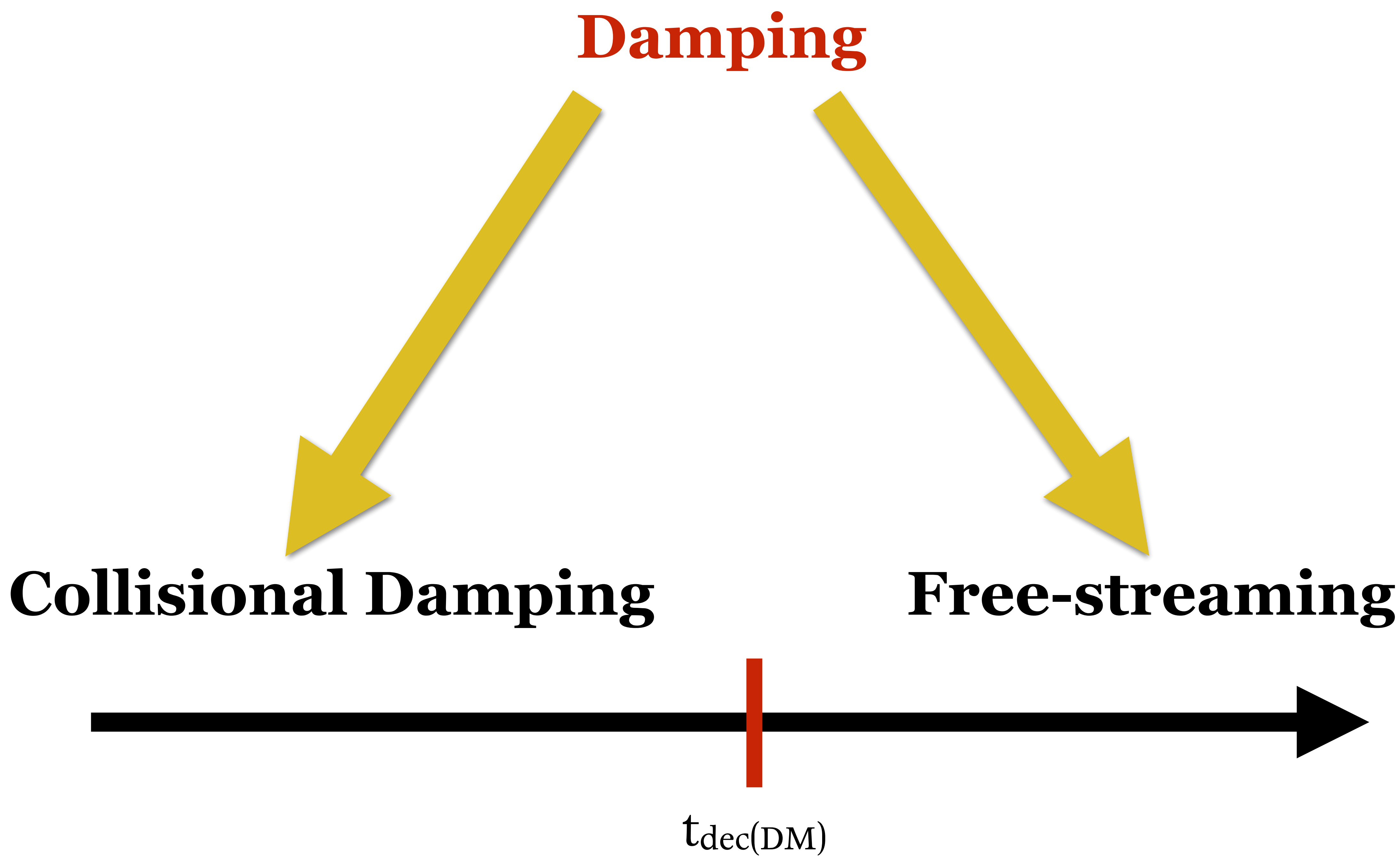
with DM interactions

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

$$\dot\mu \equiv a\sigma_{\gamma-\mathrm{DM}} n_{\mathrm{DM}}$$

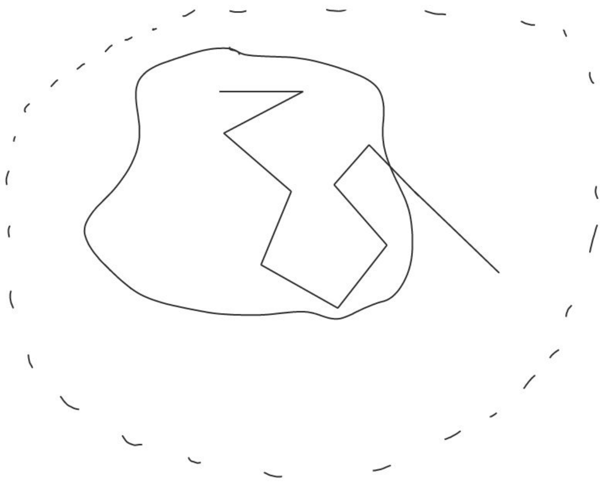
$$S \equiv \frac{3}{4}\frac{\rho_{\mathrm{DM}}}{\rho_\gamma}$$

Effects of collisions



$$l_{id}^2 \sim \frac{2\ \pi^2}{3} \int_0^{t_{\mathrm{dec(dm-i)}}} \frac{\rho_{\mathrm{i}}\ v_i^2}{\rho_t\ a^2\ \Gamma_{\mathrm{i}}} dt$$

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



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

depends on whether DM has interactions or not?

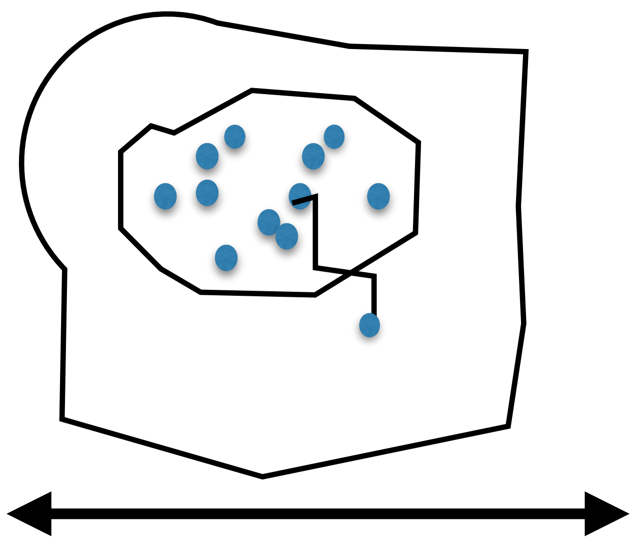
$$\boxed{l_{id}^2 = \frac{2\pi^2}{3}\int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\not{\rho}\, a^2 \Gamma_i}\left(1+\Theta_i\right) \frac{dt}{t}}$$

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

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

No DM interaction, no effect!

Collisional (Silk) damping in modern Cosmology



collisional damping length

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

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

Translation in terms of Cosmological perturbations

without DM interactions

astro-ph/0112522

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

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

with DM interactions

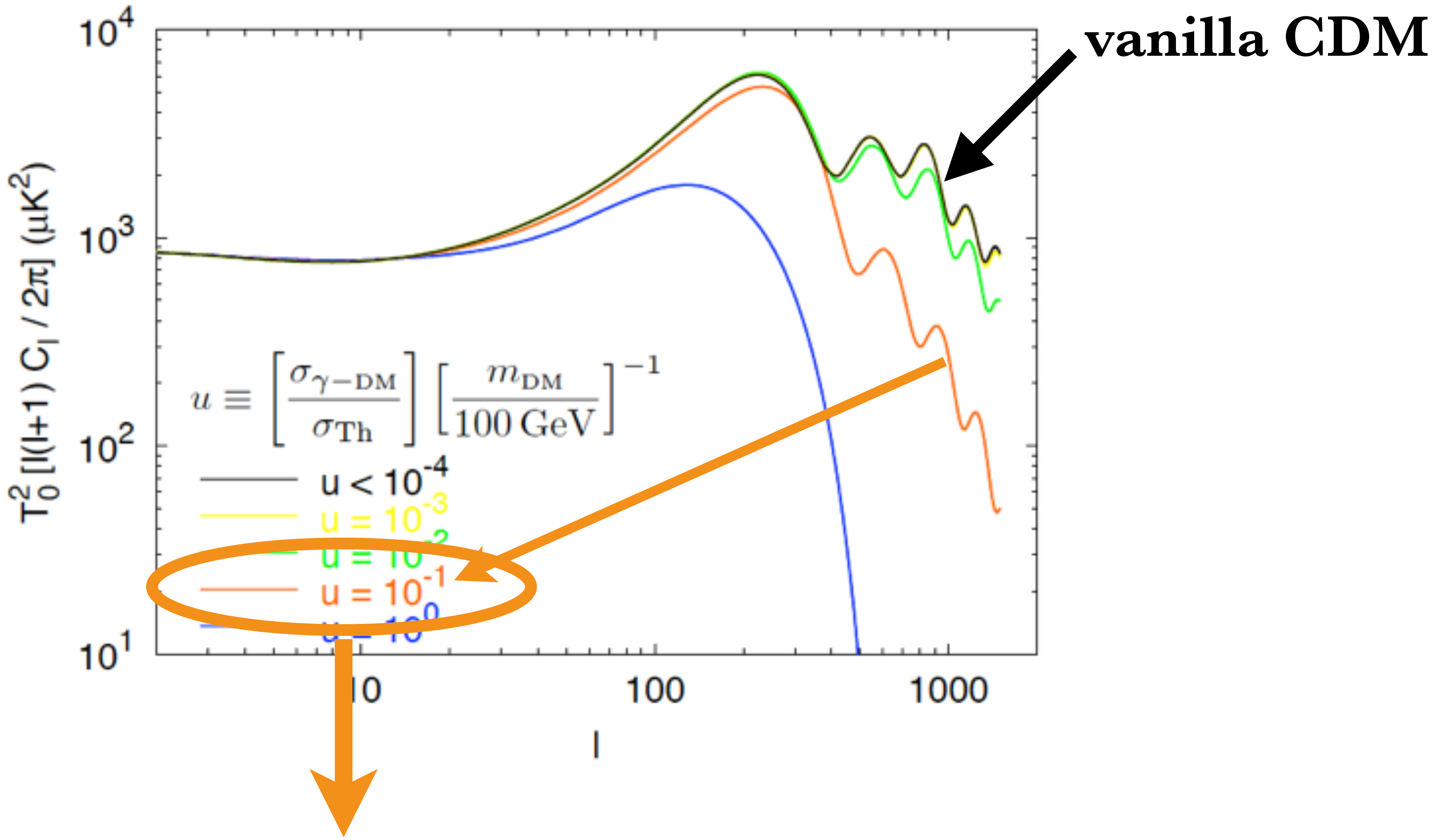
$$\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) \\
&\quad - \dot{\kappa}(\theta_\gamma - \theta_b) - \dot{\mu}(\theta_\gamma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

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

DM-photon interactions

astro-ph/0112522

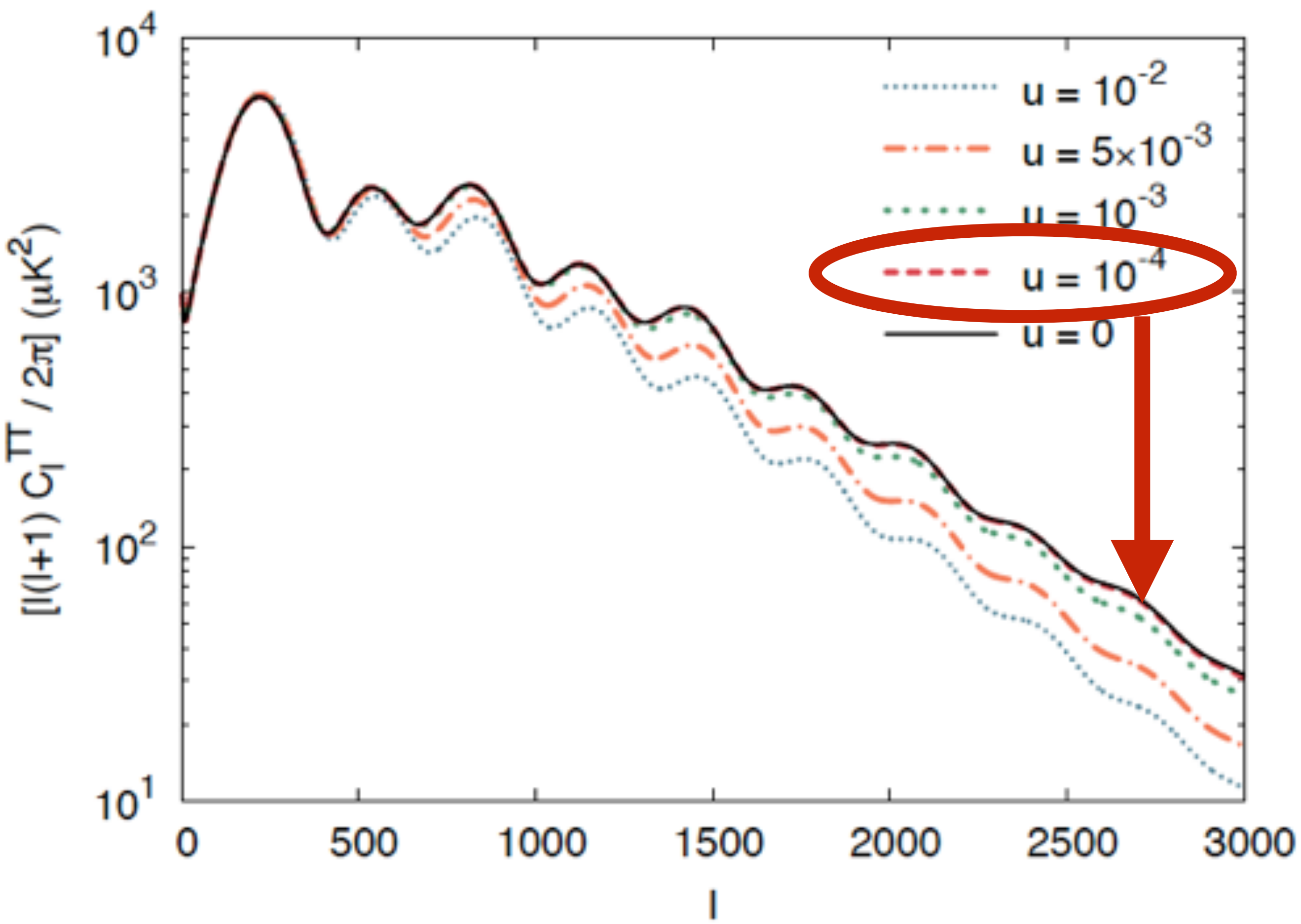
1 parameter (the ratio of cross section to the DM mass)

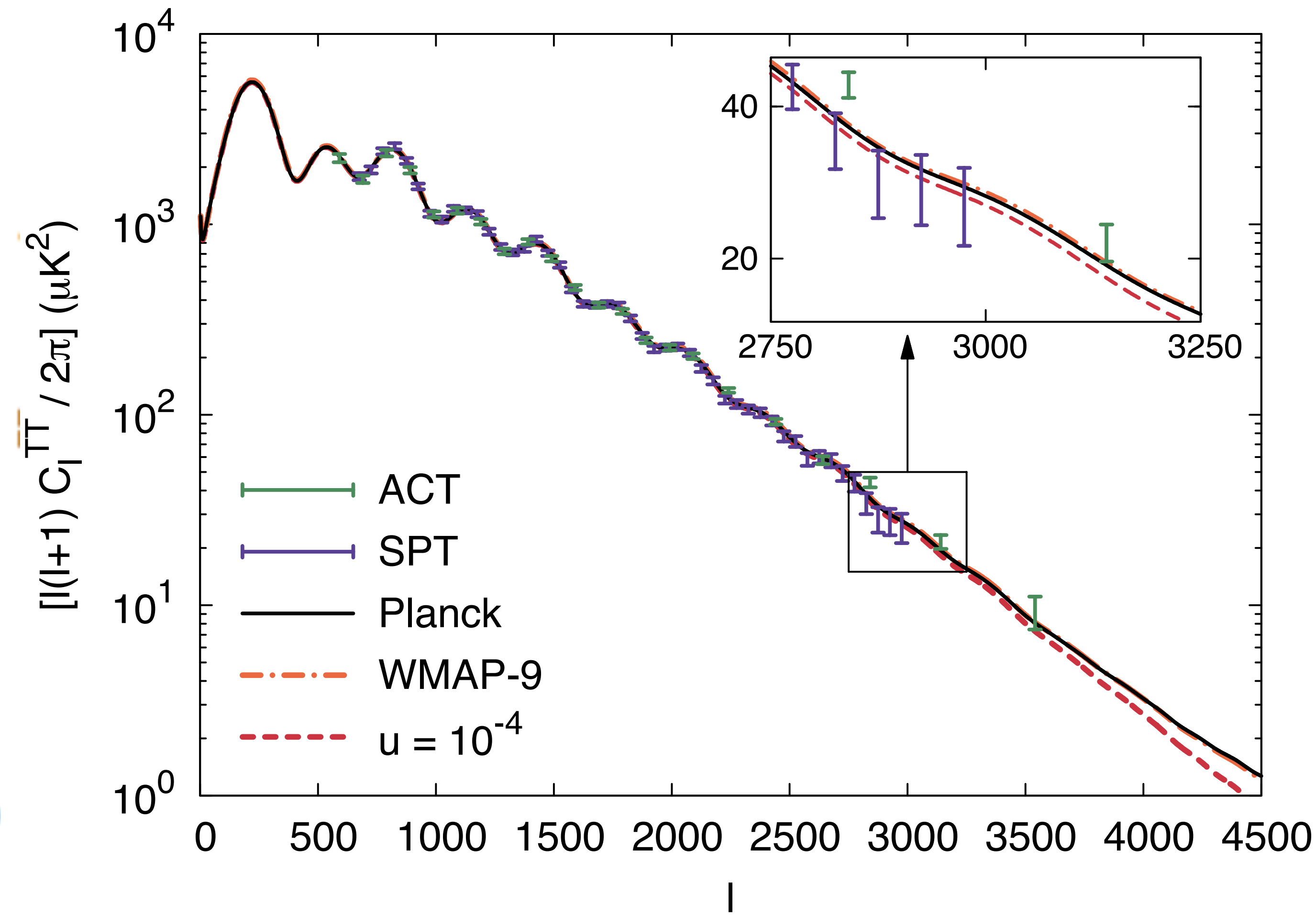


Thomson cross section;
dark matter would be a baryon… it is excluded!

Deviations to LCDM

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





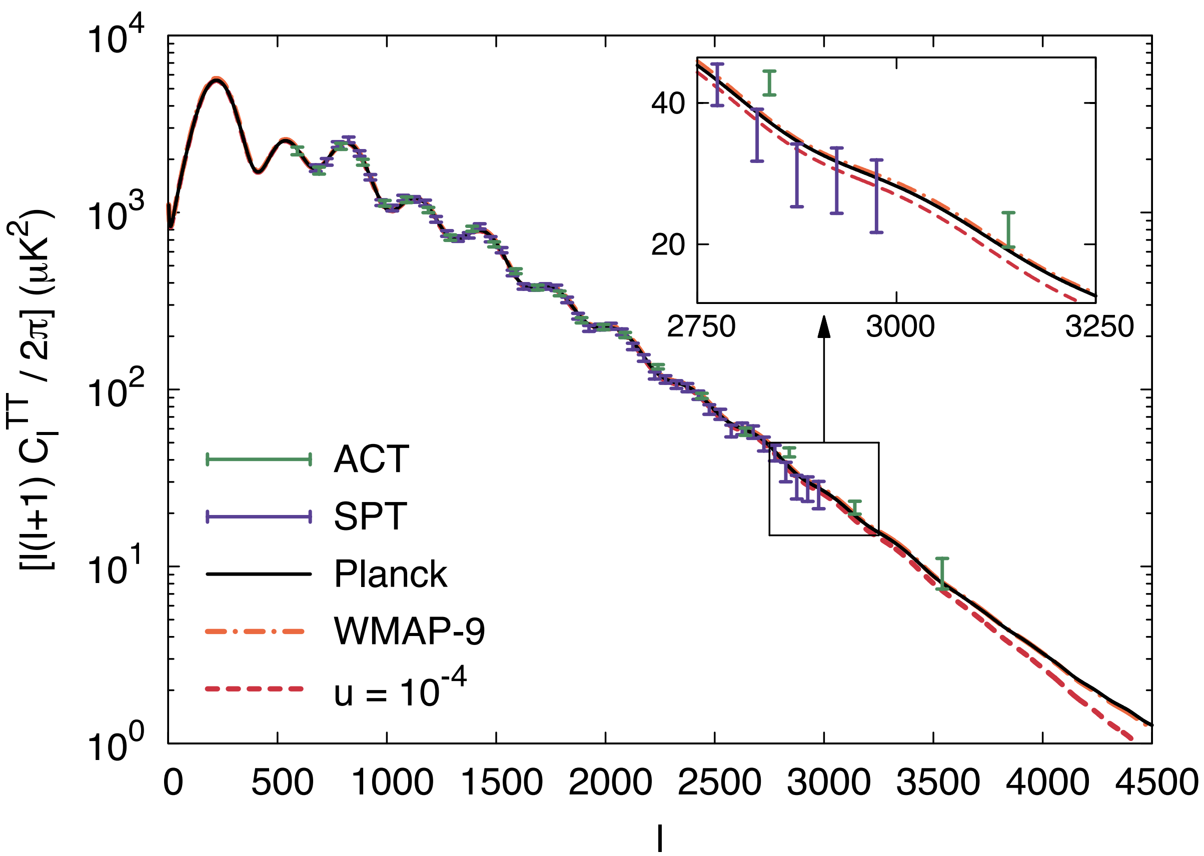
$$\sigma_{\gamma-\mathrm{DM}} < 6\ 10^{-30}\ \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)\ \mathrm{cm}^2$$

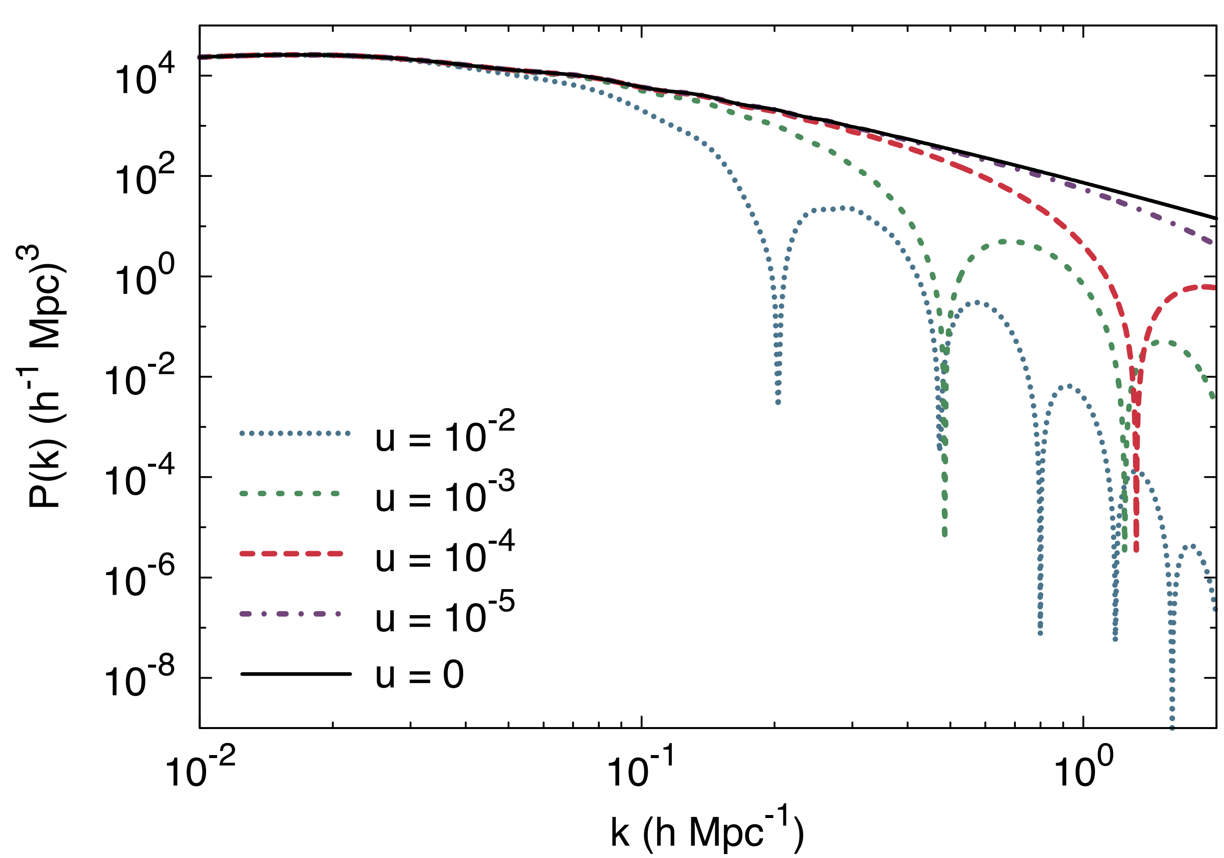
CMB alone is not probing collisionless DM!

One cannot tell whether DM has small interactions with photons or other particles!

What about structure formation?

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





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

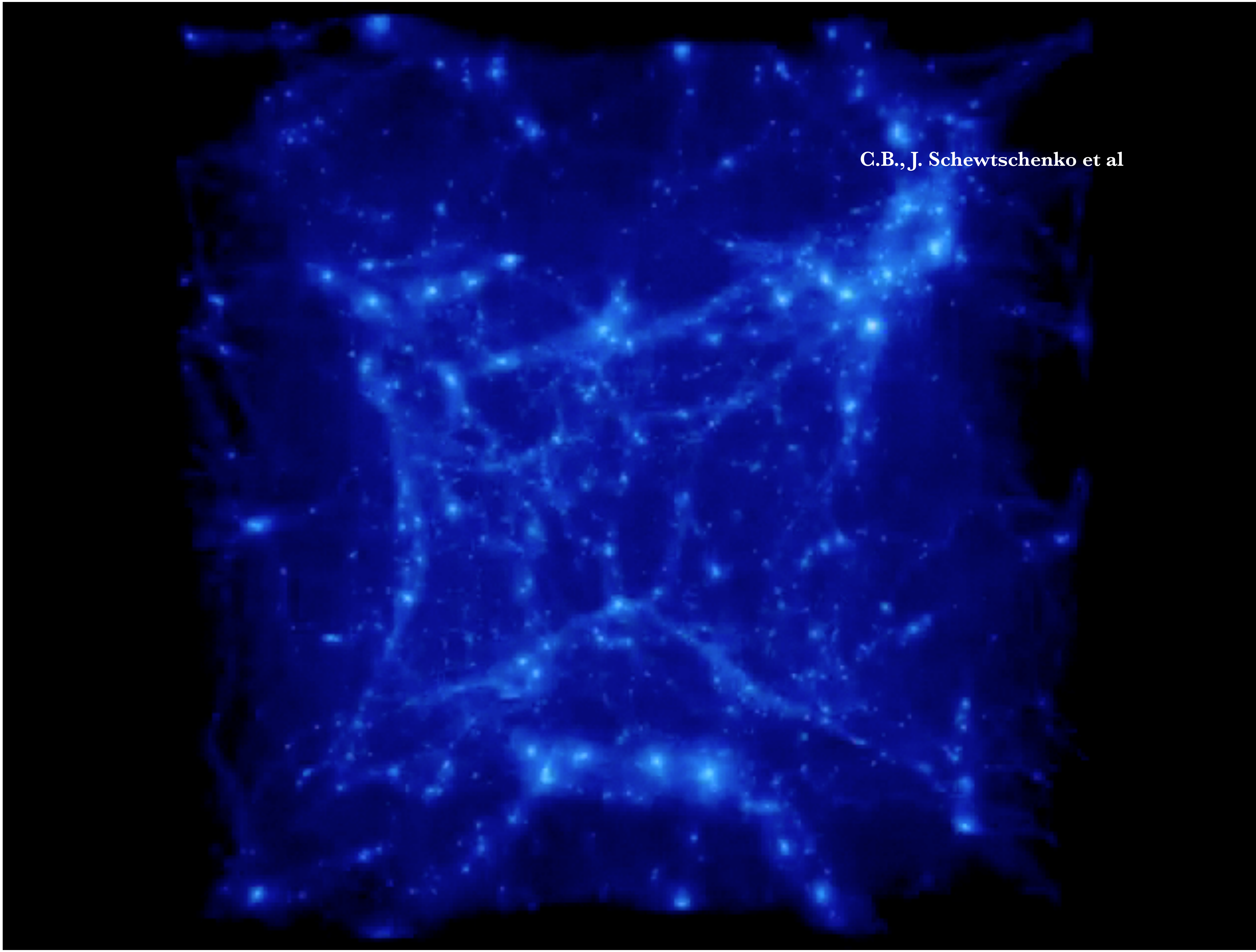
R. Wilkinson, J. Lesgourgues, C. Boehm: arXiv:1309.7588

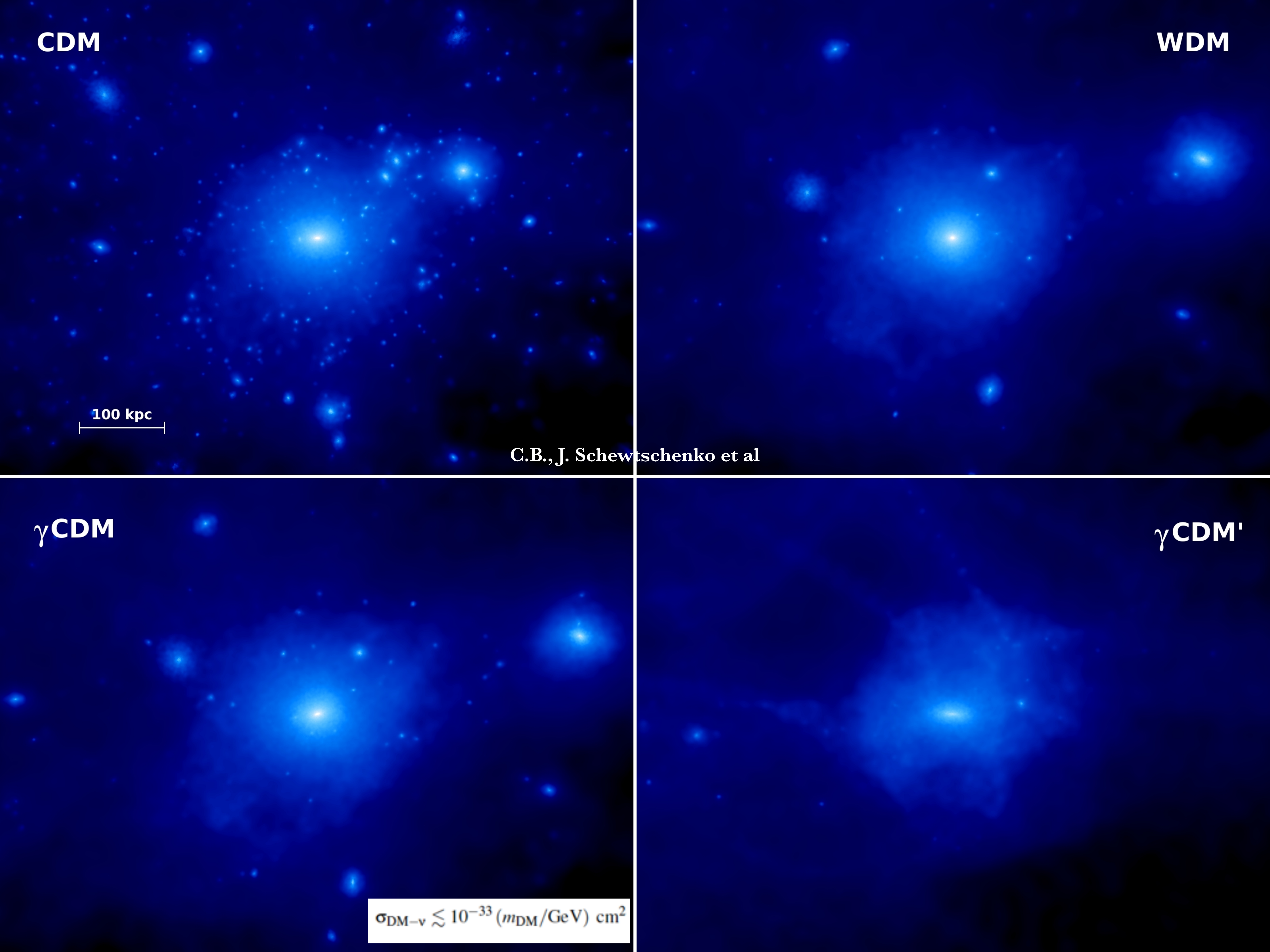
$$\delta_\gamma \sim \delta_k \cos(k\eta/\sqrt{3}) e^{-\frac{2k^2\eta}{15\dot{\kappa}}}$$

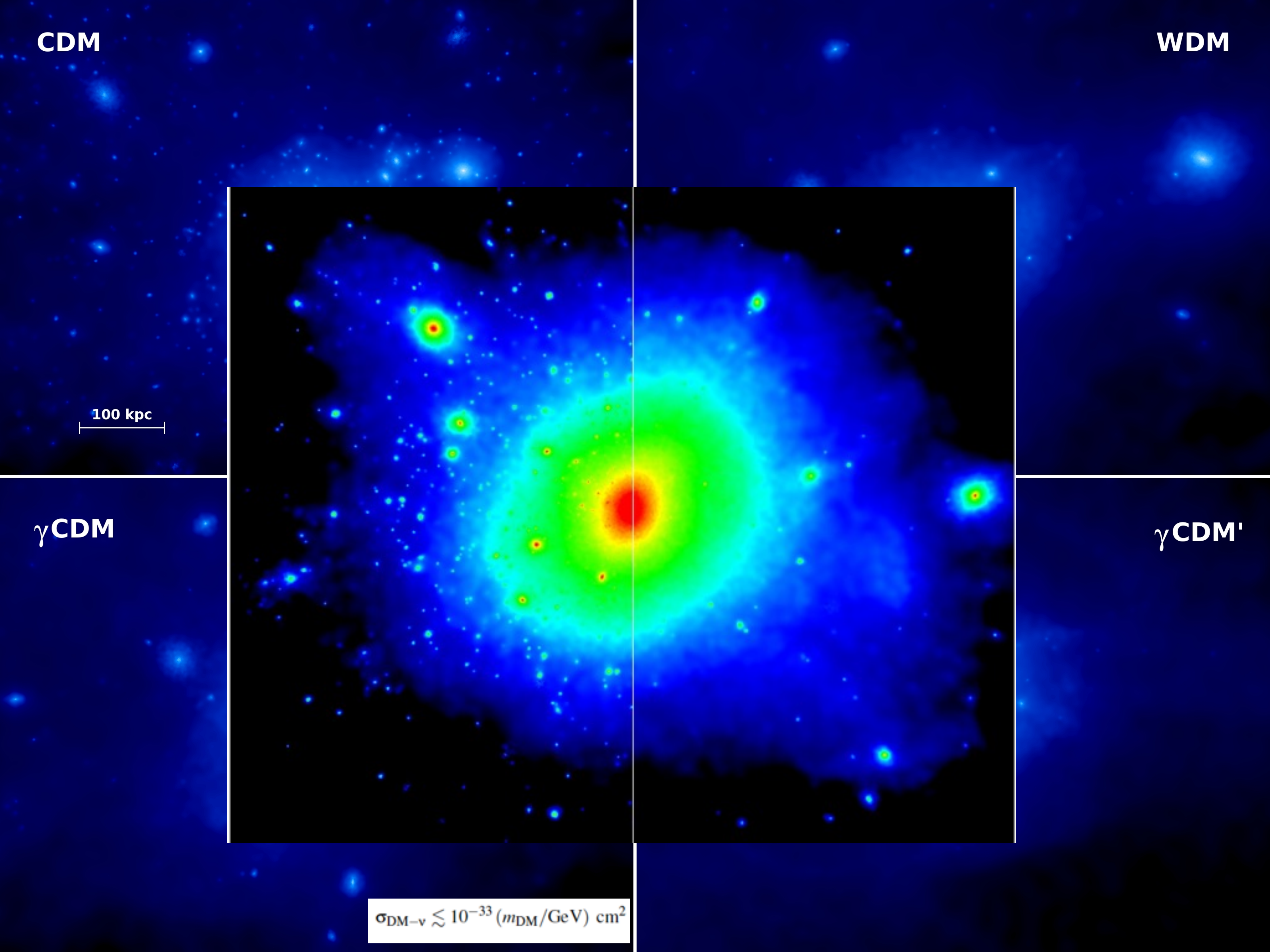
Dark Oscillations

Structure formation is sensitive to DM interactions!

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




CDM
WDM
100 kpc
C.B., J. Schewtschenko et al
γCDM
γCDM'
$\sigma_{DM-\nu} \lesssim 10^{-33}\,(m_{DM}/\mathrm{GeV})\ \mathrm{cm}^2$


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

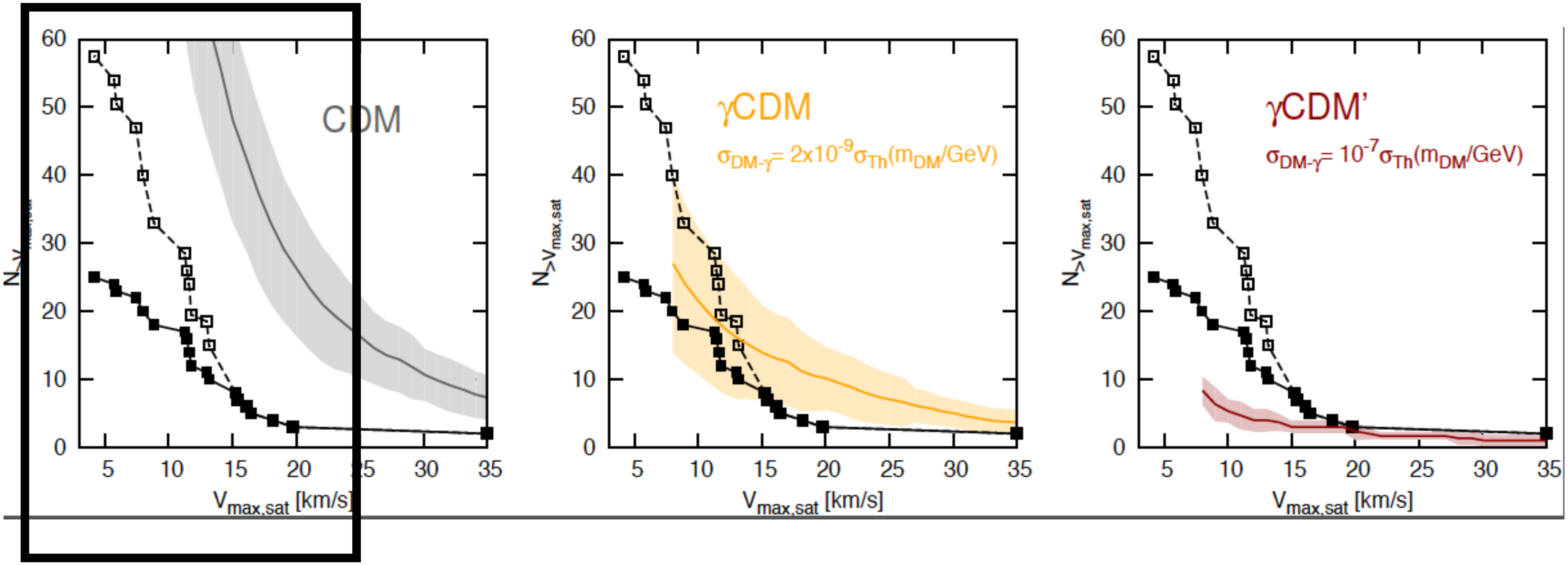
Numbers of MW satellite galaxies

C.B, J. Schewtschenko, R. Wilkinson, C. Baugh, S. Pascoli, arXiv:1404.7012

CDM prediction is well above observation

Interacting DM agrees with observation

Too many interactions

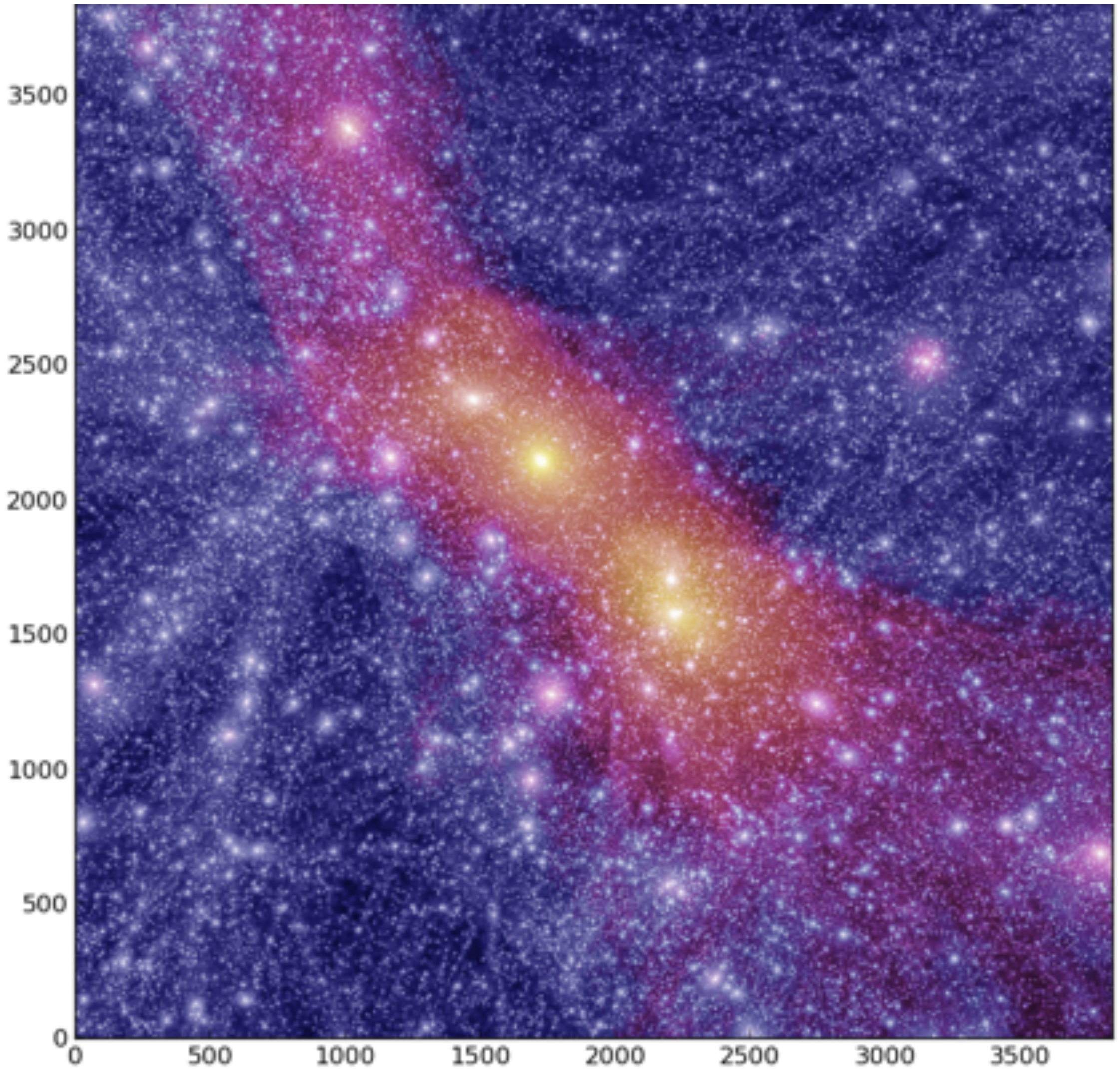


small satellites

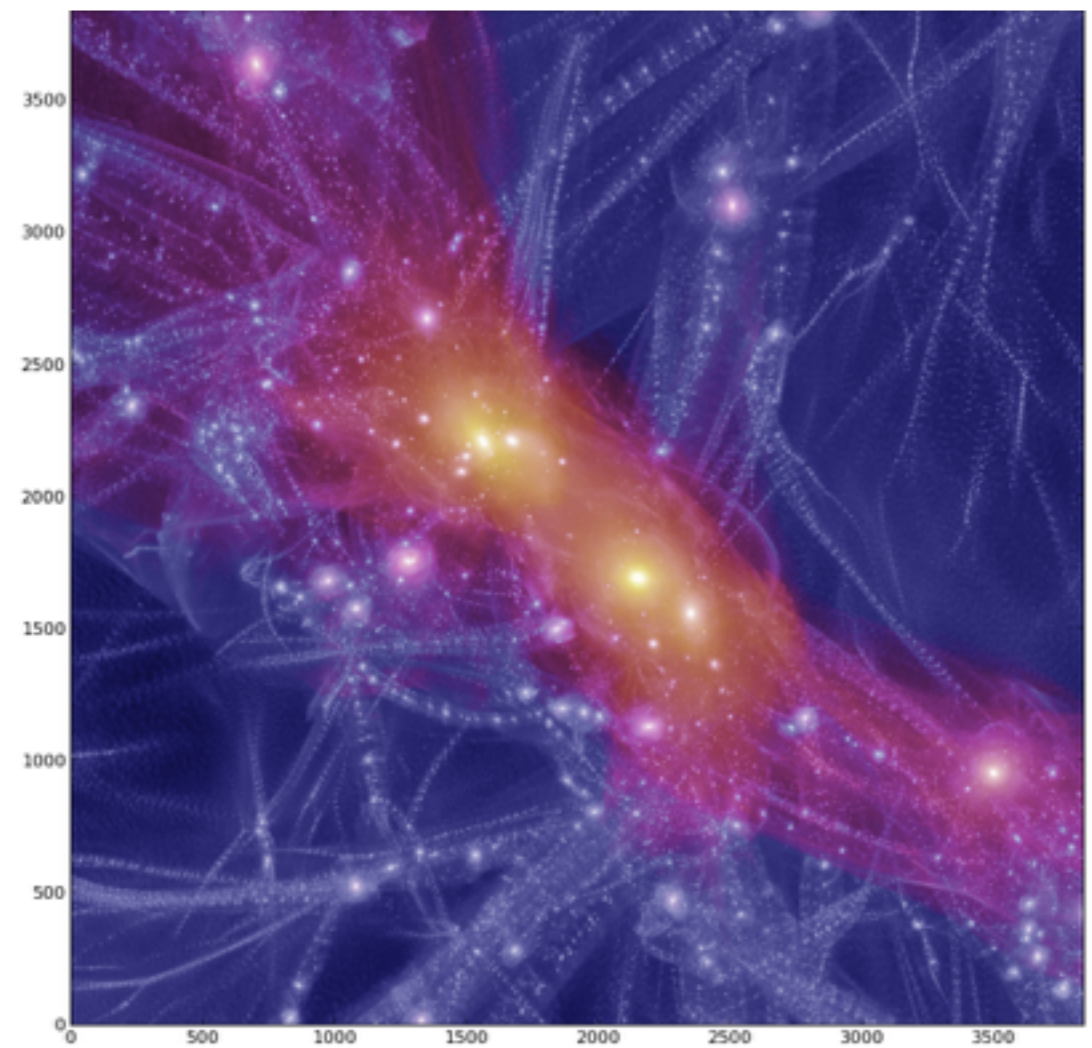
Solve the MW satellite problem!

Sterilise the MW!

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

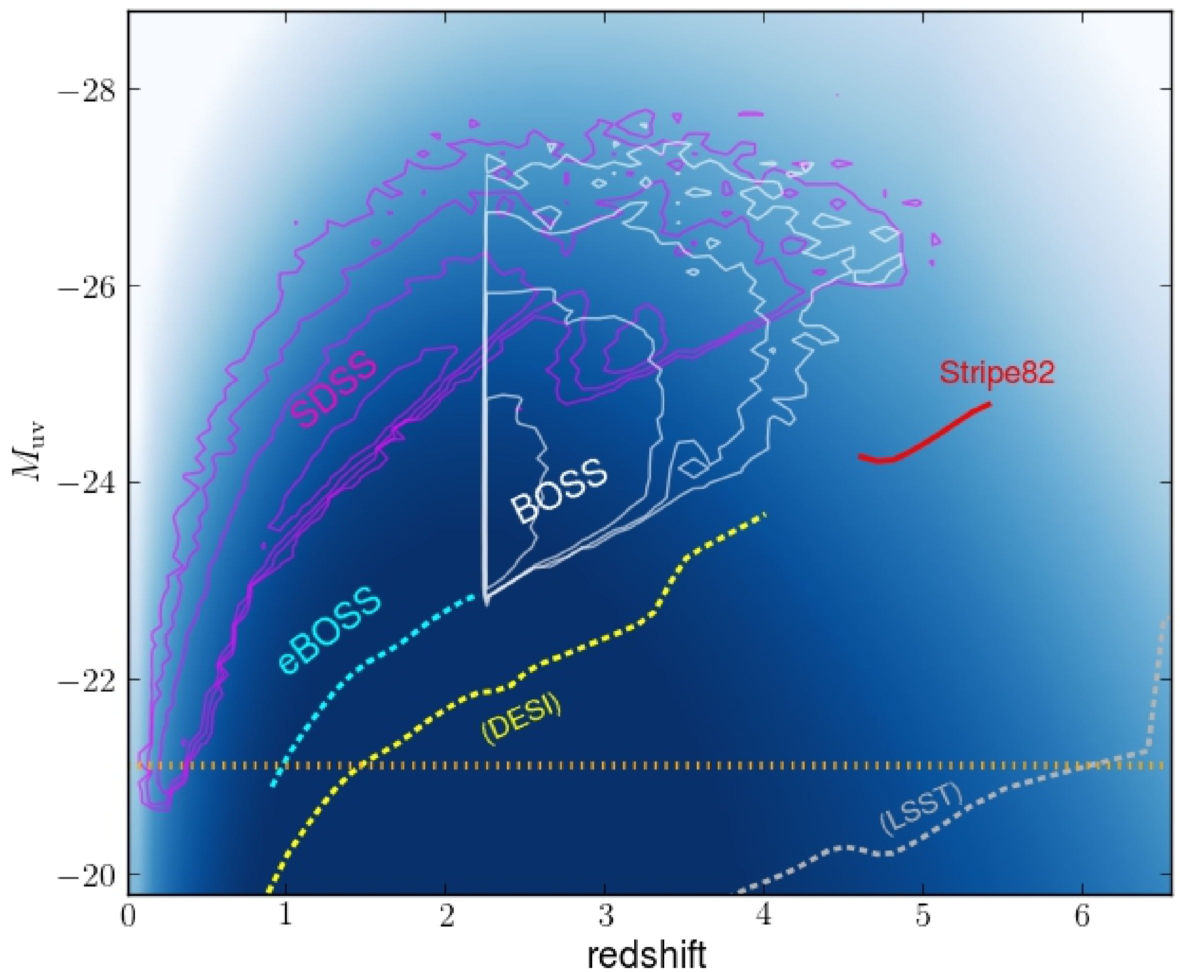


LSS in the Universe are modified too!

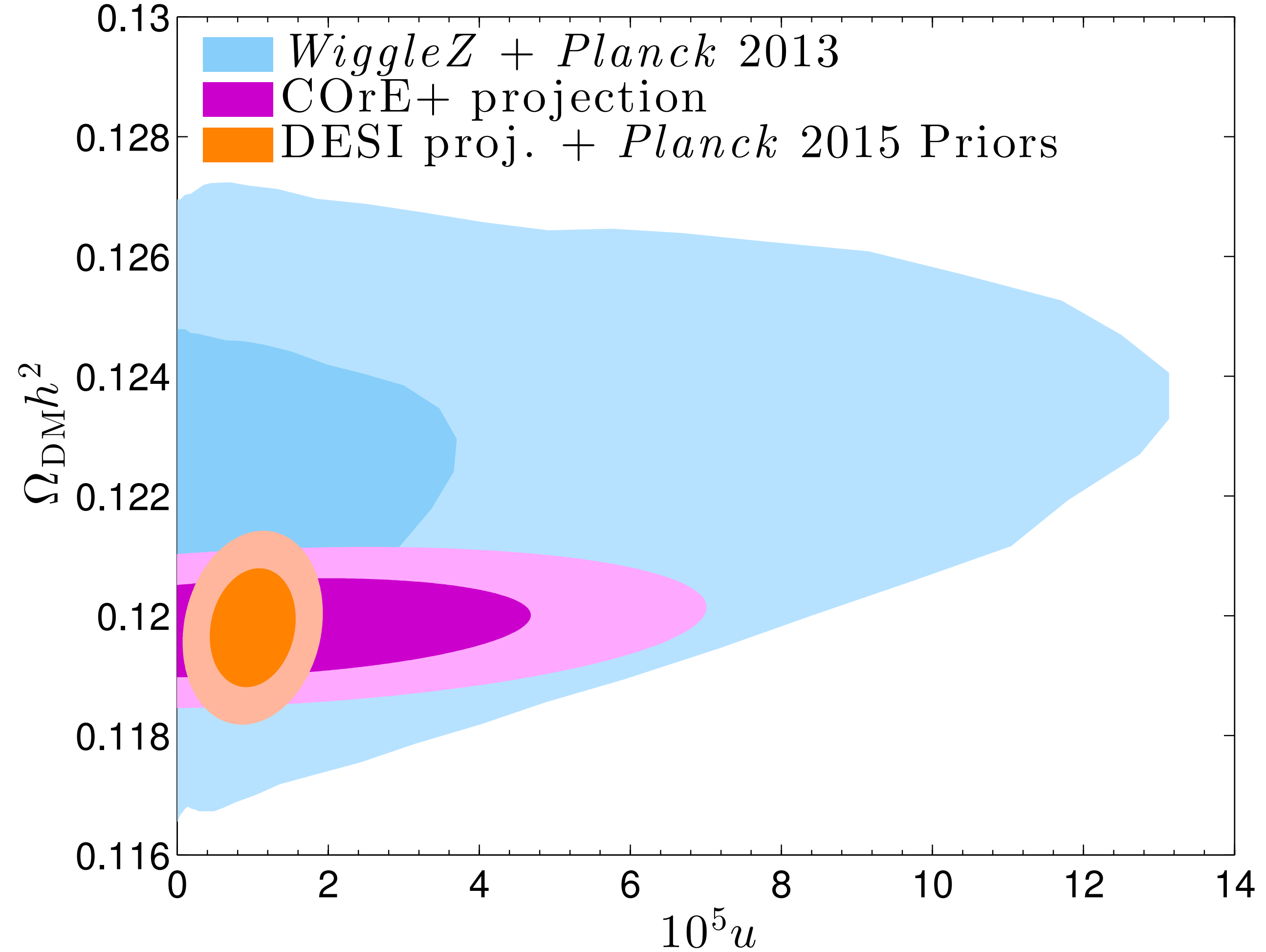


Future LSS experiments can set strong bounds

with O. Mena, M. Escudero, A. Vincent &R. Wilkinson



Courtesy JP Kneib



With DESI we gain a factor 10

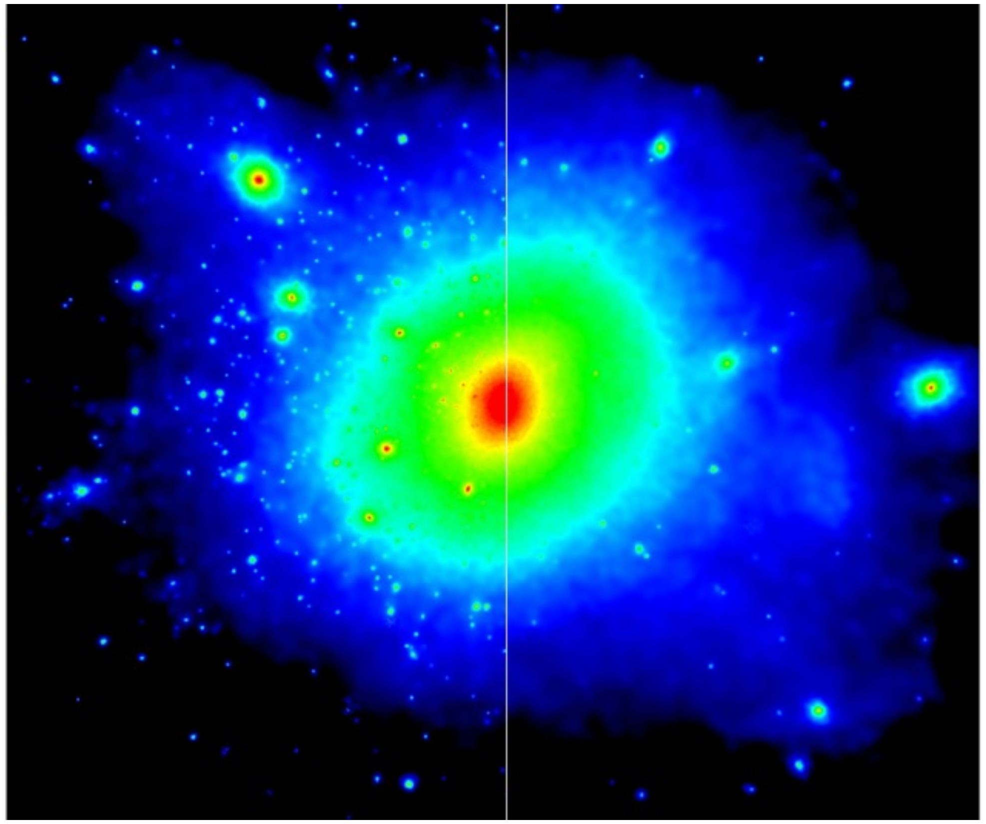
It will be amazing to see what LSST brings …

Conclusion

CMB cannot probe LCDM deviations! But P(k) can!

WIMPS are not always equivalent to collisionless particles

Small interactions can drastically change the way structures form and the inner structure of our Milky Way halo



Cosmology can constrain the microphysics of DM!

WDM & Free-streaming

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

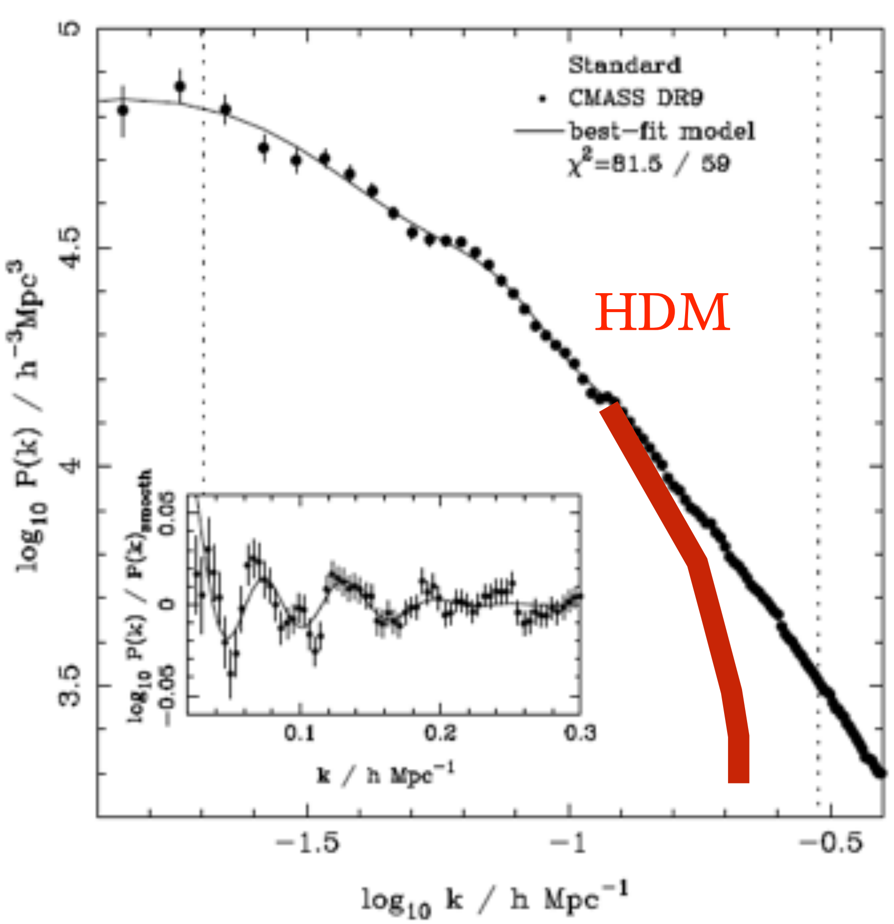
$$l_{\rm fs} = \int_{t_{\rm dec}}^{t_0} \frac{v(t)}{a(t)}\ dt$$

No interaction, tdec = "0"time;

$$\int_{t_{\rm dec}}^{t_{nr}} dt... + \int_{t_{\rm nr}}^{t_0} dt...$$

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

This calculation only depends on the moment where DM becomes non relativistic so it only depends on the **DM mass**



$$T(k) = \left[1 + (\alpha k)^{2\mu}\right]^{-5/\mu}$$

$$\alpha = 0.048 \left[\frac{m_{\rm DM}}{\rm keV}\right]^{-1.15} \left[\frac{\Omega_{\rm DM}}{0.4}\right]^{0.15} \left[\frac{h}{0.65}\right]^{1.3} \frac{\rm Mpc}{h}$$

A more generic case

Quid of a realistic situation?

depends on mass

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

depends on interactions

depends on the history of the Universe

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

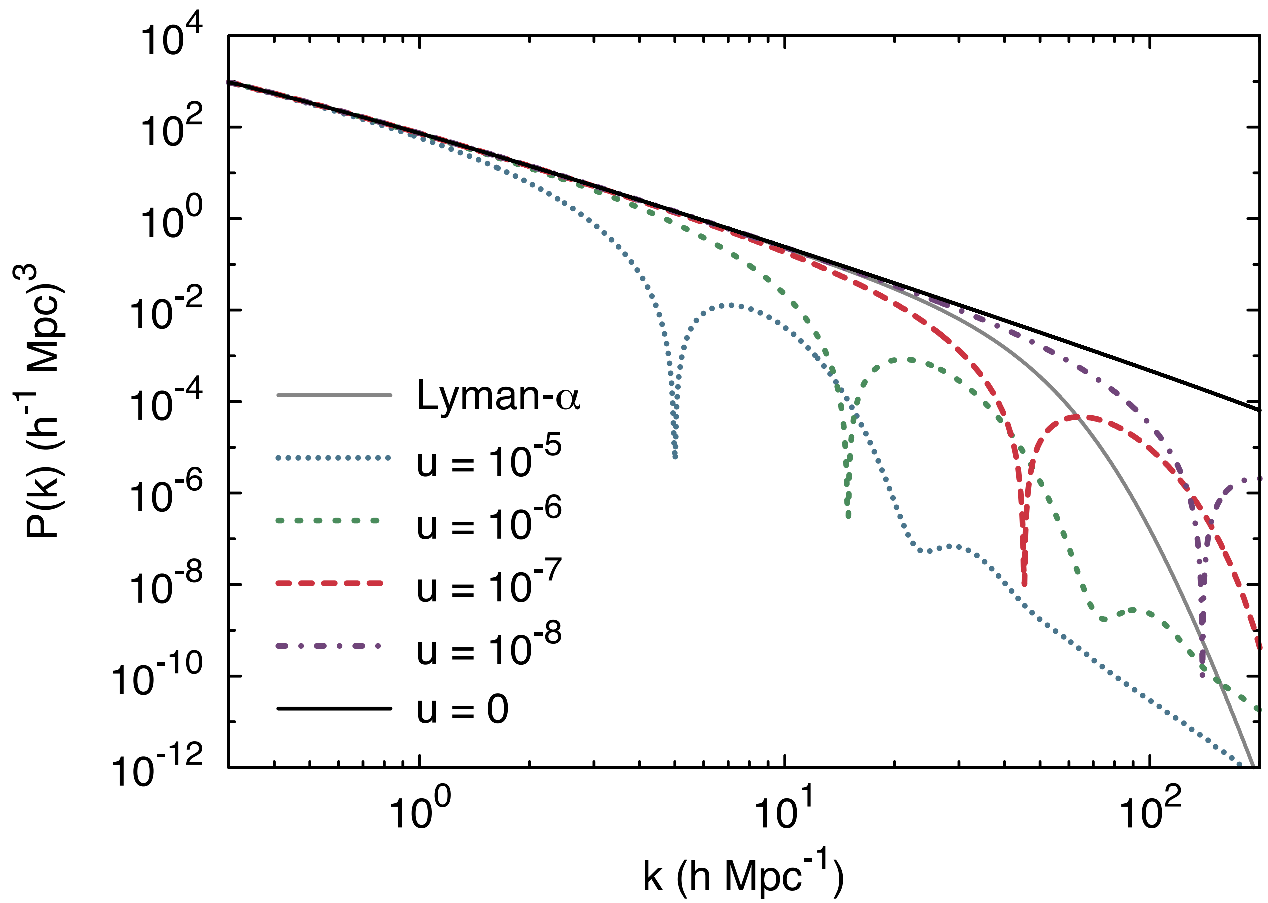
$$\int_{t_{dec}}^{t_{nr}} \frac{v(t)}{a(t)} dt \quad \text{if} \quad \mathrm{t_{dec}} < \mathrm{t_{nr}}$$

3 parameters t_{dec}, t_{nr}, t_{eq} ➡ $\Gamma,\ m_{DM},\ t_{eq}$

interaction rate

Lyman-alpha forest constraints

R. Wilkinson, C. Boehm, J. Lesgourgues: arXiv:1401.7597



Gain a factor 100 compared to CMB

Constant cross section

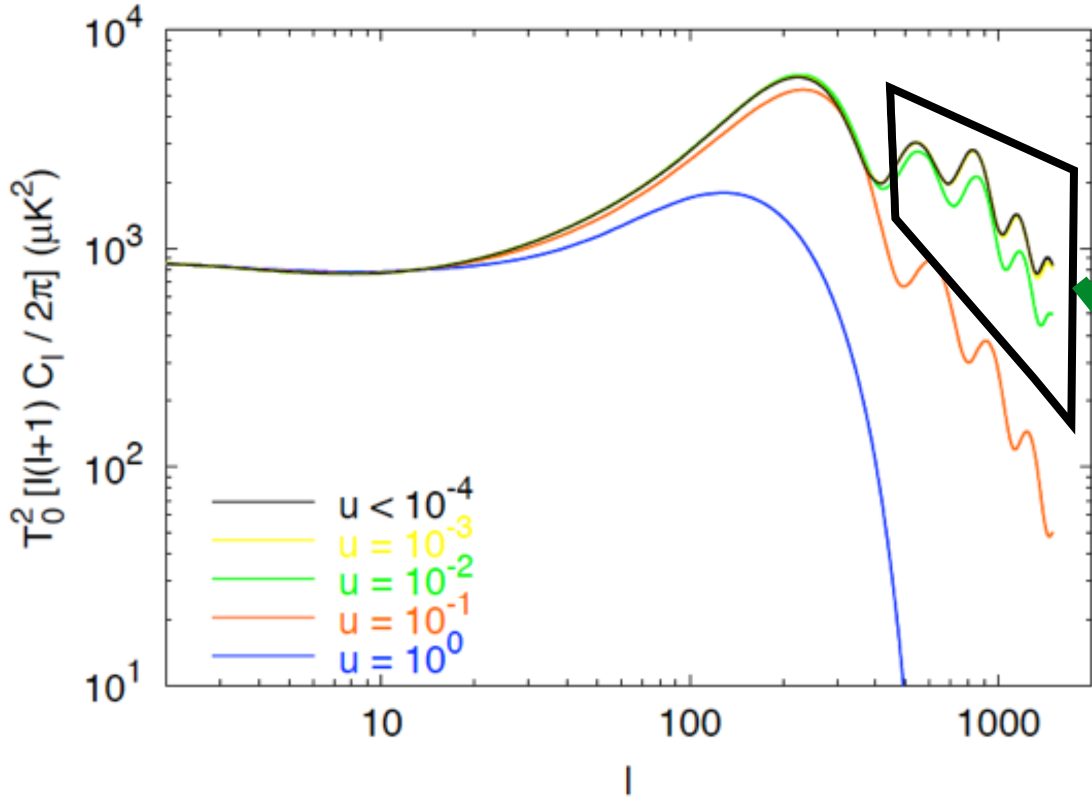
$$\sigma_{DM-\nu} \lesssim 10^{-33}\,(m_{DM}/\mathrm{GeV})\ \mathrm{cm}^2$$

T^2 *cross section*

$$\sigma_{DM-\nu,0} \lesssim 10^{-45}\,(m_{DM}/\mathrm{GeV})\ \mathrm{cm}^2$$

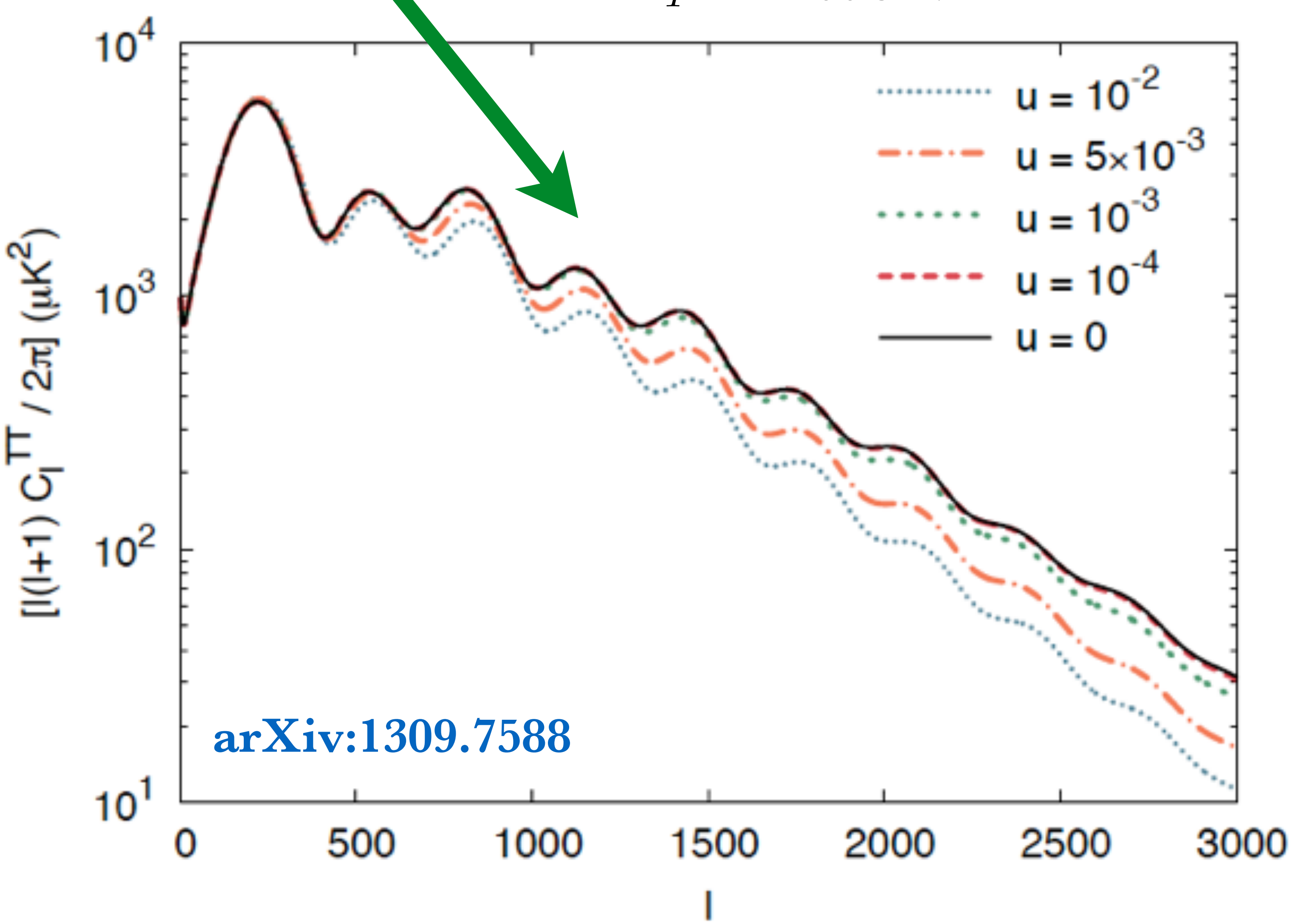
	$100\,\Omega_b h^2$	$\Omega_{DM} h^2$	$100\,h$	$10^{+9}\,A_s$	n_s	z_{reio}	N_{eff}
Lyman-α limit	$2.246^{+0.039}_{-0.042}$	$0.1253^{+0.0053}_{-0.0056}$	$71.5^{+3.0}_{-3.3}$	$2.254^{+0.069}_{-0.082}$	$0.979^{+0.016}_{-0.016}$	$11.7^{+1.2}_{-1.3}$	$3.52^{+0.36}_{-0.40}$

What is the impact on structure formation?



ZOOM IN (with Class)

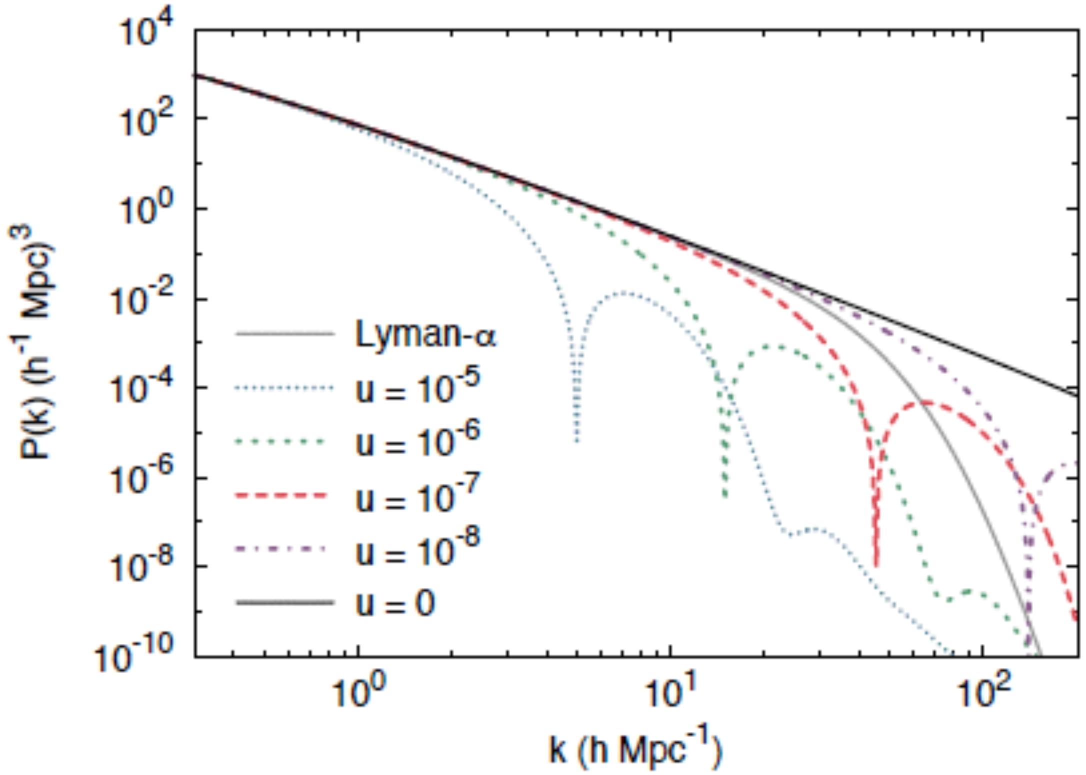
$$u = \frac{\sigma_{DM-\gamma}}{\sigma_T}\left(\frac{m_{DM}}{100\text{GeV}}\right)$$



Can these small differences resist to Planck data?

Impact on Particle Physics

R. Wilkinson, C. Boehm, J. Lesgourgues: arXiv:1401.7597



Constant cross section

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

T^2 *cross section*

$$\sigma_{\mathrm{DM}-\nu,0} \lesssim 10^{-45}\,(m_{\mathrm{DM}}/\mathrm{GeV})\ \mathrm{cm}^2$$

	$100\,\Omega_b h^2$	$\Omega_{\mathrm{DM}} h^2$	$100\,h$	$10^{+9} A_s$	n_s	z_{reio}	N_{eff}
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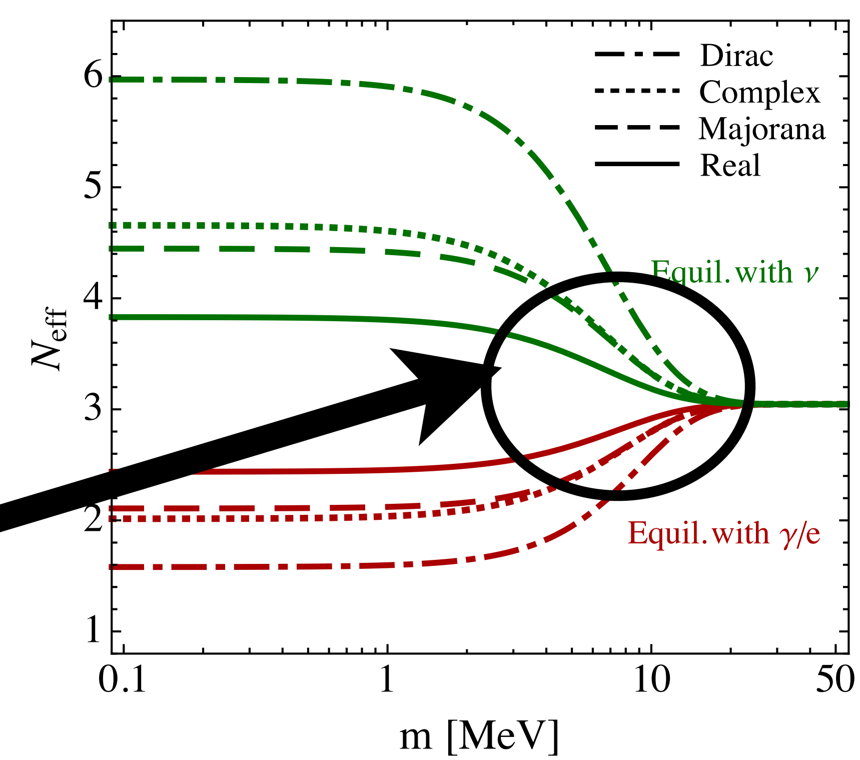
C. Boehm, M. Dolan, C. McCabe arXiv:1303.6270

Constant elastic scattering cross section

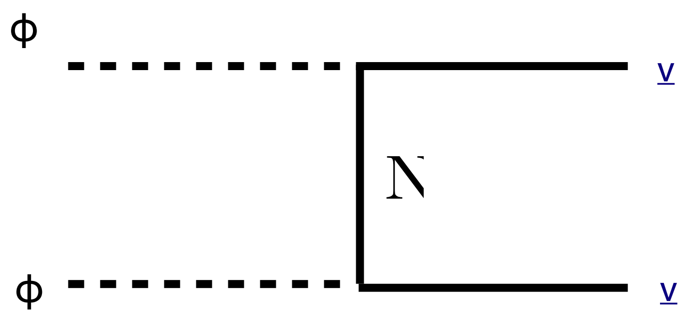
- $\sigma \sim 10^{-36}\ \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right)\ \mathrm{cm}^2$

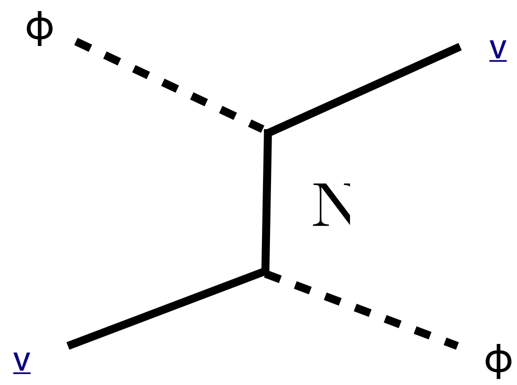
Annihilation cross section

- $\sigma v \sim 10^{-26}\ \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right)\ \mathrm{cm}^3/\mathrm{s}$



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

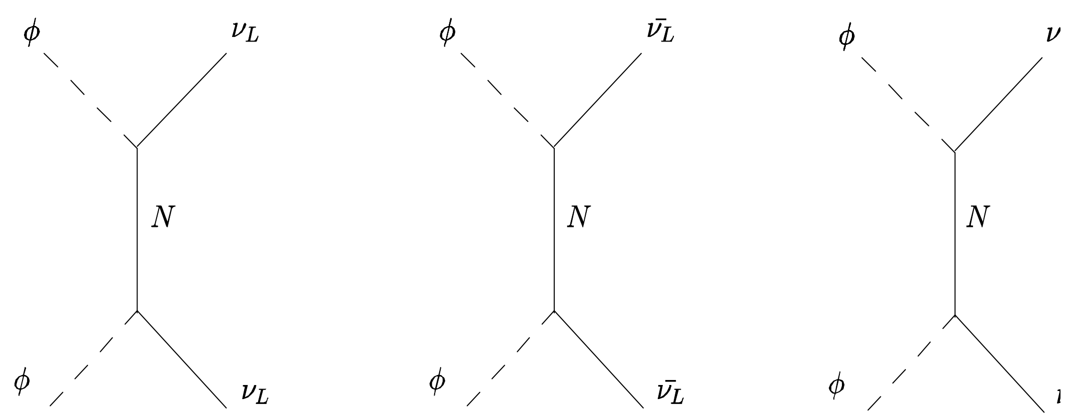


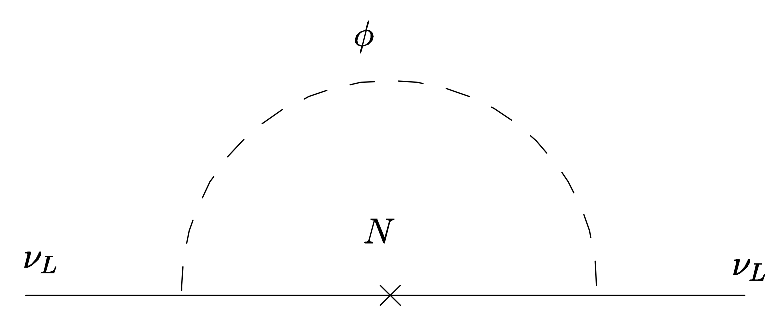


$$\sigma_{\mathrm{DM}-\nu} \simeq 4\times 10^{-36}\left(\frac{\langle\sigma v\rangle}{3\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)\ \mathrm{cm}^2$$

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

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





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

Effective theory

(N singlet of SU(2) for example)

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

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

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