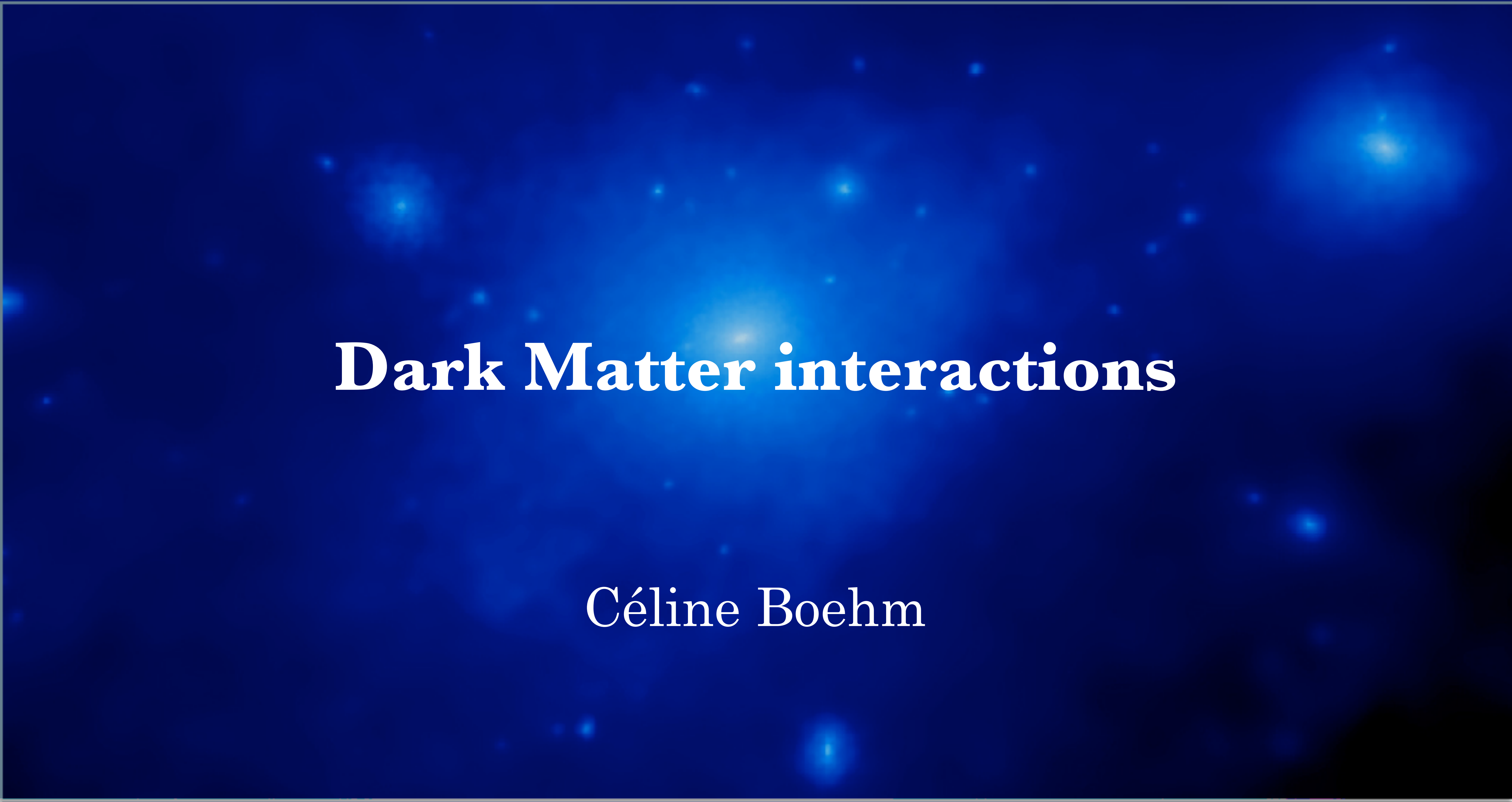


Dark Matter interactions

Céline Boehm

IPPP, Durham

LAPTH, Annecy

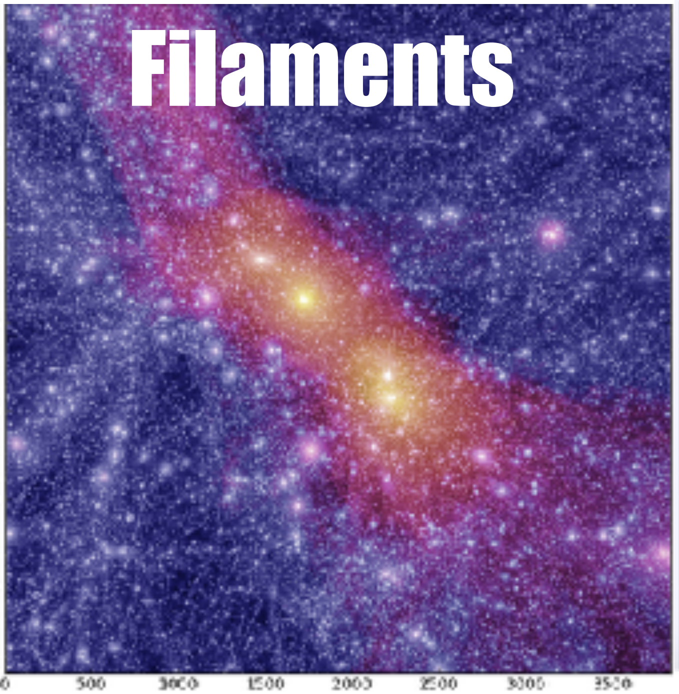
Paris, May 2017

DM is everywhere!

But we do not know what it is

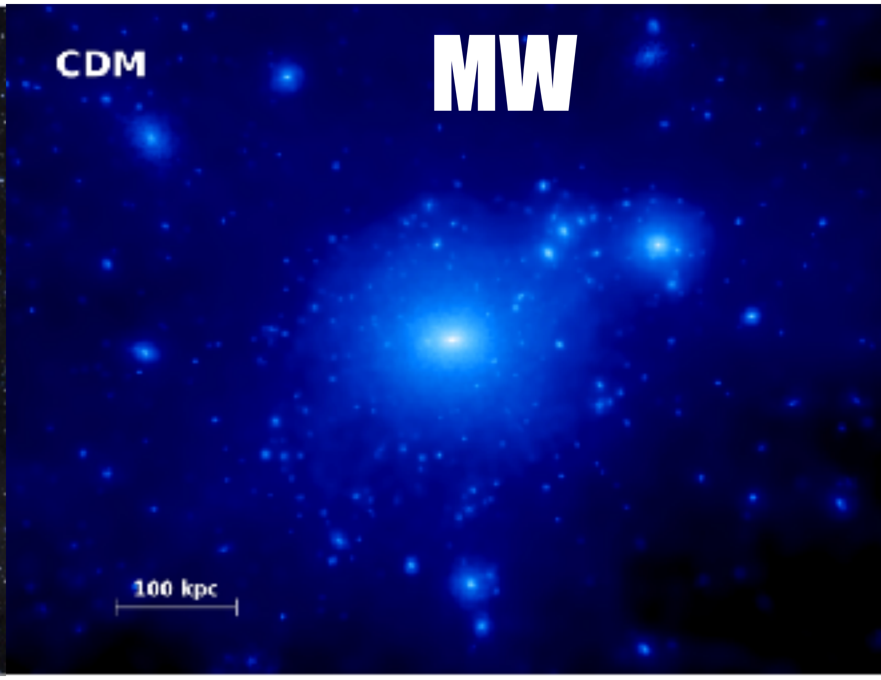
Understanding the nature of DM

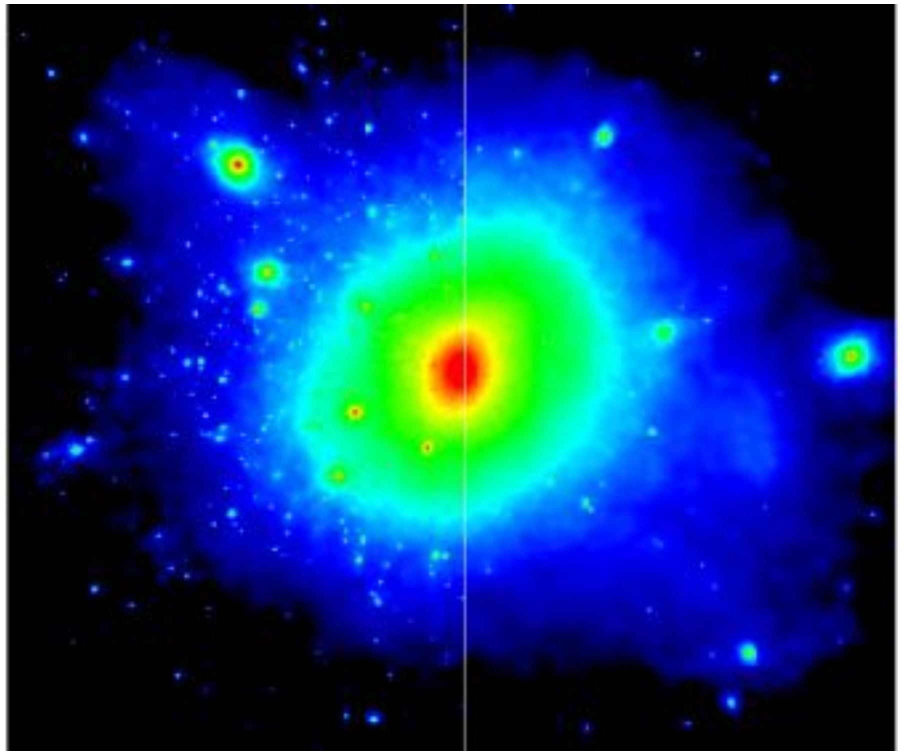
Dark Matter is (more or less) everywhere/at all scales


Filaments


Clusters

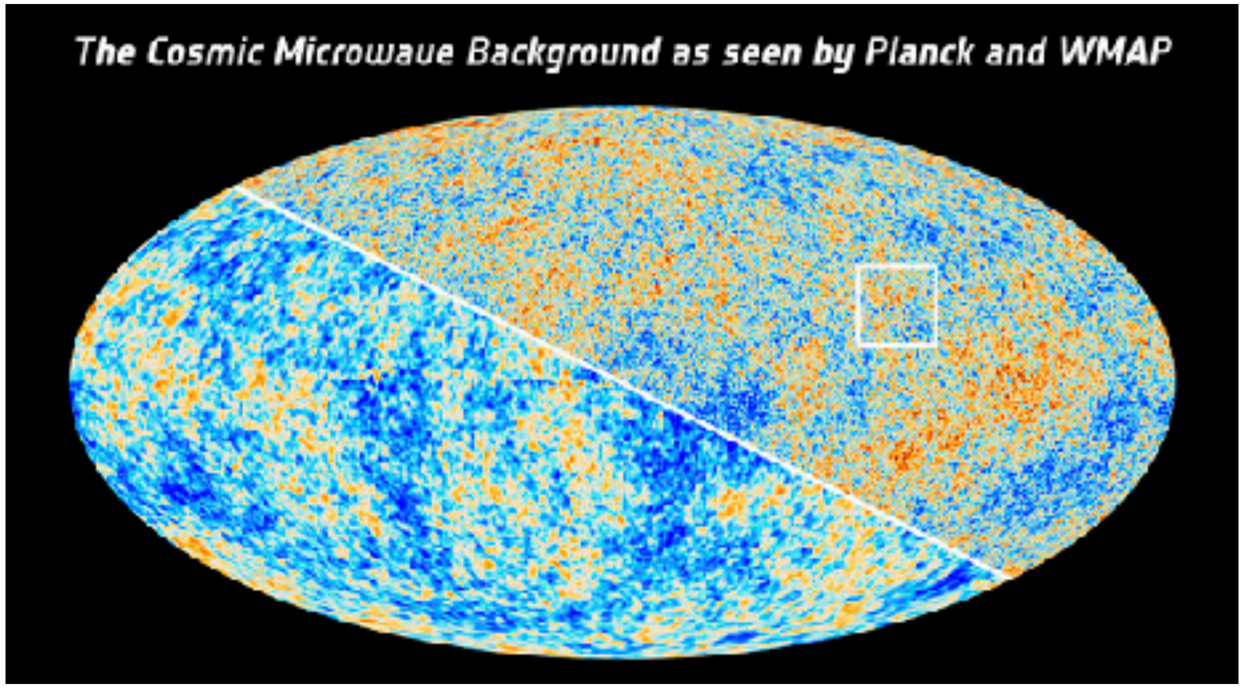
Copyright: Rogelio Bernal Andreo

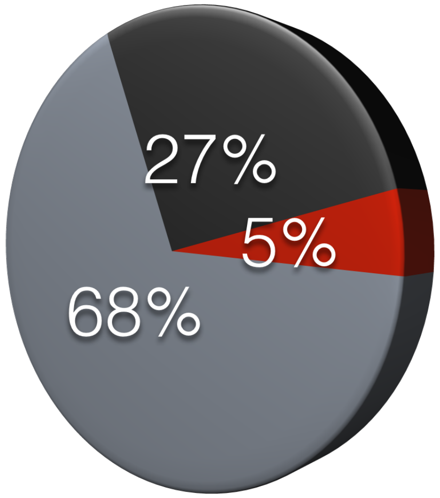

MW



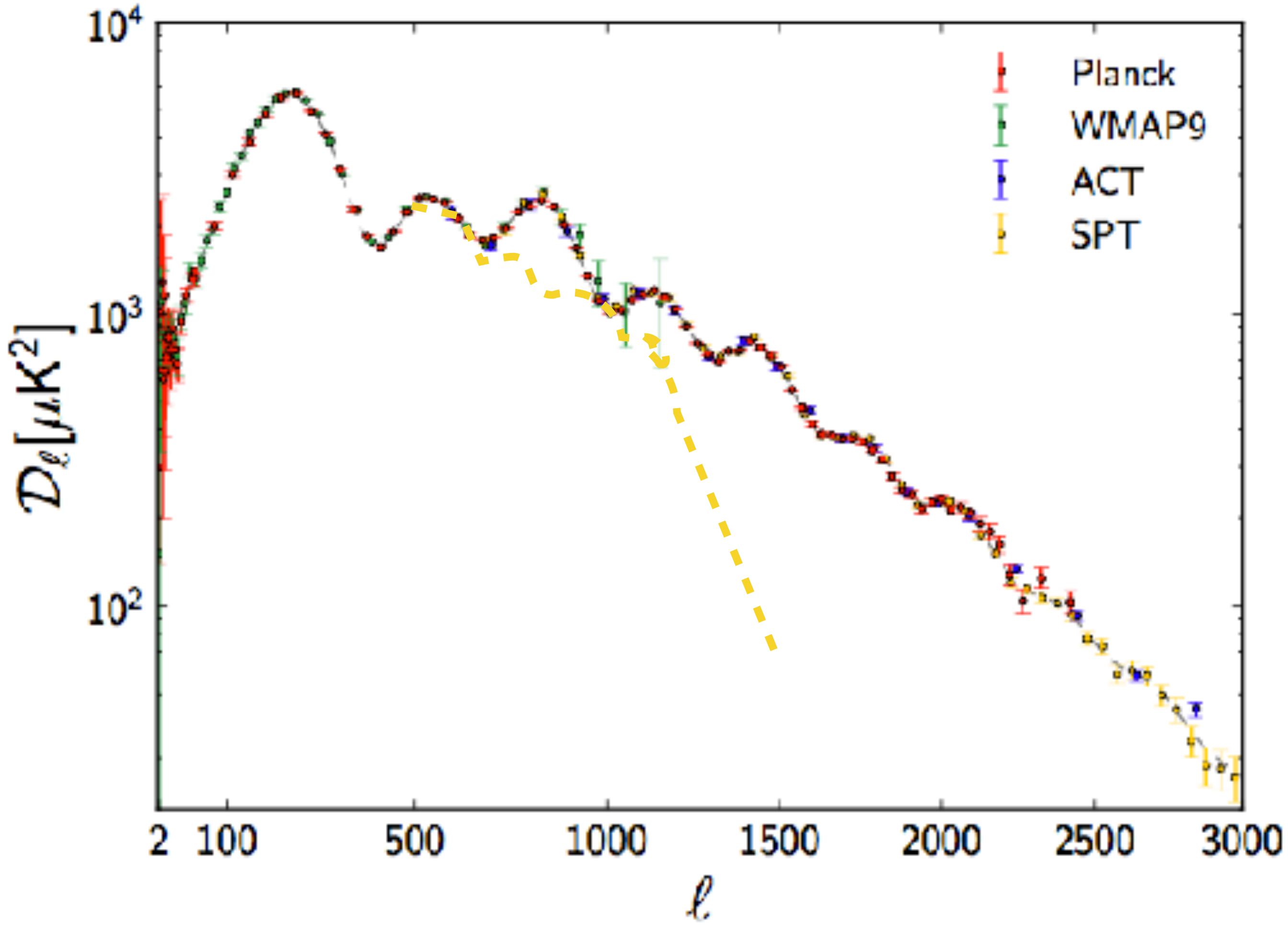
but is it related to Particle Physics?

Understanding the nature of DM





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



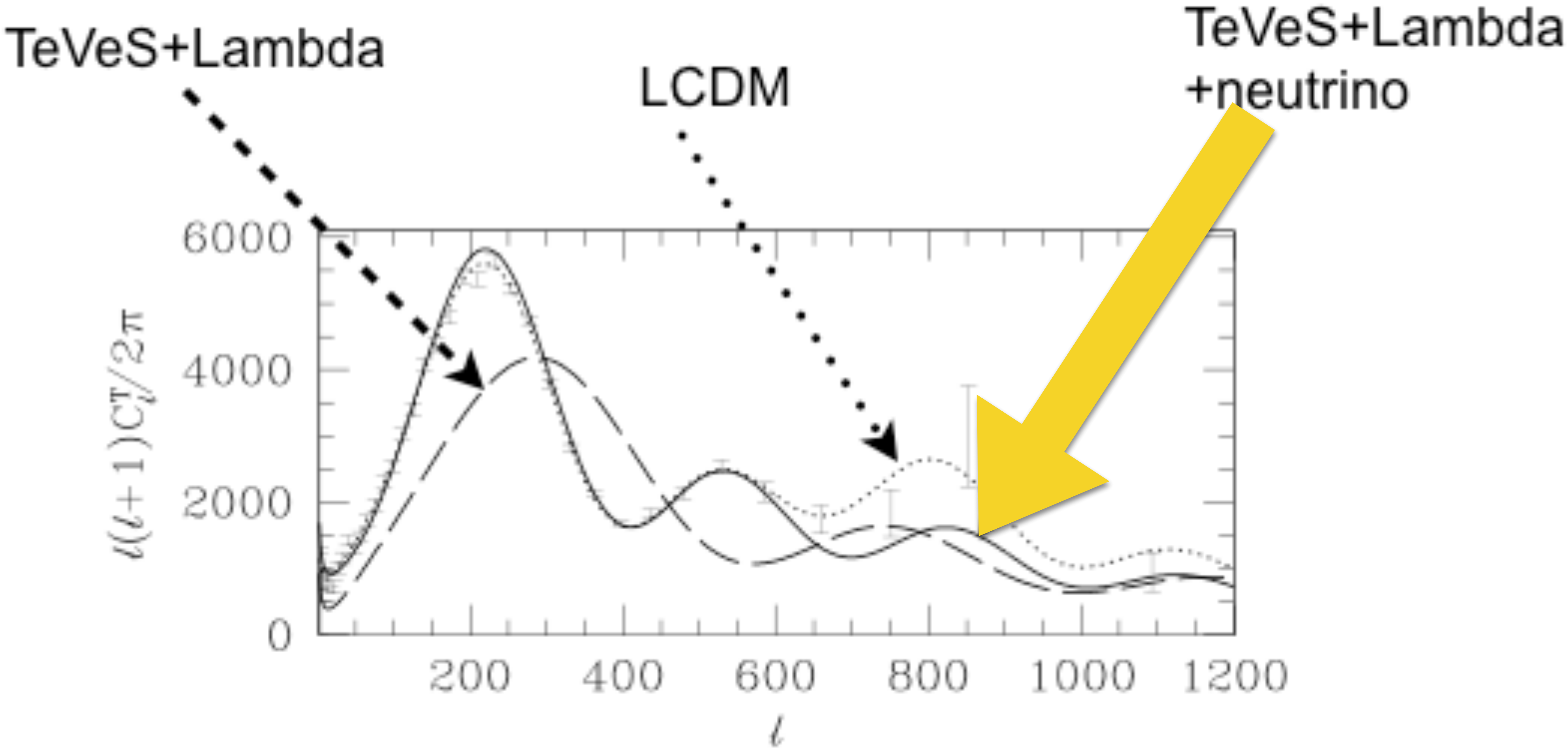
The CMB cannot be explained with baryonic DM only

A consequence of Silk damping (Nature, 1966)

Understanding the nature of DM

Mond/Bekenstein Bekenstein astro-ph/0403694

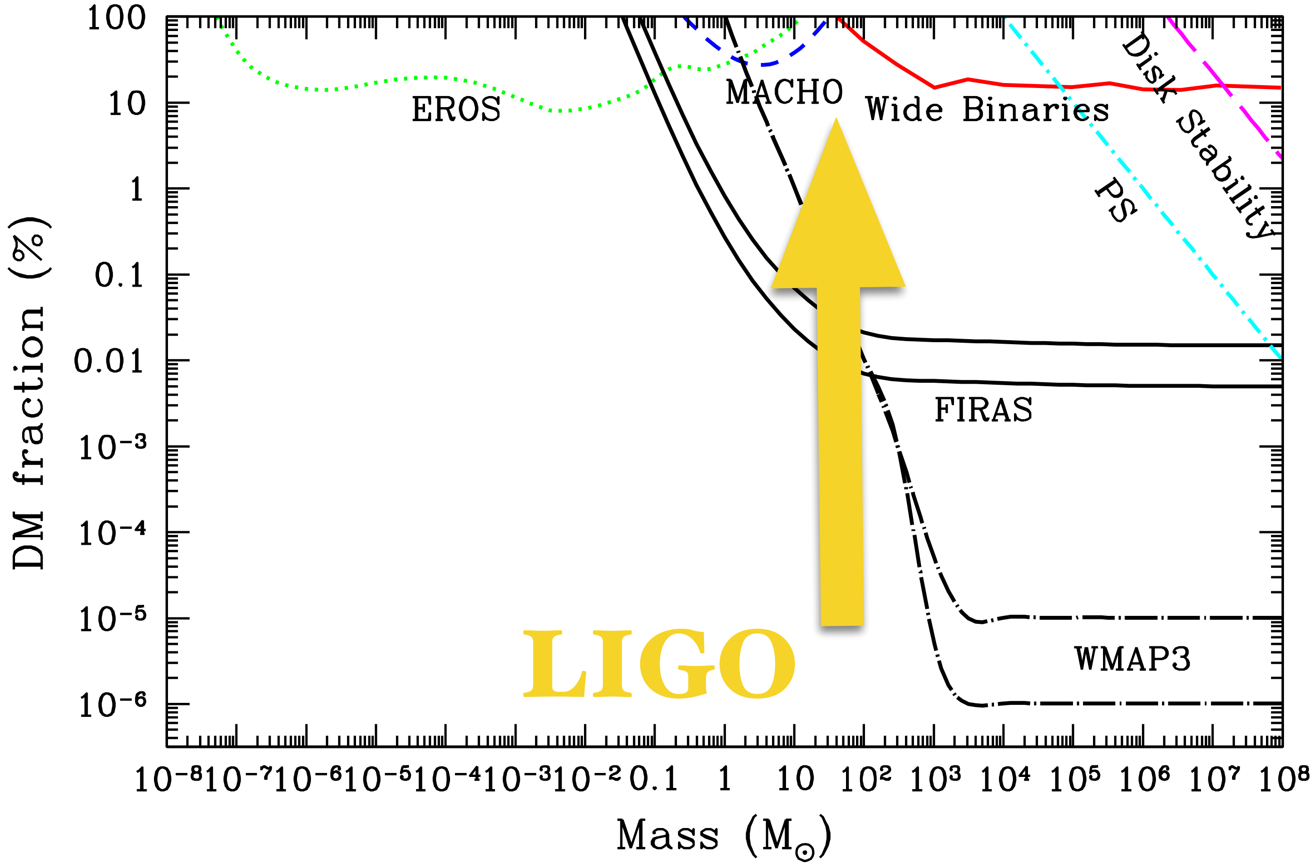
C. Skordis, D. Mota, P. Ferreira, C.Boehm : astro-ph/0505519



Not compatible with Planck 2015!

Understanding the nature of DM

0709.0524v1



Primordial Black Holes ???

arXiv:1603.00464
arXiv:1501.07565
arXiv:1607.06077

Ways to evade CMB limits

arXiv:1612.05644

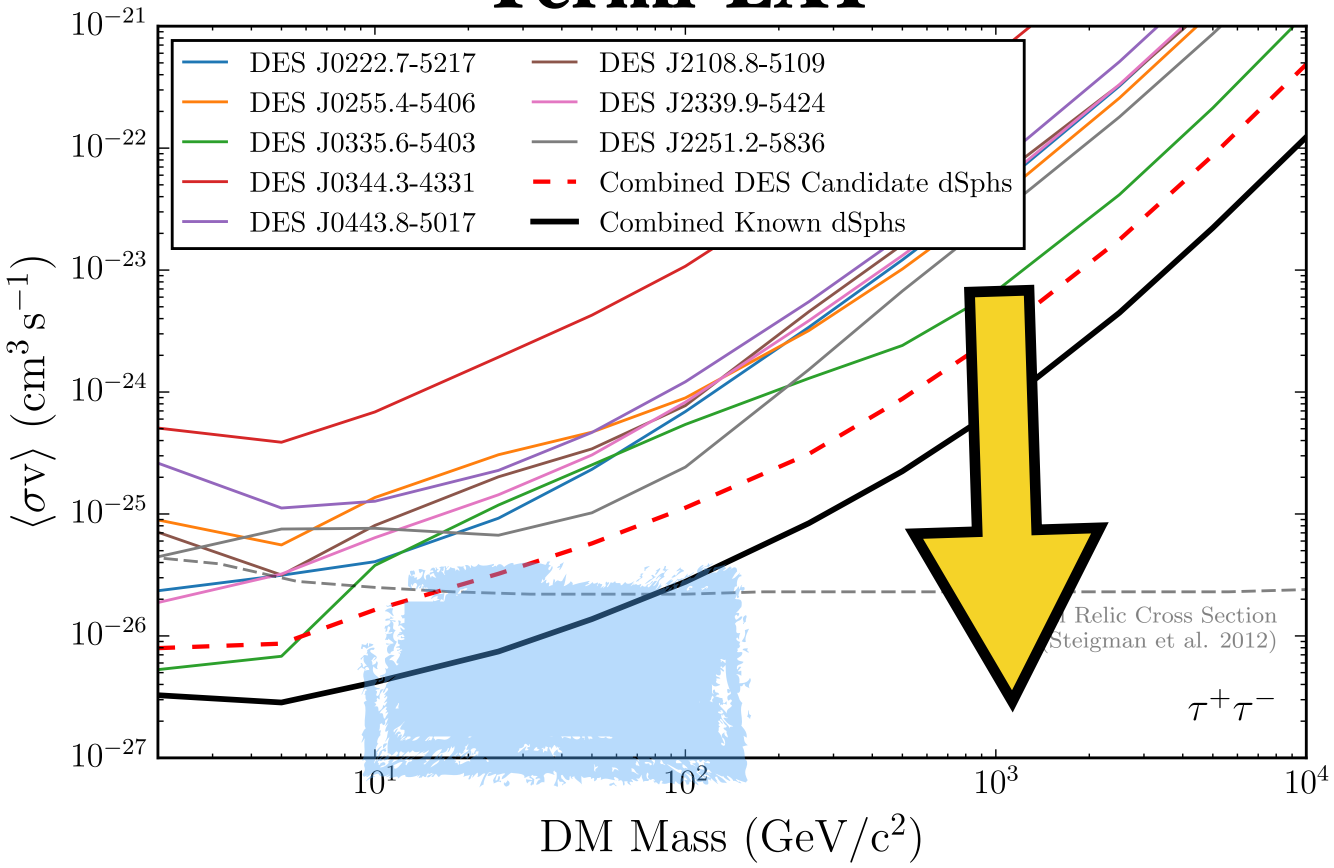
> 100 Msol ruled out as main DM component

But we still need some sort of dark matter
(at least ~ a collisionless fluid)

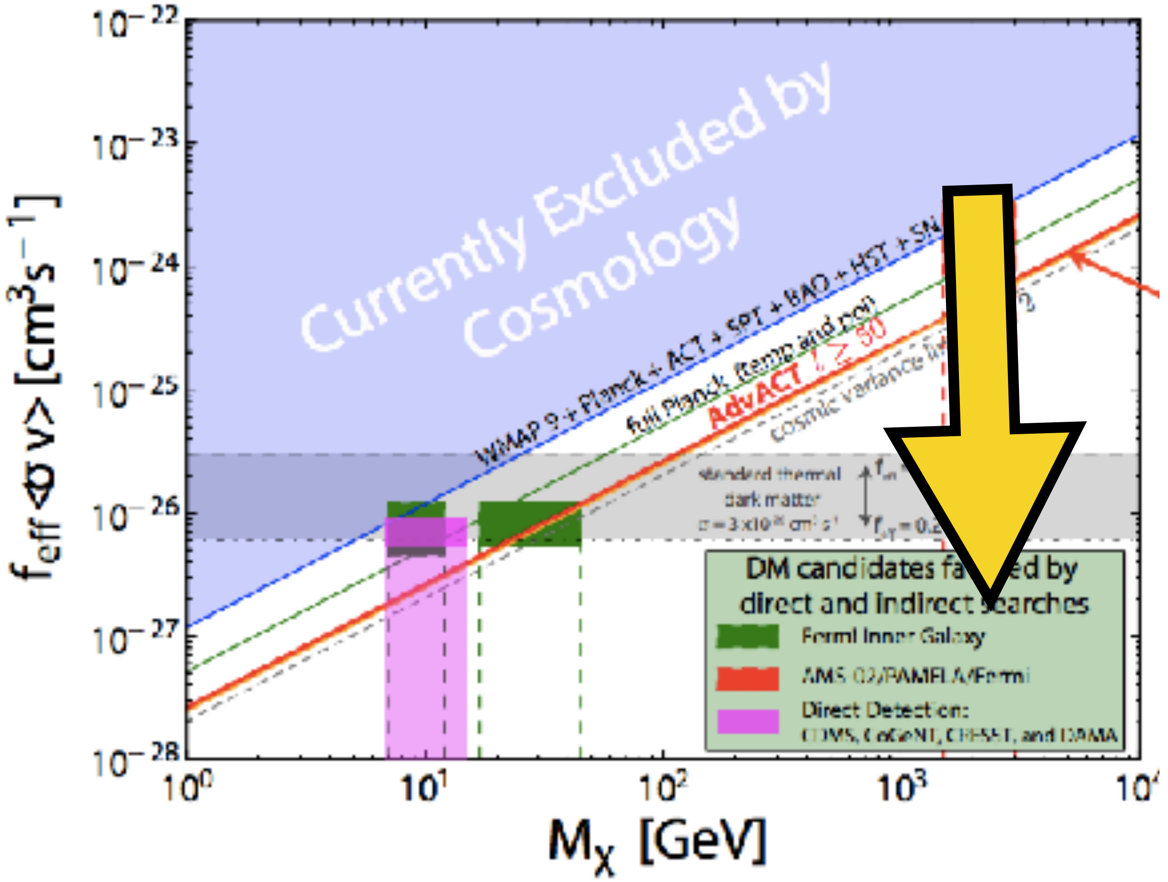
Experiments are setting stringent constraint

“Intensity” & energy frontiers in the DM world

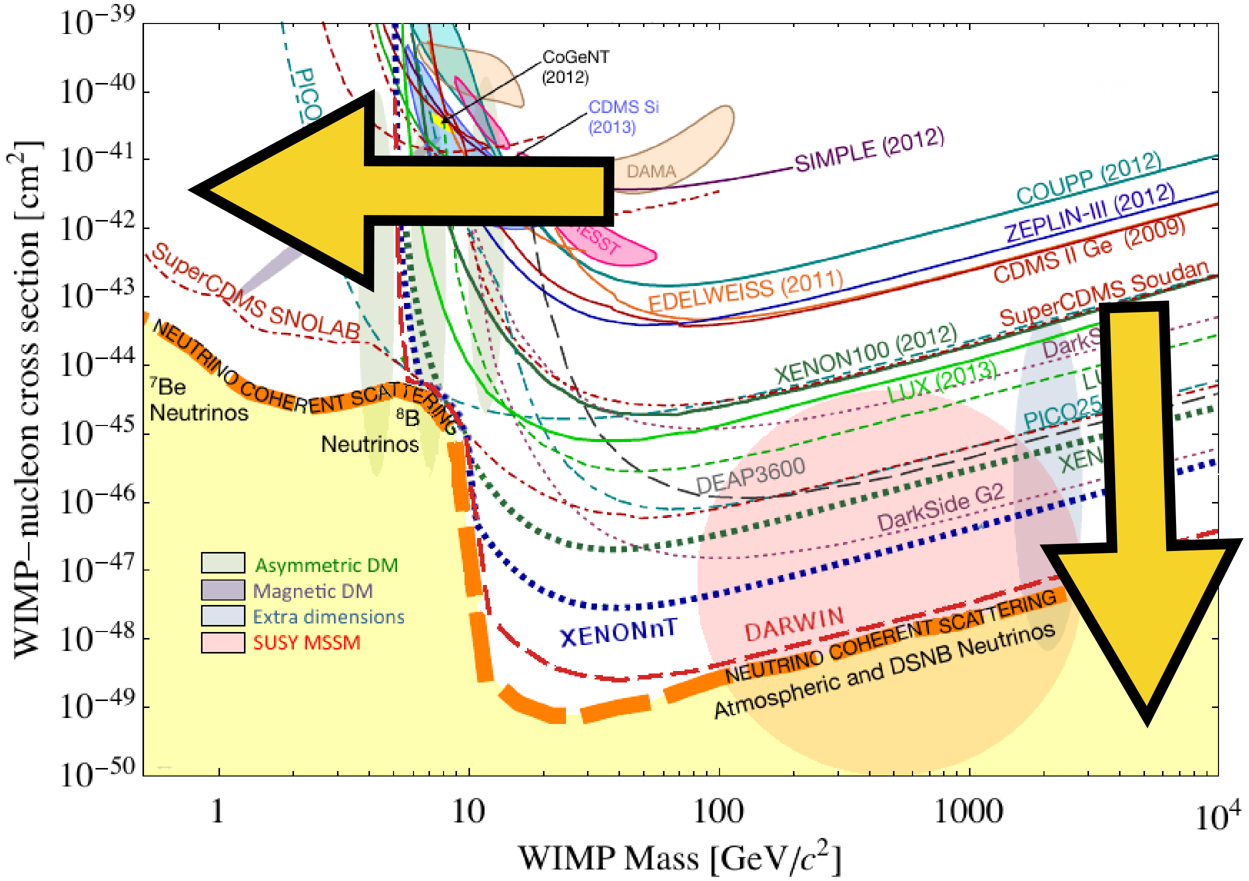
Fermi-LAT



Planck



Madhavacheril, NS, Slatyer 2014, PRD, (1310.3815)



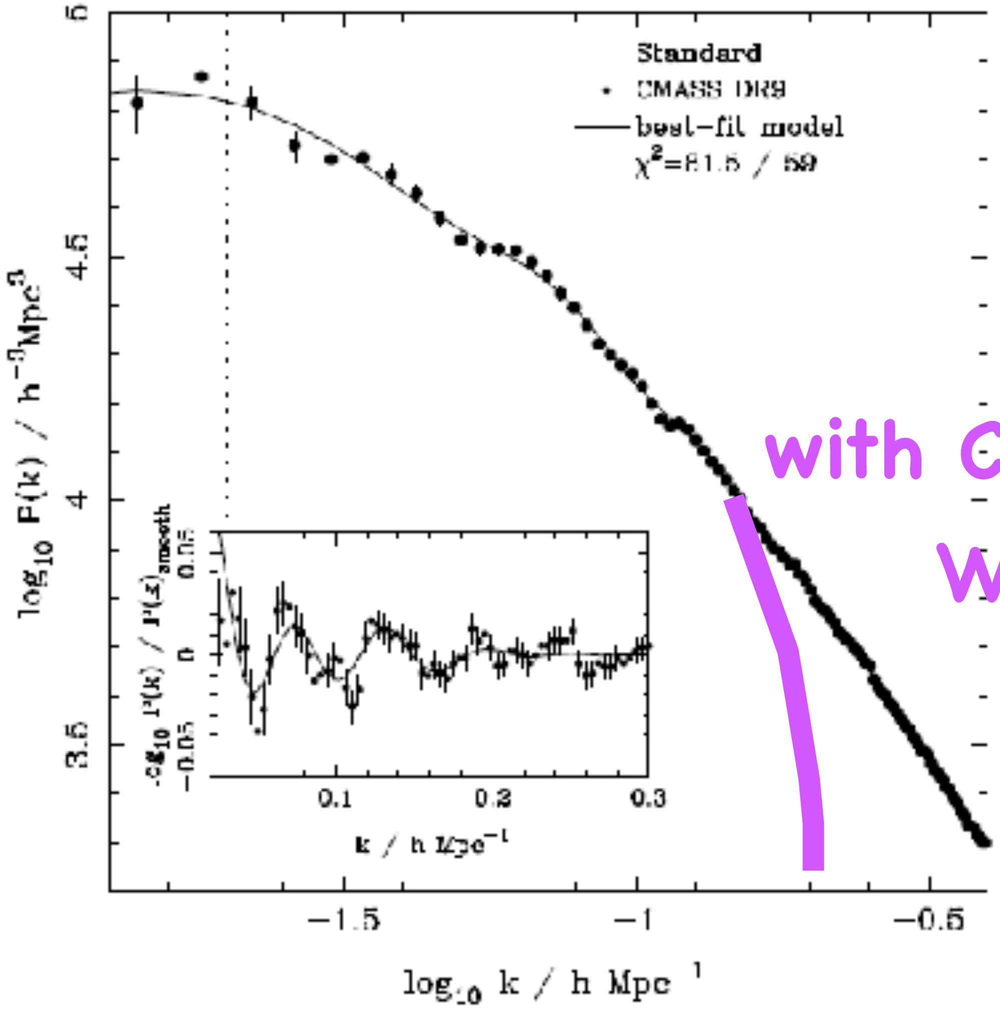
Going lower/higher DM masses
Dig deeper

What can we learn from cosmological data?

Understanding the nature of DM

weakly interacting massive particle

how do we know?
from structures!



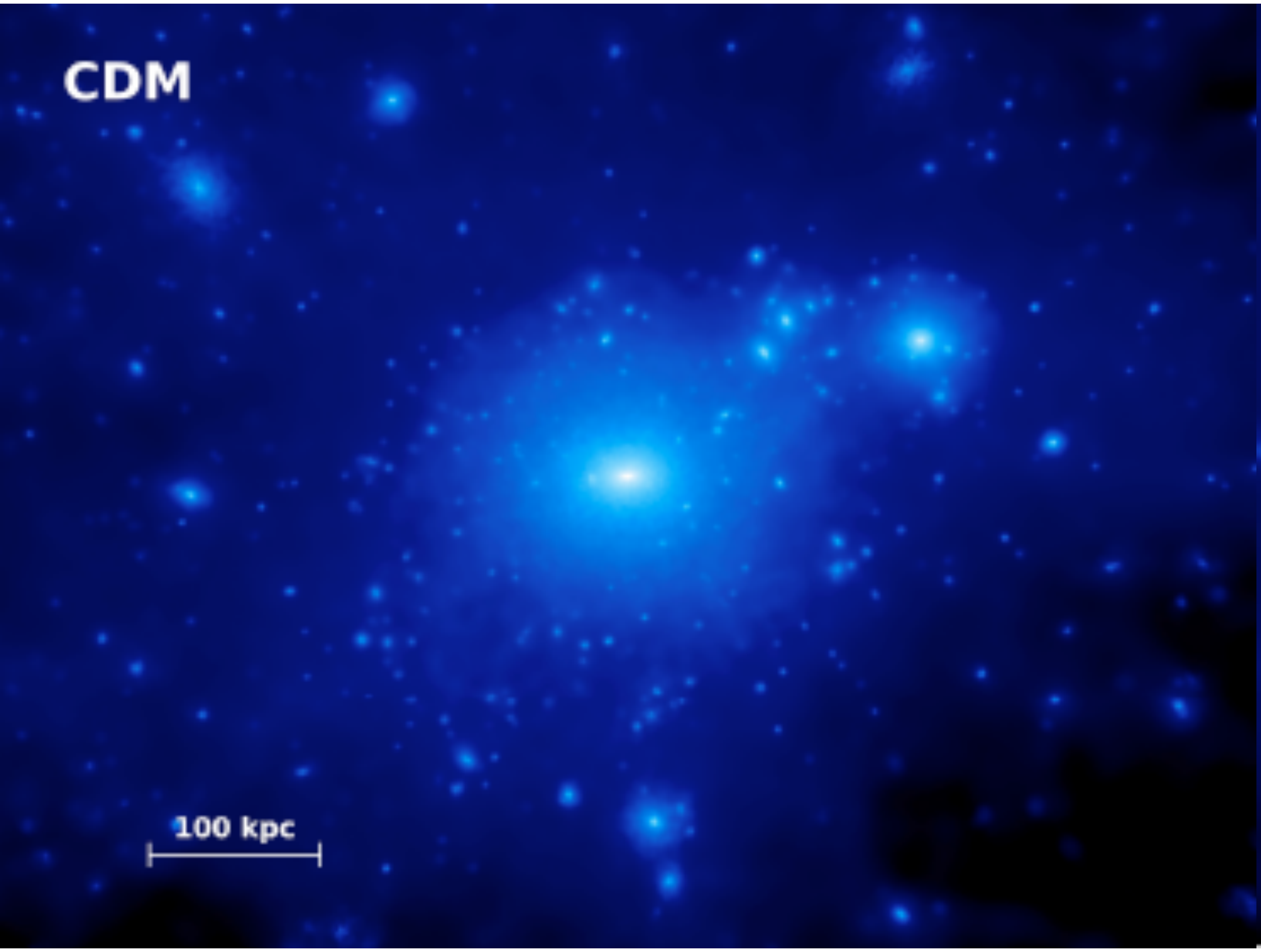
with CUT-OFF!

WDM

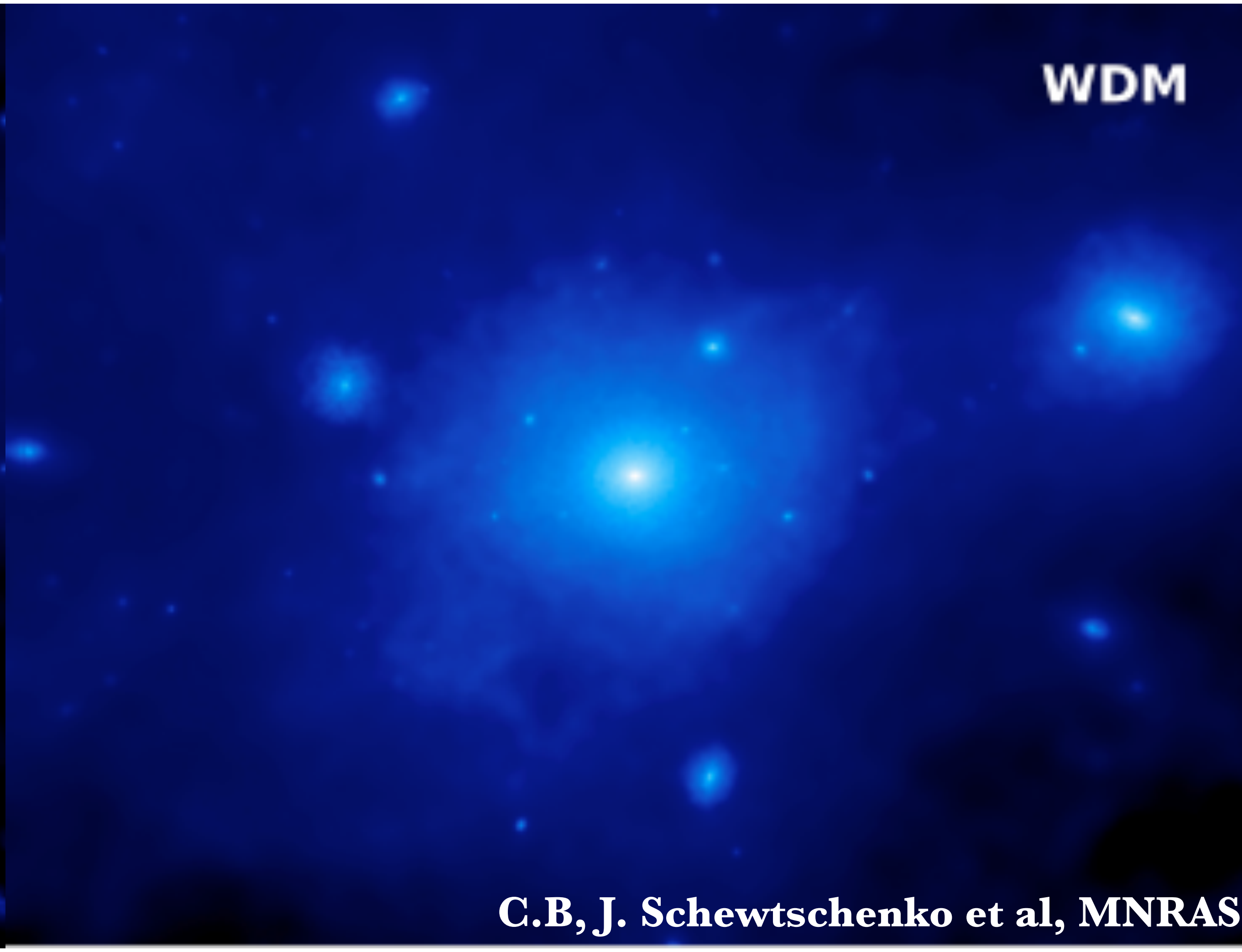
$$m_{\rm DM} \gtrsim 3{\rm keV}$$

Understanding the nature of DM

WIMPs



Particle of a 3 keV



C.B, J. Schewtschenko et al, MNRAS

DM particles need to be massive (there are exceptions) but we can't distinguish WDM from CDM yet.

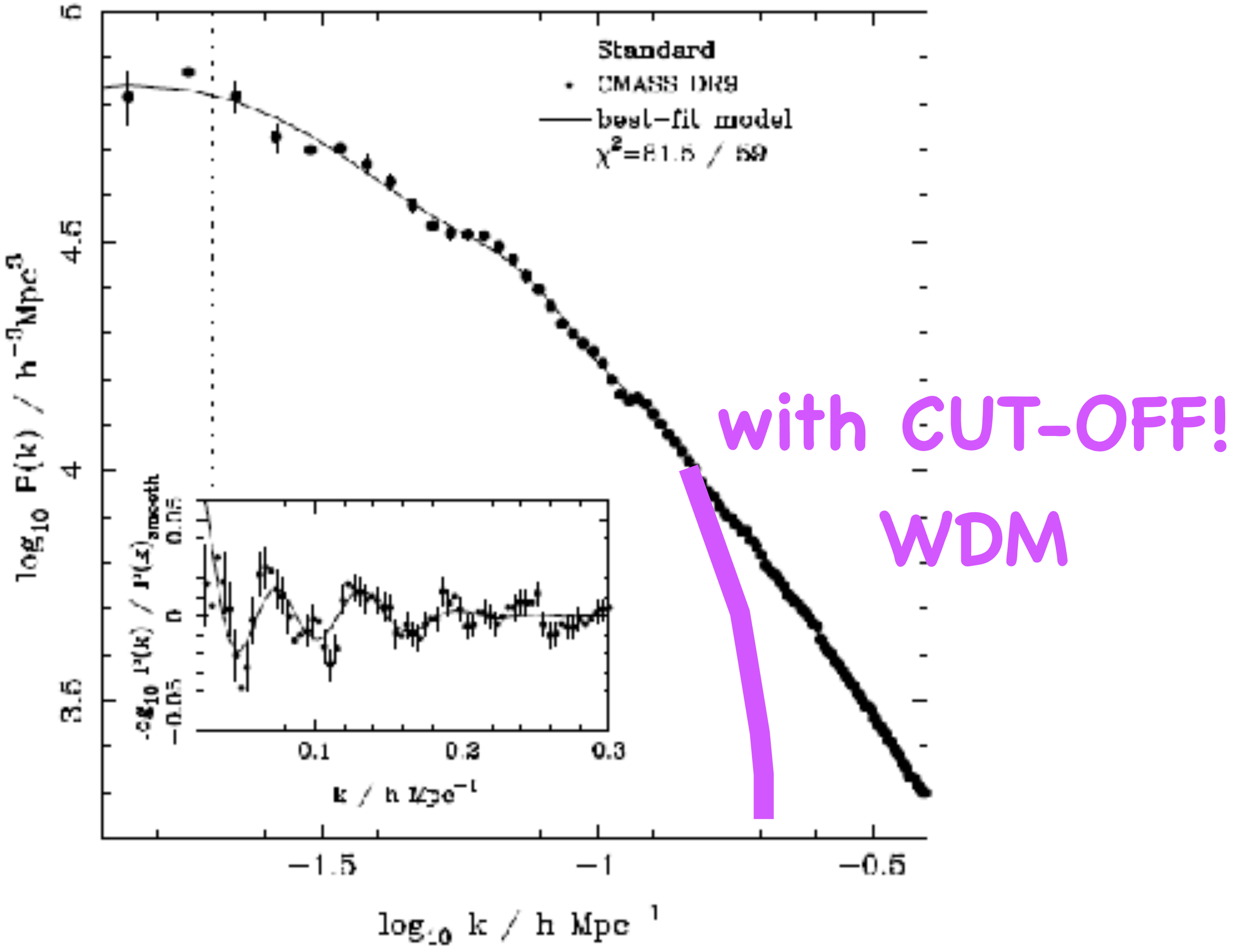
This assumes no DM interaction!

Understanding the nature of DM

weakly interacting **massive particle**

how do we know?
from structures!

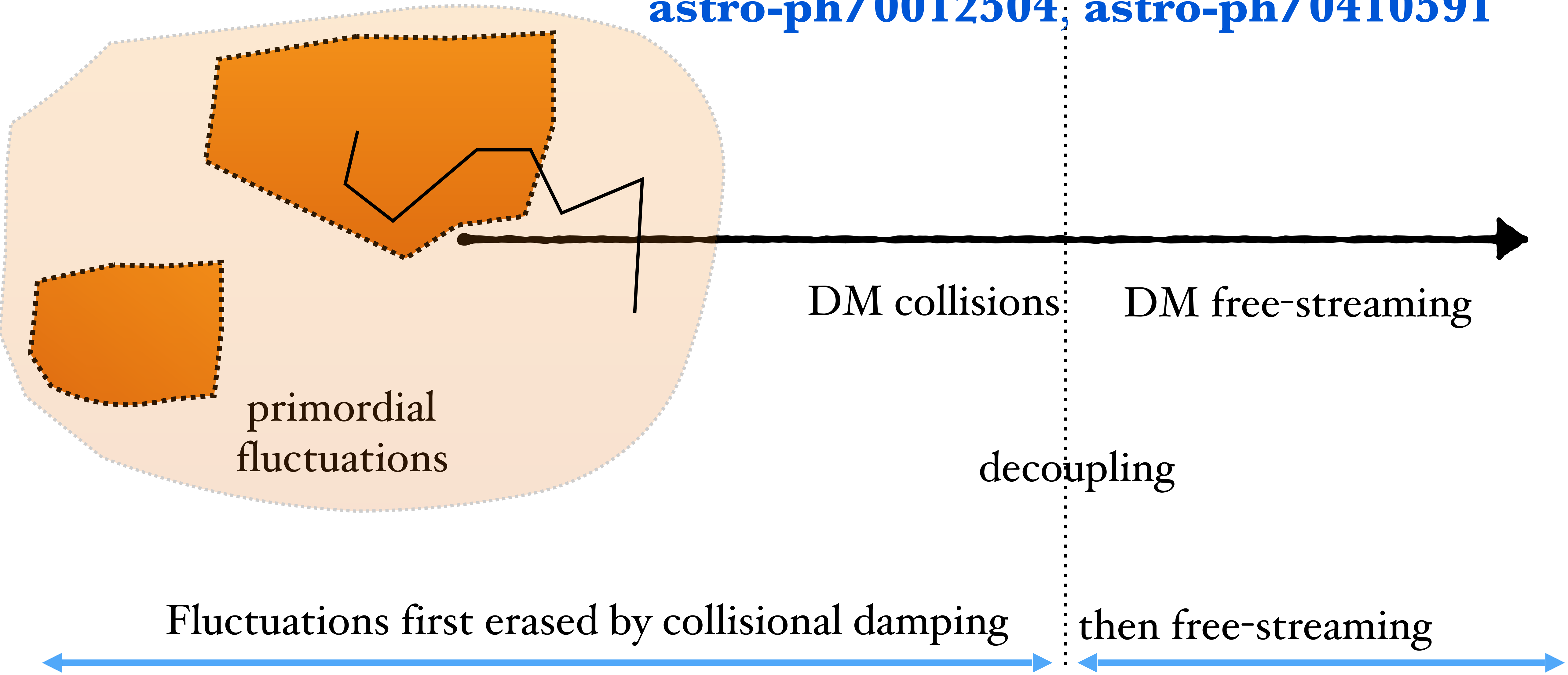
?



$$m_{\mathrm{DM}} \gtrsim 3\mathrm{keV}$$

Understanding the nature of DM

astro-ph/0012504, astro-ph/0410591



primordial fluctuations

DM collisions

DM free-streaming

decoupling

Fluctuations first erased by collisional damping

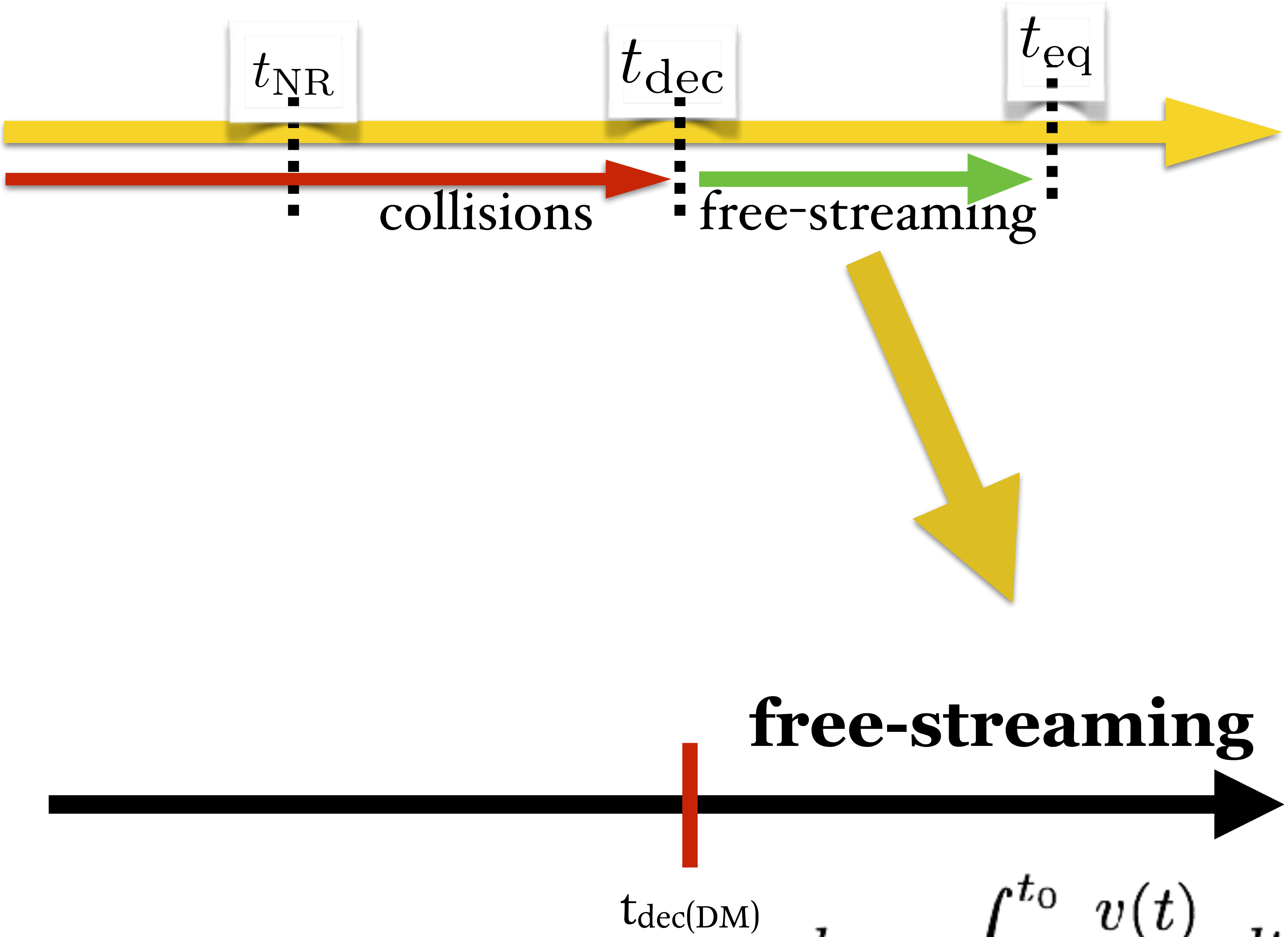
then free-streaming

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

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

astro-ph/0012504 astro-ph/0410591

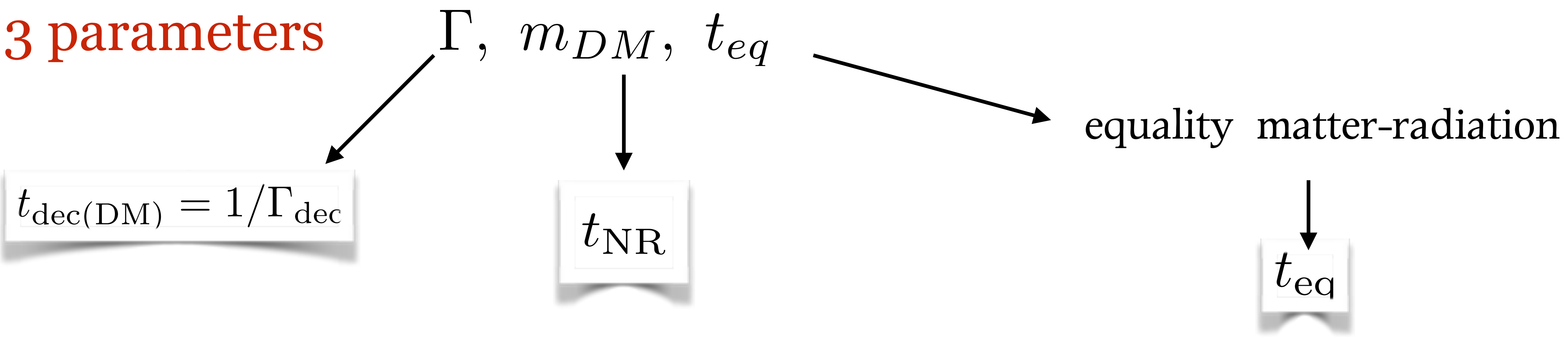
Understanding the nature of DM



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

Understanding the nature of DM

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



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

$t_{\mathrm{dec(DM)}} = 1/\Gamma_{\mathrm{dec}}$

t_{NR}

equality matter-radiation

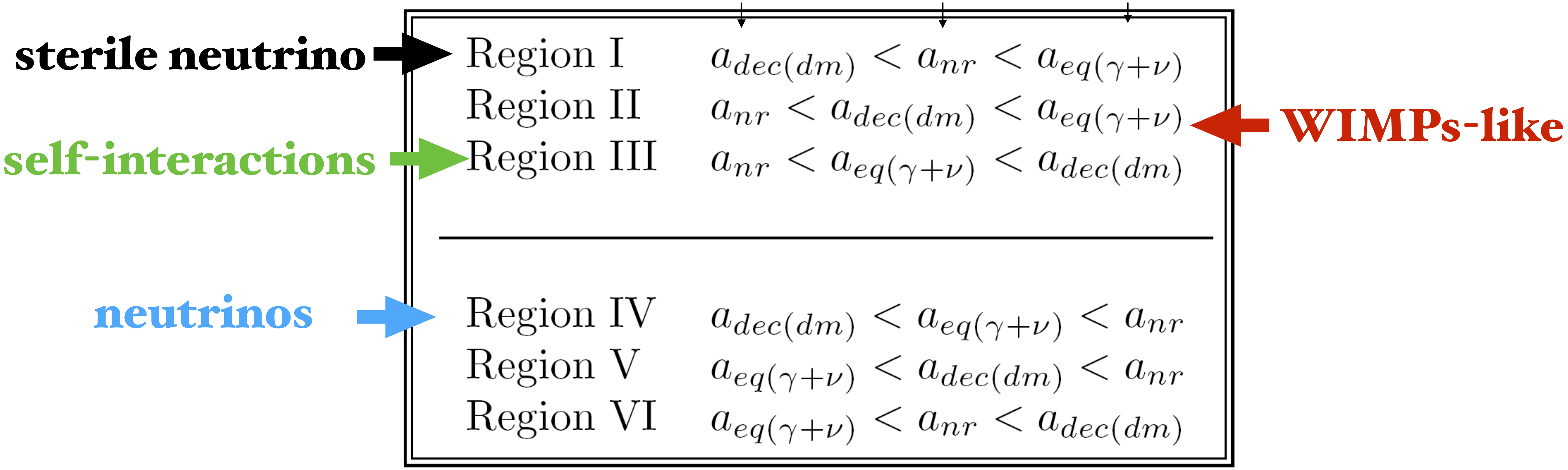
t_{eq}

3 characteristic times/scale-factors ====>> 6 DM configurations

Region I	$a_{dec(dm)} < a_{nr} < a_{eq(\gamma+\nu)}$
Region II	$a_{nr} < a_{dec(dm)} < a_{eq(\gamma+\nu)}$
Region III	$a_{nr} < a_{eq(\gamma+\nu)} < a_{dec(dm)}$
Region IV	$a_{dec(dm)} < a_{eq(\gamma+\nu)} < a_{nr}$
Region V	$a_{eq(\gamma+\nu)} < a_{dec(dm)} < a_{nr}$
Region VI	$a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$

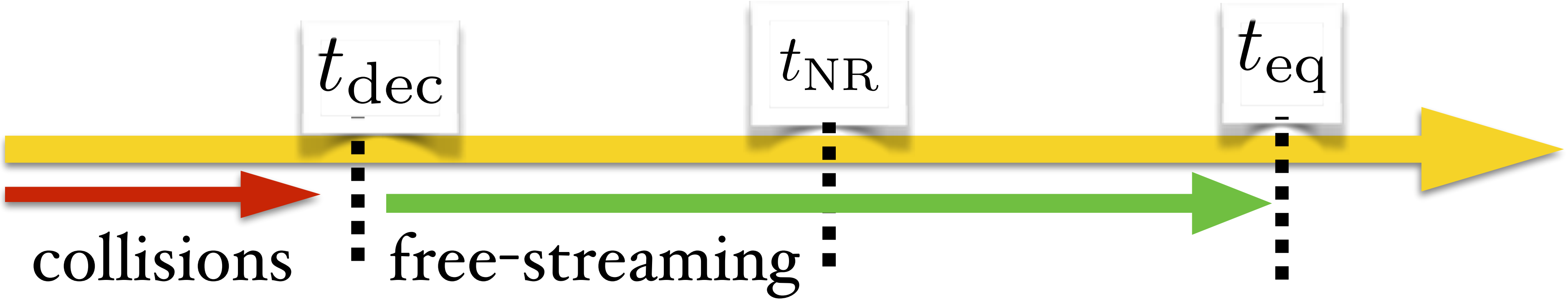
Understanding the nature of DM

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

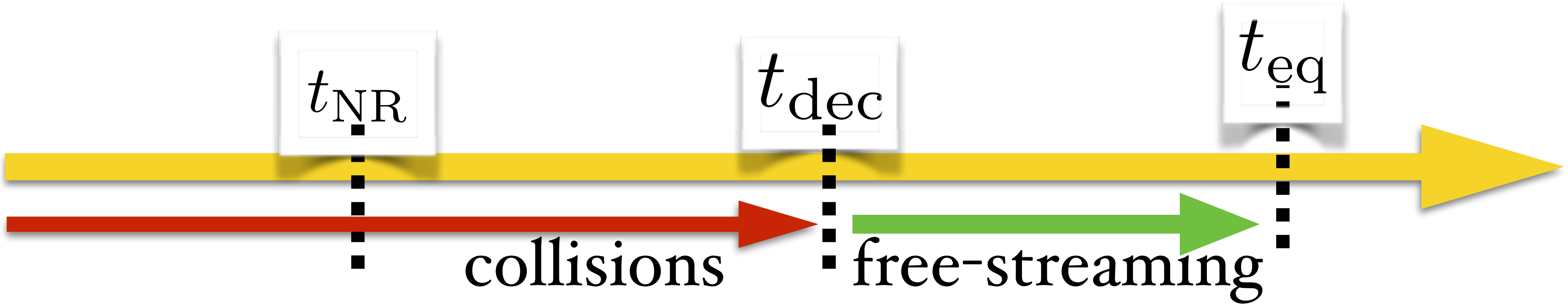


sterile neutrino	Region I	$a_{dec(dm)} < a_{nr} < a_{eq(\gamma+\nu)}$
WIMPs-like	Region II	$a_{nr} < a_{dec(dm)} < a_{eq(\gamma+\nu)}$
self-interactions	Region III	$a_{nr} < a_{eq(\gamma+\nu)} < a_{dec(dm)}$
neutrinos	Region IV	$a_{dec(dm)} < a_{eq(\gamma+\nu)} < a_{nr}$
	Region V	$a_{eq(\gamma+\nu)} < a_{dec(dm)} < a_{nr}$
	Region VI	$a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$

Massive Neutrinos

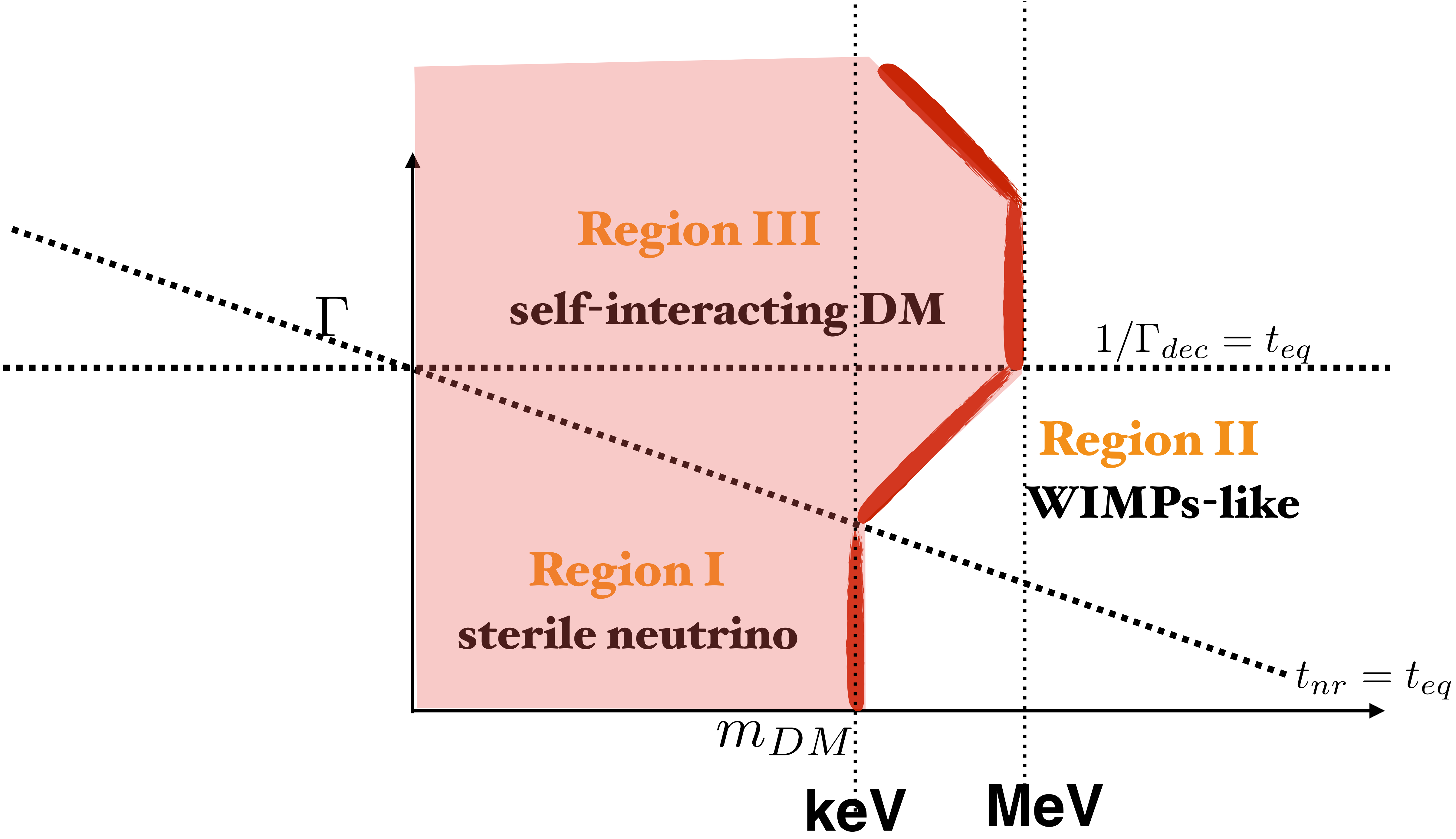


DM interactions



Understanding the nature of DM

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



Region III

self-interacting DM

Region II

WIMPs-like

Region I

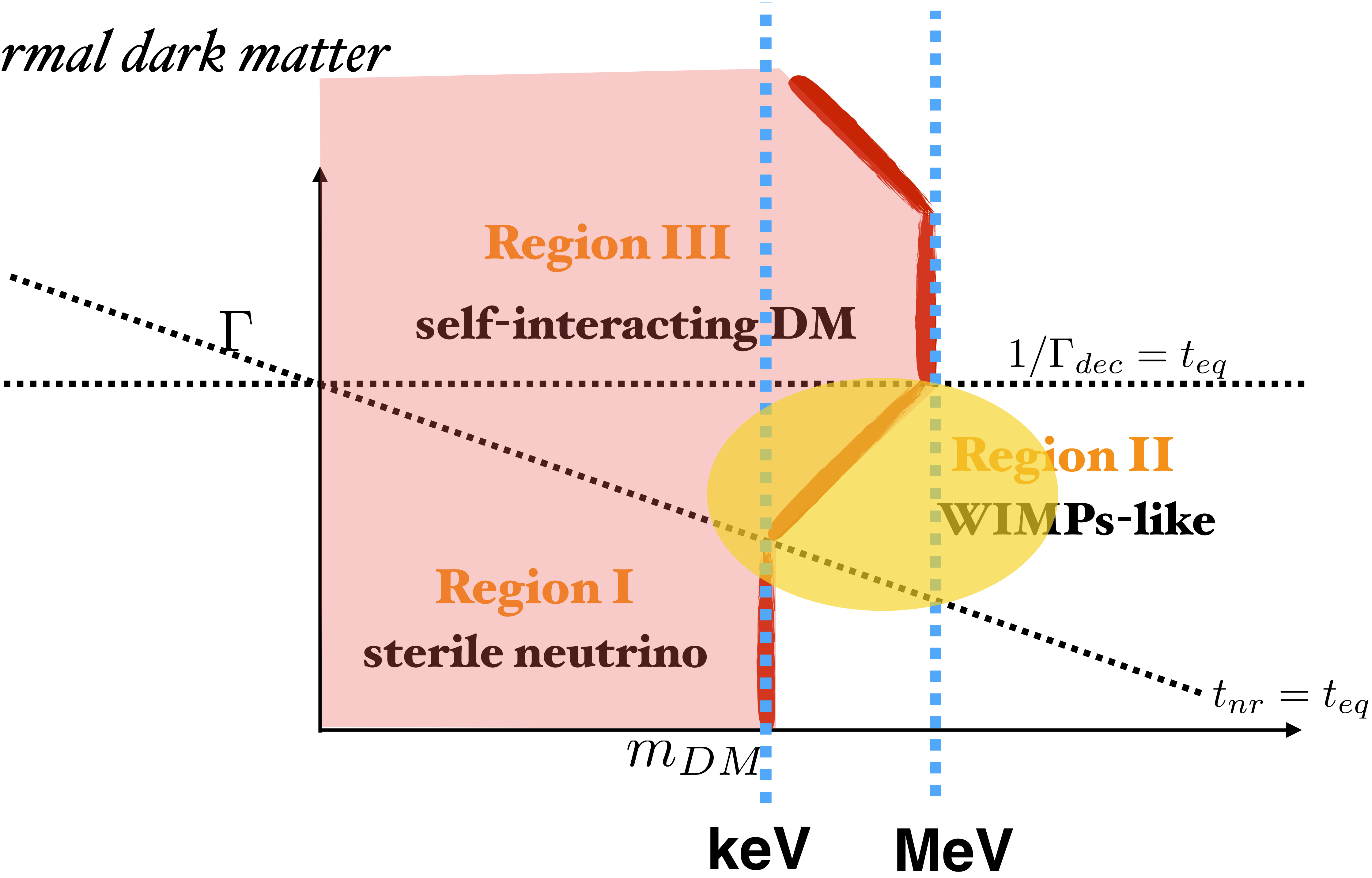
sterile neutrino

Many more DM scenarios than has been explored already

Understanding the nature of DM

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

Thermal dark matter



DM can be light, interacting and behave almost like WDM

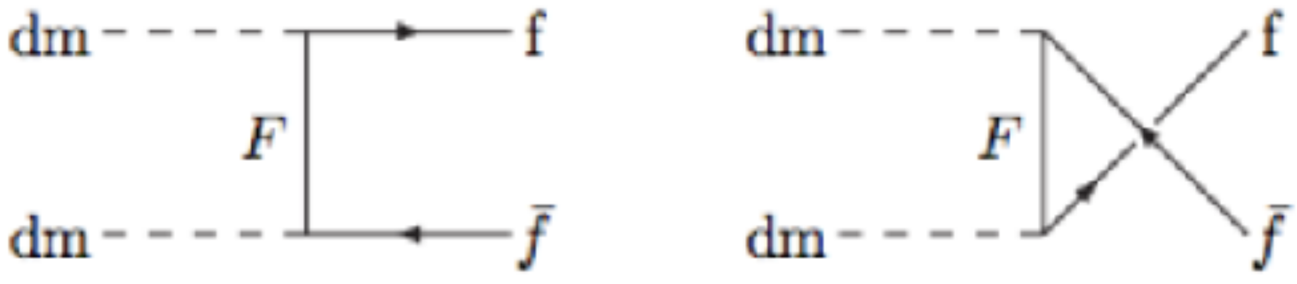
(

Questioning the relic density argument

Hut, Lee&Weinberg 77

can DM be lighter than GeV? **no but...!**

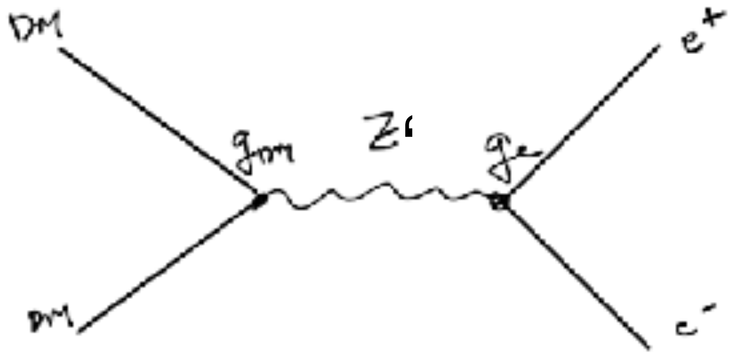
astro-ph/0208458v3 hep-ph/0305261



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

$$\sigma v \propto \frac{1}{m_F^2}$$

vector-like fermions
DM can be light!



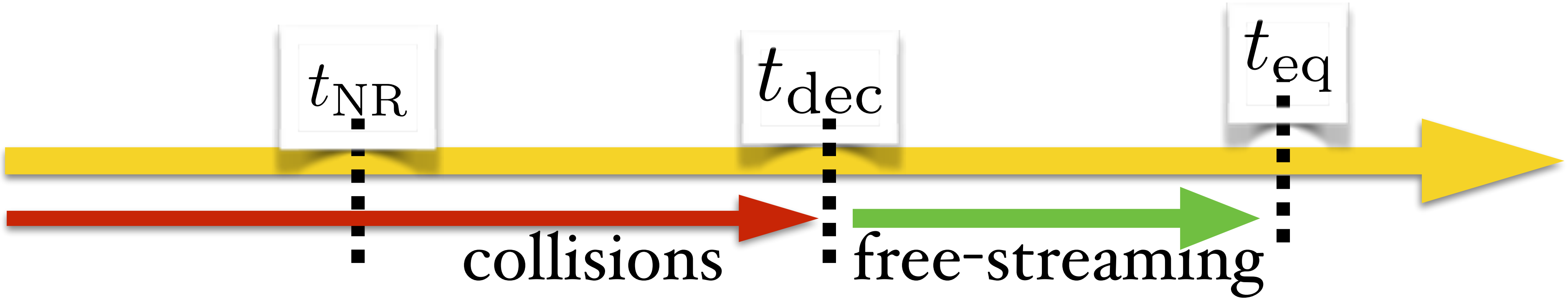
$$\sigma v \propto v^2\ \frac{m_{\rm DM}^2}{m_{Z'}^4}\ g_{\rm DM}^2\, g_e^2$$

$$m_{\rm DM} \simeq m_{Z'}$$

dark photons/Z'
DM can be light!

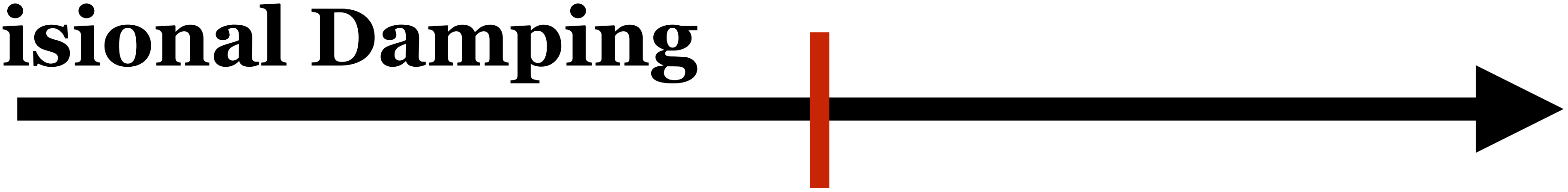
)

Understanding the nature of DM

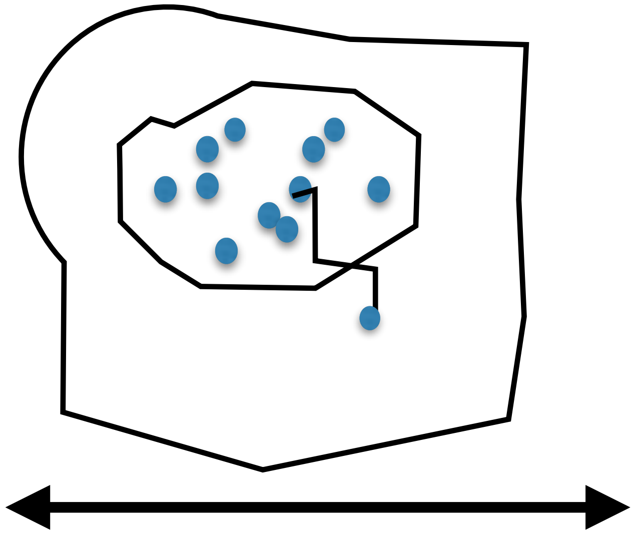


Damping

Collisional Damping



Collisional (Silk) damping in modern Cosmology



collisional damping length

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

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

Translation in terms of Cosmological perturbations

without DM interactions

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

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

with DM interactions

astro-ph/0112522

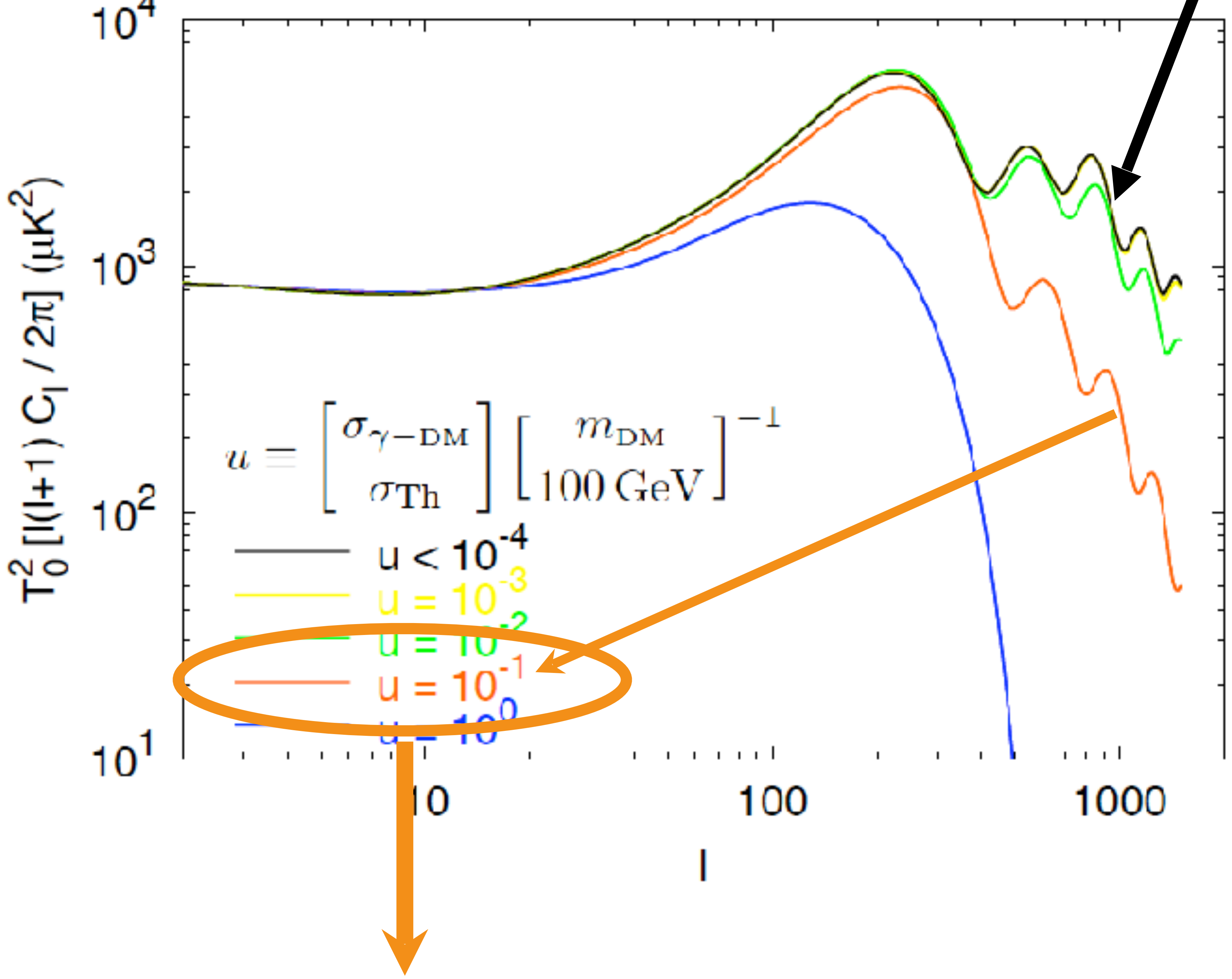
$$\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma)\\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right)\\
&\quad -\dot{\kappa}(\theta_\gamma - \theta_b) - \dot{\mu}(\theta_\gamma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

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

Dark Matter interactions

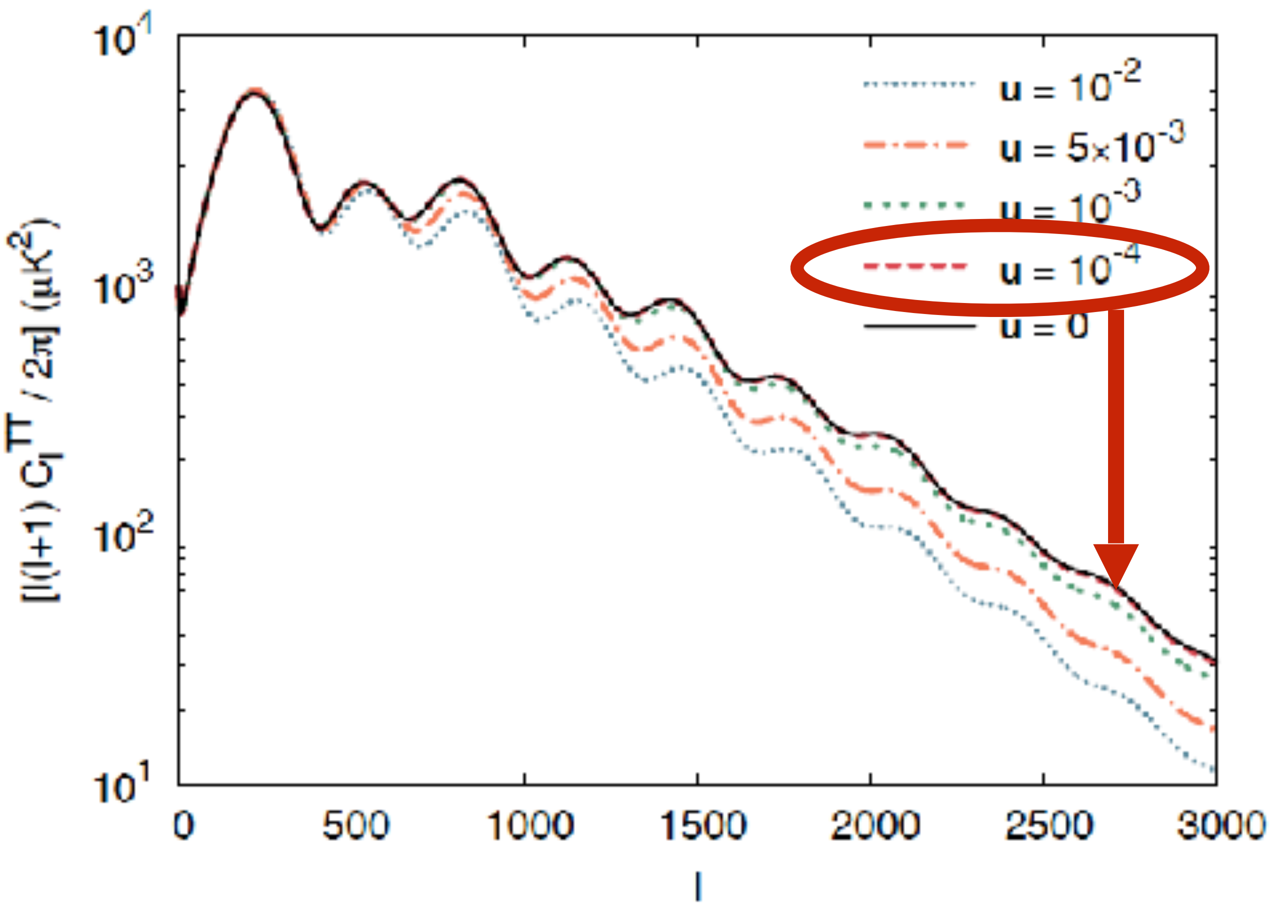
astro-ph/0112522

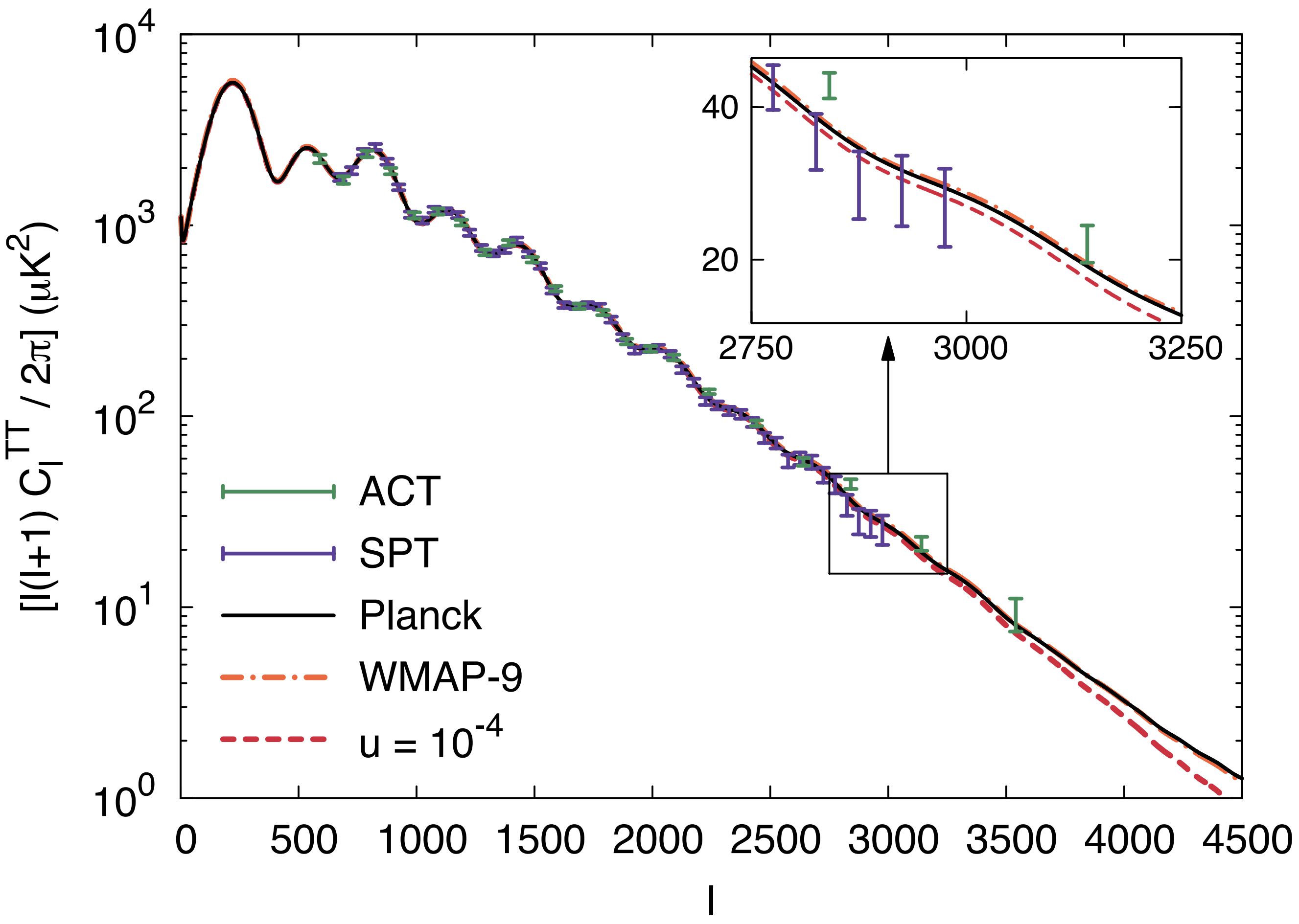
collisionless CDM



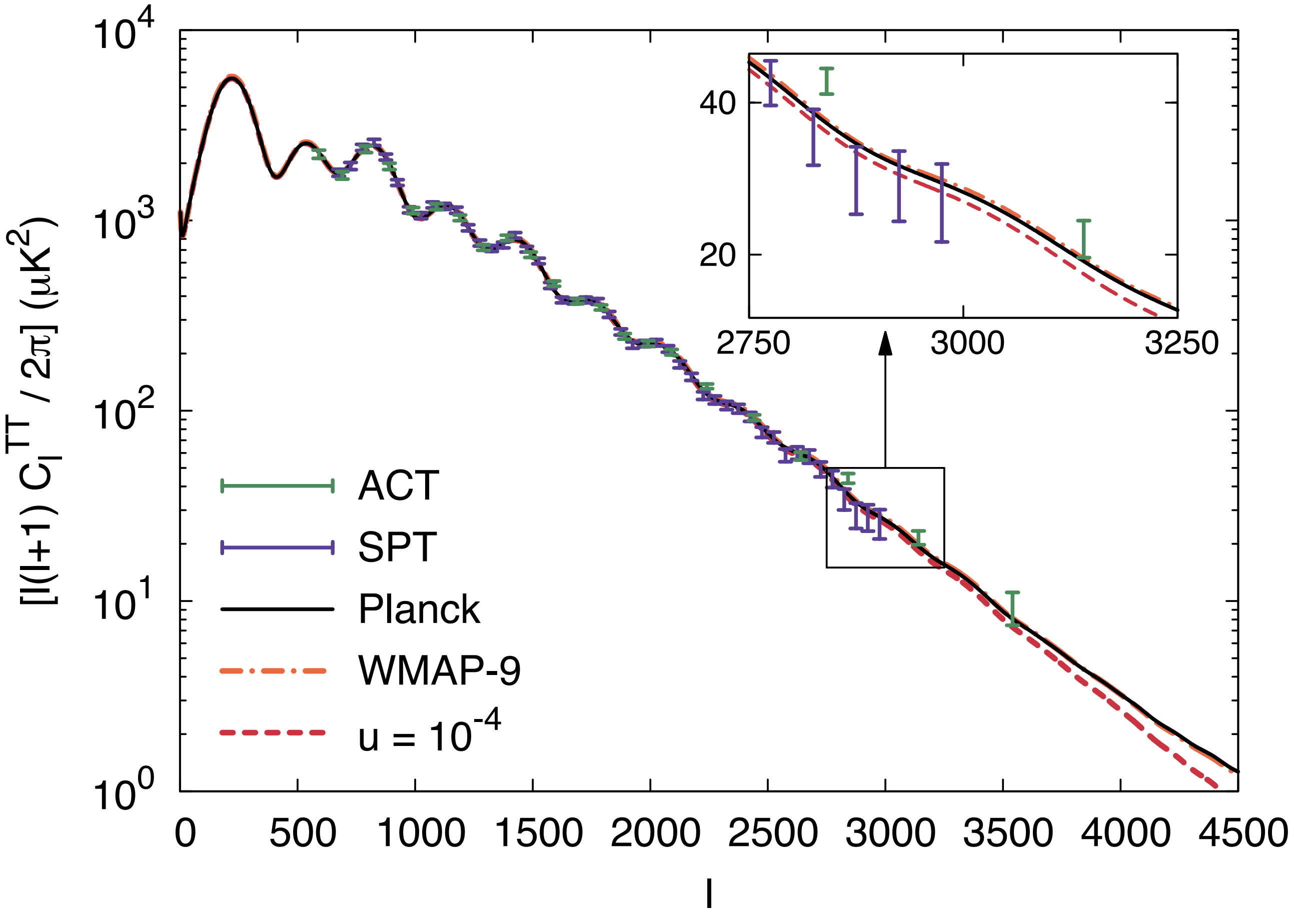
Thomson cross section

Dark Matter interactions

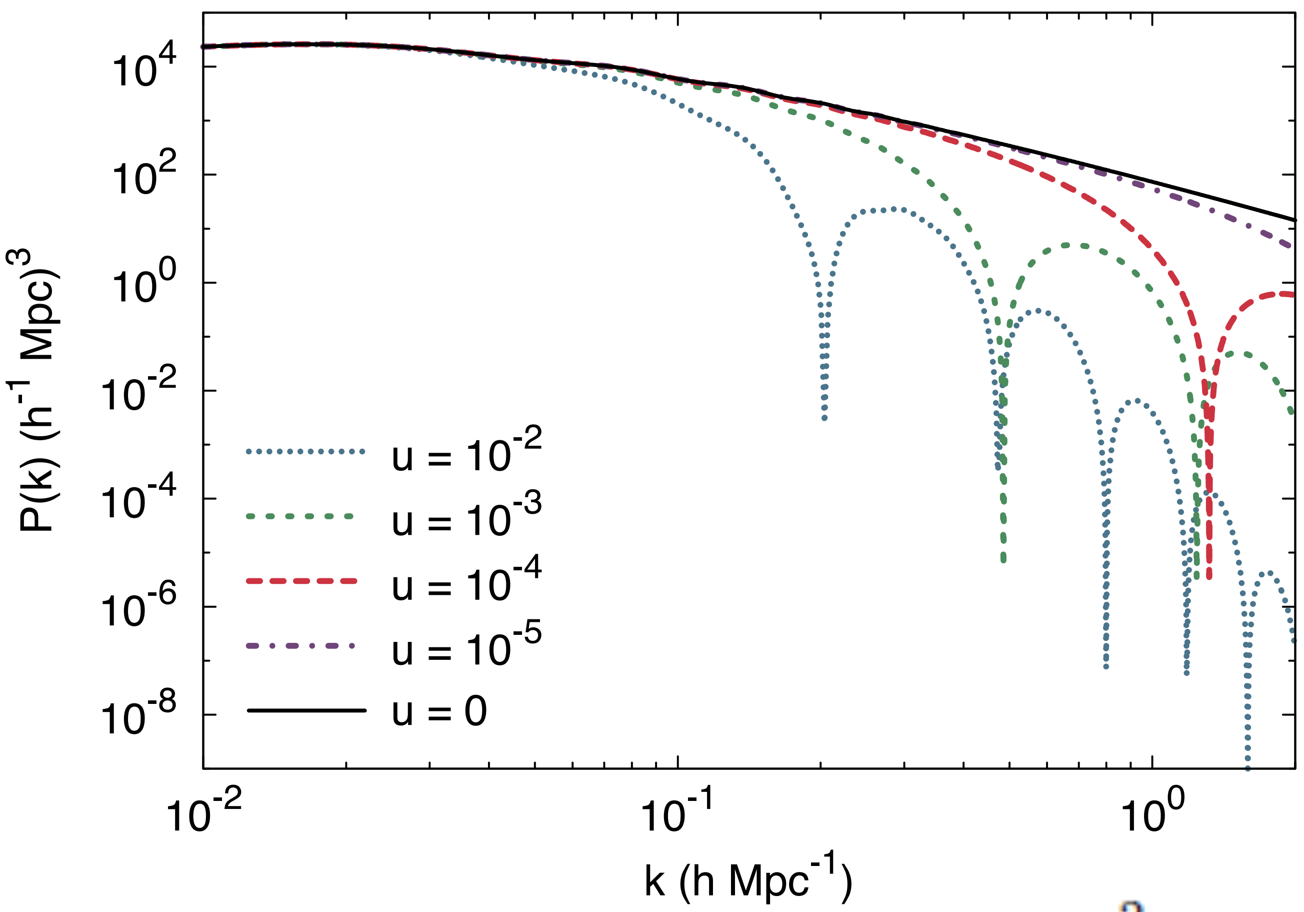




Understanding the nature of DM



e.g. DM-photon interactions



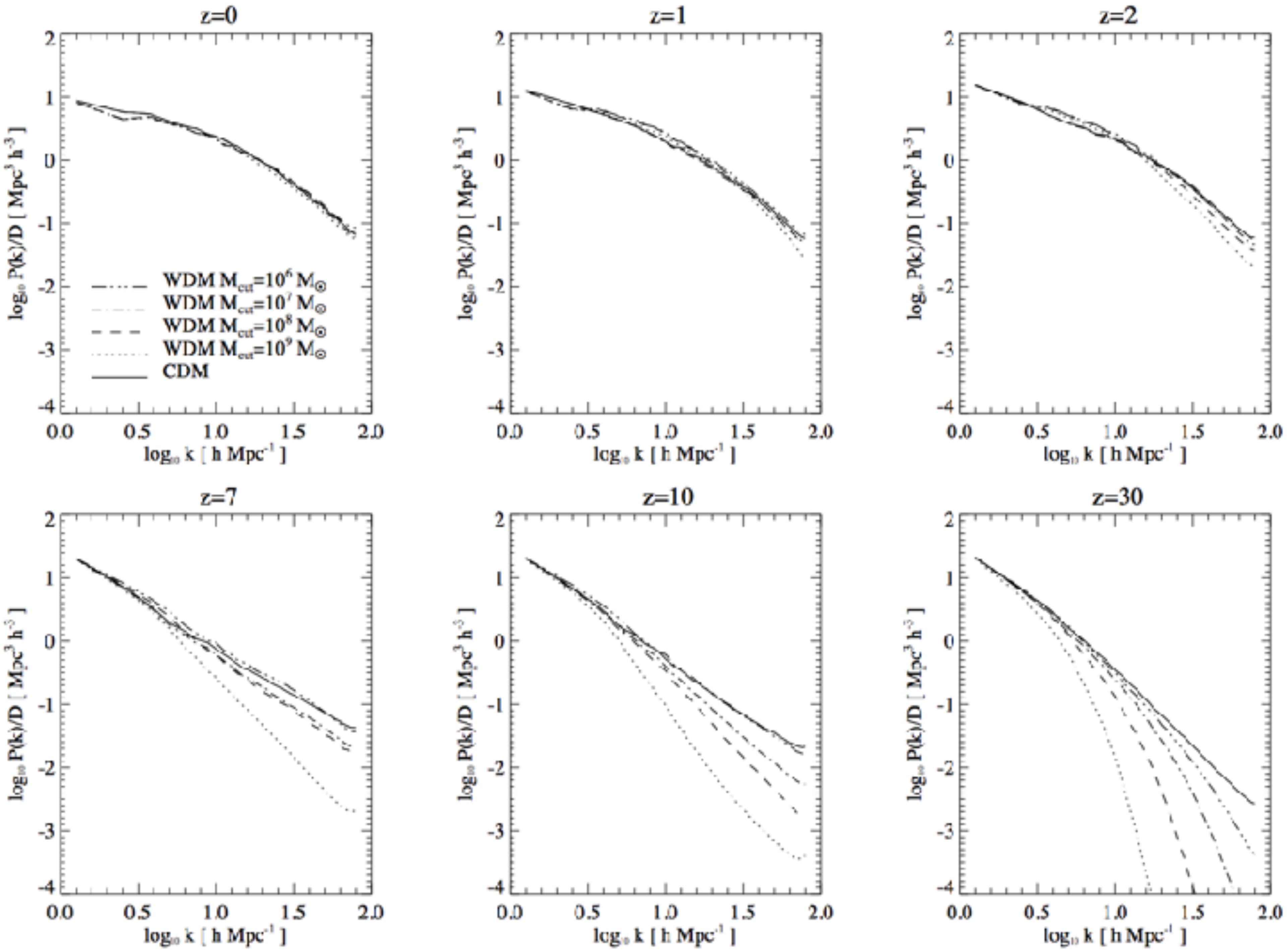
$$\delta_\gamma \sim \delta_k \cos(k\eta/\sqrt{3})\, e^{-\frac{2k^2\eta}{15\dot{\kappa}}}$$

astro-ph/0112522

Dark Oscillations **astro-ph/0406355**

Structure formation is sensitive to DM interactions!

Understanding the nature of DM



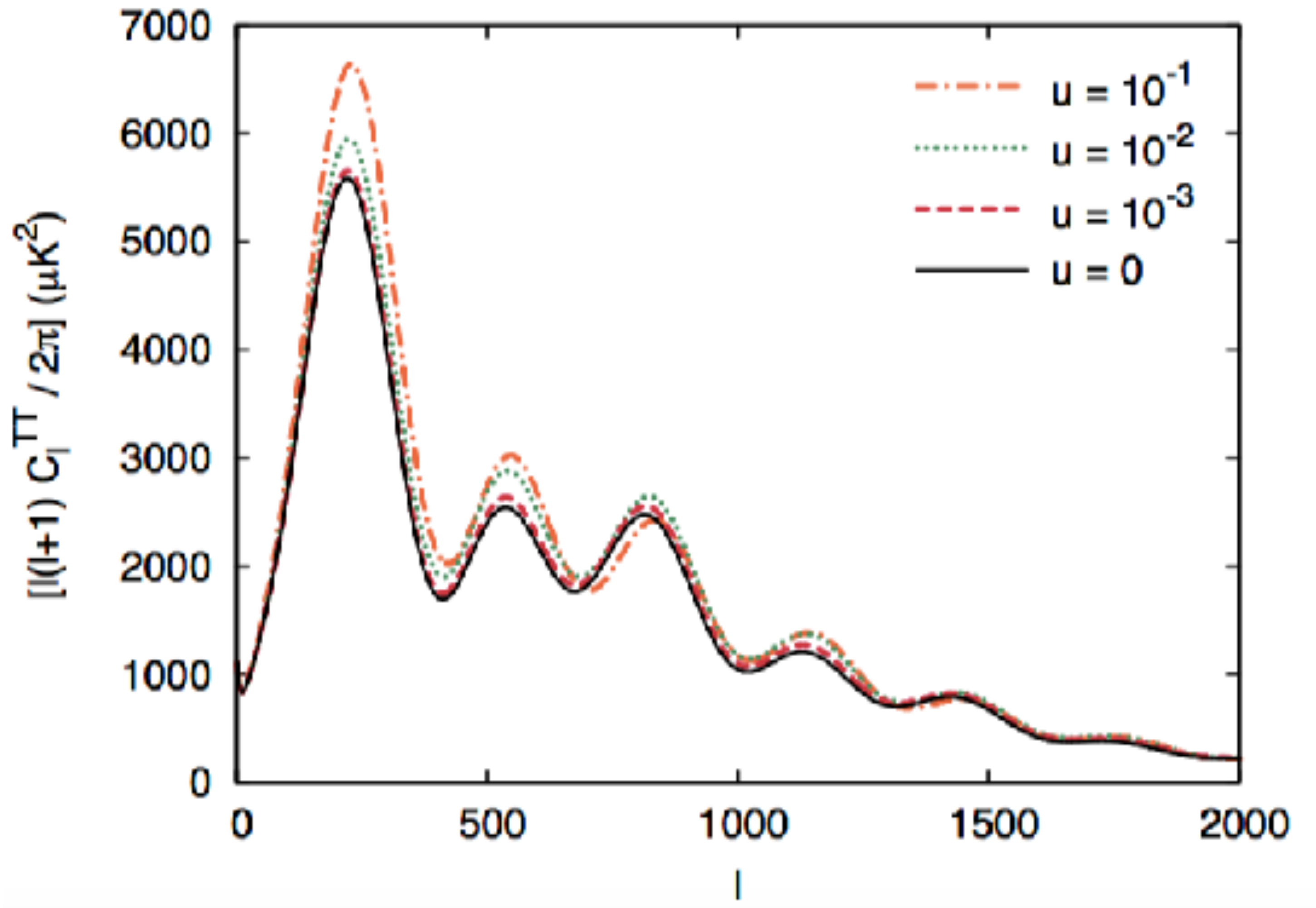
astro-ph/0309652

same evolution as for WDM

DM-neutrino interactions

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

astro-ph/0606190, arXiv:0911.4411,arXiv:astro-ph/0406355, arXiv:1310.2376, arXiv:astro-ph/0202496 [astro-ph], arXiv:1311.2937 [astro-ph.CO], arXiv:1207.3124 [astro-ph.CO], arXiv:1209.5752 [astro-ph.CO], arXiv:1212.6007

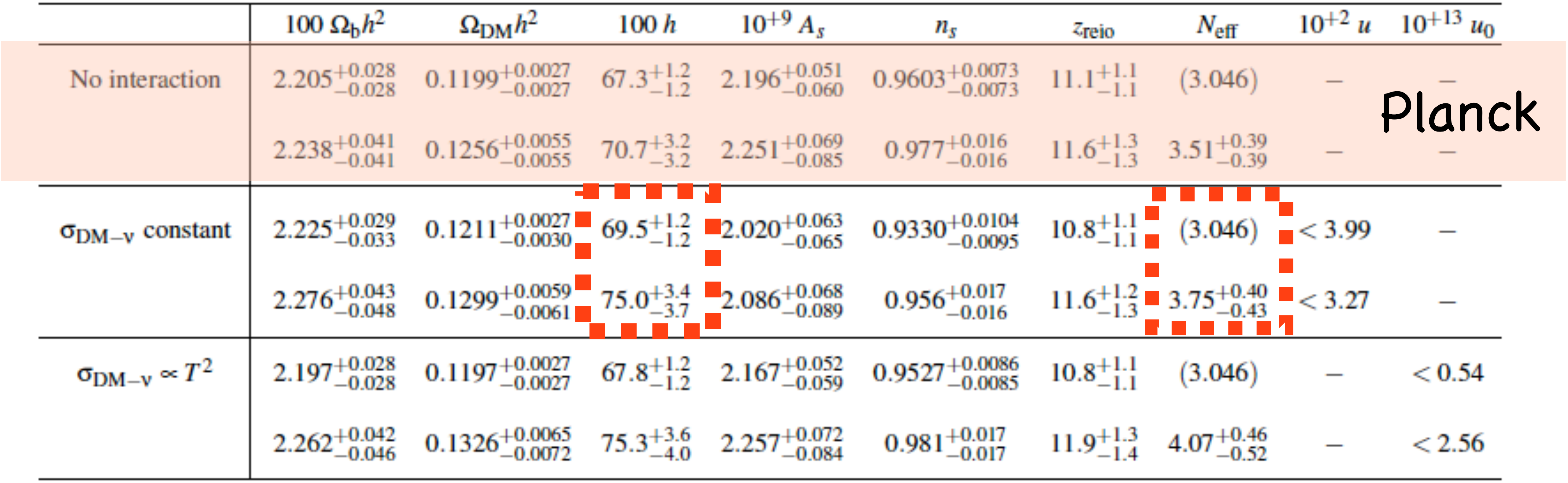


$$\sigma_{\mathrm{DM}-\nu} \lesssim 3\ 10^{-28} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)\ \mathrm{cm}^2$$

Impact on cosmological parameters

DM-nu interactions arXiv:1401.7597

CMB alone

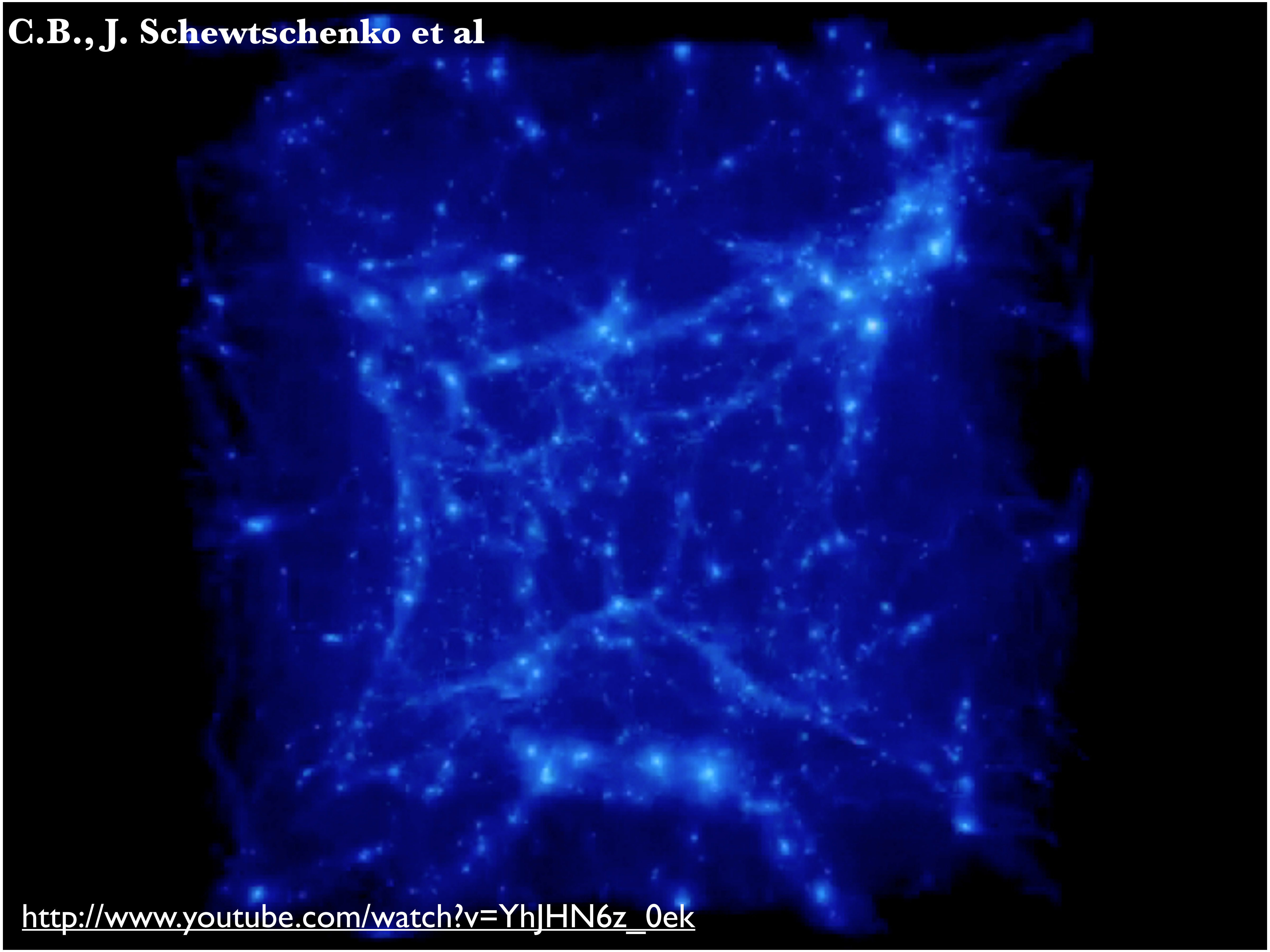


	$100\,\Omega_b h^2$	$\Omega_{DM} h^2$	$100\,h$	$10^{+9}\,A_s$	n_s	z_{reio}	N_{eff}	$10^{+2}\,u$	$10^{+13}\,u_0$
No interaction	$2.205^{+0.028}_{-0.028}$	$0.1199^{+0.0027}_{-0.0027}$	$67.3^{+1.2}_{-1.2}$	$2.196^{+0.051}_{-0.060}$	$0.9603^{+0.0073}_{-0.0073}$	$11.1^{+1.1}_{-1.1}$	(3.046)	–	–
	$2.238^{+0.041}_{-0.041}$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

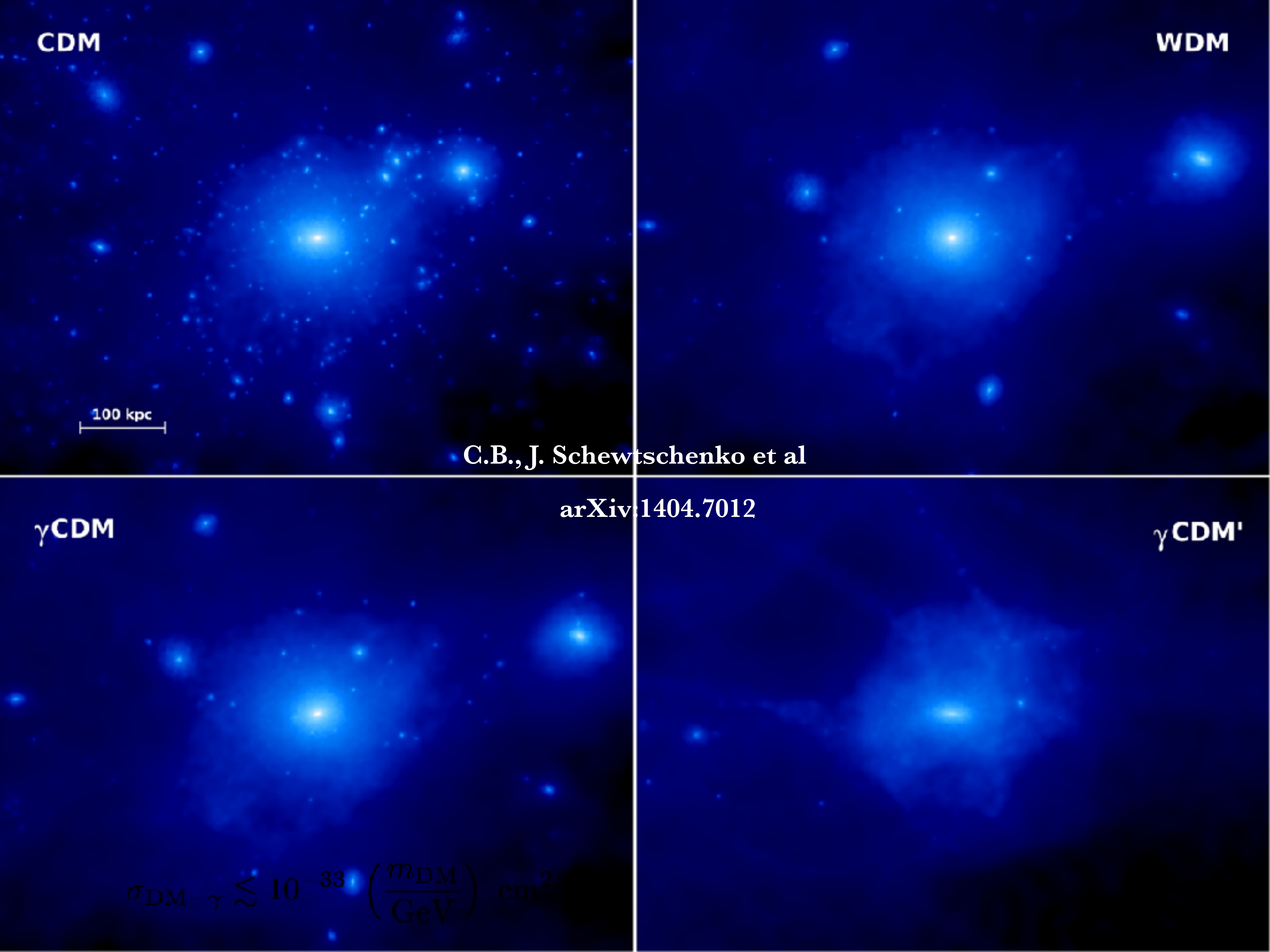
Higher H0 (shorter lifetime of the Universe) because of the additional source of damping!

The Milky Way for interacting DM



C.B., J. Schewtschenko et al

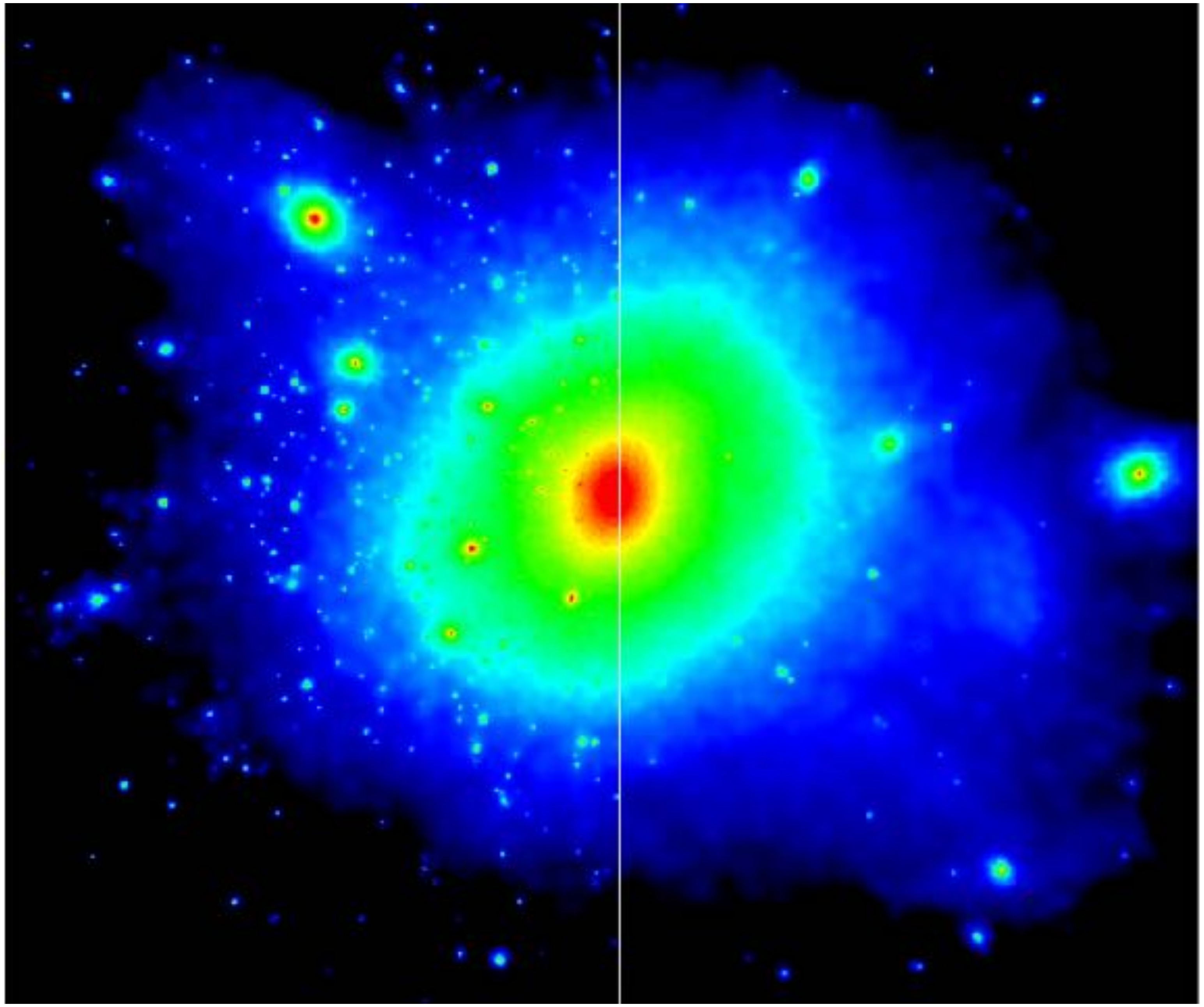
http://www.youtube.com/watch?v=YhJHN6z_0ek



C.B., J. Schewtschenko et al

arXiv:1404.7012

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



arXiv:1412.4905

arXiv:1512.06774

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

(factor 100 better than CMB)

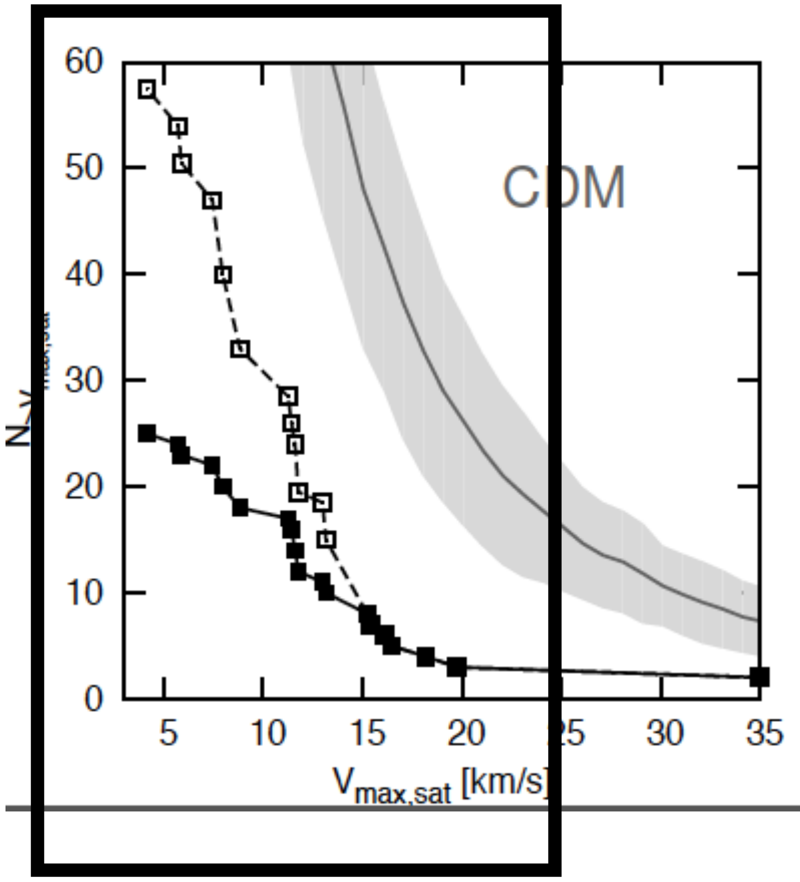
The local Universe constrains Particle Physics interactions!!!

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

Numbers of MW satellite galaxies

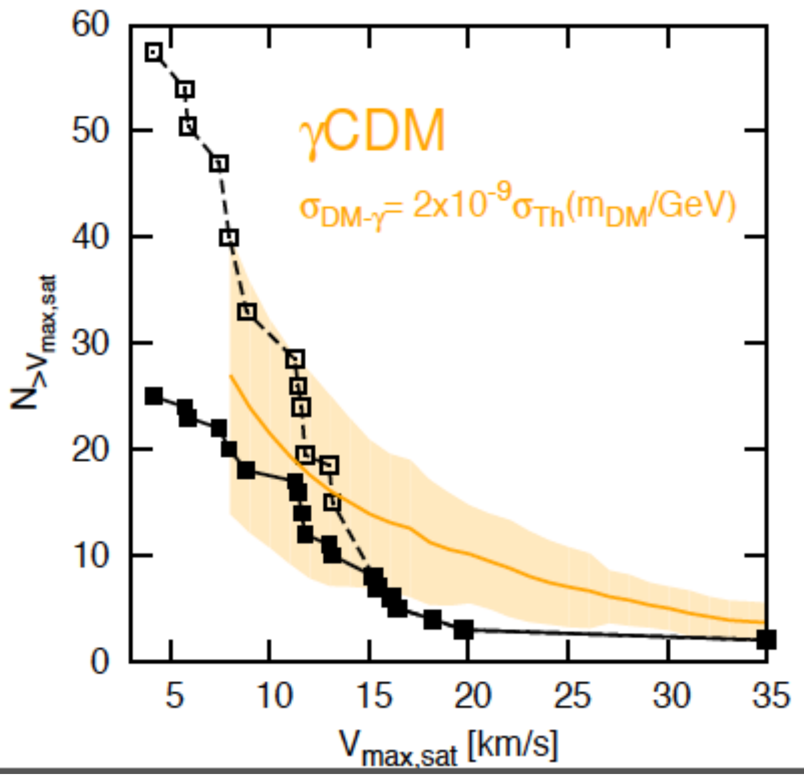
C.B, J. Schewtschenko, R. Wilkinson, C. Baugh, S. Pascoli,
arXiv:1404.7012

CDM prediction is well above observation



small satellites

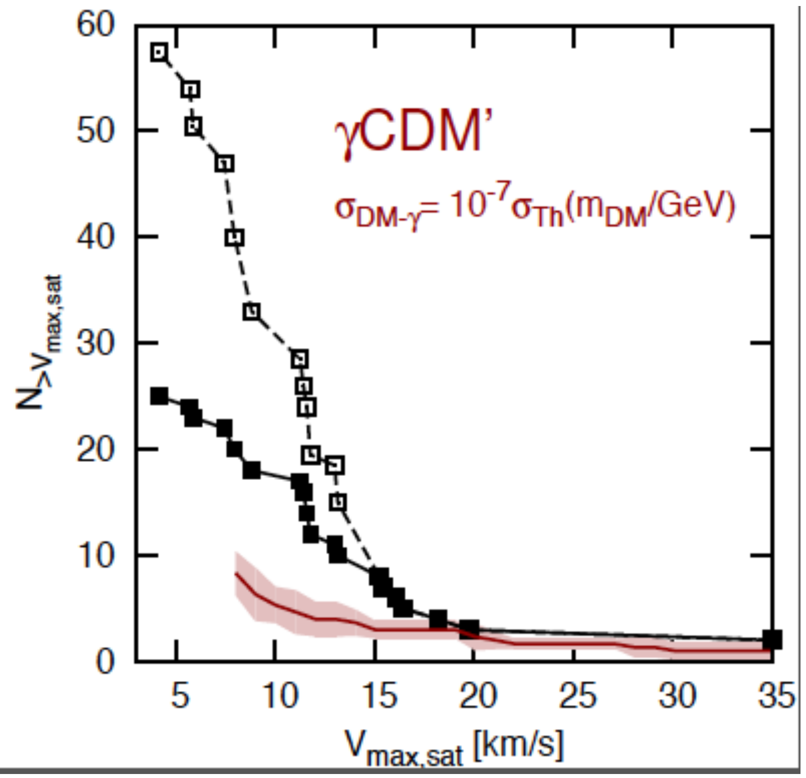
Interacting DM agrees with observation



Solve the MW satellite problem!

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

Too many interactions

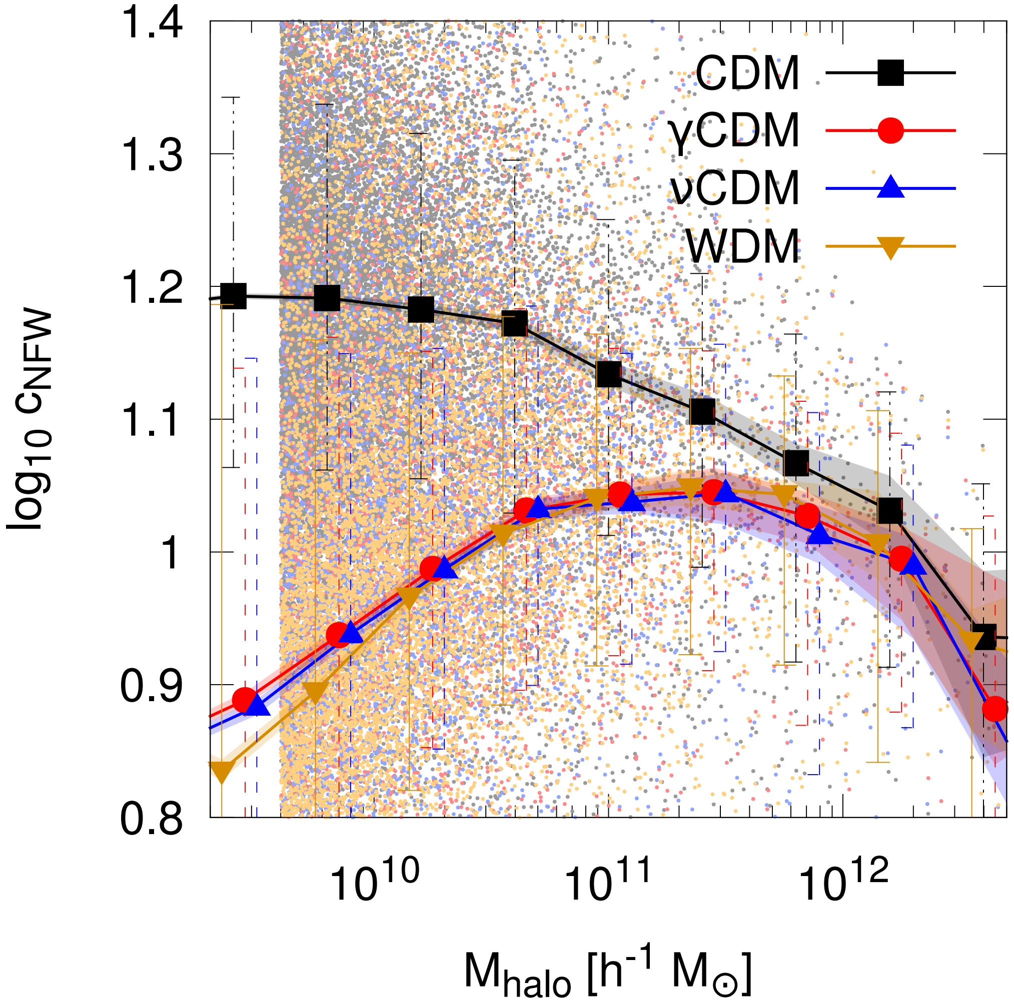


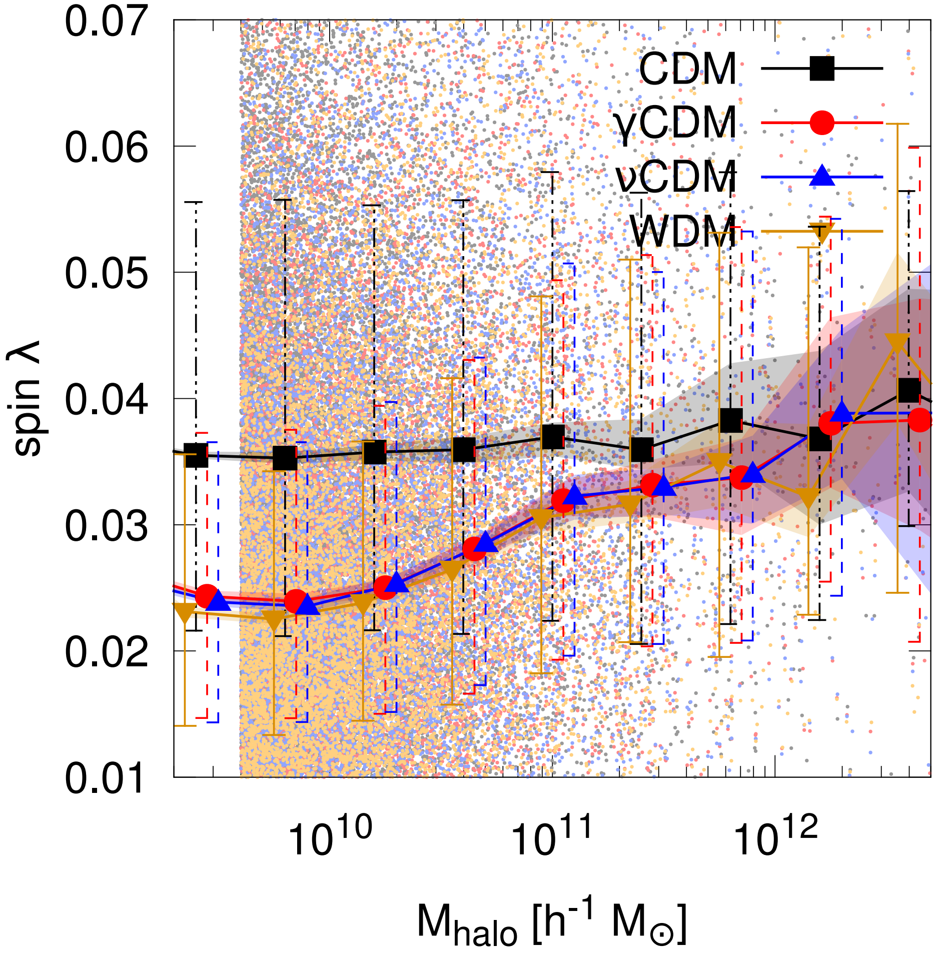
Sterilise the MW!

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

Differences with CDM

http://arxiv.org/pdf/1412.4905.pdf





Differences with CDM

1512.06774

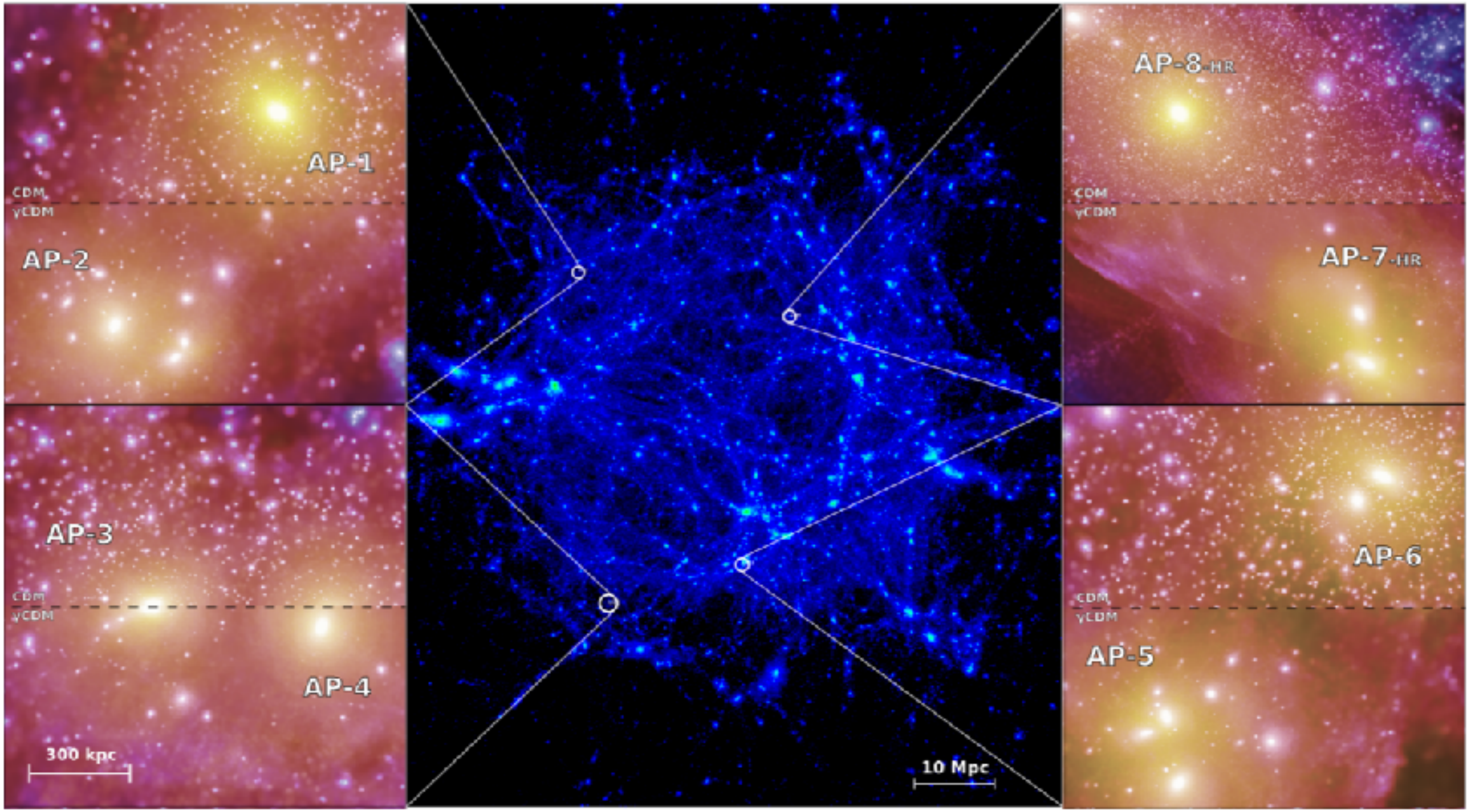
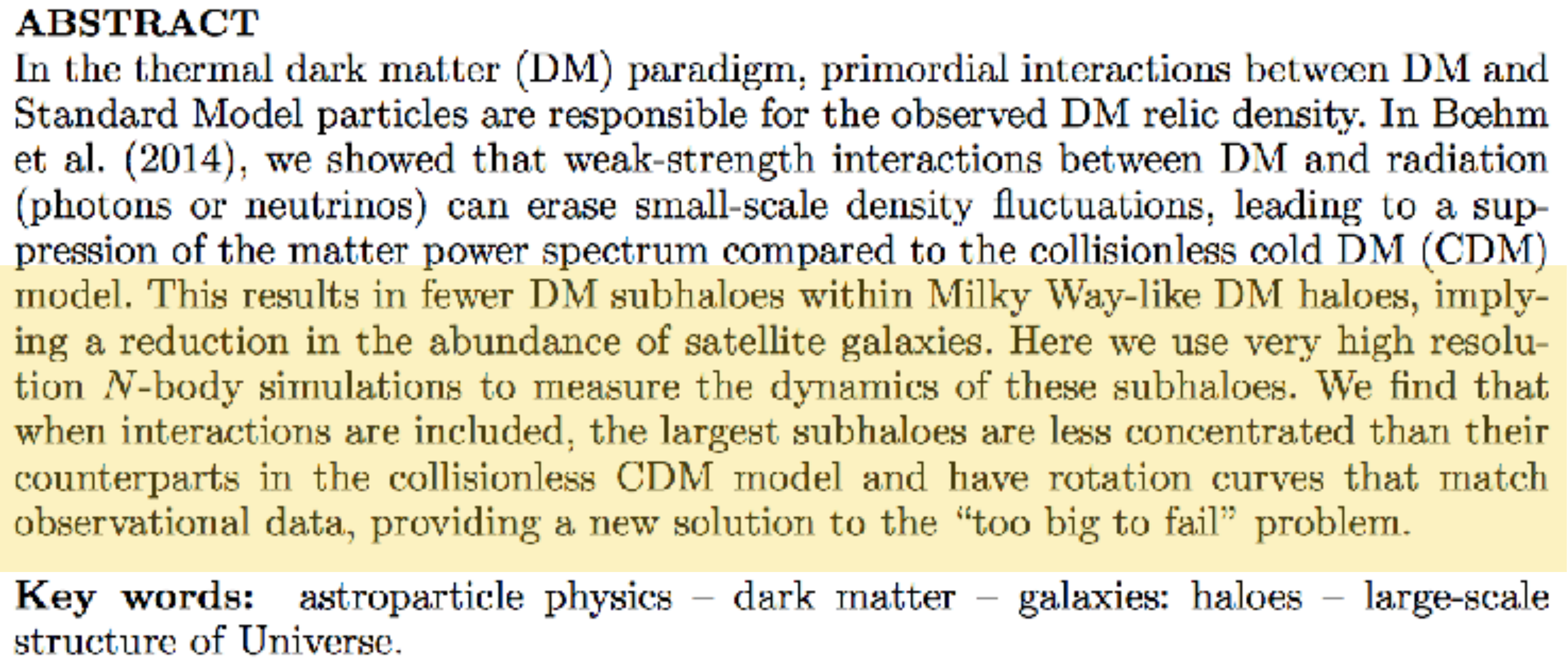


Figure 1. The centre panel shows a projection of the DM distribution in the full (100 Mpc)^3 DOVE simulation box, where the circles denote the four regions (with radii 1 h^{-1} Mpc) that are used for the "zoom" resimulations. To the left and right, each of the four Local Group candidates is rendered with the projected density encoded as brightness, where the colour scheme represents the local velocity dispersion from low (violet) to high (yellow/white). Each of these four panels is split in half with the upper and lower halves corresponding to CDM and γCDM with $\sigma_{\mathrm{DM}-\gamma} = 2 \times 10^{-9}\ \sigma_{\mathrm{Th}}\ (m_{\mathrm{DM}}/\mathrm{GeV})$ respectively. The MW-like host haloes are labelled with the identifiers listed in Tab. 1.

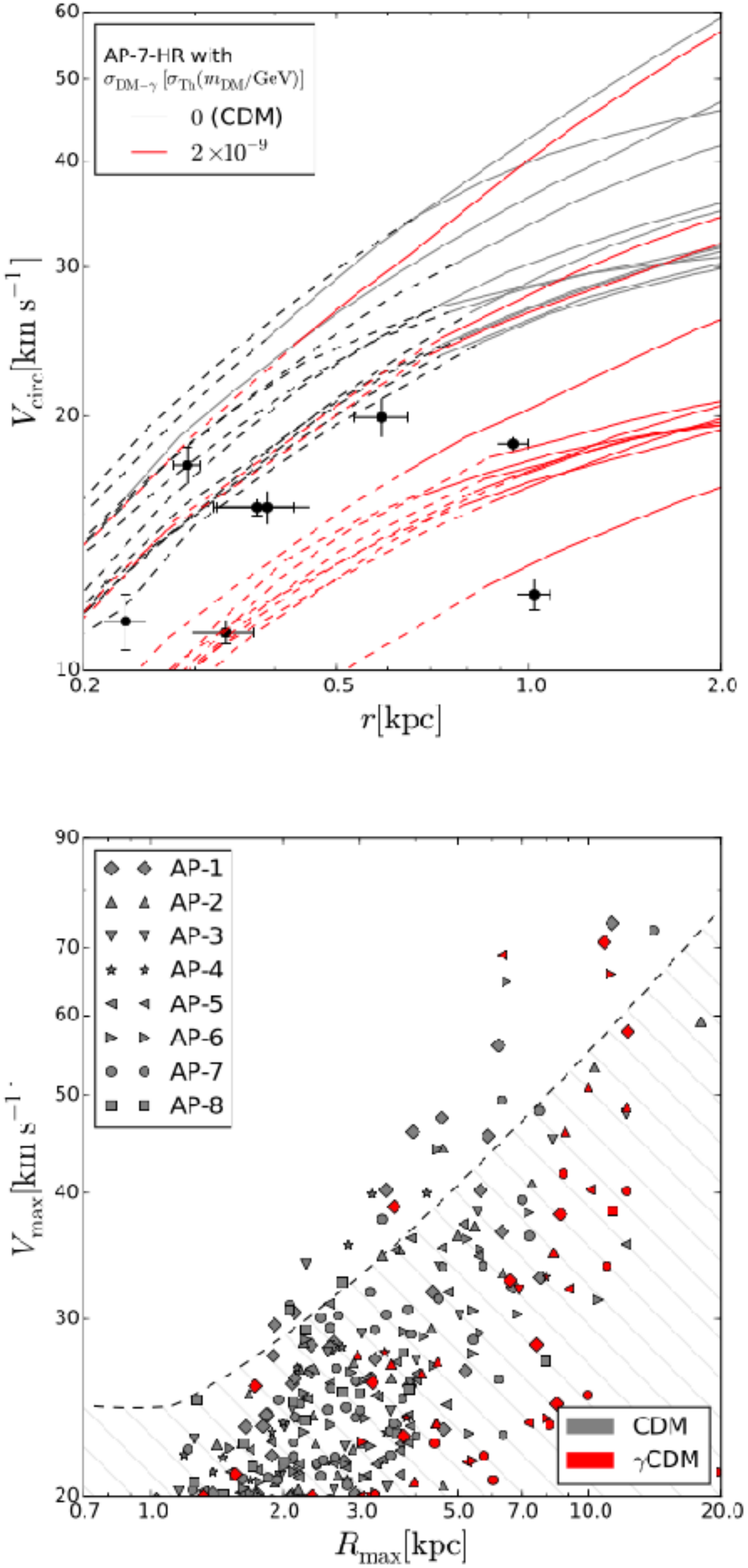
1512.06774



ABSTRACT

In the thermal dark matter (DM) paradigm, primordial interactions between DM and Standard Model particles are responsible for the observed DM relic density. In Bœhm et al. (2014), we showed that weak-strength interactions between DM and radiation (photons or neutrinos) can erase small-scale density fluctuations, leading to a suppression of the matter power spectrum compared to the collisionless cold DM (CDM) model. This results in fewer DM subhaloes within Milky Way-like DM haloes, implying a reduction in the abundance of satellite galaxies. Here we use very high resolution N-body simulations to measure the dynamics of these subhaloes. We find that when interactions are included, the largest subhaloes are less concentrated than their counterparts in the collisionless CDM model and have rotation curves that match observational data, providing a new solution to the "too big to fail" problem.

Key words: astroparticle physics – dark matter – galaxies: haloes – large-scale structure of Universe.



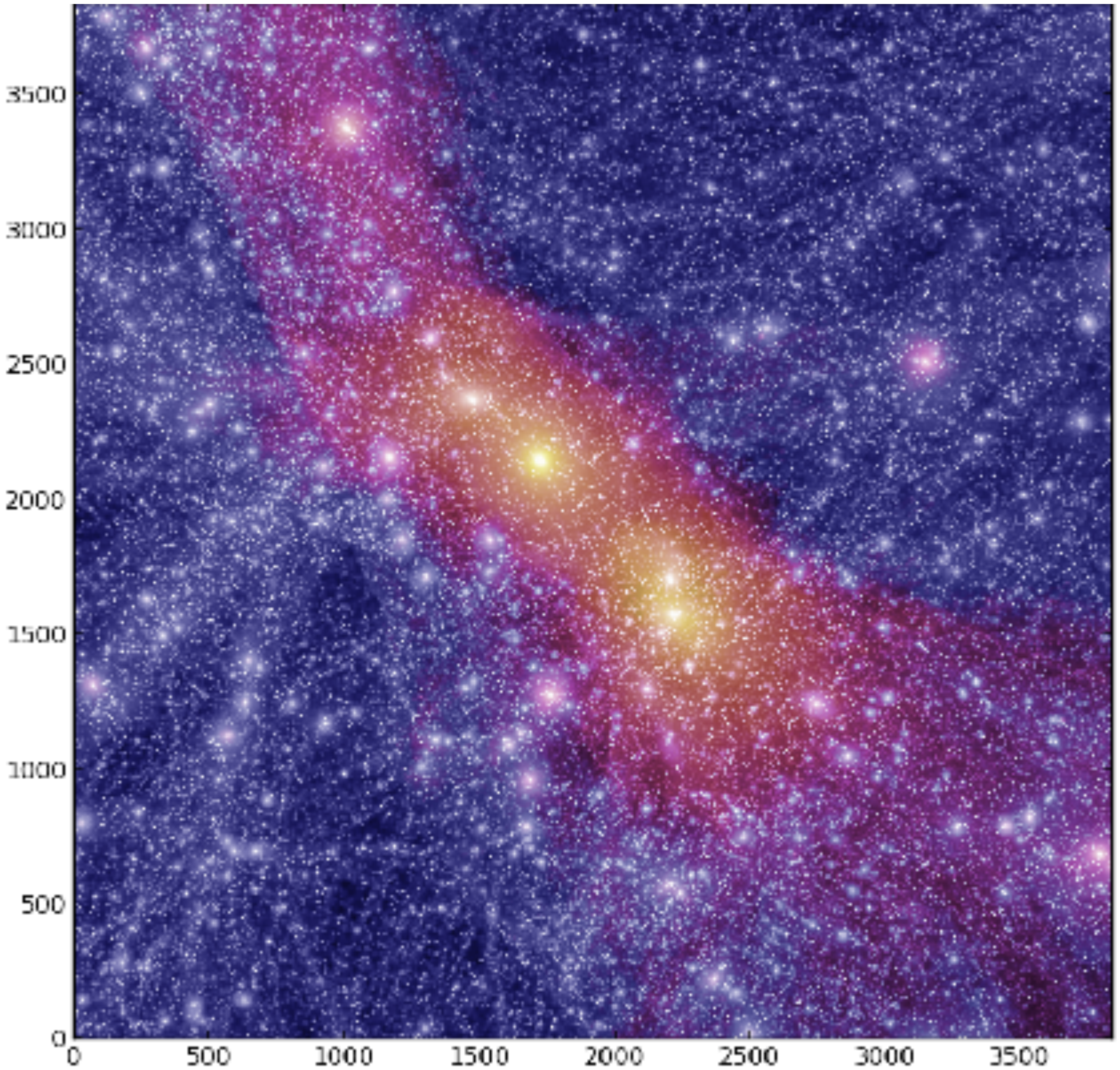
ID	M_{vir} $[10^{12}\ M_\odot]$	V_{max} [km s^{-1}]	$\sigma_{\mathrm{DM}-\gamma}$ $[\sigma_{\mathrm{Th}}\ (m_{\mathrm{DM}}/\mathrm{GeV})]$
AP-1	1.916	200.3	$0,\ 2\times10^{-9}$
AP-2	1.273	151.5	
AP-3	0.987	157.9	$0,\ 2\times10^{-9}$
AP-4	0.991	163.0	
AP-5	2.010	167.5	$0,\ 2\times10^{-9}$
AP-6	1.934	165.1	
AP-7	1.716	163.7	$0,\ 10^{-10},\ 10^{-9},$ $2\times10^{-9},\ 10^{-8}$
AP-8	1.558	193.3	

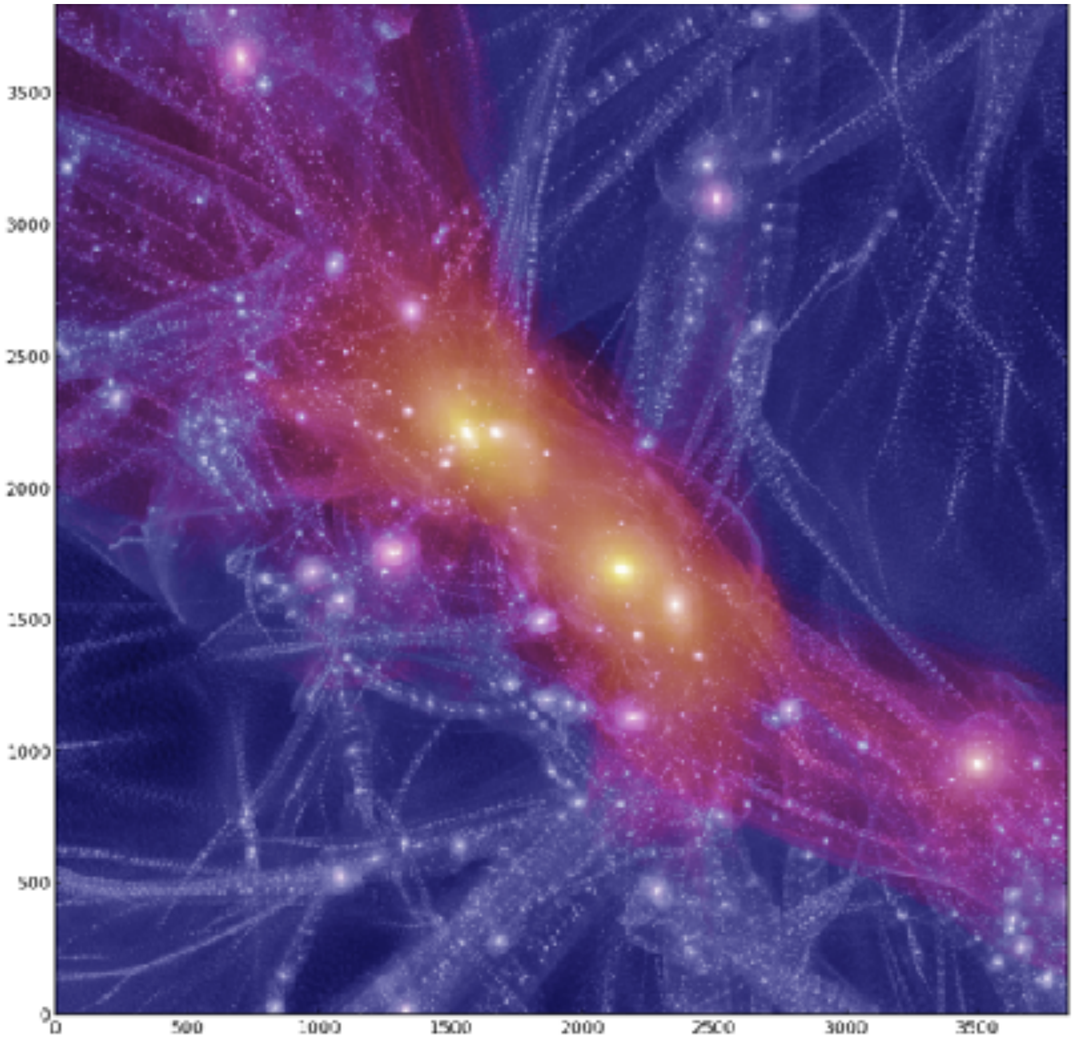
Table 1. Key properties of the MW-like haloes in the zoom resimulations (Section 2). The first column specifies the APOSTLE identifier (ID) for each MW-like halo, while the second and third columns list the virial mass, M_{vir}, and maximum circular velocity, V_{max}, respectively (for CDM). The fourth column lists the different DM–photon interaction cross sections, $\sigma_{\mathrm{DM}-\gamma}$, used in the zoom resimulations for each LG candidate, where σ_{Th} is the Thomson cross section and $\sigma_{\mathrm{DM}-\gamma}=0$ corresponds to CDM.

Figure 2. Top: the circular velocity, V_{circ}, versus radius, r, for the eleven most massive subhaloes in AP-7-HR for CDM (grey lines) and for γCDM with $\sigma_{\mathrm{DM}-\gamma}=2\times10^{-9}\ \sigma_{\mathrm{Th}}\ (m_{\mathrm{DM}}/\mathrm{GeV})$ (red lines). The dashed lines indicate where V_{circ} can still be measured from the simulation but convergence cannot be guaranteed, according to the criteria set out by Power et al. (2003). The data points correspond to the observed MW satellites with 1σ error bars (Wolf et al. 2010). Bottom: the V_{max} versus R_{max} results for all eight MW-like haloes, with the same scattering cross sections as in the top panel. The hatched region marks the 2σ confidence interval for the observed MW satellites. V_{max} is derived from the observed stellar line-of-sight velocity dispersion, $\sigma_\star$, using the assumption that $V_{\mathrm{max}}=\sqrt{3}\sigma_\star$ (Klypin et al. 1999).

LSS in the Universe are modified too!

[arXiv:1404.7012](https://arxiv.org/abs/1404.7012)

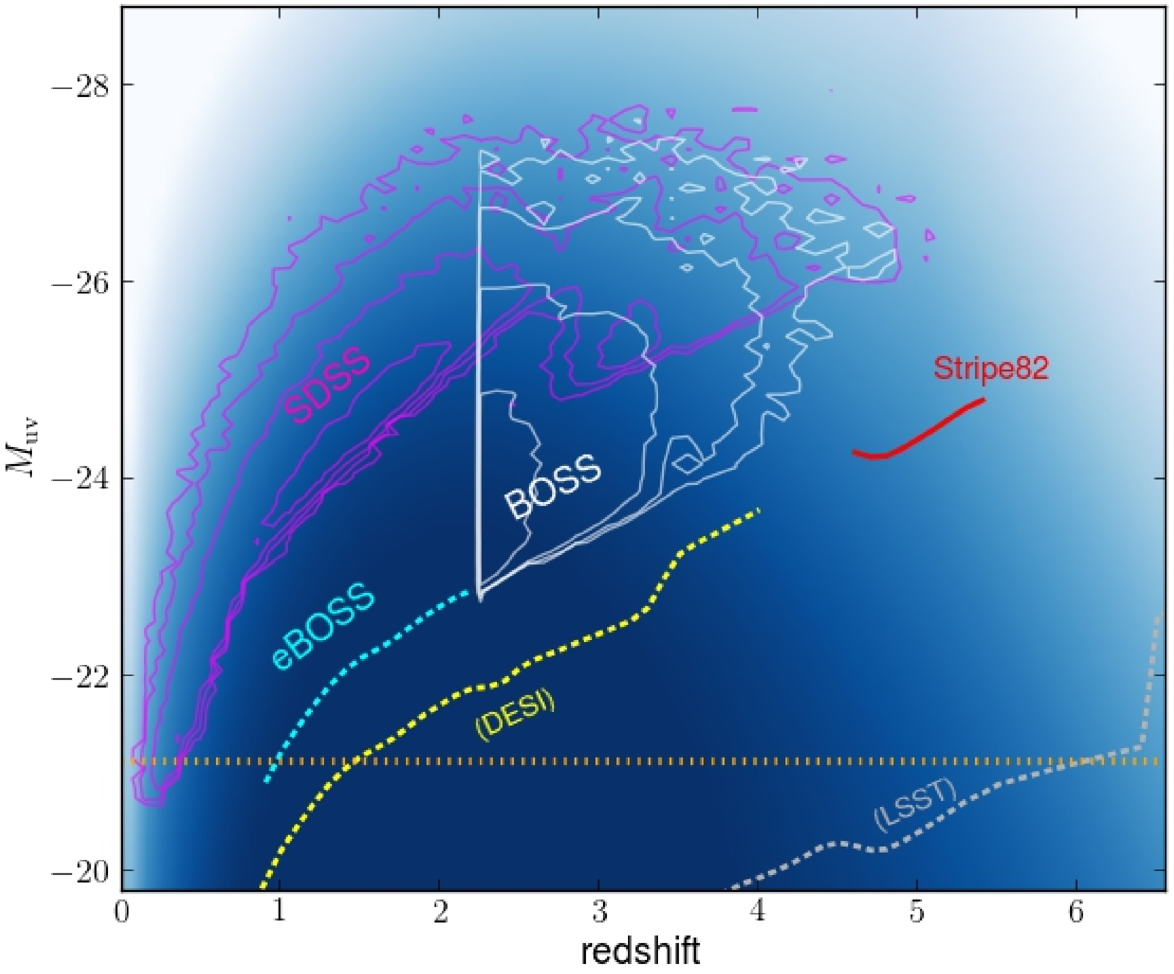




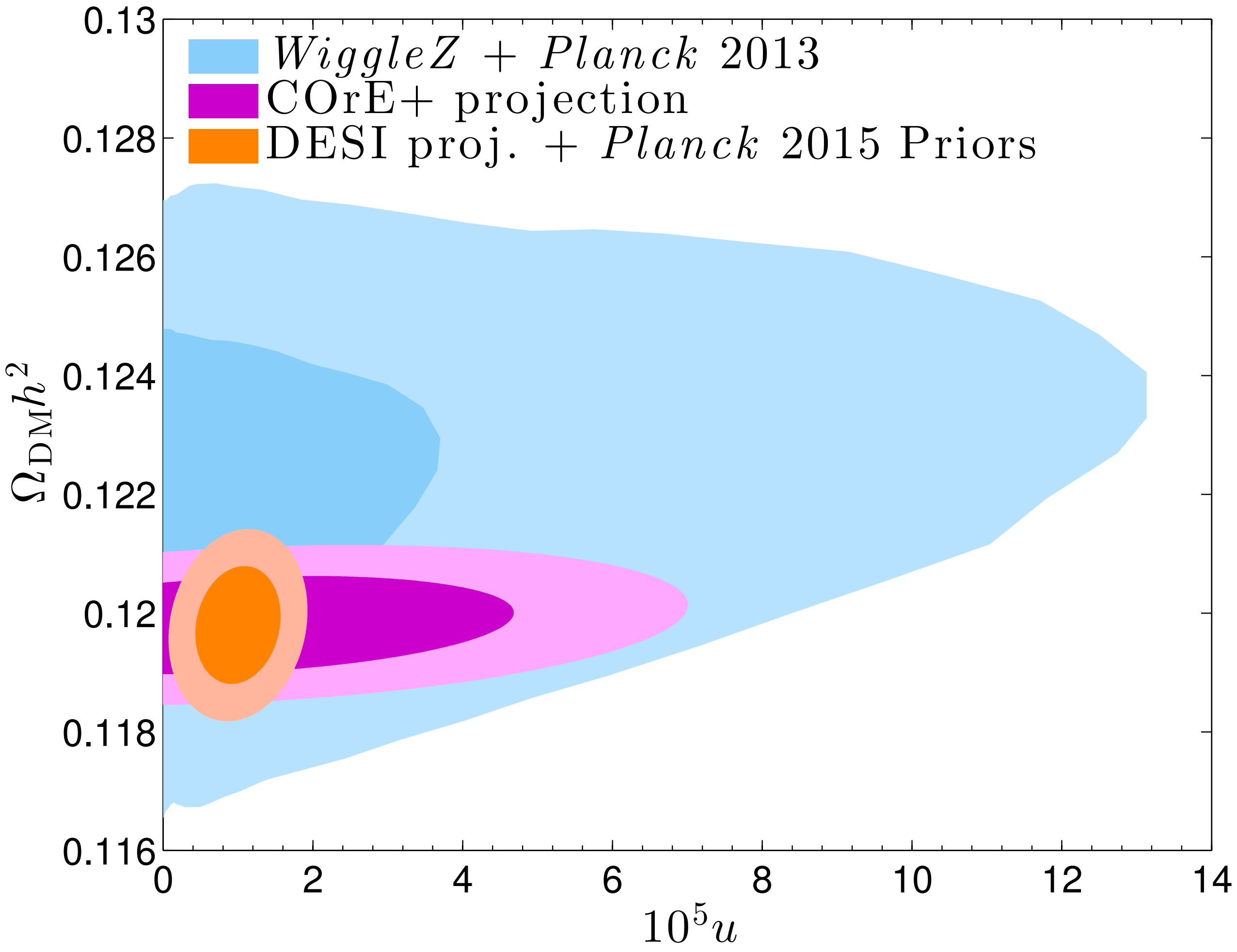
lengths 100/h Mpc and 300/h Mpc
10243 particles

Future LSS experiments can set strong bounds

arXiv:1505.06735



Courtesy JP Kneib



With DESI we gain a factor 10

It will be amazing to see what LSST brings …

Other Dark Matter interactions

Dark Matter - Dark radiation

1512.05349

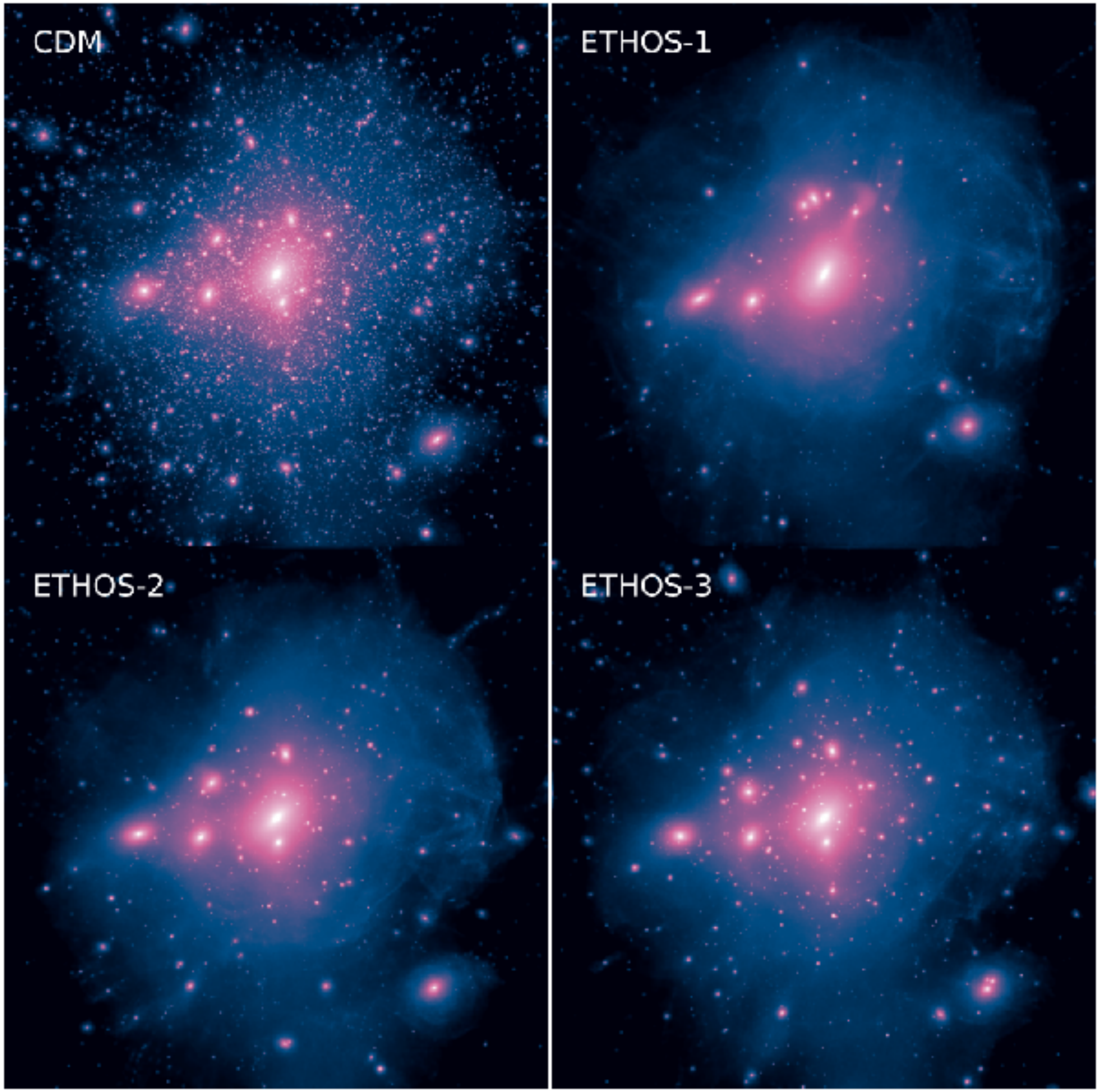
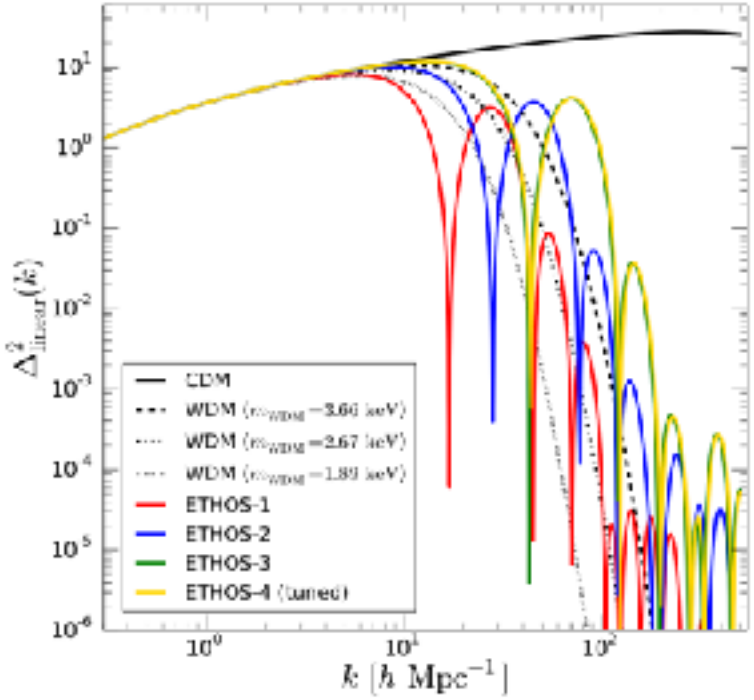


Figure 6. DM density projections of the zoom MW-like halo simulations for four different DM models. The suppression of substructure, relative to the CDM model, is evident for the ETHOS models ETHOS-1 to ETHOS-3, which have a primordial power spectrum suppressed at small scales. The projection has a side length and depth of 500 kpc.



Late-time interactions

1406.0527

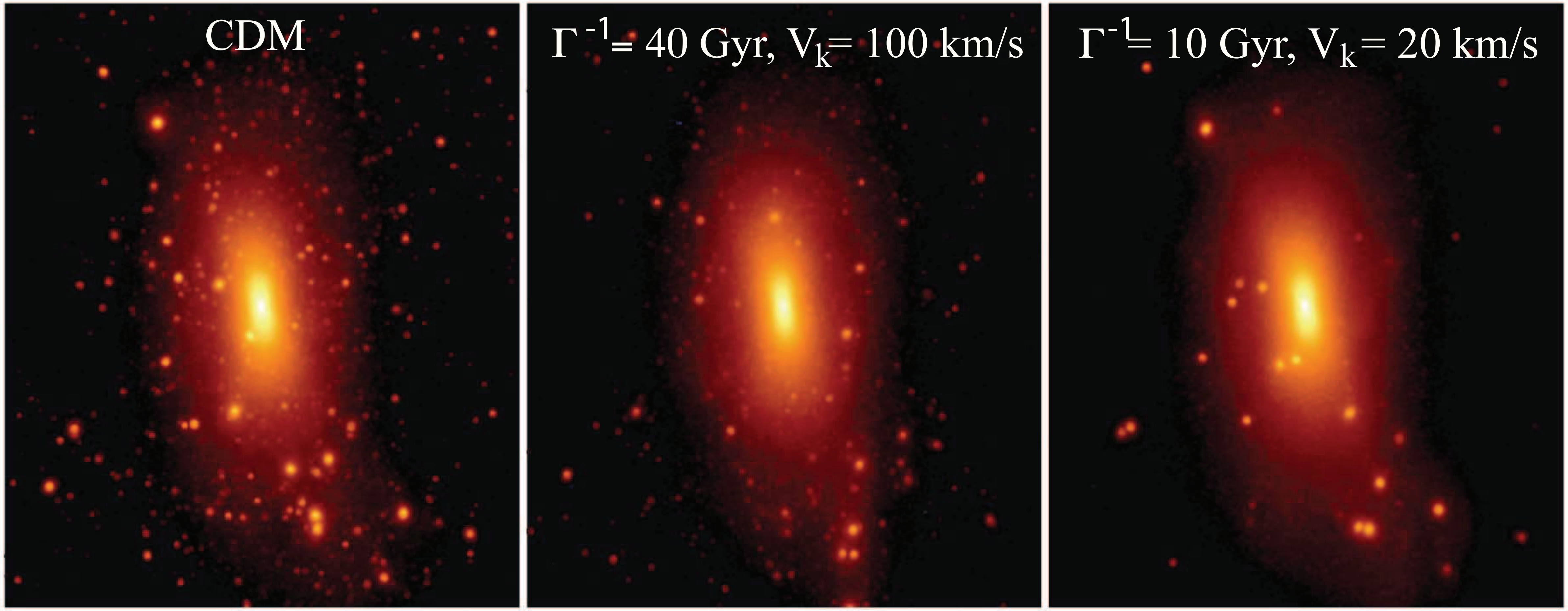


Figure 2. Small-scale structure in a Milky Way mass halo (Z12) in CDM (left) and DDM models with Γ^{-1} = 40 Gyr and V_k = 100 km/s (middle) and Γ^{-1} = 10 Gyr and V_k = 20 km/s (right) within 260 kpc of the halo centers at $z = 0$. The color scheme indicates the line-of-sight projected square of the 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.

“Astrometric” Science with Theia

Relative Astrometry ; point and stare

sub-Micro arcsecond precision + photometry (optical, 350-1000nm)

More than 200 participants

22 countries: **UK**, France, Germany, Italy, Spain, Switzerland, Poland, Portugal,Sweden, The Netherlands, Hungary, Greece, Denmark, Austria, Finland, USA, Brazil, China, Canada, India, Israel, Japan.

Open observatory (15 %) complementary science

fields of observations fixed by a call prior to the mission

THEIA

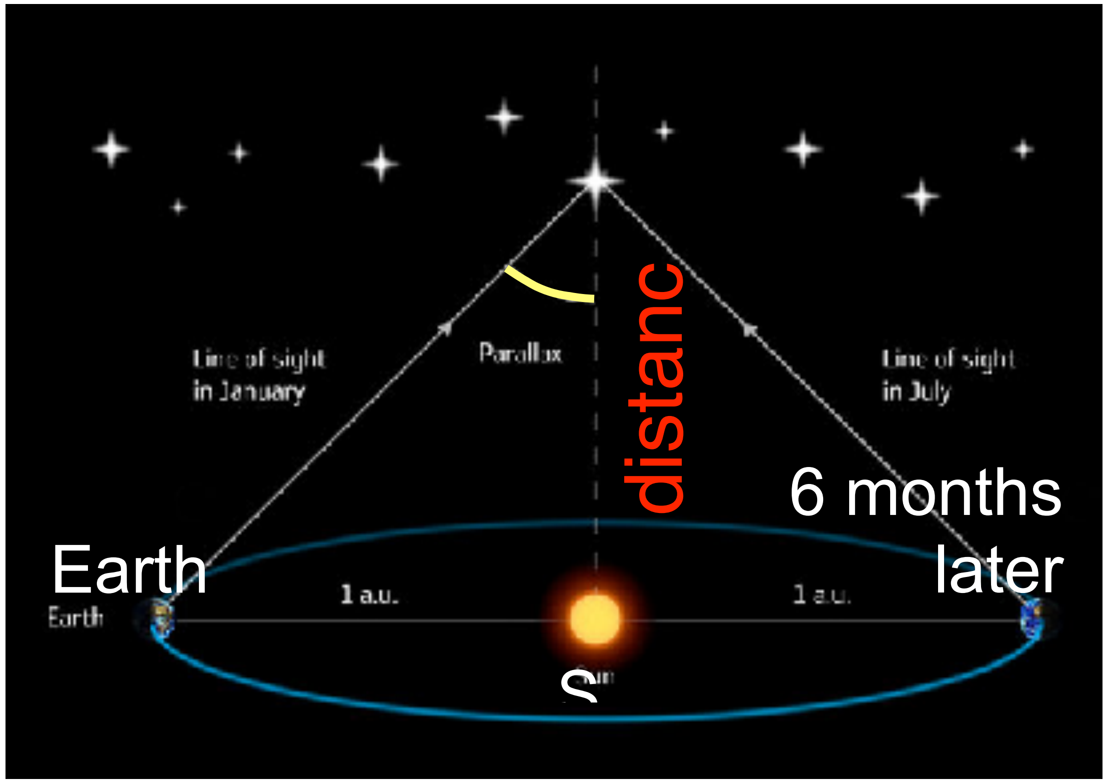
Microarcsecond Astrometric Observatory

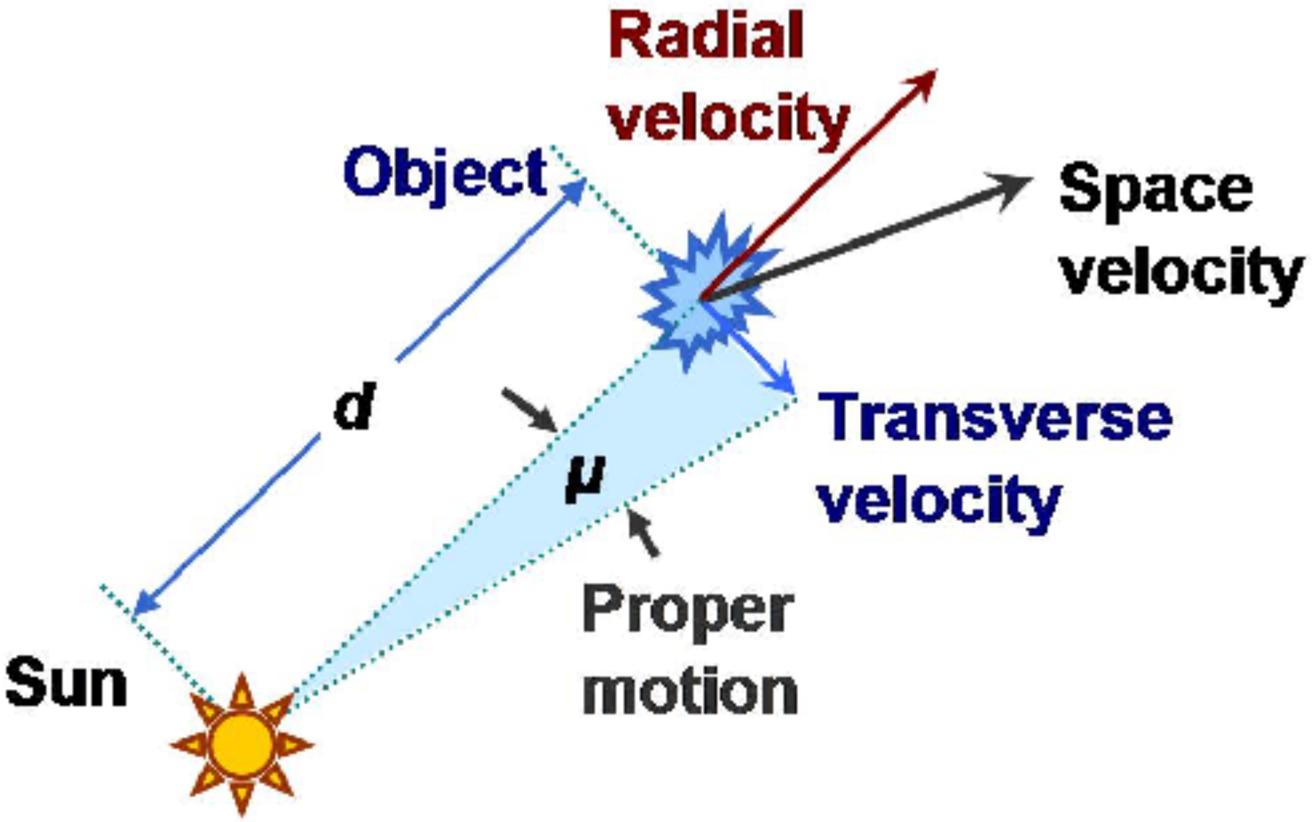
Medium-size successor of Gaia
Historically motivated by exoplanets

- **Dark Matter (70% of observational time)**
- Exoplanets
- Neutron stars

Principle

Courtesy Brew Ohare



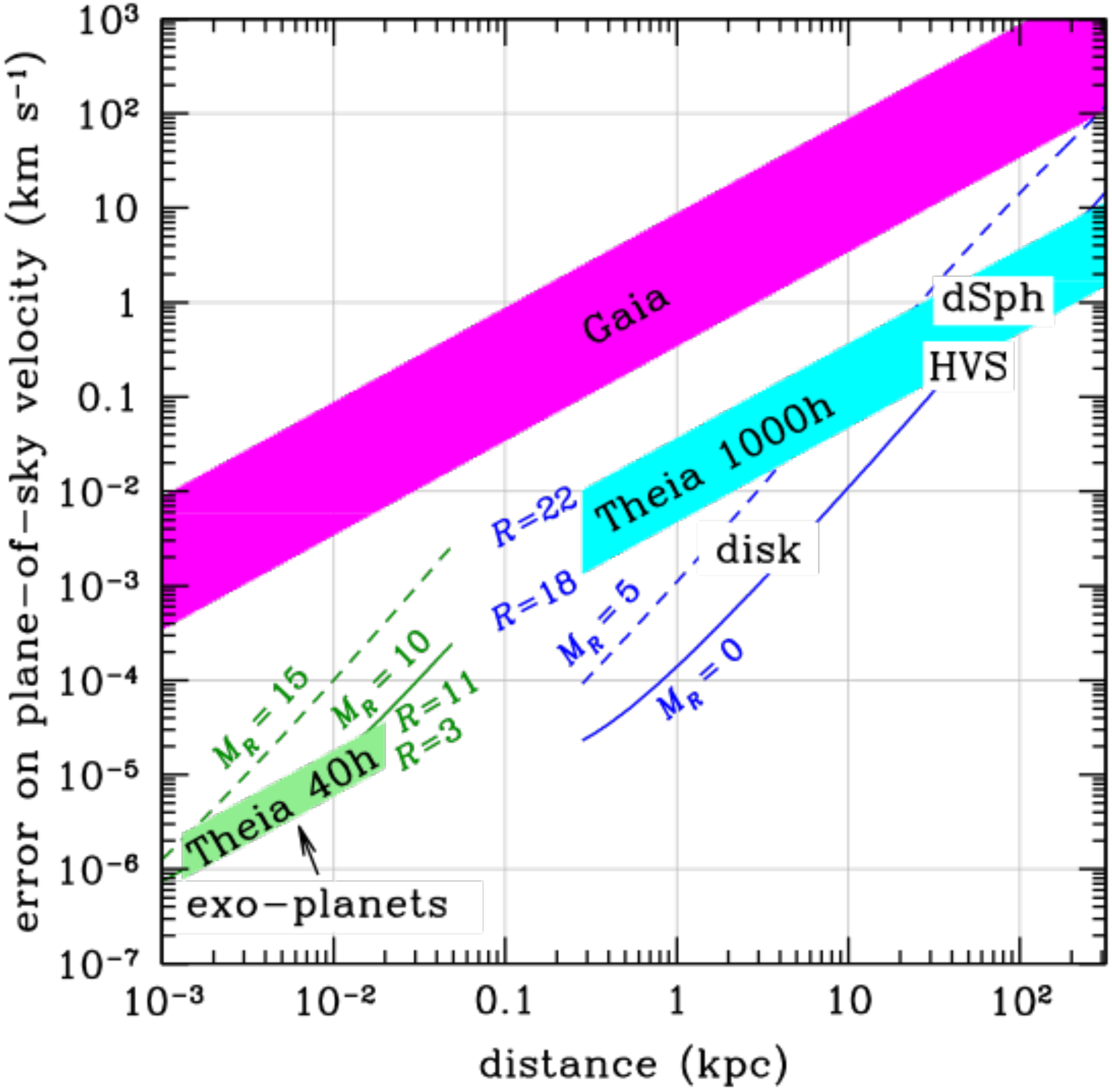


parallax

Proper motion

THEIA

Microarcsecond Astrometric Observatory



The 1000 brightest stars in Draco have magnitudes R = 17.5 to 20.5

Draco seen in one single shot

R < 22 stars in dwarfs such as Draco and Ursa Minor

THEIA

Microarcsecond Astrometric Observatory

Pessimistic case (CCDs)

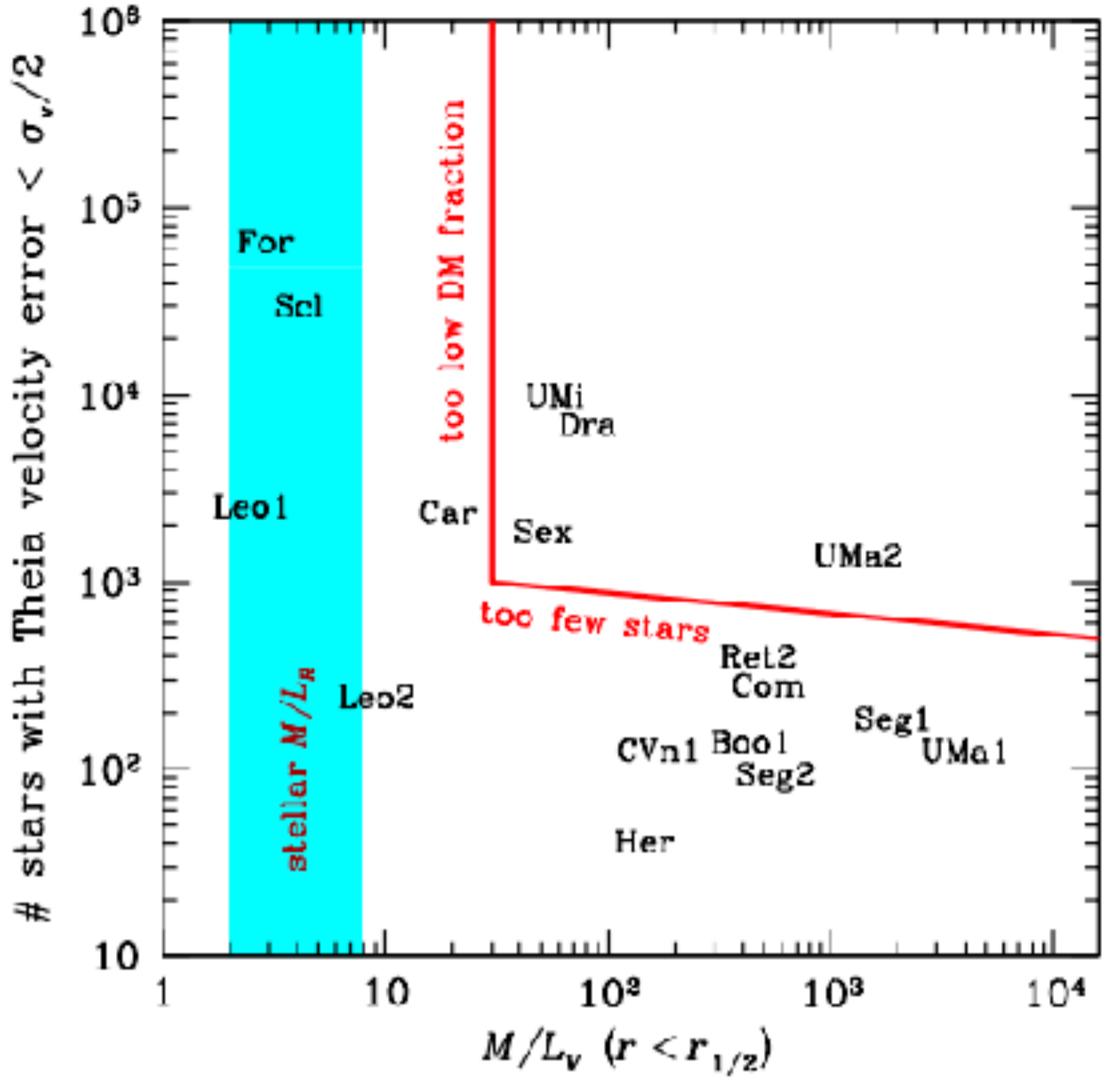
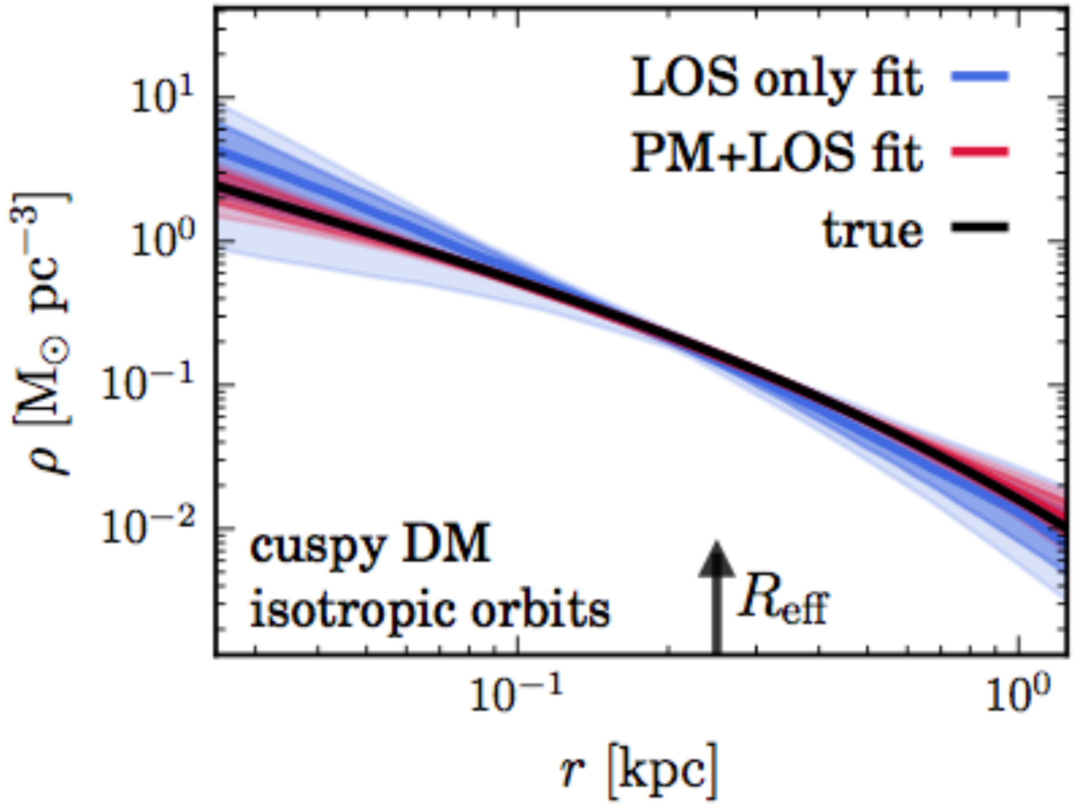


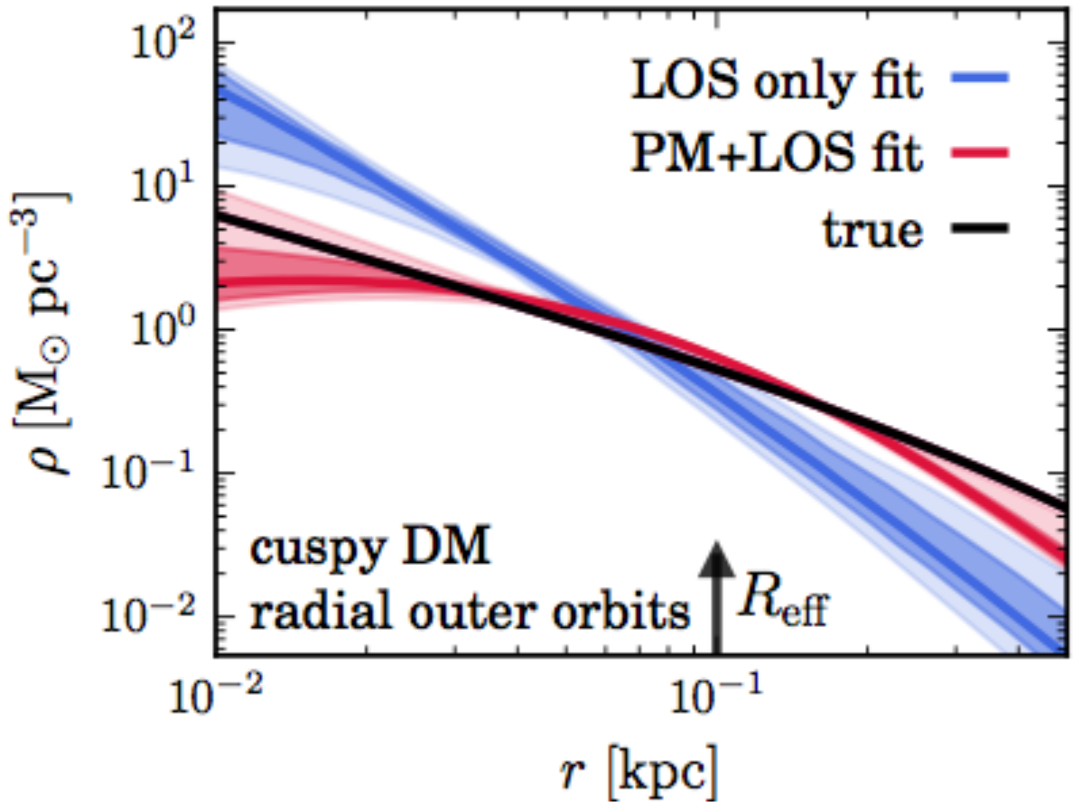
Fig. 2.1: Number of dwarf spheroidal galaxy stars within the *Theia* field with expected plane-of-sky errors lower than half the galaxy's velocity dispersion as a function of the galaxy's estimated mass-to-light ratio within the effective (half-projected-light) radius of the galaxy. Luminosities and total masses within the half-light radii are mainly from Walker et al. (2009).

Degeneracy between the radial DM profile and orbital anisotropy quantifies whether stellar orbits are more radial or more tangential in the Jeans equation (Binney & Mamon 1982).

Adding proper motions can help removing these degeneracies!

Dark Matter in dSphs





CDM halos can be heated by bursty star formation inside the stellar half light radius *$R_{1/2}$*, if star formation proceeds for long enough.

Some **dSphs like Fornax** have formed stars for almost a Hubble time and so **should have large central dark matter cores,** while others, like **Draco and Ursa Major2 should retain their steep central dark matter cusp**.

But it depends on the DM nature.

We can tell how DM is distributed and discriminate between cusp/core distributions

Theia can probe self-interactions

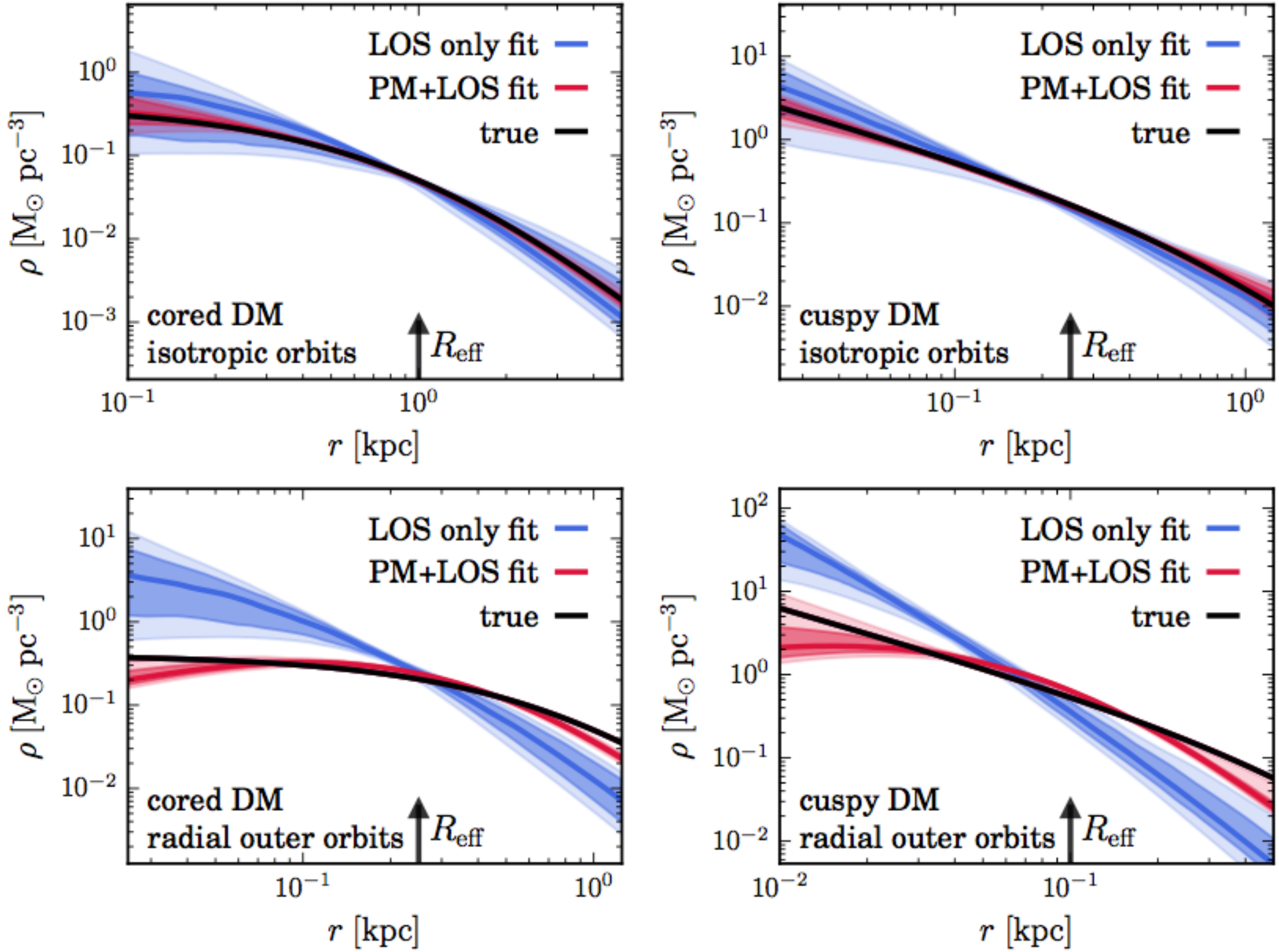


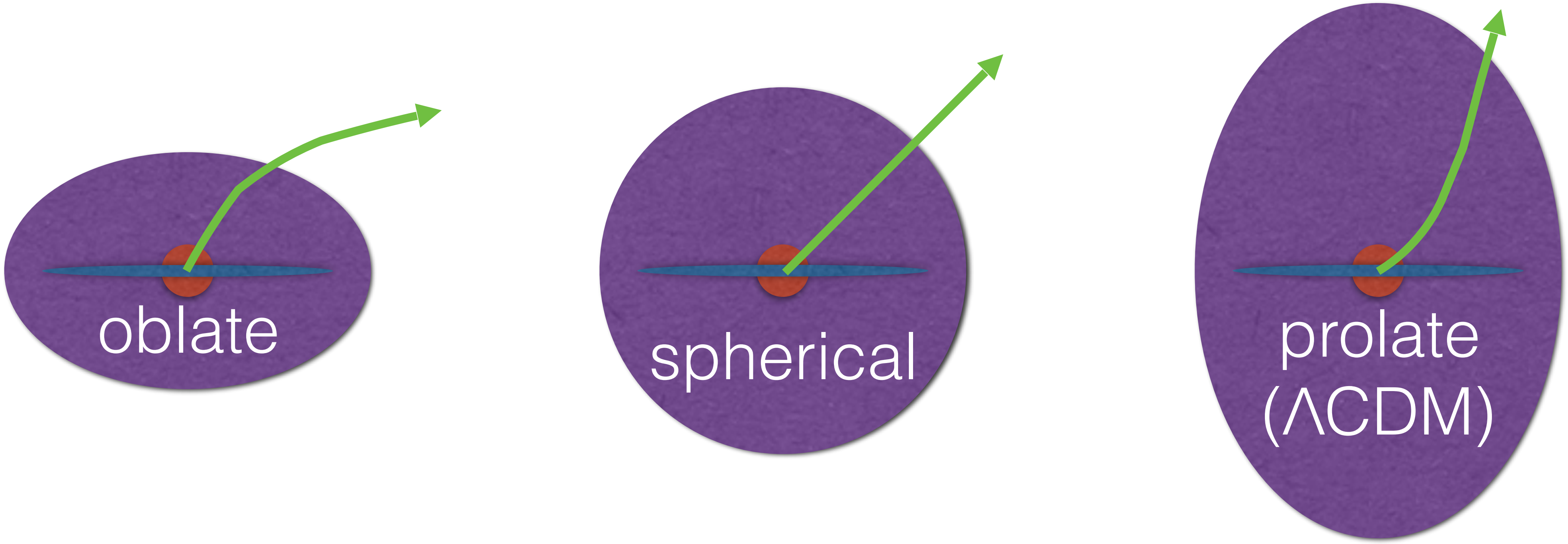
Fig. 2.2: Reconstruction of the DM halo profile of the Draco dSph without (*blue*) and with (*red*) proper motions using the mass-orbit modeling algorithm of Watkins et al. (2013). Four mocks of Draco were used, with cored (*left*) and cuspy (*right*) DM halos, and with isotropic velocities everywhere (*top*) or only in the inner regions with increasingly radial motions in the outer regions (*bottom*). The effective (half-projected light) radii of each mock is shown with the *arrows*. The stellar proper motions in the mocks were given errors, function of apparent magnitude, as expected with 1000 hours of observations spread over 4 years. Only with proper motions can the DM density profile be accurately reconstructed, properly recovering its cuspy or cored nature.

Dark Matter
Triaxiality of halos

Hypervelocity stars

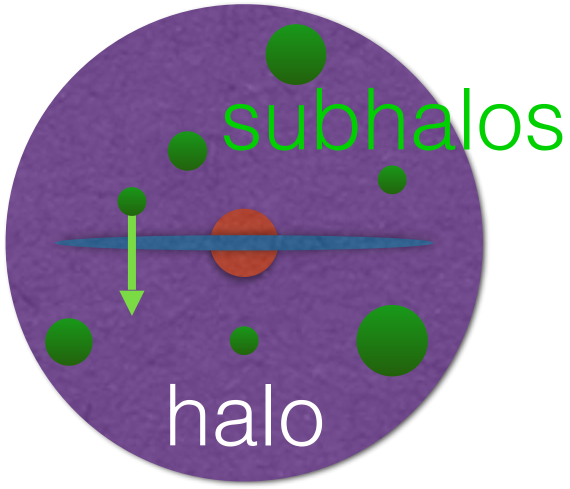
- $v > v_{esc} \sim 500$ km/s
- > 20 known today
- Too far/too faint to be seen by Gaia
- Likely originate from Galactic Center

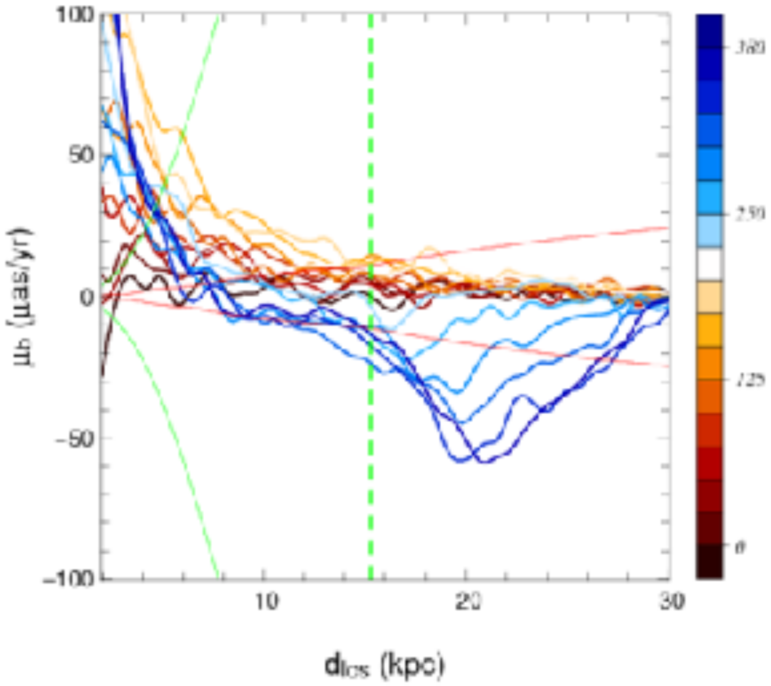
  ⇒ trajectories (transverse motions) measure shape of MW potential

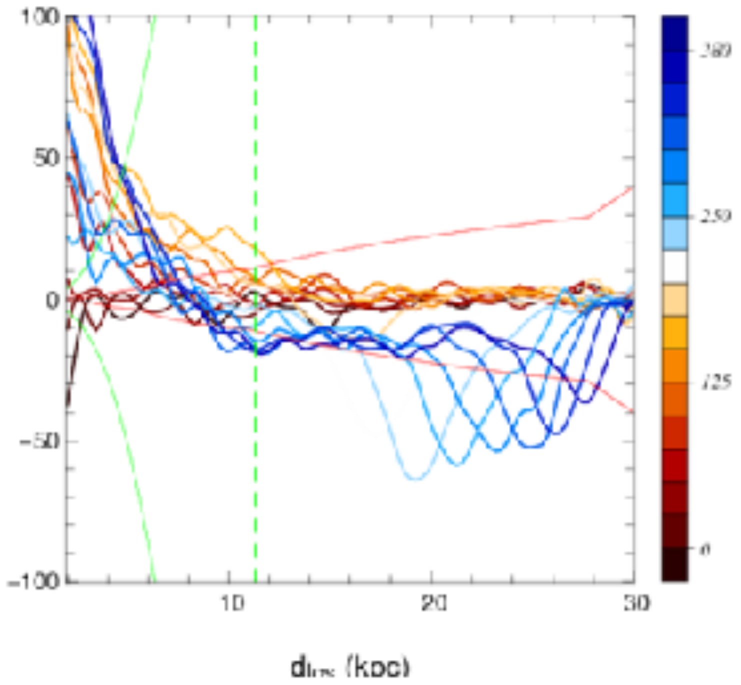


10 µas/yr accuracy required Gnedin+05
Theia → axis ratios to $\Delta(c/a) = 0.05$

Dark Matter
Masses of sub halos

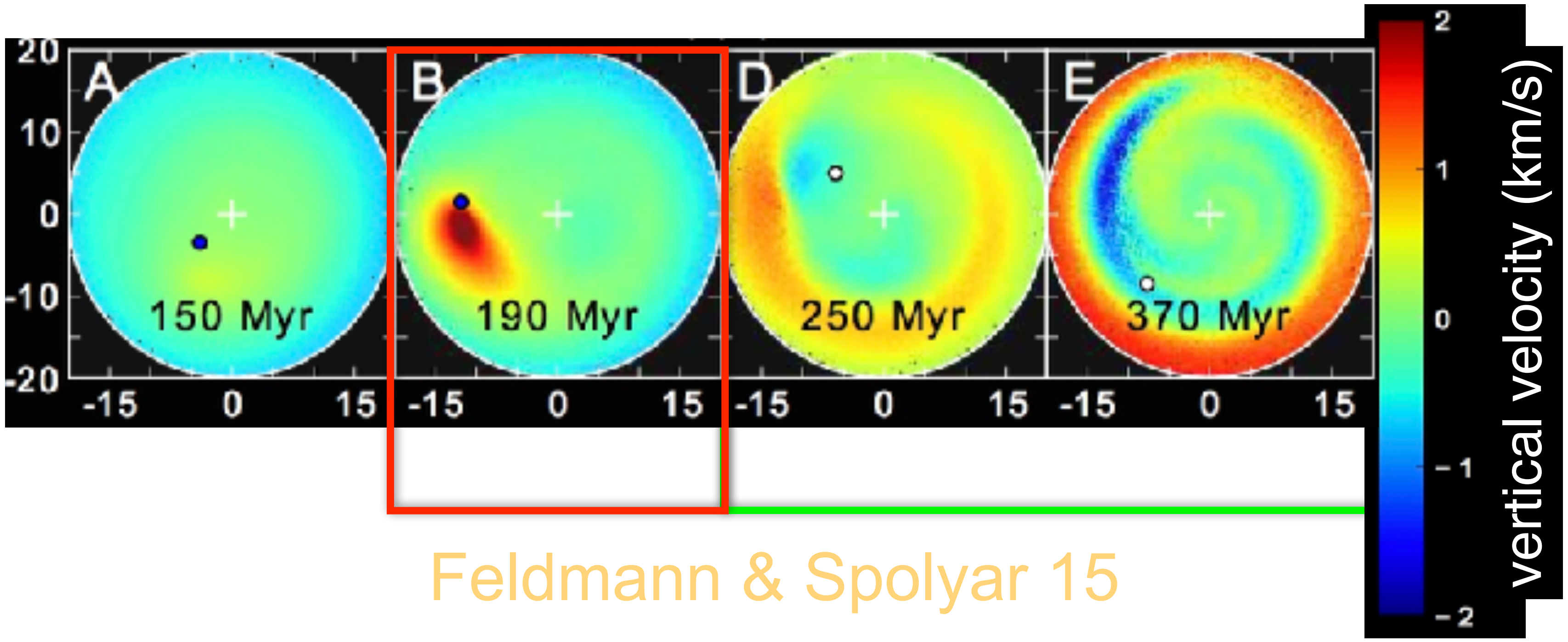






Largest effect when subhalo passes through disk

still visible after 1st passage

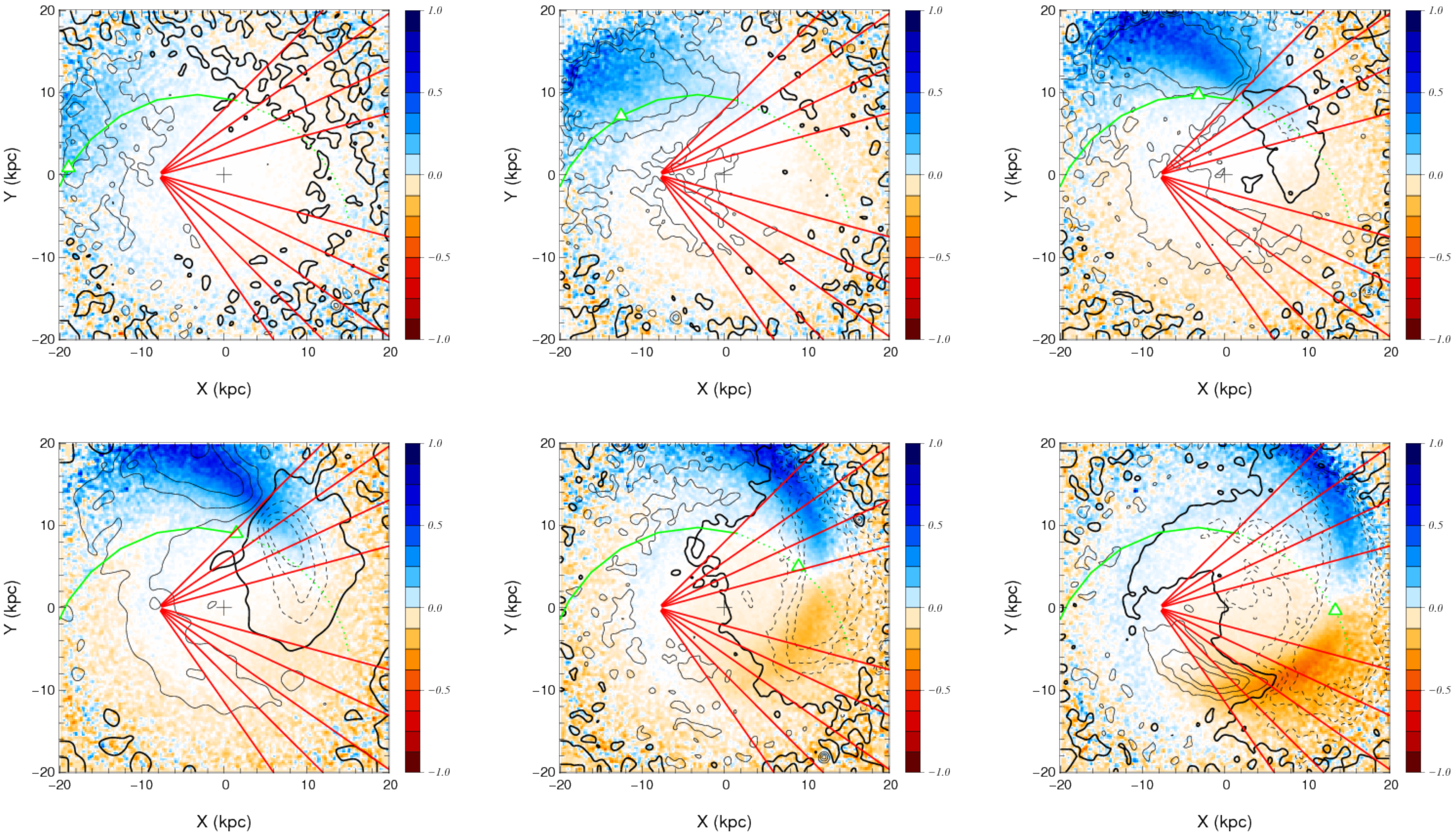


Feldmann & Spolyar 15

125 Myr **75 Myr** **25 Myr**

Before

After



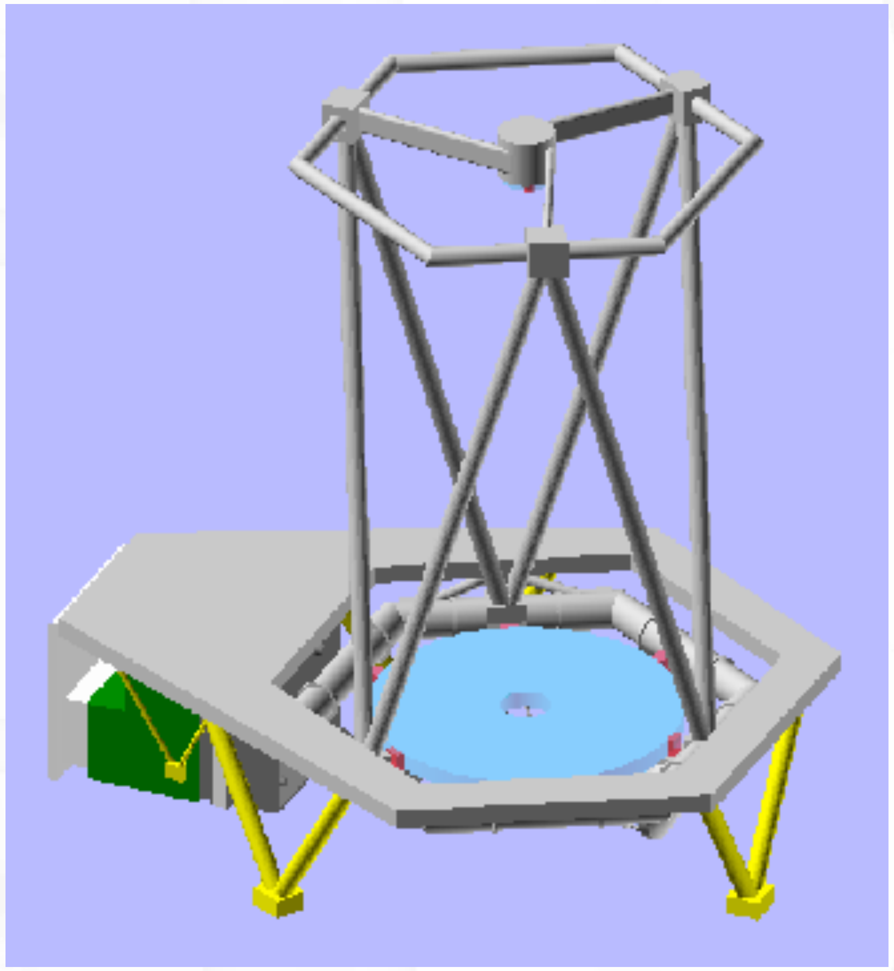
25 Myr **75 Myr** **125 Myr**

Colorbar: mean displacement
contours amplitude of bending modes in velocity space
plain line = +; dashed lines = -
triangle = actual location of sub halos

THEIA

Microarcsecond Astrometric Observatory

Korsch on-axis TMA telescope with controlled optical aberrations

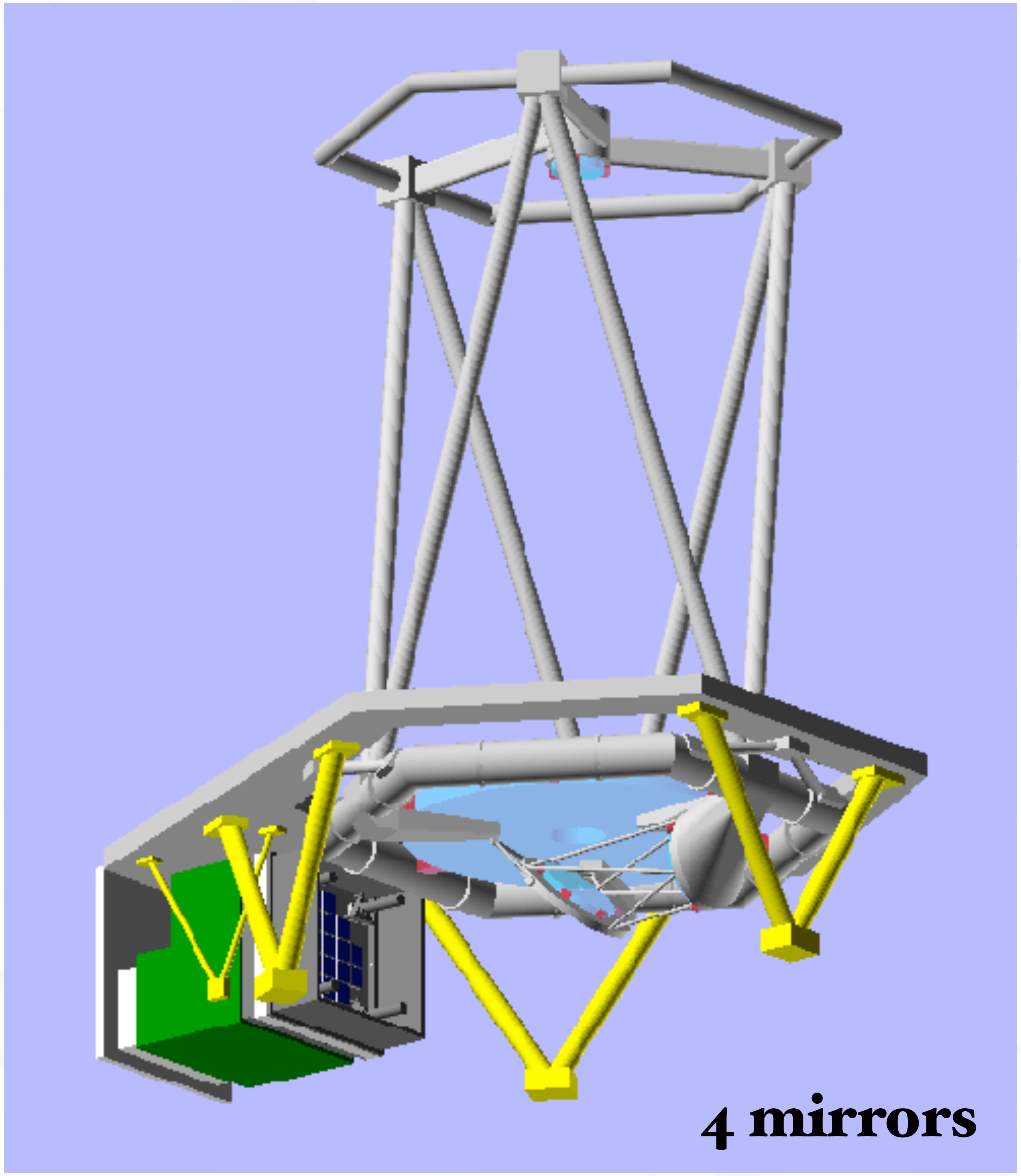


80cm primary mirror

Mission duration : 4yr (built for 8 yrs)

Optics: Zerodur, ULE or Sitall

Structures: SiC or Si3N4



4 mirrors

Understanding the nature of DM

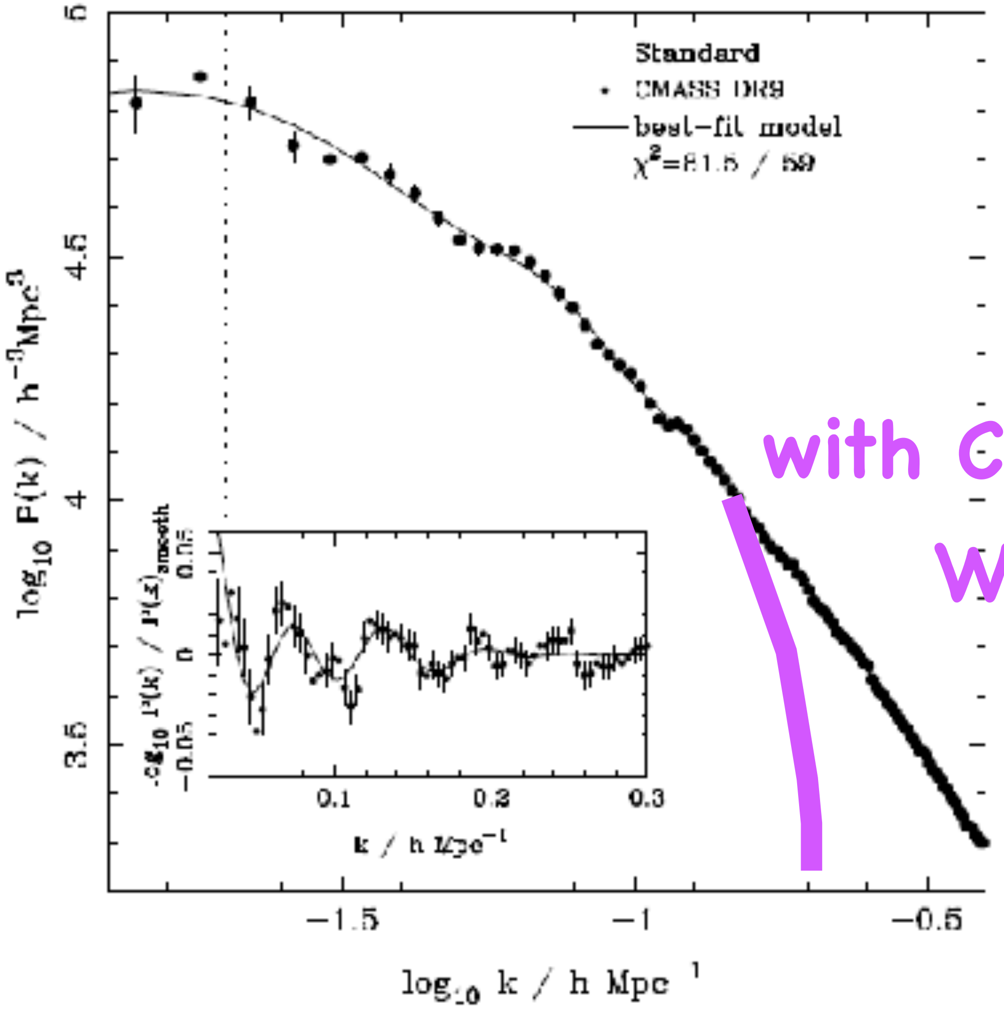
weakly interacting

...?

Not necessarily.
Data should tell!

massive particle

how do we know?
from structures!



with CUT-OFF!

WDM

$m_{\rm DM} \gtrsim 3{\rm keV}$

Conclusion

DM can have interactions

DM interactions do change the local properties

(even when primordial)

DM interactions can change Ho