Beyond WIMP DM

Beyond (vanilla) WIMP DM

Céline Boehm

credit arXiv:1404.7012

IPPP, Durham   Durham University   LAPTH, Annecy   CNRS

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PART I

A. What is a WIMP?

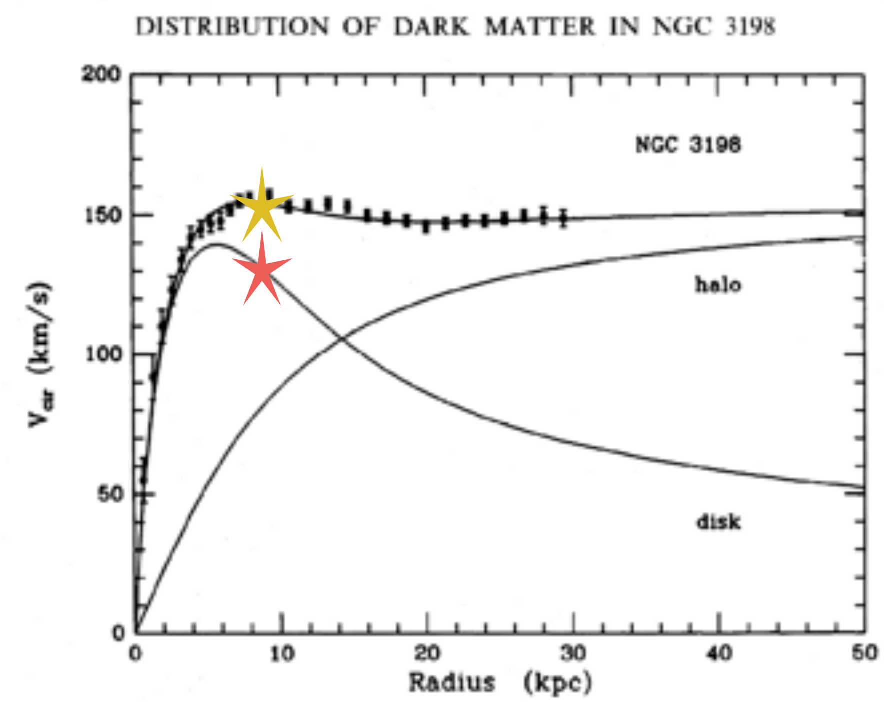
A. What is a WIMP?

def Weakly Interacting Massive Particle

Origin

$$v_c^{\,2} = \frac{G\,M(r)}{r} \qquad M(r) = \int 4\pi^2 \rho(r)\, d^3r$$

Rotational velocity of stars



Massive so as
to cluster in a halo

Weakly Interacting
based on e.m. neutral
SM particles

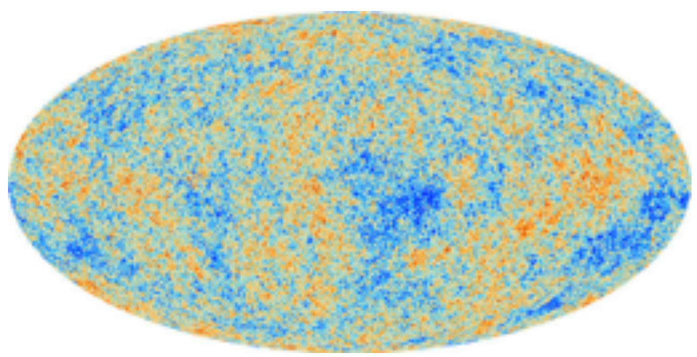
A. What is a WIMP?

<u>What everyone has in mind</u>

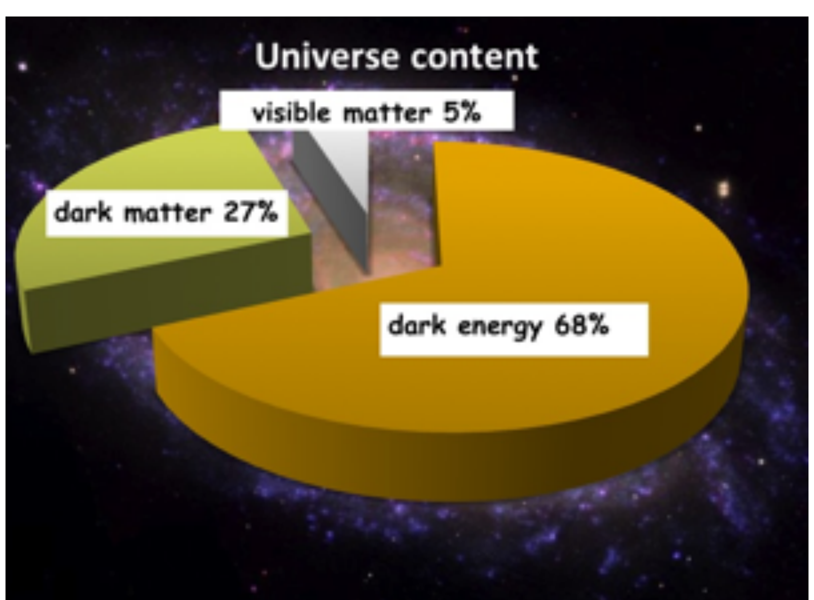
Annihilating particles heavier than MeV (in fact > GeV)

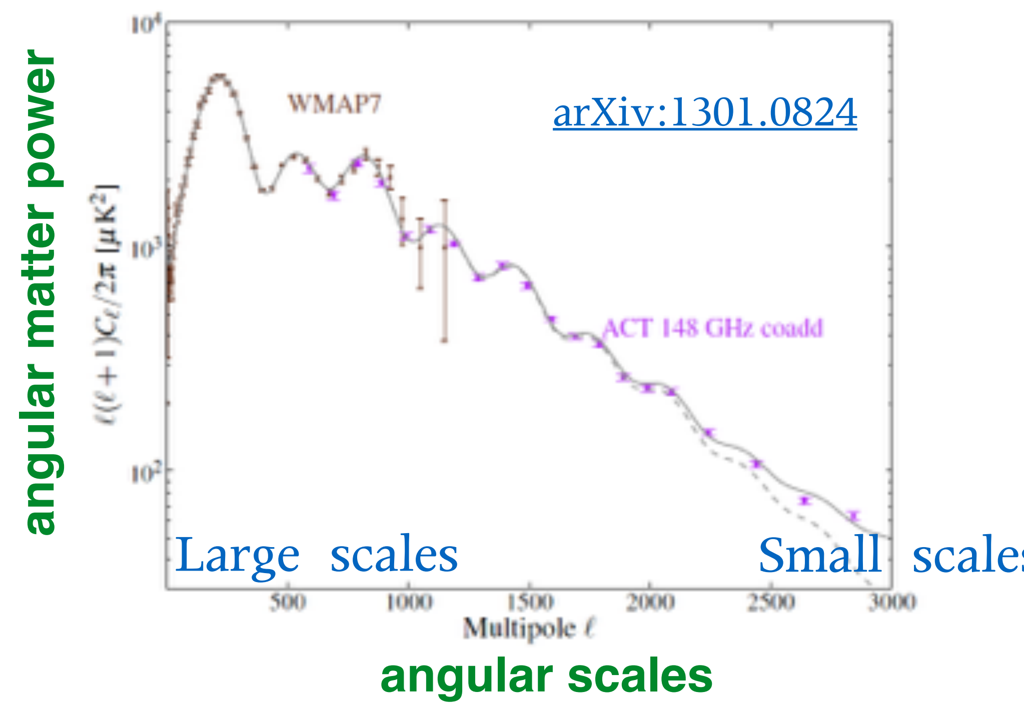
<u>Why?</u> relic density...

courtesy Planck



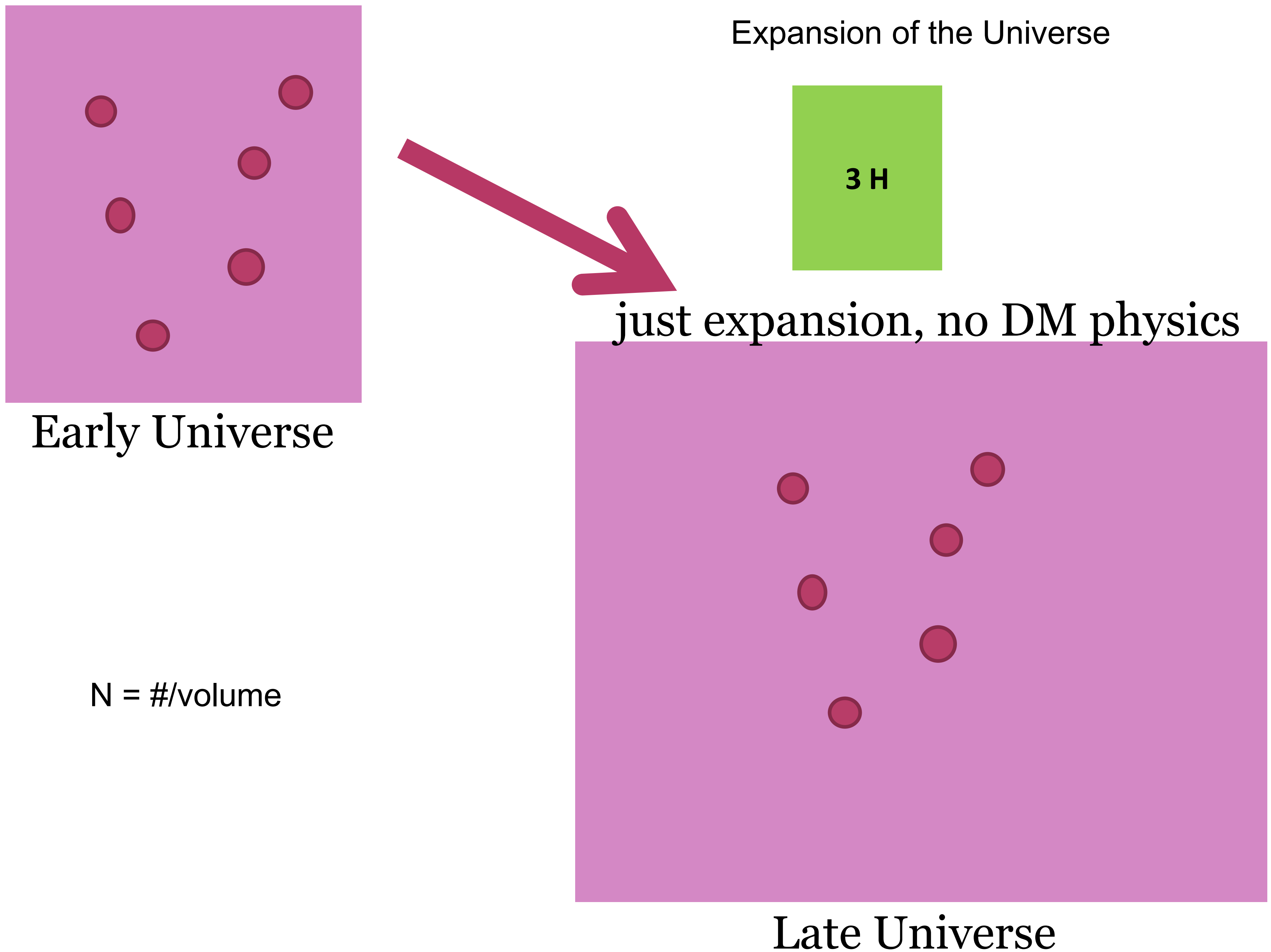
$$\frac{\delta T}{T} = \frac{\delta \rho}{\rho}$$





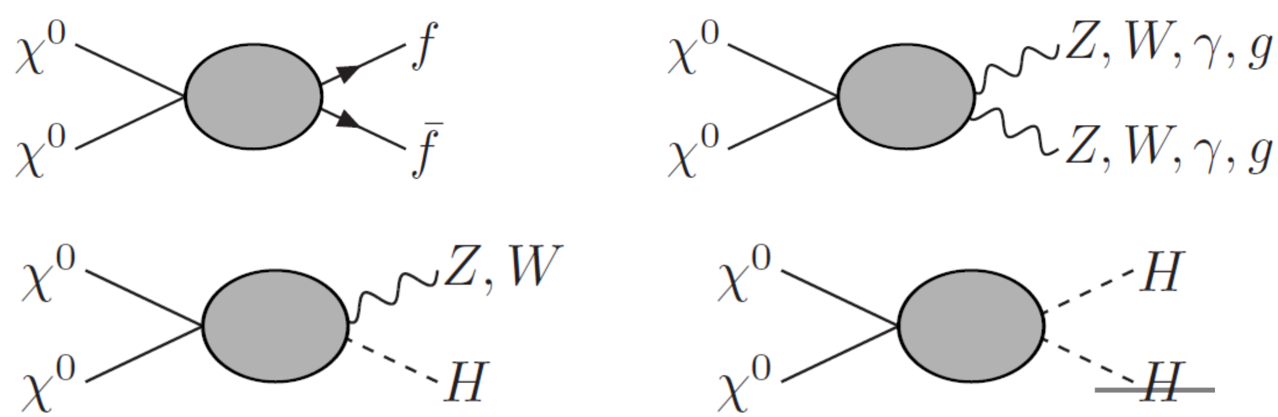
max 30% of DM!

How much DM should we expect?



Massive DM particles can overclose the Universe!

What happens when one adds annihilations?



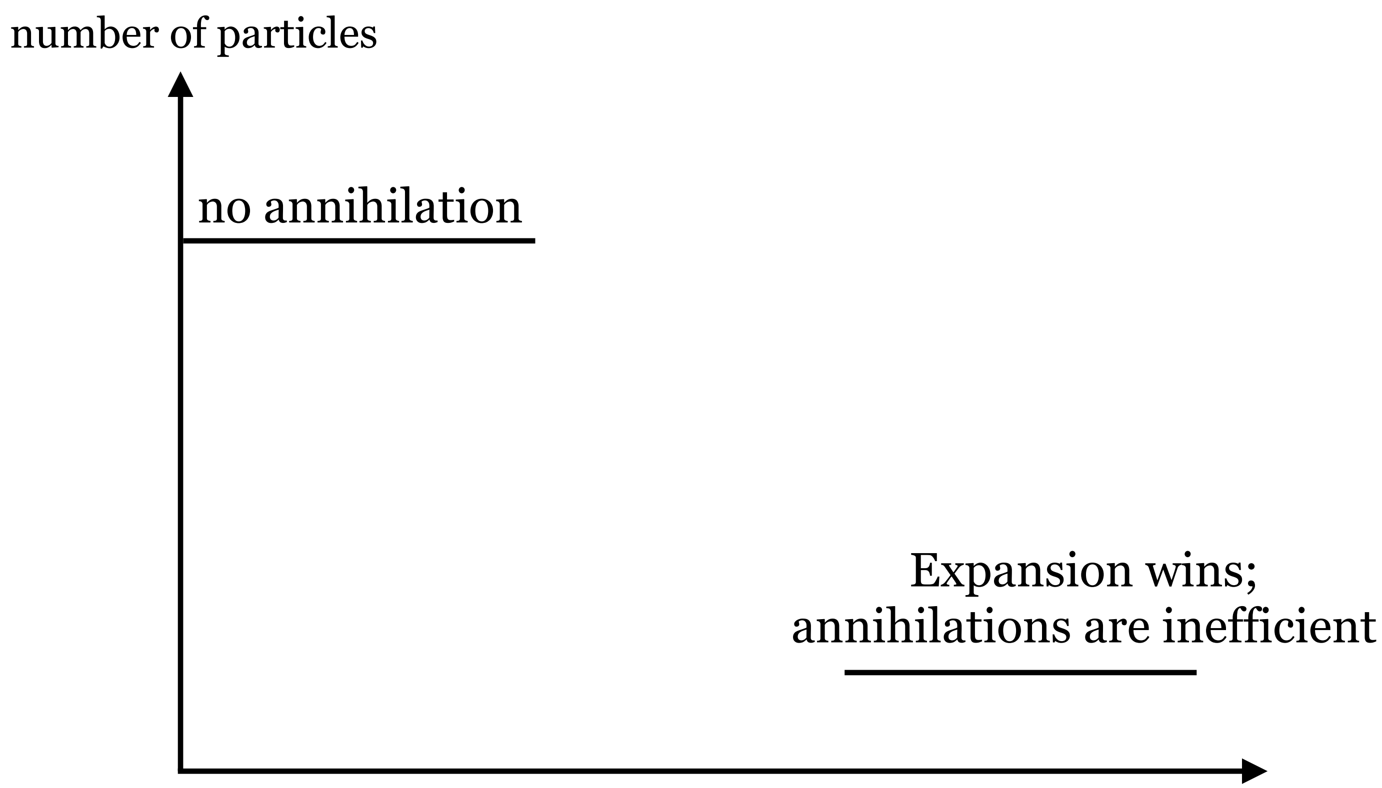
Expansion of the Universe

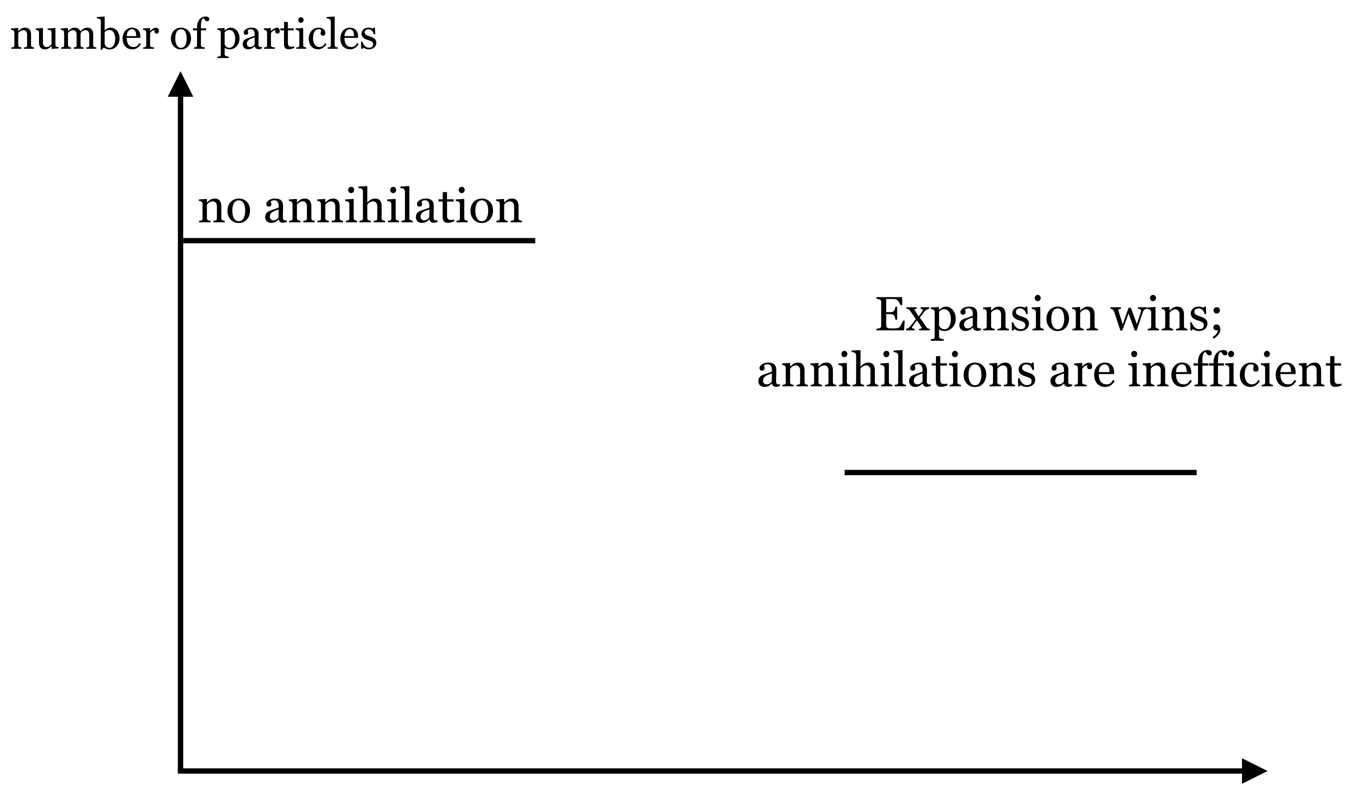
number density of DM (#/V)

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

Time evolution of the number density

Annihilation change the number density





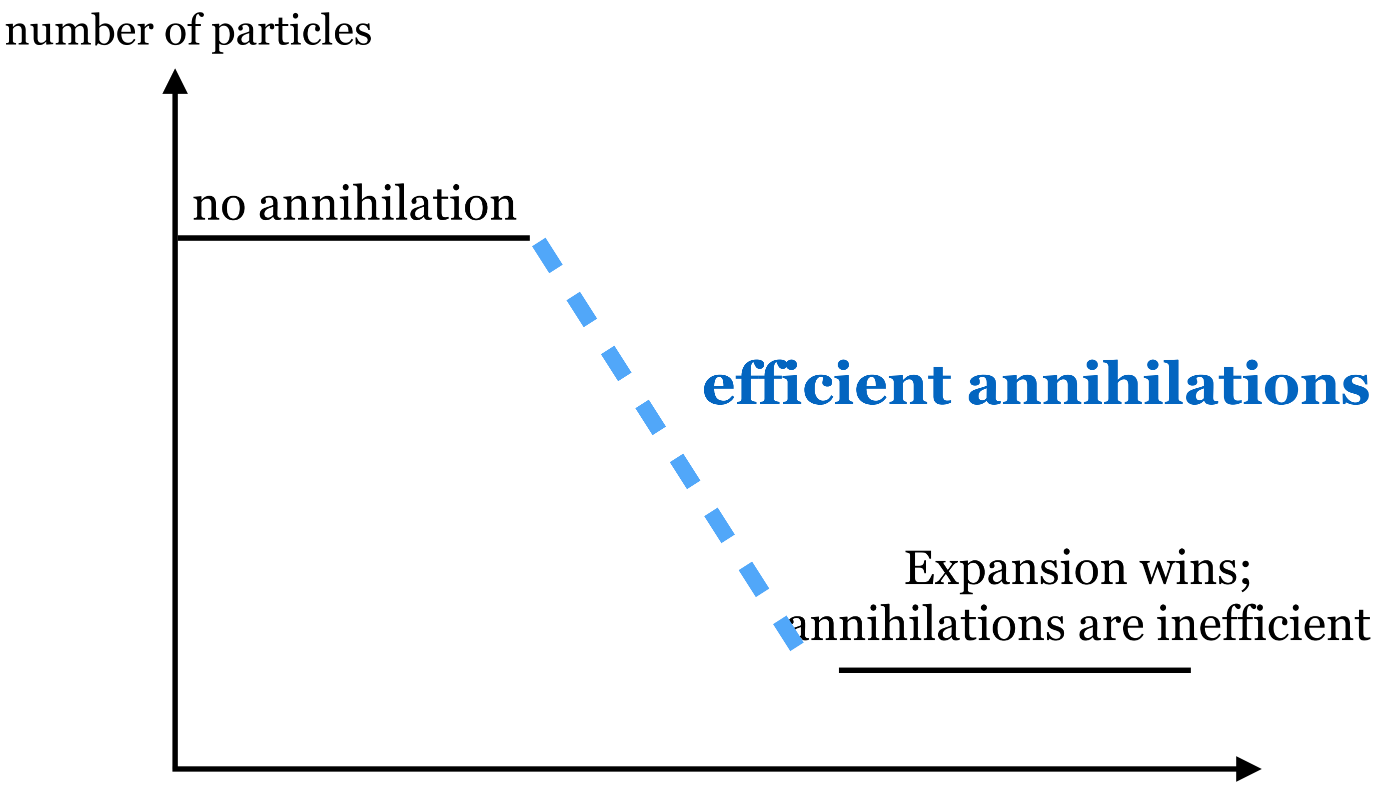
What is the difference?

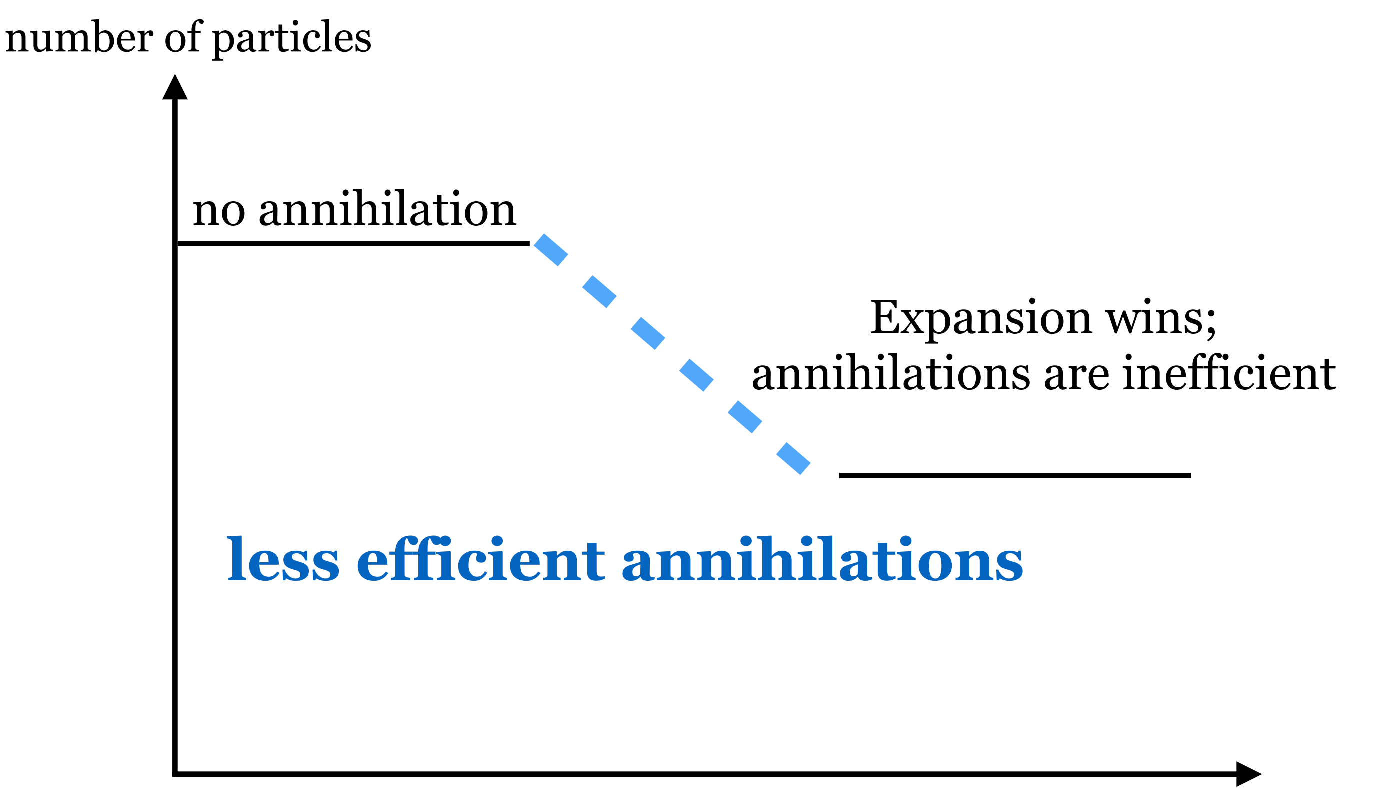
The relic density today!

What makes the difference?

The cross section

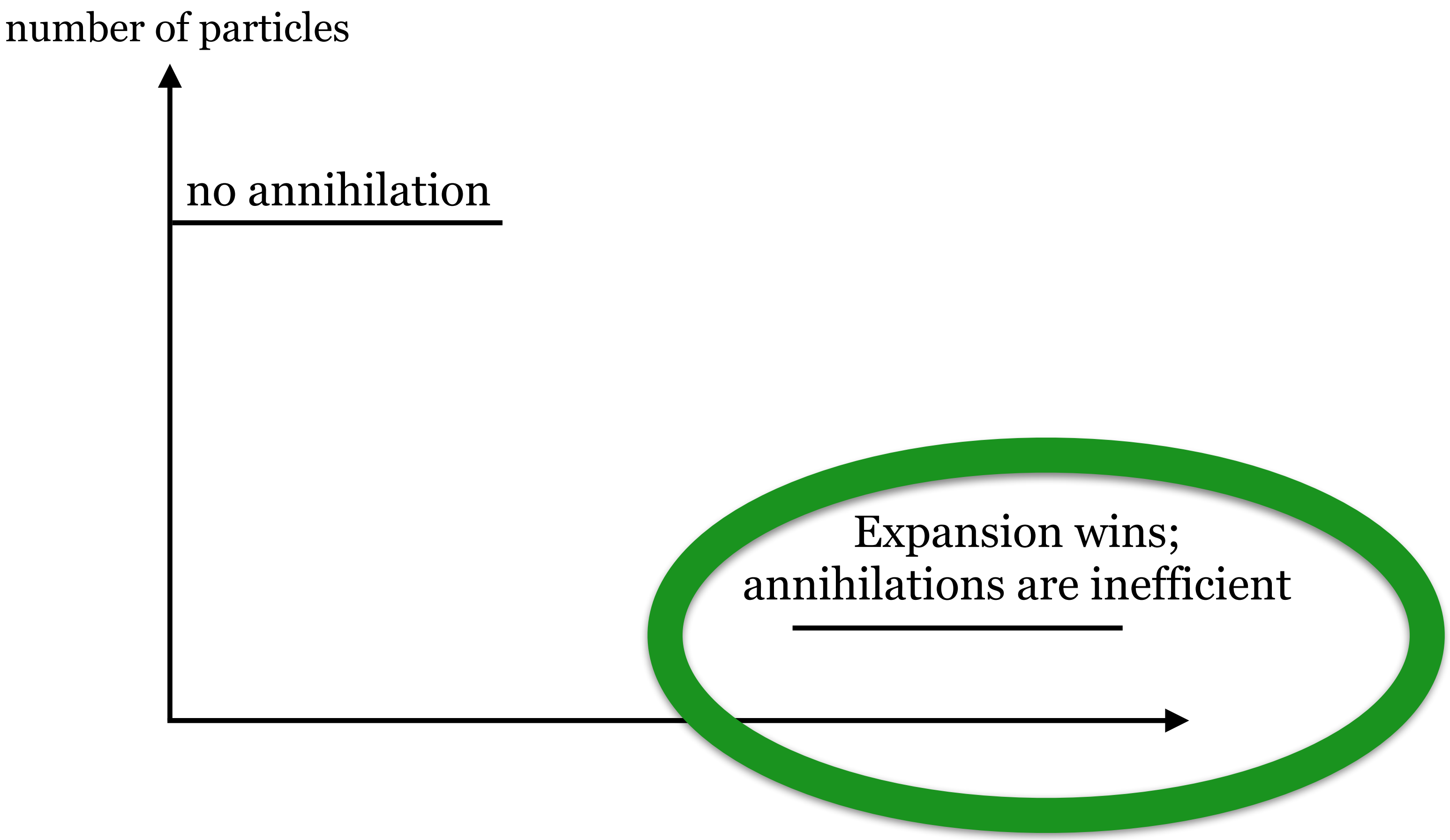
The larger the cross section
the lower the number of DM particles





Only one cross section can give the observed number of DM particles!

Notion of decoupling



The number of particles do not change anymore
The interactions are frozen-out

This is a chemical freeze-out
Interactions maintaining the thermal equilibrium can continue

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

$$\sigma v \; n_{DM}^2 \simeq H \; n_{DM} \quad \Rightarrow \quad \sigma v \; n_{DM} \simeq H$$

Numerically: ★ re-write Boltzmann to remove T^3 factors in number density by using $n = y\,T^3$

$$\frac{dy}{dt} = -\sigma v \times (y^2 - y_0^2) \times T^3$$

★ solve dy/dT instead of dy/dt

$$\frac{dy}{dT} = \frac{\sigma v}{2 t_r T_0^2} \times (y^2 - {y_0}^2)$$

Tempted to use: $$\frac{y_{i+1} - y_i}{\Delta T} = \Lambda \times (y^2 - {y_0}^2)$$???

$$\frac{y_{i+1} - y_i}{\Delta T} = \frac{\Lambda}{2} \times \left[({y_i}^2 - {y_{0_i}}^2) + ({y_{i+1}}^2 - {y_{0_{i+1}}}^2) \right]$$

Analytically:

$$\langle \sigma v \rangle n_{fo} = H_{fo} \qquad n_{fo}\, a_{fo}^3 = n_0\, a_0^3$$

$$\langle \sigma v \rangle \; n_0 \; \dot{a}_{fo}^3 \; = \; H_\alpha \, a_{fo}^{-1/\alpha}.$$

$$n_0 = \frac{H_\alpha}{\langle \sigma v \rangle} \, a_{fo}$$

$$\Omega_{dm} = \frac{m_{dm}}{\rho_c} \, \frac{H_\alpha}{\langle \sigma v \rangle} \, a_{fo}$$

$$x_{fo} = \frac{m_{dm}}{T_{fo}}$$

$$\Omega_{dm} = \frac{T_0}{\rho_c} \, \frac{H_\alpha}{\langle \sigma v \rangle} \, x_{fo}$$

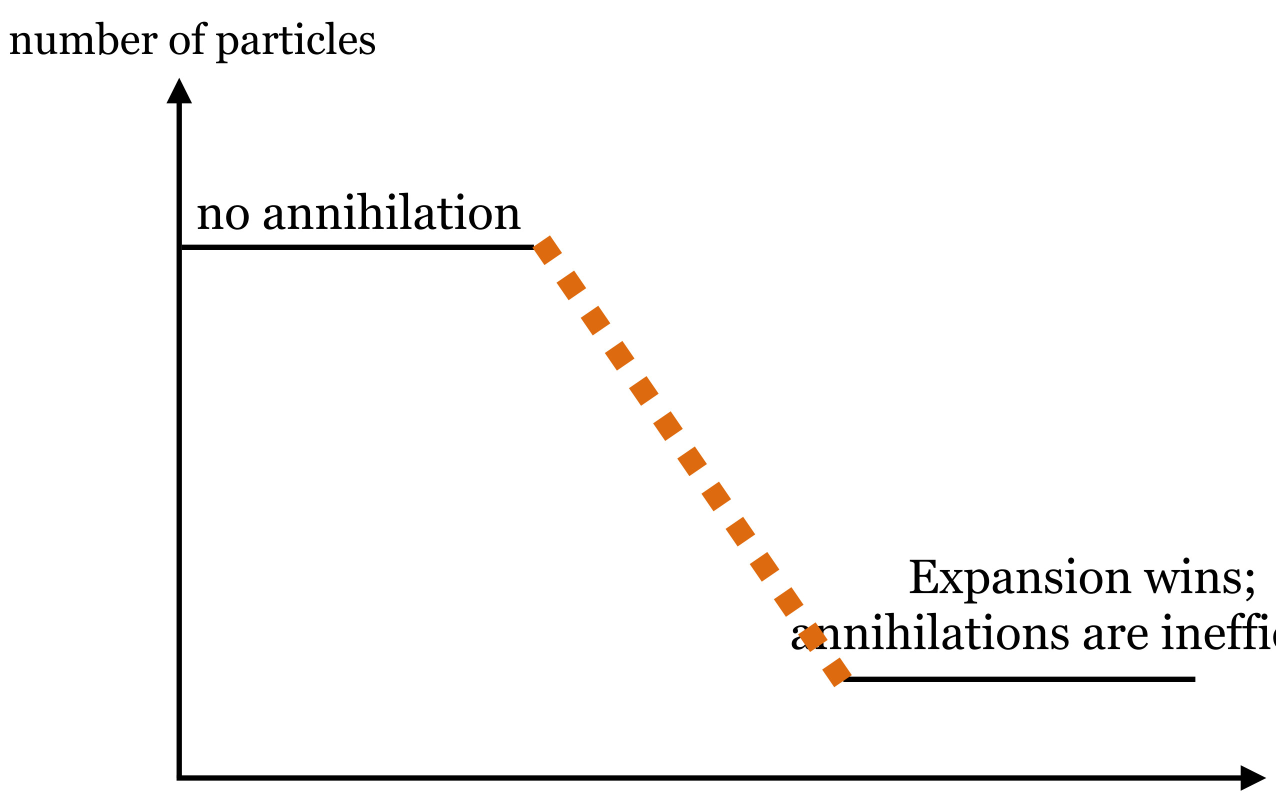
$$x_{fo}^{-1} \simeq \ln \, \frac{\langle \sigma \; v \rangle \; T_0^2 \; m}{H_\alpha \; (2\pi)^{3/2} \; \sqrt{x_{fo}}}.$$

$$x_{fo} \approx 12 + (\approx 2) \log \left(\frac{m_{dm}}{MeV} \times \frac{\sigma v}{3.10^{-26} cm^3 / s} \right)$$

$$\Omega_{dm} = \frac{T_0}{\rho_c} \frac{H_\alpha}{\langle \sigma v \rangle} x_{fo}$$

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} cm^3 sec^{-1}}{< \sigma v >}$$

$$\sigma v \approx 3 \bullet 10^{-26} cm^3 / s$$



30 %

The main point:

It is a constraint on the annihilation cross section but not on the DM mass!!

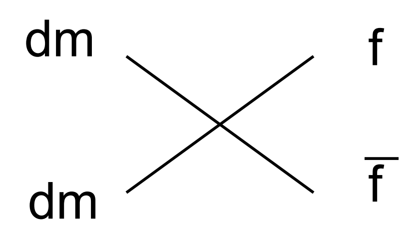
Historically

Lee&Weinberg, Hut 1977

assumed a model and this model is DM mass dependent

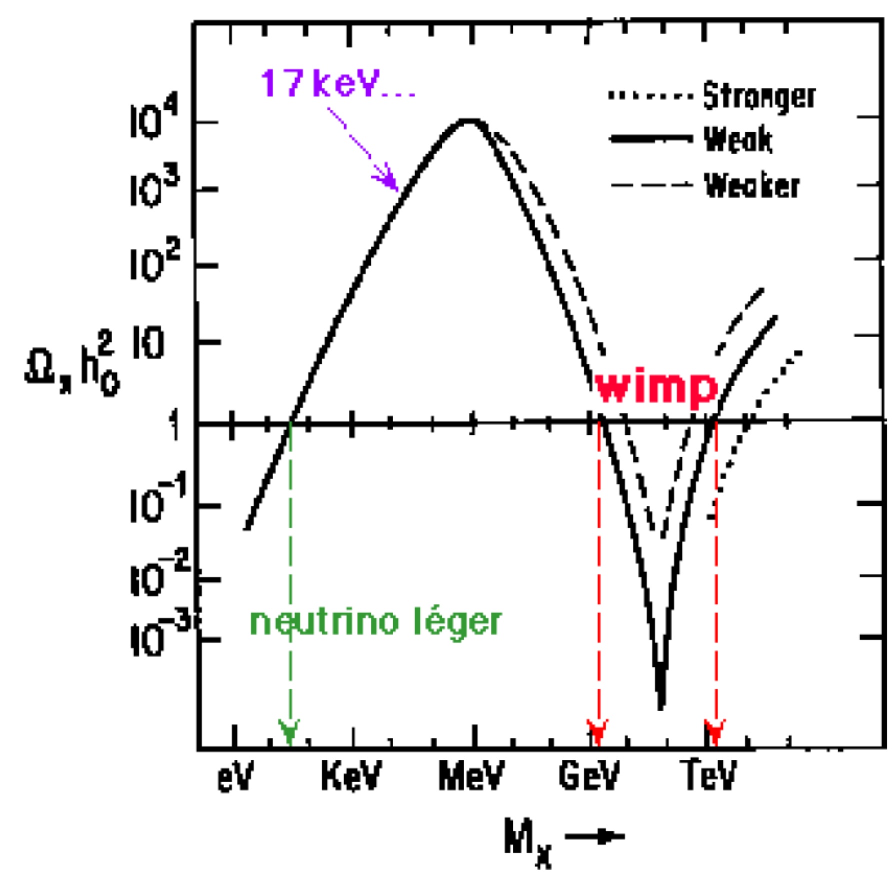
Massive neutrinos, Fermi interactions:

$$\sigma v \propto \frac{m_{dm}^2}{m_w^4}$$



- Depends mainly on mdm,
- if mdm too small, $\Omega_{dm} > 1$!

Lee-Weinberg limit:
mdm < O(GeV)

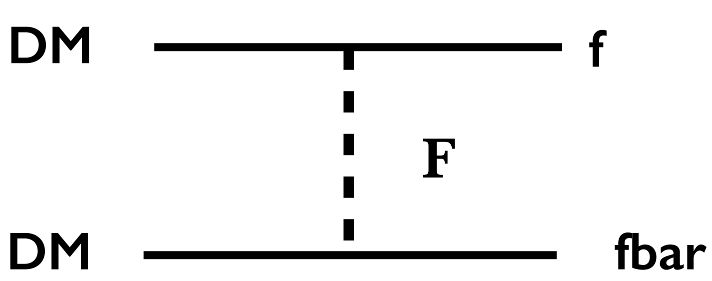


Consistent with supersymmetry so in most people's mind, thermal DM means heavy DM

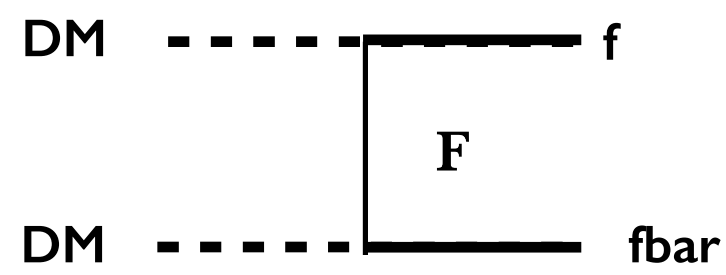
(A. What is a WIMP? Relic density)

Because of the relic density, in most people's mind (at least until a few years ago) it is a **heavy thermal annihilating particle**

But plenty of exceptions exist



Majorana DM



scalar DM

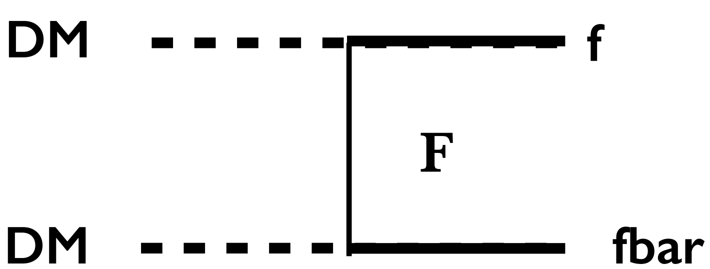
$$\sigma v \propto \frac{\left(2c_l c_r\ \mathrm{m_{DM}} + (\mathrm{c_l^2} + \mathrm{c_r^2})\ \mathrm{m_f}\right)^2}{(m_F^2 - \mathrm{m_{DM}^2} - \mathrm{m_f}^2)^2}$$

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

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

DM can be light it is a scalar or if the mediator is also light and couplings are small!

(A. What is a WIMP? Relic density)



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

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} cm^3 sec^{-1}}{< \sigma v >}$$

RD OK if the right couplings and mediator mass

We can therefore consider light DM!

How low can we go? in principle there is no limit but annihilations are only possible if they are kinematically allowed.

Above 511 keV: annihilations into e+e- possible
Below 511 keV: annihilations into neutrinos or photons

(A. What is a WIMP? Relic density)

Let us assume annihilations into neutrinos

neutrinos stay in thermal equilibrium until T~2.3 MeV

MDM > 2.3 MeV — the neutrino sector is reheated but goes back to equilibrium

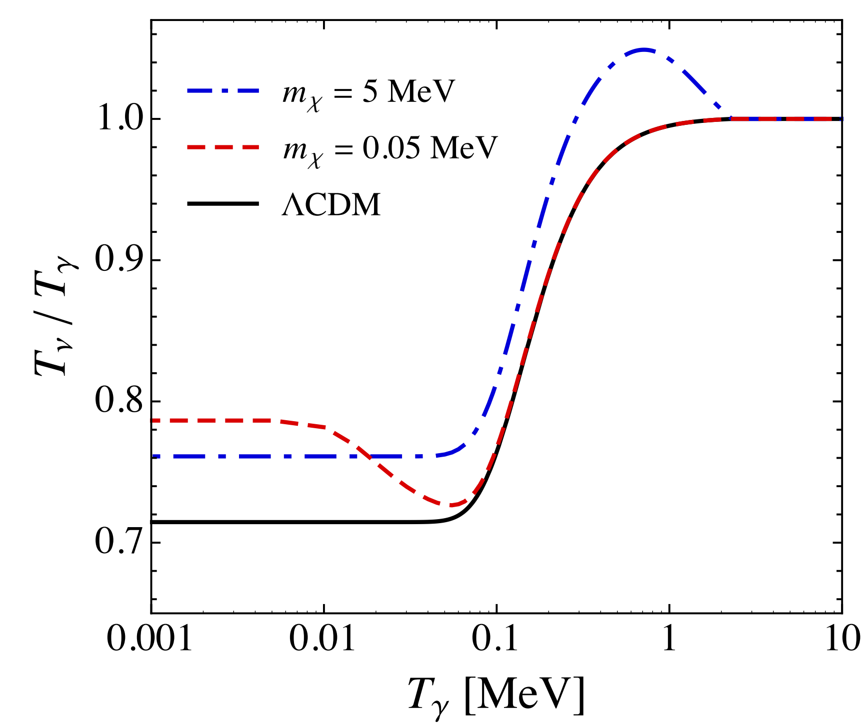
MDM < 2.3 MeV — the neutrino sector is reheated
this changes the number of relativistic degrees of freedom

Radiation as a function of photon energy density

$$\rho_{\rm R} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{T_\nu^0}{T_\gamma}\right)^4 N_{\rm eff}\right]$$

$$\rho_{\nu:\chi} = \rho_\gamma \cdot \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 \left[N_\nu + \frac{g_\chi}{2} I(y_\nu)\right] \qquad I(y) = \frac{120}{7\pi^4}\int_y^\infty d\xi \frac{\xi^2\sqrt{\xi^2 - y^2}}{e^\xi \pm 1}$$

$$N_{\rm eff}(y_\nu) = \left(\frac{T_\nu^0}{T_\gamma}\right)^{-4}\left(\frac{T_\nu}{T_\gamma}\right)^4 \left[N_\nu + \frac{g_\chi}{2} I(y_\nu)\right]$$



Impact on Helium abundance in the primordial abundance

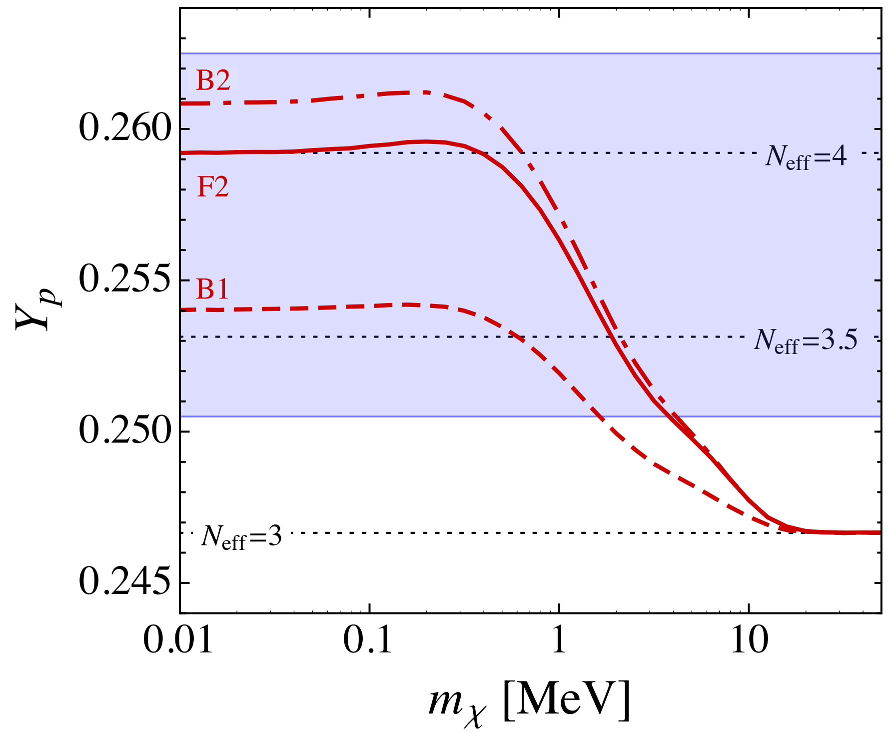
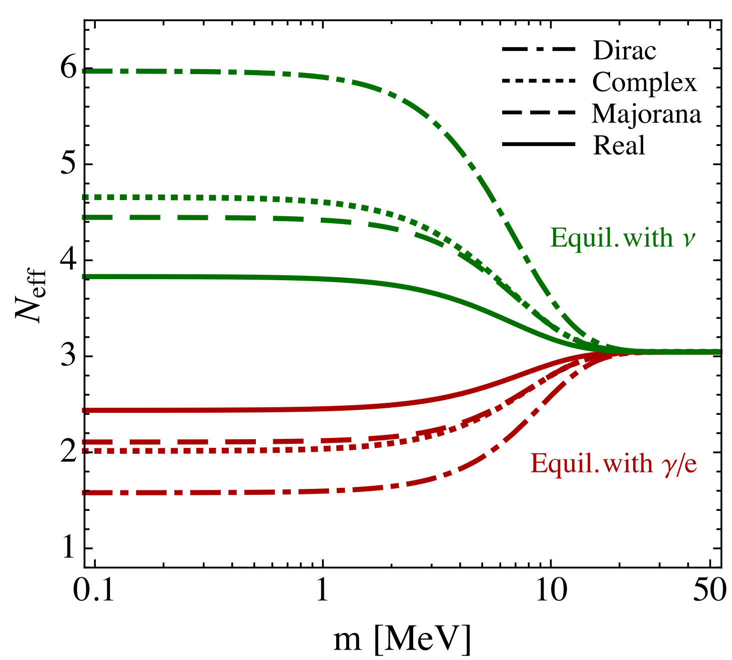


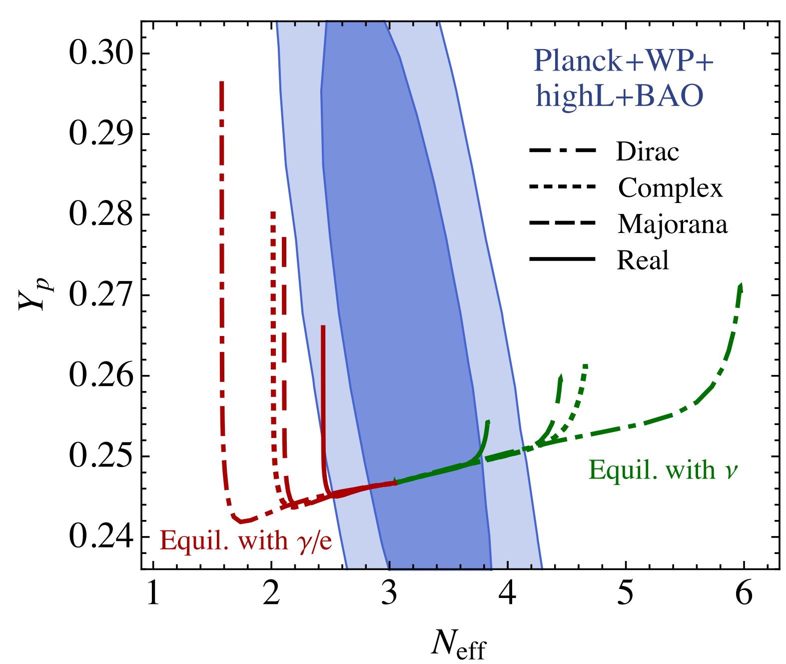
FIG. 2: The red dot-dashed, solid and dashed lines show the predictions for Y_p (upper panel) and D/H (lower panel) for a complex scalar (B2), Majorana fermion (F2) and real scalar (B1) respectively. The blue shaded region indicates the 1σ region for Y_p from [4] (with statistical and systematic errors

Recent inferences of Y_p from observations of metal-poor H II regions have been slightly higher than results from the past decade. For instance, while refs. [44] and [45] found $Y_p = 0.249 \pm 0.009$ and $Y_p = 0.2477 \pm 0.0029$ respectively, more recently, refs. [4], [46], [47] and [48] found $Y_p = 0.2565 \pm 0.0010(\text{stat.}) \pm 0.0050(\text{syst.})$, $Y_p = 0.2561 \pm 0.0108$, $Y_p = 0.2573^{+0.0033}_{-0.0088}$

Impact on CMB

much lower photon temperature (eV) instead of MeV





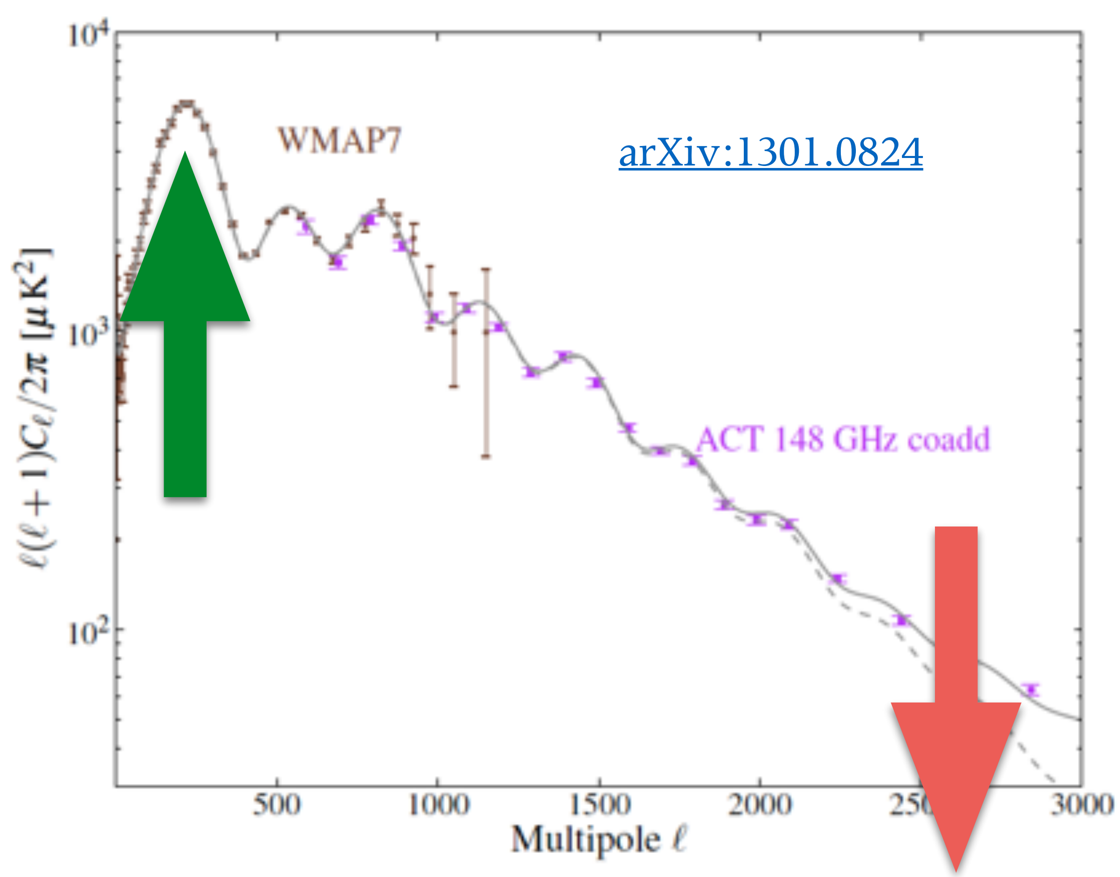
Thermal DM cannot be much lighter than a few MeV

Why is the CMB setting a limit on Neff?

Reheating the neutrino sector means hotter neutrinos.

Hotter neutrinos means they are “more” relativistic
so it becomes harder to make them clump on the scales
they were thought to clump.

This translates into more dissipation (free-streaming)
and less small-scale structures

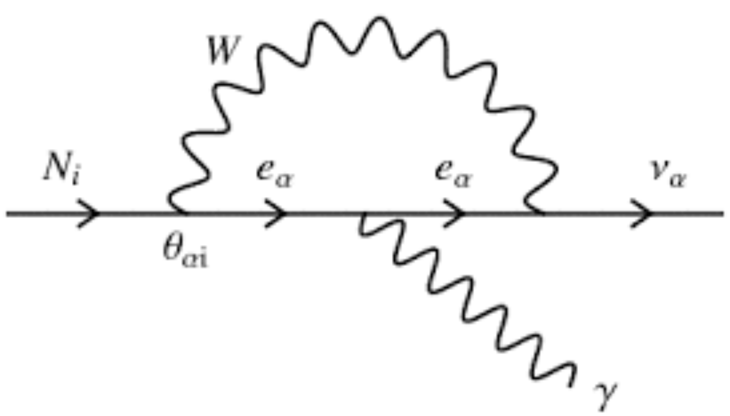


(A. What is a WIMP? Relic density)

If it is a thermal particle, then it is a particle heavier than a few MeV

It does not have to be thermal!!

Examples: sterile neutrinos, gravitinos
they are weakly interacting, massive particles
they don't annihilate though!!!



I'll include them in "Beyond WIMPs" for a reason that will become clear later

Summary PART I

A. What is a WIMP?

(A. What is a WIMP? Relic density)

If it is a thermal particle, then it is a particle heavier than a few MeV
(comes from DM annihilations + DM DM into neutrinos)

No upper limit on the mass

No lower limit on the cross section

It does not have to be thermal!!

No upper and lower limit on the mass

The decay rate can be very small

I’ll include them in “Beyond WIMPs” for a reason that will become clear later

PART II

B. WIMP and CDM

Why are WIMPs interesting really!

B. WIMP and CDM (= Cold DM; DM is a collisionless fluid)

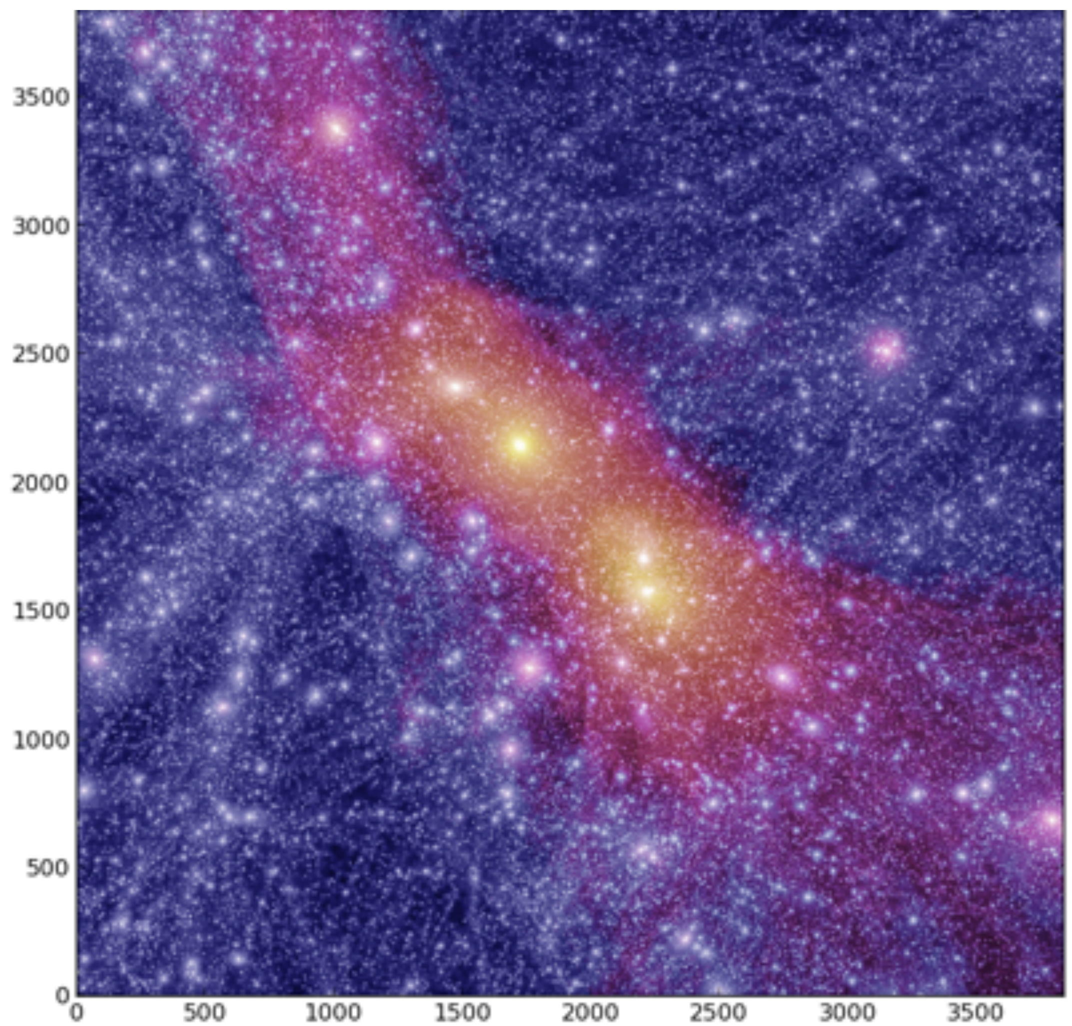
no need to know the mass; no need to know the interactions

Observations

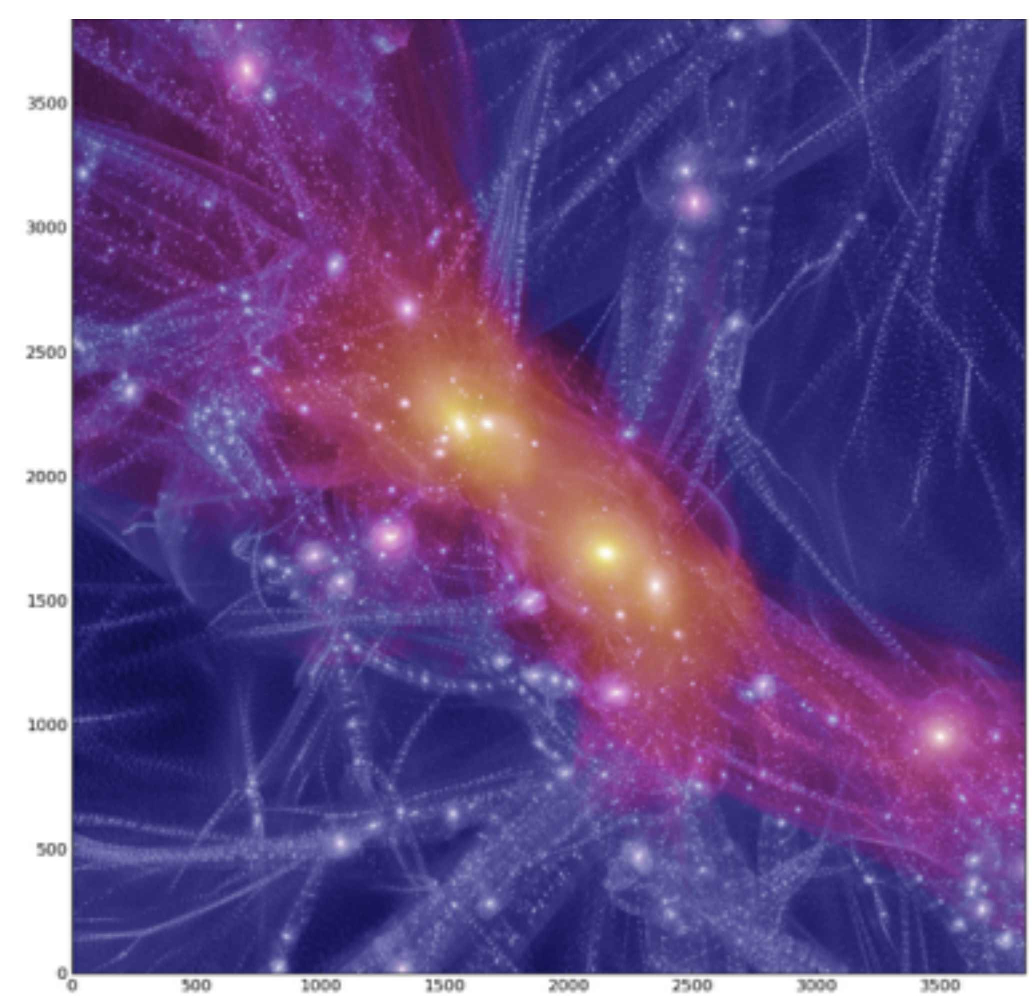
Many more galaxies and structures than in a purely baryonic Universe

A new invisible type of matter (Dark Matter)
so again if DM~ SM, then DM must have weak or super weak interactions

Simulation of what the Universe looks like



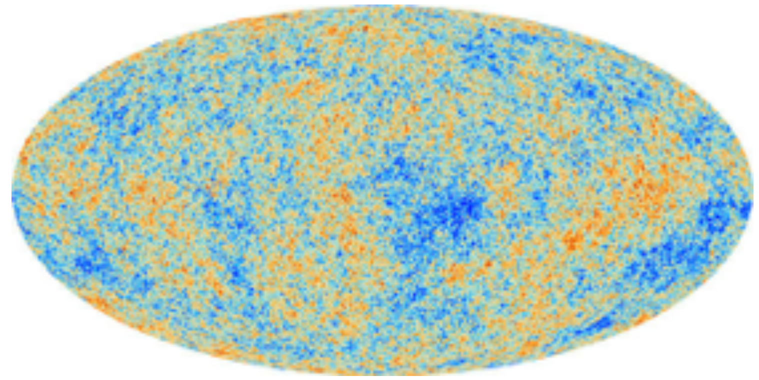
~ Simulation of what the Universe would look like without DM



Clearly it doesn't work…

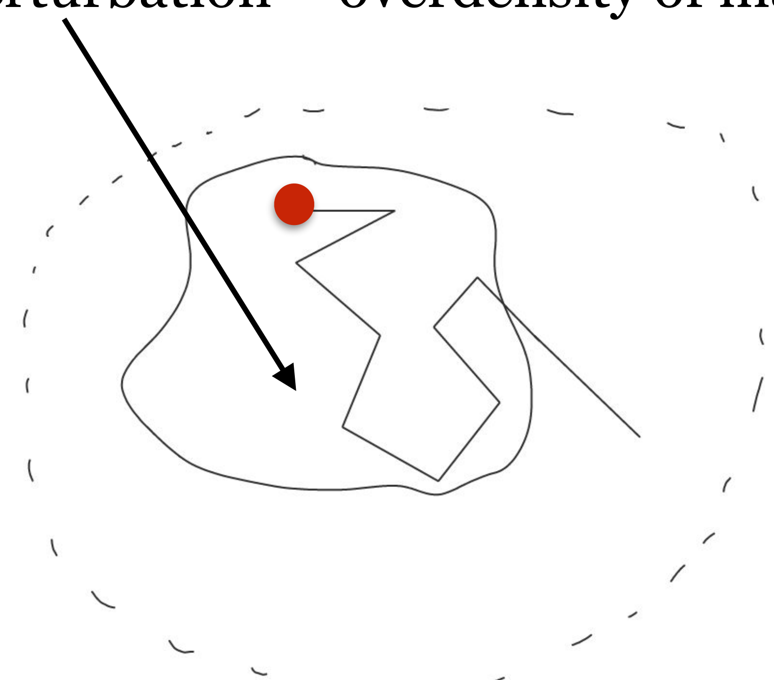
The reason is that baryons interact with photons.
This is called Silk damping.

Physics of Silk damping

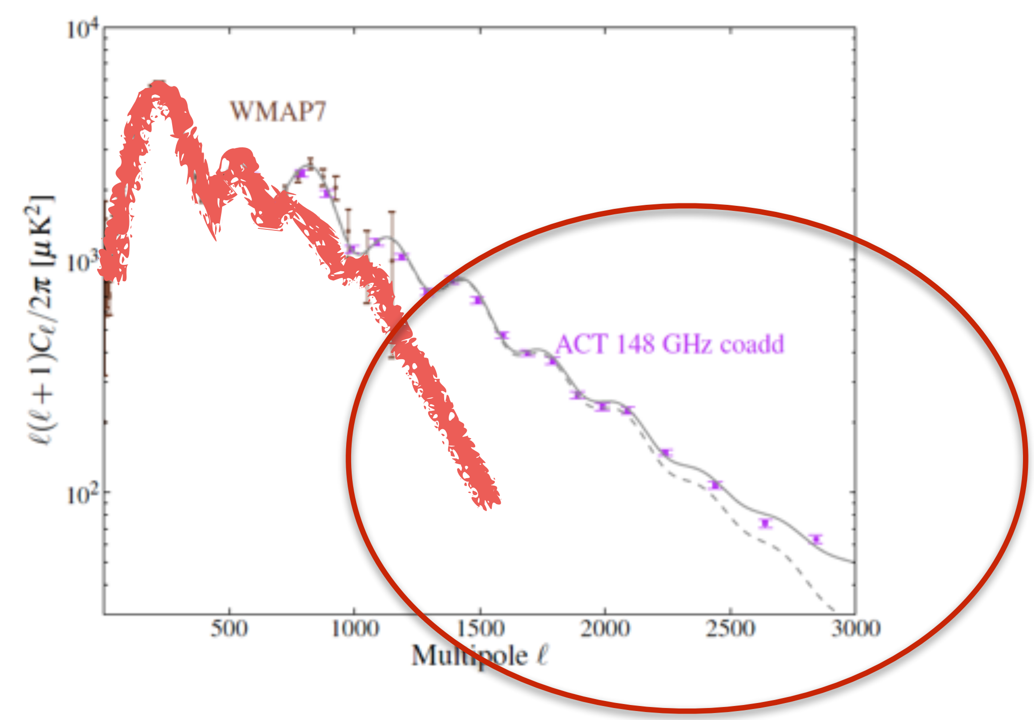


~ overdensities of a given size
give rise to structures of similar size
(after being stretched by expansion)

Perturbation = overdensity of matter



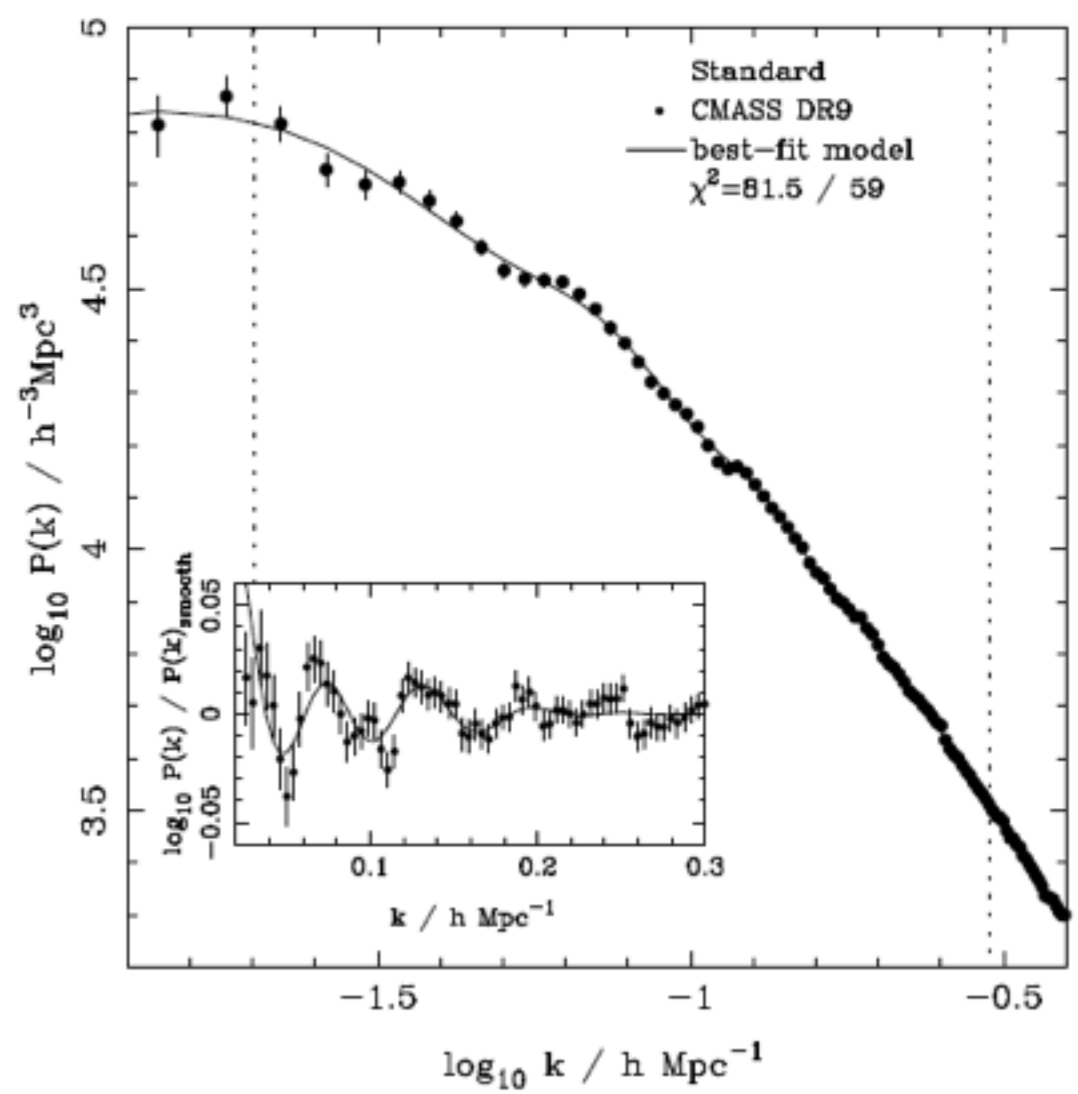
Diffusion baryon-photon interactions
The effect is large because of the Thomson cross section



Silk damping
suppression of small size perturbations

How many structures today?

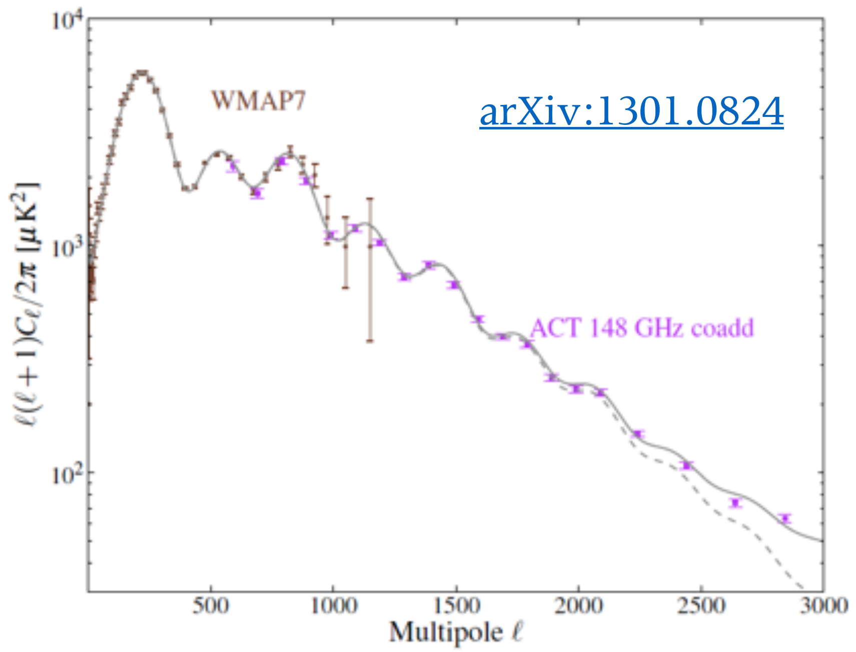
Matter power spectrum

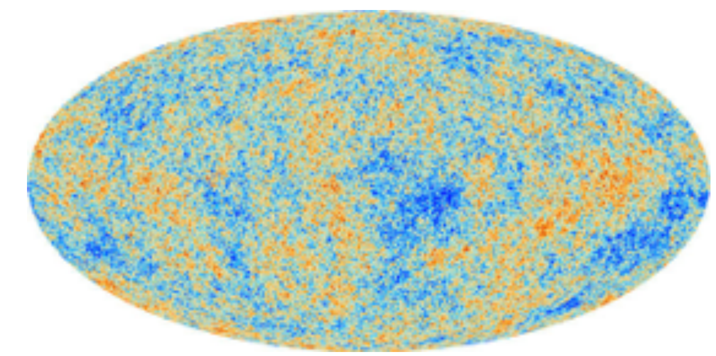


Number of structures
in Fourier space

Small fluctuations give small structures
(more complicated really, but …)

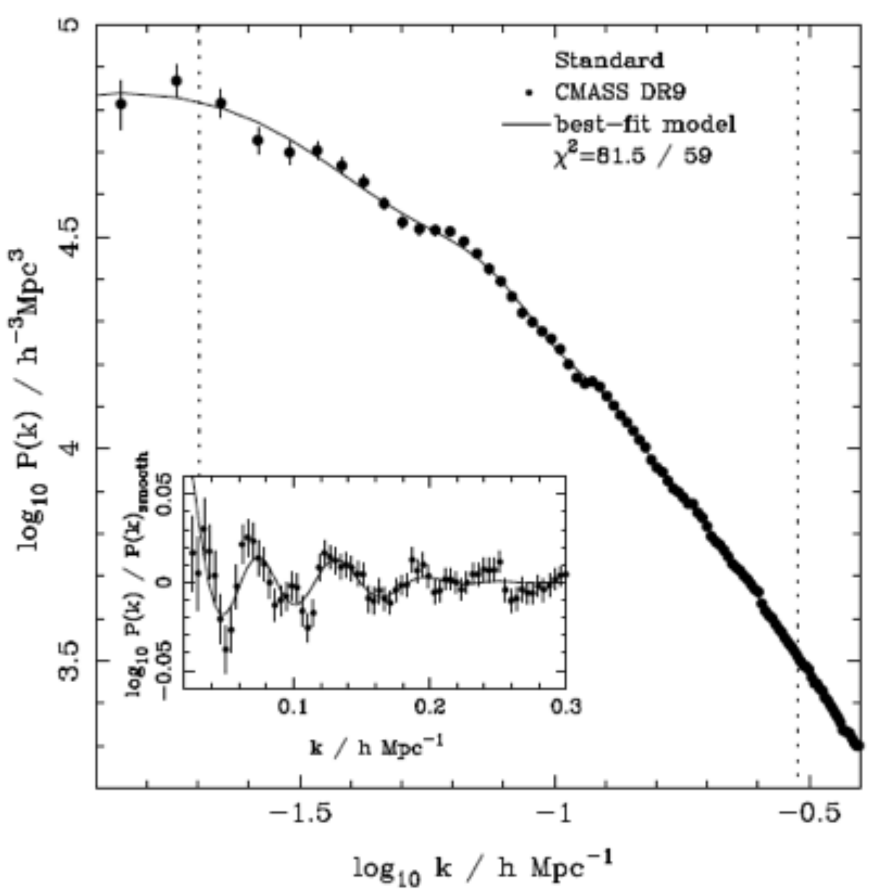
spectrum of fluctuations at last scattering surface

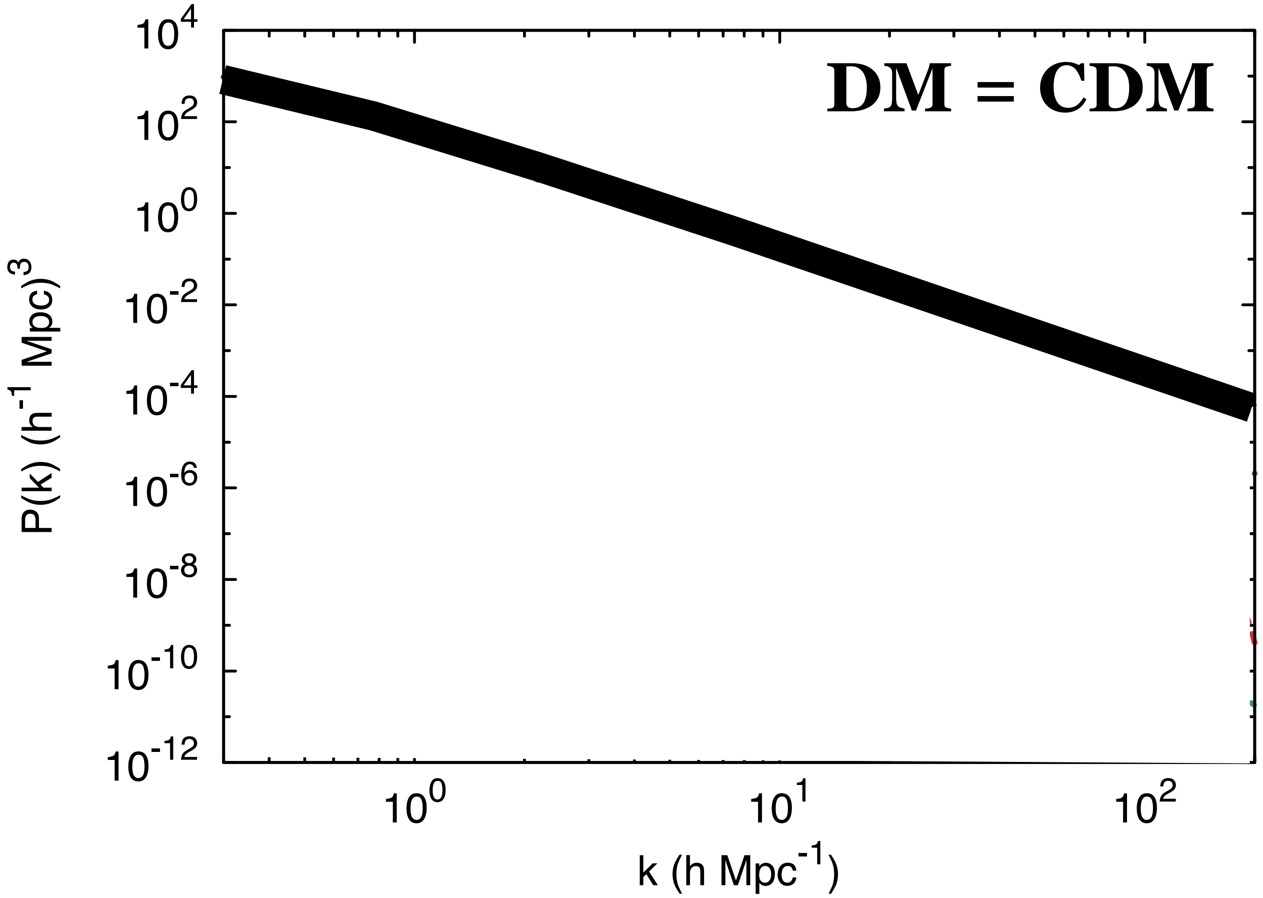


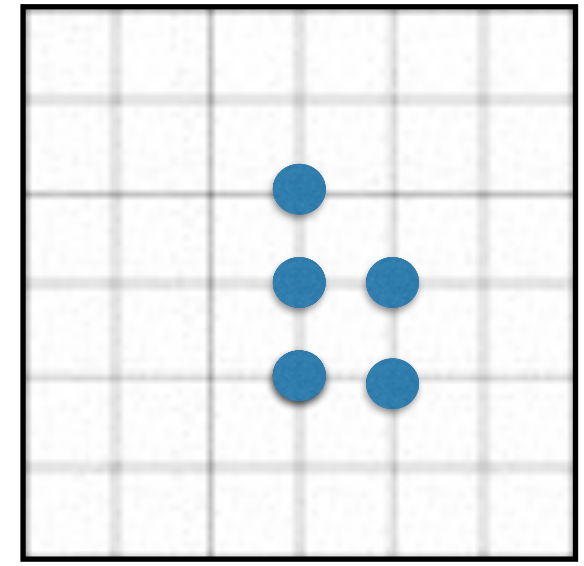


How does one pass from fluctuations to structures?

number of structures today (or small z) !



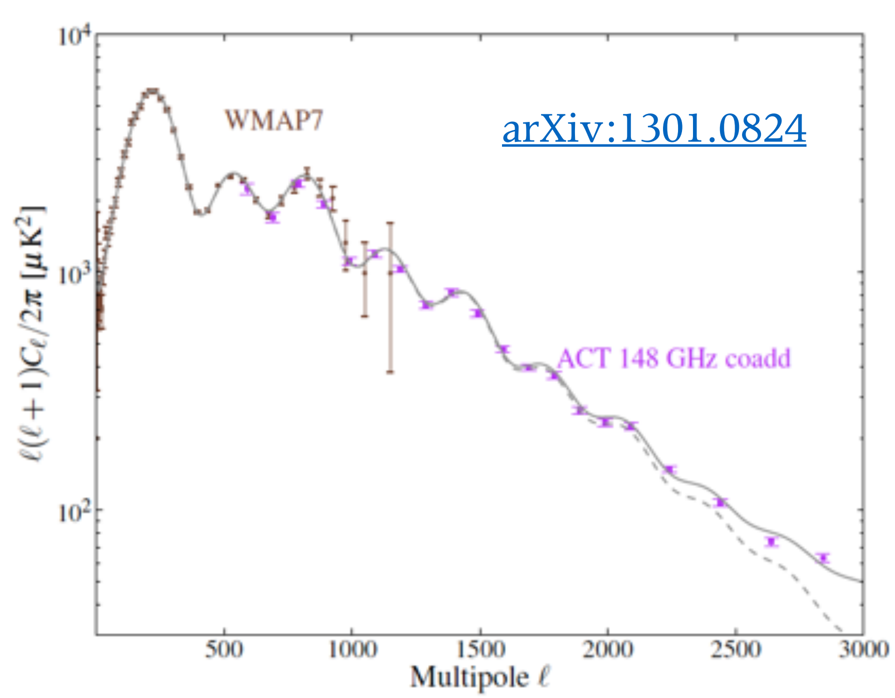


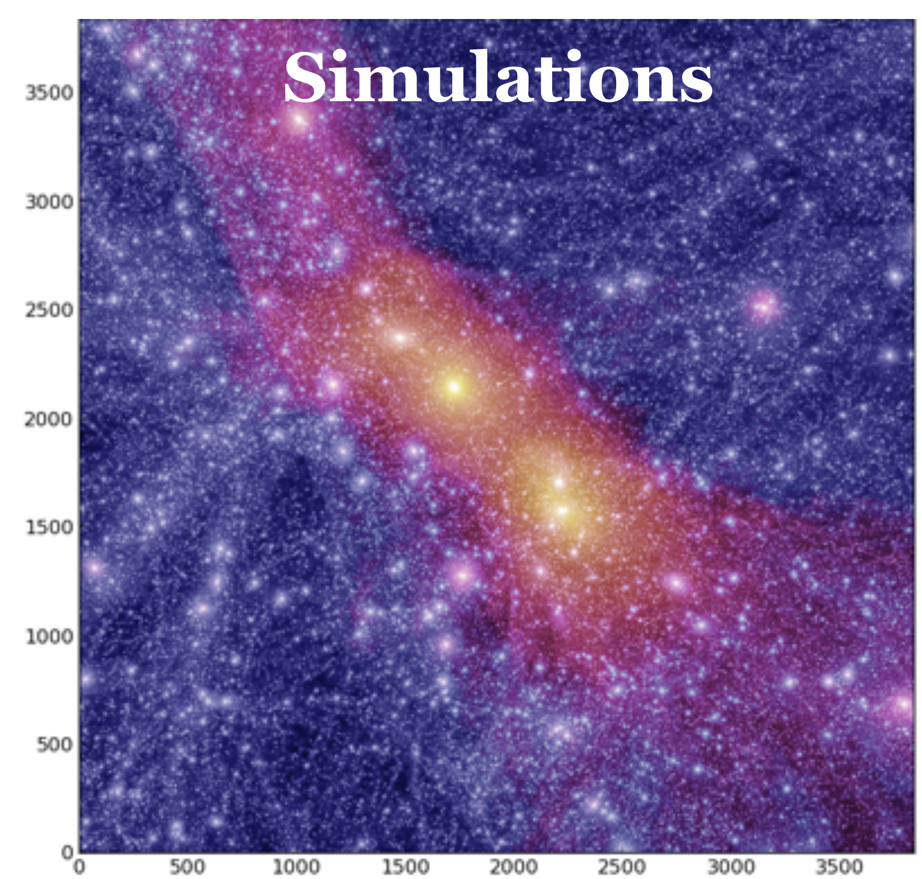


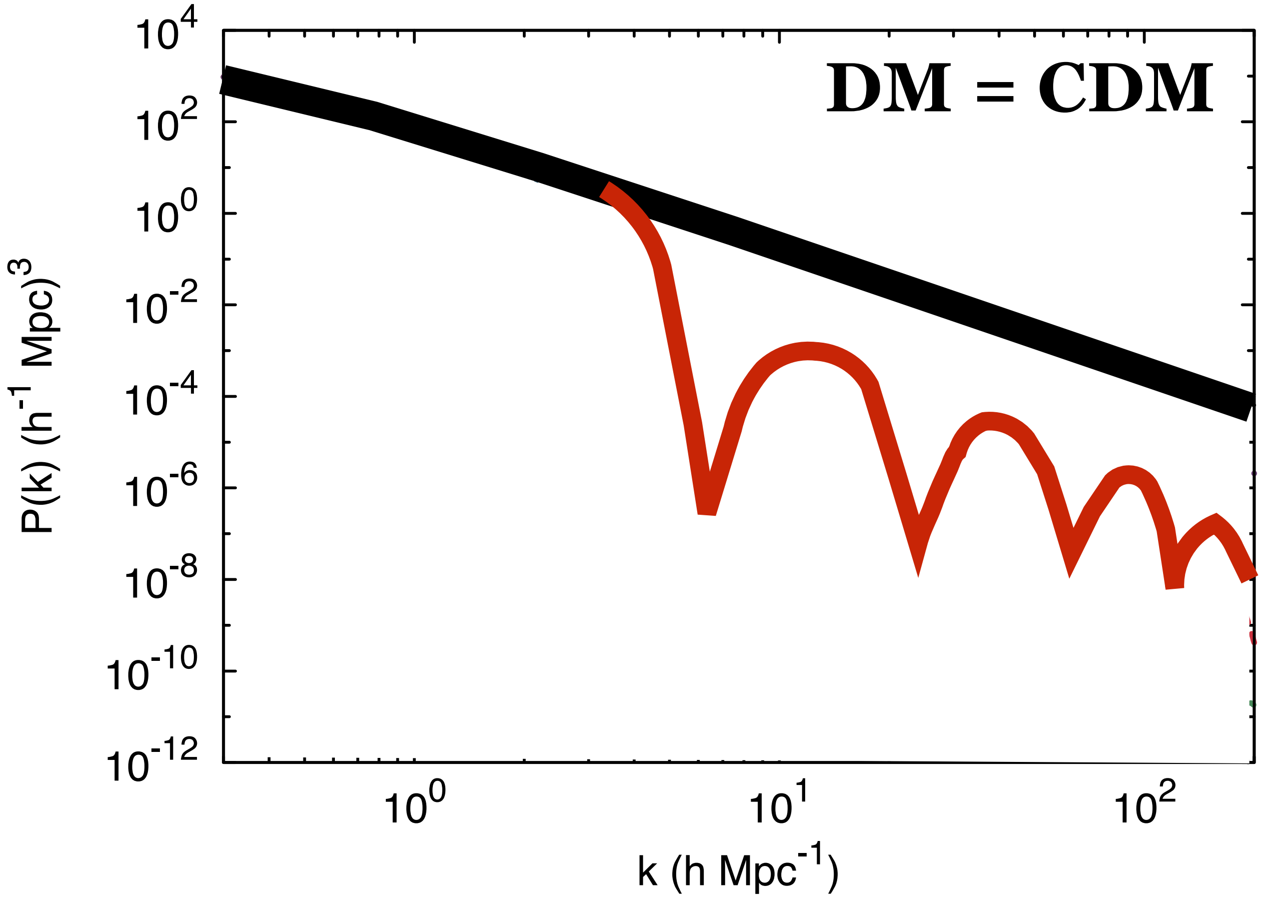
grid + Newtonian gravity

no interaction

linear P(K)
distribution of over densities before structures form







linear P(K)
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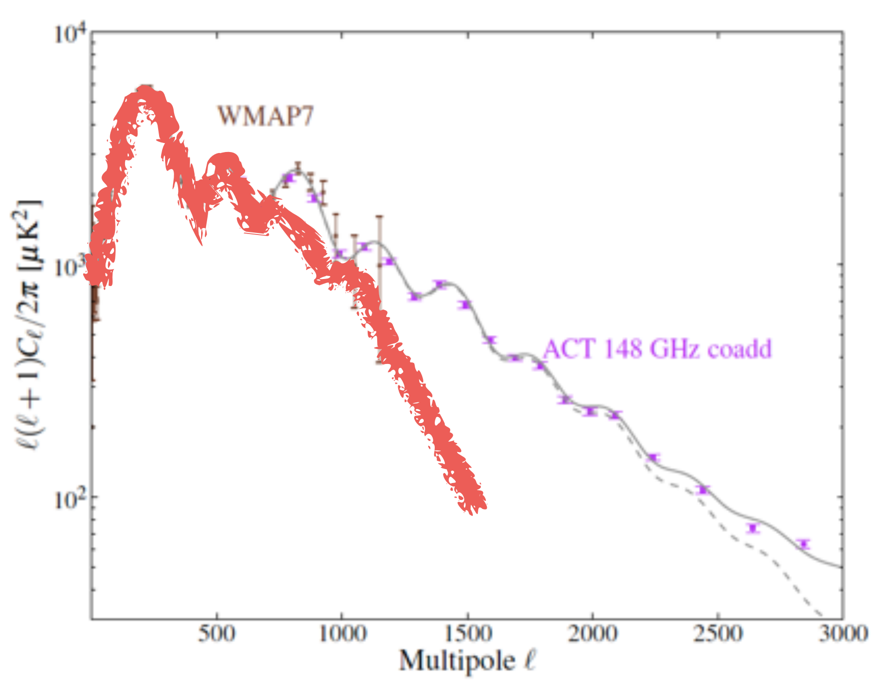
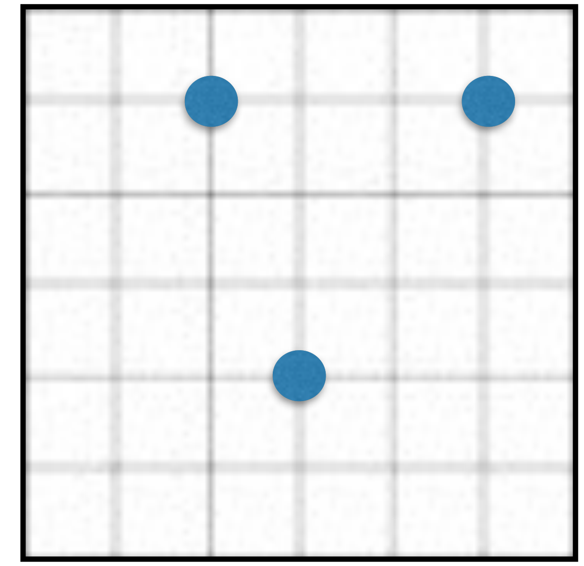
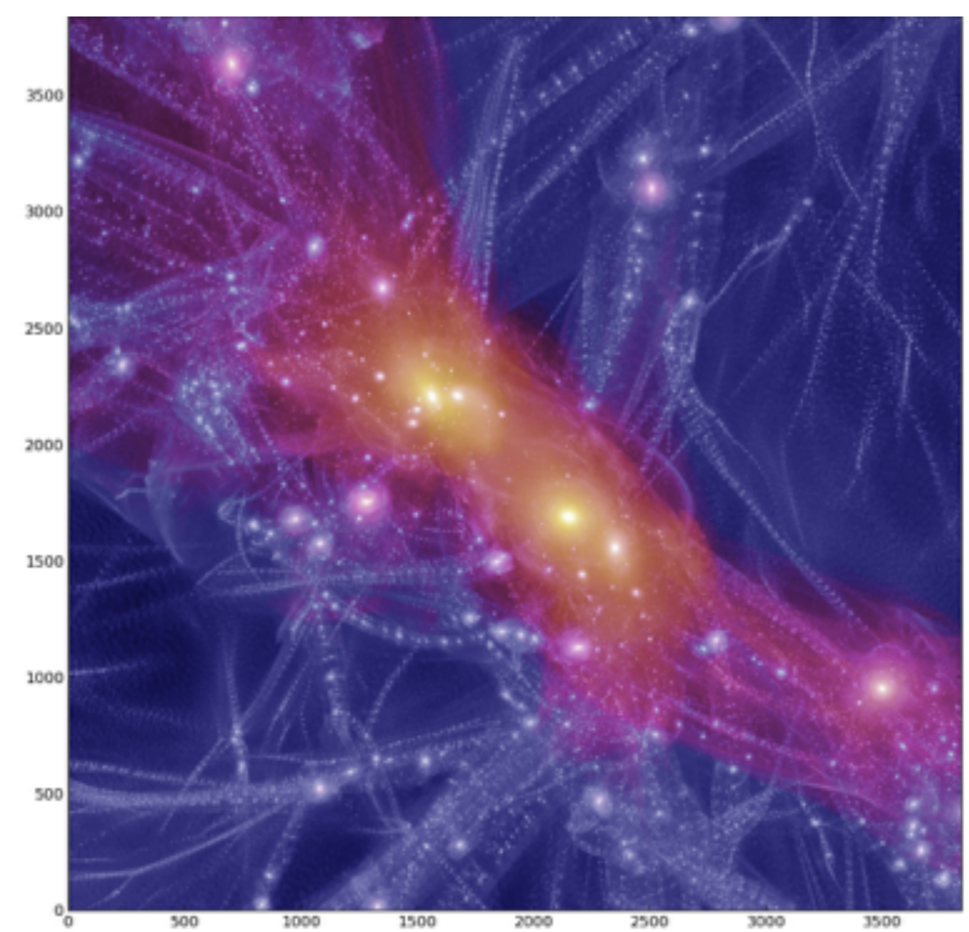




grid +
Newtonian gravity

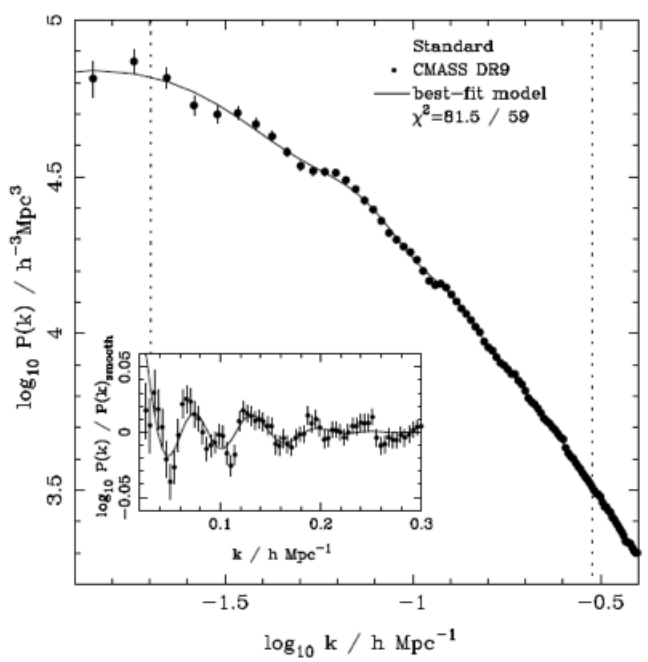
no interaction

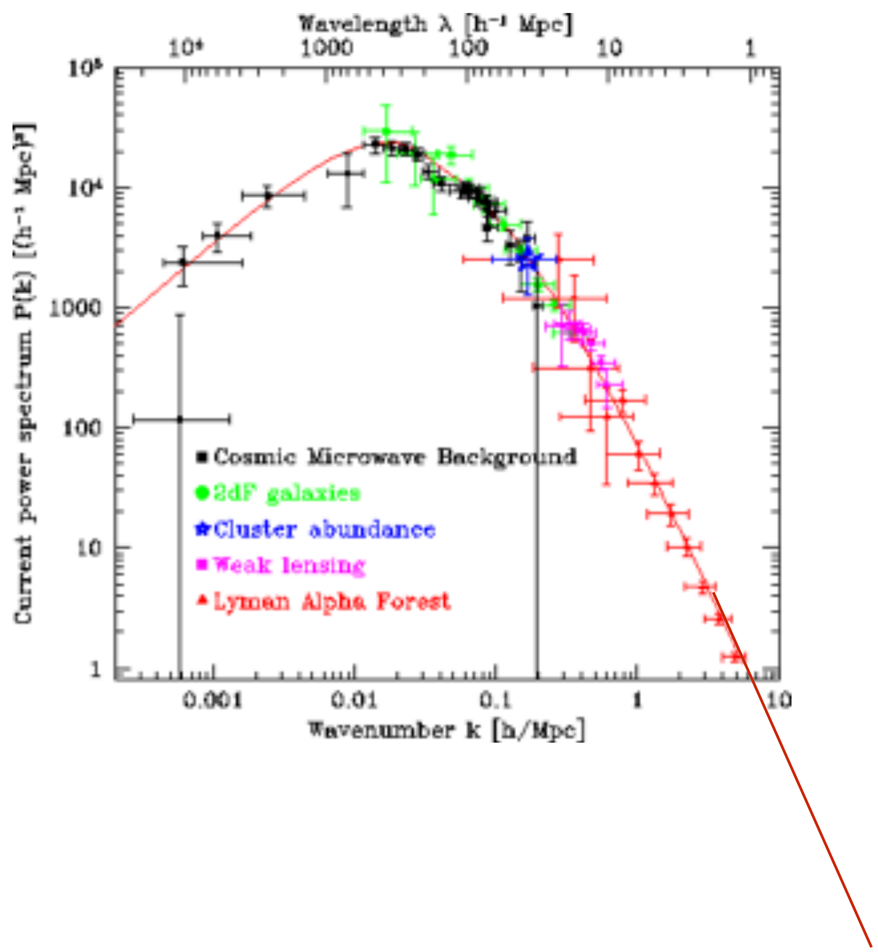


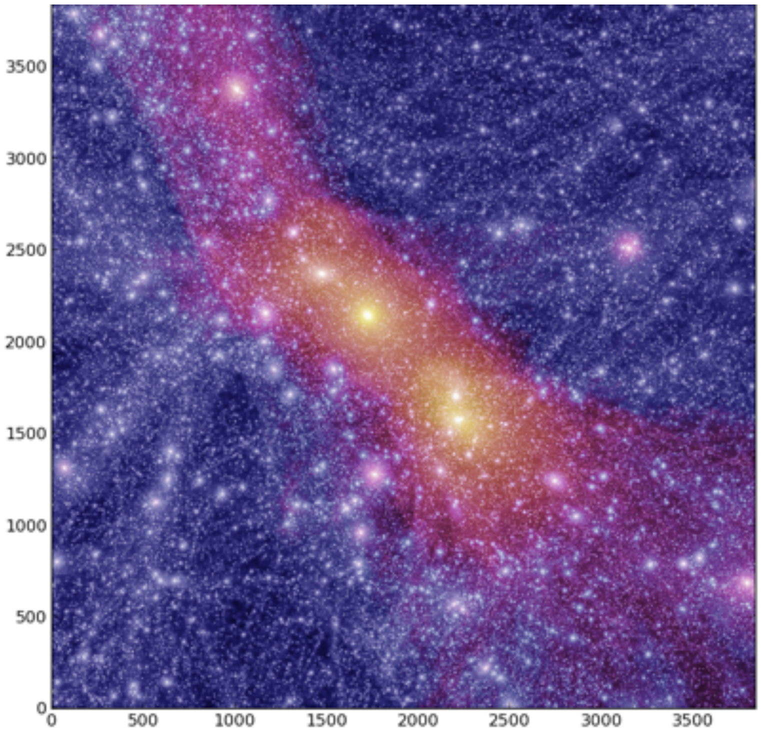
(B. WIMP and CDM: what is the link?)

Weakly Interactive Massive particles do not suffer from any damping (dissipation) mechanism that could erase the primordial fluctuations

vanilla WIMPs are CDM candidates



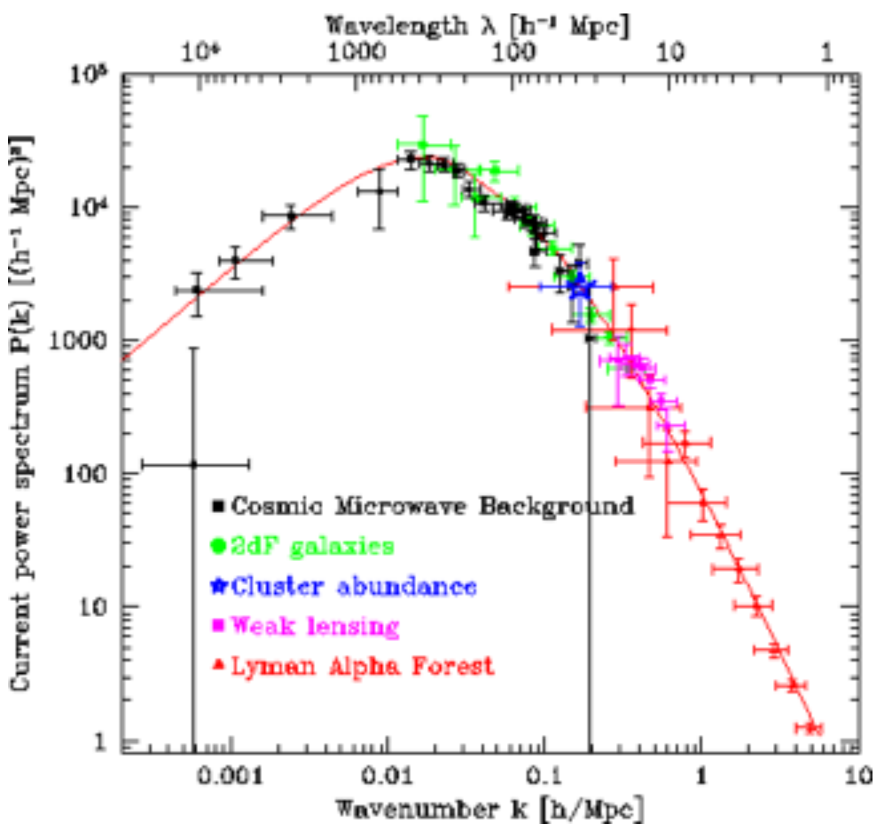




On the scales one can probe, CDM fits observations (a few problems though)
WIMPS are CDM candidates and therefore they explain what we see!

(B. WIMP and CDM: what is the link?)

But are all WIMPs CDM candidates?



will we see any deviations to CDM when we get data at lower scales?

We need to go back to the definitions and meaning

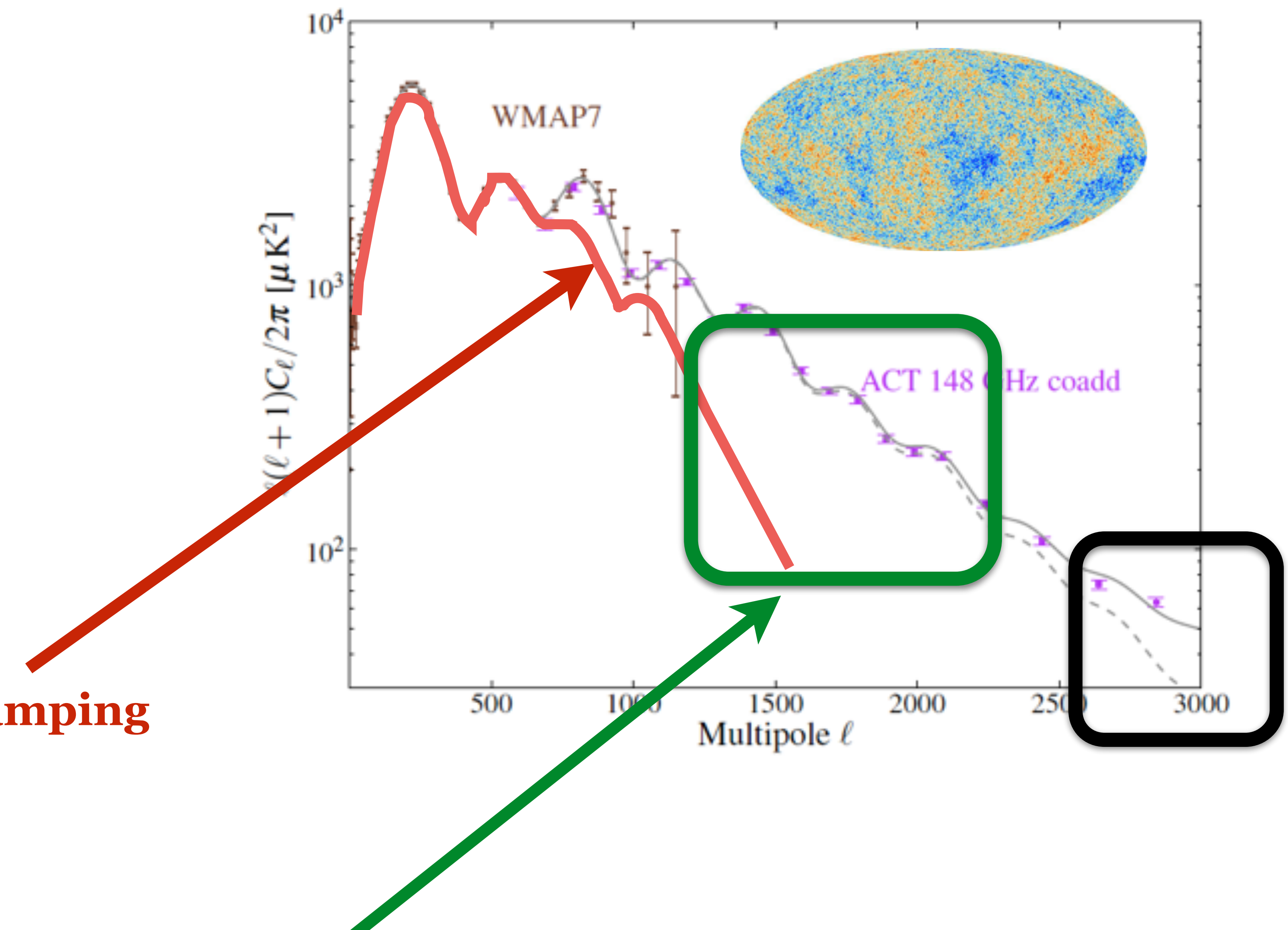
PART III

C. Alternatives to CDM

C. Alternatives to CDM

What would the Universe look like if DM is not CDM

DM could have interactions and not be massive enough to cluster as CDM



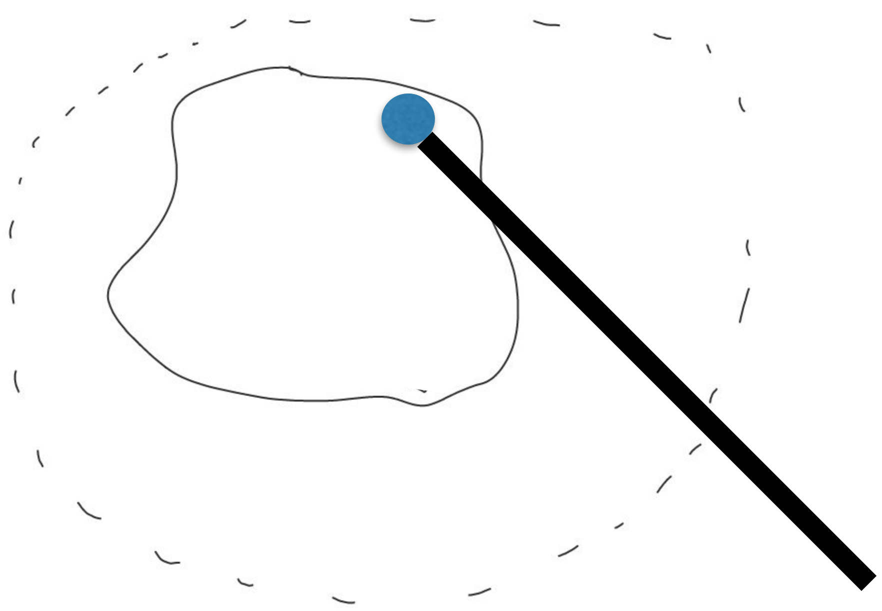
There could be deviations at scales smaller than these

Silk damping

Deviations here would be excluded

What happens if DM is light or has interactions?

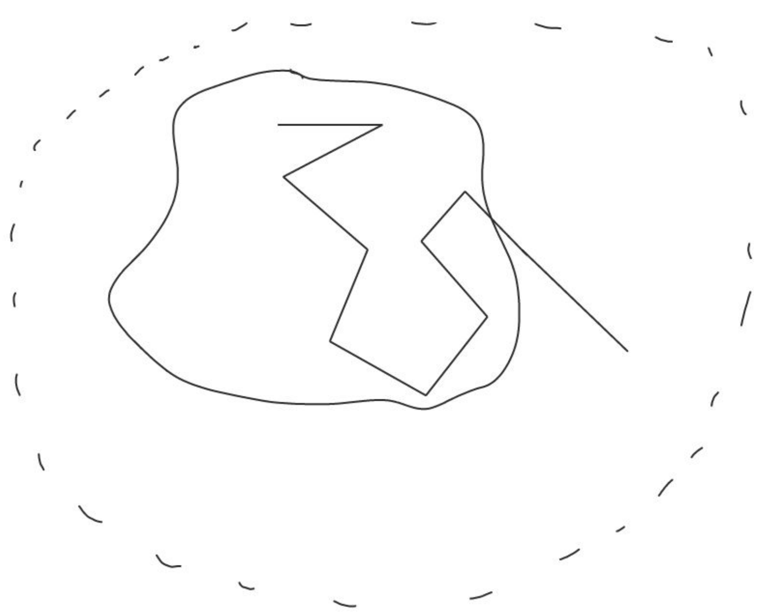
What happens if DM has no interaction but is very light



DM free-streams; distance traveled is

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

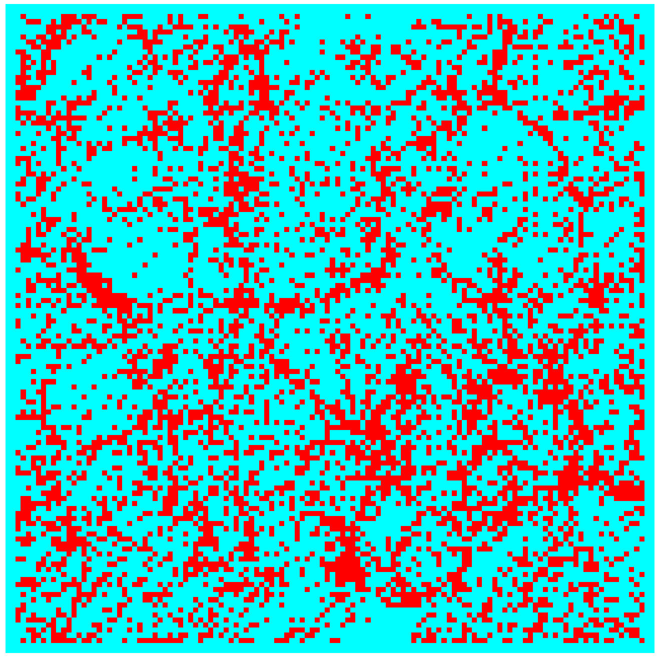
What happens if DM has interactions



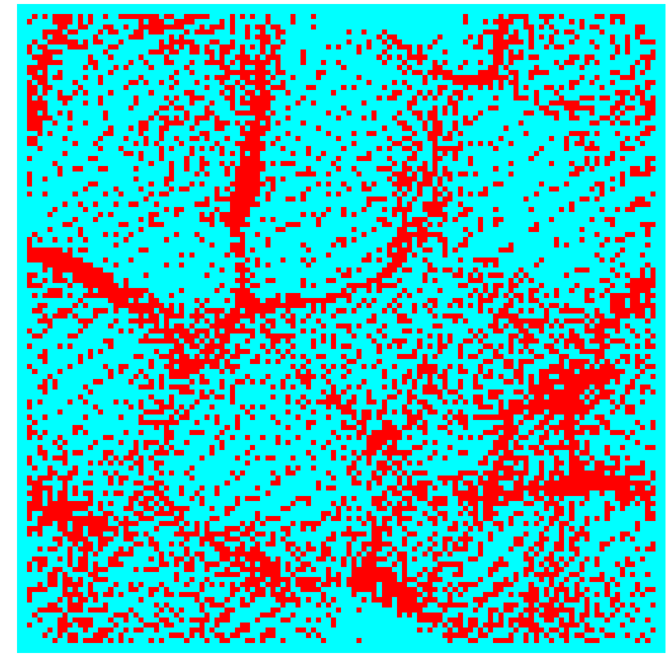
DM collides with other particles;
distance traveled is

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

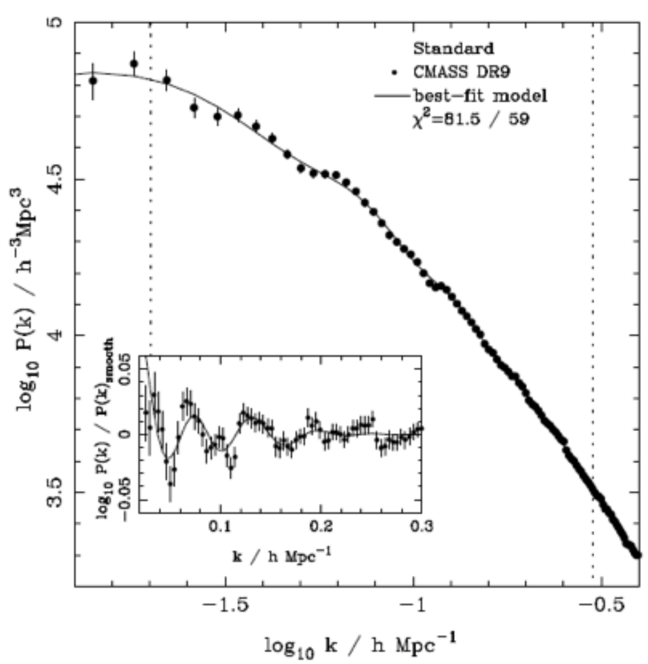
What happens if DM is relativistic?

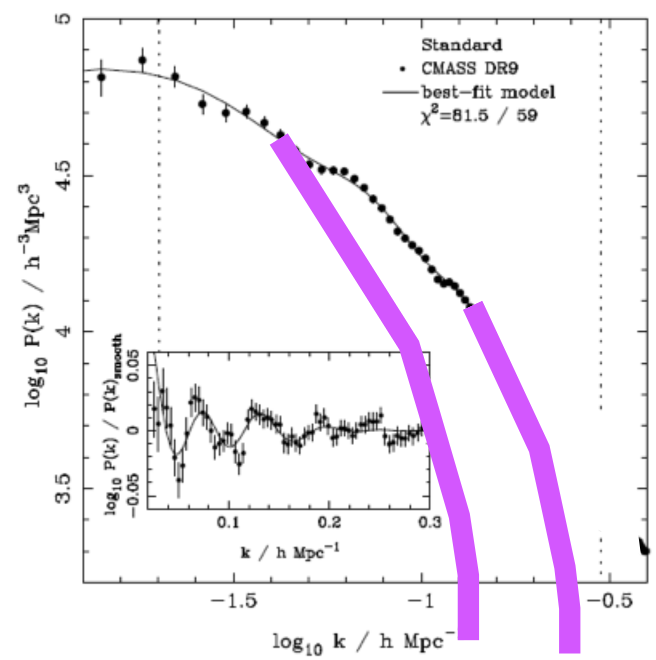


CDM



HDM





CUT-OFF depends on the DM mass

CDM has no cut-off in P(k) so very small scales fluctuations exist!

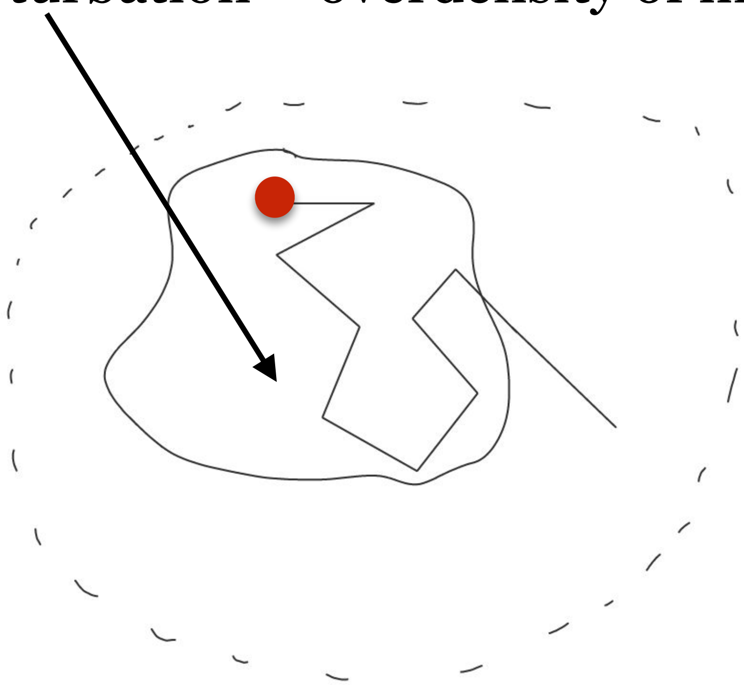
HDM has a cut-off in P(k) so very small scales fluctuations are erased!

What happens if DM has interactions

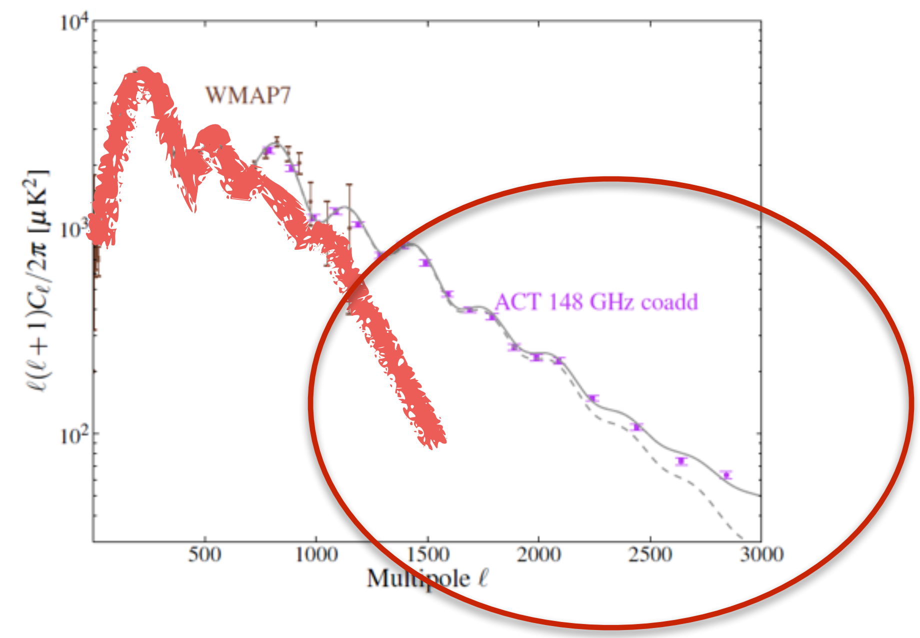
(astro-ph/0012504, astro-ph/0112522, hep-ph/0305261, astro-ph/0309652, astro-ph/0410591)

Notion of *collisional damping*

Perturbation = overdensity of matter



Diffusion DM-SM particles



Cannot be as extreme as Silk damping
but can still lead to suppression of small scale perturbations

Generalisation of Silk damping

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

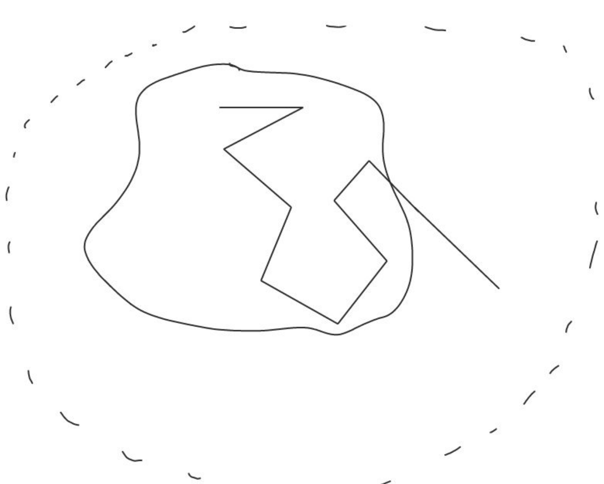
whether the species that is interacting with DM is relativistic or not

whether DM has interactions or not?

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

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

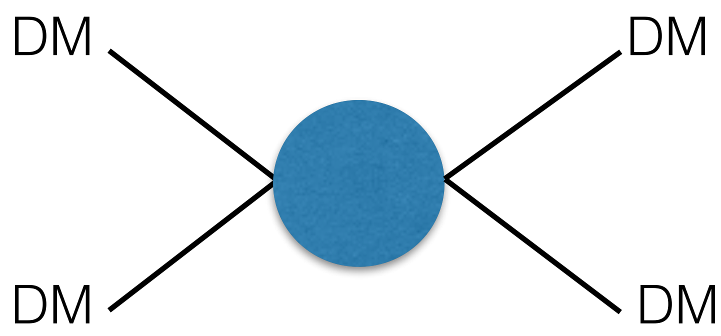
whether the species that is interacting with DM is collisional or not



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

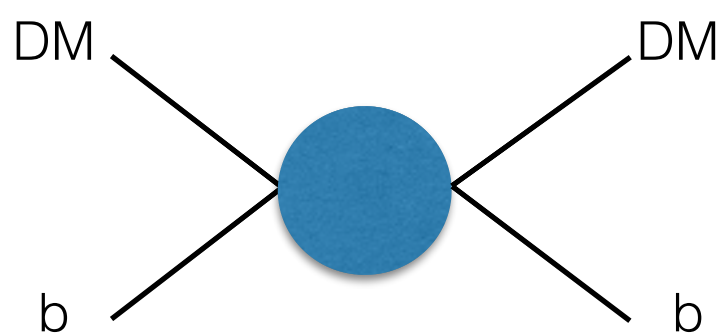
Notion of decoupling and which interactions?

$$\Gamma \simeq H$$



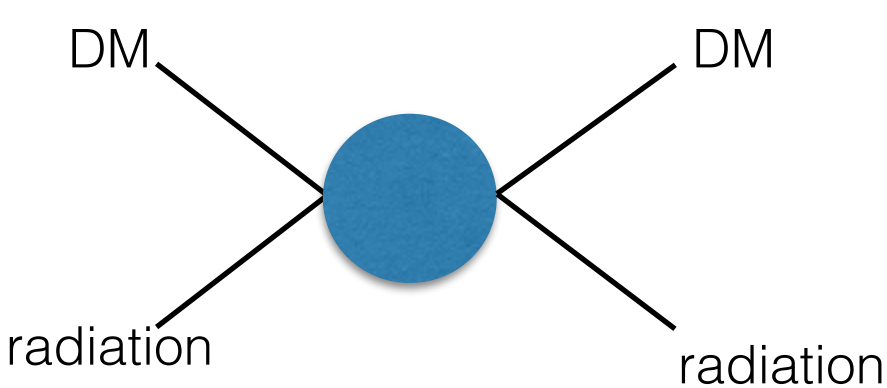
Self-interactions

$$\Gamma = (\sigma v)_{\mathrm{DM\ DM}} \times n_{\mathrm{DM}}$$



DM-baryon elastic scattering-interaction

$$\Gamma = (\sigma v)_{\mathrm{DM\ b}} \times n_{\mathrm{b}}$$



DM-radiation elastic scattering-interaction

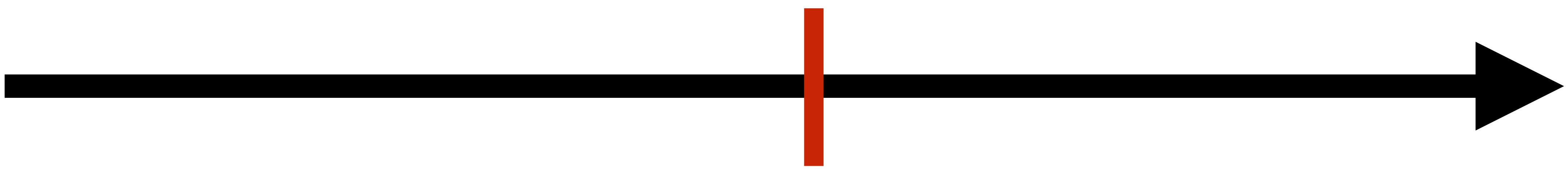
$$\Gamma = (\sigma v)_{\mathrm{DM}\ \gamma} \times n_{\gamma}$$

$$\Gamma = (\sigma v)_{\mathrm{DM}\ \nu} \times n_{\nu}$$

"DM" Physics

Both effects together!

Collisional damping free-streaming



$t_{dec(DM)}$

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

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

fluctuations are first damped by collisions!

Computing the DM free-stream length

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

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

$$\Gamma_{\mathrm{dec(DM)}} \sim H$$

Γ_{dec} is the dominant interaction rate!

$$\Gamma_{dec} = (\sigma v)_{\mathrm{DM\ DM}} \times n_{\mathrm{DM}}$$

$$\Gamma_{dec} = (\sigma v)_{\mathrm{DM\ b}} \times n_{\mathrm{b}}$$

$$\Gamma_{dec} = (\sigma v)_{\mathrm{DM}\ \gamma} \times n_{\gamma}$$

$$\Gamma_{dec} = (\sigma v)_{\mathrm{DM}\ \nu} \times n_{\nu}$$

But you also need to specify v and a(t)

One needs to specify the velocity, the scale factor and interaction rate

- mass → non relativistic transition
- matter or radiation dominated? → equality
- $\Gamma_{\rm dec(DM)} \sim H$ → $t_{\rm dec(DM)} = 1/\Gamma_{\rm dec}$

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	$a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$

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	$a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$

Region I: Hot Dark Matter

Mass < MeV

$$l_{fs}^{(I)} = 0.51\, kpc\, {g'}_*^{-\frac{1}{2}}(T_{nr}) \left(\frac{m_{dm}\kappa_{dm}(T_{nr})}{1MeV}\right)^{-1} \quad \propto \boxed{m_{DM}^{-4/3}}$$

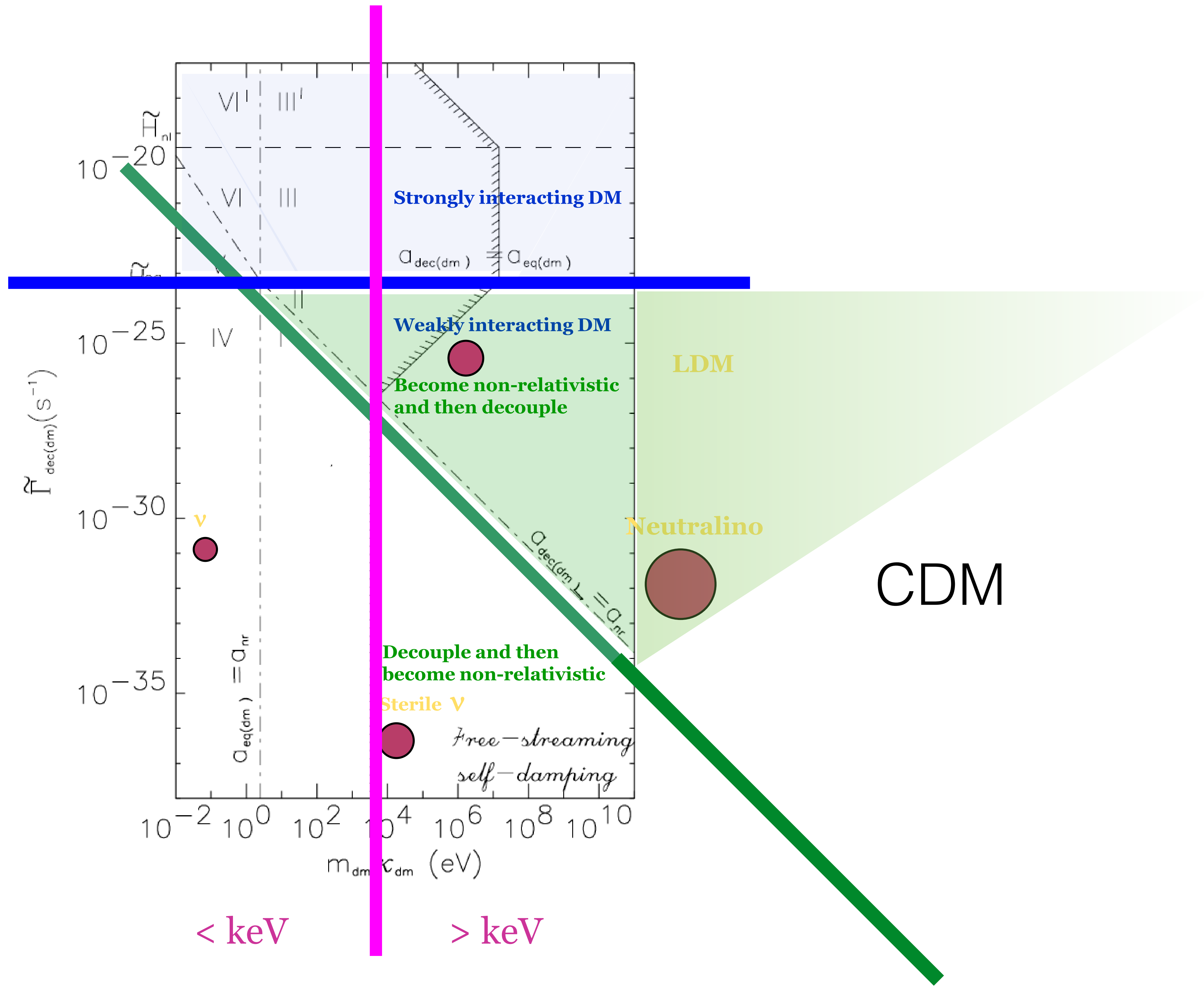
Region II: Cold Dark Matter

Interaction rate at equality

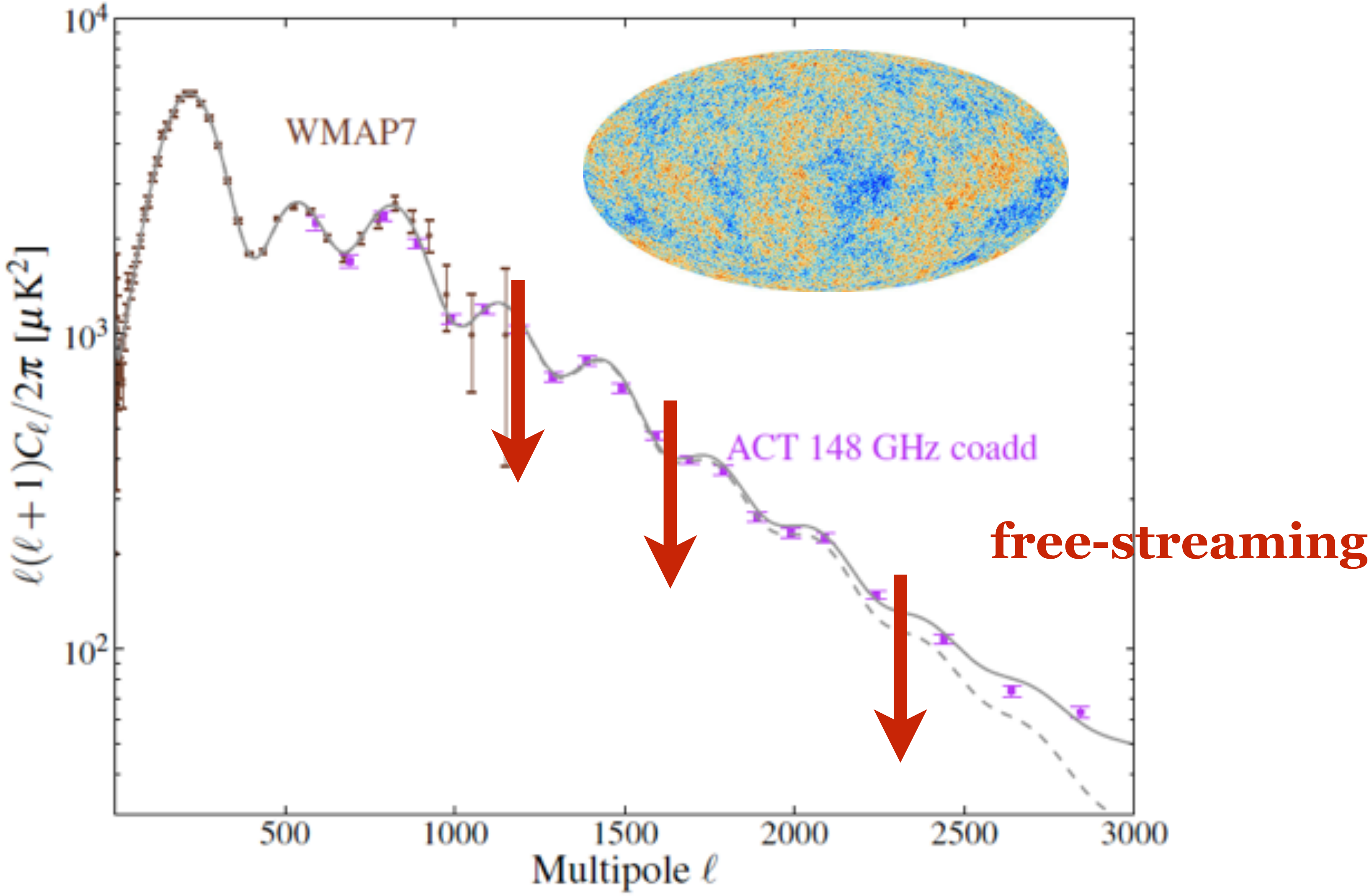
$$l_{fs}^{(II)} \sim 330\, kpc\; f\; {g'}_*^{-\frac{3}{4}}(T_{dec(dm)}) \left(\frac{m_{dm}\kappa_{dm}(T_{nr})}{1MeV}\right)^{-\frac{1}{2}} \left(\frac{\widetilde{\Gamma}_{dec(dm)}}{6\ 10^{-24} s^{-1}}\right)^{\frac{1}{2}}$$

Mass > MeV

C. Alternatives to CDM

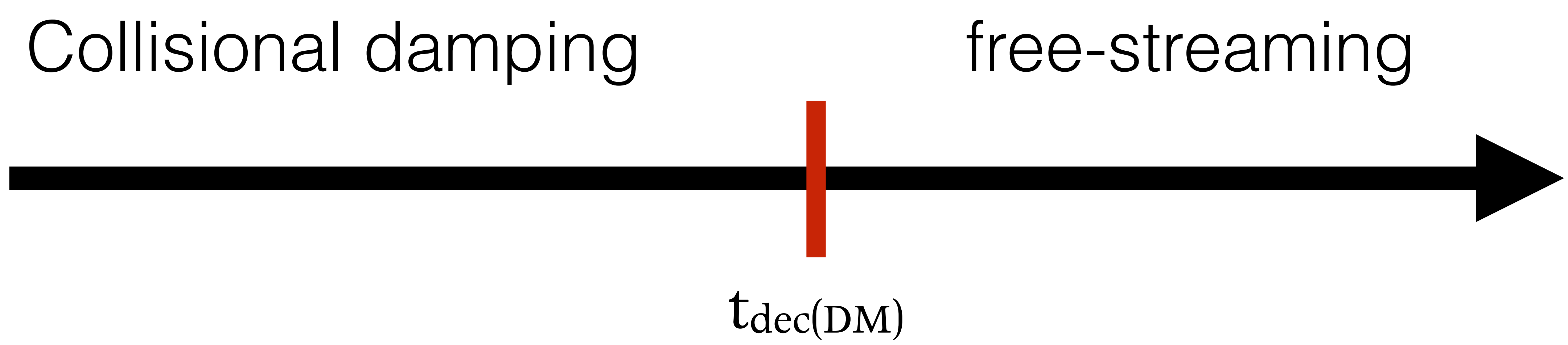


C. Alternatives to CDM



C. Alternatives to CDM

We saw the effect of the DM mass but what is the effect of interactions?



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

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

fluctuations are first damped by collisions!

Collisional damping in modern Cosmology

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

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

Translation in terms of Cosmological perturbations

without DM interactions

$$\dot\theta_b = k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma)$$

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

$$\dot\theta_{DM} = k^2\psi - \mathcal{H}\theta_{DM}\,,$$

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

with DM interactions

$$\dot\theta_b = k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma)$$

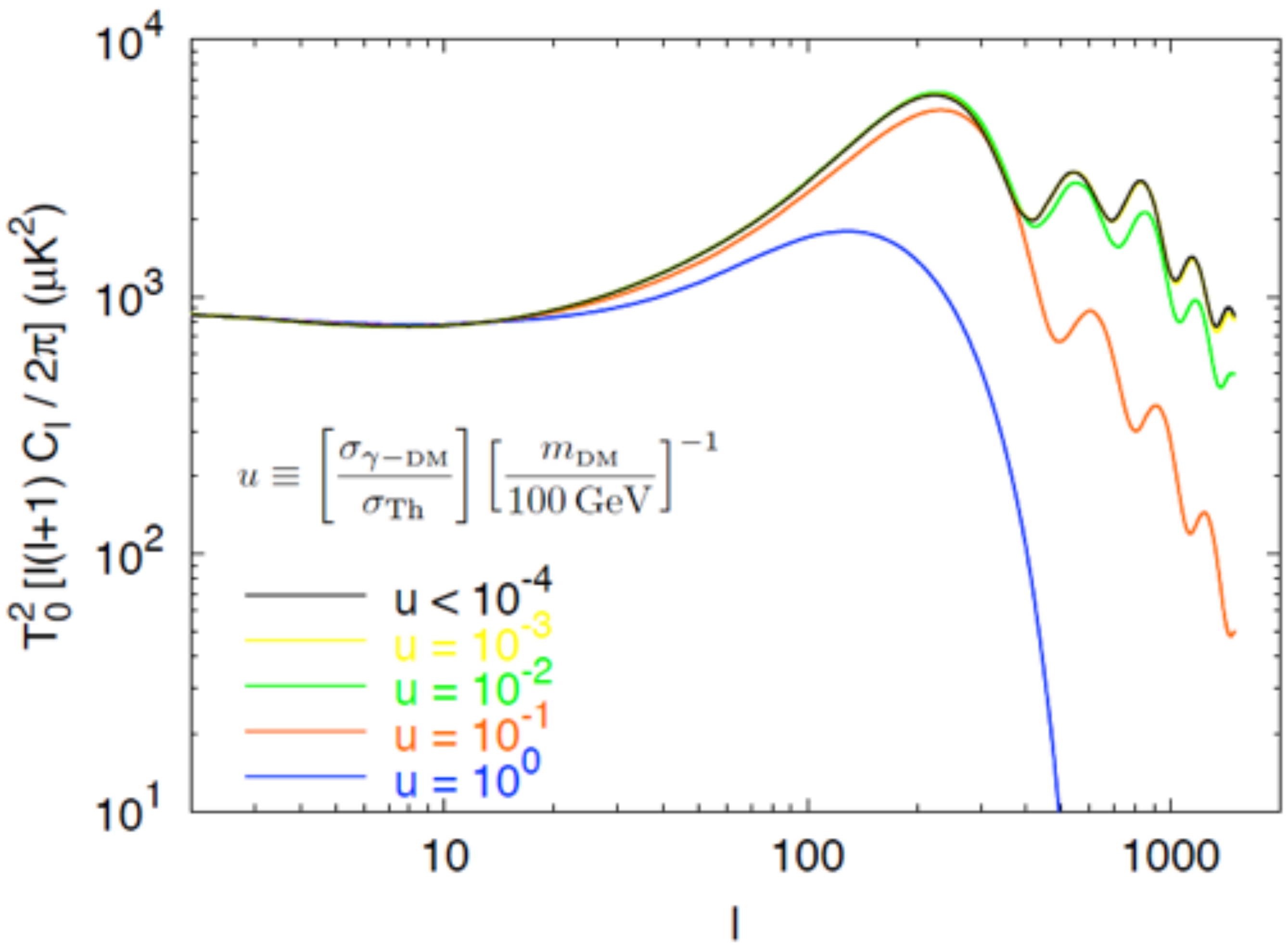
$$\dot\theta_\gamma = k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot\kappa(\theta_\gamma - \theta_b) - \dot\mu(\theta_\gamma - \theta_{DM})\,,$$

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

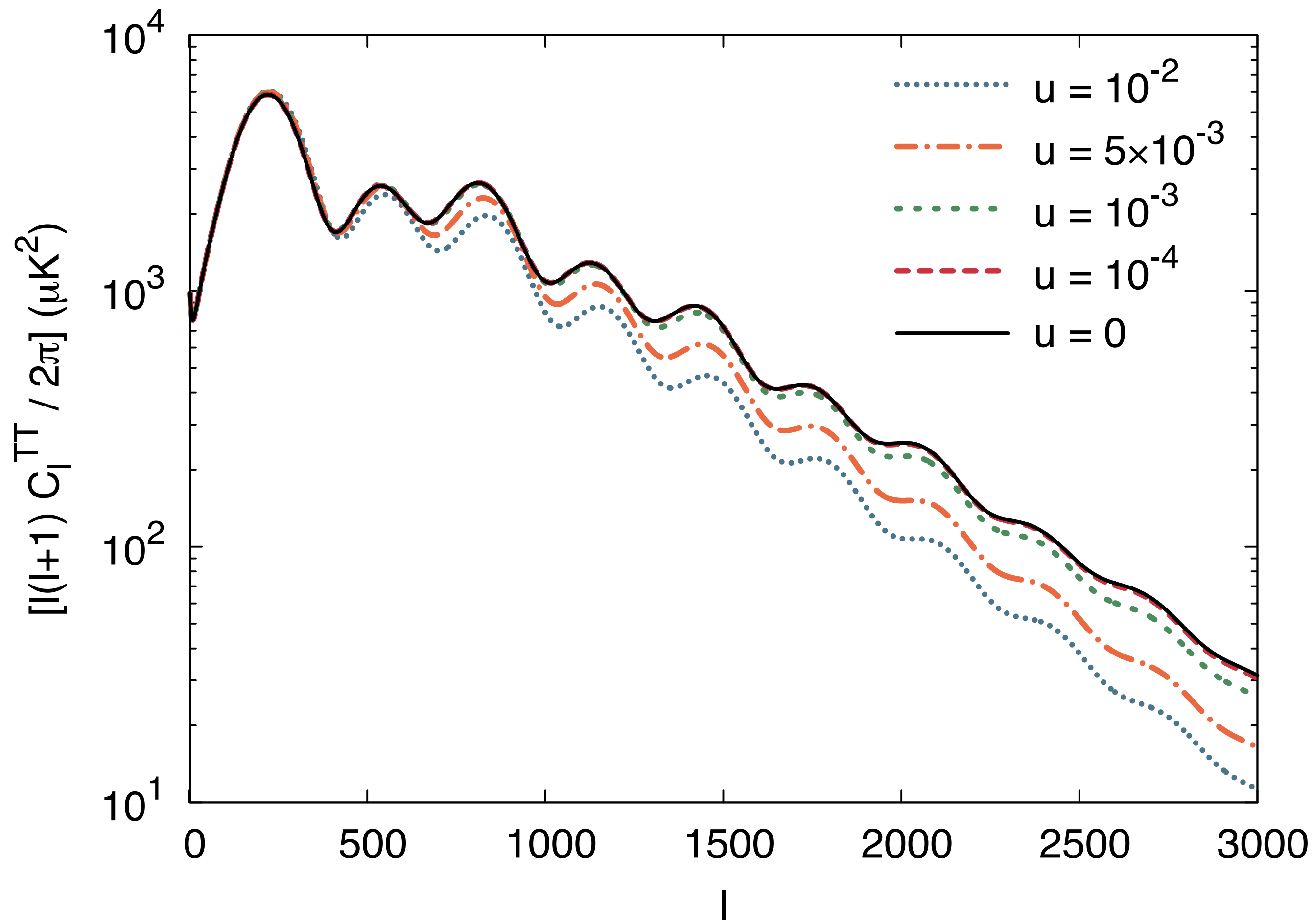
$$\dot\mu \equiv a\sigma_{\gamma-DM} n_{DM} \qquad S \equiv \frac{3}{4}\frac{\rho_{DM}}{\rho_\gamma}$$

CMB in presence of DM-photon interactions

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?

$$u \equiv \left[\frac{\sigma_{DM-\gamma}}{\sigma_{Th}}\right]\left[\frac{m_{DM}}{100\ \mathrm{GeV}}\right]^{-1}$$

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

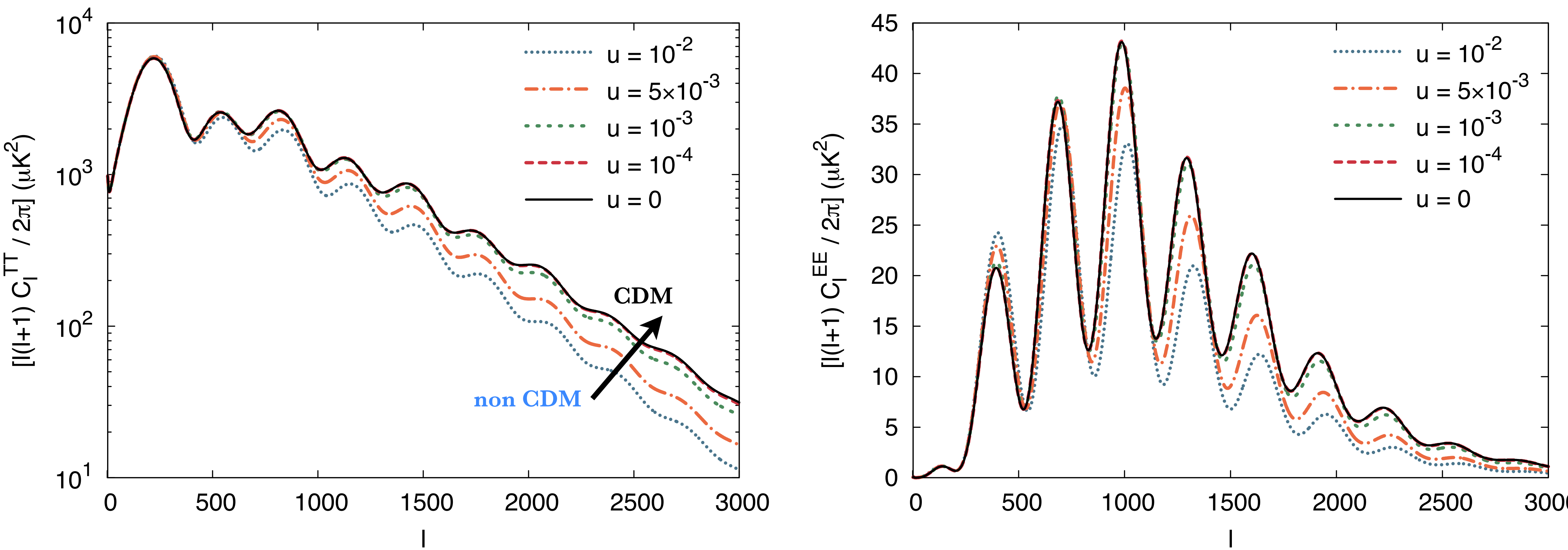


FIG. 1: The effect of DM–γ interactions on the TT (left) and EE (right) components of the CMB angular power spectrum, where the strength of the interaction is characterised by $u \equiv [\sigma_{DM-\gamma}/\sigma_{Th}]\,[m_{DM}/100\ \mathrm{GeV}]^{-1}$ ($u = 0$ corresponds to zero DM–γ coupling) and $\sigma_{DM-\gamma}$ is constant. For all the curves, we consider a flat ΛCDM model with $H_0 = 70$ km s^{-1} Mpc^{-1} ($h = 0.7$), $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ and $\Omega_b = 0.05$, where u is the only additional parameter. The new coupling has two main effects: i) a suppression of the small-scale peaks due to a combination of collisional damping and a delayed photon decoupling, and ii) a shift in the peaks to larger ℓ due to a decrease in the sound speed of the thermal plasma. (Note that $u = 10^{-4}$ is difficult to distinguish from $u = 0$ at this scale).

No need to specify a model, nor to decide whether one deals with annihilating, symmetric/asymmetric DM

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

Using Monte Python (credits Benjamin Audren).

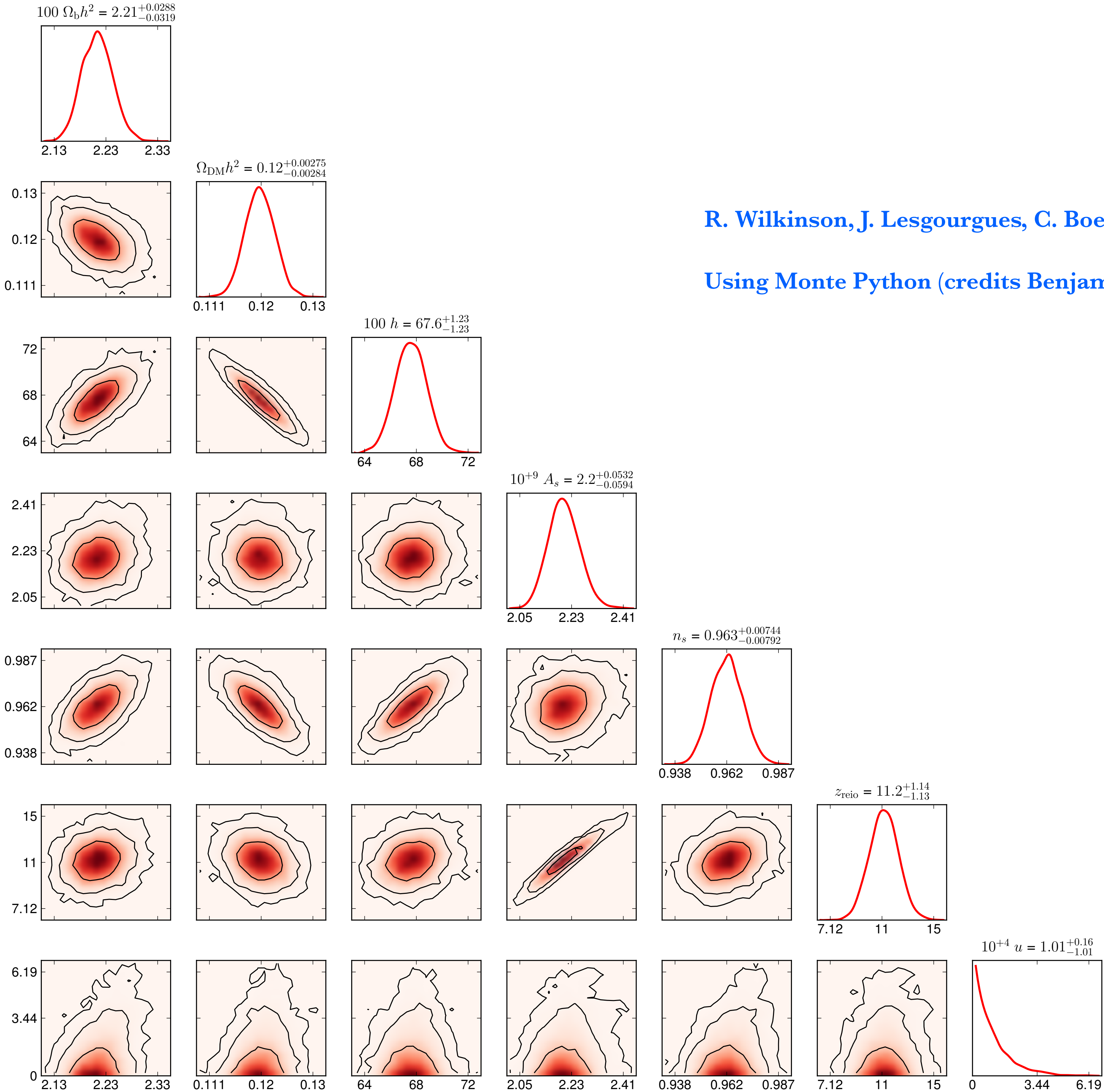


FIG. 2: Triangle plot showing the one and two-dimensional posterior distributions of the cosmological parameters set by Planck, with $u \equiv [\sigma_{DM-\gamma}/\sigma_{Th}]\,[m_{DM}/100\ \text{GeV}]^{-1}$ as a free parameter and a constant $\sigma_{DM-\gamma}$. The contour lines correspond to the 68%, 95% and 99% confidence levels. $\Omega_b h^2$ is the baryon energy density, $\Omega_{DM} h^2$ is the dark matter energy density, h is the reduced Hubble parameter, A_s is the primordial spectrum amplitude, n_s is the spectral index and z_{reio} is the reionisation redshift.

C. Alternatives to CDM

	$100\,\Omega_b h^2$	$\Omega_{DM} h^2$	$100\,h$	$10^{+9}\,A_s$	n_s	z_{reio}	$10^{+4}\,u$
Best-fit	2.199	0.1195	67.57	2.189	0.9627	11.02	$\simeq 0$
Mean $\pm$ σ	$2.210^{+0.029}_{-0.032}$	$0.1201^{+0.0028}_{-0.0028}$	$67.6^{+1.2}_{-1.2}$	$2.201^{+0.053}_{-0.059}$	$0.9625^{+0.0074}_{-0.0079}$	$11.2^{+1.1}_{-1.1}$	< 1.165
'*Planck* + WP'	$2.205^{+0.028}_{-0.028}$	$0.1199^{+0.0027}_{-0.0027}$	$67.3^{+1.2}_{-1.2}$	$2.196^{+0.051}_{-0.060}$	$0.9603^{+0.0073}_{-0.0073}$	$11.1^{+1.1}_{-1.1}$	–

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

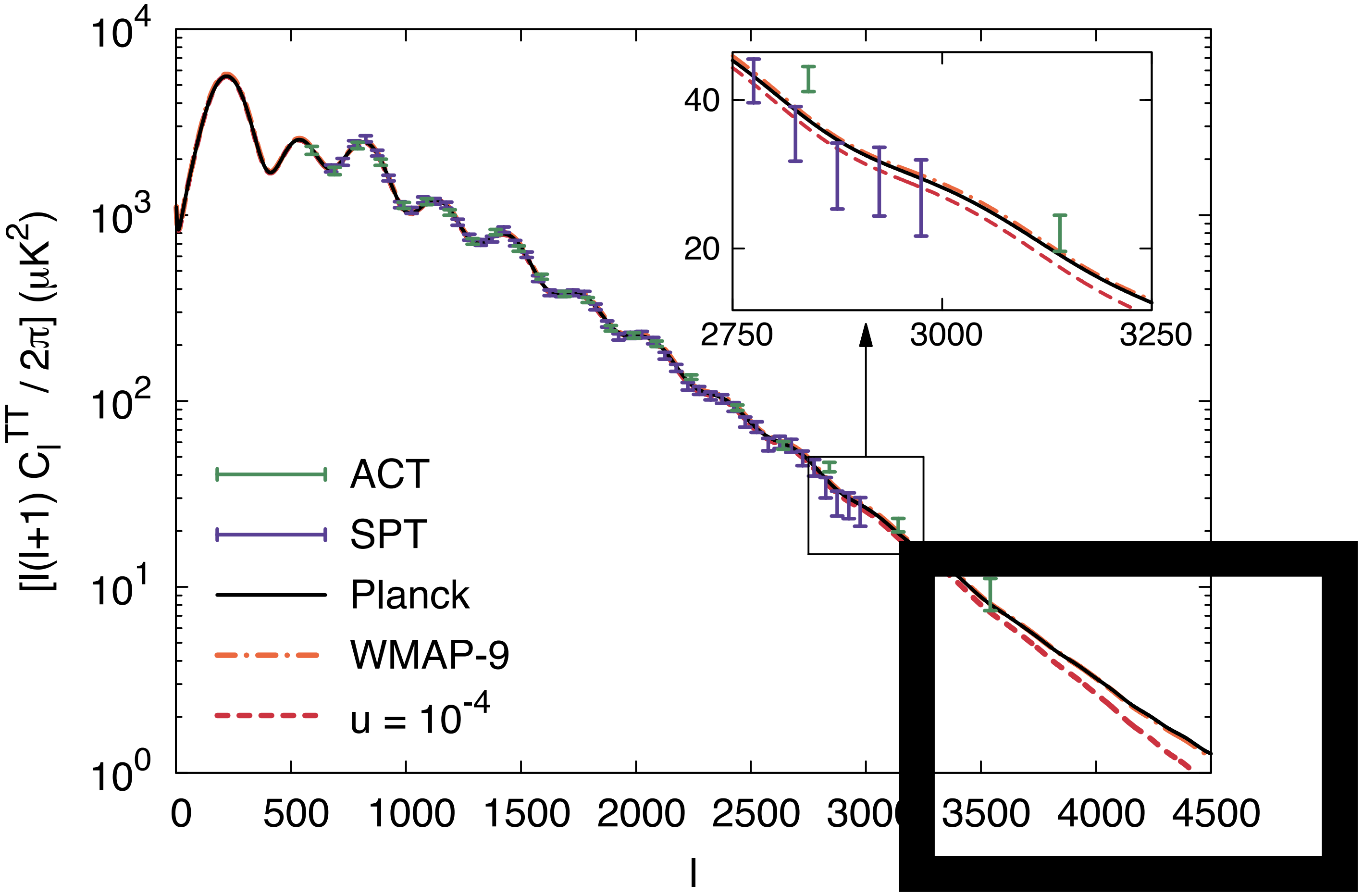
DM-photons interactions with

$$\sigma \sim 6\ 10^{-29}\mathrm{cm}^2 \left(\frac{\mathrm{m_{dm}}}{100\mathrm{GeV}}\right)$$

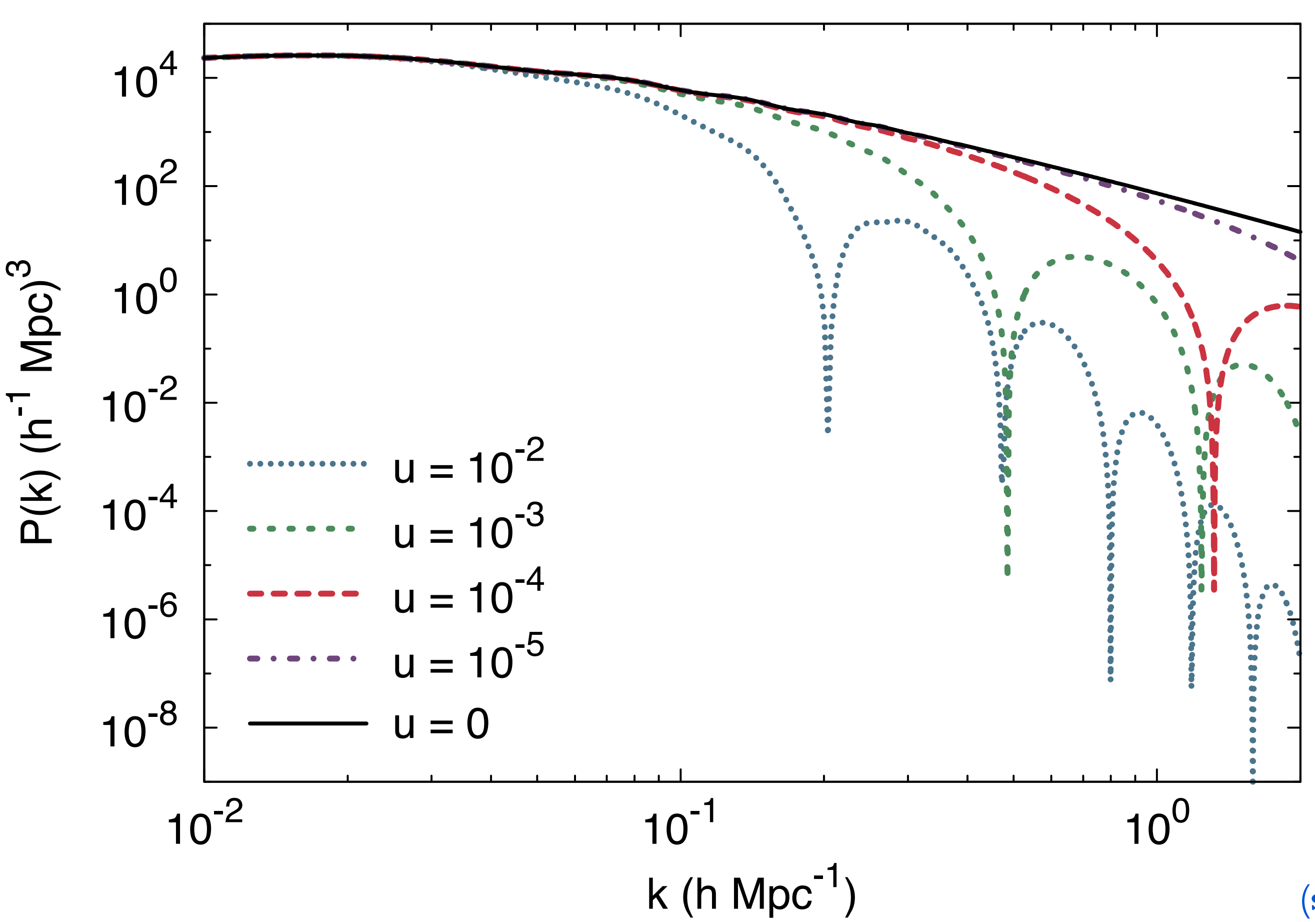
fit the CMB!

There can be alternatives to CDM. It is a question of scales!

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



Where “small” interactions induce CDM deviations



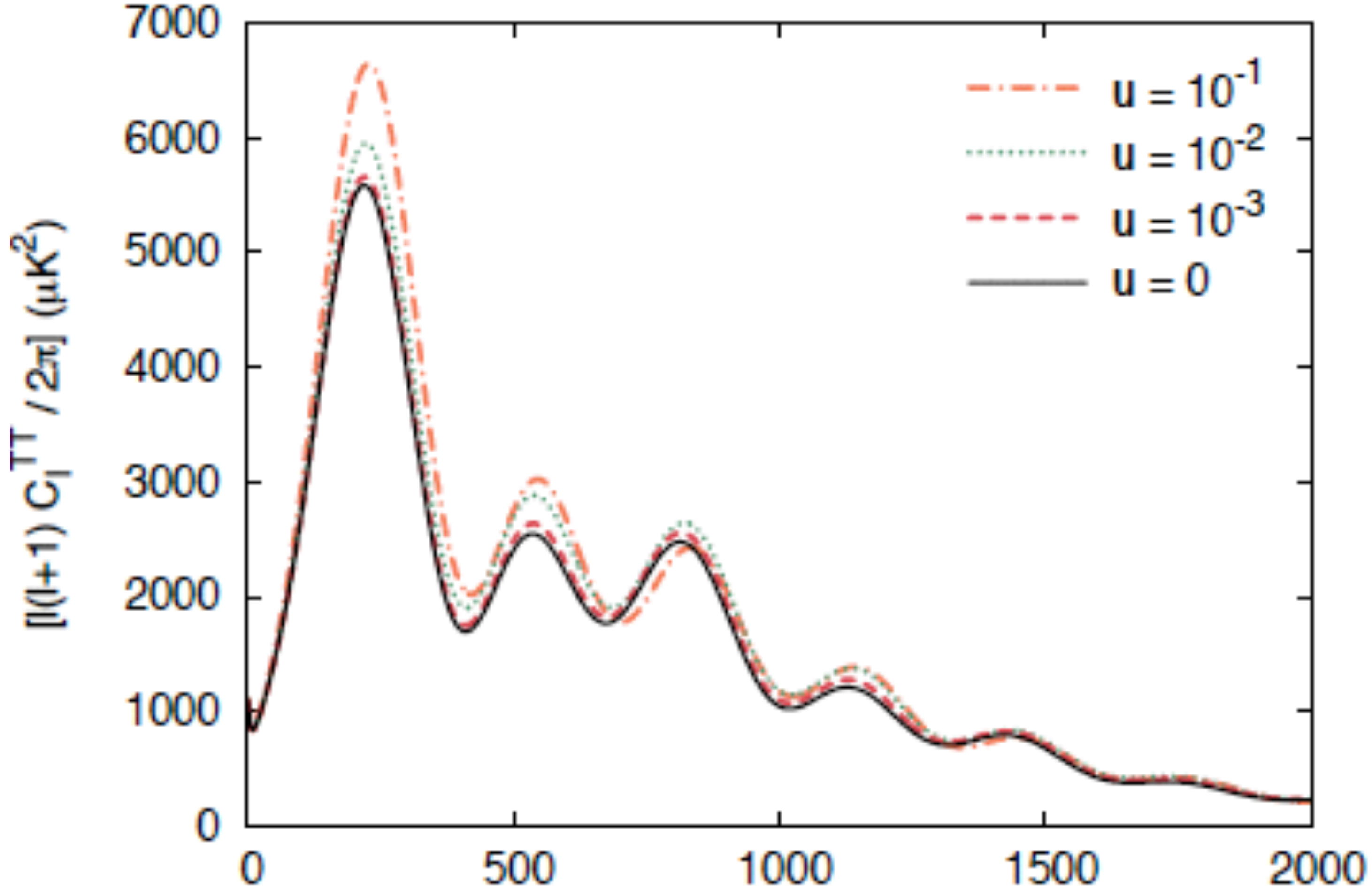
Dark Oscillations in the matter power spectrum

Lyman alpha improves our CMB constraint by several order of magnitudes

(same as C. Boehm, Riazuelo, S. Hansen, R. Schaeffer : astro-ph/0112522)

DM-neutrino interactions and CMB

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



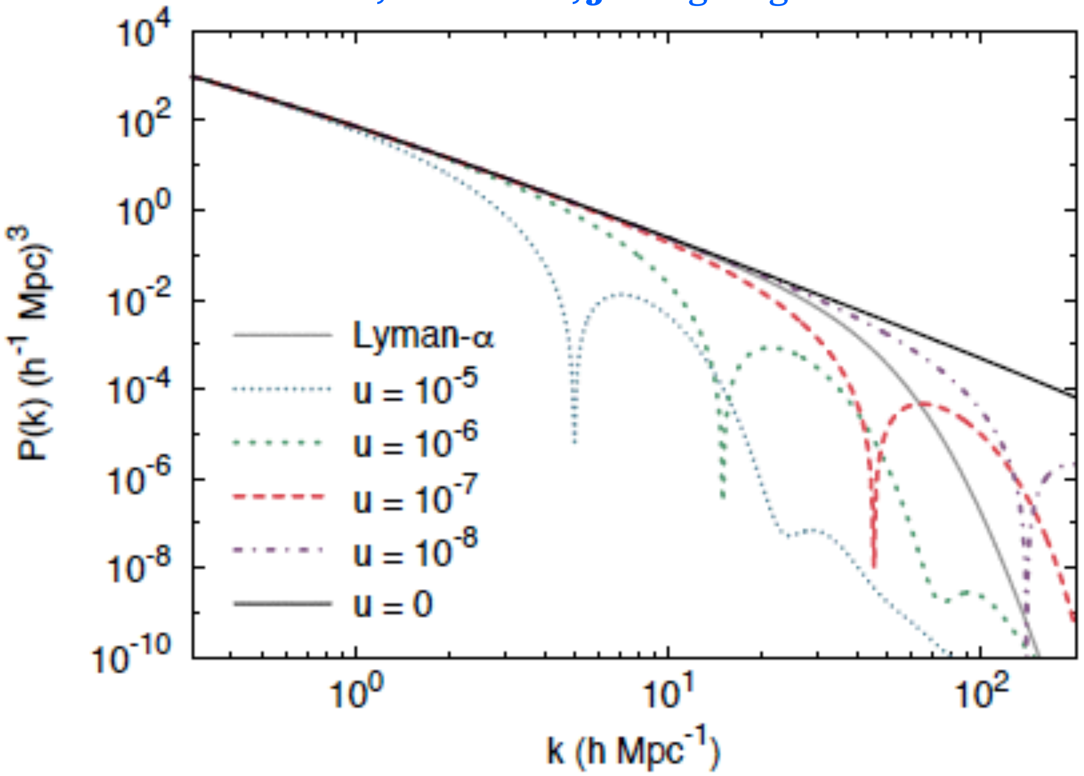
When perturbations cross the Hubble radius during matter domination, if DM is still efficiently coupled to neutrinos, it contributes to the fast mode solution. Thus, DM is gravitationally coupled to the photon–baryon fluid, leading to a gravitational boosting effect (unlike in the standard model for which metric fluctuations are frozen during matter domination). This effect contributes to the enhancement of the first peak.

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}(\theta_\nu - \theta_{DM}) ,$$
$$\dot{\theta}_{DM} = k^2\psi - \mathcal{H}\theta_{DM} - S^{-1}\dot{\mu}(\theta_{DM} - \theta_\nu) ,$$

The neutrino free-streaming is enhanced and the neutrino also follow for a while the DM which starts to cluster.

C. Alternatives to CDM

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}
Lyman-α limit	$2.246^{+0.039}_{-0.042}$	$0.1253^{+0.0053}_{-0.0056}$	$71.5^{+3.0}_{-3.3}$	$2.254^{+0.069}_{-0.082}$	$0.979^{+0.016}_{-0.016}$	$11.7^{+1.2}_{-1.3}$	$3.52^{+0.36}_{-0.40}$

DM interactions with neutrinos change the H0 value!

Planck's analysis assumes no DM physics...

C. Alternatives to CDM

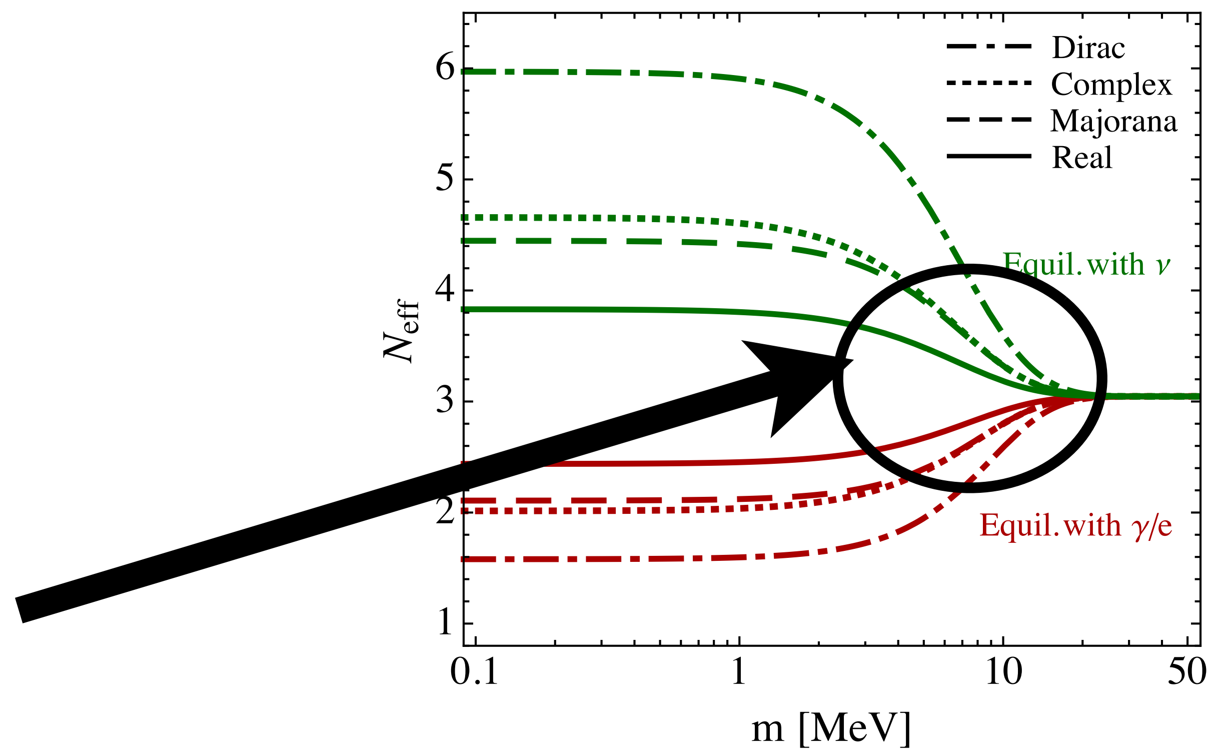
C. Boehm, M. Dolan, C. McCabe arXiv:1303.6270

Constant elastic scattering cross section

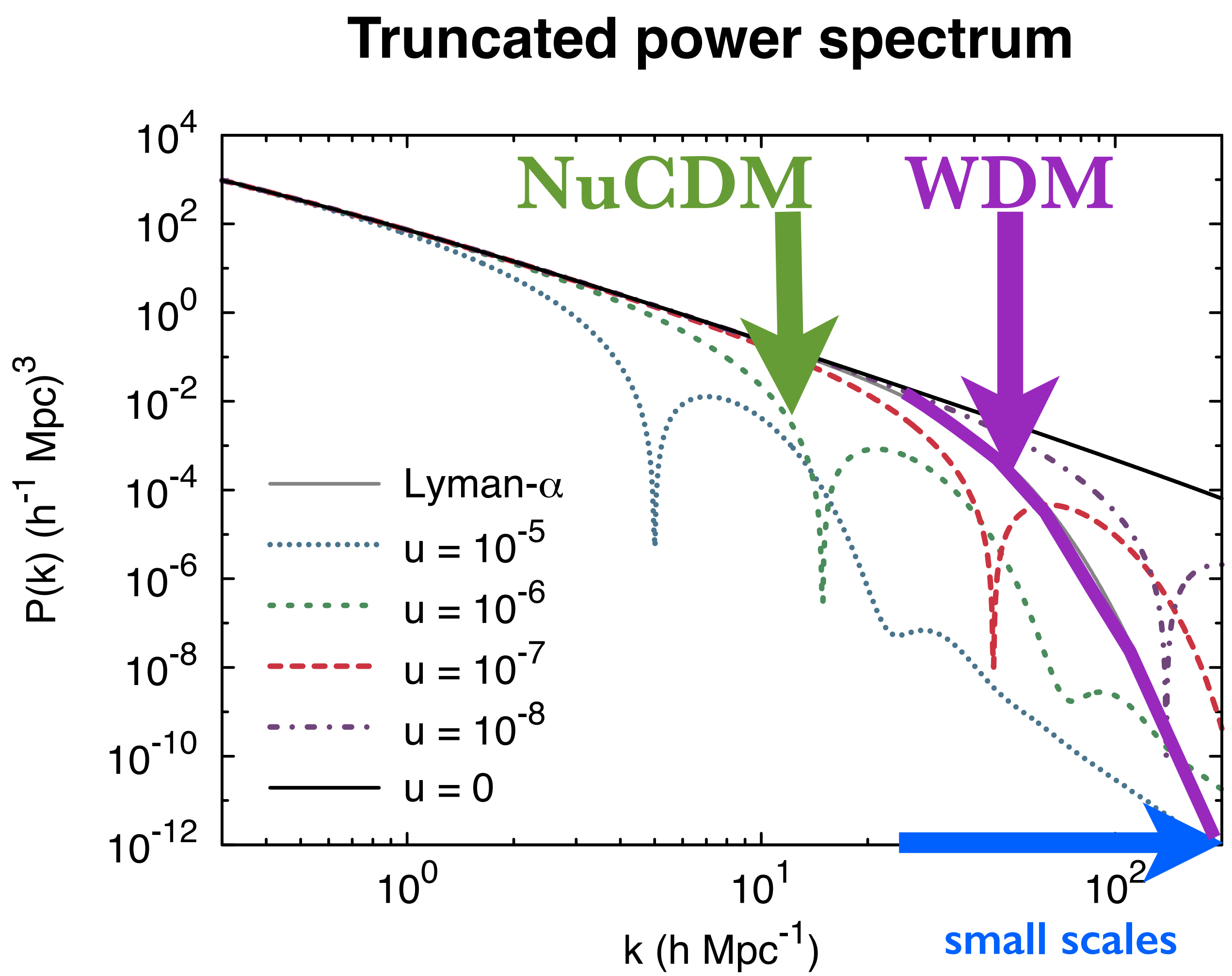
$$\sigma \sim 10^{-36} \left(\frac{m_{\rm DM}}{\rm MeV}\right) \ {\rm cm}^2$$

Annihilation cross section

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



C. Alternatives to CDM



"Bumps" (equivalent to BAO)

1) The formation of small structures should be modified

2) Modifications should be less drastic than in WDM but they should still be important and visible.

3) by analogy with WDM we expect :

- **A different number of Milky Way satellites**
- **A different number of small-scale structures**

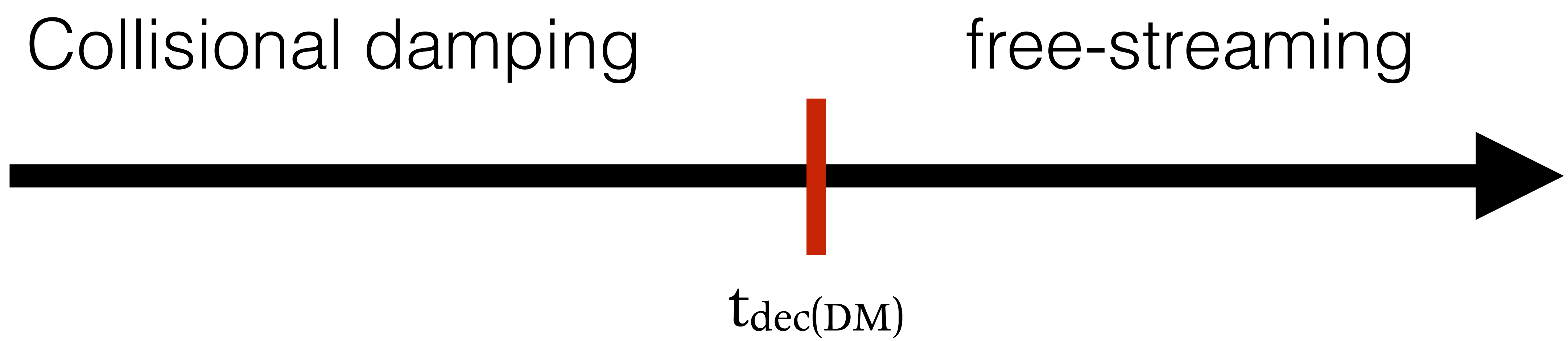
There is a very rich (structure formation) phenomenology which remains to be explored

Recap PART III

C. Alternatives to CDM

C. Alternatives to CDM

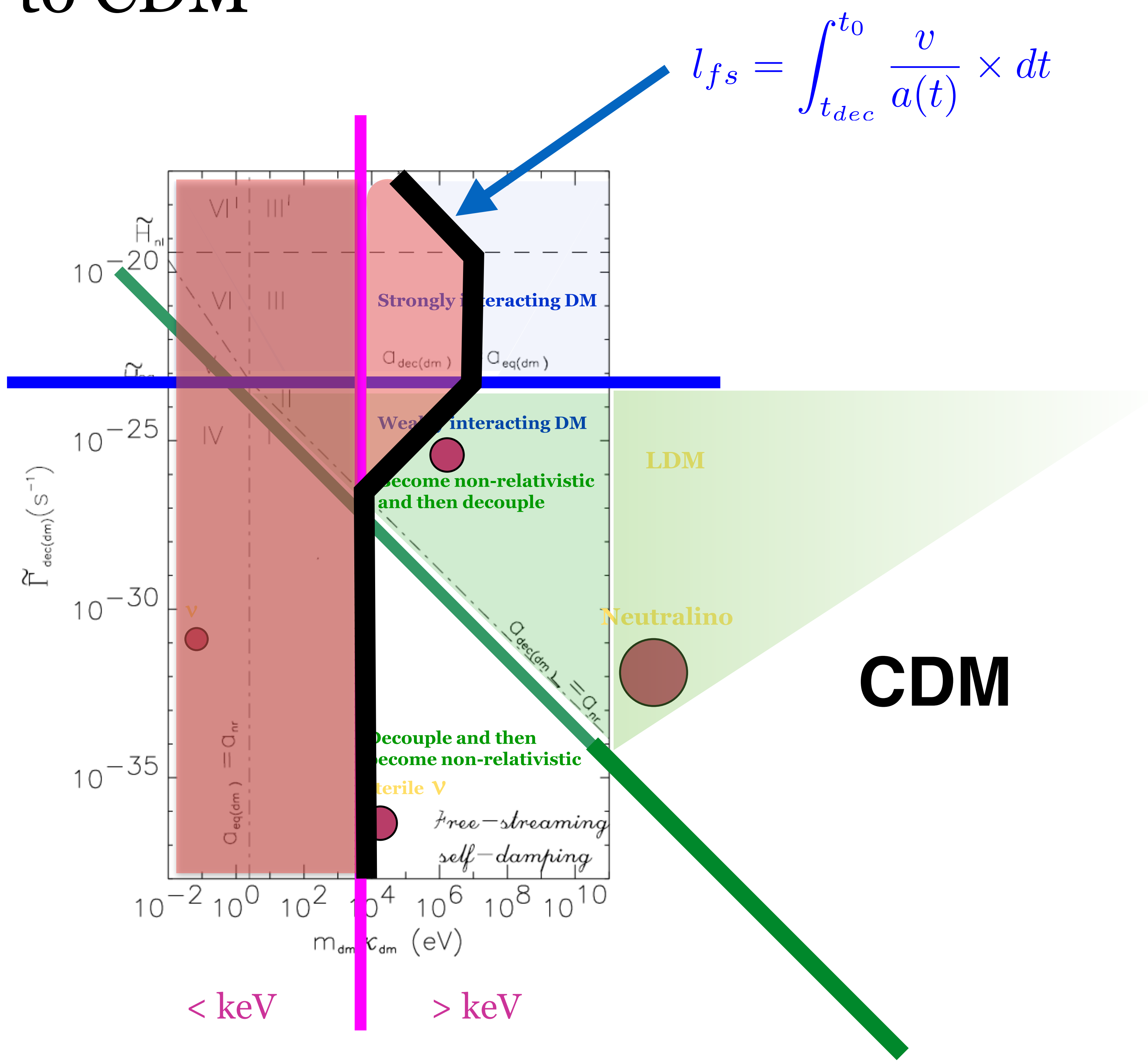
fluctuations are first damped by collisions!



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

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

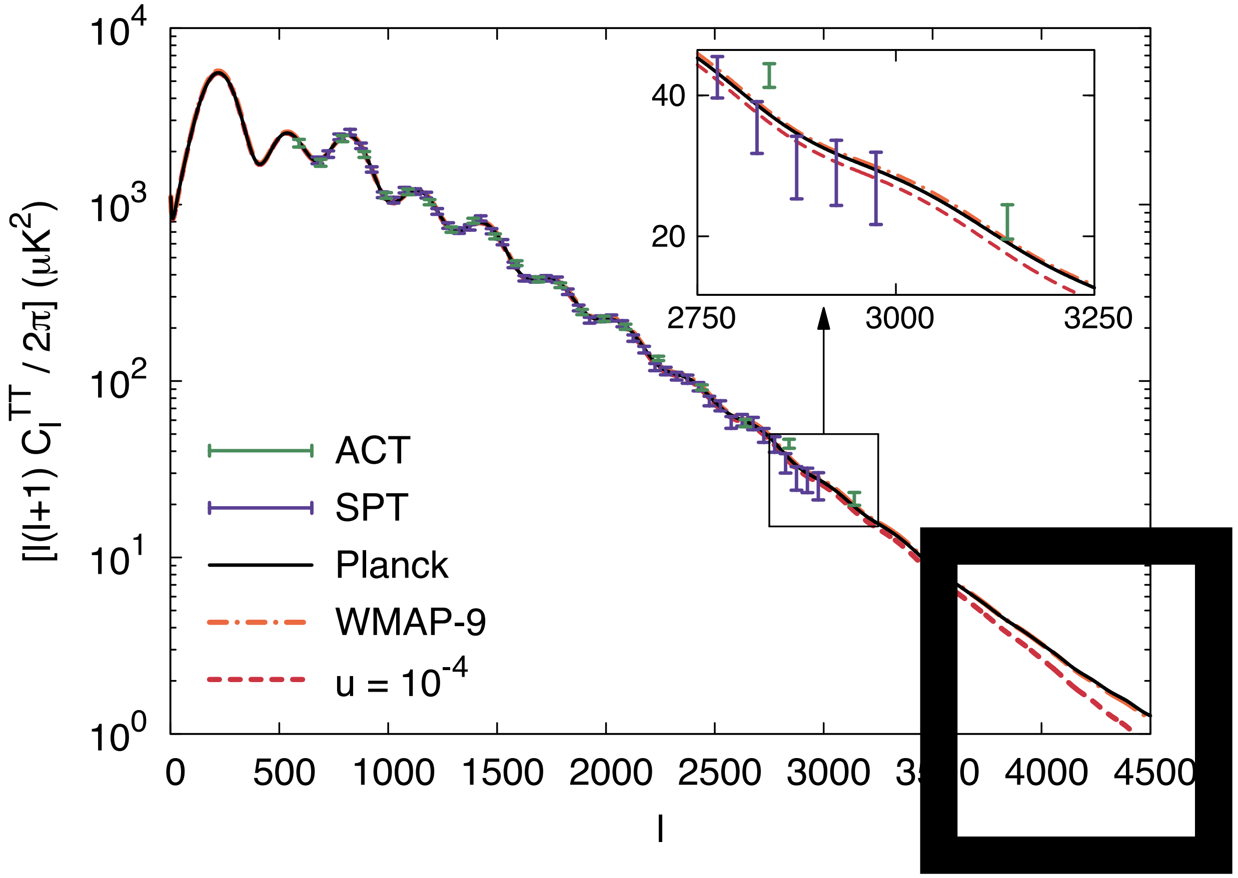
C. Alternatives to CDM

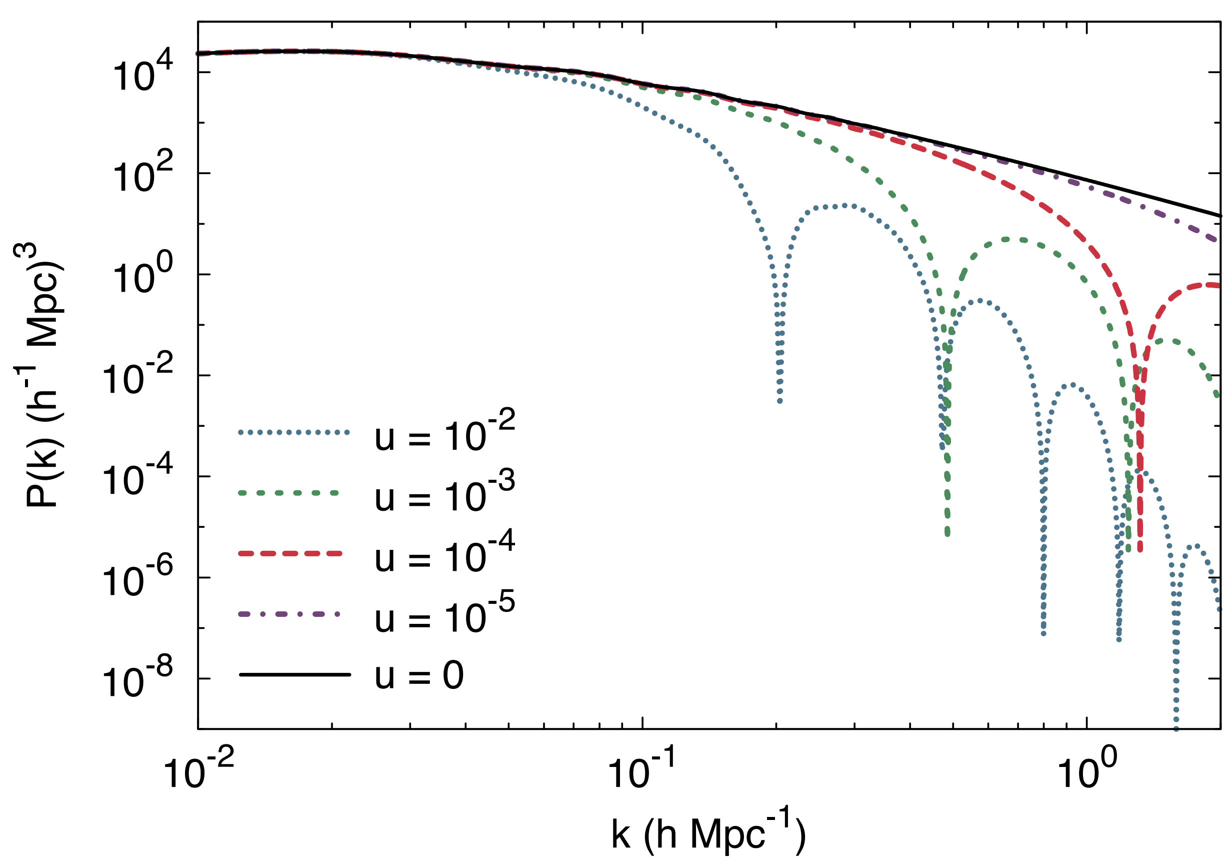


The free-streaming scale can be computed generically
The collisional damping scale cannot.

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

If coupled to neutrinos or photons
(or baryons, or self-interacting, provided that the cross section is very large)





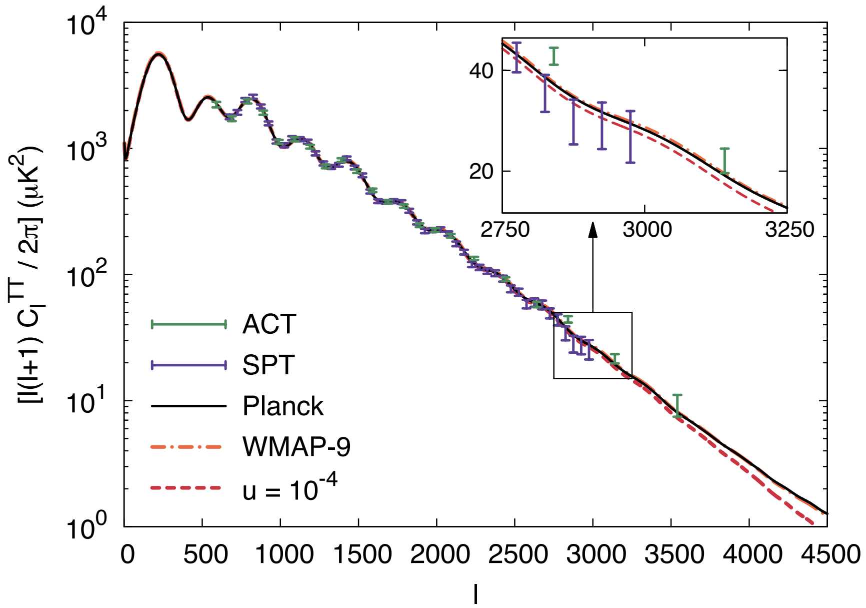
R. Wilkinson, J. Lesgourgues, C. Boehm: arXiv:1309.7588

(same as C. Boehm, Riazuelo, S. Hansen, R. Schaeffer : astro-ph/0112522)

PART IV

D. Cosmology predictions from alternative WIMPs

Why alternatives to CDM ?

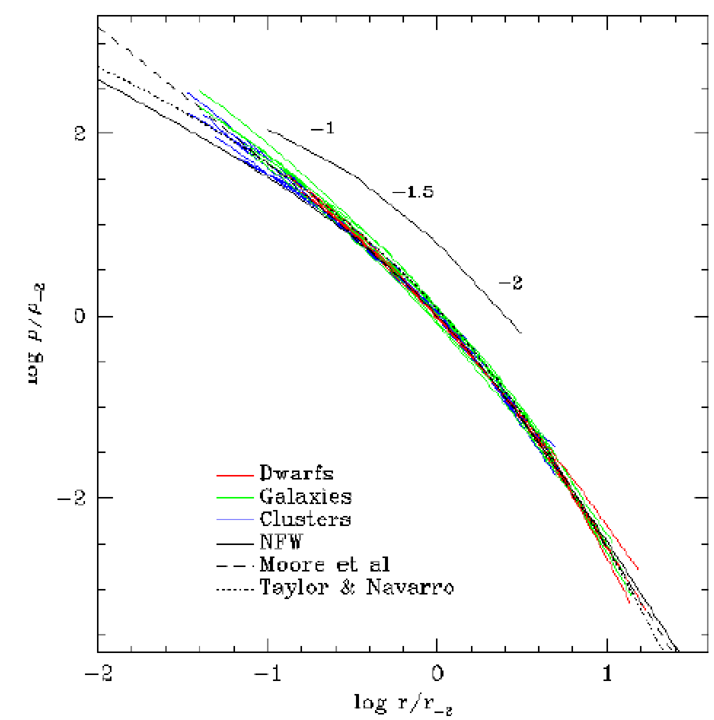


testing alternatives is
a mean to probe CDM itself!

3 problems

1) Milky Way satellites

Our own Milky Way halo contains subhalos.
Each/Some of them contain galaxies which are called satellites
At present we don't detect as many as predicted by CDM



2) DM halo profile of dwarf galaxies

Observed profiles are not NFW (unlike CDM predictions)

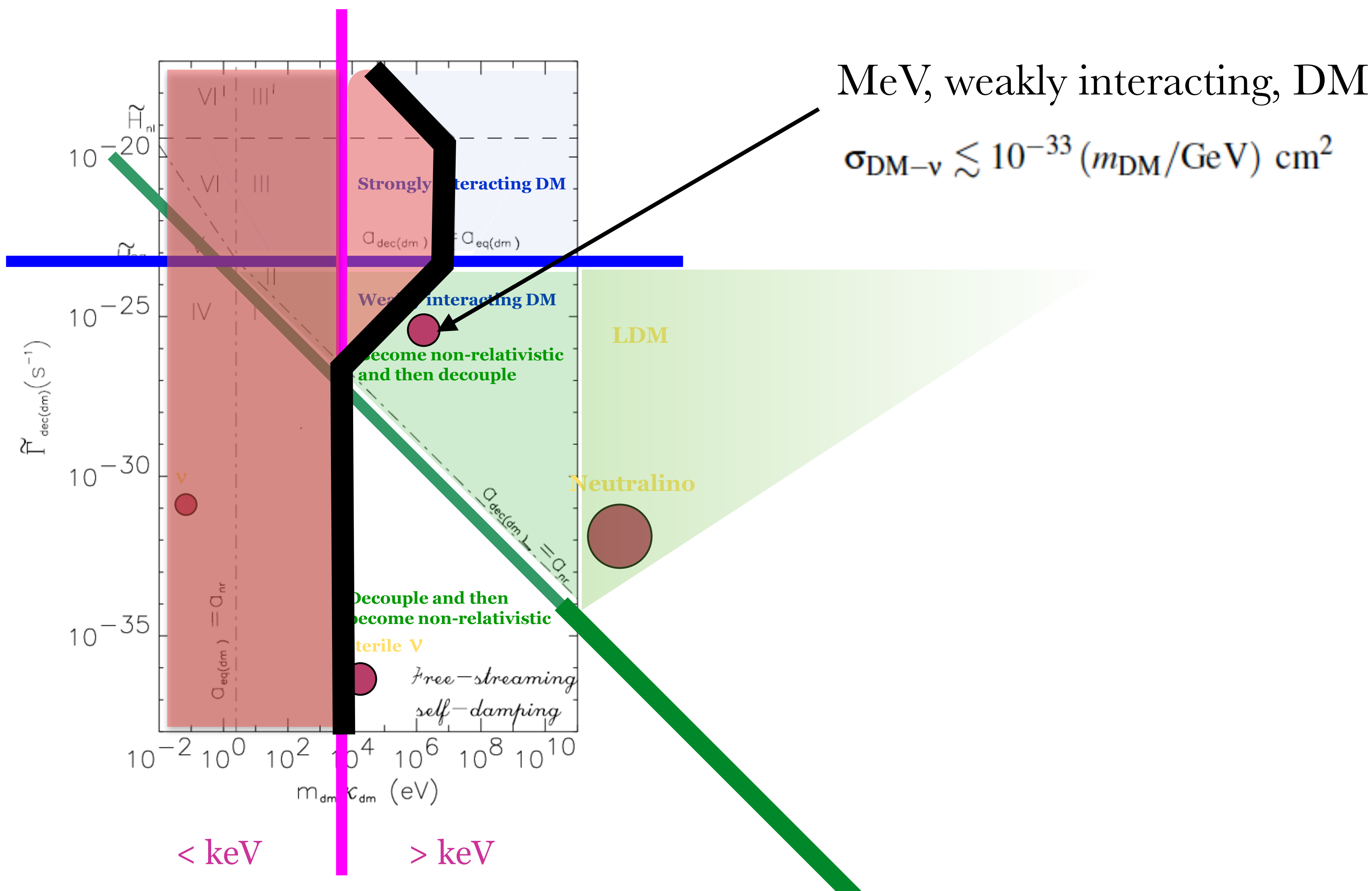
3) Too big to fail

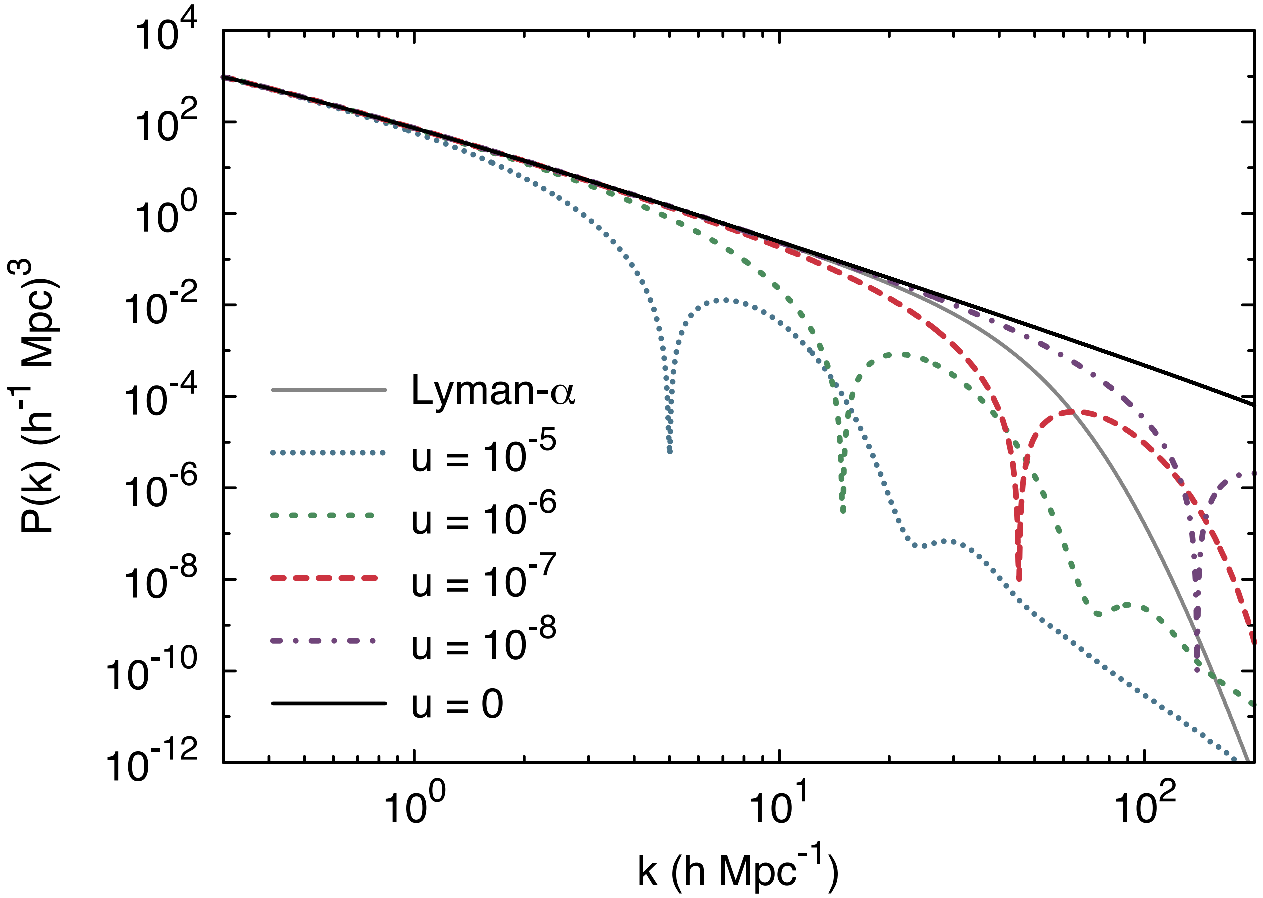
Some MW companion galaxies that are predicted in CDM are too big not to form stars
so there should be visible. Yet they can't be found in surveys.

Interacting DM

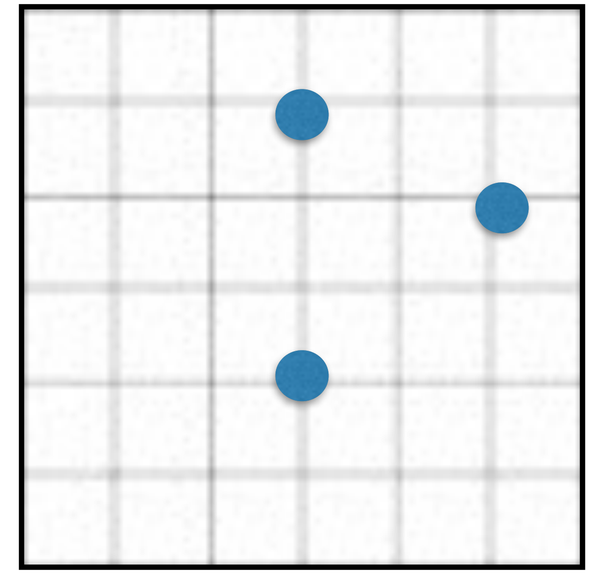
The main damping mechanism comes from the collisions!

The free-streaming length is not necessarily negligible but ...



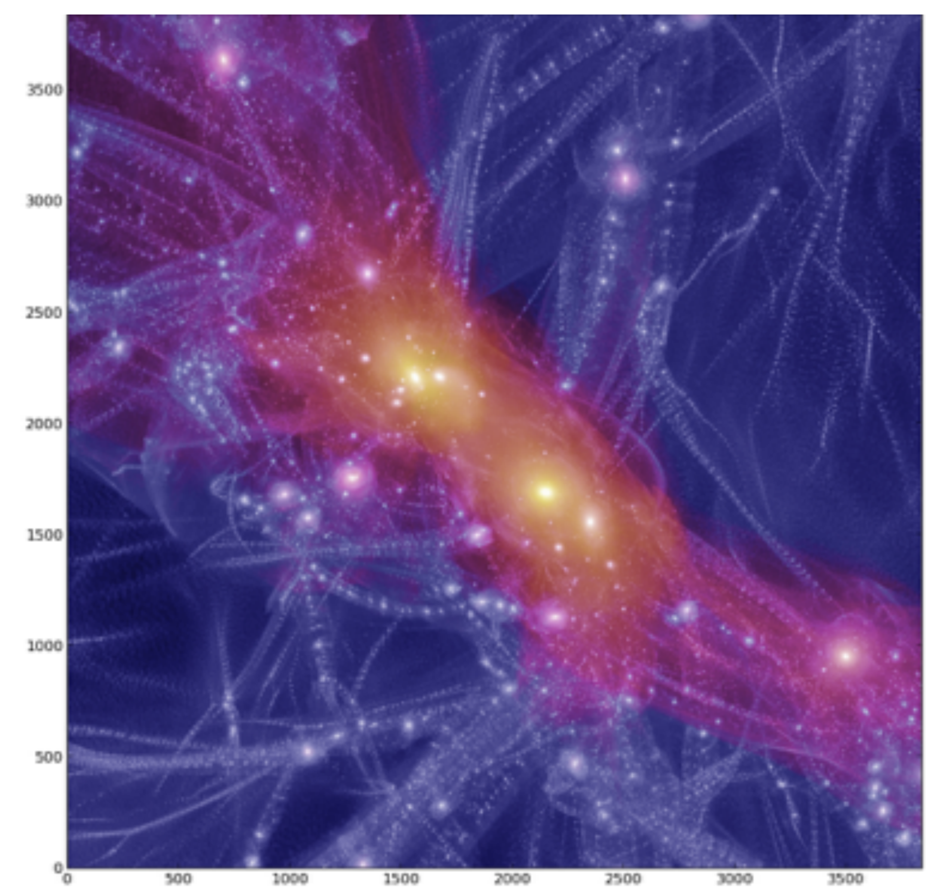


DM = IDM

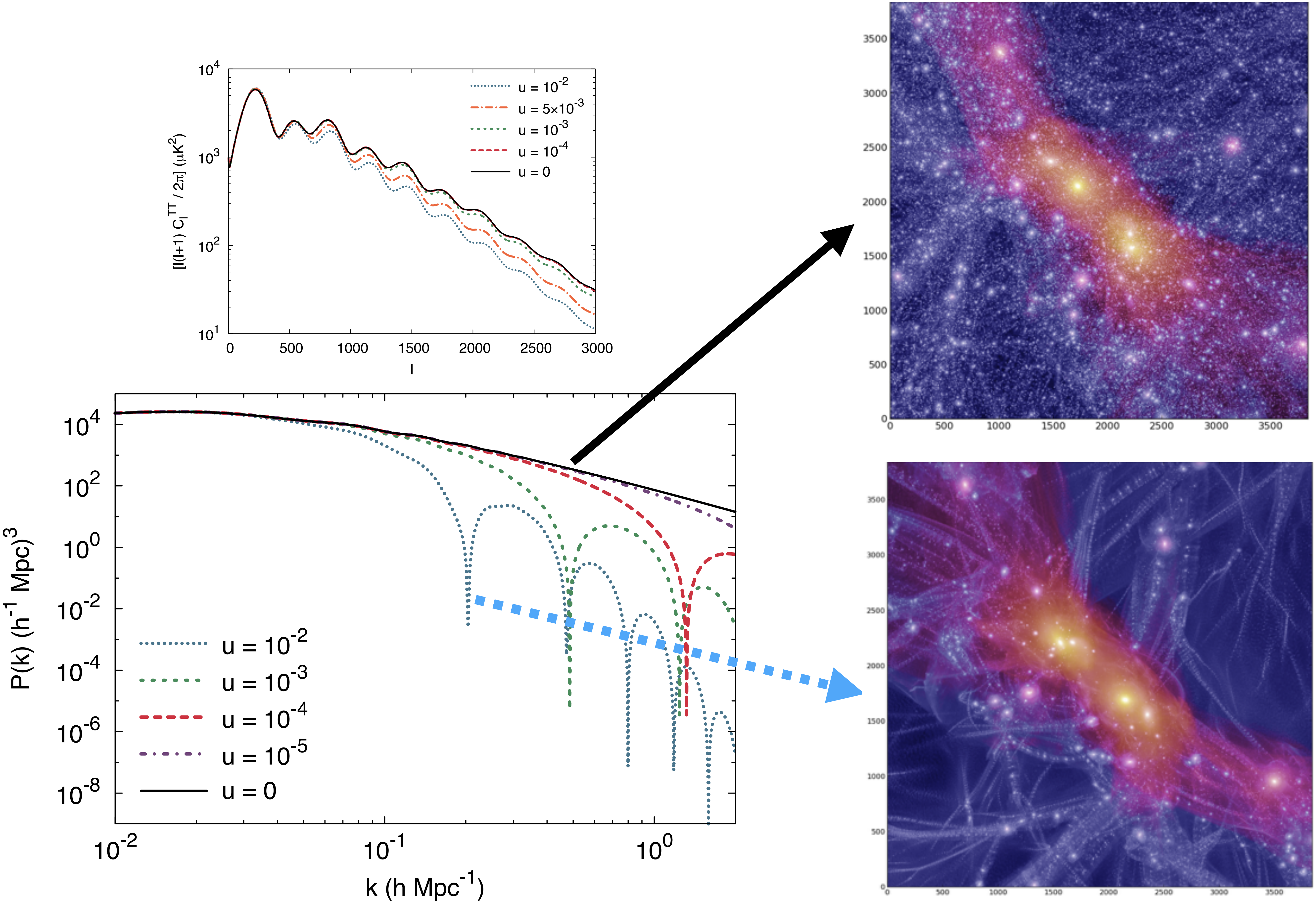


grid + Newtonian gravity

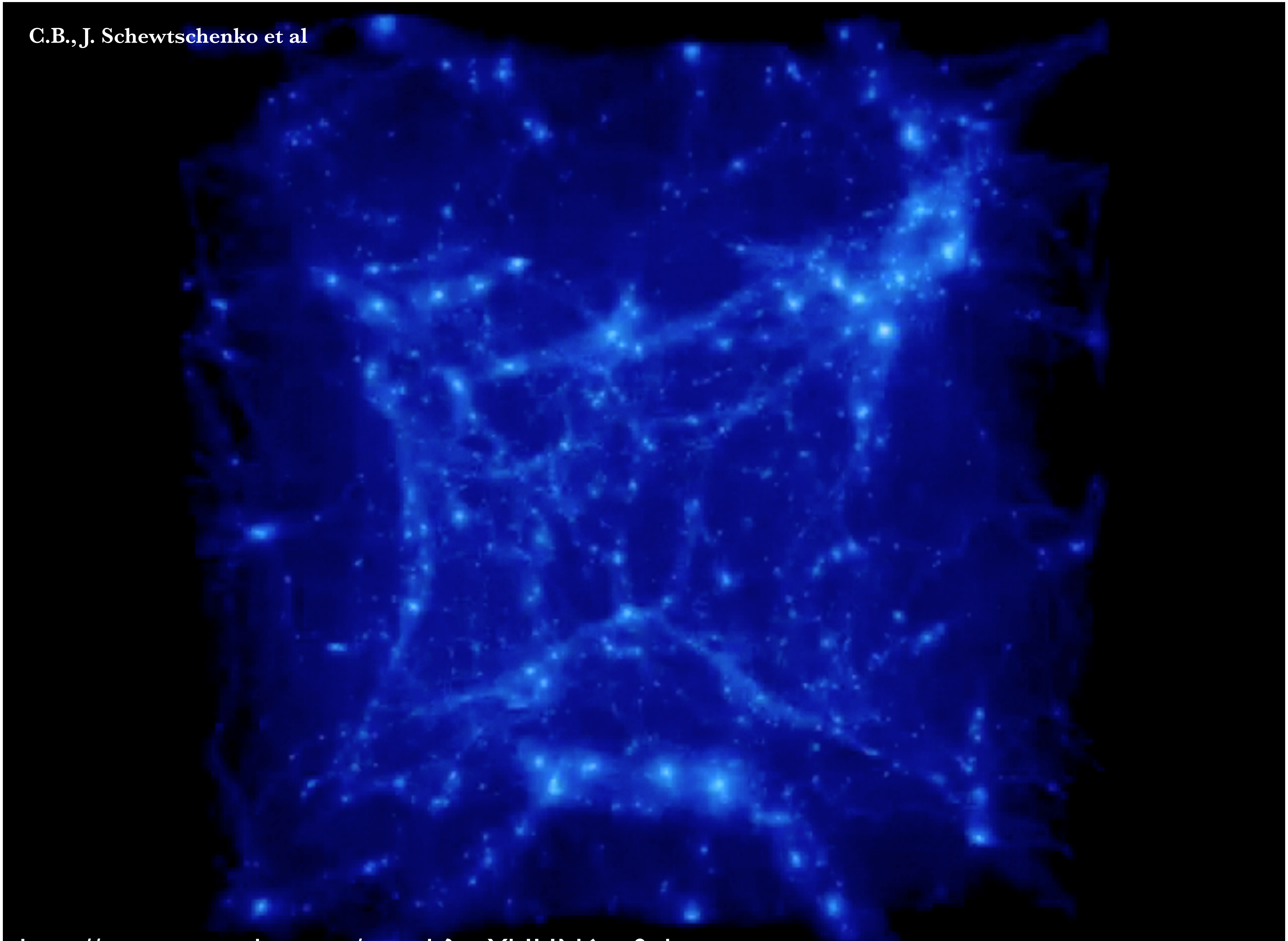
linear and non linear evolution



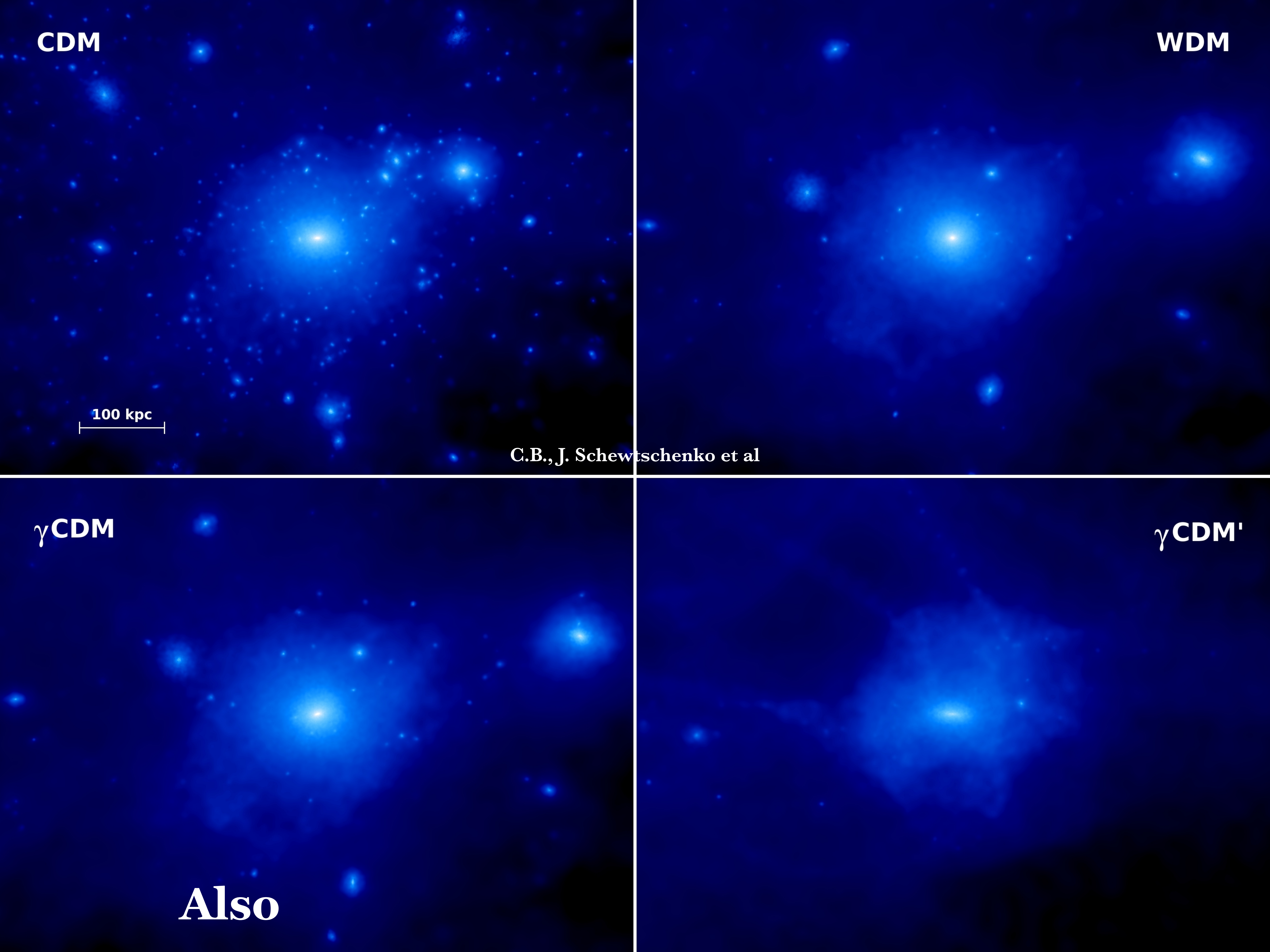
What would the Universe look like if DM interactions?

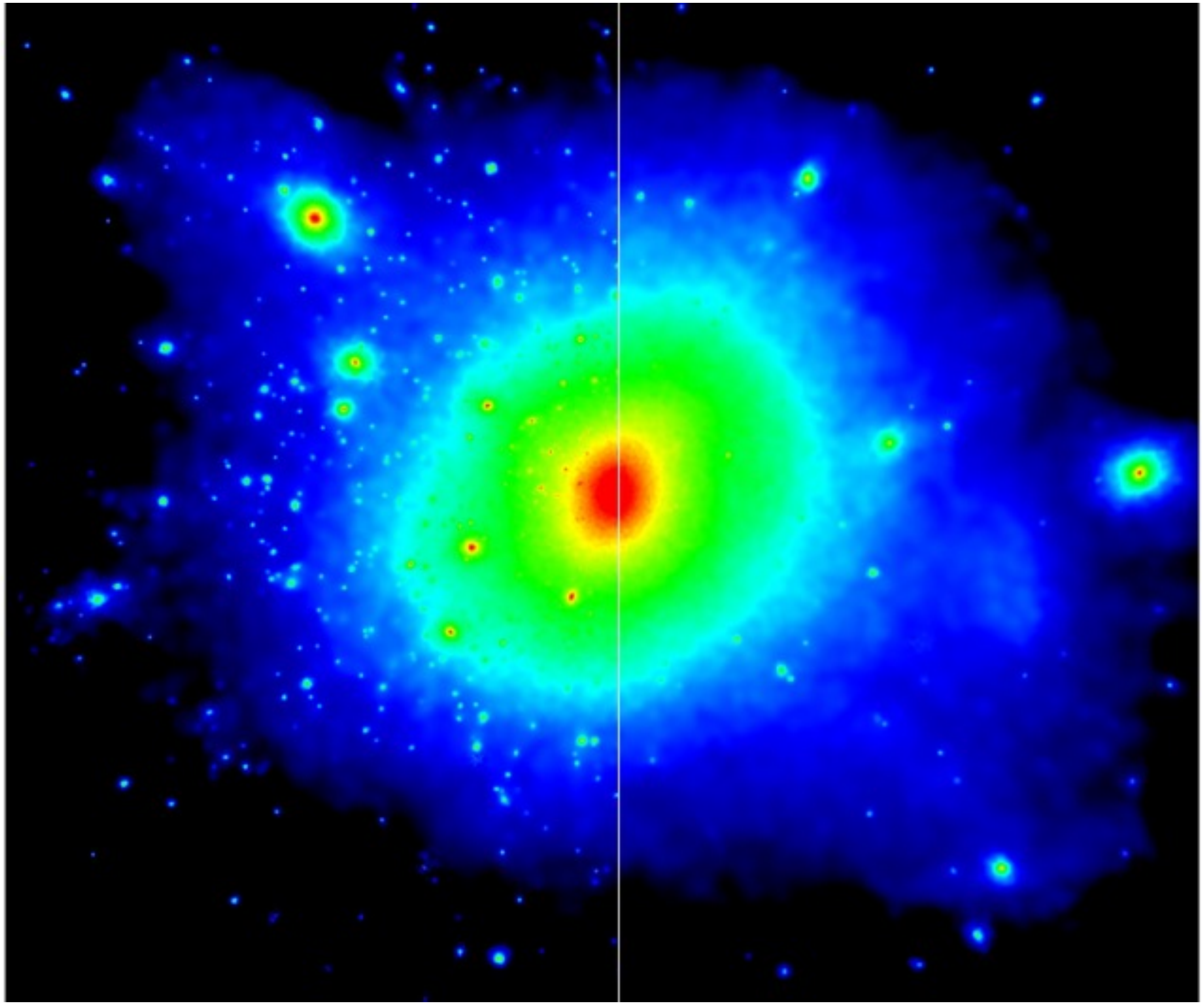


What would the Milky Way look like if DM interactions?



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


CDM
WDM
100 kpc
C.B., J. Schewtschenko et al
γCDM
γCDM'
Also



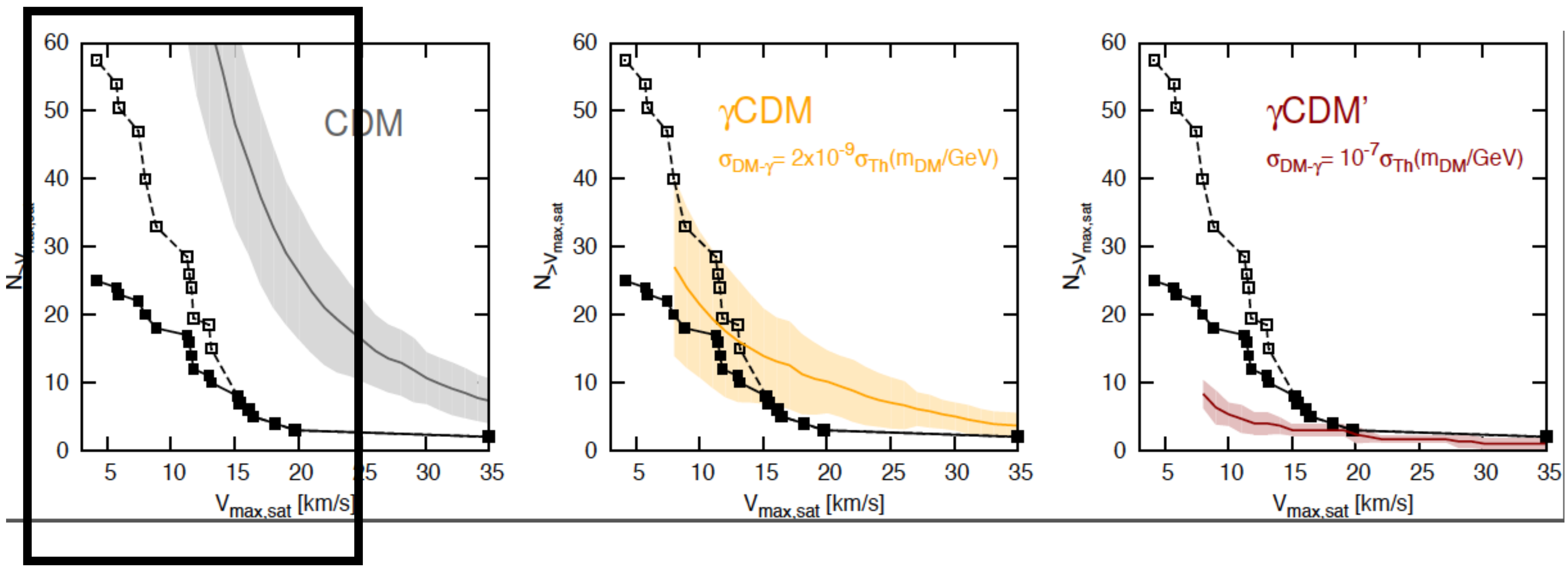
Translation in terms of numbers of satellite galaxies

C. Boehm, 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



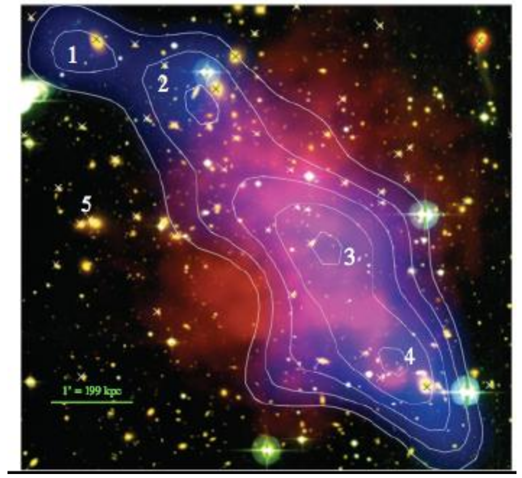
small satellites

Solve the MW satellite problem!

Sterilise the MW!

self - interacting DM

Galaxies are correlated with DM

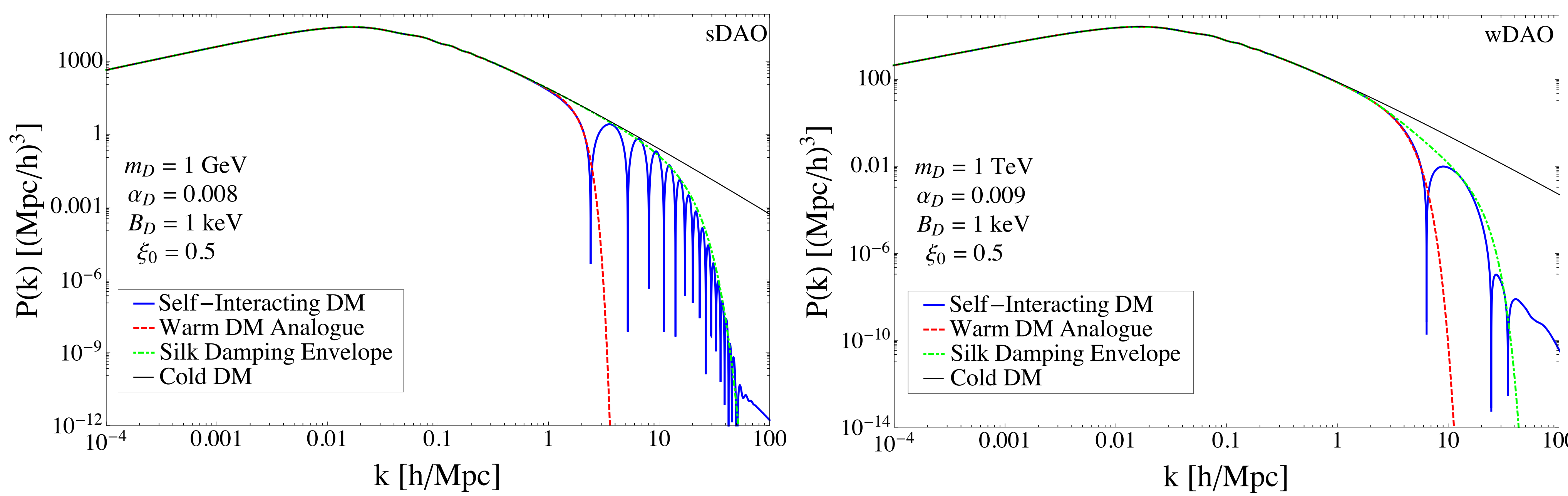


Cosmic wreck train

Galaxies are not correlated with DM

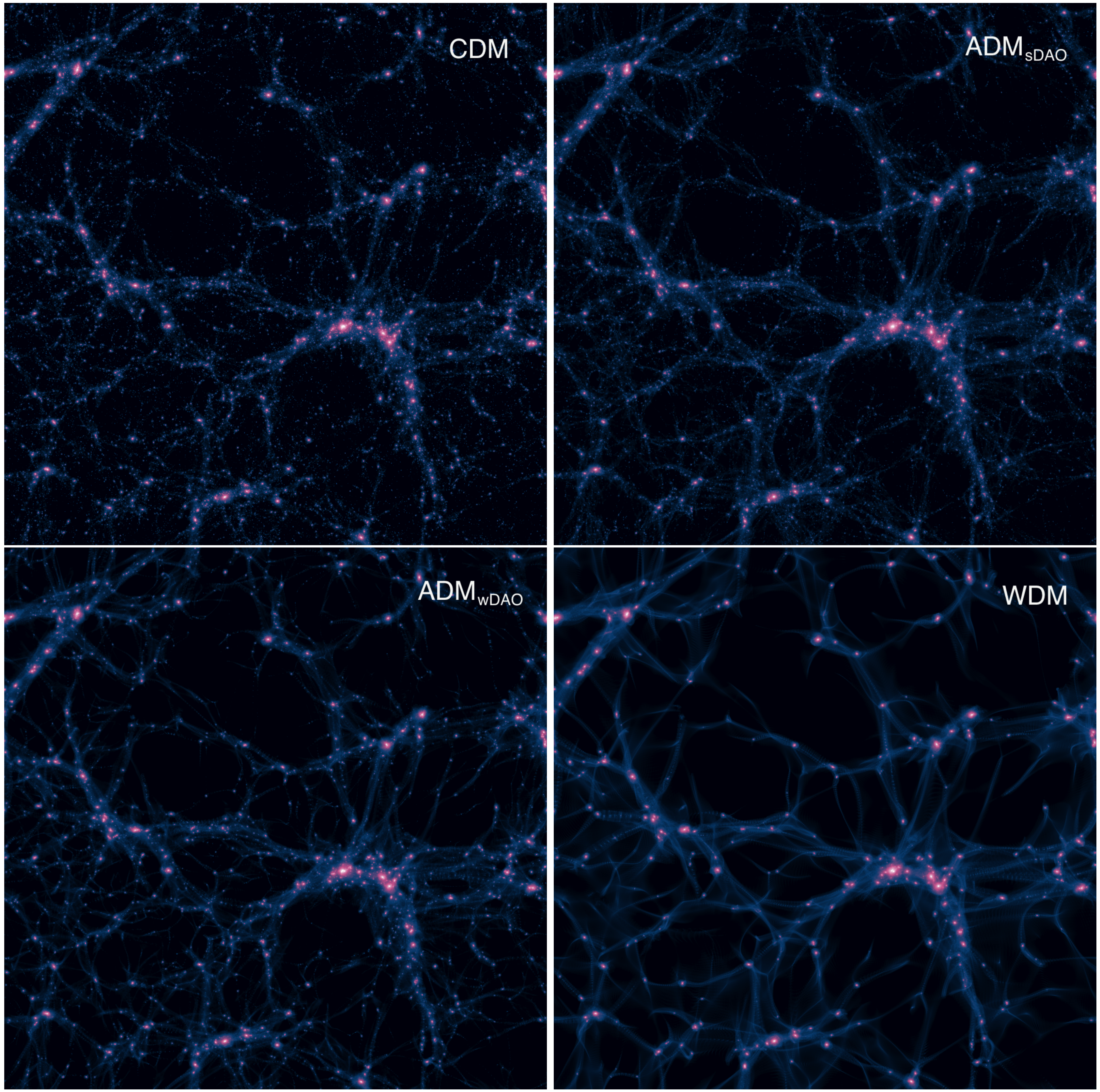
The cross section needs to be ~ Thomson
You need the same type of configurations

1405.2075



Self - interacting DM

1405.2075



Decaying DM

1406.0527

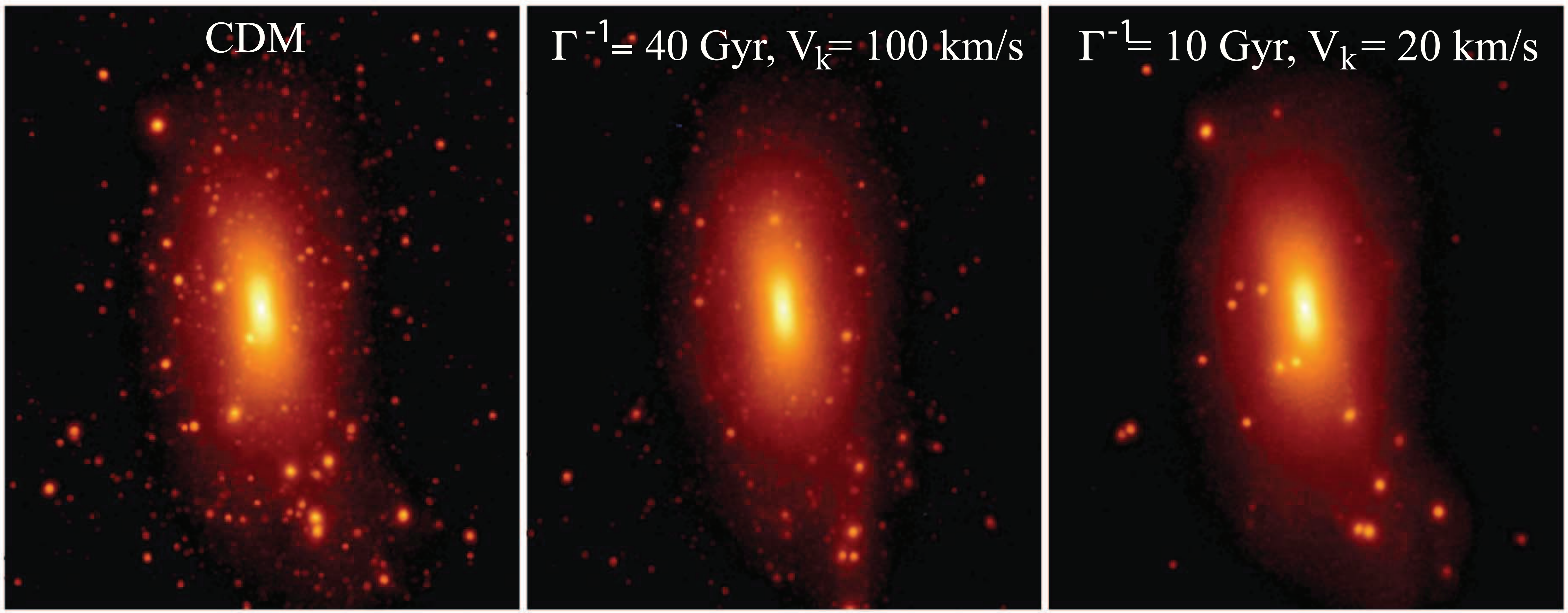
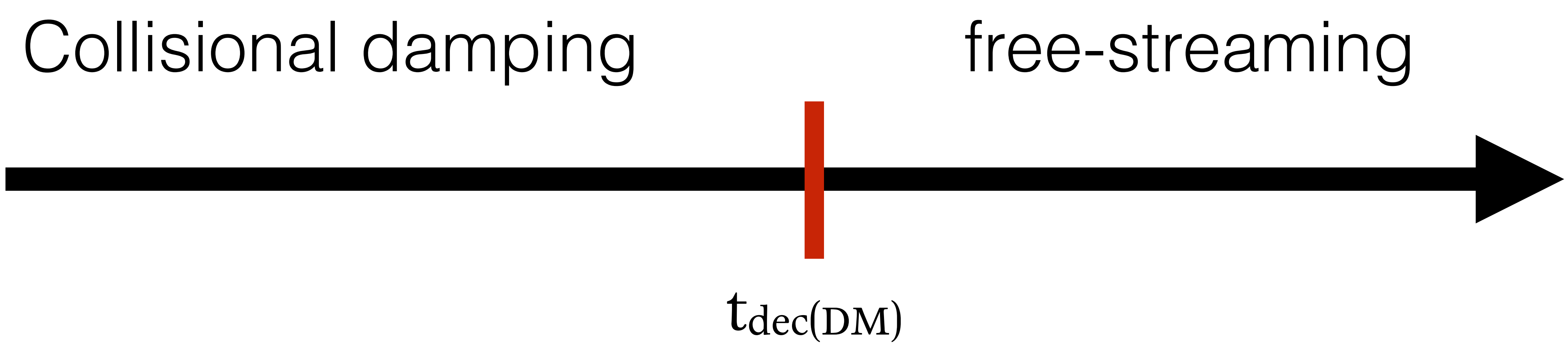


Figure 2. Small-scale structure in a Milky Way mass halo (Z12) in CDM (left) and DDM models with Γ^{-1} = 40 Gyr and V_k = 100 km/s (middle) and Γ^{-1} = 10 Gyr and V_k = 20 km/s (right) within 260 kpc of the halo centers at $z = 0$. The color scheme indicates the line-of-sight projected square of the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

WDM



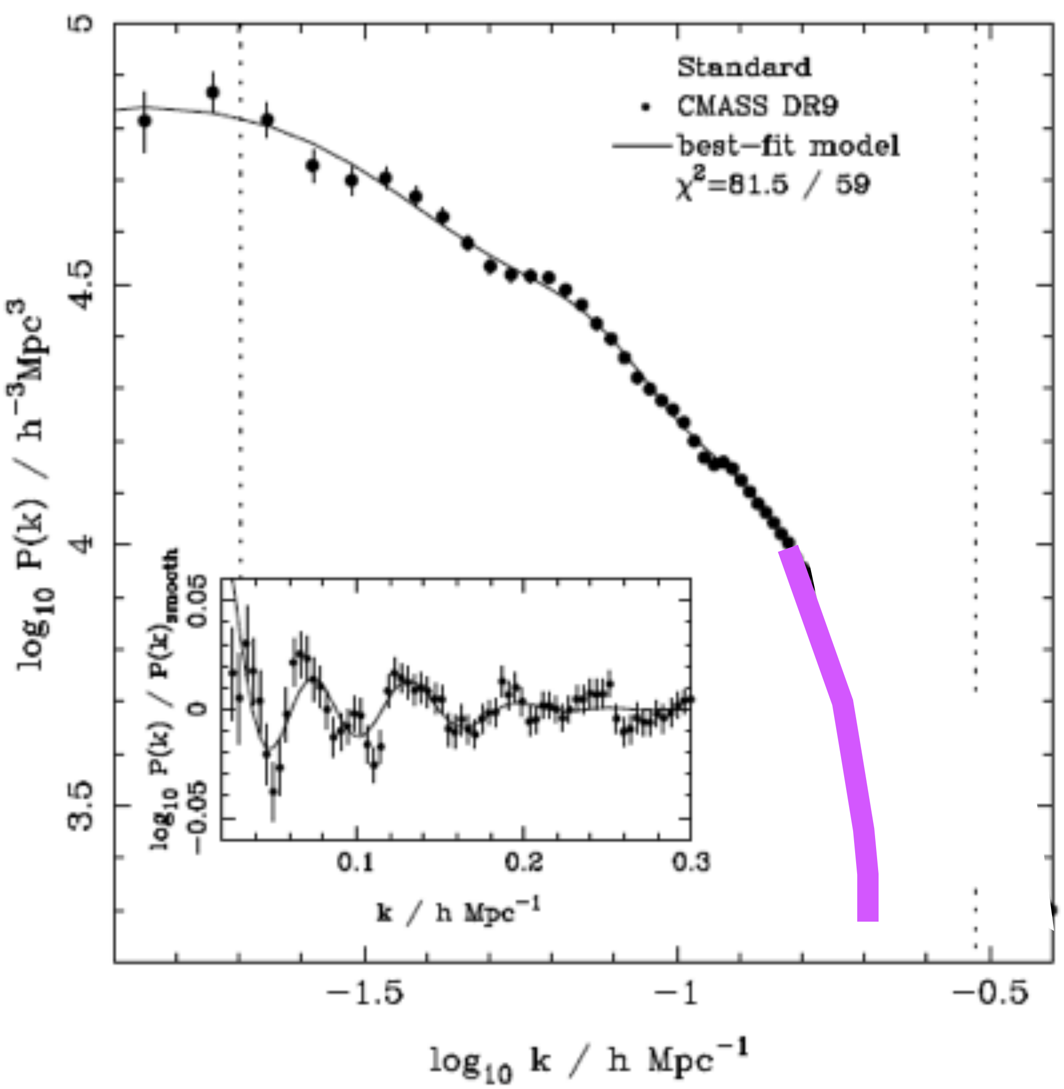
$$l_{id}^2 \sim \frac{2\ \pi^2}{3} \int_0^{t_{\rm dec(dm-i)}} \frac{\rho_{\rm i}\ v_i^2}{\rho_t\ a^2\ \Gamma_{\rm i}} dt$$

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

candidates with a damping length of about ~100 kpc

But in everybody's mind, WDM= candidates with a free-streaming length of about ~100 kpc

WDM

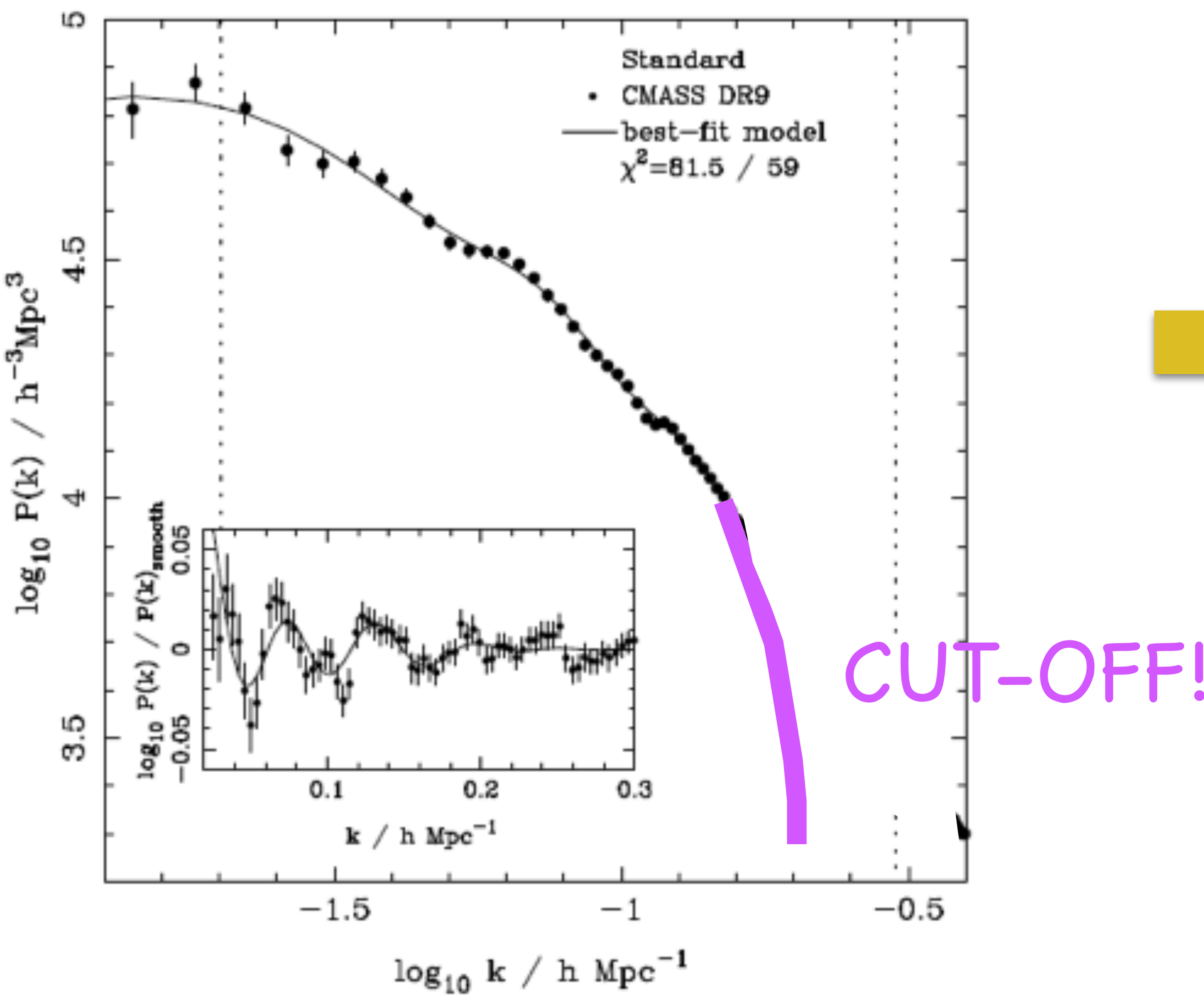


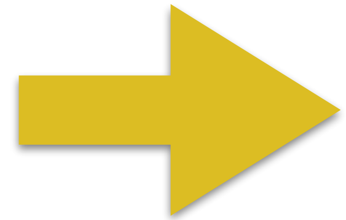
The cut-off is determined by the free-streaming scale and should be about 100 kpc

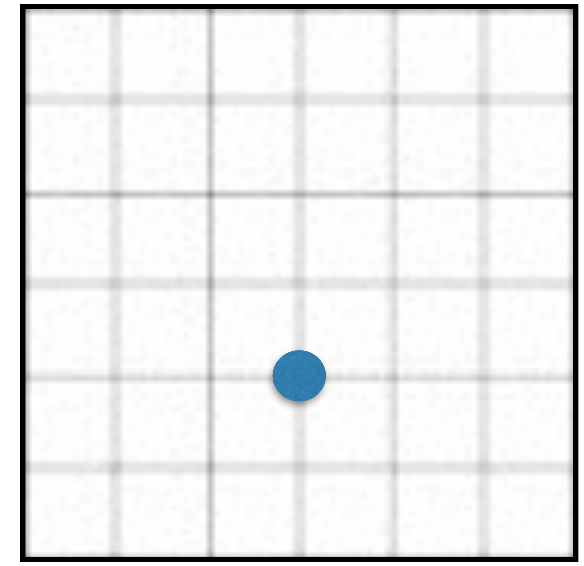
$$l_{fs} \propto m_{\rm DM}^{-4/3}$$

This translates into a DM mass of a few keV

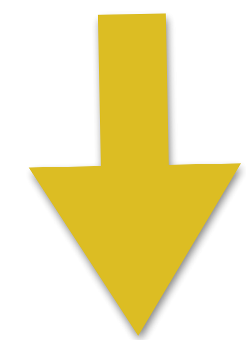
the scale moves with the observations!



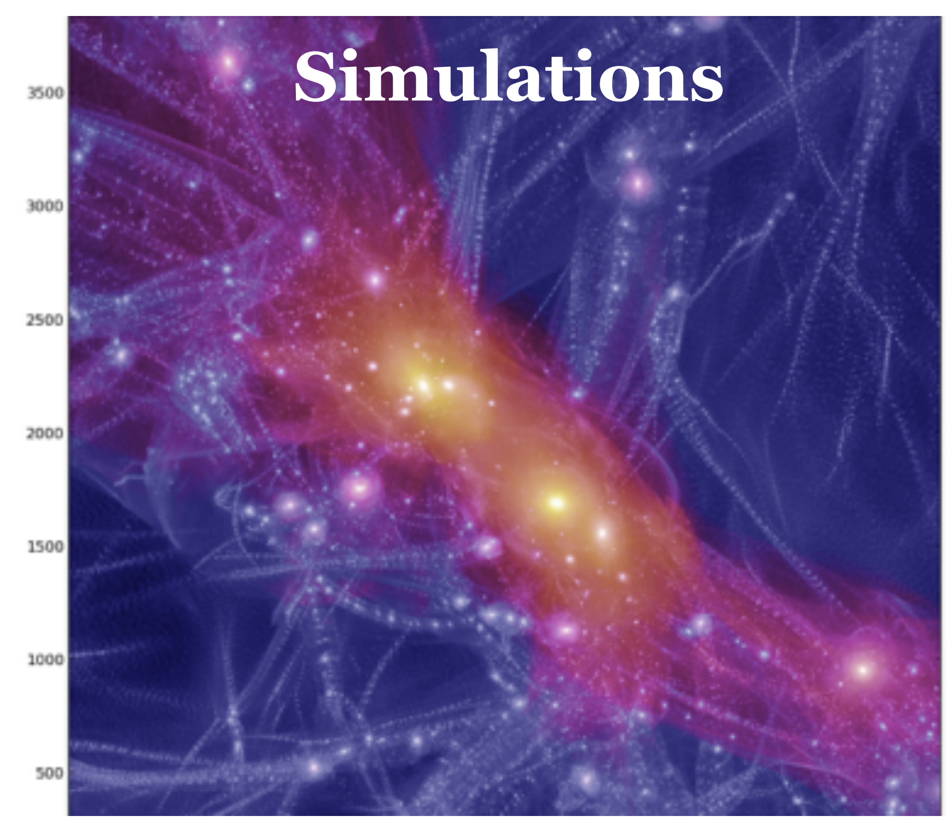




grid +
Newtonian gravity



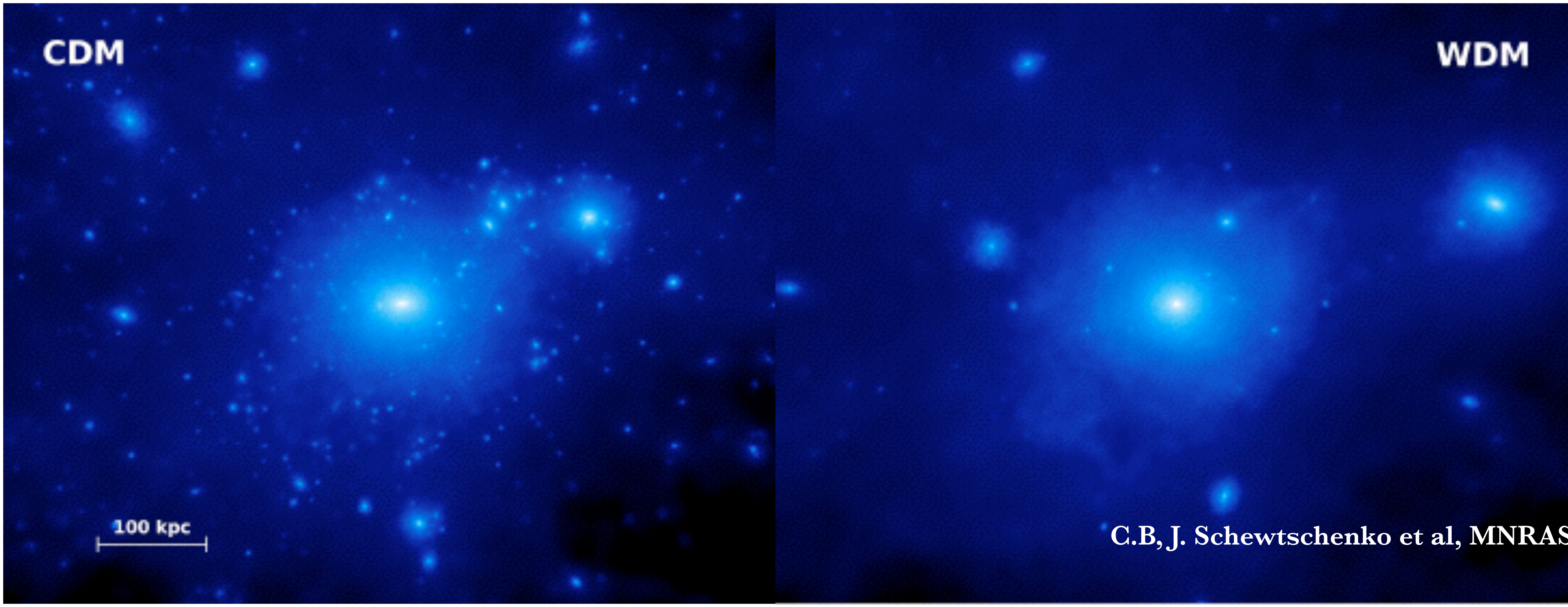
no interaction



DM particles must be heavy

Heavy particle; mass unspecified

Particle of a 3 keV

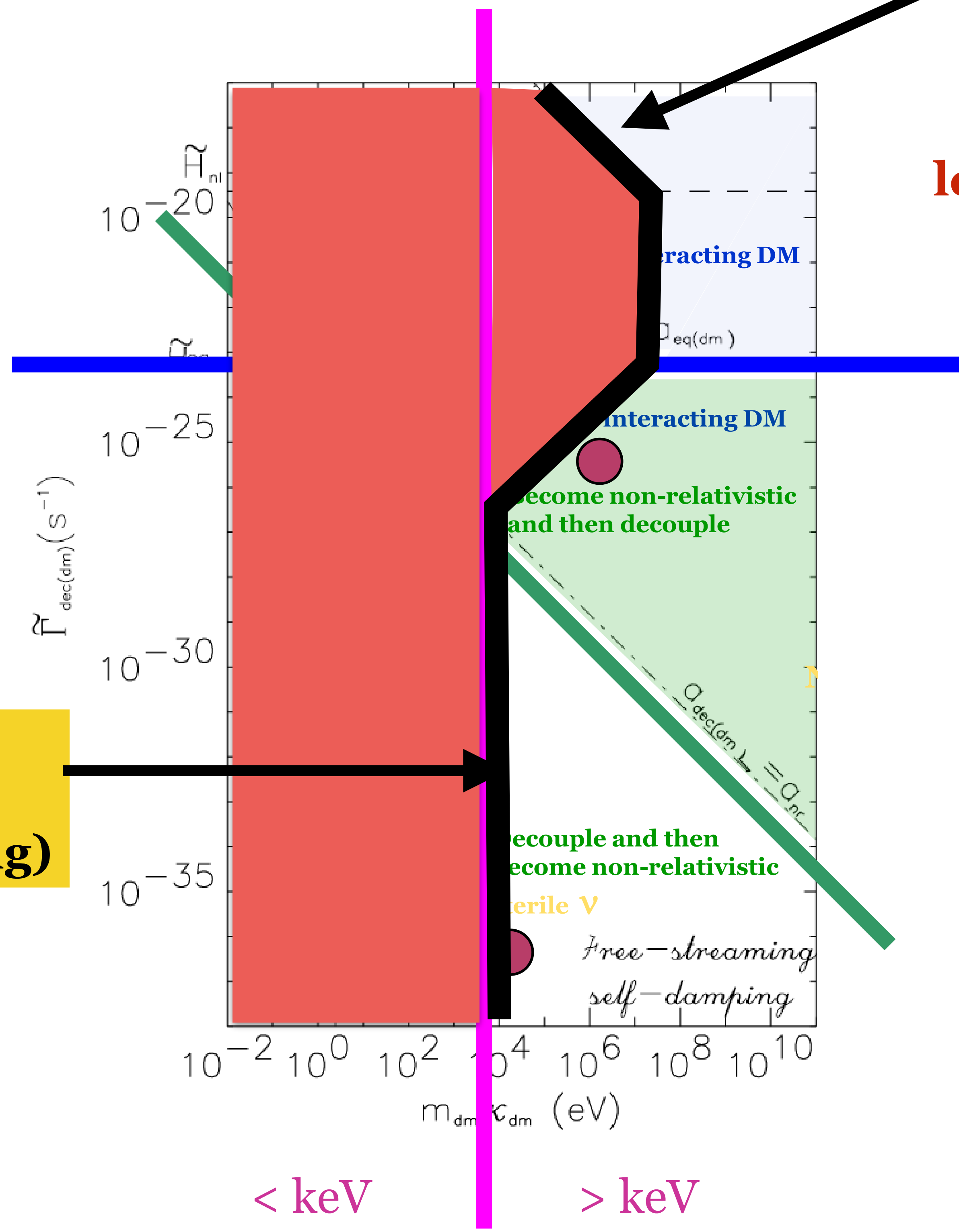


WDM

candidates with a f.s. length of about 100 kpc

but maybe their **collisonal damping length is larger though!**

=> prohibitive cut-off

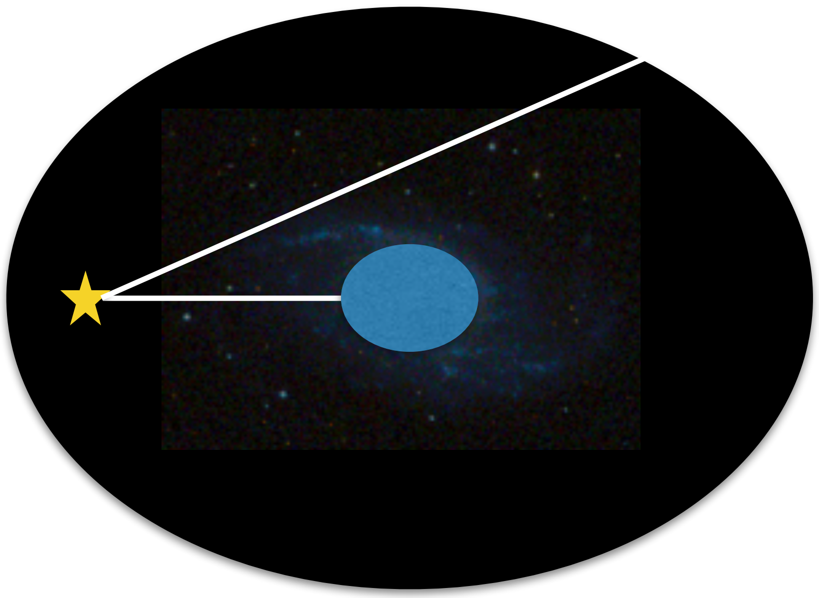


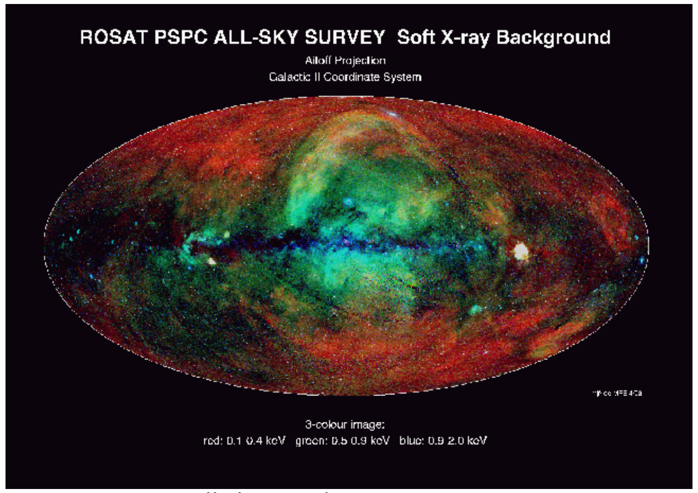
sterile neutrino (just free-streaming; no collisional damping)

PART V

E. Beyond WIMP DM candidates and particle physics

Can DM explain anomalous e.m. signals in the galaxy?

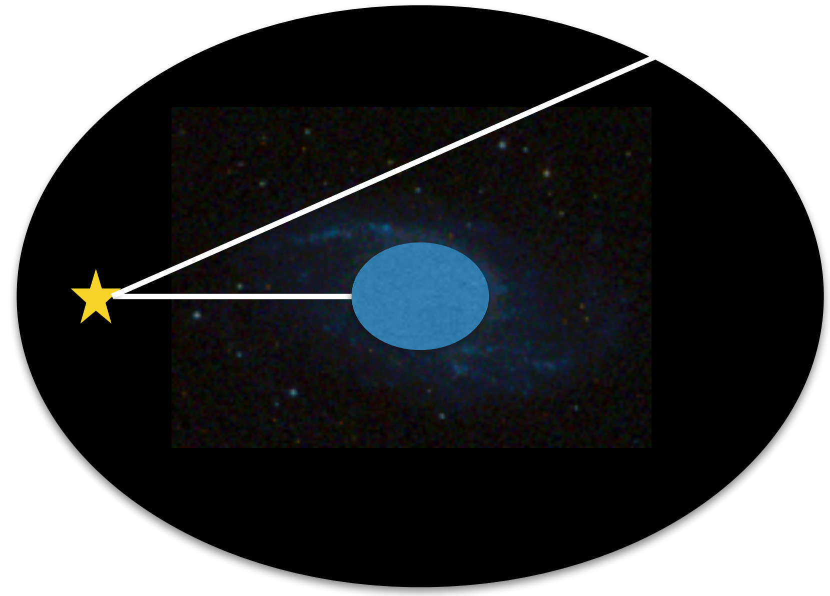




Rosat, Xray, all sky, credit MPE

Emission maps from the galaxy, X-ray, Gamma-ray, …

Can DM explain anomalous e.m. signals in the galaxy?



$$r = \sqrt{l^2 + d^2 - 2\,d\,l\,\cos\psi}, \qquad l_\pm = d\,\cos\psi \pm \sqrt{r^2 - d^2\,\sin^2\psi}$$

where $a = \sqrt{r^2 - d^2\,\sin^2\psi}$ and where $l_+ = l_- + 2a$

$$\int dl\,\left[\frac{\rho_{dm}}{\rho_0}\right]^2 = \int_b^{r_m} dr \frac{1}{r^{2\gamma-1}\,\sqrt{r^2-b^2}}$$

where $r_m < r_s$ and $b = d\,\sin\psi$. Using now $v^2 = (r^2 - b^2)/b^2$ we find that

$$\int dl\,\left[\frac{\rho_{dm}}{\rho_0}\right]^2 = \left(\frac{r_s}{b}\right)^{2\gamma} b \int_0^{\frac{\sqrt{(r_m^2-b^2)}}{b}} \frac{dv}{(1+v^2)^{2\gamma/2}}$$

$$= \left(\frac{r_m}{b}\right)^{2\gamma} b\,\left[I_\gamma(v)\right]_0^{\frac{\sqrt{(r_m^2-b^2)}}{b}}$$

NFW!

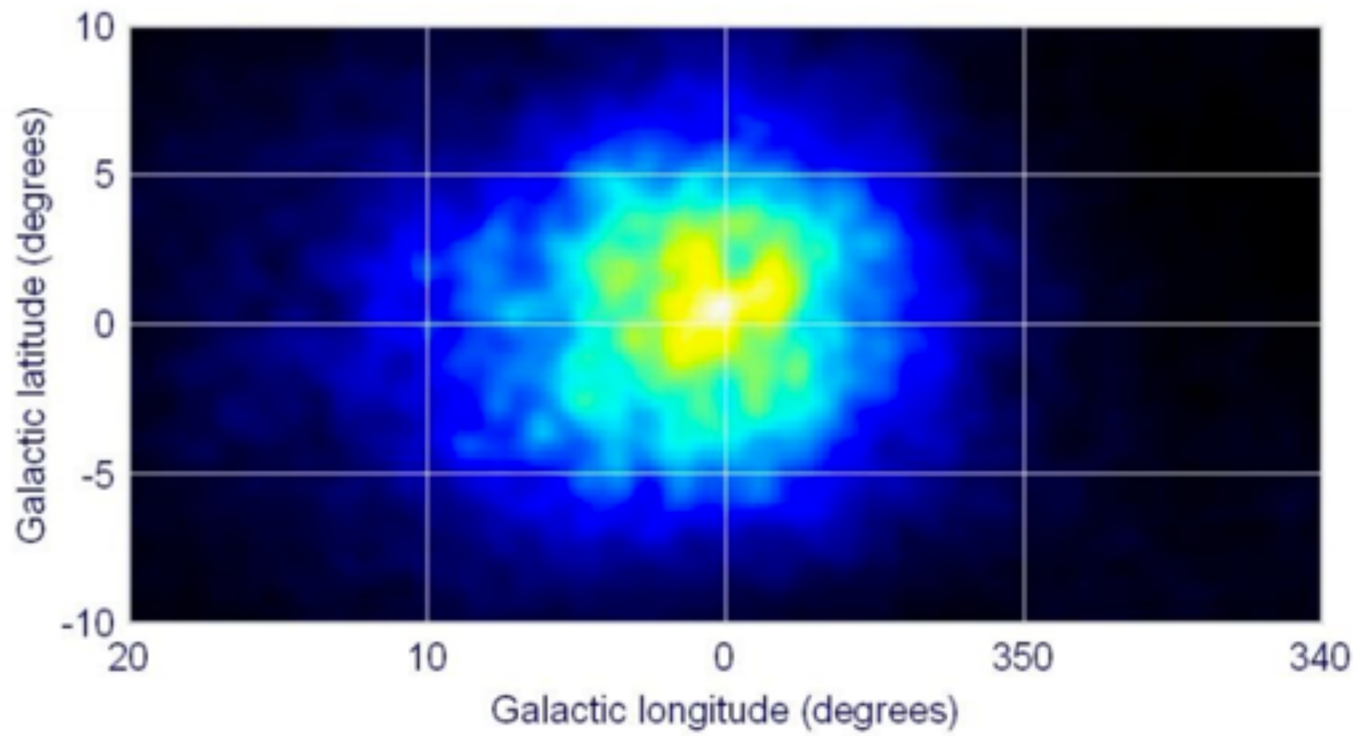
$$\left[I_1\right]_0^{\frac{\sqrt{(r_s^2-b^2)}}{b}} = \arctan\left(\frac{\sqrt{r_m^2-b^2}}{b}\right)$$

NFW

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

$$\begin{aligned} \phi_X \simeq \; & 6 \times 10^{-5}/\mathrm{cm}^2/\mathrm{s} \left(\frac{\sigma v}{10^{-26}\mathrm{cm}^3/\mathrm{s}}\right) \left(\frac{\rho_0}{0.3\mathrm{GeV}/\mathrm{cm}^3}\right)^2 \\ & \times \frac{g_X}{2} \times \left(\frac{m_{dm}}{\mathrm{GeV}}\right)^{-2} \times \left(\frac{r_s}{8.5\mathrm{kpc}}\right)^2 \times \left(\frac{d}{8.5\mathrm{kpc}}\right)^{-1} \\ & \times \left[\zeta \arctan\left(\frac{\sqrt{r_s^2 - d^2\zeta^2}}{d\, \zeta}\right)\right]_{-\delta}^{+\delta} \qquad (20) \end{aligned}$$

MeV DM and 511 keV

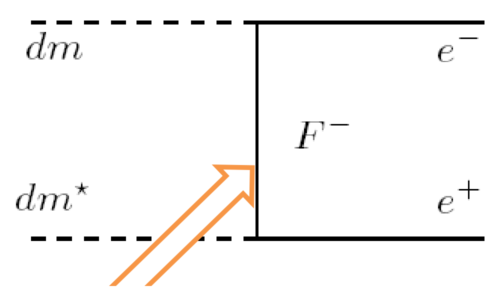


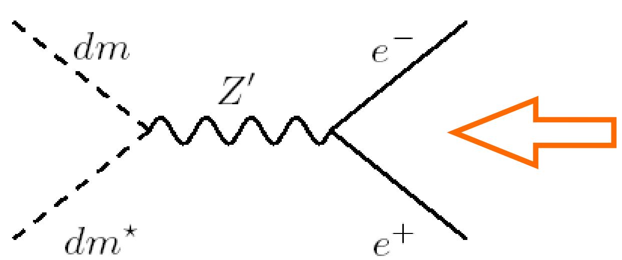
511 keV

DM DM -> e- e+

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

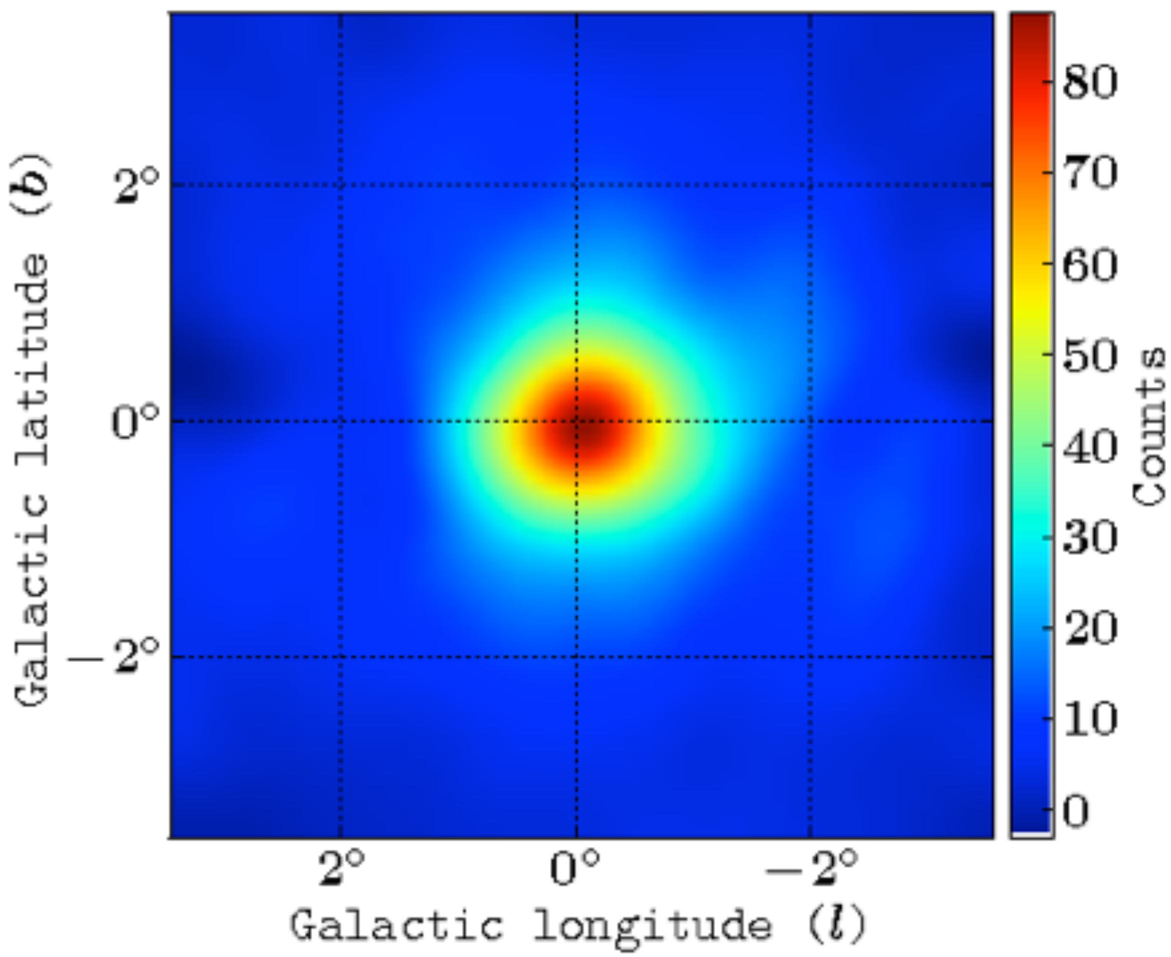
signal at LHC?





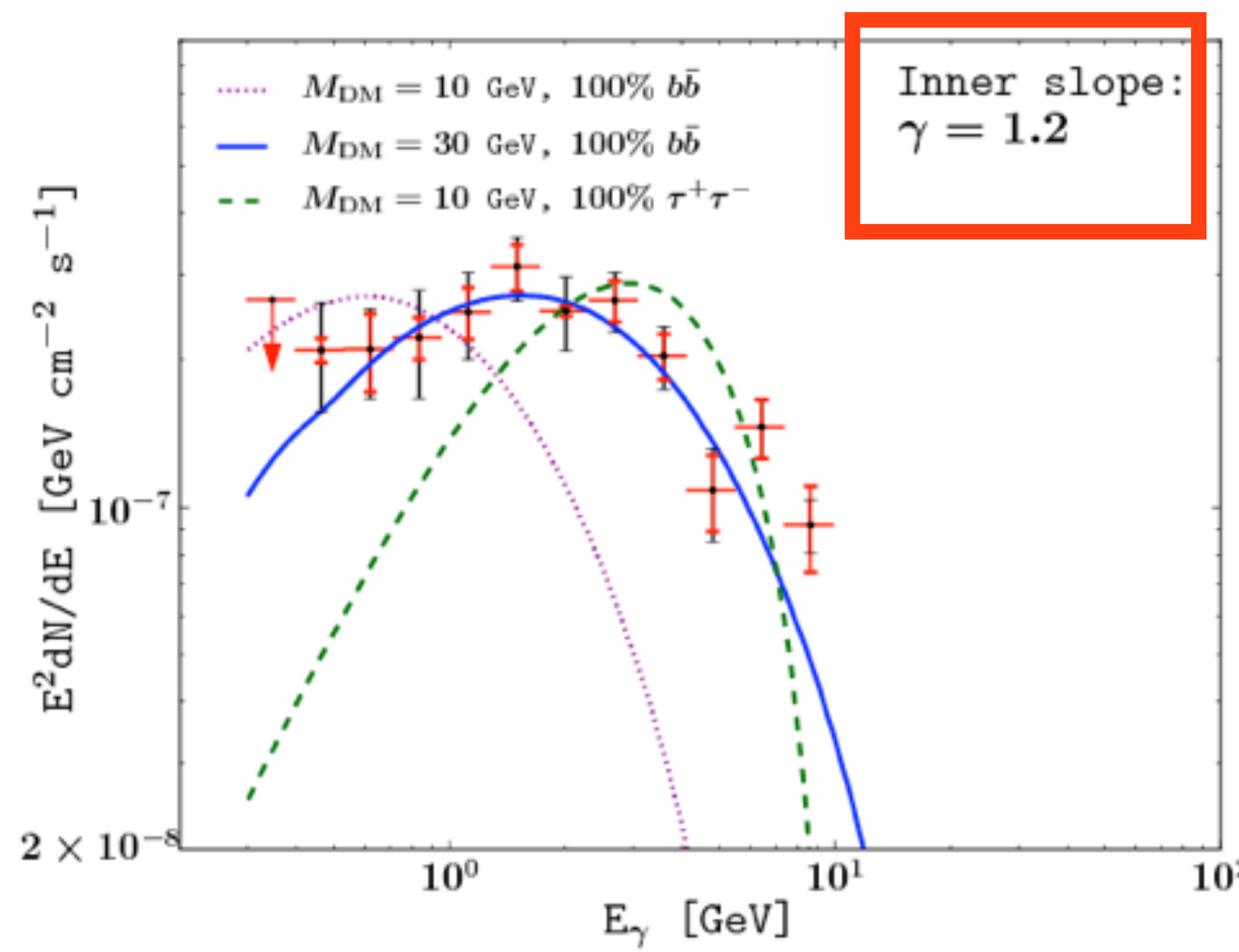
very constrained now

The GeV excess



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

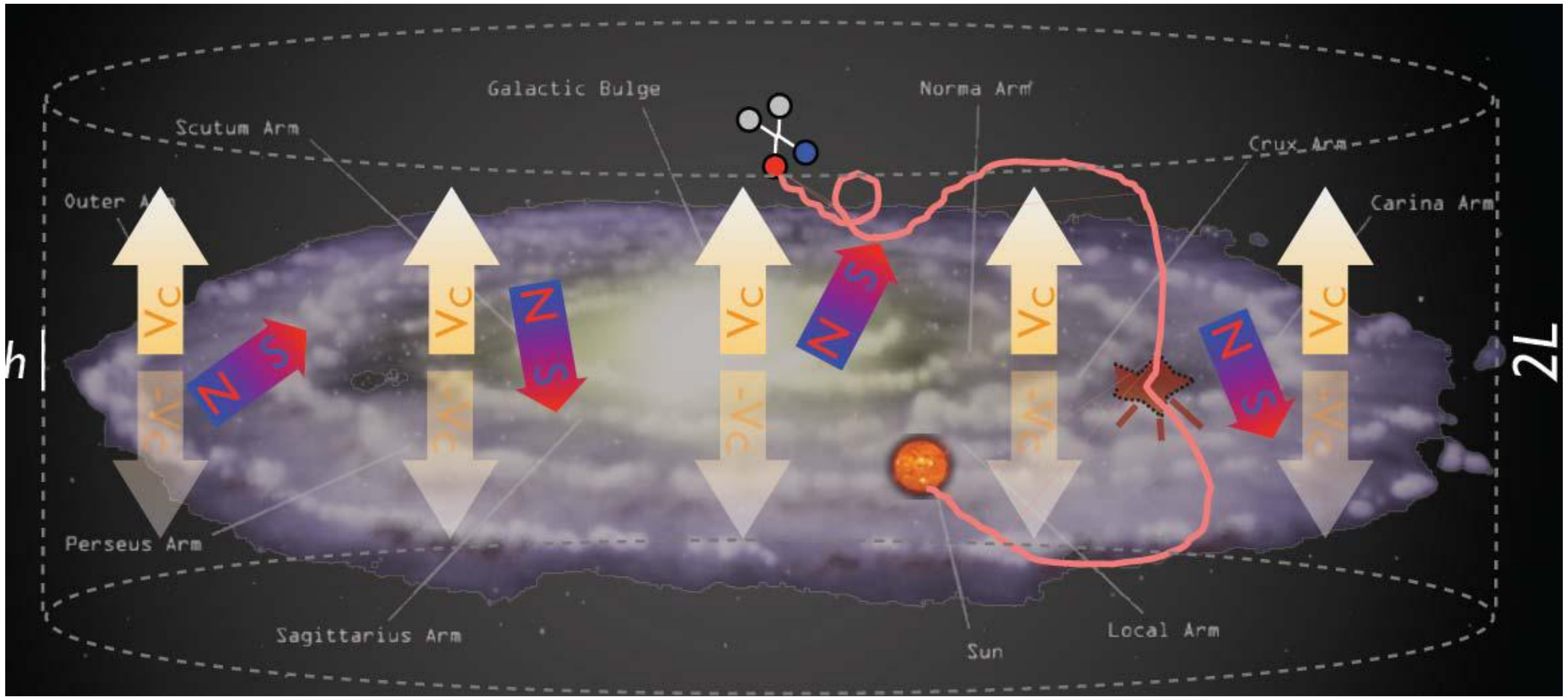
arXiv:1306.5725, Gordon et al
Hooper&Goodenough 2009
FERMI-LAT 2009



DM can produce cosmic rays which eventually produce electrons.
Electrons can diffuse spatially and lose energy.

- Propagation...

courtesy P. Salati



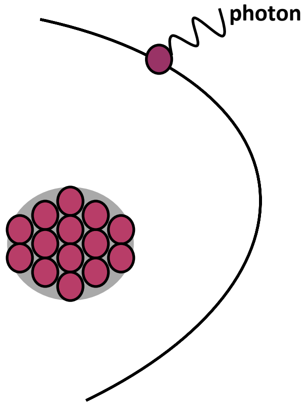
losses | source

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

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

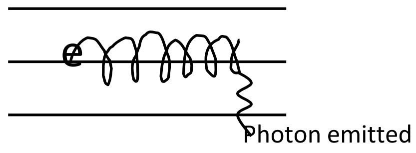
- **Bremsstrahlung**

$$b_{\text{brem}}(E) = 8\alpha_f r_e^2 n_e c E \left\{ \ln(2\frac{E}{m_e c^2}) - \frac{1}{3} \right\}$$



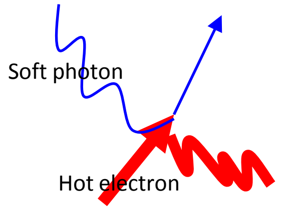
- **Inverse Compton & Synchroton**

$$b_{\text{IC/sync}}(E) = \frac{4}{3}\sigma_T c \beta^2 \gamma^2 U_{\text{cmb/mag}}$$



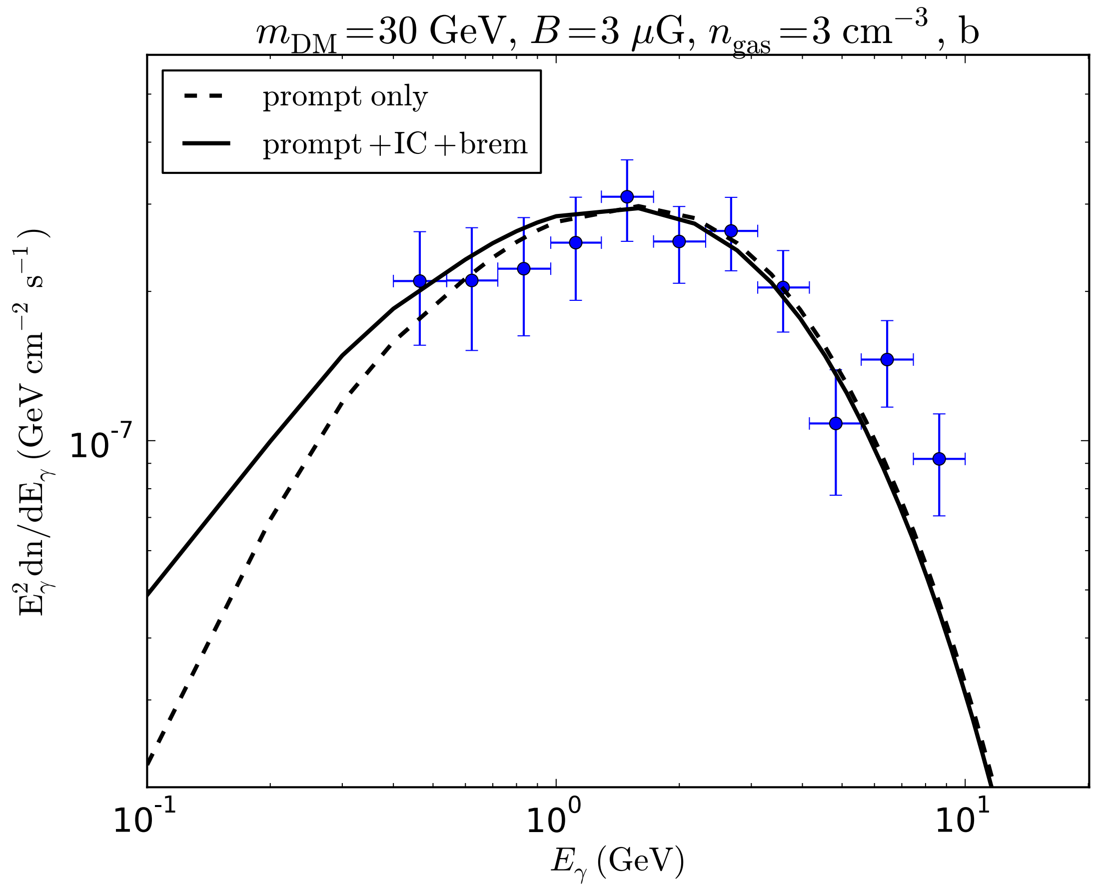
- **Coulomb interactions**

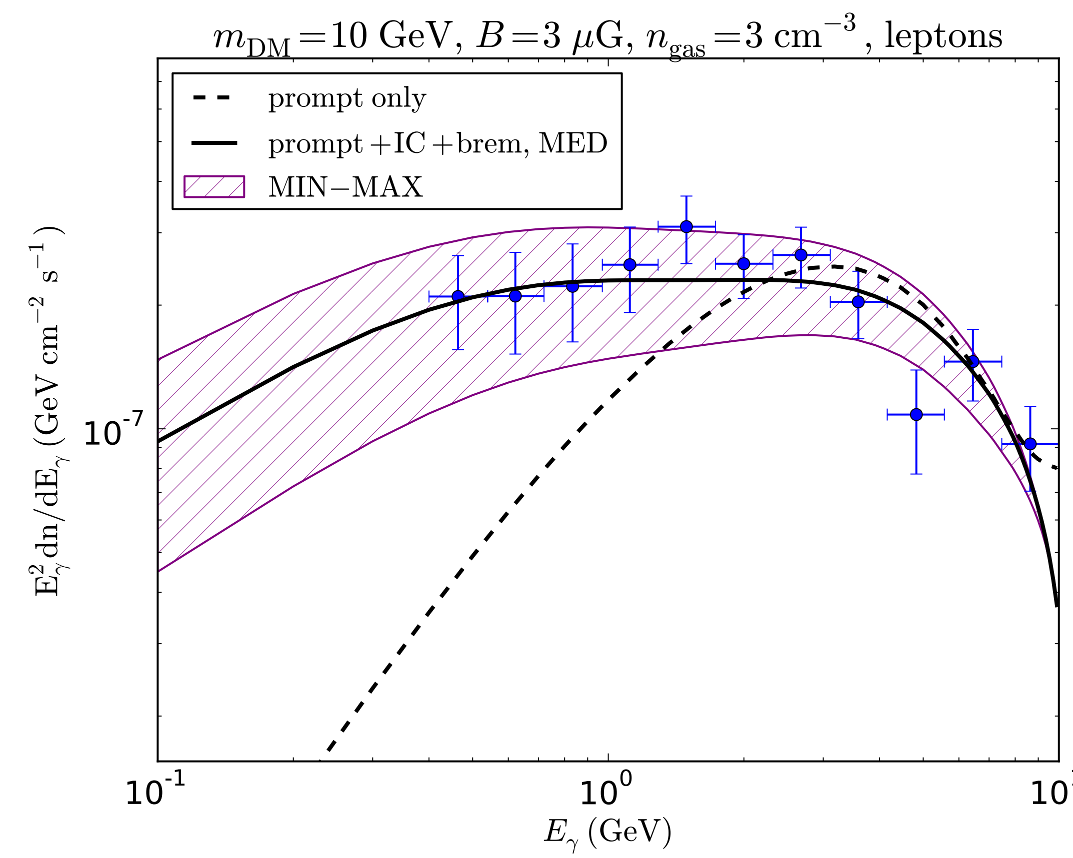
$$b_{\text{coul}}(E) = 2\pi r_e^2 m_e c^3 n_e \beta^{-1} \left\{ \ln\left(\frac{E m_e c^2}{4\pi r_e \hbar^2 c^2 n_e} \right) - \frac{3}{4} \right\}$$



Where are simulations most useful?

T. Lacroix, CB, J. Silk, 2014



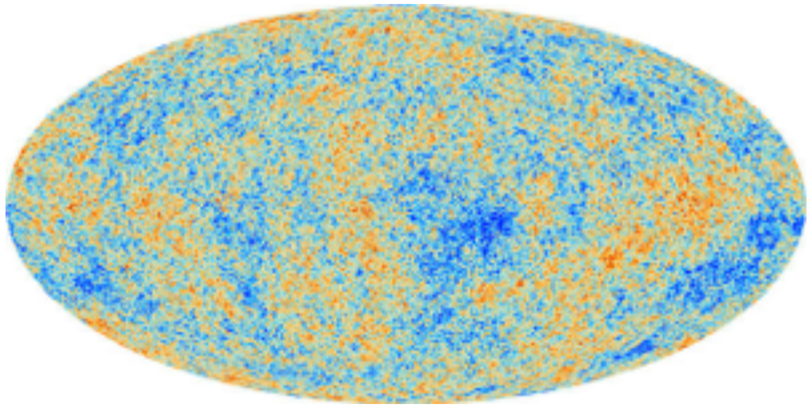


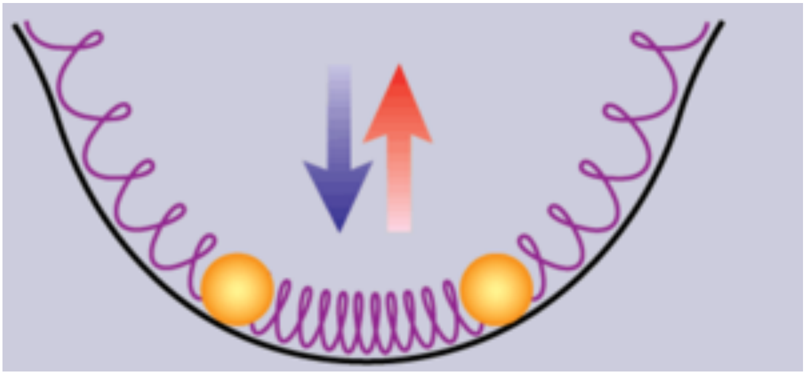
Propagation is important for leptons.
It changes the interpretation.

10-30 GeV DM particles ??? (but probably not thermal and yet annihilating!)

That is it!

pressure baryon-photon last scattering



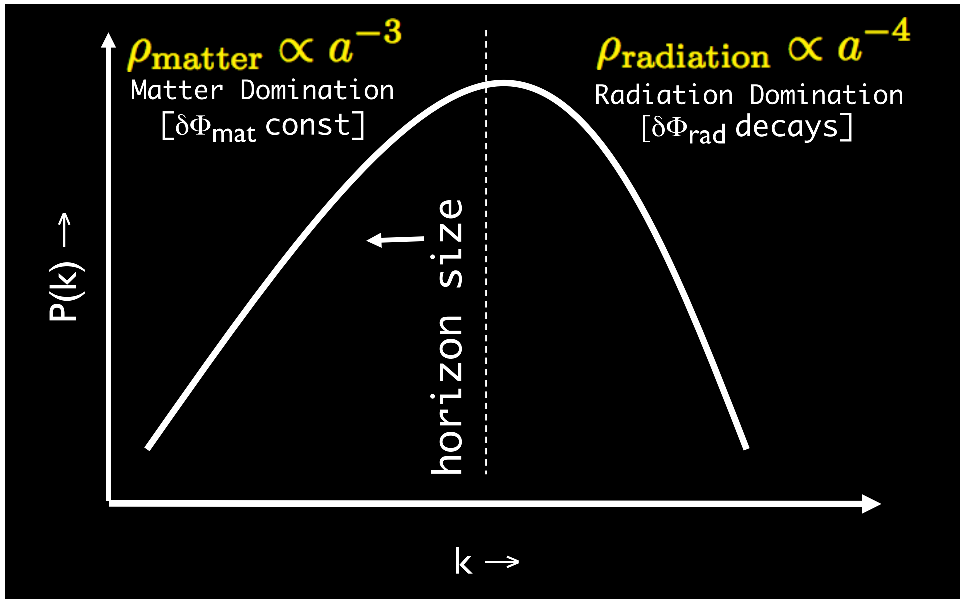


accoustic oscillations generated
(fight within pressure and gravity)

Last scattering surface

Horizon: d ~ c t; when fluctuations enter the horizon, they become causal

Courtesy Abazajian



Once matter dominated, the fluctuations (over density of matter) can grow

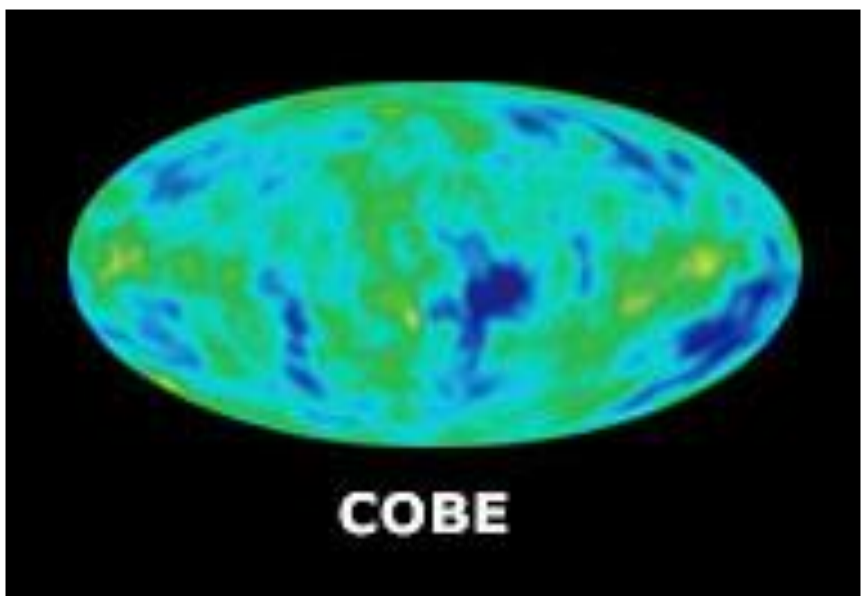
Non linear evolution

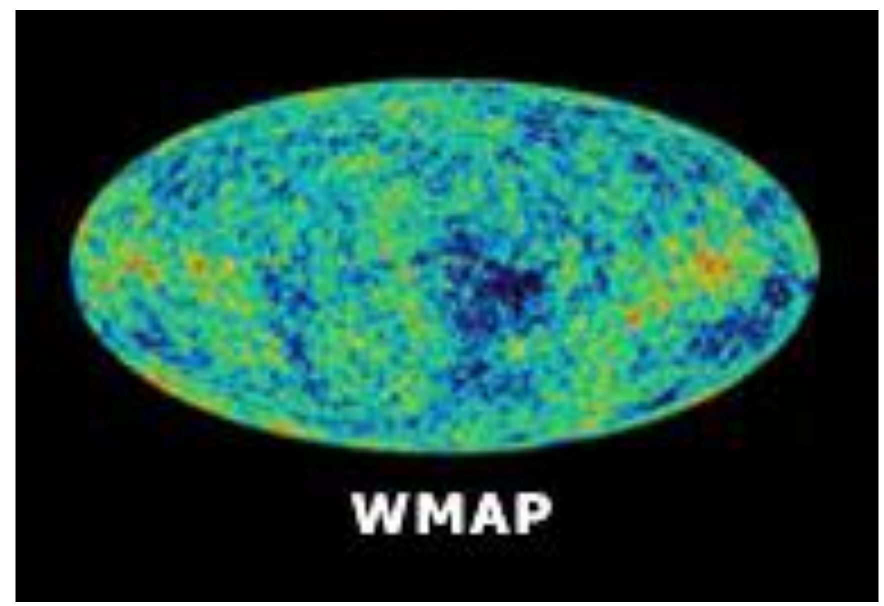
Peebles, Silk, ...(1960s/1970s): Primordial fluctuations should be at the origin of galaxy and cluster formation but they experience dissipation

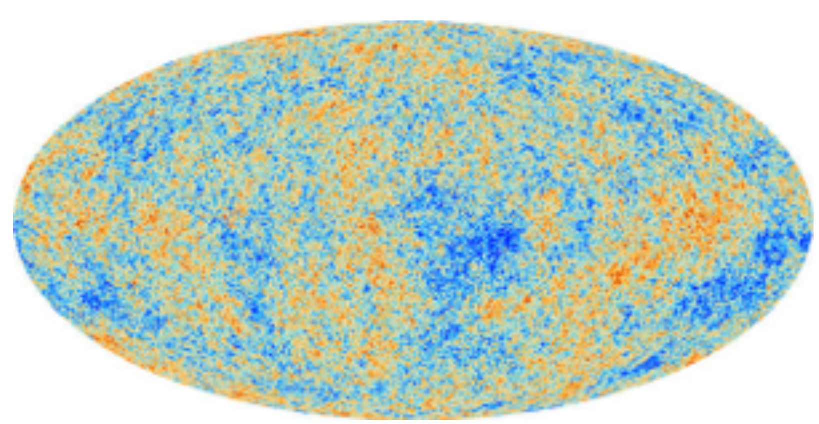
COBE 1992: Discovery of tiny inhomogeneties:
$DT/T \sim 10^{-5}$ at last scattering surface (when photons freely propagate)

Conclusion:

- large-scale structures originate from regions of space where matter agglomerates.
- These regions should have existed at last scattering surface.







Planck