Title: The peculiar case of light thermal dark matter particles

Date: Sep 13, 2017 02:00 PM

URL: http://pirsa.org/17090054

Abstract: <p>I will review the phenomenology of light thermal dark matter candidates and their implications for astrophysics and cosmology. </p>

The peculiar case of Light Thermal Dark Matter

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PI, Sept 2017

Evidence for Dark Matter

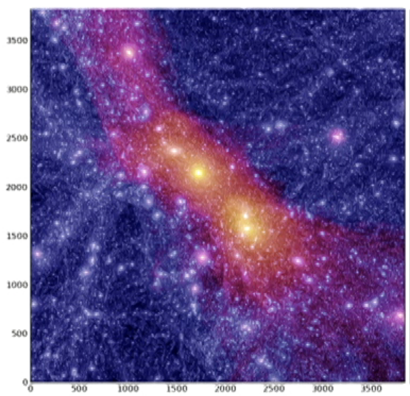
An invisible substance which dominates the matter content of the Universe

Dark Matter is everywhere

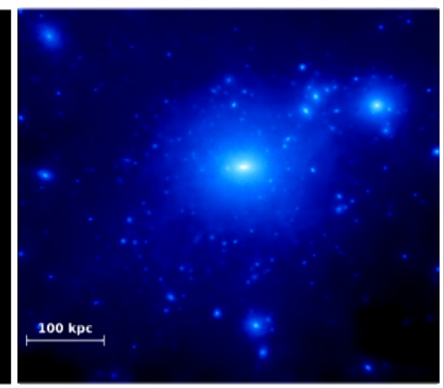
Cluster of galaxies

NGC 6814 Credit: NASA

NGC 4621 Credit: WikiSky/SDSS



Durham's simulations 2014



Durham's simulations 2014

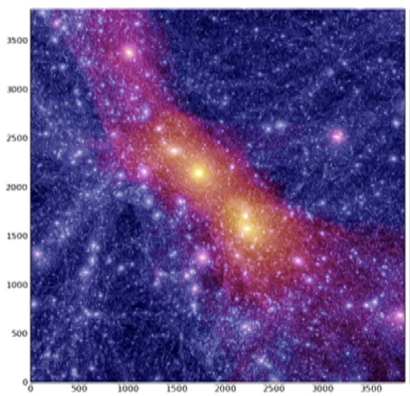
But what is the DM?

Dark Matter is everywhere

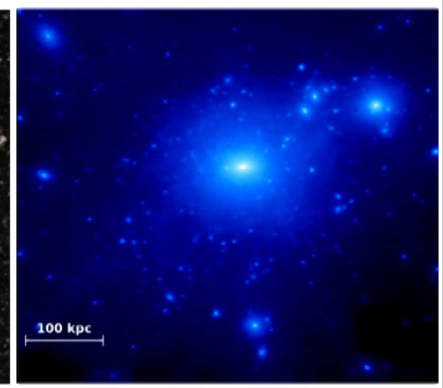
Cluster of galaxies

NGC 6814 Credit: NASA

NGC 4621 Credit: WikiSky/SDSS



Durham's simulations 2014



Durham's simulations 2014

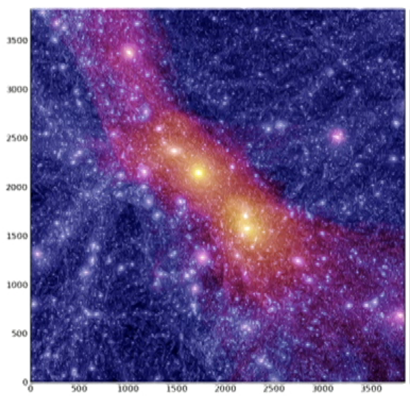
But what is the DM?

Dark Matter is everywhere

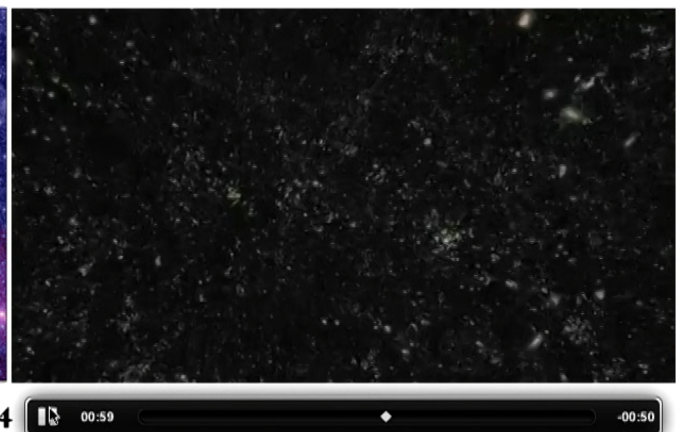
Cluster of galaxies

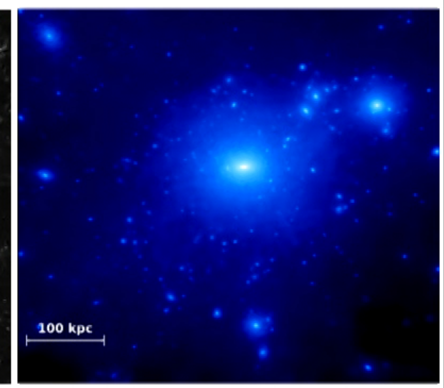
NGC 6814 Credit: NASA

NGC 4621 Credit: WikiSky/SDSS



Durham's simulations 2014





Durham's simulations 2014

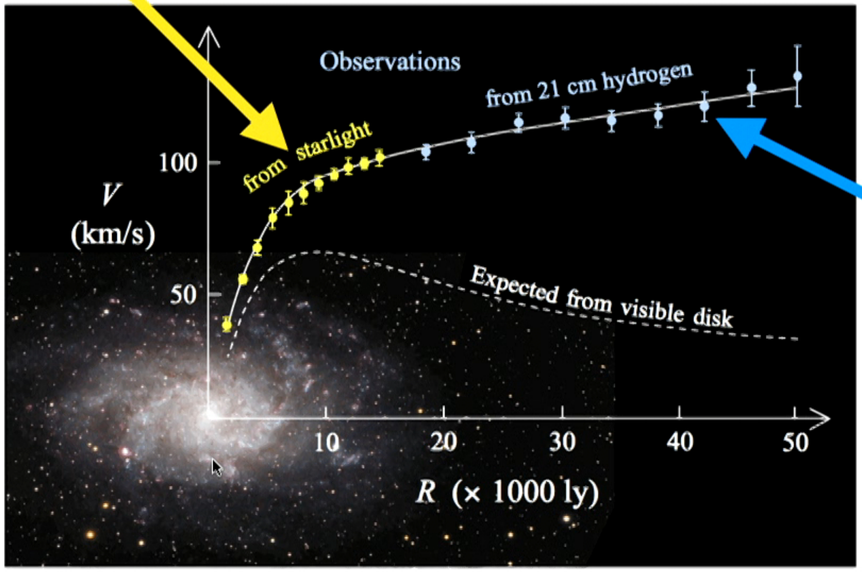
But what is the DM?

Dark Matter ensures the stability of galaxies

Galaxies rotate— Slipher (1914)

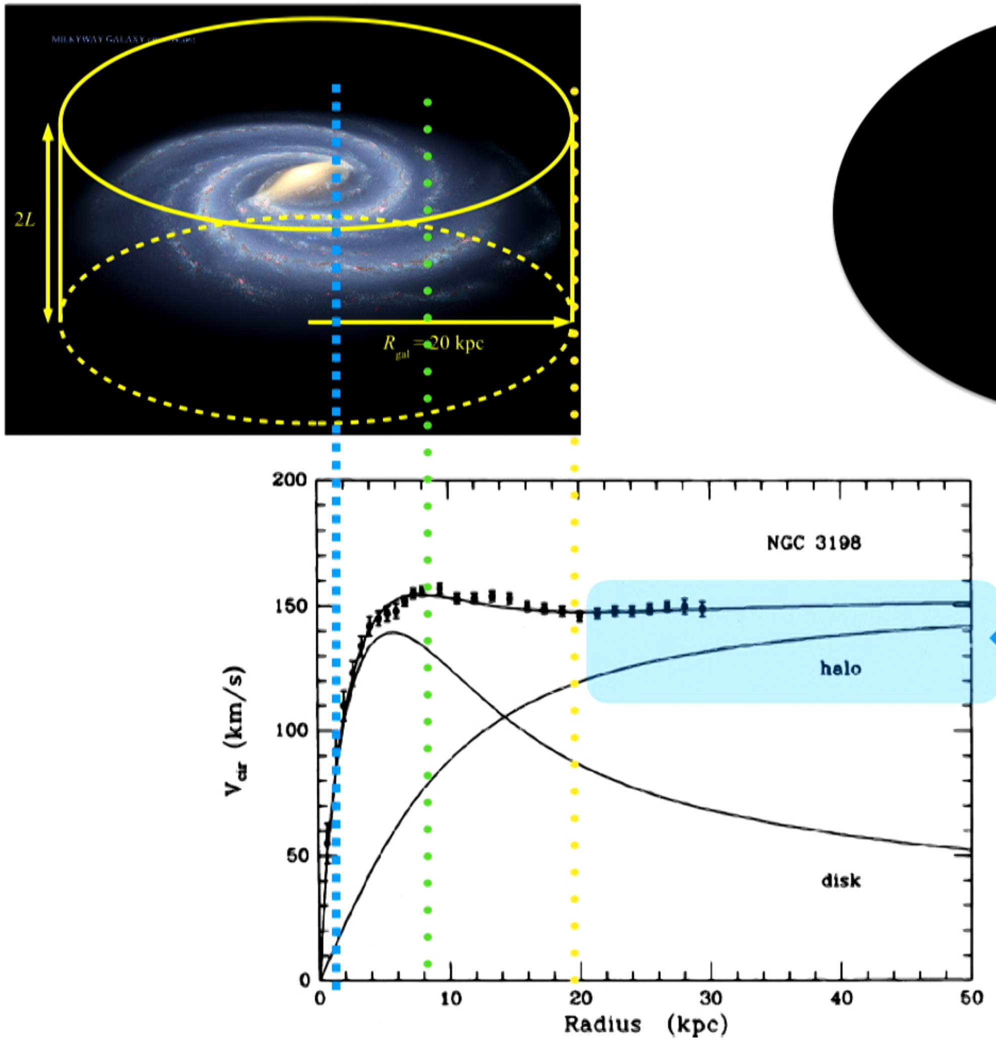
Freeman (1970) for M33 and NGC 300
Rotation curve peaks at the edge of the optical disk.
About 1/3 of the mass is outside the optical radius.

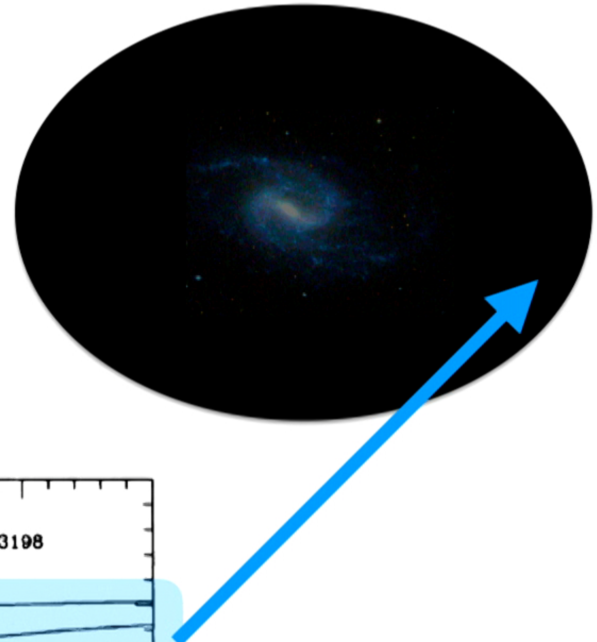
1970ApJ...159..379R



Shostak & Rogstad (1973),
Seielstad & Wright (1973).
M31: (Roberts 1975a,
Roberts & Whitehurst 1975);
Final straw: Bosma (1978)

There is a halo of dark matter all around us





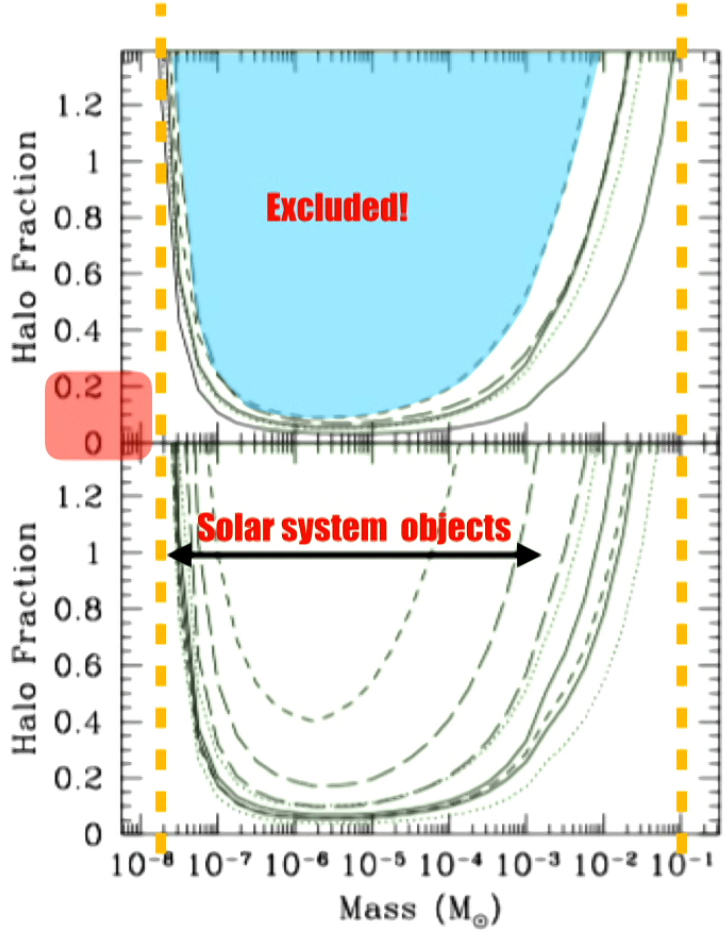
$$v_c^{\,2} = \frac{G\,M(r)}{r}$$

$$v \simeq 10^{-3}\ c$$

Galactic Dark Matter

What is the halo made of?

Is the dark matter made of compact objects?



EROS and MACHO

(La Silla vs Mount Stromlo Observatory, Australia)

Earth $3\ 10^{-6}\ M_\odot$

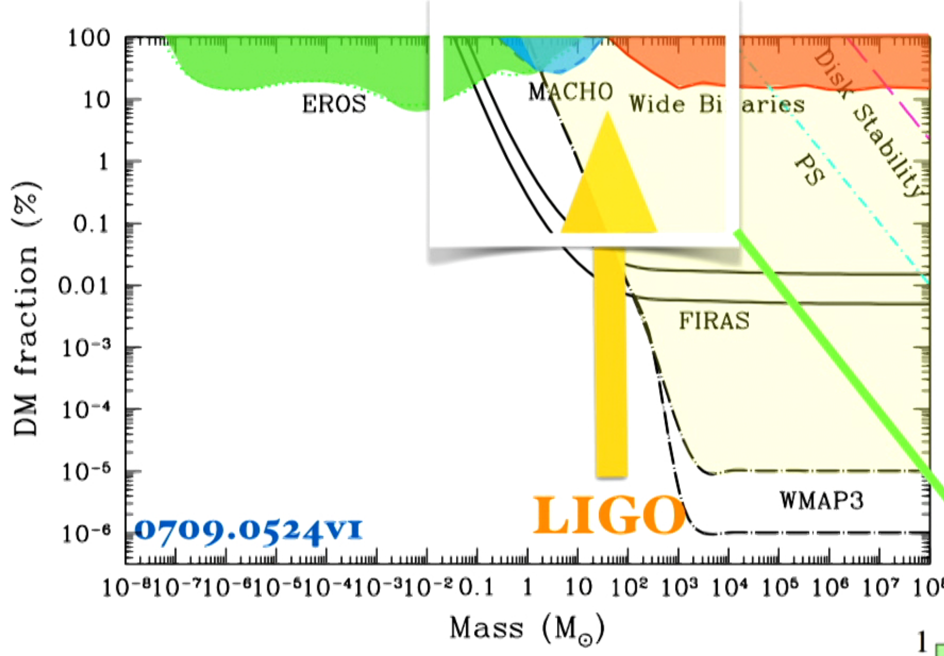
Jupiter $\simeq\ 10^{-3}\ M_\odot$

Pluto $\simeq 6\ 10^{-8}\ M_\odot$

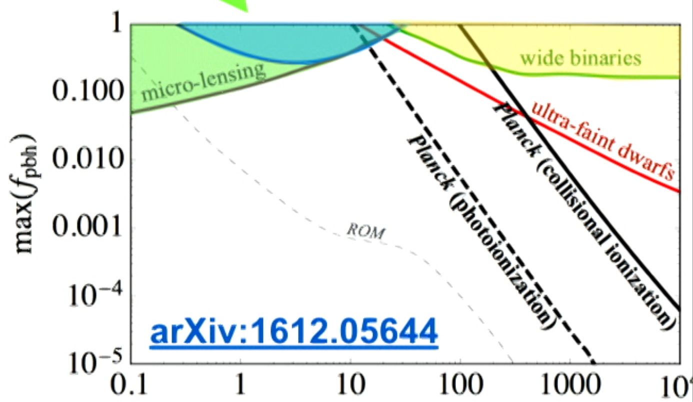
MACHO fraction < 10%

Fig. 3.— Halo fraction upper limit (95% c.l.) versus lens mass for the five EROS models (top) and the eight MACHO models (bottom). The line coding is the same as in Figure 2.

Can Primordial Black Holes be the DM?



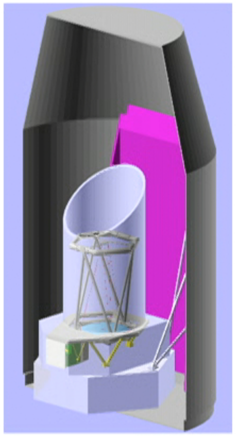
arXiv:1603.00464
arXiv:1501.07565
arXiv:1607.06077

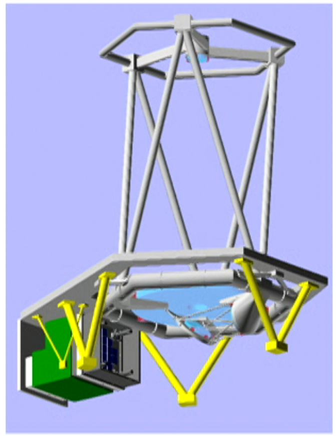


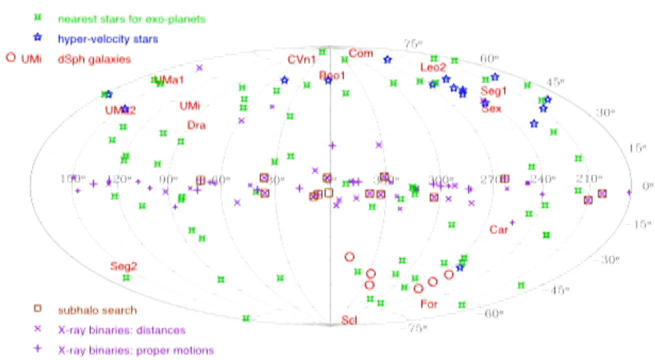
an ensemble of PBH in the 1-100 Msol range might be allowed.

Can Primordial Black Holes be the DM?

Theia (optical)   Small-Jasmine (IR)







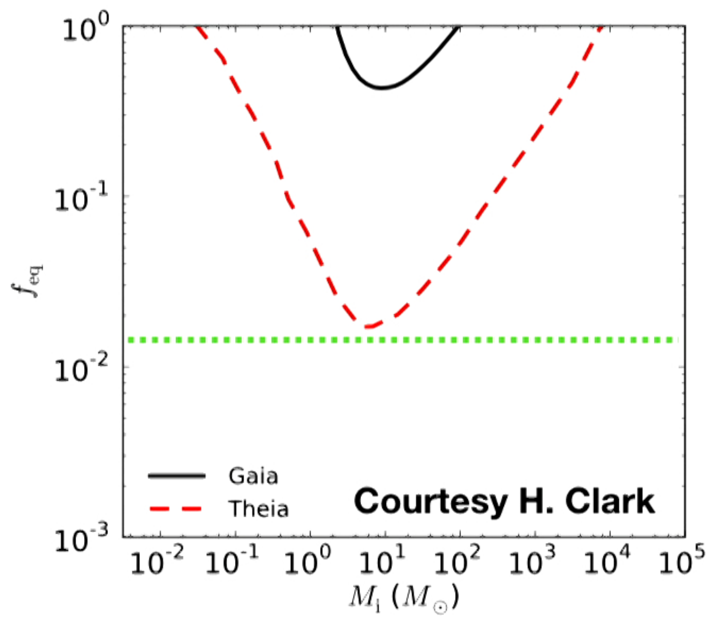


Fig. 2.8: Projected sensitivity of *Theia* to the fraction of dark matter in the form of ultracompact minihalos (UCMHs) of mass M_i at the time of matter-radiation equality. Smaller masses probe smaller scales, which correspond to earlier formation times (and therefore to *later* stages of inflation). A UCMH mass of 0.1 $M_\odot$ corresponds to a scale of just 700 pc. Expected constraints from *Gaia* are given for comparison, showing that *Theia* will provide much stronger sensitivity, as well as probe smaller scales and earlier formation times than ever reached before.

Dark Matter in the Universe

Other evidence

Gravitational lensing evidence…

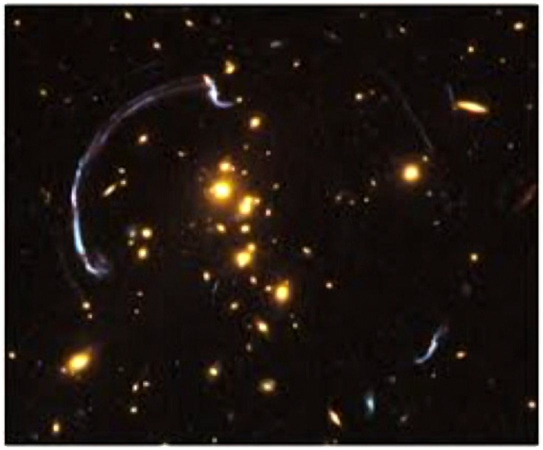
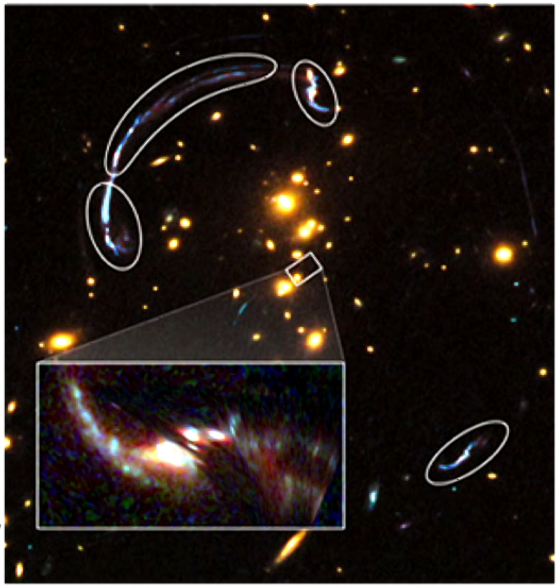


Illustration Credit: NASA, ESA, and Z. Levay (STScI)
Science Credit: NASA, ESA, J. Rigby
(NASA Goddard Space Flight Center), K. Sharon
(Kavli Institute for Cosmological Physics, University of Chicago),
and M. Gladders and E. Wuyts (University of Chicago)

Reconstruction of the brightest galaxy whose image has been distorted by the gravity of a distant galaxy cluster.



The small rectangle in the center shows the location of the background galaxy on the sky if the intervening galaxy cluster were not there.
The rounded outlines show distinct, distorted images of the background galaxy resulting from lensing by the mass in the cluster. The image at lower left is a reconstruction of what the lensed galaxy would look like in the absence of the cluster, based on a model of the cluster's mass distribution derived from studying the distorted galaxy images.

Gravitational lensing evidence…

Red = X-rays emitted by the gas (Thomson interactions, Bremsstrahlung,…)
Blue = where the gravitational potential is the deepest

Dark Matter did not interact with the gas nor with itself

$$\Rightarrow \quad \sigma \lesssim 10^{-24} \mathrm{cm}^2$$ **1 barn, like Thomson**

How do galaxies form in the Universe?

- Citations to the Article (85) (Citation History)
- Refereed Citations to the Article
- Also-Read Articles (Reads History)
- Translate This Page

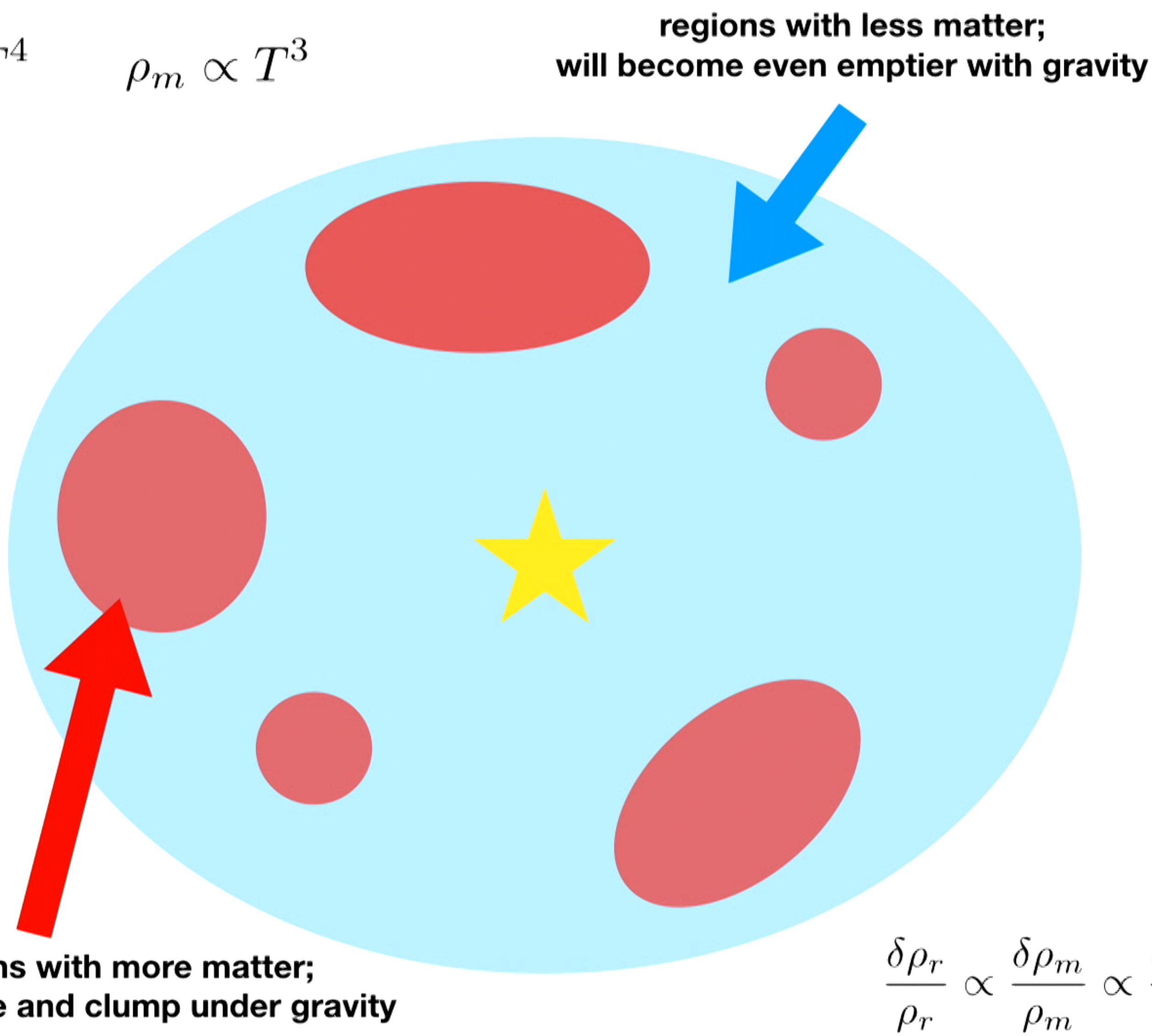
Title:	The Gravitational Instability of the Universe
Authors:	Peebles, P. J. E.
Publication:	Astrophysical Journal, vol. 147, p.859 (ApJ Homepage)
Publication Date:	03/1967
Origin:	ADS
DOI:	10.1086/149077
Bibliographic Code:	1967ApJ...147..859P

It is argued that the expanding Universe is unstable against the growth of gravitational perturbations. The argument is directed towards two problems, the physical conditions in the early, highly contracted phase of the expanding Universe and the formation of galaxies.

Followed Peebles, P. J. E., *Astrophys. J.*, **142**, 1317 (1965)

http://adsabs.harvard.edu/abs/1970ApJ...162..815P

$\rho_r \propto T^4$ $\rho_m \propto T^3$

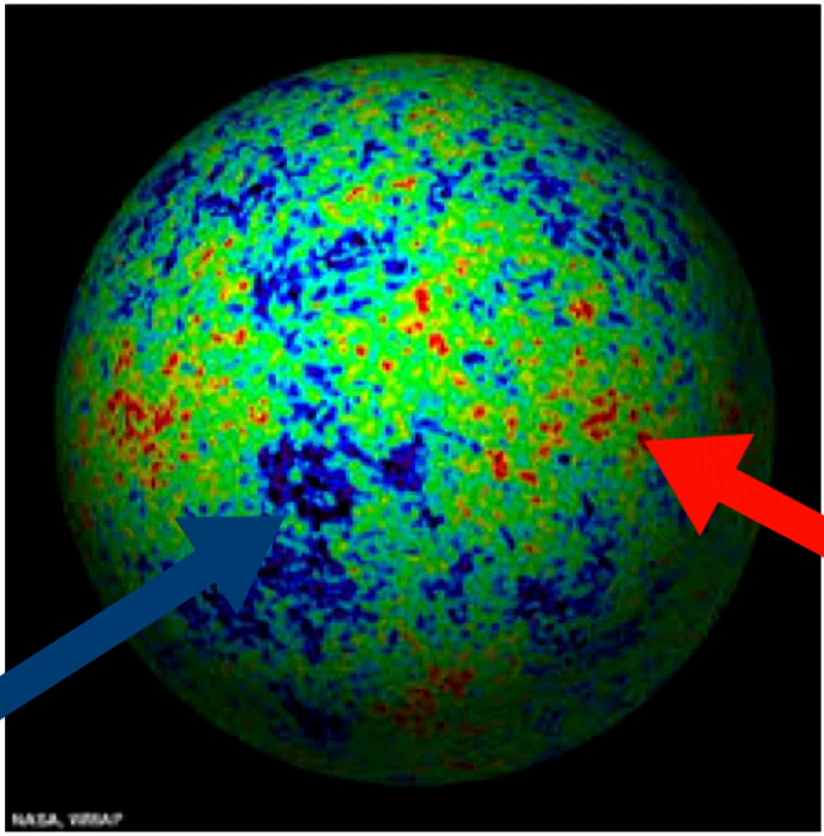


$$\frac{\delta\rho_r}{\rho_r} \propto \frac{\delta\rho_m}{\rho_m} \propto \frac{\delta T}{T}$$

Anisotropies of temperature

$$\bar{T} = 2.7K$$

2003, WMAP



hotter regions

colder regions

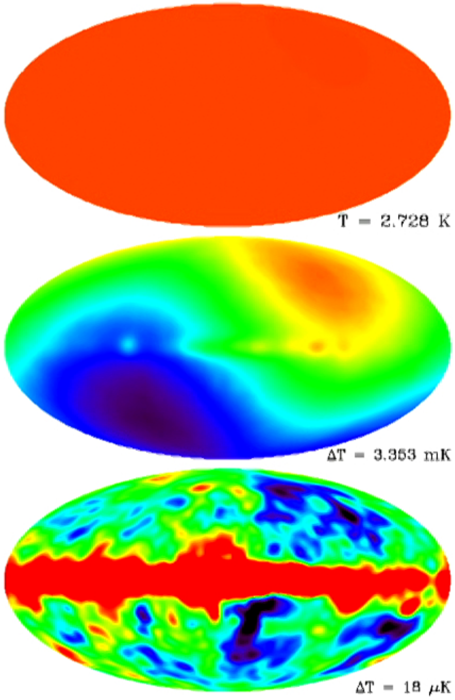
$$\frac{\delta T}{T} \simeq 10^{-5}$$

Anisotropies of temperature

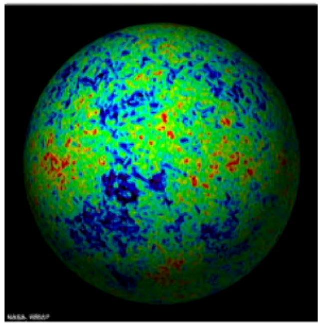
$$Y_0^0 = cst$$

$$Y_1^0 = \cos\theta$$

$$Y_l^m$$

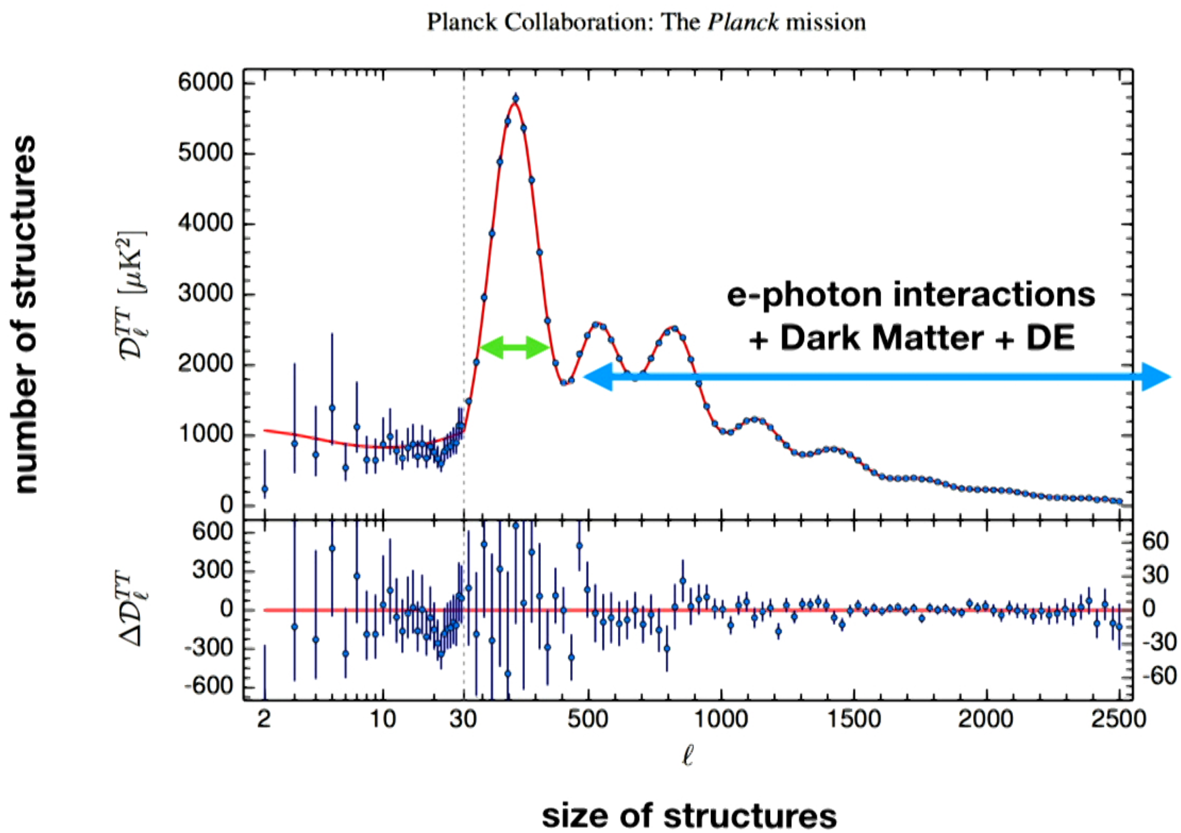


The higher l, the more details you get



l > 2000

Anisotropies of temperature

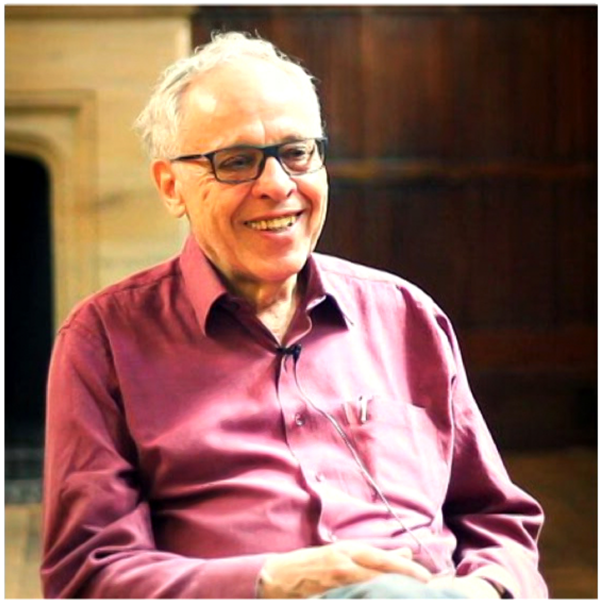


the suppression of small-scales is indicative of the presence of baryons

Anisotropies of temperature

baryonic fluctuations

baryonic fluctuations do not survive the baryon scattering off the photon background.
(Question first asked by Misner for neutrinos)



J. Silk

letters to nature

Nature **215**, 1155 - 1156 (09 September 1967); doi:10.1038/2151155a0

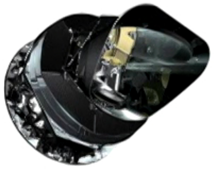
Fluctuations in the Primordial Fireball

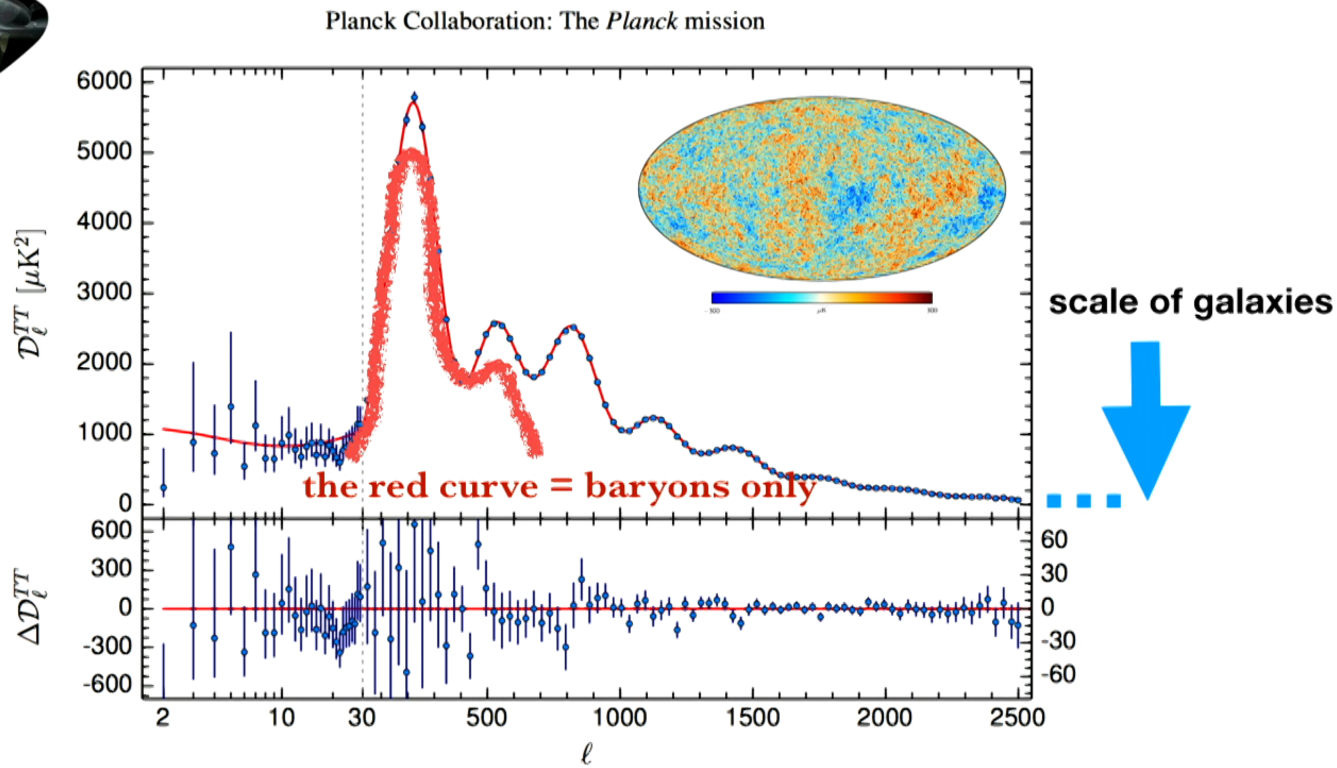
JOSEPH SILK

Harvard College Observatory, Cambridge, Massachusetts.

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible ?

Anisotropies of temperature

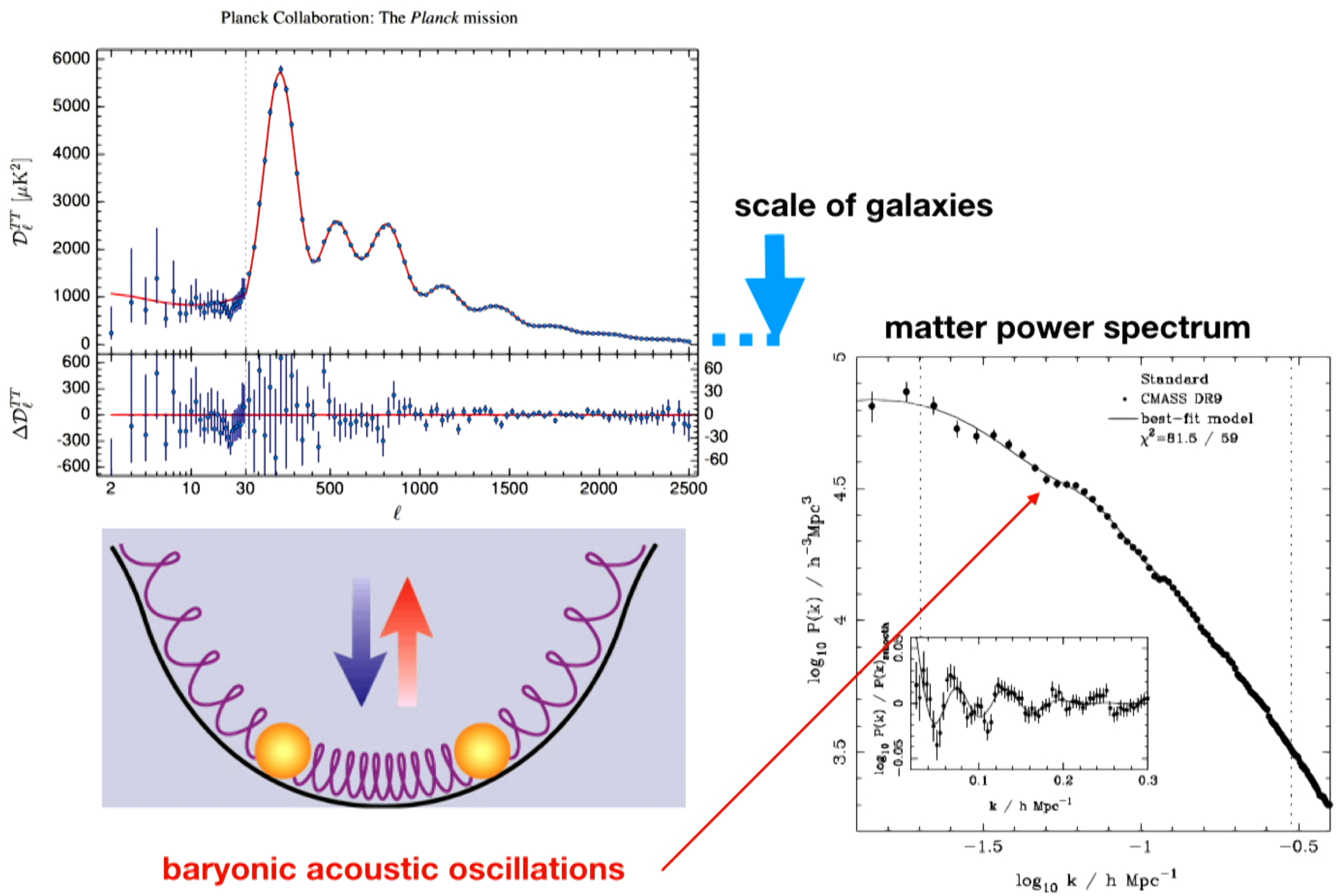




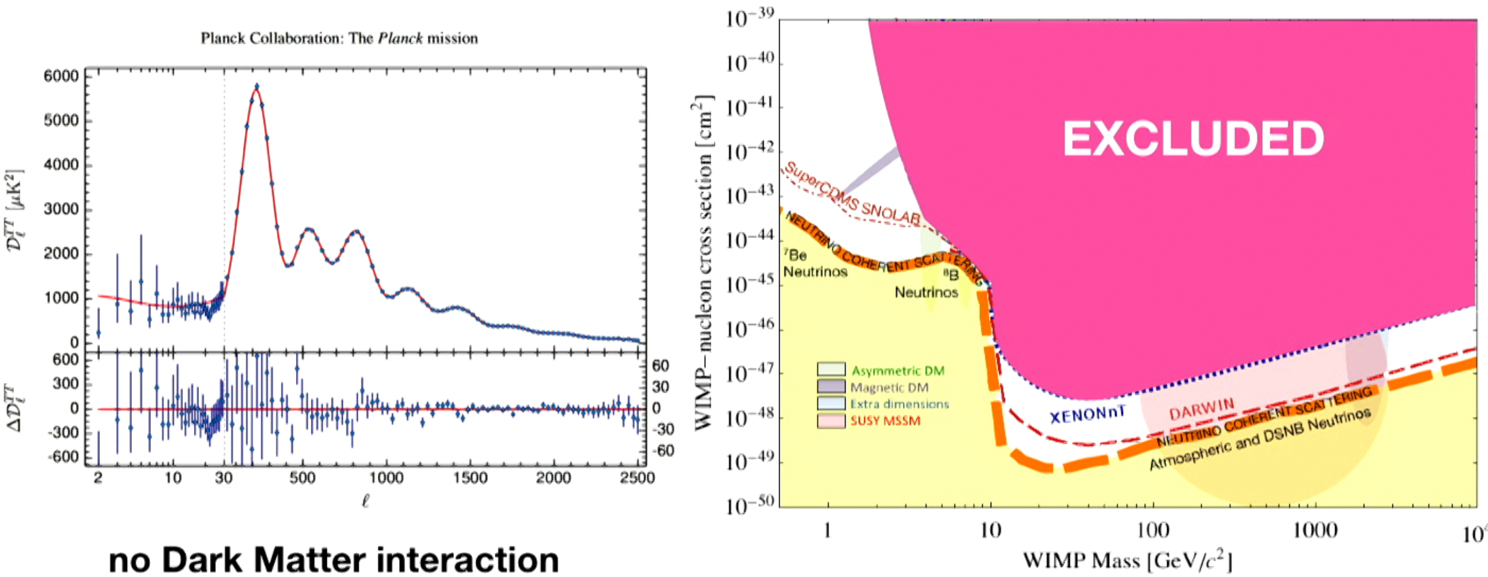
No large-scale fluctuations if "baryons" dominate the matter density

Therefore there must be more dark matter than baryons

Anisotropies of temperature



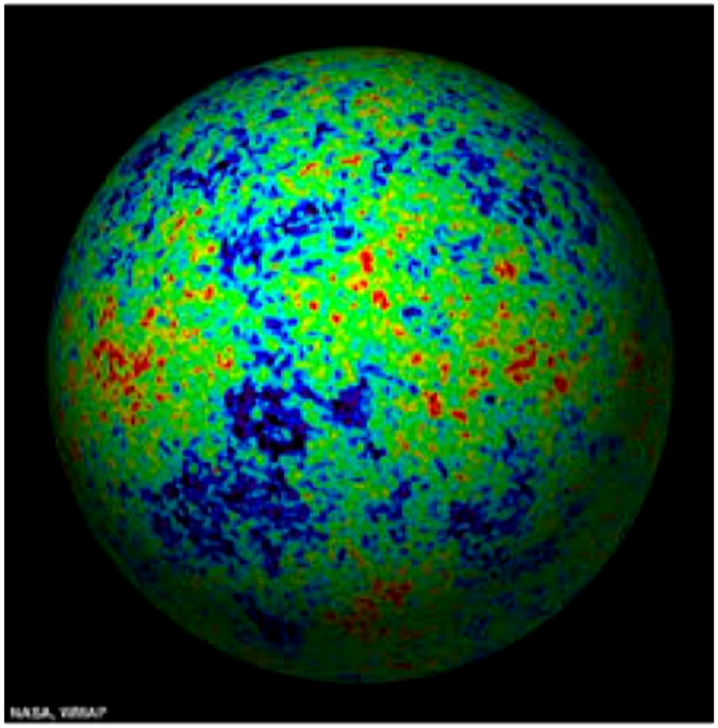
Is Dark Matter collisionless?



no Dark Matter interaction

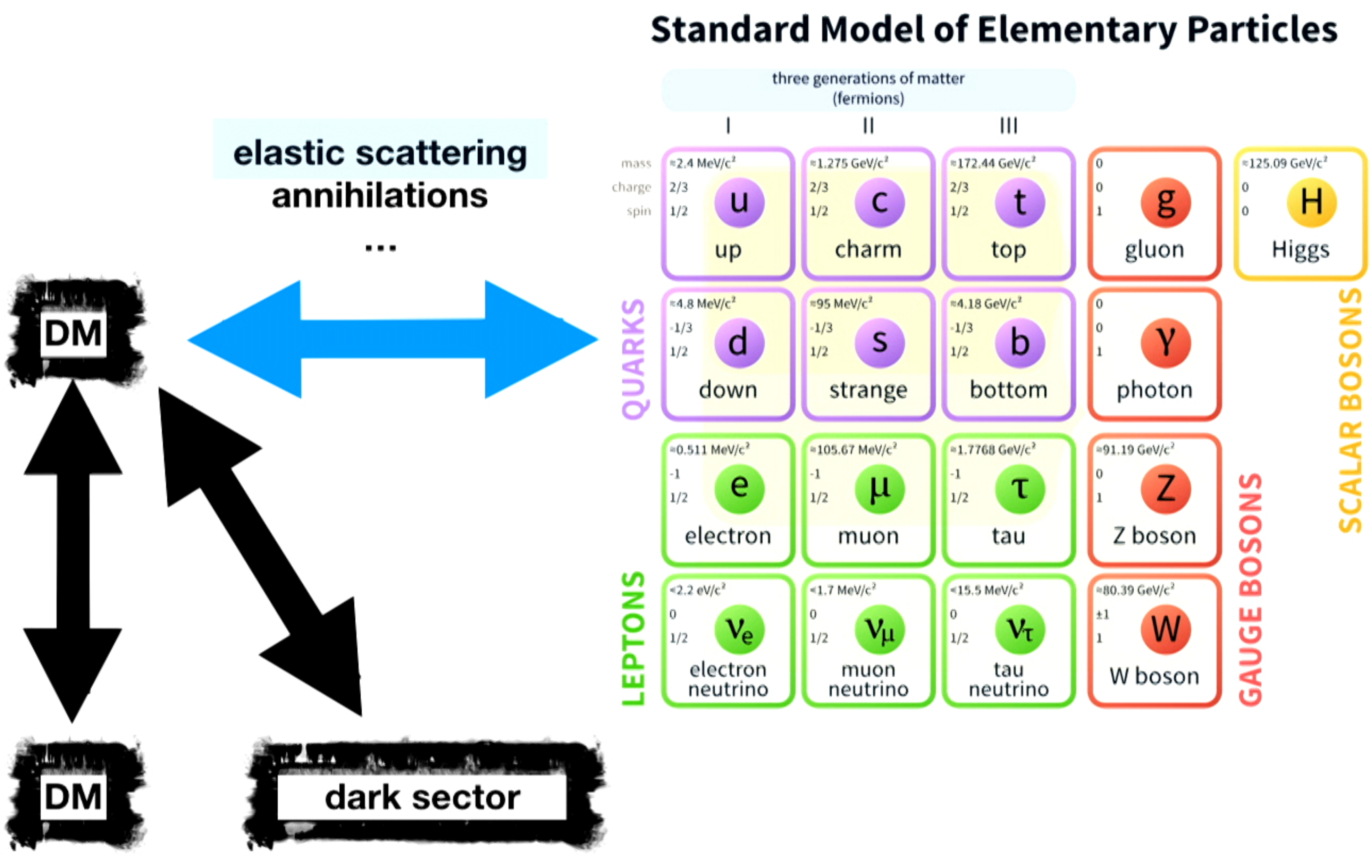
assumption: Dark Matter interactions

Is Dark Matter collisionless?



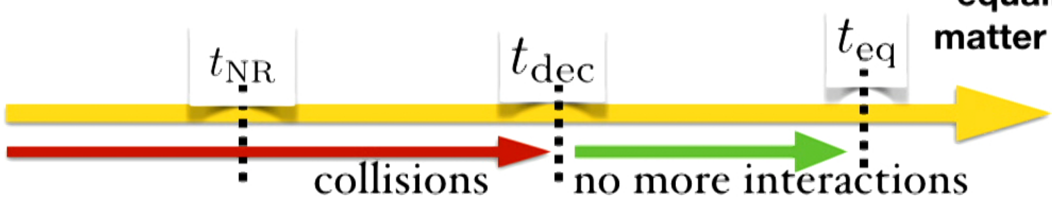
we shouldn't see this pattern if the DM had interactions (depending on the strength of the interactions)

Dark Matter interactions



Dark Matter interactions

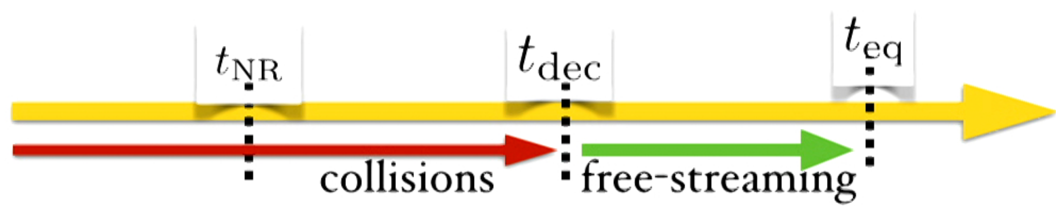
equality between matter and radiation



Damping

Collisional Damping	Free-streaming
effect of the DM interactions	DM has no more interactions
diffusion length	it is free to propagate
generalisation of Silk damping	

Dark Matter interactions



mean-free path

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

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

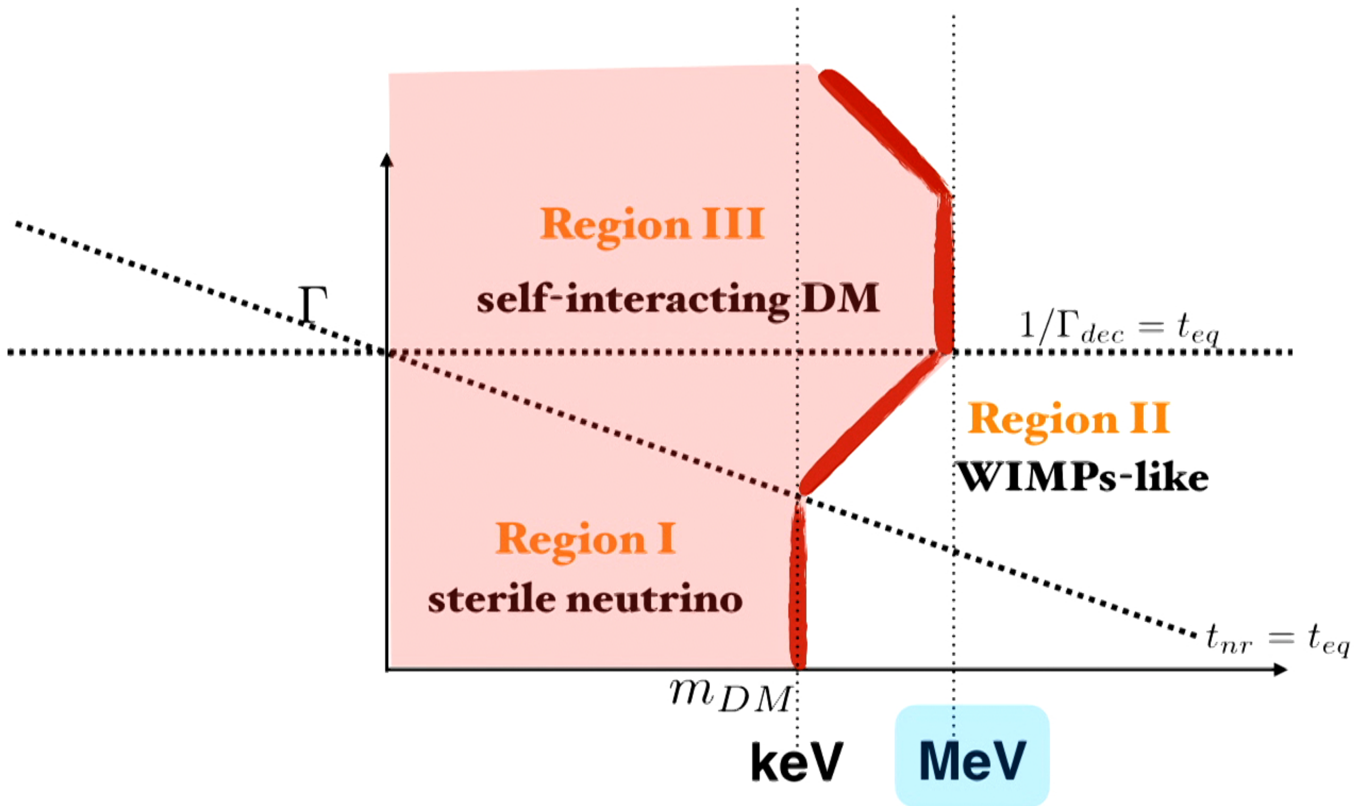
fluctuations are first damped by collisions!

Let us focus on Free-streaming

(the last thing to occur)

Dark Matter Free-streaming

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

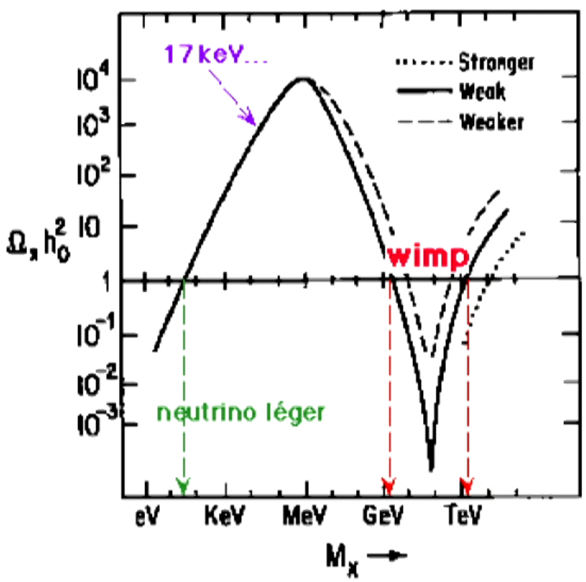


Many more DM scenarios than has been explored already

Can we have light thermal DM?

The Hut, Lee&Weinberg argument

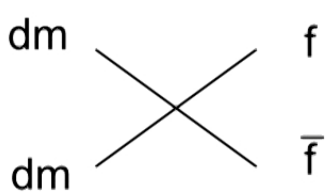
Can we have light thermal DM? **no!**



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

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

$$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

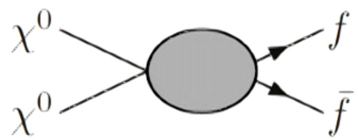


$$\sigma\ \mathrm{v} \propto \frac{\mathrm{m_{dm}}^2}{\mathrm{m_w}^4} \Rightarrow \Omega_{\mathrm{DM}} h^2 \propto m_{\mathrm{DM}}^{-2}$$

Exceptions to Hut, Lee&Weinberg

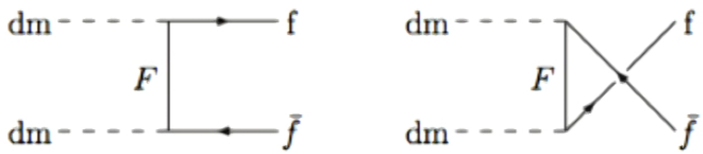
astro-ph/0208458v3 hep-ph/0305261

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



What kind of mediator?

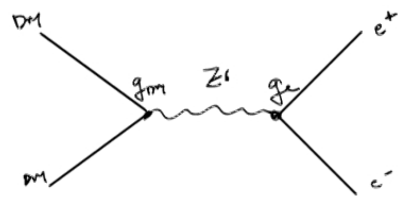
vector-like fermions



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

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

dark photons/Z'

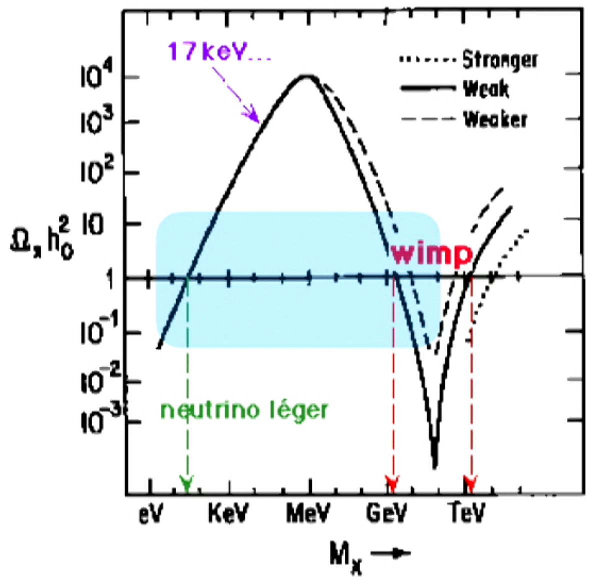


$$\sigma v \propto v^2\ \frac{m_{\rm DM}^2}{m_{Z'}^4}\ g_{\rm DM}^2\, g_e^2$$

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

DM can be light!

yes we can have light DM!



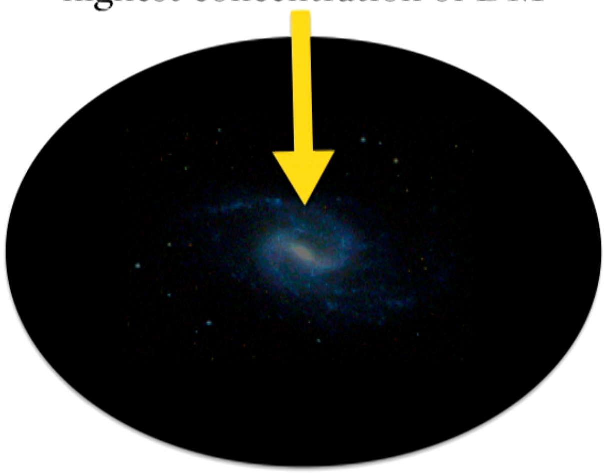
Why not considering MeV, keV etc DM??

Did we discover light DM?

$$\chi\chi \rightarrow e^+e^-$$

astro-ph/0309686

highest concentration of DM

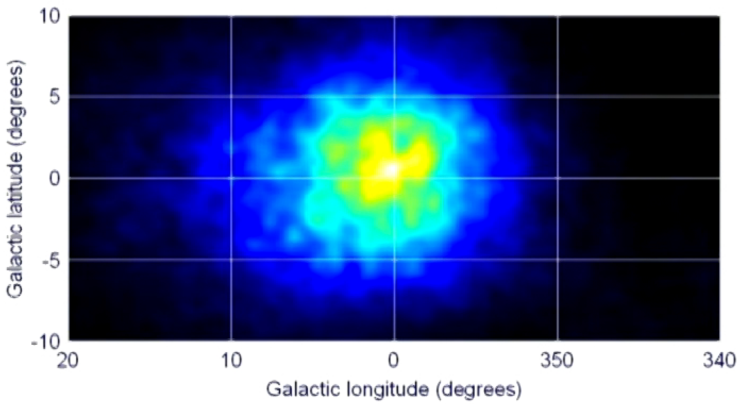


$$e^+e^- \rightarrow \gamma\gamma$$

Positronium formation

$\gamma\gamma$ 511 keV (para)

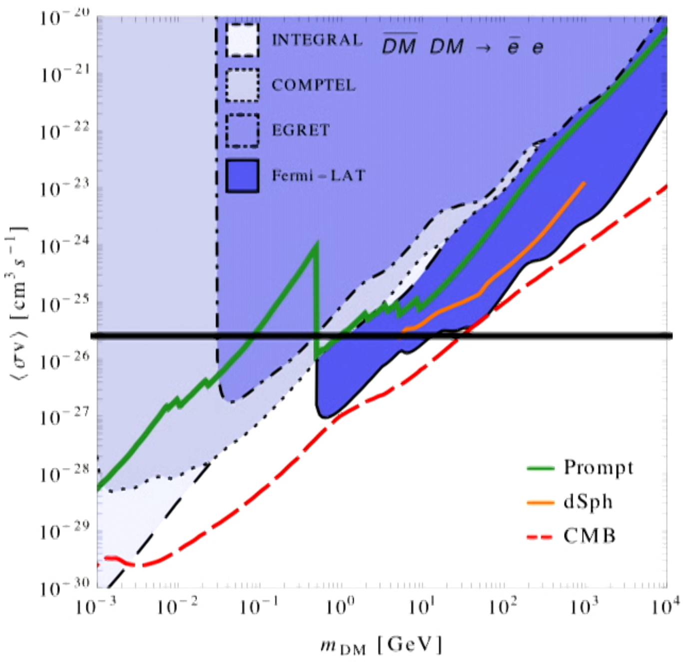
$\gamma\gamma\gamma$ continuum (ortho)

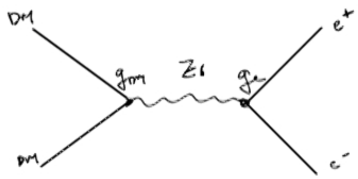


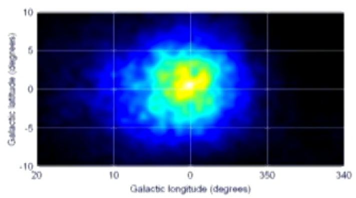
Indirect detection and relic density

astro-ph/0208458 hep-ph/0305261

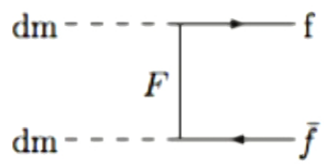
Courtesy T. Jubb







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



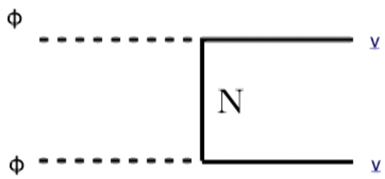
$$\sigma v \sim 3\ 10^{-26}\ {\rm cm}^3/{\rm s}$$

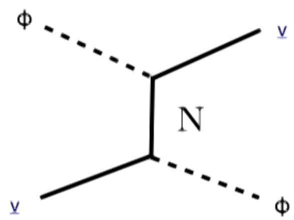
$$\sigma v \propto \frac{1}{m_F^2}$$

A combination of both is necessary to explain the 511 keV line

A connexion with neutrino masses?

Effective theory
(N singlet of SU(2) for example)

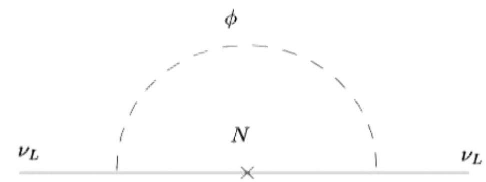




$$\sigma_{DM-\nu} \simeq 4\times 10^{-36} \left(\frac{\langle\sigma v\rangle}{3\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)\,\mathrm{cm}^2$$

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

hep-ph/0612228

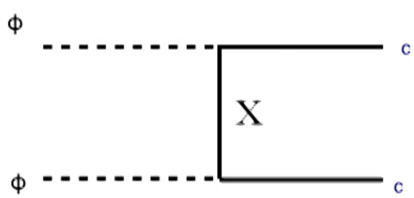


$$m_{\nu_L} \simeq \sqrt{\frac{\langle\sigma v_r\rangle}{128\,\pi^3}}\, m_N^2(1+m_\phi^2/m_N^2)\,\ln\left(\frac{\Lambda^2}{m_N^2}\right)$$

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

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

Annihilations into a dark sector and multi components DM



+ Phi decay

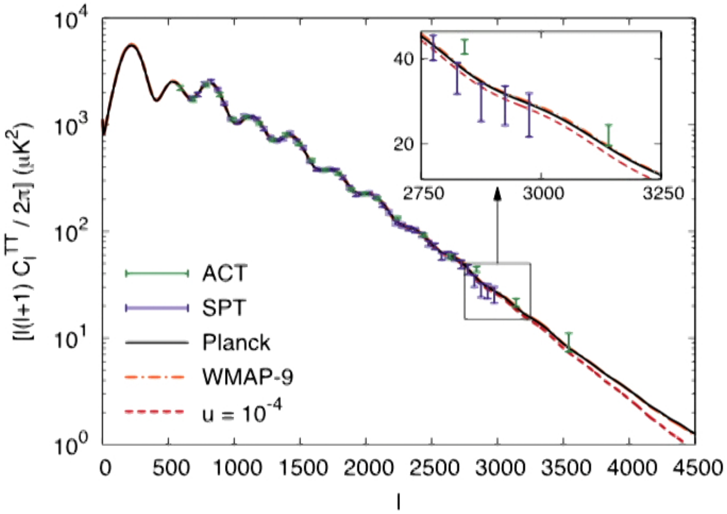
But also relax the RD constraint

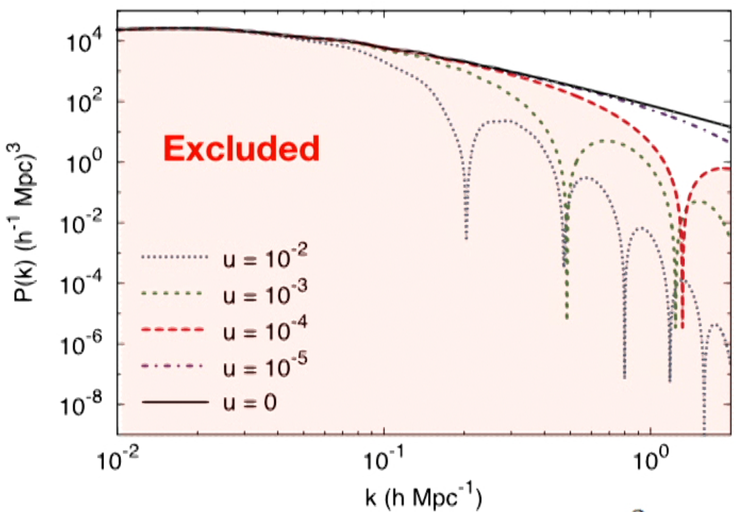
arXiv:0711.4866 arXiv:1005.1655

Dark Matter collisional damping

They change the way matter is distributed in the Early Universe

astro-ph/0112522





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

Fight between pressure (interaction) and gravity

Structure formation is sensitive to DM interactions!

Dark Matter collisional damping

Impact on cosmological parameters

Paper to be submitted

Changes the age of the Universe

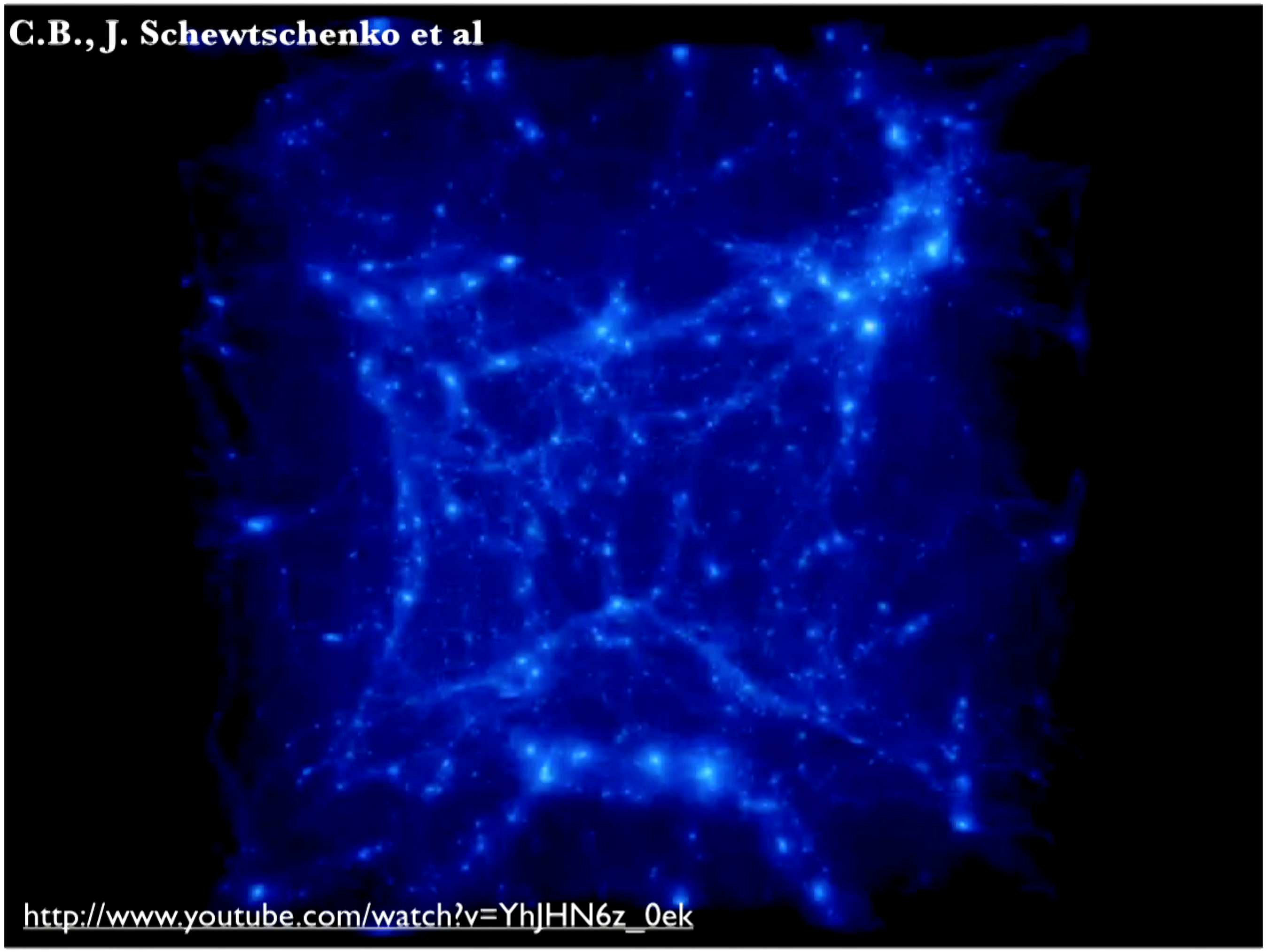
Higher H0 (shorter lifetime)

Changes the number of structures at 8 Mpc

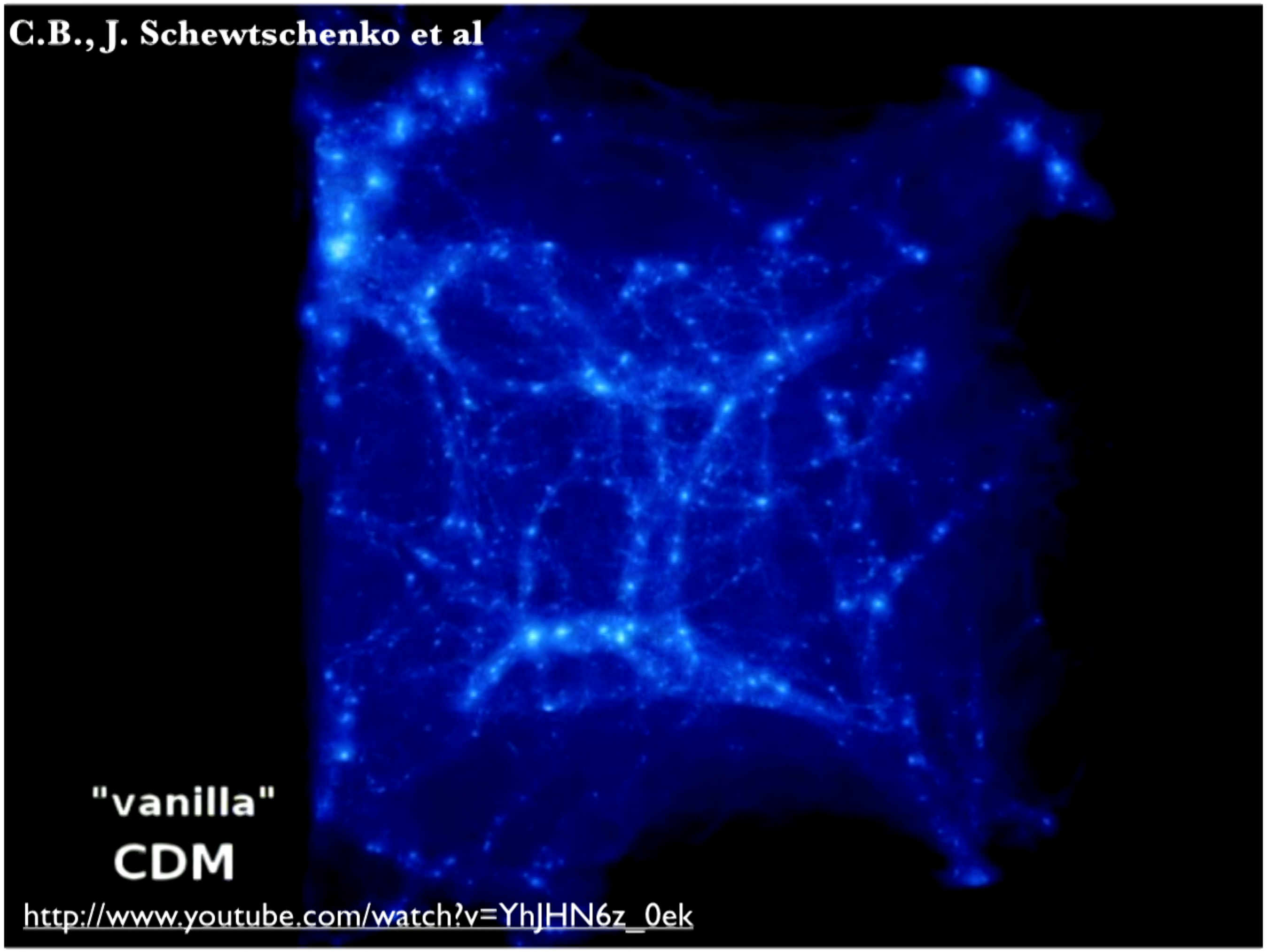
arXiv:1401.7597

Changes the number of degrees of freedom
(but in reality very slightly)

The Milky Way for interacting DM

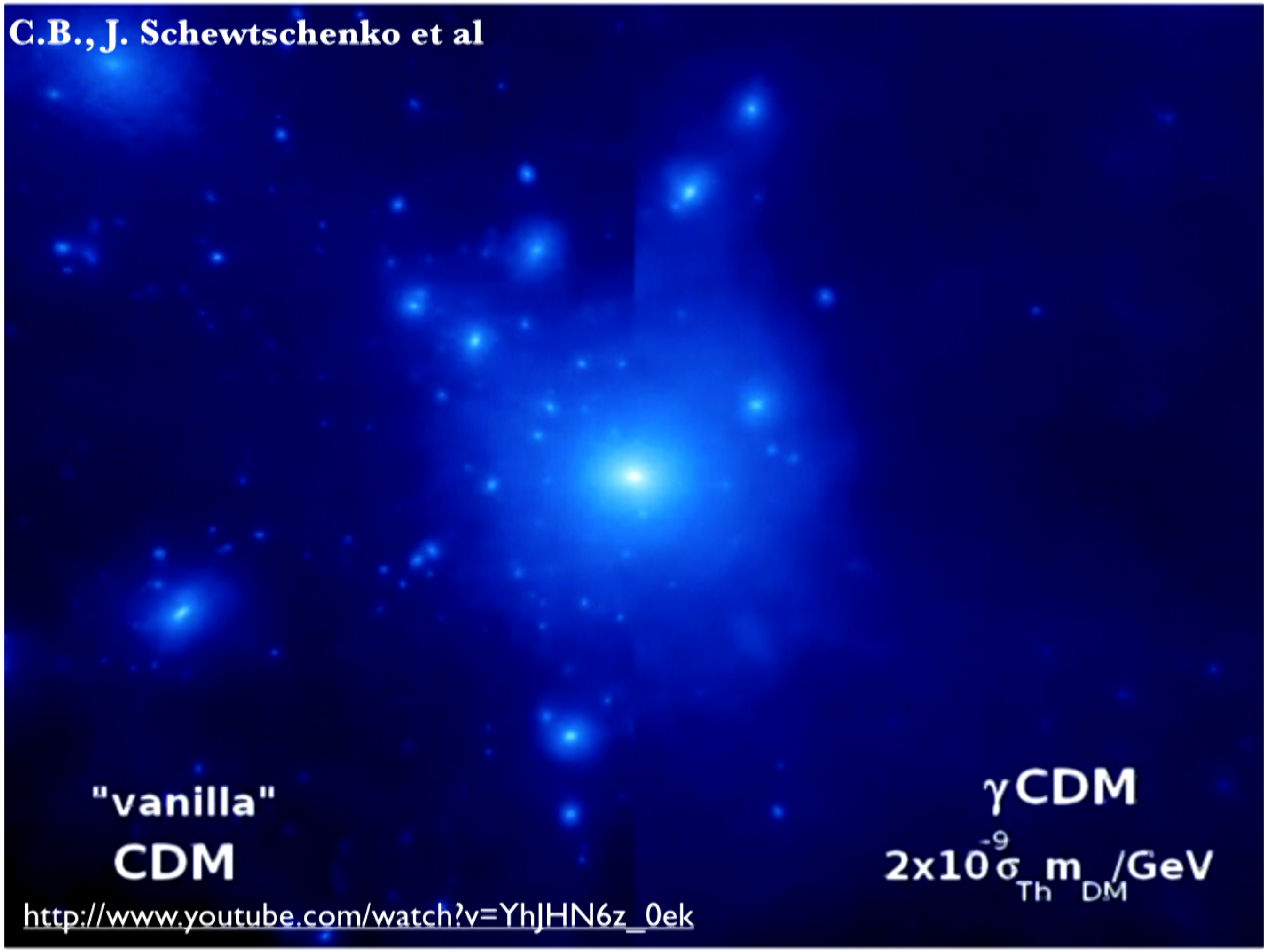


The Milky Way for interacting DM

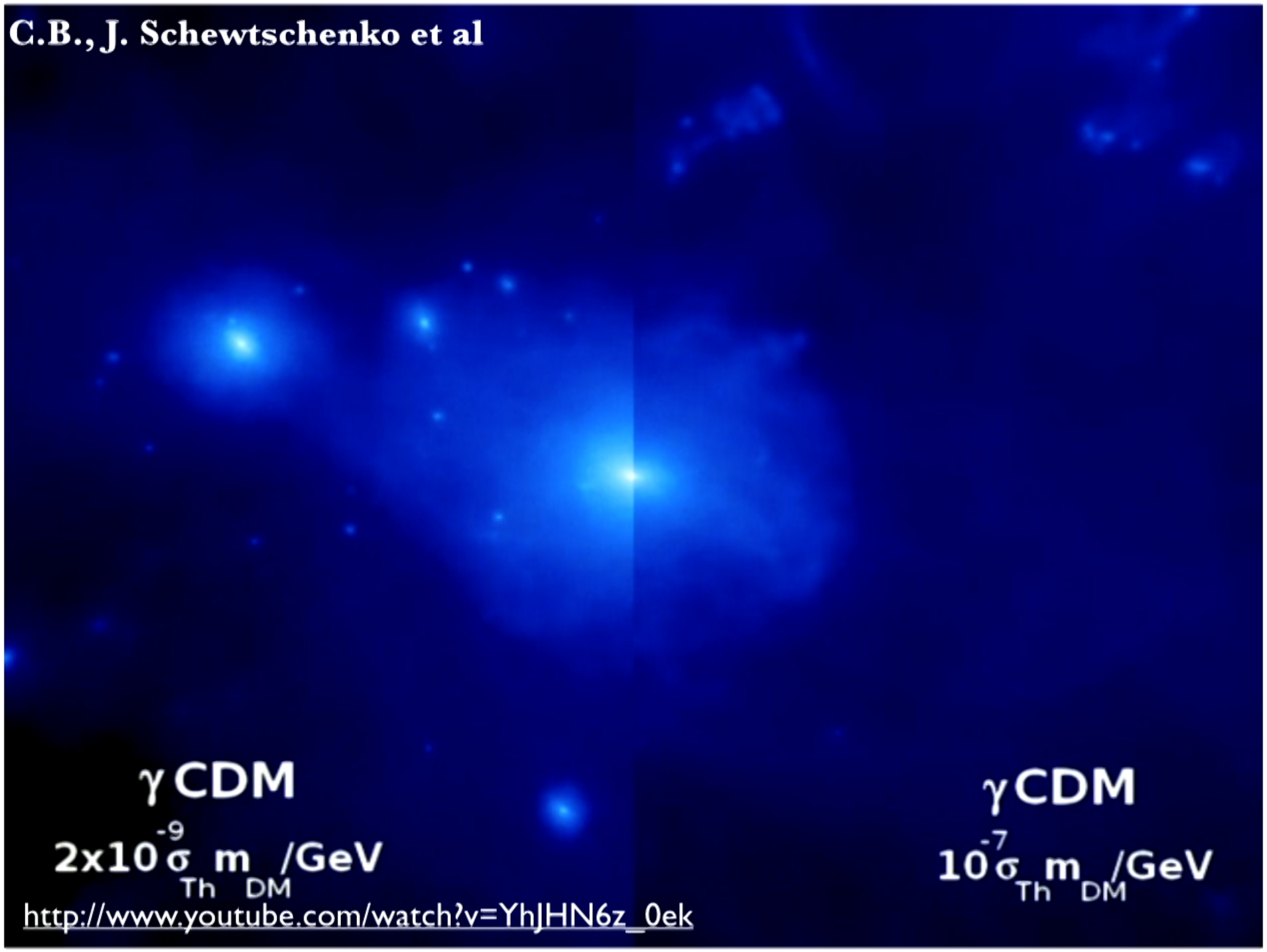


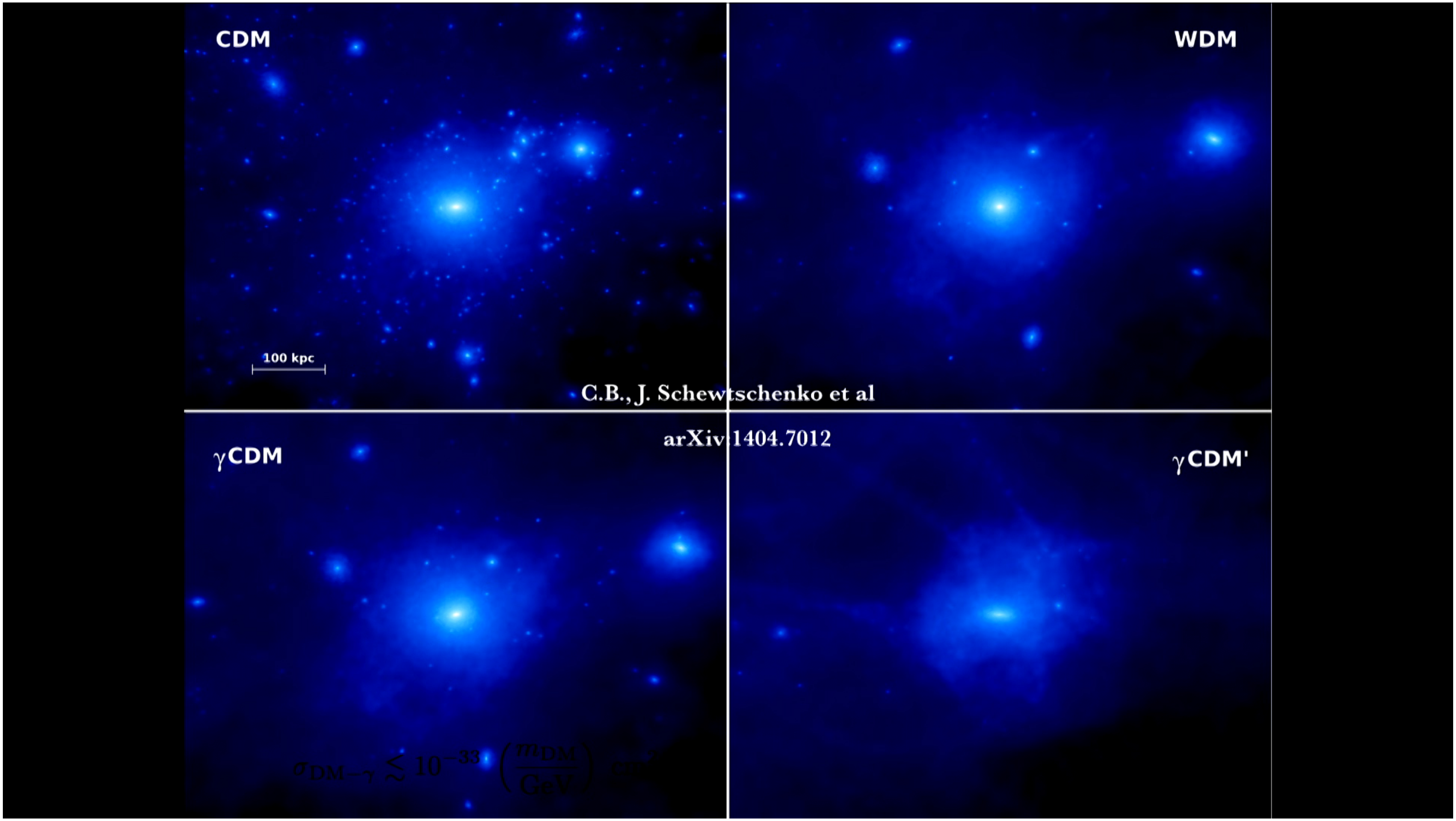
The Milky Way for interacting DM

The Milky Way for interacting DM



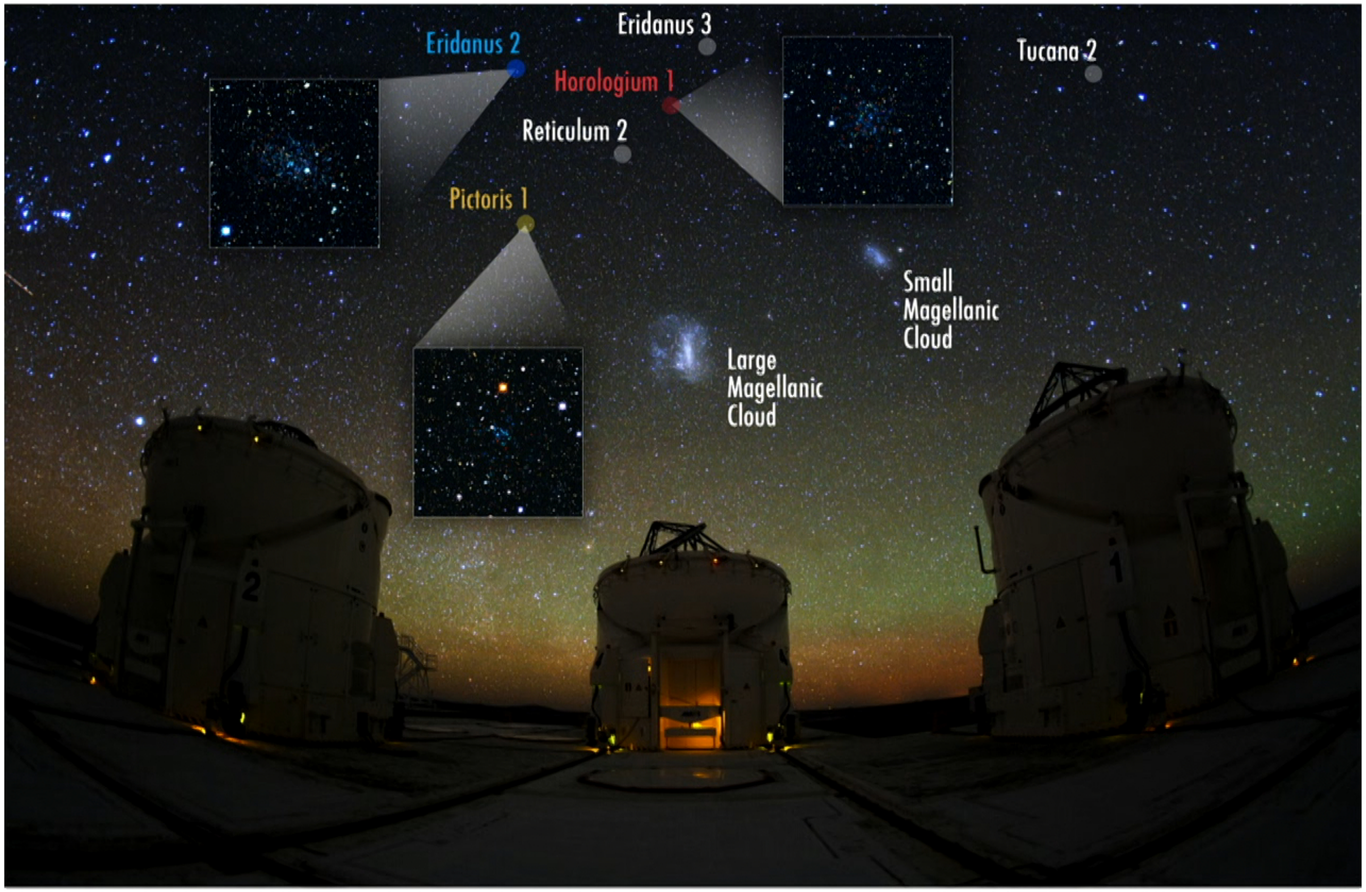
The Milky Way for interacting DM





CDM
WDM
100 kpc
C.B., J. Schewtschenko et al
arXiv:1404.7012
γCDM
γCDM'

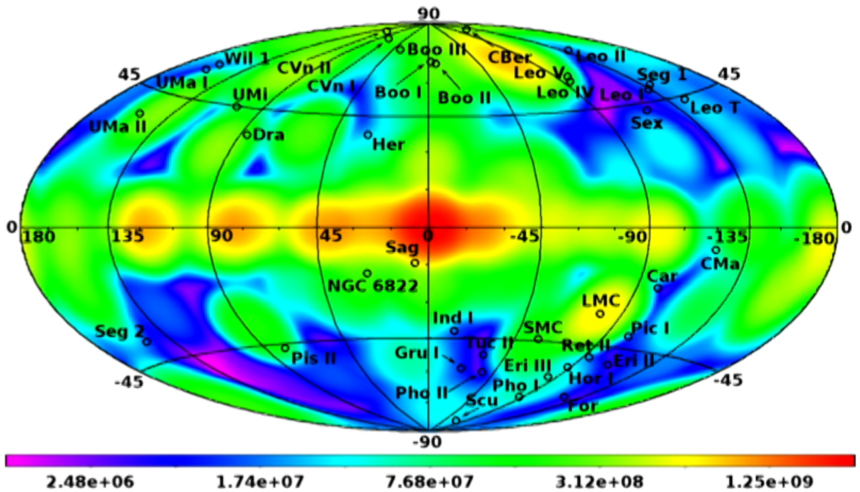
Indirect detection



faint objects which are DM dominated

How many dwarf galaxies?

40 observed versus 10000-100000 predicted

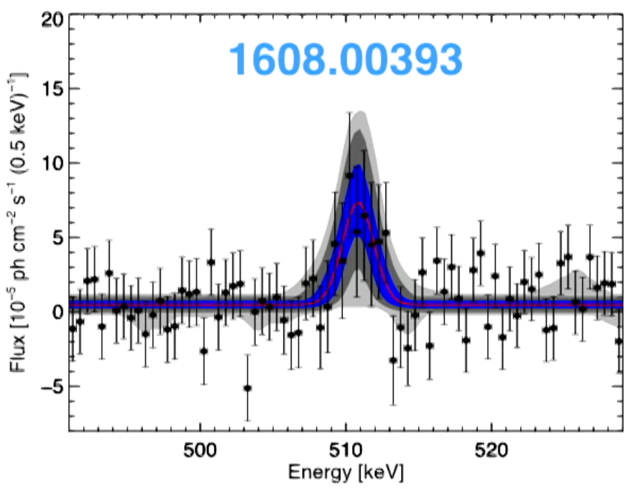


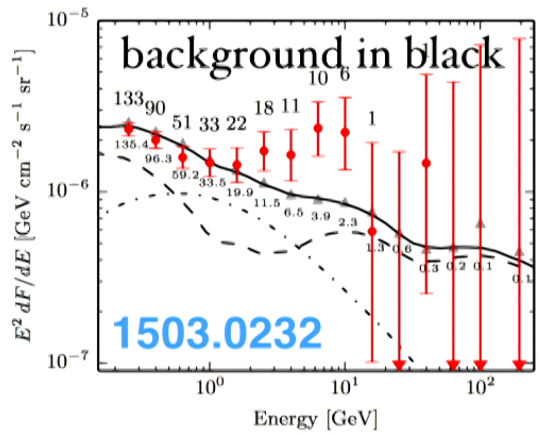
The answer depends on the DM physics

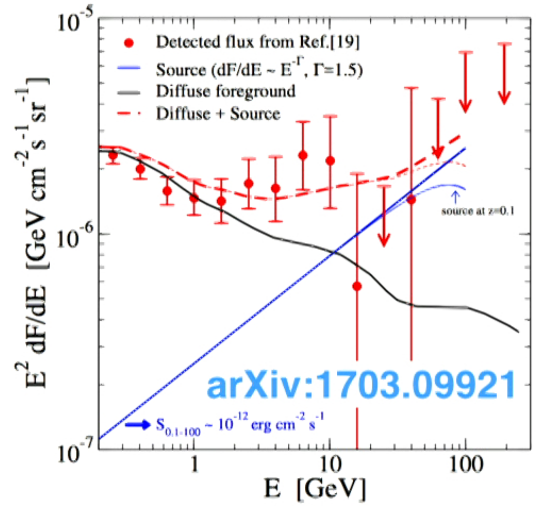
Reticulum II

Excess of gamma-rays (GeV range) but also 511 keV and radio

511 keV



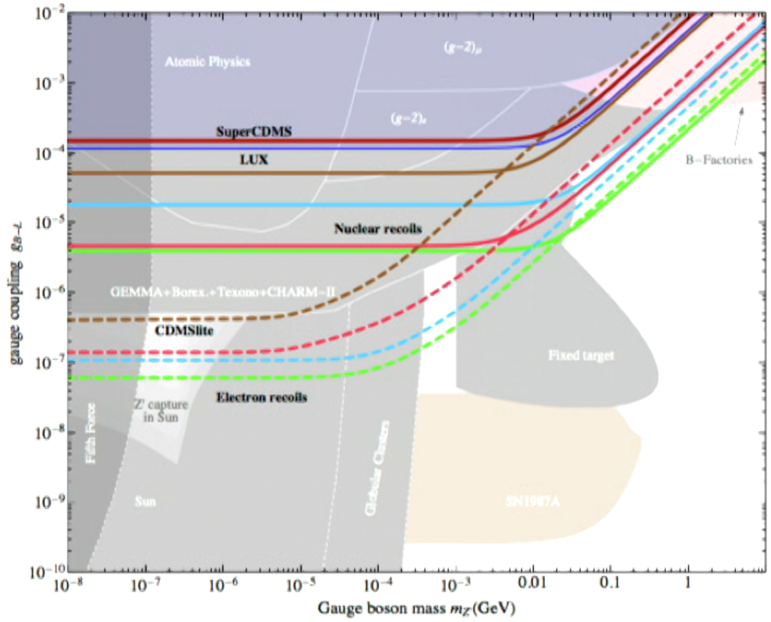


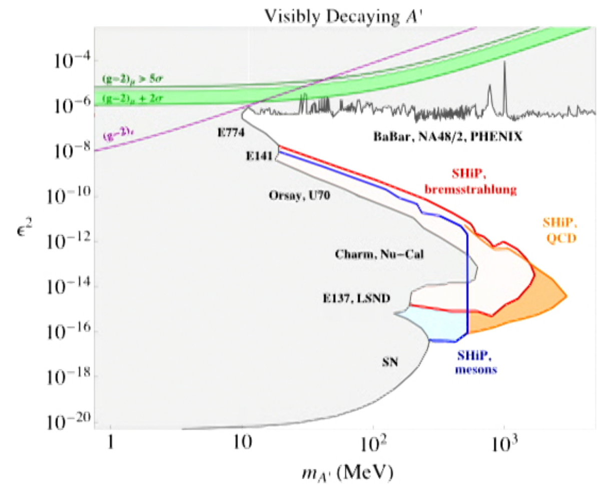


So

have we discovered
light dark matter?

Searching for Z'/dark photons





Effects of Weakly Interacting Slim Particles in Cavities with a Moving Boundary Condition

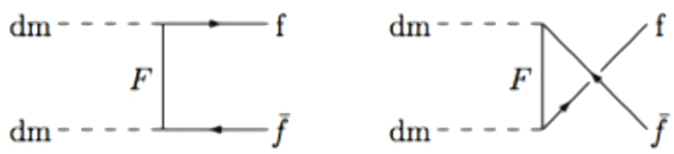
Ariel Arza

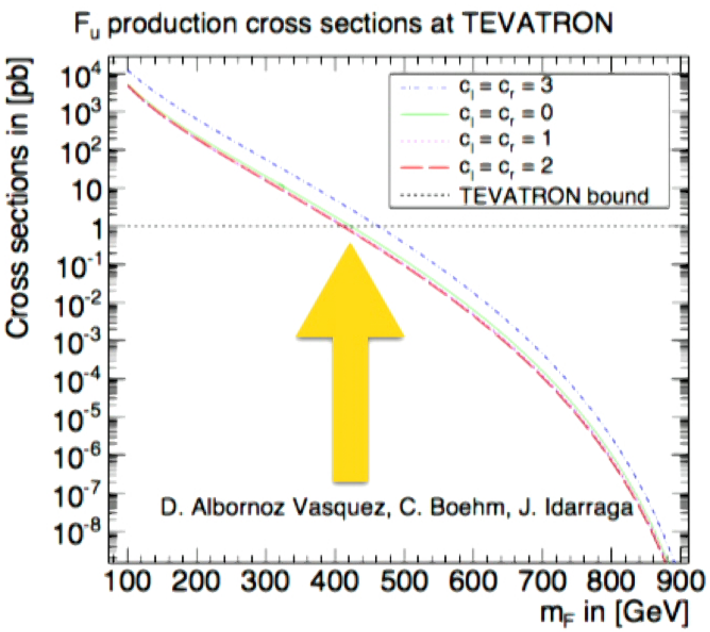
May 10, 2017

e-Print: arXiv:1705.03906 [hep-ph] | PDF

T-channel mediators at LHC

first example of simplified models at LHC



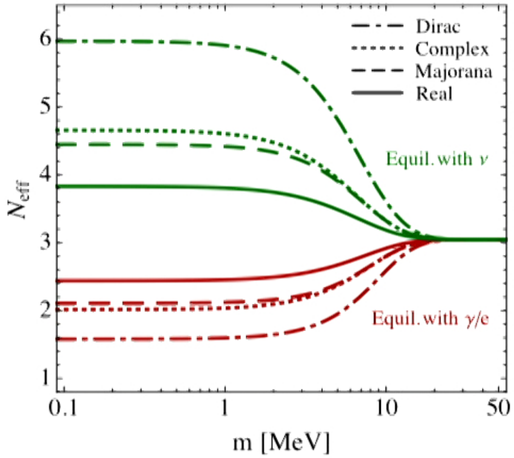


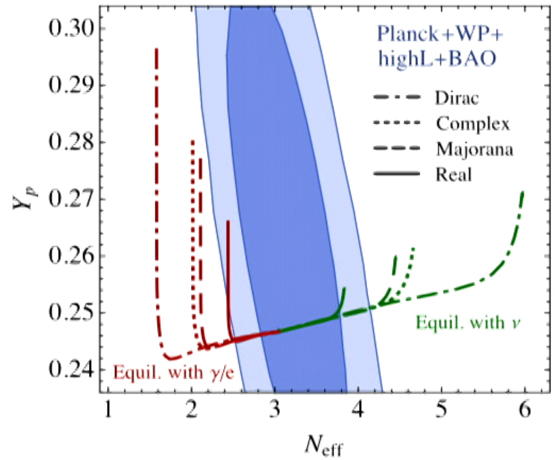
0912.5373

The mediator can be produced through the exchange of DM

Ruled out (now) up to TeV

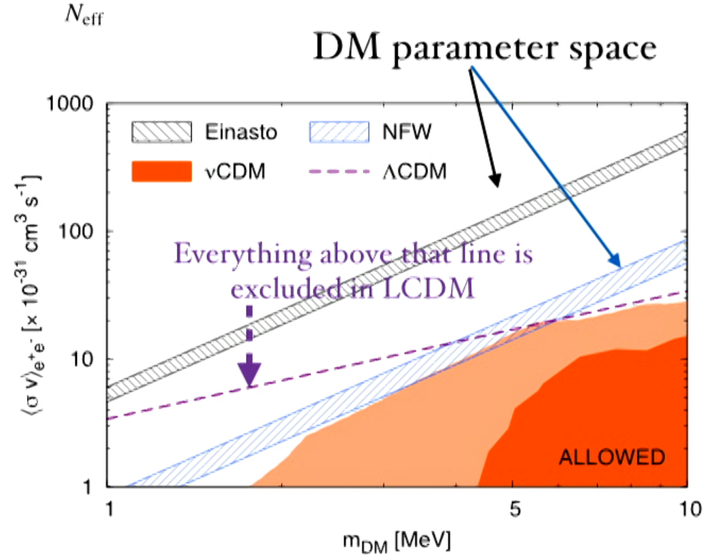
Impact on baryons





reheat neutrinos
not good

number of neutrino-like species



injection of e- at late time
not good....

Conclusion

Light DM initially motivated by structure formation

Model building was rather appealing

But unsuccessful despite many false alerts and beautiful features

Learnt a bit more about the DM parameter space