Title: New strategies to probe dark matter microphysics

Date: May 27, 2015 03:30 PM

URL: http://pirsa.org/15060002

Abstract: Identifying the nature of dark matter is one of the most challenging problems in physics. There is a general consensus that dark matter is a weakly interacting particle and predominantly cold, yet the Cold Dark Matter (CDM) hypothesis remains to be verified. I will show that next cosmological surveys could play a leading role in understanding the dark matter microphysics.

New Dark Matter probes

Céline Boehm

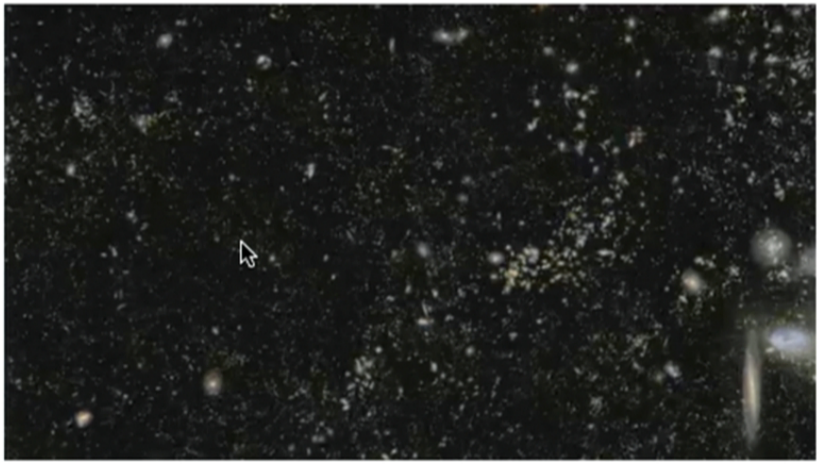
credit arXiv:1404.7012

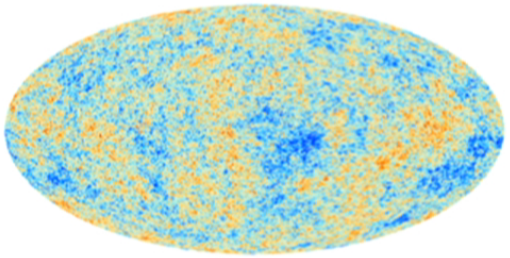
IPPP, Durham

LAPTH, Annecy

PI, 27 May 2015

Modern Cosmology has unraveled a new type of matter





Measurement of the matter power spectrum
at relatively large scales

But a new invisible form of matter is needed (Dark Matter)

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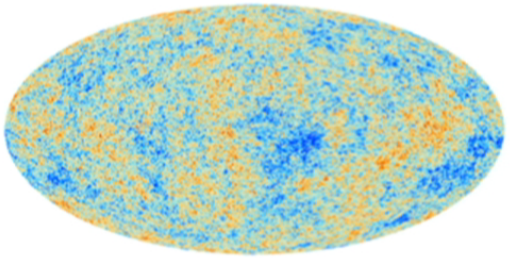

Measurement of the matter power spectrum
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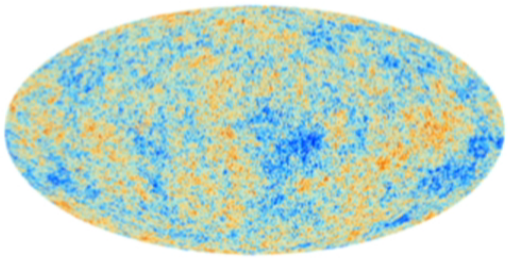
But a new invisible form of matter is needed (Dark Matter)

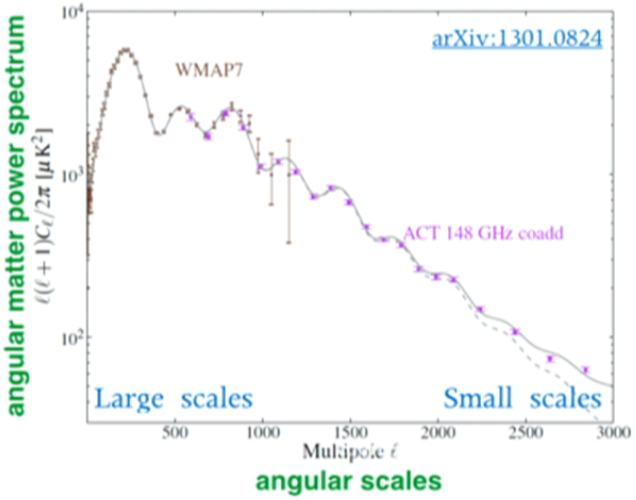
Lessons from CMB

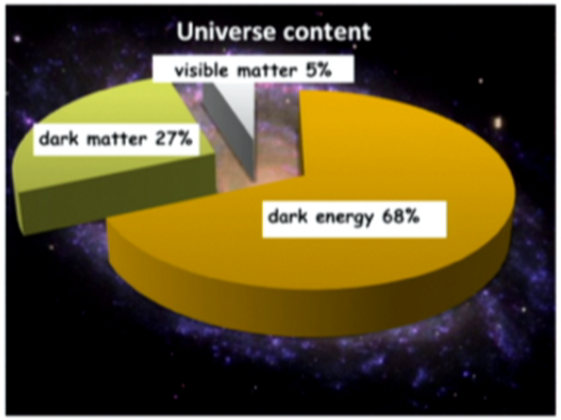
Fluctuations in the matter energy density is at the origin of galaxies

courtesy Planck



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

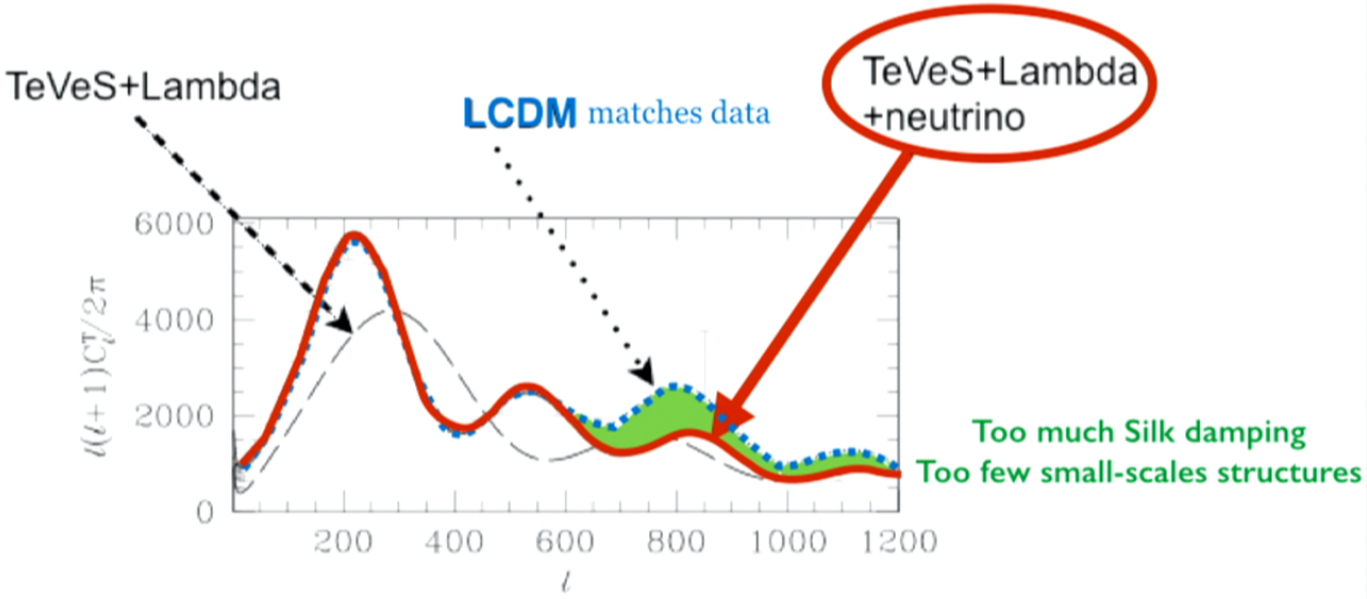




A Universe without DM is not a good Universe

TeVeS (relativistic MOND, only baryons; no DM)

Bekenstein astro-ph/0403694



Suppression at small scales unavoidable

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

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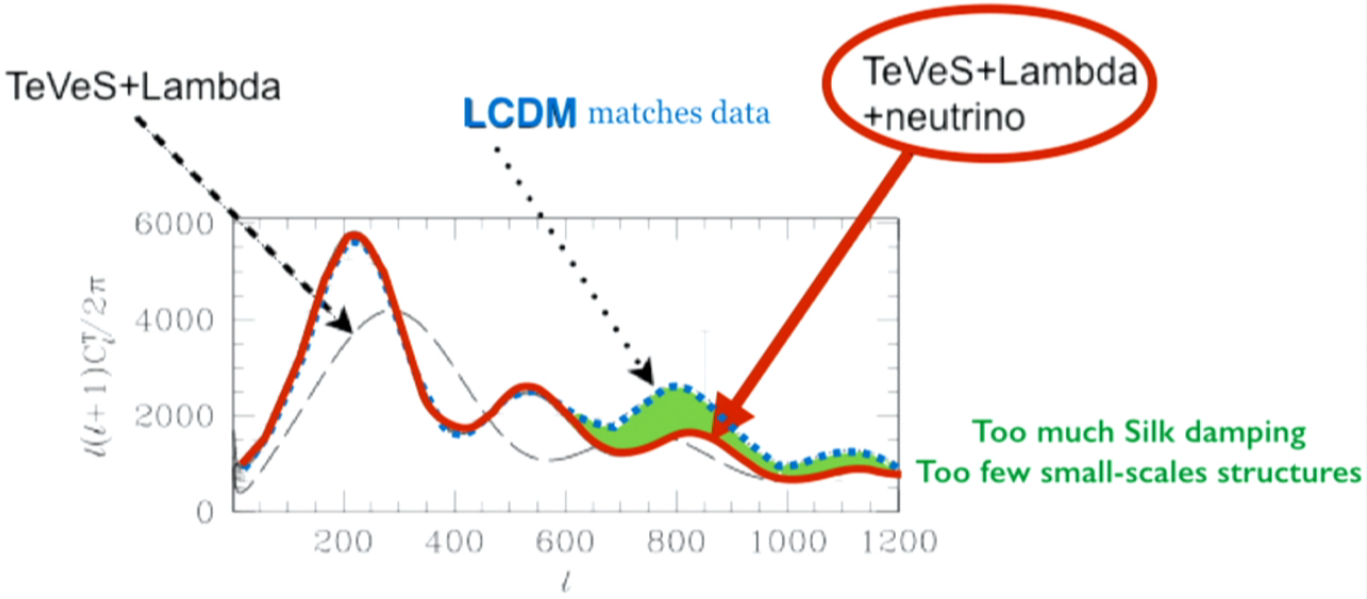

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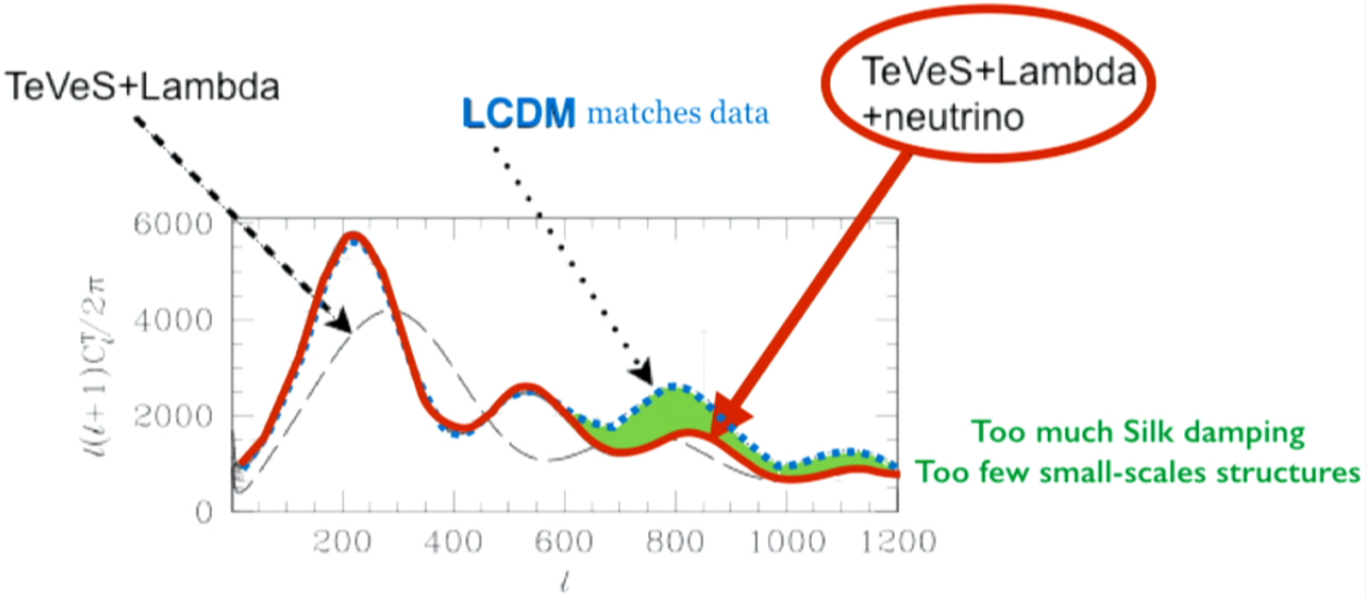

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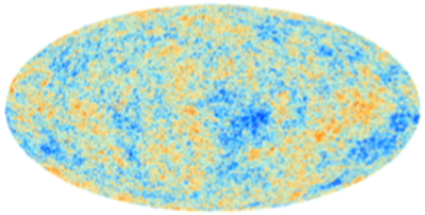
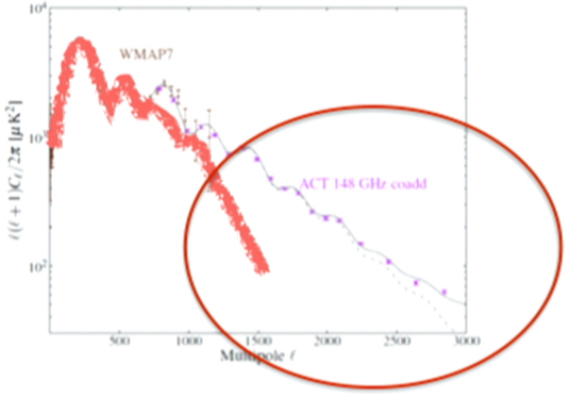
Physics of Silk damping



Overdensity of matter (fluctuations)



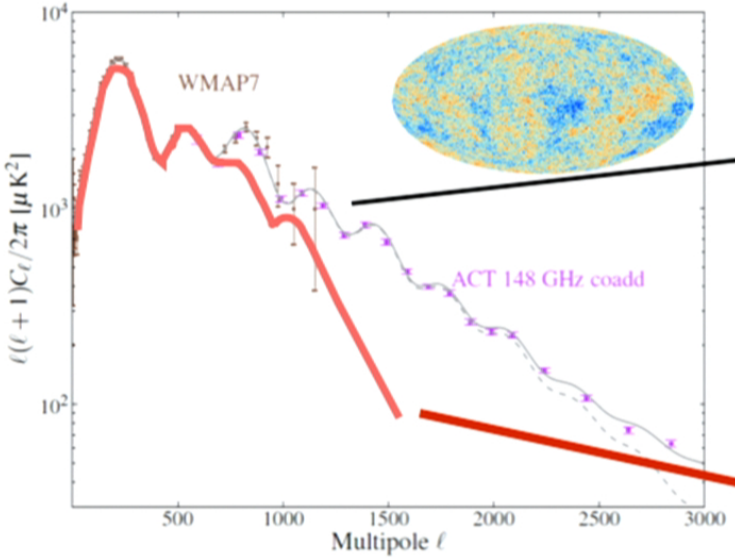
Diffusion due to baryon-photon interactions

The effect is large because

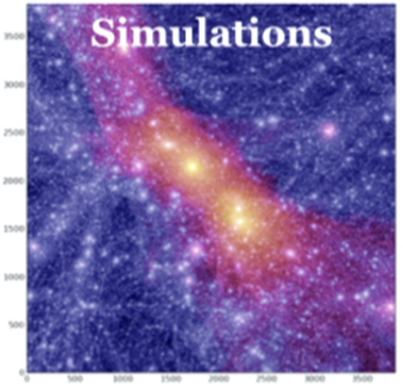
The Thomson cross section is large
The number density of photons is large
The photons are relativistic

Silk damping
suppression of small size fluctuations

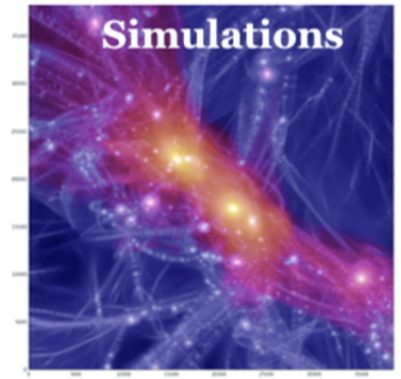
What would the Universe look like if no DM?



if CDM



closer to

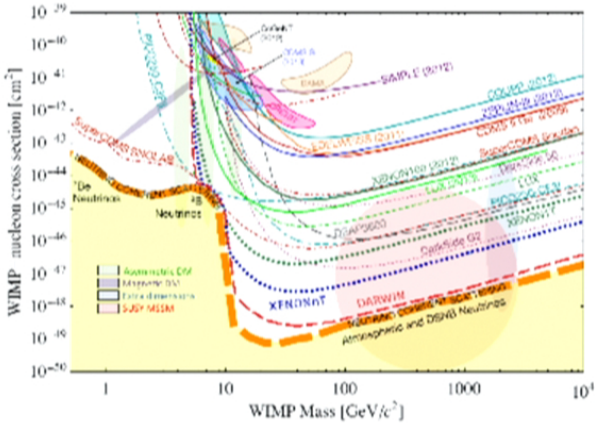


baryon-like

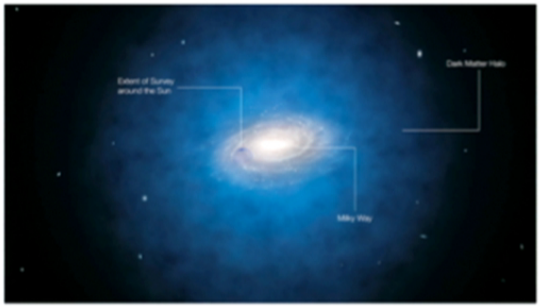
The weakly interacting massive particle paradigm makes sense!

3 main strategies to discover DM particles

Direct detection



Indirect detection



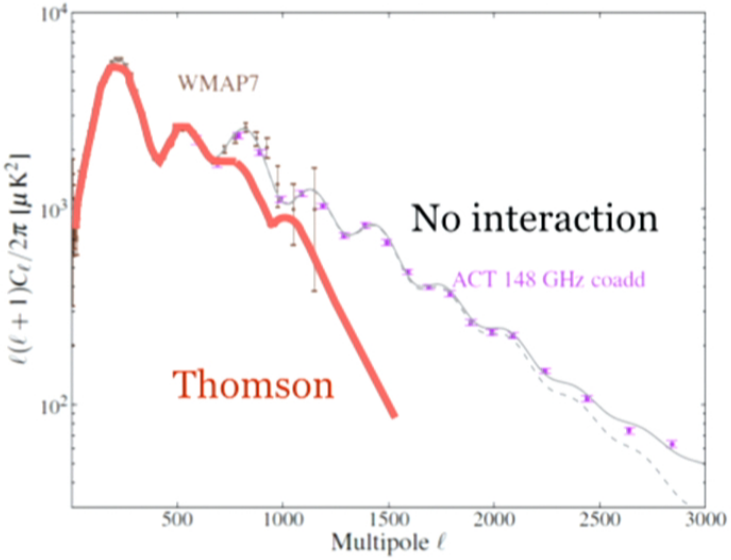
LHC

Or ...

you can try to exploit galaxy surveys

starting point: doubt everything you know!

Is dark matter really weakly interacting? (current paradigm)



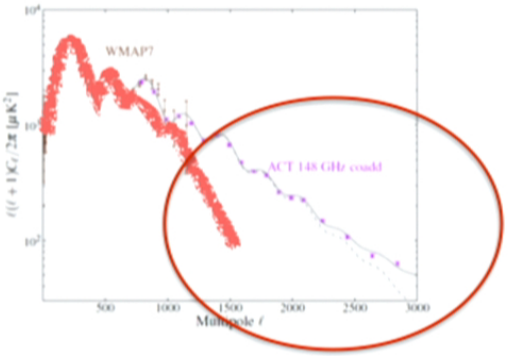
What would happen if DM had weak but non negligible interactions?

Notion of *collisional damping*

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

Perturbation = overdensity of matter

Diffusion DM-SM
the effect should be large depending on the cross section



Silk damping
suppression of small size perturbations

Generalisation of Silk damping

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

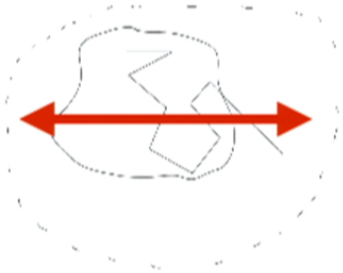
whether the species that is interacting with DM is relativistic or not

whether DM has interactions or not?

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

astro-ph/0012504 astro-ph/0410591

damping scale



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

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

Collisional damping in modern Cosmology

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

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

Translation in terms of Cosmological perturbations

without DM interactions

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

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

with DM interactions

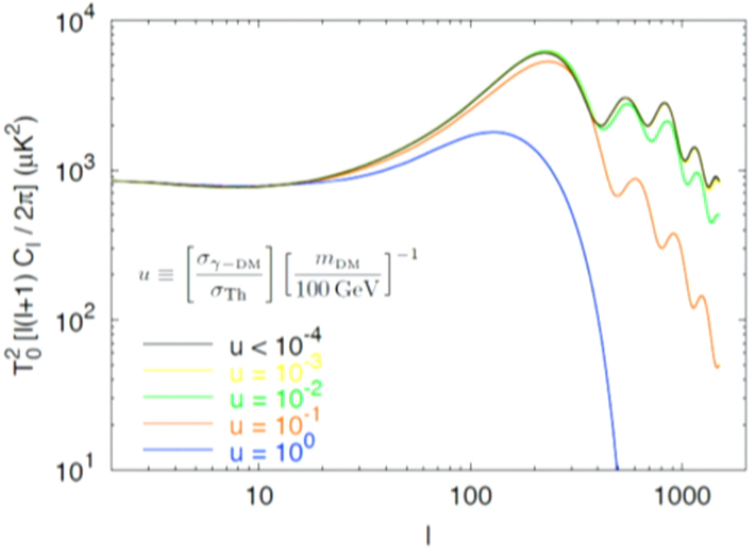
$$\begin{aligned}
\dot{\theta}_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) \\
&\quad -\dot{\kappa}(\theta_\gamma - \theta_b) - \dot{\mu}(\theta_\gamma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

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

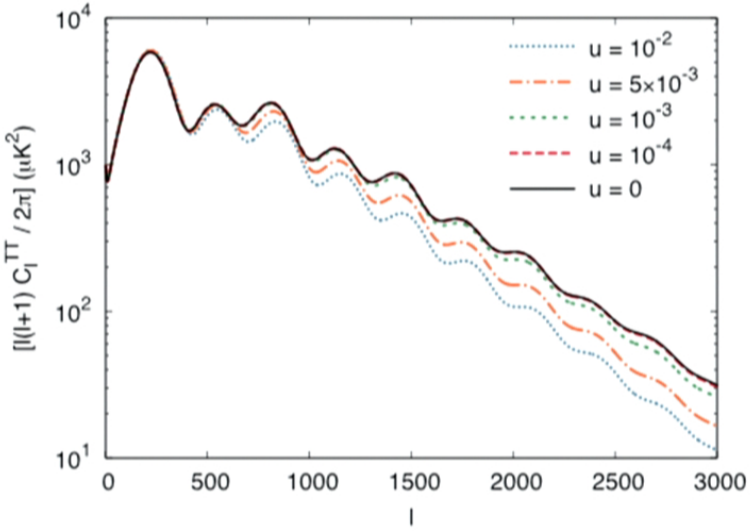
What would the CMB look like if DM interacts?

DM-photon interactions (but DM-neutrinos are similar)

C.B&Riazuelo et al: astro-ph/0112522



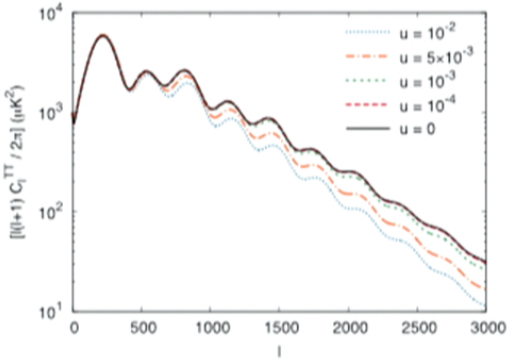
R. Wilkinson, CB et al : arXiv:1309.7588



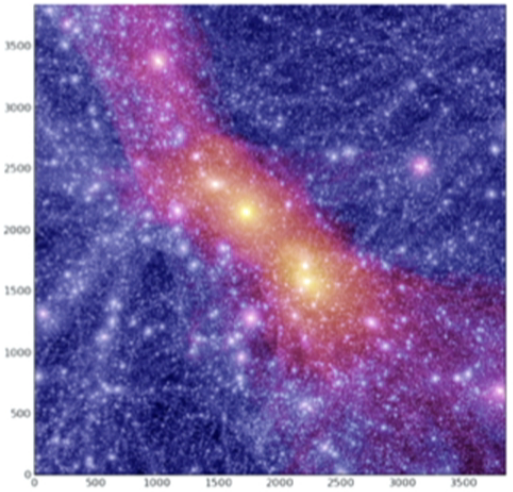
$u = 1$ Thomson interactions — dark matter is even more interacting than a baryon!

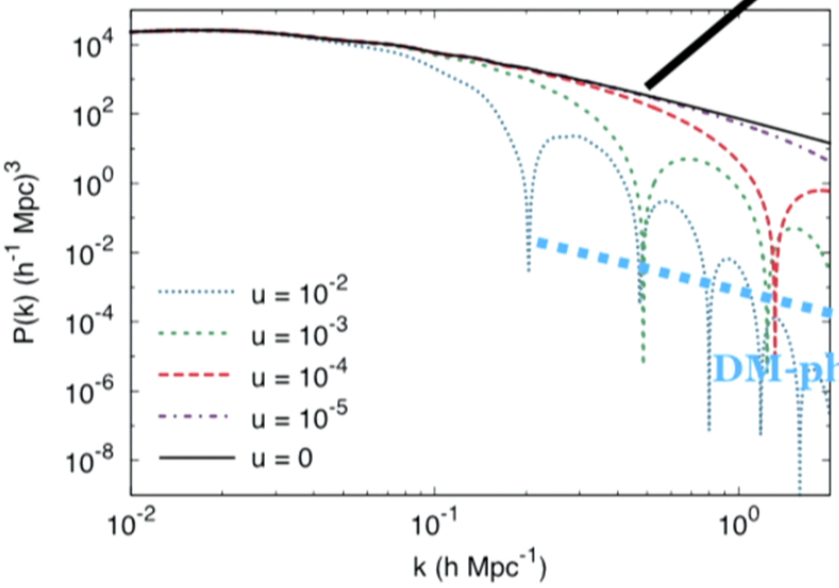
$u = 10^{-4} \Rightarrow \sigma \sim 6\ 10^{-31} \left(\frac{m_{DM}}{\mathrm{GeV}}\right)\ \mathrm{cm}^2$ — dark matter is not a baryon:
Can you tell it is coupled to photons?

The Universe in case of interacting DM

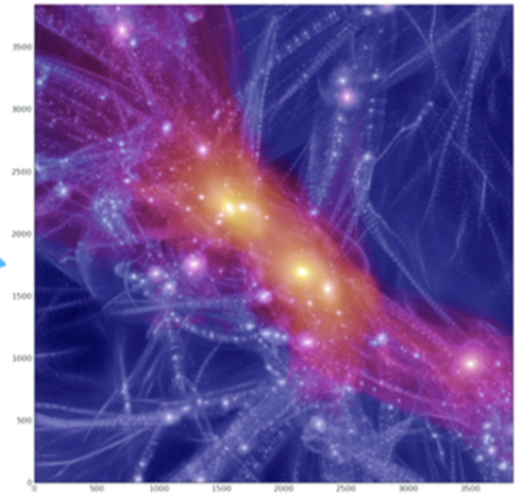


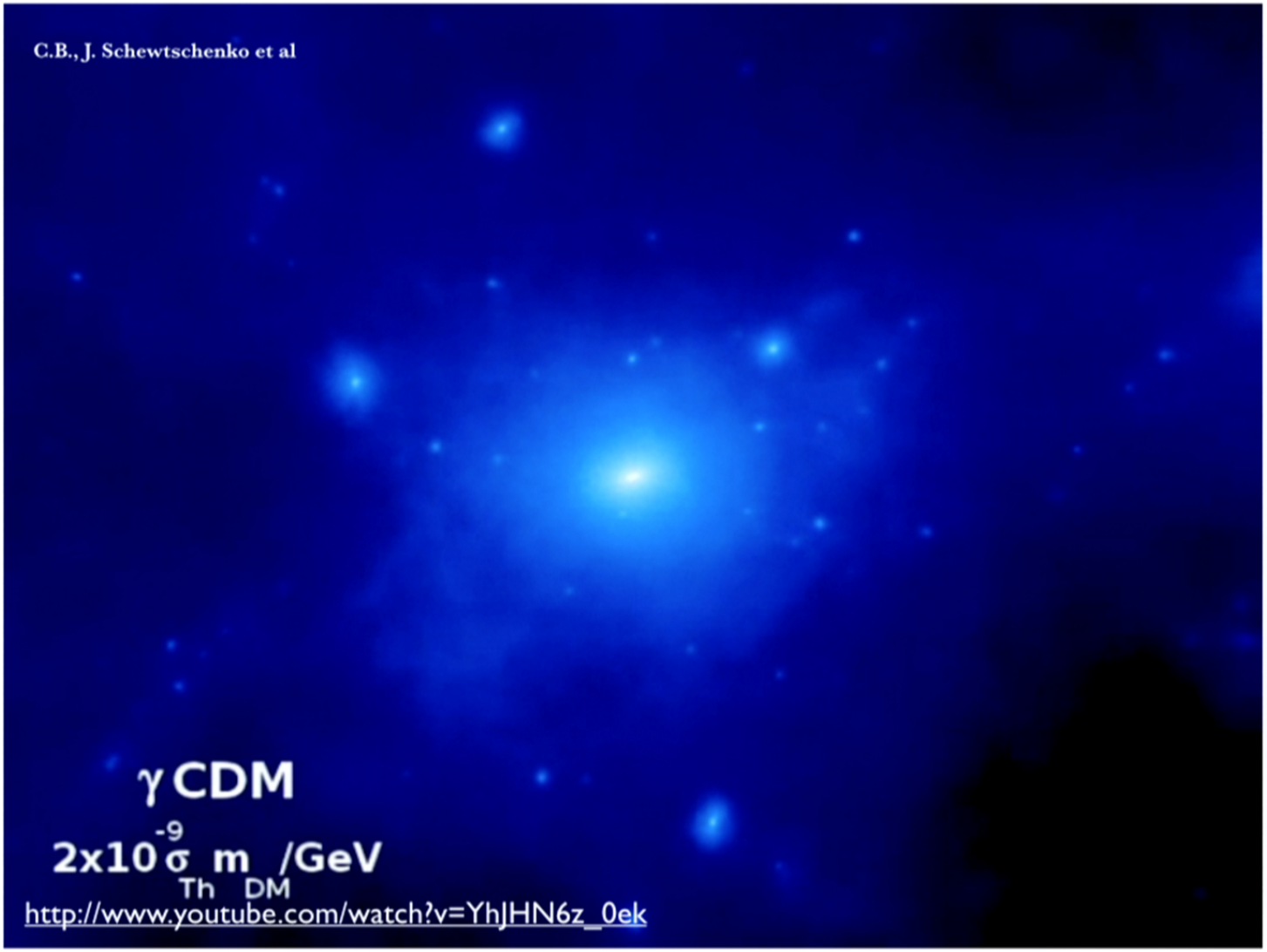
LCDM

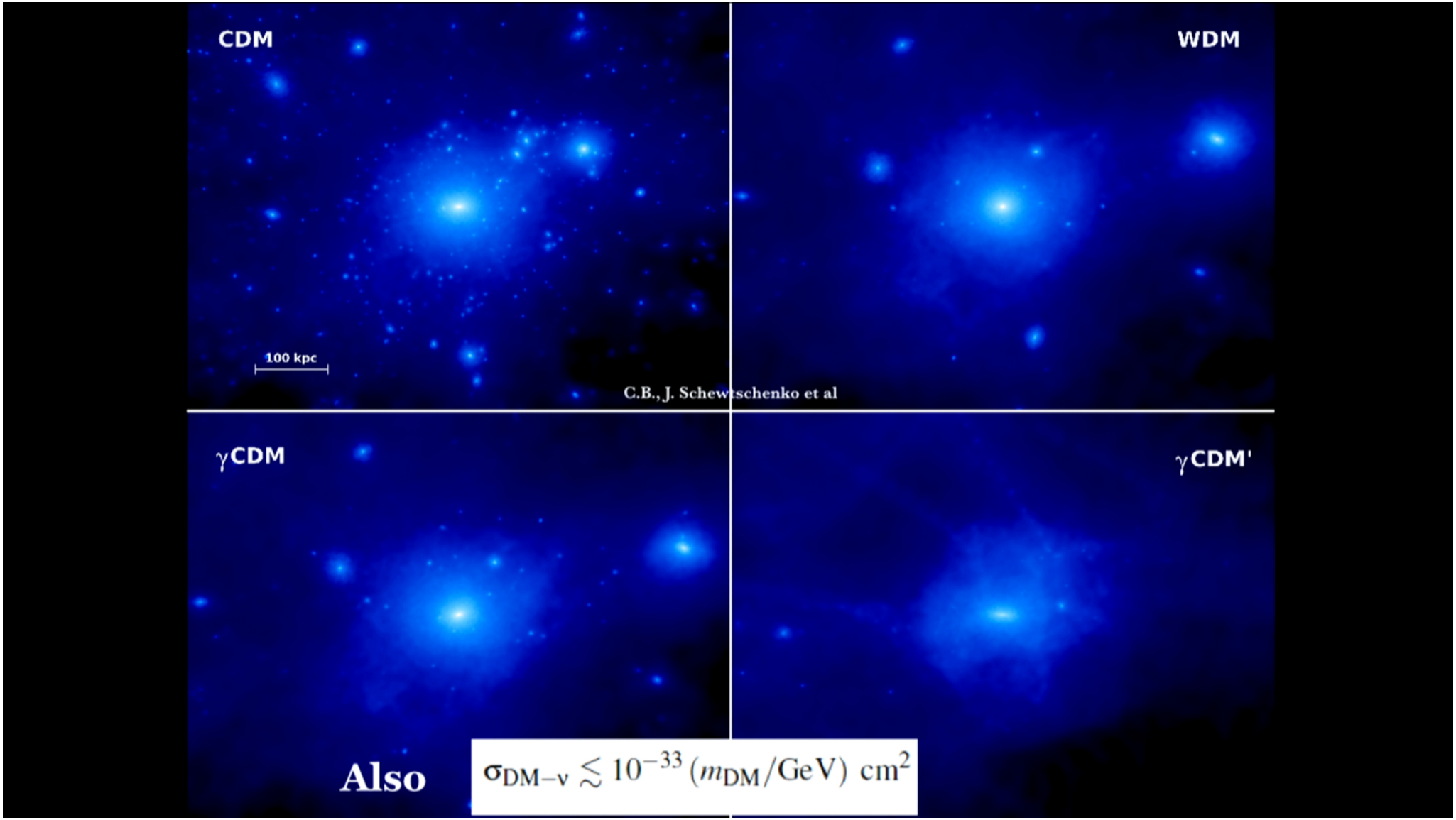


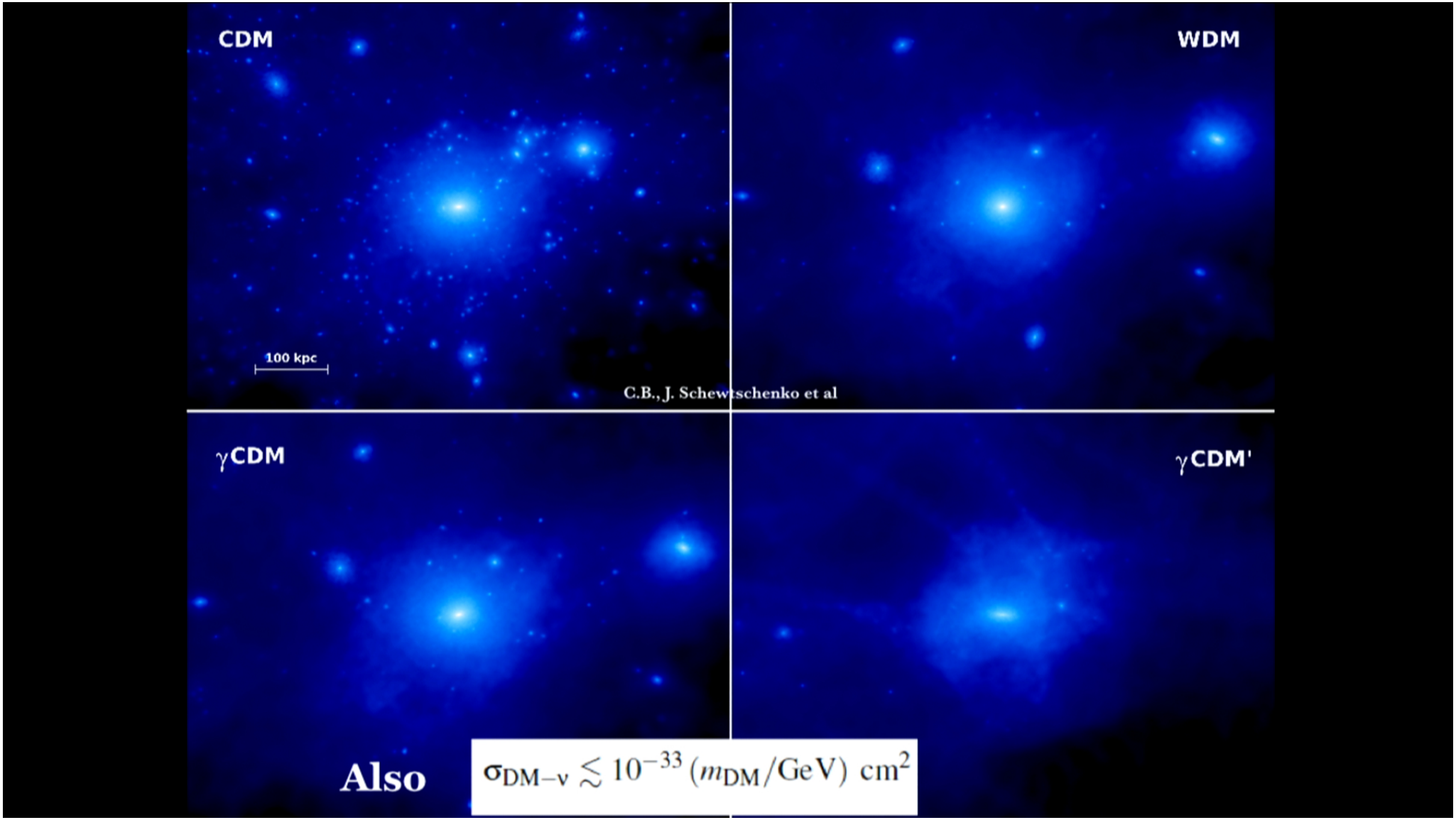


DM-photon




C.B., J. Schewtschenko et al
γ CDM
2x10^-9 σ_Th m_DM /GeV
http://www.youtube.com/watch?v=YhJHN6z_0ek


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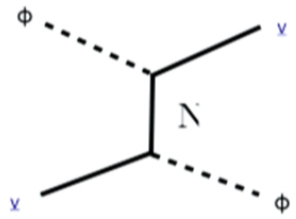
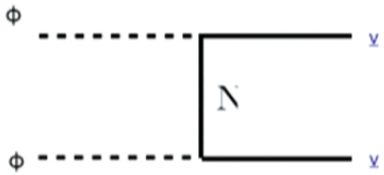
Potential link with neutrino physics

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





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

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

MeV DM requires couplings of about 3 10^-3

Effective theory

(N singlet of SU(2) for example)

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

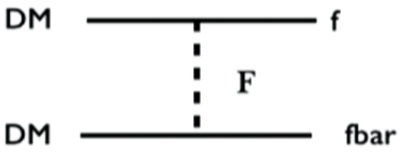
With **MeV DM** (m_N=m_{DM}) one obtains

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

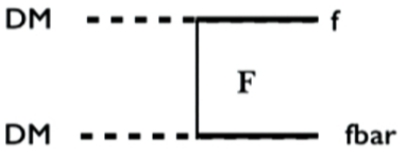
$$\sigma_{\mathrm{DM}-\nu} \simeq 1.2\ 10^{-36}\left(\frac{m_N}{MeV}\right)^2\left(\frac{\langle\sigma v\rangle}{3\ 10^{-26}\ \mathrm{cm^3/s}}\right)\left(\frac{m_{\mathrm{DM}}}{MeV}\right)^{-2}\ \mathrm{cm^2}$$

Light thermal DM?

$$\Omega_{DM}h^2 \propto \frac{10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\sigma v}$$



Majorana DM



scalar DM

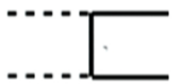
$$\sigma v \propto \frac{\left(2c_l c_r\ \mathrm{m_{DM}} + (\mathrm{c_l^2} + \mathrm{c_r^2})\ \mathrm{m_f}\right)^2}{\left(m_F^2 - \mathrm{m_{DM}^2} - \mathrm{m_f}^2\right)^2}$$

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

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

Fermionic DM scenario depends on both DM and mediator masses.
Scalar DM scenario depends only on the mediator mass

DM can be light if the mediator is also light and couplings are small!



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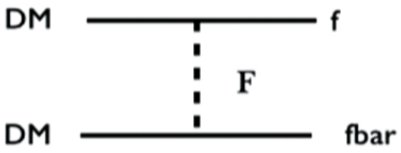
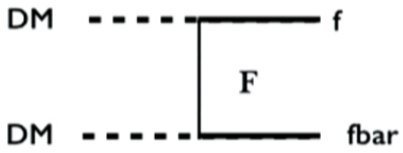


Majorana DM



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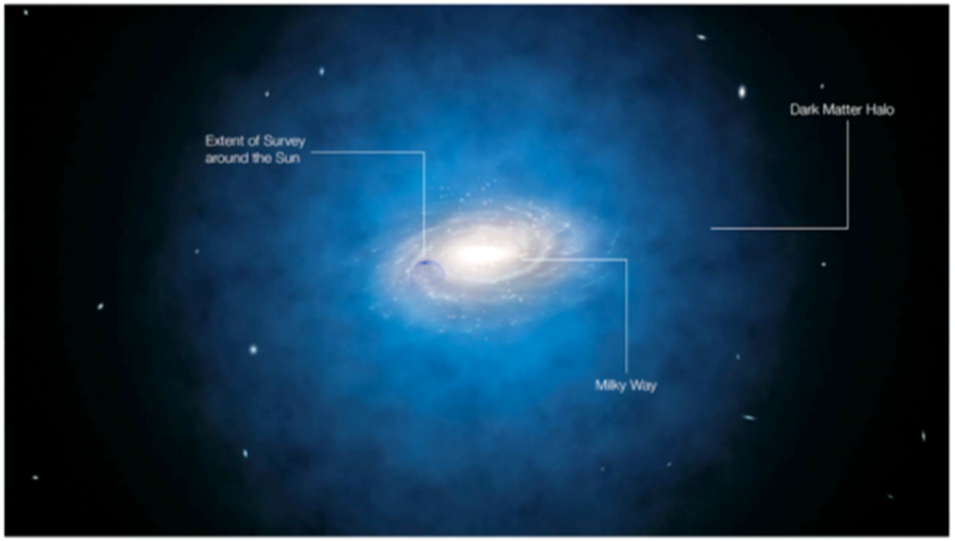
Indirect detection

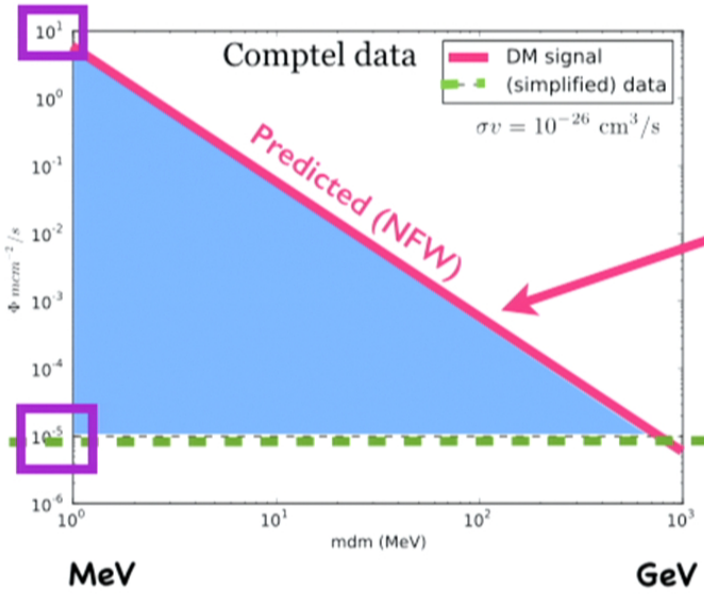


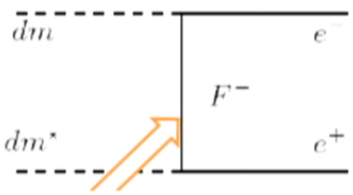
annihilations DM DM —> SM SM + photons

$$\frac{d\phi}{dE} = \frac{1}{8\,\pi}\left(\frac{\sigma v}{m_\chi{}^2}\right) \underbrace{\sum_i \mathrm{BR_i}\,\frac{\mathrm{dN_i}}{\mathrm{dE}}}_{=1}\,\xi^2 \boxed{\text{Only depends on the DM profile}\quad \int \mathrm{dl}\;\rho_\chi^2(\mathrm{l})} \Rightarrow \Phi_{\mathrm{prompt}} \propto \frac{\sigma v}{\mathrm{m_{DM}}{}^2}\int dl\;\rho^2(l)$$

Gamma rays constrain the light mass range

astro-ph/0208458 & hep-ph/030526





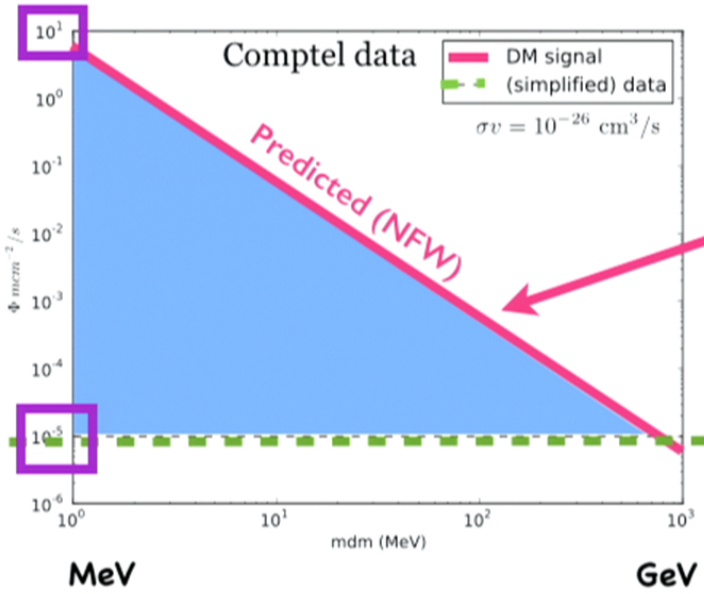
$$\Phi^{GC}_{\rm obs}(< 1.5^\circ) \sim 5.9 \left(\frac{m_{\rm DM}}{\rm MeV}\right)^{-2} \left(\frac{\sigma v}{10^{-26}\ {\rm cm}^3/{\rm s}}\right) {\rm cm}^{-2}\ {\rm s}^{-1}$$

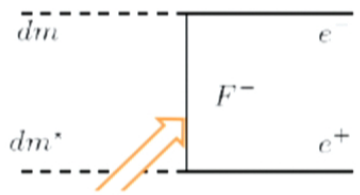
observations (rough guide!)

LIGHT (thermal) DM needs p-wave annihilations or neutral final states

Gamma rays constrain the light mass range

astro-ph/0208458 & hep-ph/030526





$$\Phi^{GC}_{\rm obs}(< 1.5^\circ) \sim 5.9 \left(\frac{m_{\rm DM}}{\rm MeV}\right)^{-2} \left(\frac{\sigma v}{10^{-26}\ {\rm cm}^3/{\rm s}}\right) {\rm cm}^{-2}\ {\rm s}^{-1}$$

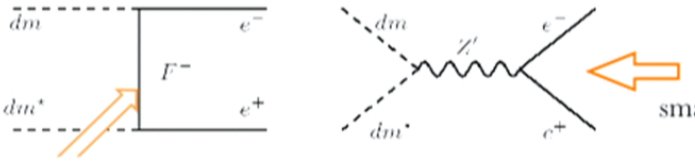
observations (rough guide!)

LIGHT (thermal) DM needs p-wave annihilations or neutral final states

Light (MeV - 10 GeV) DM

astro-ph/0208458

too many gamma-rays
unless it is suppressed



correct abundance
small indirect detection signal

Are light annihilating Dark Matter particles possible?

astro-ph/0208458

C. Boehm[1], T. A. Enßlin[2], J. Silk[1]

[1] *Denys Wilkinson Laboratory, Astrophysics Department, OX1 3RH Oxford, England UK;*
[2] *Max-Planck-Institut für Astrophysik Karl-Schwarzschild-Str. 1, Postfach 13 17, 85741 Garching*

(Dated: 22 August 2002)

We investigate the status of light Dark Matter (DM) particles from their residual annihilation and discuss the range of the DM mass and total annihilation cross section compatible with gamma-rays experiment data. We find that particles as light as a few 10 MeV or up to $\sim$ 10 GeV could perhaps represent an interesting alternative to the standard picture of very massive WIMPs.

So in principle no reason to neglect the low mass range!

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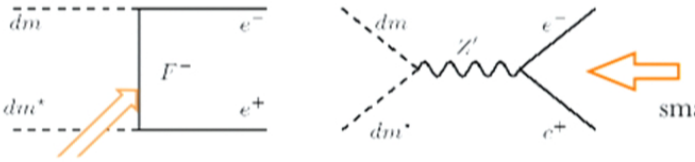

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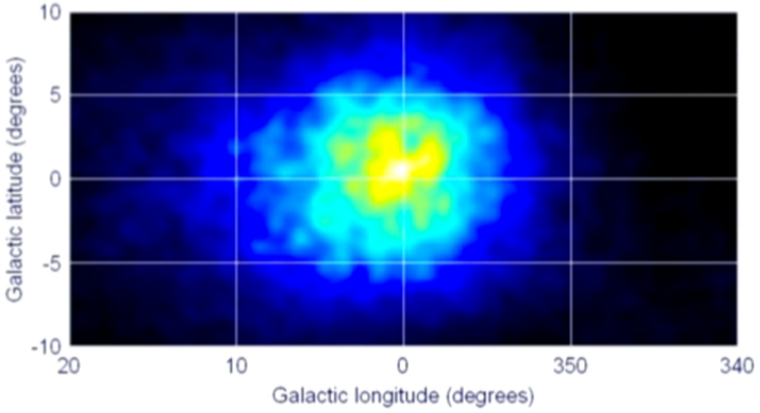
Related signals: the 511 keV line

astro-ph/0309686

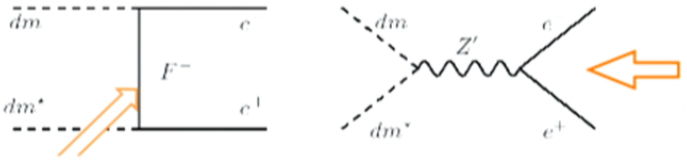


511 keV

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
and not necessarily a good fit

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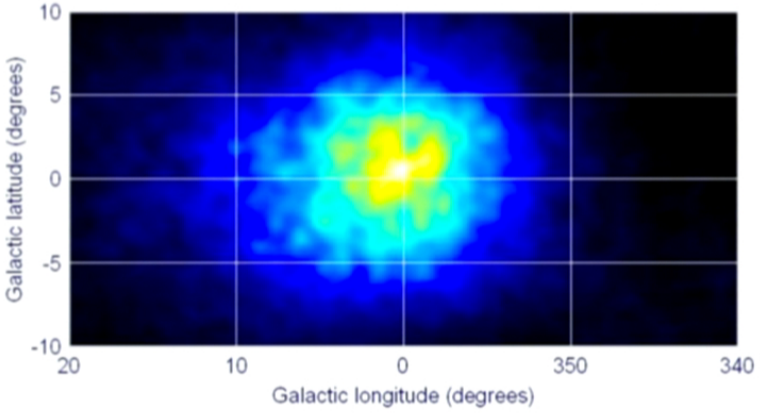

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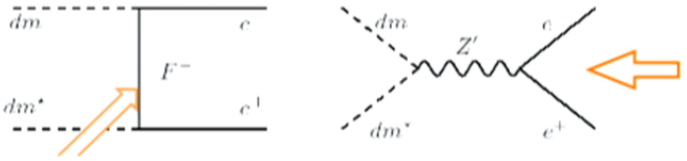

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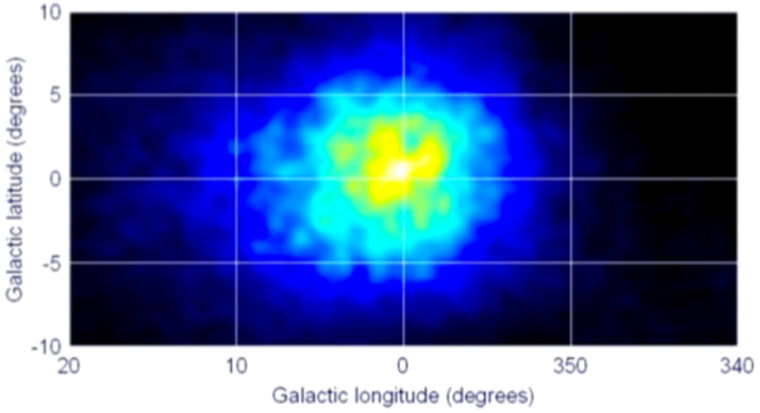

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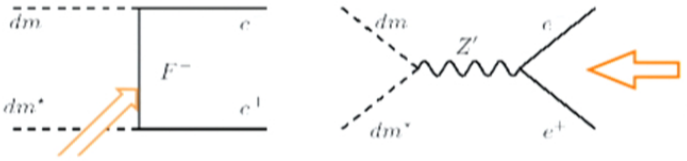

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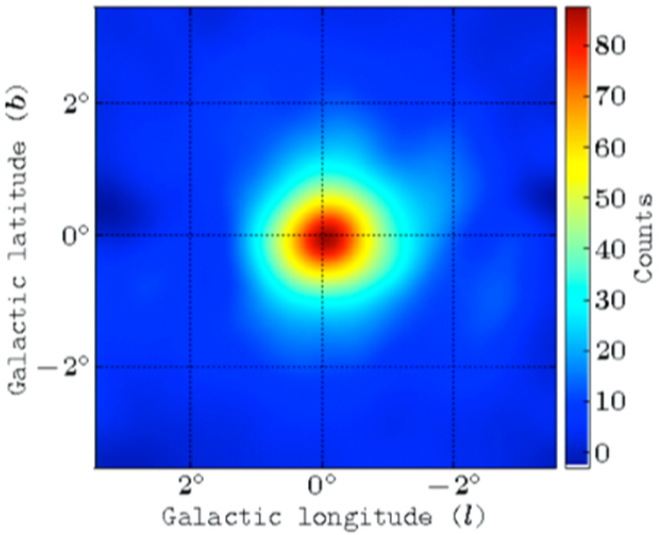
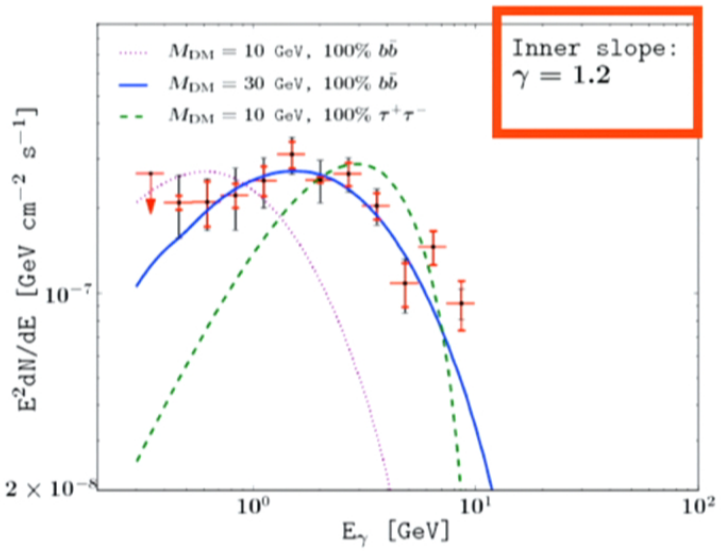
Related signals: the gamma-ray excess



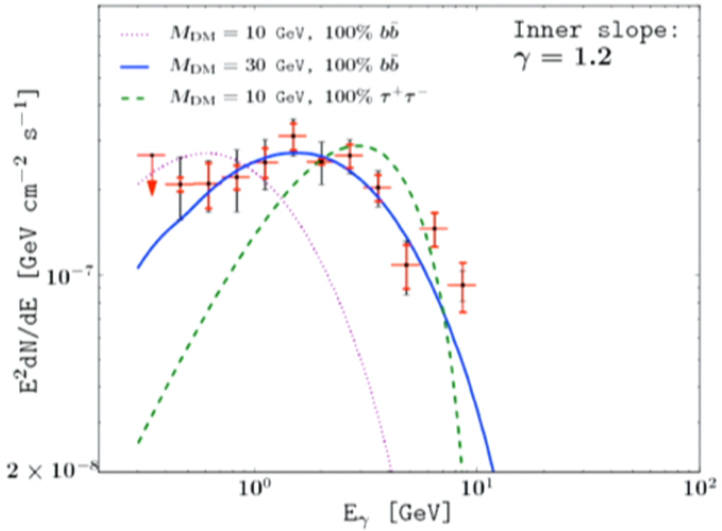
10-30 GeV DM annihilating mostly into b-quarks or muons can fit the FERMI-LAT data...

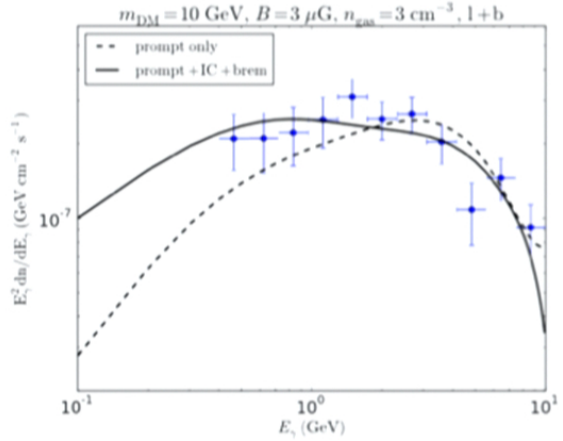


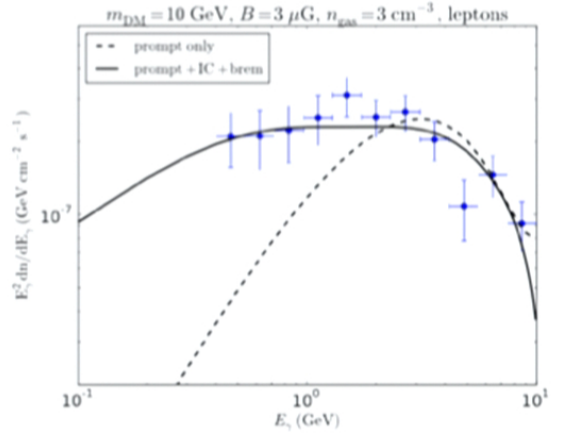
Fermi collaboration 2009
Hooper&Goodenough 2009
D. Hooper and T. Linden: arXiv: 1110.0006
C. Gordon & O. Macias: arXiv:1306.5725

Related signals: the gamma-ray excess

But propagation of cosmic ray cannot be neglected







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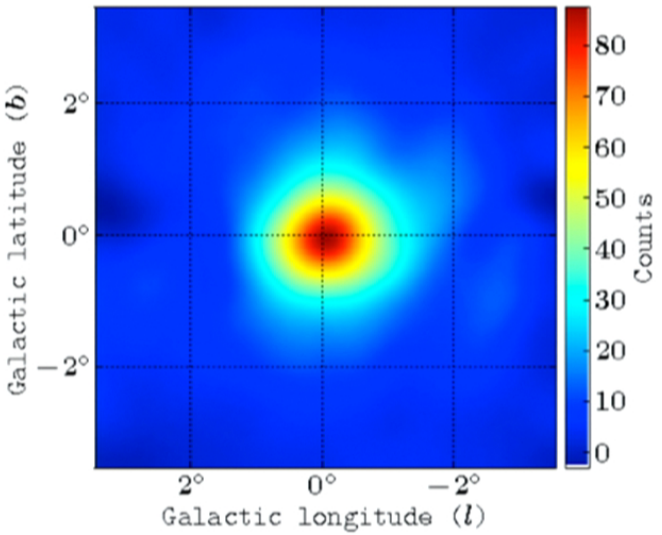

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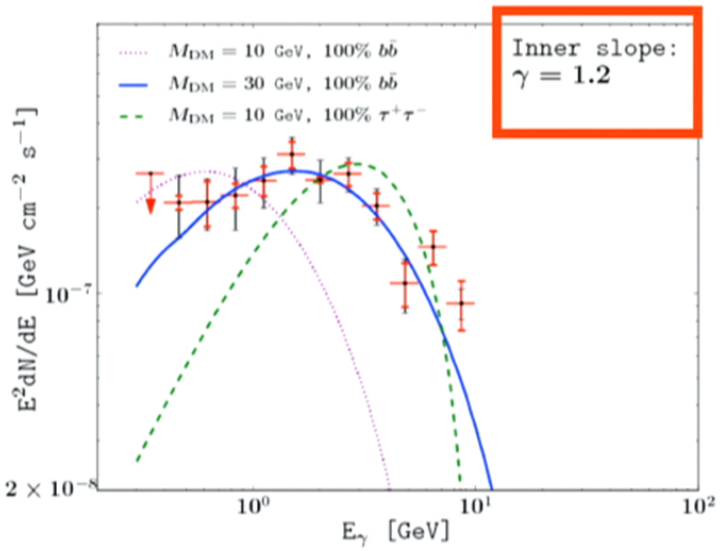

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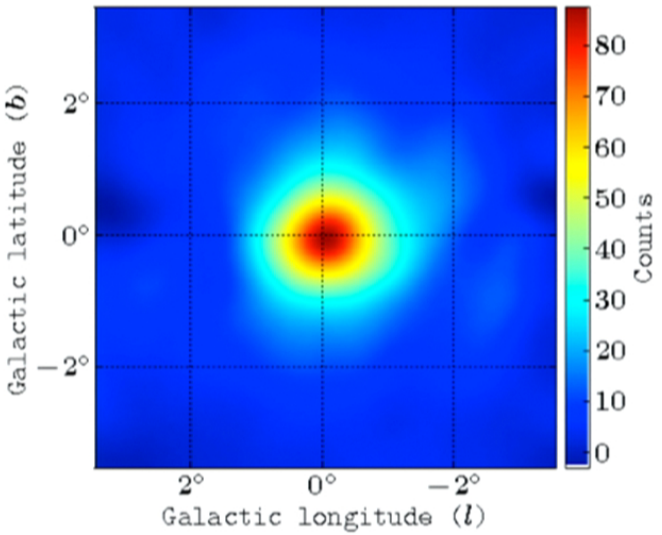

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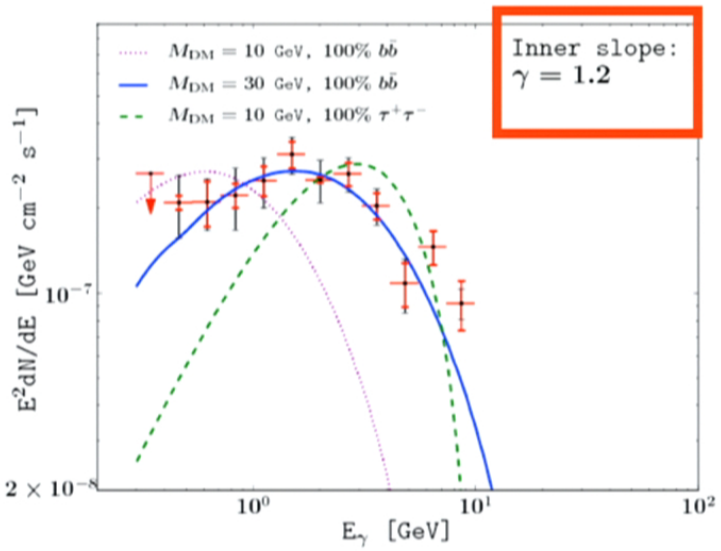

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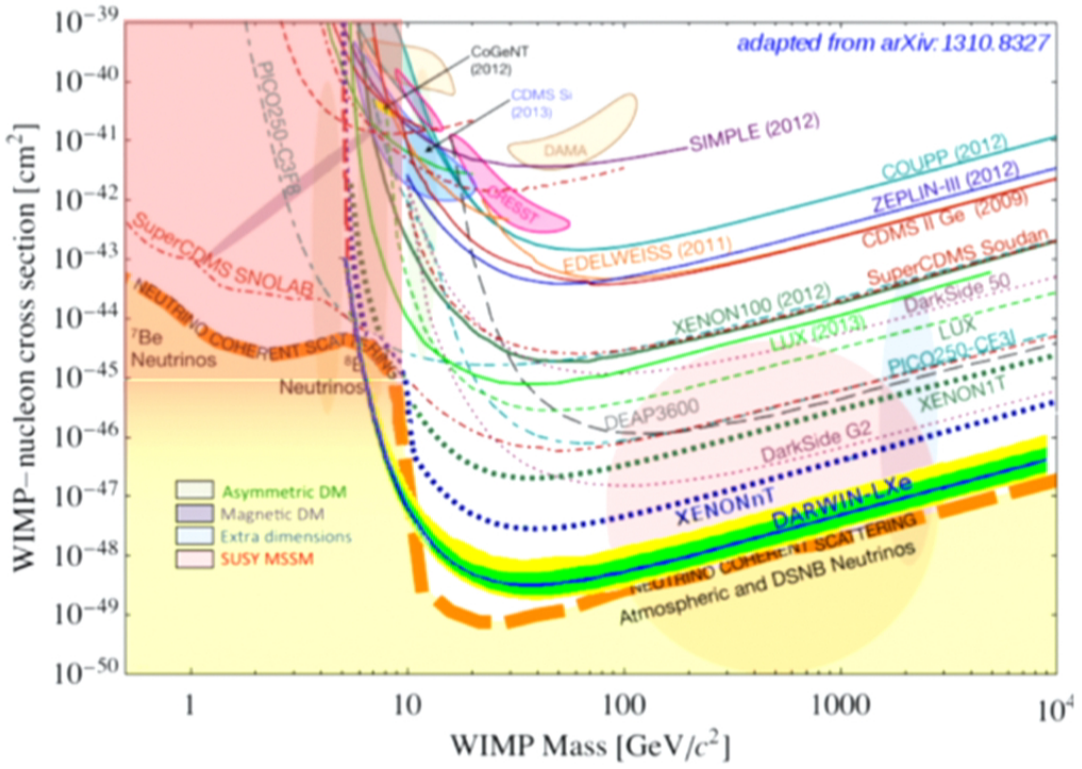
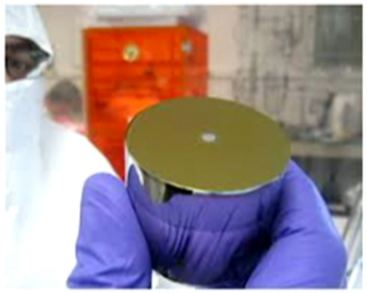
Evidence in Direct detection experiments?

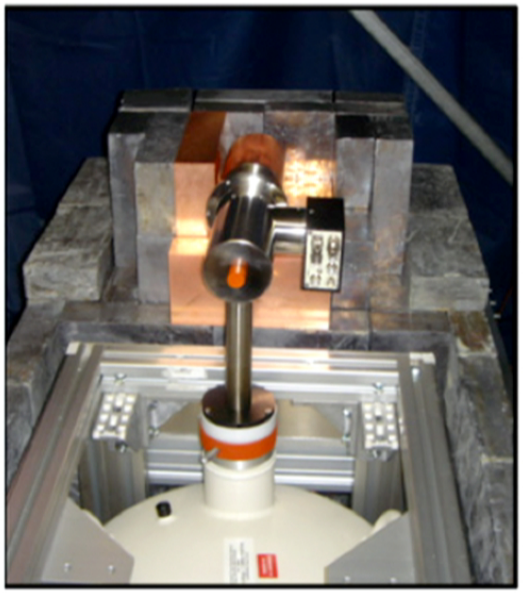


CoGeNT

p-type semiconductor



Soudan Underground



high-purity germanium crystal cooled to liquid nitrogen temperature

The surface of detector is an inert 'dead layer'. Between the dead layer and the bulk is a ~ 1 mm thick 'transition layer'. As the transition region is on the outside of the detector module,

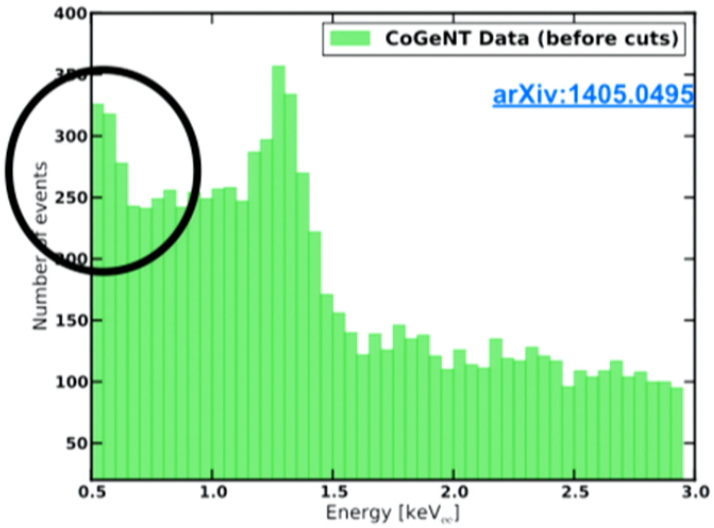
Events at the transition region = 'surface events'.

No background discrimination

CoGeNT

J. Davis, C. McCabe, C. Boehm arXiv:1405.0495

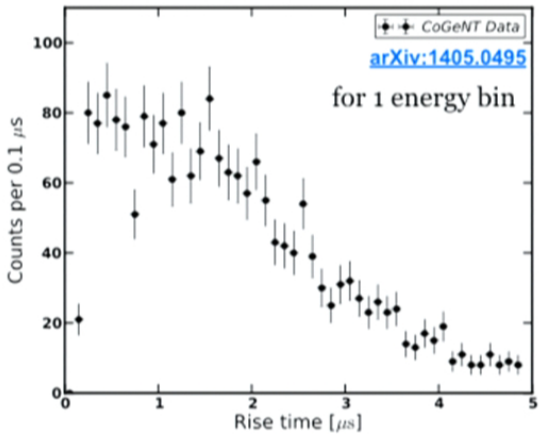
Where DM lies

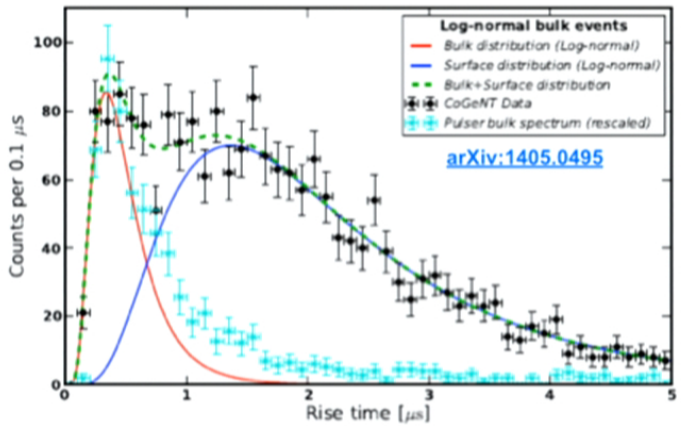


collect ionisation charge

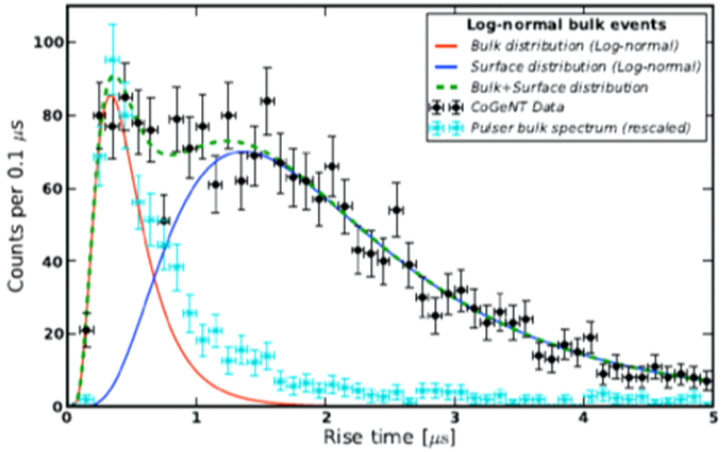
signal+background

To discriminate one can use the rise time of events





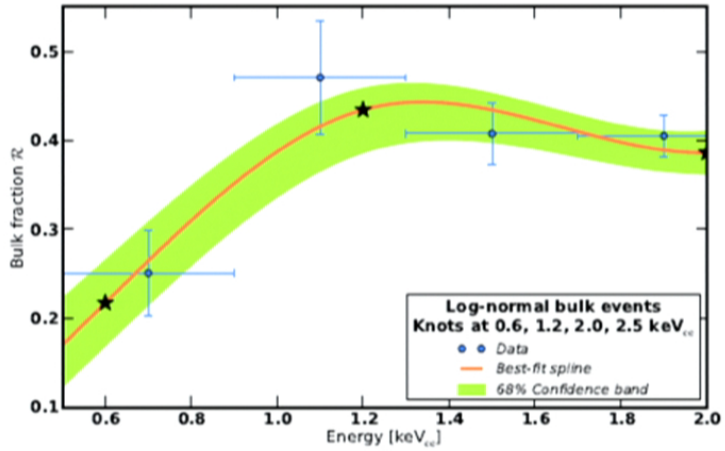
Number of signal events?



DM-like events (faster as charge collection is better)
background-like events

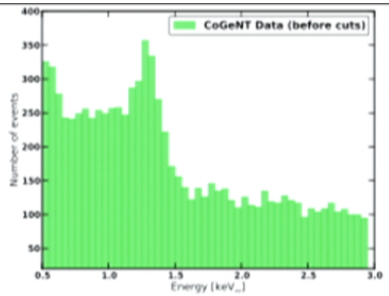
Integrated log-normals: number of red/blue events

Ratio of bulk to surface (red to blue) gives the proportion of DM-like events which have been measured.

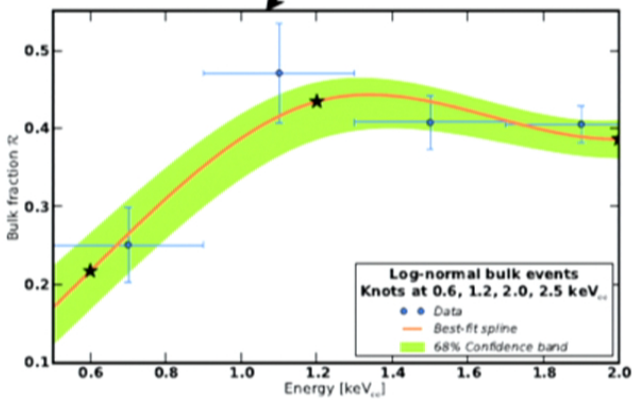


But it is an energy dependent statement.
So one needs to define this ratio for each energy bin.

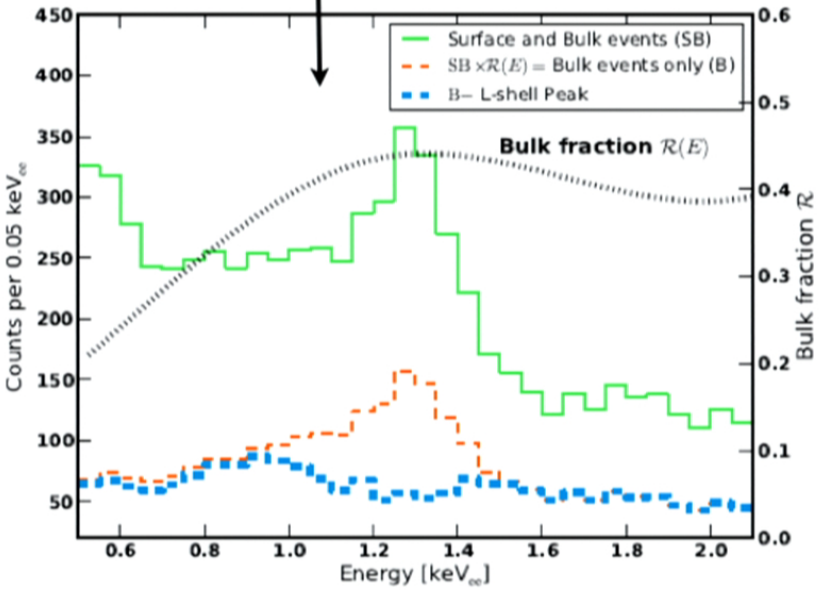
Procedure



take the curve



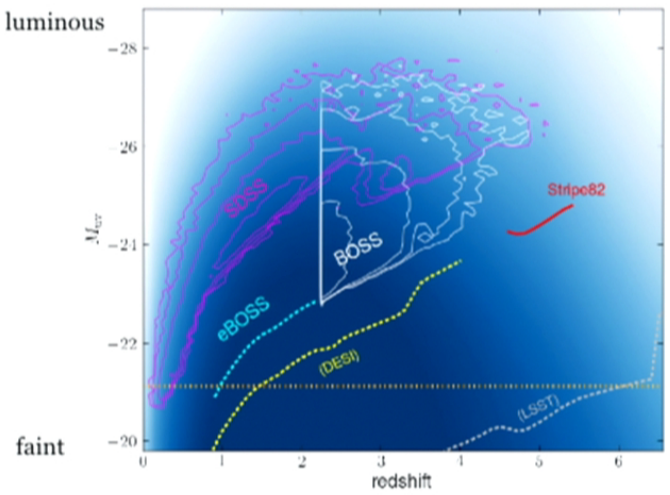
multiply it with the data



The spectrum you get does not contain surface events anymore

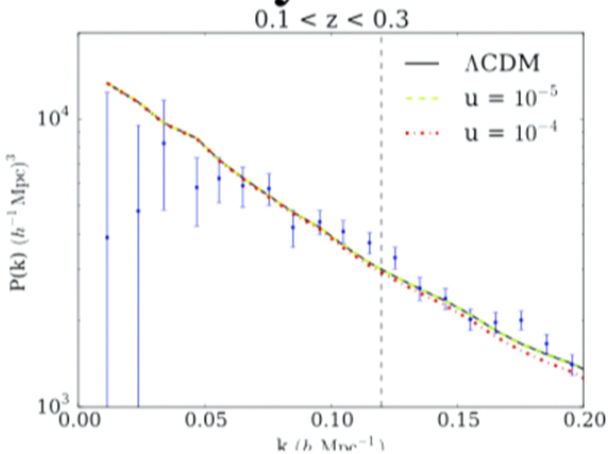
The future? Complementarity!!!

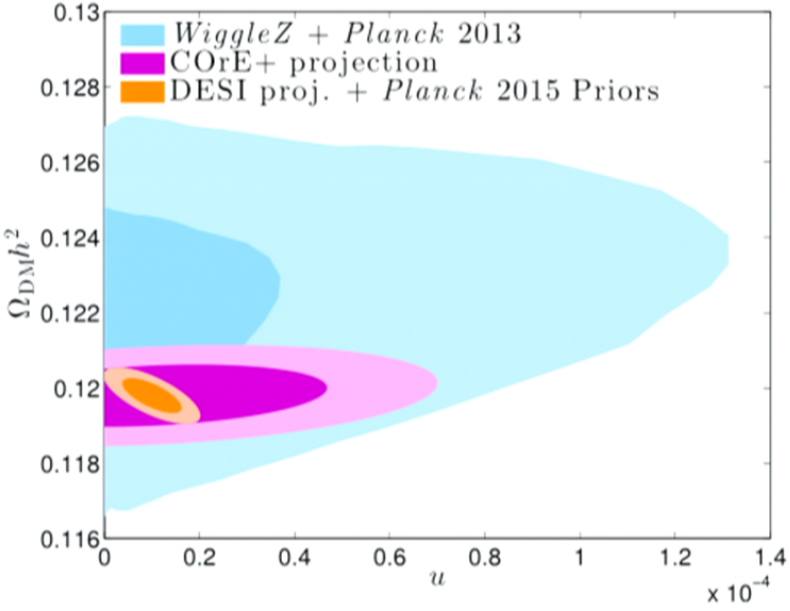
many surveys: eBOSS, DESI, LSST, ...



Courtesy JP Kneib

$$M - M^\star = -2.5 \log\left(\frac{L}{L^\star}\right)$$





Conclusion

We can probe DM microphysics using

Direct detection
Indirect detection
LHC (particle physics experiments)

Large scale surveys

(probing LCDM will be essential if no discovery in lab experiments!)

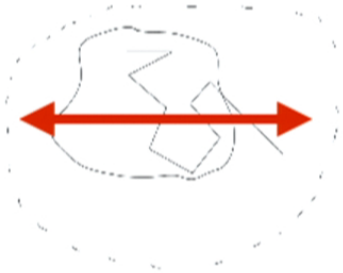
whether the species that is interacting with DM is relativistic or not

whether DM has interactions or not?

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

astro-ph/0012504 astro-ph/0410591

damping scale



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

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