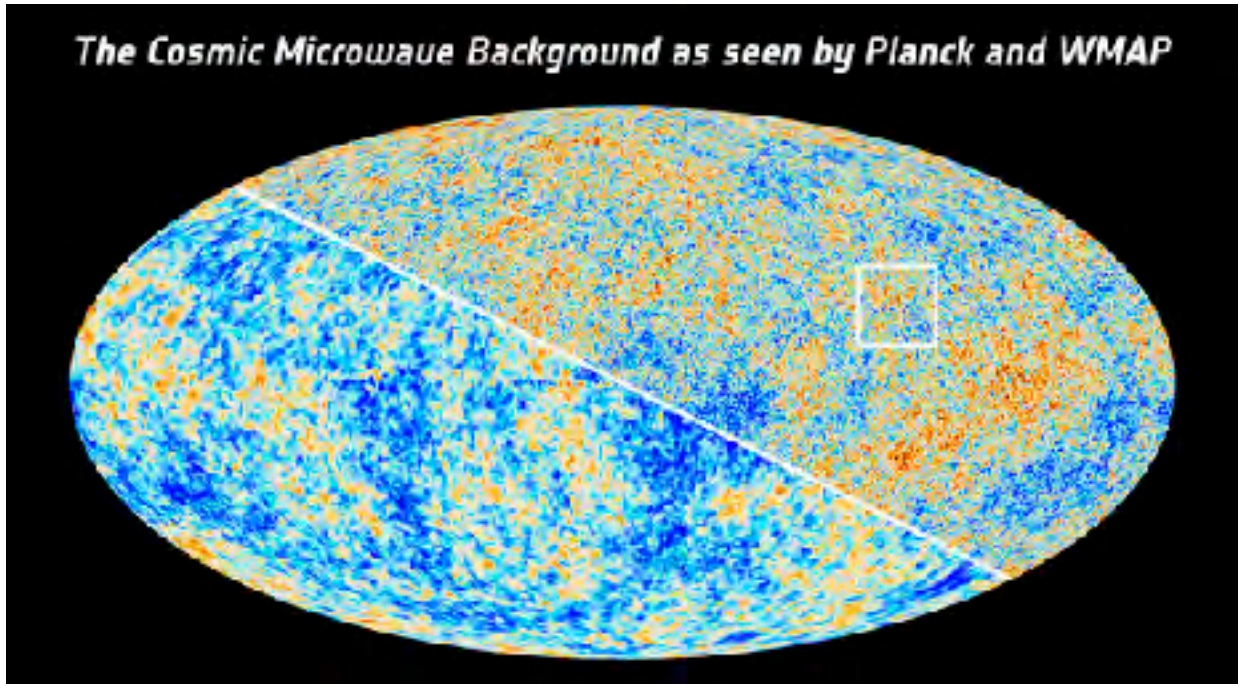
Direct detection and astrophysics

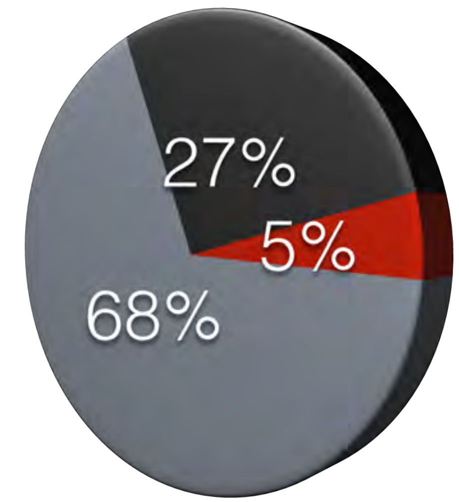
Céline Boehm

IPPP, Durham Durham University **LAPTH, Annecy**

Caastro, Jan 2017

The need for non-baryonic matter

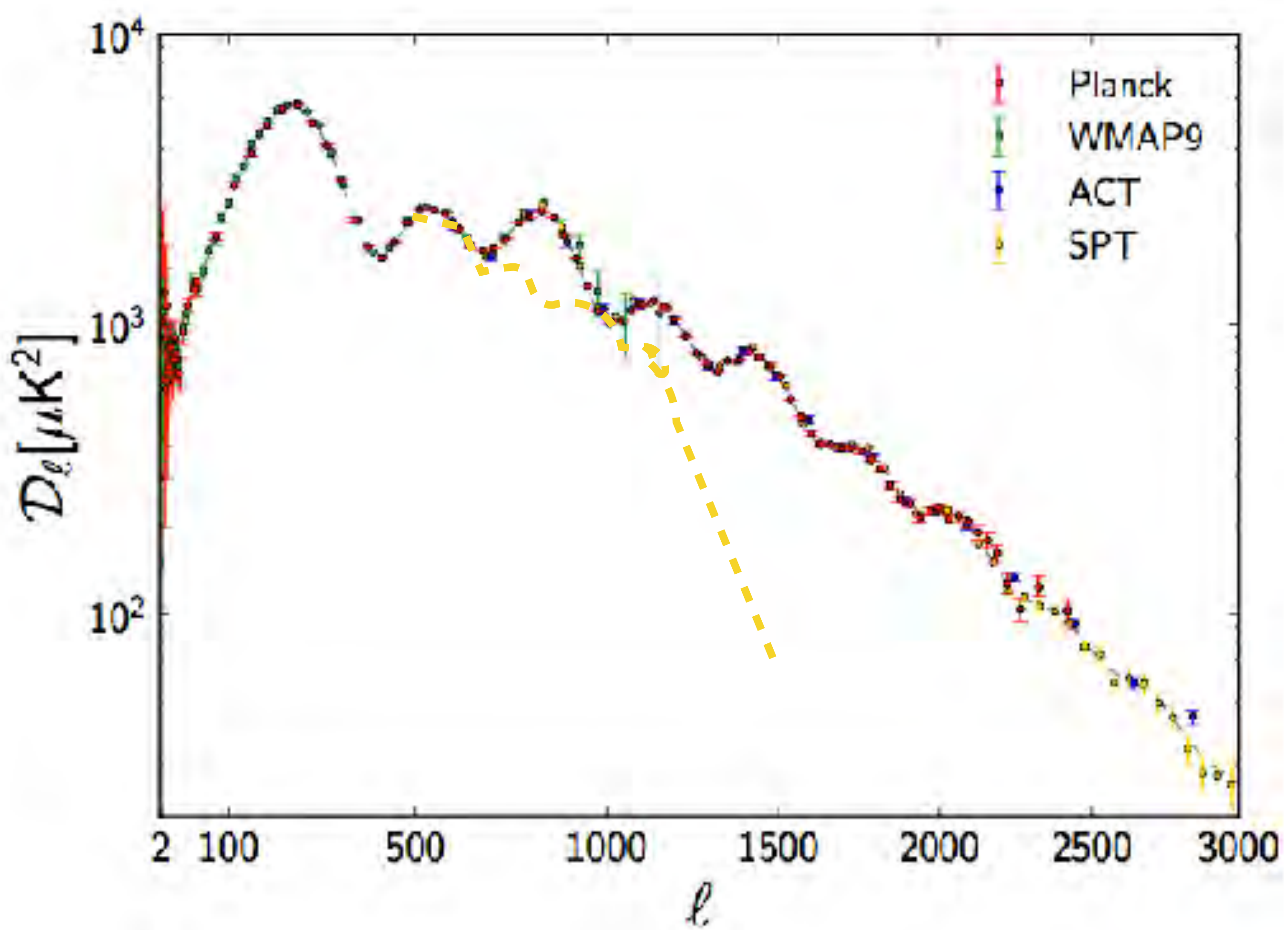




$$\dot{\theta}_b = k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}(\theta_b - \theta_\gamma)$$

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

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



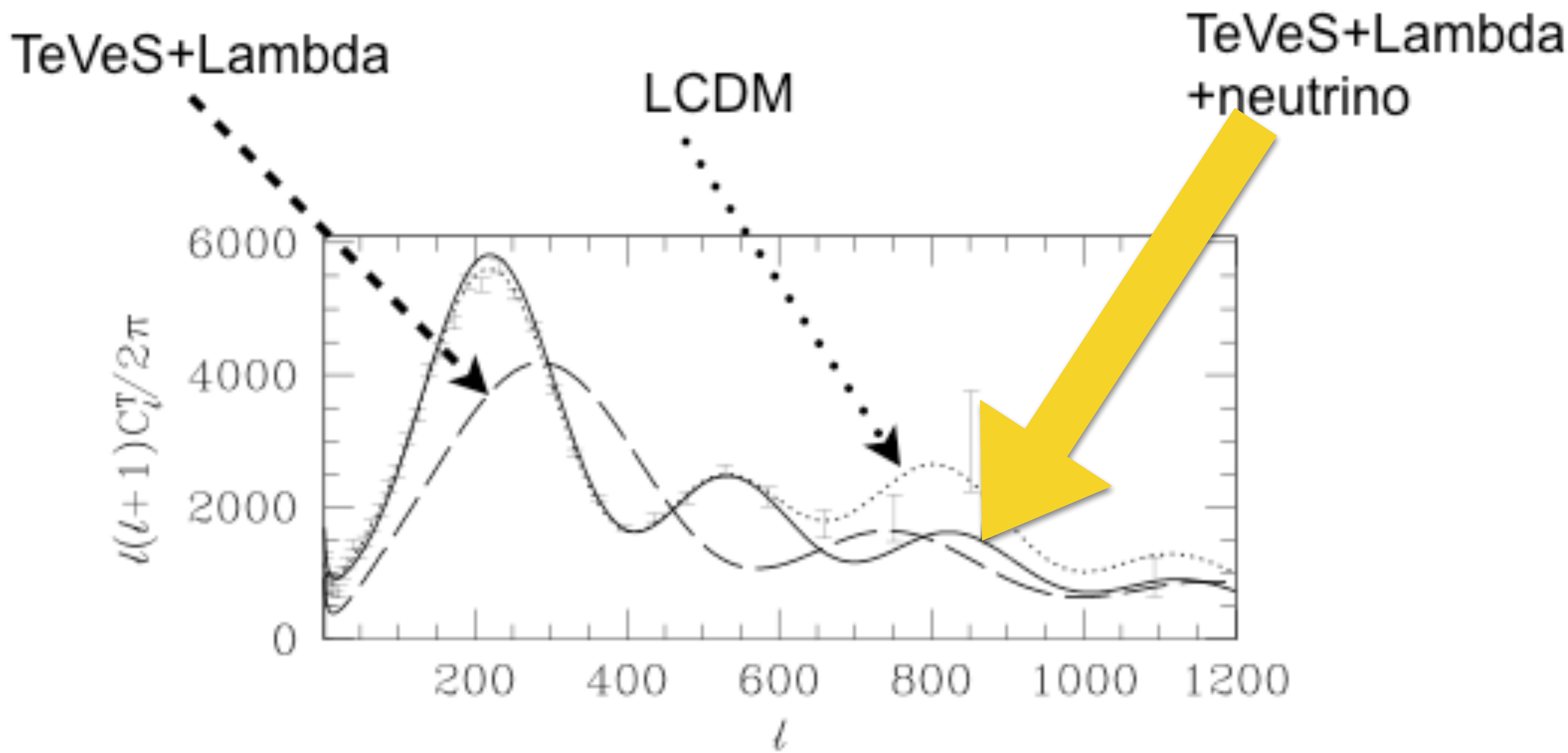
The CMB cannot be explained with baryonic DM only

A consequence of Silk damping (Nature, 1966)

The DM particle hypothesis

Mond/Bekenstein **Bekenstein** **astro-ph/0403694**

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

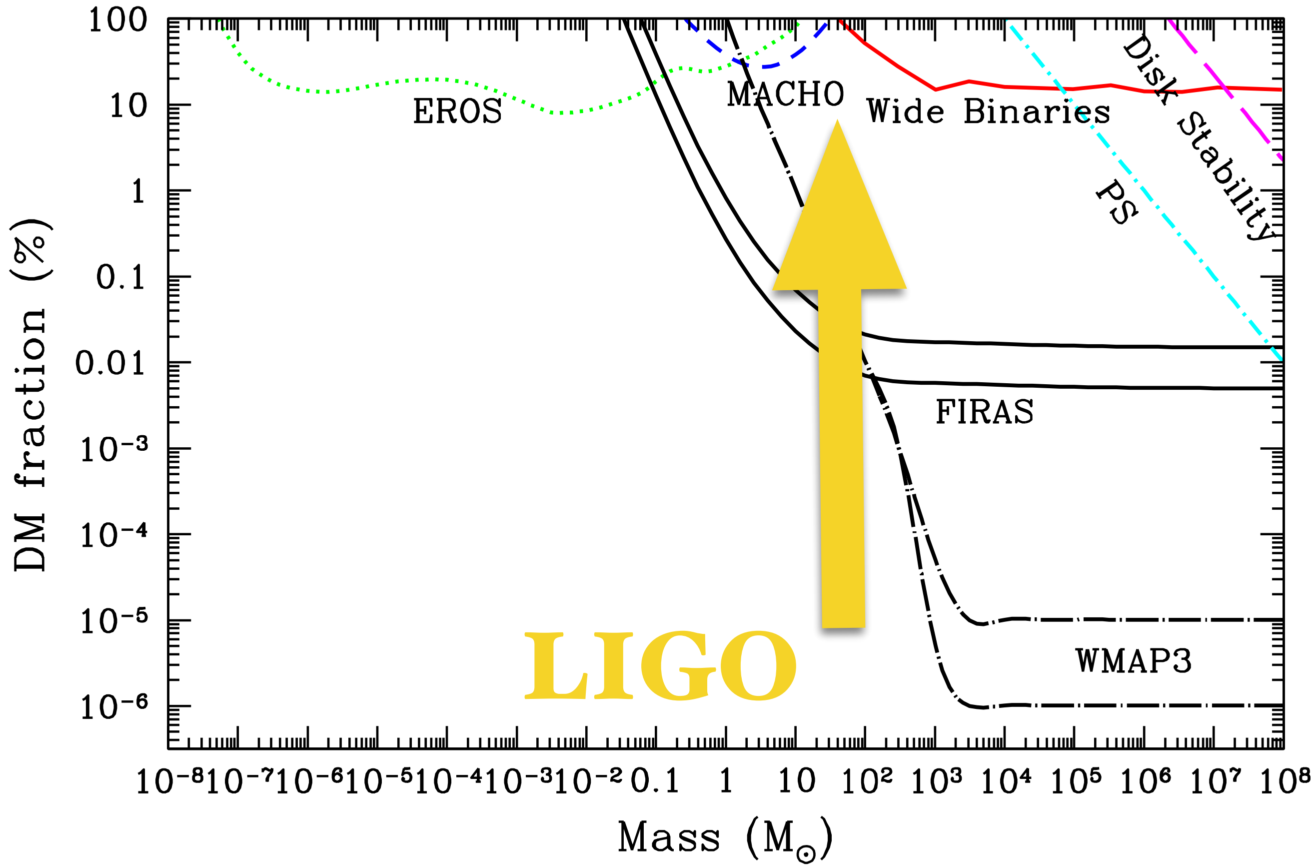


Impossible to explain Planck 2015!
This is called the Silk damping (1967)

A DM-like fluid is needed!

The need for a collisionless fluid

0709.0524v1



Primordial Black Holes ???

arXiv:1603.00464
arXiv:1501.07565
arXiv:1607.06077

Ways to evade CMB limits

arXiv:1612.05644

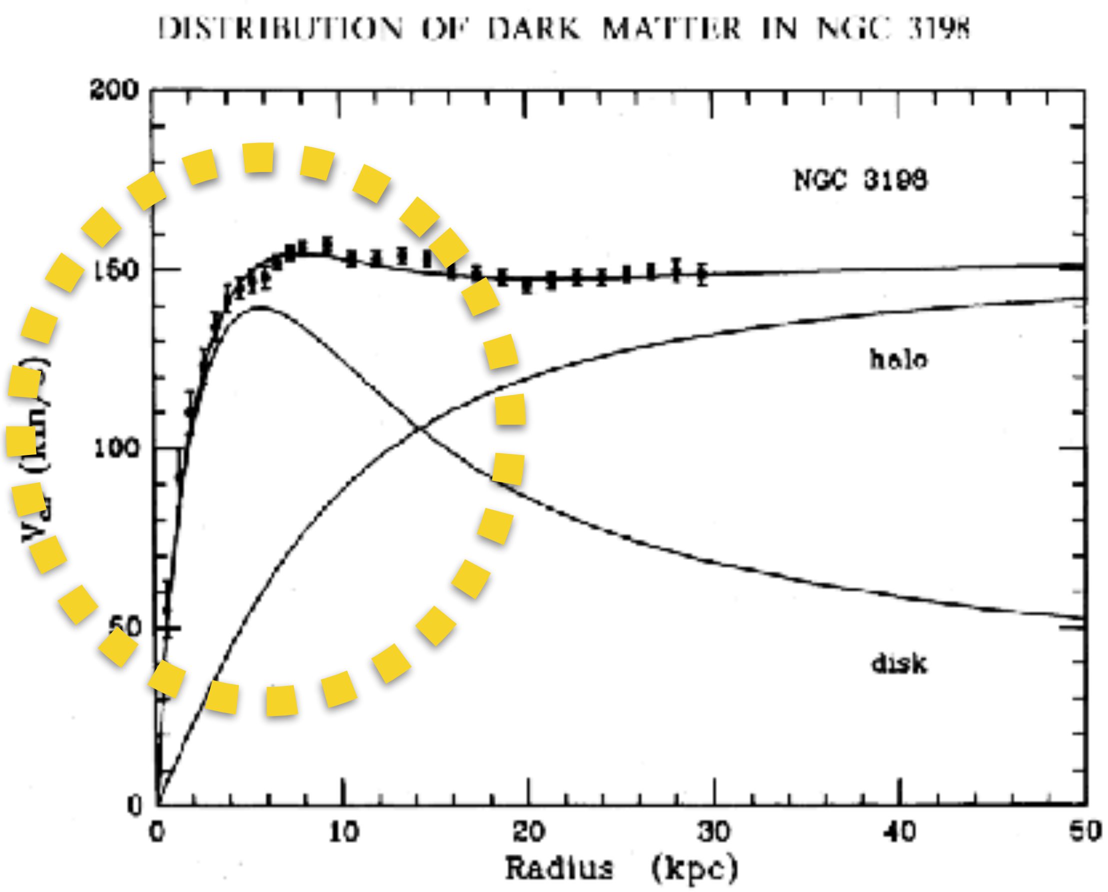
> 100 Msol ruled out as main DM component

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

WIMPs are still the simplest explanation

How do we test the particle hypothesis?

The DM halo



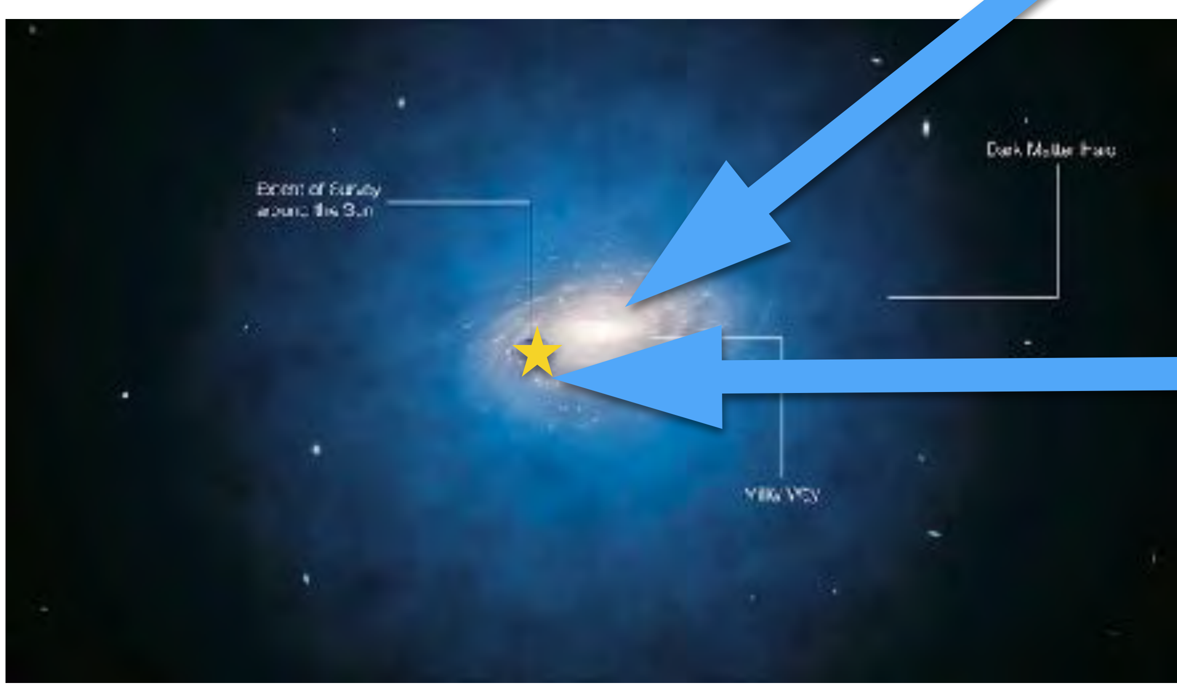
$$v_c^{\,2} = \frac{G\,M(r)}{r}$$

$$M(r) = \int 4\pi^2 \rho(r)\, d^3r$$

$$M(r) = M\_dm + M\_baryons$$

DM is a subcomponent
Its density is the highest

great for Indirect Detection



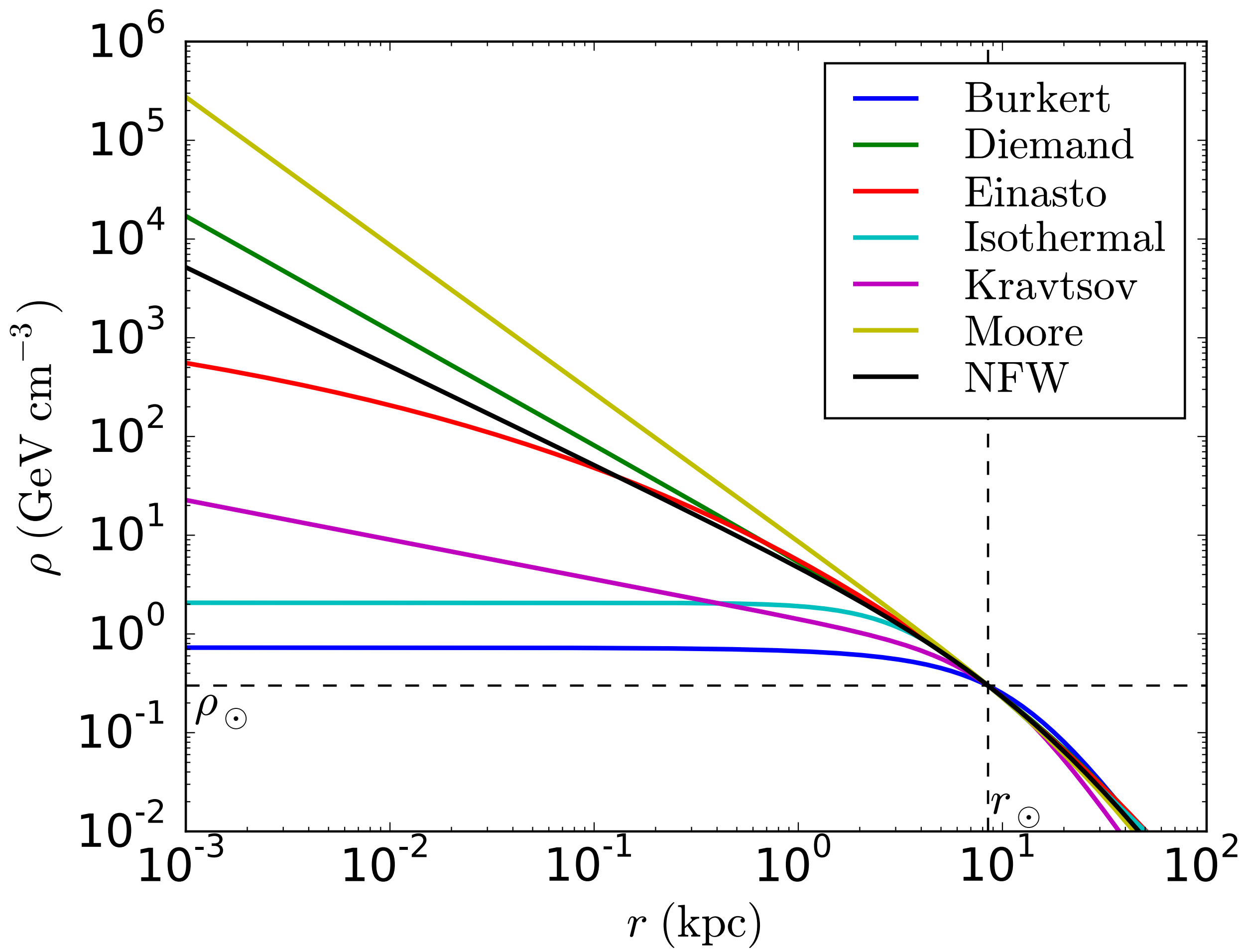
DM is dominant.
Its density is low

great for direct Detection

Potential issues

Indirect Detection

$$\phi \propto \int dl \;\rho(r)^{1,2}$$



Courtesy: T. Lacroix

$$\rho_{\mathrm{NFW_{gen}}}(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_0}\right)^{\alpha}\right]^{-\frac{\beta-\gamma}{\alpha}}$$

Direct Detection

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\sigma(q)}{2m\mu^2}\,\rho\,\eta(E,t)$$

$$\eta(E,t) = \int_{v_{\min}(E)}^{\infty} \frac{f(v,u_e(t))}{v}\,\mathrm{d}^3v$$

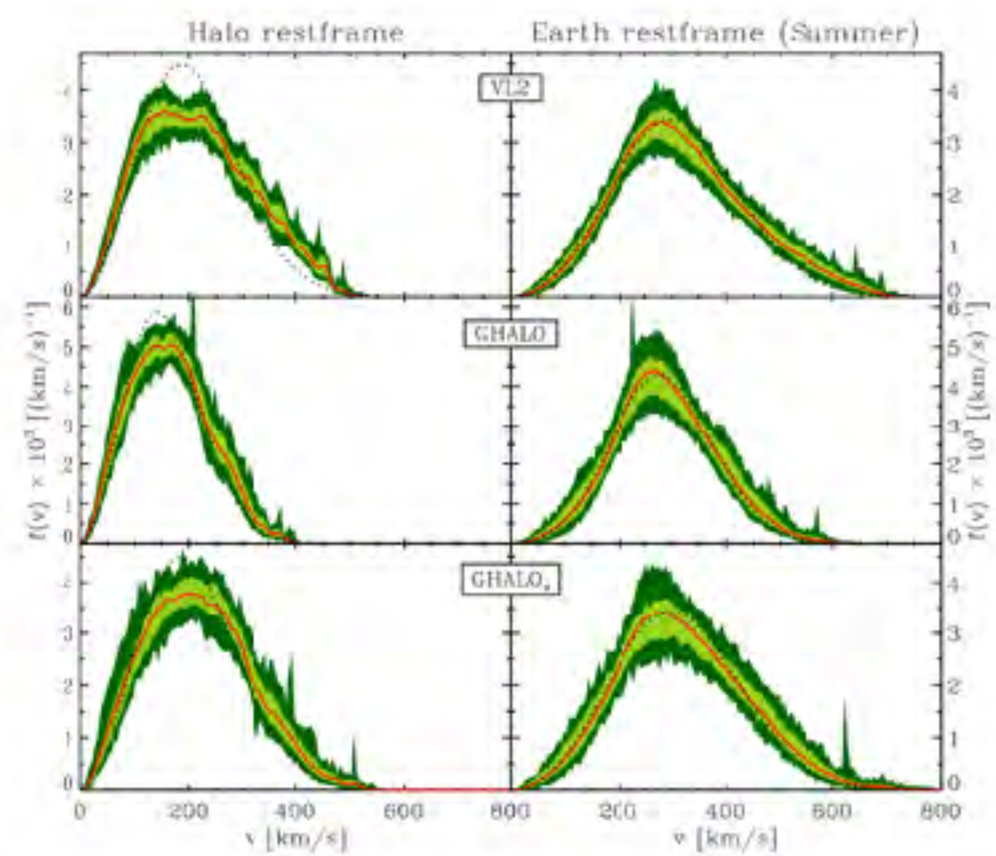
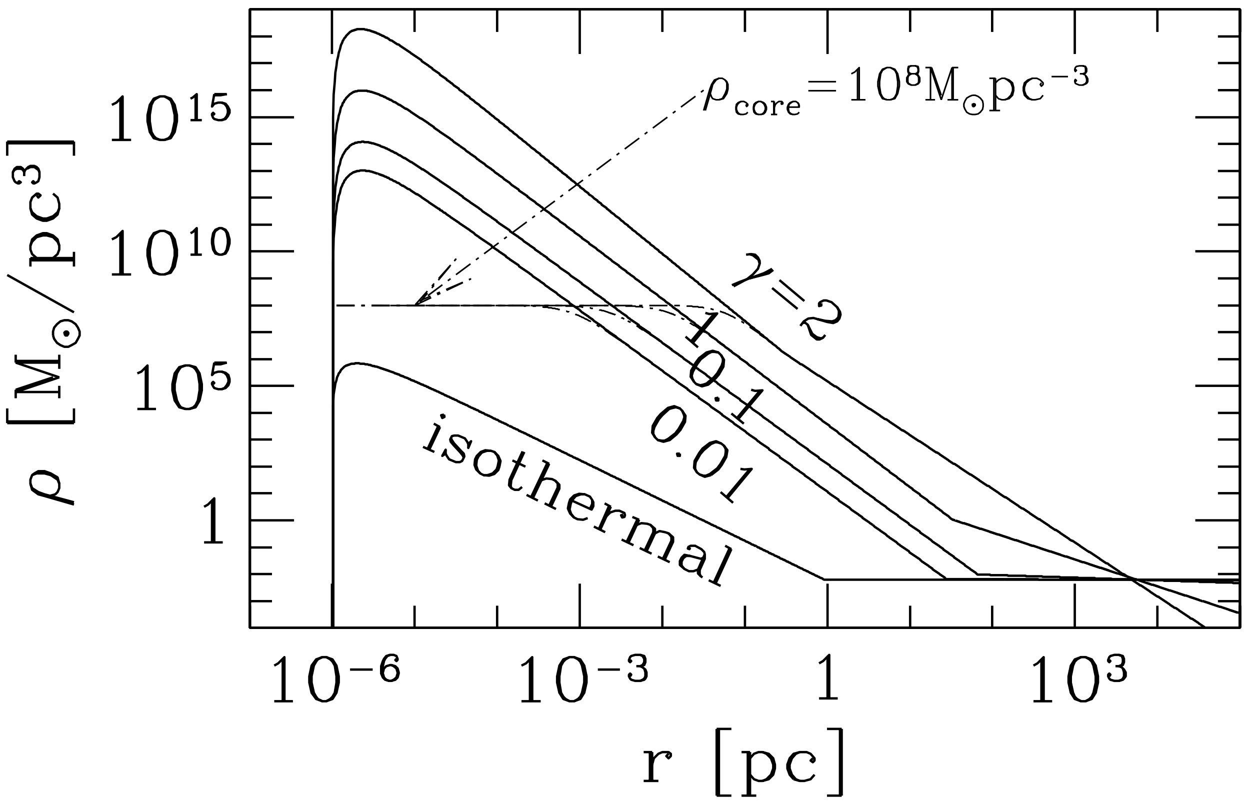


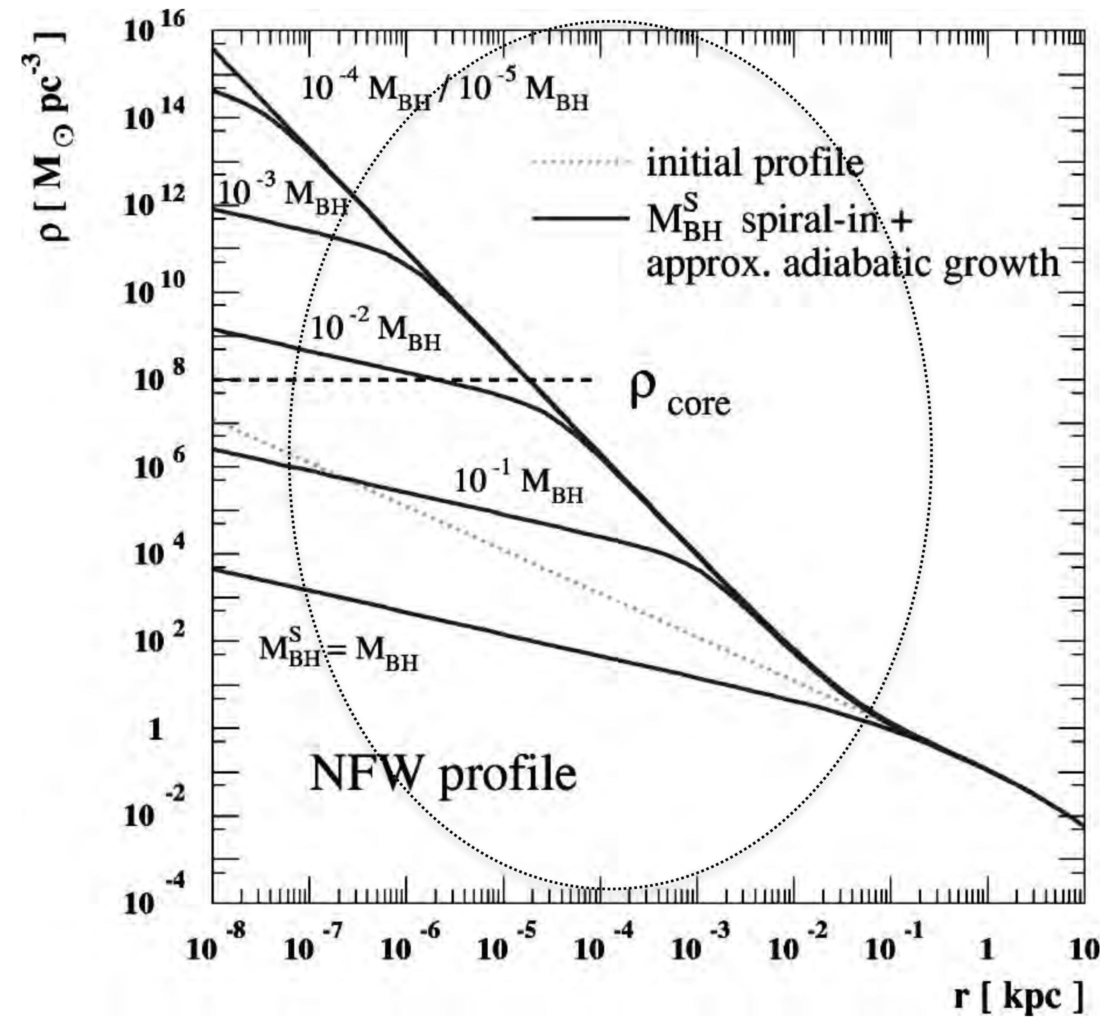
Figure 2. Velocity distribution functions: the left panels are in the host halo's restframe, the right panels in the restframe of the Earth on June 2nd, the peak of the Earth's velocity relative to Galactic DM halo. The solid red line is the distribution for all particles in a 1 kpc wide shell centered at 8.5 kpc, the light and dark green shaded regions denote the 68% scatter around the median and the minimum and maximum values over the 100 sample spheres, and the dotted line represents the best-fitting Maxwell-Boltzmann distribution.

JCAP02(2010)030

see A. Peter's talk

DM accretion near Black Holes





Condition of formation of spikes:

* BHs at the center of galaxies can grow adiabatically
* Adiabatic growth inside a population of stars enhances the density of stars

Why not enhancement of DM density?

Ipser & Sikivie (1987): isothermal ->r^-3/2, Gondolo & Silk (1999) : NFW -> 7/3

Electromagnetic emission from cosmic rays from DM

Cluster of galaxies

Milky Way

Dwarf galaxies

AGNs (Cen A, ESO)

cosmic rays **gamma rays** **radio/submm**

decay DM —-> SM SM (SM)

annihilations DM DM —> SM SM

Indirect detection signatures

Injection of cosmic rays at high energy (> keV!)

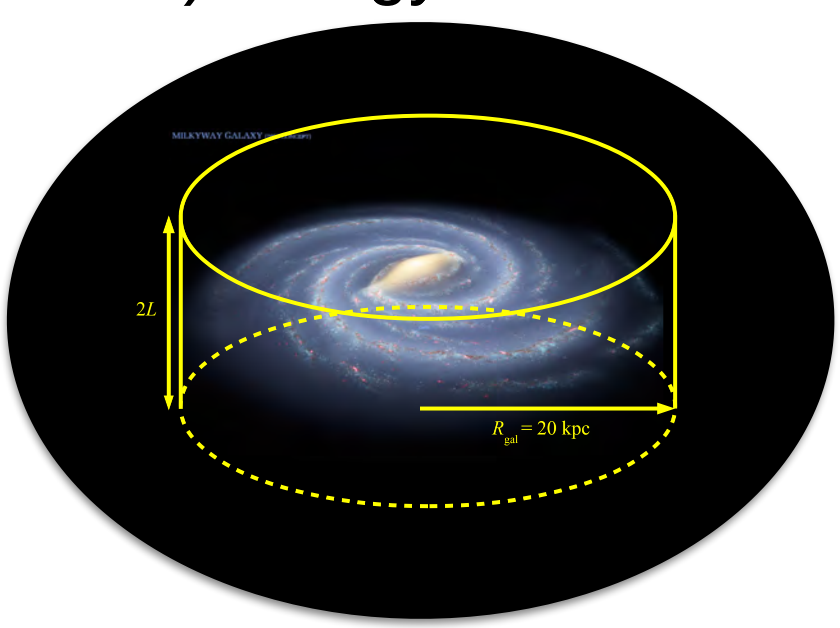
If mdm >> MeV Prompt emission (gamma-ray)

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

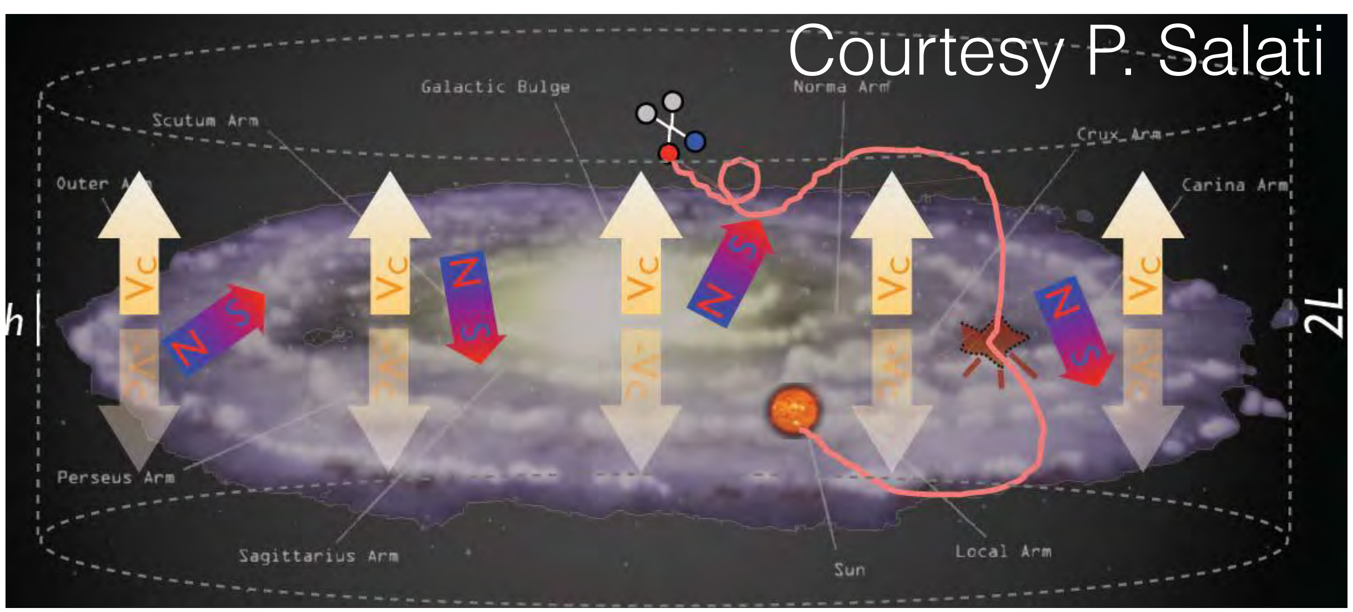
Only depends on the DM profile

Inverse Compton (gamma-ray)
Synchrotron (radio/submm)

1) Spatial diffusion
2) Energy losses



"propagation" of cosmic rays
gives rise to typical energy spectra

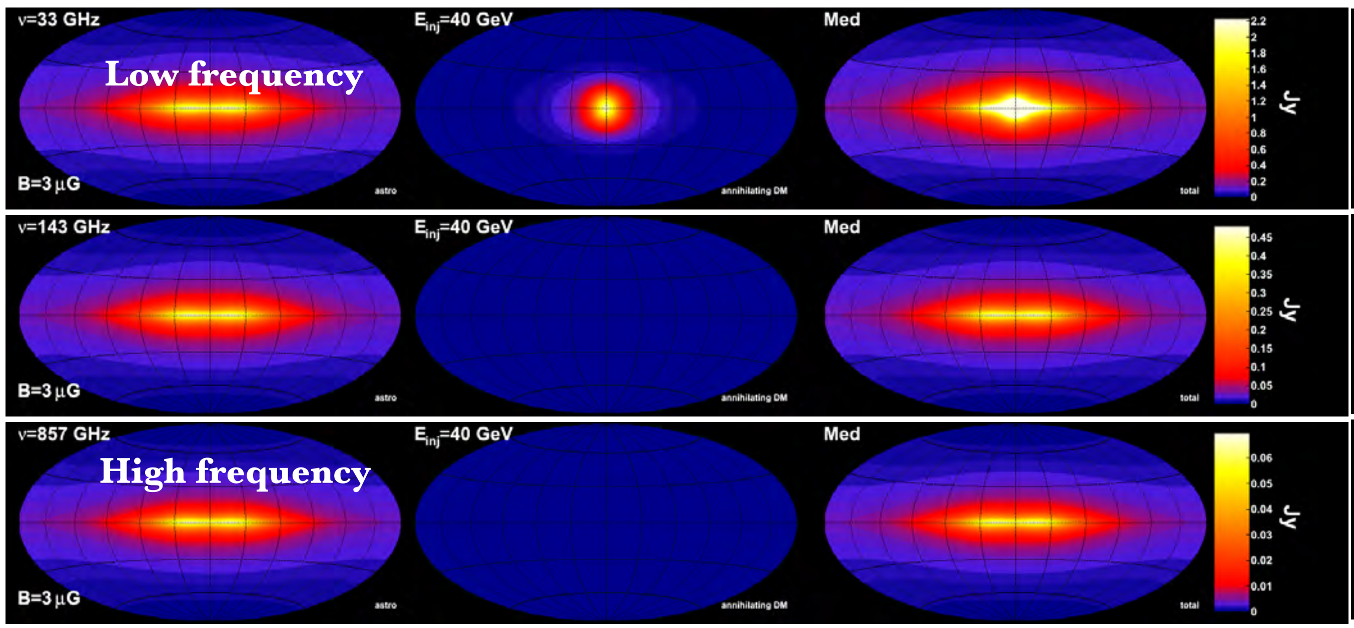


Submm constraints

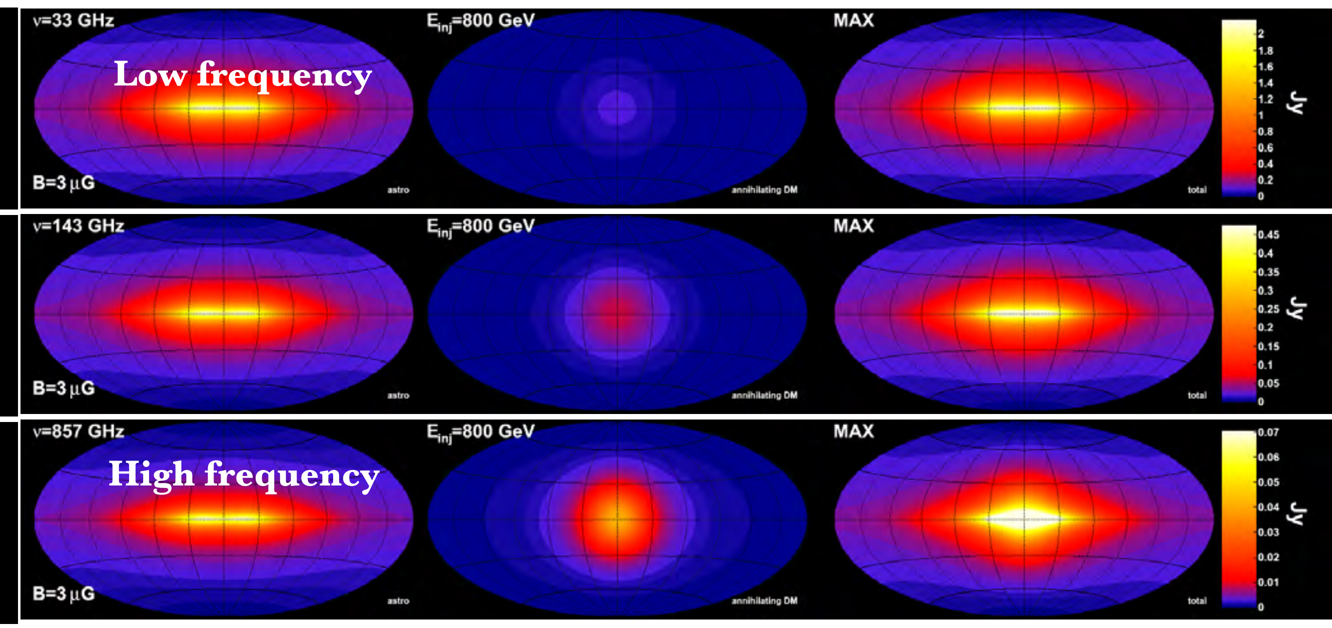
arXiv:1105.4689

our Milky Way

Astrophysical sources | DM | Sum



Astrophysical sources | DM | Sum



40 GeV DM

Expected signature in LFI

800 GeV DM

Expected signature in HFI

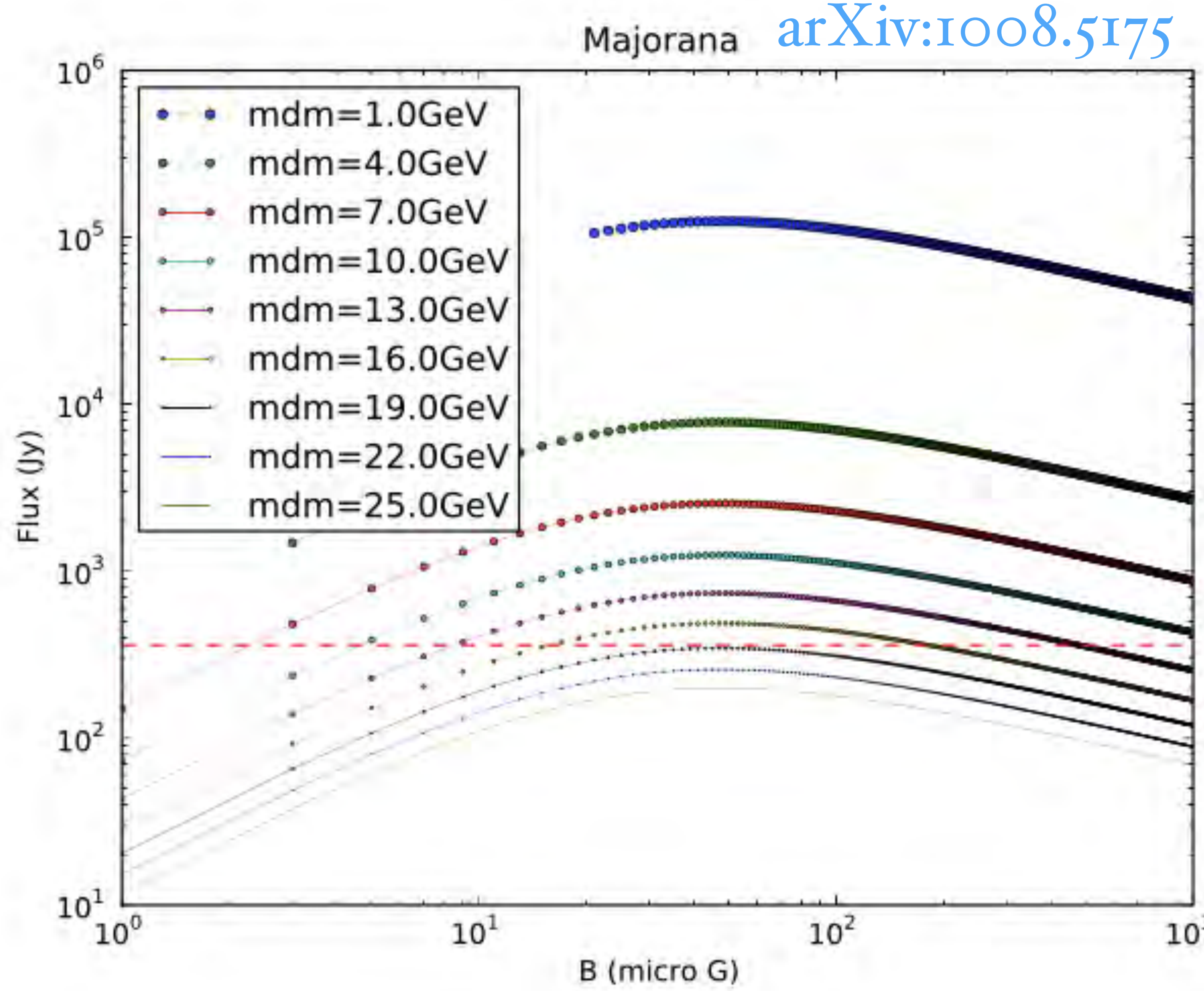
No signal!

Radio constraints

our Milky Way

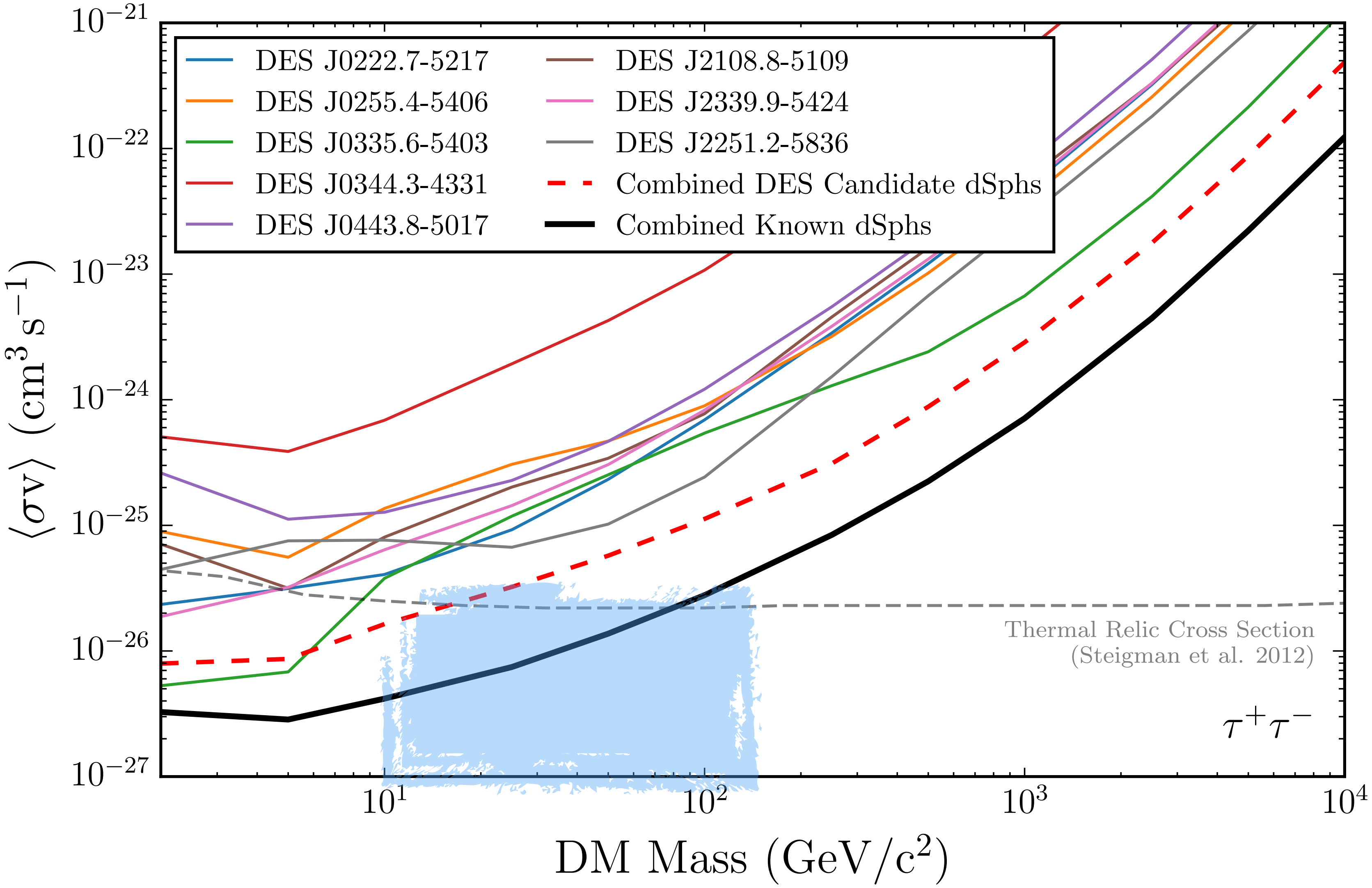
330 MHz

arXiv:1008.5175

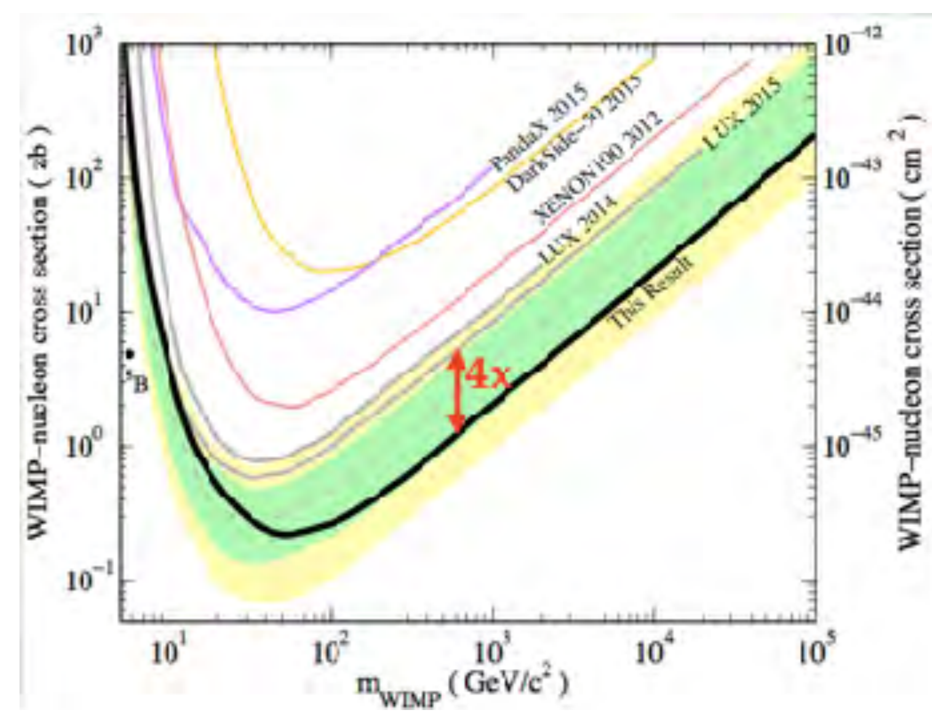


Excludes up to 10 GeV particles for normal B field values

Gamma-rays in dSphs



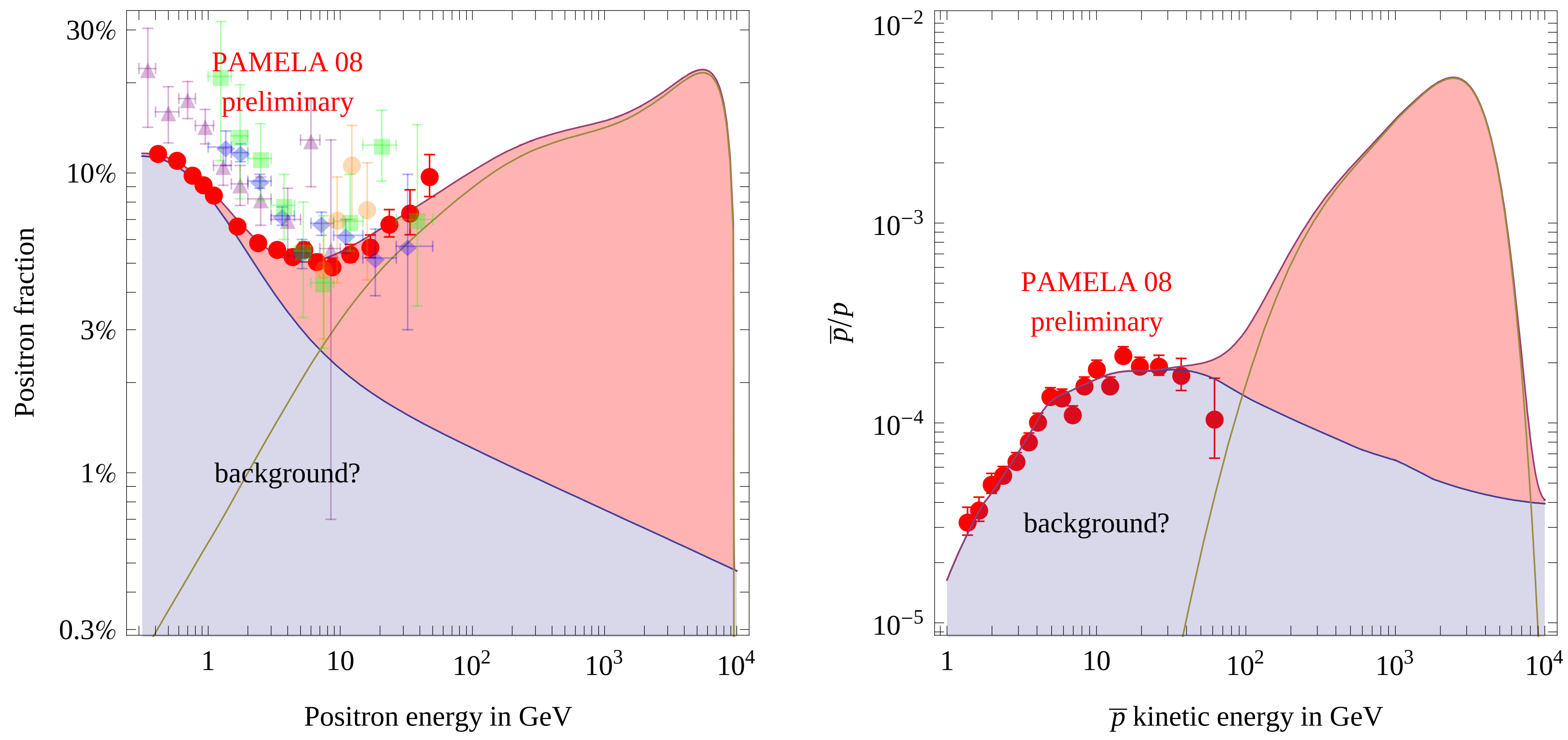
Thermal DM already partially excluded!

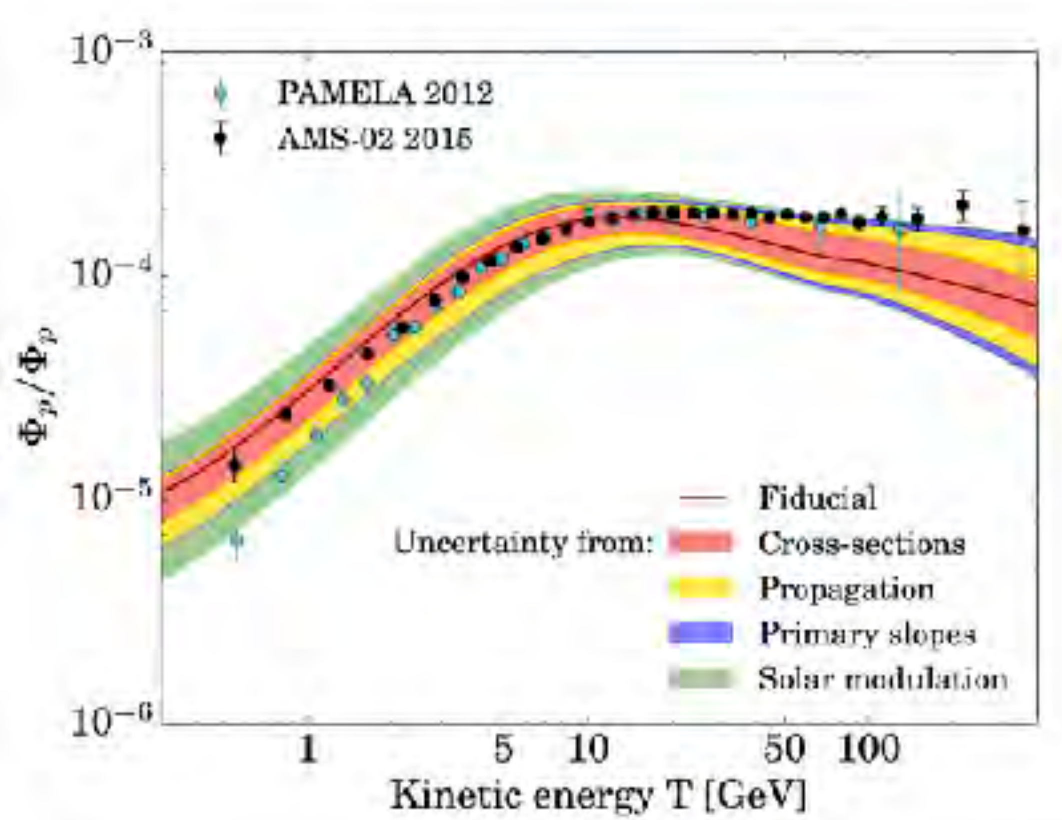


~ 3 order of magnitude to catch up DD limits though the process aren't the same!

I'll comment again on this!

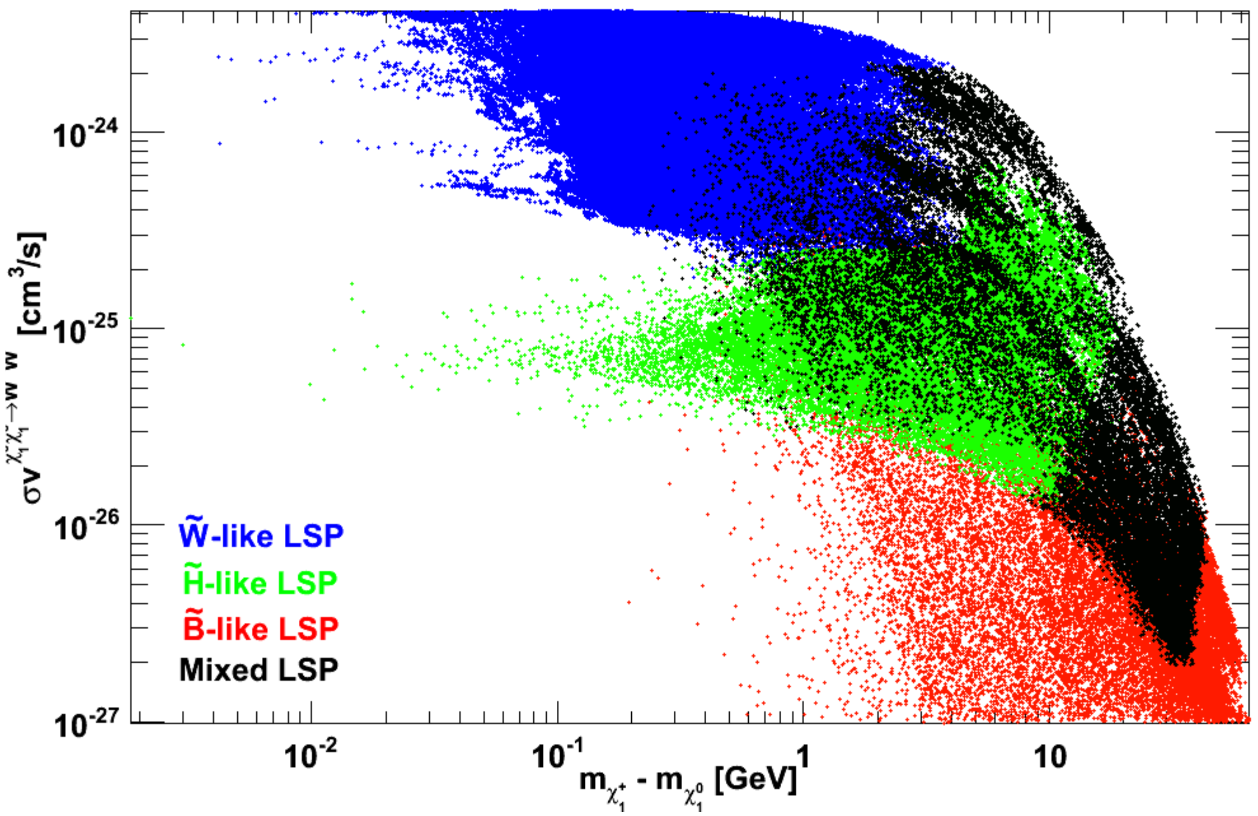
Antiprotons

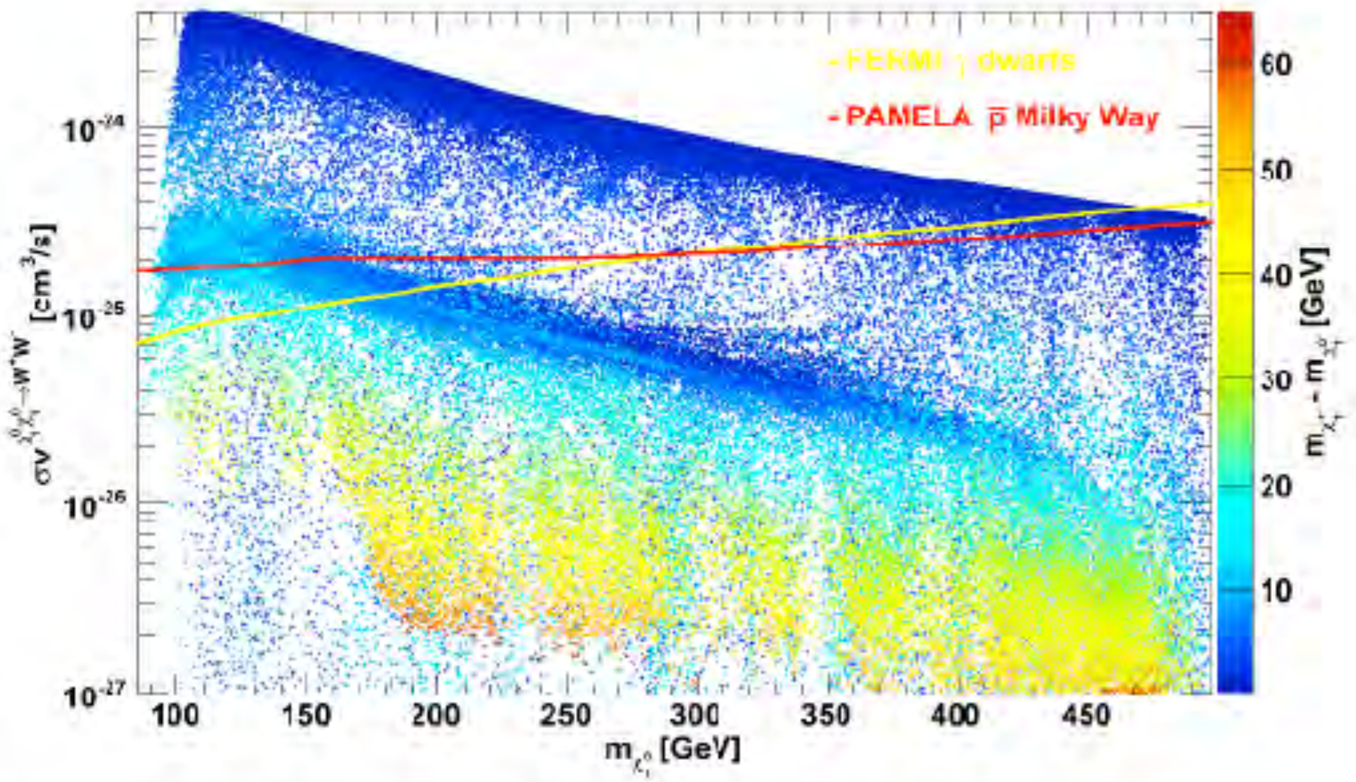




Constraints on neutralino annihilating into W+W-

arXiv:1208.5009





We can exclude certain cross section and masses

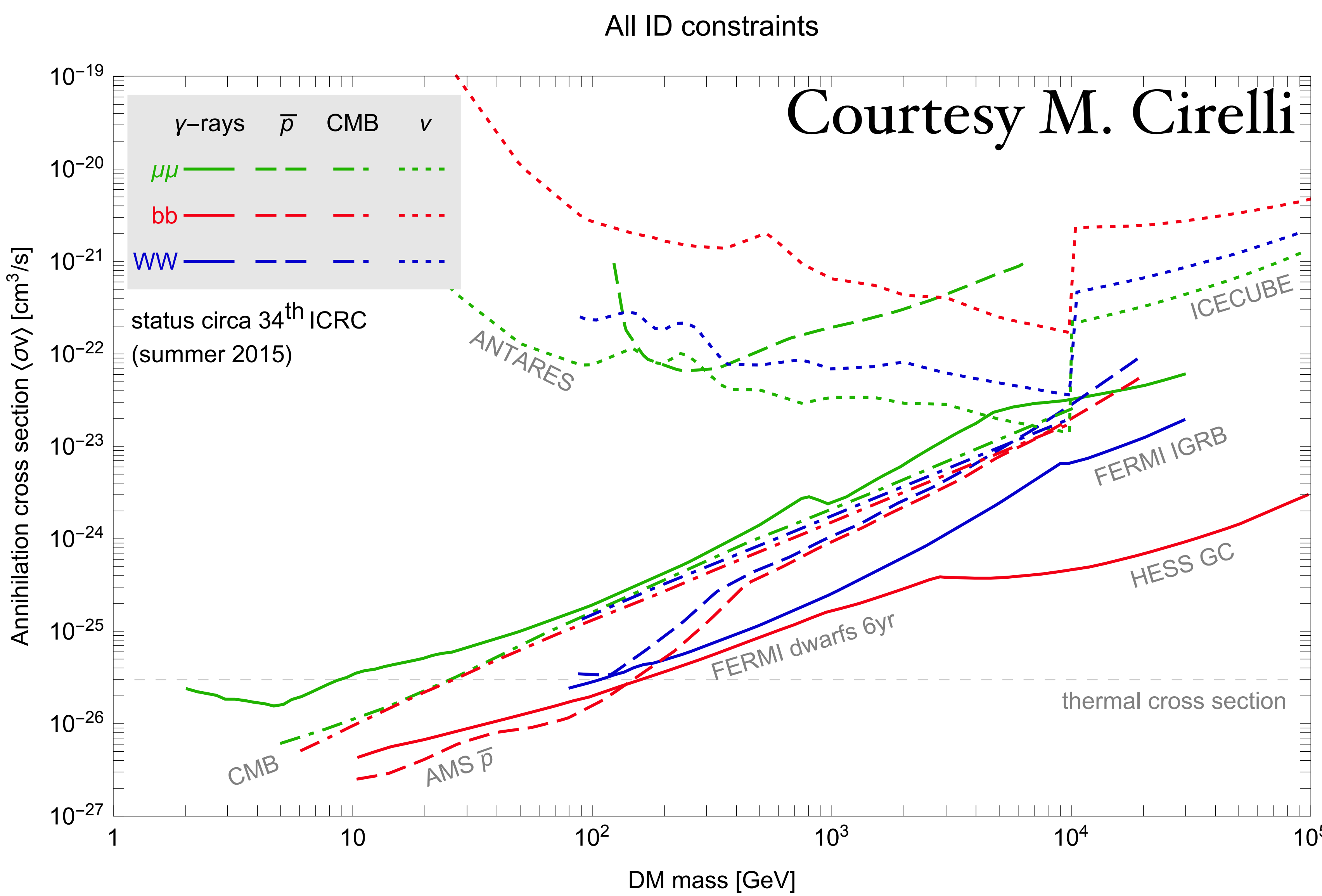
- ✓ One can exclude values of the annihilation cross section versus the neutralino mass
- ✓ From the value of the annihilation cross section, one can exclude the neutralino composition

One can therefore exclude certain neutralino composition on the sole basis of the anti-proton flux predicted in these DM scenarios.

Also recently arXiv:1401.6212

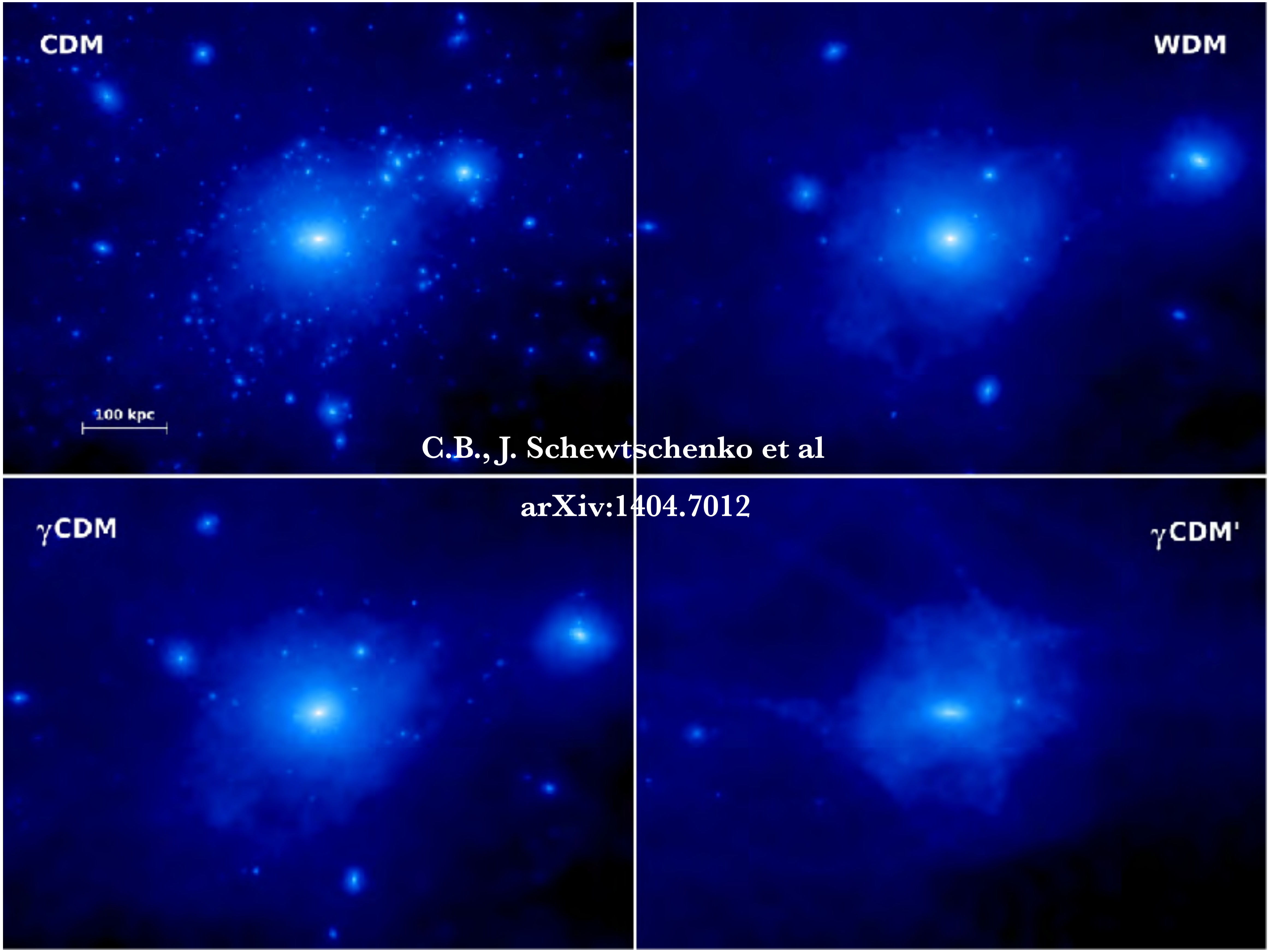
Gamma-rays

dSphs + MW + CMB



In reality one can constrain light DM (< 10 GeV) too!

$$\sigma v < 10^{-31} \left(\frac{m_{\rm DM}}{\rm MeV}\right)^2 \ {\rm cm}^3/{\rm s}$$ **for < O(GeV)**



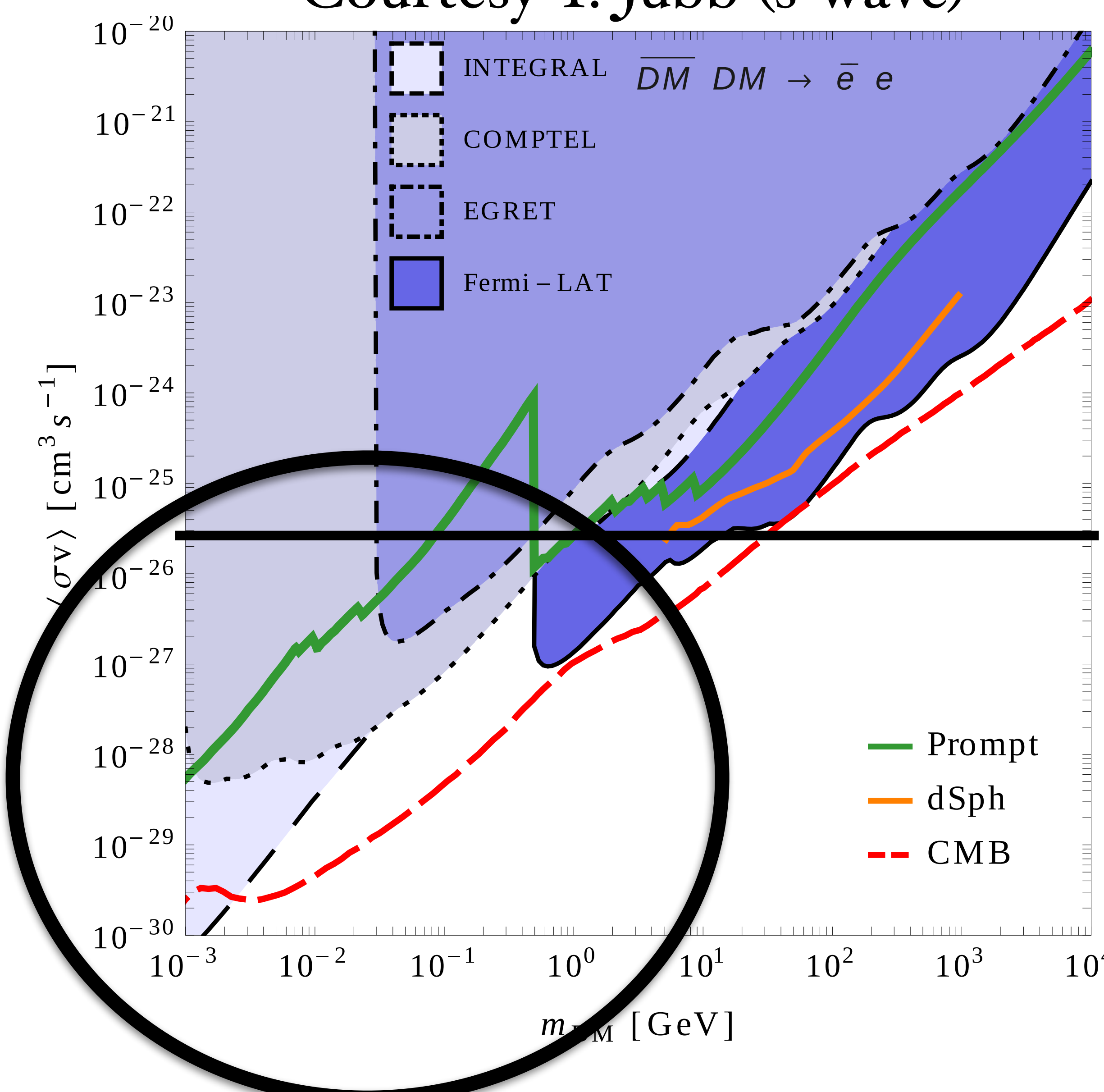
$$\sigma_{\rm DM-\gamma} \lesssim 10^{-33} \left(\frac{m_{\rm DM}}{\rm GeV}\right) \ {\rm cm}^2$$

same with neutrinos

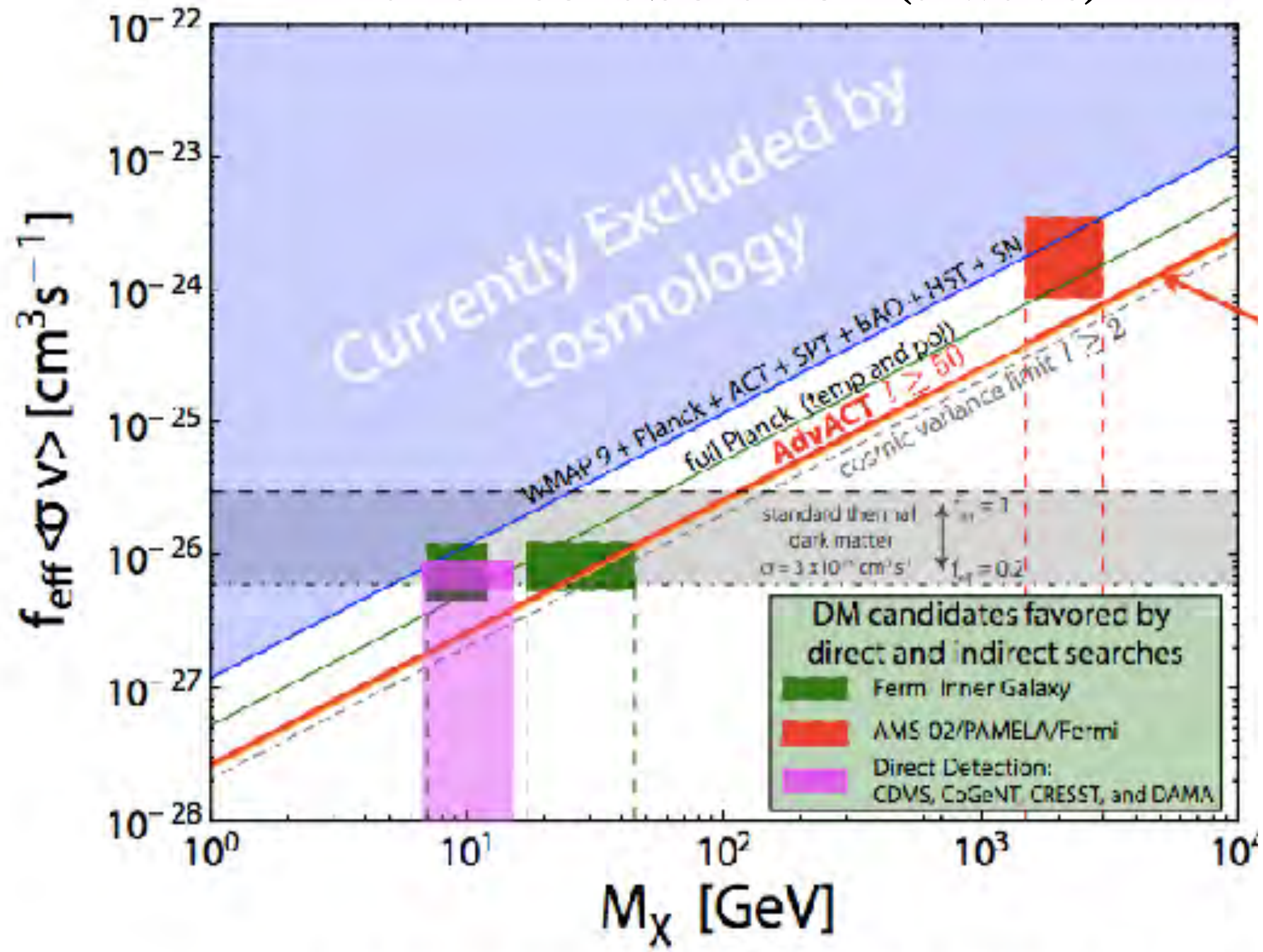
Indirect detection limits have strong impact on mDM < 10 GeV

DM can be lighter than a few GeV! But ...

Courtesy T. Jubb (s-wave)



Planck collaboration (s-wave)

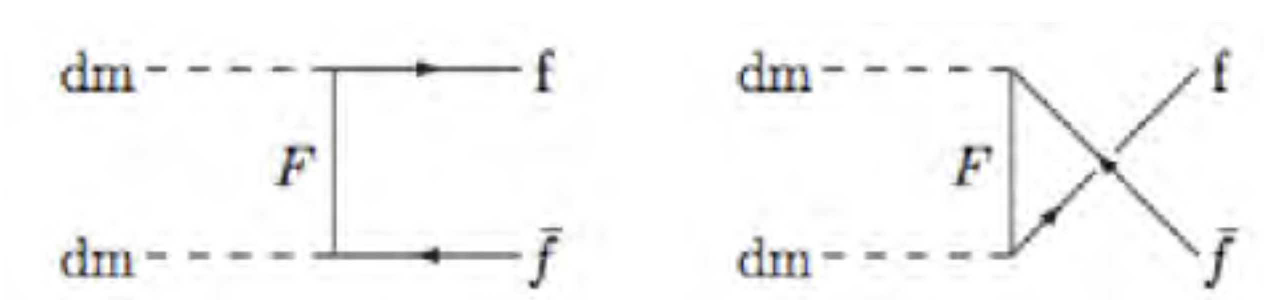


Madhavacheril, NS, Slatyer 2014, PRD, (1310.3815)

For light DM, the annihilation cross section into electrons needs to be very suppressed!

Indirect detection limits have strong impact on mDM < 10 GeV

The cross section can be independent of the DM mass!



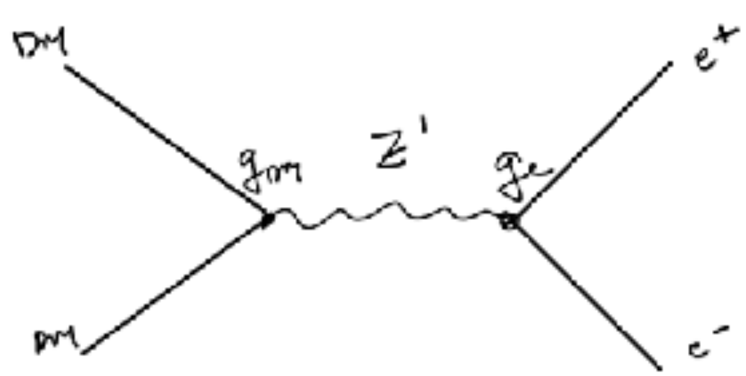
non chiral couplings

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

CB, P. Fayet, hep-ph/0305261

Feng& Kumar (0803.4196)

The mediator can be very light!



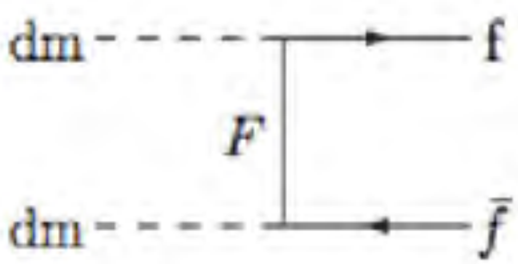
$$\sigma v \propto v^2 \frac{m_{\rm DM}^2}{m_{Z'}^4} \, g_{\rm DM}^2 \, g_e^2$$

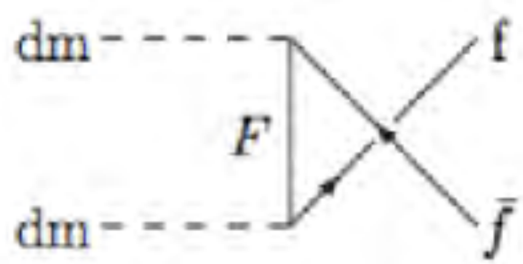
CB, P. Fayet, hep-ph/0305261

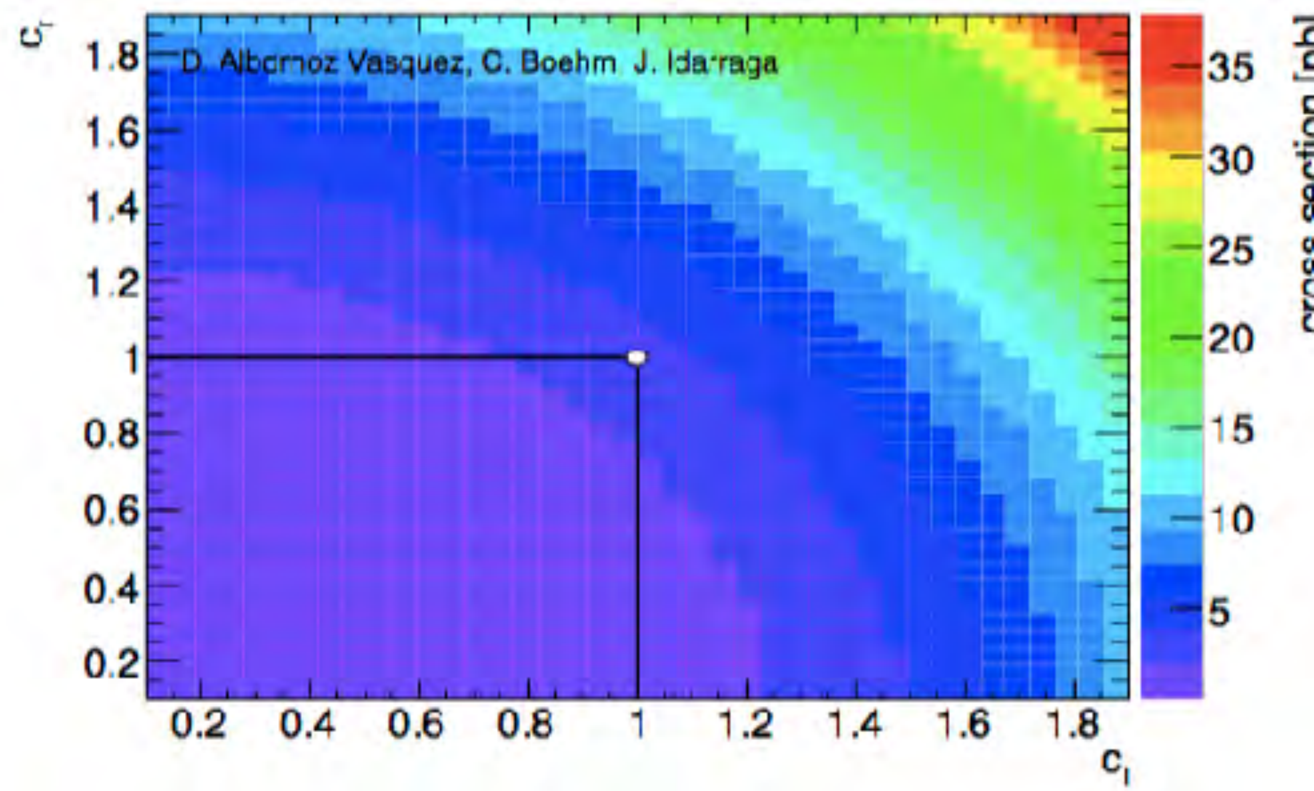
In the early Universe (c=1), light DM means light Z' for thermal RD and adjust couplings

In late Universe, light DM is ~ fine because the cross section is velocity dependent

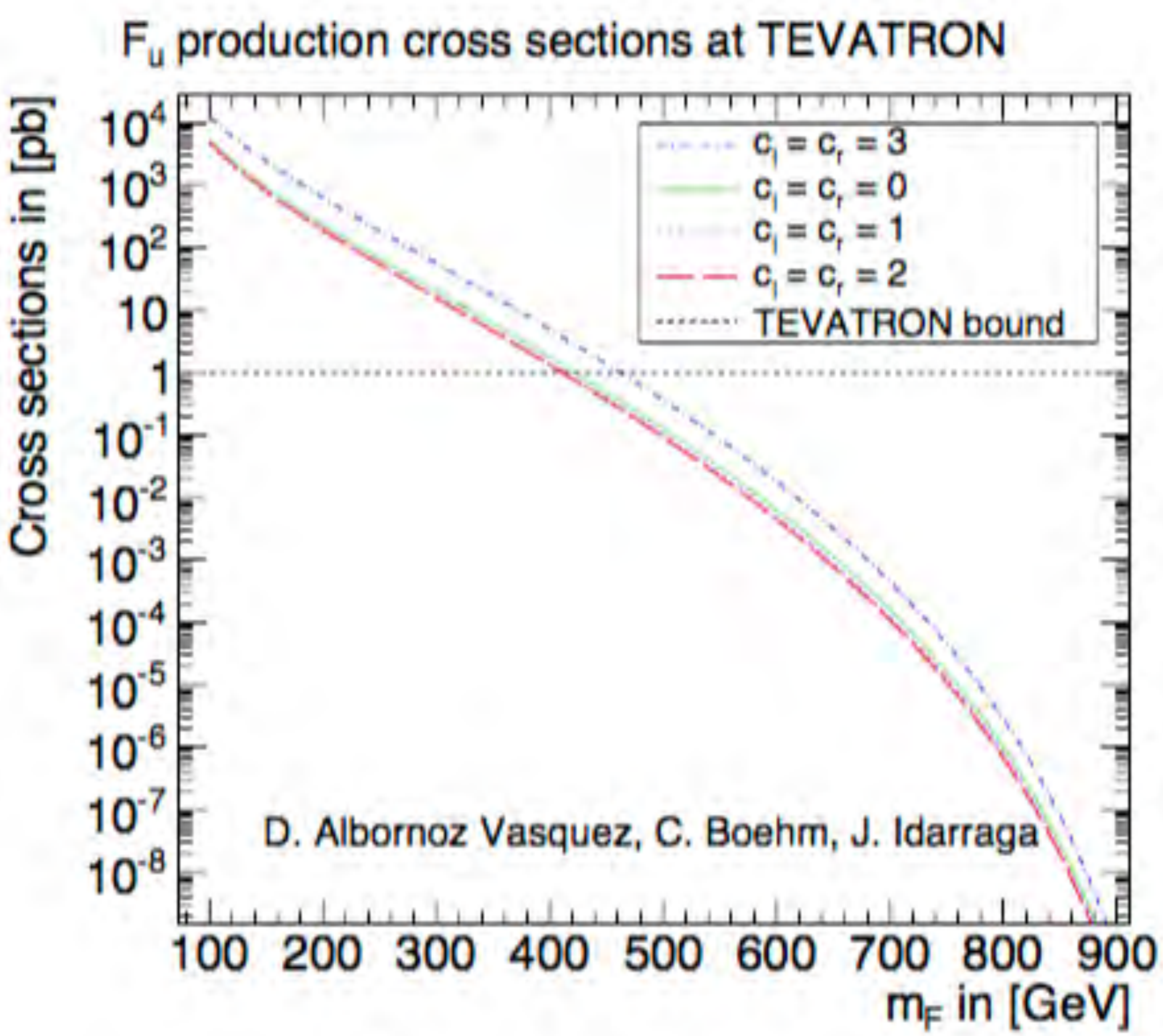
Signature of light DM (t-channel mediators) at LHC







0912.5373

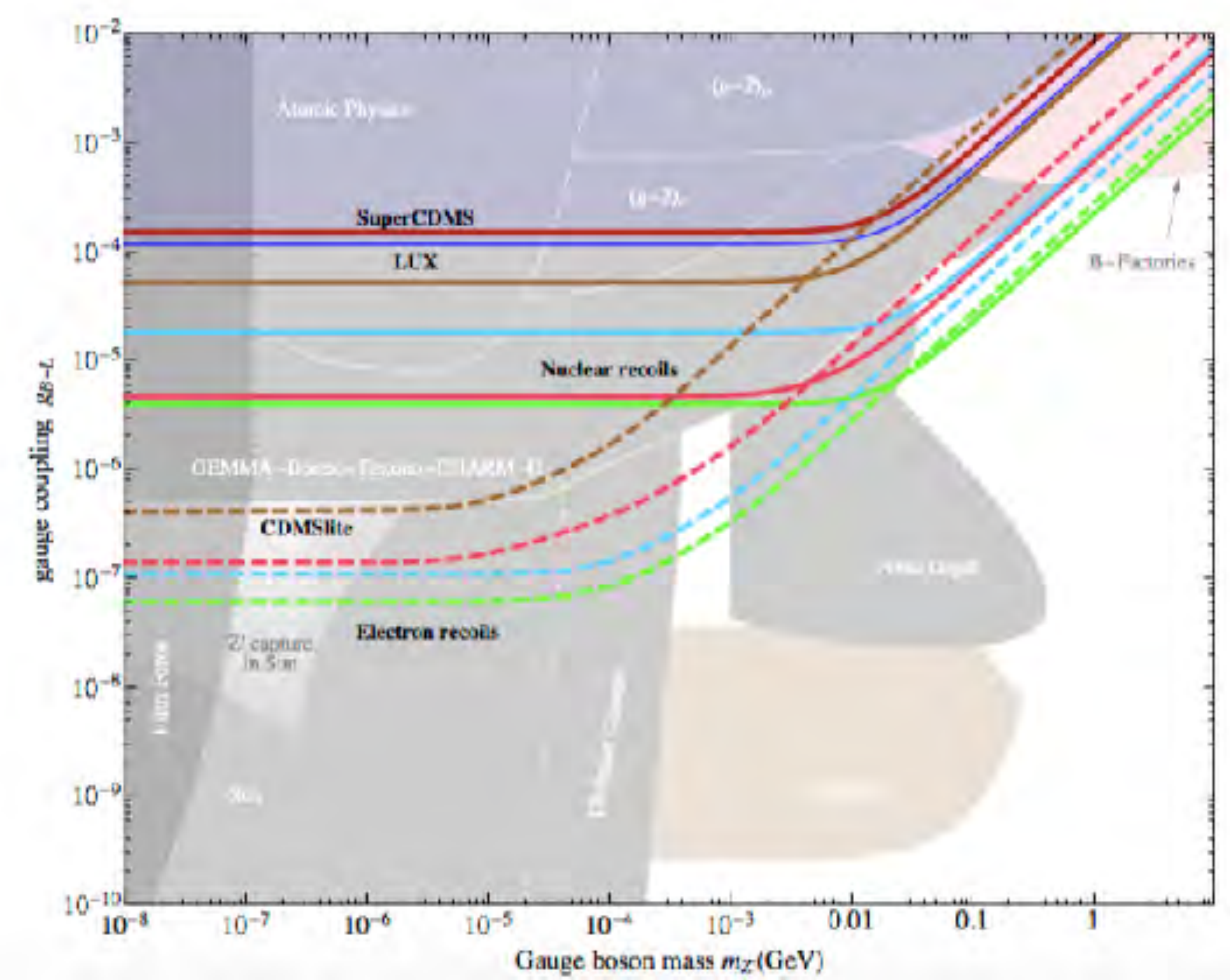


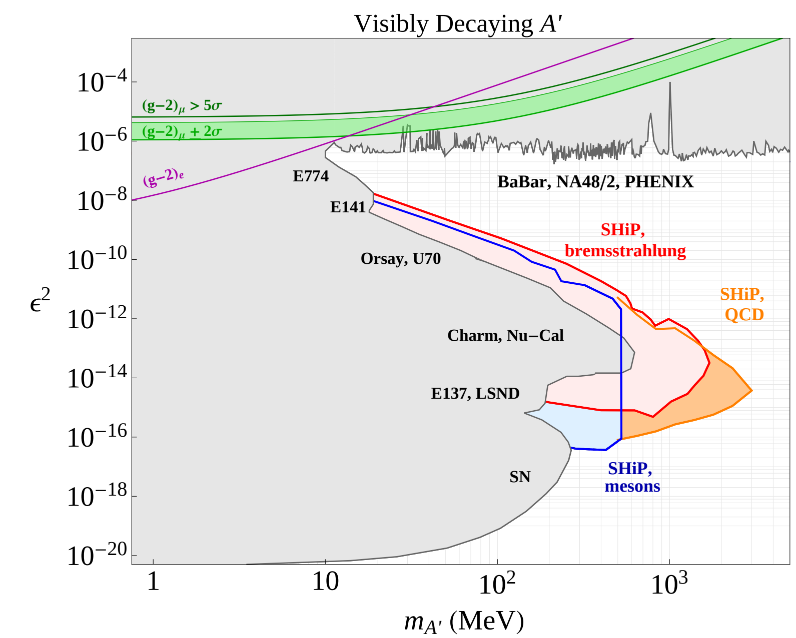
first example of simplified models at LHC

The mediator can be produced through the exchange of DM

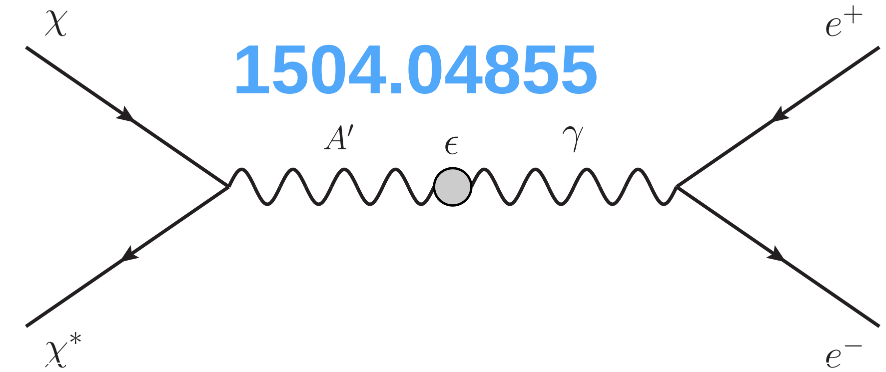
Strong constraints!

But Light DM particles are being ruled out

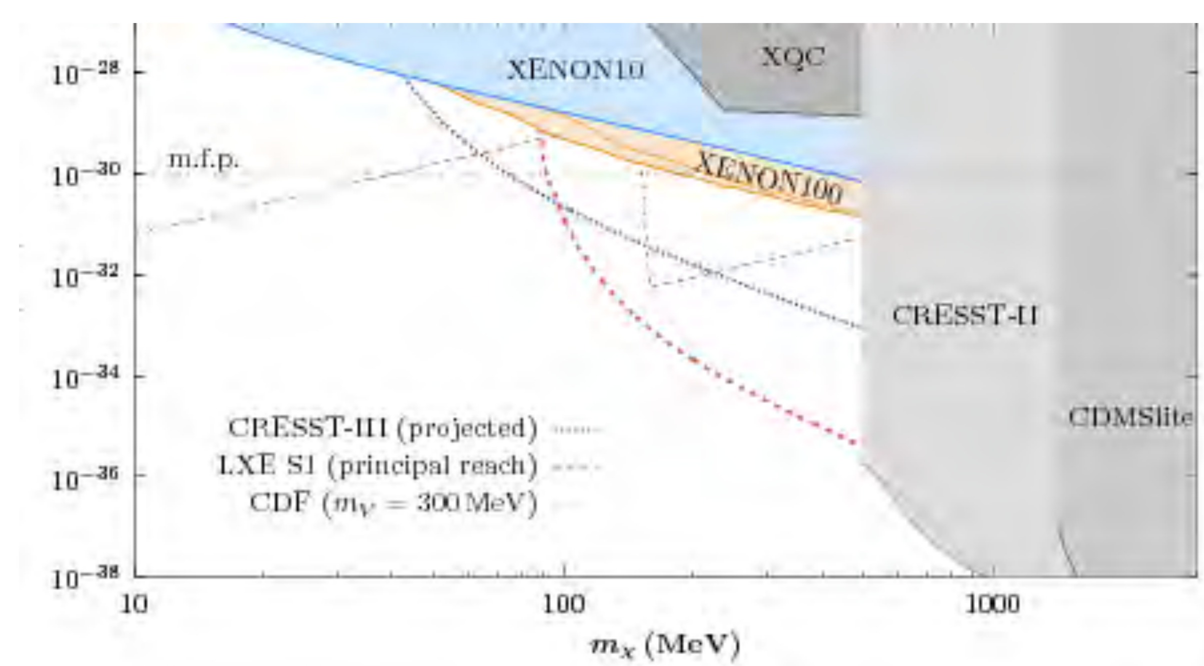




1504.04855



1607.01789

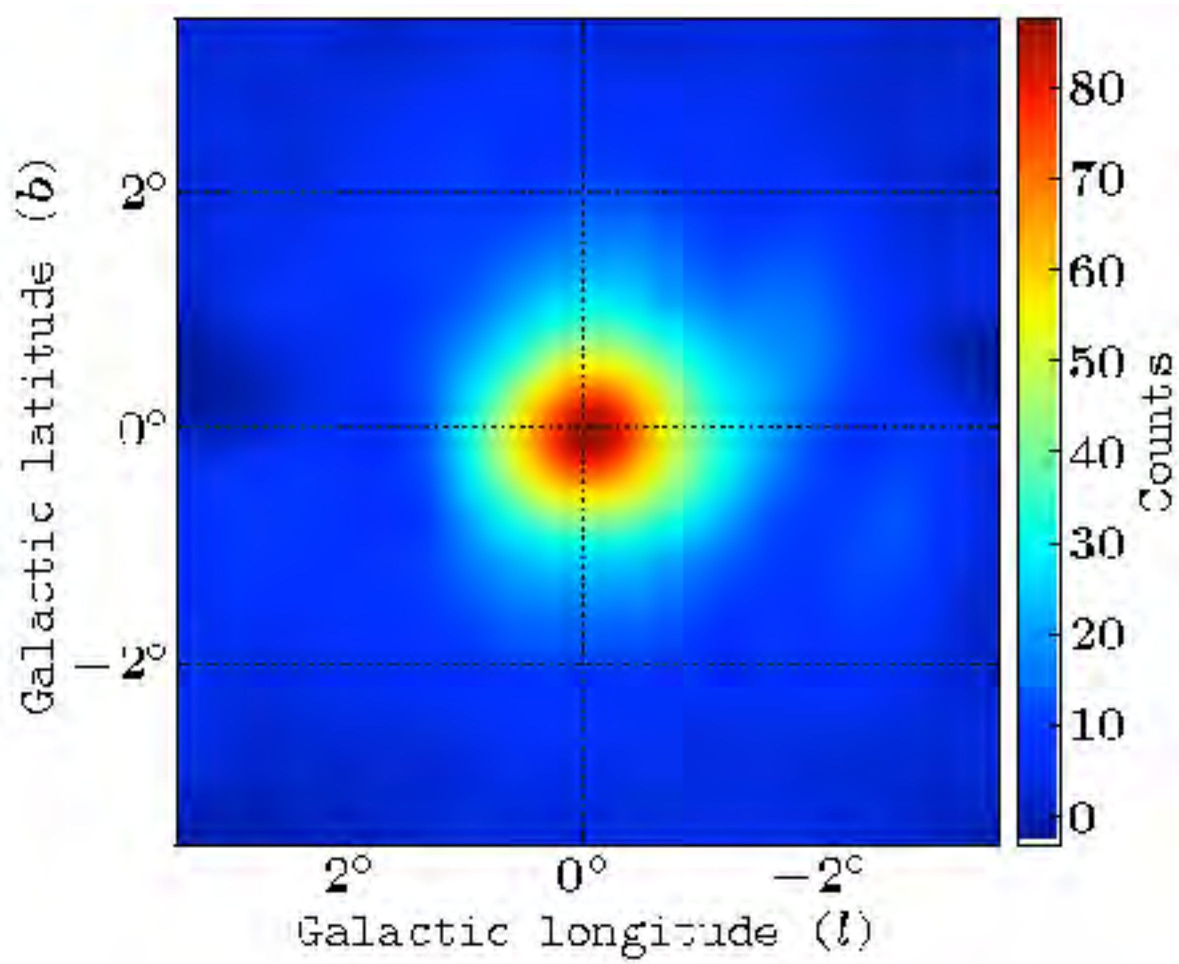


BDX arXiv:1406.3028, Dafne/Kloe, arXiv:1606.08849&: arXiv:1604.08206

arXiv:1412.8378 arXiv:1407.0993

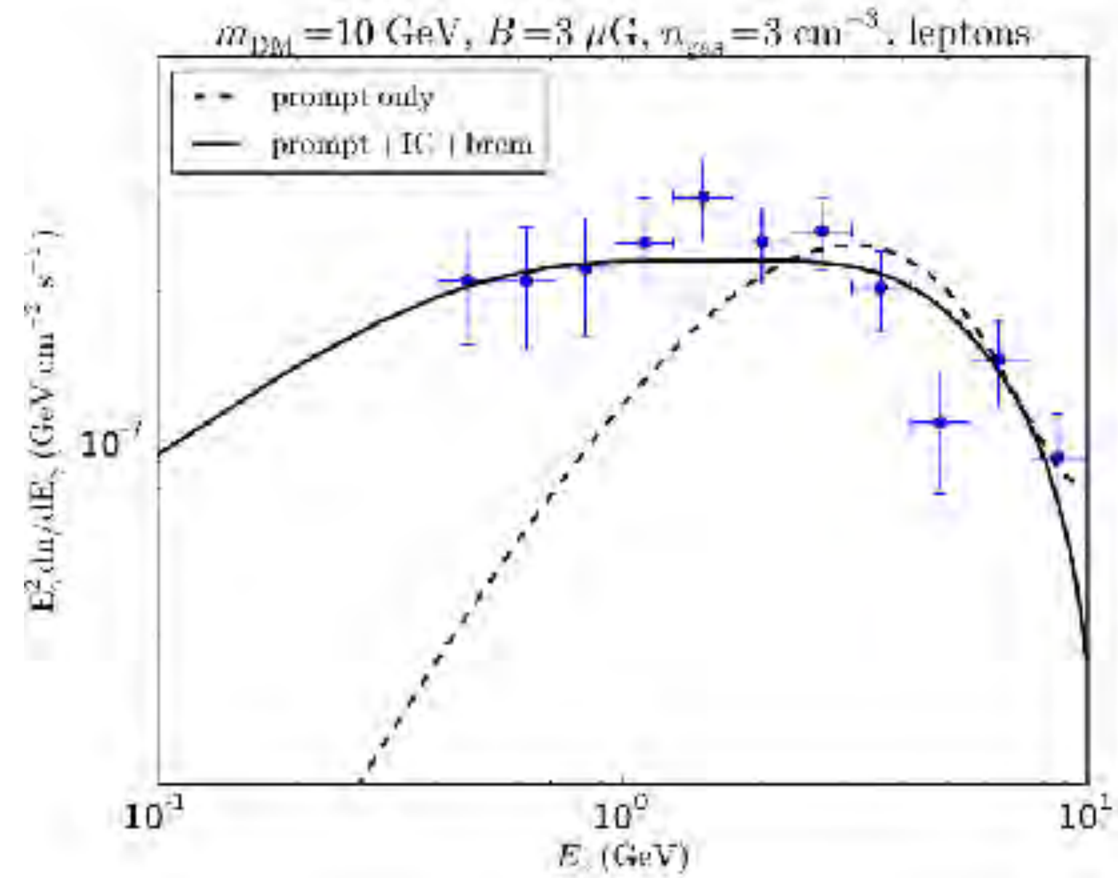
The GeV excess (still room for relatively light DM)

FERMI-LAT data



10-30 GeV DM annihilating mostly into b-quarks or muons

Hooper&Goodenough 2009
FERMI-LAT 2009
arXiv:1306.5725

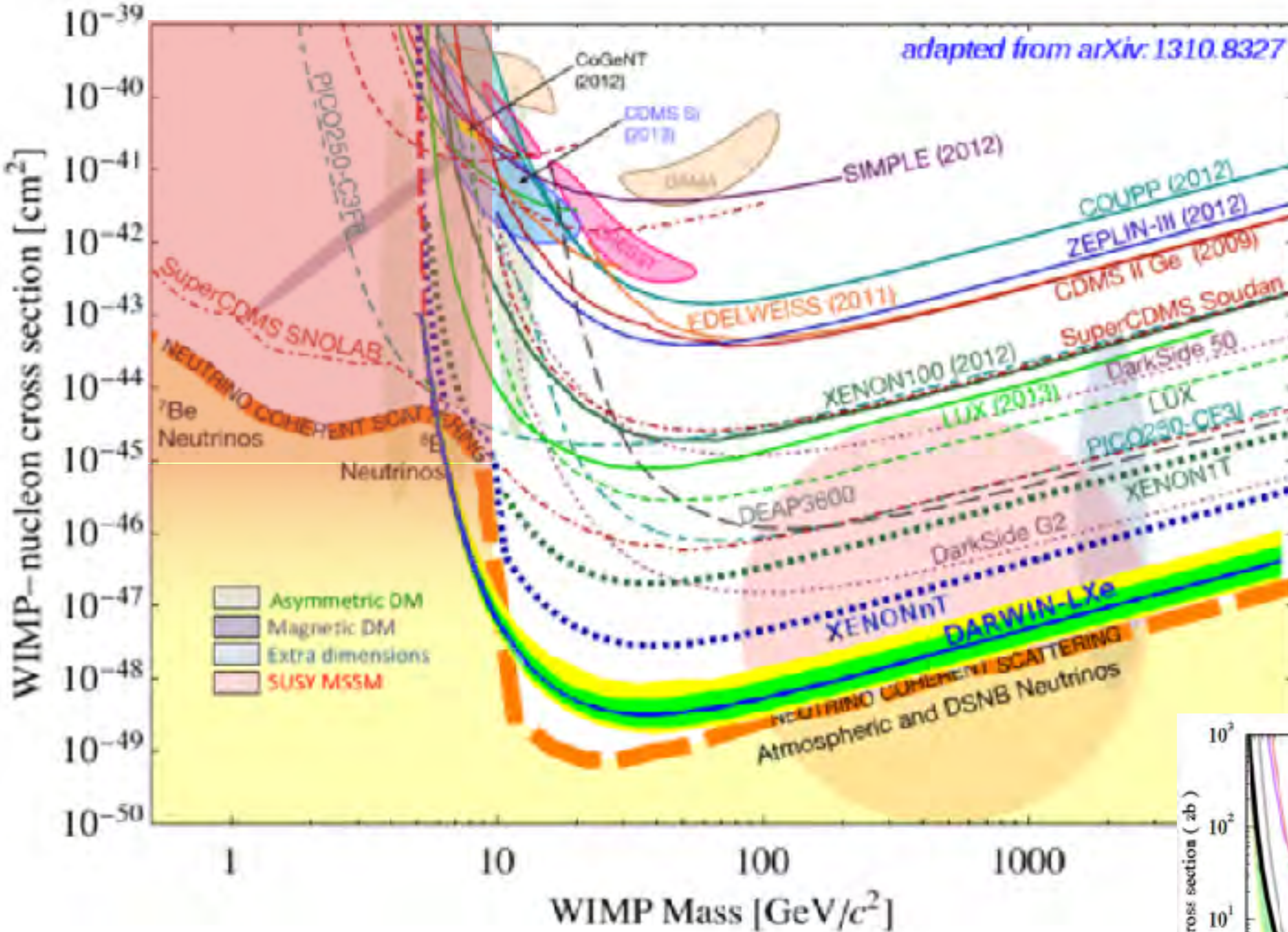


Leptons work too…

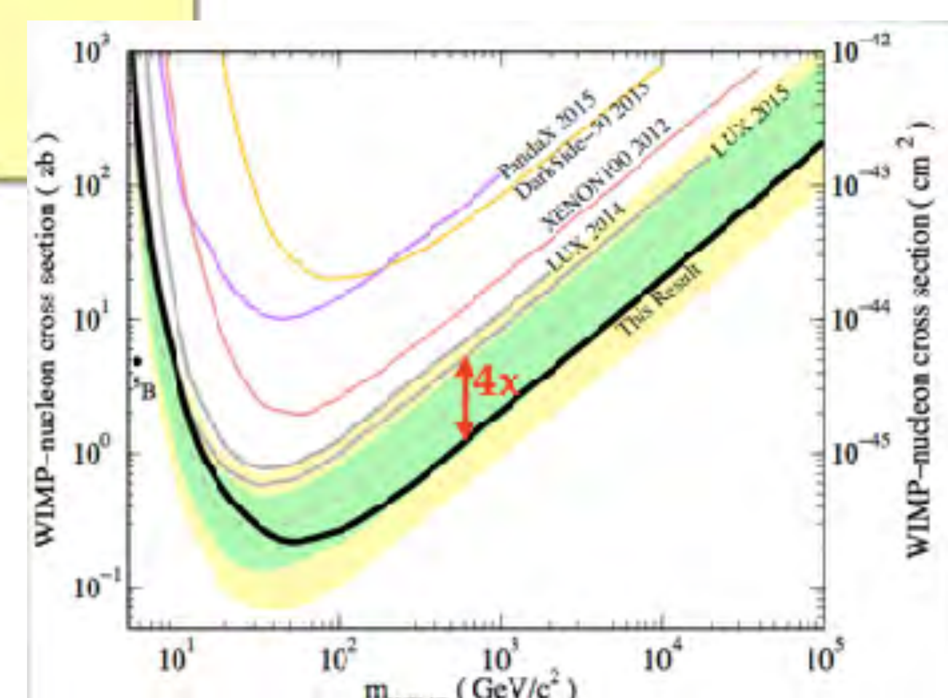
T. Lacroix, CB, J. Silk, 2014

Probably astrophysical sources but …

Direct detection experiments can be compared to ID and LHc searches!



$$\eta(E,t) = \int_{v_{\min}(E)}^{\infty} \frac{f(v, u_{\mathrm{e}}(t))}{v} \mathrm{d}^3 v$$



Simplified models

hep-ph/0305261

	Scalar	Fermion	Vector
DM	ϕ	χ	X^μ
Mediator	A	ψ	V^μ
SM (fermions)	–	f	–

Notice the ~!!!

Model Number	DM	Mediator	Interaction	Elastic Scattering	Near Future Reach?	
					Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

arXiv:1404.0022

New types of DM-nuclei interactions

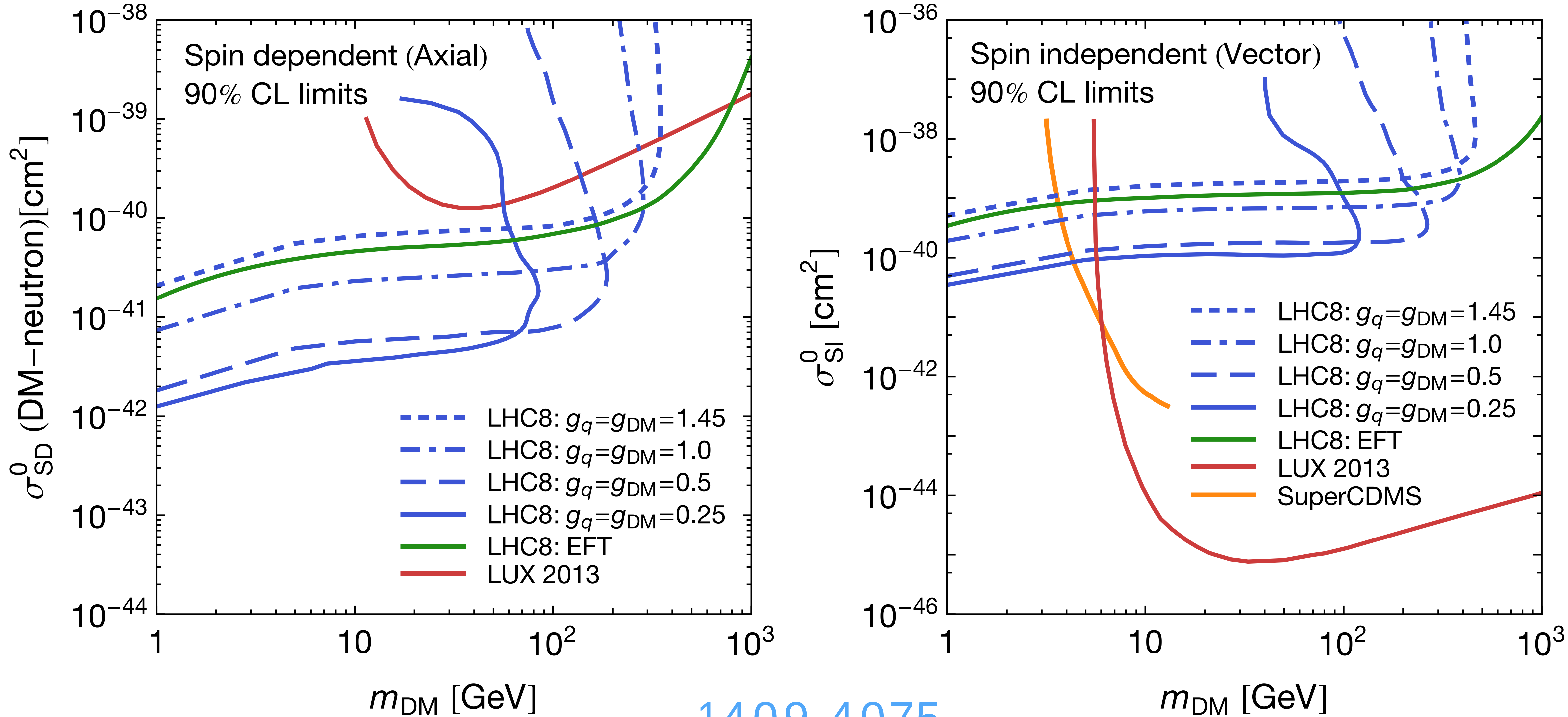
new models, new operators, new couplings to nuclei!

	SI $\mathcal{O}_1^{NR}$	SD $\mathcal{O}_4^{NR}$	SD $\mathcal{O}_6^{NR}$	SD $\mathcal{O}_7^{NR}$	SI $\mathcal{O}_8^{NR}$	SD $\mathcal{O}_9^{NR}$	SD $\mathcal{O}_{10}^{NR}$	SI $\mathcal{O}_{11}^{NR}$	SD $\mathcal{O}_{13}^{NR}$	SD $\mathcal{O}_{14}^{NR}$
1/2-S	$g_{f,s}g_{\chi,s}$		$g_{f,p}g_{\chi,p}$				$g_{f,p}g_{\chi,s}$	$g_{f,s}g_{\chi,p}$		$g_{f,s}g_{\chi,p}$
1/2*-V	$g_{f,v}g_{\chi,v}$	$g_{f,a}g_{\chi,a}$		$g_{f,a}g_{\chi,v}$	$g_{f,v}g_{\chi,a}$	$g_{f,a}g_{\chi,v}$				
1/2-V		$g_{f,a}g_{\chi,a}$			$g_{f,v}g_{\chi,a}$					
1/2-$S^\pm$	$\|g_s^2\| - \|g_p^2\|$	$\|g_s^2\| + \|g_p^2\|$								
1/2*-$S^\pm$	$\|g_s^2\| \pm \|g_p^2\|$	$\|g_s^2\| + \|g_p^2\|$								
1/2-$V^\pm$	$\|g_v^2\| - \|g_a^2\|$	$\|g_v^2\| + \|g_a^2\|$								
1/2*-$V^\pm$	$\|g_v^2\| \pm \|g_a^2\|$	$\|g_v^2\| + \|g_a^2\|$								
0-S	$g_\chi g_{f,s}$						$g_\chi g_{f,p}$			
0-V	$g_\chi g_{f,v}$			$g_\chi g_{f,a}$			$g_\chi g_{f,a}$			
0-$F^\pm$	$\|g_s\|^2 \pm \|g_p\|^2$						$g_p g_s^\dagger - g_s g_p^\dagger$			
0-$F^\pm$	$\|g_s\|^2 \pm \|g_p\|^2$						$g_p g_s^\dagger \pm g_s g_p^\dagger$			
1-S	$g_\chi g_{f,s}$						$g_\chi g_{f,p}$			
1-V ($\mathcal{V}_1$)		$\mathrm{Im}(g_\chi)g_v$	$\mathrm{Im}(g_\chi)g_v$		$\mathrm{Im}(g_\chi)g_a$			$\mathrm{Re}(g_\chi)g_a$	$\mathrm{Re}(g_\chi)g_v$	
1-V ($\mathcal{V}_2$)	$\mathrm{Im}(g_\chi)g_v$			$\mathrm{Im}(g_\chi)g_a$			$\mathrm{Re}(g_\chi)g_a$			
1-V ($\mathcal{V}_3$)		$\mathrm{Re}(g_\chi)g_a$	$\mathrm{Re}(g_\chi)g_a$		$\mathrm{Re}(g_\chi)g_v$	$\mathrm{Re}(g_\chi)g_v$		$\mathrm{Im}(g_\chi)g_v$		$\mathrm{Im}(g_\chi)g_a$
1-$F^\pm$	$\|g_s\|^2 \pm \|g_p\|^2$				$g_v g_a^\dagger + g_a g_v^\dagger$	$g_v g_a^\dagger + g_a g_v^\dagger$	$g_v g_a^\dagger - g_a g_v^\dagger$			
1*-$F^\pm$	$\|g_s\|^2 \pm \|g_p\|^2$					$g_v g_a^\dagger + g_a g_v^\dagger$	$g_v g_a^\dagger - g_a g_v^\dagger$	$g_v g_a^\dagger + g_a g_v^\dagger$		

main operators

new operators

most of them suppressed by spin and/or velocity but ..

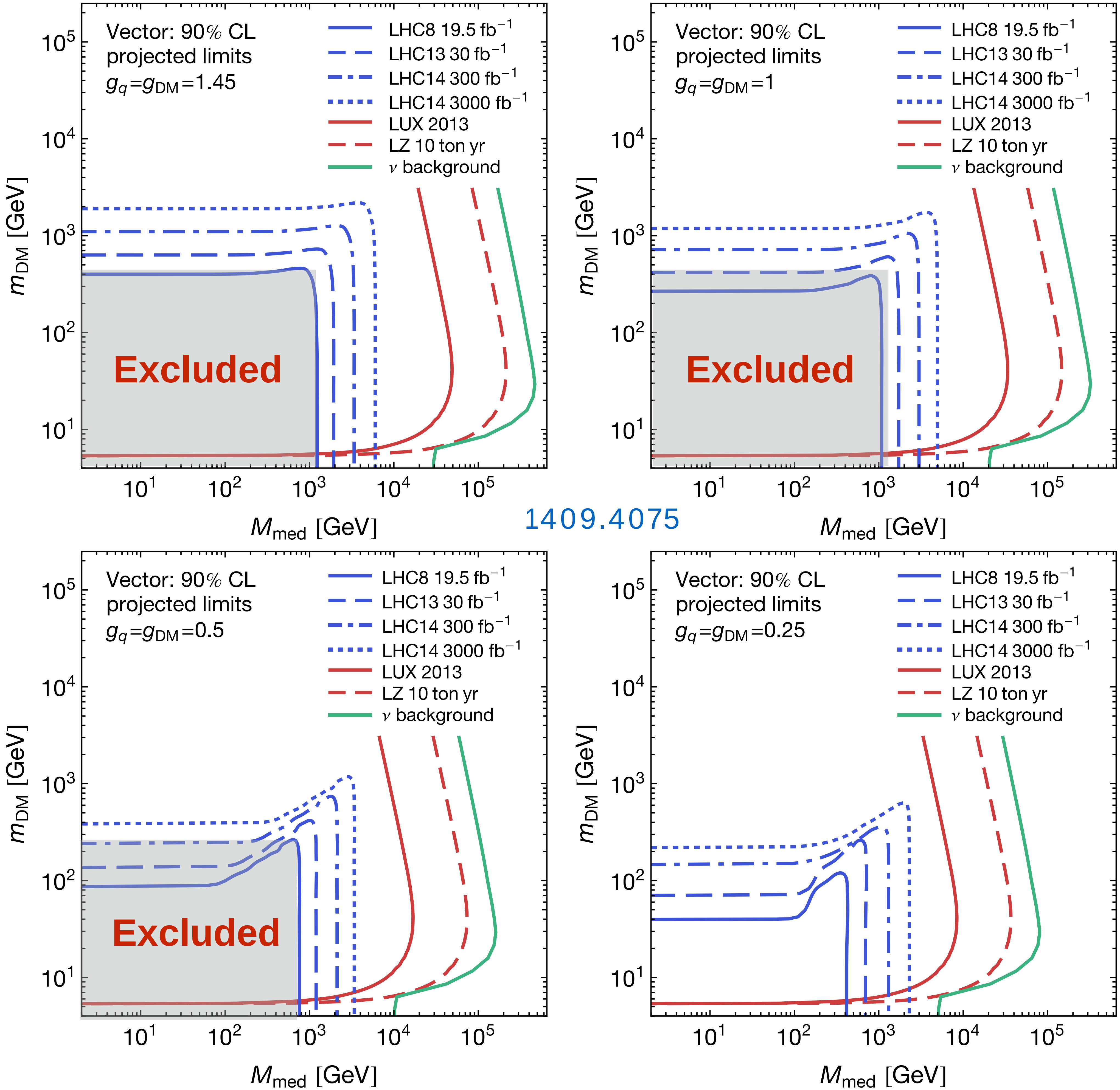


1409.4075

Competition between DD and LHC (monojets)

EFT not valid at low mass so simplified models!

no resonance



Vector: 90% CL
projected limits
$g_q = g_{DM} = 1.45$
LHC8 19.5 fb^{-1}
LHC13 30 fb^{-1}
LHC14 300 fb^{-1}
LHC14 3000 fb^{-1}
LUX 2013
LZ 10 ton yr
ν background
Excluded
m_{DM} [GeV]
M_{med} [GeV]
Vector: 90% CL
projected limits
$g_q = g_{DM} = 1$
LHC8 19.5 fb^{-1}
LHC13 30 fb^{-1}
LHC14 300 fb^{-1}
LHC14 3000 fb^{-1}
LUX 2013
LZ 10 ton yr
ν background
Excluded
m_{DM} [GeV]
M_{med} [GeV]
1409.4075
Vector: 90% CL
projected limits
$g_q = g_{DM} = 0.5$
LHC8 19.5 fb^{-1}
LHC13 30 fb^{-1}
LHC14 300 fb^{-1}
LHC14 3000 fb^{-1}
LUX 2013
LZ 10 ton yr
ν background
Excluded
m_{DM} [GeV]
M_{med} [GeV]
Vector: 90% CL
projected limits
$g_q = g_{DM} = 0.25$
LHC8 19.5 fb^{-1}
LHC13 30 fb^{-1}
LHC14 300 fb^{-1}
LHC14 3000 fb^{-1}
LUX 2013
LZ 10 ton yr
ν background
m_{DM} [GeV]
M_{med} [GeV]

Conclusion

Stringent limits from Direct and Indirect detection

Still room for new physics but constrained!

We need to pay attention to the cosmology

as this can affect all our estimates!