Circular polarisation as a new probe of BSM physics in space

Céline Boehm

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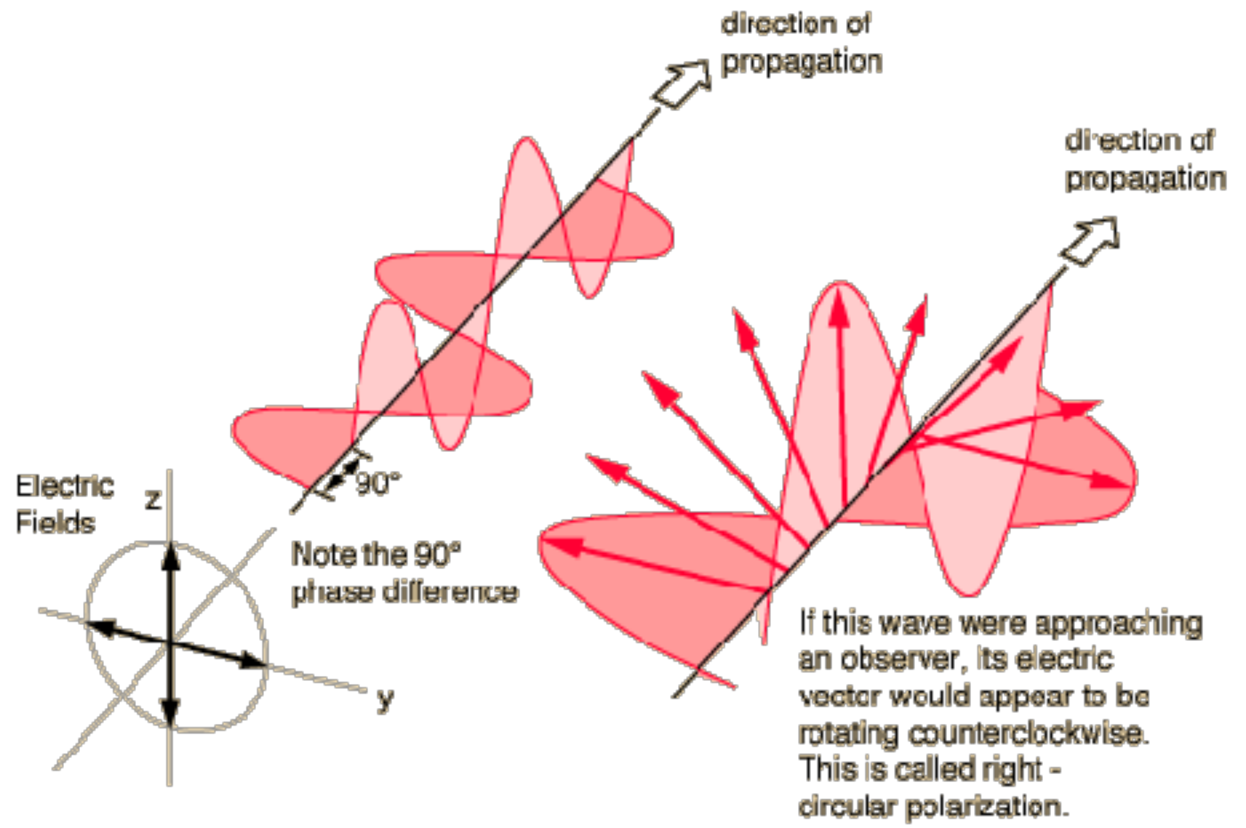
arXiv:1701.02754

Courtesy Hyper physics



IPPP, Durham   LAPTH, Annecy

CERN April 2017

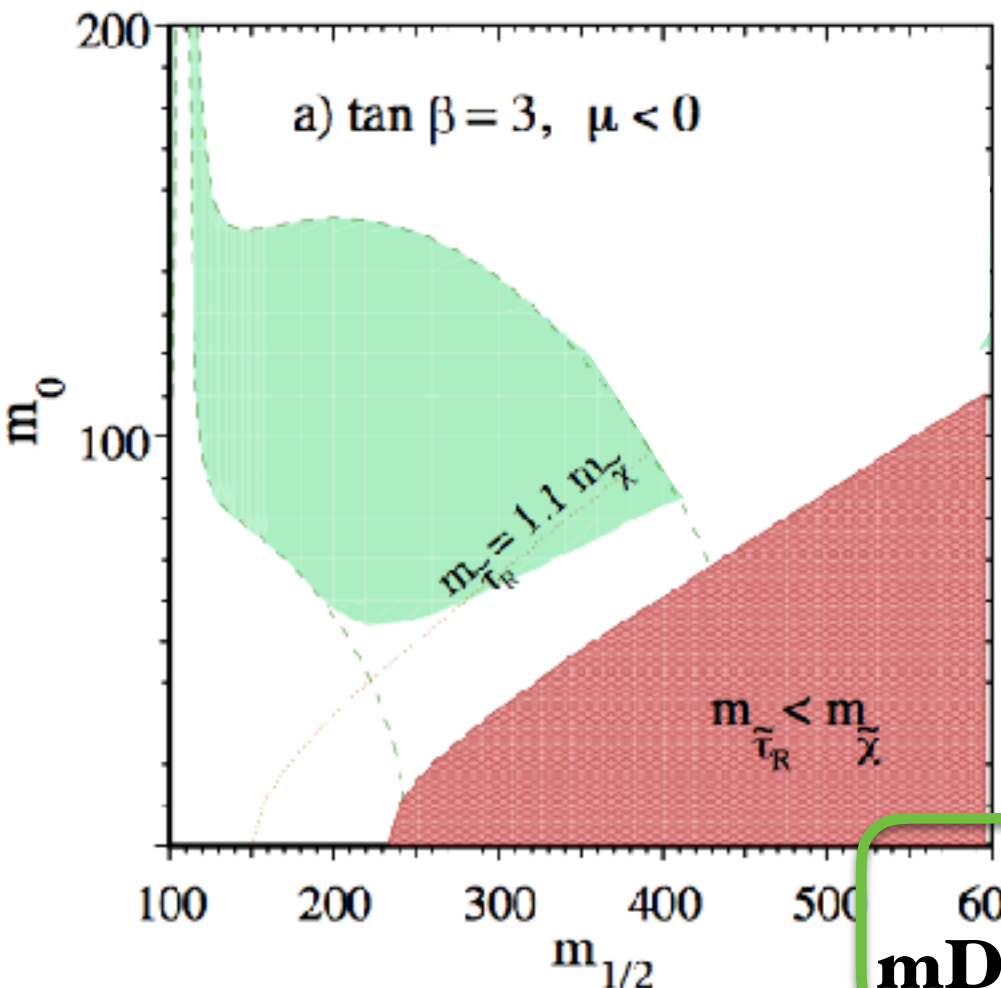
Quick recap of the DM world

“Intensity” & energy frontiers in the DM world

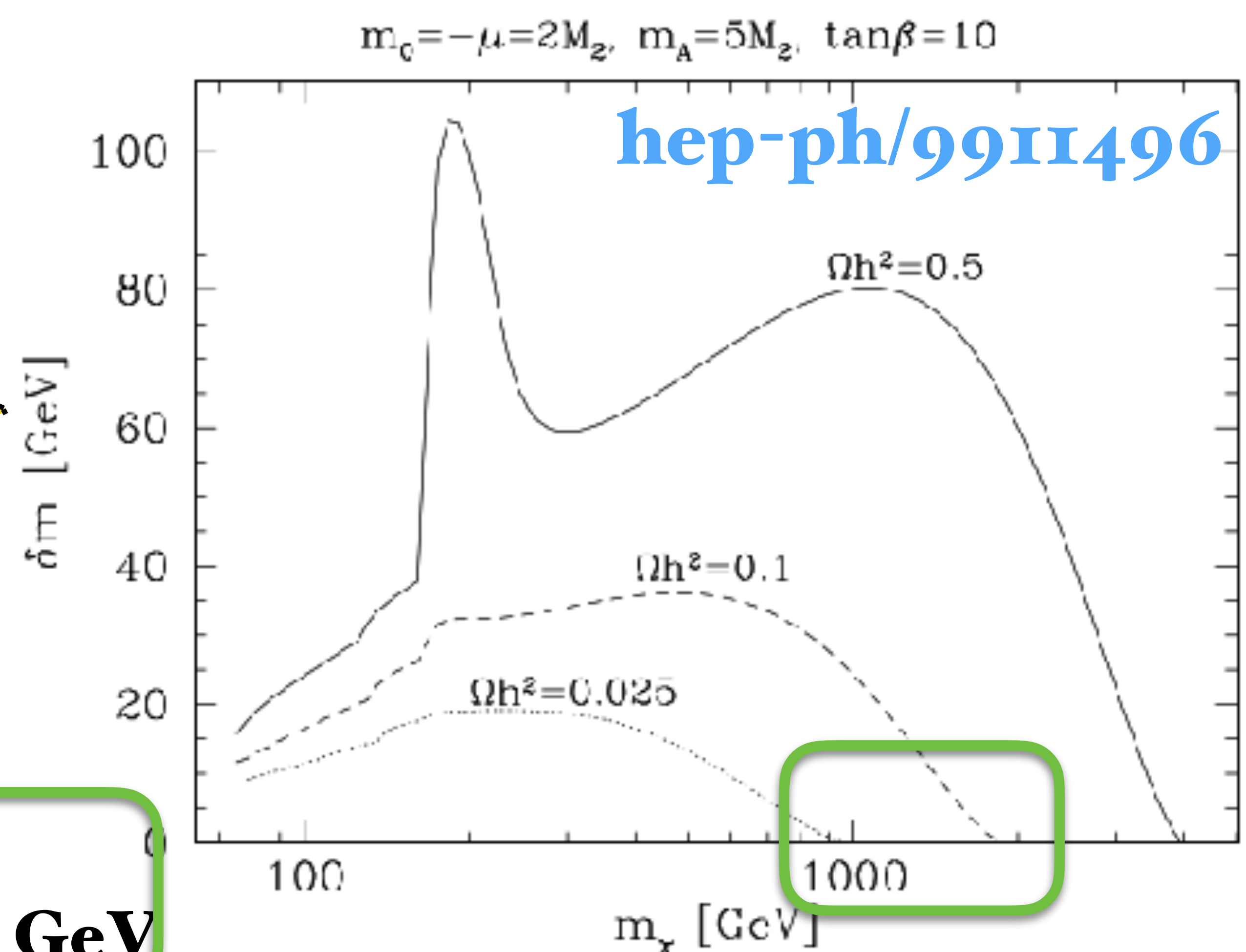
Energy is critical as DM may be heavy

Supersymmetry Extra-Dimensions …

Relic density criterion alone (before WMAP!)



mDM << 300 GeV



Larger DM masses need higher energy colliders!

“Intensity” & energy frontiers in the DM world

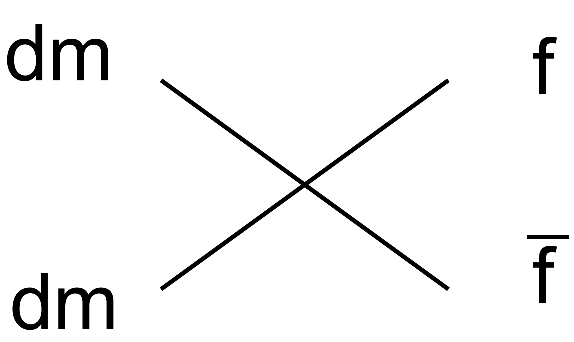
Intensity is critical! **not only for new heavy mediators but also for Dark (5th) force**

Hut, Lee&Weinberg 77

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

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

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



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

$$\Omega_{\rm DM} h^2 \propto m_{\rm DM}^{-2}$$

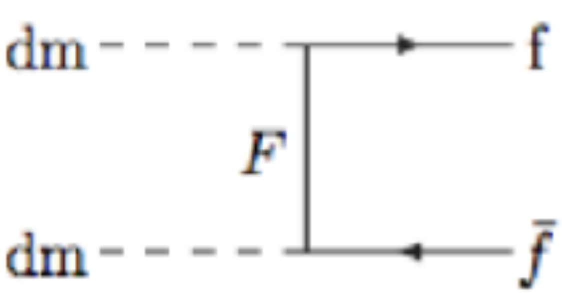
Dark Matter heavier than a proton unless new types of interactions

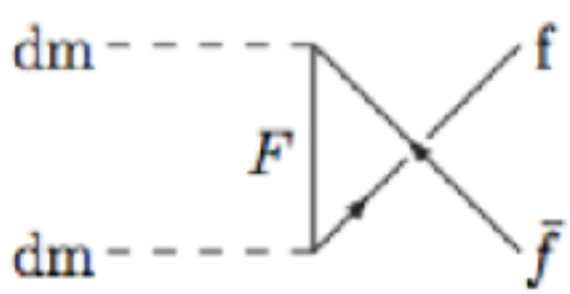
“Intensity” & energy frontiers in the DM world

Intensity is critical! astro-ph/0208458v3 hep-ph/0305261

$$\Omega_{\rm DM} h^2 \propto \cancel{m_{\rm DM}^{-2}} \quad \text{or....}$$

Dark 5th force and vector-like fermions



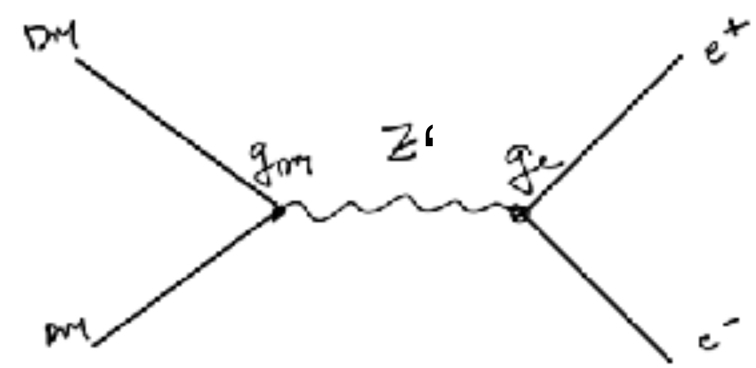


$$\sigma v \propto \frac{1}{m_F^4} \left((C_l^2 + C_r^2)\; m_f + 2 C_l\, C_r\, m_F \right)^2$$

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

mirror fermions

Such heavy mediators need fb, ab luminosity!



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

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

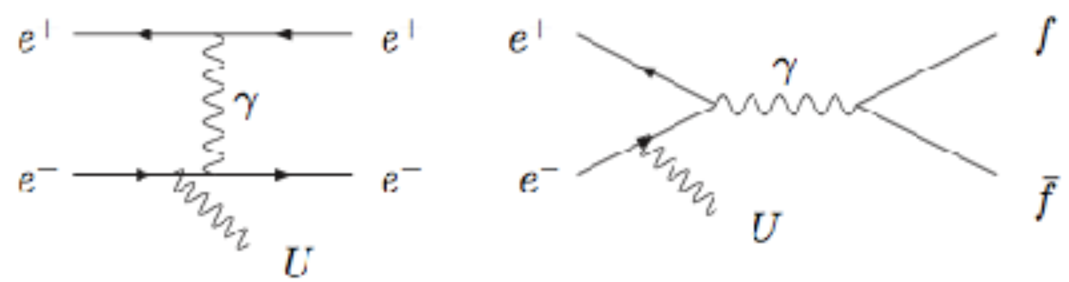
dark photons/dark Z’

Light DM and mediator but intensity is crucial!

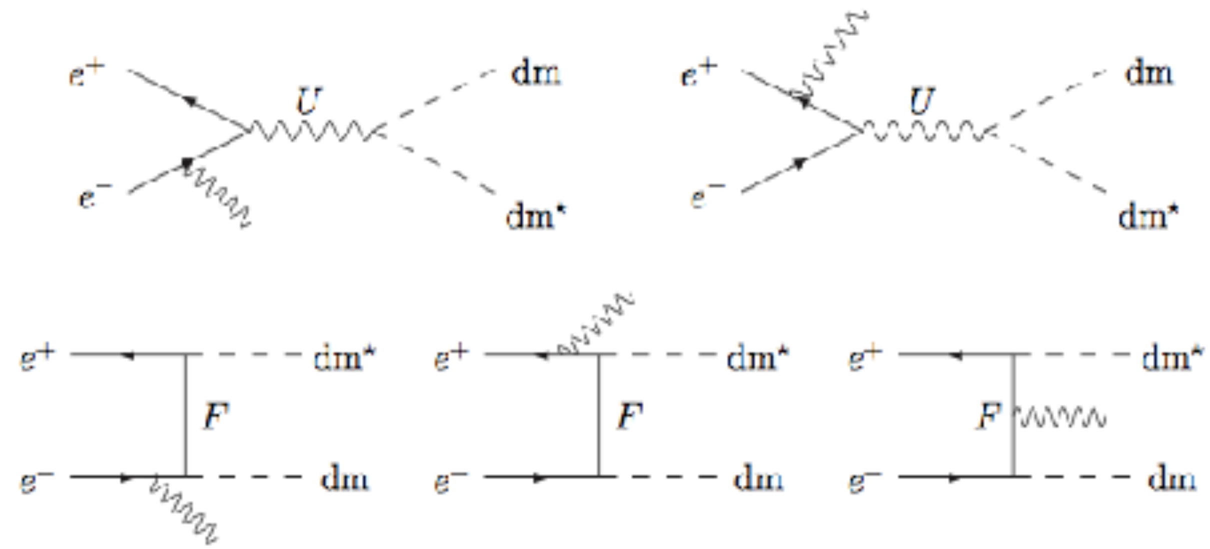
Low E. intensity frontier ...

U-strahlung.

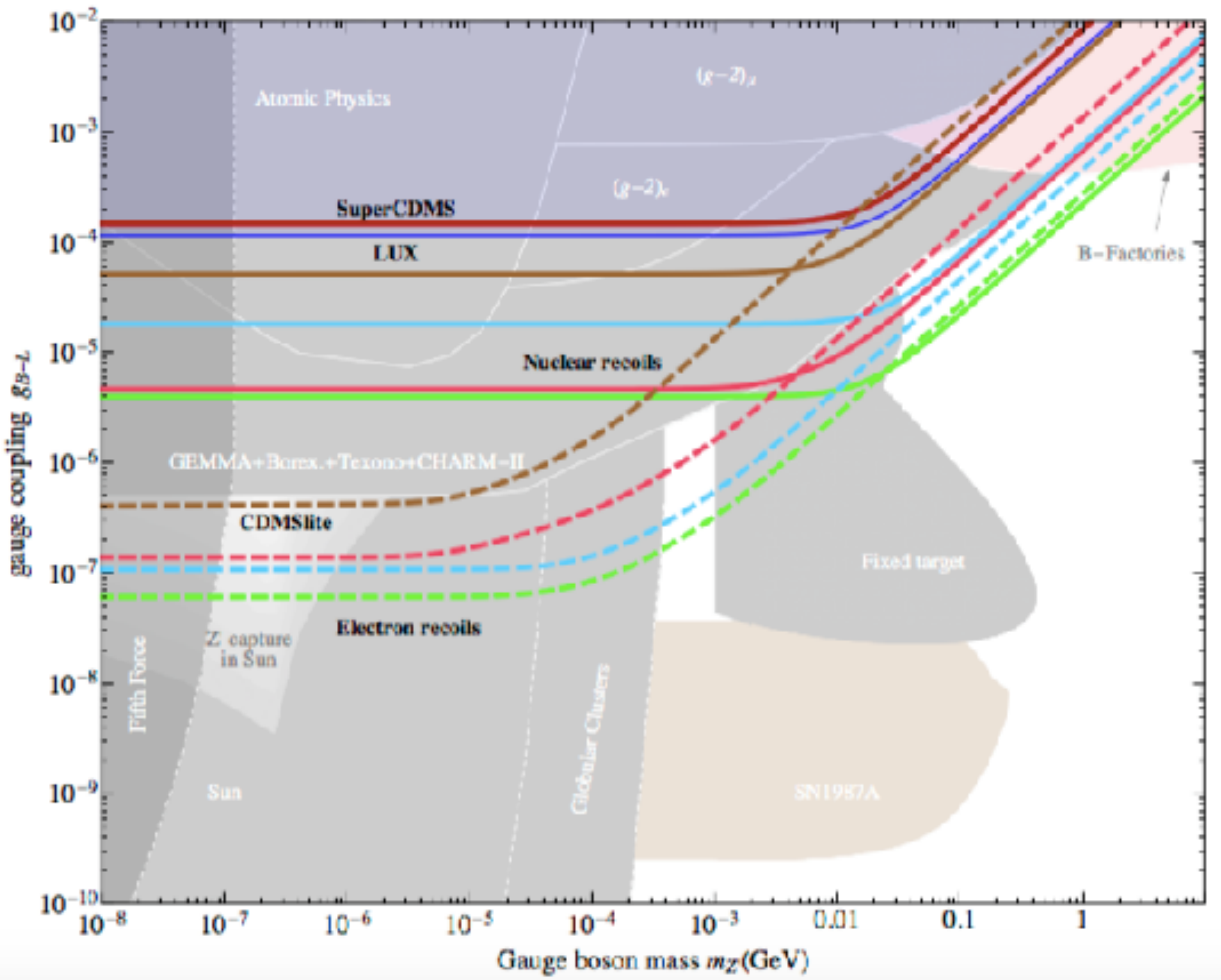
hep-ph/0305261

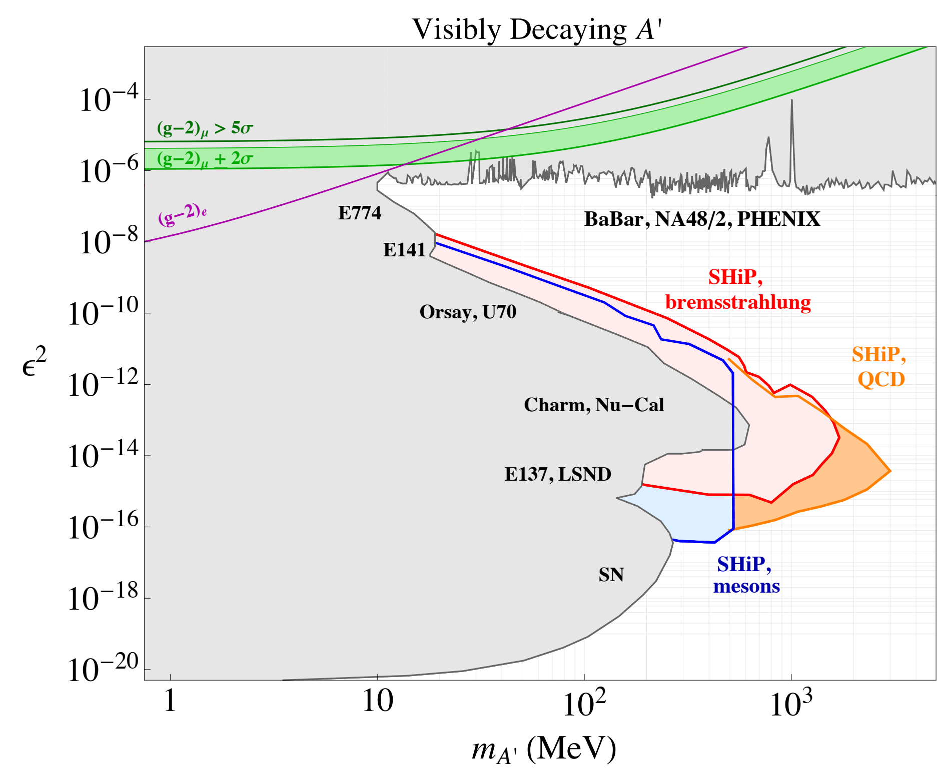


U = Z'



arXiv:1604.01025

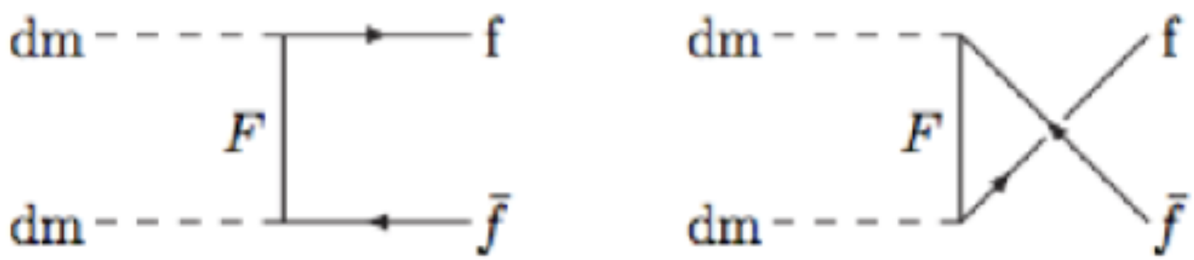




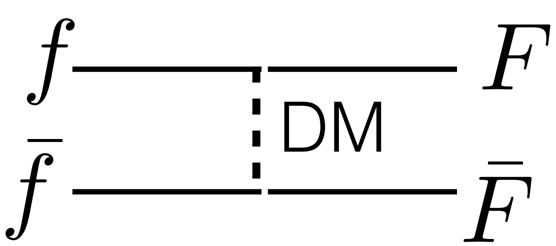
1406.3028, 1412.8378
1606.08849 1407.0993
1604.08206 1607.01789
1504.04855

High E. intensity frontier ...

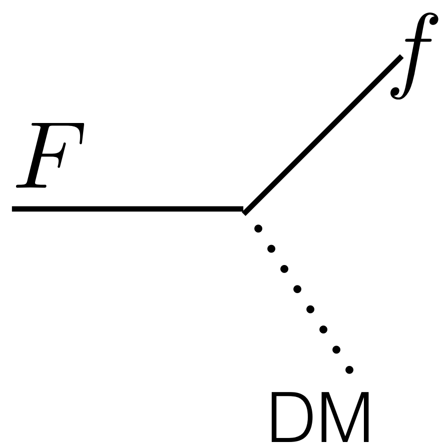
0912.5373



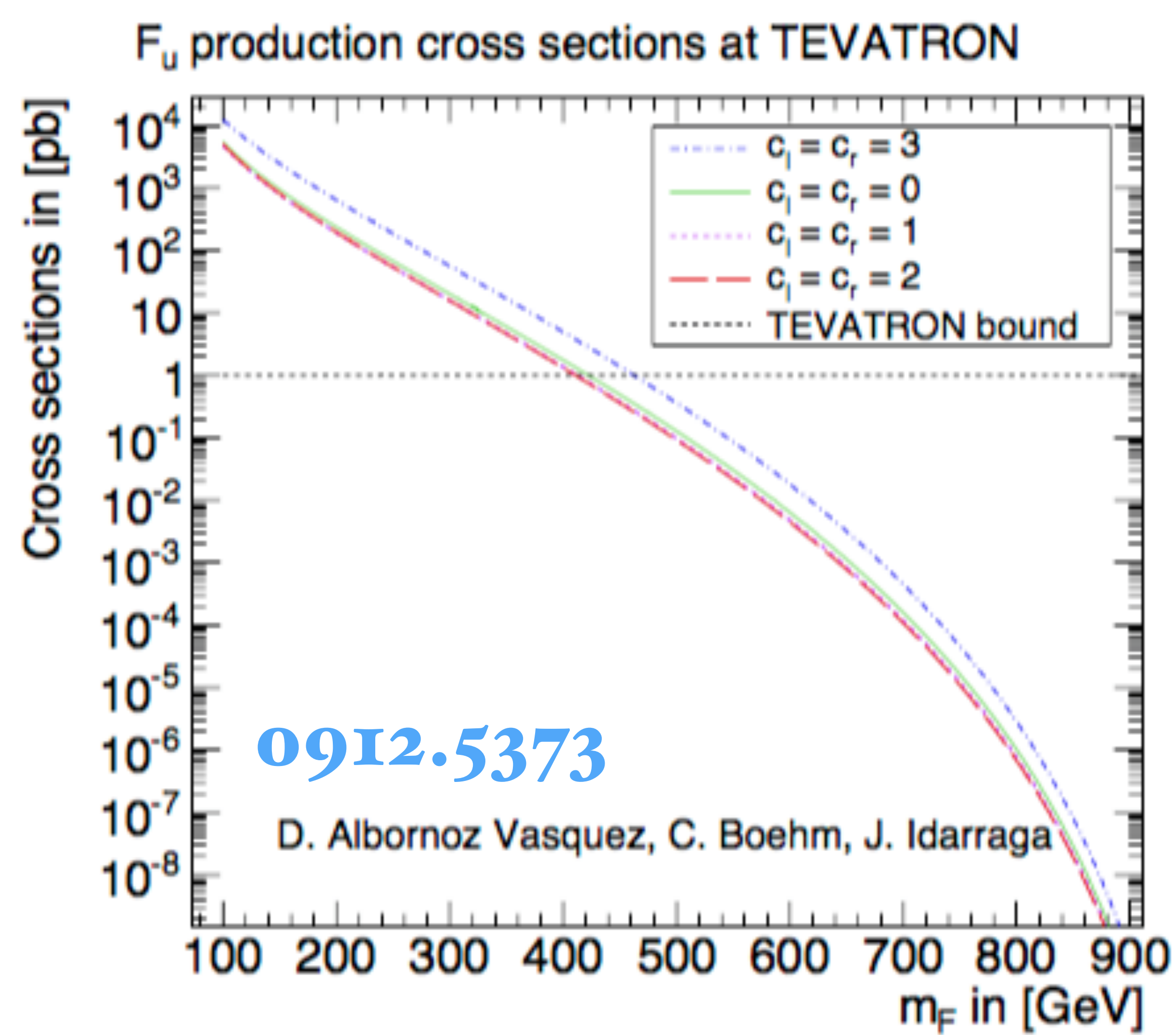
t-channel mediators



+other diagrams



The mediator is produced through the DM exchange

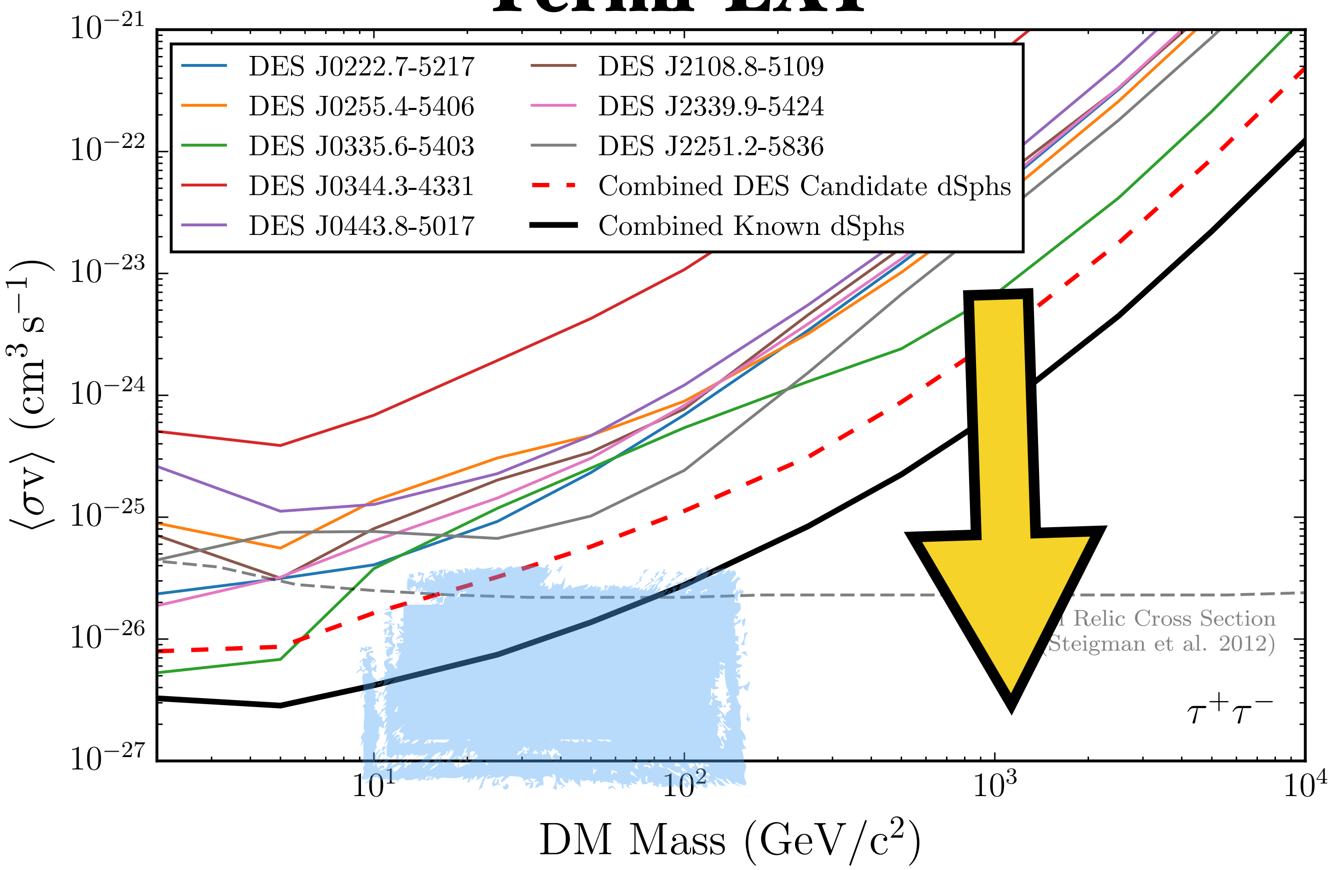


first example of DM searches
in colliders
using simplified models

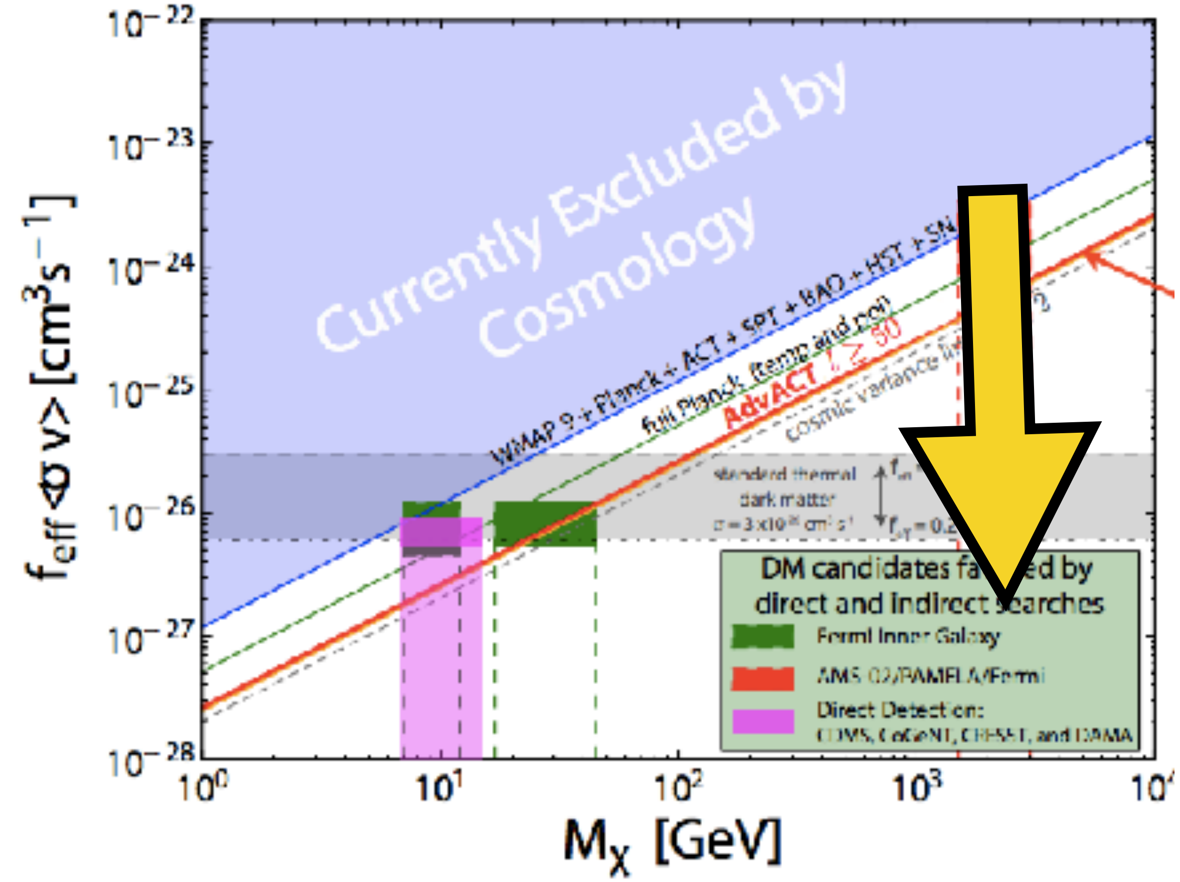
Astrophysical/Astroparticle observations are going the same direction…

“Intensity” & energy frontiers in the DM world

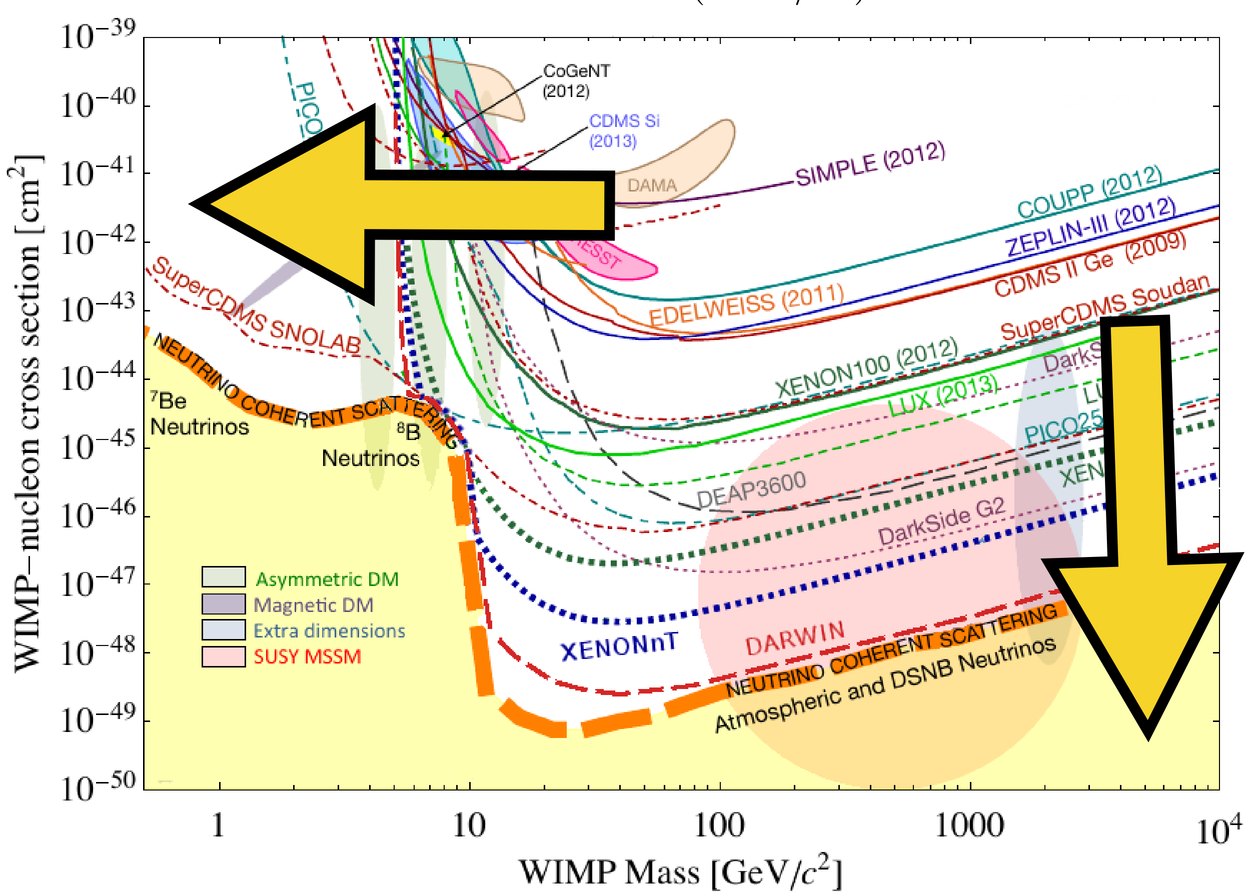
Fermi-LAT



Planck



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



Going lower/higher DM masses

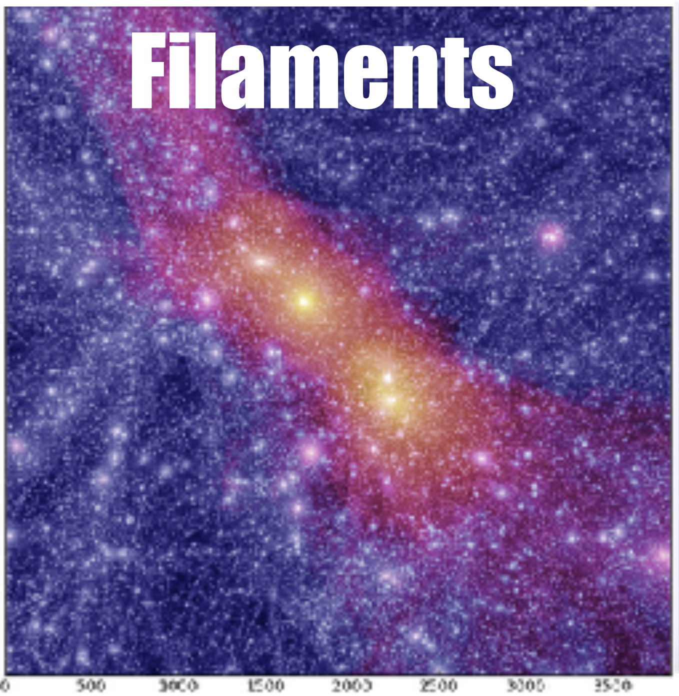
Dig deeper

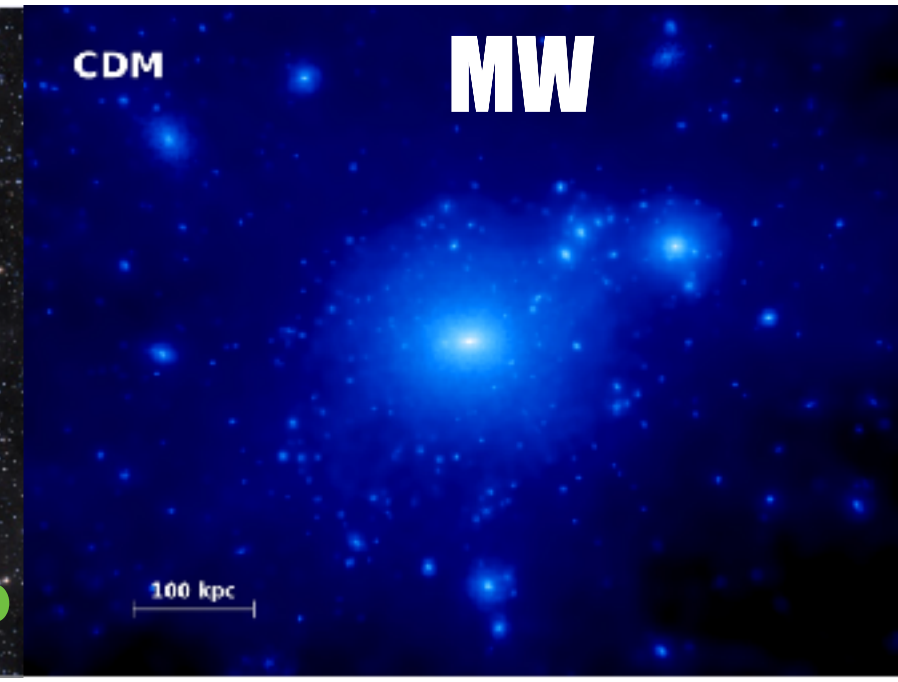
And yet

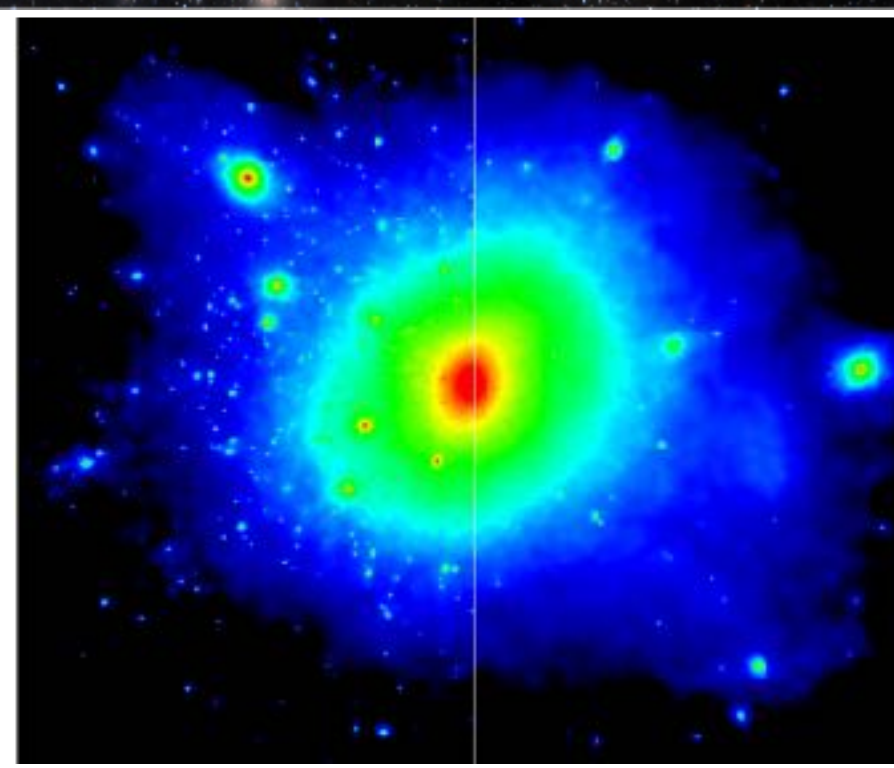
DM is everywhere!

The landscape for new searches

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



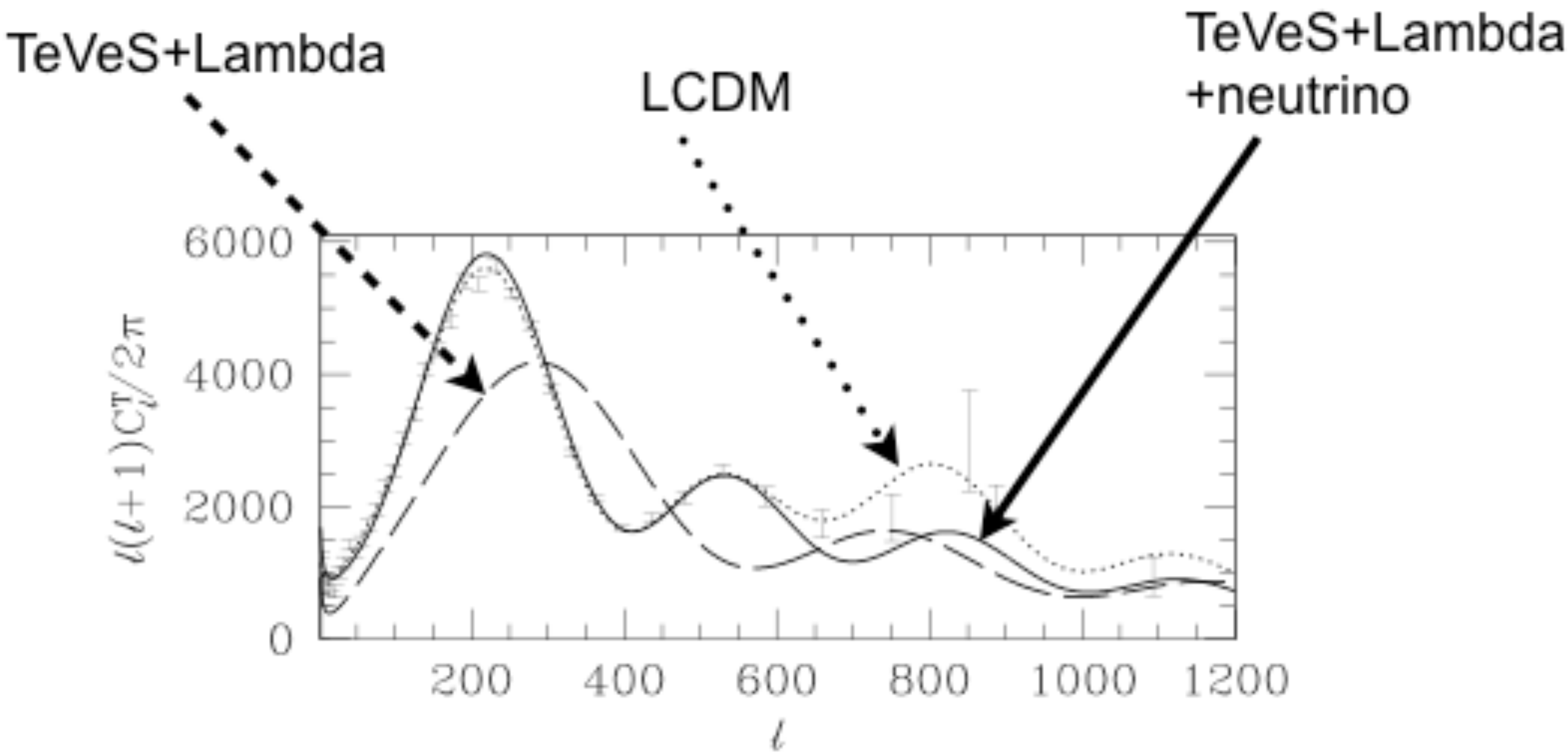




Once upon a time in a DM-free world

Mond/Bekenstein Bekenstein astro-ph/0403694

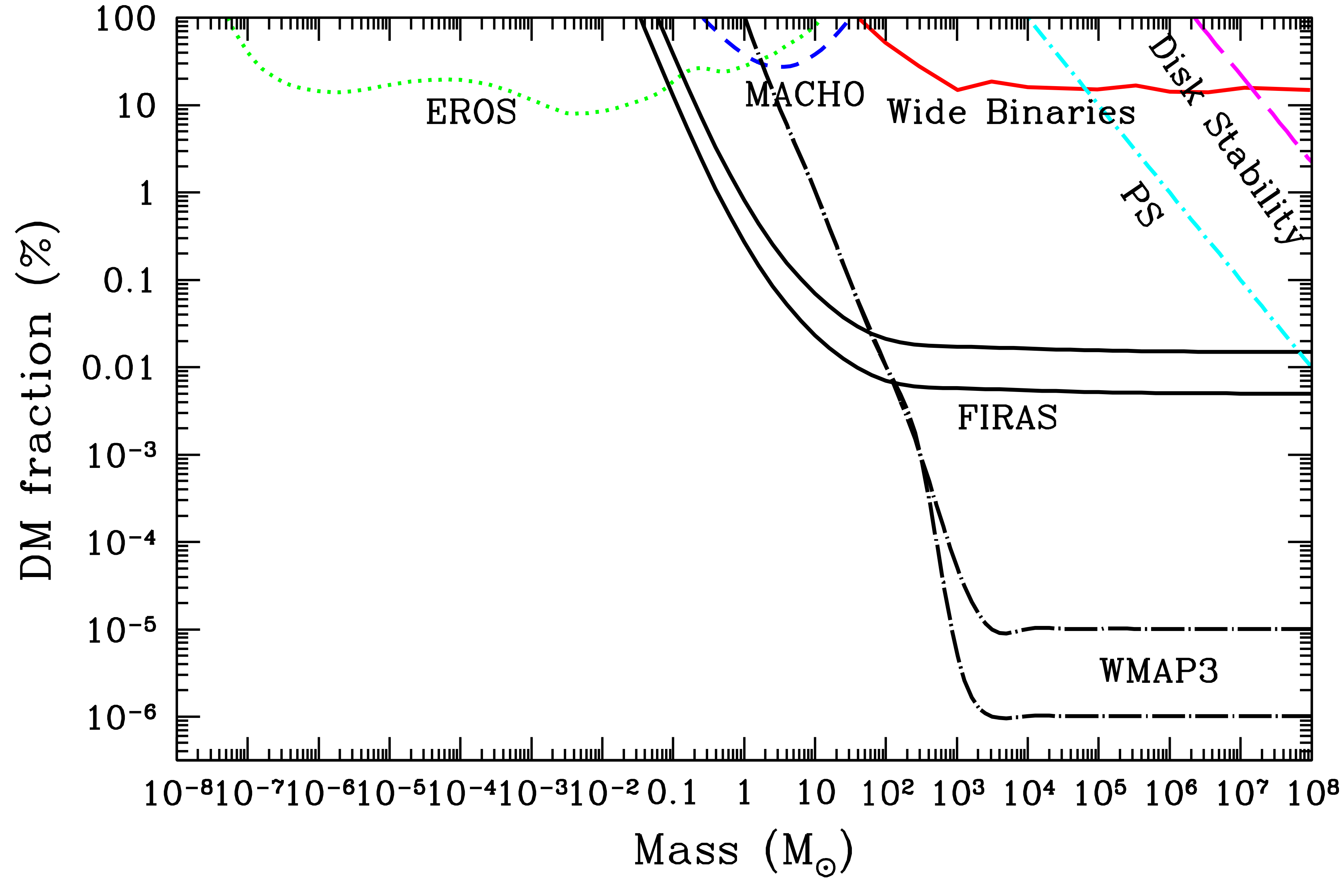
C. Skordis, D. Mota, P. Ferreira, C.Boehm : astro-ph/0505519



Impossible to explain Planck 2015!

Once upon a time in a DM-free world

Black Holes 0709.0524v1



A fraction of PBH is possible but one still needs a collisionless fluid.

Back to basics

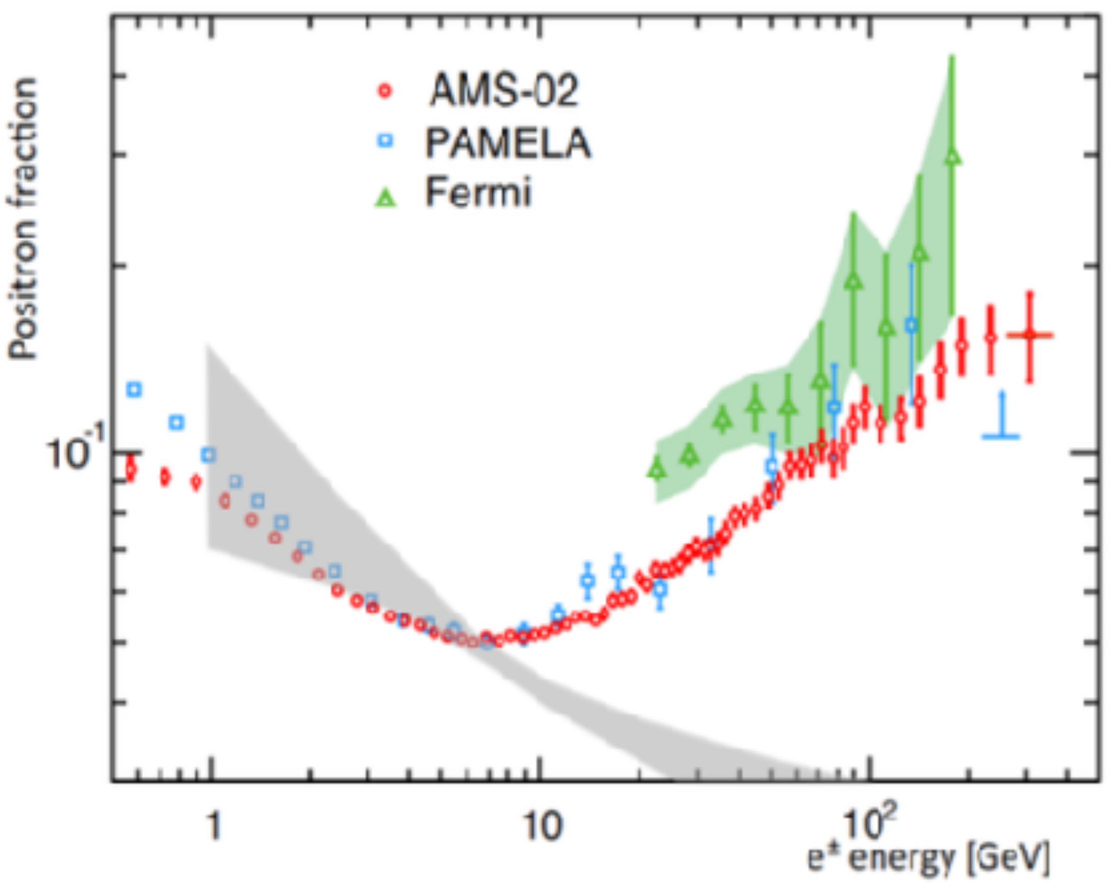
The real proof of DM comes from astrophysics/cosmology

natural colliders: AGNs > 10 TeV

but many anomalies and DM is always a good fit!

AMS 02

perhaps not so DM after all...



1702.08436

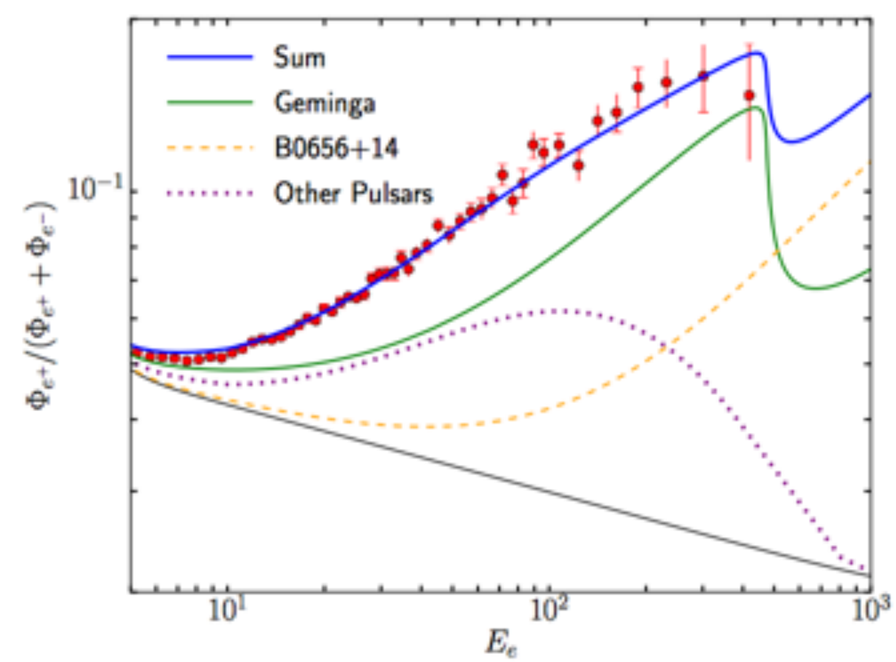


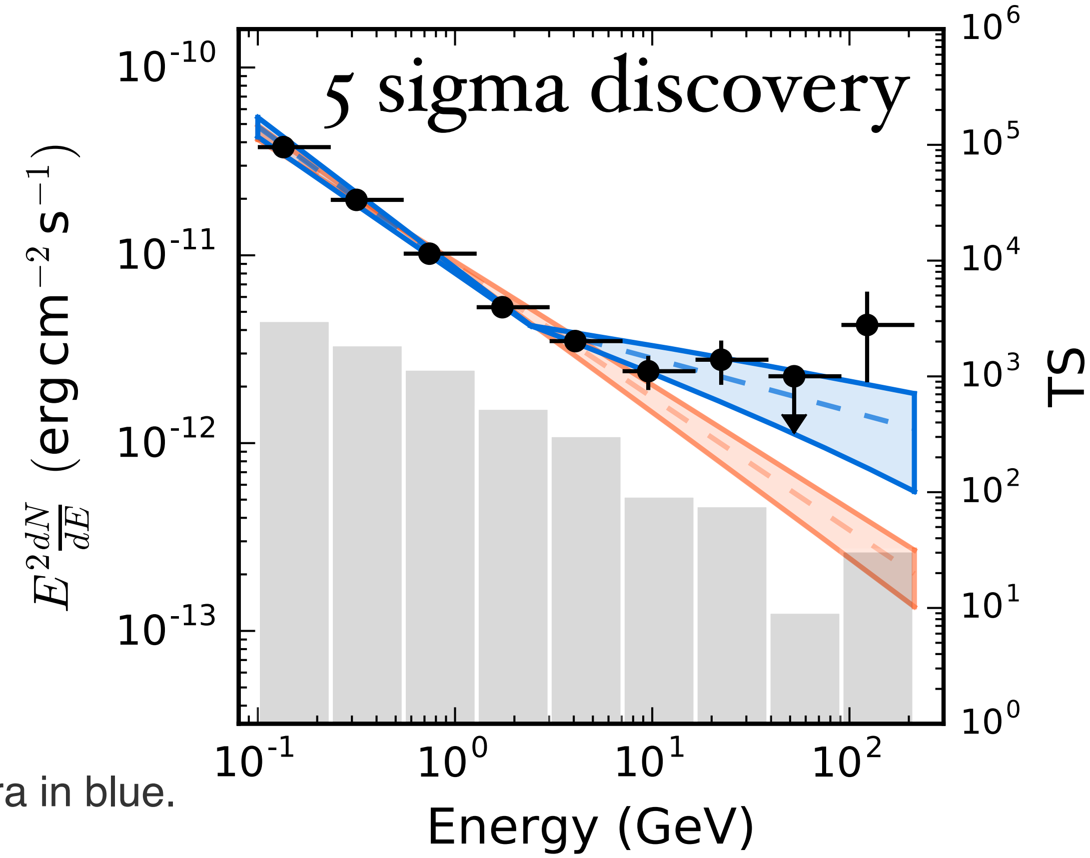
Figure 6. As in Fig. 5, but showing contributions from Geminga, B0656+14, and from all pulsars more than 0.5 kpc from the Solar System. For each source, we adopted $\alpha = 1.9$, $E_c = 49$ TeV, $v_c = 554$ km/s $\times (r_{\rm region}/10\,{\rm pc})$, and normalized their contributions with $\tau = 4.3 \times 10^3$ years, adopting a total birth rate of two pulsars per century in the Milky Way. While we expect many of these parameters to vary from pulsar-to-pulsar, making a detailed prediction of this kind difficult and possibly unreliable, this calculation provides significant support for the conclusion that a sizable fraction of the observed positron excess originates from pulsars.

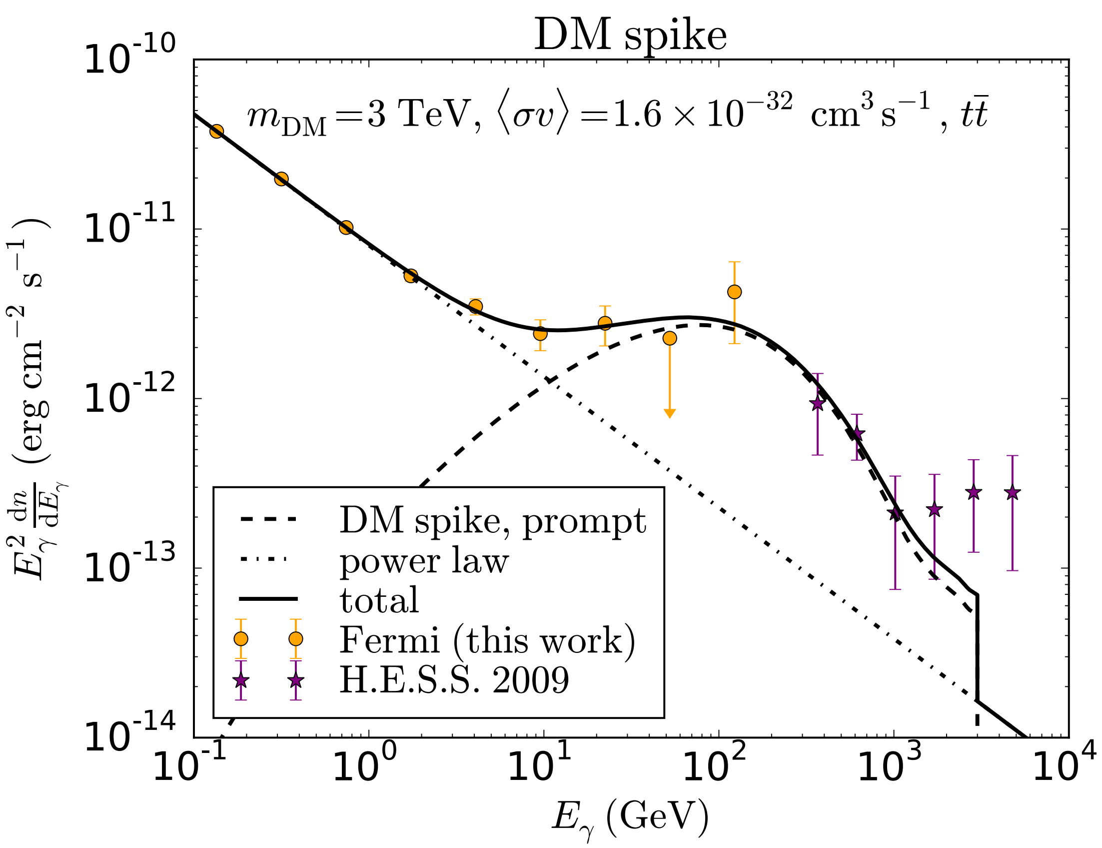
Centaurus A

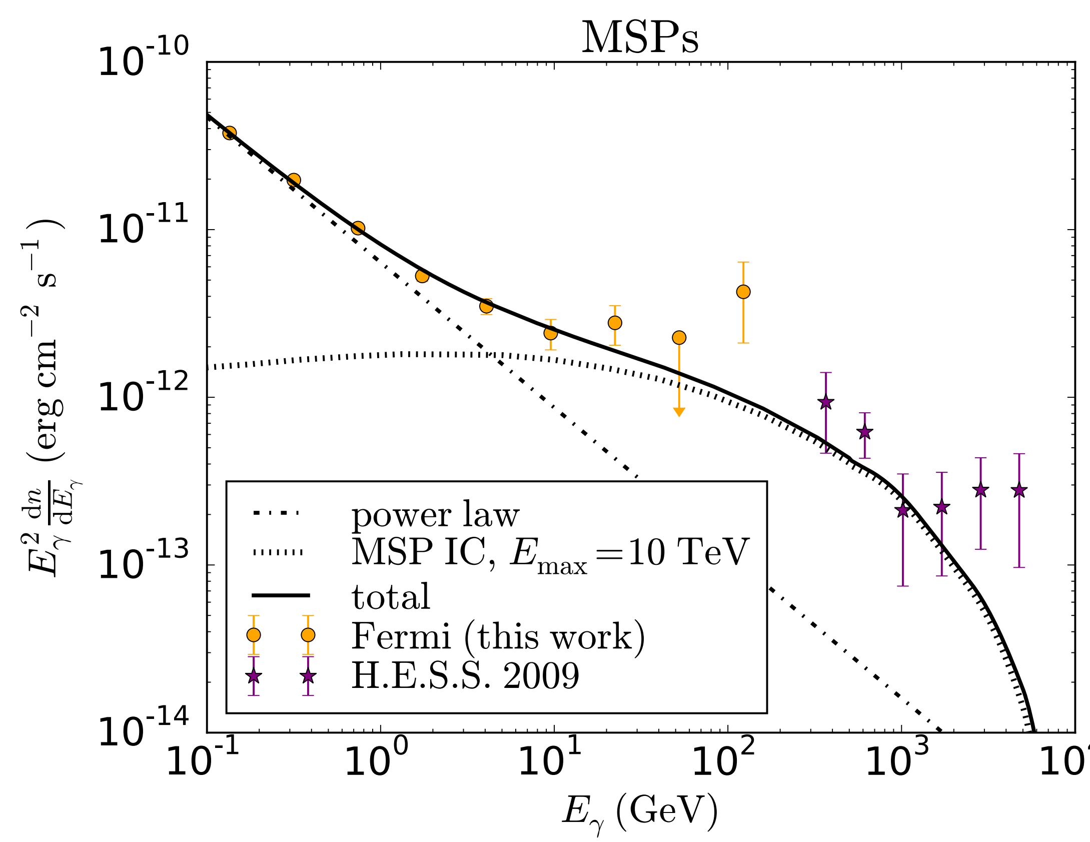
1603.05469

3-5 Mpc away

870-micron data from LABOCA on APEX in orange. X-ray data from Chandra in blue.
Visible light data from the Wide Field Imager (WFI) in "true colour".



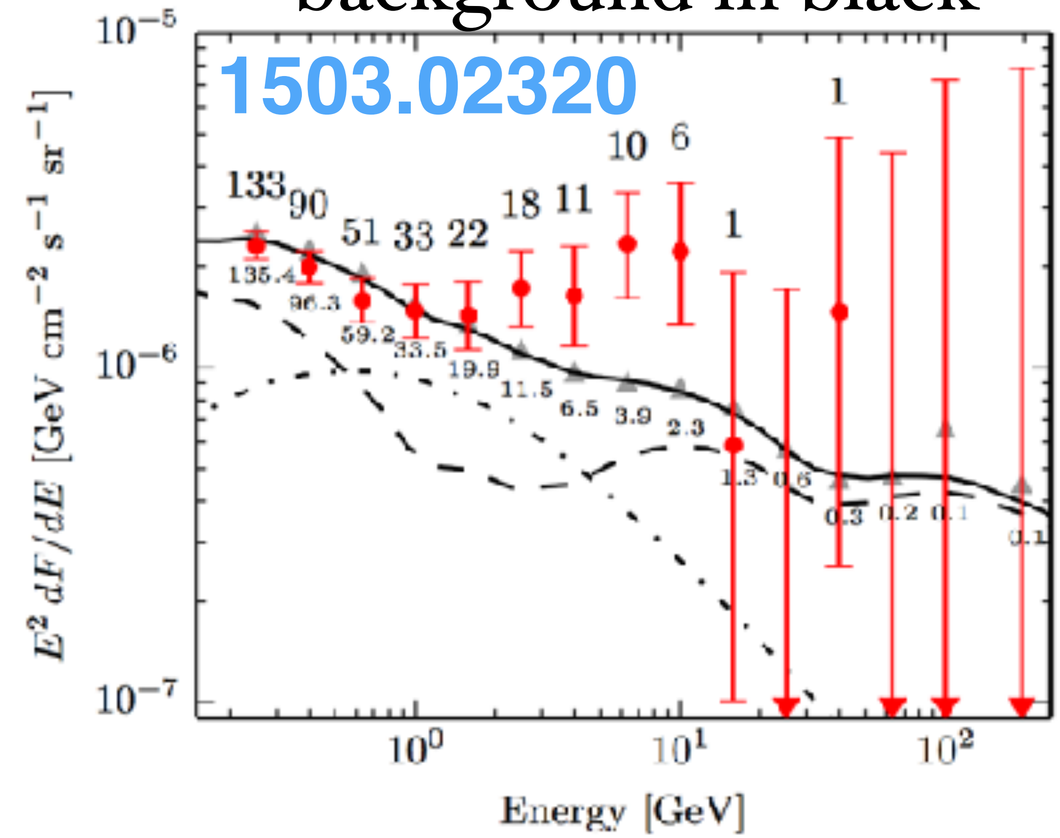




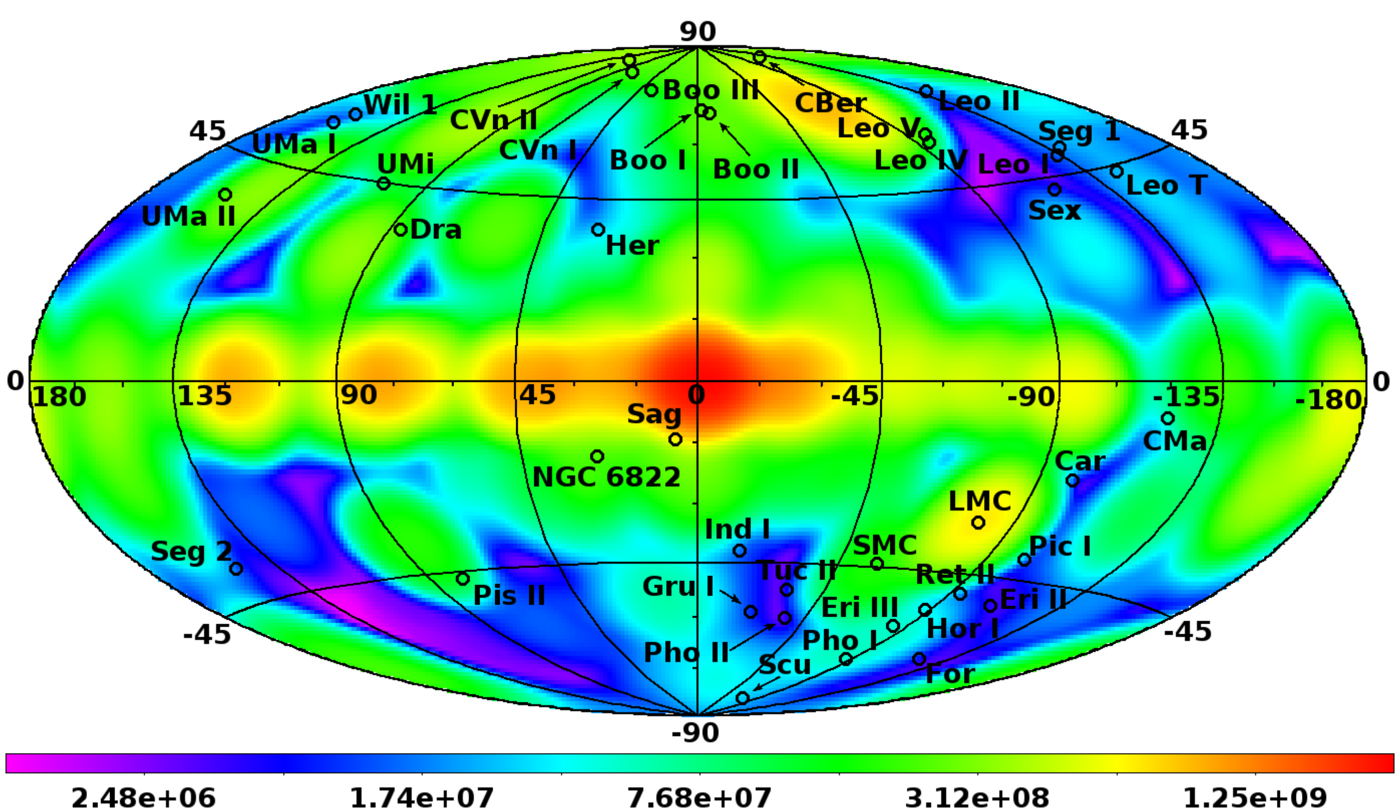
Reticulum II (?)

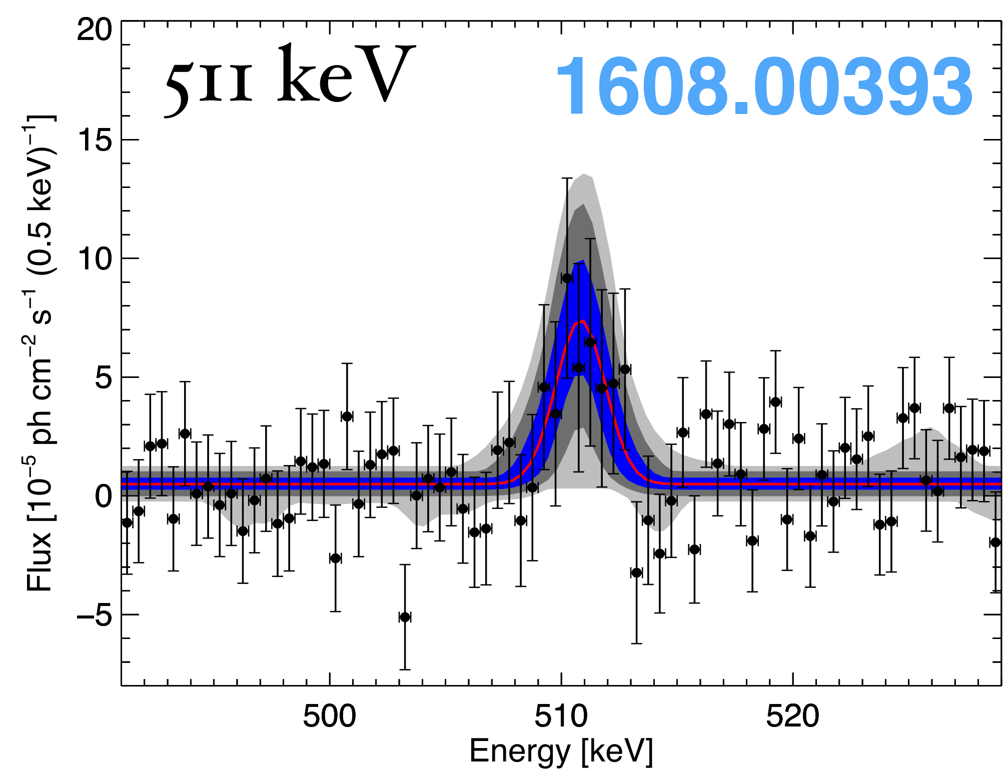
Excess of gamma-ray
in the GeV range but also
at 511 keV...

background in black



Integral/SPI exposure map
Courtesy: T. Siegert





Can we discriminate DM from astro sources?

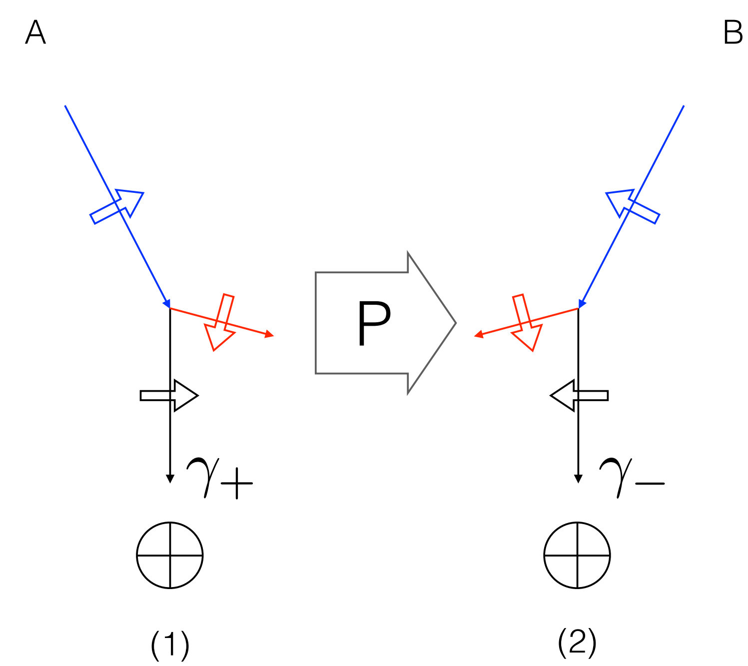
Circular polarisation

$$\epsilon_1^\mu(k) = (0,1,0,0)$$
$$\epsilon_2^\mu(k) = (0,0,\frac{k_z}{|k_z|},0).$$

$$\epsilon_\pm^\mu(k) = \frac{1}{\sqrt{2}}(\mp\epsilon_1^\mu - i\epsilon_2^\mu)$$

At process level : needs an excess of + over - or vice versa

arXiv:1701.02754



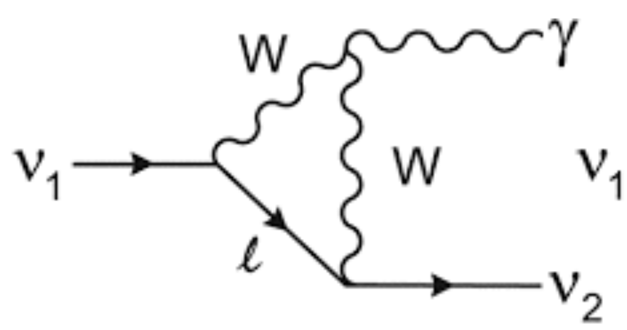
If P violation, then one state may be dominant.

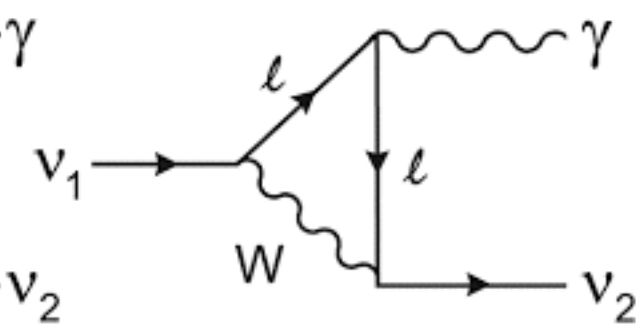
Processes with gamma_5 are promising

In the Universe : needs P and CP violation

Asymmetry in number densities

Check with neutrino decay





$$\mathcal{A}(\nu_i \to \nu_j \gamma) = -i\sigma^{\mu\nu}\epsilon_\mu q_\nu (\mu_{ij} + i\varepsilon_{ij}\gamma_5)$$

$$\begin{matrix}\mu_{ij} \\ i\varepsilon_{ij}\end{matrix} = -\frac{3eG_f}{32\sqrt{2}\pi^2}(m_{\nu_i} \pm m_{\nu_j}) \sum_{l=e,\mu,\tau} U_{il}^\dagger U_{lj}\left(-2 + \frac{m_l^2}{m_W^2}\right).$$

$$\boxed{\Gamma(\nu_i \to \nu_j \gamma) = \frac{1}{8\pi}\left(\frac{m_{\nu_i}^2 - m_{\nu_j}^2}{m_{\nu_i}}\right)^3 \left(|\mu_{ij}|^2 + |\varepsilon_{ij}|^2\right)}$$

$$\frac{\Gamma(\nu_i \to \nu_j \gamma_+)}{\Gamma(\nu_i \to \nu_j \gamma)} = \frac{|\mu_{ij} - i\varepsilon_{ij}|^2}{2\left(|\mu_{ij}|^2 + |\varepsilon_{ij}|^2\right)} = \frac{m_{\nu_i}^2}{m_{\nu_j}^2 + m_{\nu_i}^2}$$

$$\frac{\Gamma(\nu_i \to \nu_j \gamma_-)}{\Gamma(\nu_i \to \nu_j \gamma)} = \frac{|\mu_{ij} + i\varepsilon_{ij}|^2}{2\left(|\mu_{ij}|^2 + |\varepsilon_{ij}|^2\right)} = \frac{m_{\nu_j}^2}{m_{\nu_j}^2 + m_i^2}$$

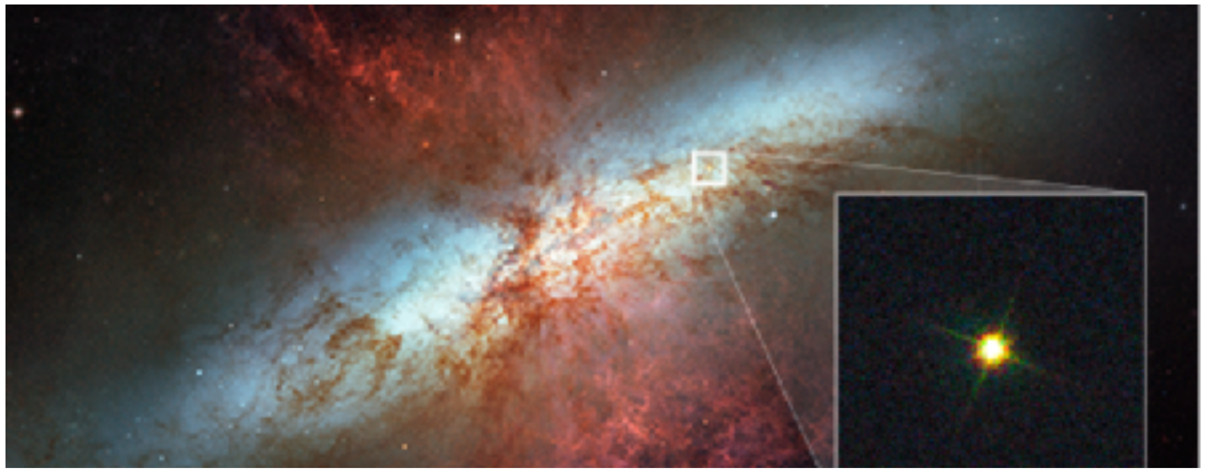
$$\boxed{\begin{aligned} m_{\nu_1} &= 8.5 \times 10^{-4}\ \text{eV} \\ m_{\nu_2} &= 8.7 \times 10^{-3}\ \text{eV} \\ m_{\nu_3} &= 5.016 \times 10^{-2}\ \text{eV}\end{aligned}}$$

$$\Gamma(\nu_3 \to \nu_1\gamma_+)/\Gamma(\nu_3 \to \nu_1\gamma) = 0.99$$

$$\Gamma(\nu_3 \to \nu_2\gamma_+)/\Gamma(\nu_3 \to \nu_2\gamma) = 0.96$$

circular polarisation! Almost 100%

SM Neutrino decay



HST composite image of a supernova explosion SN 2014J in M82,
at a distance of approximately 11.5 million light-years from Earth.
Using a ground-based telescope, the explosion was discovered on Jan 21, 2014.
The photograph was taken on January 31, as the SN approached its peak brightness

$$\phi_{\nu_i \to \nu_j \gamma_\pm} = \frac{\dot{n}_{\nu,0}}{4\pi D^2} f_i \left(1 - e^{-\frac{m_{\nu_i}}{E_\nu}\frac{D}{c}\Gamma_{\nu_i \to \nu_j \gamma_\pm}}\right)$$

$$\phi_{\nu_i \to \nu_j \gamma_\pm} \simeq \phi_{\nu,0} \frac{m_{\nu_i}}{E_\nu} \frac{D}{c} f_i \, \Gamma_{\nu_i \to \nu_j \gamma_\pm}$$

fi = fraction of neutrino "i"

circular polarisation!

Net circular polarisation

$$\phi^{\nu_i}_{\gamma,pol} = (\xi - \bar{\xi}) \left(\phi_{\nu_i \to \nu_j \gamma_+} - \phi_{\nu_i \to \nu_j \gamma_-}\right)$$

$$\phi^{\nu_i}_{\gamma,pol} = \phi_{\nu,0} \frac{m_{\nu_i}}{E_\nu} \frac{D}{c} f_i \, \Delta_{CP} \, \Gamma_{\nu_i,pol}$$

$$\phi^{\nu_i}_{\gamma,pol} \simeq 10^{16} f_i \, \Delta_{CP} \left(\frac{m_{\nu_i}}{\mathrm{eV}}\right) \left(\frac{\Gamma_{\nu_i,pol}}{s^{-1}}\right) \; ph \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}.$$

$$\Delta_{CP} = (\xi - \bar{\xi})$$
$$\xi = n_{\nu_i}/(n_{\nu_i} + n_{\bar{\nu}_i})$$
$$\bar{\xi} = n_{\bar{\nu}_i}/(n_{\nu_i} + n_{\bar{\nu}_i})$$

SM & BSM neutrino decay

$$\phi^{\nu_i}_{\gamma,pol} \simeq 10^{16} f_i \, \Delta_{CP} \left(\frac{m_{\nu_i}}{\mathrm{eV}}\right) \left(\frac{\Gamma_{\nu_i,pol}}{s^{-1}}\right) \; ph \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}.$$

for a 10 kpc SN emitting a MeV neutrino flux $\phi_{\nu,0} \sim 10^{10} \ \mathrm{cm}^{-2} \ \mathrm{s}^{-1}$

$$\Gamma_{\nu_i,pol} = (\Gamma_{\nu_i \to \nu_j \gamma_+} - \Gamma_{\nu_i \to \nu_j \gamma_-}) \quad \longrightarrow \quad \Gamma_{\nu_i,pol} = \Gamma_{\nu_i \to \nu_j \gamma_+}$$

"Standard Model" (massive) neutrinos

$$\Gamma(\nu_3 \to \nu_2 \gamma) = 1.27 \times 10^{-51} \ s^{-1}$$

So the corresponding flux is invisible ...
unless the source produces a huge amount of neutrinos

But if we allow for new Physics, we can expect fluxes of

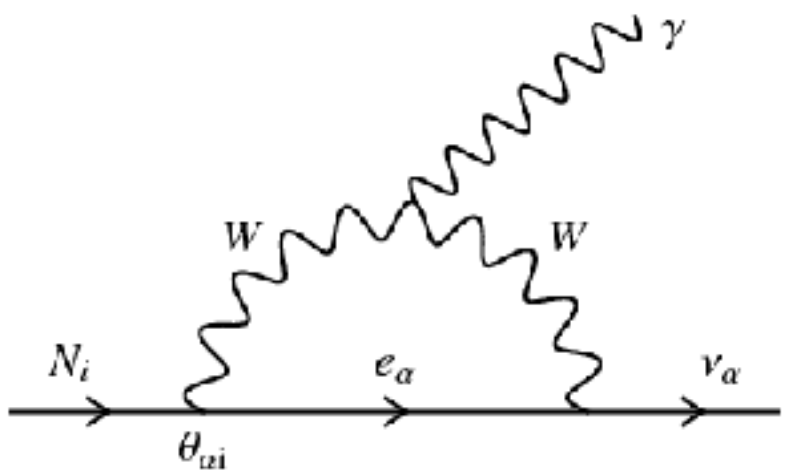
If we request the decay rate to be < 10-17/s

$$\phi^{\nu_i}_{\gamma,pol} < 2 \times 10^{-2} \left(\frac{m_{\nu_i}}{\mathrm{eV}}\right) \; ph \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$$

Back to DM: sterile neutrino decay

(was the object of 1610.04532 though no estimates)

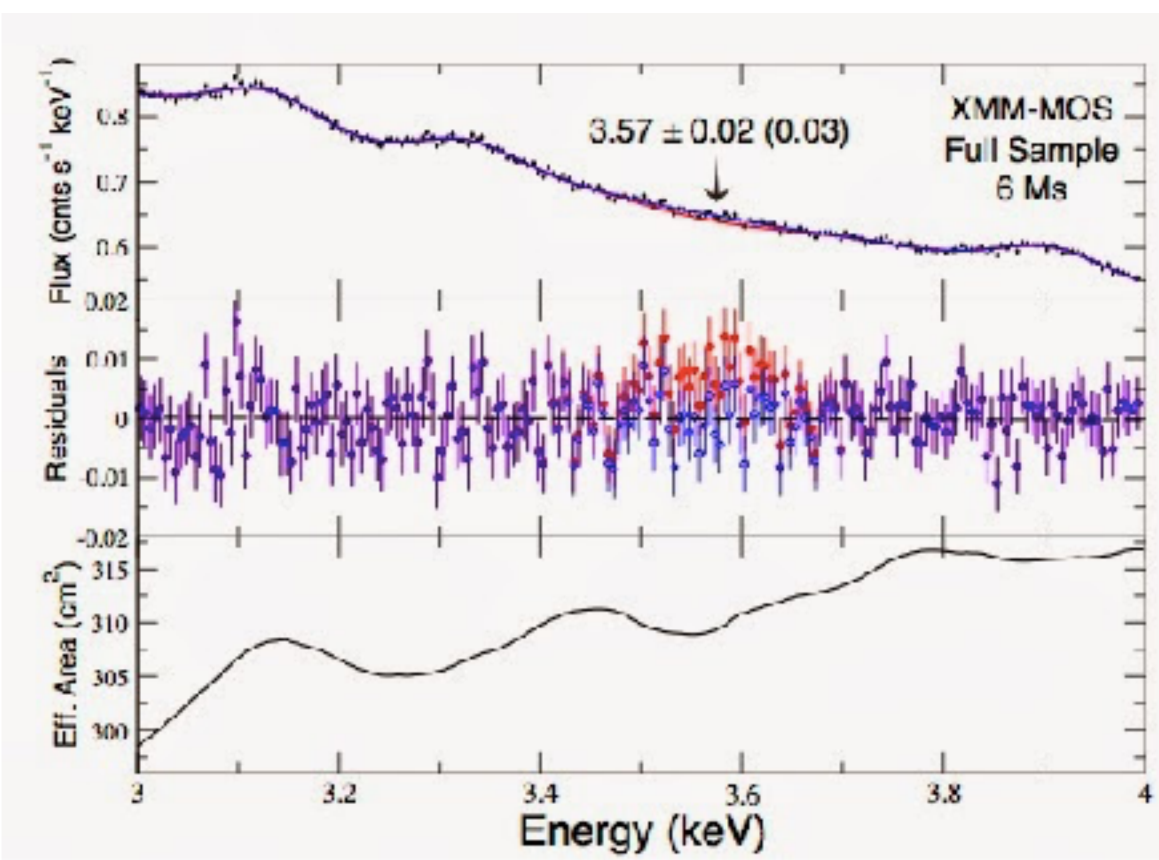
Sterile neutrinos **(Gravitinos etc)**

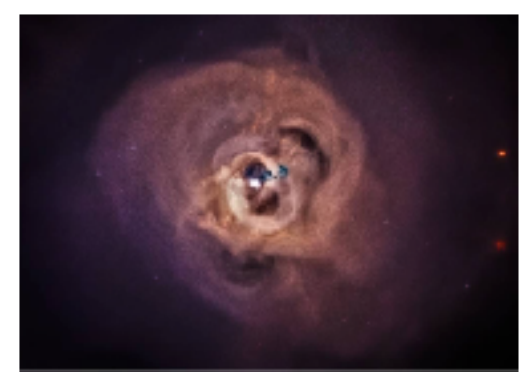


$$E_\gamma = \frac{m_{sterile\ \nu}}{2}$$

7 keV line

seen in Perseus cluster (+ in few others)
but Hitomi did not see the line



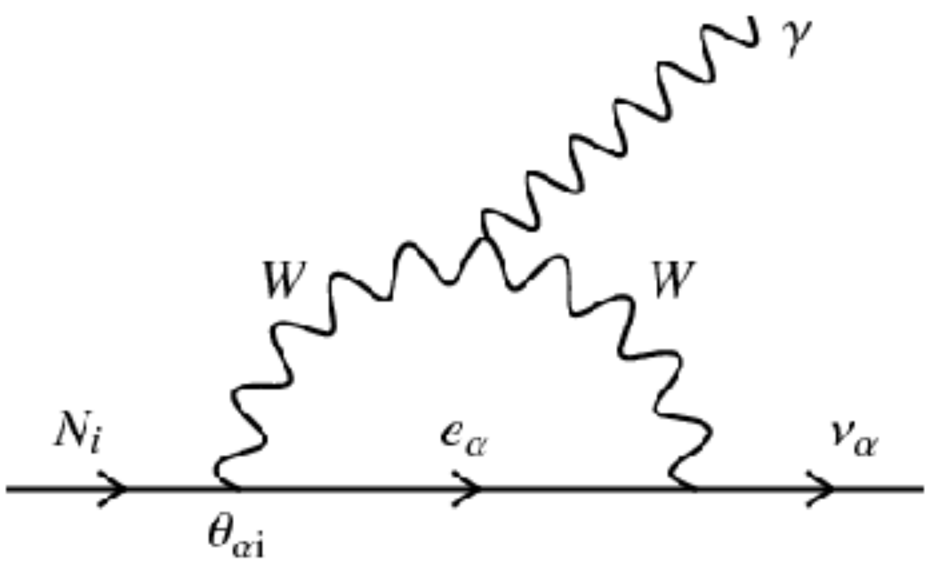


3.5 keV ~ Potassium (Bananas ...)

arxiv.org/pdf/1409.4143v1
arxiv.org/abs/1408.1699v1

Back to DM: sterile neutrino decay

(was the object of 1610.04532 though no estimates)



$$\Gamma_{\nu_s} = 1.38 \times 10^{-30} \left(\frac{\sin^2(2\theta)}{10^{-8}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^5 \ \mathrm{s}^{-1}$$

$$\phi_{pol} = \Delta^{\nu_s}_{CP} \, \Gamma_{\nu_s} \int_{FoV} d\Omega \int ds(r) \, \frac{\rho_{\mathrm{DM}}(r)}{m_{\mathrm{DM}}} (1+z)^{-1}$$

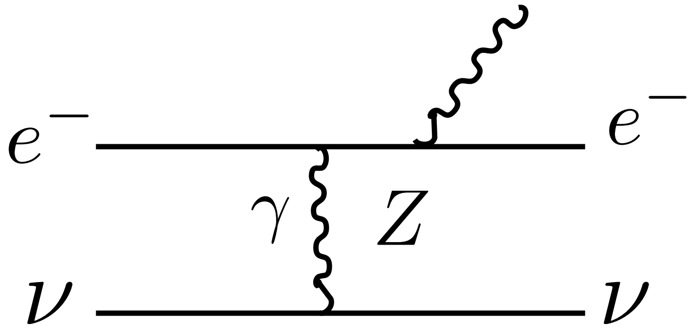
100% circular polarisation

For Perseus and a 7 keV sterile neutrino z=0.0179, rs = 164/h kpc, d=70 Mpc

$$\Gamma_{\nu_s} \simeq 1.63 \ 10^{-28} \mathrm{s}^{-1} \qquad \sin^2(2\theta) \sim 7 \times 10^{-11}$$

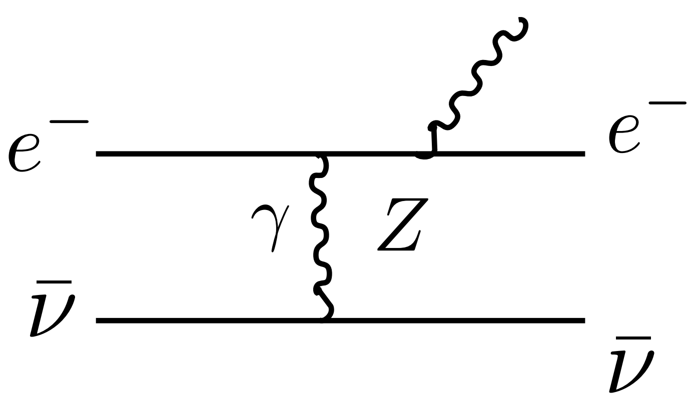
$$\boxed{\phi^{Perseus}_{pol,\ 3.5keV} \sim \ 10^{-6} \ \Delta^{\nu_s}_{CP} \ \ ph \ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

Application 3: neutrinos scattering off electrons



same with e+ and anti-nu
(muon neutrino here)

$\sqrt{S}$	cross-section	γ_+ (%)	γ_- (%)	net pol (%)	$E_{\min}$ (γ)
1 TeV	1.0 pb	43	57	-14.1 ± 1.2	100 GeV
1 TeV	3.1 pb	47	53	-6.3 ± 1.2	10 GeV
1 TeV	5.3 pb	48	52	-3.2 ± 1.2	1 GeV
100 GeV	0.35 pb	36	64	-28.5 ± 1.2	10 GeV
100 GeV	1.19 pb	44	56	-11.2 ± 1.2	1 GeV
10 GeV	0.0052 pb	34	66	-32.7 ± 1.2	1 GeV
10 GeV	0.0185 pb	44	56	-12.6 ± 1.2	0.1 GeV

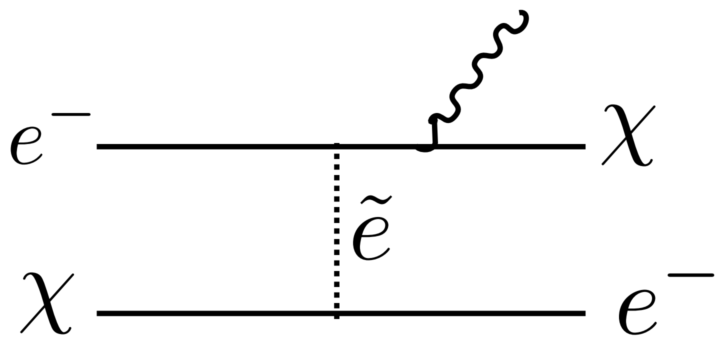


same with e+ and nu

$\sqrt{S}$	Cross section	γ_+ (%)	γ_- (%)	net pol (%)	$E_{\min}(\gamma)$
1 TeV	1.0 pb	54	46	8.8 ± 1.2	100 GeV
1 TeV	3.0 pb	52	48	4.2 ± 1.2	10 GeV
1 TeV	5.1 pb	51	49	2.6 ± 1.2	1 GeV
100 GeV	0.30 pb	55	45	9.8 ± 1.2	10 GeV
100 GeV	1.00 pb	52	48	4.2 ± 1.2	1 GeV
10 GeV	0.0042 pb	59	41	17.2 ± 1.2	1 GeV
10 GeV	0.015 pb	53	47	6.4 ± 1.2	0.1 GeV

we could probe the distribution of neutrinos near astro sources

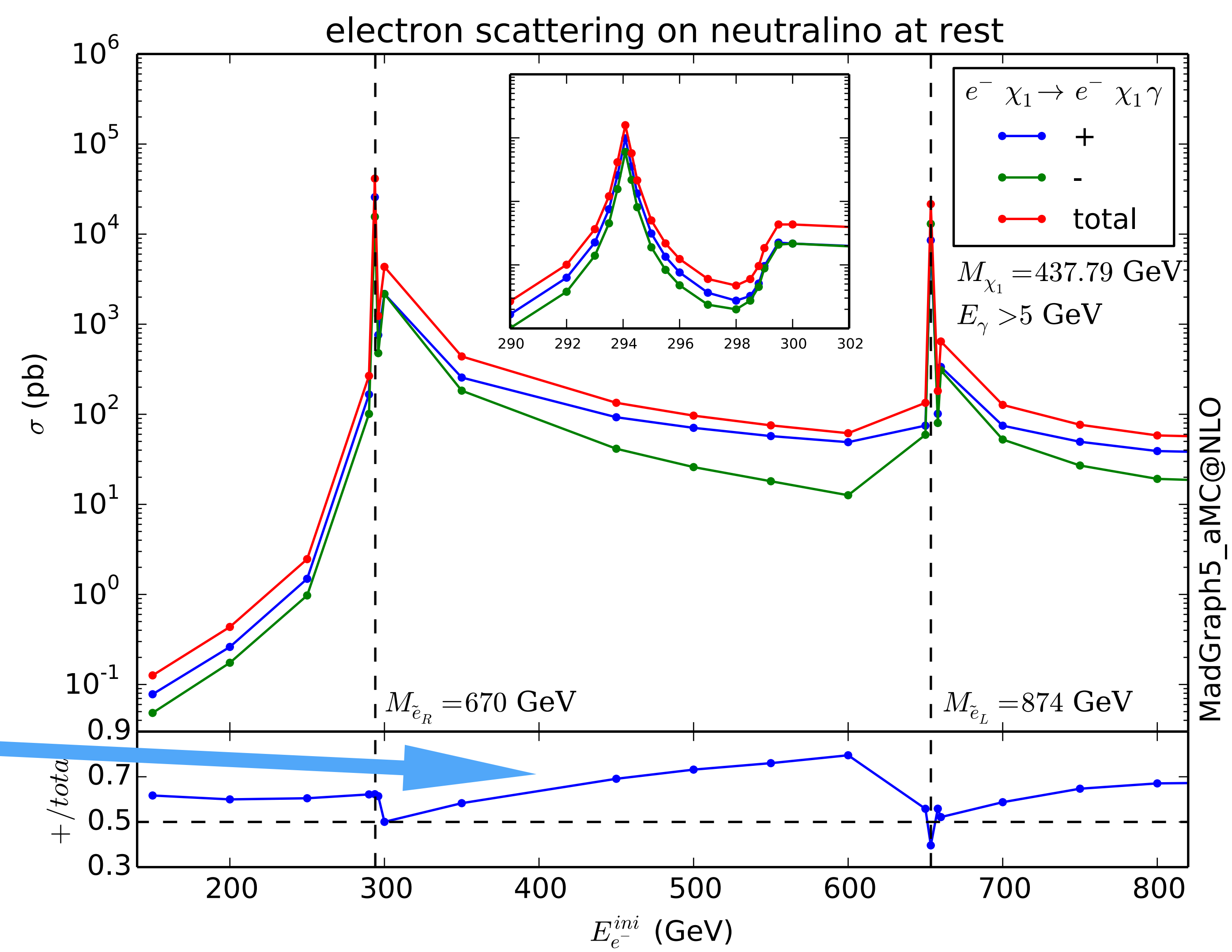
Application 4: dark matter scattering off electrons



selectrons are scalar particles but
their couplings are sensitive to electron chirality

One also expects the generation of a circular polarisation

$$
\begin{aligned}
sign(\mu) &> 0 \\
m_0 &= 550 \text{ GeV} \\
m_{1/2} &= 1020 \text{GeV} \\
\tan\beta &= 19.16 \\
A_0 &= -2878 \text{GeV}
\end{aligned}
$$

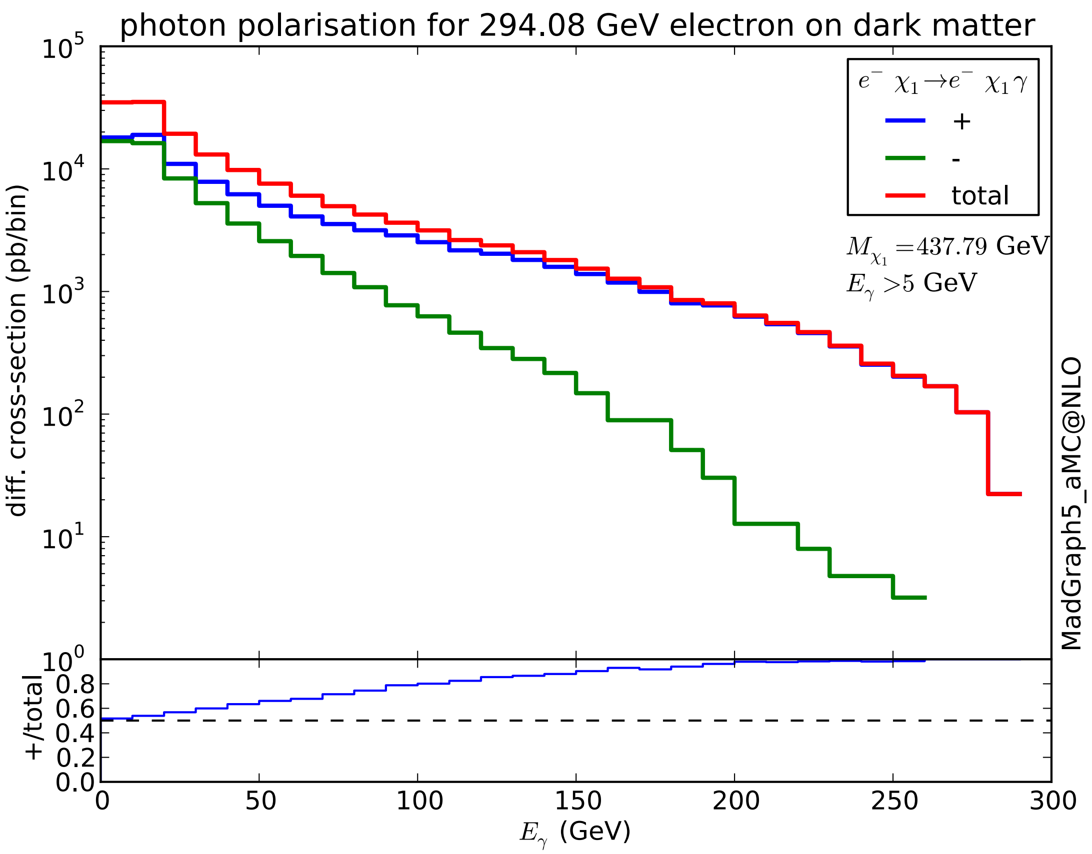


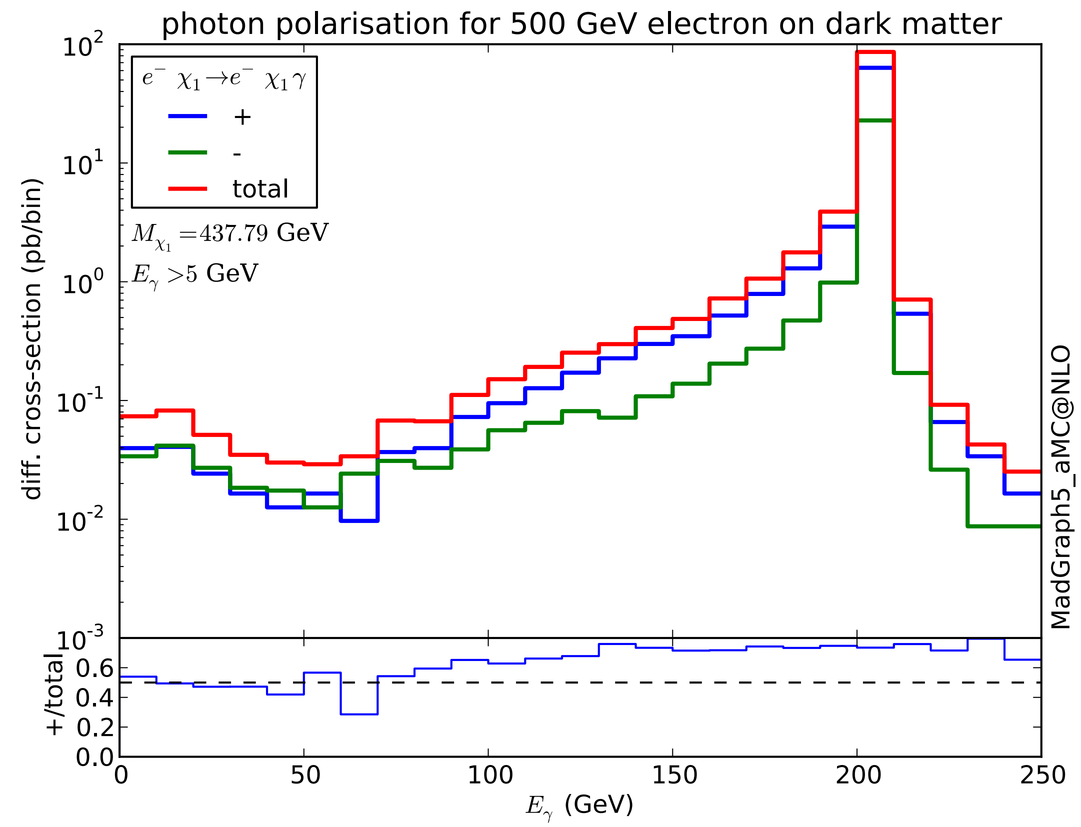
Polarisation signal is there

providing that the number of positrons
is not as high as that of electrons!

Application 4: dark matter scattering off electrons

Photon spectrum for a fixed electron energy

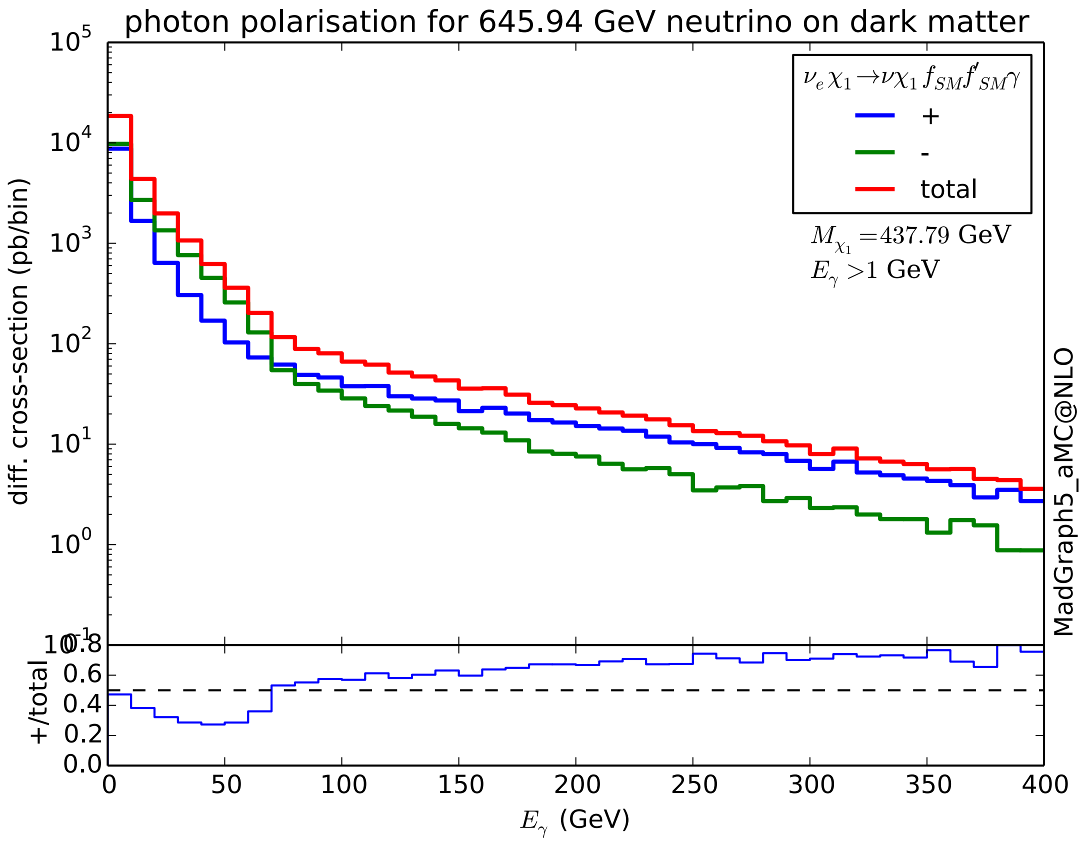




Because the photon energy spectra are so different we may be able to reconstruct high energy electrons produced in jets and scattering off the DM halo

Application 5: dark matter scattering off neutrinos

$$\chi_0\ \nu_i \to \chi_0\ \nu_j\ f^{\pm}_{SM,i}\ f'^{\mp}_{SM,j}\ \gamma,$$



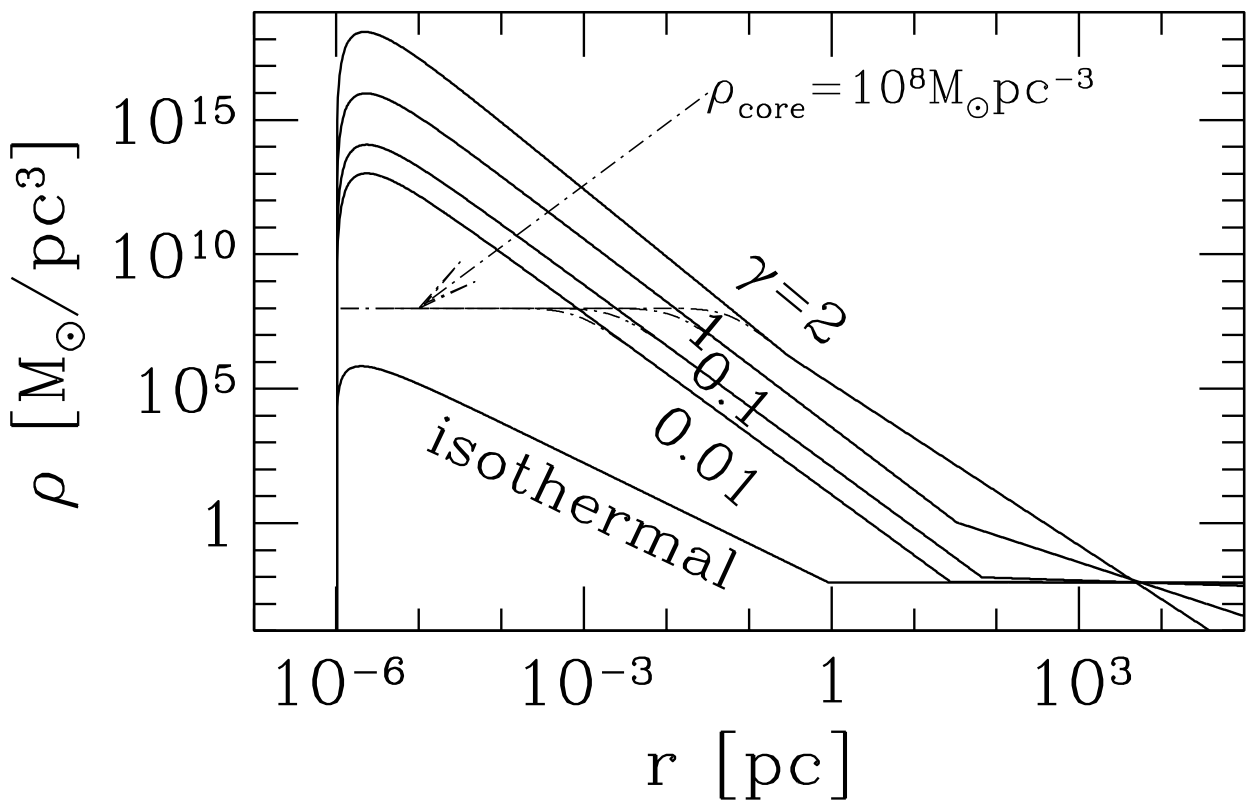
could be applied also to neutrino-DM interactions for "complicated" processes

Many more applications … Exploration phase

Dark Matter
Near Black Holes

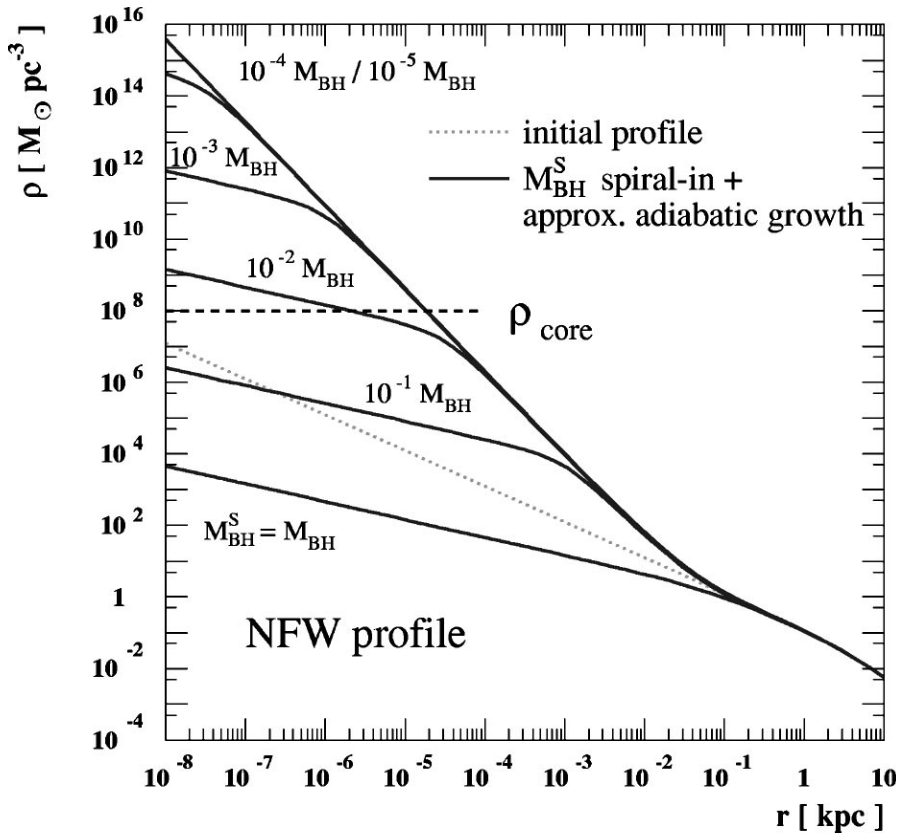
DM accretion near Black Holes

Gondolo&Silk 1999



Strong enhancement of DM profile

Ullio et al 2001



though depends on the BH seeds

Condition of formation of spikes:

- BHs at the center of galaxies can grow adiabatically
- Adiabatic growth

Ipser & Sikivie (1987): isothermal ->r^-3/2,

Gondolo & Silk (1999) : NFW -> 7/3

Spikes in the DM density distribution

Conservation of momentum in adiabatic growth from initial to final state

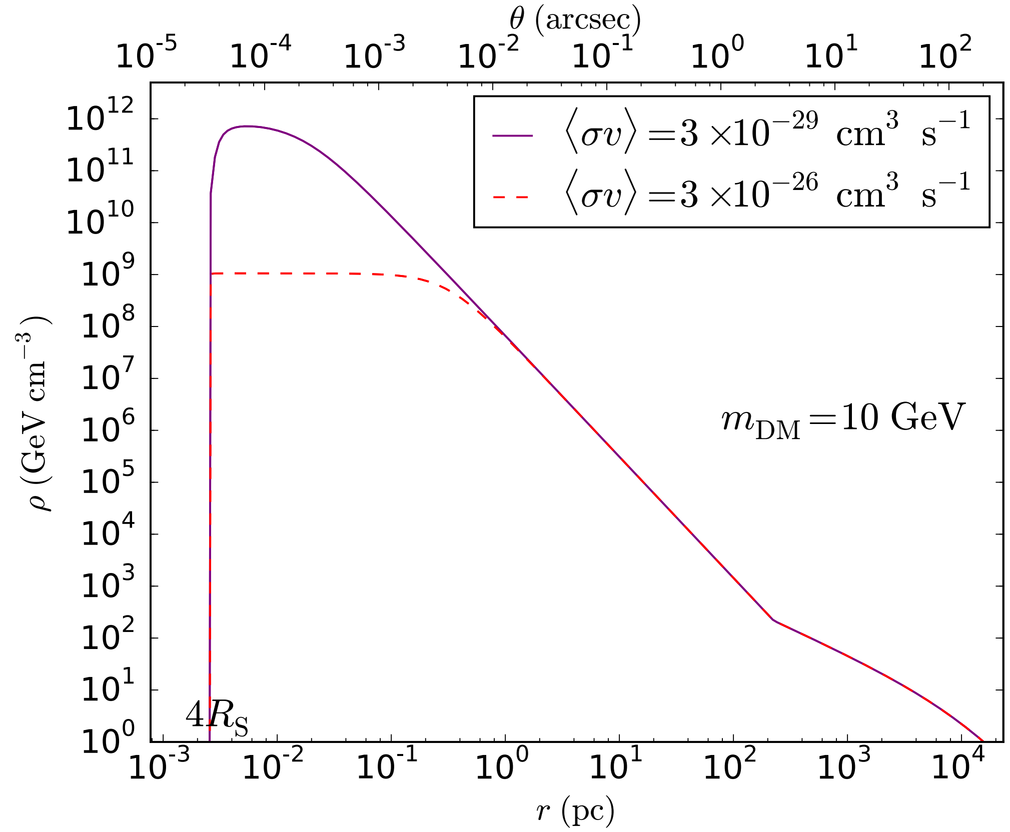
$$r\ v(r) = cst$$

$$v(r) = (GM(r)/r)^{1/2}$$

$$\int_0^{r_\mathrm{i}} \rho_\mathrm{i}(r) r^2\,\mathrm{d}r = \int_0^{r_\mathrm{f}} \rho_\mathrm{f}(r) r^2\,\mathrm{d}r$$

$$\boxed{\gamma_\mathrm{sp} = \frac{9-2\gamma}{4-\gamma}.}$$

NFW: 7/3 inner slope



$$\rho_\mathrm{sat} = \frac{m_\mathrm{DM}}{\langle\sigma v\rangle\, t_\mathrm{BH}}$$

+ spikes can be destroyed by galaxy dynamics.

stellar heating (+ mergers, non adiabatic contraction)

Implication of a DM spike for the Milky Way

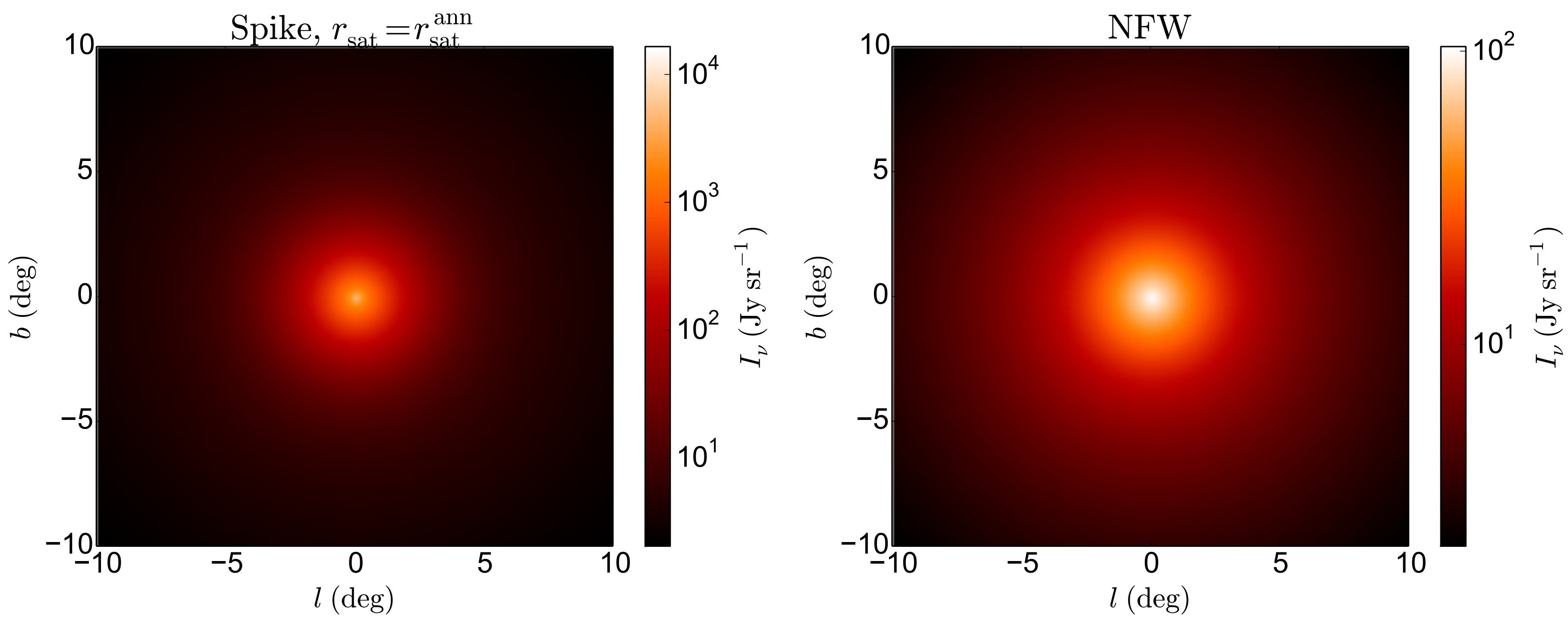
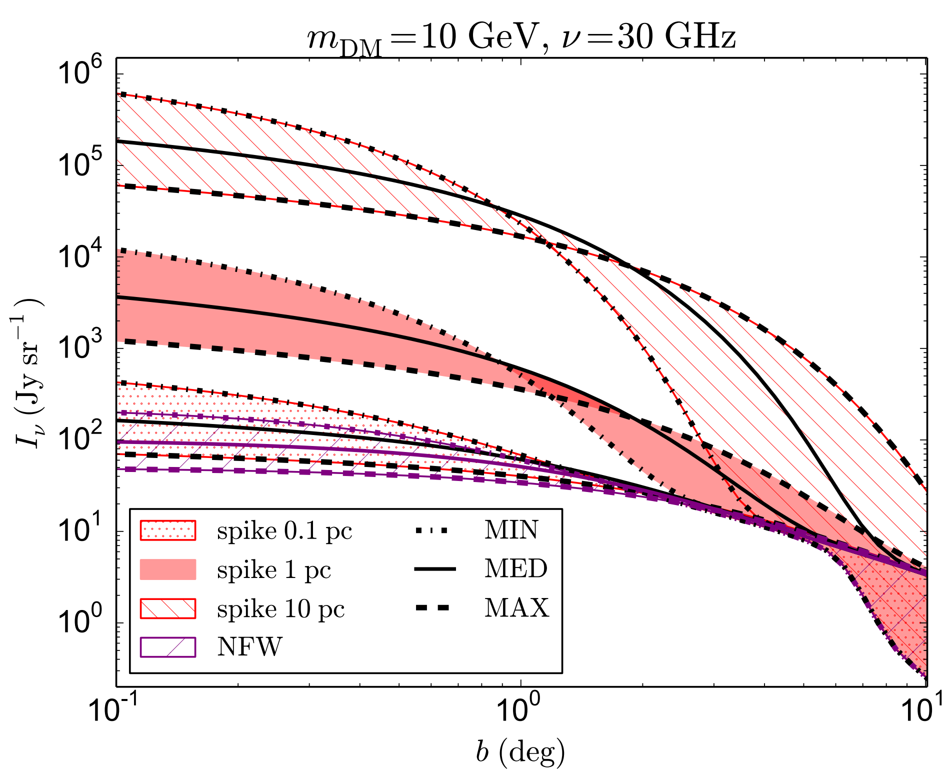
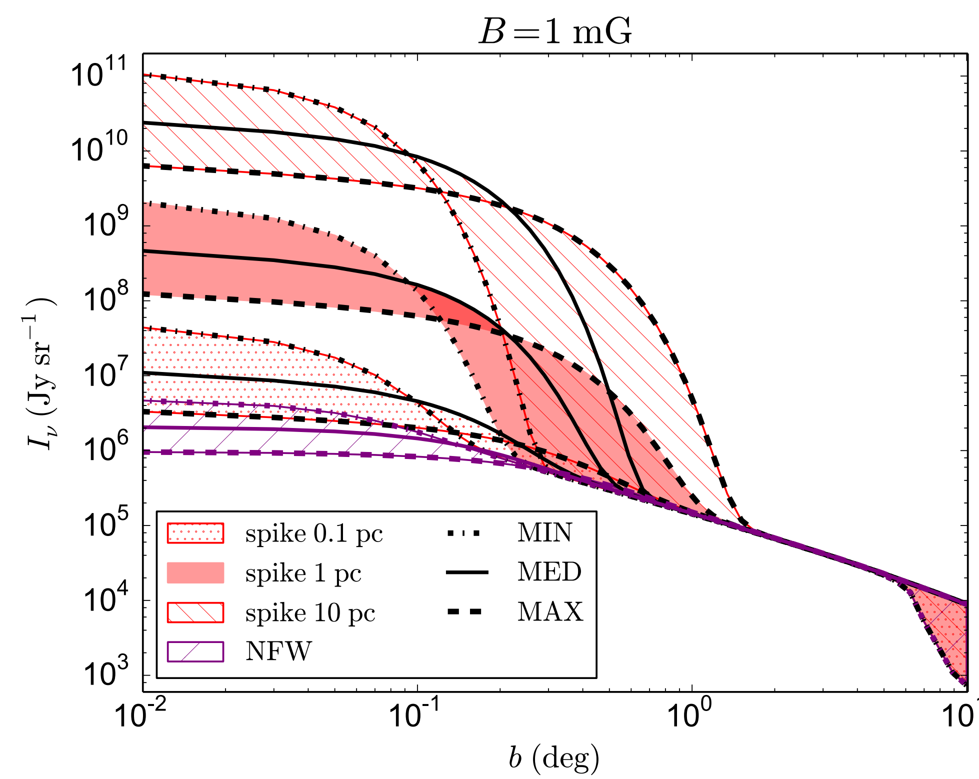


Figure 7.1: 30 GHz maps of the synchrotron intensity induced by 10 GeV DM particles, for $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1}, $B = 3$ μG, and the MED set of propagation parameters. The DM profiles used are a spiky profile with $\gamma_{\mathrm{sp}} = 7/3$, $R_{\mathrm{sp}} = 1$ pc, with $r_{\mathrm{sat}} = r_{\mathrm{sat}}^{\mathrm{ann}}$ (**left panel**), and the NFW profile (**right panel**).

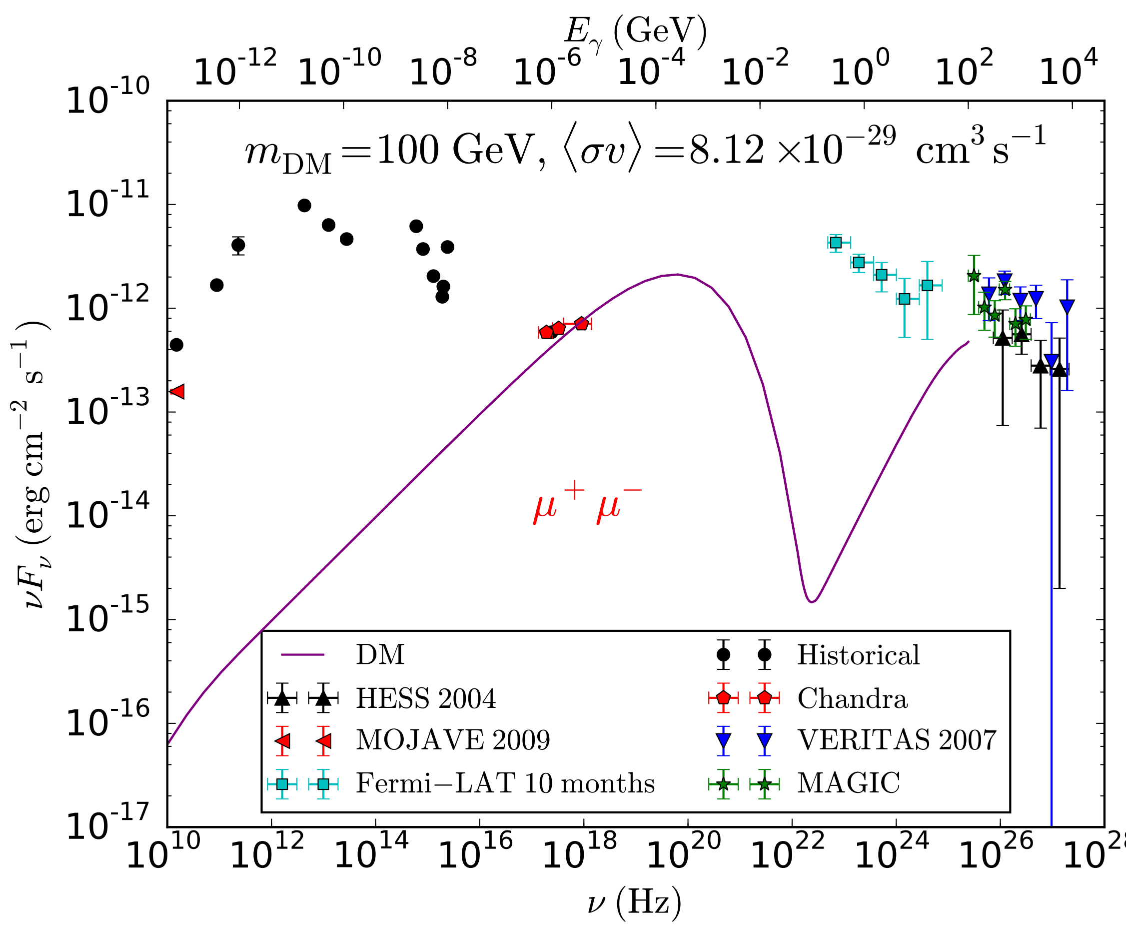


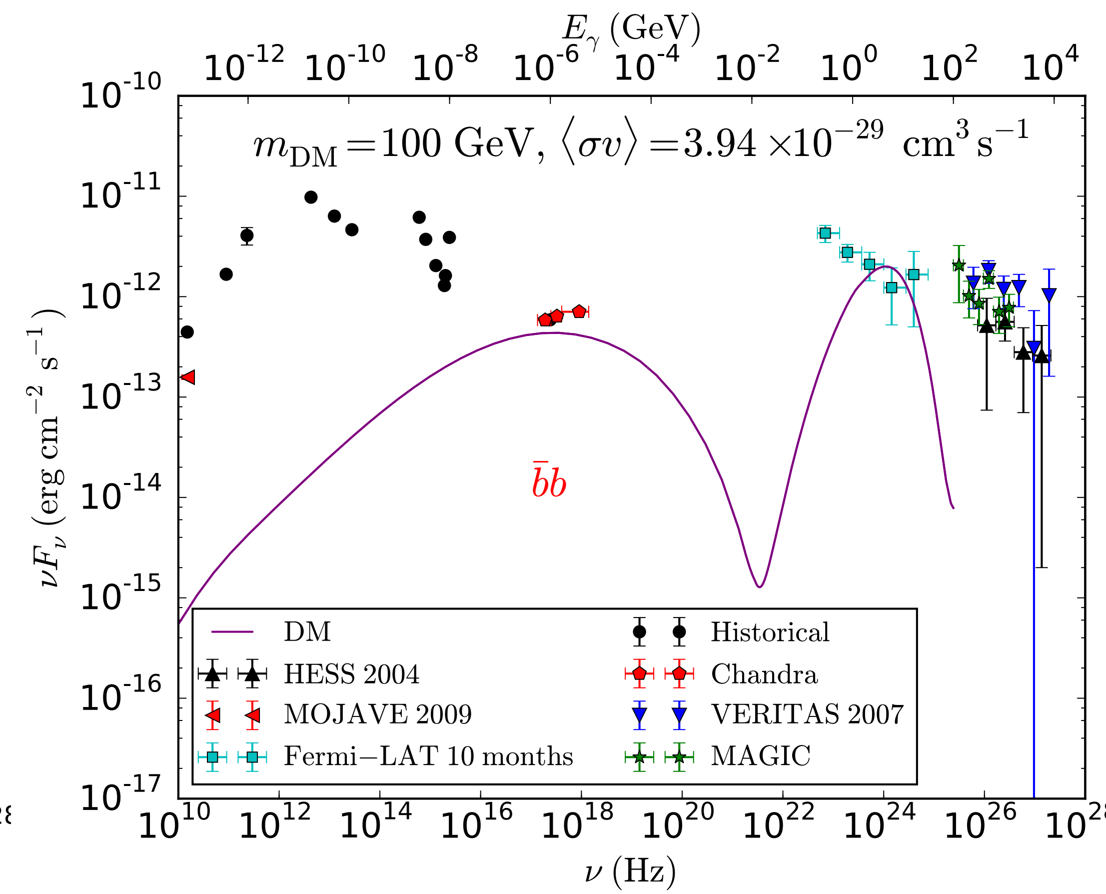


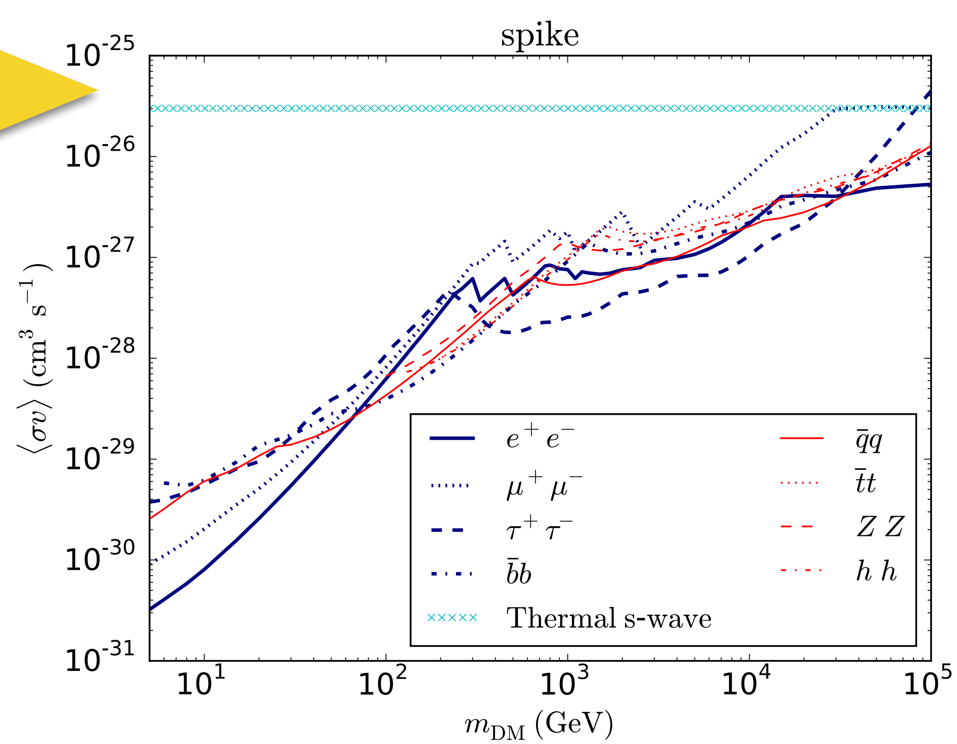
Implications for AGNs M87

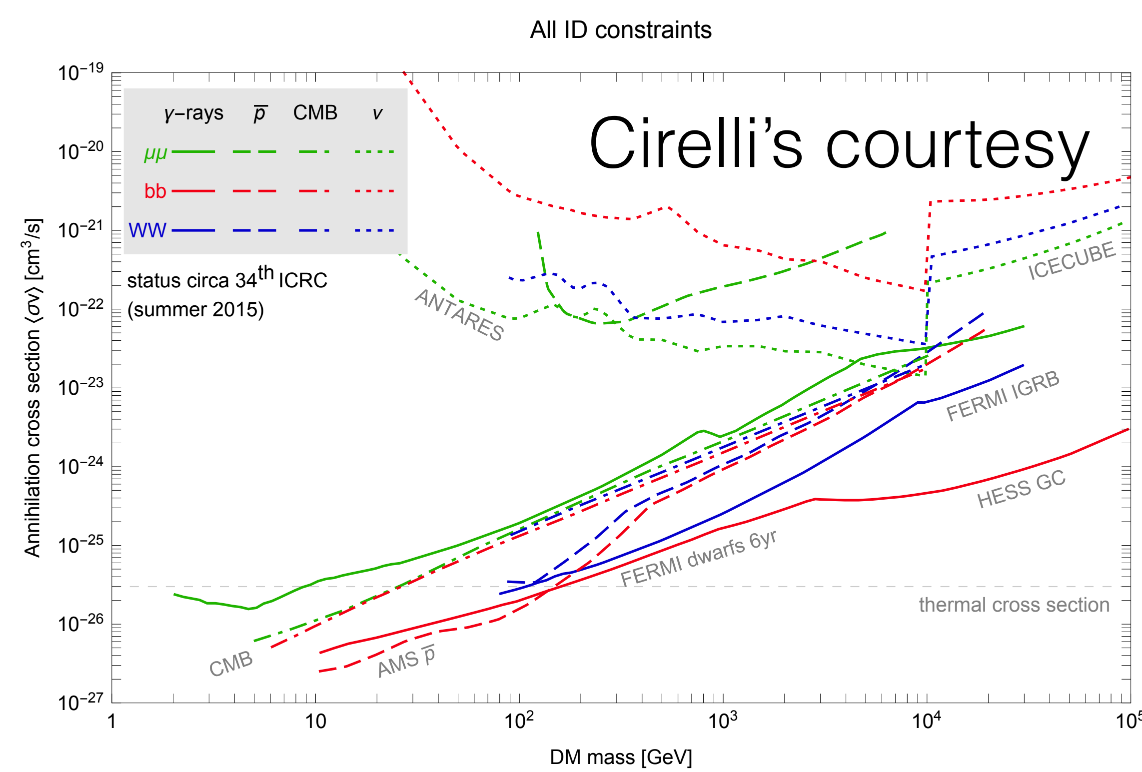
(Virgo, 16 Mpc,~ 200 x heavier than MW)

adiabatic spike with $\rho \propto r^{-7/3}$









Conclusion

"Standard Model" (massive) neutrinos

$$\Gamma(\nu_3 \to \nu_2 \gamma) = 1.27 \times 10^{-51} \ s^{-1}$$

Invisible!

Beyond Standard Model (massive) neutrinos

$$\phi^{\nu_i}_{\gamma,pol} < 2 \times 10^{-2} \left(\frac{m_{\nu_i}}{\text{eV}}\right) \ ph\,\text{cm}^{-2}\,\text{s}^{-}$$

Can help to test new neutrino interactions

Sterile neutrino decay $\phi^{Perseus}_{pol,\ 3.5keV} \sim \ 10^{-6} \ \Delta^{\nu_s}_{CP} \ \ ph \ \text{cm}^{-2}\text{s}^{-1}$

Neutrino and DM scattering off electrons & neutrinos