Searching for spectral features in the γ-ray sky

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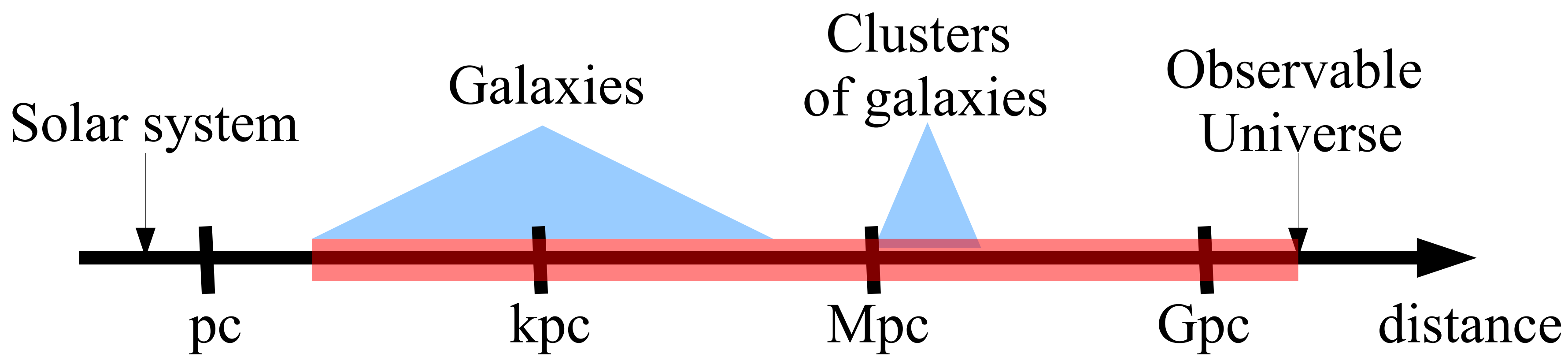
Oslo
5 November 2014

Outline

- Motivation
- Indirect dark matter searches with gamma-rays.
- Overcoming backgrounds
- Gamma-ray spectral features
- A simple model generating spectral features.
- Conclusions

There is evidence for particle dark matter in a wide range of distance scales



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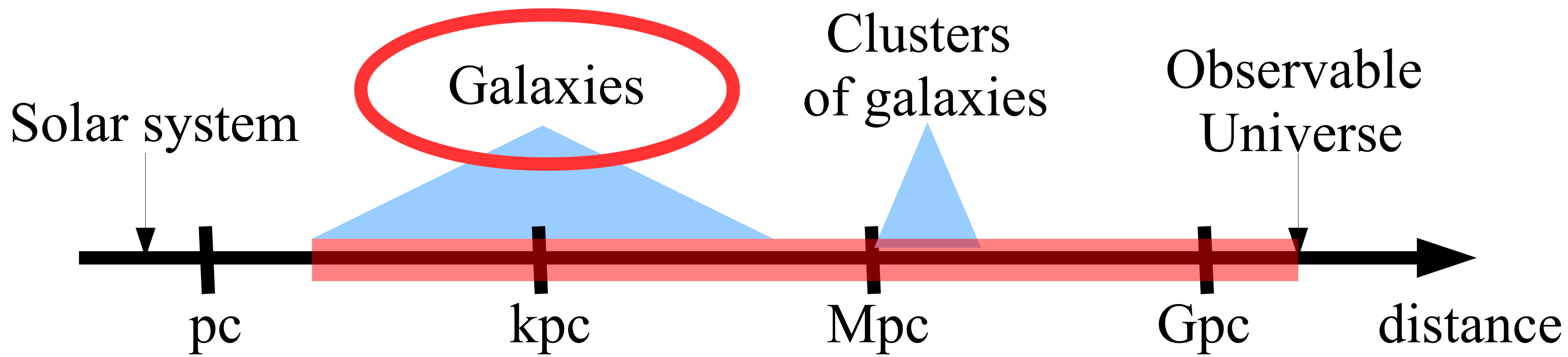

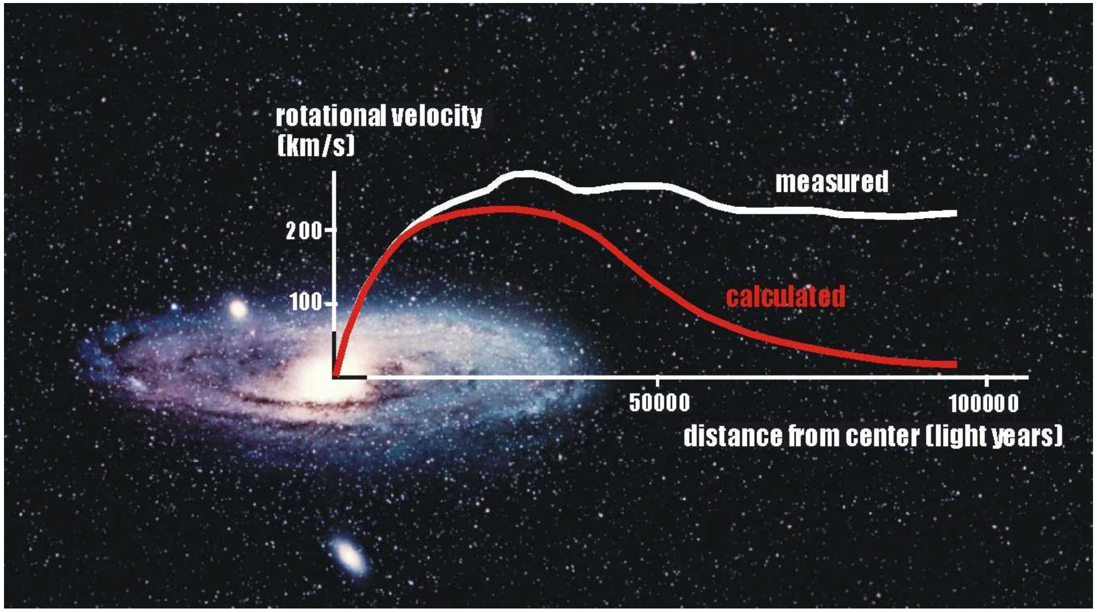

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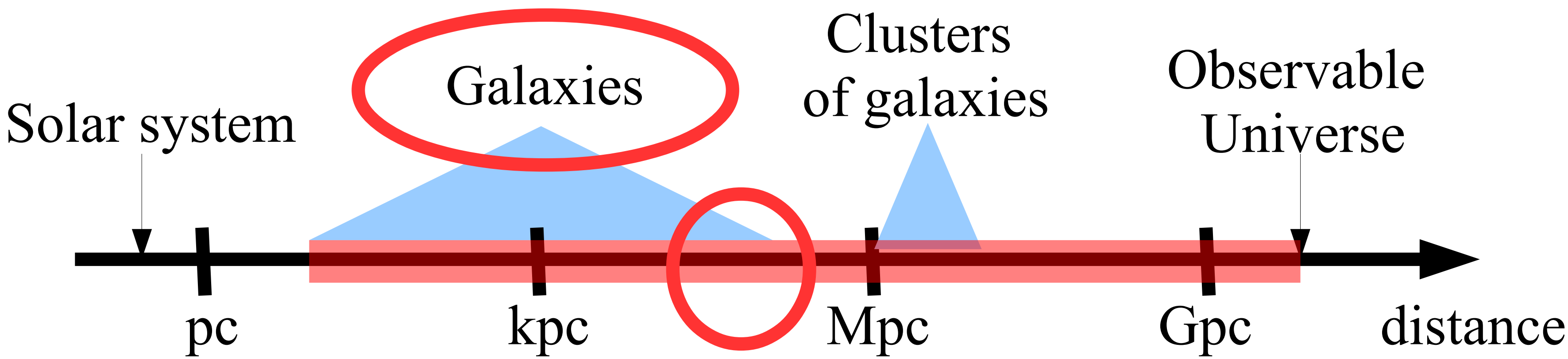

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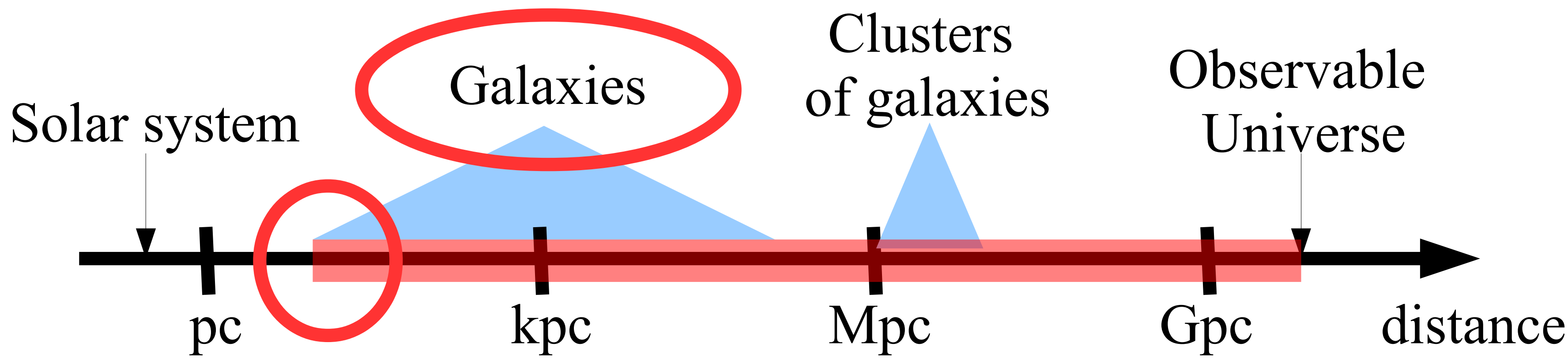

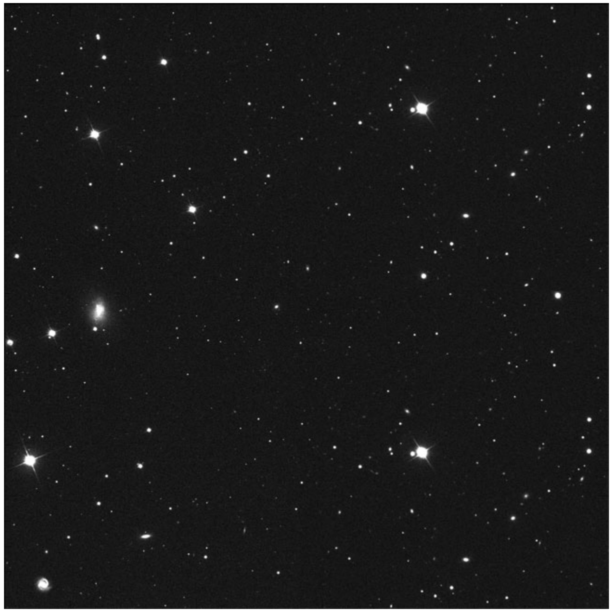

Segue 1 (discovered by the SDSS in 2006)

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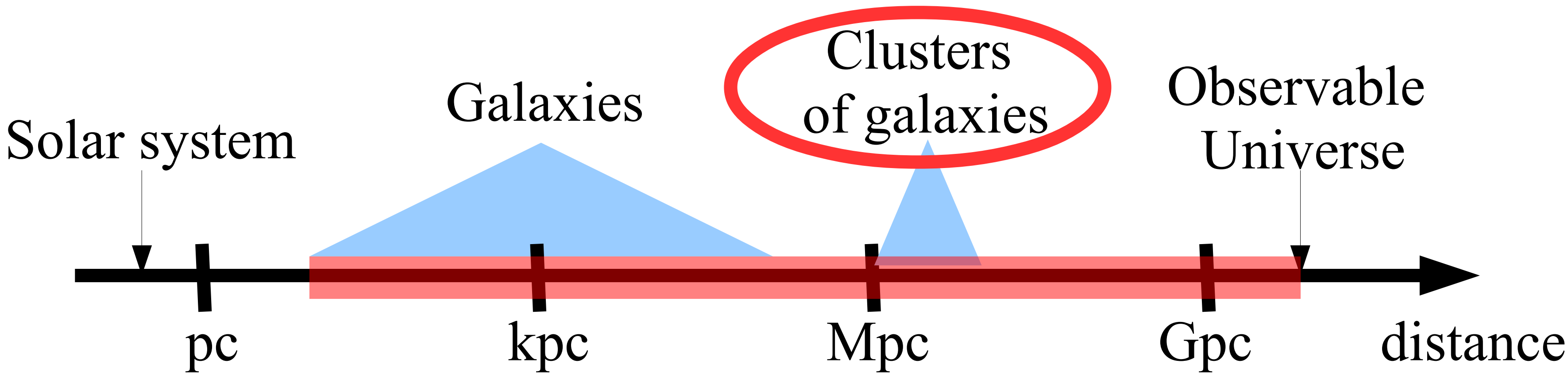

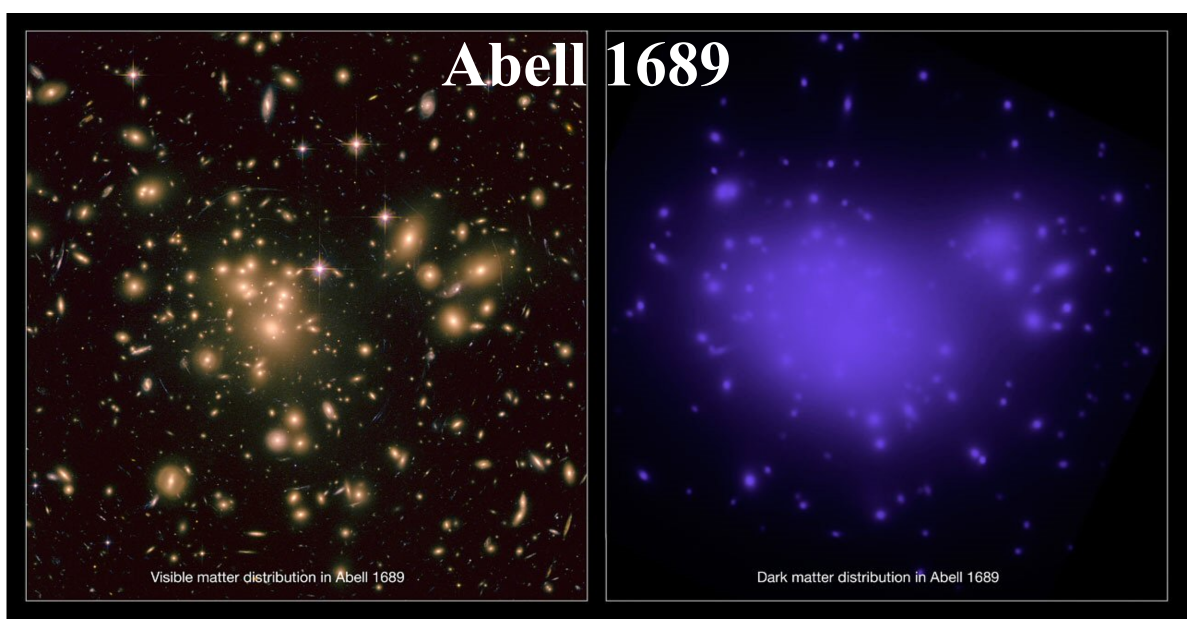

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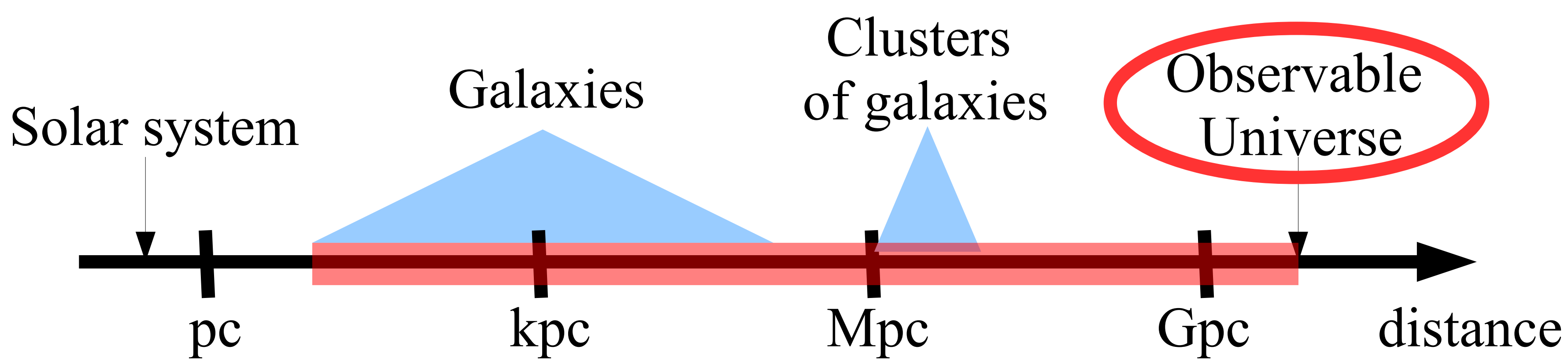

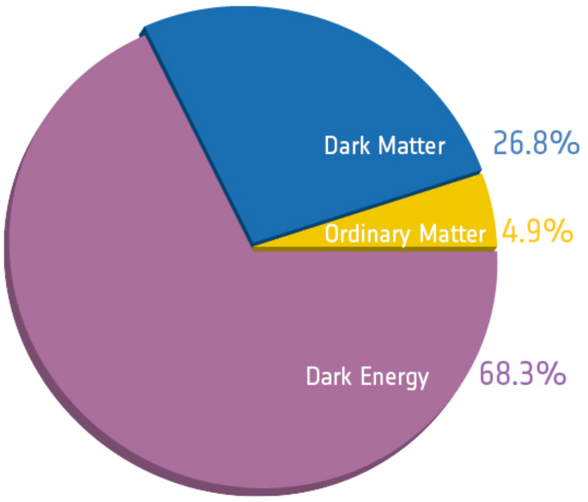

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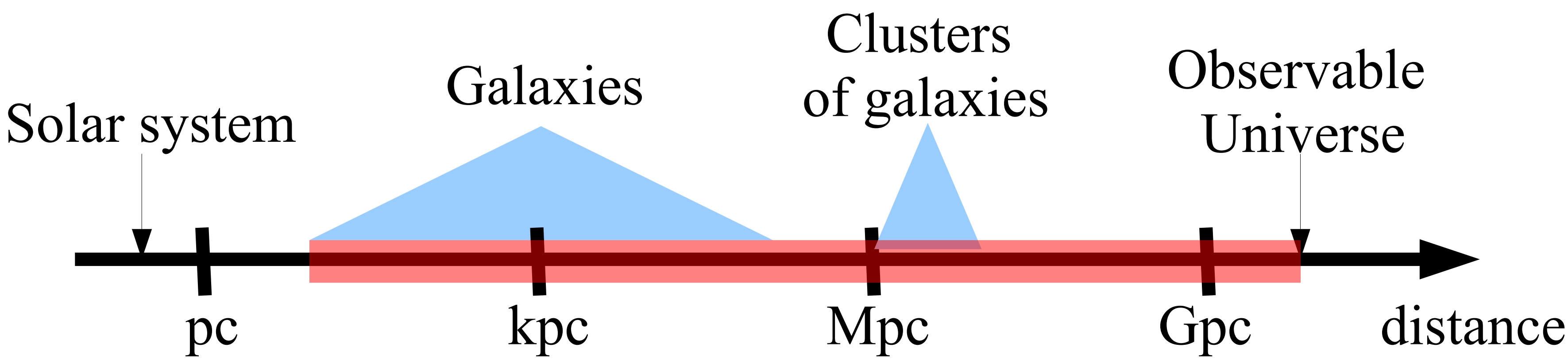

The discovery of the dark matter was one (among the many) great discoveries in Physics of the 20th century.

In fact, it was one of the first particles for which there was evidence:

Electron - Thomson, 1897
Proton - Rutherford, 1919
Neutron - Chadwick, 1932
Positron – Anderson, 1932
First evidence for dark matter - Zwicky, 1933

LIGHT UNFLAVORED MESONS $(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	(2.00 ± 0.25) $\times 10^{-4}$		30
$e^+\nu_e$	[b]	(1.230 ± 0.004) $\times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	(7.39 ± 0.05) $\times 10^{-7}$		70
$e^+\nu_e\pi^0$		(1.036 ± 0.006) $\times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		(3.2 ± 0.5) $\times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		< 5 $\times 10^{-6}$	90%	70

DARK MATTER

$J =$?

Mass $m =$?
Mean life $\tau =$?

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?	?	?	?

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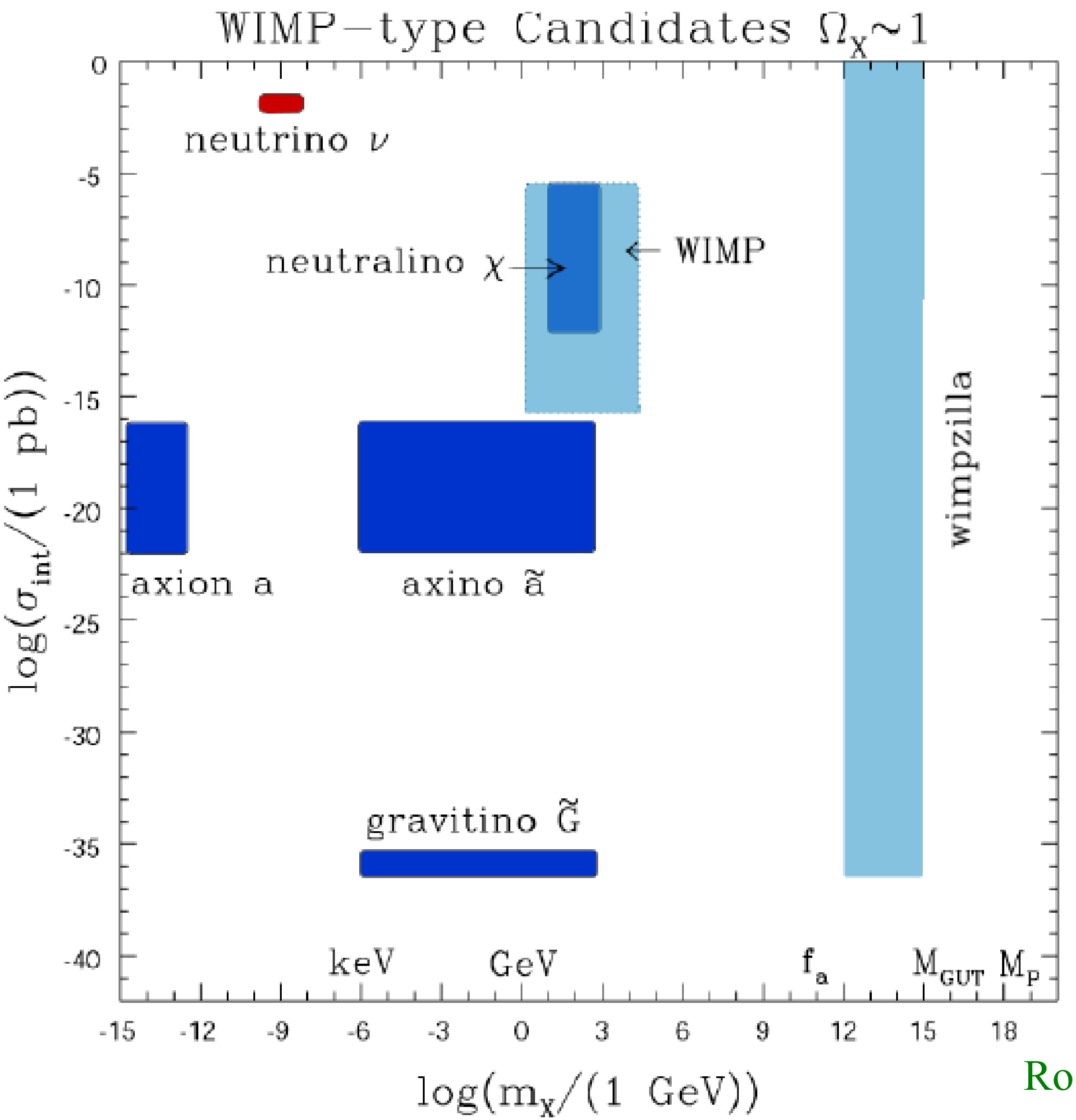
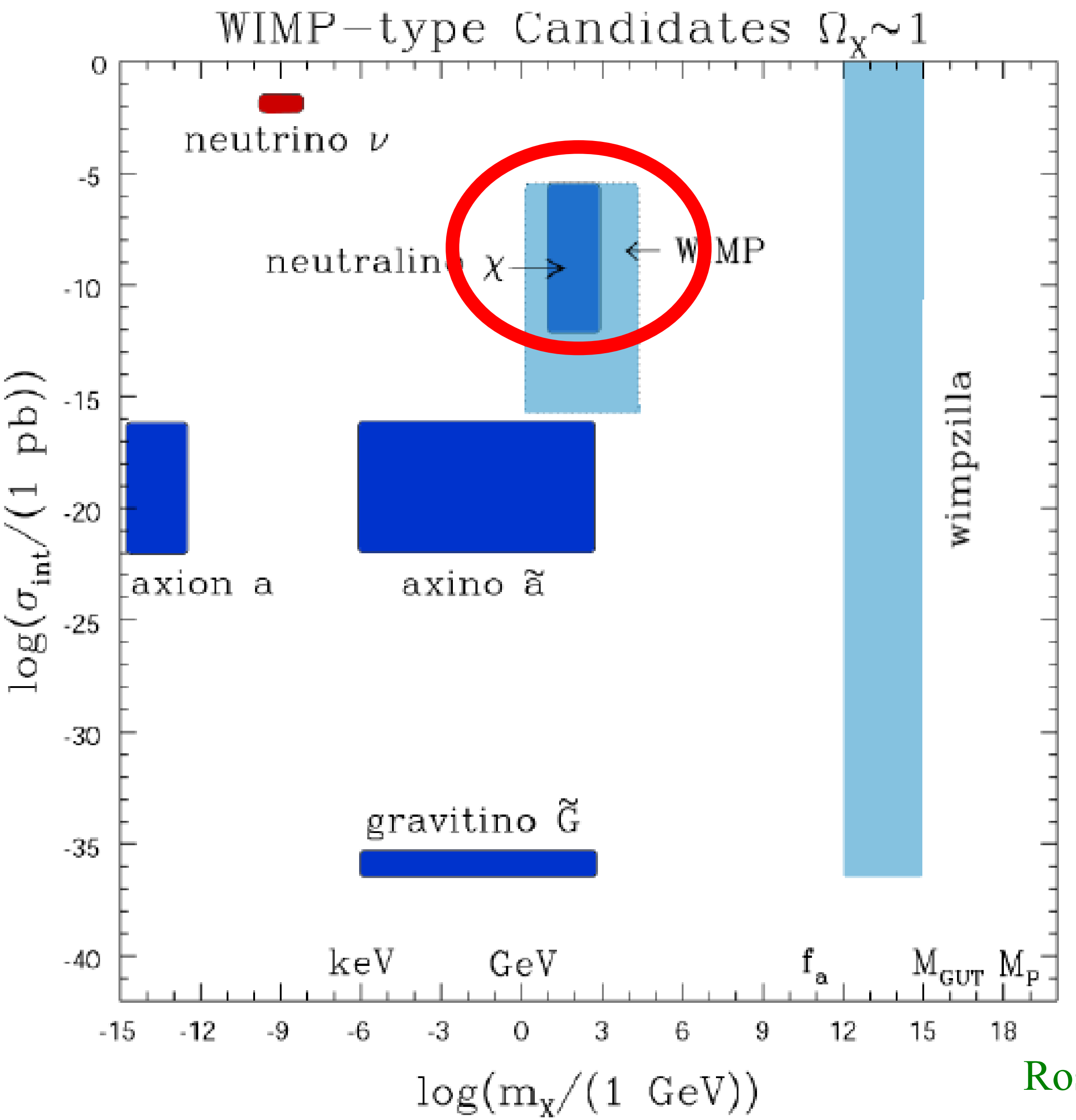
Goal for the 21st century: identify the properties of the dark matter particle



WIMP−type Candidates $\Omega_\chi \sim 1$
neutrino ν
neutralino χ
WIMP
wimpzilla
axion a
axino $\tilde{a}$
gravitino $\tilde{G}$
keV
GeV
f_a
M_{GUT}
M_P
$\log(\sigma_{int}/(1\ \mathrm{pb}))$
$\log(m_\chi/(1\ \mathrm{GeV}))$
0
-5
-10
-15
-20
-25
-30
-35
-40
-15
-12
-9
-6
-3
0
3
6
9
12
15
18

Roszkowski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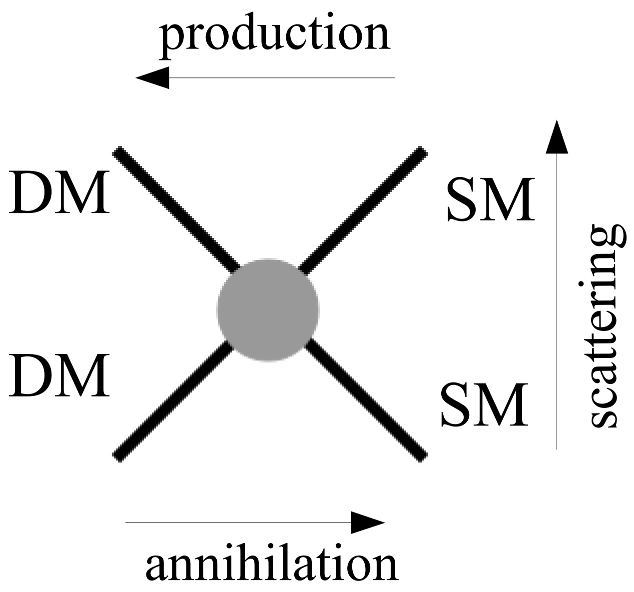
Roszkowski

WIMP dark matter



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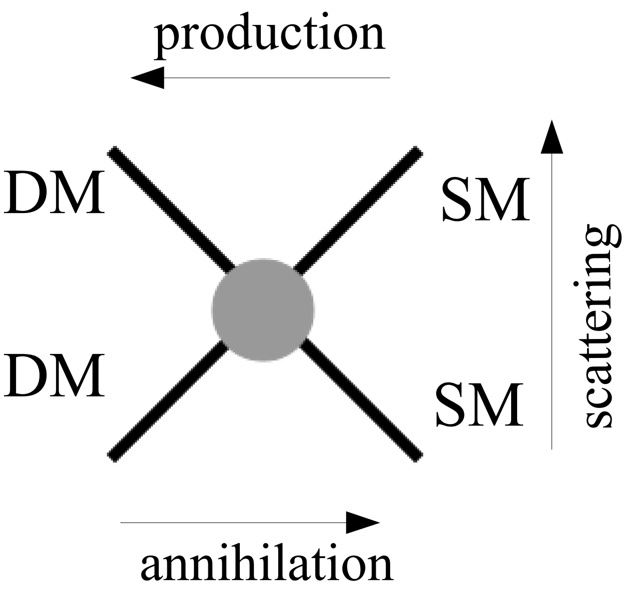

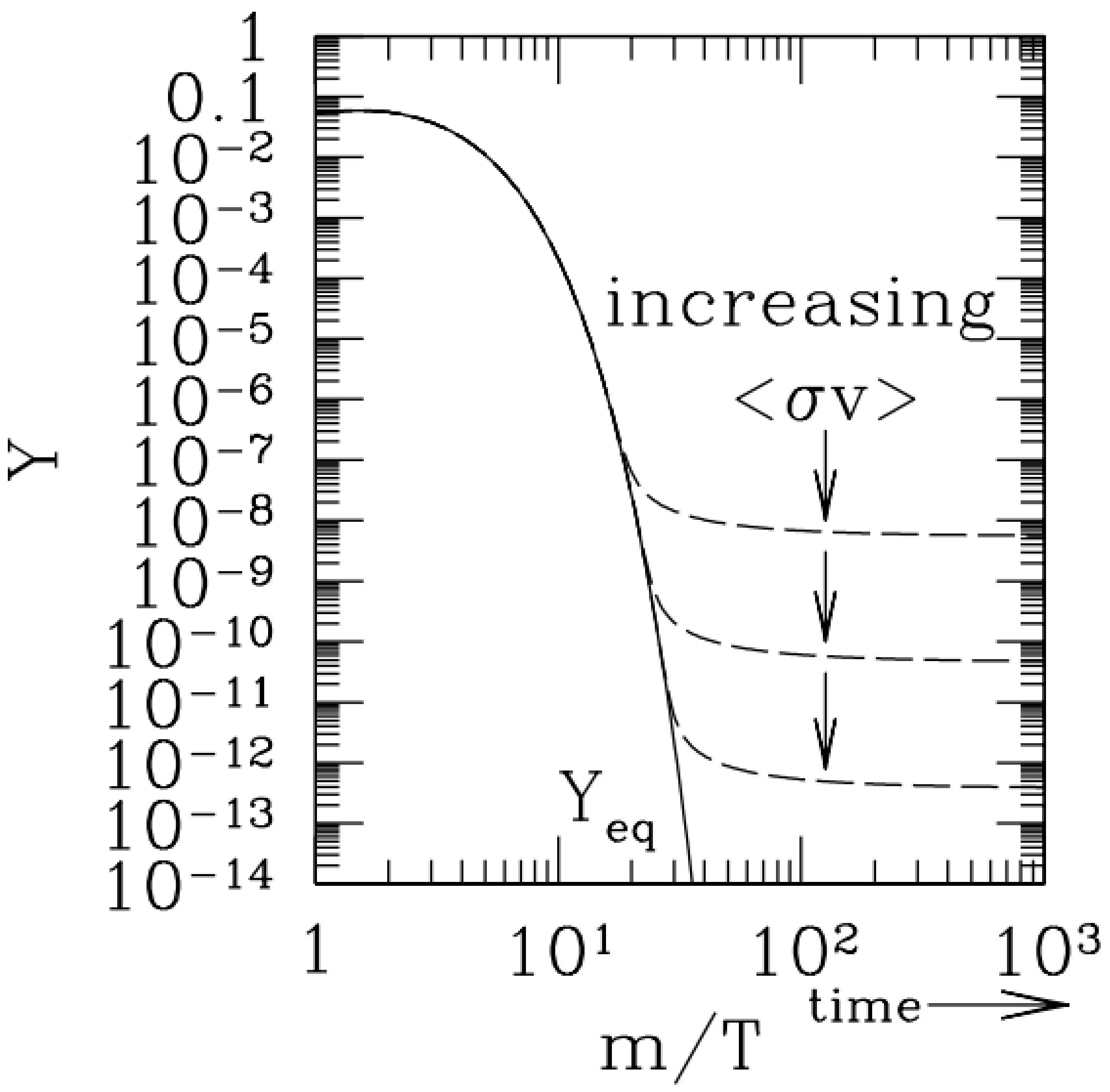

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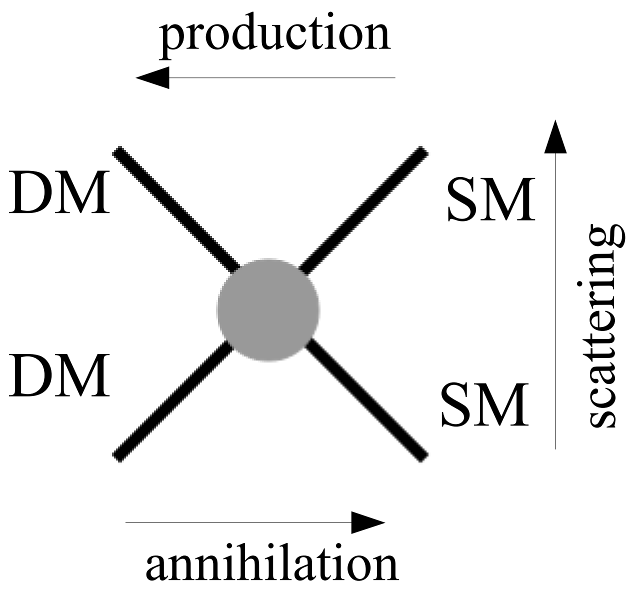
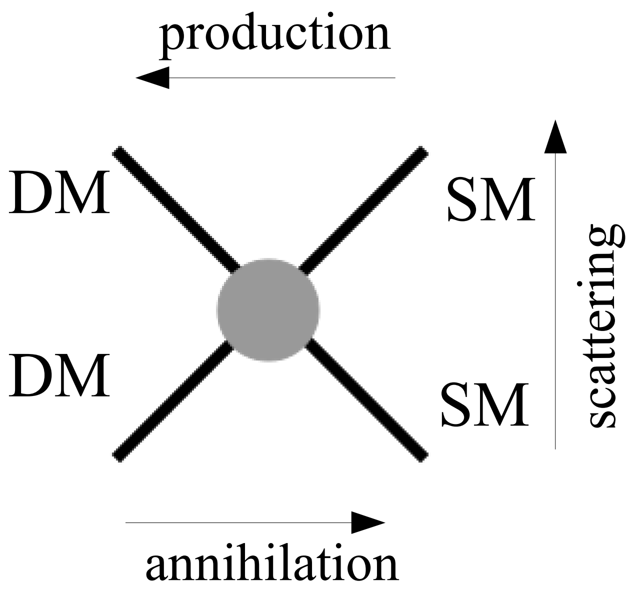


Assuming that the dark matter particles were in thermal equilibrium with the SM in the Early Universe, their relic abundance reads:

$$\Omega h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

WIMP dark matter



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Correct dark matter abundance, $\Omega_{\mathrm{DM}} h^2 \simeq 0.1$, if

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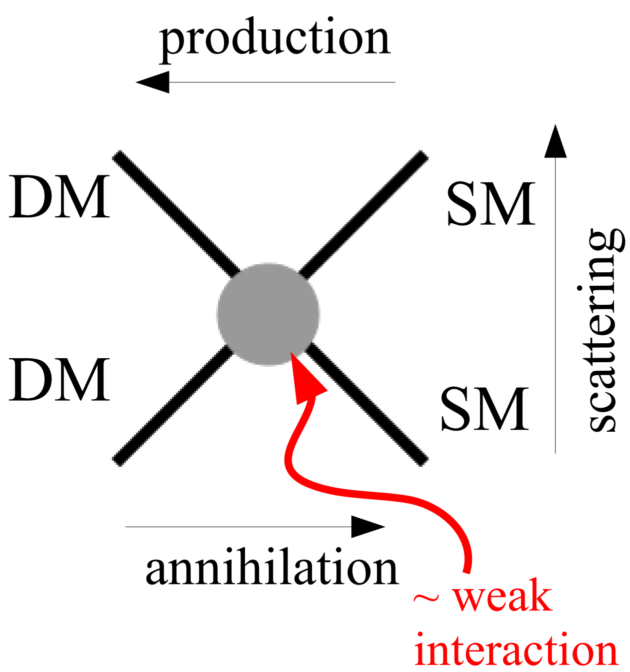

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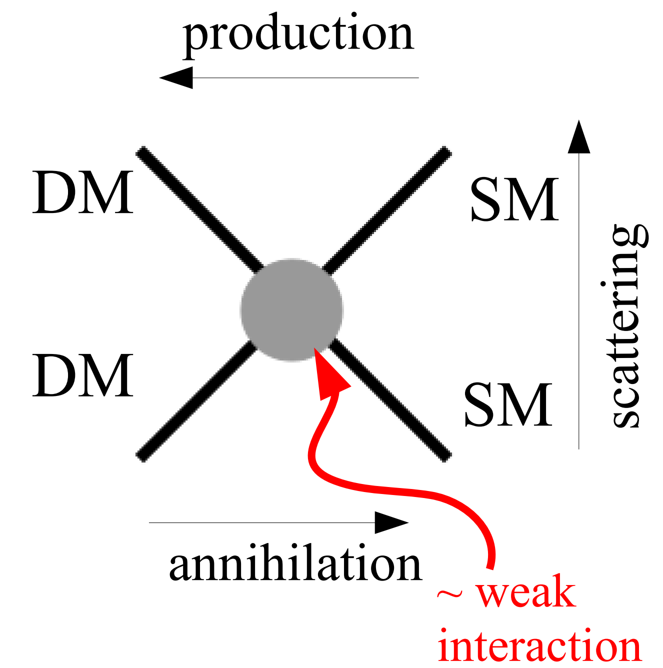

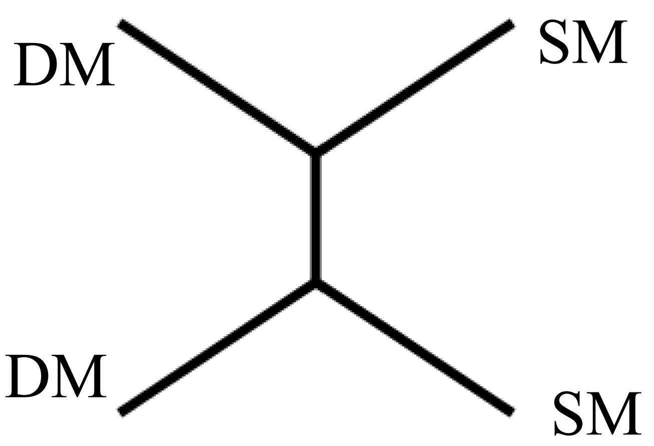

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$$\sigma \sim \frac{g^4}{m_{\mathrm{DM}}^2} = 1\,\mathrm{pb}$$

$$m_{\mathrm{DM}} \sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$$

(provided $g \sim g_{\mathrm{weak}} \sim 0.1$)

LUX

CMS

ATLAS

MAGIC

Xe
XENON
Dark Matter Project

fermi
Gamma-ray
Space Telescope

PaMeLa

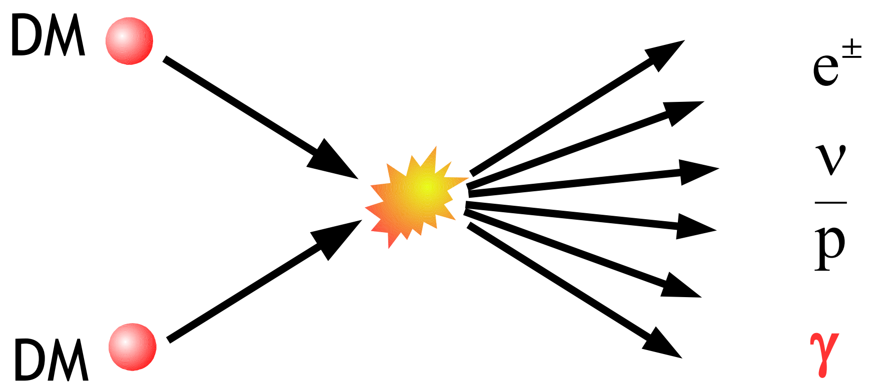
H E S S

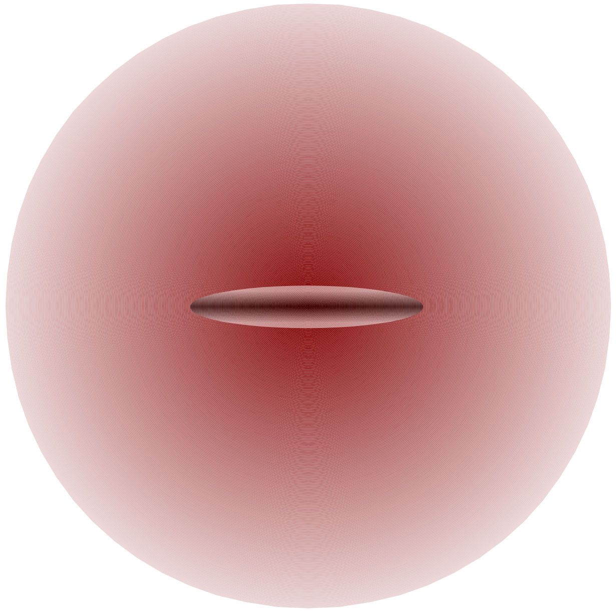
Alpha Magnetic Spectrometer
AMS-02
Europe • Asia
North America

VERITAS

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Dark matter searches with gamma-rays





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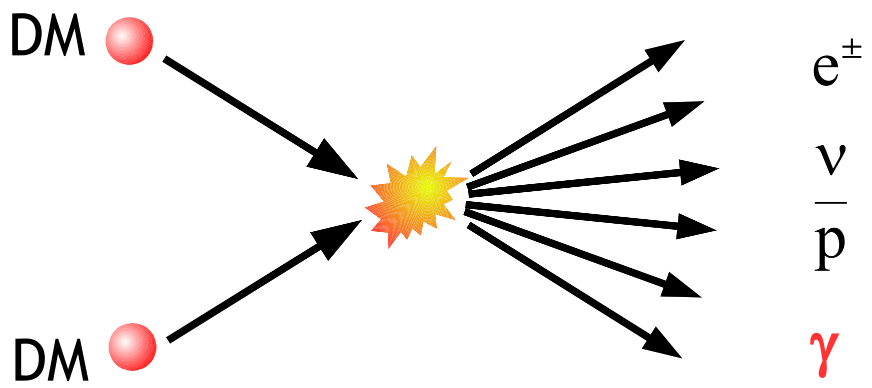
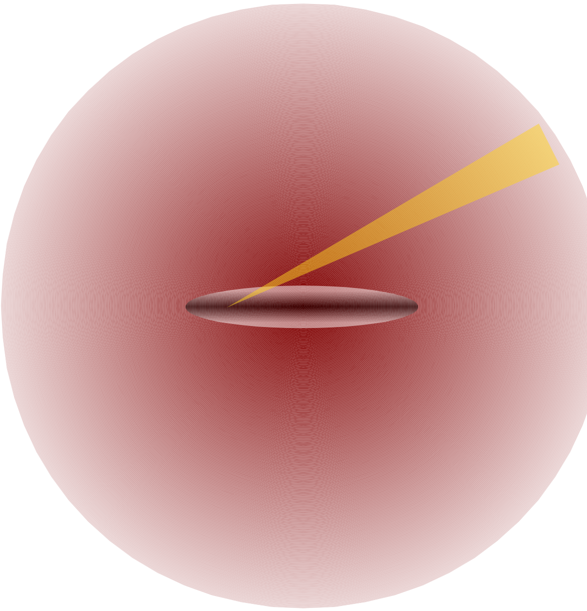




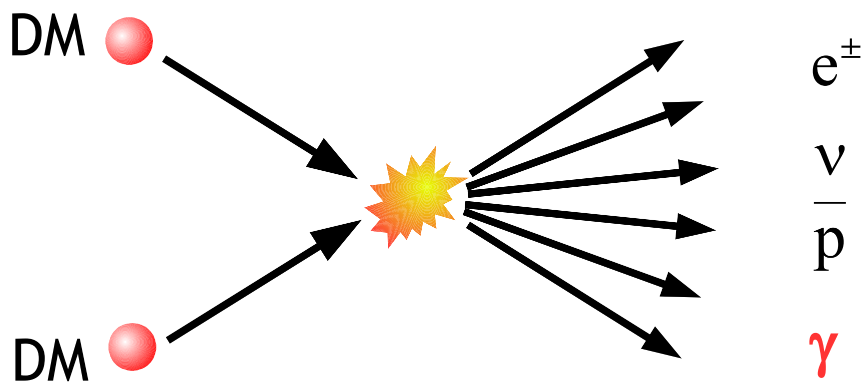
Expected gamma-ray flux in a given direction:

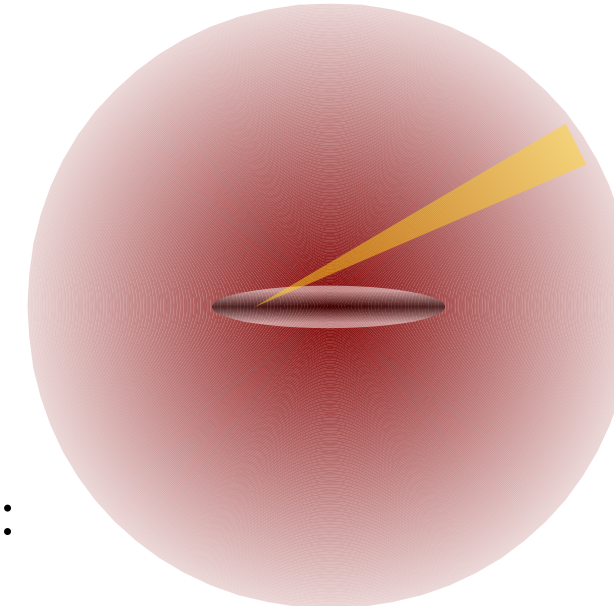
$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann} v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right] \times \int_{\rm l.o.s.} \rho^2(\vec{l})\,d\vec{l}$$

Source term (particle physics)

Line-of-sight integral (astrophysics)

Dark matter searches with gamma-rays





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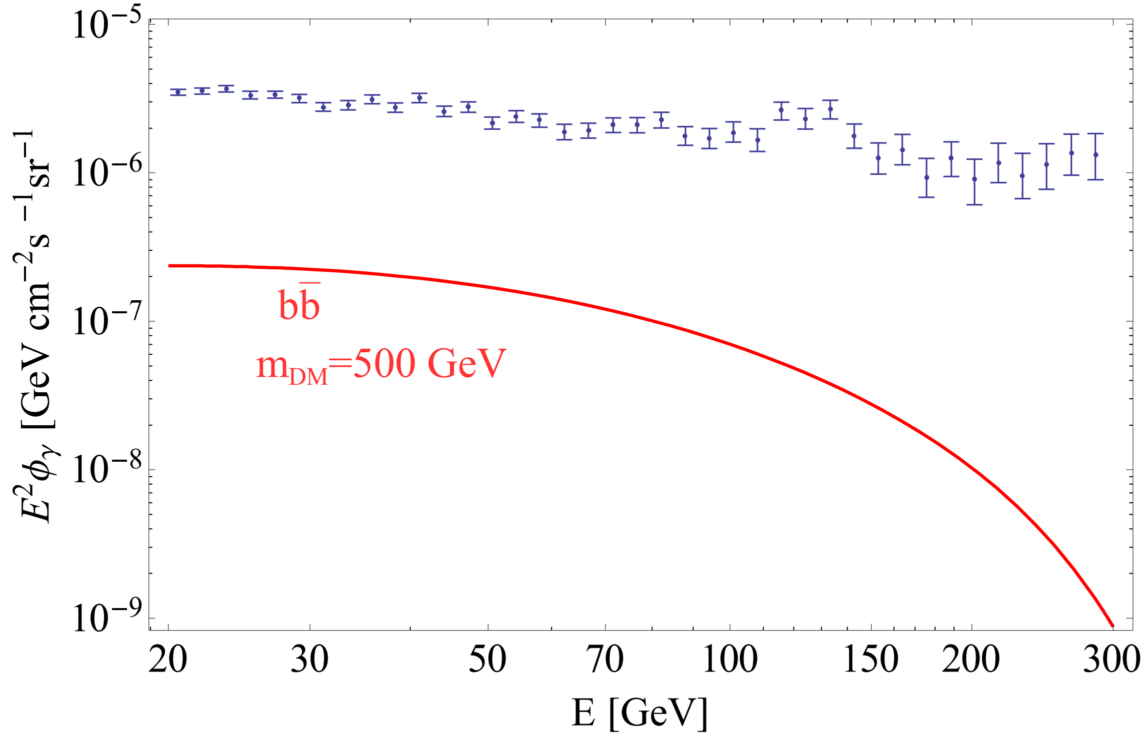
Which $\langle \sigma\, v \rangle$? A well motivated choice:

$$\boxed{\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}}$$

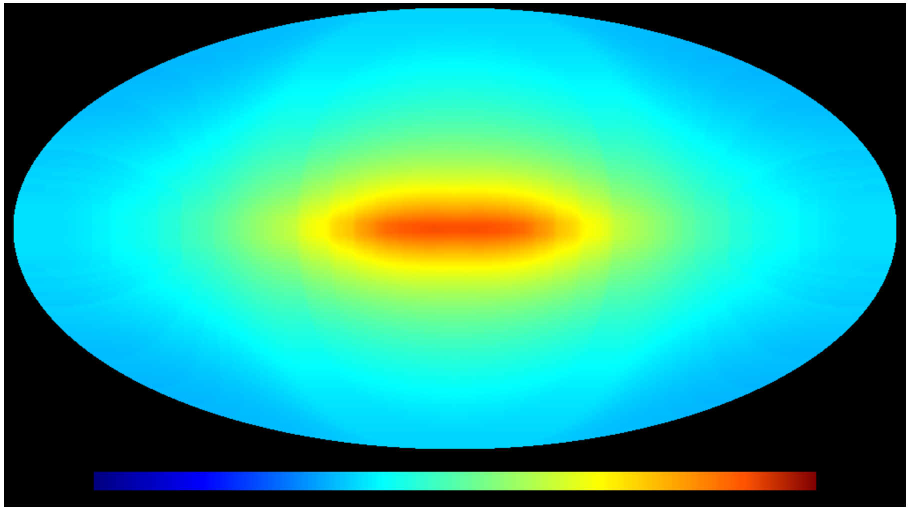
As required by thermal production. First milestone for exclusion.

Problem for discovery: for typical channels and typical masses, the expected flux lies well below the background.

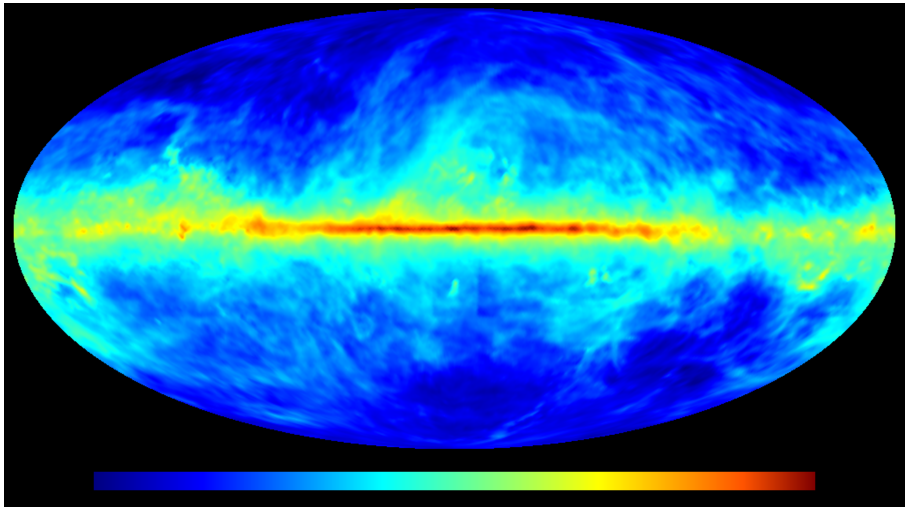


Do we understand backgrounds to the ~1% accuracy?

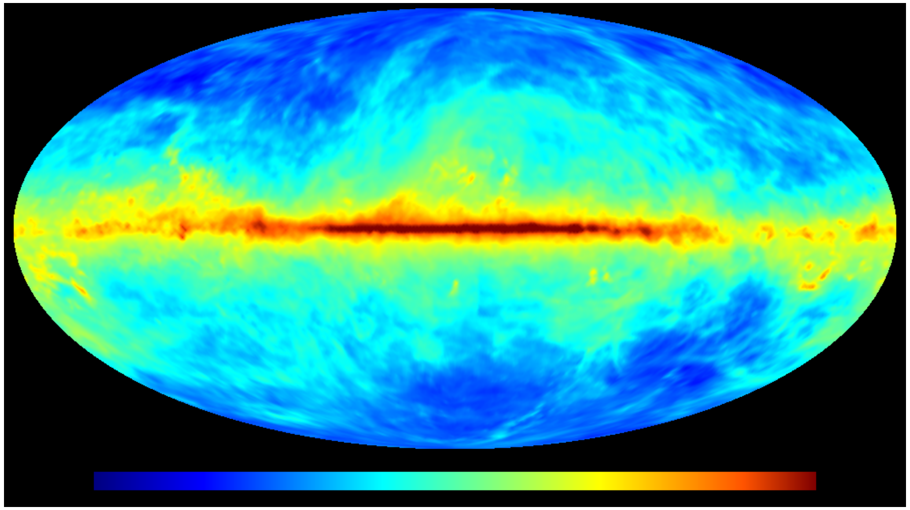
modelling of the diffuse emission



Inverse Compton



bremmstrahlung



π^0-decay

Great progress in understanding the diffuse gamma-ray emission, but unfortunately a detailed picture is still lacking.

Always possible to use the gamma-ray data to set constraints on the dark matter properties (and should be done).

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Always possible to use the gamma-ray data to set constraints on the dark matter properties (and should be done).

However, to convincingly claim a dark matter signal it is necessary to convincingly subtract the astrophysical background.

Overcoming backgrounds

Strategy 1: Search for a gamma-ray excess with the spatial morphology expected from an annihilation signal

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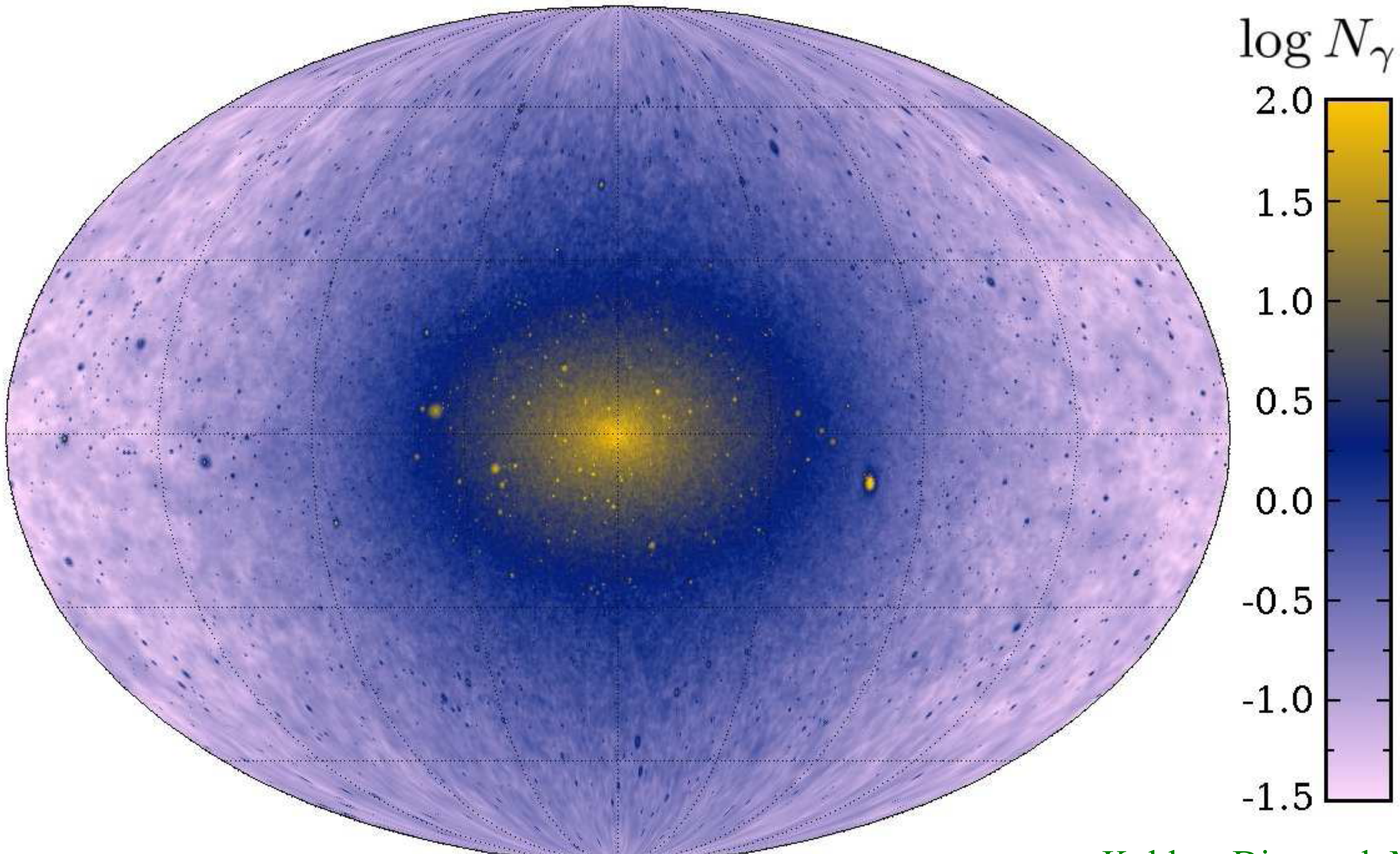
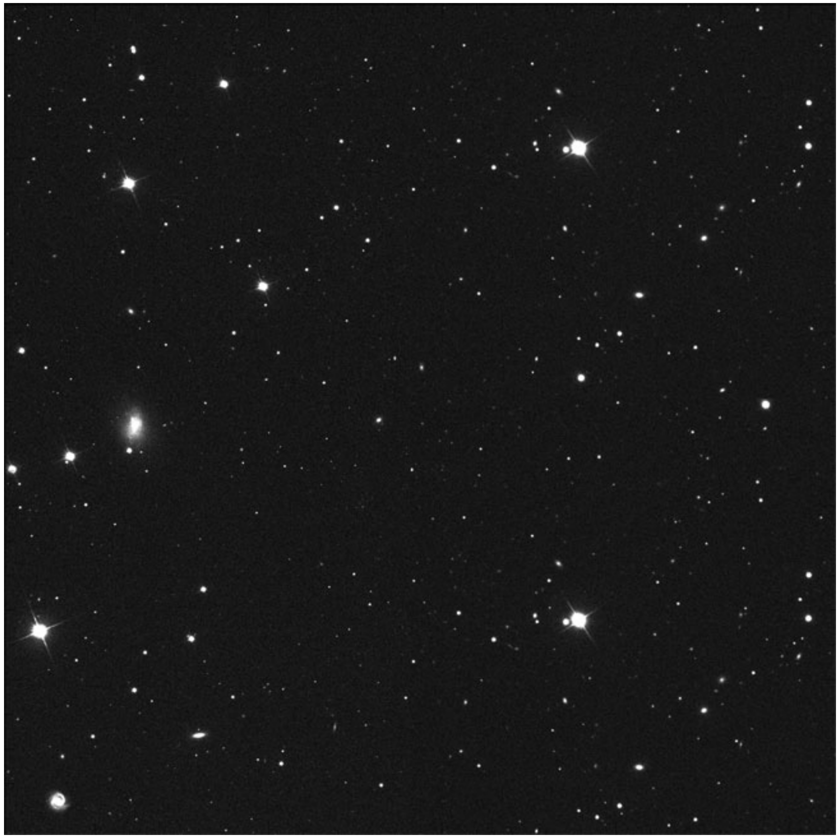


Kuhlen, Diemand, Madau

Overcoming backgrounds

Strategy 1: Search for a gamma-ray excess with the spatial morphology expected from an annihilation signal

A promising target for detection: dwarf galaxies



Segue 1: Optical image

Overcoming backgrounds

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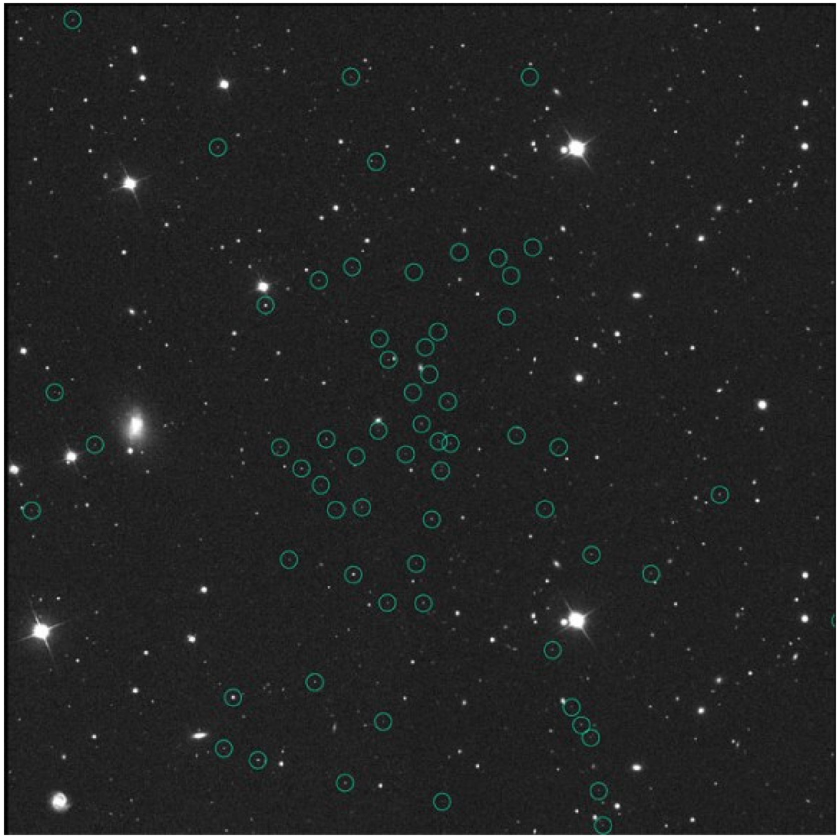

Segue 1: Optical image

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Segue 1: Optical image

Mass-to-light ratio $\sim 3400\ M_\odot/L_\odot$

Most DM-dominated object known so far!

Overcoming backgrounds

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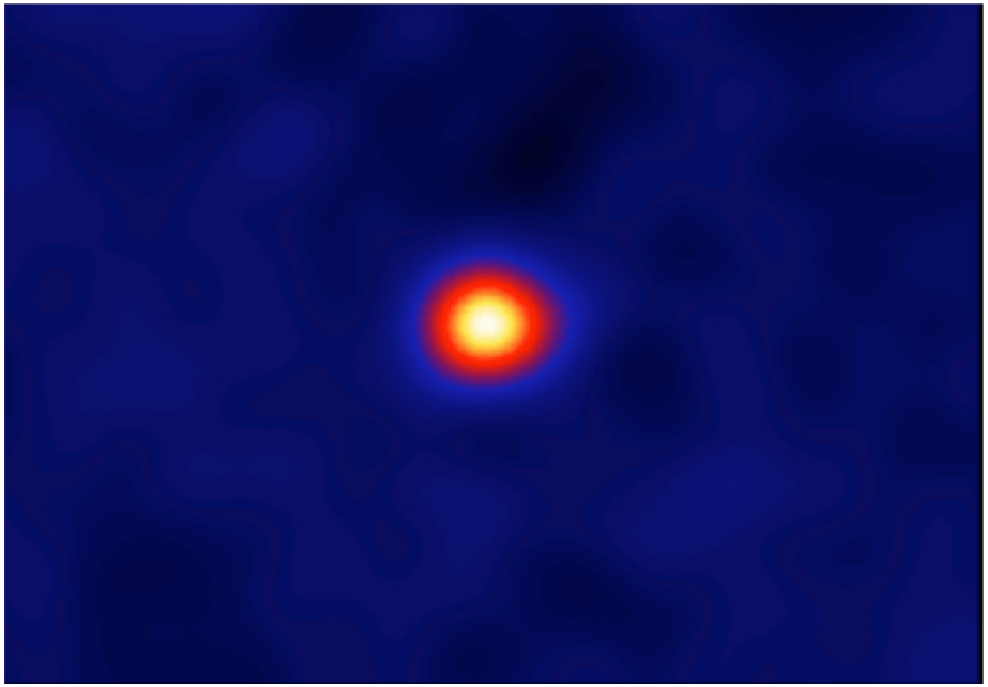
A promising target for detection: dwarf galaxies



Segue 1: Gamma-ray image
(simulated!)

Overcoming backgrounds

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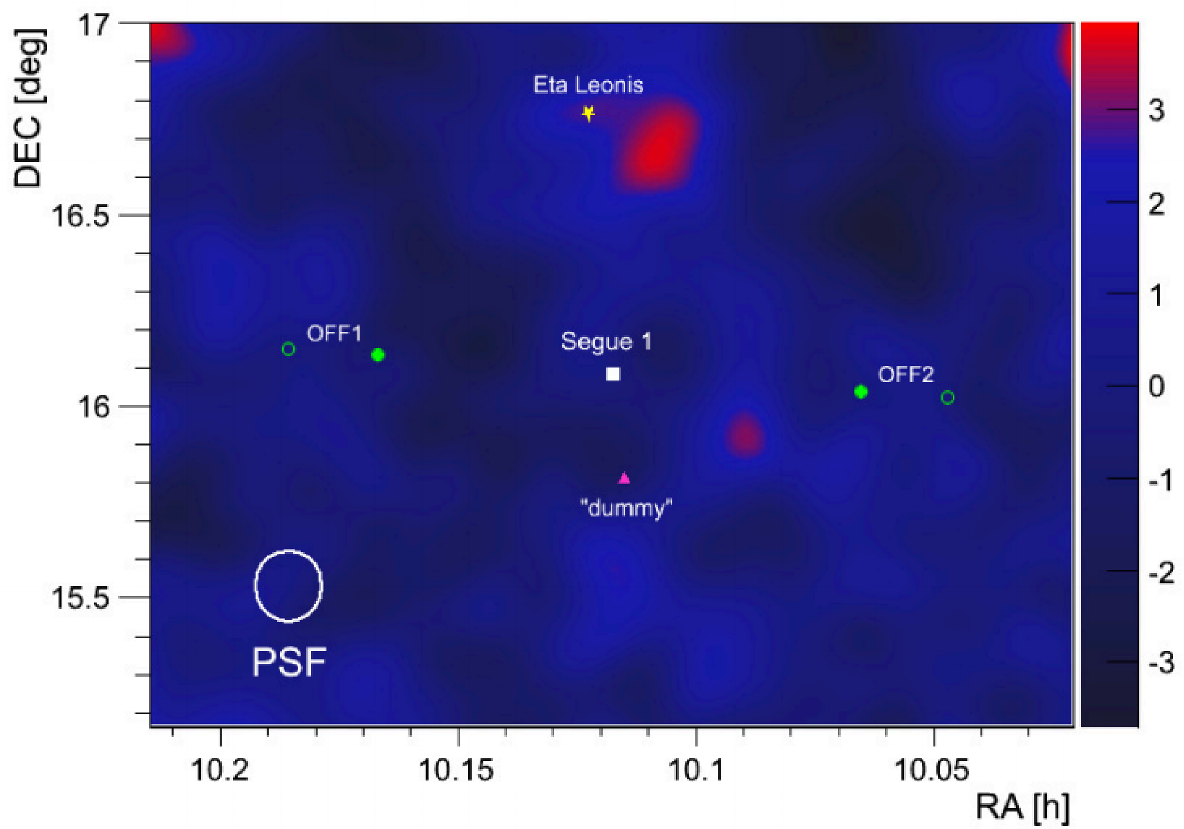

Gamma-ray image taken with the MAGIC telescopes

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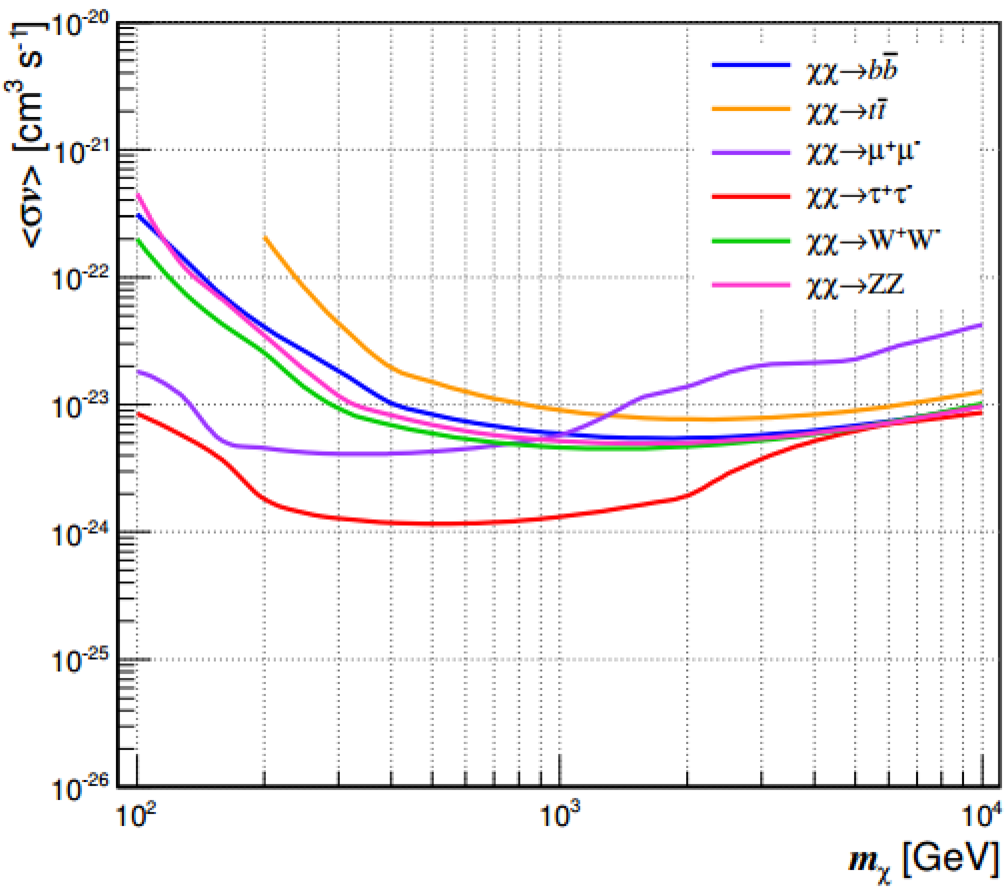

MAGIC coll.
arXiv:1312.1535

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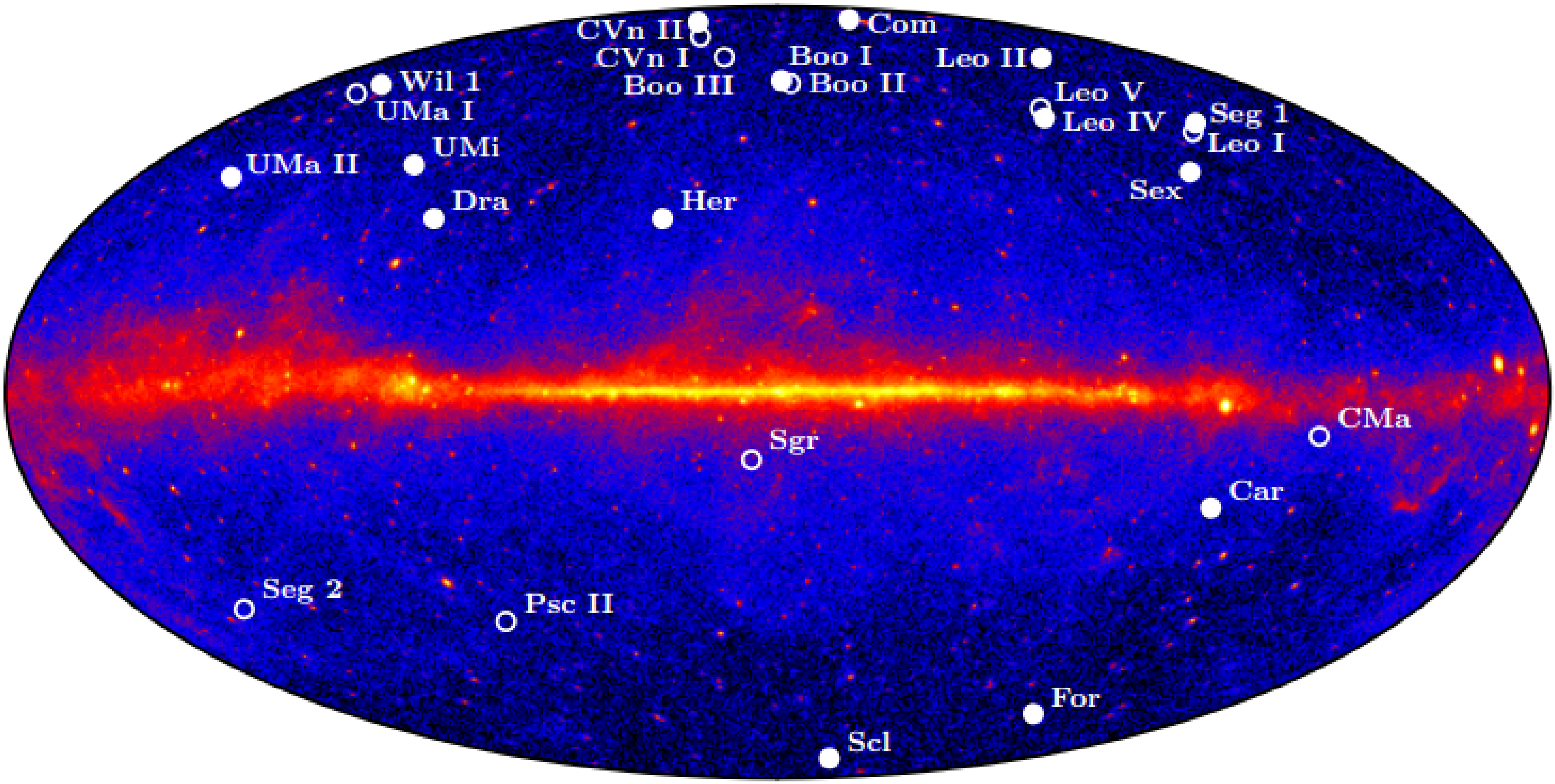

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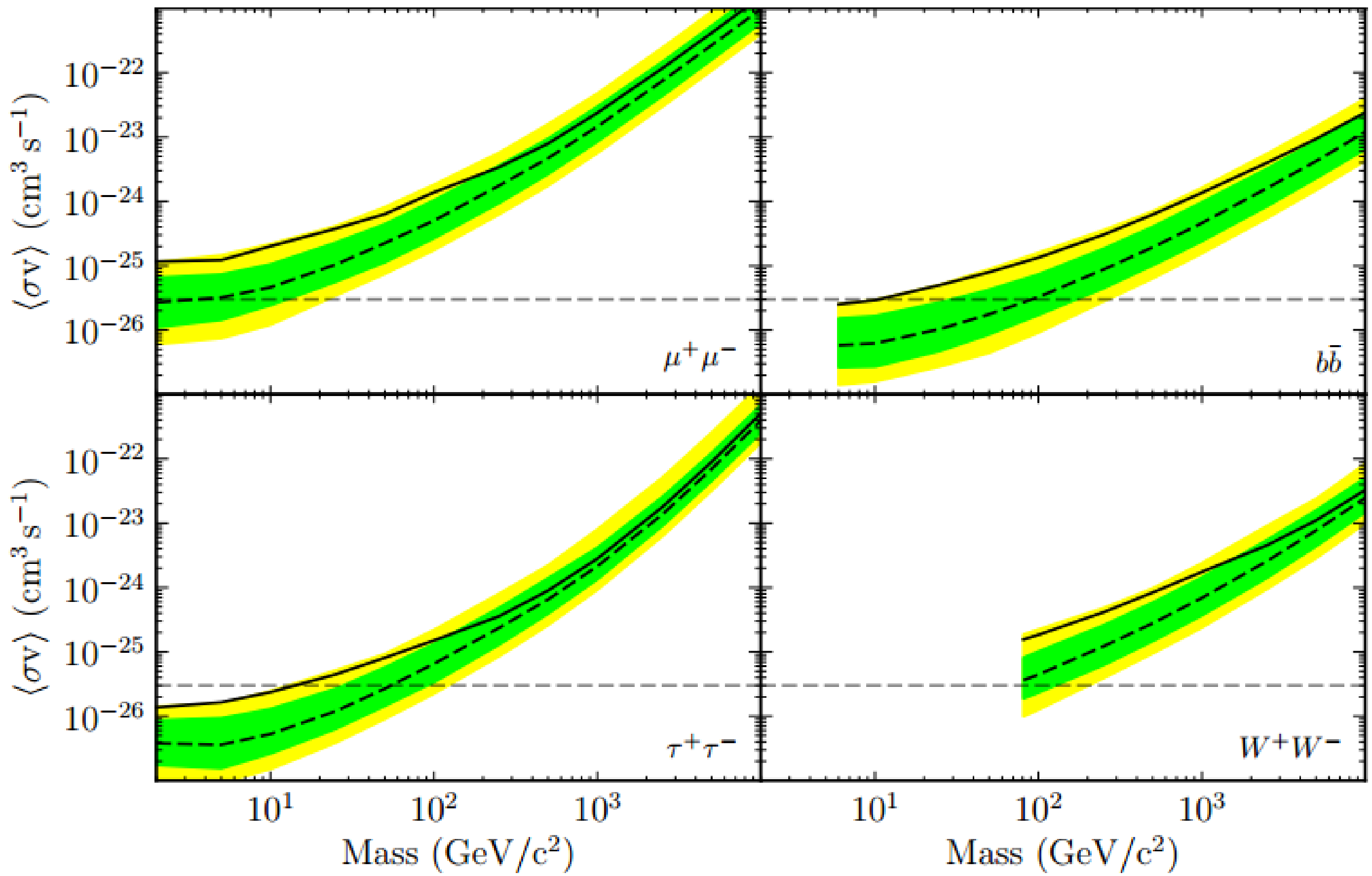

Fermi-LAT coll.
arXiv:1310.0828

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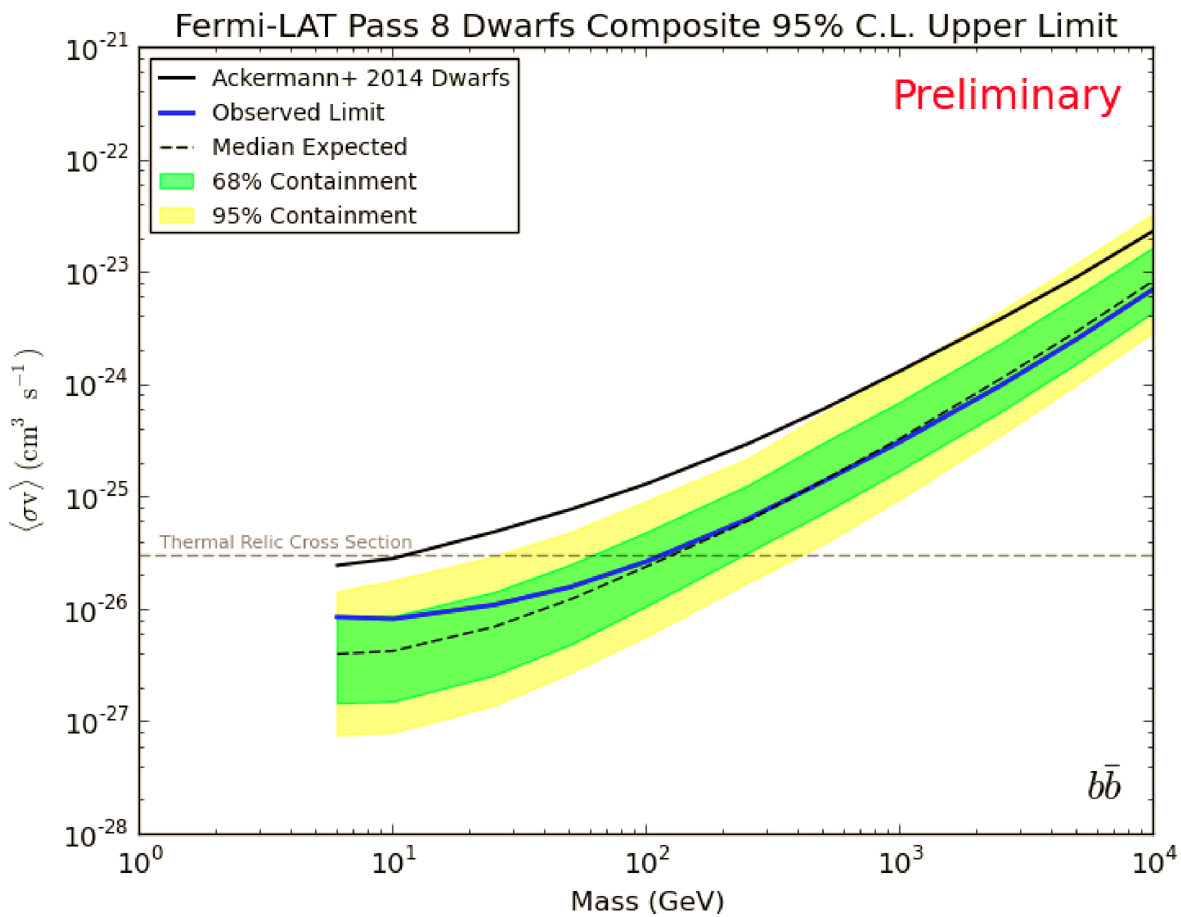
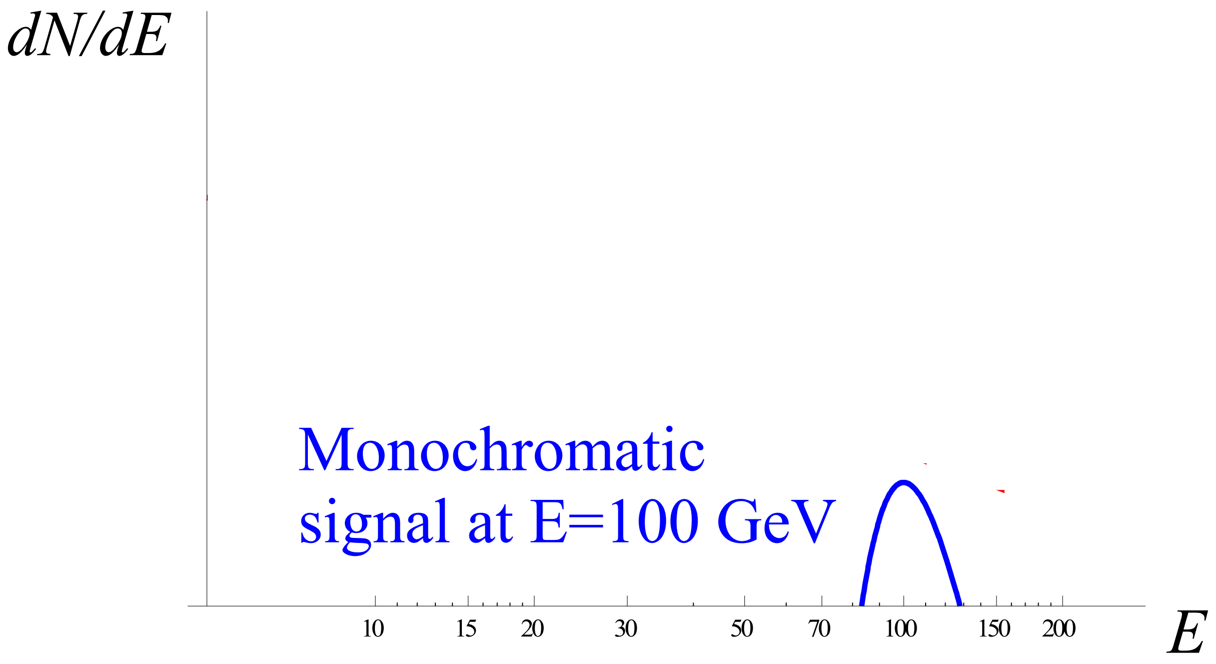


B. Anderson
Fermi Symposium
20-24 October 2014

Overcoming backgrounds

Strategy 2: Search for a gamma-ray excess with an energy spectrum qualitatively different from the background.

Idea:



Overcoming backgrounds

Strategy 2: Search for a gamma-ray excess with an energy spectrum qualitatively different from the background.

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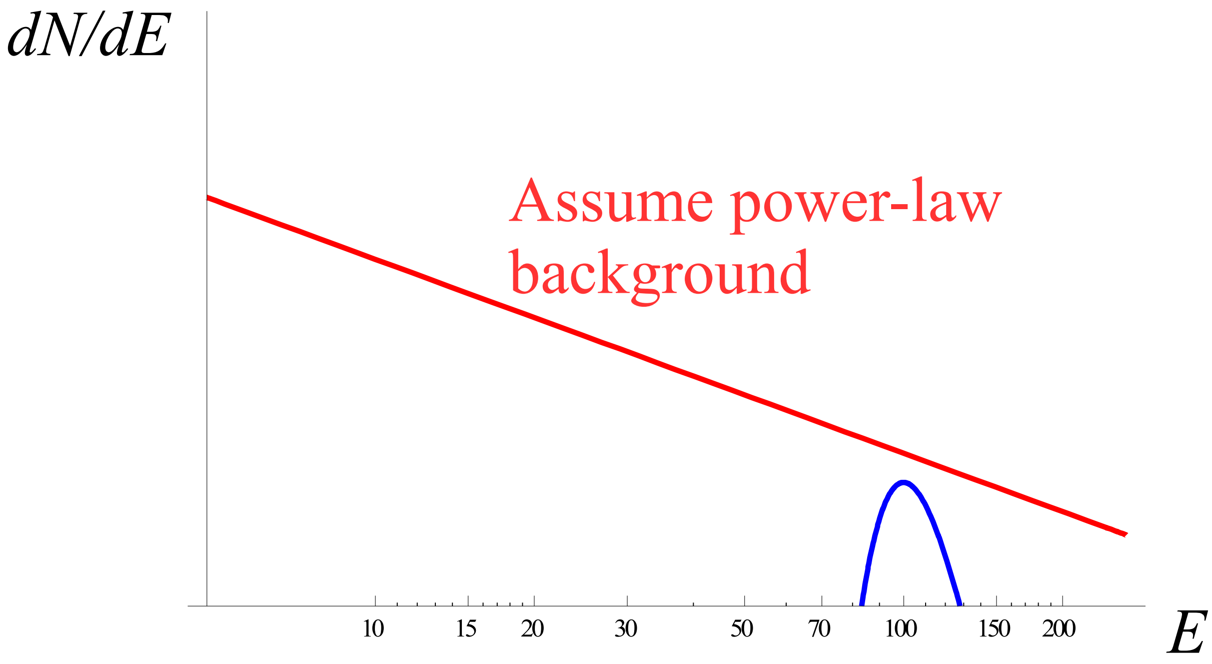

Overcoming backgrounds

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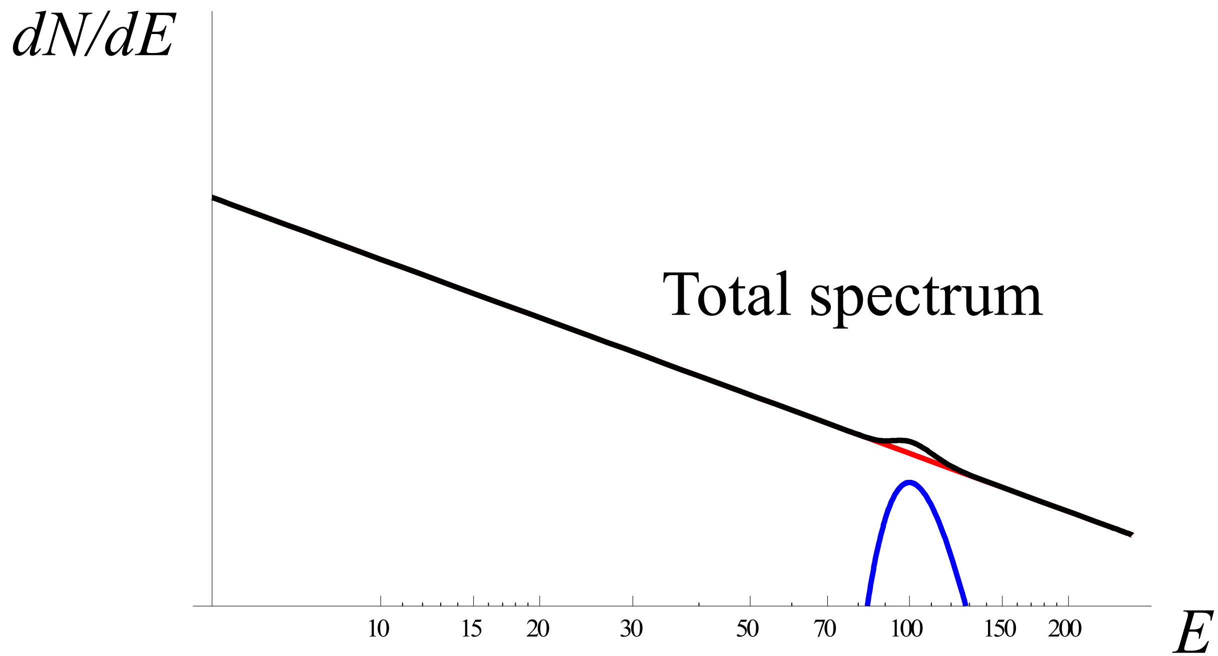
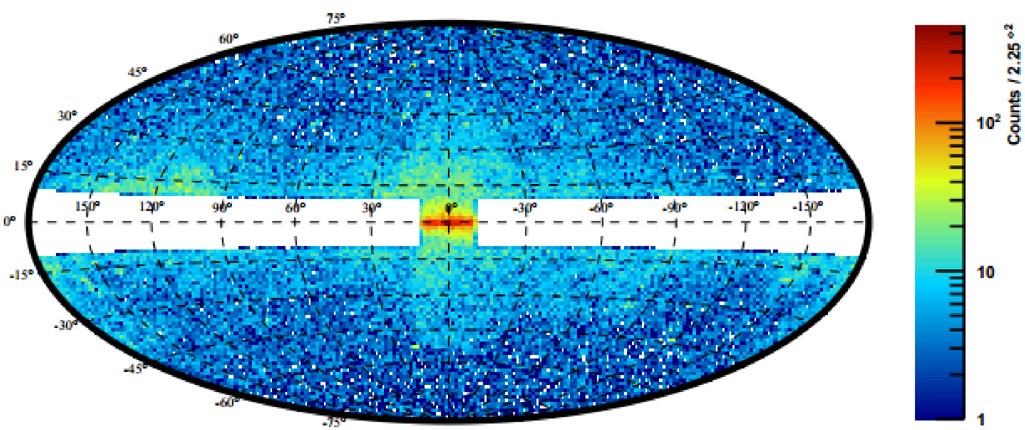


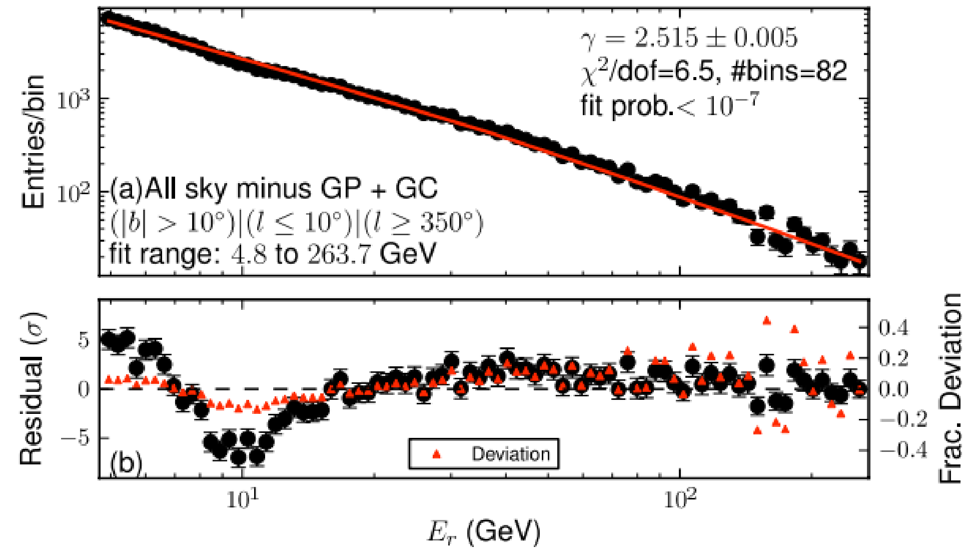
Fit data to $$\frac{dN}{dE} = aE^{-\alpha} + b\delta(E - E_0)$$

Overcoming backgrounds

Strategy 2: Search for a gamma-ray excess with an energy spectrum qualitatively different from the background.

Data don't really look like a power law…





Overcoming backgrounds

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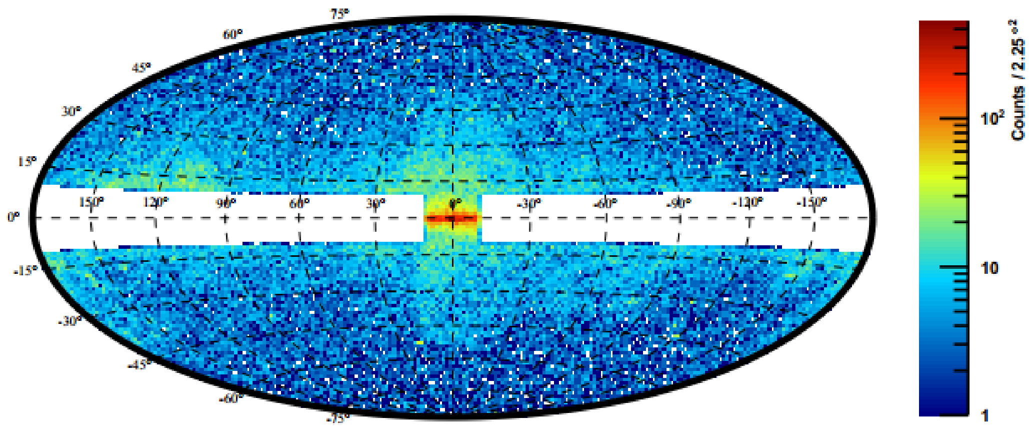

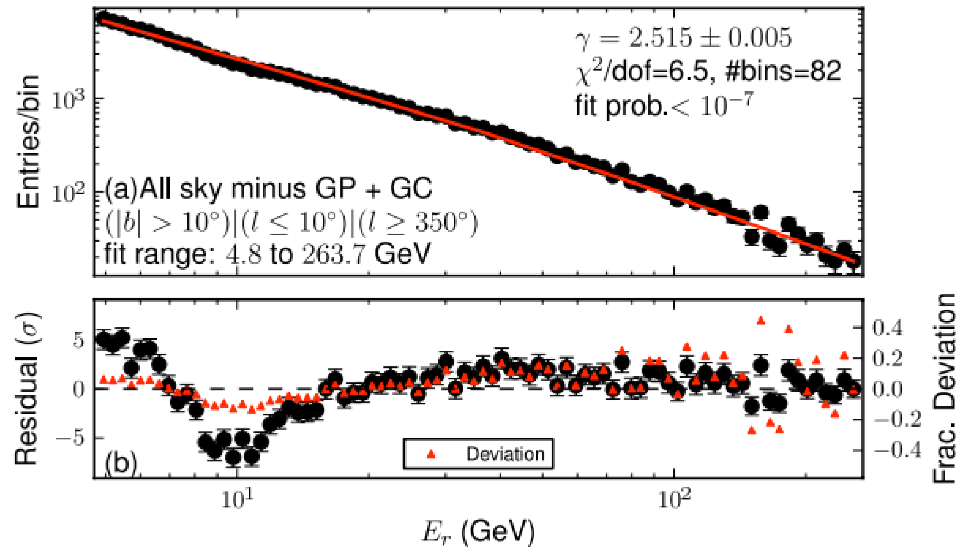

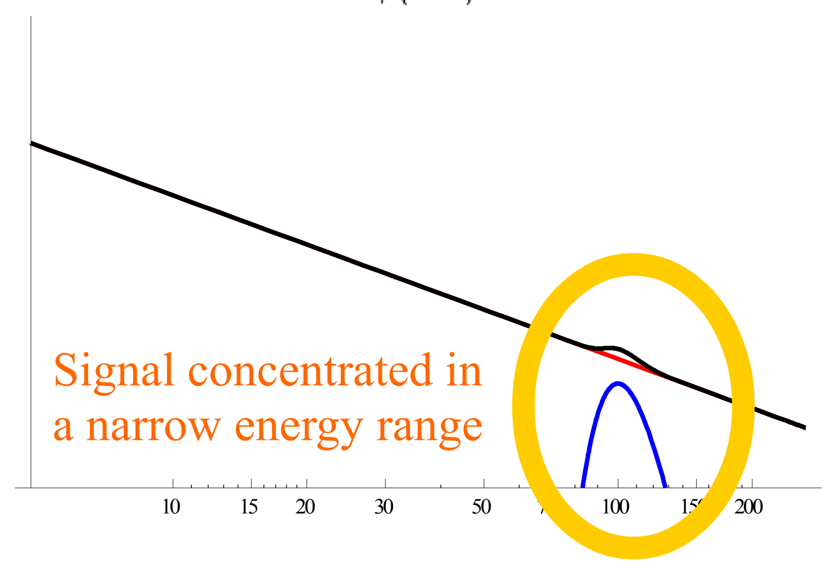

Overcoming backgrounds

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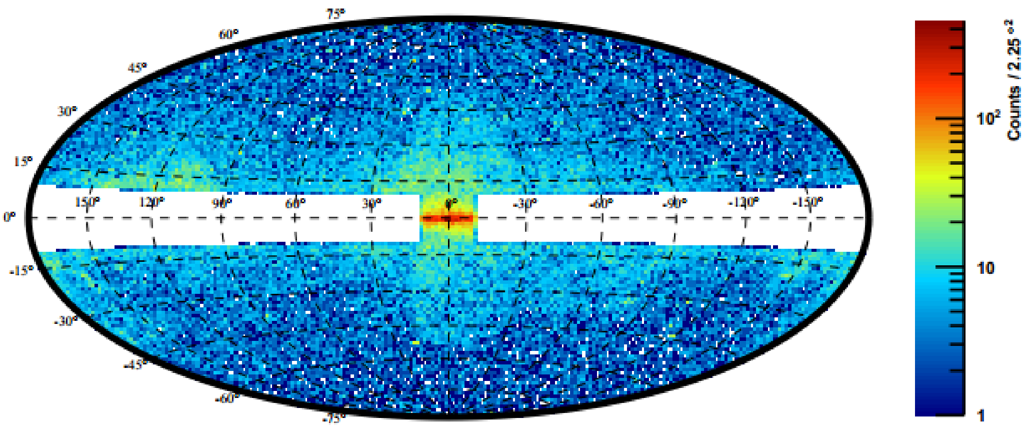
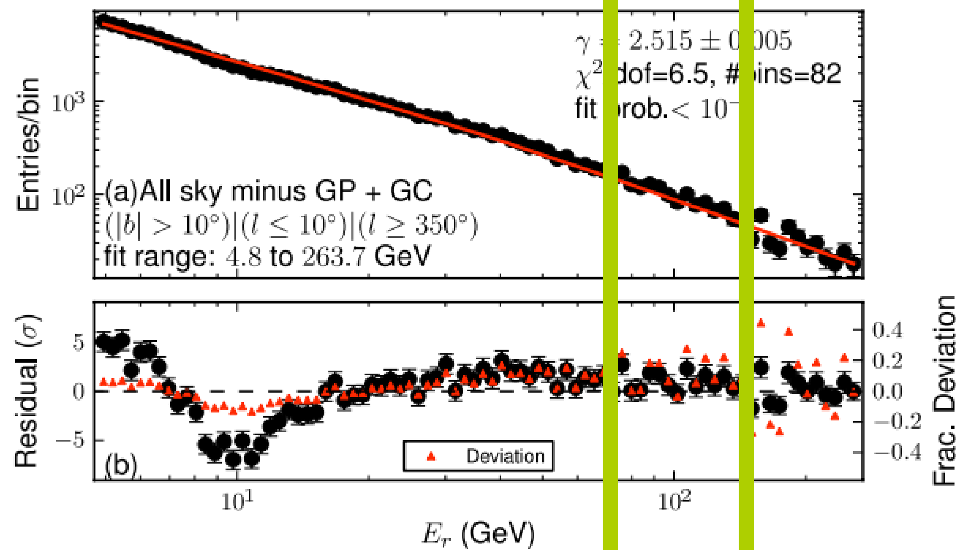
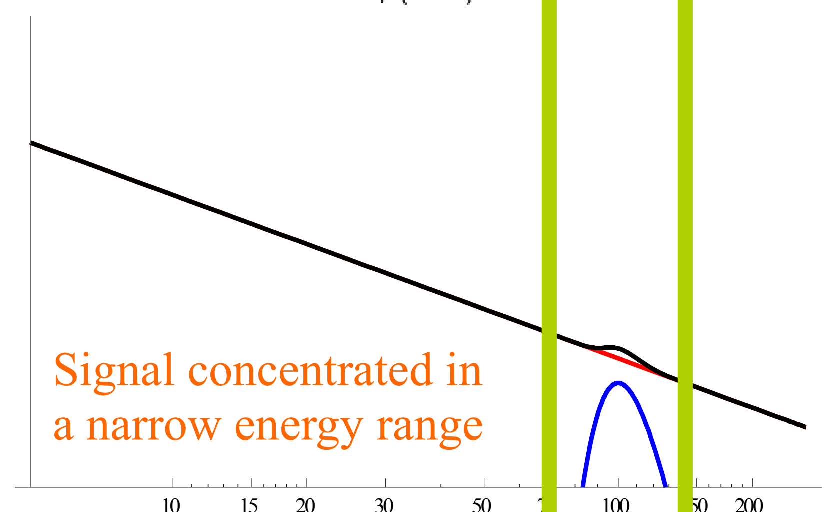




In a narrow energy window, the background resembles a power-law (↪Taylor's theorem)

$$\frac{dN}{dE} = aE^{-\alpha} + b\delta(E - E_0)$$



Overcoming backgrounds

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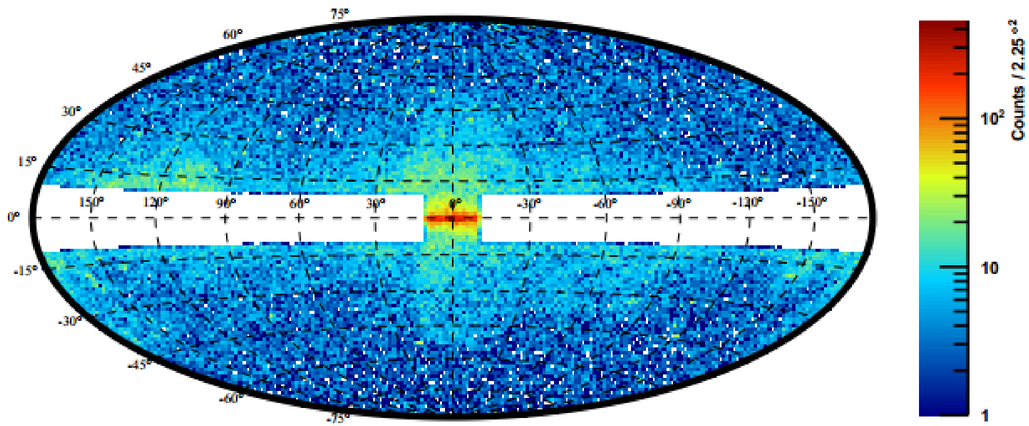
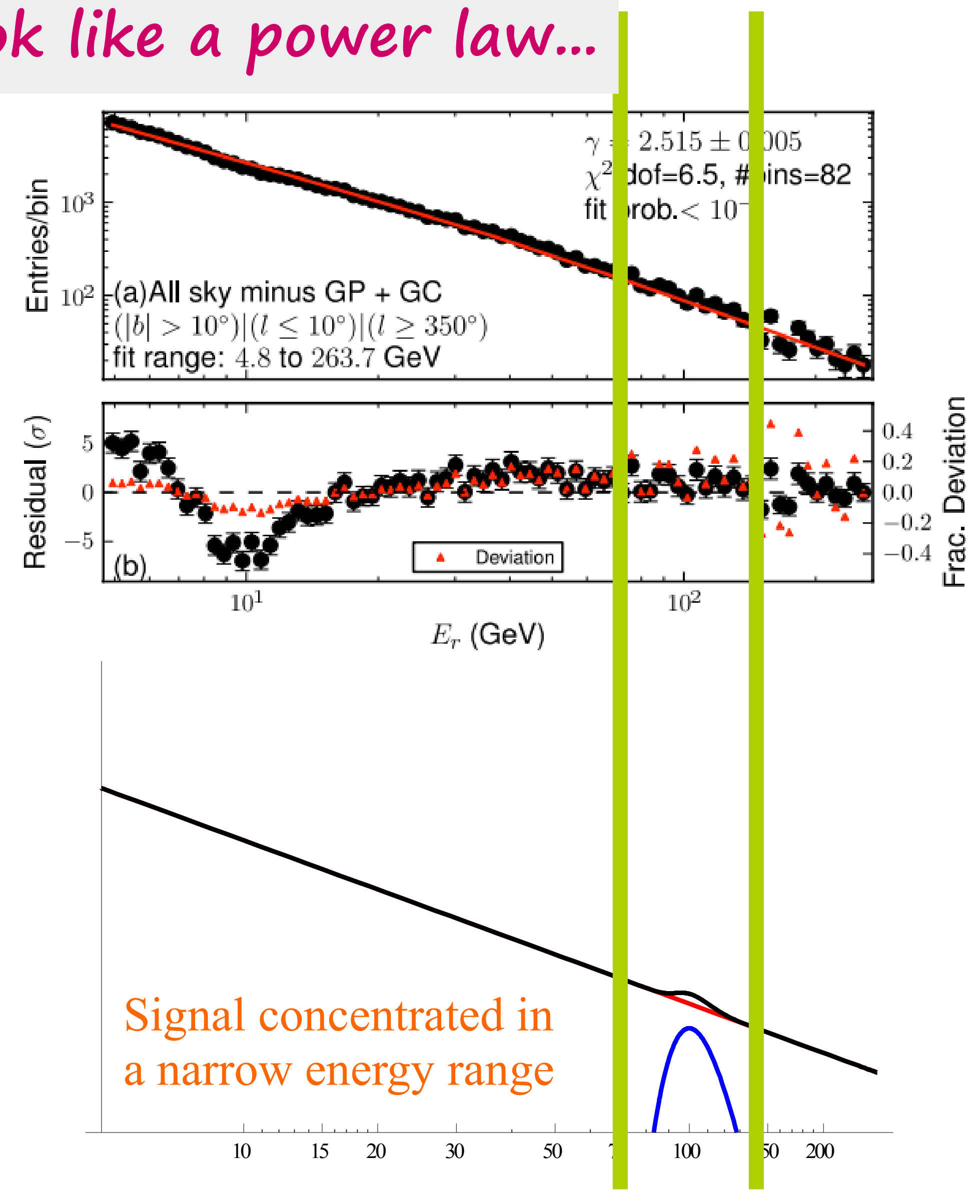


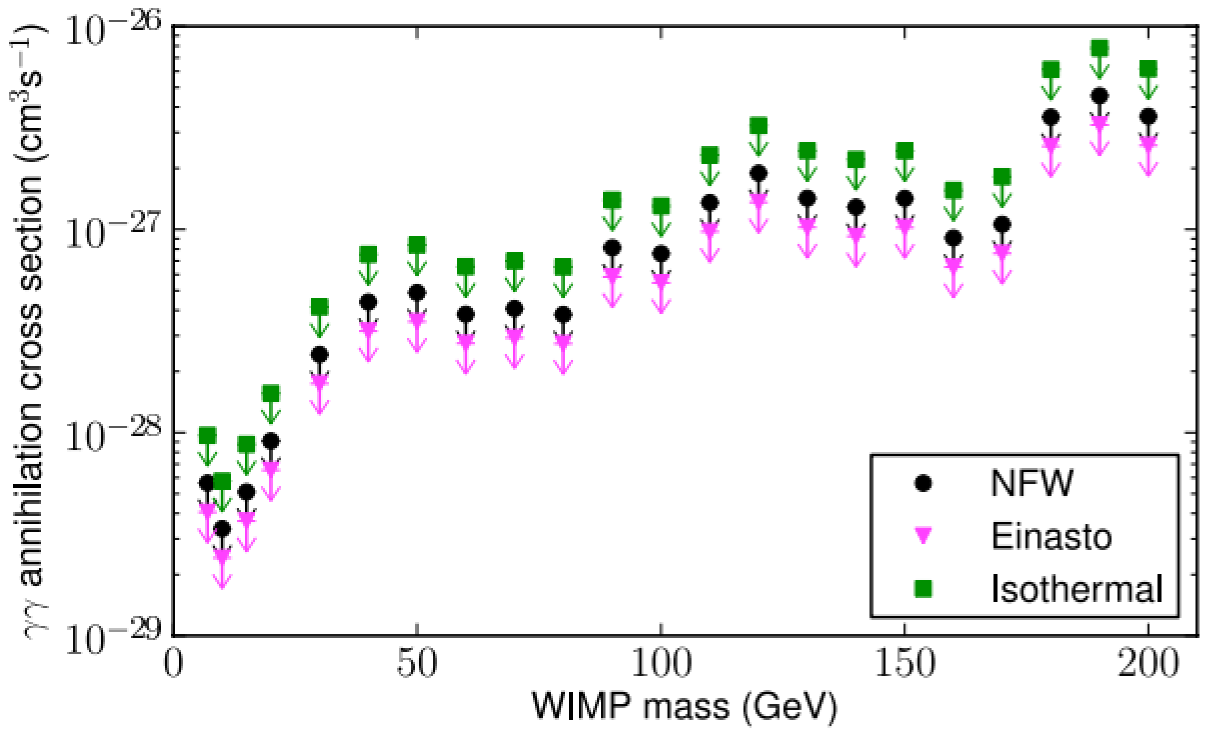


Repeat the search with different windows postulating a signal at different DM masses.

"sliding energy window"

Overcoming backgrounds

Strategy 2: Search for a gamma-ray excess with an energy spectrum qualitatively different from the background.



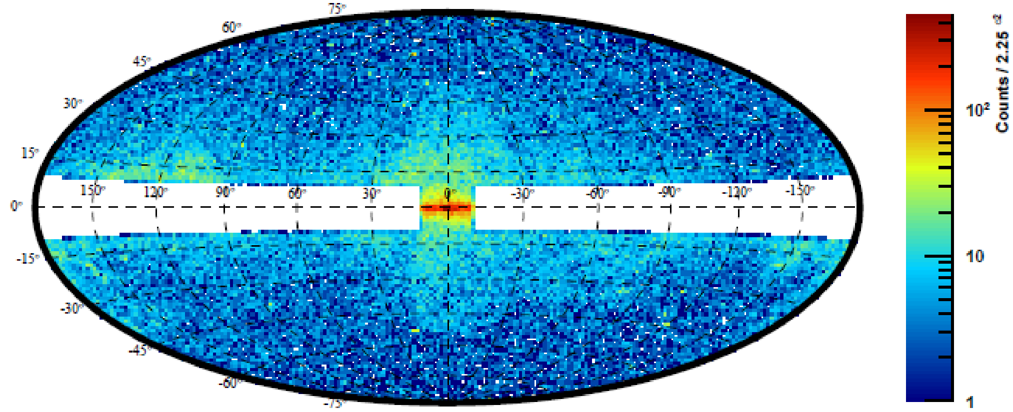
Fermi. Coll.
arXiv:1205.2739

Overcoming backgrounds

Strategy 3: Combine both methods. Search for gamma-ray spectral features in regions where it is most likely to find a signal.

Traditional approach: select a geometrically simple region of the sky and search for features.

e.g region |b|>10° plus a 20°×20° square centered at the Galactic Center (Fermi coll.)



Overcoming backgrounds

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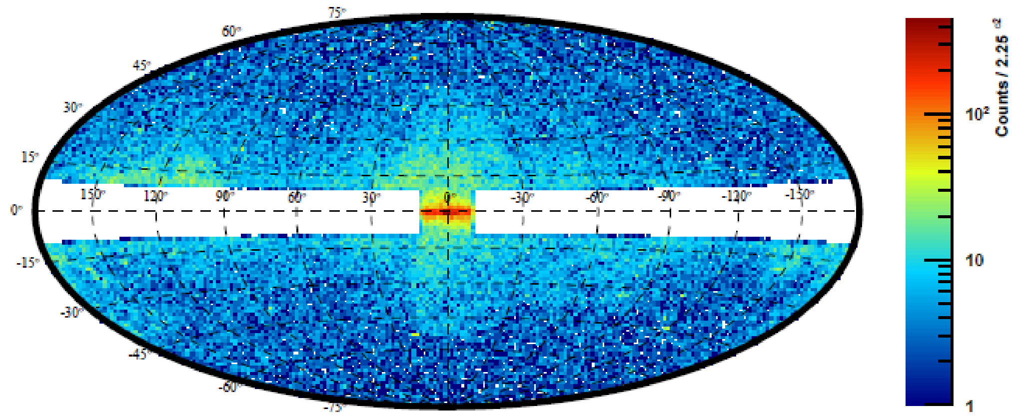
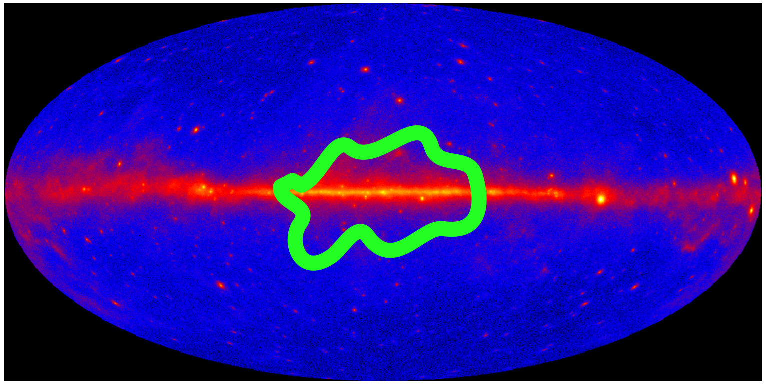


Disadvantage: in the chosen region the background could be too large and bury the signal

Instead, choose regions where, for a given dark matter profile, the signal-to-background ratio is maximized

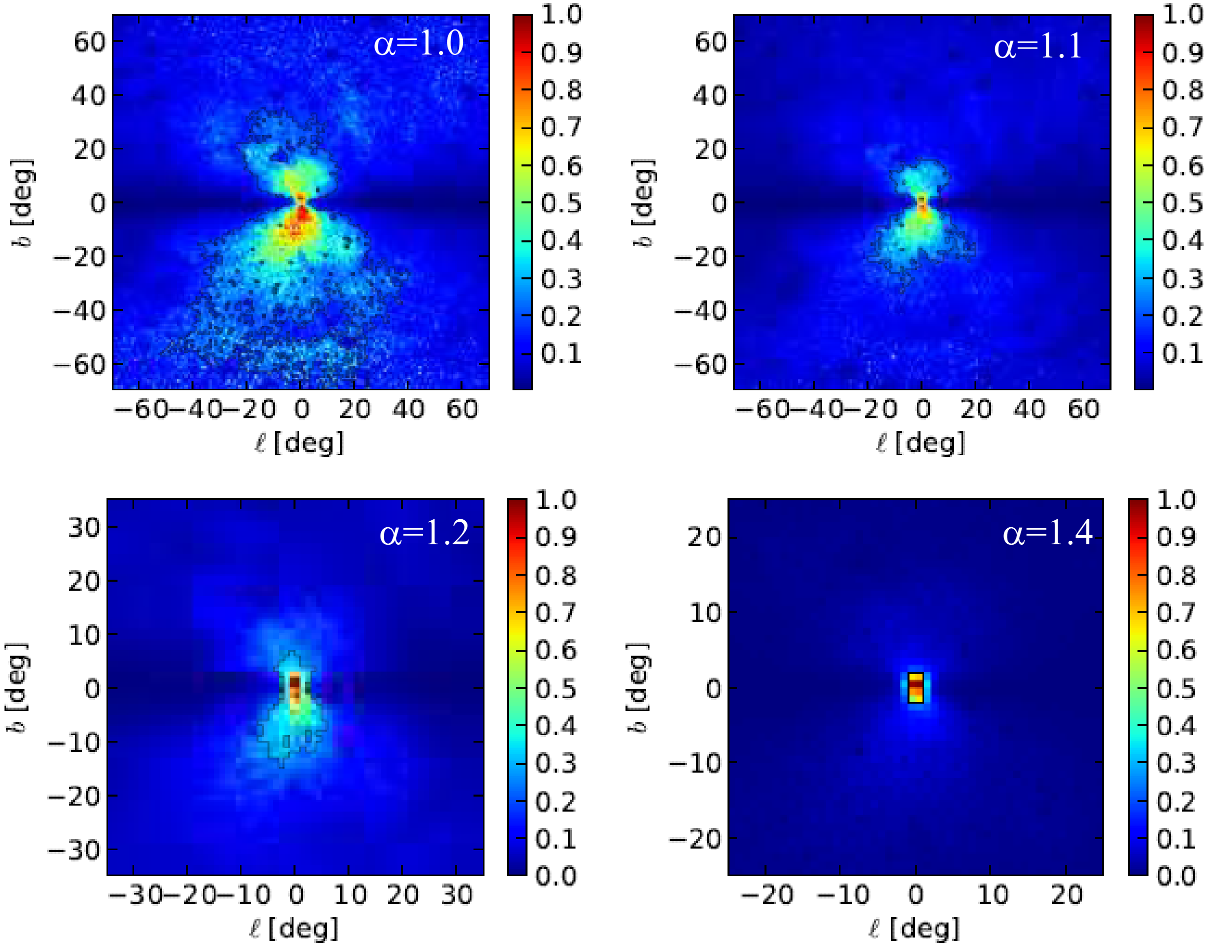


Overcoming backgrounds

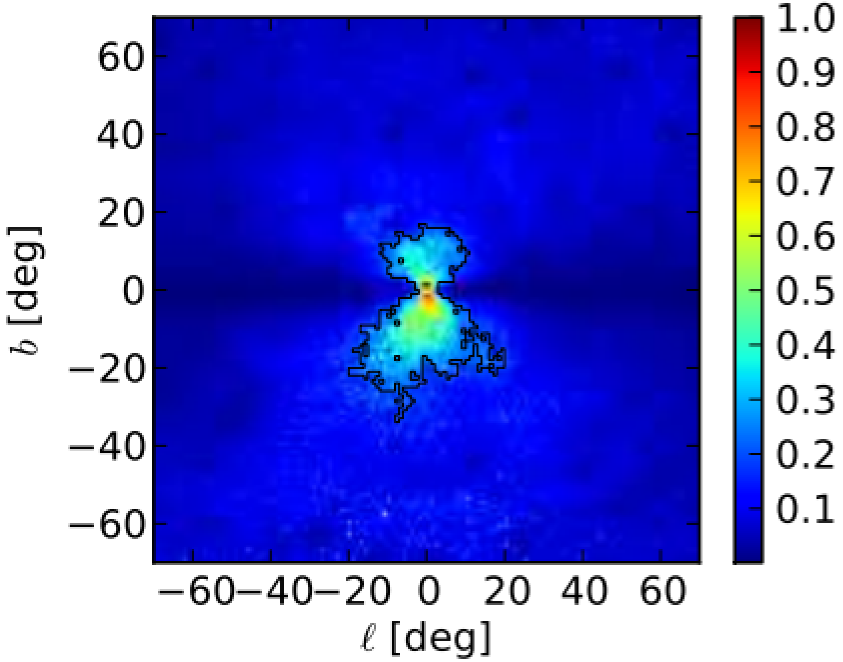
Consider a generalized NFW profile

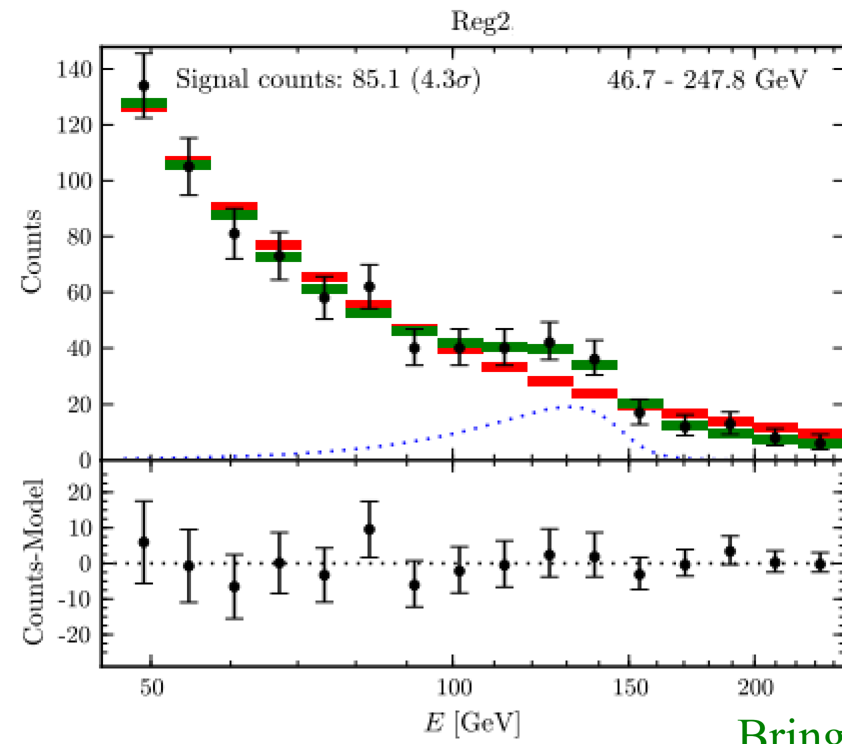
$$\rho_\chi(r) \propto \frac{1}{(r/r_s)^\alpha \, (1 + r/r_s)^{3-\alpha}}$$

Target regions which maximize the signal-to-background ratio:

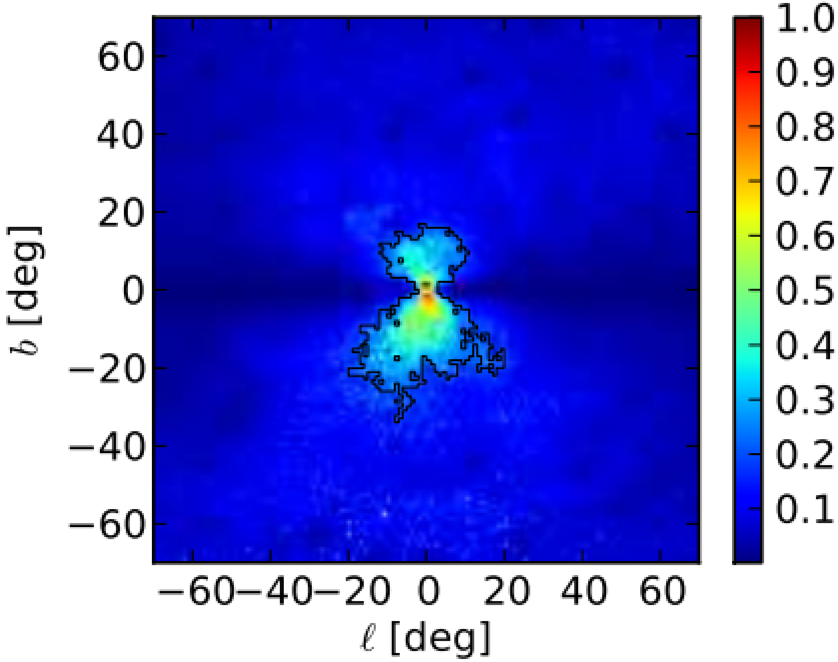


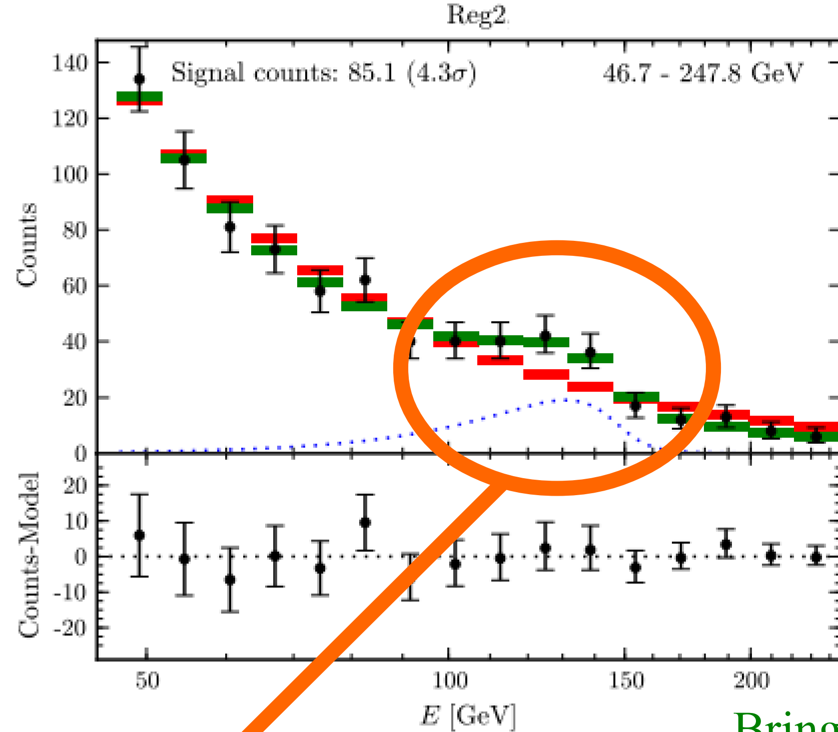
Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312





Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312





Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

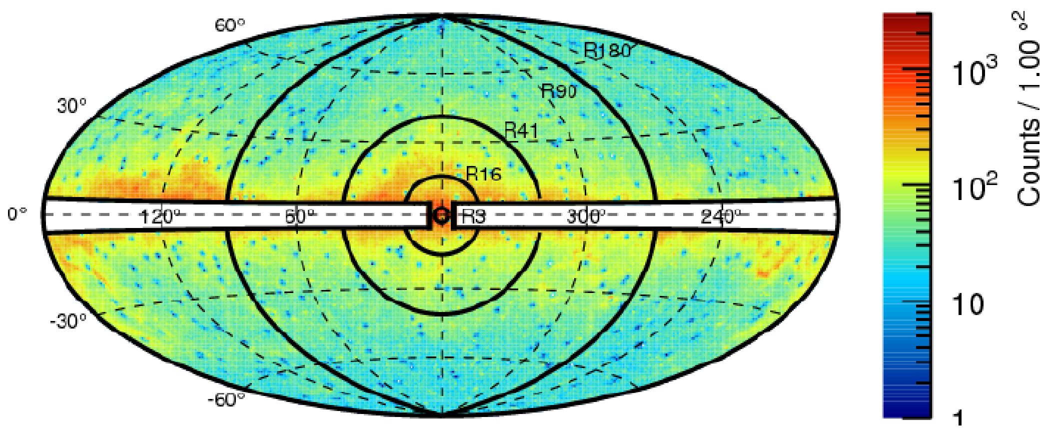
Hint for a line-like gamma ray excess at 130 GeV!

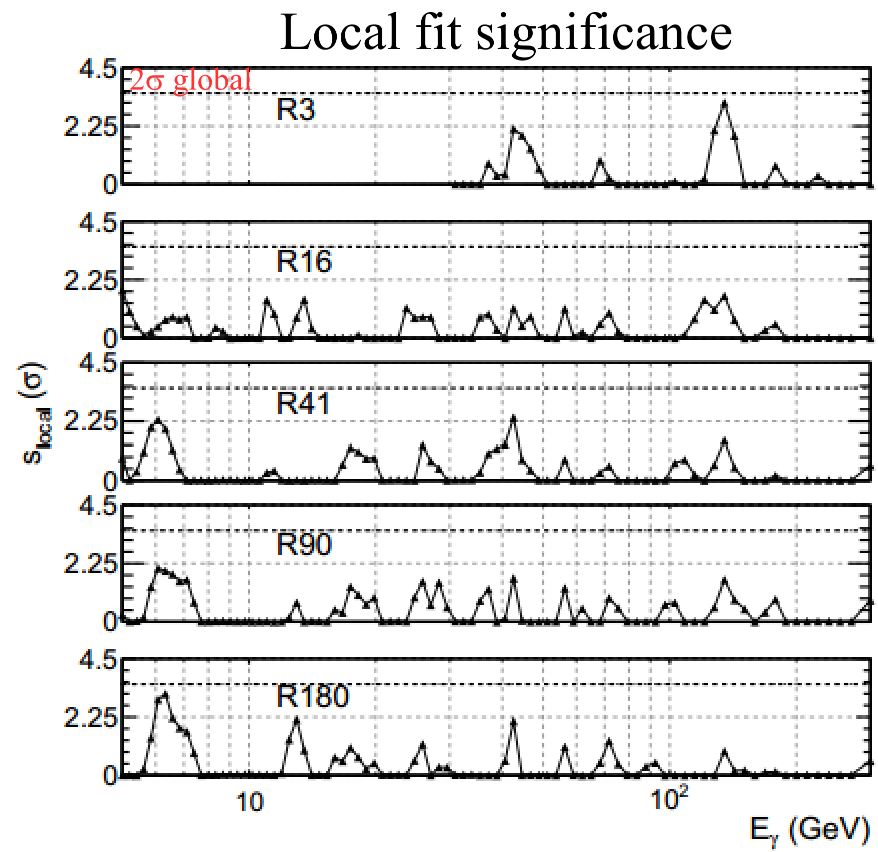
(with a local significance of more than 4σ!)

See also
Weniger, arXiv:1204.2797
Su, Finkbeiner, arXiv:1206.1616
Tempel, Hektor, Raidal, arXiv:1205.1045
…

Latest news on the 130 GeV excess

Fermi-LAT collaboration
arXiv:1305.5597



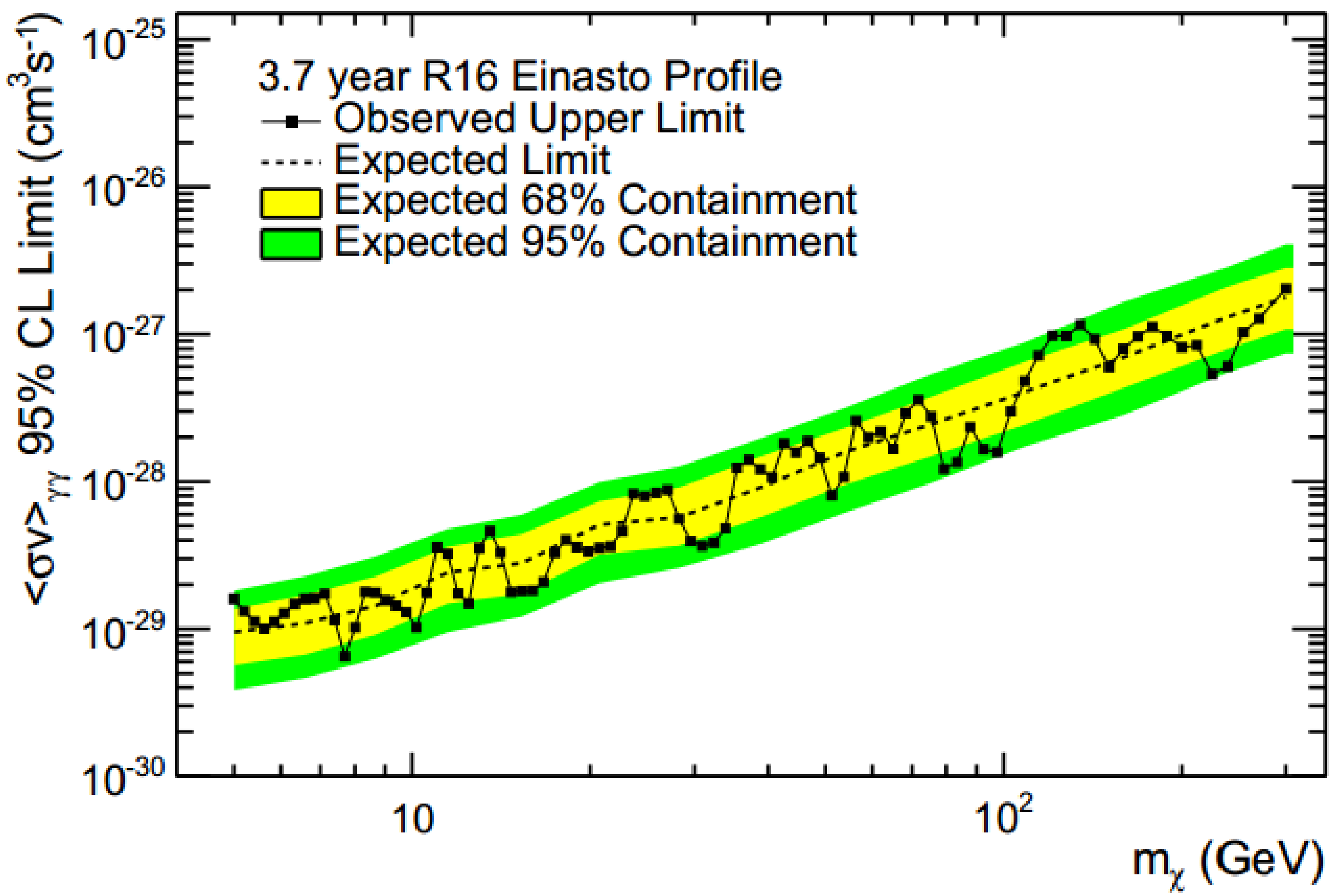


Profile	Annihilation ROI	Annihilation J-factor (10^{22} GeV^2 cm^{-5})	Decay ROI	Decay J-factor (10^{23} GeV cm^{-2})
NFW Contracted	R3	13.9	R180	2.42
Einasto	R16	8.48	R180	2.49
NFW	R41	8.53	R180	2.46
Isothermal	R90	6.94	R180	2.80

Significance reduced to 3.3σ (1.6σ with LEE)

The 130 GeV excess was probably a statistical fluke

Latest news on the 130 GeV excess



Fermi-LAT collaboration
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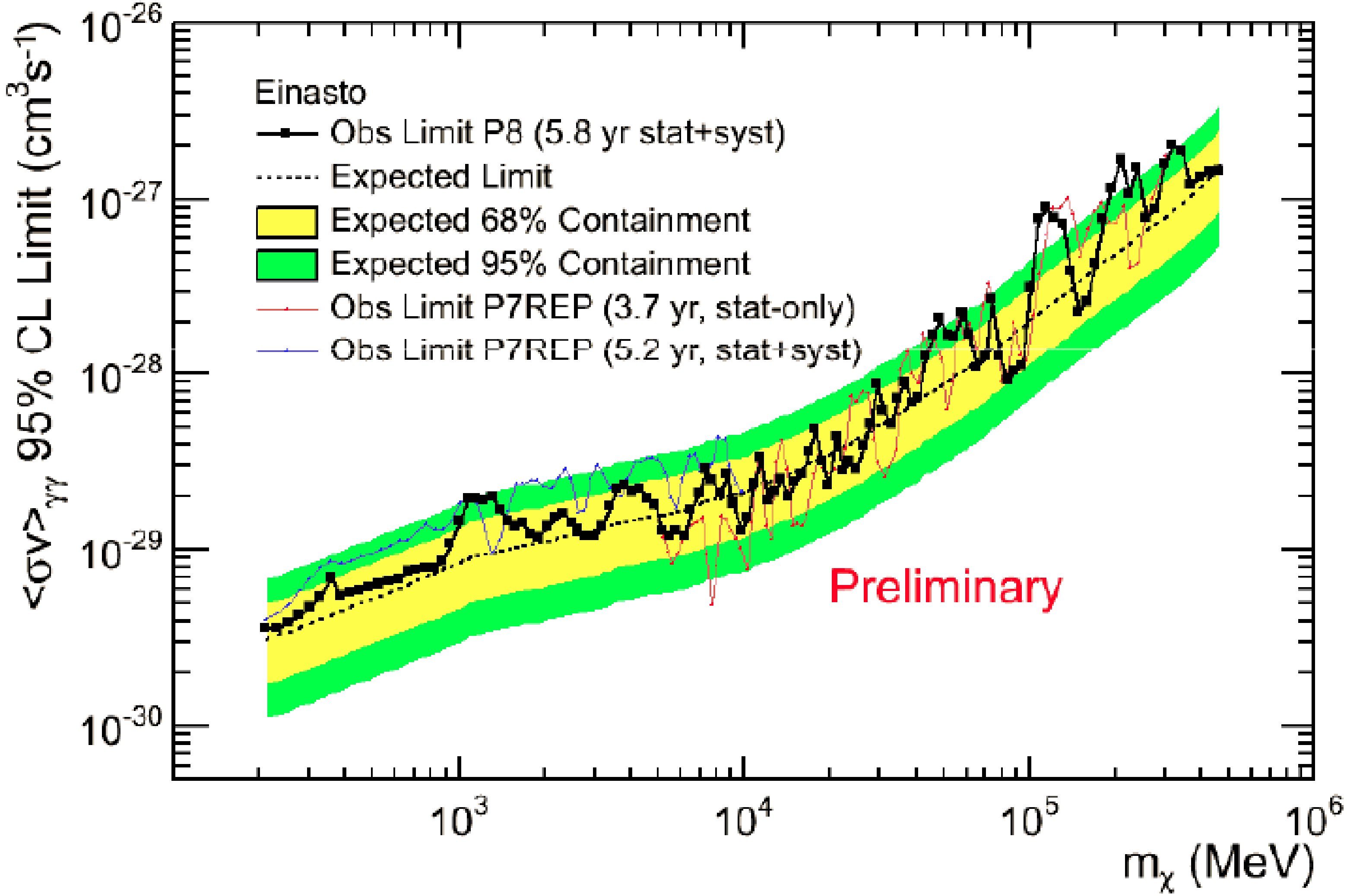
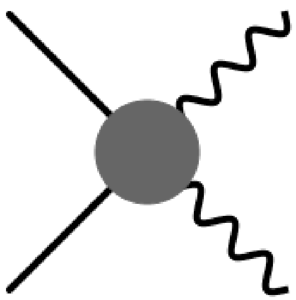


A. Albert
Fermi Symposium
20-24 October 2014

Gamma-ray spectral features in Particle Physics

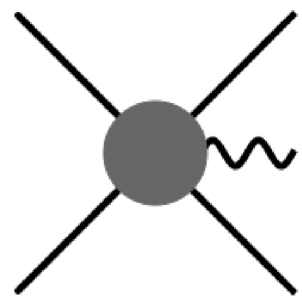
Three gamma-ray spectral features have been identified:

Gamma ray line



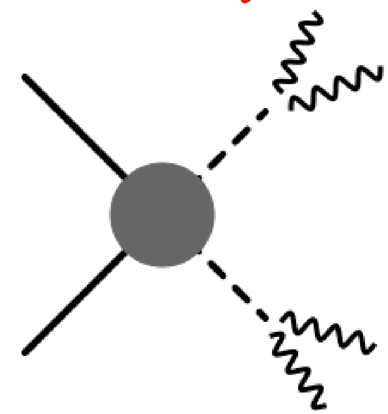
Srednicki, Theisen, Silk '86
Rudaz '86
Bergstrom, Snellman '88

Internal bremsstrahlung



Bergstrom '89
Flores, Olive, Rudaz '89
Bringmann, Bergstrom, Edsjo '08

Gamma ray box

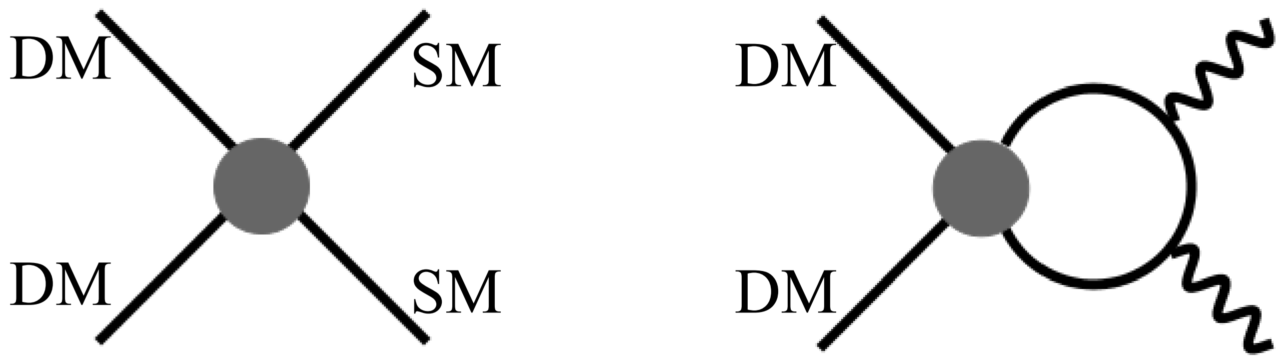


AI, Lopez Gehler, Pato '12

Gamma-ray lines

The dark matter particle is electrically neutral.

The annihilation DM DM → γ γ arises at the one loop level



Monochromatic line → Very distinctive spectrum!

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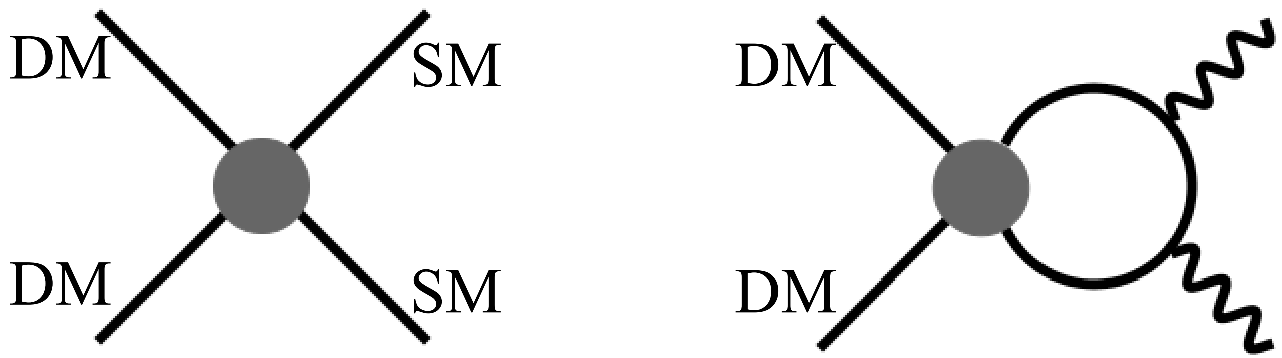
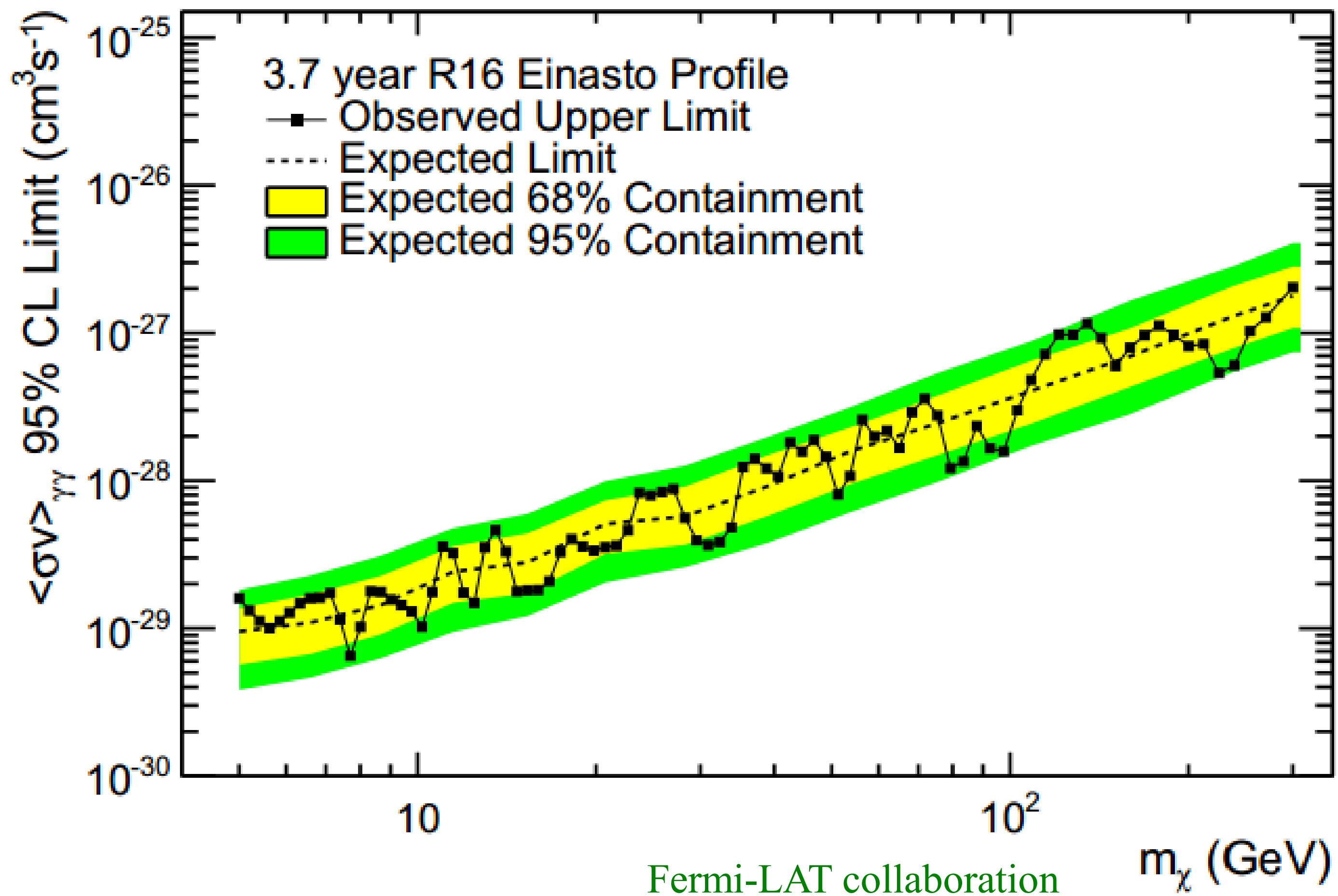


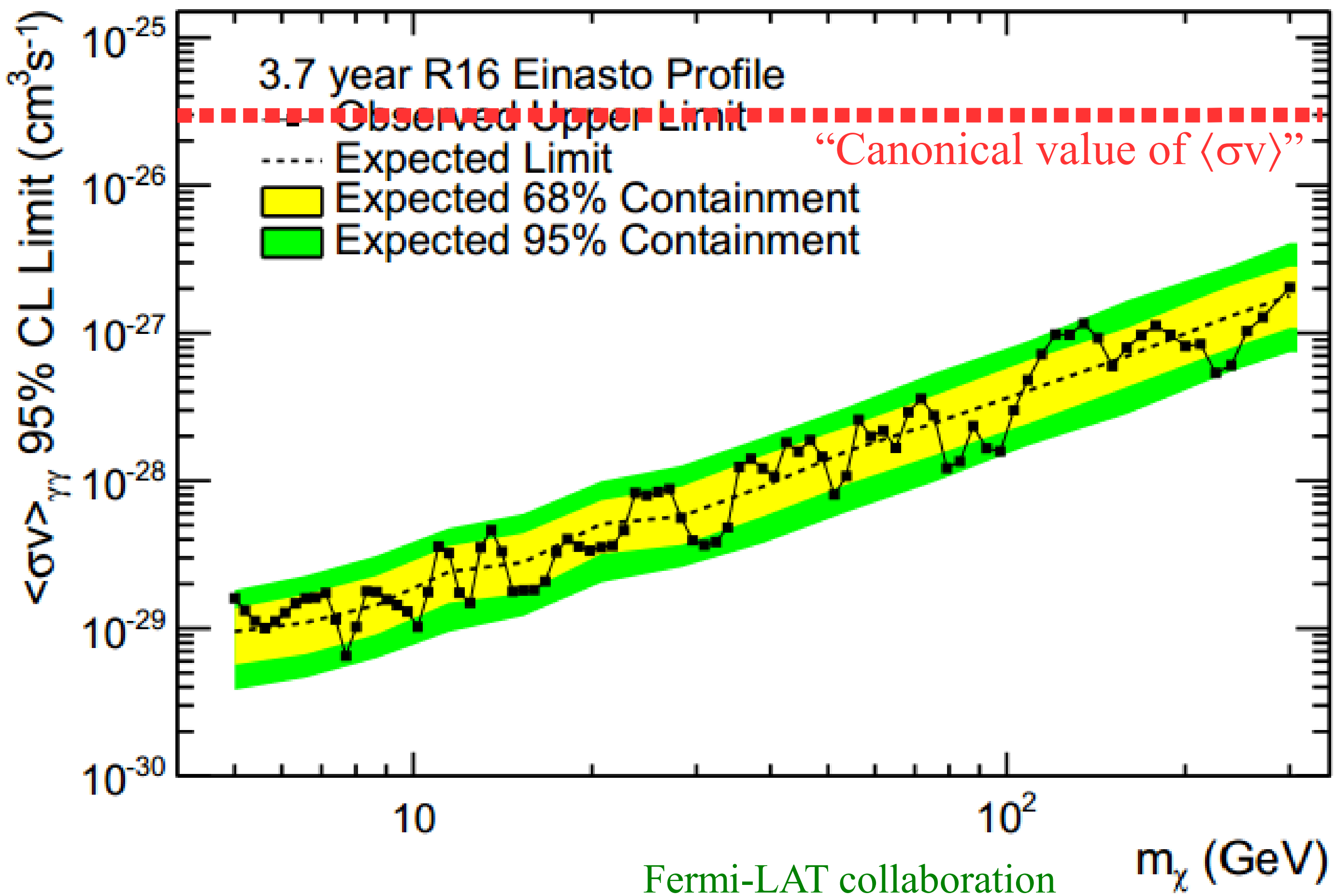
Monochromatic line → Very distinctive spectrum!

However, with a very suppressed rate:

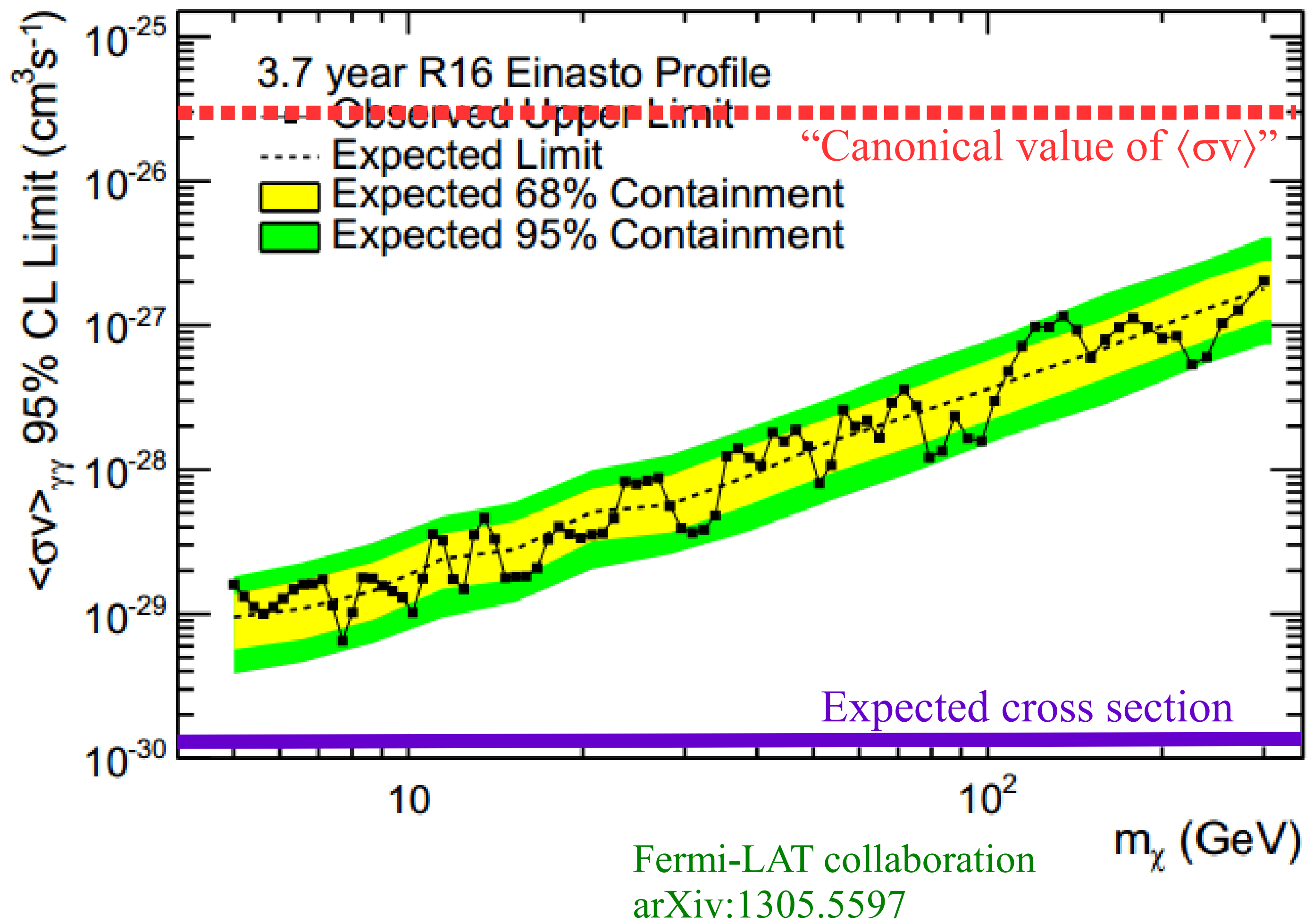
$$(\sigma v)_{\gamma\gamma} \sim \mathcal{O}(\alpha^2)(\sigma v)_{\rm thermal} \sim 10^{-30}{\rm cm}^3{\rm s}^{-1}$$



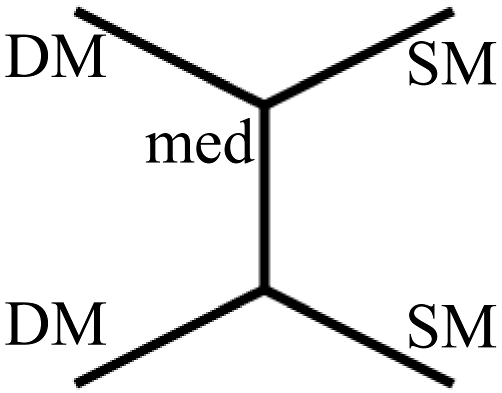
Fermi-LAT collaboration
arXiv:1305.5597



Fermi-LAT collaboration
arXiv:1305.5597


3.7 year R16 Einasto Profile
Observed Upper Limit
Expected Limit
Expected 68% Containment
Expected 95% Containment
“Canonical value of ⟨σv⟩”
Expected cross section
$\langle\sigma v\rangle_{\gamma\gamma}$ 95% CL Limit ($cm^3 s^{-1}$)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10
10^2
m_χ (GeV)
Fermi-LAT collaboration
arXiv:1305.5597

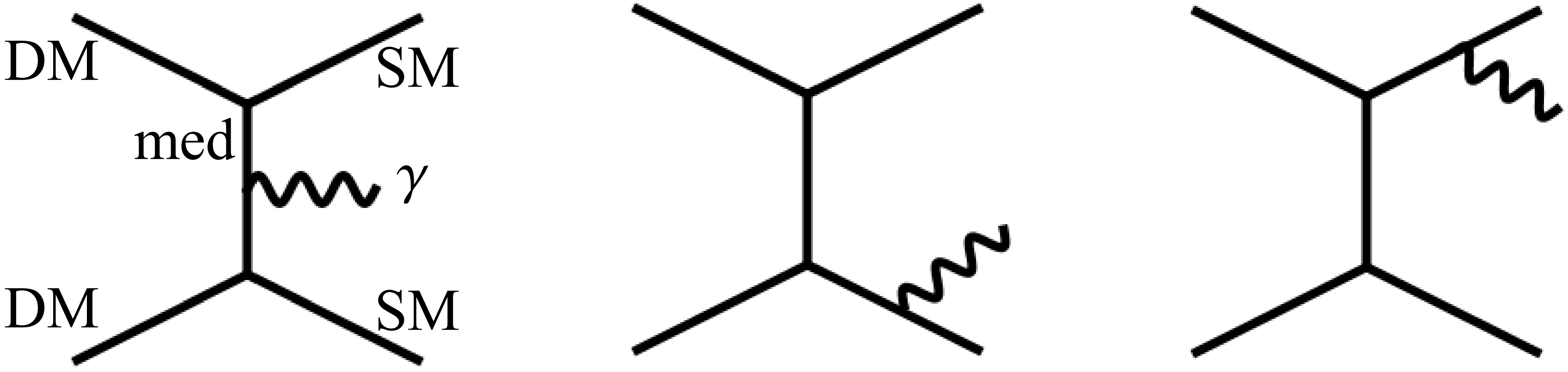
Internal bremsstrahlung



Assume a model where the dark matter particle annihilates into Standard Model light particles via the interaction with a mediator in the t-channel

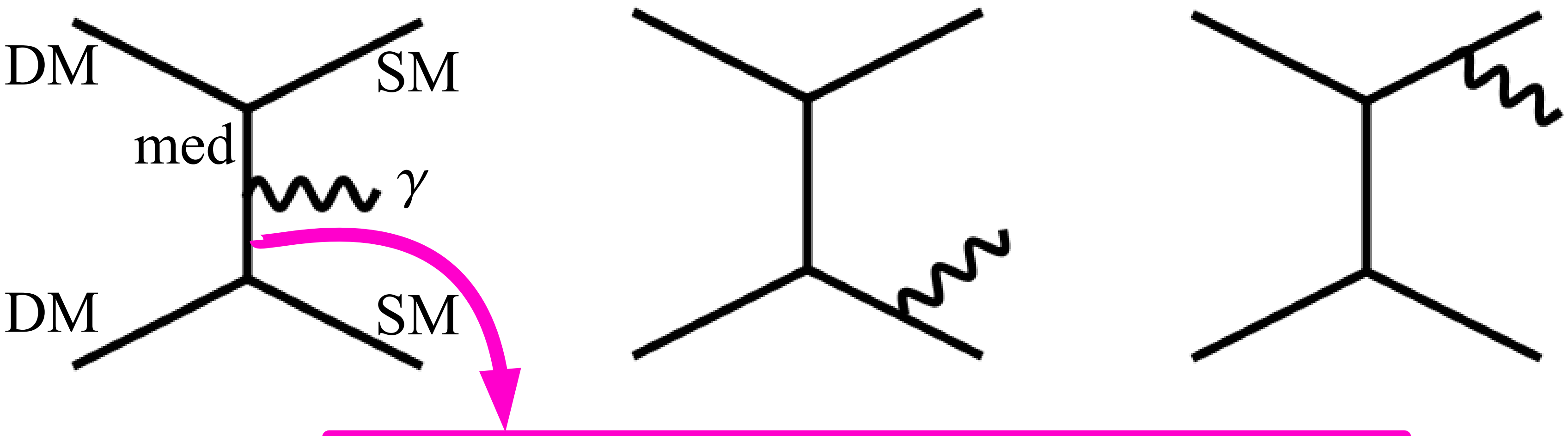
Internal bremsstrahlung

Diagrams contributing to the process DM DM → SM SM γ:



Internal bremsstrahlung

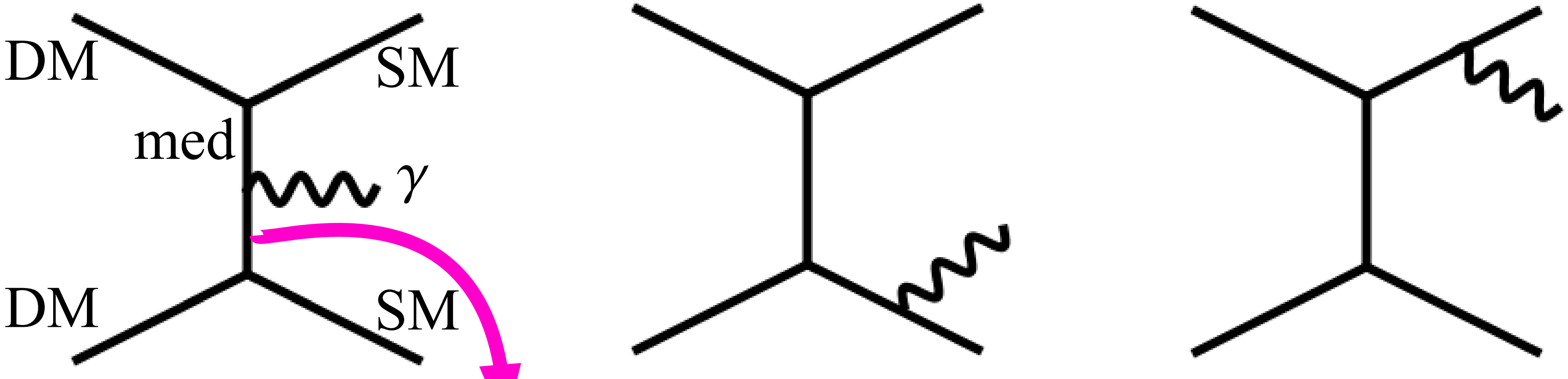
Diagrams contributing to the process DM DM → SM SM γ:



$$\Delta(p) \propto \left((p_{\rm DM} - p_{\rm SM})^2 - m_{\rm med}^2\right)^{-1}$$
$$\approx \left(m_{\rm DM}^2 - 2m_{\rm DM}E_{\rm SM} - m_{\rm med}^2\right)^{-1}$$

Internal bremsstrahlung

Diagrams contributing to the process DM DM $\rightarrow$ SM SM γ:

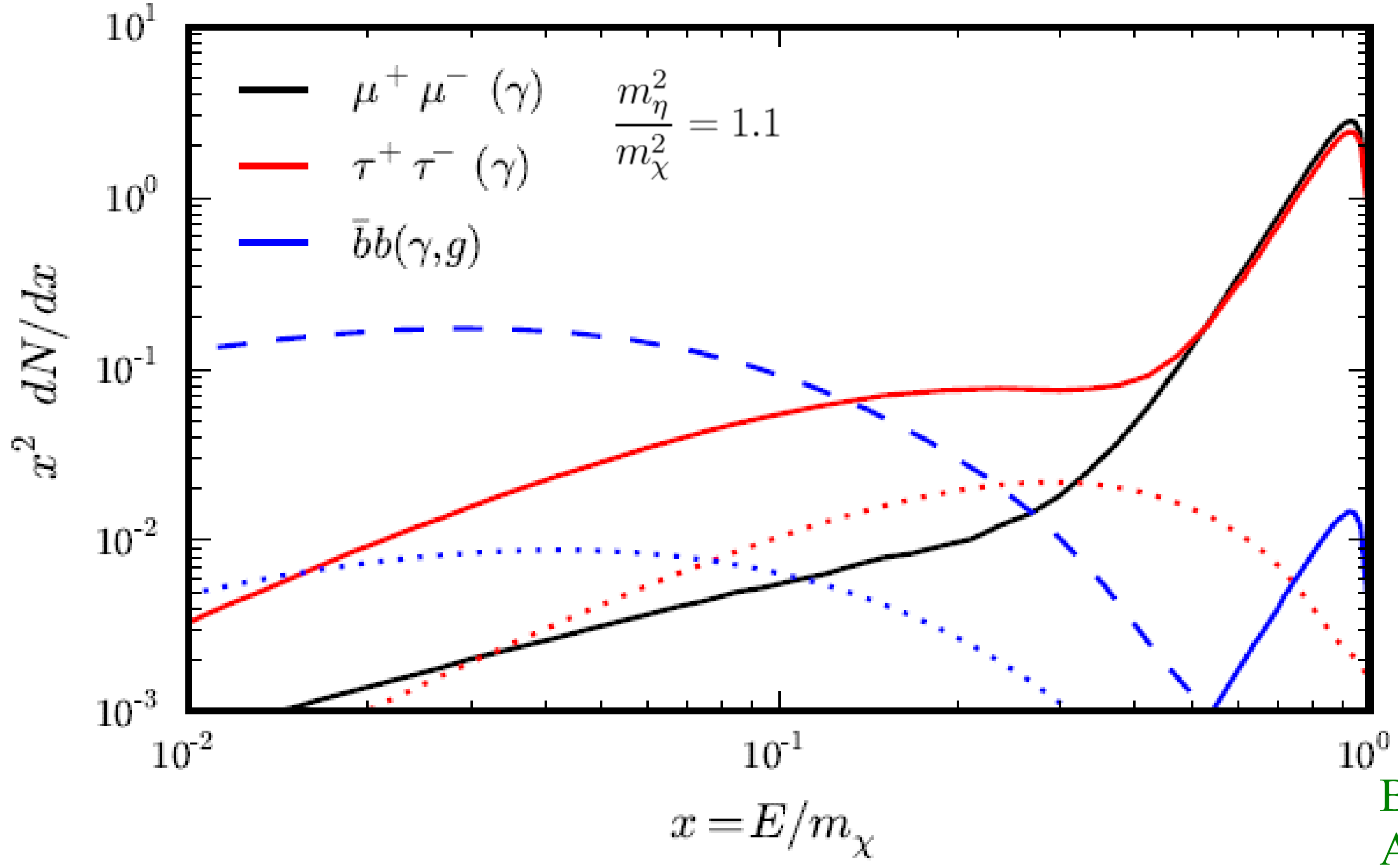


$$\Delta(p) \propto \left((p_{\rm DM} - p_{\rm SM})^2 - m_{\rm med}^2\right)^{-1} \approx \left(m_{\rm DM}^2 - 2m_{\rm DM}E_{\rm SM} - m_{\rm med}^2\right)^{-1}$$

In the case $m_{\rm DM} \approx m_{\rm med}$ the scalar propagator gets enhanced when $E_{\rm SM}$ is small.

Enhancement of the amplitude (and the rate) when E_γ is close to the kinematic end-point.

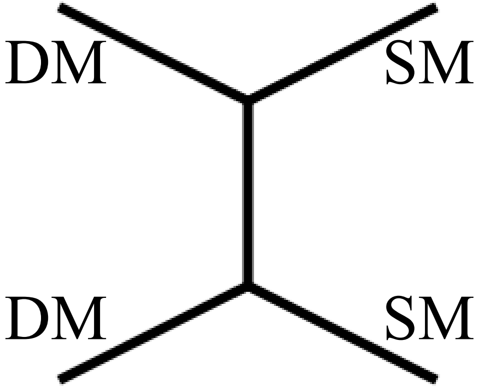
Internal bremsstrahlung



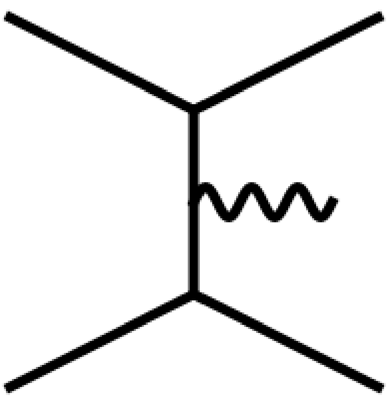
Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

Internal bremsstrahlung

Expected annihilation cross section for the 2 → 3 process.



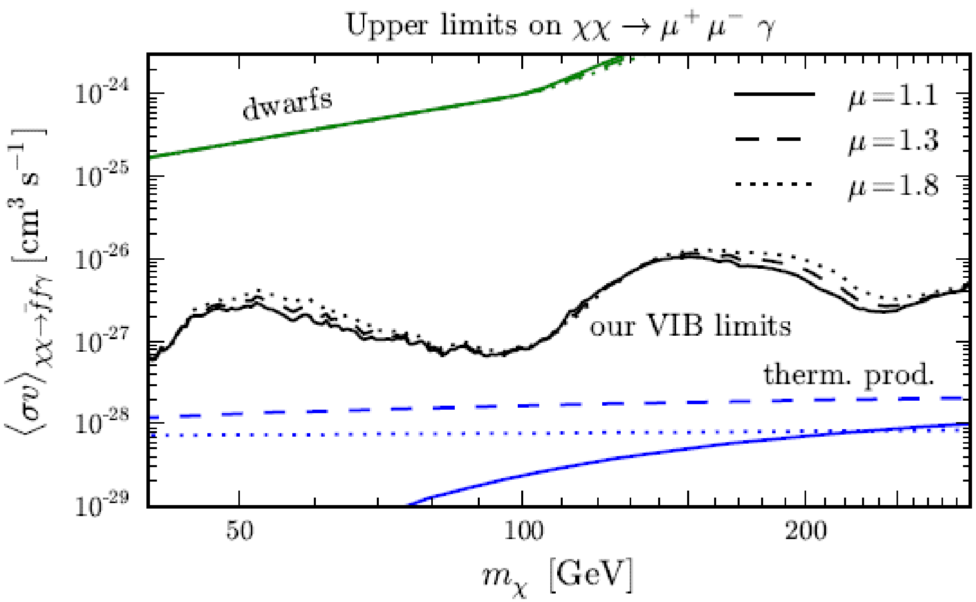
$$\langle \sigma v \rangle^{2\to2}_{f.o.} \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

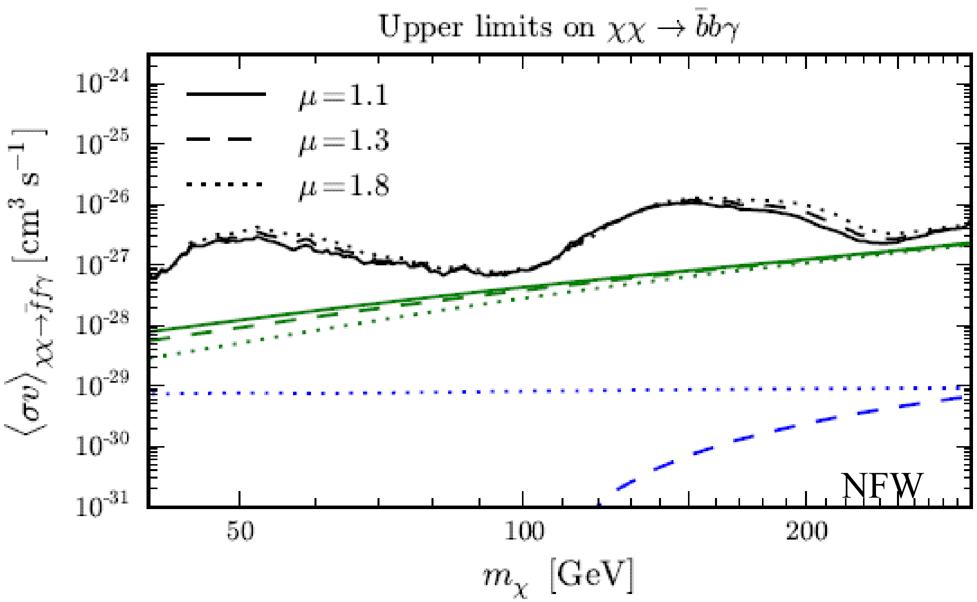


+ ...

$$\langle \sigma v \rangle^{2\to3}_{G.C.} \sim \frac{\alpha}{0.3\pi} \langle \sigma v \rangle^{2\to2}_{f.o.} \sim 10^{-28} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Limits on the annihilation cross section from the Fermi-LAT data





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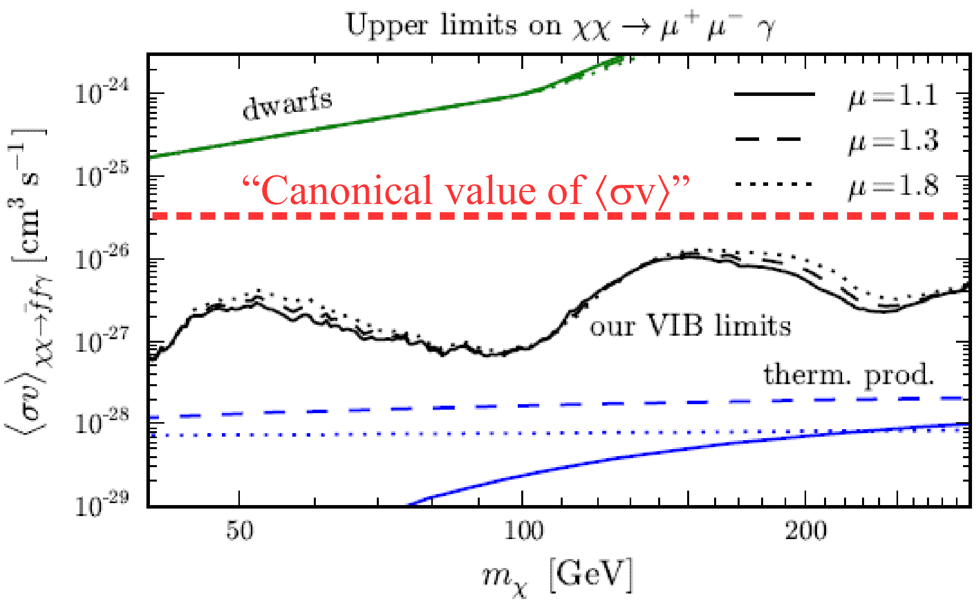

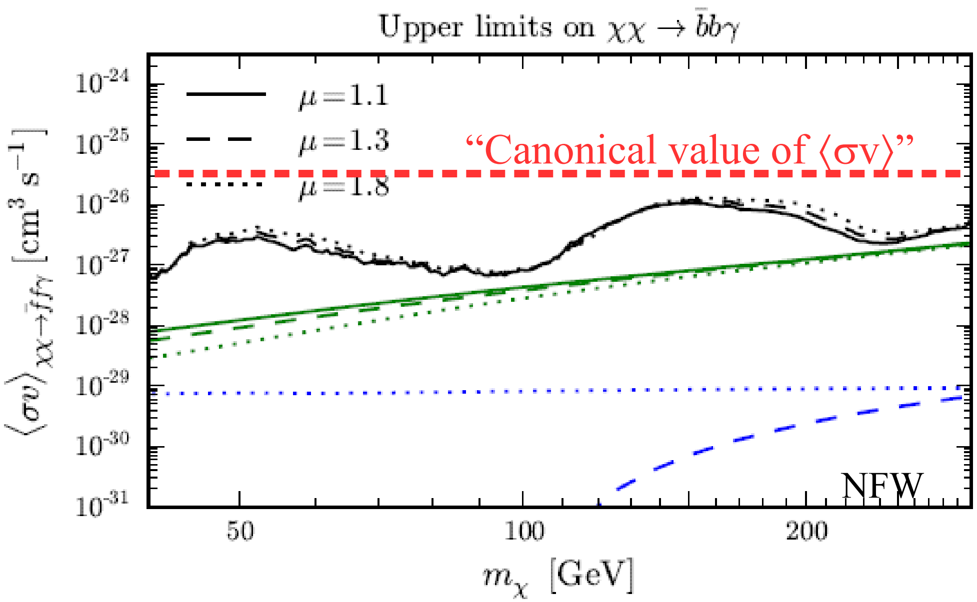

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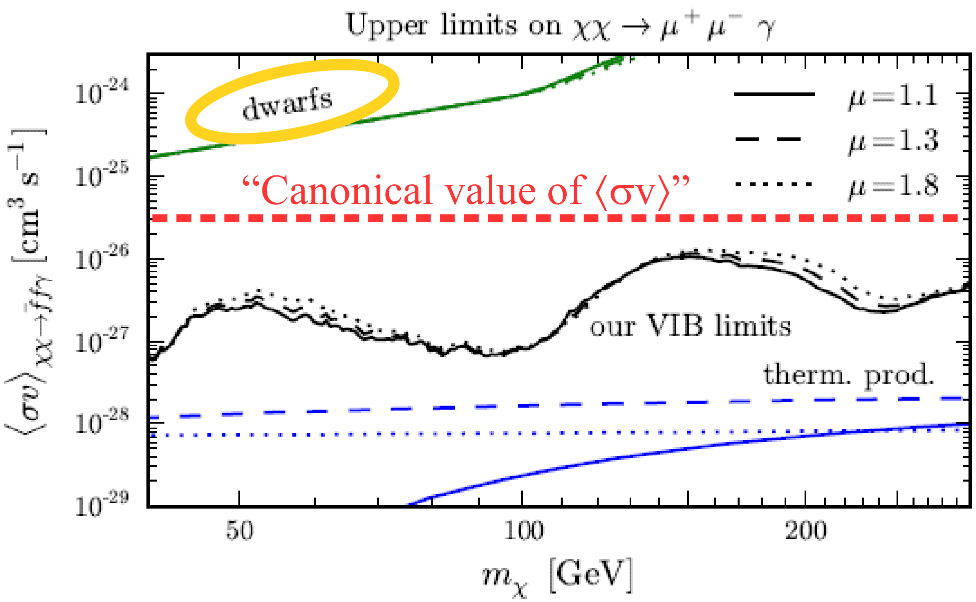
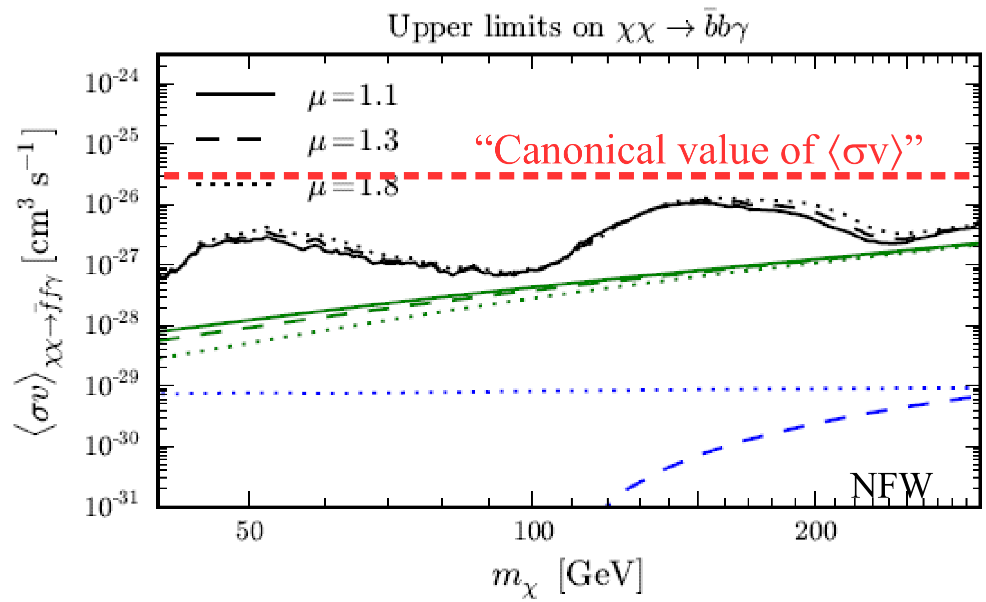


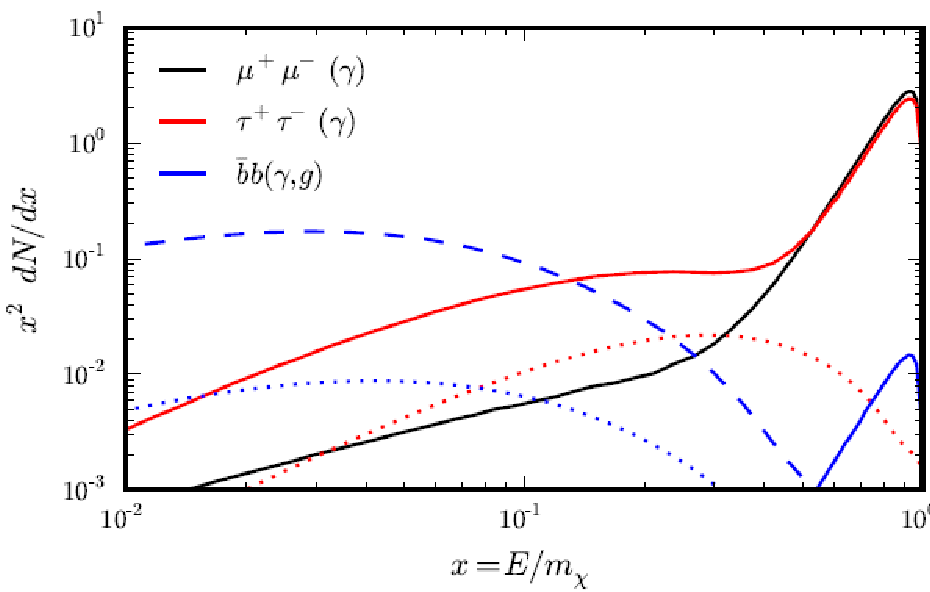


Limit on the total annihilation cross section from dwarf galaxy observations

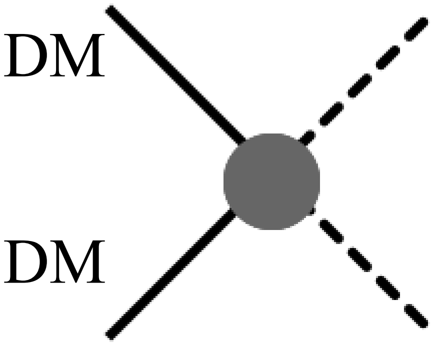
$$\langle\sigma v\rangle < 8\pi \frac{m_\chi^2}{N_\gamma^{\rm tot}} \times 5.0 \times 10^{-30} \mathrm{cm^3 s^{-1} GeV^{-2}}$$

$N_\gamma^{\rm tot}$= Number of photons with E=1-100 GeV

Geringer-Sameth, Koushiappas, arXiv:1108.2914

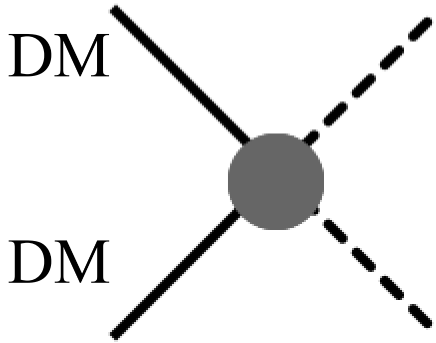


Gamma-ray box



Assume on shell production of an intermediate scalar, ϕ.

Gamma-ray box



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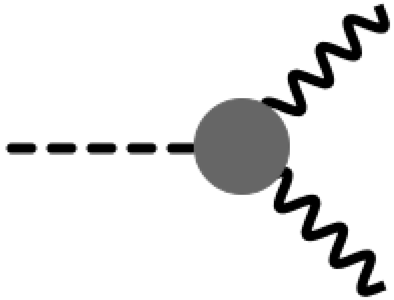
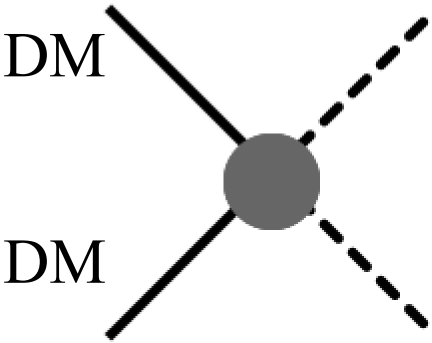


Assume that the scalar decays into two photons

Photon spectrum in the rest frame of the scalar

$$\frac{dN}{dE_\gamma^{\mathrm{RF}}} = 2\delta(E_\gamma^{\mathrm{RF}} - m_\phi/2)$$

Gamma-ray box



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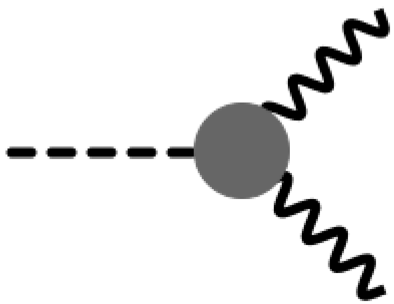

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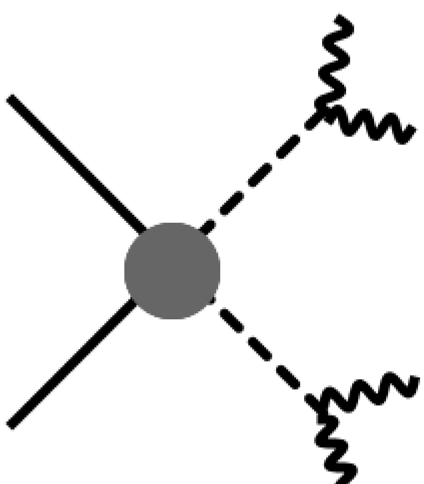
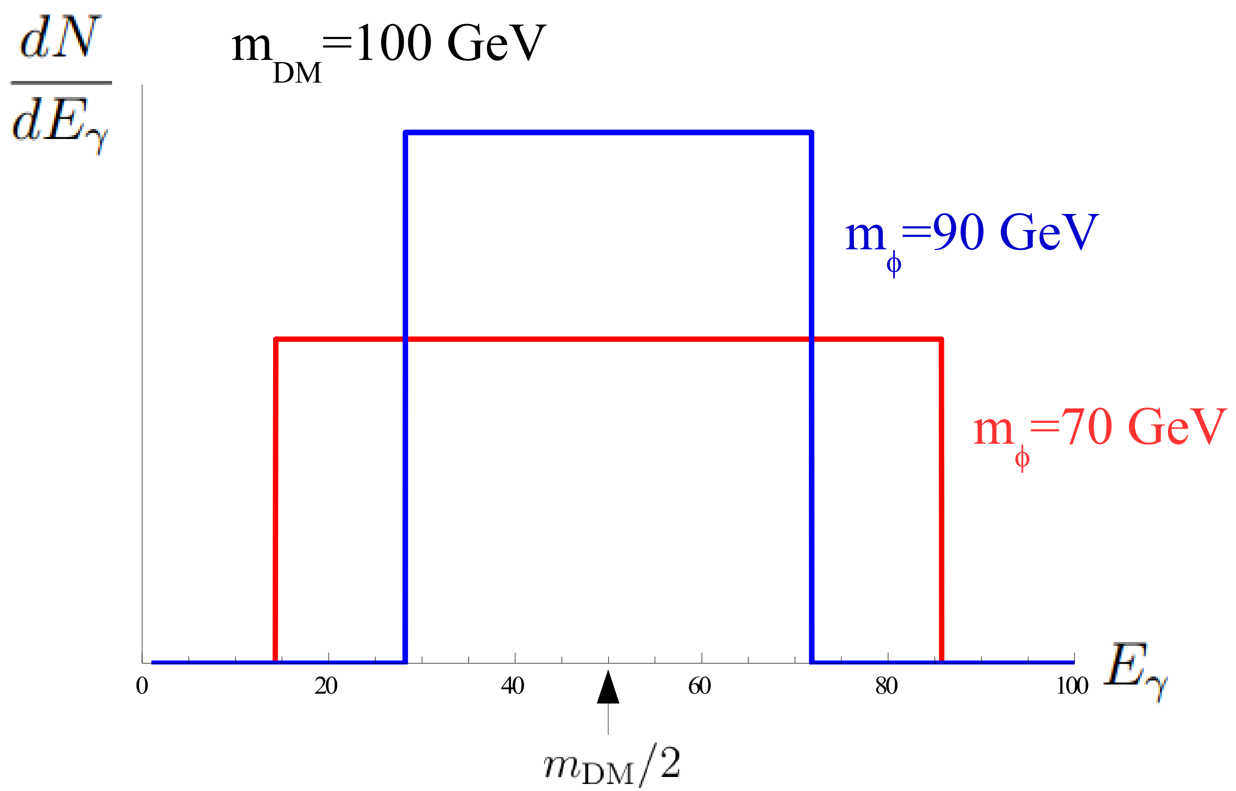


Photon spectrum in the galactic frame

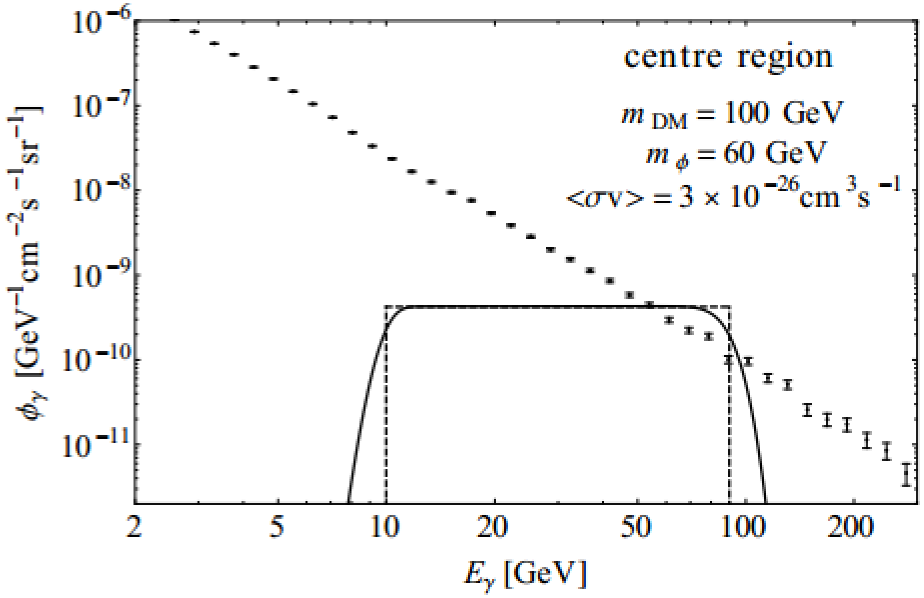
$$\frac{dN}{dE_\gamma} = \frac{4}{\Delta E}\Theta(E_\gamma - E_-)\Theta(E_+ - E_\gamma)$$

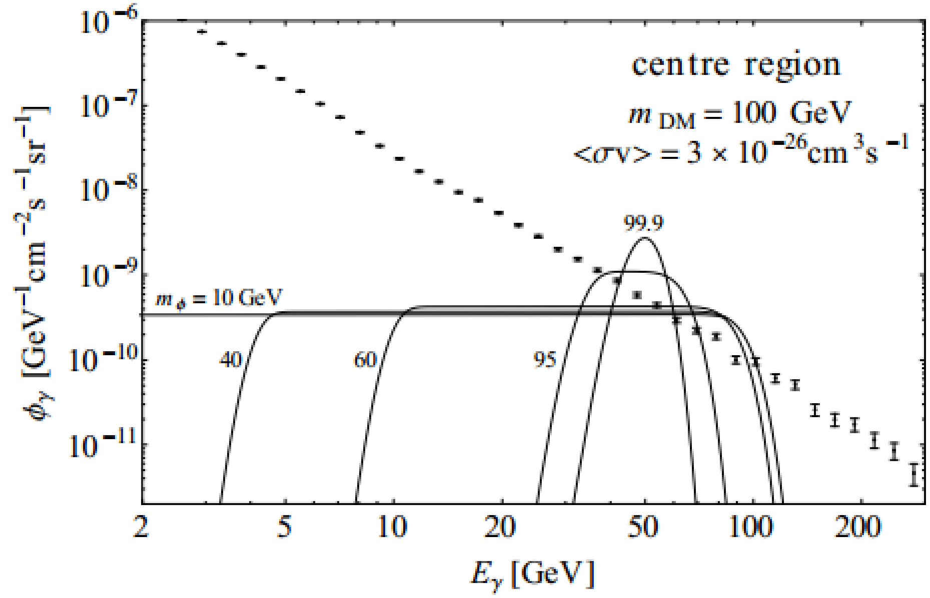
$$\frac{dN}{dE_\gamma} = \frac{4}{\Delta E}\Theta(E_\gamma - E_-)\Theta(E_+ - E_\gamma)$$

"box-shaped spectrum"

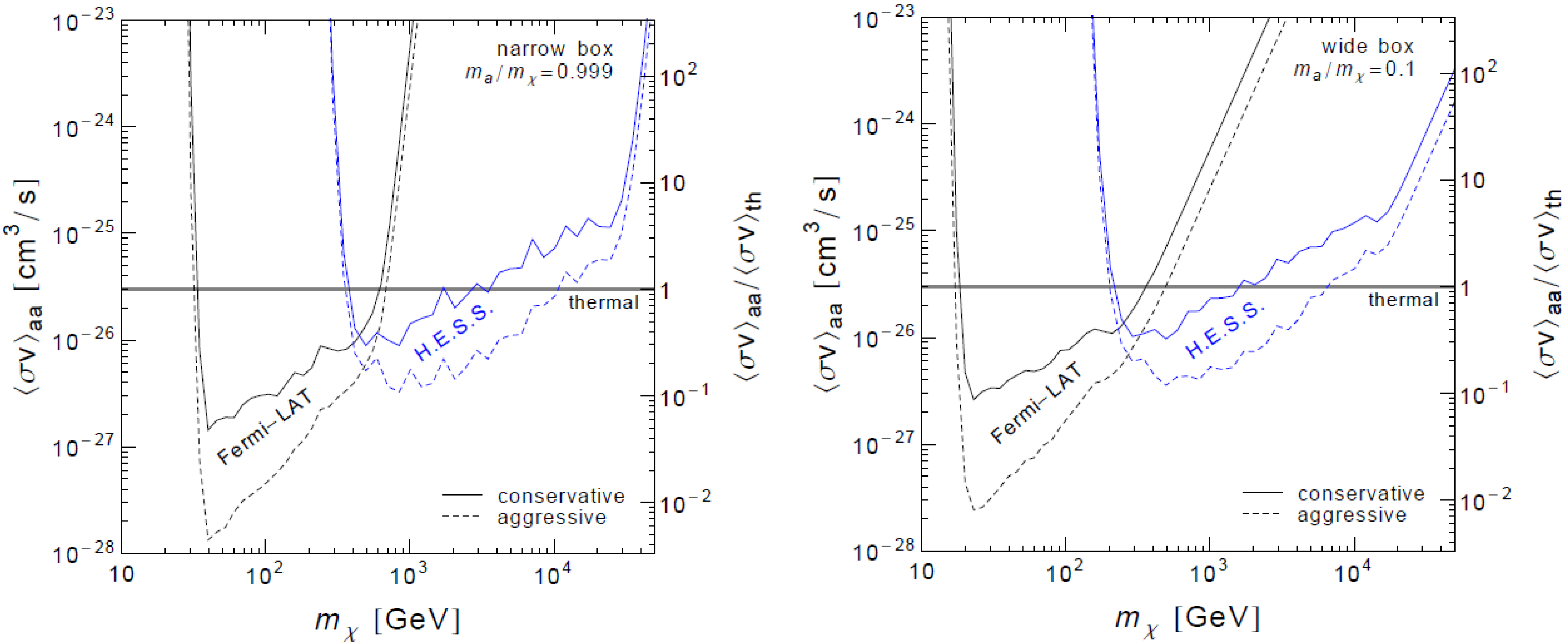


New aspect: the spectral feature arises from a tree level 2→2 annihilation. The strength of the signal could be unsuppressed, depending on the cross section DM DM → ϕϕ and BR(ϕ→γγ).

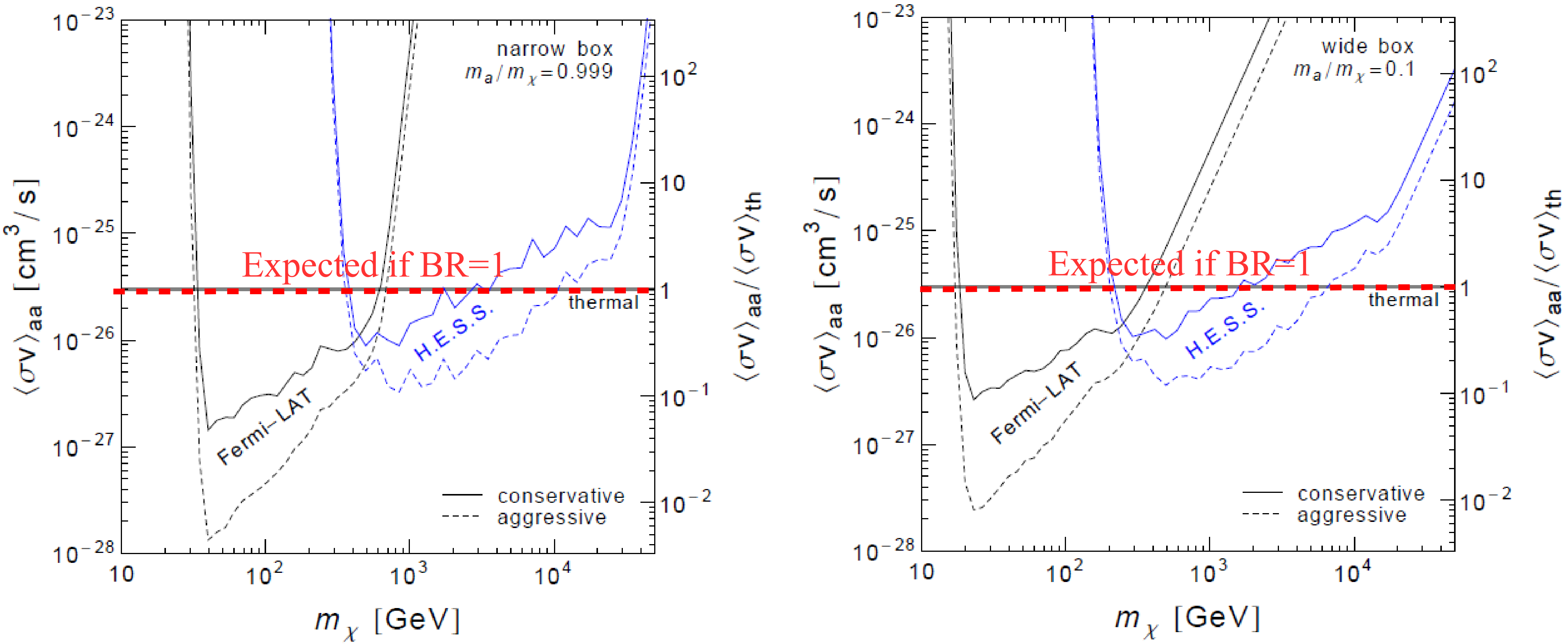




AI, Lopez Gehler, Pato
arXiv:1205.0007



AI, Lee, Lopez Gehler, Park, Pato
arXiv:1303.6632



AI, Lee, Lopez Gehler, Park, Pato
arXiv:1303.6632

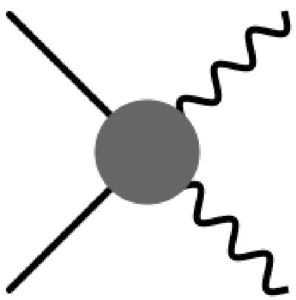
Gamma-ray spectral features in Particle Physics

Recapitulation

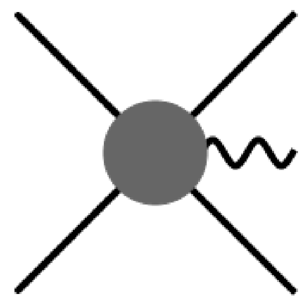
"Smoking gun" for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

Three gamma-ray spectral features have been identified:

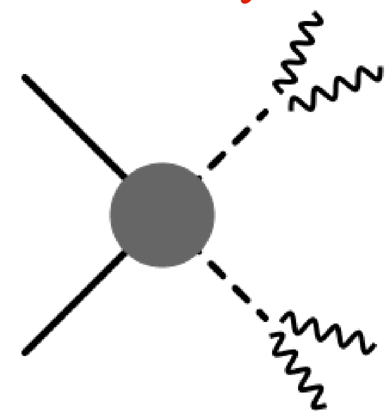
Gamma ray line

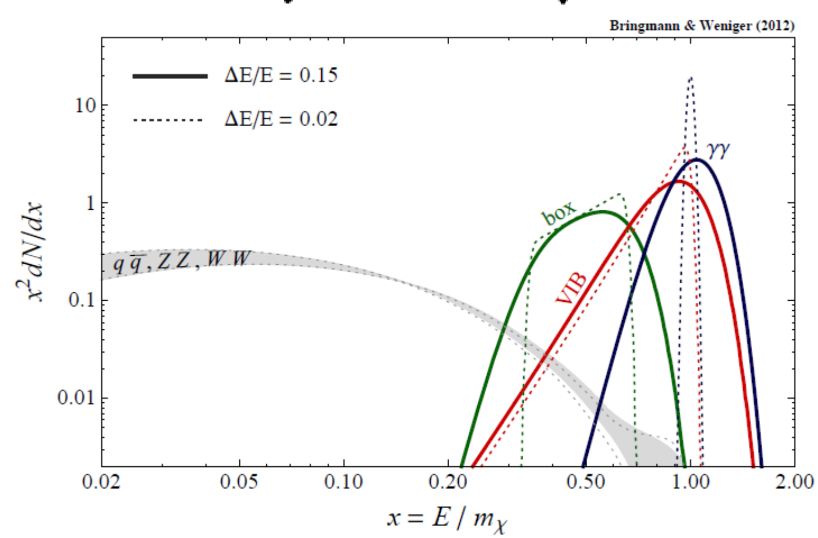


Internal bremsstrahlung



Gamma ray box





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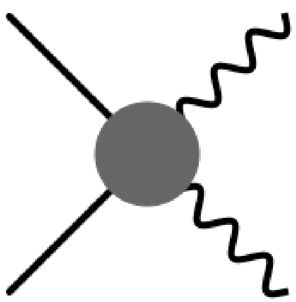
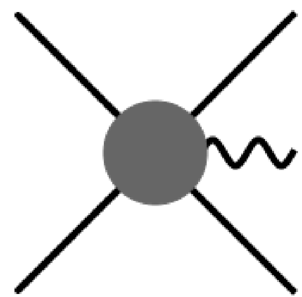


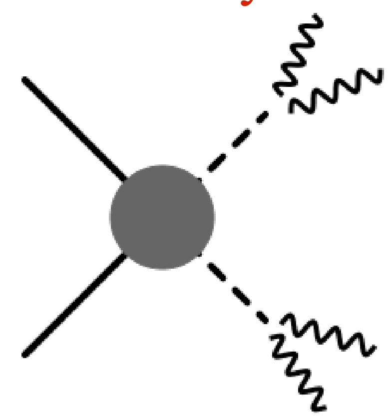
$$\langle \sigma v \rangle^{\text{expected}} \lesssim 10^{-30} \text{cm}^3 \text{s}^{-1}$$

Internal bremsstrahlung



$$\langle \sigma v \rangle^{\text{expected}} \lesssim 10^{-28}\, \text{cm}^3\, \text{s}^{-1}$$

Gamma ray box



$$\langle \sigma v \rangle^{\text{expected}} \lesssim 10^{-26}\, \text{cm}^3\, \text{s}^{-1}$$

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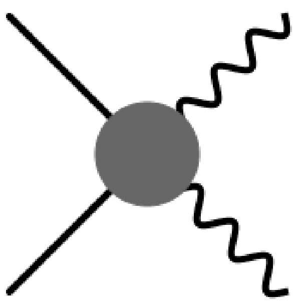

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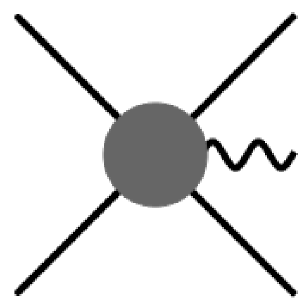

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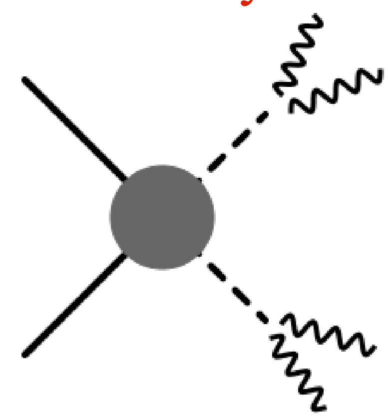
Gamma ray box



$\langle\sigma v\rangle^{\rm expected} \lesssim 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$

Rather suppressed rates...

Could the observation of spectral features be precluded by other experiments?

A simplified model generating spectral features

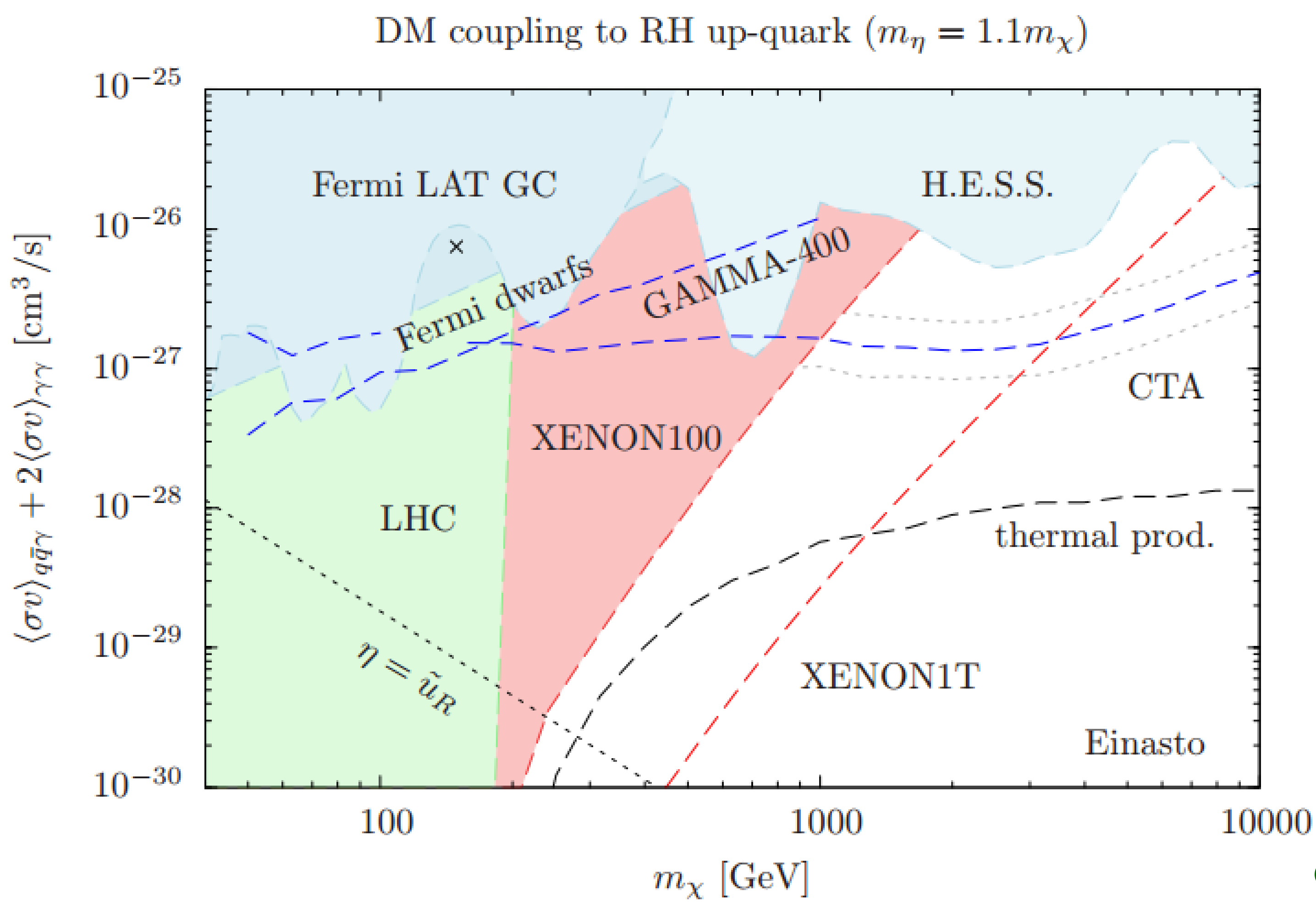
Consider a toy model consisting on a Majorana dark matter particle, χ, an intermediate charged scalar particle, η, and a light SM fermion, f.

Interaction Lagrangian: $\mathcal{L}_{\rm int} = -y\bar{\chi} f_R \eta + \rm{h.c.}$

Simple model, but rich phenomenology

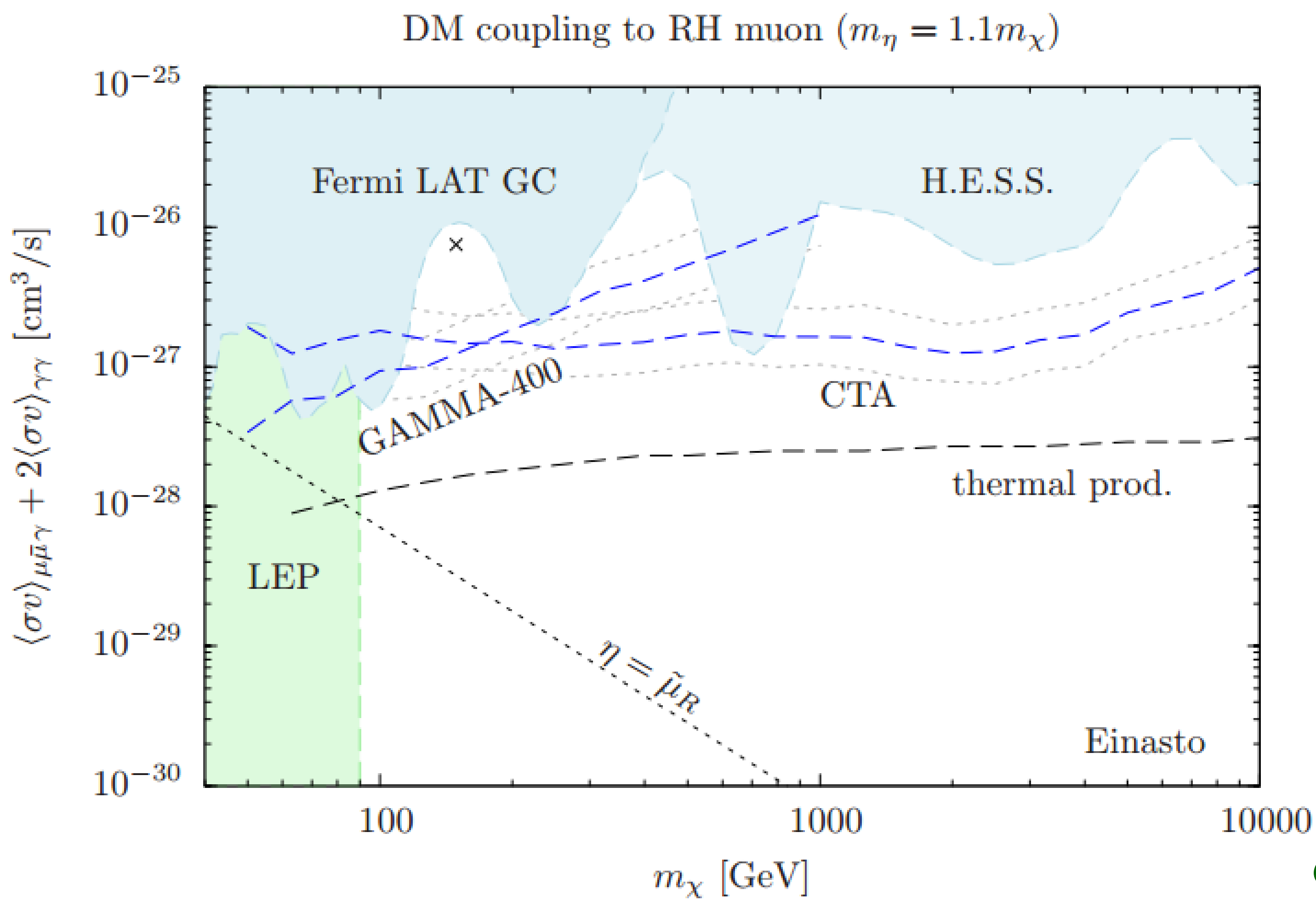
- Gamma-ray spectral features
- Antimatter production in annihilations.
- Signals at direct detection experiments.
- Signals at colliders.
- High energy neutrinos from the Sun.

Limits on the model parameters from XENON100 and from the LHC translate into limits on the production rate of spectral features.



Garny, AI, Pato, Vogl
arXiv:1306.6342

The limits from XENON100 and from the LHC are weaker for "leptophilic" models.



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Conclusions

- The indirect search for dark matter is hindered by the existence of large (and still poorly understood) astrophysical backgrounds.

- In order to claim a dark matter signal, it is necessary to devise strategies to suppress the backgrounds.

- A promising approach consists in searching for sharp features in the gamma-ray spectrum. No known astrophysical process can produce such a signal in the 100 GeV - TeV range → "smoking gun" for DM detection.

- From the particle physics side, spectral features are predicted in simple models. The predicted rates are usually fairly small.

- Other observations already constrain the possibility of observing gamma-ray spectral features. Important to assess the prospects to observe a signal in future experiments.

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Thank you for your attention!