# Searching for sharp gamma-ray spectral features from dark matter annihilation


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30 October 2015

# Motivation

Indirect dark matter detection:

- Test of particle DM
  - Information on the parameters of the dark sector (DM mass, couplings...)
  - Complementary to direct detection and collider searches

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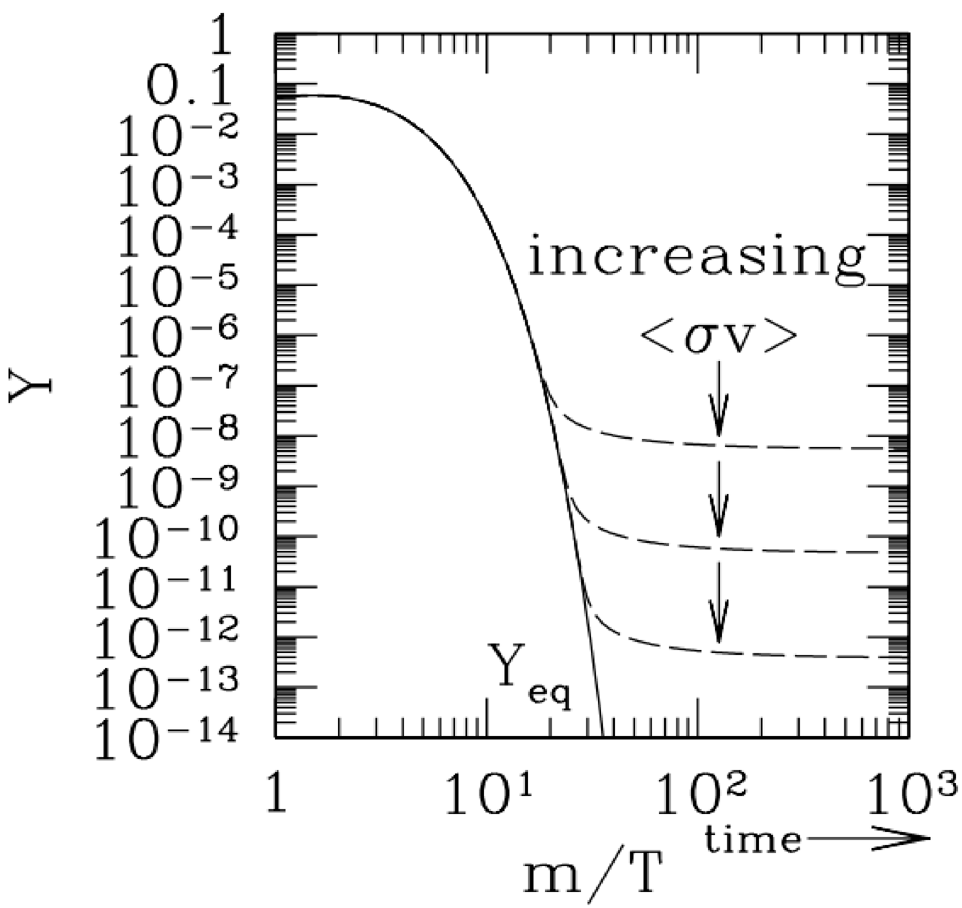
Indirect dark matter detection:

Test of particle DM

Information on the parameters of the dark sector (DM mass, couplings...)

Complementary to direct detection and collider searches

Test of DM production via thermal freeze-out

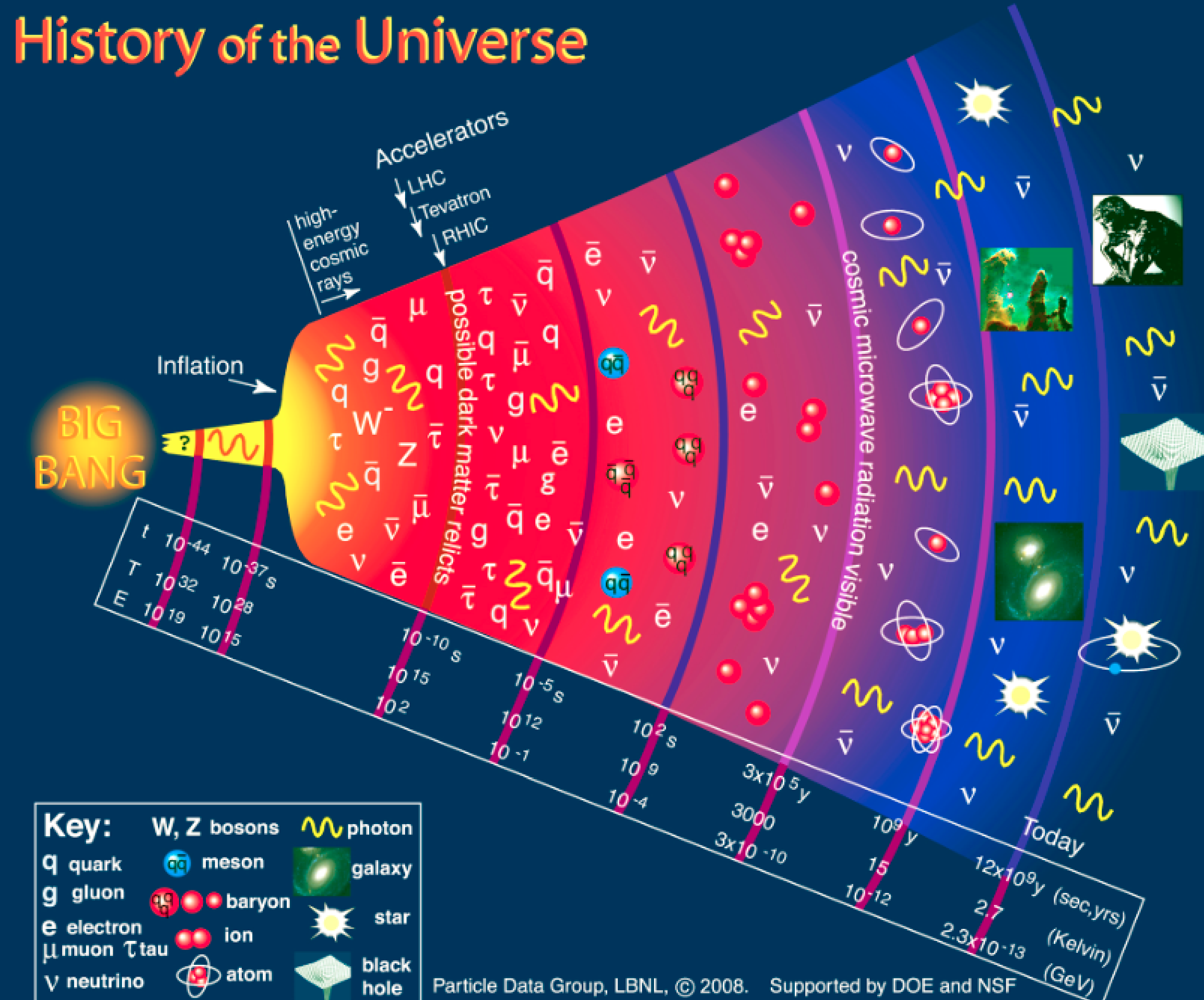



Under plausible conditions, the expected relic abundance is:

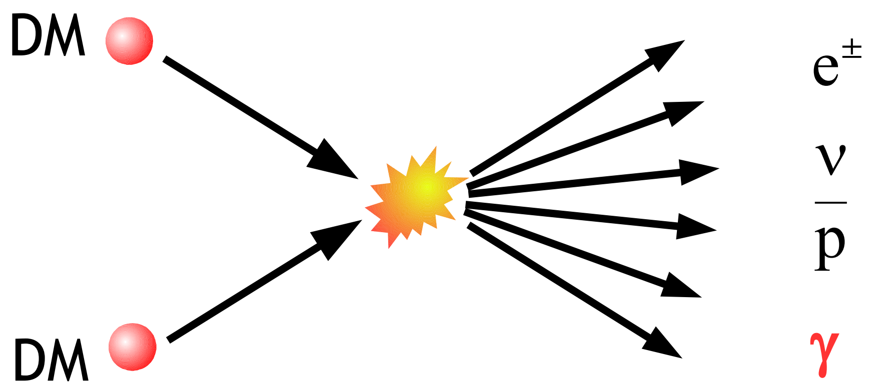
$$\boxed{\Omega h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}}$$

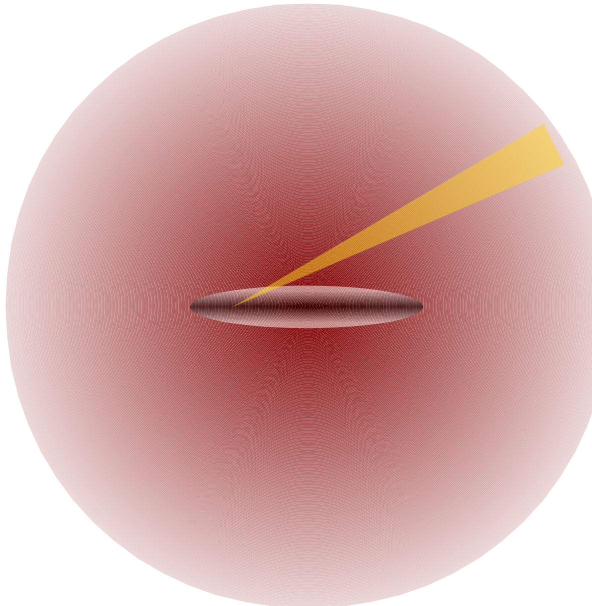
Correct dark matter abundance, $\Omega_{DM}h^2 \simeq 0.1$, if

$$\boxed{\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} = 1\,\mathrm{pb} \cdot c}$$


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t $10^{-44}$ $10^{-37}$ s $10^{-10}$ s $10^{-5}$ s $10^{2}$ s $3\times10^{5}$ y $10^{9}$ y $12\times10^{9}$ y (sec,yrs)
T $10^{32}$ $10^{28}$ $10^{15}$ $10^{12}$ $10^{9}$ 3000 15 2.7 (Kelvin)
E $10^{19}$ $10^{15}$ $10^{2}$ $10^{-1}$ $10^{-4}$ $3\times10^{-10}$ $10^{-12}$ $2.3\times10^{-13}$ (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

# Dark matter searches with gamma-rays

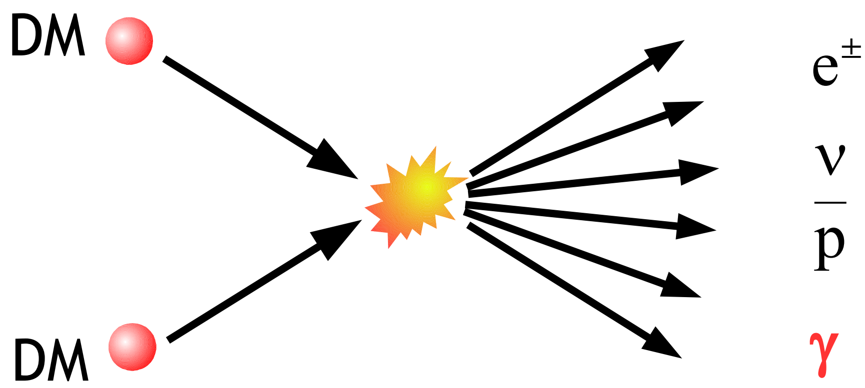


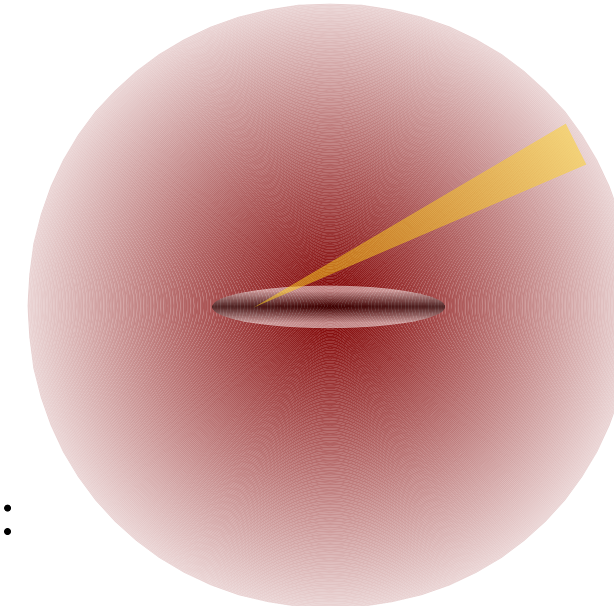



Expected gamma-ray flux in a given direction:

$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi} \underbrace{\left[ \frac{(\sigma v)}{2m_{\rm DM}^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f \right]}_{\substack{\text{Source term} \\ \text{(particle physics)}}} \times \underbrace{\int_{\rm l.o.s.} \rho^2(\vec{l}) d\vec{l}}_{\substack{\text{Line-of-sight integral} \\ \text{(astrophysics)}}}$$

# Dark matter searches with gamma-rays



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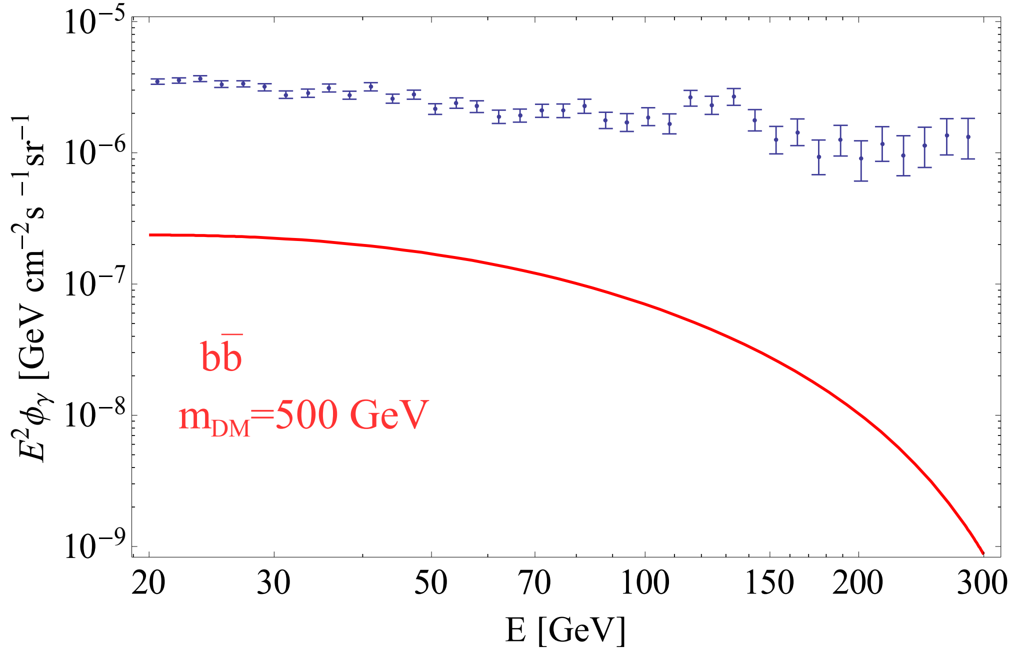
Which $(\sigma\ v)$? A well motivated choice:

$$\boxed{(\sigma v) \simeq 3 \times 10^{-26}\, \mathrm{cm}^3\, \mathrm{s}^{-1}}$$

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.

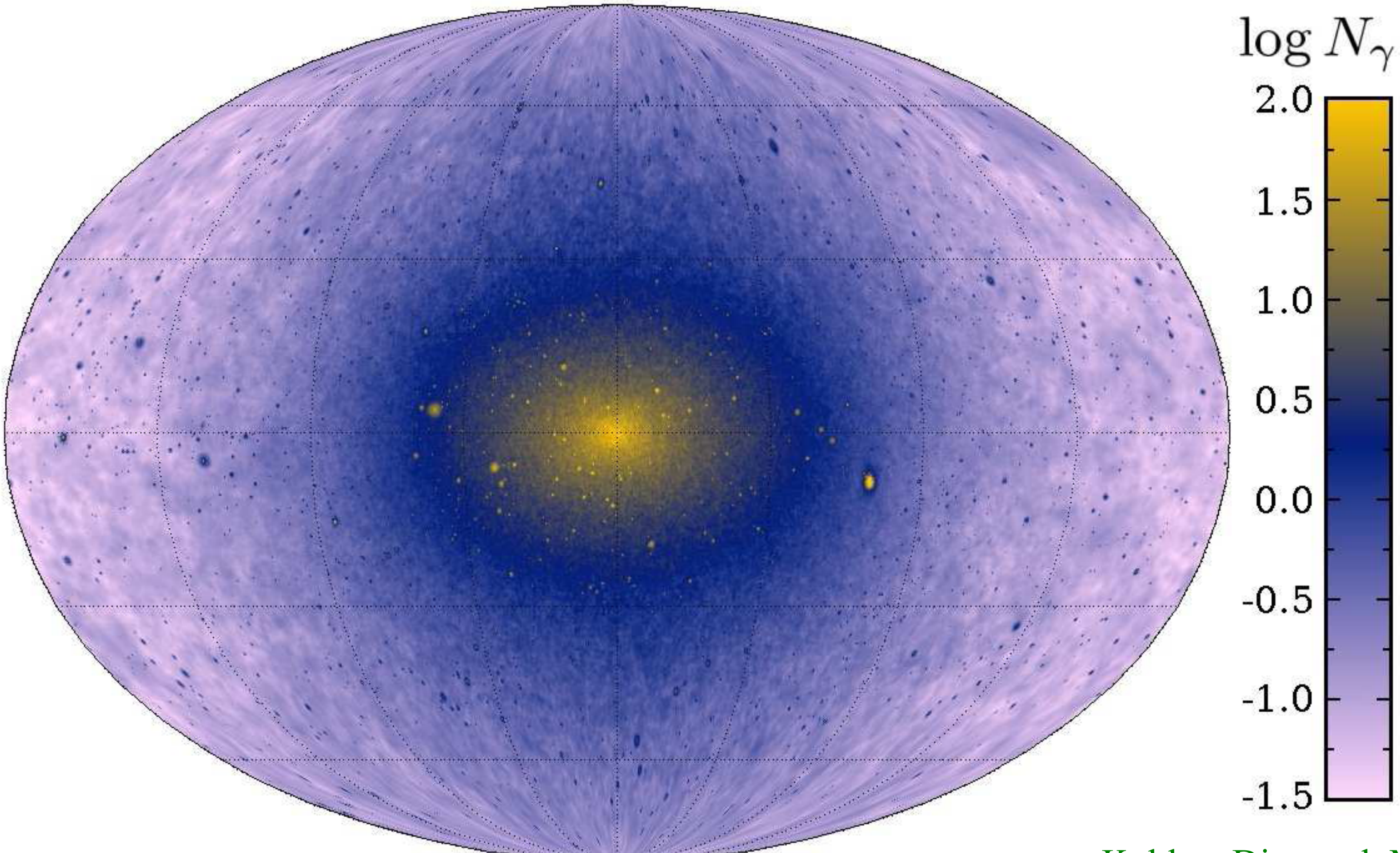



The detection of the signal requires to understand the astrophysical backgrounds to the ~10% accuracy

- Sources
- Diffuse galactic emission
- Fermi bubbles
- Isotropic (extragalactic) component

# Overcoming backgrounds

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

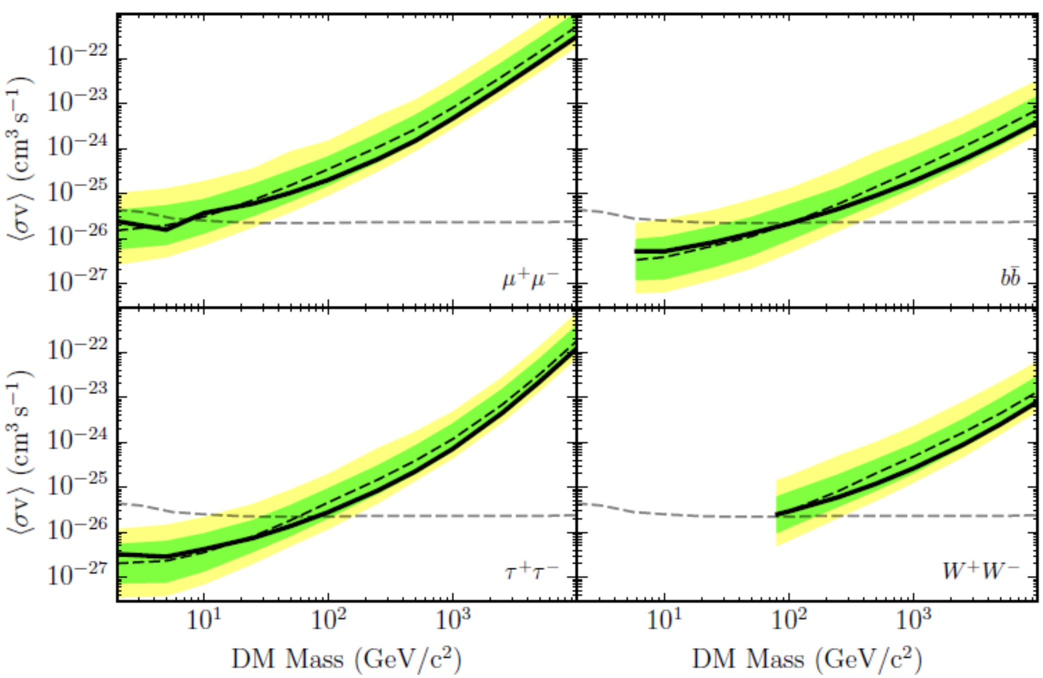


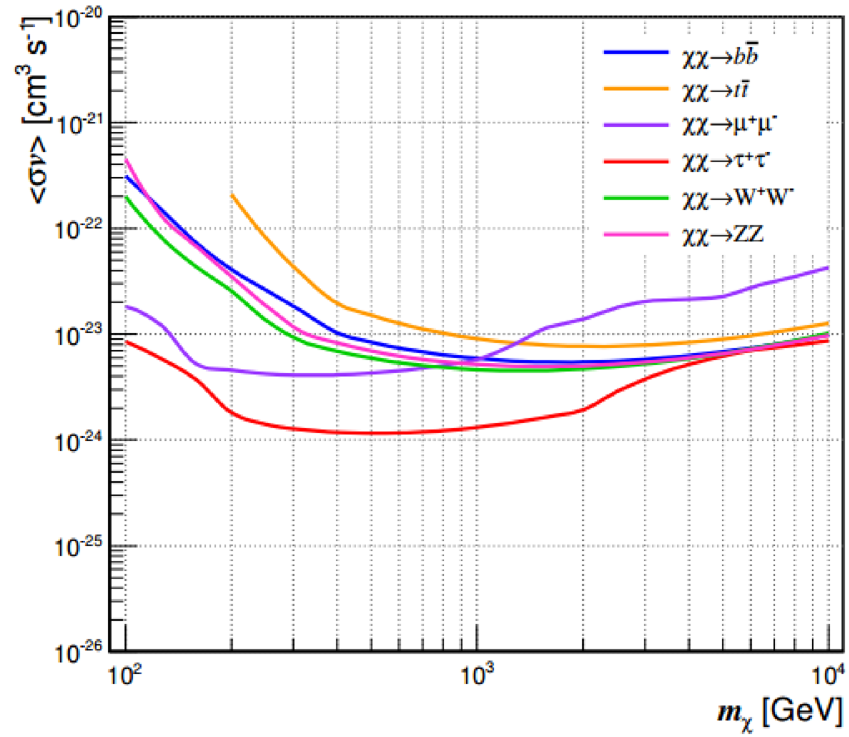

Kuhlen, Diemand, Madau

# 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



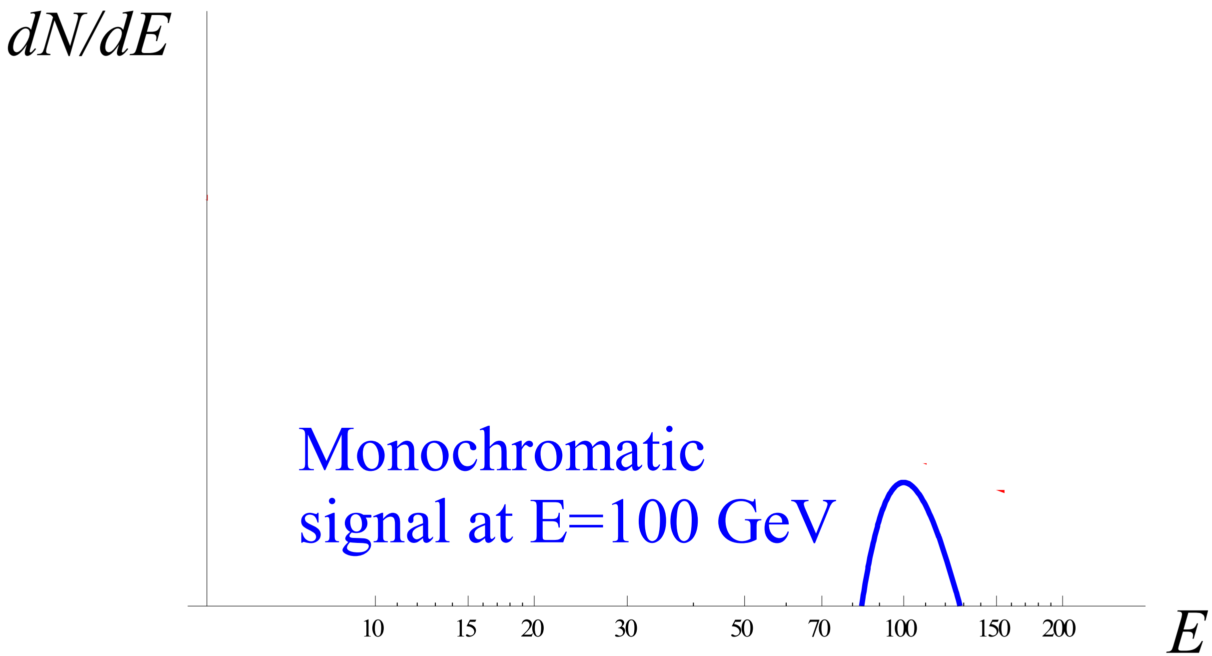

Fermi-LAT collaboration
arXiv:1503.02641

MAGIC collaboration
arXiv:1312.1535

# Overcoming backgrounds

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

**Idea:**



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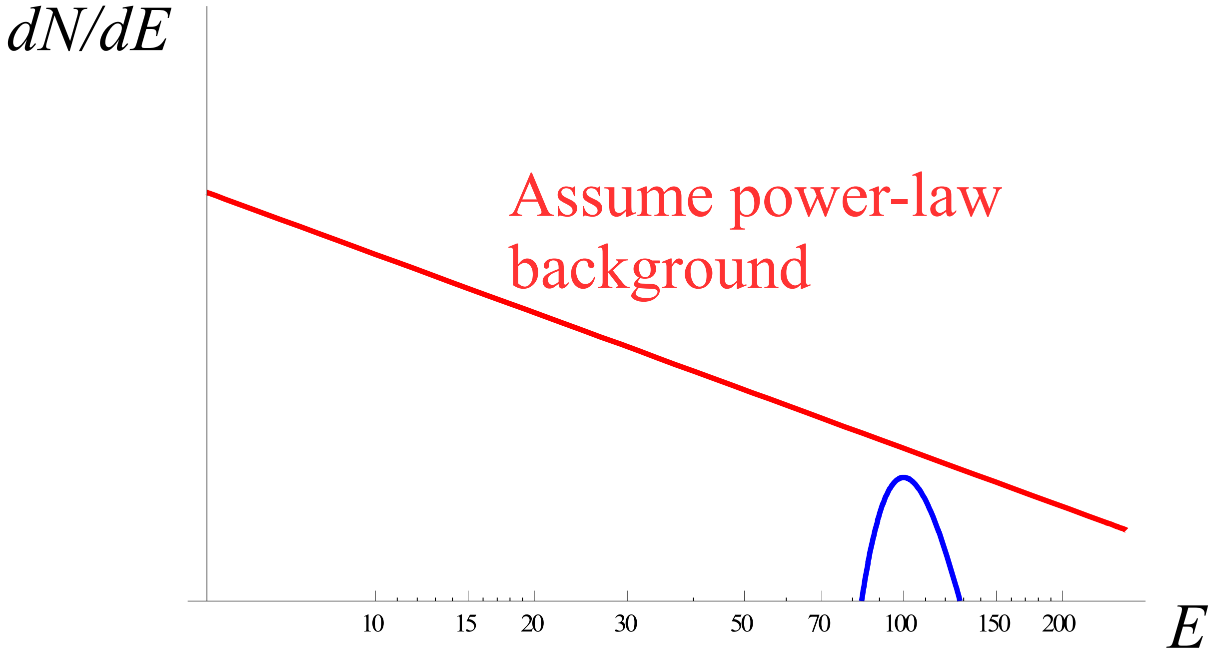

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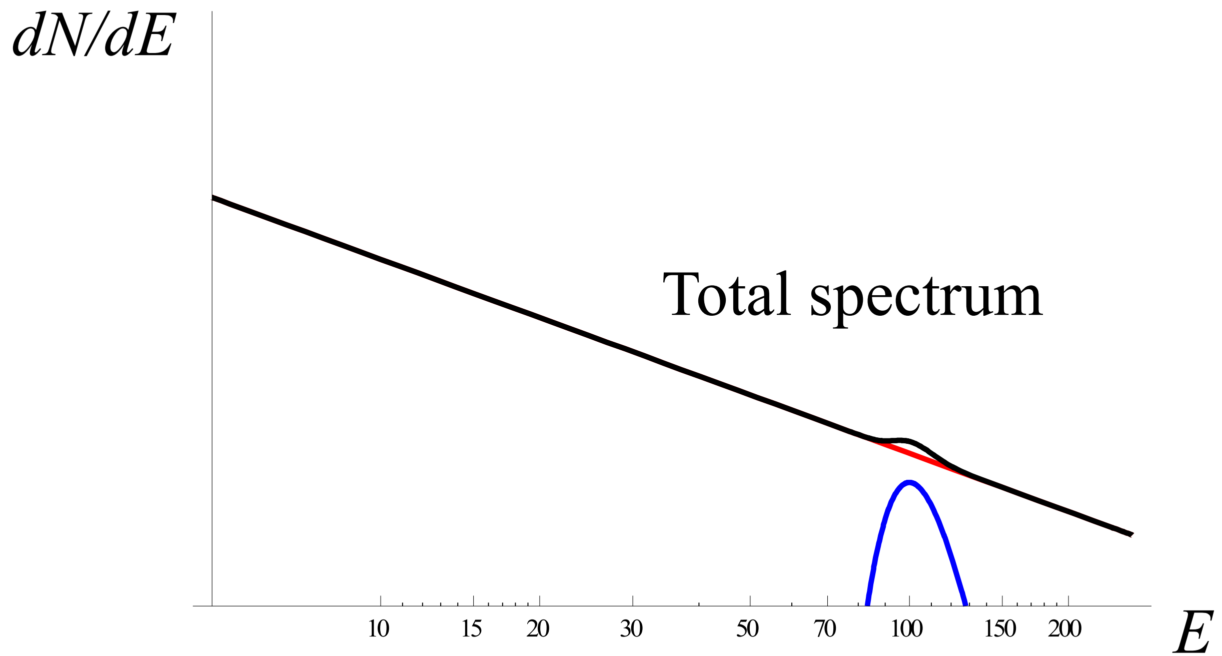


Fit data to $\dfrac{dN}{dE} = aE^{-\alpha} + b\delta(E - E_0)$

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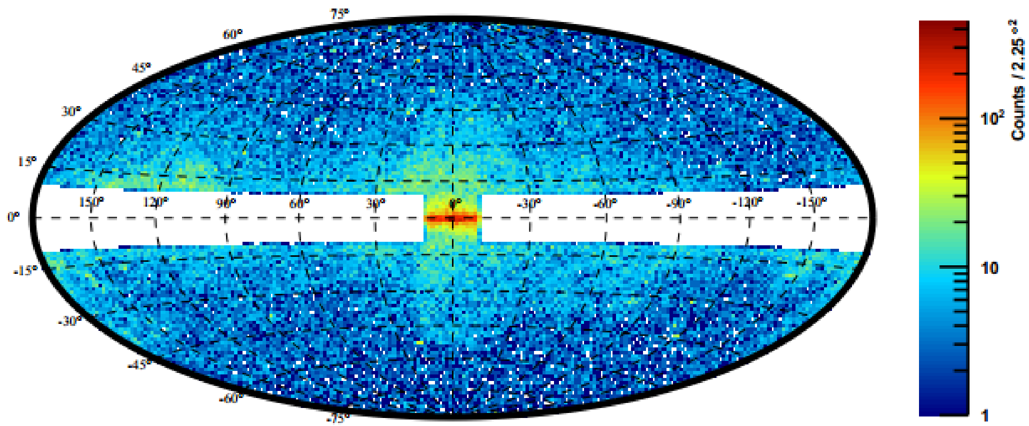
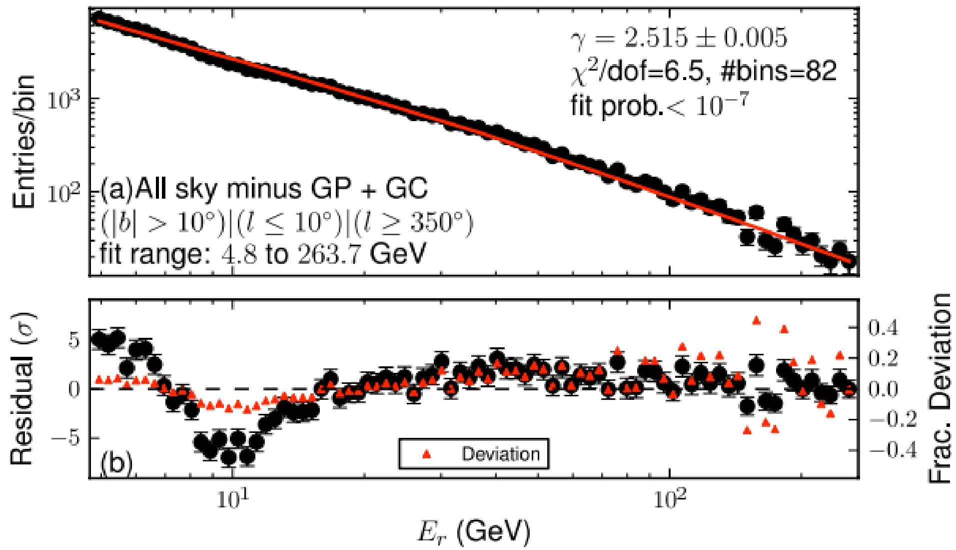
*Data don't really look like a power law…*



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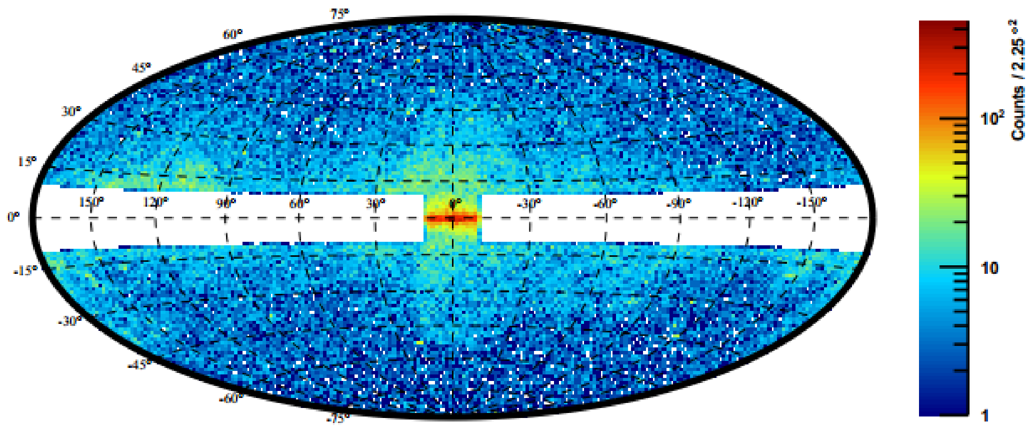


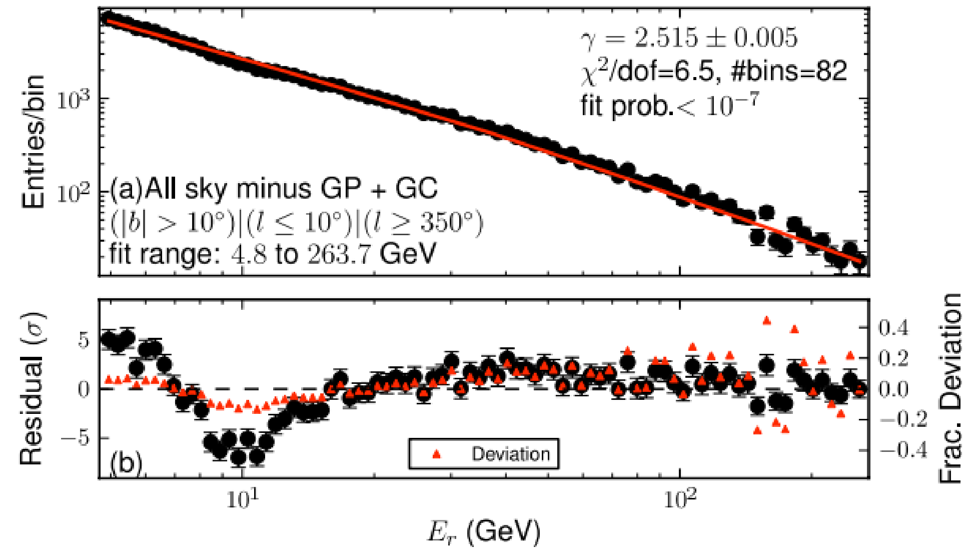


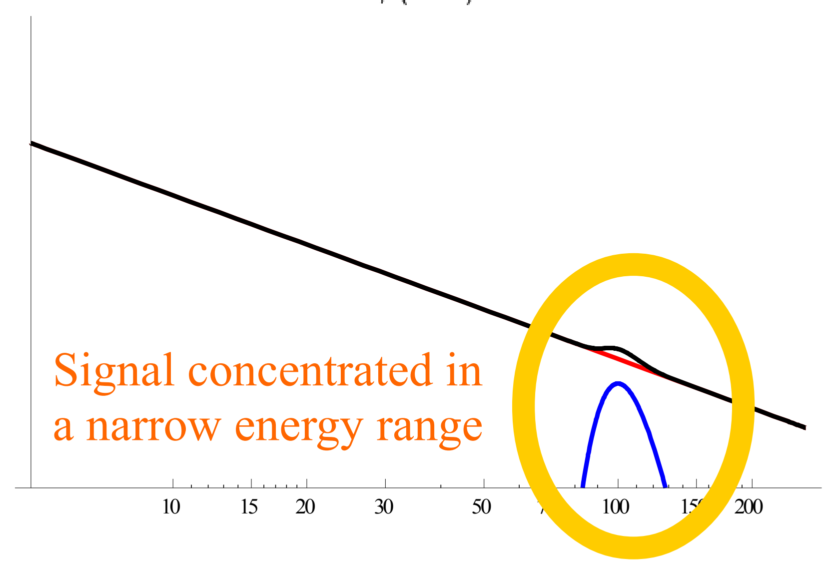

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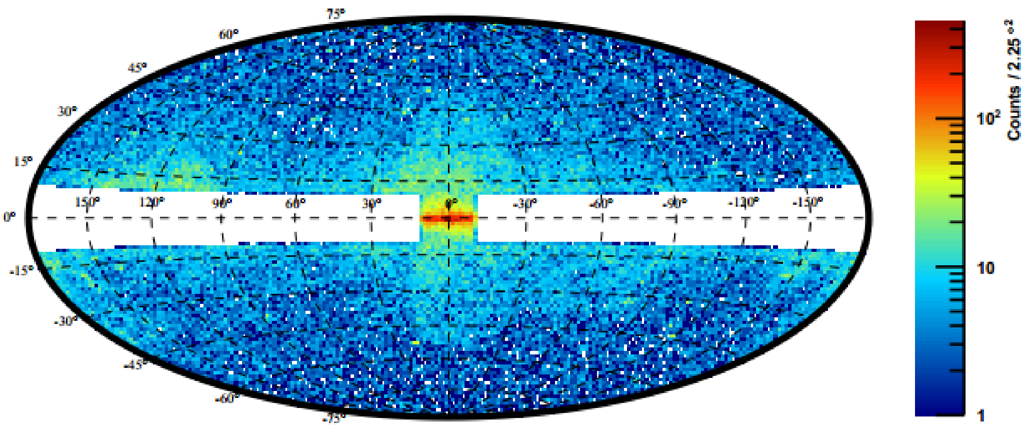


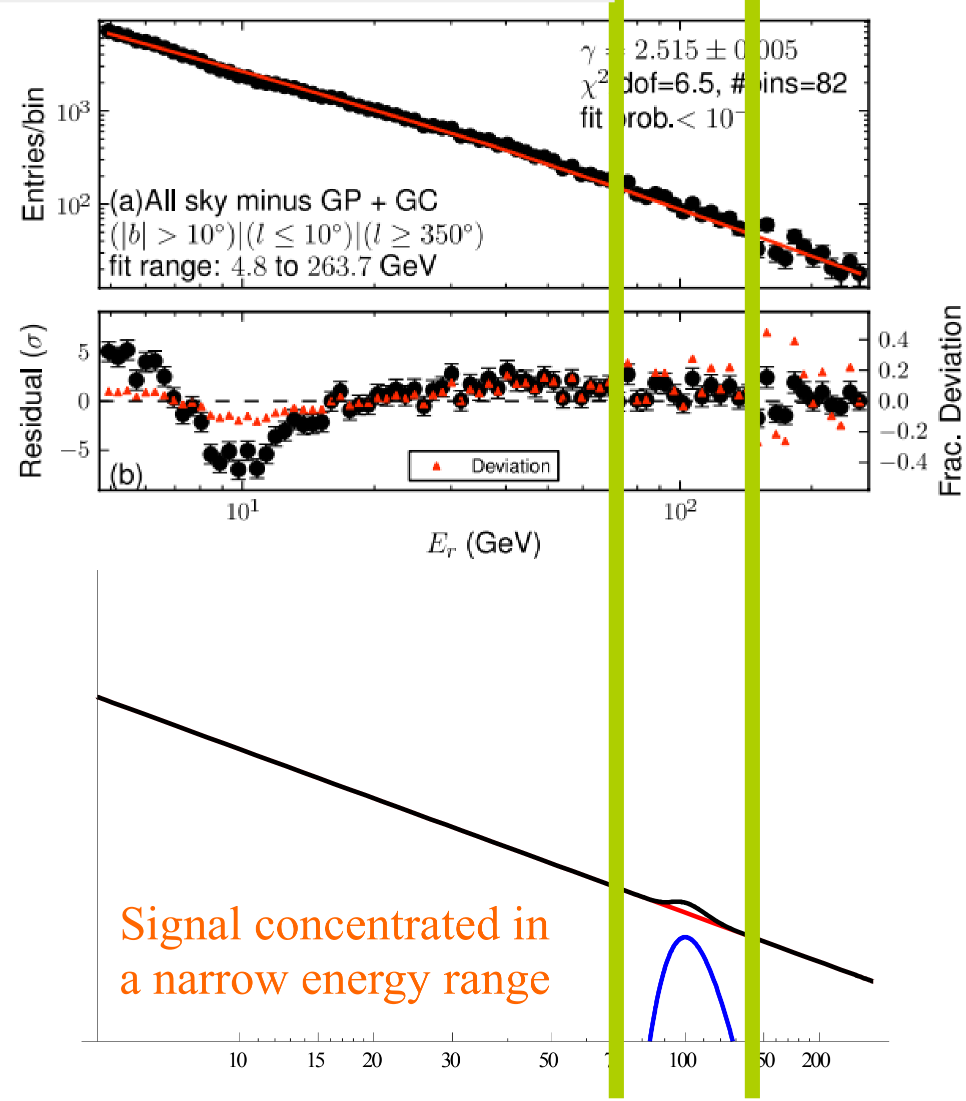


In a narrow energy interval, the background resembles a power-law (Taylor's theorem)

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

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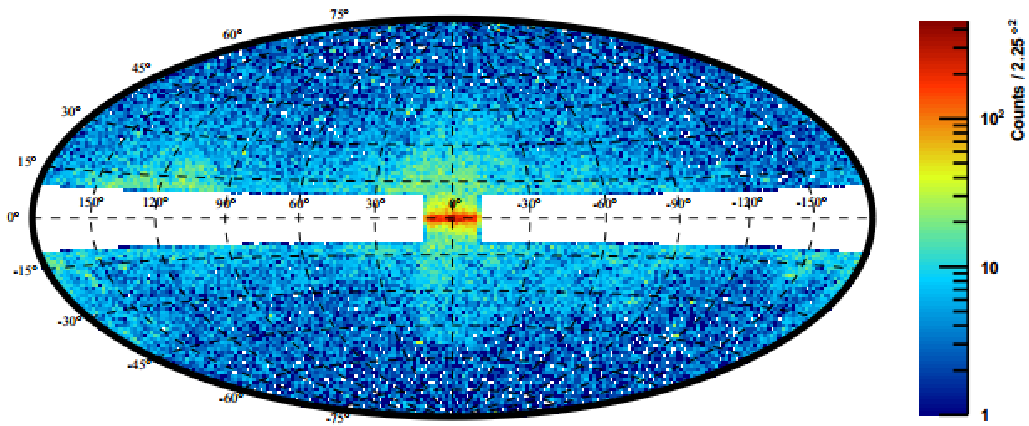
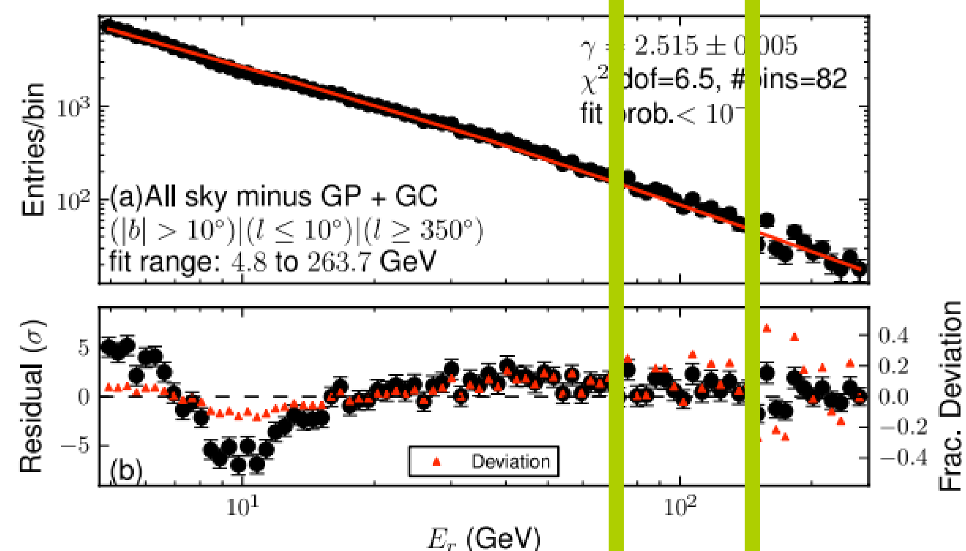
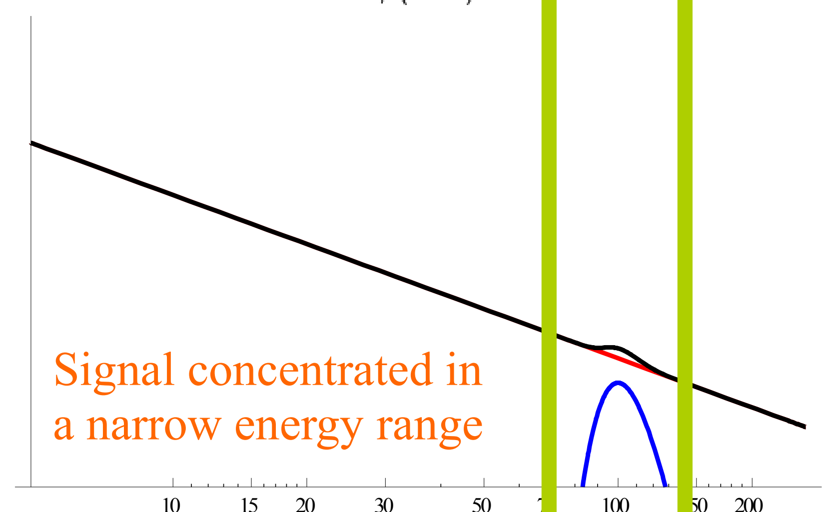



Repeat the search with different "windows" postulating a signal at different DM masses.



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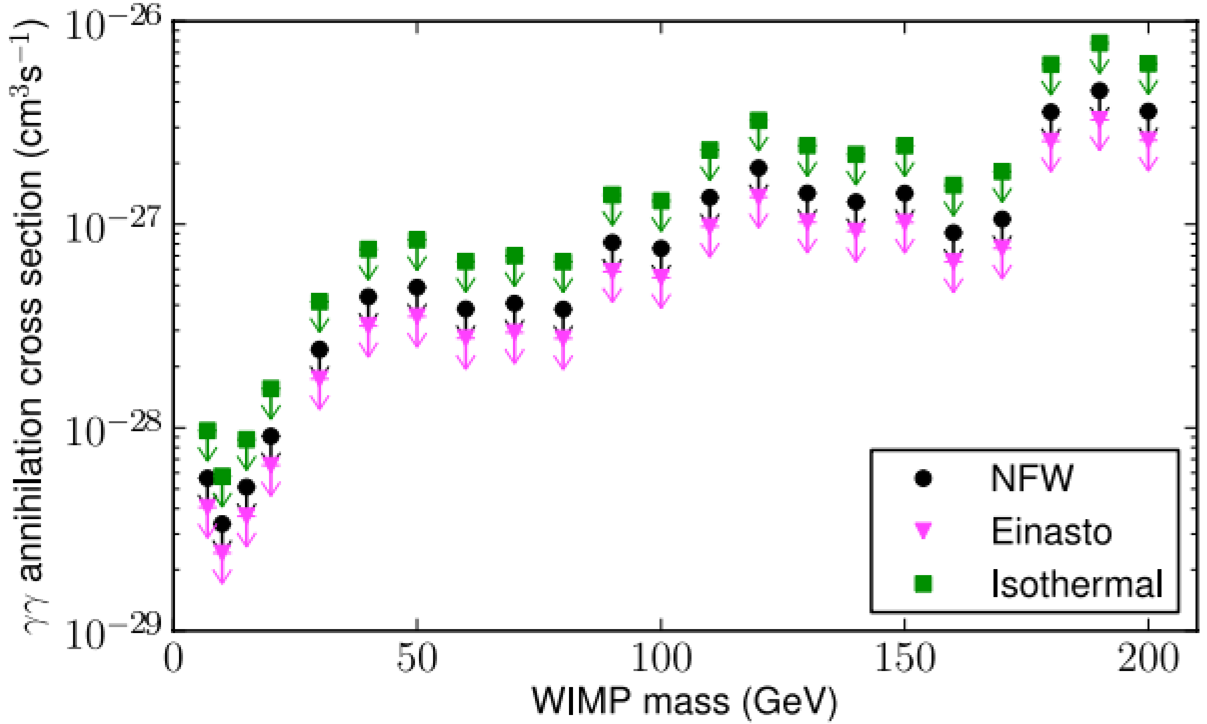


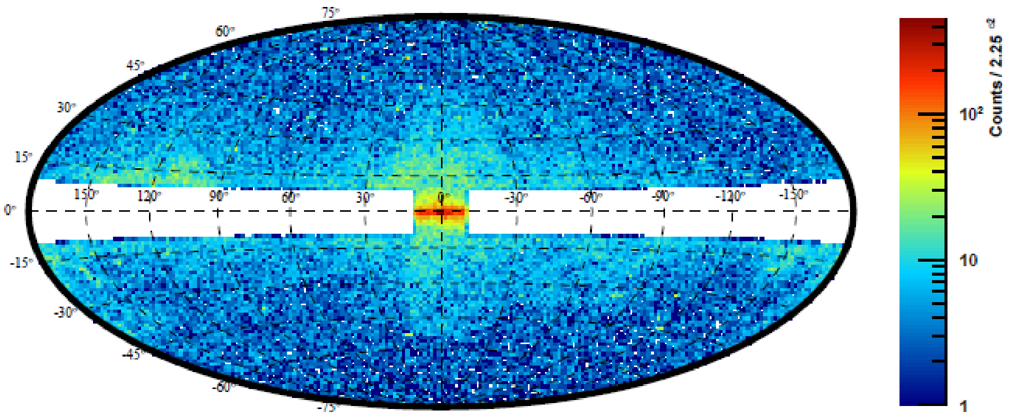

Fermi collaboration
arXiv:1205.2739

# Overcoming backgrounds

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

Former 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.)



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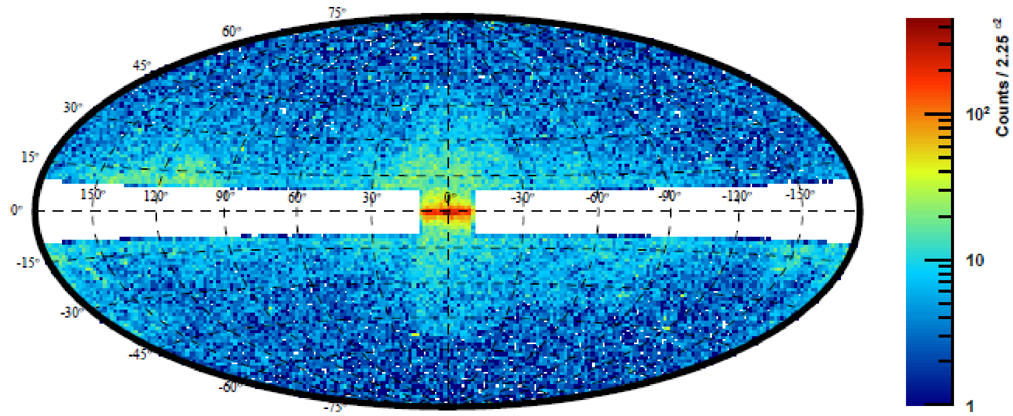
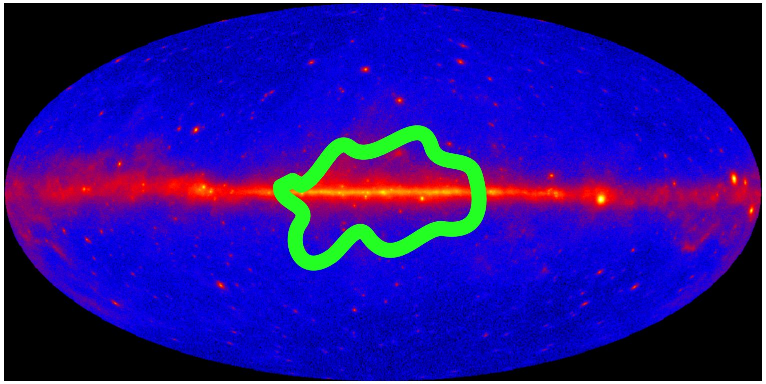



Disadvantage: in the chosen region the background could be too large and bury the signal

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



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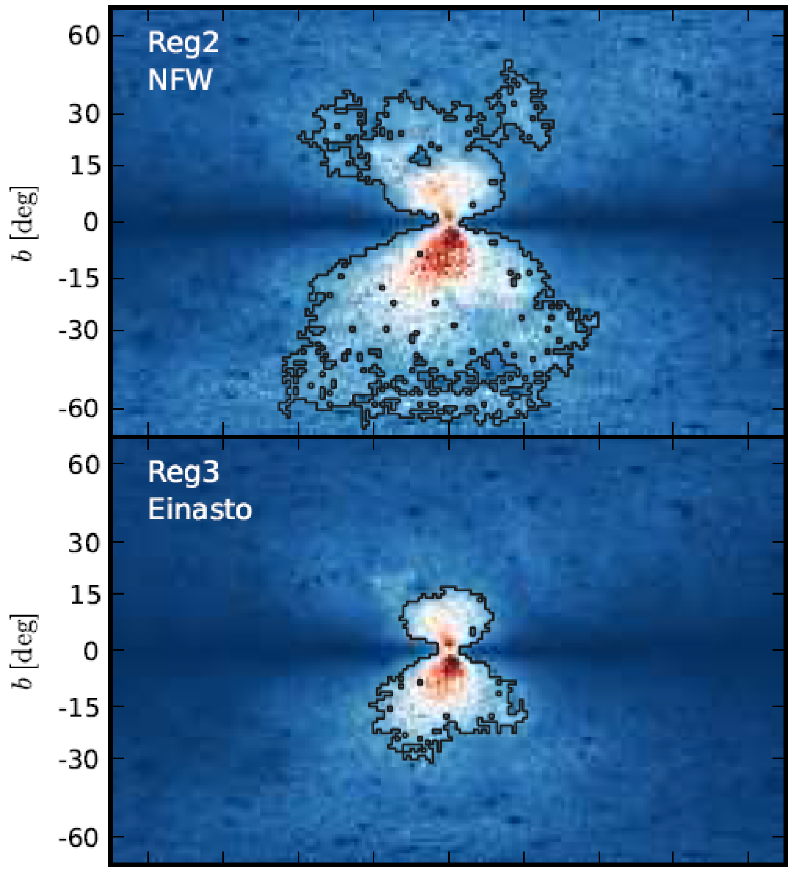


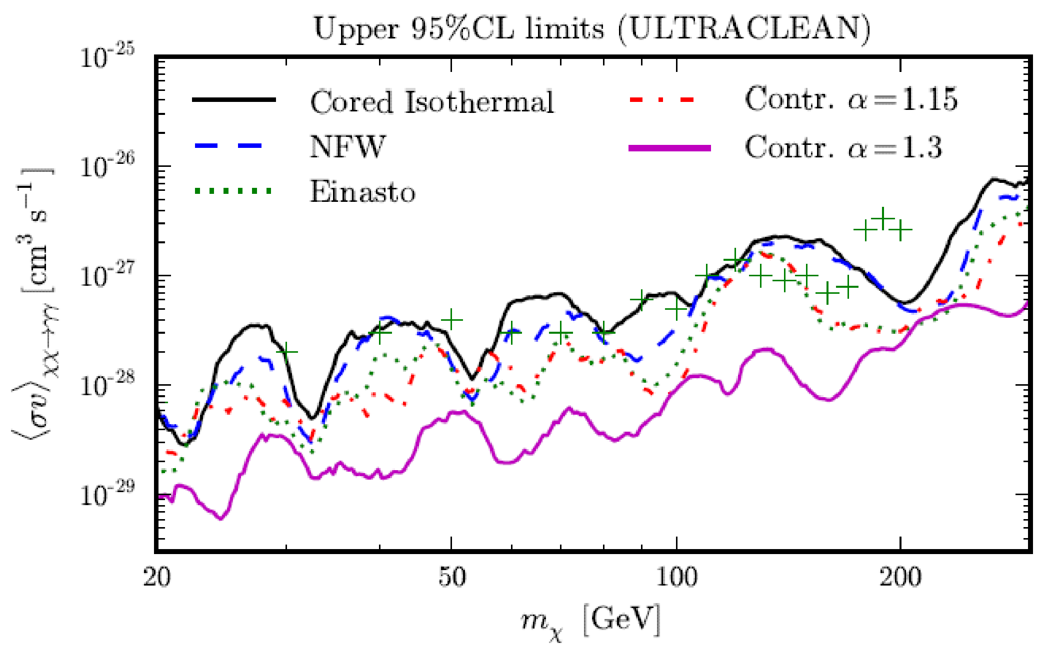


Weniger, arXiv:1204.2797
Bringmann, Huang, AI, Vogl, Weniger , arXiv:1203.1312

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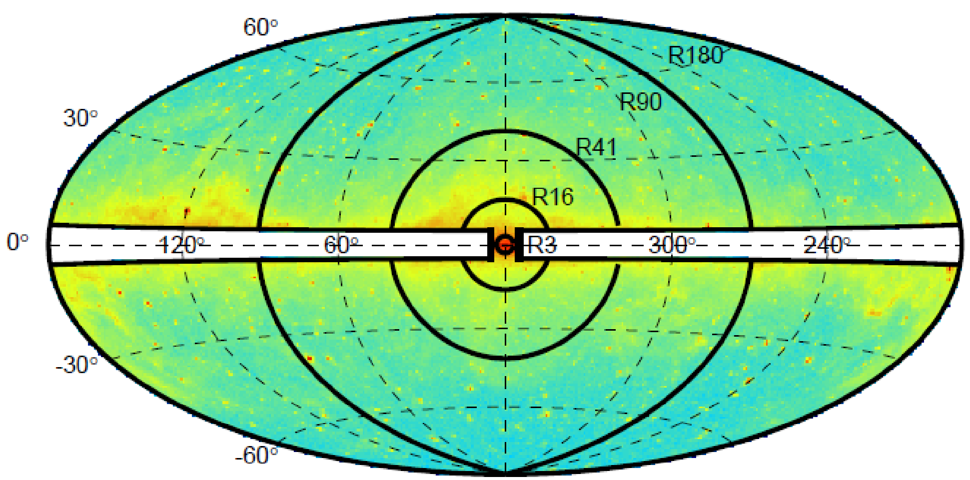


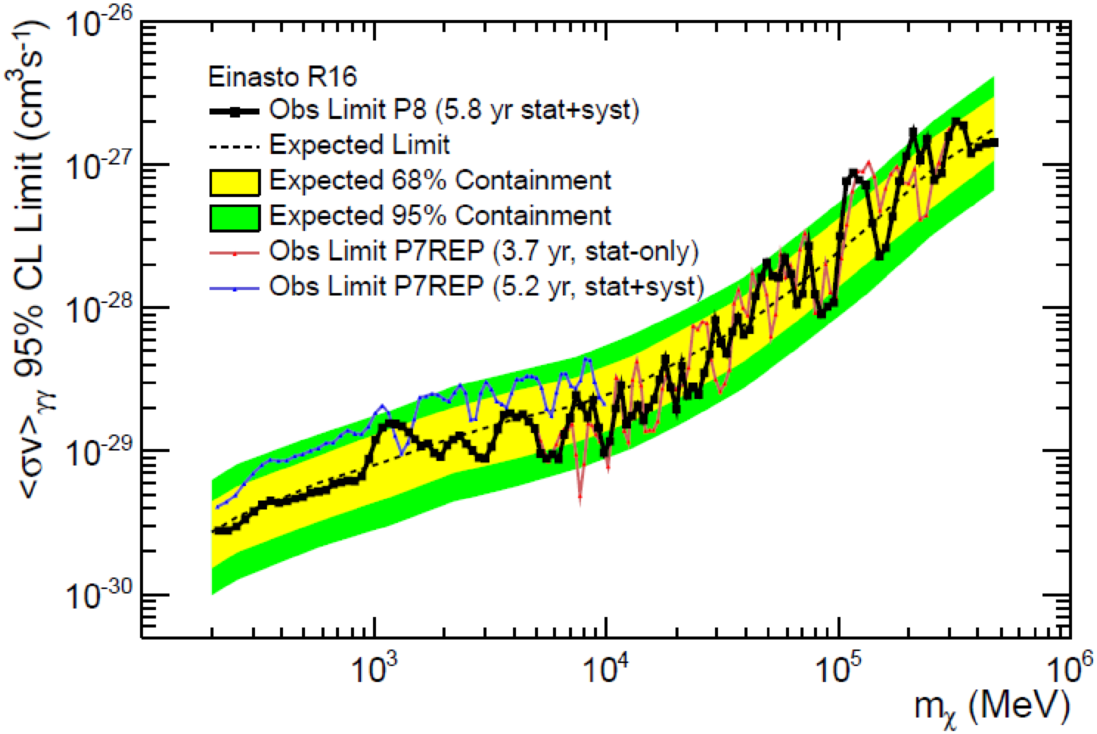


Fermi collaboration
arXiv:1503.02641

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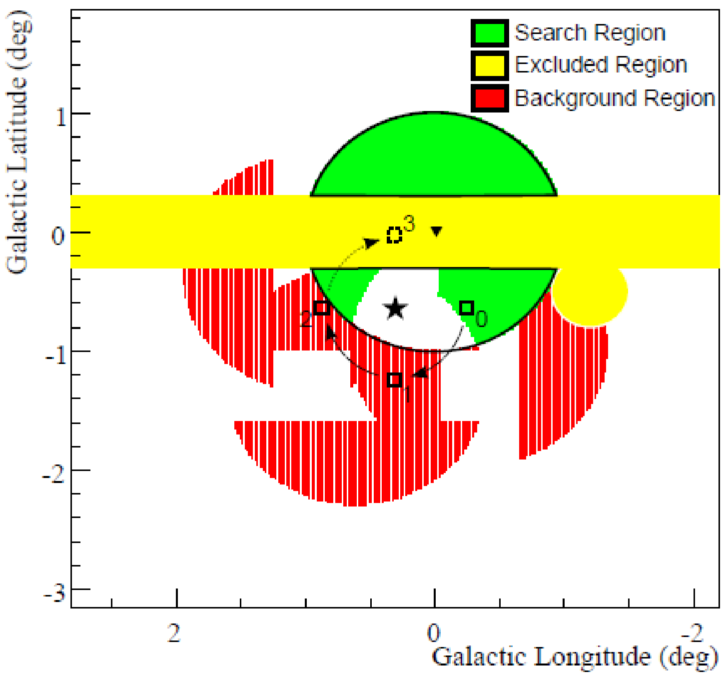
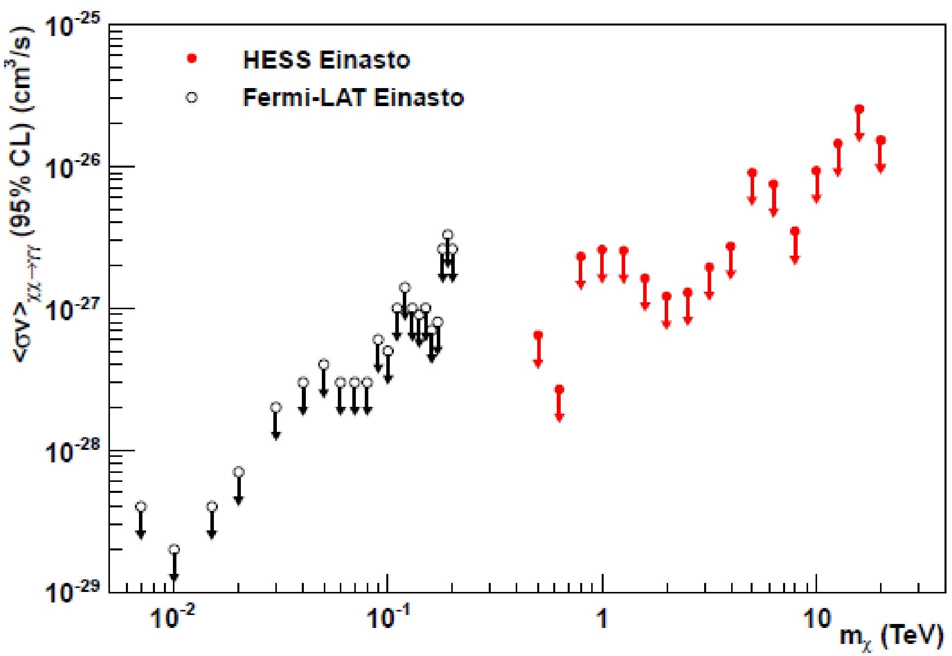


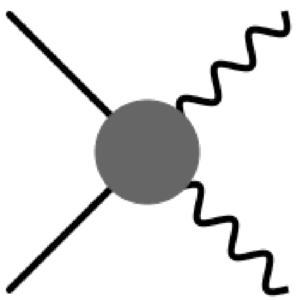




H.E.S.S. collaboration
arXiv:1301.1173

# Gamma-ray spectral features in Particle Physics

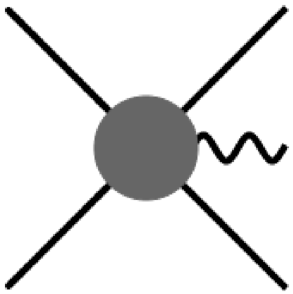
Three gamma-ray spectral features have been identified:

Gamma ray line



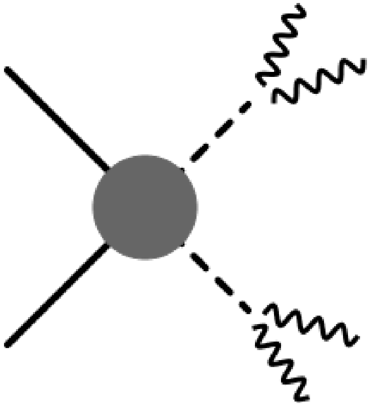
Srednicki, Theisen, Silk '86
Rudaz '86
Bergstrom, Snellman '88

Internal bremsstrahlung



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

Gamma ray box

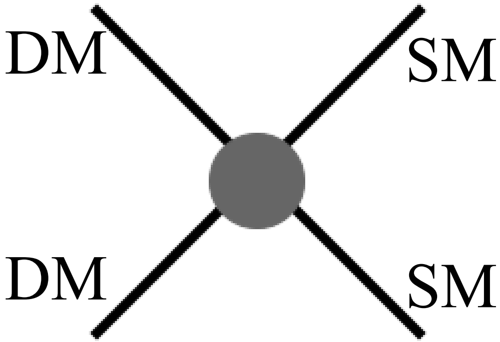


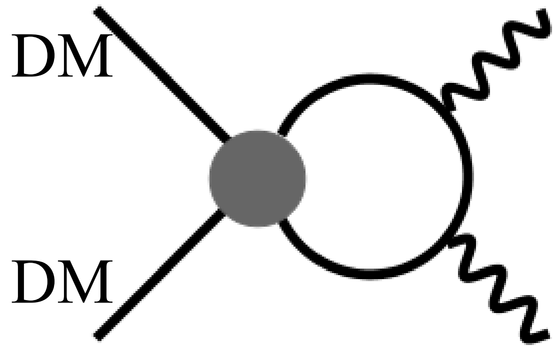
AI, Lopez Gehler, Pato '12

# Gamma-ray lines

The dark matter particle is electrically neutral.

The annihilation DM DM → $\gamma\,\gamma$ arises at the one loop level




Monochromatic signals are quite generic in WIMP models

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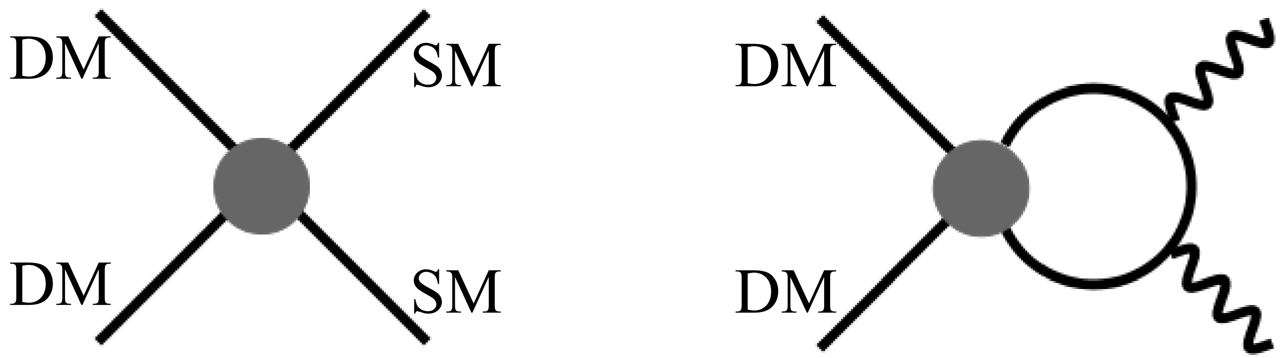
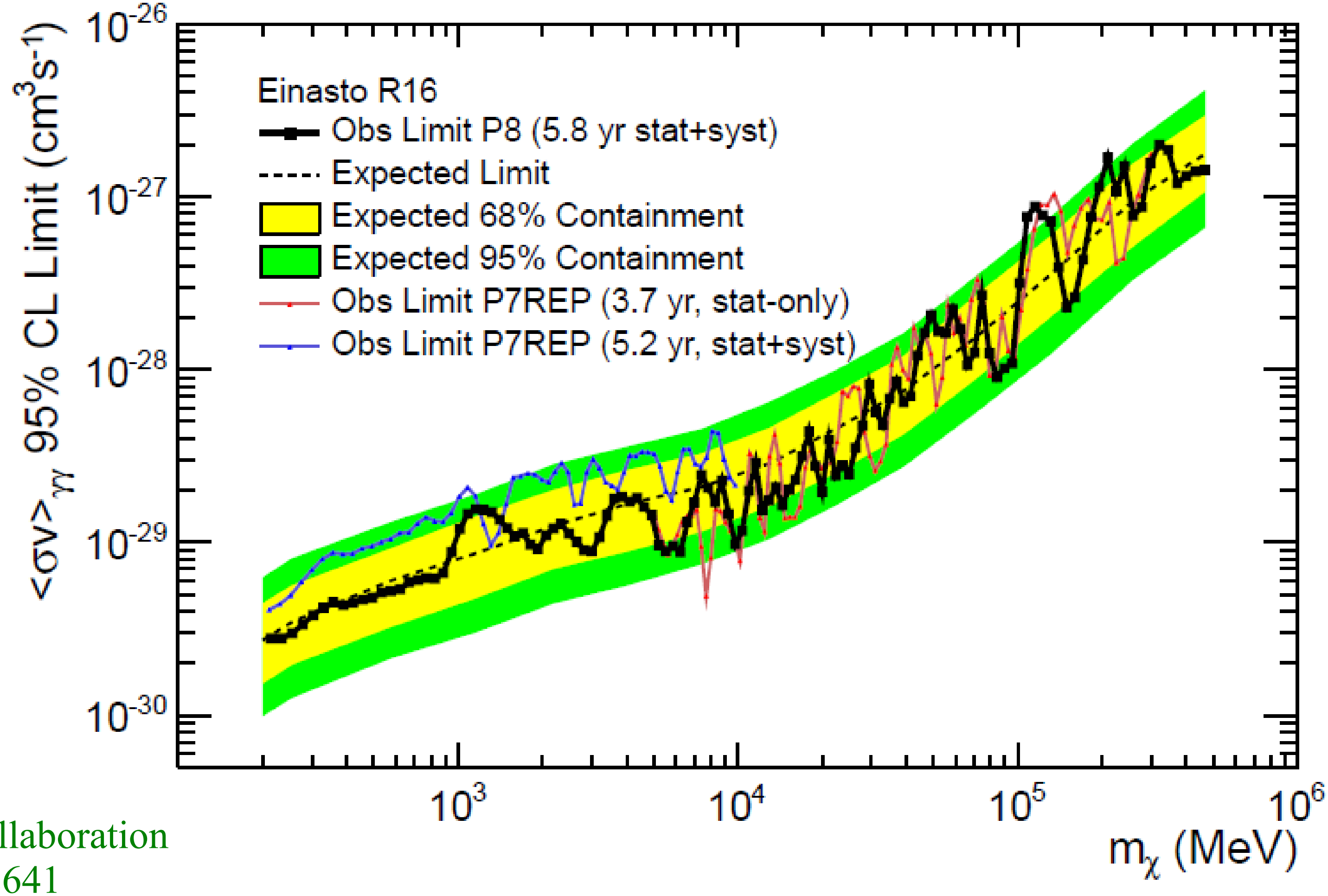



Monochromatic signals are quite generic in WIMP models

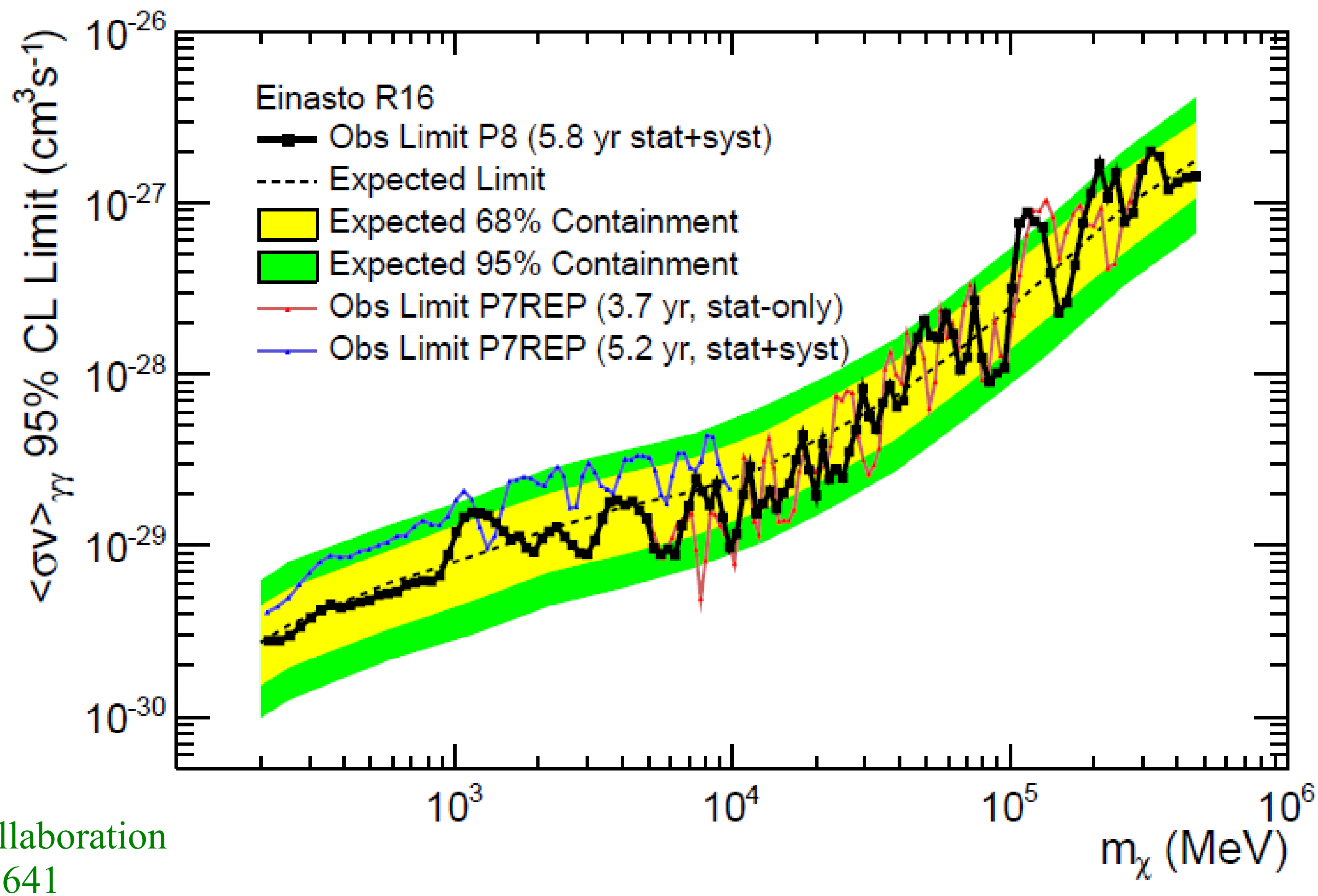
However, with rates generically very suppressed:

$$\boxed{(\sigma v)_{\gamma\gamma} \sim \left(\frac{\alpha}{4\pi}\right)^2 \langle \sigma v \rangle_{\mathrm{thermal}} \sim 10^{-32}\,\mathrm{cm}^3\mathrm{s}^{-1}}$$




Fermi-LAT collaboration
arXiv:1503.02641

“Canonical value of ⟨σv⟩”

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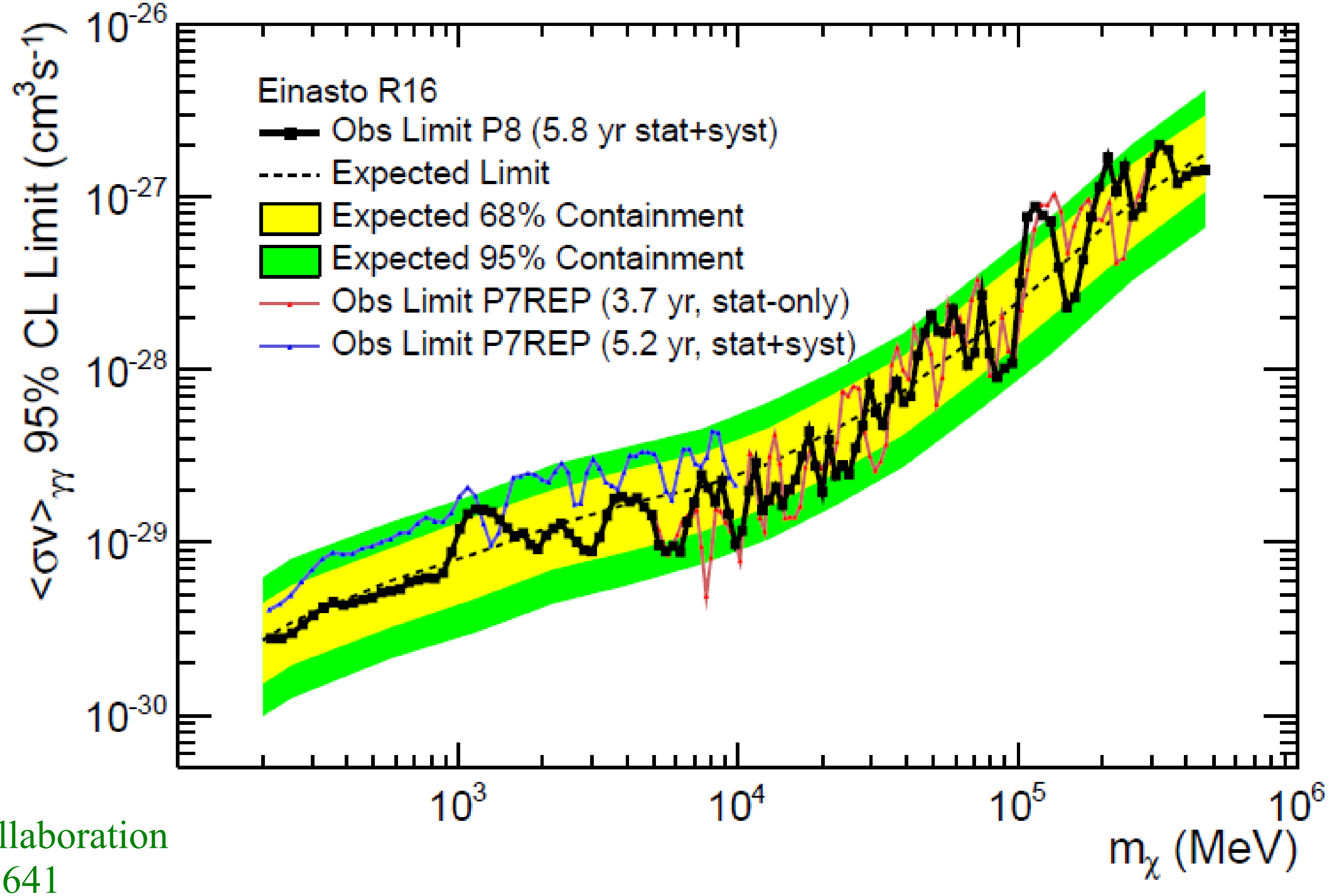
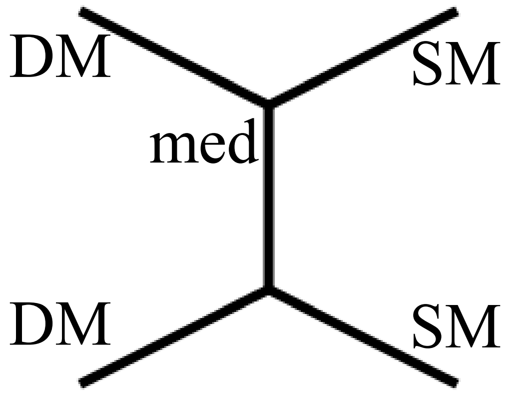



Fermi-LAT collaboration
arXiv:1503.02641

Expected cross section

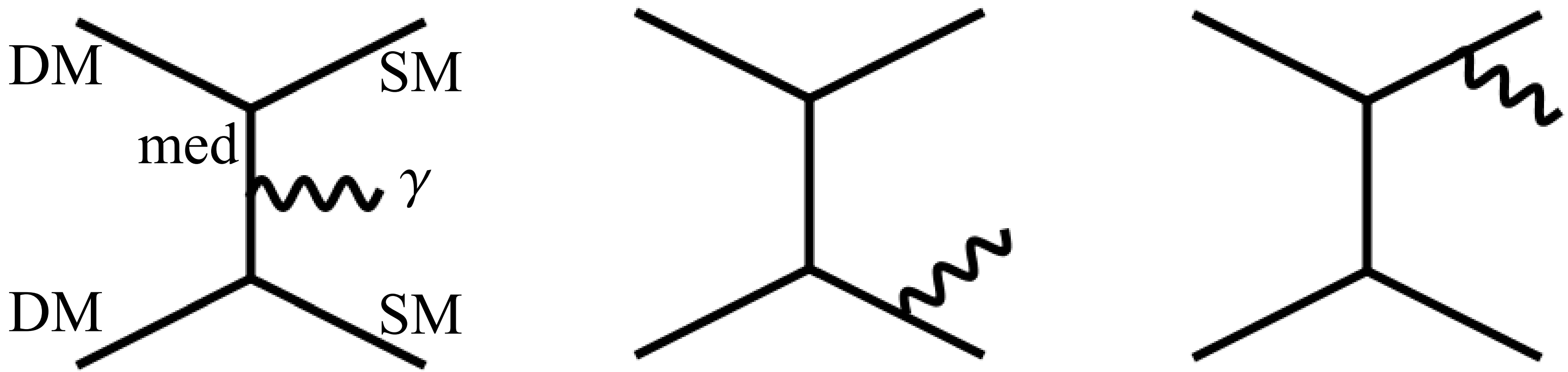
# Internal bremsstrahlung




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 $\rightarrow$ SM SM $\gamma$:



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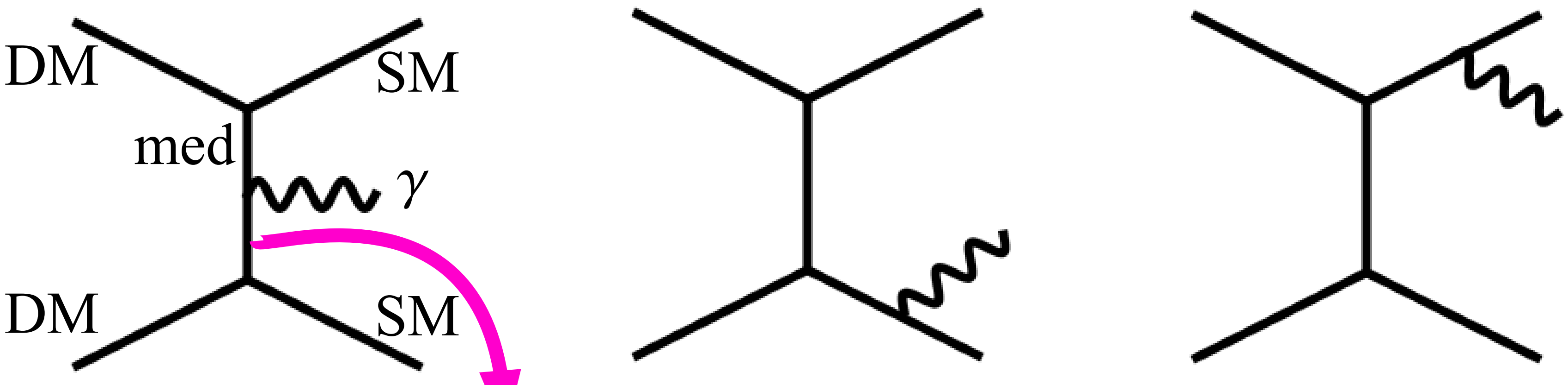


$$
\boxed{\begin{aligned}
\Delta(p) &\propto \left((p_{\rm DM} - p_{\rm SM})^2 - m_{\rm med}^2\right)^{-1} \\
&\approx \left(m_{\rm DM}^2 - 2 m_{\rm DM} E_{\rm SM} - m_{\rm med}^2\right)^{-1}
\end{aligned}}
$$

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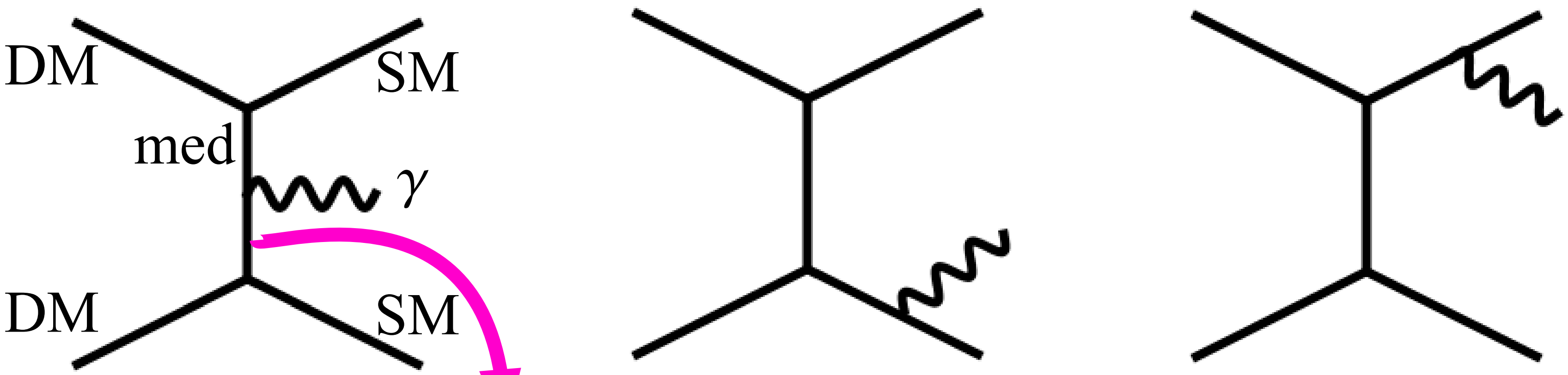
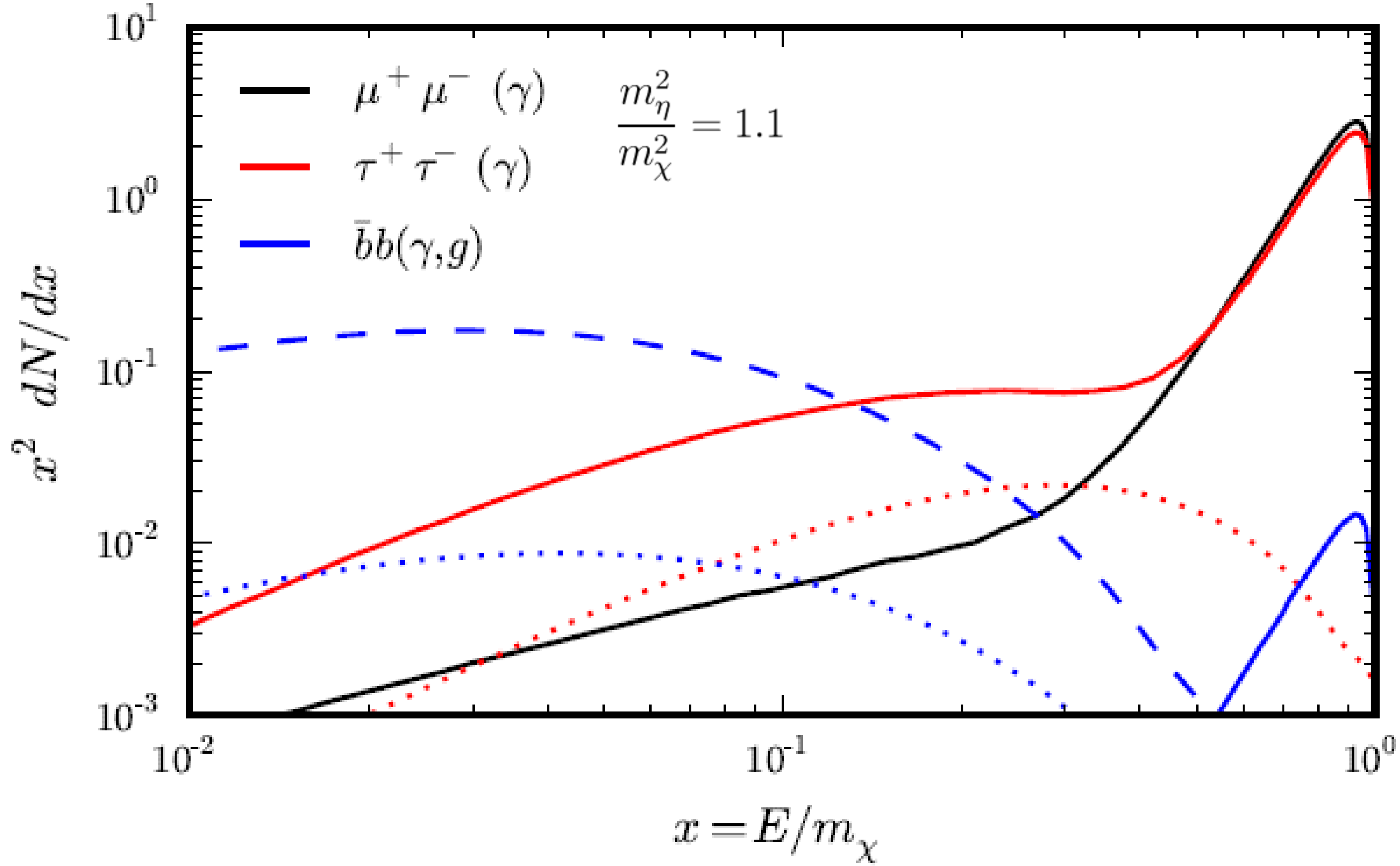



$$\boxed{\begin{aligned}\Delta(p) &\propto \left((p_{\mathrm{DM}} - p_{\mathrm{SM}})^2 - m^2_{\mathrm{med}}\right)^{-1} \\ &\approx \left(\cancel{m^2_{\mathrm{DM}}} - 2m_{\mathrm{DM}}E_{\mathrm{SM}} - \cancel{m^2_{\mathrm{med}}}\right)^{-1}\end{aligned}}$$

In the case $m_{\mathrm{DM}} \approx m_{\mathrm{med}}$ the scalar propagator gets enhanced when $E_{\mathrm{SM}}$ is small (which corresponds to $E_\gamma$ large).

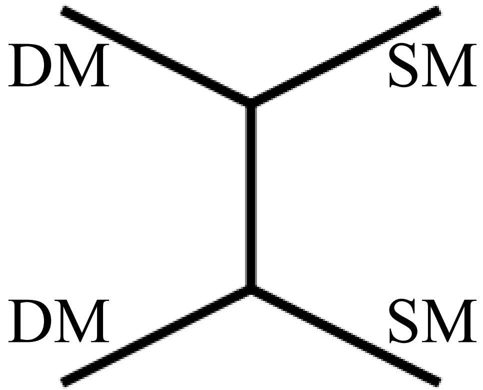
Enhancement of the amplitude (and the rate) when $E_\gamma$ is close to the kinematic end-point.

# Internal bremsstrahlung

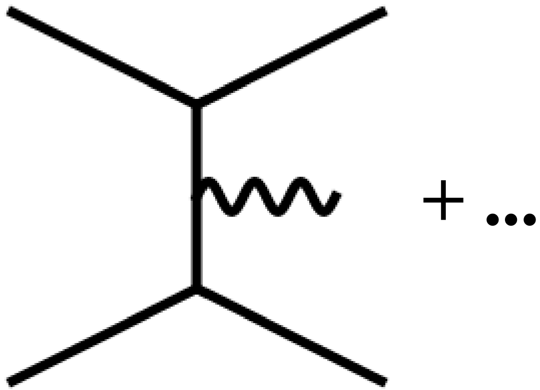


# Internal bremsstrahlung

Expected annihilation cross section for the 2 → 3 process.

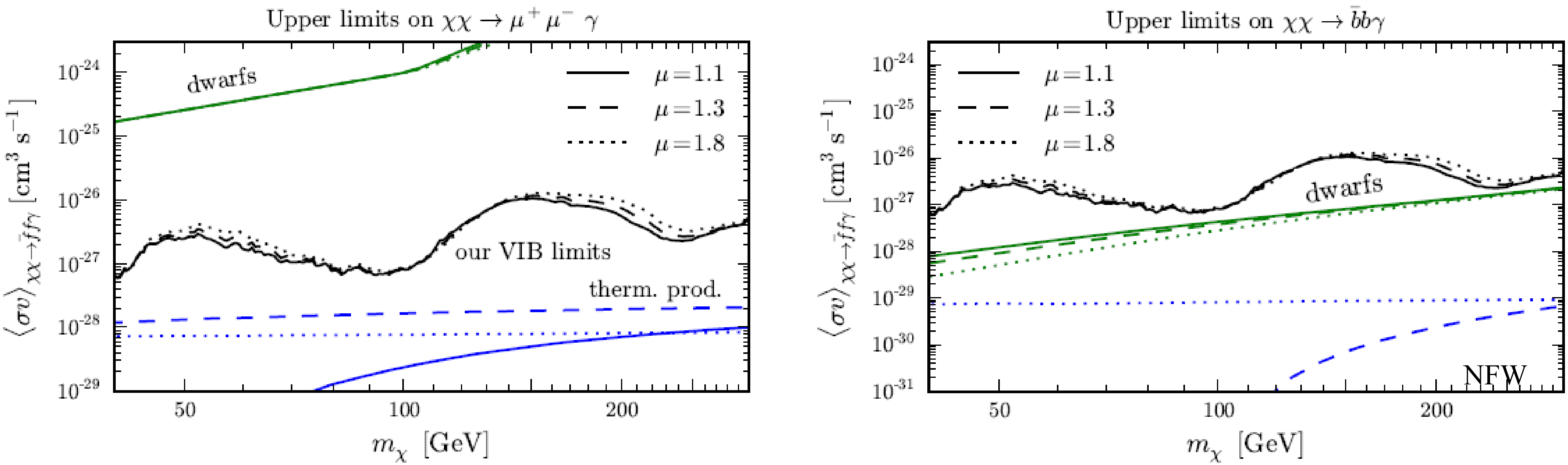



$$\boxed{\langle \sigma v \rangle_{\rm thermal} \simeq 3 \times 10^{-26}\, {\rm cm^3 s^{-1}}}$$



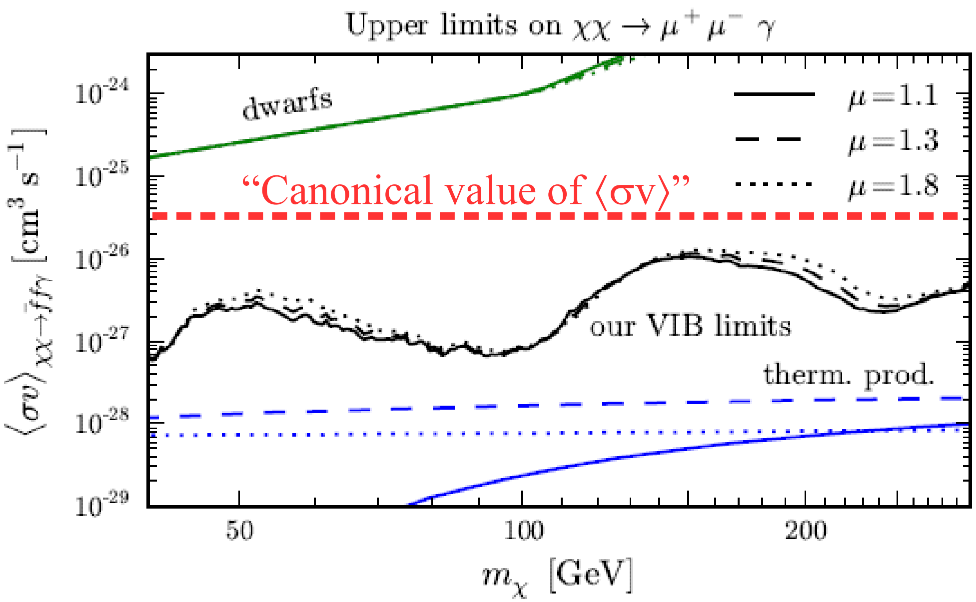

$$\boxed{(\sigma v)_{2\to 3} \sim \frac{\alpha}{\pi} \langle \sigma v \rangle_{\rm thermal} \;\sim 10^{-28}\, {\rm cm^3 s^{-1}}}$$

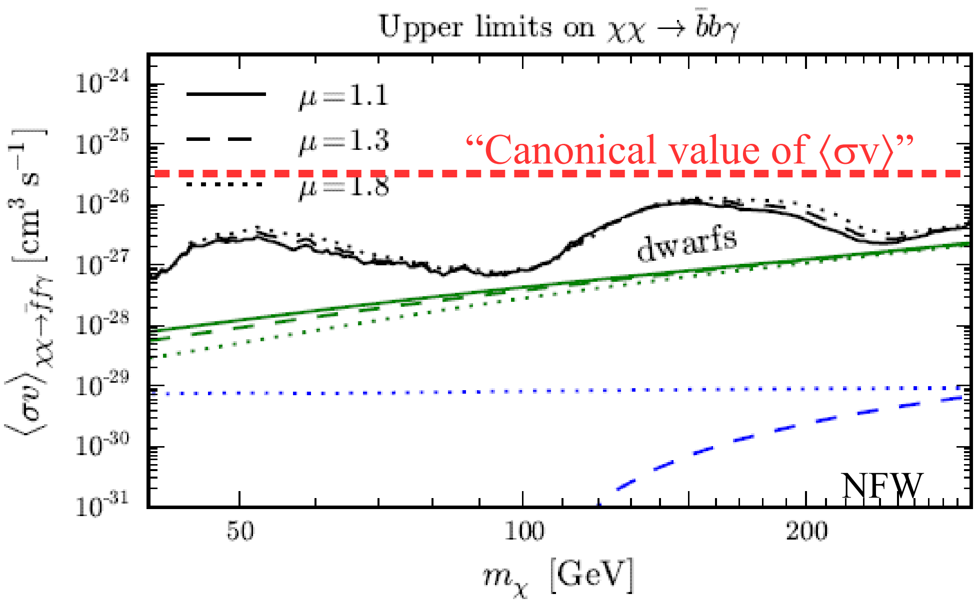
# Limits on the annihilation cross section from the Fermi-LAT data




Bringmann, Huang, AI, Vogl, Weniger

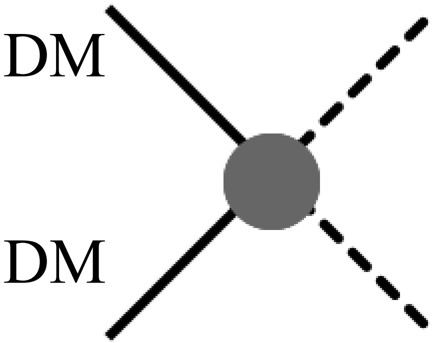
# Limits on the annihilation cross section from the Fermi-LAT data




Bringmann, Huang, AI, Vogl, Weniger

# Gamma-ray box




Assume on shell production of an intermediate scalar, $\phi$.

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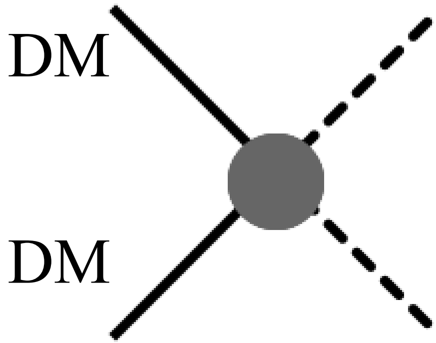


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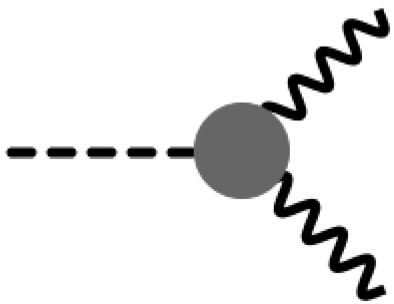

Assume that the scalar decays into two photons

Photon spectrum in the rest frame of the scalar

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

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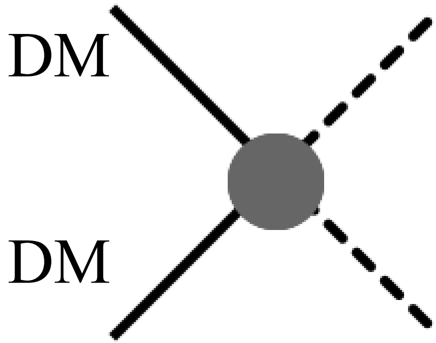


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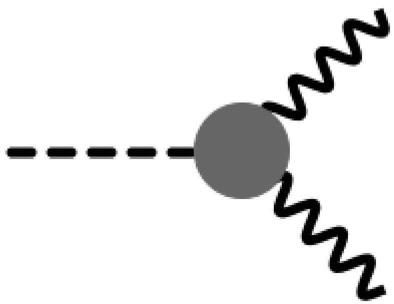

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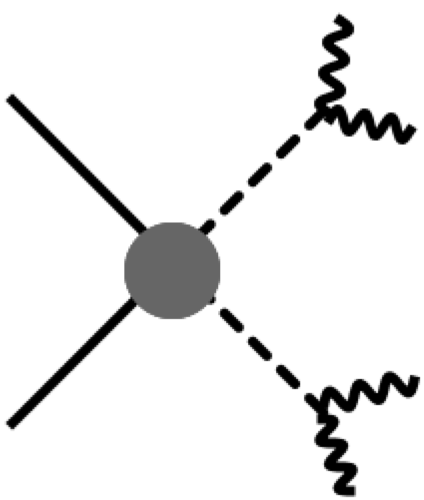

Photon spectrum in the galactic frame

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

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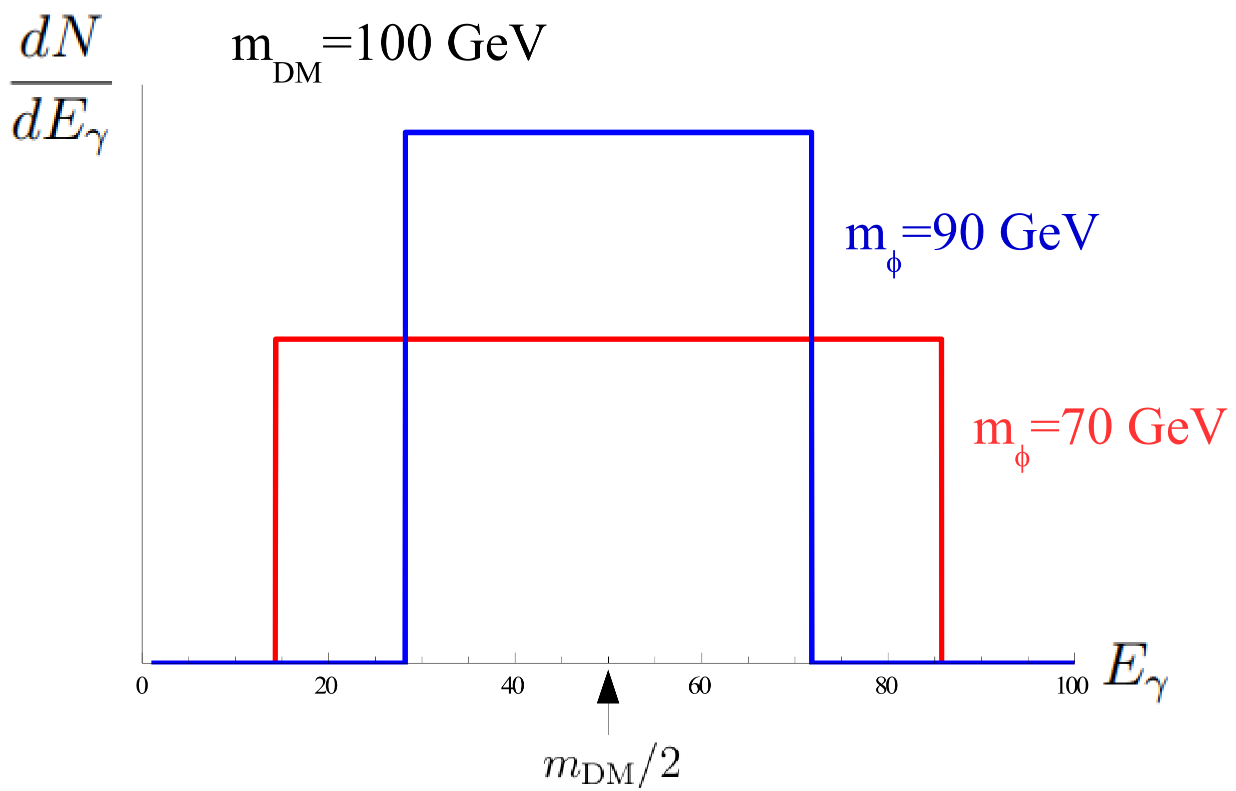
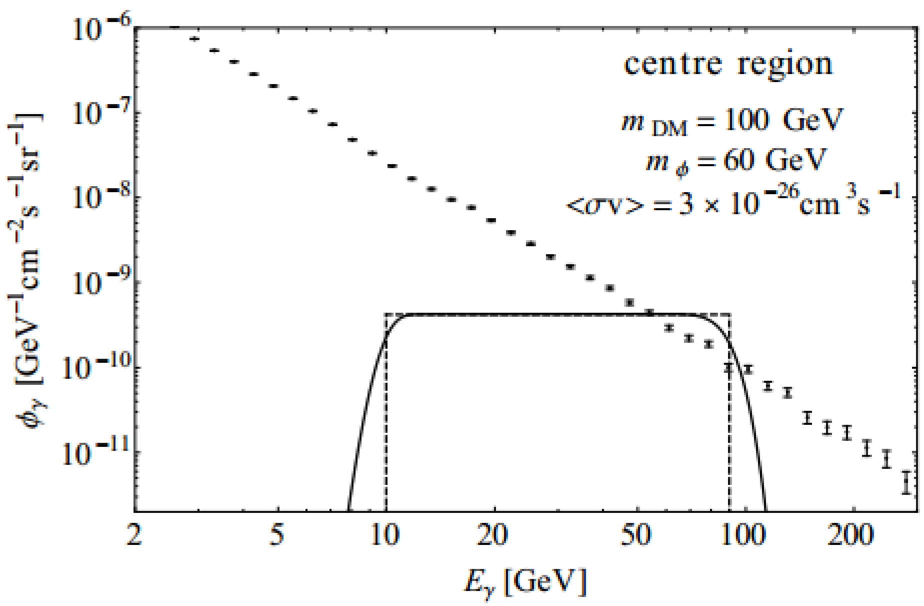
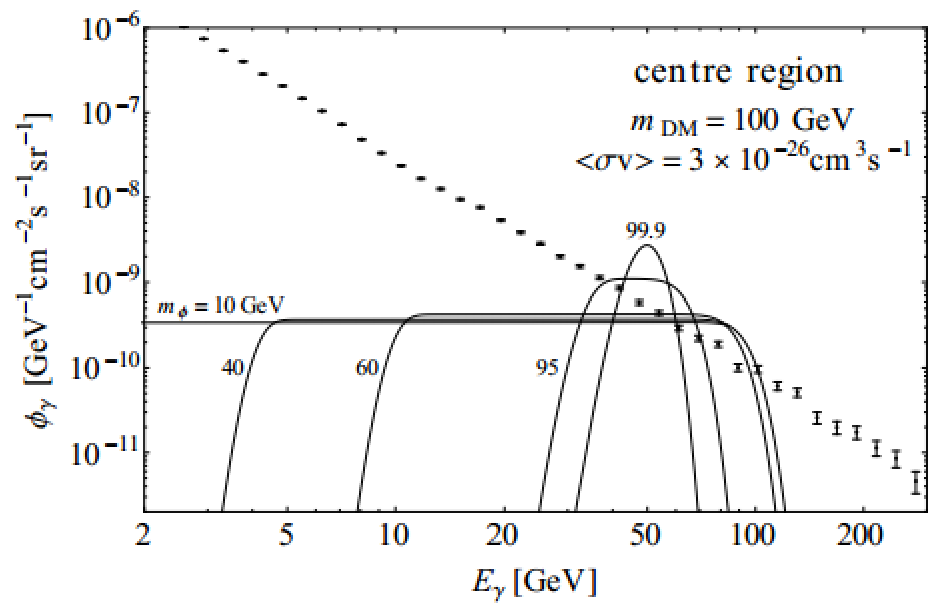
"box-shaped spectrum"

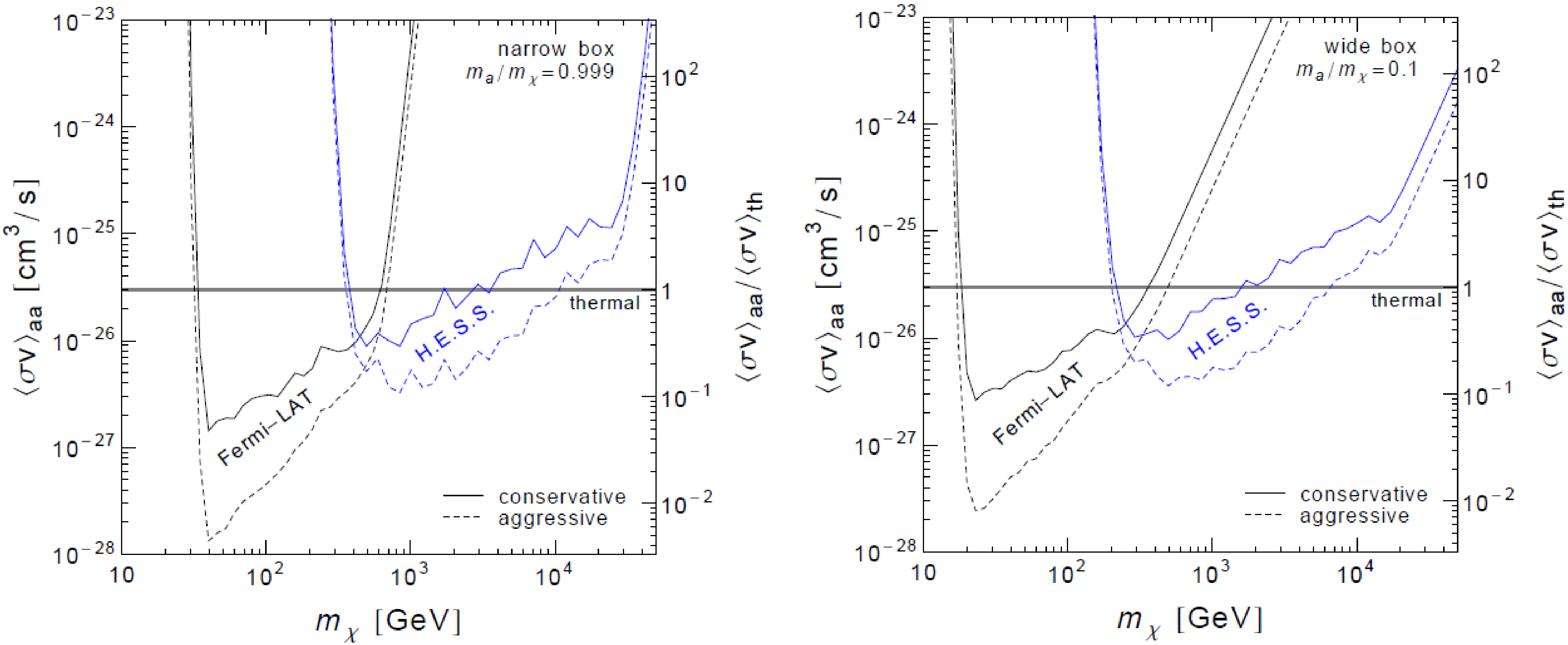


<u>New aspect:</u> the spectral feature arises from a tree level 2→2 annihilation. The strength of the signal could be unsuppressed, depending on the cross section DM DM → ϕϕ and BR(ϕ→γγ).

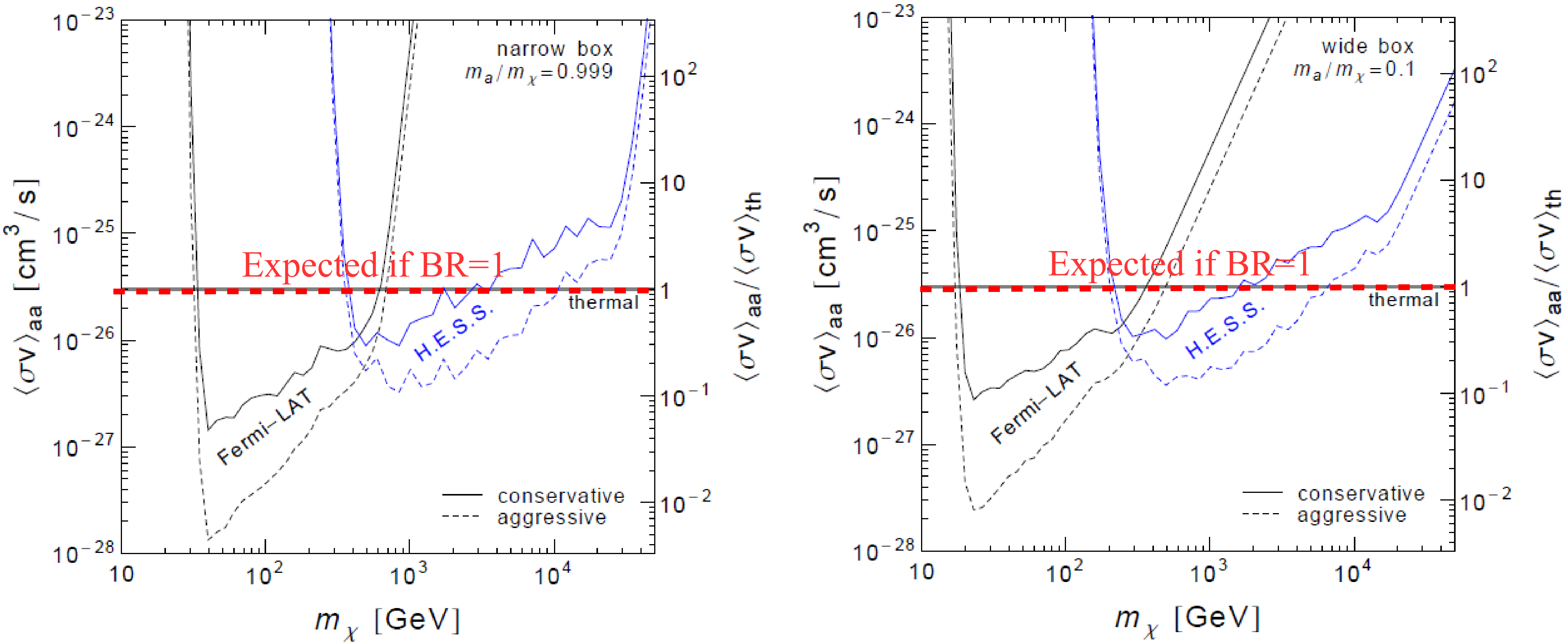



AI, Lopez Gehler, Pato




AI, Lee, Lopez Gehler, Park, Pato



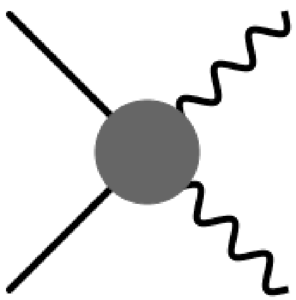
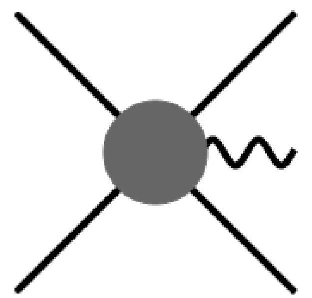
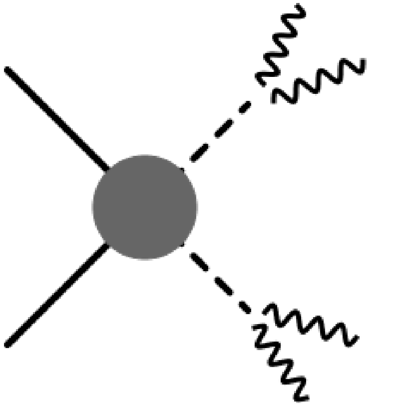

AI, Lee, Lopez Gehler, Park, Pato

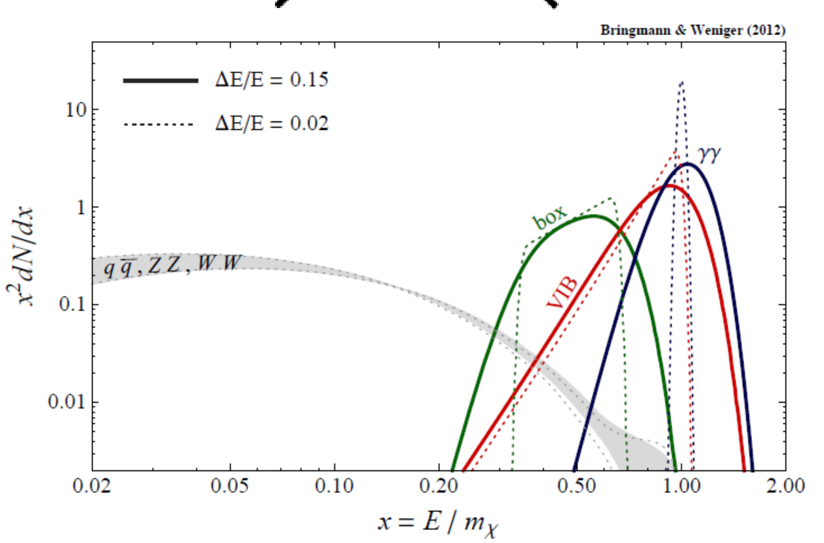
# Gamma-ray spectral features in Particle Physics

## 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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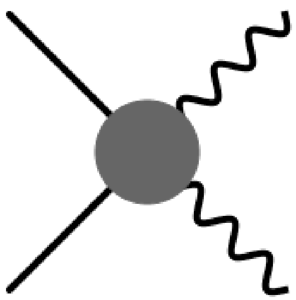
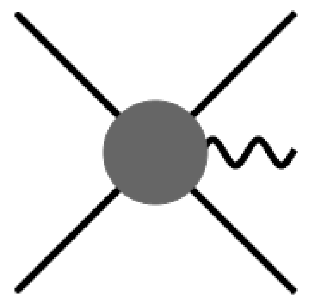


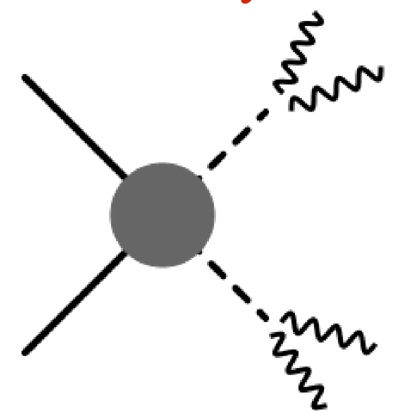
$$\boxed{(\sigma v)^{\text{expected}} \sim 10^{-32}\,\text{cm}^3\text{s}^{-1}}$$

Internal bremsstrahlung



$$\boxed{(\sigma v)^{\text{expected}} \sim 10^{-28}\,\text{cm}^3\text{s}^{-1}}$$

Gamma ray box



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

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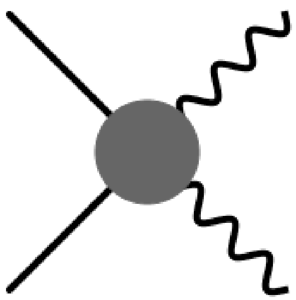

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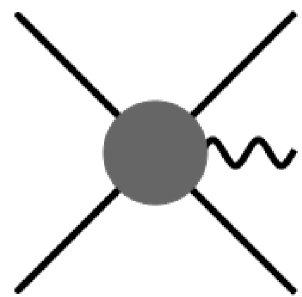

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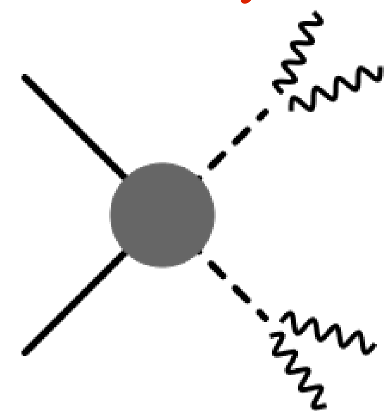

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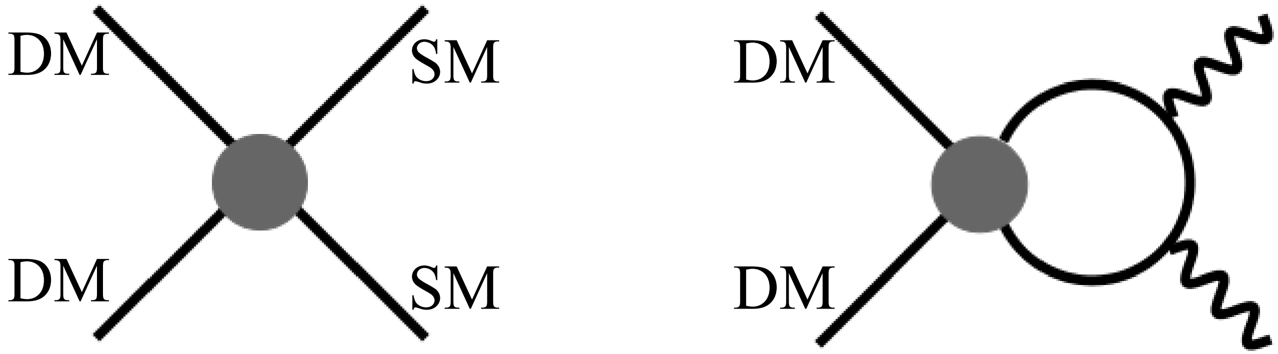
Rather suppressed rates...

# Some recipes to generate intense spectral features

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




$$\boxed{(\sigma v)_{\gamma\gamma} \sim \left(\frac{\alpha}{4\pi}\right)^2 \langle\sigma v\rangle_{\rm thermal} \sim 10^{-32}\,{\rm cm^3 s^{-1}}}$$

Some possible ways-out:

1) The relation of $(\sigma v)_{\gamma\gamma}$ with the thermal value is more involved.

2) The one loop calculation cannot be trusted.

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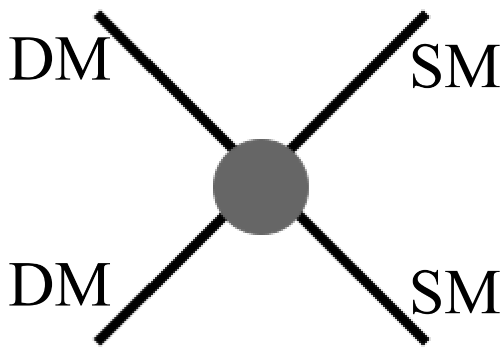


$$(\sigma v) = a + b v^2 + c v^4 + \ldots$$

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{a + 3b \frac{m_{\rm DM}}{T_{\rm fo}} + 20c \frac{m_{\rm DM}^2}{T_{\rm fo}^2}}$$

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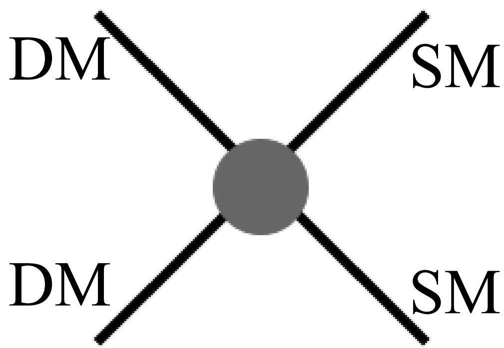


$$(\sigma v) = a + bv^2 + cv^4 + \ldots$$

$$\Omega h^2 \simeq \frac{2.5 \times 10^{-10}\,\mathrm{GeV}^{-2}}{a + 3b\frac{m_{\rm DM}}{T_{\rm fo}} + 20c\frac{m_{\rm DM}^2}{T_{\rm fo}^2}}$$

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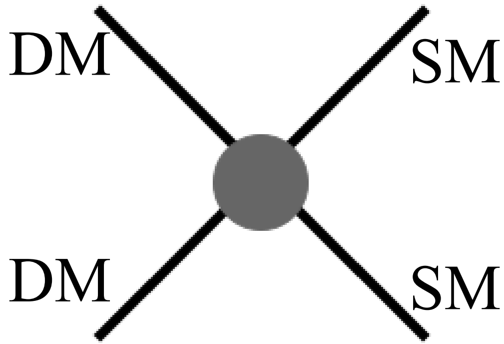


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1st term dominates $\rightarrow a \simeq 2.5 \times 10^{-9}\,\mathrm{GeV}^{-2}$

2nd term dominates $\rightarrow b \simeq 1.7 \times 10^{-8}\,\mathrm{GeV}^{-2}$

3rd term dominates $\rightarrow c \simeq 5 \times 10^{-8}\,\mathrm{GeV}^{-2}$

Increasing strength of the effective interaction

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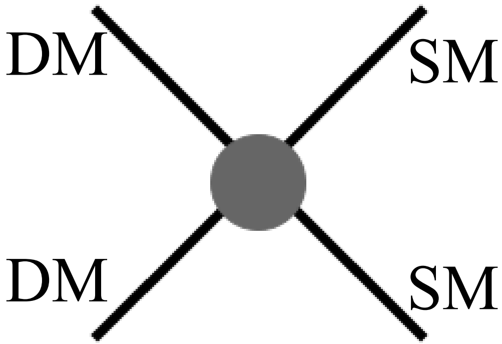


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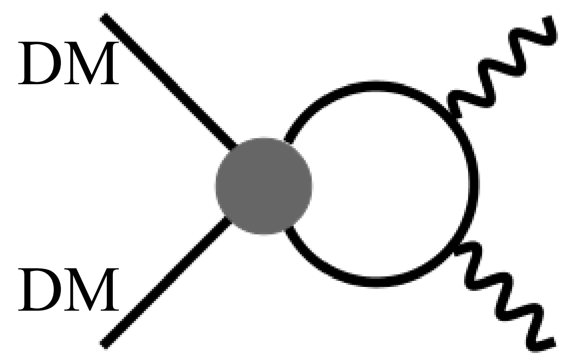


Increasing intensity of the gamma-line (and internal bremsstrahlung) signal.

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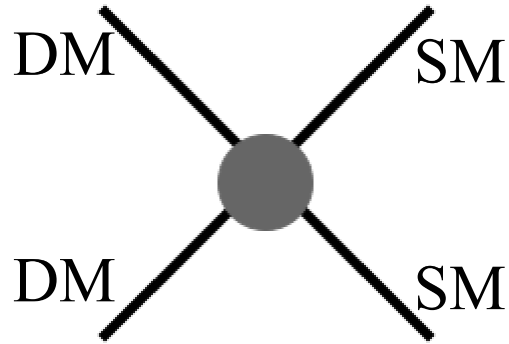


$$(\sigma v) = a + bv^2 + cv^4 + \dots$$

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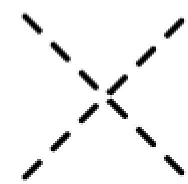
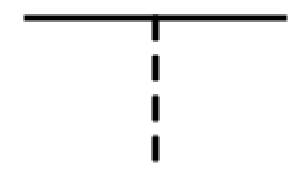
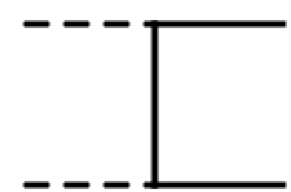
1st term dominates $\rightarrow a \simeq 2.5 \times 10^{-9}\,\mathrm{GeV}^{-2}$ Real singlet scalar



2nd term dominates $\rightarrow b \simeq 1.7 \times 10^{-8}\,\mathrm{GeV}^{-2}$ Majorana fermion with scalar mediator

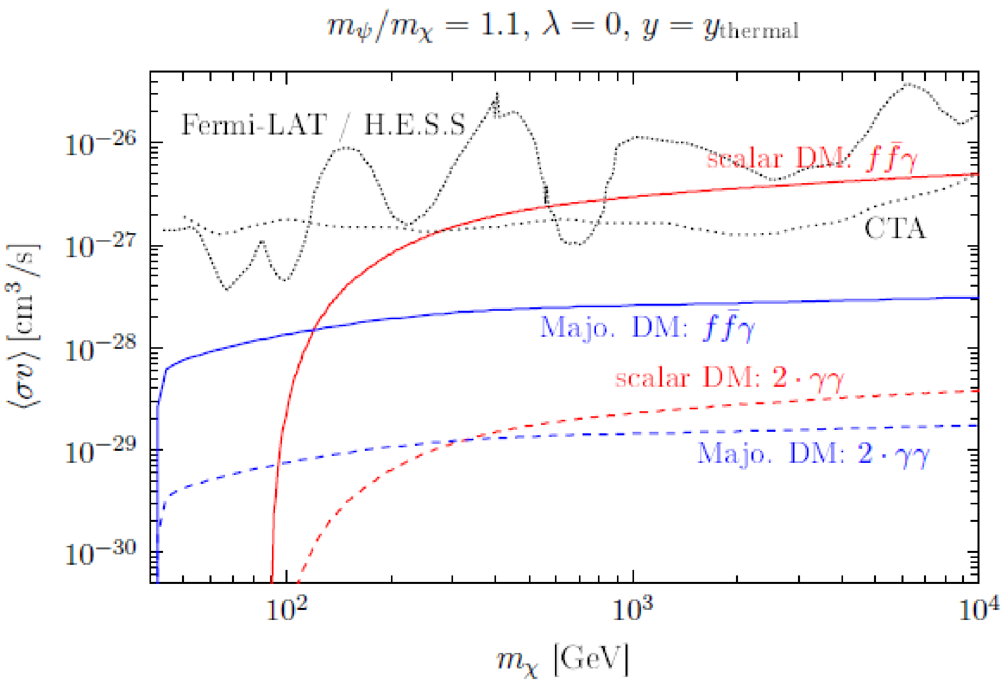


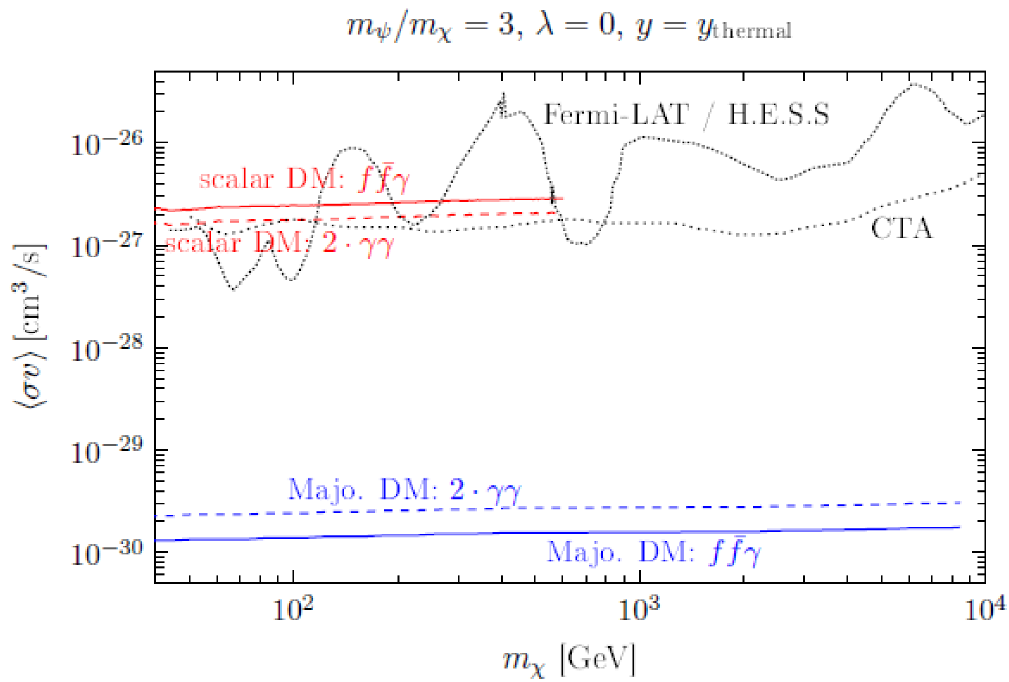
3rd term dominates $\rightarrow c \simeq 5 \times 10^{-8}\,\mathrm{GeV}^{-2}$ Real singlet scalar with fermion mediator



# For scalar DM with fermion mediator

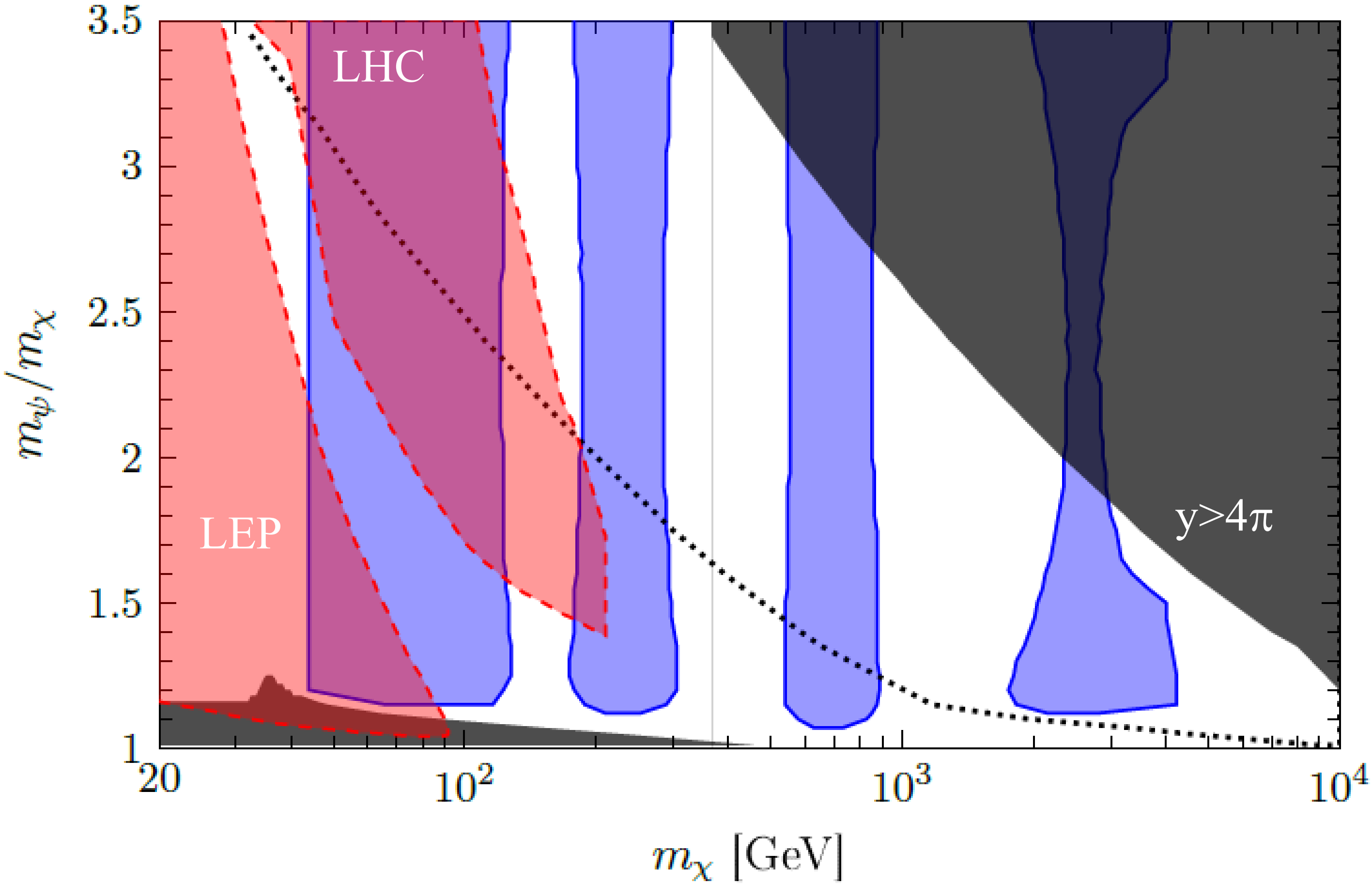
$$(\sigma v)_{\gamma\gamma} \sim \frac{10}{3}\frac{\alpha^2}{\pi^2}\frac{m_{\rm med}^4}{m_{\rm DM}^4}\frac{m_{\rm DM}^2}{60T_{\rm fo}^2}\langle\sigma v\rangle_{\rm th}$$




AI, Wild, Totzauer
See also Giacchino, Lopez-Honorez, Tytgat

$\lambda = 0,\ y = y_{\text{thermal}}(\lambda, m_\chi, m_\psi)$: existing constraints

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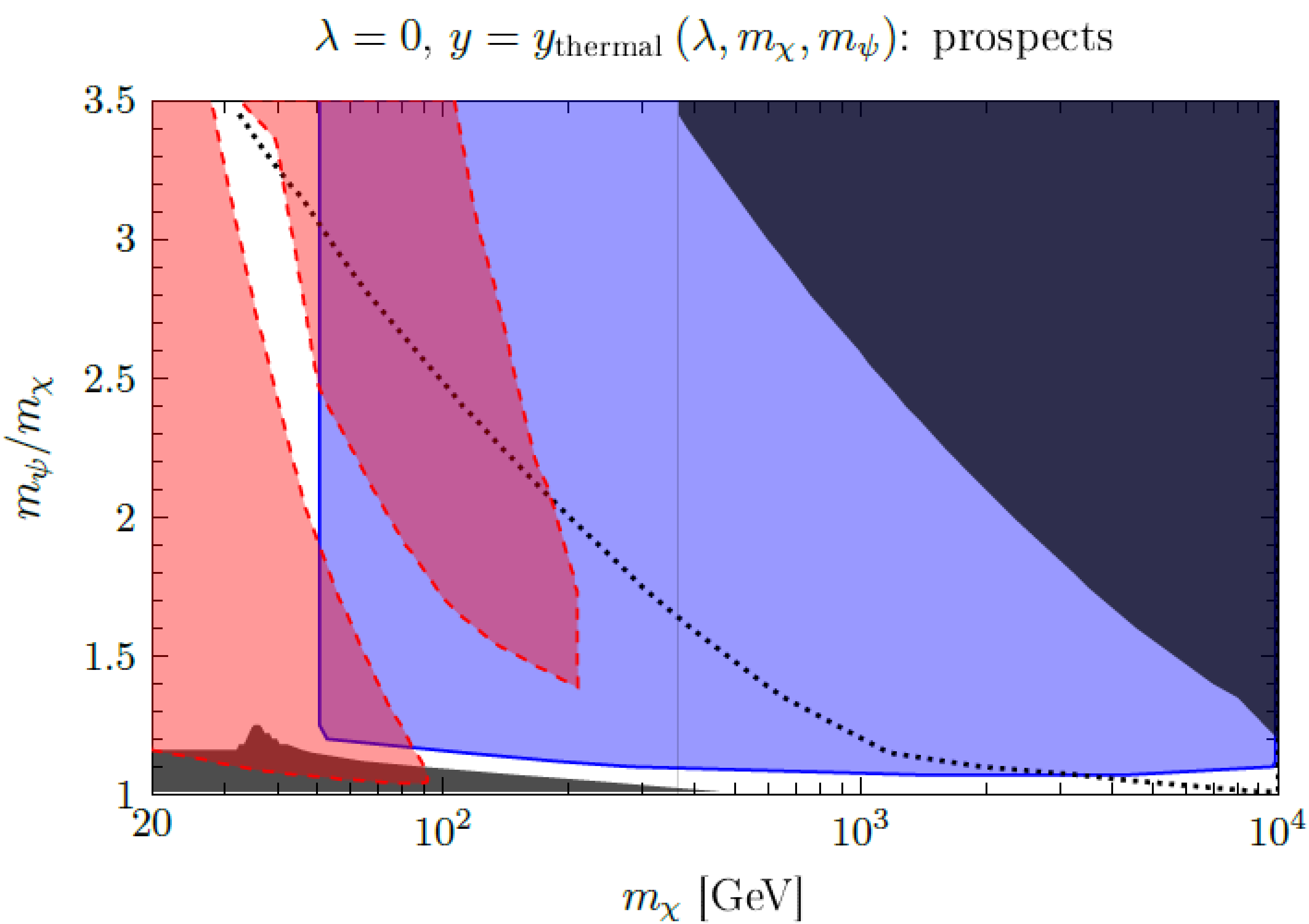


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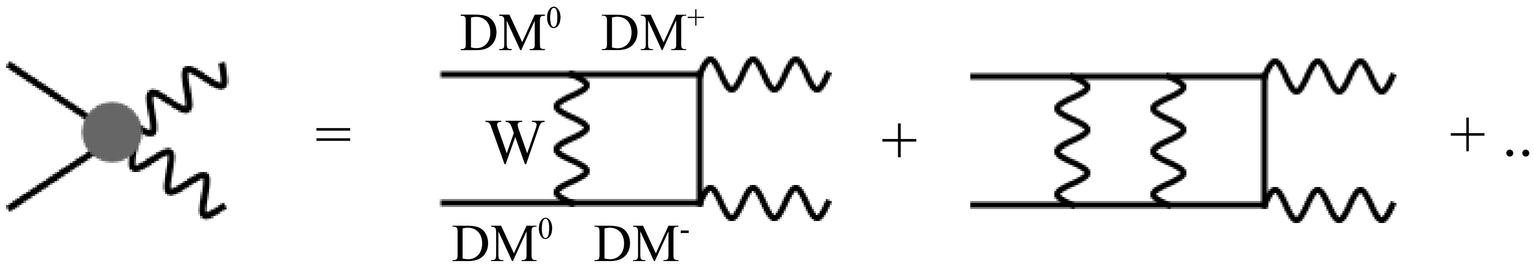
2) The one loop calculation cannot be trusted

Consider a dark matter candidate charged under $SU(2)_L$

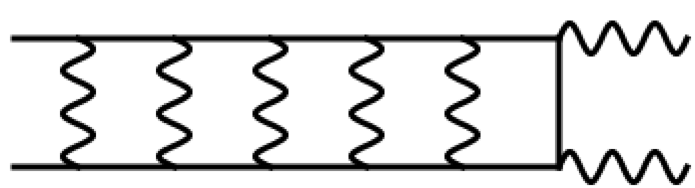



The expansion parameter is not $\alpha_2$, but rather $\frac{\alpha_2 m_{\rm DM}}{M_W}$

The one loop calculation cannot be trusted if

$$m_{\rm DM} \gtrsim \frac{M_W}{\alpha_2} \sim 2\,{\rm TeV}$$

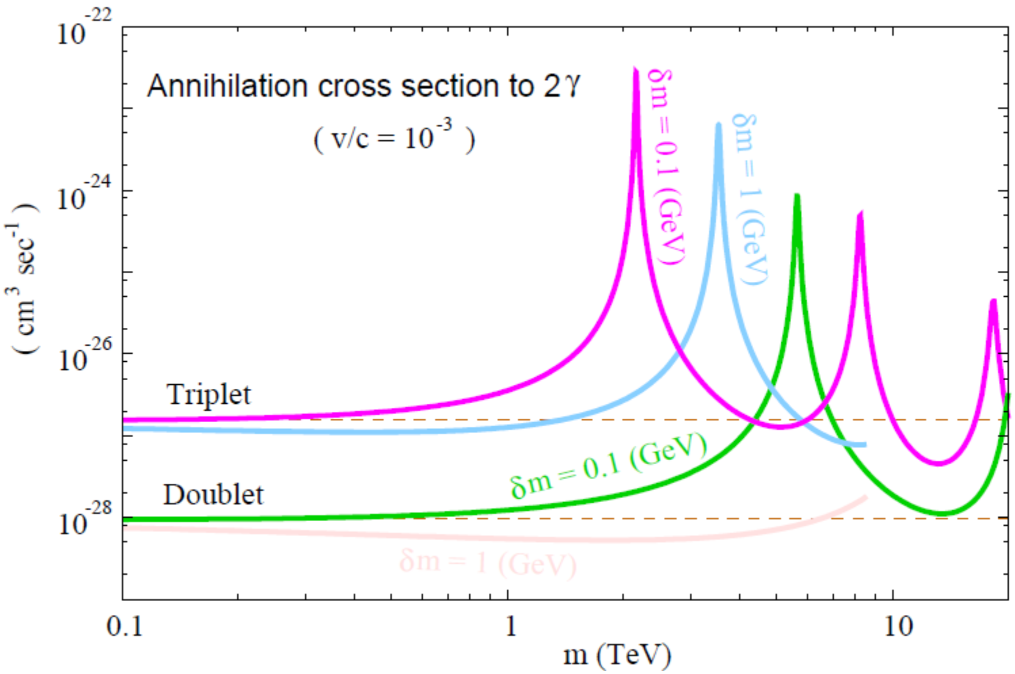
Necessary to resum diagrams at all loops



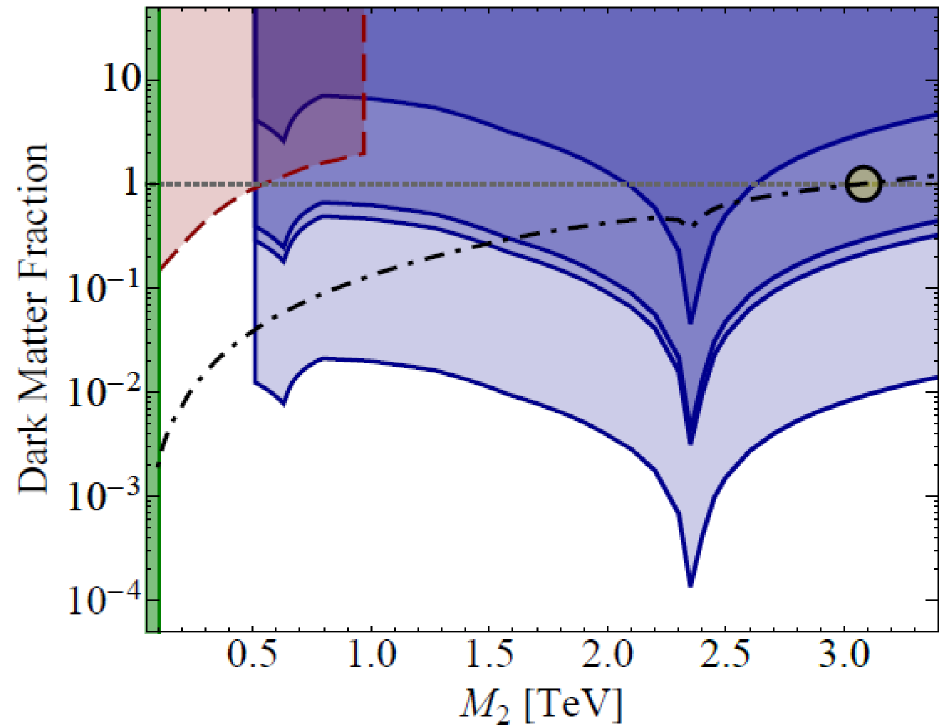
$\longrightarrow$ Generically leads to an enhancement of the cross section (Sommerfeld enhancement).

(Hisano, Matsumoto, Nojiri)

# Wino dark matter

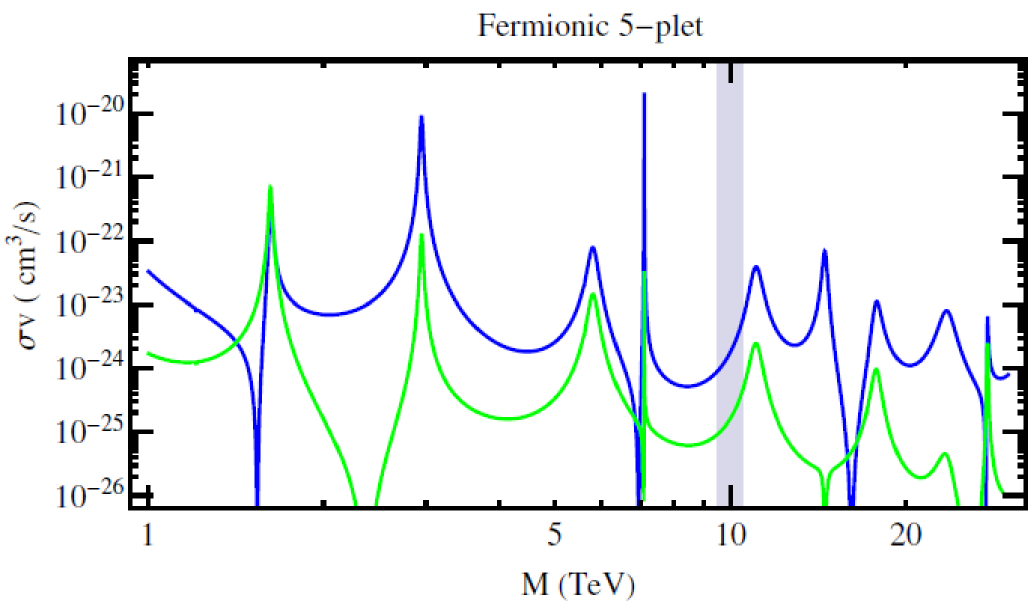


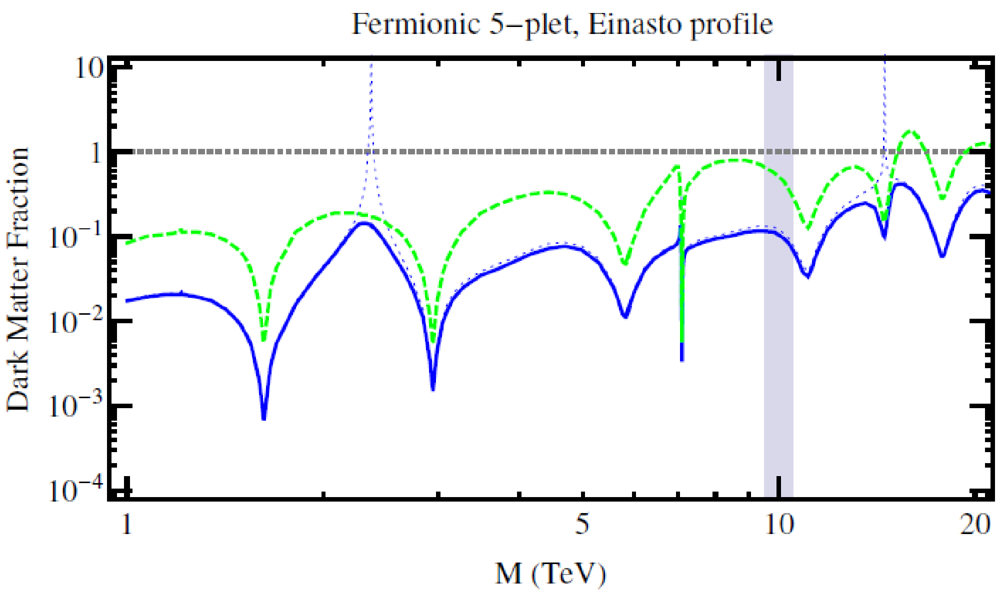

Hisano, Matsumoto, Nojiri




Cohen, Lisanti, Pierce, Slatyer

# Minimal dark matter (fermion 5-plet)




Garcia-Cely, Ibarra, Lamperstorfer, Tytgat
See also Cirelli, Hambye, Panci, Sala, Taoso

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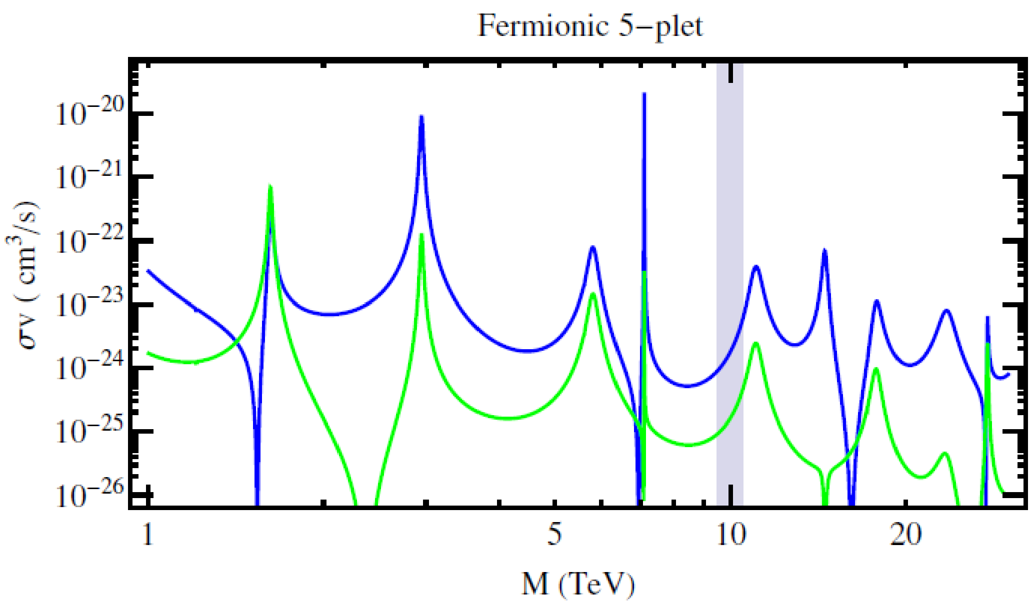


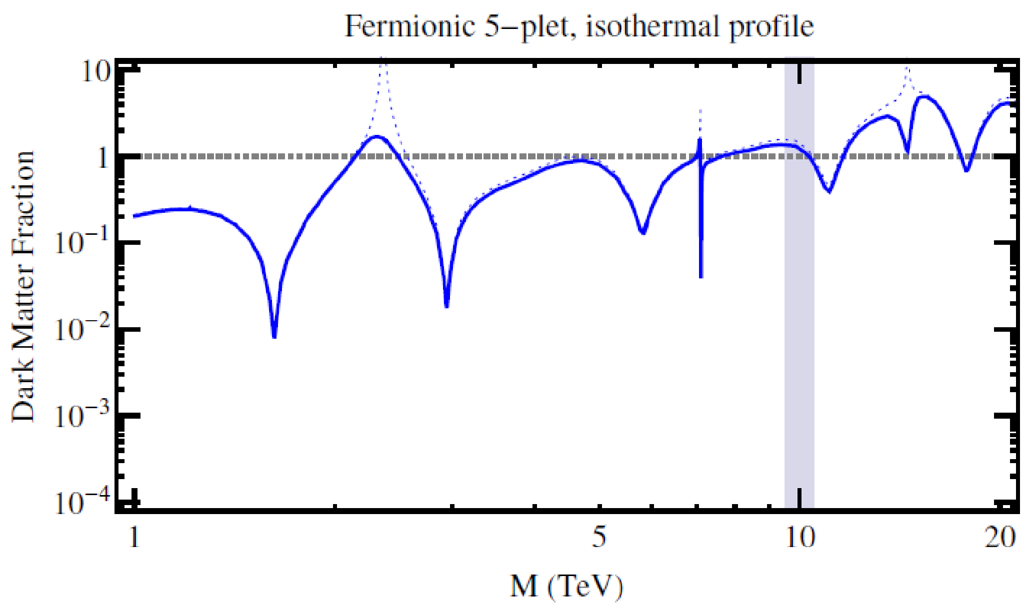


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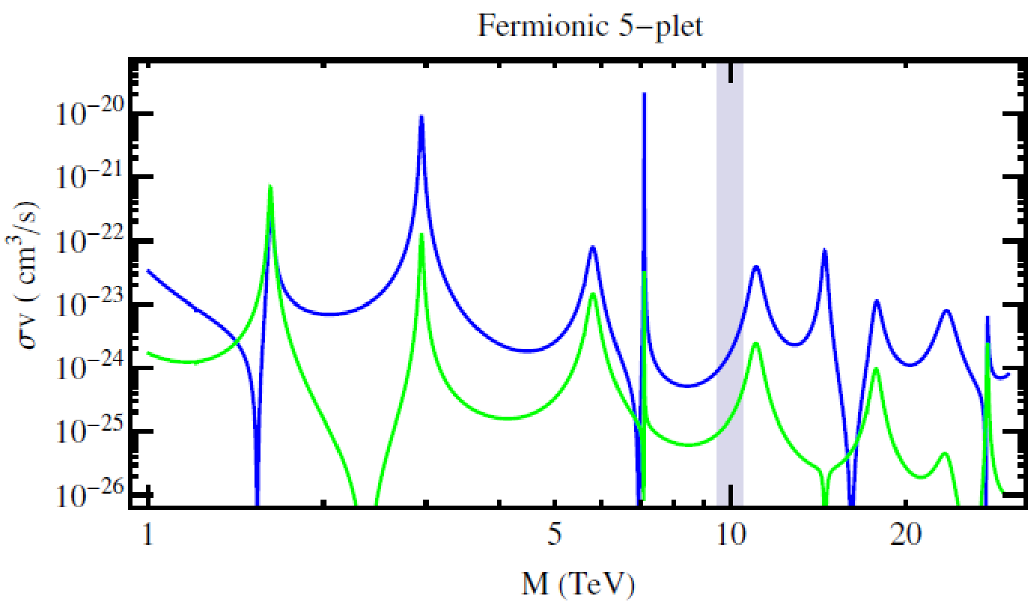


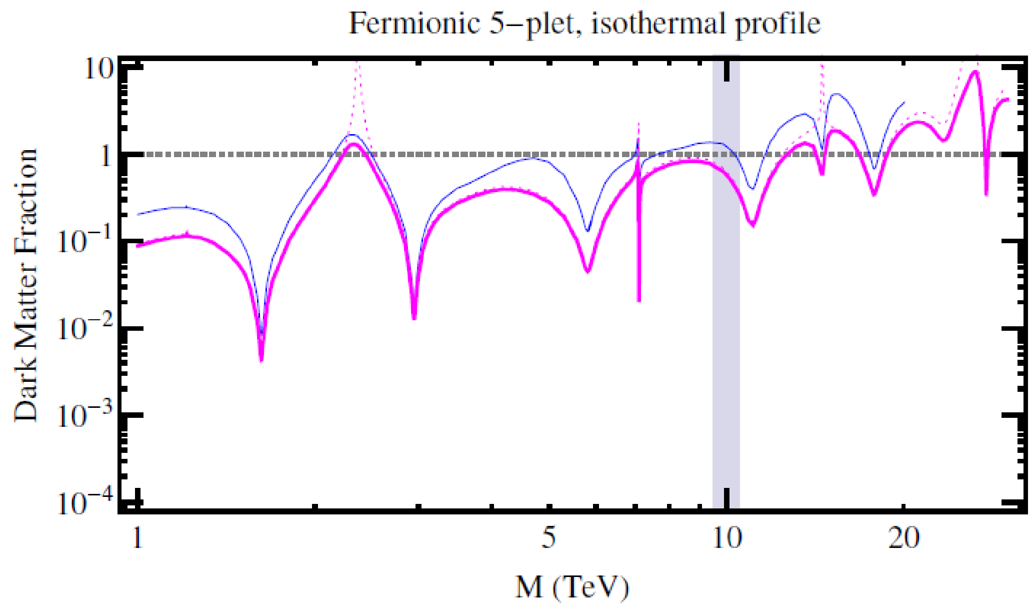


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# Conclusions

- The identification of a DM annihilation signal would be a groundbreaking discovery, with implications for Particle Physics and Cosmology.
- A promising approach to search for DM annihilations consists in searching for sharp features in the gamma-ray spectrum. No known astrophysical process can produce such a signal in the 10 GeV – multi TeV range → "smoking gun" for DM detection.
- In general faint, although fairly intense in some well-motivated dark matter scenarios of thermal production.
- Present observations already probe the parameter space of some of those models, even for large DM masses, which are virtually inaccessible to other detection approaches.
- Future experiments (H.E.S.S. II, CTA) will continue closing in on the parameter space of the model. Dark matter signals could be around the corner.