Dark Matter Physics

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Technische Universität München

Summer Institute 2016
Xi-Tou
August 2016

Outline

Lecture 1: Evidence for dark matter.

Lecture 2: Dark matter production. Indirect detection.

Lecture 3: Indirect detection (cont.), direct detection.

Indirect Dark Matter Searches

Indirect dark matter searches

General idea:

1) Dark matter particles annihilate or decay producing a flux of stable particles: photons, electrons, protons, positrons, antiprotons or (anti-)neutrinos.

2) These particles propagate through the galaxy and through the Solar System. Some of them will reach the Earth.

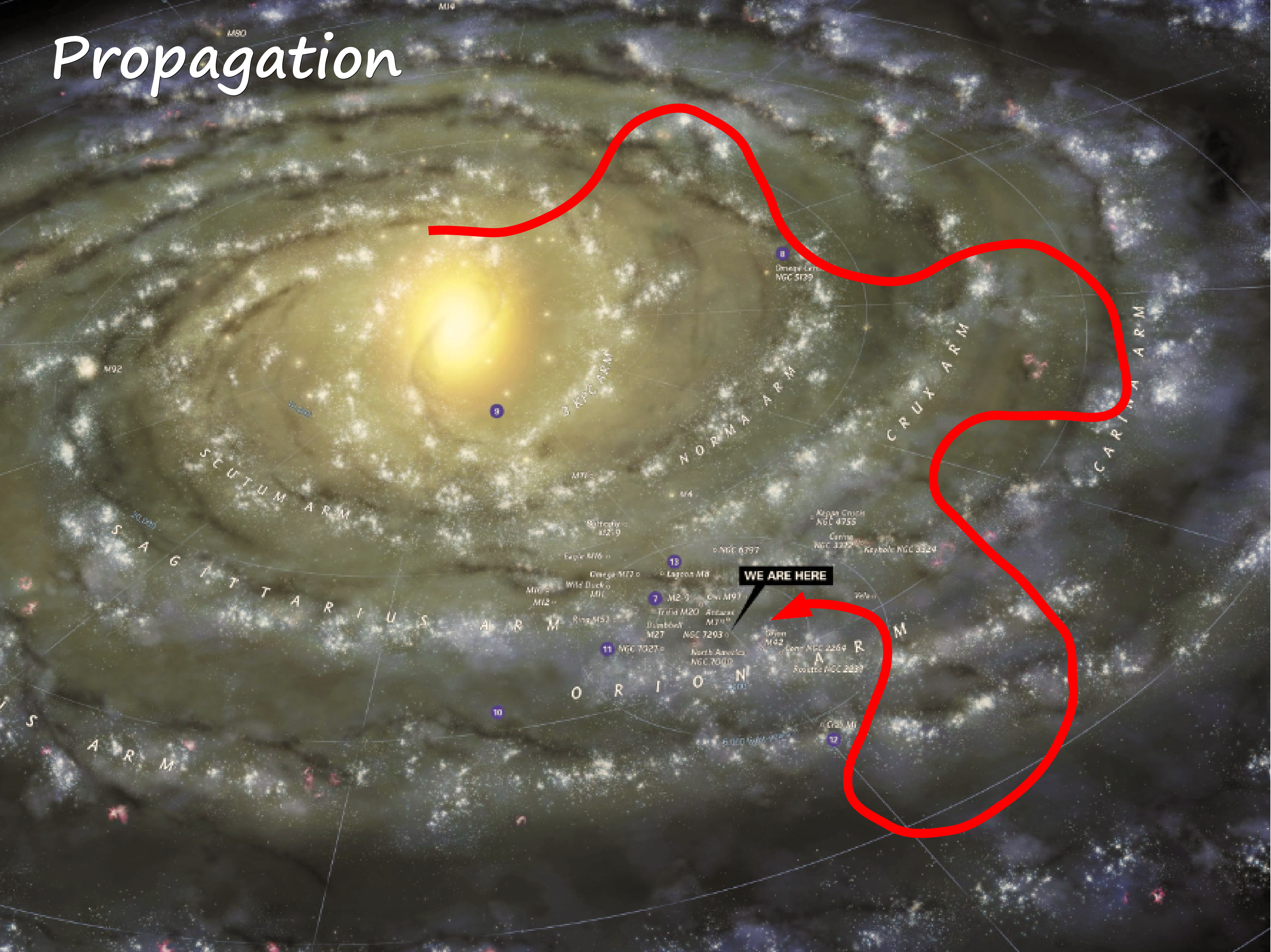
3) The products of the dark matter annihilations or decays are detected together with other particles produced in astrophysical processes (for example, cosmic ray collisions with nuclei in the interstellar medium). The existence of dark matter can then be inferred if there is a significant excess in the fluxes compared to the expected astrophysical backgrounds.

Indirect dark matter searches

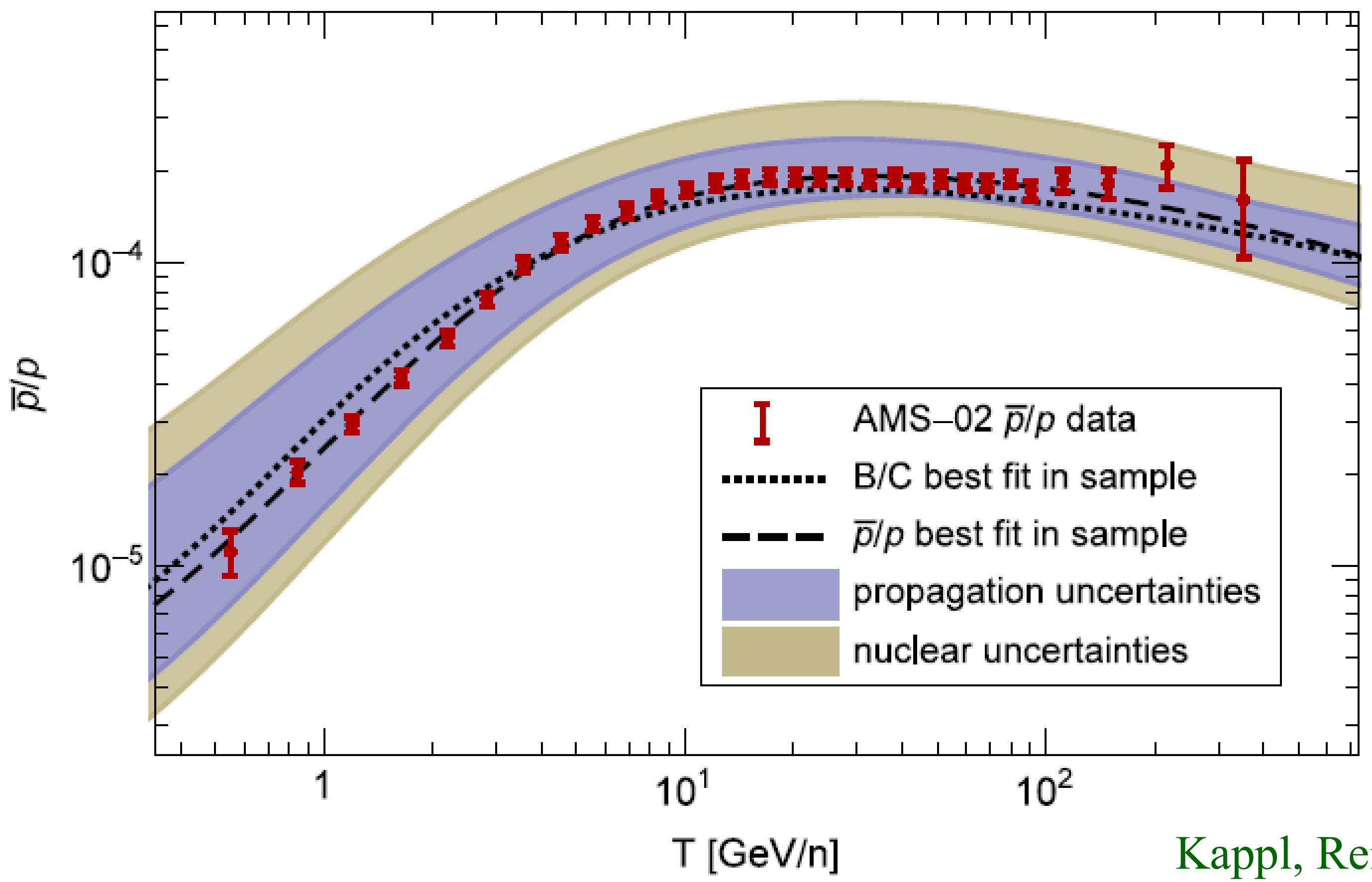
Production			Antimatter
Propagation	}	of	{ Gamma-rays
Detection			Neutrinos

Antimatter

Propagation



Experimental results: antiprotons



Kappl, Reinert, Winkler
arXiv:1506.04145

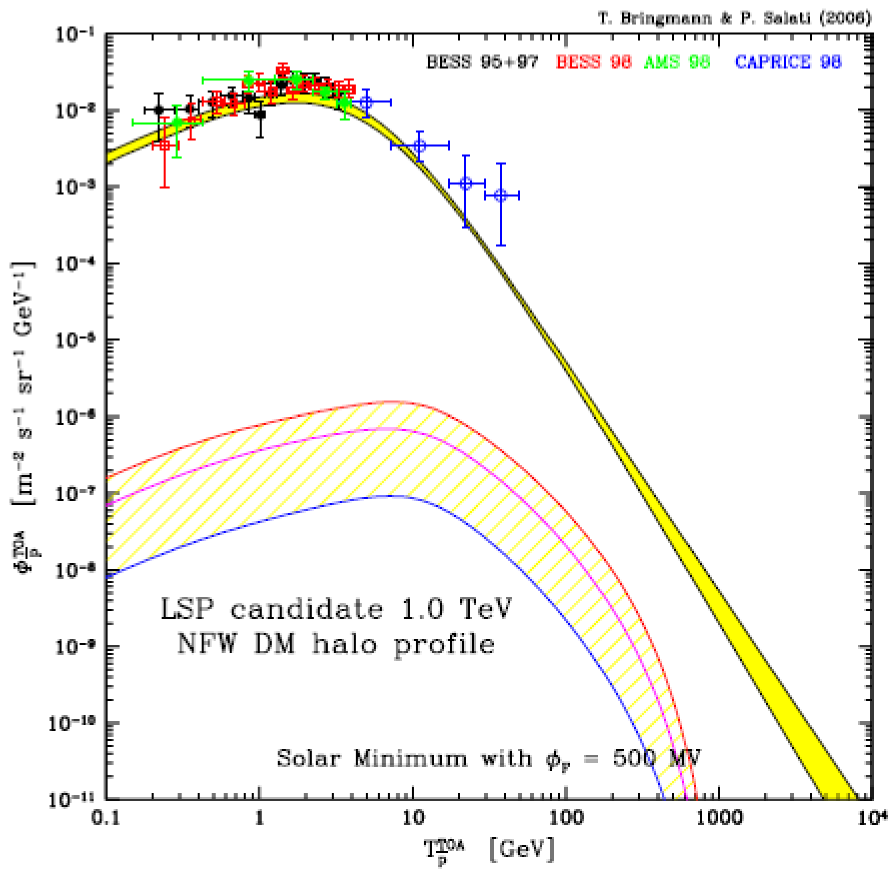
Fairly good agreement between the measurements and the theoretical predictions from collisions of cosmic rays on the interstellar medium $p\,p \rightarrow \bar{p}\,X$

Expectations from theory

A concrete example in the minimal supersymmetric standard model.

TeV $\times 10^{-26}$ cm^{3}s^{-1}

DM model	m	$\langle\sigma_{\rm ann}v\rangle$	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	ZZ	W^+W^-	HH	gg
LSP1.0	1.0	0.46	-	-	-	-	-	-	-	100	-	-



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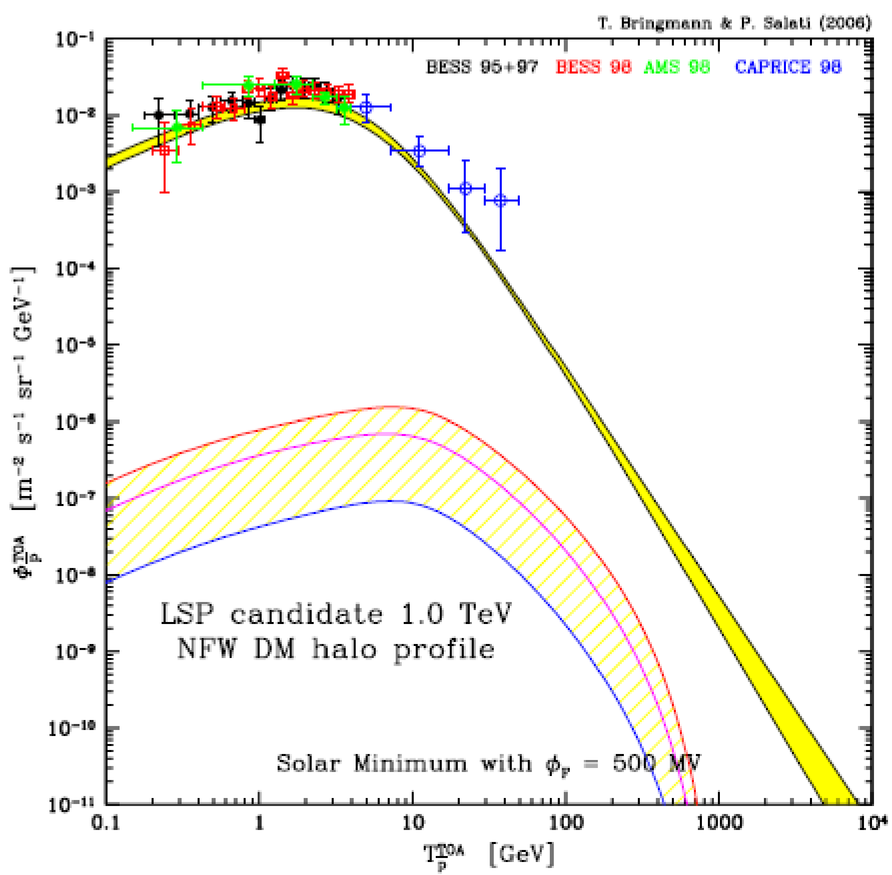
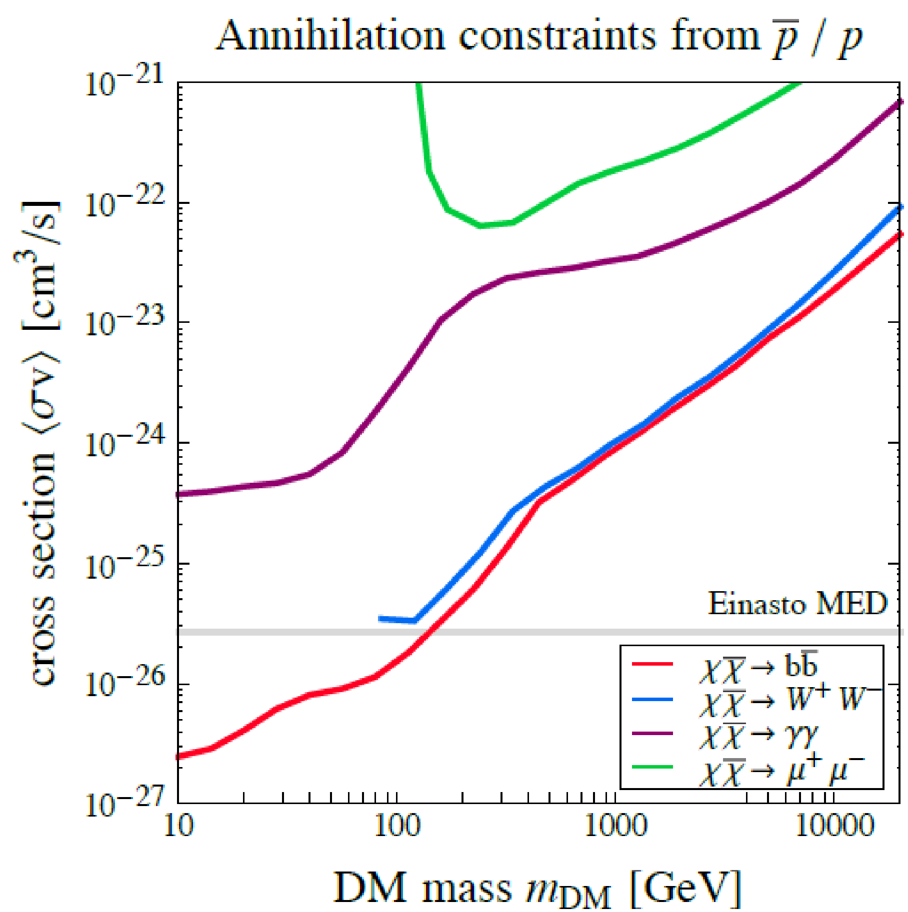
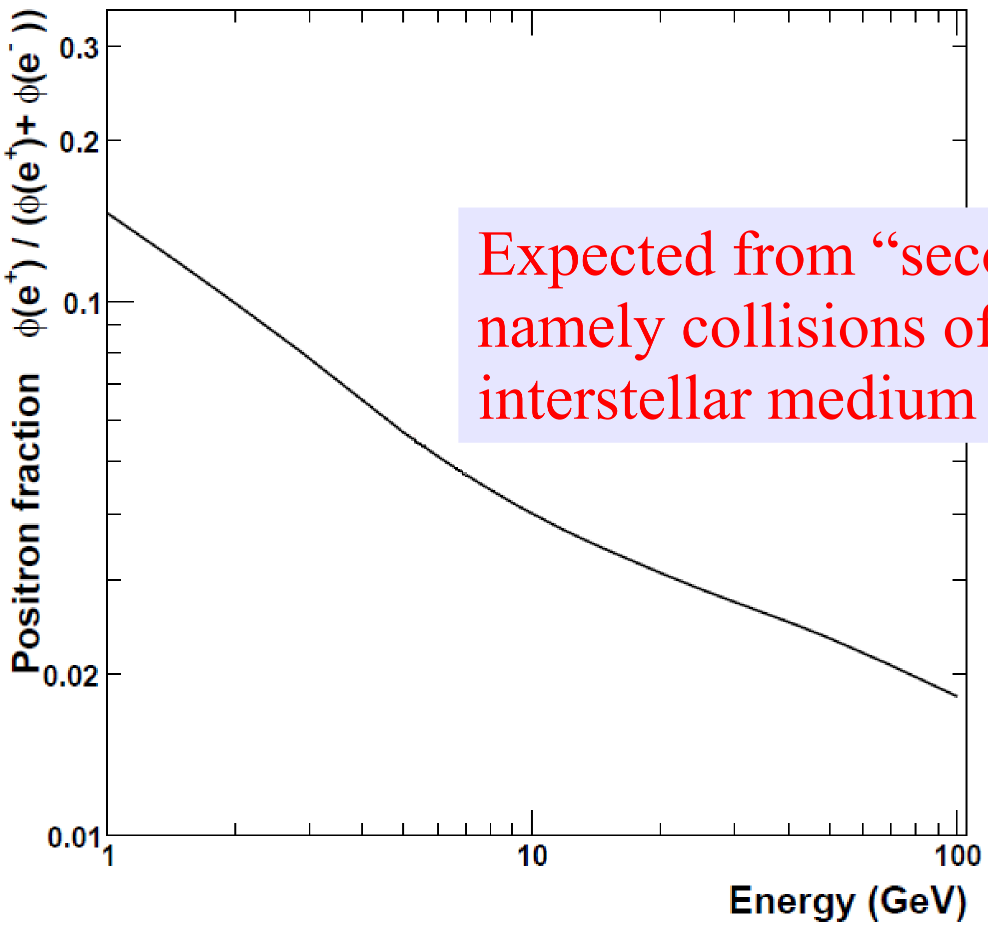




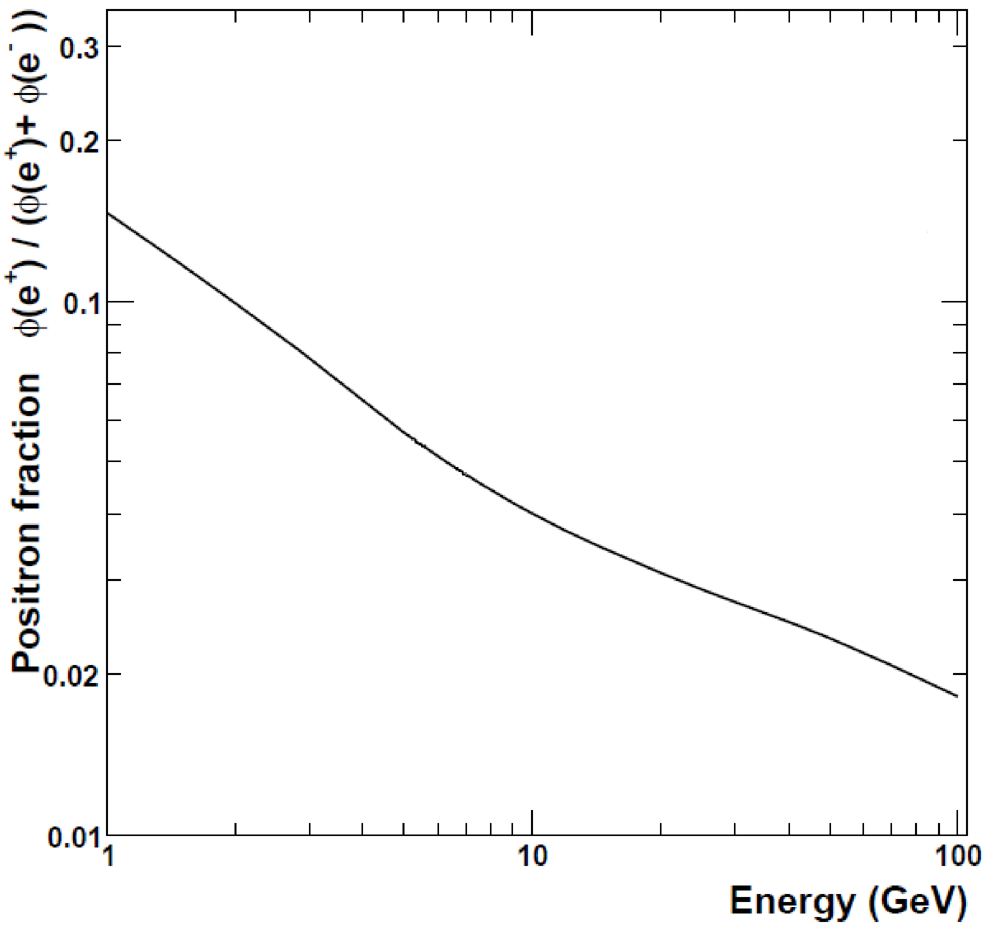
Giesen et al
arXiv:1504.04276

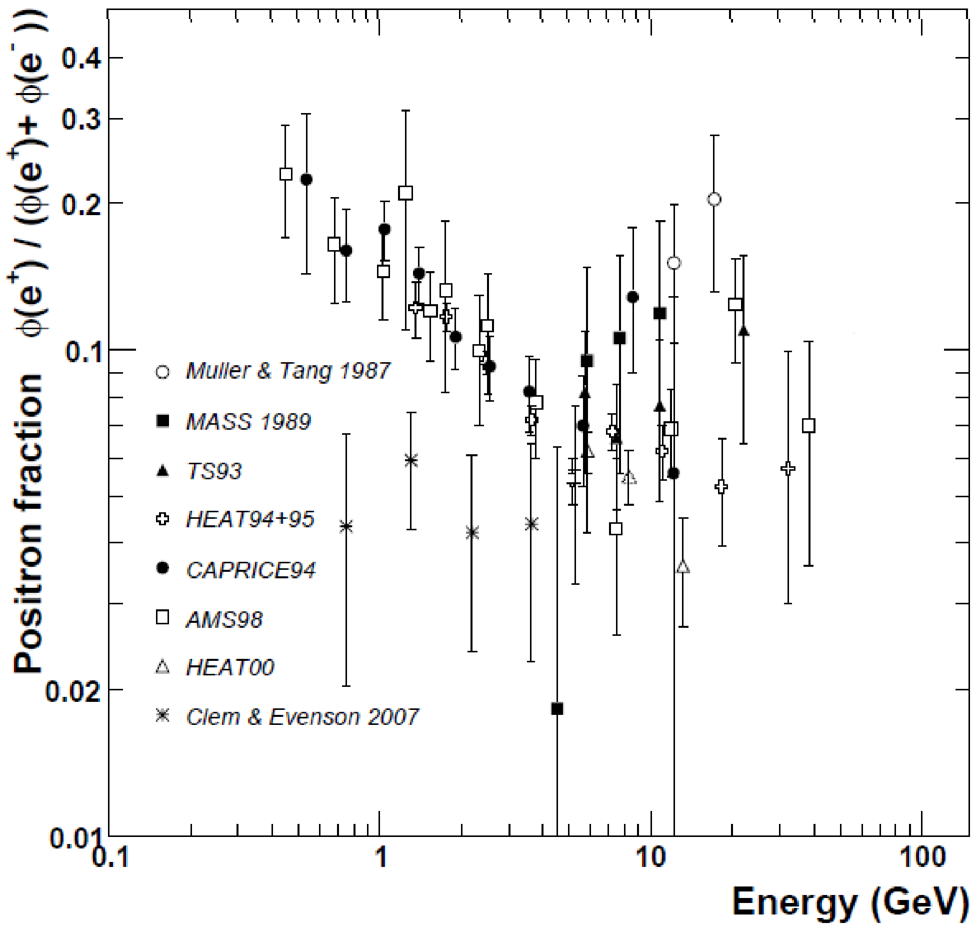
Experimental results: positrons



Expected from "secondary production", namely collisions of cosmic rays on the interstellar medium ($p\ p \rightarrow e^+ X$).

Experimental results: positrons





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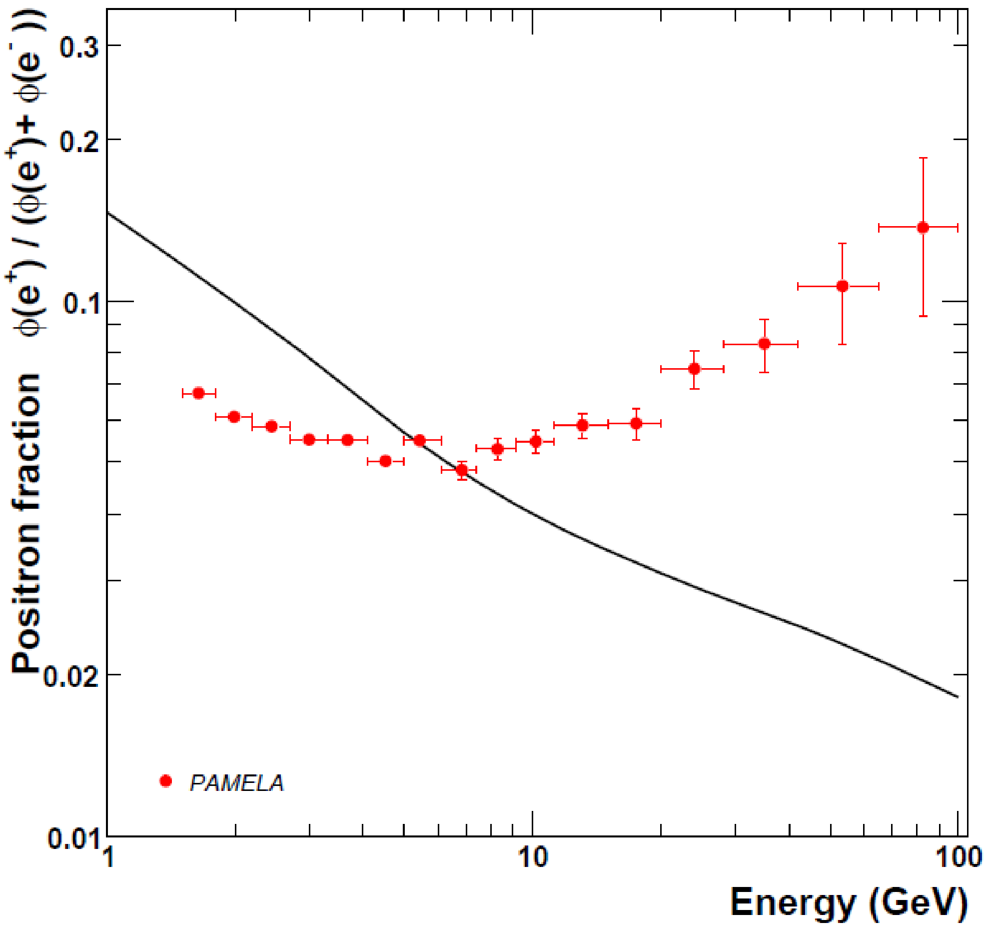
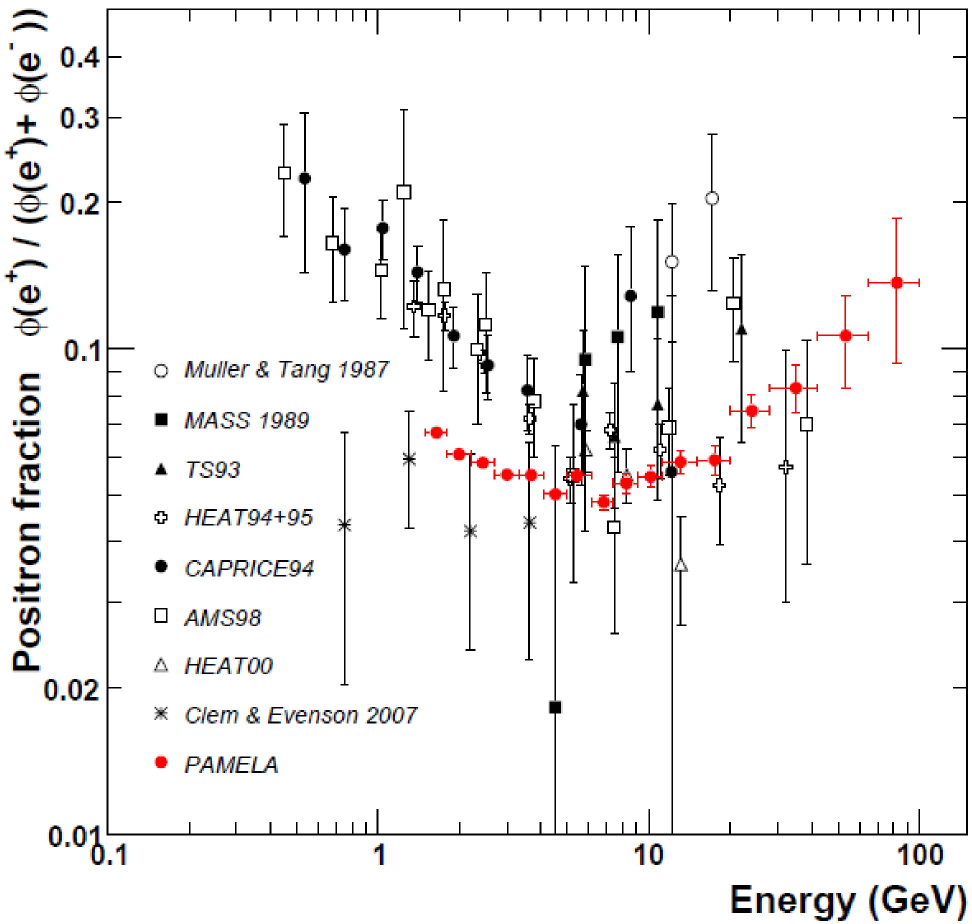
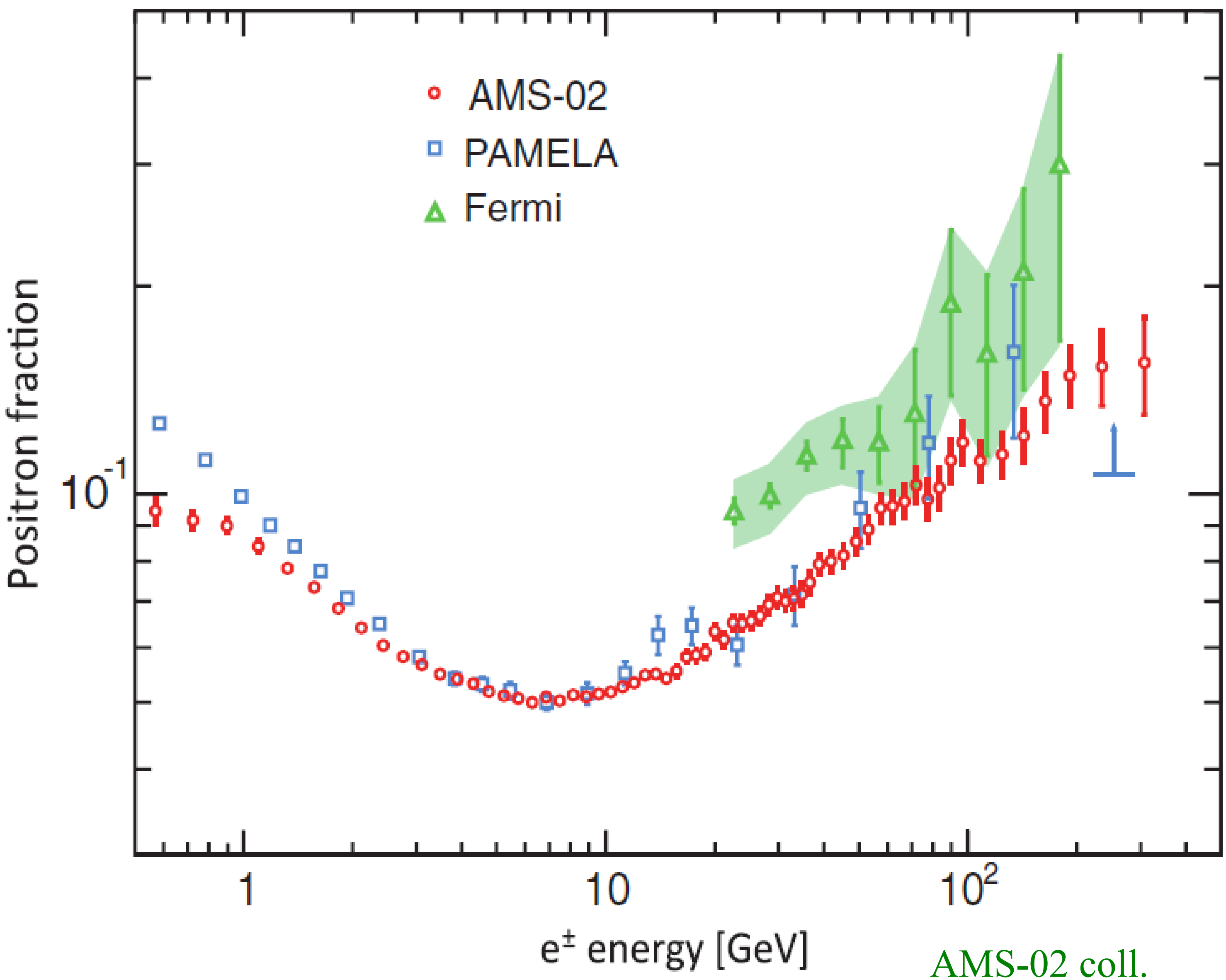




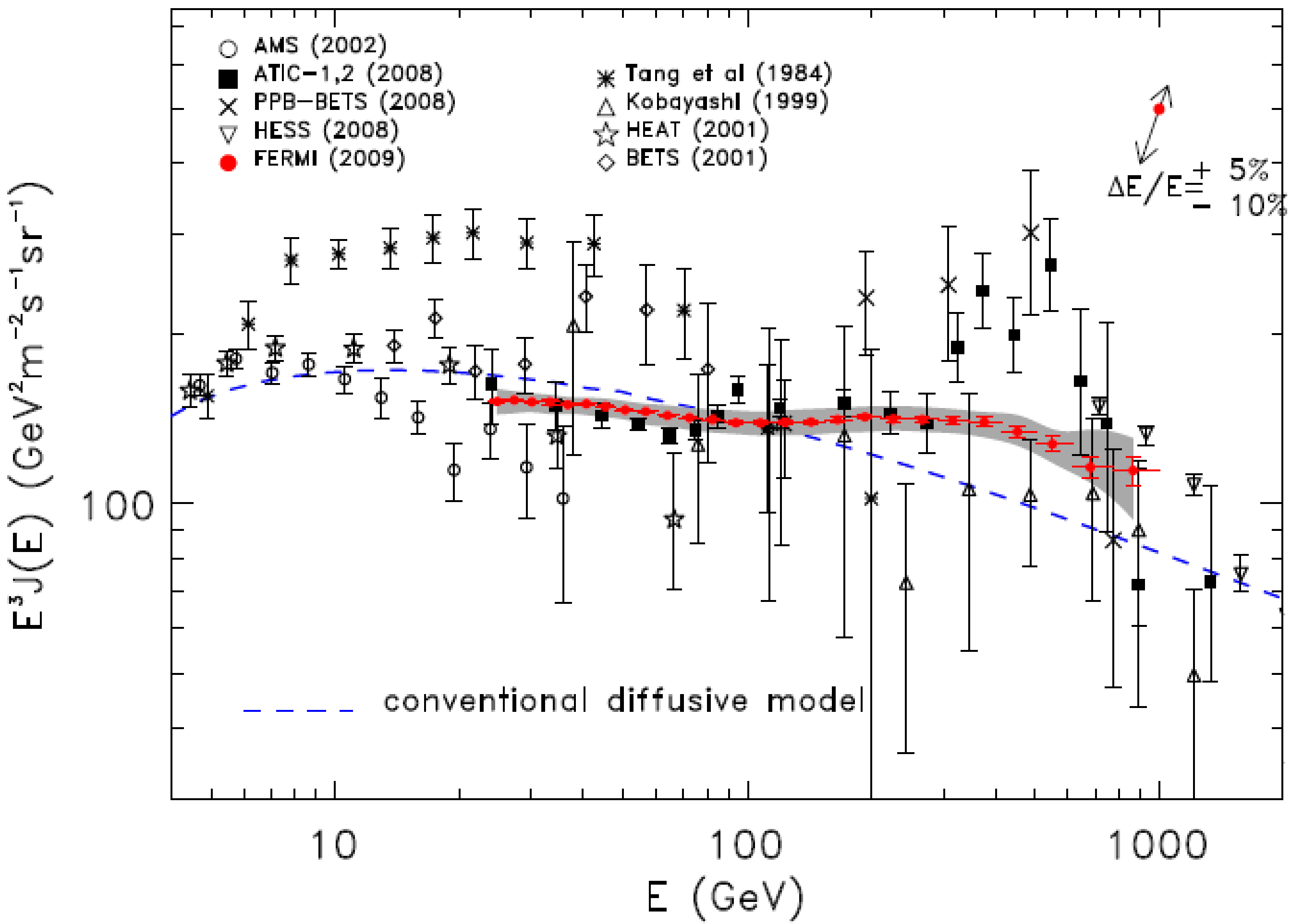
PAMELA coll.
arXiv:0810.4995

Experimental results: positrons



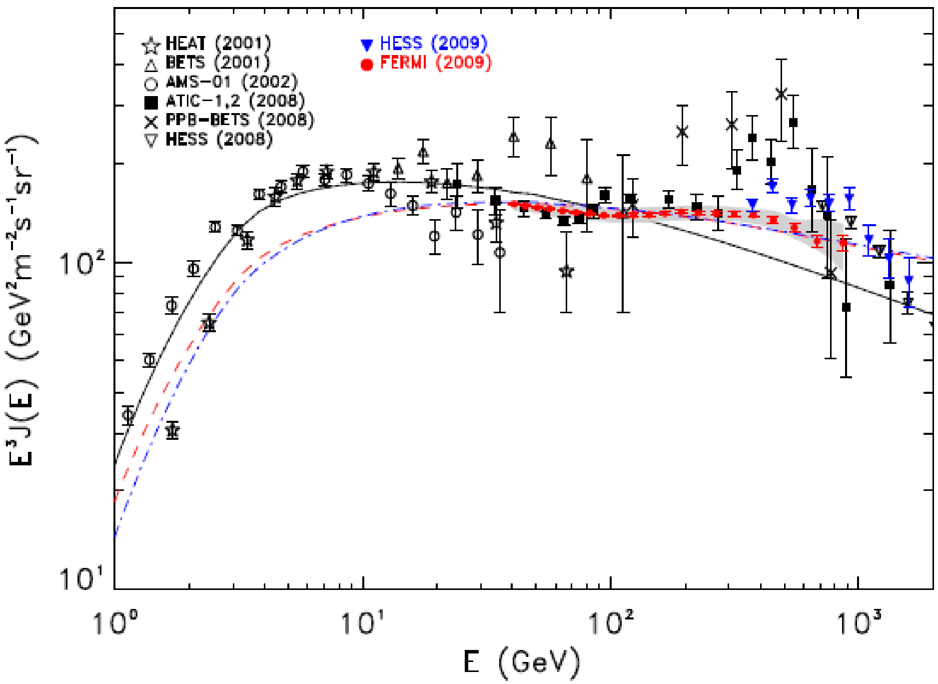
AMS-02 coll.
Phys.Rev.Lett. 110 (2013) 14, 141102

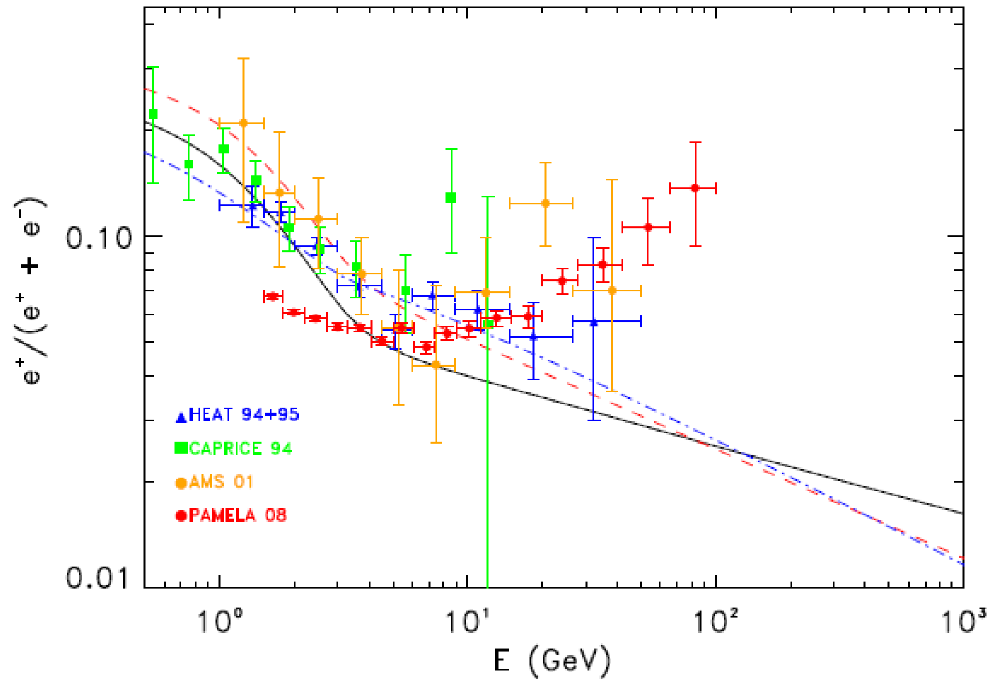
More puzzles: the electron+positron flux



Abdo et al.
ArXiv:0905.0025

More puzzles: the electron+positron flux





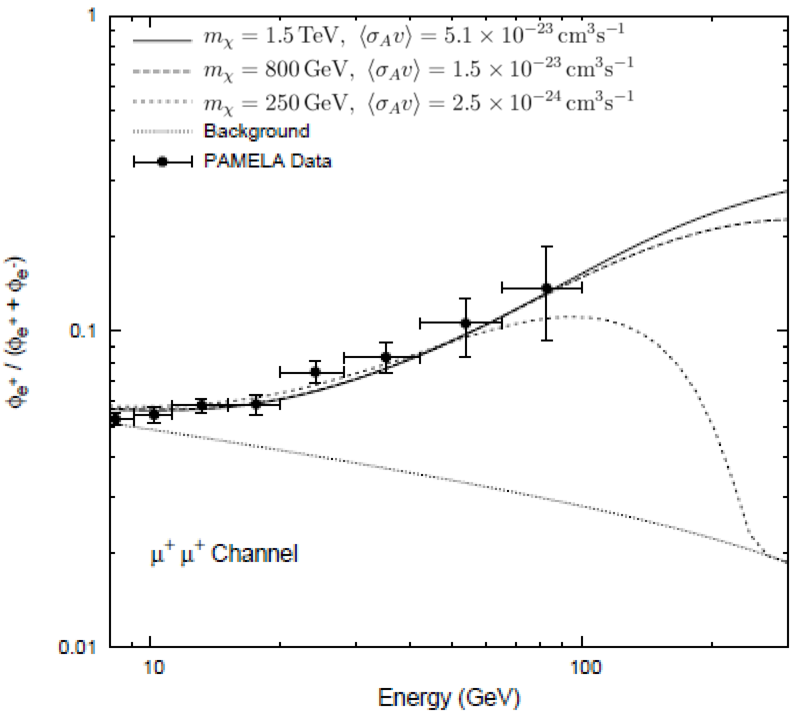
Evidence for a primary component of positrons

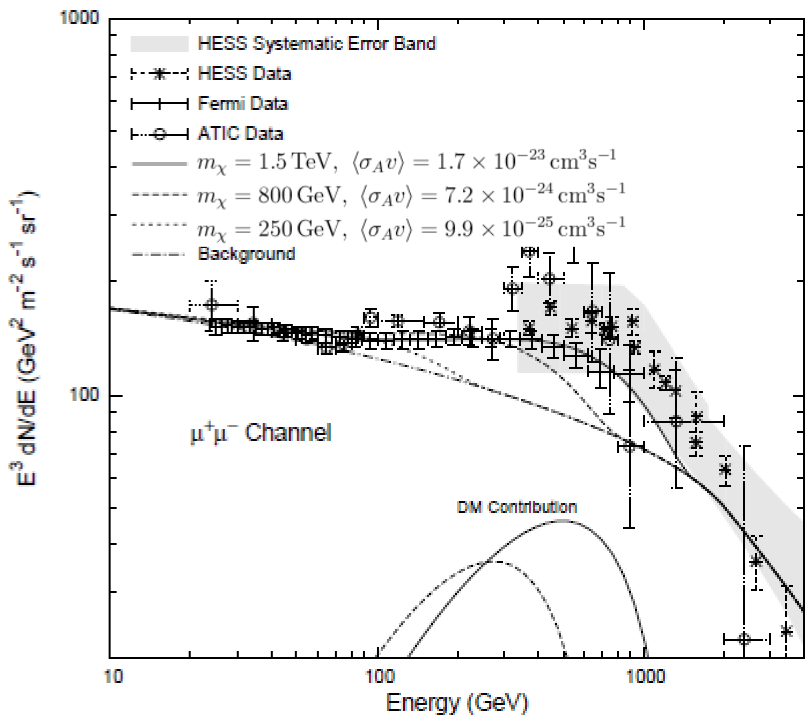
(possibly accompanied by electrons)

Dark matter interpretation

An electron/positron excess could arise from dark matter annihilations ...

$$\chi\chi \to \mu^+\mu^-$$

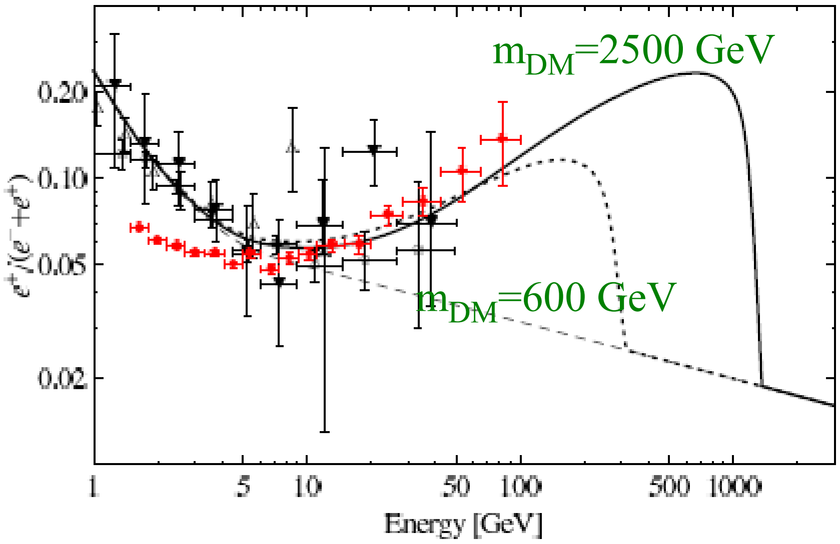


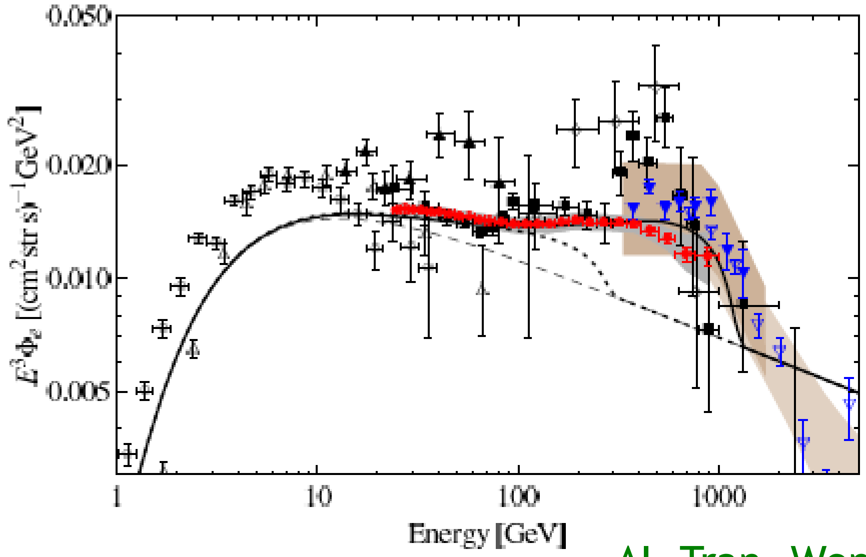


Cholis et al.
arXiv:0811.3641

… or dark matter decays

$$\psi \to \ell^+ \ell^- \nu$$

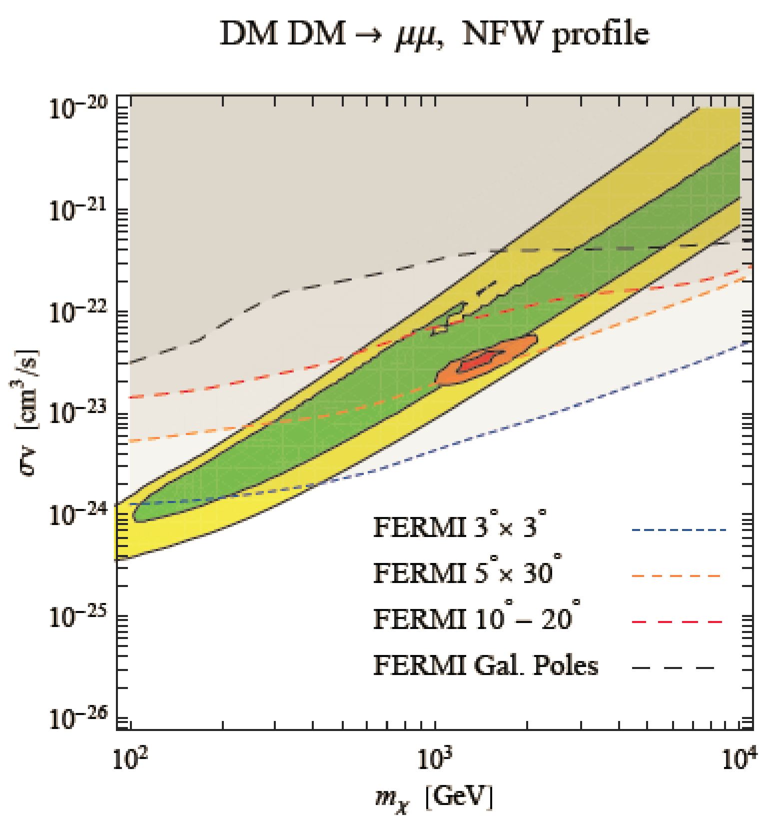




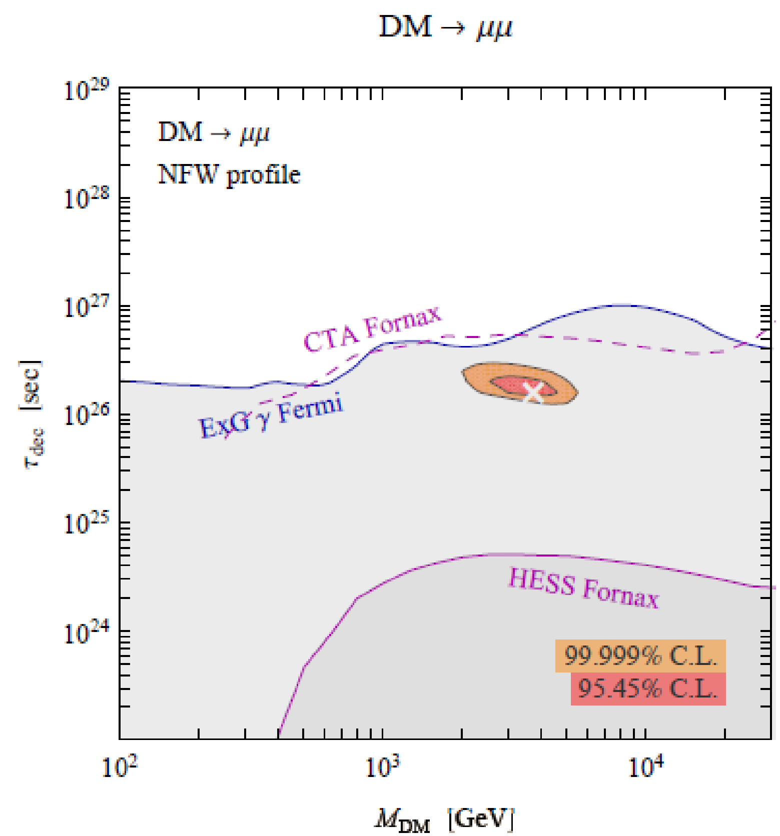
Al, Tran, Weniger
arXiv:0906.1571

Is this the first non-gravitational evidence of dark matter?

"Extraordinary claims require extraordinary evidence"
Carl Sagan



Cirelli et al., arXiv:0912.0663



Cirelli et al., arXiv:1205.5283

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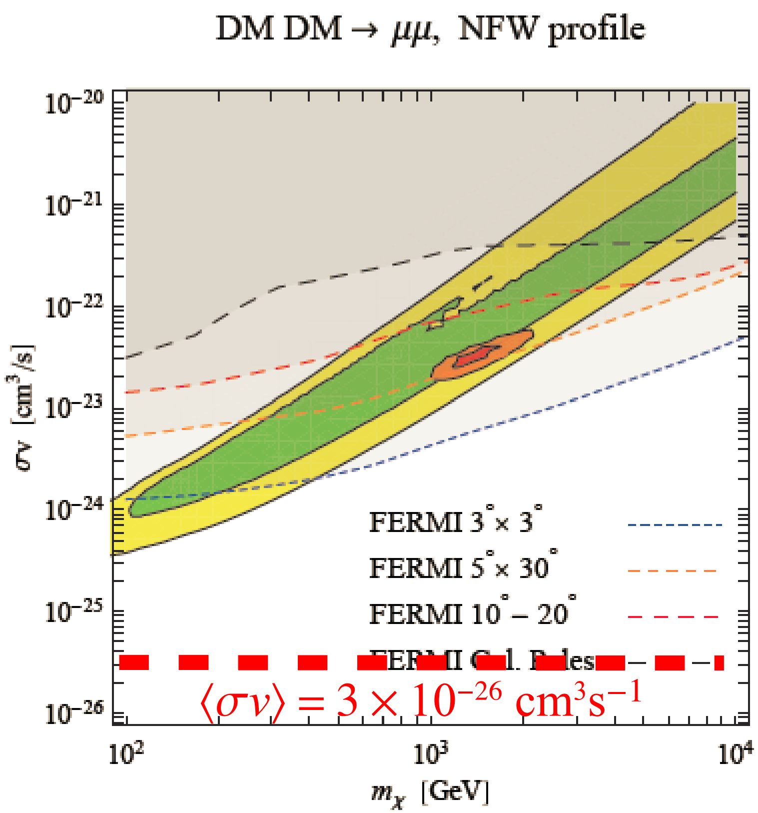

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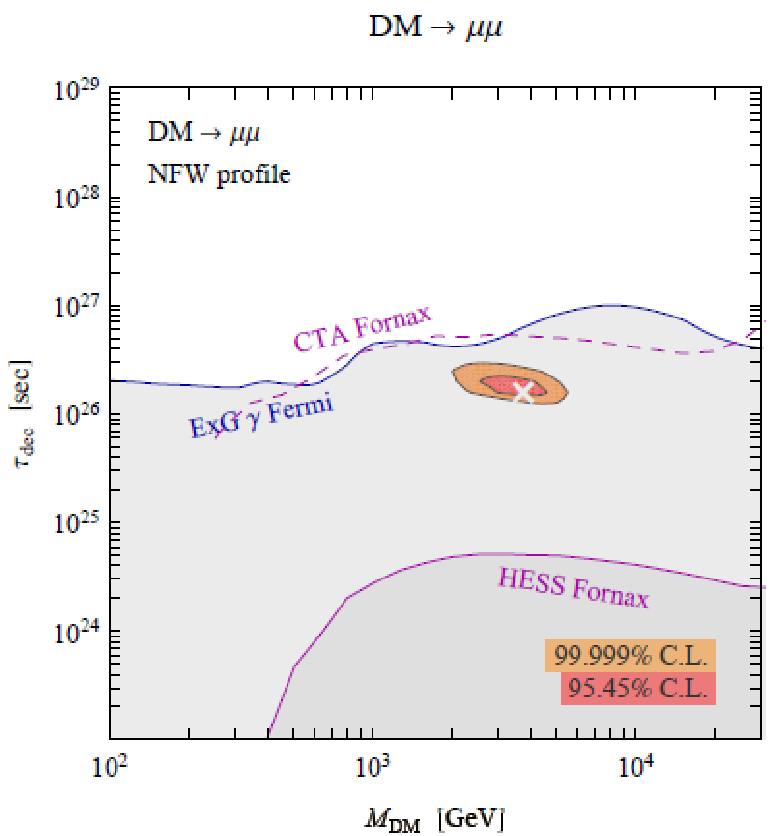
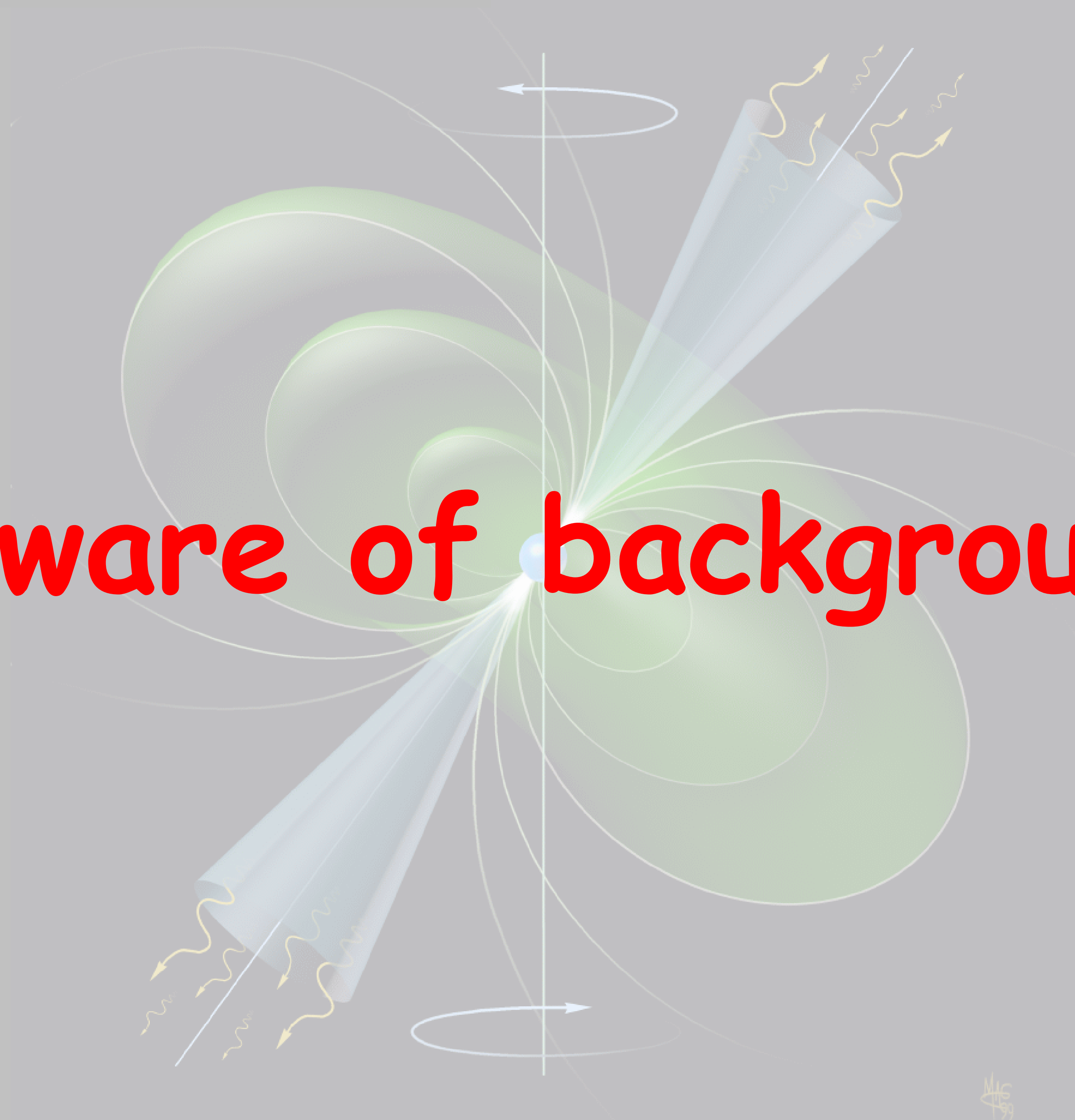
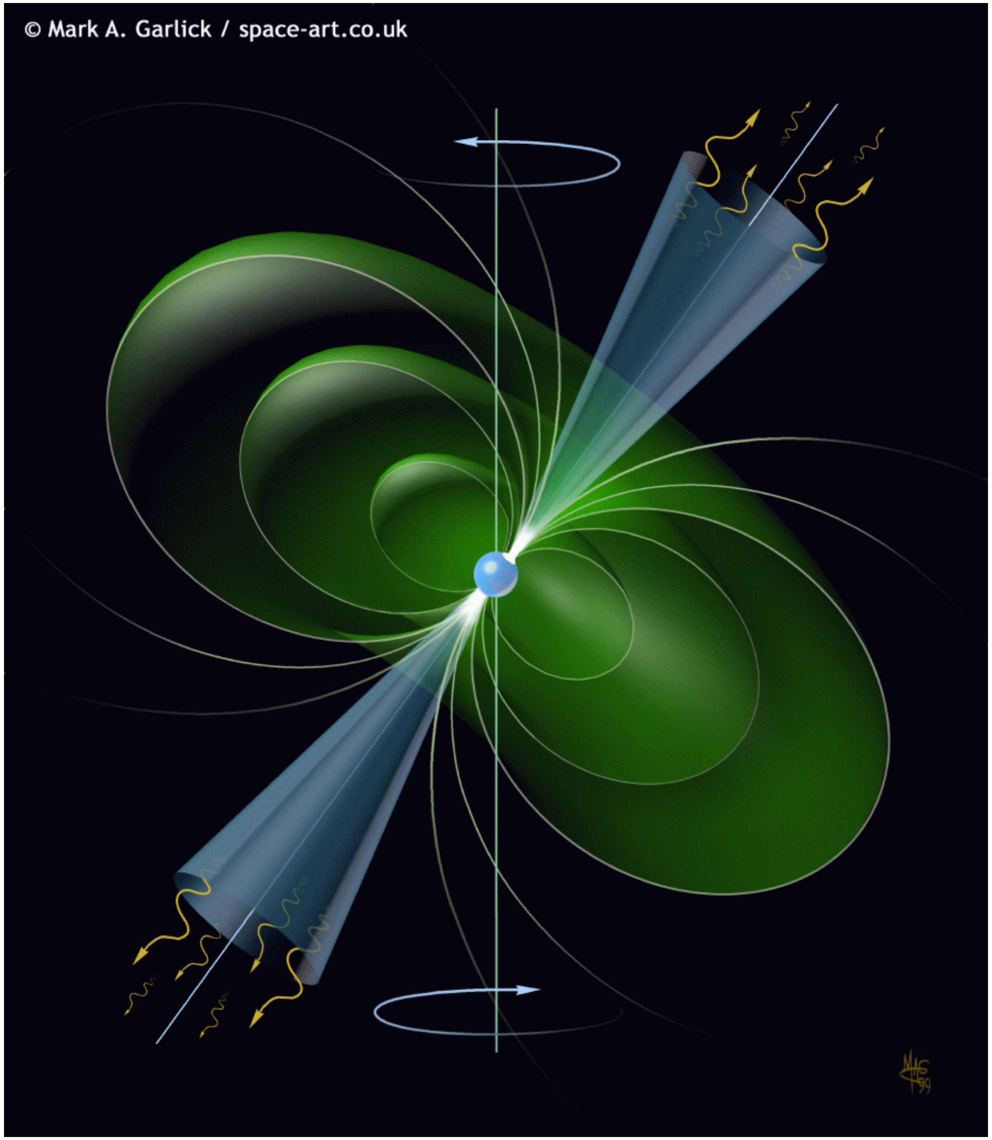


Cirelli et al., arXiv:1205.5283

Beware of backgrounds!



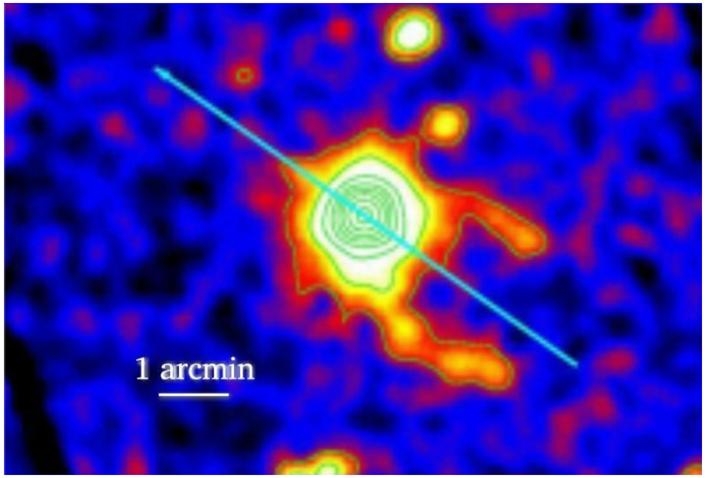
Pulsars <u>are</u> sources of high energy electrons & positrons



Atoyan, Aharonian, Völk '95
Chi, Cheng, Young '95
Grimani '04

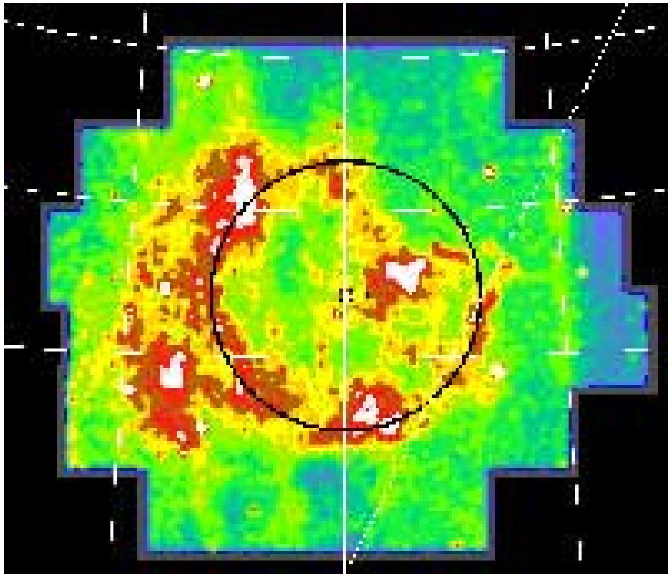
Pulsar explanation I: Geminga + Monogem

Grasso et al.



Geminga

T=370 000 years
D=157 pc

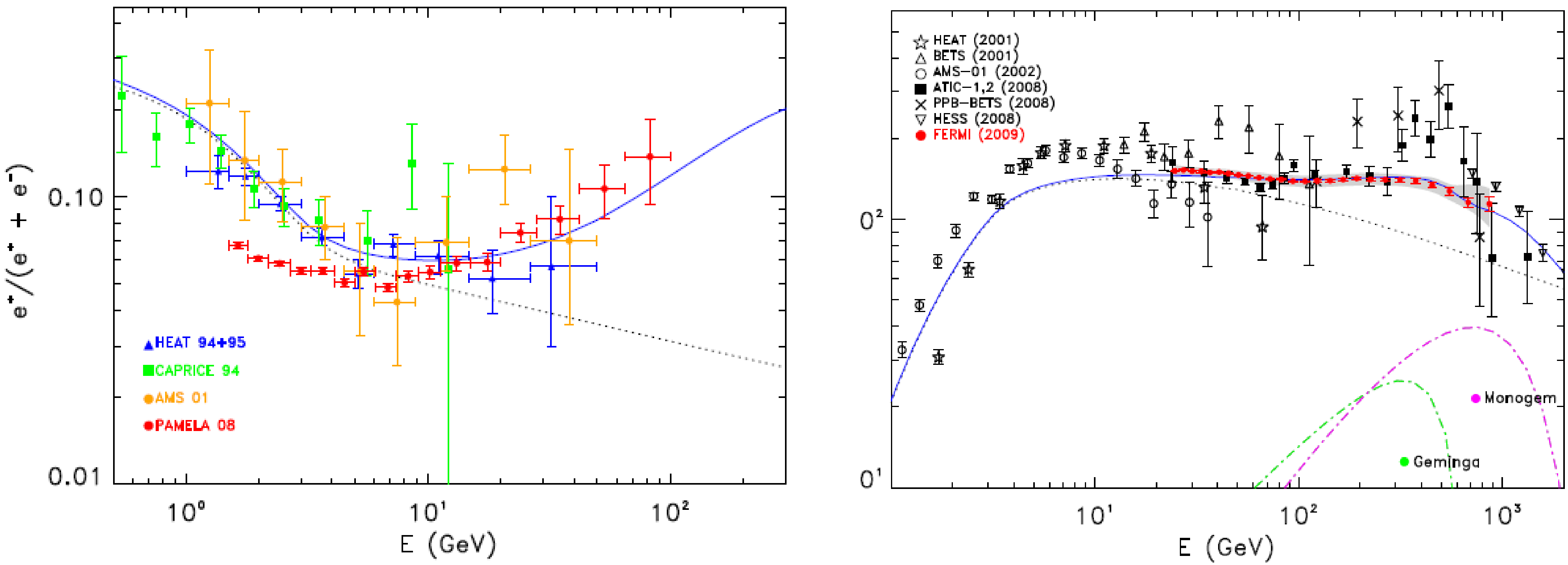


Monogem (B0656+14)

T=110 000 years
D=290 pc

Pulsar explanation I: Geminga + Monogem

Grasso et al.

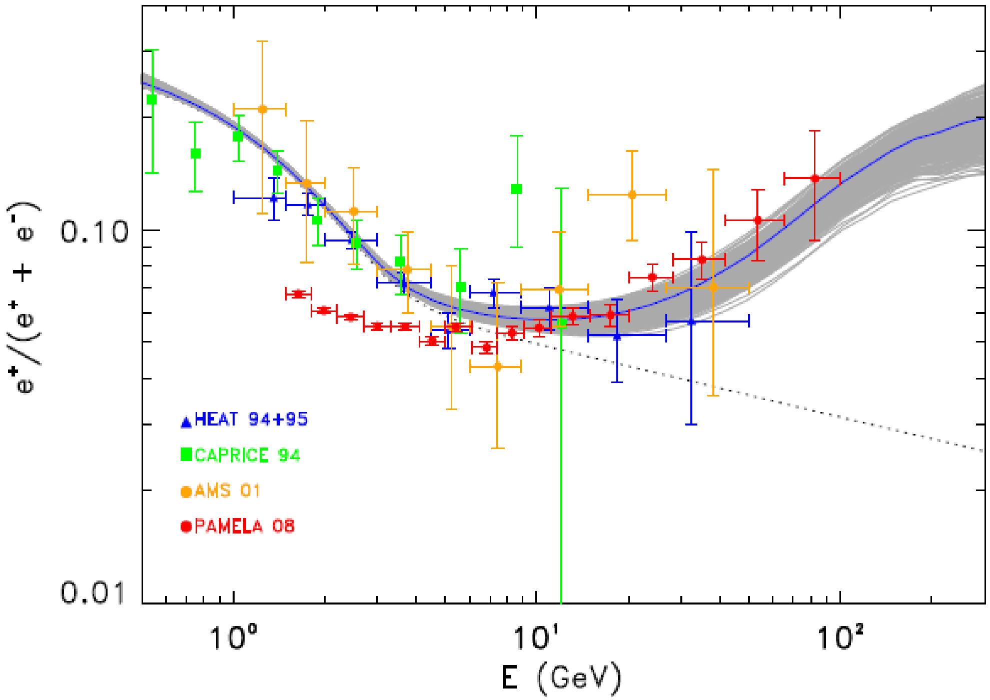


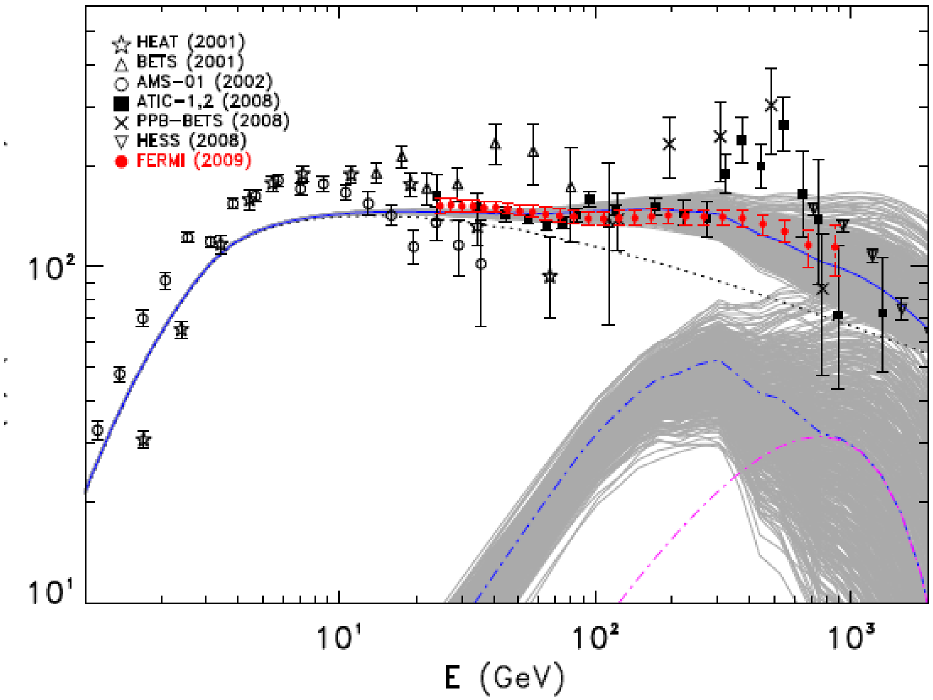
Nice agreement. However, it is <u>not</u> a prediction!

- $dN_e/dE_e \propto E_e^{-1.7} \exp(-E_e/1100\ \mathrm{GeV})$
- Energy output in e^+e^- pairs: 40% of the spin-down rate

Pulsar explanation II: Multiple pulsars

Grasso et al.





- $dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/E_0)$, $1.5 < \alpha < 1.9$, $800\ \text{GeV} < E_0 < 1400\ \text{GeV}$
- Energy output in e^+e^- pairs: between 10-30% of the spin-down rate

The origin of the positron excess is still unclear:

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- Dark matter? Probably not.

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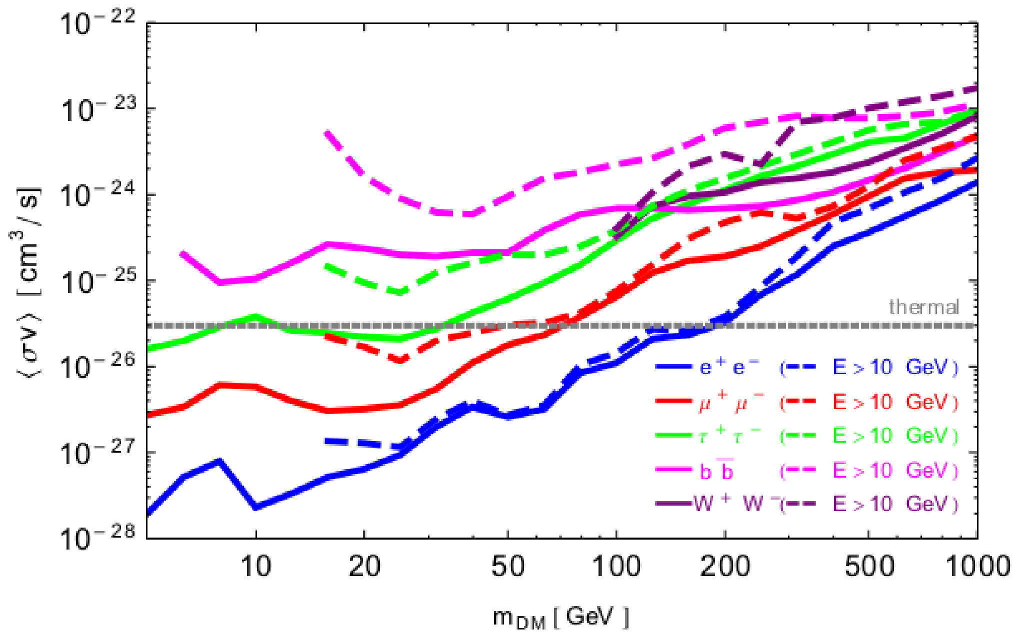
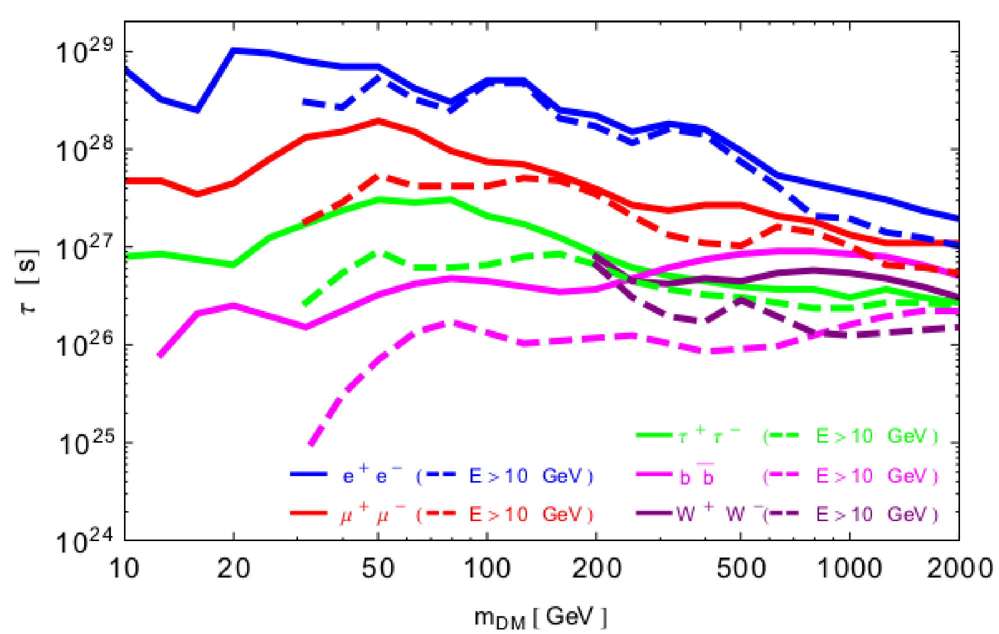
- Dark matter? Probably not.
- Pulsars? Perhaps yes.
- Something else? Perhaps yes.
- Regardless of the origin of the positron excess, the positron data can be used to set limits on the dark matter parameters.

Latest limits from the positron fraction:





AI, Lamperstorfer, Silk '13
See also Bergström et al. '13

Gamma-rays

Production of gamma-rays

The gamma ray flux from dark matter annihilations/decays has two components:

- Inverse Compton Scattering radiation of electrons/positrons produced in the annihilation/decay.
- Always smooth spectrum.

- Prompt radiation of gamma rays produced in the annihilation/decay (final state radiation, pion decay...)
- May contain spectral features.

Inverse Compton Scattering radiation

The inverse Compton scattering of electrons/positrons from dark matter annihilation/decay with the interstellar and extragalactic radiation fields produces gamma rays.

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma^{*}$$

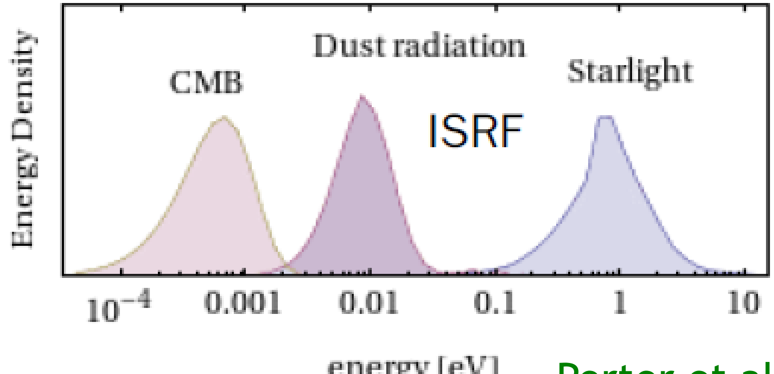
$e^{\pm}$ from dark matter annihilation/decay
$E_e \lesssim 1$ TeV

Upscattered photon

$$E_{\gamma^*} \leq 4 \left(\frac{E_e}{m_e} \right)^2 E_\gamma$$

This produces
$E_{\gamma*} \lesssim 100$ GeV

Interstellar radiation field (starlight, thermal radiation of dust, CMB)



Porter et al.

Prompt radiation

Annihilation

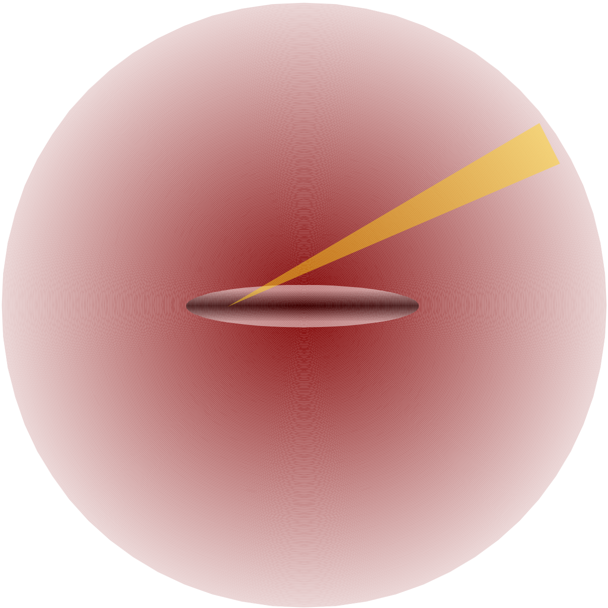
$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right]\times\int_{\rm l.o.s.}\rho^2(\vec{l})\,d\vec{l}$$

Source term (particle physics)

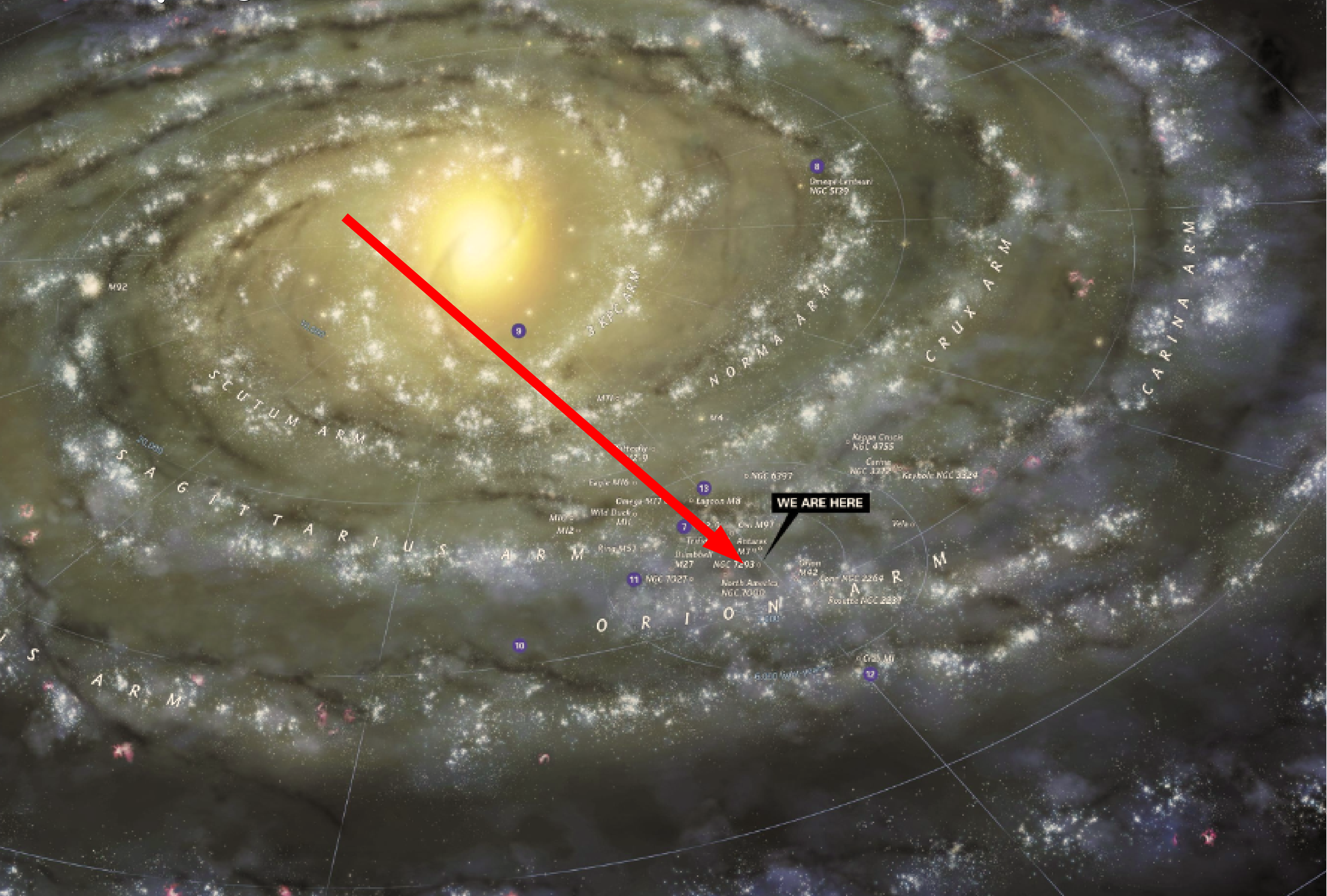
Line-of-sight integral (astrophysics)

Decay

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

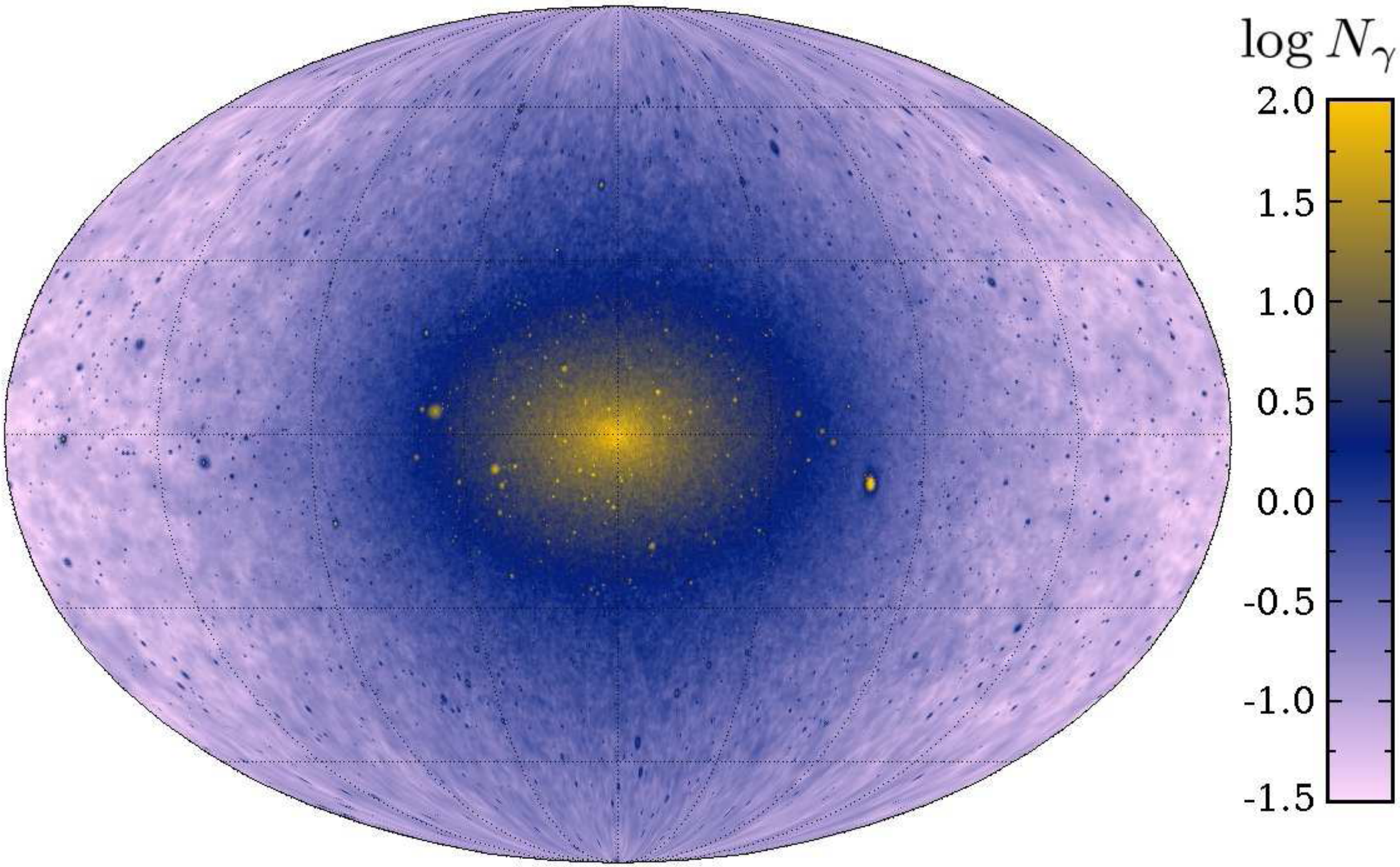


Propagation



Where to look for annihilating dark matter

Baltz et al. arXiv:0806.2911



Kuhlen, Diemand, Madau

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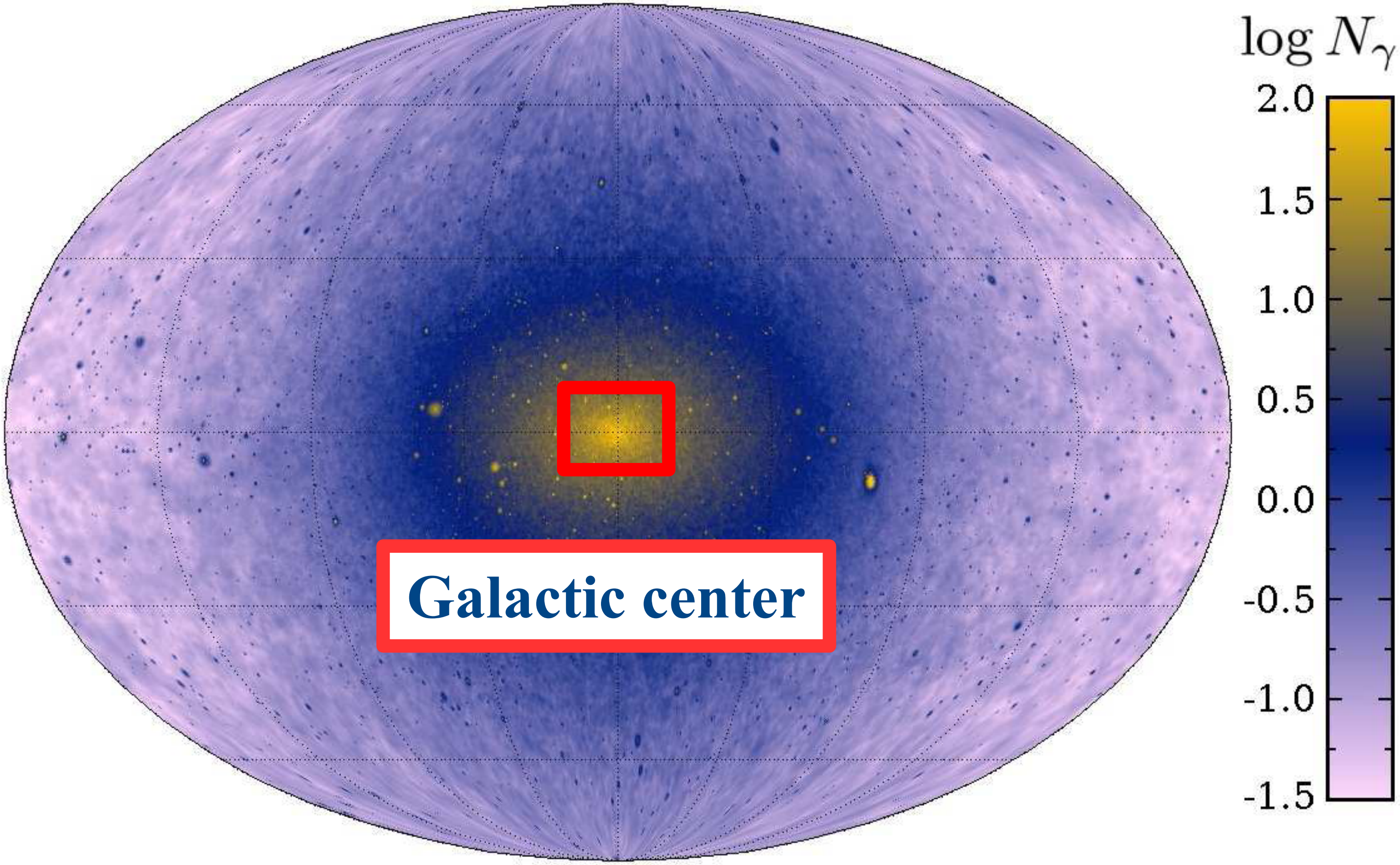

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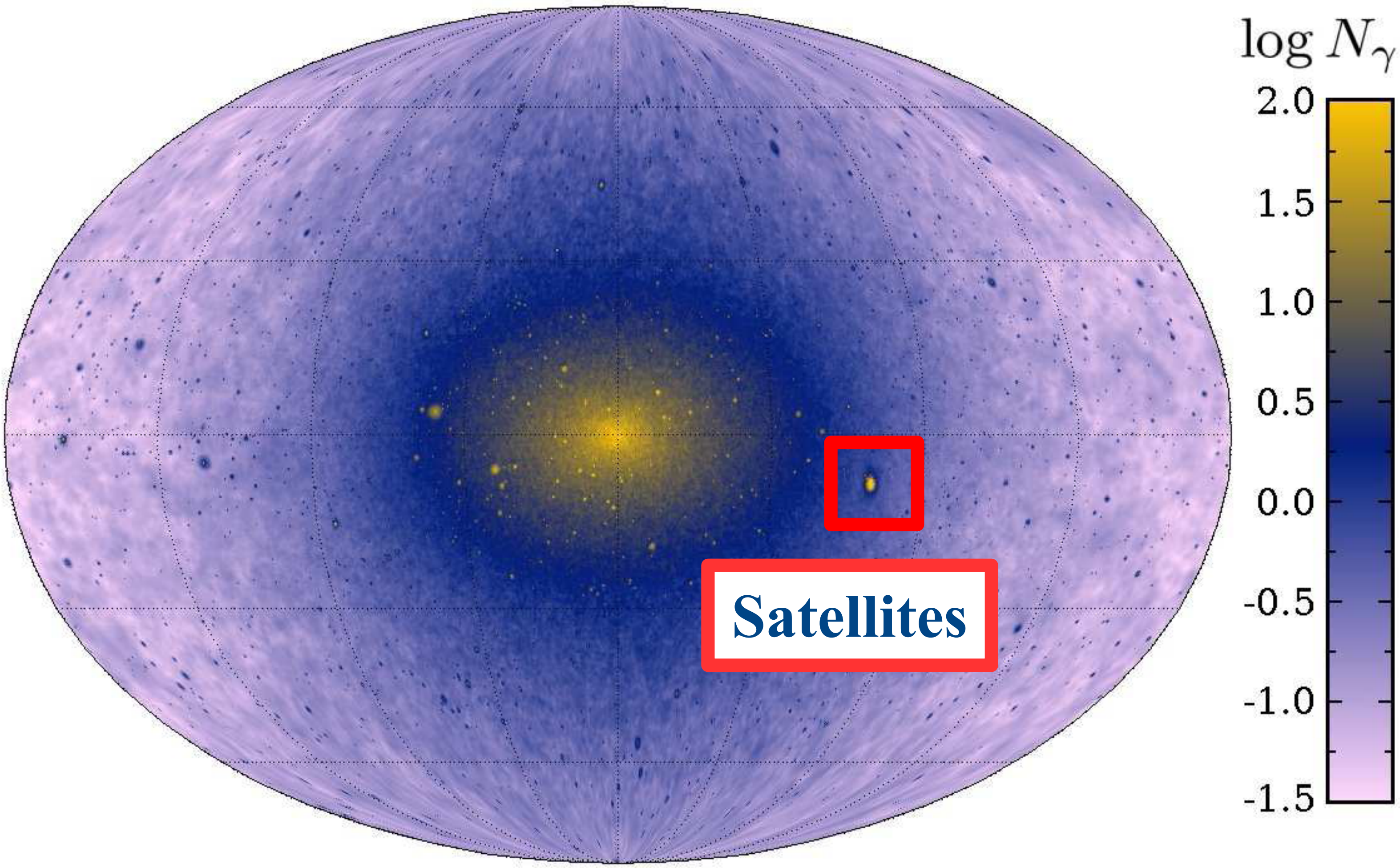

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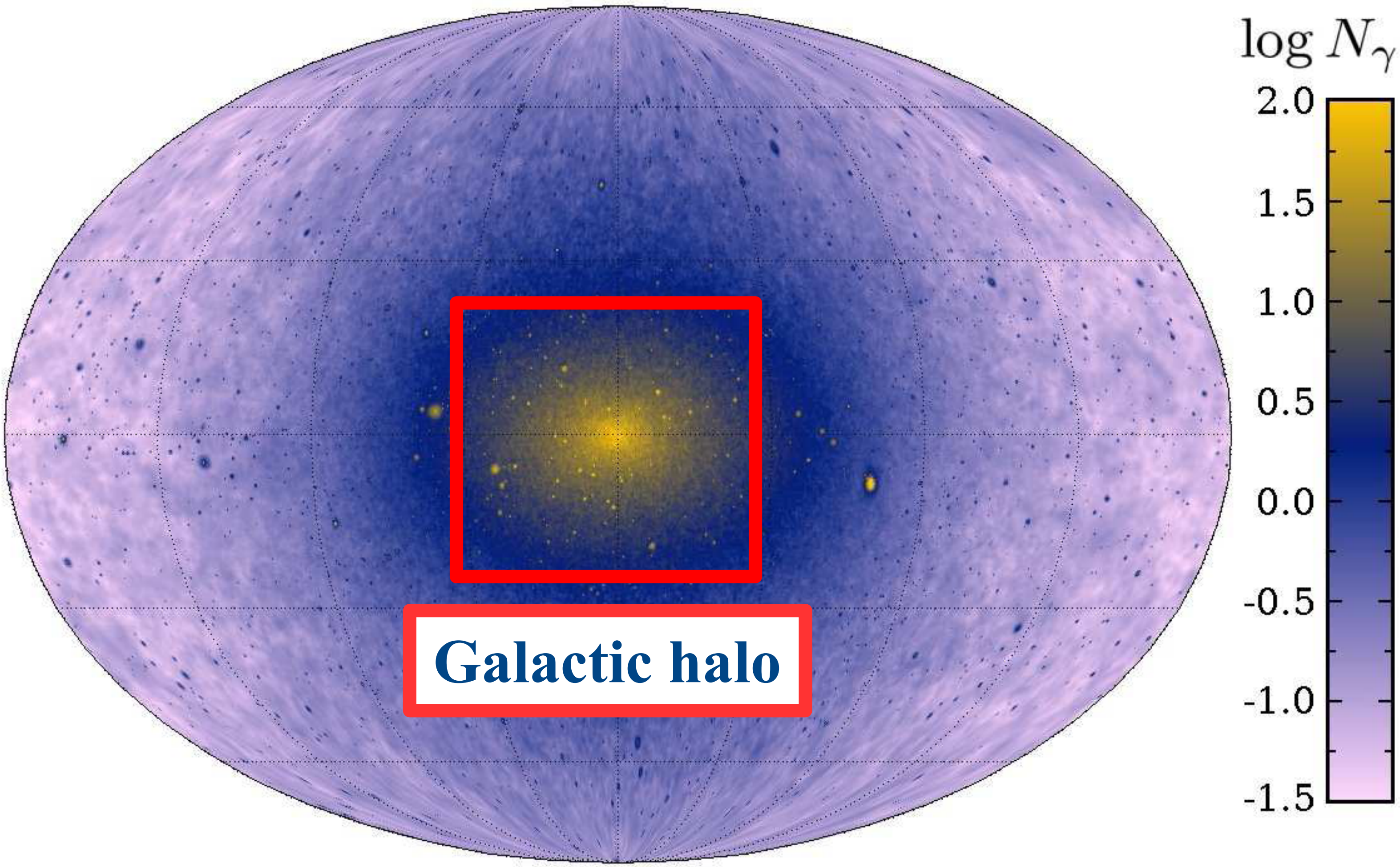

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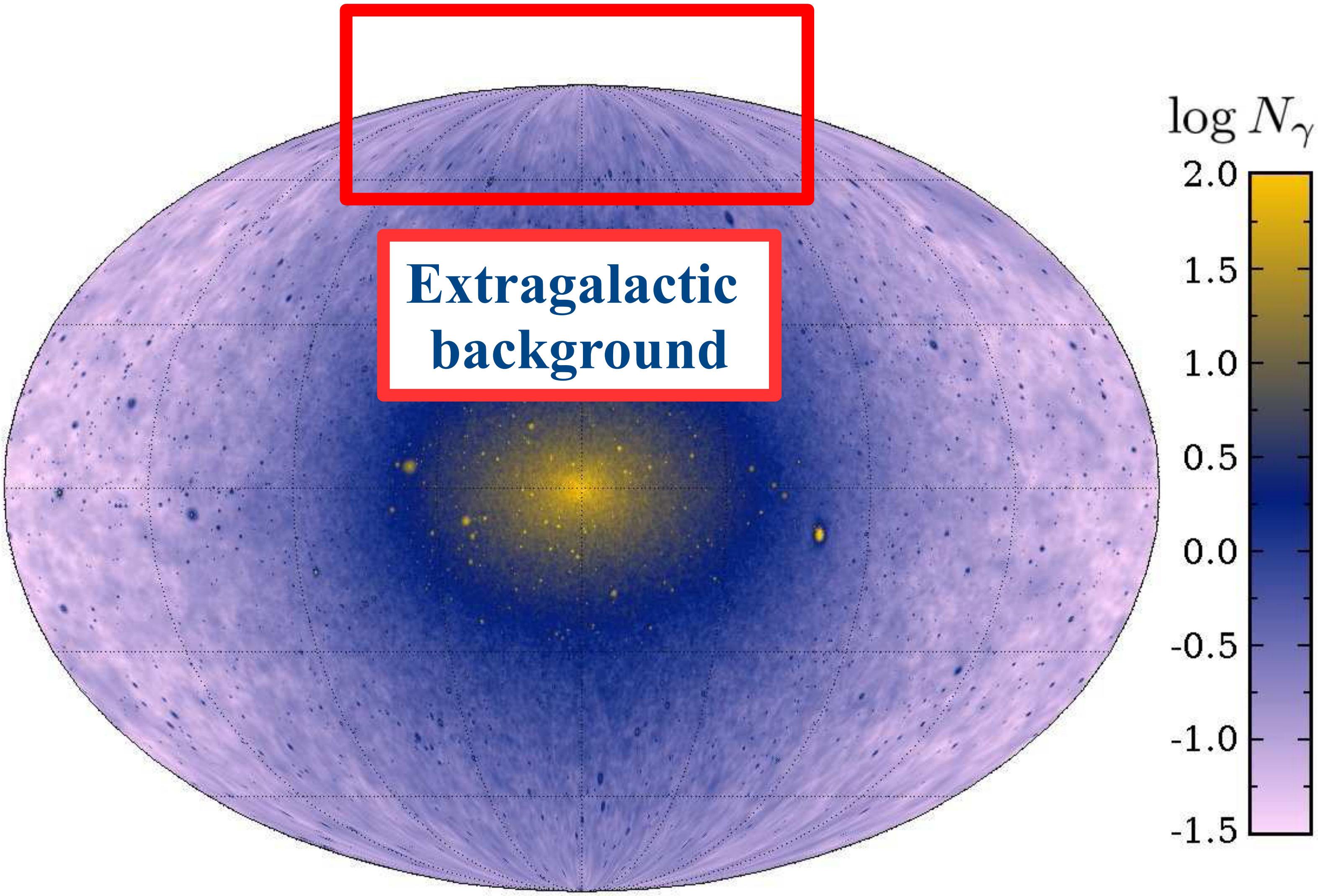

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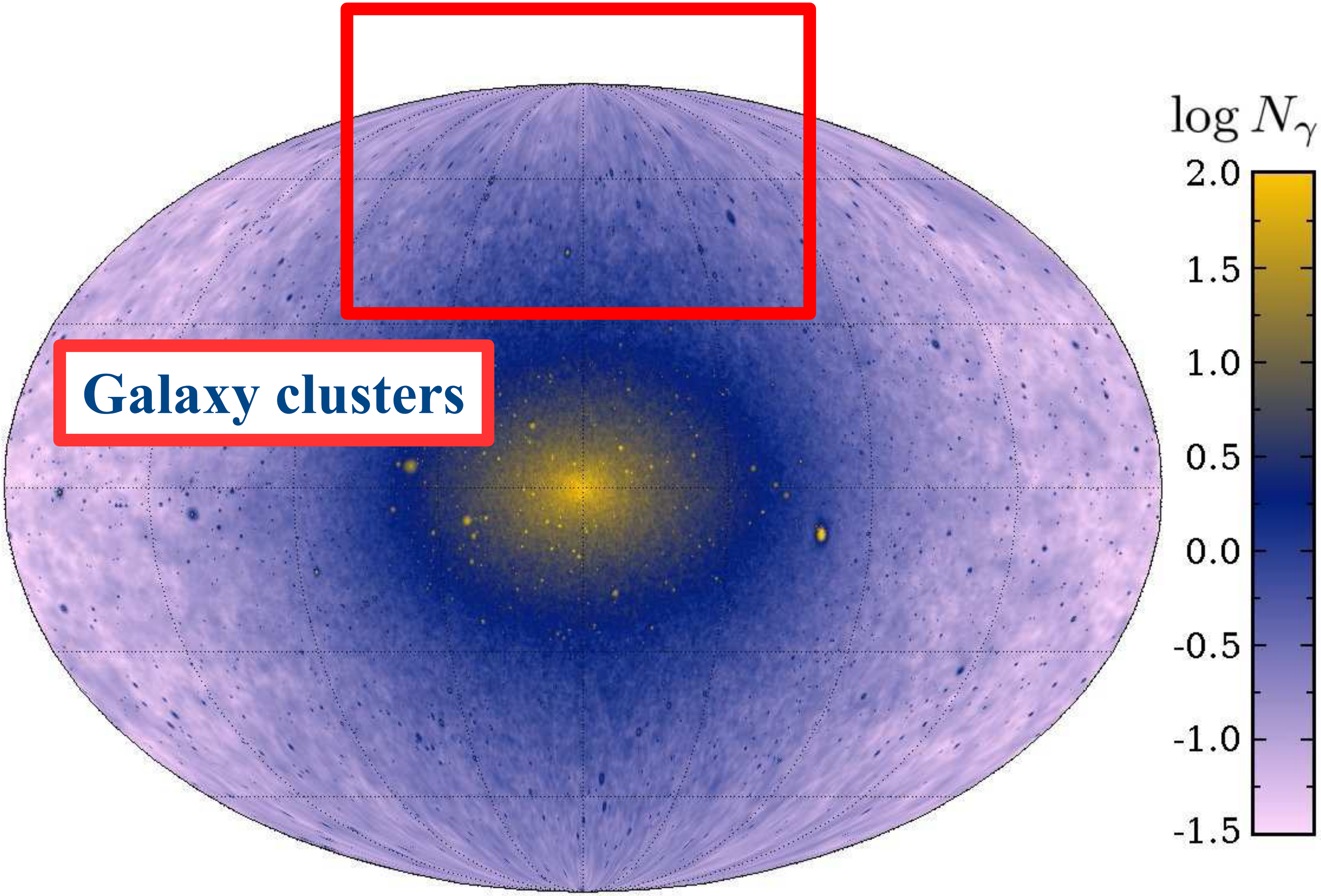

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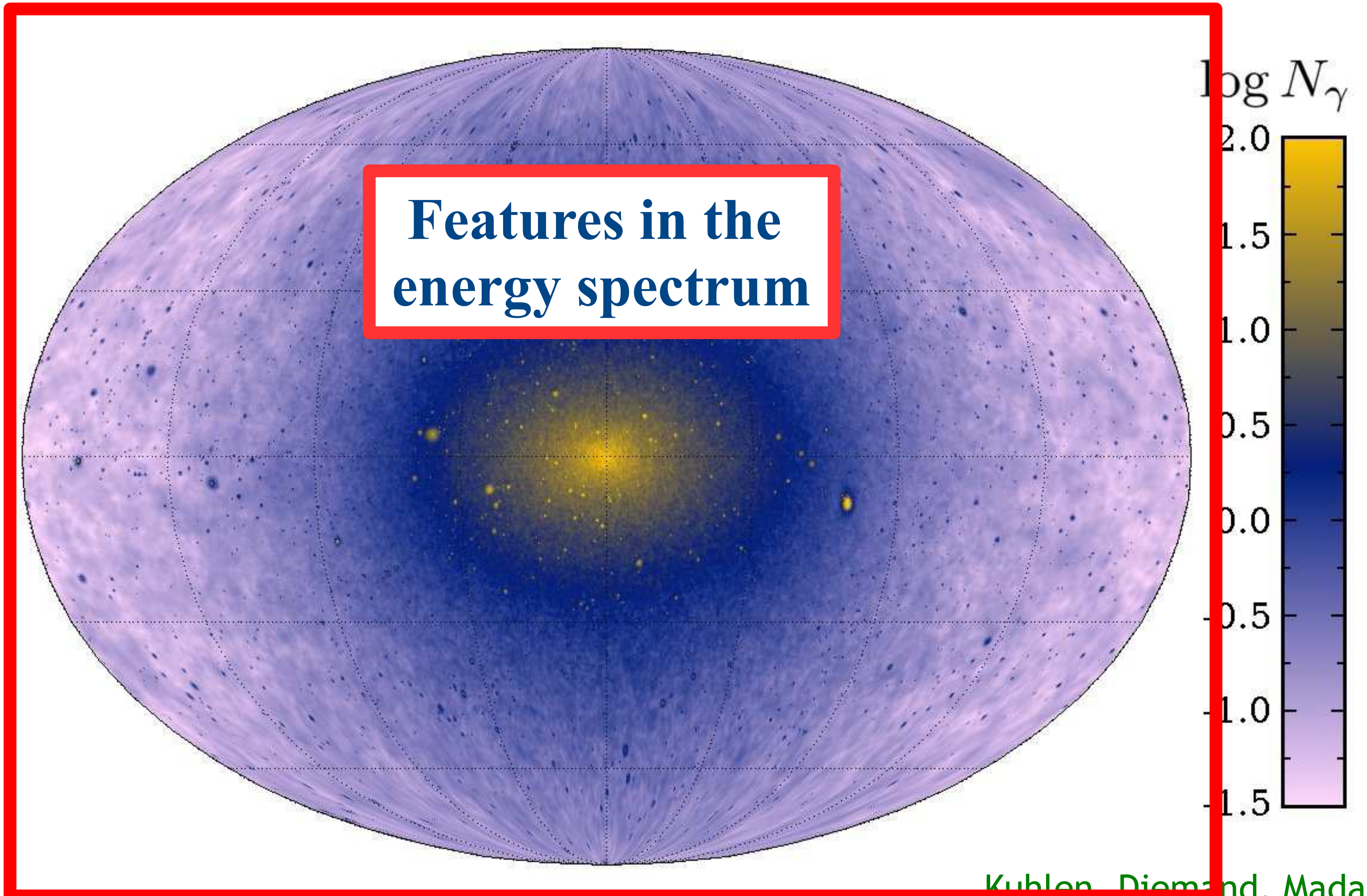
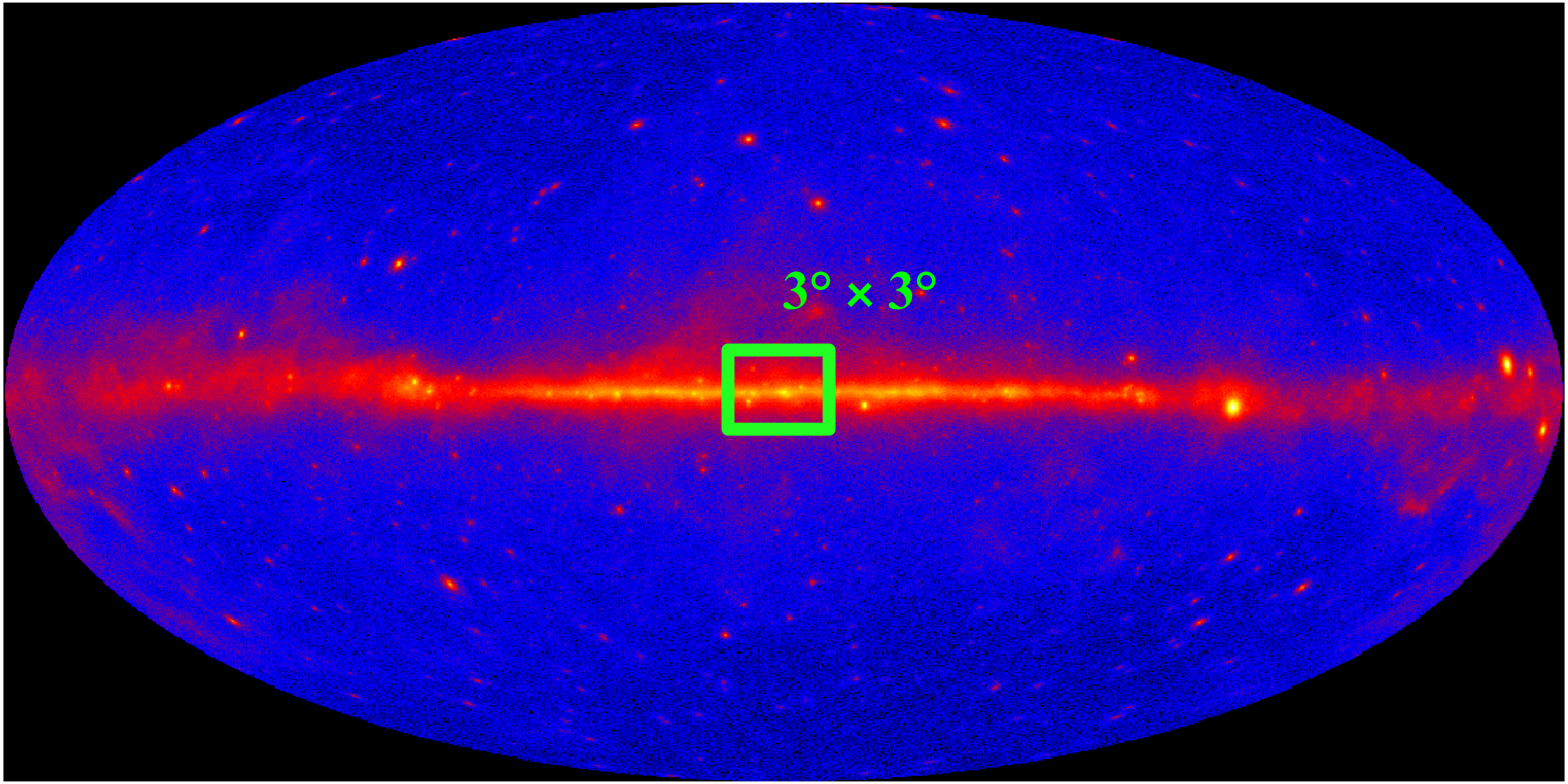


Kuhlen, Diemand, Madau

Diffuse Galactic emission

Divide the sky in different regions:



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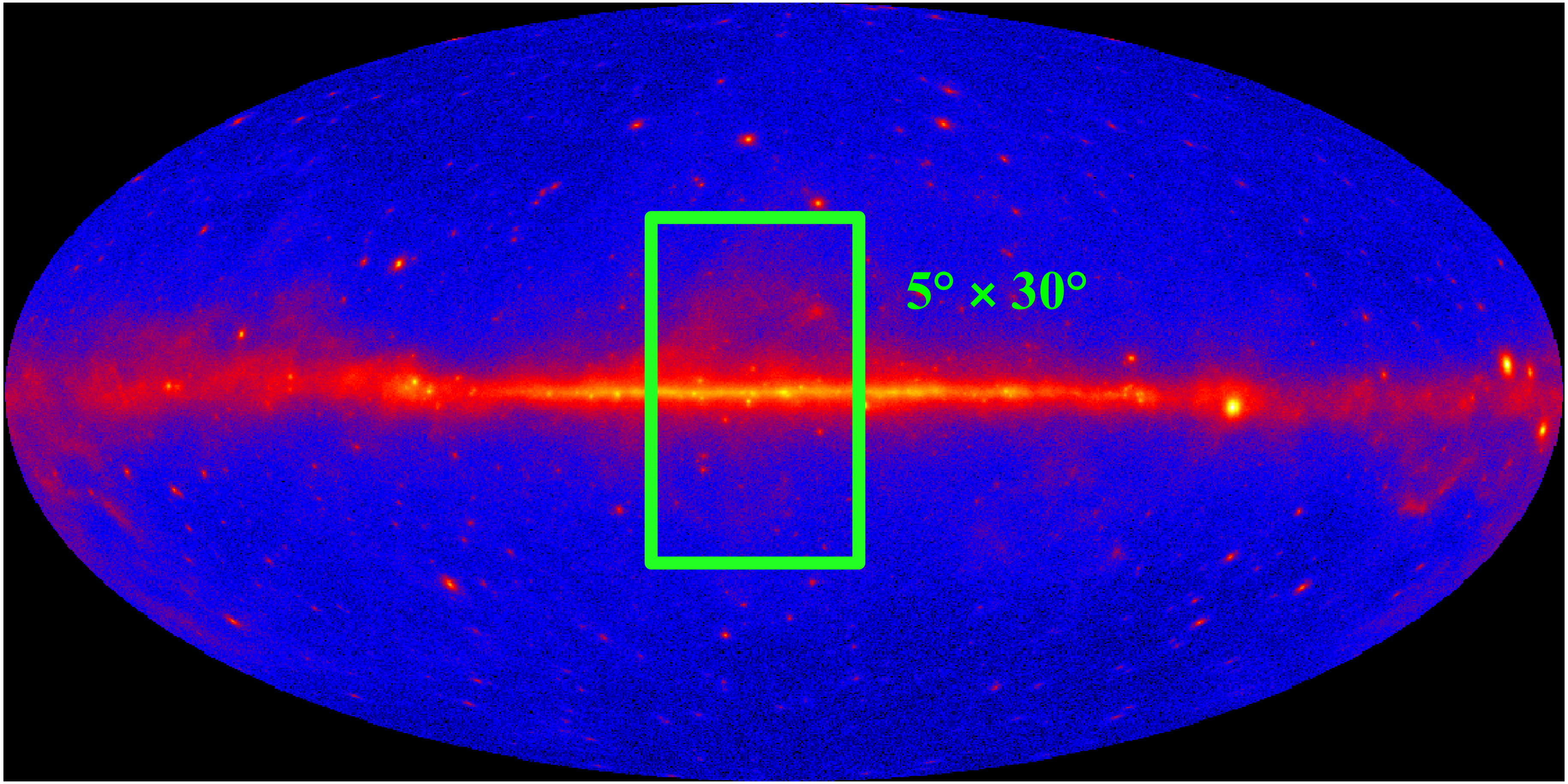

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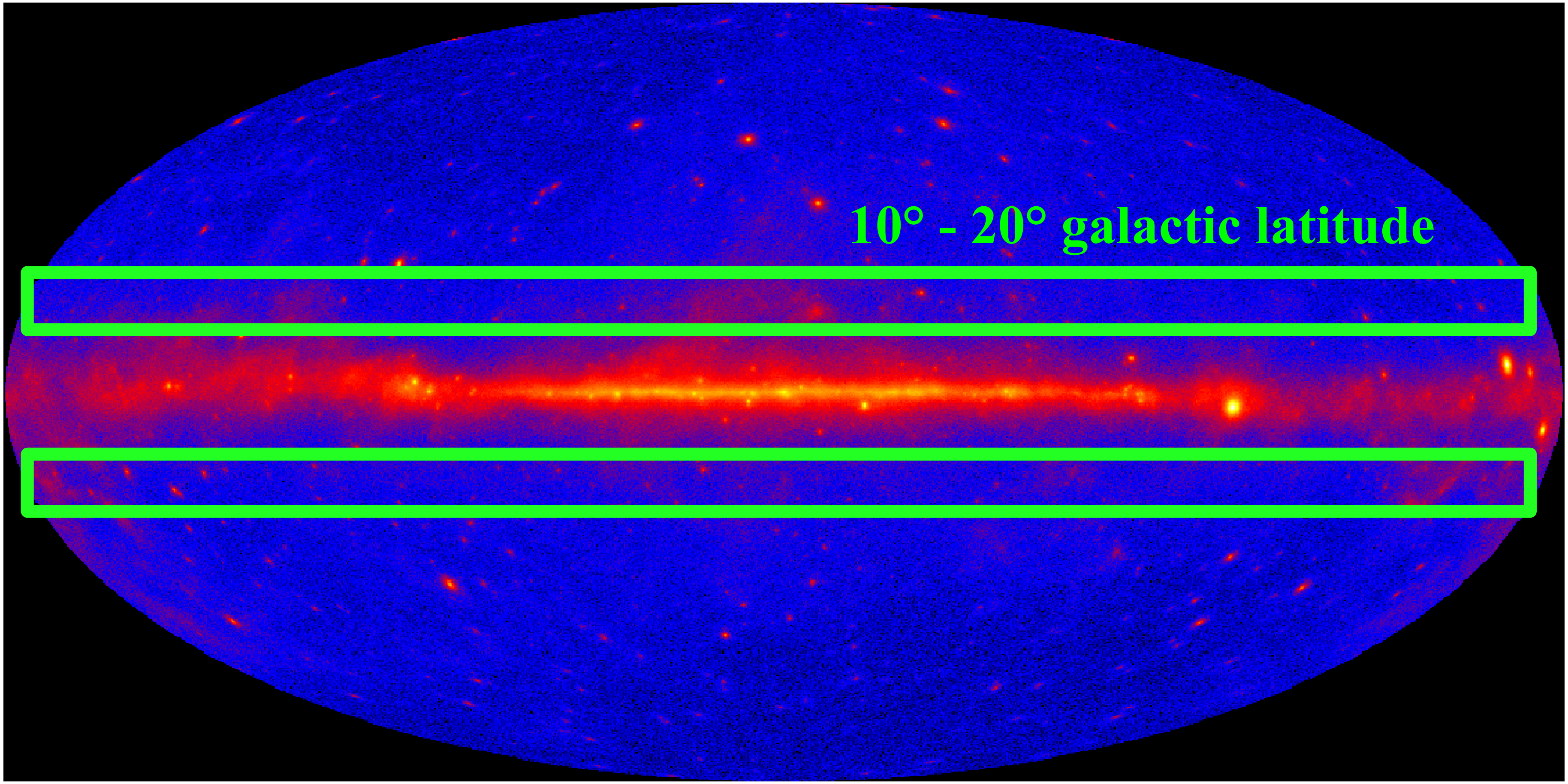

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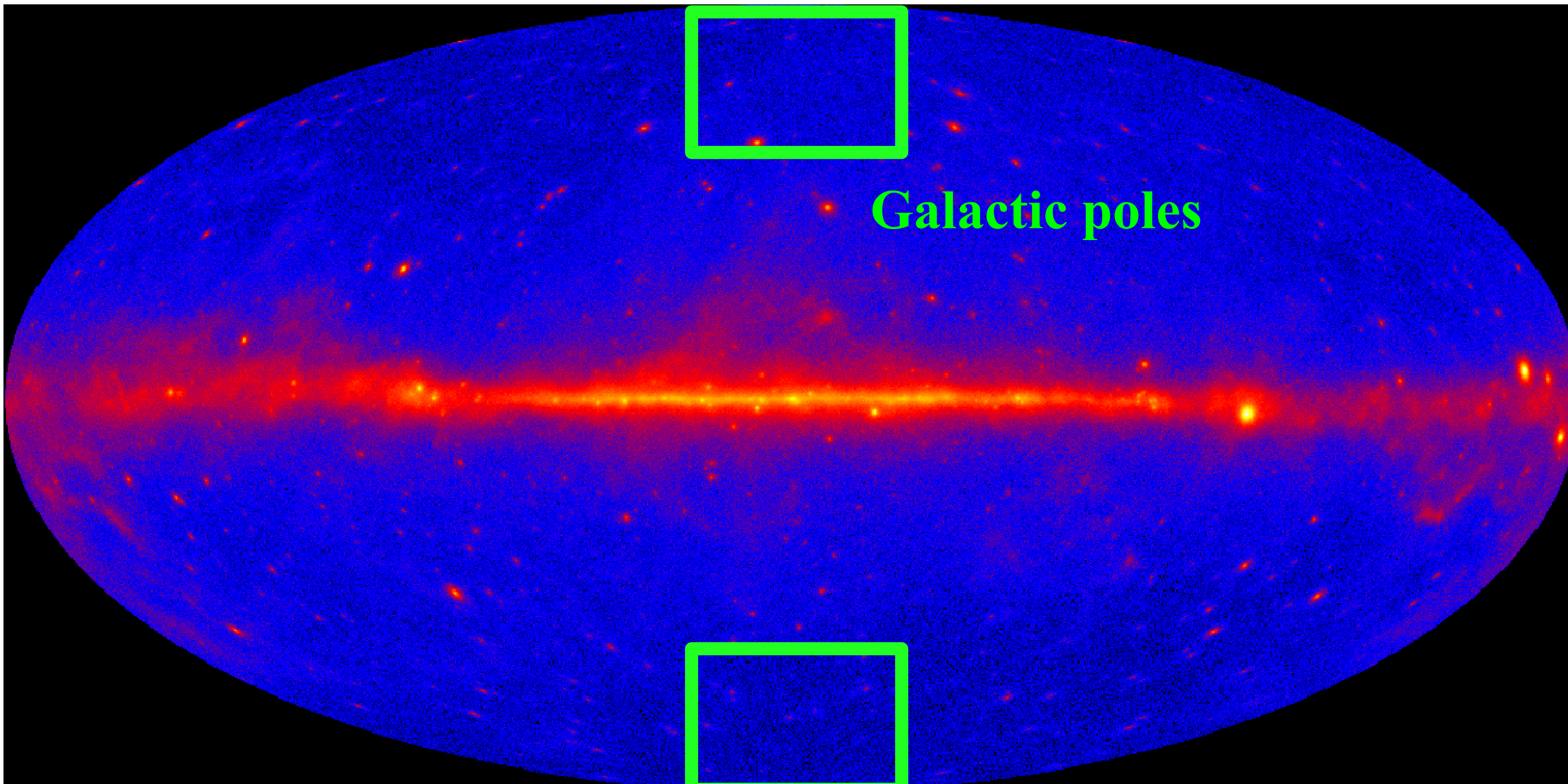
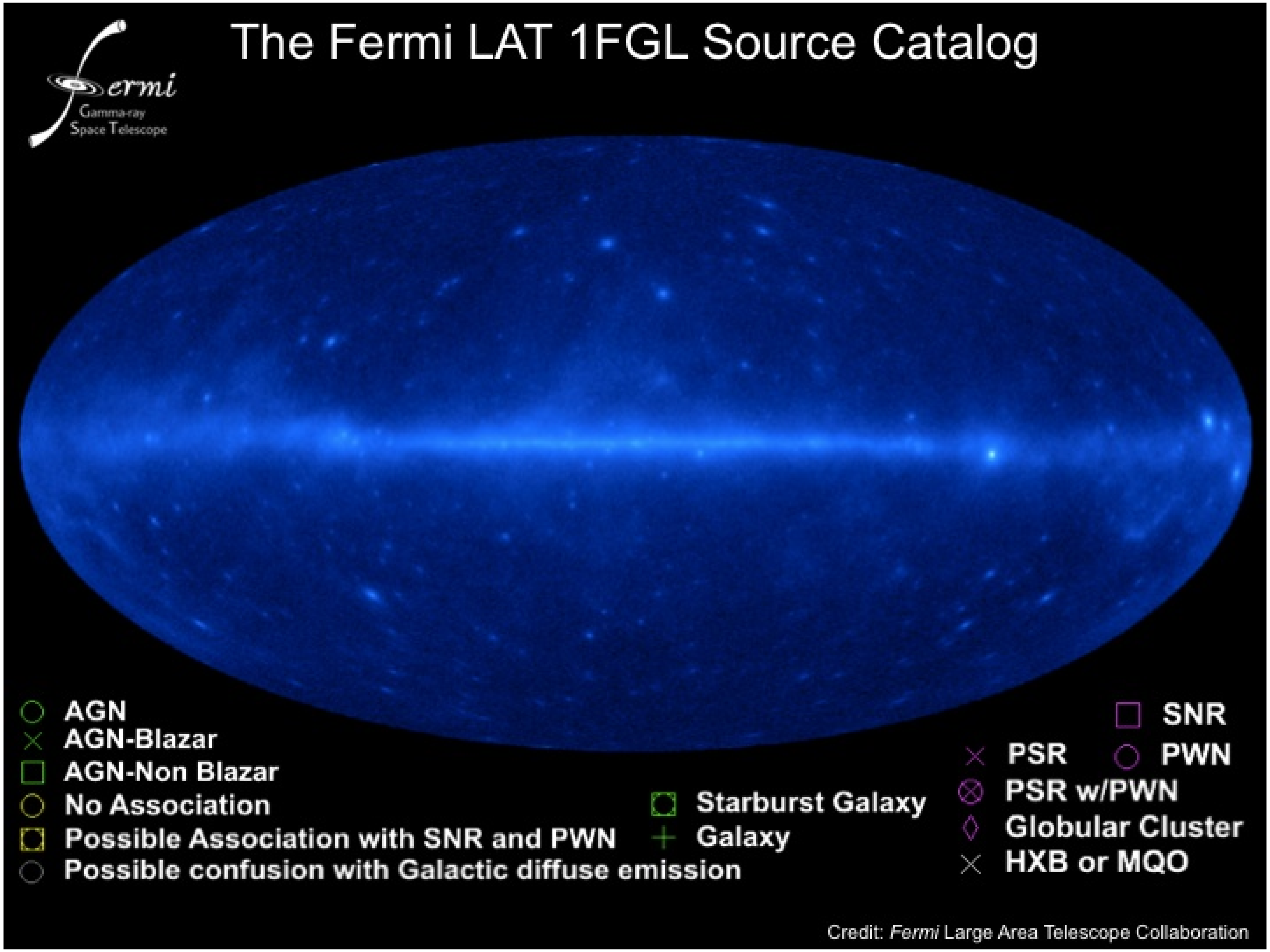
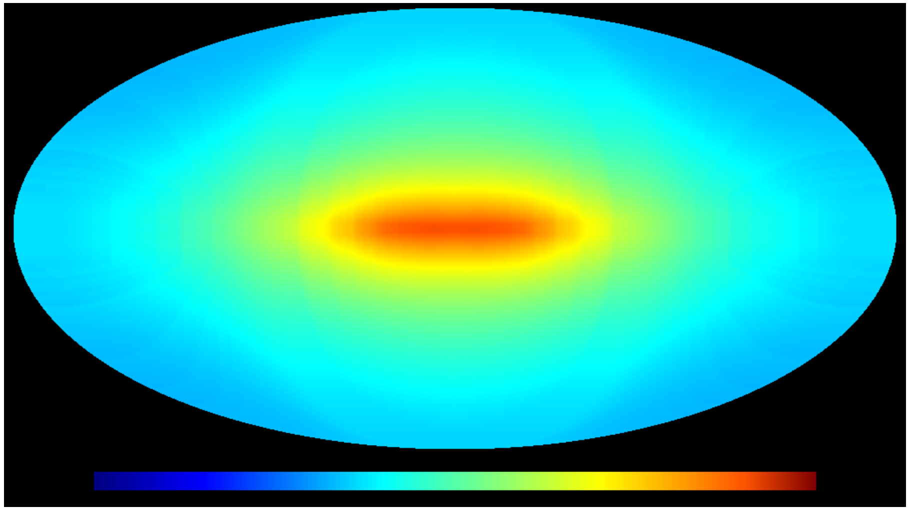


But beware of backgrounds when searching for dark matter...

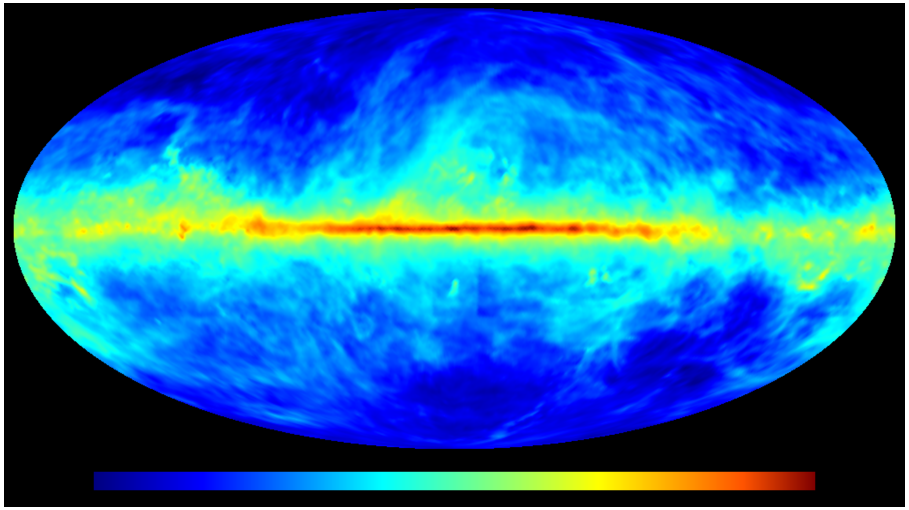
Background I: sources



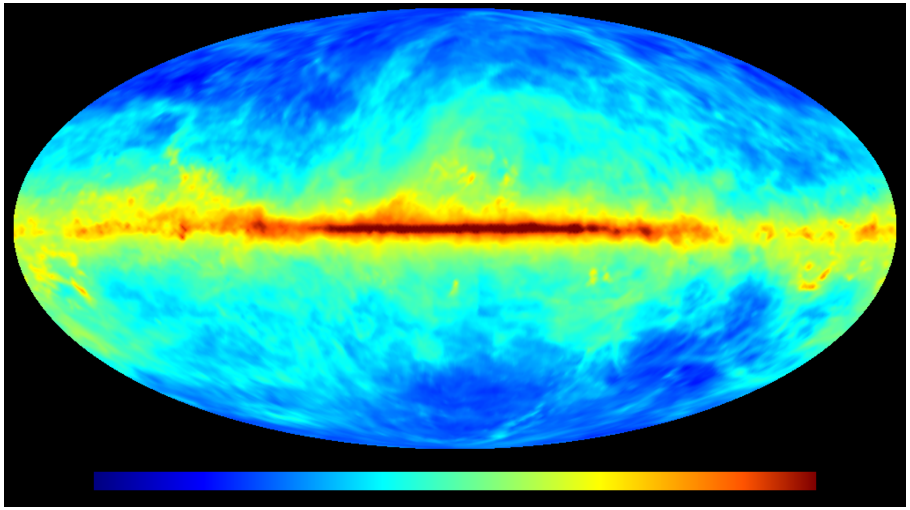
Background II: modelling of the diffuse emission



Inverse compton

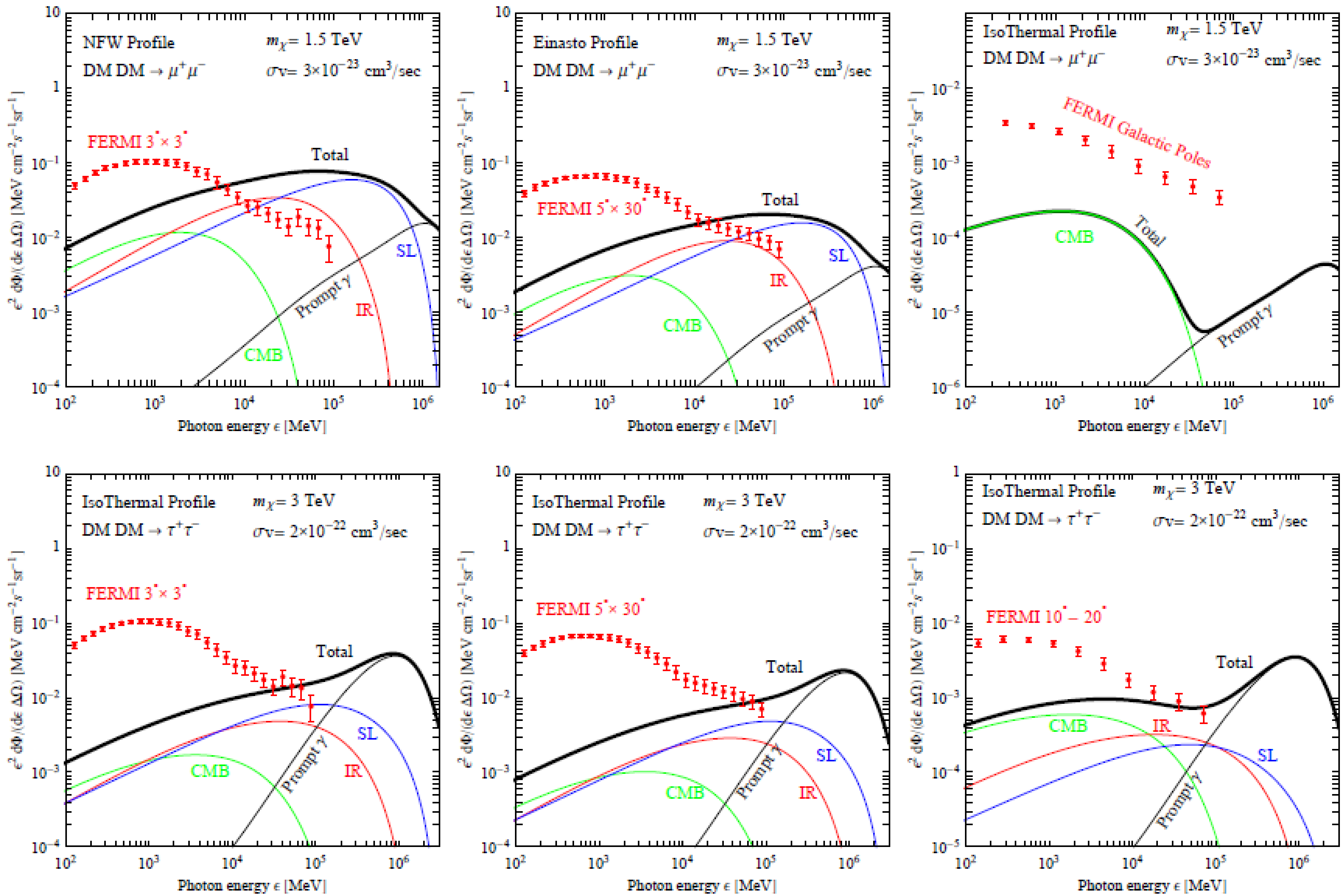


Bremmstrahlung

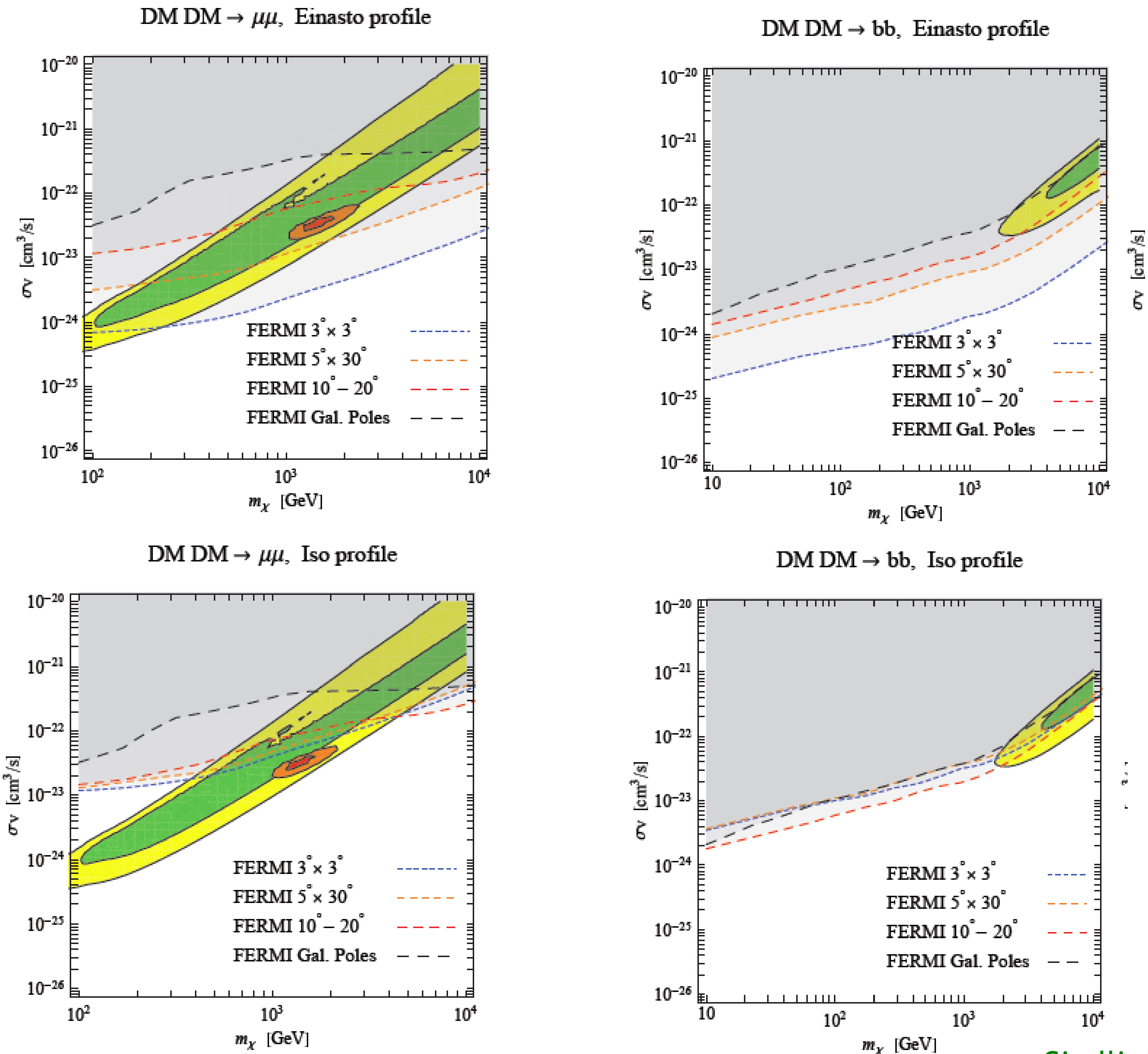


π^0-decay

Conservative approach: demand that the flux from dark matter annihilation does not exceed the measured flux

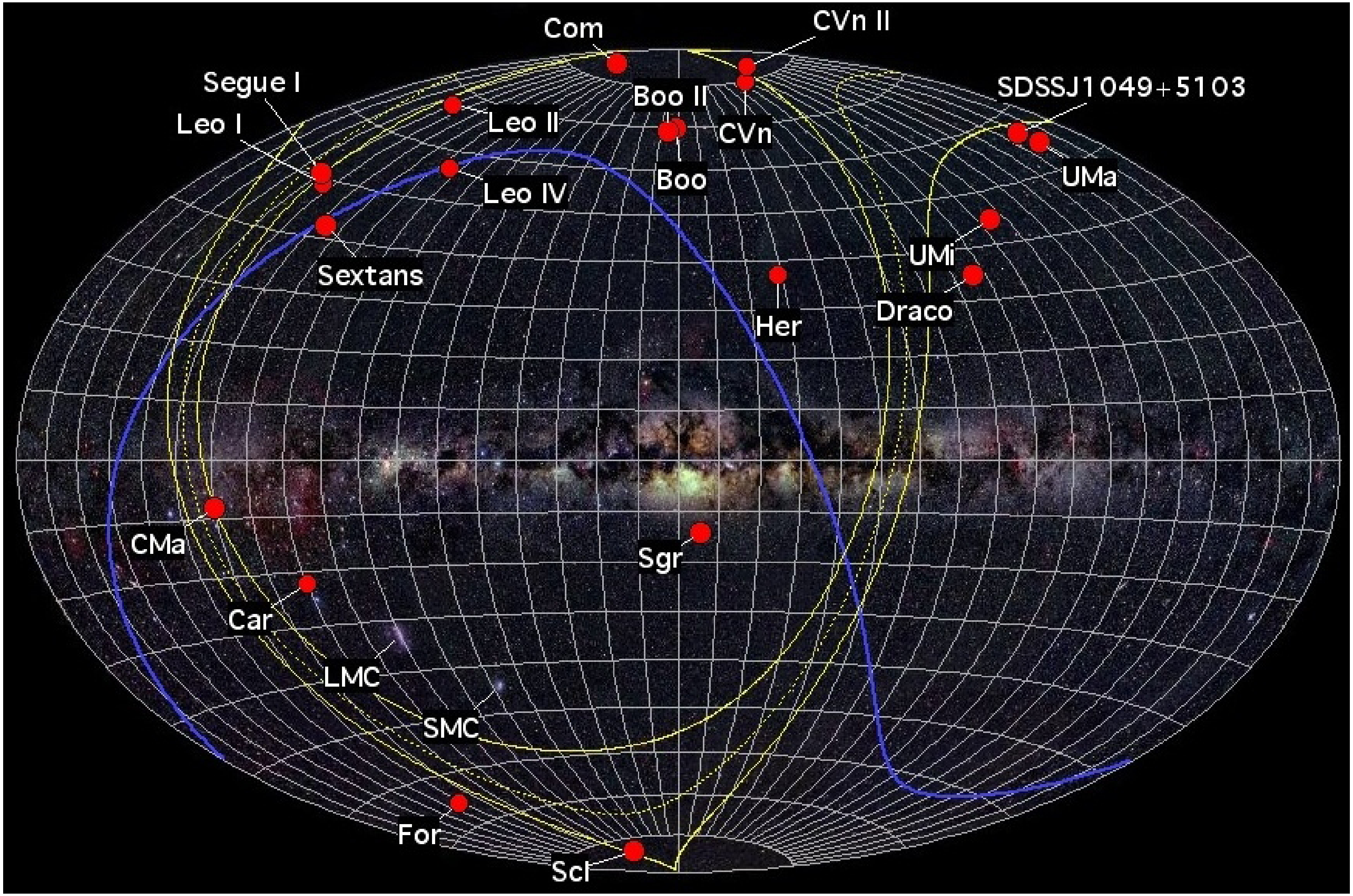


Cirelli, Panci, Serpico



Cirelli, Panci, Serpico

Dwarf spheroidal galaxies



Name	Distance (kpc)	year of discovery	$M_{1/2}/L_{1/2}$ ref. 8	l	b	Ref.
Ursa Major II	30± 5	2006	4000^{+3700}_{-2100}	152.46	37.44	1,2
Segue 2	35	2009	650	149.4	-38.01	3
Willman 1	38± 7	2004	770^{+930}_{-440}	158.57	56.78	1
Coma Berenices	44± 4	2006	1100^{+800}_{-500}	241.9	83.6	1,2
Bootes II	46	2007	1800??	353.69	68.87	6,7
Bootes I	62±3	2006	1700^{+1400}_{-700}	358.08	69.62	6
Ursa Minor	66± 3	1954	290^{+140}_{-90}	104.95	44.80	4,5
Sculptor	79± 4	1937	18^{+6}_{-5}	287.15	-83.16	4,5
Draco	76± 5	1954	200^{+80}_{-60}	86.37	34.72	4,5,9
Sextans	86± 4	1990	120^{+40}_{-35}	243.4	42.2	4,5
Ursa Major I	97±4	2005	1800^{+1300}_{-700}	159.43	54.41	6
Hercules	132±12	2006	1400^{+1200}_{-700}	28.73	36.87	6
Fornax	138± 8	1938	$8.7^{+2.8}_{-2.3}$	237.1	-65.7	4,5
Leo IV	160±15	2006	260^{+1000}_{-200}	265.44	56.51	6

Relatively close

High mass-to-light ratio:
dwarf galaxies contain large
amounts of dark matter

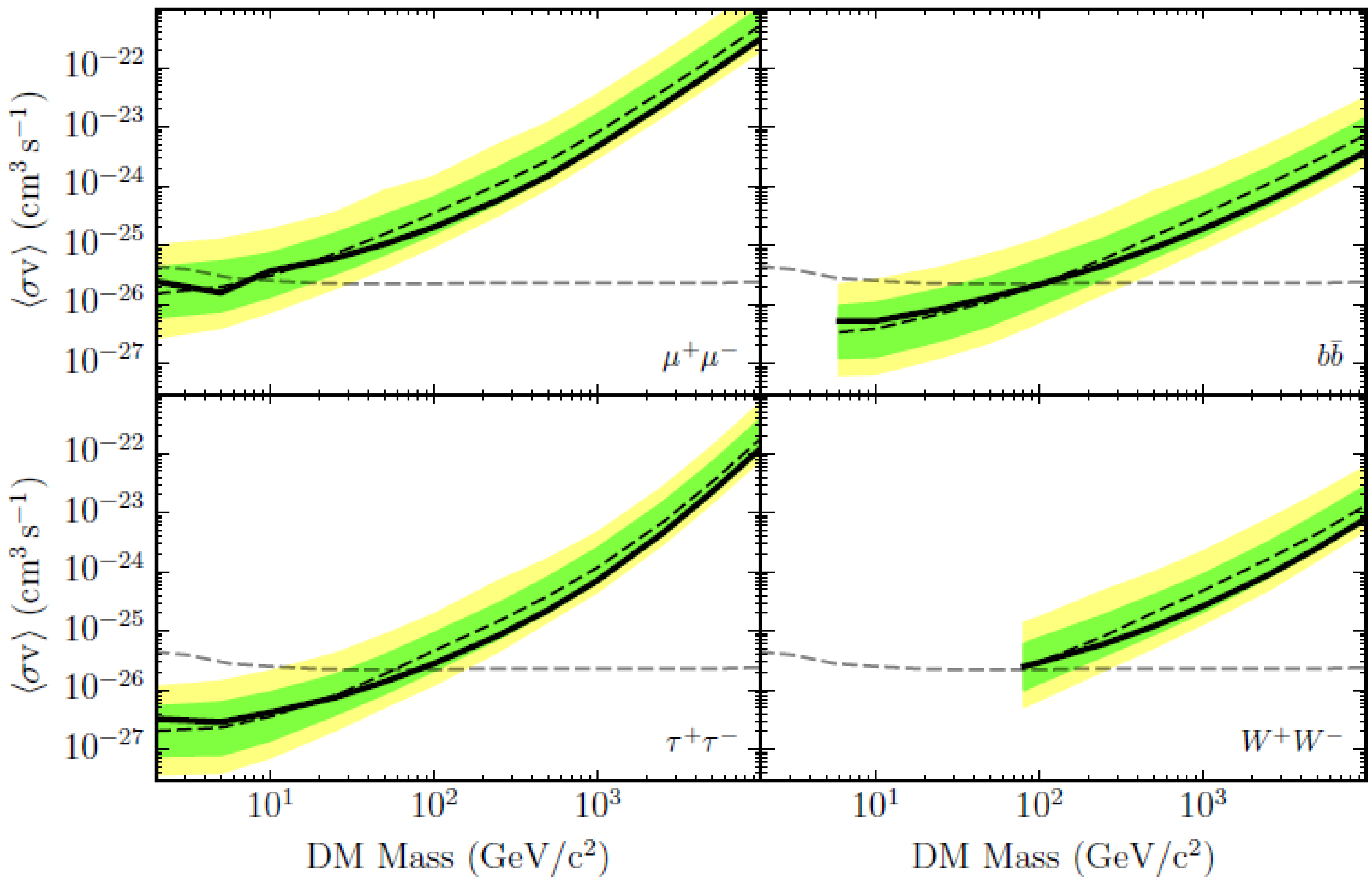
Assume a Navarro-Frenk-White dark matter halo profile inside the tidal radius:

$$\rho(r) = \begin{cases} \frac{\rho_s r_s^3}{r(r_s+r)^2} & \text{for} \quad r < r_t \\ 0 & \text{for} \quad r \geq r_t \end{cases}$$

Name	ρ_s $(M_\odot \ pc^{-3})$	r_s (kpc)	J^{NFW} $(10^{19} GeV^2 cm^{-5})$
Segue 1	1.65	0.05	0.97
Ursa Major II	0.17	0.25	0.57
Segue 2	0.61	0.06	0.1
Willman 1	0.417	0.17	0.84
Coma Berenices	0.232	0.22	0.42
Usra Minor	0.04	0.97	0.35
Sculptor	0.063	0.52	0.12
Draco	0.13	0.50	0.43
Sextans	0.079	0.36	0.05
Fornax	0.04	1.00	0.11

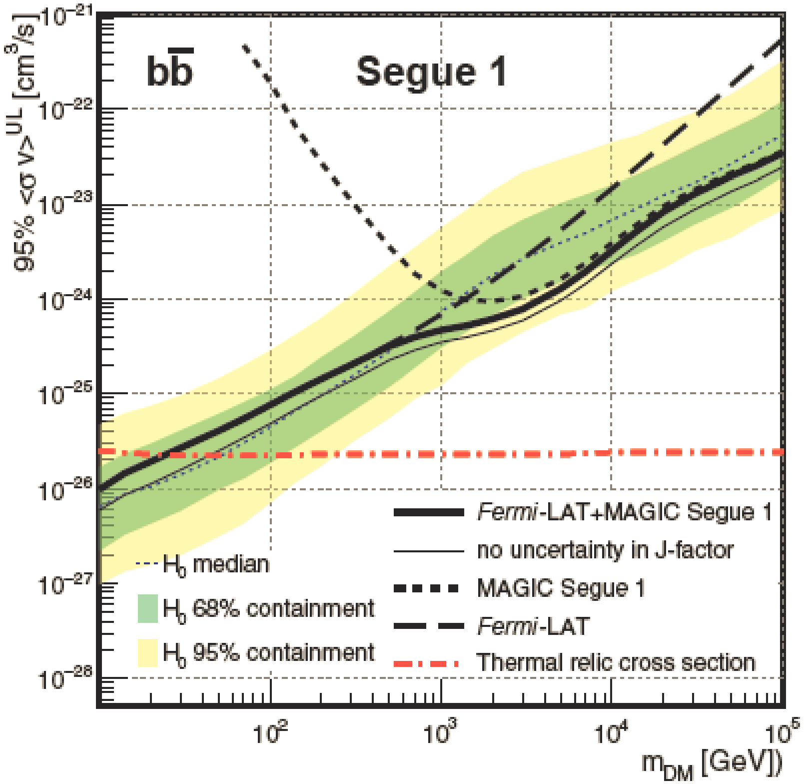
$$J(\psi) = \int_{l.o.s} dl(\psi) \rho^2(l(\psi))$$

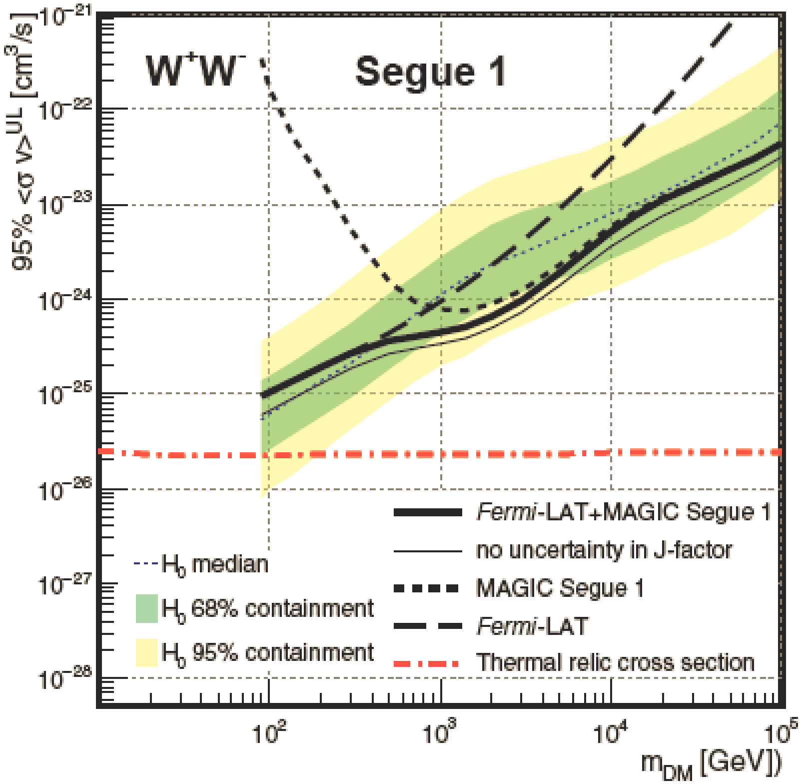
Constraints on WIMP dark matter models



Fermi coll.
arXiv:1503.02641

Constraints on WIMP dark matter models

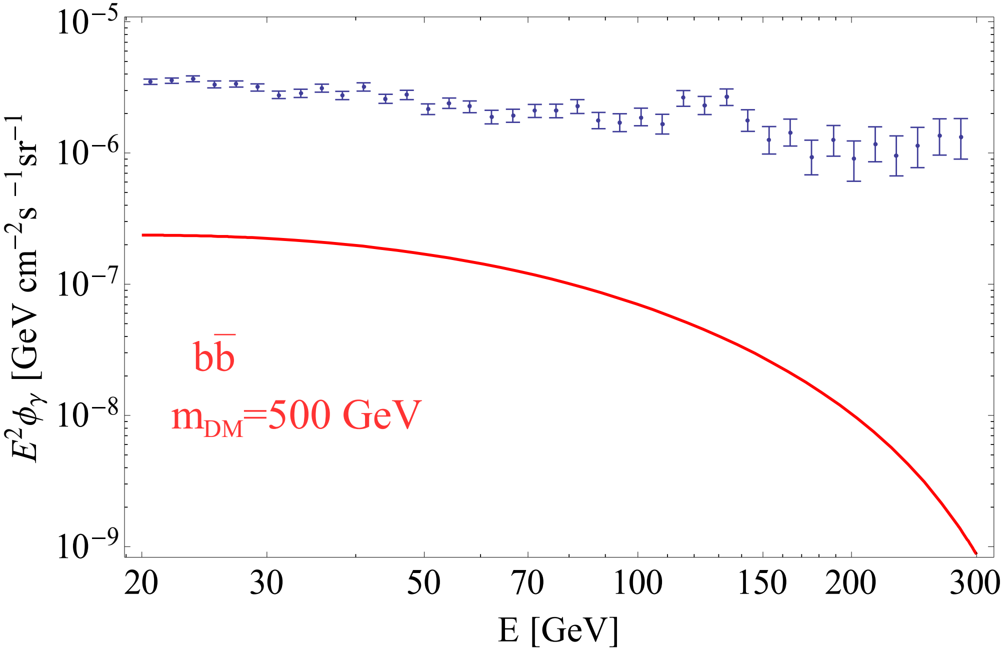




Fermi + MAGIC
arXiv:1601.06590

Gamma-ray features

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



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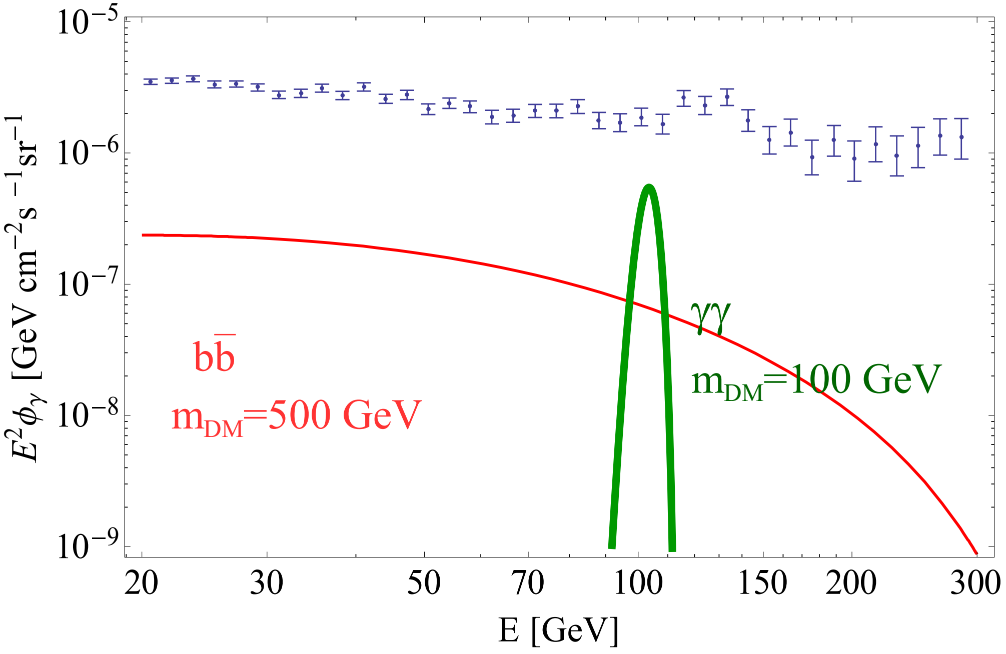
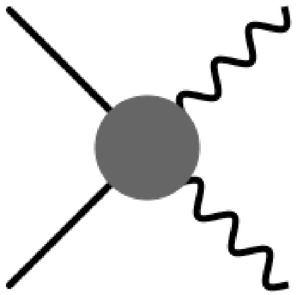


"Smoking gun" for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

Gamma-ray features

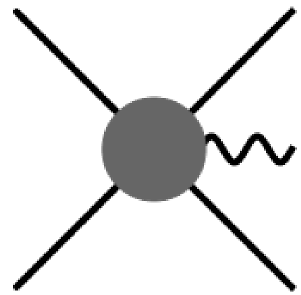
Three gamma-ray spectral features have been identified:

Gamma ray line



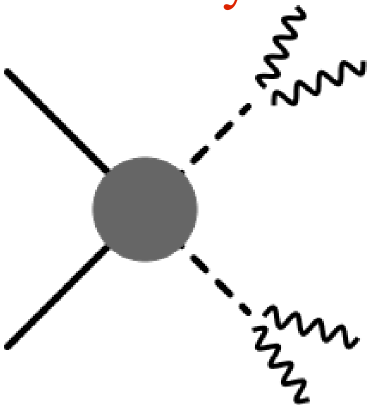
Srednicki, Theisen, Silk '86
Rudaz '86
Bergstrom, Snellman '88

Internal bremsstrahlung

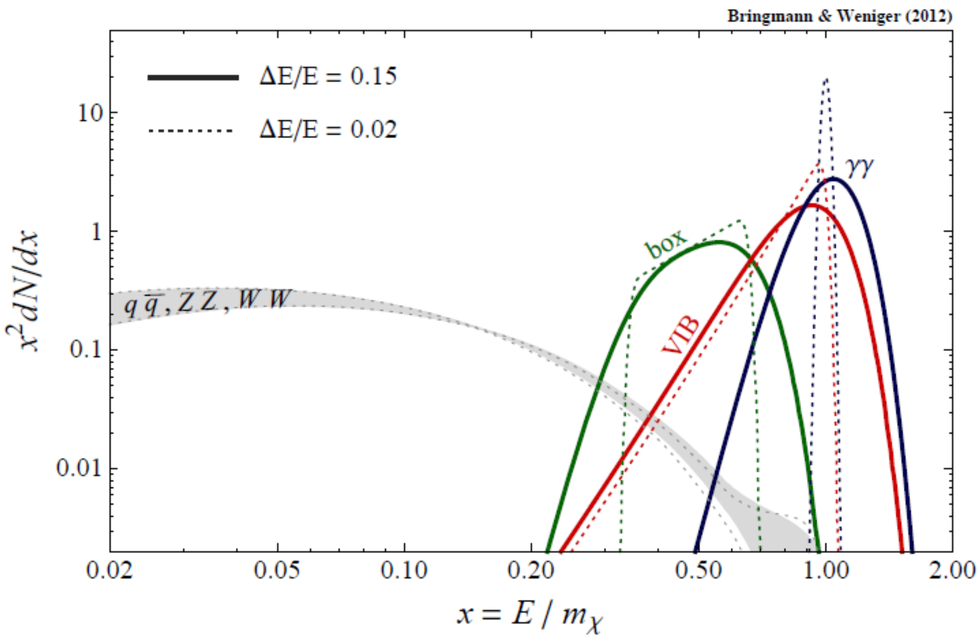


Bergstrom '89
Flores, Olive, Rudaz '89
Bringmann,Bergstrom, Edsjo '08

Gamma ray box



AI, Lopez Gehler, Pato '12



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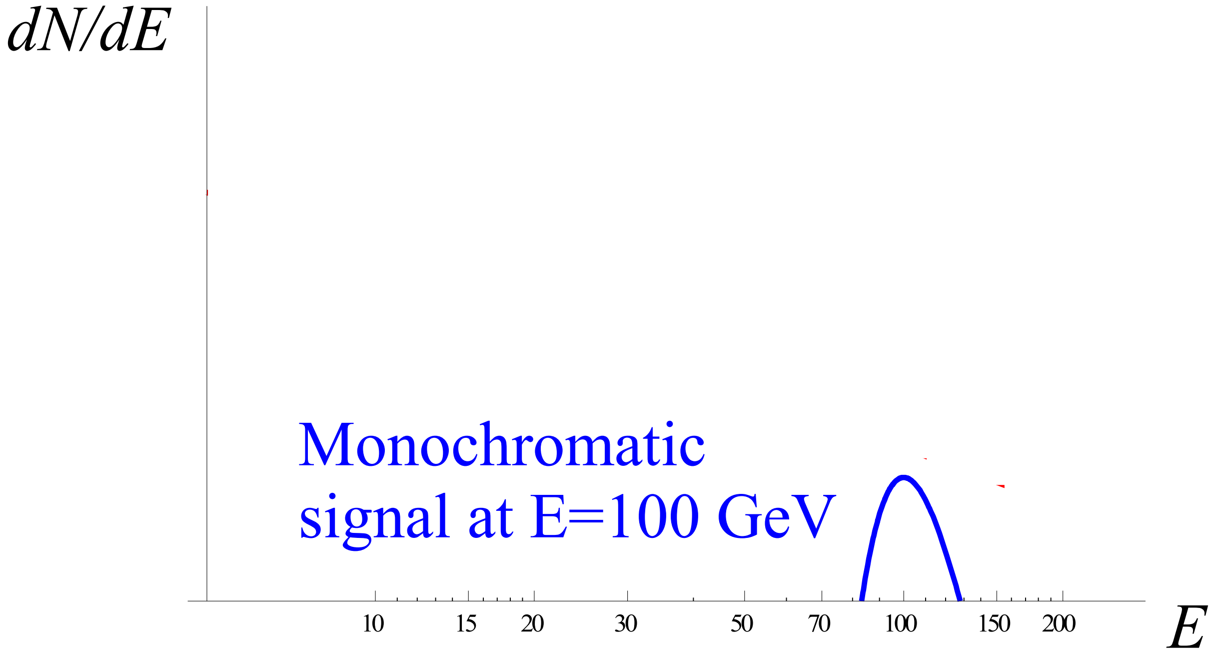

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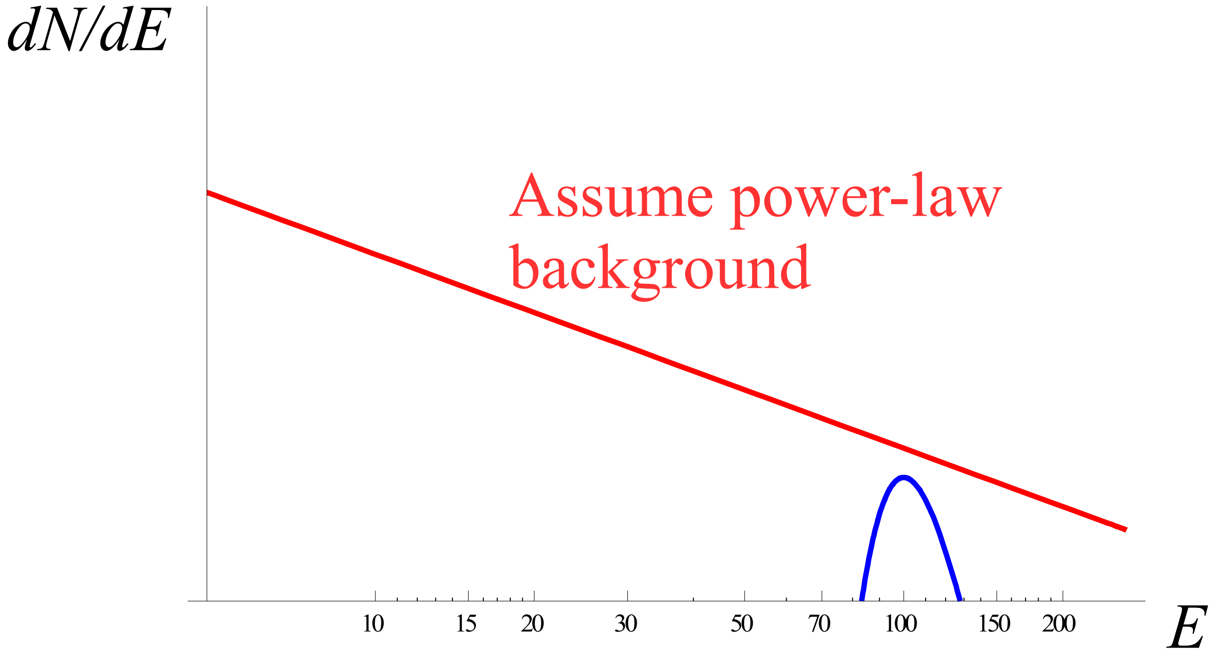

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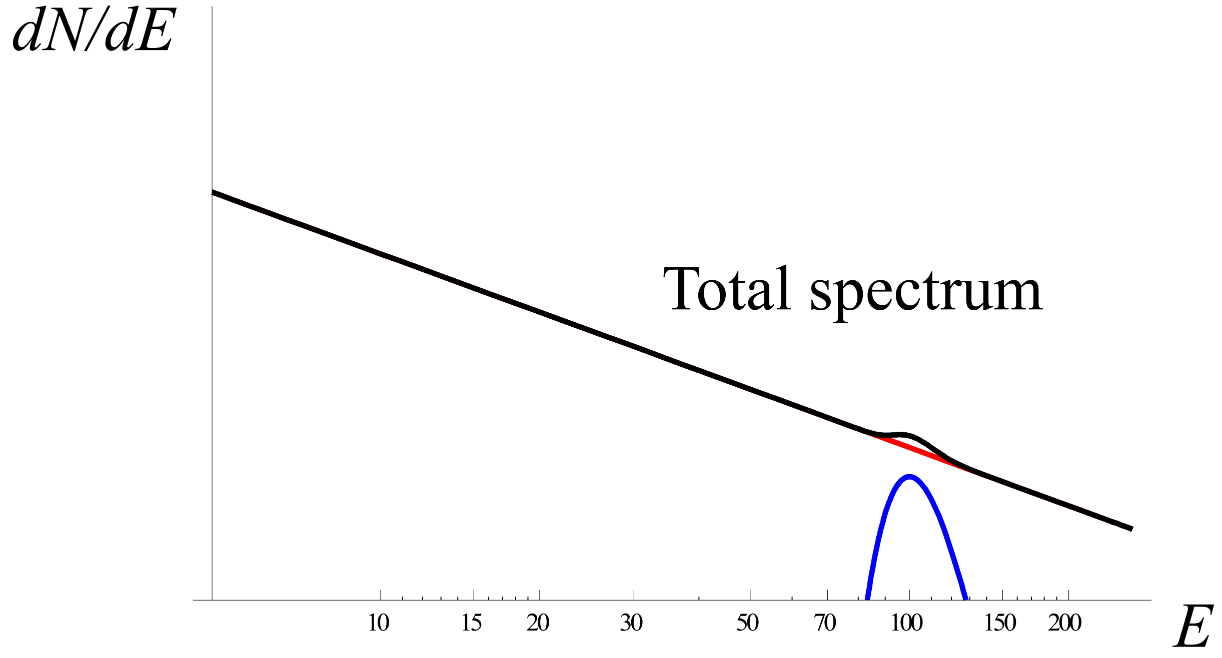
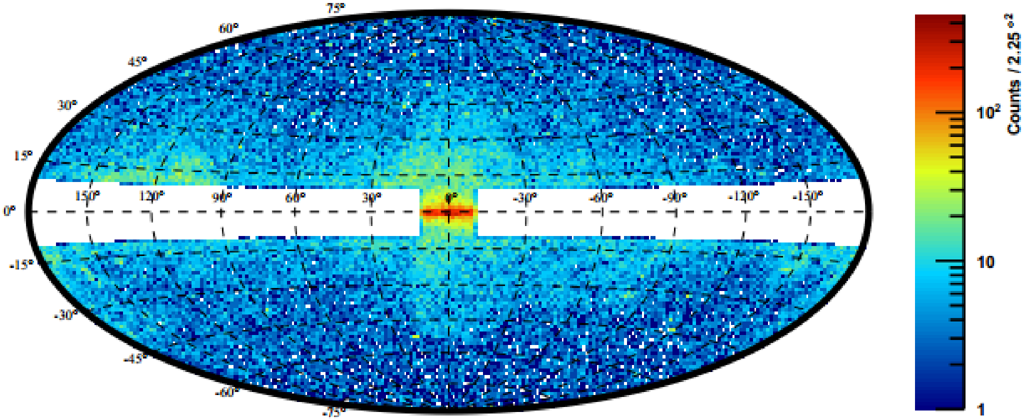


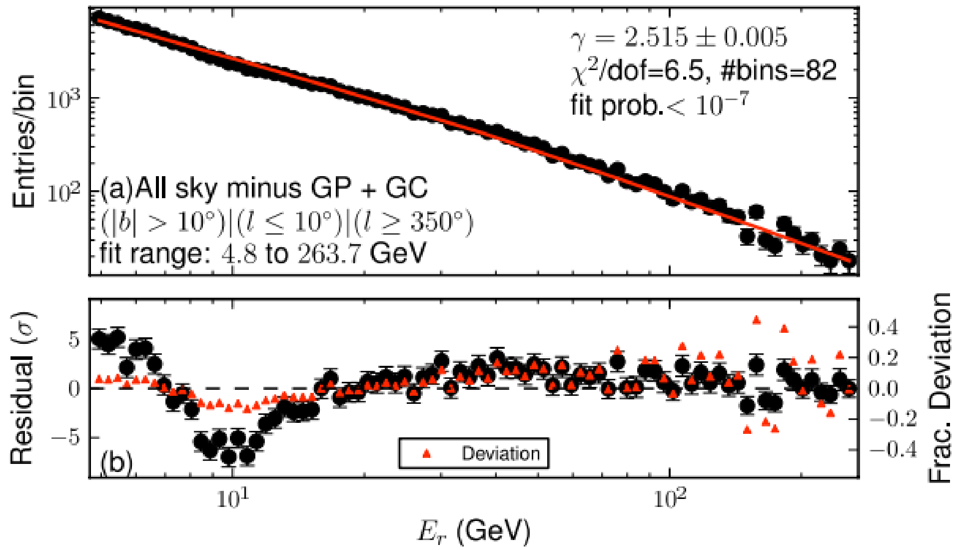
Fit data to $$\frac{dN}{dE} = aE^{-\alpha} + b\delta(E - E_0)$$

Gamma-ray features

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

Data don't really look like a power law...





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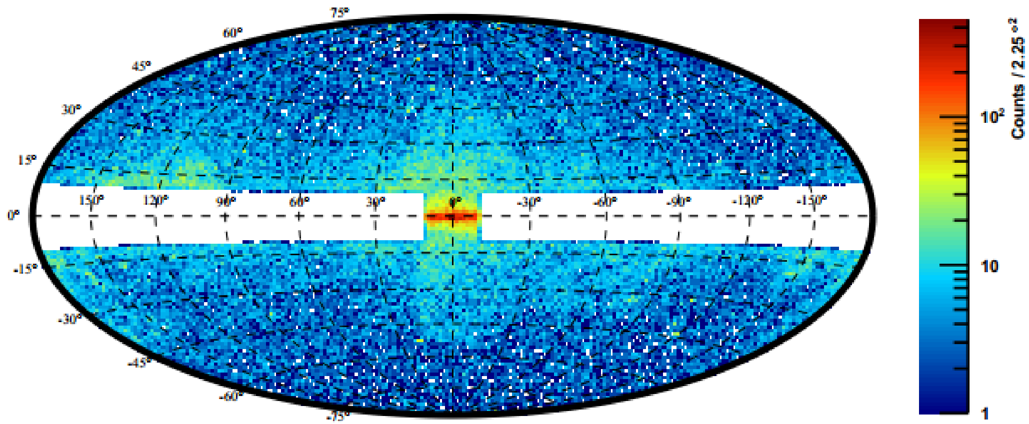

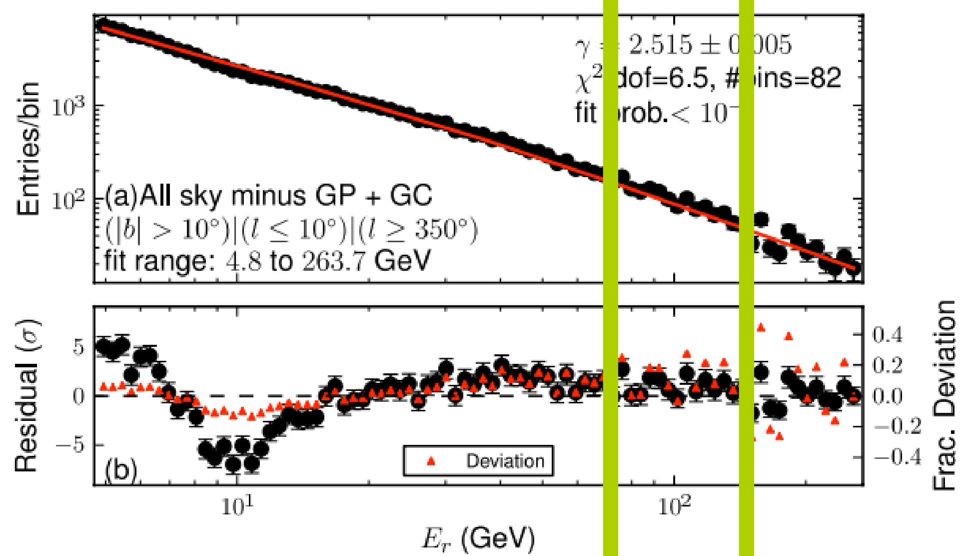

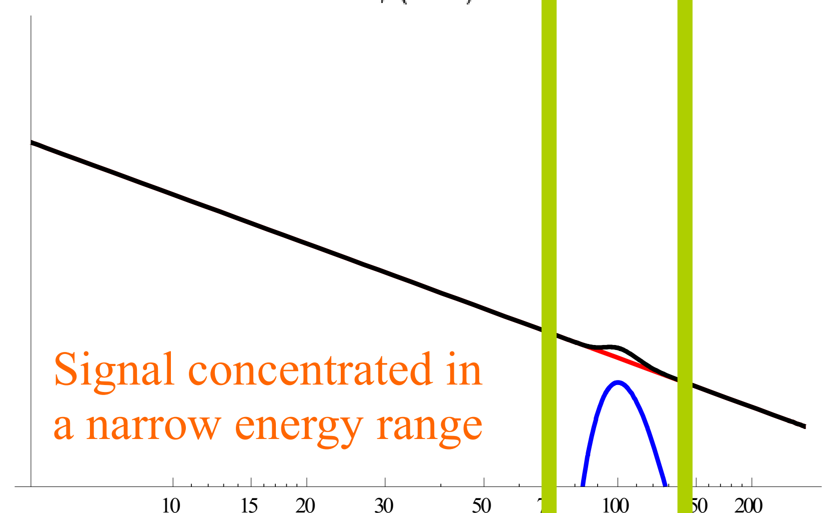

Signal concentrated in a narrow energy range

Gamma-ray features

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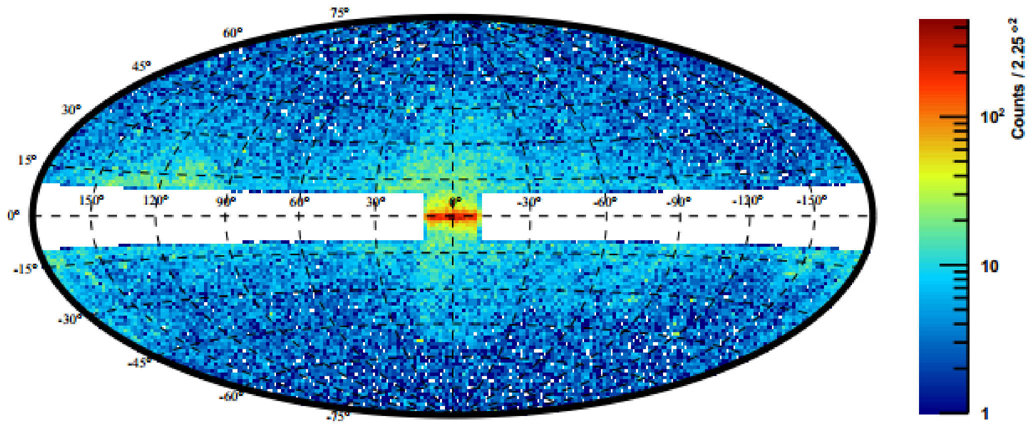
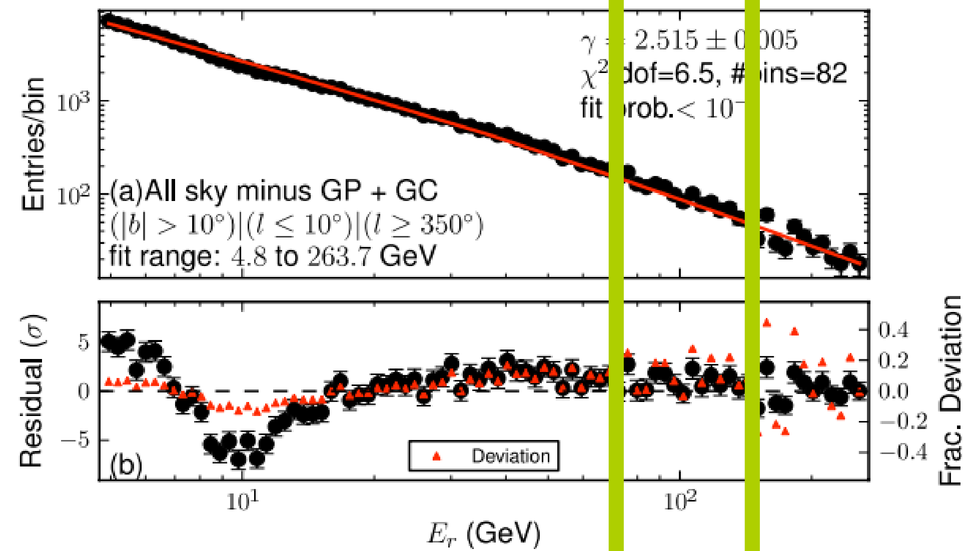
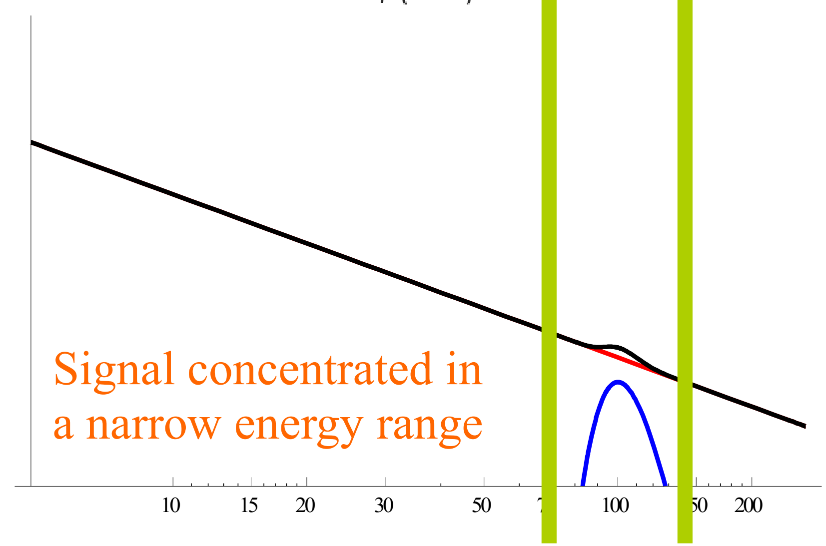




In a narrow energy interval, the background resembles a power-law (Taylor's theorem)

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



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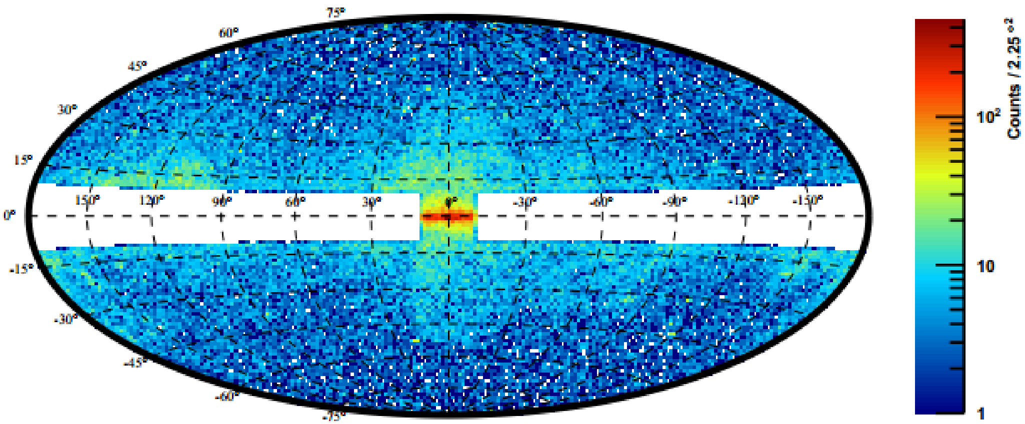
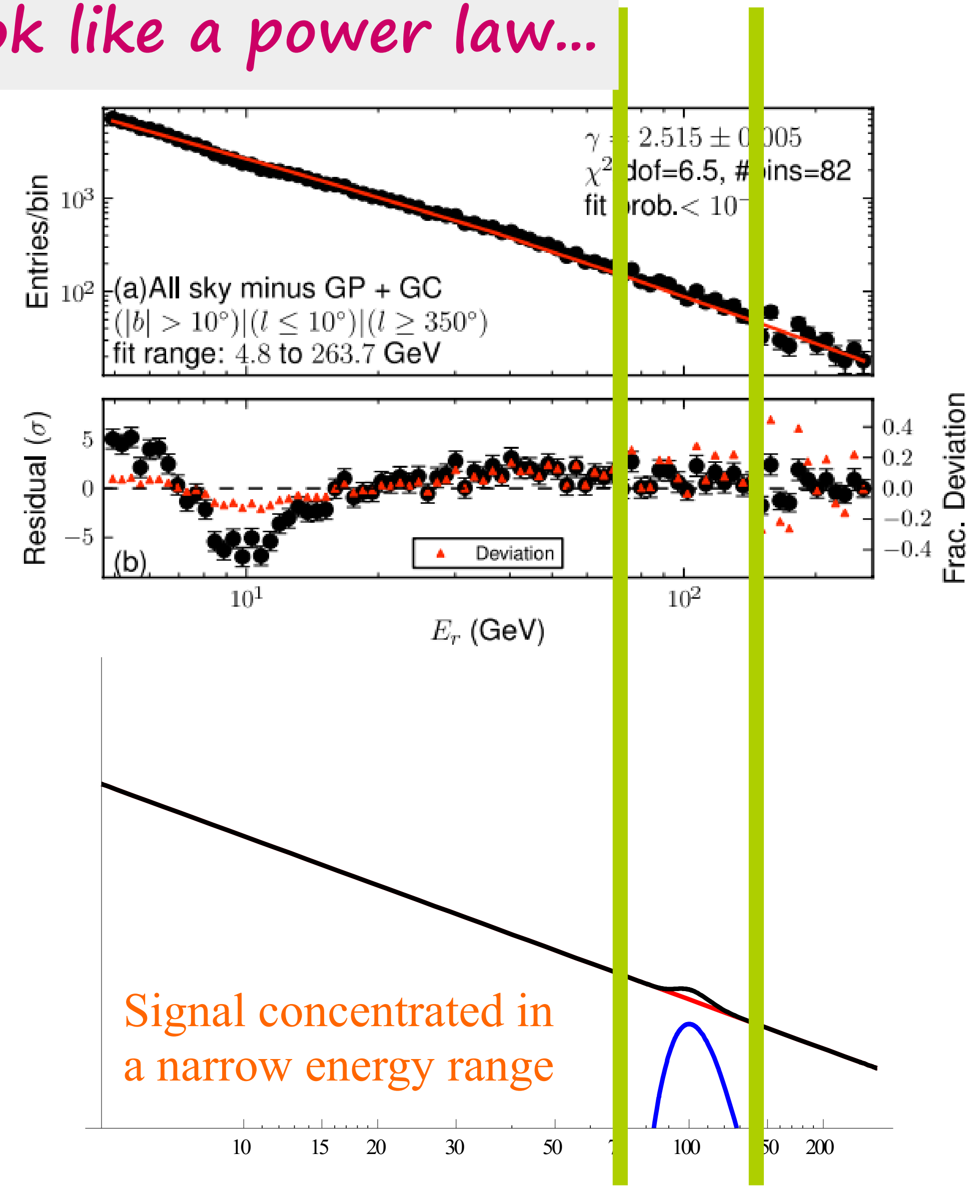
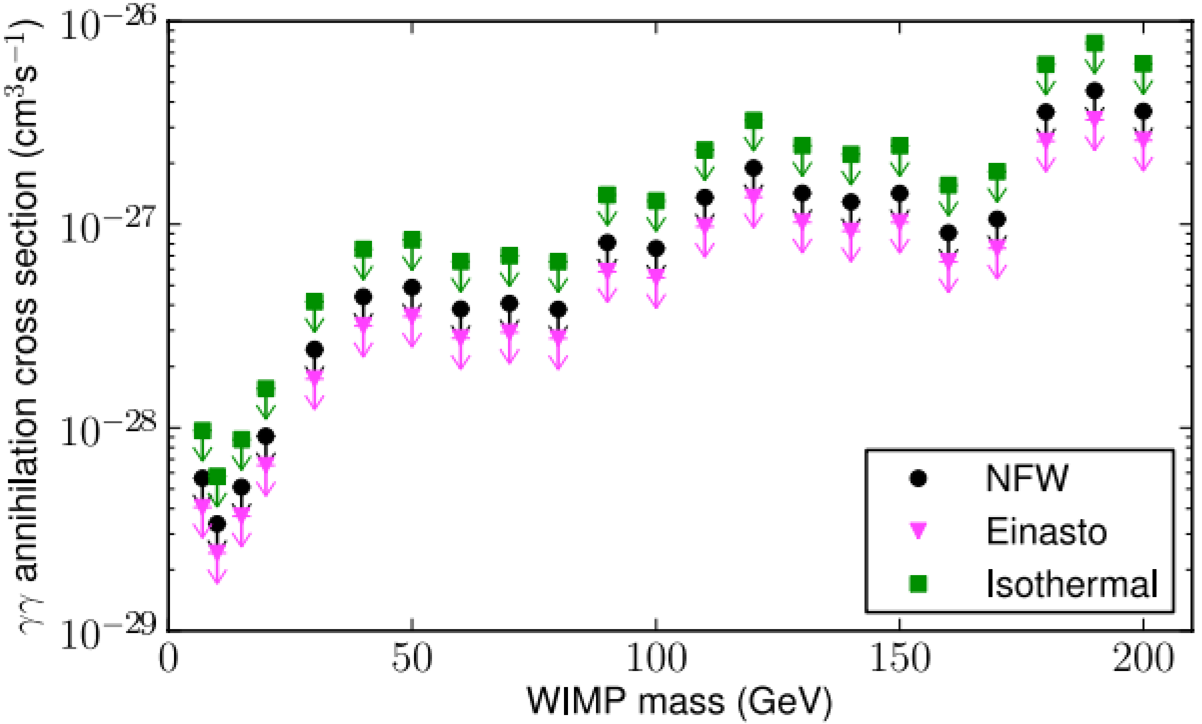




Repeat the search with different "windows" postulating a signal at different DM masses.

Gamma-ray features

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



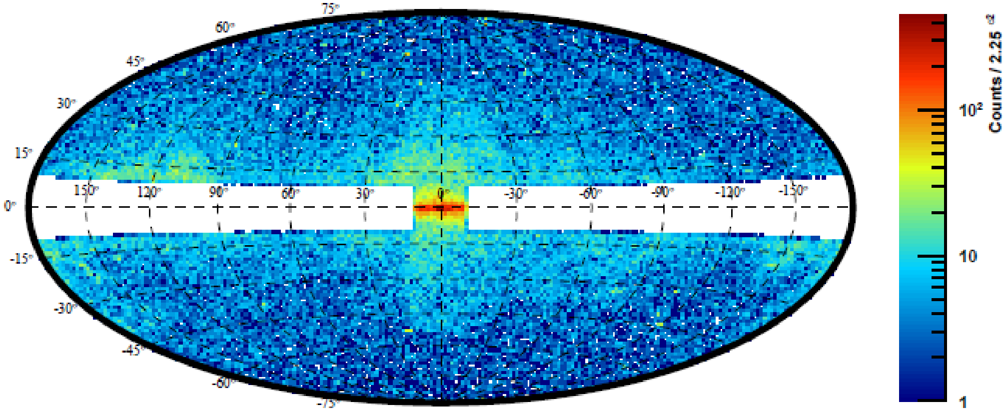
Fermi collaboration
arXiv:1205.2739

Gamma-ray features

One can do better searching 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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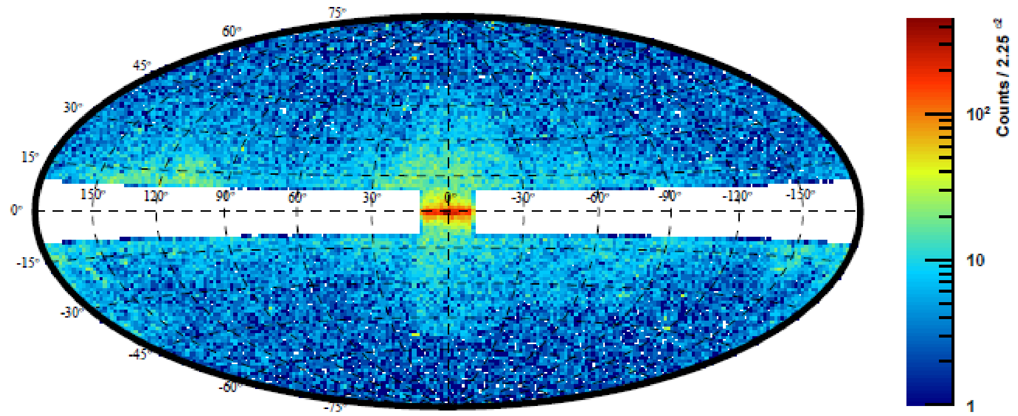
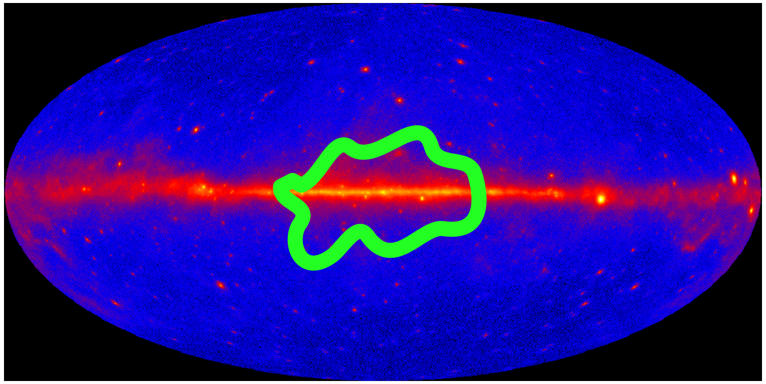


Disadvantage: in the chosen region the background could be too large and bury the signal

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



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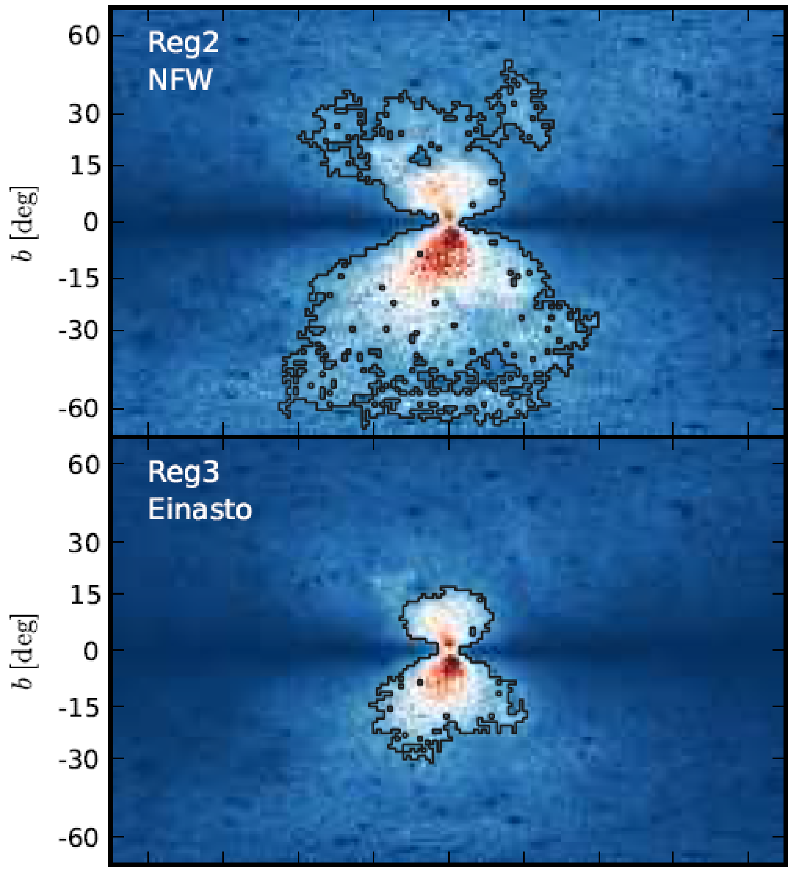

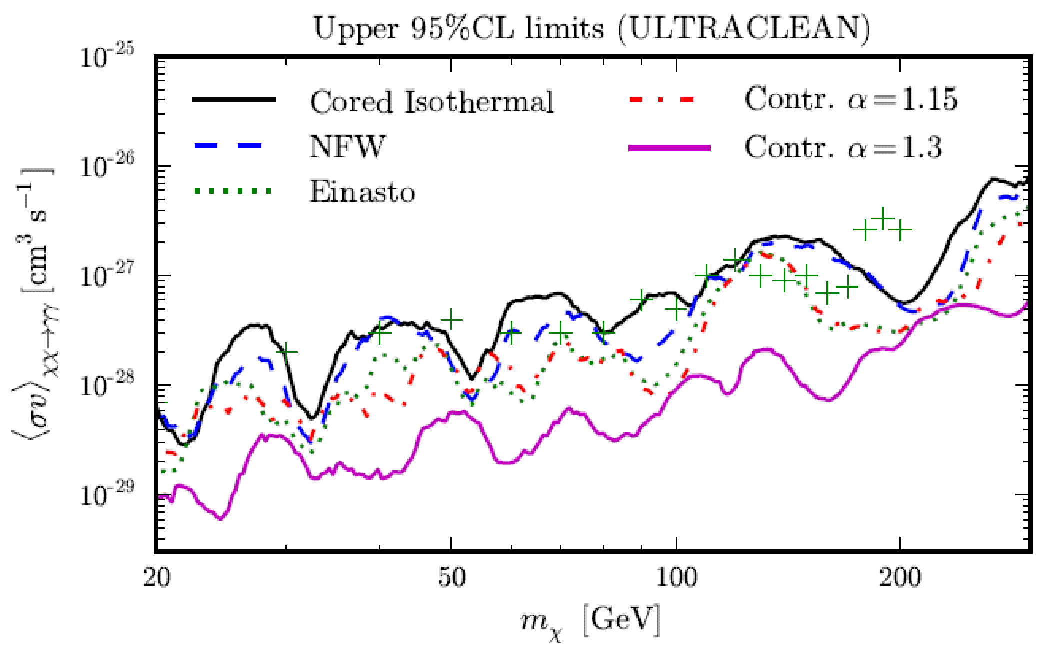

Bringmann, Huang, AI, Vogl, Weniger , arXiv:1203.1312
Weniger, arXiv:1204.2797

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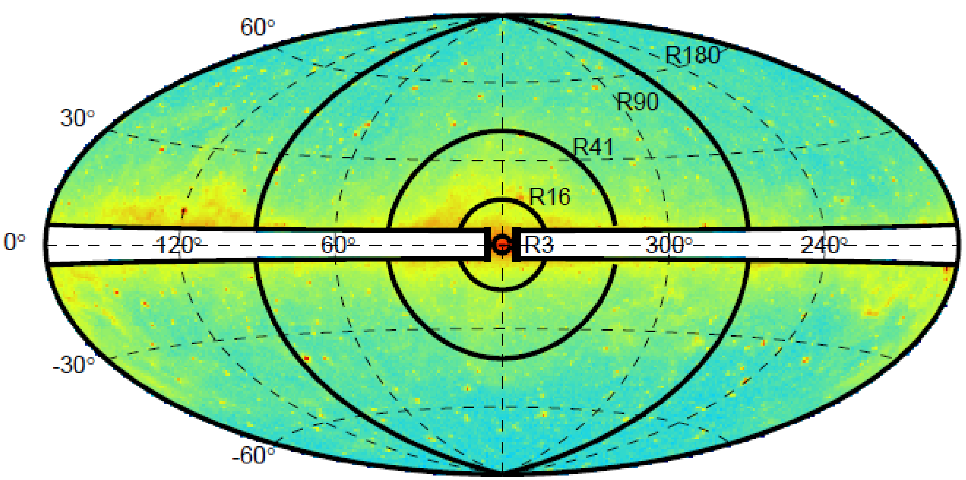

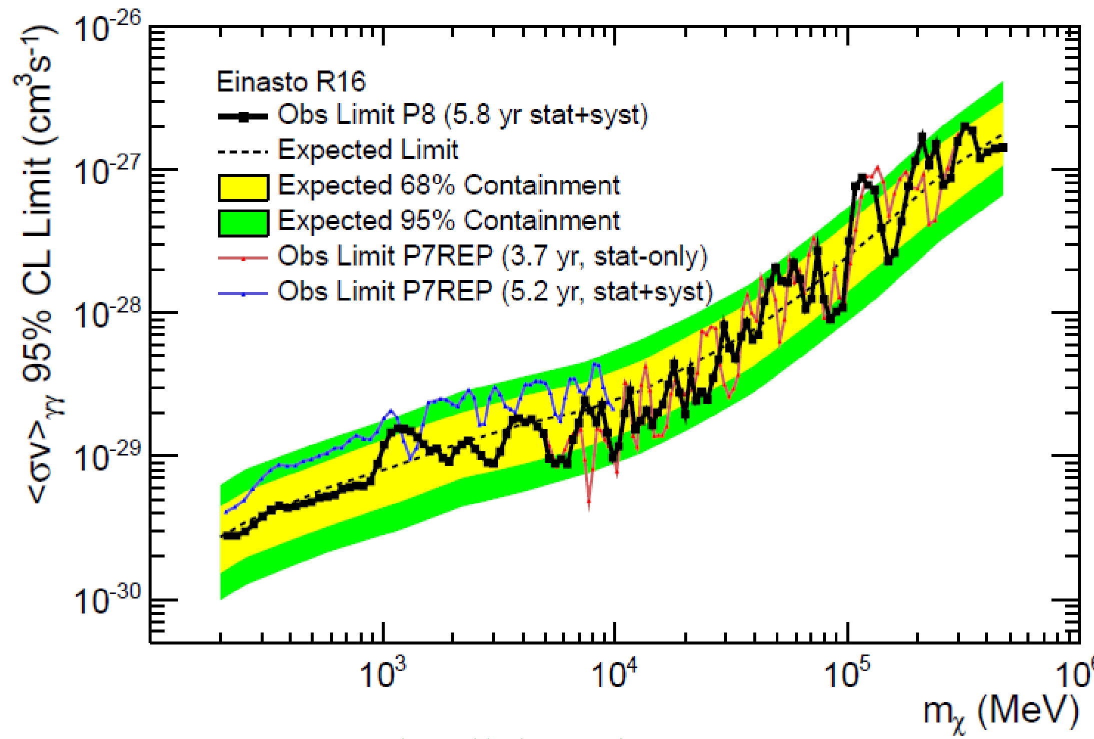

Fermi collaboration
arXiv:1503.02641

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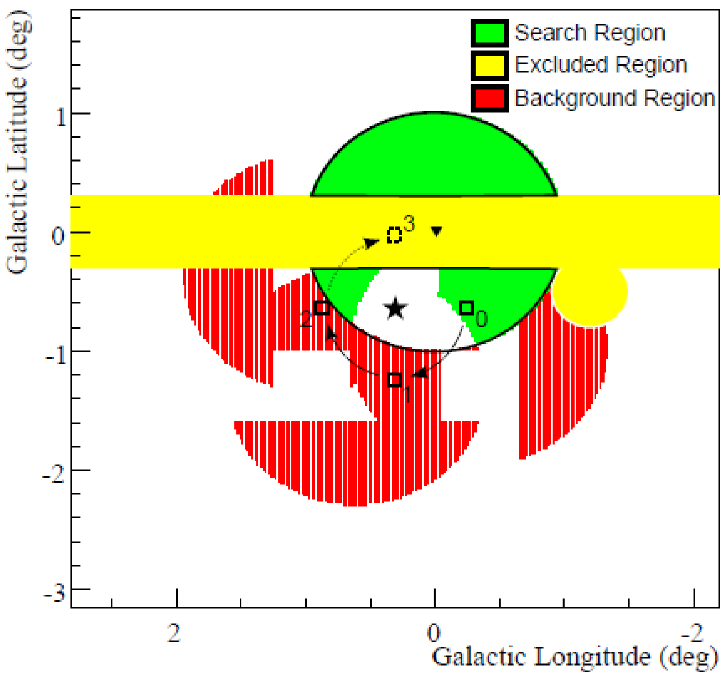
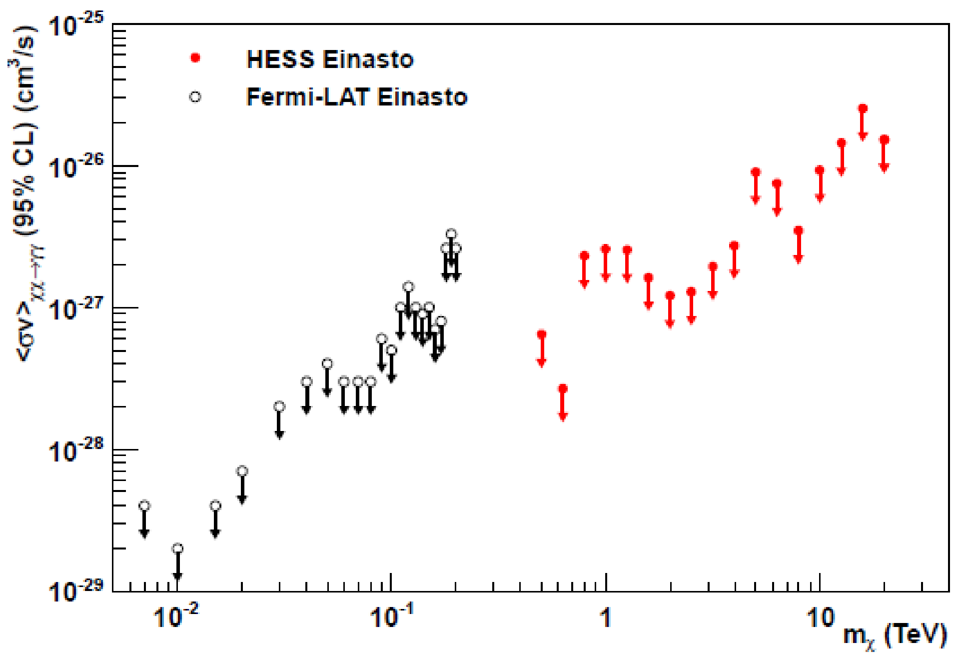
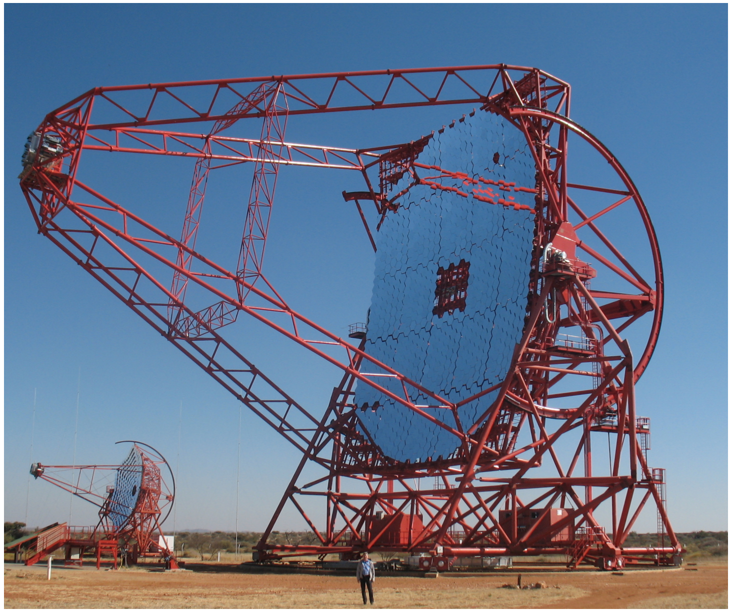




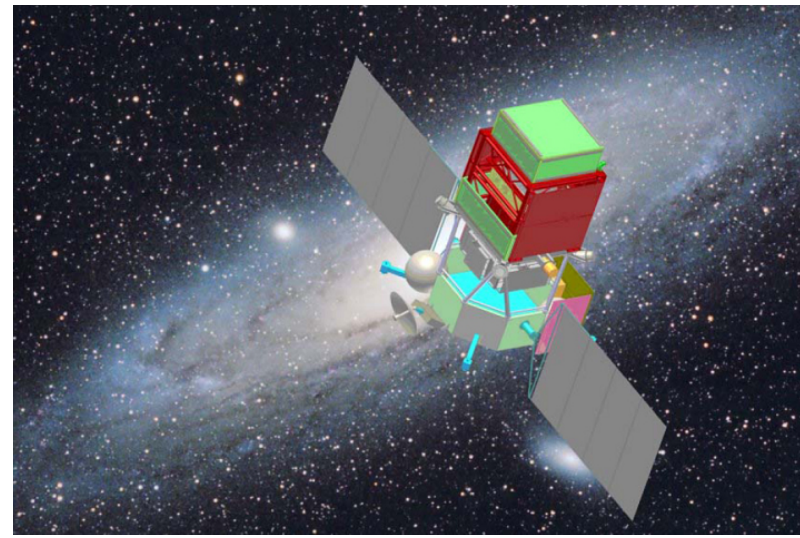
H.E.S.S. collaboration
arXiv:1301.1173

Bright future for dark matter searches using gamma-rays!

H.E.S.S. II – in operation

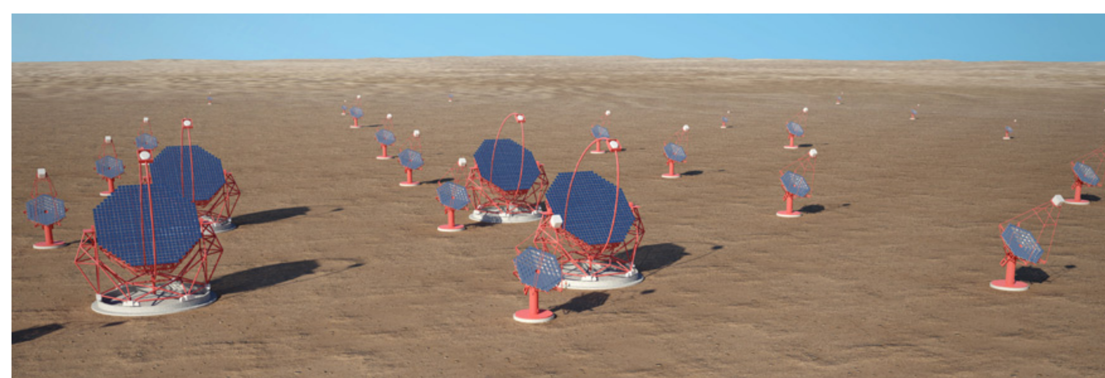


GAMMA 400 – Launch in 2021



DAMPE – Launched in 2015

CTA – Construction starting in 2017



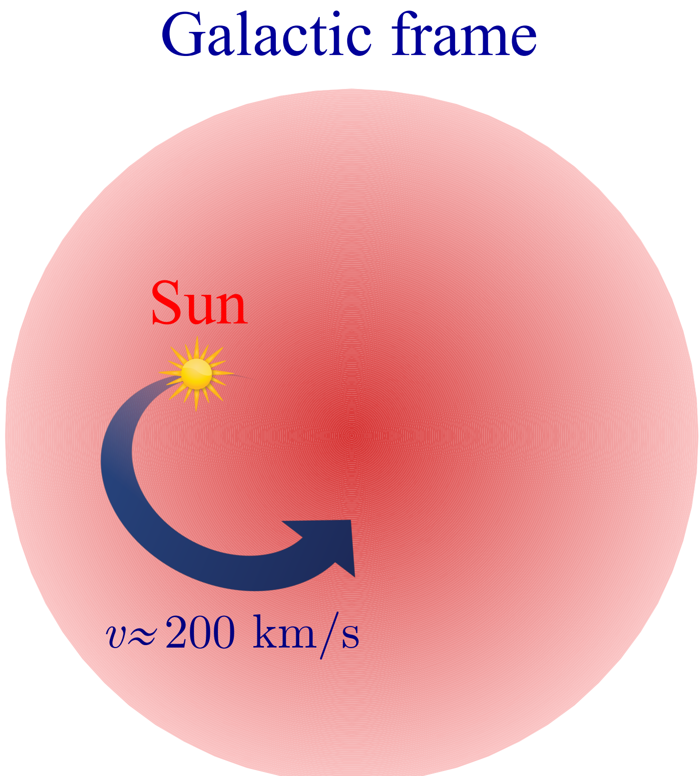
Direct Dark Matter Searches

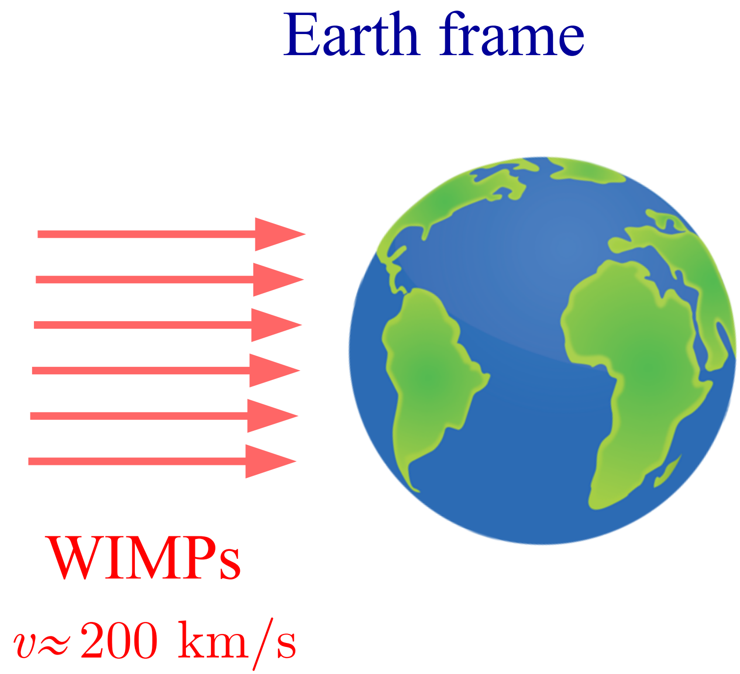
Direct dark matter searches

Direct dark matter searches

General idea:

1) The Sun (and the Earth) is moving through a “gas” of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.





Direct dark matter searches

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1) The Sun (and the Earth) is moving through a "gas" of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.

2) Once in a while a dark matter particle will interact with a nucleus.

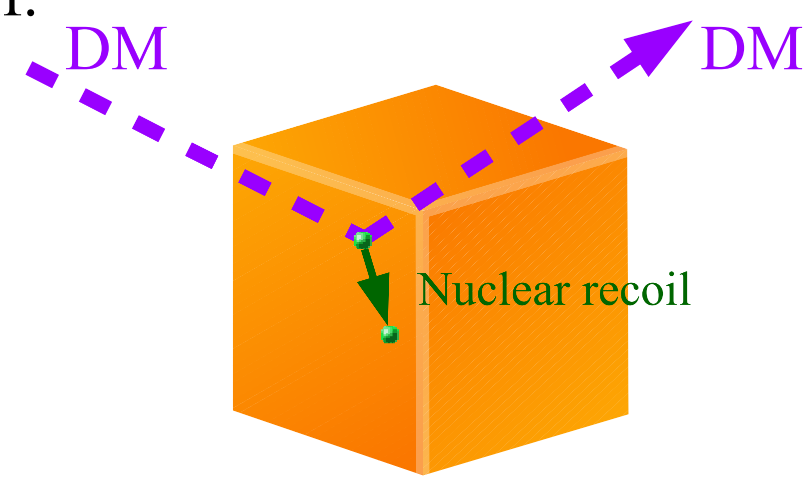
Direct dark matter searches

General idea:

1) The Sun (and the Earth) is moving through a “gas” of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.

2) Once in a while a dark matter particle will interact with a nucleus.

3) The nucleus gains momentum and recoils. The existence of dark matter can then be inferred if there is a significant excess in the number of recoils compared to the expected recoils induced by natural radioactivity in the lab or in the detector itself.



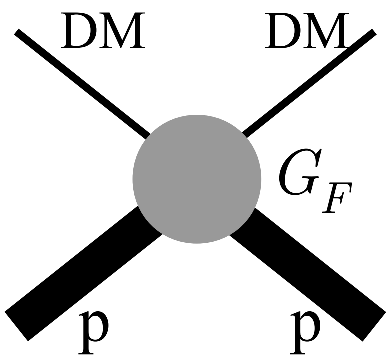
Simple idea ...

… but very challenging in practice!

Challenges in direct dark matter detection

- Expected scattering cross section

Assume that the DM interacts with a proton via a weak interaction



$$\sigma \sim \frac{1}{32\pi} G_F^2 \mu^2$$

$$\mu = \text{reduced mass} = \frac{m_{\rm DM} m_p}{m_{\rm DM} + m_p} \simeq m_p$$

$$\boxed{\sigma \sim 5 \times 10^{-4}\,\text{pb}}$$

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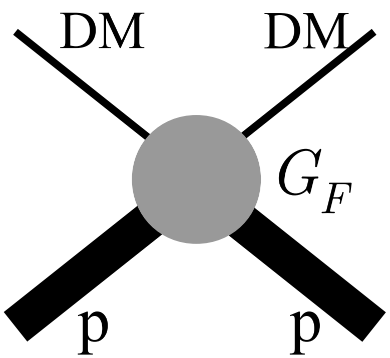

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$$\boxed{\sigma \sim 5 \times 10^{-4}\,\text{pb}}$$

- Expected flux

$$\text{Flux} = \text{density} \times \text{velocity}$$

$$\rho_{\rm DM} = 0.38\,\text{GeV}/\text{cm}^3 \qquad \text{velocity} \sim 200\,\text{km}/\text{s}$$

$$\underset{m=100\text{ GeV}}{\leadsto} n = 3.8 \times 10^{-3}\,\text{WIMPs}/\text{cm}^3$$

$$\boxed{\text{flux} \sim 10^5\,\text{WIMPs}/\text{cm}^2\,\text{s}}$$

(For m=100 GeV)

Challenges in direct dark matter detection

- Expected interaction rate

Rate = flux × number of targets × cross section

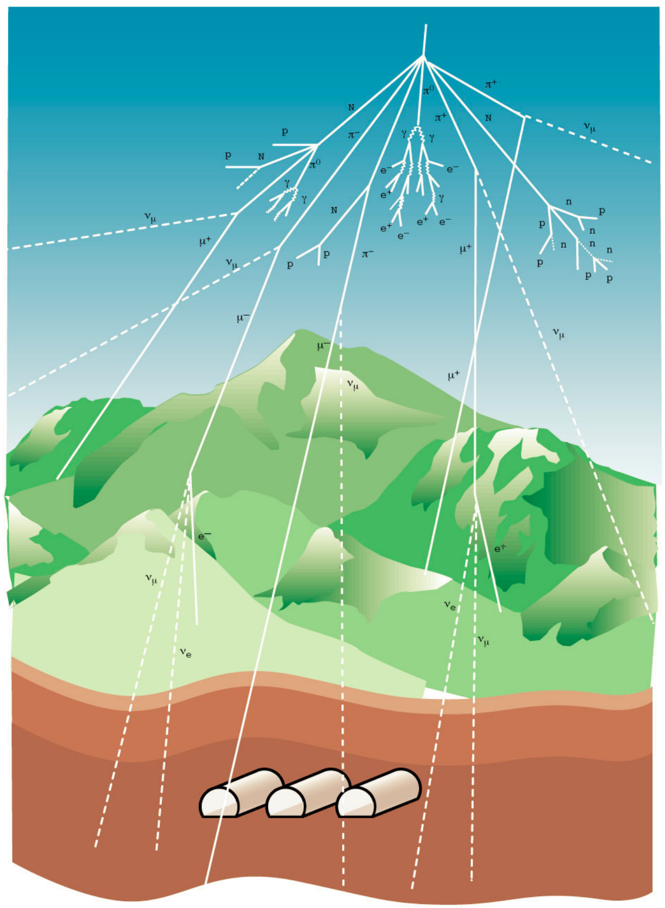
10^5 cm^{-2} s^{-1} — For a 70 kg person, 10^{29} protons — 5×10^{-40} cm^{-2}

Rate ~ 1 interaction per day, producing nuclear recoils

However, cosmic ray interactions and the natural radioactivity also produce nuclear recoils, with a much much larger rate.
How to distinguish the signal events from the background events?

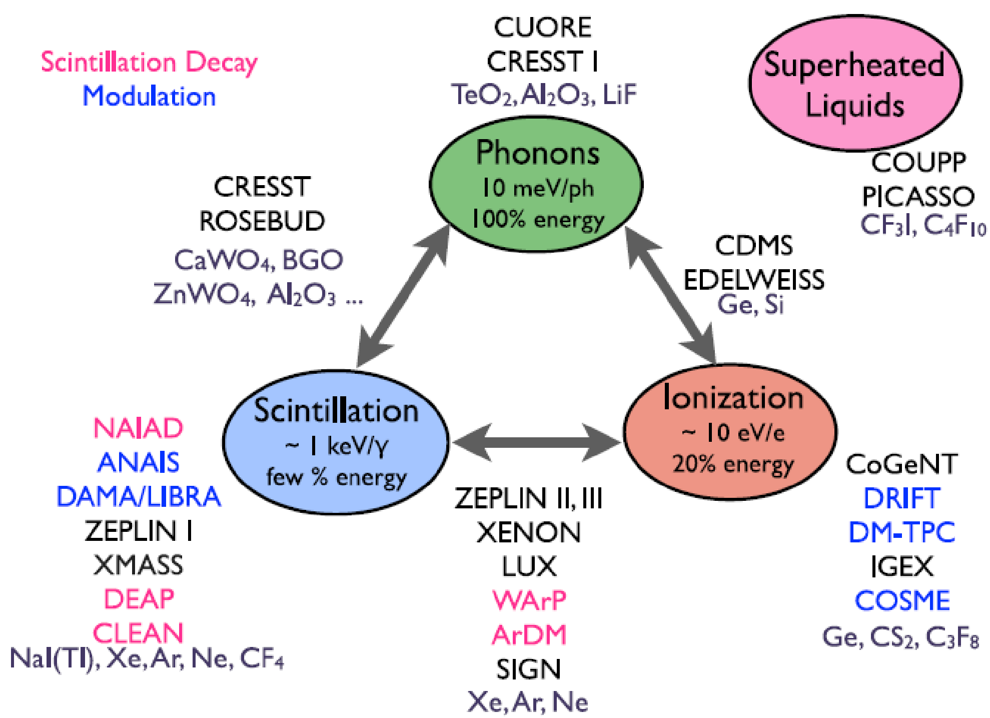
Reducing backgrounds

1) Take experiments deep underground



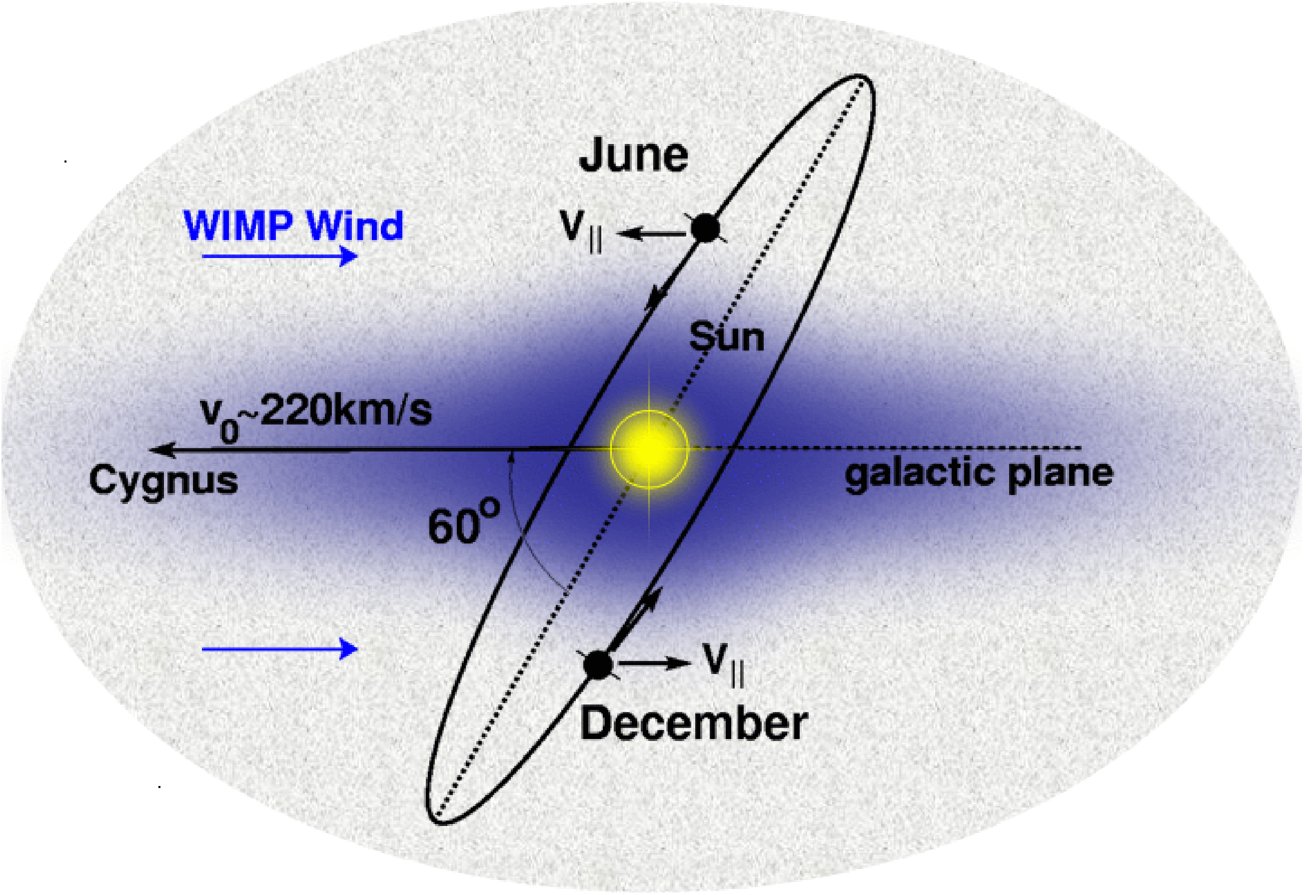
2) Shield the detector against natural radioactivity in the laboratory.

3) Devise techniques to further reduce residual backgrounds

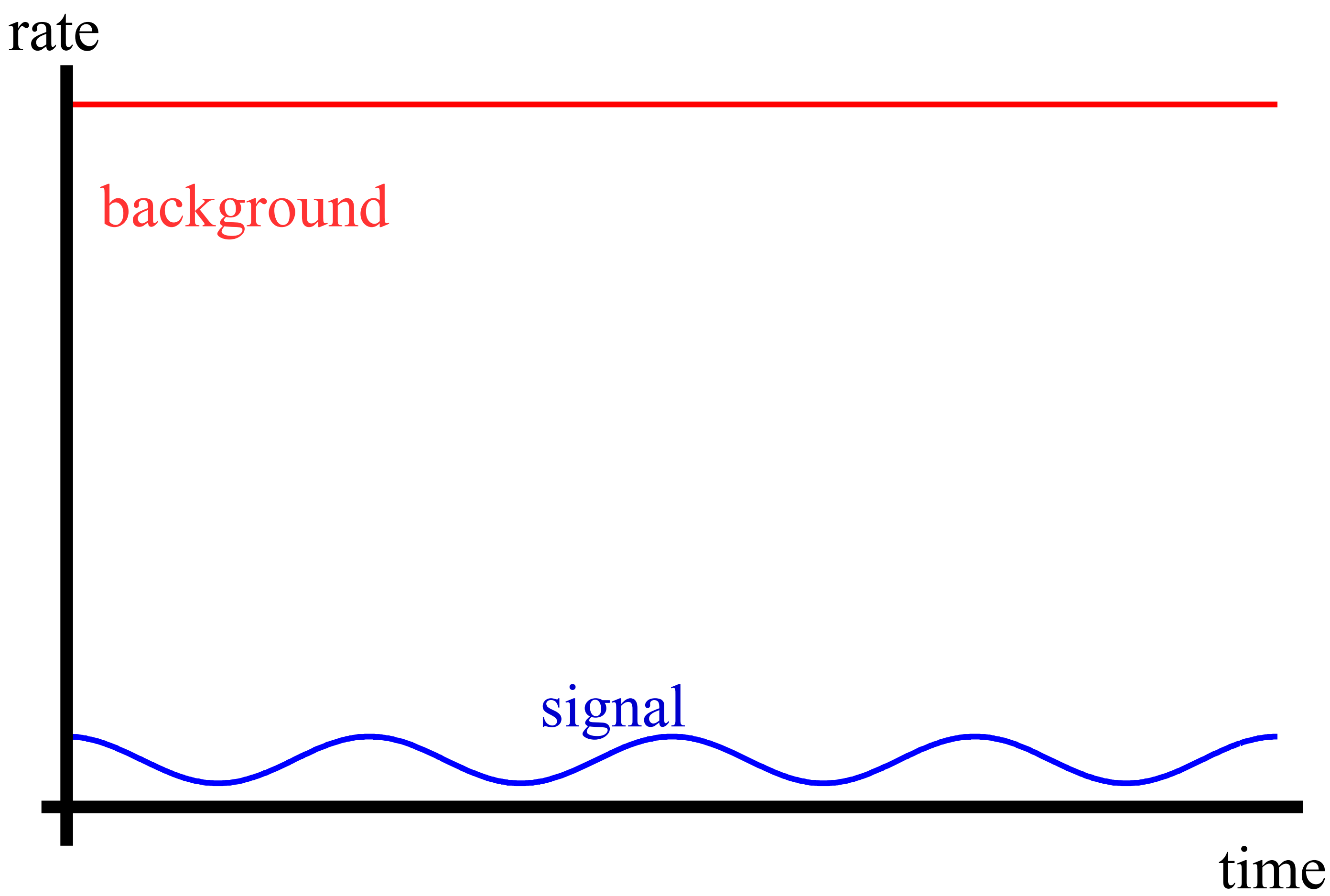


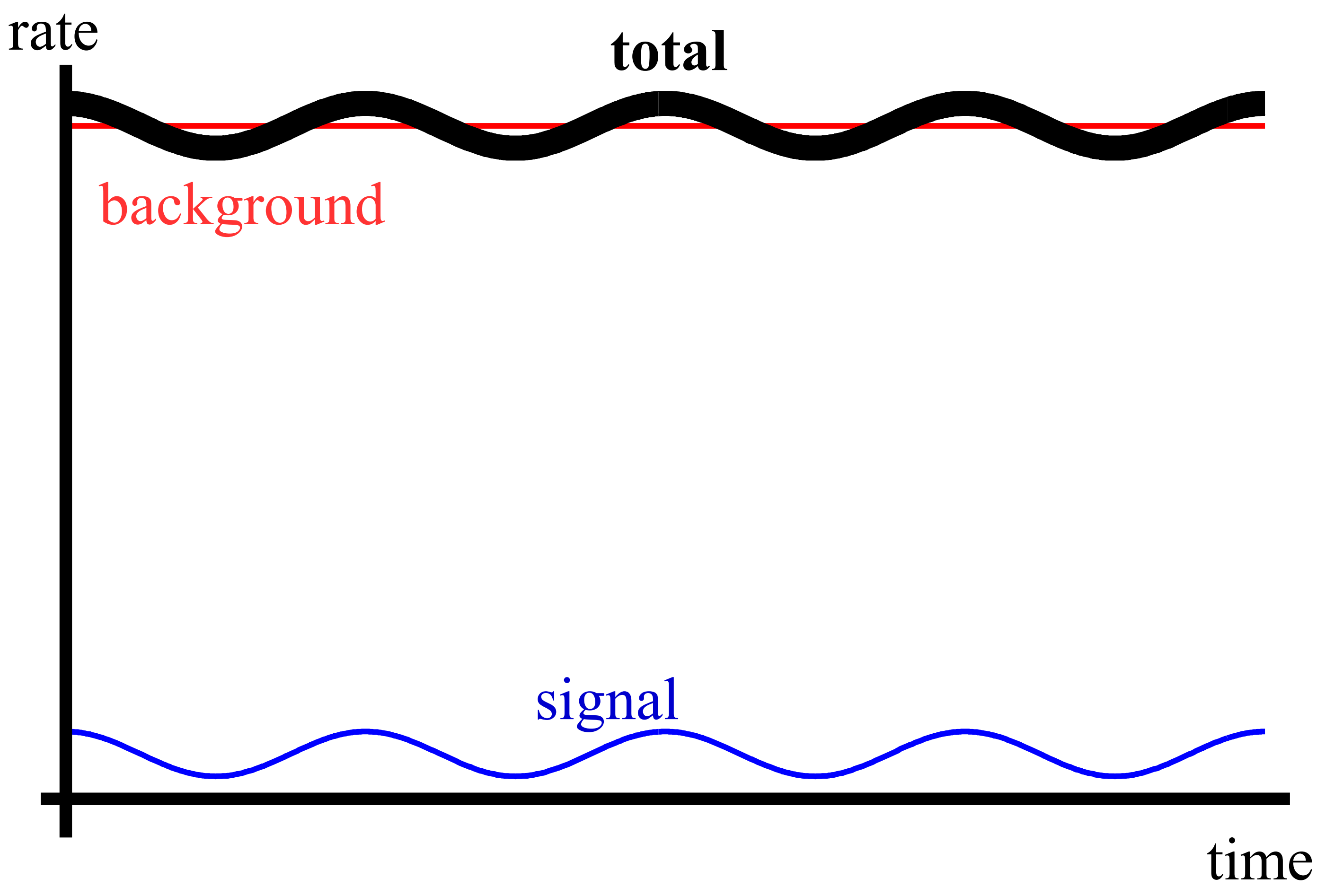
Reducing backgrounds

3') Search for an event rate with a time dependence characteristic of a dark matter signal: annual modulation.



The Earth velocity relative to the WIMP wind is time dependent.
From the Earth frame, the WIMP flux is time dependent, and thus the event rate.


rate
background
signal
time


rate
total
background
signal
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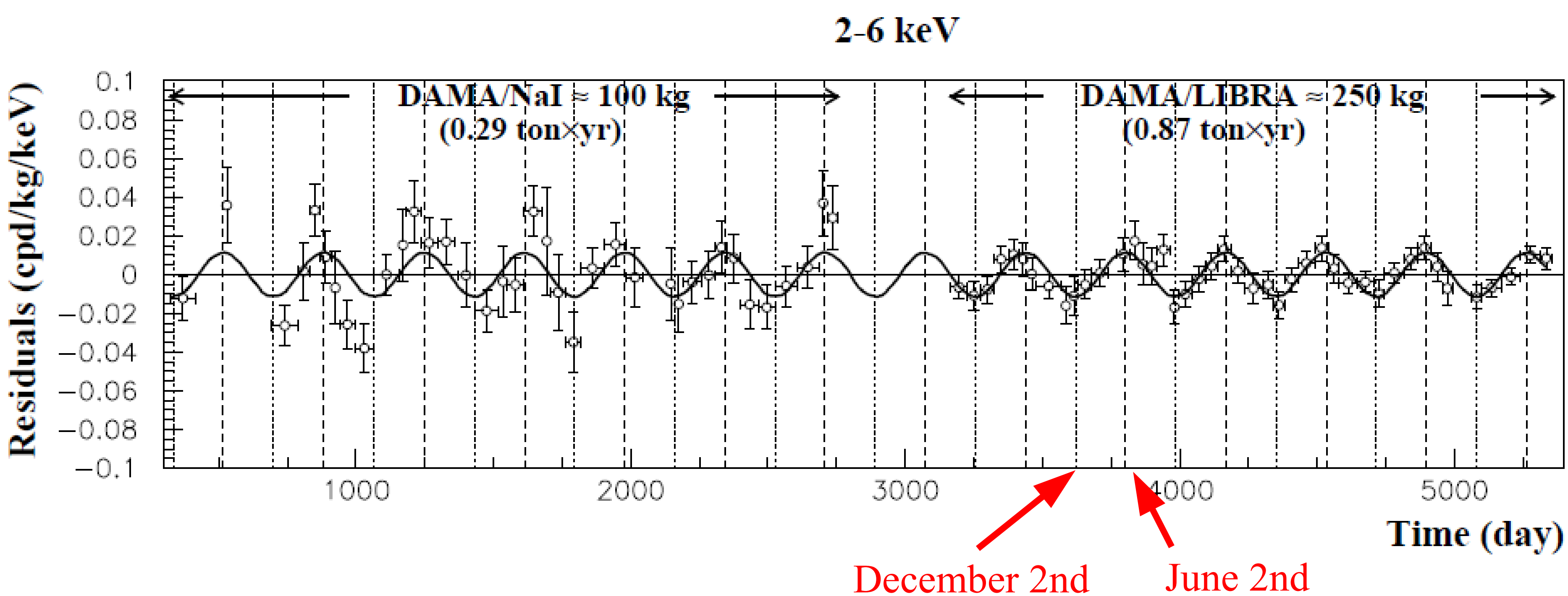
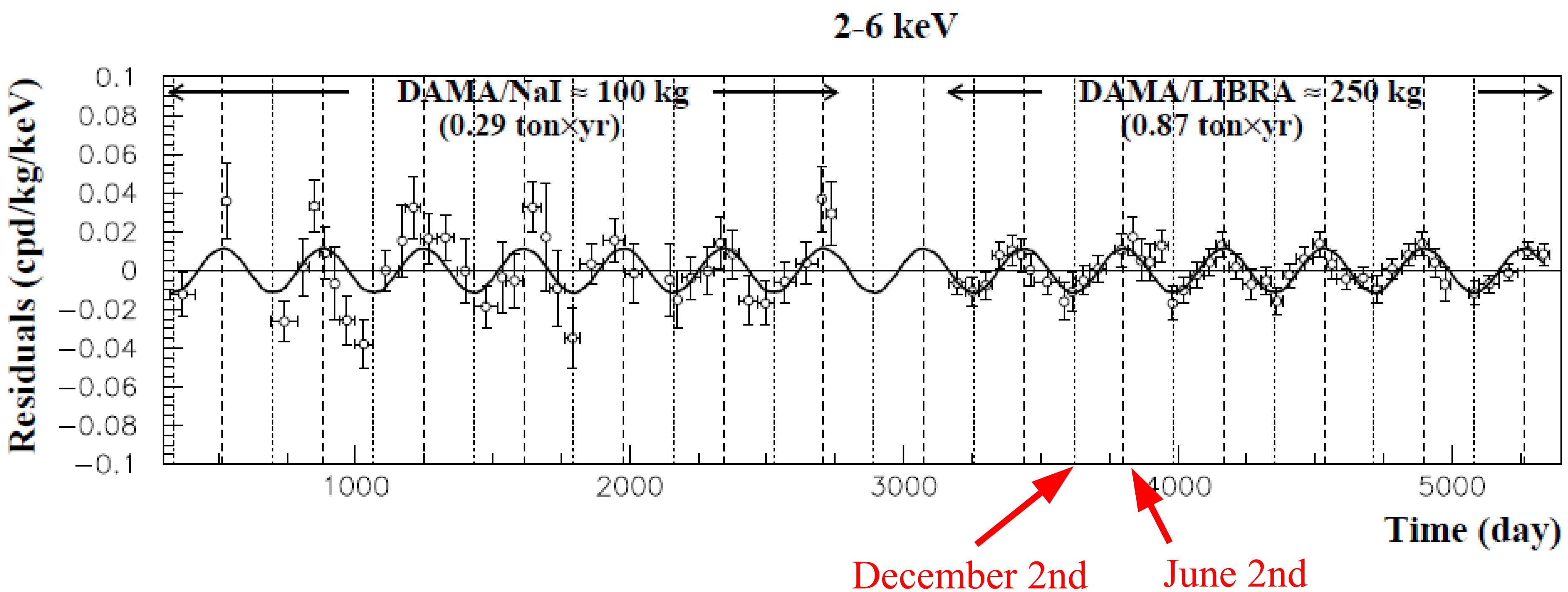


2-6 keV
DAMA/NaI ≈ 100 kg
(0.29 ton×yr)
DAMA/LIBRA ≈ 250 kg
(0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
1000
2000
3000
4000
5000
Time (day)
December 2nd
June 2nd



DM interpretation very controversial! More later…

Some experiments have reported detection, however, and despite the huge effort in reducing backgrounds, there is at the moment no unambiguous DM signal from direct detection experiments.

Very strong limits on the interaction rate

Exp: less than one event for an exposure of 3.3×10^4 kg-day

$\Rightarrow$ Interaction rate $< 3\times10^{-5}$ /(kg day)

$\Rightarrow$ In a 70 kg person, interaction rate $< 2\times10^{-3}$ /day

Before, and assuming m_{DM}=100 GeV and interactions mediated by the weak force, we estimated 1 /day.

Very strong limits on the DM properties

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Important: the momentum transferred in the scattering to the target is small:

Typical kinetic energy of a DM particle at the location of the Earth:

$$E_{\rm kin} = \frac{1}{2} m_{\rm DM} v^2 \underset{m_{\rm DM} = 100\,{\rm GeV}}{\sim} 30\,{\rm keV}$$

$\Rightarrow$ Momentum transferred < Ekin ~ 30 keV

$\Rightarrow$ The DM cannot "see" the constituents of the nucleus

$\rightsquigarrow$ Coherent scattering with the whole nucleus.

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Assume for the moment that all DM particles have the same velocity v

Interaction rate with one nucleus in the detector = flux $\times$ cross section

$$R = \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}} \, v \, \sigma_{\mathrm{DM,N}}(v, E_R)$$

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Assume for the moment that all DM particles have the same velocity v

Interaction rate with one nucleus in the detector = flux × cross section

$$R = \frac{\rho_{\rm DM}}{m_{\rm DM}}\, v\, \sigma_{\rm DM,N}(v, E_R)$$

Differential event rate

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM}}\, v\, \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Assume for the moment that all DM particles have the same velocity v

Interaction rate with one nucleus in the detector = flux × cross section

$$R = \frac{\rho_{\rm DM}}{m_{\rm DM}}\, v\, \sigma_{\rm DM,N}(v, E_R)$$

Differential event rate

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM}}\, v\, \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM} m_N}\, v\, \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}} m_N} \int_{v_{\min}}^{\infty} d^3v \, v \, f(\vec{v}) \, \frac{d\sigma_{\mathrm{DM,N}}}{dE_R}(v, E_R)$$

(units: counts/kg/day/keV)

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

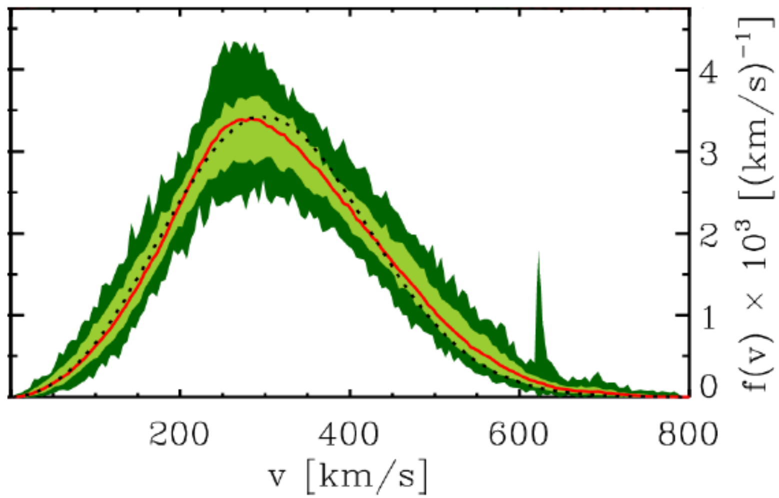
$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM} m_N} \int_{v_{\rm min}}^{\infty} d^3v \, v \, f(\vec{v}) \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

Local DM density

ASTROPHYSICS

dark matter
Velocity distribution
(Maxwellian?)

$$f(\vec{v}) \sim \exp(-|\vec{v}|^2/v_0^2)$$



Implications for Particle Physics

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Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM} m_N} \int_{v_{\rm min}}^{\infty} d^3v\, v\, f(\vec{v}) \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

Dark matter mass

PARTICLE PHYSICS

(and nuclear physics)

DM-nucleus cross section

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM} m_N} \int_{v_{\rm min}}^{\infty} d^3v\, v\, f(\vec{v})\, \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

Target nucleus mass

DETECTOR CHARACTERISTICS

Implications for Particle Physics

How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

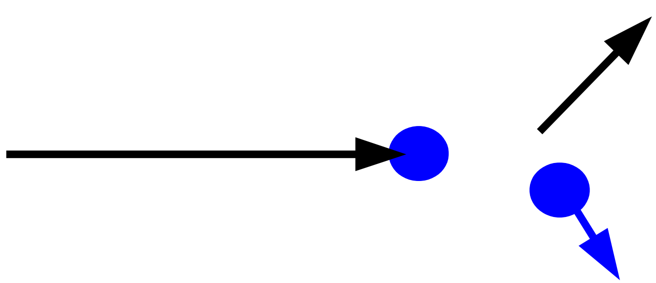
Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM} m_N} \int_{v_{\rm min}}^{\infty} d^3v \, v \, f(\vec{v}) \, \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

Minimum DM velocity to produce a recoil with energy E_R.

PARTICLE PHYSICS+DETECTOR



$$v_{\rm min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}}$$

$$\mu_N = m_{\rm DM} m_N / (m_{\rm DM} + m_N)$$

Implications for Particle Physics

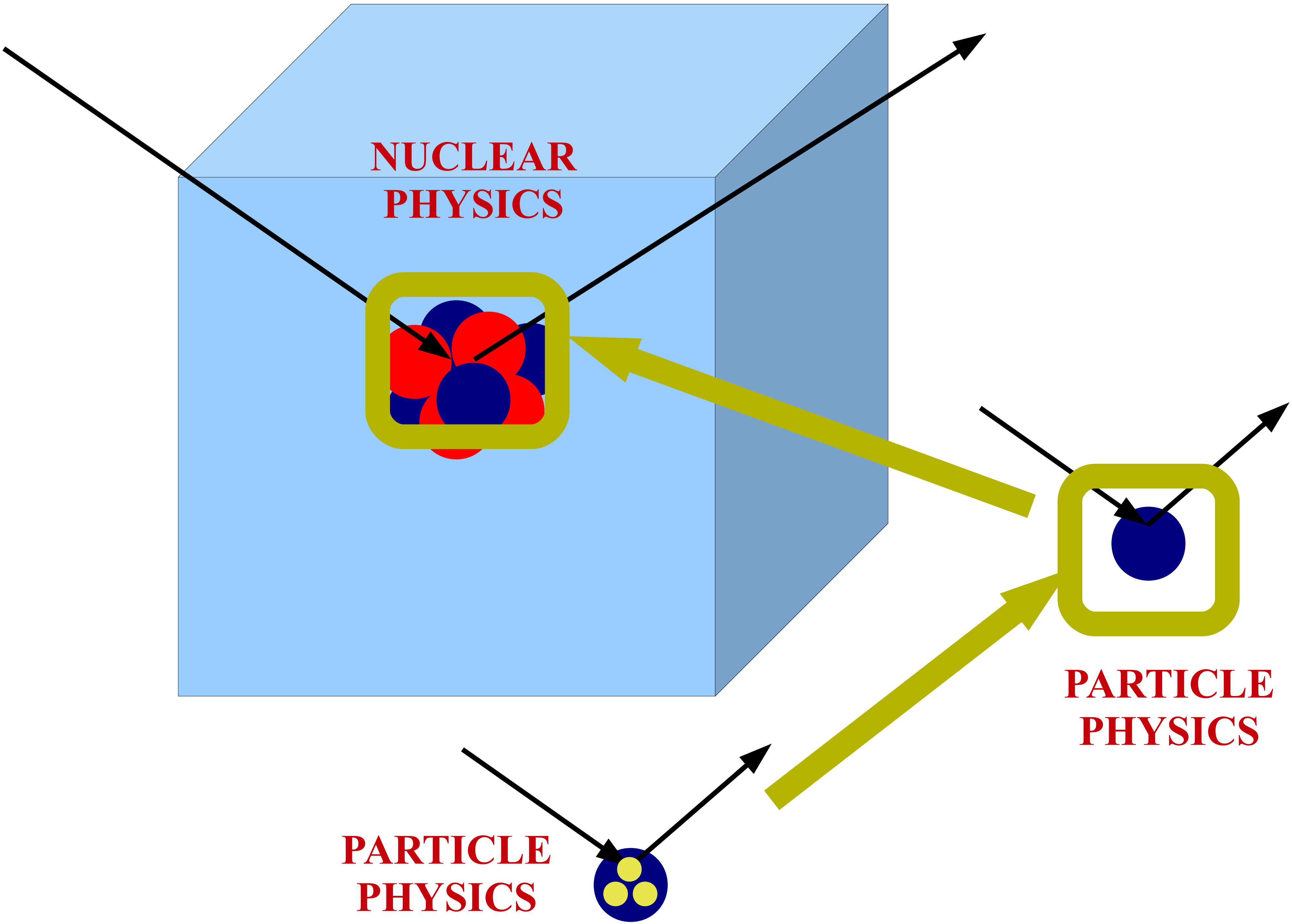
How to translate an upper limit on the scattering rate into an upper limit on the scattering cross section?

Dark matter particles in the Solar System have a velocity distribution $f(v)$

Event rate is calculated by integrating over all possible recoil energies

$$R = \int_{E_T}^{\infty} \frac{\rho_0}{m_{\rm DM} m_N} \int_{v_{\rm min}(E_R)}^{\infty} d^3v \, v \, f(\vec{v}) \, \frac{d\sigma_{\rm DM,N}}{dE_R}(v, E_R)$$

threshold energy of the detector.
Typically a few keV.


NUCLEAR PHYSICS
PARTICLE PHYSICS
PARTICLE PHYSICS

From partons to nuclei

From the fundamental point of view, the relevant quantity is the dark matter – parton cross section.

Consider a Majorana dark matter particle. The most general Lagrangian consistent with the gauge symmetry is:

$$\mathcal{L}_{\rm eff} = \bar{\tilde{\chi}}^0_1 \, \gamma^\mu \gamma_5 \, \tilde{\chi}^0_1 \, \bar{q}_i \, \gamma_\mu \left(\alpha_{1i} + \alpha_{2i}\gamma_5\right) q_i + \alpha_{3i} \, \bar{\tilde{\chi}}^0_1 \, \tilde{\chi}^0_1 \, \bar{q}_i \, q_i$$
$$+ \alpha_{4i} \, \bar{\tilde{\chi}}^0_1 \, \gamma_5 \, \tilde{\chi}^0_1 \, \bar{q}_i \, \gamma_5 \, q_i + \alpha_{5i} \, \bar{\tilde{\chi}}^0_1 \, \tilde{\chi}^0_1 \, \bar{q}_i \, \gamma_5 \, q_i + \alpha_{6i} \, \bar{\tilde{\chi}}^0_1 \, \gamma_5 \, \tilde{\chi}^0_1 \, \bar{q}_i \, q_i$$

Velocity dependent in the non-relativistic limit. Negligible.

From partons to nuclei

From the fundamental point of view, the relevant quantity is the dark matter – parton cross section.

Consider a Majorana dark matter particle. The most general Lagrangian consistent with the gauge symmetry is:

$$
\begin{aligned}
\mathcal{L}_{\rm eff} =& \bar{\tilde{\chi}}^0_1 \, \gamma^\mu \gamma_5 \, \tilde{\chi}^0_1 \, \bar{q}_i \, \gamma_\mu \, (\alpha_{1i} + \alpha_{2i}\gamma_5) \; q_i + \alpha_{3i} \, \bar{\tilde{\chi}}^0_1 \, \tilde{\chi}^0_1 \, \bar{q}_i \, q_i \\
&+ \alpha_{4i} \, \bar{\tilde{\chi}}^0_1 \, \gamma_5 \, \tilde{\chi}^0_1 \, \bar{q}_i \, \gamma_5 \, q_i + \alpha_{5i} \, \bar{\tilde{\chi}}^0_1 \, \tilde{\chi}^0_1 \, \bar{q}_i \, \gamma_5 \, q_i + \alpha_{6i} \, \bar{\tilde{\chi}}^0_1 \, \gamma_5 \, \tilde{\chi}^0_1 \, \bar{q}_i \, q_i
\end{aligned}
$$

CP violating

From partons to nuclei

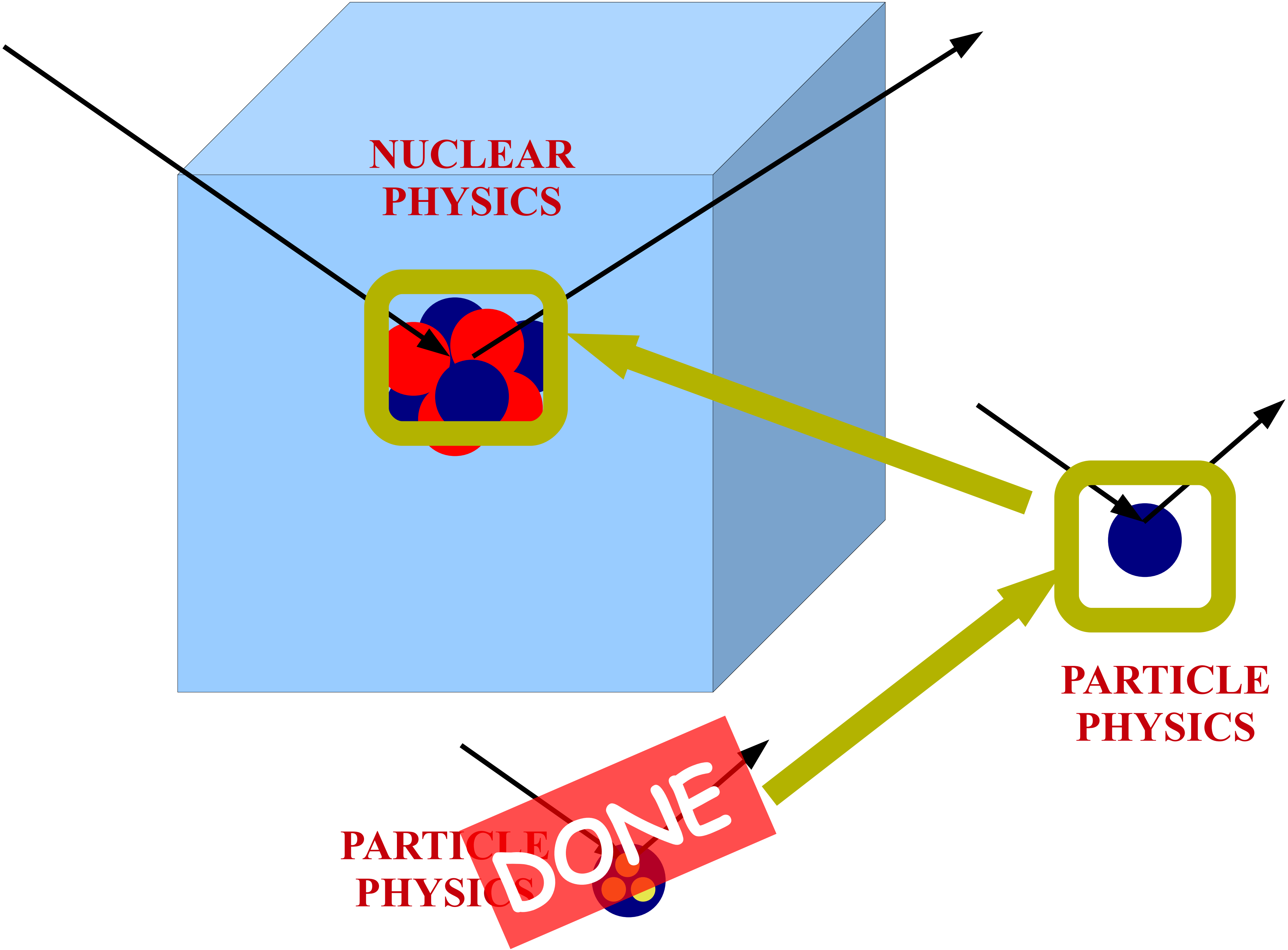
From the fundamental point of view, the relevant quantity is the dark matter – parton cross section.

Consider a Majorana dark matter particle. The most general Lagrangian consistent with the gauge symmetry is:

$$\mathcal{L}_{\rm eff} = \bar{\tilde{\chi}}_1^0 \, \gamma^\mu \gamma_5 \, \tilde{\chi}_1^0 \, \bar{q}_i \, \gamma_\mu \, (\alpha_{1i} + \alpha_{2i}\gamma_5) \, q_i + \alpha_{3i} \, \bar{\tilde{\chi}}_1^0 \, \tilde{\chi}_1^0 \, \bar{q}_i \, q_i$$
$$+ \alpha_{4i} \, \bar{\tilde{\chi}}_1^0 \, \gamma_5 \, \tilde{\chi}_1^0 \, \bar{q}_i \, \gamma_5 \, q_i + \alpha_{5i} \, \bar{\tilde{\chi}}_1^0 \, \tilde{\chi}_1^0 \, \bar{q}_i \, \gamma_5 \, q_i + \alpha_{6i} \, \bar{\tilde{\chi}}_1^0 \, \gamma_5 \, \tilde{\chi}_1^0 \, \bar{q}_i \, q_i$$

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$ Axial-vector coupling

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$$ Scalar coupling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From partons to nuclei

Spin independent term $\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$

The matching from the parton level to the hadronic level is described by means of form factors:

$$\langle p|m_q \bar{q}q|p\rangle \equiv m_p f_{Tq}^p$$

Experimentally, for the proton

$$f_{Tu}^p = 0.020 \pm 0.004, \quad f_{Td}^p = 0.026 \pm 0.005, \quad f_{Ts}^p = 0.118 \pm 0.062$$

(and for the neutron $f_{Tu}^n = f_{Td}^p$, $f_{Td}^n = f_{Tu}^p$, and $f_{Ts}^n = f_{Ts}^p$)

From partons to nuclei

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$$

The spin independent cross section between the WIMP and all the individual protons and neutrons is:

$$\sigma_{SI} = \frac{4\mu_N^2}{\pi}[Zf^p + (A-Z)f^n]^2$$

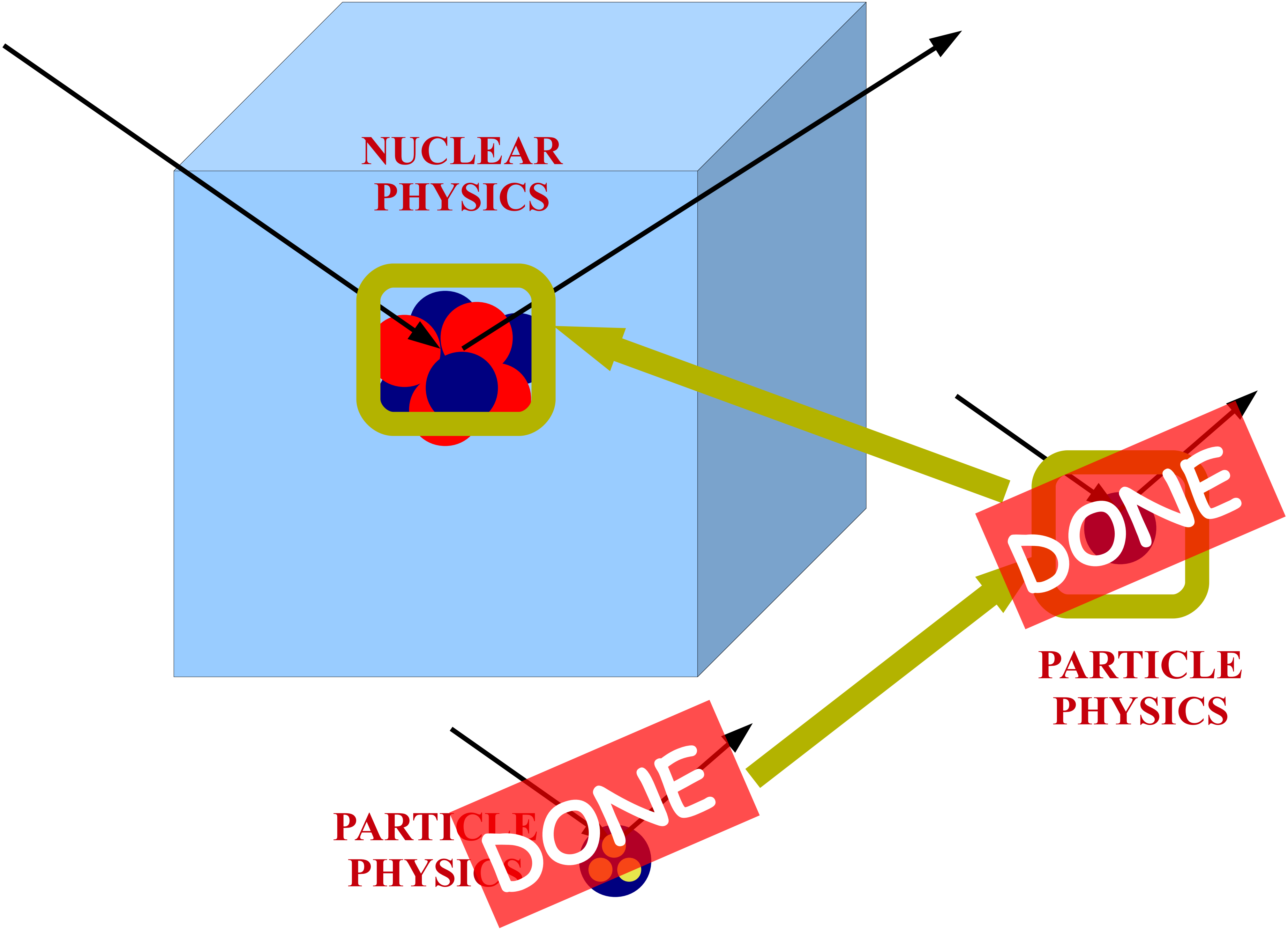
$$\frac{f^p}{m_p} = \sum_{q=u,d,s} \frac{\alpha_q^S}{m_q} f_{Tq}^p + \frac{2}{27} f_{TG}^p \sum_{q=c,b,t} \frac{\alpha_q^S}{m_q}$$

Coupling to quarks

Coupling to gluons

$$m_p f_{Tq}^p \equiv \langle p | m_q \bar{q} q | p \rangle$$

$$f_{TG}^p = 1 - \sum_{q=u,d,s} f_{Tq}^p$$



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From partons to nuclei

Lastly, the total differential cross section between the WIMP and the nucleus should take into account the internal structure of the nucleus → Nuclear form factor

$$\left(\frac{d\sigma_{DM,N}}{dE_R}\right) = \frac{m_N \sigma_{SI} F^2(E_R)}{2\mu_N^2 v^2}$$

The nuclear form factor is usually parametrized as:

$$F^2(q) = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 \exp\left[-q^2 s^2\right]$$

$$R_1 = \sqrt{R^2 - 5s^2} \quad R \simeq 1.2\, A^{1/2}\ \text{fm}.$$

$$s \simeq 1\ \text{fm}$$

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$$

$$\sigma_{SI} = \frac{4\mu_N^2}{\pi}\left[Z f^p(\alpha_q^S) + (A - Z) f^n(\alpha_q^S)\right]^2$$

$$\left(\frac{d\sigma_{DM,N}}{dE_R}\right) = \frac{m_N \sigma_{SI} F^2(E_R)}{2\mu_N^2 v^2}$$

$$R = \int_{E_T}^{\infty} dE_R \, \frac{\rho_0}{m_N m_{\rm DM}} \int_{v_{min}}^{\infty} dv \, v f(v) \frac{d\sigma_{DM,N}}{dE_R}$$

From partons to nuclei

Spin dependent term

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

The matching from the parton level to the hadronic level is described by means of form factors:

$$\langle n|\bar{q}\gamma_\mu\gamma_5 q|n\rangle = 2s_\mu^{(n)}\Delta_q^{(n)}$$

Spin of the nucleon

From experiments

$$\Delta_u^{(p)} = 0.84 \pm 0.03 \qquad \Delta_d^{(p)} = -0.43 \pm 0.03 \qquad \Delta_s^{(p)} = -0.09 \pm 0.03$$

$$\Delta_u^{(n)} = \Delta_d^{(p)} \qquad \Delta_d^{(n)} = \Delta_u^{(p)} \qquad \Delta_s^{(n)} = \Delta_s^{(p)}$$

From partons to nuclei

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

The spin dependent cross section between the WIMP and all the individual protons and neutrons is:

$$\sigma_{\rm SD} = \frac{32}{\pi} G_F^2 \mu_N^2 \Lambda^2 J(J+1)$$

$$\Lambda \equiv \frac{1}{J}\left(a_{\rm p}\langle S_{\rm p}\rangle + a_{\rm n}\langle S_{\rm n}\rangle\right)$$

$$a_{\rm p} = \sum_q \frac{\alpha_{2q}}{\sqrt{2}G_f}\Delta_q^{(\rm p)},$$

$$a_{\rm n} = \sum_i \frac{\alpha_{2q}}{\sqrt{2}G_f}\Delta_q^{(\rm n)}$$

DM model dependent

Expectation values of the spins of the proton and the neutron in the nucleus → NUCLEAR PHYSICS

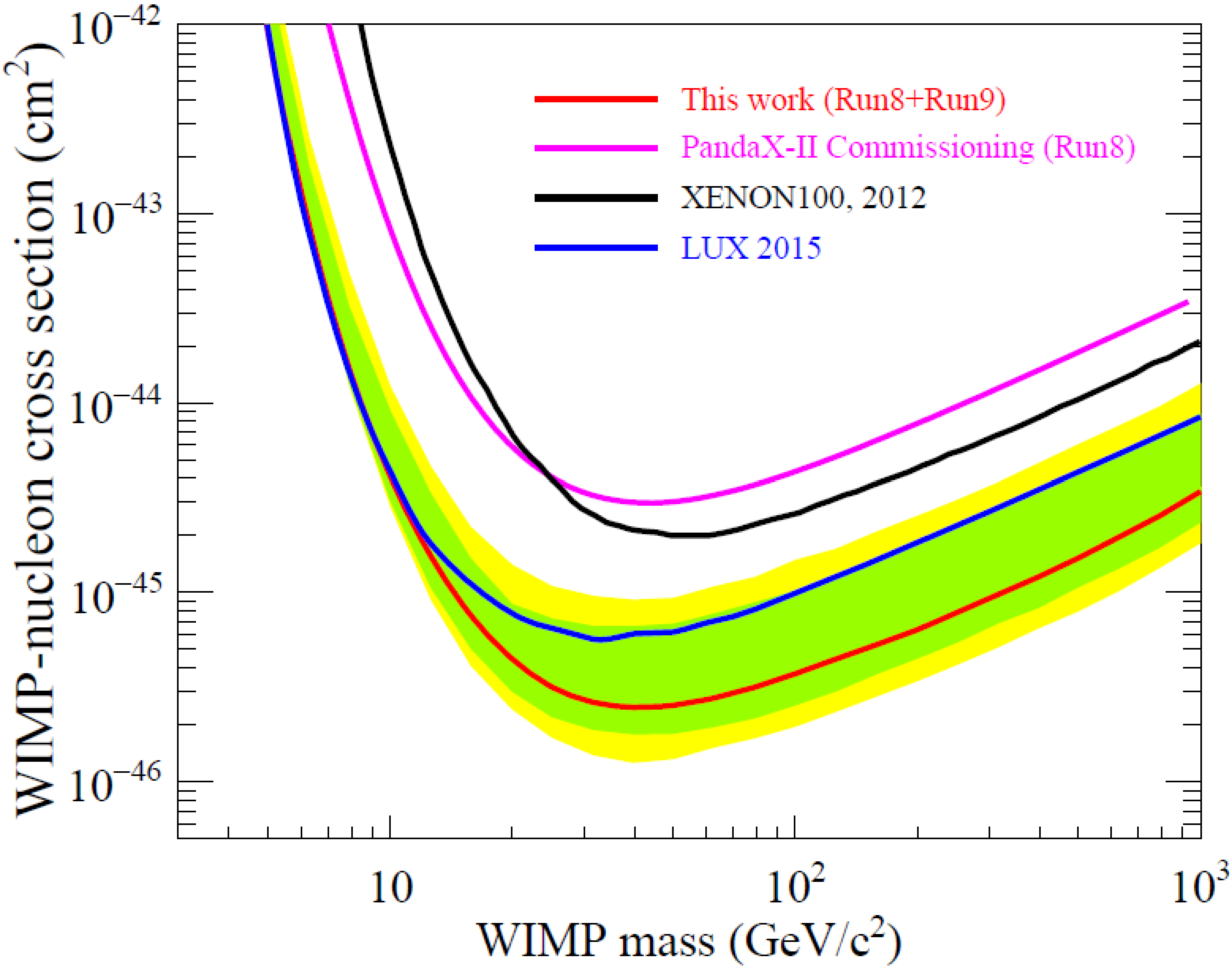
$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

$$\sigma_{\rm SD} = \frac{32}{\pi} G_F^2 \mu_N^2 \Lambda^2 J(J+1)$$

$$\left(\frac{d\sigma_{DM,N}}{dE_R}\right) = \frac{16 m_N}{\pi v^2} \Lambda^2 G_F^2 J(J+1) \frac{S(E_R)}{S(0)}$$

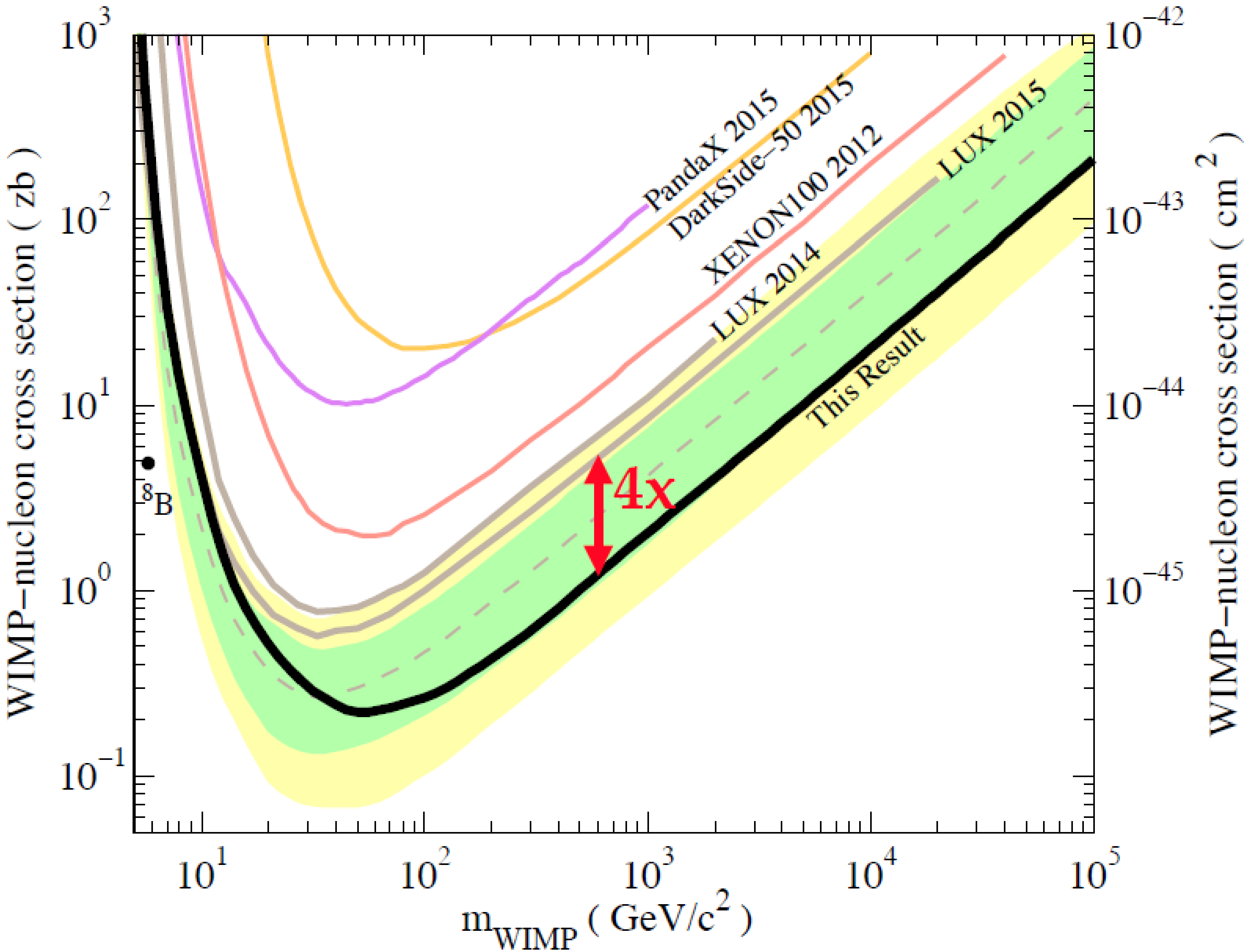
$$R = \int_{E_T}^{\infty} dE_R \, \frac{\rho_0}{m_N m_{\rm DM}} \int_{v_{min}}^{\infty} dv \, v f(v) \frac{d\sigma_{DM,N}}{dE_R}$$

Experimental results. SI interaction



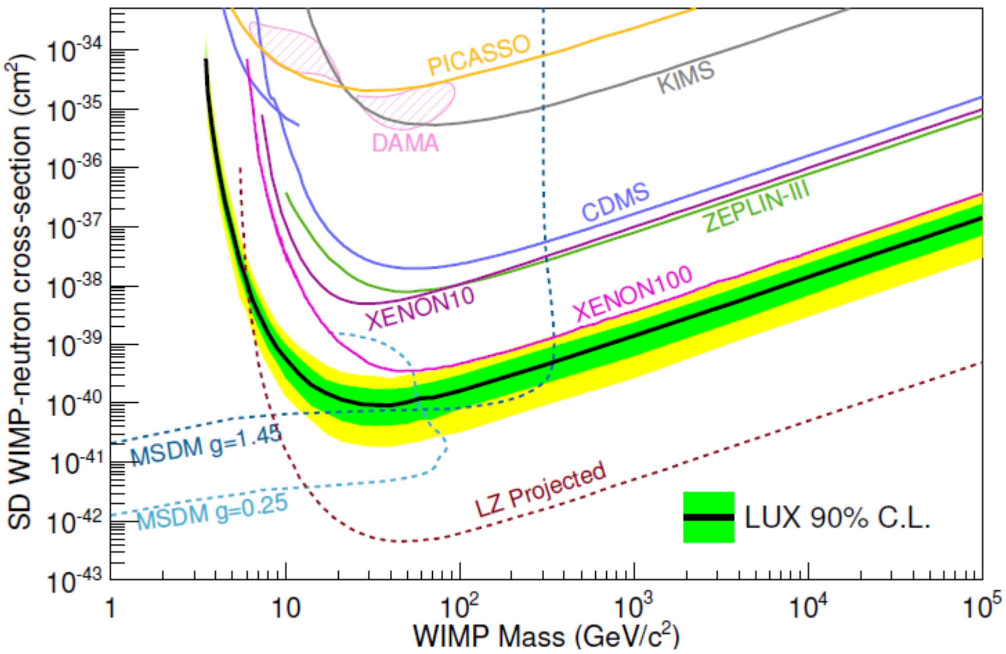
PandaX coll. ArXiv:1607.07400 (accepted in PRL on 16 Aug 2016)

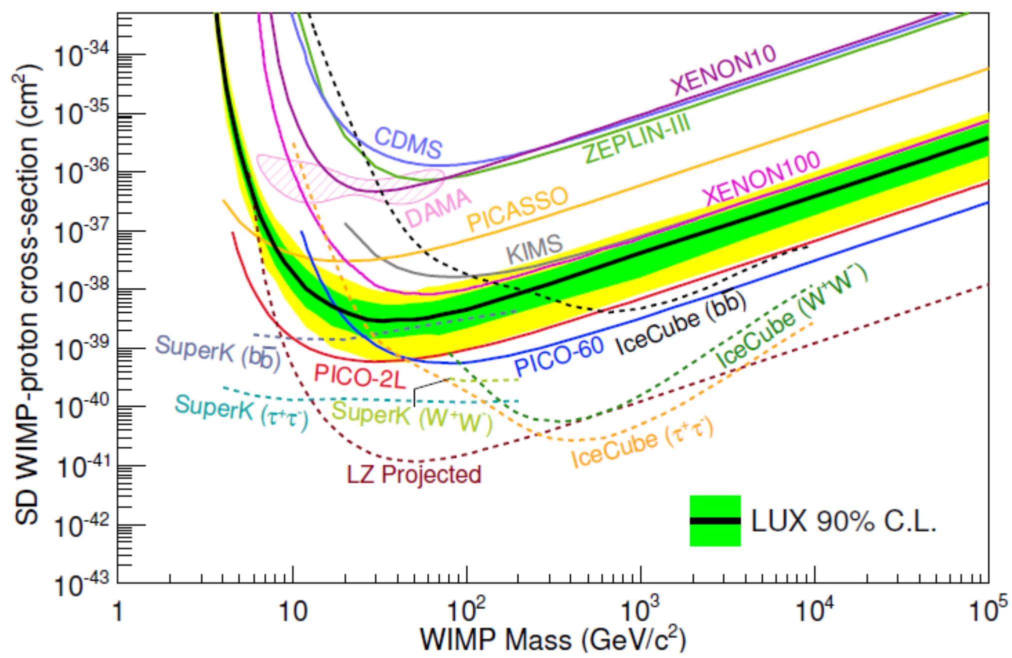
Experimental results. SI interaction



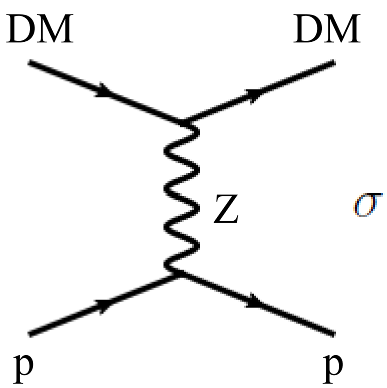
LUX coll. Presented at the IDM conference on 21 July 2016

Experimental results. SD interaction



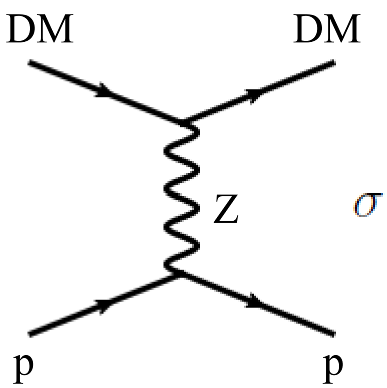


Bright future in direct dark matter searches



$$\sigma \sim 10^{-40}\,\mathrm{cm}^2$$

Bright future in direct dark matter searches



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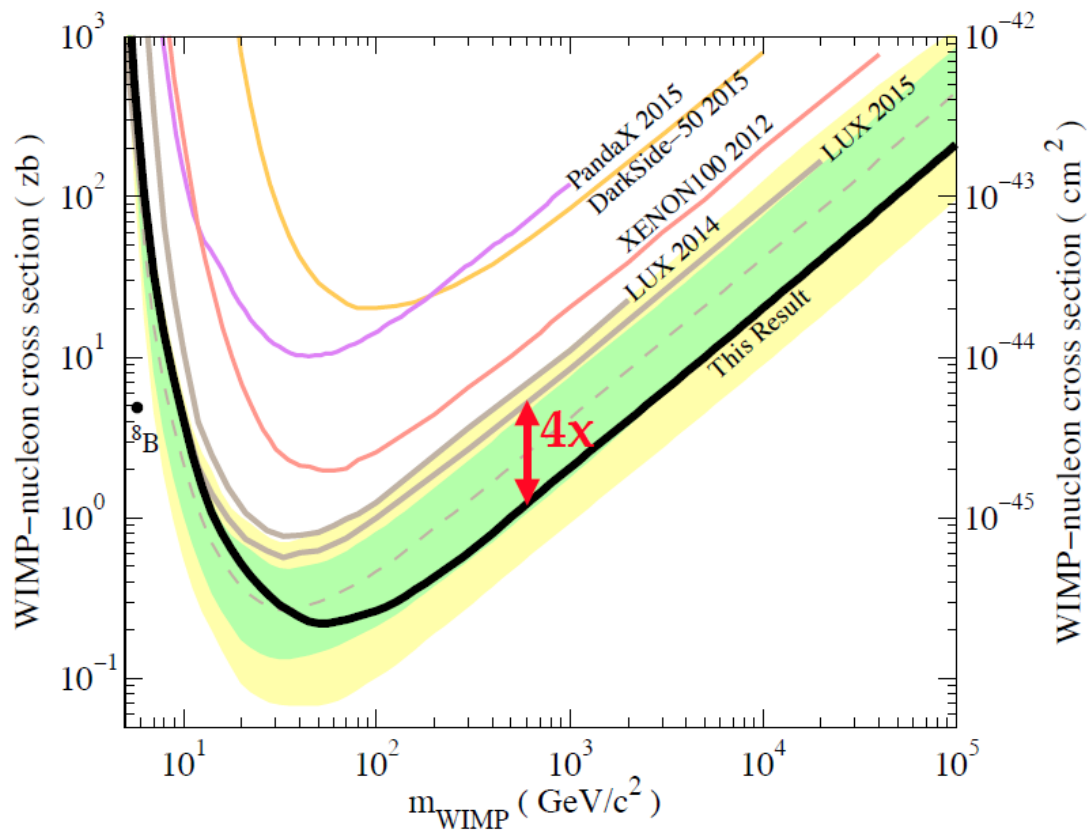
Tree-level Z-exchange



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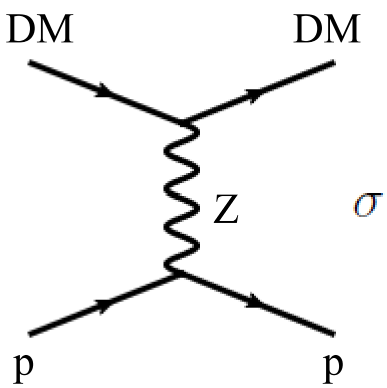

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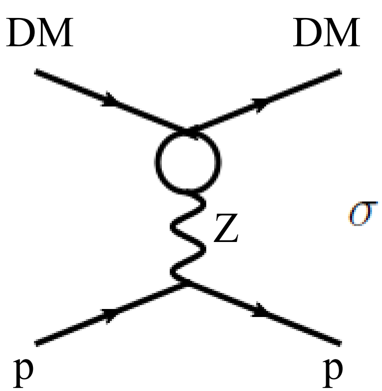
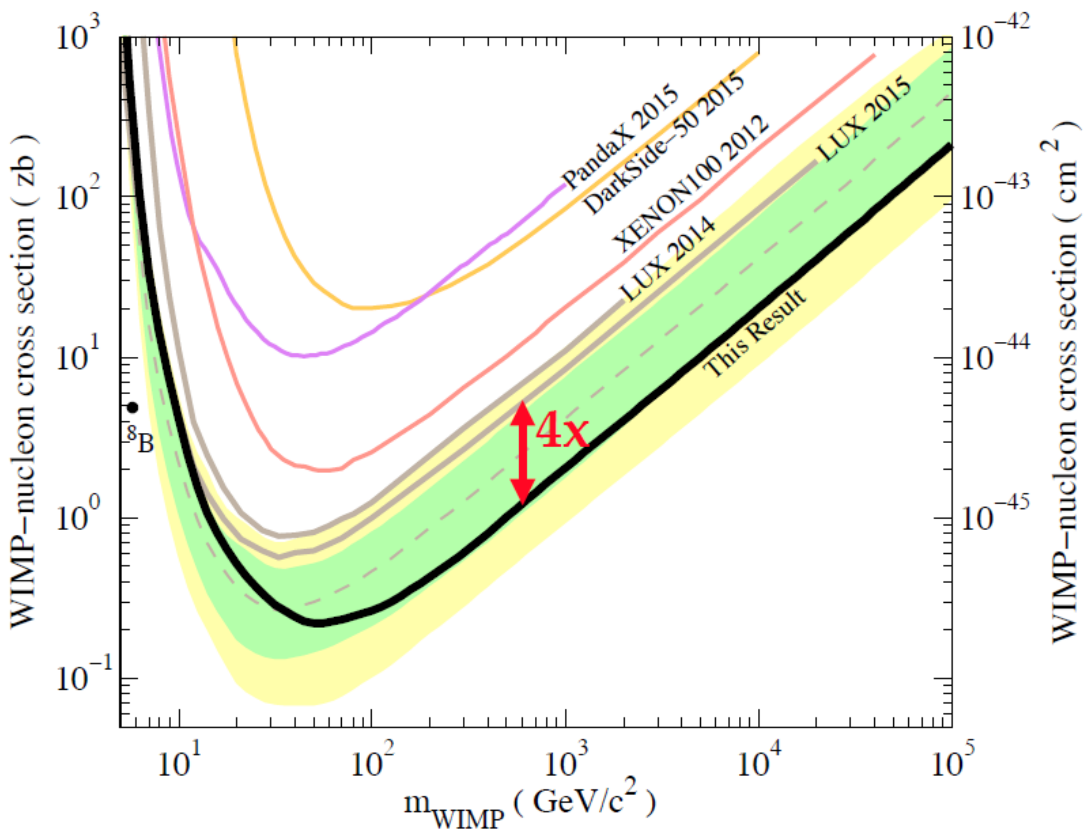


$\sigma \sim 10^{-45}\,\mathrm{cm}^2$



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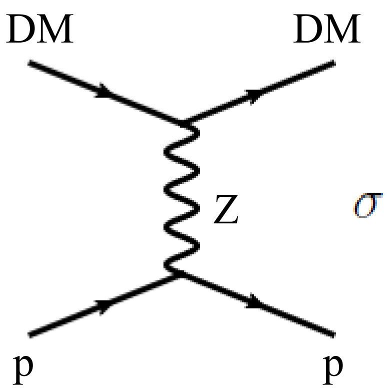

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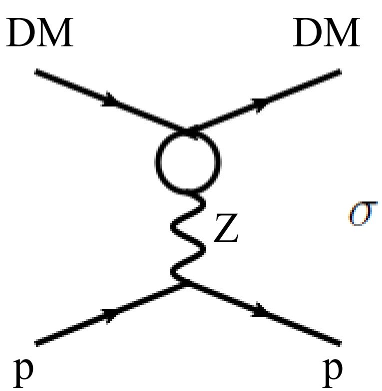

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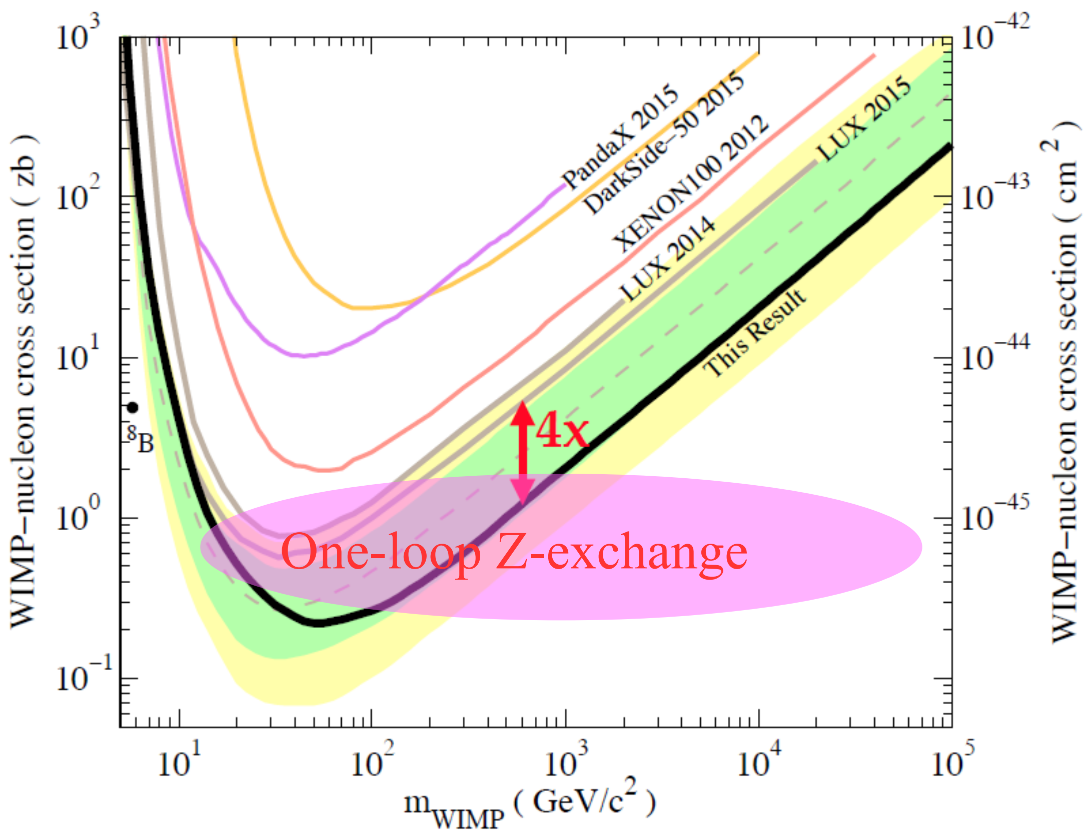
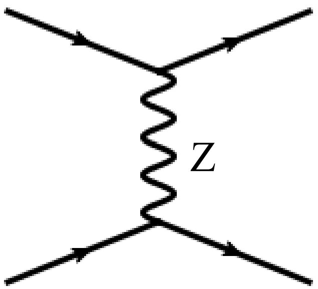


Bright future in direct dark matter searches



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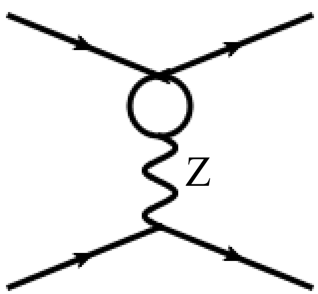

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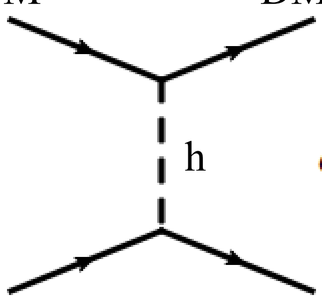
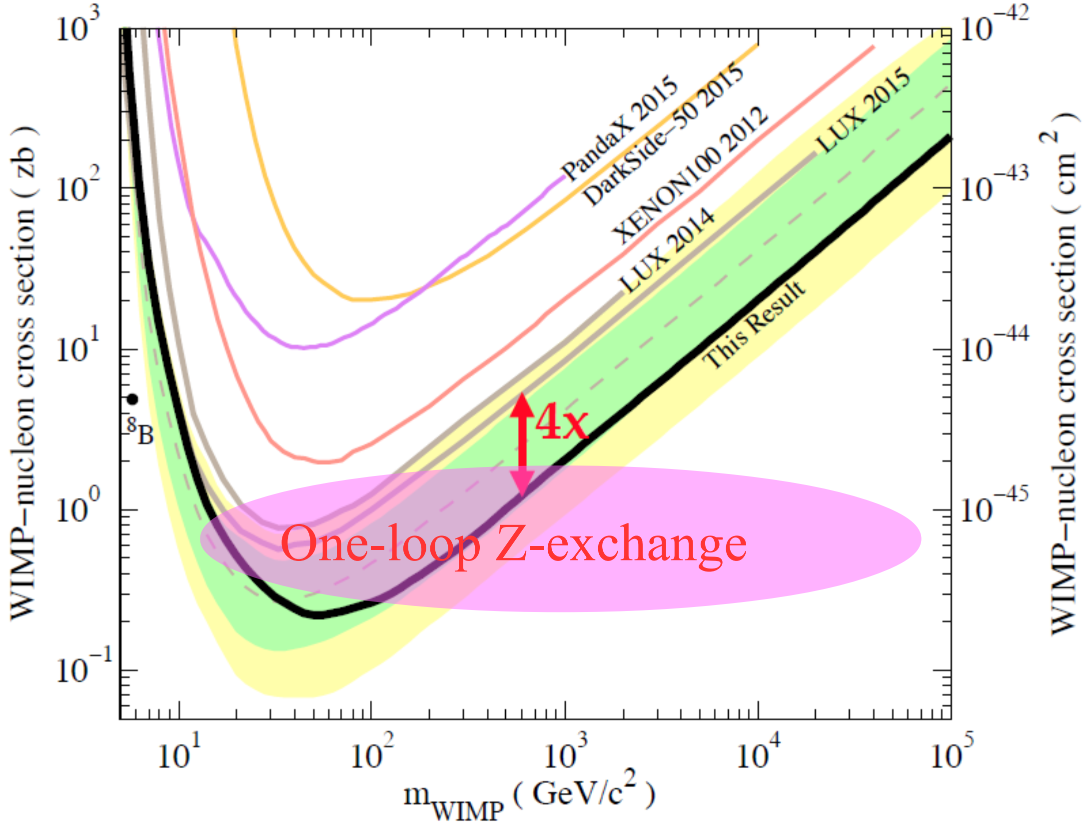
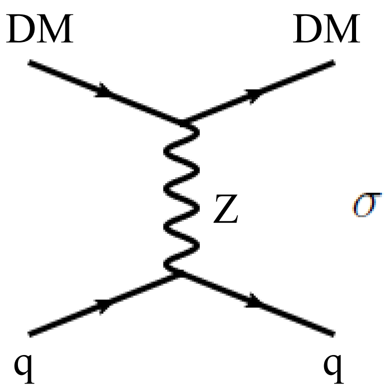


$\sigma \lesssim 10^{-45}\,\text{cm}^2$

Tree-level Z-exchange



Bright future in direct dark matter searches



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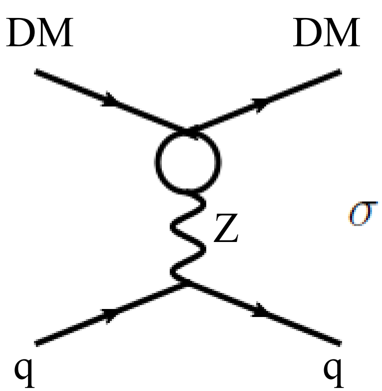

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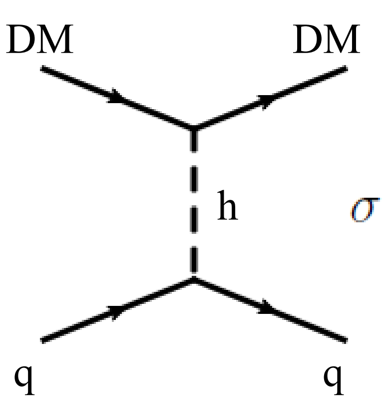

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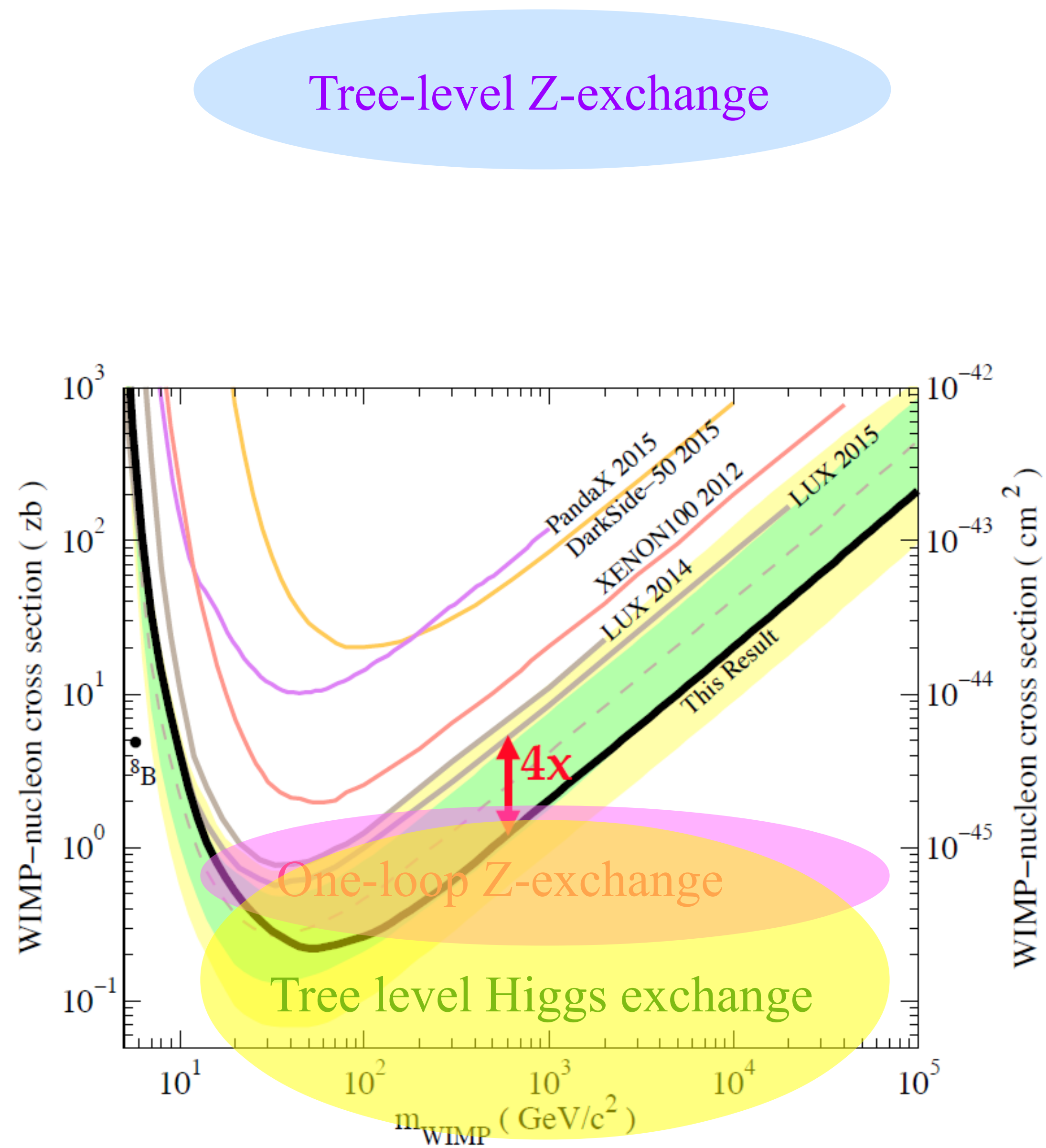

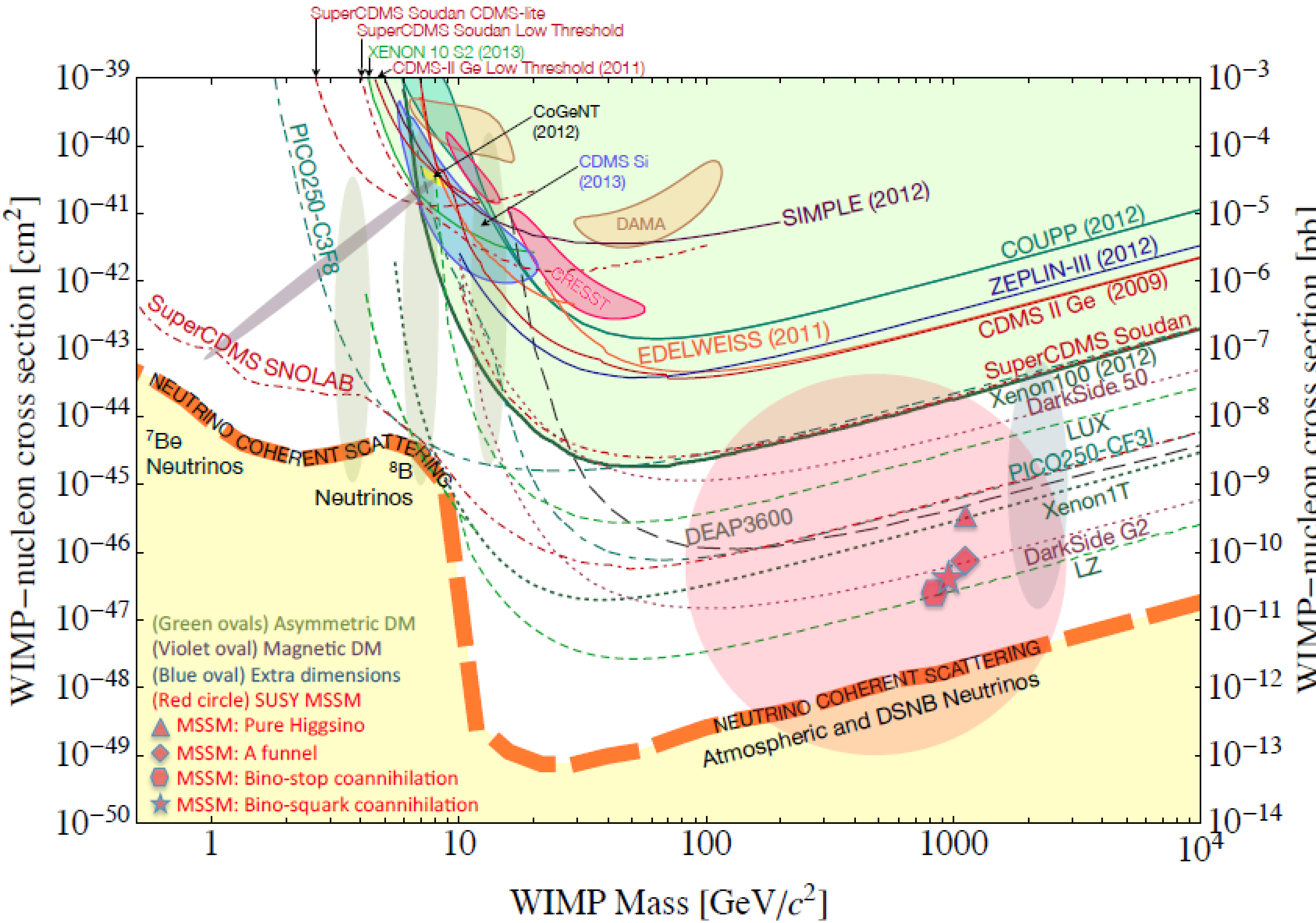

SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]

Concluding remarks

1- Zwicky's observations of 1933

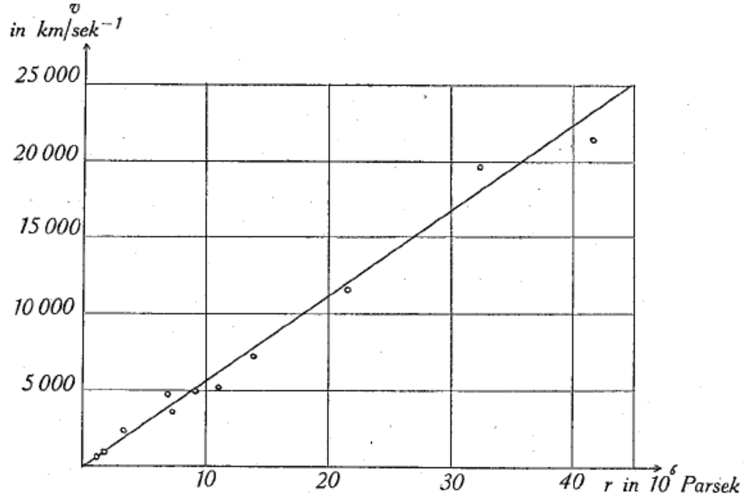

Fig. 2.

Concluding remarks

1- Zwicky's observations of 1933

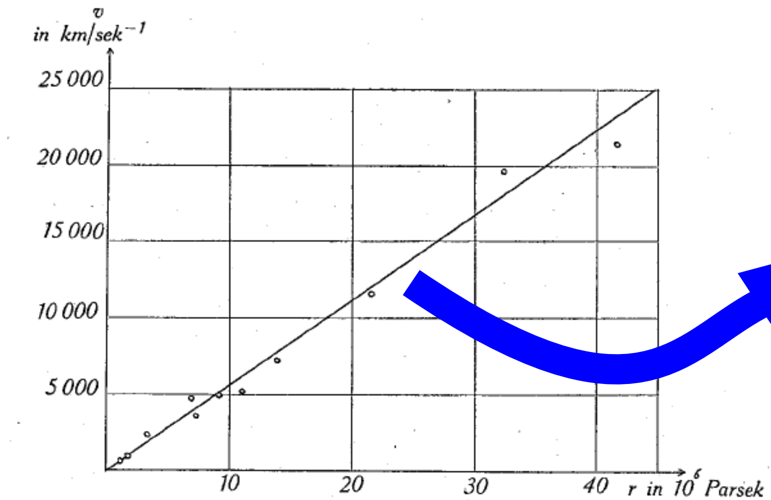

Fig. 2.

80 years later, we still don't know what is producing this.

Concluding remarks

1- Zwicky's observations of 1933

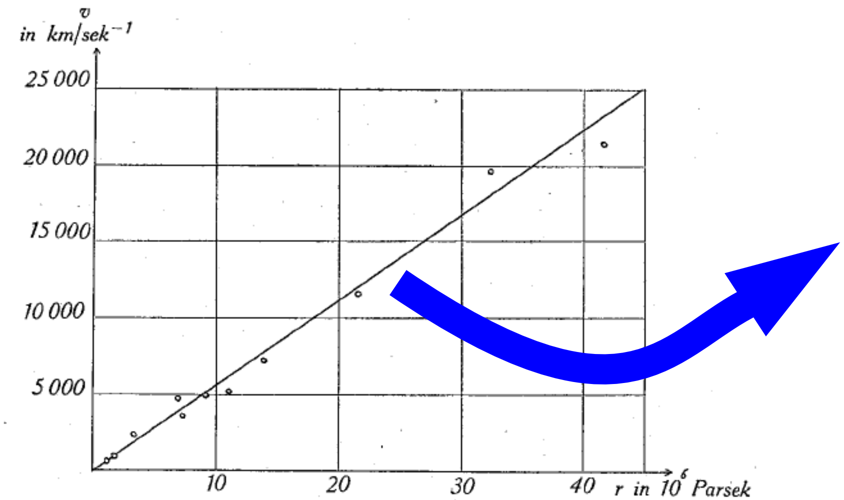

Fig. 2.

80 years later, we still don't know what is producing this.

2- If the dark matter is constituted by WIMPs, there are good chances to observe new signals in this decade. Exciting times ahead!

Concluding remarks

1- Zwicky's observations of 1933

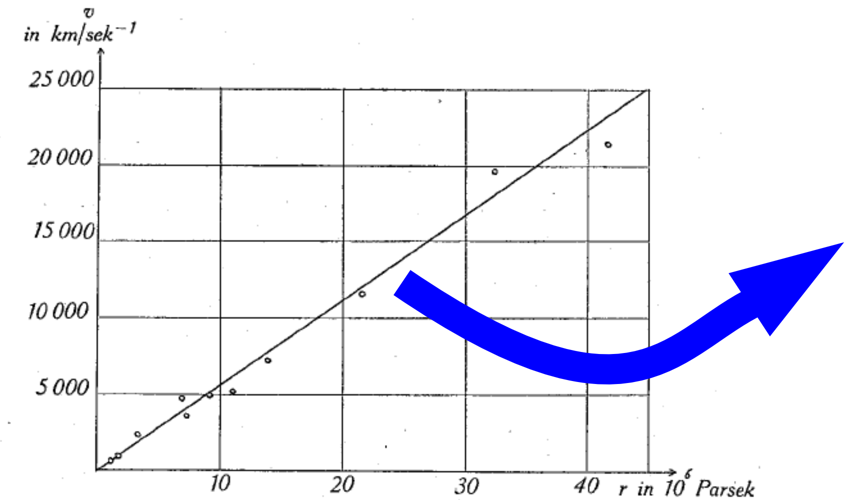

Fig. 2.

80 years later, we still don't know what is producing this.

2- If the dark matter is constituted by WIMPs, there are good chances to observe new signals in this decade. Exciting times ahead!

3- BUT, the dark matter particle could not be a WIMP. Or perhaps the astronomical observations of galaxies, clusters of galaxies, etc. are explained by something completely different (not yet proposed). Keep an open mind.

Thank you for your attention!