# Dark Matter

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Summer School
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ICTP, Trieste
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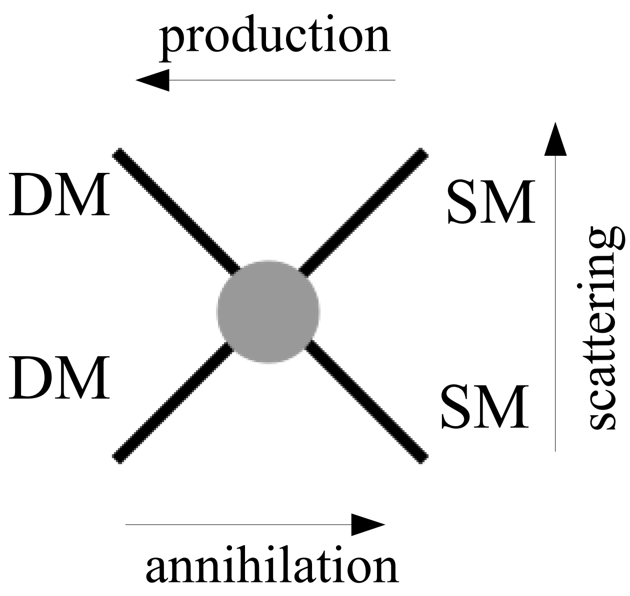
# Main results from the previous lecture

## WIMP dark matter



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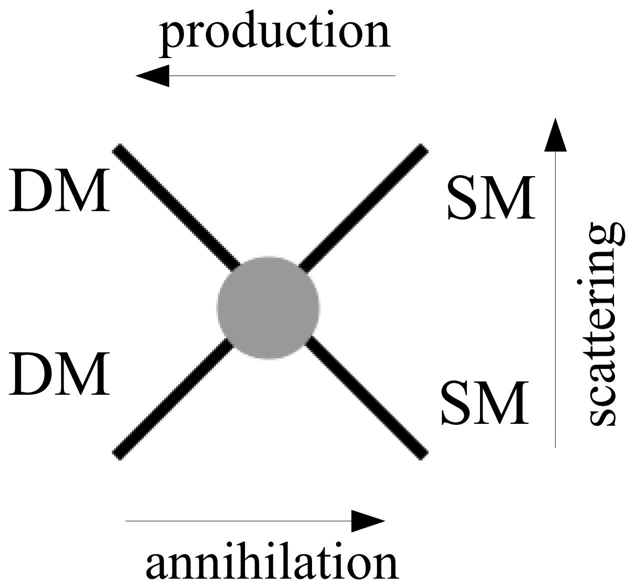


Relic abundance of DM particles

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

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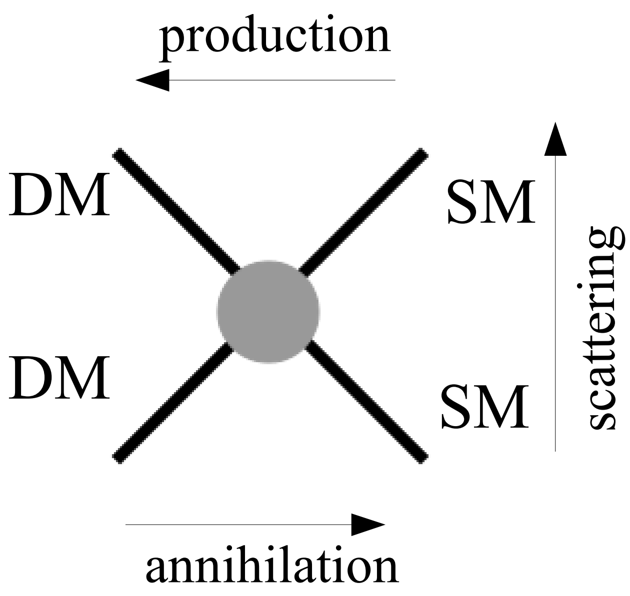


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Correct relic density if

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

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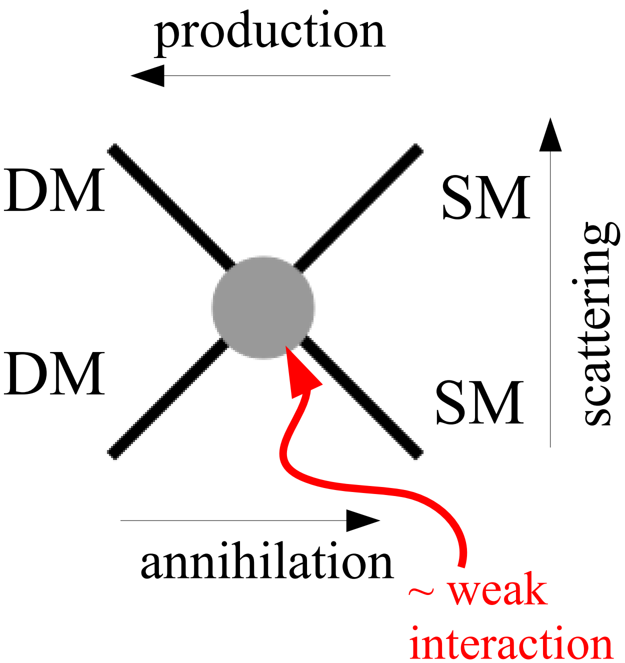


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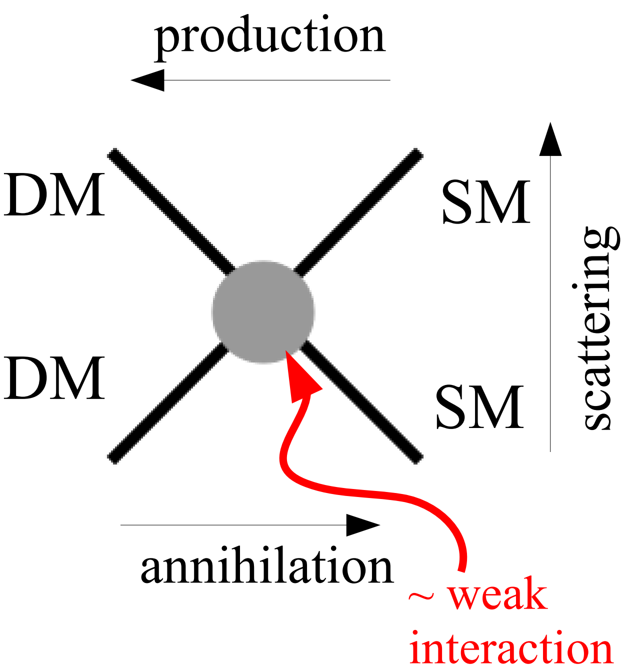


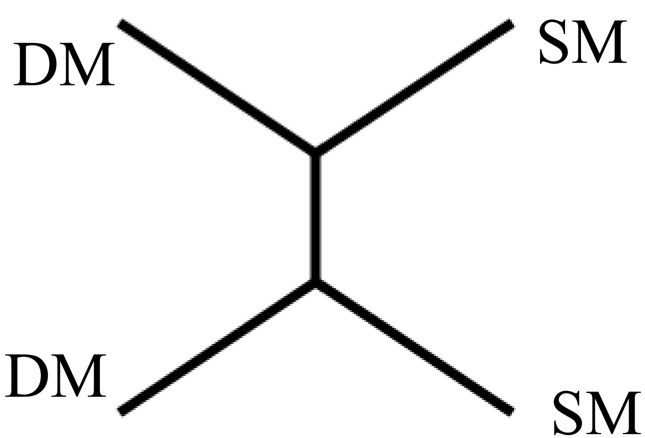


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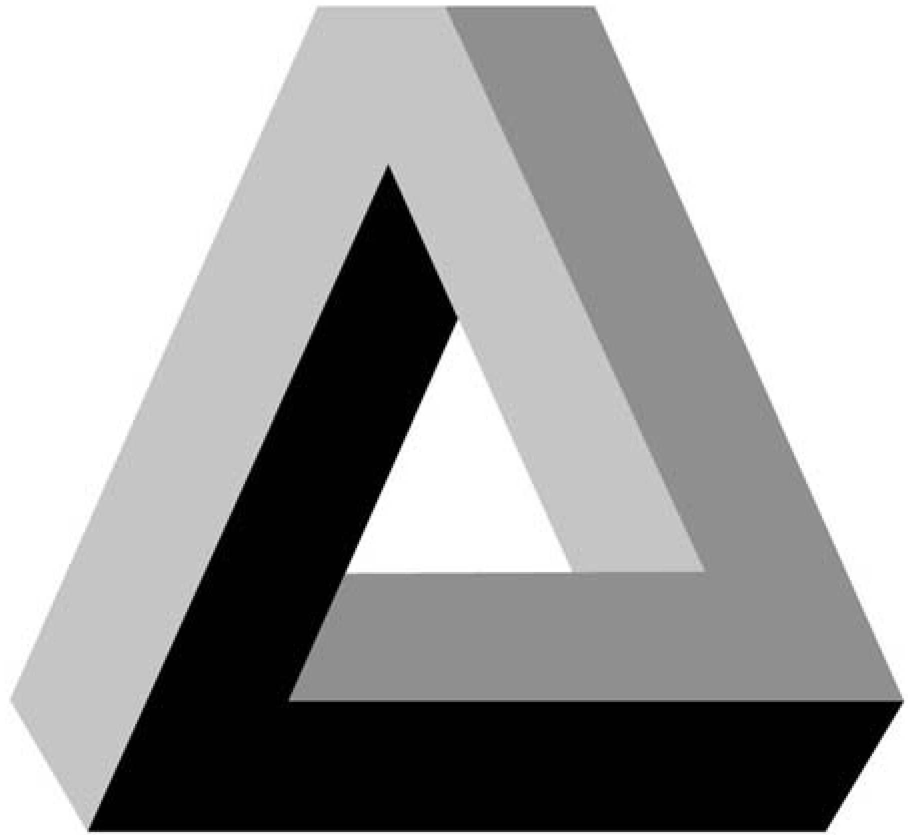
$$\sigma \sim \frac{g^4}{m_{\mathrm{DM}}^2} = 1\,\mathrm{pb}$$

$$m_{\mathrm{DM}} \sim 10\,\mathrm{GeV} - 1\,\mathrm{TeV}$$

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

**Direct detection**

DM nucleus $\rightarrow$ DM nucleus



**Indirect detection**

DM DM $\rightarrow \gamma$ X, $e^+e^-$... (annihilation)

DM $\rightarrow \gamma$ X, $e^+$X... (decay)

**Collider searches**

pp $\rightarrow$ DM X

## Direct detection

DM nucleus $\rightarrow$ DM nucleus

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DM nucleus → DM nucleus

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DM DM → γ X, $e^+e^-$... (annihilation)

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pp → DM X

## Direct detection

DM nucleus $\rightarrow$ DM nucleus

## Indirect detection

DM DM $\rightarrow \gamma$ X, $e^+e^-$... (annihilation)

DM $\rightarrow \gamma$ X, $e^+$X... (decay)

## Collider searches

pp $\rightarrow$ DM X

# 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.

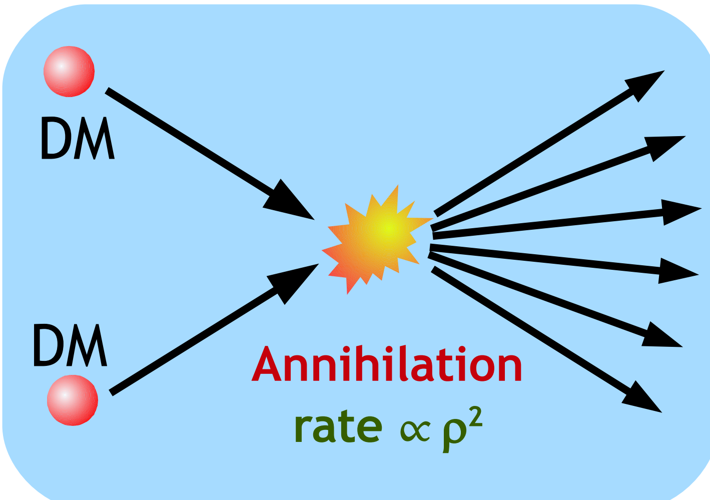
# Indirect dark matter searches

| | | | |
|---|---|---|---|
| Production | | | Antimatter |
| Propagation | } | of { | Gamma-rays |
| Detection | | | Neutrinos |

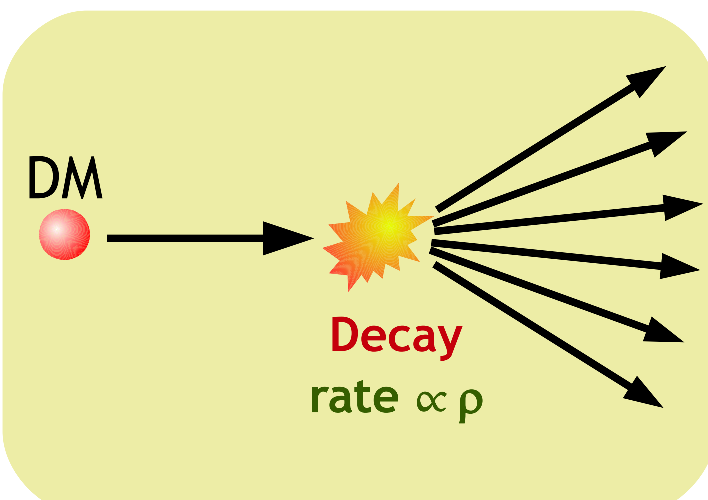
# Antimatter

# Production

The production is described by the source function: number of particles produced at a given position per unit volume, unit time and unit energy.

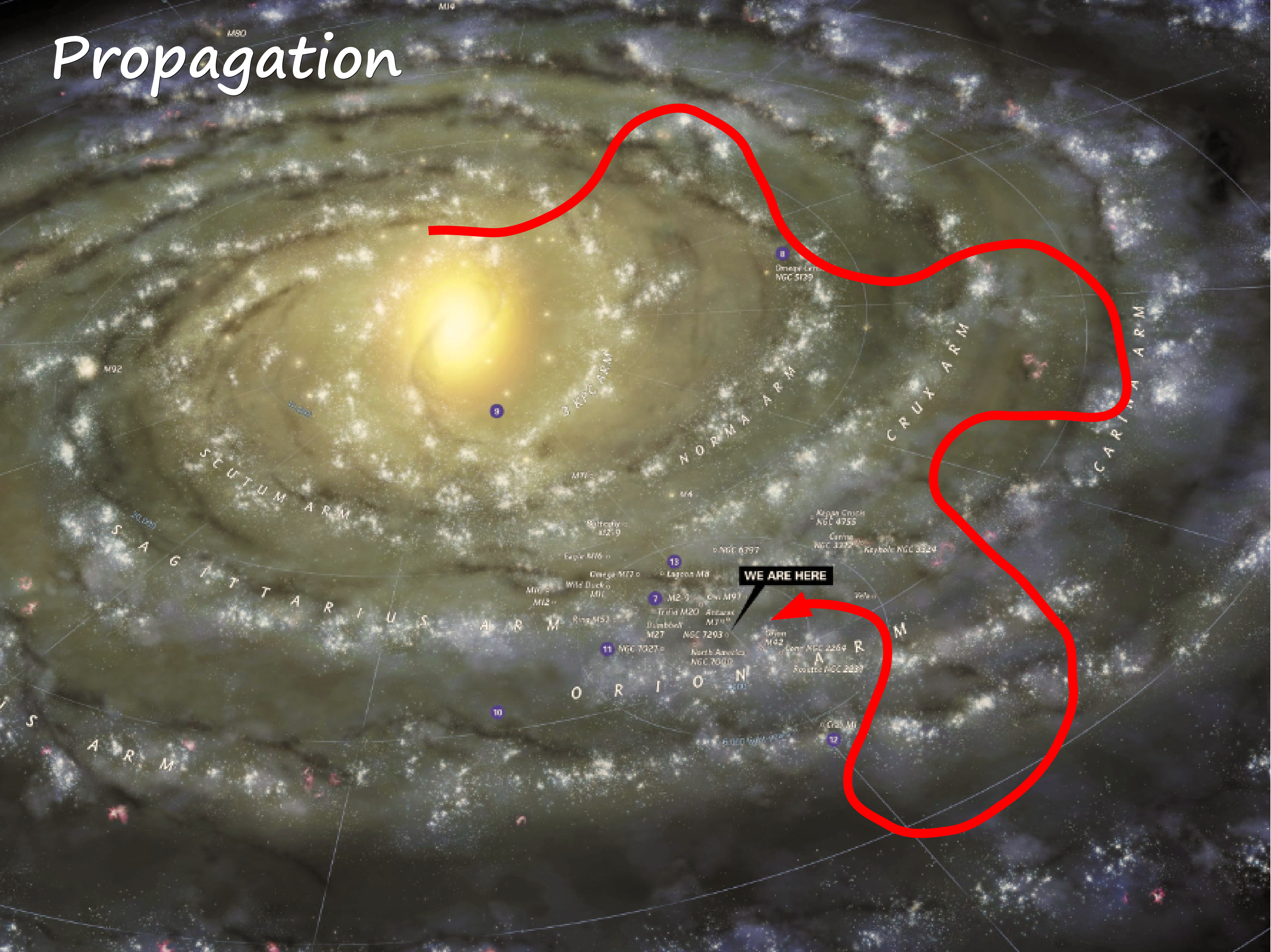



$$Q(E,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_{\rm DM}^2}\langle\sigma v\rangle\frac{dN}{dE}$$

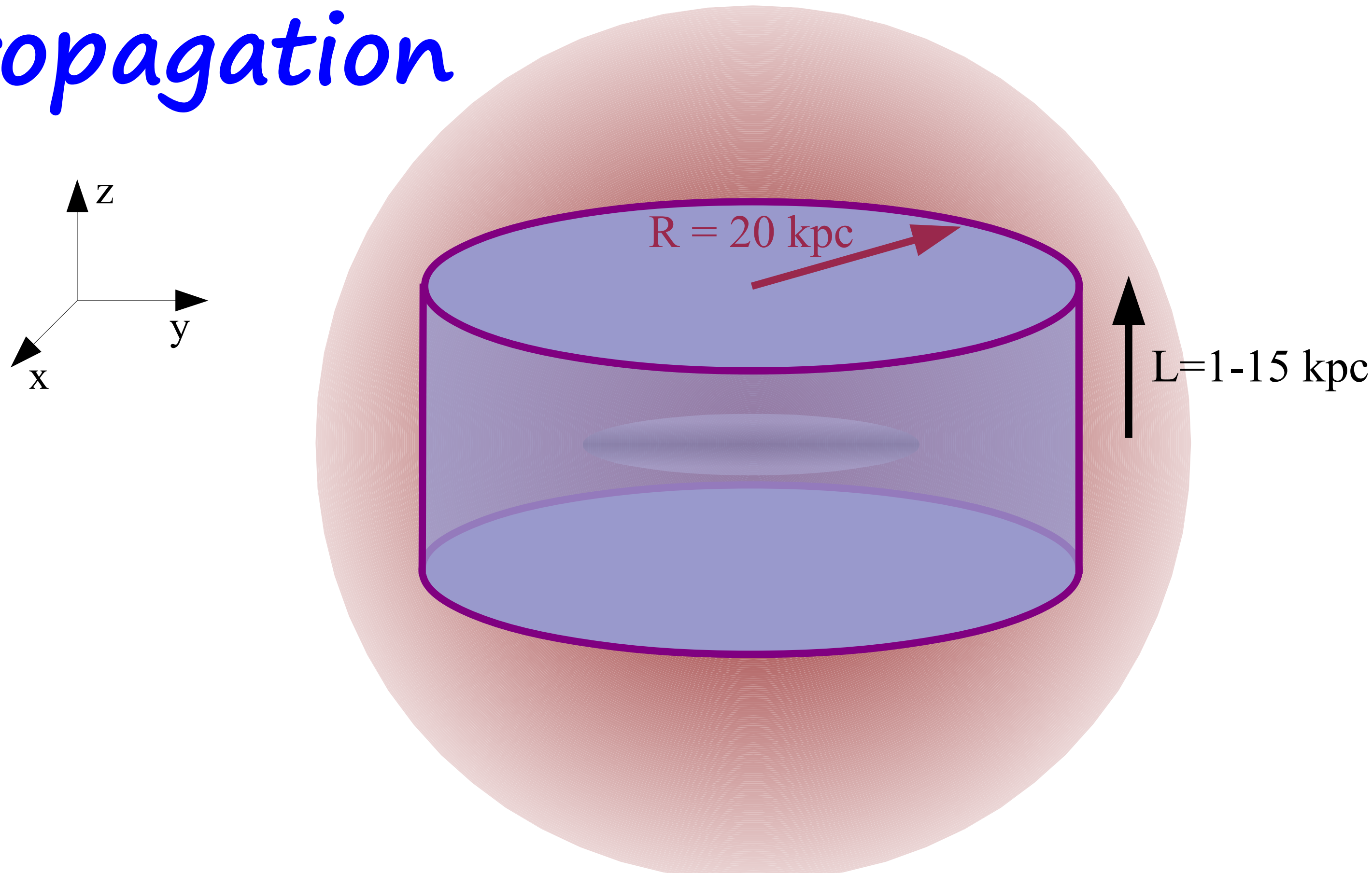



$$Q(E,\vec{r}) = \frac{\rho(\vec{r})}{m_{\rm DM}}\frac{1}{\tau_{\rm DM}}\frac{dN}{dE}$$

# Propagation



# Propagation



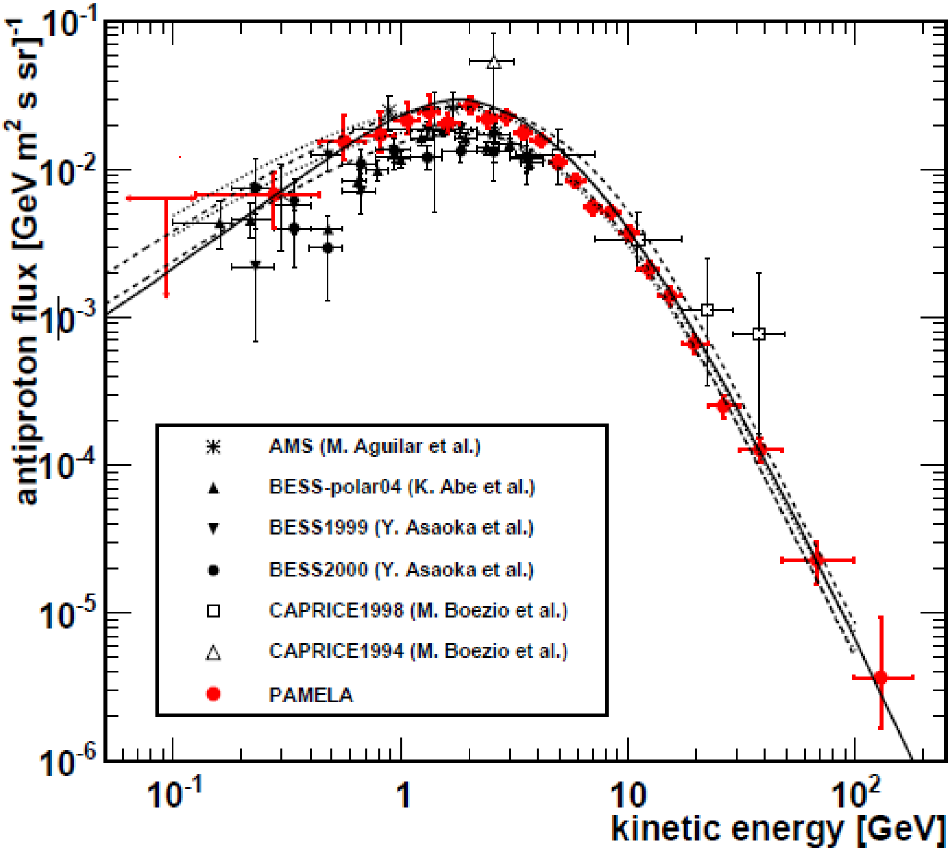

$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r}) \ .$$

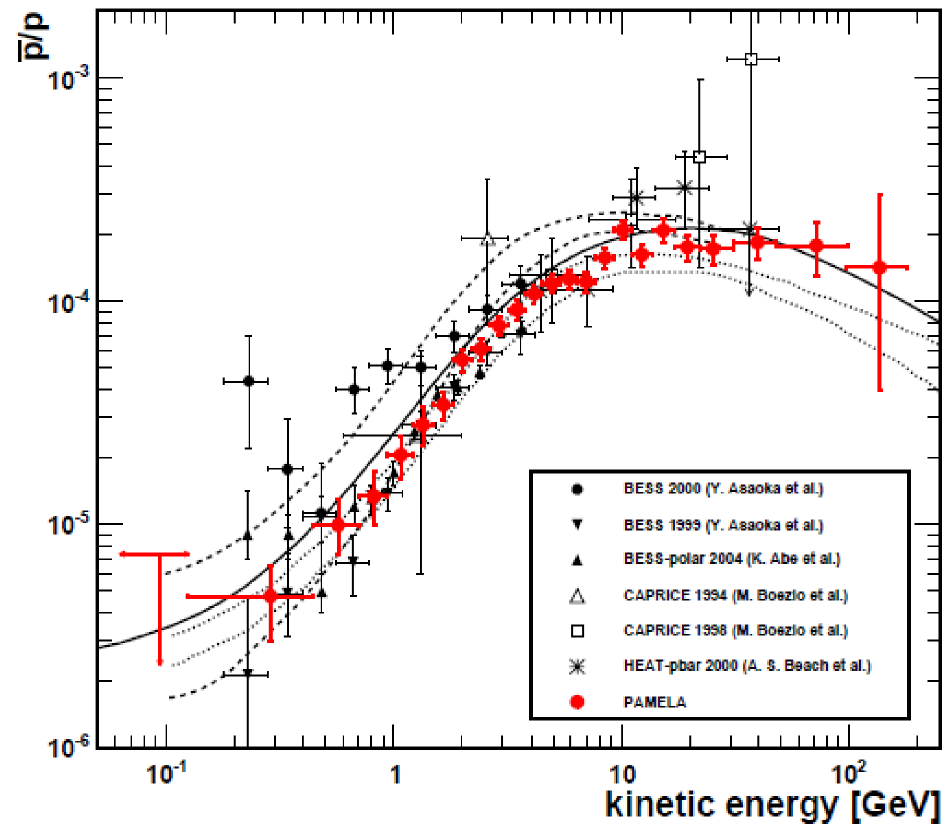
$f$ : number density of antiparticles per unit kinetic energy

**interstellar antimatter flux:**

$$\Phi^{\rm IS}(T) = \frac{dN}{dt\, dS\, dT\, d\Omega} = \frac{v}{4\pi} f(T)$$

# Experimental results: antiprotons




PAMELA collaboration
arXiv:1007.0821

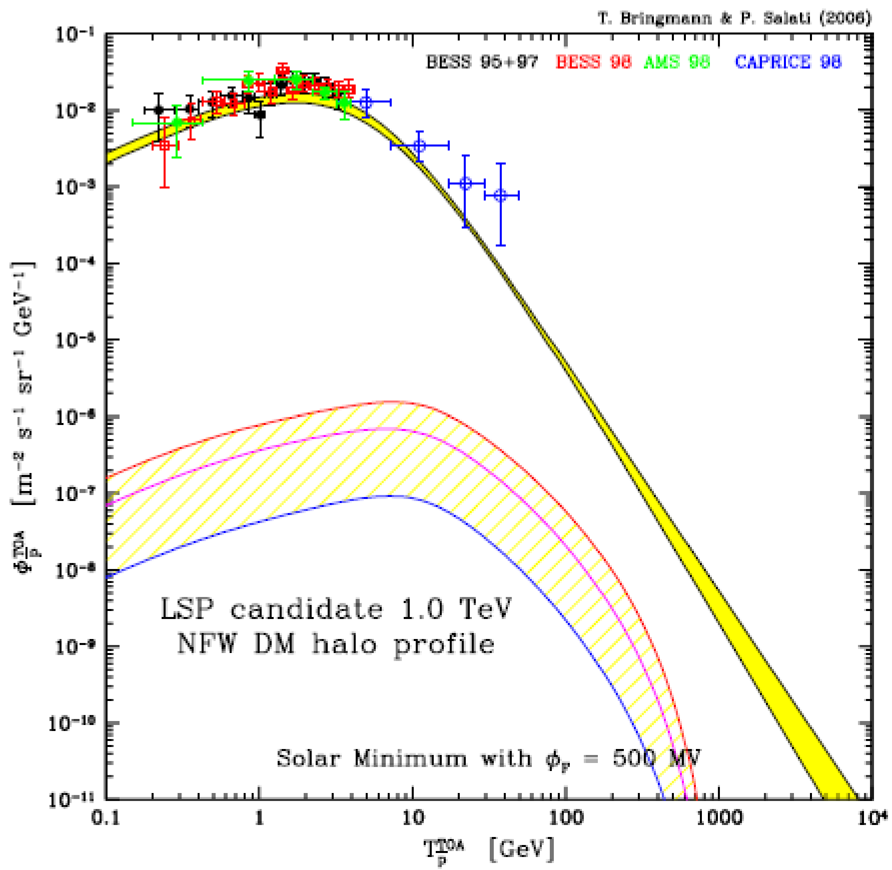
**Fairly good agreement between the measurements and the theoretical predictions from collisions of cosmic rays on the interstellar medium $p\, p \rightarrow \bar{p}\, X$**

# Expectations from theory

A concrete example in the minimal supersymmetric standard model.

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

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



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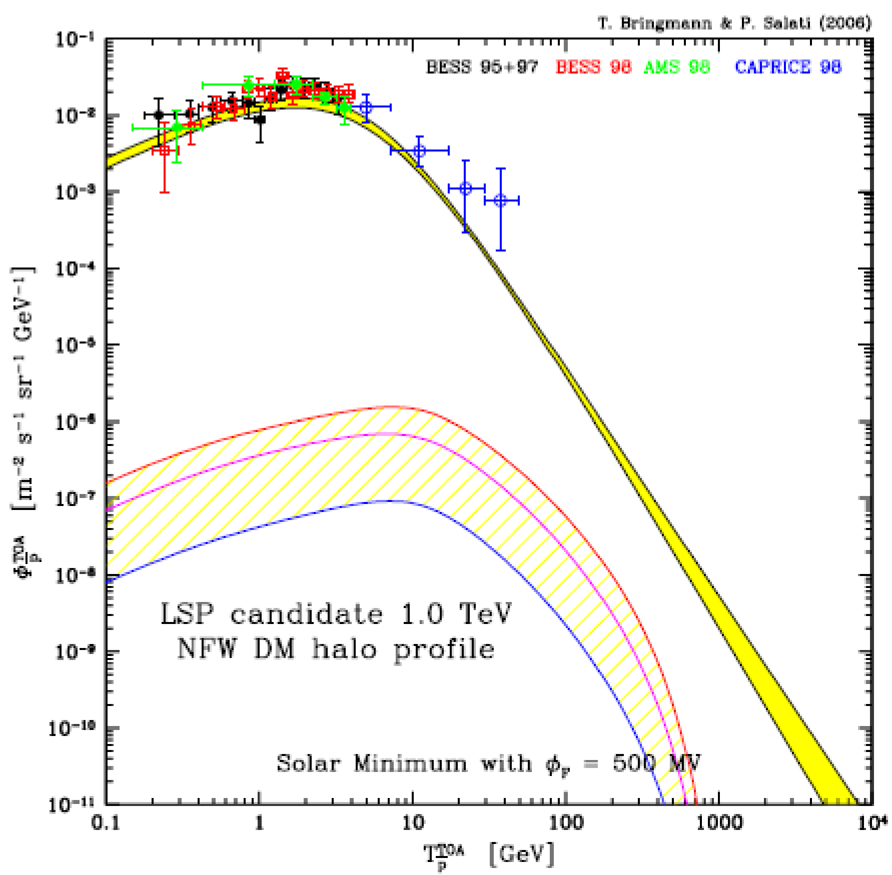


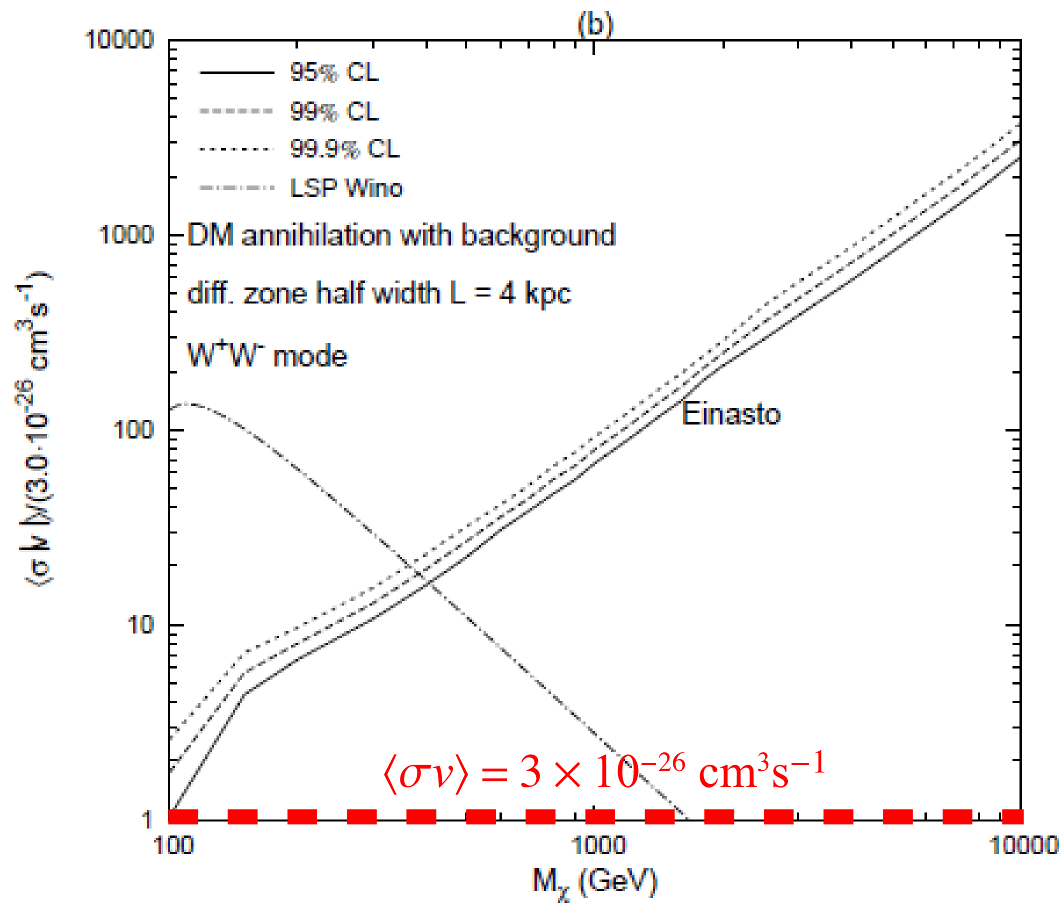

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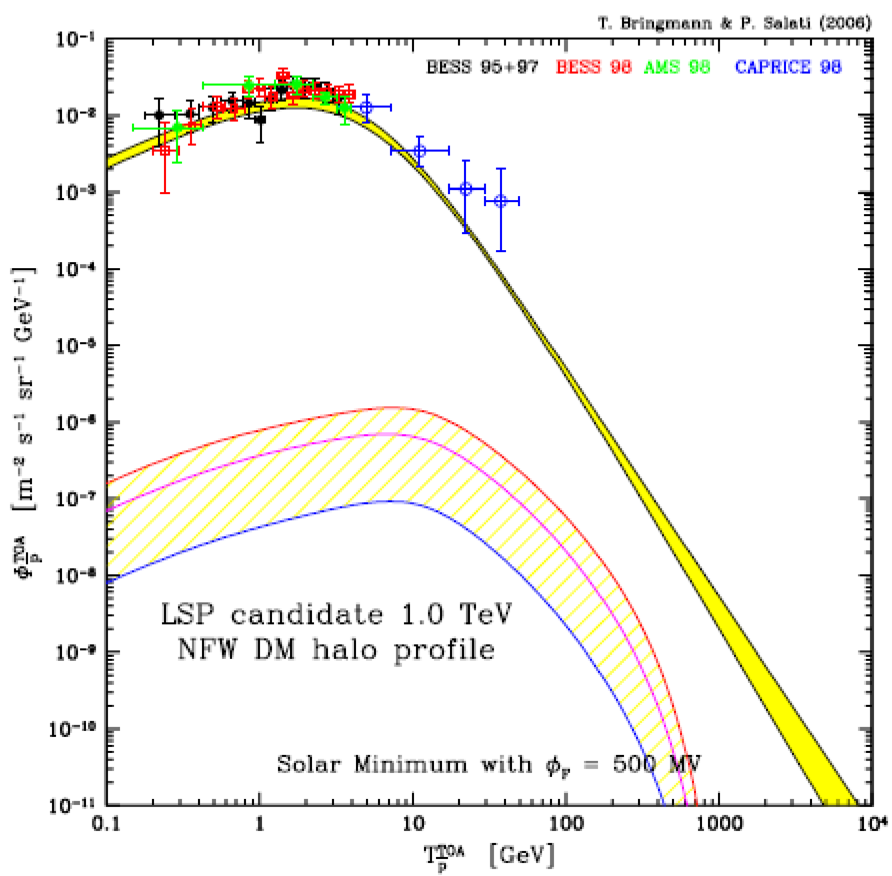
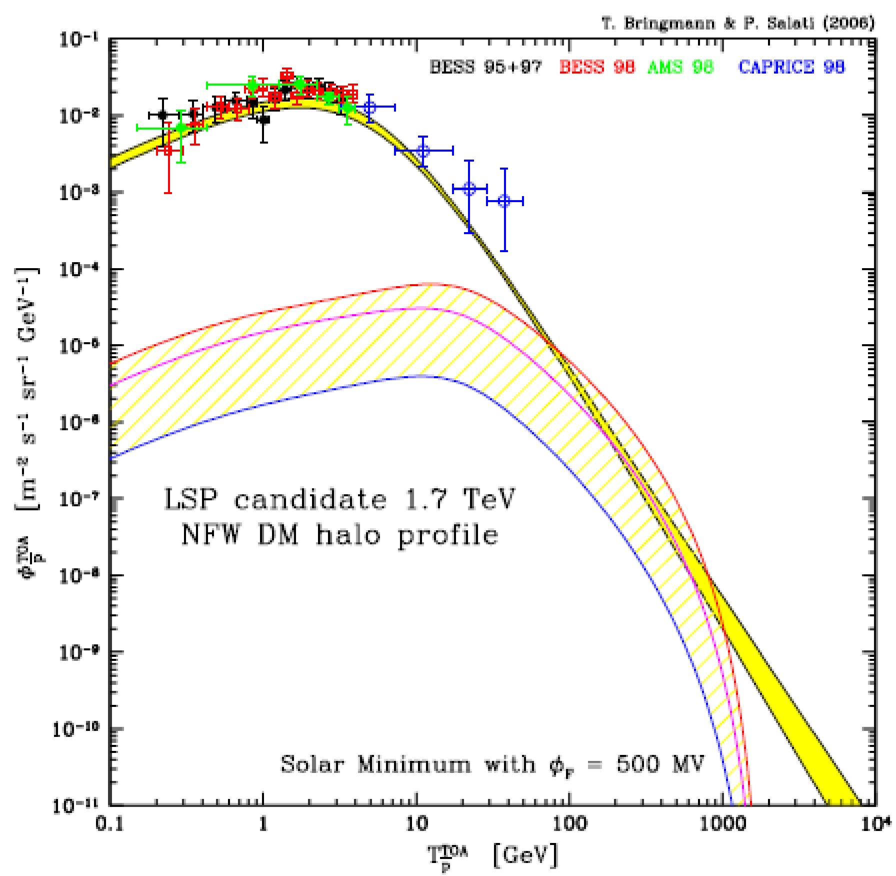
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LSP1.0 | 1.0 | 0.46 | - | - | - | - | - | - | - | 100 | - | - |
| LSP1.7 | 1.7 | 102 | - | - | - | - | - | - | 20.1 | 79.9 | - | - |



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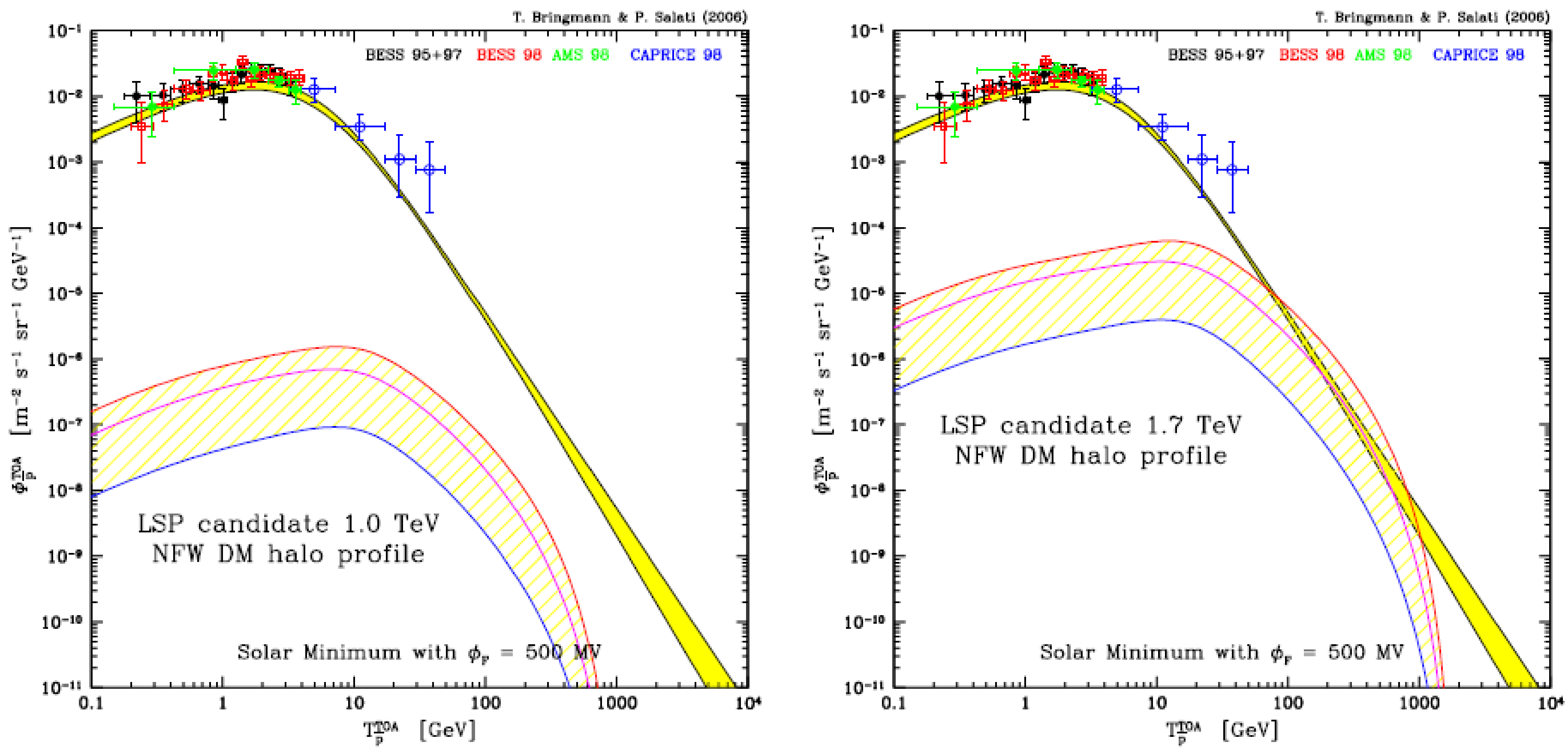
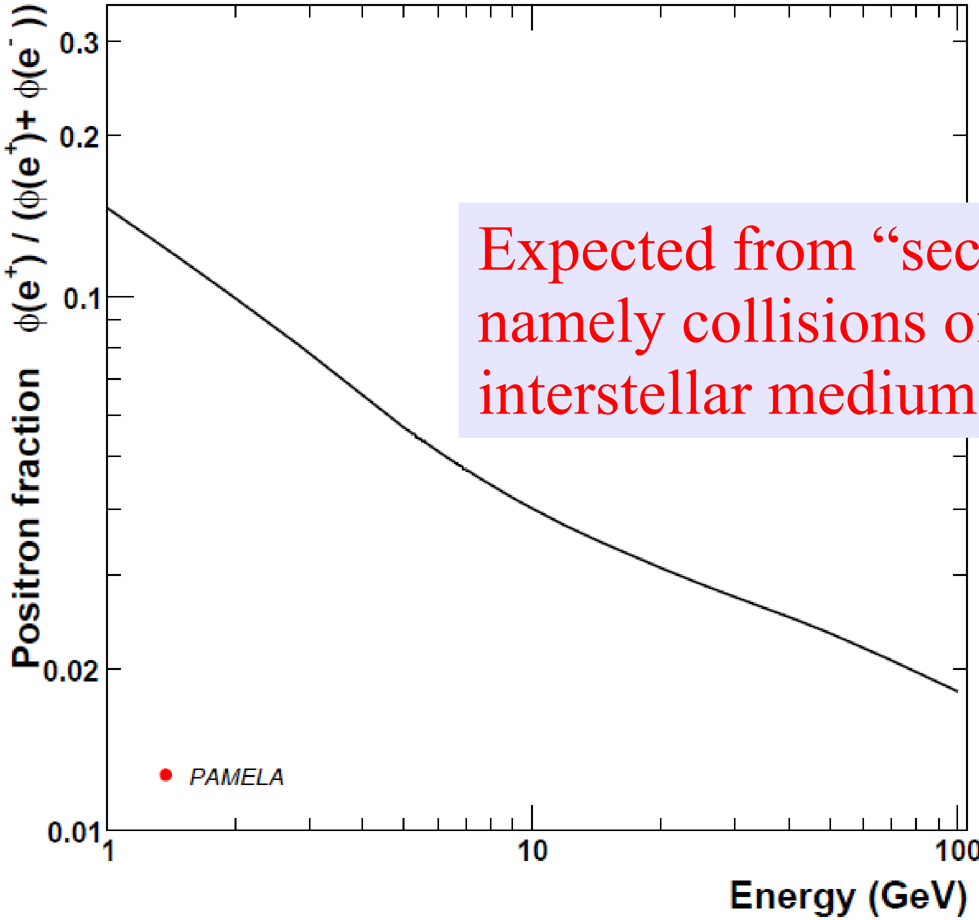
| LSP1.0 | 1.0 | 0.46 | - | - | - | - | - | - | - | 100 | - | - |
| LSP1.7 | 1.7 | 102 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

Annihilation rate "boosted"!



# Experimental results: positrons




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

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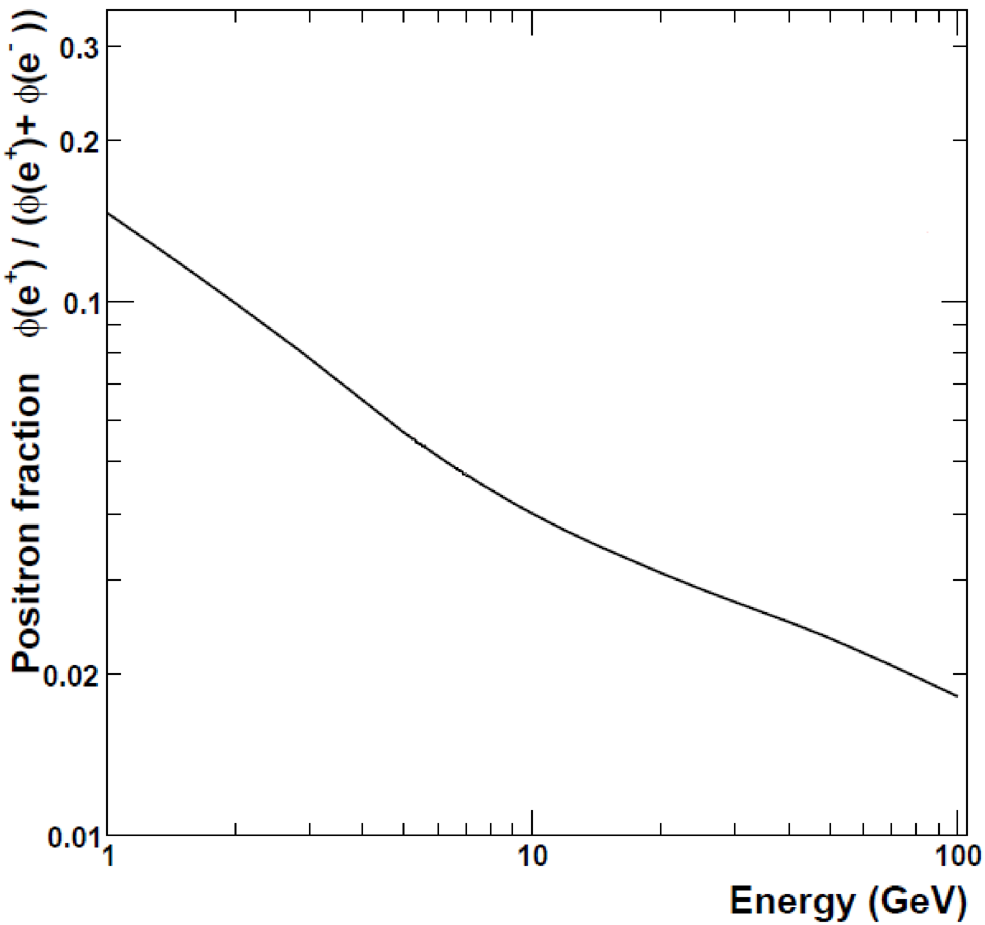


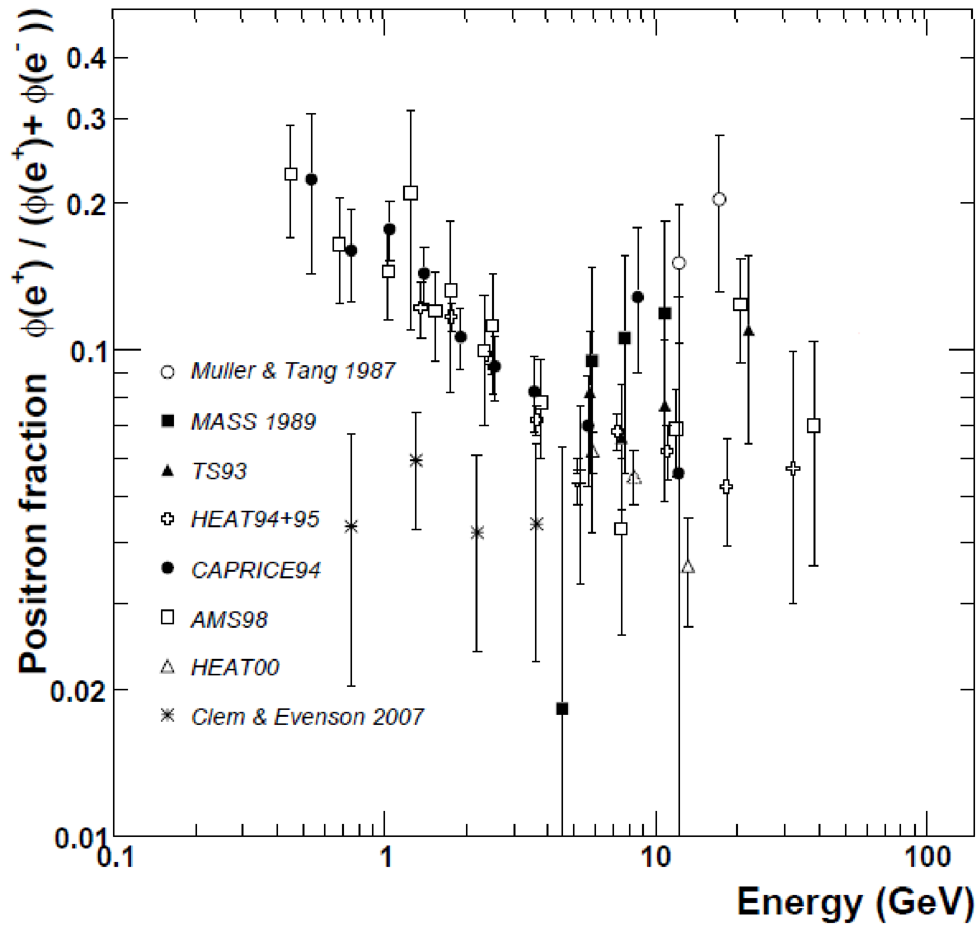

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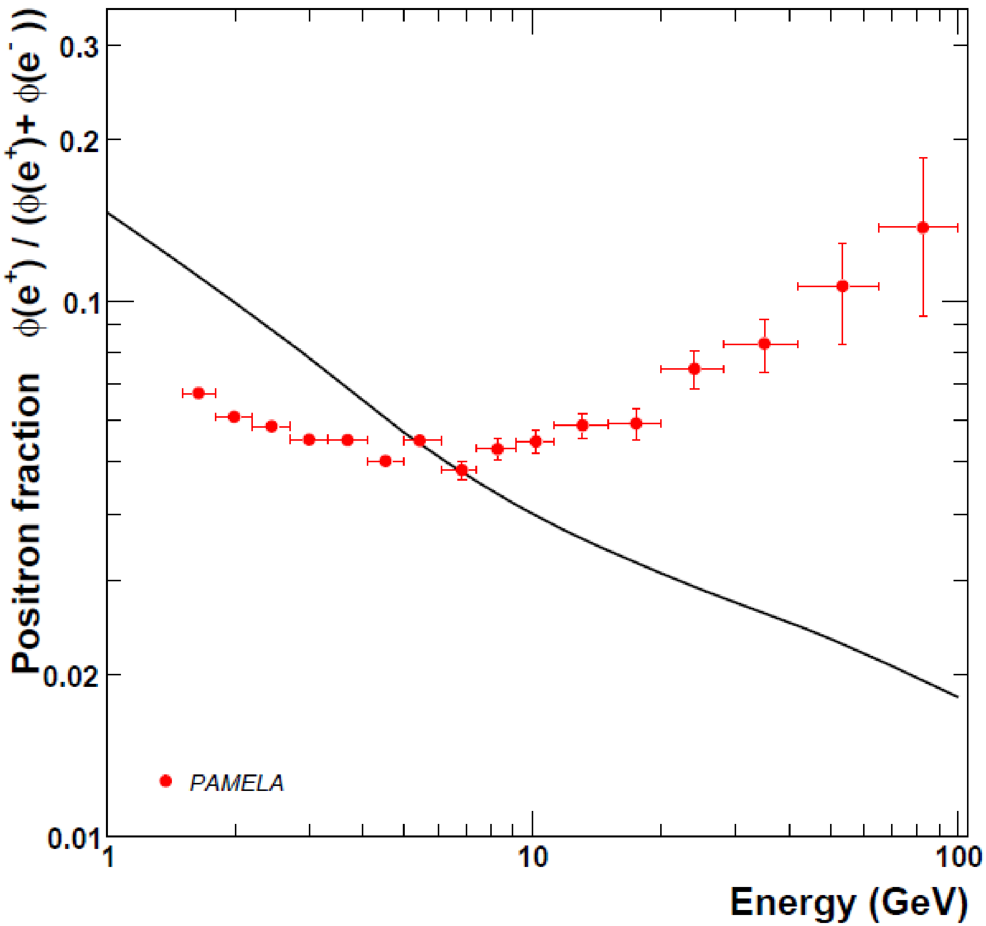
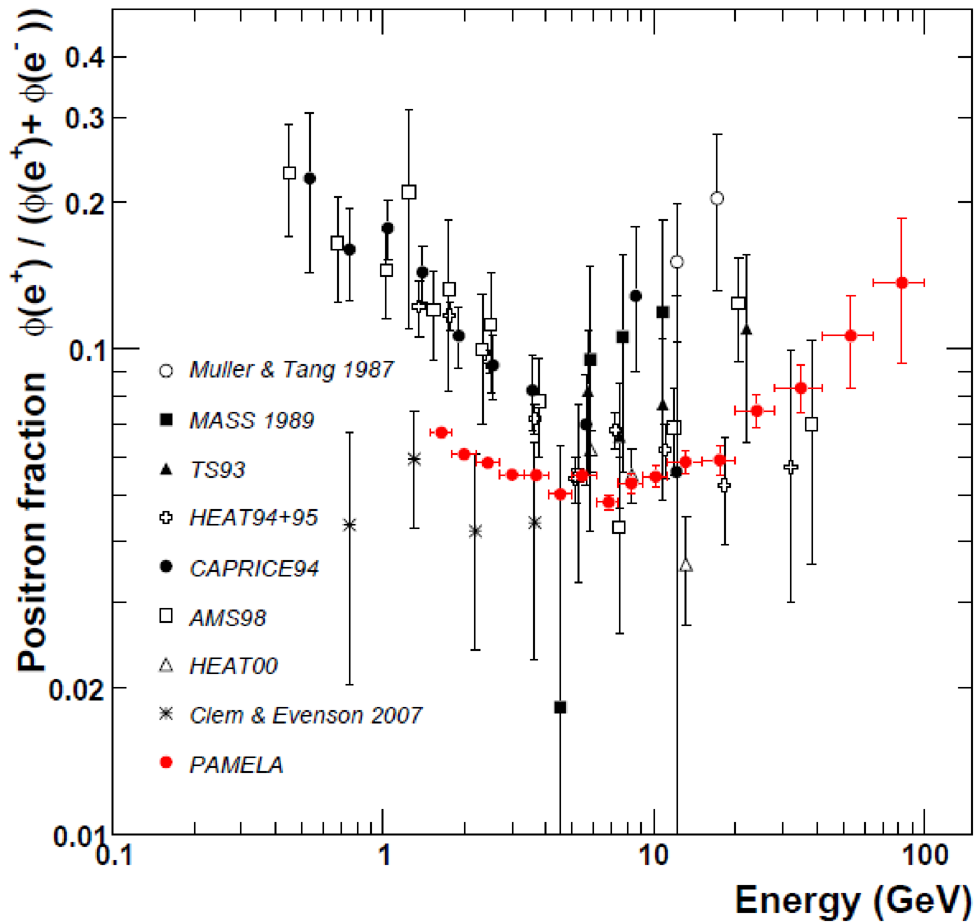
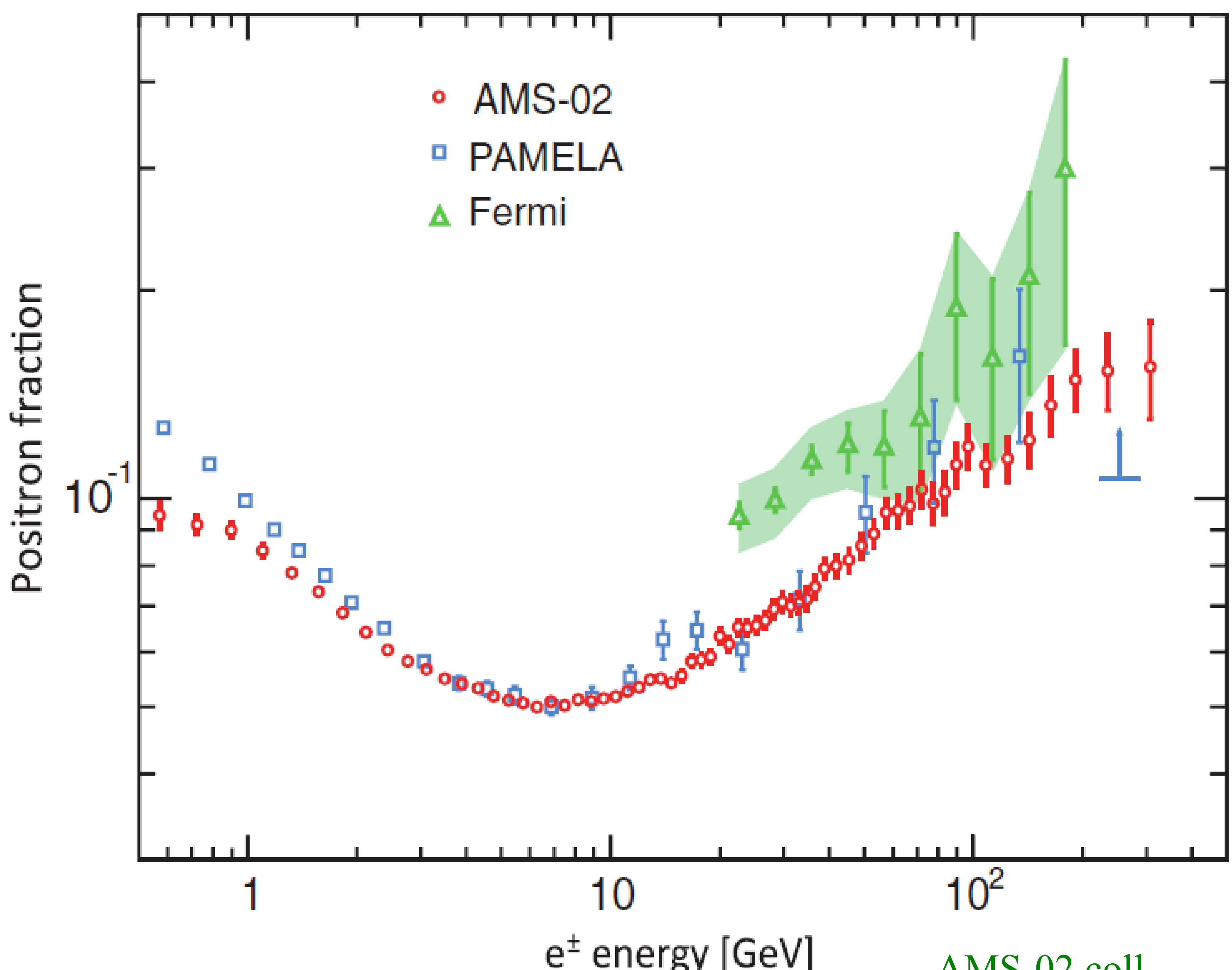


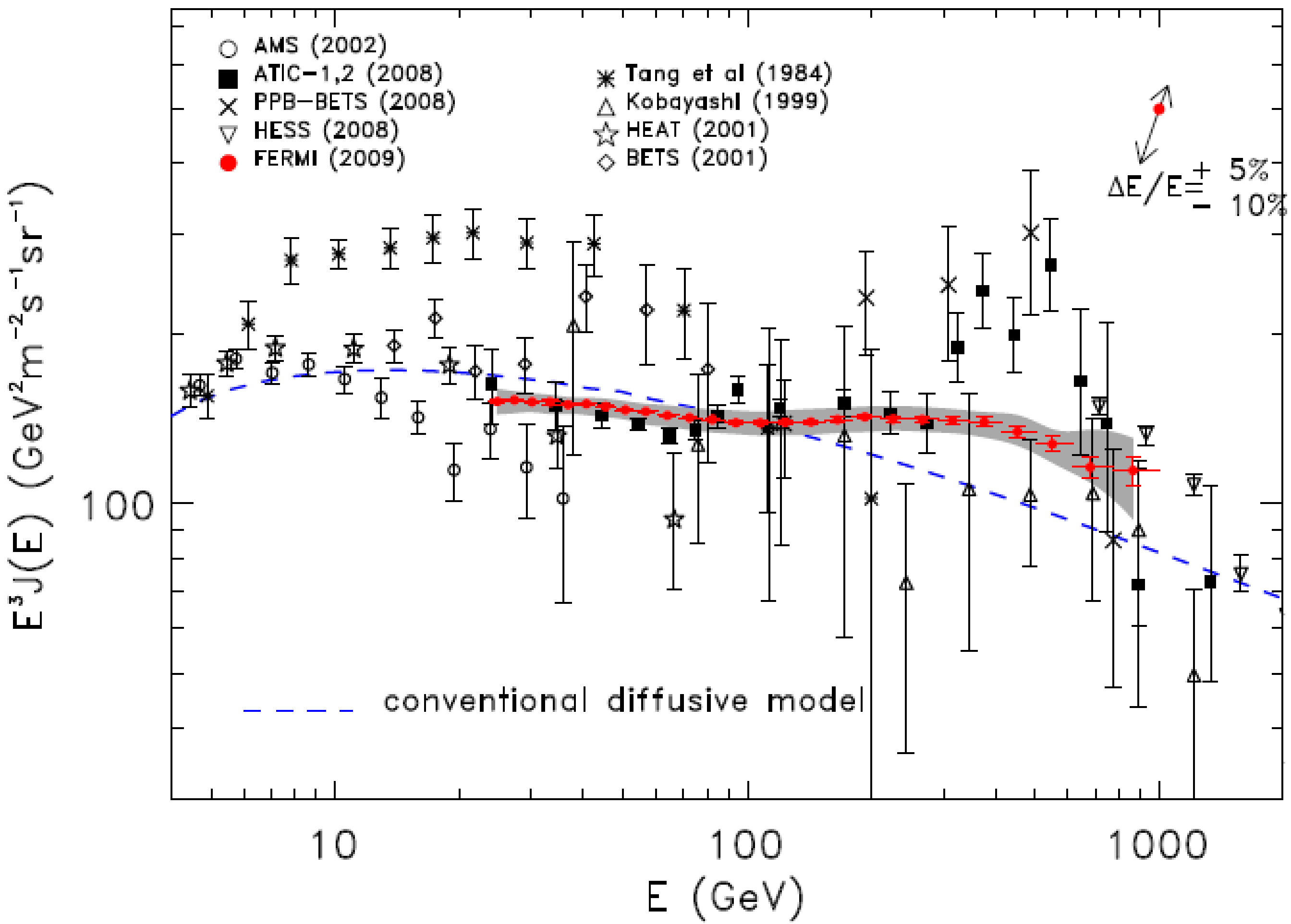

PAMELA coll.
arXiv:0810.4995

# Experimental results: positrons



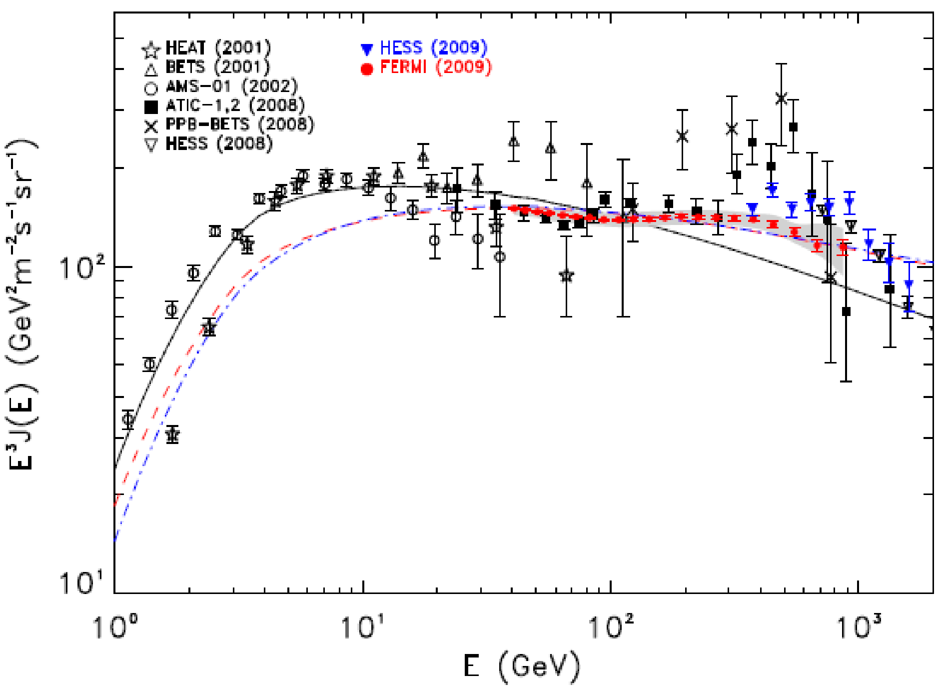

AMS-02 coll.
Phys.Rev.Lett. 110 (2013) 14, 141102

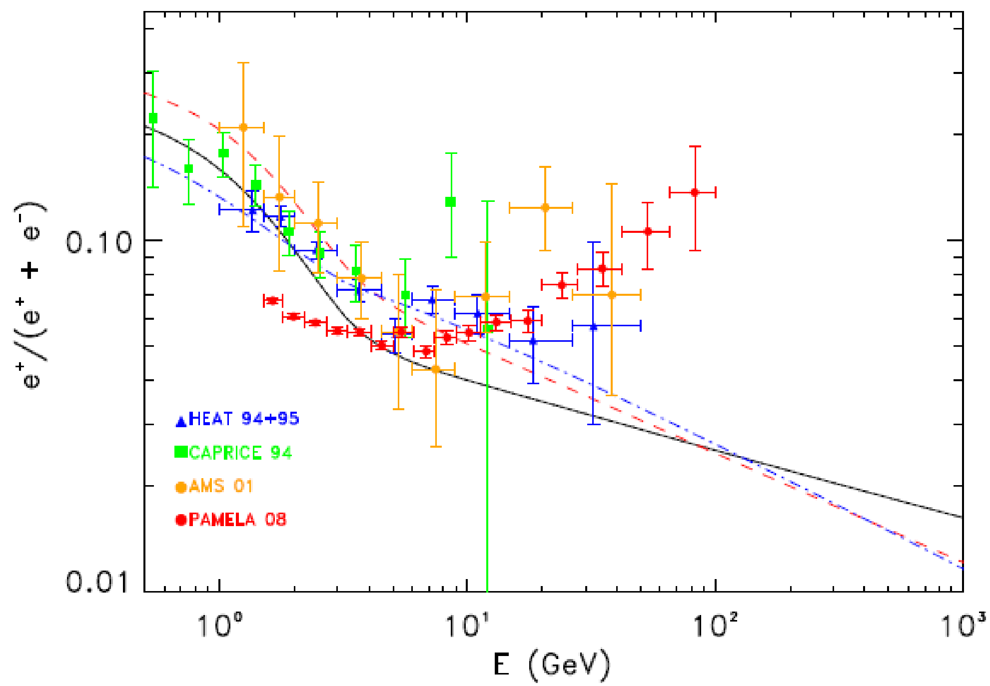
# More puzzles: the electron+positron flux




Abdo et al.
ArXiv:0905.0025

# Present situation:



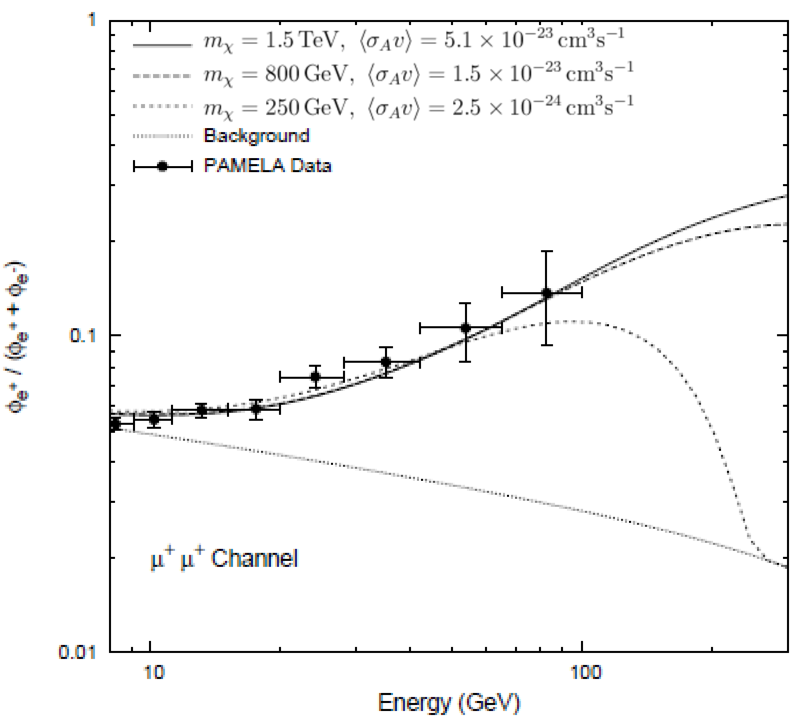



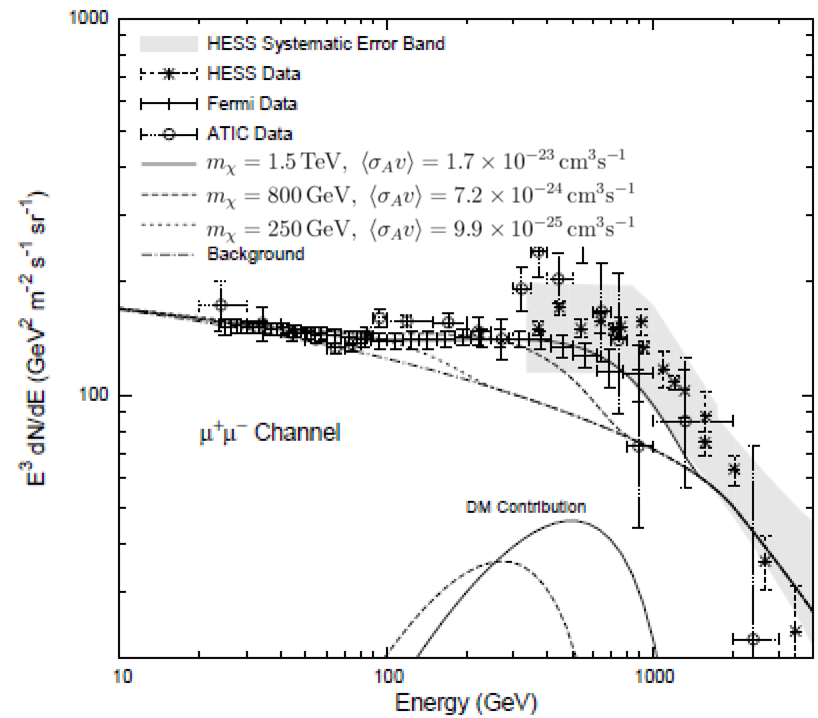

**Evidence for a primary component of positrons**
**(possibly accompanied by electrons)**

# Dark matter interpretation

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

$$\chi\chi \rightarrow \mu^+\mu^-$$

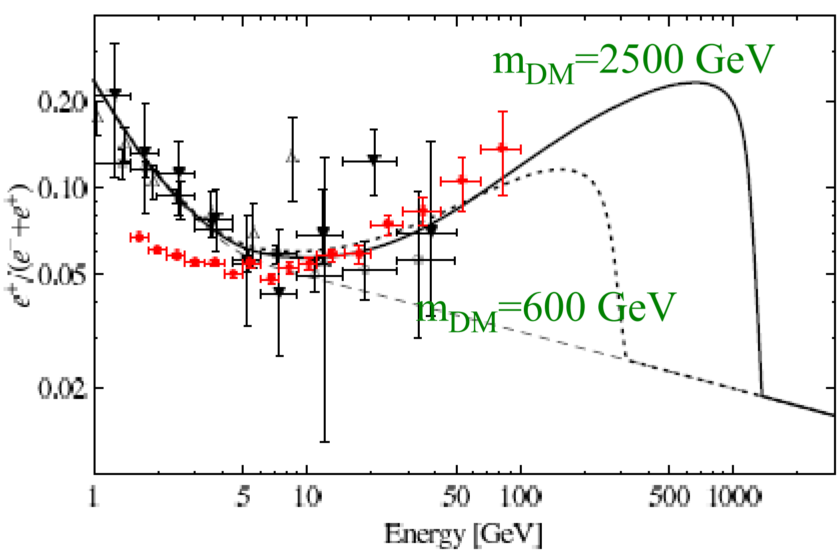


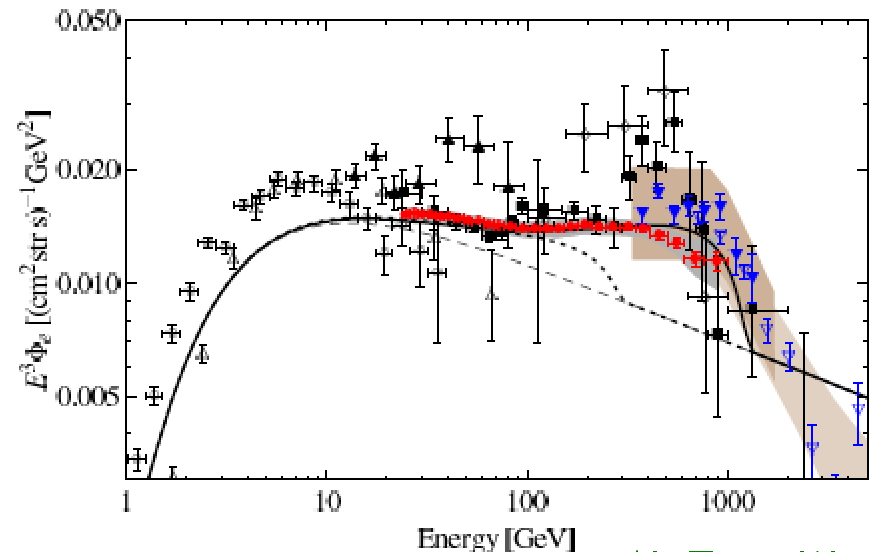




Cholis et al.
arXiv:0811.3641

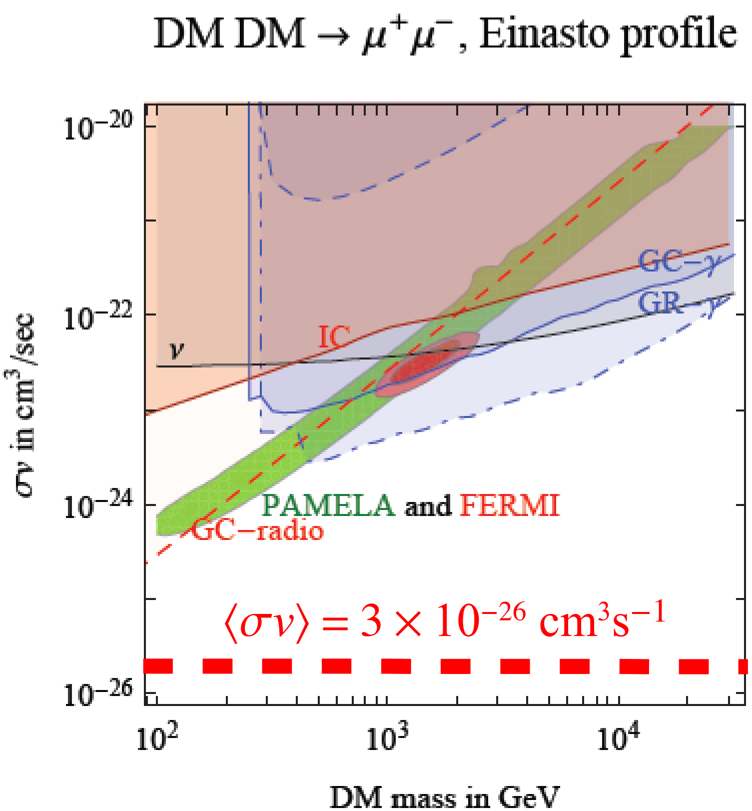
# … or dark matter decays

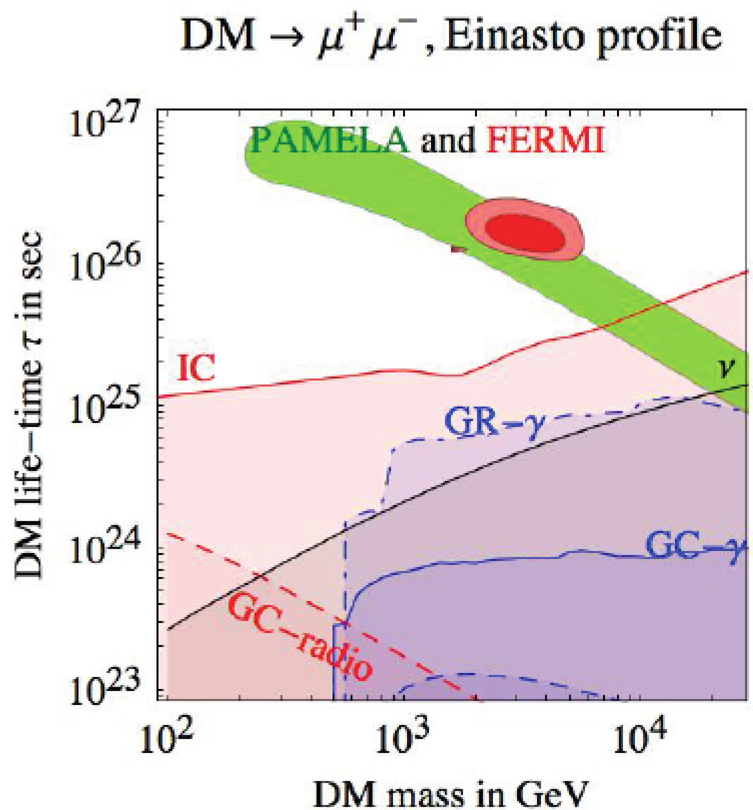
“Democratic” decay $\psi \rightarrow \ell^+ \ell^- \nu$




AI, Tran, Weniger
arXiv:0906.1571

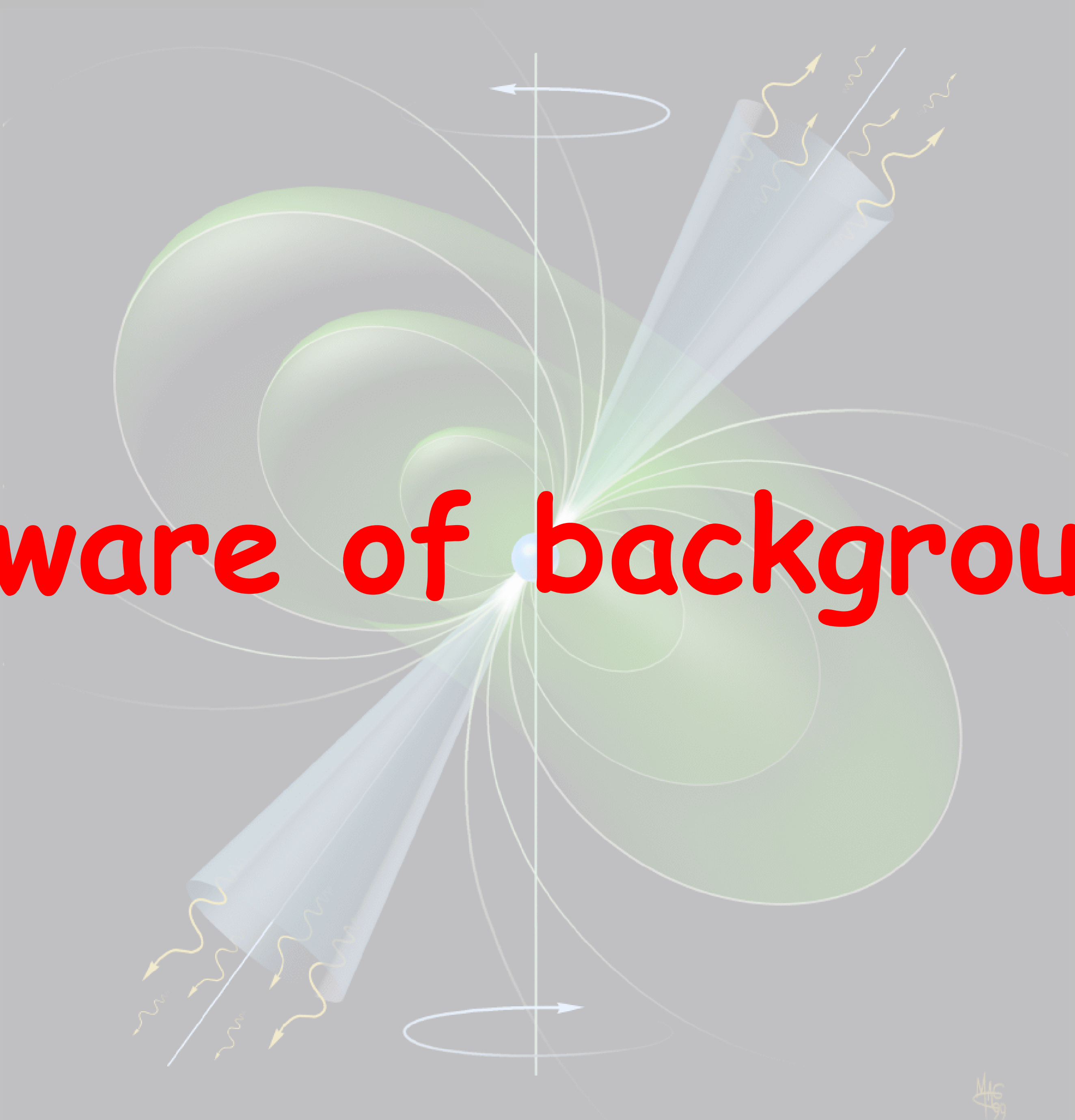



**Is this the first non-gravitational evidence of dark matter?**

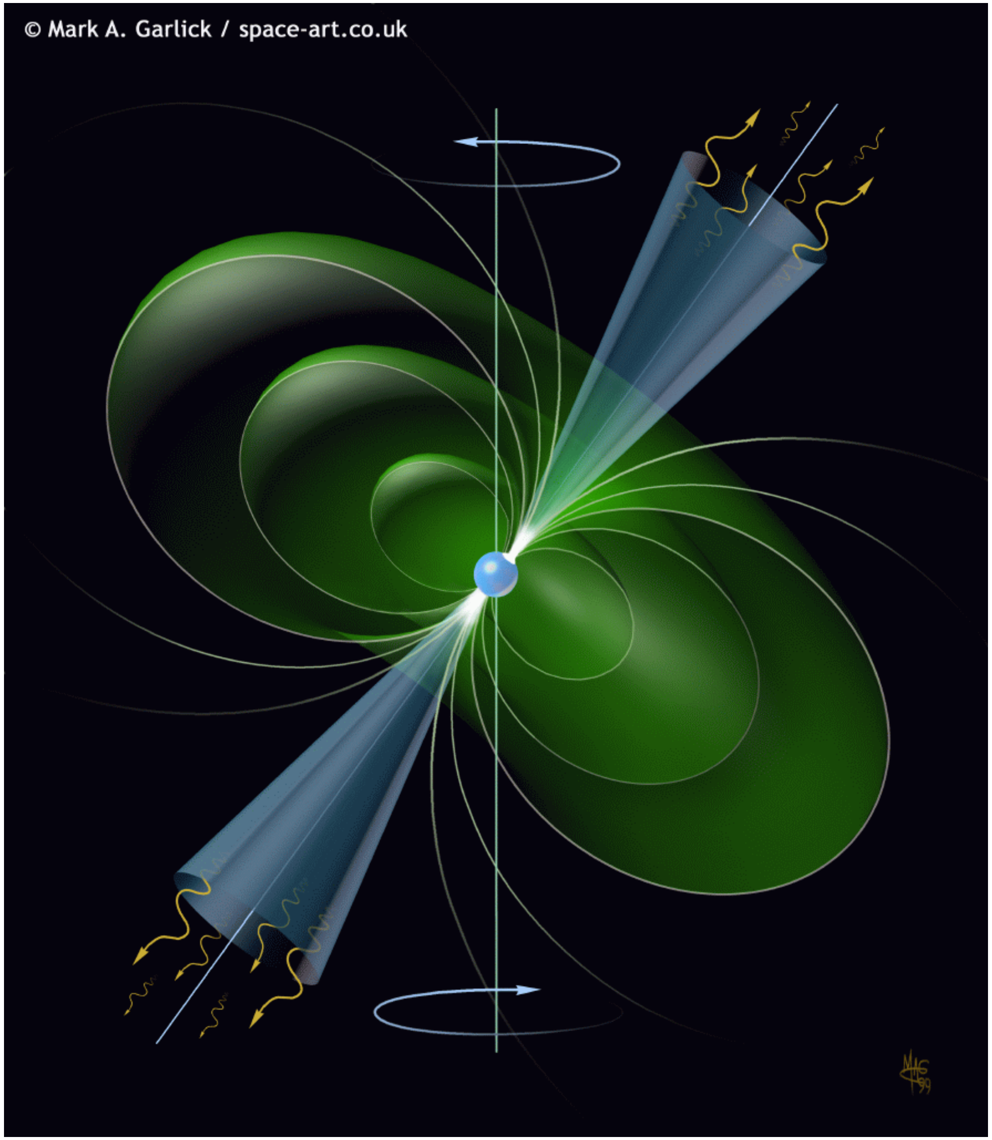
"Extraordinary claims require extraordinary evidence"
Carl Sagan

# Beware of backgrounds!

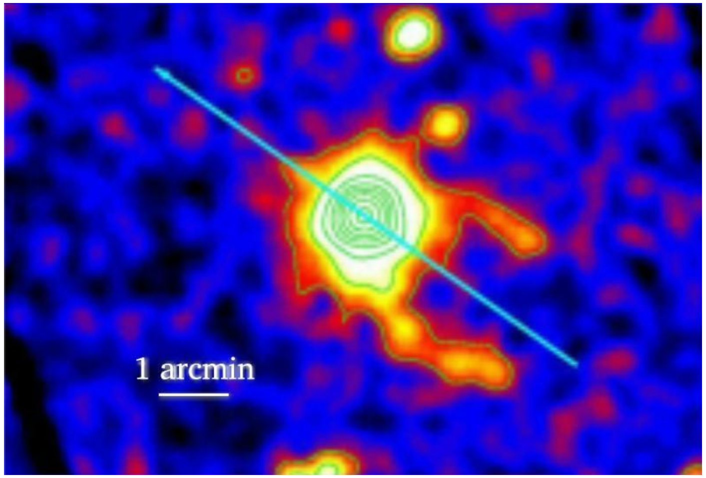


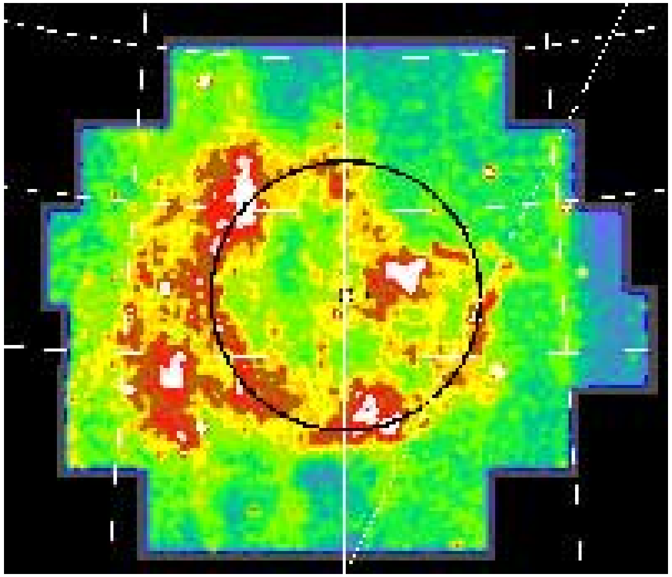
# Pulsars <u>are</u> sources of high energy electrons & positrons

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



# Pulsar explanation I: Geminga + Monogem



Geminga

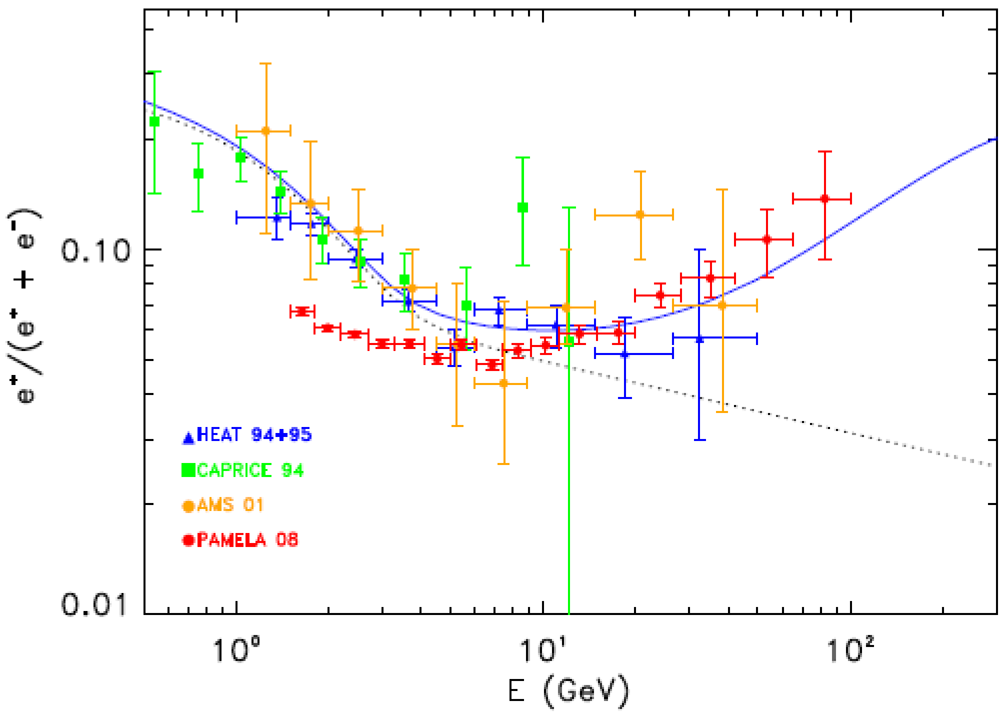
T=370 000 years
D=157 pc

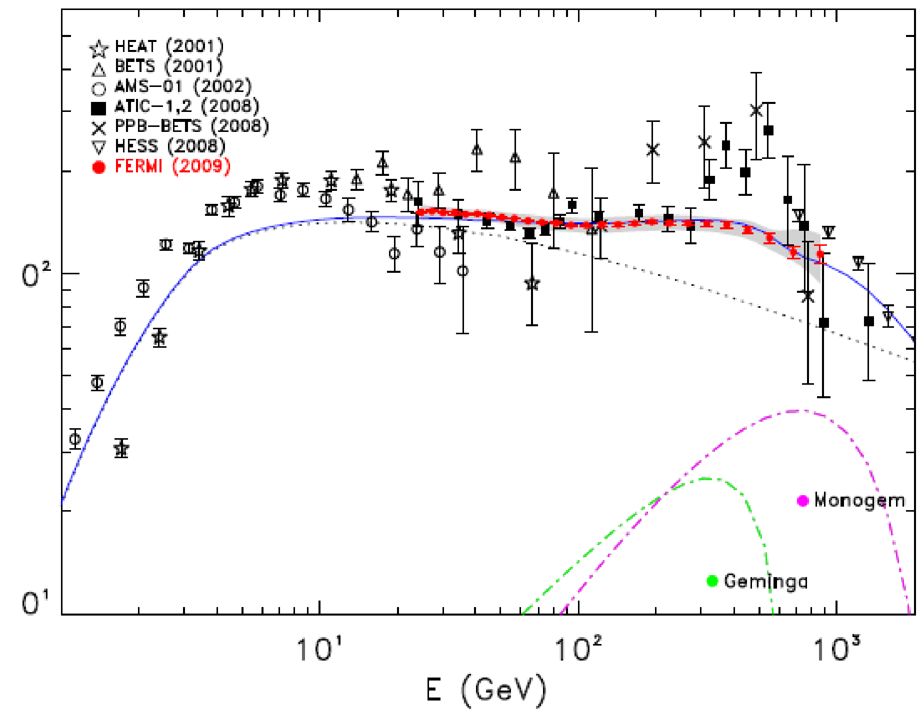
Monogem (B0656+14)

T=110 000 years
D=290 pc

# Pulsar explanation I: Geminga + Monogem

Grasso et al.



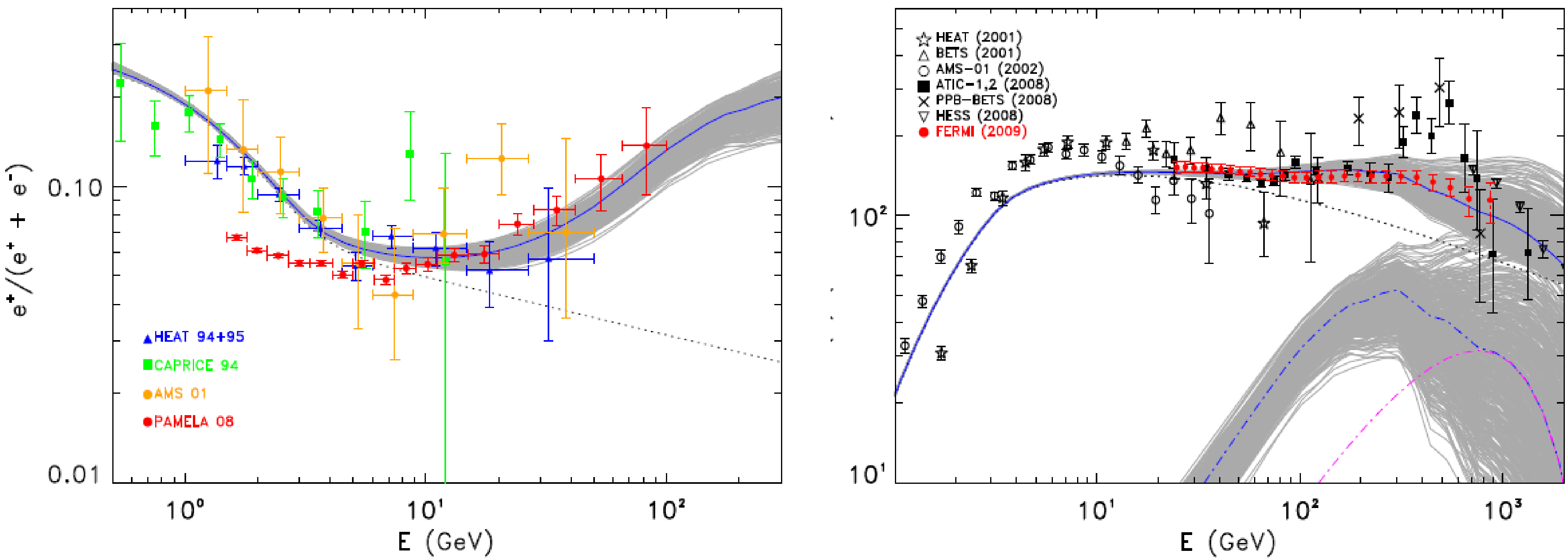




Nice agreement. However, it is <u>not</u> a prediction!

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

# Pulsar explanation II: Multiple pulsars

Grasso et al.




- $dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/E_0)$, $1.5 < \alpha < 1.9$, $800$ GeV $< E_0 <$ 1400 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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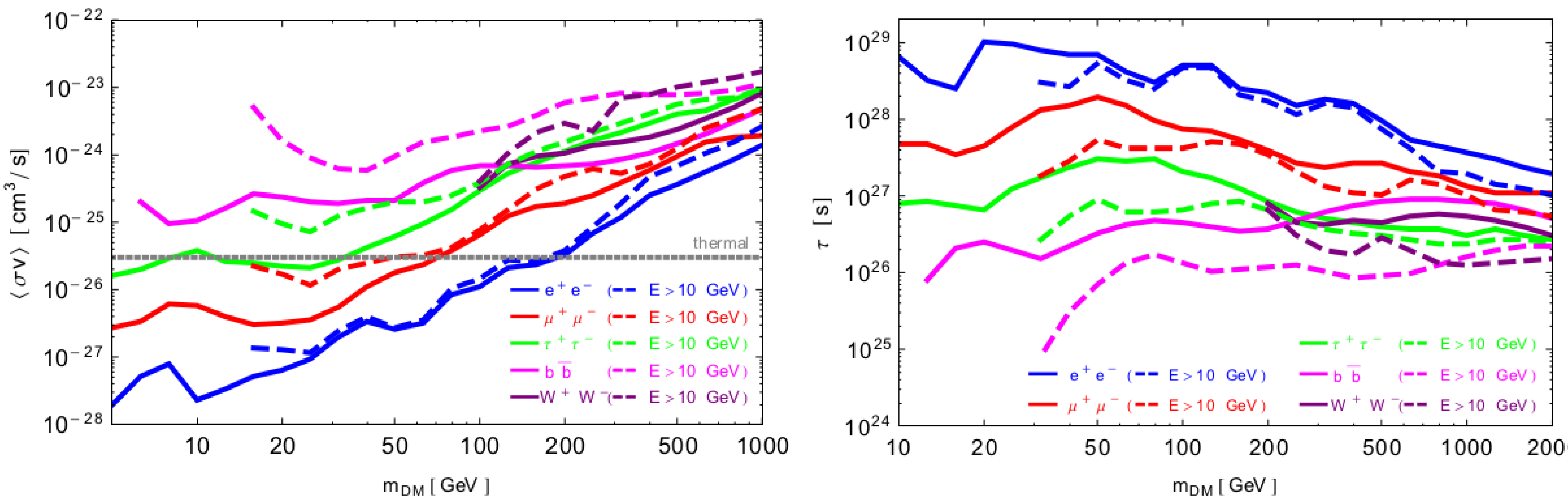
- Dark matter? Probably not.
- Pulsars? Perhaps yes.
- Something else? Perhaps yes.
- Regardless of the origin of the positron excess, the positron data can be used to set limits on the dark matter parameters.

# Latest limits from the positron fraction:

- Use AMS-02 data
- Make a fit of a model with secondary positrons + source + dark matter




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.

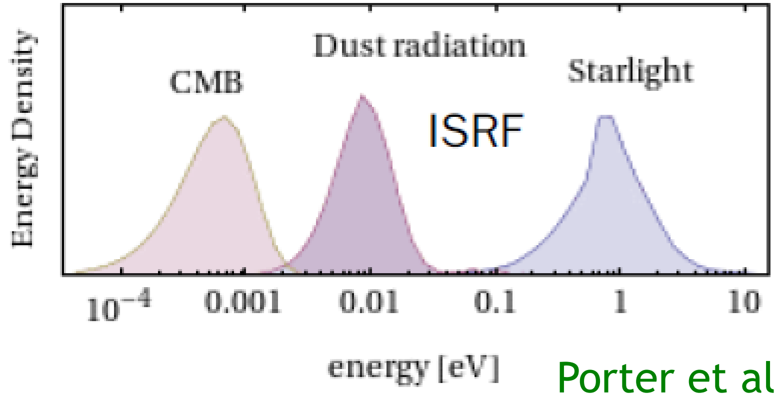
# Inverse Compton Scattering radiation

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

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




Porter et al.

Upscattered photon

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

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

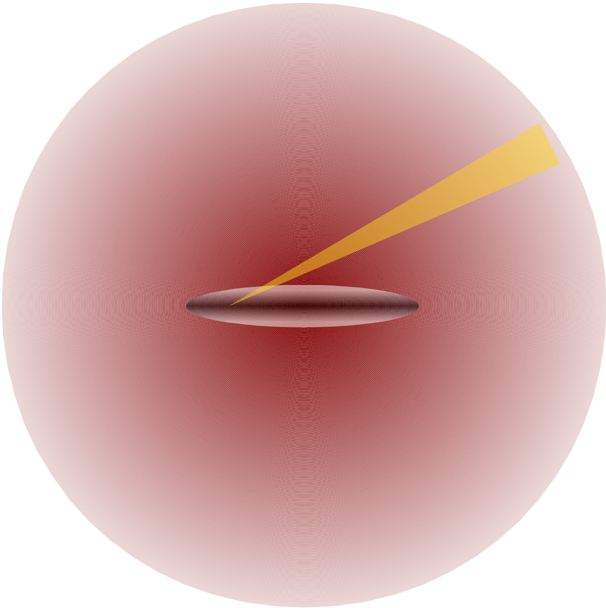
# Prompt radiation

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



# Prompt radiation

Annihilation

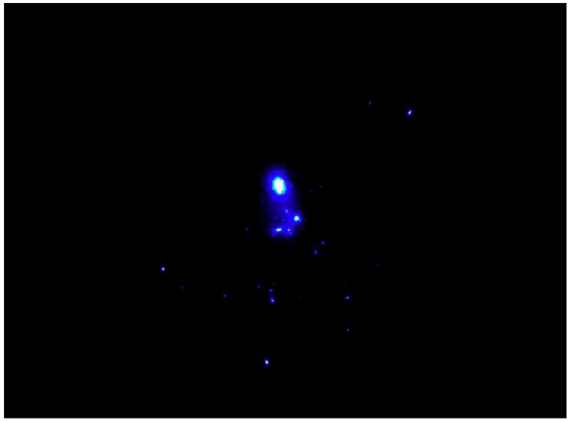
$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann} v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right] \times \int_{\rm l.o.s.} \rho^2(\vec{l})\, d\vec{l}$$

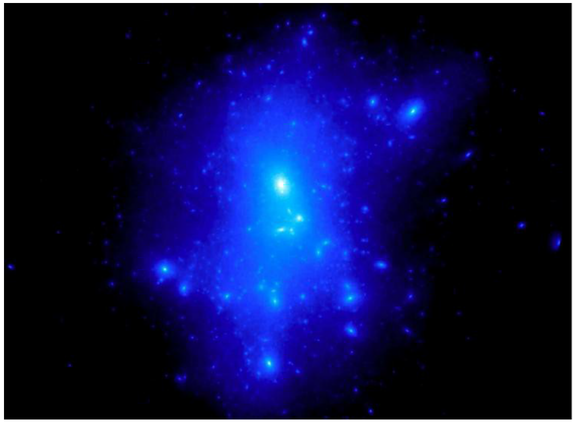
Source term (particle physics)

Line-of-sight integral (astrophysics)

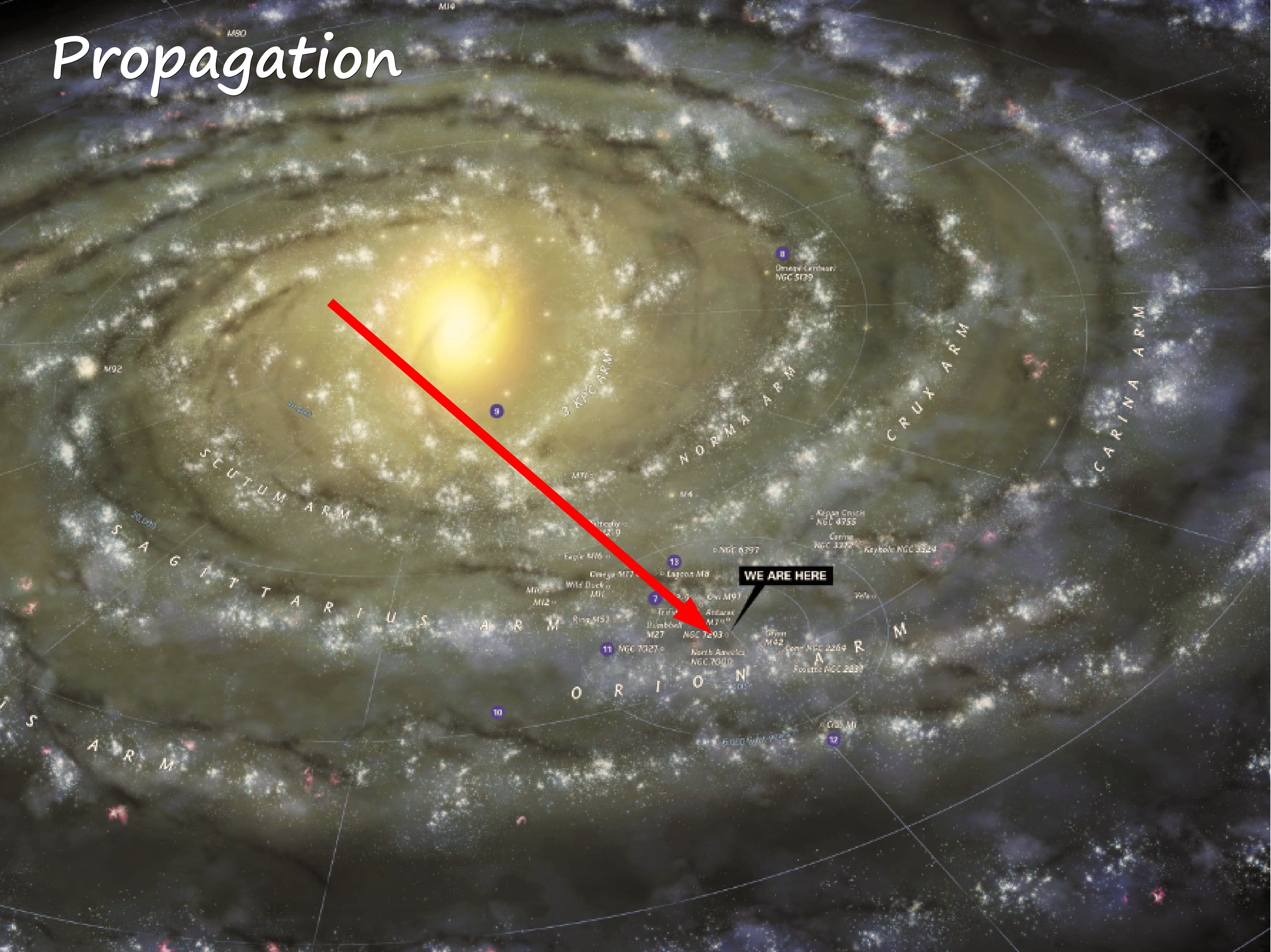
Decay

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



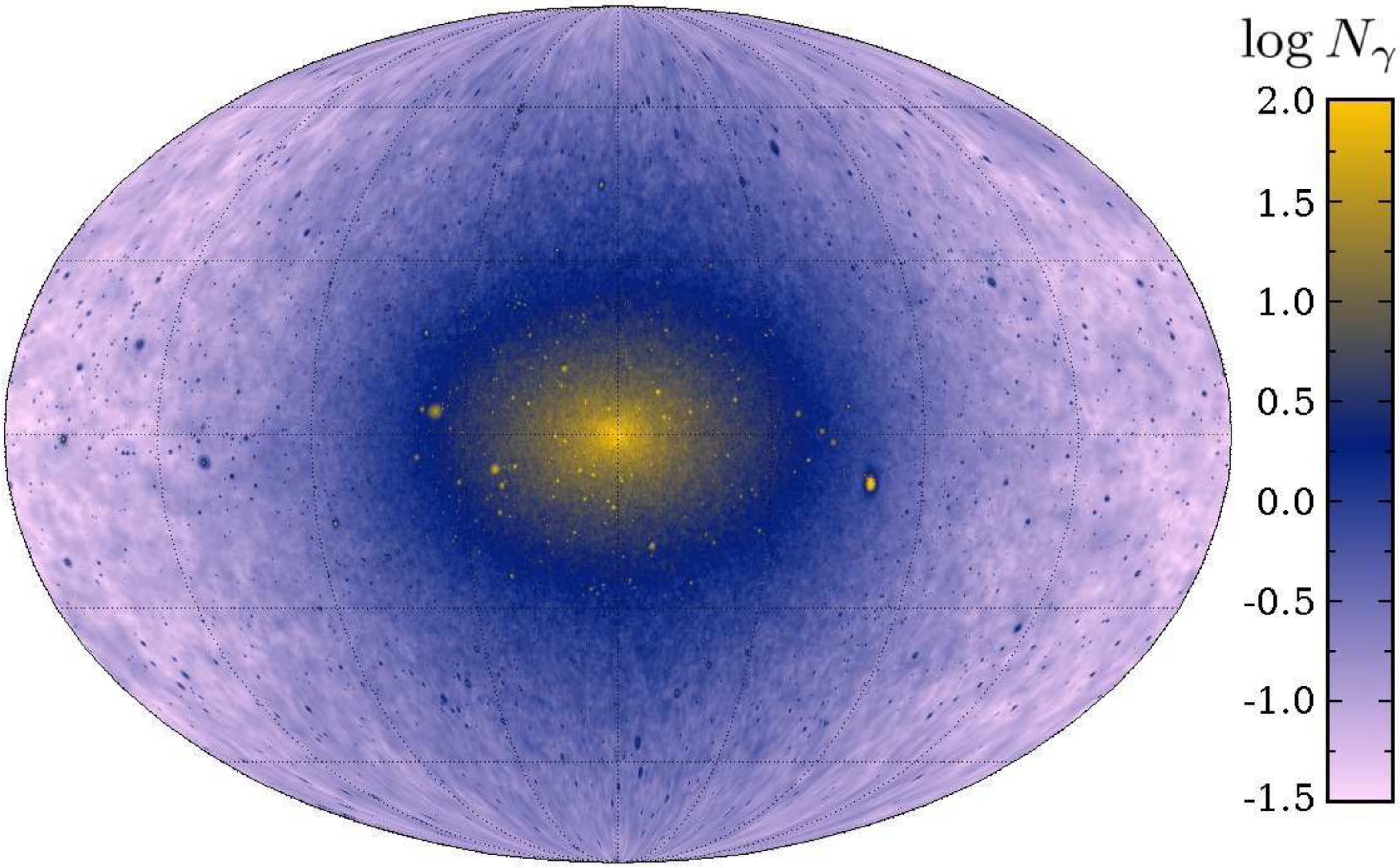


# Propagation



# Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911




Kuhlen, Diemand, Madau

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Baltz et al.
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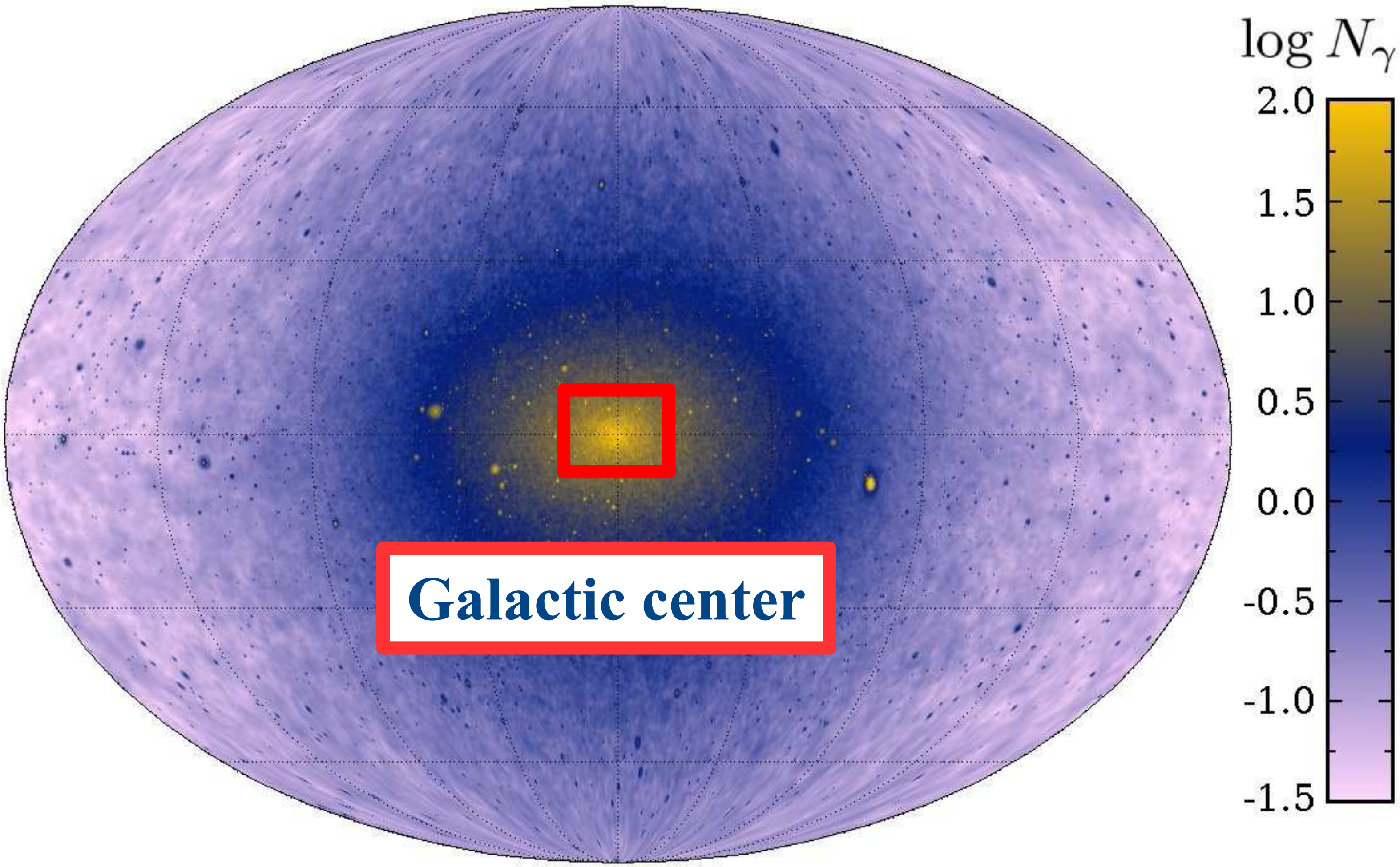


Kuhlen, Diemand, Madau

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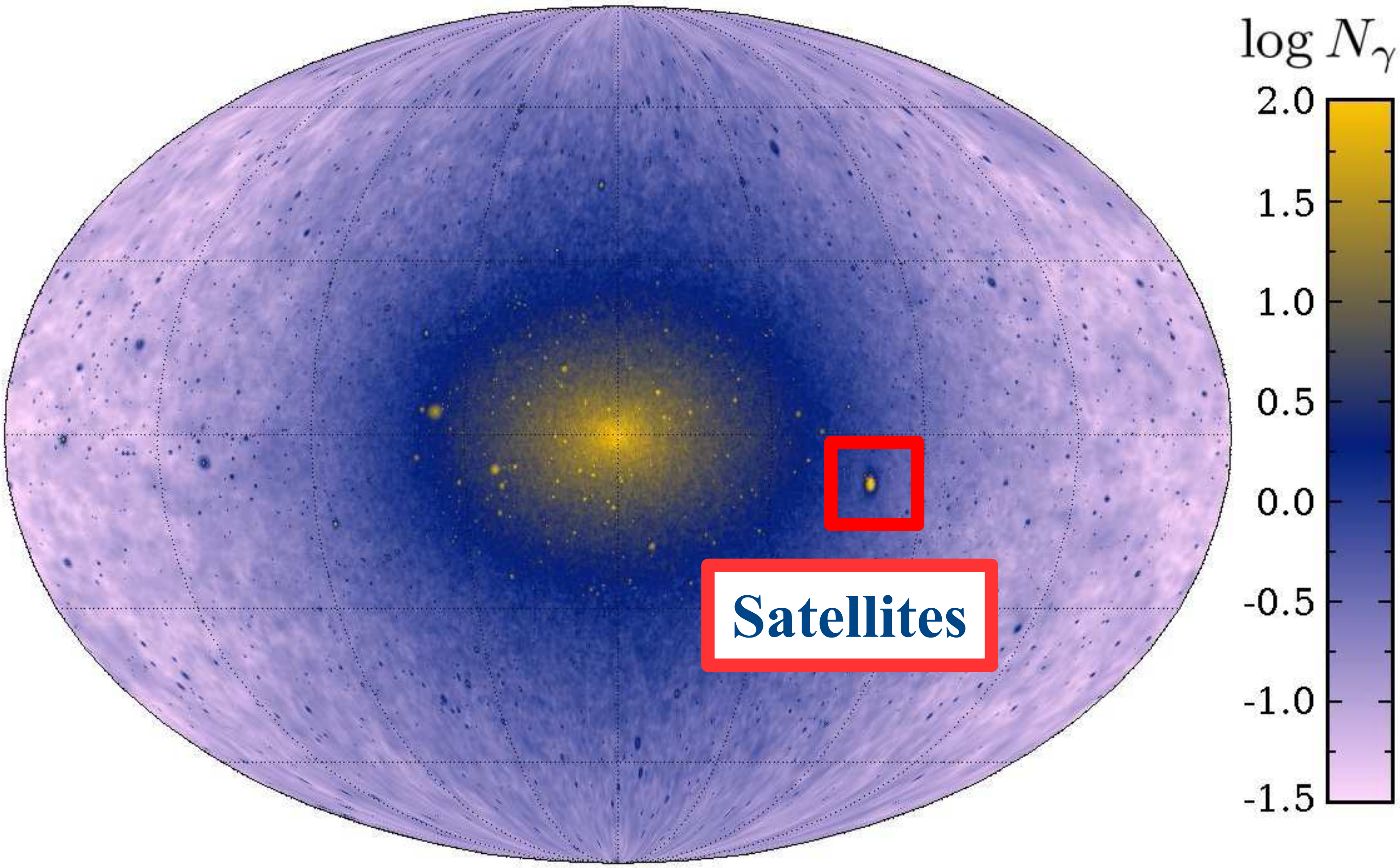


Kuhlen, Diemand, Madau

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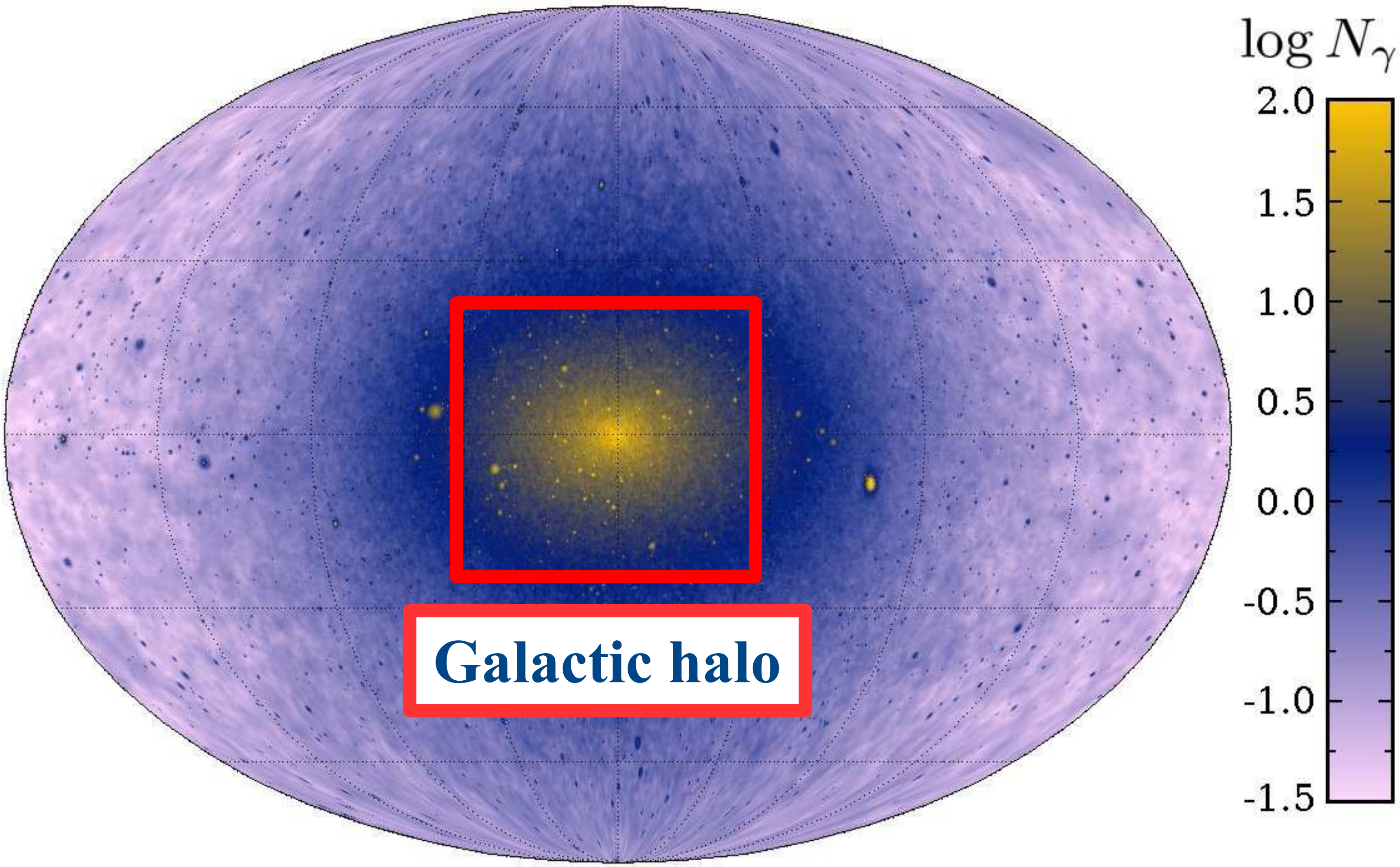


Kuhlen, Diemand, Madau

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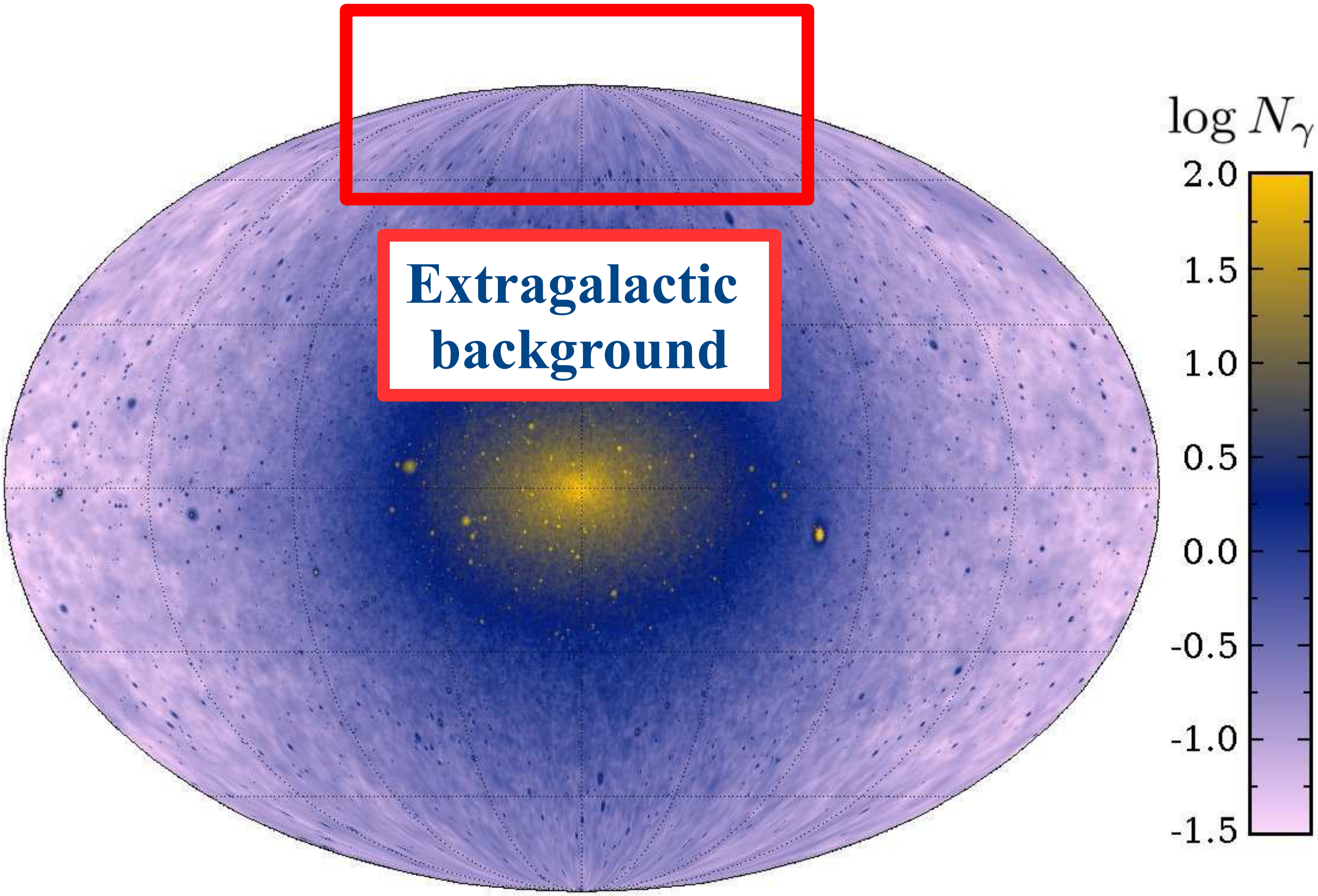


Kuhlen, Diemand, Madau

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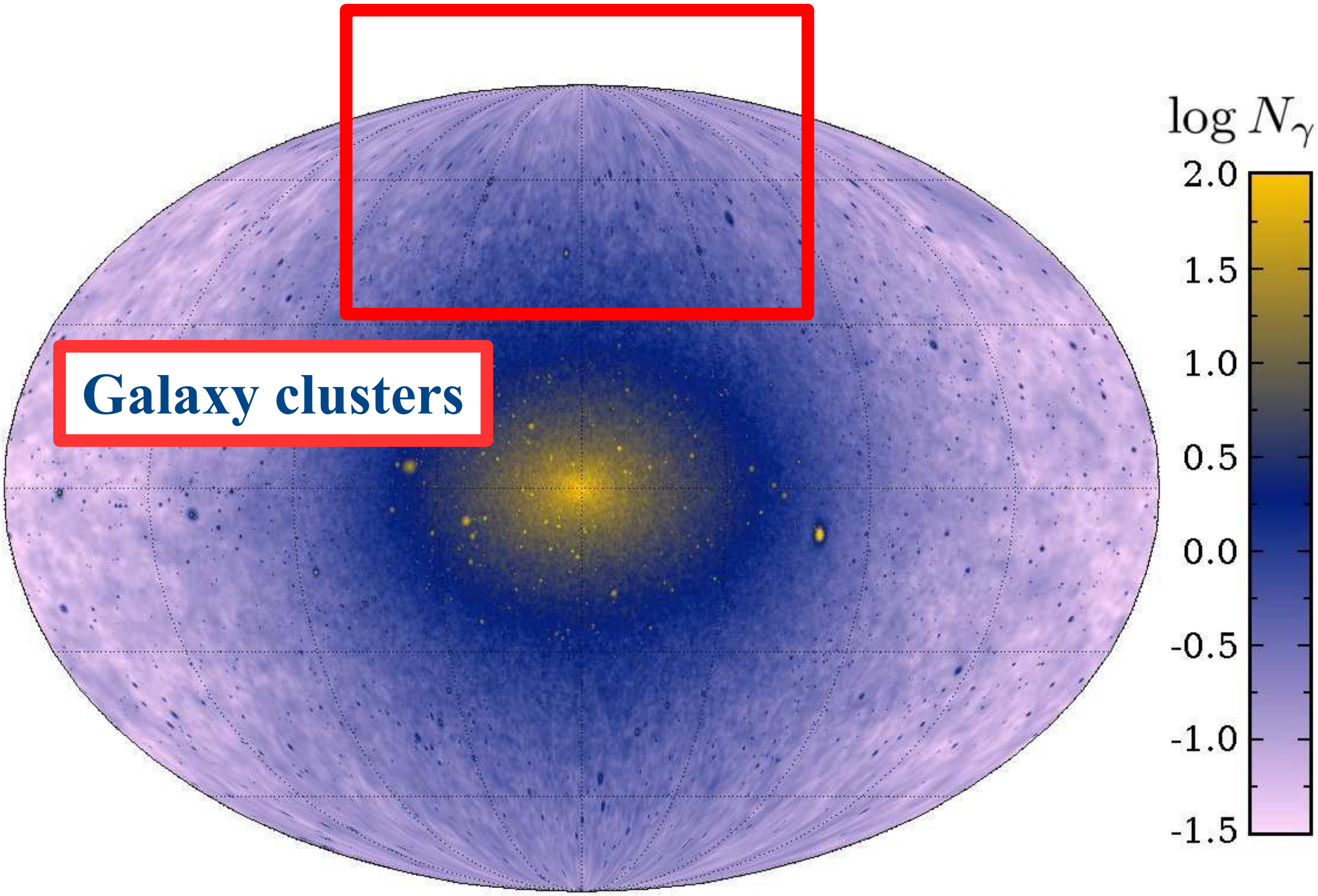


Kuhlen, Diemand, Madau

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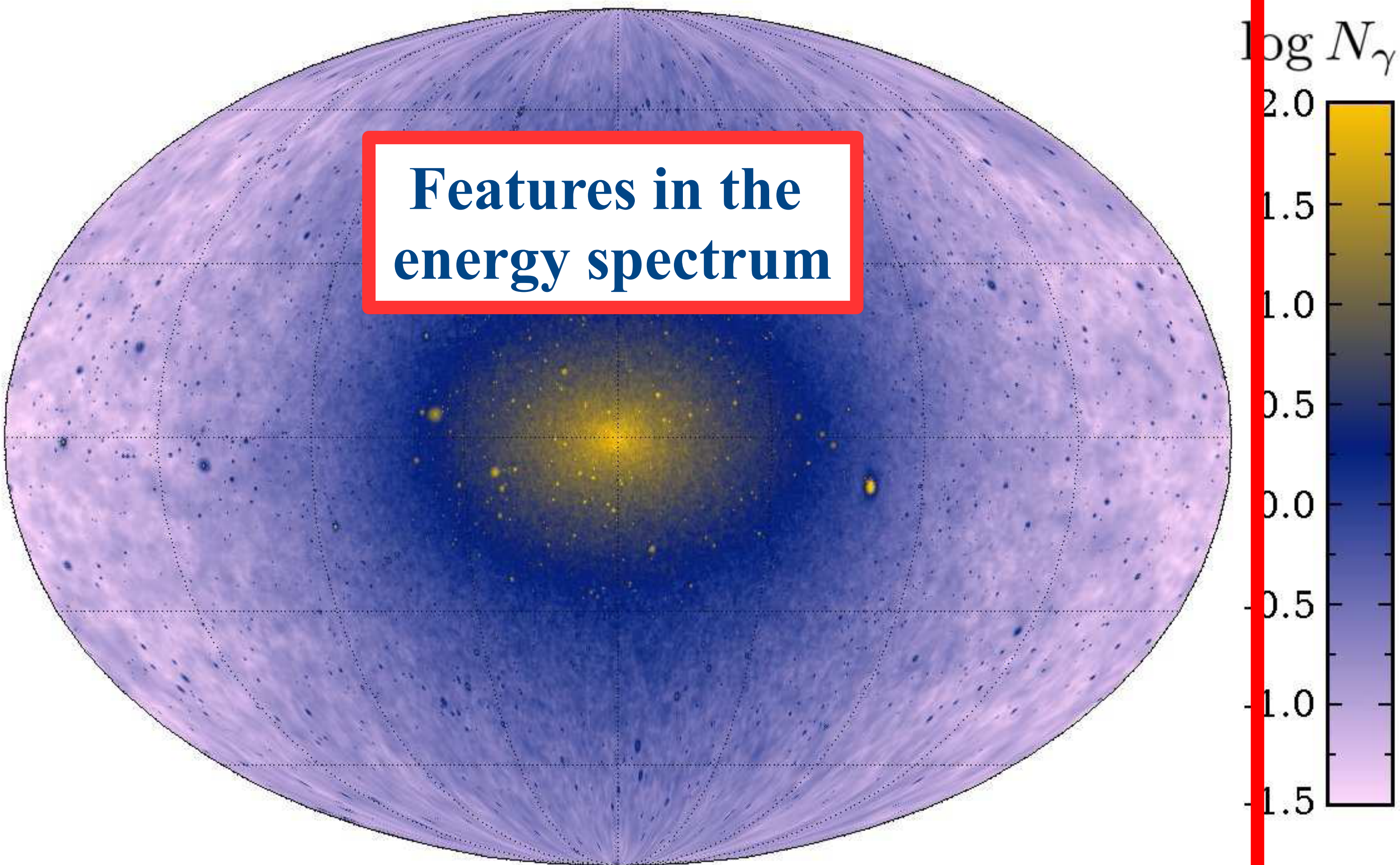
Baltz et al.
arXiv:0806.2911

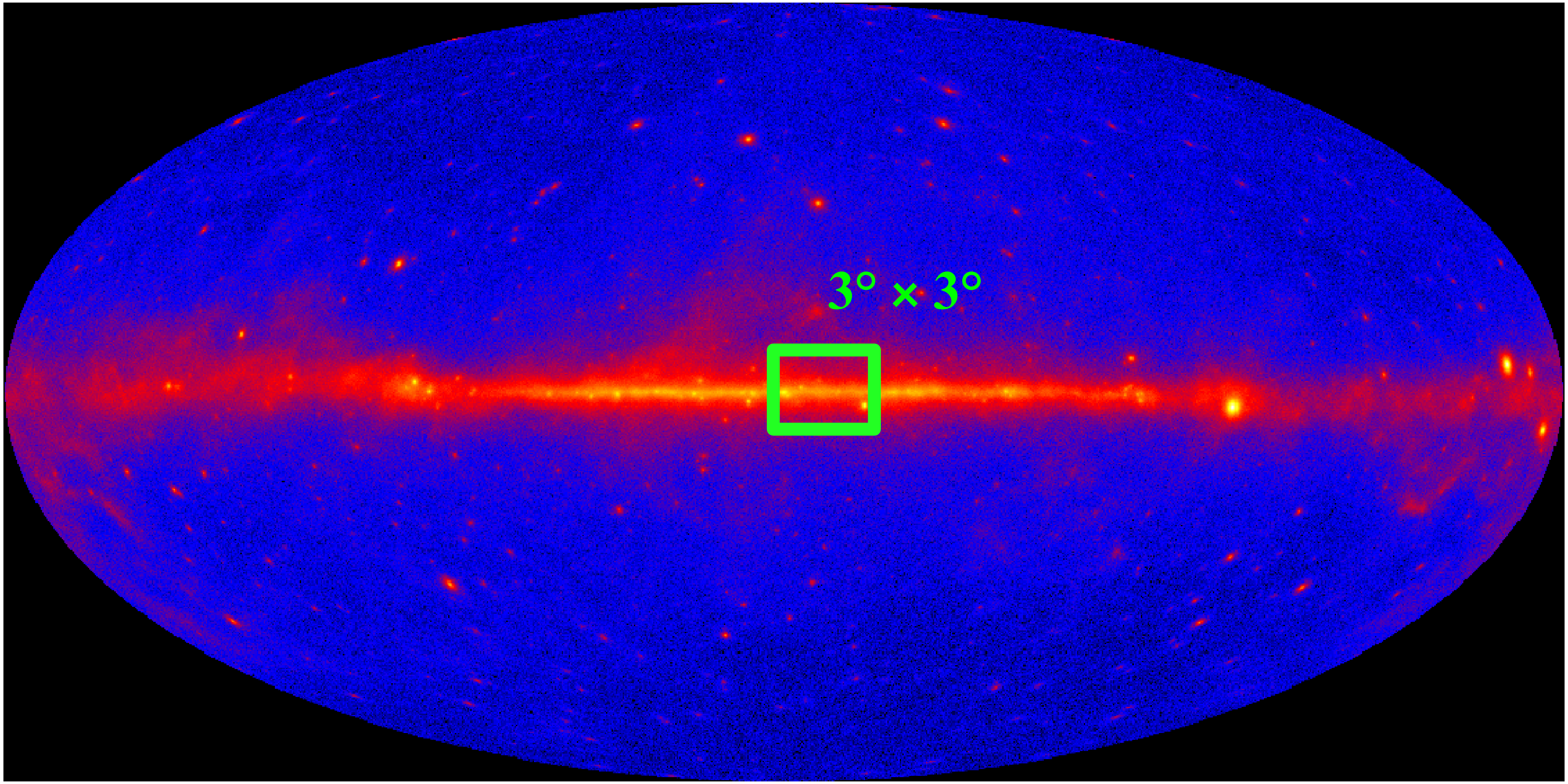



**Features in the energy spectrum**

Kuhlen, Diemand, Madau

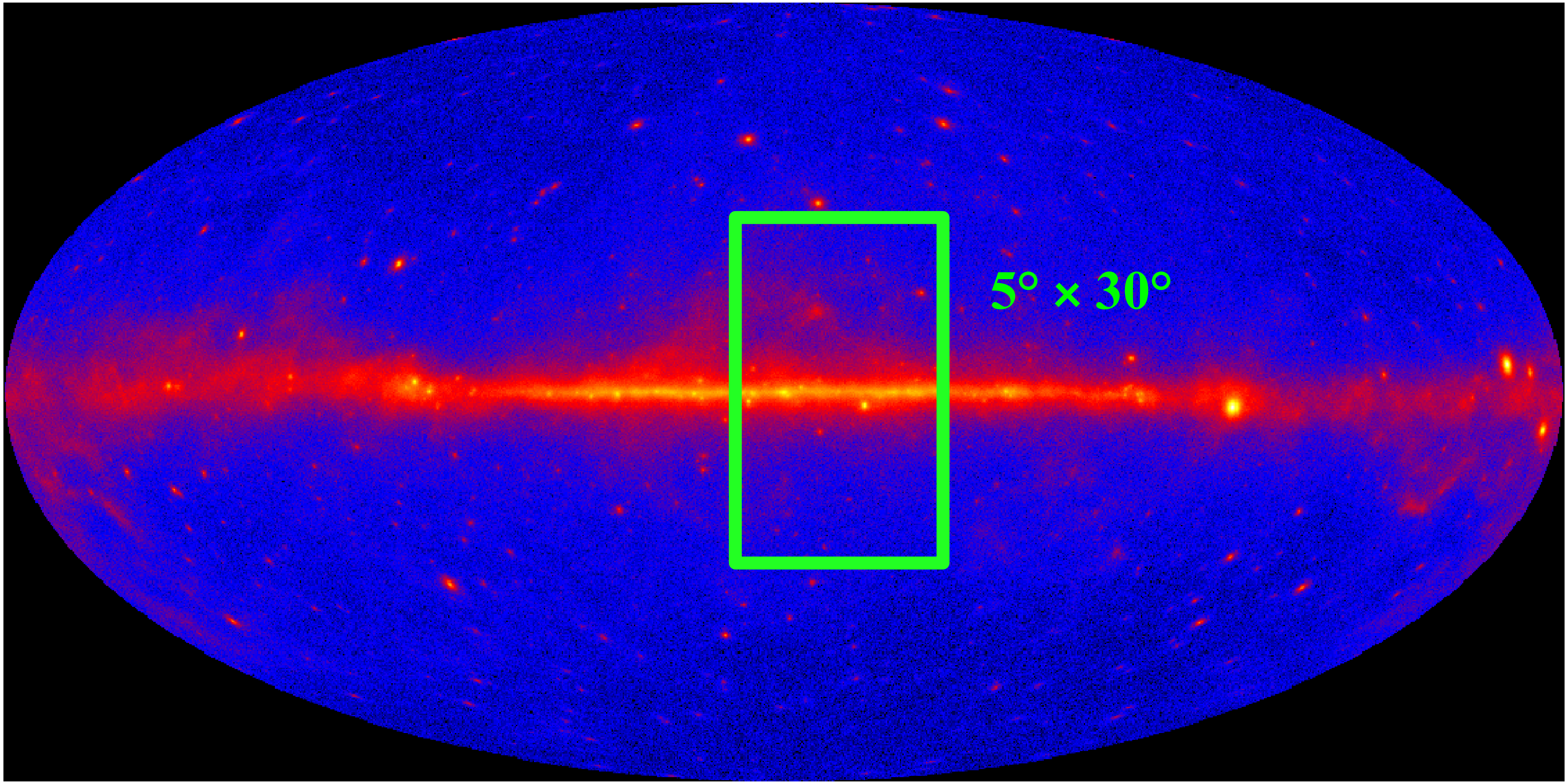
# Diffuse Galactic emission

Divide the sky in different regions:



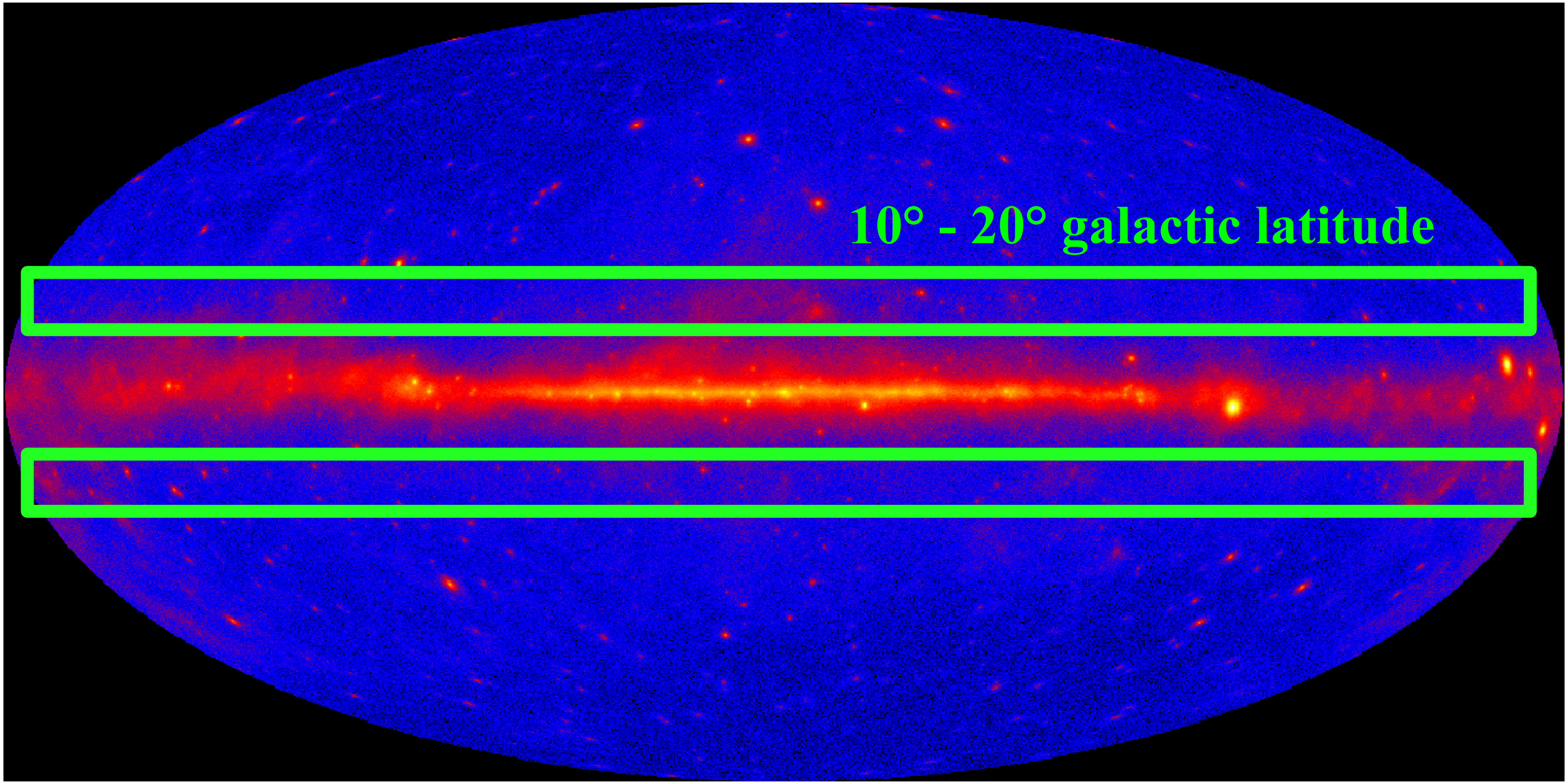
# Diffuse Galactic emission

Divide the sky in different regions:



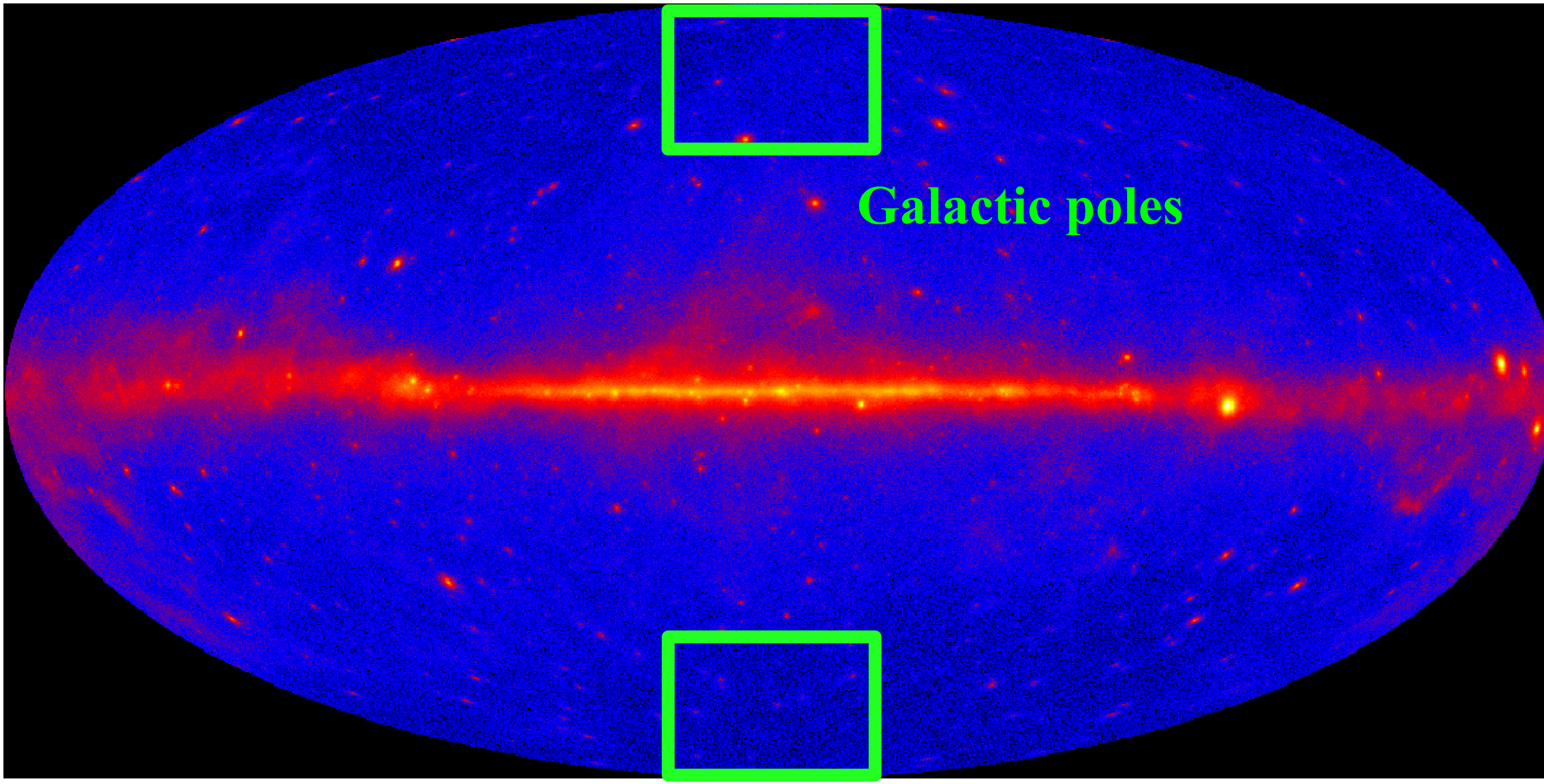
# Diffuse Galactic emission

Divide the sky in different regions:



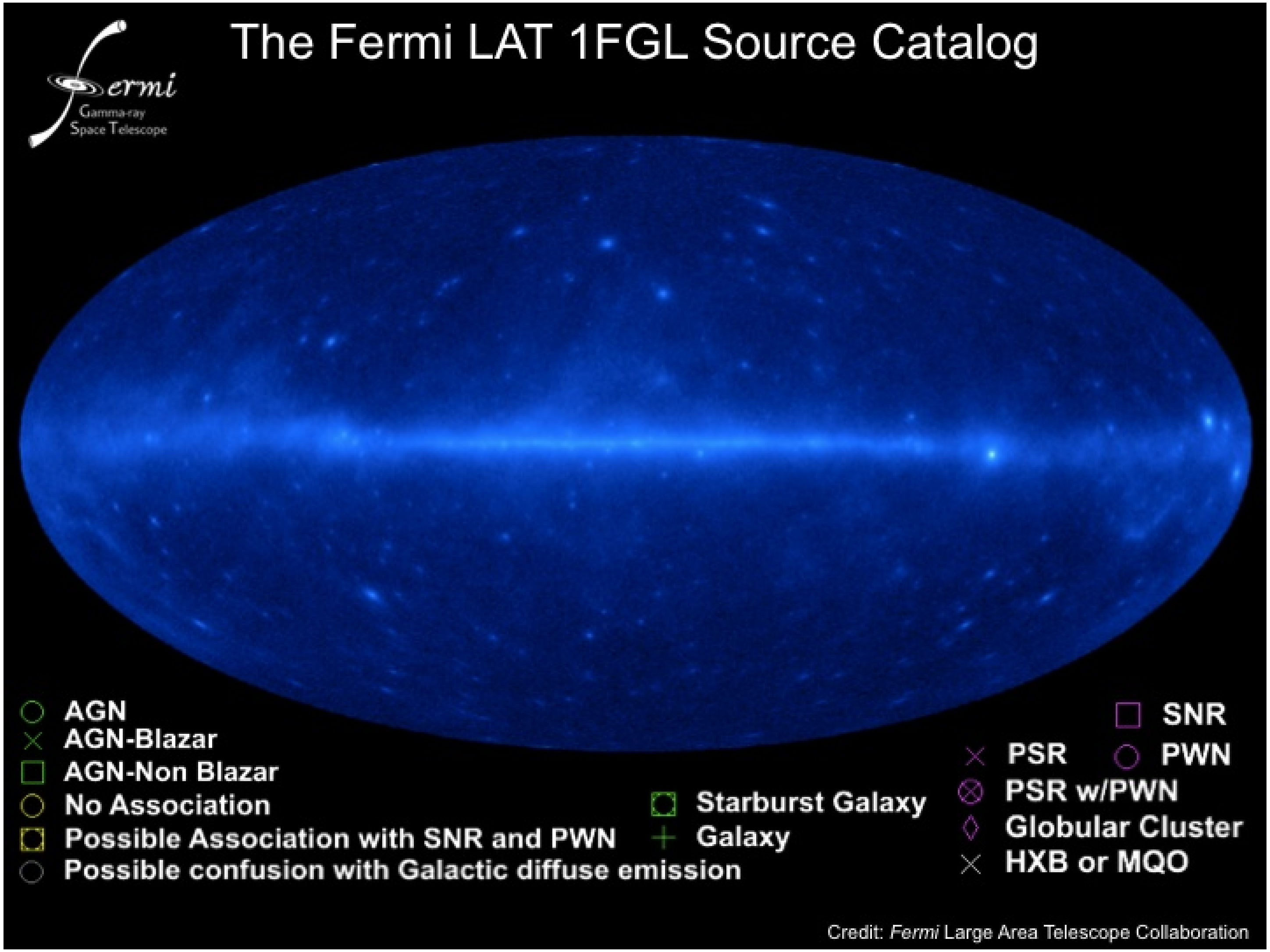
# Diffuse Galactic emission

Divide the sky in different regions:

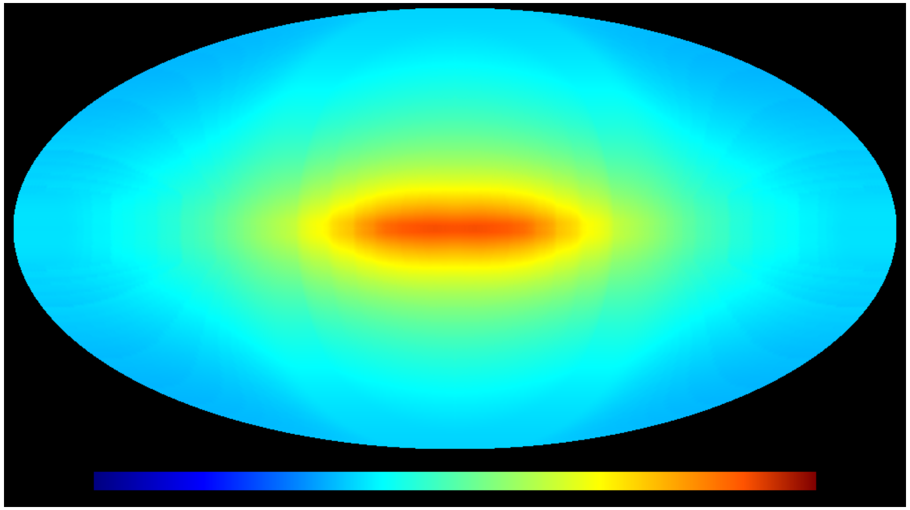


But beware of backgrounds when searching for dark matter...

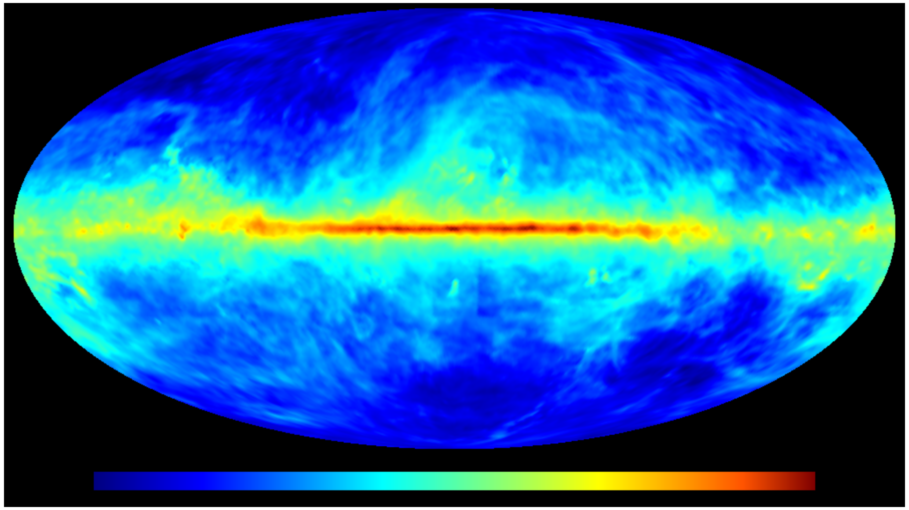
Background I: sources



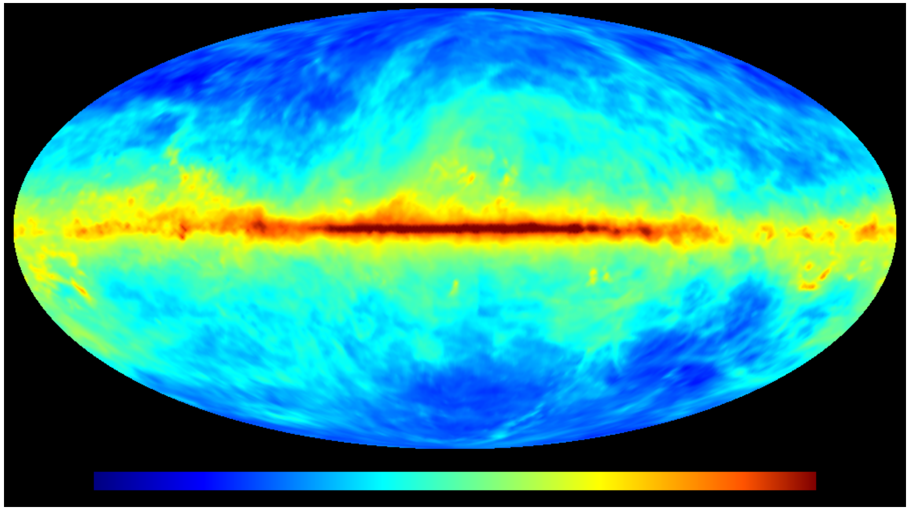
# Background II: modelling of the diffuse emission



Inverse Compton

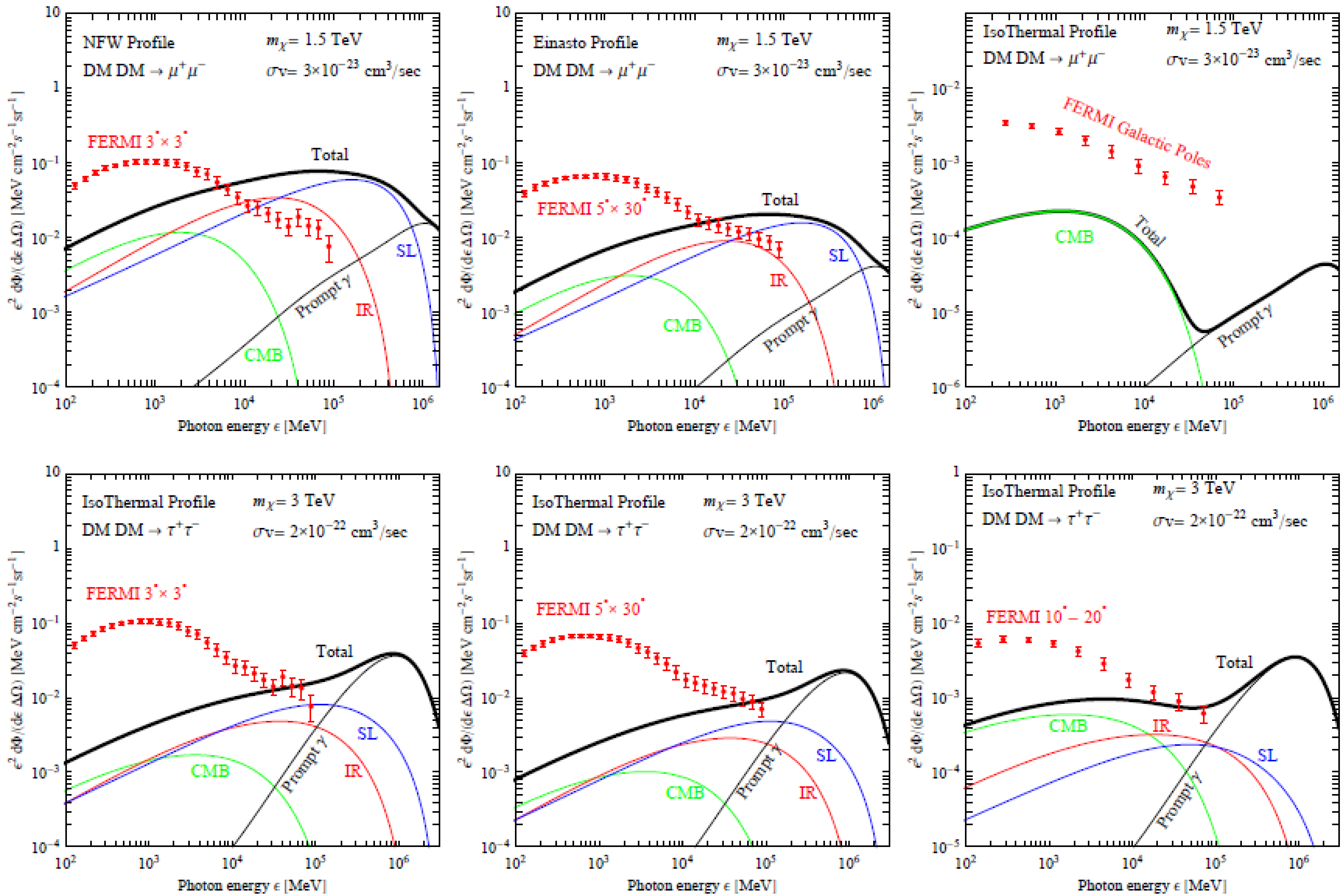


Bremmstrahlung

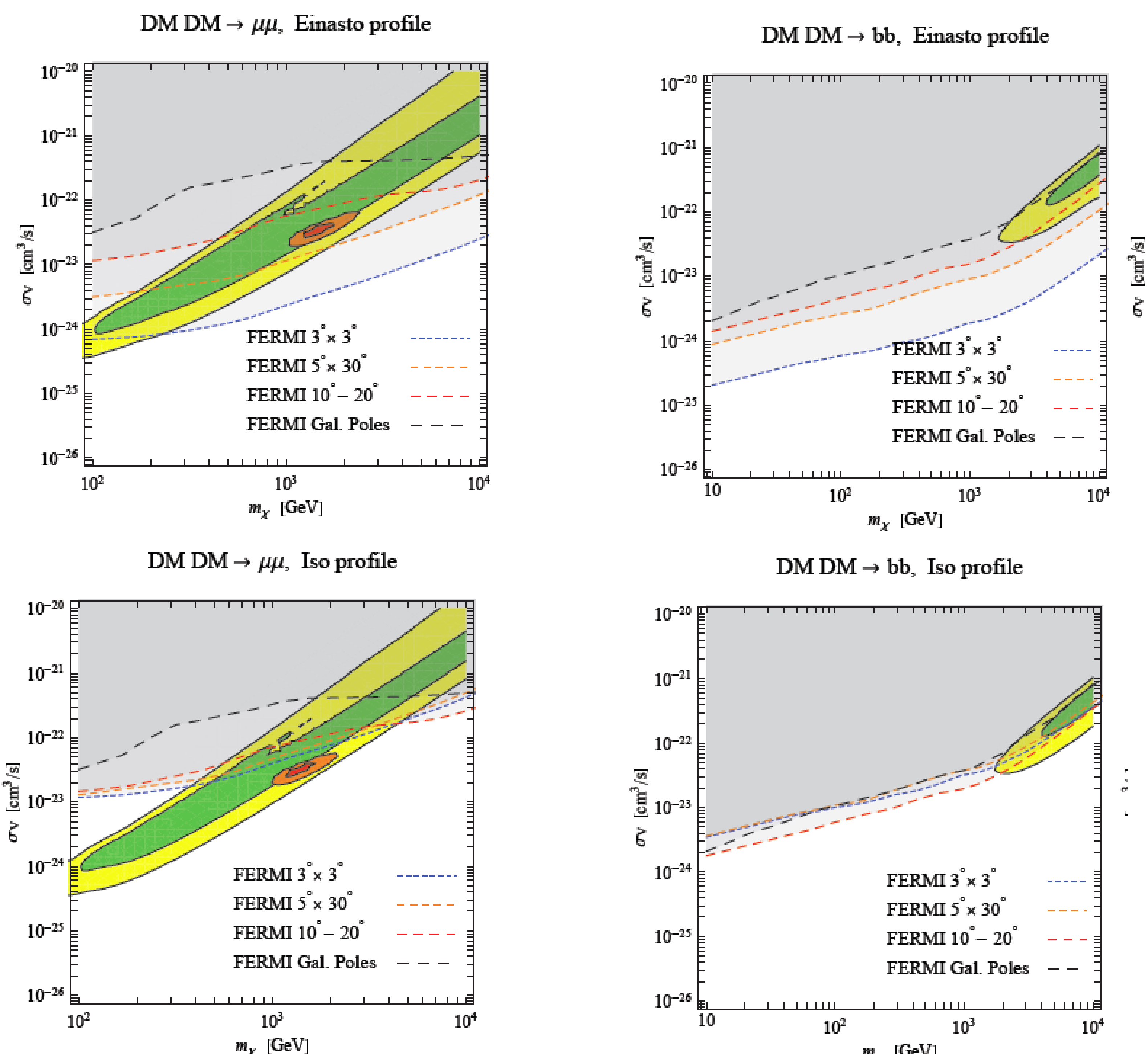


$\pi^0$-decay

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

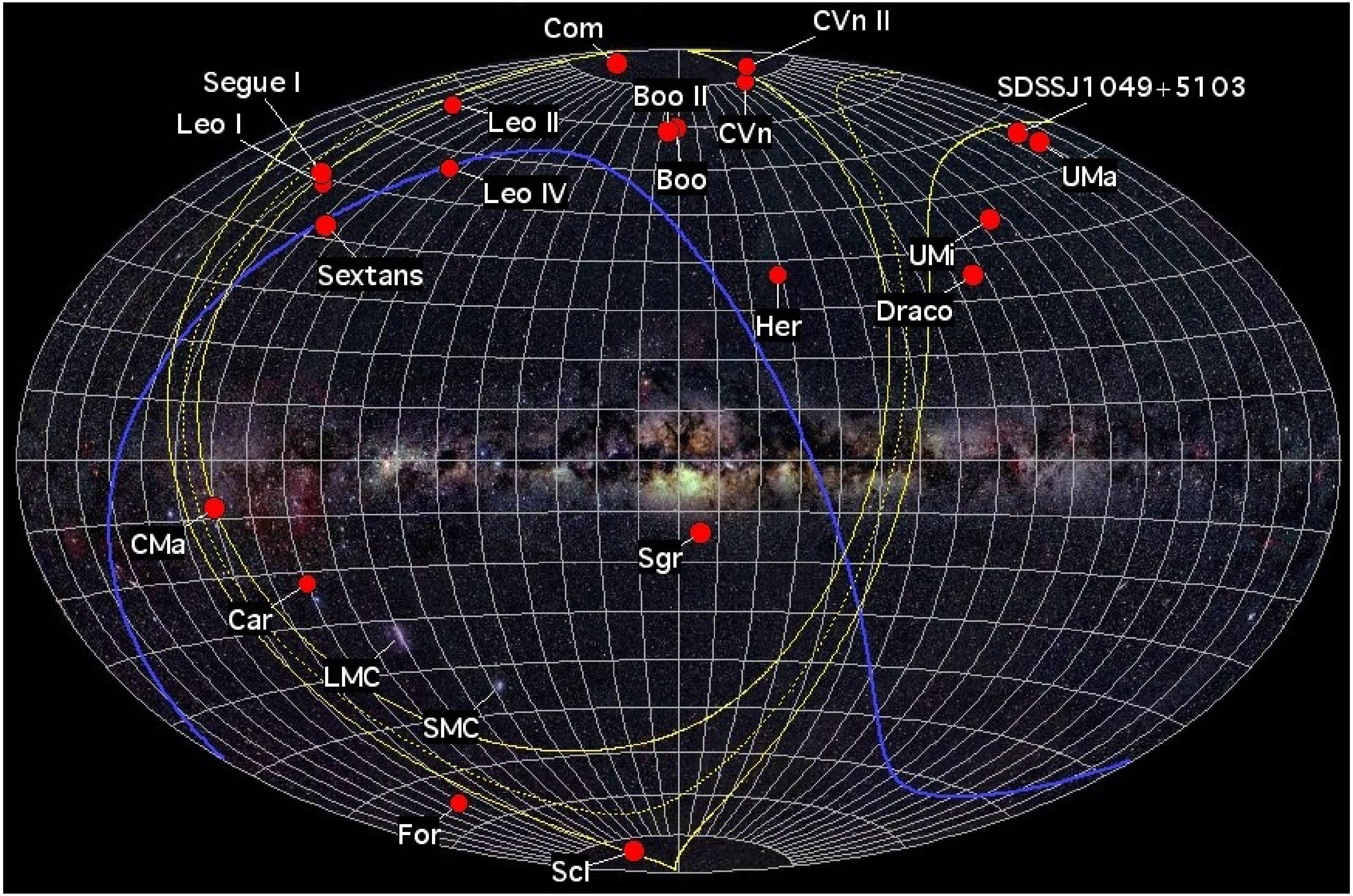



Cirelli, Panci, Serpico




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 | 18000?? | 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

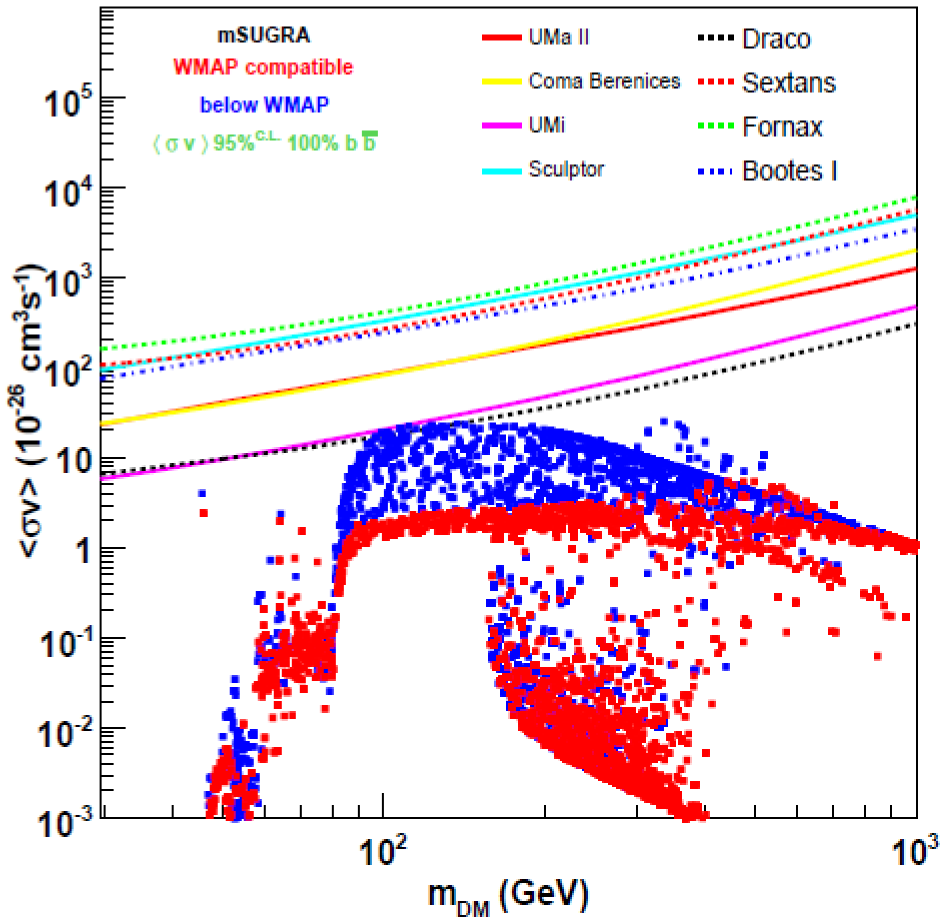
Assume a Navarro-Frenk-White dark matter halo profile inside the tidal radius:

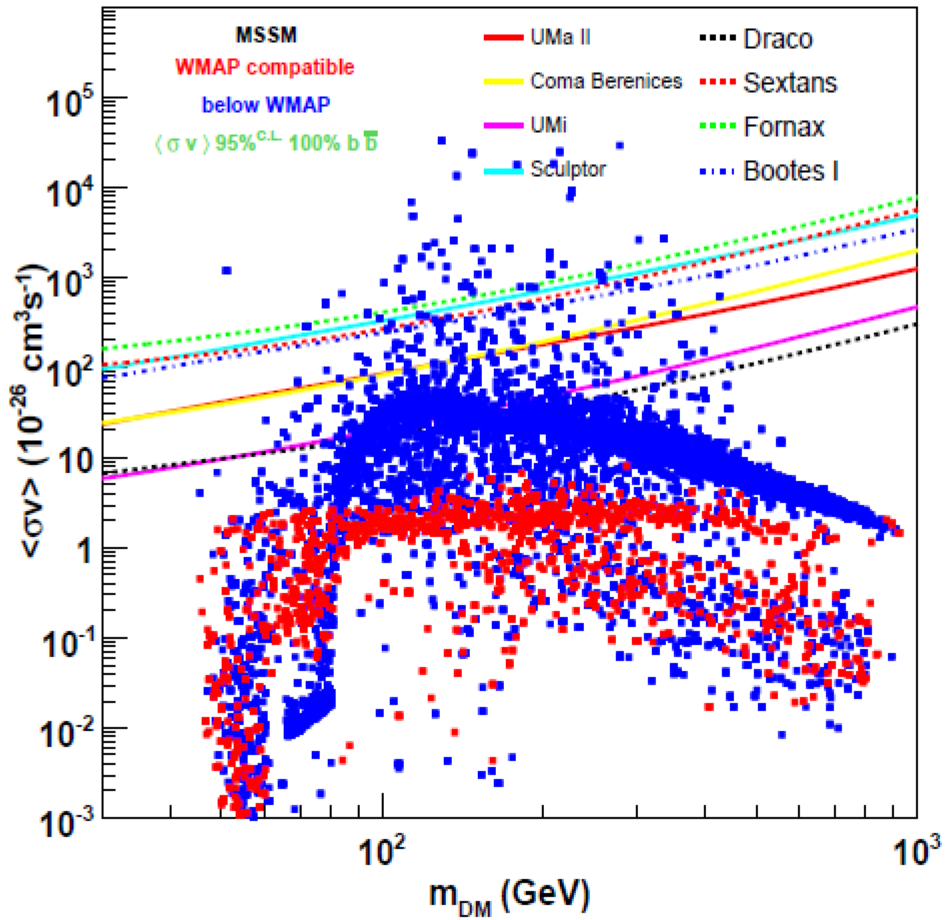
$$\rho(r) = \begin{cases} \frac{\rho_s r_s^3}{r(r_s+r)^2} & \text{for} \quad r < r_t \\ 0 & \text{for} \quad r \geq r_t \end{cases}$$

| Name | $\rho_s$ ($M_\odot\ pc^{-3}$) | $r_s$ ($kpc$) | $J^{NFW}$ ($10^{19} GeV^2 cm^{-5}$) |
|---|---|---|---|
| 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

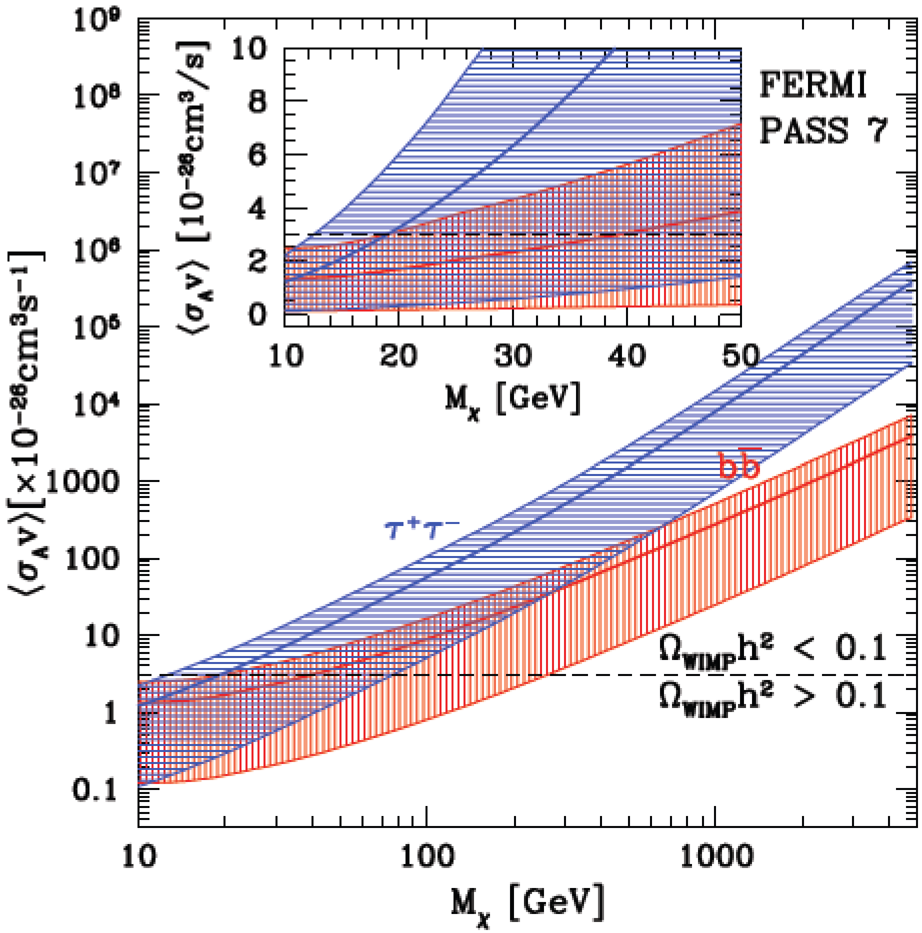


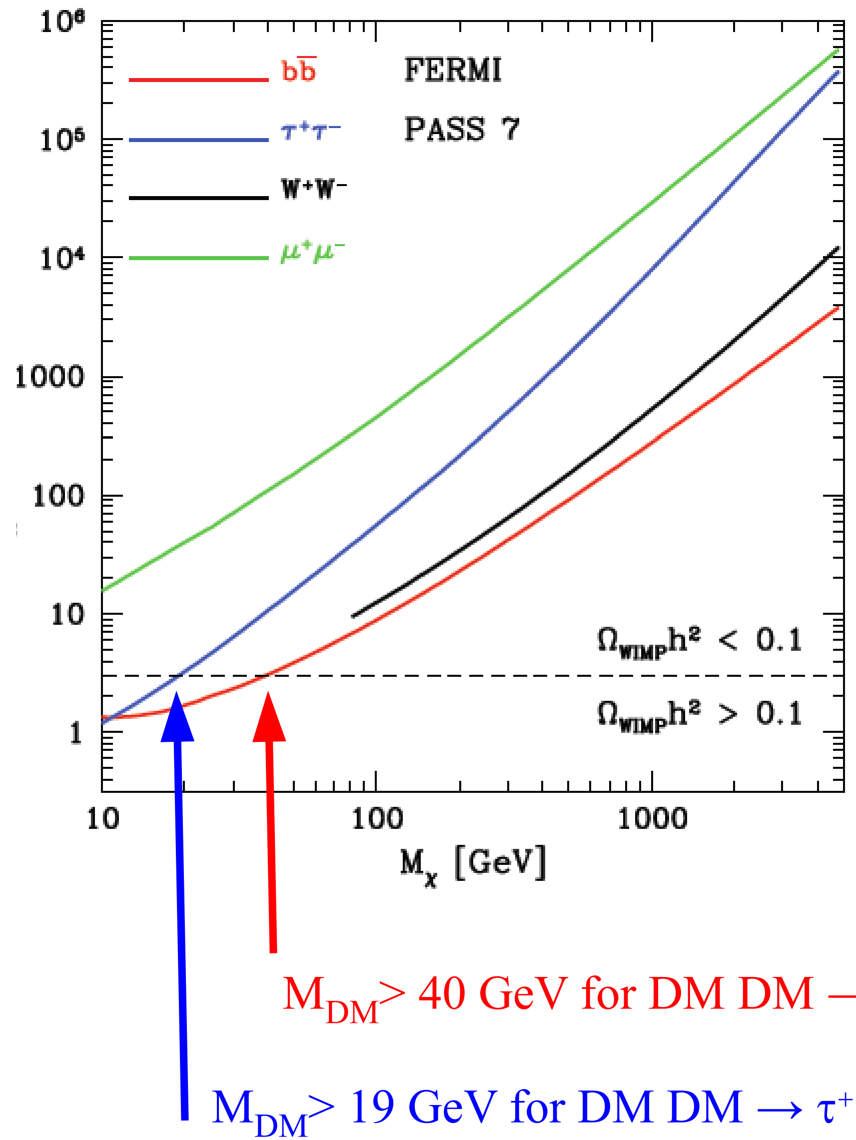




Fermi coll.
arXiv:1001.4531

# Closing in on light WIMP scenarios from dwarf galaxy observations

Geringer-Sameth, Koushiappas '11



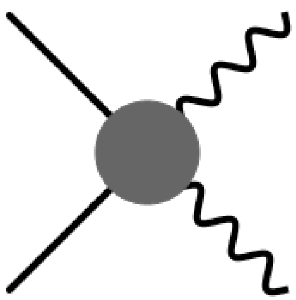
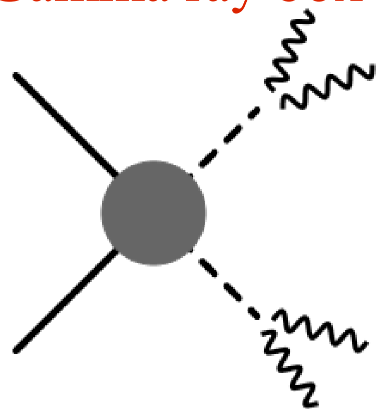
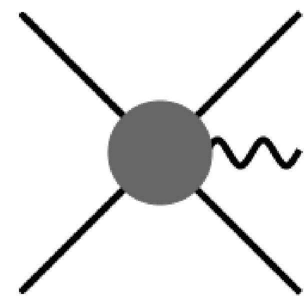

$M_{DM}$> 40 GeV for DM DM $\rightarrow b\,\bar{b}$

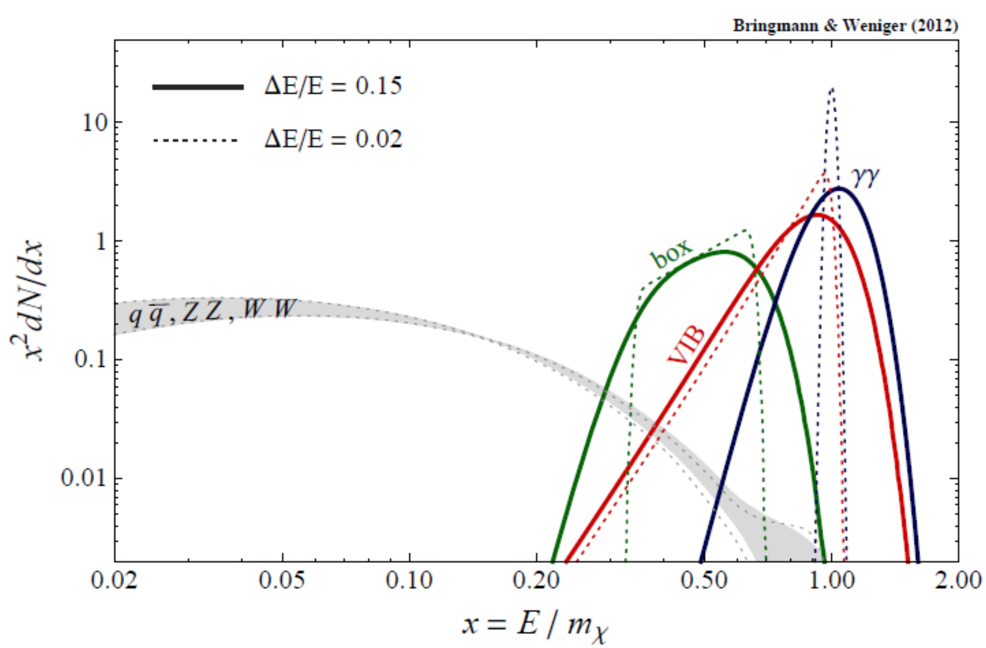
$M_{DM}$> 19 GeV for DM DM $\rightarrow \tau^+\,\tau^-$

# Gamma-ray features

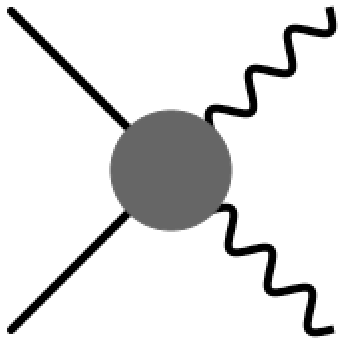
"Smoking gun" for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

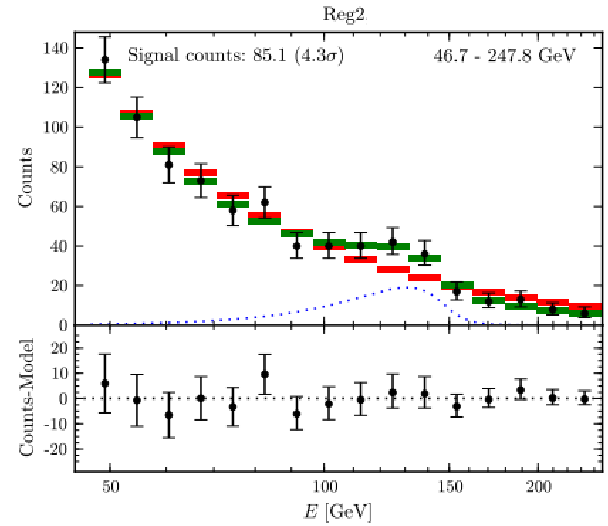
Three gamma-ray spectral features have been identified:

| Gamma ray line | Gamma ray box | Internal bremsstrahlung |
| --- | --- | --- |
|  |  |  |

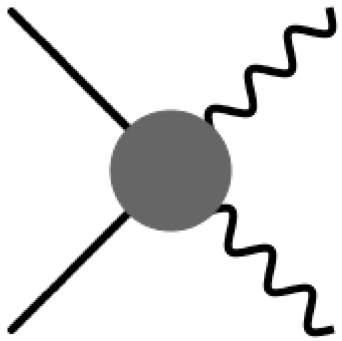


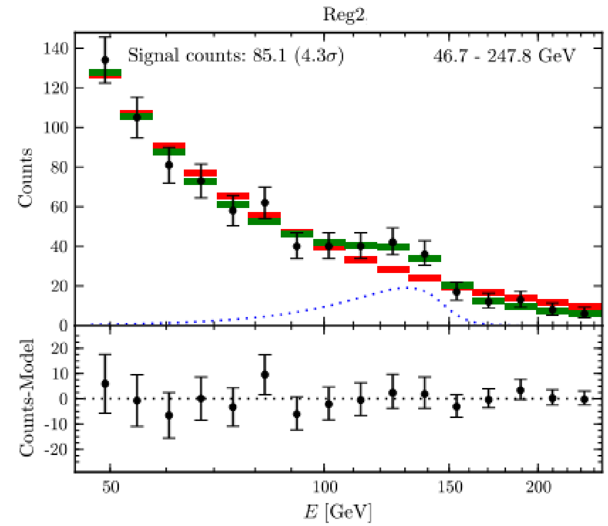
# Gamma-ray lines

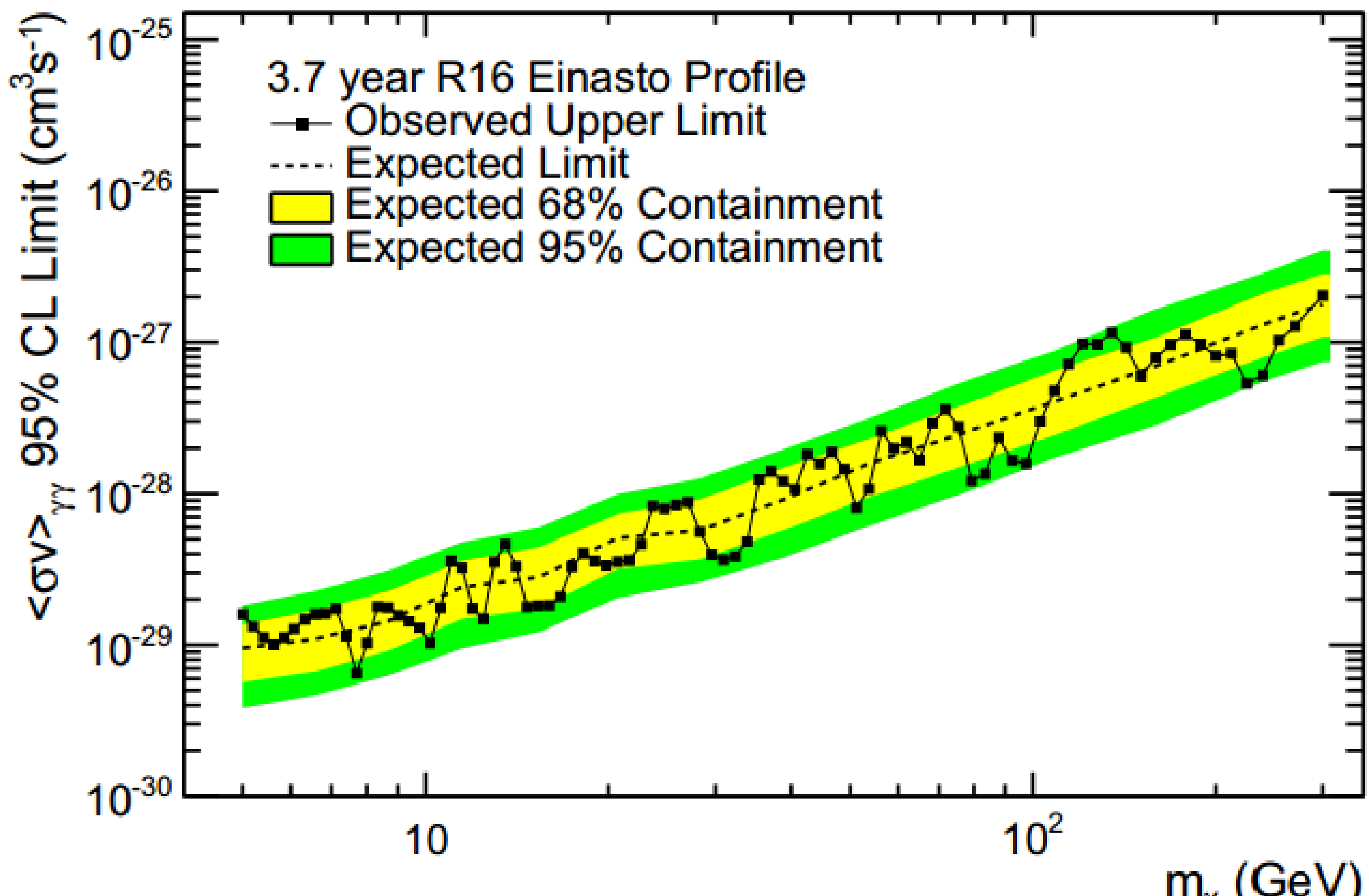




# Gamma-ray lines

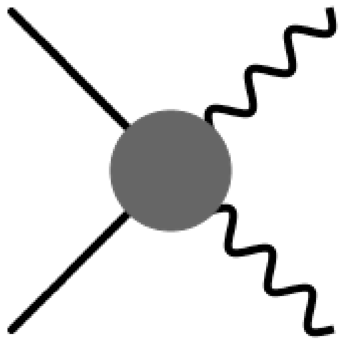


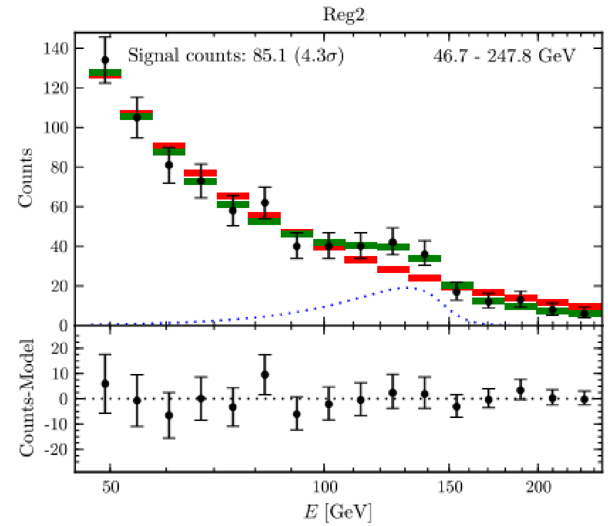


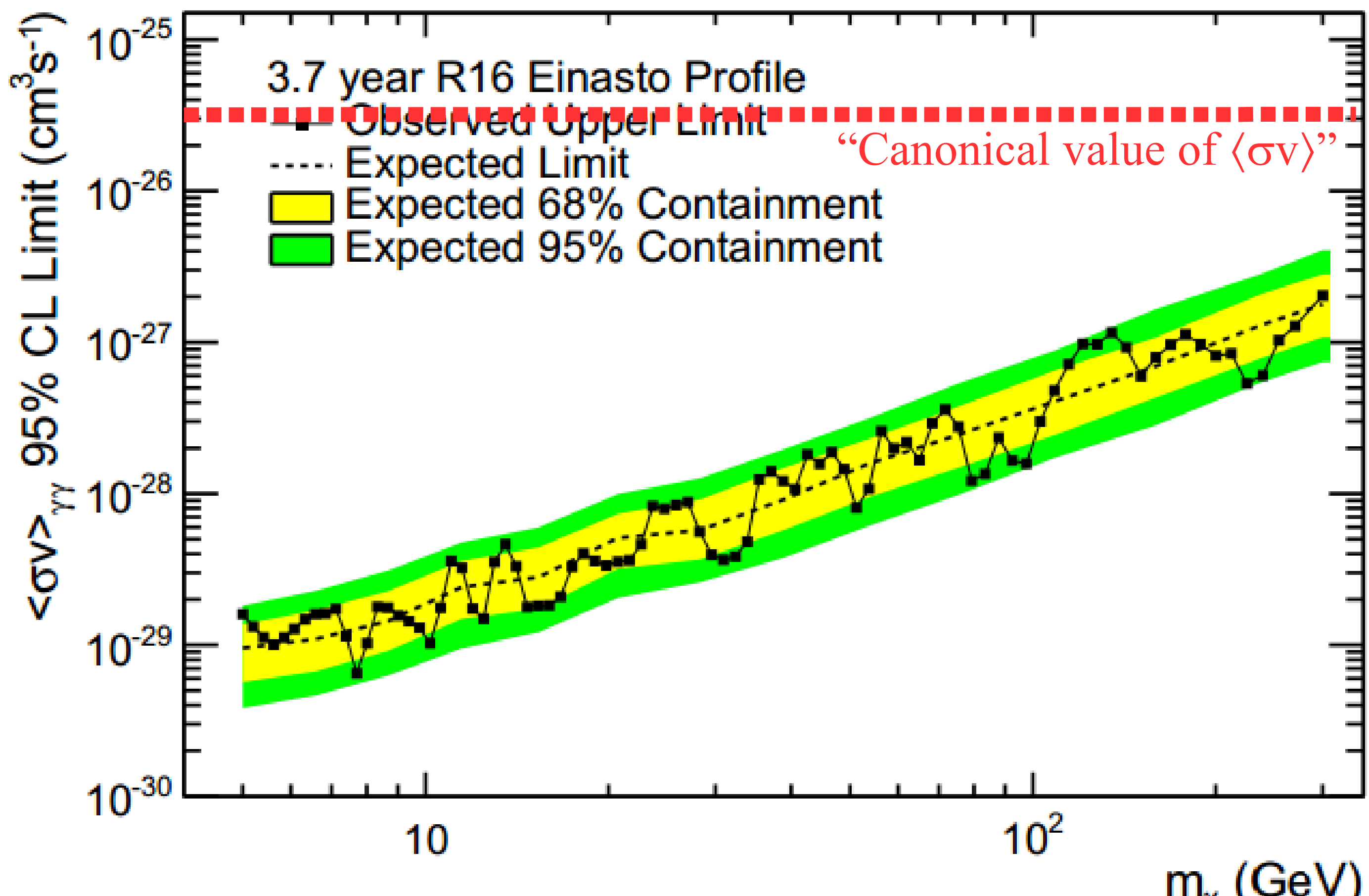




Fermi-LAT col.
arXiv:1305.5597

# Gamma-ray lines

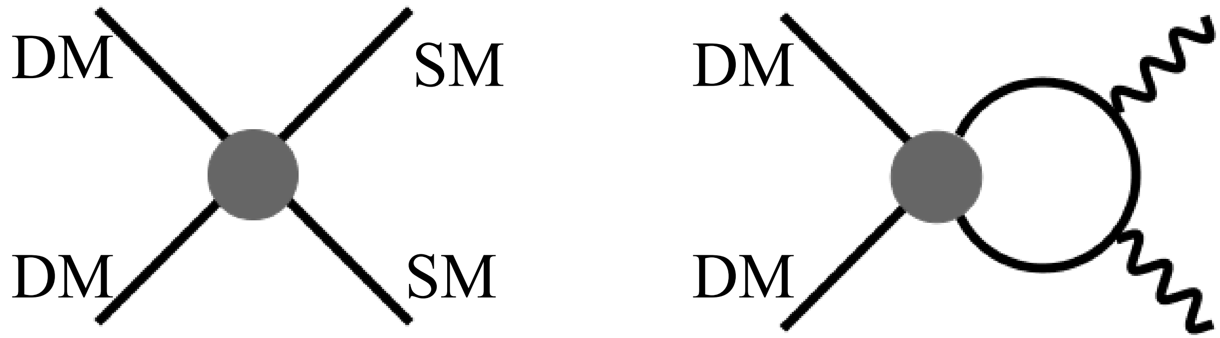




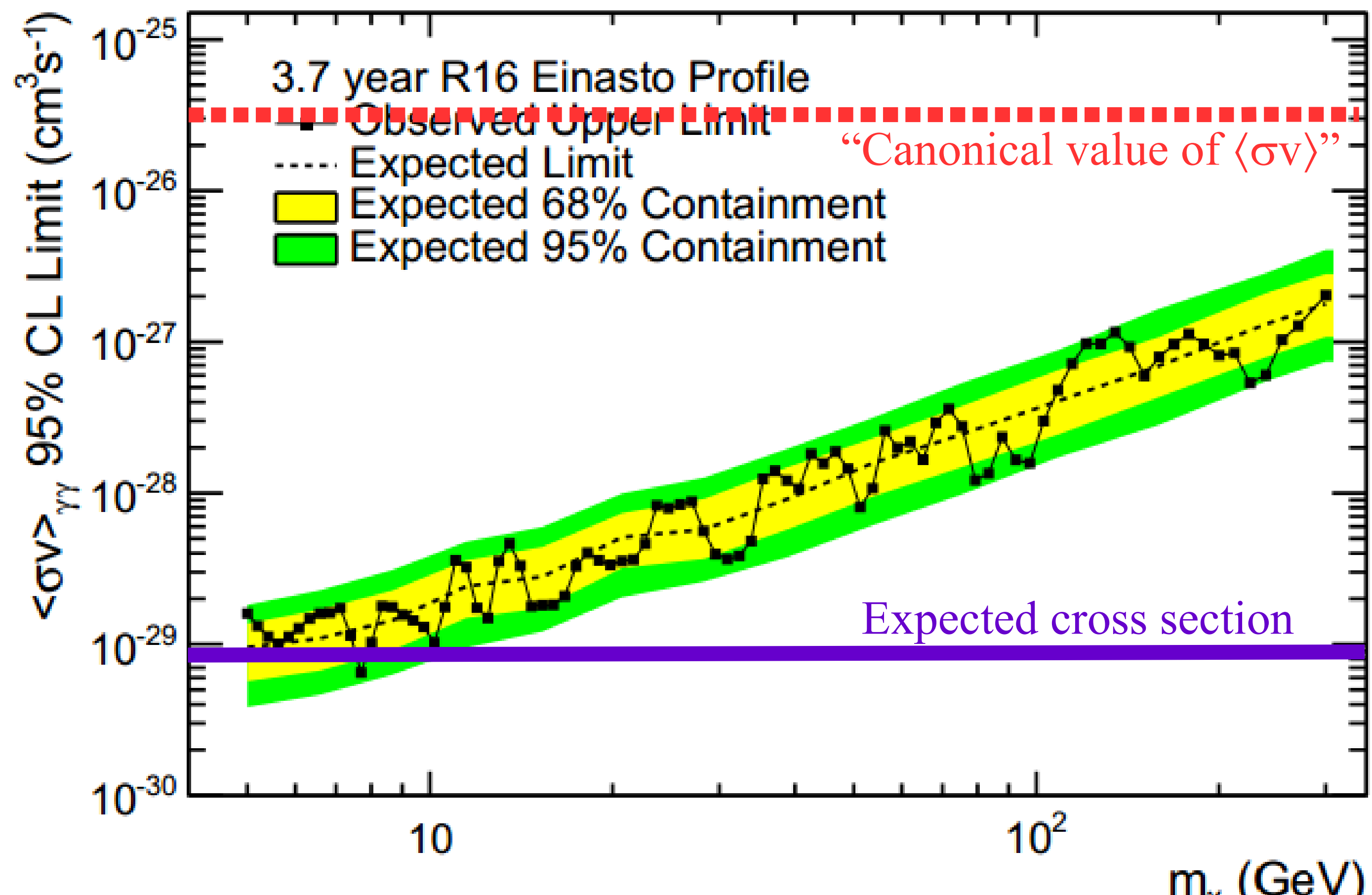




Fermi-LAT col.
arXiv:1305.5597

# Gamma-ray lines

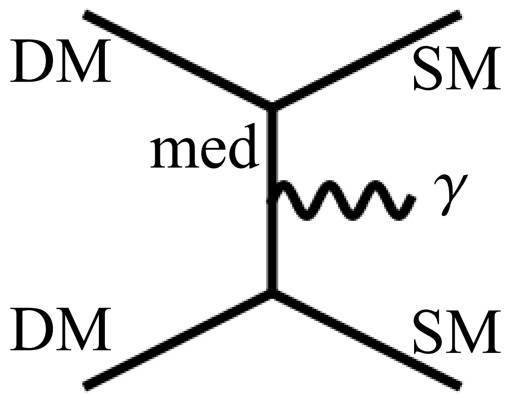


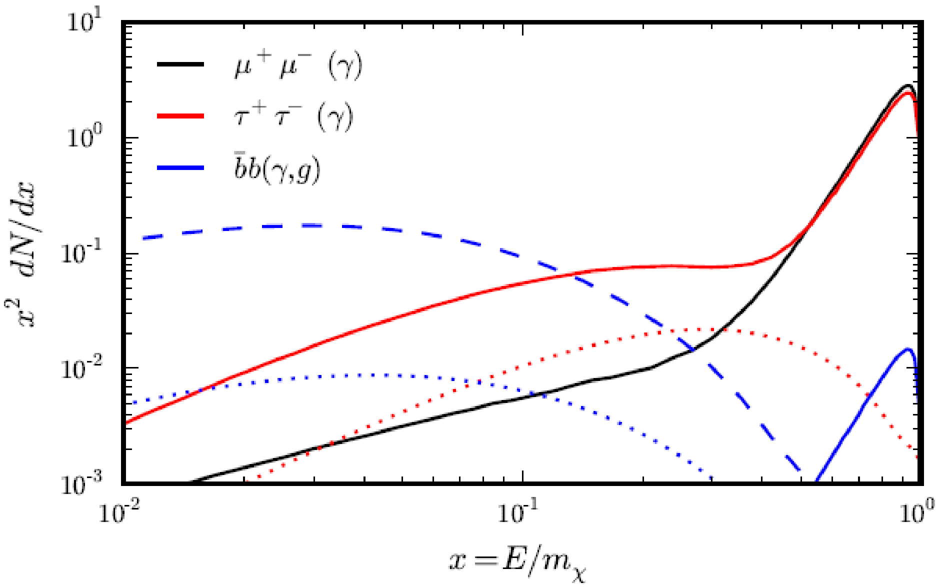

$$(\sigma v)_{\gamma\gamma} \sim \mathcal{O}(\alpha^2)(\sigma v)_{\rm thermal} \sim 10^{-30} {\rm cm}^3 {\rm s}^{-1}$$



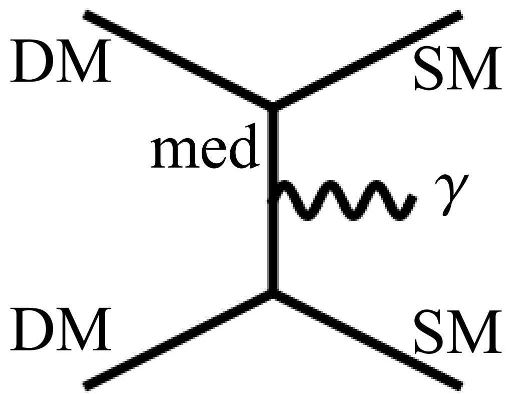

Fermi-LAT col.
arXiv:1305.5597

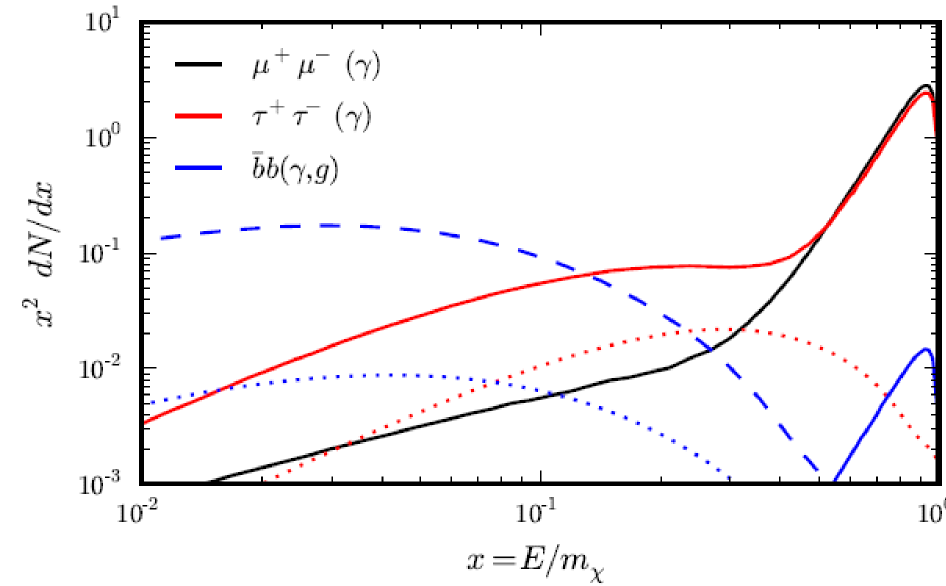
# Internal Bremsstrahlung

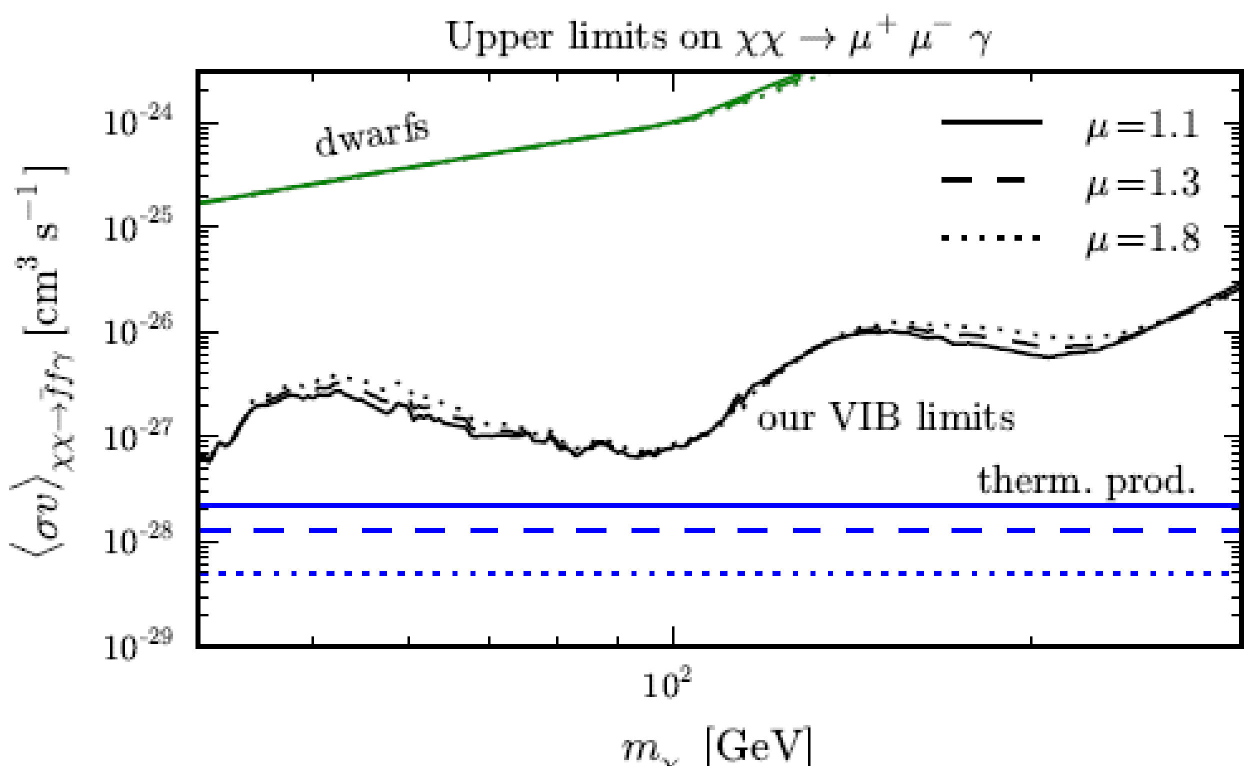


# Internal Bremsstrahlung

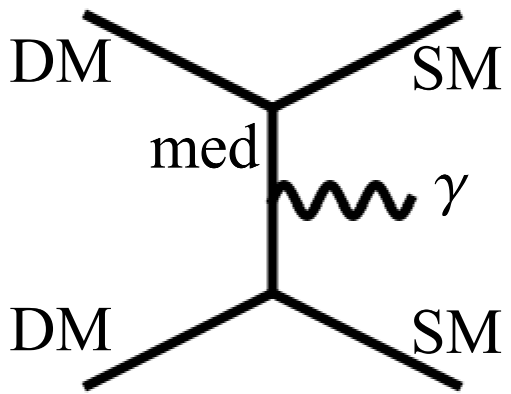


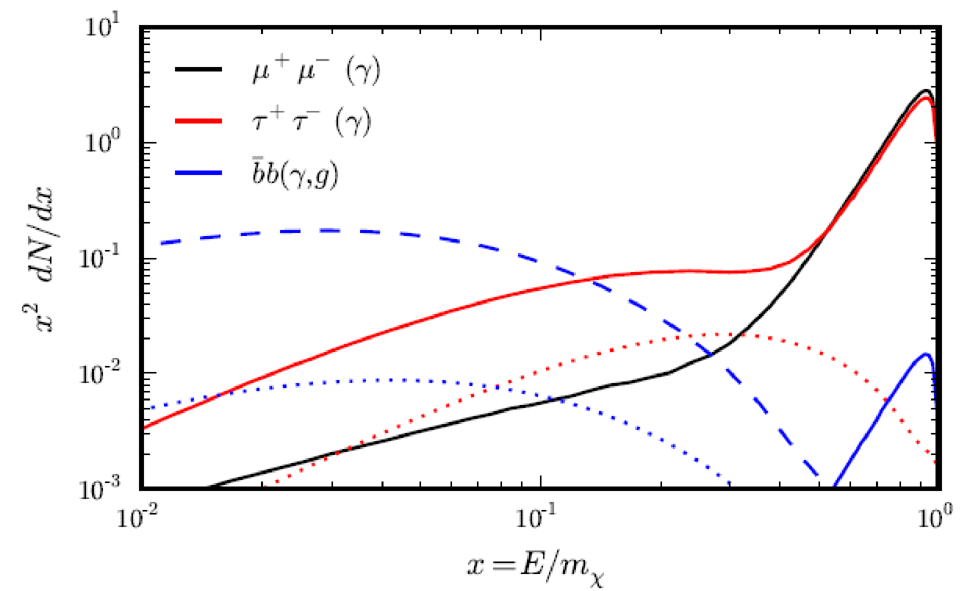



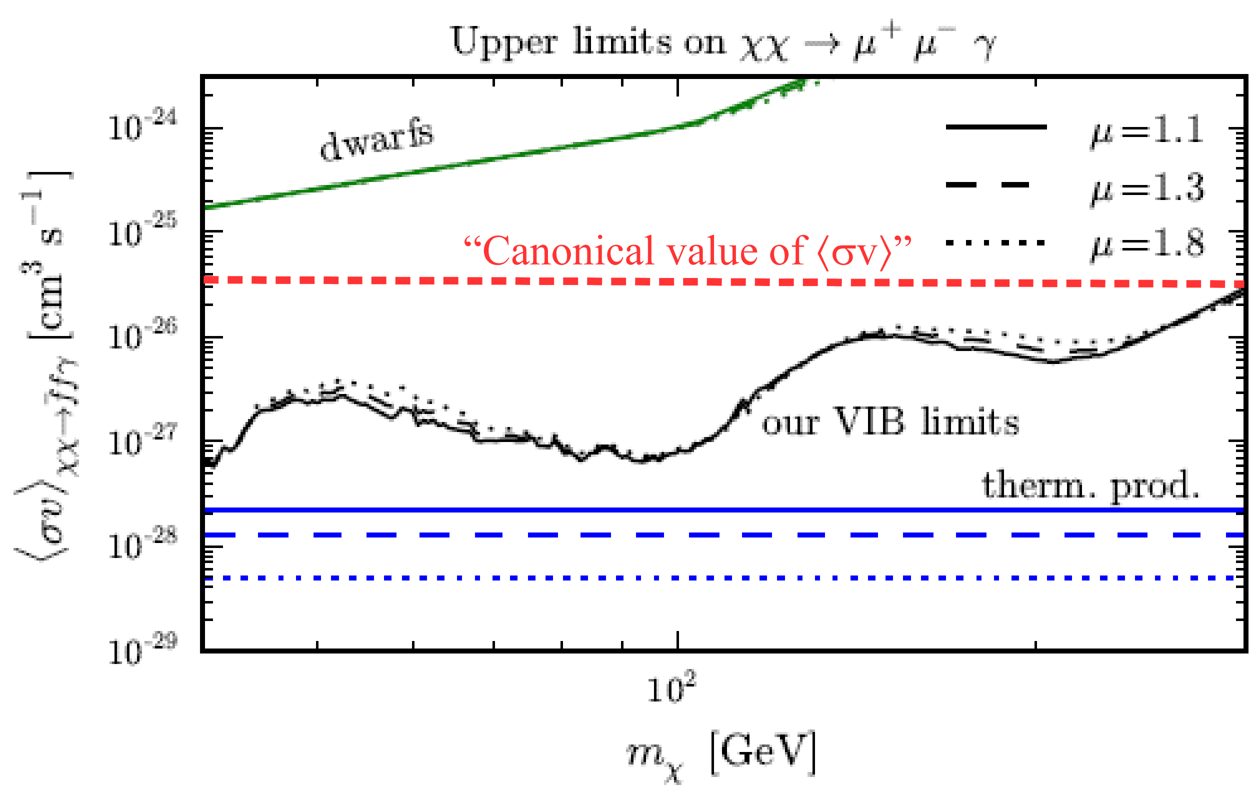




Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

# Internal Bremsstrahlung

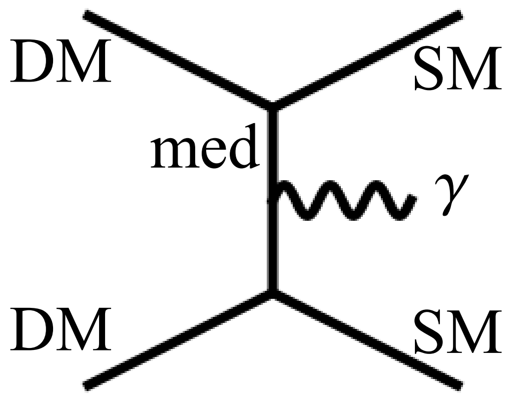


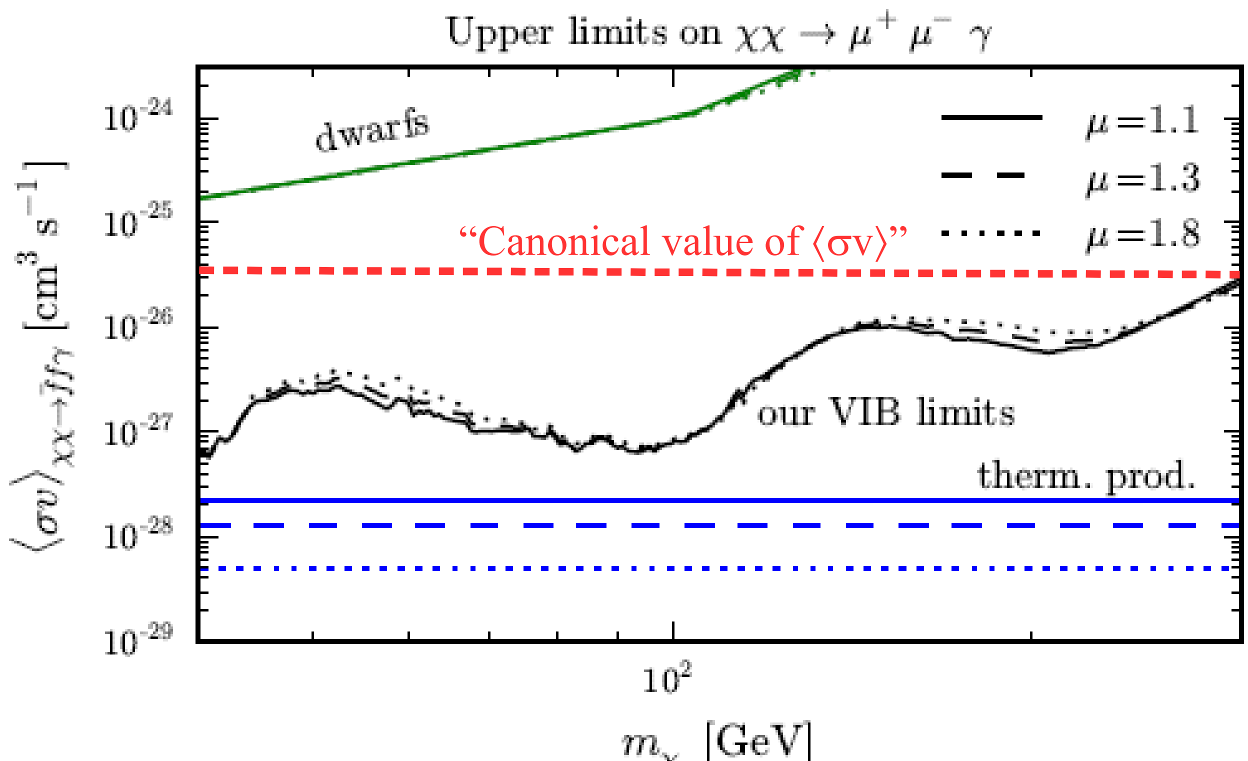




Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

# Internal Bremsstrahlung



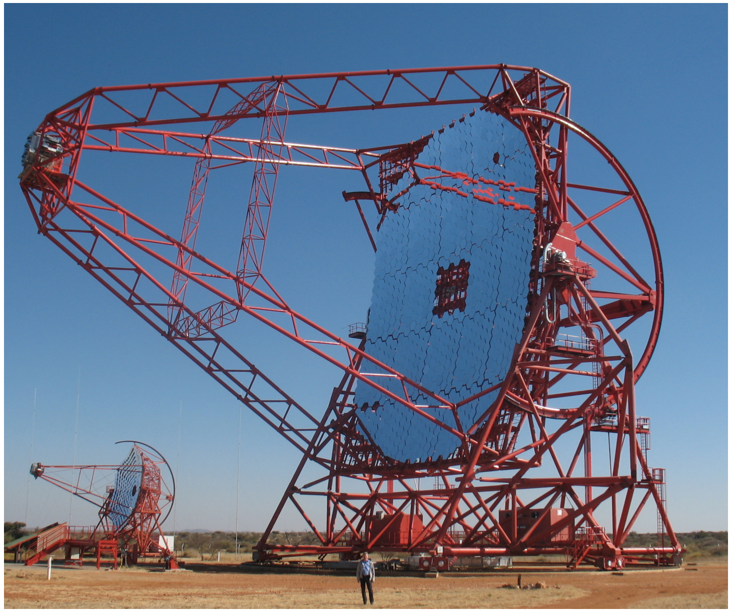

$$\langle \sigma v \rangle^{2\to3}_{G.C.} \sim \frac{\alpha}{0.3\pi} \langle \sigma v \rangle^{2\to2}_{f.o.} \sim 10^{-28} \mathrm{cm}^3 \mathrm{s}^{-1}$$



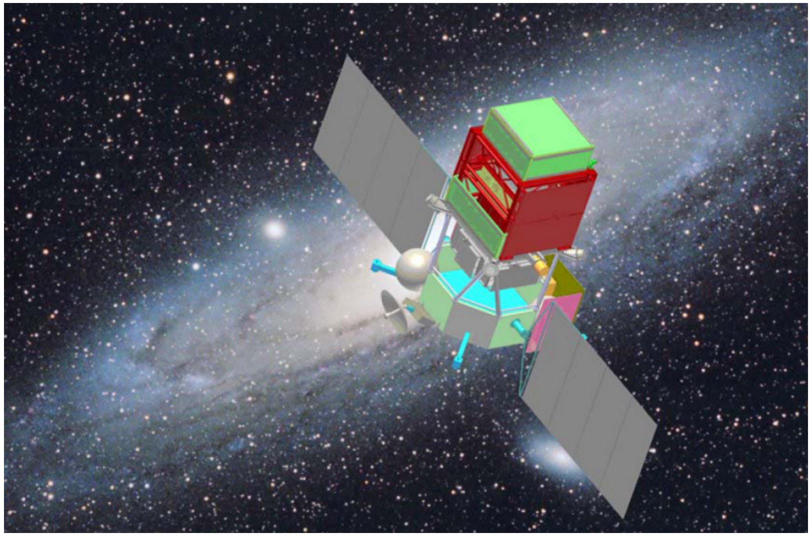

Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

# Bright future for dark matter searches using gamma-rays!

H.E.S.S. II – in operation

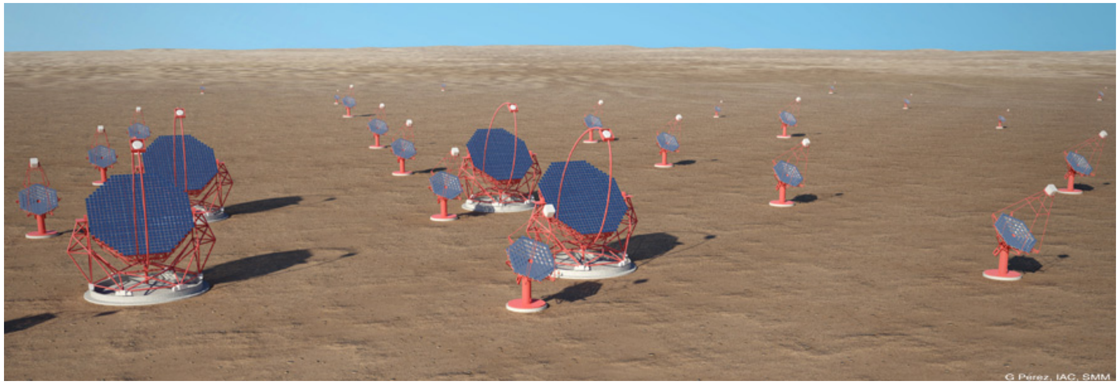


GAMMA 400 – Launch in 2018



DAMPE – Launch in 2015

CTA – Construction starting in 2017



# Direct
# Dark Matter
# Searches

# Direct dark matter searches

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## 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.

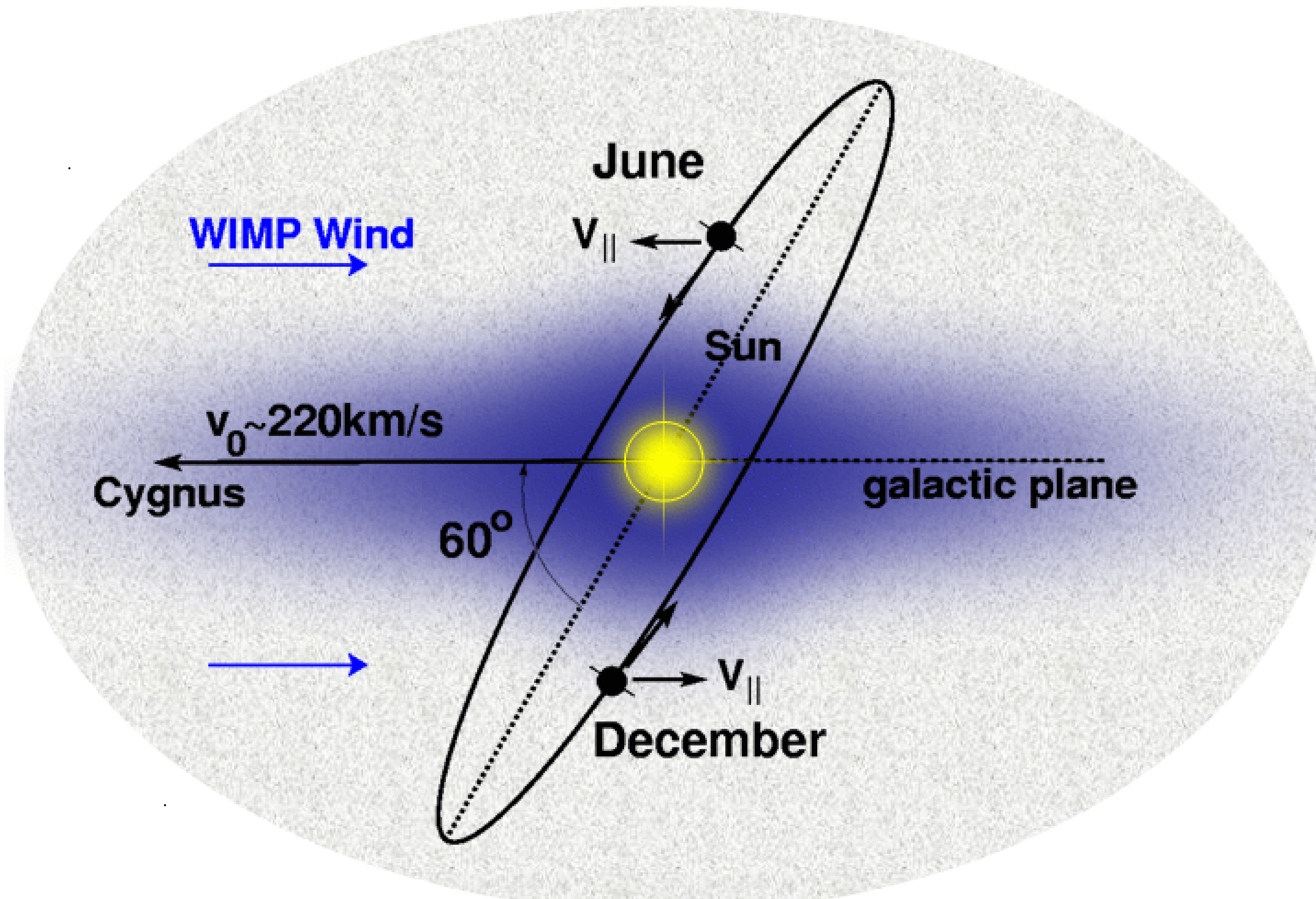
2) Once in a while a dark matter particle will interact with a nucleus.

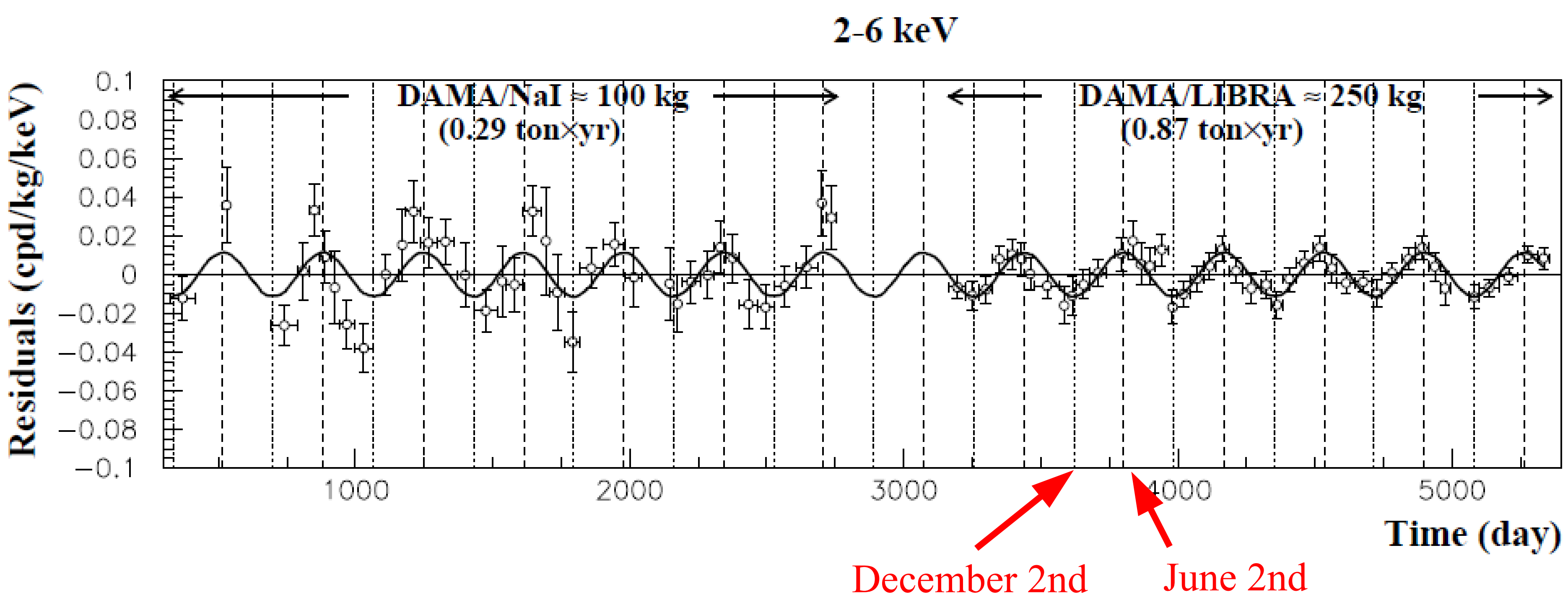
3) The nucleus gains momentum and recoils. The existence of dark matter can then be inferred if there is a significant excess in the number of recoils compared to the expected recoils induced by natural radiactivity in your lab or in your detector.

Simple idea ...

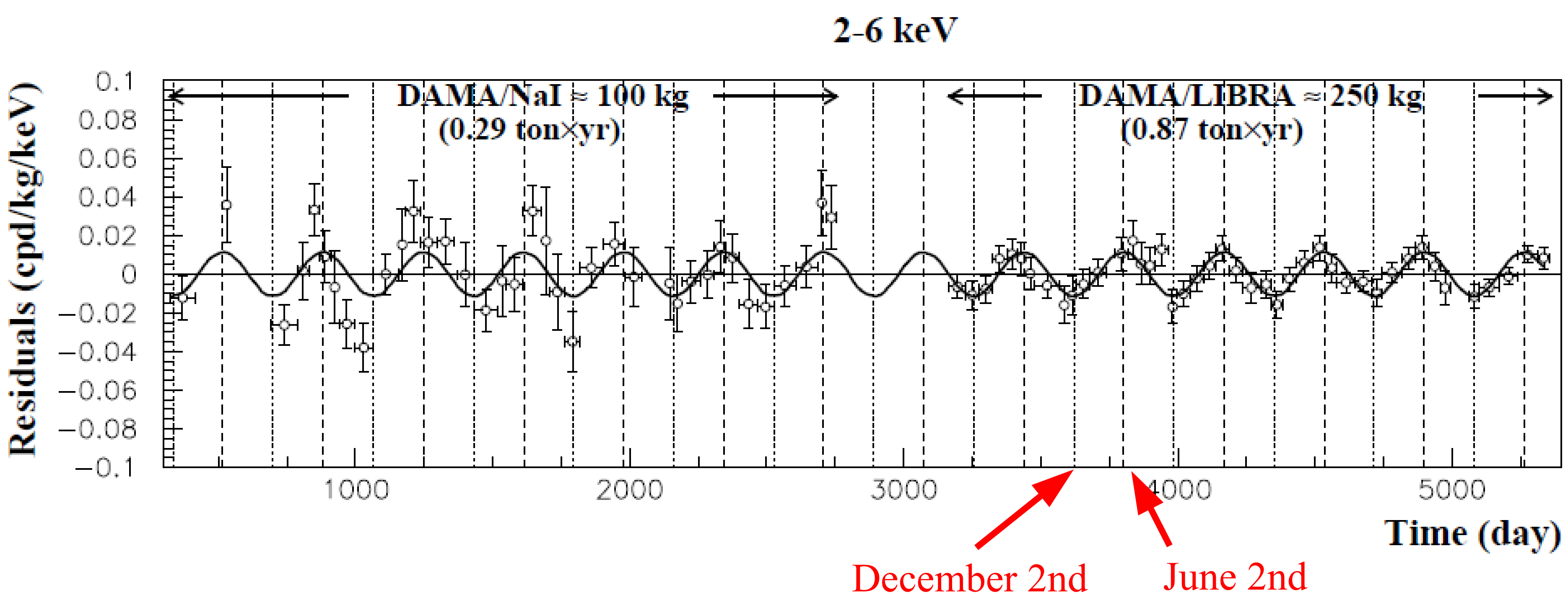
… but very challenging in practice!

# Annual modulation

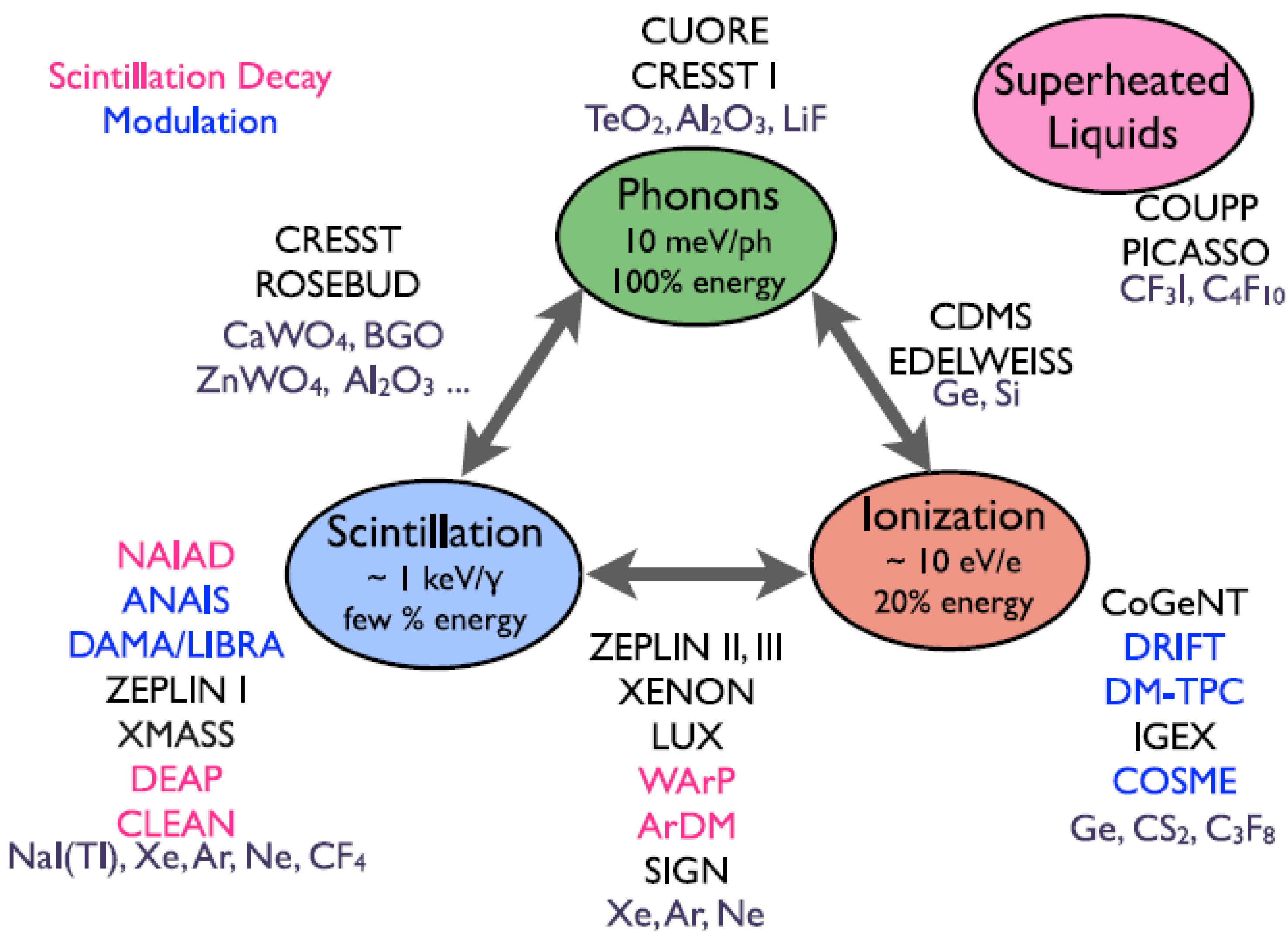


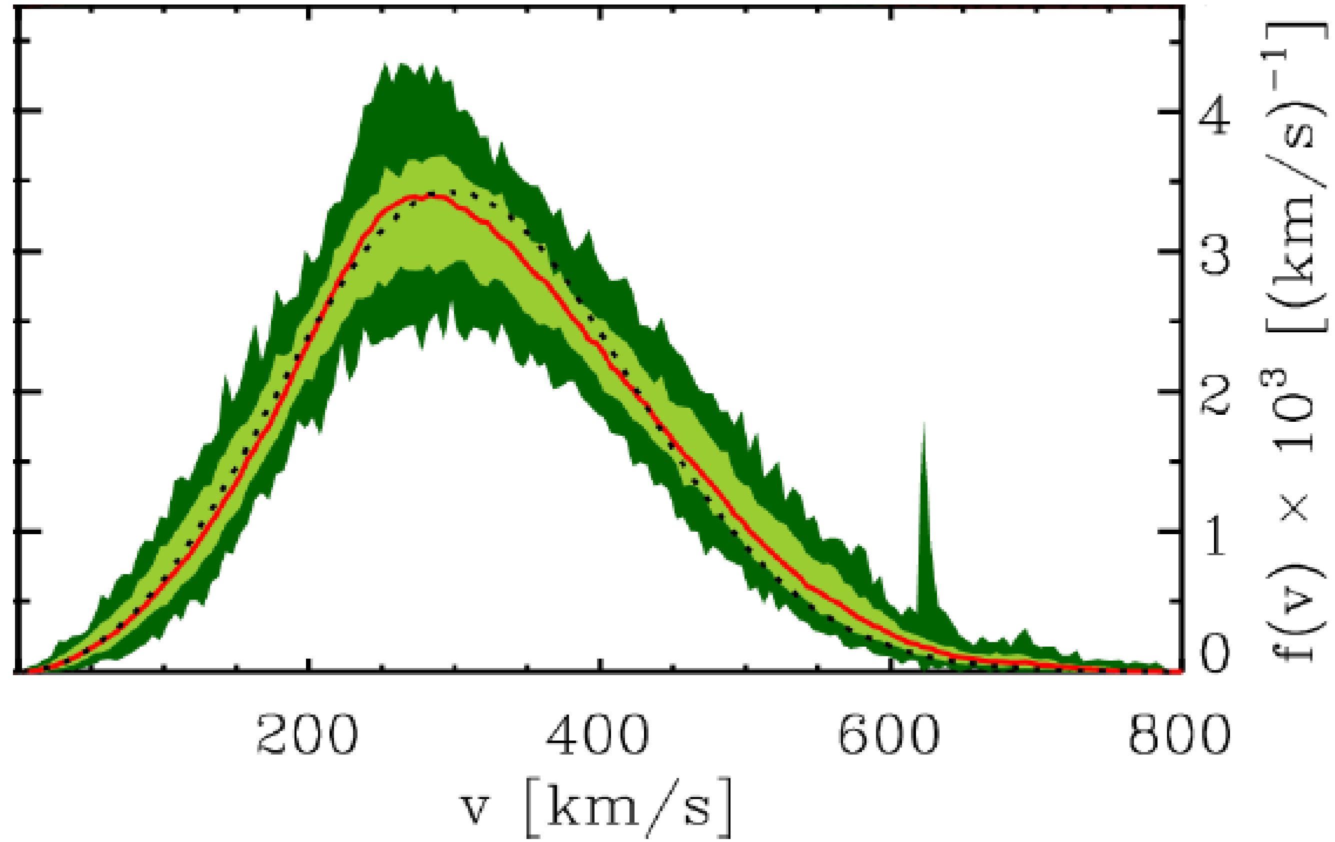


2-6 keV
DAMA/NaI ≈ 100 kg
(0.29 ton×yr)
DAMA/LIBRA ≈ 250 kg
(0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
1000
2000
3000
4000
5000
Time (day)
December 2nd
June 2nd

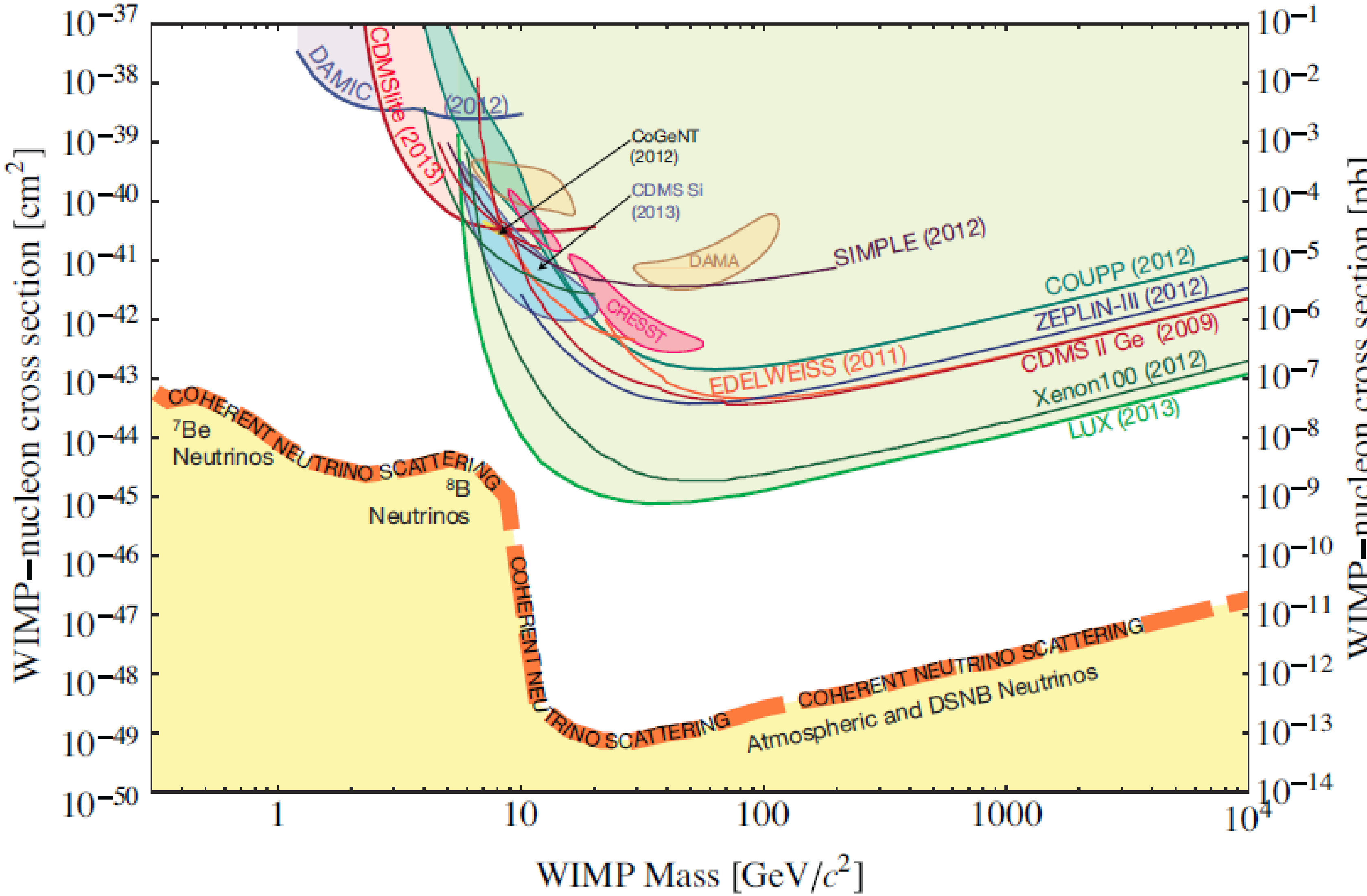



**DM interpretation very controversial! More later…**

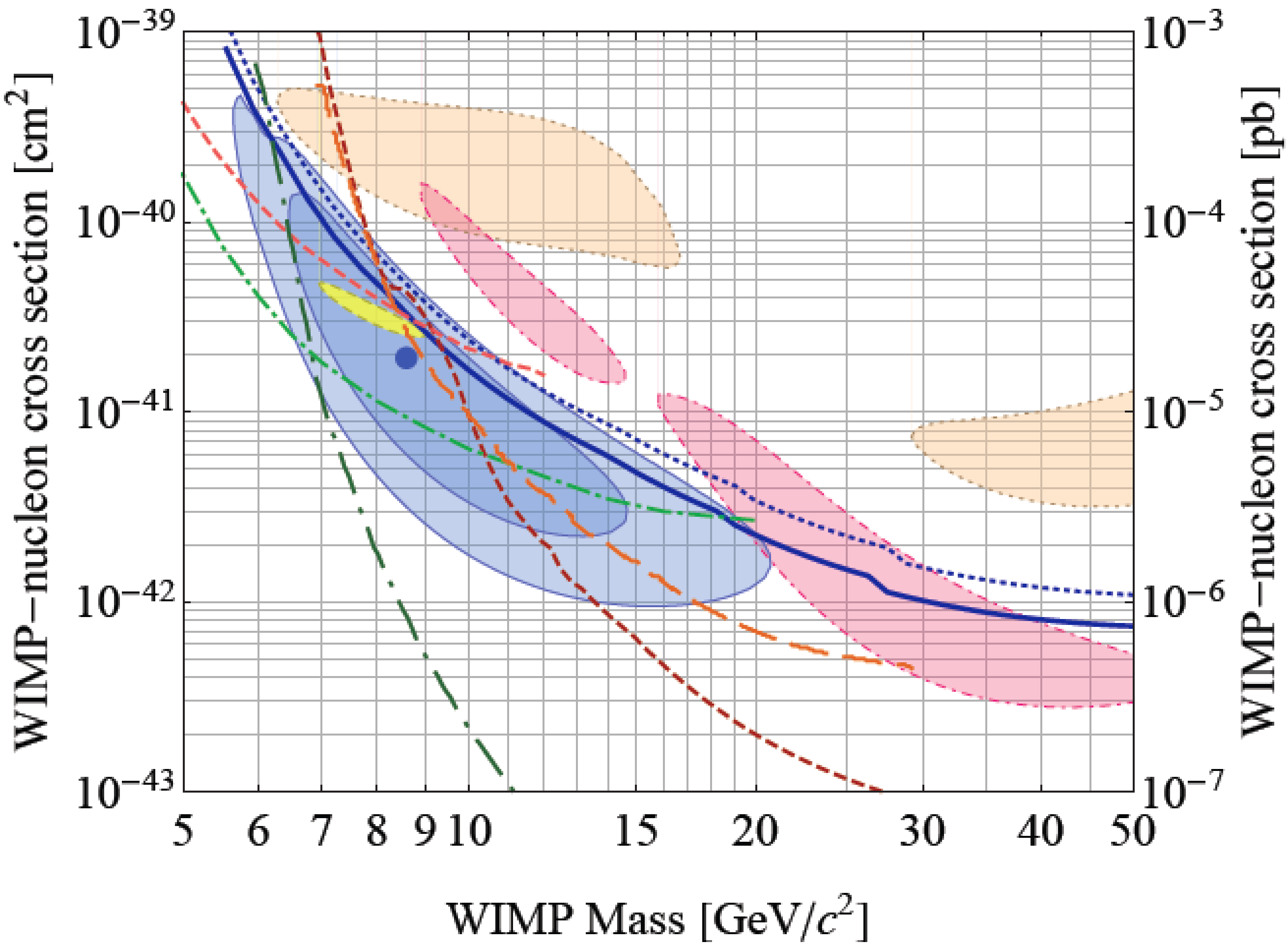

Scintillation Decay
Modulation
CUORE
CRESST I
$TeO_2$, $Al_2O_3$, LiF
Superheated Liquids
COUPP
PICASSO
$CF_3I$, $C_4F_{10}$
Phonons
10 meV/ph
100% energy
CRESST
ROSEBUD
$CaWO_4$, BGO
$ZnWO_4$, $Al_2O_3$ ...
CDMS
EDELWEISS
Ge, Si
Scintillation
~ 1 keV/γ
few % energy
Ionization
~ 10 eV/e
20% energy
NAIAD
ANAIS
DAMA/LIBRA
ZEPLIN I
XMASS
DEAP
CLEAN
NaI(Tl), Xe, Ar, Ne, $CF_4$
ZEPLIN II, III
XENON
LUX
WArP
ArDM
SIGN
Xe, Ar, Ne
CoGeNT
DRIFT
DM-TPC
IGEX
COSME
Ge, $CS_2$, $C_3F_8$



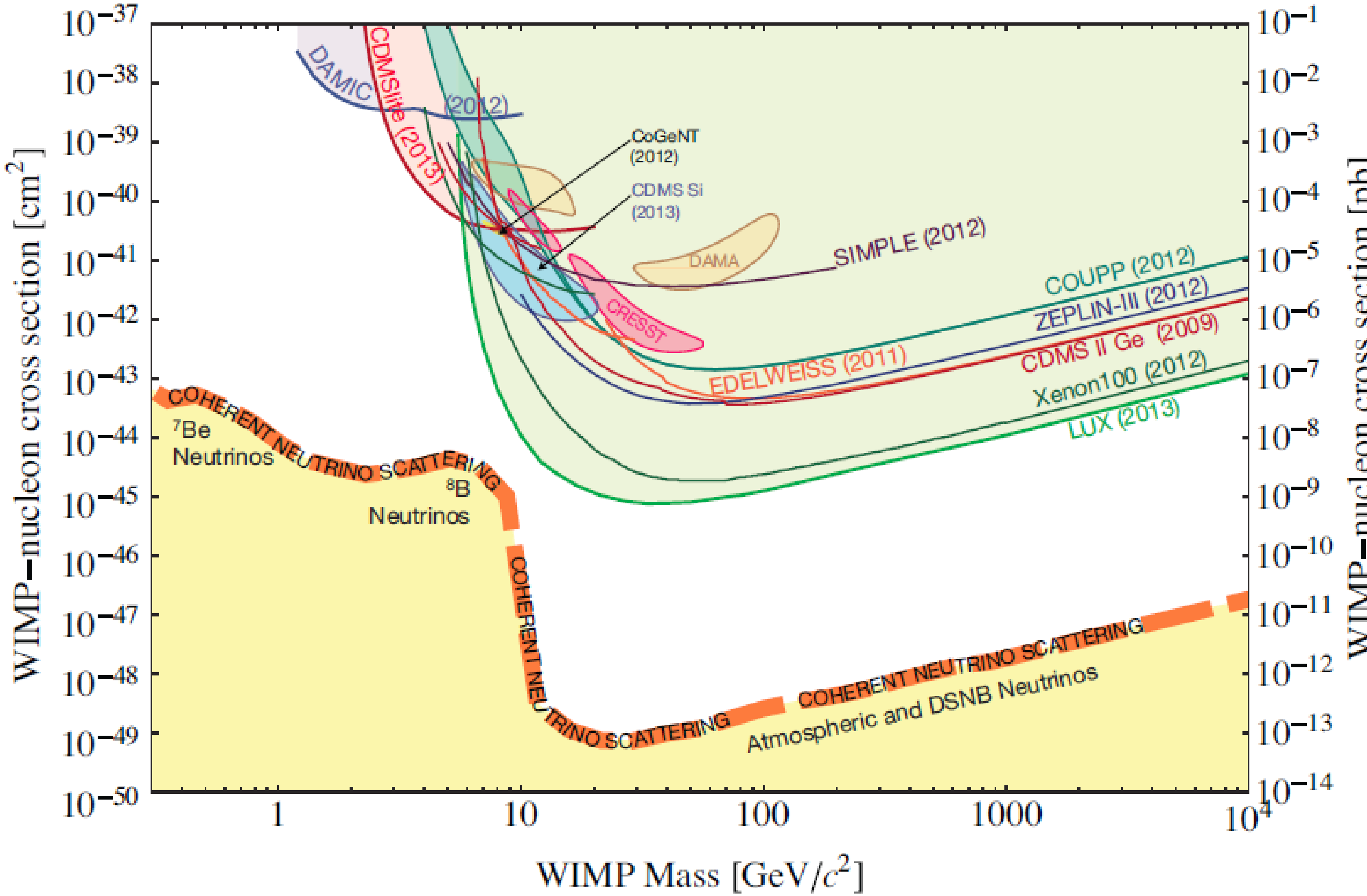

Kuhlen et al.'09



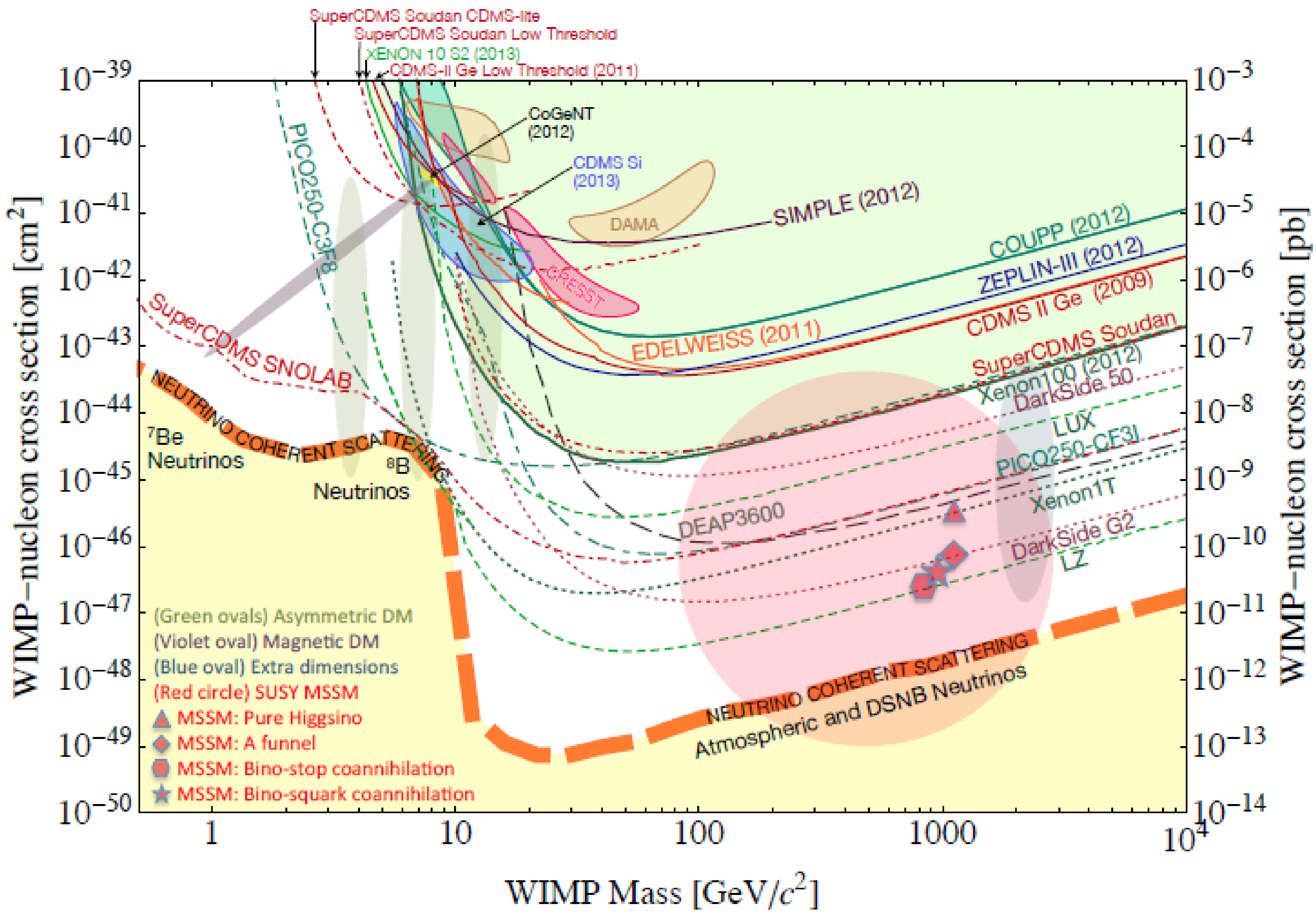

Billard, Figueroa-Feliciano, Strigari '14




arXiv:1304.4279




Billard, Figueroa-Feliciano, Strigari '14



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)
PICO250-C3F8
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
NEUTRINO COHERENT SCATTERING
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]