Dark Matter Hunt

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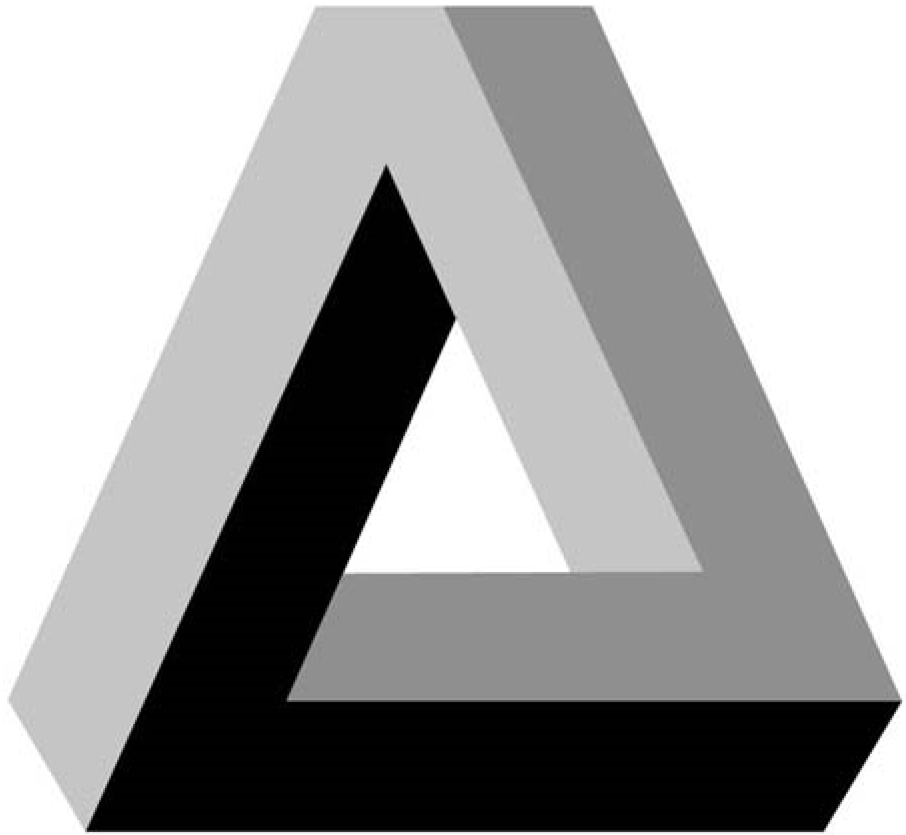
Cargese
July 2014

Direct detection

$\mathrm{DM\ nucleus} \rightarrow \mathrm{DM\ nucleus}$



Indirect detection

$\mathrm{DM\ DM} \rightarrow \gamma\, X,\ e^{+}e^{-}\ldots$ (annihilation)

$\mathrm{DM} \rightarrow \gamma\, X,\ e^{+}X\ldots$ (decay)

Collider searches

$pp \rightarrow \mathrm{DM}\ X$

Direct detection

DM nucleus → DM nucleus

Indirect detection

DM DM → γ X, e^+e^-... (annihilation)

DM → γ X, e^+X... (decay)

Collider searches

pp → DM X

Direct detection

DM nucleus $\to$ DM nucleus

Indirect detection

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

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

Collider searches

pp $\to$ DM X

Direct detection

DM nucleus $\rightarrow$ DM nucleus

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

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

Collider searches

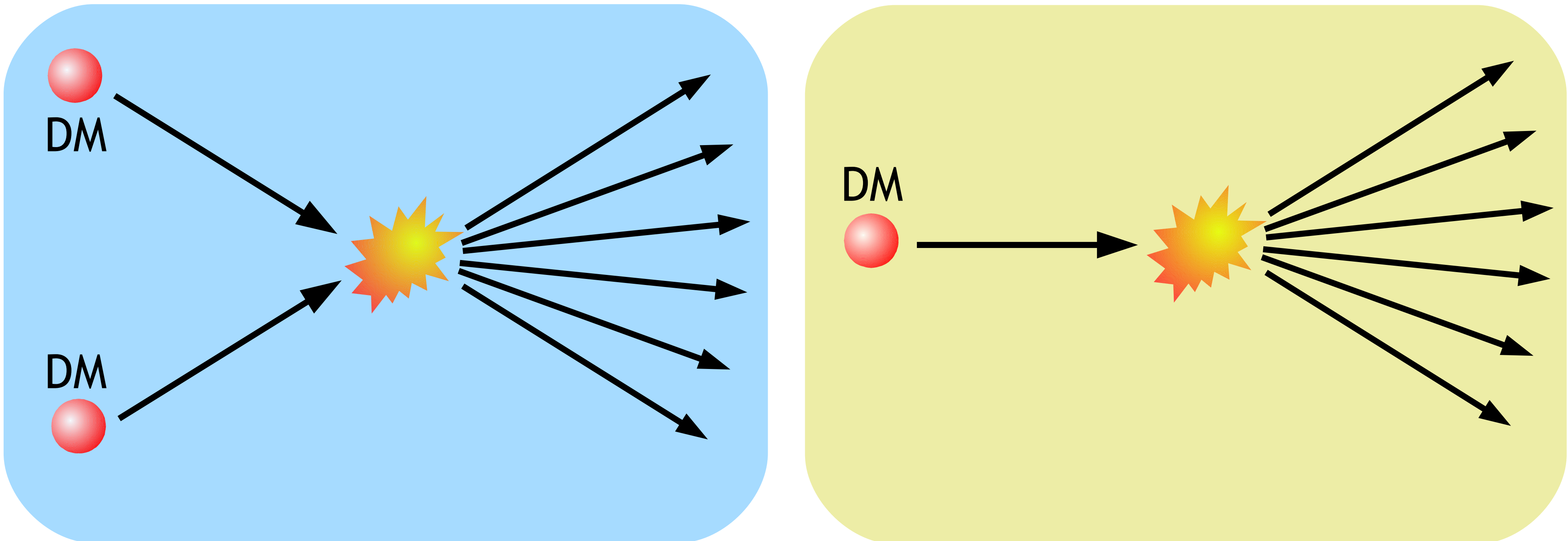
pp $\rightarrow$ DM X

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.



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.

Indirect dark matter searches

General idea:

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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.

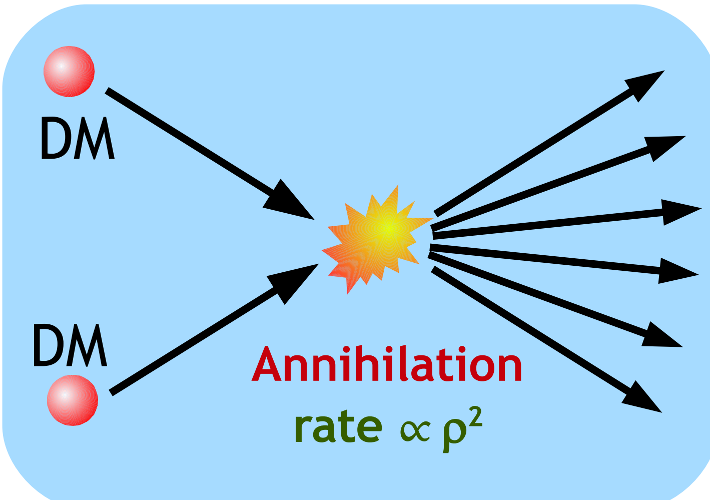
Indirect dark matter searches

Production			Antimatter
Propagation	}	of	{ Gamma-rays
Detection			Neutrinos

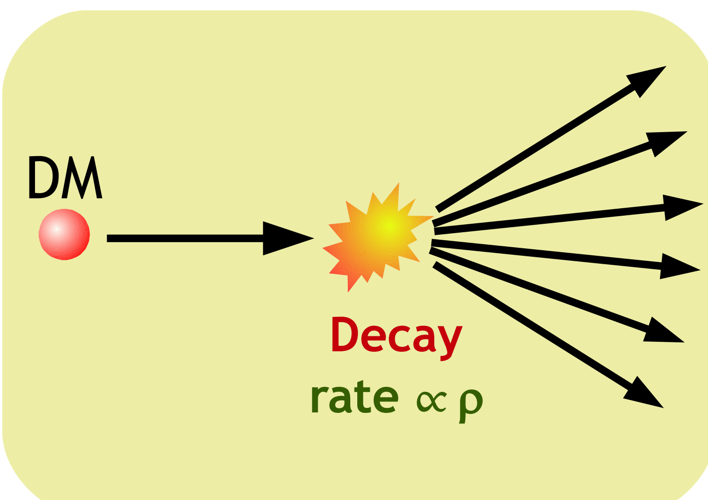
Antimatter

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.

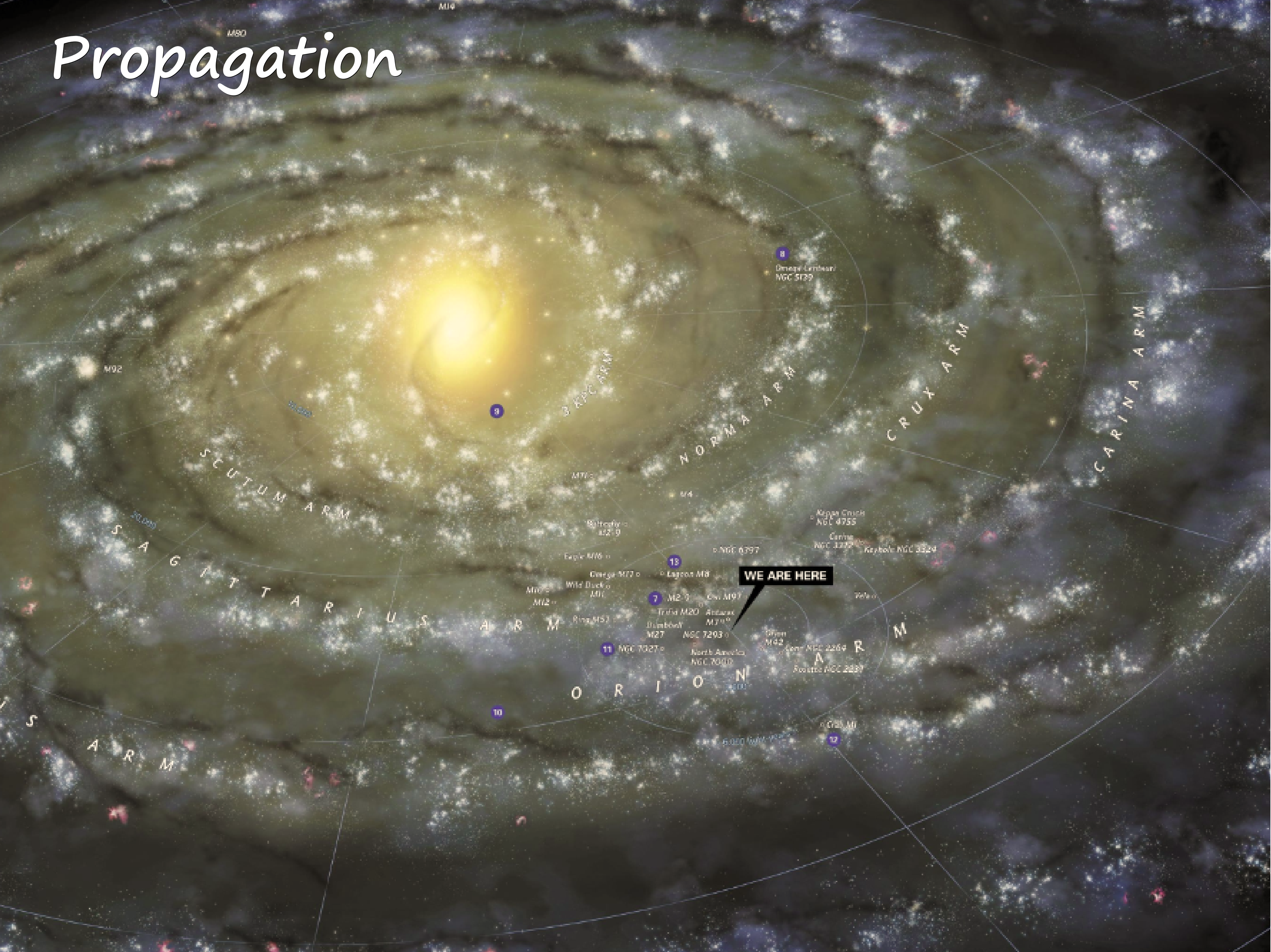


$$Q(E,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_{\mathrm{DM}}^2}\langle\sigma v\rangle\frac{dN}{dE}$$



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

Propagation



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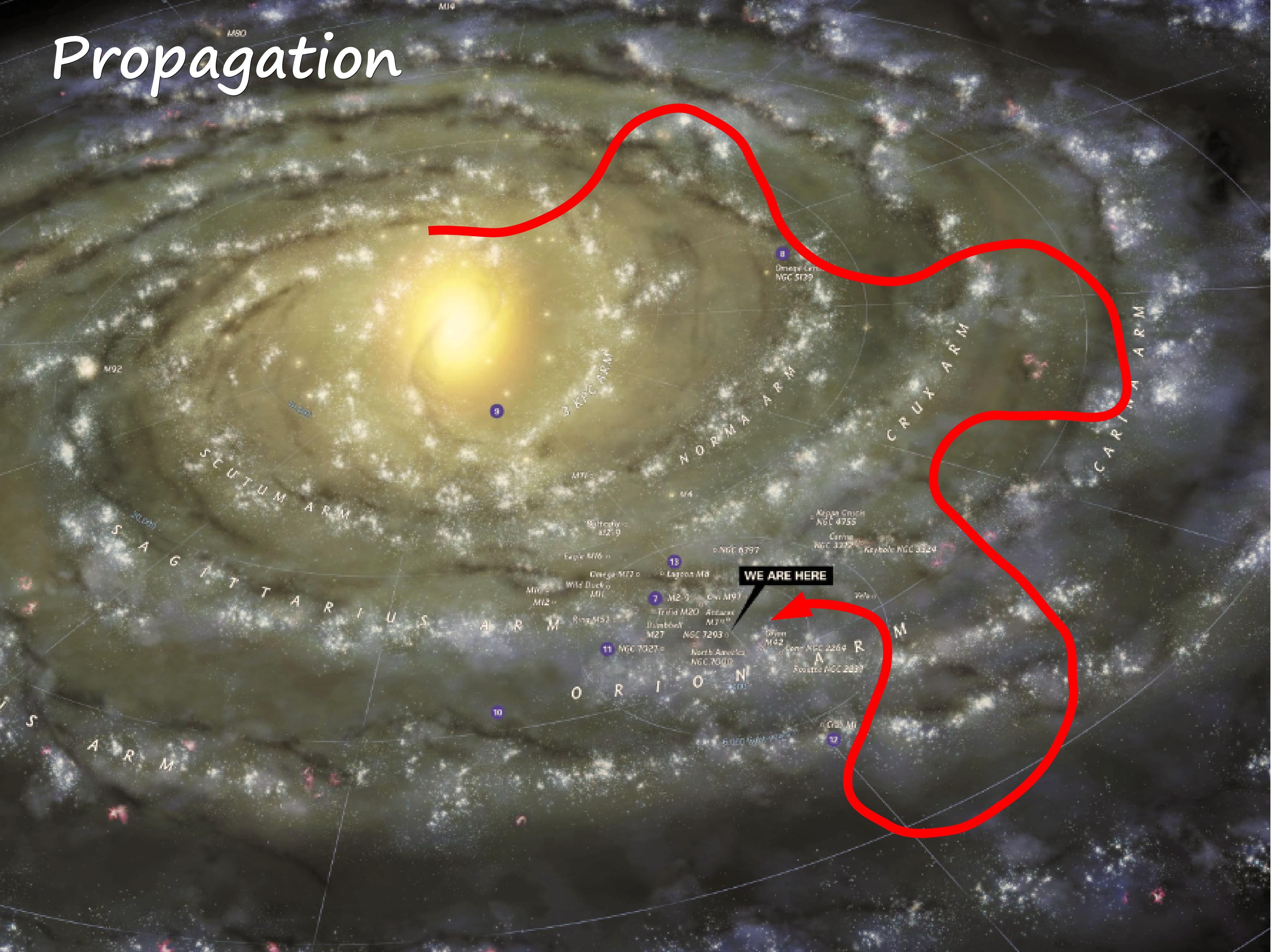

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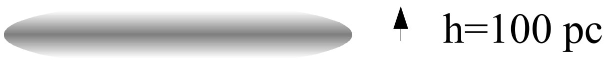

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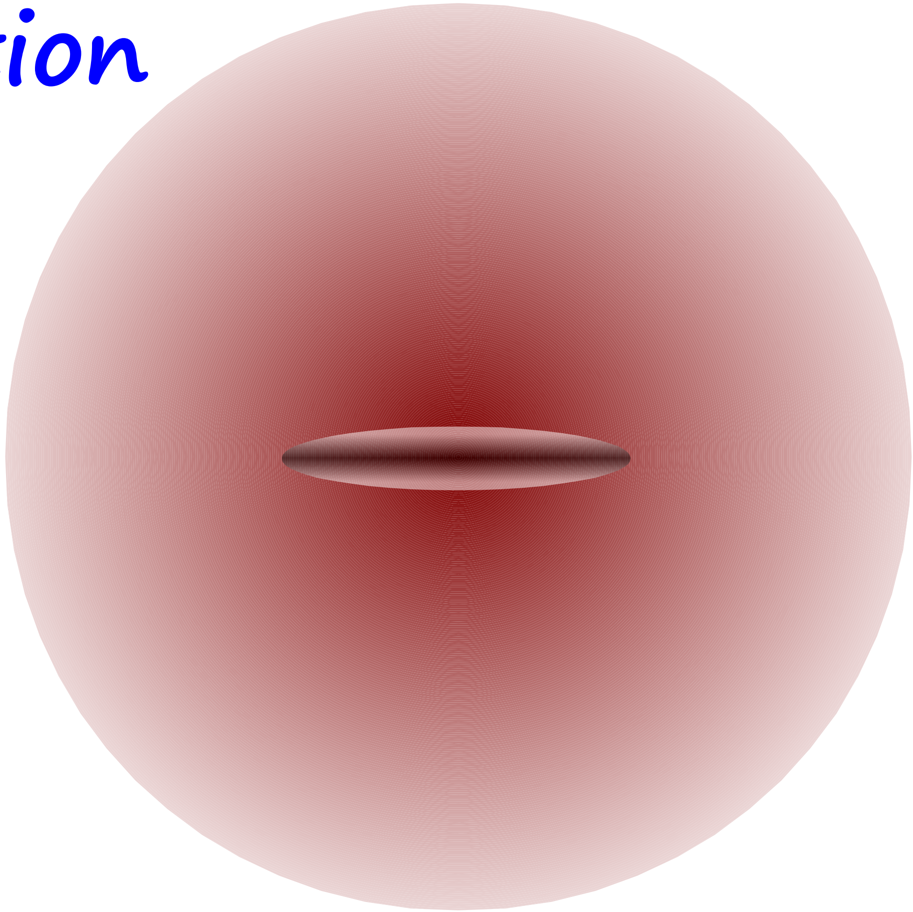

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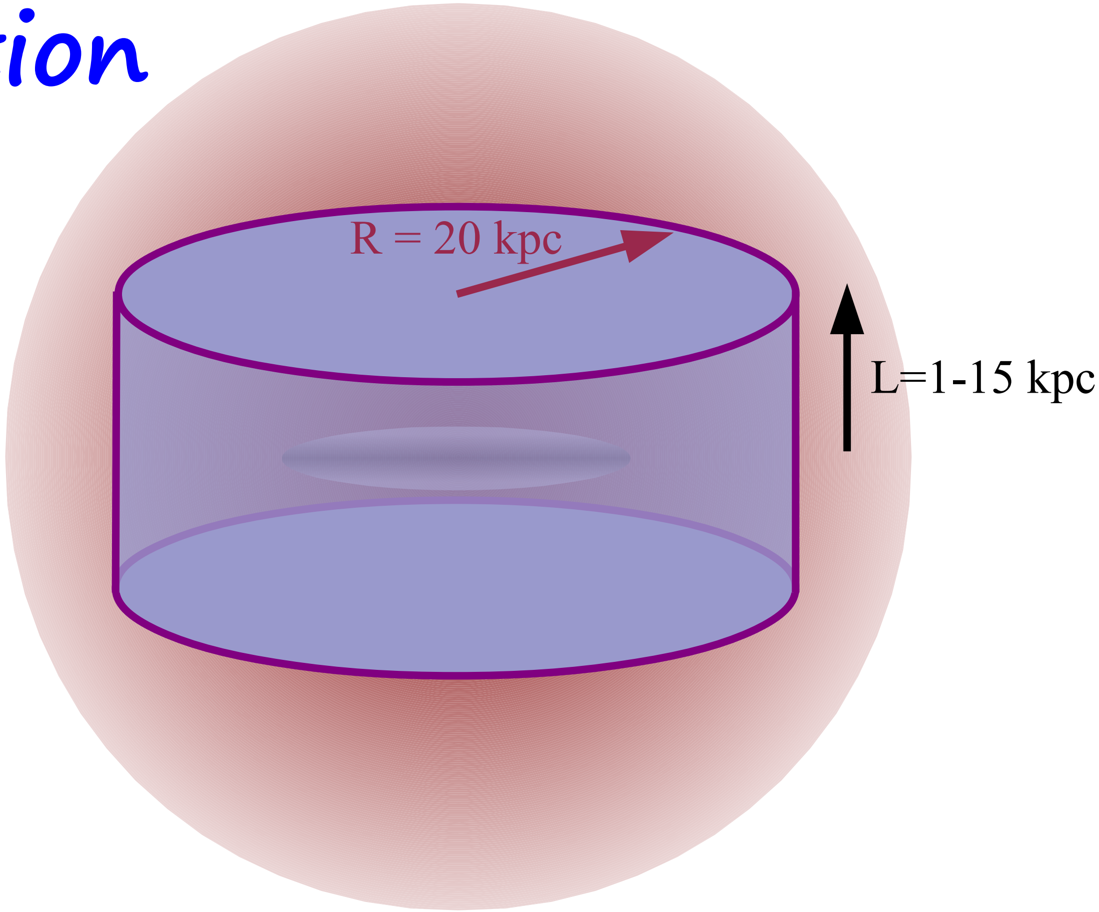
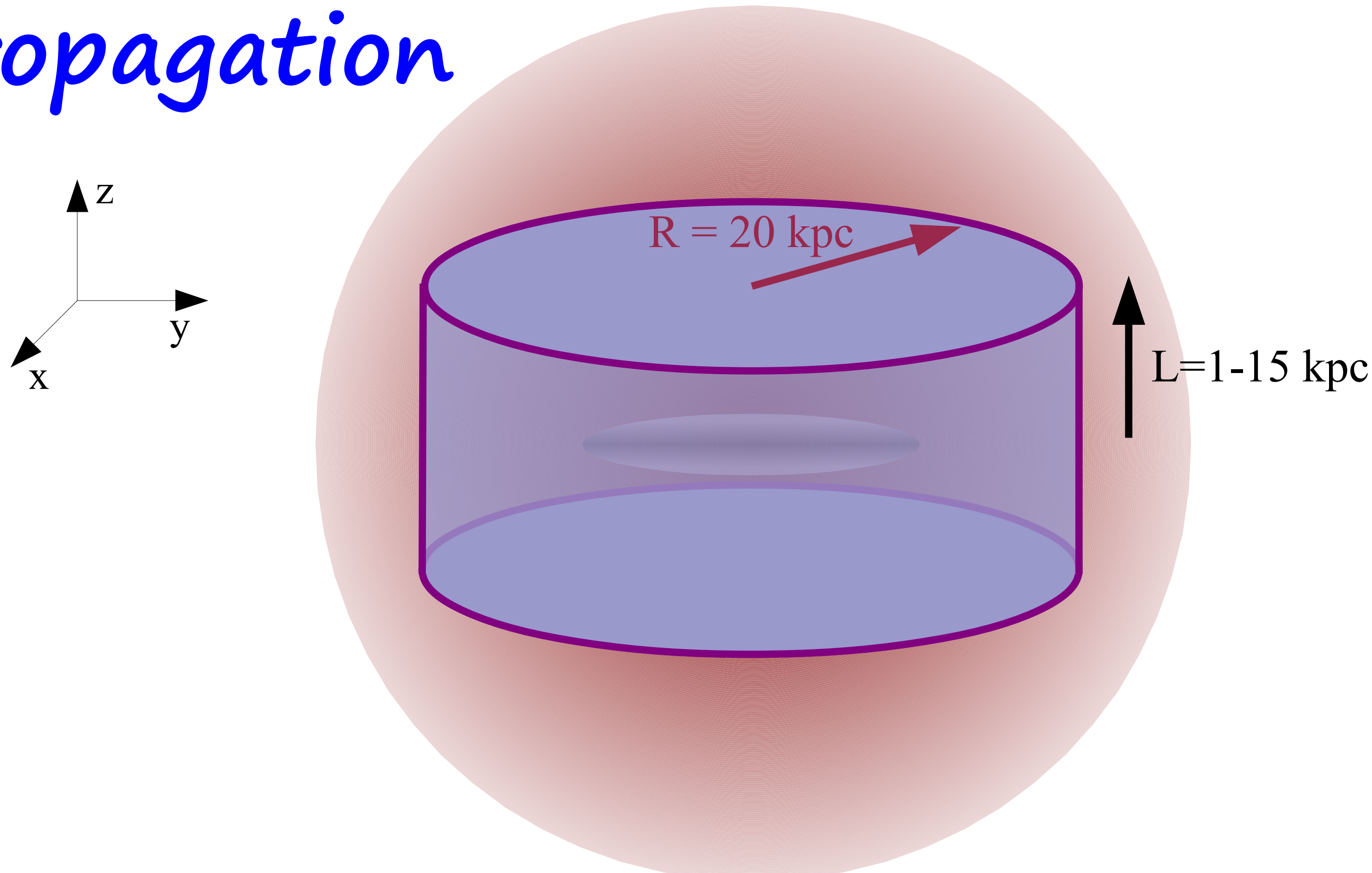


Propagation



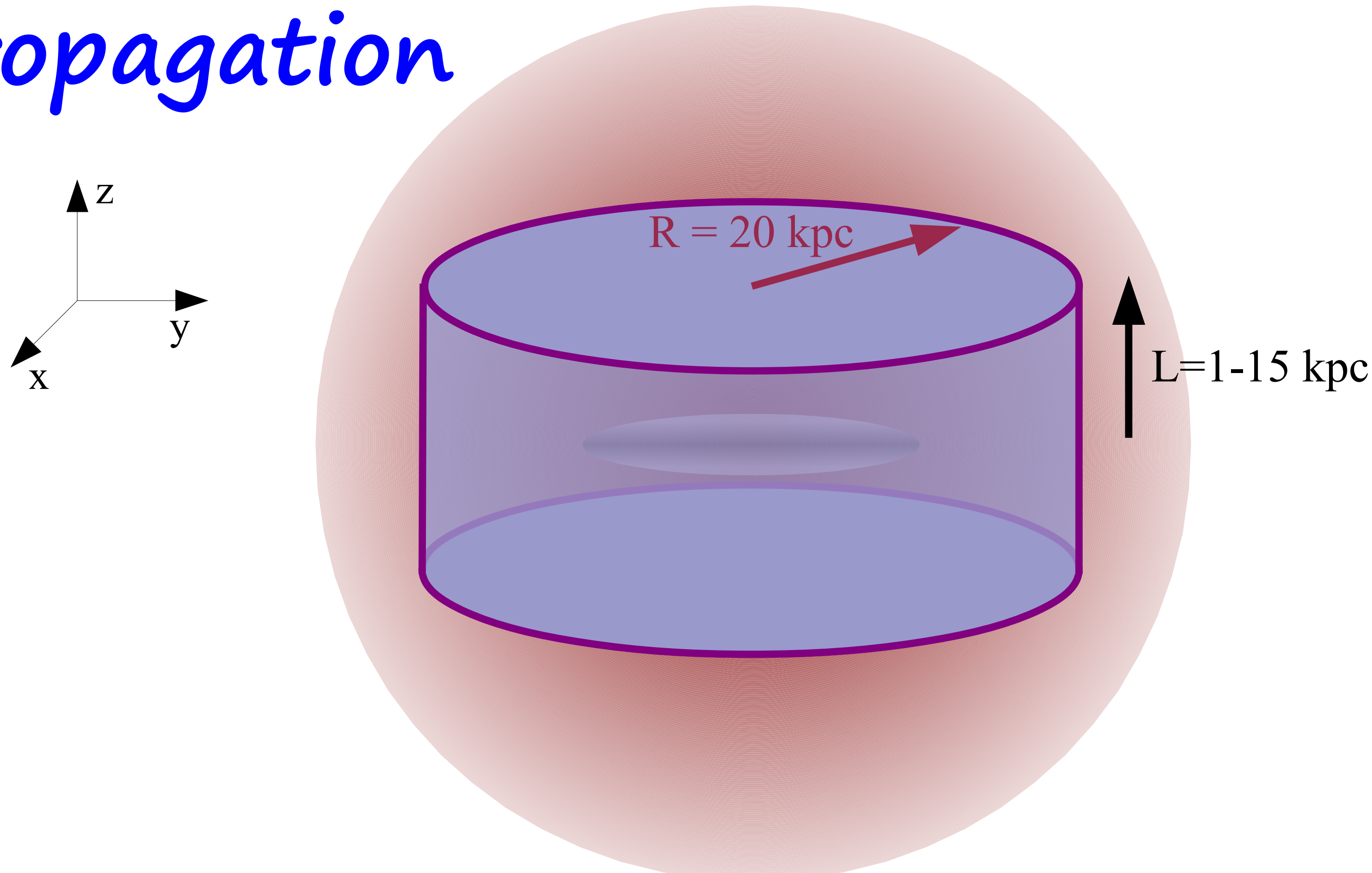
$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r}) \ .$$

f : number density of antiparticles per unit kinetic energy

interstellar antimatter flux:

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

Propagation



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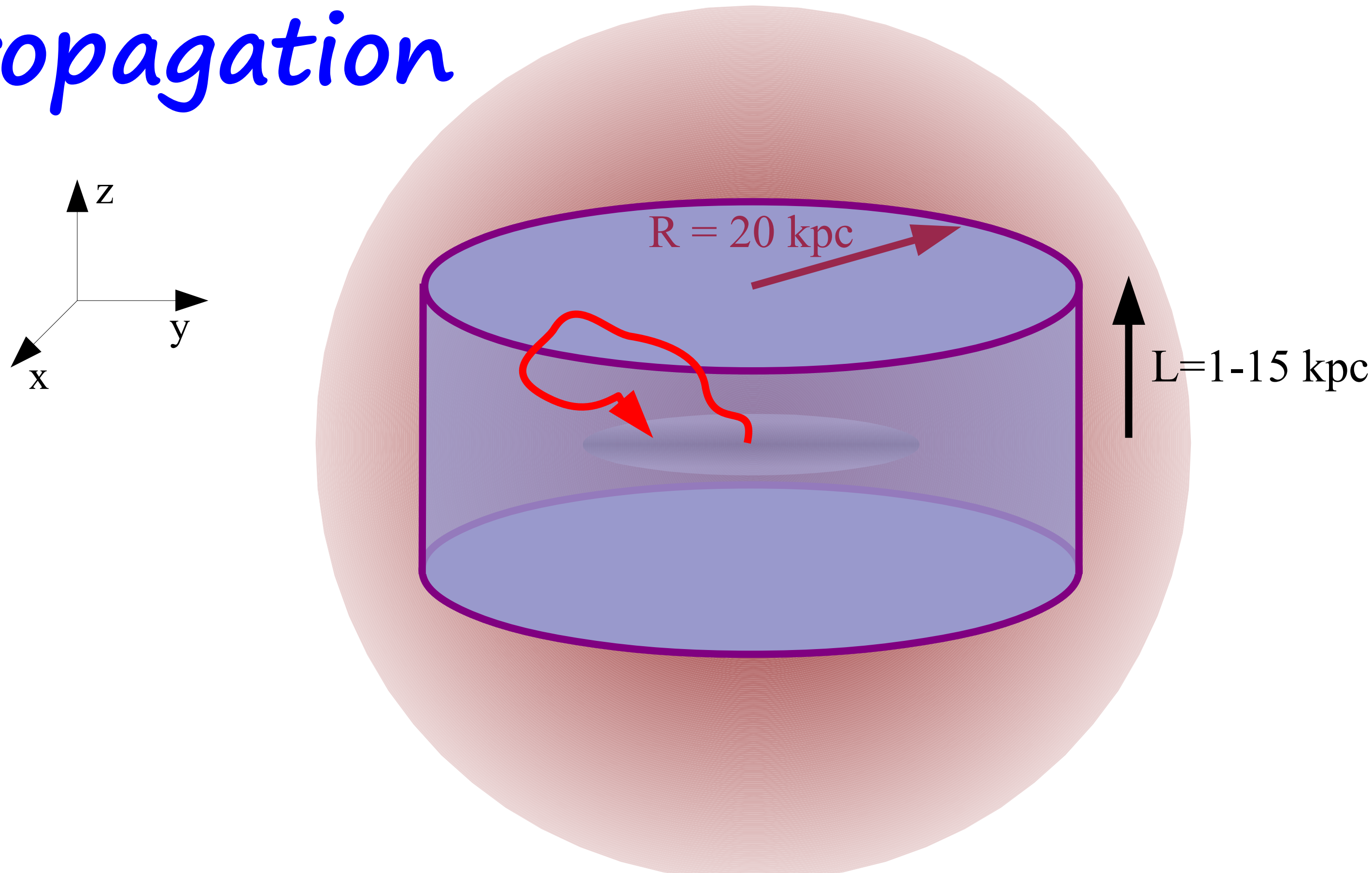
Source term

$$Q(T,\vec{r}) = \begin{cases} \frac{1}{2}\frac{\rho^2(\vec{r})}{m_{\rm DM}^2}\langle\sigma v\rangle \frac{dN}{dT} & \text{dark matter annihilation} \\ \frac{\rho(\vec{r})}{m_{\rm DM}}\frac{1}{\tau_{\rm DM}}\frac{dN}{dE} & \text{dark matter decay} \end{cases}$$

Propagation



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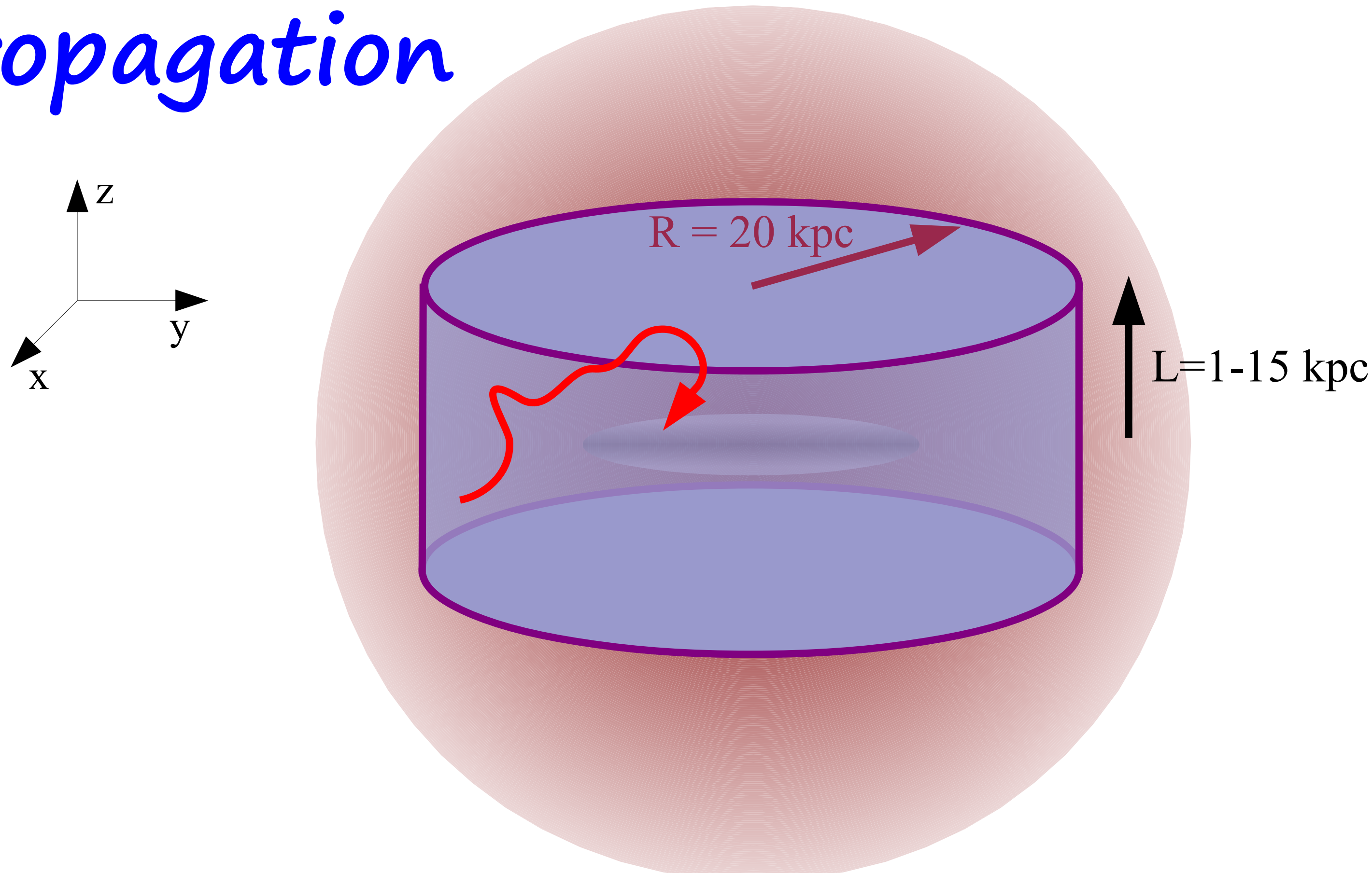

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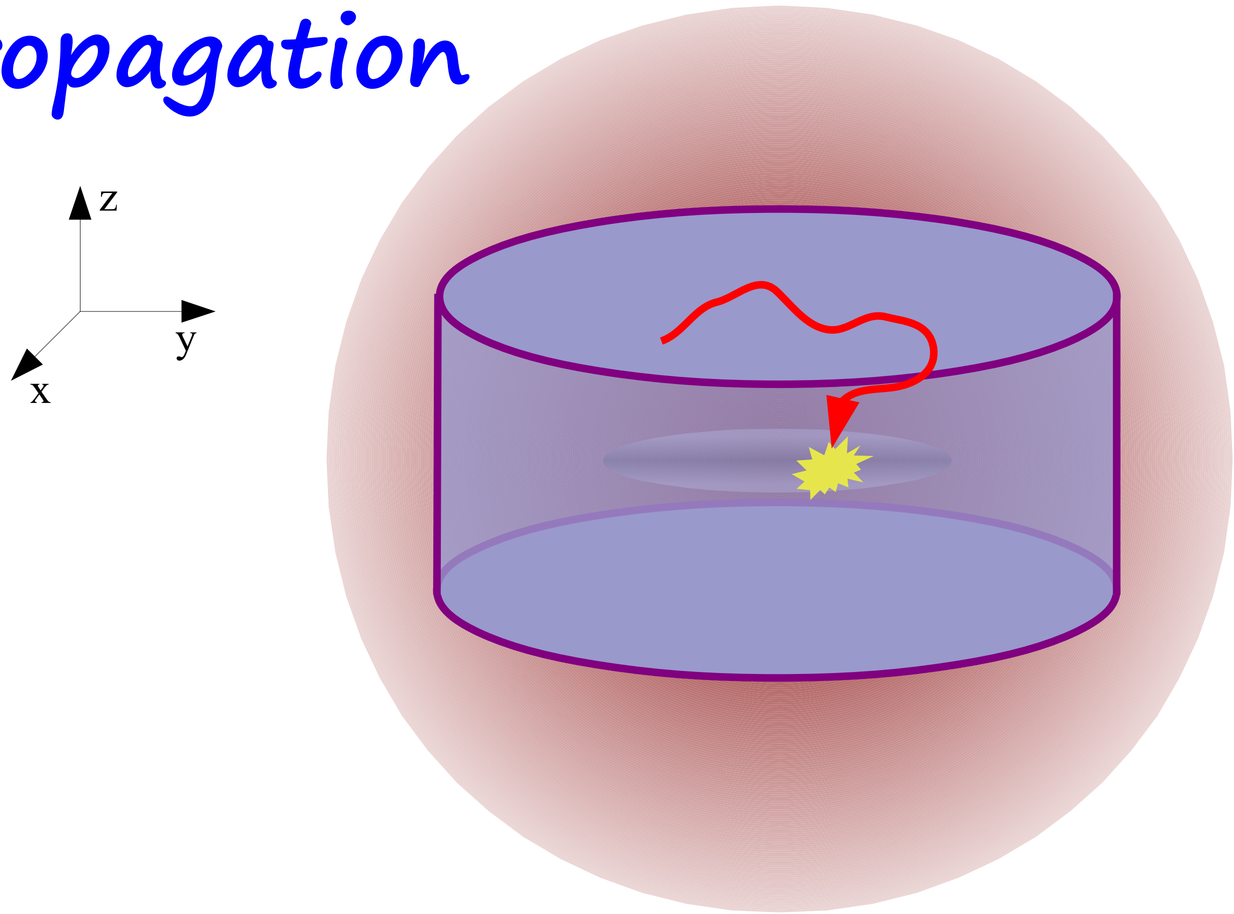

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Annihilation term

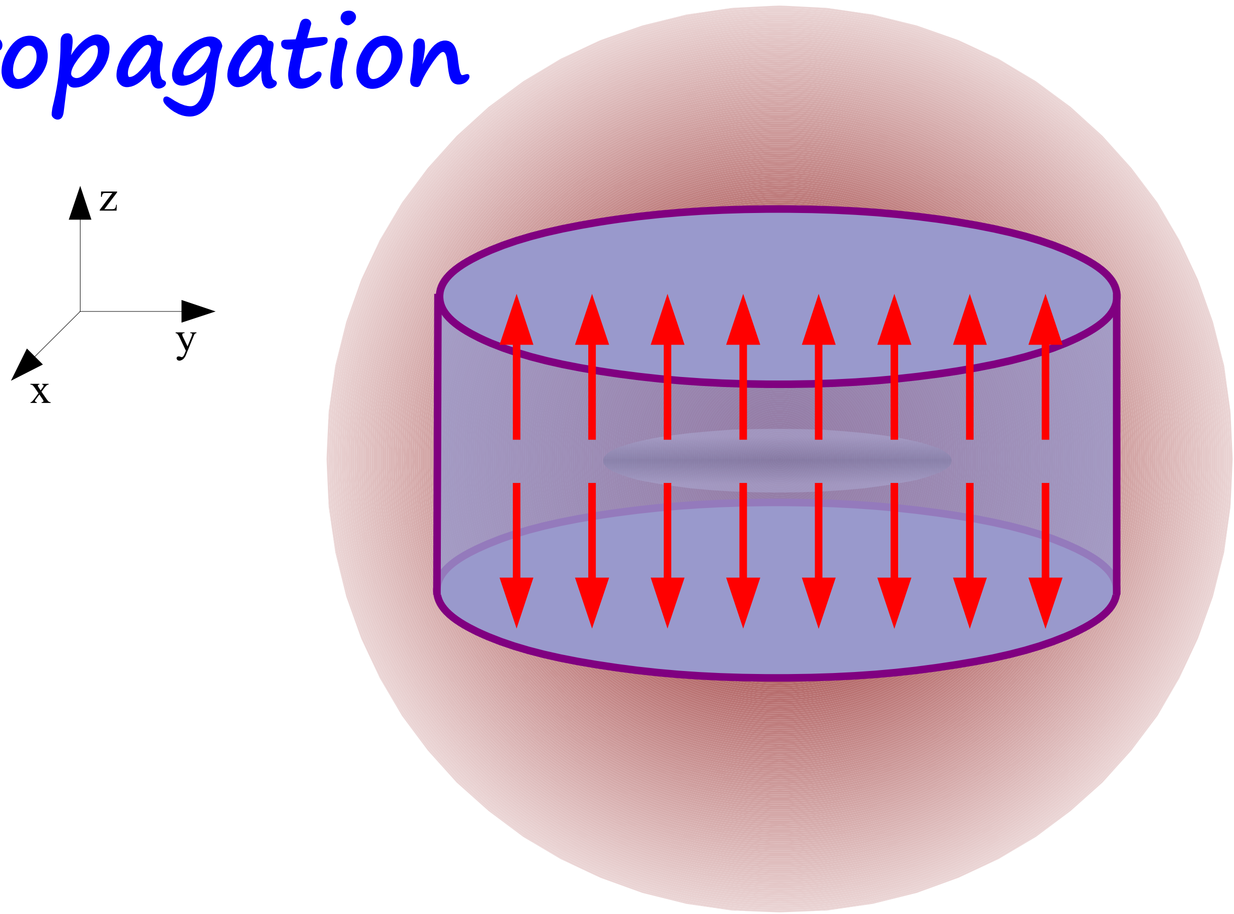
Negligible for positrons.
For antiprotons,

$$\Gamma_{\rm ann} = (n_{\rm H} + 4^{2/3} n_{\rm He})\sigma^{\rm ann}_{\bar{p}p} v_{\bar{p}} \,.$$

$$\sigma^{\rm ann}_{\bar{p}p}(T) = \begin{cases} 661\,(1 + 0.0115\,T^{-0.774} - 0.948\,T^{0.0151})\ \text{mbarn}\,, & T < 15.5\ \text{GeV}\,, \\ 36\,T^{-0.5}\ \text{mbarn}\,, & T \geq 15.5\ \text{GeV}\,, \end{cases}$$

Tan, Ng

Propagation



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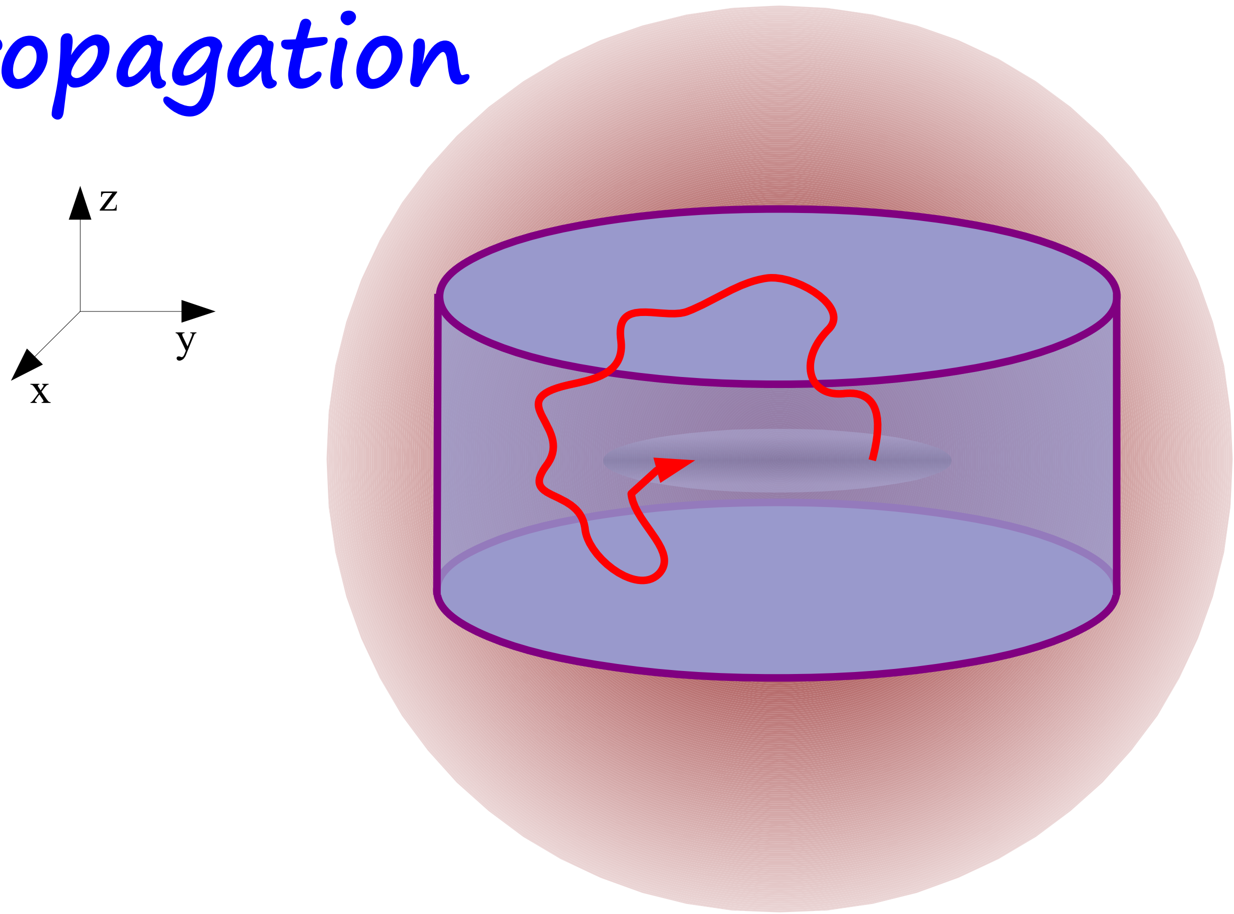
Convection term

- Due to the Milky Way galactic wind.
- It drifts particles away from the Galactic disk.
- Difficult to model. Assume:

$$\vec{V}_c(\vec{r}) = V_c \ \mathrm{sign}(z) \ \vec{k}$$

Propagation



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Energy loss term

- Due to inverse Compton scattering on the interstellar radiation field (starlight, thermal radiation of dust, CMB) and synchrotron radiation.
- Negligible for antiprotons and antideuterons
- Can be modelled

• Energy loss due to Inverse Compton scattering: $e^{+}\gamma \rightarrow e^{+}\gamma$

$$b_{\rm ICS}(E_e,\vec{r}) = \int_0^\infty d\epsilon \int_\epsilon^{E_\gamma^{\rm max}} dE_\gamma (E_\gamma - \epsilon) \frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} f_{\rm ISRF}(\epsilon,\vec{r})$$

Number density of photons in ISRF

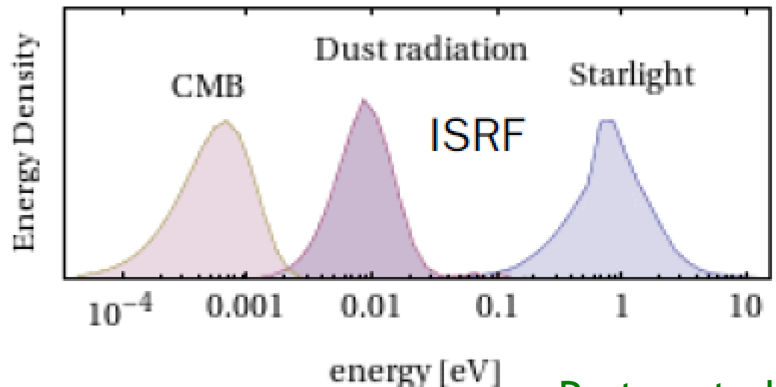
$$\frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} = \frac{3}{4}\frac{\sigma_{\rm T}}{\gamma_e^2\,\epsilon} \times \left[2q\ln q + 1 + q - 2q^2 + \frac{1}{2}\frac{(q\Gamma)^2}{1+q\Gamma}(1-q)\right]$$

$\gamma_e = E_e/m_e \longrightarrow$ Lorentz factor.

$\Gamma_e = 4\,\gamma_e\,\varepsilon/m_e$

$q = E_\gamma/\Gamma(E_e - E_\gamma)$

$\sigma_T = 0.67$ barn $\longrightarrow$ Compton scattering cross section in the Thomson limit.



Porter et al.

• Energy loss due to synchrotron radiation:

$$b_{\rm sync}(E_e,\vec{r}) = \frac{4}{3}\sigma_T \gamma_e^2 \frac{B^2}{2}$$

$$B = 6\mu G \exp(-|z|/5{\rm kpc} - r/20{\rm kpc})$$

Approximately $b(E) = \frac{E^2}{E_0 \tau_E}$, with $E_0 = 1\,{\rm GeV}$ and $\tau_E = 10^{16}$s

- Energy loss due to Inverse Compton scattering: $e^+\gamma \to e^+\gamma$

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$\gamma_e = E_e/m_e \longrightarrow$ Lorent[...]

$\Gamma_e = 4\,\gamma_e\,\varepsilon/m_e$

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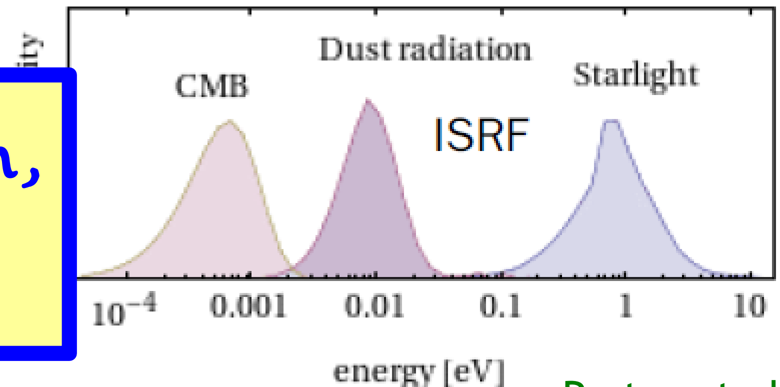
$\sigma_T = 0.67$ barn $\longrightarrow$ Compton scattering cross section in the Thomson limit.

Not very well known, though...



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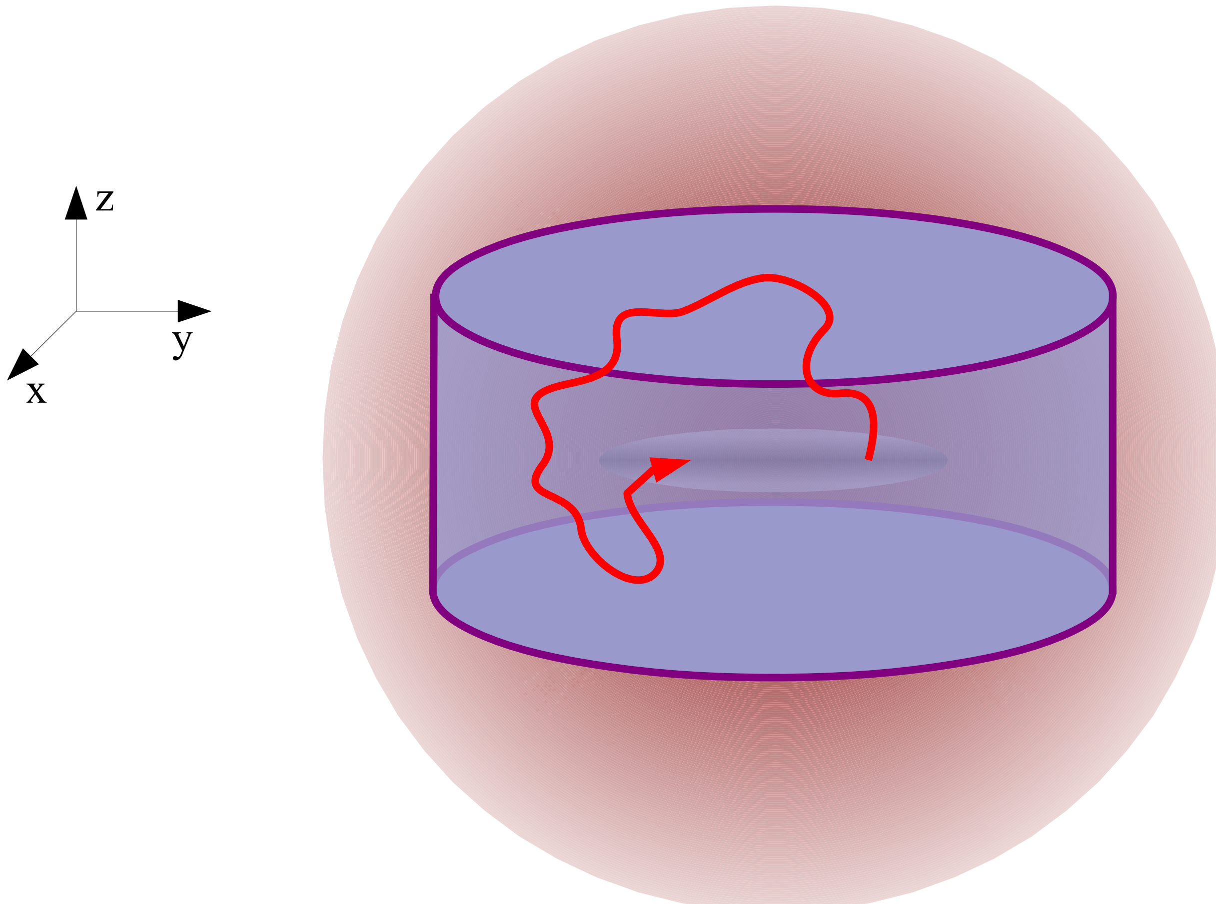

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Diffusion term

- Due to the tangled magnetic field of the Galaxy.
- Difficult to model. Assume

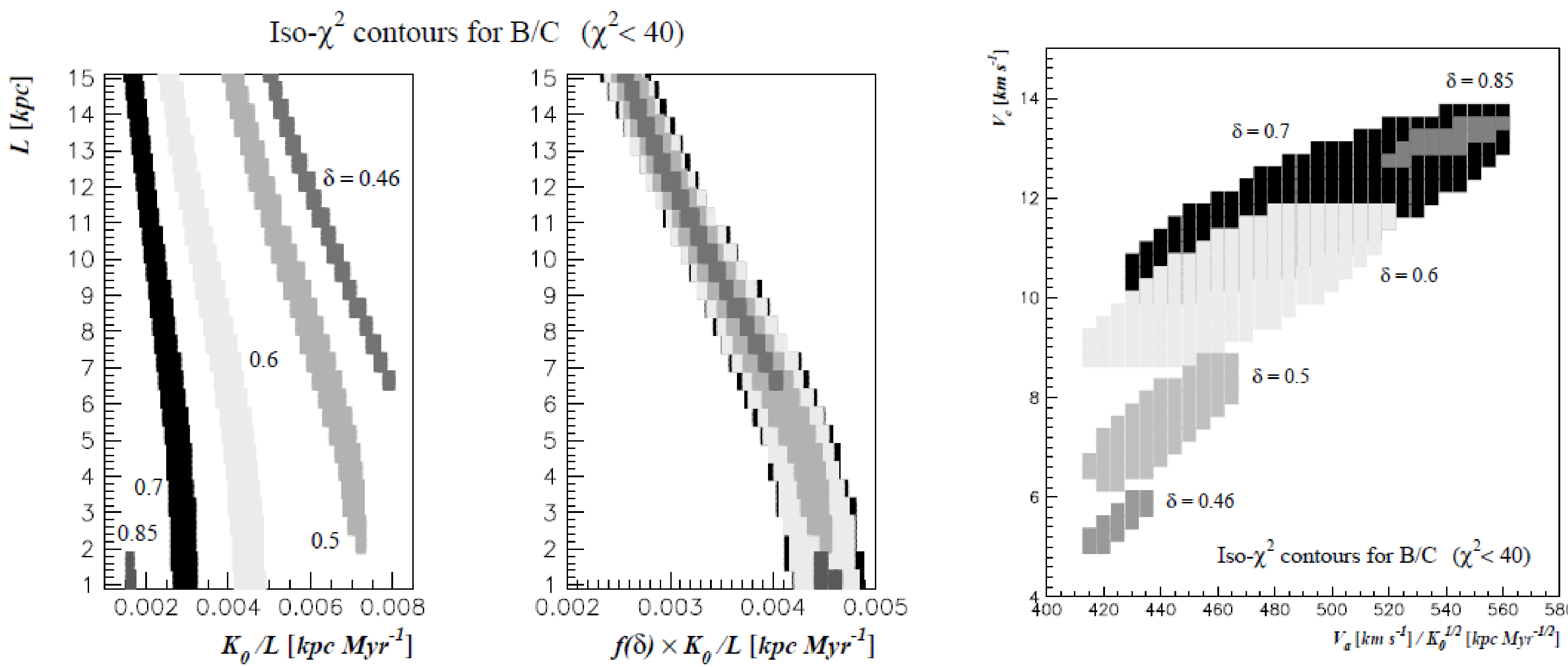
$$K(T) = K_0 \, \beta \, \mathcal{R}^\delta$$

β = velocity
$\mathcal{R}$ = rigidity

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

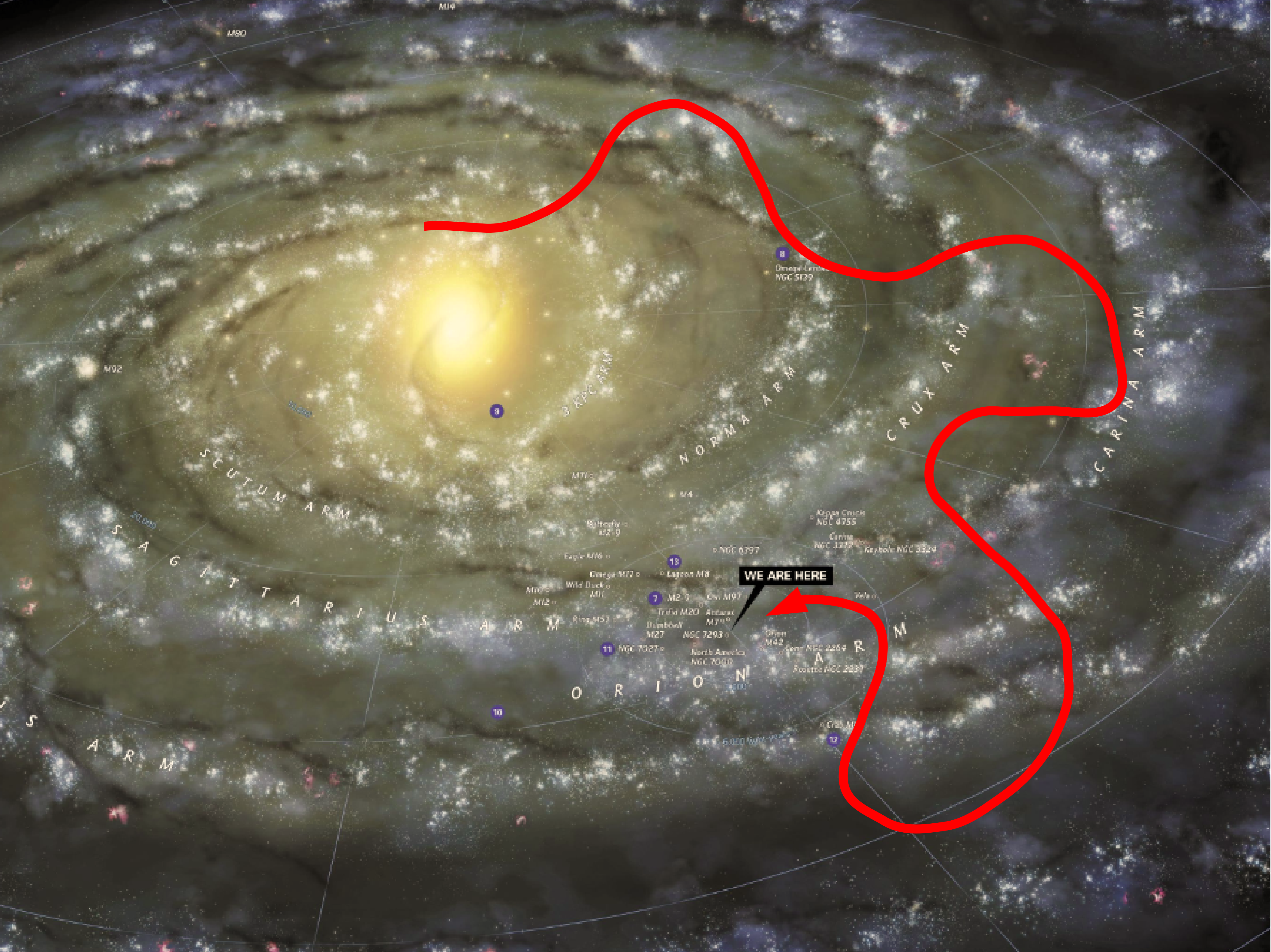
$$K(T) = K_0\;\beta\;\mathcal{R}^\delta \qquad\qquad \vec{V}_c(\vec{r}) \;=\; V_c\;\text{sign}(z)\;\vec{k}$$

K_0, δ, V_c (as well as L) must be determined with measurements of other cosmic ray species (mainly B/C ratio).



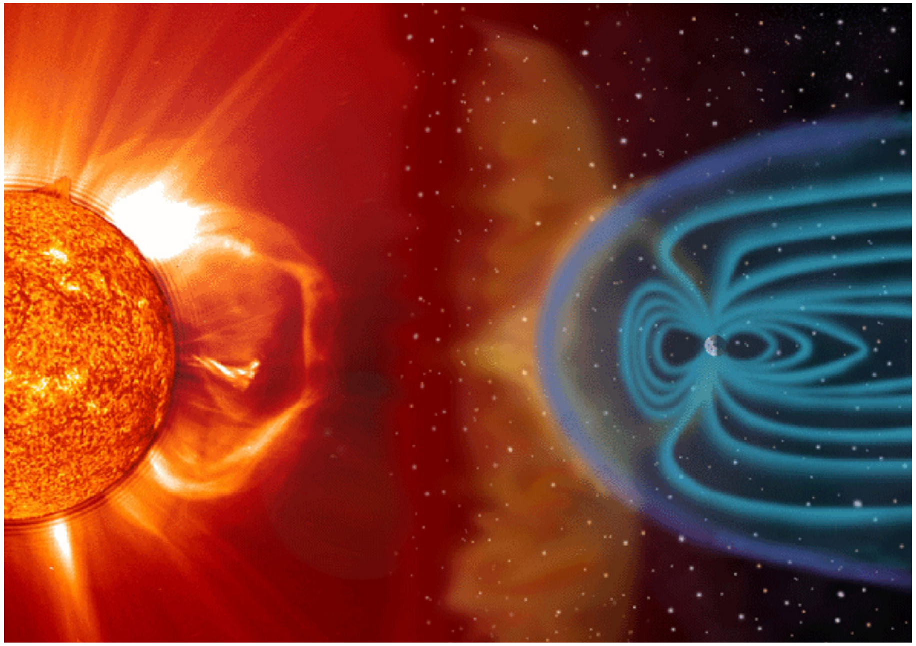
Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Maurin, Donato, Taillet, Salati '01



M80
M92
3 KPC ARM
NORMA ARM
CRUX ARM
CARINA ARM
SCUTUM ARM
SAGITTARIUS ARM
ORION ARM
Omega Centauri
NGC 5139
Kappa Crucis
NGC 4755
Keyhole NGC 3324
NGC 6397
Eagle M16
Lagoon M8
Omega M17
Wild Duck
M11
M12
Trifid M20
Antares
Ring M57
Dumbbell
M27
NGC 7293
Orion
M42
Cone NGC 2264
Rosette NGC 2237
NGC 7027
North America
NGC 7000
Vela
M4
WE ARE HERE

Propagation inside the Solar System



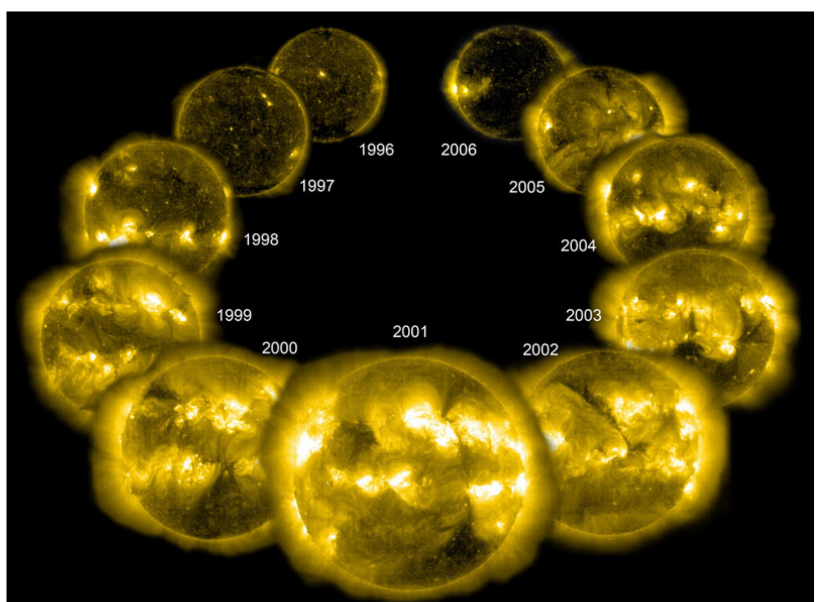
In the “force field approximation”,the flux at the top of the atmosphere (TOA) is related to the interstellar flux (IS) by

$$\Phi_{e^\pm}^{\rm TOA}(E_{\rm TOA}) = \frac{E_{\rm TOA}^2}{E_{\rm IS}^2}\,\Phi_{e^\pm}^{\rm IS}(E_{\rm IS})$$

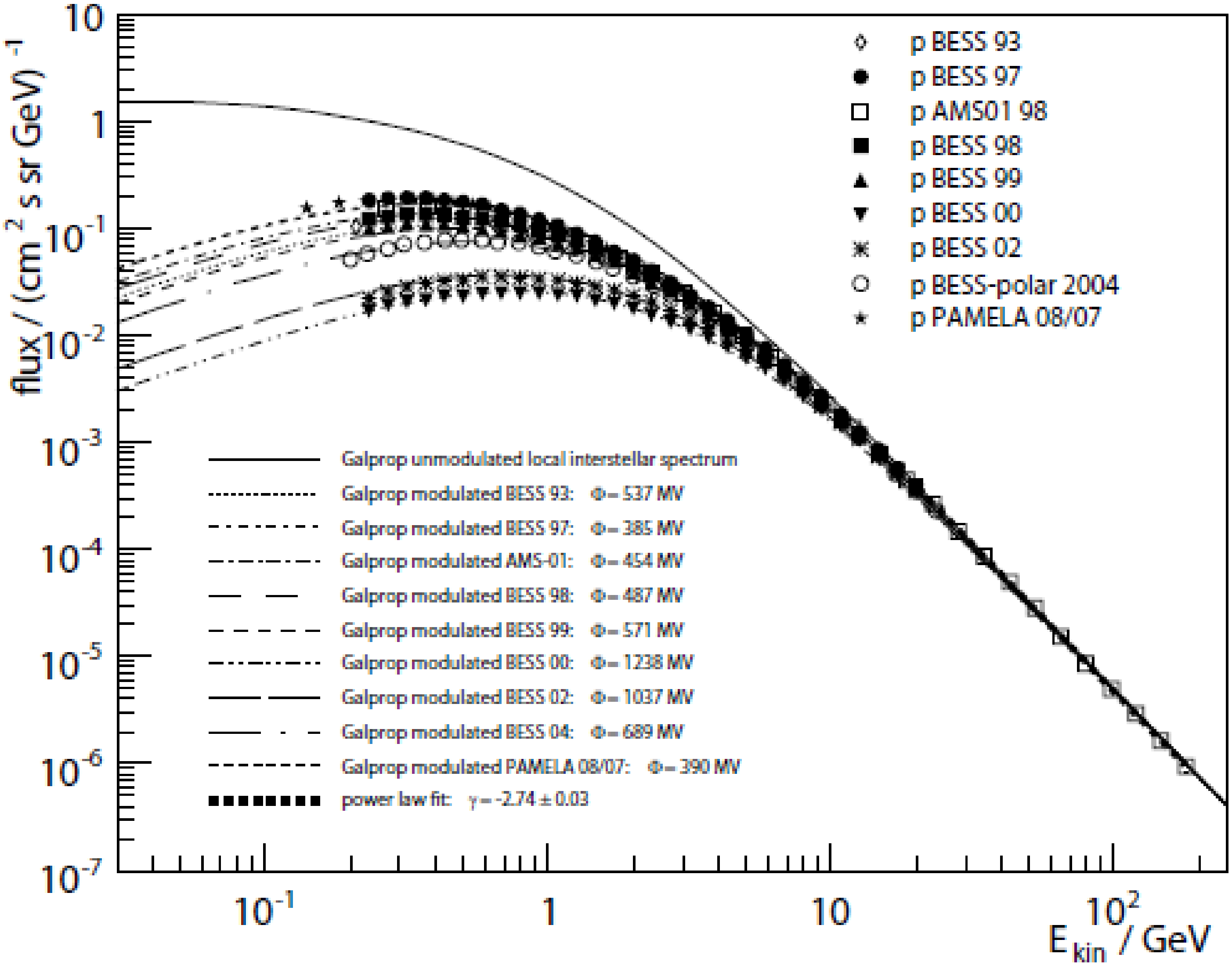
$$E_{\rm IS} = E_{\rm TOA} + \phi_F$$

solar modulation parameter

ϕ_F=500 MV – 1.3 GV

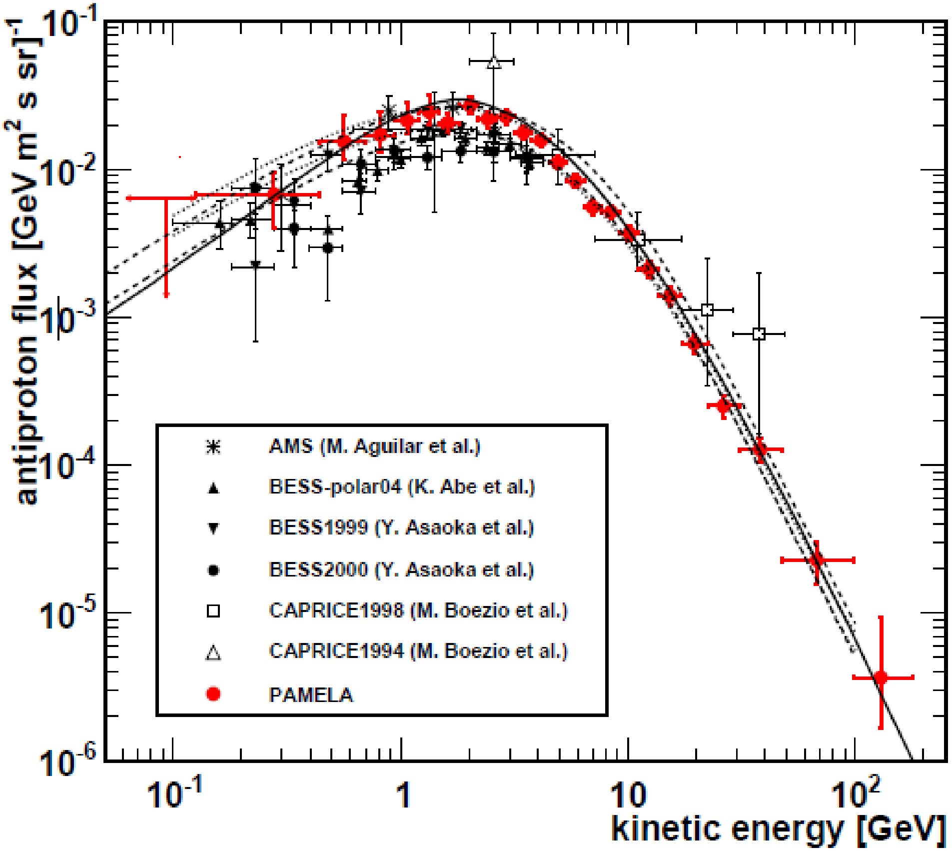


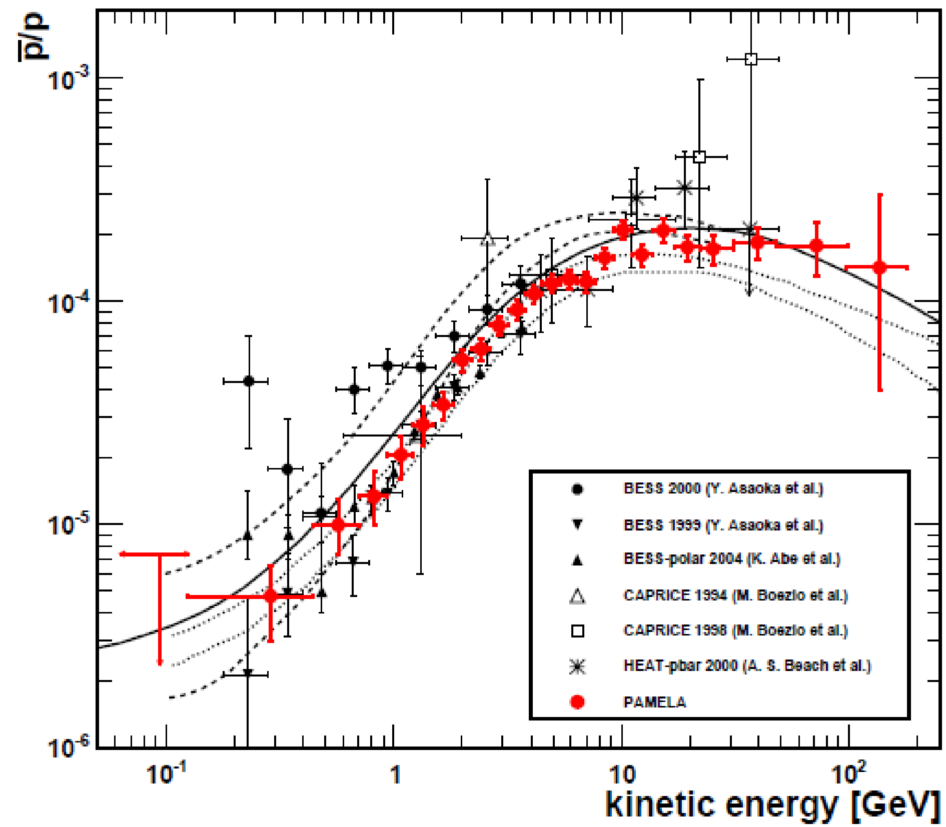
Cosmic ray proton spectrum as measured by BESS, AMS-01 and PAMELA



Gast, Schael '09

Experimental results: antiprotons





PAMELA collaboration
arXiv:1007.0821

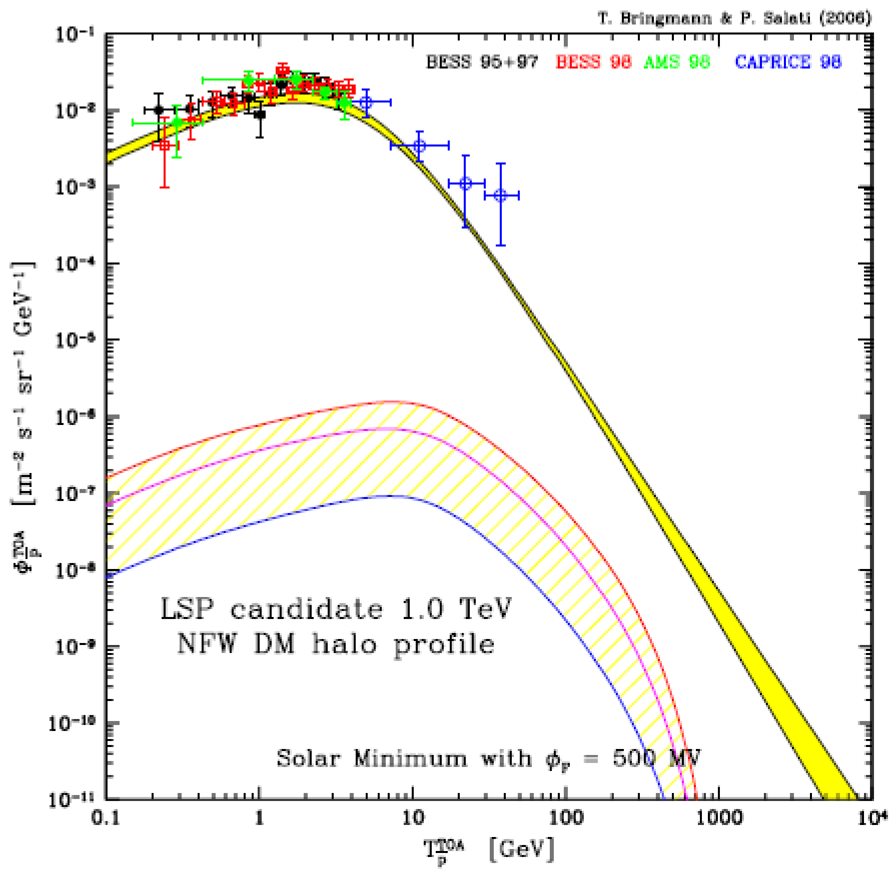
Fairly good agreement between the measurements and the theoretical predictions from collisions of cosmic rays on the interstellar medium $p\, p \to \bar{p}\, X$

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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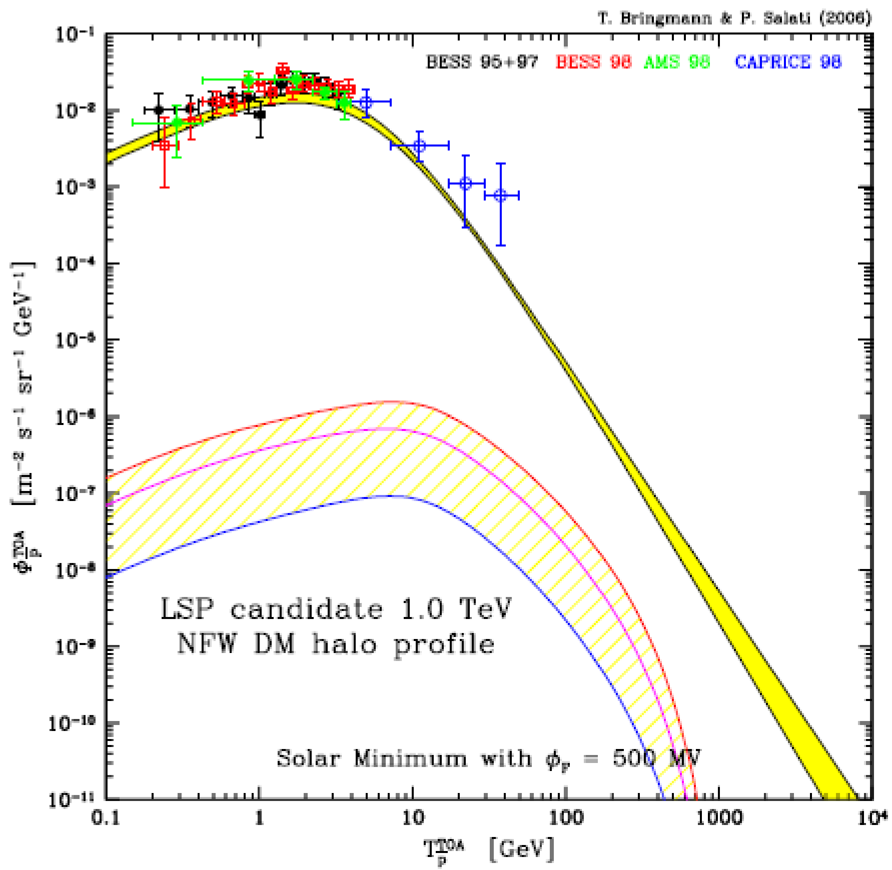

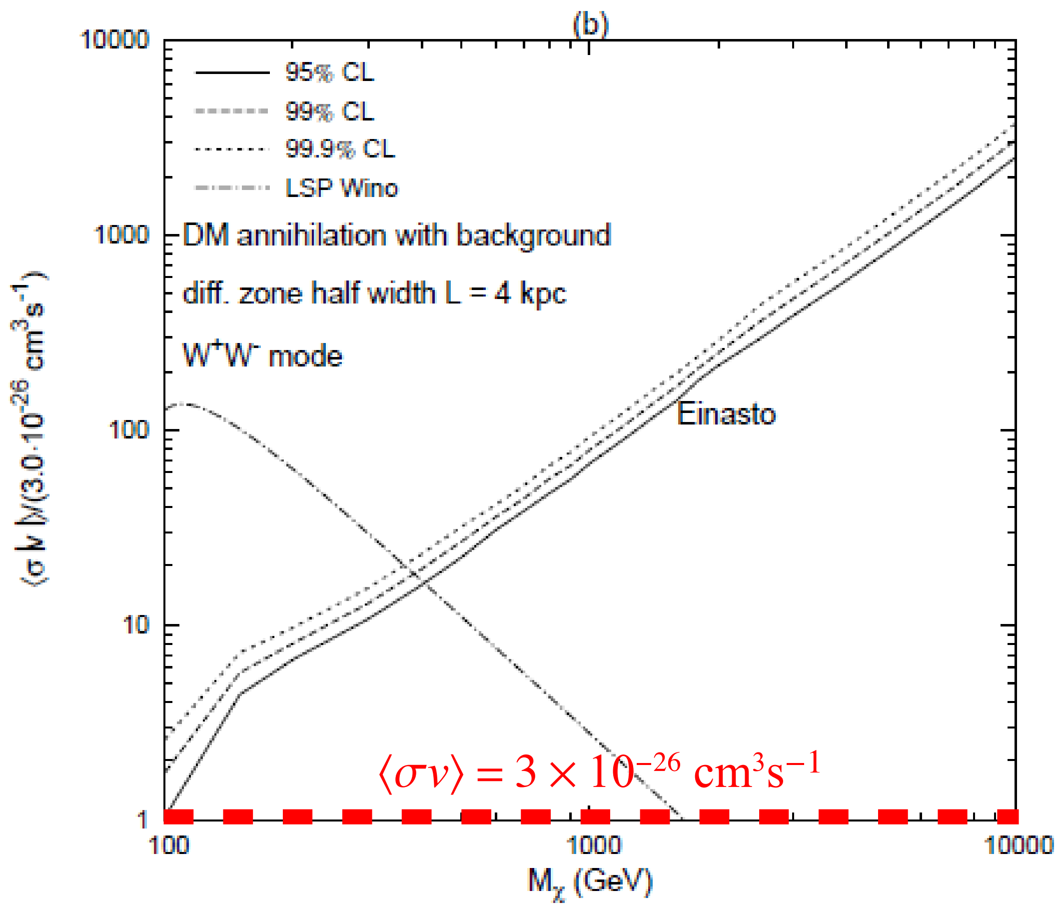

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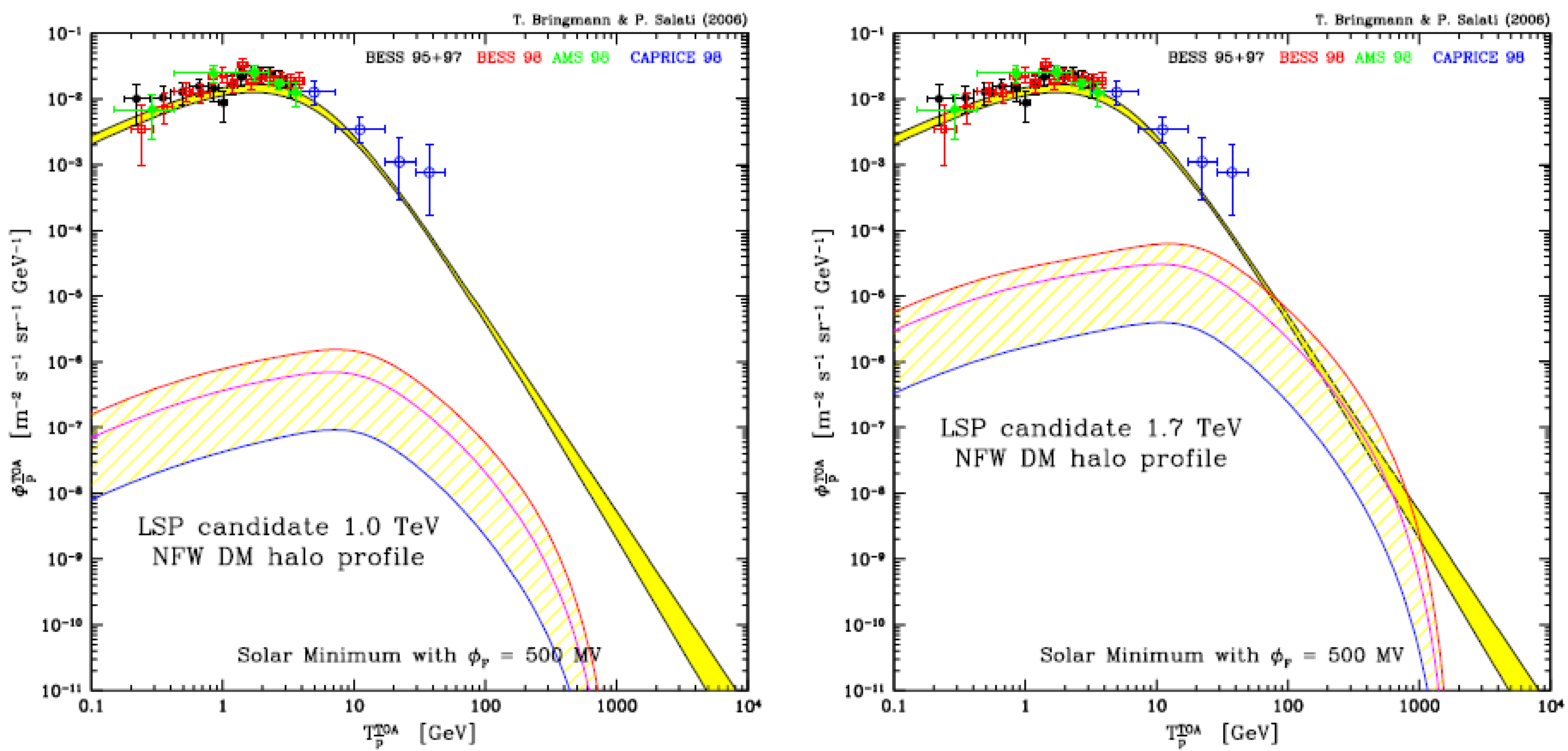
LSP1.0	1.0	0.46	-	-	-	-	-	-	-	100	-	-
LSP1.7	1.7	102	-	-	-	-	-	-	20.1	79.9	-	-



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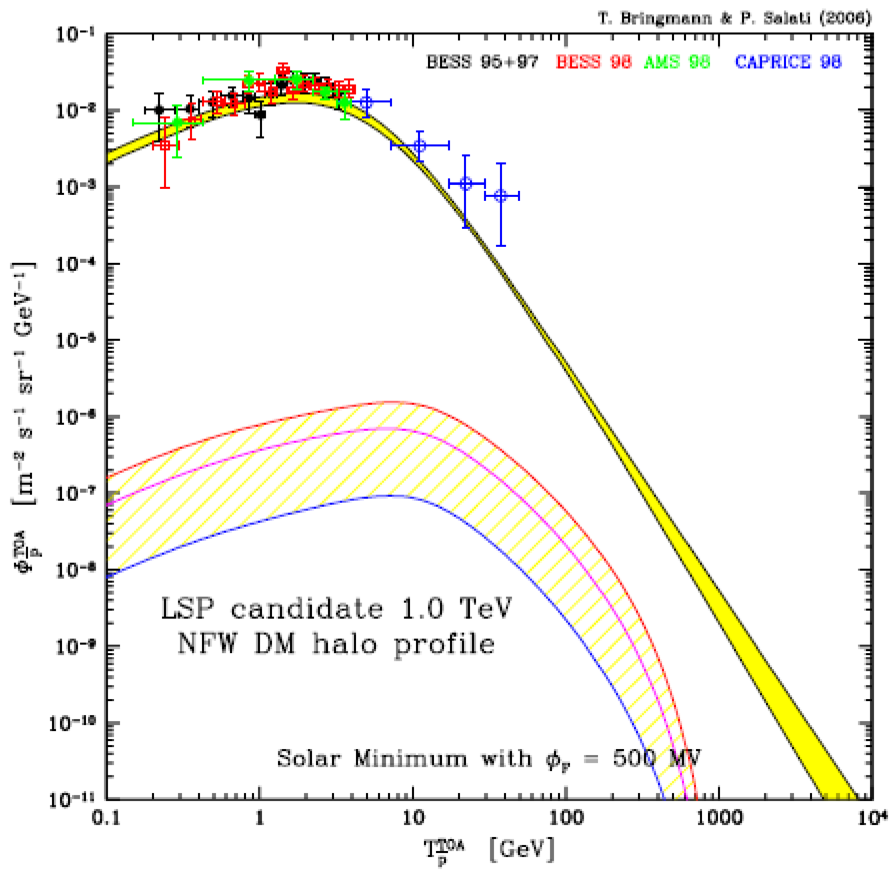
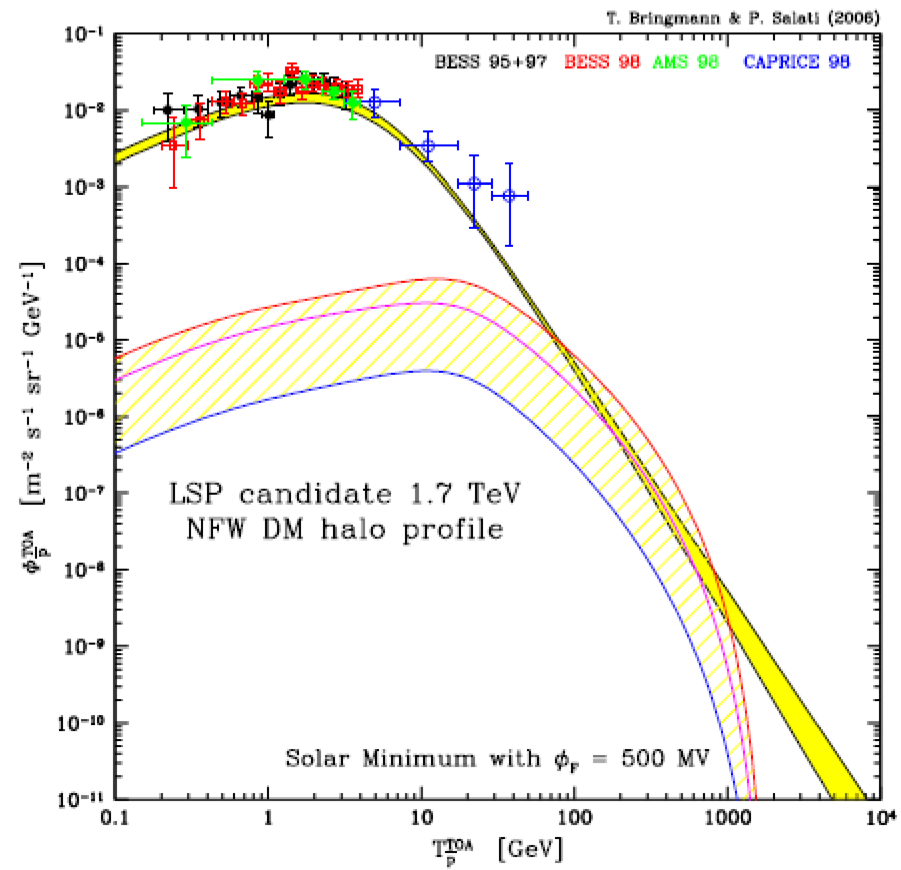
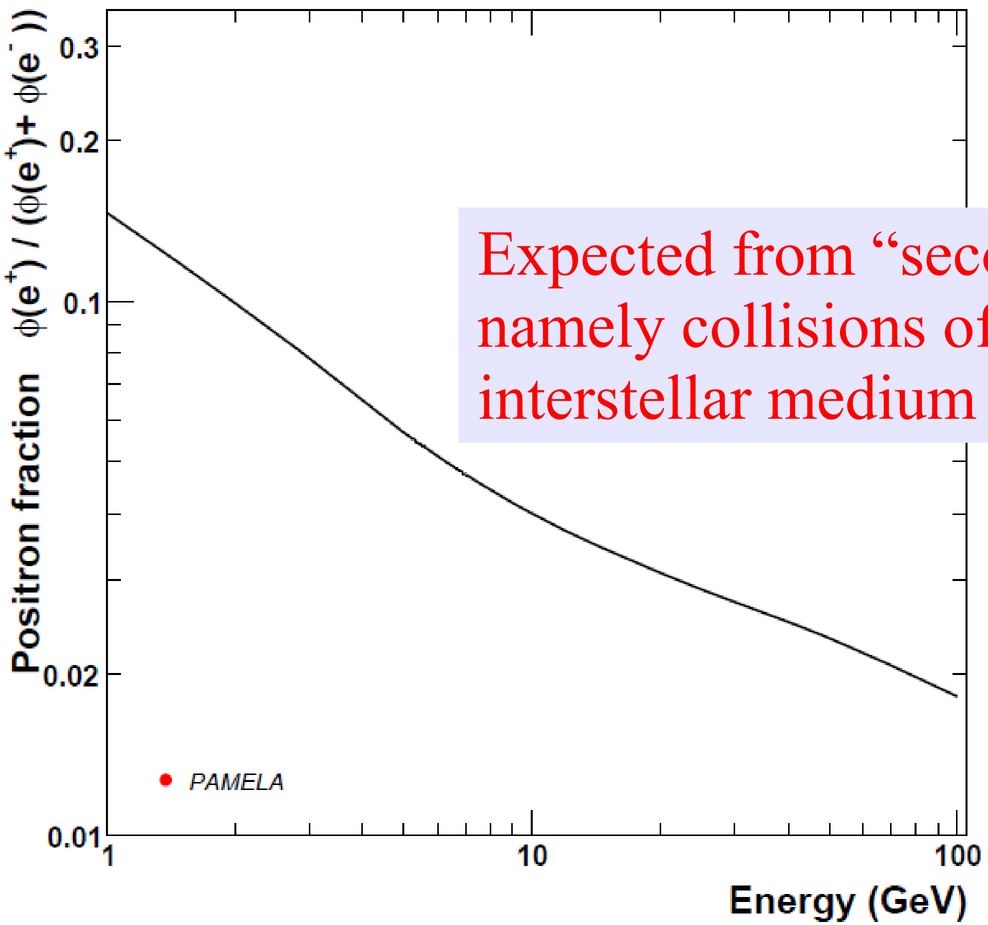
LSP1.0	1.0	0.46	-	-	-	-	-	-	-	100	-	-
LSP1.7	1.7	102	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Annihilation rate "boosted"!



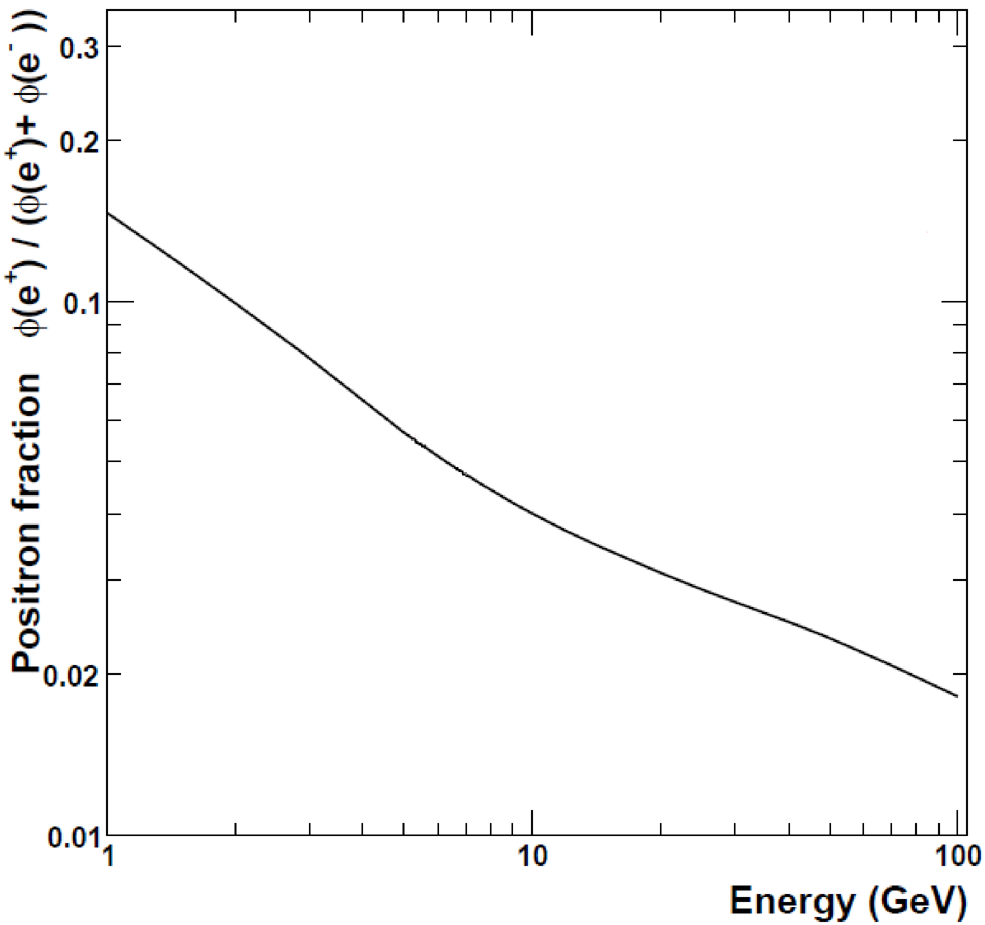


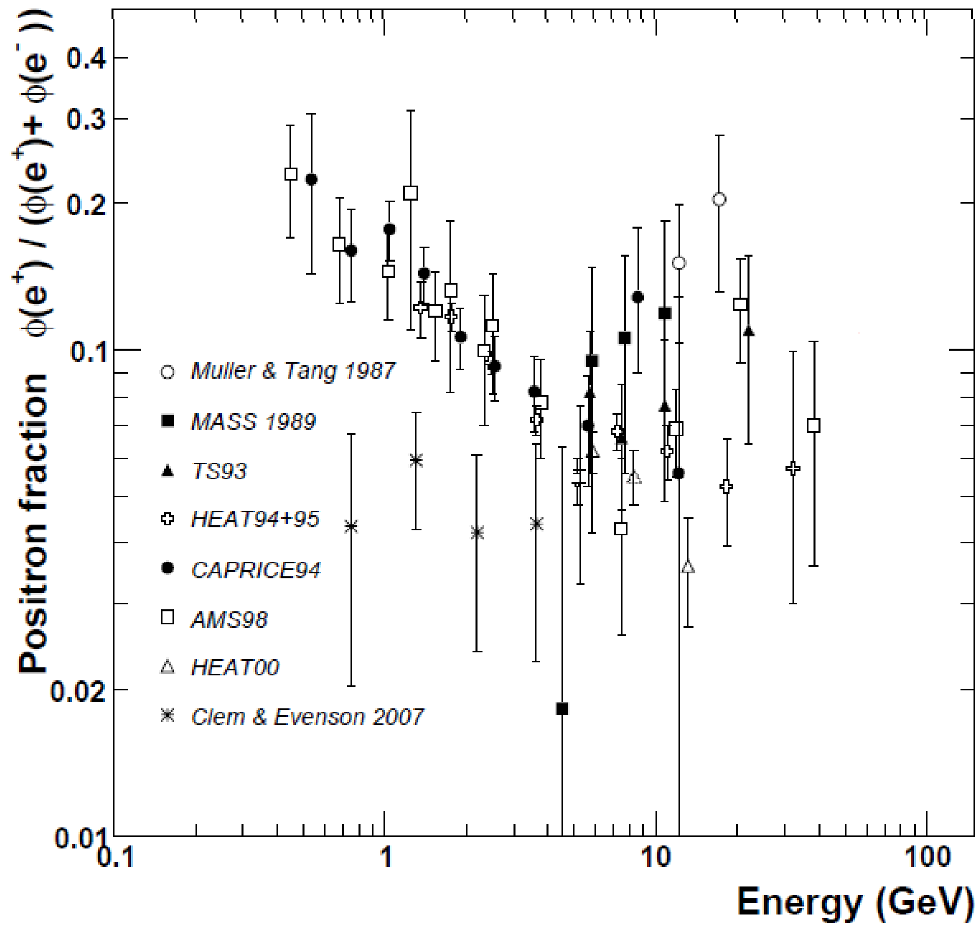
Experimental results: positrons



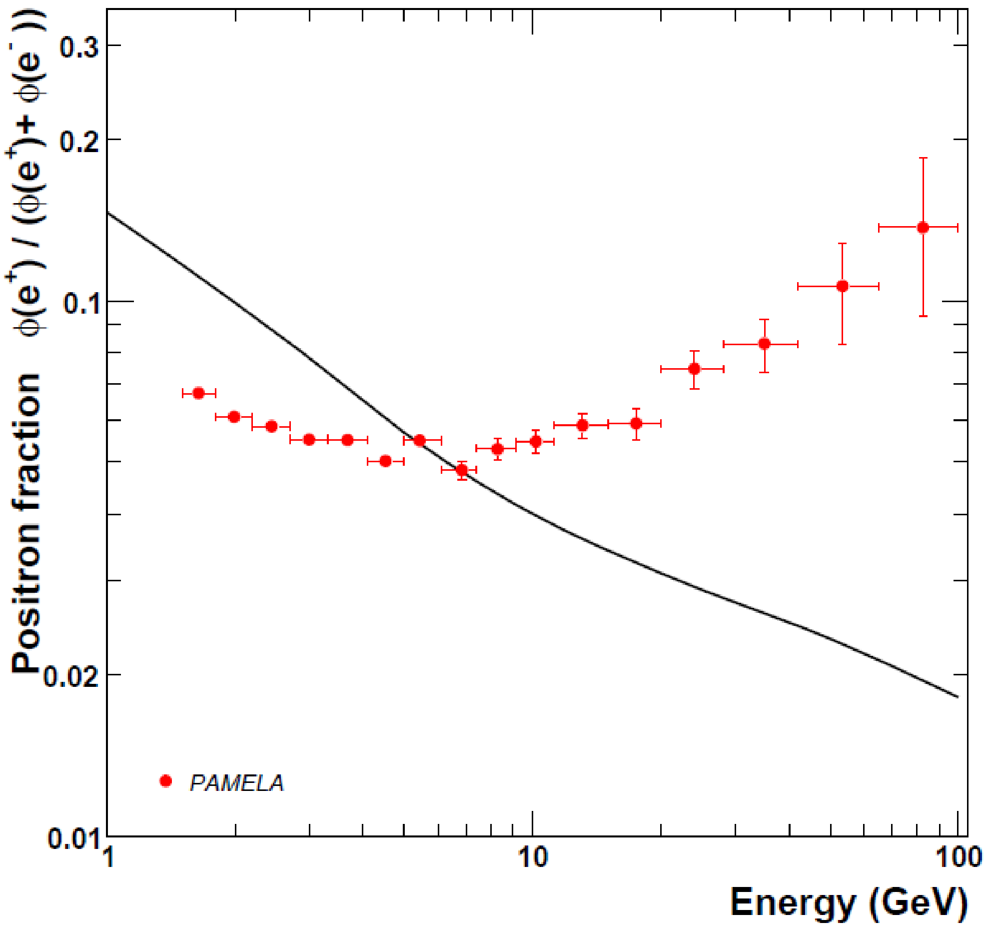
Expected from "secondary production", namely collisions of cosmic rays on the interstellar medium ($p\,p \to e^+ X$).

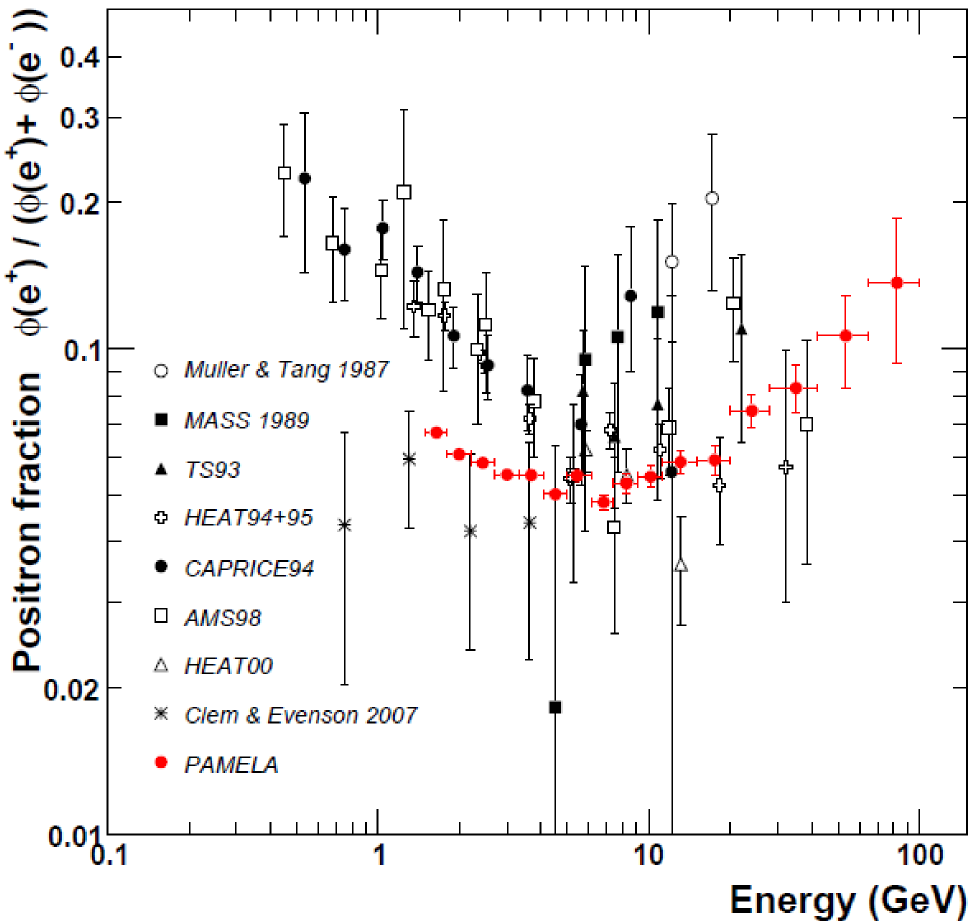
Experimental results: positrons





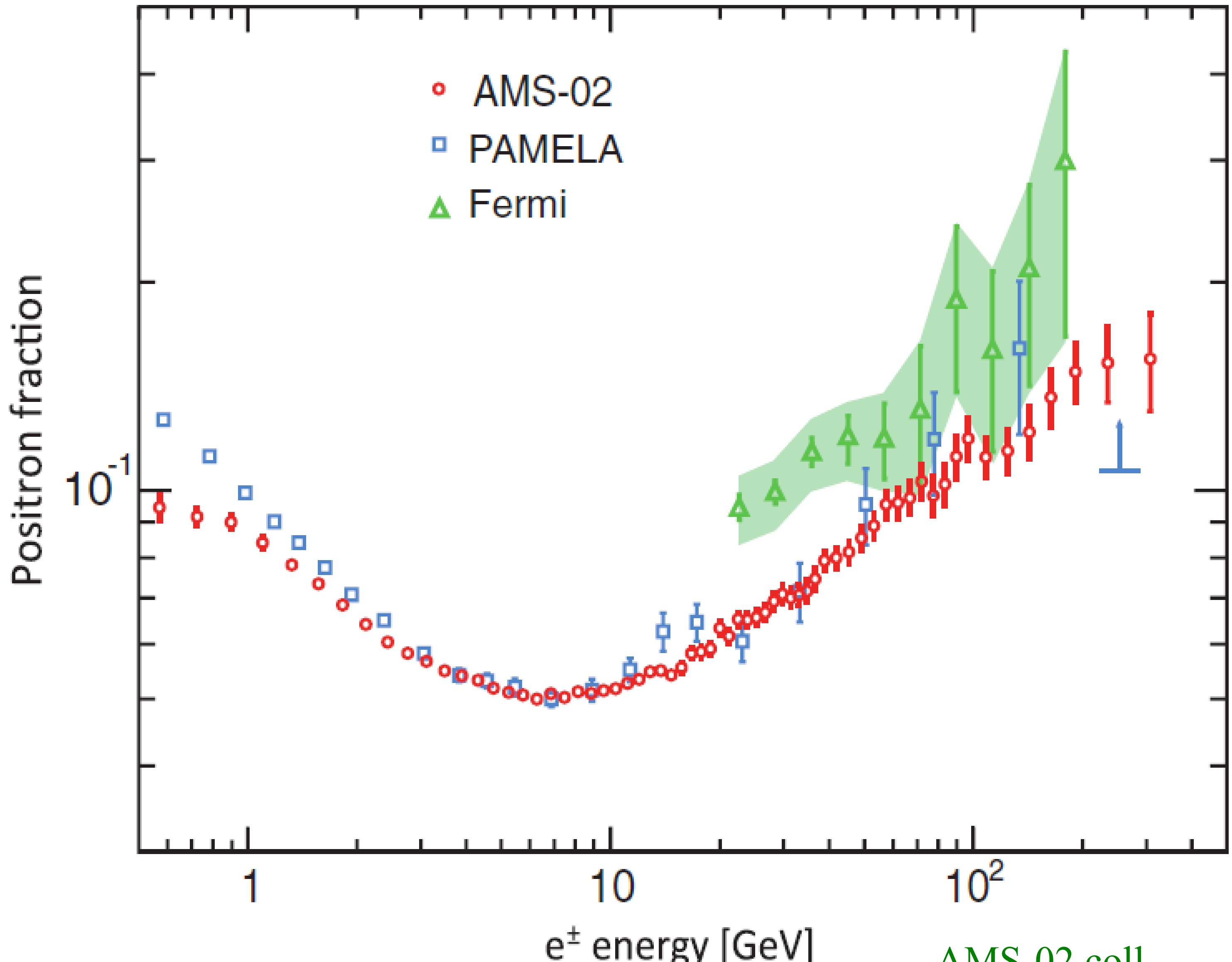
Experimental results: positrons





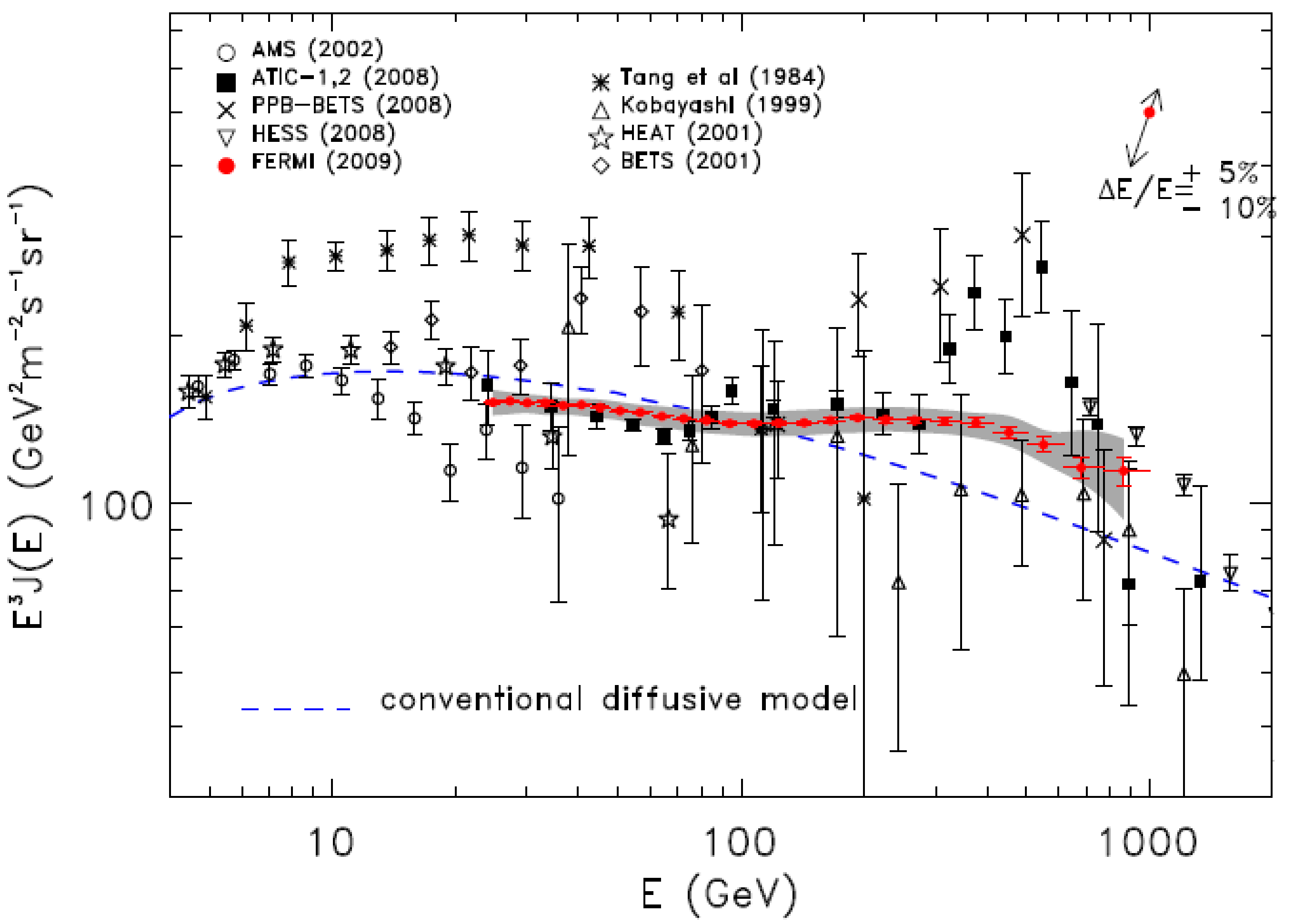
PAMELA coll.
arXiv:0810.4995

Experimental results: positrons



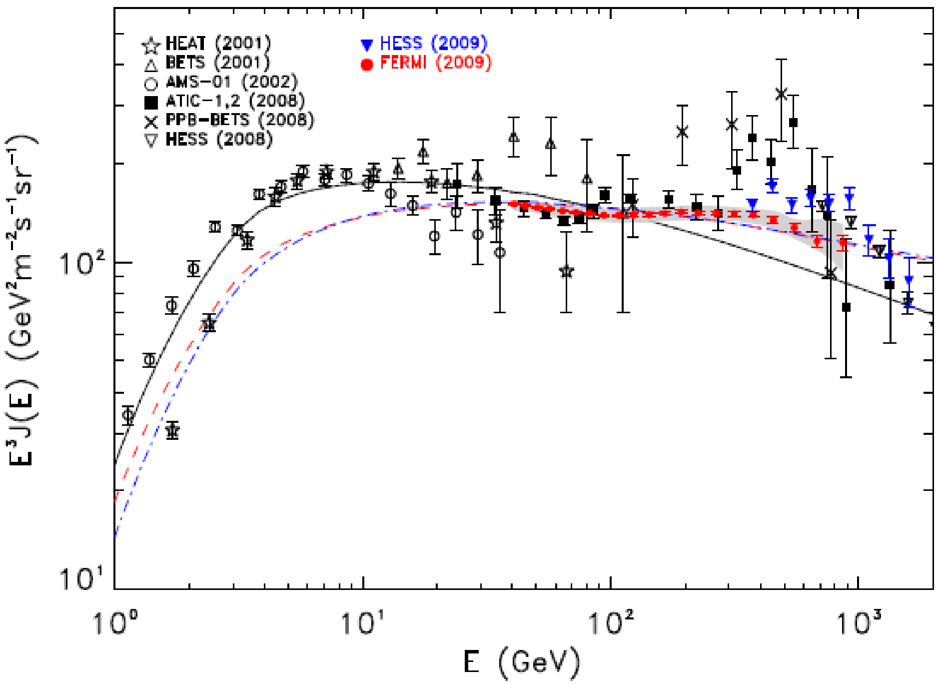
AMS-02 coll.
Phys.Rev.Lett. 110 (2013) 14, 141102

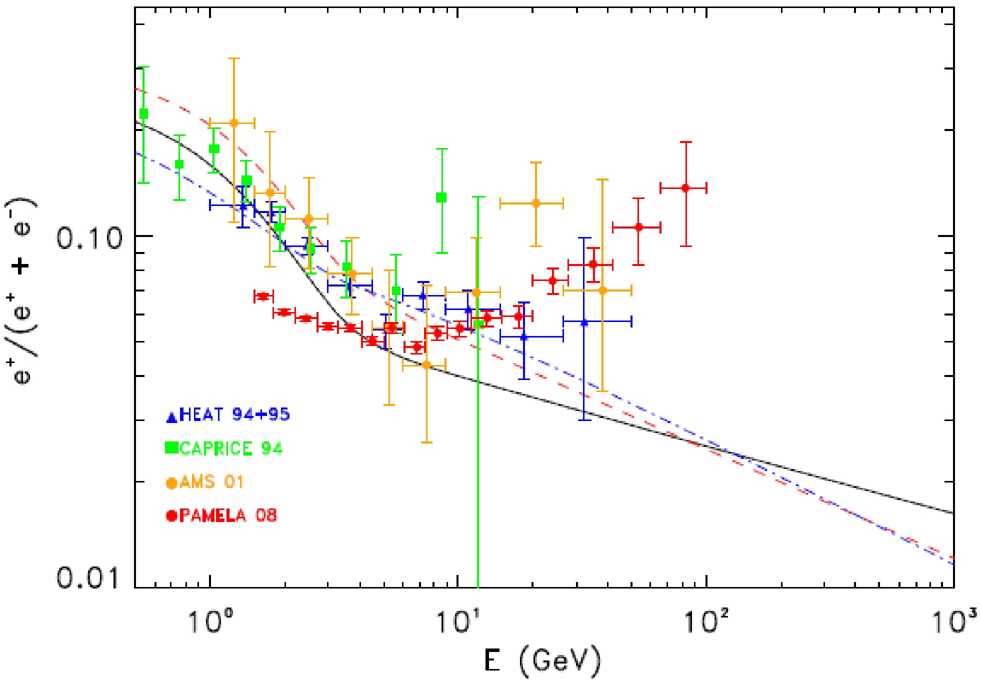
More puzzles: the electron+positron flux



Abdo et al.
ArXiv:0905.0025

Present situation:





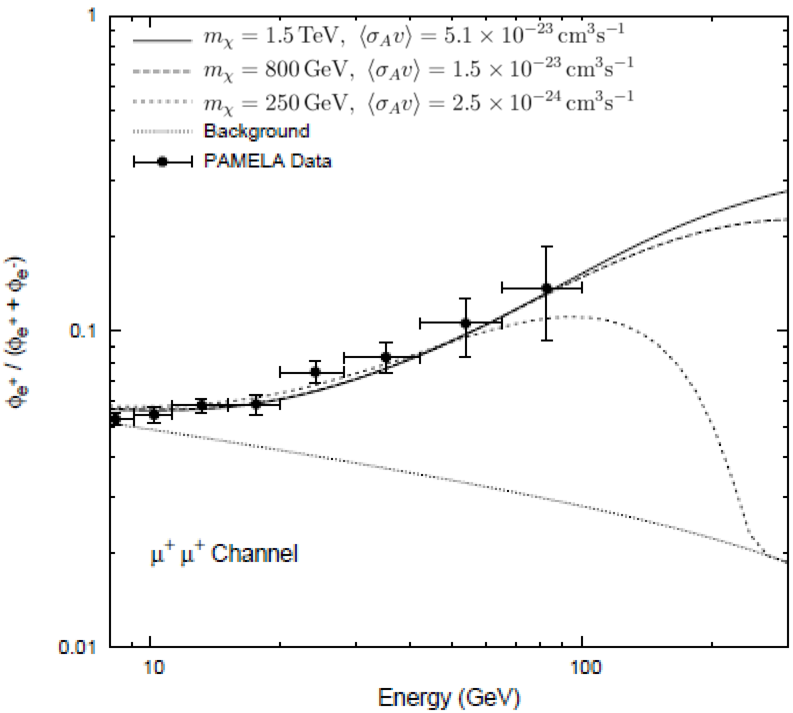
Evidence for a primary component of positrons

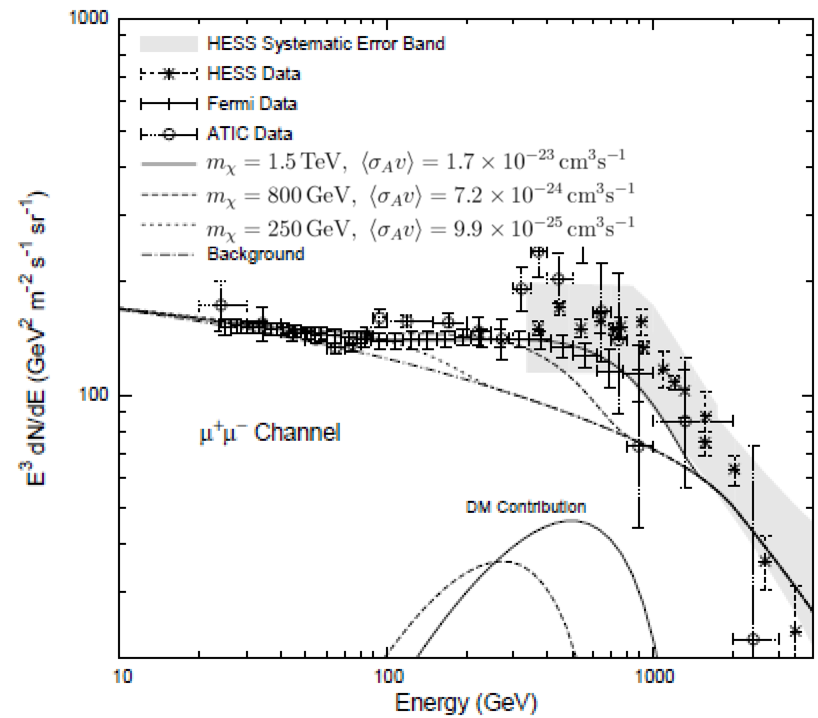
(possibly accompanied by electrons)

Dark matter interpretation

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

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

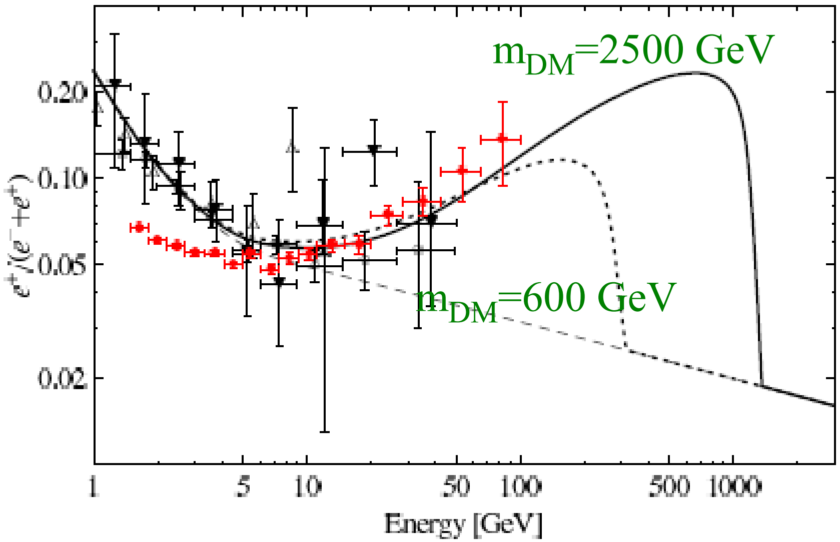


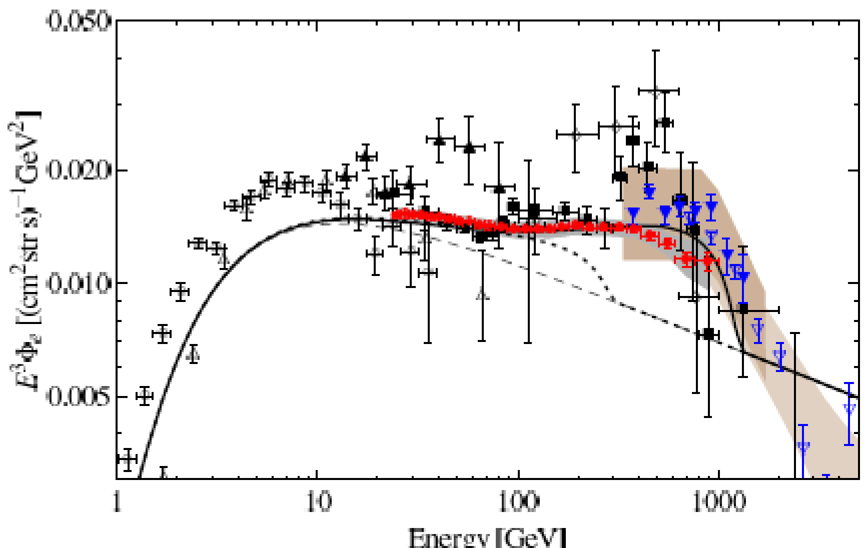


Cholis et al.
arXiv:0811.3641

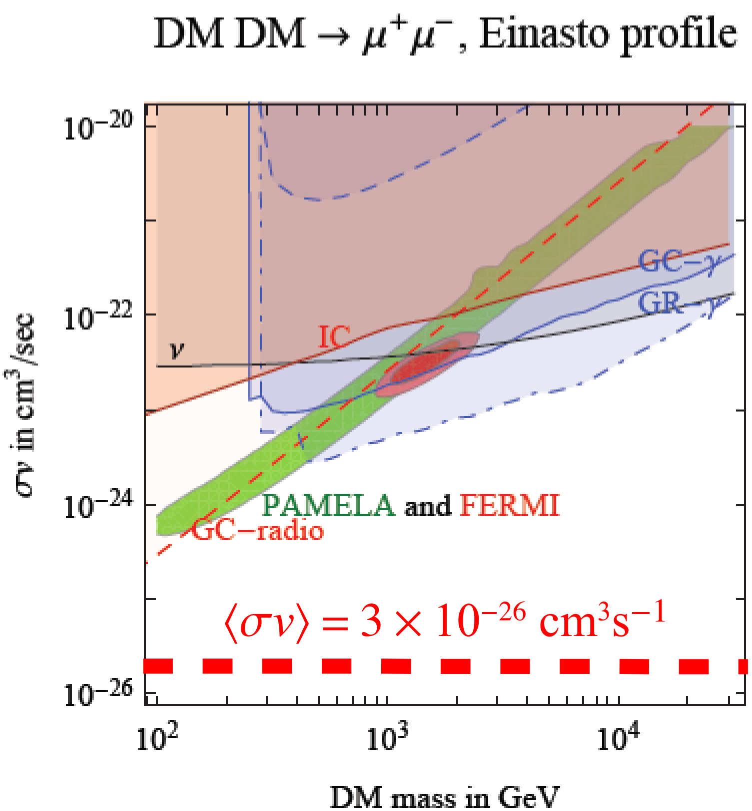
… or dark matter decays

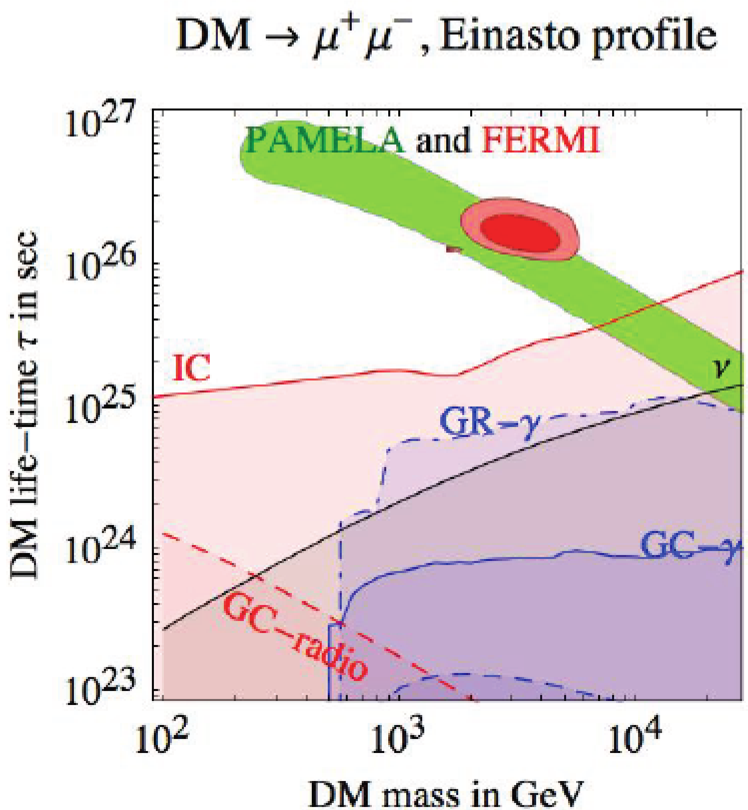
"Democratic" decay $\psi \to \ell^+ \ell^- \nu$





AI, Tran, Weniger
arXiv:0906.1571



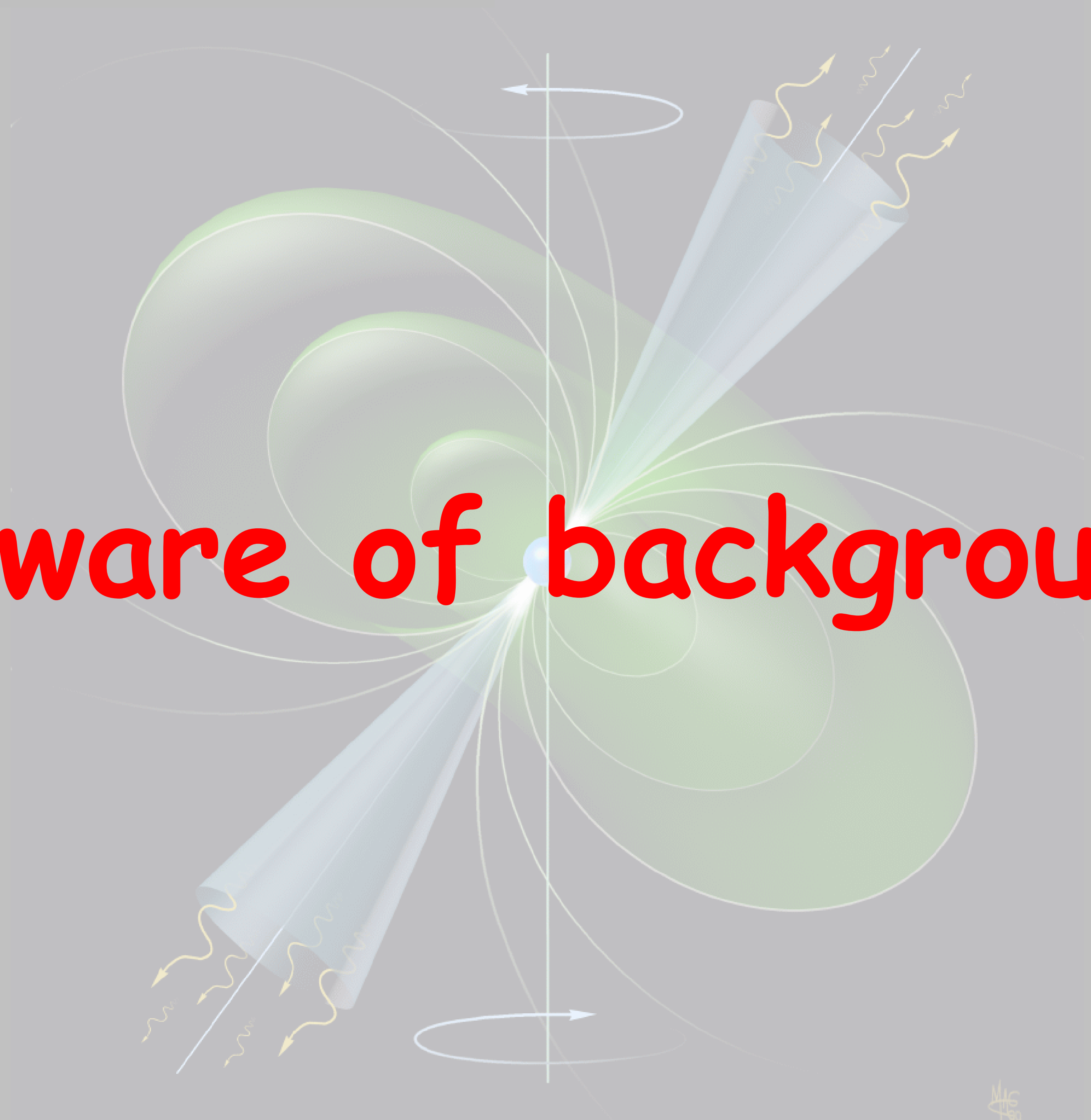


Is this the first non-gravitational evidence of dark matter?

"Extraordinary claims require extraordinary evidence"

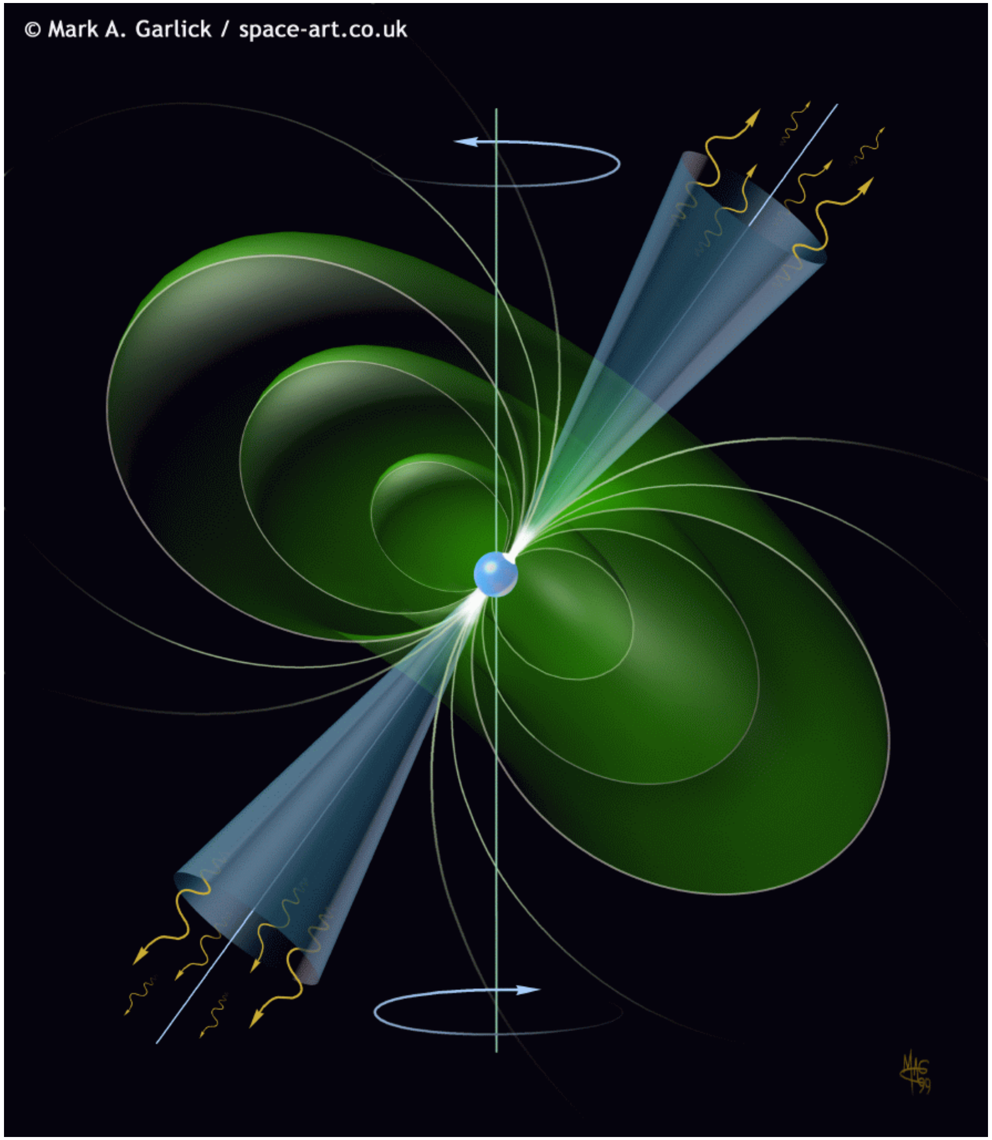
Carl Sagan

Beware of backgrounds!

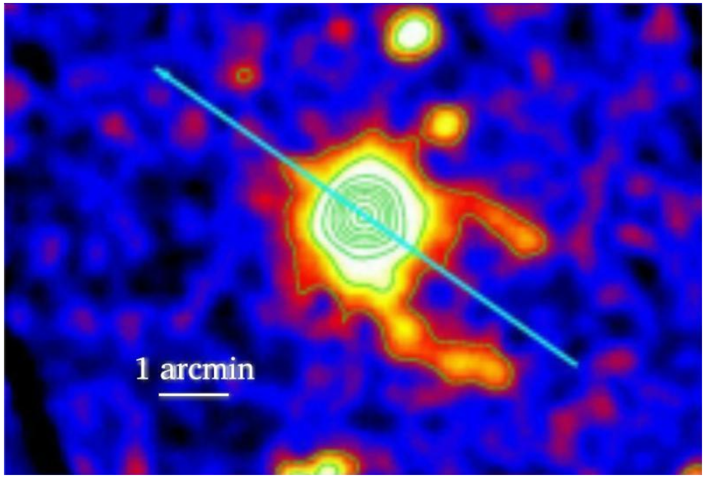


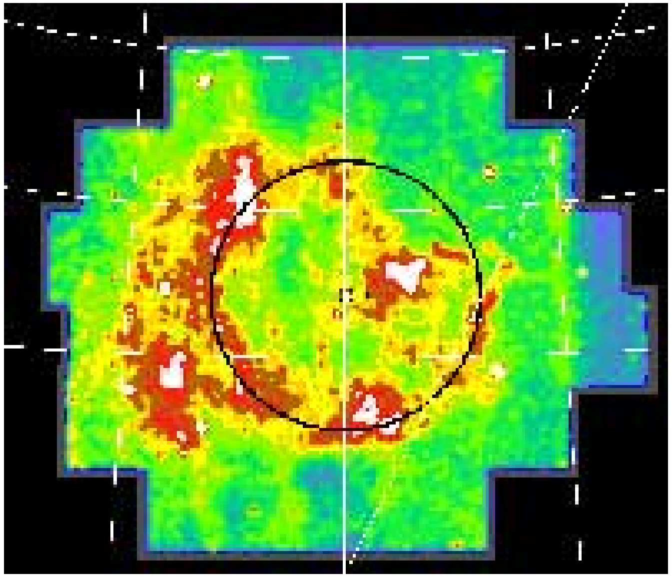
Pulsars <u>are</u> sources of high energy electrons & positrons

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



Pulsar explanation I: Geminga + Monogem





Geminga

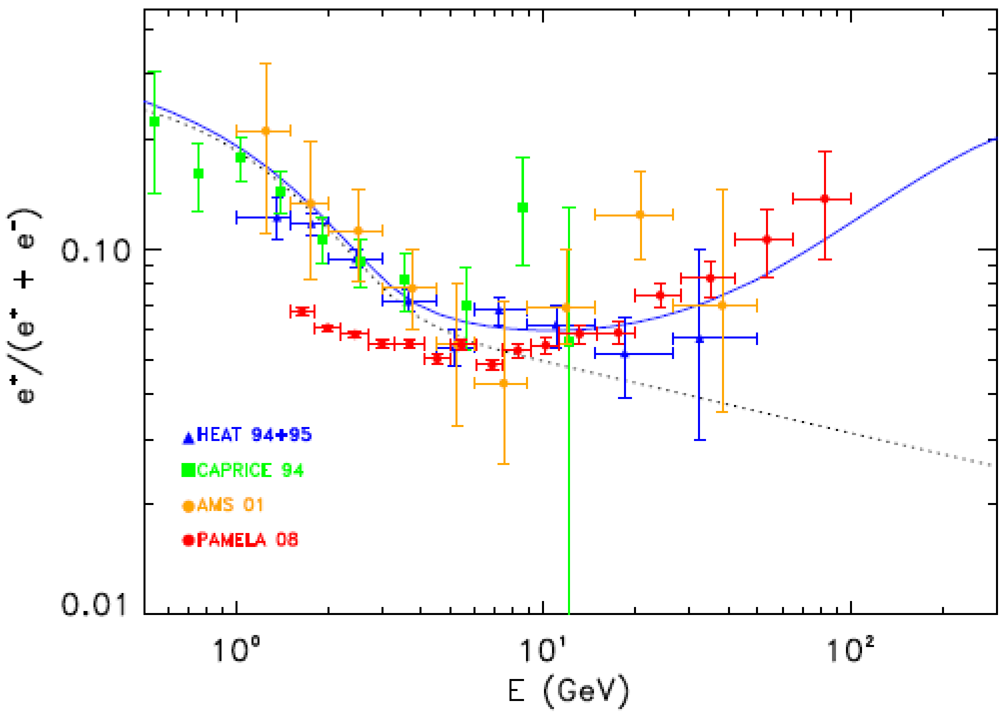
T=370 000 years
D=157 pc

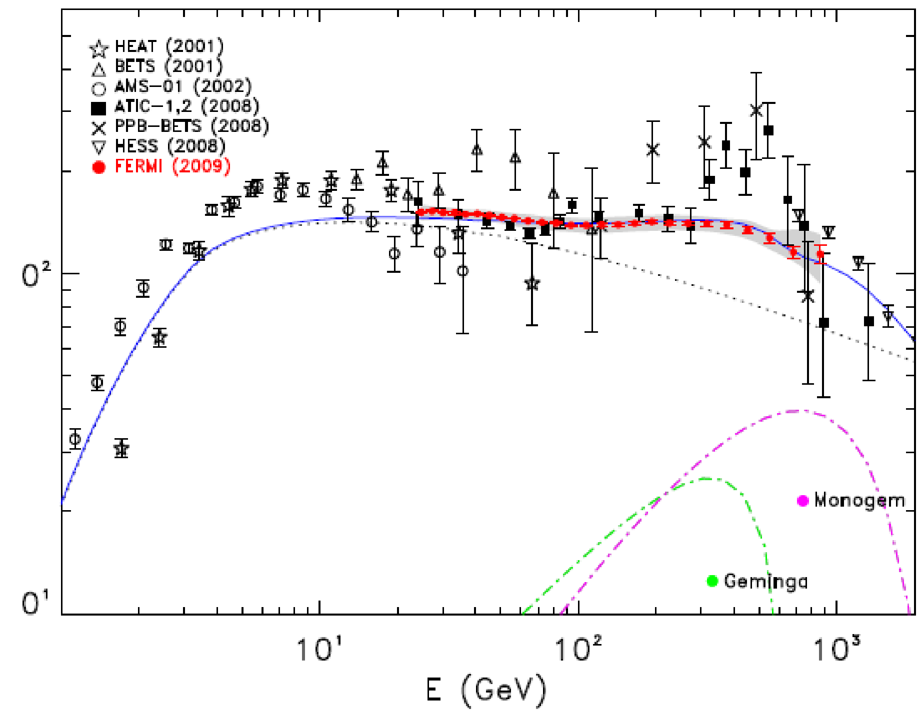
Monogem (B0656+14)

T=110 000 years
D=290 pc

Pulsar explanation I: Geminga + Monogem

Grasso et al.



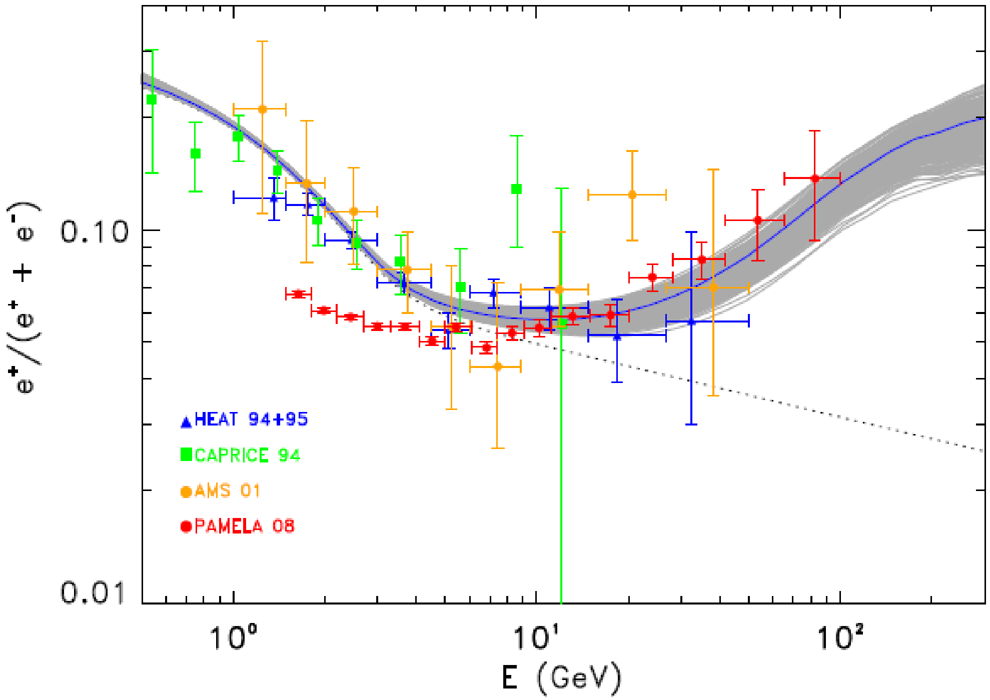


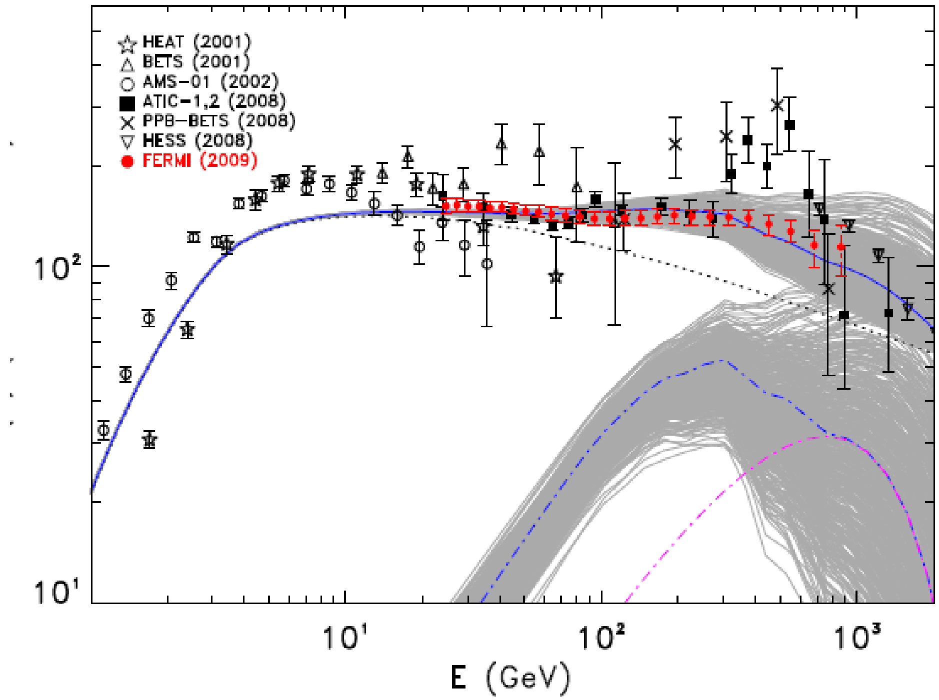
Nice agreement. However, it is <u>not</u> a prediction!

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

Pulsar explanation II: Multiple pulsars

Grasso et al.





- $dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/E_0)$, $1.5 < \alpha < 1.9$, $800\ \mathrm{GeV} < E_0 < 1400\ \mathrm{GeV}$
- 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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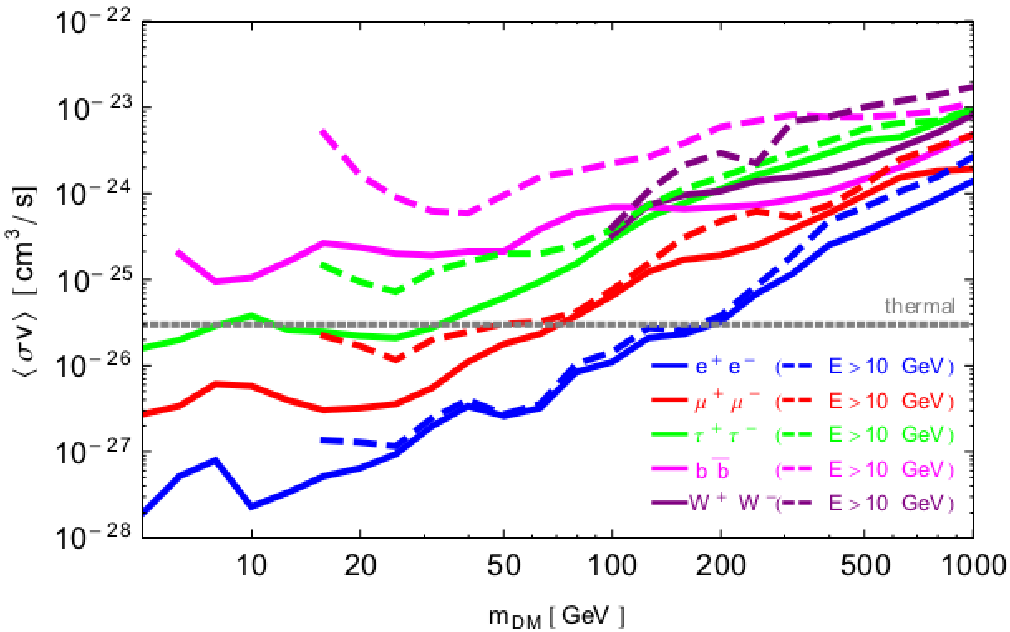
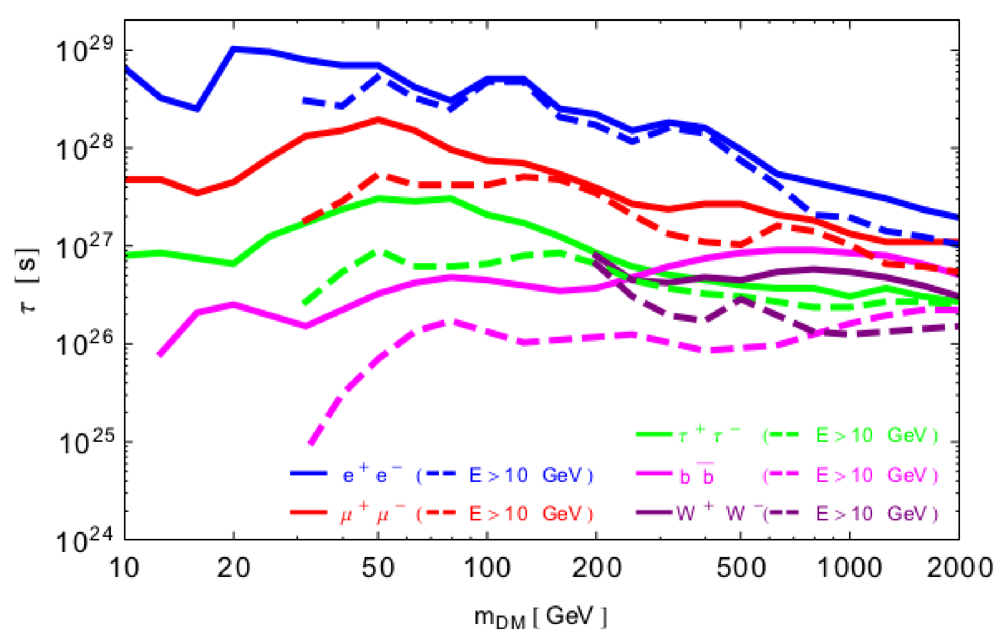
The origin of the positron excess is still unclear:

- 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.

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

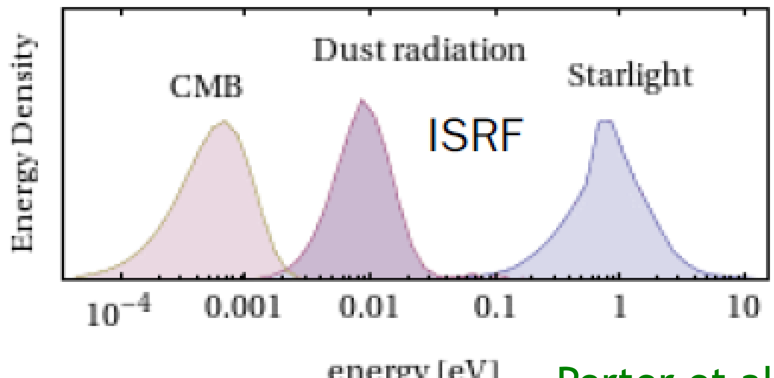
$e^{\pm}$ from dark matter annihilation/decay $E_e \lesssim 1$ TeV

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

Upscattered photon

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

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



Porter et al.

Prompt radiation

Annihilation

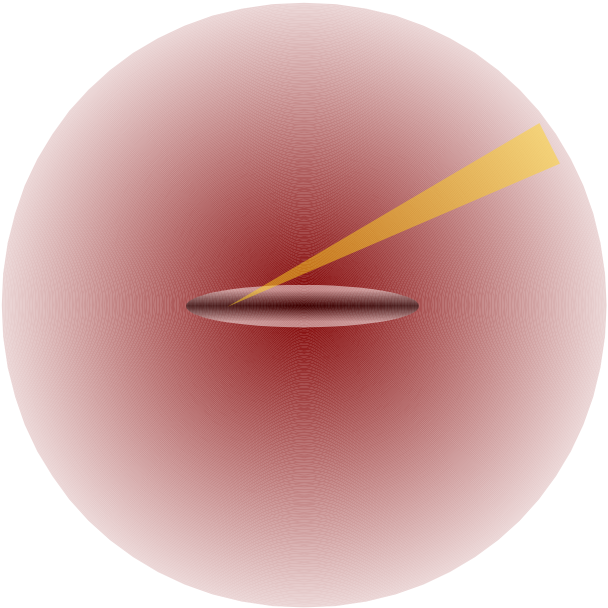
$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann} v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right] \times \int_{\rm l.o.s.} \rho^2(\vec{l})\, d\vec{l}$$

Source term
(particle physics)

Line-of-sight integral
(astrophysics)

Decay

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



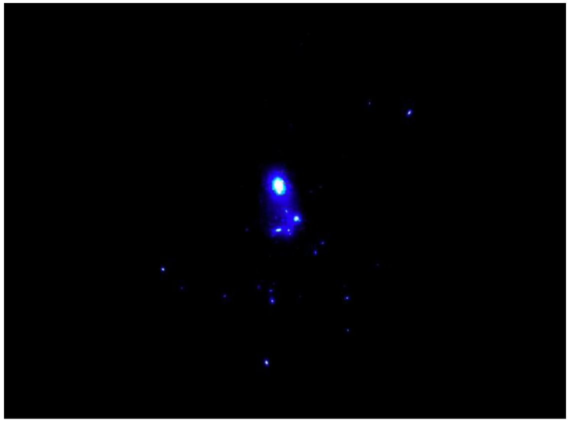
Prompt radiation

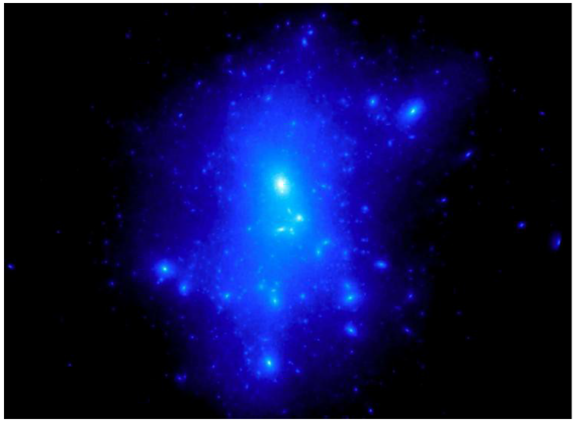
Annihilation
$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann} v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right] \times \int_{\rm l.o.s.} \rho^2(\vec{l})\, d\vec{l}$$

Source term (particle physics)

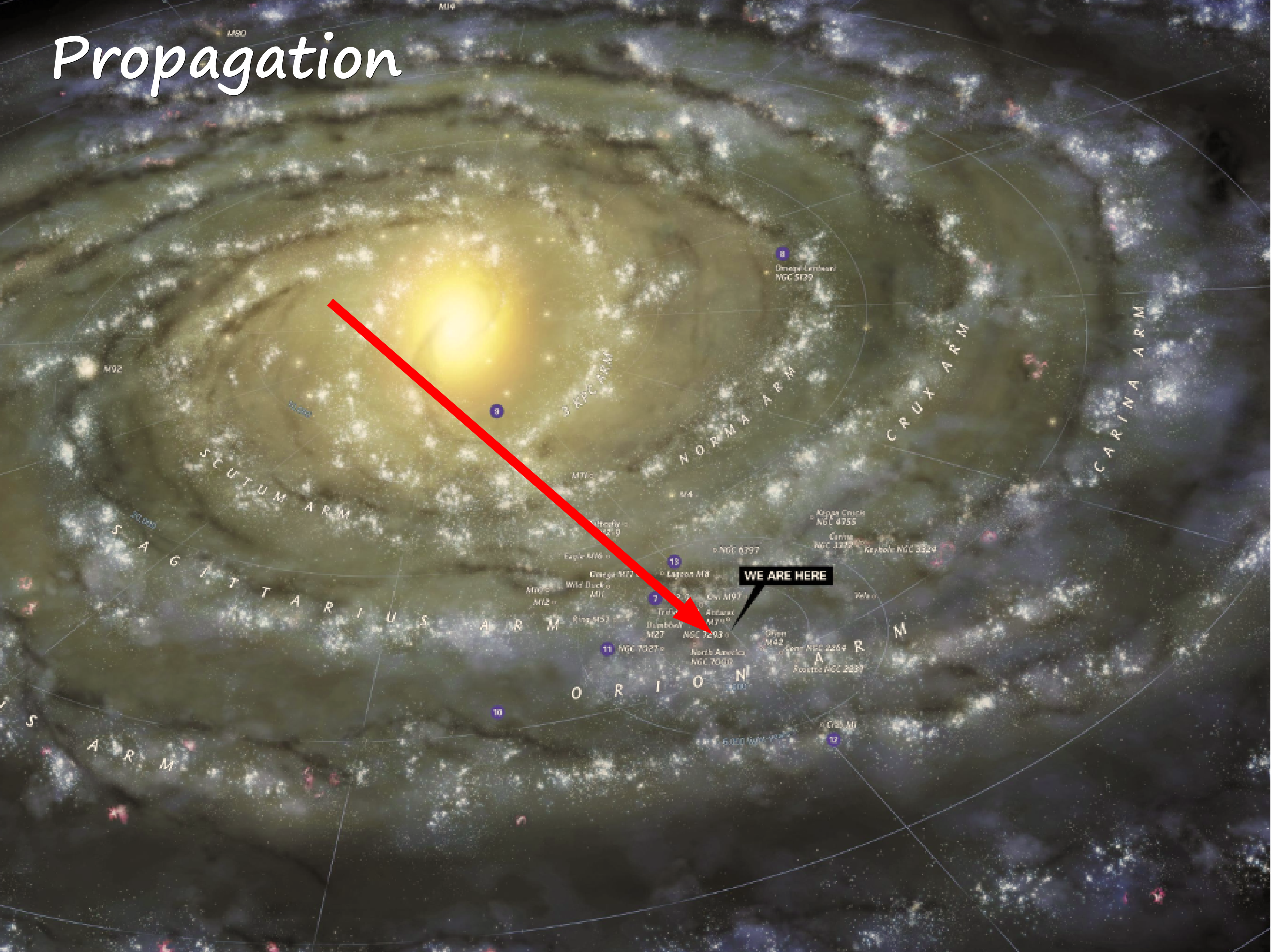
Line-of-sight integral (astrophysics)

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



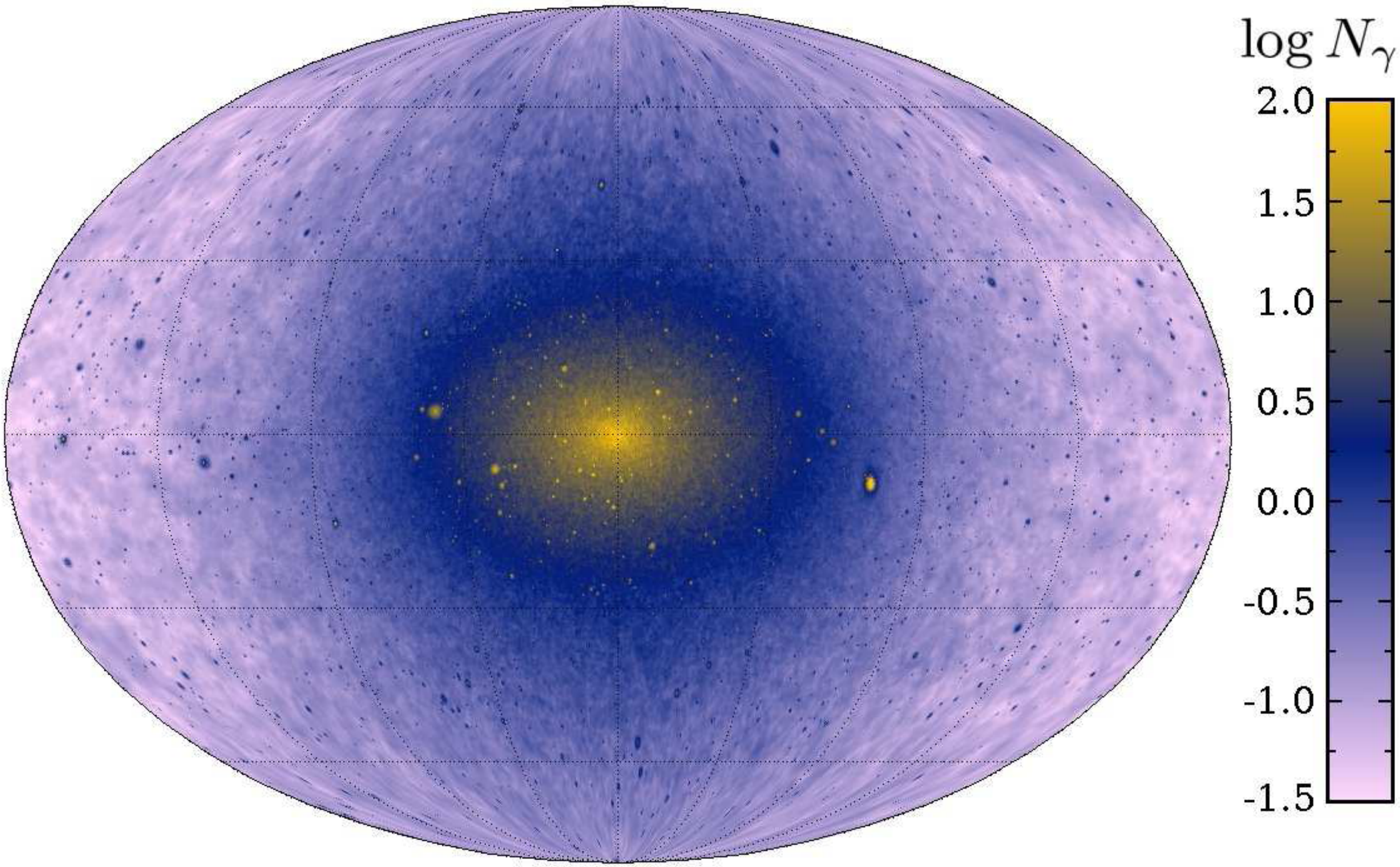


Propagation



Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911



Kuhlen, Diemand, Madau

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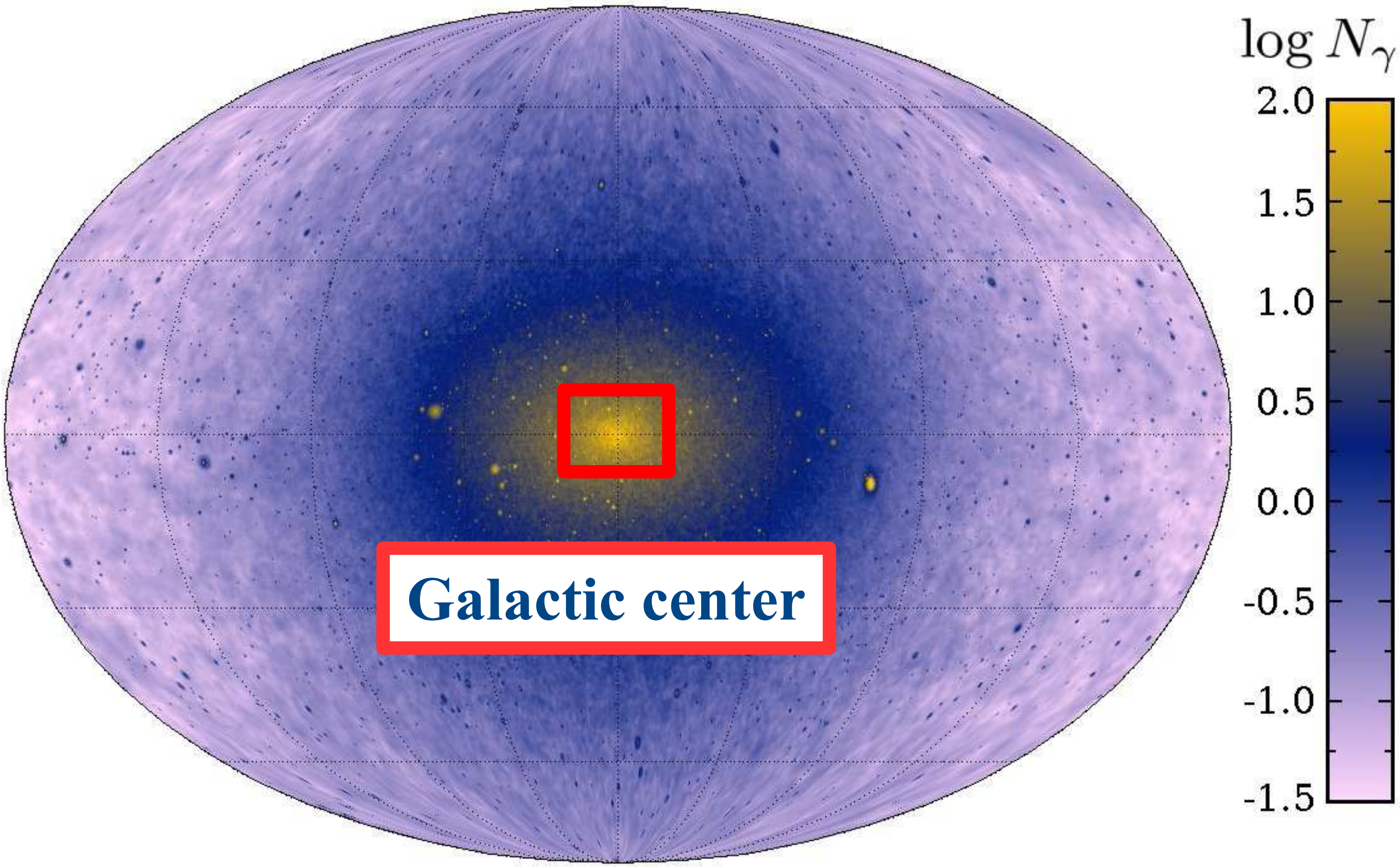

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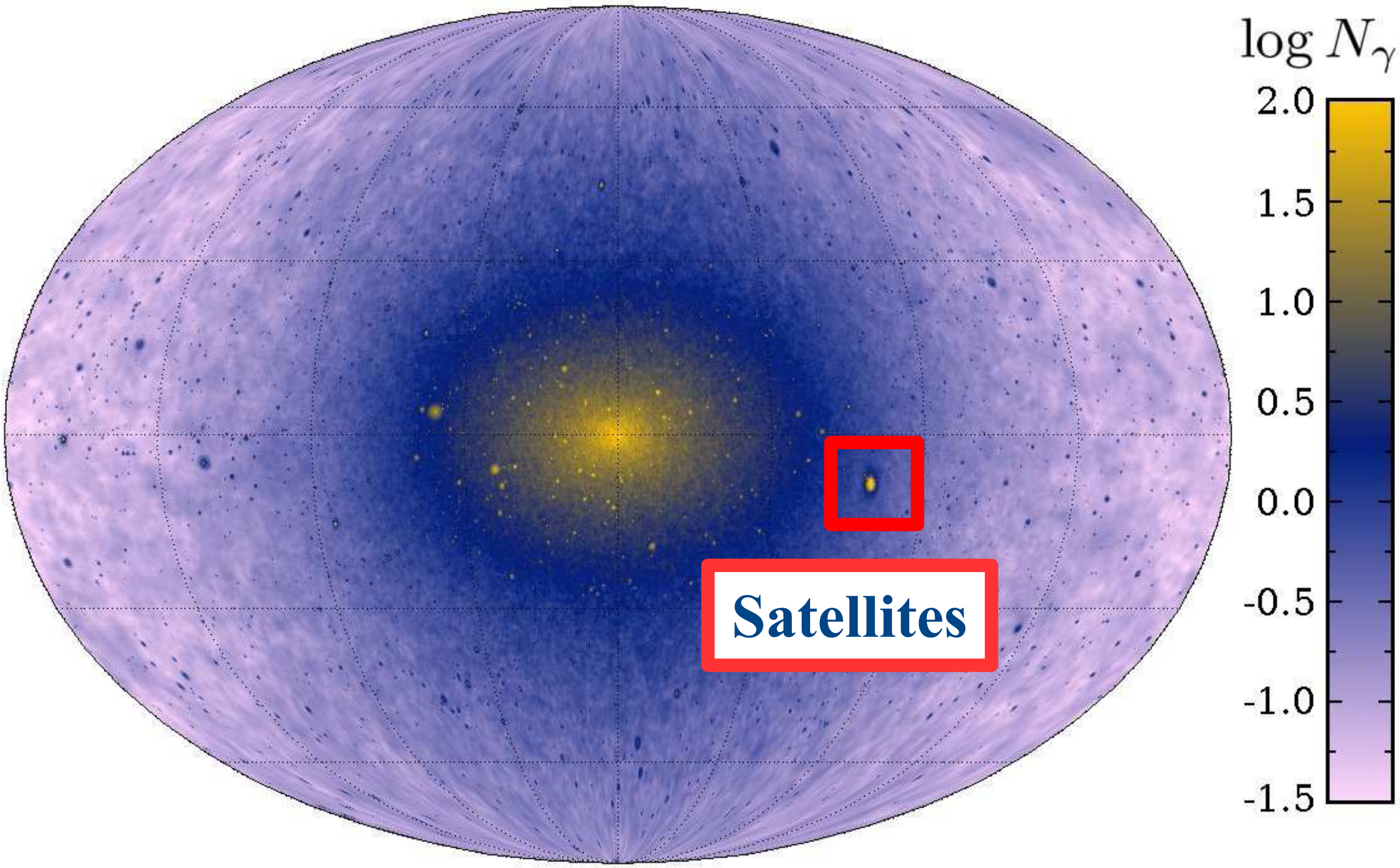

Kuhlen, Diemand, Madau

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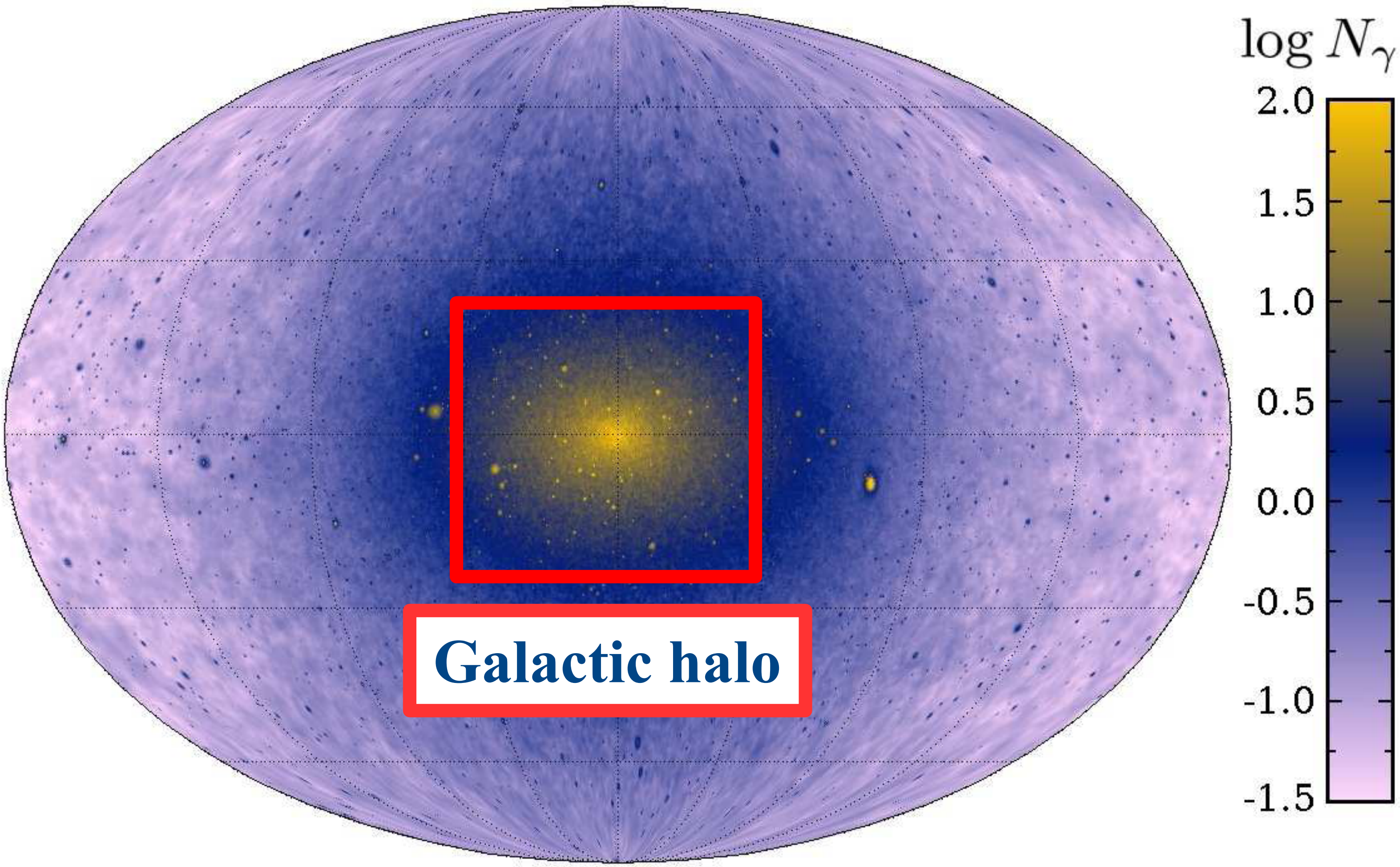

Kuhlen, Diemand, Madau

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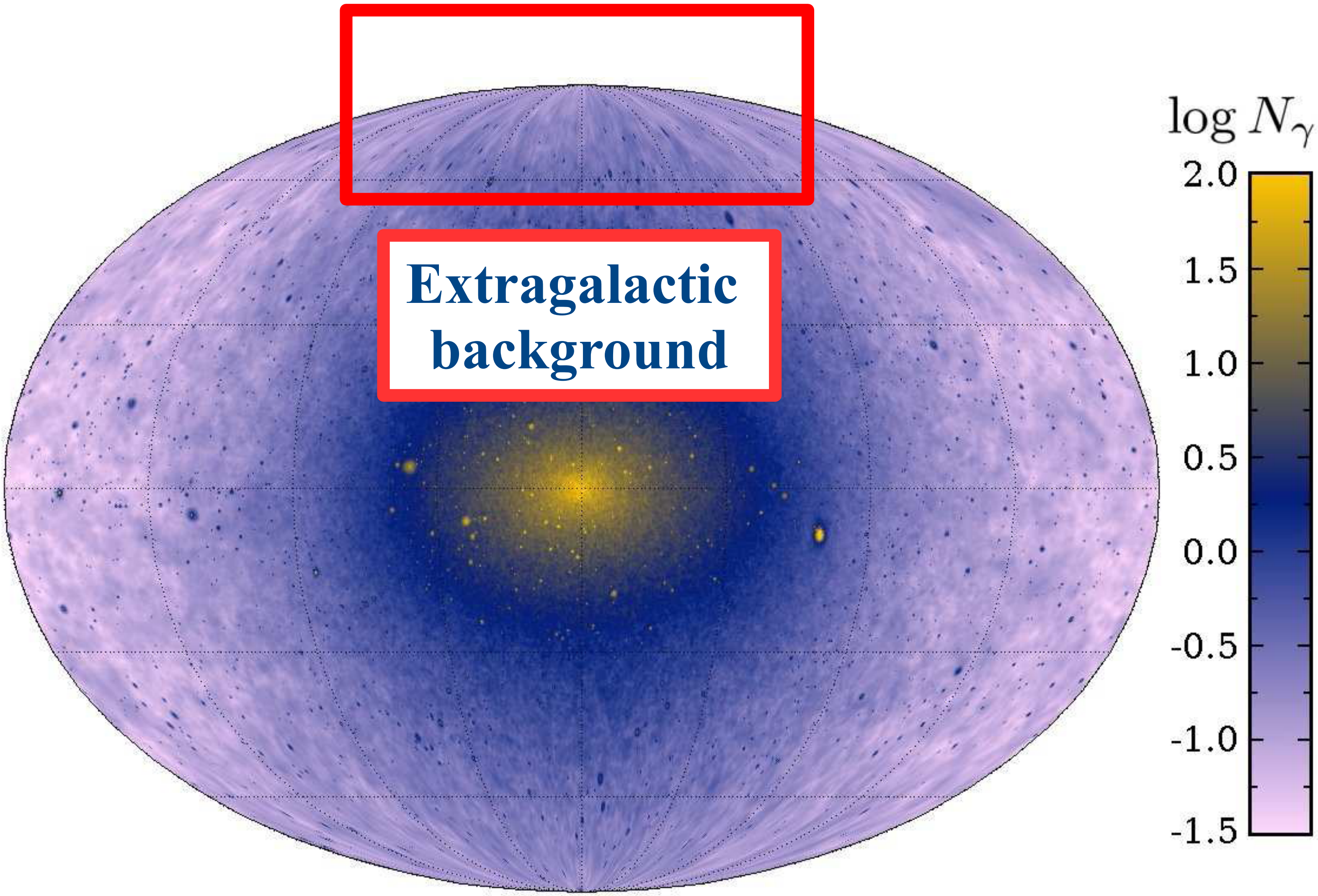

Kuhlen, Diemand, Madau

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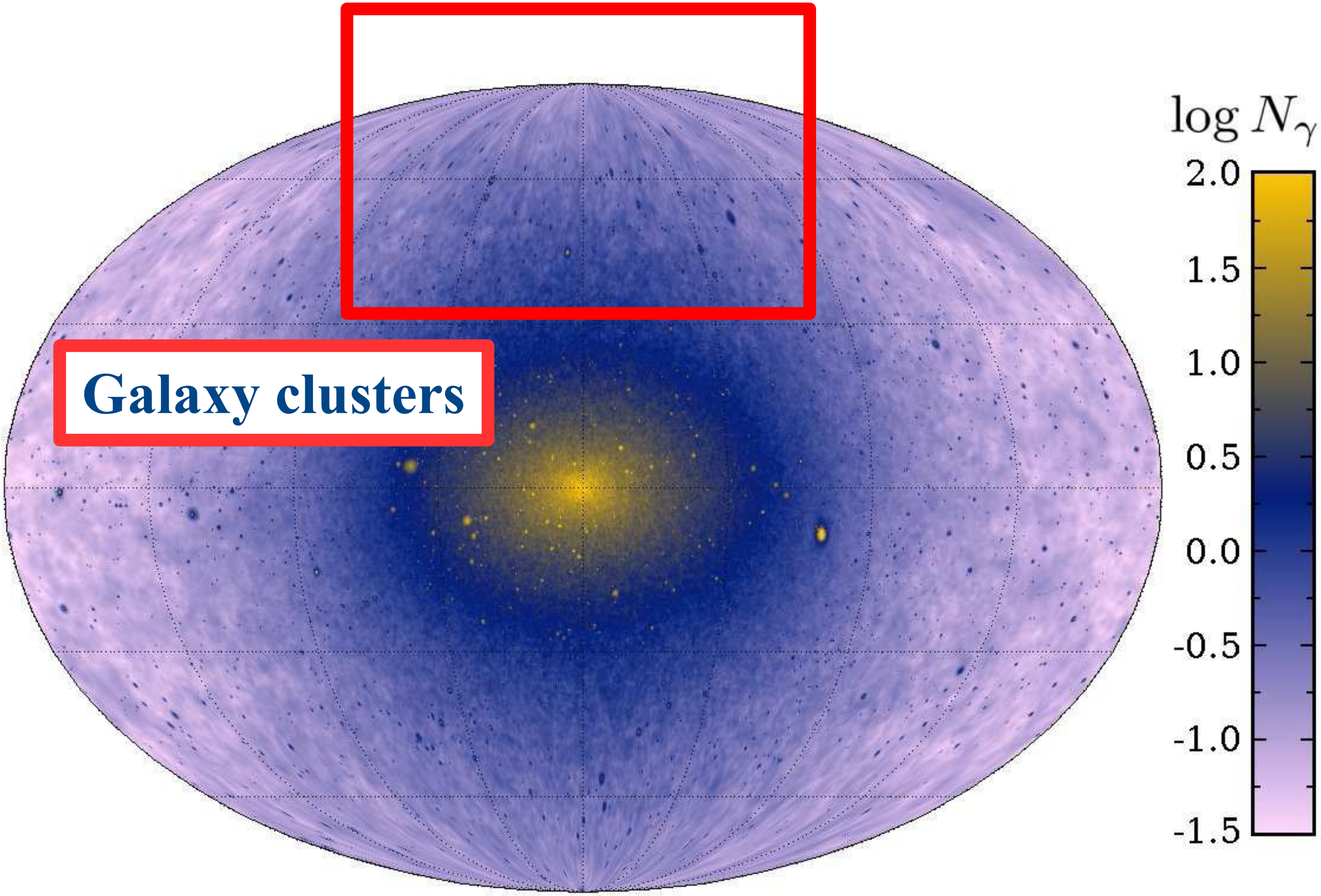
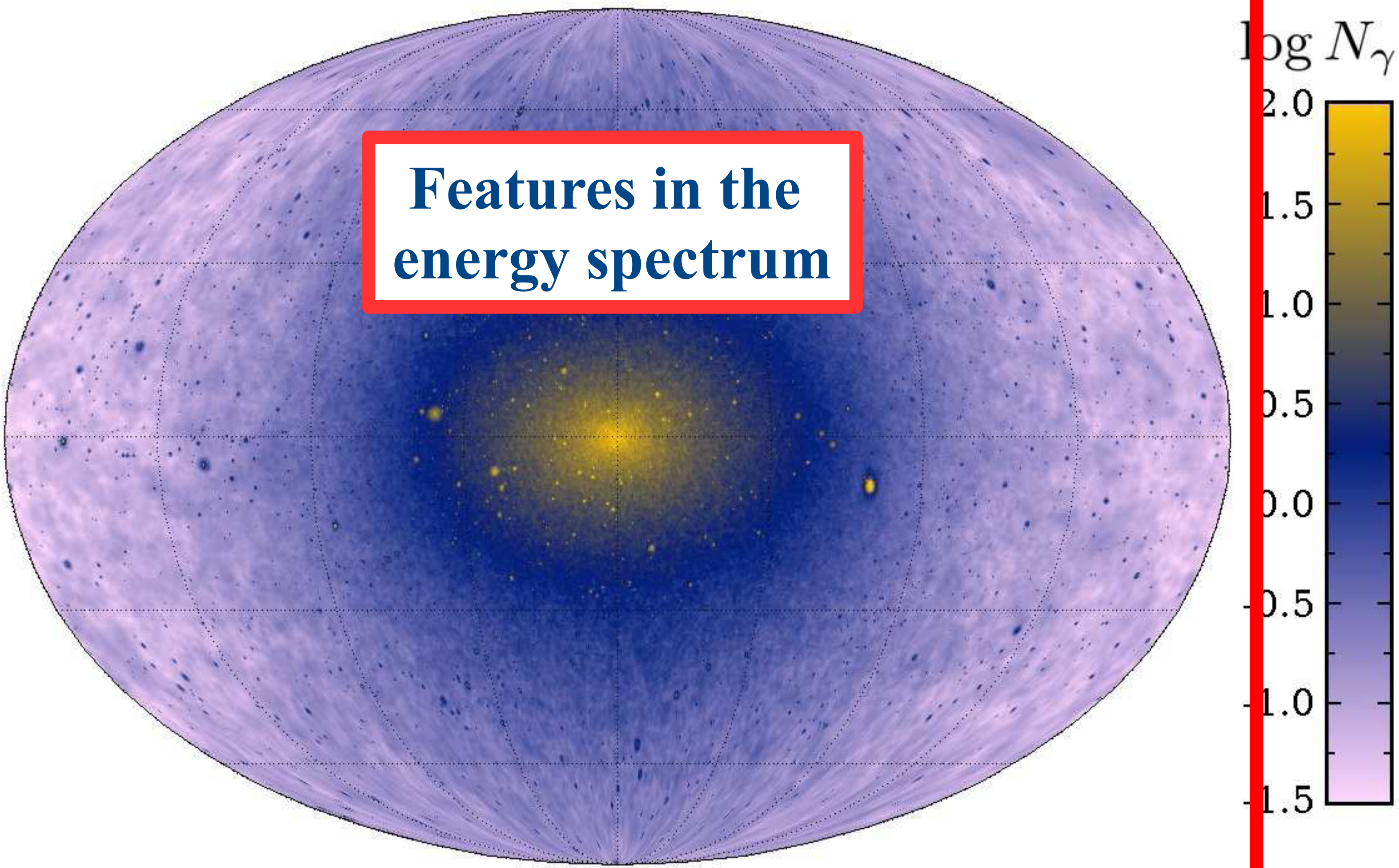


Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911

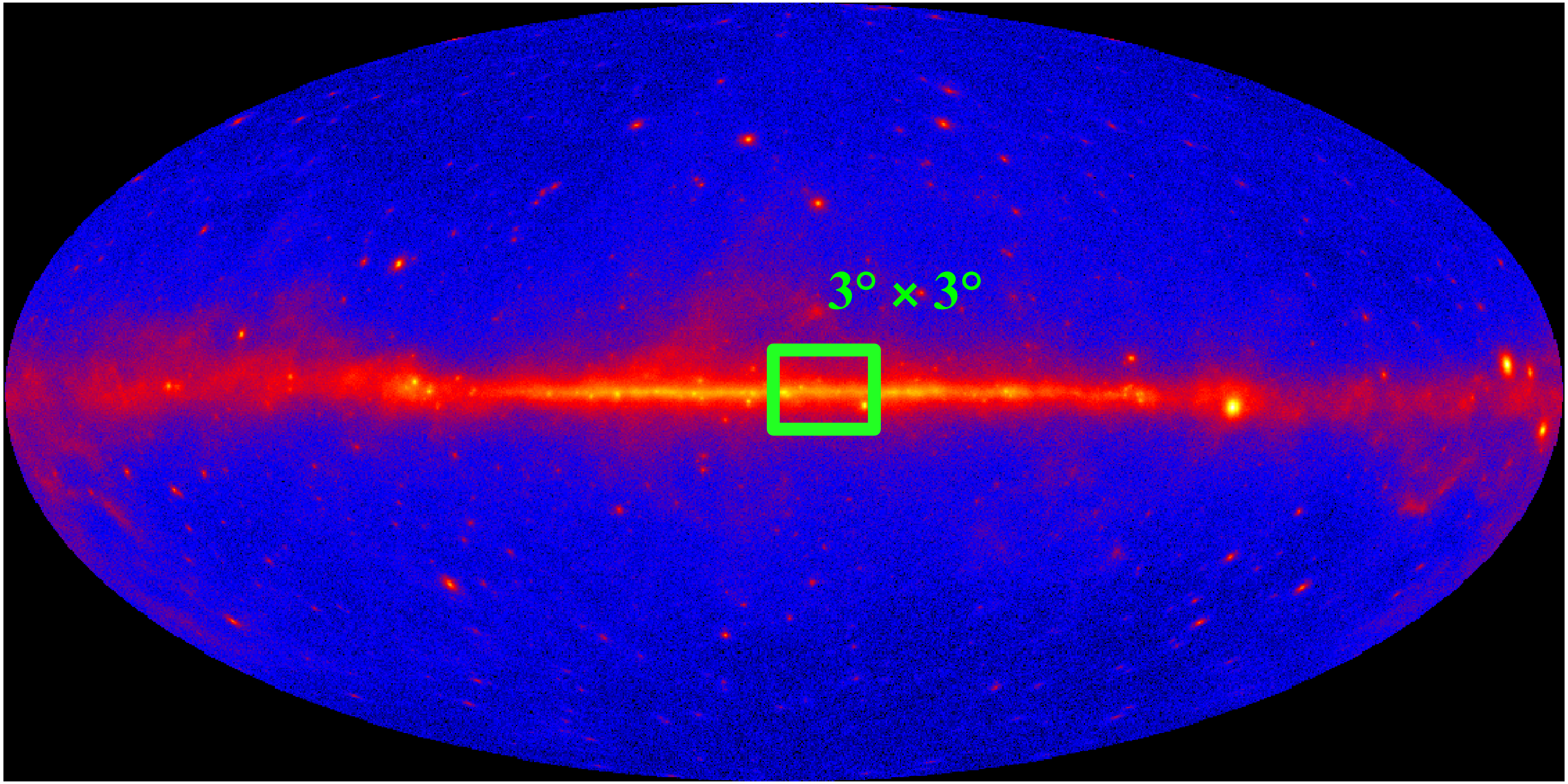


Features in the energy spectrum

Kuhlen, Diemand, Madau

Diffuse Galactic emission

Divide the sky in different regions:



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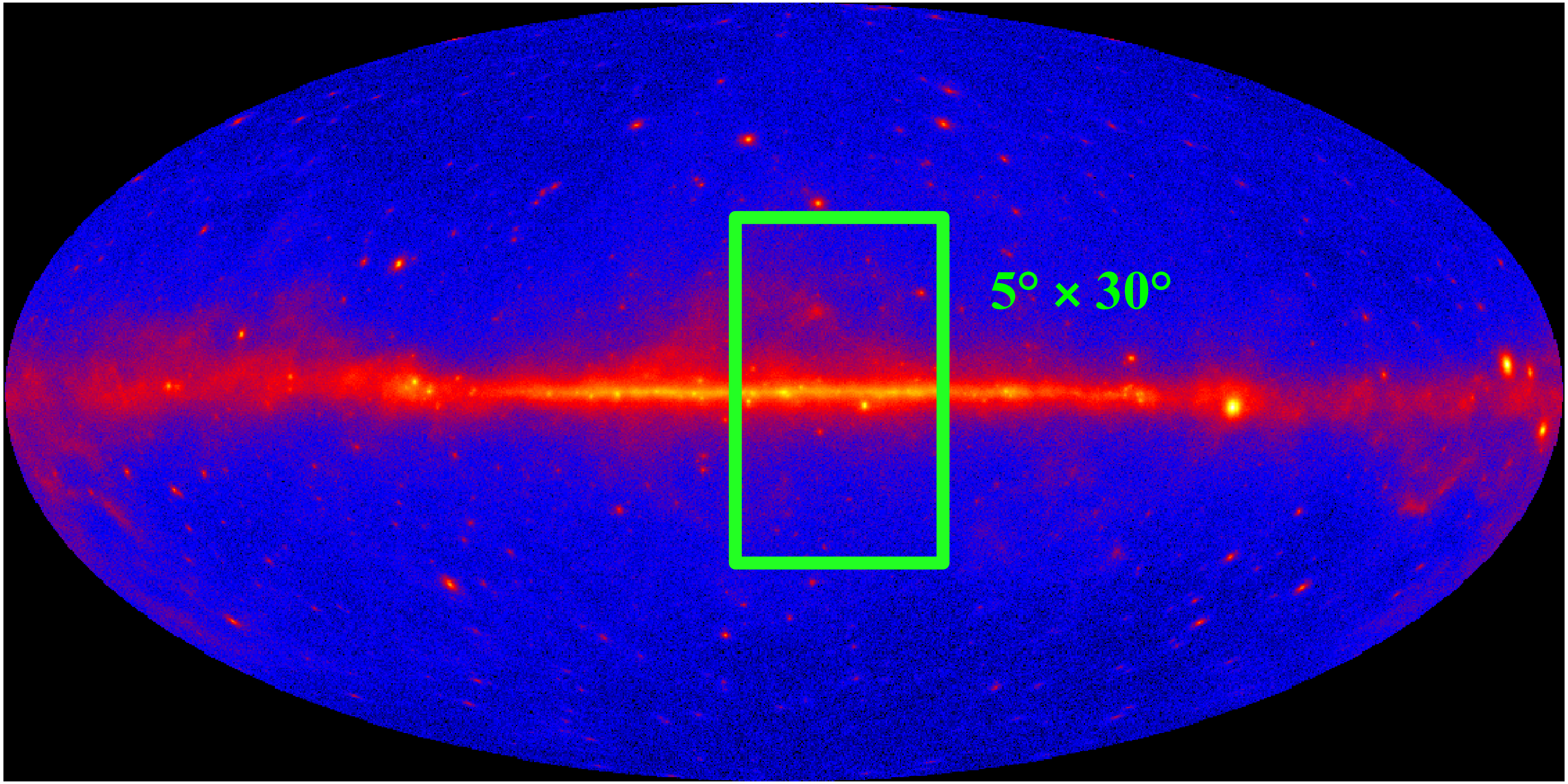

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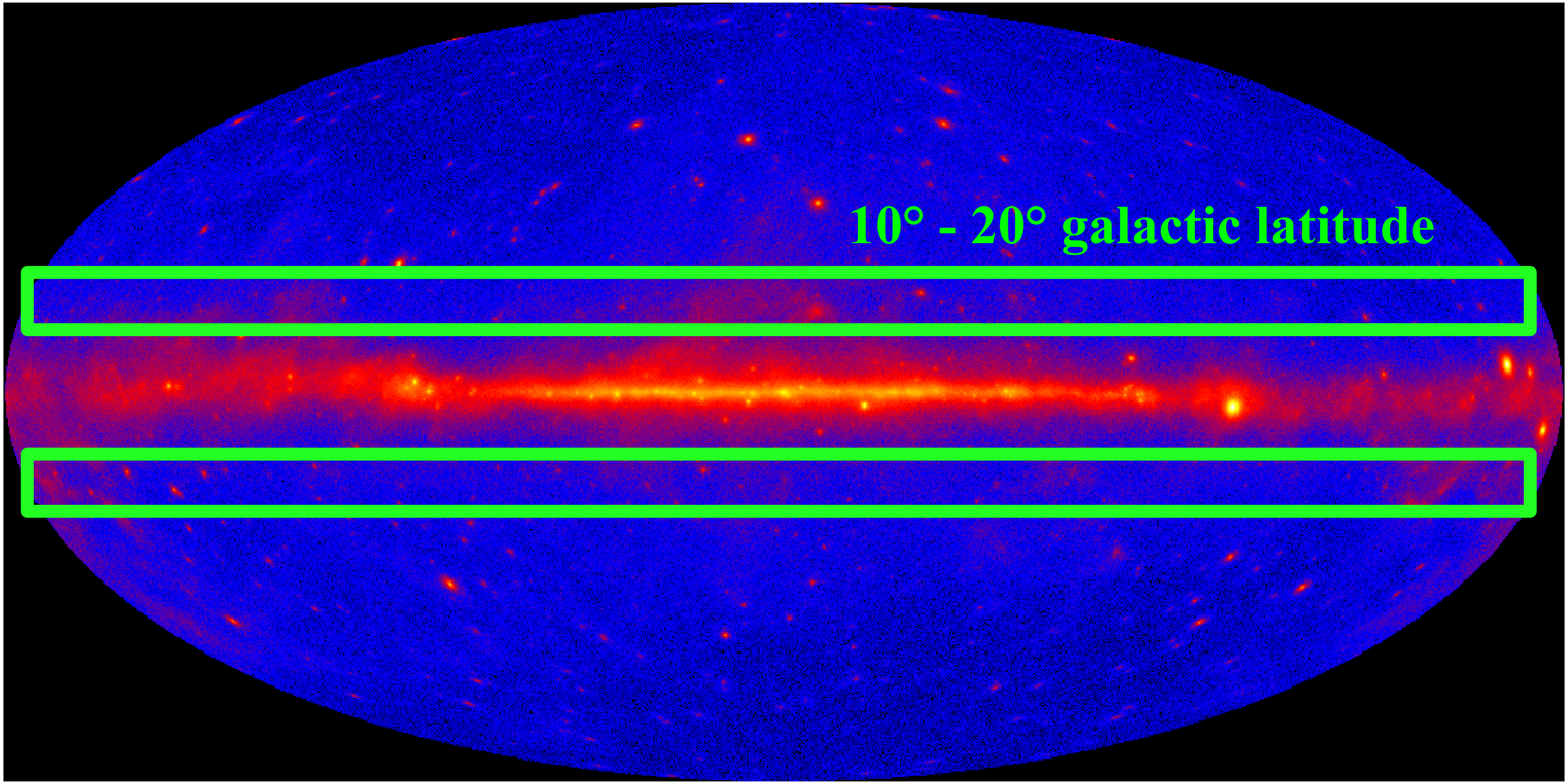

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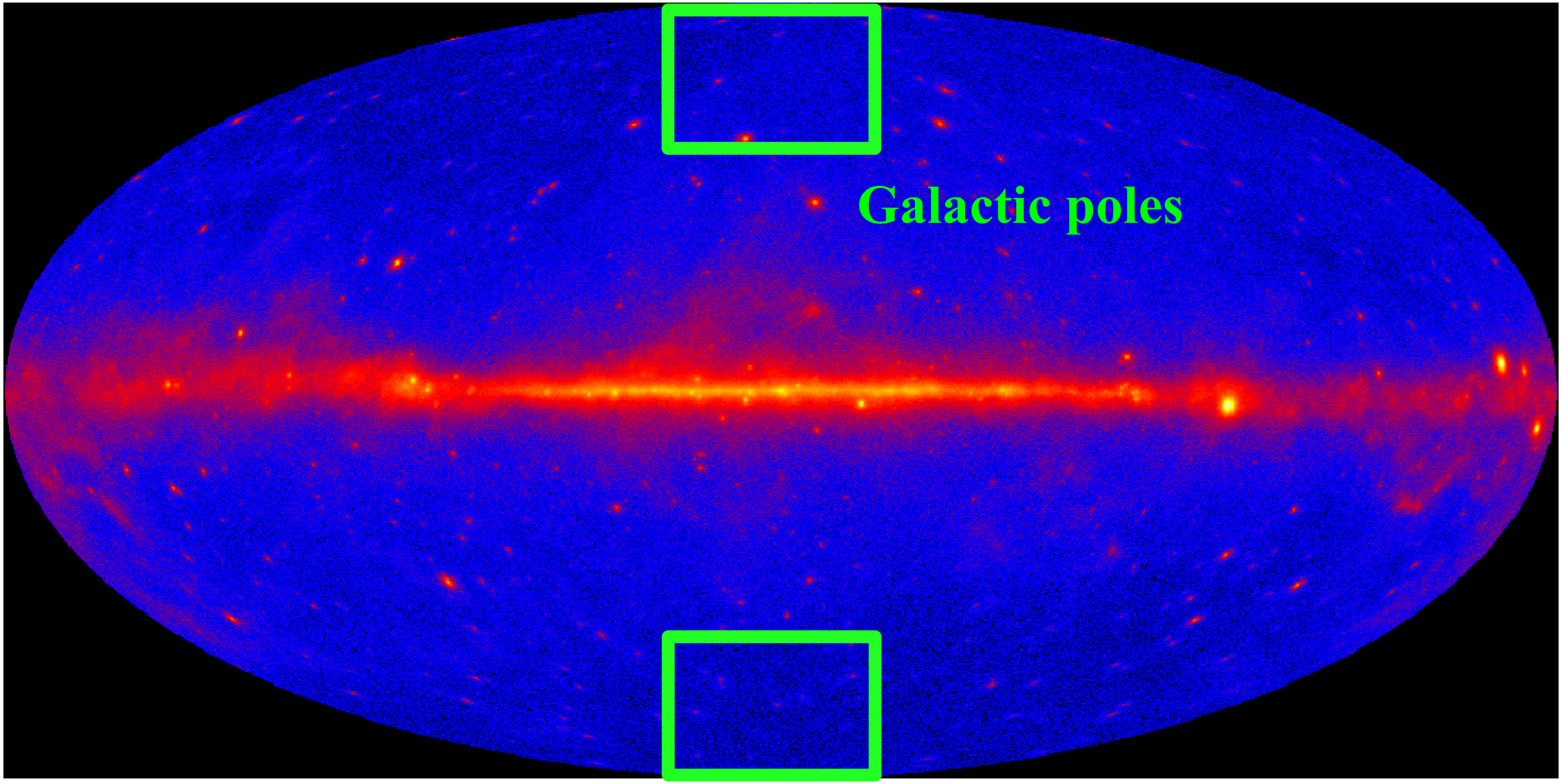
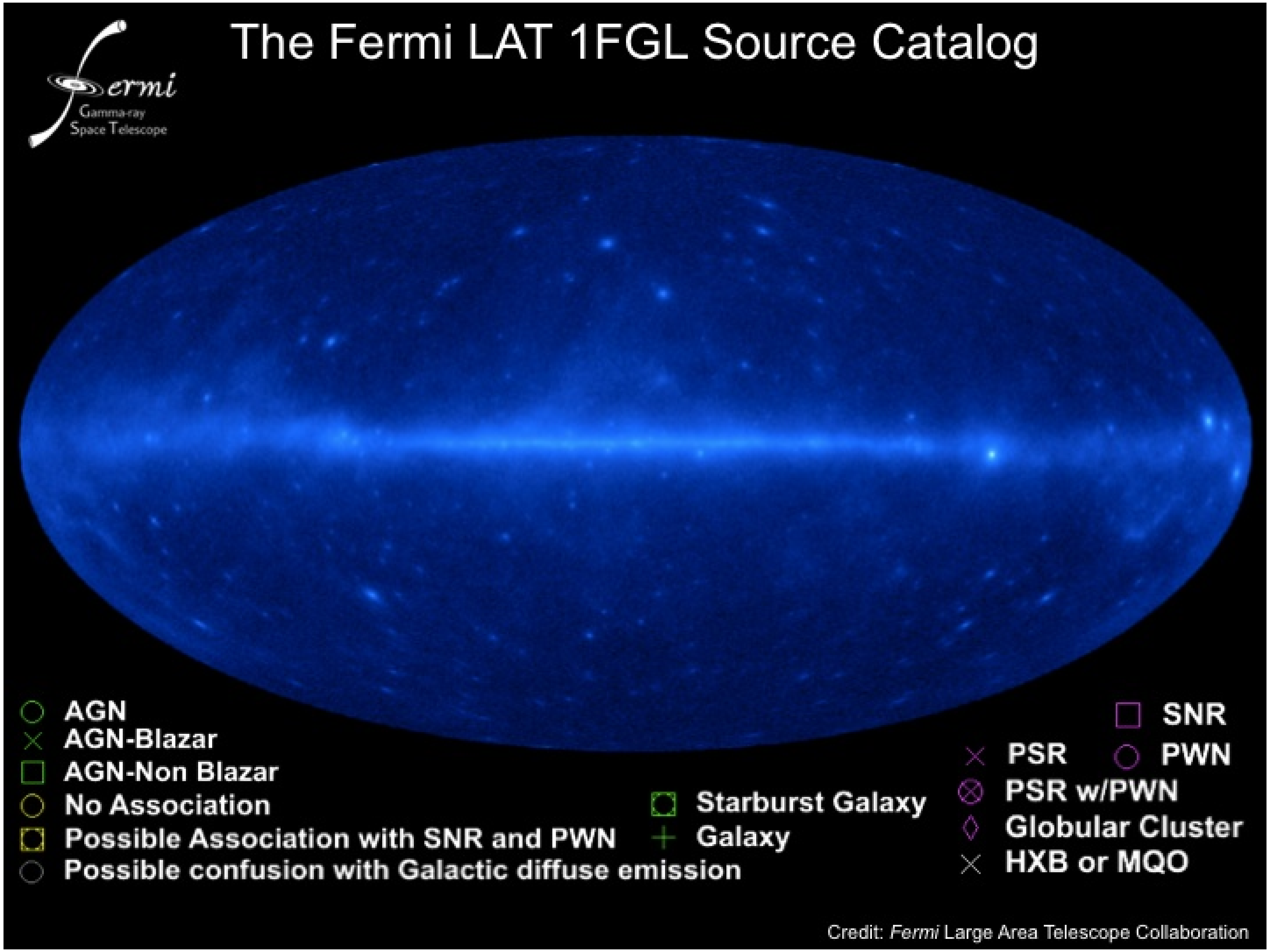
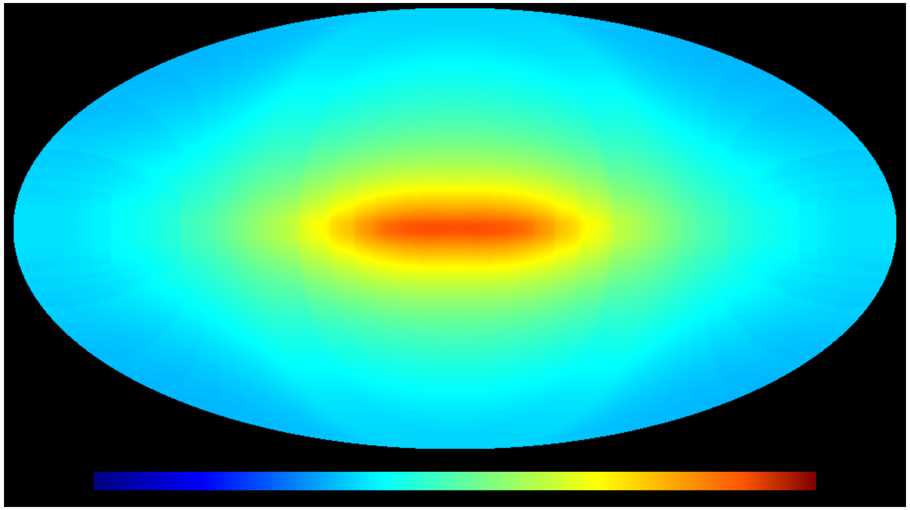


But beware of backgrounds when searching for dark matter...

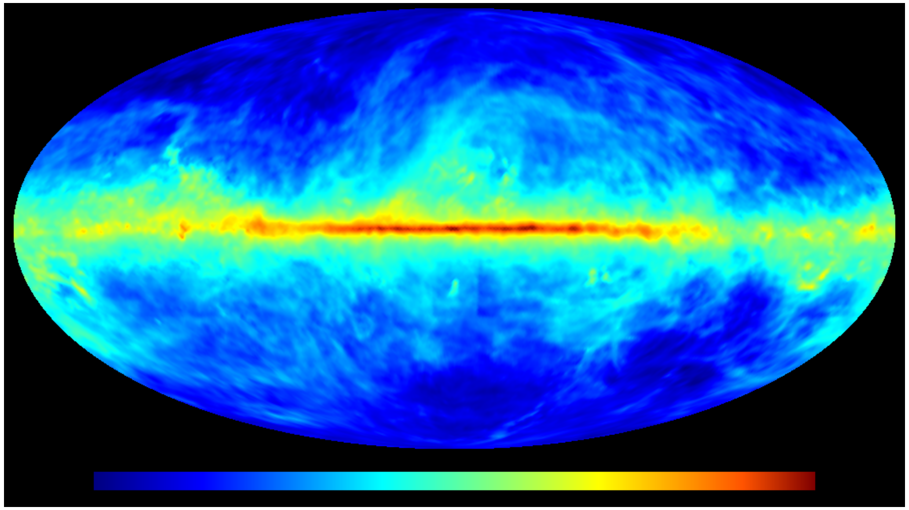
Background I: sources



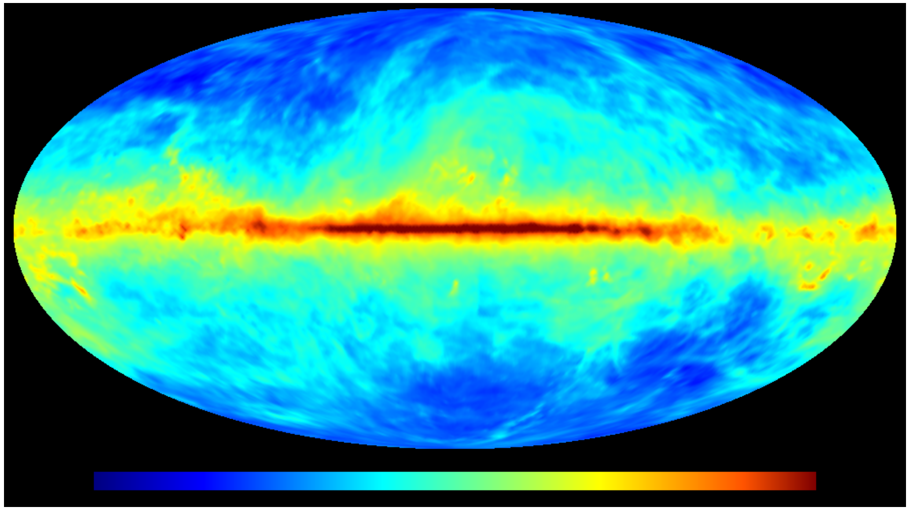
Background II: modelling of the diffuse emission



Inverse compton

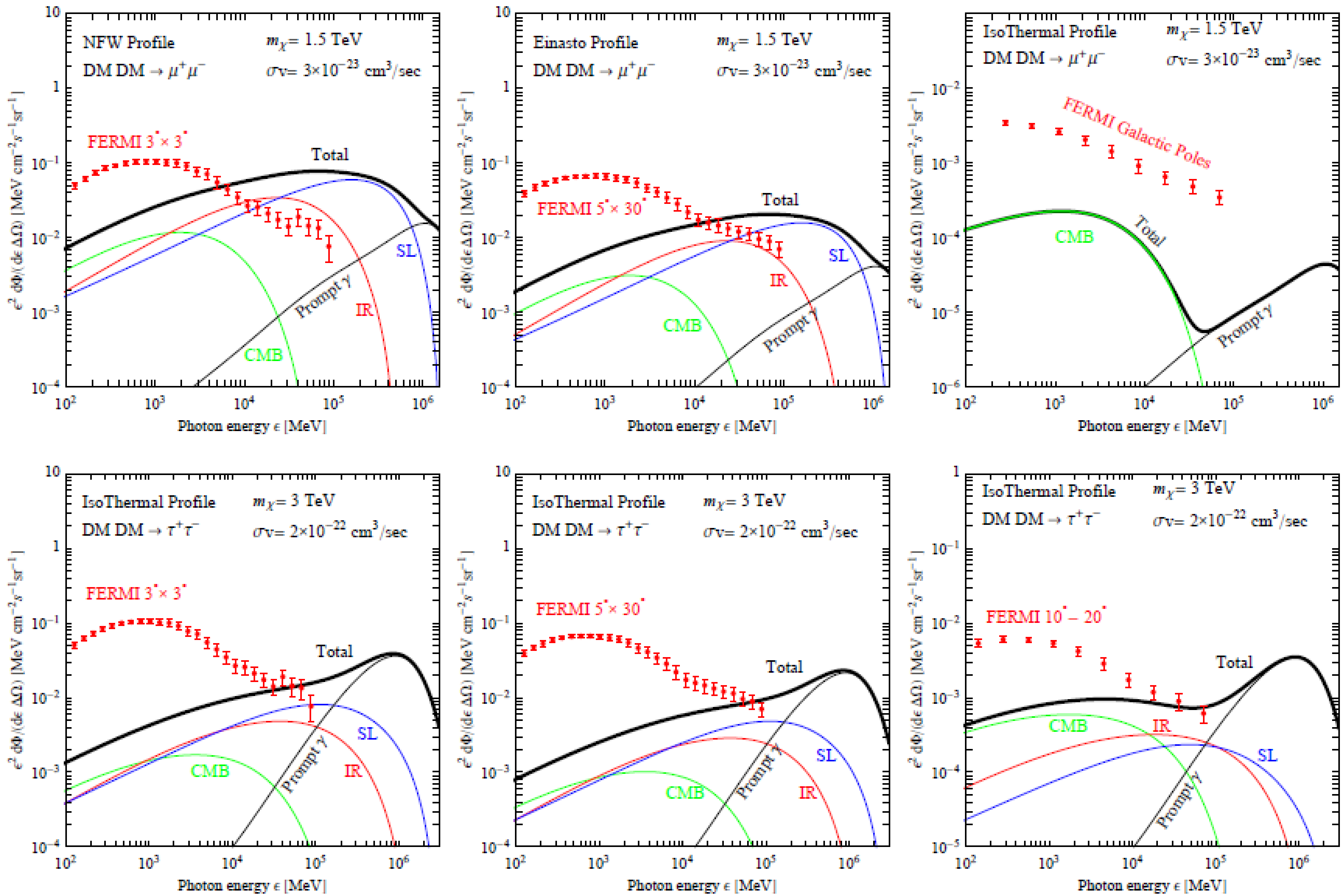


Bremmstrahlung

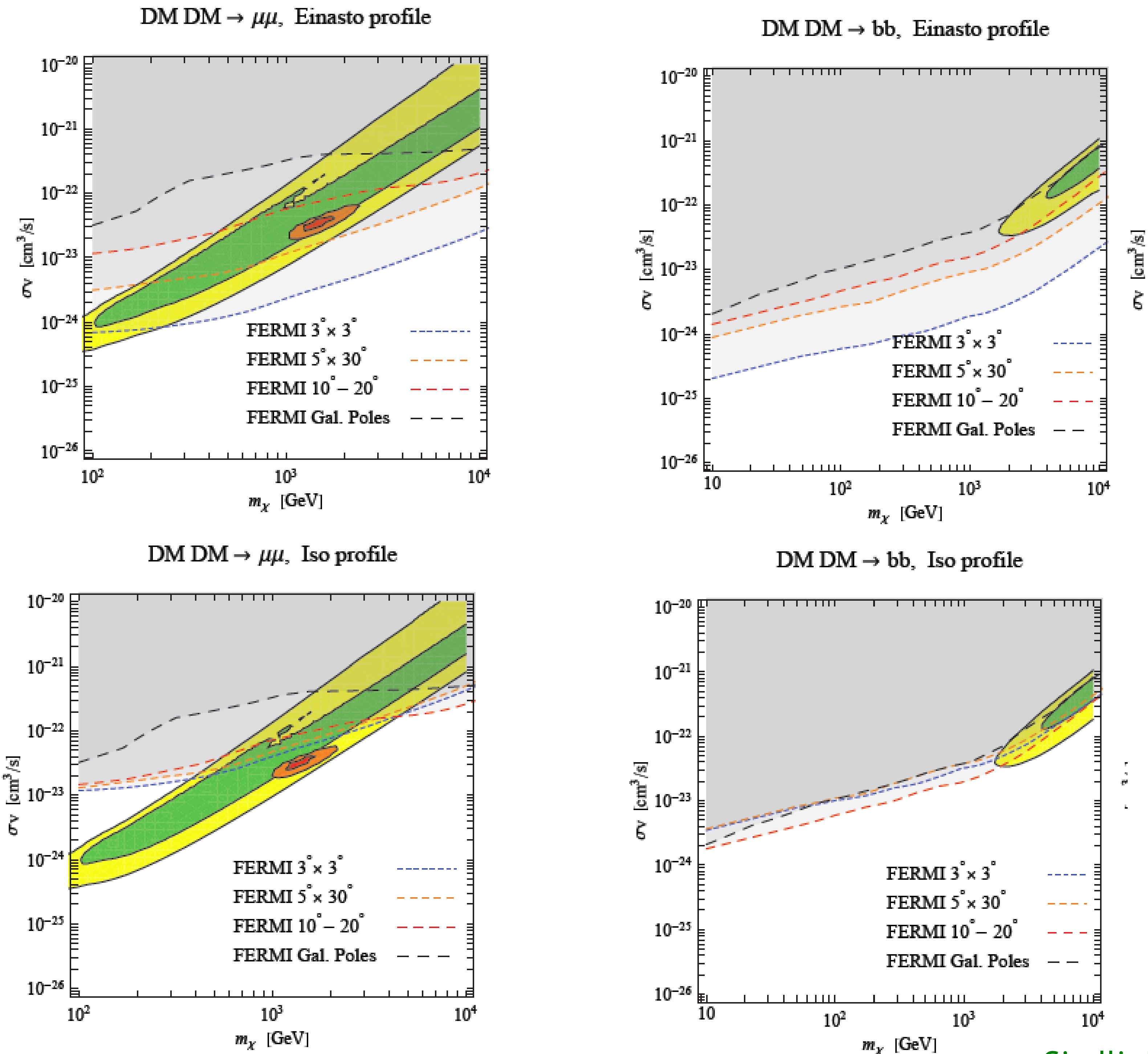


π^0-decay

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

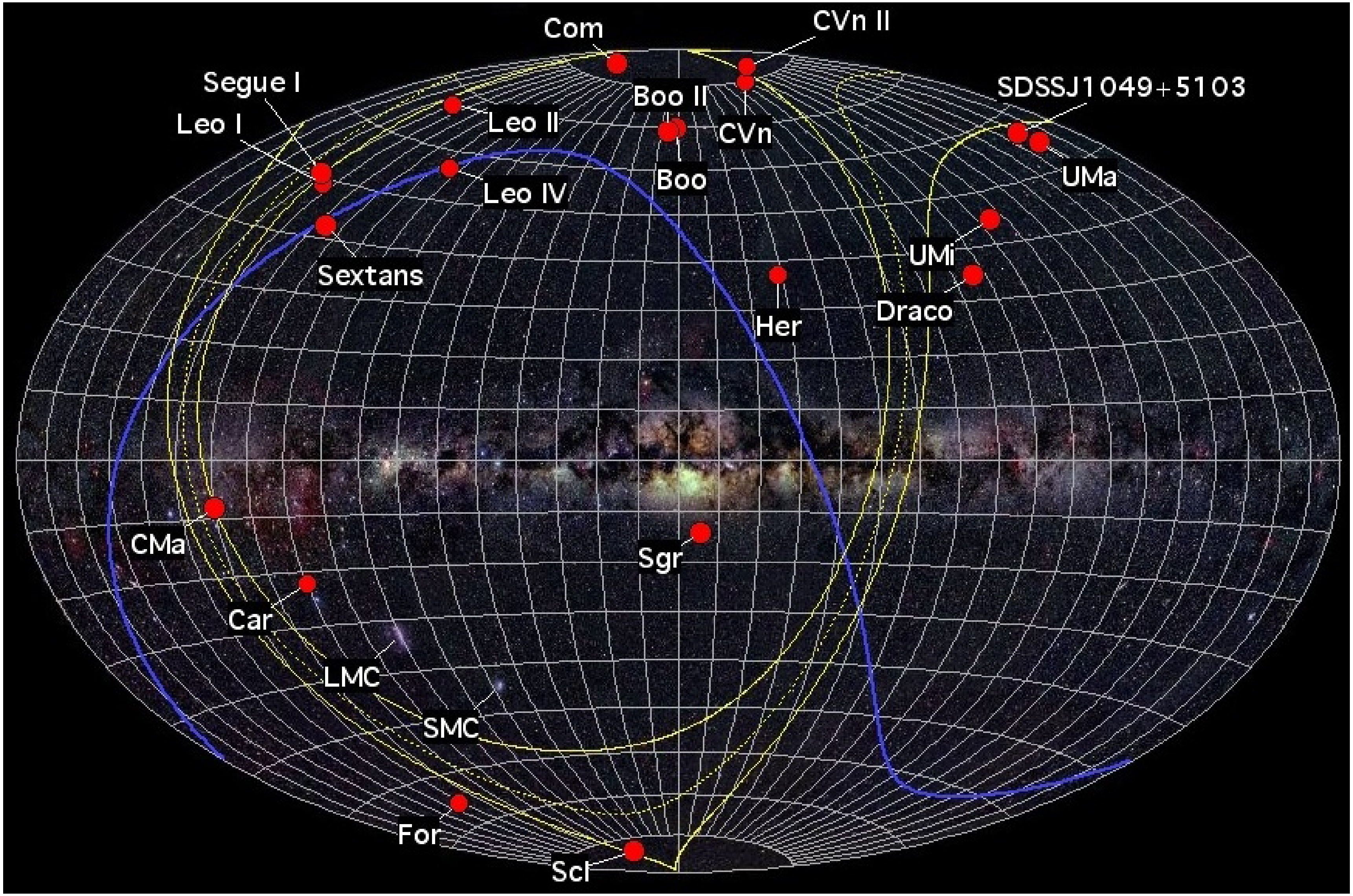


Cirelli, Panci, Serpico



Cirelli, Panci, Serpico

Dwarf spheroidal galaxies



Name	Distance (kpc)	year of discovery	$M_{1/2}/L_{1/2}$ ref. 8	1	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

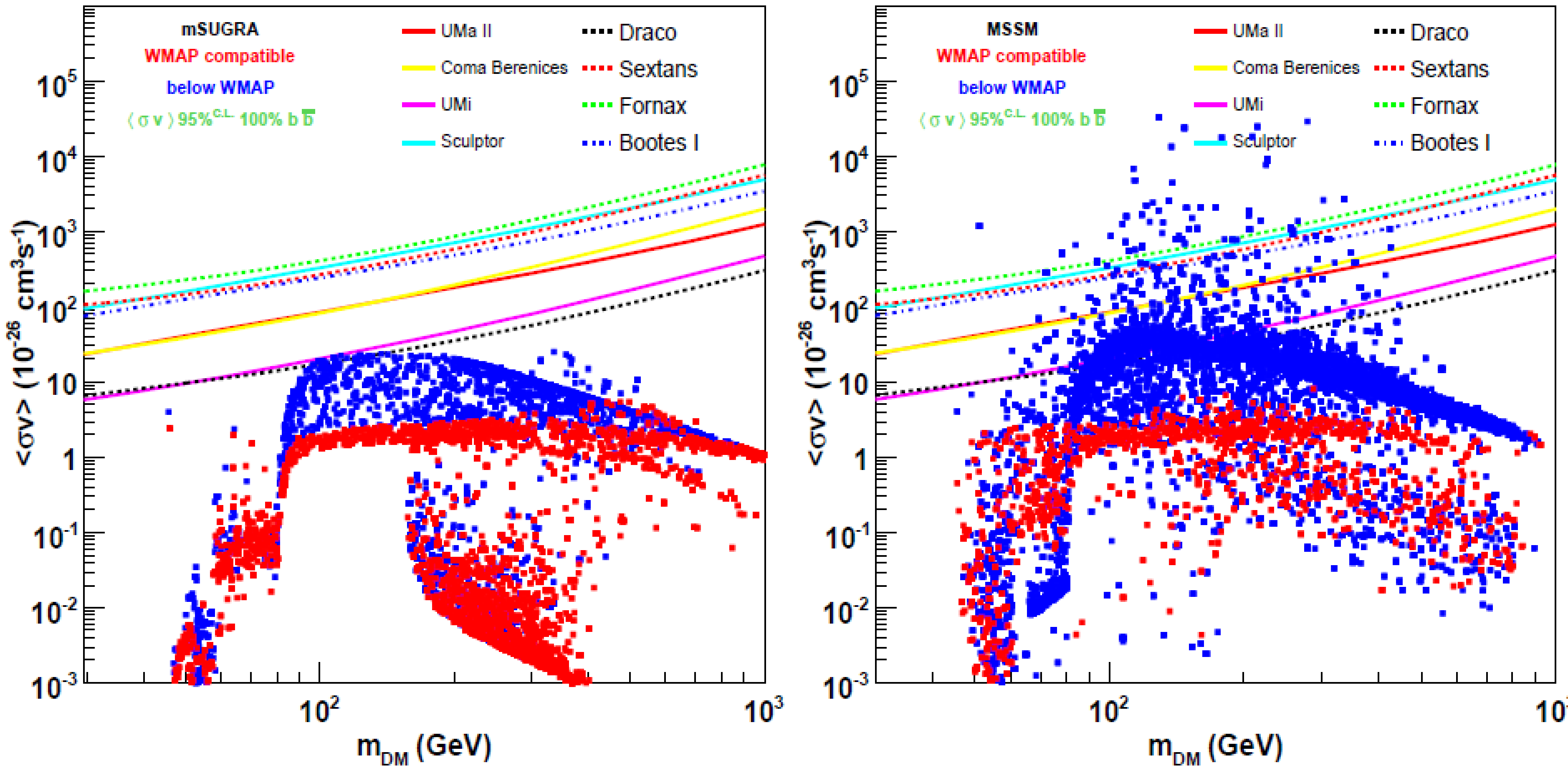
Assume a Navarro-Frenk-White dark matter halo profile inside the tidal radius:

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

Name	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

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

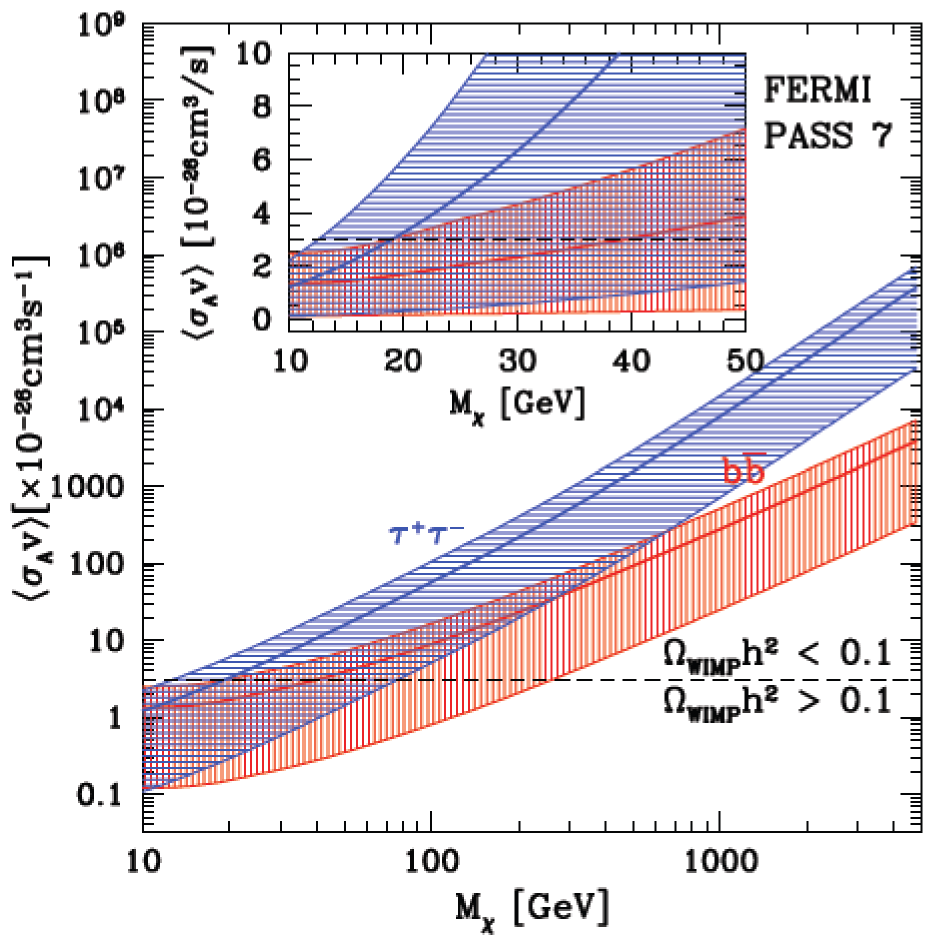
Constraints on WIMP dark matter models

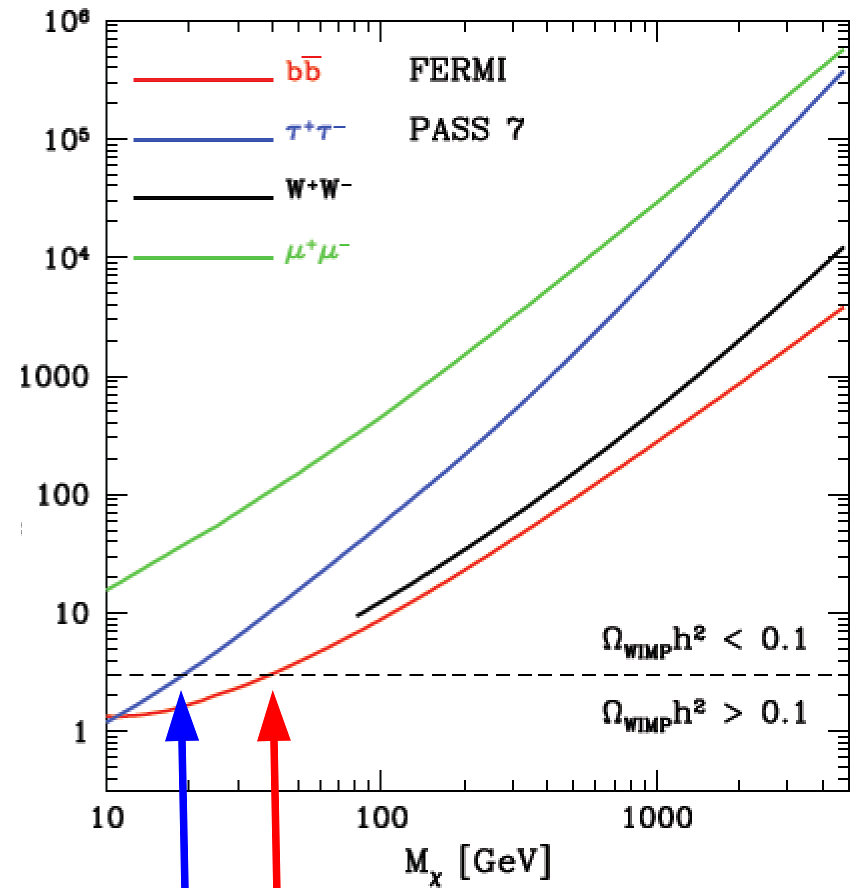


Fermi coll.
arXiv:1001.4531

Closing in on light WIMP scenarios from dwarf galaxy observations

Geringer-Sameth, Koushiappas '11





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

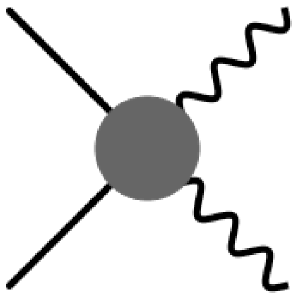
M_{DM}> 19 GeV for DM DM → $\tau^+ \tau^-$

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:

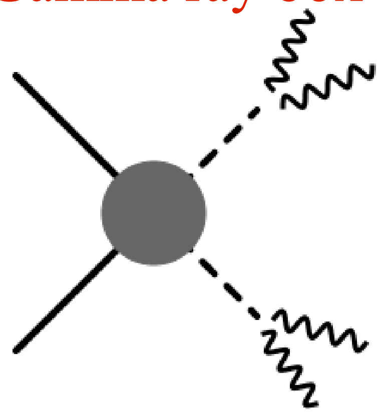
Gamma ray line



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

$$\langle \sigma v \rangle^{\rm expected} \lesssim 10^{-29}\,{\rm cm}^3\,{\rm s}^{-1}$$

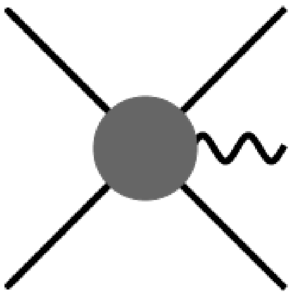
Gamma ray box



AI, Lopez Gehler, Pato '12

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

Internal bremsstrahlung



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

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

Gamma-ray features

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

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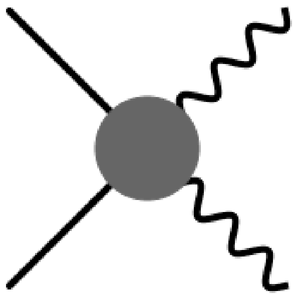

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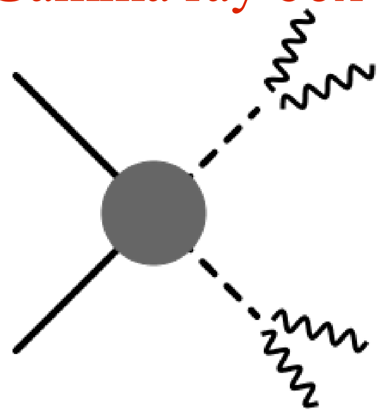

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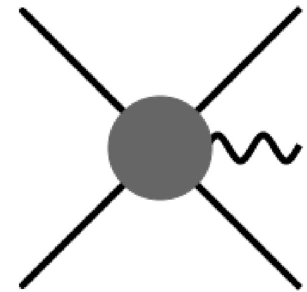
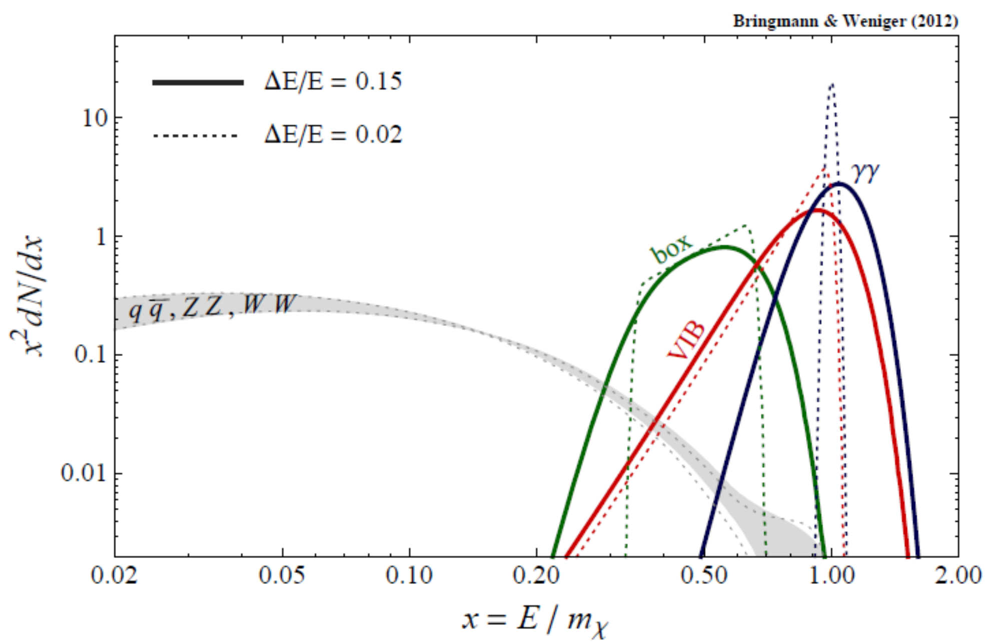
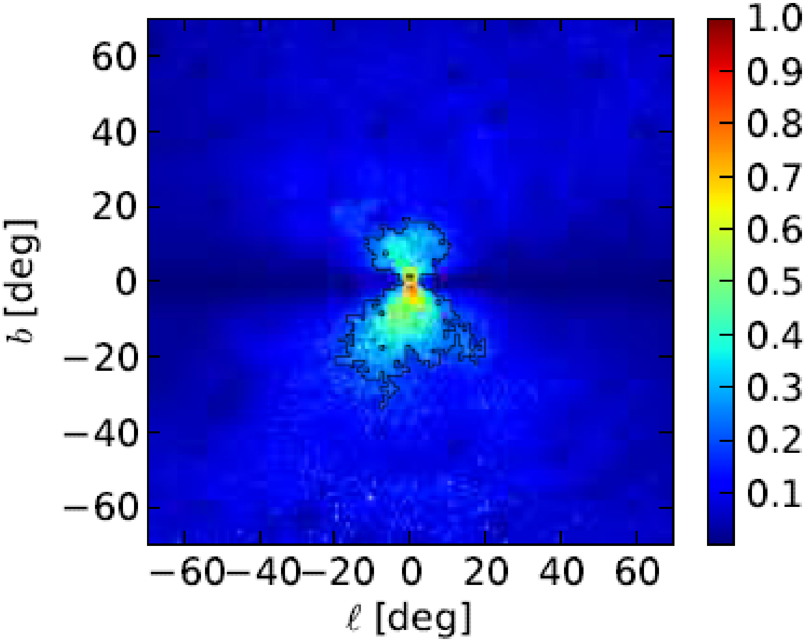
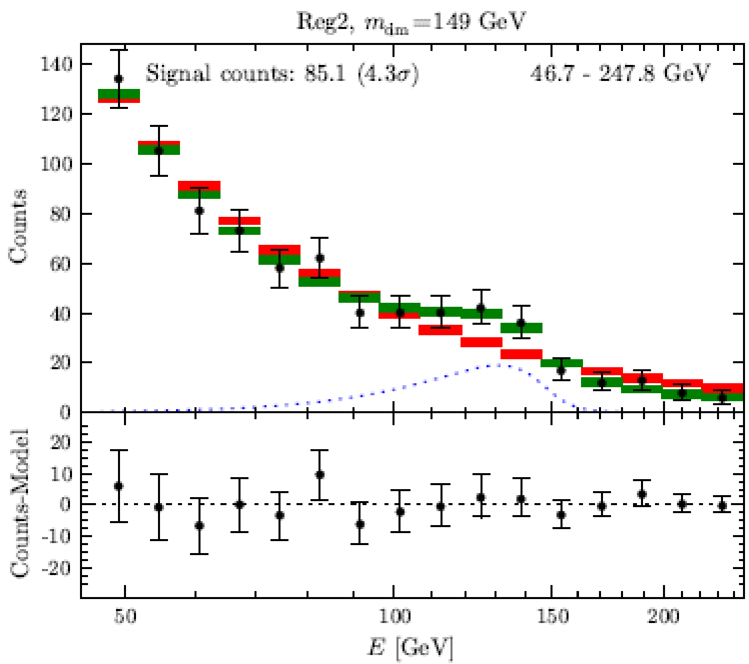




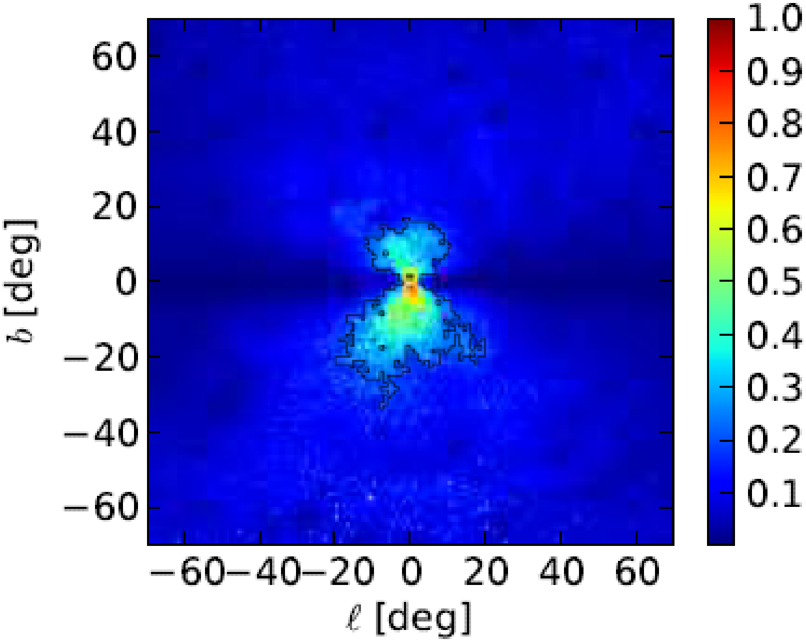
Searching for spectral features with the Fermi-LAT

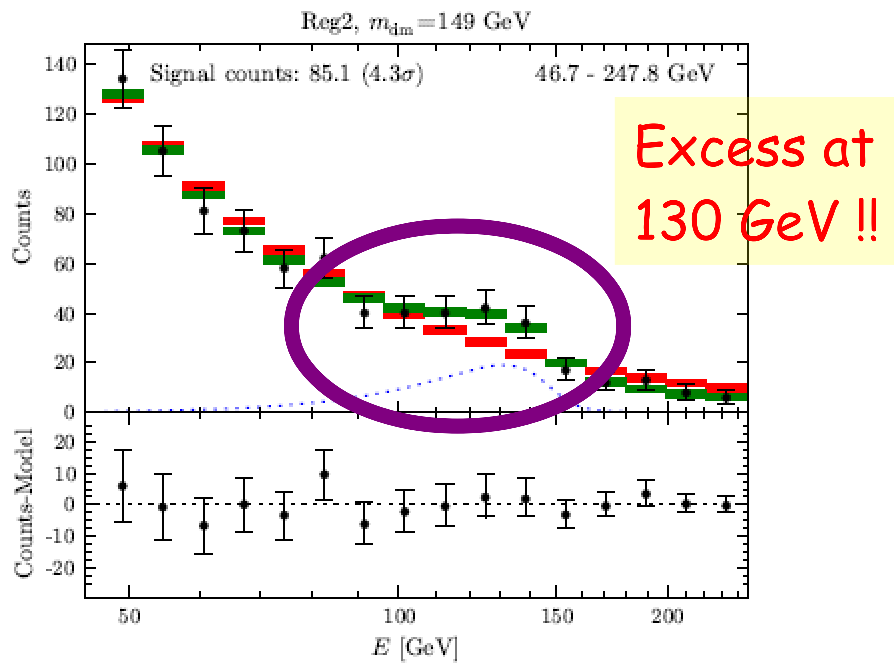




Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

Searching for spectral features with the Fermi-LAT





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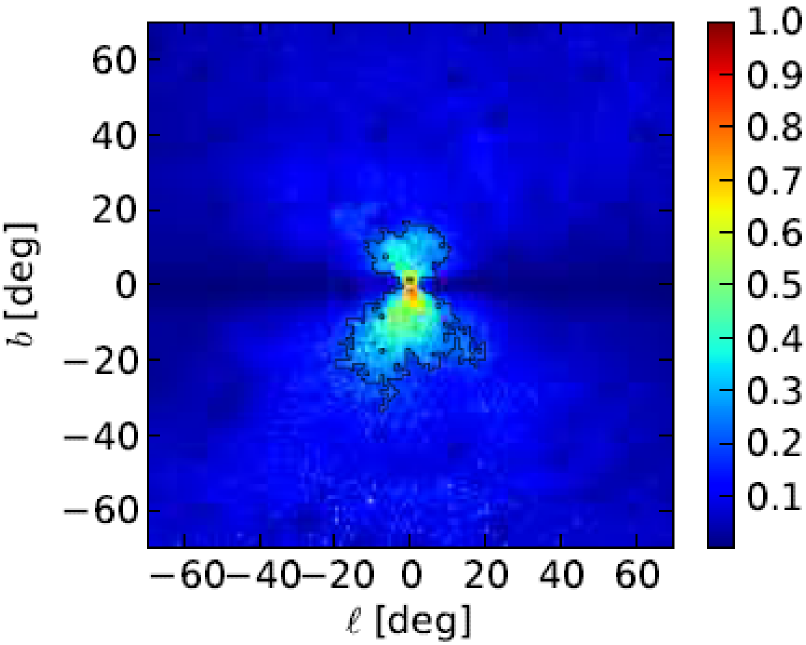
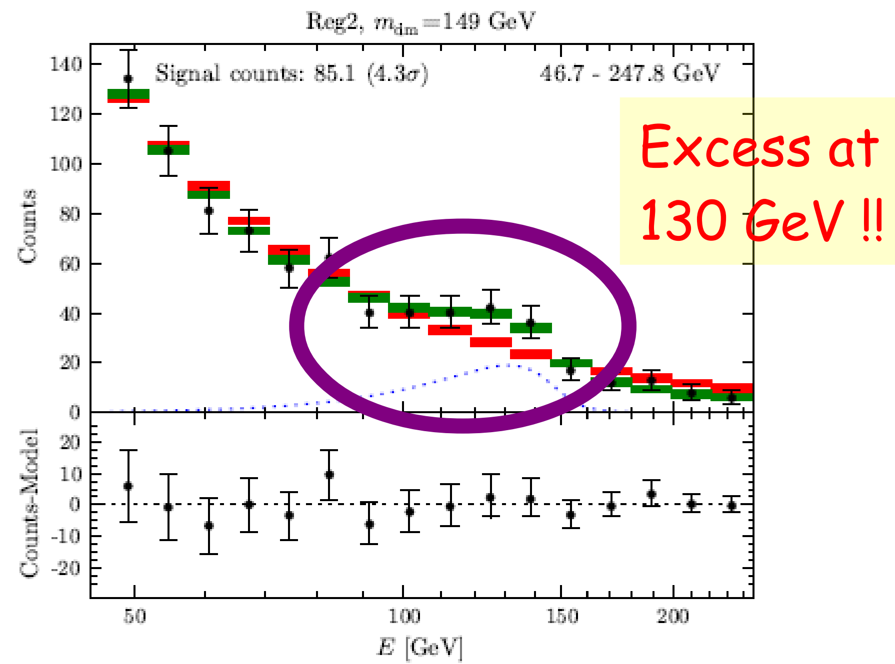
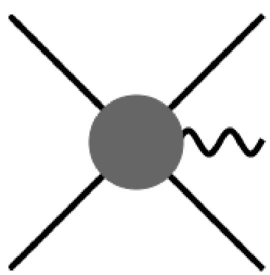




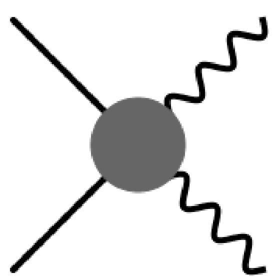
Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312



$$m_\chi = (149 \pm 4)\ \text{GeV}$$

$$\langle \sigma v \rangle = (5.7 \pm 1.4) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

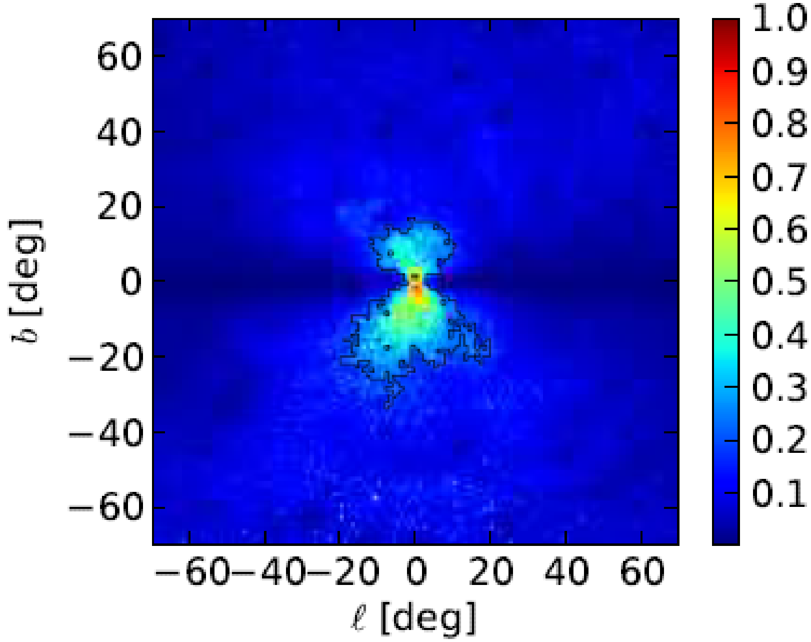
4.3 σ (3.1 σ with LEE)

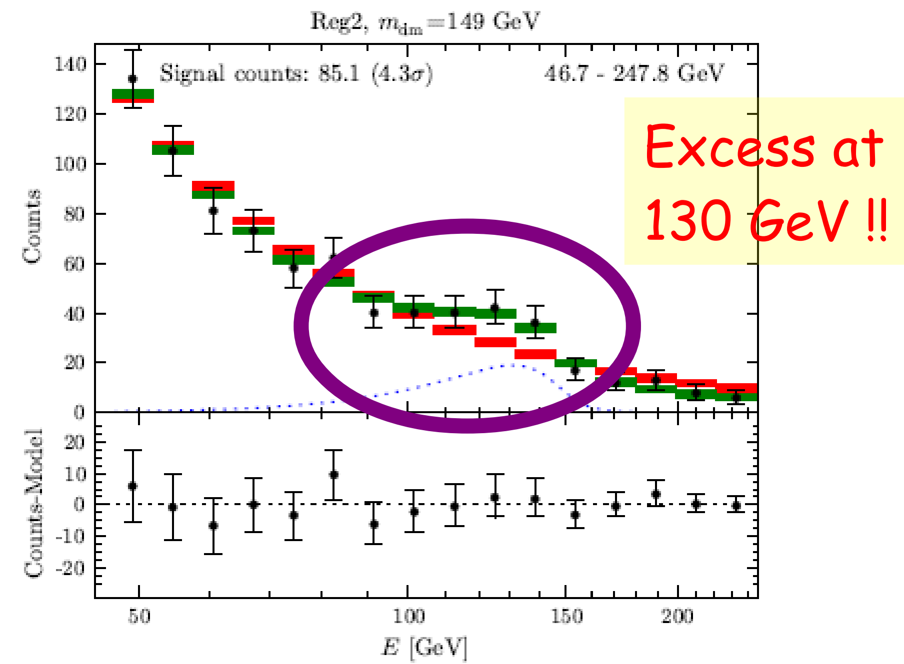


$$m_\chi \sim 130\ \text{GeV}$$

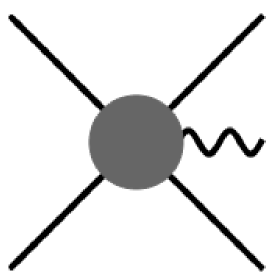
$$\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma} \sim 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

Searching for spectral features with the Fermi-LAT





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



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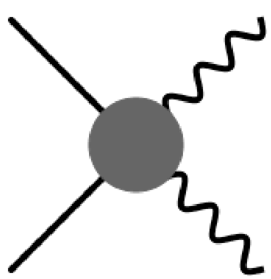


$$m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}\ \text{GeV}$$

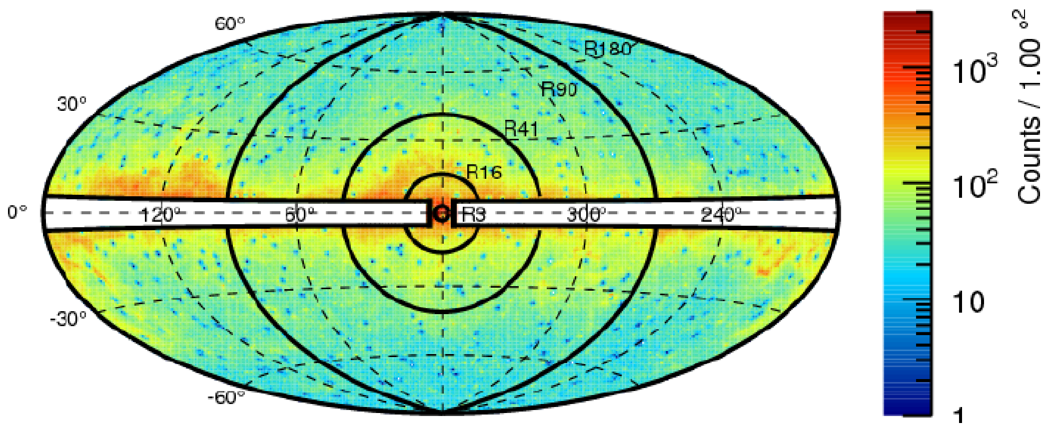
$$\langle \sigma v \rangle = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

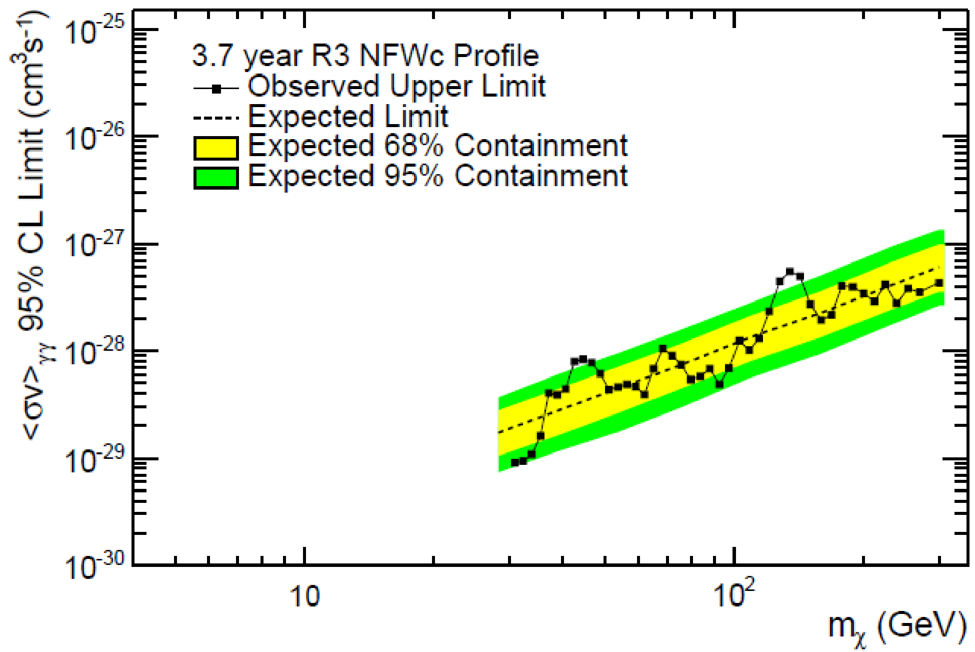
4.6 σ (3.3 σ with LEE)

Weniger,
arXiv:1204.2797

Latest news on the 130 GeV excess

Fermi-LAT collaboration
arXiv:1305.5597



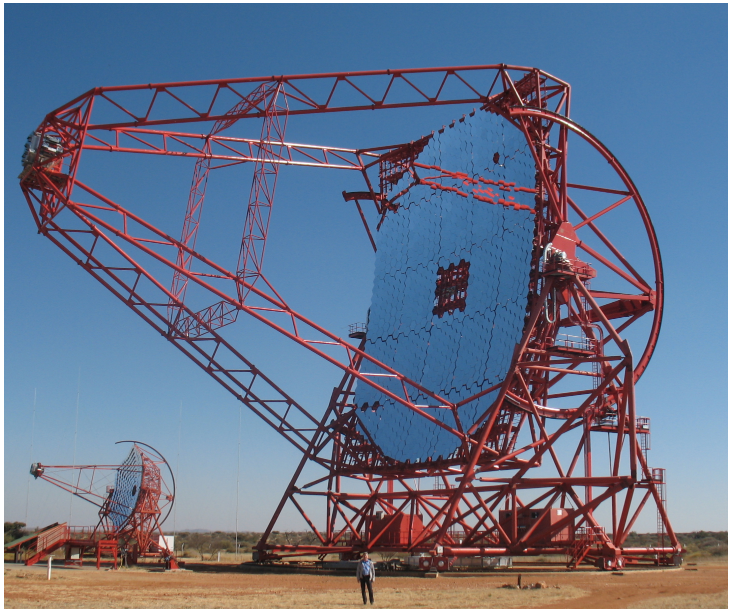


Significance reduced to 3.3σ (1.6σ with LEE)

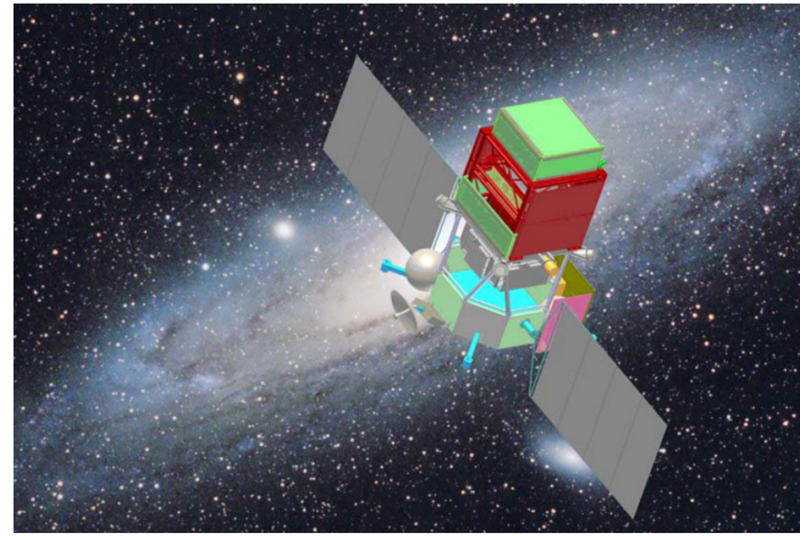
The 130 GeV excess could be just a statistical fluke

Bright future for dark matter searches using gamma-rays!

H.E.S.S. II – in operation

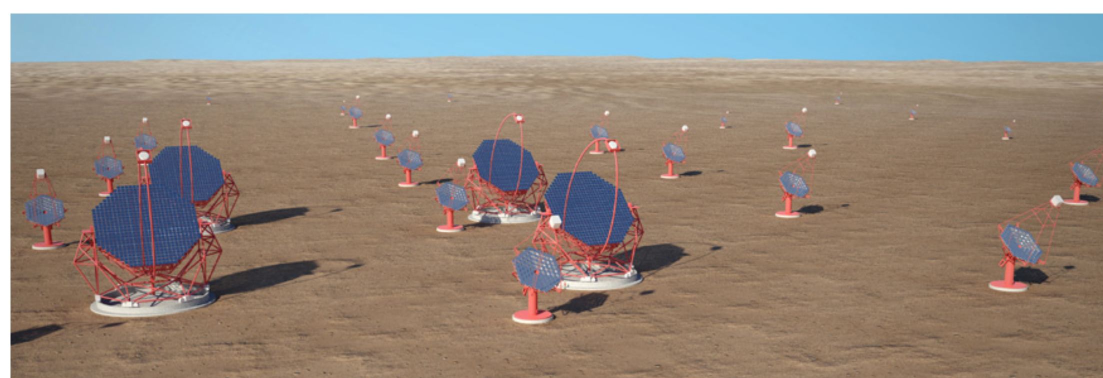


GAMMA 400 – Launch in 2018



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.

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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.

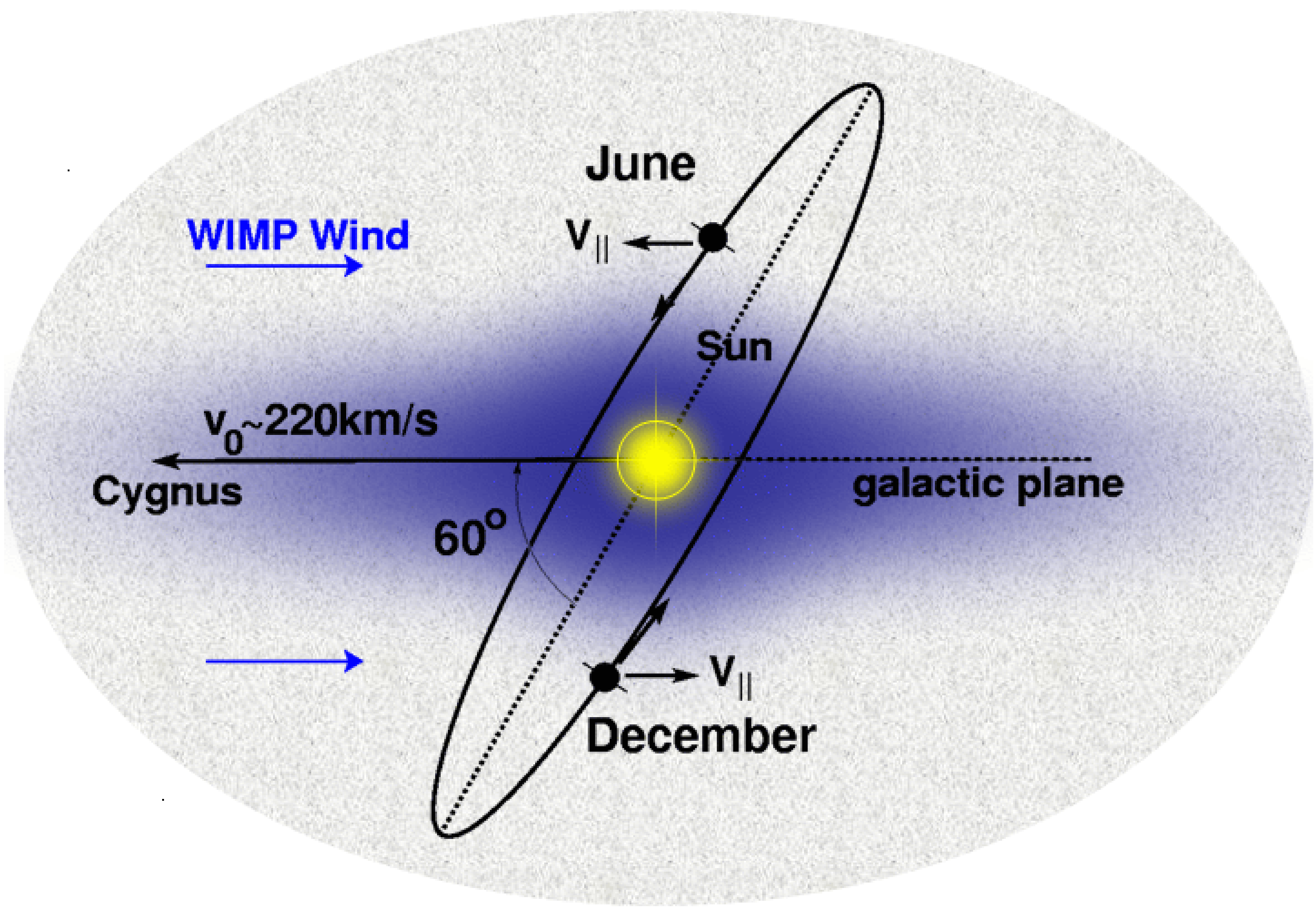
2) Once in a while a dark matter particle will interact with a nucleus.

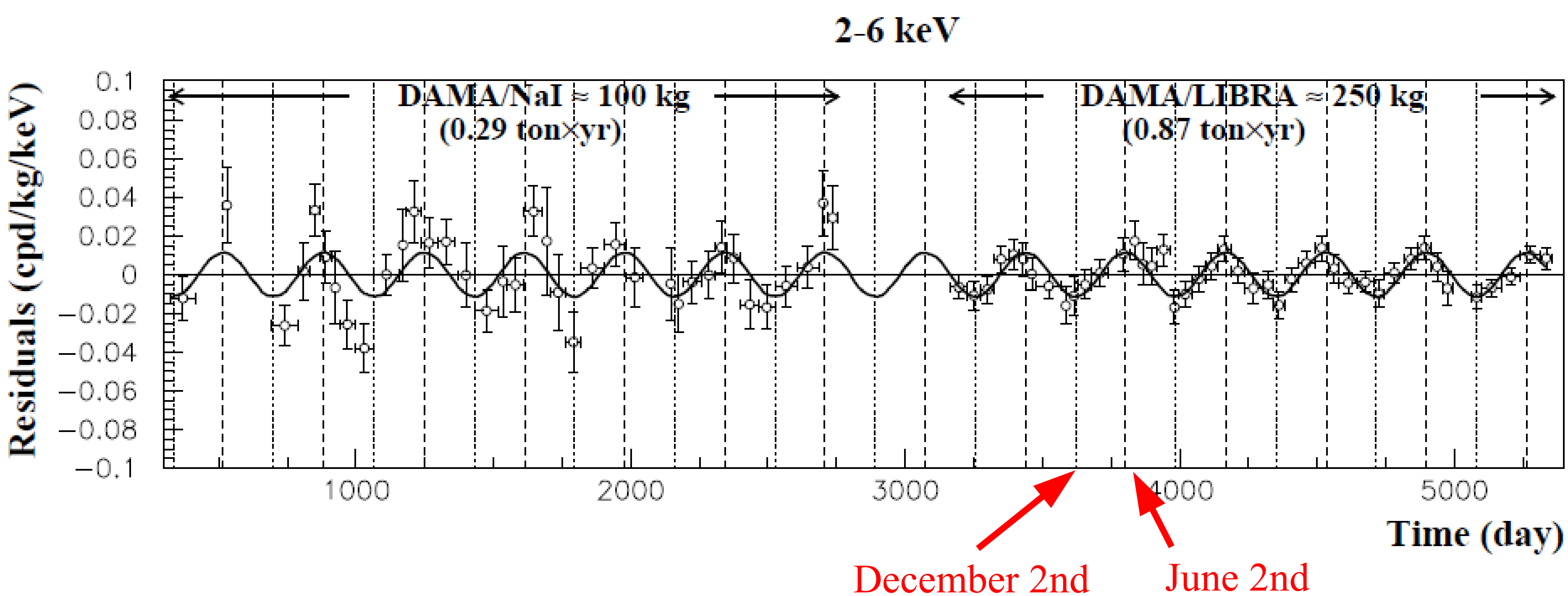
3) The nucleus gains momentum and recoils. The existence of dark matter can then be inferred if there is a significant excess in the number of recoils compared to the expected recoils induced by natural radiactivity in your lab or in your detector.

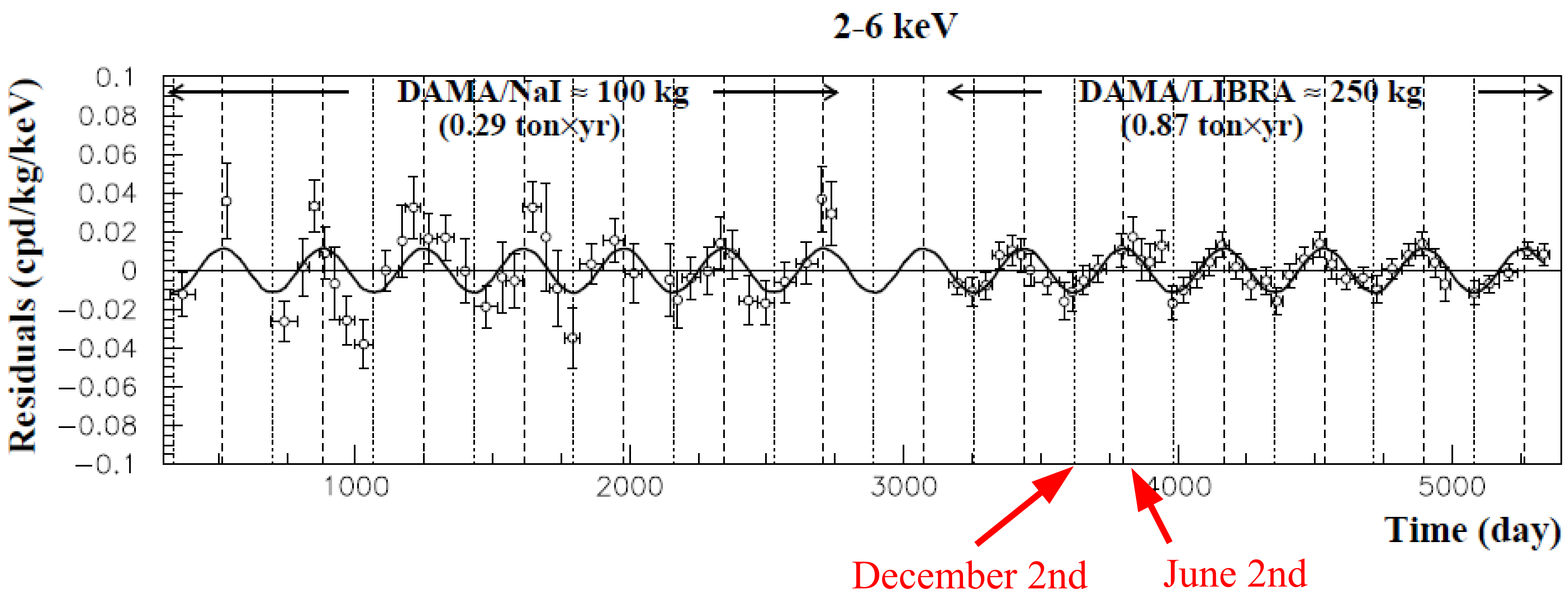
Simple idea ...

… but very challenging in practice!

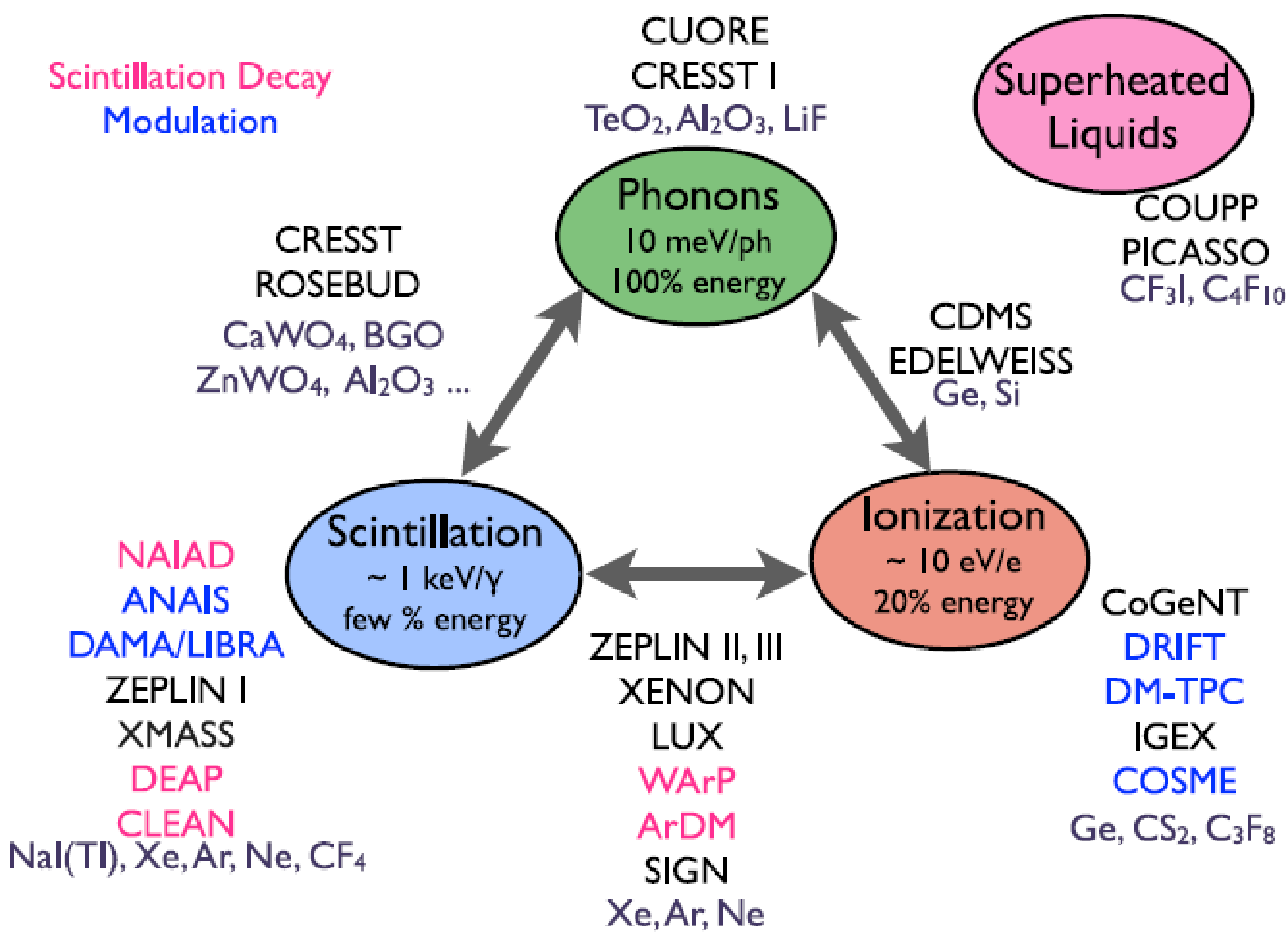
Annual modulation

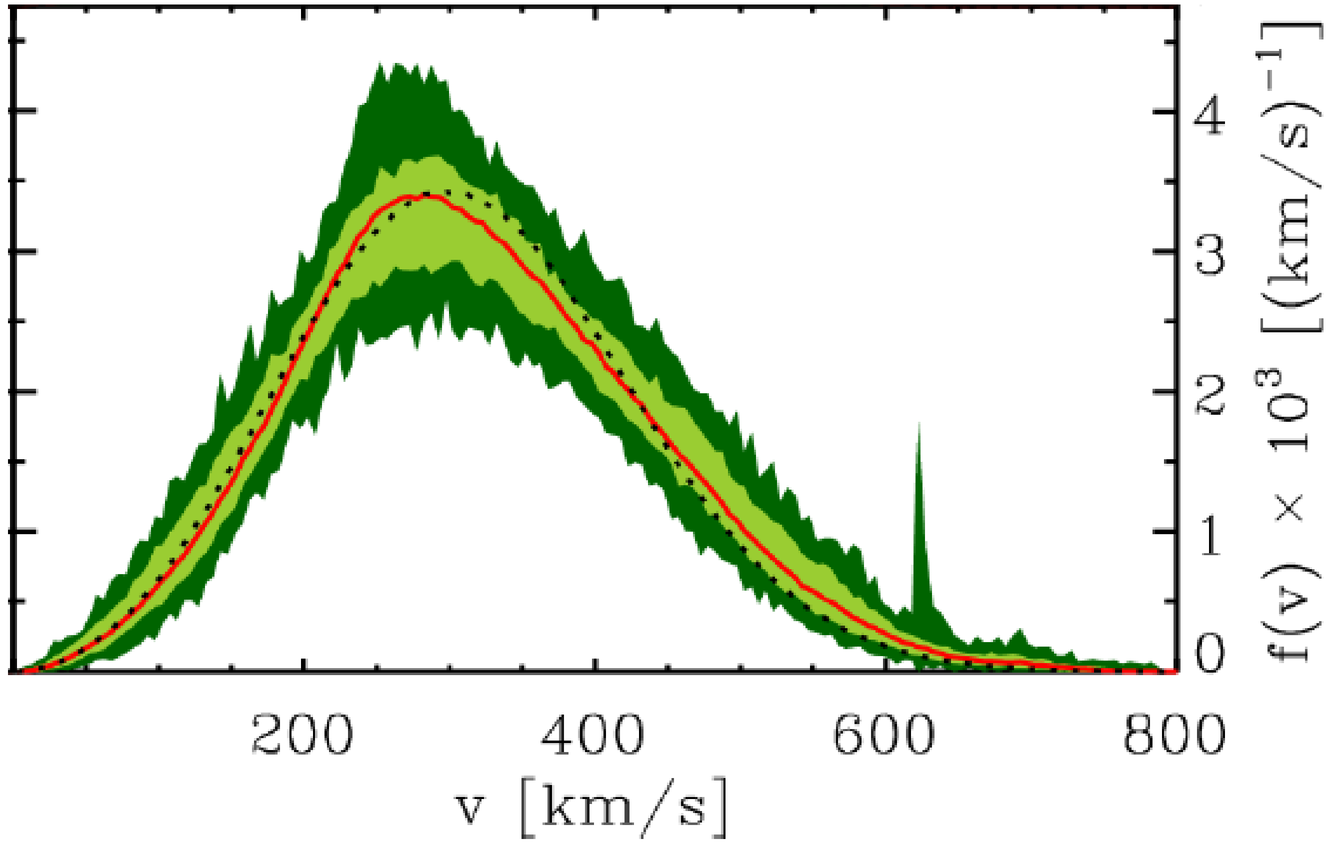



2-6 keV
DAMA/NaI ≈ 100 kg
(0.29 ton×yr)
DAMA/LIBRA ≈ 250 kg
(0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
1000
2000
3000
4000
5000
Time (day)
December 2nd
June 2nd

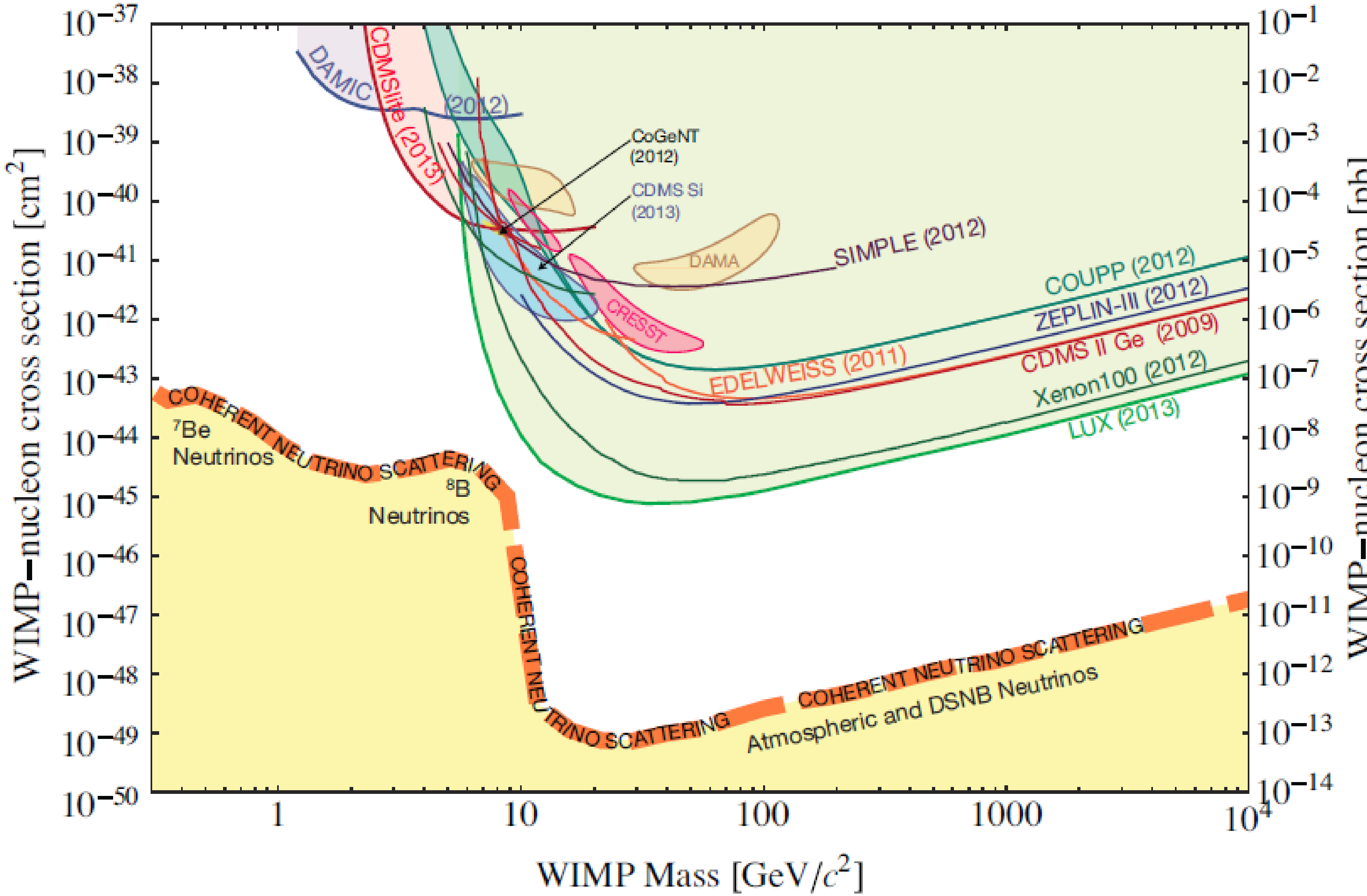


DM interpretation very controversial! More later…

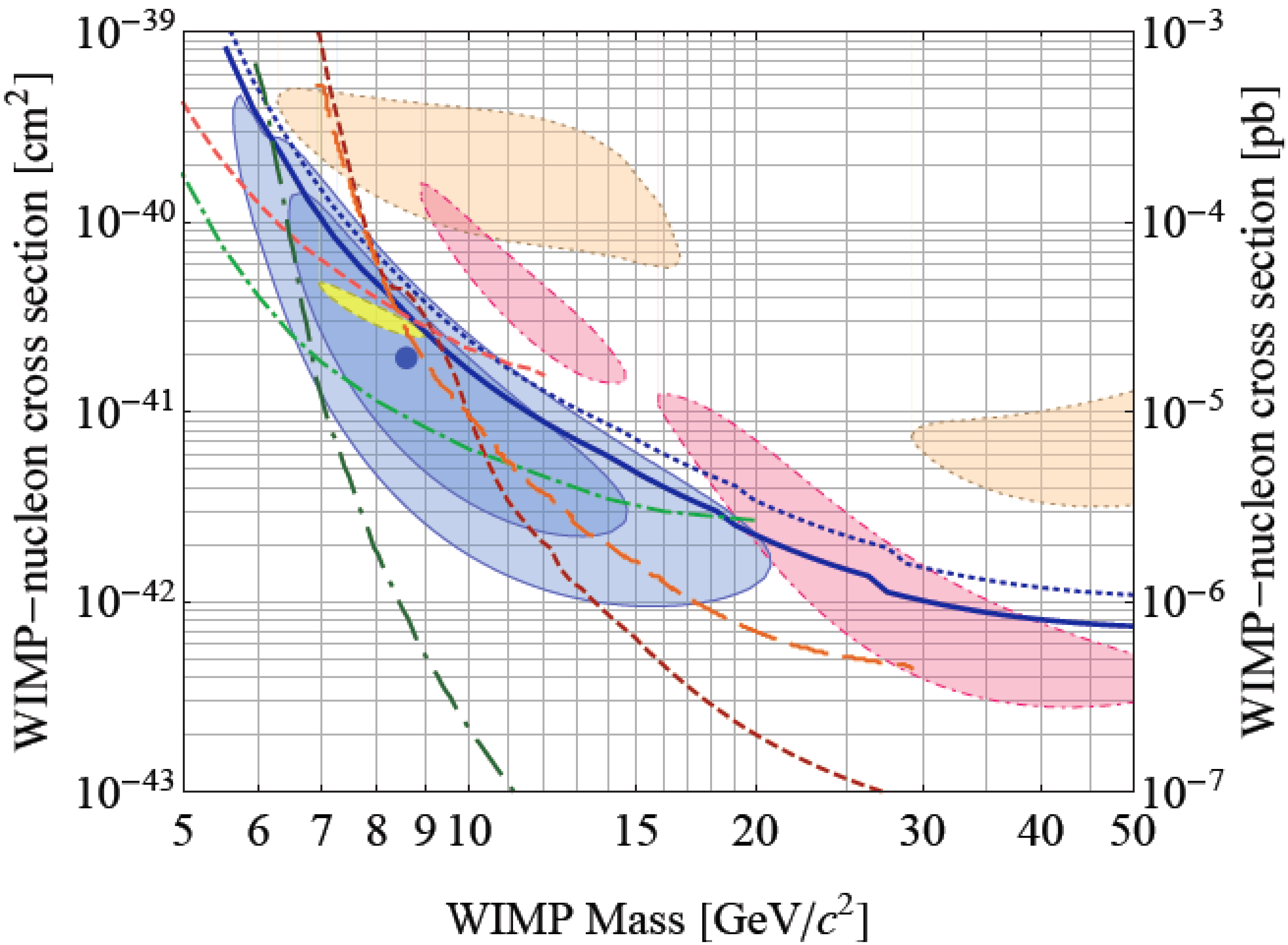

Scintillation Decay
Modulation
CUORE
CRESST I
TeO_2, Al_2O_3, LiF
Superheated Liquids
Phonons
10 meV/ph
100% energy
COUPP
PICASSO
CF_3I, C_4F_{10}
CRESST
ROSEBUD
$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 ...
CDMS
EDELWEISS
Ge, Si
Scintillation
~ 1 keV/γ
few % energy
Ionization
~ 10 eV/e
20% energy
NAIAD
ANAIS
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



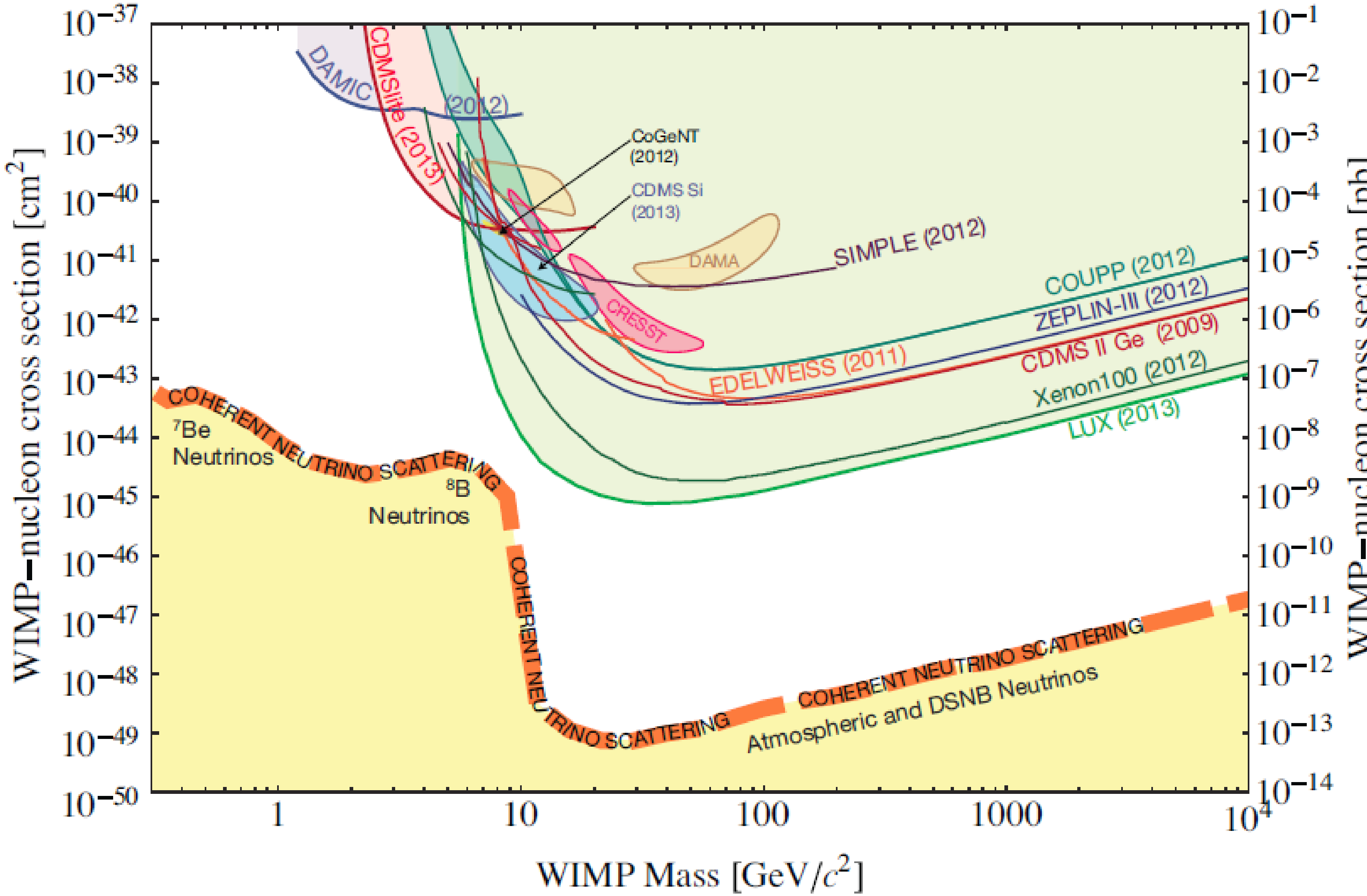
Kuhlen et al.'09



Billard,, Figueroa-Feliciano, Strigari '14



arXiv:1304.4279



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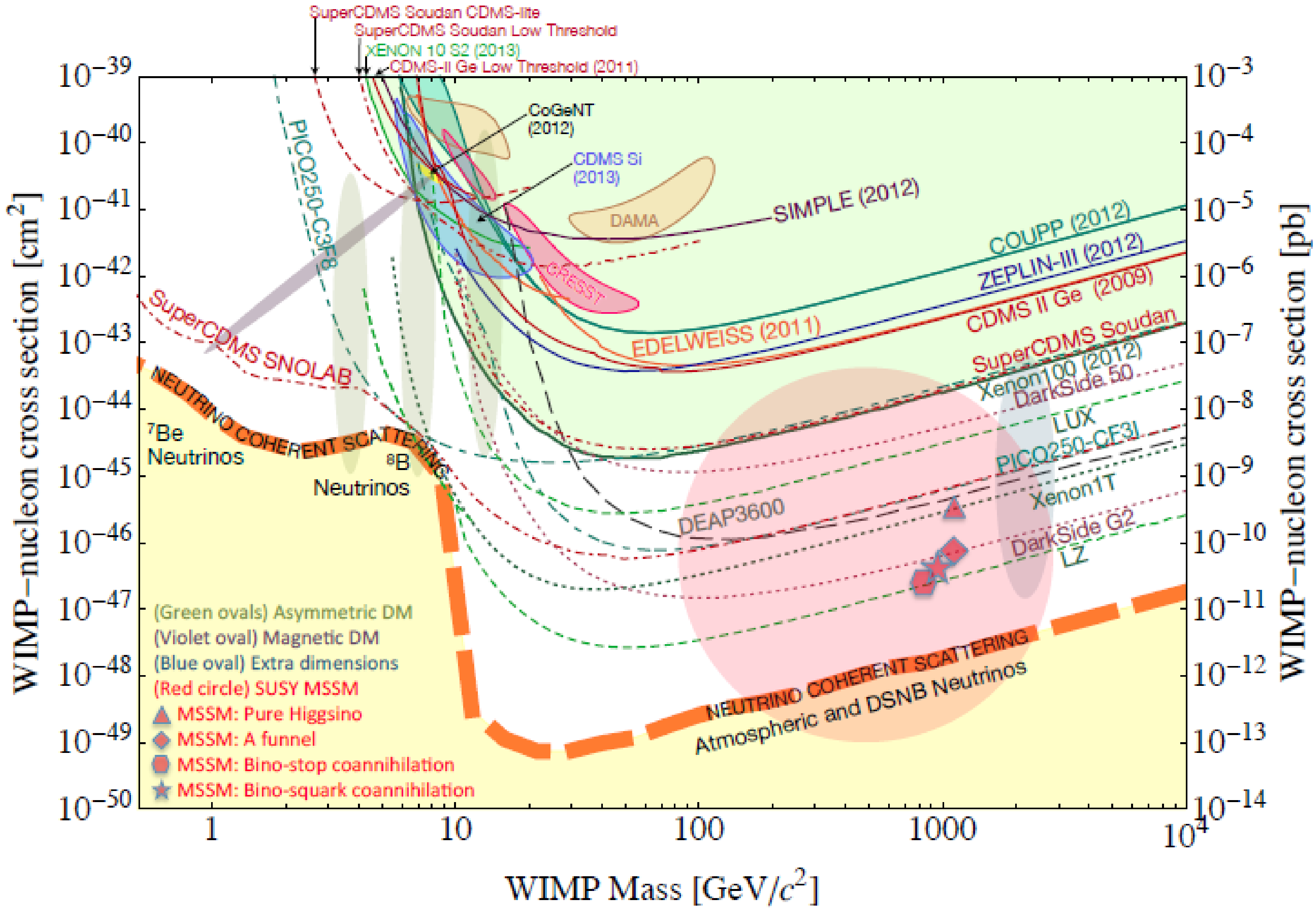
SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 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]

List of conclusions

End of list

Concluding remarks

1- Zwicky's observations of 1933

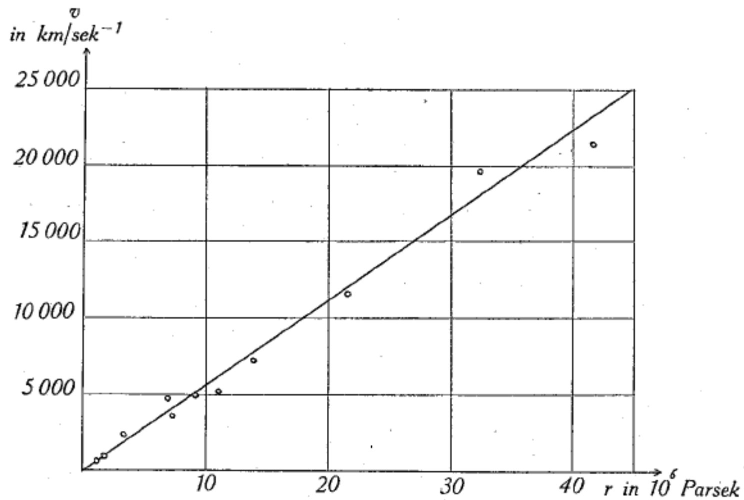

Fig. 2.

Concluding remarks

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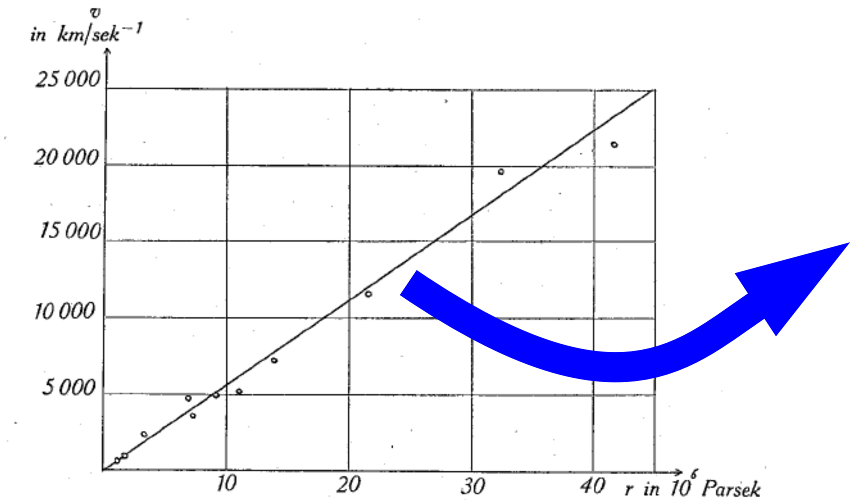

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80 years later, we still don't know what is producing this.

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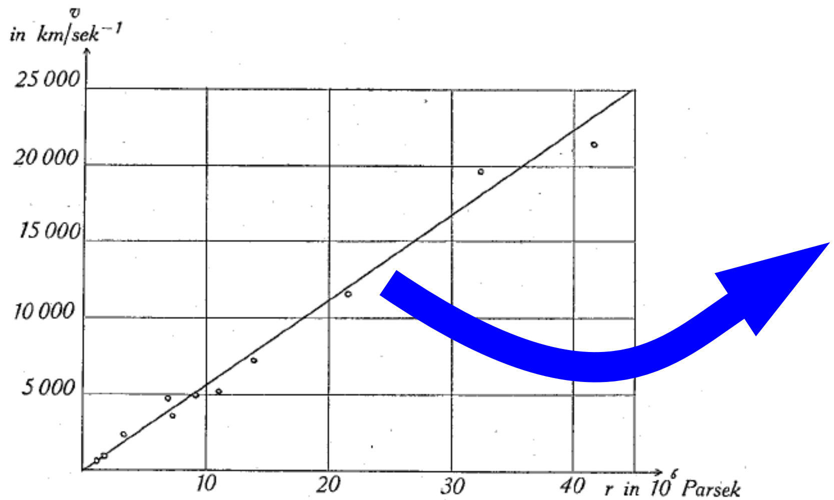

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2- If the dark matter is constituted by WIMPs, there are good chances to observe new signals in this decade. Exciting times ahead!

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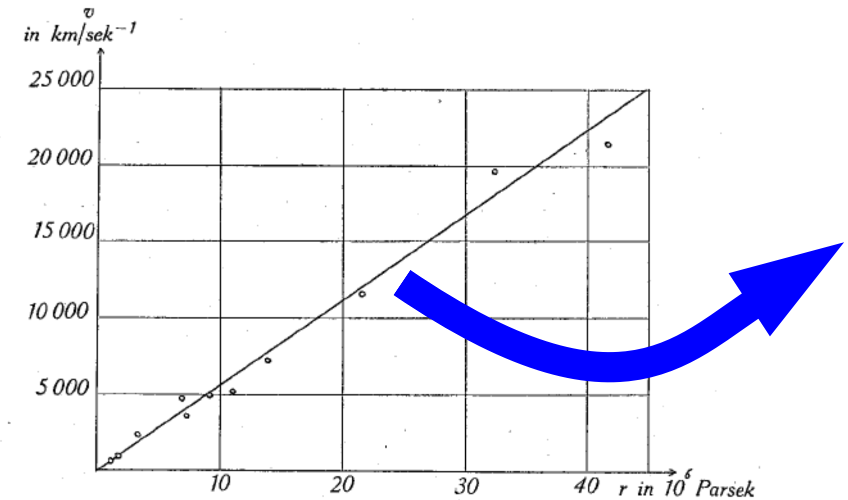

Fig. 2.

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!