Indirect Dark Matter Detection

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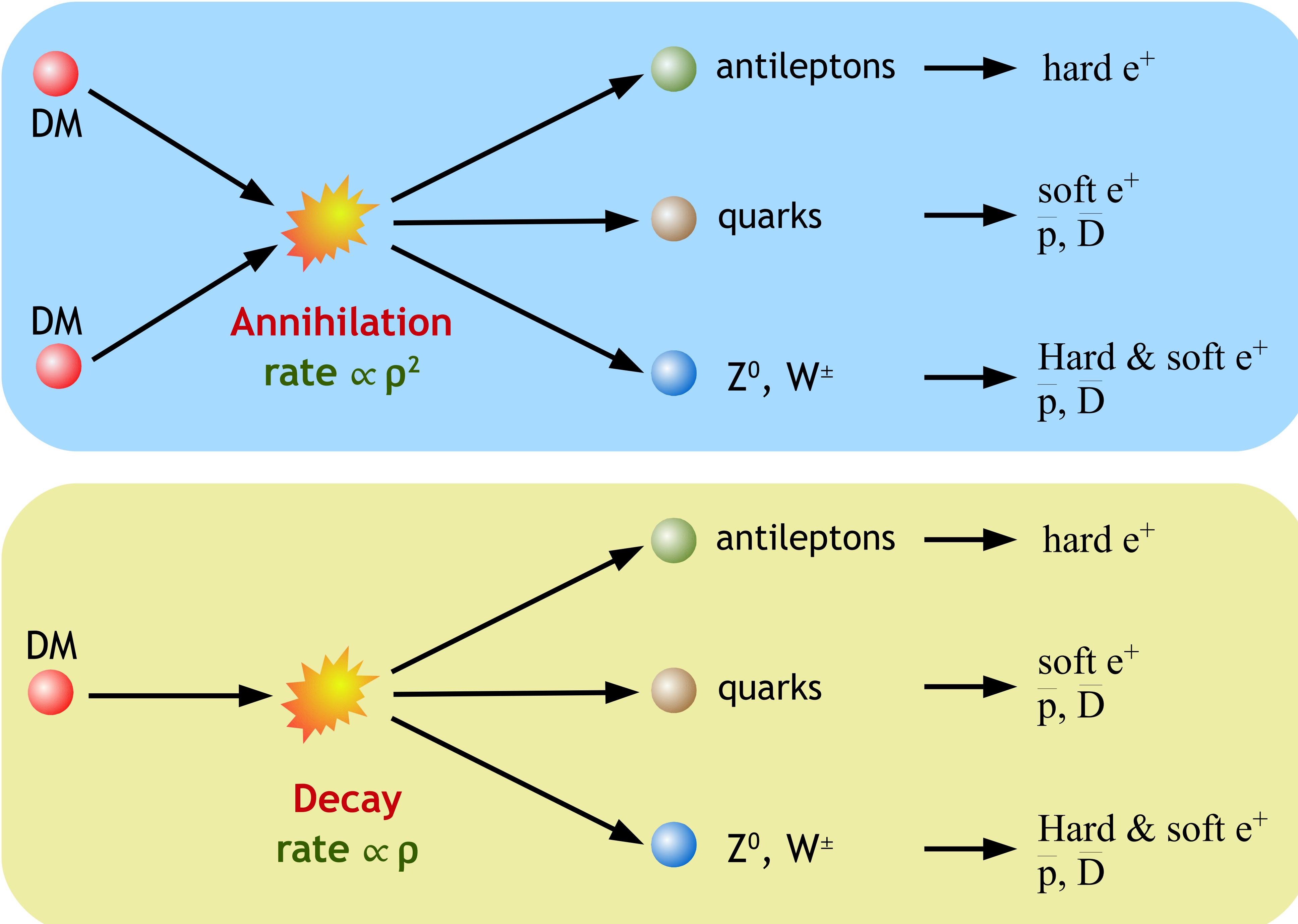
Technische Universität München

Zakopane
May 2012

Indirect dark matter searches

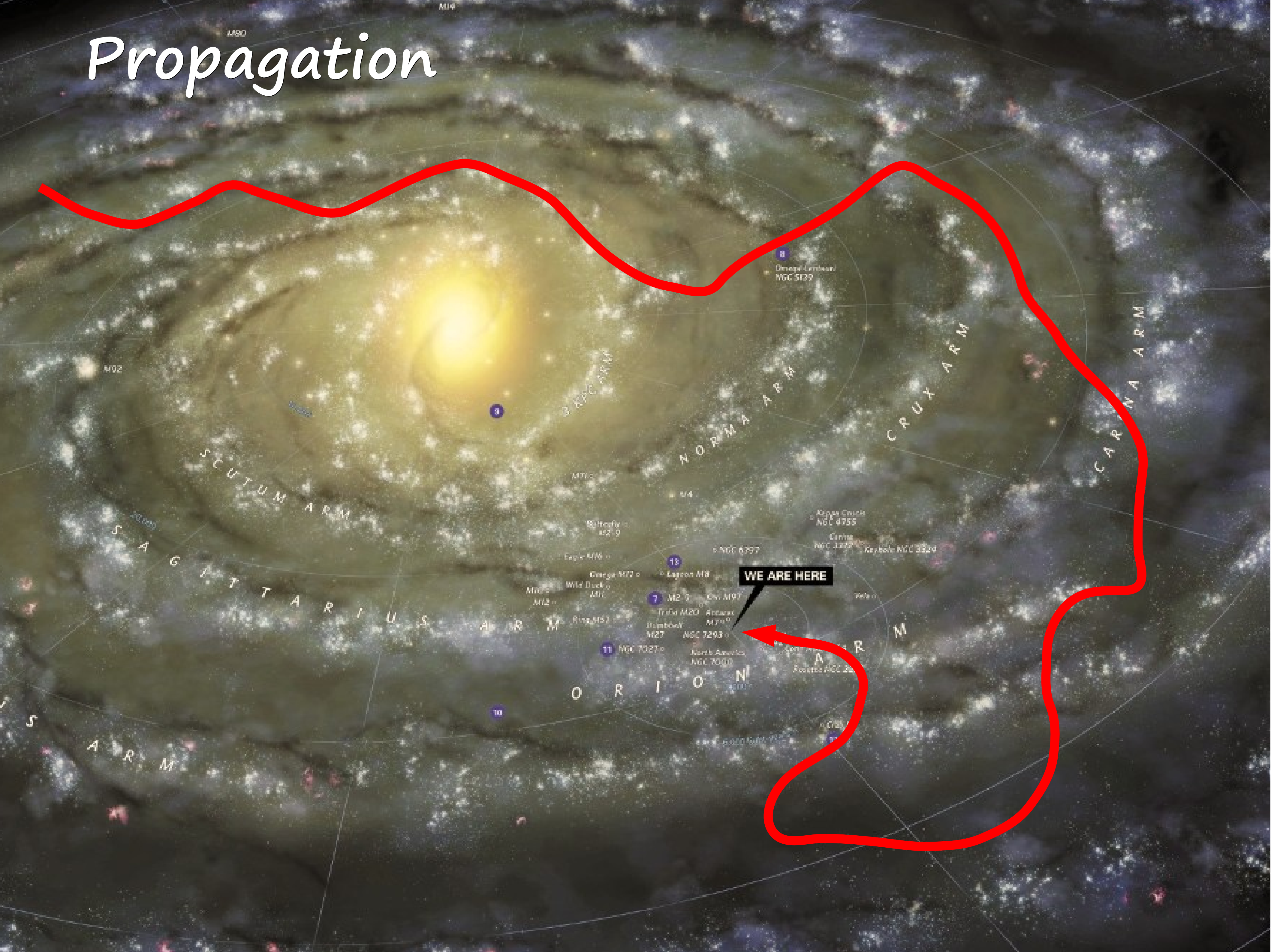
Production				Antimatter
Propagation	}	of	{	Gamma-rays
Detection				Neutrinos

Production

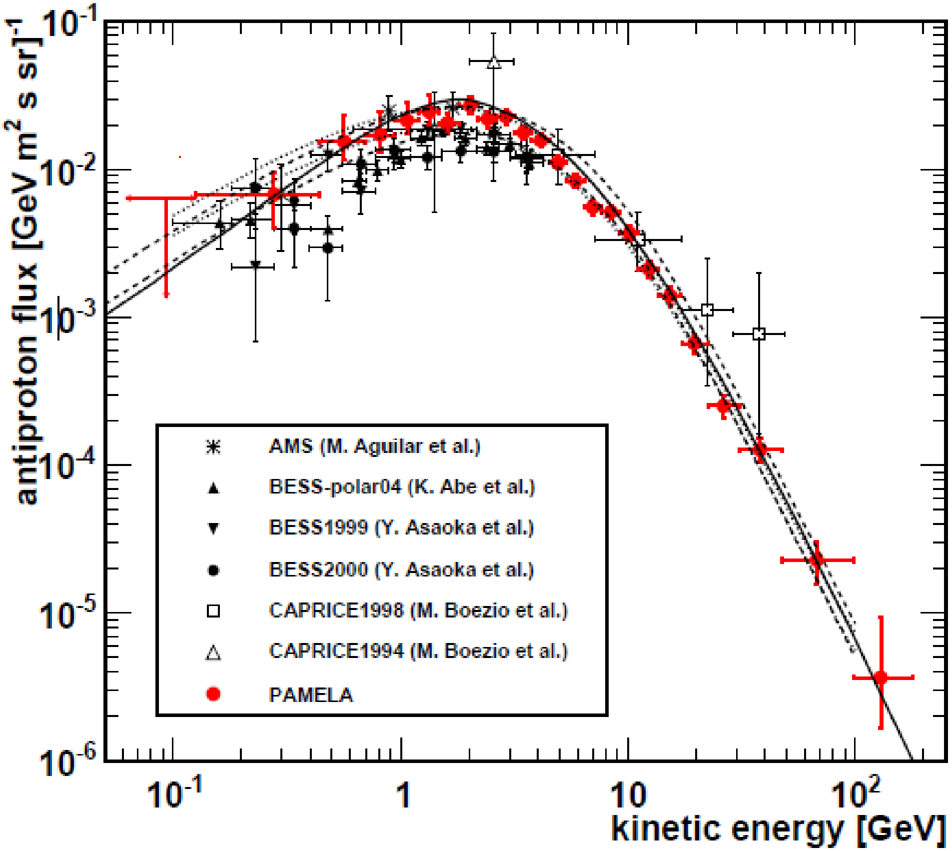


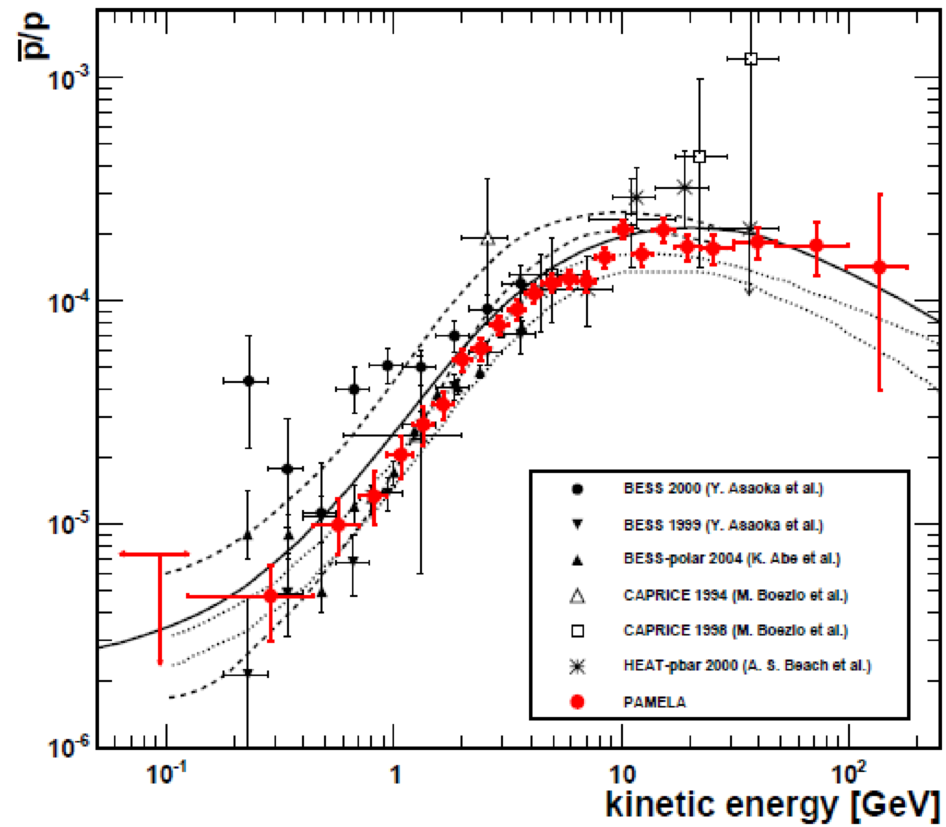
DM
DM
Annihilation
rate ∝ ρ²
antileptons
hard e+
quarks
soft e+
p̄, D̄
Z0, W±
Hard & soft e+
p̄, D̄
DM
Decay
rate ∝ ρ
antileptons
hard e+
quarks
soft e+
p̄, D̄
Z0, W±
Hard & soft e+
p̄, D̄

Propagation



Experimental results: antiprotons





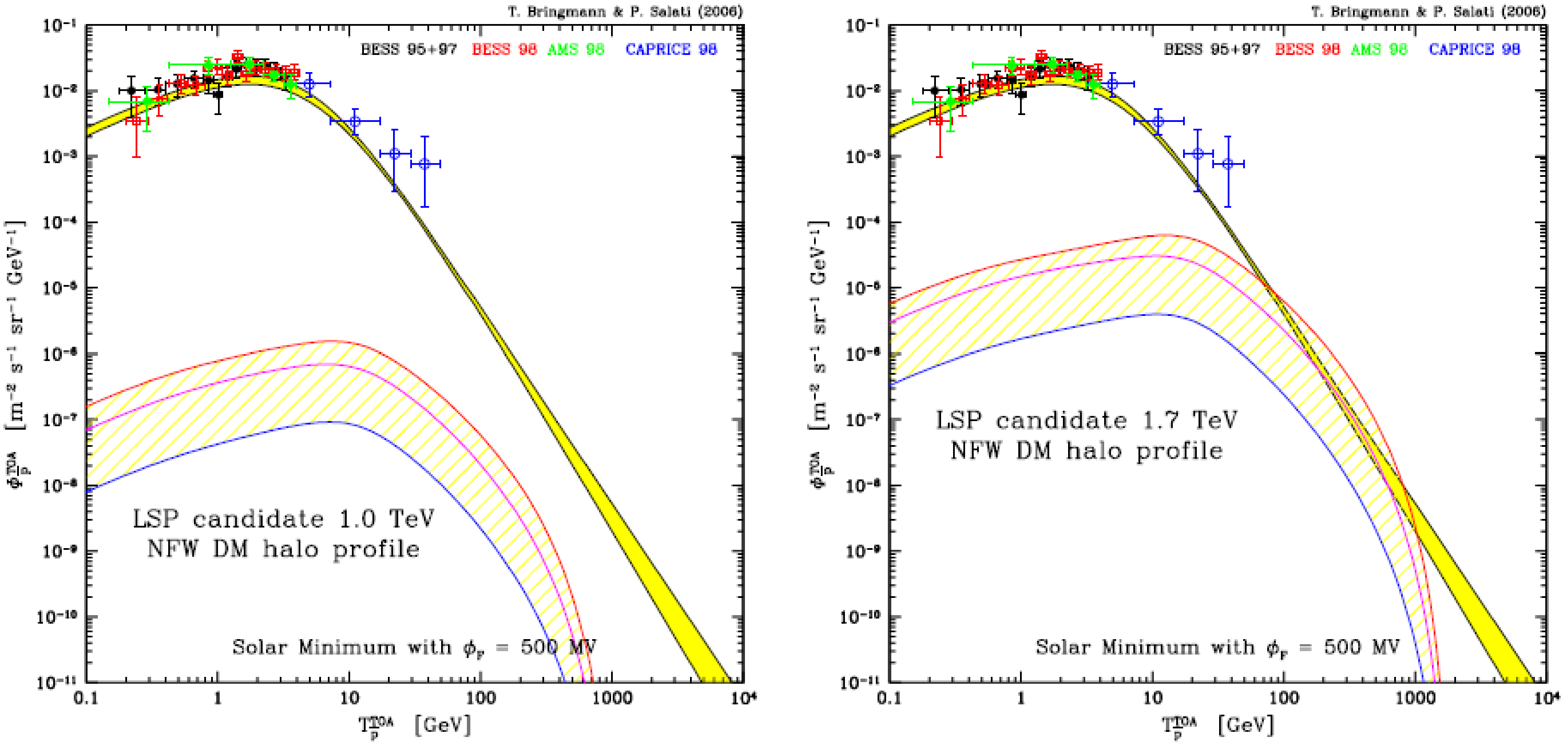
PAMELA collaboration
arXiv:1007.0821

Fairly good agreement between the measurements and the theoretical predictions from spallation.

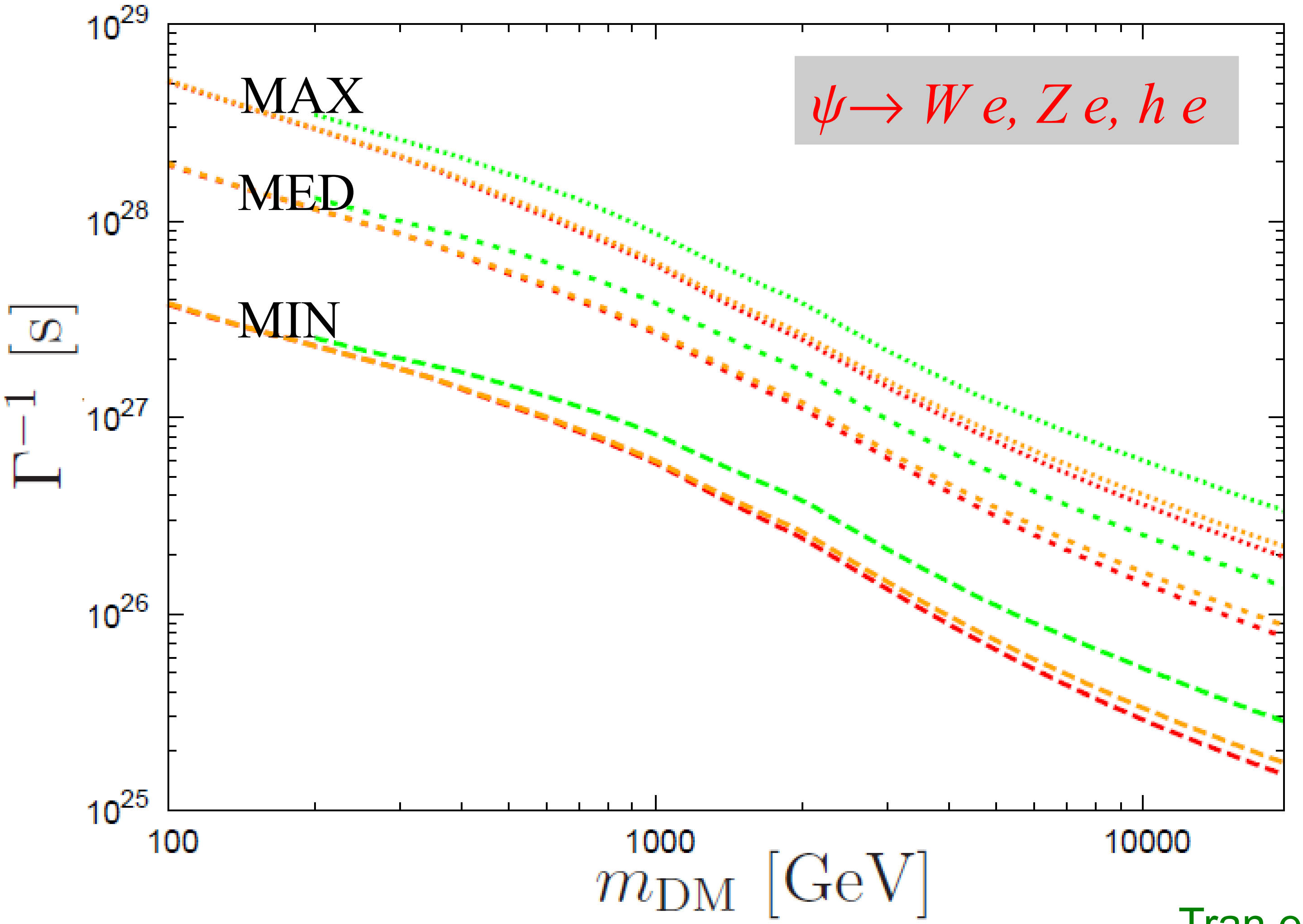
Annihilating dark matter: Lightest SUSY particle

$\times 10^{-26}$ 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	-	-
LSP1.7	1.7	102	-	-	-	-	-	-	20.1	79.9	-	-

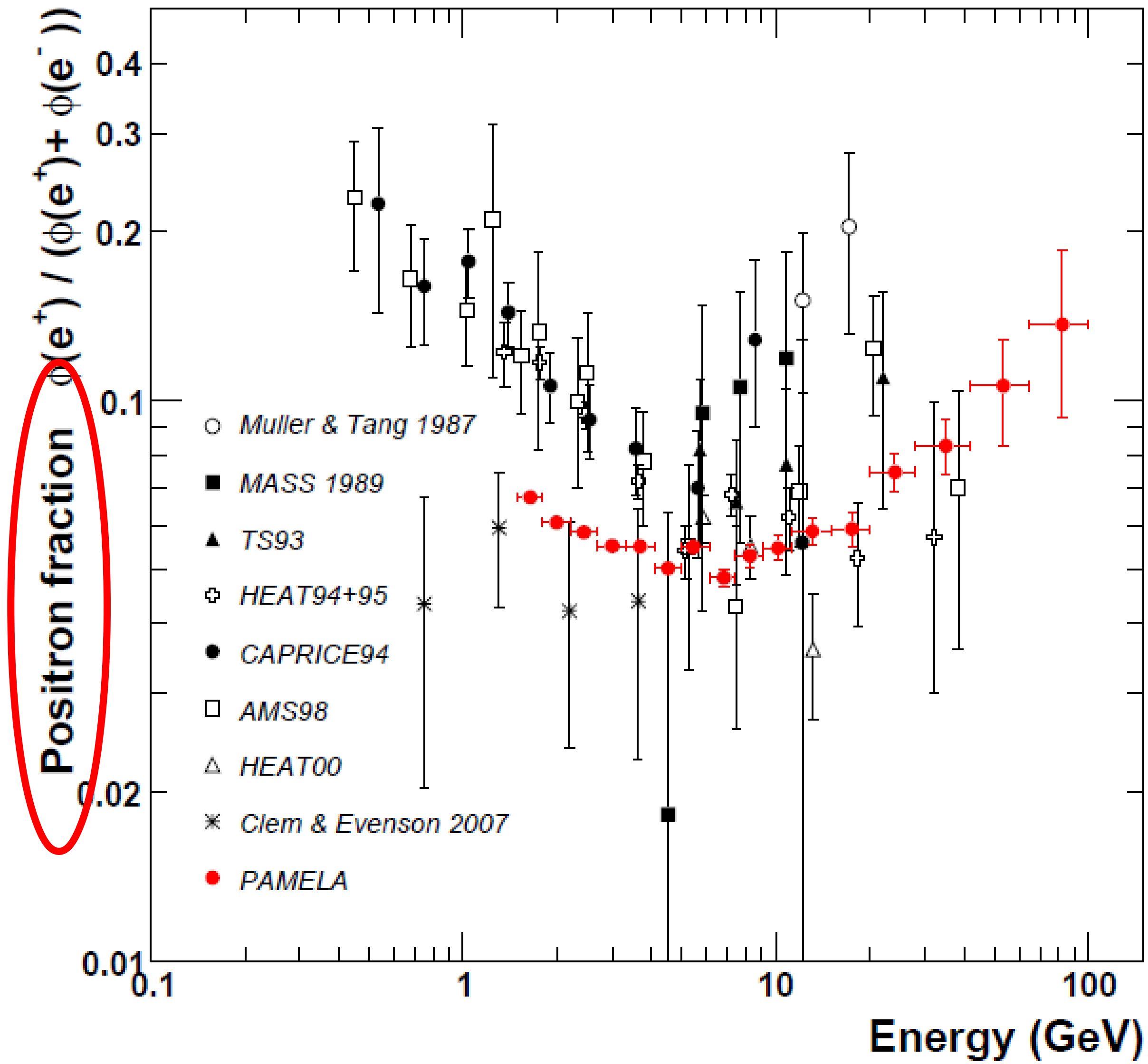


Decaying dark matter

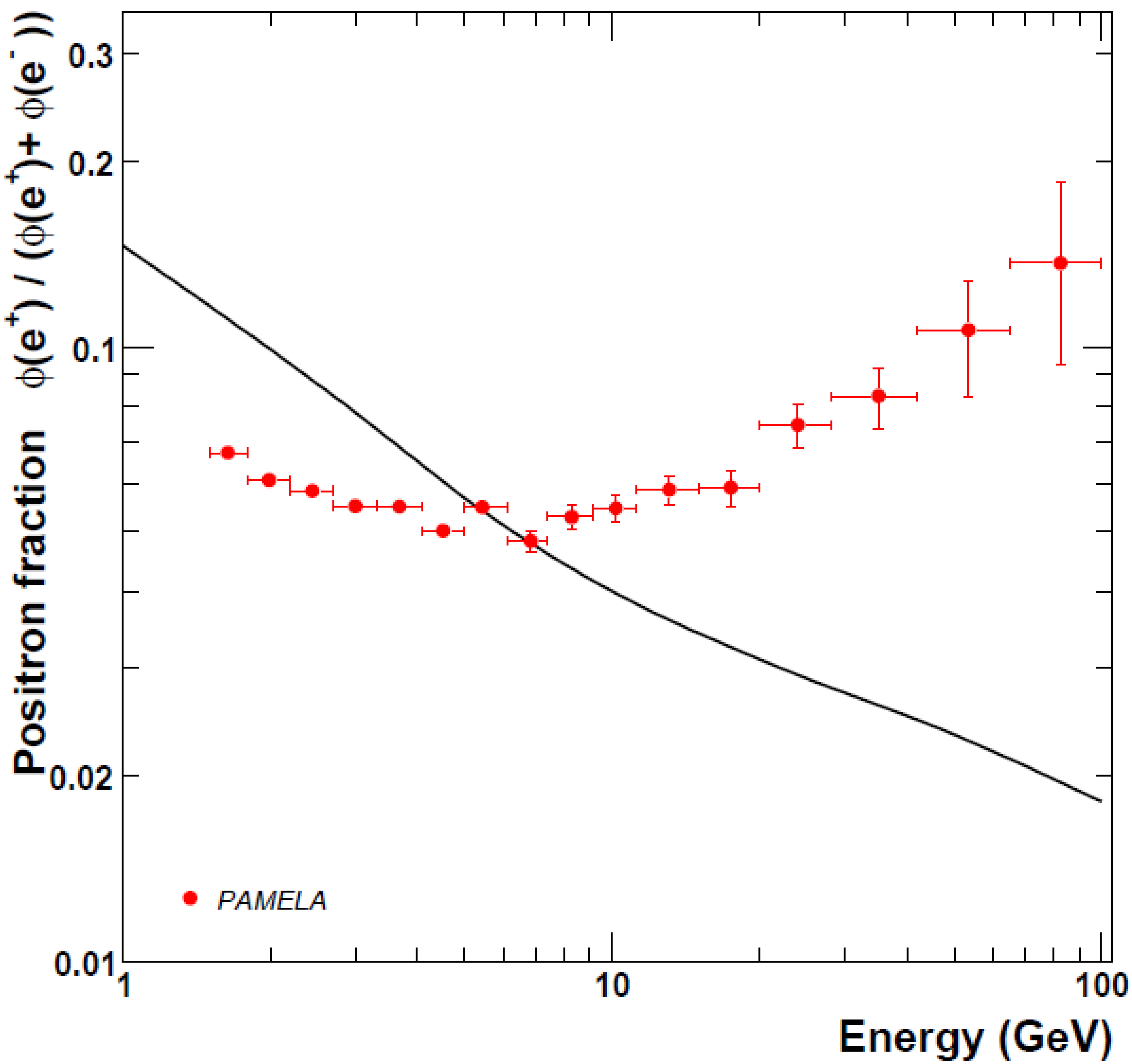


Tran et al.

Experimental results: positrons



PAMELA collaboration
arXiv:0810.4995



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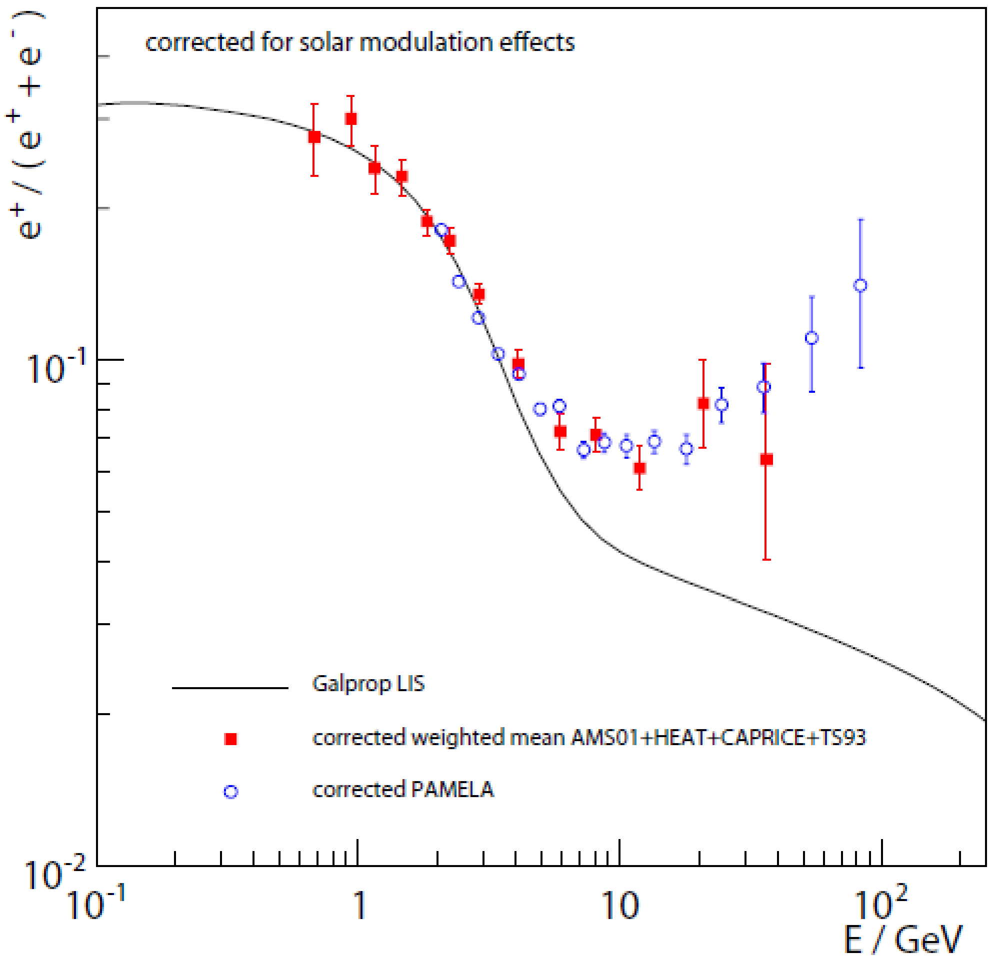


Gast, Schael '09

Fig. 6. Positron fraction data corrected for solar modulation effects according to the Galprop conventional model. PAMELA data have been corrected based on the charge-sign dependent model, the weighted mean of the previously published data has been corrected based on a charge-symmetric model using $\phi = 442\,\mathrm{MV}$.

PAMELA excess at high energies?

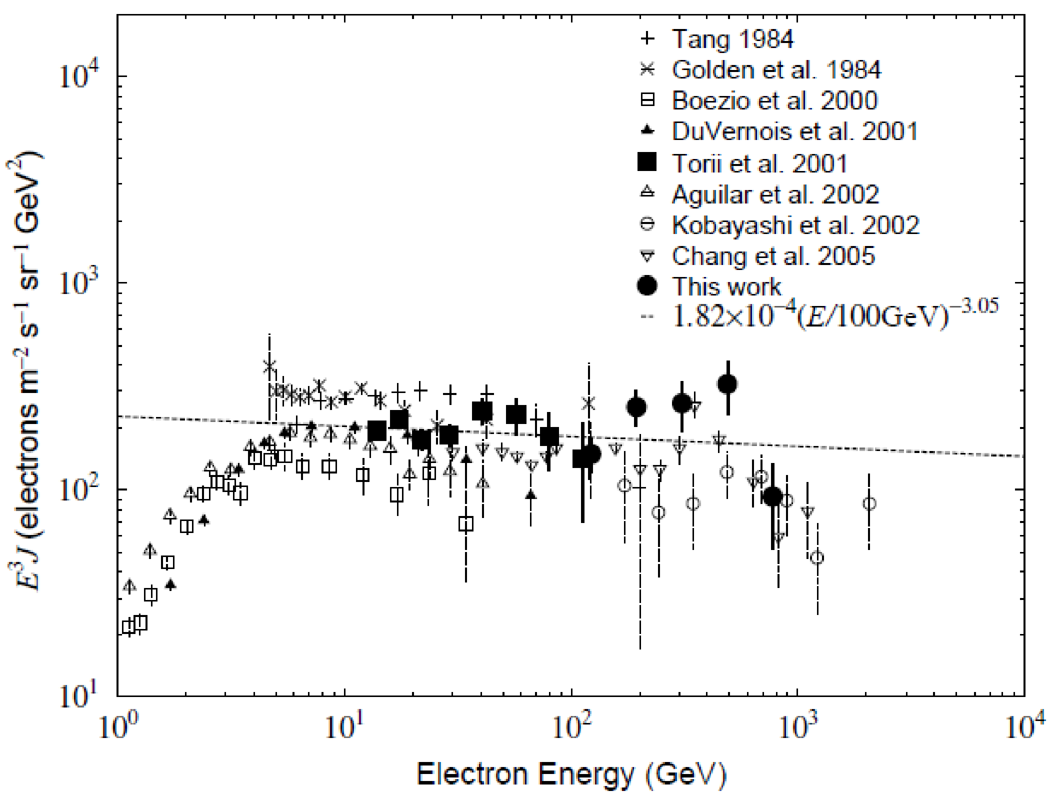
Theoretical calculation of the background positron fraction:

$$\mathrm{PF} = \frac{\Phi_{e^+}}{\Phi_{e^-} + \Phi_{e^+}}$$

Secondary positrons $\longrightarrow$ Calculable

Secondary electrons $\longrightarrow$ Calculable

Primary electrons $\longrightarrow$ To be determined by experiments



Experiment	power law index α
AMS-01 [29]	3.15 ± 0.04
ATIC [30]	3.14 ± 0.08
BETS [31], [32]	3.05 ± 0.05
CAPRICE [33]	3.47 ± 0.34
HEAT [34]	2.82 ± 0.16
MASS [35]	2.89 ± 0.10

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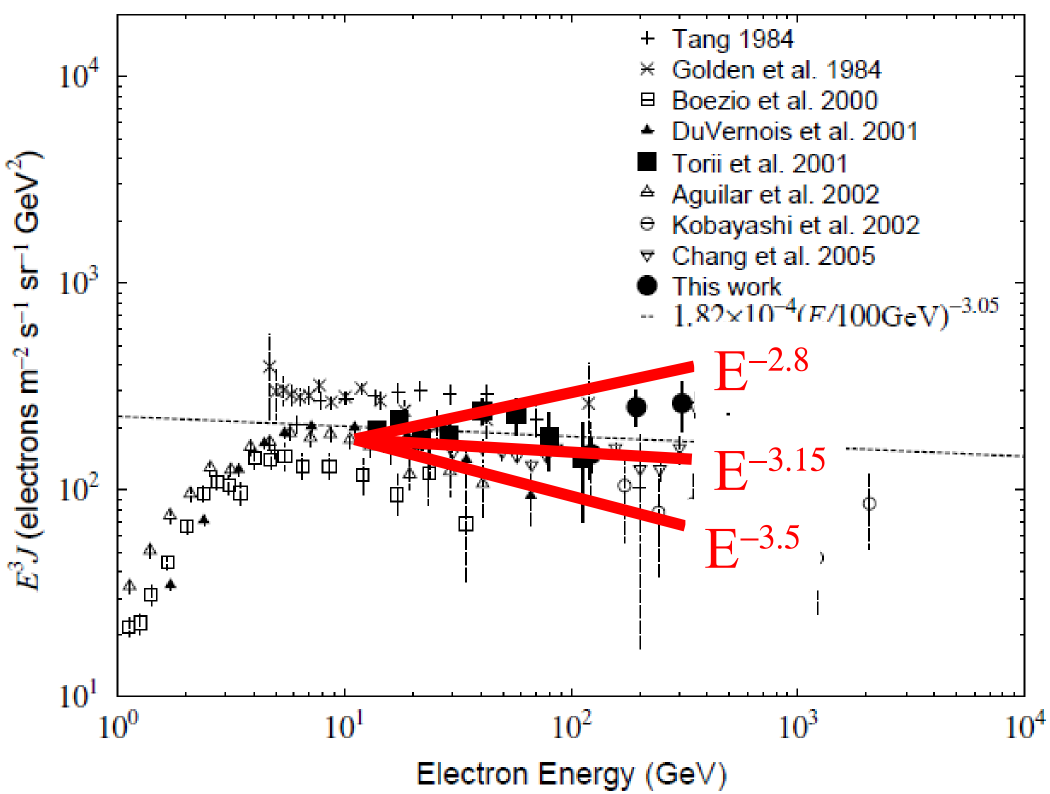

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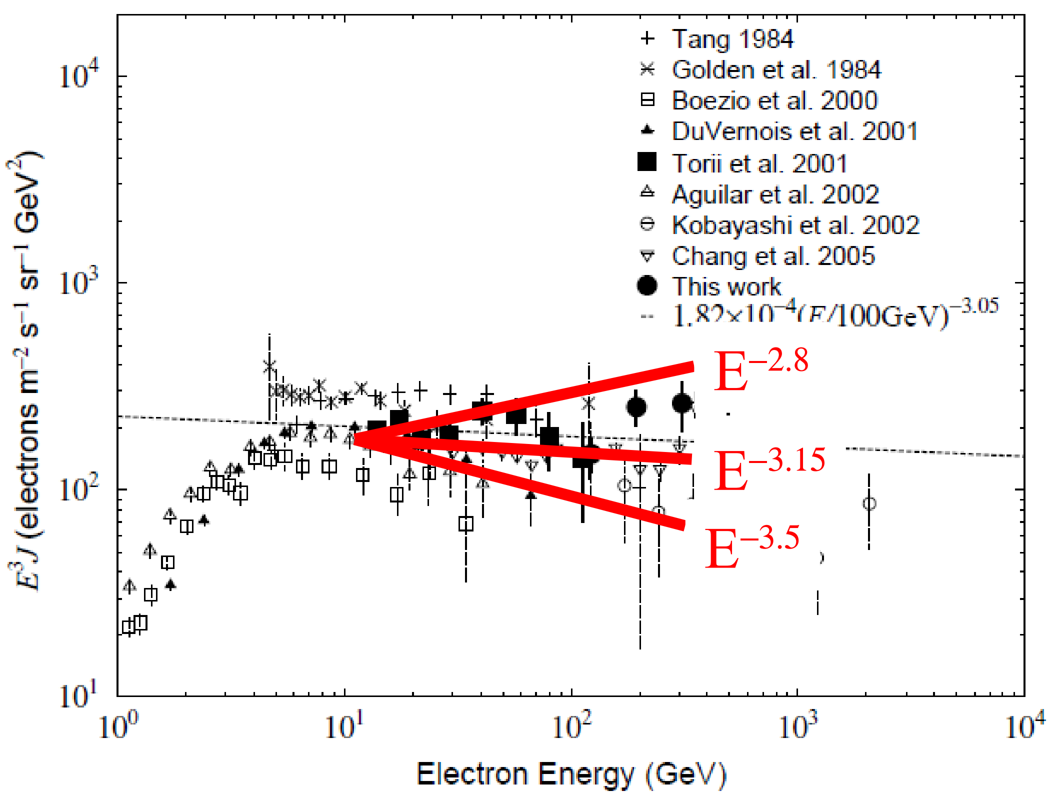
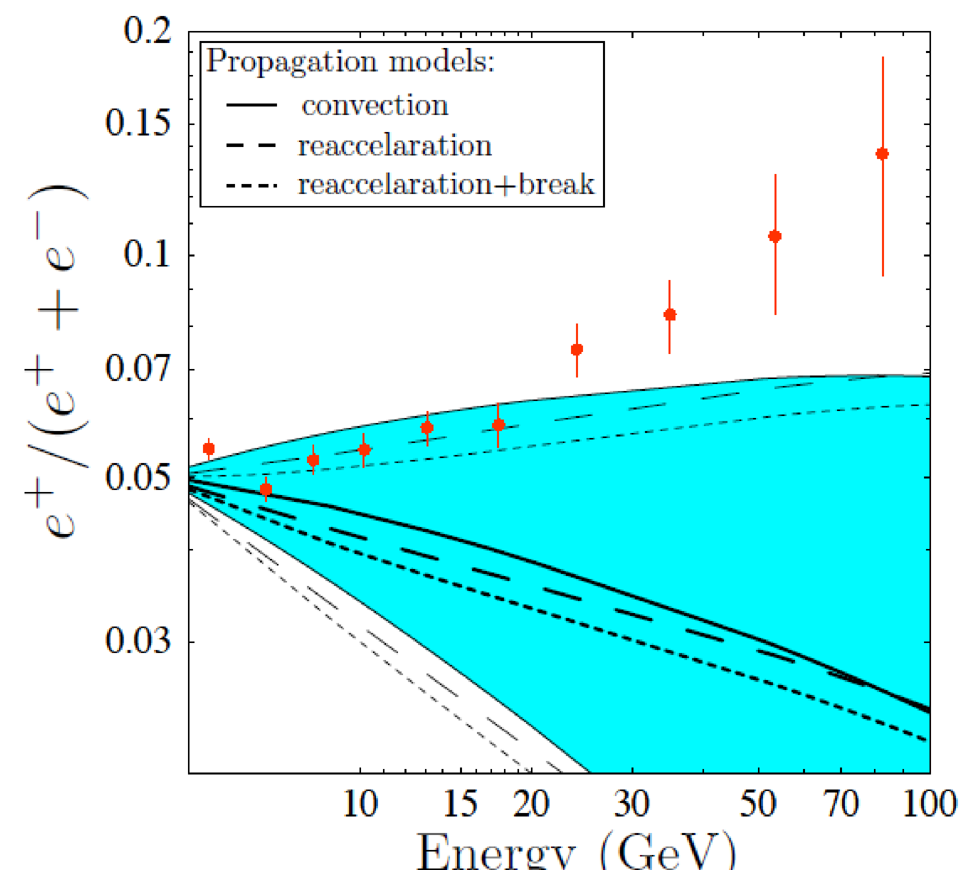
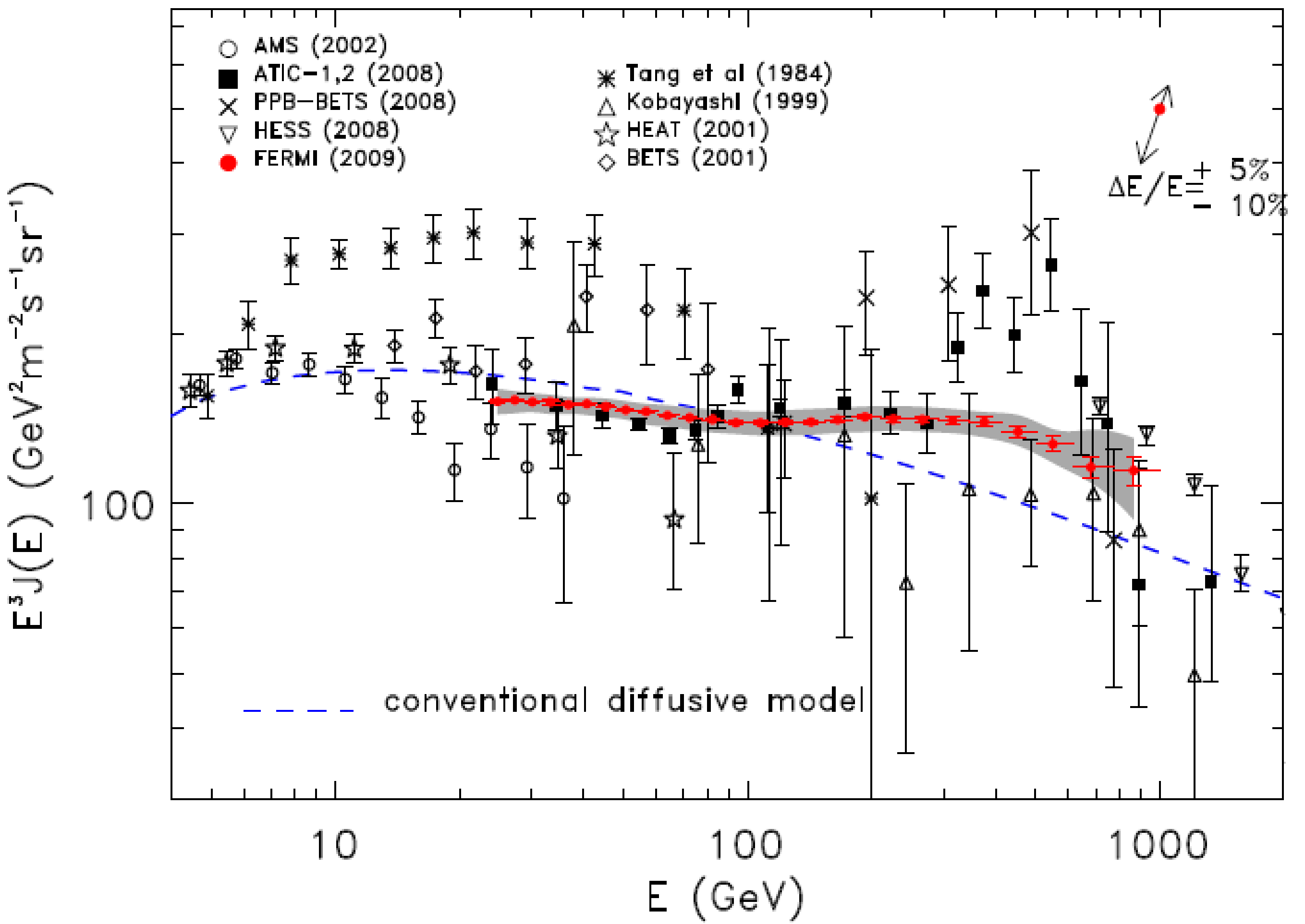
Harnik, Kribs '08

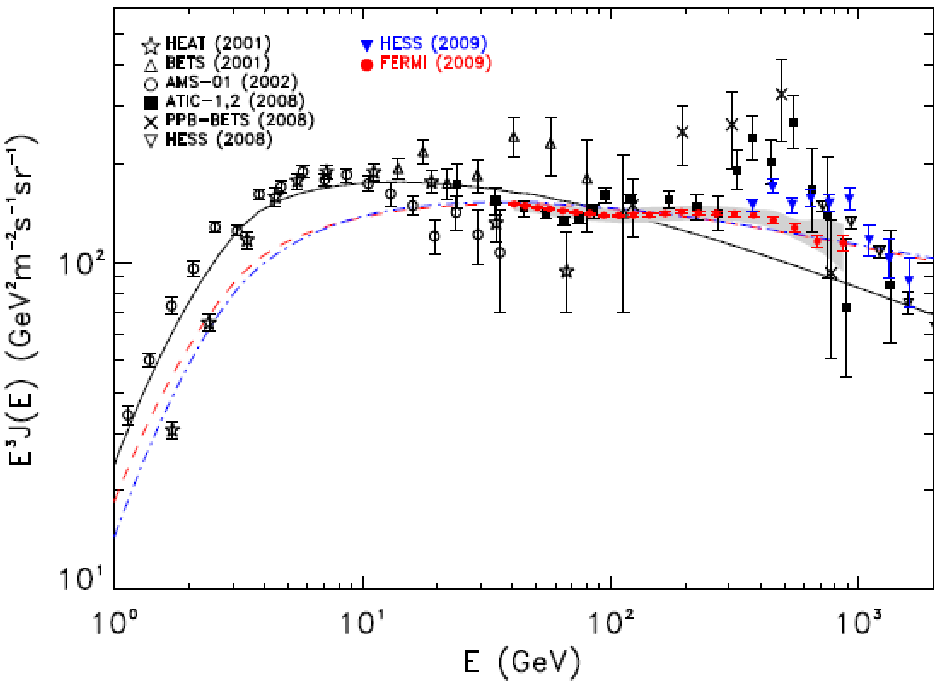


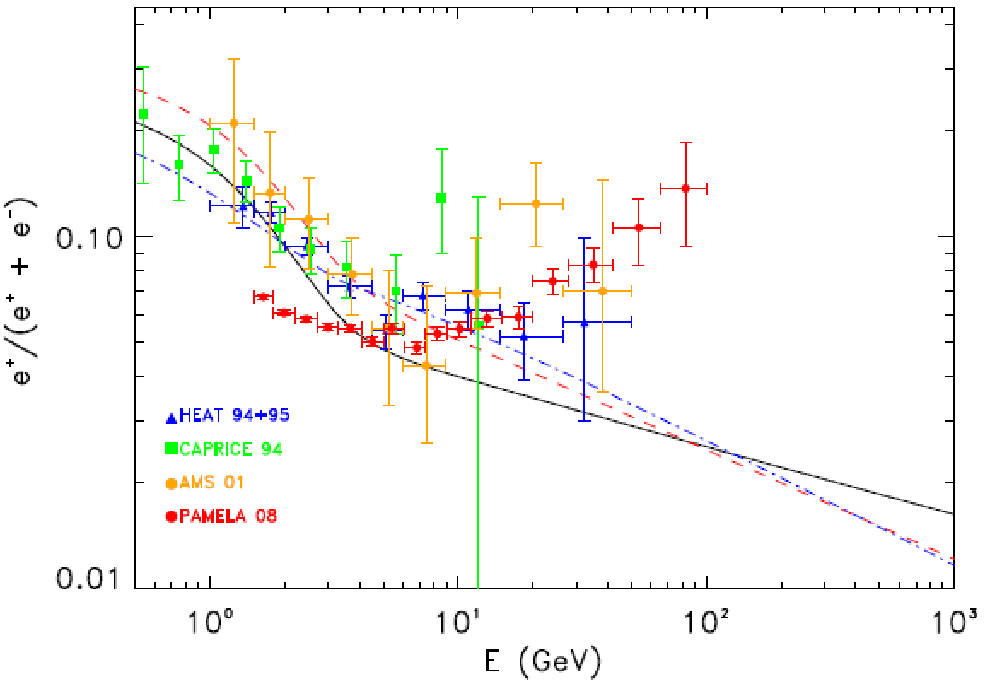




Abdo et al.
ArXiv:0905.0025

Present situation:





Evidence for a primary component of positrons

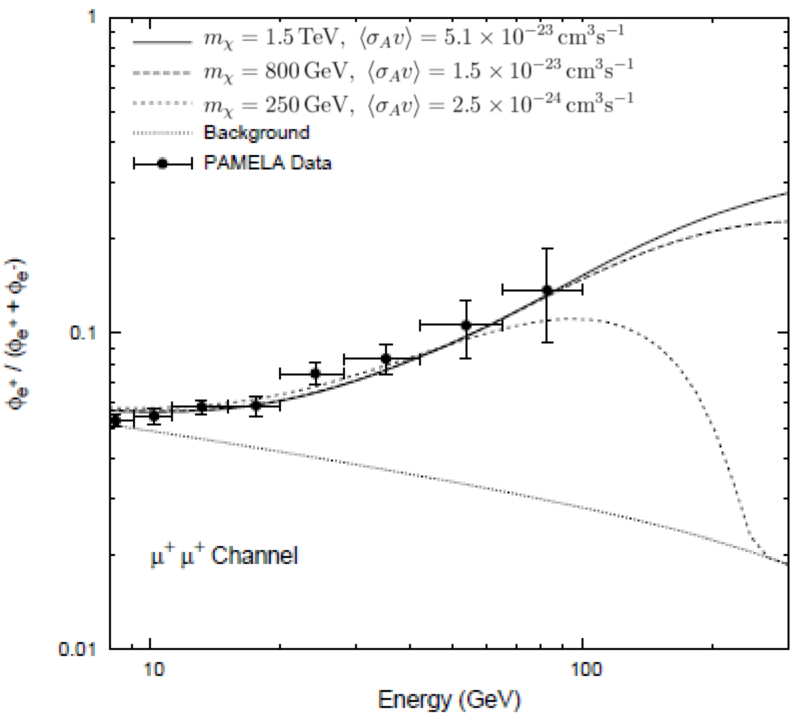
(possibly accompanied by electrons)

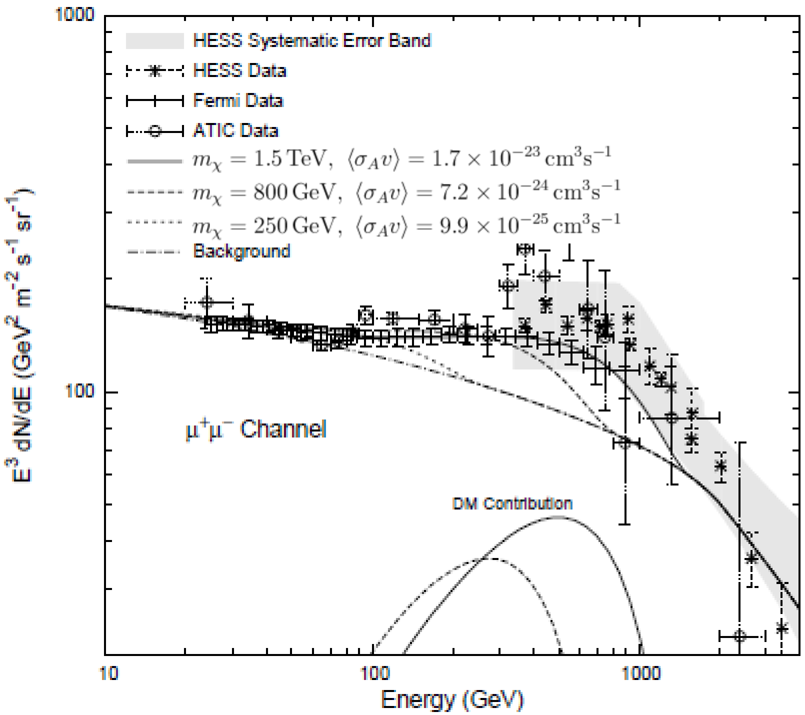
Astrophysical sources? Pulsars, SN remnants

New particle physics? DM annihilation, DM decay

Annihilating dark matter

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



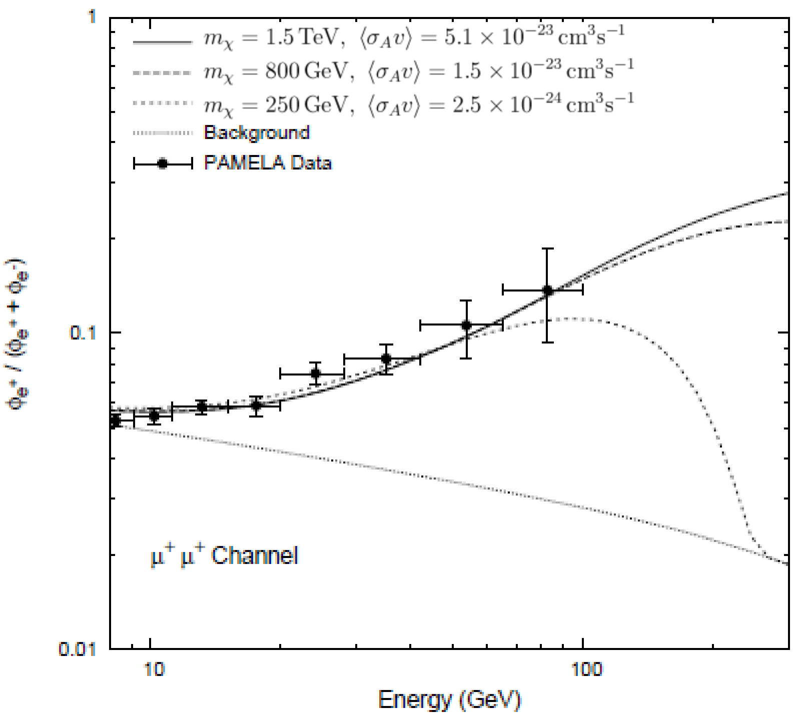


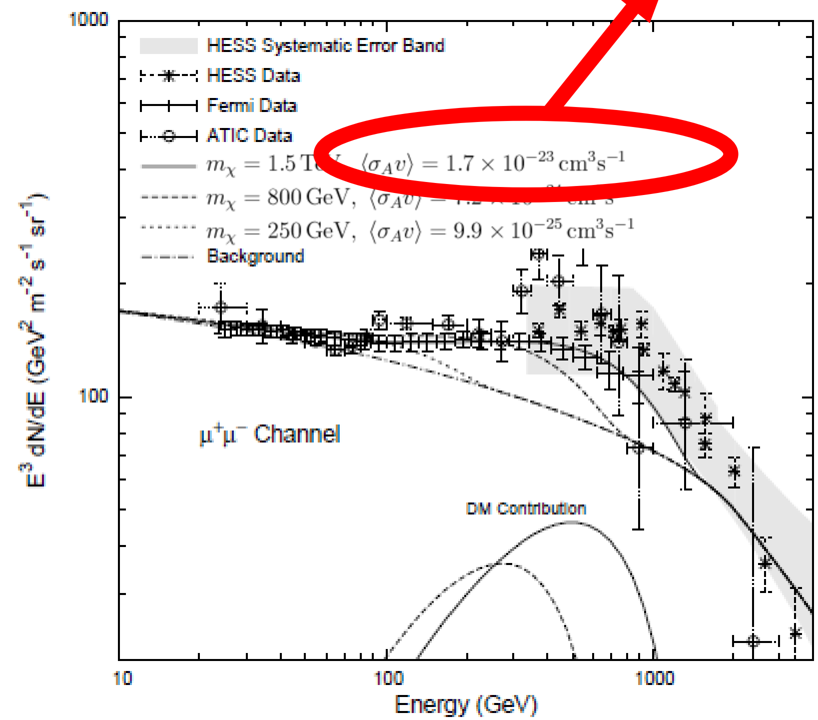
Cholis et al.
arXiv:0811.3641

Annihilating dark matter

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

600 times larger than the thermal cross section

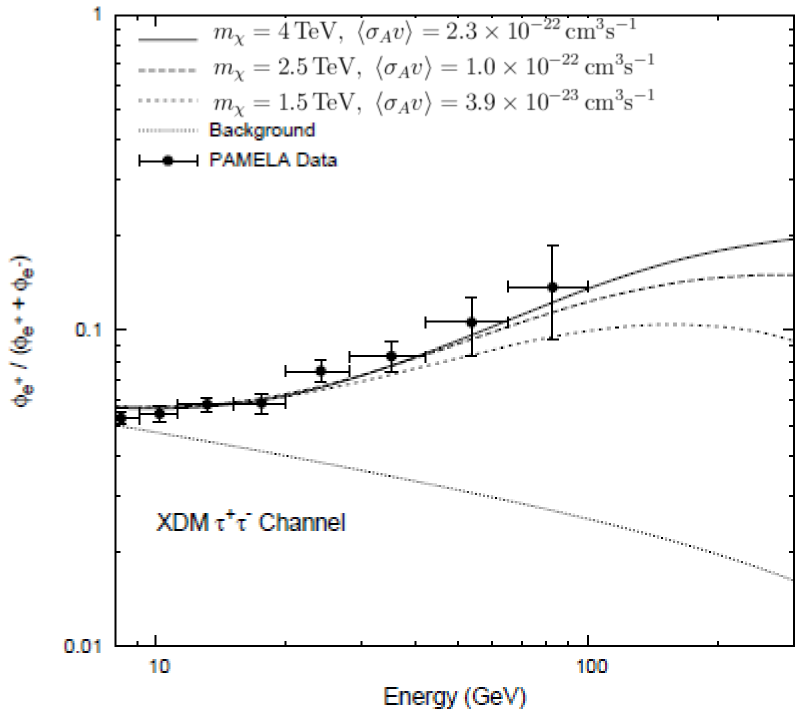


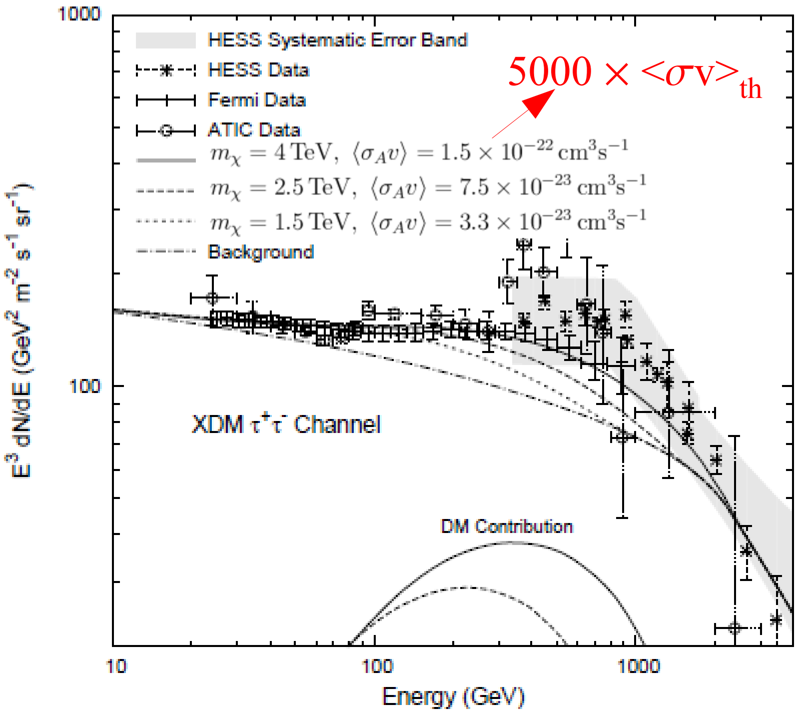


Cholis et al.
arXiv:0811.3641

Annihilating dark matter

$$\chi\chi \to \phi\phi, \text{ followed by } \phi \to \tau^+\tau^-$$

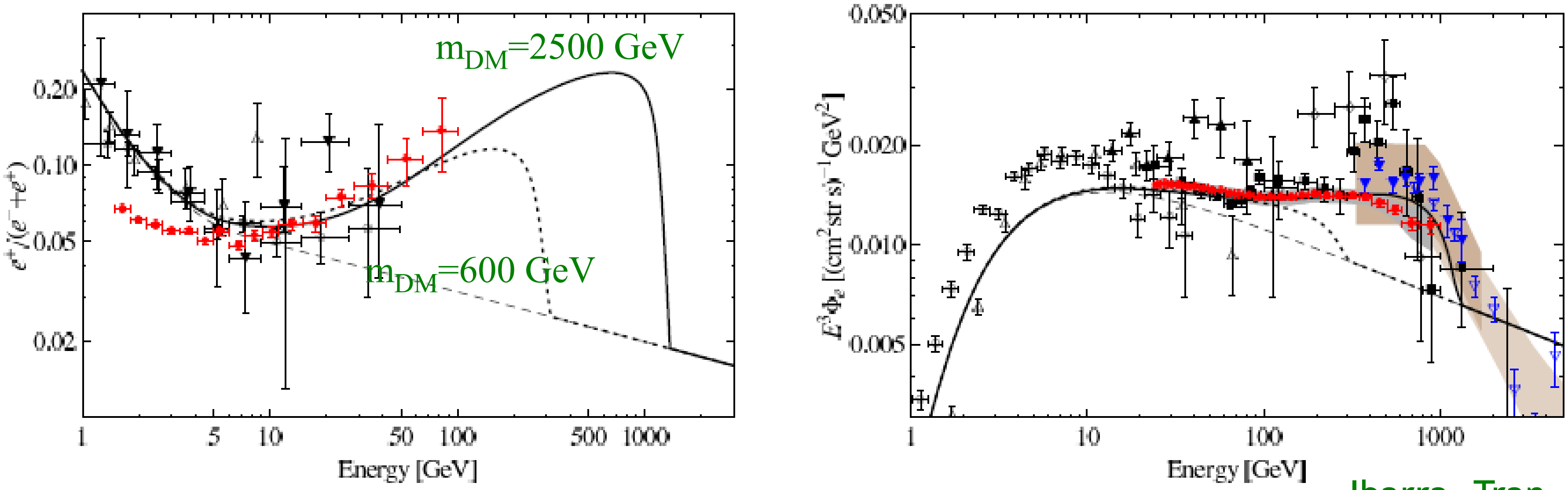




Cholis et al.
arXiv:0811.3641

Decaying dark matter

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



Ibarra, Tran, Weniger
arXiv:0906.1571

$\tau = 1.5 \times 10^{26}$ s

Conclusion from these plots:

the electron/positron excesses could be explained by the annihilation/decay of dark matter particles.

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

"Extraordinary claims require extraordinary evidence"

Carl Sagan

Instrumental problem?

High energy positrons are difficult to discriminate from protons.
And there are many more protons in cosmic rays than positrons!

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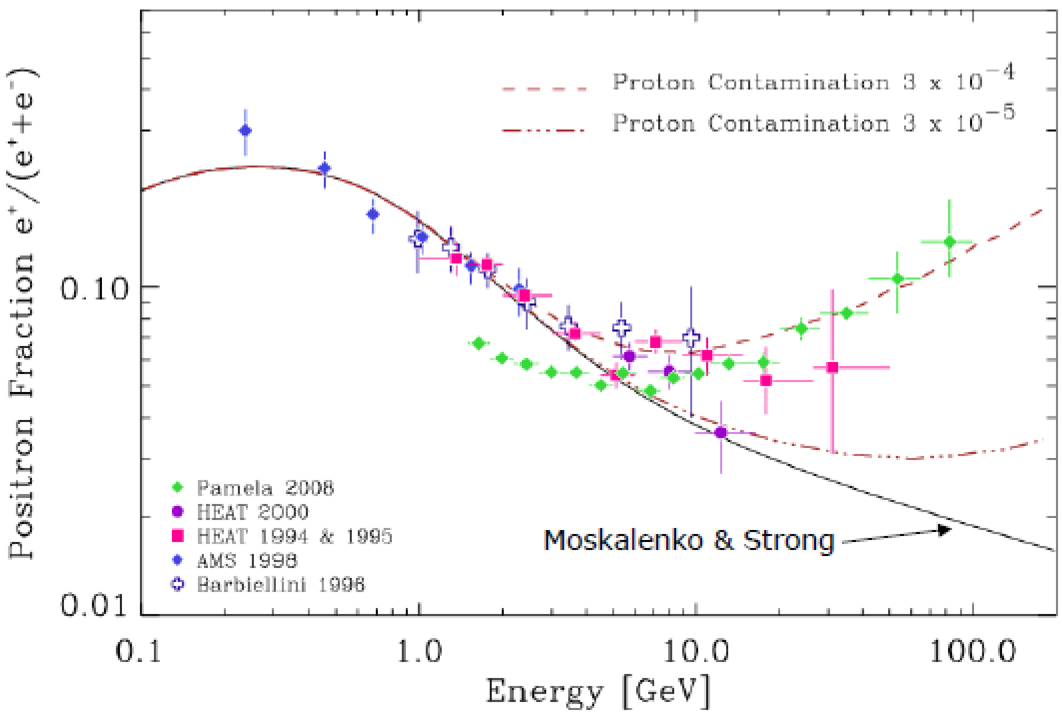
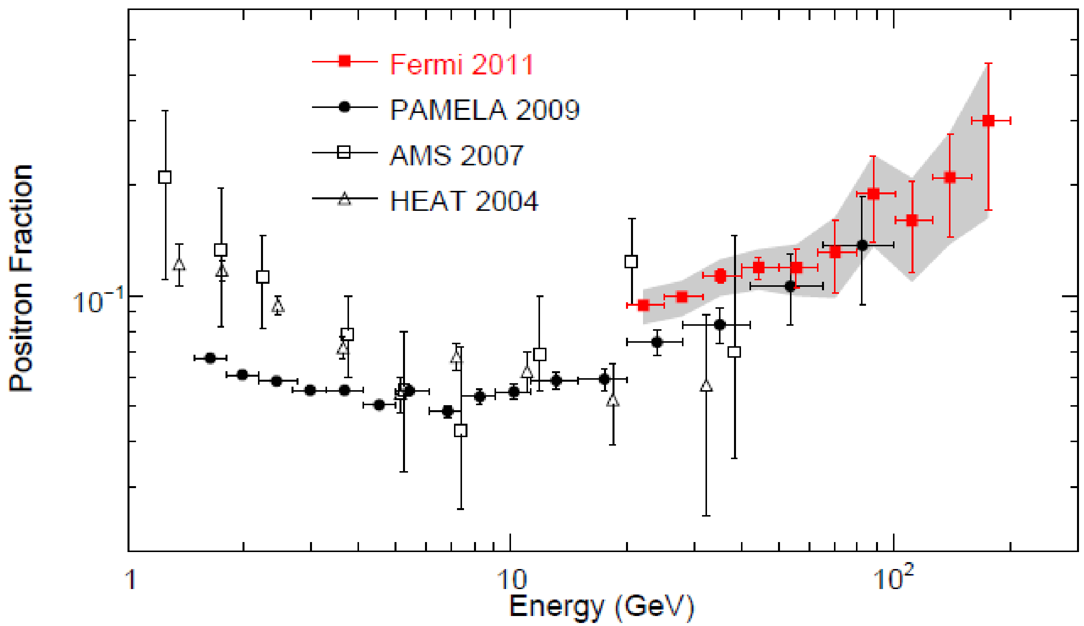
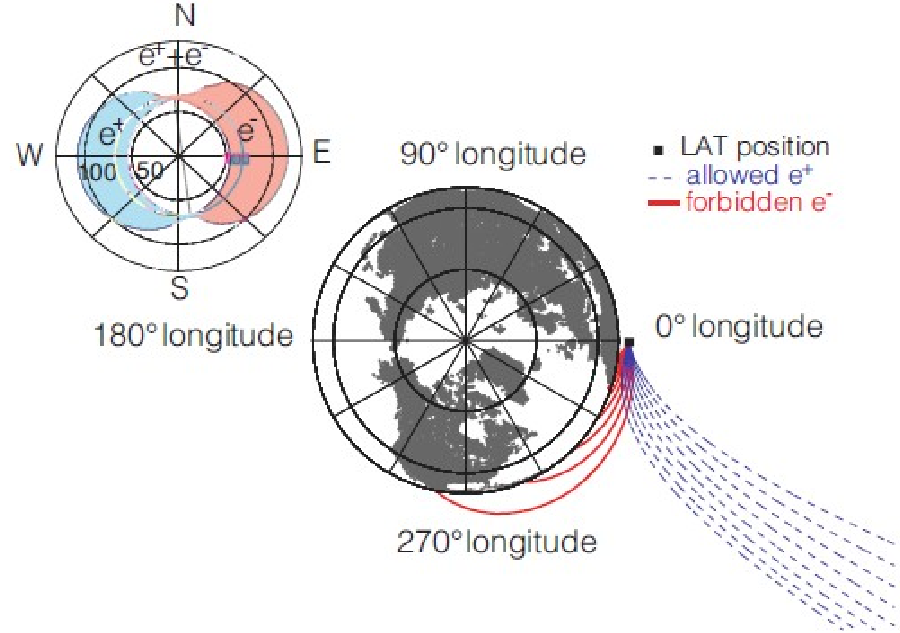


Schubnell

PAMELA claims a proton rejection of one part in 10^5.

• Fermi-LAT has confirmed the positron excess! Fermi coll. arXiv:1109.0521

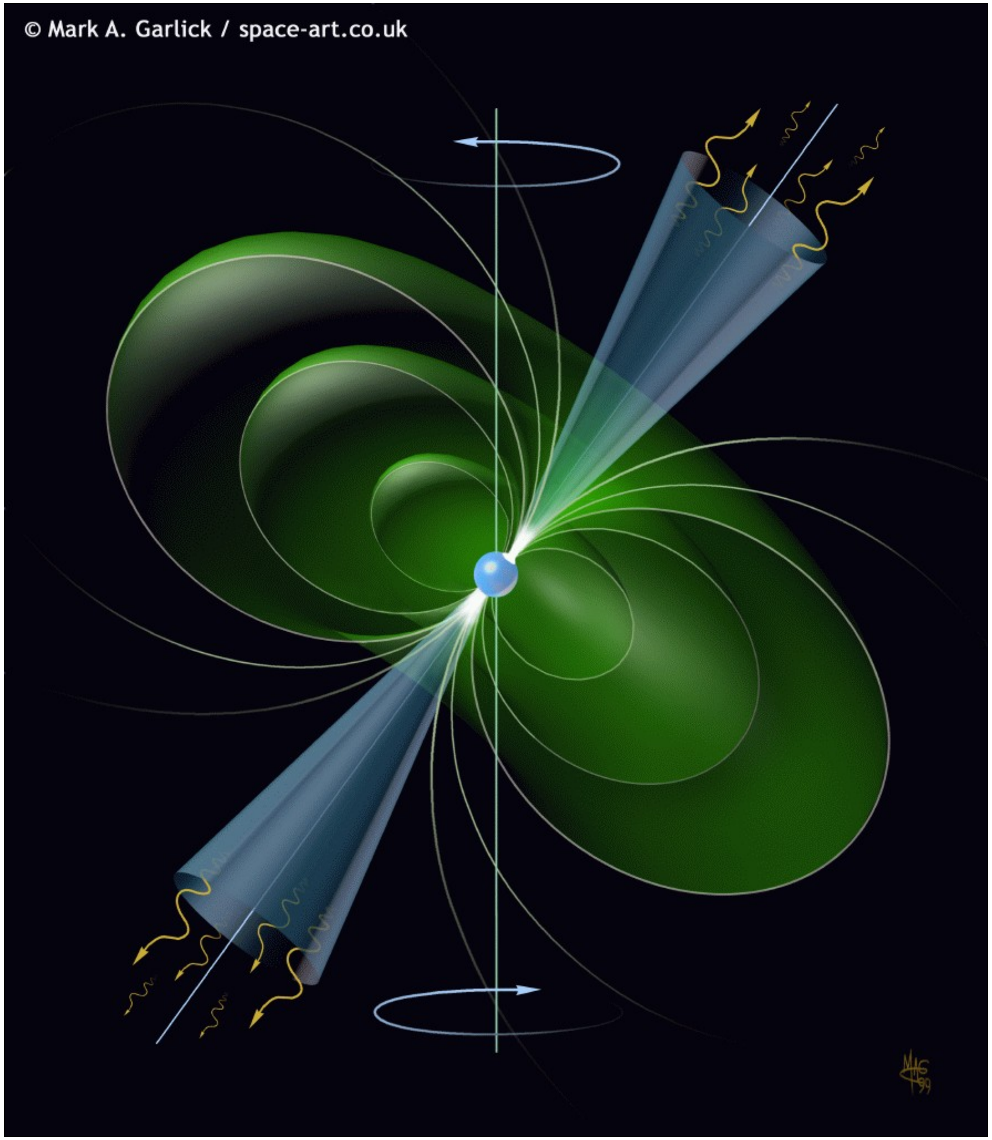




• More independent measurements soon by AMS-02

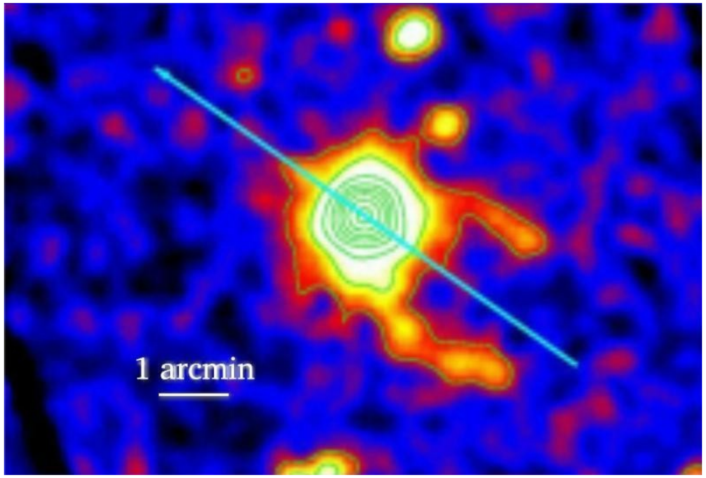
Astrophysical interpretations

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



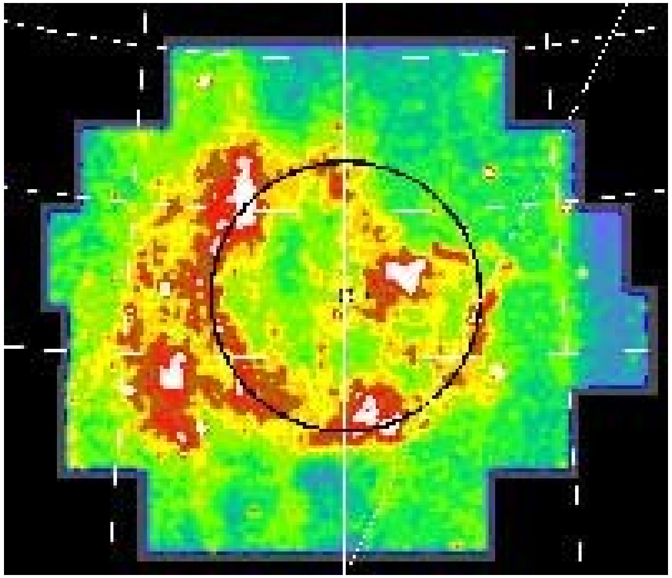
Atoyan, Aharonian, Völk;
Chi, Cheng, Young;
Grimani

Pulsar explanation I: Geminga + Monogem



Geminga

T=370 000 years
D=157 pc

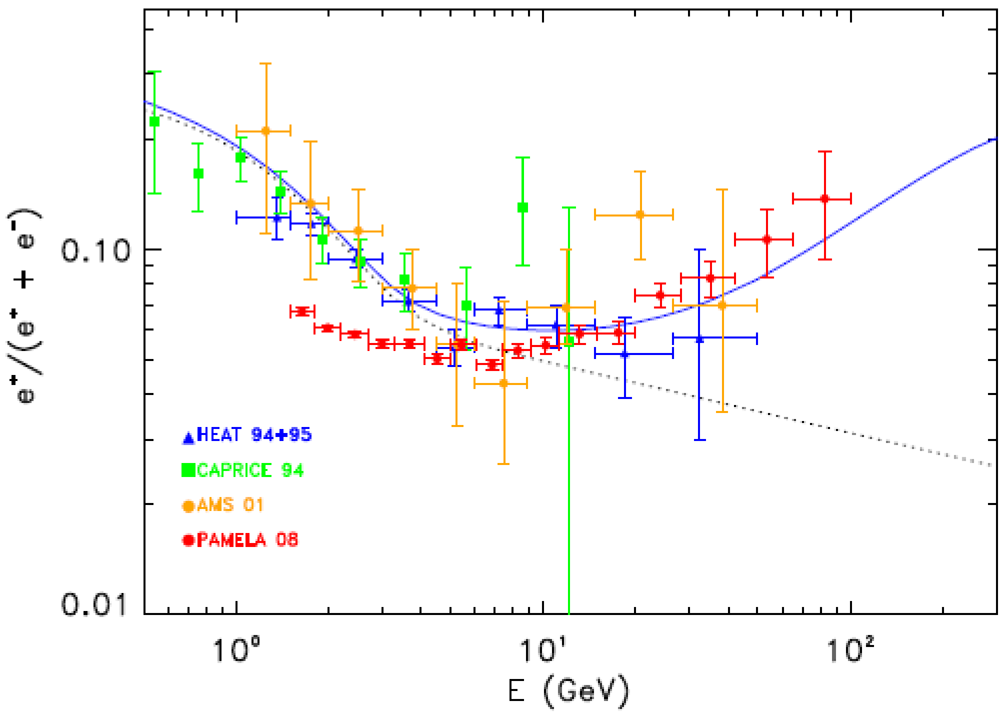


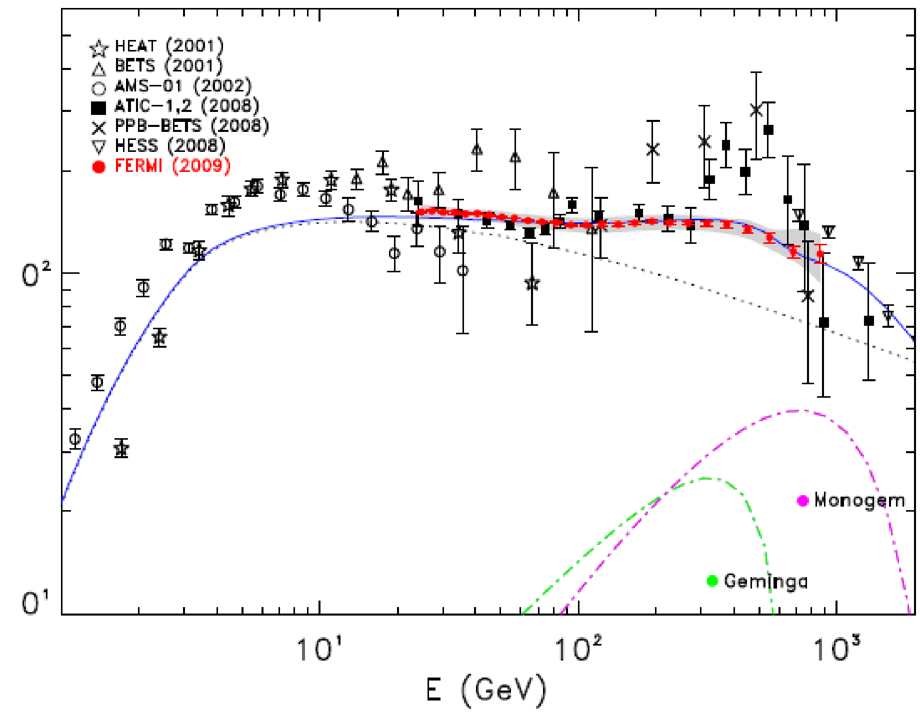
Monogem (B0656+14)

T=110 000 years
D=290 pc

Pulsar explanation I: Geminga + Monogem

Grasso et al.



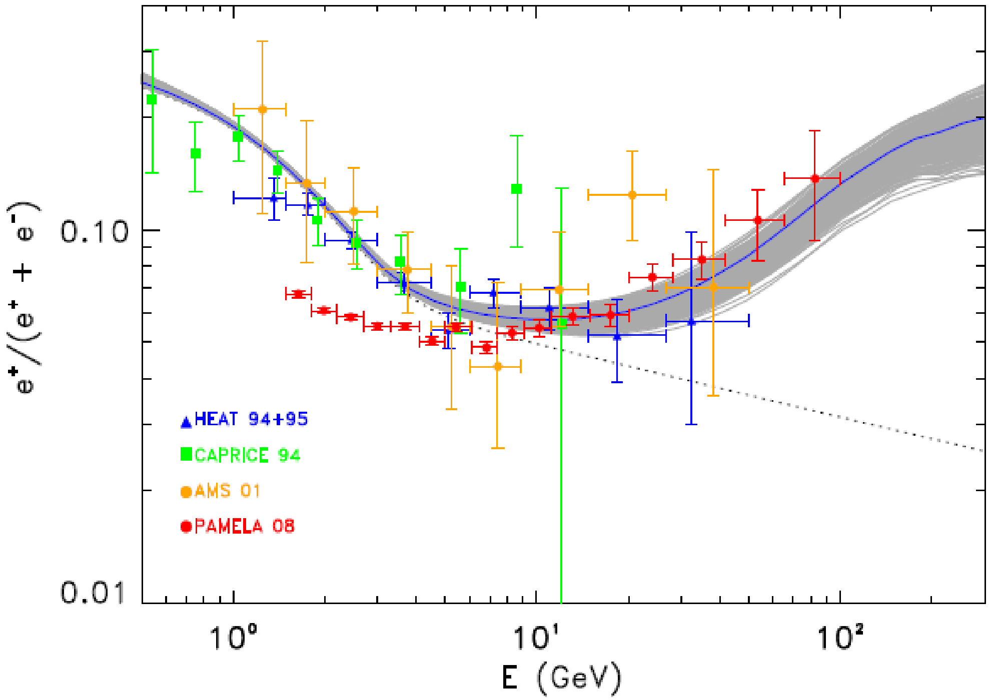


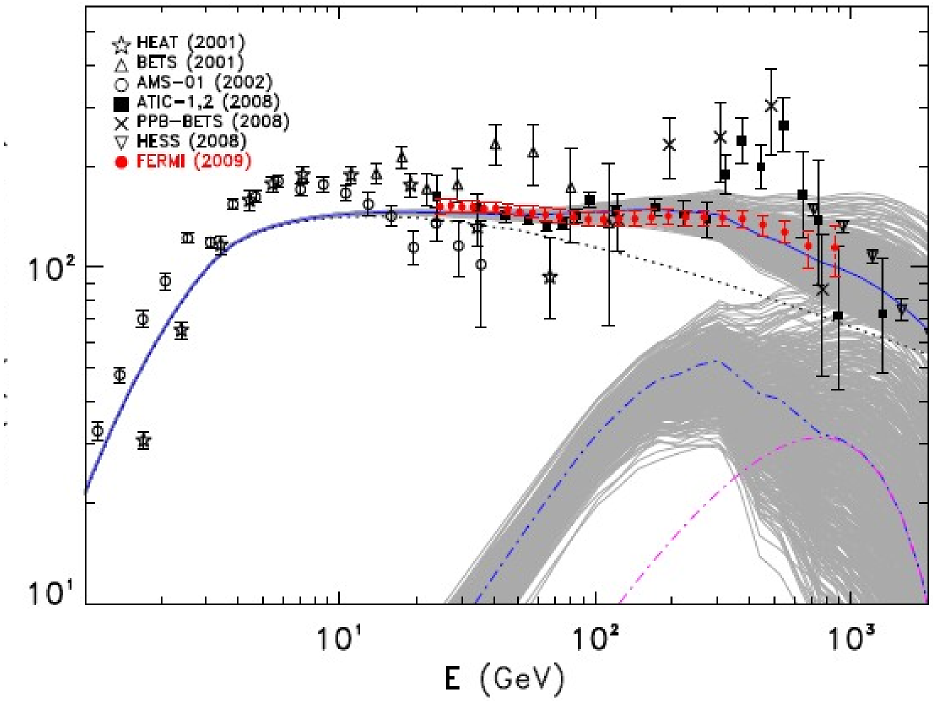
Nice agreement. However, it is not a prediction!

- $dN_e/dE_e \propto E_e^{-1.7} \exp(-E_e/1100\ \mathrm{GeV})$
- 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

More later about

the dark matter explanations to

the electron/positron excesses

Gamma rays

Production of gamma-rays

The gamma ray flux from dark matter annihilation/decay 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

Production rate of gamma rays due to IC scattering of $e^{\pm}$ on the ISRF:

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

$$\frac{dR_{\gamma}^{\mathrm{IC}}(\vec{r})}{dE_{\gamma}} = \int_{0}^{\infty} d\epsilon \int_{m_e}^{\infty} dE_e \, \frac{d\sigma^{\mathrm{IC}}(E_e, \epsilon)}{dE_{\gamma}} f_{e^{\pm}}(E_e, \vec{r}) f_{\mathrm{ISRF}}(\epsilon, \vec{r})$$

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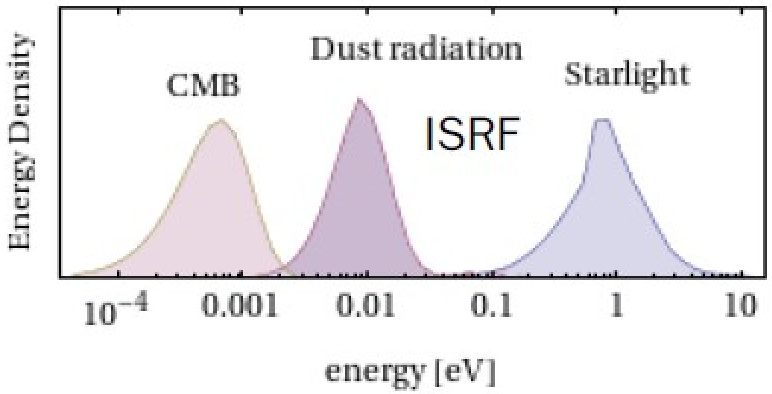
Number density of photons of the ISRF



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Number density of electrons/positrons.
$\rightarrow$ Transport equation.

$$0 = \frac{\partial f_{e^\pm}}{\partial t} = \nabla \cdot [K(E_e,\vec{r})\nabla f_{e^\pm}] + \frac{\partial}{\partial E_e}[b(E_e,\vec{r}) f_{e^\pm}] - \nabla \cdot [\vec{V}_c(\vec{r}) f_{e^\pm}] - 2h\delta(z)\Gamma_{\rm ann} f_{e^\pm} + Q_{\rm DM}(E_e,\vec{r})$$

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For electrons with E>10 GeV, the transport equation is dominated by the energy loss term. Therefore

$$f_{e^\pm}(E_e,\vec{r}) \simeq \frac{1}{b(E_e,\vec{r})}\int_{E_e}^\infty Q_{\rm DM}(E'_e,\vec{r})\, dE'_e = \begin{cases} \dfrac{1}{b(E_e,\vec{r})}\displaystyle\int_{E_e}^\infty \frac{\rho(\vec{r})^2\langle\sigma_{\rm ann} v\rangle}{2m^2_{\rm DM}}\frac{dN_e}{dE'_e}\, dE'_e \\ \dfrac{1}{b(E_e,\vec{r})}\displaystyle\int_{E_e}^\infty \frac{\rho(\vec{r})}{\tau_{\rm DM}\, m_{\rm DM}}\frac{dN_e}{dE'_e}\, dE'_e \end{cases}$$

with $b(E_e,\vec{r}) \simeq 10^{-16} E_e^2 ({\rm GeV})\, {\rm s}^{-1}$

Production rate of gamma rays due to IC scattering of $e^{\pm}$ on the ISRF:

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

$$\frac{dR_\gamma^{\rm IC}(\vec{r})}{dE_\gamma} = \int_0^\infty d\epsilon \int_{m_e}^\infty dE_e \, \frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} f_{e^\pm}(E_e,\vec{r}) f_{\rm ISRF}(\epsilon,\vec{r})$$

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

σ_T=0.67 barn ⟶ Compton scattering cross section in the Thomson limit.

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

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

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

Production rate of gamma rays due to IC scattering of $e^{\pm}$ on the ISRF:

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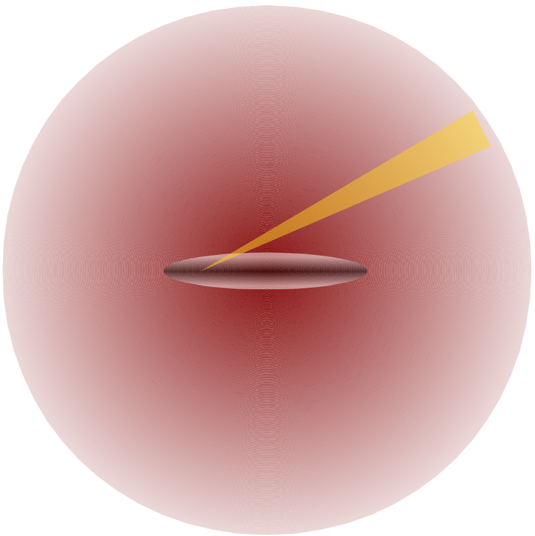
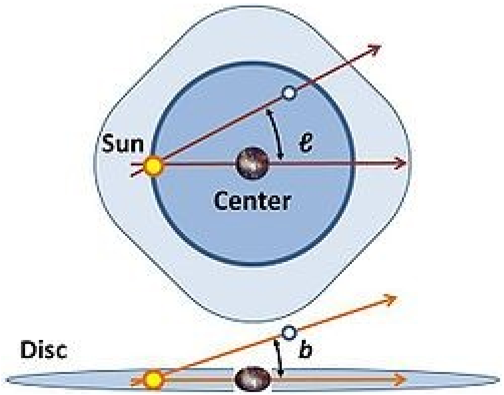
Finally, the differential flux in the direction (l, b)



$$\frac{dJ_{\text{halo-IC}}}{dE_{\gamma}}(l, b) = 2 \times \frac{1}{4\pi} \int_{0}^{\infty} ds \, \frac{dR_{\gamma}^{\mathrm{IC}}[r(s, l, b)]}{dE_{\gamma}}$$

$$r(s, l, b) = \sqrt{s^2 + R_{\odot}^2 - 2 s R_{\odot} \cos b \cos l}$$



Prompt radiation

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

Halo component

Extragalactic component

Prompt radiation

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

Halo component

Annihilation

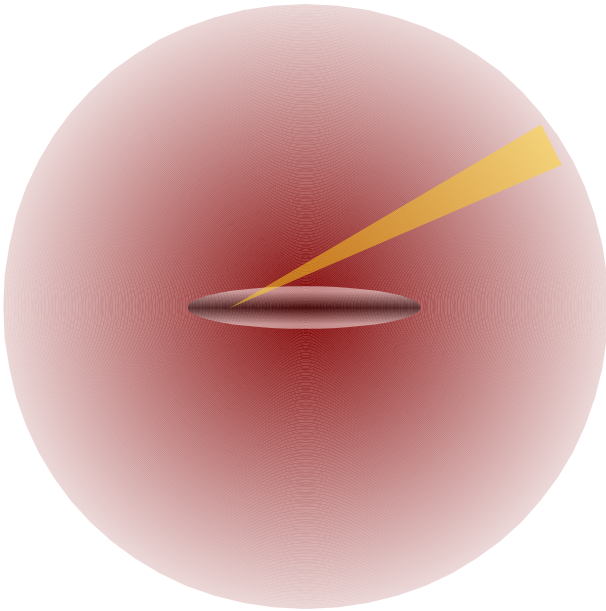
$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right] \times \int_{\rm l.o.s.} \rho^2(\vec{l})\,d\vec{l}$$

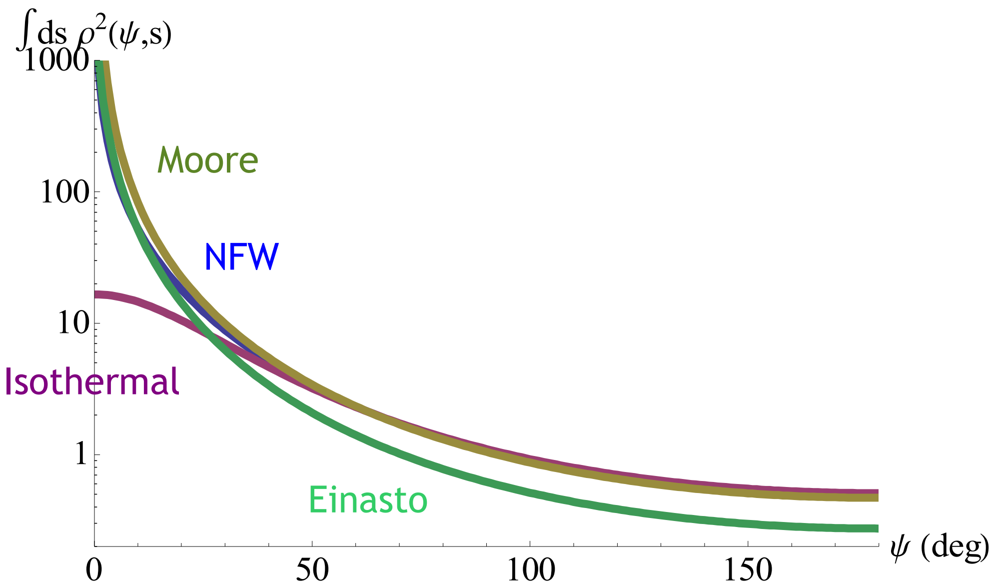
Source term (particle physics)

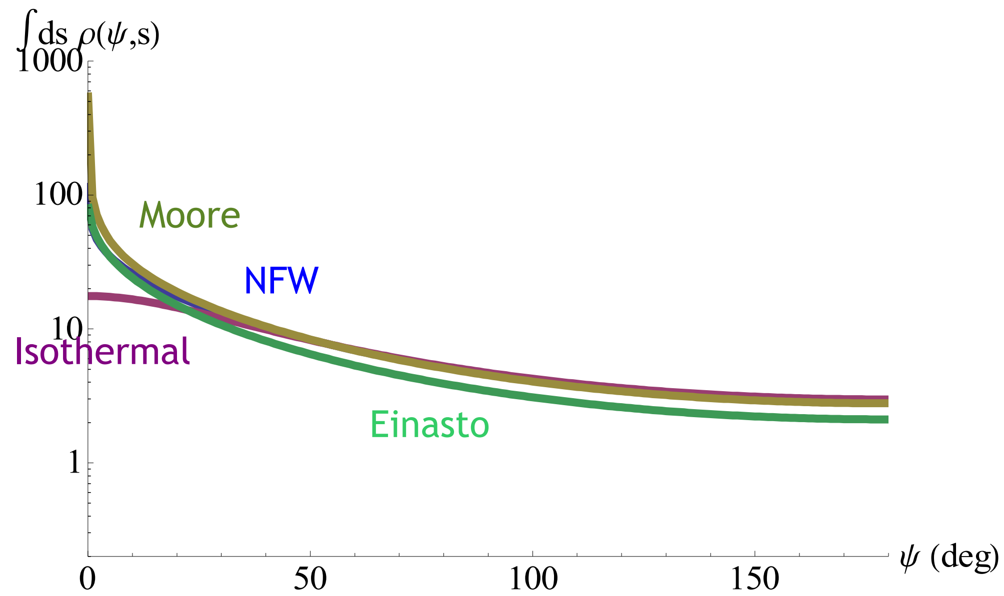
Line-of-sight integral (astrophysics)

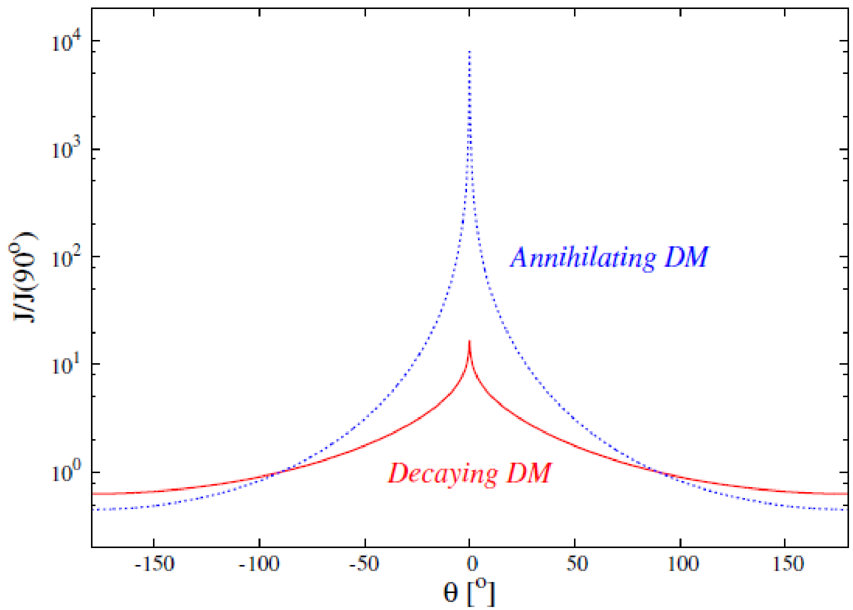
Decay

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







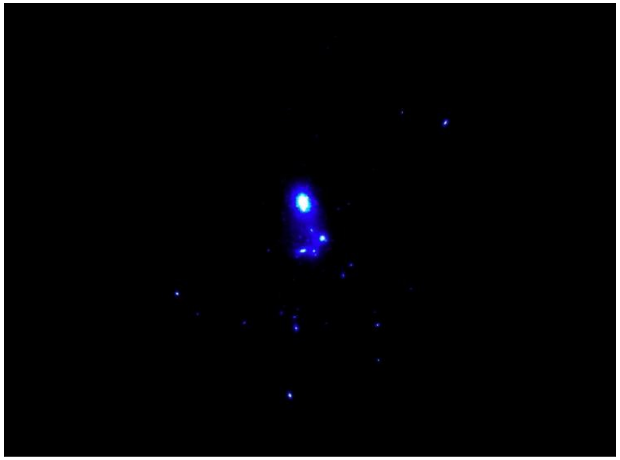


Bertone, Buchmüller, Covi, AI
arXiv:0709.2299

Prompt radiation: Effect of substructures

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

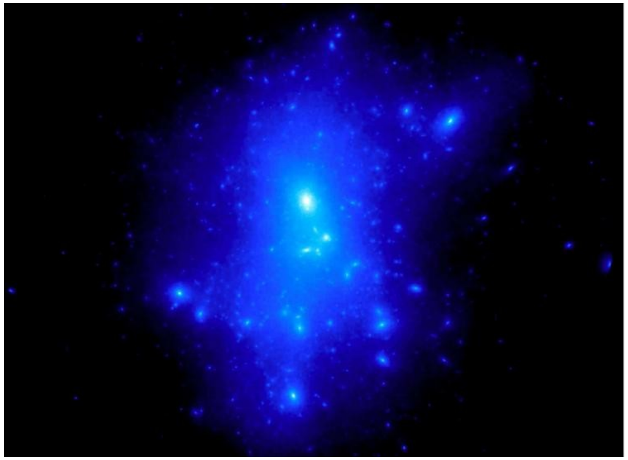
Halo component



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

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

Halo component

Summary:

- Depends on the dark matter profile. Strong dependence in the direction of the galactic center and mild at high latitudes ($|b|>10^\circ$)
- Even if the profile is spherically symmetric, the flux at Earth depends on the direction of observation.

Prompt radiation

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

Extragalactic component

- Isotropic

Prompt radiation

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

Extragalactic component

- Isotropic
- Redshifted

Annihilation

$$\frac{dJ_{\rm eg}}{dE_\gamma} = \frac{c}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2}\frac{\Omega^2_{\rm DM}\rho^2_{\rm c}}{m^2_{\rm DM}}\int_0^\infty dz\frac{1}{H(z)}\frac{dN_\gamma\left[(1+z)E_\gamma\right]}{dE_\gamma}\,e^{-\tau(E_\gamma,z)}$$

Decay

$$\frac{dJ_{\rm eg}}{dE_\gamma} = \frac{c}{4\pi}\frac{\Omega_{\rm DM}\rho_{\rm c}}{m_{\rm DM}\tau_{\rm DM}}\int_0^\infty dz\frac{1}{H(z)}\frac{dN_\gamma\left[(1+z)E_\gamma\right]}{dE_\gamma}\,e^{-\tau(E_\gamma,z)}$$

12.8 Gyr ago

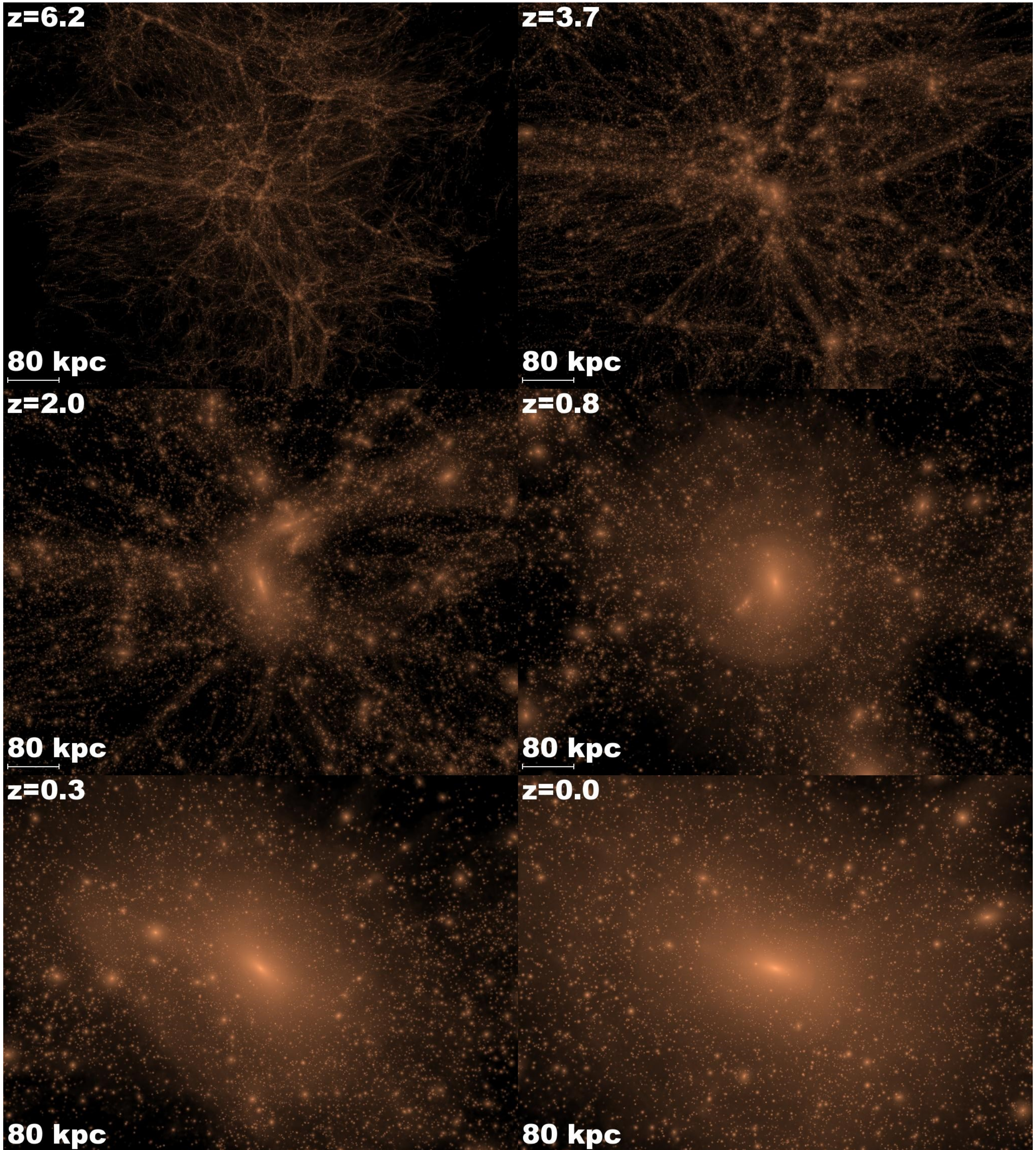
12 Gyr ago

10.3 Gyr ago

6.8 Gyr ago

3.4 Gyr ago

Now



Prompt radiation

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

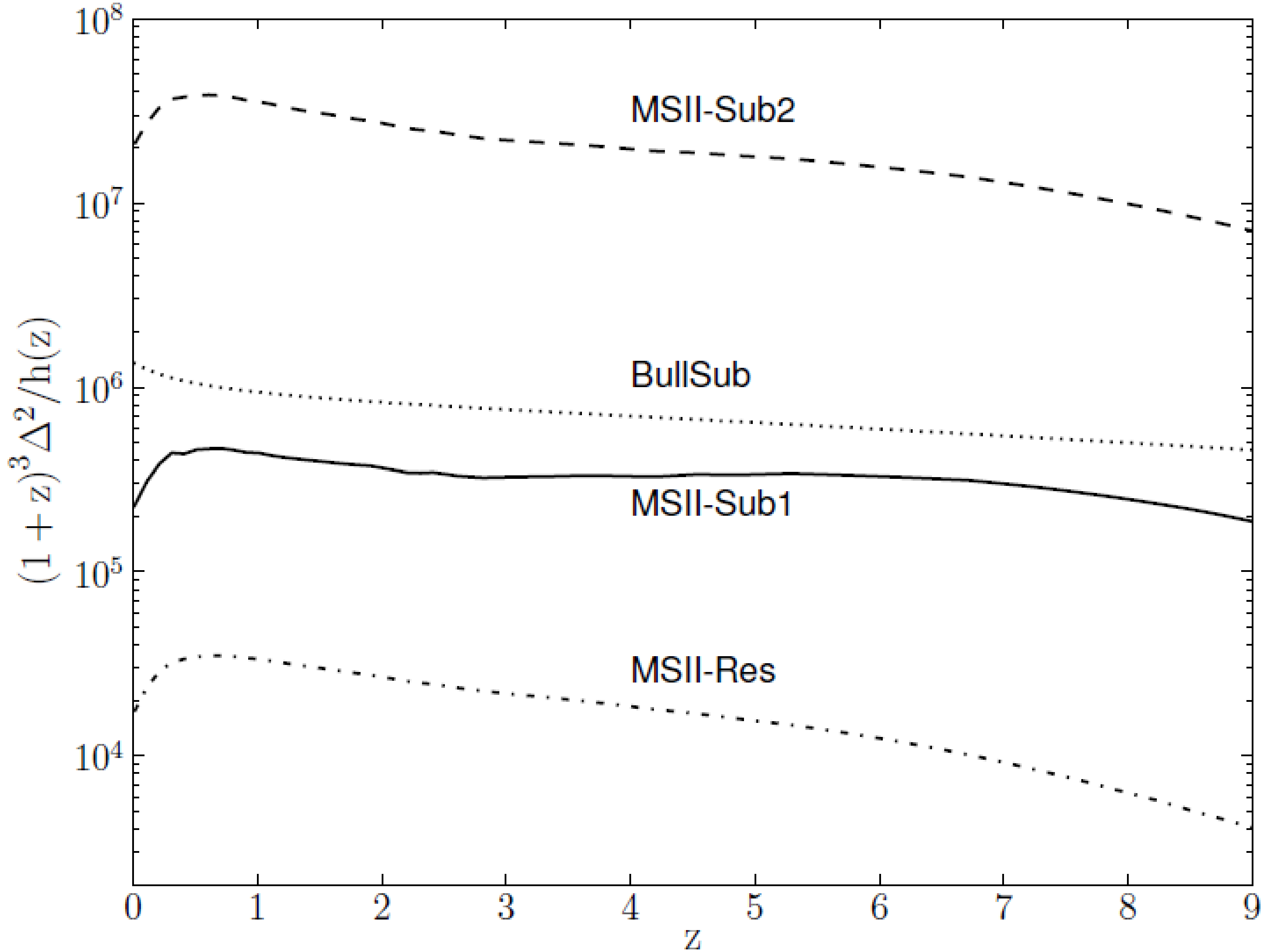
Extragalactic component

- Isotropic
- Redshifted

Enhancement

Annihilation $$\frac{dJ_{\rm eg}}{dE_\gamma} = \frac{c}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2}\frac{\Omega^2_{\rm DM}\rho_c^2}{m^2_{\rm DM}}\int_0^\infty dz\frac{1}{H(z)}\frac{dN_\gamma\left[(1+z)E_\gamma\right]}{dE_\gamma}(1+z)^3\Delta^2(z)\; e^{-\tau(E_\gamma,z)}$$

Decay $$\frac{dJ_{\rm eg}}{dE_\gamma} = \frac{c}{4\pi}\frac{\Omega_{\rm DM}\rho_c}{m_{\rm DM}\tau_{\rm DM}}\int_0^\infty dz\frac{1}{H(z)}\frac{dN_\gamma\left[(1+z)E_\gamma\right]}{dE_\gamma}\; e^{-\tau(E_\gamma,z)}$$



Fermi coll.
arXiv:1002.4415

Prompt radiation

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

Extragalactic component

- Isotropic
- Redshifted
- Attenuated due to pair production $\gamma\gamma \rightarrow e^+e^-$

Annihilation $$\frac{dJ_{\rm eg}}{dE_\gamma} = \frac{c}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2}\frac{\Omega_{\rm DM}^2\rho_{\rm c}^2}{m_{\rm DM}^2}\int_0^\infty dz \frac{1}{H(z)}\frac{dN_\gamma\left[(1+z)E_\gamma\right]}{dE_\gamma}(1+z)^3\Delta^2(z)\, e^{-\tau(E_\gamma,z)}$$

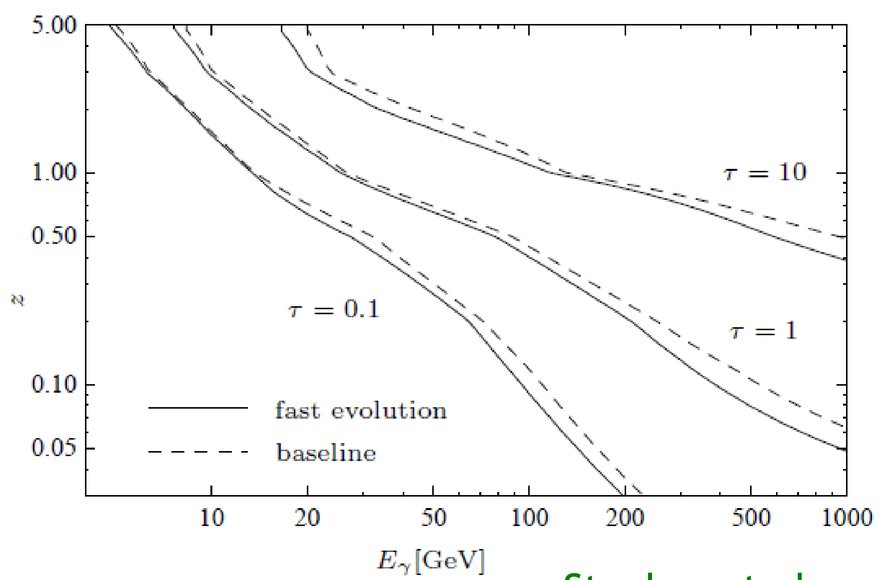
Decay $$\frac{dJ_{\rm eg}}{dE_\gamma} = \frac{c}{4\pi}\frac{\Omega_{\rm DM}\rho_{\rm c}}{m_{\rm DM}\tau_{\rm DM}}\int_0^\infty dz \frac{1}{H(z)}\frac{dN_\gamma\left[(1+z)E_\gamma\right]}{dE_\gamma}\, e^{-\tau(E_\gamma,z)}$$

Prompt radiation

$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

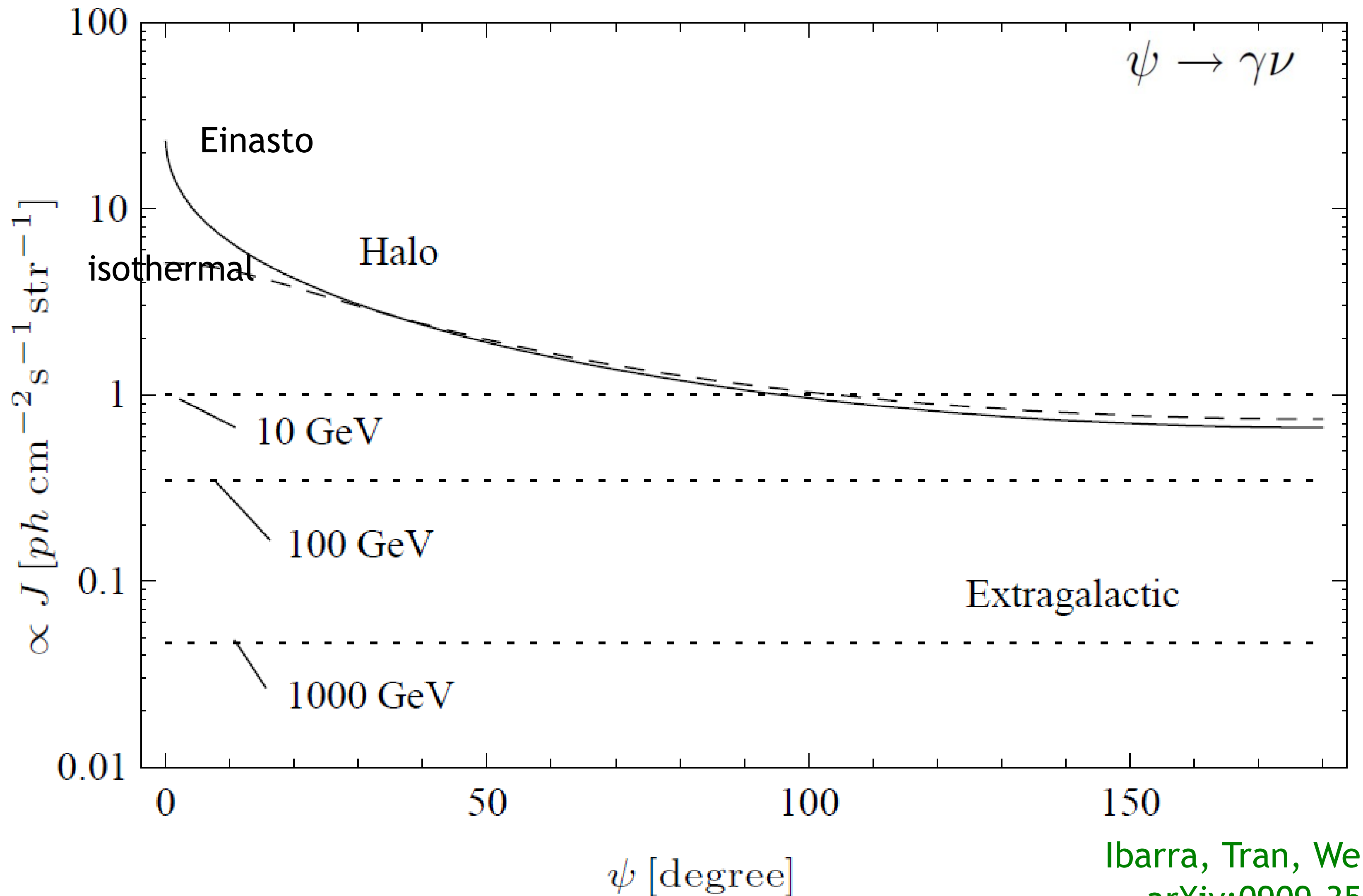
Extragalactic component

- Isotropic
- Redshifted
- Attenuated due to pair production $\gamma\gamma \rightarrow e^+e^-$



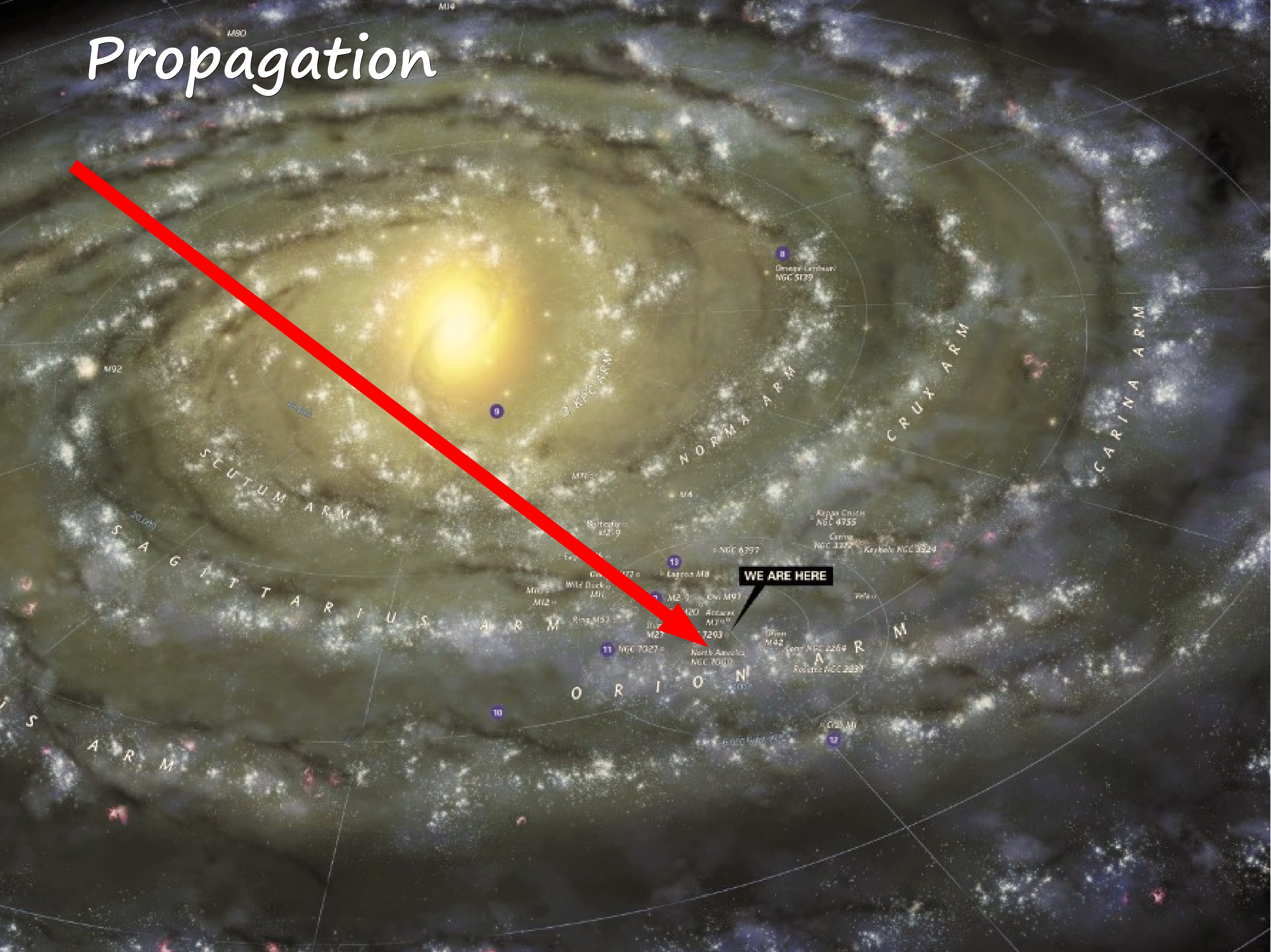
Stecker et al.

Impact of attenuation: decaying dark matter



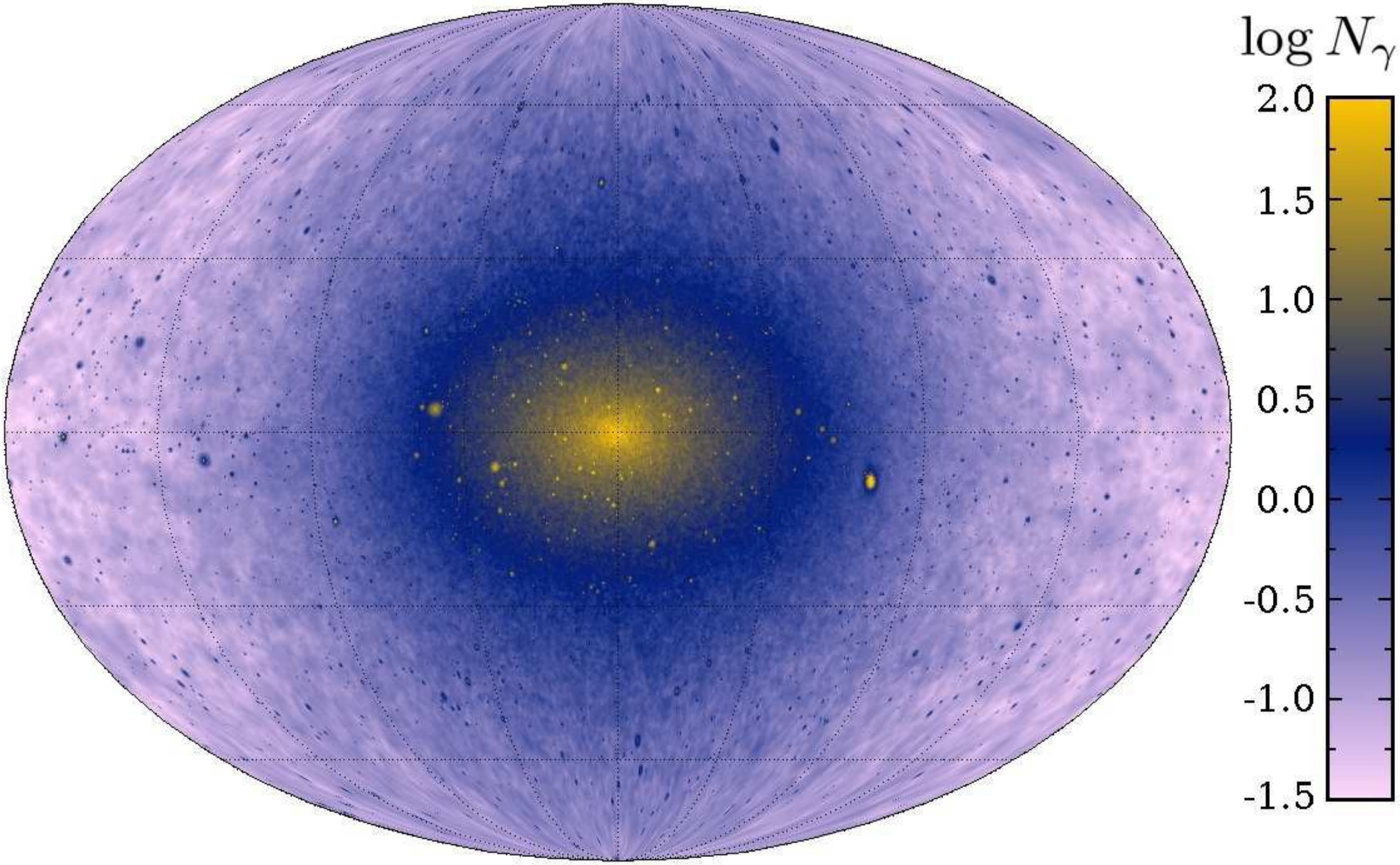
Ibarra, Tran, Weniger
arXiv:0909.3514

Propagation



Where to look for annihilating dark matter

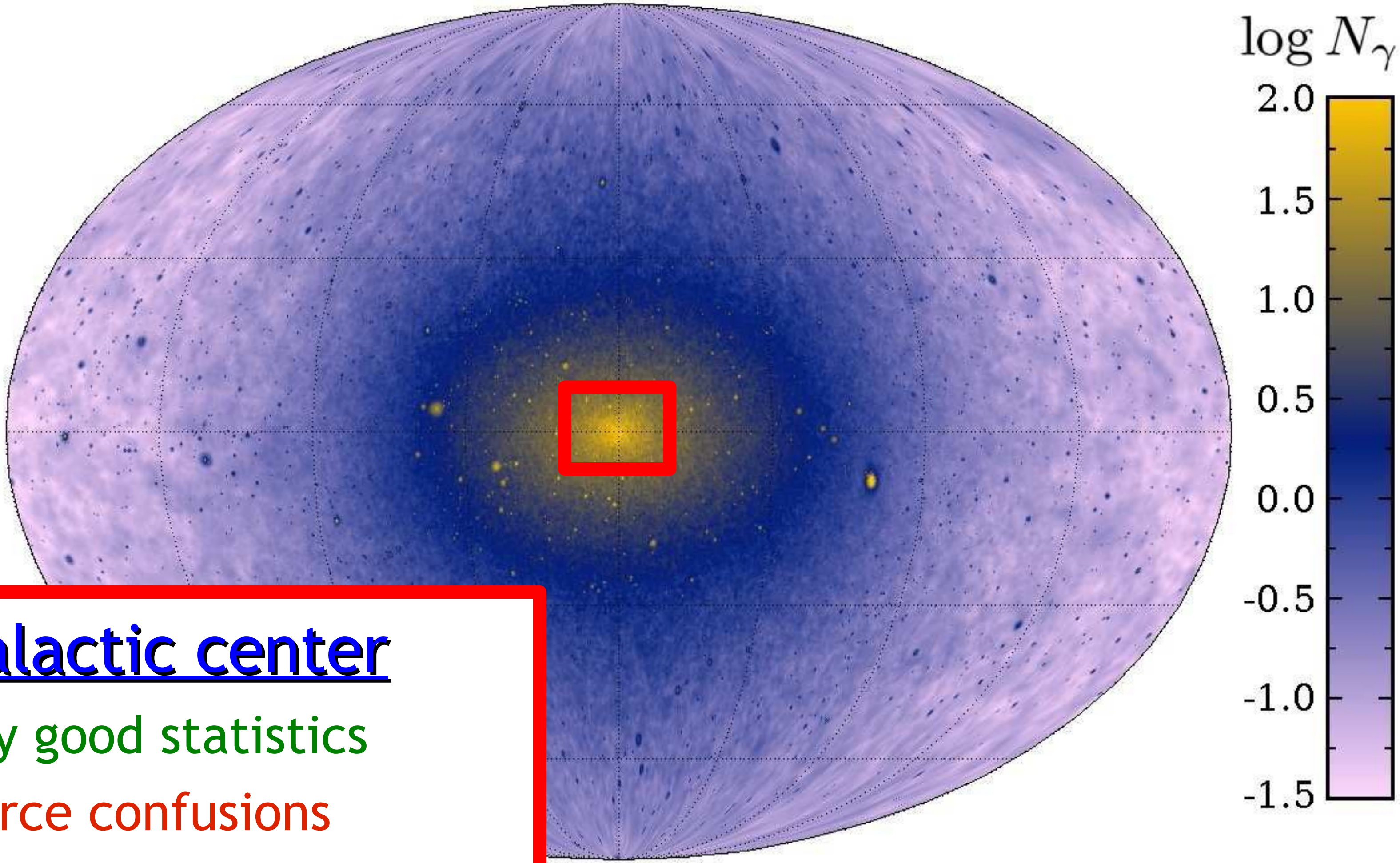
Baltz et al.
arXiv:0806.2911



Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al. arXiv:0806.2911



Kuhlen, Diemand, Madau

Galactic center

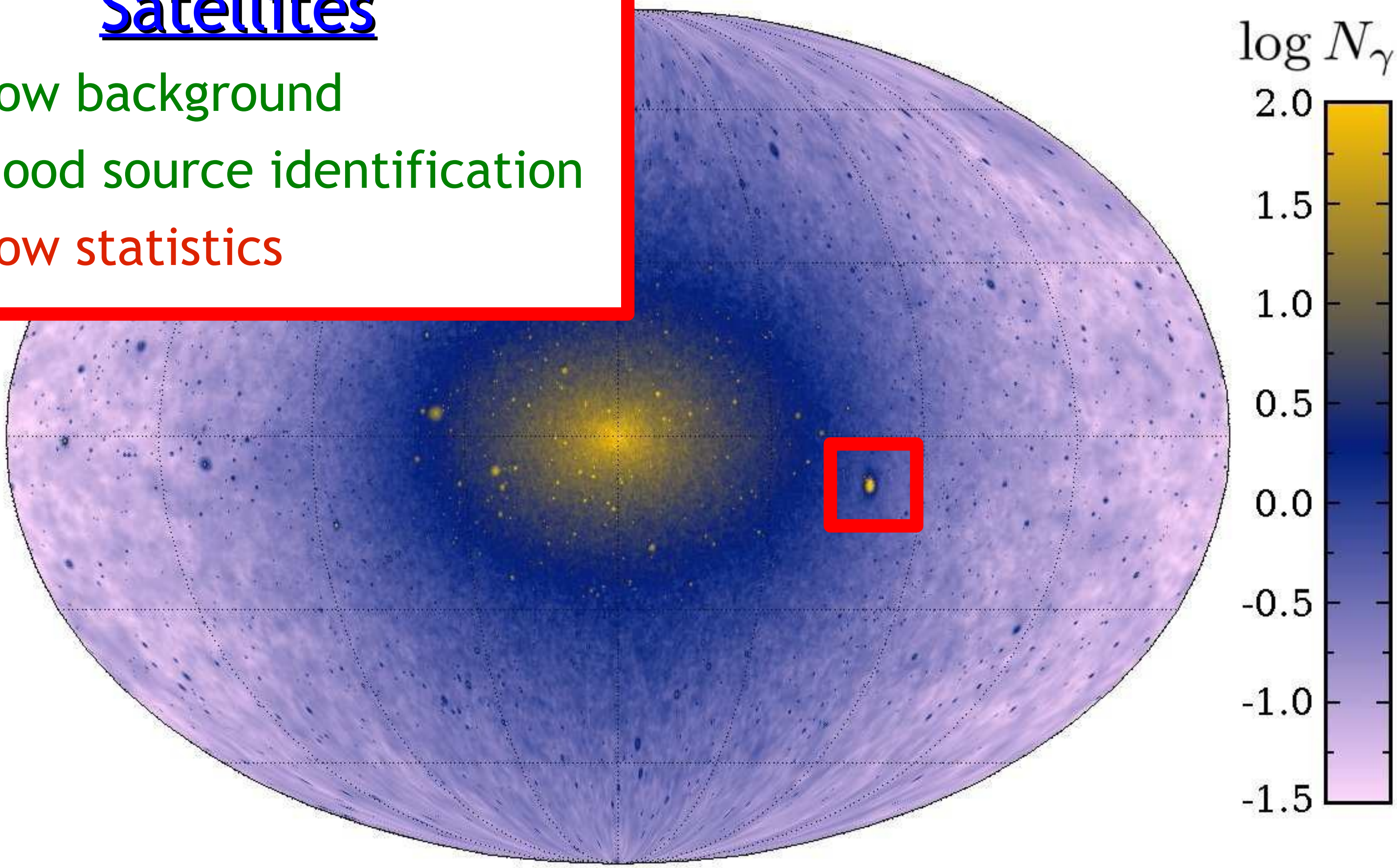
- Very good statistics
- Source confusions
- Uncertainties in diffuse background modelling

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911

Satellites

- Low background
- Good source identification
- Low statistics



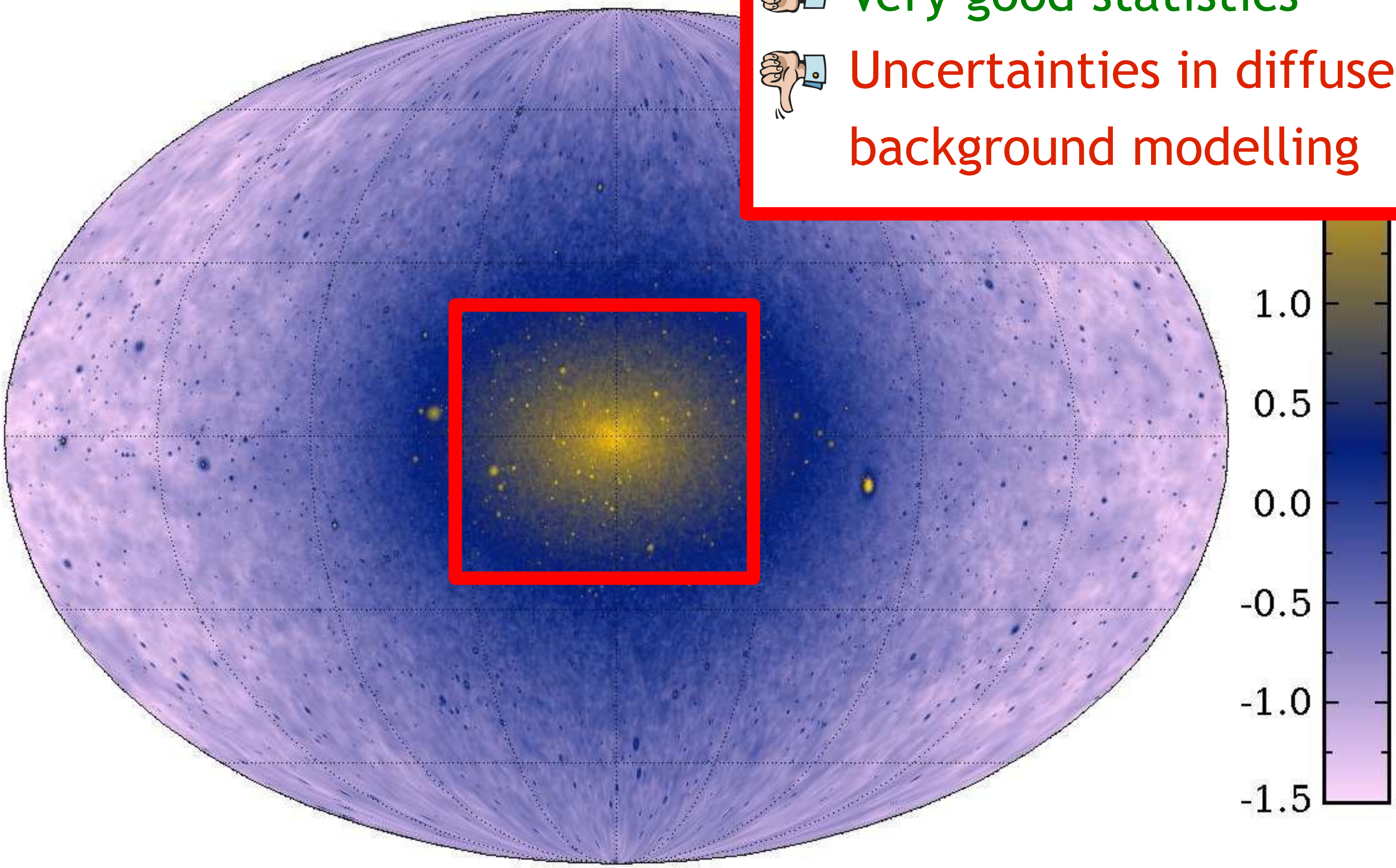
Kuhlen, Diemand, Madau

Where to look for *annihilating* dark matter

Baltz et al.
arXiv:0806.2911

Galactic halo

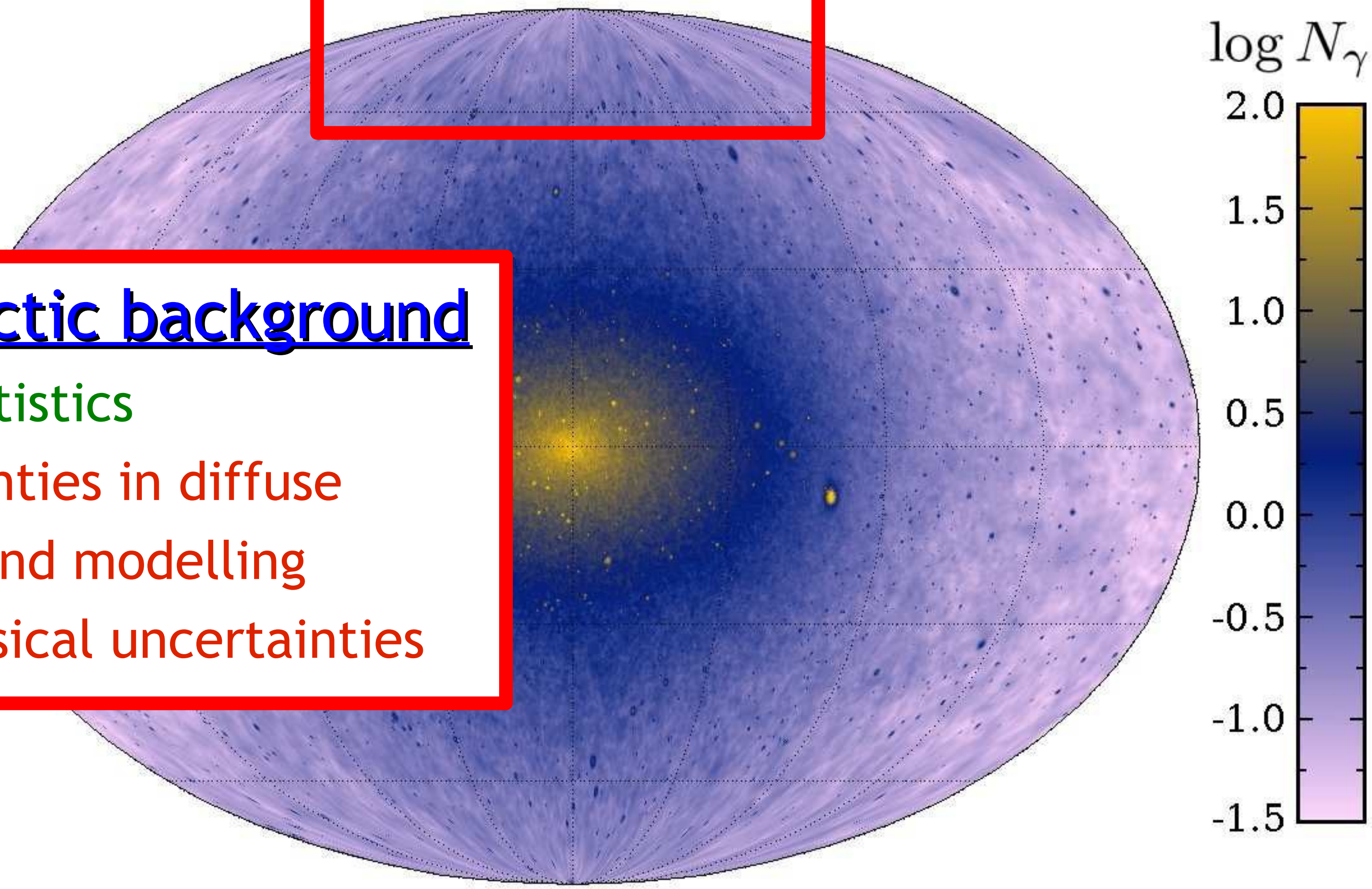
- Very good statistics
- Uncertainties in diffuse background modelling



Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911



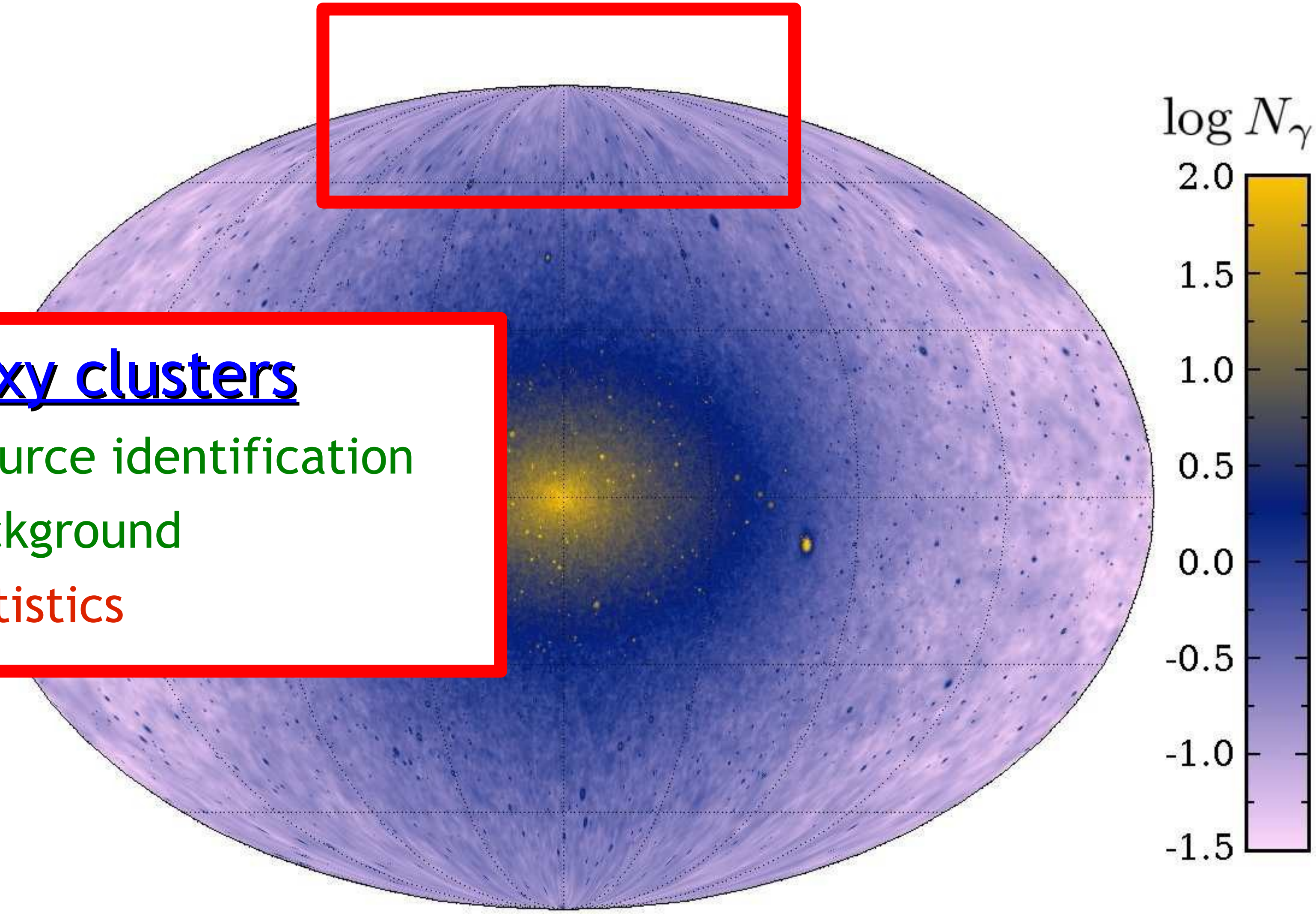
Extragalactic background

- Good statistics
- Uncertainties in diffuse background modelling
- Astrophysical uncertainties

Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911



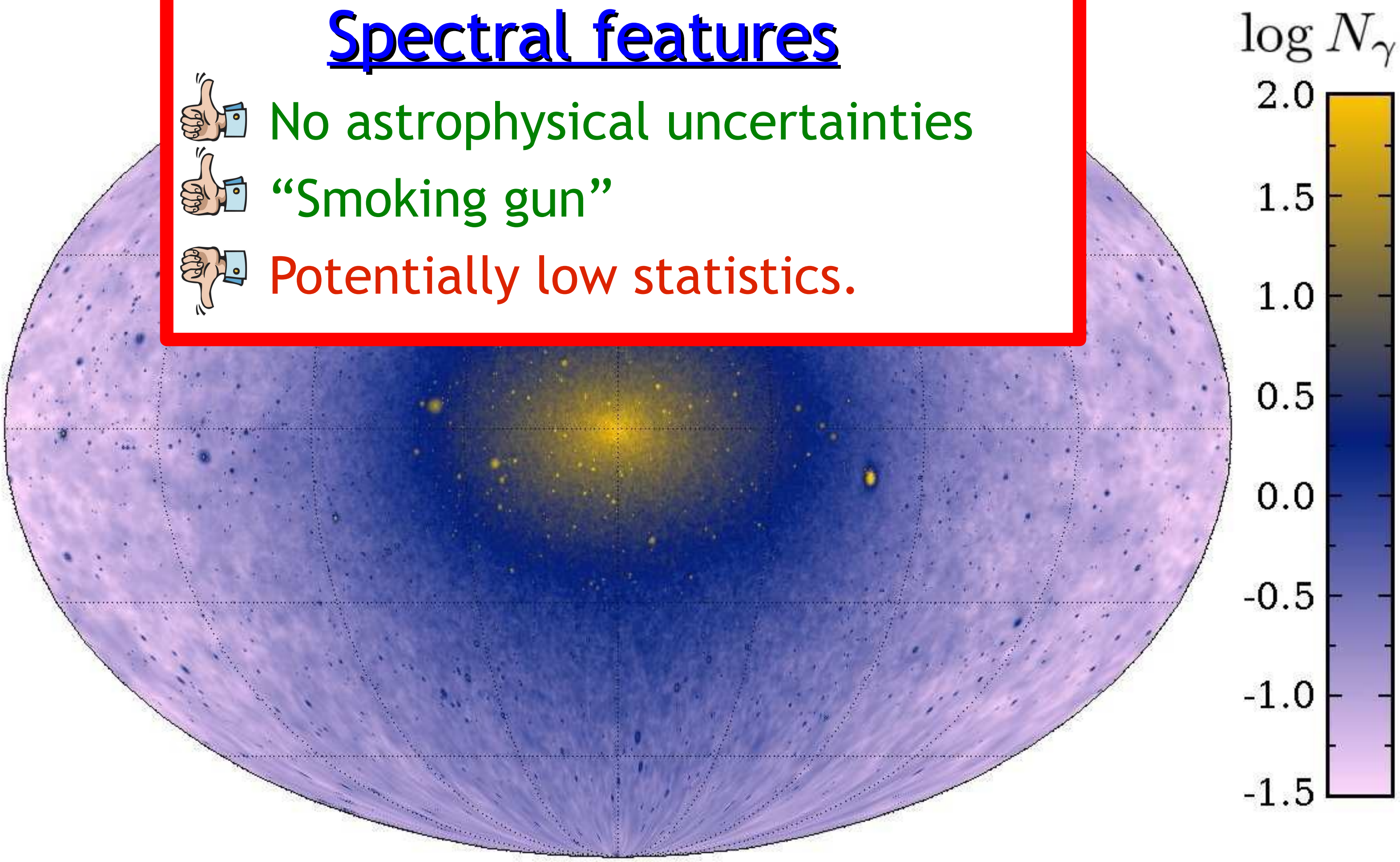
Galaxy clusters

- 👍 Good source identification
- 👍 Low background
- 👎 Low statistics

Kuhlen, Diemand, Madau

Where to look for *annihilating* dark matter

Baltz et al.
arXiv:0806.2911



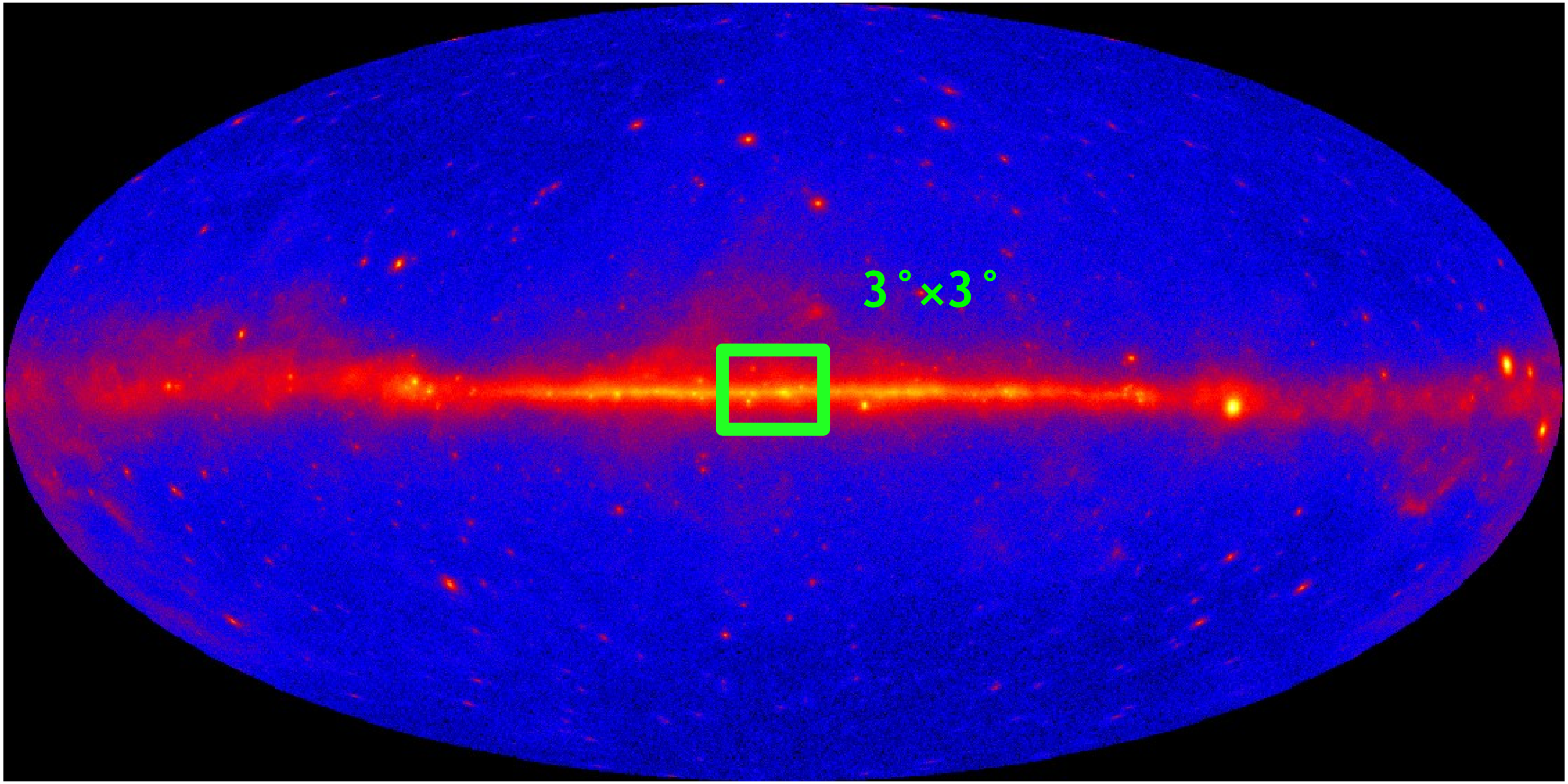
Spectral features

- 👍 No astrophysical uncertainties
- 👍 "Smoking gun"
- 👎 Potentially low statistics.

Kuhlen, Diemand, Madau

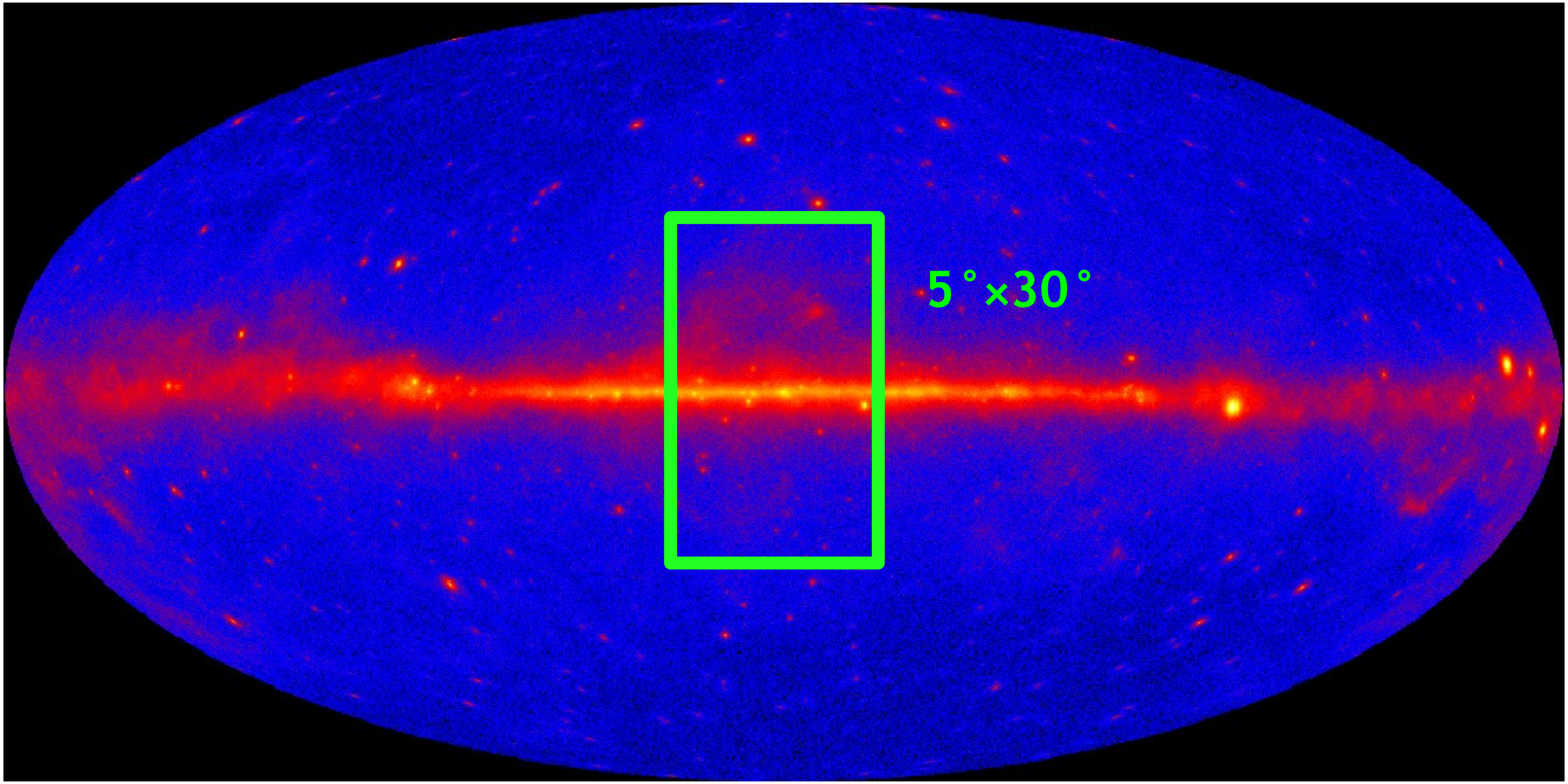
Diffuse Galactic emission

Divide the sky in different regions:



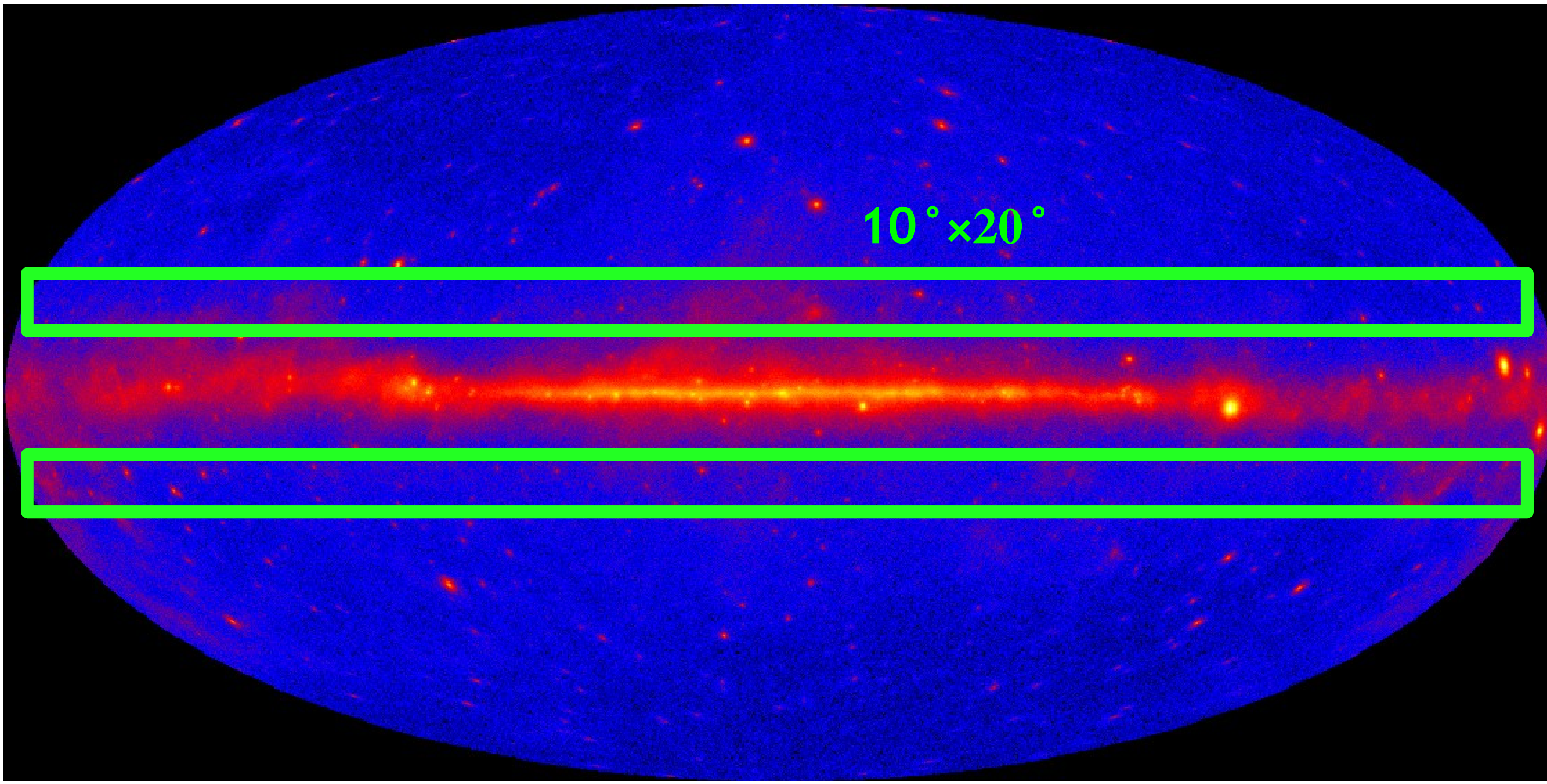
Diffuse Galactic emission

Divide the sky in different regions:



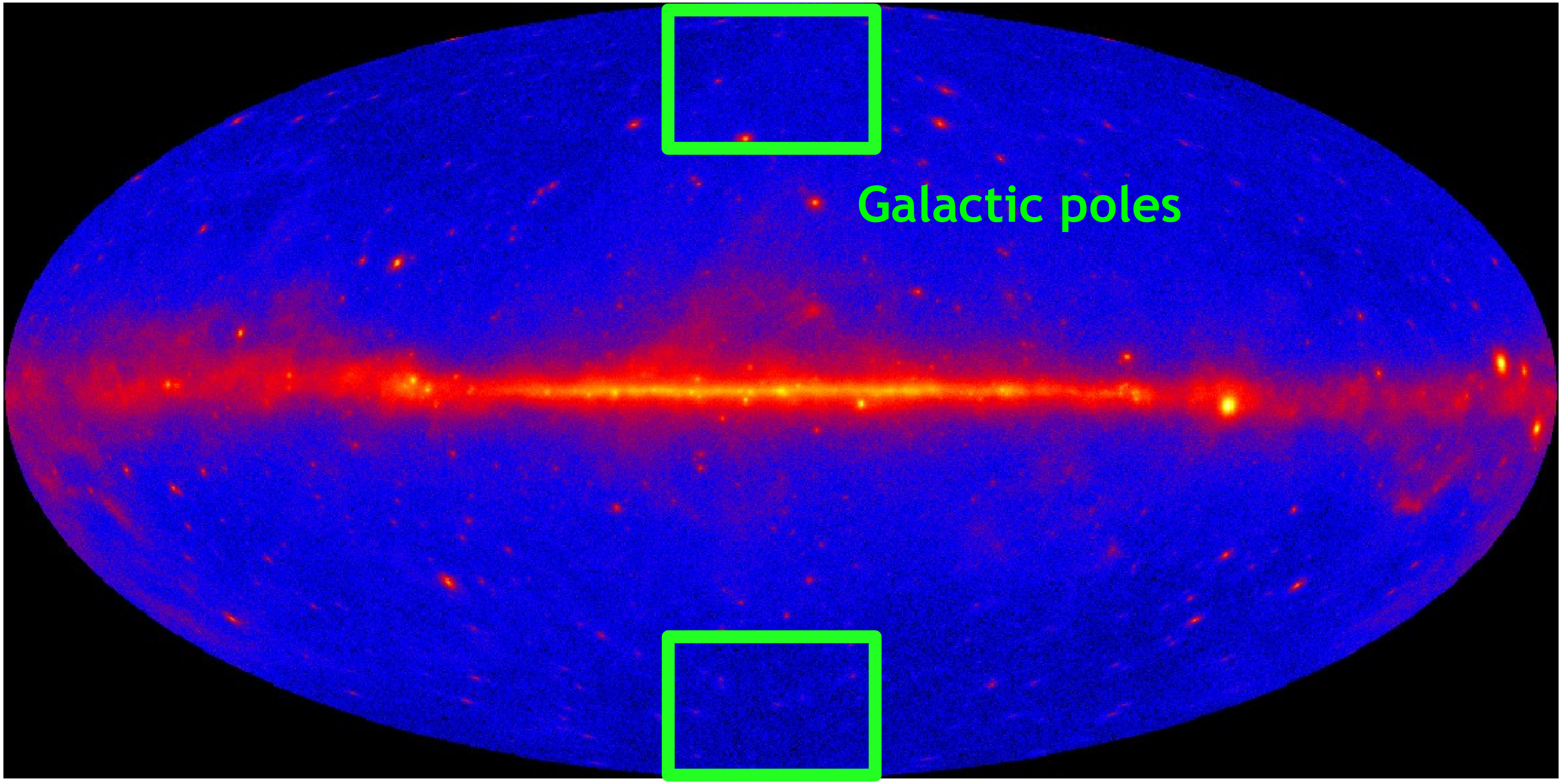
Diffuse Galactic emission

Divide the sky in different regions:



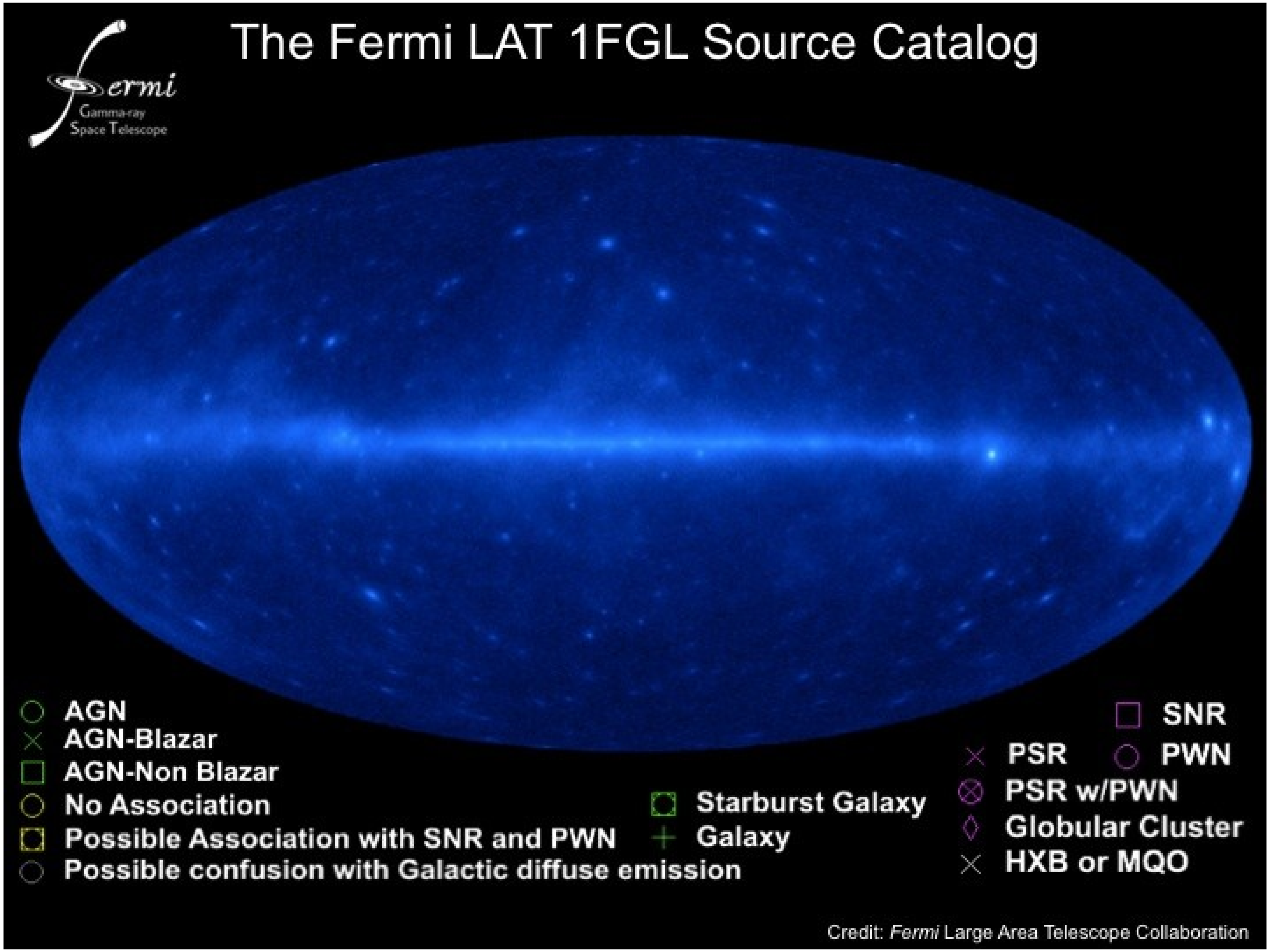
Diffuse Galactic emission

Divide the sky in different regions:

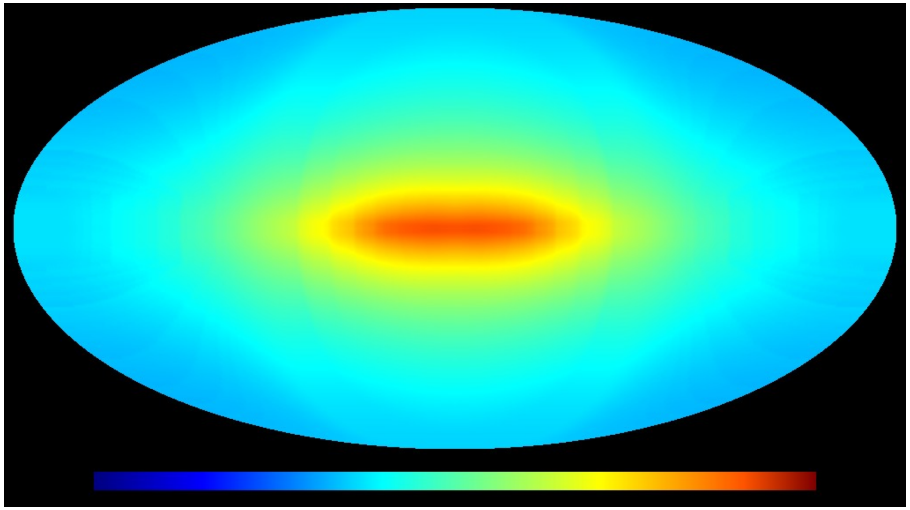


But beware of backgrounds when searching for dark matter...

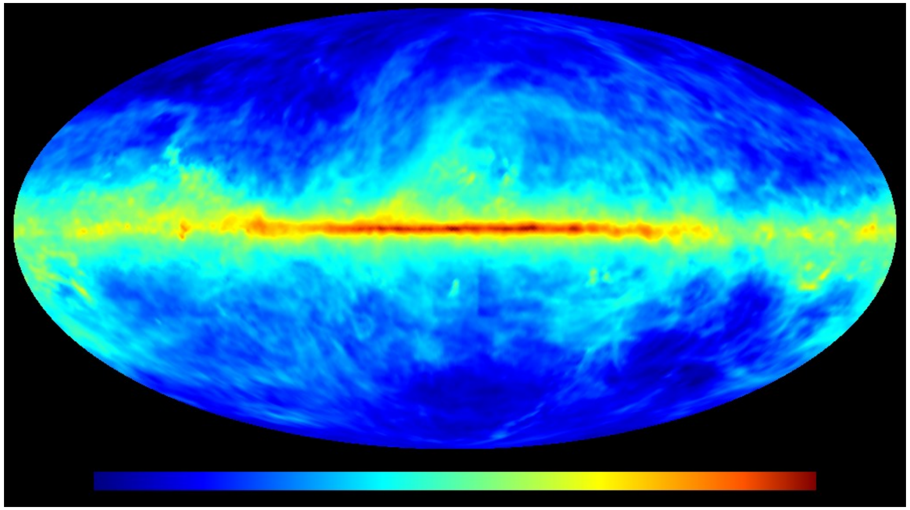
Background I: sources



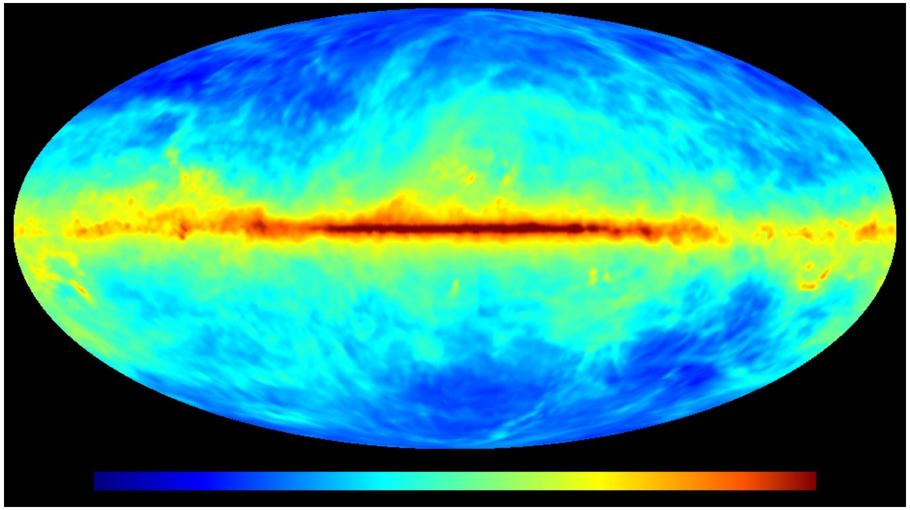
Background II: modelling of the diffuse emission



Inverse compton

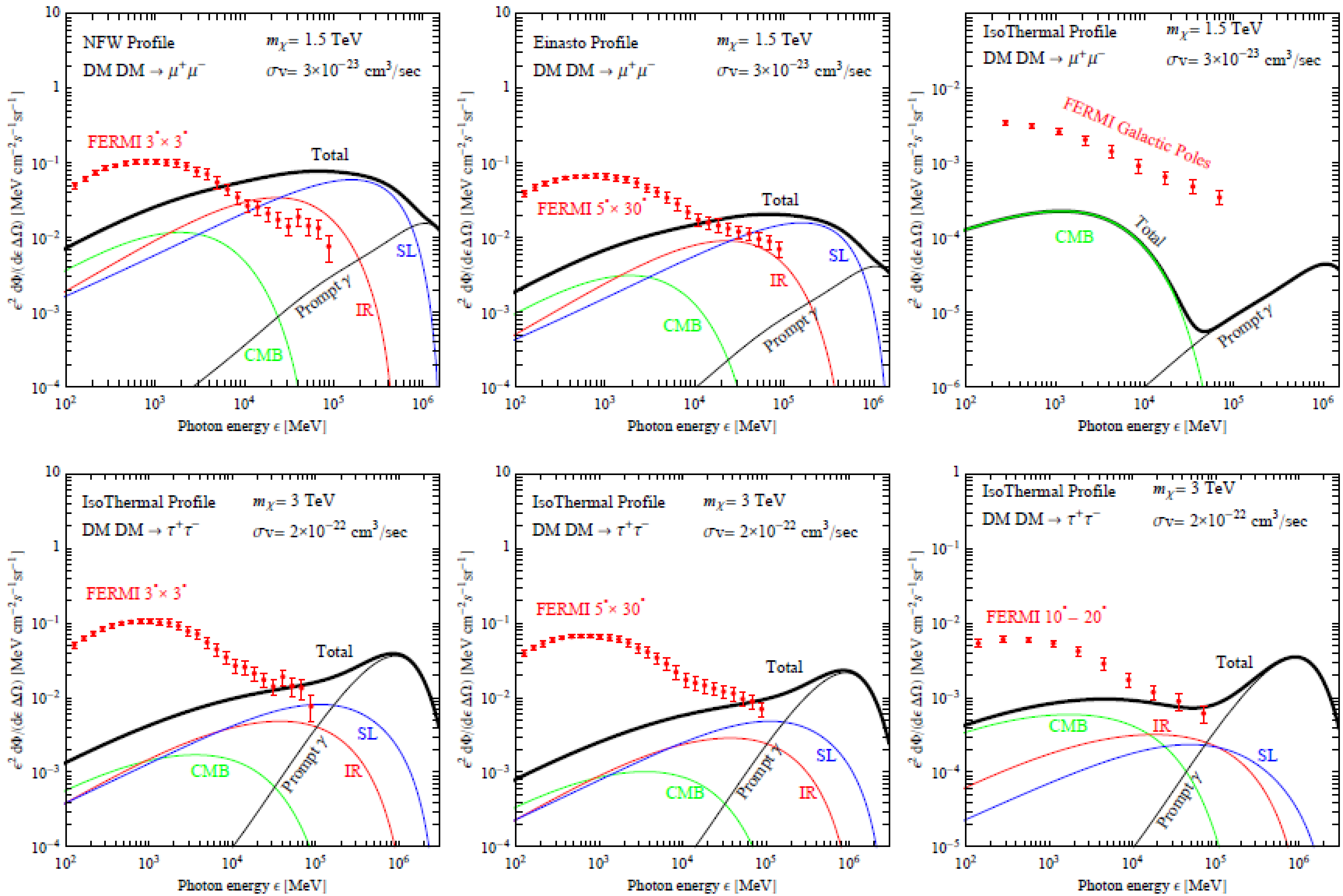


bremmstrahlung



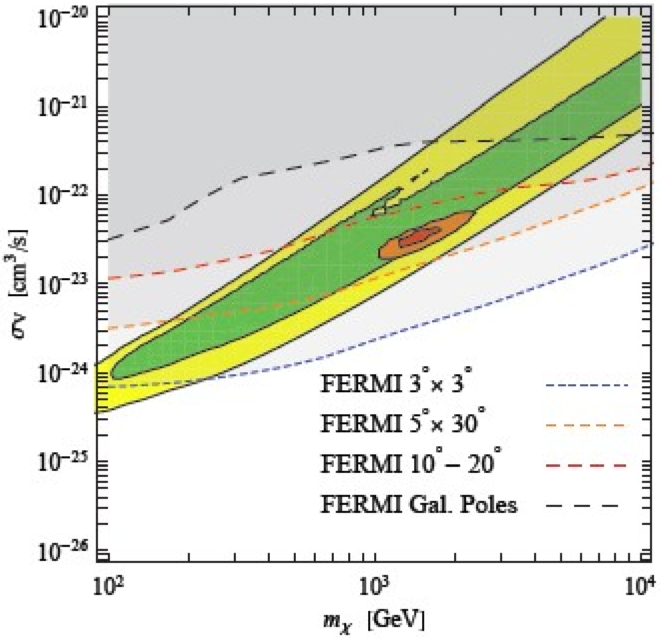
π^0-decay

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

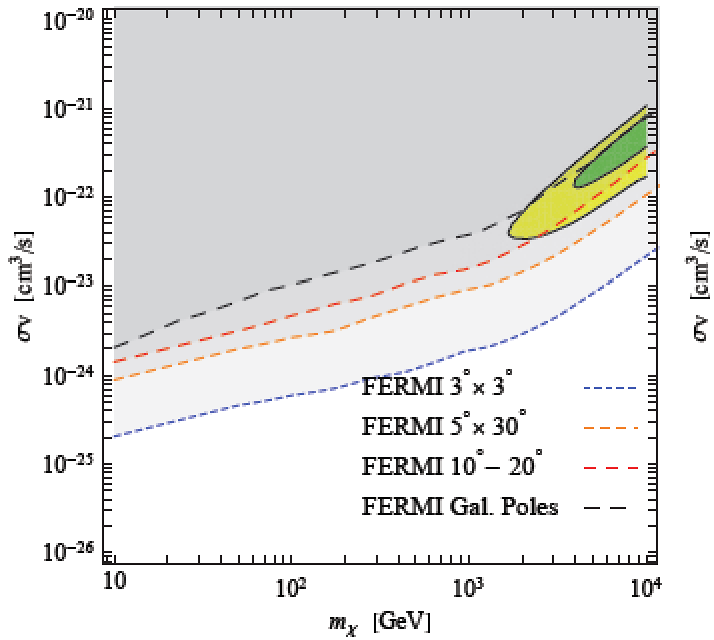


Cirelli, Panci, Serpico

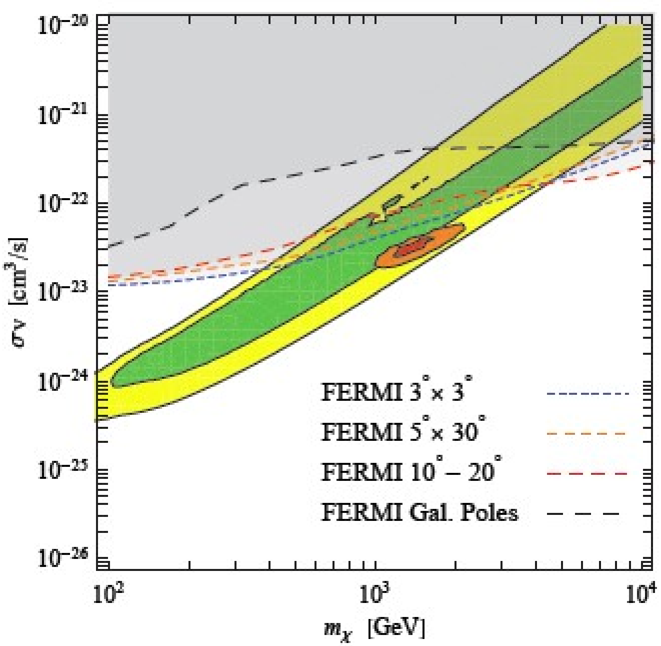
DM DM → $\mu\mu$, Einasto profile



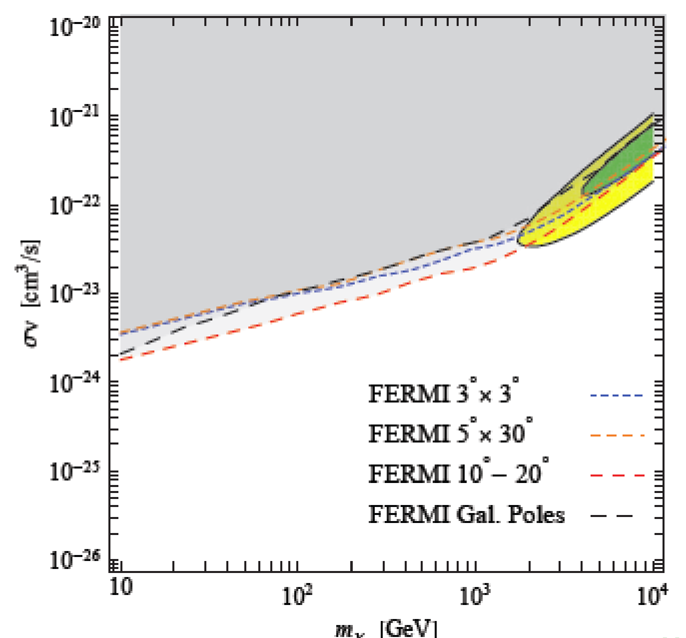
DM DM → bb, Einasto profile



DM DM → $\mu\mu$, Iso profile

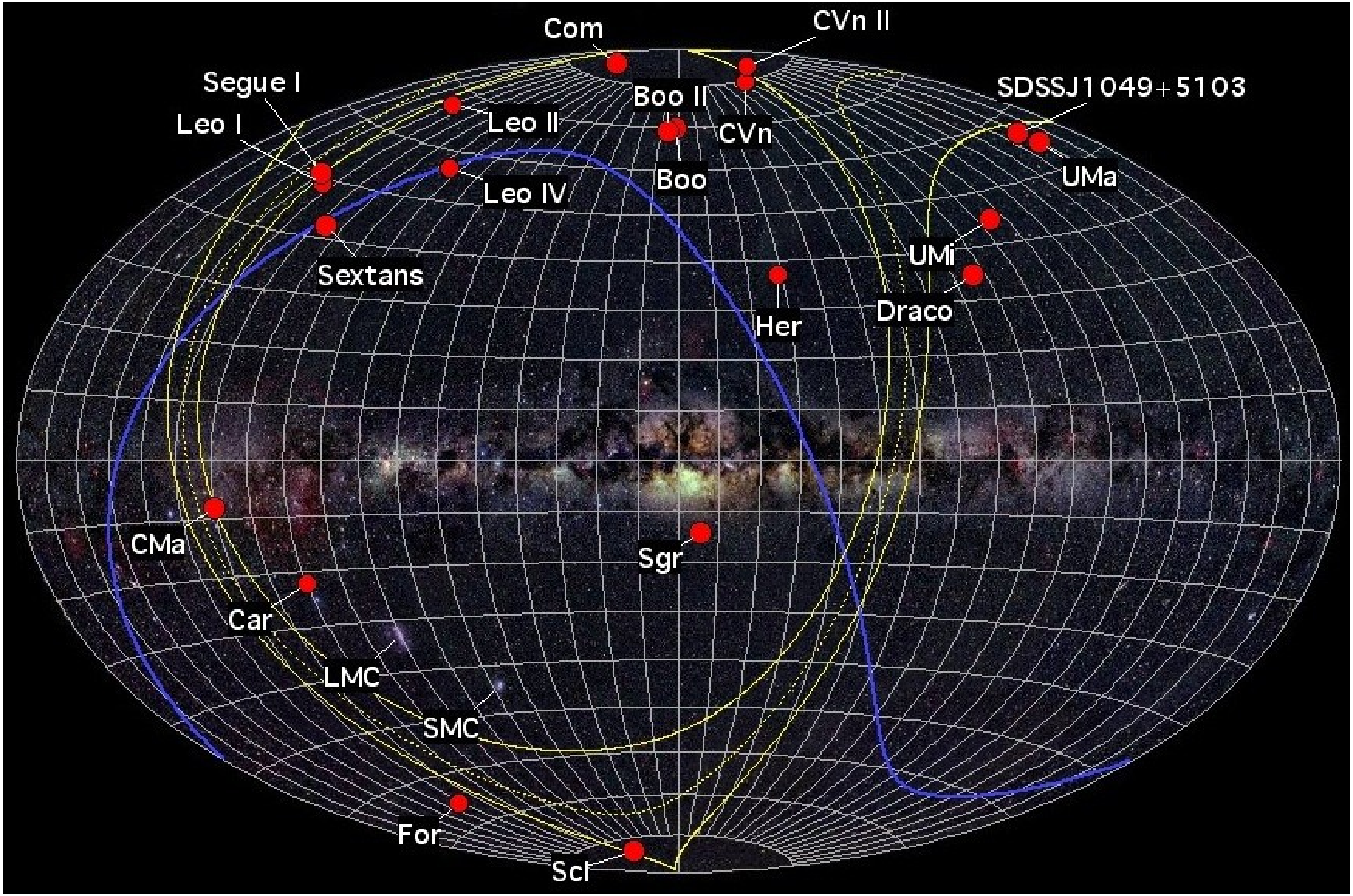


DM DM → bb, Iso profile



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

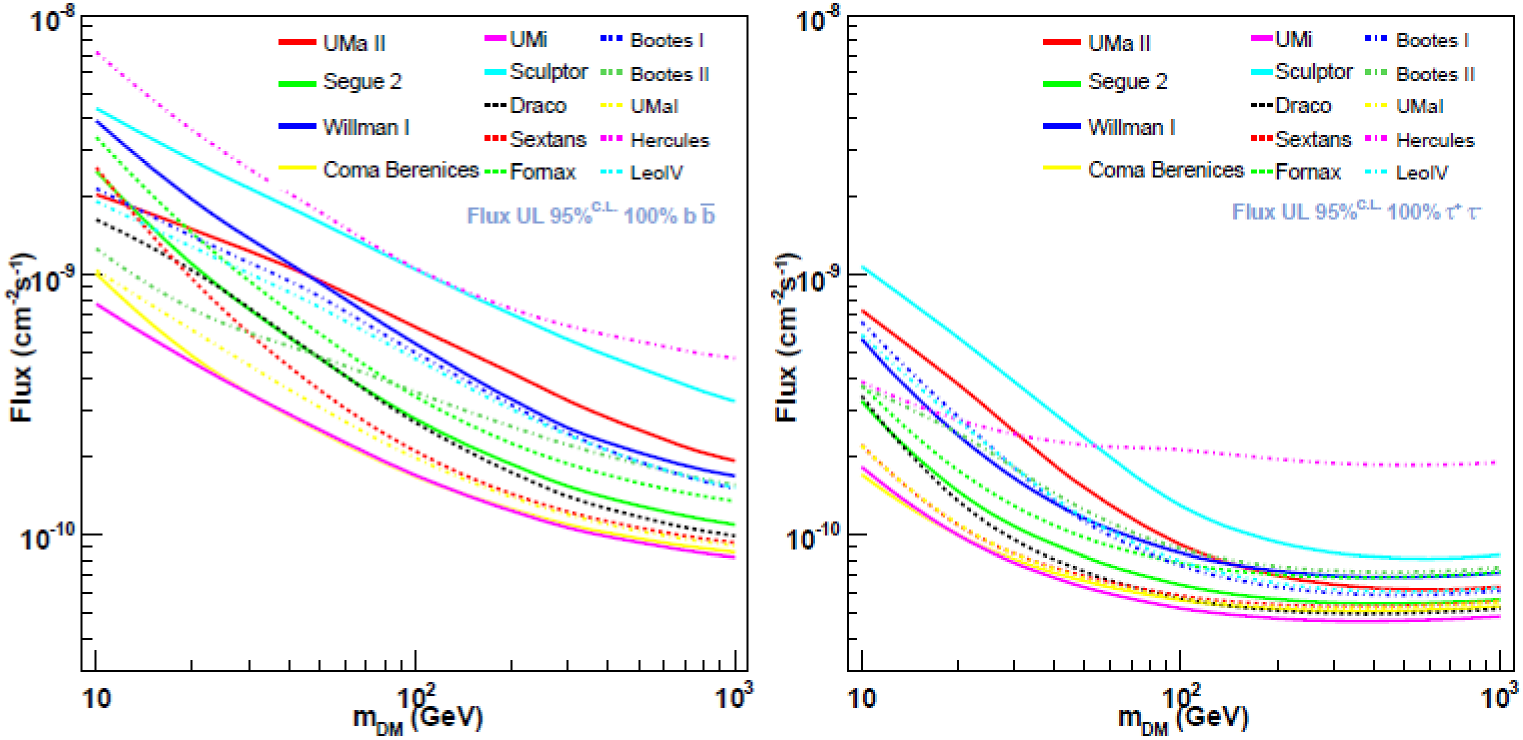
Assume a Navarro-Frenk-White dark matter halo profile inside the tidal radius:

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

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

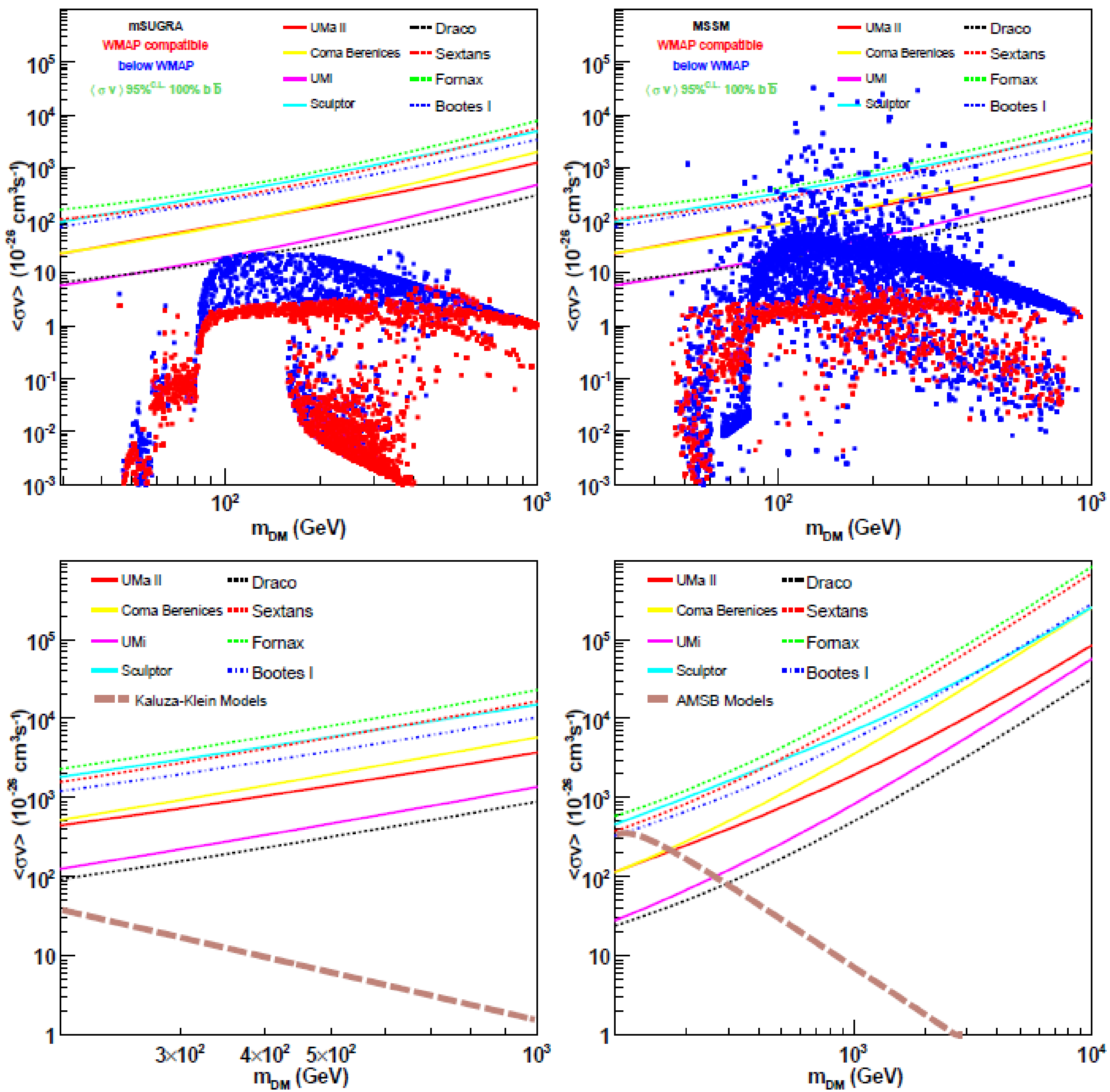
$$J(\psi) = \int_{\text{l.o.s}} dl(\psi)\rho^2(l(\psi))$$

Flux upper limits



Fermi coll.
arXiv:1001.4531

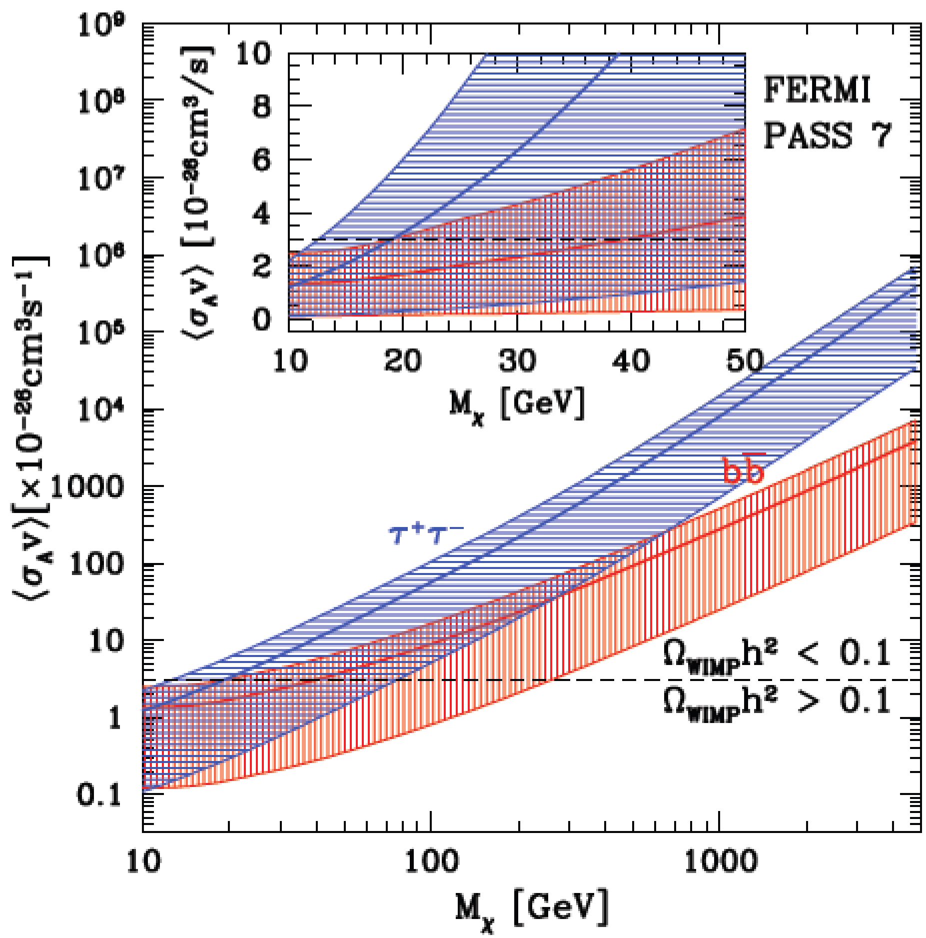
Constraints on annihilating WIMPs

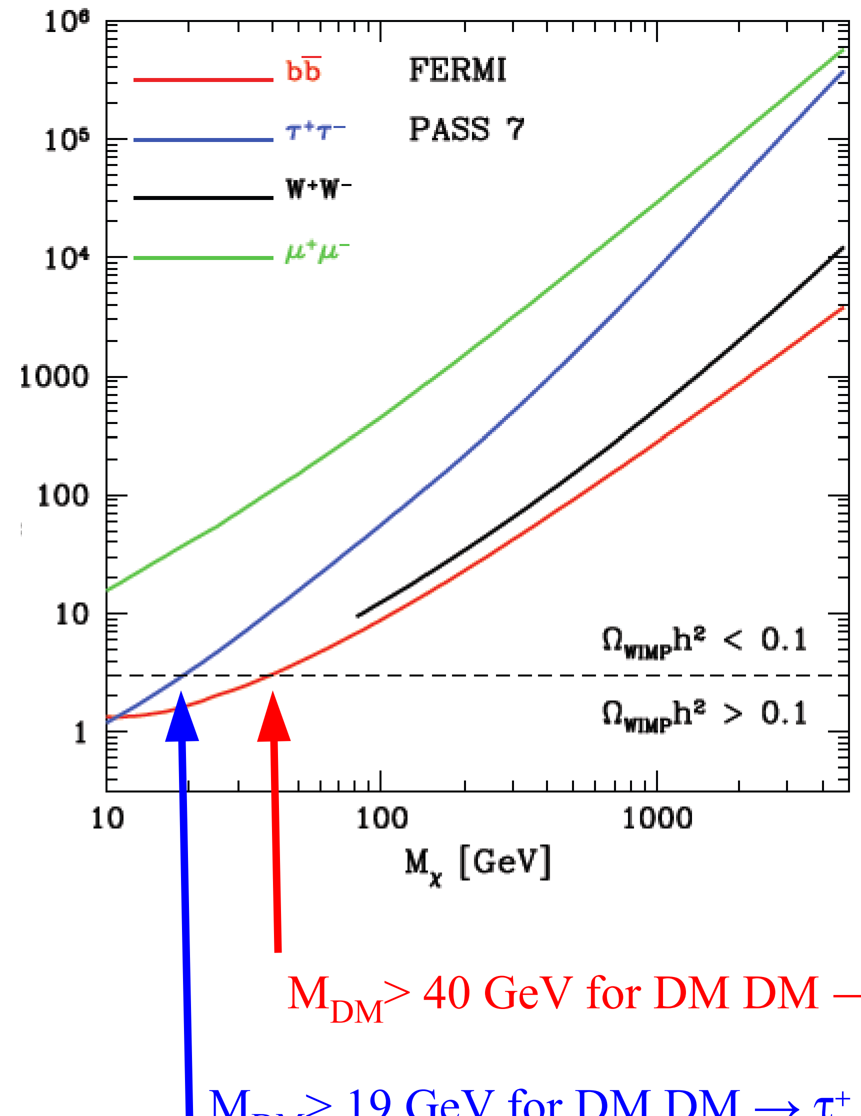


Fermi coll.
arXiv:1001.4531

Closing in 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

Strategy: search for a feature in the gamma-ray spectrum which cannot be mimicked by any (known) astrophysical source:

- If not observed → strong limits on models (background substraction very efficient)
- If observed, unequivocal sign of dark matter

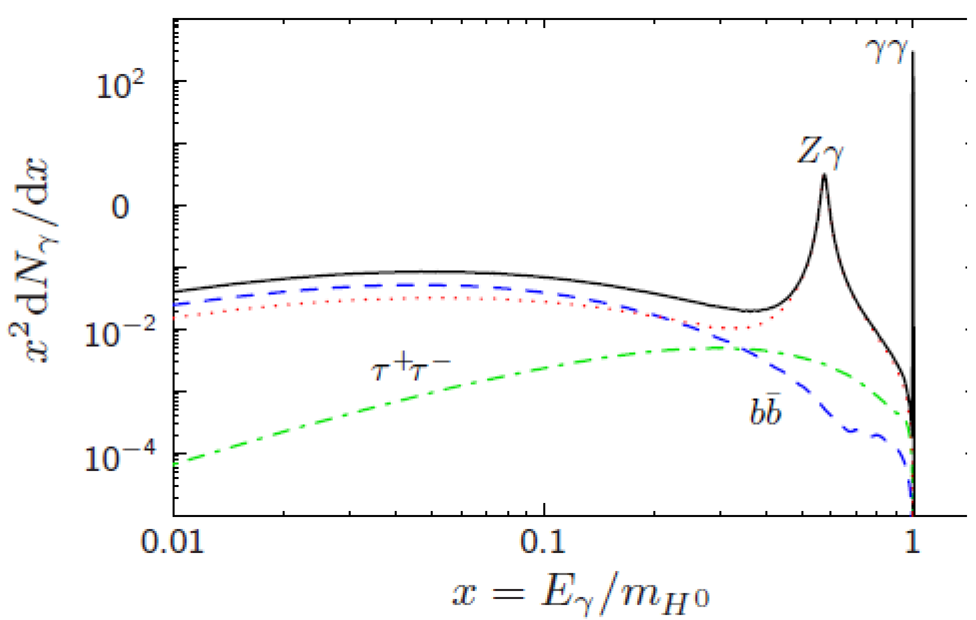
Gamma-ray lines | **Gamma-ray boxes** | **Virtual Internal Bremsstrahlung**

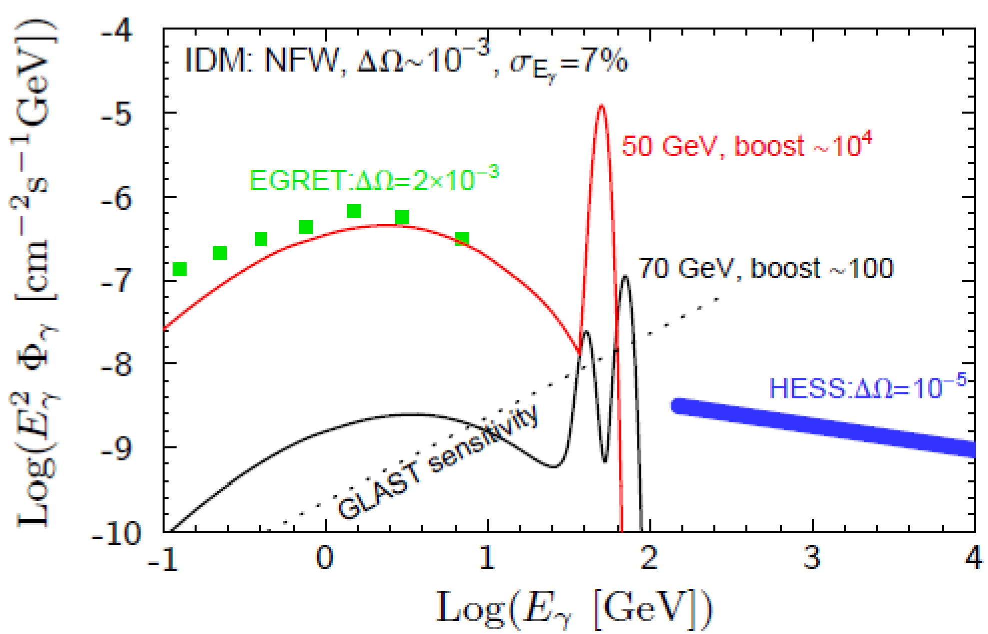
Gamma-ray lines

Produced in the annihilation DM DM → $\gamma\gamma$

Predicted to be fairly intense in some concrete models

- Inert Higgs





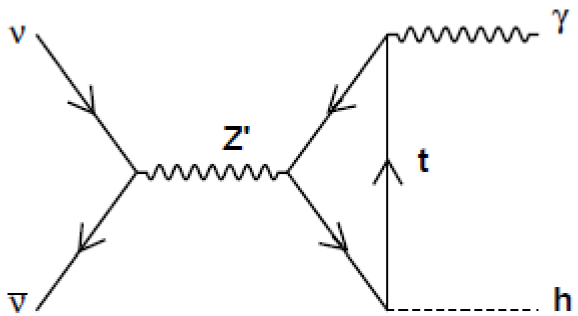
Gustafsson, Lundström, Bergström, Edsjö

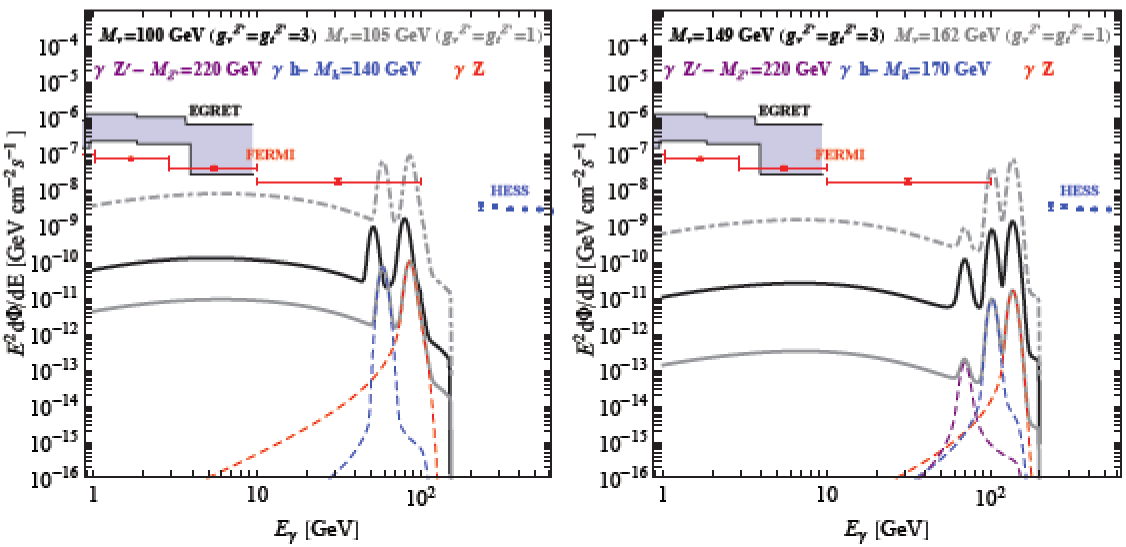
Gamma-ray lines

Produced in the annihilation DM DM $\rightarrow \gamma\gamma$

Predicted to be fairly intense in some concrete models

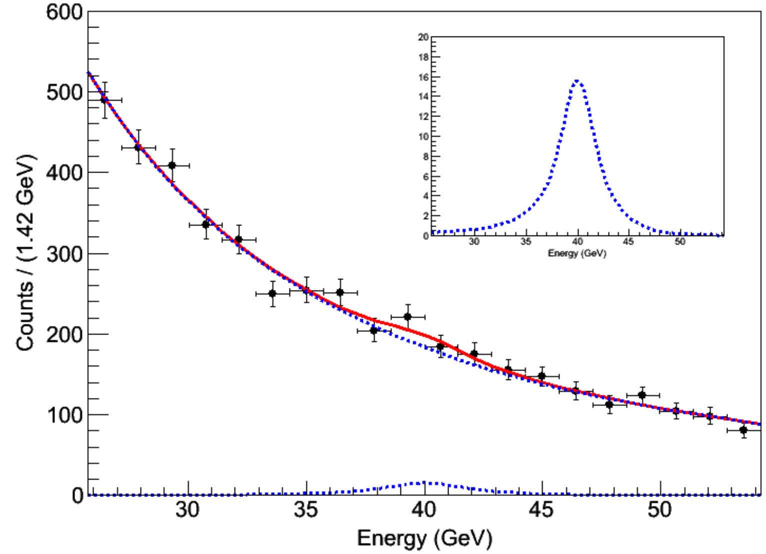
- Dirac fermion coupled to a Z'





Jackson et al.
arXiv: 0912.0004

Gamma-ray lines



E_γ (GeV)	95%CLUL (10^{-9} cm^{-2}s^{-1})	$\langle\sigma v\rangle_{\gamma\gamma}$ [γZ] (10^{-27} cm^{3}s^{-1}) NFW	Einasto	Isothermal
30	3.5	0.3 [2.6]	0.2 [1.9]	0.5 [4.5]
40	4.5	0.7 [4.2]	0.5 [3.0]	1.2 [7.2]
50	2.4	0.6 [2.7]	0.4 [1.9]	1.0 [4.6]
60	3.1	1.1 [4.2]	0.8 [3.0]	1.8 [7.3]
70	1.2	0.6 [2.0]	0.4 [1.4]	1.0 [3.4]
80	0.9	0.5 [1.7]	0.4 [1.2]	0.9 [2.9]
90	2.6	2.0 [6.0]	1.5 [4.3]	3.5 [10.3]
100	1.4	1.4 [3.8]	1.0 [2.8]	2.4 [6.6]
110	0.9	1.0 [2.7]	0.7 [1.9]	1.7 [4.6]
120	1.1	1.6 [4.0]	1.1 [2.9]	2.7 [6.9]
130	1.8	3.0 [7.3]	2.1 [5.3]	5.1 [12.6]
140	1.9	3.5 [8.4]	2.5 [6.0]	6.0 [14.3]
150	1.6	3.5 [8.2]	2.5 [5.9]	6.0 [14.1]
160	1.1	2.7 [6.3]	2.0 [4.5]	4.7 [10.9]
170	0.6	1.7 [4.0]	1.3 [2.9]	3.0 [6.8]
180	0.9	2.7 [6.1]	1.9 [4.4]	4.6 [10.4]
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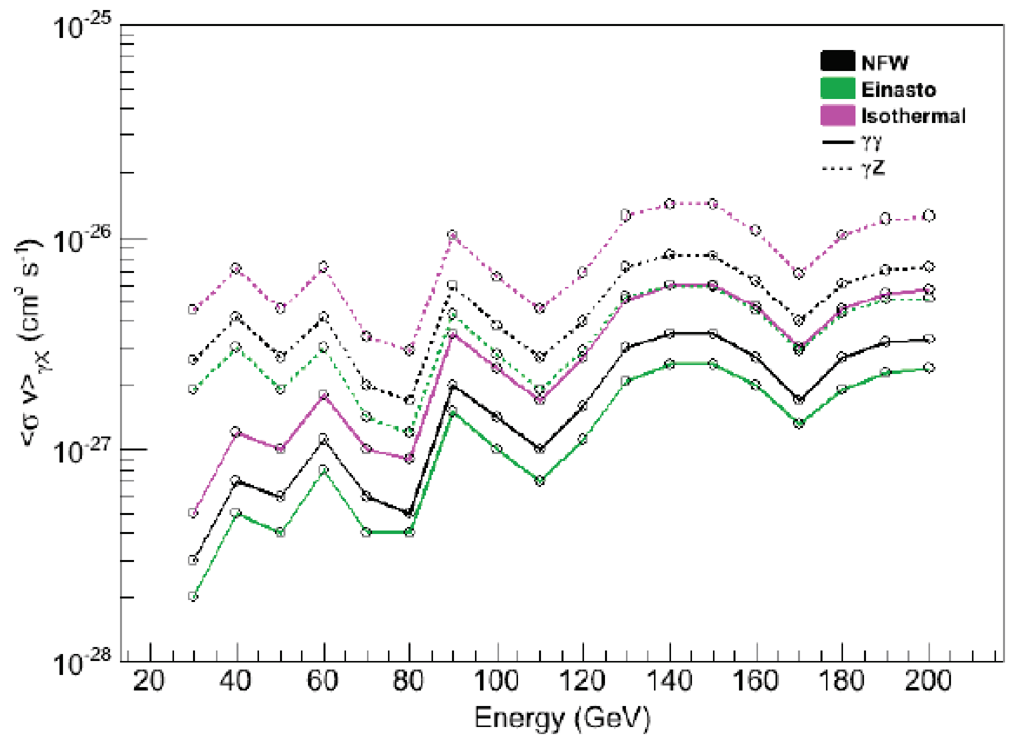
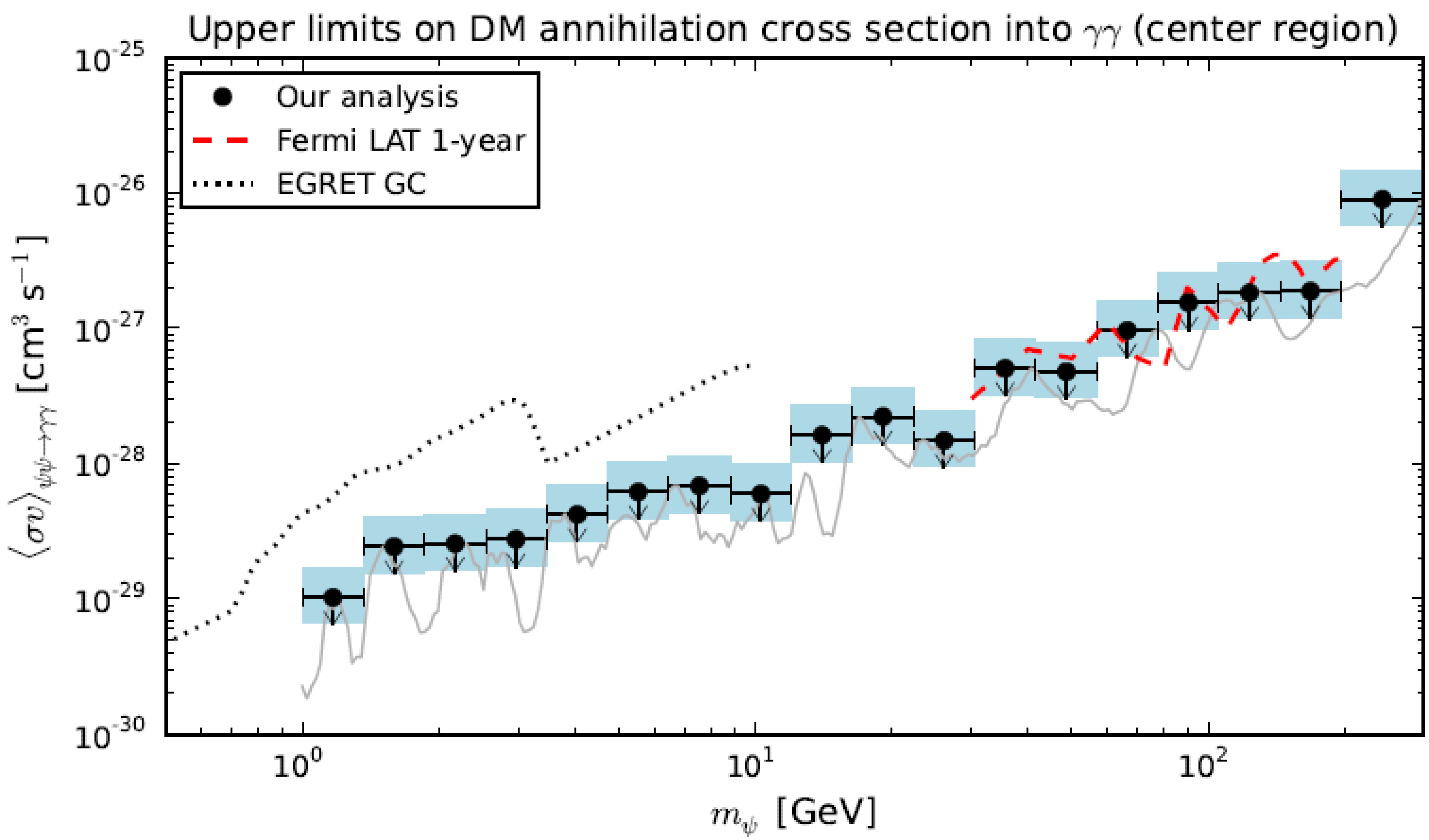


Fermi coll.
arXiv:1001.4836

Gamma-ray lines



Vertongen, Weniger
arXiv:1101.2610

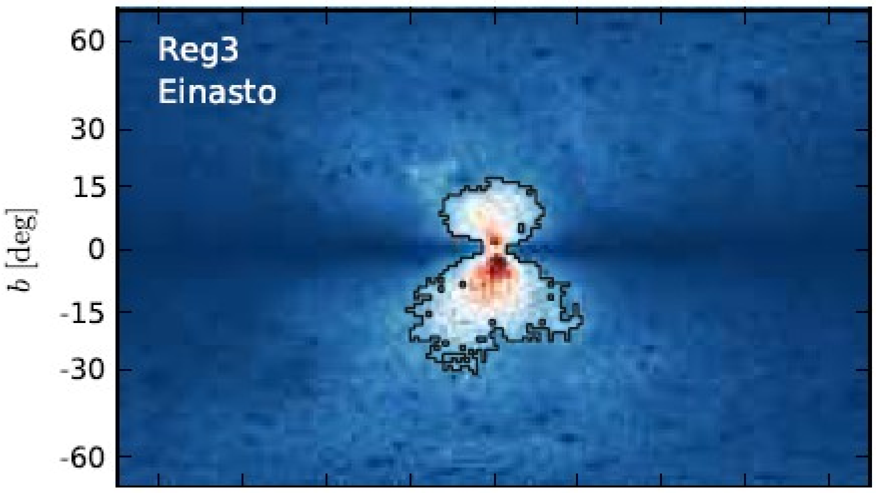
Gamma-ray lines

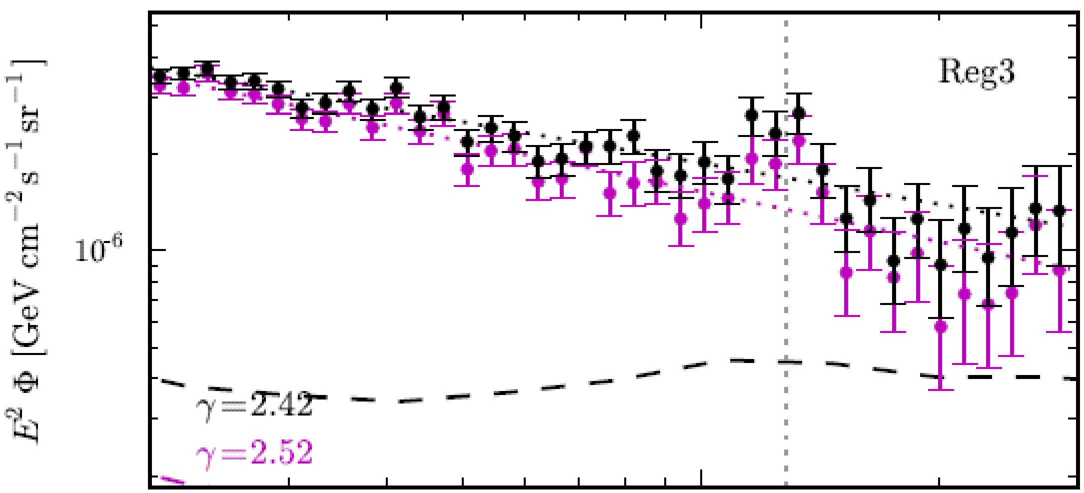
A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

Christoph Weniger

Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

E-mail: weniger@mppmu.mpg.de





arXiv:1204.2797

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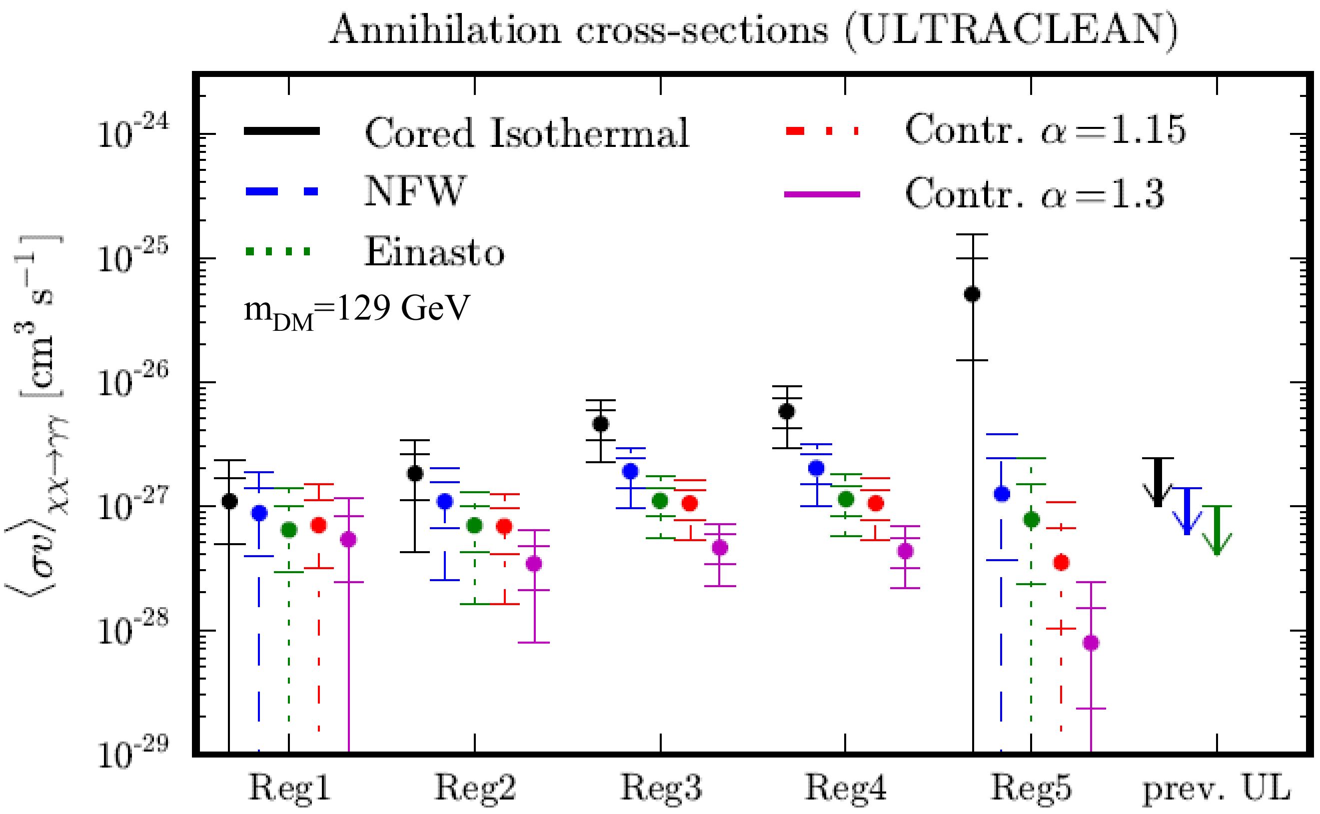

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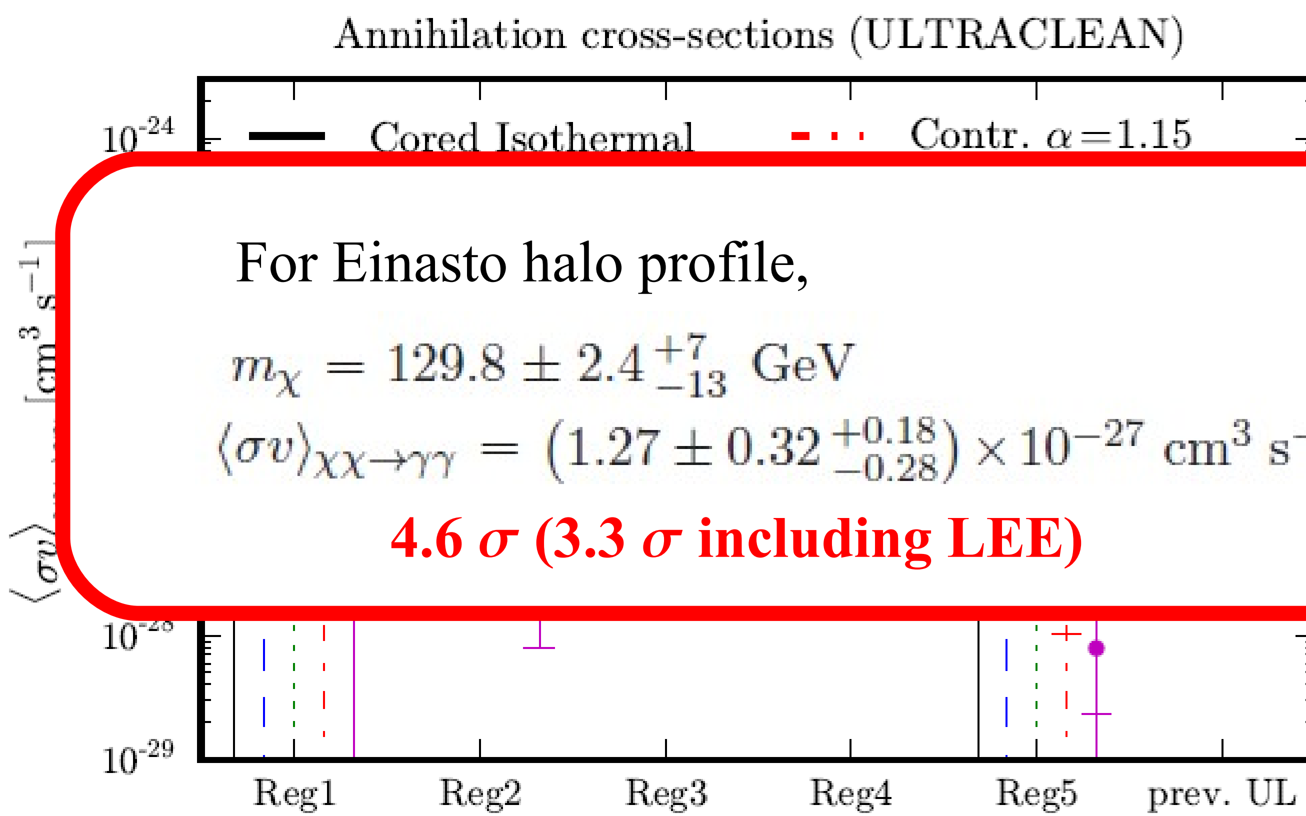


For Einasto halo profile,

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

$$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}$$

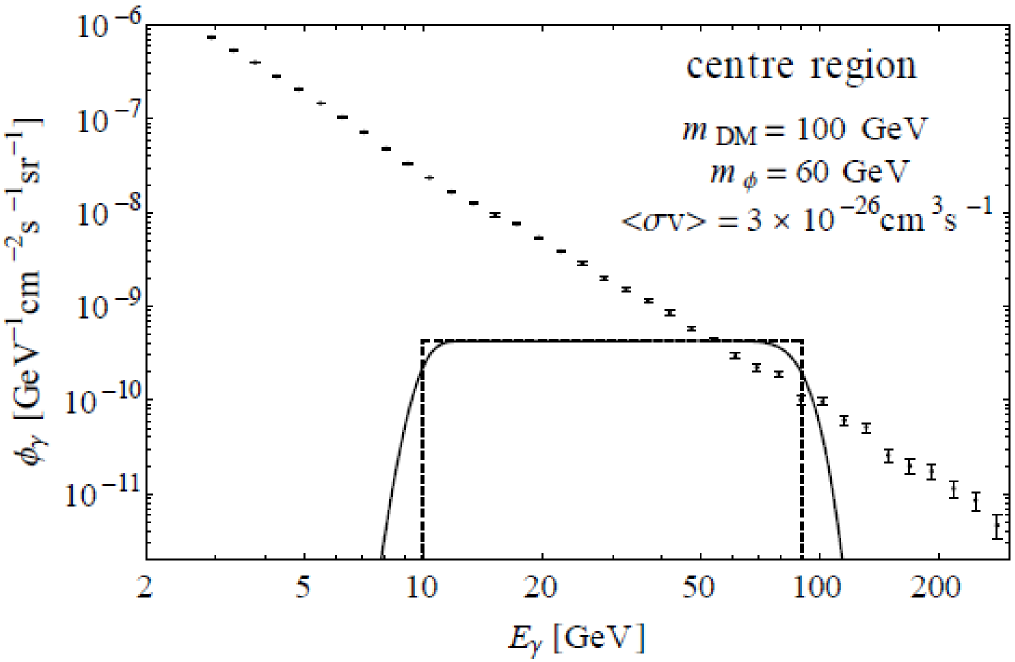
4.6 σ (3.3 σ including LEE)

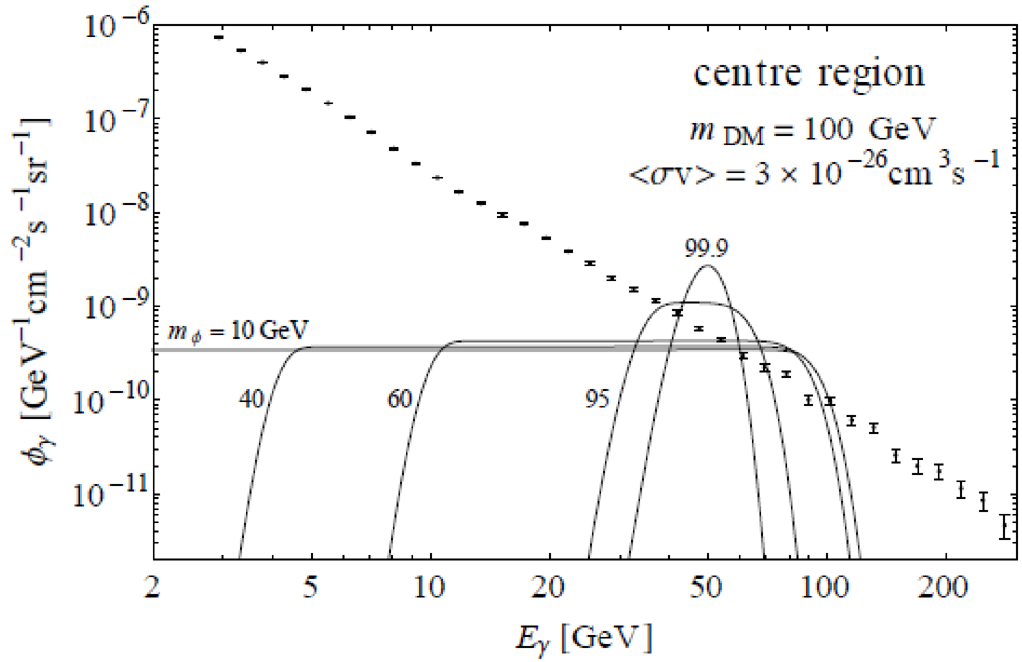
arXiv:1204.2797

Gamma-ray boxes

Consider the cascade decay: DM DM → $\phi\,\phi$

$\phi \to \gamma\,\gamma$





AI, Lopez-Gehler, Pato
arXiv:1205.0007

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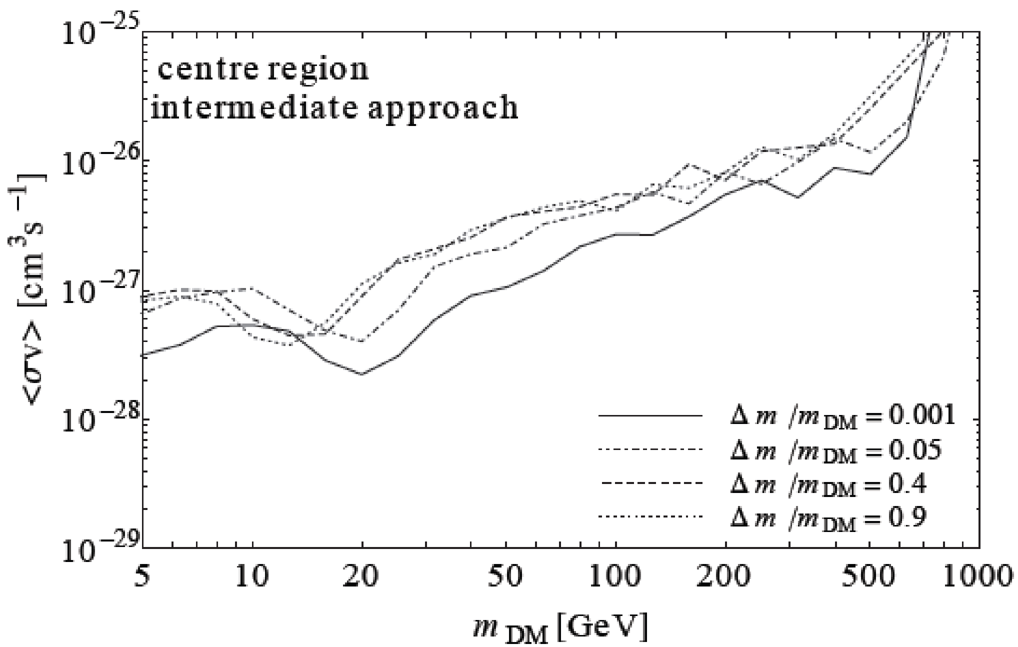

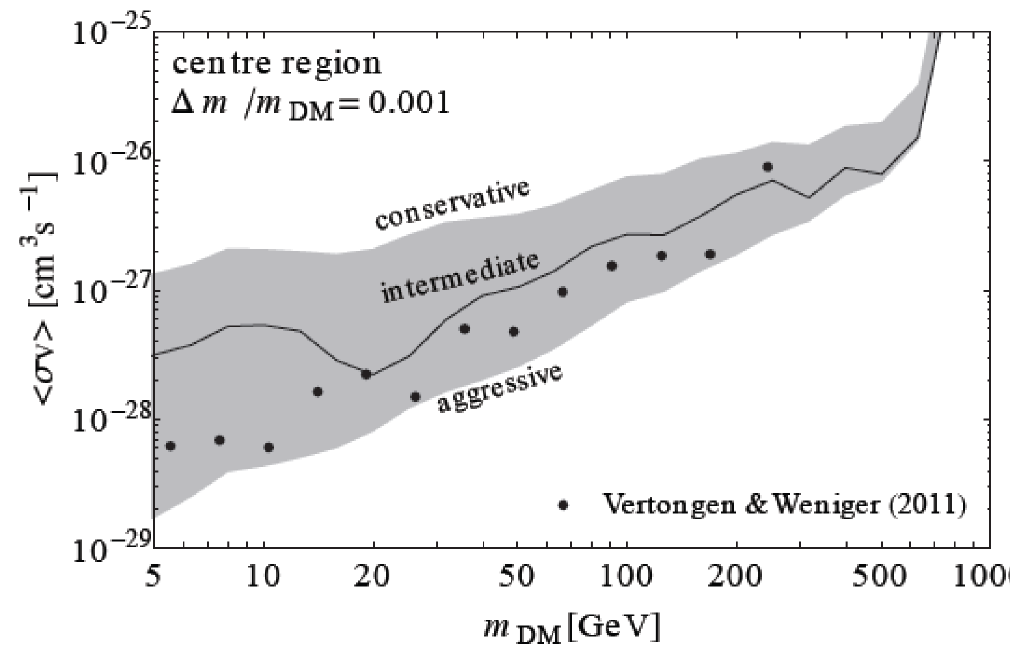

AI, Lopez-Gehler, Pato
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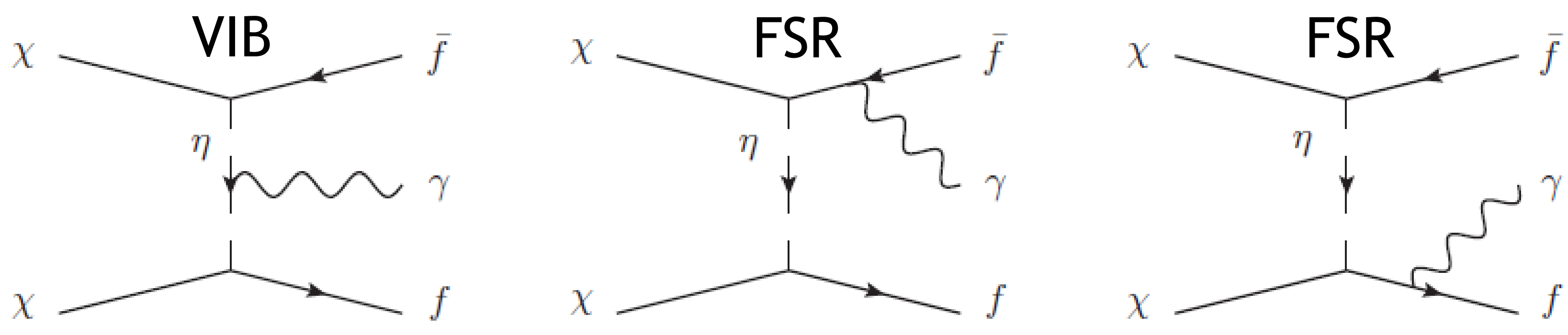
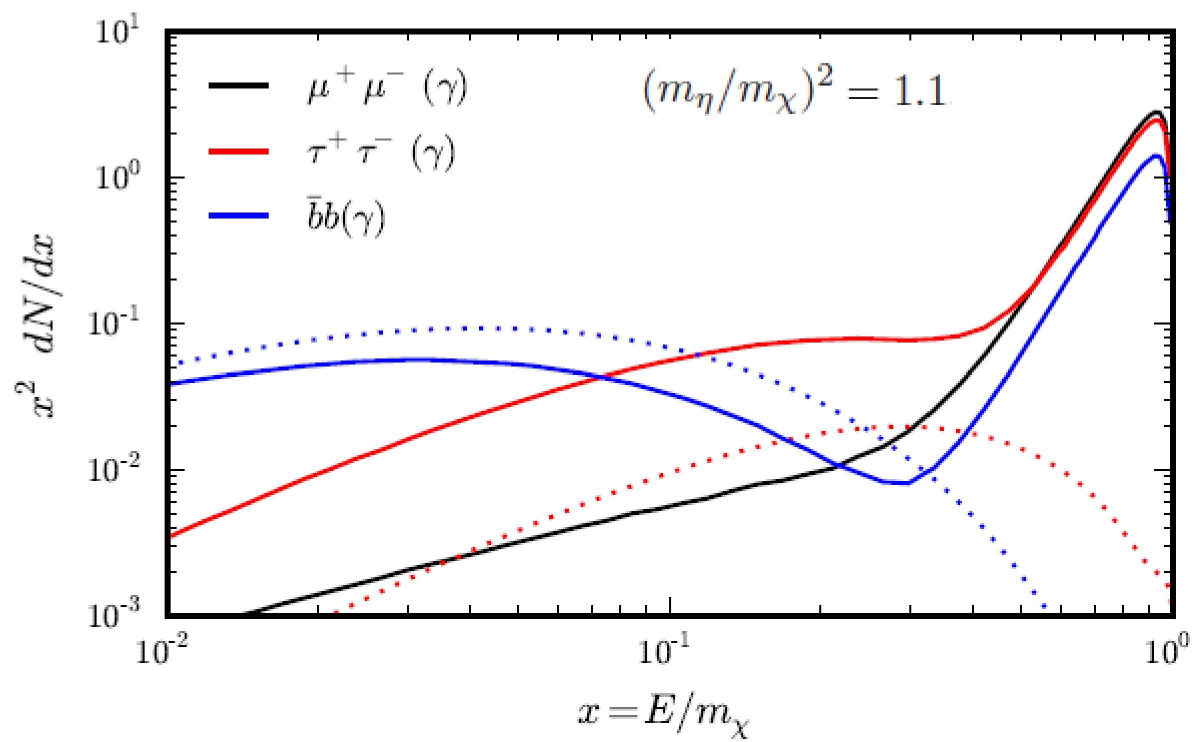
Virtual internal Bremsstrahlung

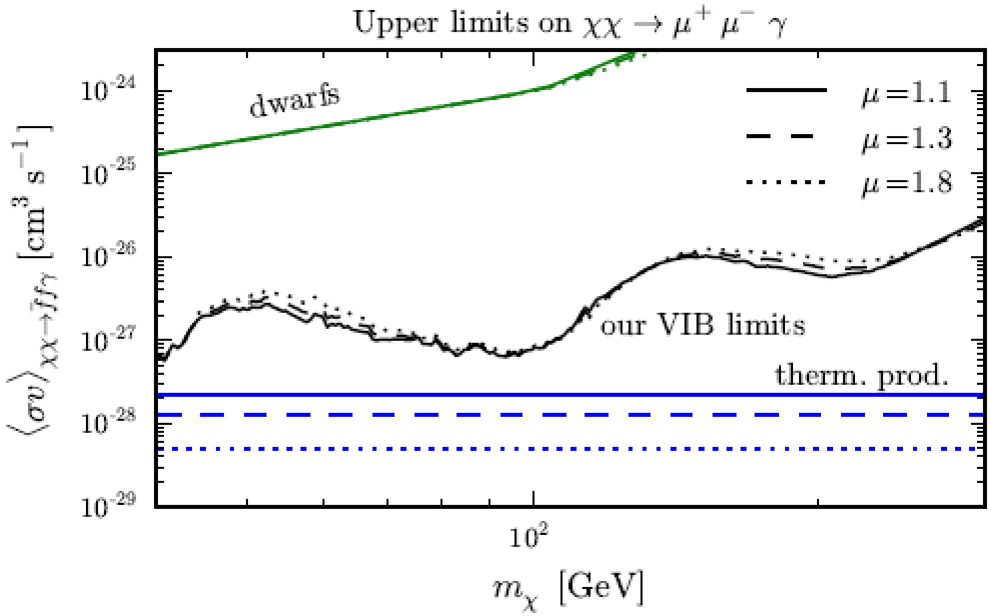
Bergström
Flores, Olive, Rudaz

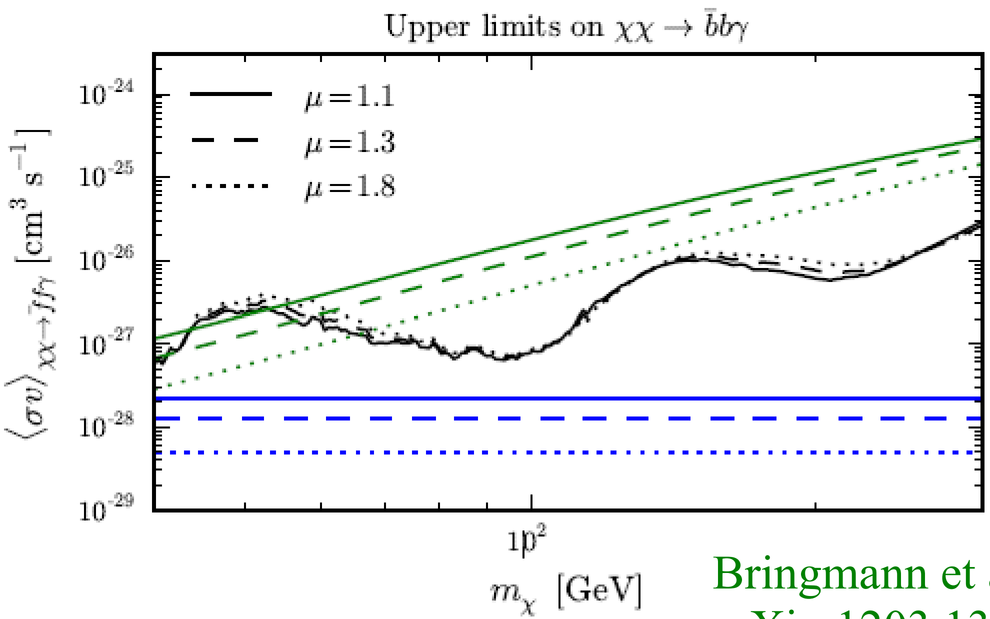




Bringmann et al.
arXiv:1203.1312

Virtual internal Bremsstrahlung





Bringmann et al.
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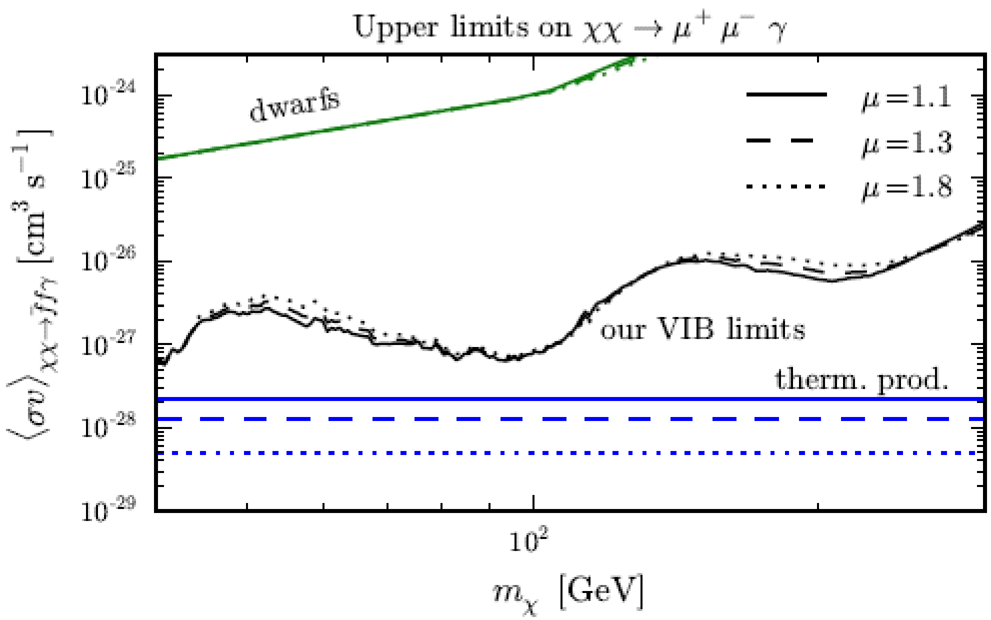
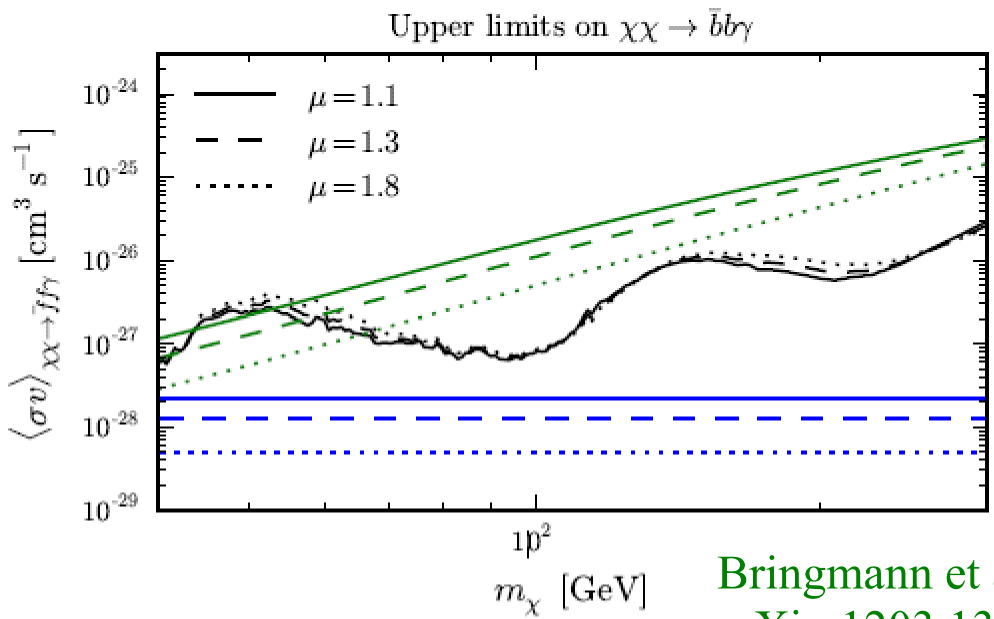
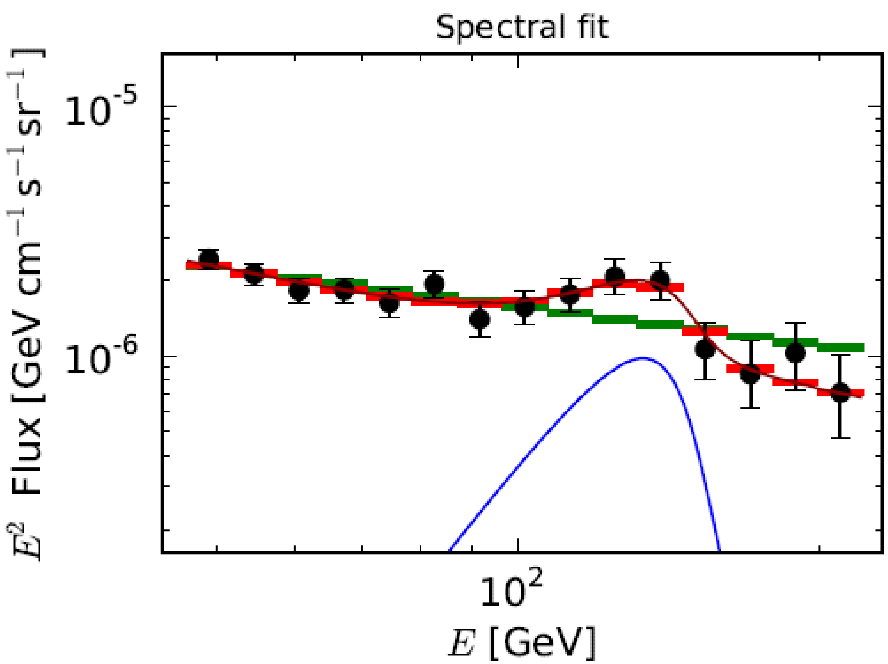




Bringmann et al.
arXiv:1203.1312



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

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

4.3 σ (3.1 σ with LEE)

Where to look for decaying dark matter

Bertone et al.
arXiv:0709.2299

A priori, same targets as for annihilating dark matter:

- Diffuse galactic background (galactic center, galactic halo)
- Dwarf galaxies.
- Clusters of galaxies.
- Isotropic (“extragalactic”) background.
- Gamma-ray lines.

Where to look for *decaying* dark matter

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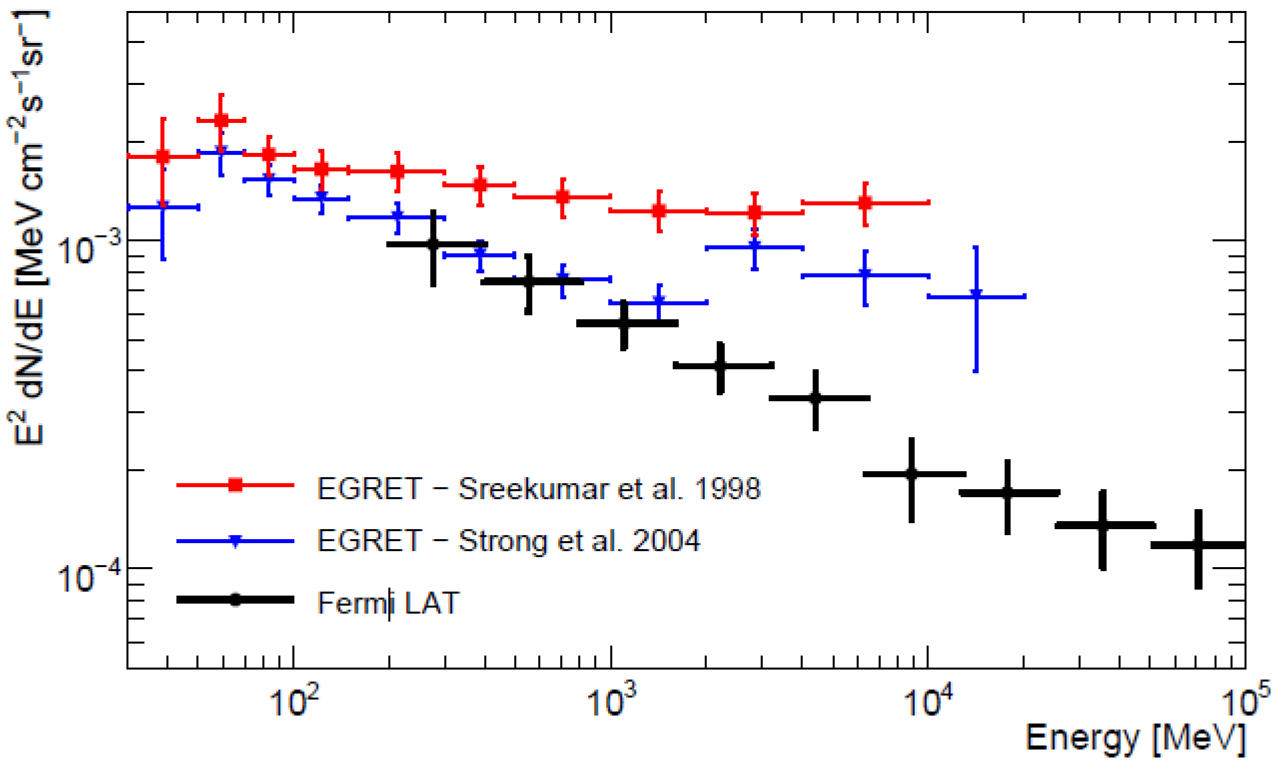
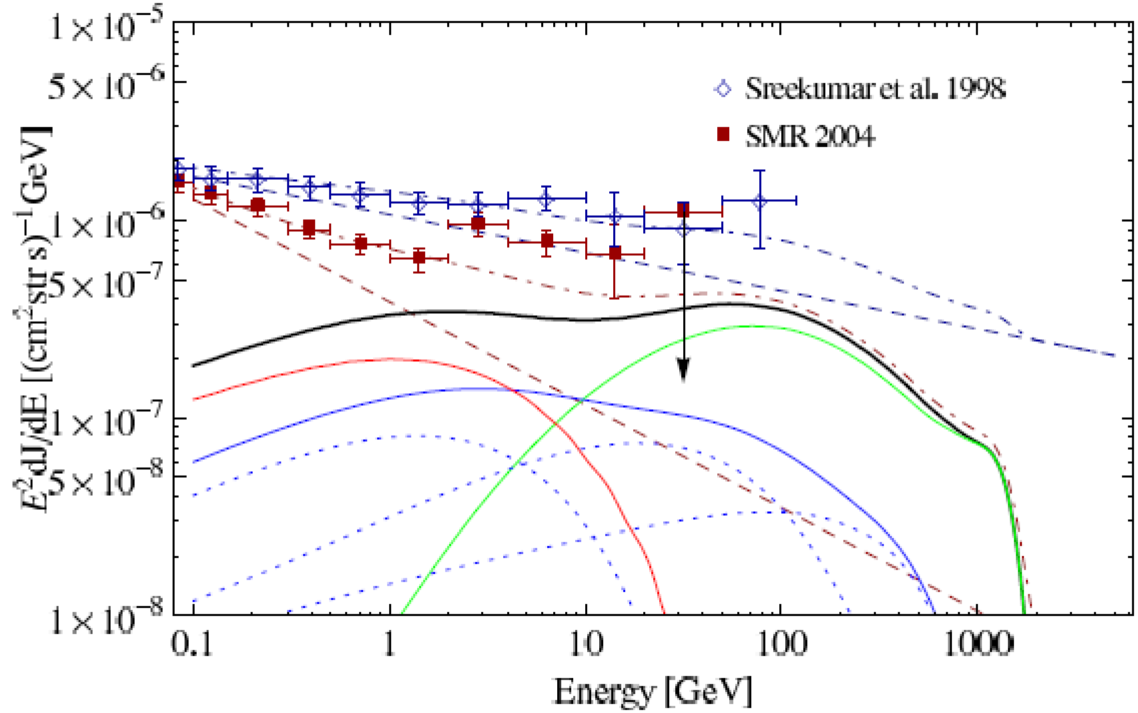
Isotropic ("extragalactic") background



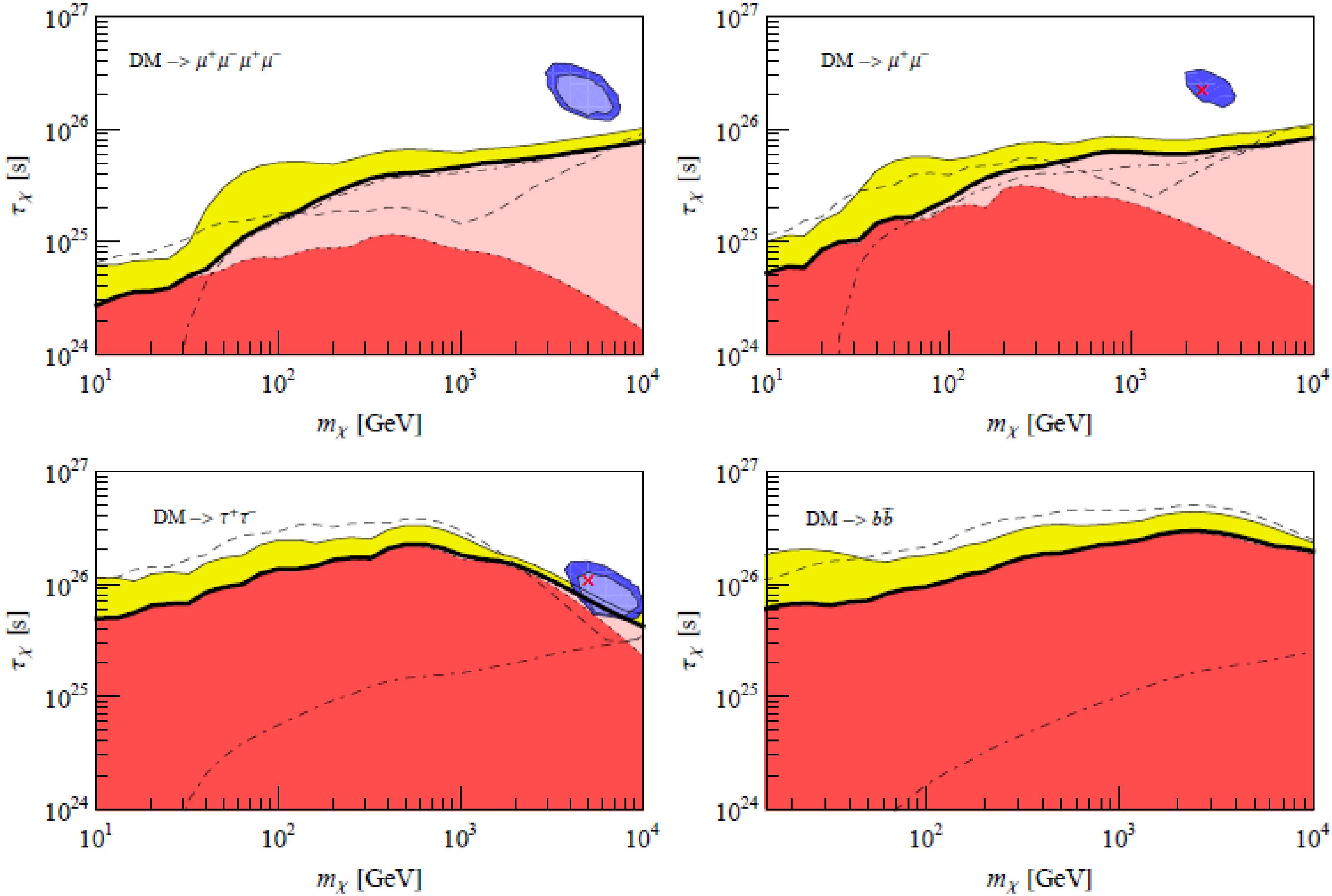
Fermi coll.
arXiv:1002.3603

$$\psi_{\rm DM} \rightarrow W^{\pm}\mu^{\mp}$$



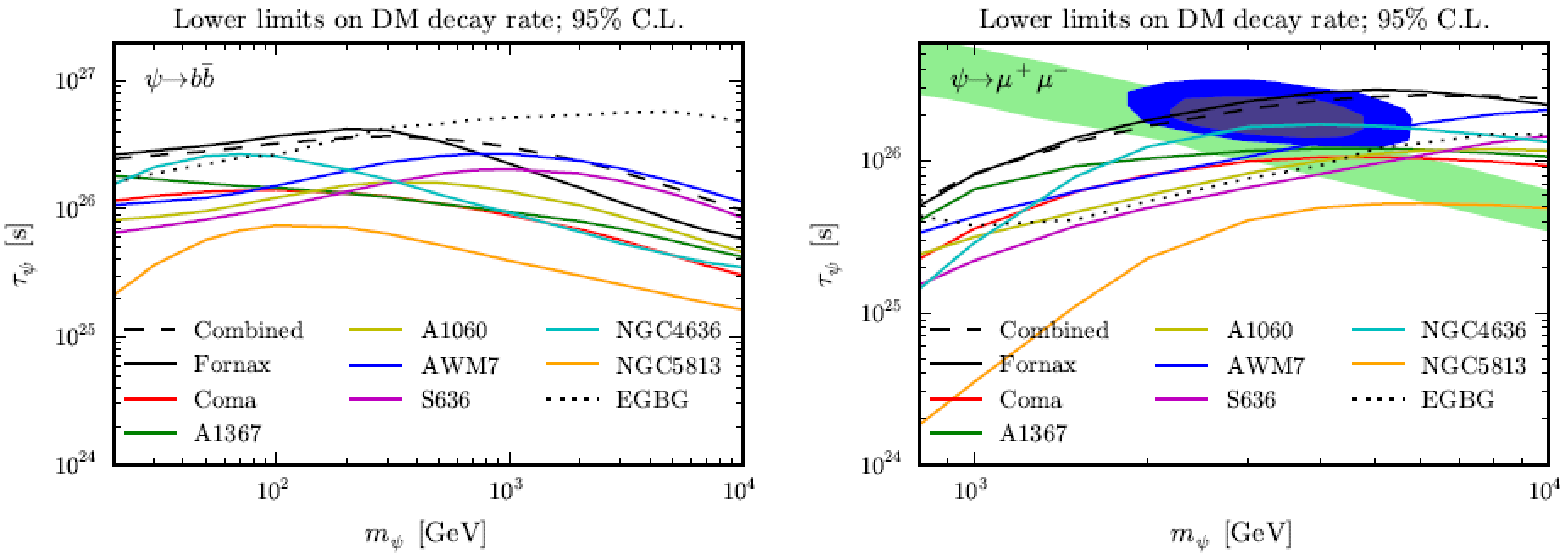
m=3000 GeV, $\tau = 2.1\times10^{26}$ s.

Average flux, excluding galactic disk



Zhang et al.

Clusters of galaxies



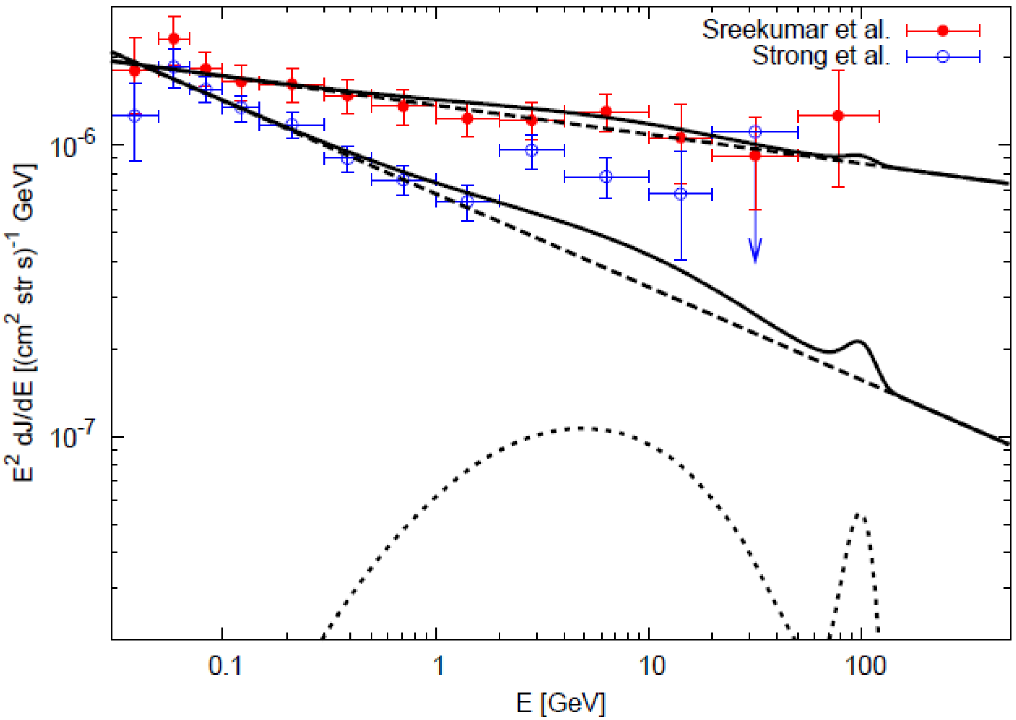
Huang et al.

Gamma-ray lines

Inequivocal sign of dark matter. No (known) astrophysical source can produce a gamma-ray line

Predicted to be fairly intense in some concrete models

- Gravitino in general SUSY models
(without imposing R-parity conservation)



m=200 GeV
$\tau = 7\times 10^{26}$ s

Buchmüller et al.

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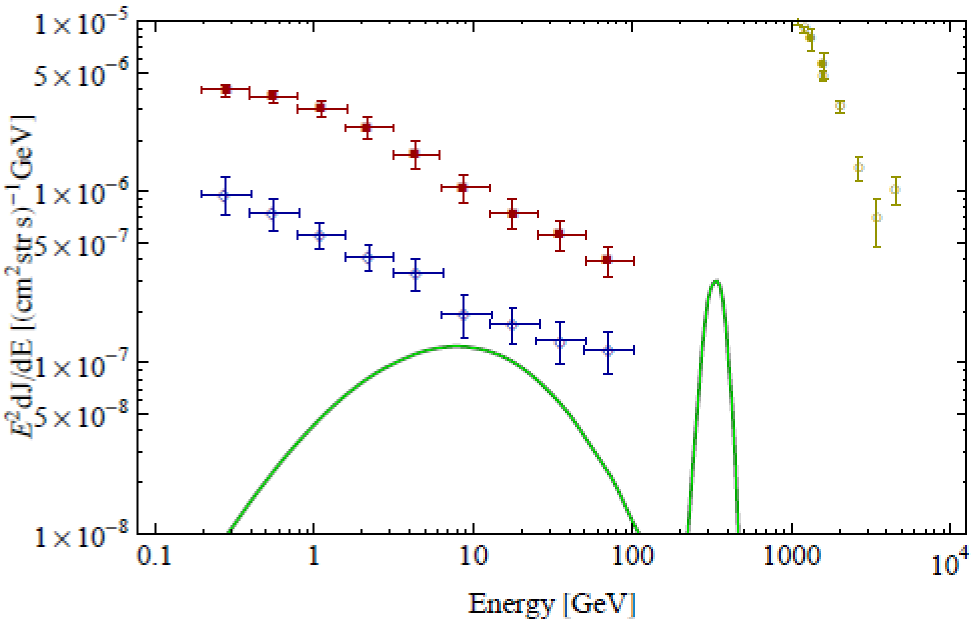

m=600 GeV
τ=1.1×10^{27} s

Arina, Hambye, Al, Weniger

	$\eta\eta$	$h\eta$	hh	$\gamma\eta$	$Z\eta$	γh	Zh
Branching Ratios	-	0.04	0.62	0.002	0.003	0.15	0.18

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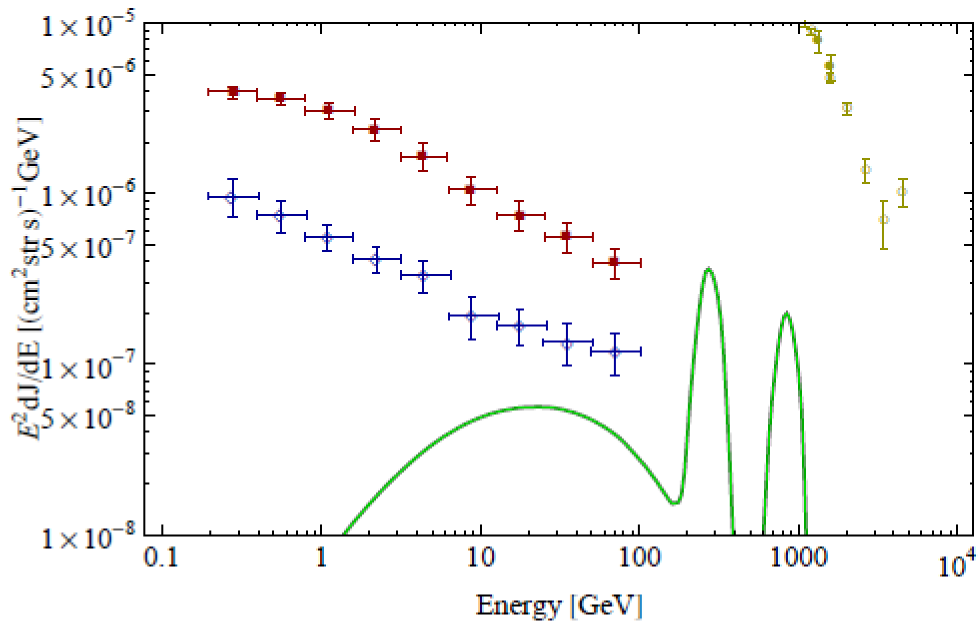

m=1550 GeV
τ=1.6×10^{27} s

Arina, Hambye, Al, Weniger

	$Z\eta$	$\gamma\eta$	Zh	γh
Branching Ratios	0.028	0.79	0.041	0.14

Gamma-ray lines

E_γ (GeV)	95%CLUL (10^{-9} cm^{-2}s^{-1})	$\tau_{\gamma\gamma}$ [γZ] (10^{28} s) NFW	Einasto	Isothermal
30	3.5	17.6 [4.2]	17.8 [4.2]	17.5 [4.2]
40	4.5	10.1 [2.9]	10.3 [2.9]	10.0 [2.9]
50	2.4	15.5 [5.0]	15.7 [5.1]	15.4 [5.0]
60	3.1	9.8 [3.5]	10.0 [3.5]	9.7 [3.5]
70	1.2	21.6 [8.2]	21.9 [8.3]	21.5 [8.1]
80	0.9	26.0 [10.4]	26.4 [10.5]	25.8 [10.3]
90	2.6	7.7 [3.2]	7.8 [3.2]	7.6 [3.1]
100	1.4	12.6 [5.4]	12.8 [5.4]	12.5 [5.3]
110	0.9	18.9 [8.2]	19.2 [8.3]	18.8 [8.2]
120	1.1	13.3 [5.9]	13.5 [6.0]	13.2 [5.9]
130	1.8	7.6 [3.4]	7.8 [3.5]	7.6 [3.4]
140	1.9	7.0 [3.2]	7.1 [3.3]	7.0 [3.2]
150	1.6	7.5 [3.5]	7.6 [3.5]	7.4 [3.4]
160	1.1	10.2 [4.8]	10.4 [4.8]	10.1 [4.7]
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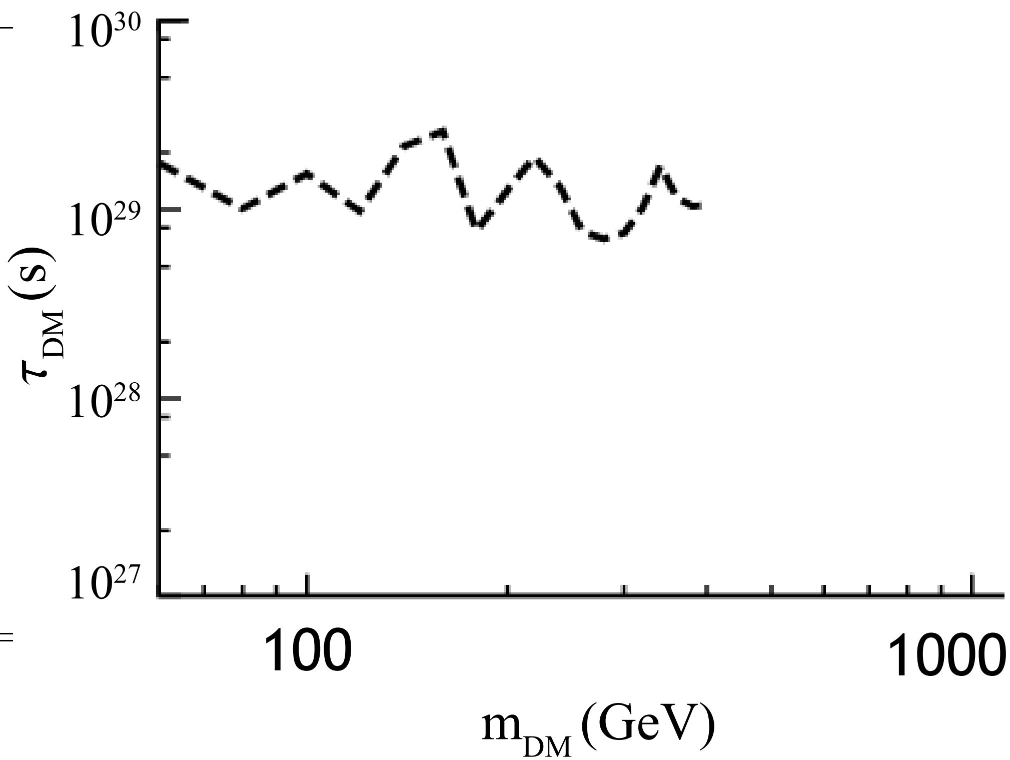
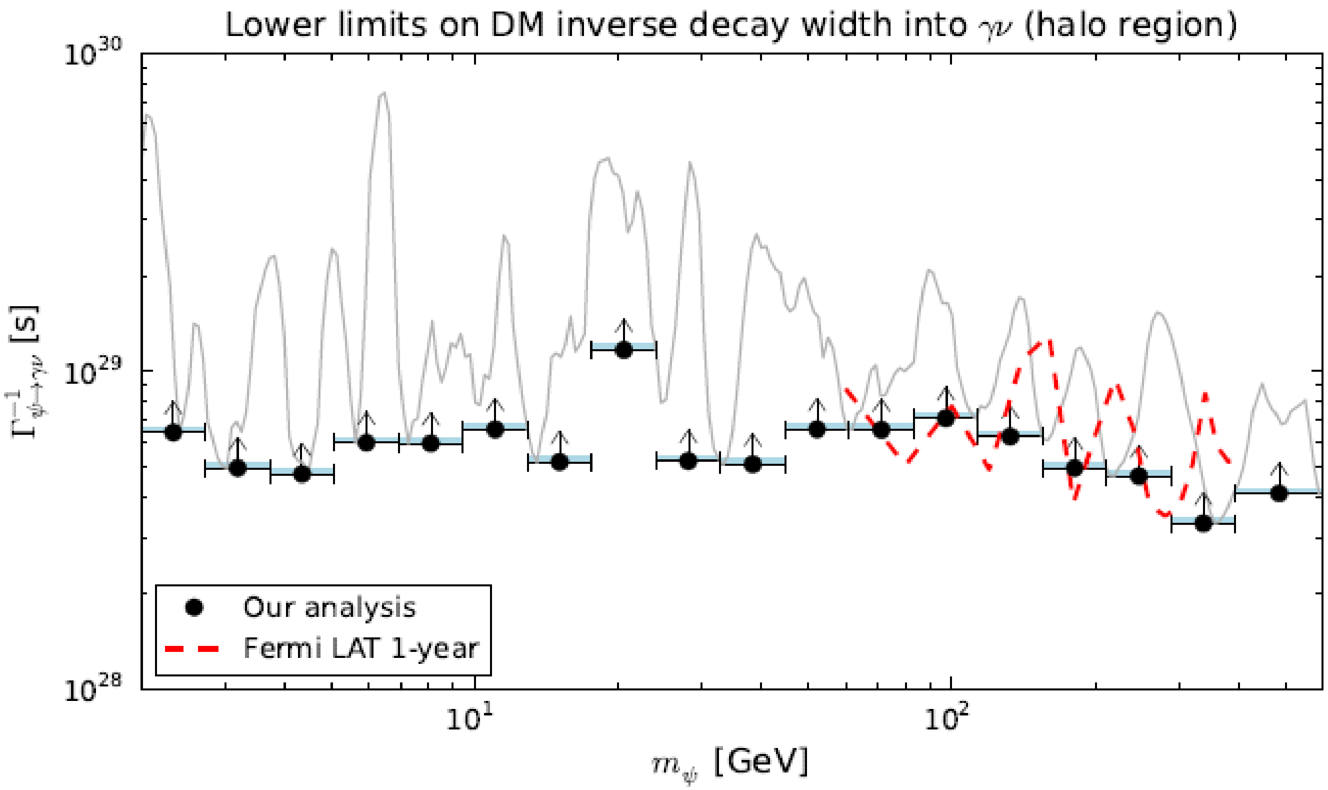
Fermi coll.
arXiv:1001.4836

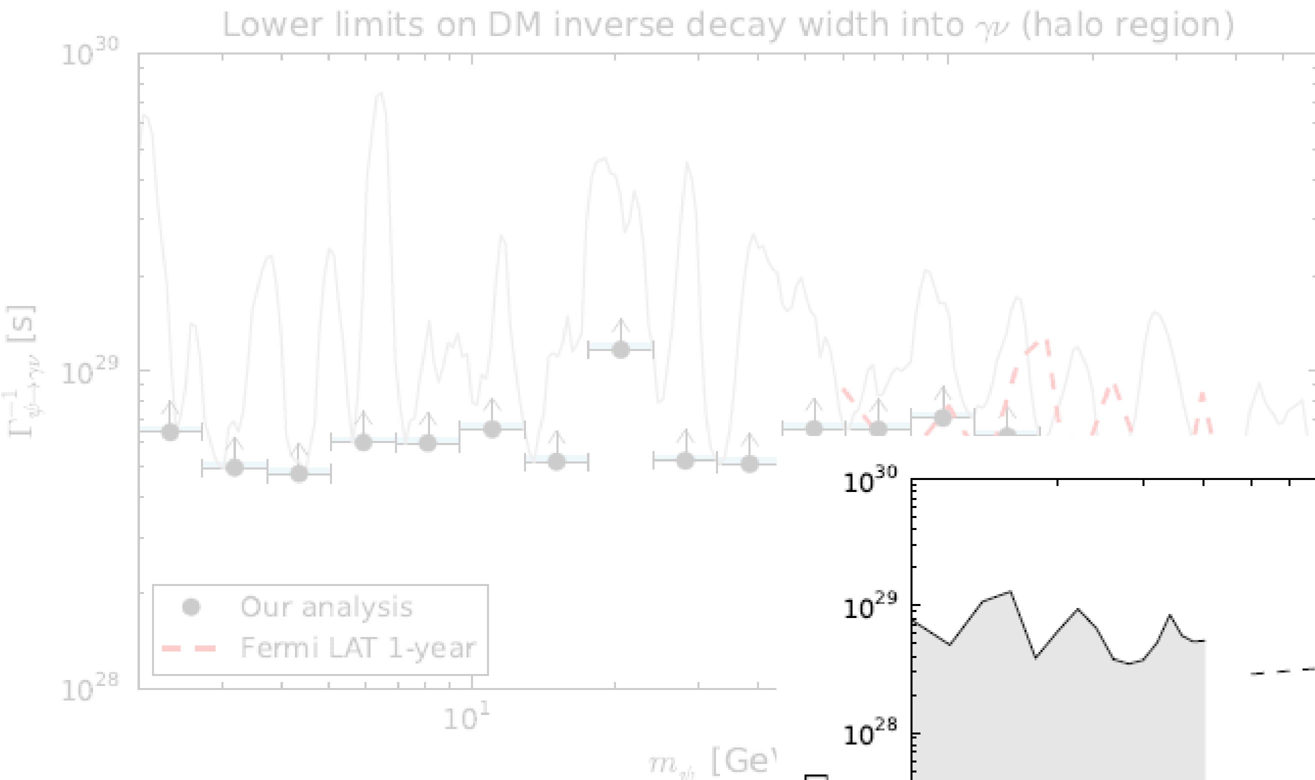


Gamma-ray lines

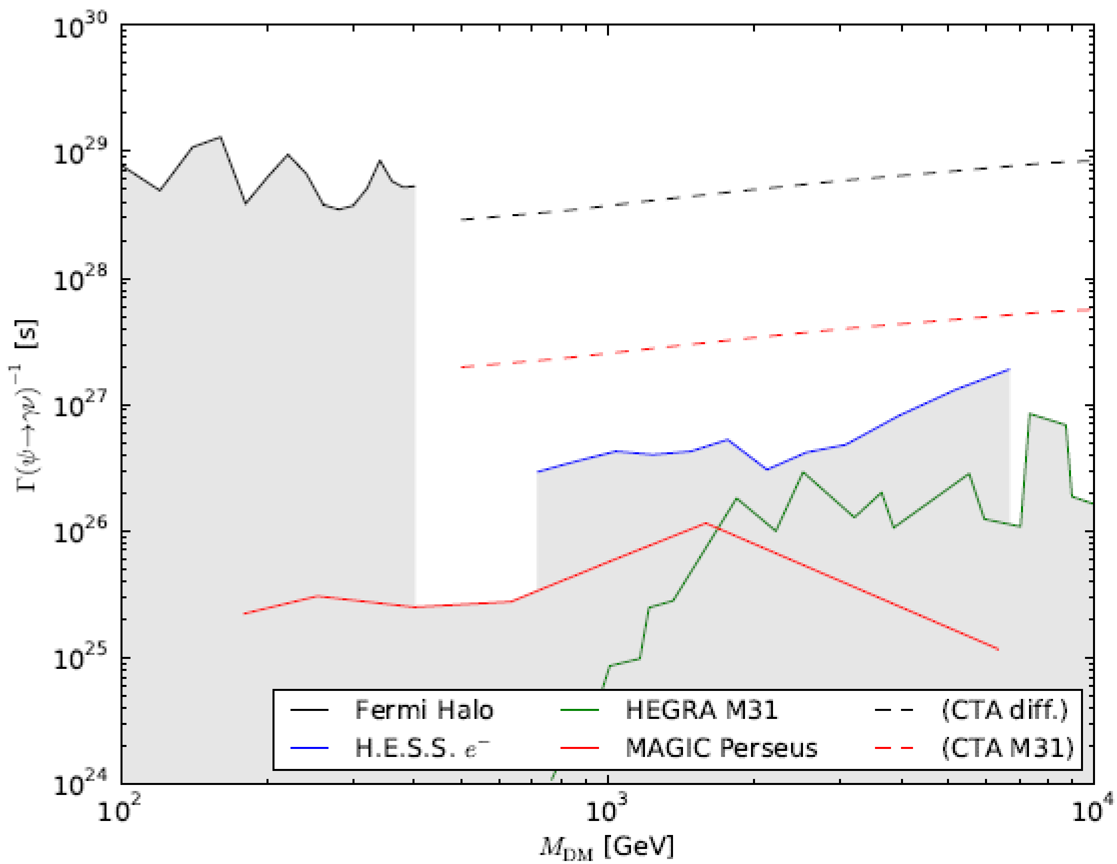


Vertongen, Weniger
1101.2610

Gamma-ray lines



Vertongen, Weniger
1101.2610



Garny et al.
1011.3786

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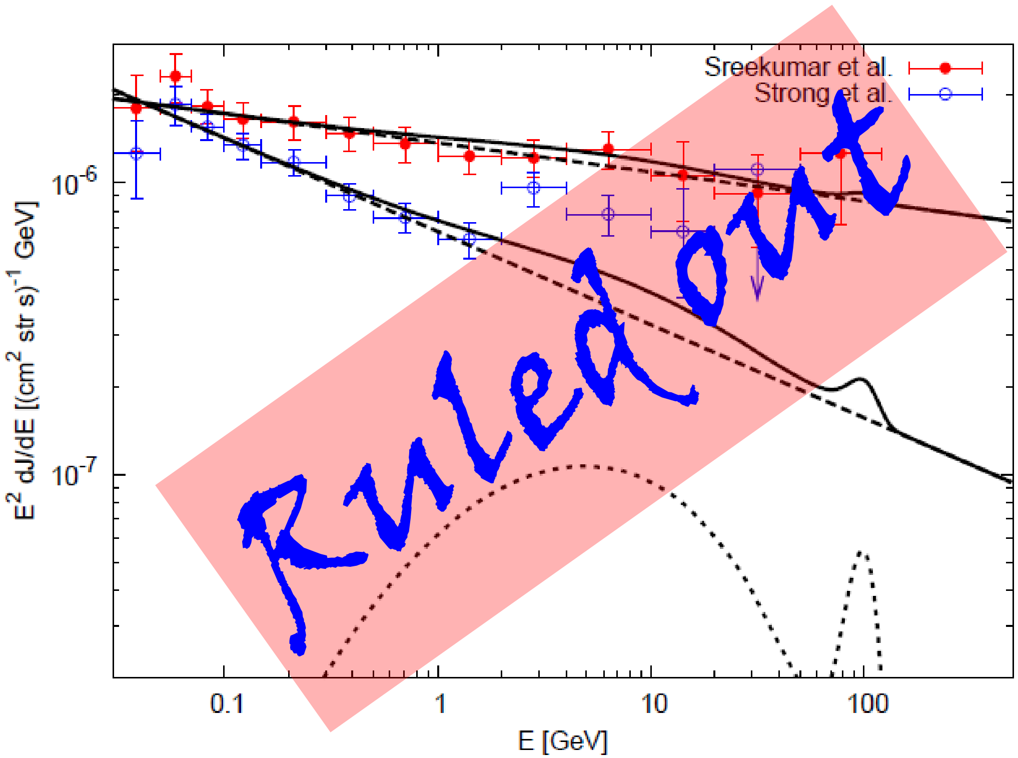


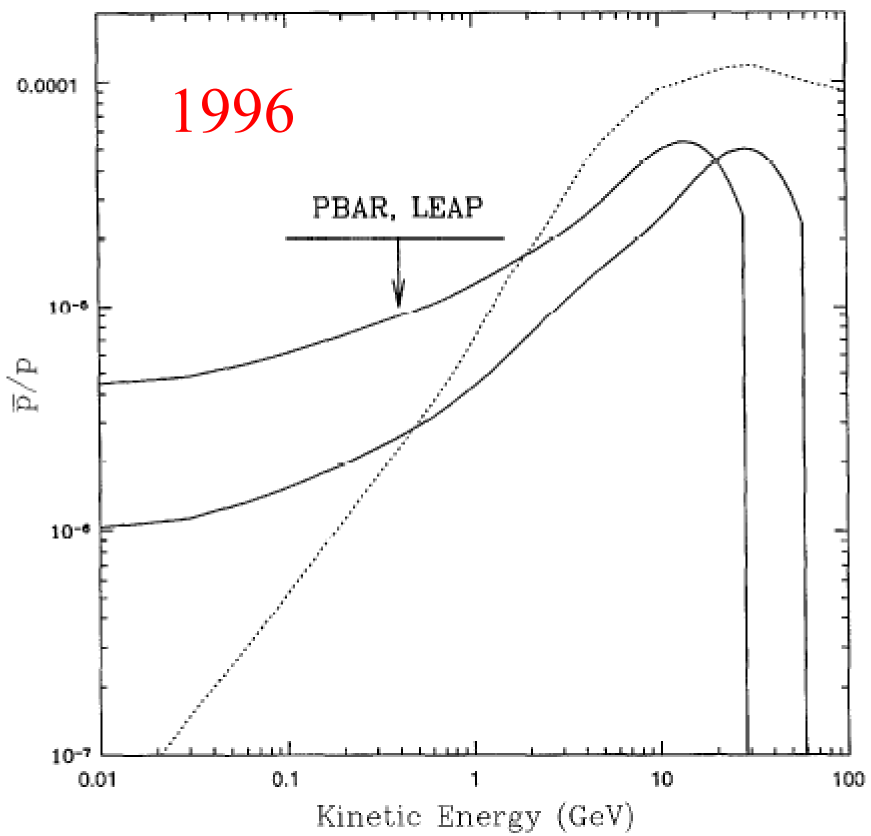
m=200 GeV

$\tau=7\times10^{26}$ s

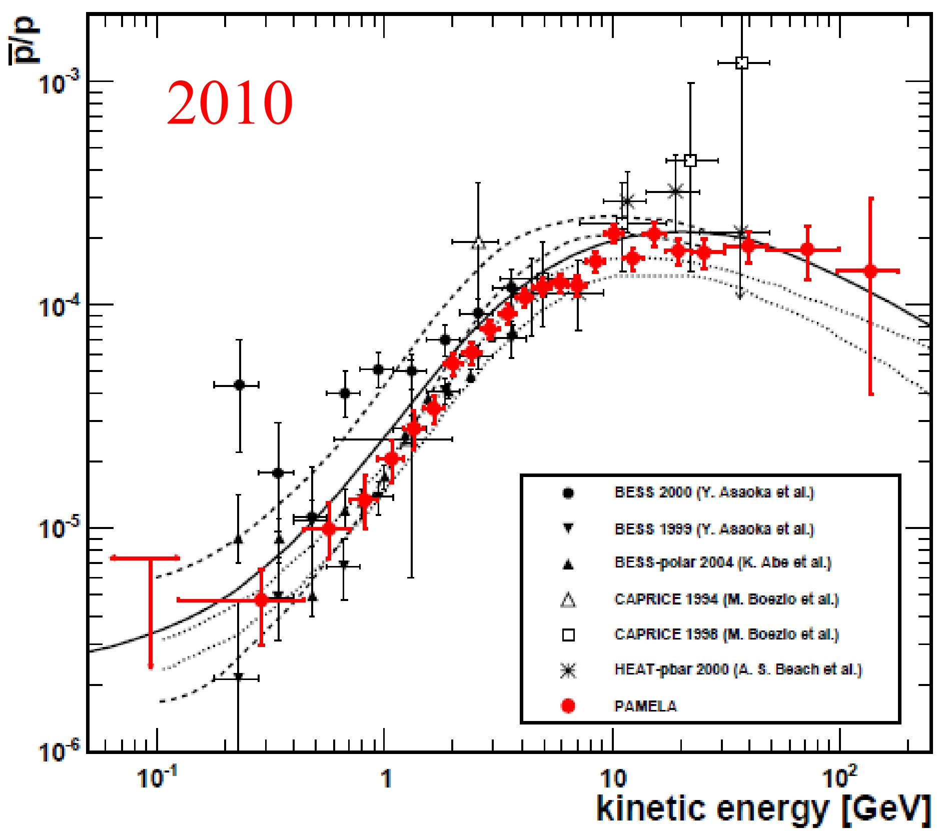
Buchmüller et al.

Conclusions

■ We have entered an era where indirect searches provide strong constraints on the dark matter properties. Or from the optimistic point of view, there exists (perhaps for the first time) a discovery potential.



Jungman, Kamionkowski, Griest



Conclusions

■ We have entered an era where indirect searches provide strong constraints on the dark matter properties. Or from the optimistic point of view, there exists (perhaps for the first time) a discovery potential.

■ A few anomalies have been reported, which can be interpreted as originated from dark matter annihilations/decays. Very exciting, but caution should prevail over excitement. Look for smoking guns and for correlations in signals in different channels/energies.

■ Bright future in indirect dark matter searches: AMS-02, IceCube, CTA... New surprises (and new challenges) are surely awaiting us.