10 July 2011
ISAPP 2011 - Heidelberg

Seeing Dark Matter in cosmic rays?!?

Marco Cirelli
(CERN-TH & CNRS IPhT Saclay)

in collaboration with:
A.Strumia (Pisa)
N.Fornengo (Torino)
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M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (Saclay)
F.Iocco (Saclay + IAP Paris)
P.Serpico (CERN)

0808.3867 [astro-ph]
Nuclear Physics B 813 (2009)
JCAP 03 009 (2009)
Physics Letters B 678 (2009)
Nuclear Physics B 821 (2009)
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Nuclear Physics B 840 (2010)
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and work in progress

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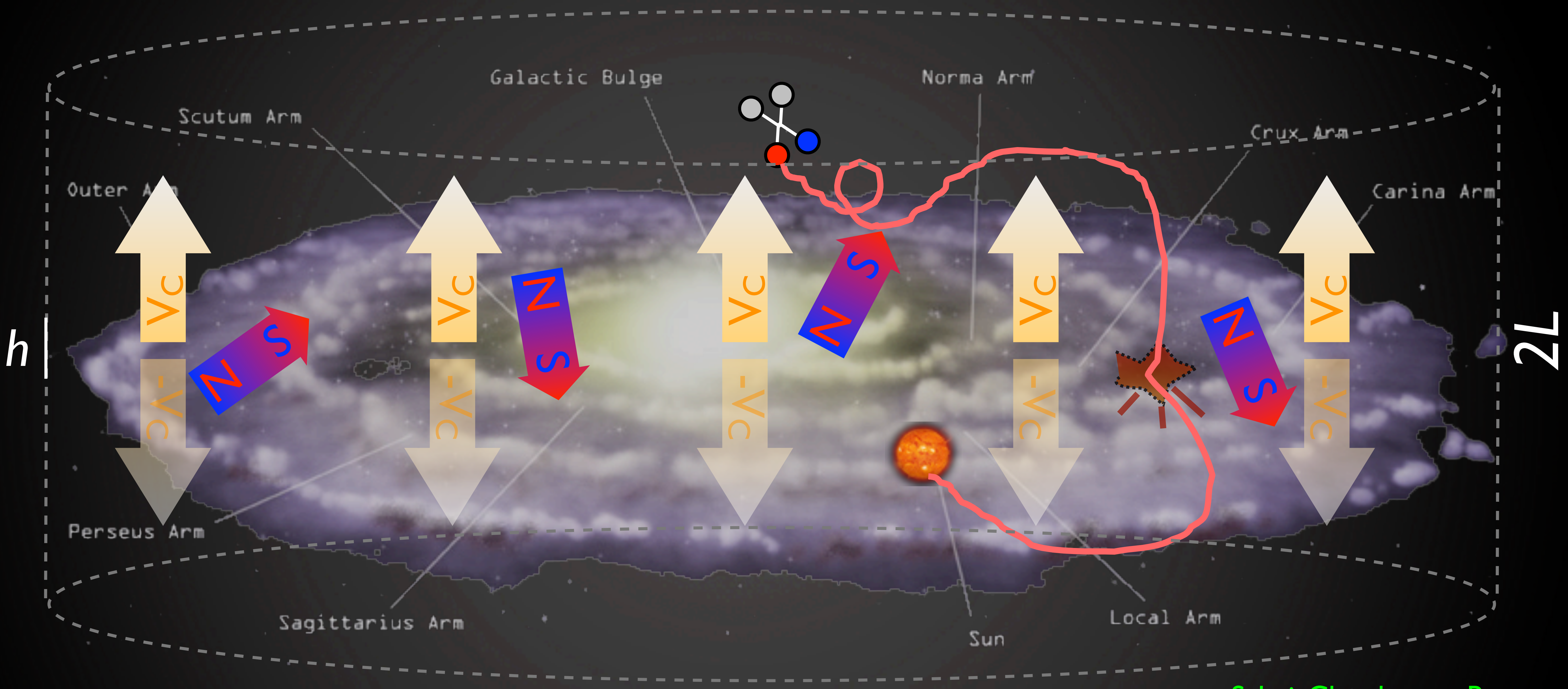
Indirect Detection

$\bar{p}$ and e^+ from DM annihilations in halo



Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

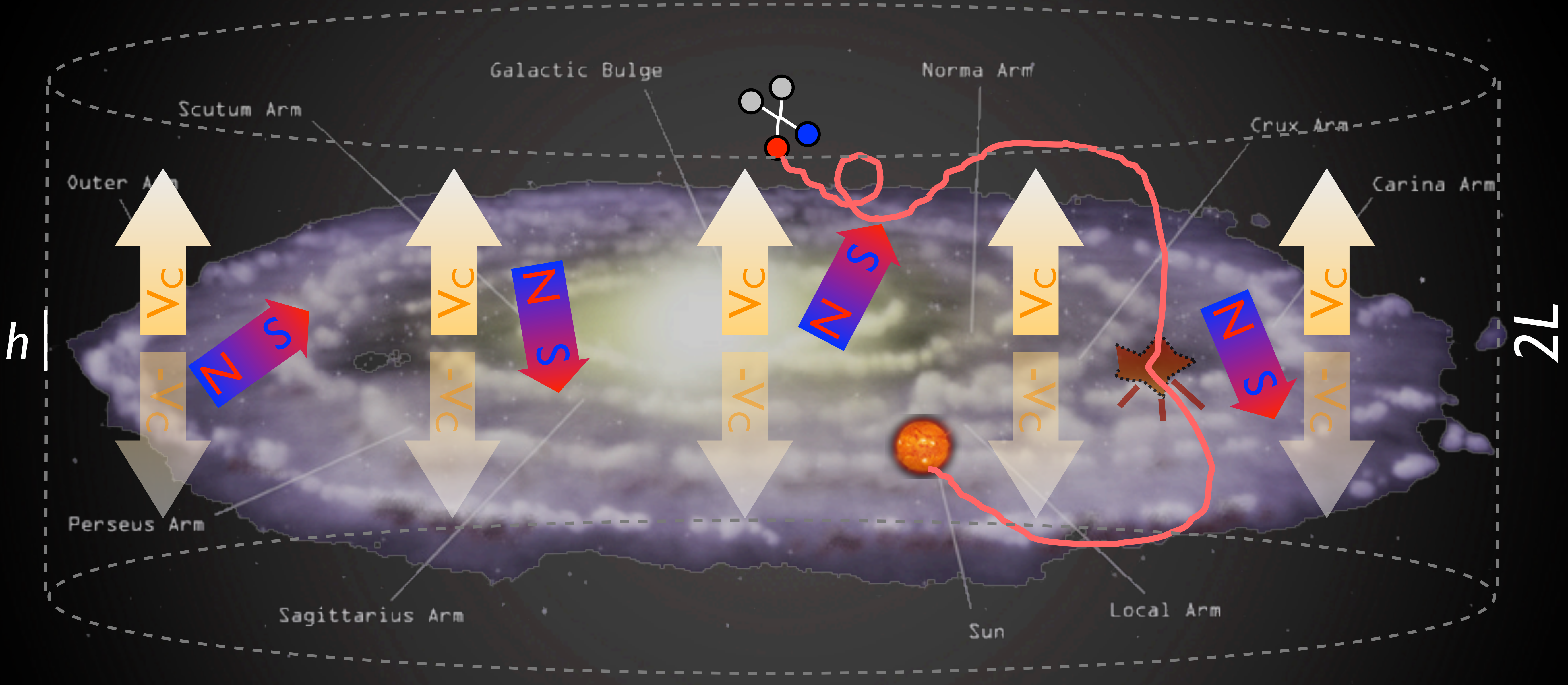
spectrum

$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\mathrm{inj}} - 2h\delta(z)\Gamma_{\mathrm{spall}}f$$

diffusion energy loss convective wind source spallations

Indirect Detection

$\bar{p}$ and e^+ from DM annihilations in halo



What sets the overall expected flux?

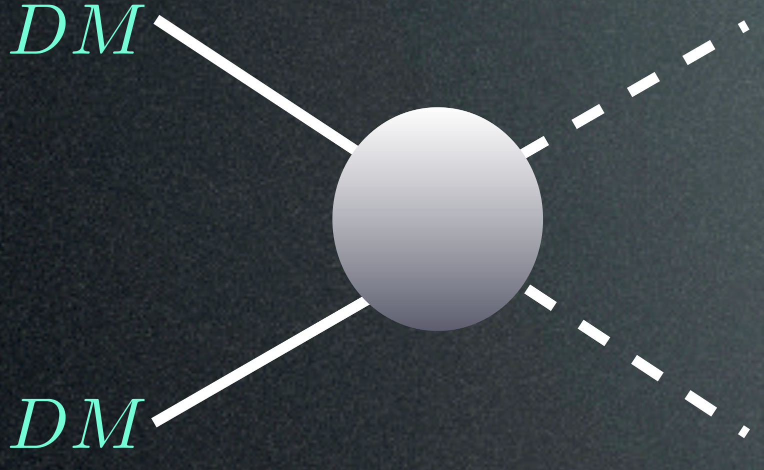
$$\text{flux} \propto \underbrace{n^2}_{\text{astro\& cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

reference cross section:

$\sigma v = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$

Computing the theory predictions

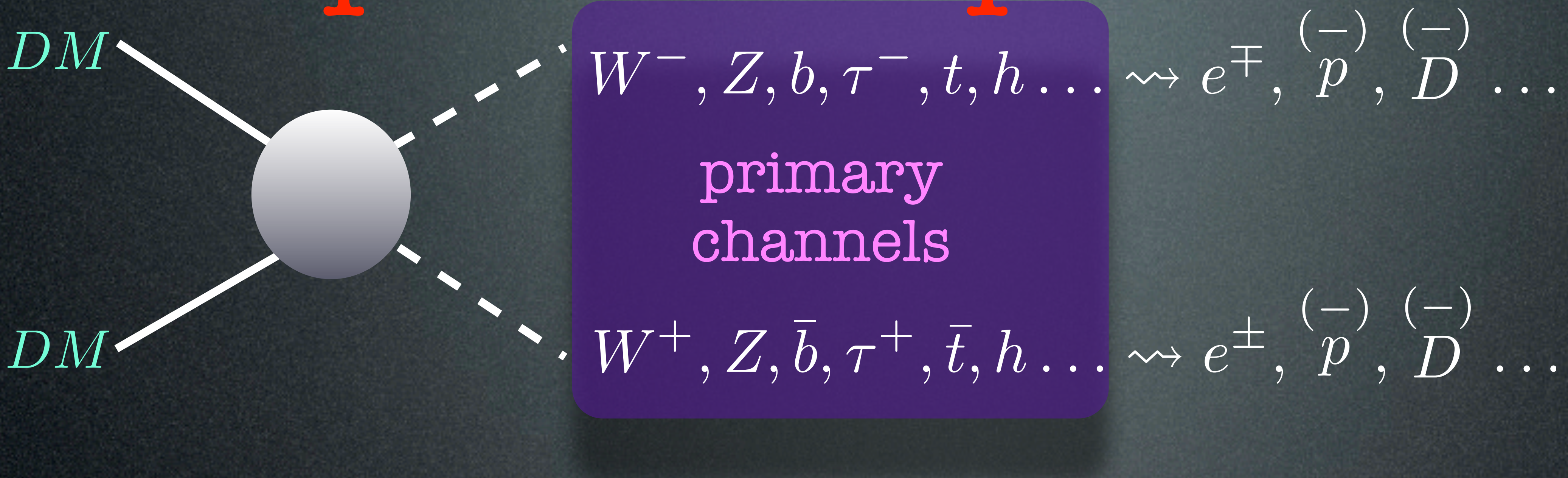
Spectra at production



$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$$

Spectra at production



DM

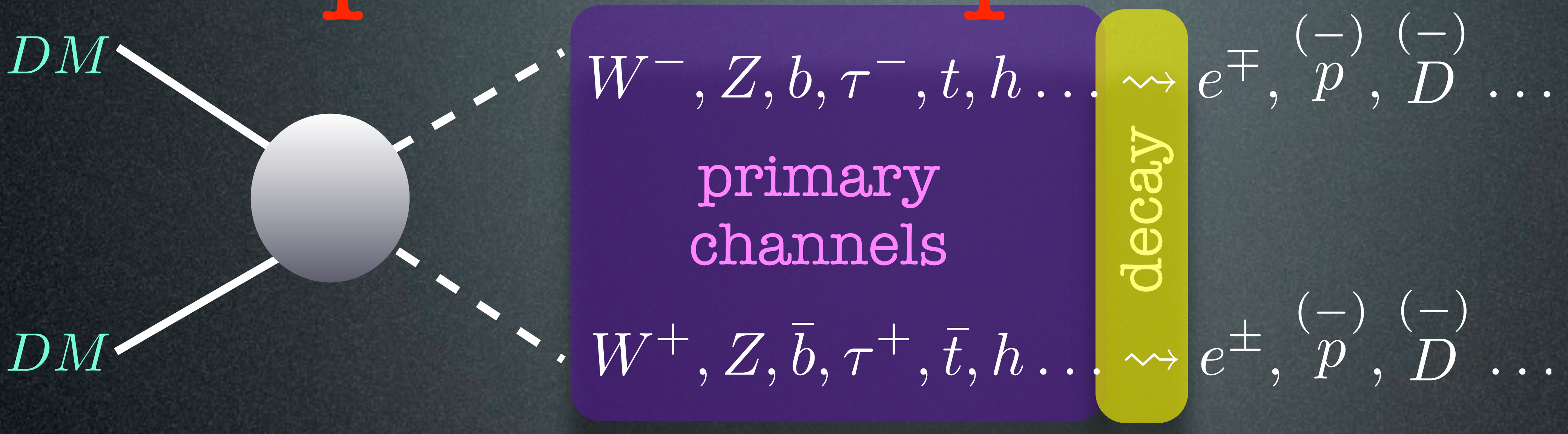
DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

Spectra at production



DM

DM

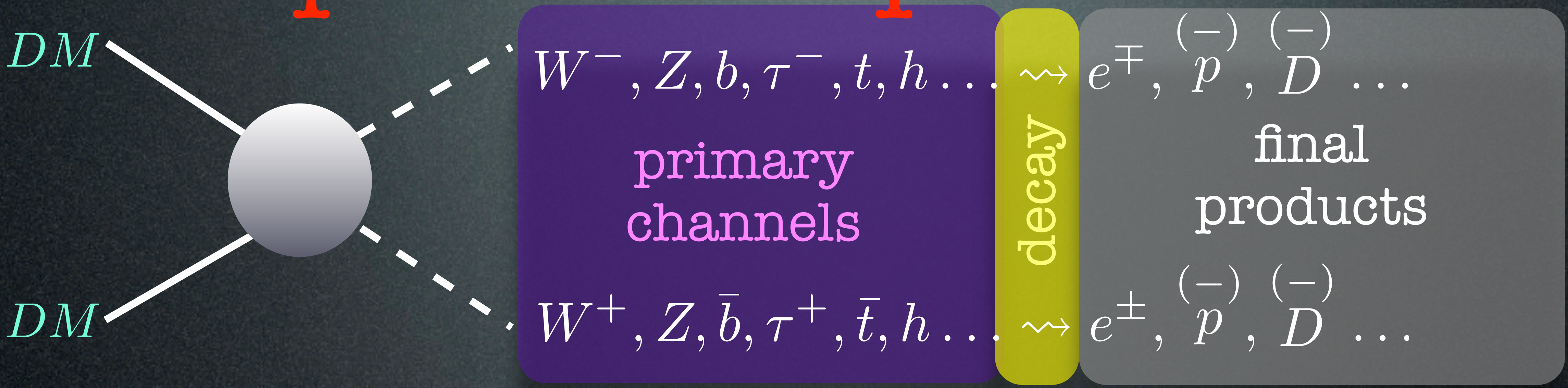
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary channels

decay

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

Spectra at production



DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

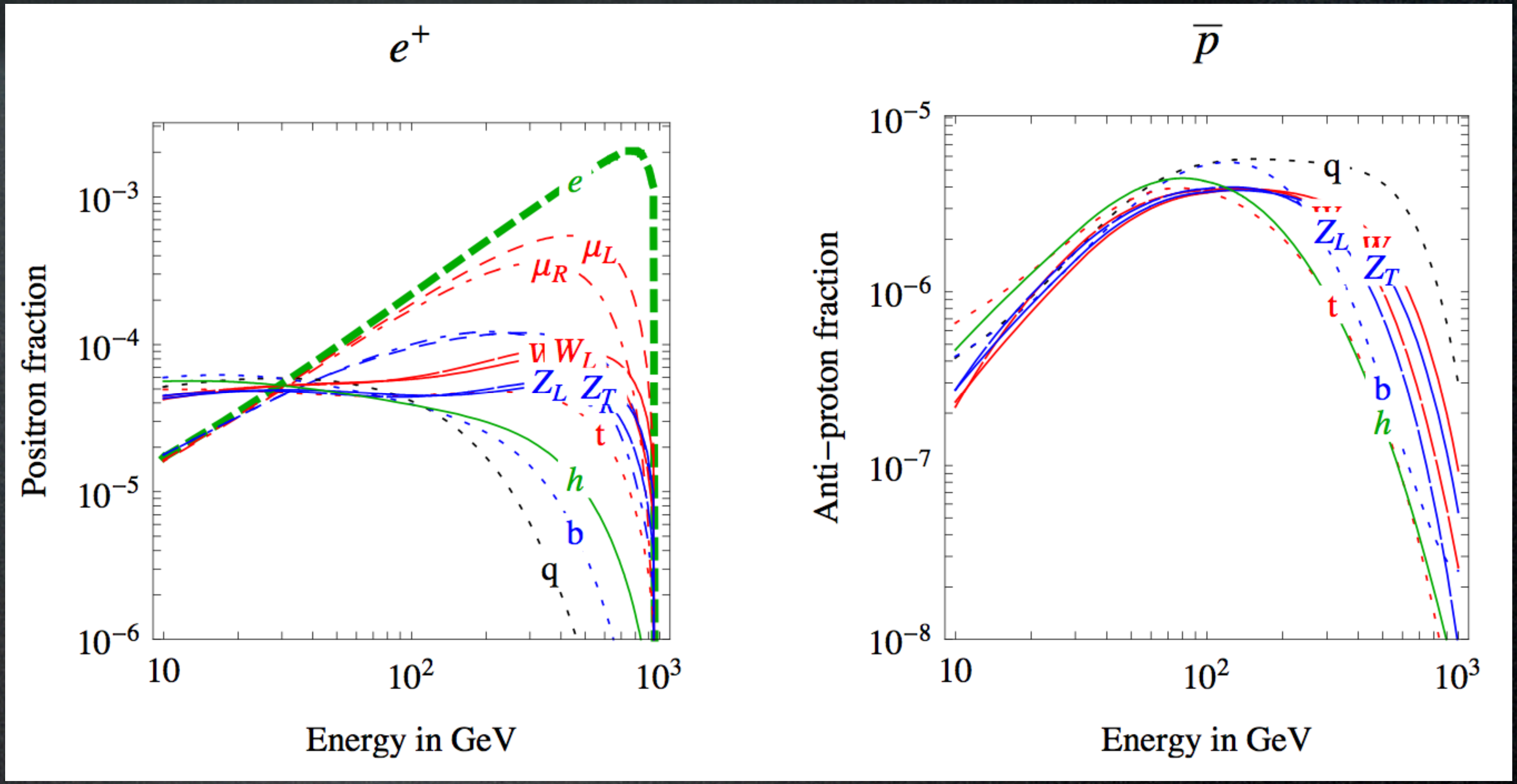
primary channels

decay

final products

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

DM



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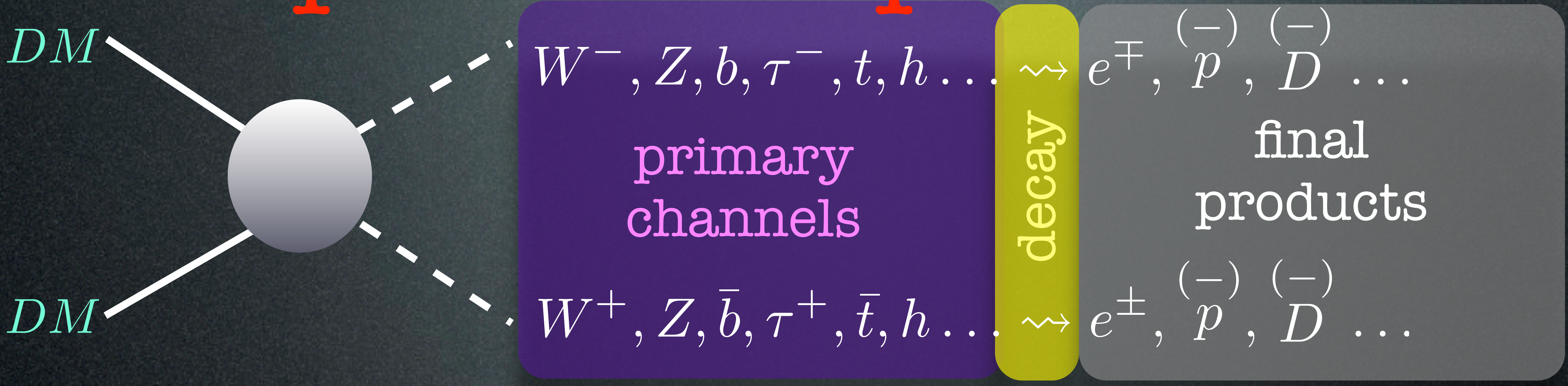

DM

DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

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final products

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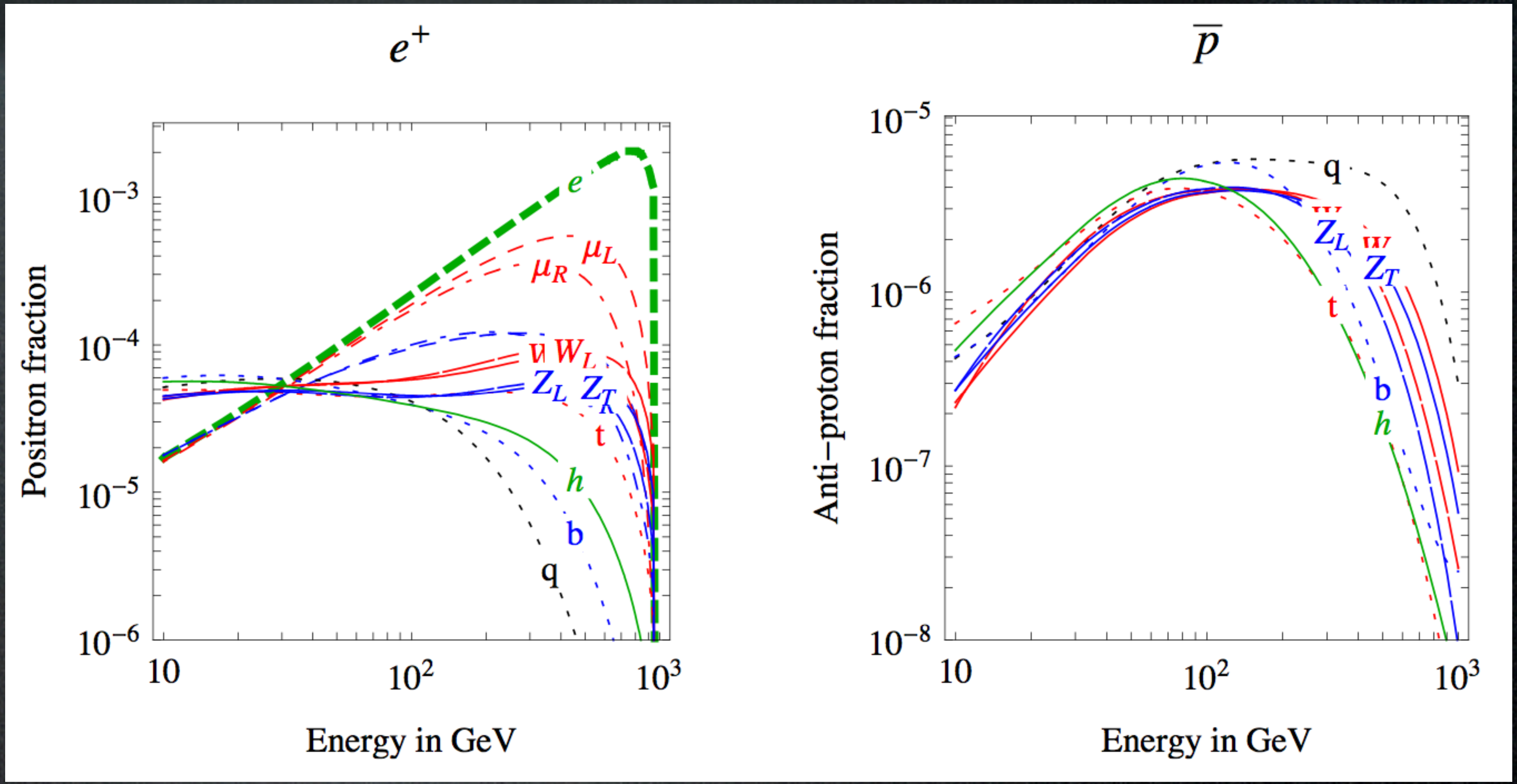


So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)

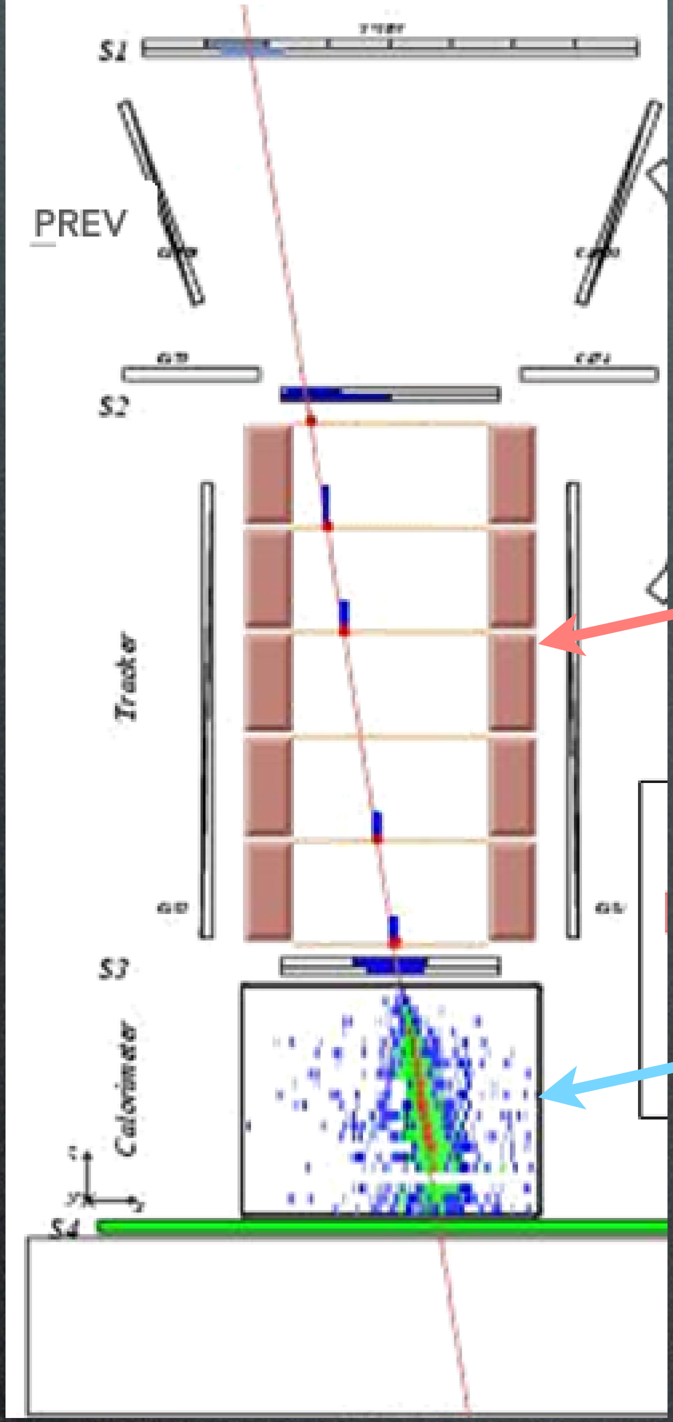
Comparing with data

Data sets

Positrons from PAMELA:

Payload for
Anti-
Matter
Exploration and
Light-nuclei
Astrophysics

92 GeV positron event



calibrated on accelerator fluxes

magnetic spectrometer:
charge and energy

calorimeter: $e^{\pm}$ vs $p/\bar{p}$

(make showers) (swipe thru)

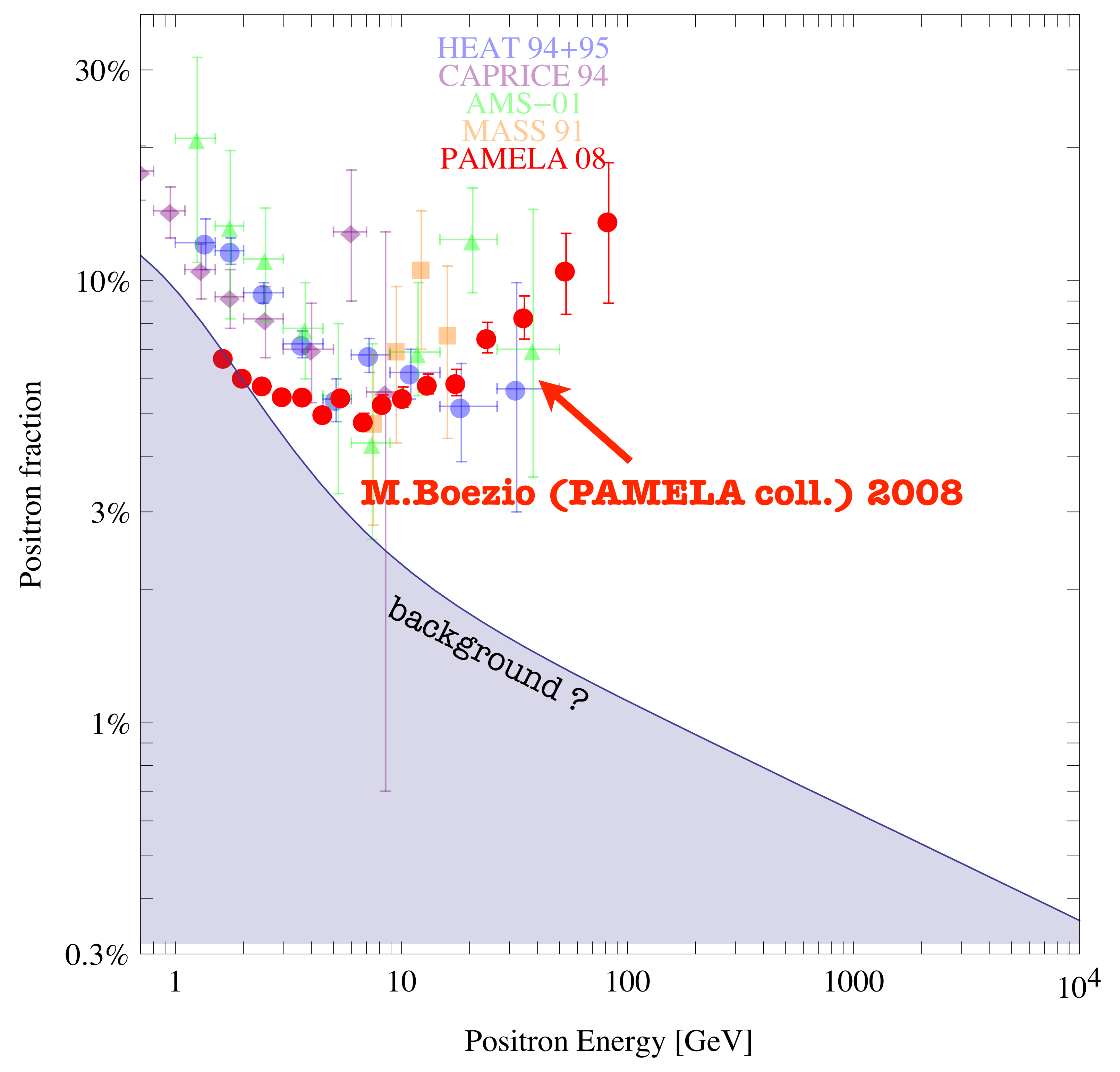
Big challenge: backgnd contamination
from p (10^4 more numerous at 100 GeV)

Data sets

Positrons from PAMELA:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\frac{e^+}{e^+ + e^-}$



(9430 e⁺ collected)

(errors statistical only,
that’s why larger at high energy)

[backgnd]

Data sets

Positrons from PAMELA:

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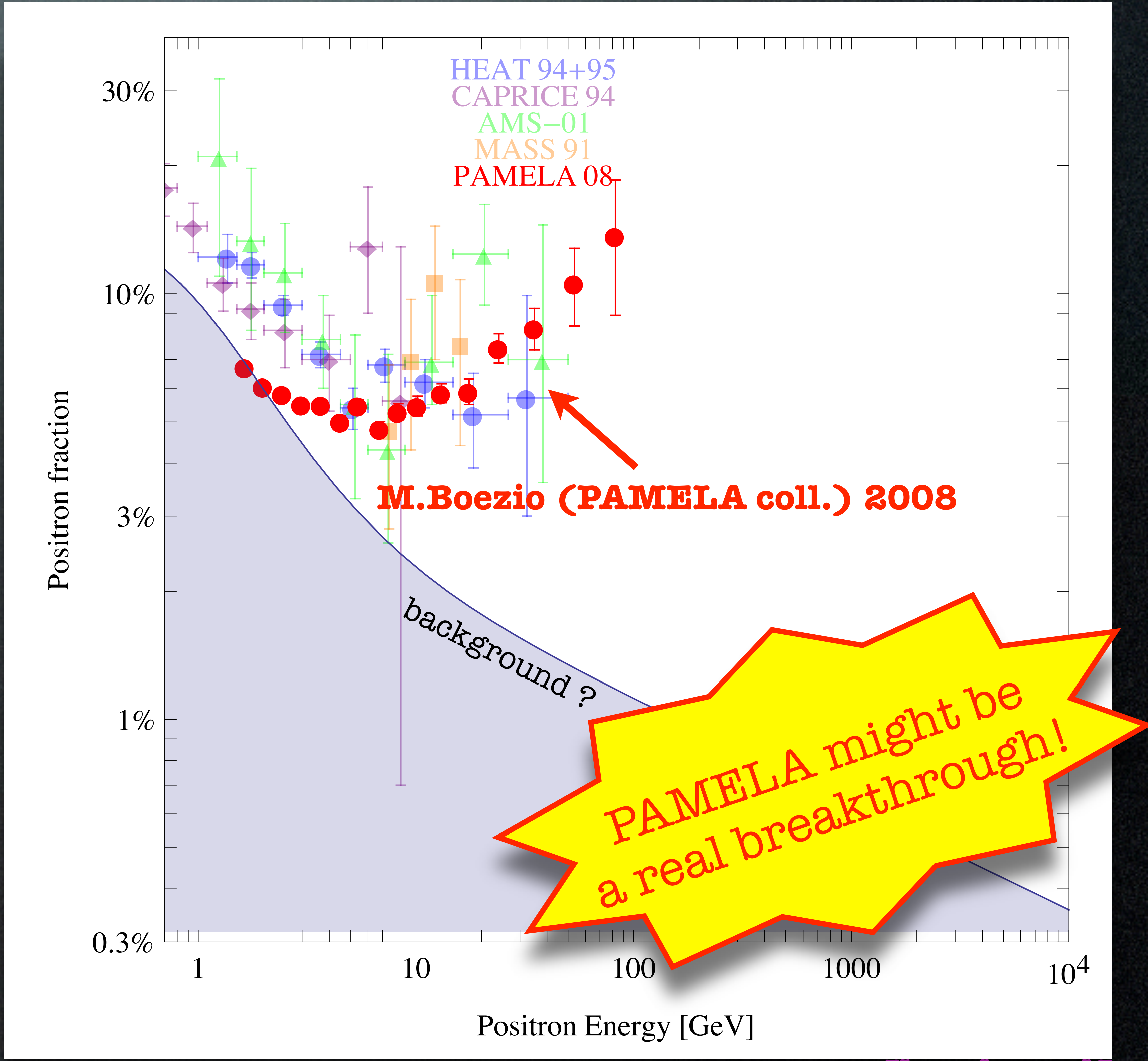
- very large flux!

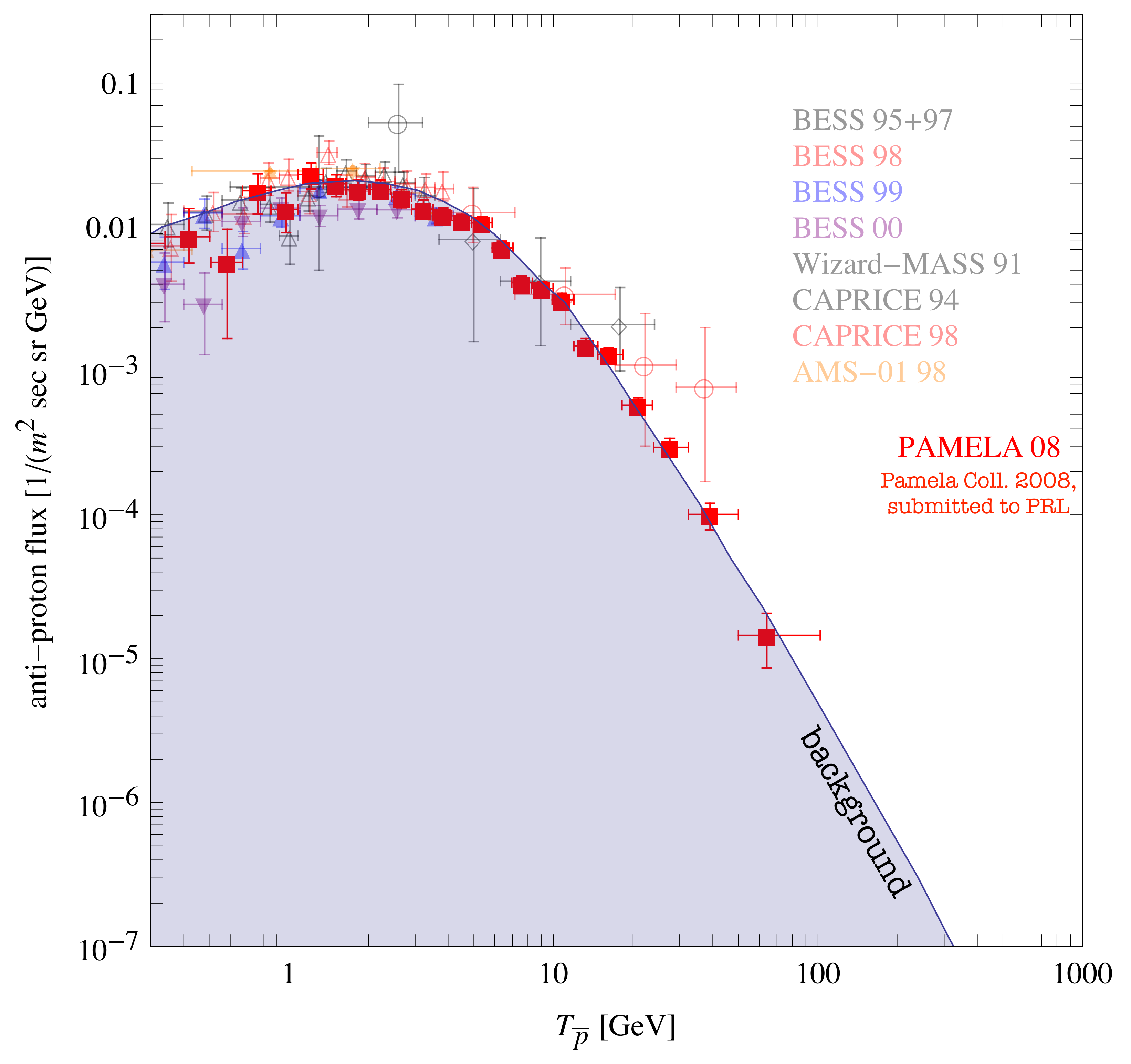


[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background



(about 1000 $\bar{p}$ collected)

Background

(

Background

Background computations for positrons:

main source: CR nuclei spallating on IS gas

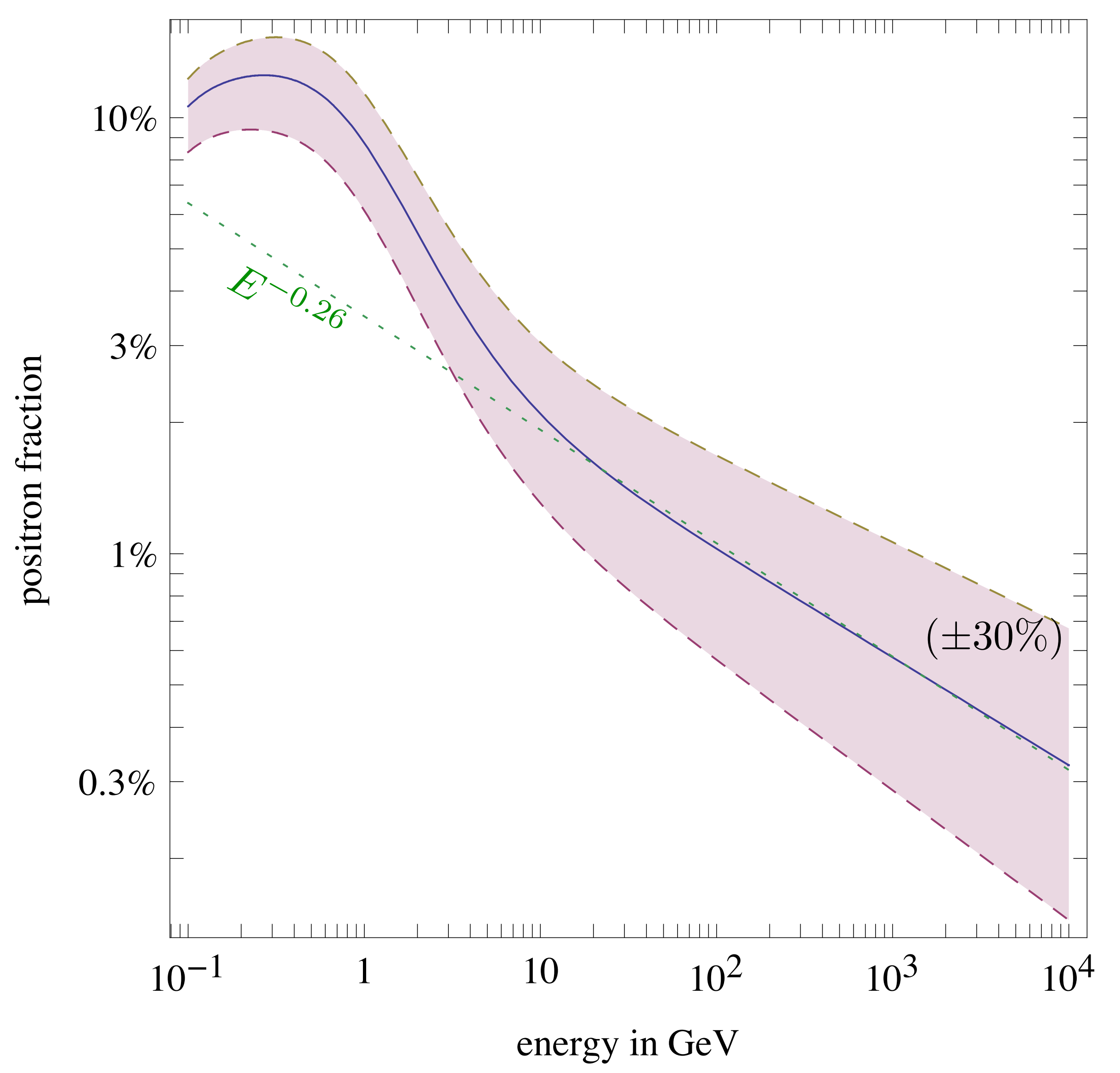
$$\Phi^{\mathrm{bkg}}_{e^+} = \frac{4.5\, E^{0.7}}{1 + 650\, E^{2.3} + 1500\, E^{4.2}}$$

$$\Phi^{\mathrm{bkg}}_{e^-} = \Phi^{\mathrm{bkg,\,prim}}_{e^-} + \Phi^{\mathrm{bkg,\,sec}}_{e^-} = \frac{0.16\, E^{-1.1}}{1 + 11\, E^{0.9} + 3.2\, E^{2.15}} + \frac{0.70\, E^{0.7}}{1 + 110\, E^{1.5} + 580\, E^{4.2}}$$

Baltz, Edsjo 1999

On the basis of CR simulations of
Moskalenko, Strong 1998

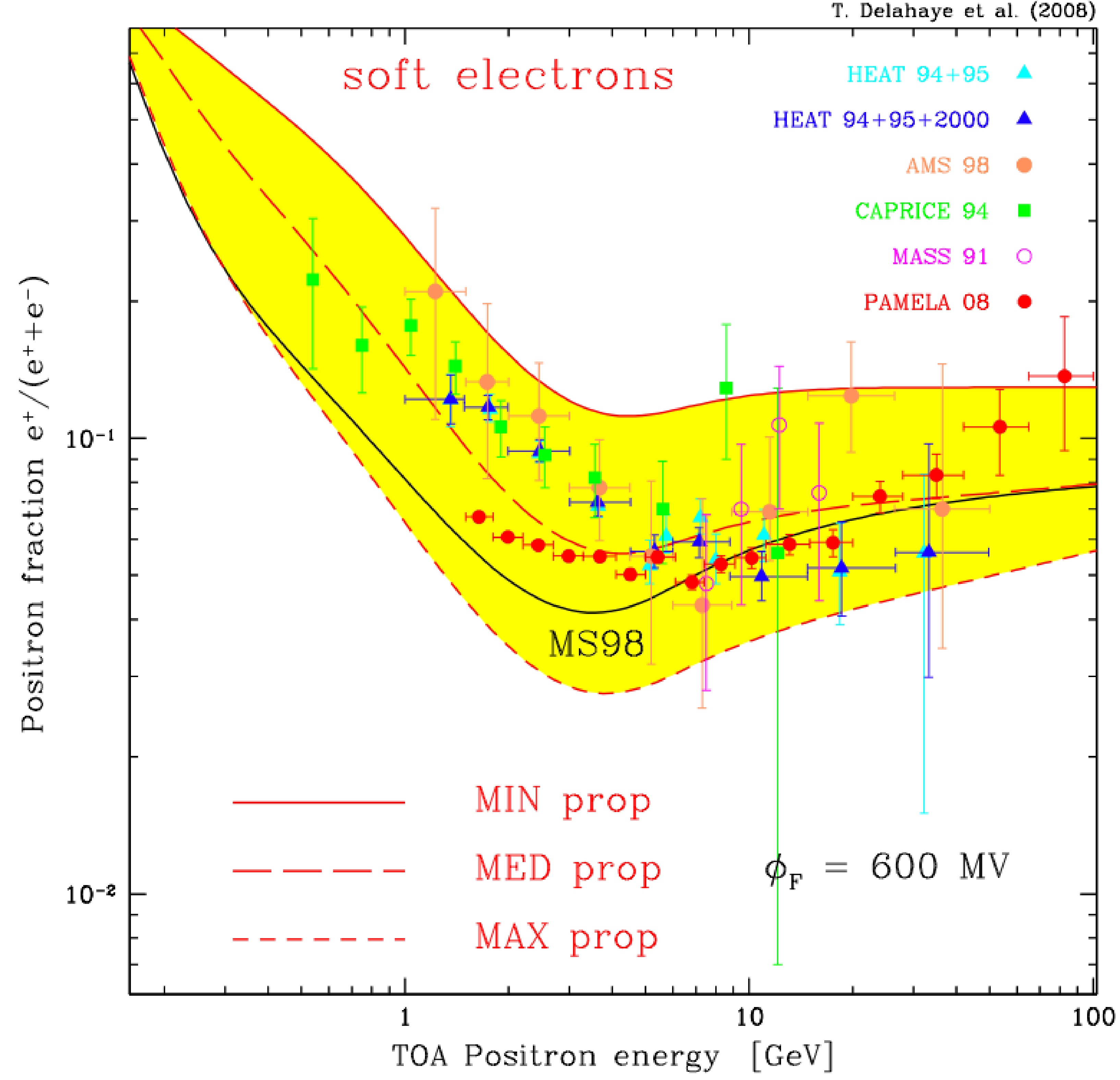
More recently:
Delahaye et al., 0809.5268
P.Salati, Cargese 2007



We marginalize w.r.t. the slope
$E^p, \quad p = \pm 0.05$
and let normalization free.

Background

Background estimation for positrons:



T.Delahaye et al., 09.2008

using new measuremens of electron fluxes

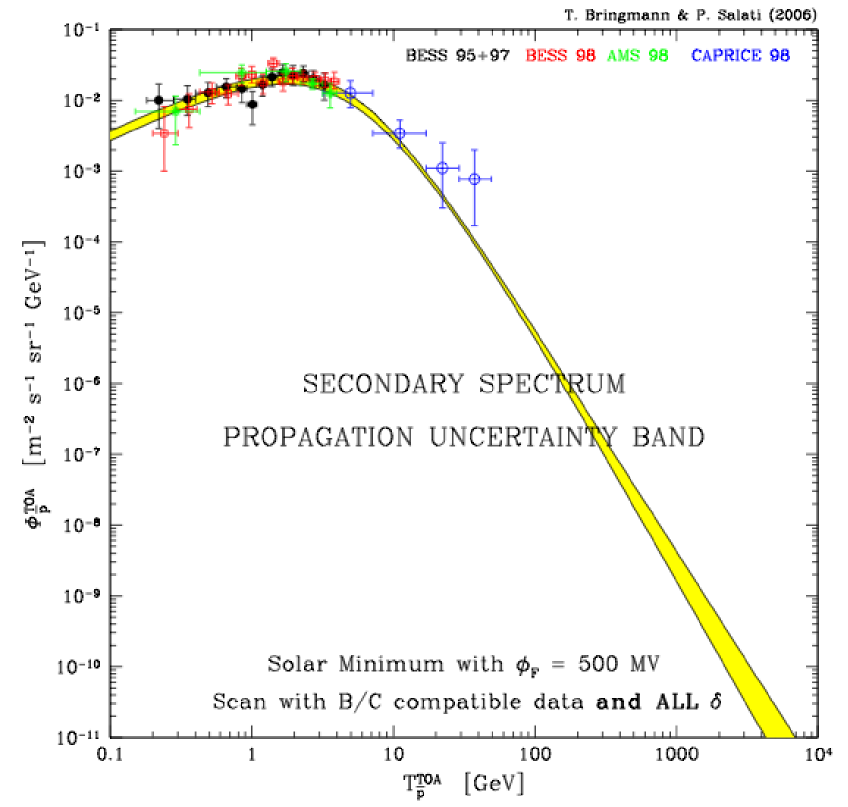
Casadei, Bindi 2008

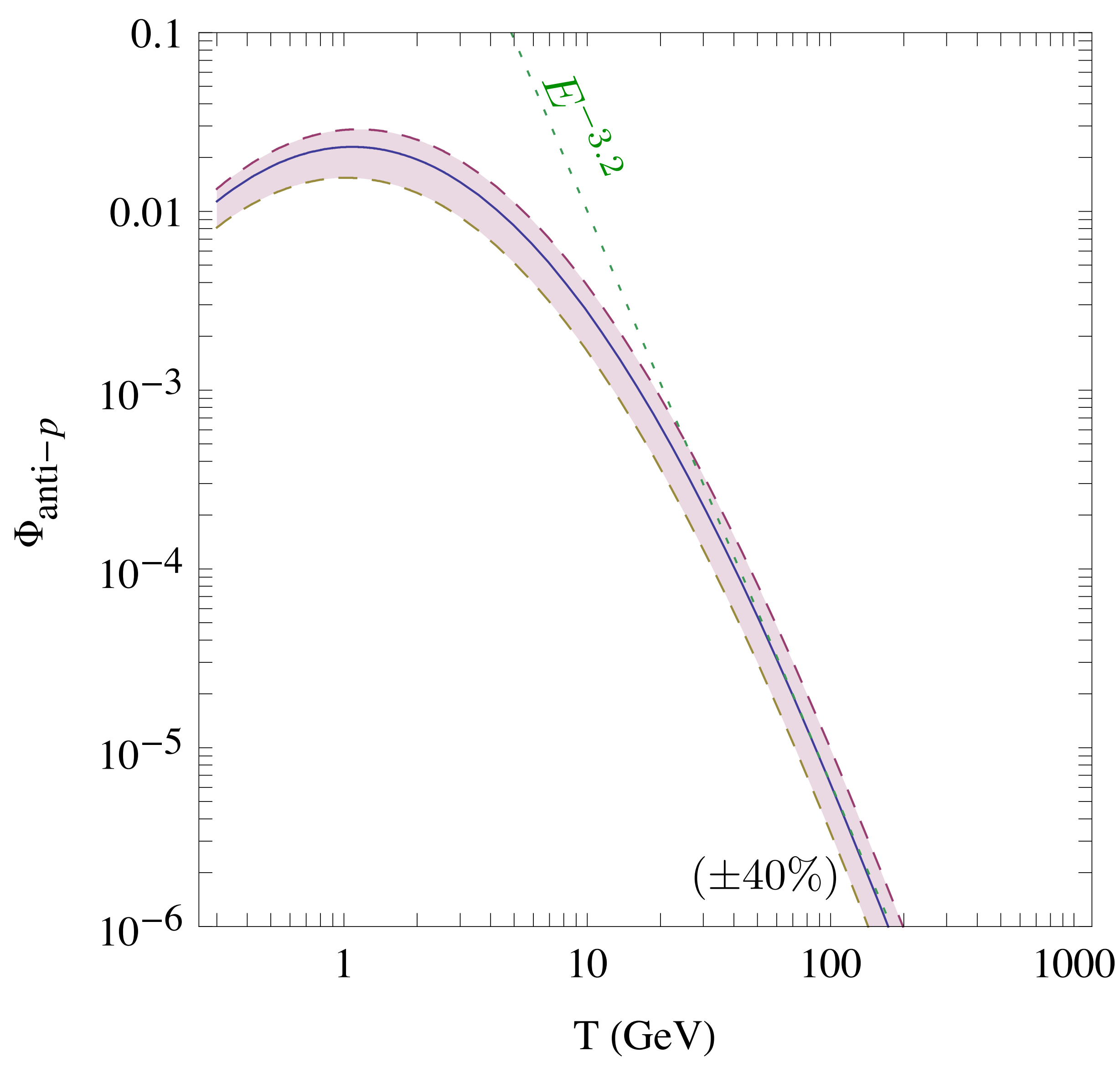
Background

Background computations for antiprotons:

$$\log_{10}\Phi_{\bar{p}}^{\rm bkg} = -1.64 + 0.07\,\tau - \tau^2 - 0.02\,\tau^3 + 0.028\,\tau^4 \qquad \tau = \log_{10}T/{\rm GeV}$$

Bringmann, Salati 2006





We marginalize w.r.t. the slope $E^p, \quad p = \pm 0.05$ and let normalization free.

Background

Results

Which DM spectra can fit the data?

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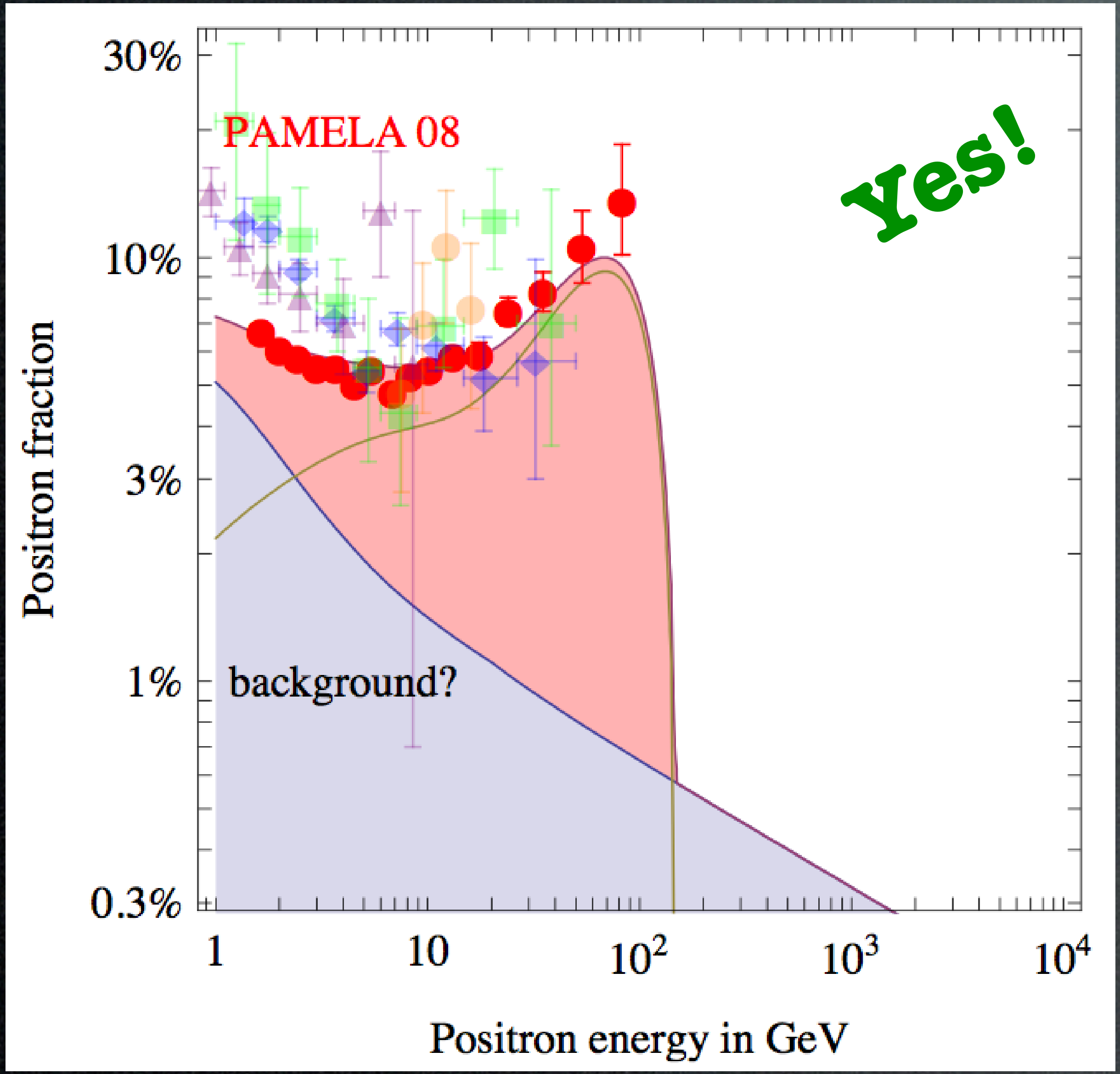
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\rm DM} = 150\,{\rm GeV}$

-annihilation $\rm DM\ DM \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



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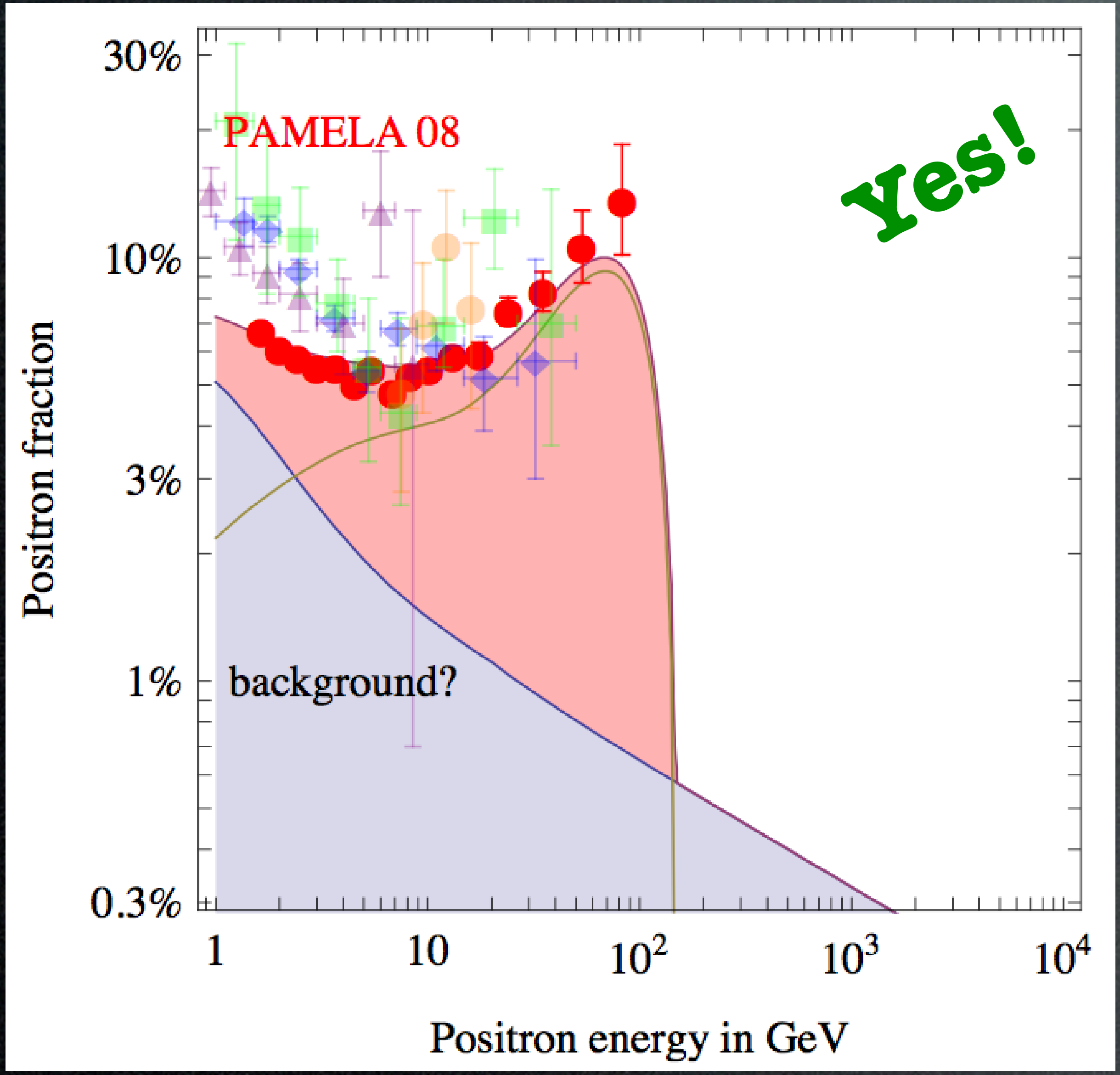
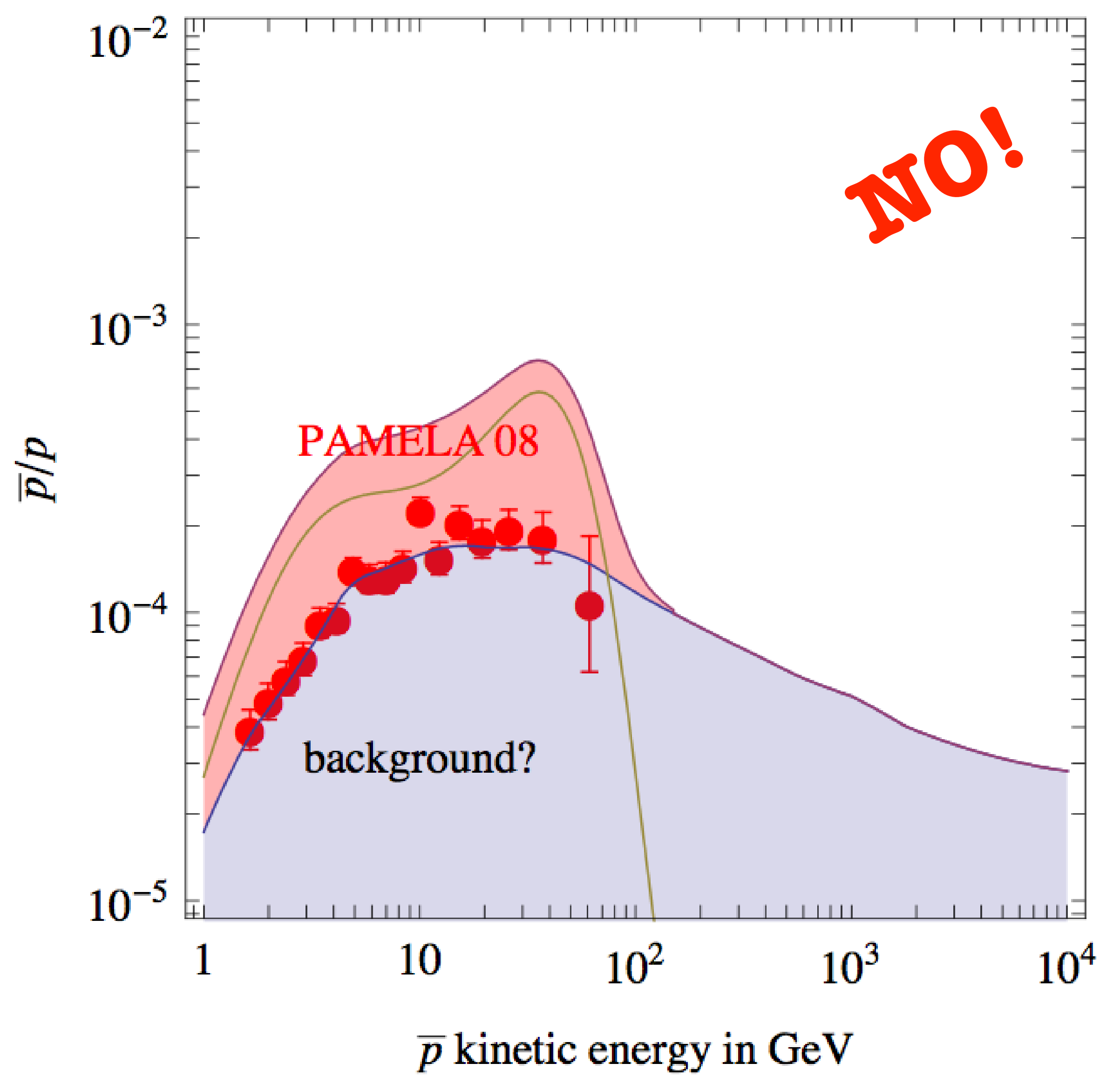


Anti-protons:



[insisting on Winos]

Results

Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

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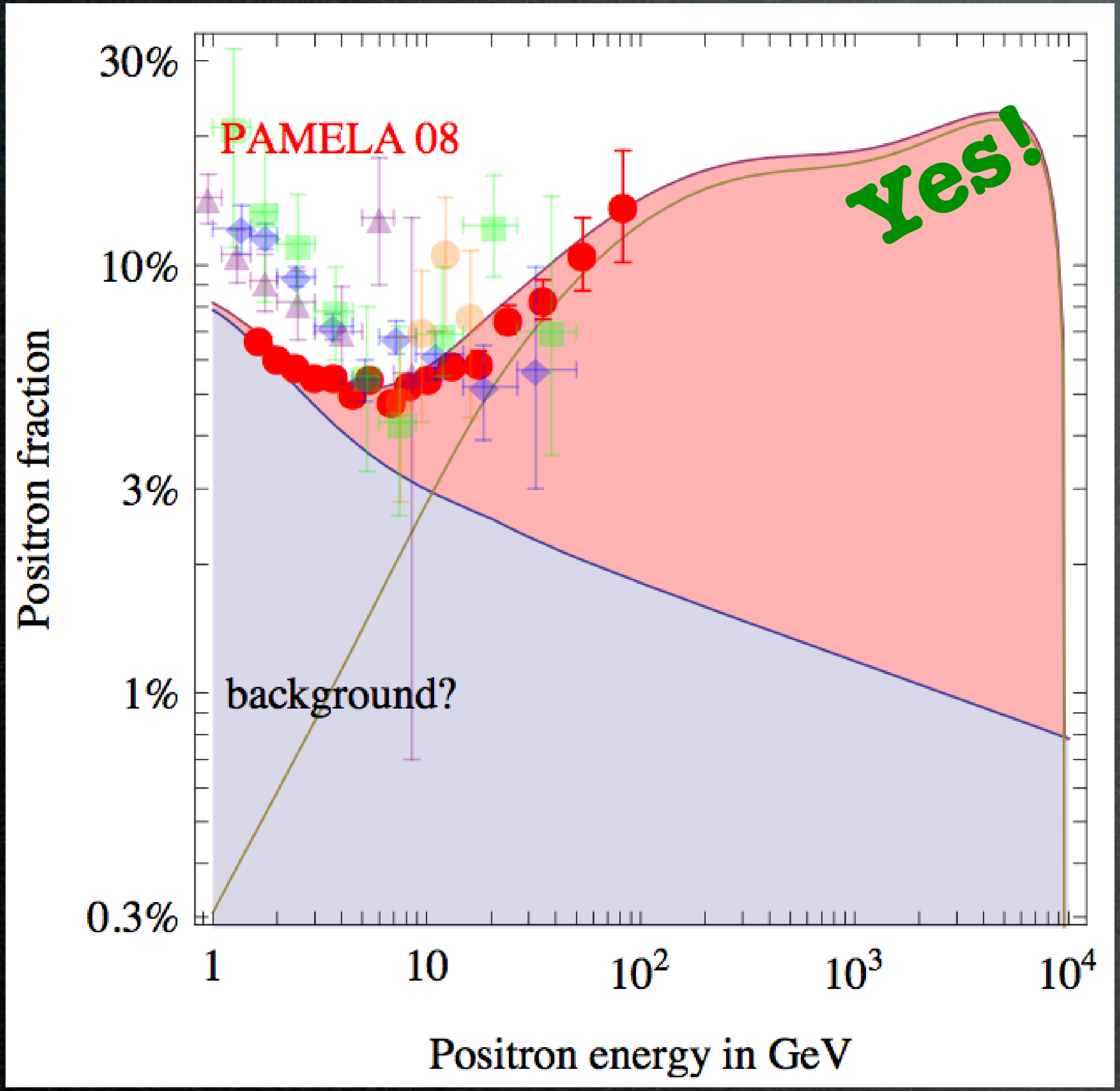

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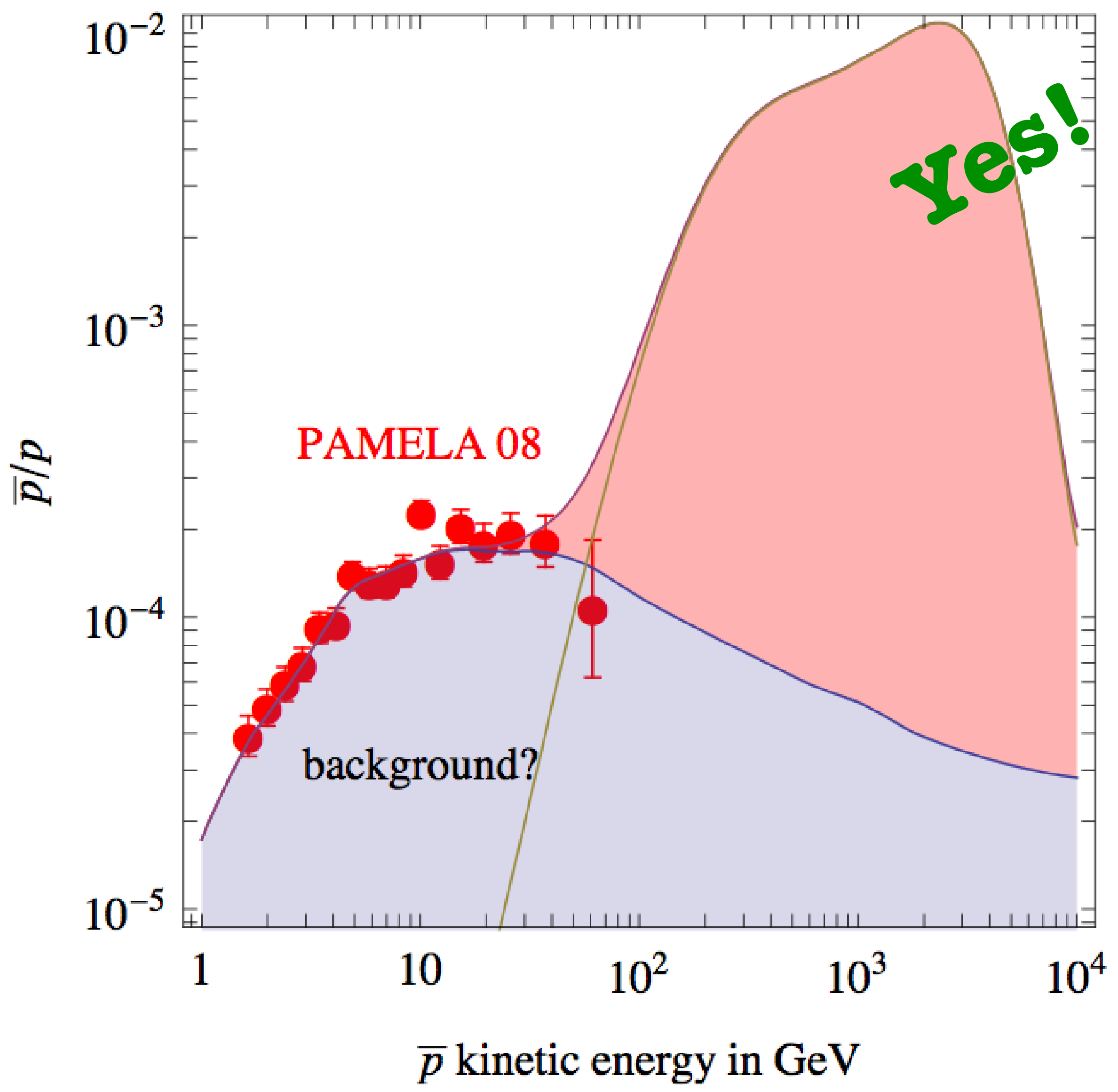

Results

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E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

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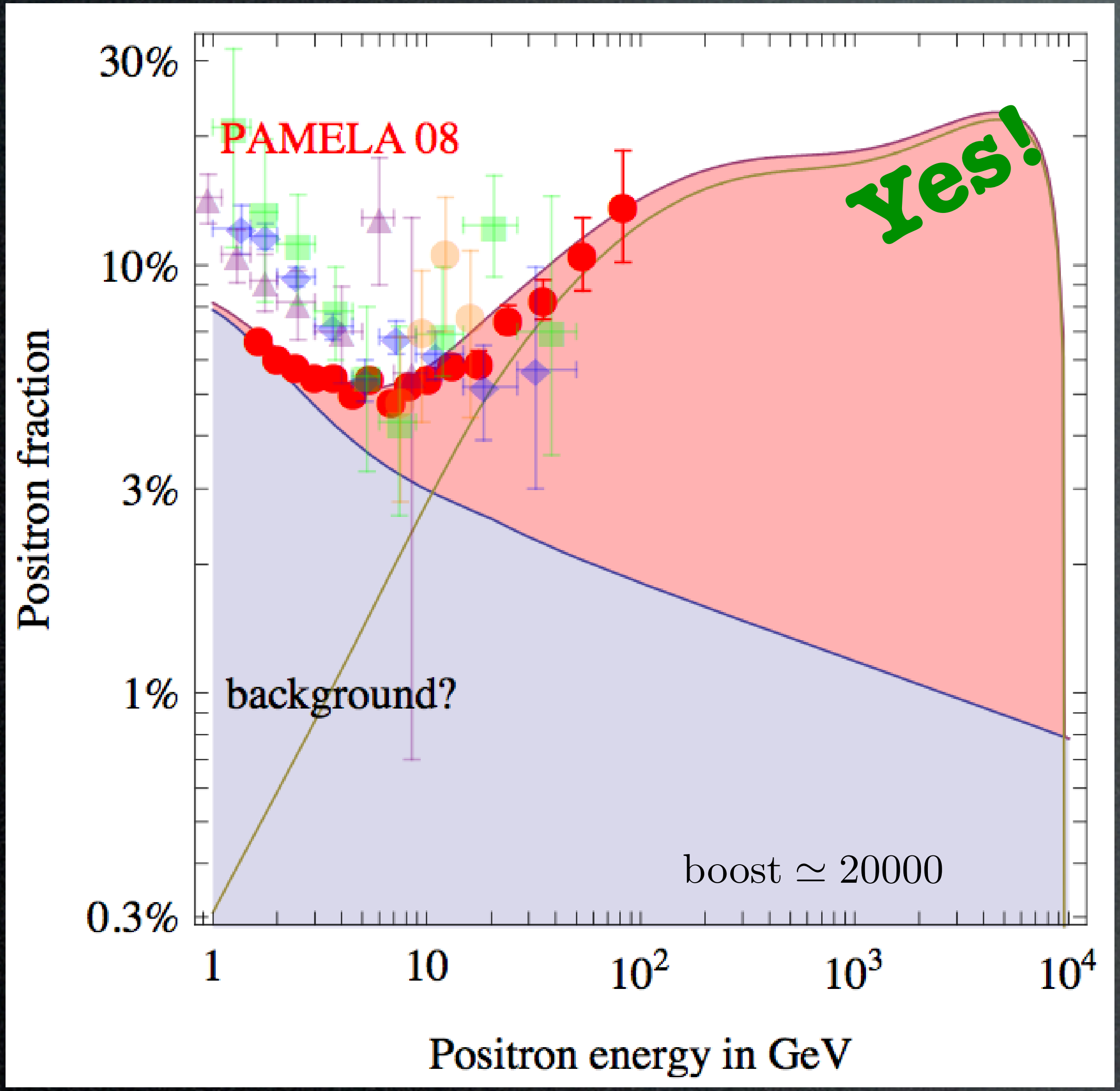
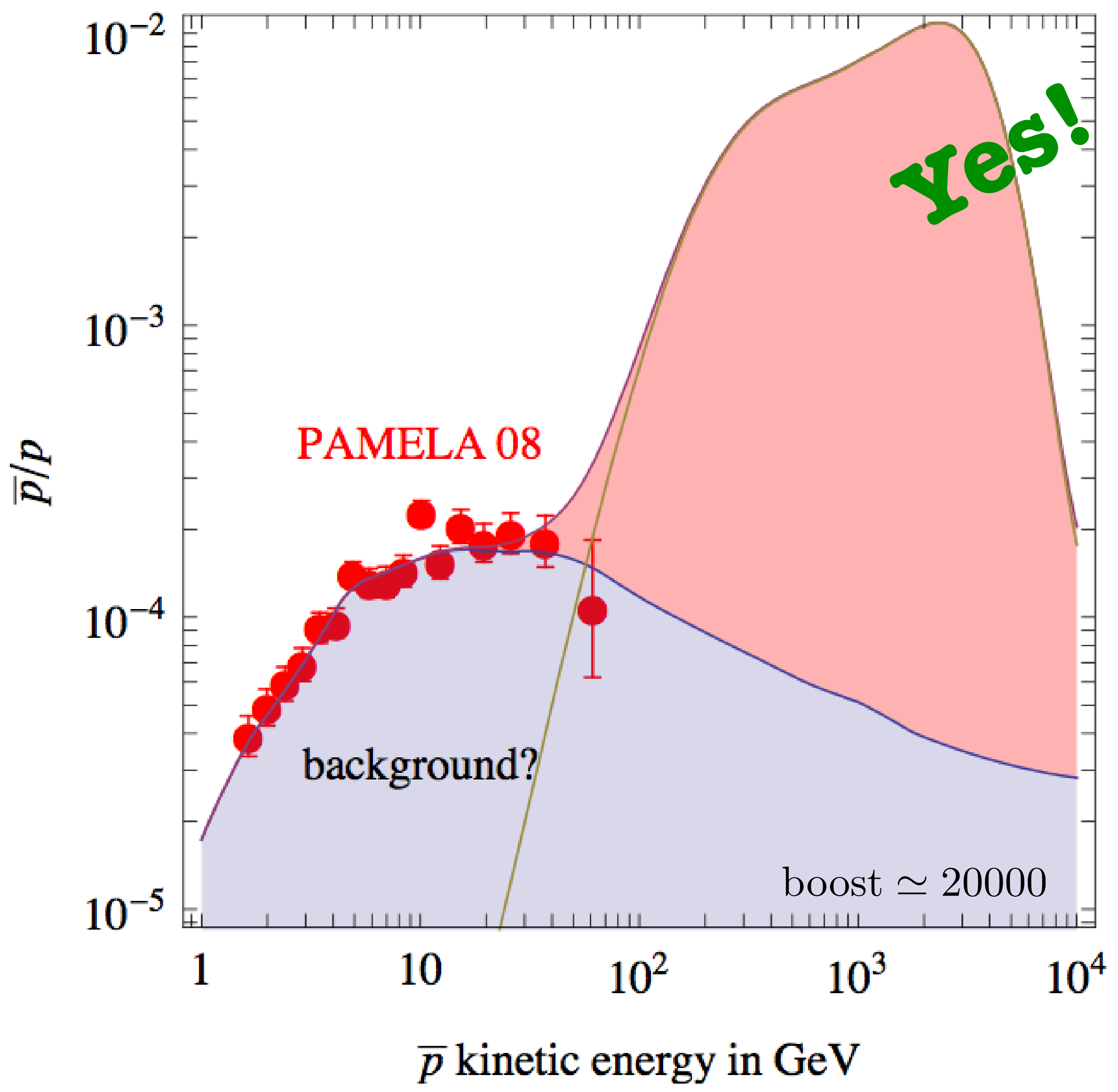
but...: -cross sec $\sigma_{\rm ann}v = 6\cdot 10^{-22}{\rm cm}^3/{\rm sec}$

Mmm...

Positrons:



Anti-protons:

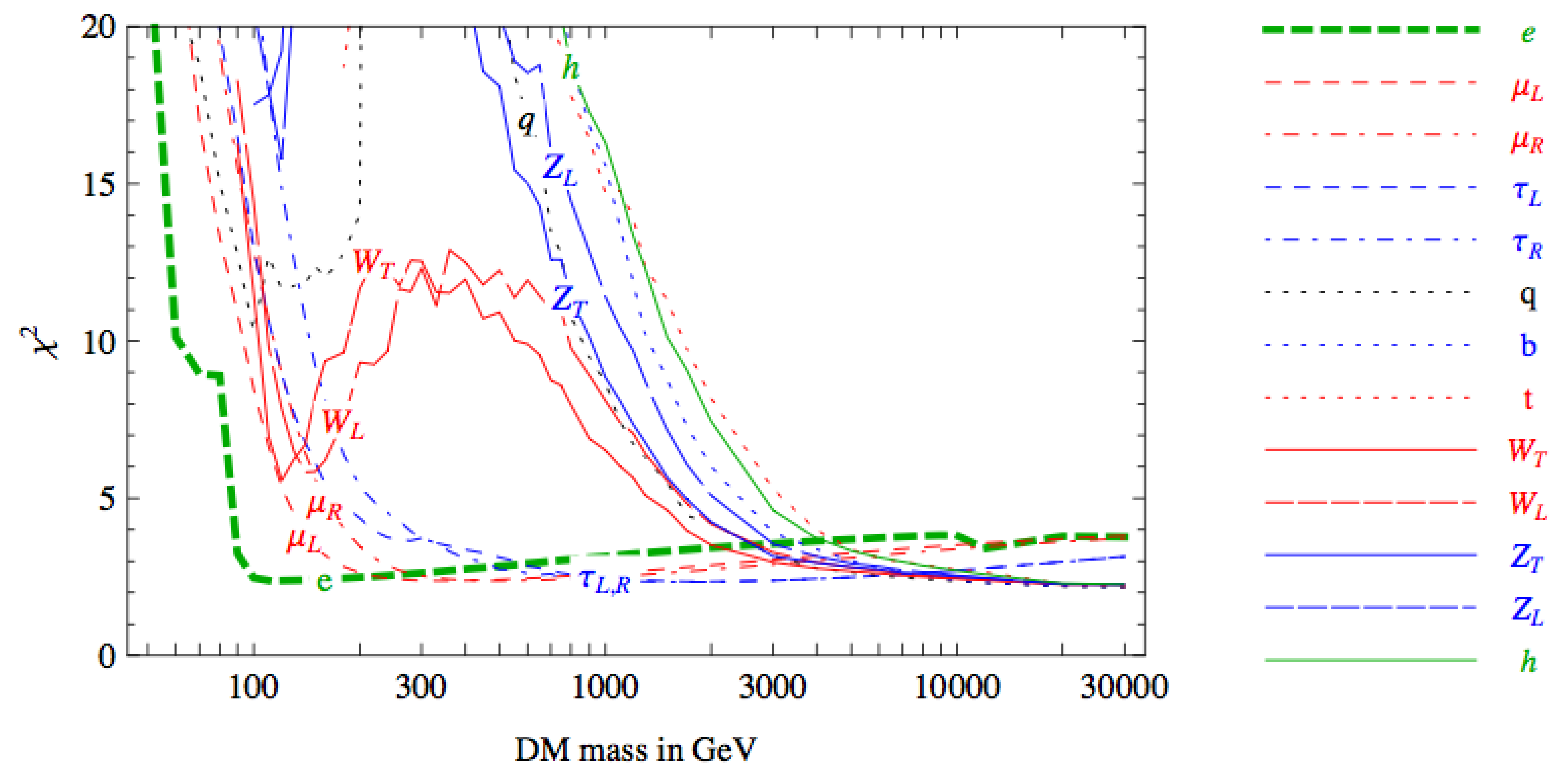


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons only

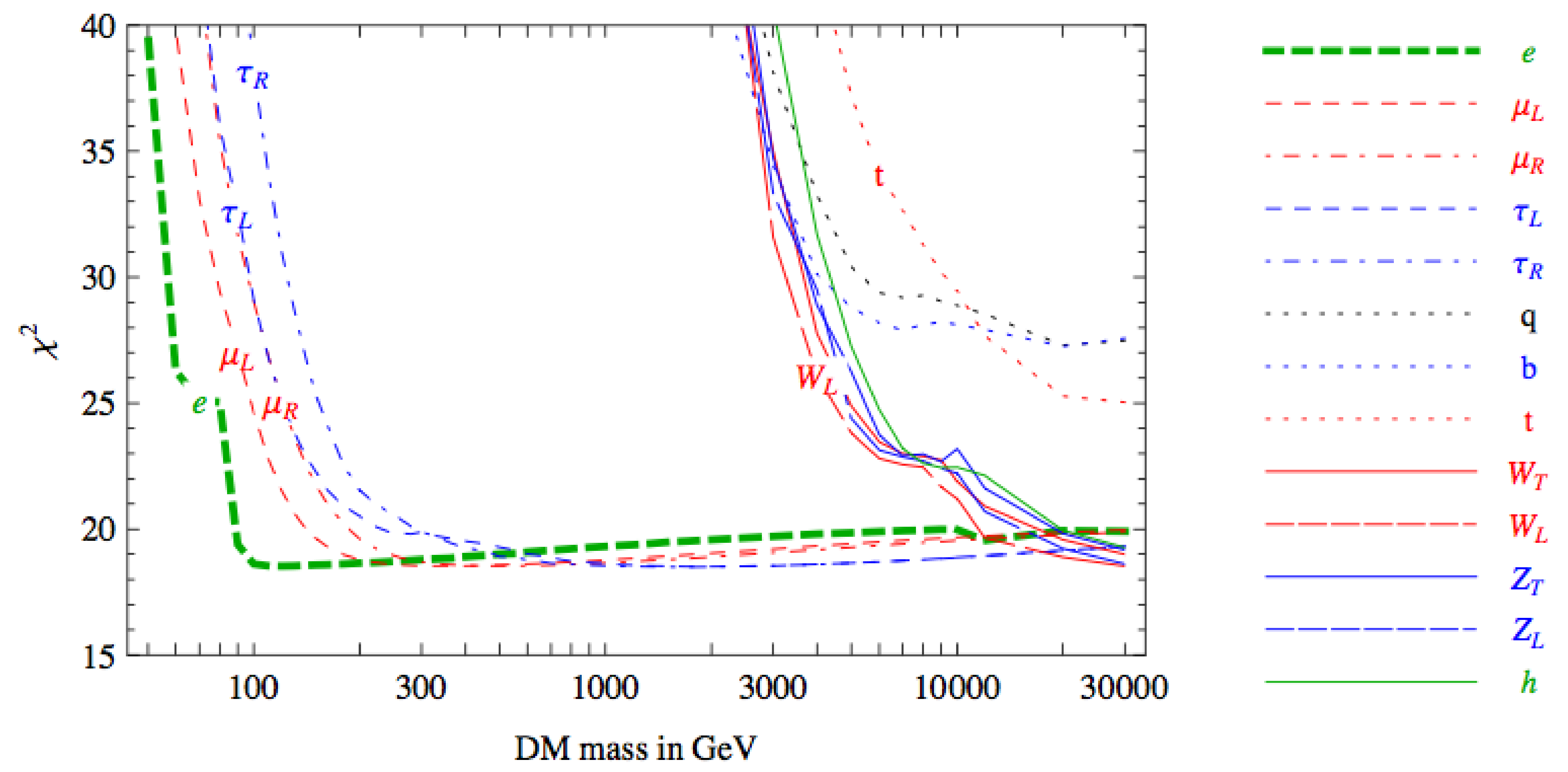


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons

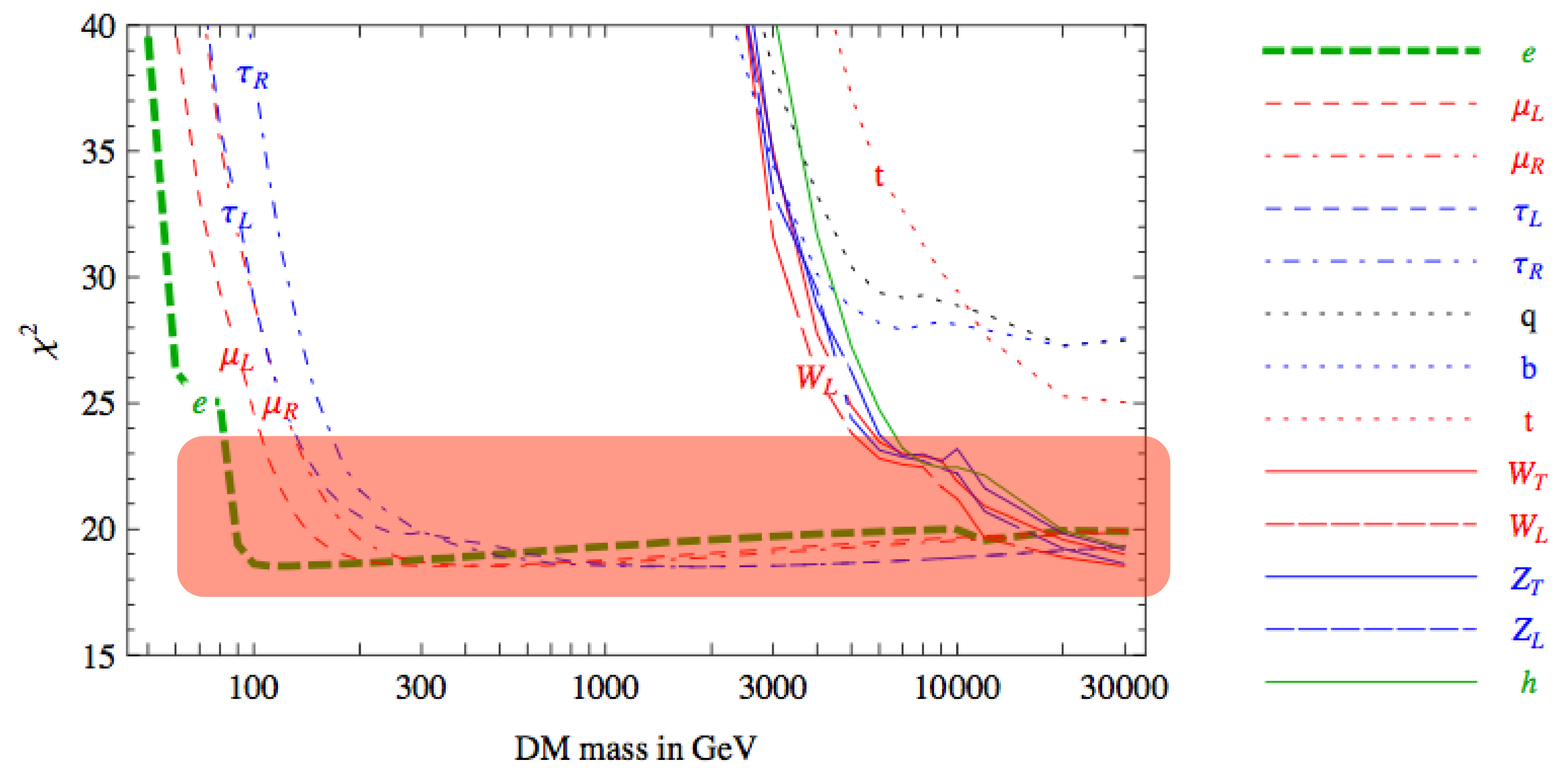


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



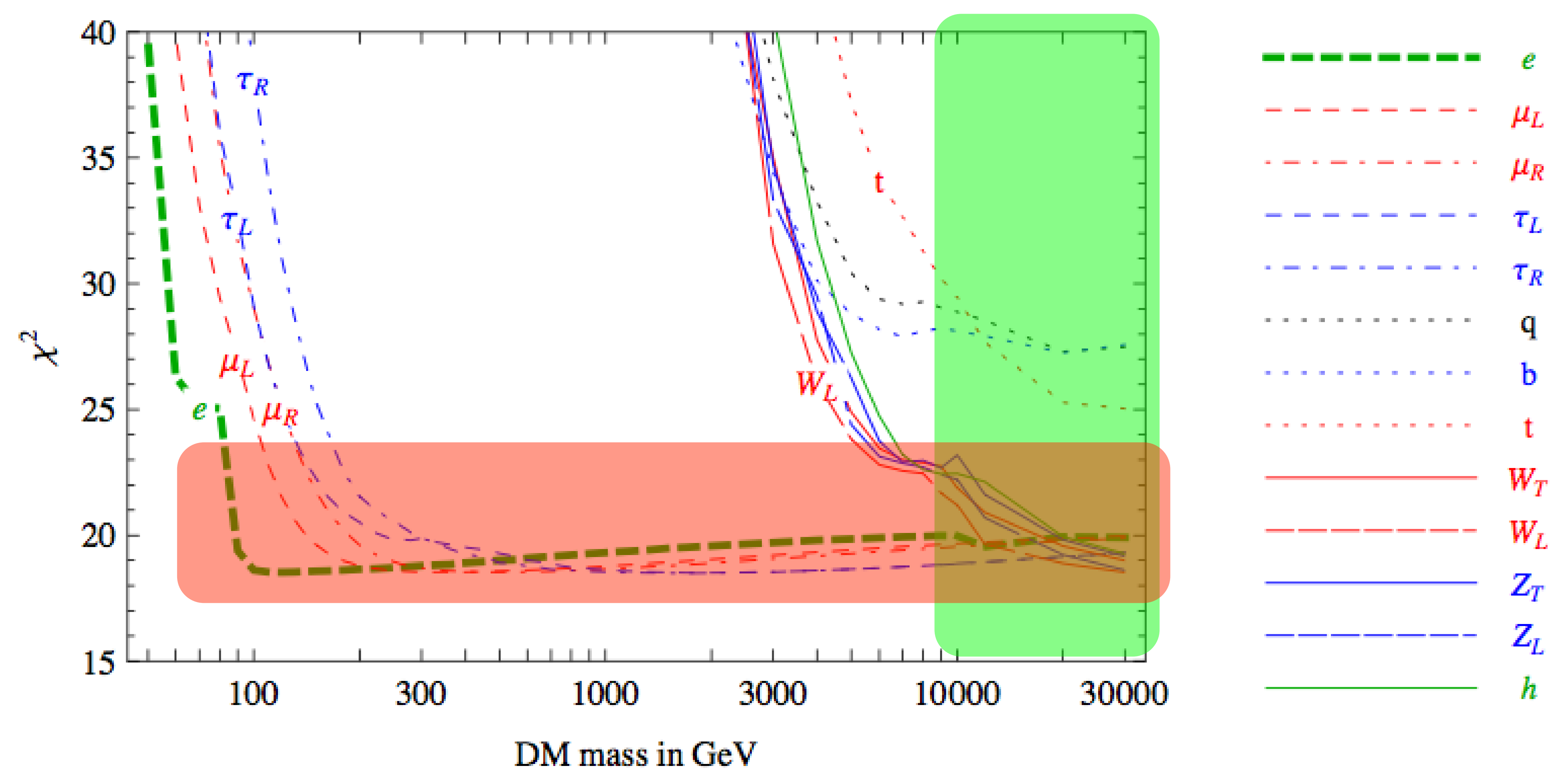
(1) annihilate into leptons (e.g. $\mu^+\mu^-$)

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



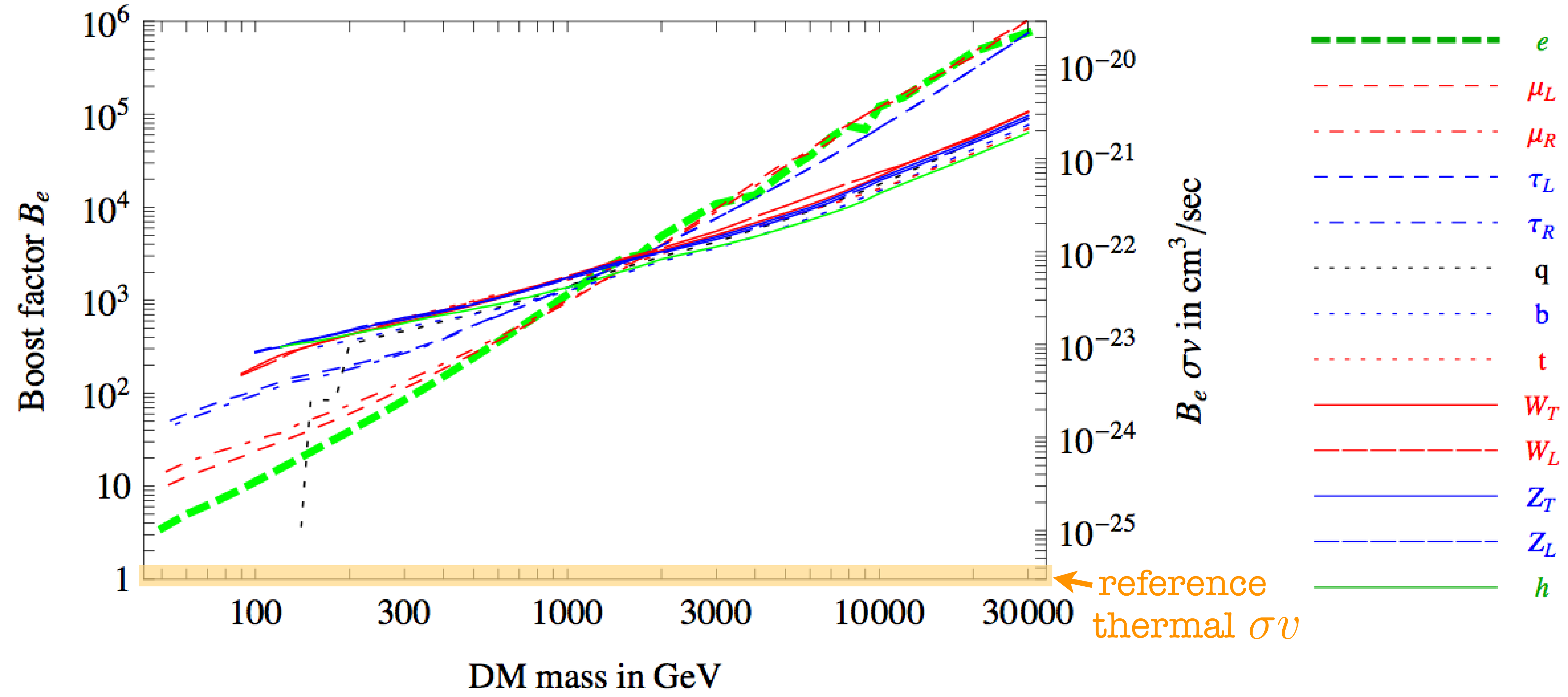
(1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

Results

Which DM spectra can fit the data?

Model-independent results:

Cross section required by PAMELA



reference thermal σv

Data sets

Electrons + positrons from ATIC, PPB-BETS:

PPB-BETS
(Japan)

Polar
Patrol
Balloon
of the
Balloon-borne
Electron
Telescope with
Scintillating
fibers

ATIC (Usa **+ Germany, Russia, China**)

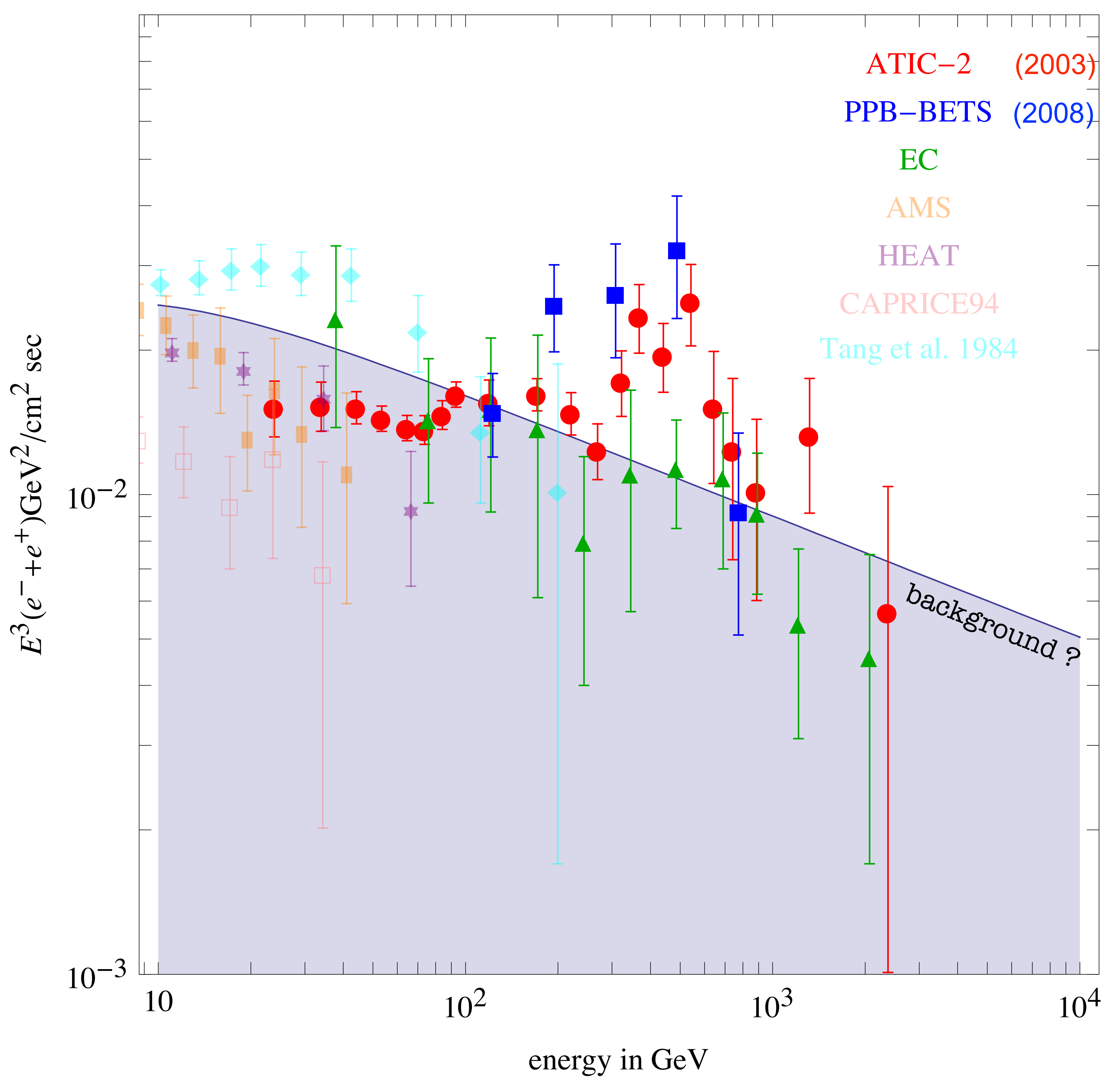
Advanced
Thin
Ionization
Calorimeter

- bigger/denser: higher energy
- calorimeter only, no magnet: no charge discrimination

Data sets

Electrons + positrons from ATIC, PPB-BETS:

- an $e^+ + e^-$ excess at $\sim$700 GeV??



(ATIC: 1724 $e^+ + e^-$ collected at >100 GeV; 4σ above bkgnd)

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-annihilation ${\rm DM\ DM} \to \mu^+\mu^-$

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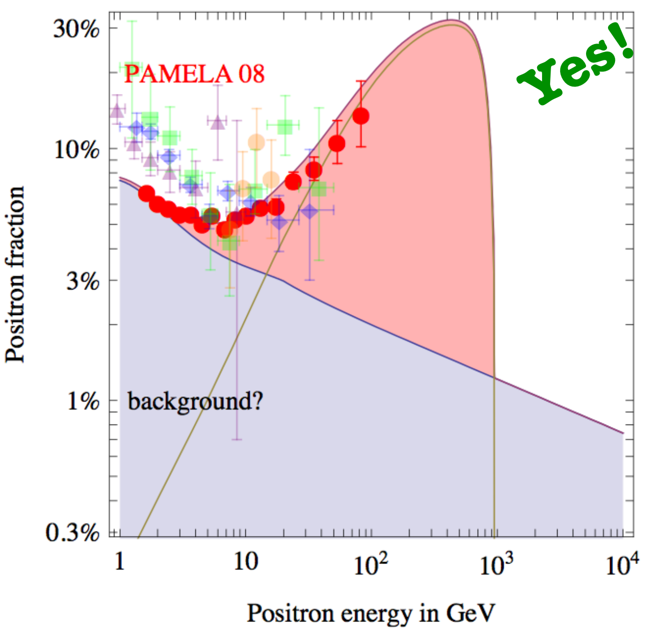
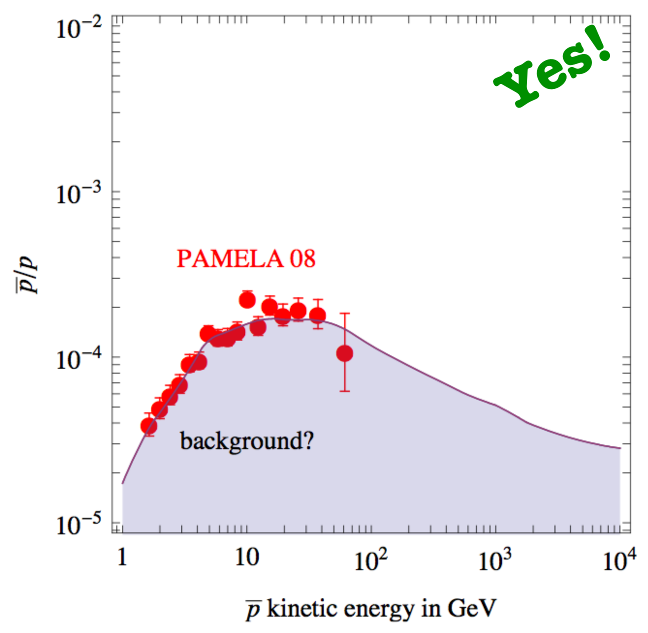
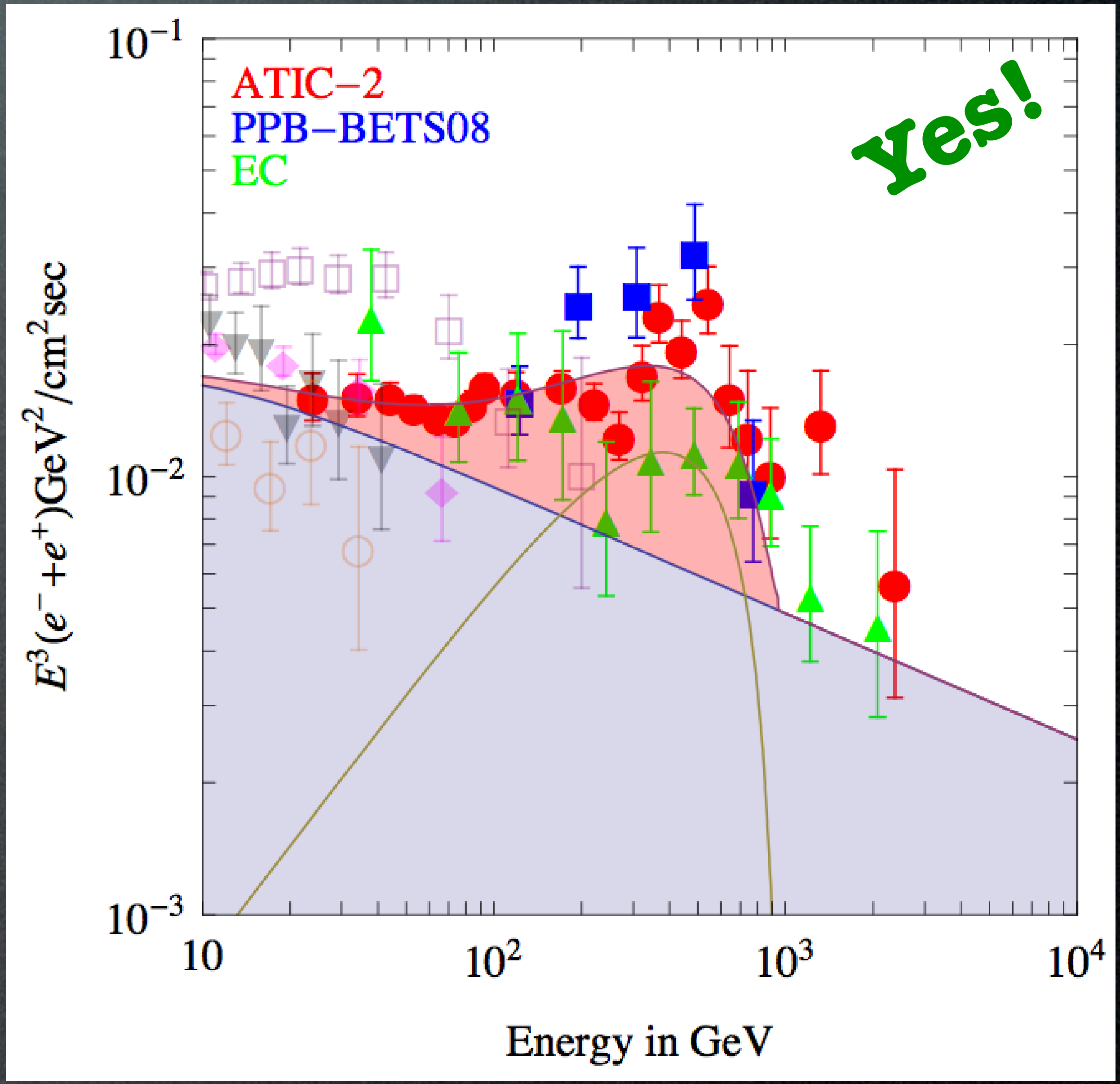


Anti-protons:



Electrons + Positrons:



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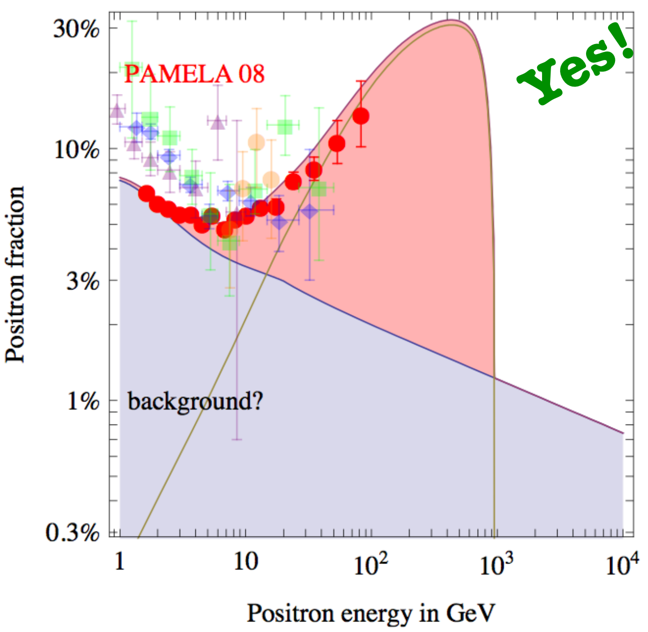

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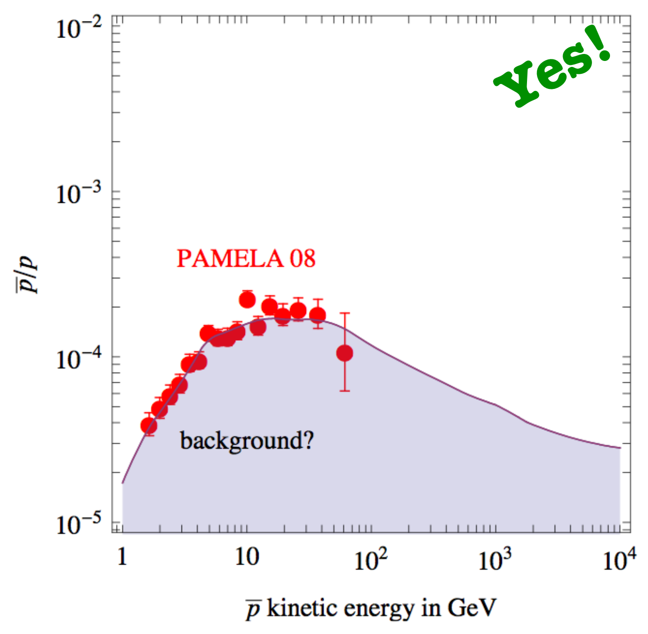

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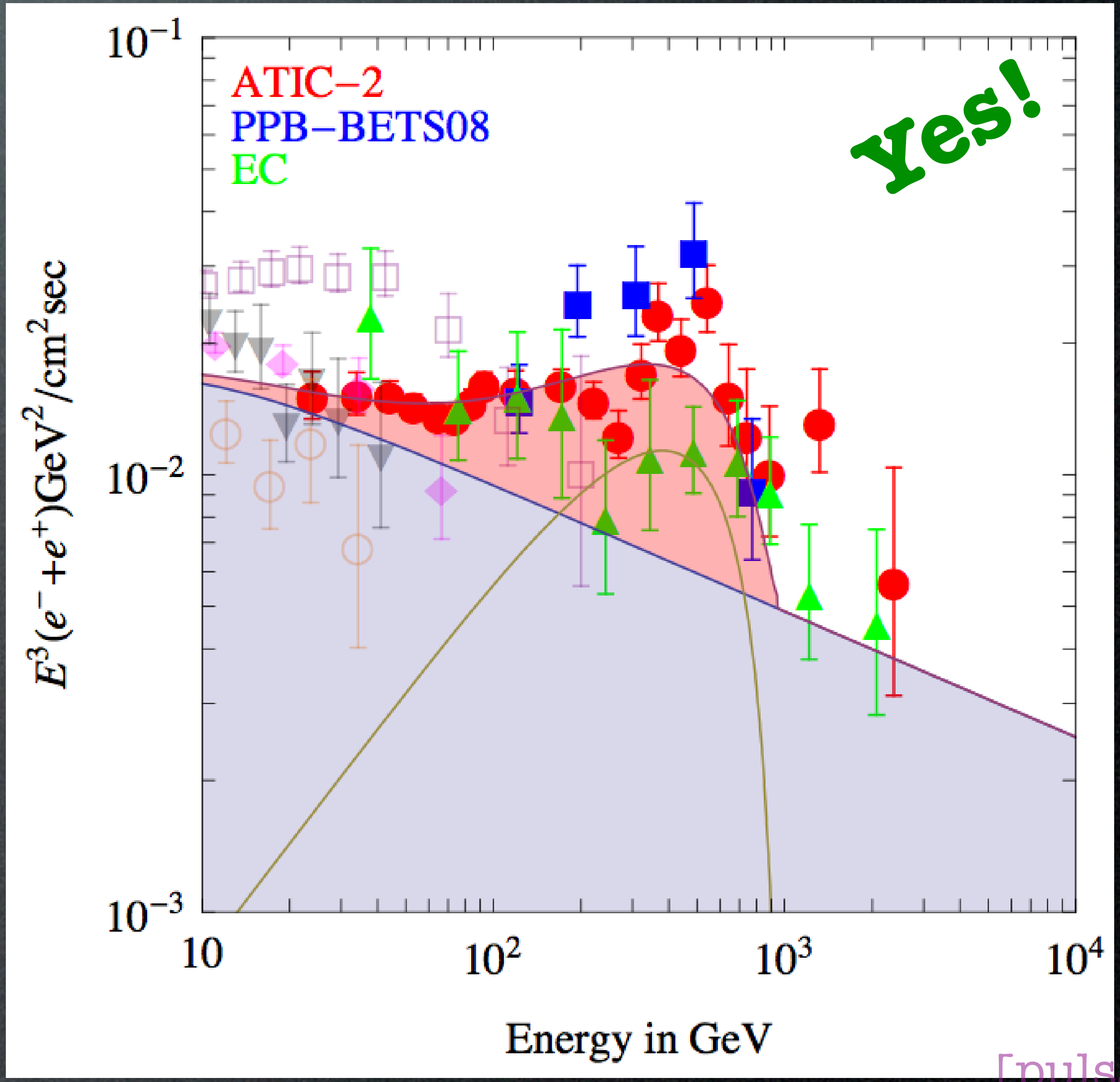

[pulsar]

Have we identified the DM for the first time???

Arkani-Hamed, Weiner et al. 0810: Yes!
+ a ton of others

Results

Which DM can fit the data?

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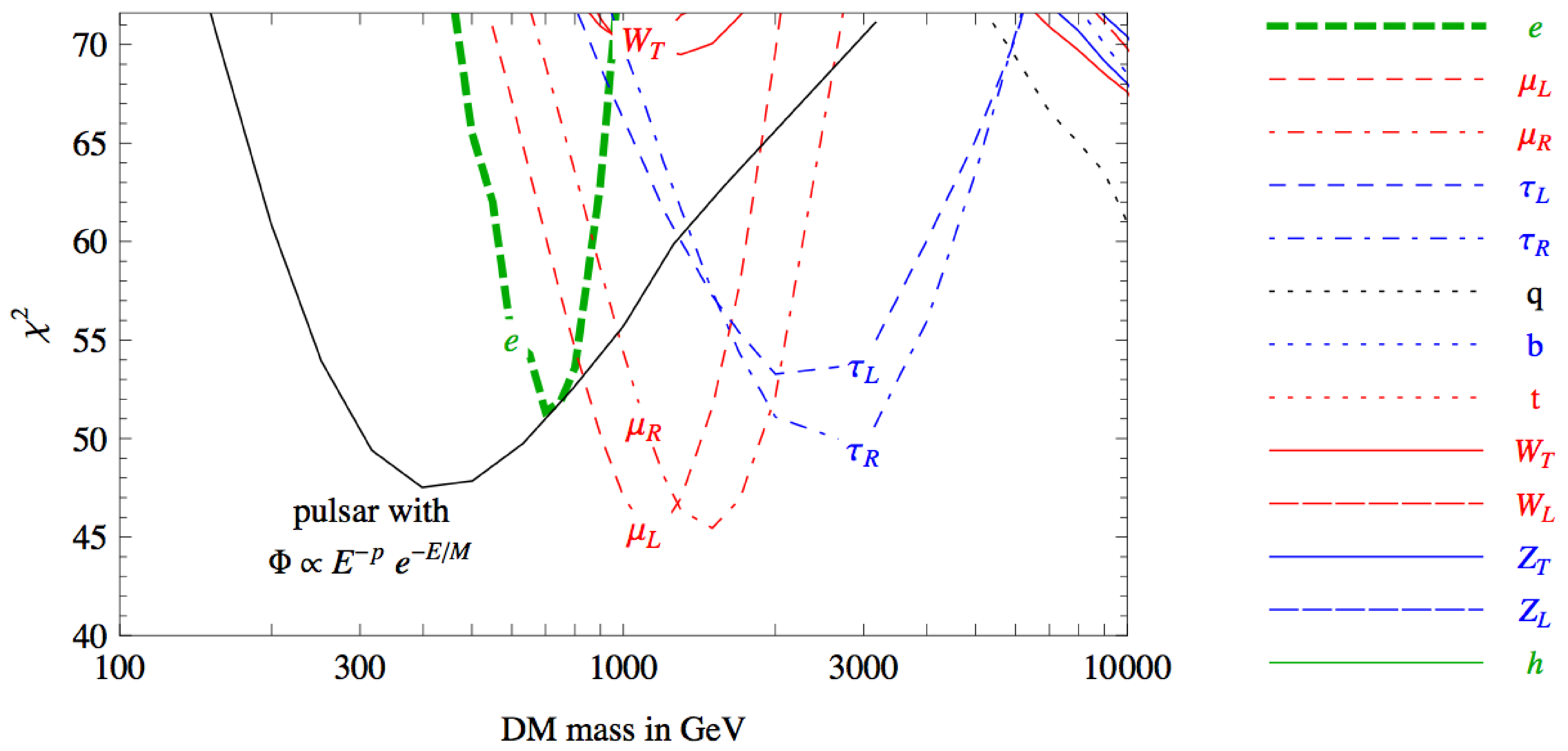
Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons* + balloon experiments



*adding anti-protons does not change much, non-leptonic channels give too smooth spectrum for balloons

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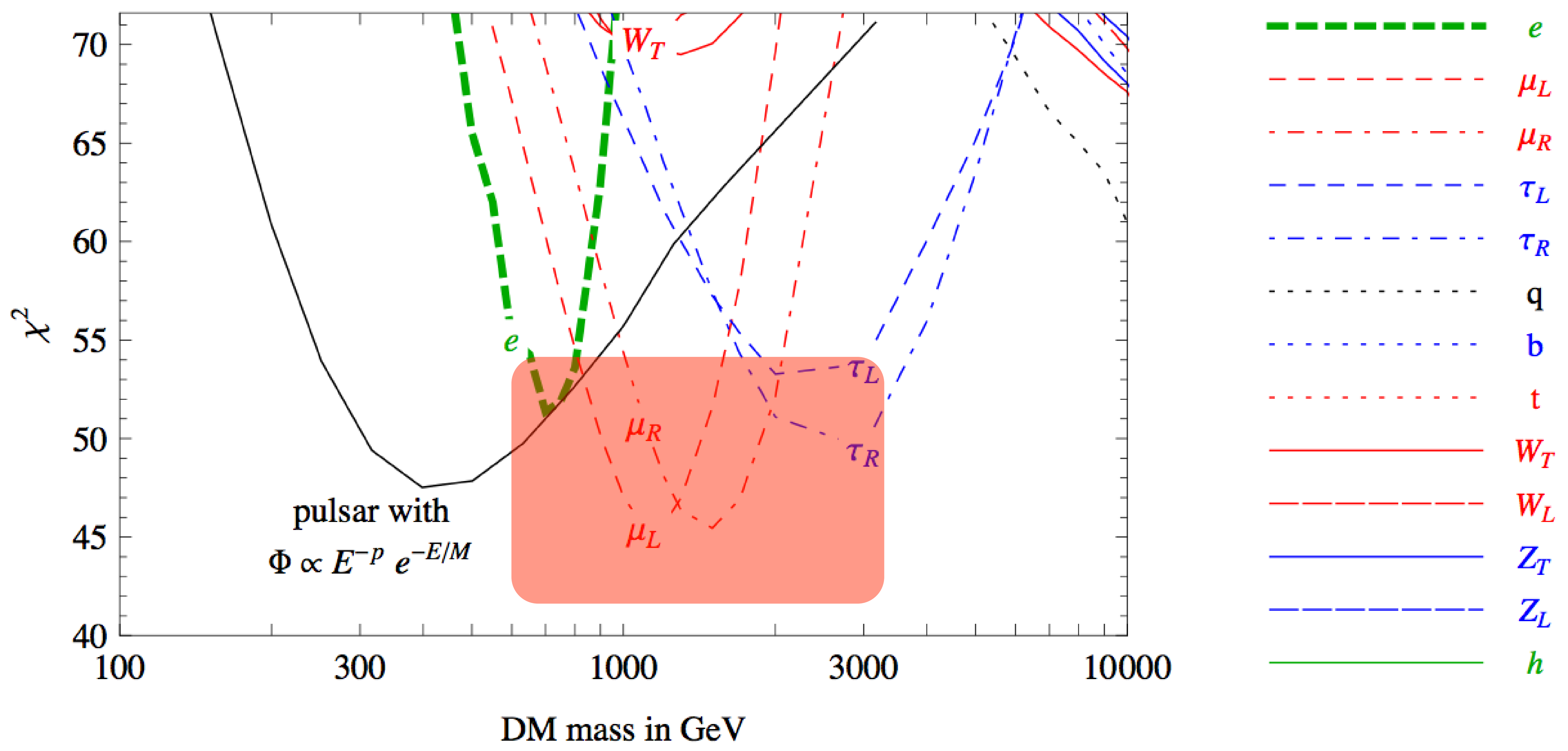
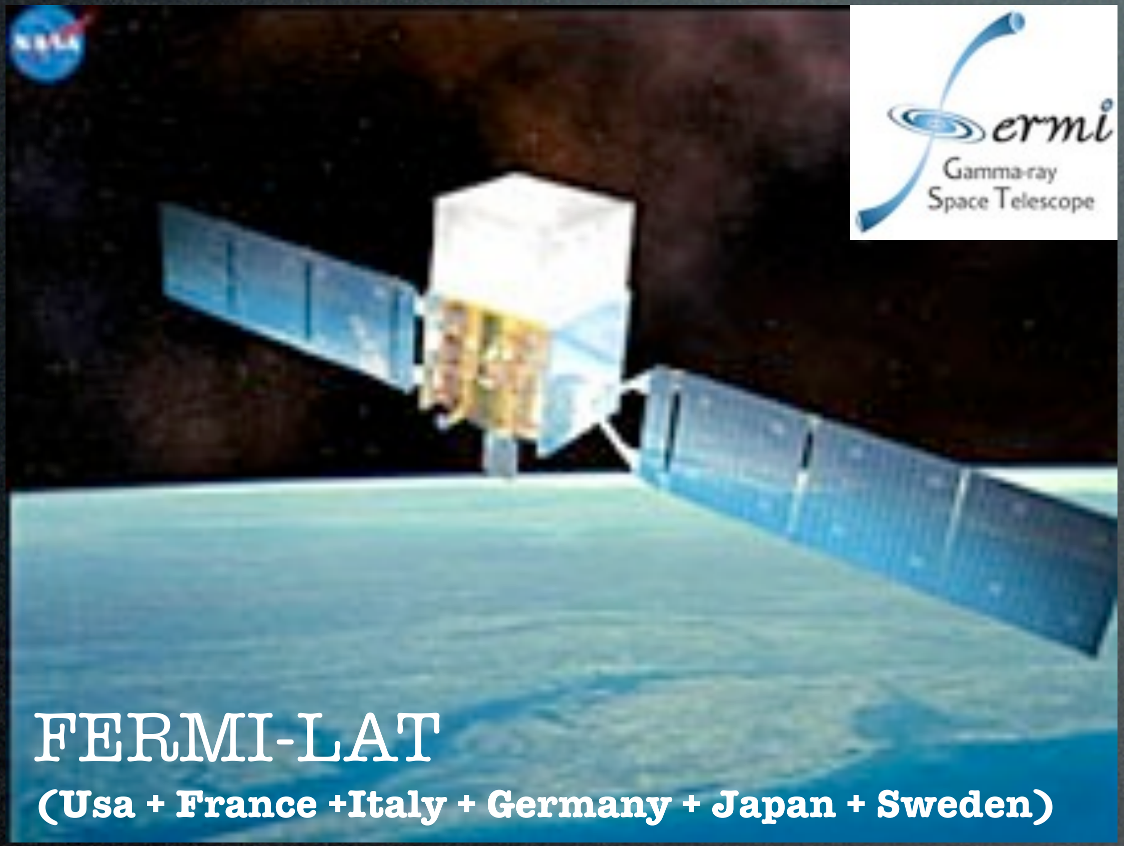
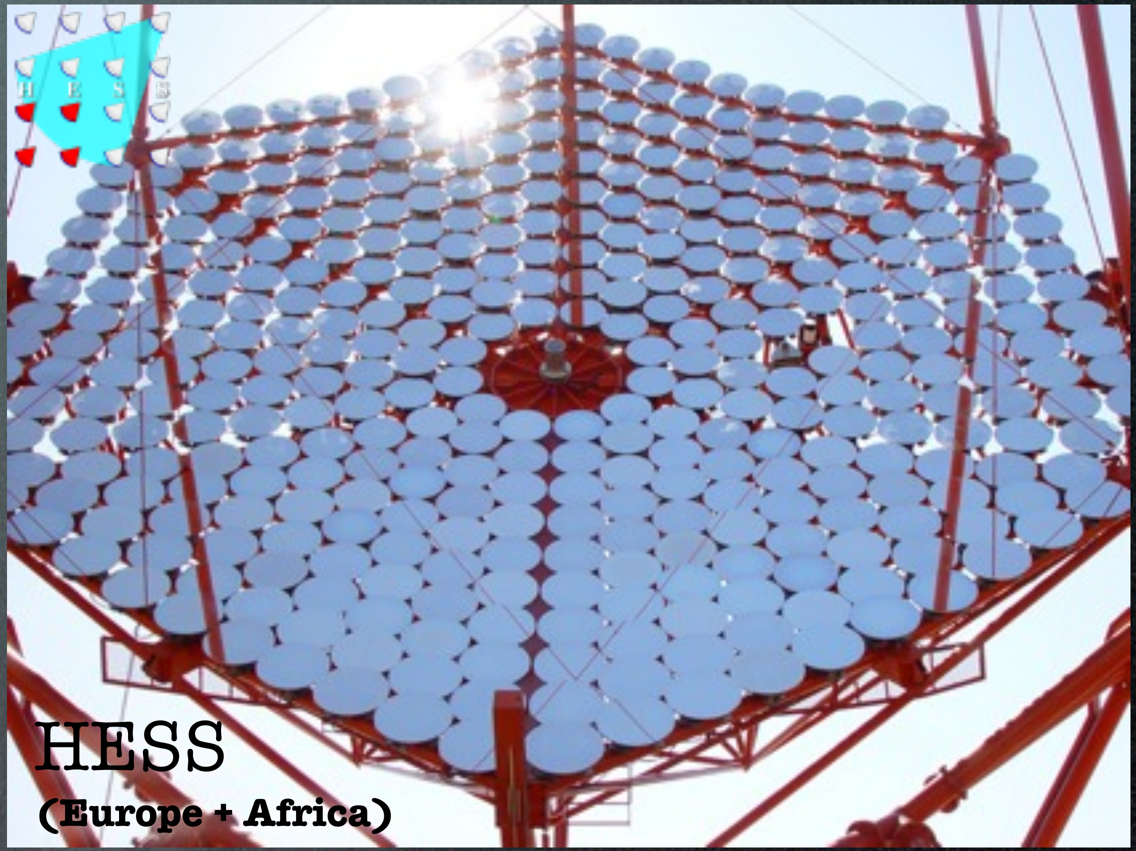


(1) annihilate into leptons (e.g. $\mu^+\mu^-$), mass ~1 TeV

Data sets

Electrons + positrons from FERMI and HESS:





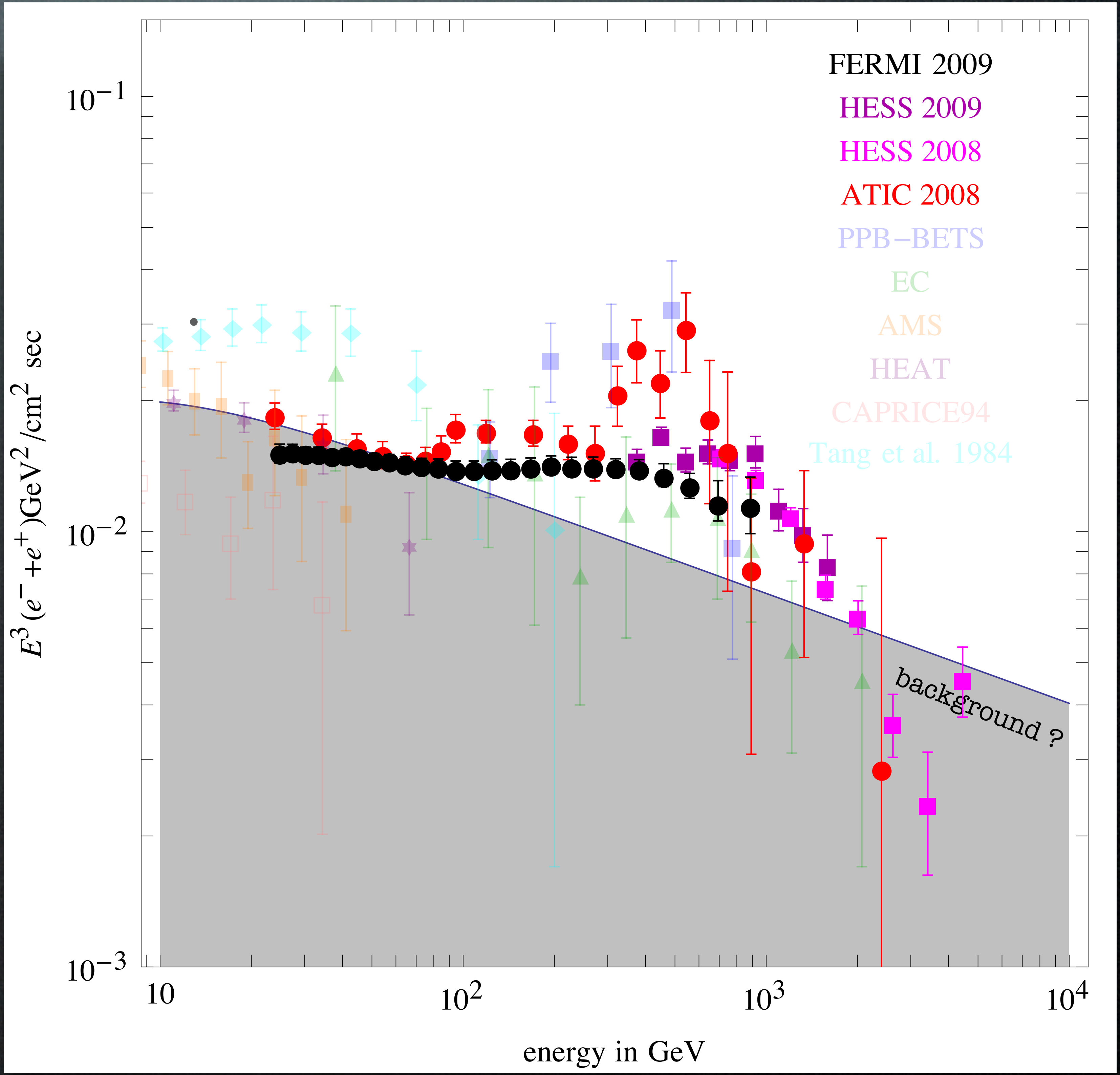
"Designed as a high-sensitivity gamma-ray observatory, the FERMI Large Area Telescope is also an electron detector with a large acceptance"

"The very large collection area of ground-based gamma-ray telescopes gives them a substantial advantage over balloon/satellite based instruments in the detection of high-energy cosmic-ray electrons."

Data sets

Electrons + positrons adding FERMI and HESS:

- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?



[formerly predicted GLAST sensitivity]

Results

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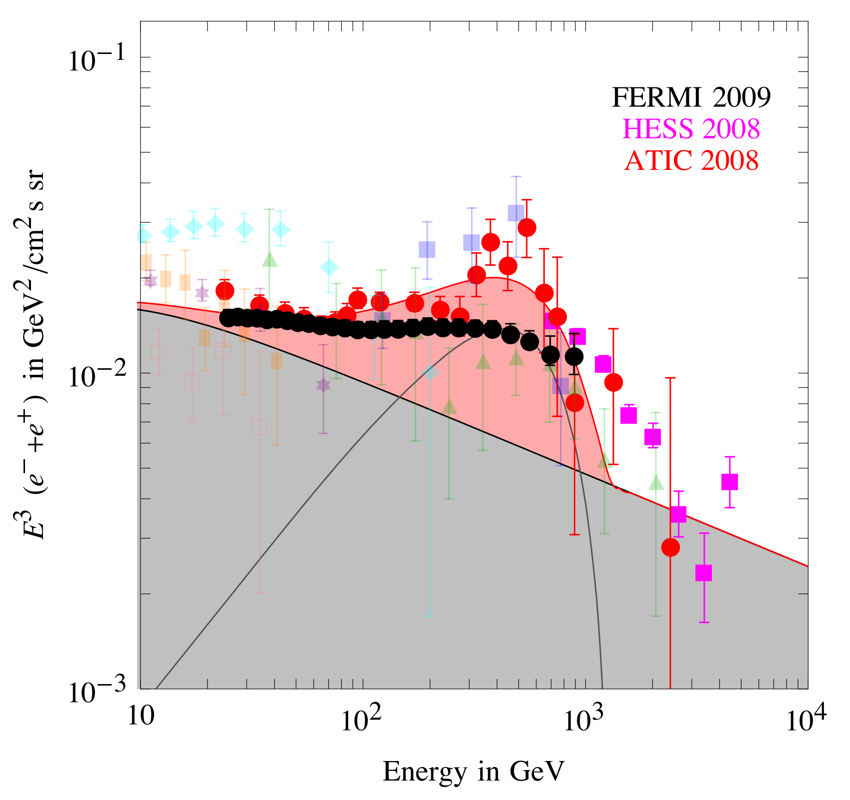
$\mu^+\mu^-, M_{\rm DM} \simeq 1\,{\rm TeV}$



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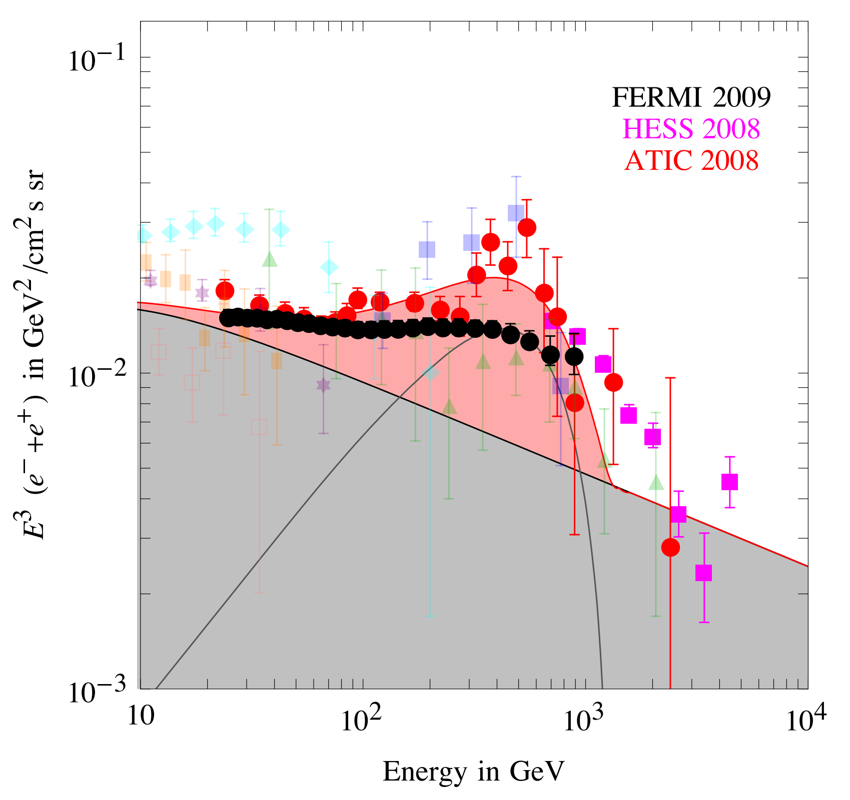
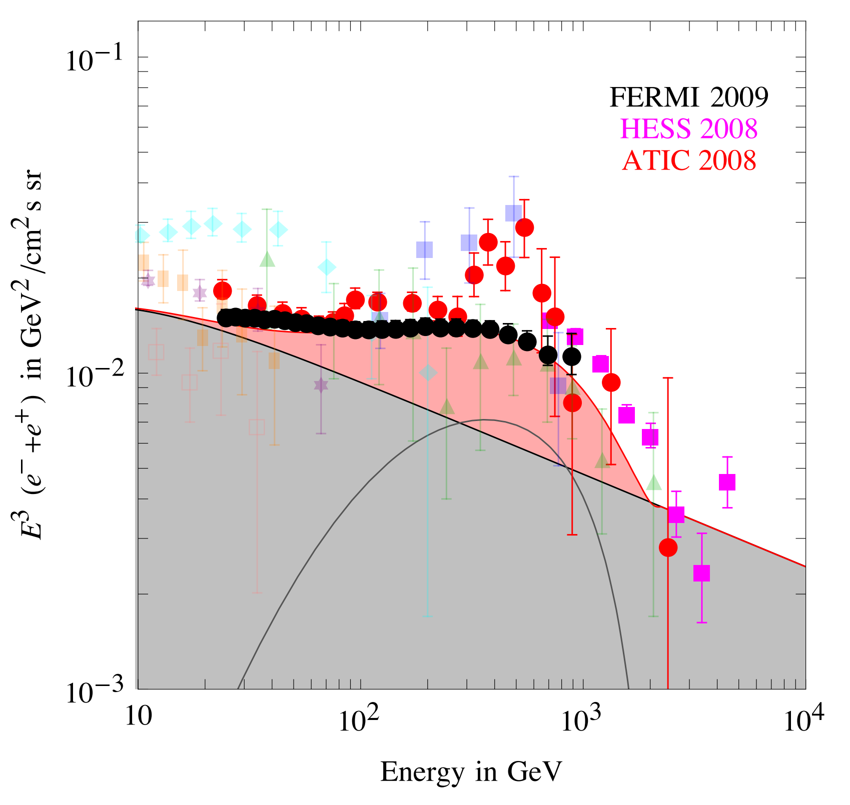


$\tau^+\tau^-, M_{\rm DM} \simeq 2\,{\rm TeV}$



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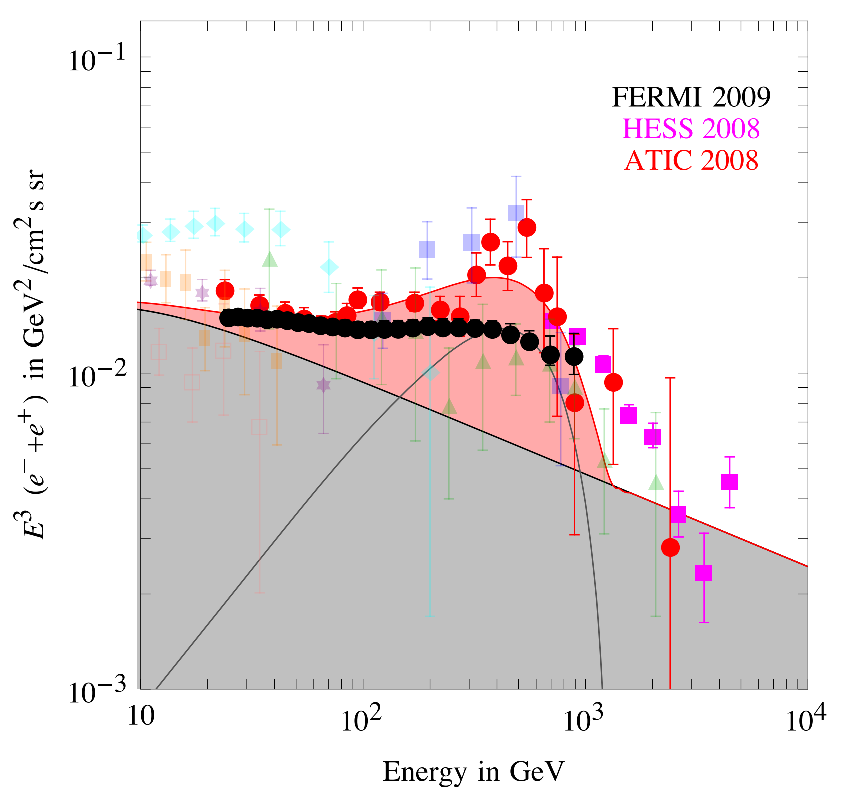
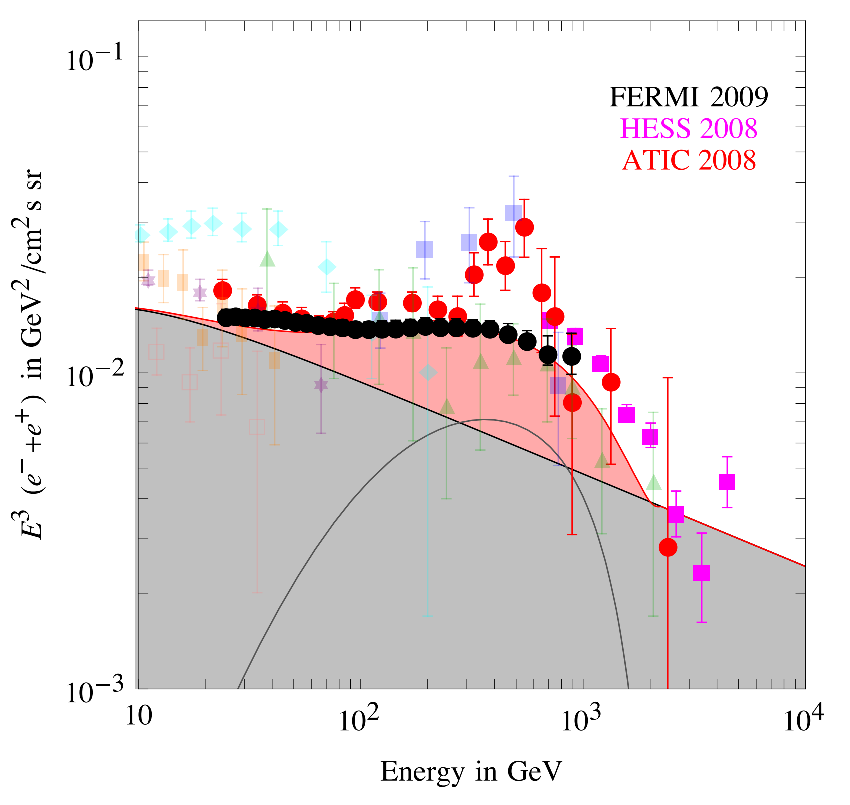
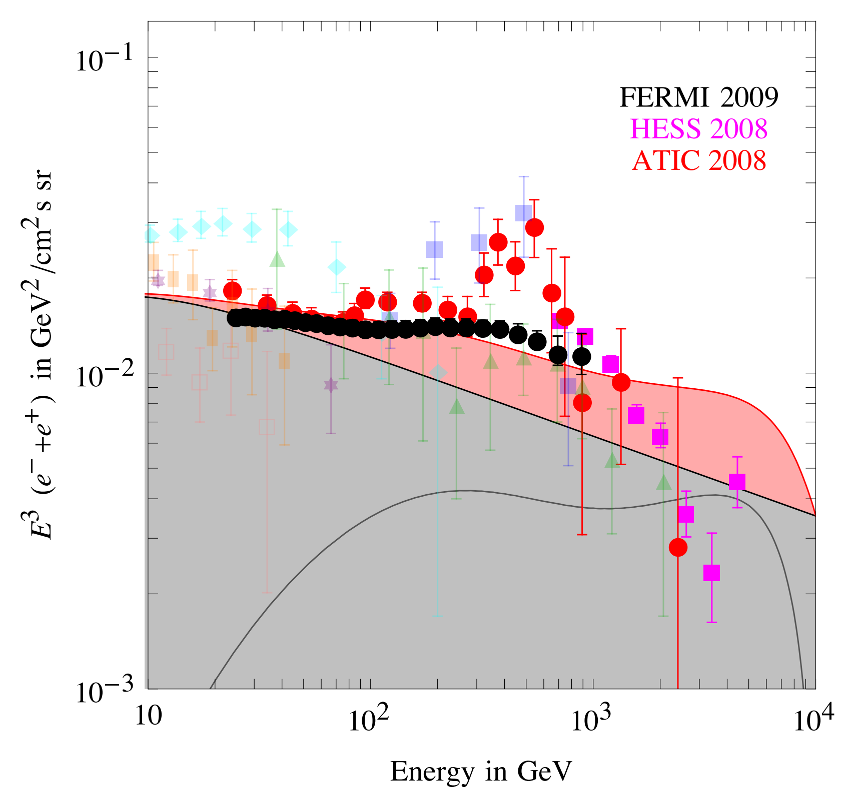


$\tau^+\tau^-, M_{\rm DM} \simeq 2$ TeV



$W^+W^-, M_{\rm DM} \simeq 10$ TeV



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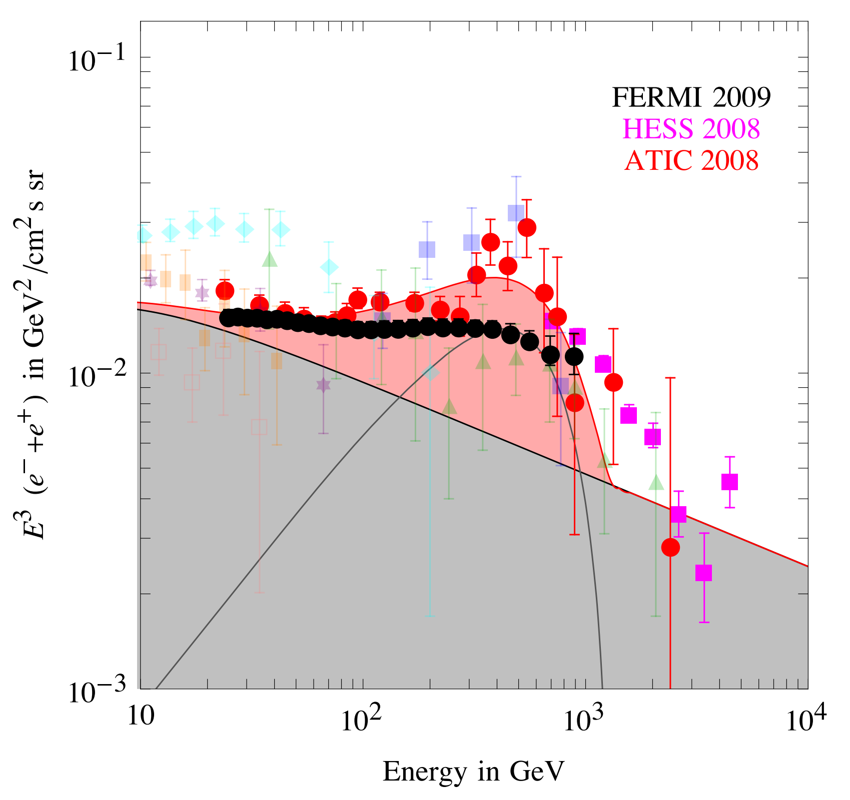
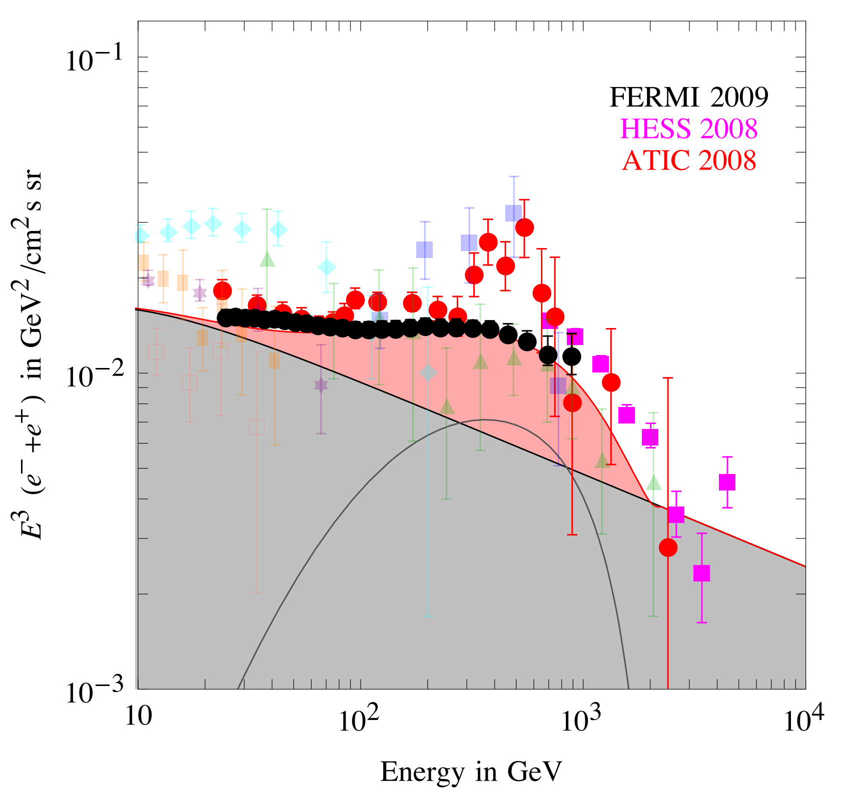


Notice:

- same spectra still fit PAMELA positron and anti-protons!

$\tau^+\tau^-, M_{\rm DM} \simeq 2\,{\rm TeV}$



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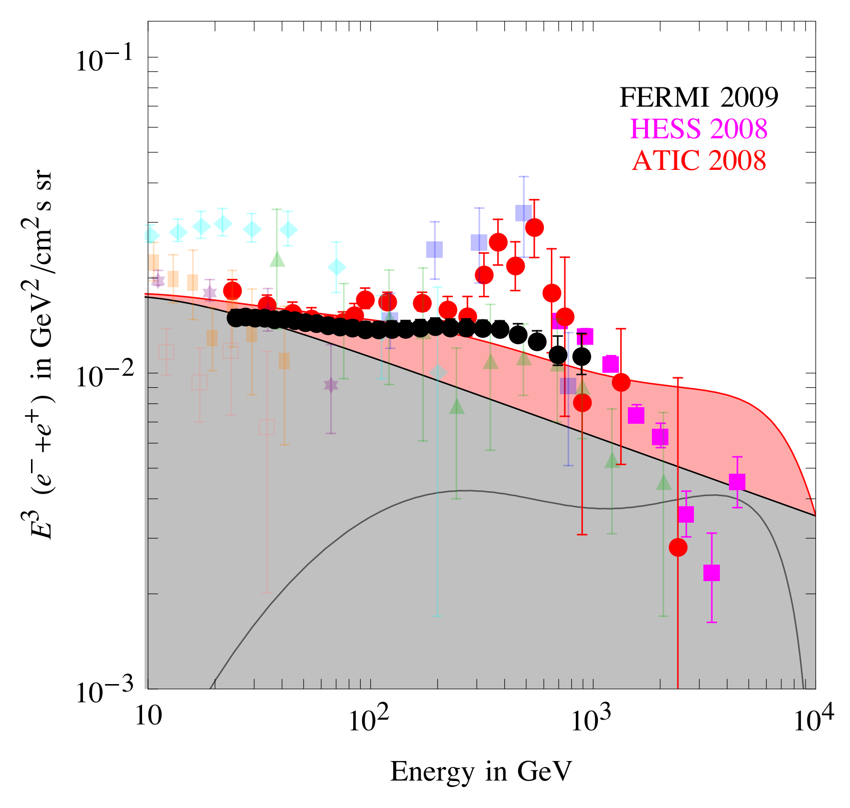

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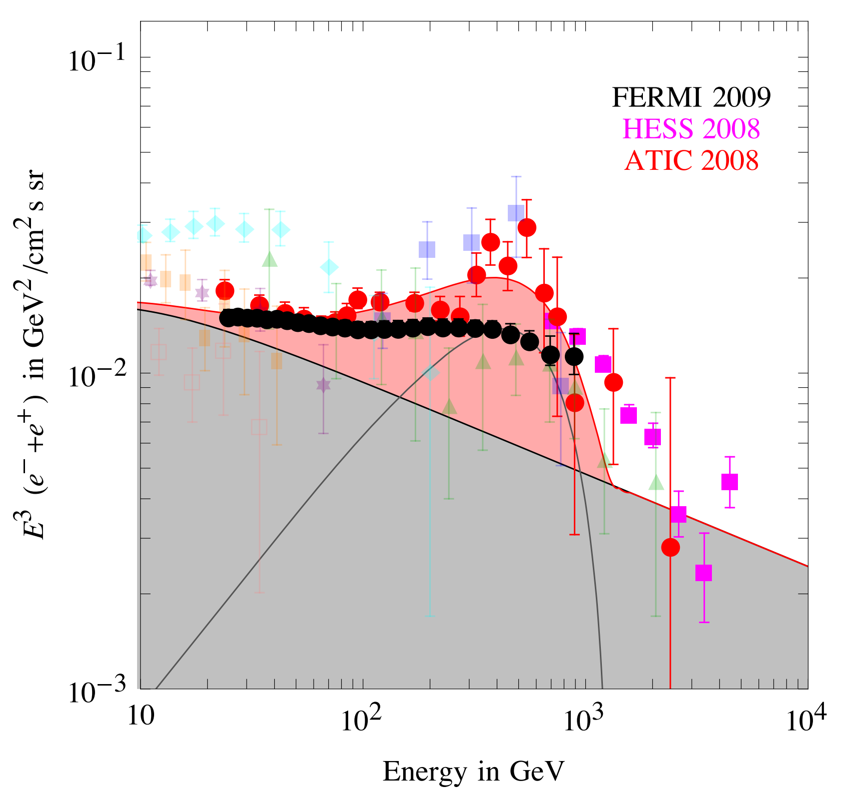

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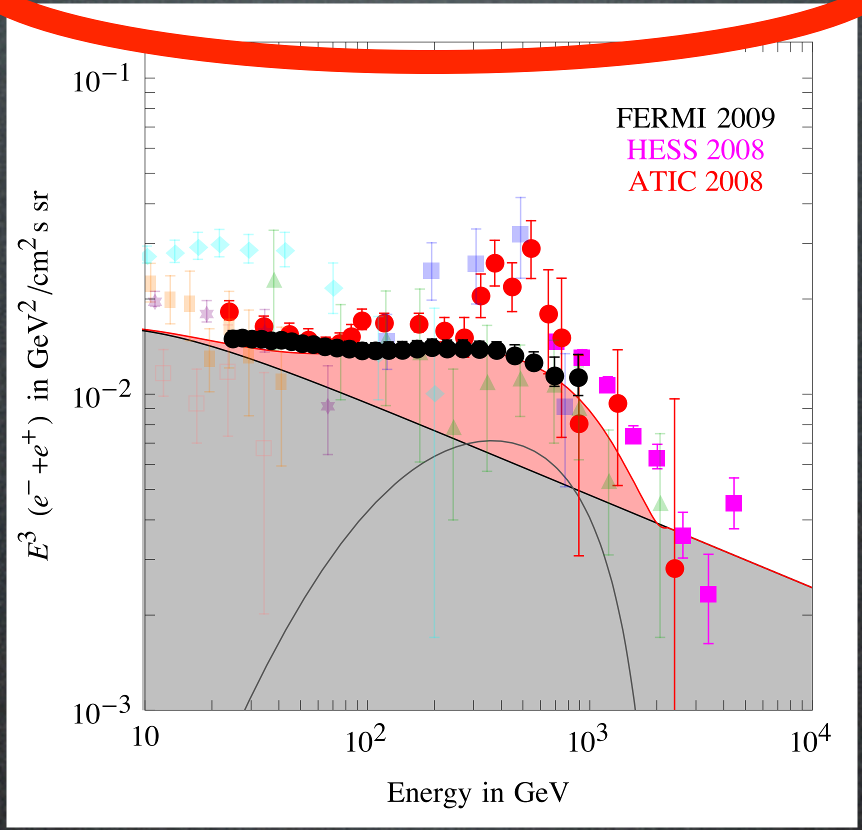

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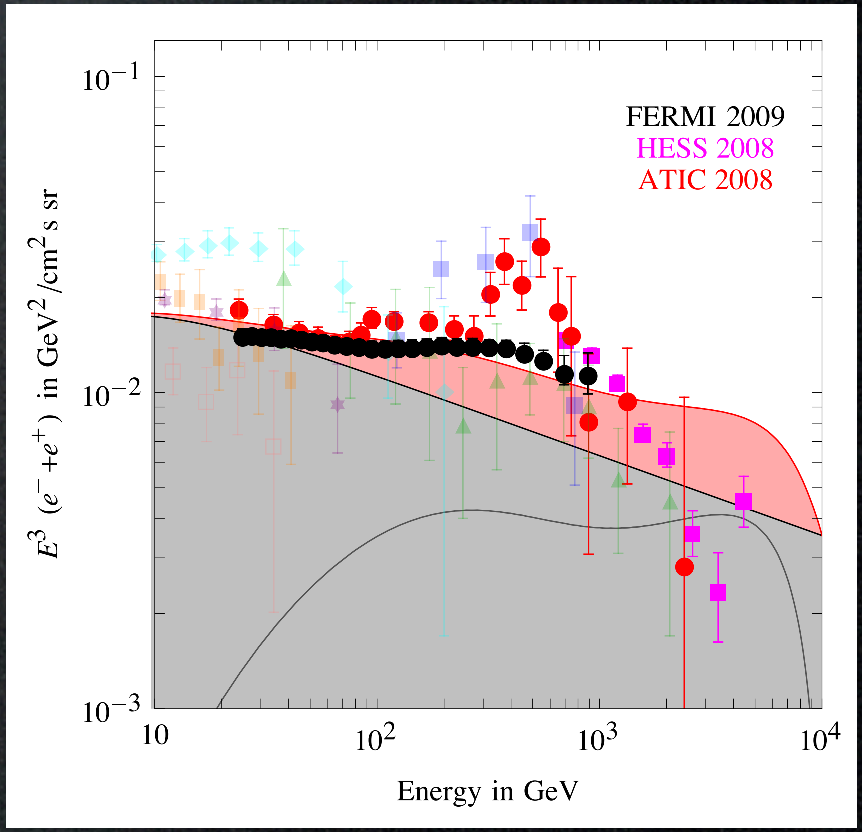


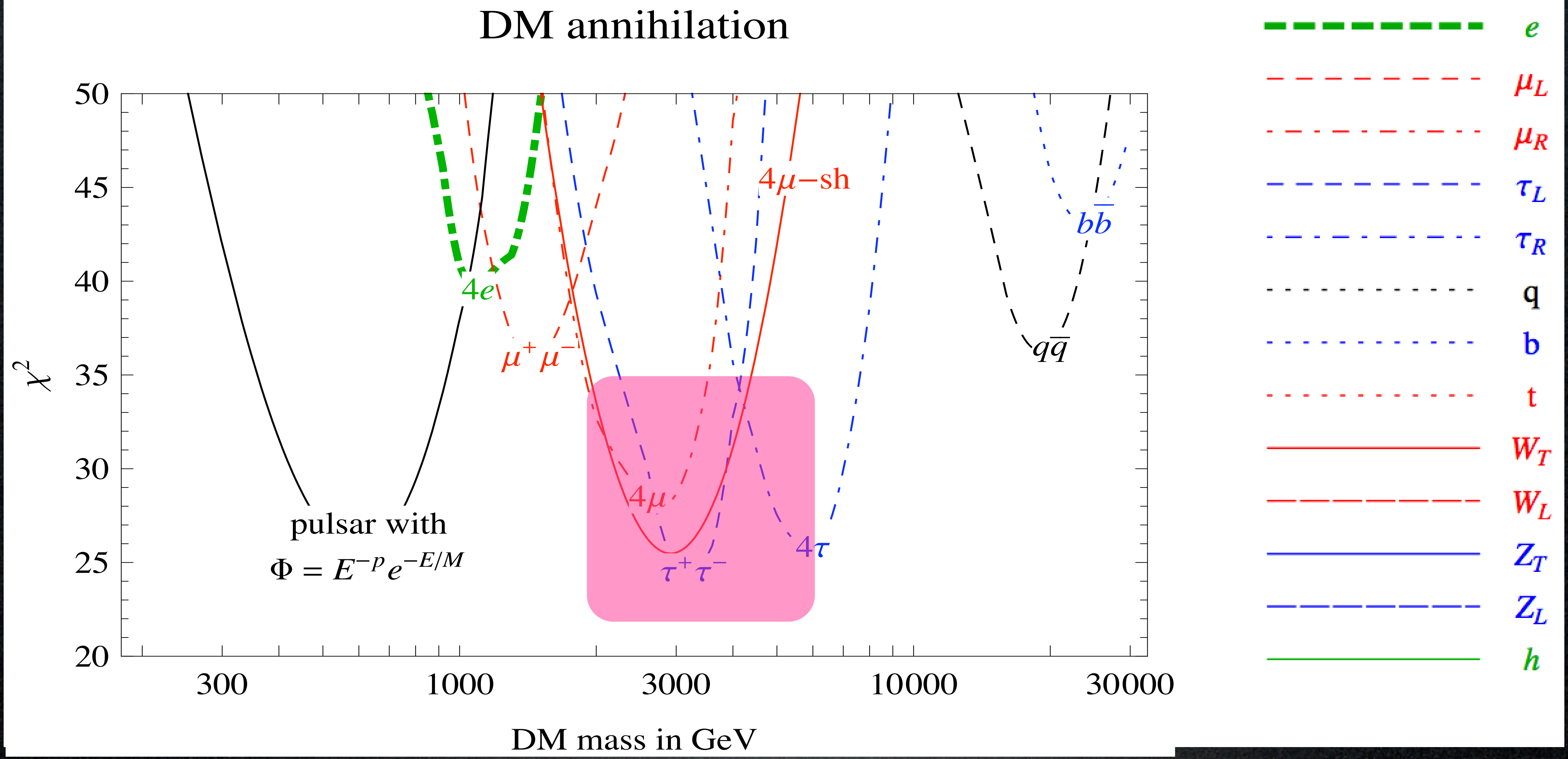
- no features in FERMI => $M_{\rm DM} > 1\ \mathrm{TeV}$
- a ‘cutoff’ in HESS => $M_{\rm DM} \lesssim 3\ \mathrm{TeV}$
- smooth lepton spectrum

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA + FERMI + HESS (no balloon):



Strumia, Papucci et al. 0905.0480

see also: Bergstrom, Edsjo, Zaharijas 0905

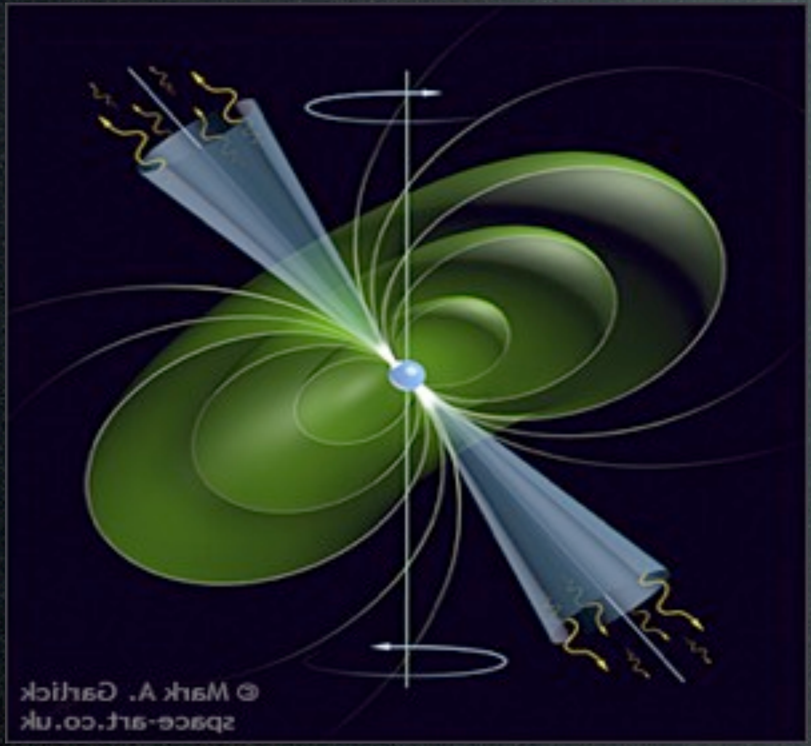
(1) annihilate into leptons (e.g. $\tau^+\tau^-$), mass ~3 TeV

Astrophysical explanation?

Astrophysical explanation?

[others?]

Or perhaps it's just a young, nearby pulsar...



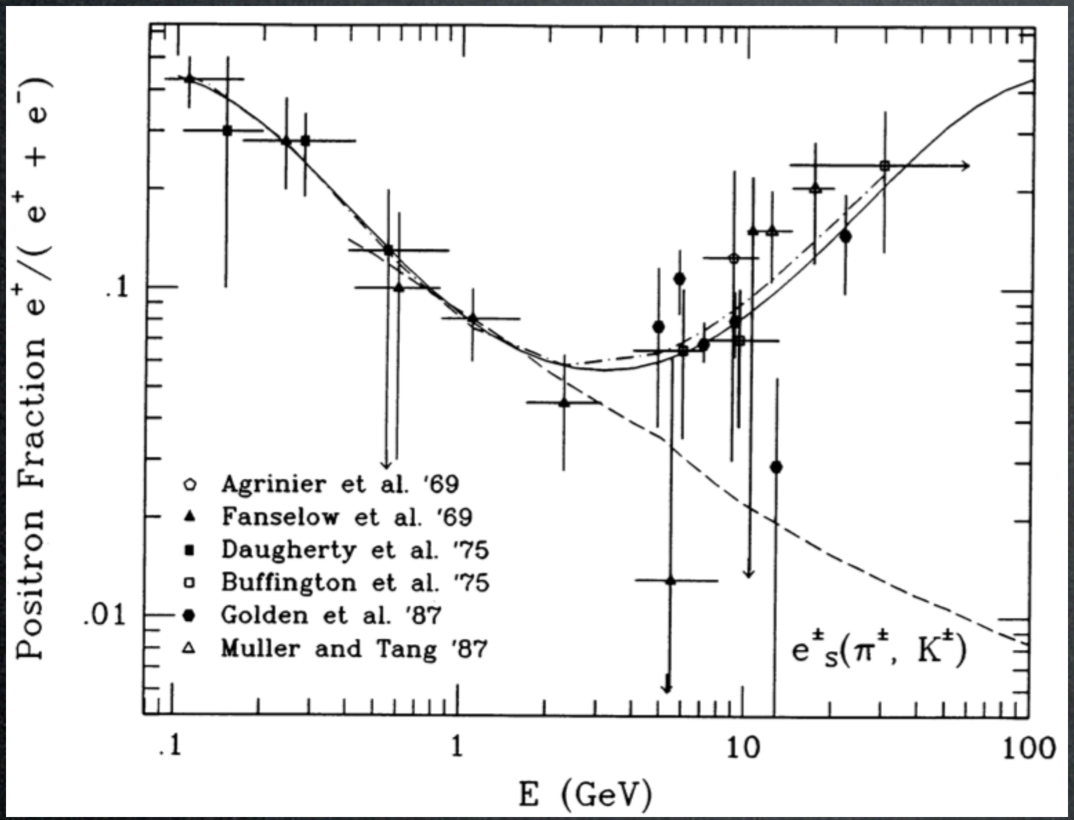
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \to 10^5$ yr (typical total energy output: 10^{46} erg).

Must be young (T < 10^5 yr) and nearby (< 1 kpc);
if not: too much diffusion, low energy, too low flux.

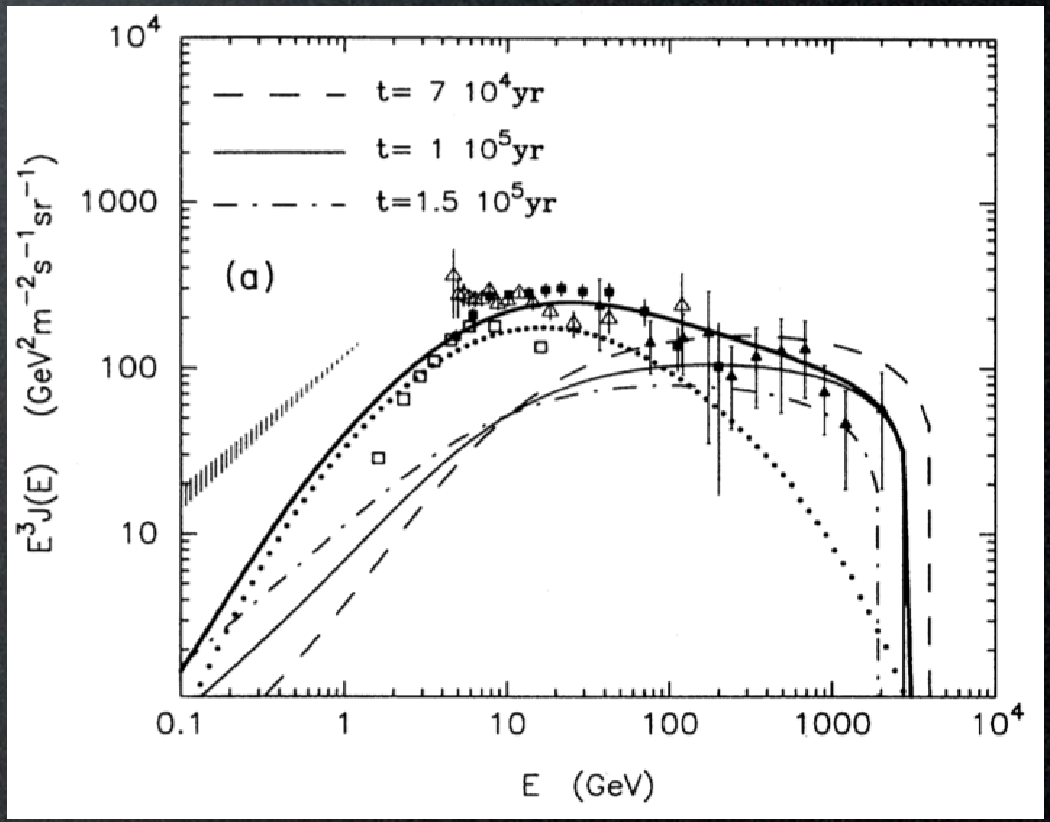
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

($1.4 < p < 2.4$, Profumo 2008)

Not a new idea:



A.Boulares, APJ 342 (**1989**)



Atoyan, Aharonian, Volk (**1995**)

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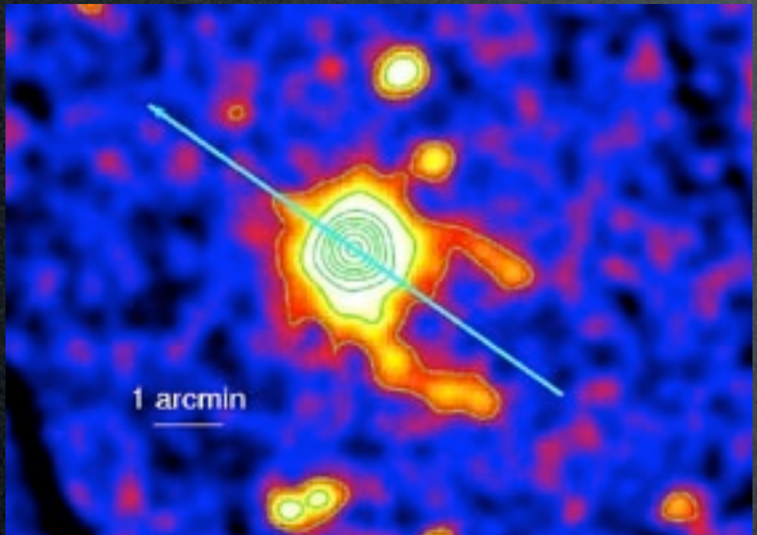

Geminga pulsar
(funny that it means:
"it is not there" in milanese)

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Try the fit with known nearby pulsars:

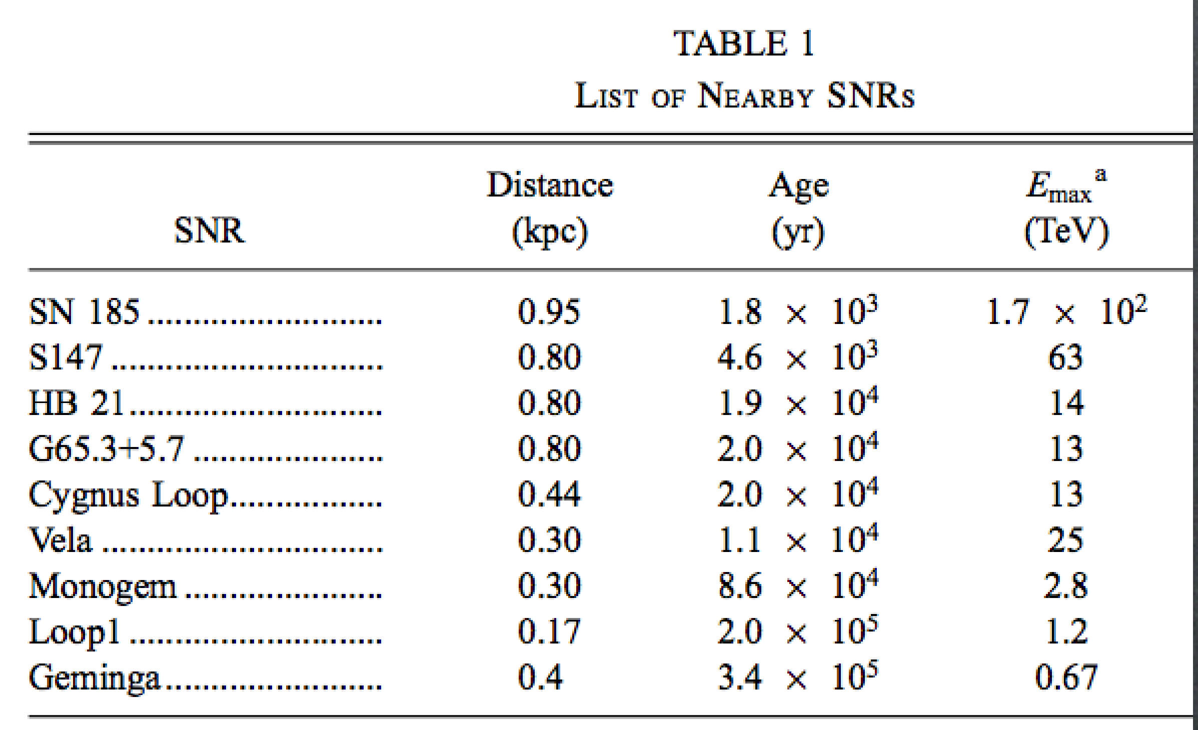
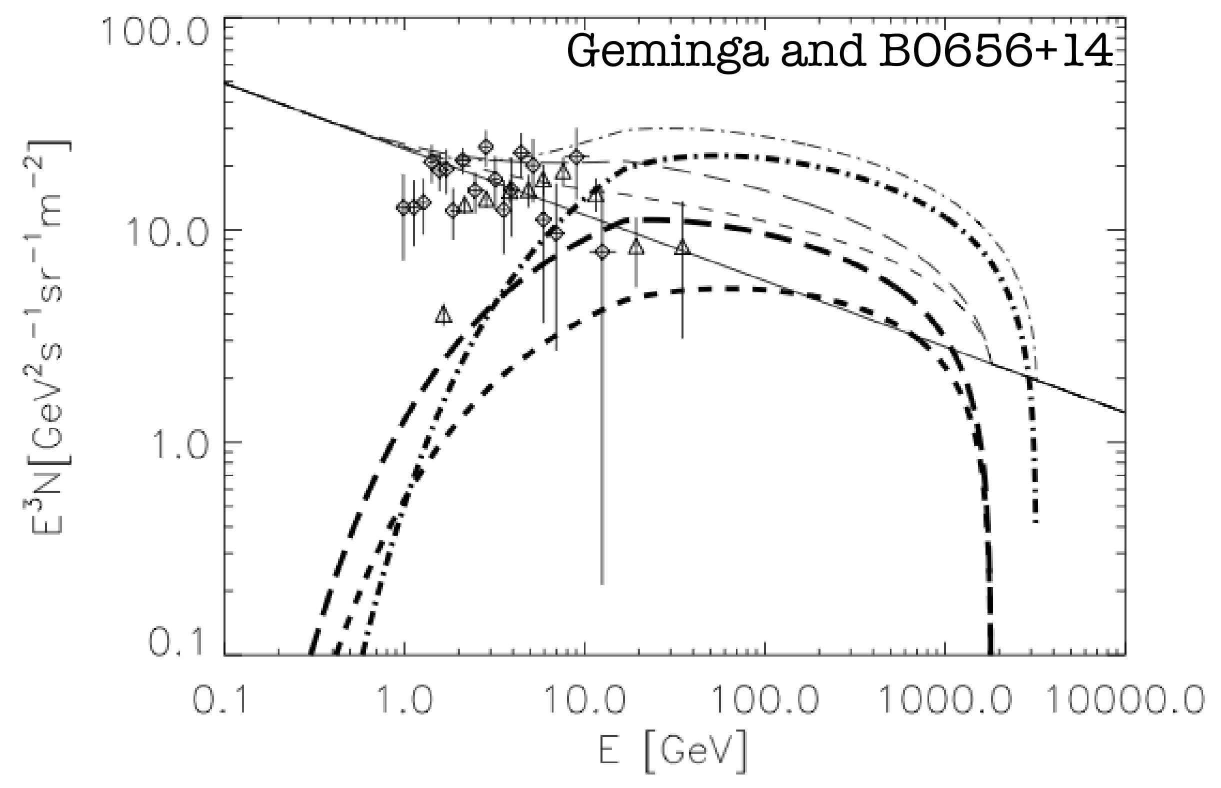


TABLE 1
List of Nearby SNRs

SNR	Distance (kpc)	Age (yr)	$E_{\max}$[a] (TeV)
SN 185	0.95	1.8×10^3	1.7×10^2
S147	0.80	4.6×10^3	63
HB 21	0.80	1.9×10^4	14
G65.3+5.7	0.80	2.0×10^4	13
Cygnus Loop	0.44	2.0×10^4	13
Vela	0.30	1.1×10^4	25
Monogem	0.30	8.6×10^4	2.8
Loop1	0.17	2.0×10^5	1.2
Geminga	0.4	3.4×10^5	0.67



Büshing, de Jager et al. 0804.0220

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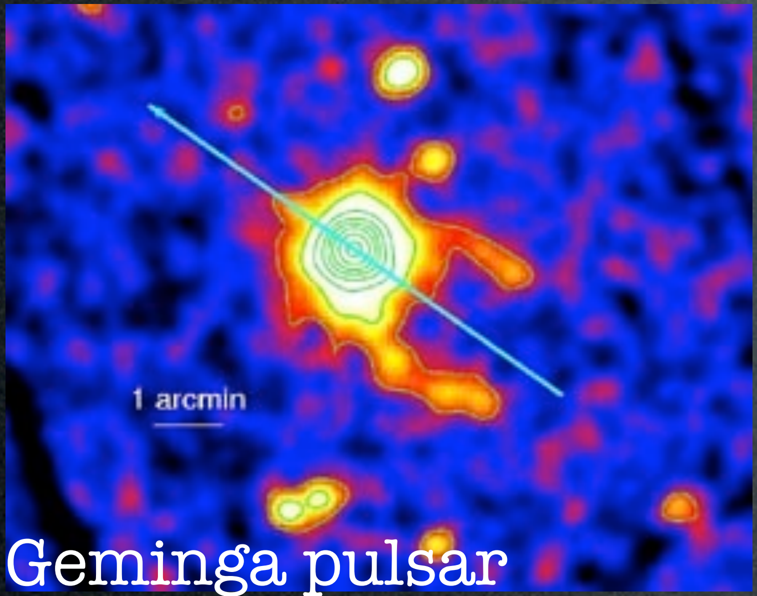

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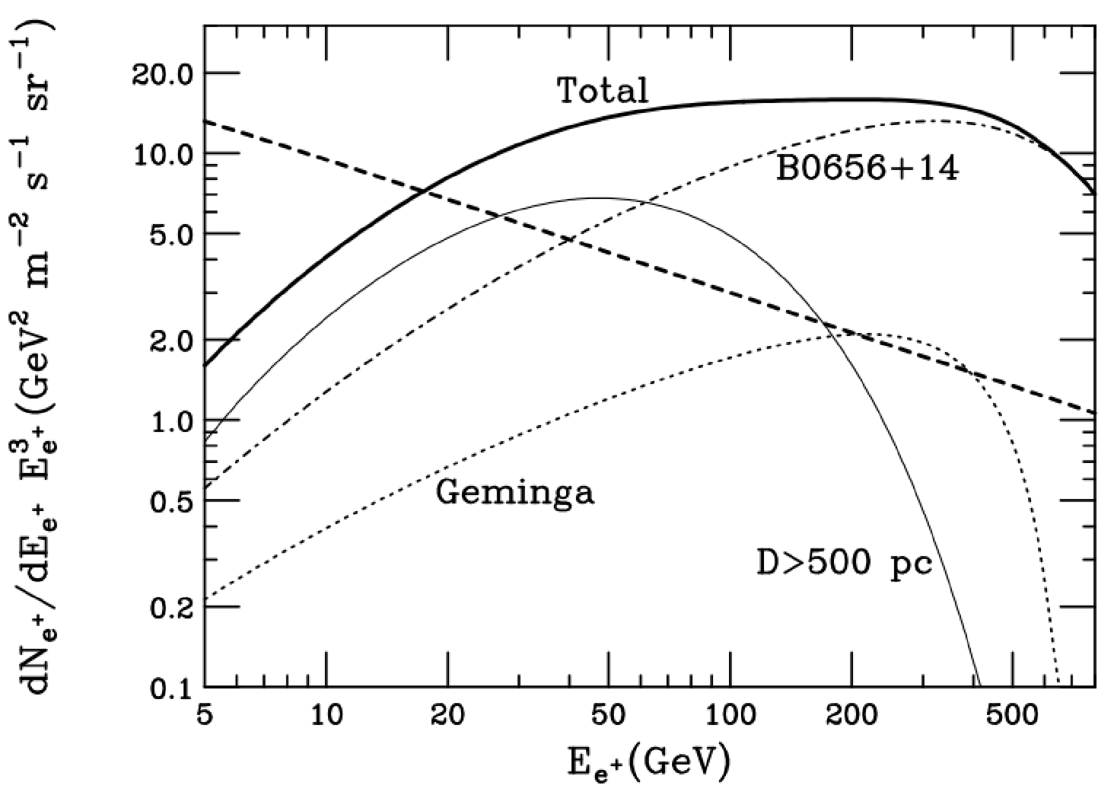
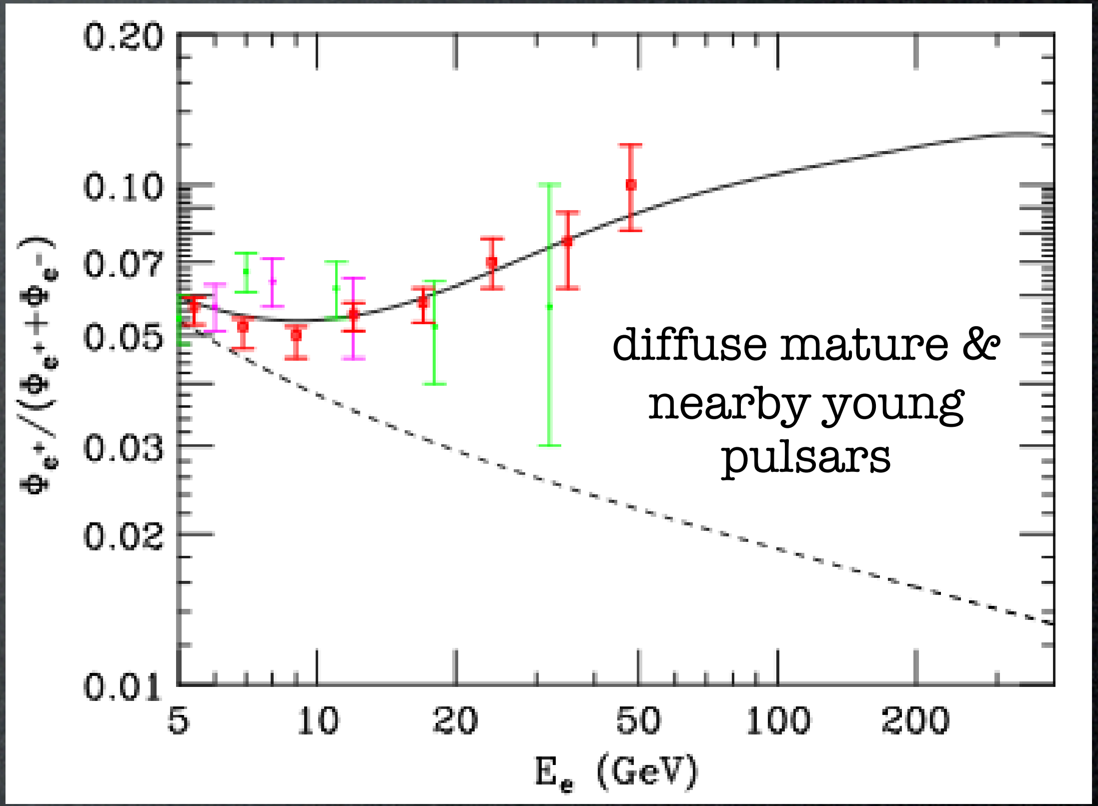
Try the fit with known nearby pulsars and diffuse mature pulsars:





Hooper, Blasi, Serpico 2008

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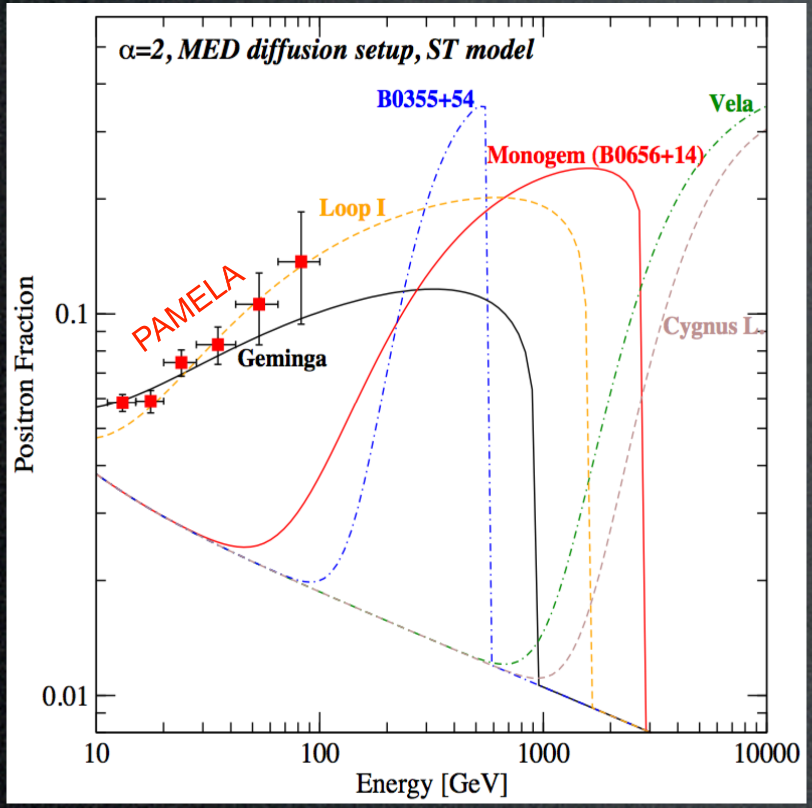
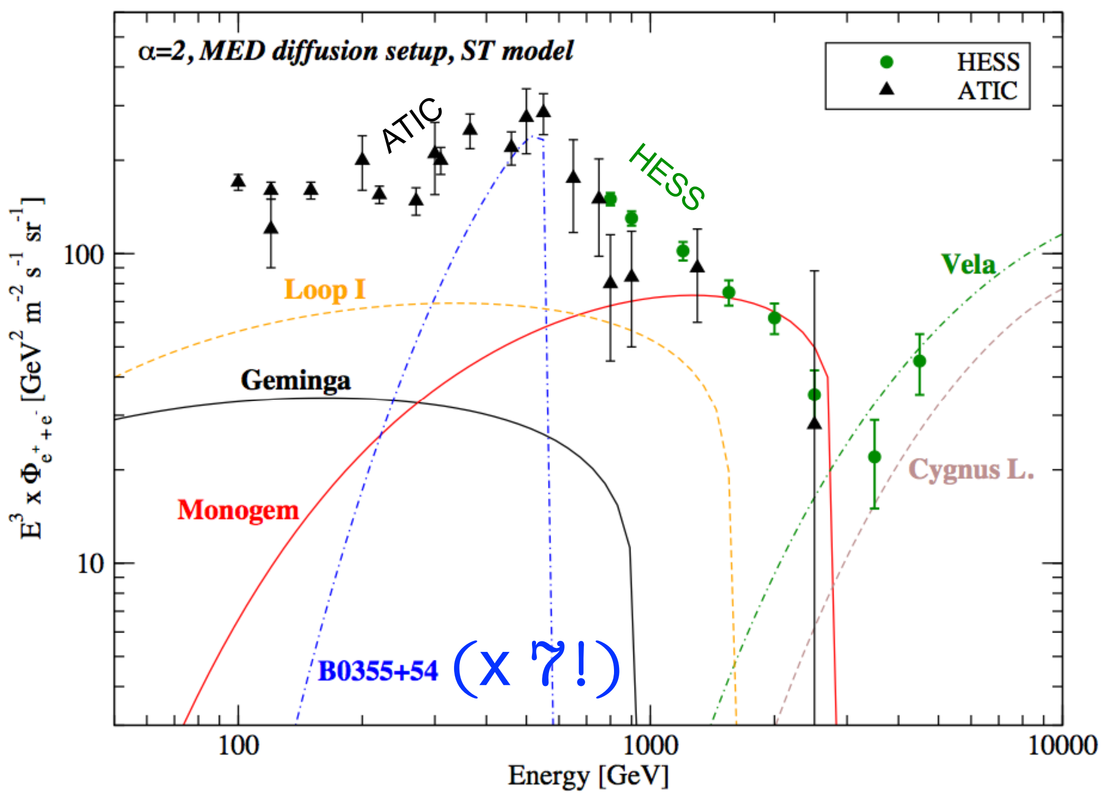
ATIC needs a different (and very powerful) source:





(x 7!)

Profumo 0812.4457

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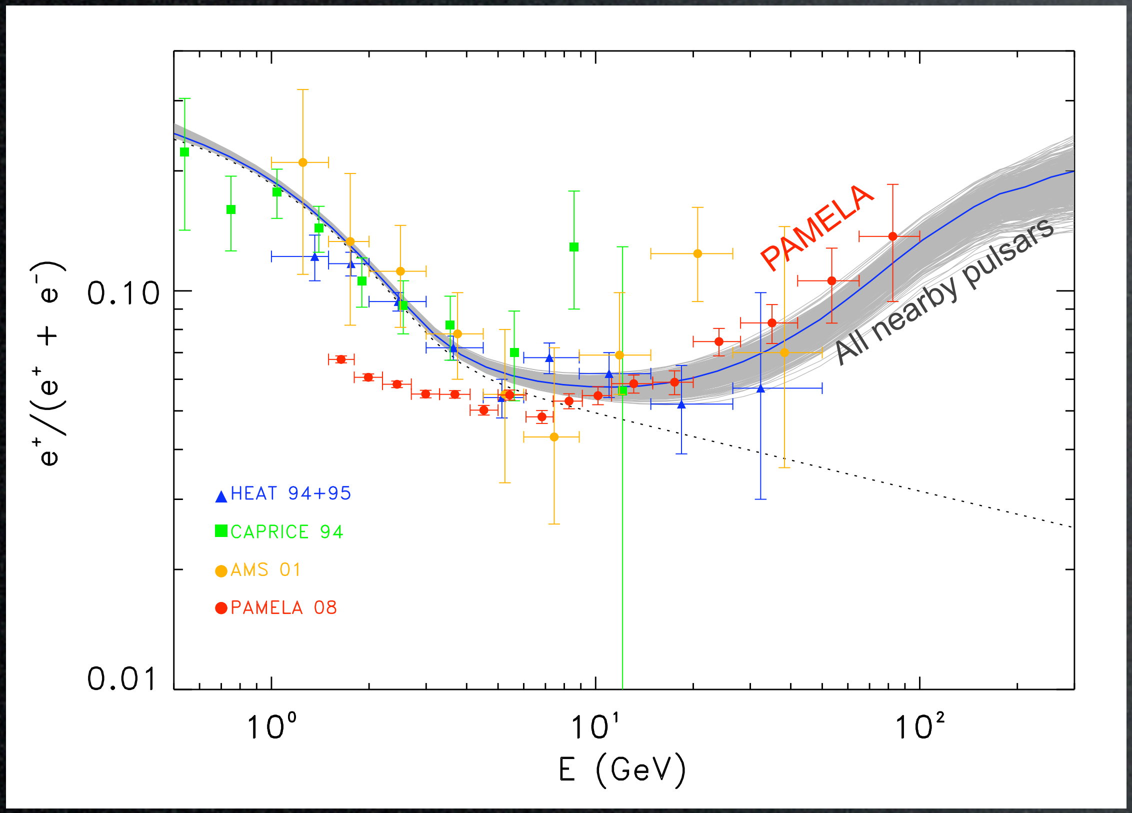
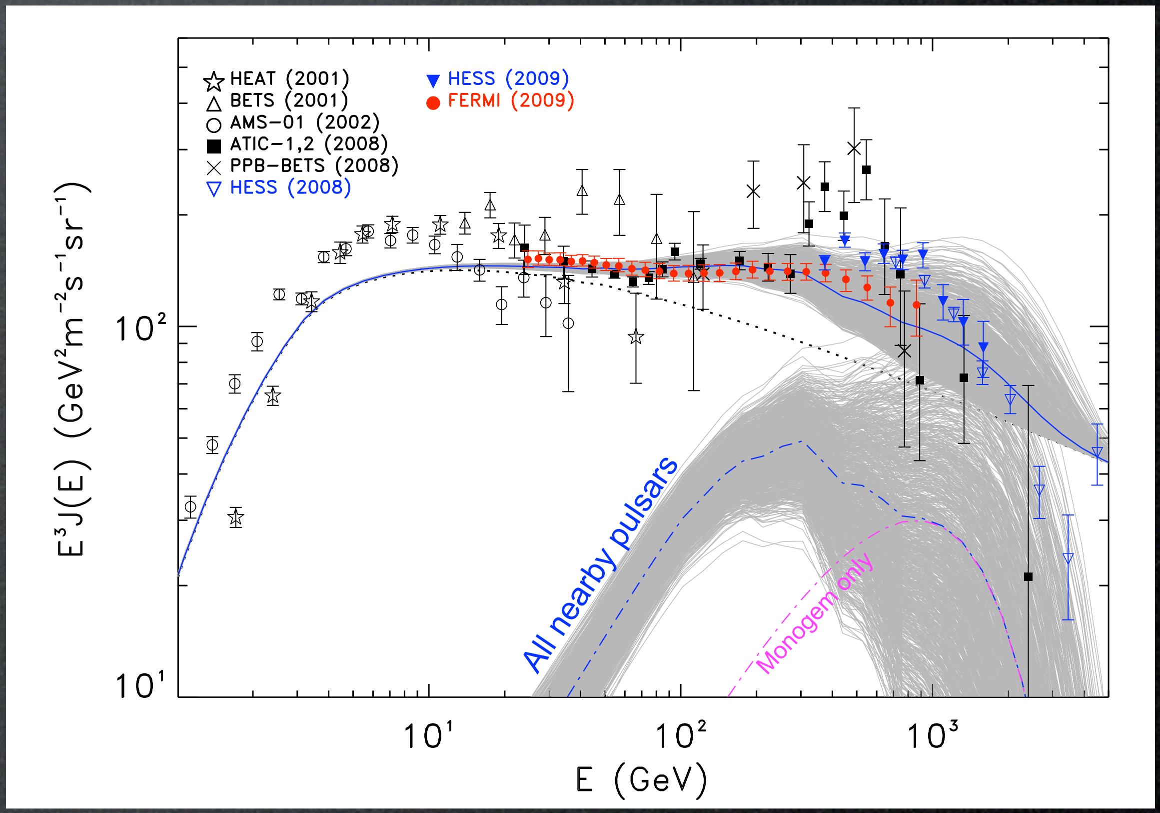
PAMELA + FERMI + HESS can be well fitted by pulsars:





D.Grasso et al.
(sub-FERMI collab.)
0905.0636

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Open issue.

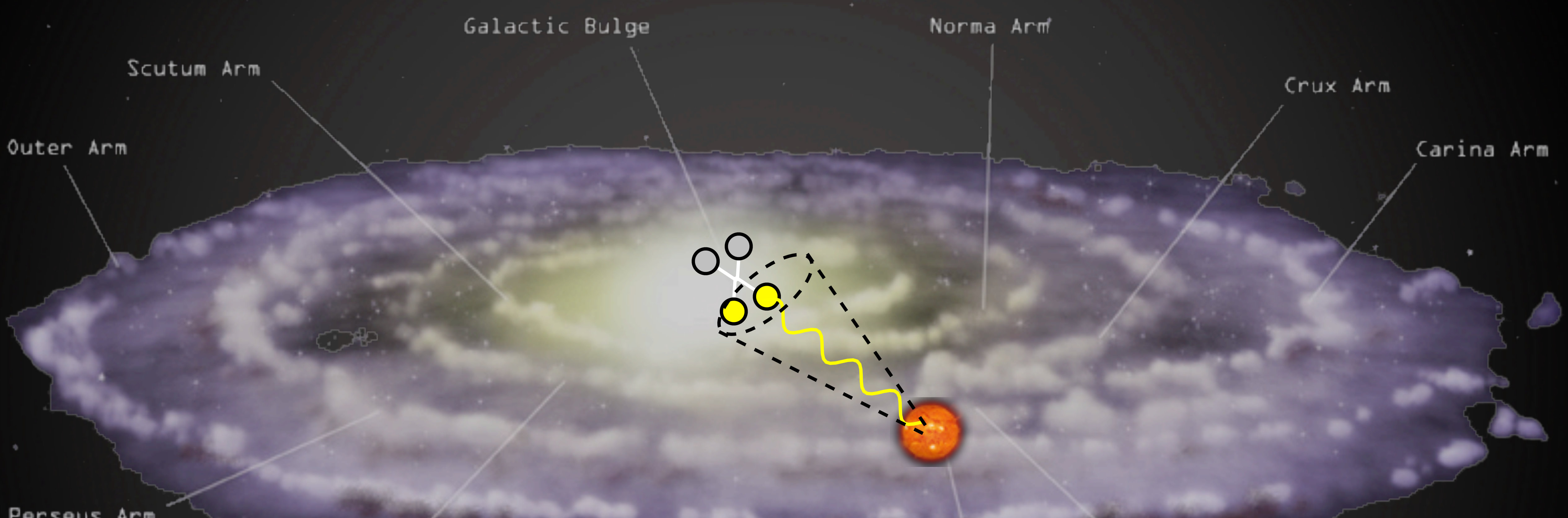
(look for anisotropies,
(both for single source and collection in disk)
antiprotons, gammas...
(Fermi is discovering a pulsar a week)
or shape of the spectrum...)

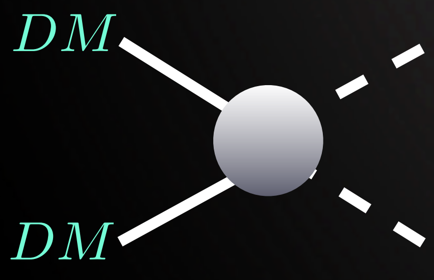
e.g. Yuksel, Kistler, Stanev 0810.2784
Hall, Hooper 0811.3362

[back]

Indirect Detection

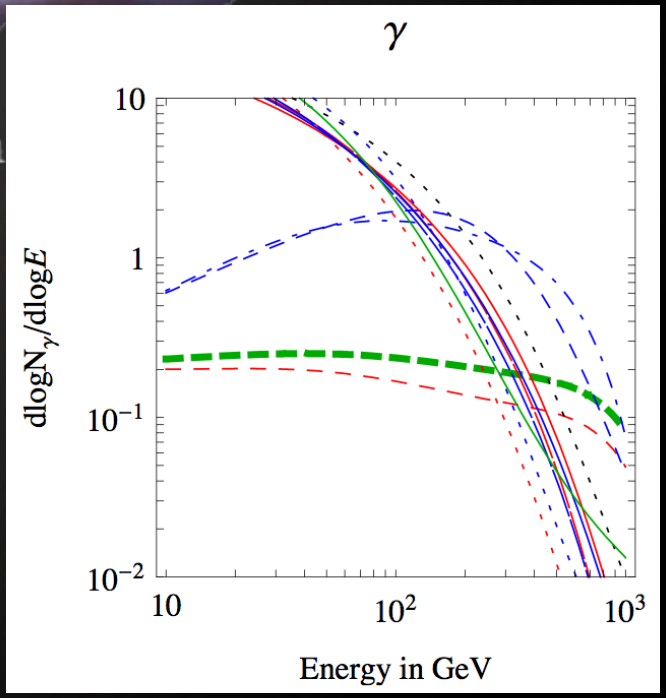
γ from DM annihilations in galactic center





$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

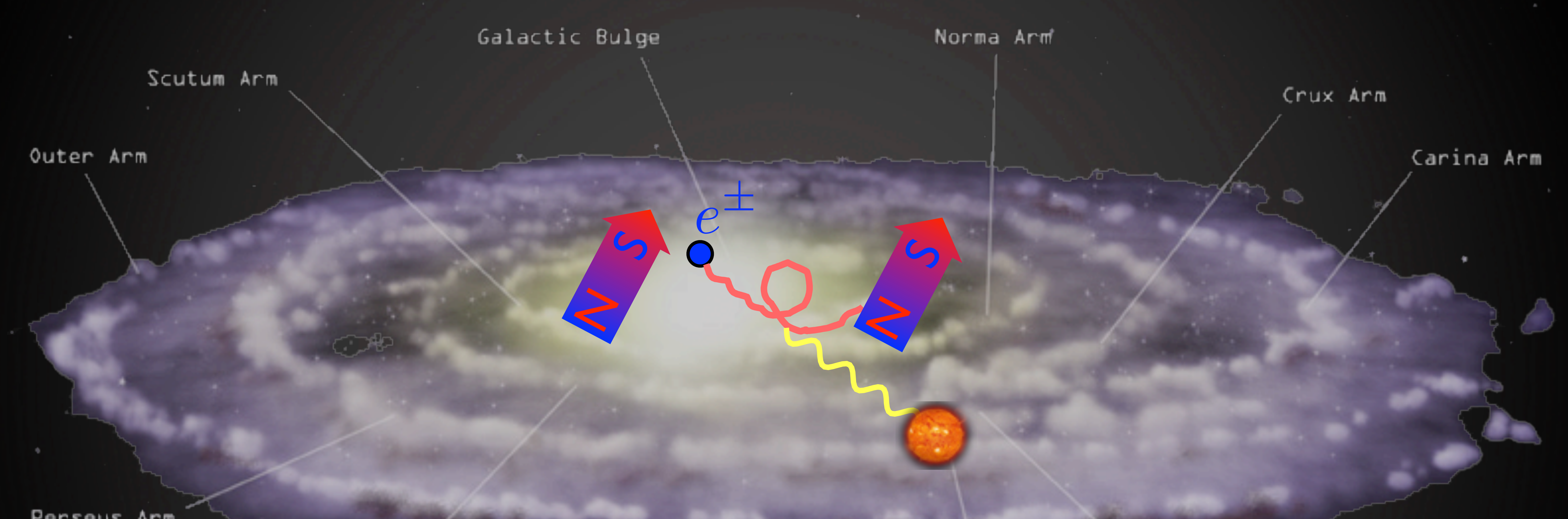
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

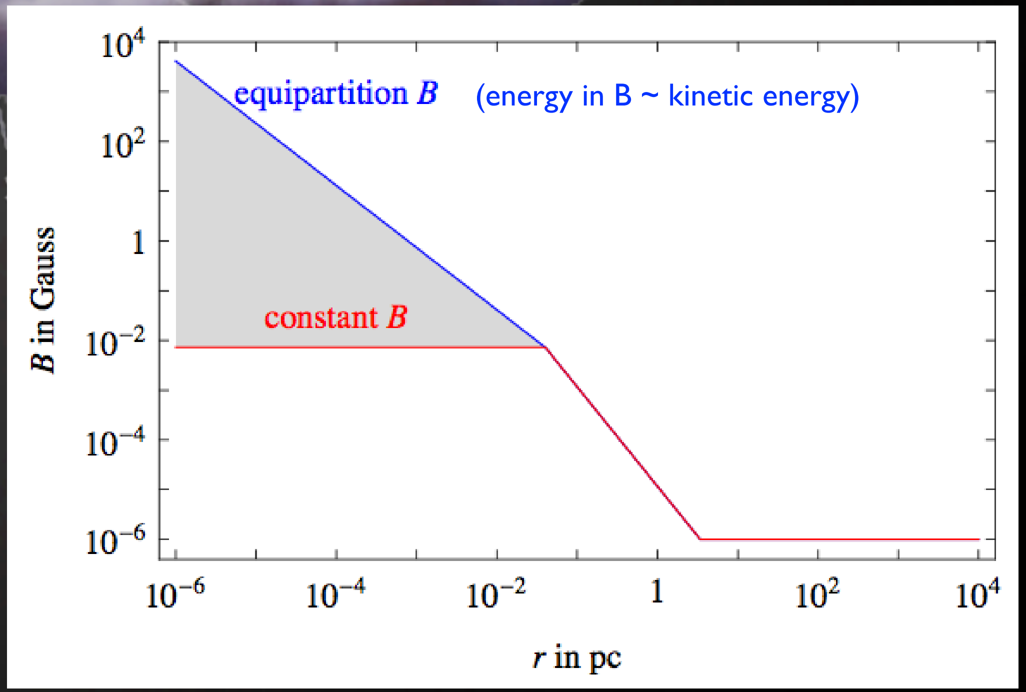


typically sub-TeV energies

Indirect Detection

radio-waves from synchrotron radiation of $e^{\pm}$ in GC



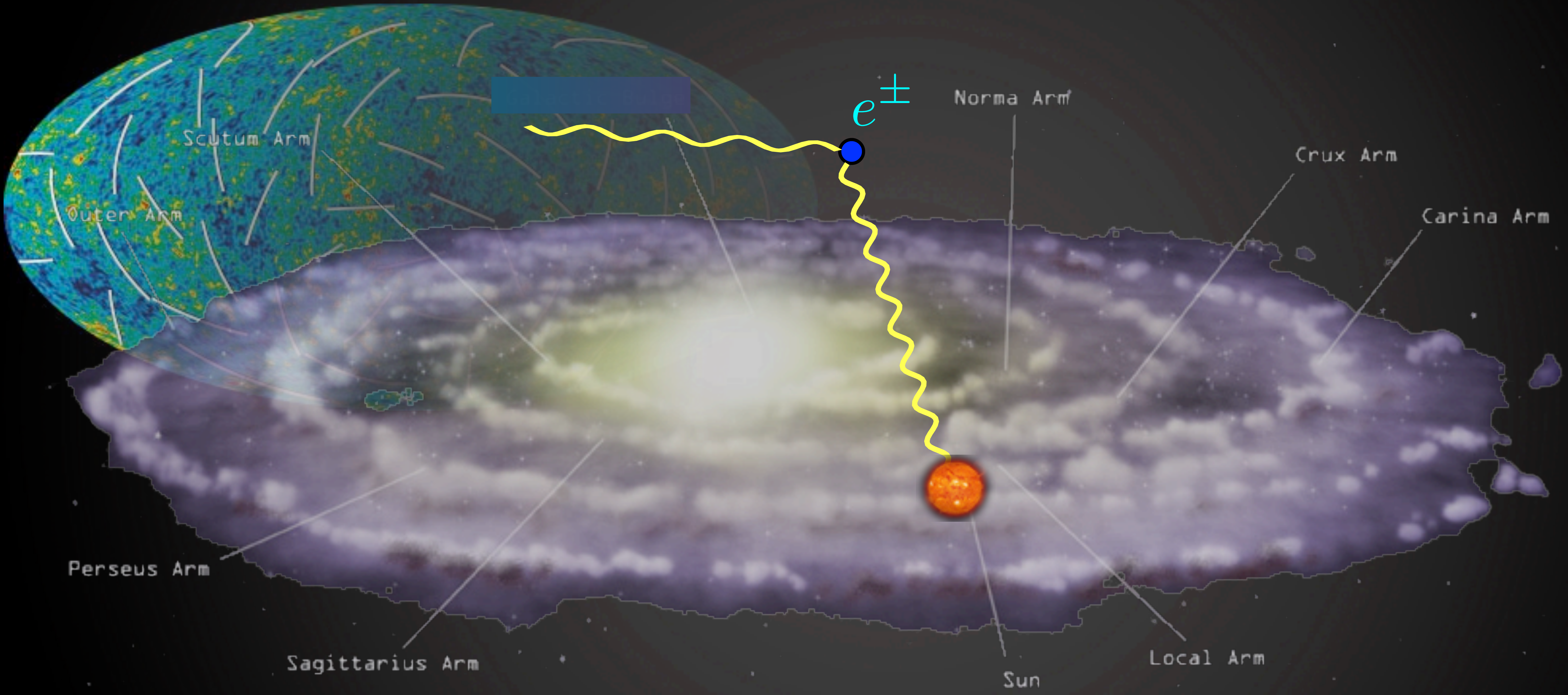


- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

(assuming ‘scrambled’ B; in principle, directionality could focus emission, lift bounds by O(some))

Indirect Detection

γ from Inverse Compton on $e^{\pm}$ in halo

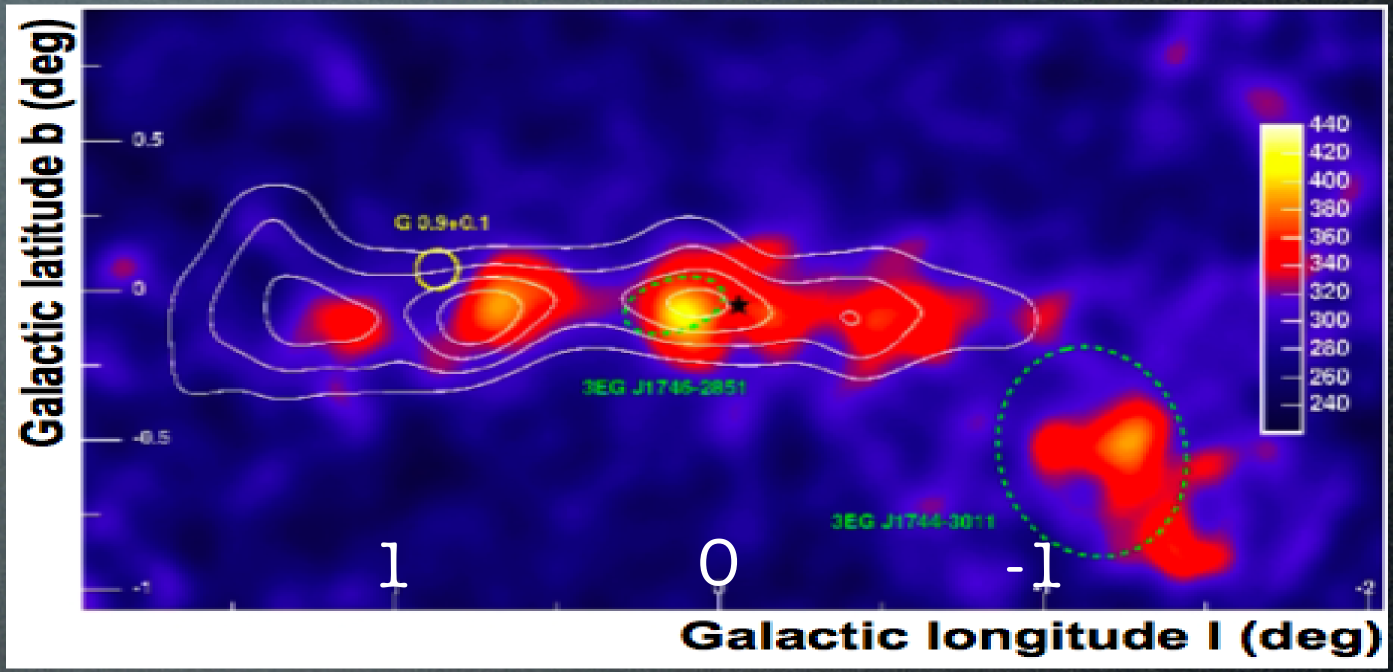


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Comparing with data

Gamma constraints

HESS has detected γ-ray emission from Gal Center and Gal Ridge. The DM signal must not excede that.



a.

HESS coll.

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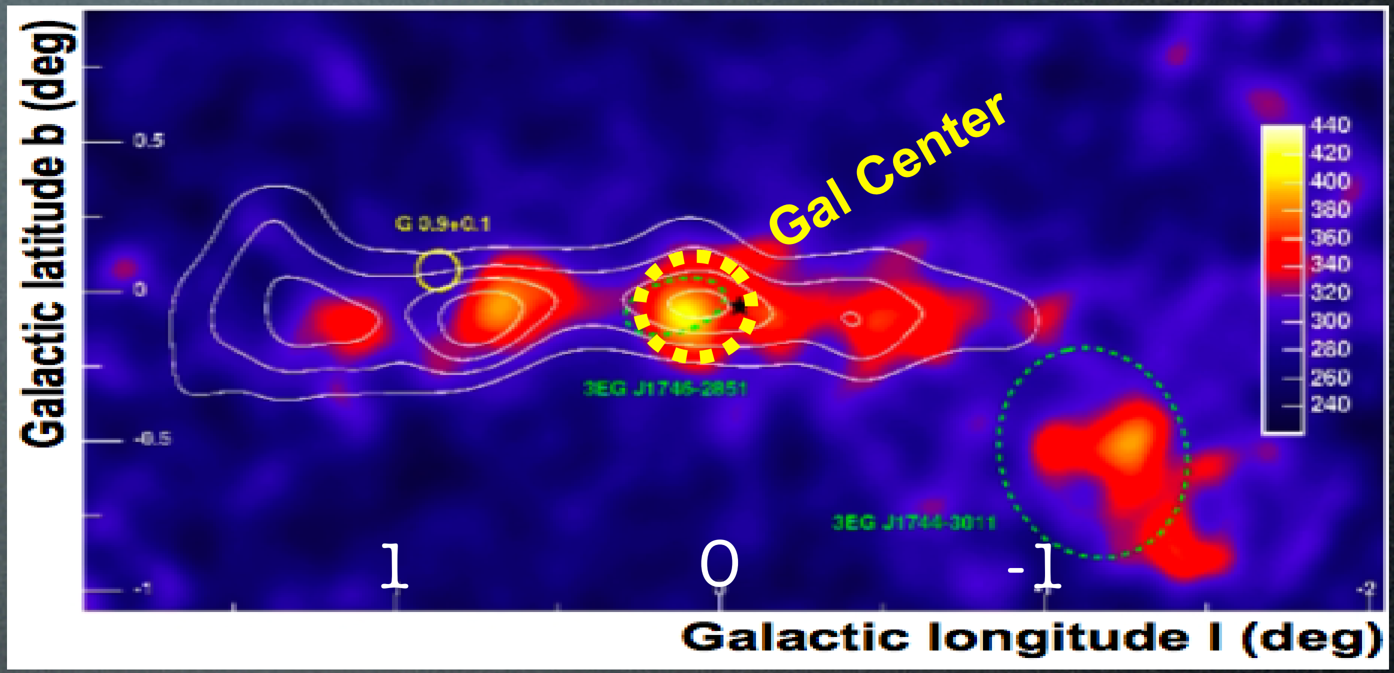

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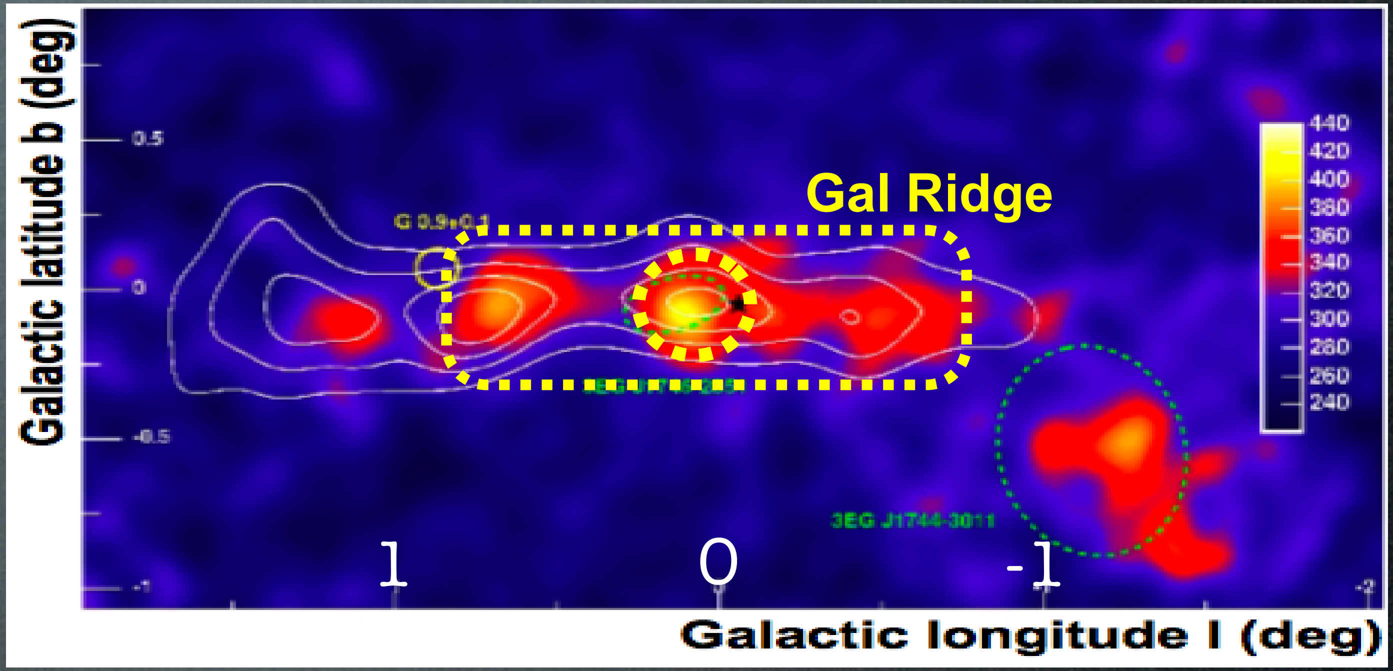

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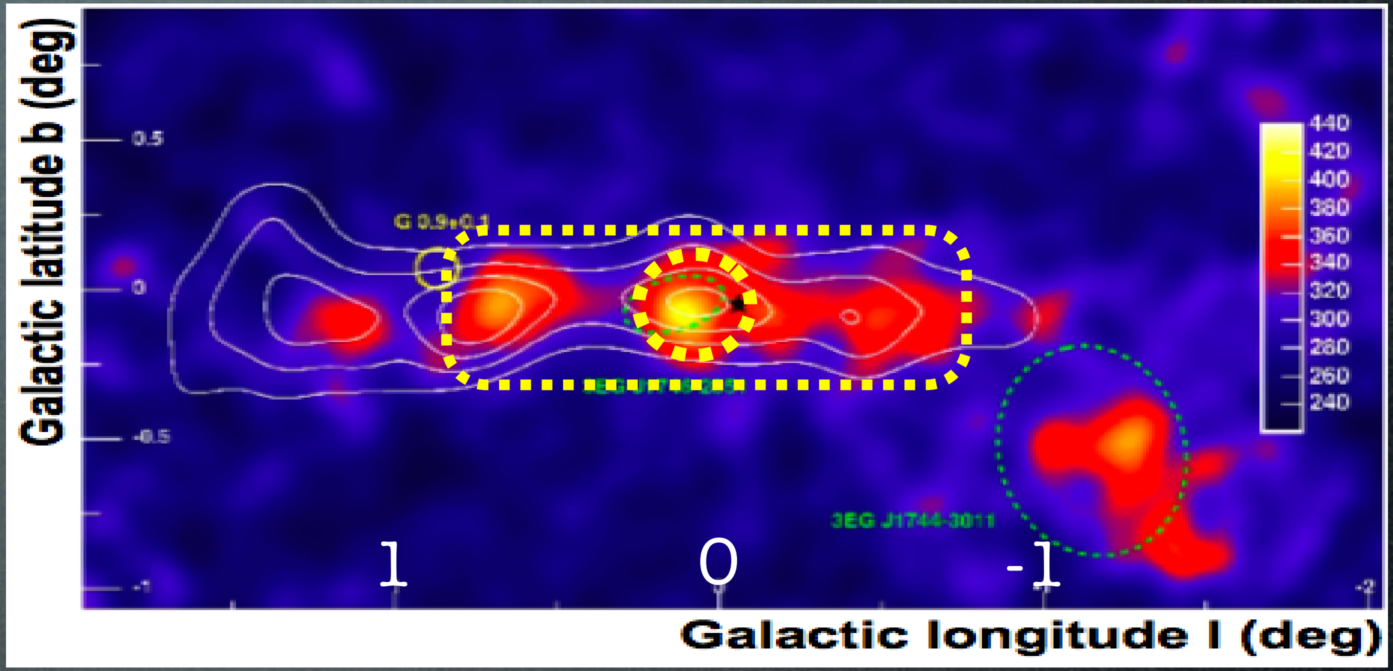
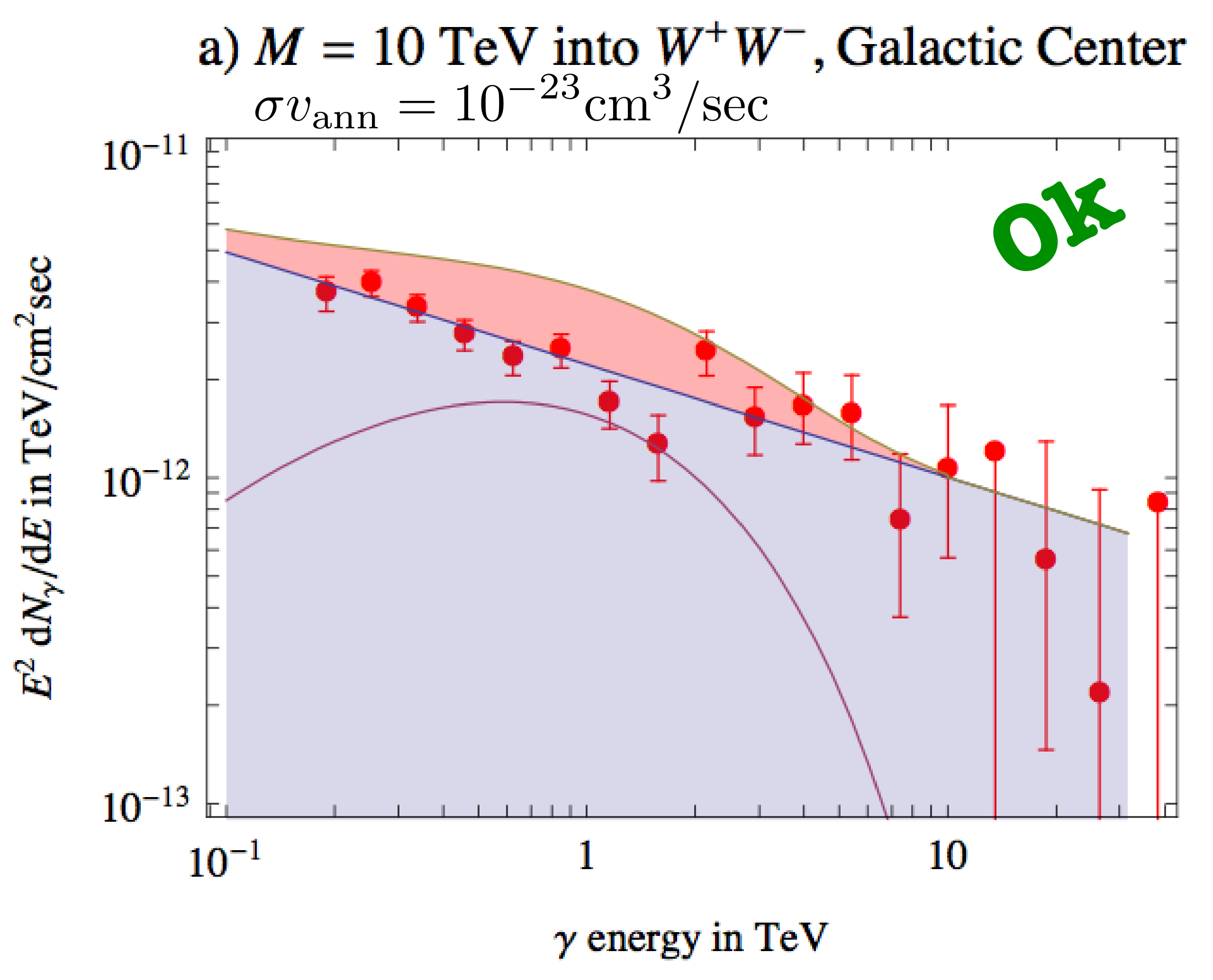


a.

HESS coll.



Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

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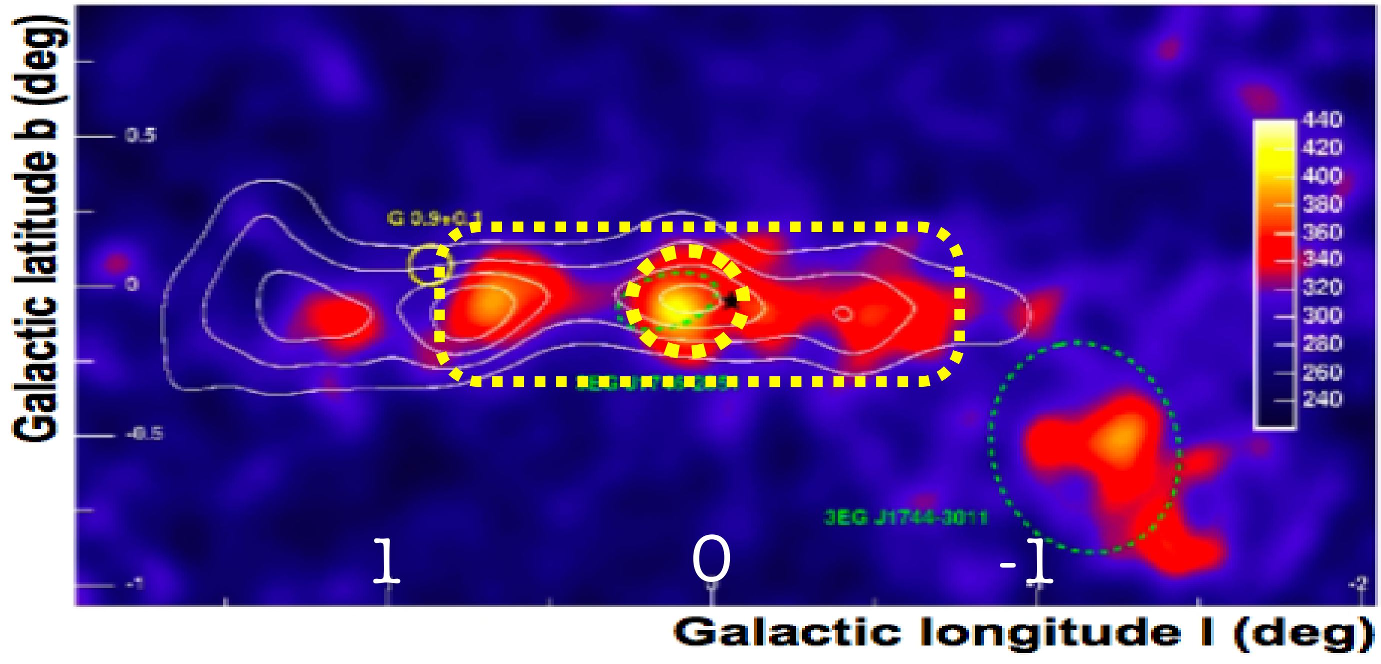
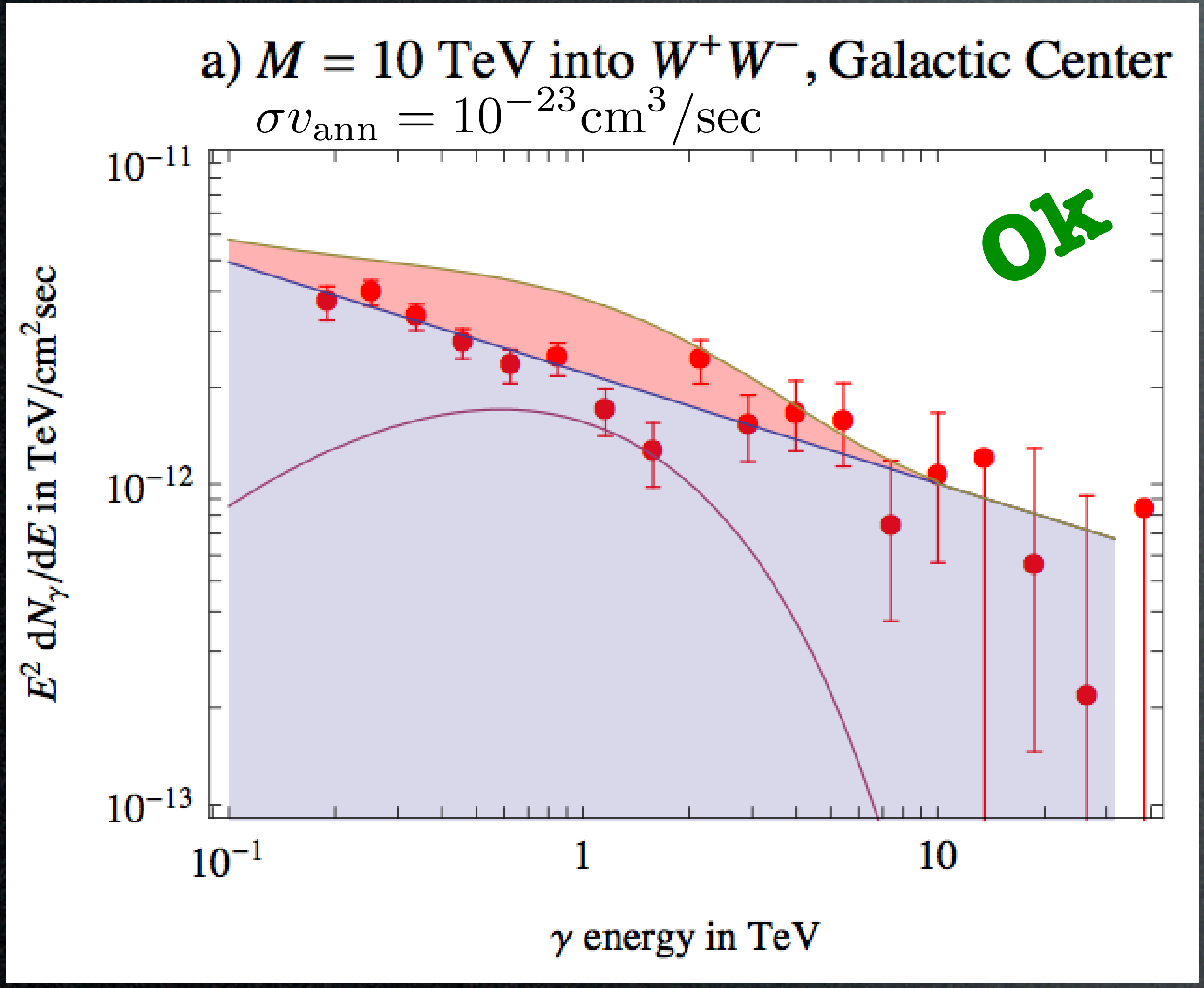
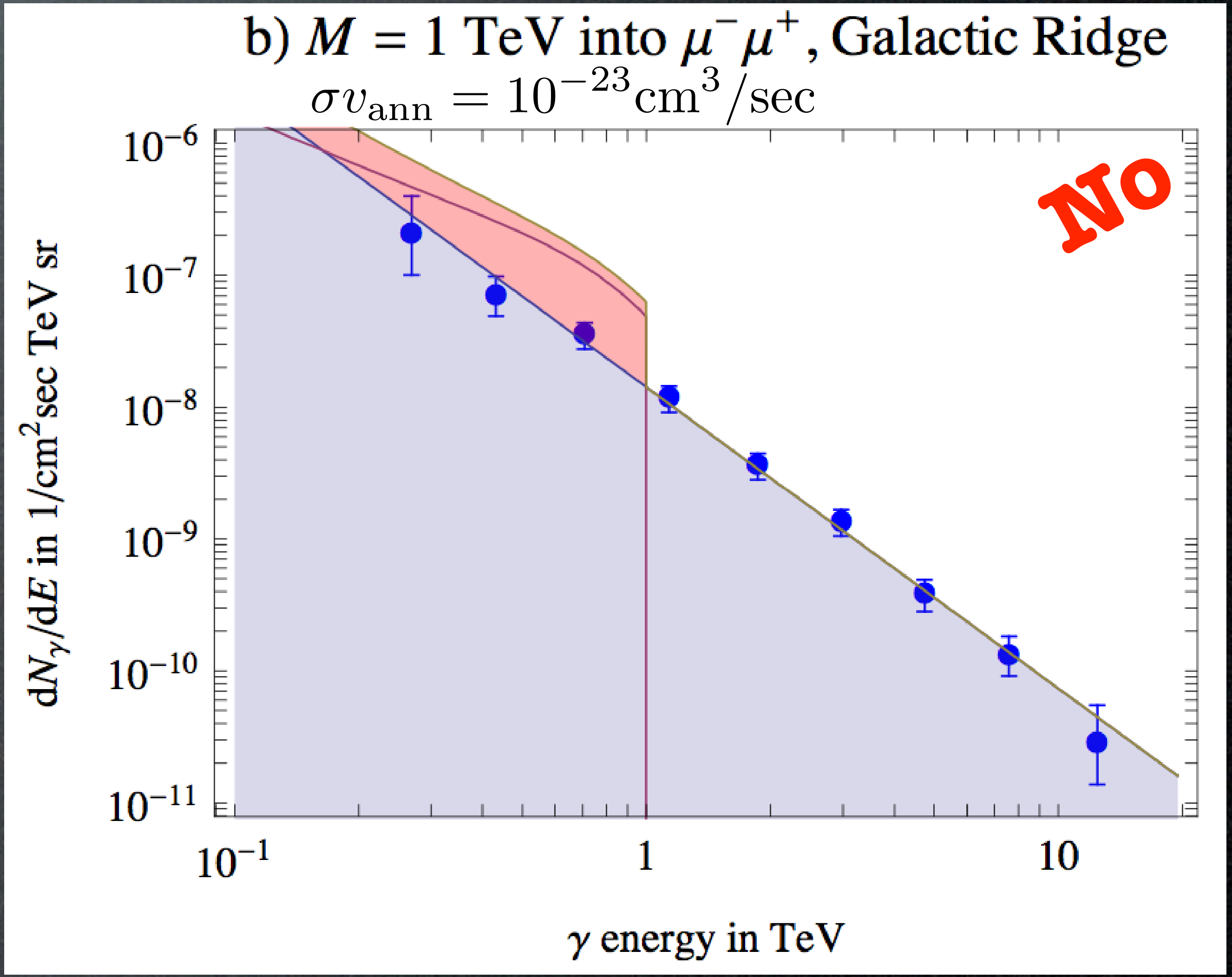


a.

HESS coll.


a) $M = 10$ TeV into W^+W^-, Galactic Center
$\sigma v_{\rm ann} = 10^{-23} {\rm cm}^3/{\rm sec}$

Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

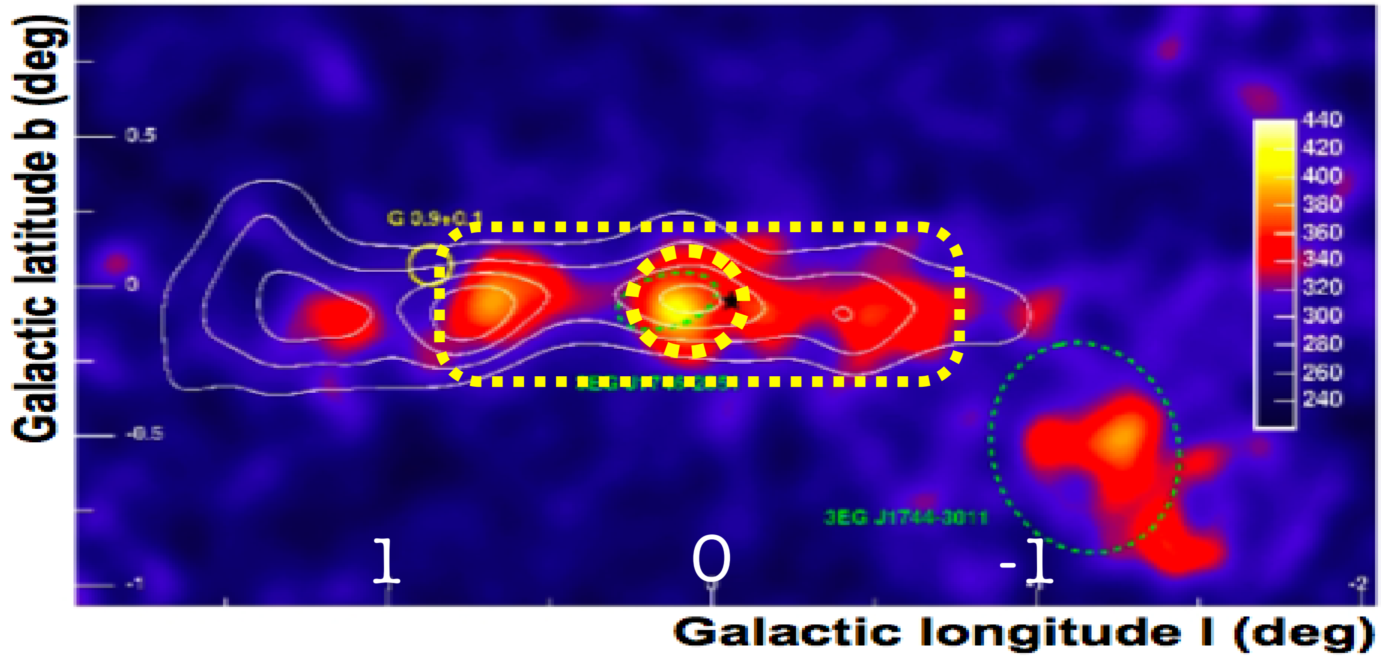

b) $M = 1$ TeV into $\mu^-\mu^+$, Galactic Ridge
$\sigma v_{\rm ann} = 10^{-23} {\rm cm}^3/{\rm sec}$

Data: HESS coll., astro-ph/0603021

Gamma constraints

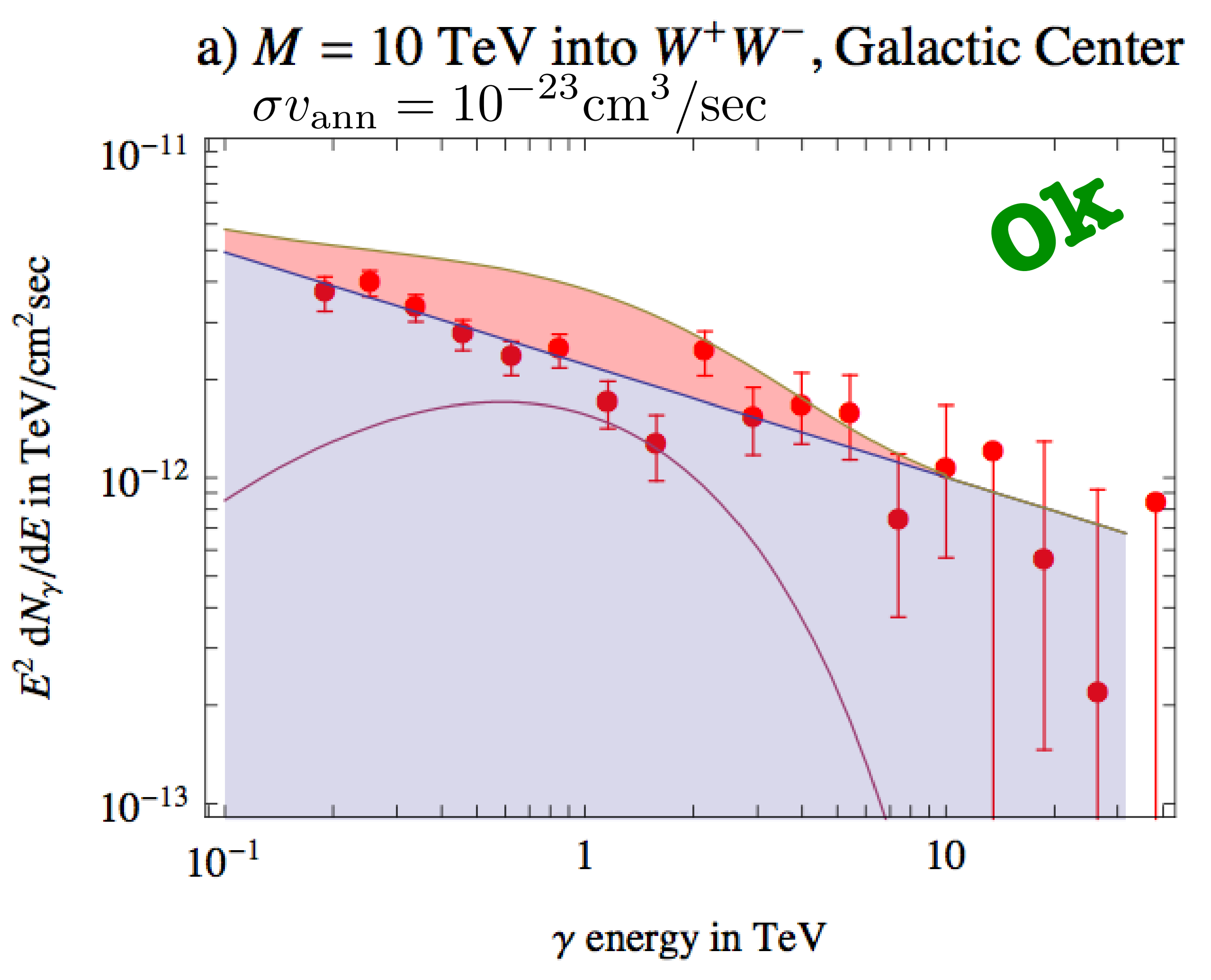
HESS has detected γ-ray emission from Gal Center and Gal Ridge. The DM signal must not excede that.

Moreover: no detection from Sgr dSph => upper bound. b.



a.

HESS coll.



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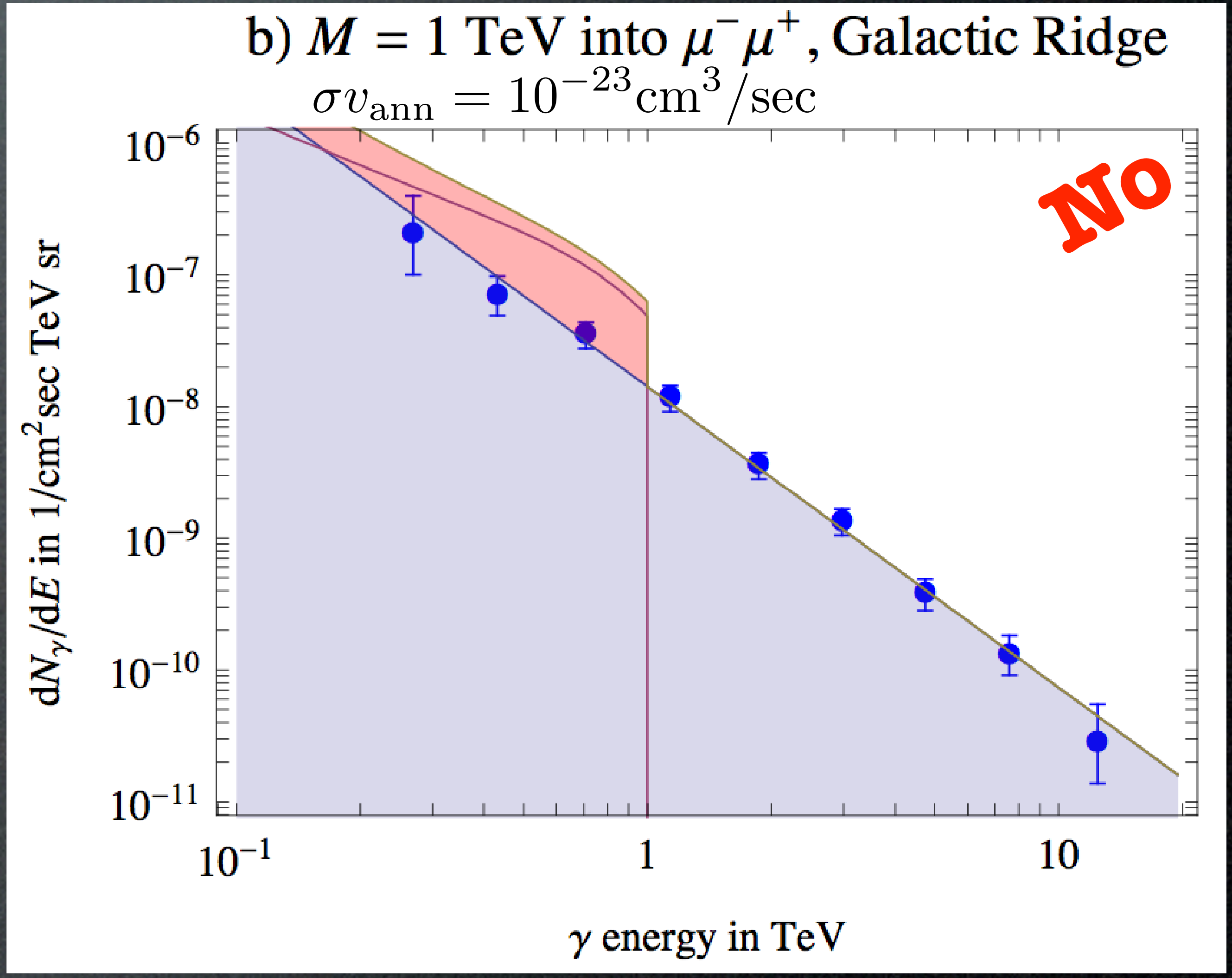
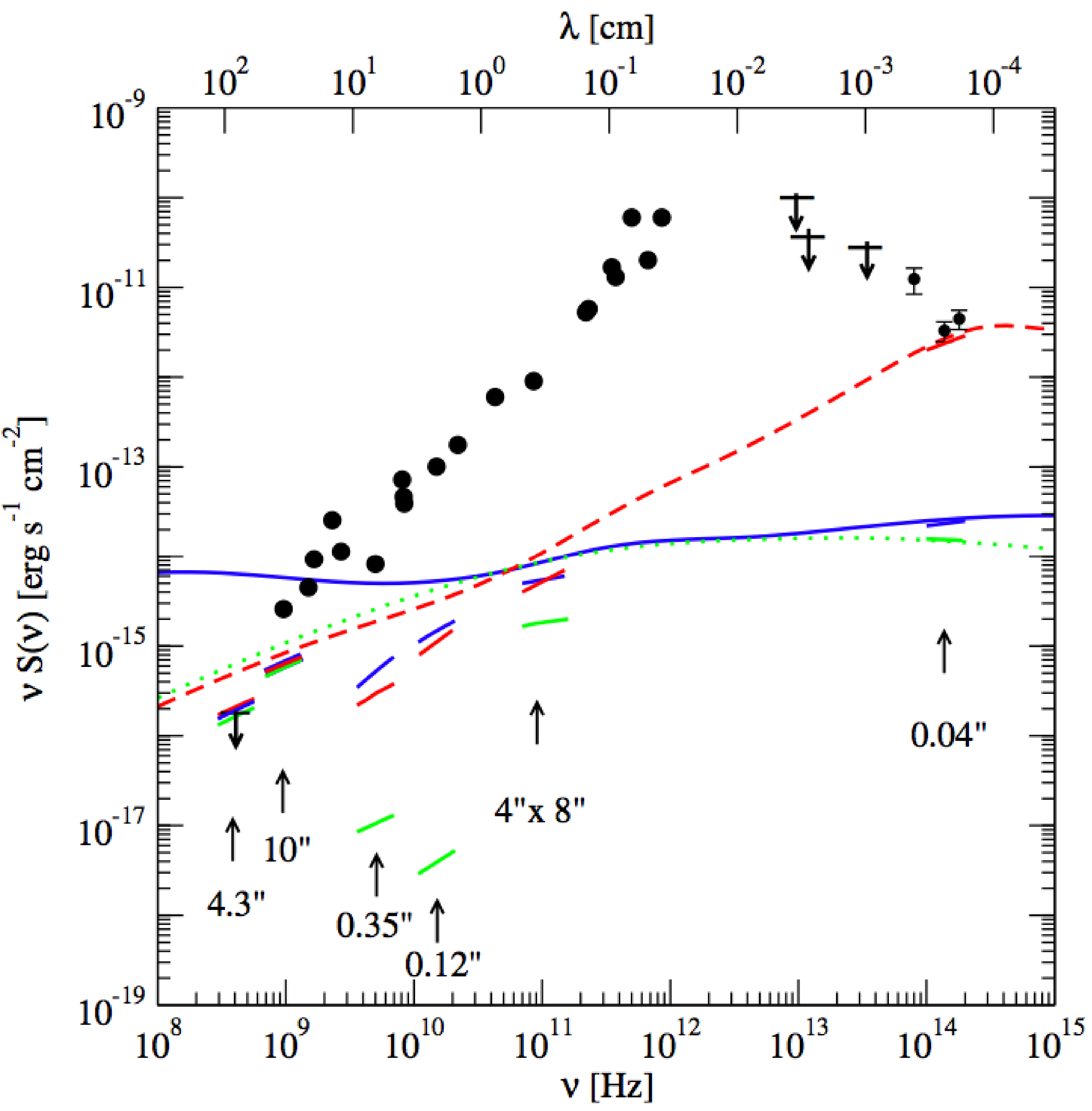


b) M = 1 TeV into $\mu^-\mu^+$, Galactic Ridge
$\sigma v_{\rm ann} = 10^{-23}\mathrm{cm}^3/\mathrm{sec}$

Data: HESS coll., astro-ph/0603021

Gamma constraints

Several observations detected radio to IR emission from the Gal Center. The DM signal must not excede that.

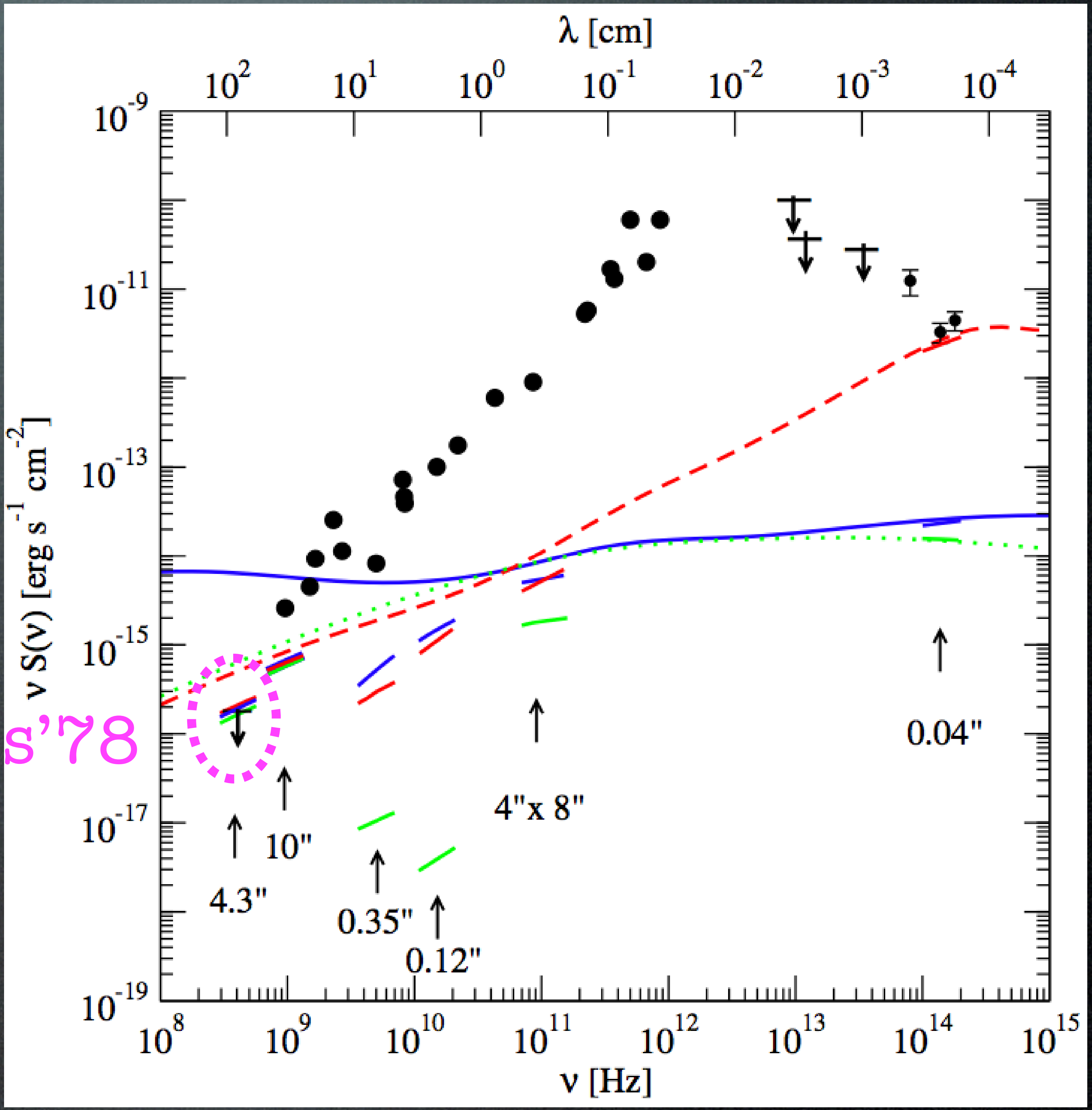


Regis, Ullio PRD 78 (2008)

Gamma constraints

Several observations detected radio to IR emission from the Gal Center. The DM signal must not excede that.

Davies 1978 upper bound at 408 MHz.



Davies'78

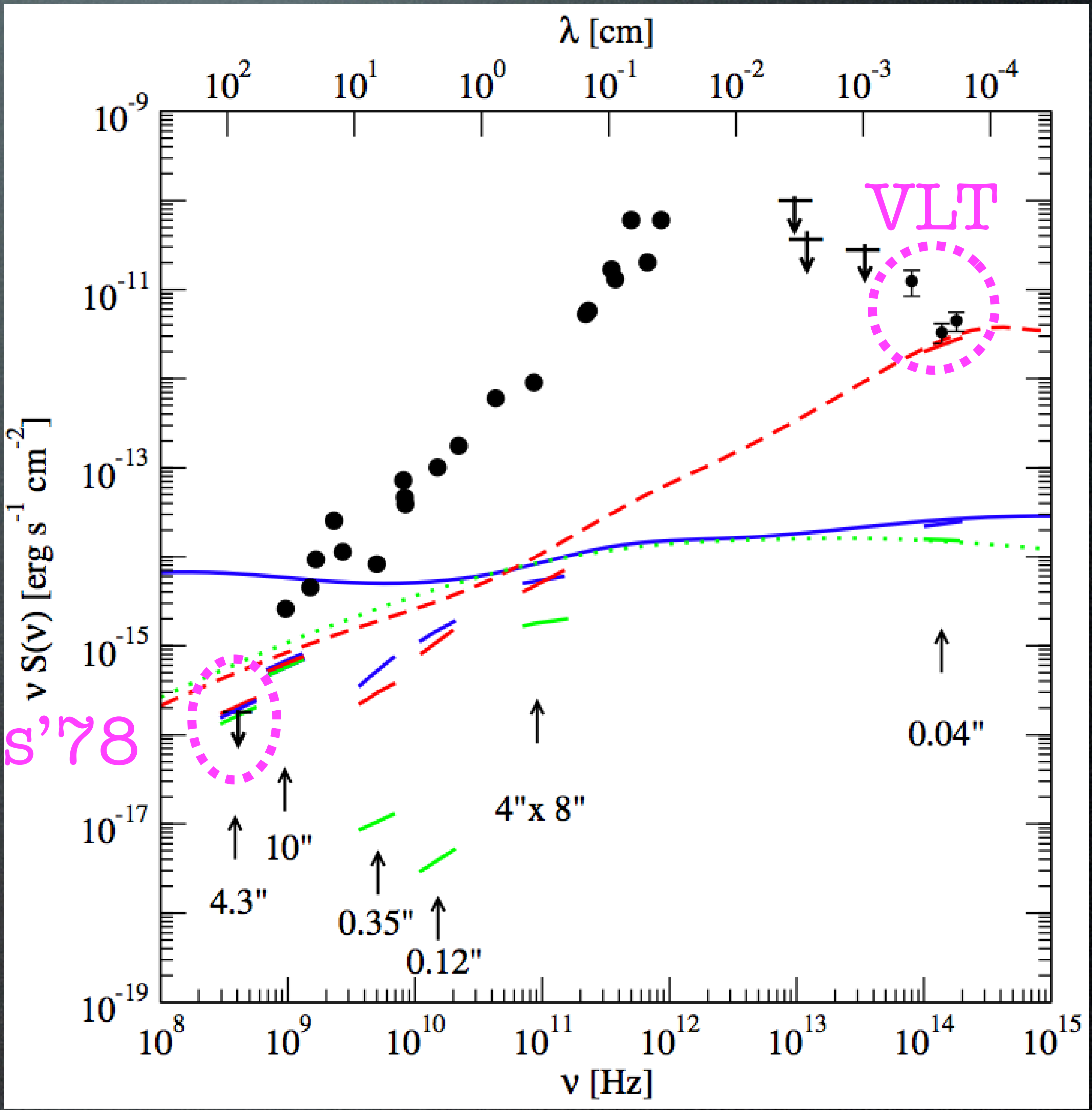
Regis, Ullio PRD 78 (2008)

Gamma constraints

Several observations detected radio to IR emission from the Gal Center. The DM signal must not excede that.

Davies 1978 upper bound at 408 MHz.

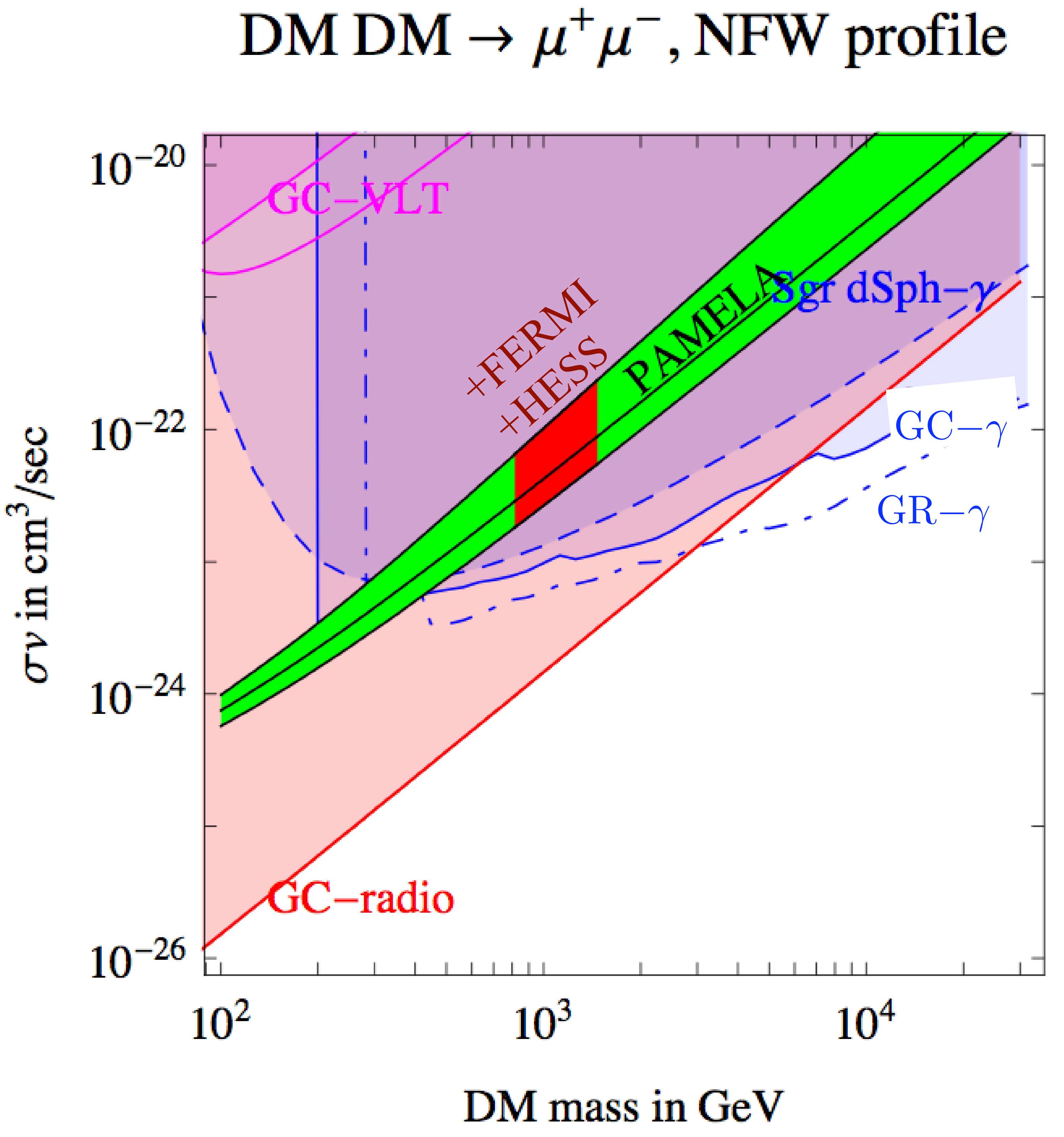
VLT 2003 emission at 10^{14} Hz.



integrate emission over a small angle corresponding to angular resolution of instrument

Regis, Ullio PRD 78 (2008)

Gamma constraints

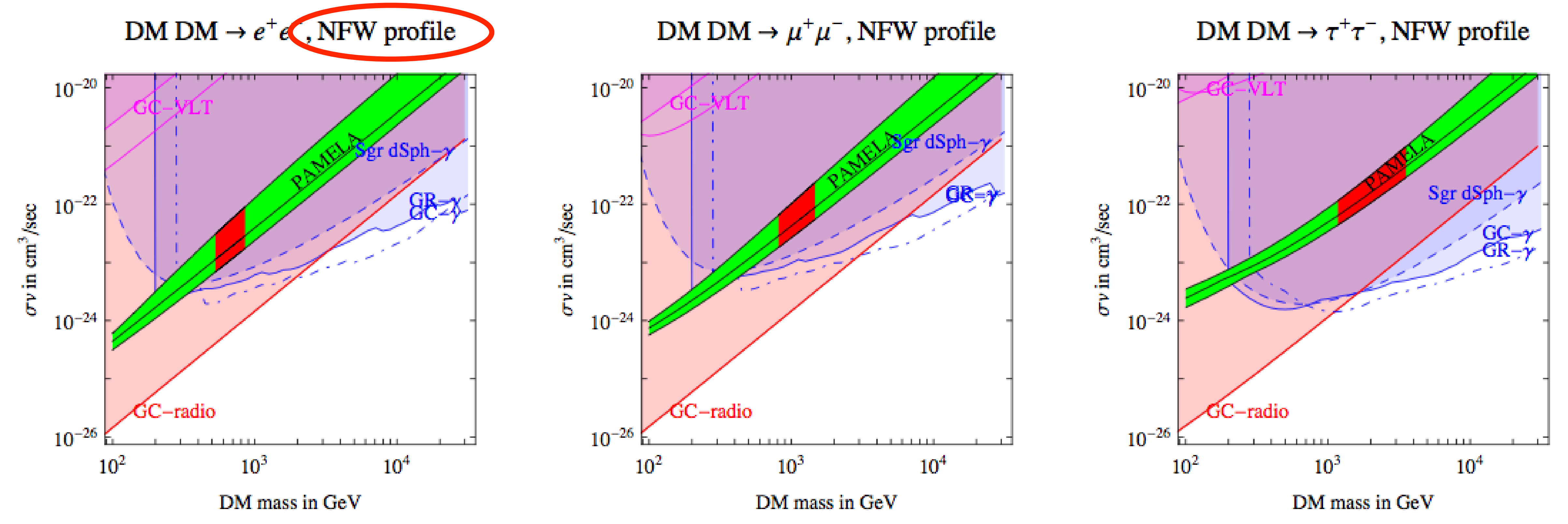


Bertone, Cirelli, Strumia, Taoso 0811.3744

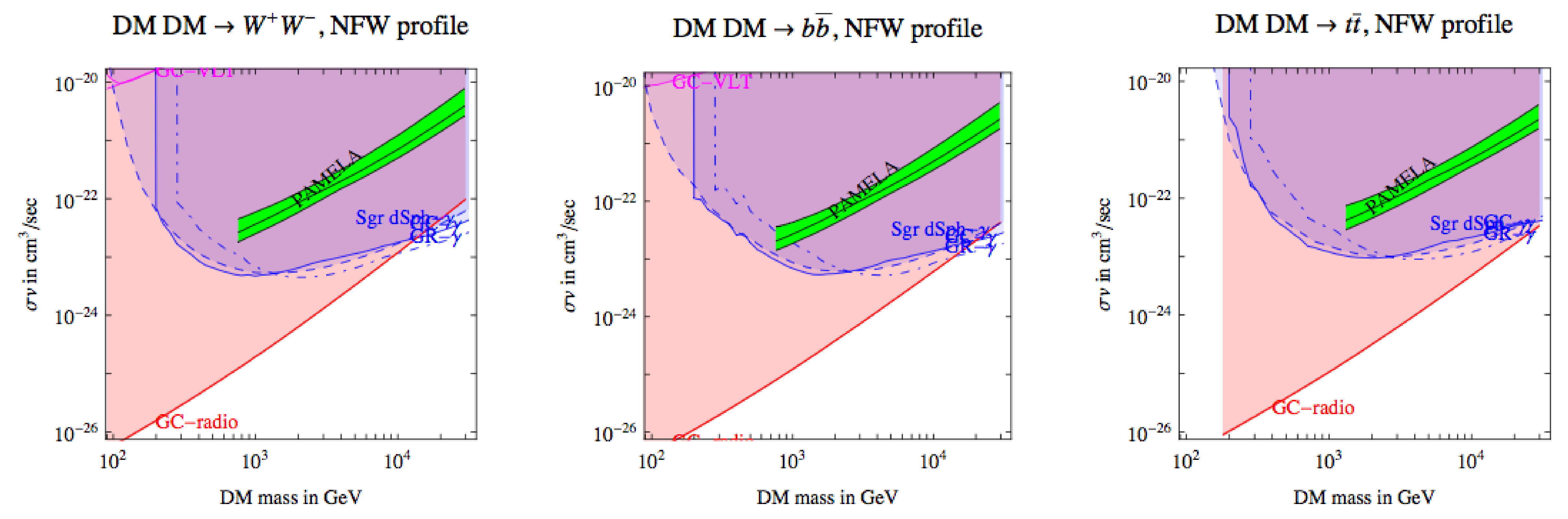
a+b+c.

The PAMELA +FERMI regions are in conflict with gamma constraints, unless...

Gamma constraints

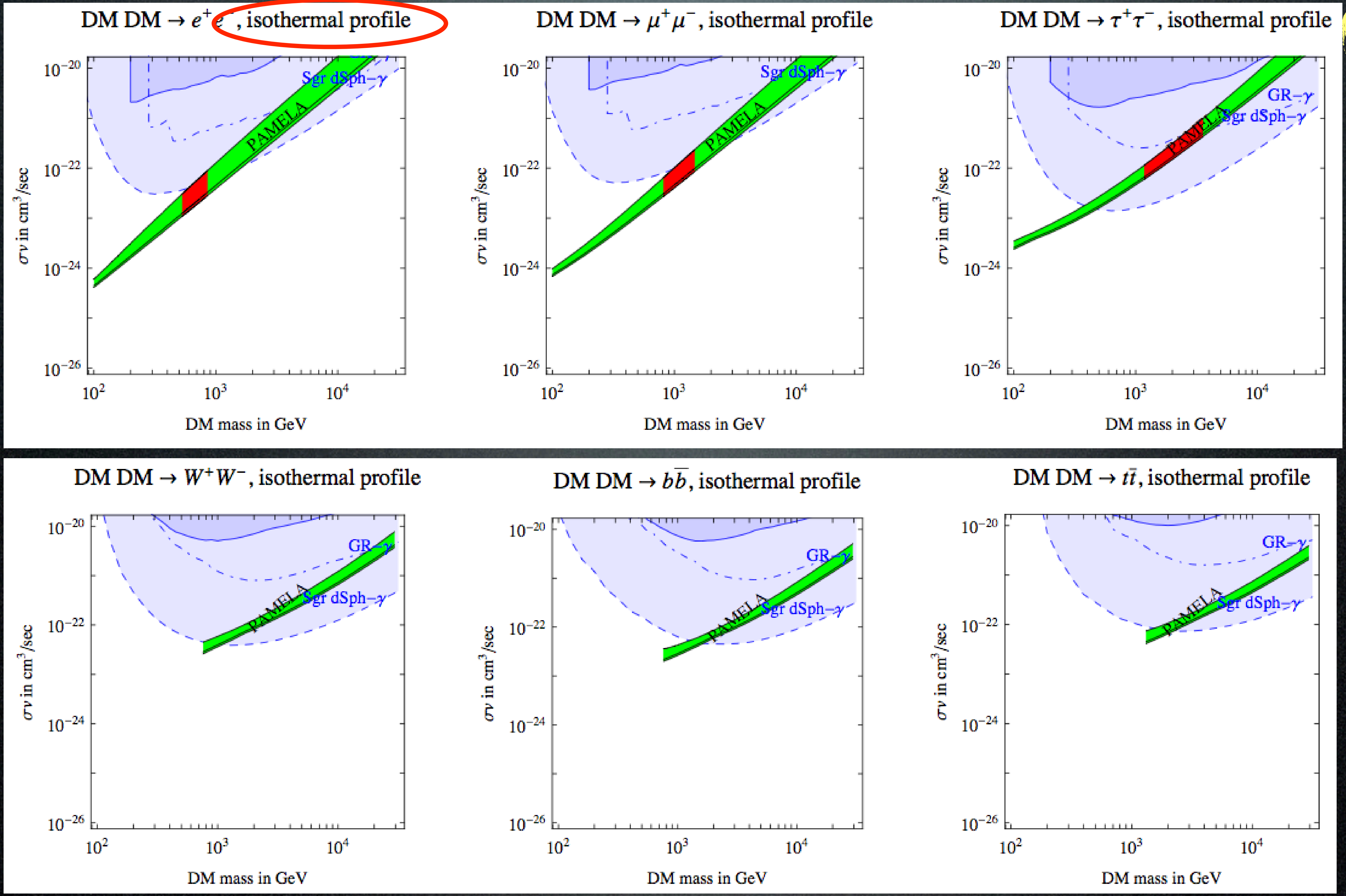


a+b+c.



Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints



a+b+c.

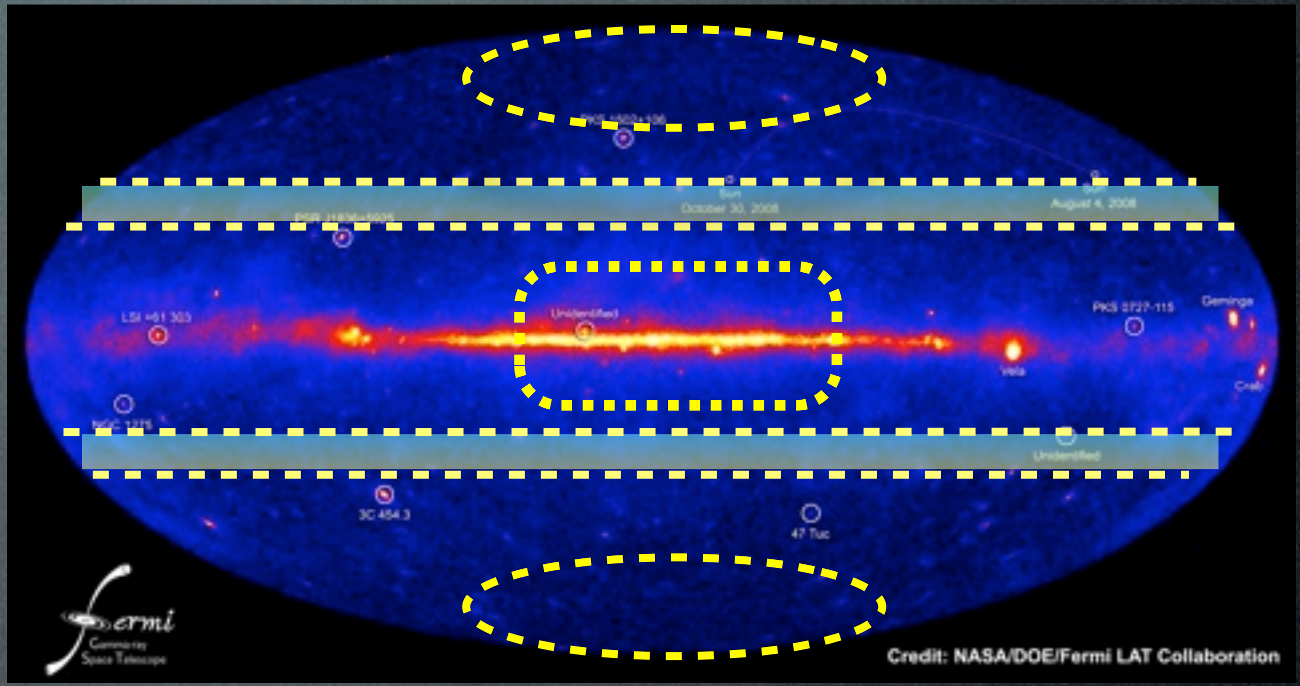
Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

Gamma constraints

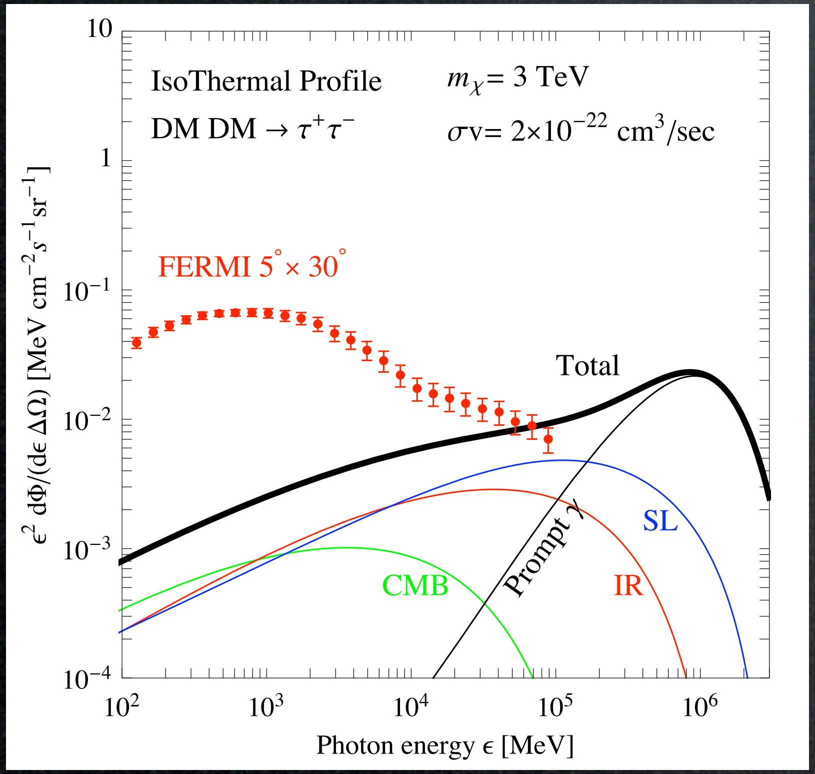
FERMI has measured diffuse γ-ray emission. The DM signal must not excede that.

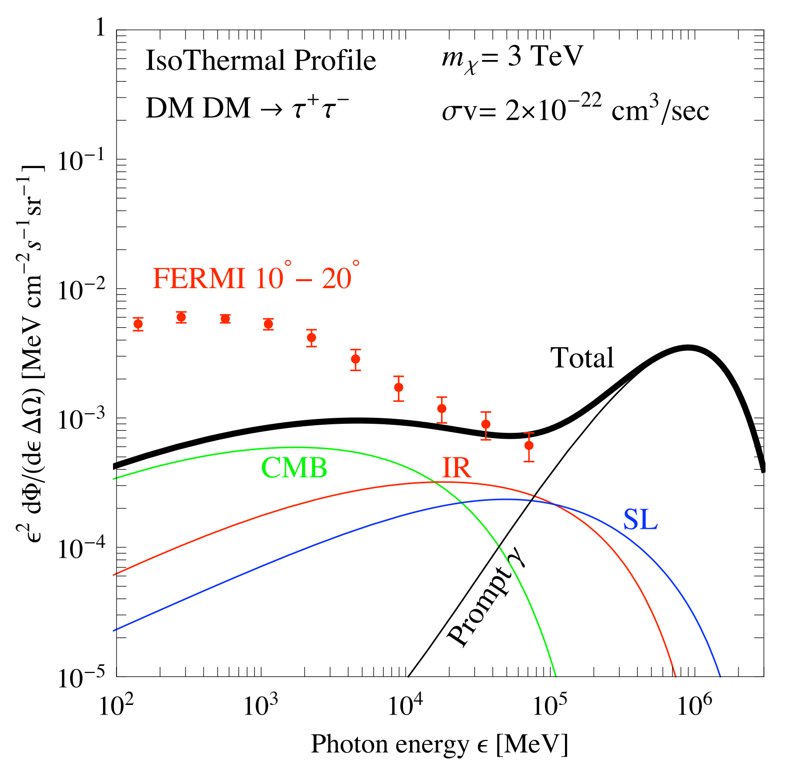
d.

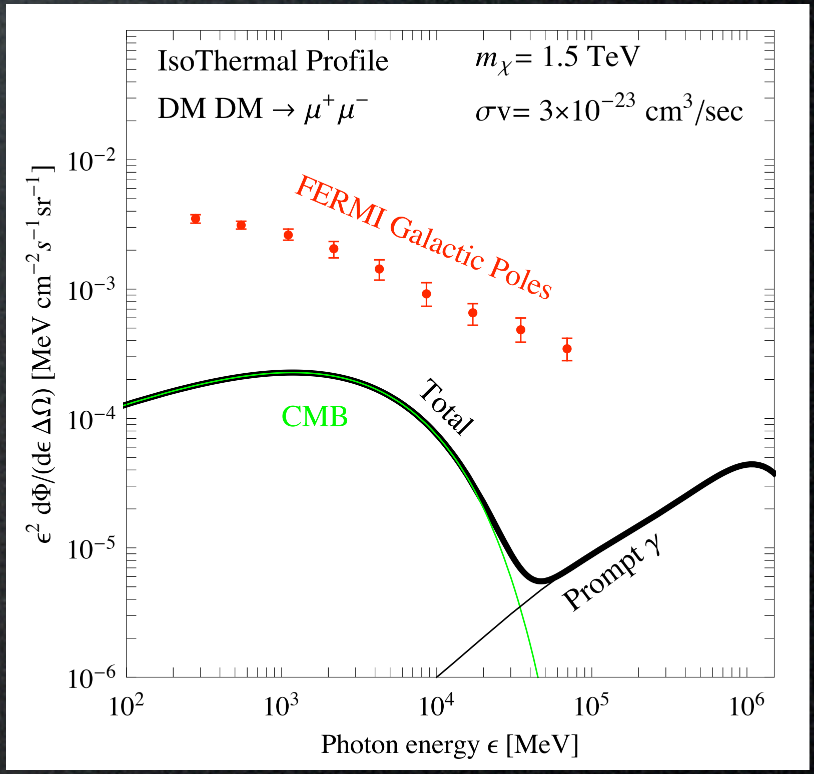


Credit: NASA/DOE/Fermi LAT Collaboration

FERMI coll.



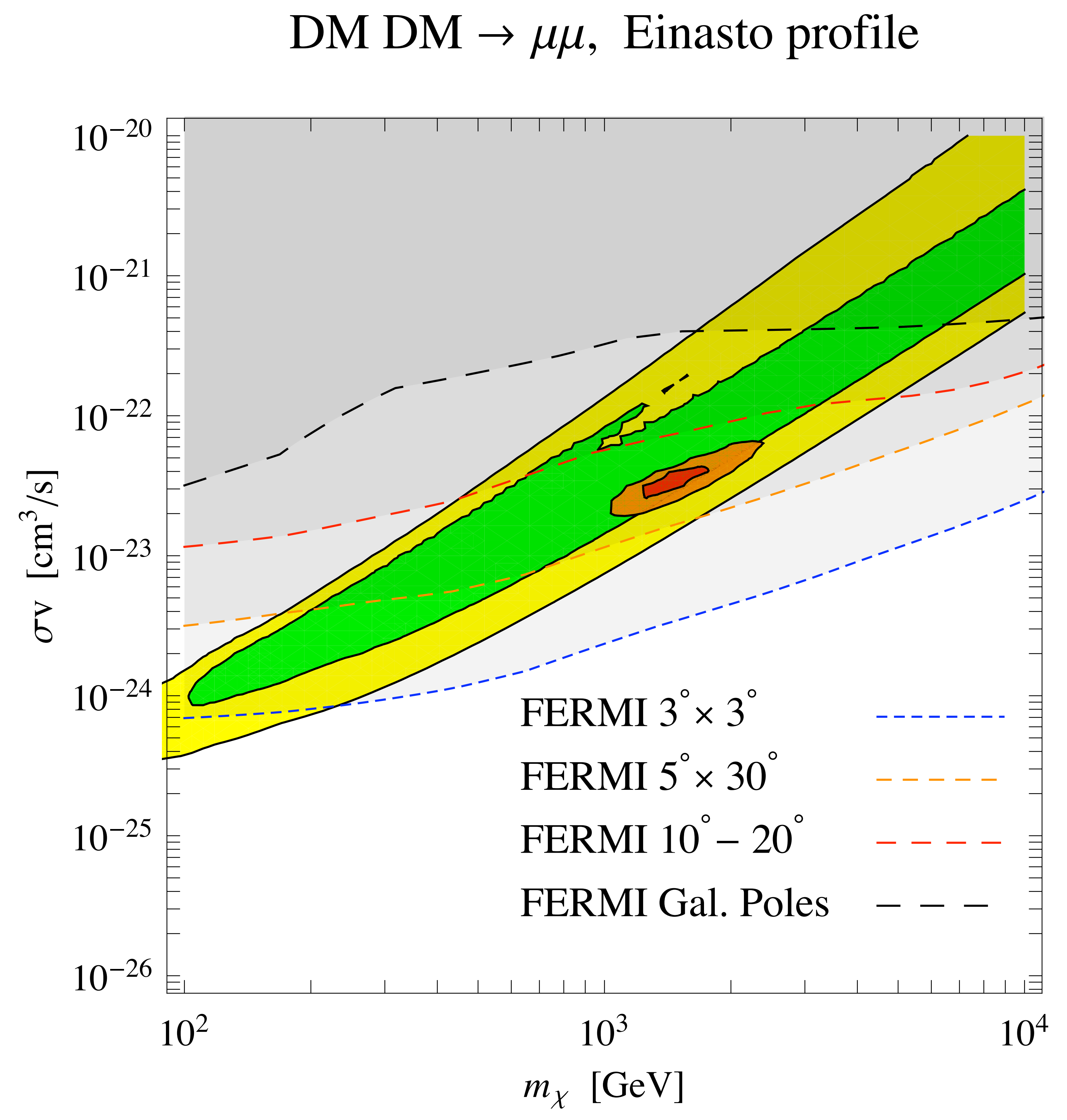




Data: FERMI coll., several talks and papers

Cirelli, Panci, Serpico 0912.0663

Inverse Compton γ constraints



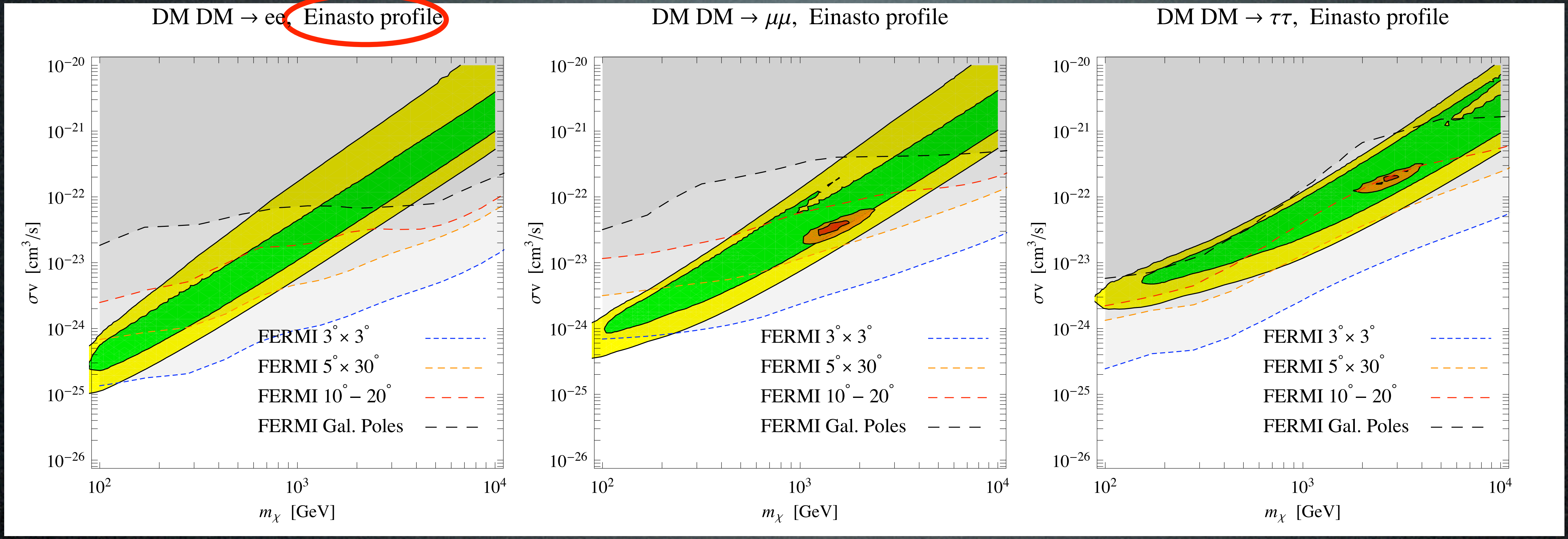
Cirelli, Panci, Serpico 0912.0663

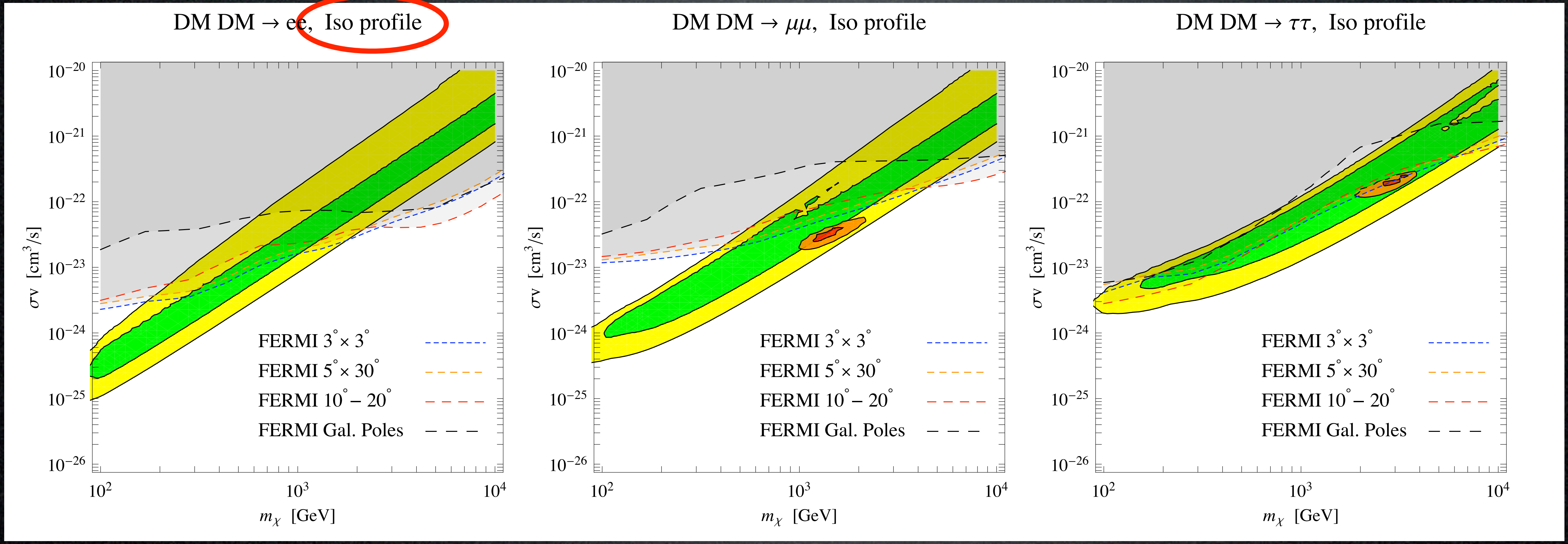
d.

The PAMELA and FERMI regions are in conflict with these gamma constraints, and here...

Inverse Compton γ constraints

d.





Cirelli, Panci, Serpico 0912.0663

Challenges for the ‘conventional’ DM candidates

Needs:	**SuSy DM**	**KK DM**
- TeV or multi-TeV masses	difficult	ok
- no hadronic channels	difficult	difficult
- no helicity suppression	no	ok

for any Majorana DM,
s-wave annihilation cross section

$$\sigma_{\rm ann}(\mathrm{DM}\,\overline{\mathrm{DM}} \to f\bar{f}) \propto \left(\frac{m_f}{M_{\rm DM}}\right)^2$$

Enhancement

How to reconcile $\sigma = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$ with $\sigma \simeq 10^{-23} \mathrm{cm}^3/\mathrm{sec}$?

- DM is produced non-thermally: the annihilation cross section today is unrelated to the production process

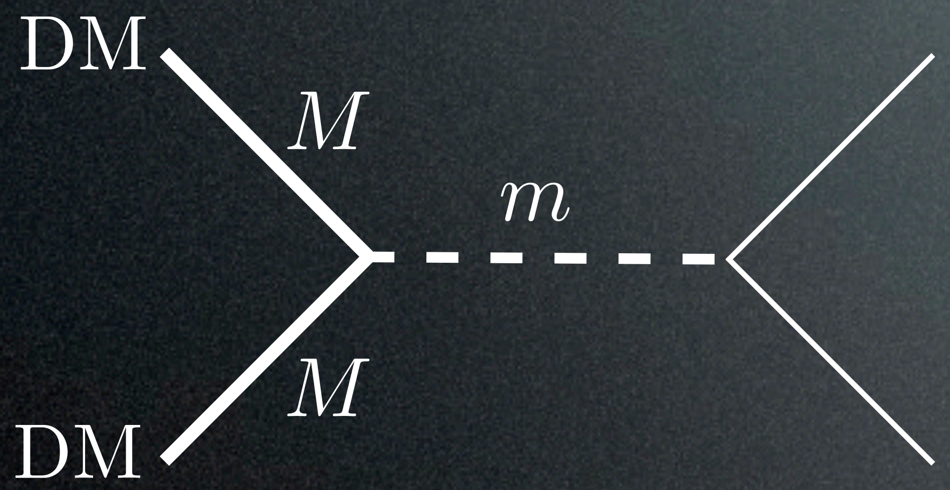
	at freeze-out	***today***
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$

\+ (Wimponium)

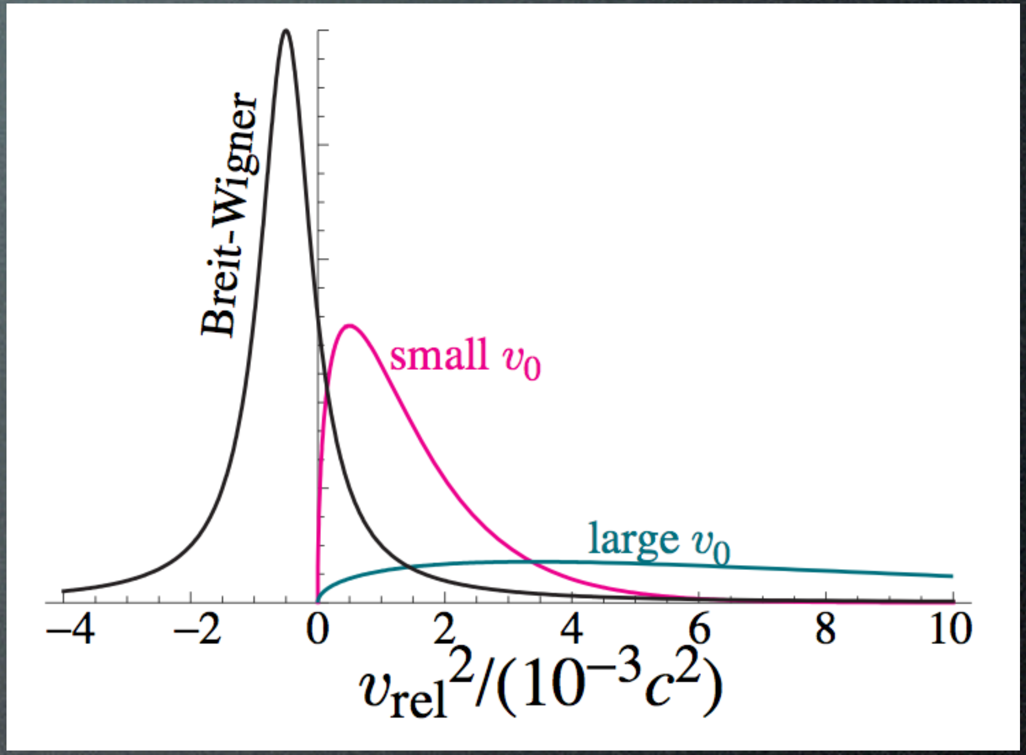
Resonance Enhancement

Cirelli, Kadastik, Raidal, Strumia, 2008, Sec.2
Ibe, Murayama, Yanagida 0812.0072
P.Nath et al. 0810.5762

DM annihilation via a narrow resonance just below the threshold:



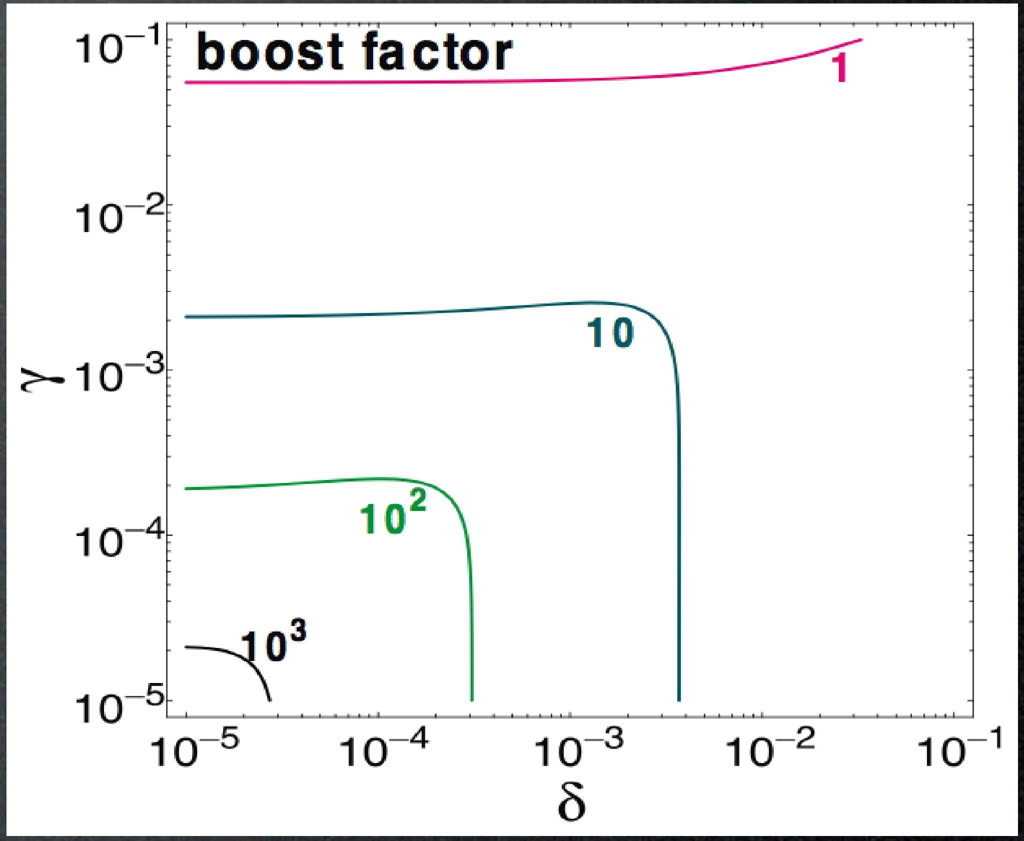
$$m \lesssim 2M$$



$$\sigma = \frac{16\pi}{E^2\bar\beta_i\beta_i}\frac{m^2\Gamma^2}{(E_{\rm cm}^2-m^2)^2+m^2\Gamma^2}B_iB_f$$

$$\langle\sigma v_{\rm rel}\rangle \simeq \frac{32\pi}{m^2\bar\beta_i}\frac{\gamma^2}{(\delta+\xi v_0^2)^2+\gamma^2}B_iB_f$$

$$m^2 = 4M^2(1-\delta) \qquad \gamma = \Gamma/m$$



Enhancement can reach 10^3 with very fine tuned models.

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Sommerfeld, Ann.Phys. 403, 257 (1931)

Hisano et al., 2003-2006:
in part. hep-ph/0307216, 0412403, 0610249

Cirelli, Tamburini, Strumia 0706.4071

Arkani-Hamed et al., 0810.0713

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

A classical analogy:

Arkani-Hamed et al. 0810.0713

$$\sigma_0 = \pi R^2$$

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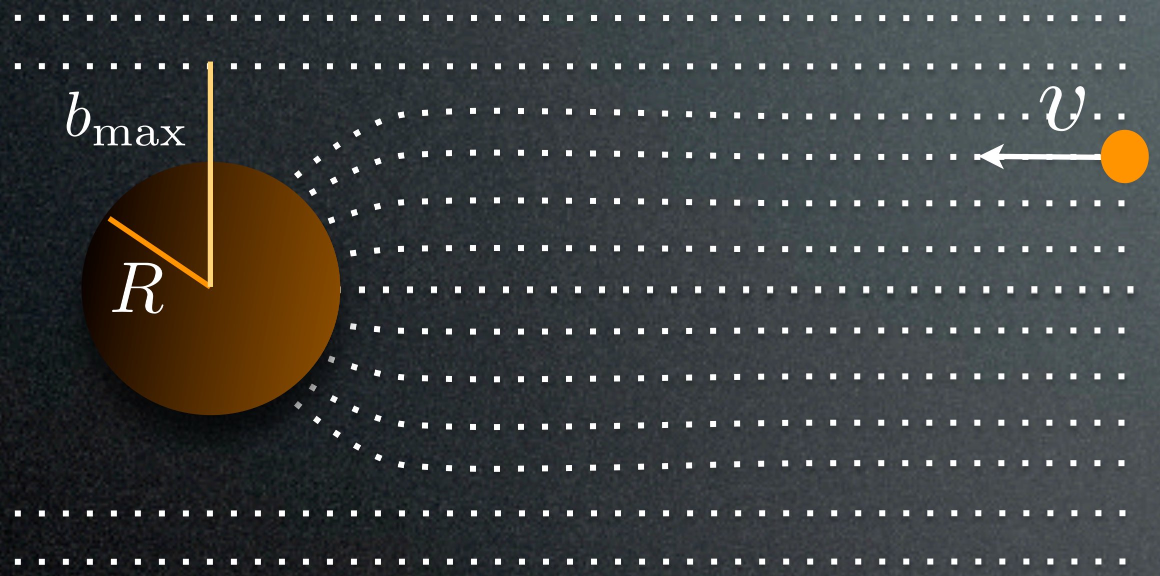

$$\sigma_0 = \pi R^2$$

$$\sigma = \pi R^2 \left(1 + \frac{2G_N M/R}{v^2}\right)$$

with $v_{\rm esc}^2 = 2G_N M/R$

For $v \gg v_{\rm esc}$ then $\sigma \rightarrow \sigma_0$

For $v \ll v_{\rm esc}$ then $\sigma \gg \sigma_0$

i.e. $E_{\rm kin} < U_{\rm pot}$ (i.e. the deforming potential is not negligible)

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Cirelli, Strumia, Tamburini 0706.4071

$\psi(\vec{r})$ wave function of two DM particles ($\vec{r} = \vec{r}_1 - \vec{r}_2$)

obeys (reduced) Schrödinger equation:

(V does not depend on time)

$$-\frac{1}{M}\frac{d^2\psi}{dr^2} + V \cdot \psi = M\nu^2\psi$$

velocity

potential due to exchange of force carriers

At $r = 0$: annihilation

$\sigma_{\text{ann}} \propto \psi\Gamma\psi$ with Γ such that $\langle \text{DM DM}|\Gamma|\text{final}\rangle$

Sommerfeld enhancement:

$$R = \frac{\sigma_{\text{ann}}}{\sigma^0_{\text{ann}}} = \left|\frac{\psi(\infty)}{\psi(0)}\right|^2$$

unperturbed cross section

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071

$$-\frac{1}{M}\frac{d^2\psi}{dr^2}+V\cdot\psi=M\nu^2\psi$$

with $V=-\frac{\alpha}{r}e^{-m_V\,r}$

parameters are: α,ν,m_V,M $\left(\alpha=\frac{g^2}{4\pi}\approx\frac{1}{137}\right)$

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Yukawa potential:

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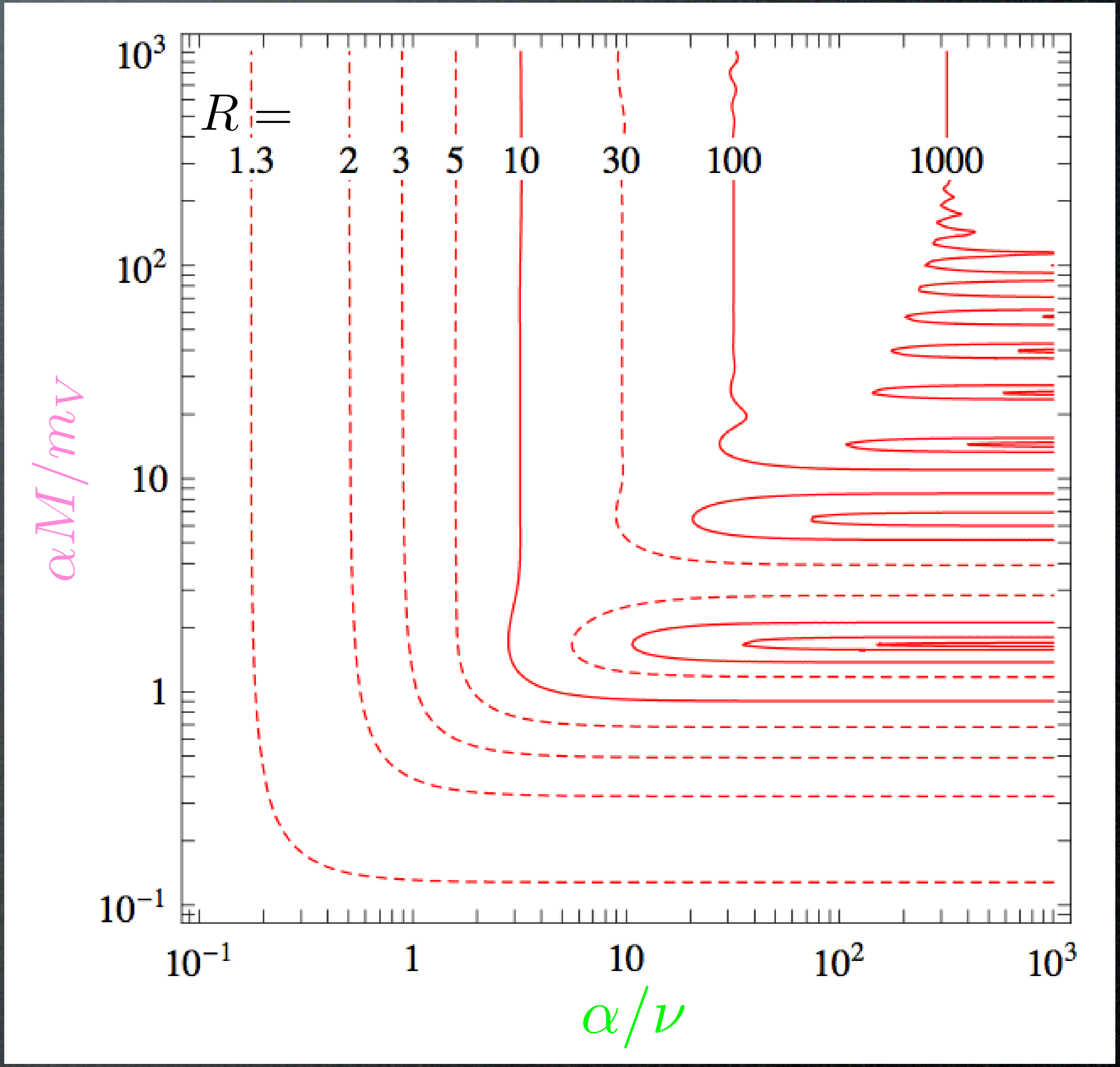
$$\text{with}\quad V = -\frac{\alpha}{r}e^{-m_V\,r}$$

parameters are: α, ν, m_V, M

R depends on: α/ν and $\alpha M/m_V$

Cirelli, Strumia, Tamburini 0706.4071



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Cirelli, Strumia, Tamburini 0706.4071

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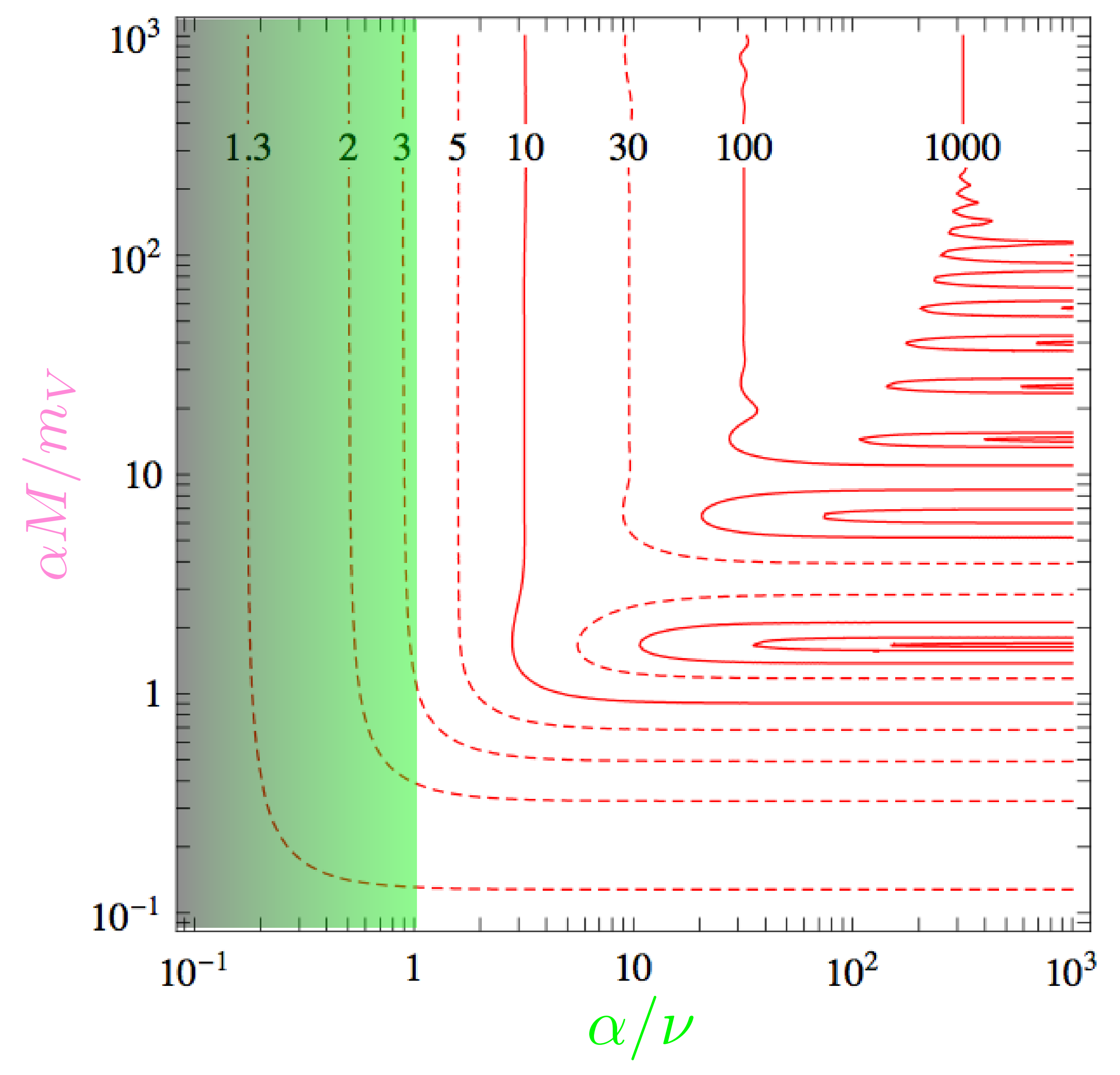
$$\text{with} \quad V = -\frac{\alpha}{r}e^{-m_V r}$$

parameters are: α, ν, m_V, M

R depends on: α/ν and $\alpha M/m_V$

The effect is relevant for:

$\alpha/\nu \gtrsim 1$ i.e. small velocities
i.e today but not at f.o.



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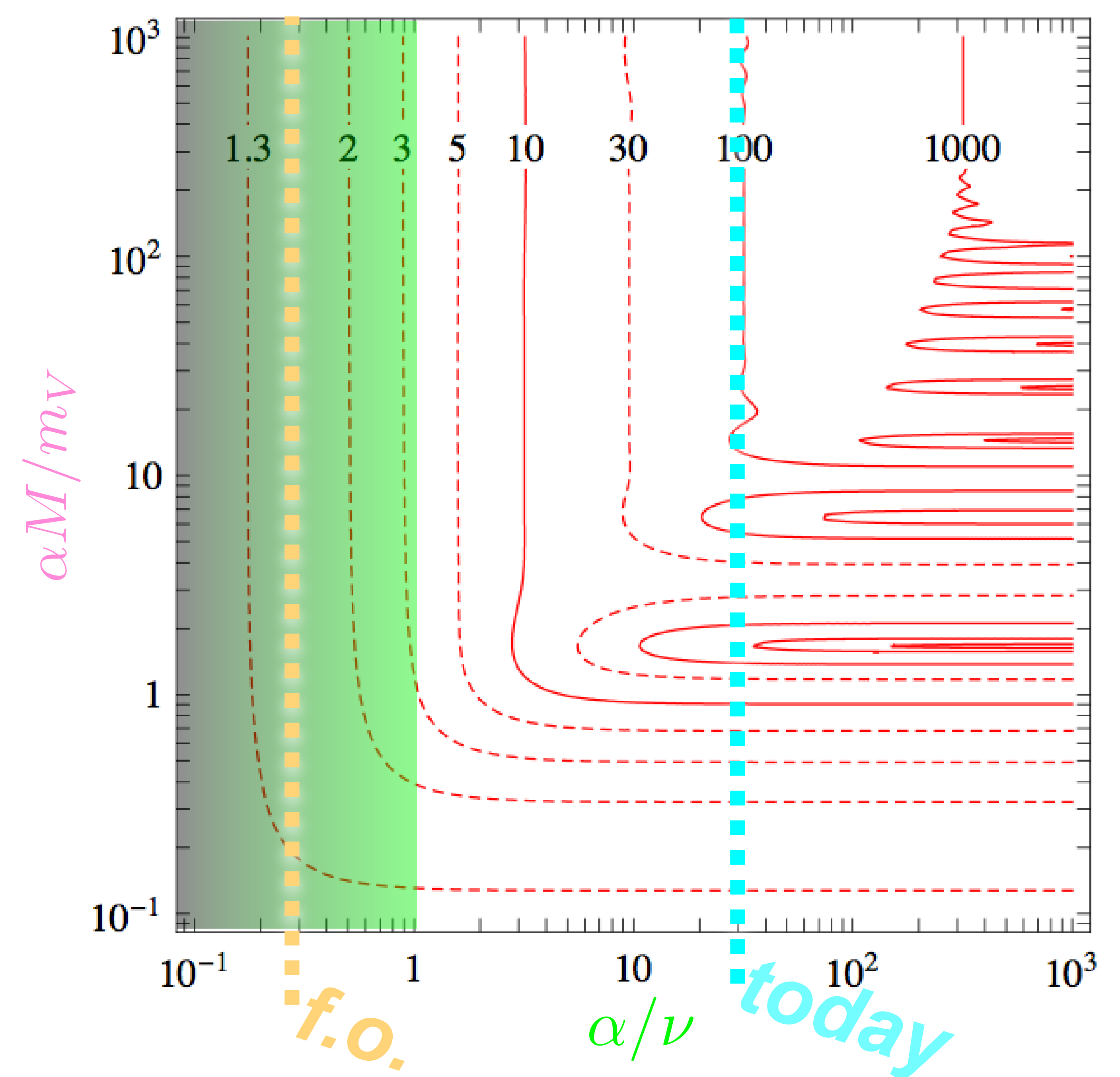
Cirelli, Strumia, Tamburini 0706.4071



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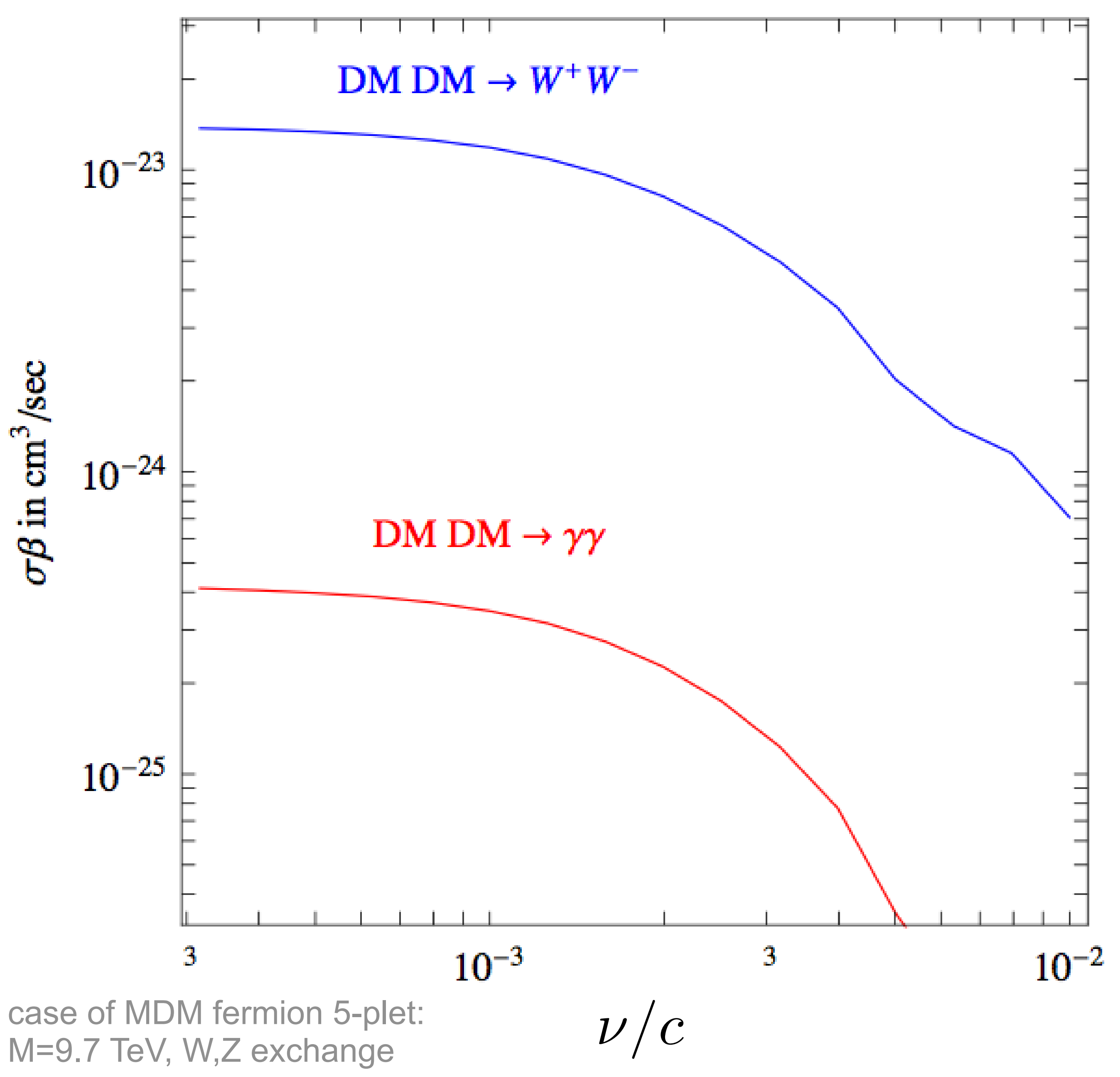
Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378



case of MDM fermion 5-plet:
M=9.7 TeV, W,Z exchange

Sommerfeld Enhancement

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Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378

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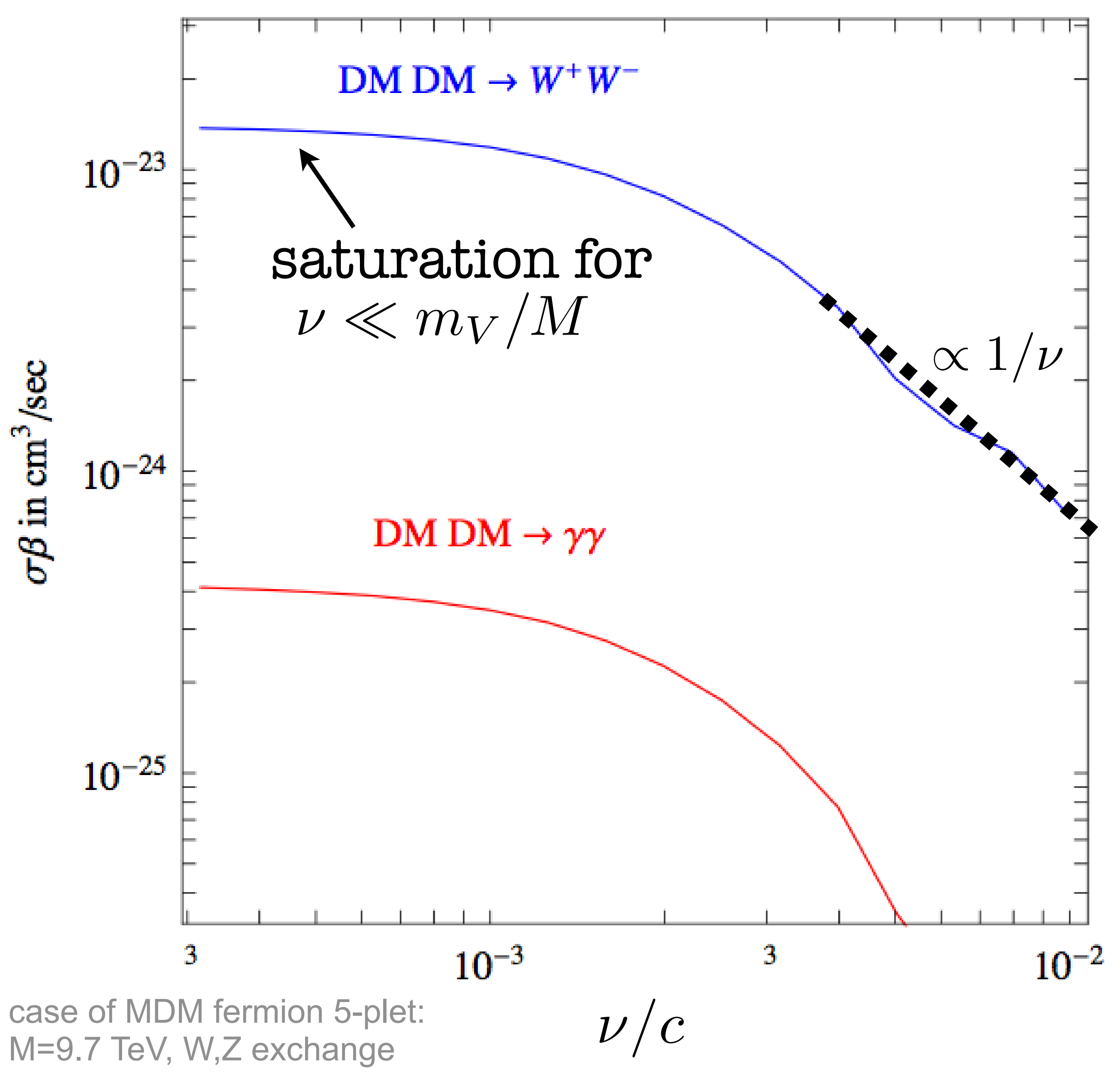

saturation for
$\nu \ll m_V/M$

case of MDM fermion 5-plet:
M=9.7 TeV, W,Z exchange

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The effect is relevant for:

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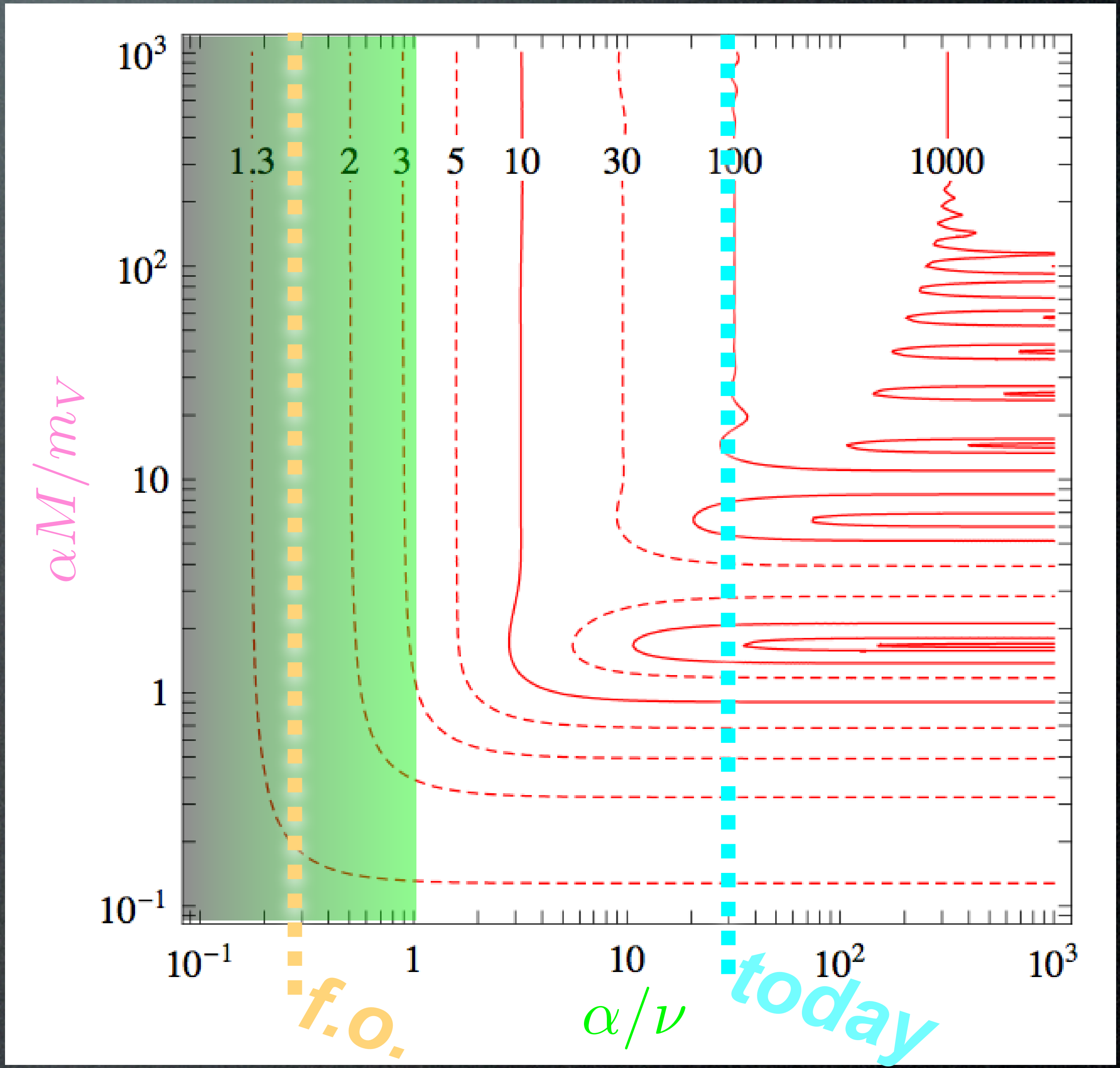


Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Yukawa potential:

$$-\frac{1}{M}\frac{d^2\psi}{dr^2} + V\cdot\psi = M\nu^2\psi$$

with $V = -\frac{\alpha}{r}e^{-m_V\, r}$

parameters are: α, ν, m_V, M

R depends on: α/ν and $\alpha M/m_V$

The effect is relevant for:

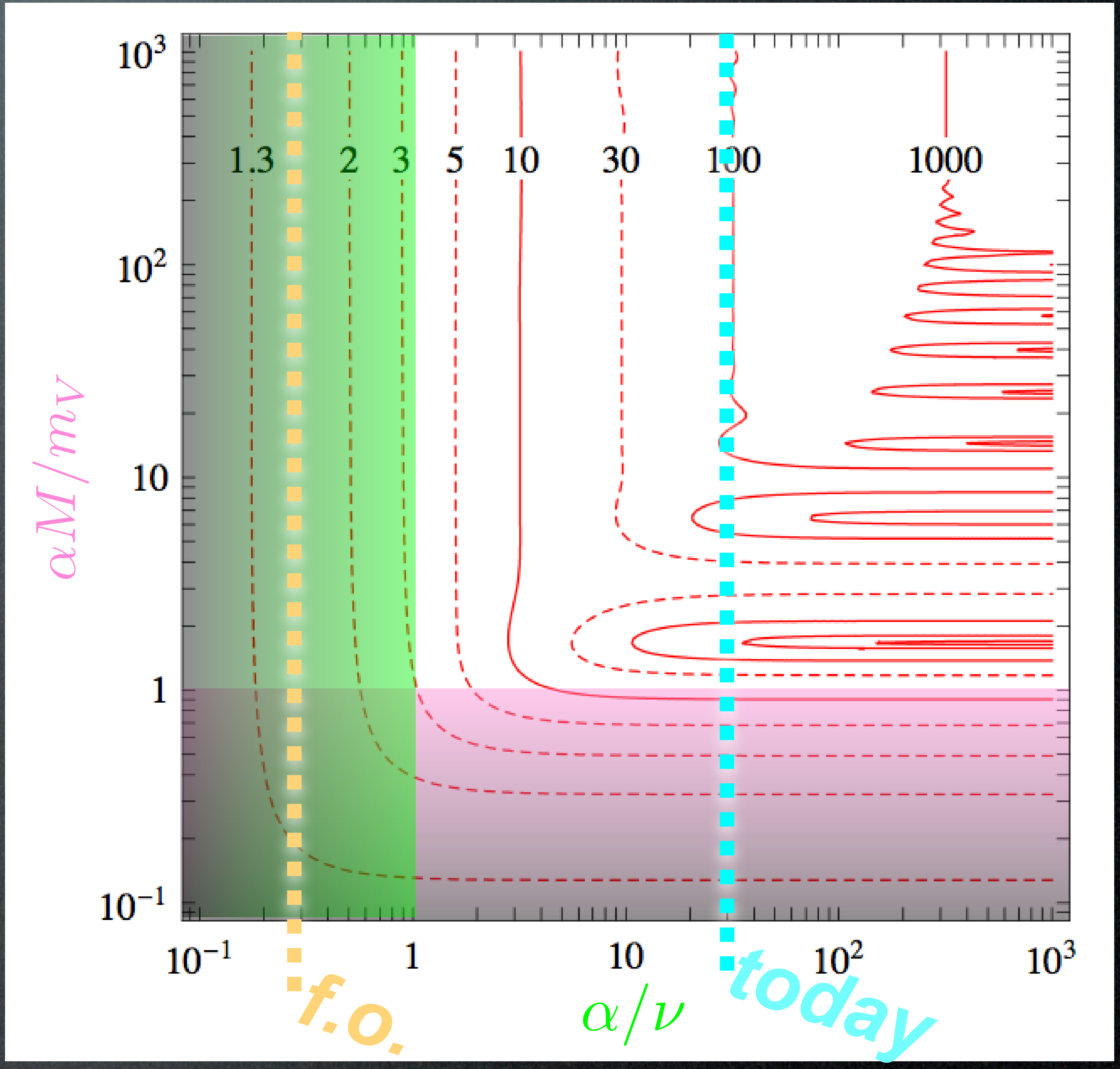
$\alpha/\nu \gtrsim 1$ i.e. small velocities
i.e today but not at f.o.

$\alpha M/m_V \gtrsim 1$ i.e. long range forces

for SM weak: $m_V \to M_{W,Z}$
$M \to \text{multi-TeV}$

for 1 TeV DM: need $m_V \to \text{GeV}$

Cirelli, Strumia, Tamburini 0706.4071



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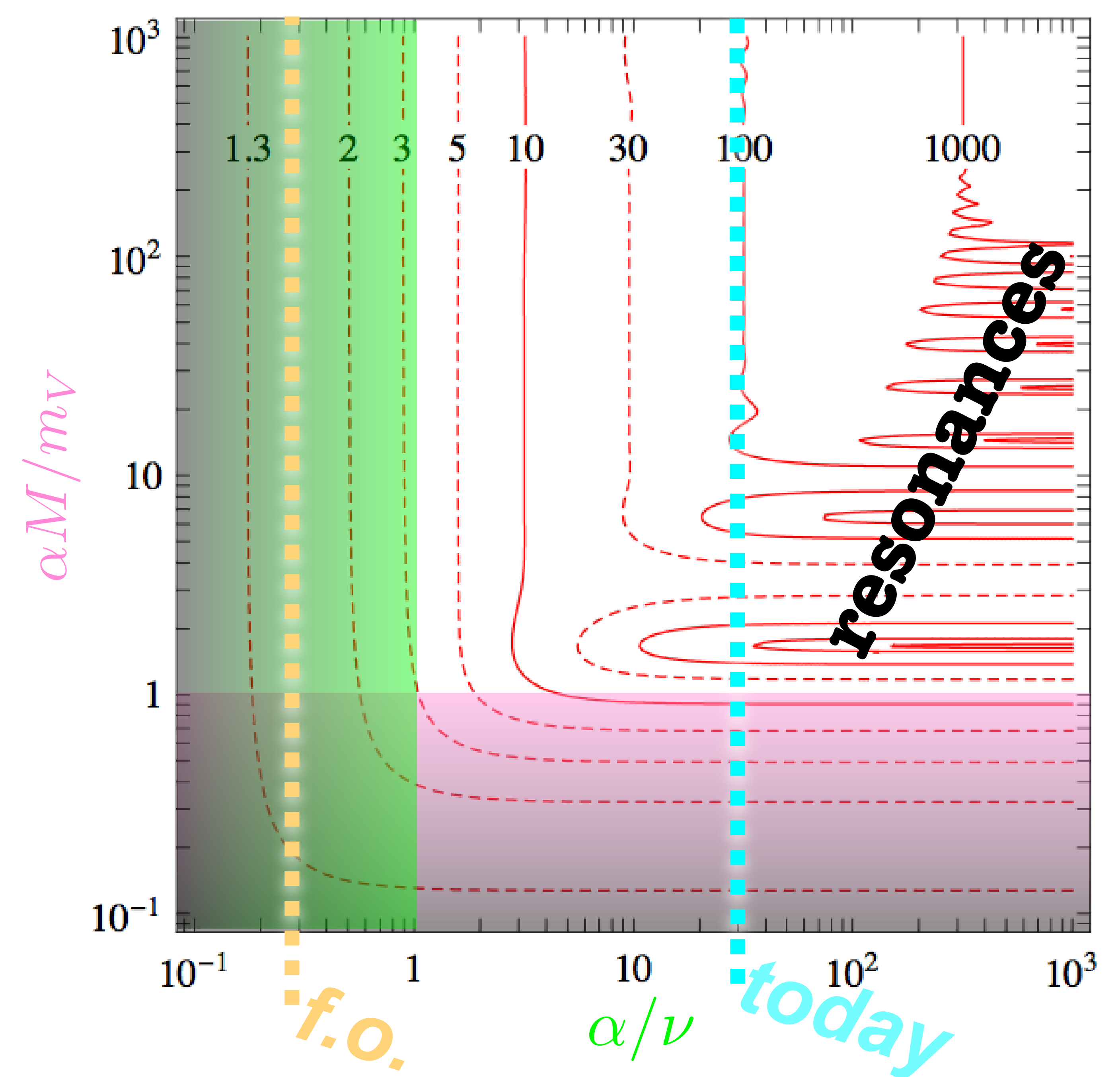

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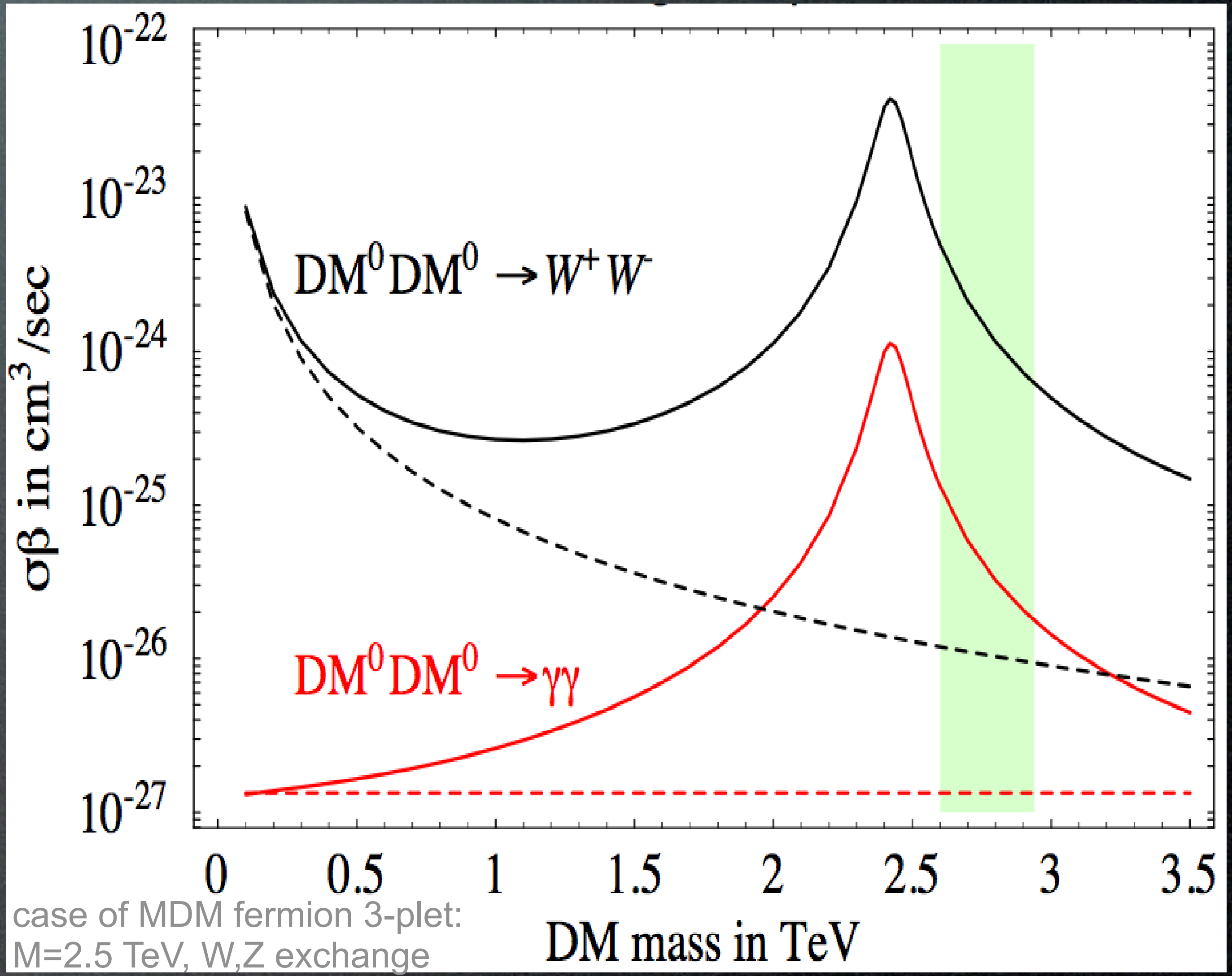
Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378



case of MDM fermion 3-plet:
M=2.5 TeV, W,Z exchange

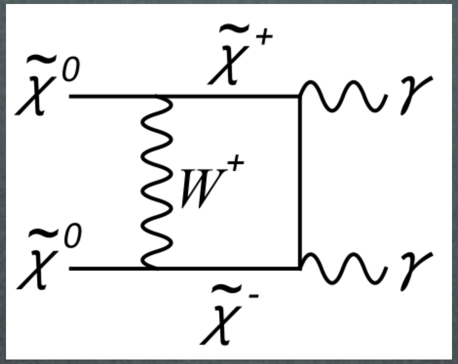
Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

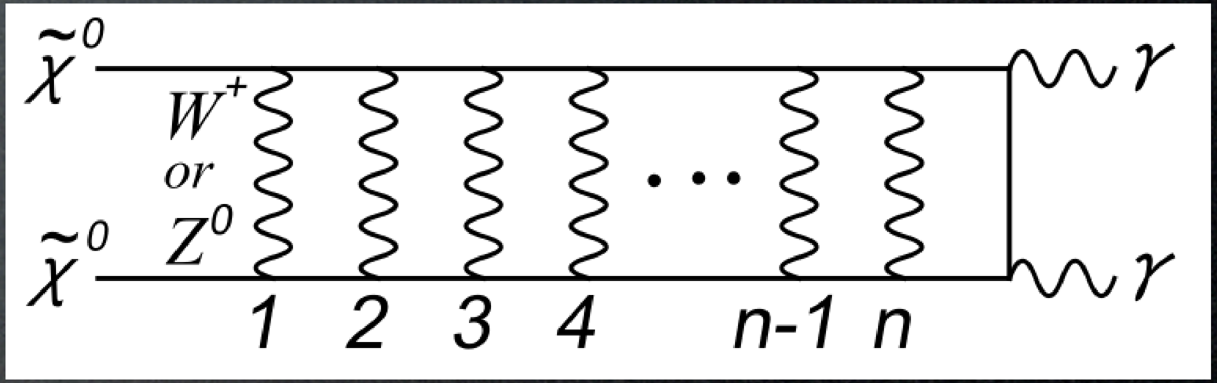
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



Adding a rung to the ladder: $\times \left(\frac{\alpha M}{m_W}\right)$



For $\alpha M/m_V \gtrsim 1$ the perturbative expansion breaks down,
need to resum all orders
i.e.: keep the full interaction potential.

Sommerfeld Enhancement

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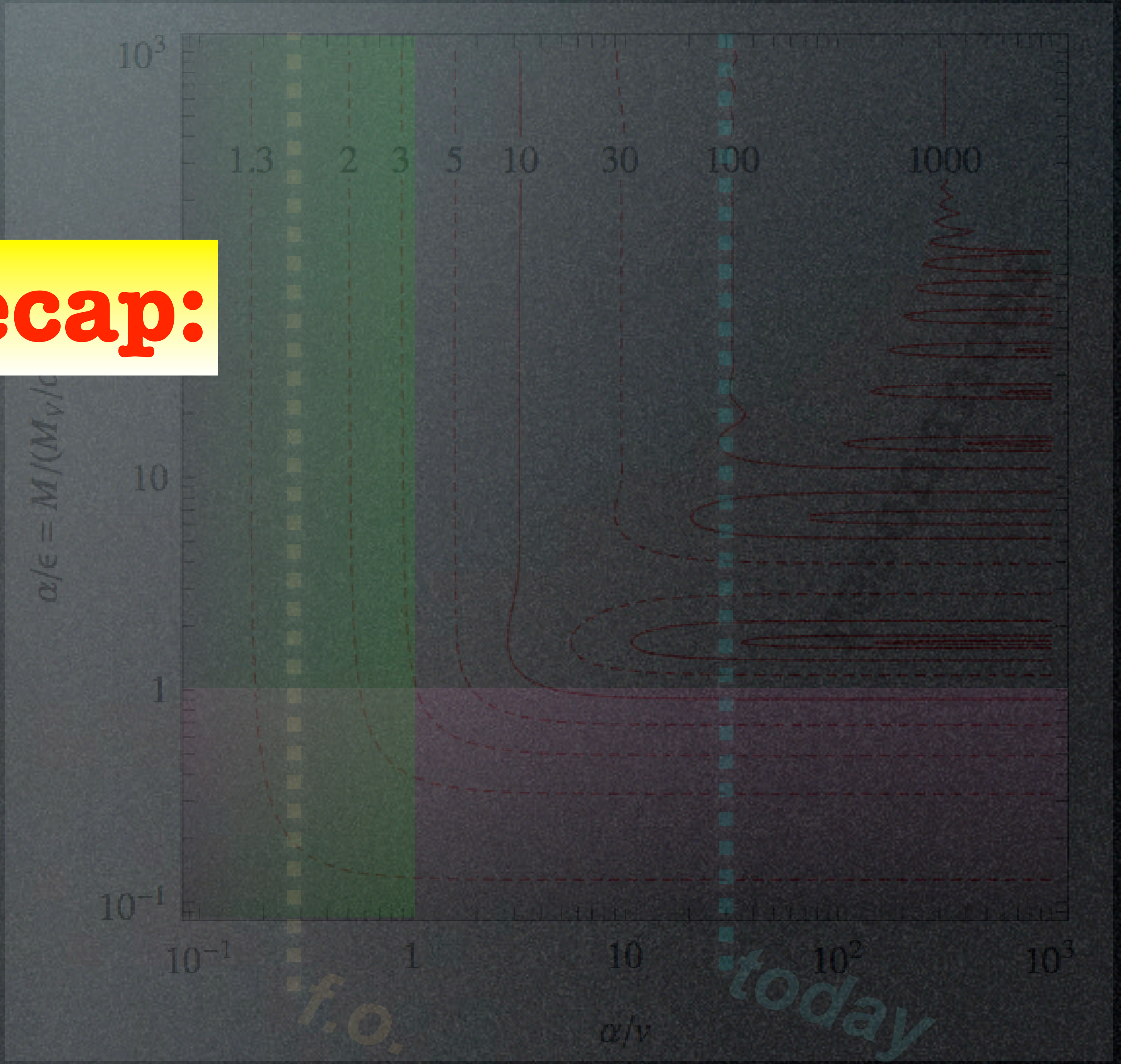
Recap:

Cirelli, Strumia, Tamburini 0706.4071



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Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

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  New models with a rich Dark sector

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- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

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Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

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The "Theory of DM"

Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

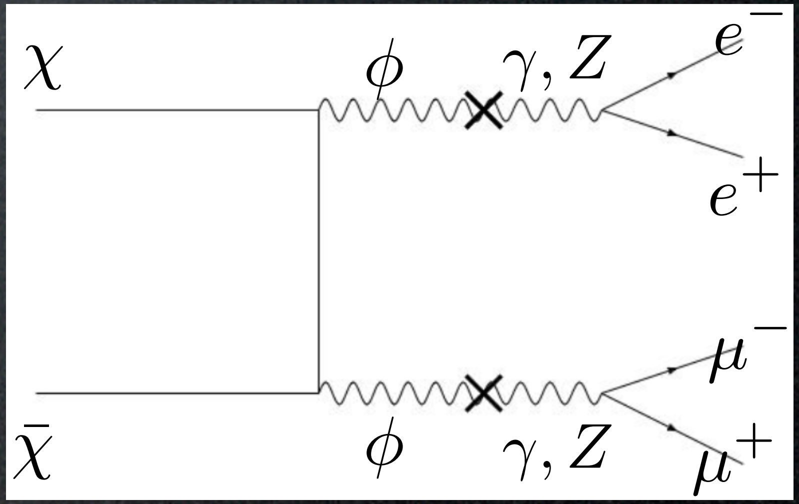
χ Dark Matter particle, decoupled from SM, mass $M \sim 700+\ \mathrm{GeV}$

ϕ new gauge boson ("Dark photon"),

couples only to DM, with typical gauge strength, $m_\phi \sim \text{few GeV}$

- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:

$\alpha M/m_V \gtrsim 1$ fulfilled



- decays only into e^+e^- or $\mu^+\mu^-$ for kinematical limit

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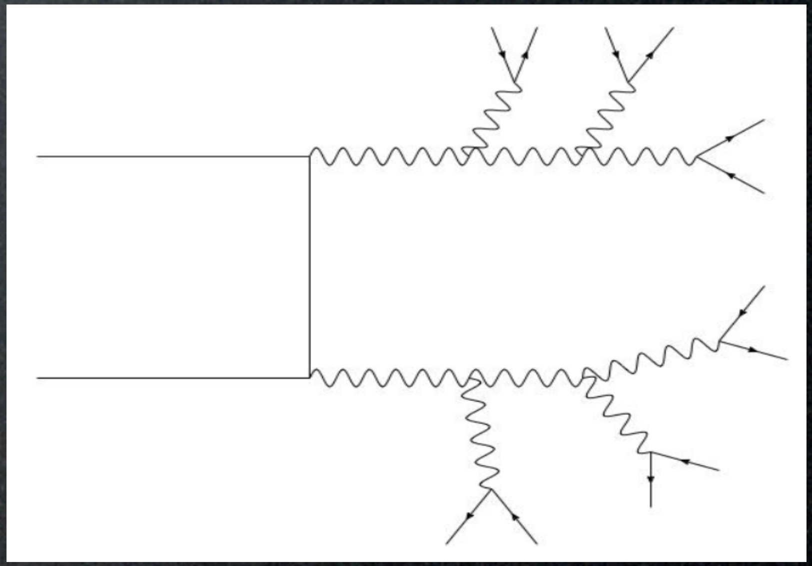
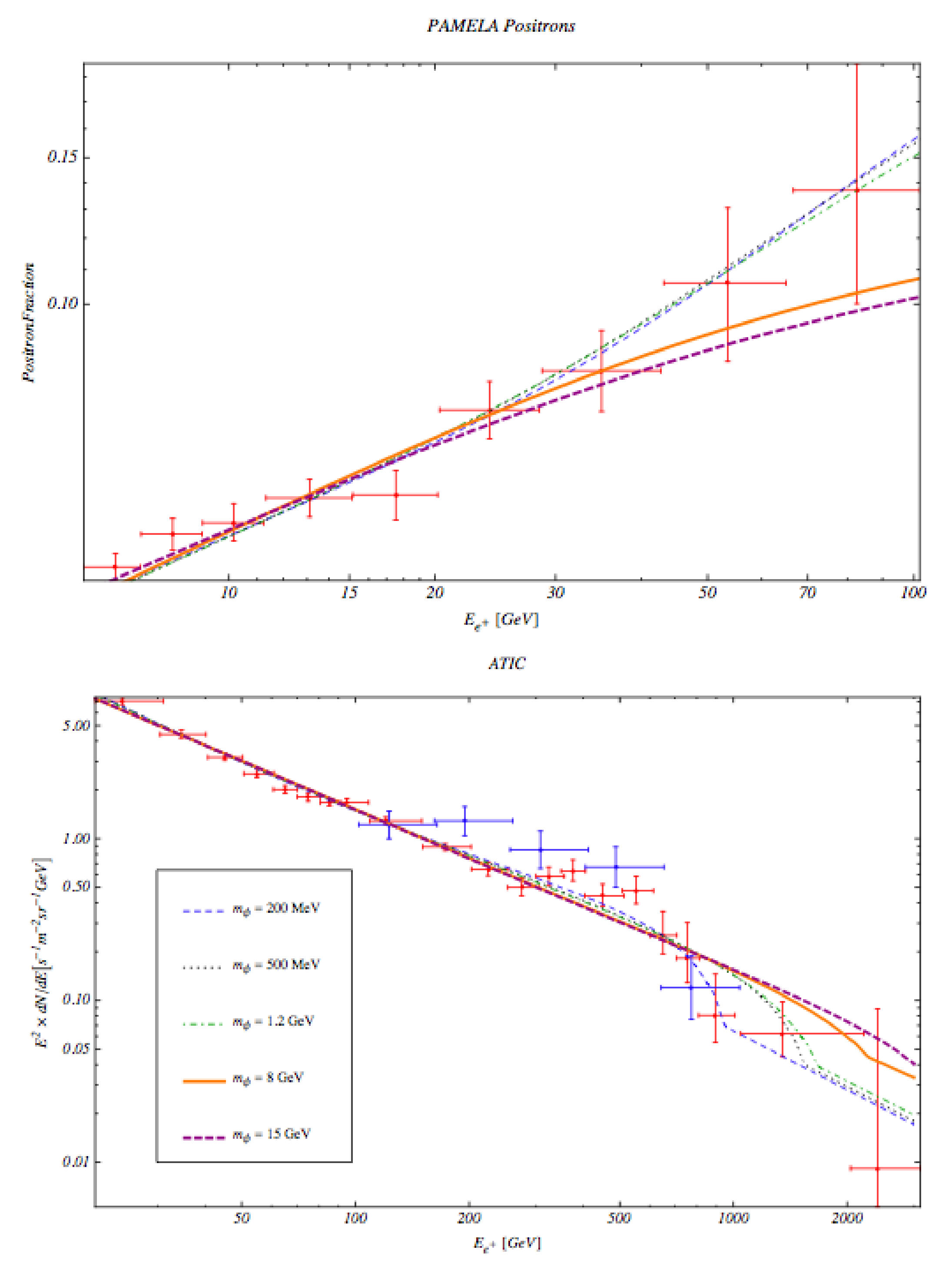


Extras:

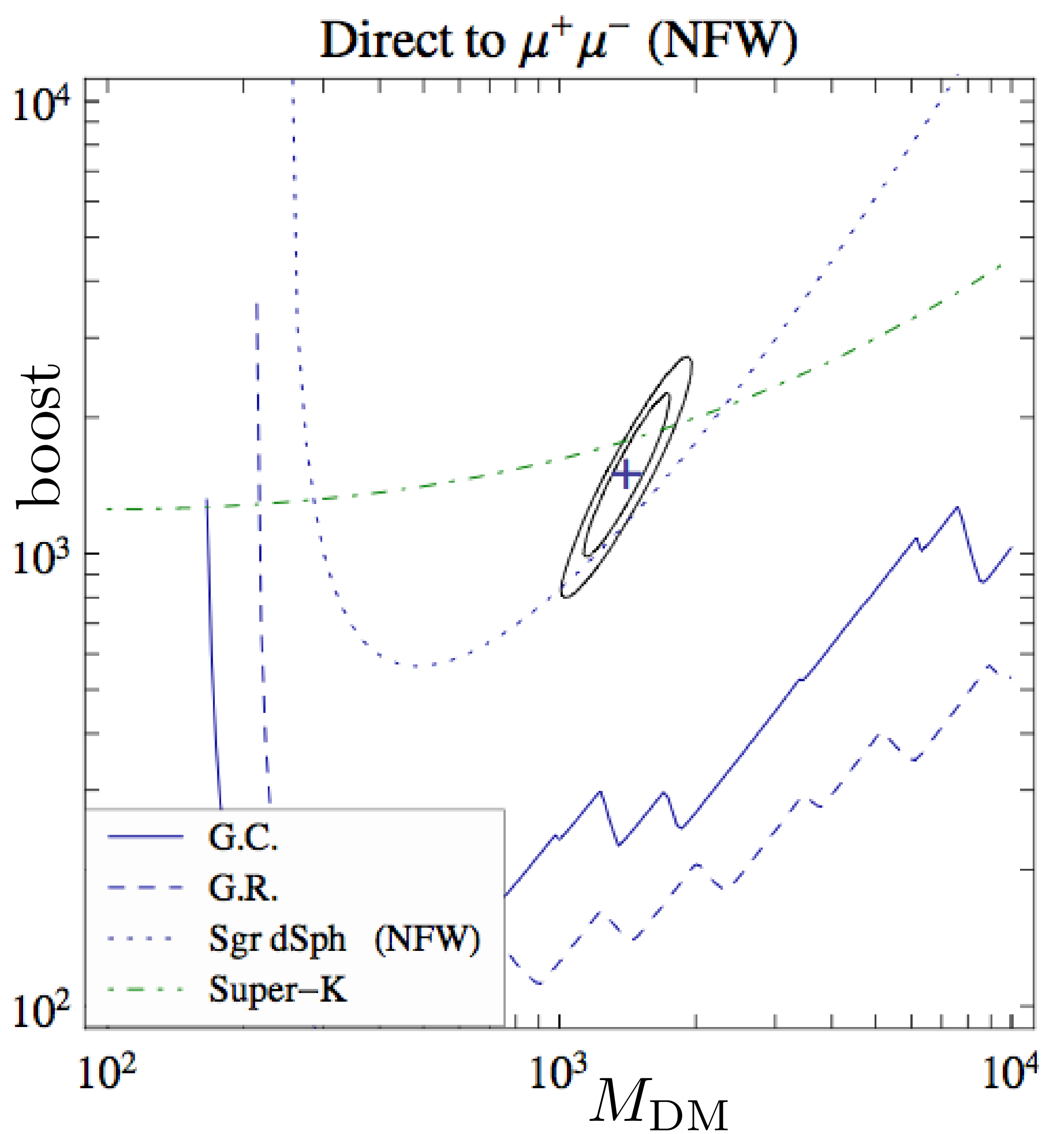
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200\ \mathrm{KeV}$ (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The “Theory of DM”

Phenomenology:



Meade, Papucci, Volanski
0901.2925



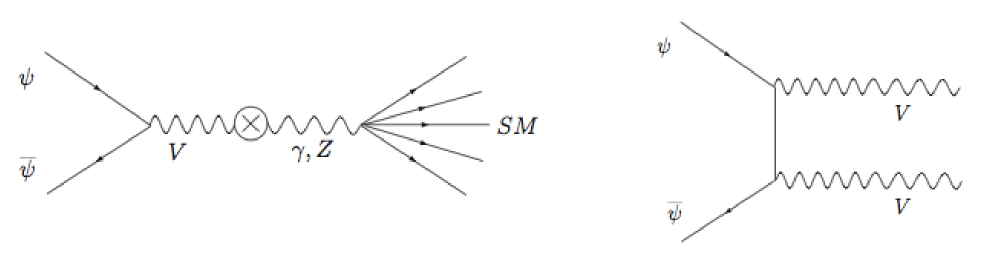
Mardon, Nomura, Stolarski,
Thaler 0901.2926

Variations

(selected)

- pioneering: Secluded DM, U(1) Stückelberg extension of SM

  Pospelov, Ritz et al 0711.4866 P.Nath et al 0810.5762



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

- singlet-extended UED: χ is KK RNnu, ϕ is an extra bulk singlet

  Bai, Han 0811.0387

- split UED: χ annihilates only to leptons because quarks are on another brane

  Park, Shu 0901.0720

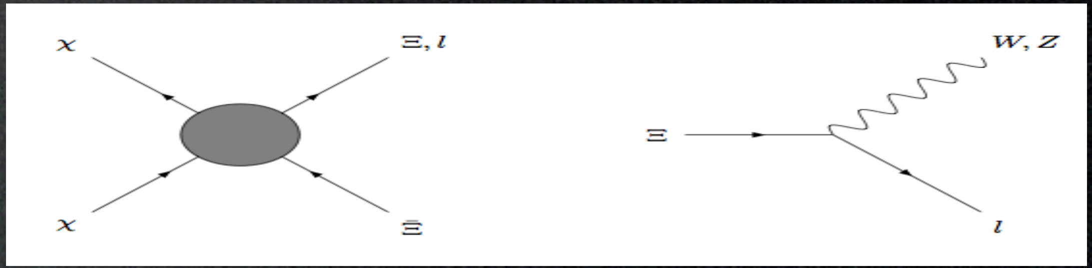
- DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson

  Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399 $(m_\phi \sim \text{tens GeV})$

- New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly

  $(\sim \text{TeV})$ $(\sim \text{100s GeV})$

  Phalen, Pierce, Weiner 0901.3165



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Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

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- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

Decaying DM

DM need not be absolutely stable,
just $\tau_{\rm DM} \gtrsim \tau_{\rm universe} \simeq 4.3\ 10^{17} {\rm sec}$.

The current CR anomalies can be due to decay with:

$$\tau_{\rm decay} \approx 10^{26} {\rm sec}$$

Motivations from theory?

- dim 6 suppressed operator in GUT

Arvanitaki, Dimopoulos et al., 2008+09

$$\tau_{\rm DM} \simeq 3 \cdot 10^{27} {\rm sec} \left(\frac{1\ {\rm TeV}}{M_{\rm DM}} \right)^5 \left(\frac{M_{\rm GUT}}{2 \cdot 10^{16}\ {\rm GeV}} \right)^4$$

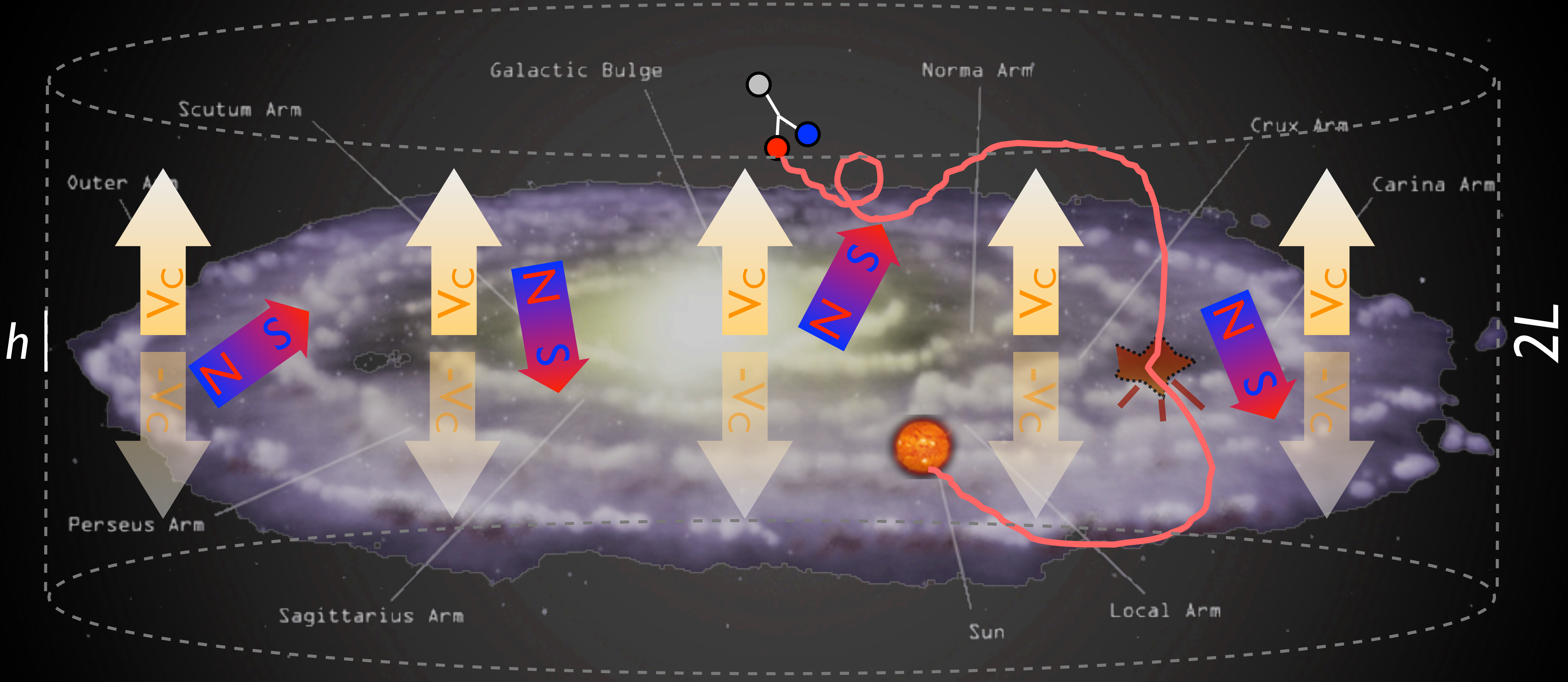
- or in TechniColor

Nardi, Sannino, Strumia 2008

- gravitino in SuSy with broken R-parity...

Indirect Detection

$\bar{p}$ and e^+ from DM decay in halo



What sets the overall expected flux?

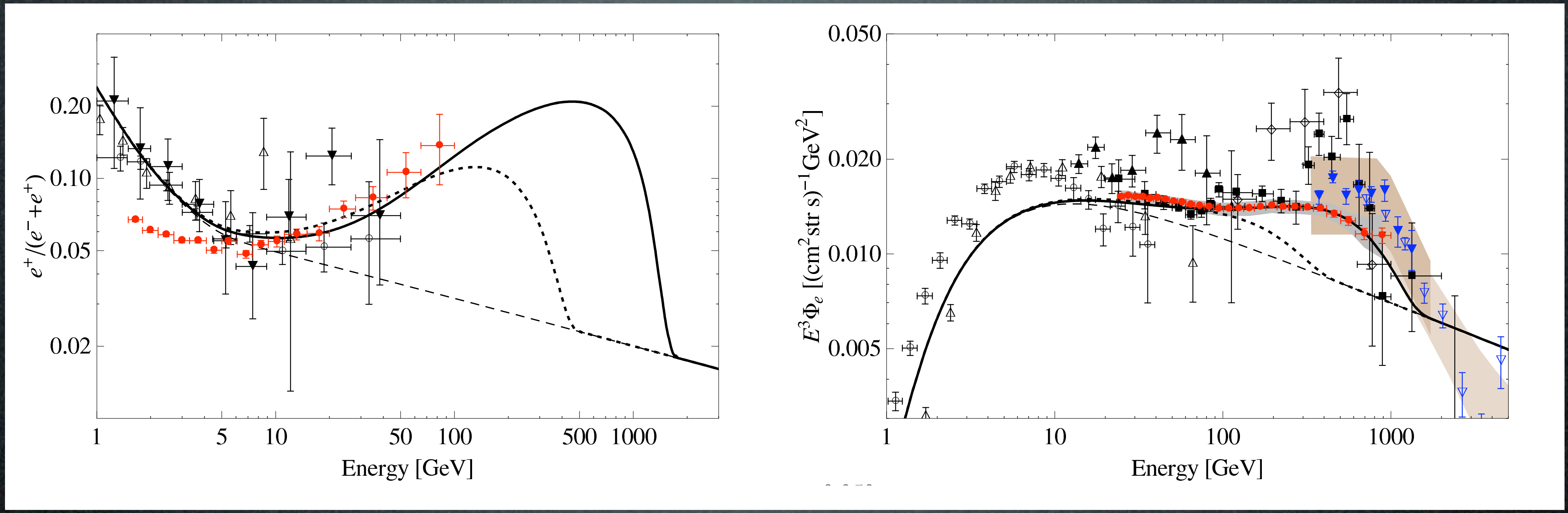
$$\text{flux} \propto n\,\Gamma_{\text{decay}}$$

$$\Gamma^{-1}_{\text{decay}} = \tau_{\text{decay}} \approx 10^{26}\text{sec}$$

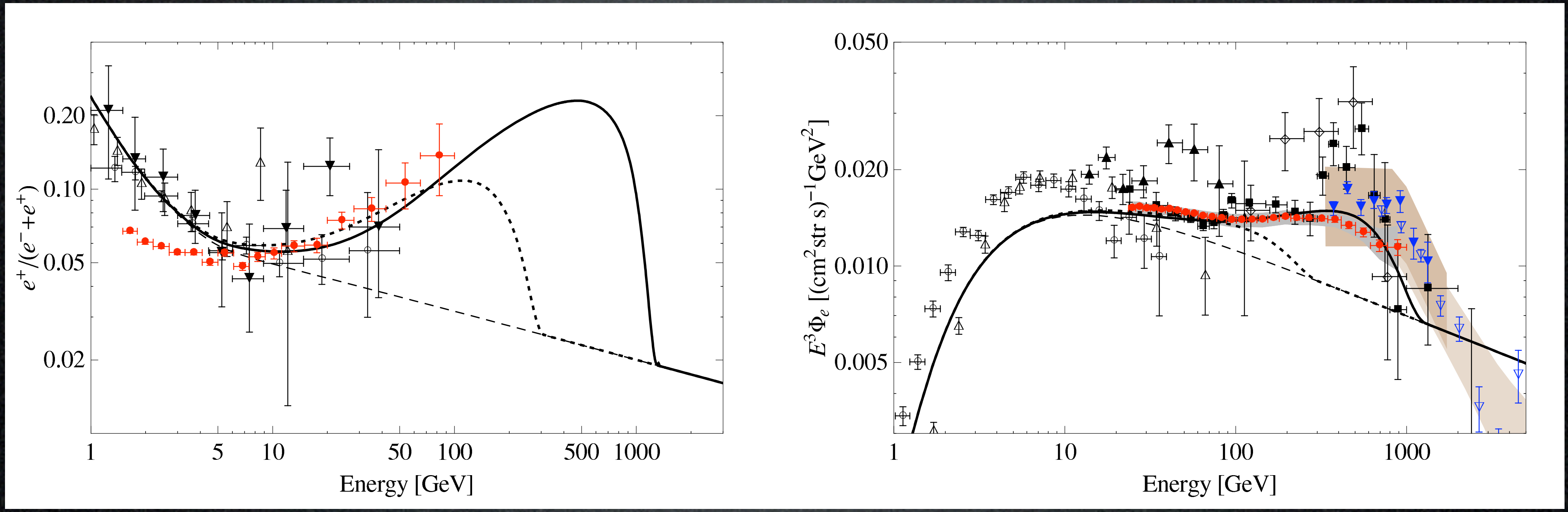
Decaying DM

Which DM spectra can fit the data?

E.g. a fermionic $\mathrm{DM} \to \mu^+\mu^-\nu$ with $M_{\mathrm{DM}} = 3.5\,\mathrm{TeV}$:



E.g. a scalar $\mathrm{DM} \to \mu^+\mu^-$ with $M_{\mathrm{DM}} = 2.5\,\mathrm{TeV}$:

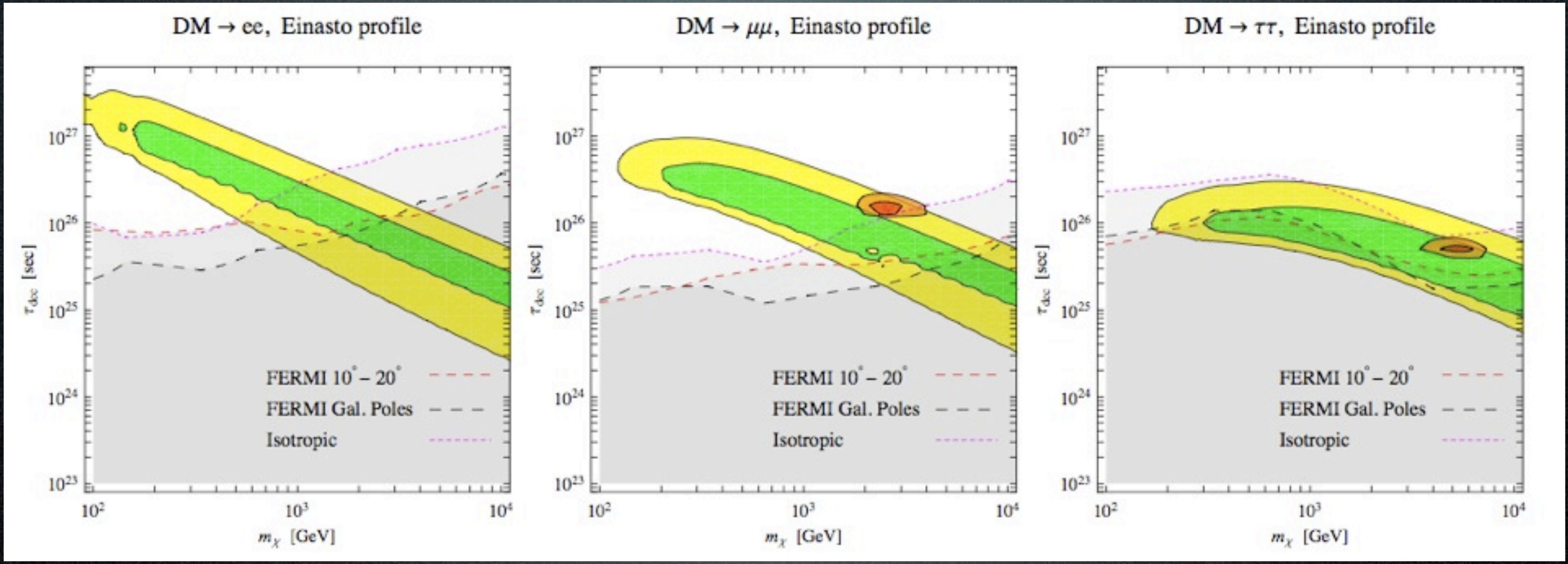


Ibarra, Tran, Weniger 2009

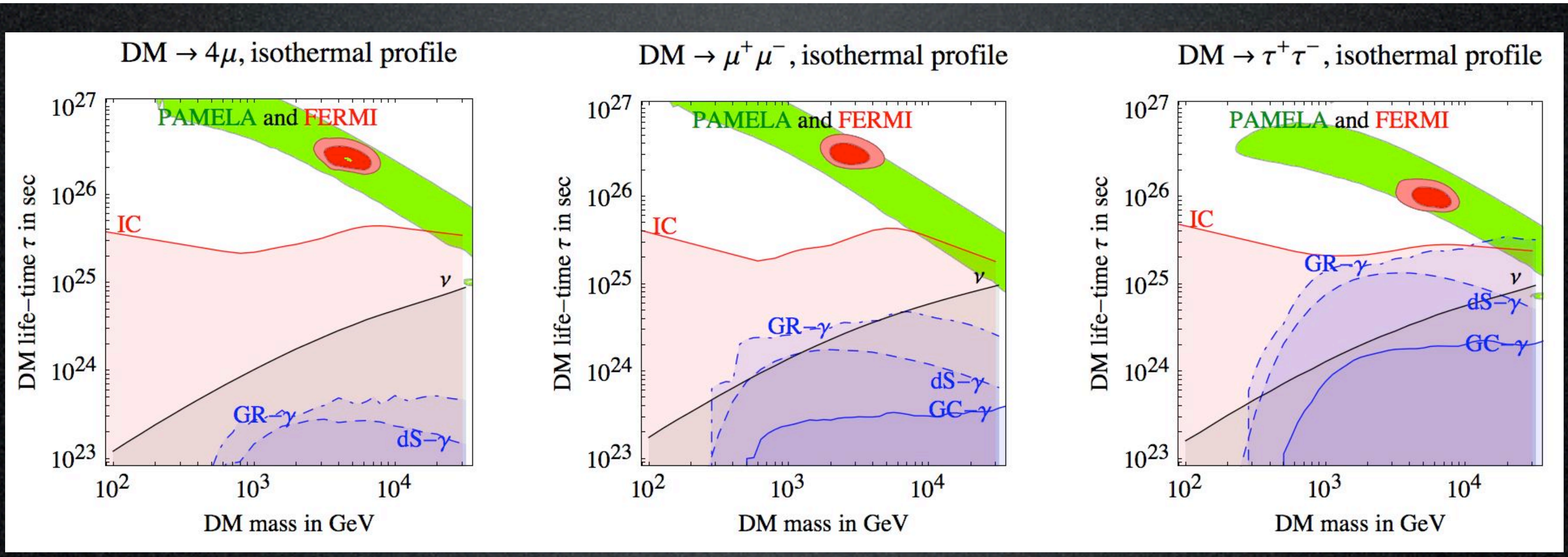
Decaying DM

Beware of gamma ray constraints

(but no radio, neutrino constraints)



Cirelli, Panci, Serpico 0912. 0663



Strumia, Papucci et al. 0905.0480

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You need a quick **reference** for formulæ and methods
to compute indirect detection signals?

You want to compute all **signatures** of your DM model in
positrons, electrons, neutrinos, gamma rays...
but you don’t want to mess around with astrophysics?

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We provide ingredients and recipes for computing signals of TeV-scale
Dark Matter annihilations and decays in the Galaxy and beyond.

Cirelli, Corcella, Hektor,
Hütsi, Kadastik, Panci,
Raidal, Sala, Strumia

1012.4515 [hep-ph]

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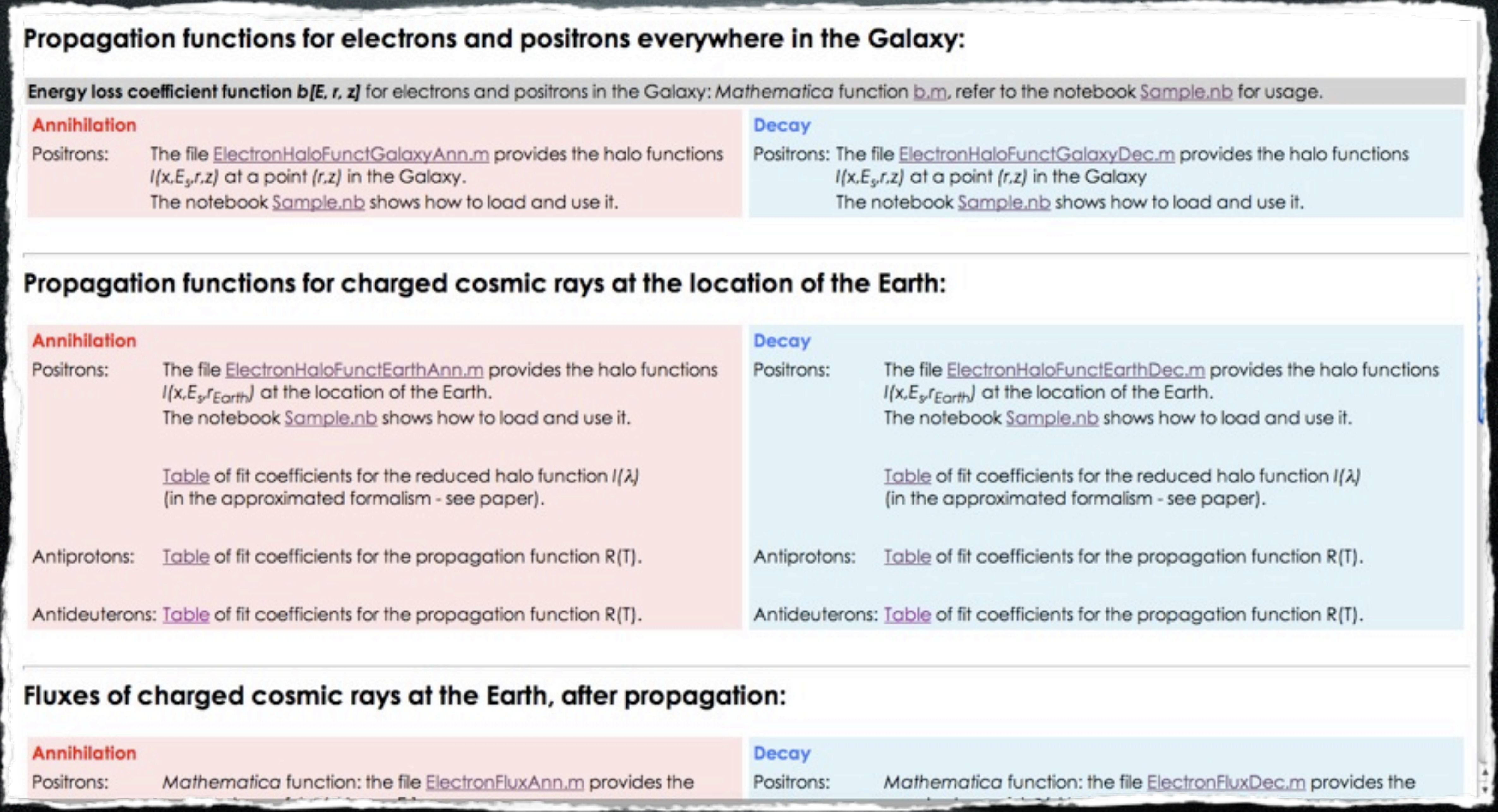

Propagation functions for electrons and positrons everywhere in the Galaxy:

Energy loss coefficient function *b[E, r, z]* for electrons and positrons in the Galaxy: *Mathematica* function b.m, refer to the notebook Sample.nb for usage.

Annihilation

Positrons: The file ElectronHaloFunctGalaxyAnn.m provides the halo functions *I*(x,E_s,r,z) at a point (r,z) in the Galaxy.
The notebook Sample.nb shows how to load and use it.

Decay

Positrons: The file ElectronHaloFunctGalaxyDec.m provides the halo functions *I*(x,E_s,r,z) at a point (r,z) in the Galaxy
The notebook Sample.nb shows how to load and use it.

Propagation functions for charged cosmic rays at the location of the Earth:

Annihilation

Positrons: The file ElectronHaloFunctEarthAnn.m provides the halo functions *I*$(x,E_s,r_{\rm Earth})$ at the location of the Earth.
The notebook Sample.nb shows how to load and use it.

Table of fit coefficients for the reduced halo function $I(\lambda)$ (in the approximated formalism - see paper).

Antiprotons: Table of fit coefficients for the propagation function R(T).

Antideuterons: Table of fit coefficients for the propagation function R(T).

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Antiprotons: Table of fit coefficients for the propagation function R(T).

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Fluxes of charged cosmic rays at the Earth, after propagation:

Annihilation

Positrons: *Mathematica* function: the file ElectronFluxAnn.m provides the

Decay

Positrons: *Mathematica* function: the file ElectronFluxDec.m provides the

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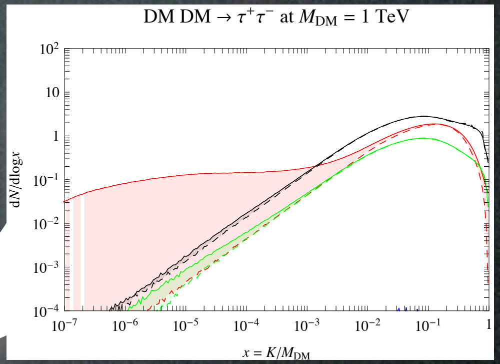
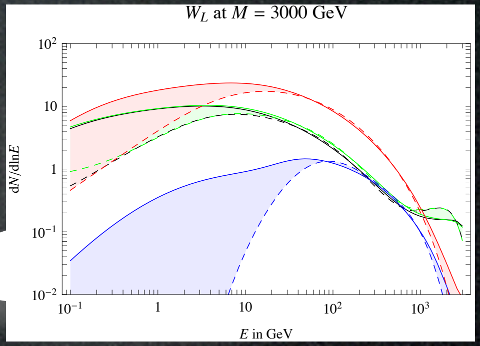
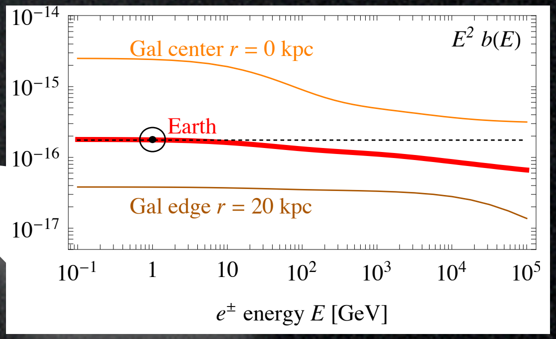
Main added value features:



- ☑ compare different MCs



- ☑ include EW corrections
  Ciafaloni, Riotto et al., 1009.0224



- ☑ improved $e^{\pm}$ propagation
- ☑ improved ICS γ-ray computation

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Conclusions (of this talk)

The PAMELA, ATIC, FERMI, HESS 'excesses' are
a typical example:
signal! discovery? check... cross-check constraints...

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Interplay data-theory:

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Interplay data-theory:

The data (PAMELA, ATIC, HESS, FERMI…)
point to a “weird” DM so theorists try to reinvent the field:
- DM is very heavy
- annihilates into leptons and not anti-protons
- huge cross section (boost? Sommerfeld?)
- must not produce too many gammas

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Did we find DM in CR???

I don’t know. I feel it’s very unlikely, but...