13 march 2009
XIII Neutrino Telescopes, Venezia

PAMELA, ATIC and Dark Matter

Marco Cirelli
(CNRS, IPhT-CEA/Saclay)

in collaboration with:
A.Strumia (Pisa)
N.Fornengo (Torino)
M.Tamburini (Pisa)
R.Franceschini (Pisa)
M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)

Nuclear Physics B 753 (2006)
Nuclear Physics B 787 (2007)
Nuclear Physics B 800 (2008)
0808.3867 [astro-ph]
Nuclear Physics B 813 (2009)
JCAP03 009 (2009)
and work in progress

Questions

1. Are we seeing Dark Matter in cosmic rays?

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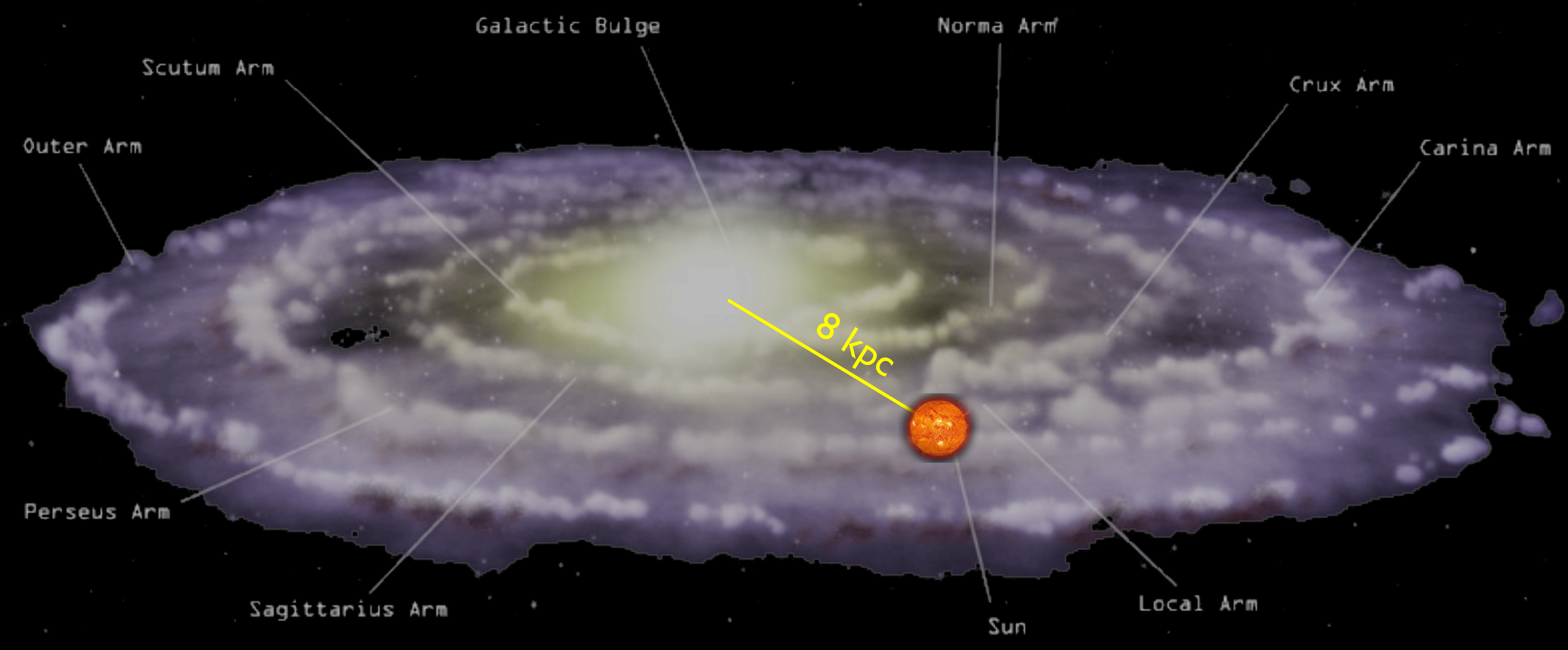
1. Are we seeing Dark Matter in cosmic rays?

2. Why there is new theory of DM on the arXiv every day?

Indirect Detection

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



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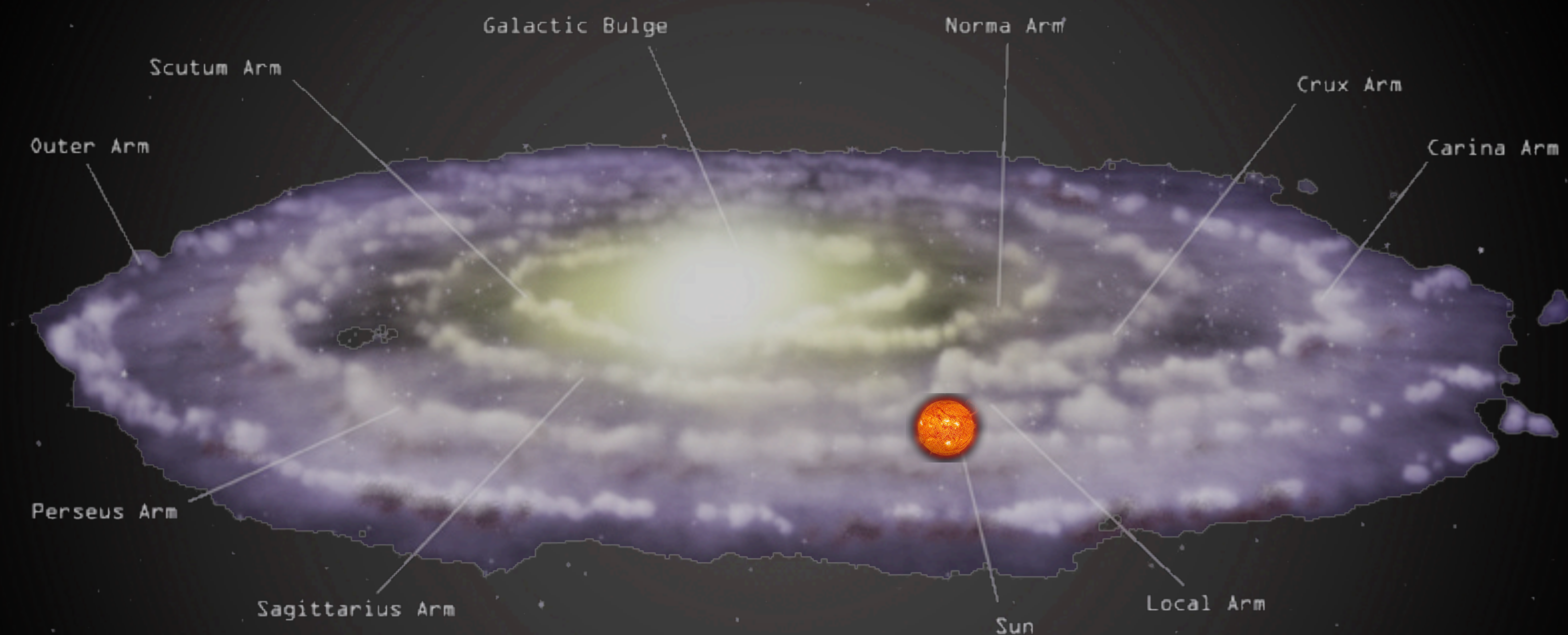

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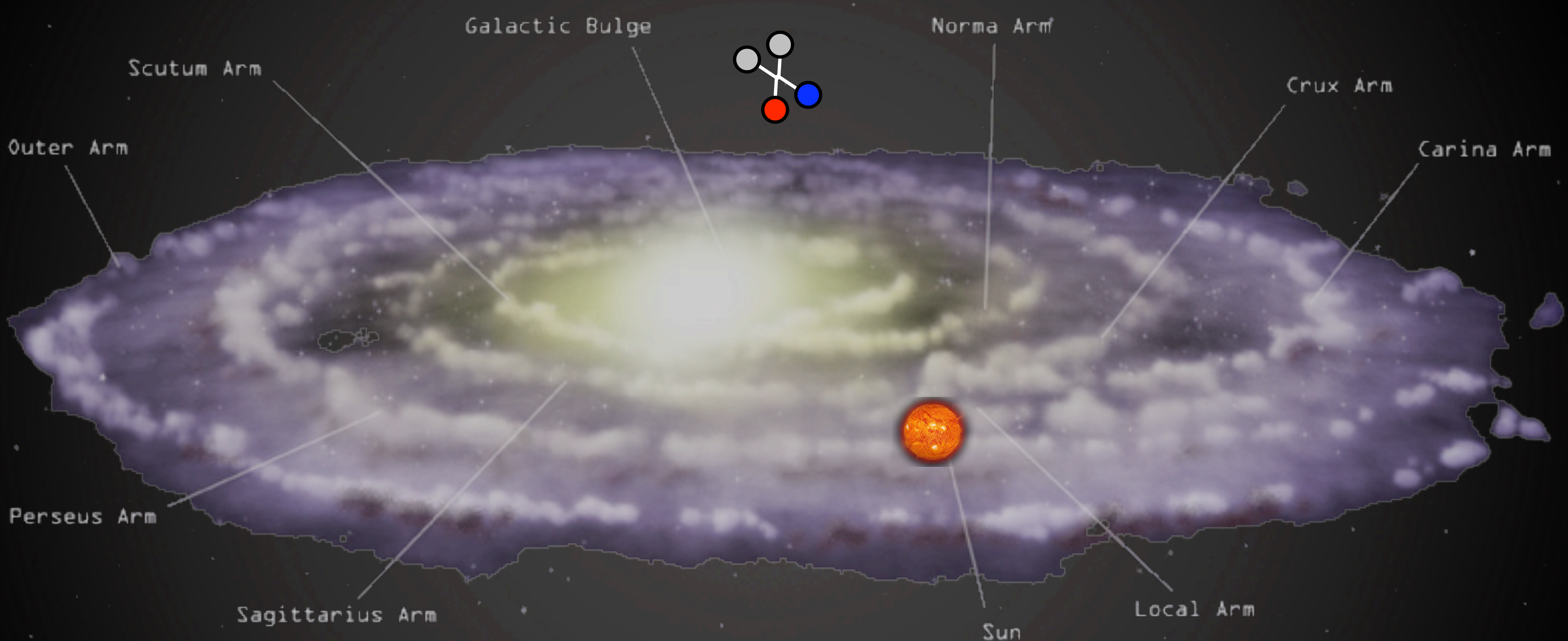

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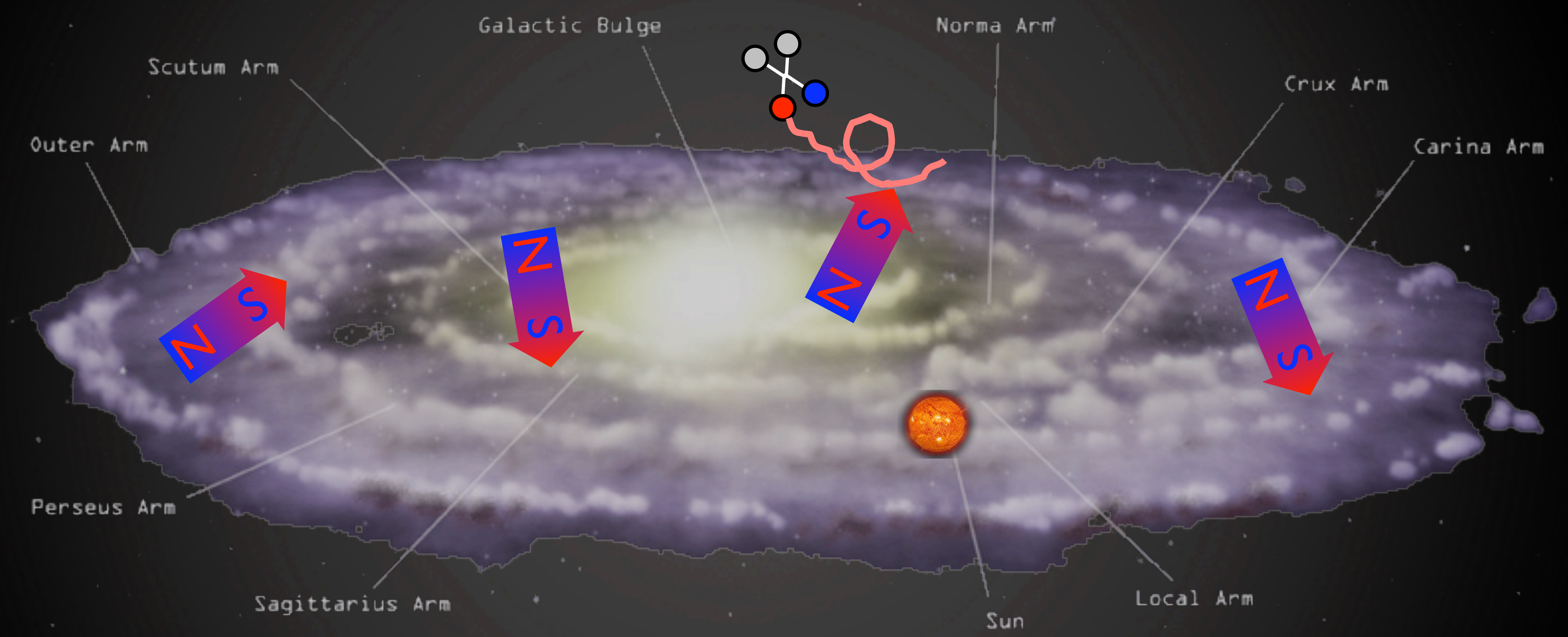

Indirect Detection

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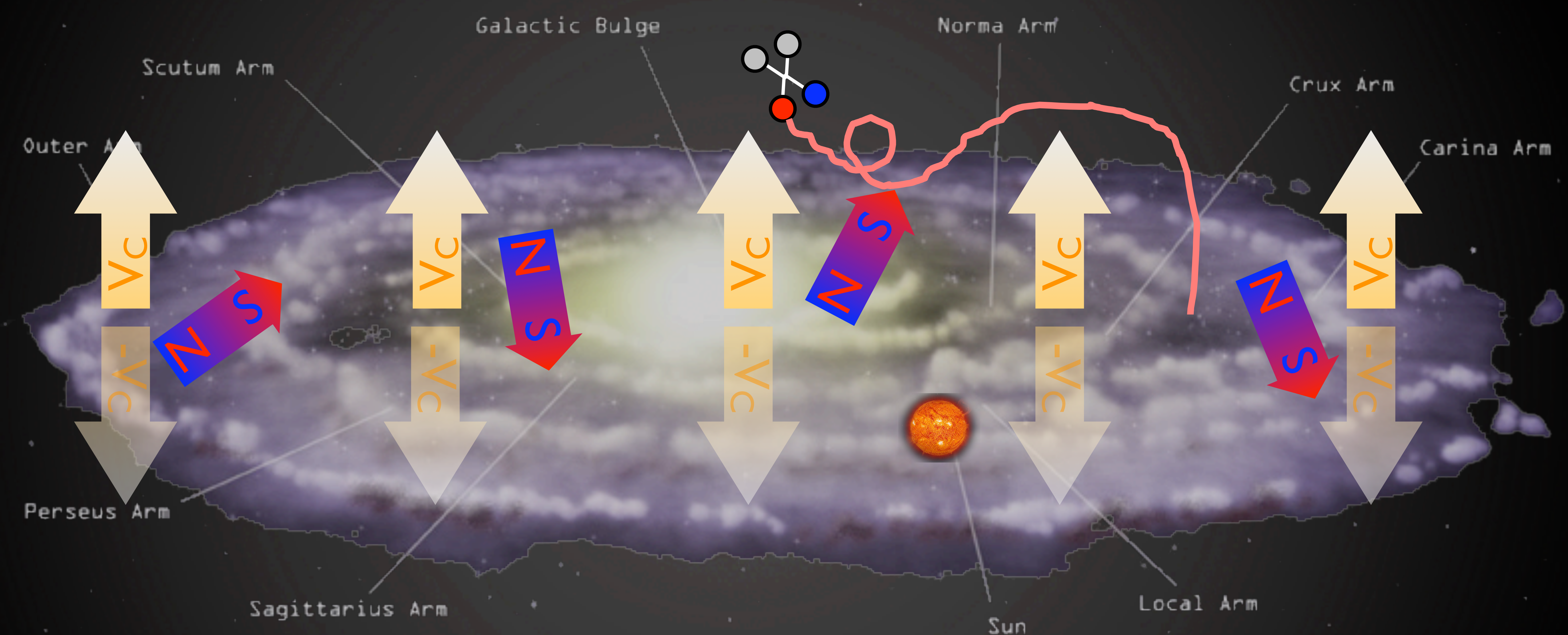
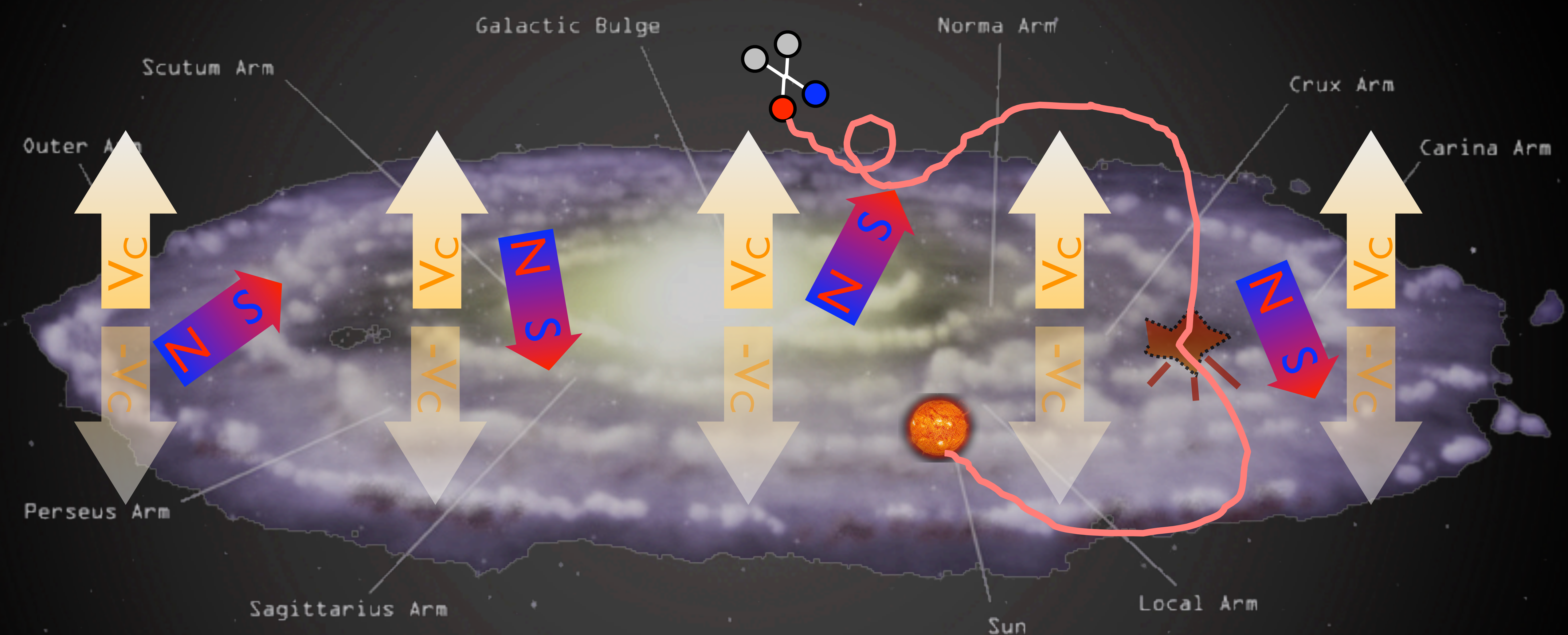


Indirect Detection

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



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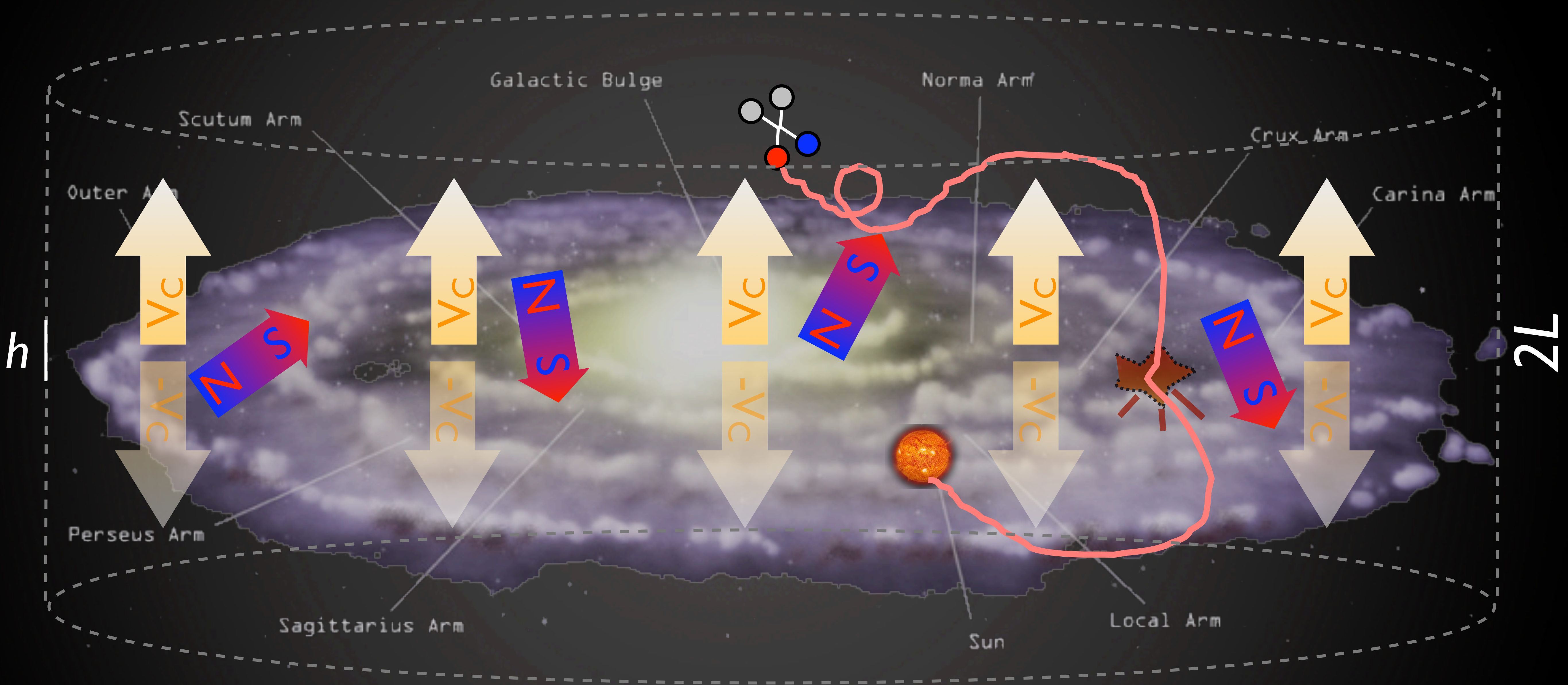


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

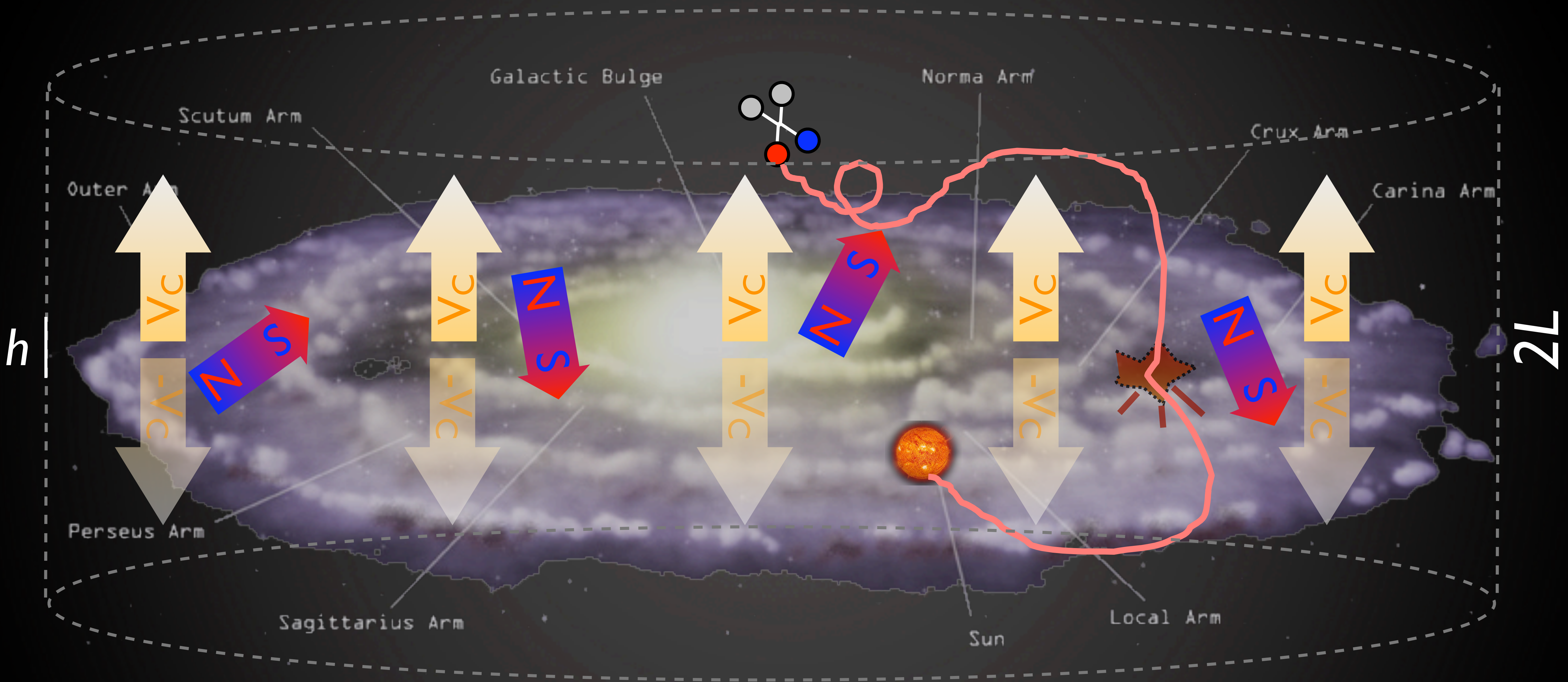
spectrum

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

diffusion energy loss convective wind source spallations

Indirect Detection

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

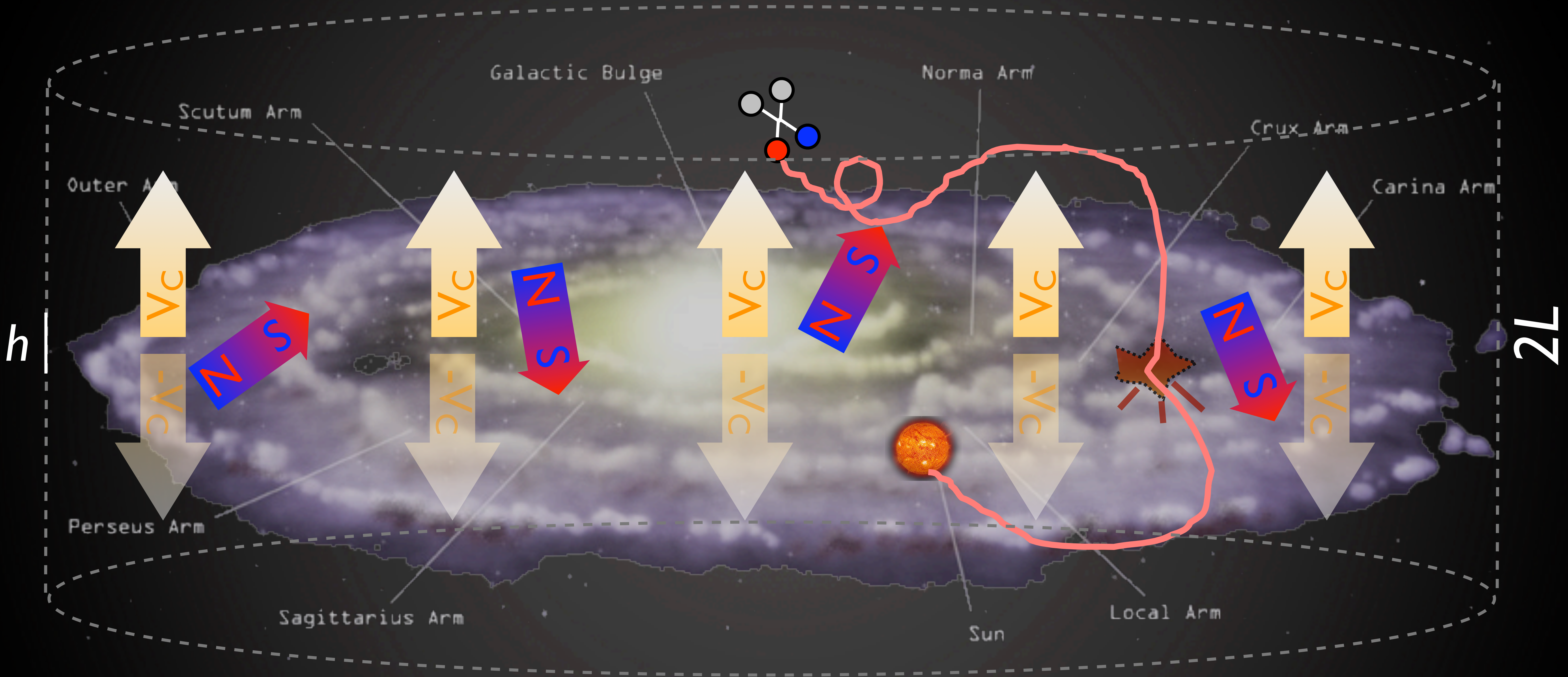


What sets the overall expected flux?

$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

Indirect Detection

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



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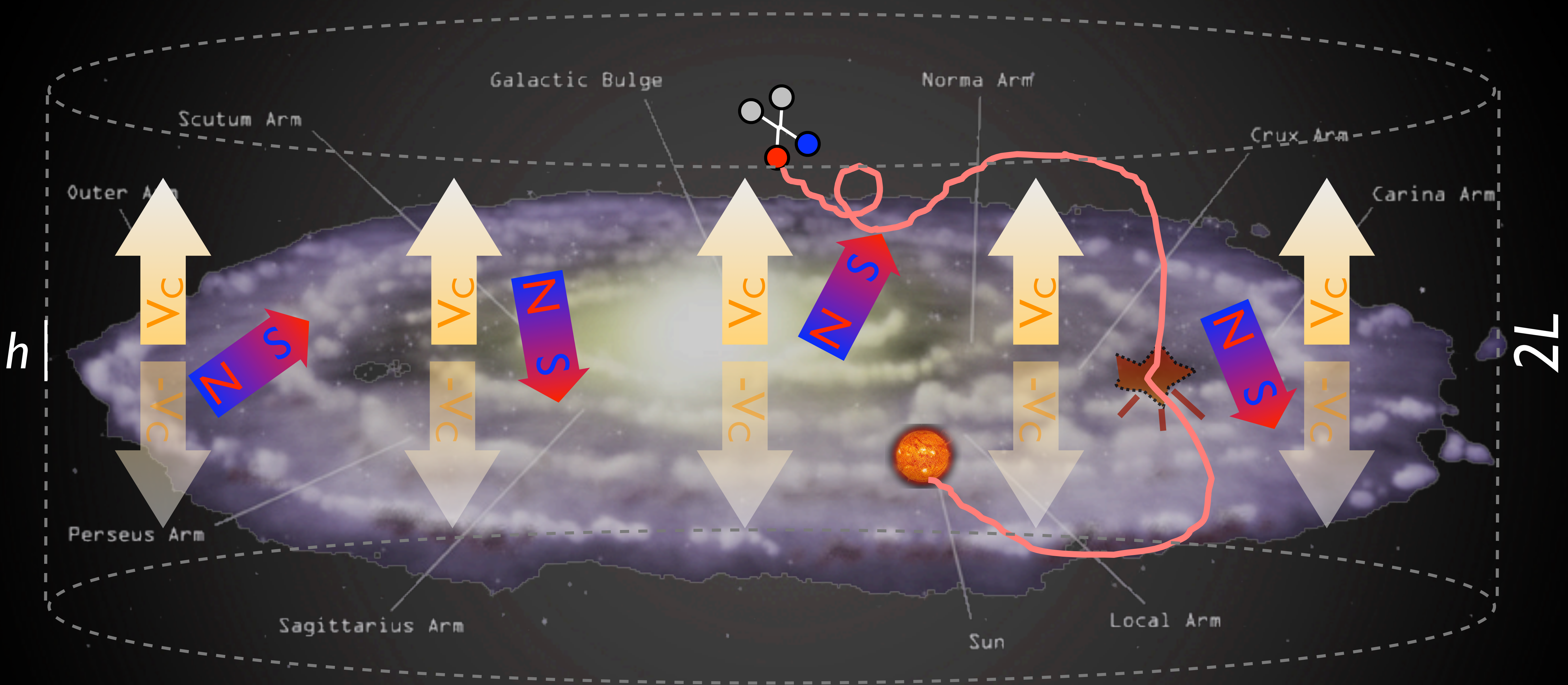
astro& cosmo

particle

Indirect Detection

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



What sets the overall expected flux?

$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

astro& cosmo

particle

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

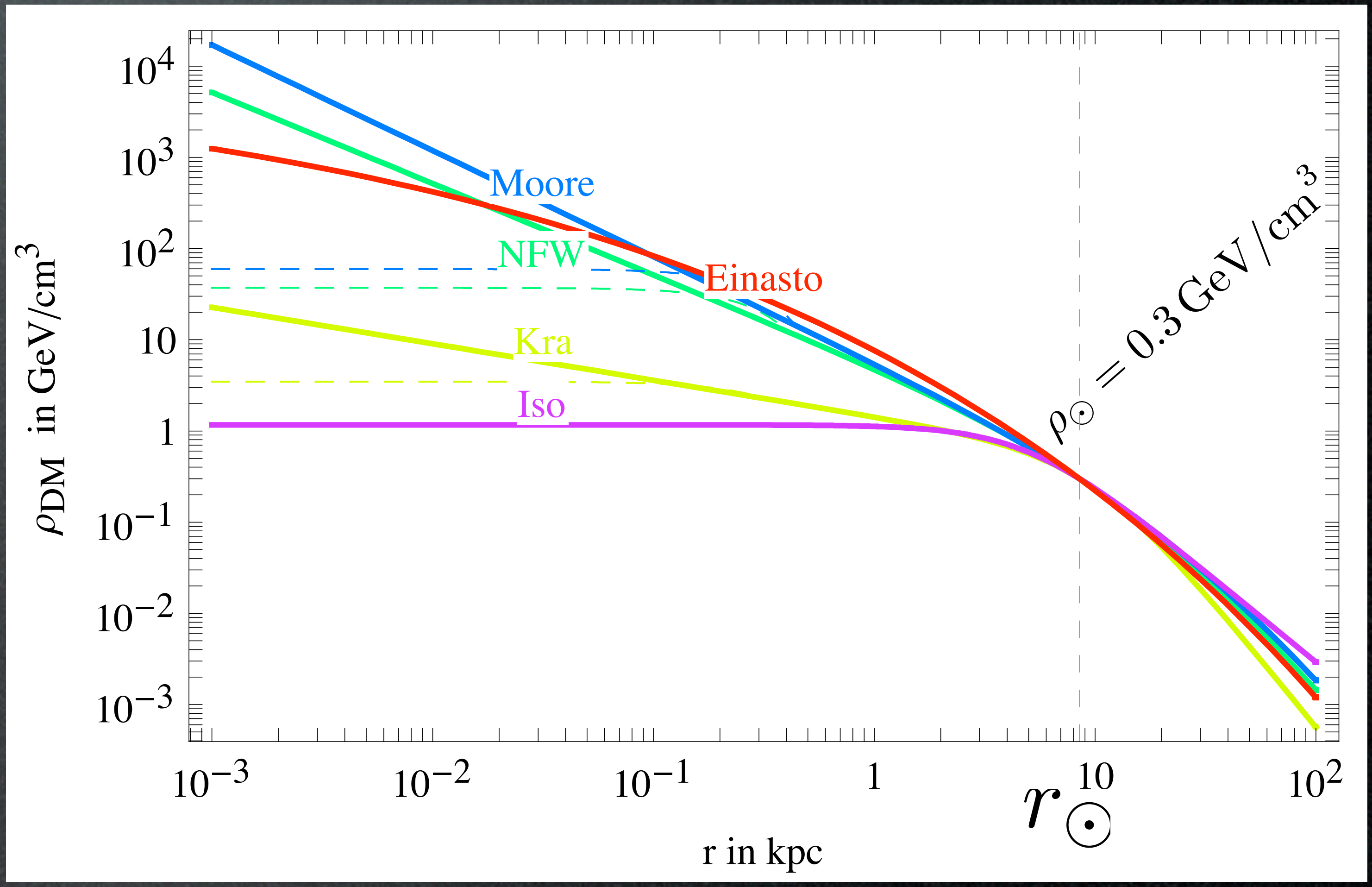
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

At small r: $\rho(r) \propto 1/r^\gamma$

$$\rho(r) = \rho_s \cdot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

Einasto | $\alpha = 0.17$ $r_s = 20\,\text{kpc}$ $\rho_s = 0.06\,\text{GeV/cm}^3$

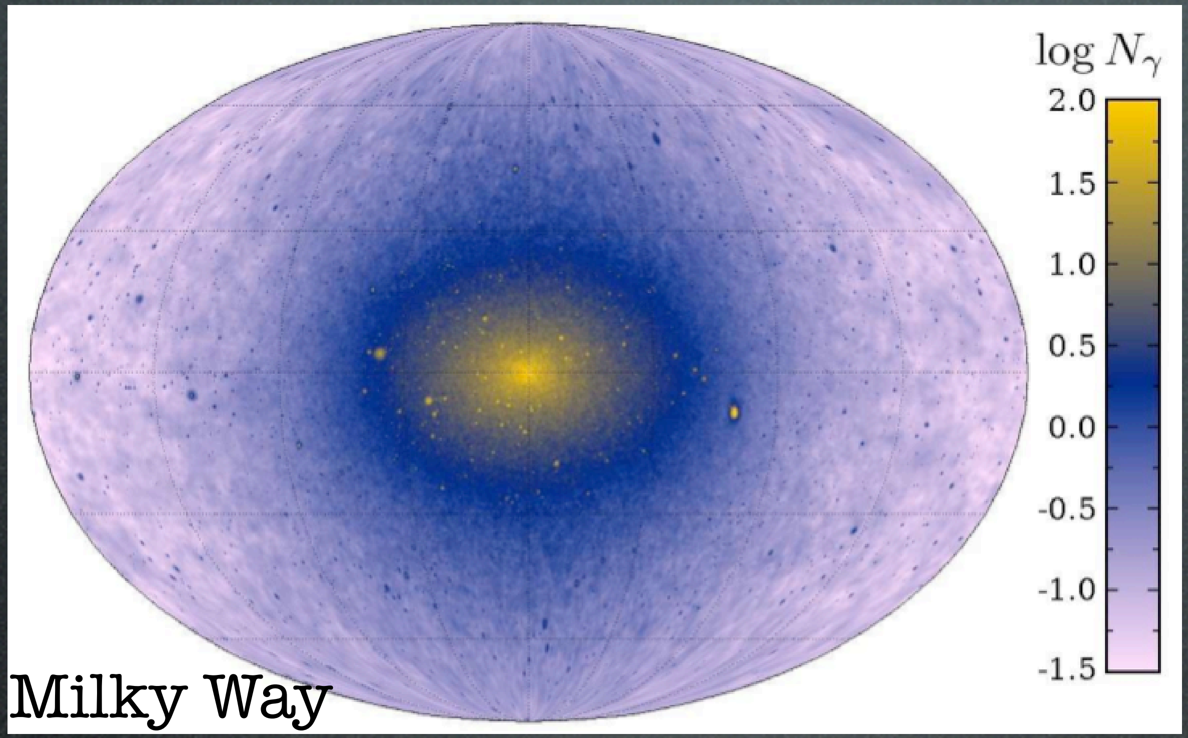


cuspy: NFW, Moore
mild: Einasto
smooth: isothermal

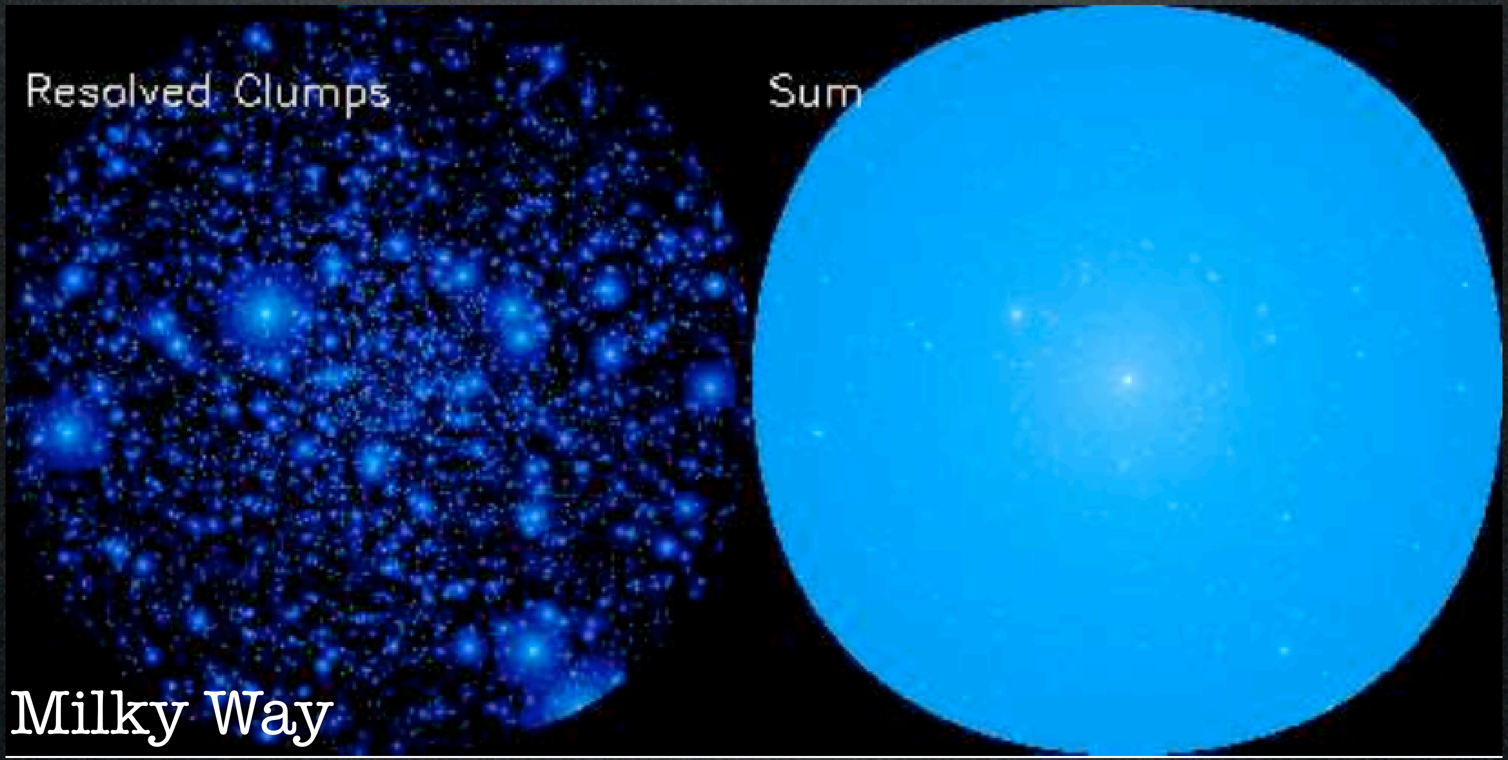
Indirect Detection

Boost Factor: local clumps in the DM halo enhance the density, boost the flux from annihilations. Typically: $B \simeq 1 \to 20 \quad (10^4)$

For illustration:



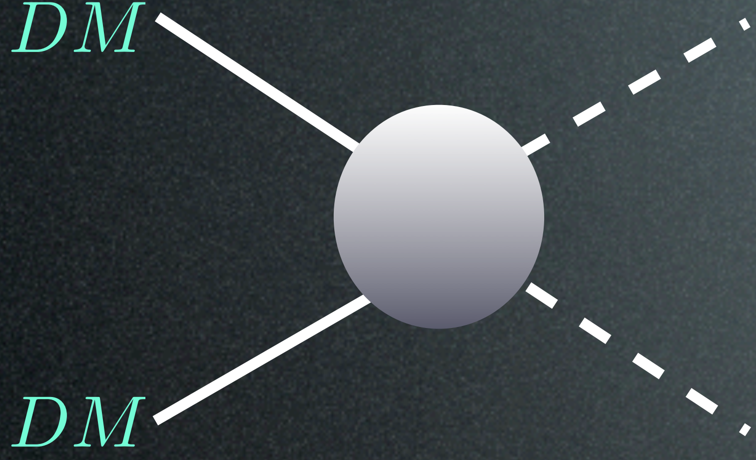
Kuhlen, Diemand, Madau 2007



Bertone, Branchini, Pieri 2007

Computing the theory predictions

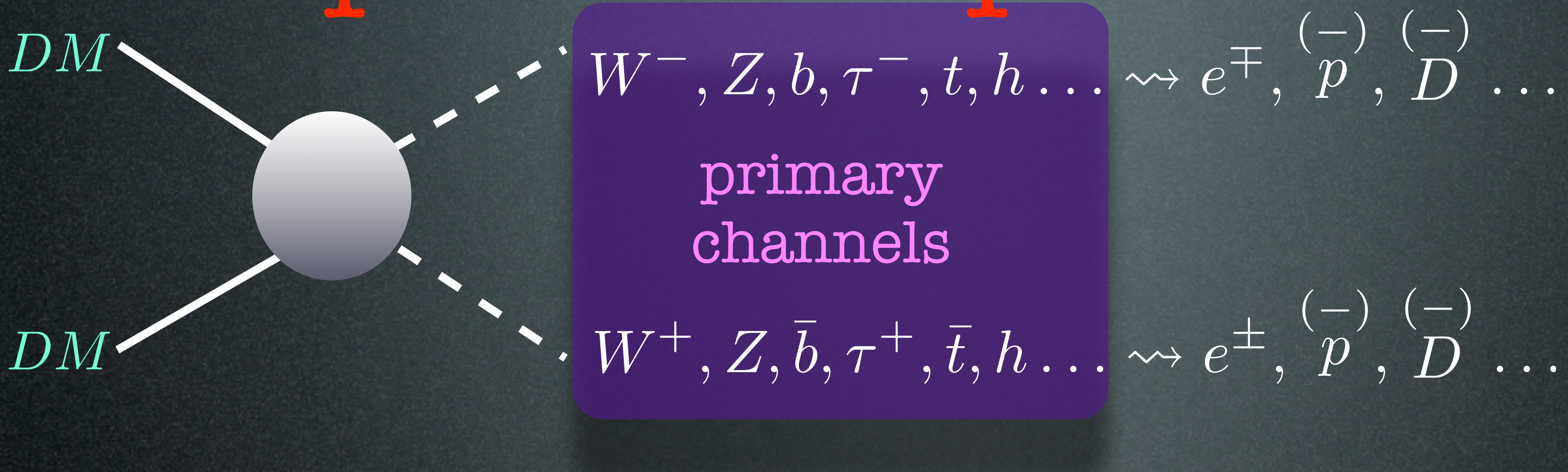
Spectra at production



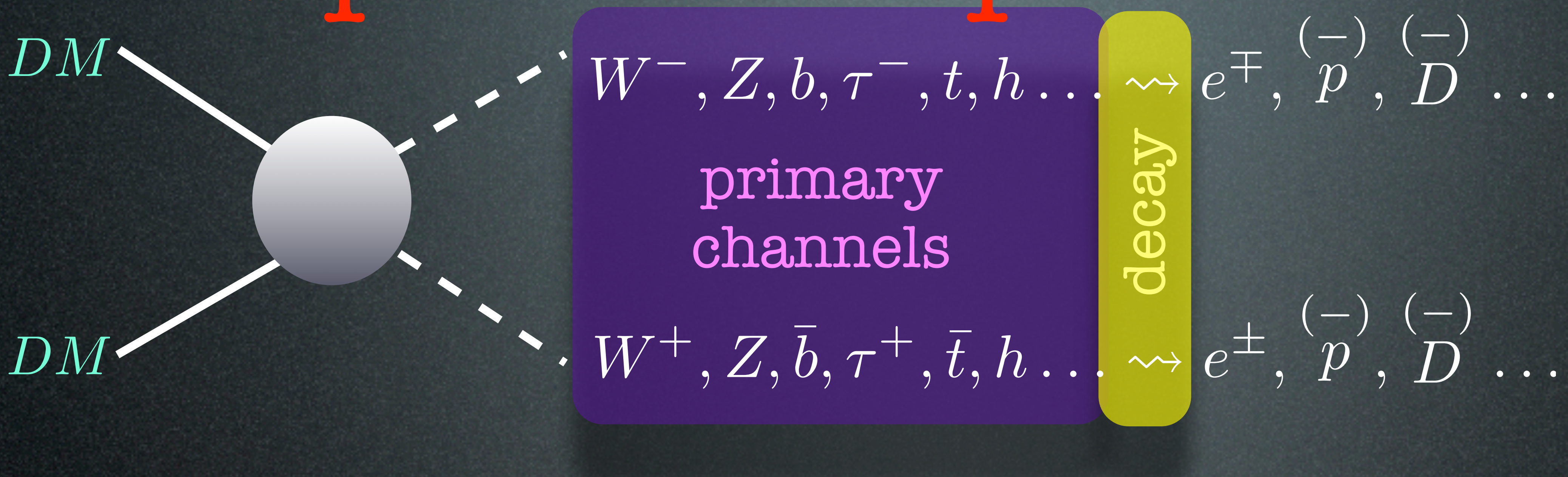
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

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

Spectra at production



Spectra at production



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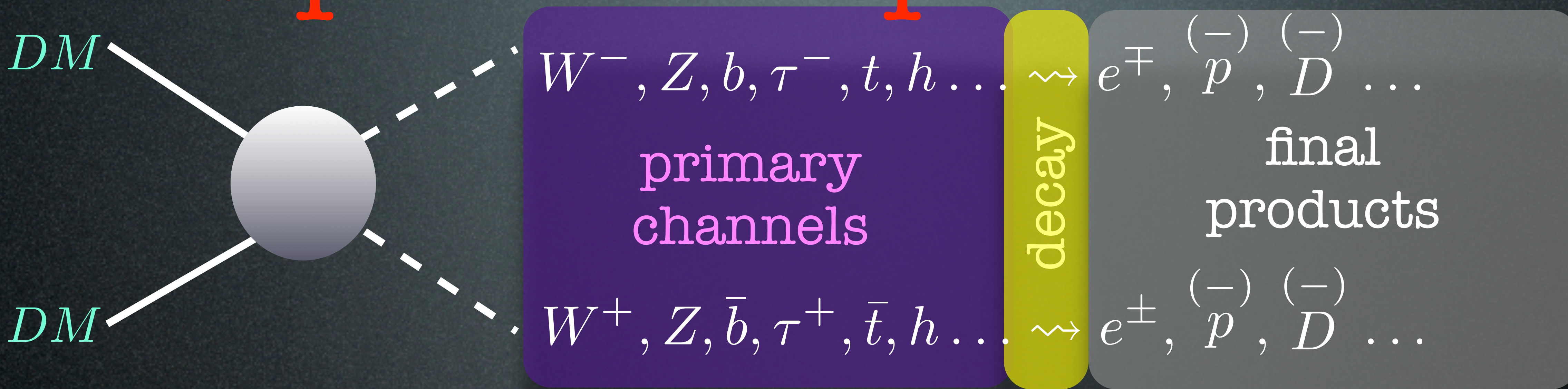

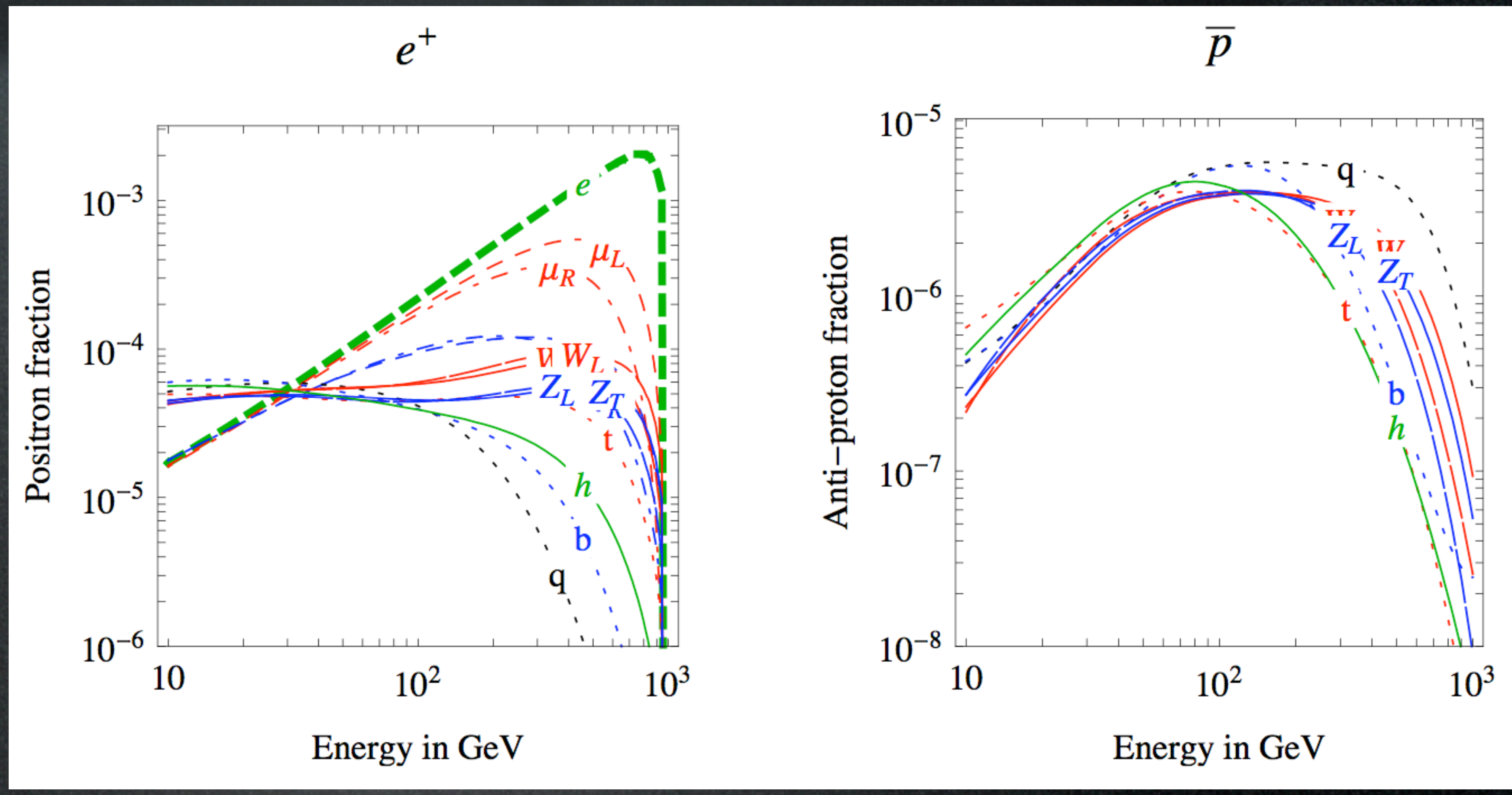

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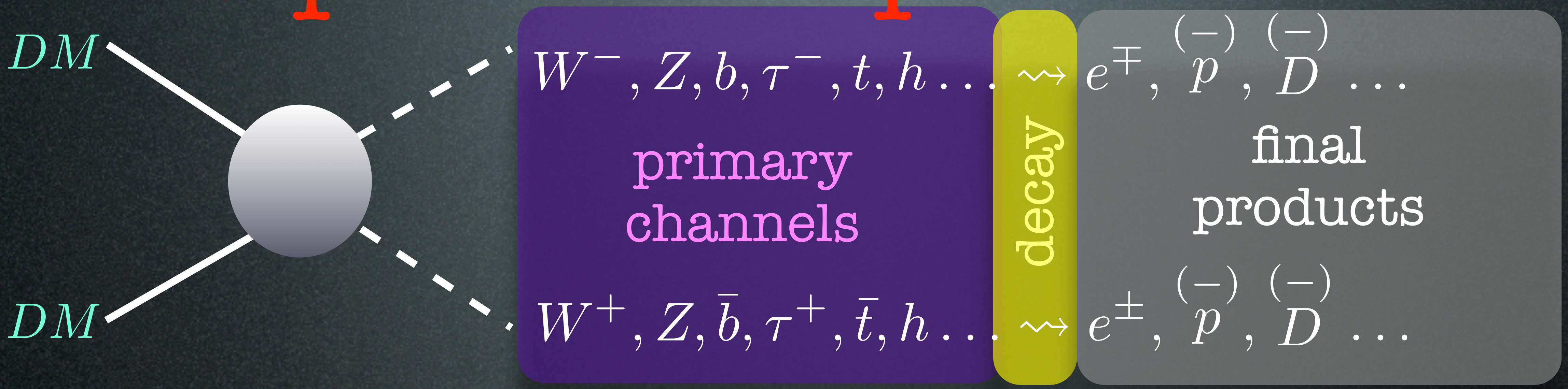
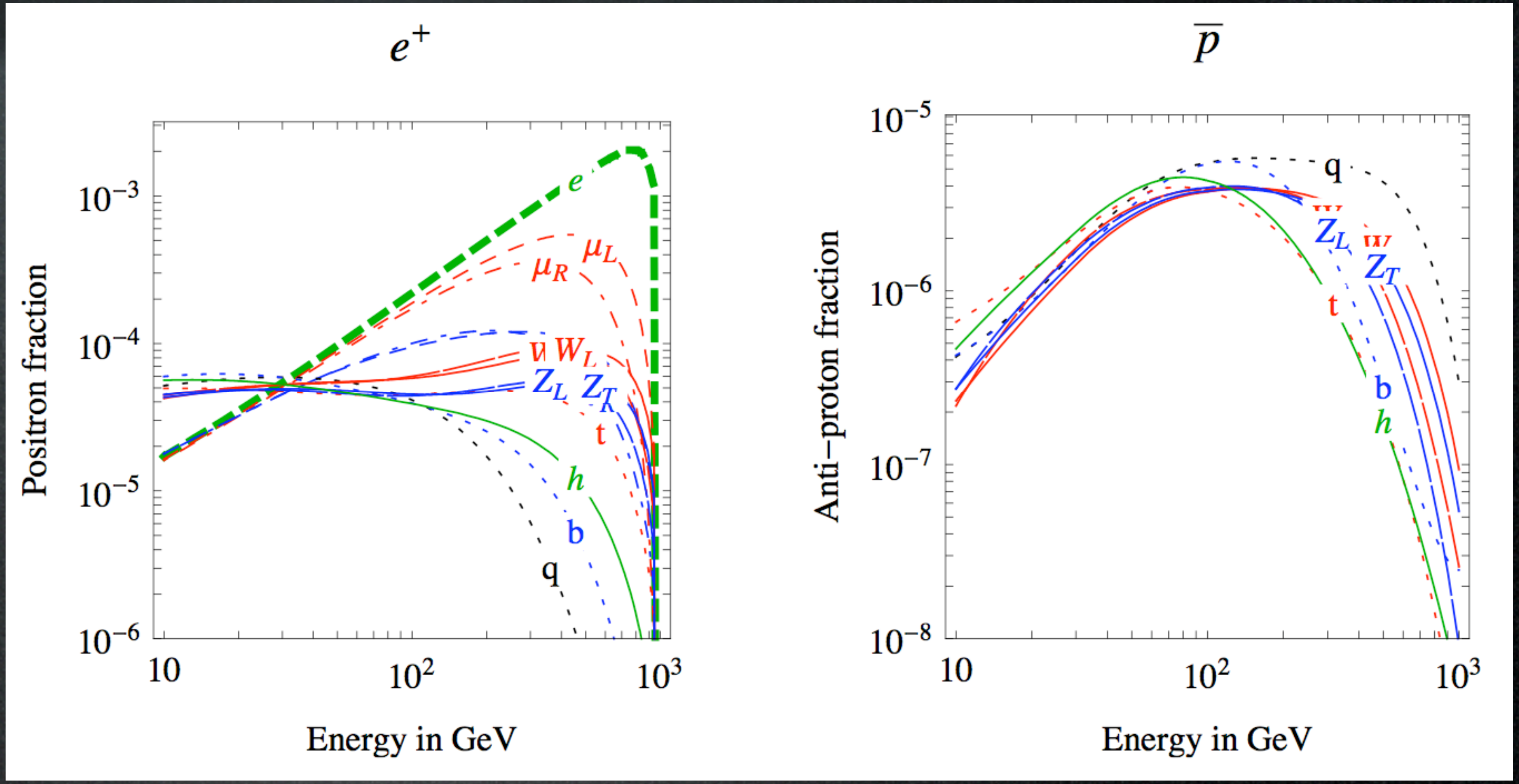




So what are the particle physics parameters?

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

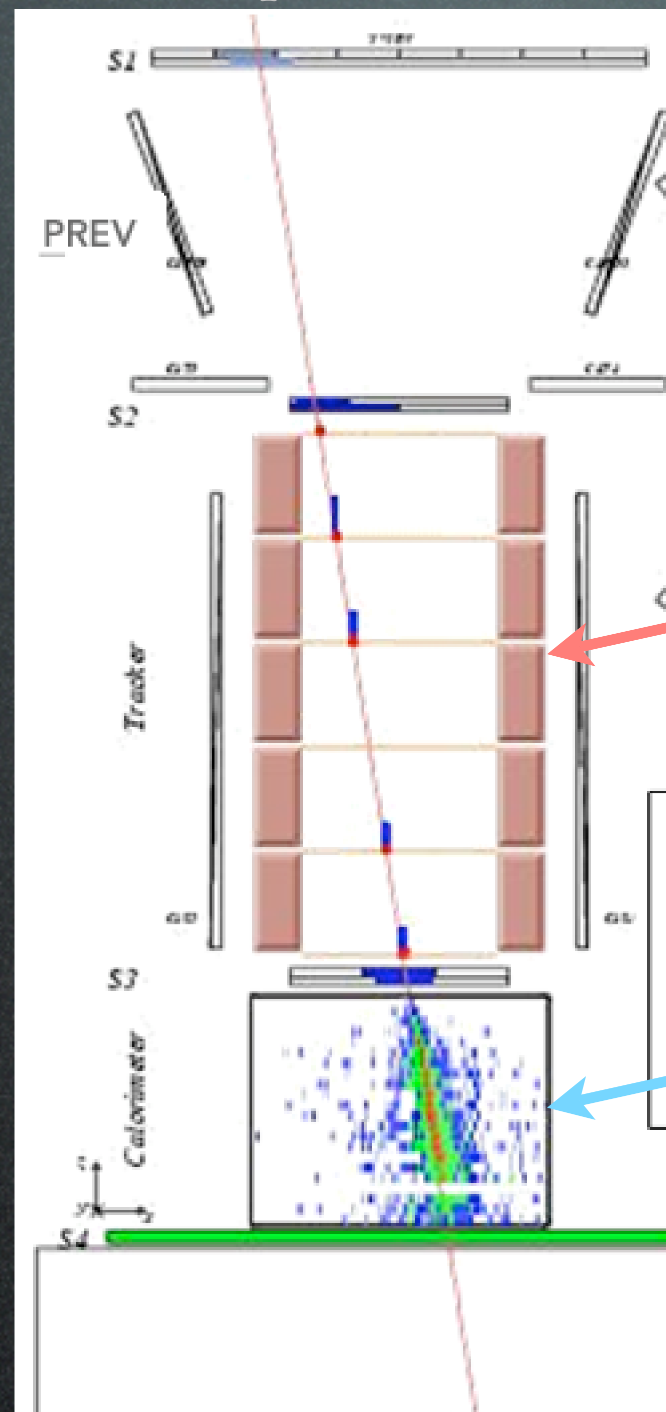
Comparing with data

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

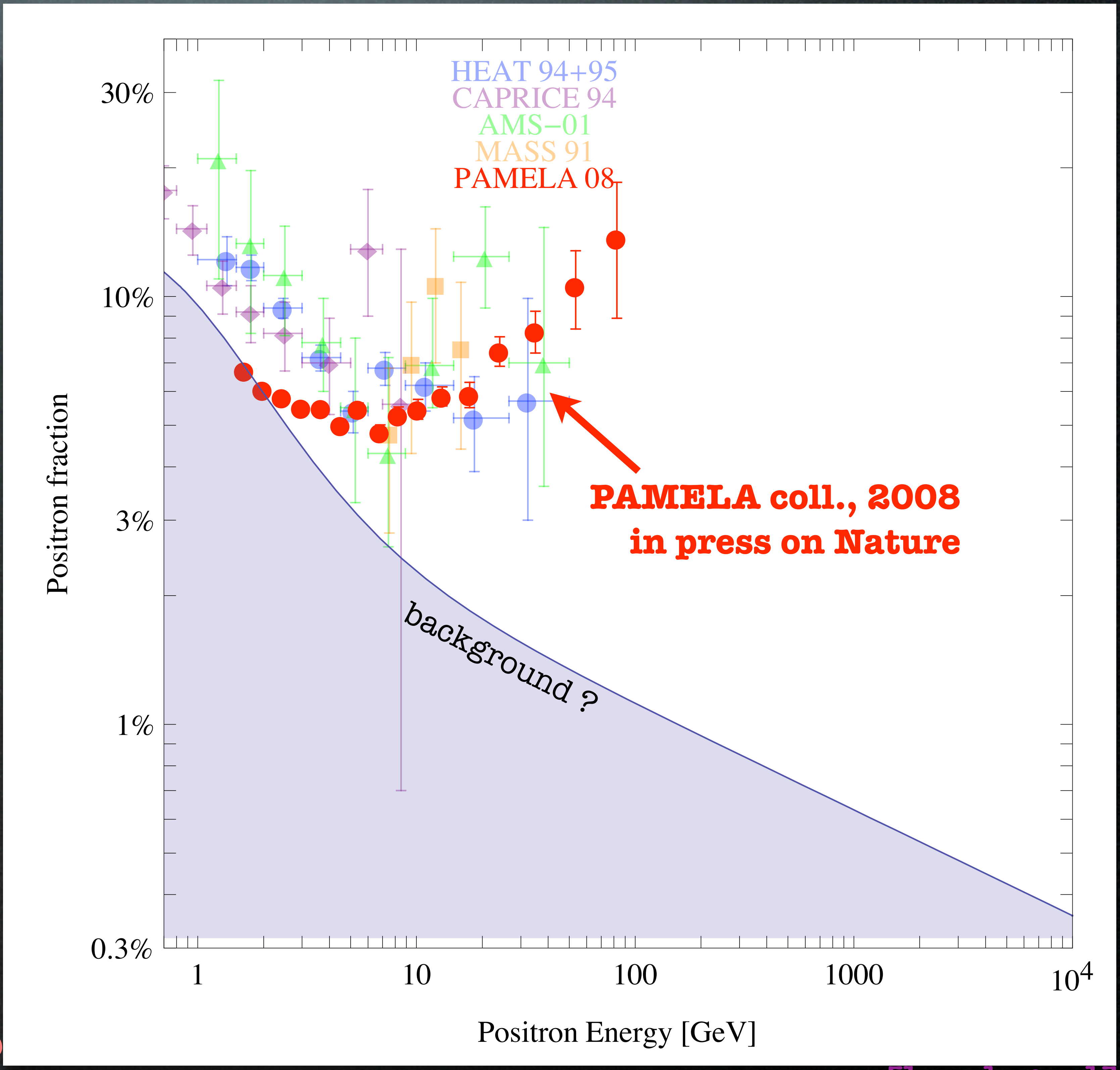
Positrons from PAMELA:

- 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

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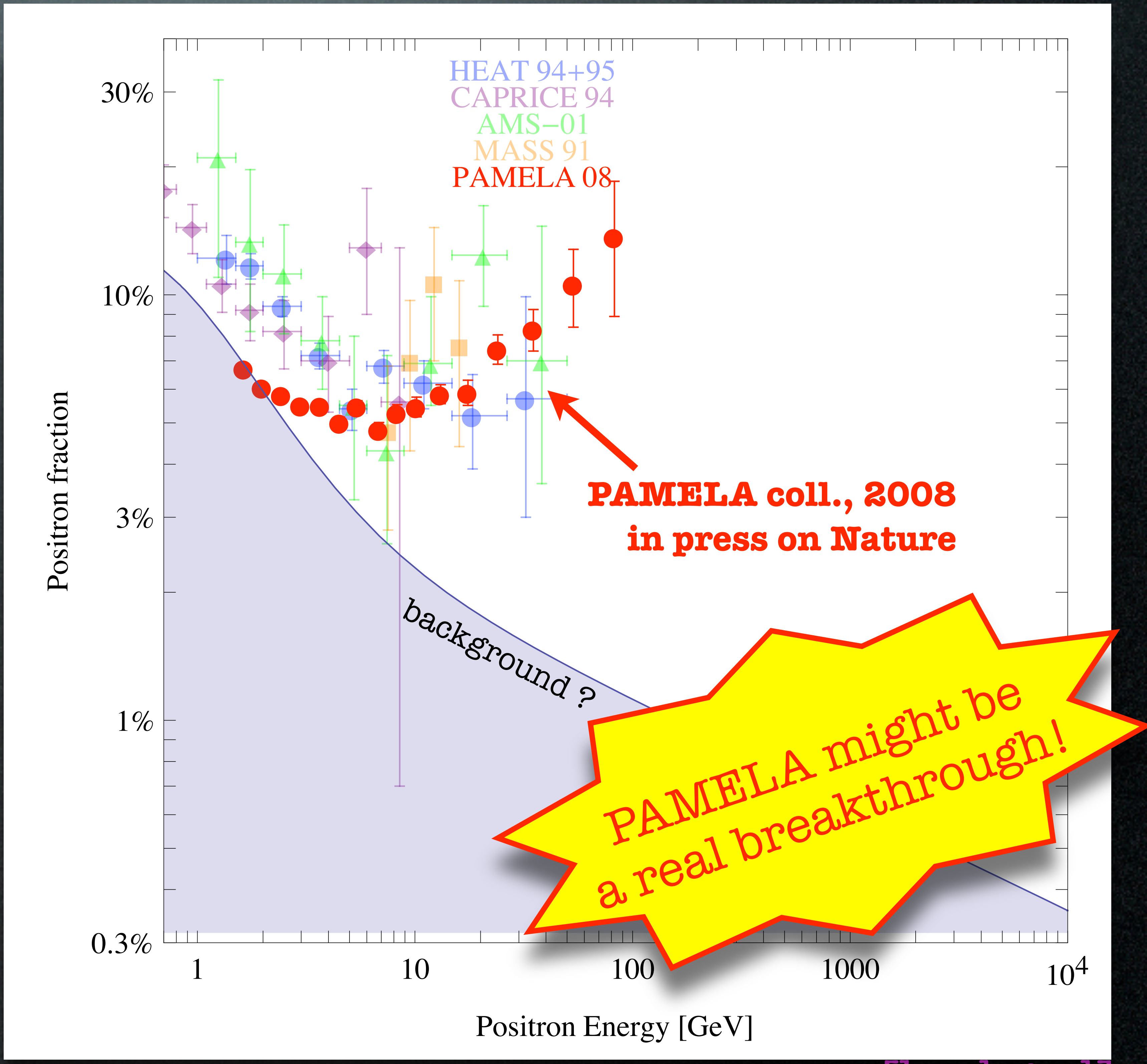
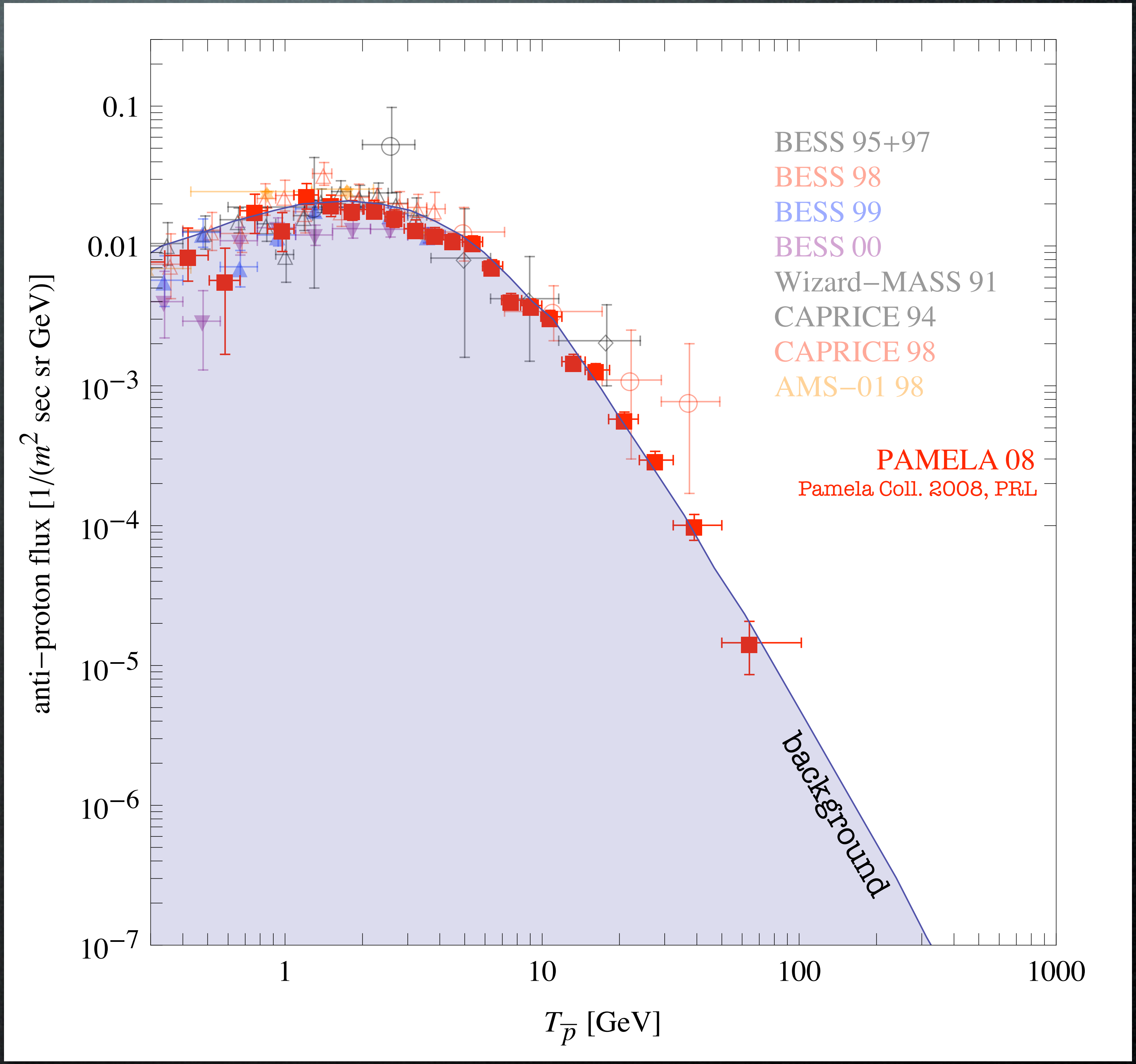


[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background



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

Results

Which DM spectra can fit the data?

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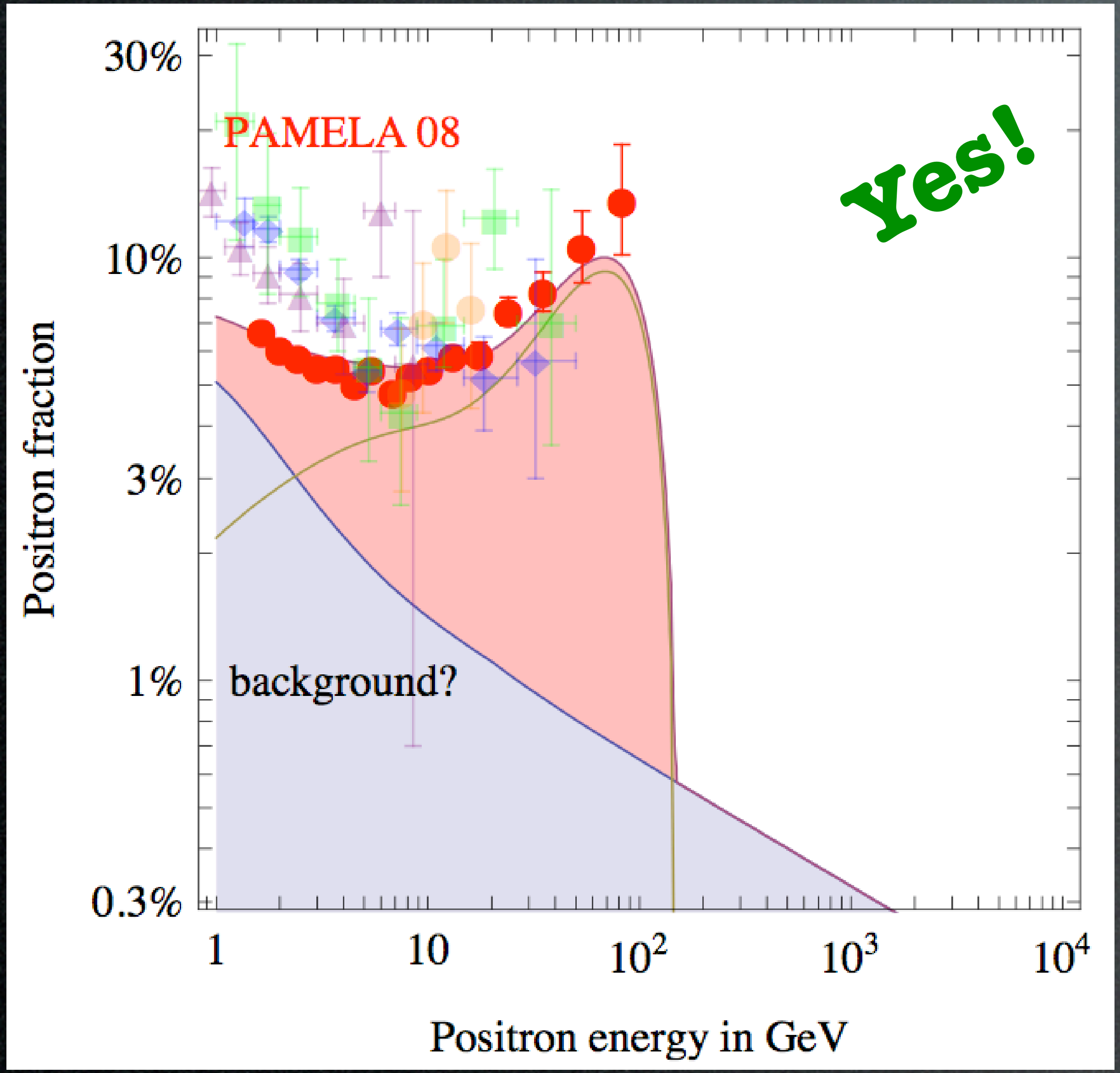
Which DM spectra can fit the data?

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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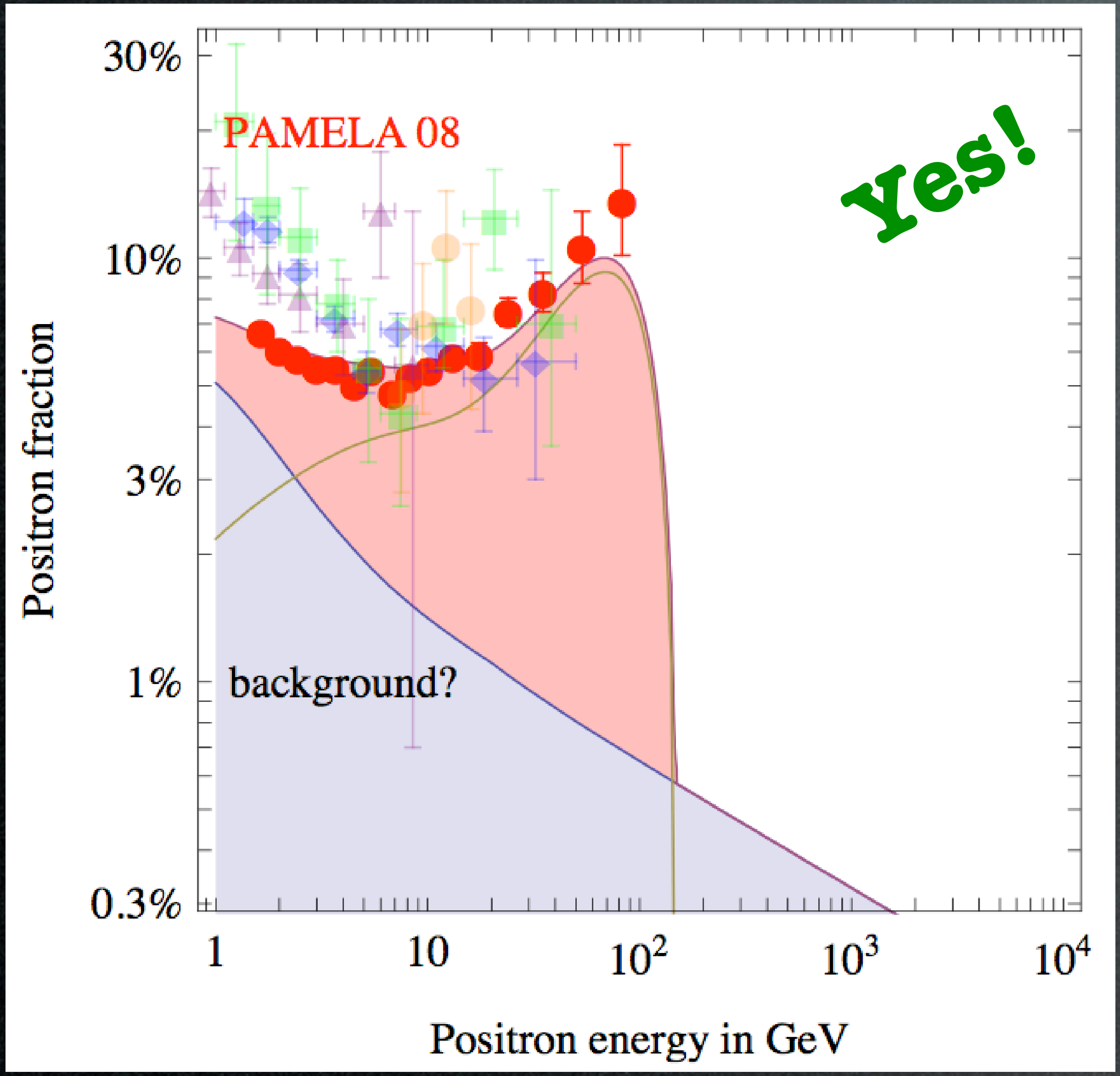
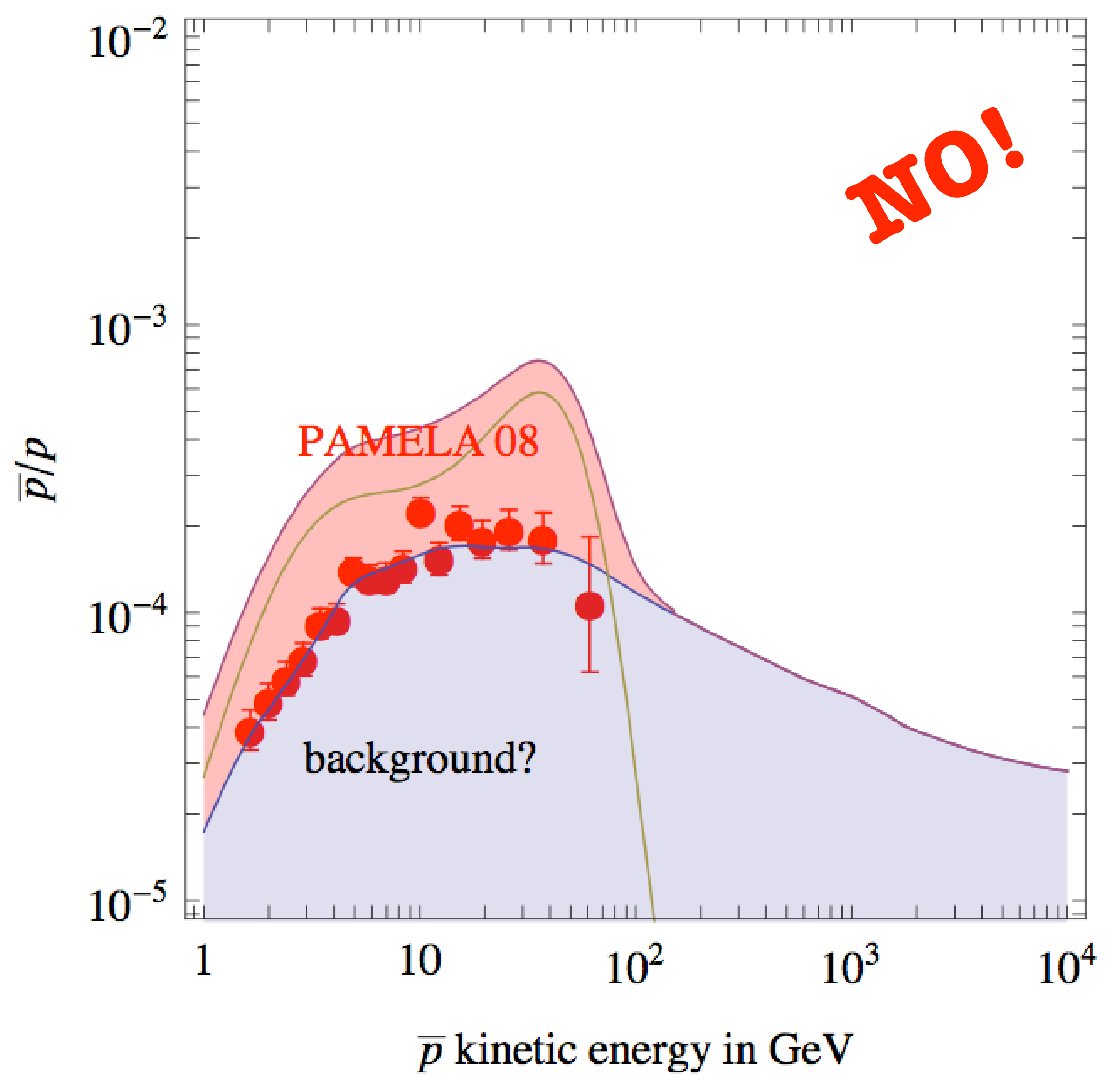


Anti-protons:



[insisting on Winos]

Results

Which DM spectra can fit the data?

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

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

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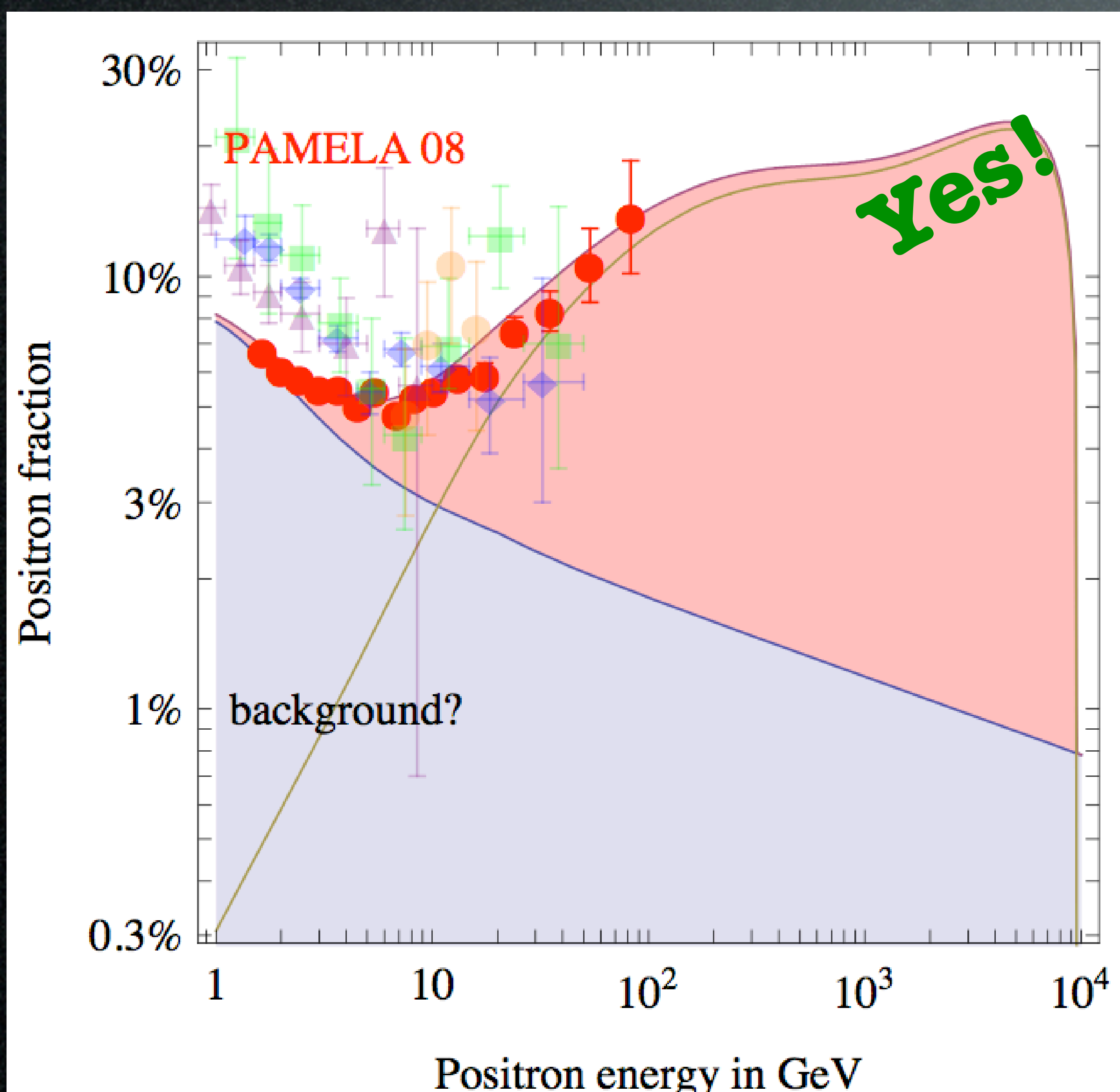

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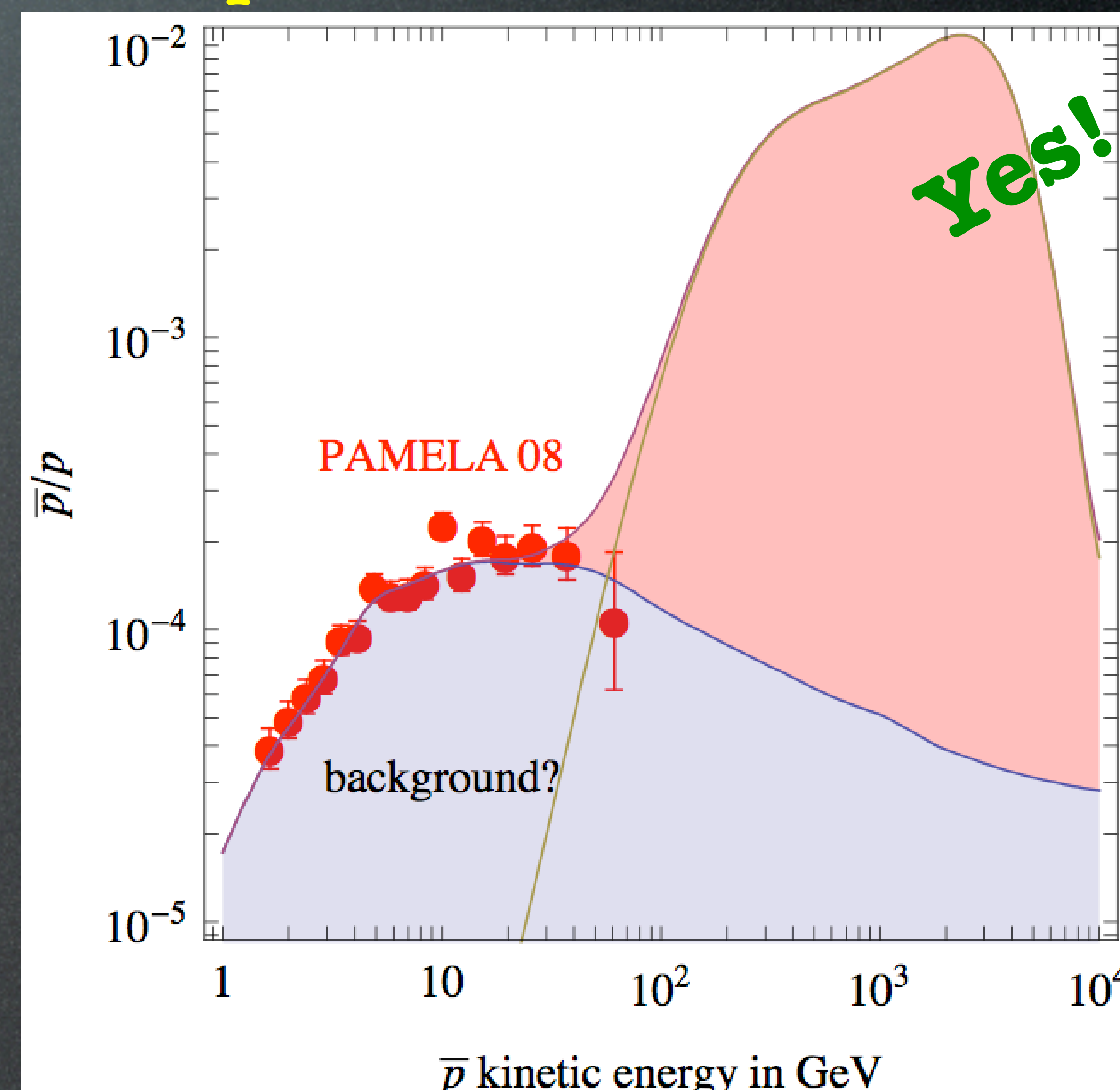


Results

Which DM spectra can fit the data?

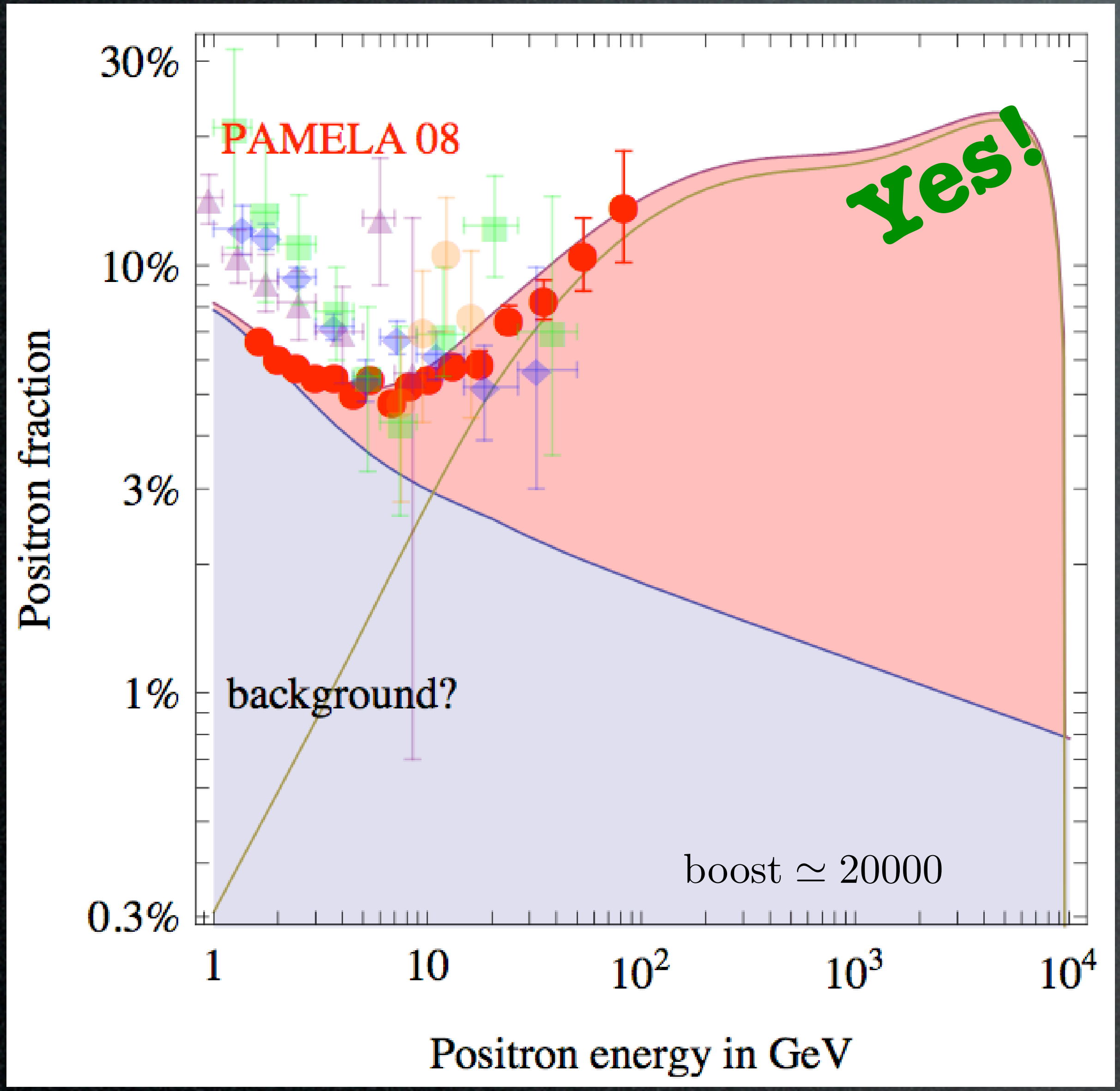
E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

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

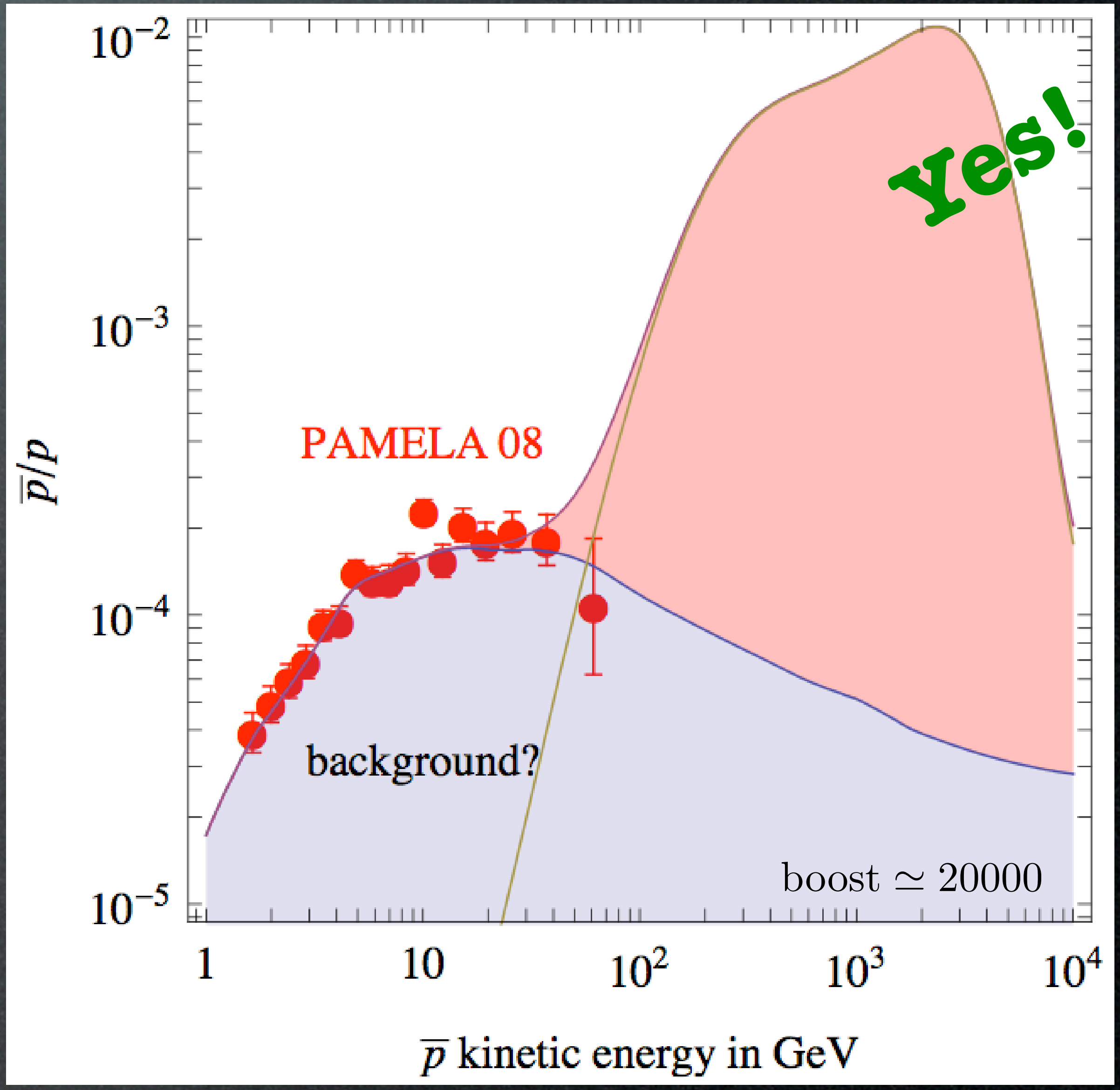
but...: -cross sec $\sigma_{\rm ann} v = 6 \cdot 10^{-22} {\rm cm}^3/{\rm sec}$

Mmm...

Positrons:



Anti-protons:



Results

Which DM spectra can fit the data?

E.g. Minimal DM: -mass $M_{\rm DM} = 9.7\,{\rm TeV}$

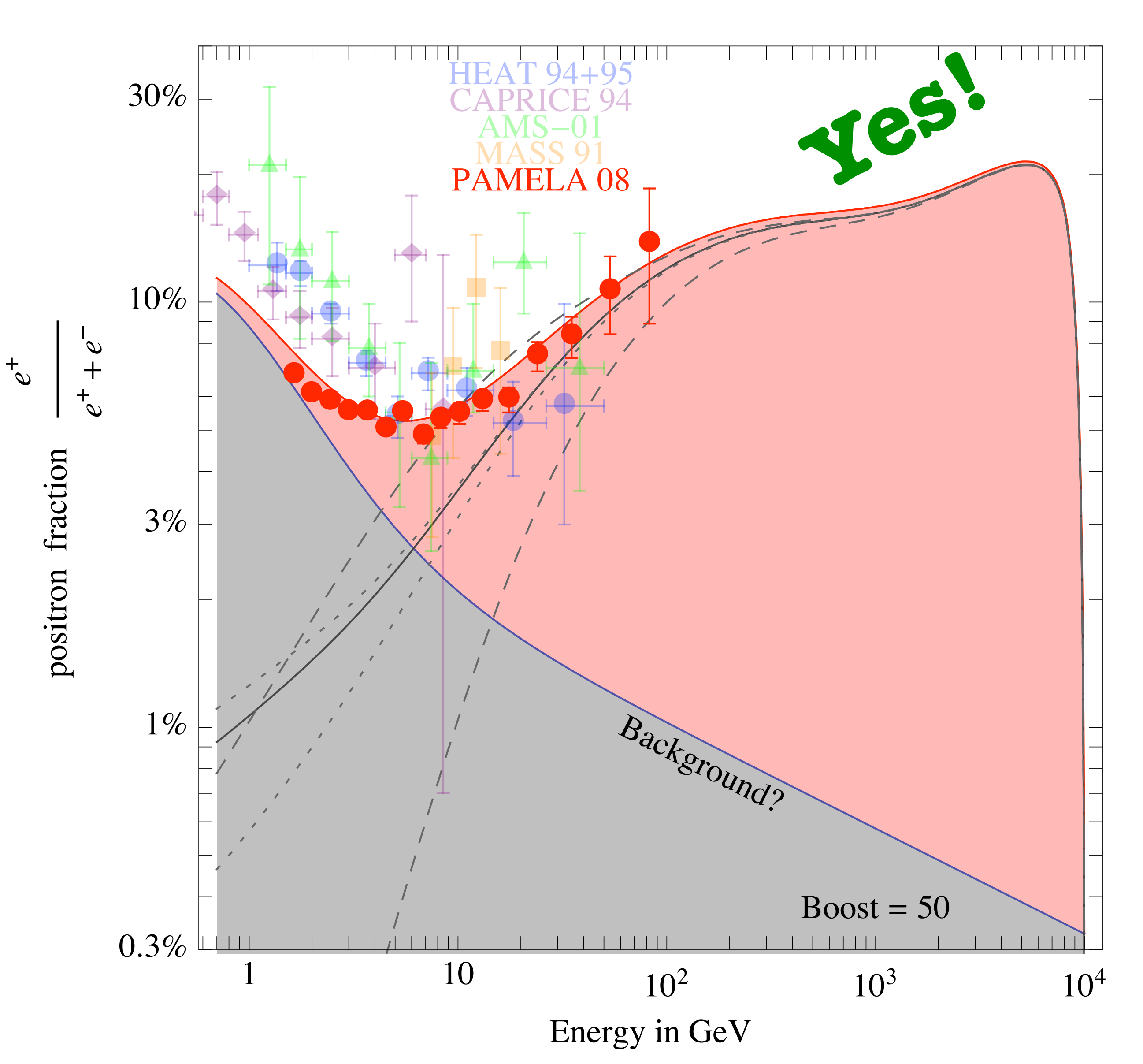
[Cirelli, Strumia et al. 2006]

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

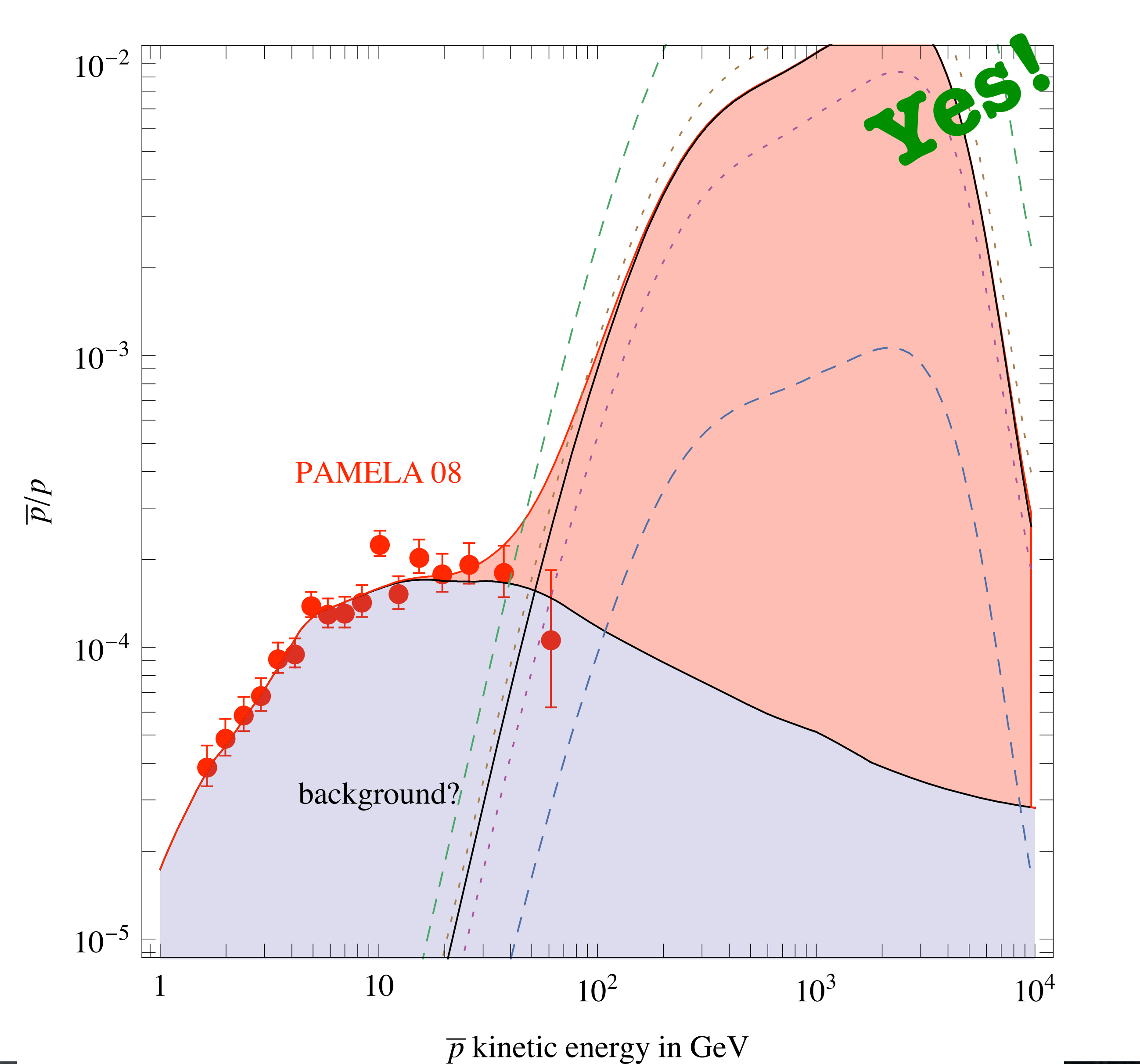
-boost $B \simeq 30$ Yes!

[thanks to **Sommerfeld** enhancement]

Positrons:



Anti-protons:

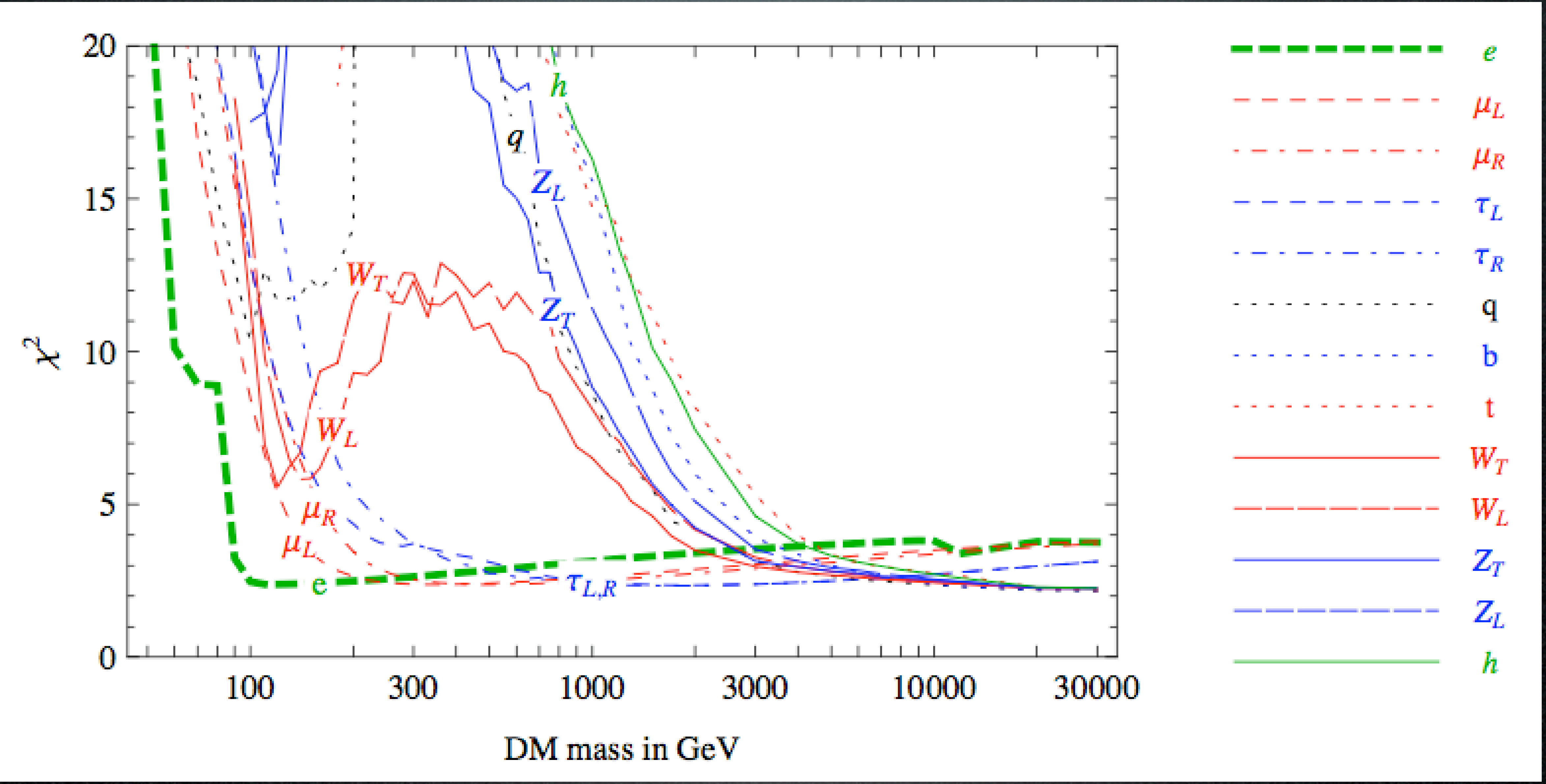


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons only

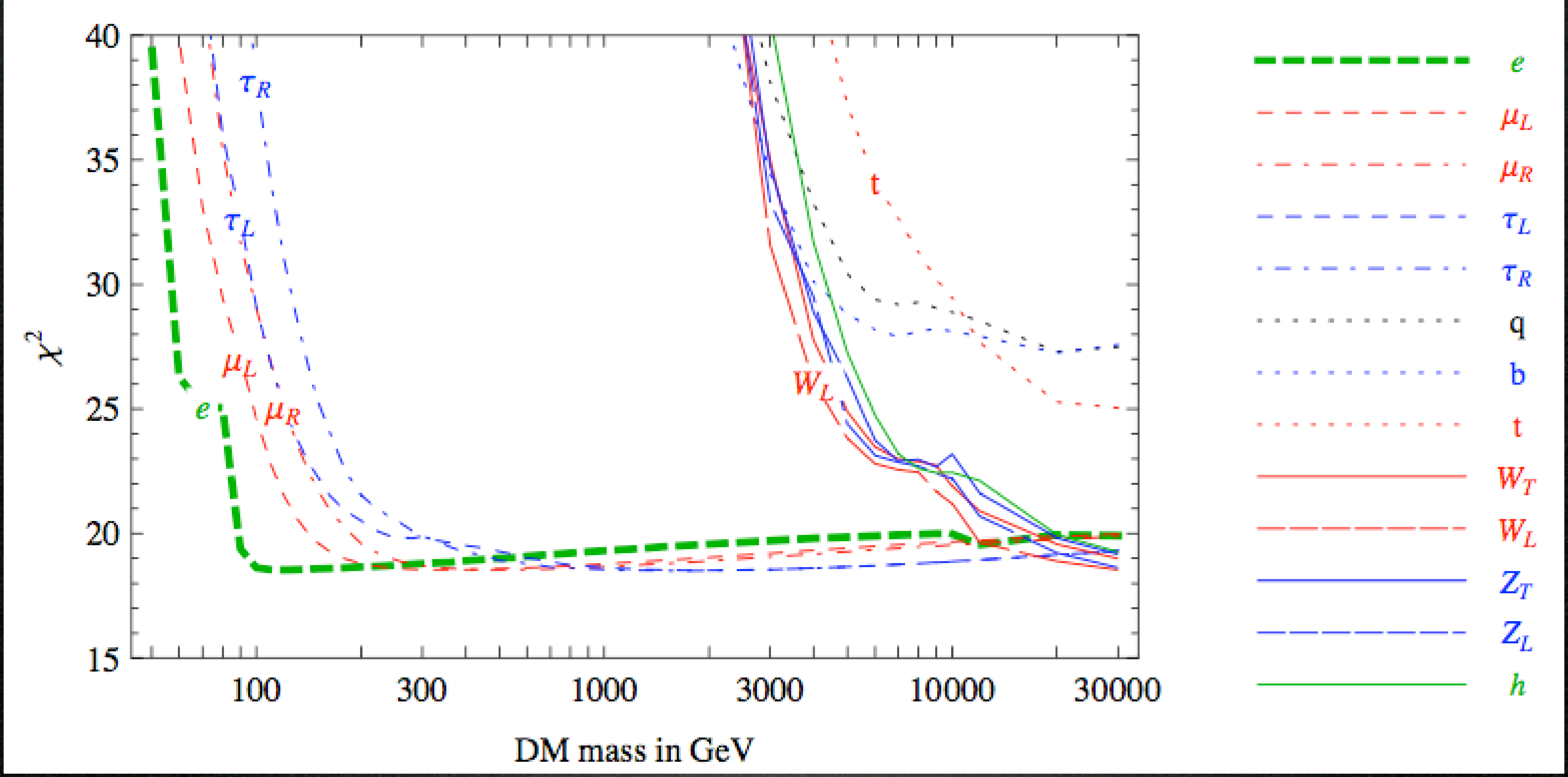


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons

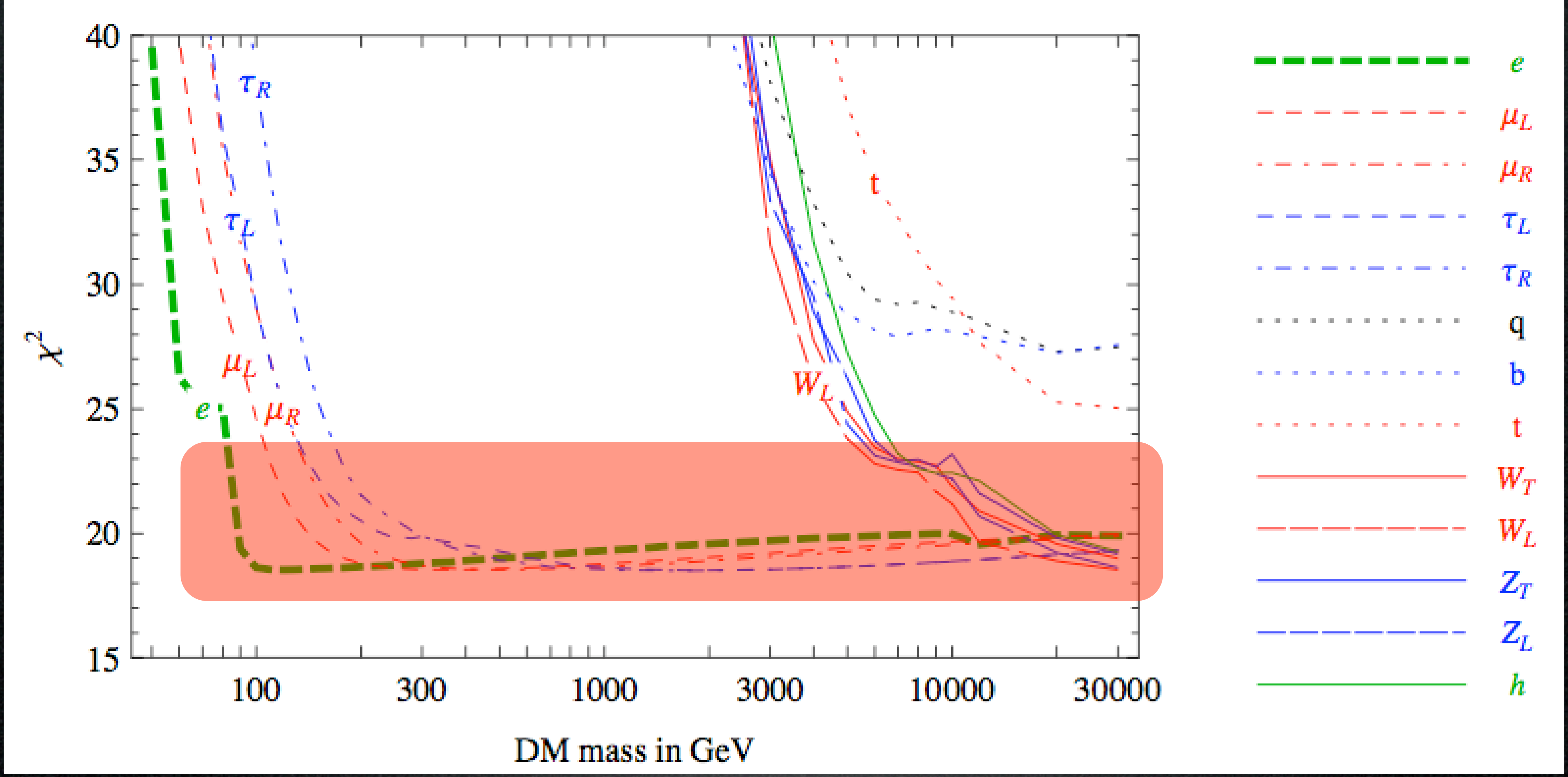


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



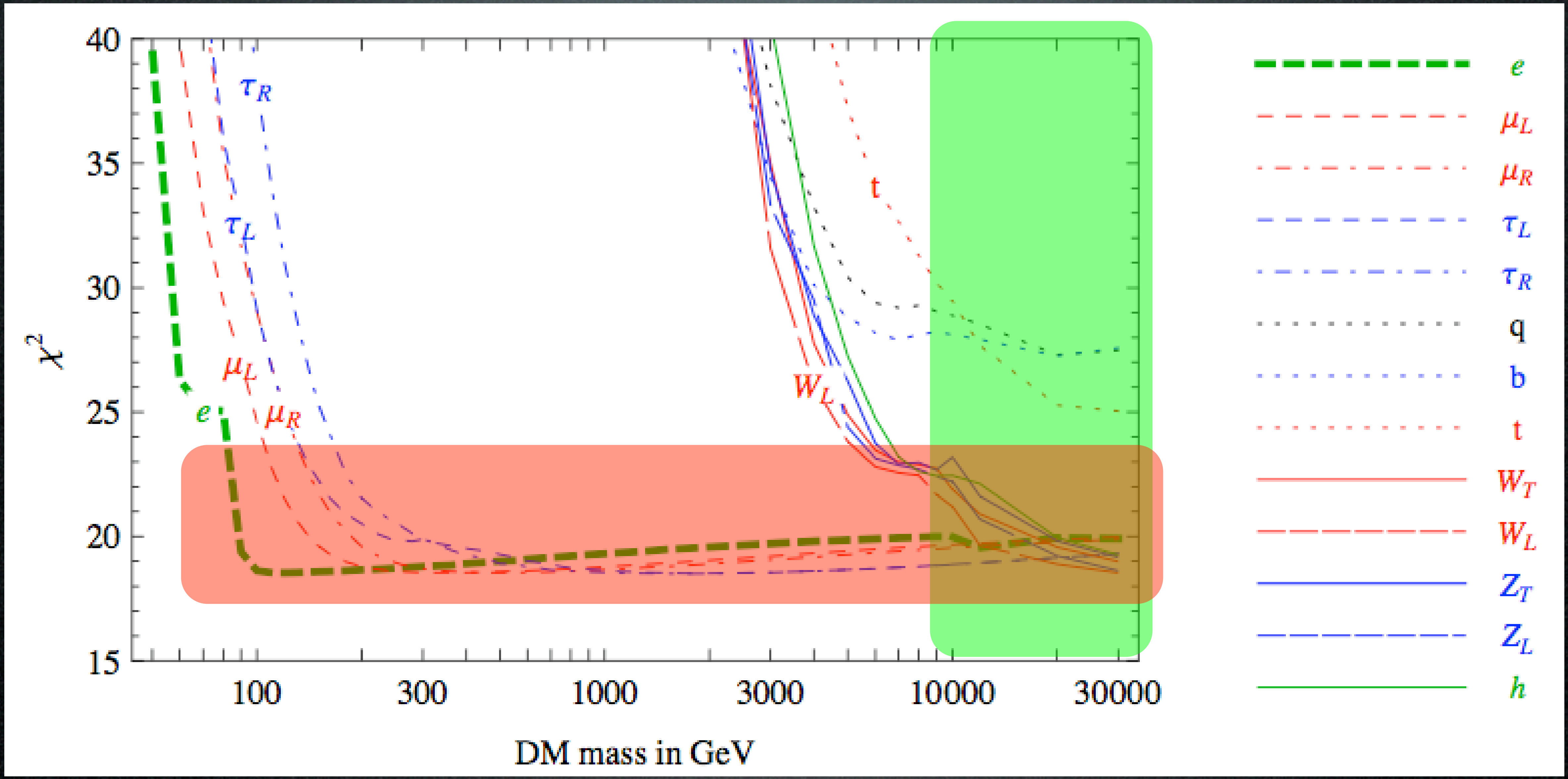
(1) annihilate into leptons (e.g. $\mu^+\mu^-$)

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



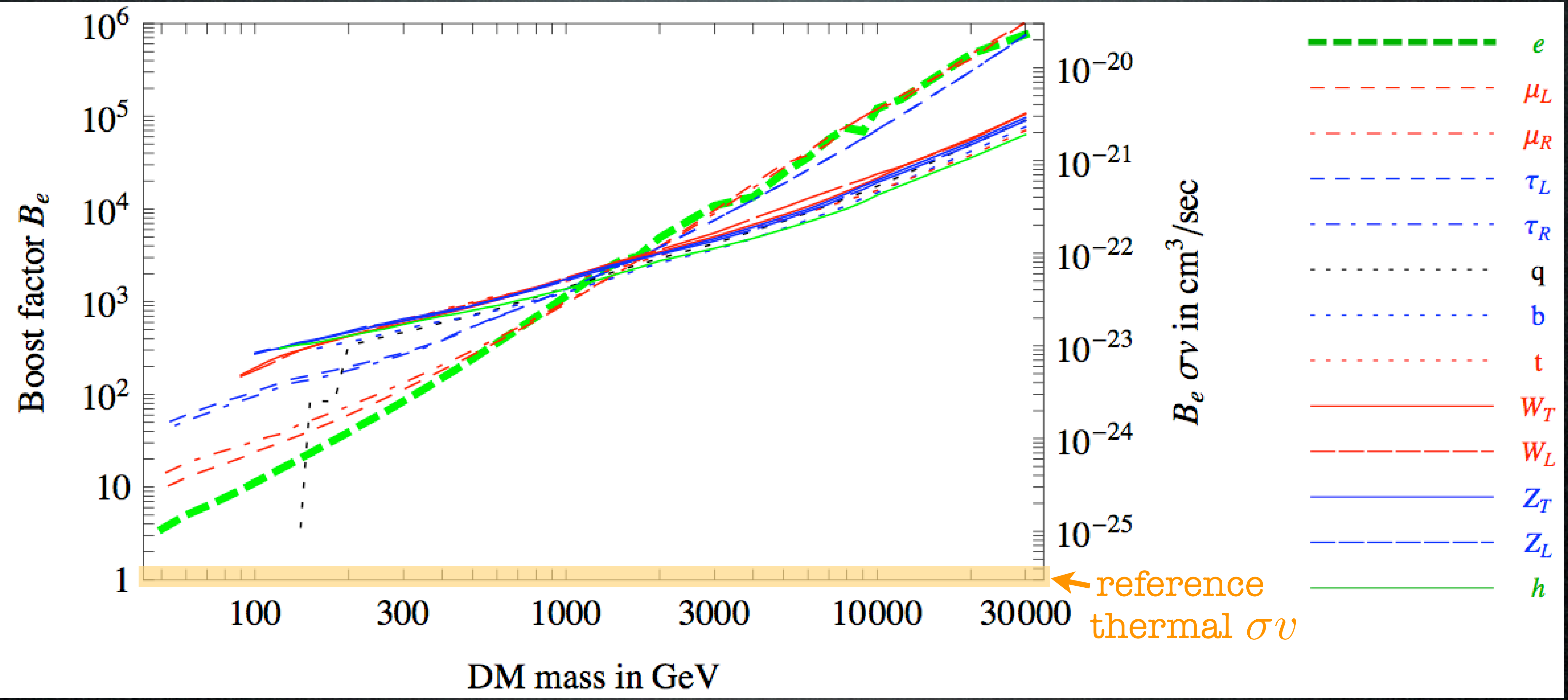
(1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

Results

Which DM spectra can fit the data?

Model-independent results:

Boost required by PAMELA



Data sets

Electrons + positrons from ATIC, PPB-BETS:

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

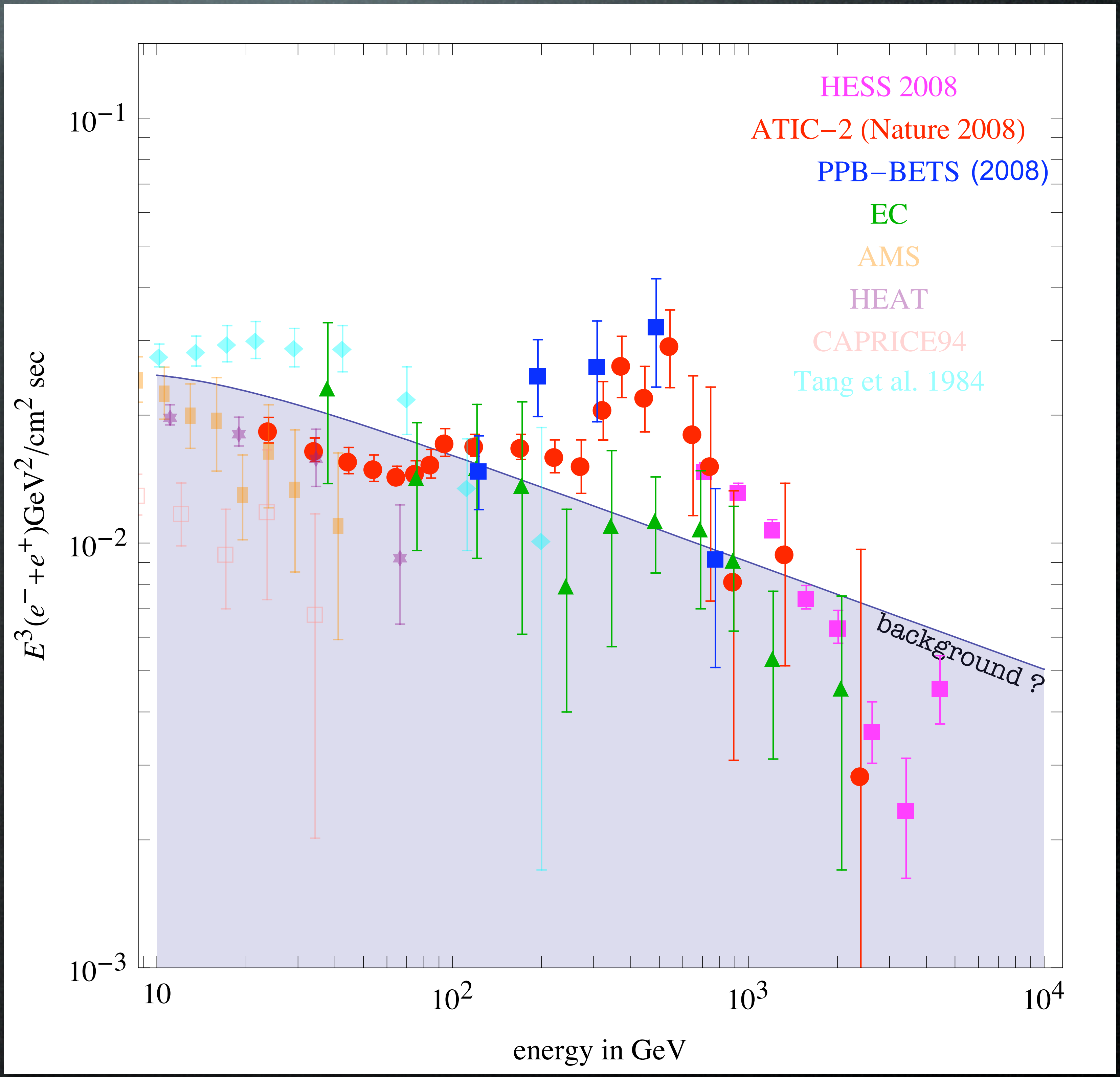
Advanced
Thin
Ionization
Calorimeter

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

Data sets

Electrons + positrons from ATIC, PPB-BETS and HESS!:

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



HESS:
very interesting (independent!)
but difficult analysis
(particle ID: contamination
from gamma & hadronic showers):
are these upper limits?

[future data from GLAST]

Results

Which DM spectra can fit the data?

A DM with: -mass $M_{\rm DM} = 1\,{\rm TeV}$

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

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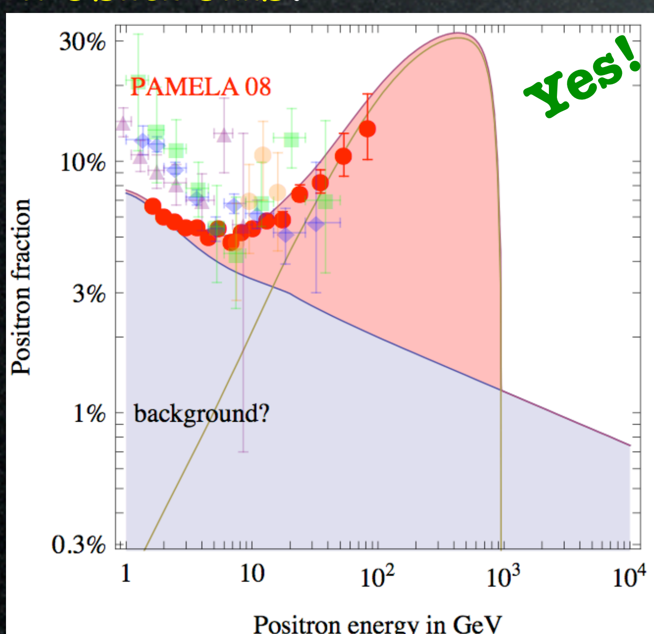
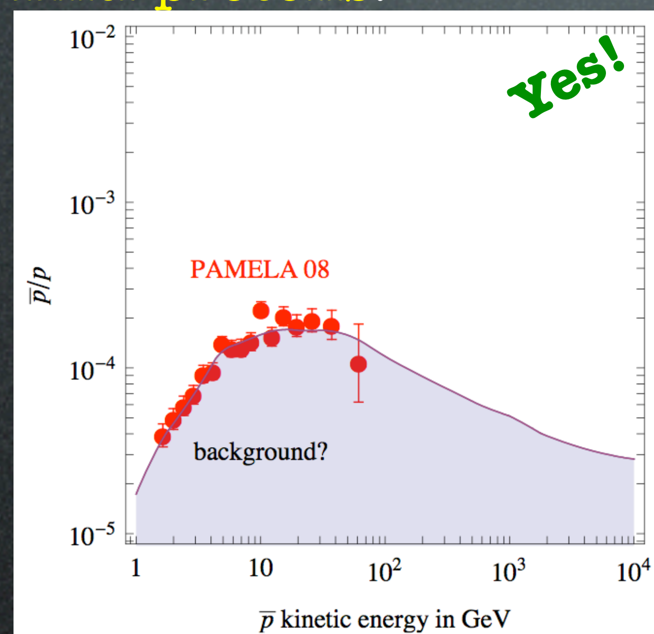
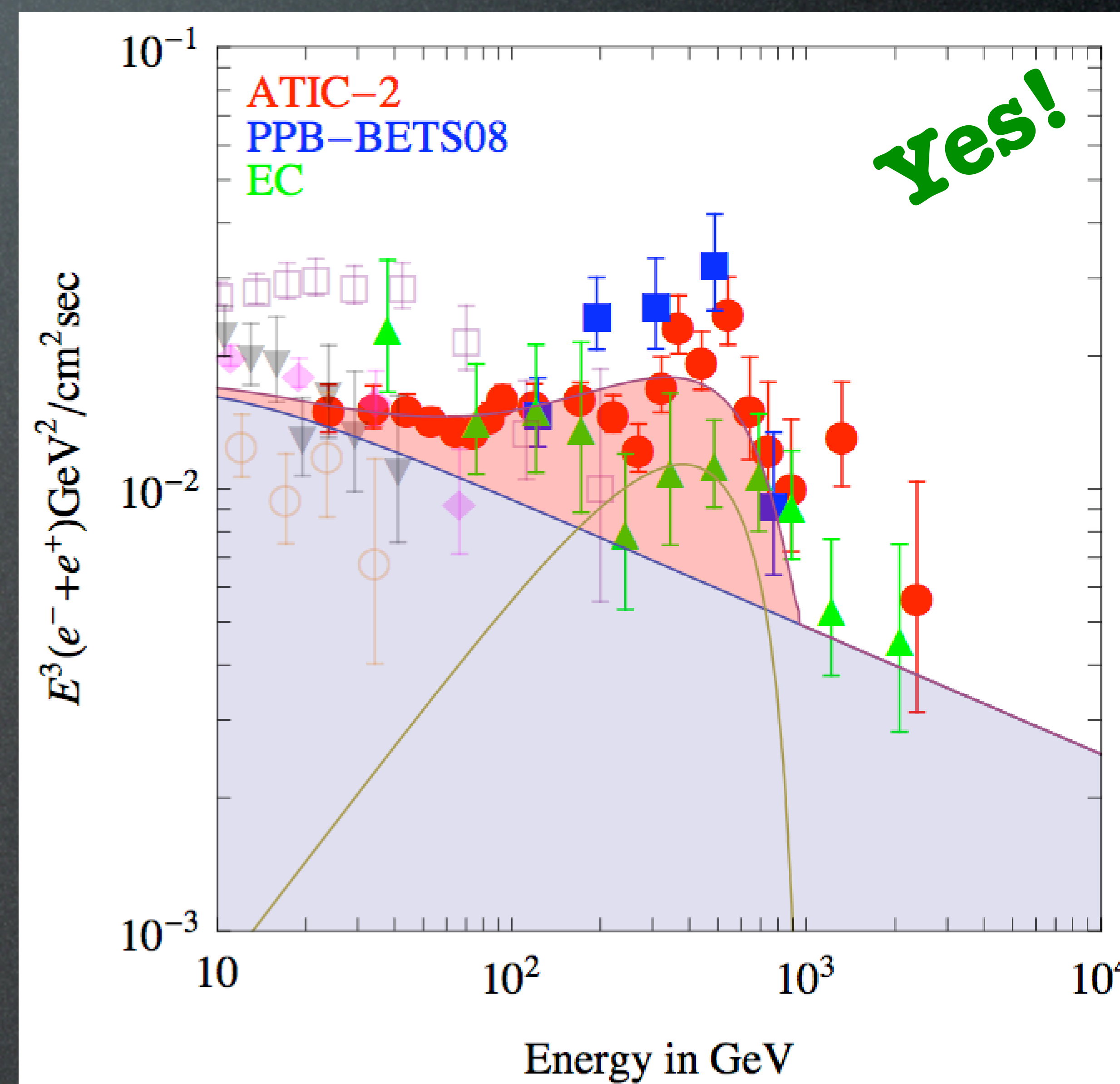


Anti-protons:



Electrons + Positrons:



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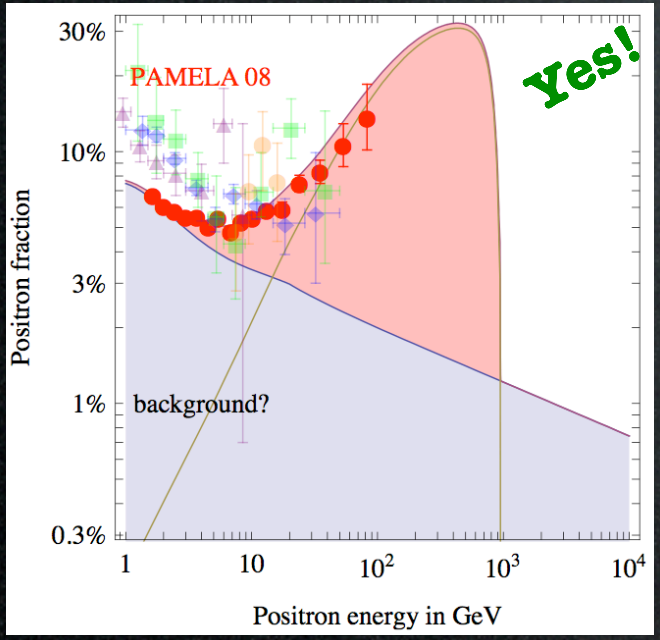
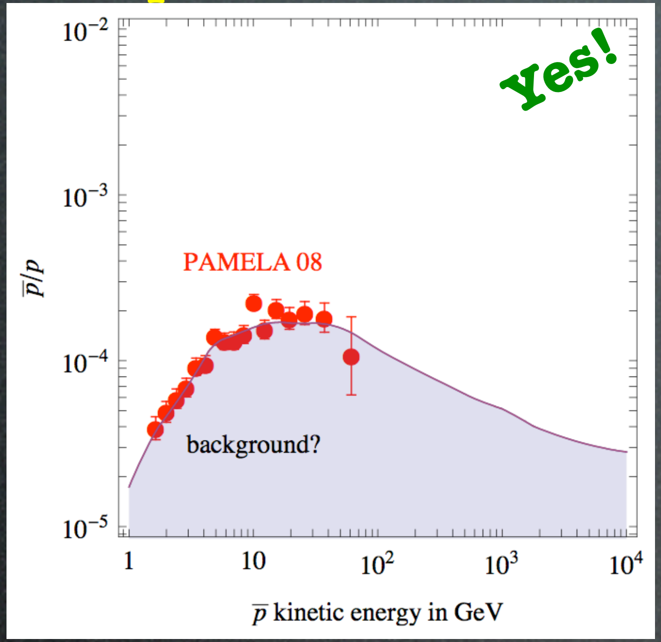


Anti-protons:



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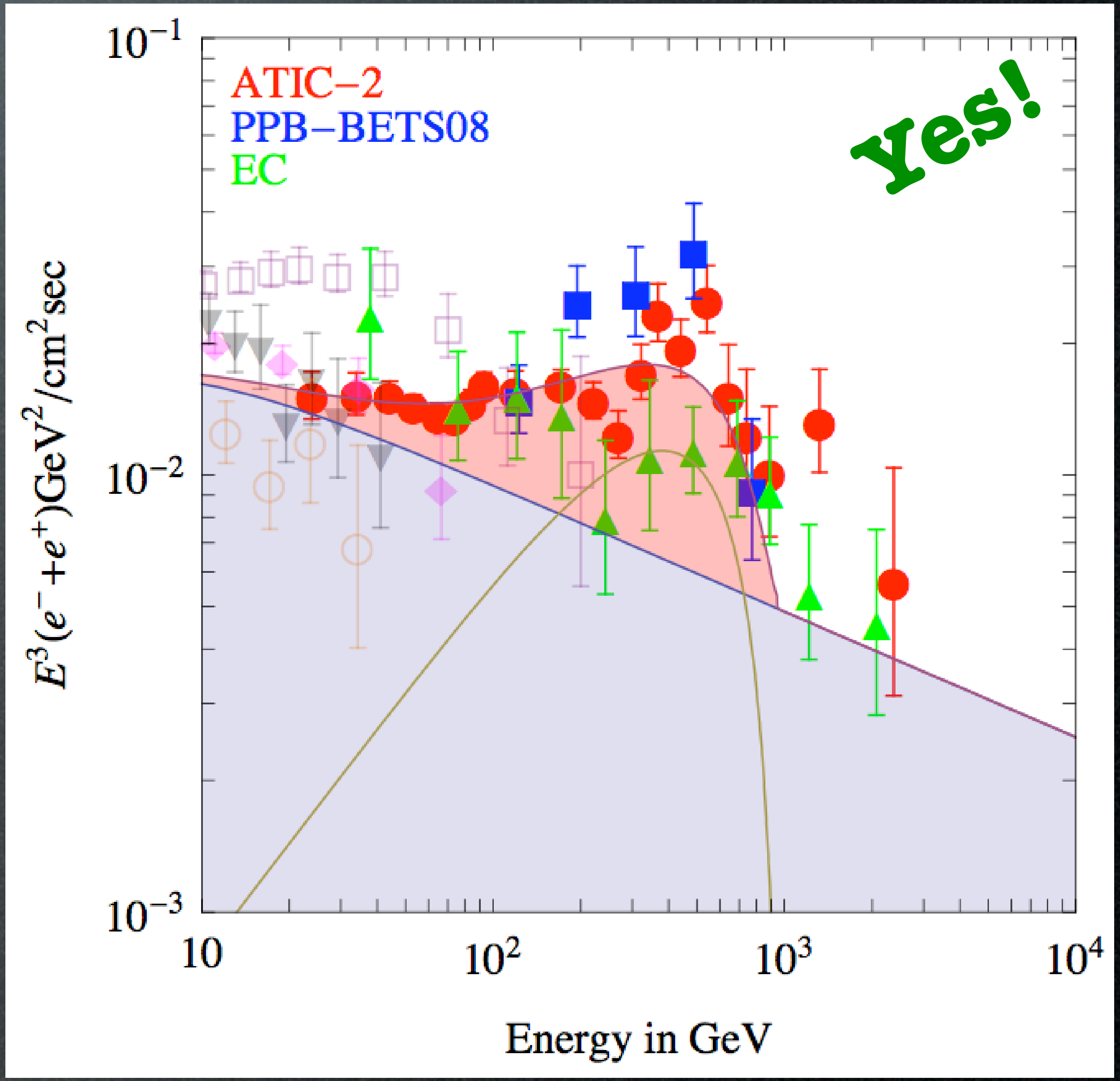

Have we identified the DM for the first time???

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

Results

Which DM can fit the data?

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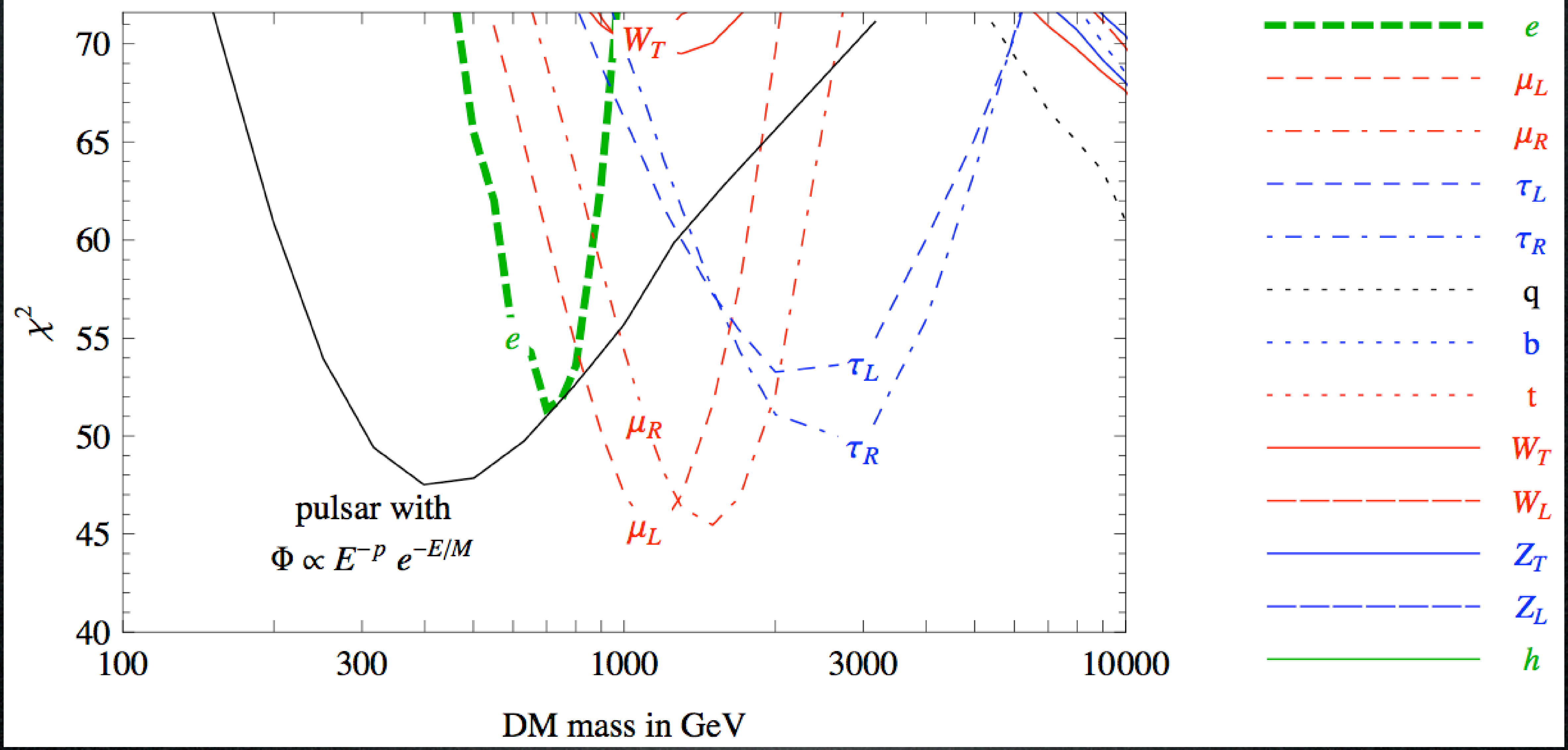
Results

Which DM spectra can fit the data?

Model-independent results:

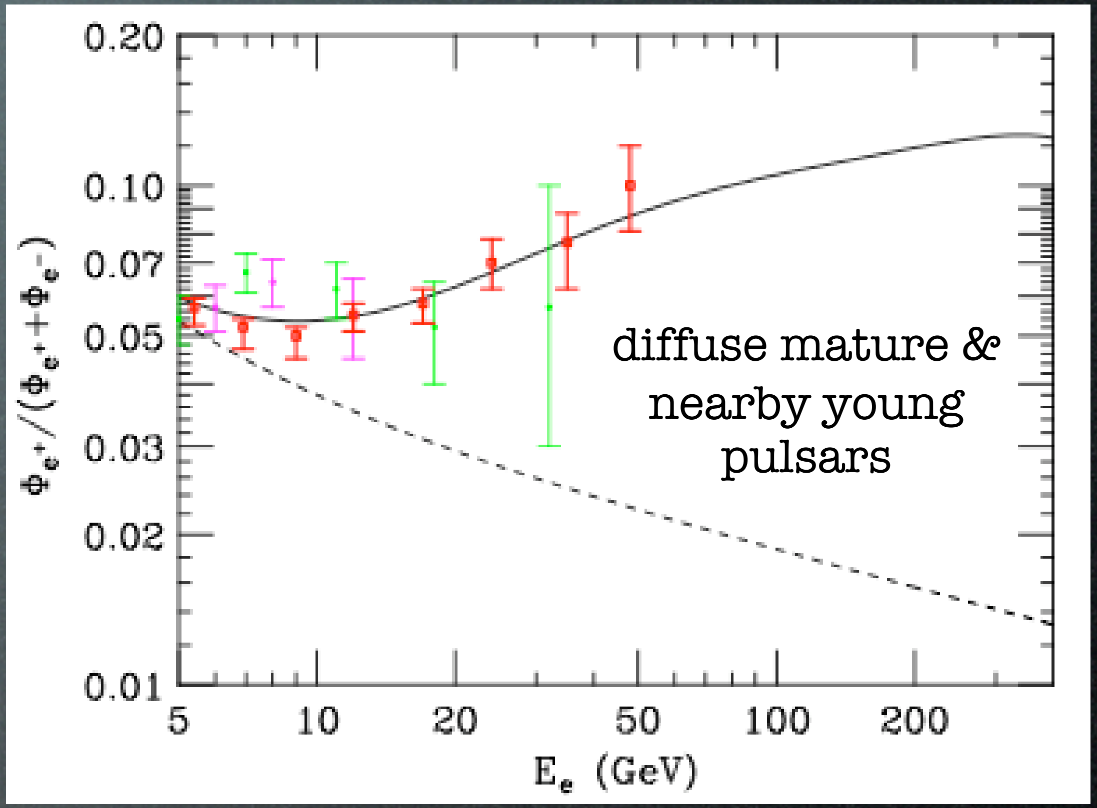
fit to PAMELA positrons* + balloon experiments



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

Two important remarks

A. Maybe it's just a pulsar, or other astrophysics



Hooper, Blasi, Serpico 2008
Profumo 0812.4457

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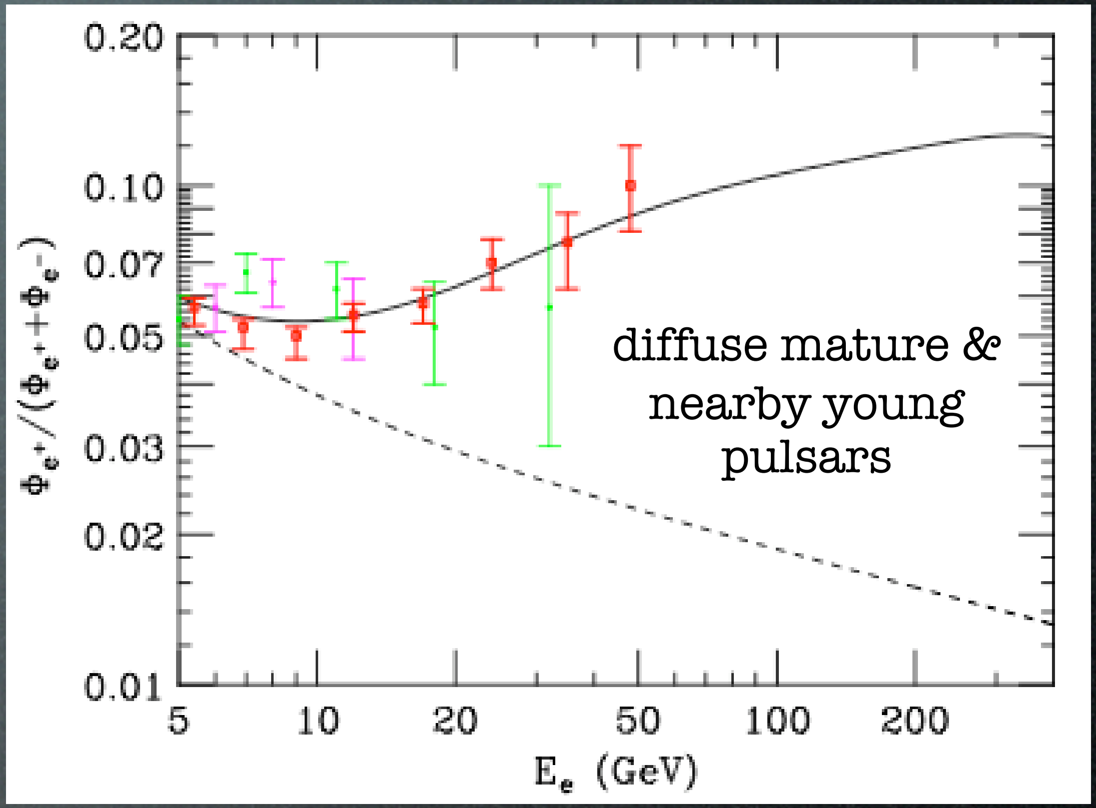

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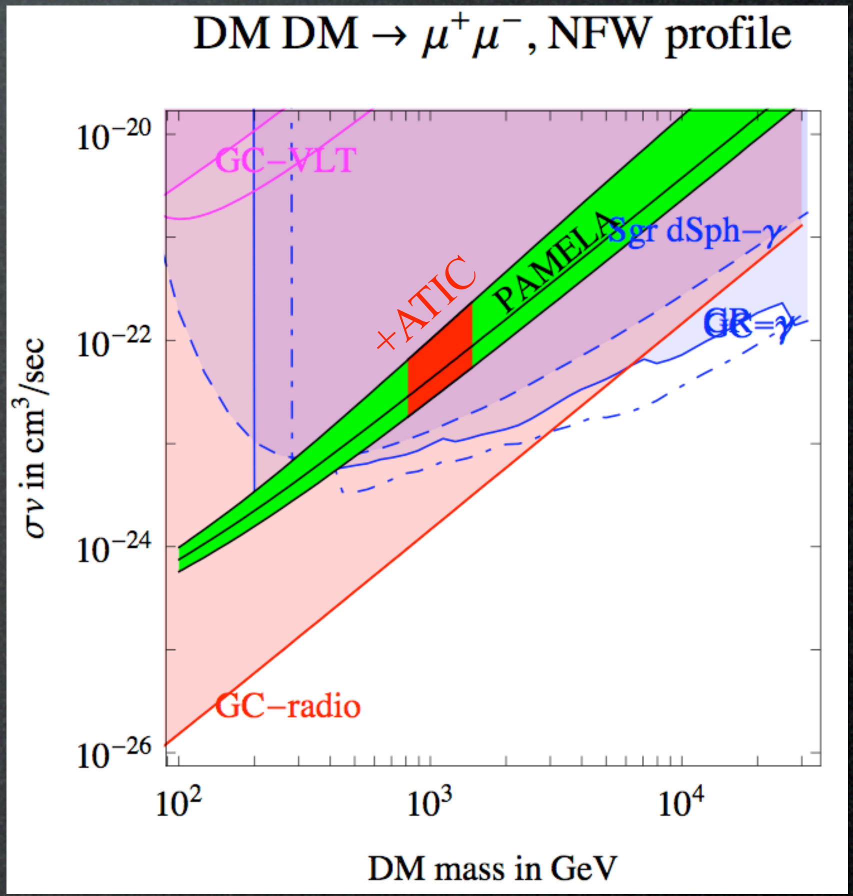
B. Associated gamma ray and radio constraints from the GC and dwarf galaxies are severe



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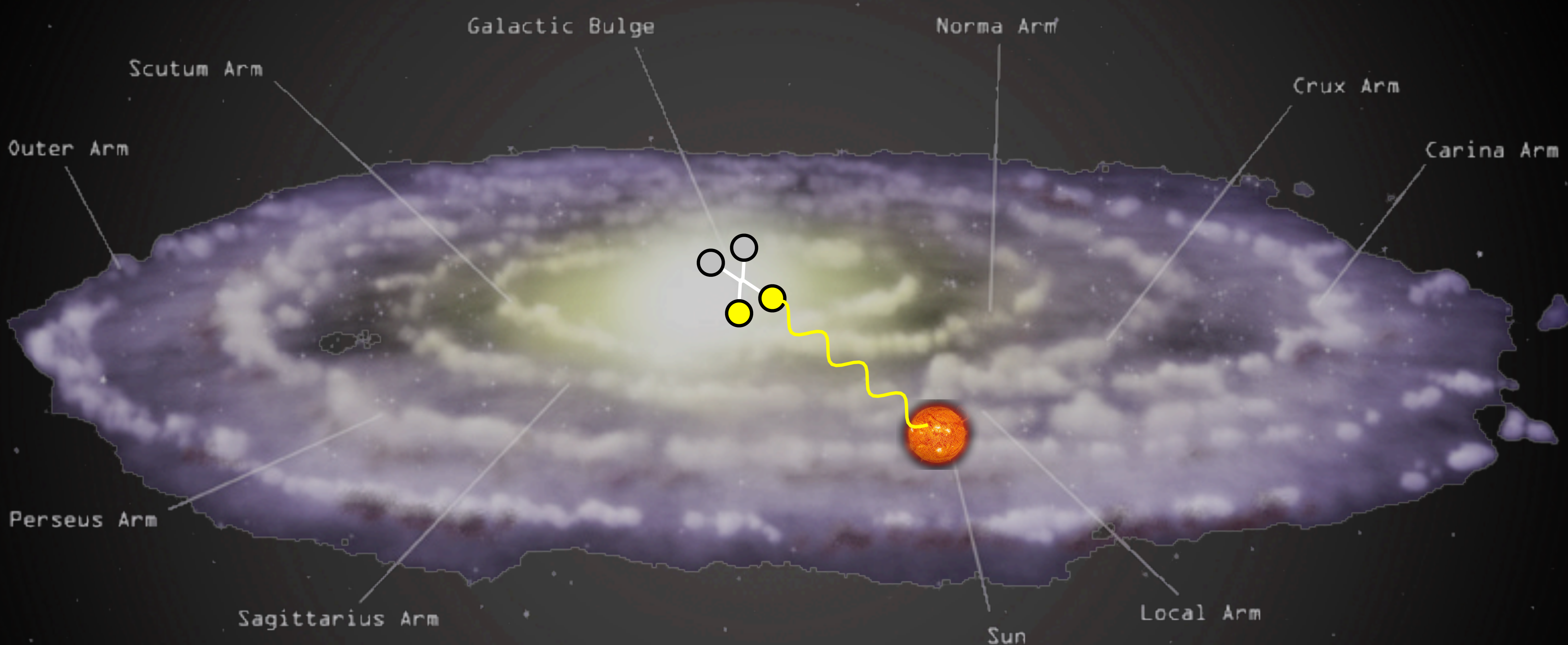
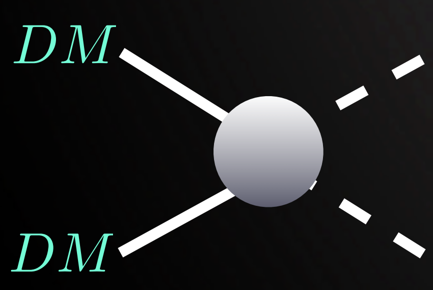
[jump to conclusions]

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

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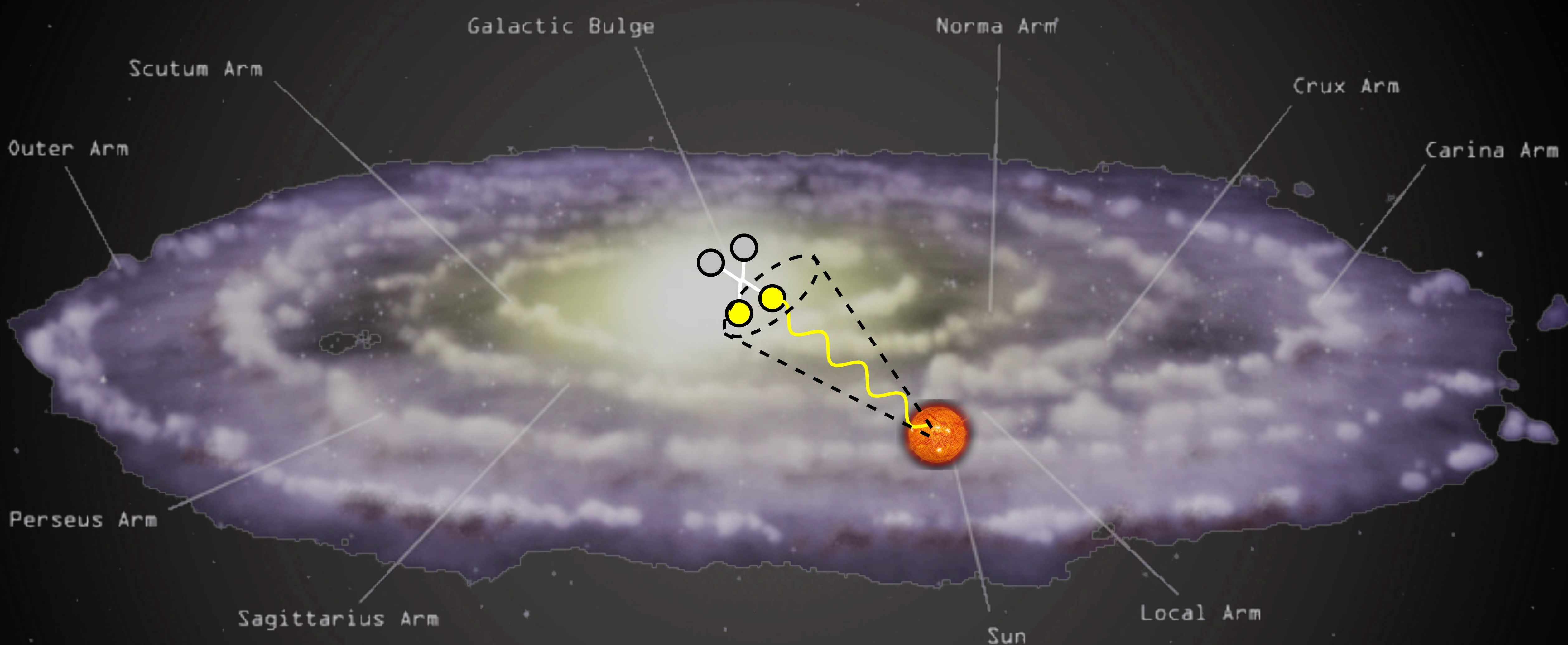

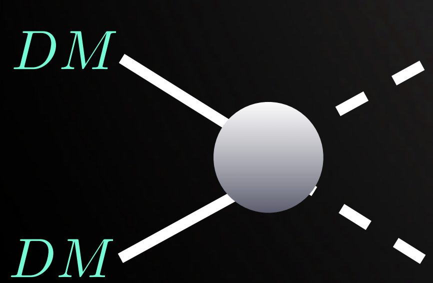

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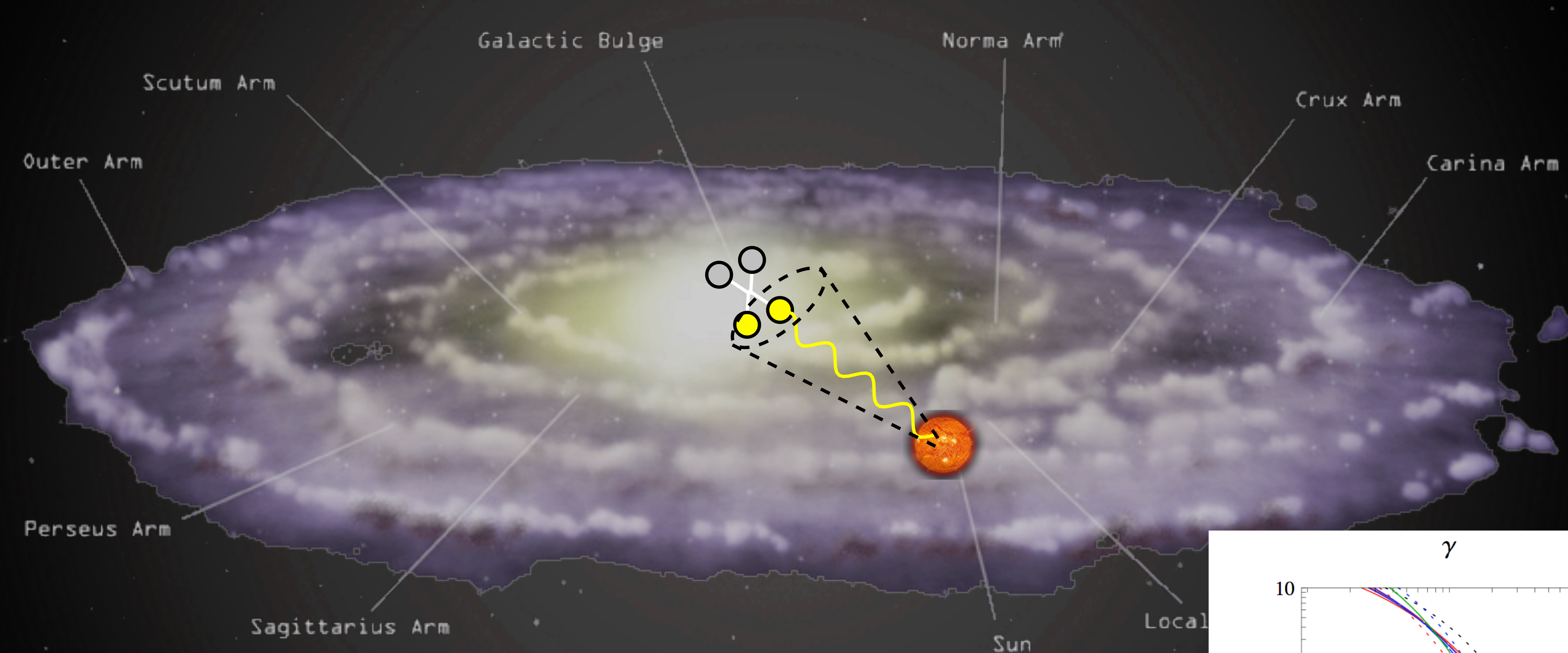

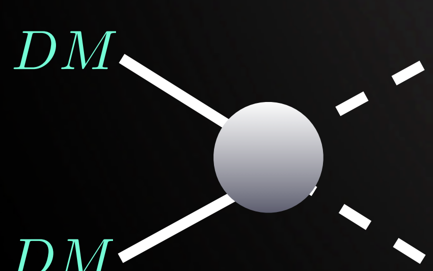

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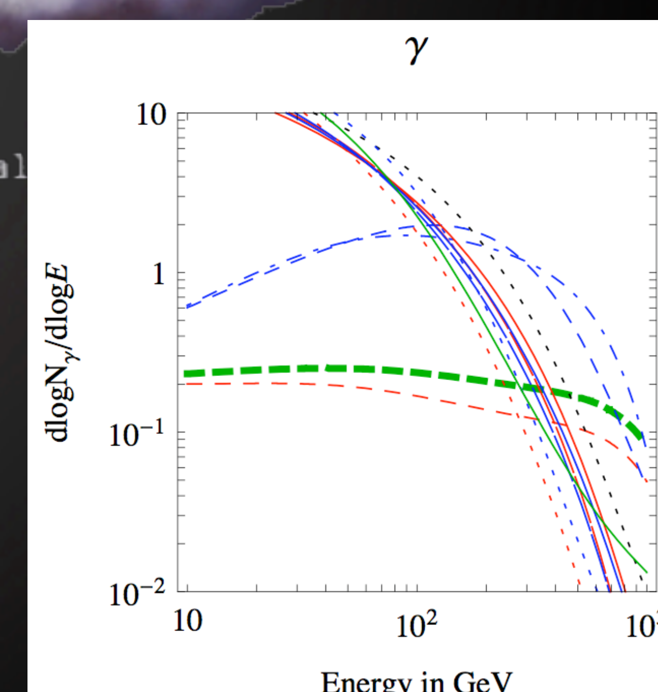
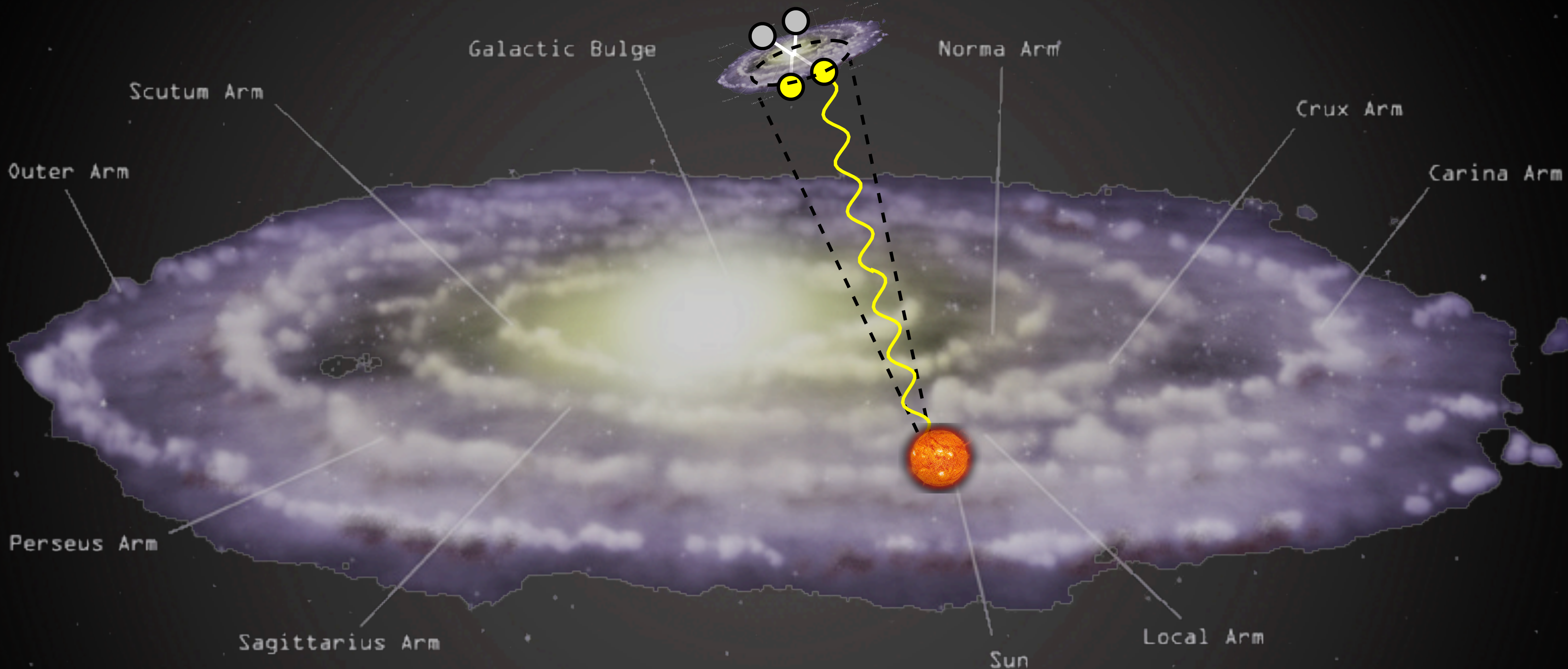
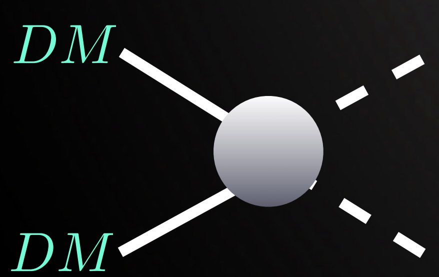


typically sub-TeV energies

Indirect Detection

γ from DM annihilations in Sagittarius Dwarf





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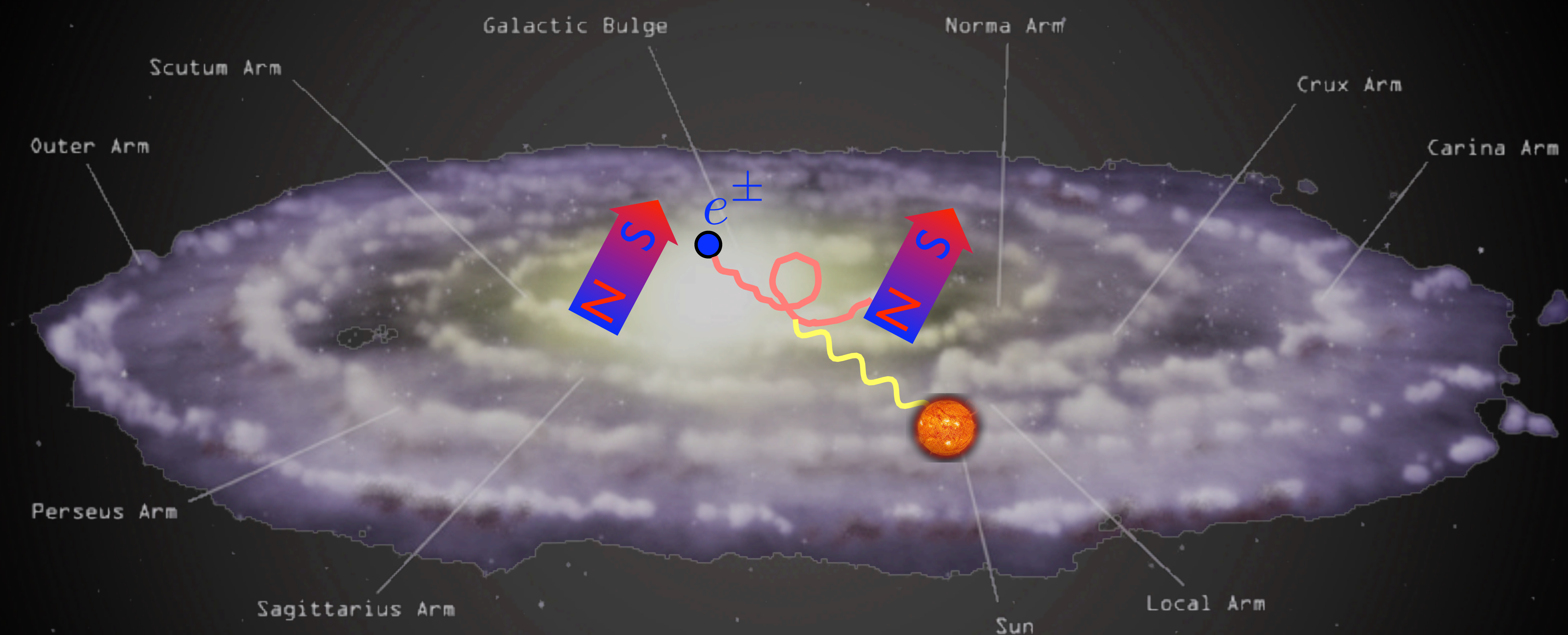
Indirect Detection

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



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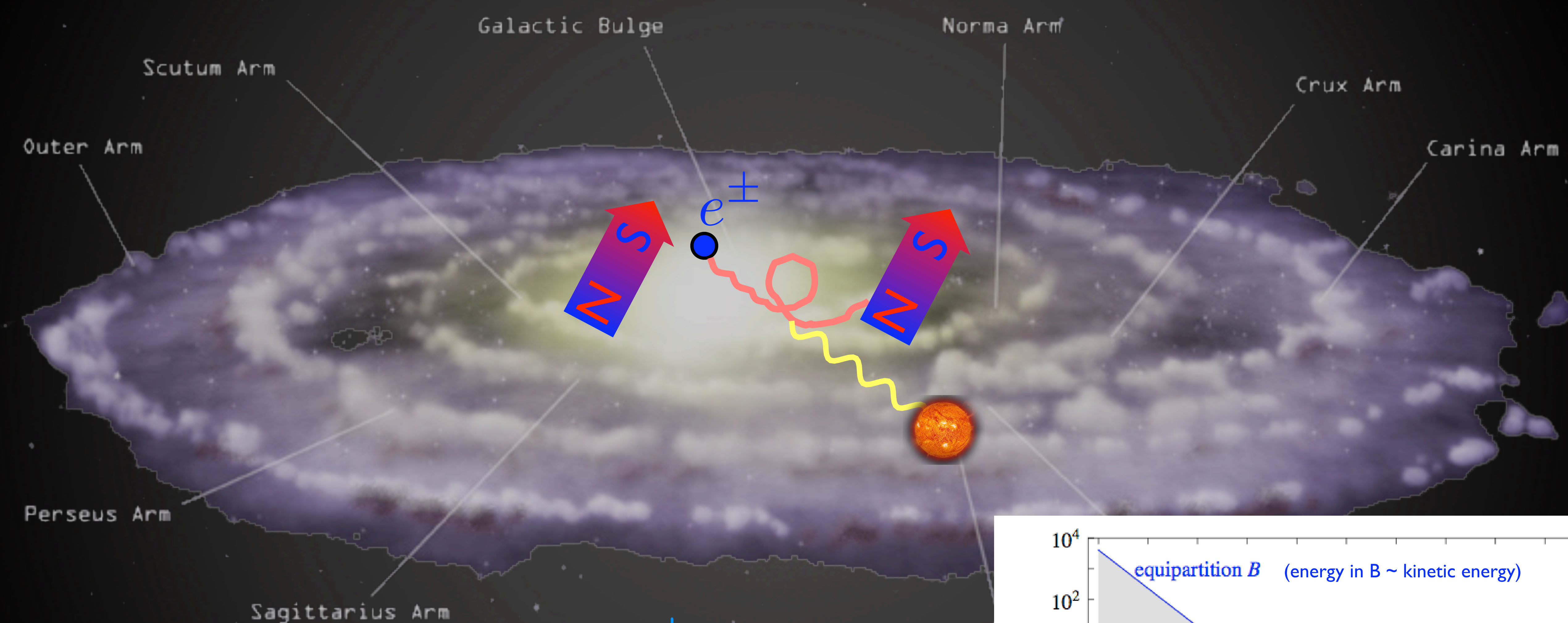
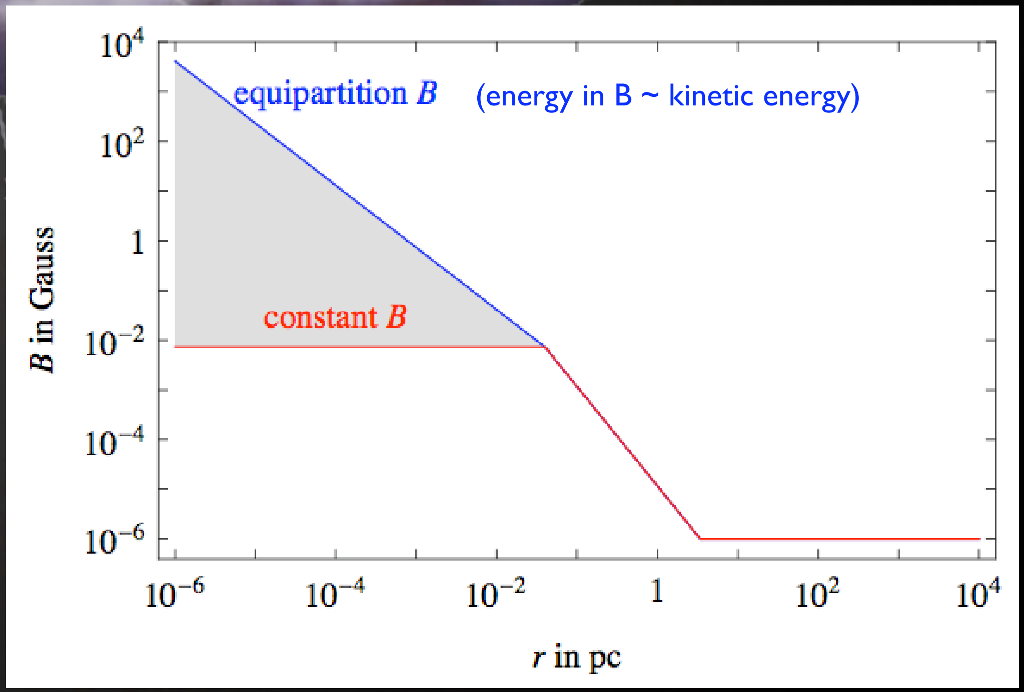




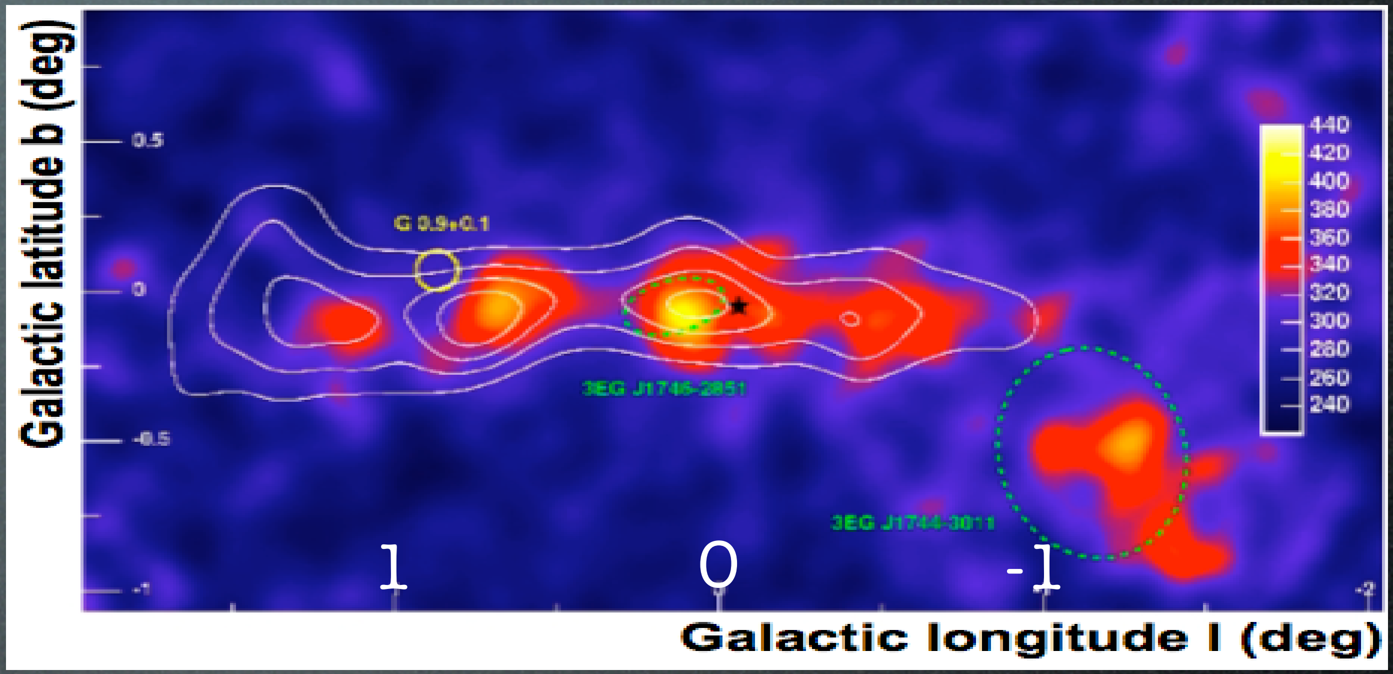
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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

Comparing with data

Gamma constraints

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



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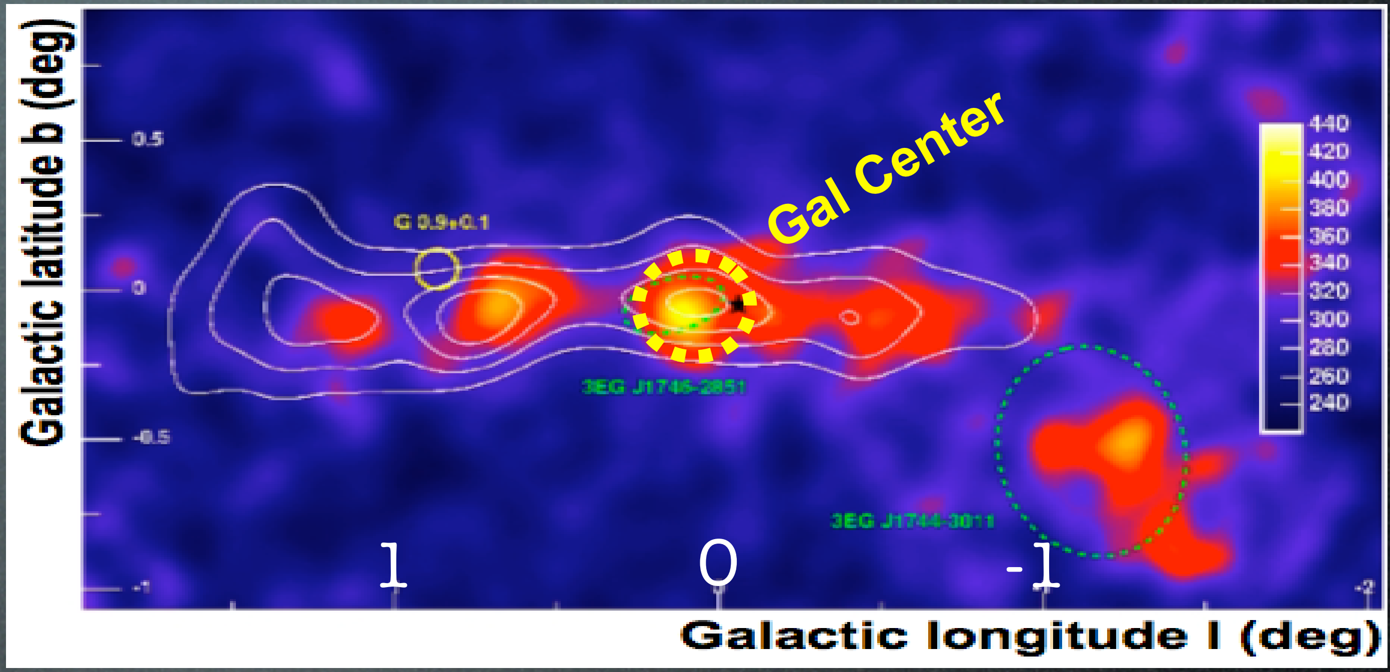

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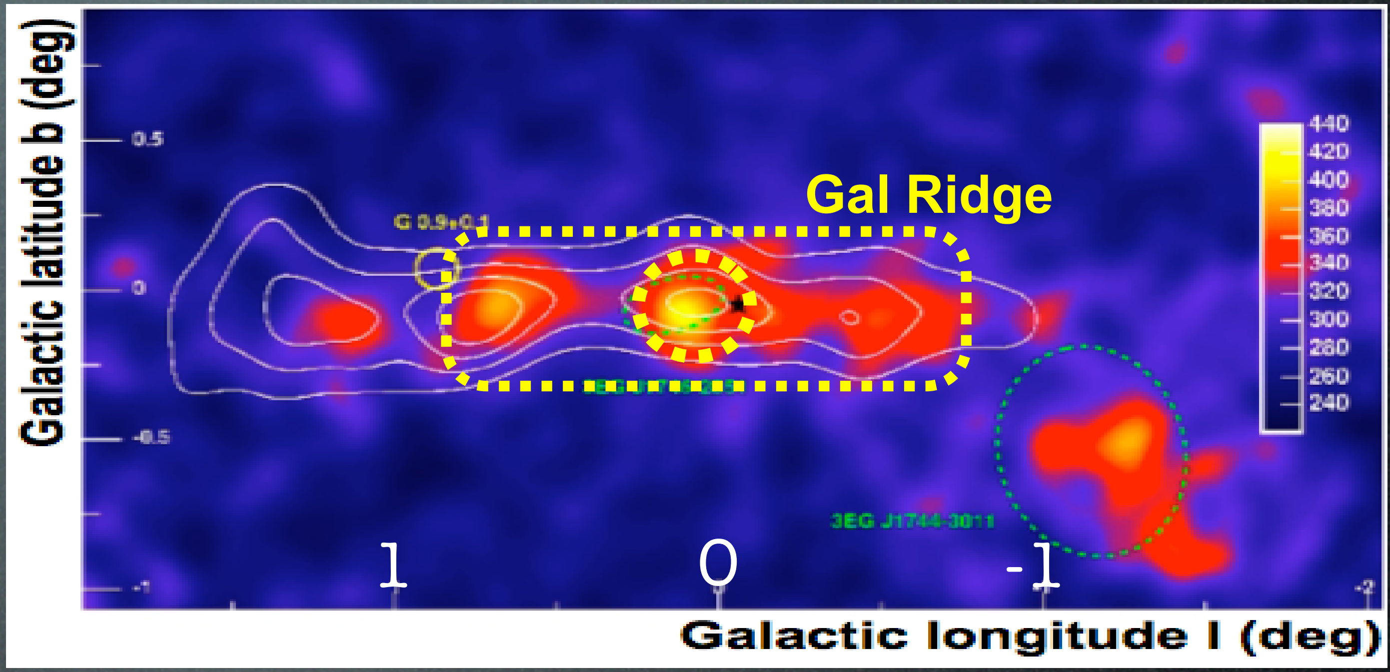

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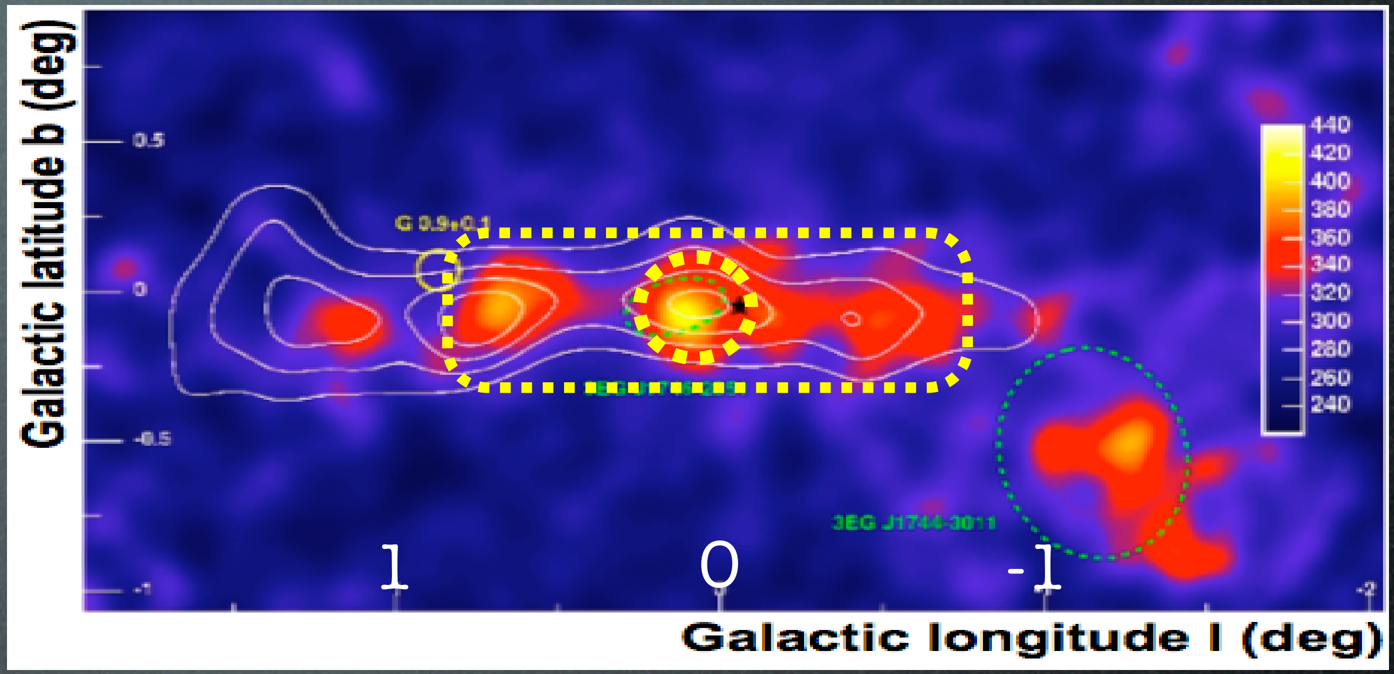

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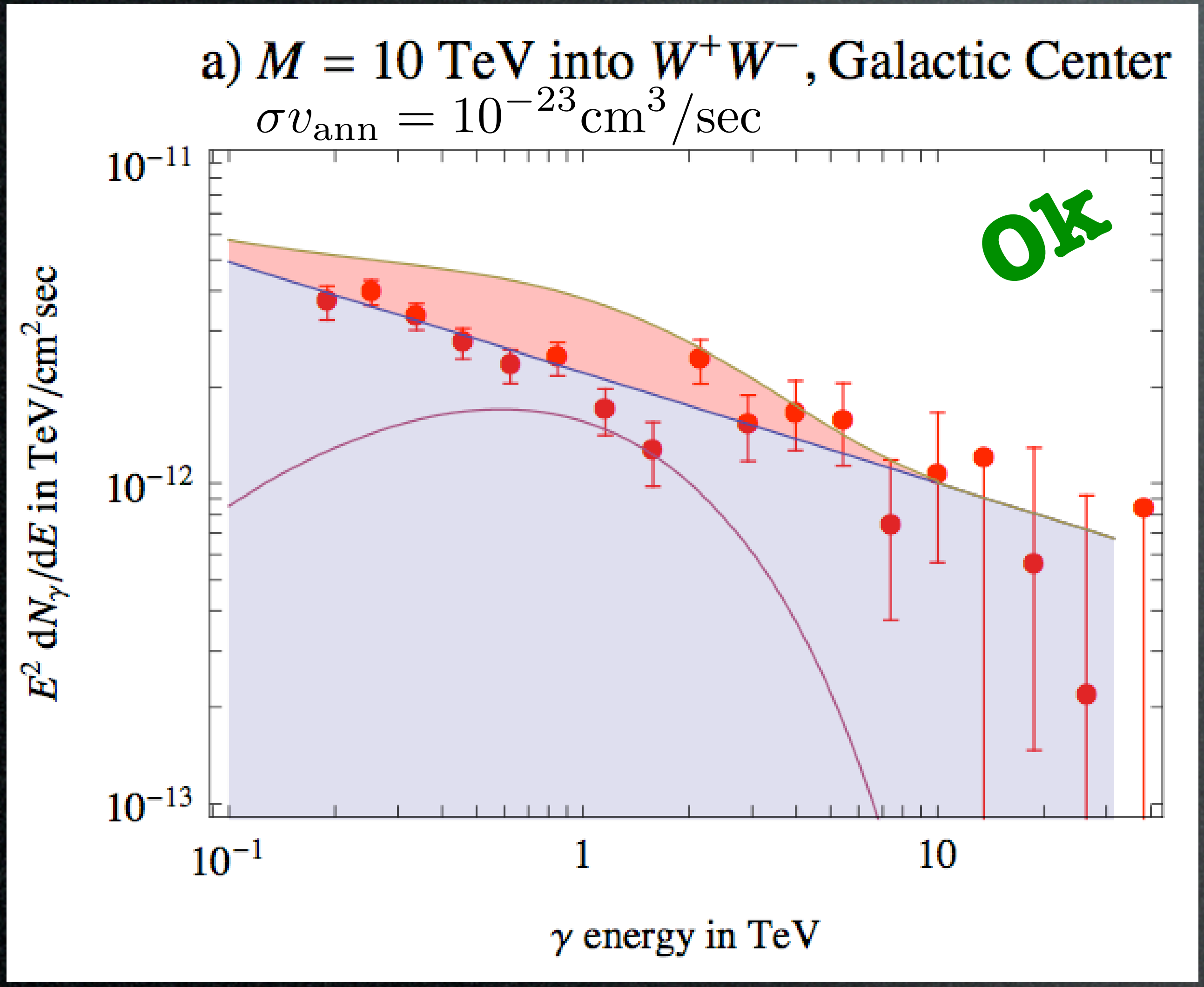

Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

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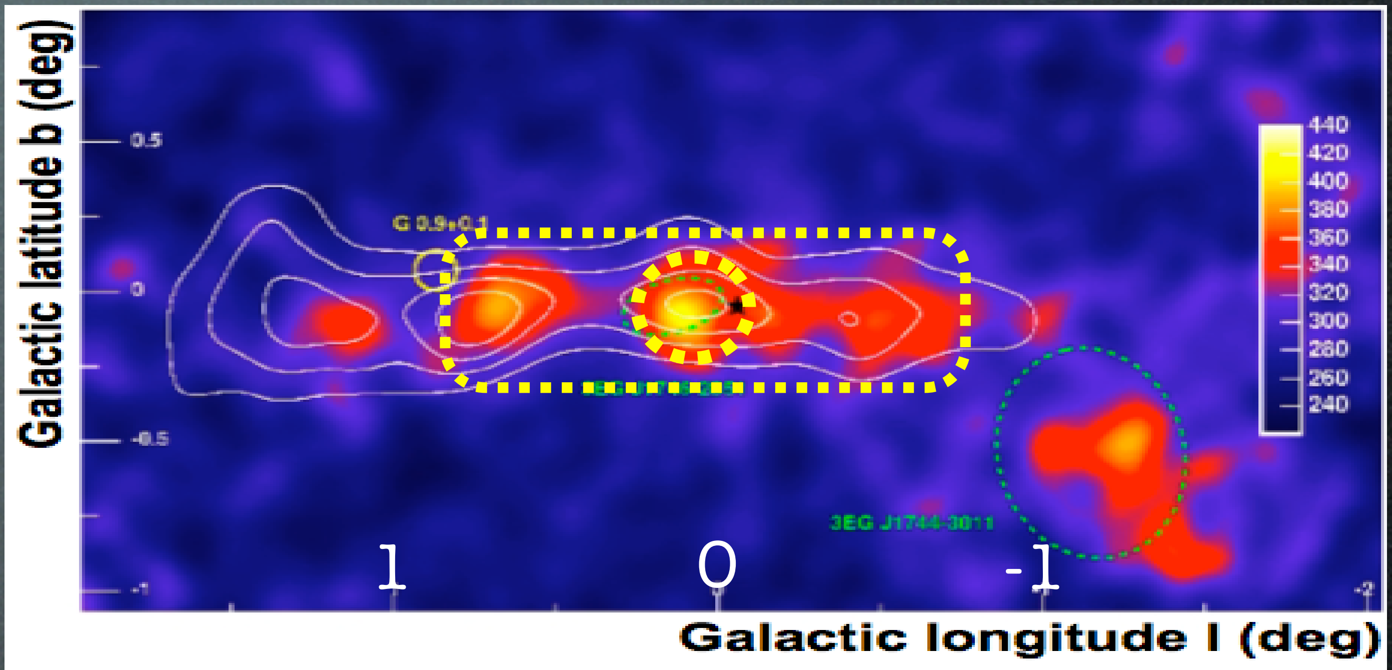

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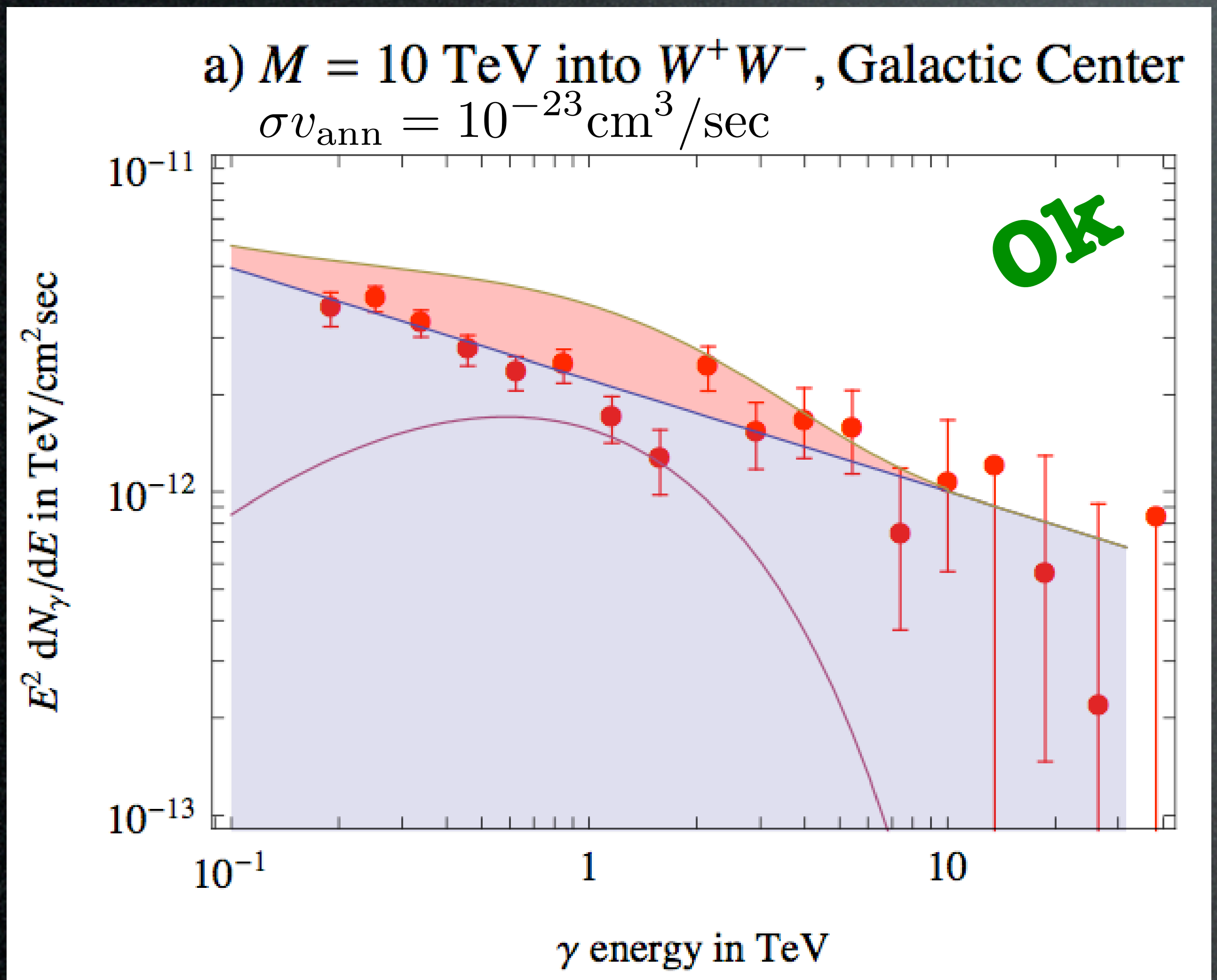

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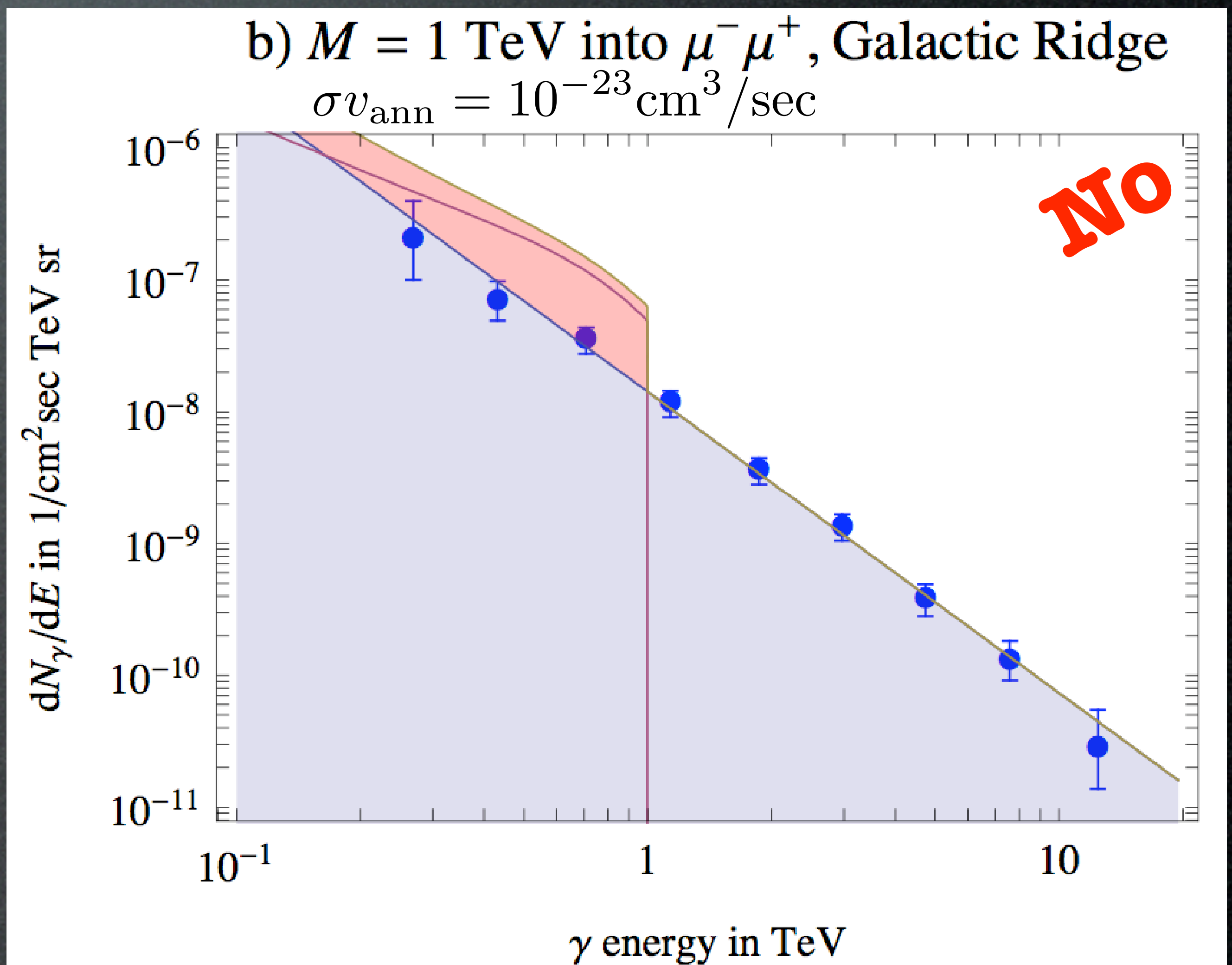

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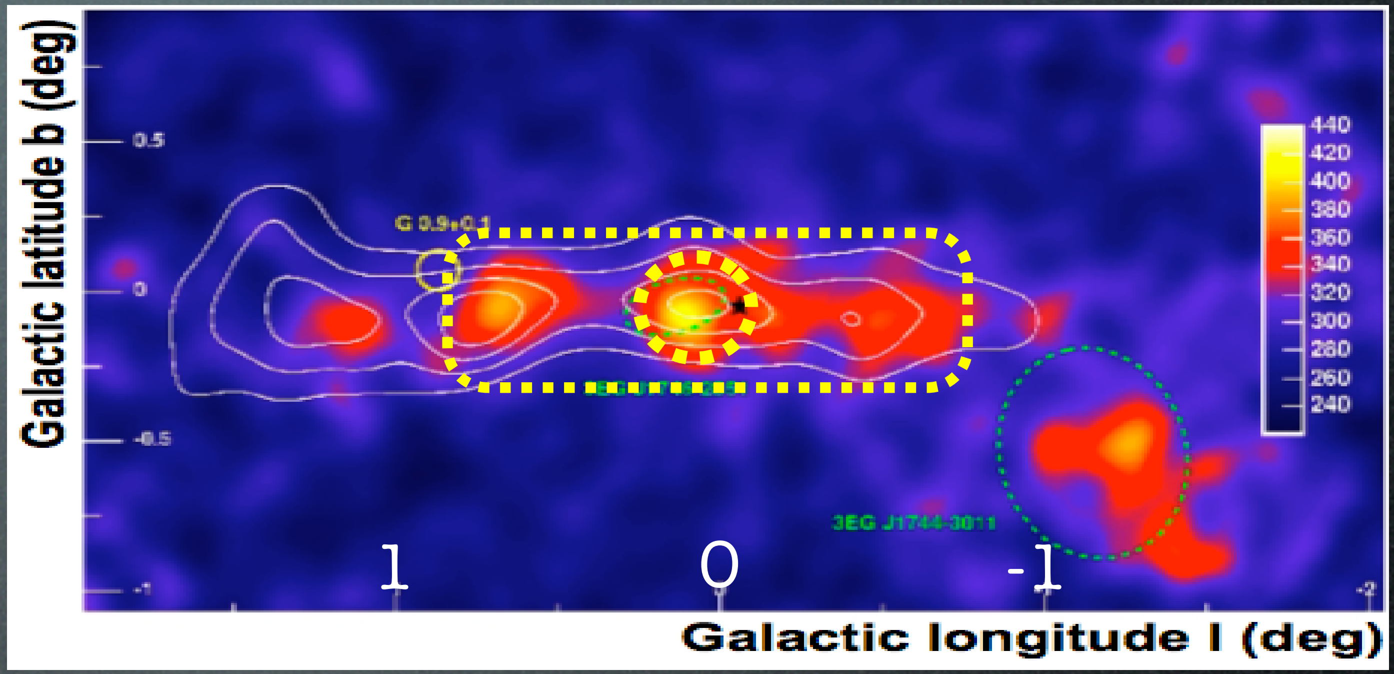
Moreover: no detection from Sgr dSph => upper bound.



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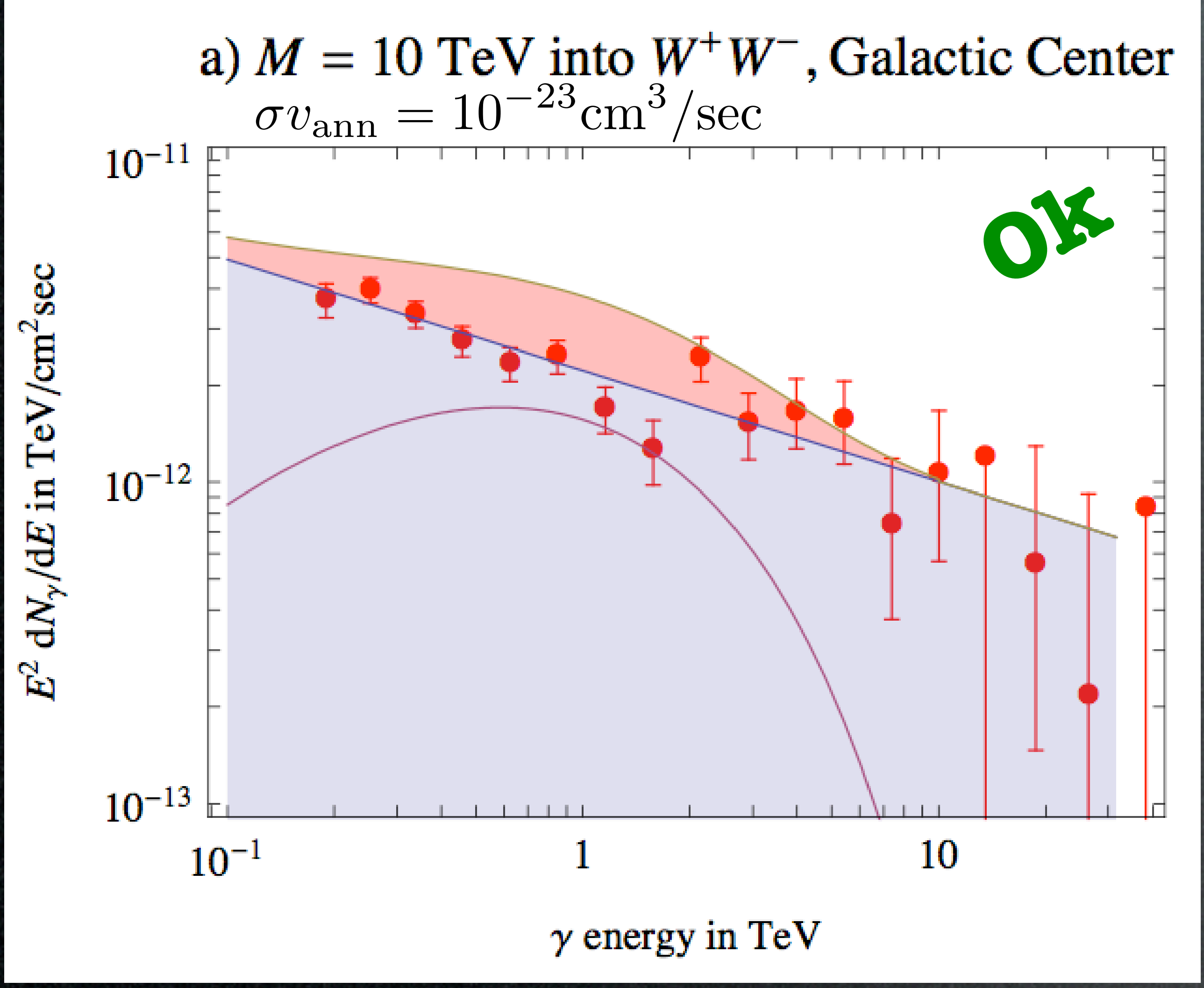

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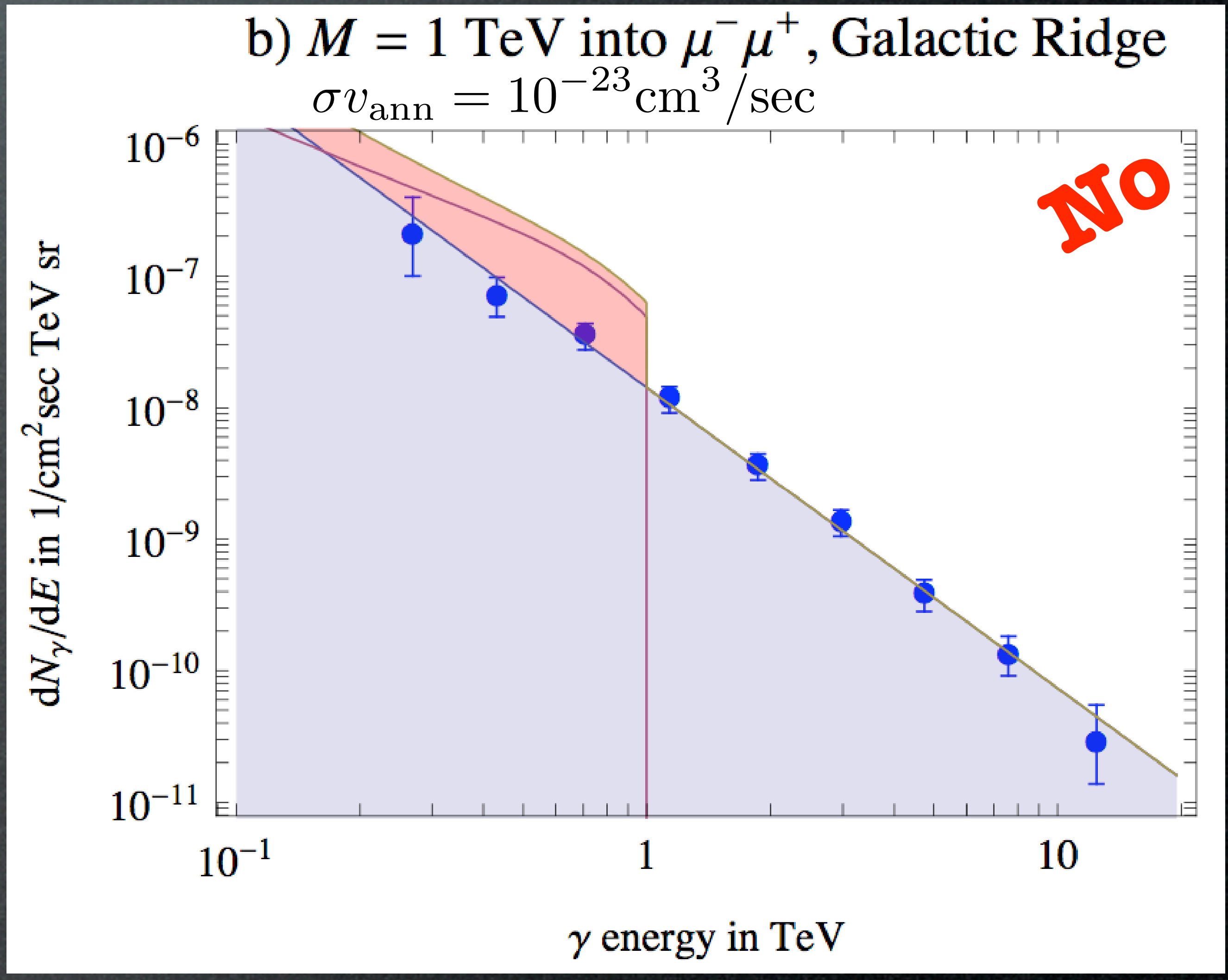

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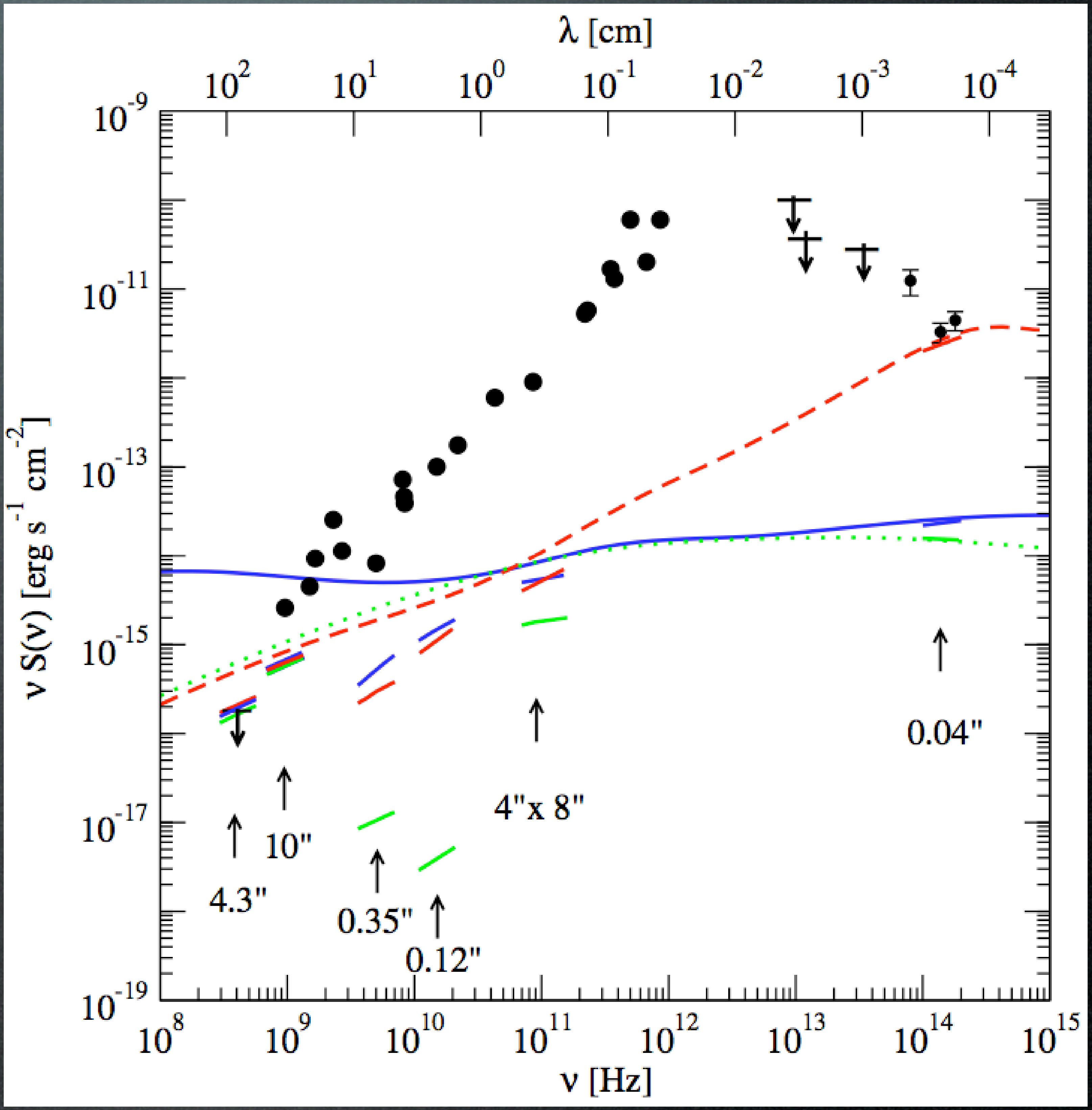

Regis, Ullio PRD 78 (2008)

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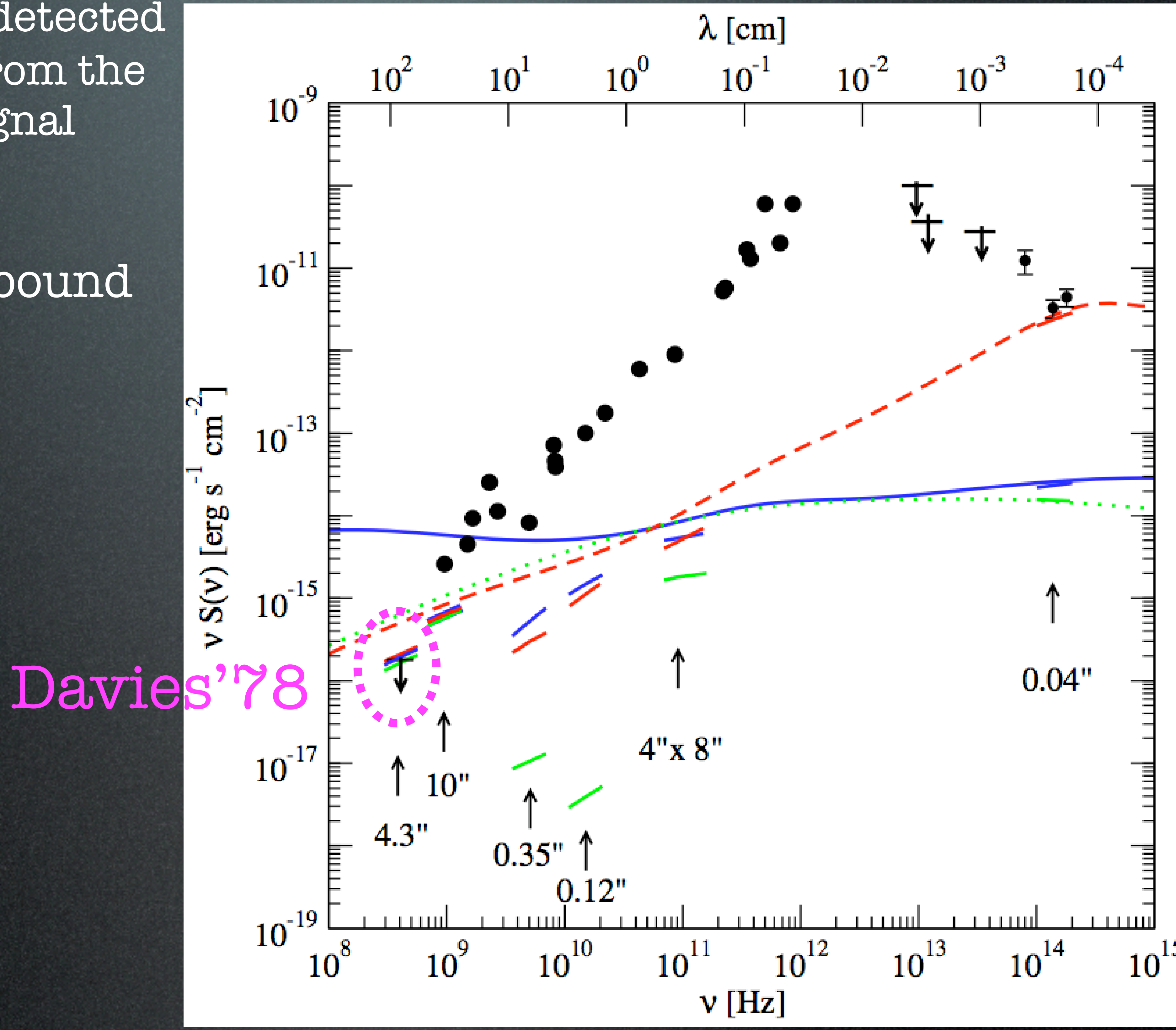

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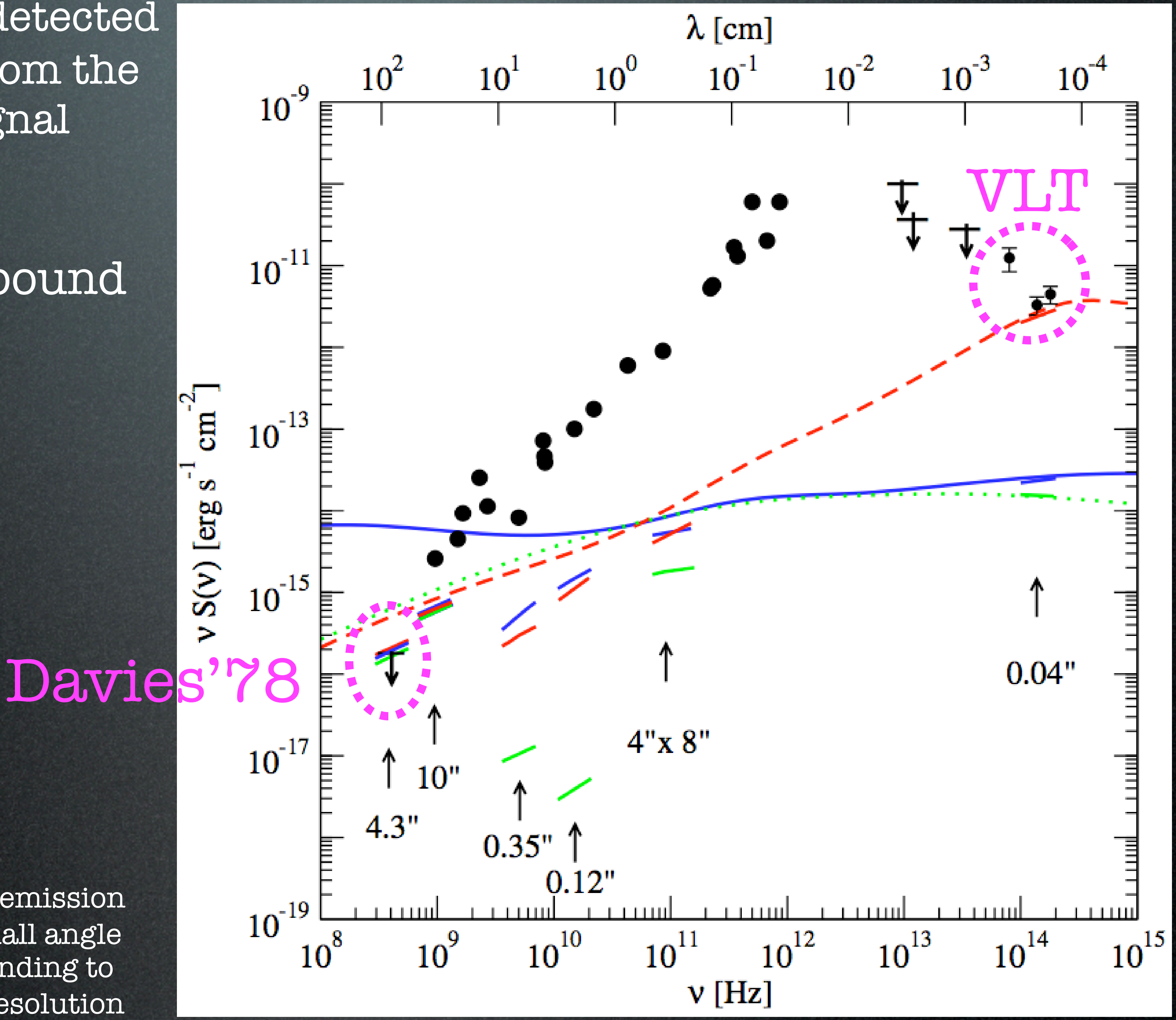
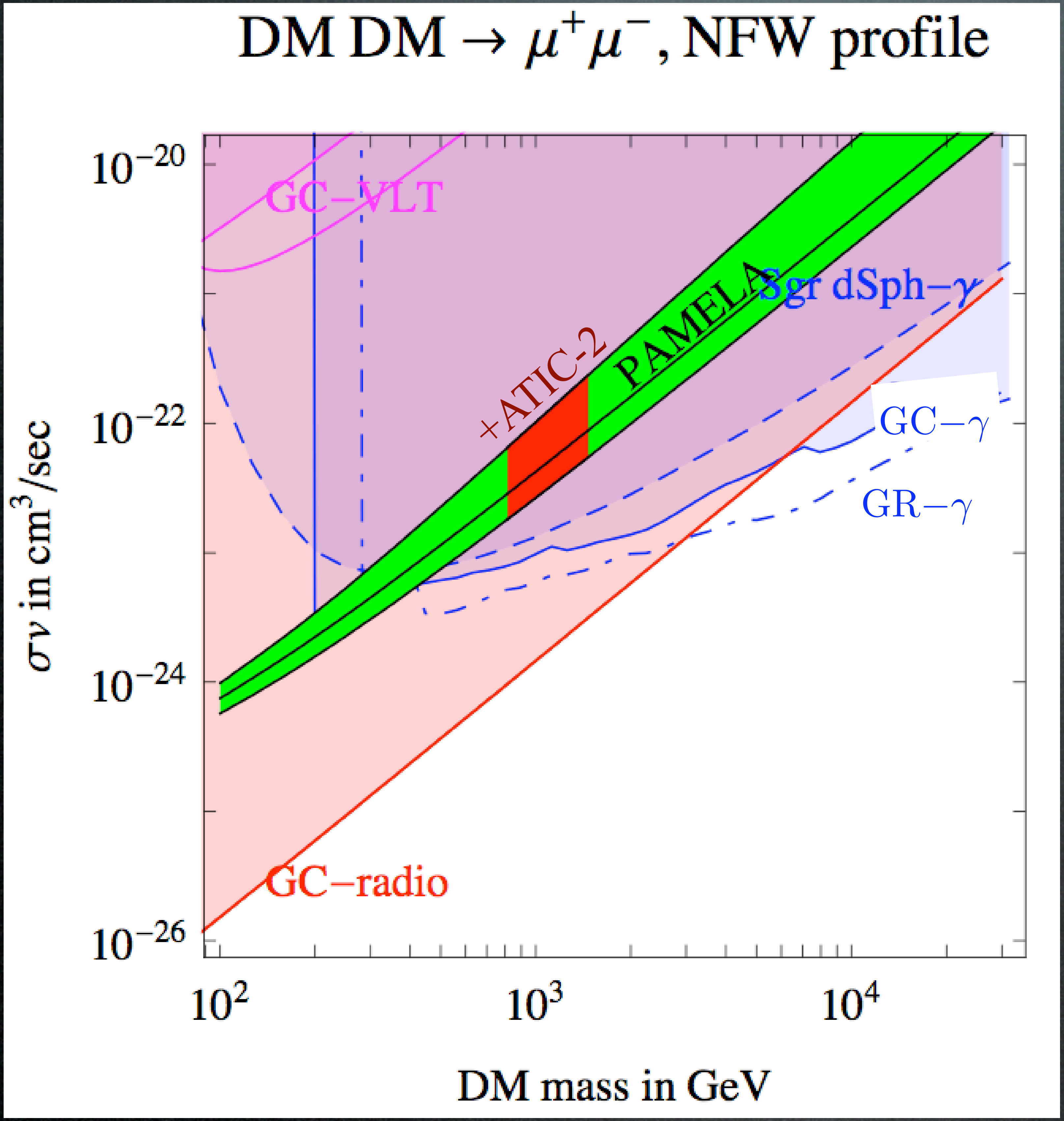
VLT 2003 emission at 10^{14} Hz.



Regis, Ullio PRD 78 (2008)

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

Gamma constraints



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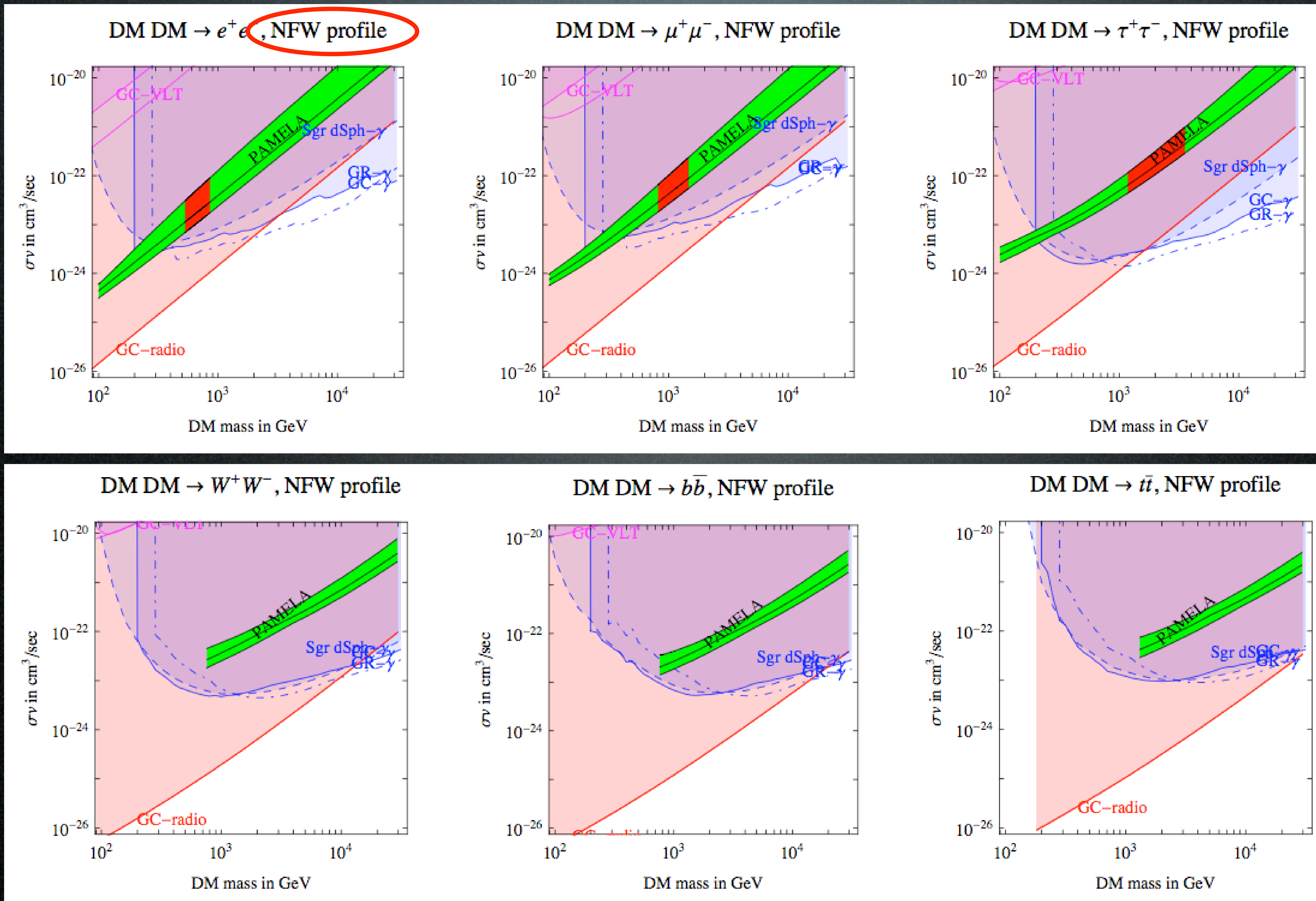
The PAMELA and ATIC regions are in conflict with gamma constraints, unless...

Gamma constraints



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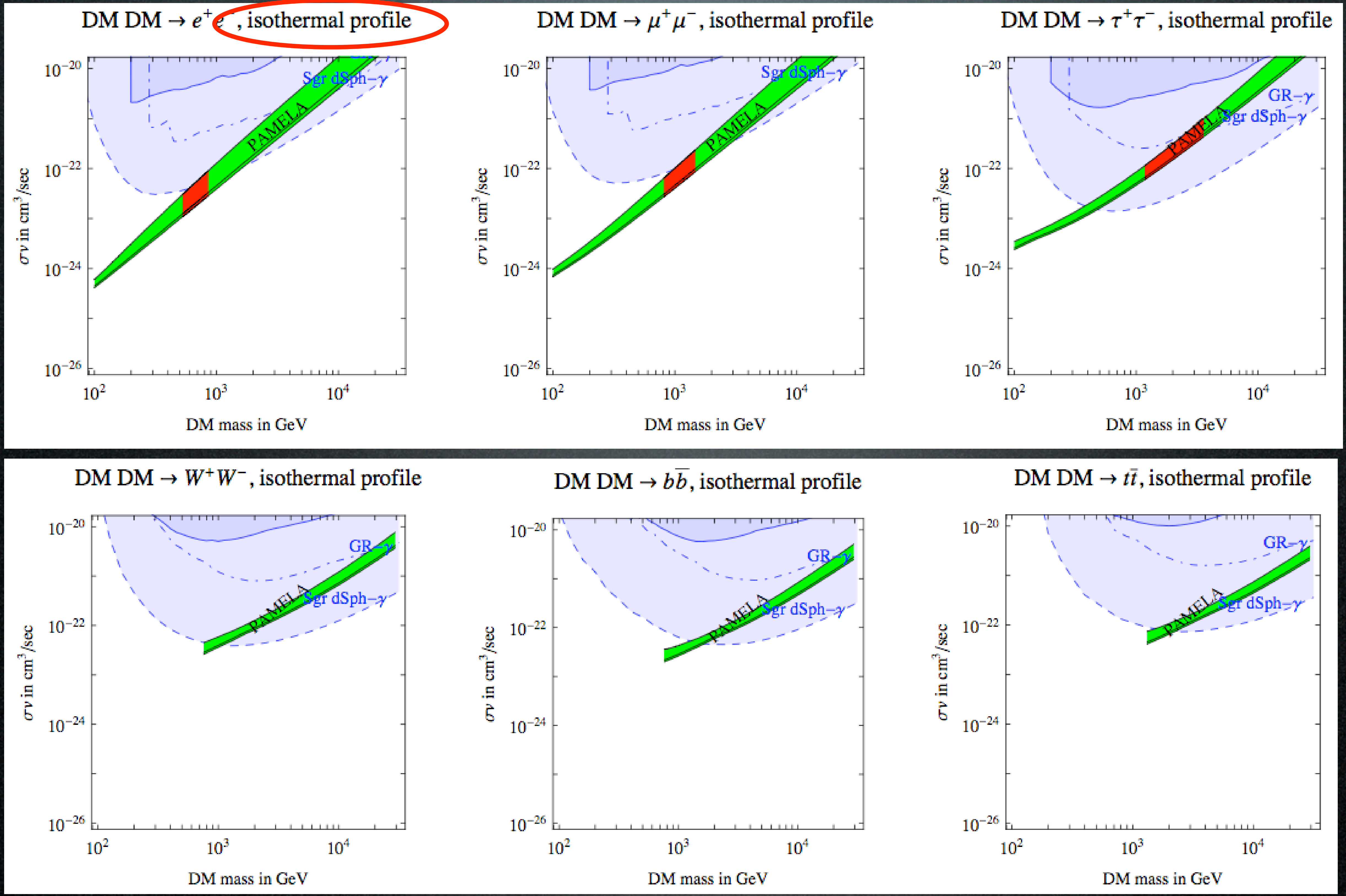
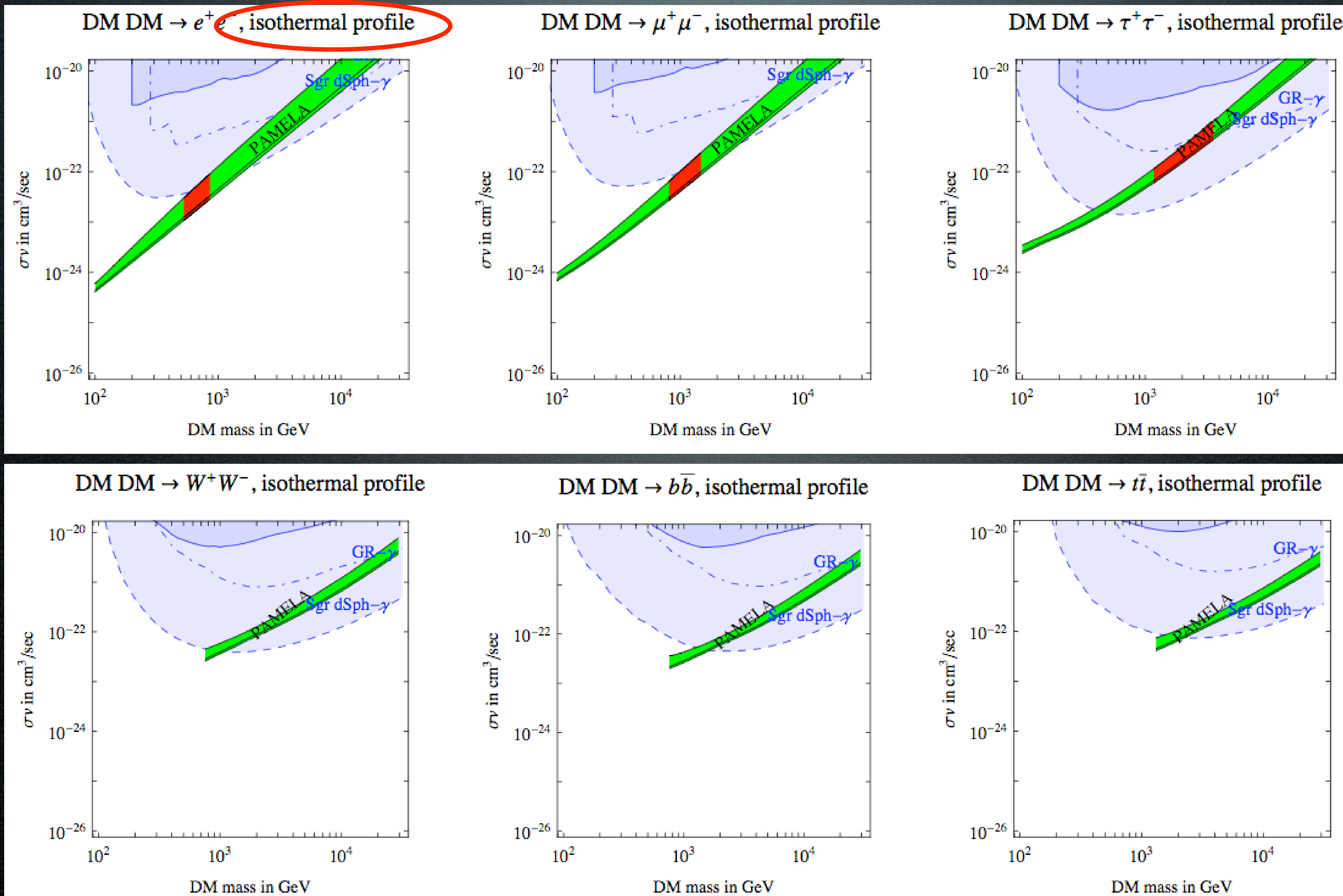


Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

Or: take different boosts here (at Earth, for e^+) than there (at GC, for gammas).

Or: take ad hoc DM profiles (truncated at 100 pc, with central void..., after all we don't know).

Answers

1. Are we seeing Dark Matter in cosmic rays?

2. Why there is new theory of DM on the arXiv every day?

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Because the signals point to a "weird" DM so theorists try to reinvent the field:

- DM is heavyish
- annihilates into leptons and not anti-protons
- huge cross section (boost? Sommerfeld?)
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Upcoming data: Fermi, ATIC-4, Pamela, AMS-02..

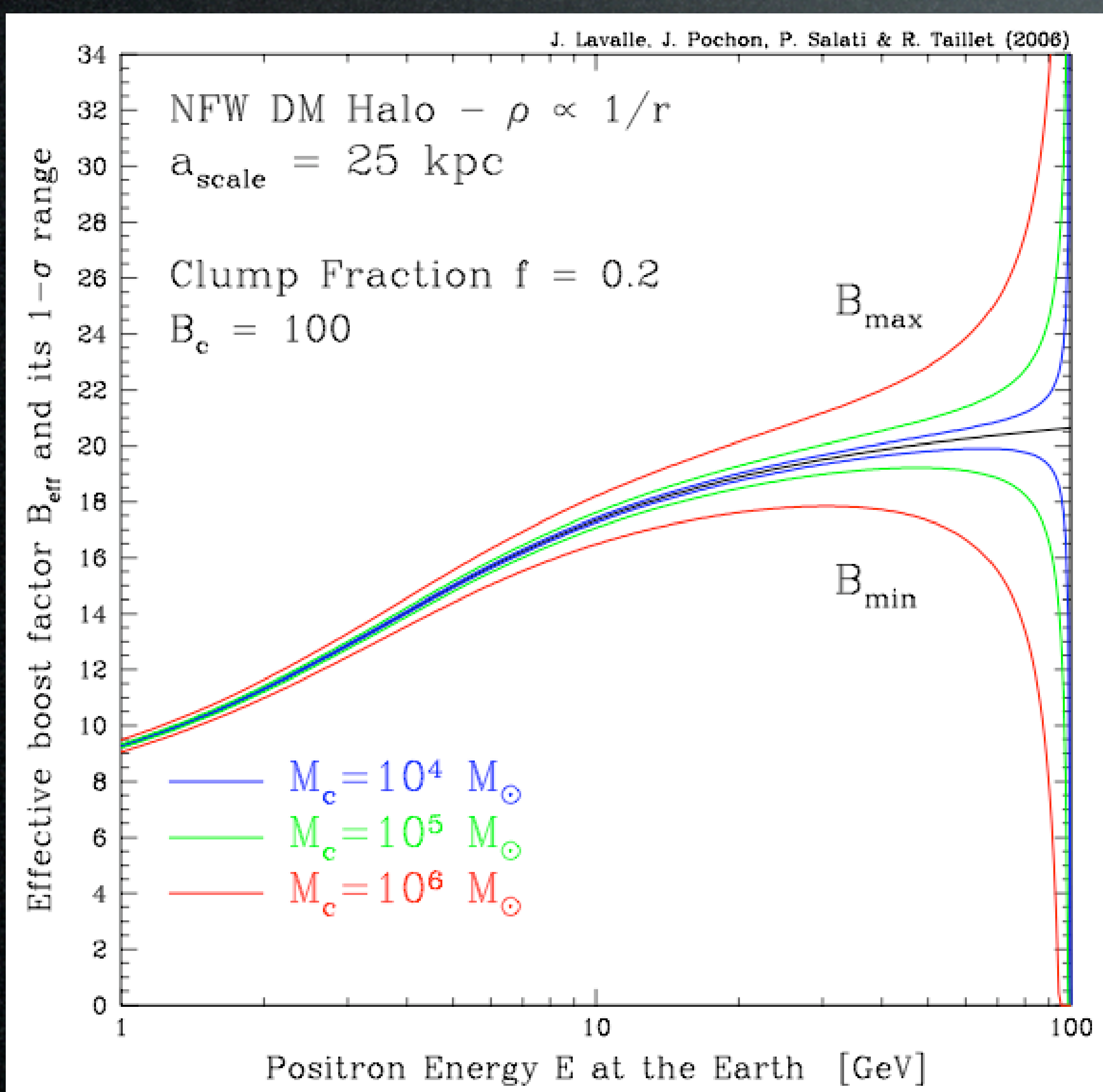
Back up slides

Indirect Detection

Boost Factor: local clumps in the DM halo enhance the density, boost the flux from annihilations. Typically: $B \simeq 1 \to 20 \quad (10^4)$

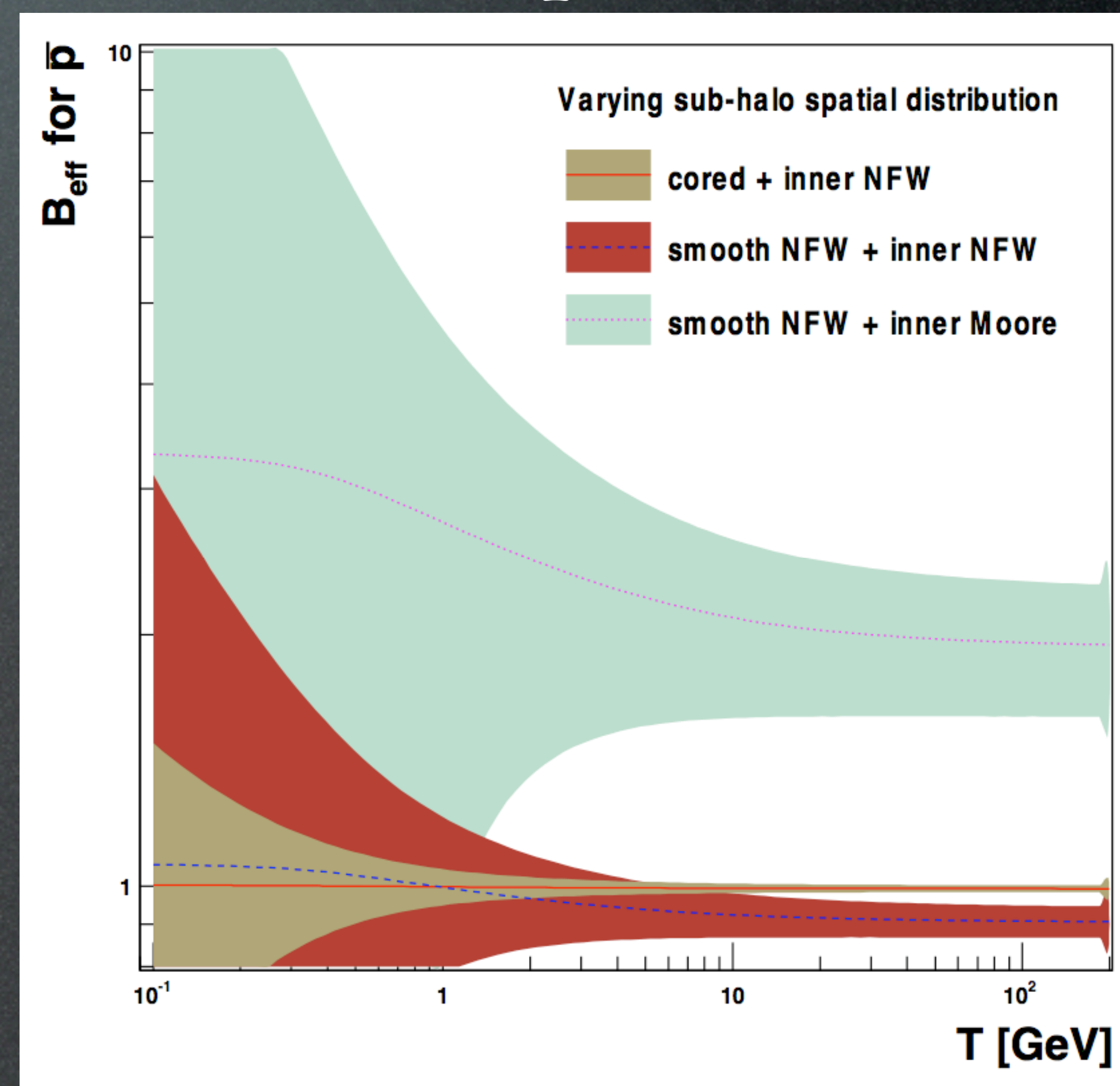
In principle, B is different for e^+, anti-p and gammas,
energy dependent,
dependent on many astro assumptions (inner density profile of clump, tidal disruptions and smoothing...),
with an energy dependent variance, at high energy for e^+, at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons

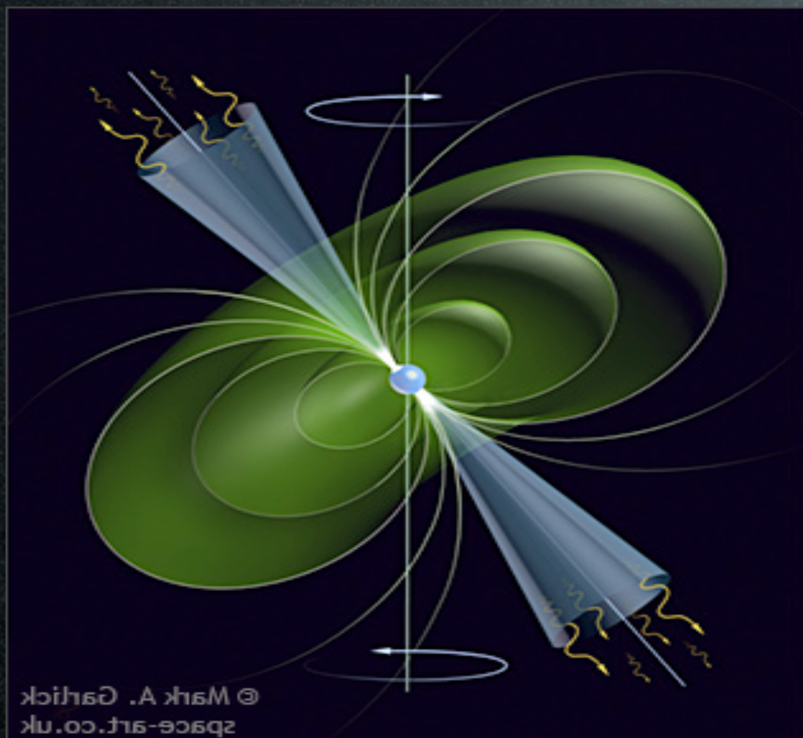


Lavalle et al. 2007

Astrophysical explanation?

[others?]

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



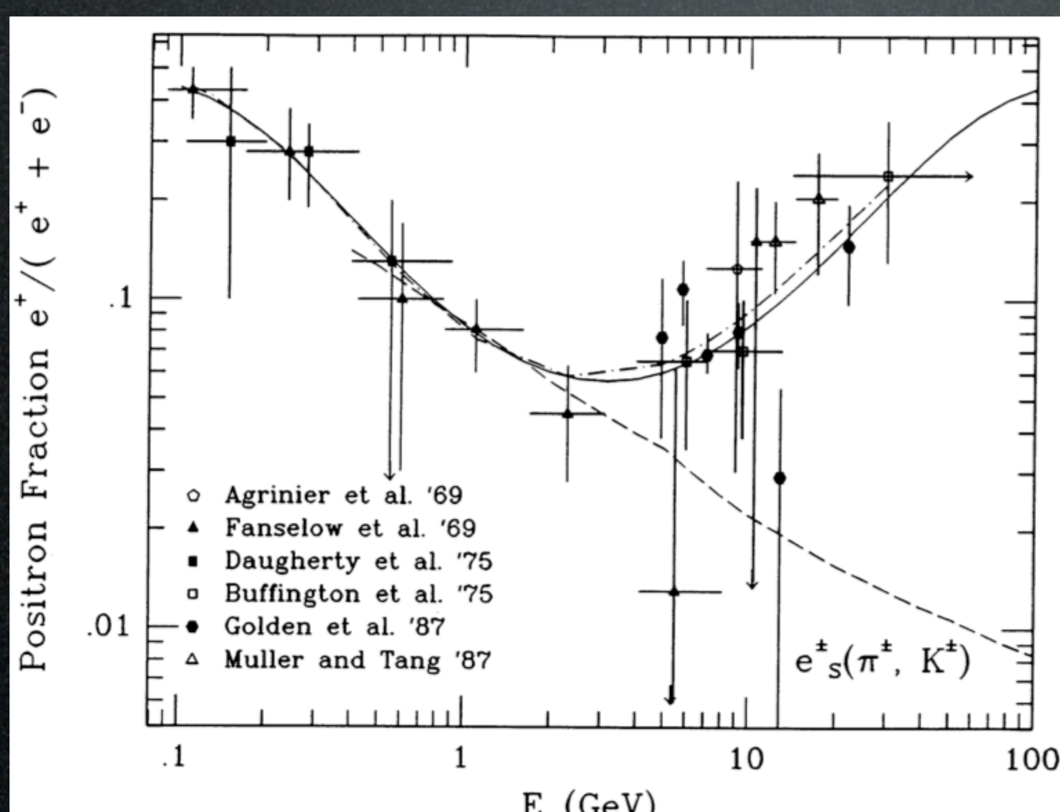
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \to 10^5$ yr (typical total energy output: 10^{46} erg).

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

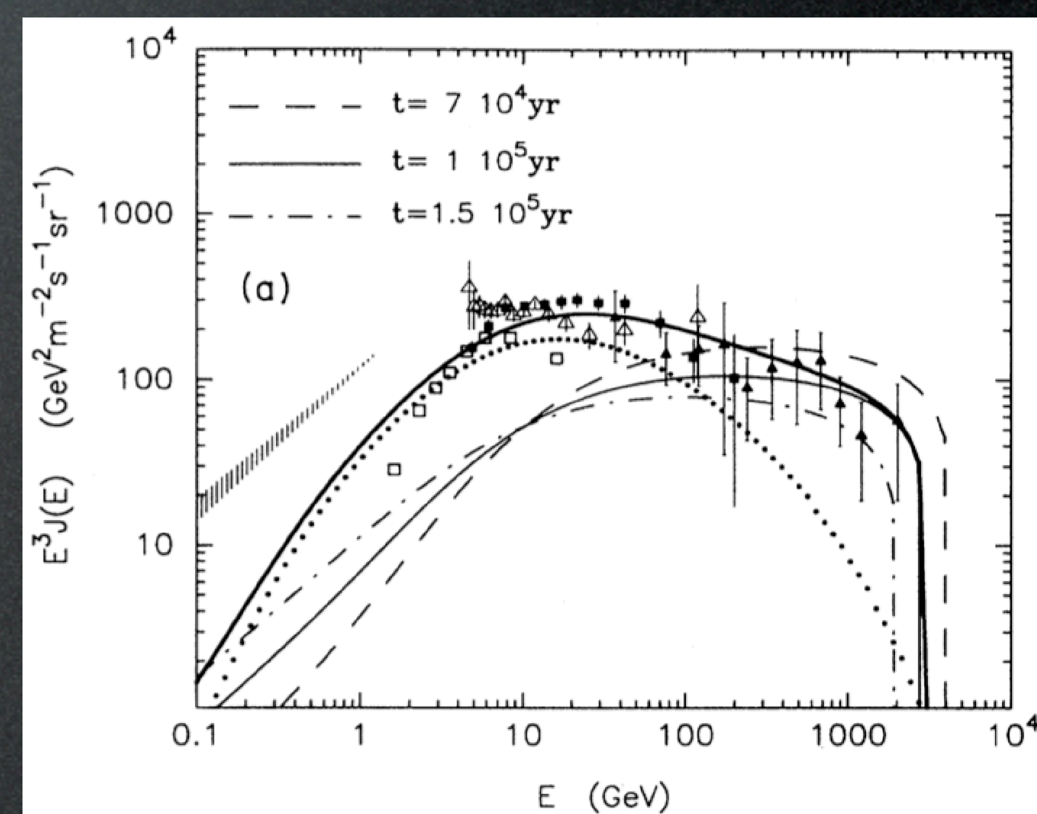
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

Not a new idea:



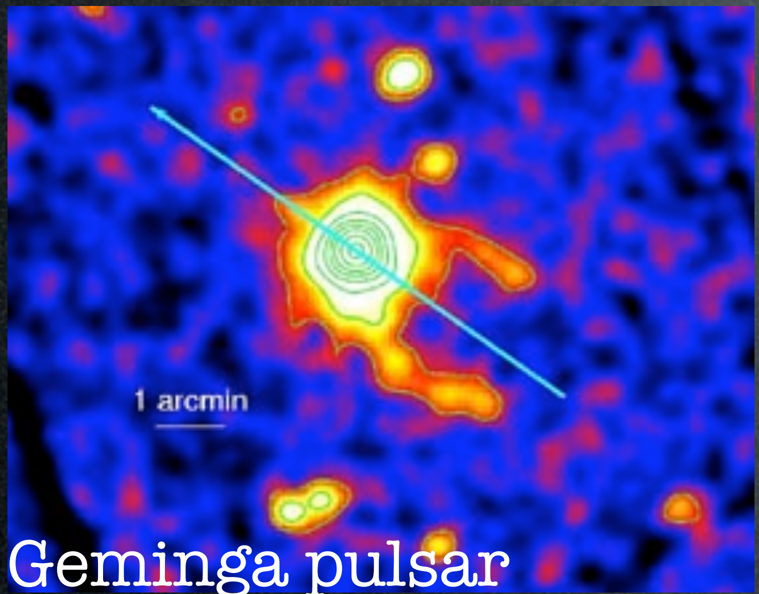
A.Boulares, APJ 342 (**1989**)



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

Astrophysical explanation?

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



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

'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.

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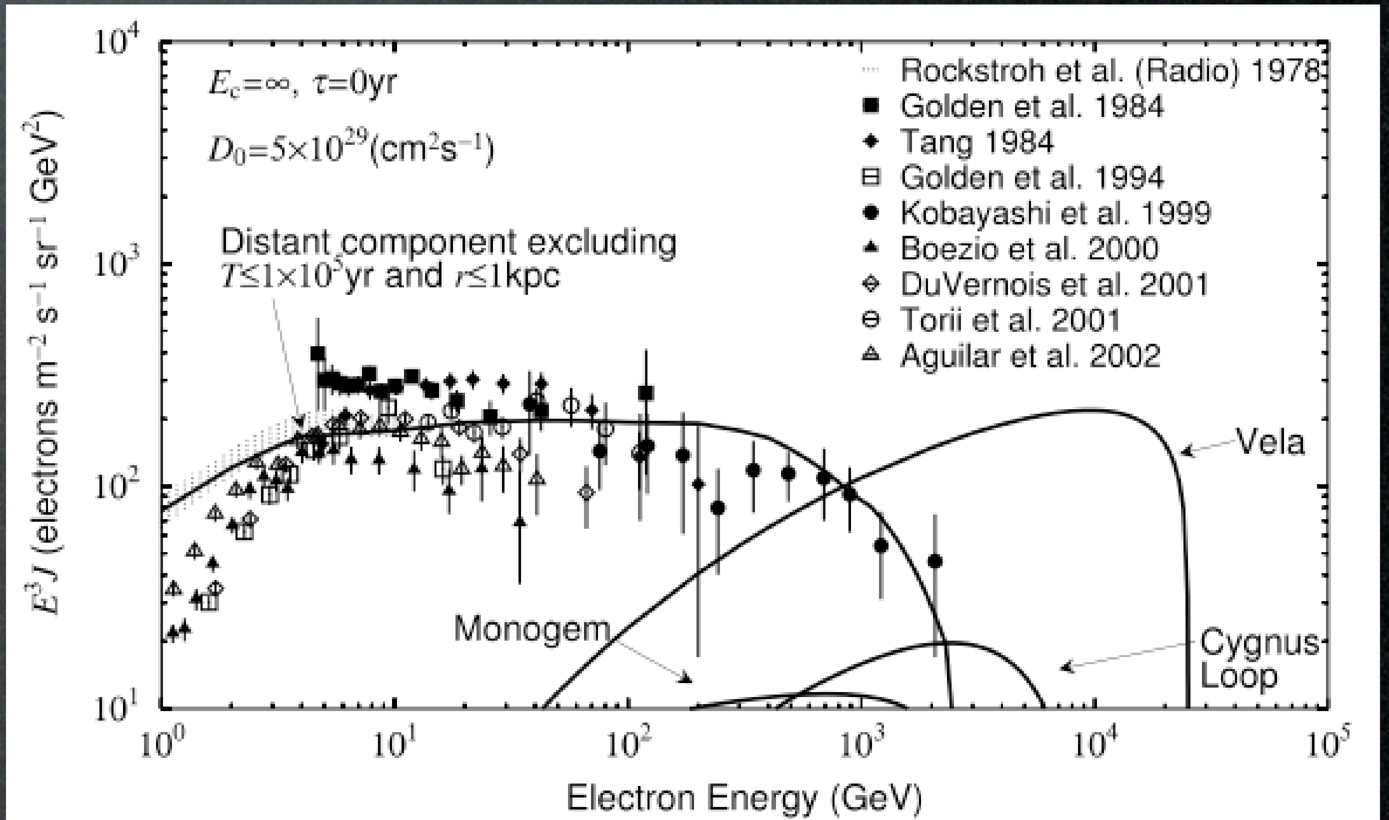
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

Kobayashi, Komori et al. 2004



Kobayashi, Komori et al. 2004

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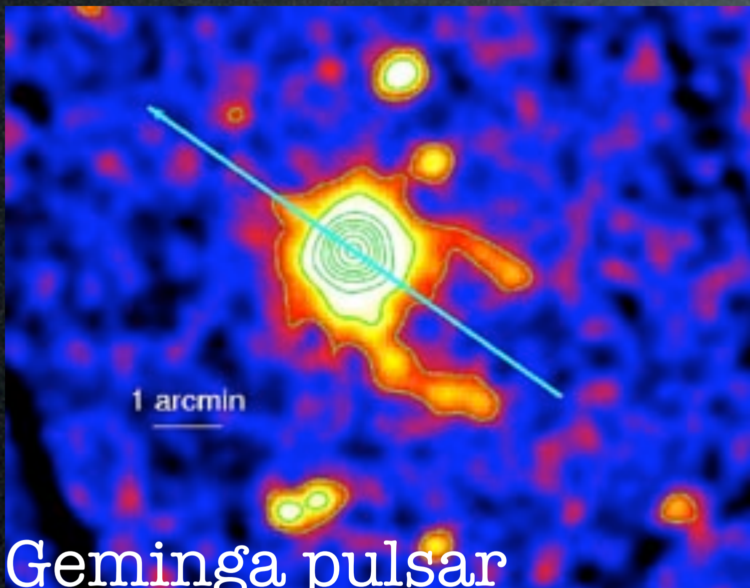

'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \to 10^5$ yr.

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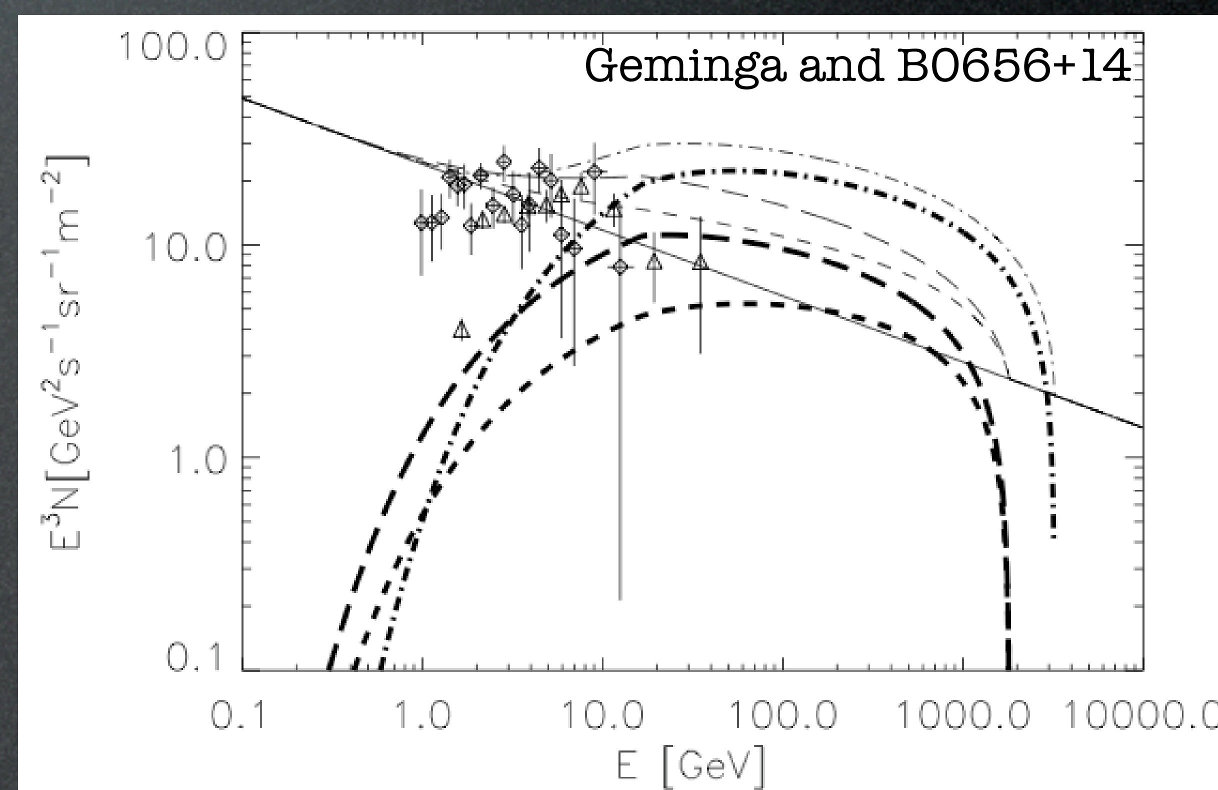

Büshing, de Jager et al. 0804.0220

Astrophysical explanation?

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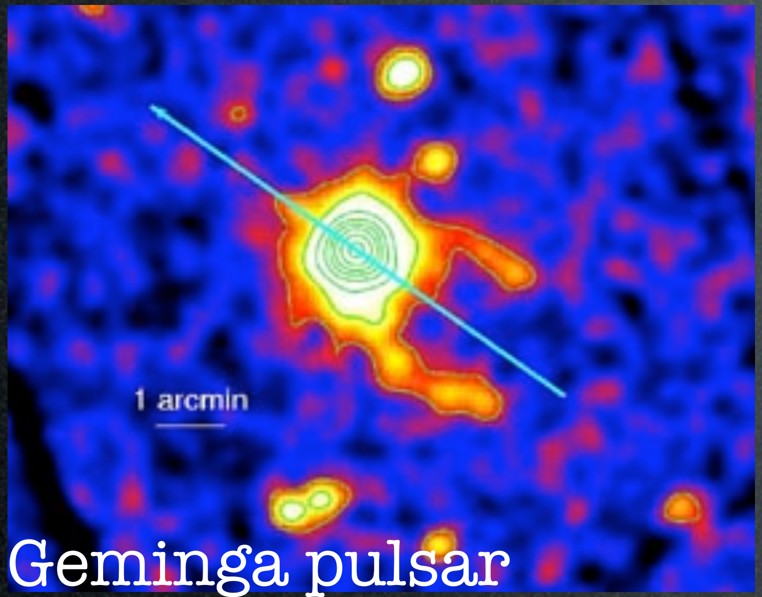

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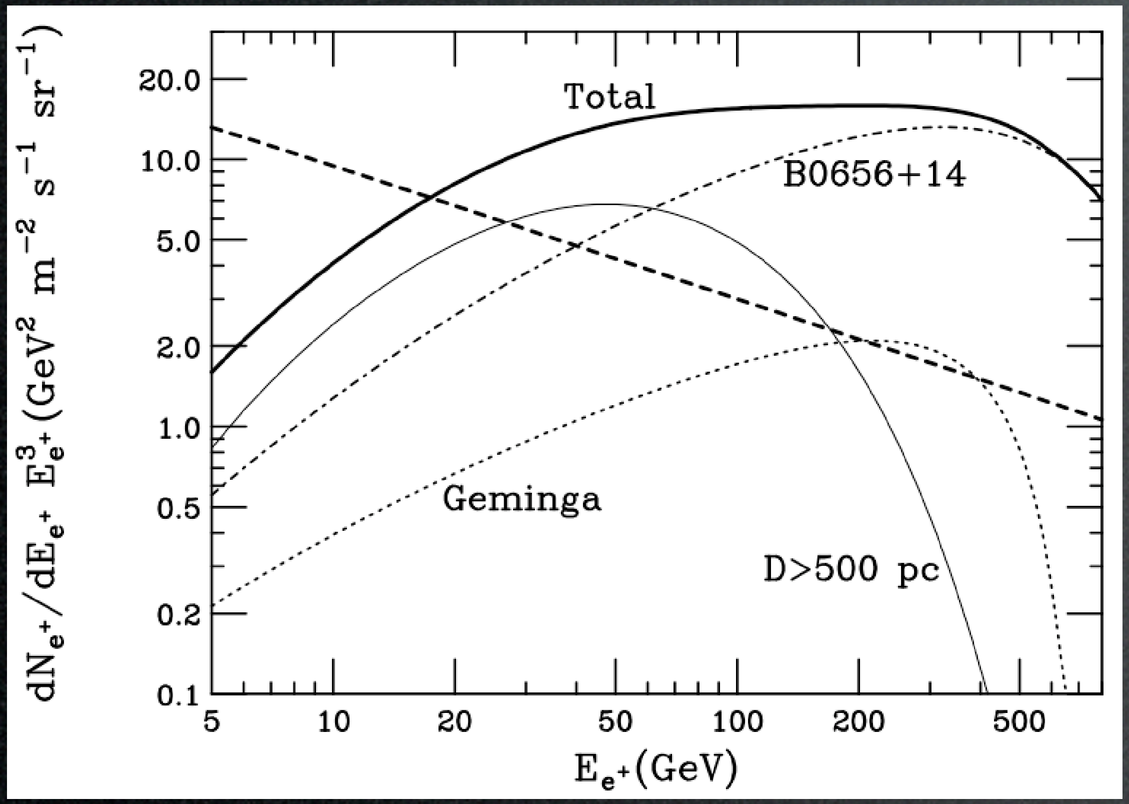
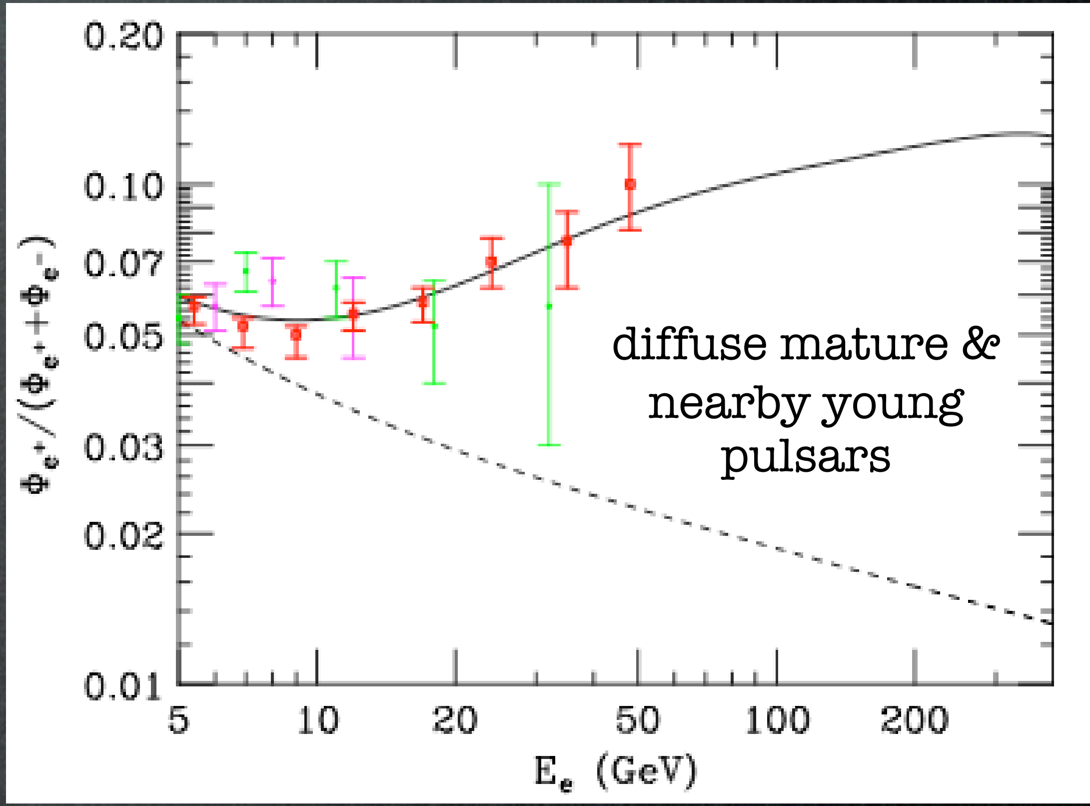
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

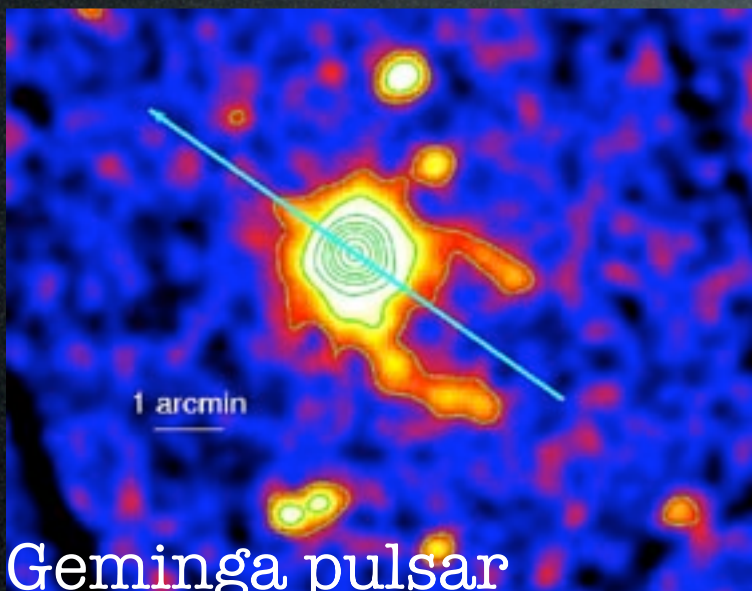




Hooper, Blasi, Serpico 2008

Astrophysical explanation?

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



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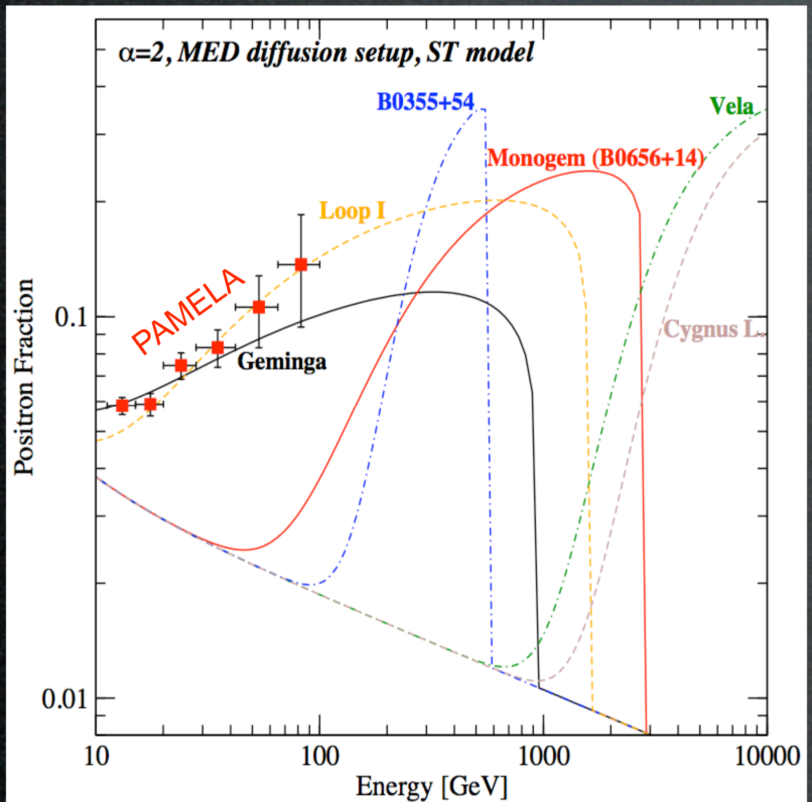
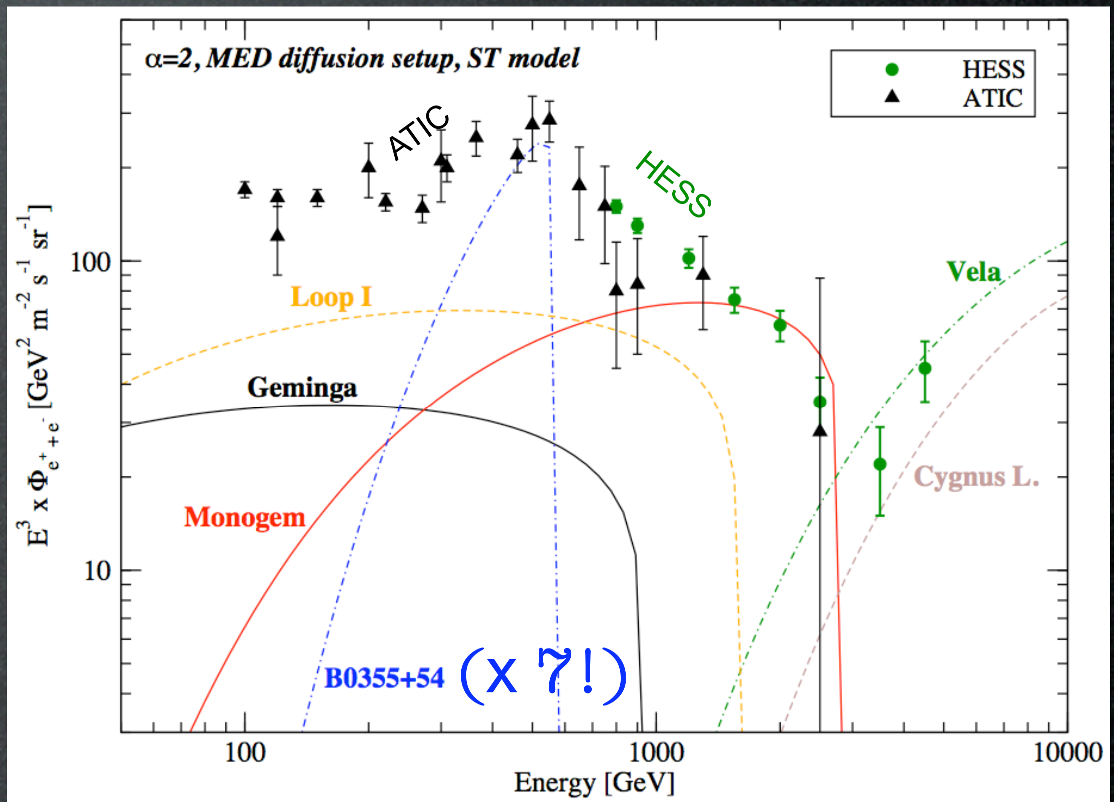
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

But ATIC needs a different (and very powerful) source:

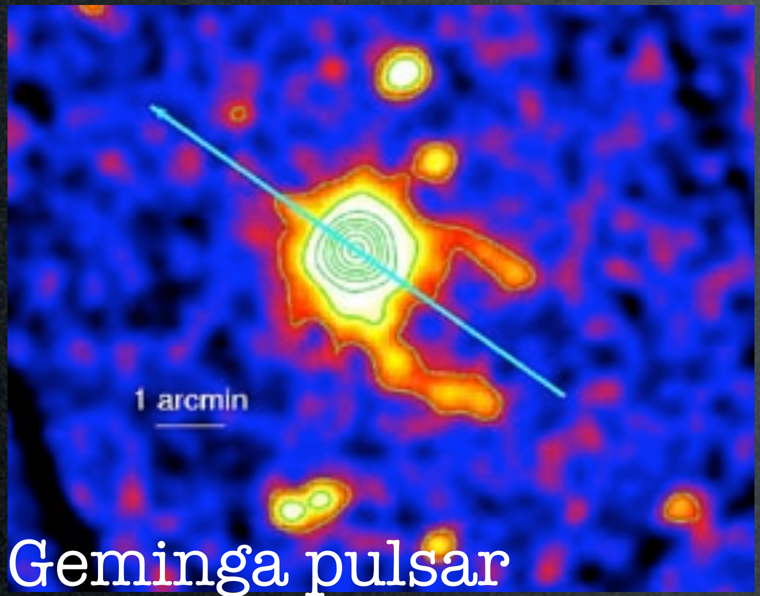




Profumo 0812.4457

Astrophysical explanation?

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



Geminga pulsar

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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

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

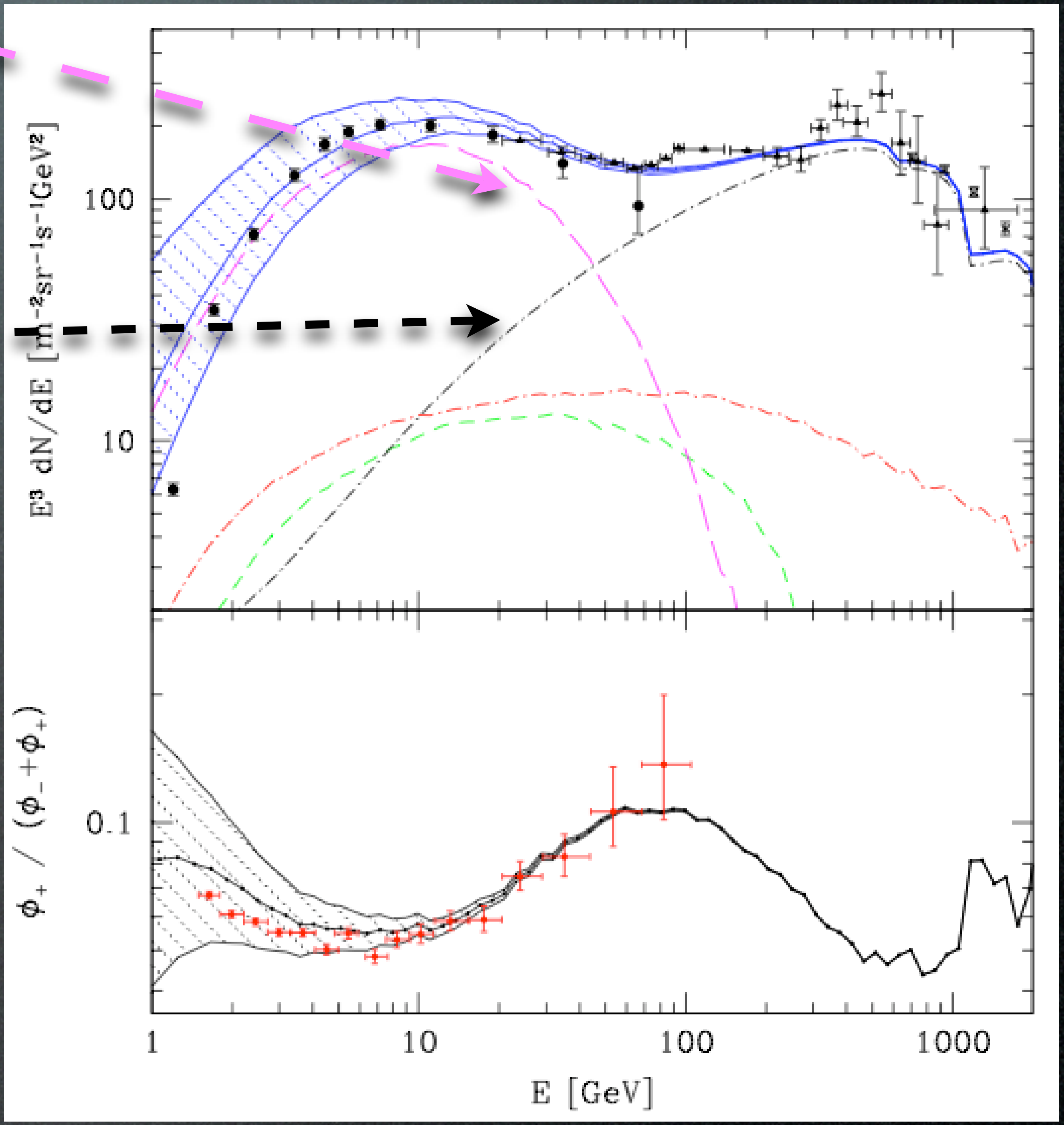
[back]

Indirect Detection

Background estimation for positrons:

SNRs in the spiral arm as sources of electrons (not positrons), whose flux drops at 10 GeV for energy loss = PAMELA

additional more local SNRs inject further electrons at 100 GeV = ATIC



Tsvi Piran et al. 0902.0376

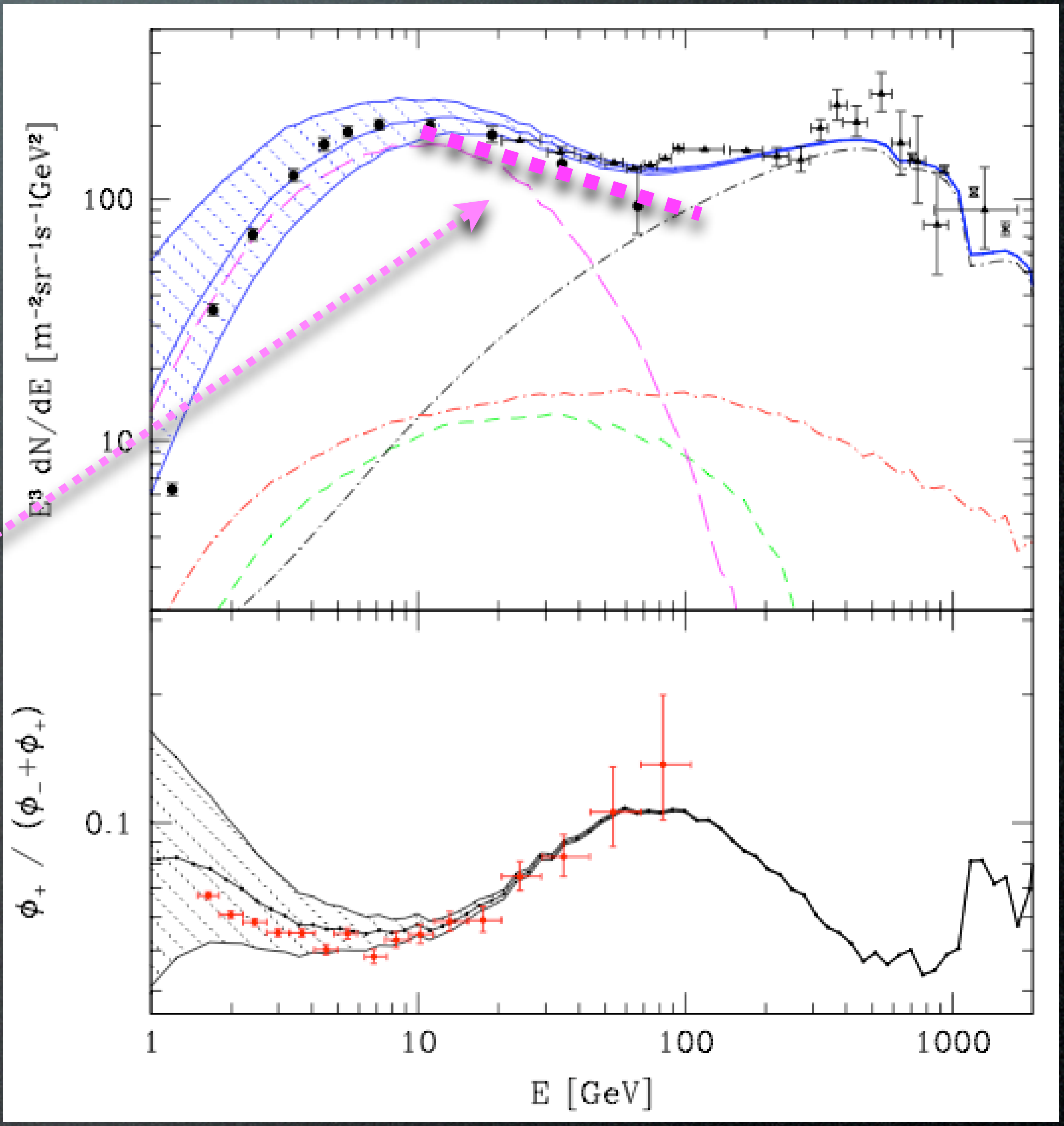
Indirect Detection

Background estimation for positrons:

SNRs in the spiral arm as sources of electrons (not positrons), whose flux drops at 10 GeV for energy loss = PAMELA

additional more local SNRs inject further electrons at 100 GeV = ATIC

But: *preliminary* PAMELA data on absolute e^- flux show harder spectrum ($E^{-3.33}$) than this prediction...; do nearby sources agree with B/C...?



Tsvi Piran et al. 0902.0376

Astrophysical explanation?

see S.Profumo, 0812.4457

the electron spectrum has a steep deepening!

T.Delahaye et al., 09.2008
Casadei, Bindi 2004
Tsvi Piran et al., 0902.0376

- difficult to get PAMELA slope?
- does it explain ATIC or HESS?

CR proton collisions on giant molecular clouds produce e^+e^-!

Dogiel, Sharov 1990

- does not work at E > 30 GeV

Coutu et al (HEAT), 1990

Gamma Ray Bursts produce e^+e^-!

Ioka 0812.4851

- maybe, constrained by gammas

β^+ decays of ^{56}Co in SN produce e^+!

ICRC 1990

- low energy and low flux

...

[back]

DM detection

direct detection

production at colliders

indirect

γ from annihil in galactic center and from synchrotron emission

HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, AMS02, **balloons**

$\bar{p}$ from annihil in galactic halo or center

$\bar{D}$ from annihil in galactic halo or center

$\nu, \bar{\nu}$ from annihil in massive bodies