5 May 2009
TANGO in PARIS

PAMELA, ATIC & C. vs Dark Matter annihilations

Marco Cirelli
(CNRS, IPhT-CEA/Saclay)

in collaboration with:
A.Strumia (Pisa)
M.Raidal (Tallin)
M.Kadastik (Tallin)
G.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (Saclay)

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0808.3867 [astro-ph]
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and work in progress

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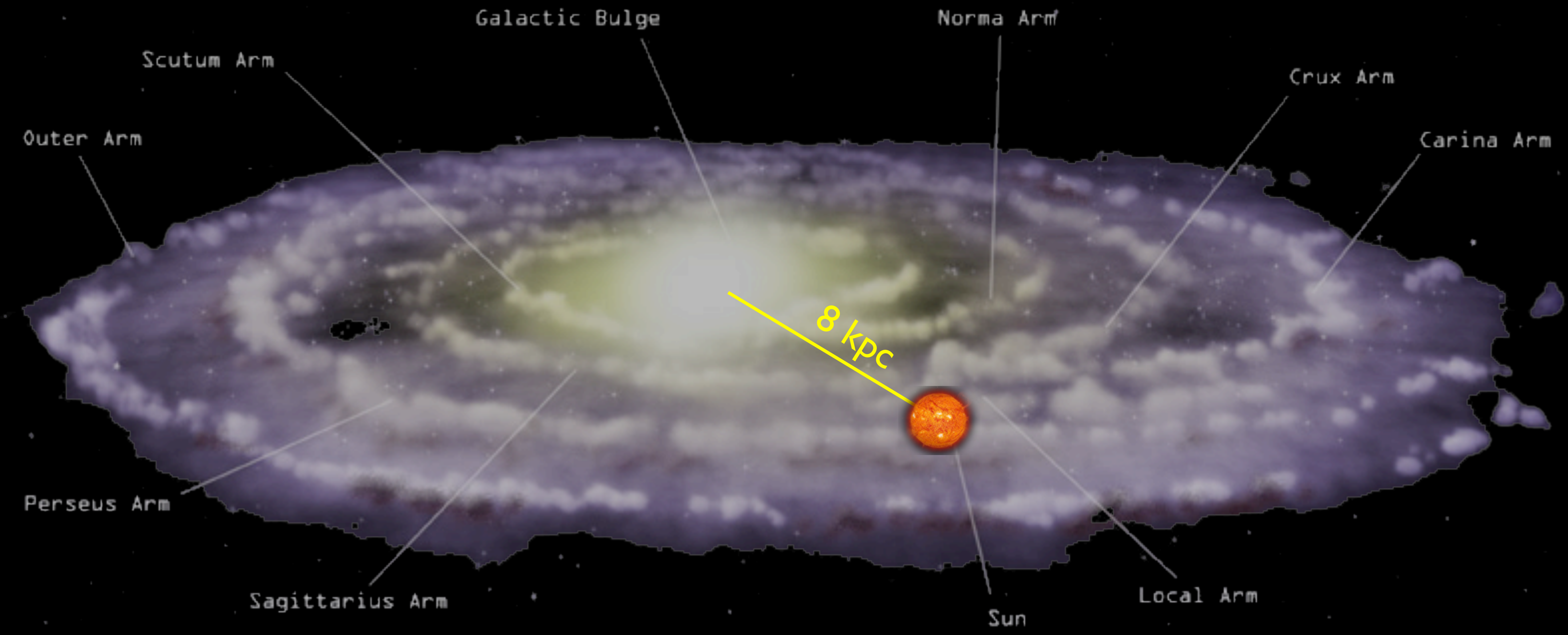
Indirect Detection

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



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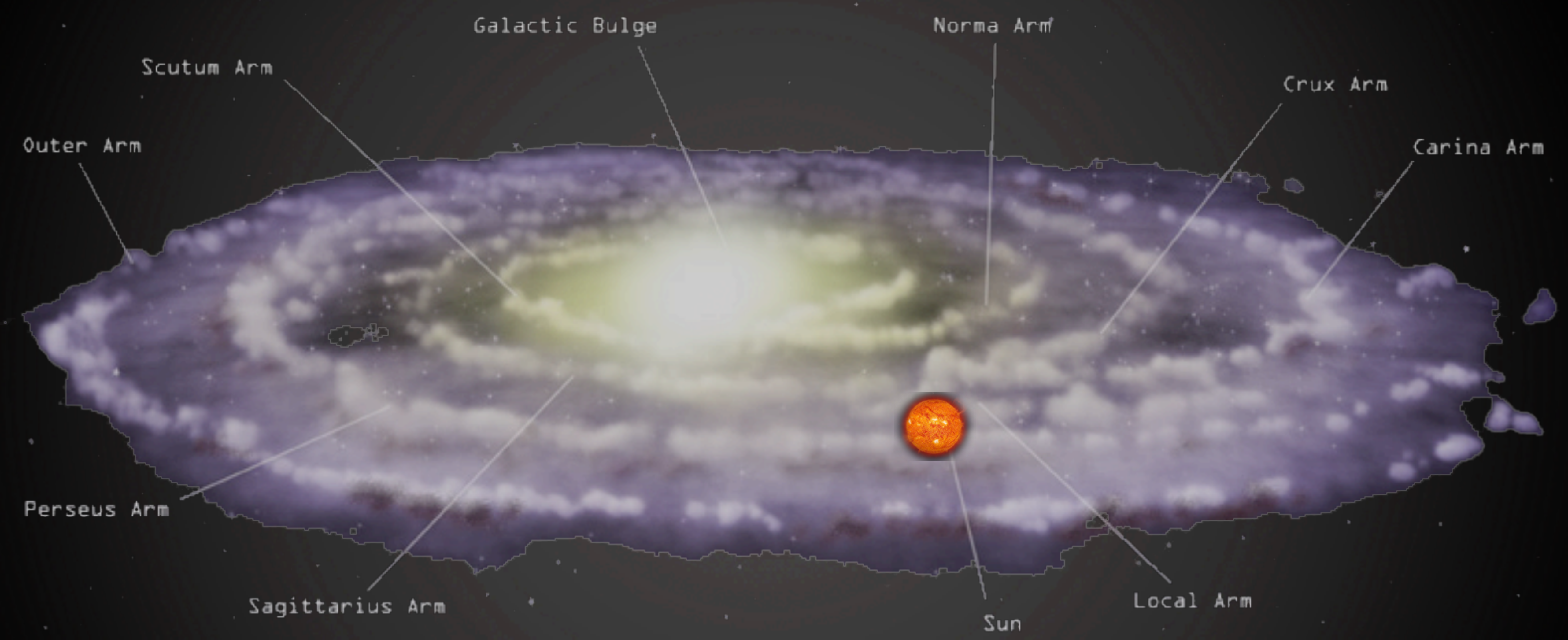

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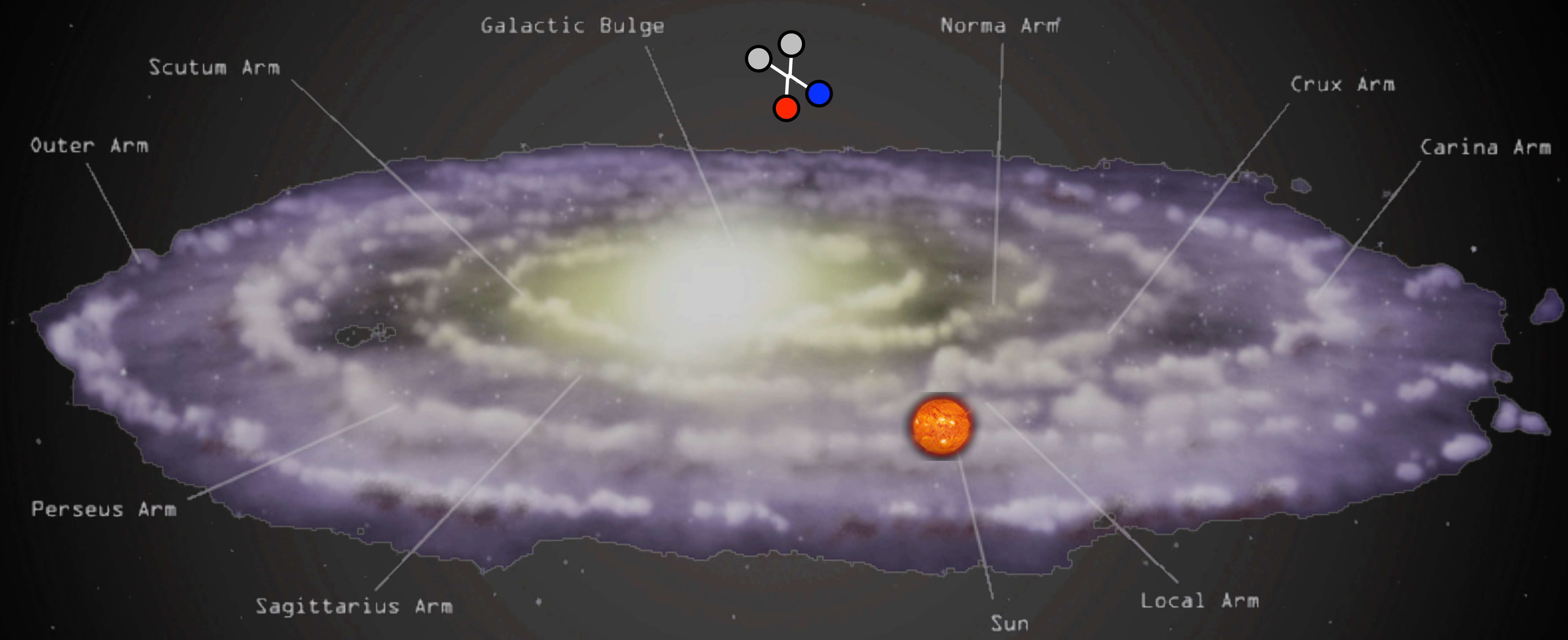

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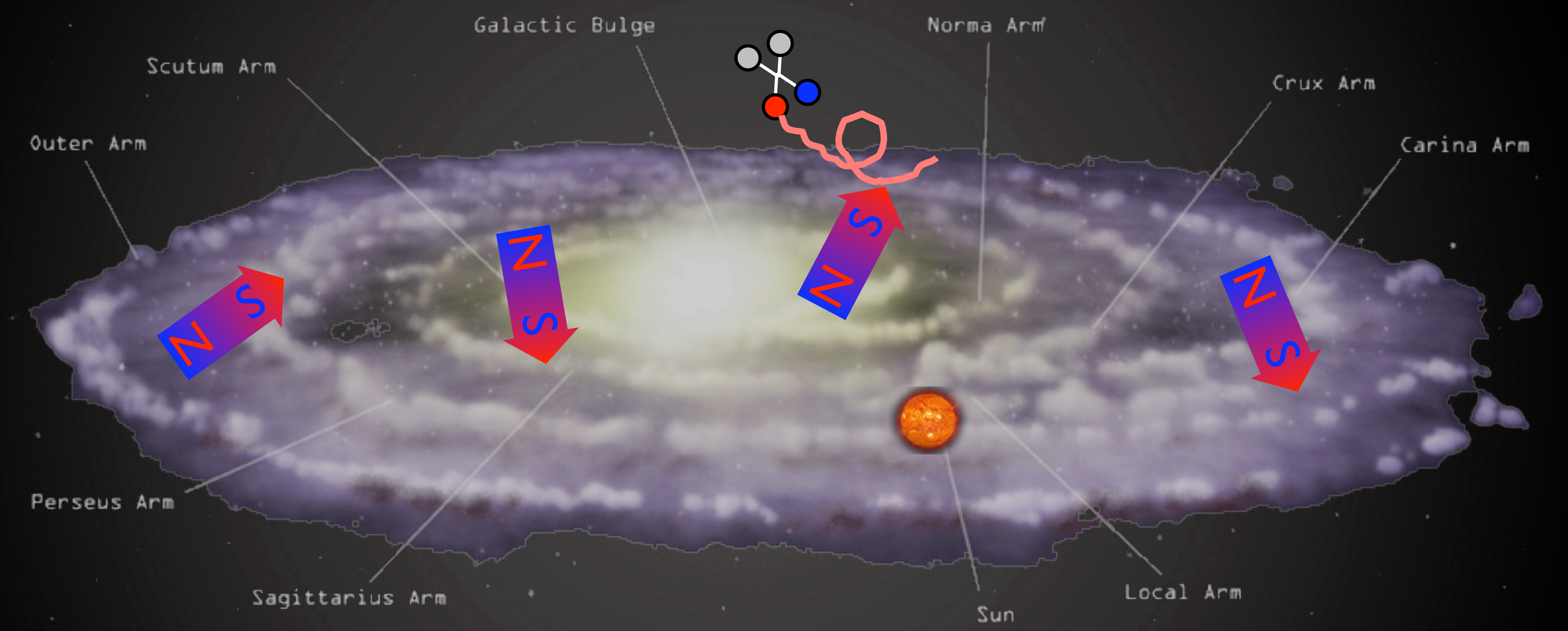

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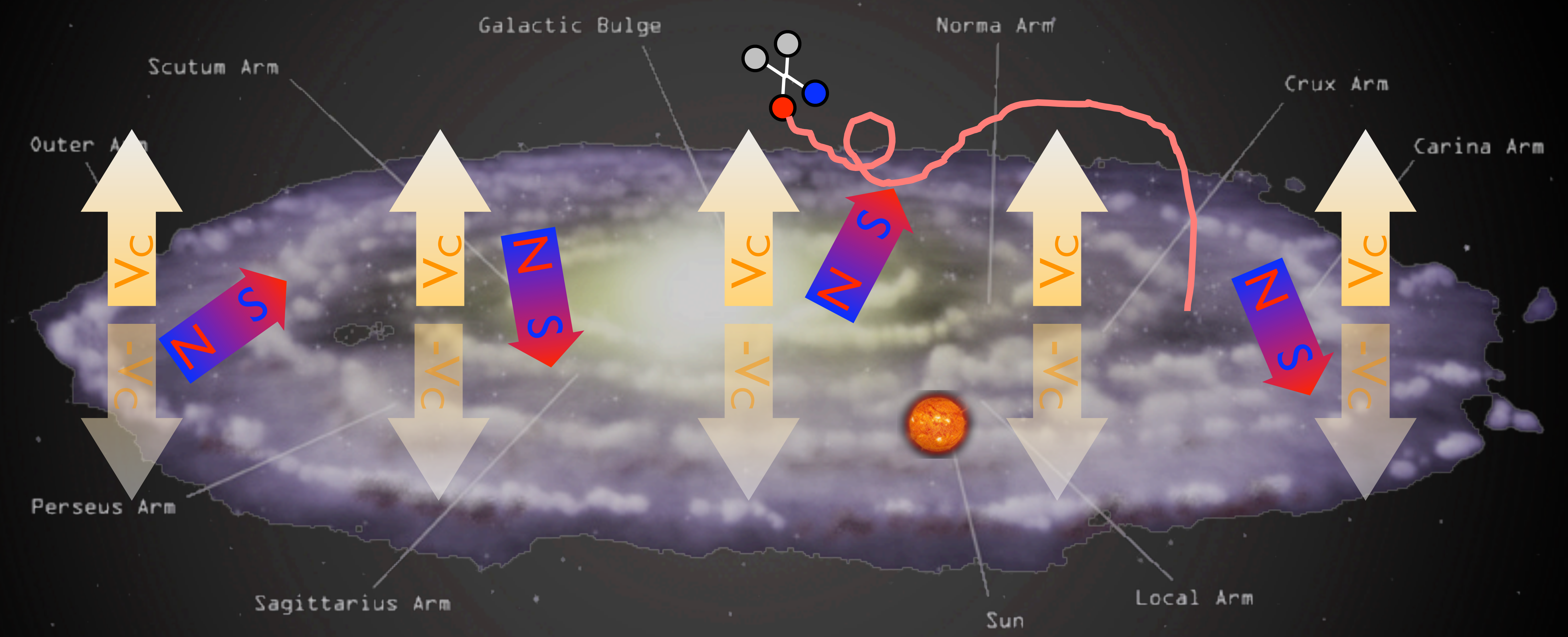

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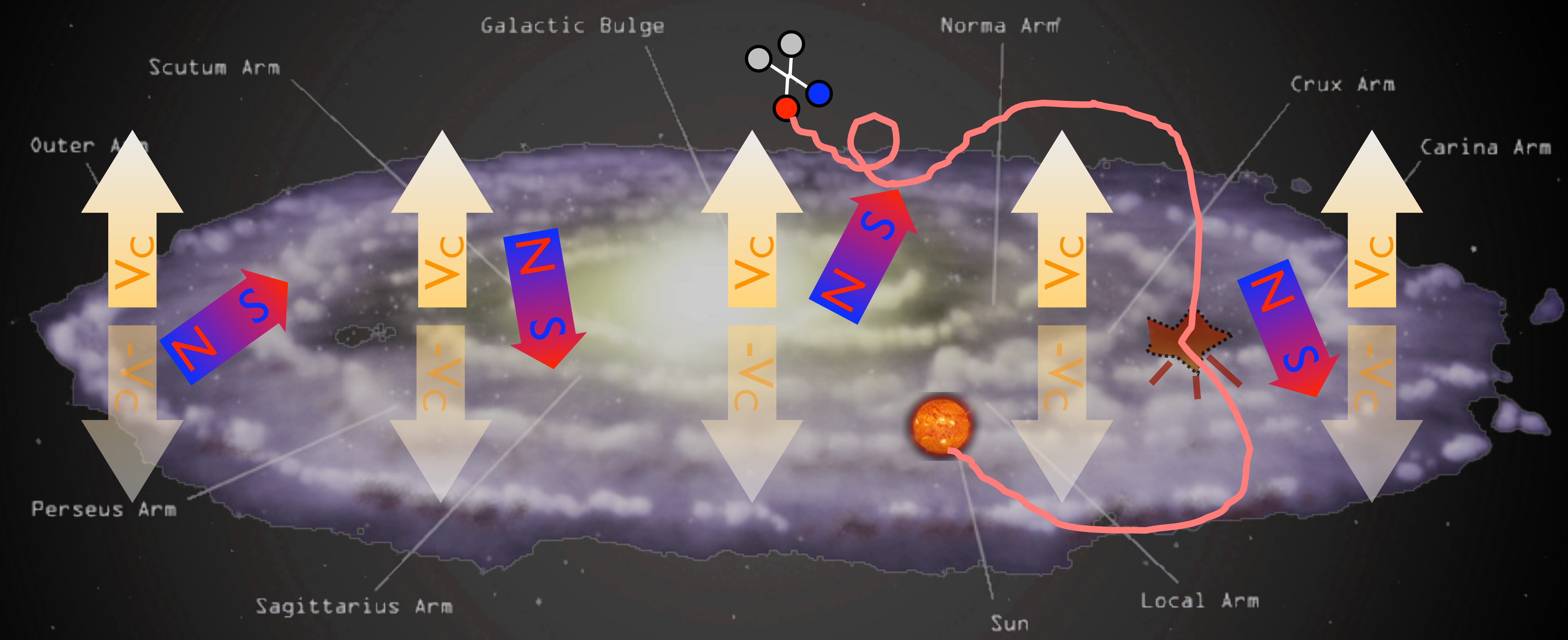

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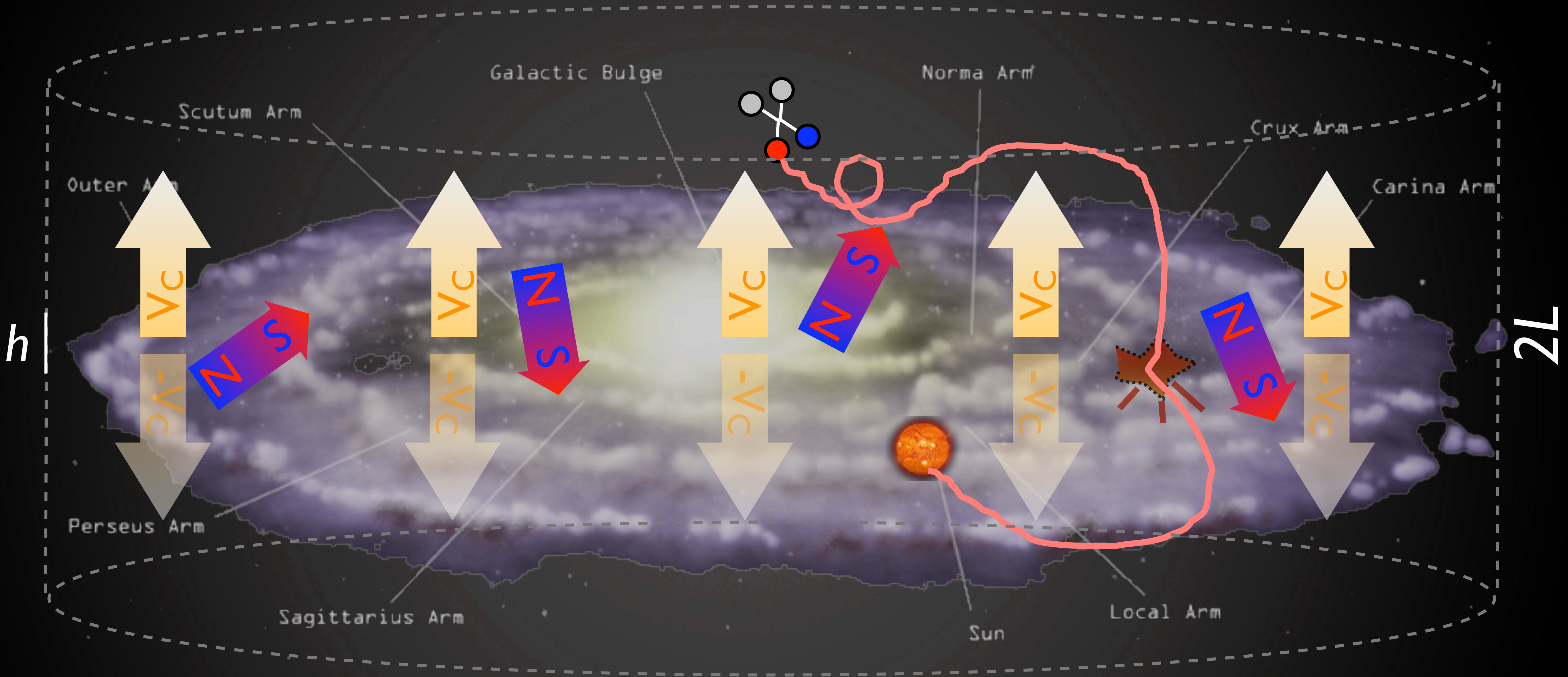


spectrum

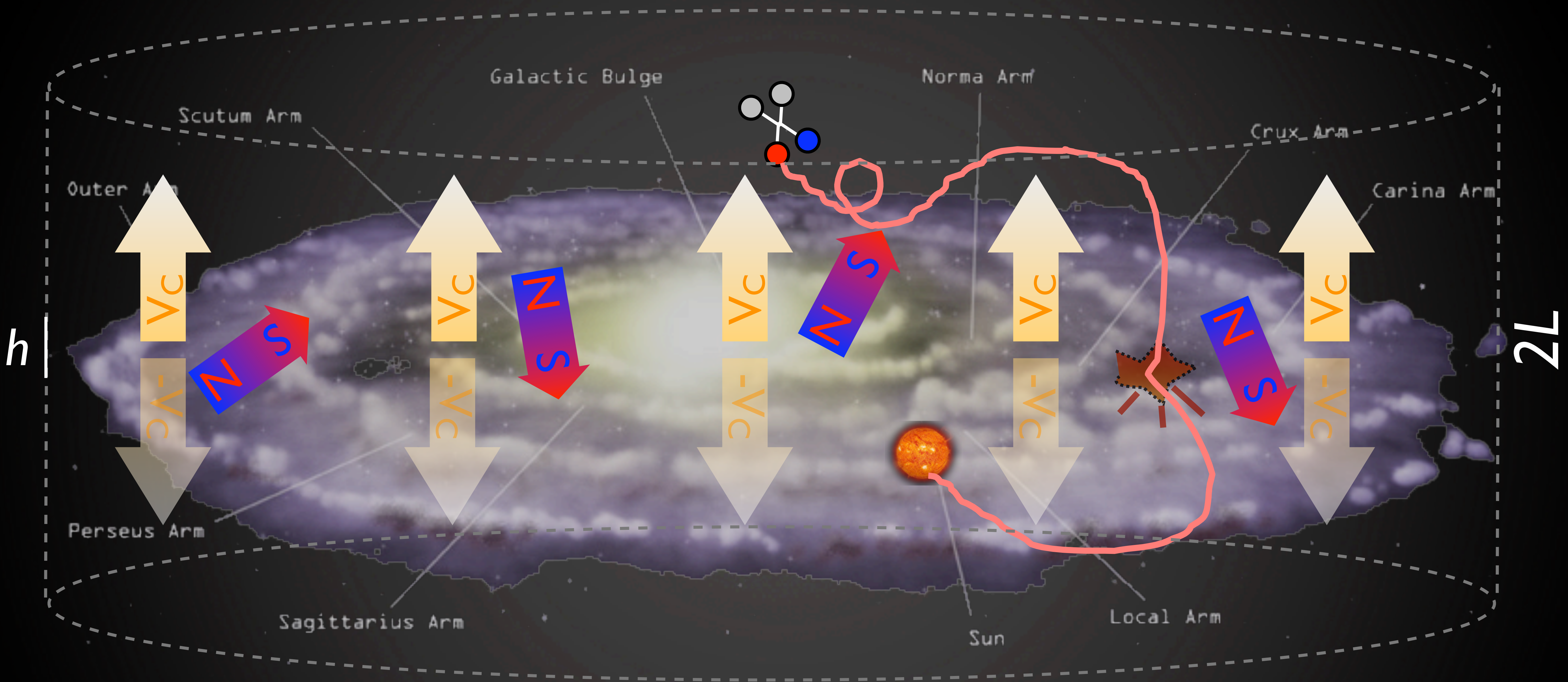
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}(b(E)f) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

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

Indirect Detection

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

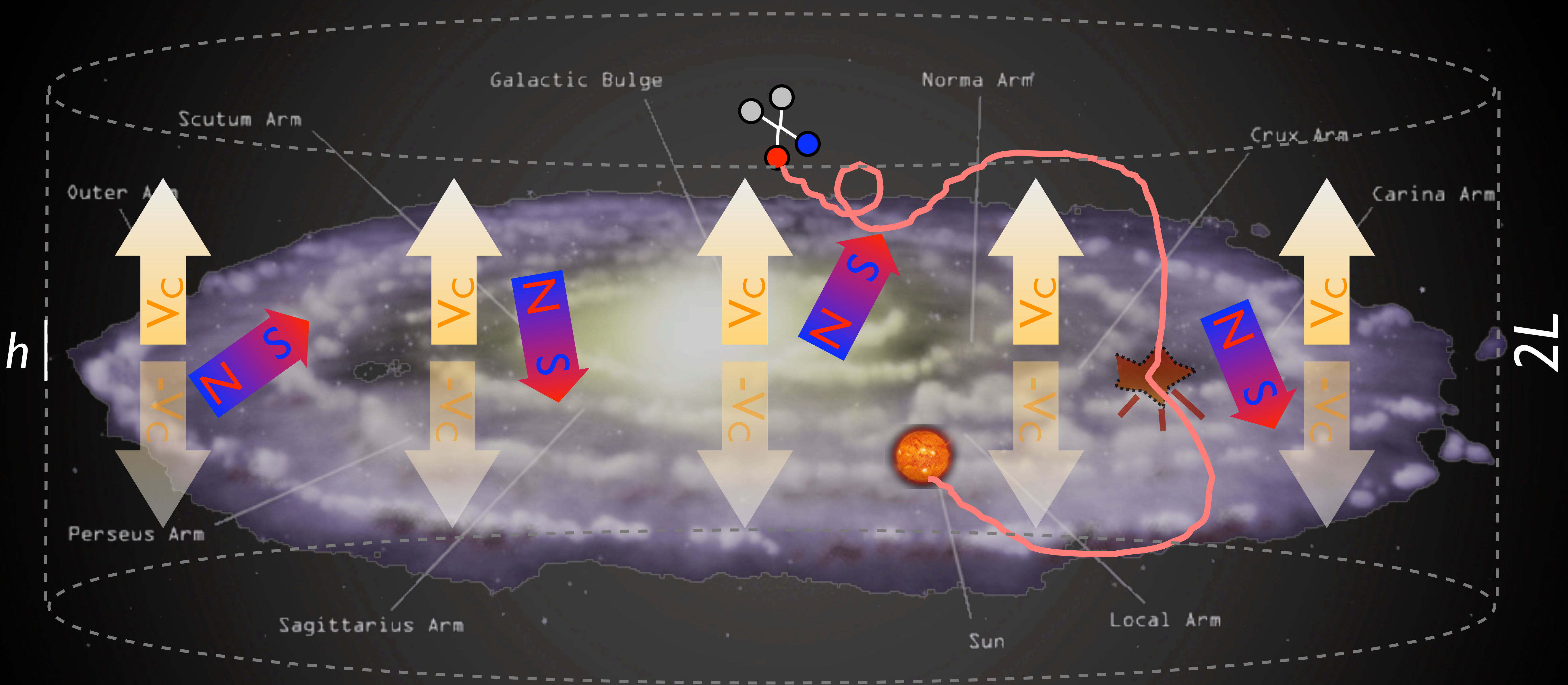


What sets the overall expected flux?

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

Indirect Detection

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



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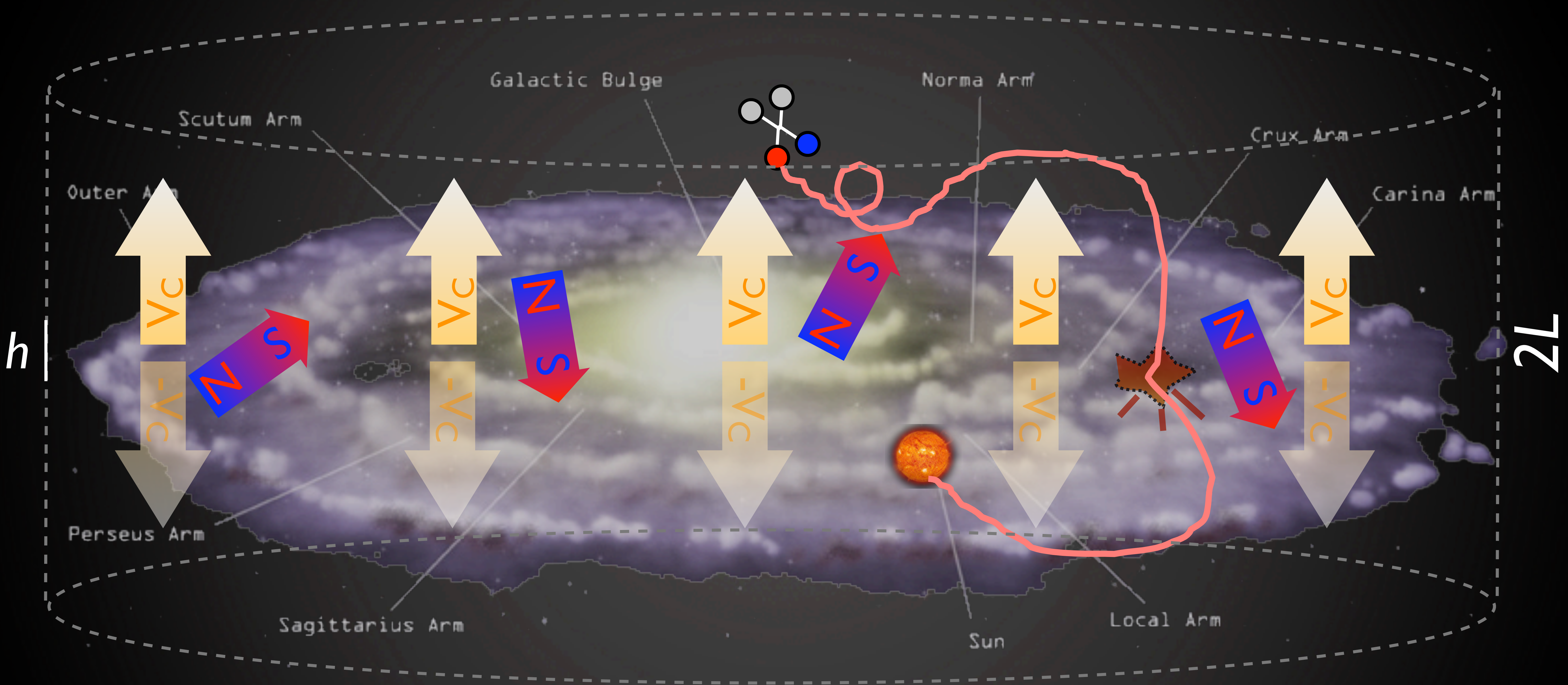
astro& cosmo

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:

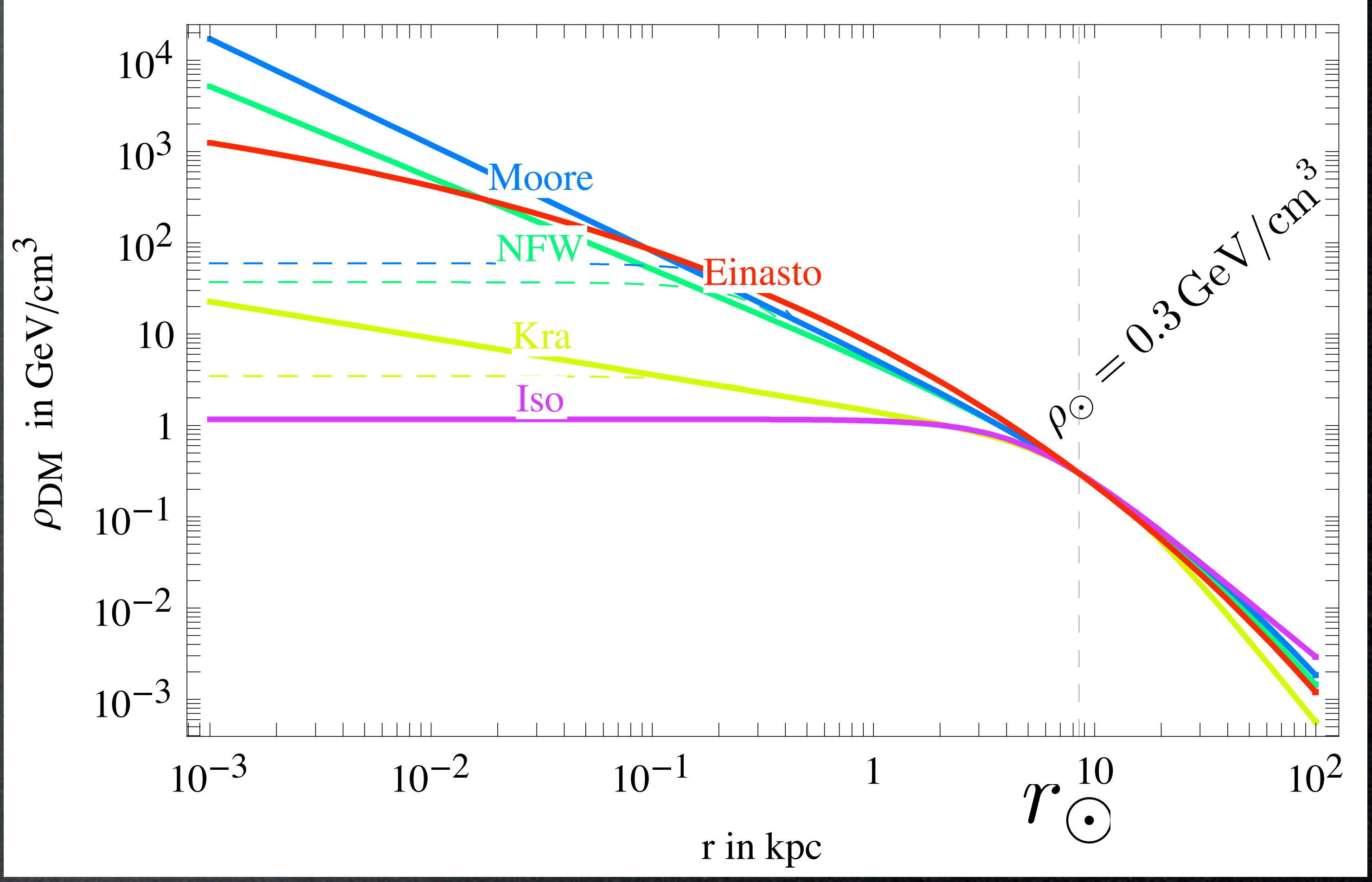
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

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

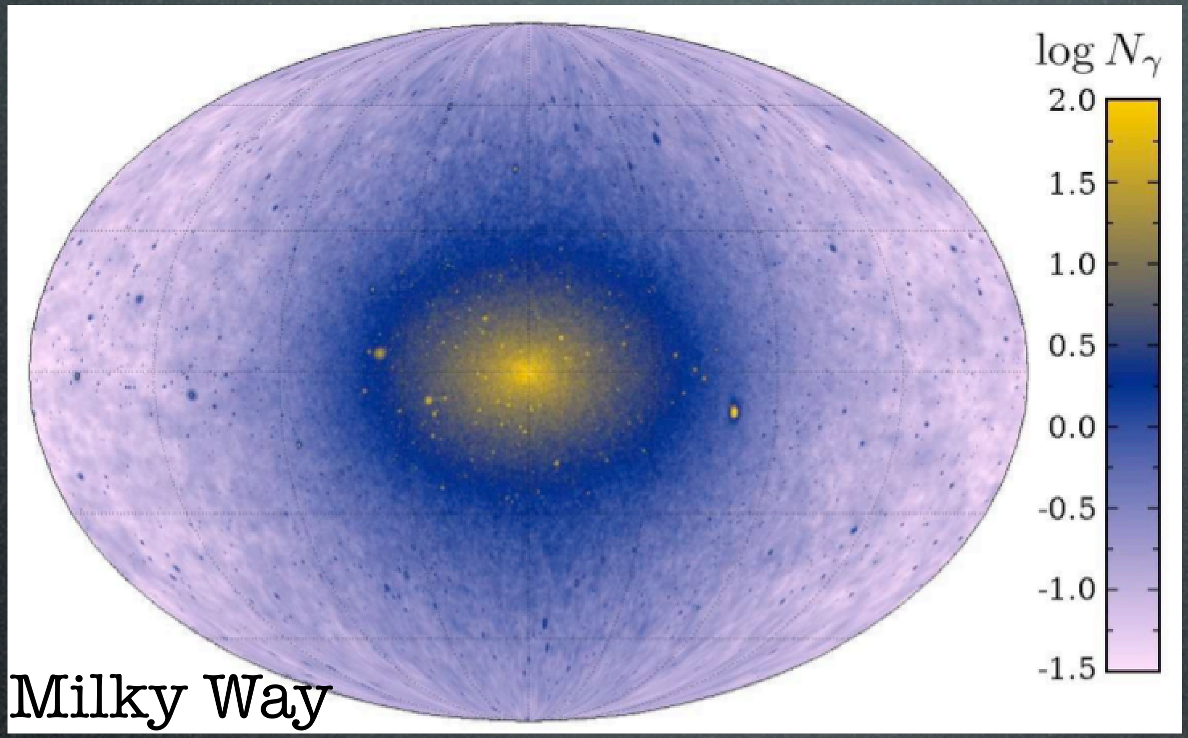


cuspy: NFW, Moore
mild: Einasto
smooth: isothermal

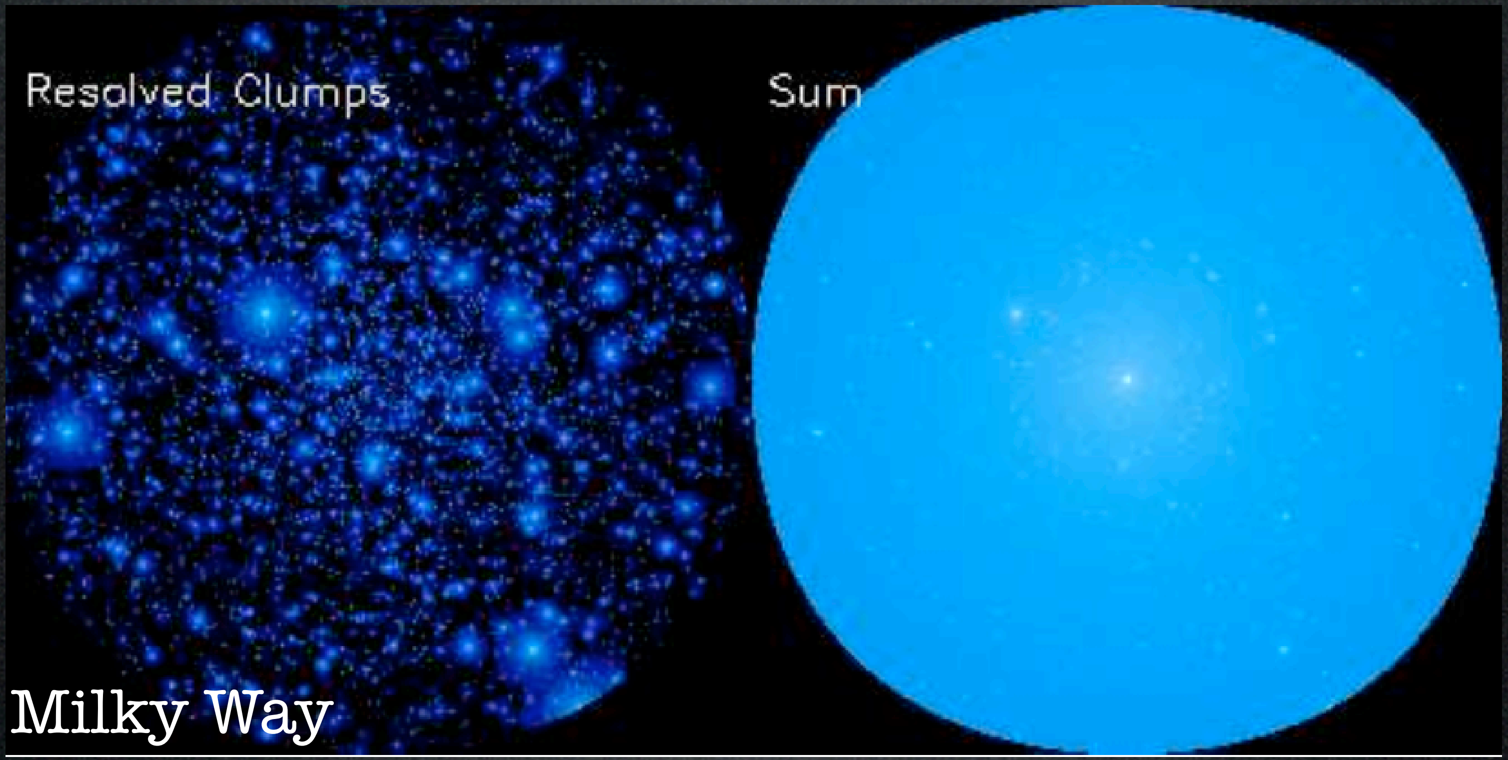
Indirect Detection

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

For illustration:



Kuhlen, Diemand, Madau 2007

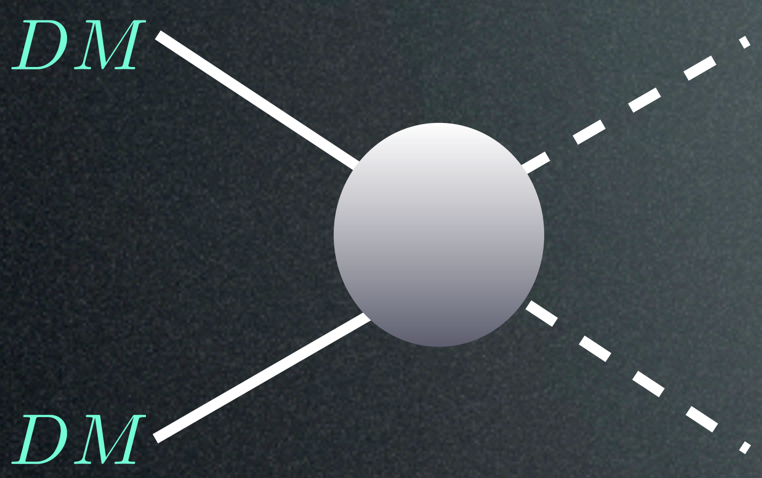


Bertone, Branchini, Pieri 2007

see:
Lavalle's talk
today

Computing the theory predictions

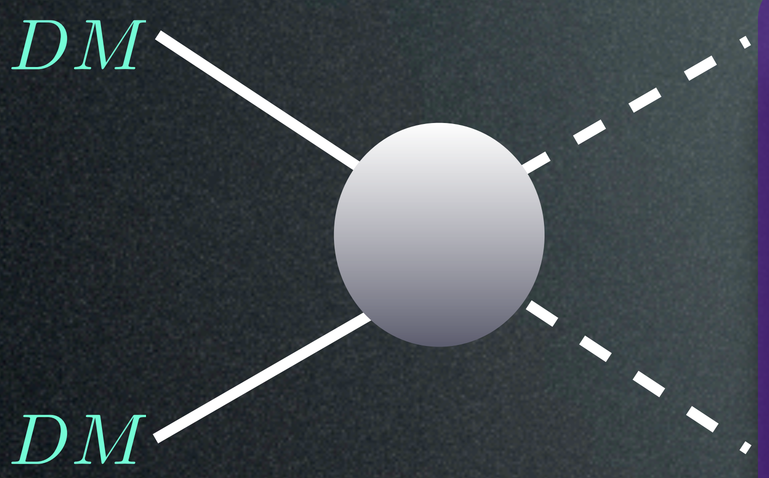
Spectra at production



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

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

Spectra at production

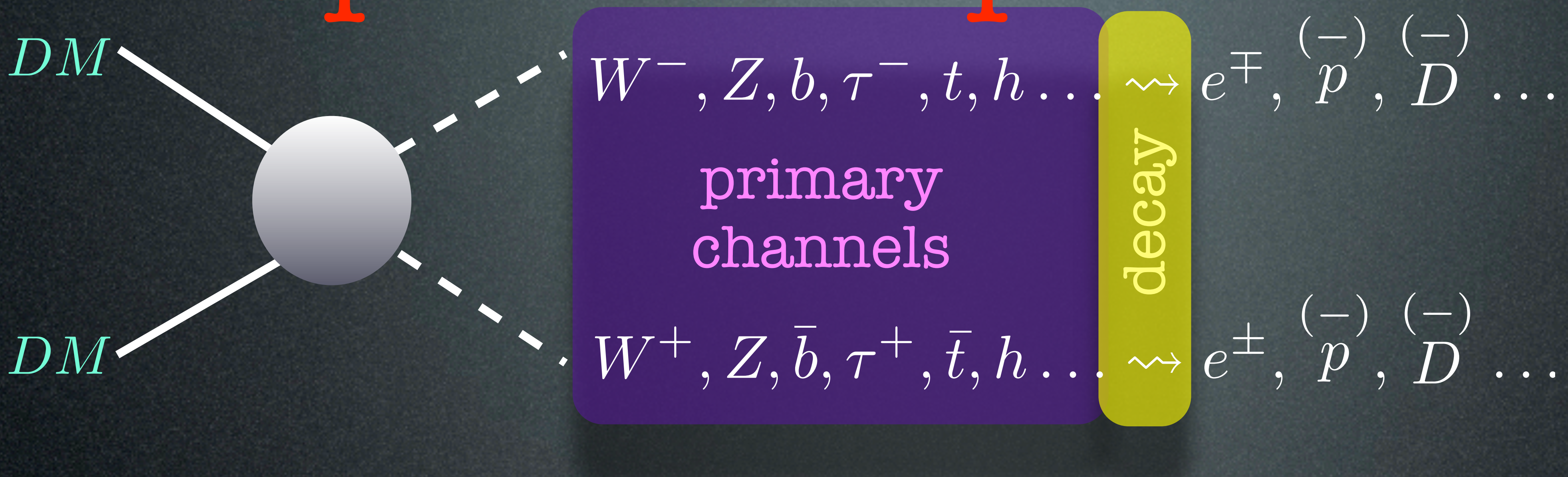


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary channels

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

Spectra at production



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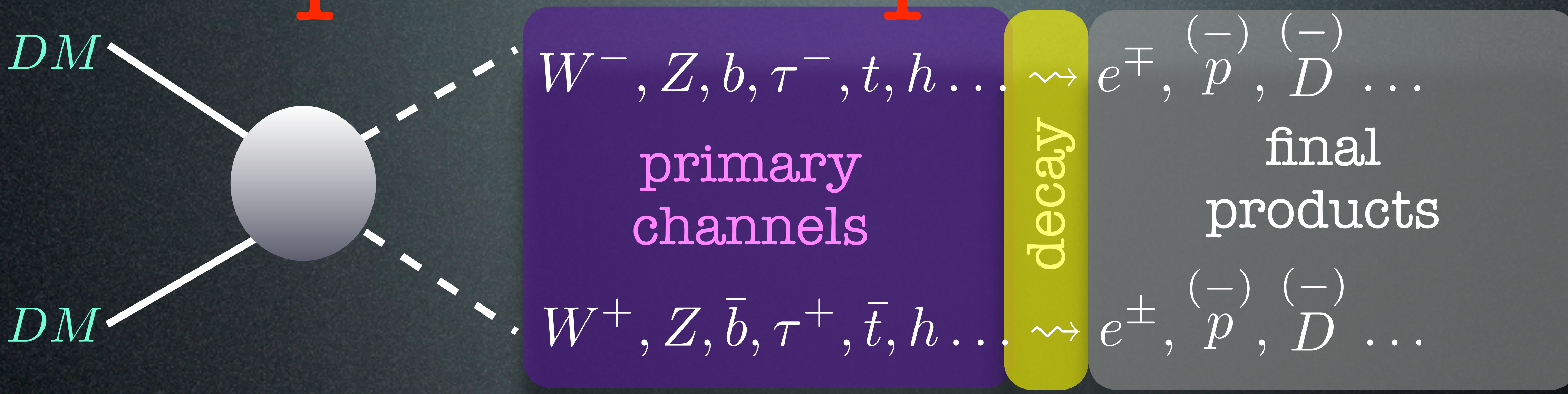

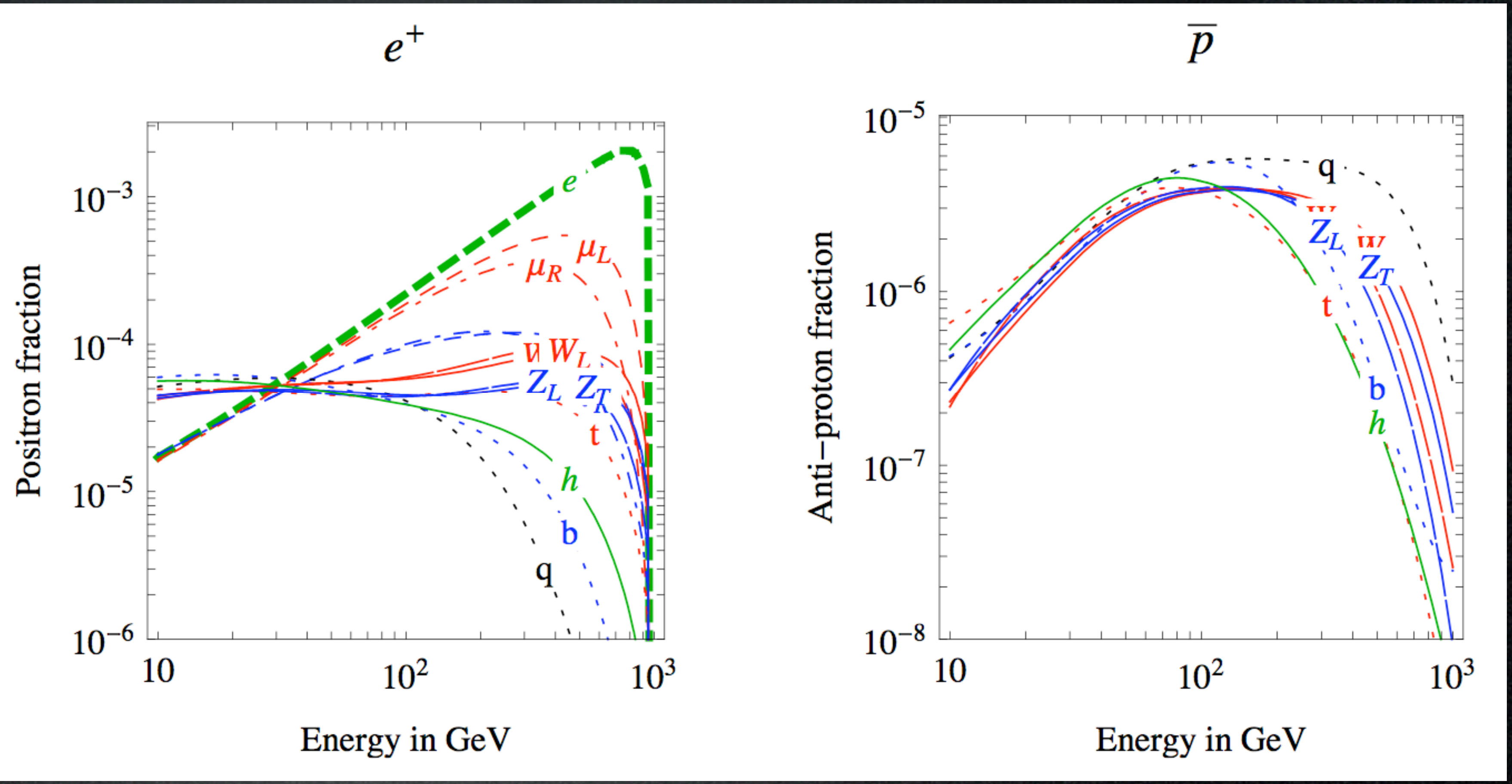

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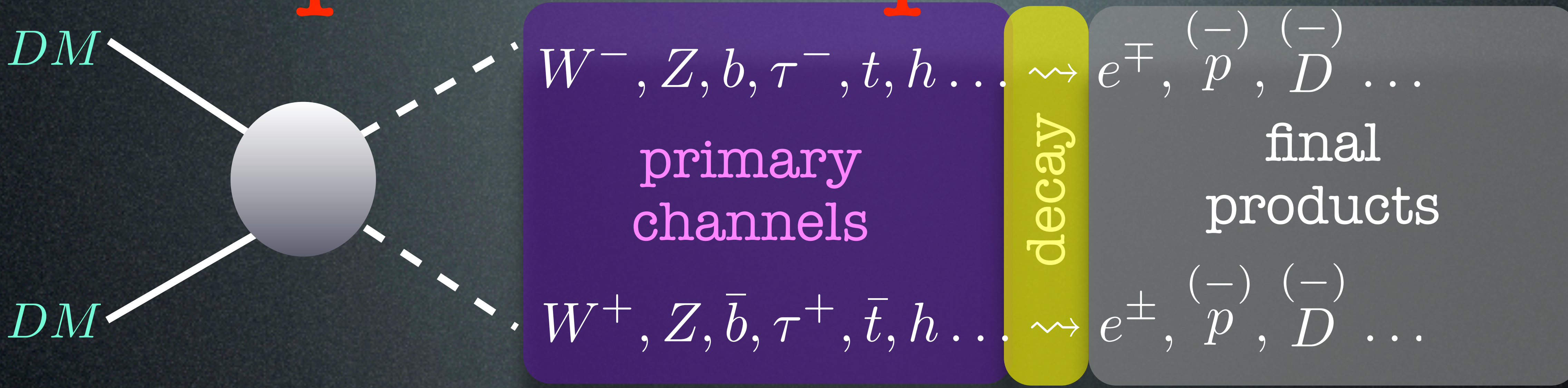
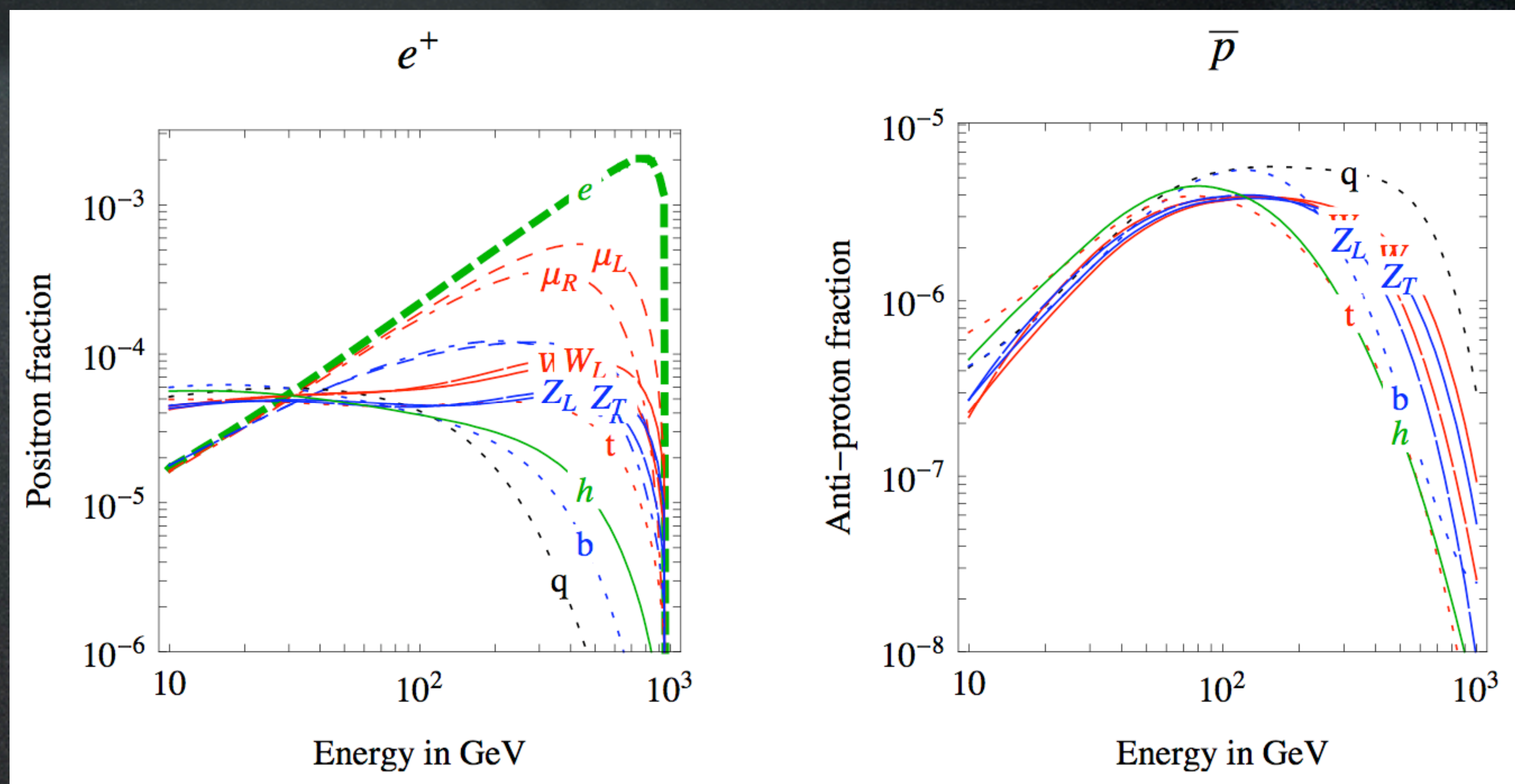




So what are the particle physics parameters?

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

Comparing with data

Data sets

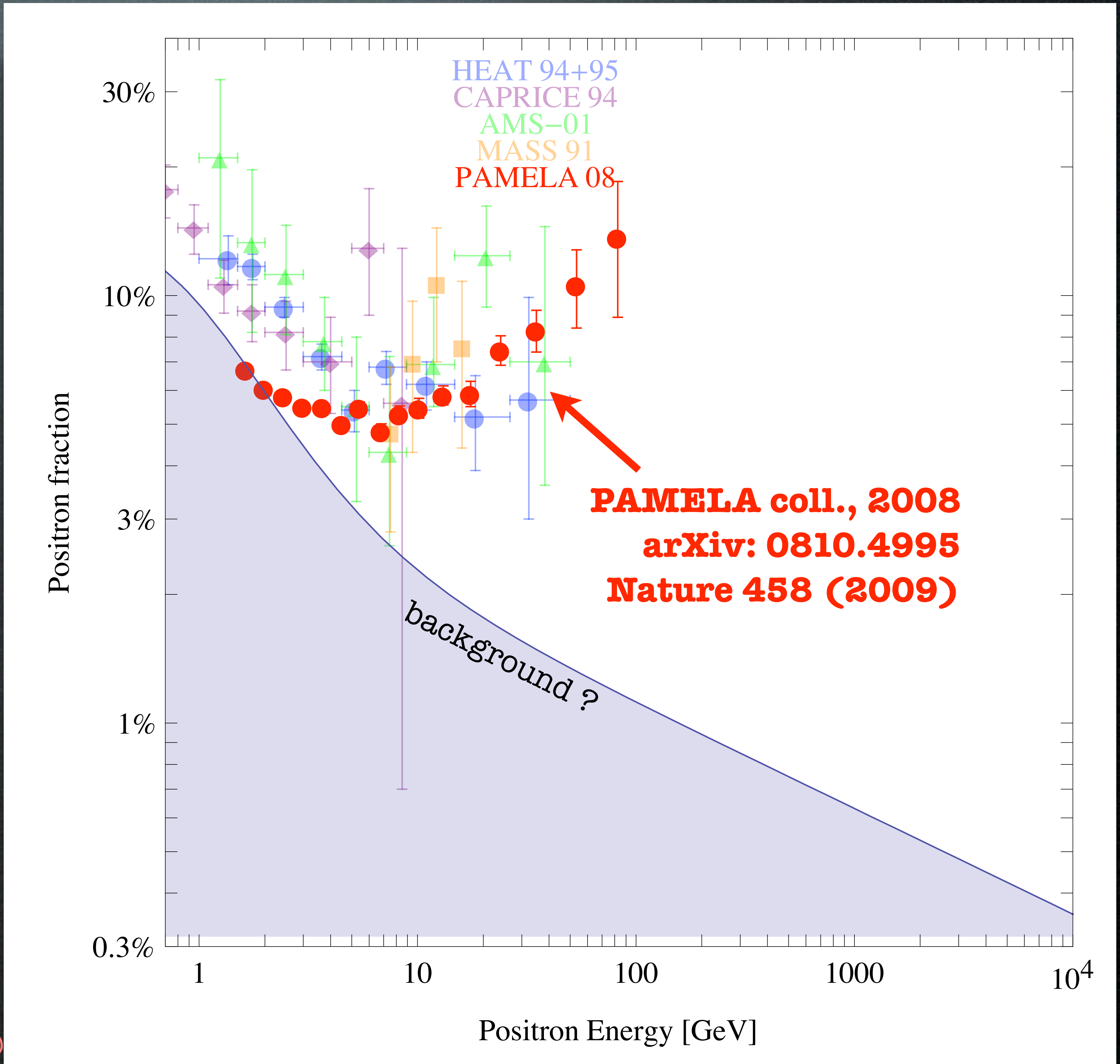
Positrons from PAMELA:

- 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)

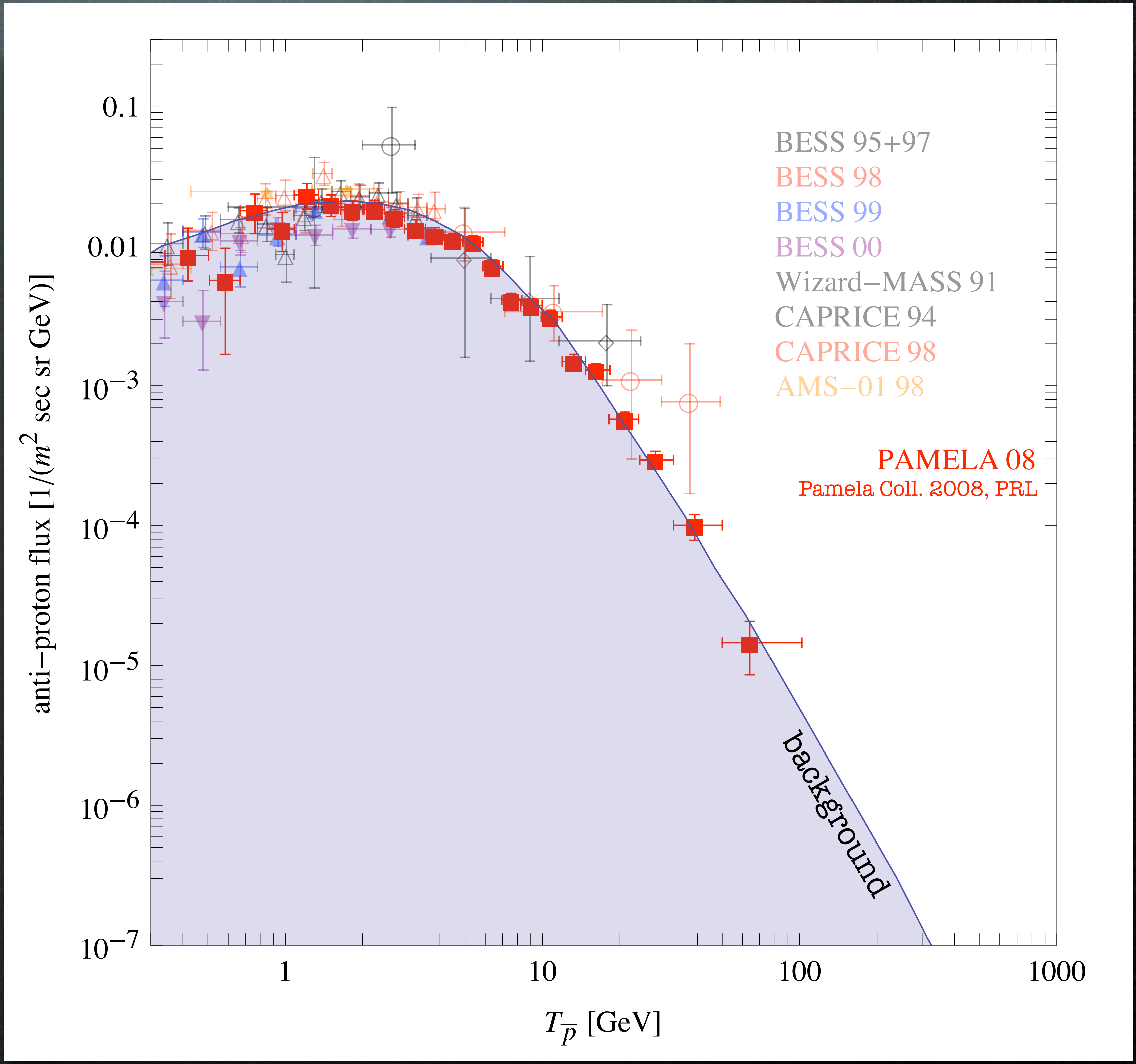


[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background



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

Results

Which DM spectra can fit the data?

Results

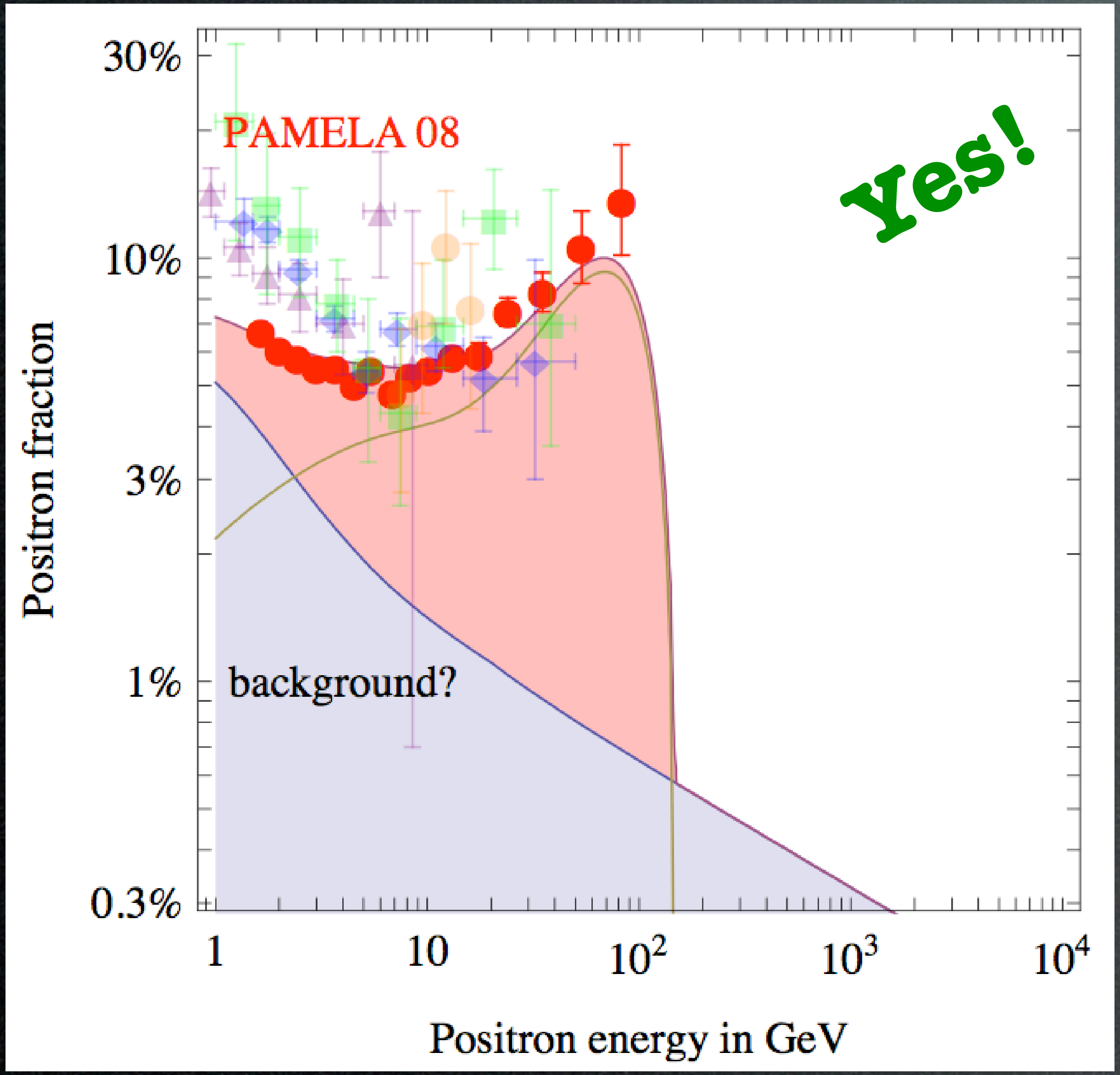
Which DM spectra can fit the data?

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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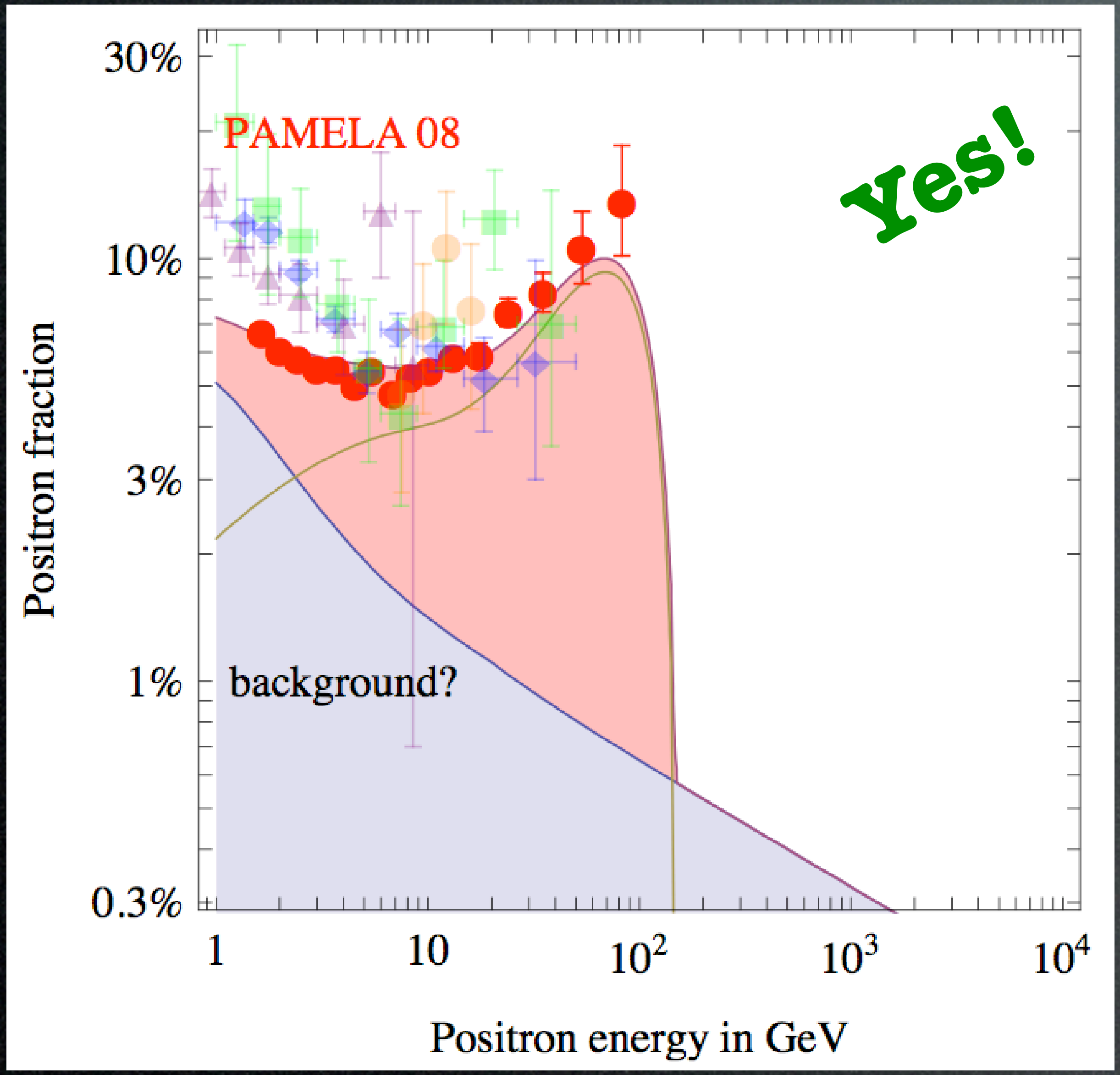
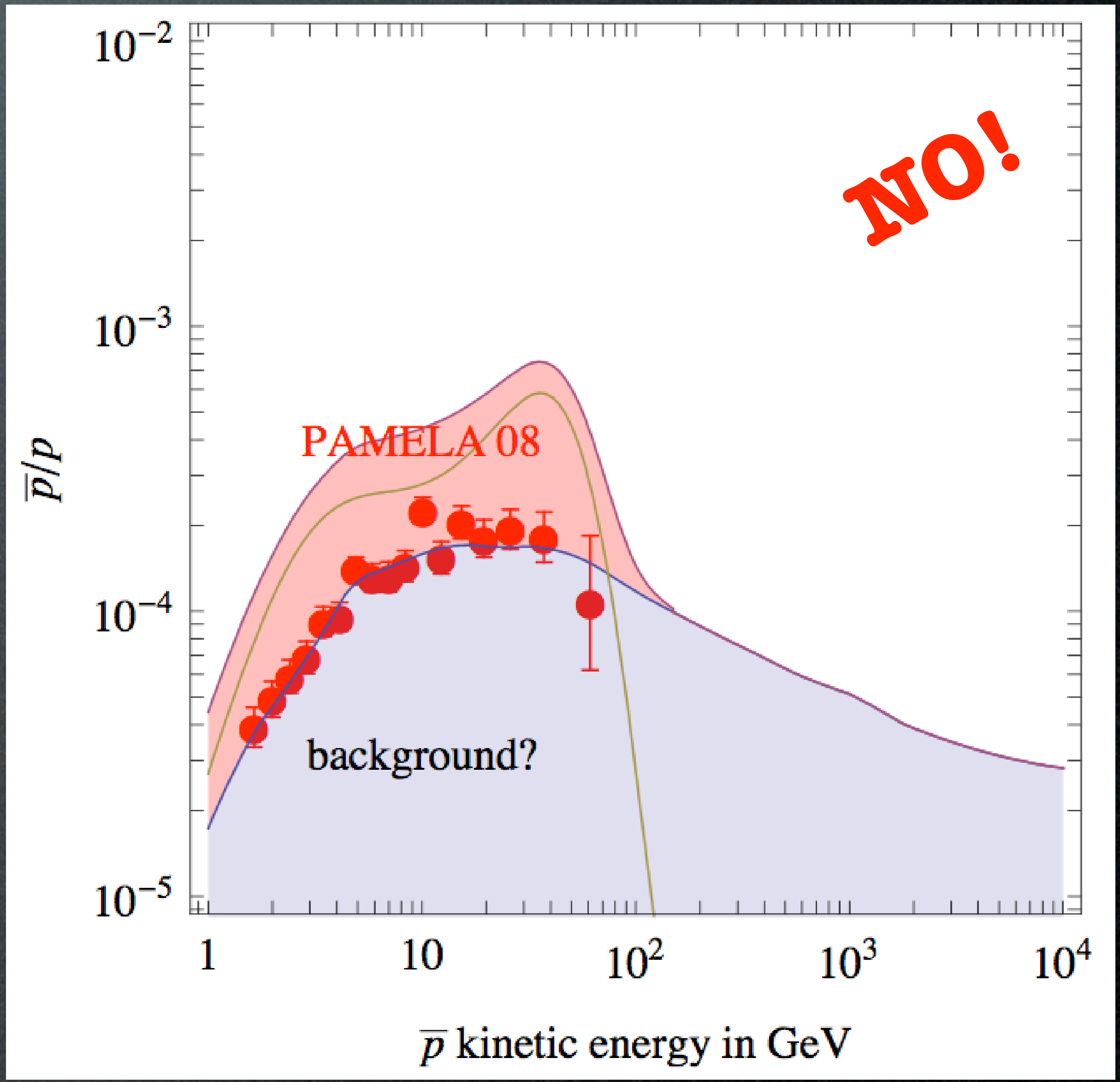


Anti-protons:



[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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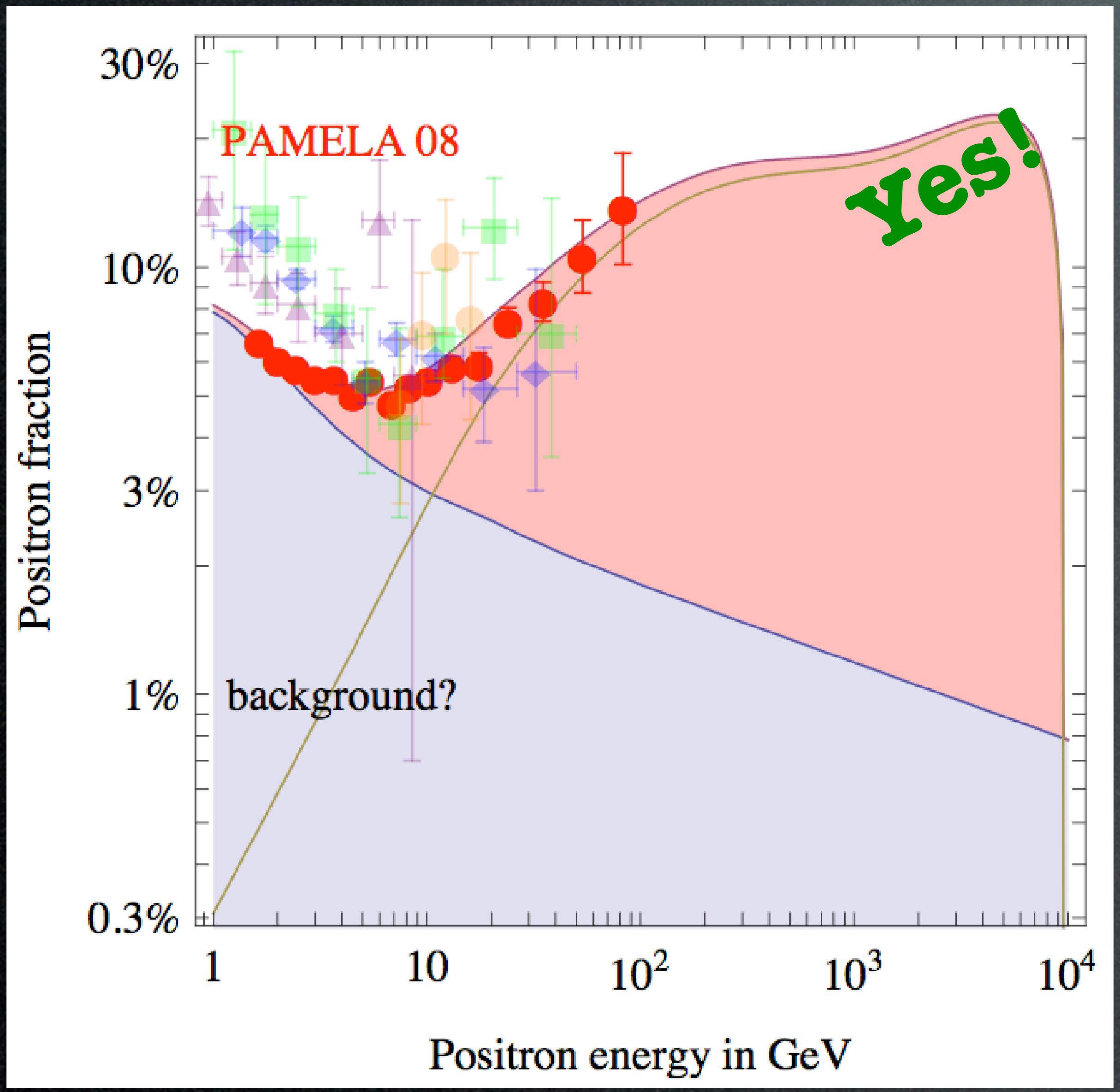

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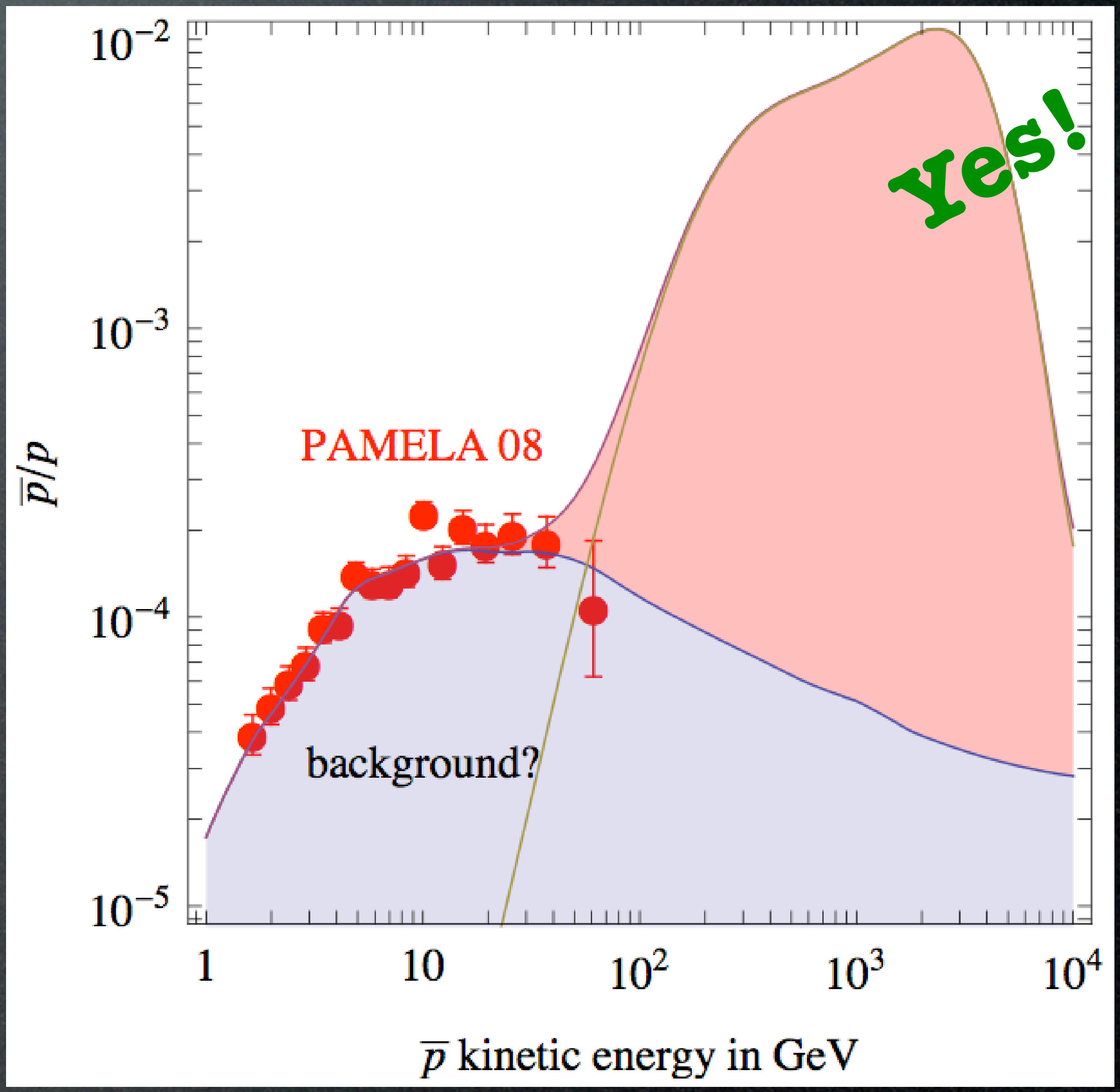


Results

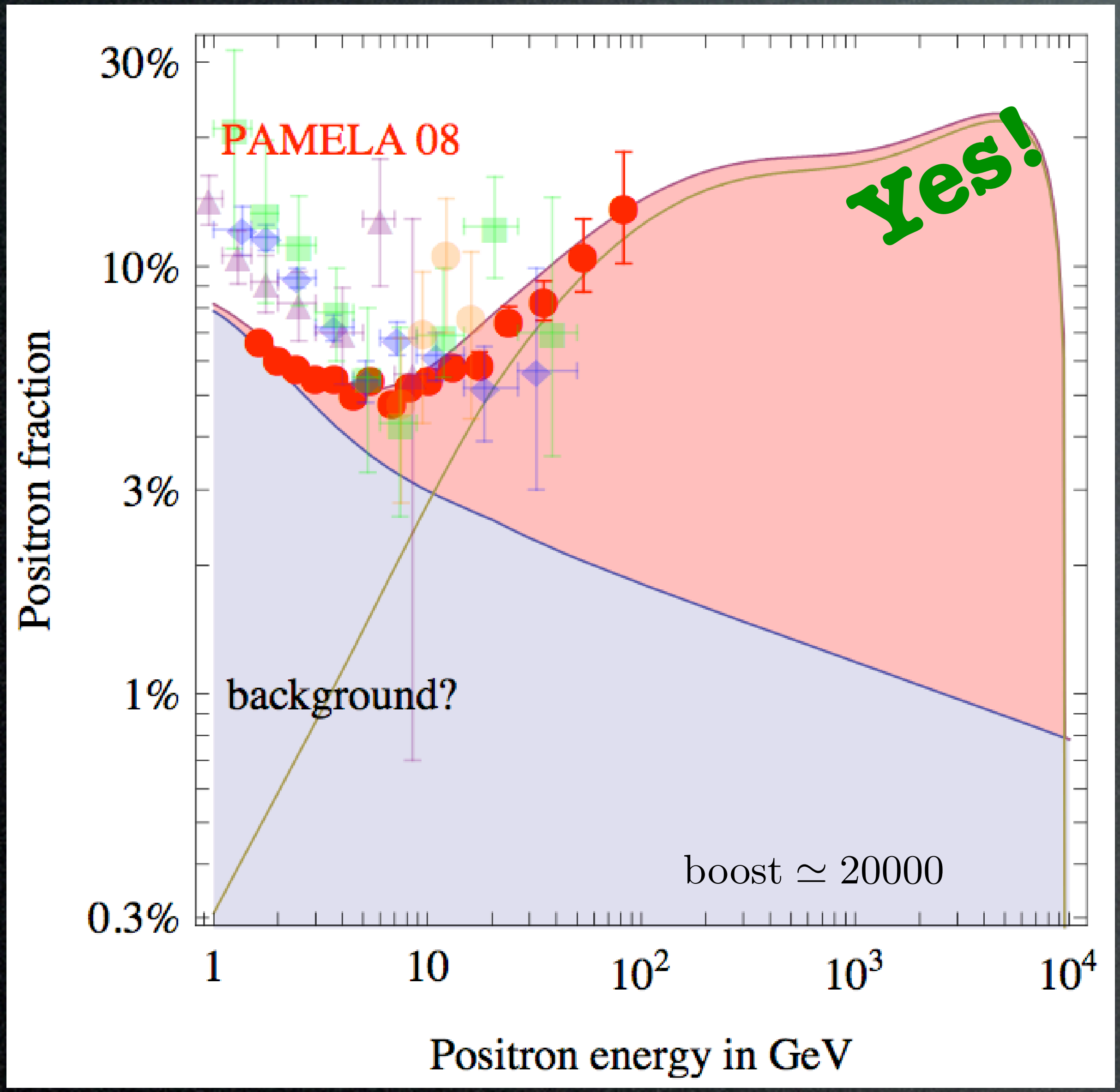
Which DM spectra can fit the data?

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

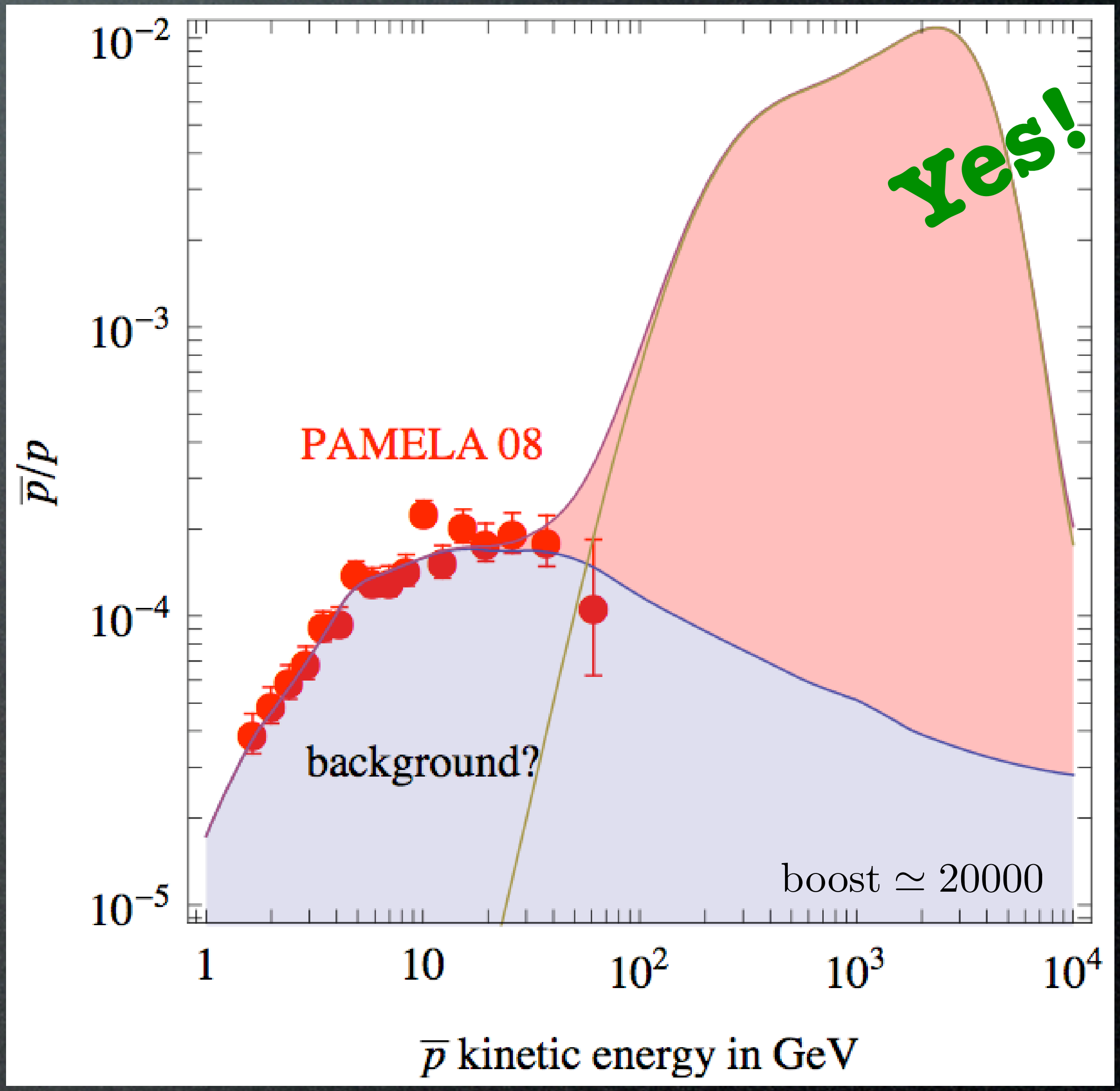
-annihilation $\text{DM DM} \to W^+W^-$

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 $M_{\rm DM} = 9.7\,\text{TeV}$

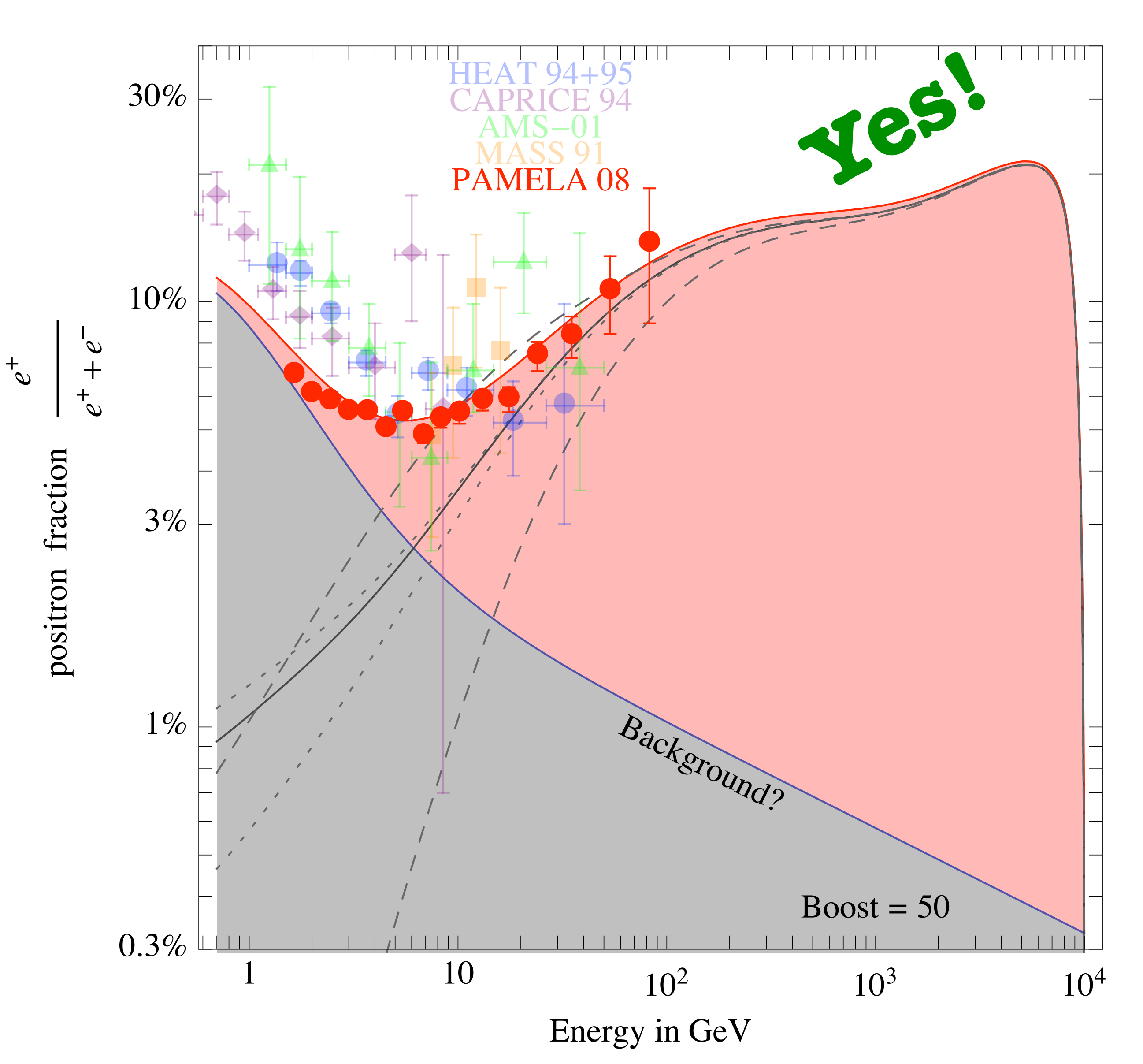
[Cirelli, Strumia et al. 2006]

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

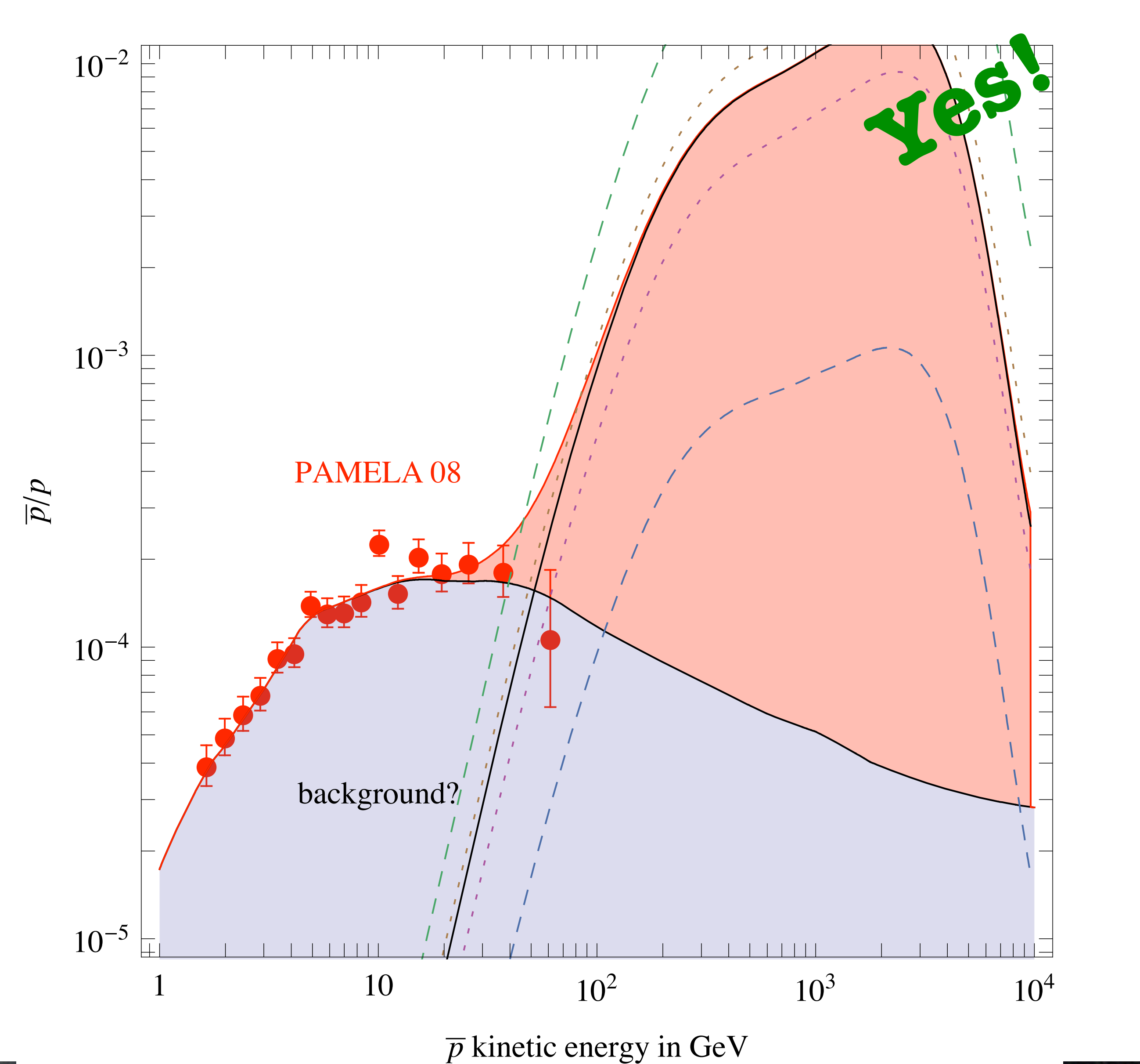
-boost $B \simeq 30$ Yes!

[thanks to **Sommerfeld** enhancement]

Positrons:



Anti-protons:

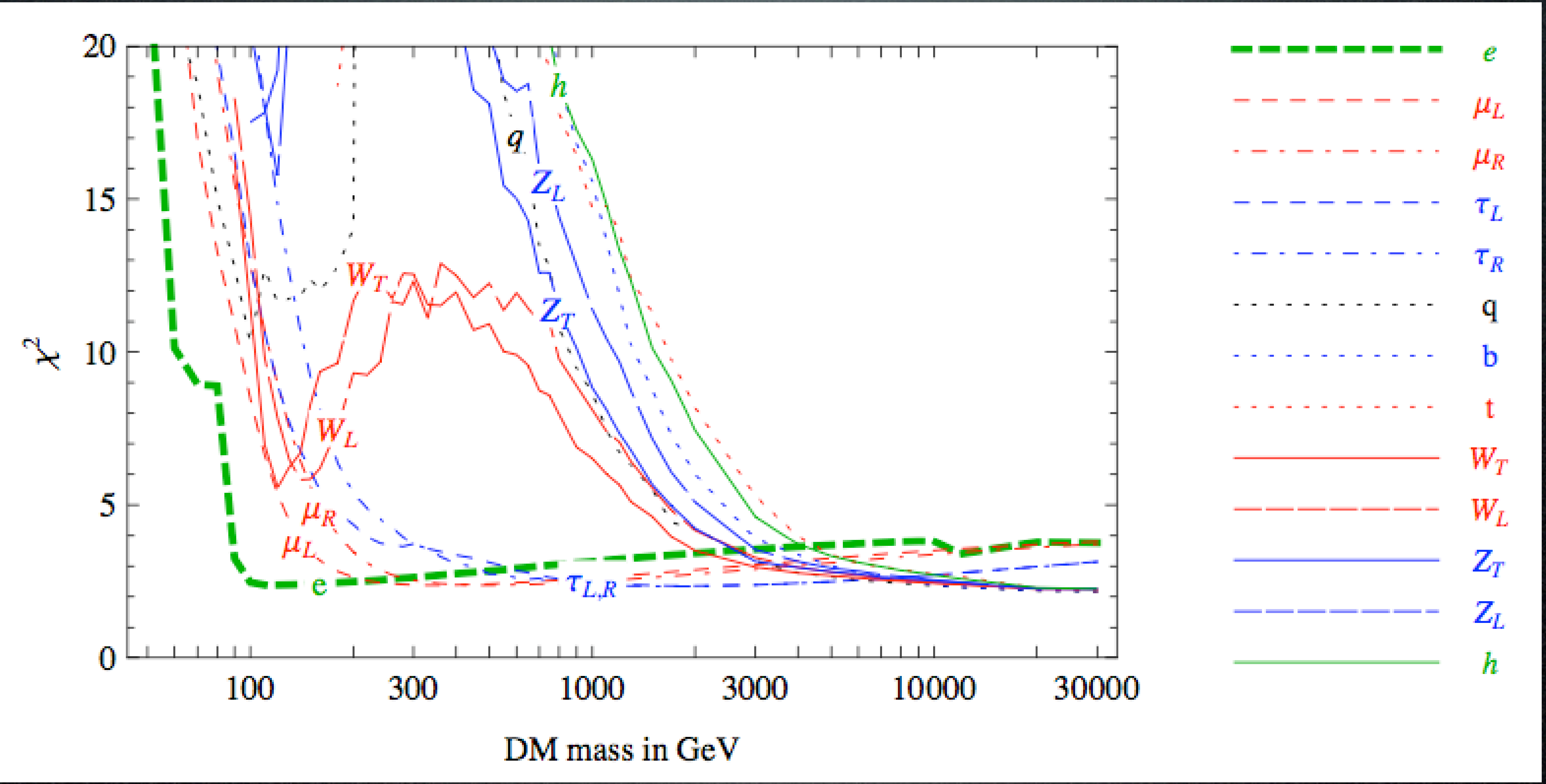


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons only

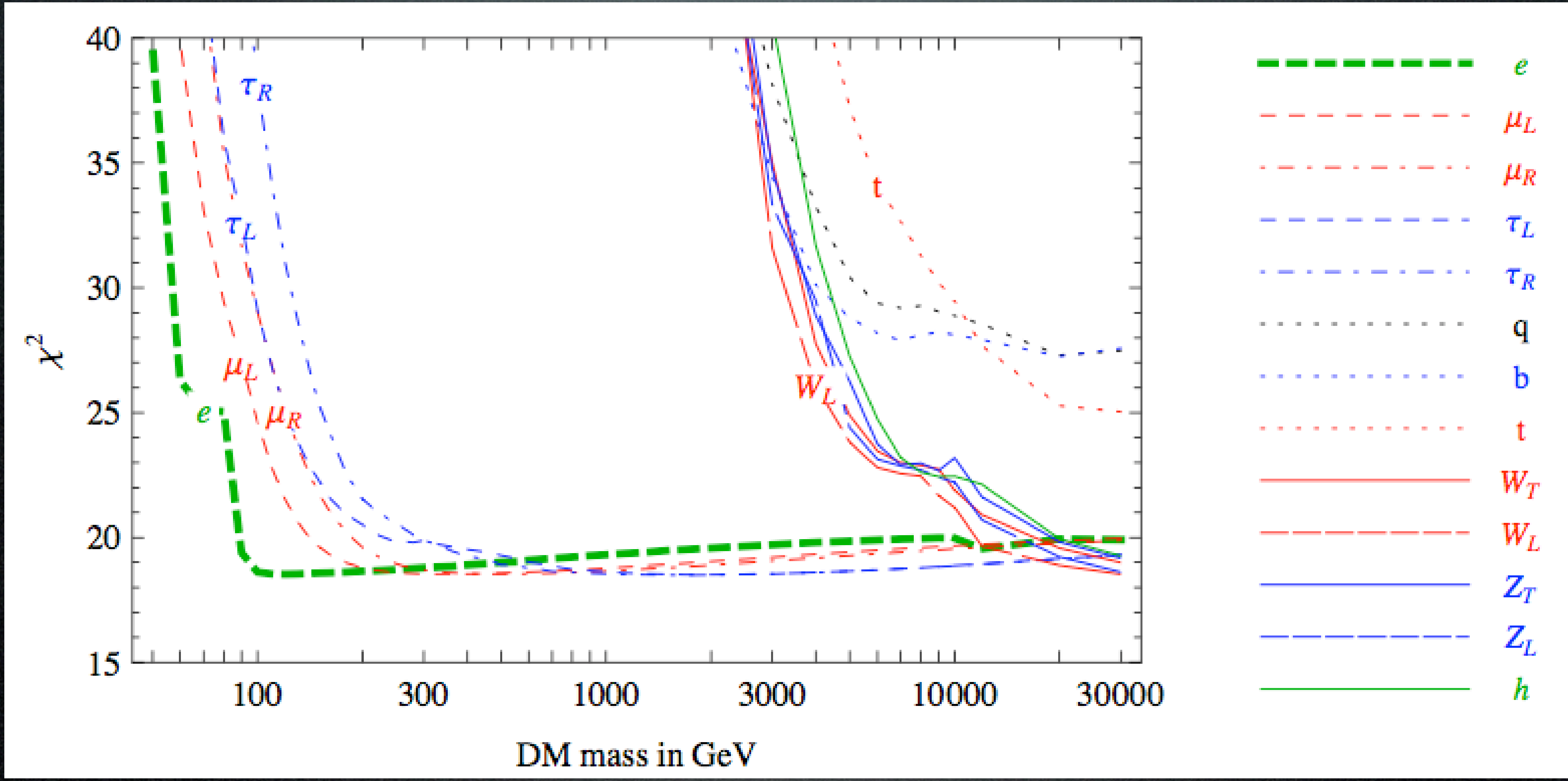


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



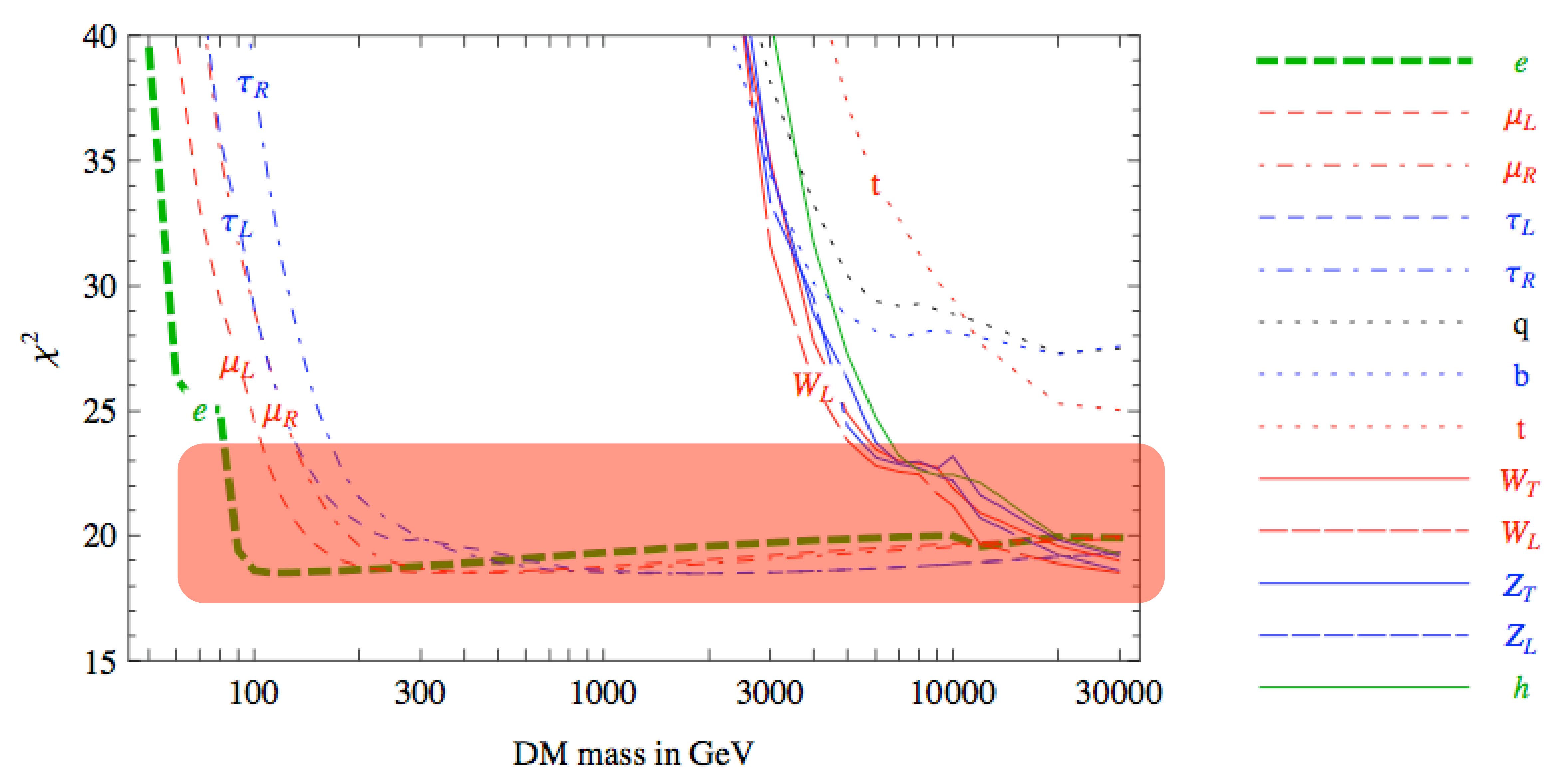
see also: Donato's talk today

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



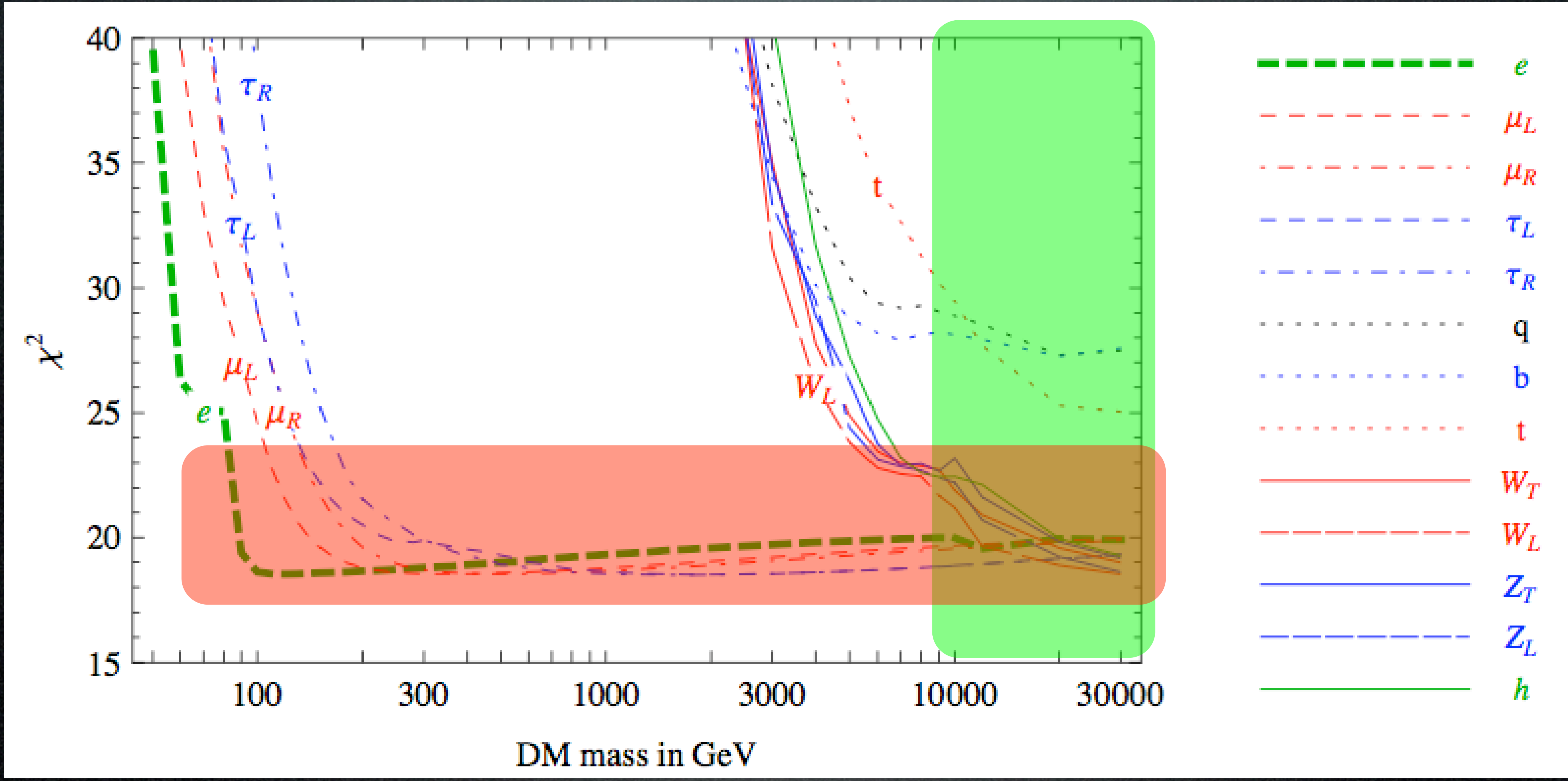
(1) annihilate into leptons (e.g. $\mu^+\mu^-$)

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



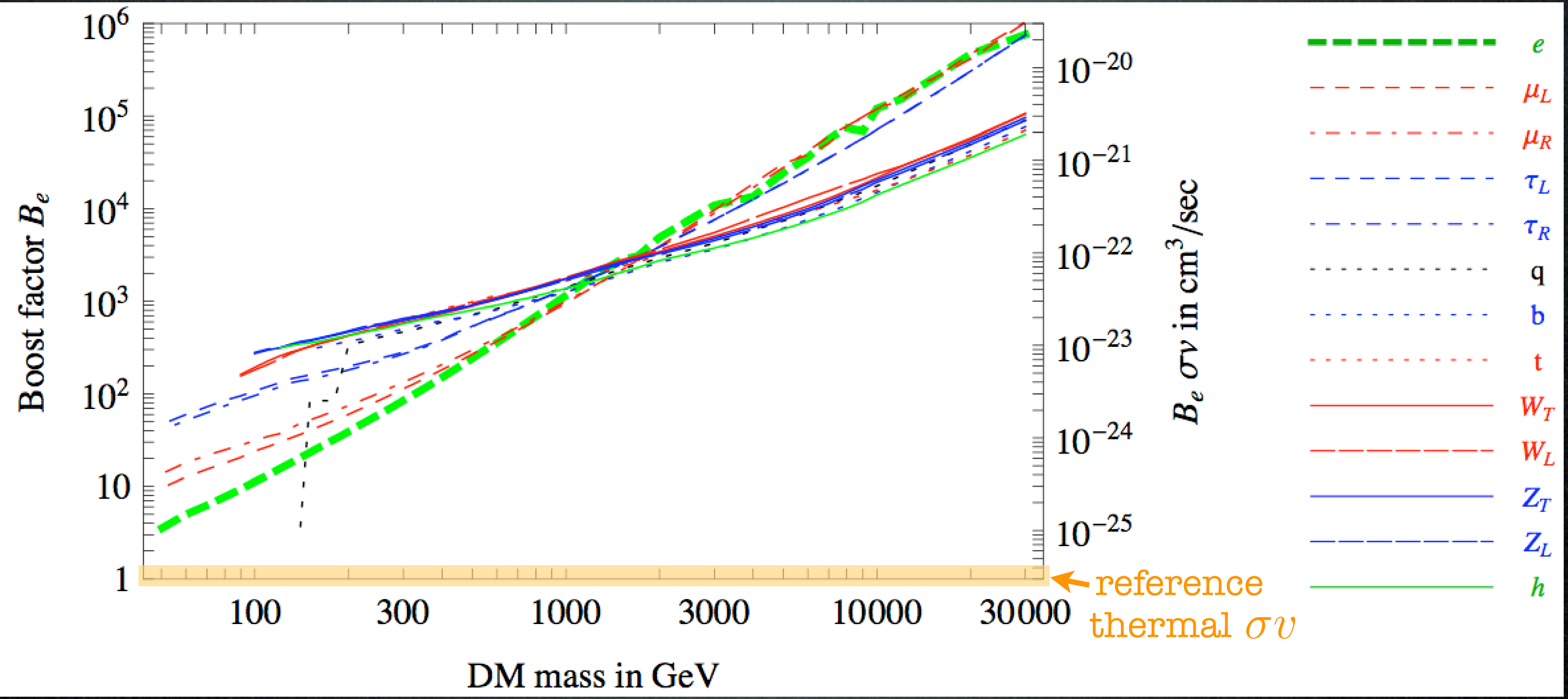
(1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

Results

Which DM spectra can fit the data?

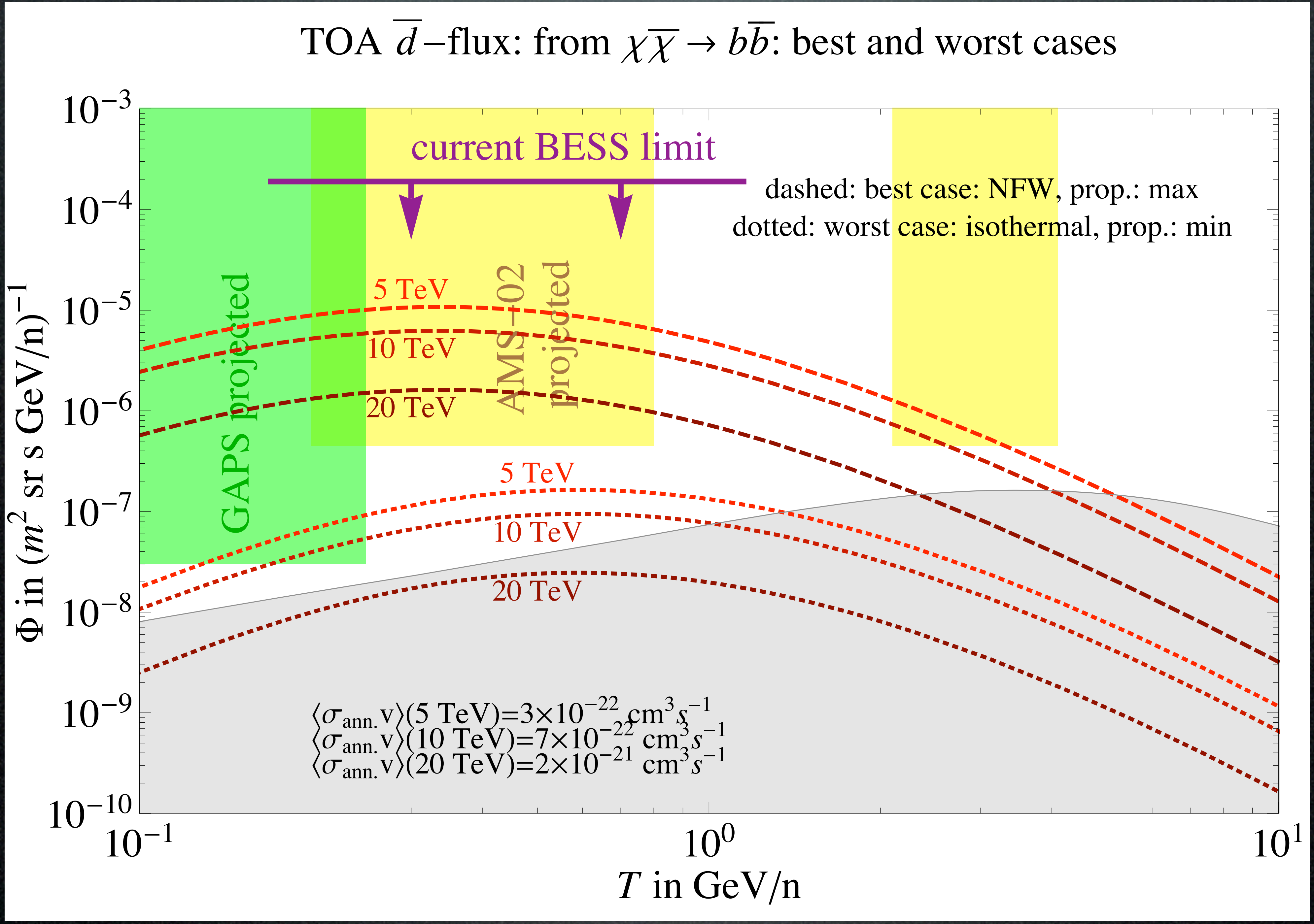
Model-independent results:

Boost required by PAMELA



Aside: anti-deuterium

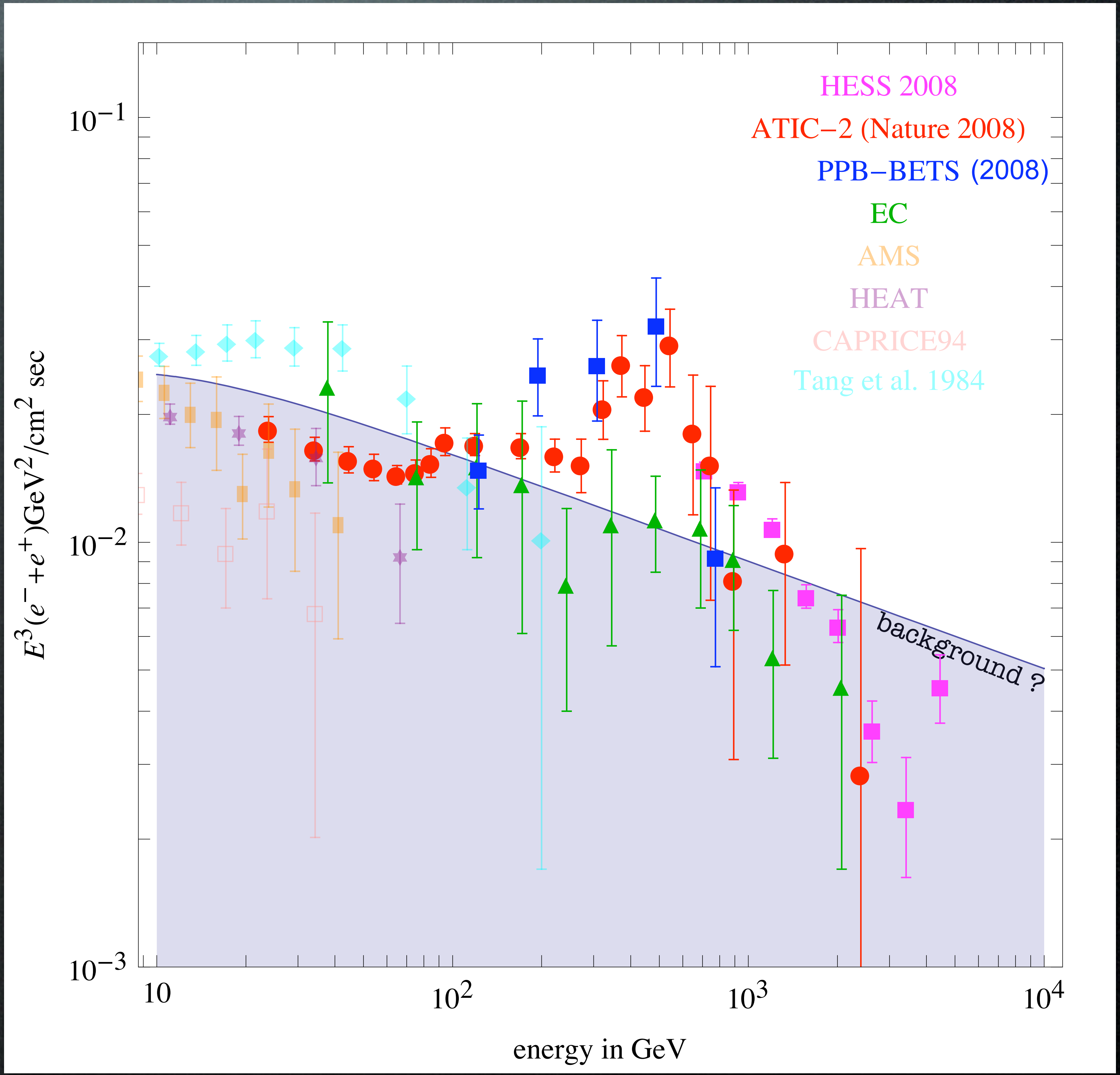
The signals from heavy, non-leptons-only DM are interesting!



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 ${\rm DM\ DM} \rightarrow \mu^+\mu^-$

Results

Which DM spectra can fit the data?

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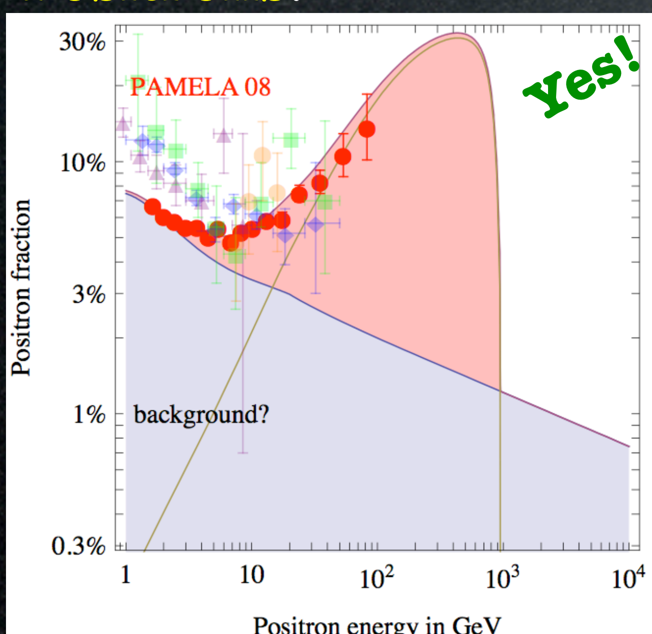
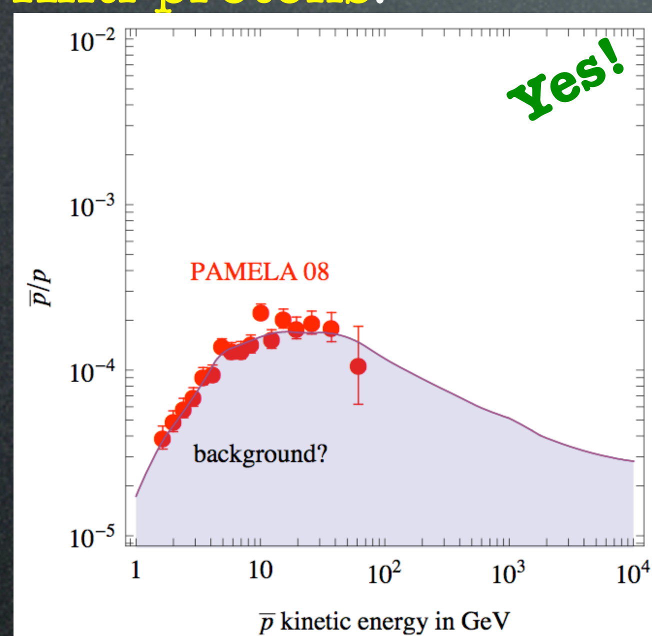
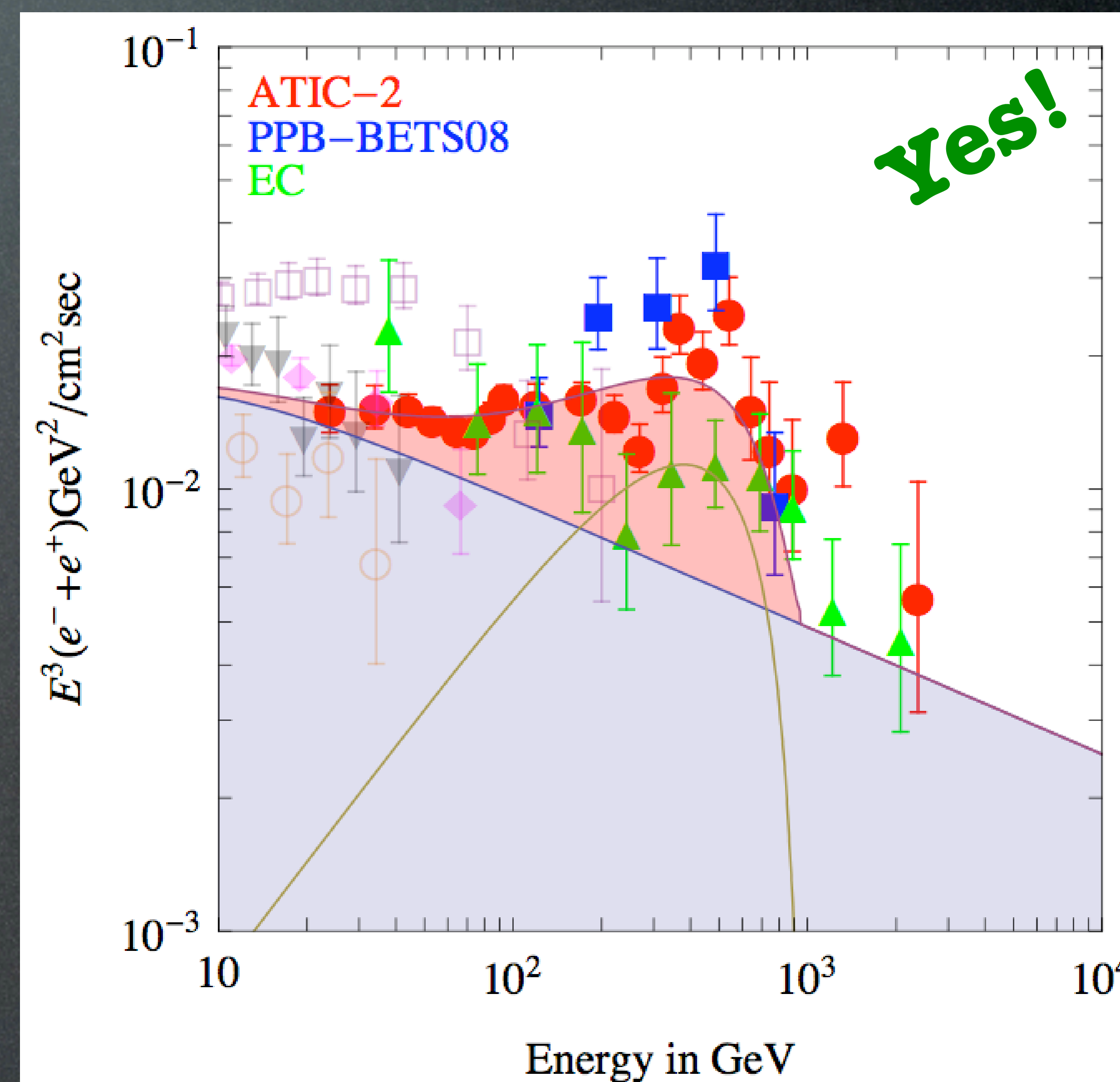
Positrons:



Anti-protons:



Electrons + Positrons:



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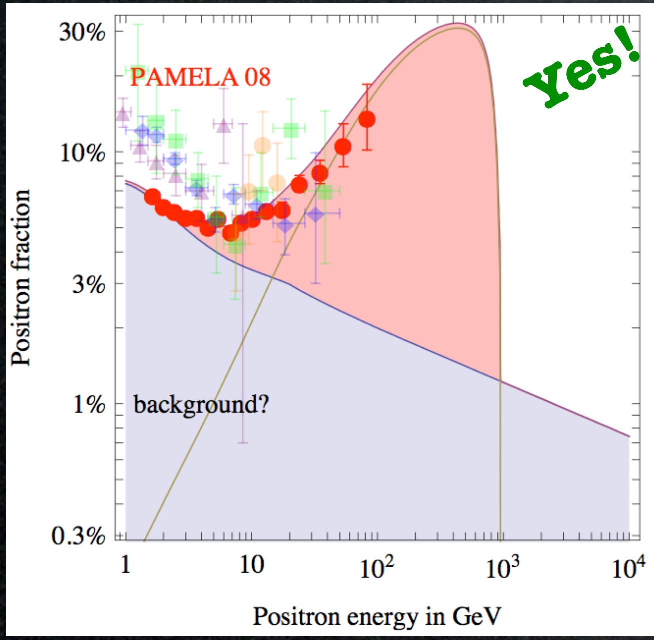

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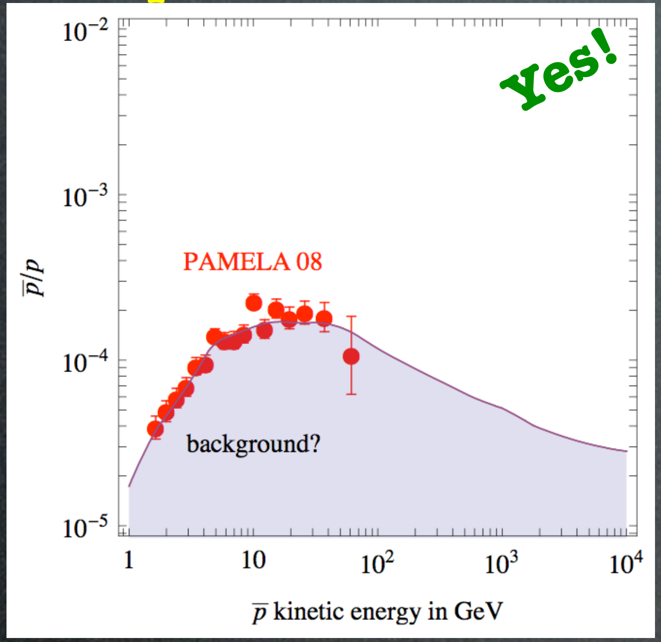

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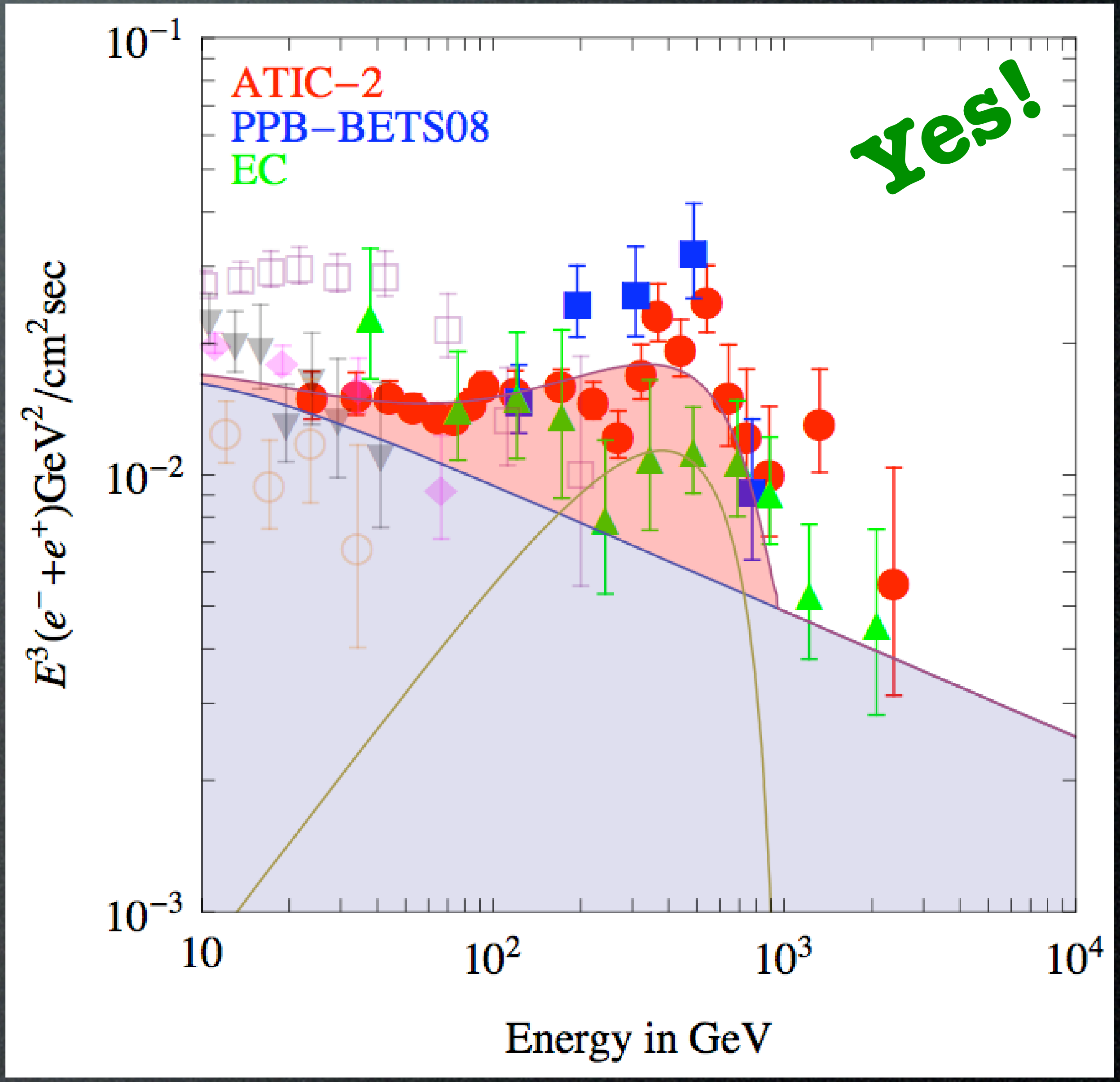

Have we identified the DM for the first time?

Results

Which DM can fit the data?

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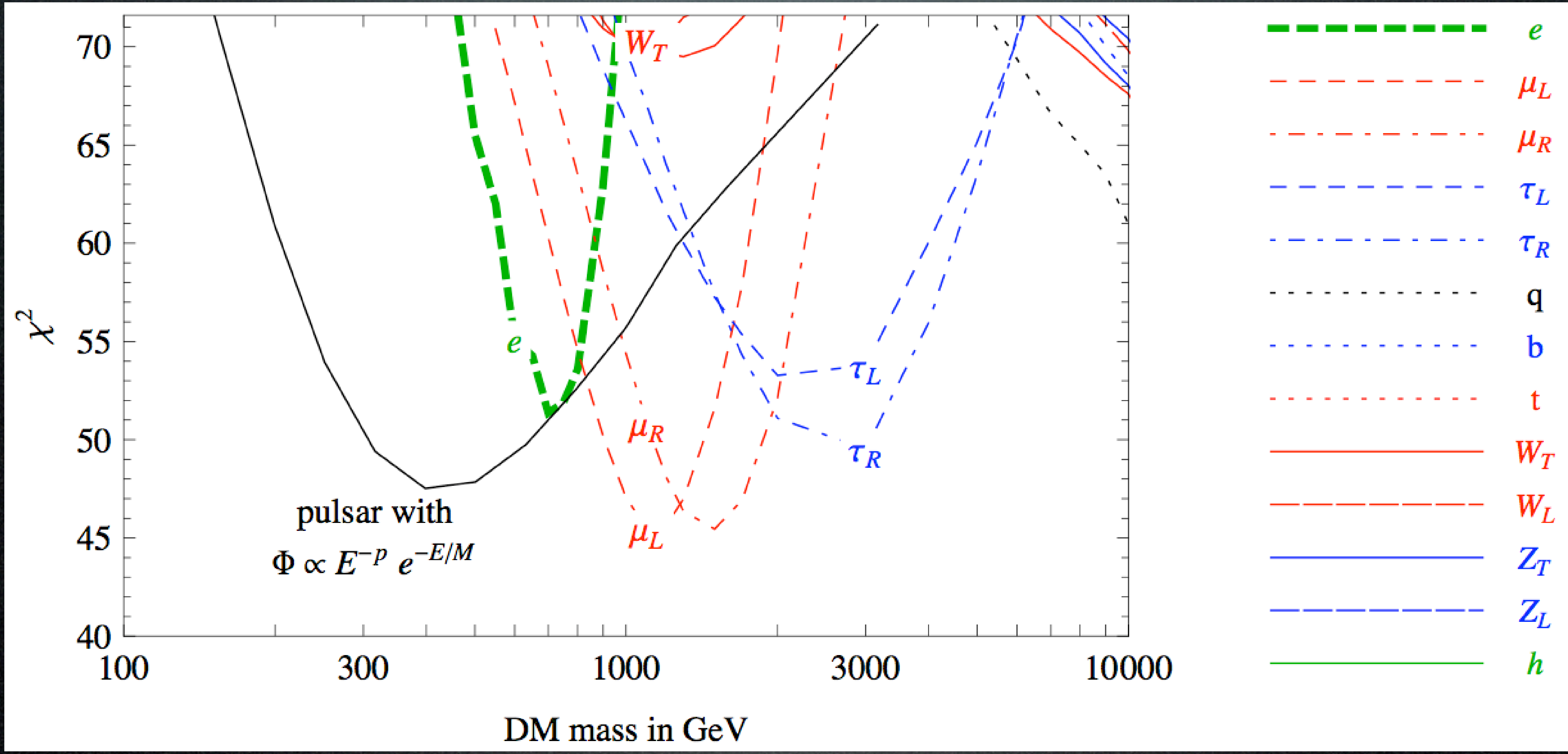
Results

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

Results

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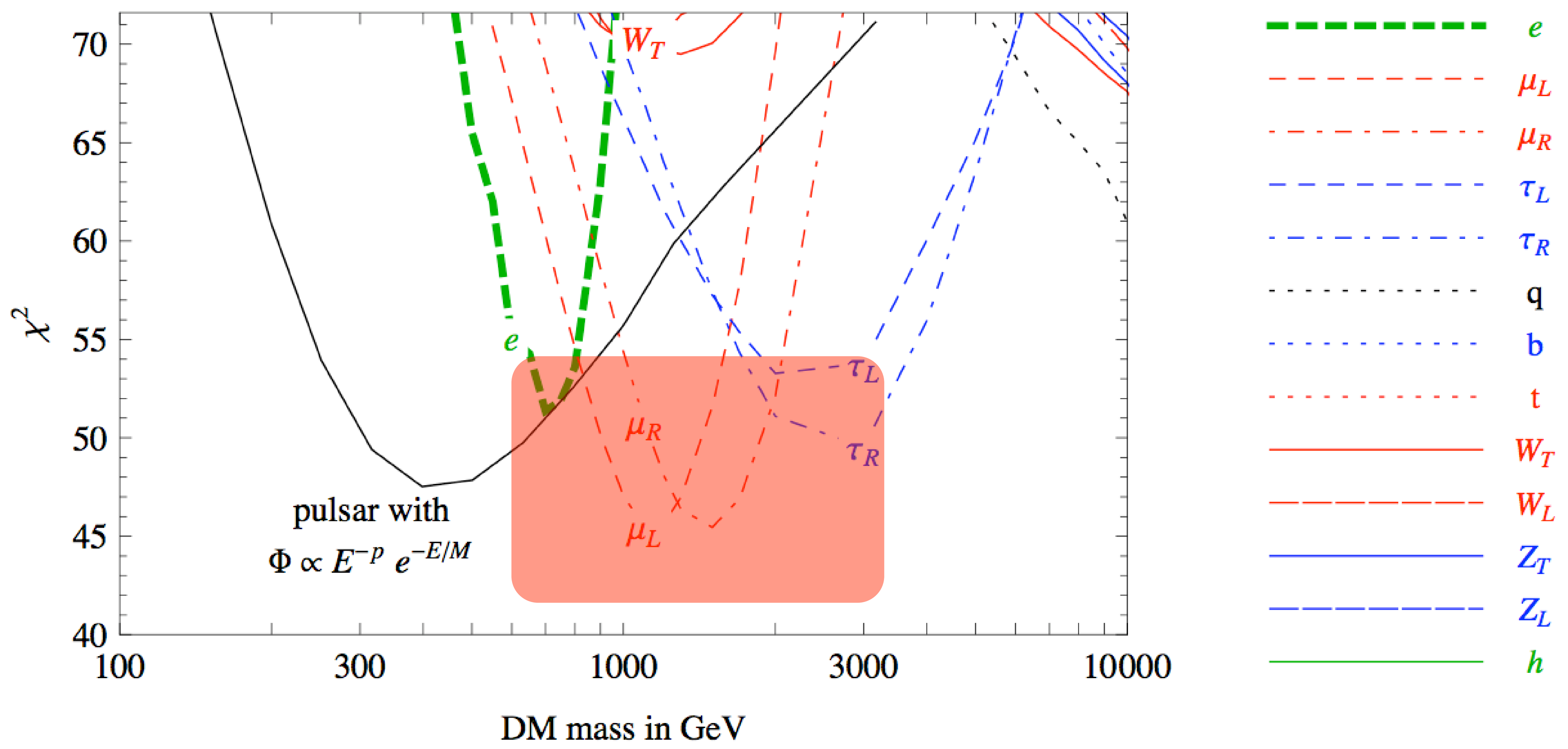


(1) annihilate into leptons (e.g. $\mu^+\mu^-$), mass ~1 TeV

Data sets

Electrons + positrons from FERMI:

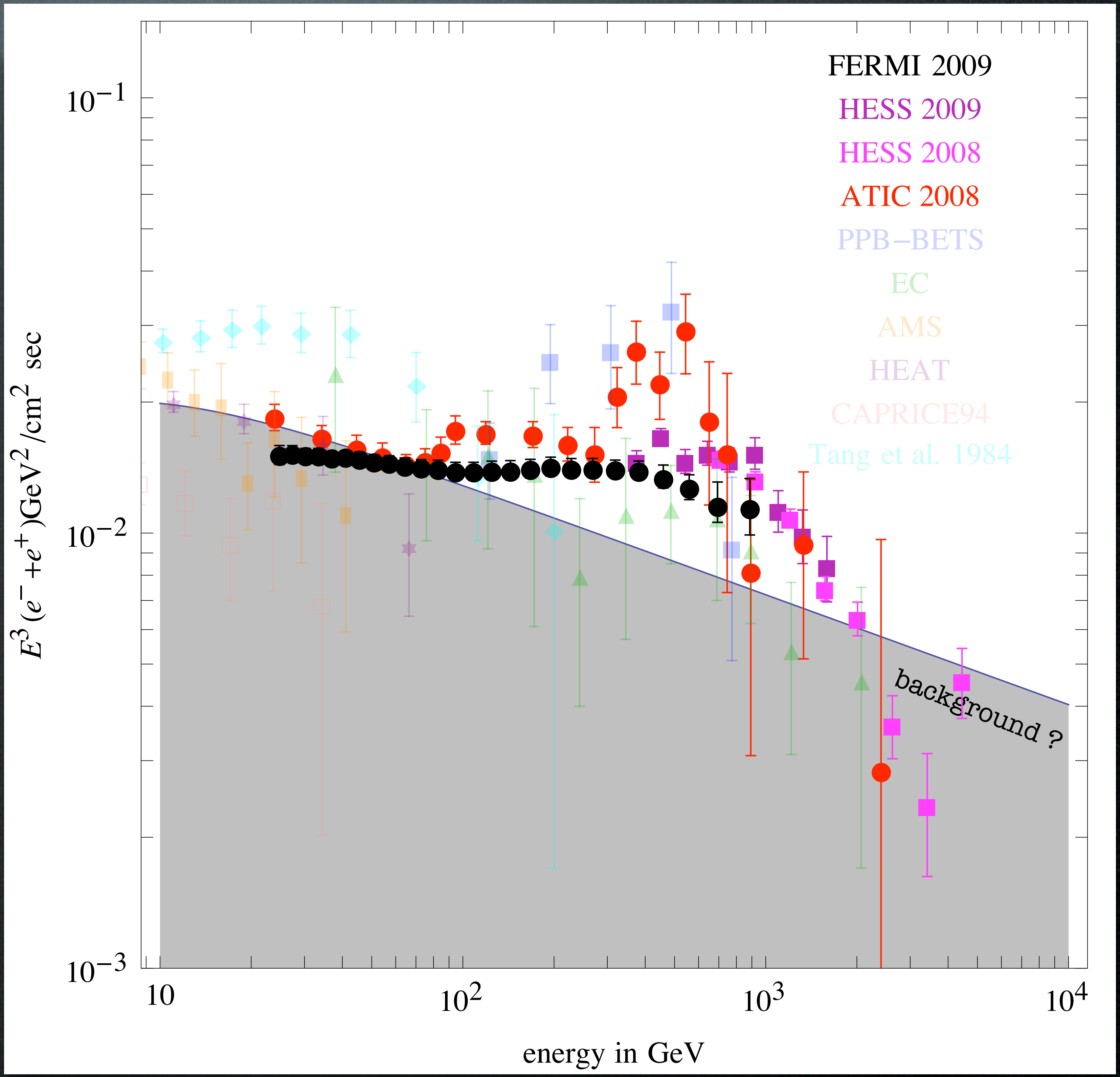
Fermi
Gamma-ray
Space Telescope

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

Data sets

Electrons + positrons adding FERMI:

- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$



[formerly predicted GLAST sensitivity]

Results

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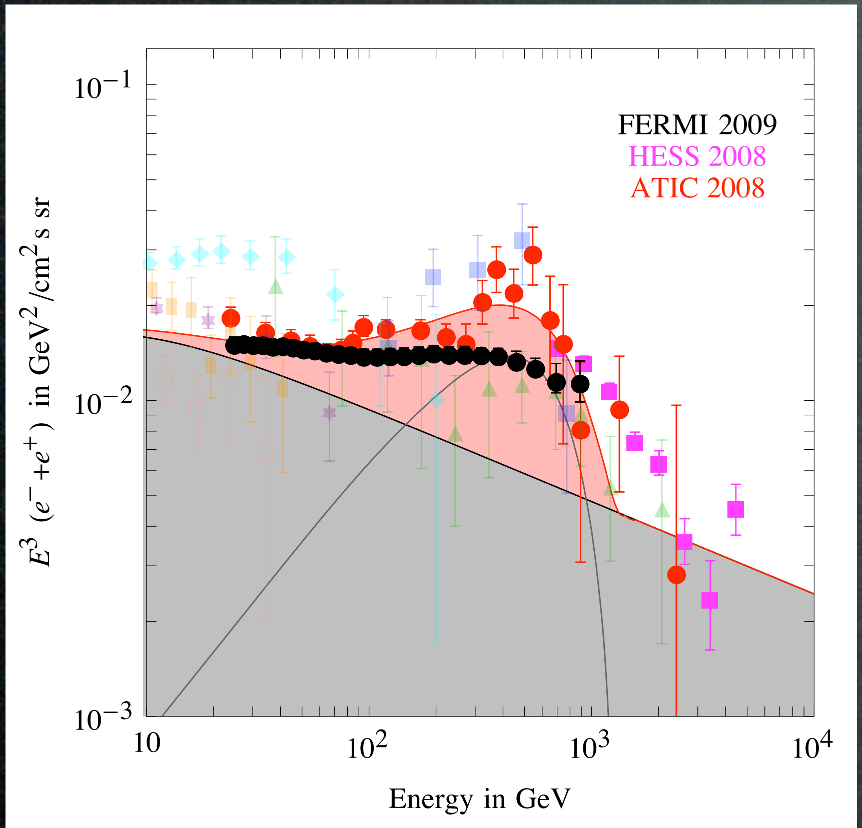
$\mu^+\mu^-, M_{\rm DM} \simeq 1\ \rm TeV$



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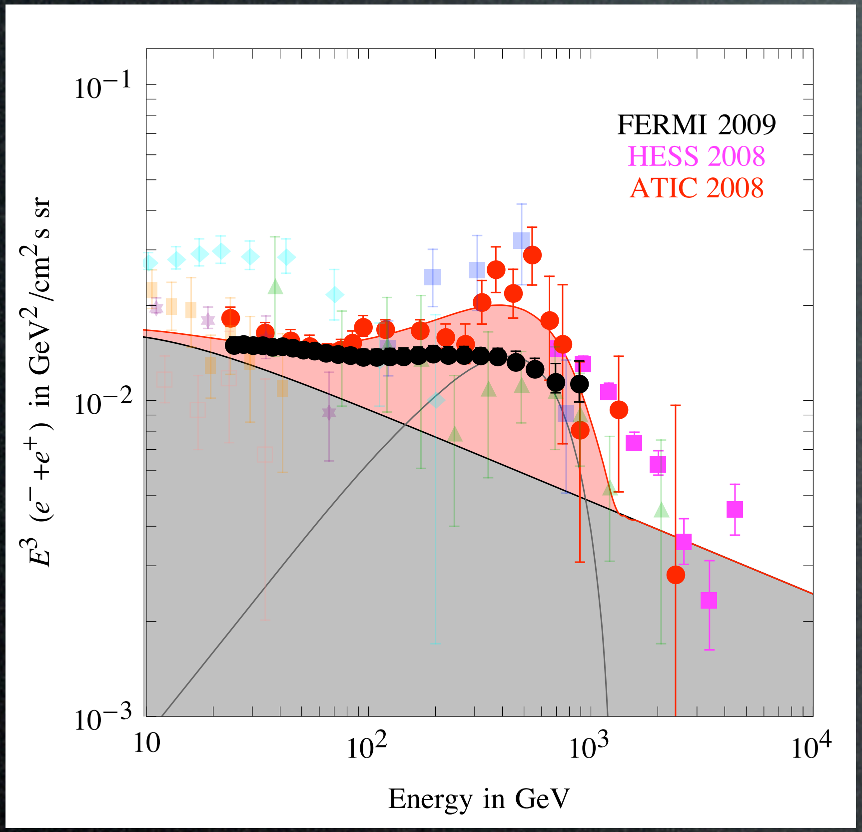
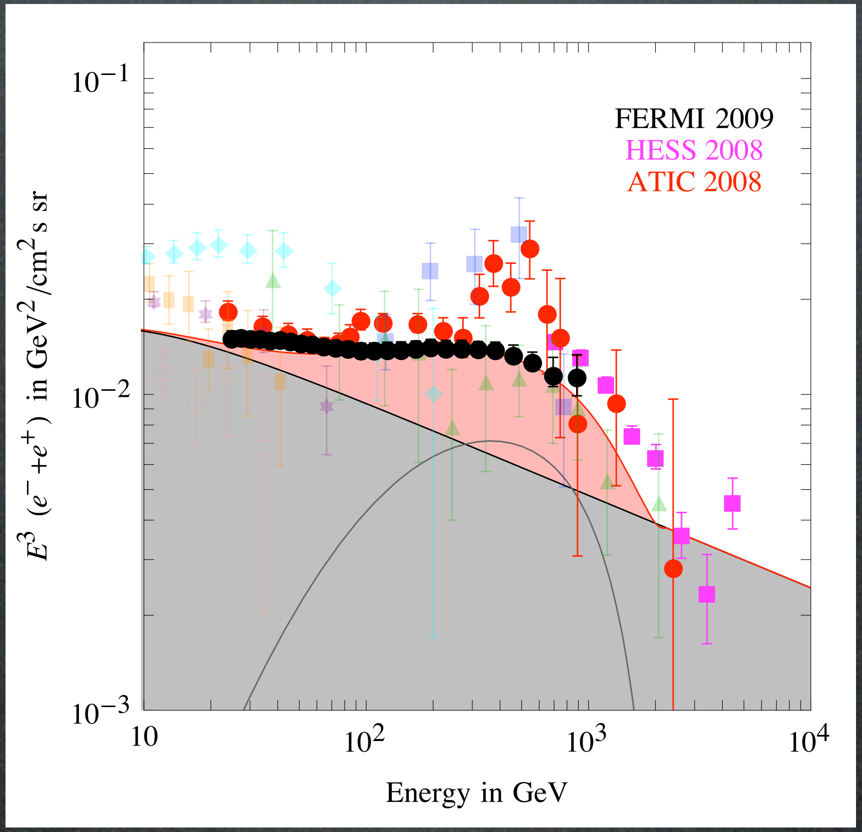


$\tau^+\tau^-, M_{\rm DM} \simeq 2\,\text{TeV}$



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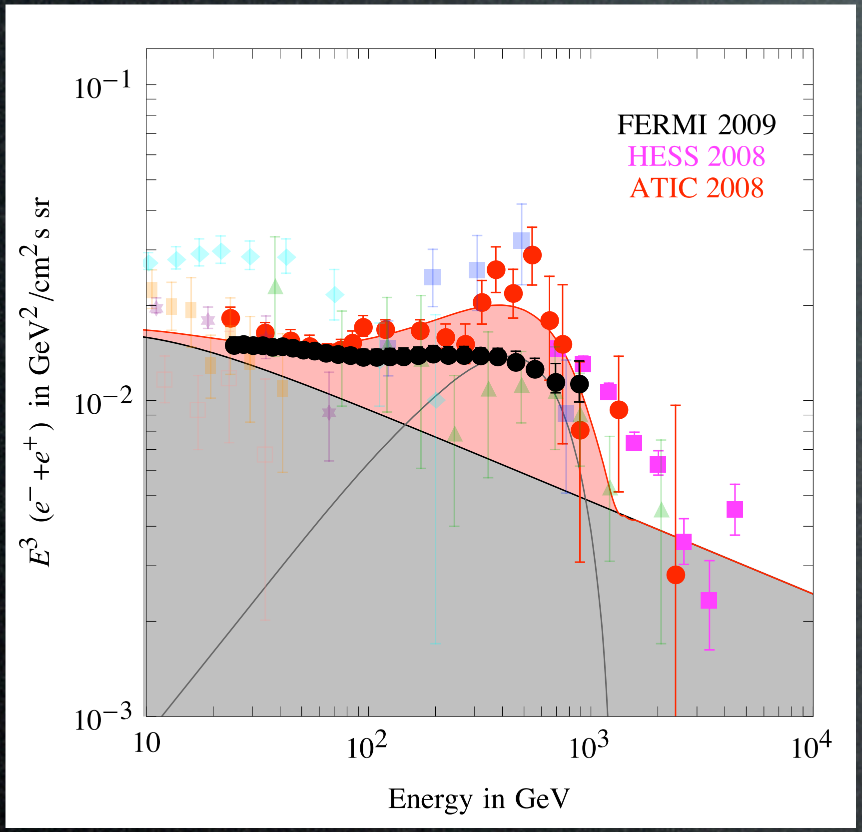

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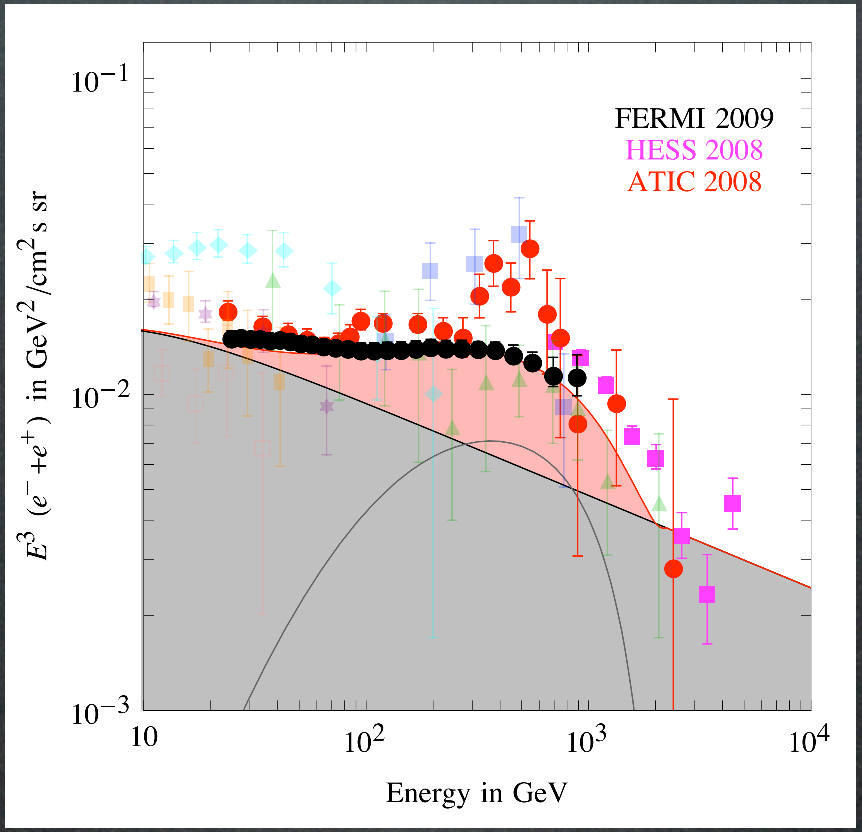

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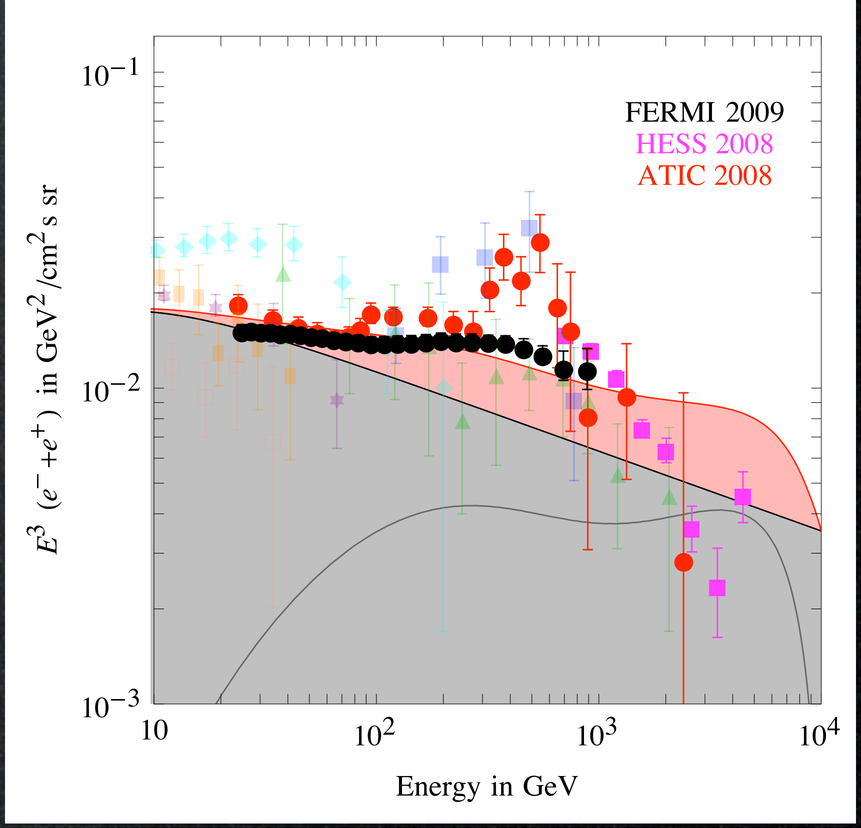

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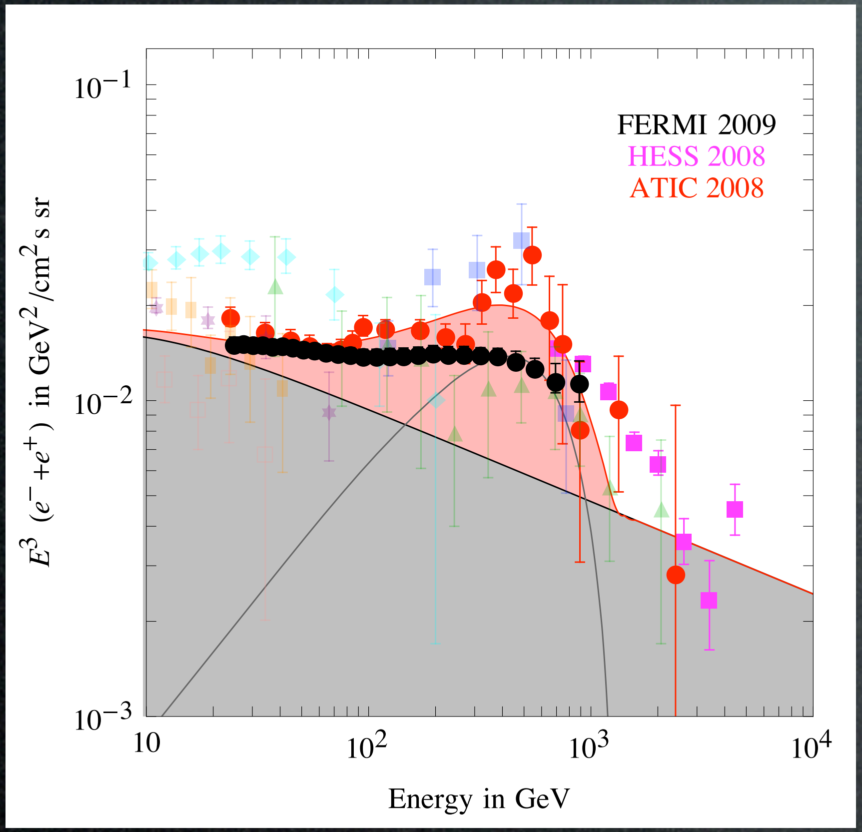

Notice:
- same spectra still fit PAMELA positron and anti-protons!

Caveats:
- scanning **non-**systematically propagation parameters
- varying background (within errors)
- annihilations only (direct ones; and no decay)

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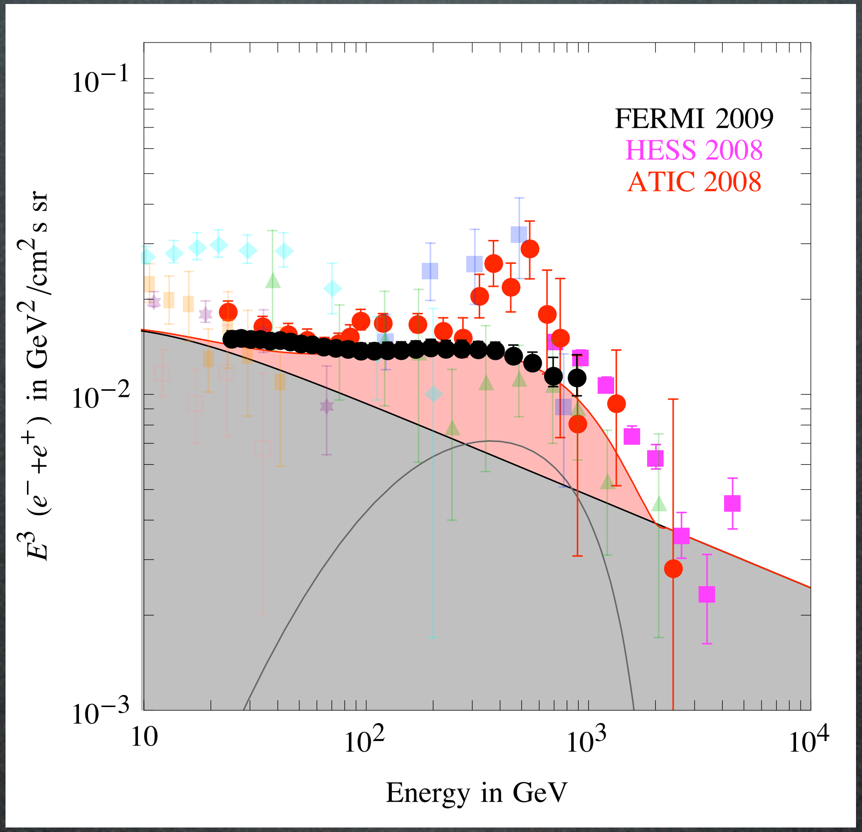

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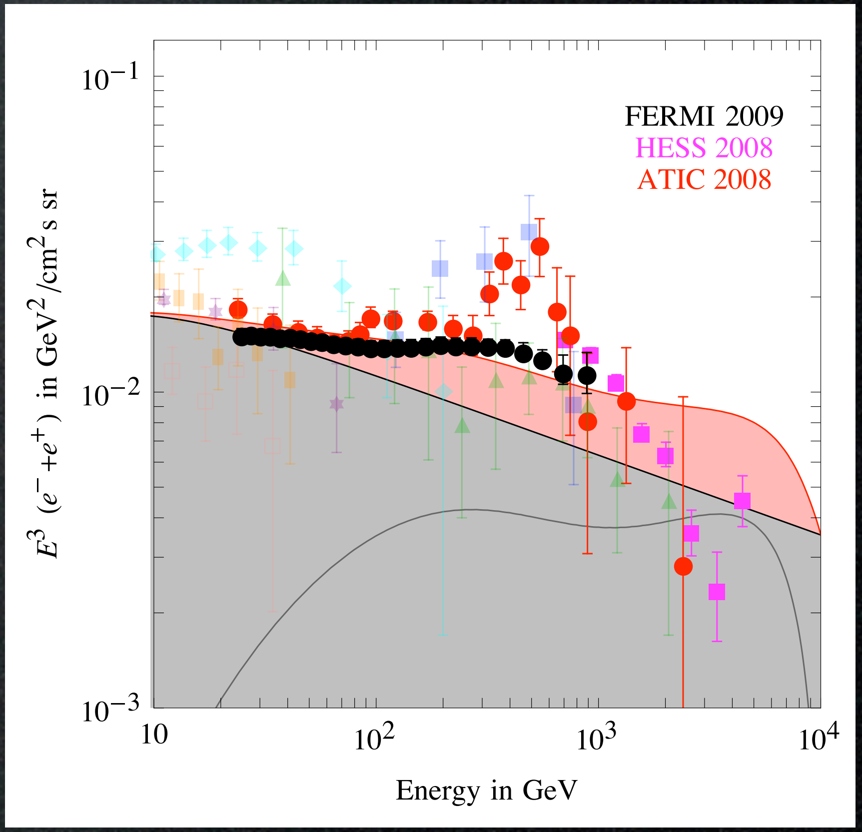

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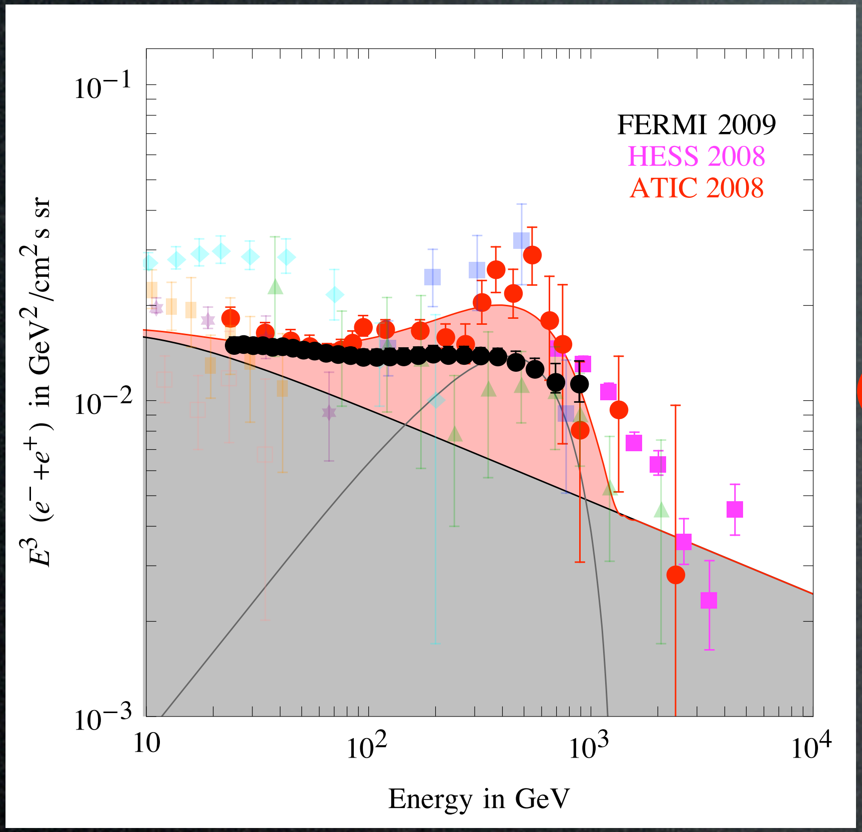

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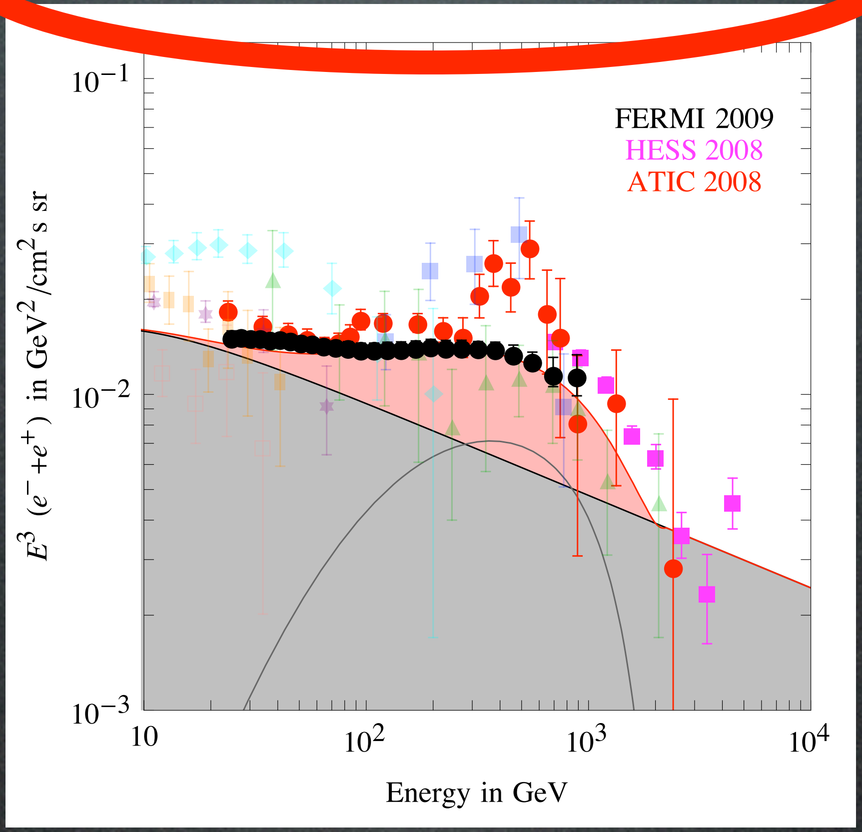

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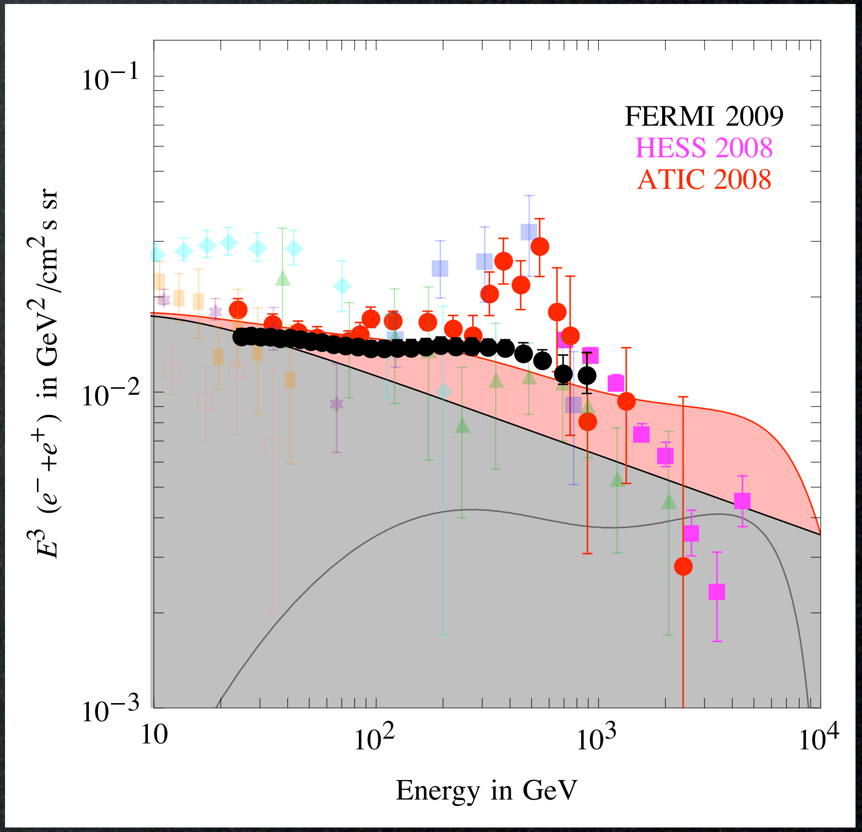

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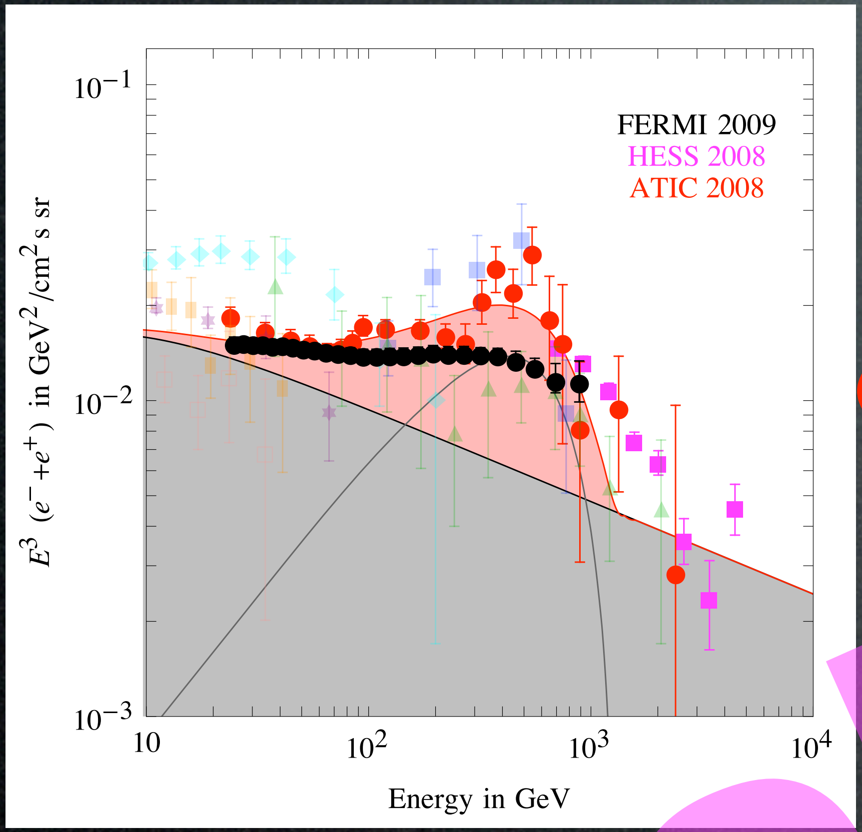

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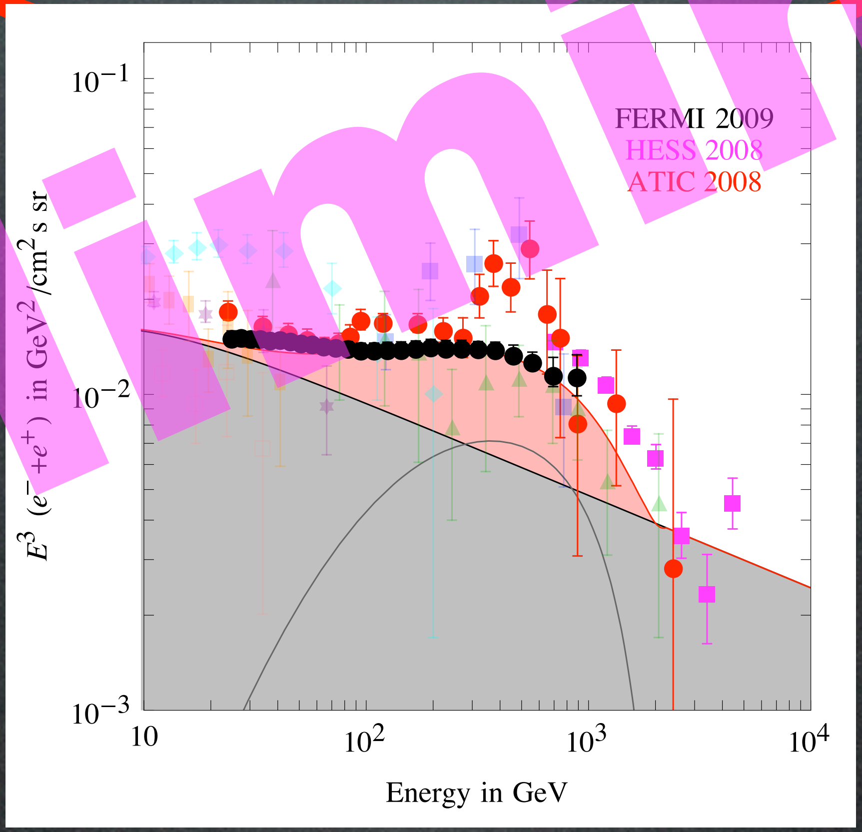

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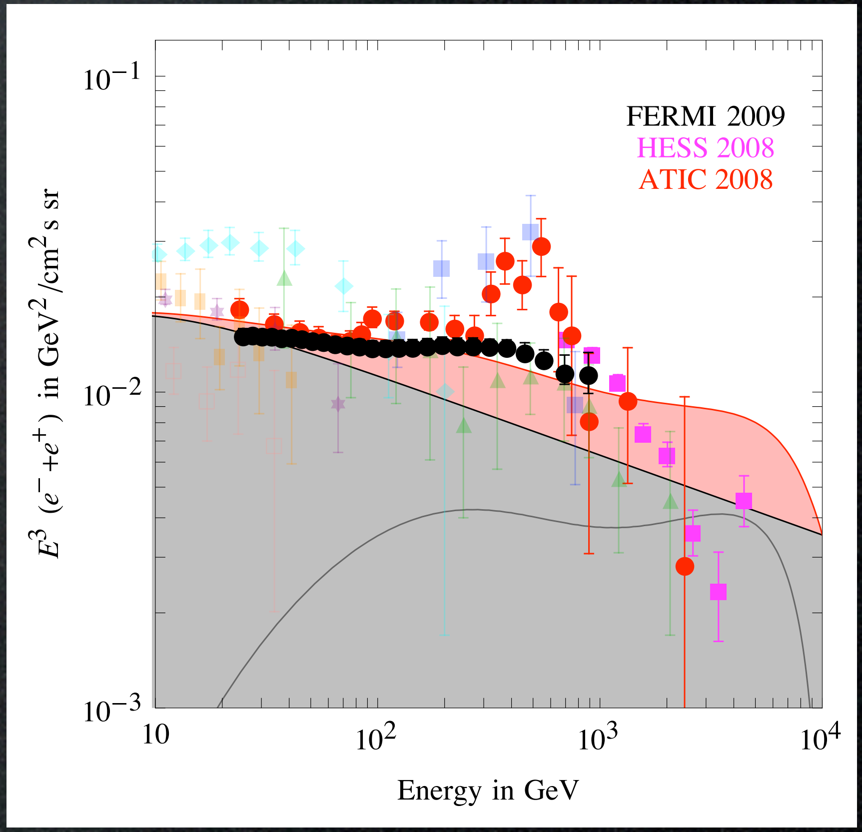

Preliminary

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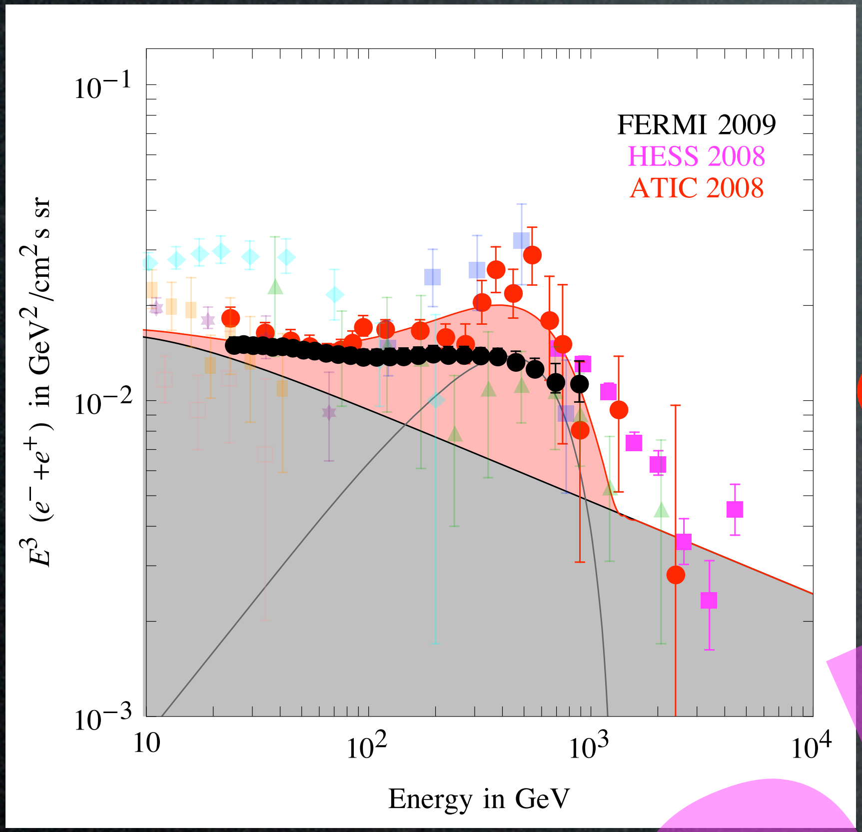

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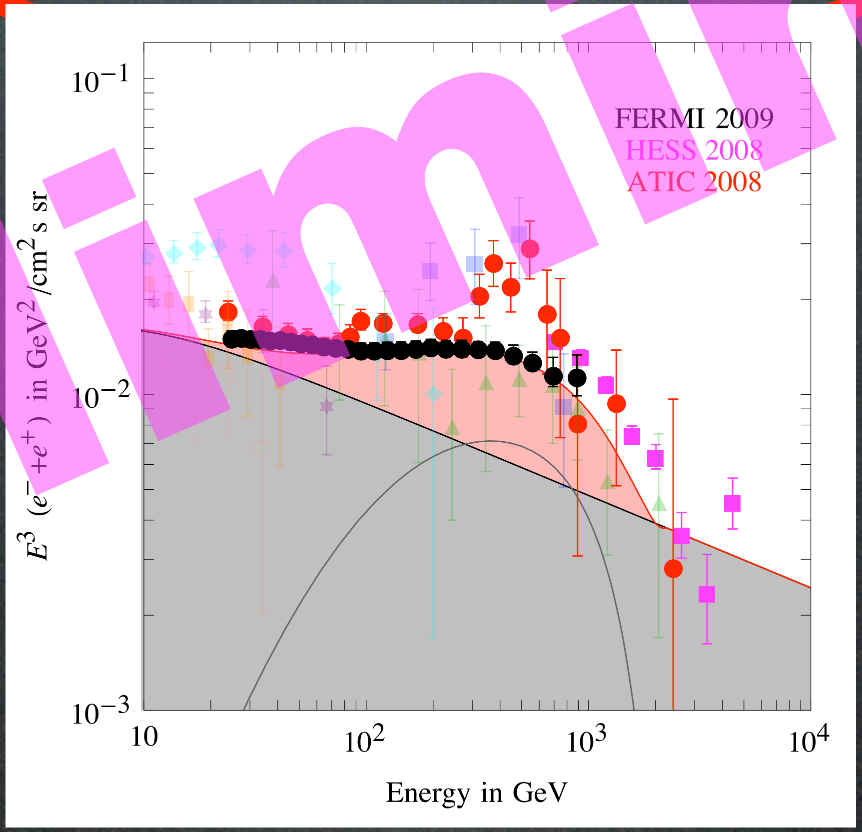

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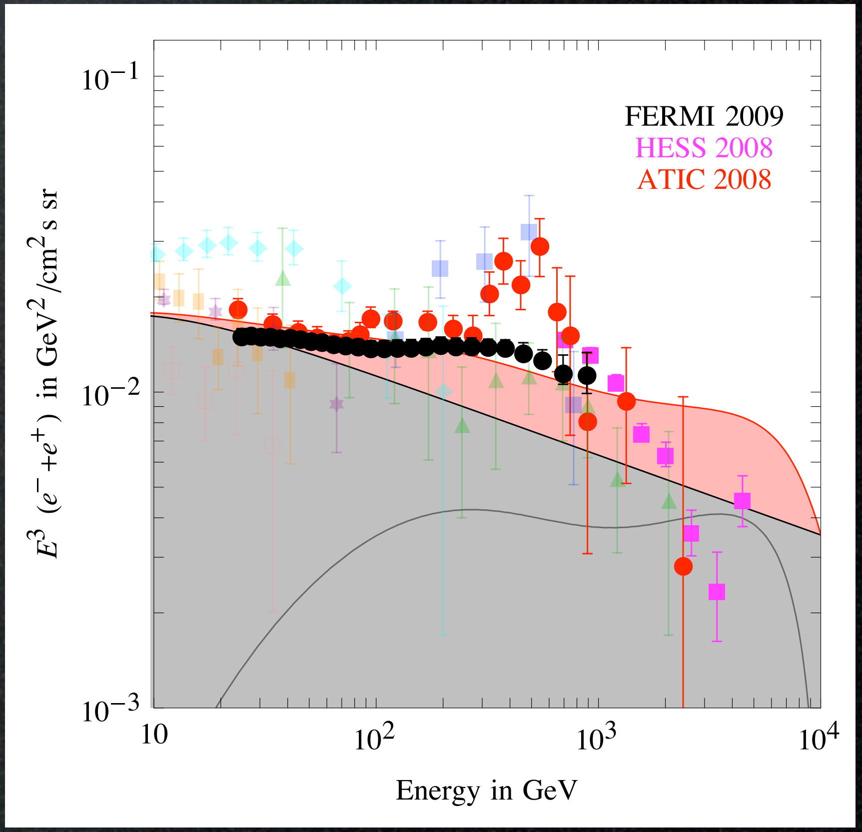


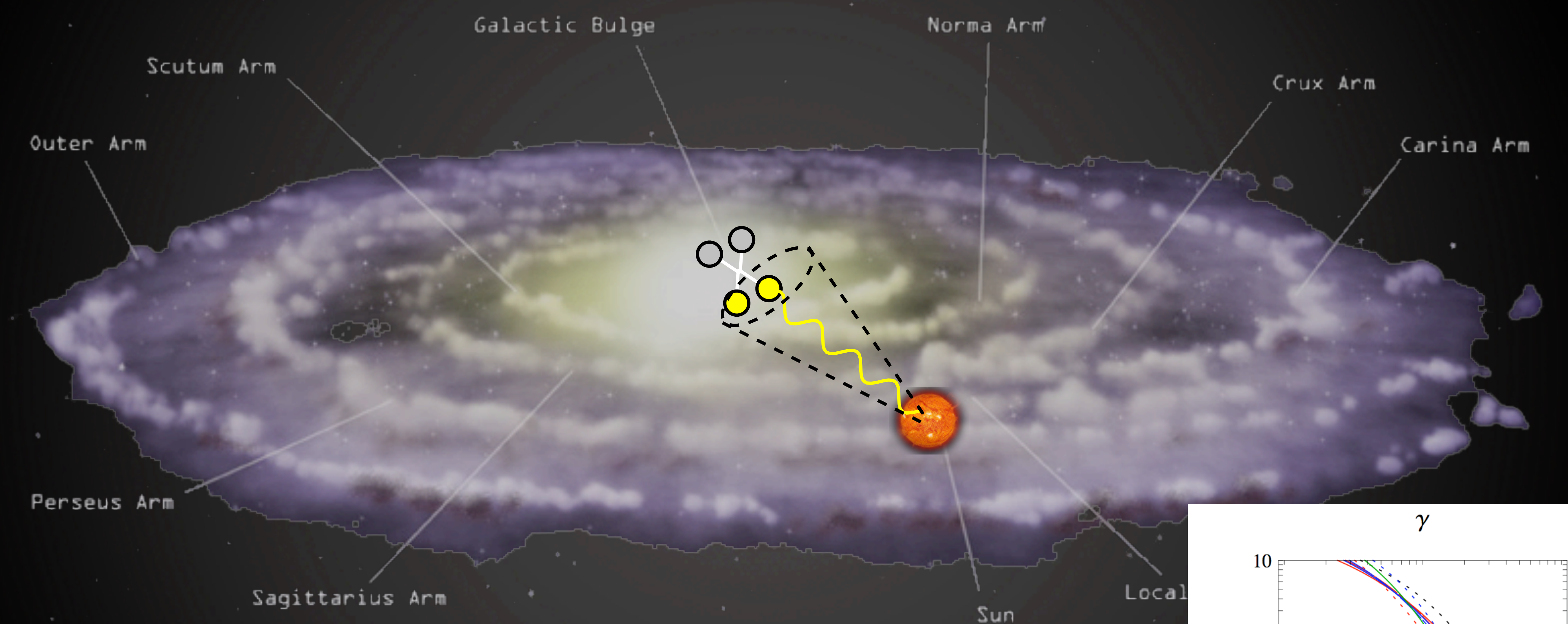
Preliminary

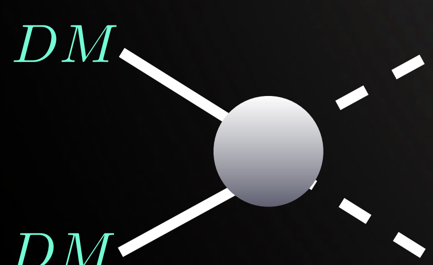
See e.g. Strumia, Papucci et al. (to appear)

see also: Bergstrom, Edsjo, Zaharijas today

Indirect Detection

γ from DM annihilations in galactic center





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

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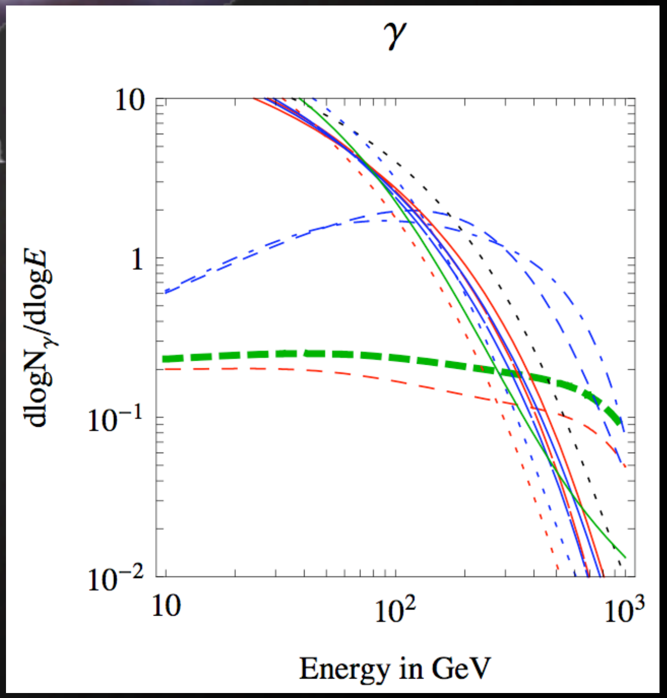
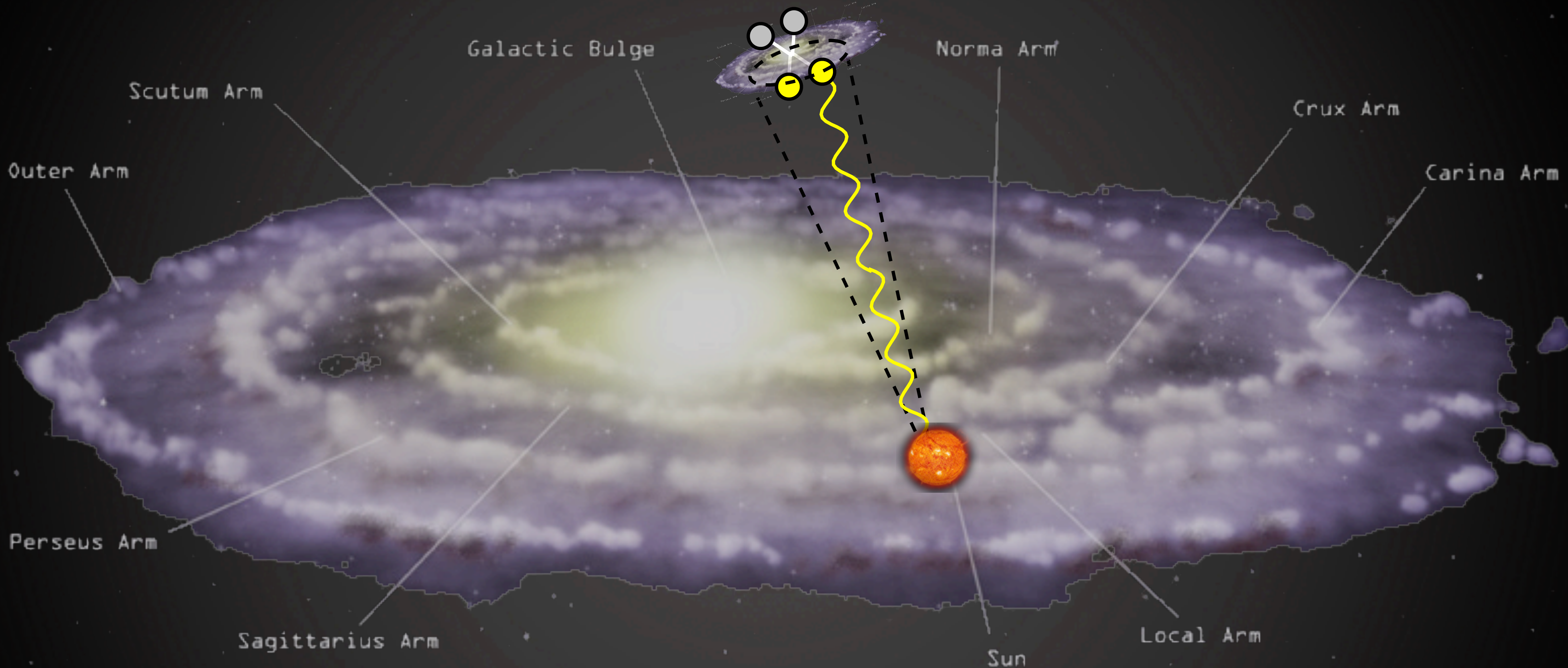
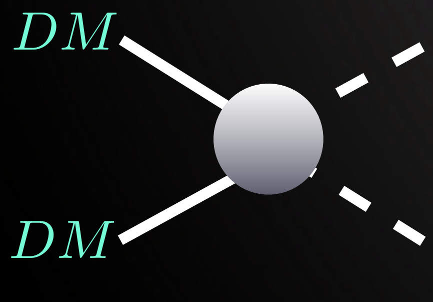


typically sub-TeV energies

Indirect Detection

γ from DM annihilations in Sagittarius Dwarf





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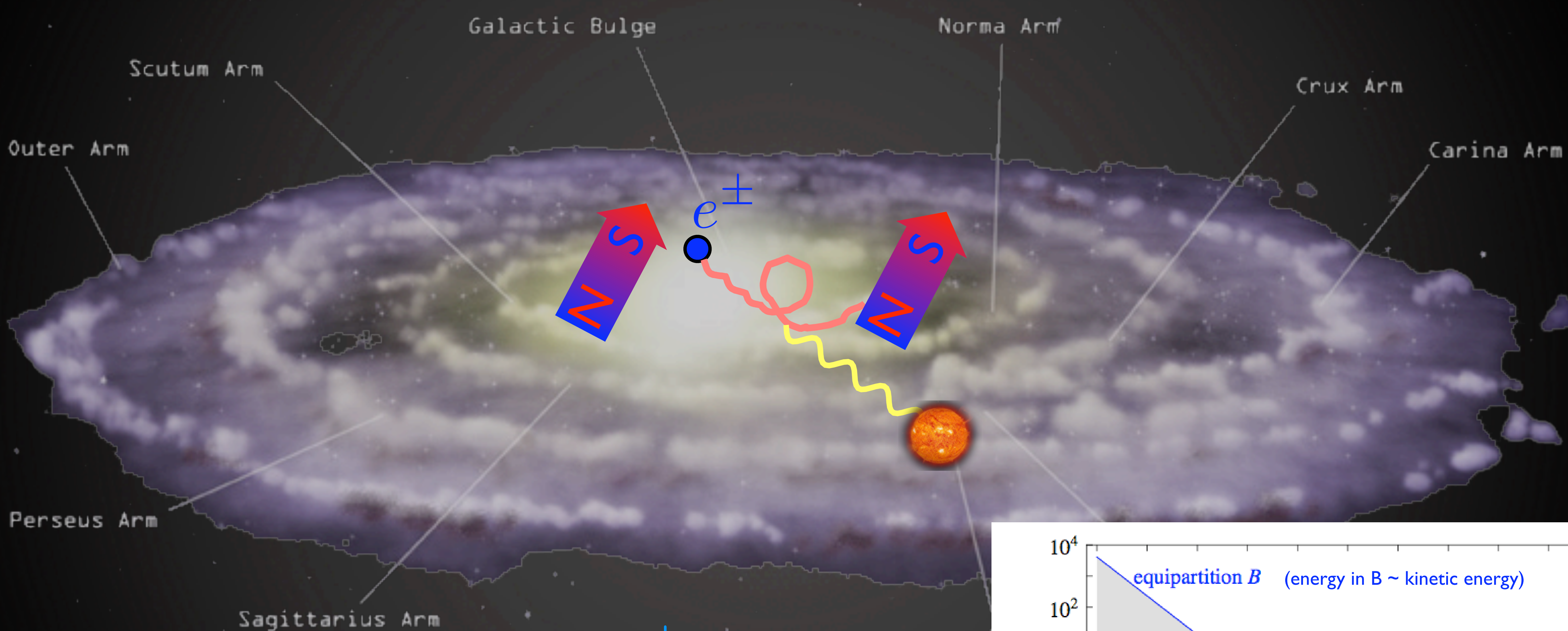
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

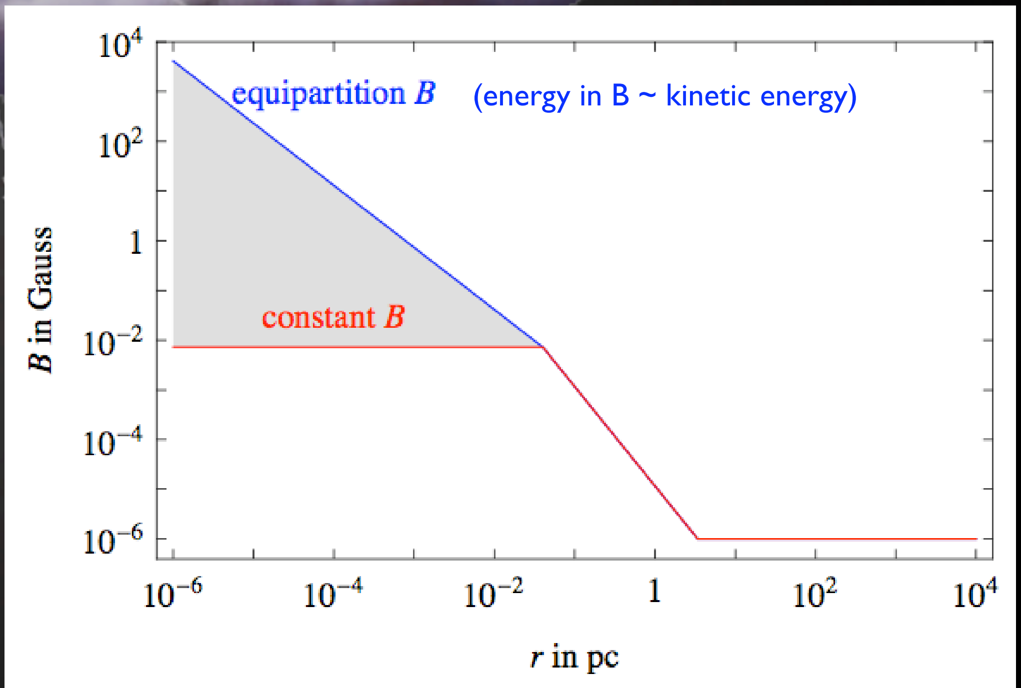
Indirect Detection

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



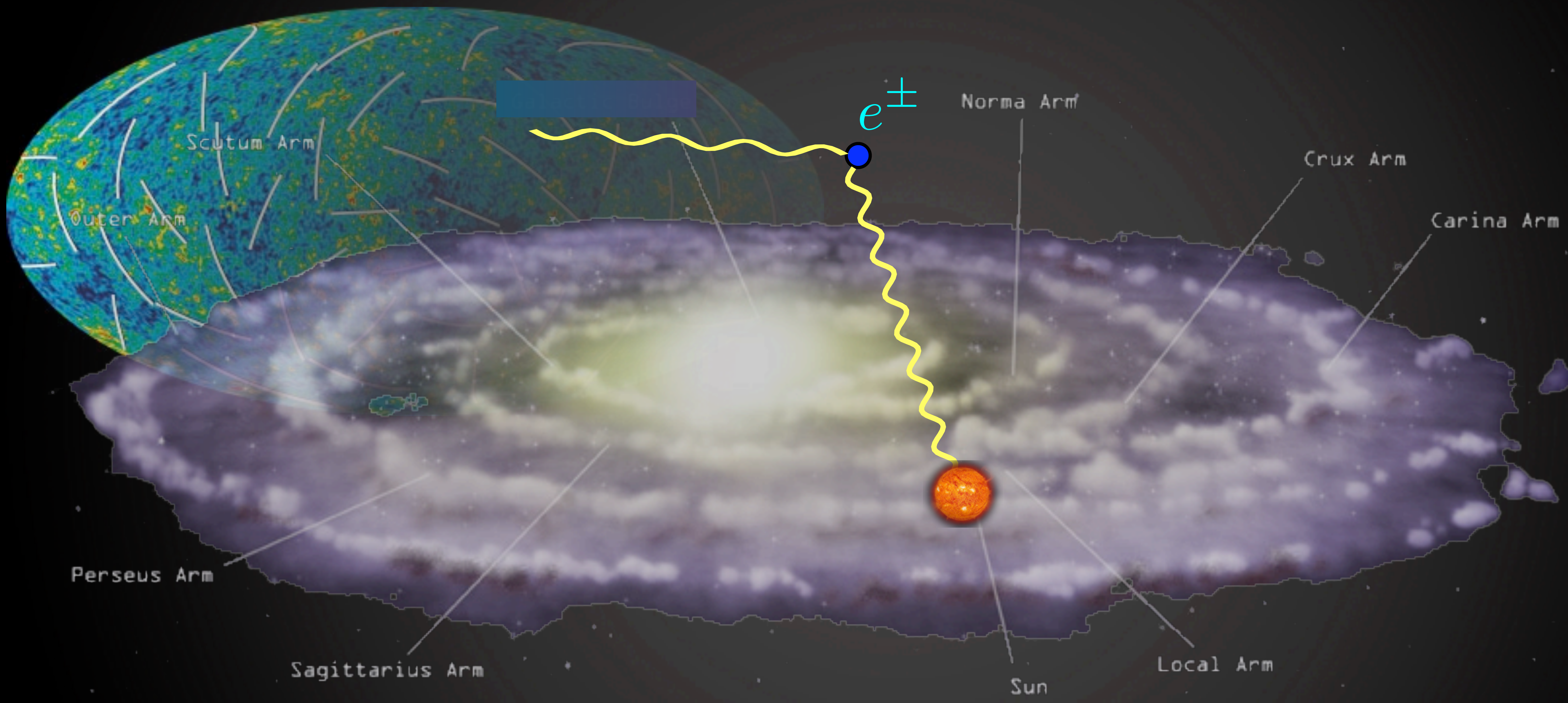
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

(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

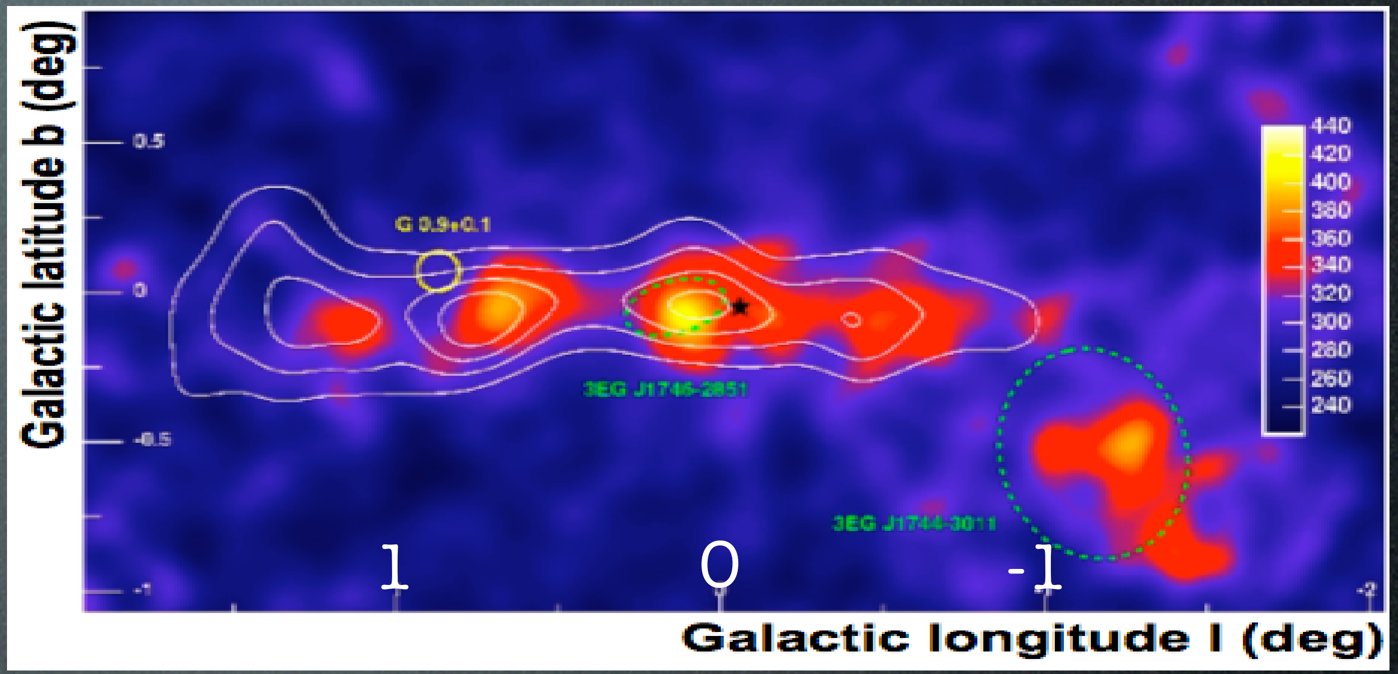


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Comparing with data

Gamma constraints

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



HESS coll.

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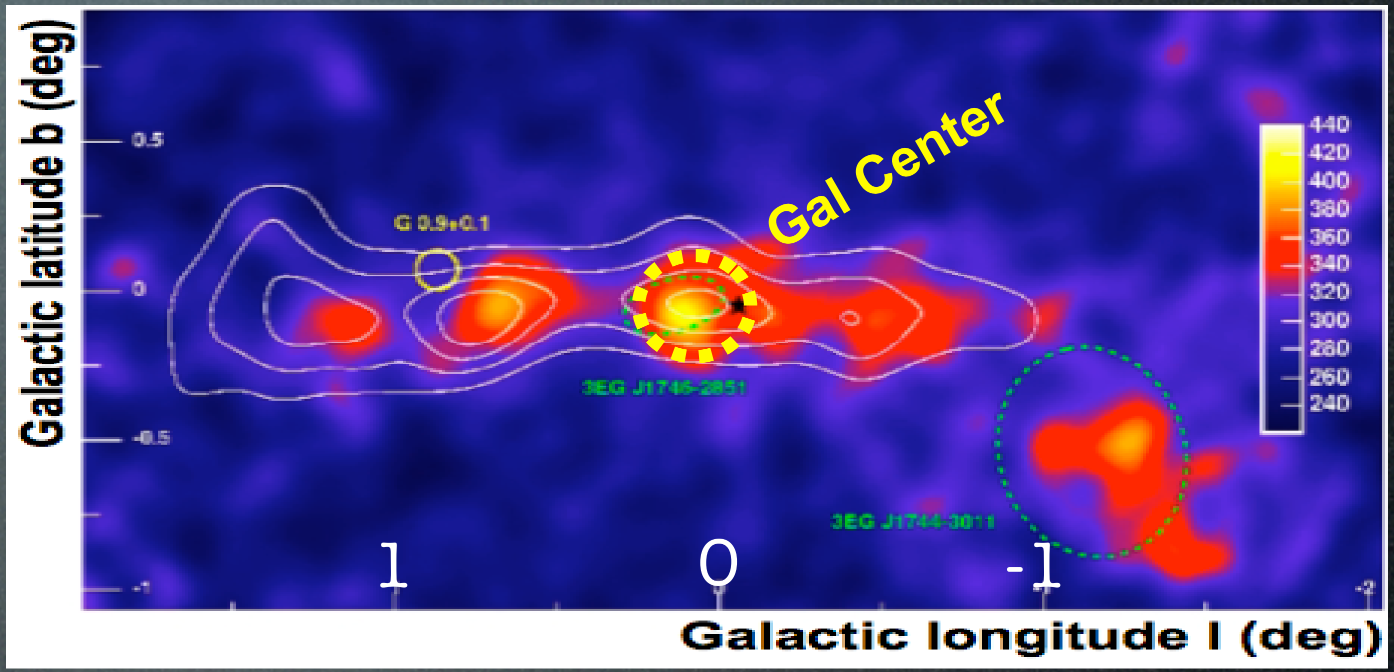

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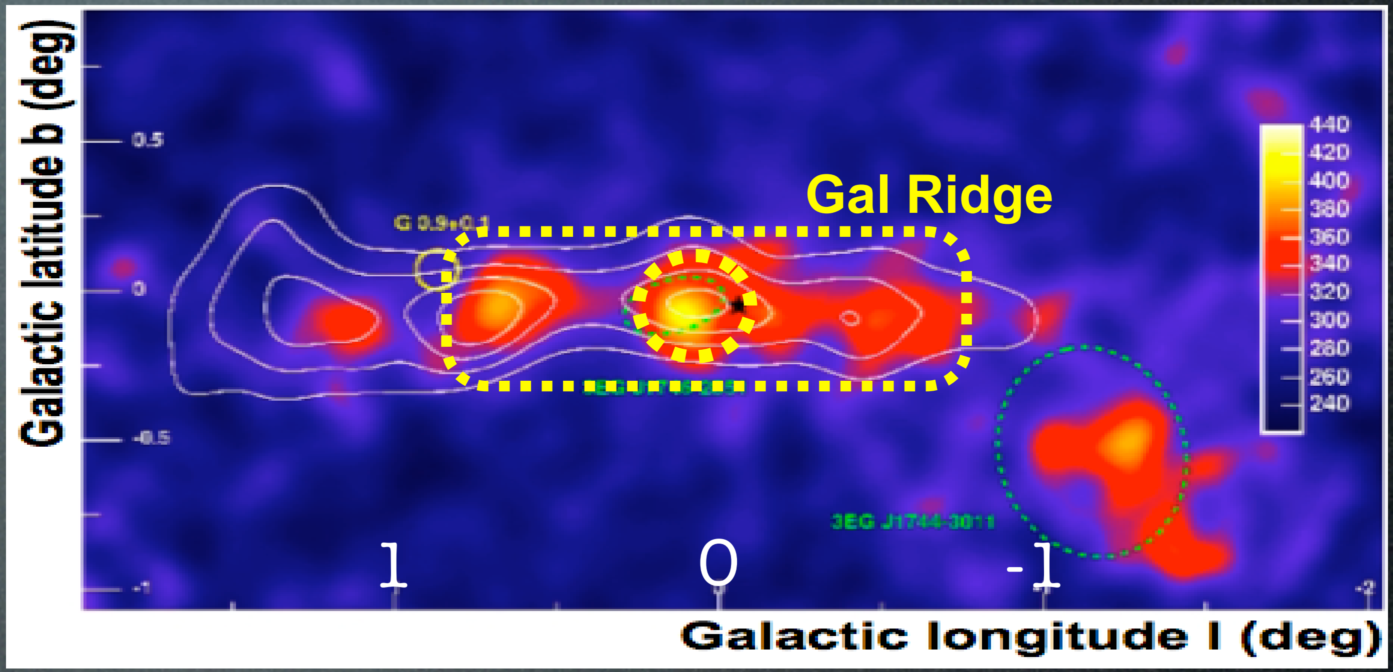

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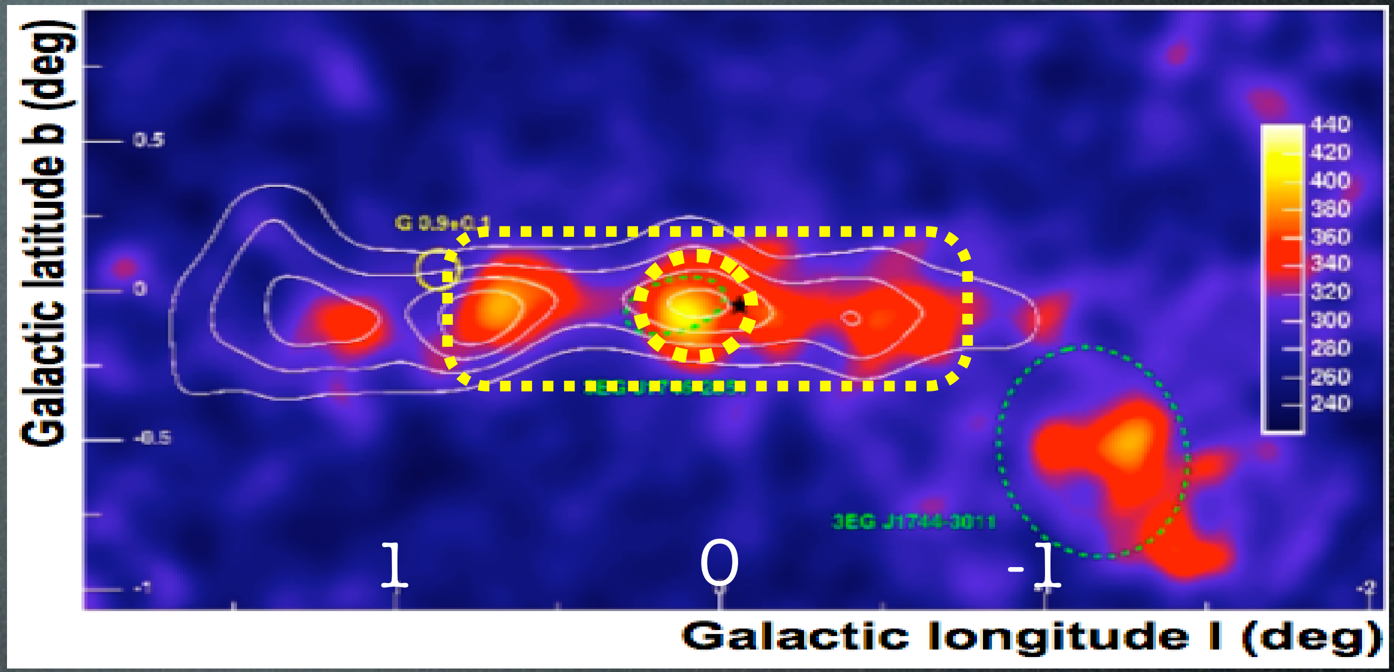

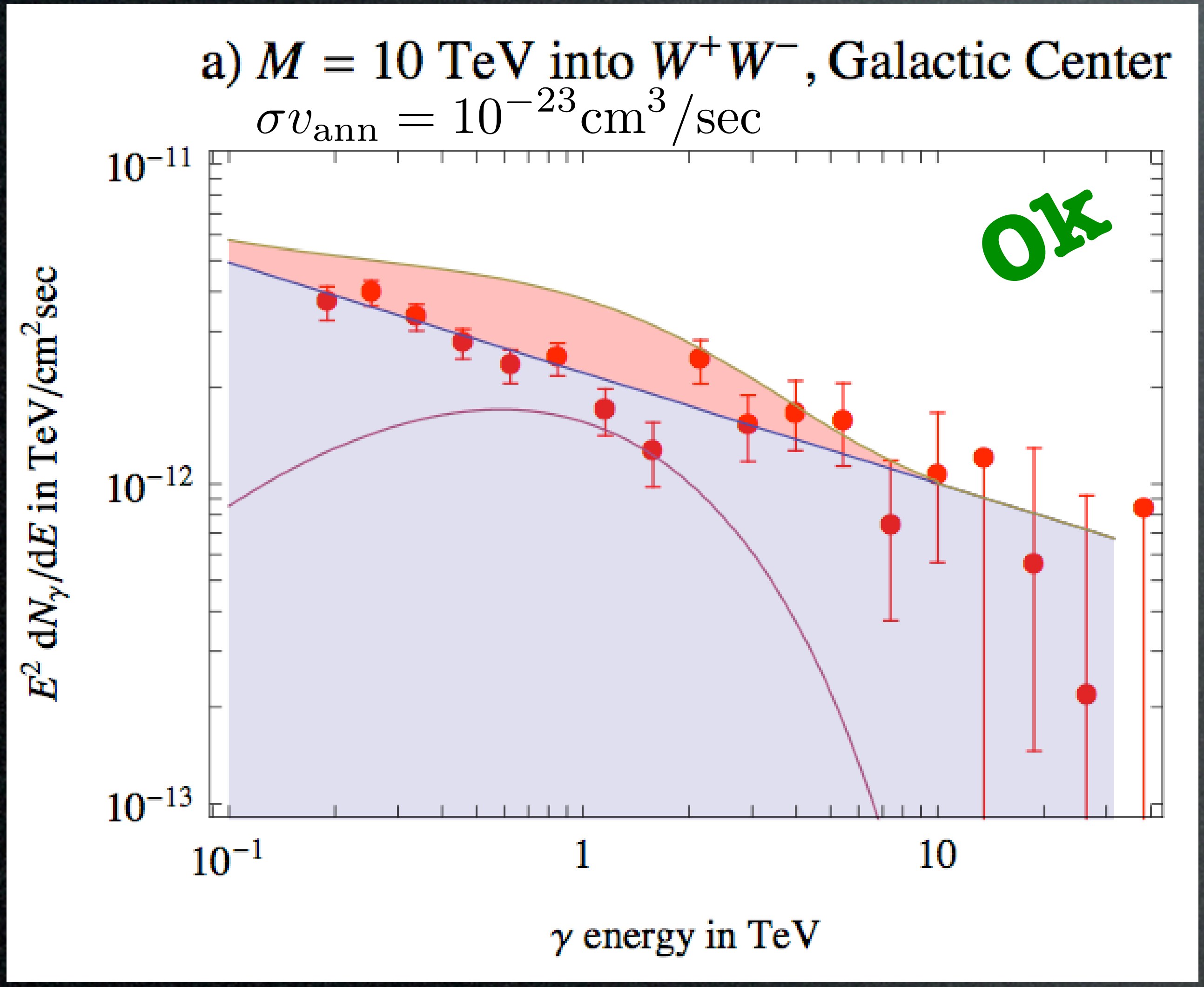

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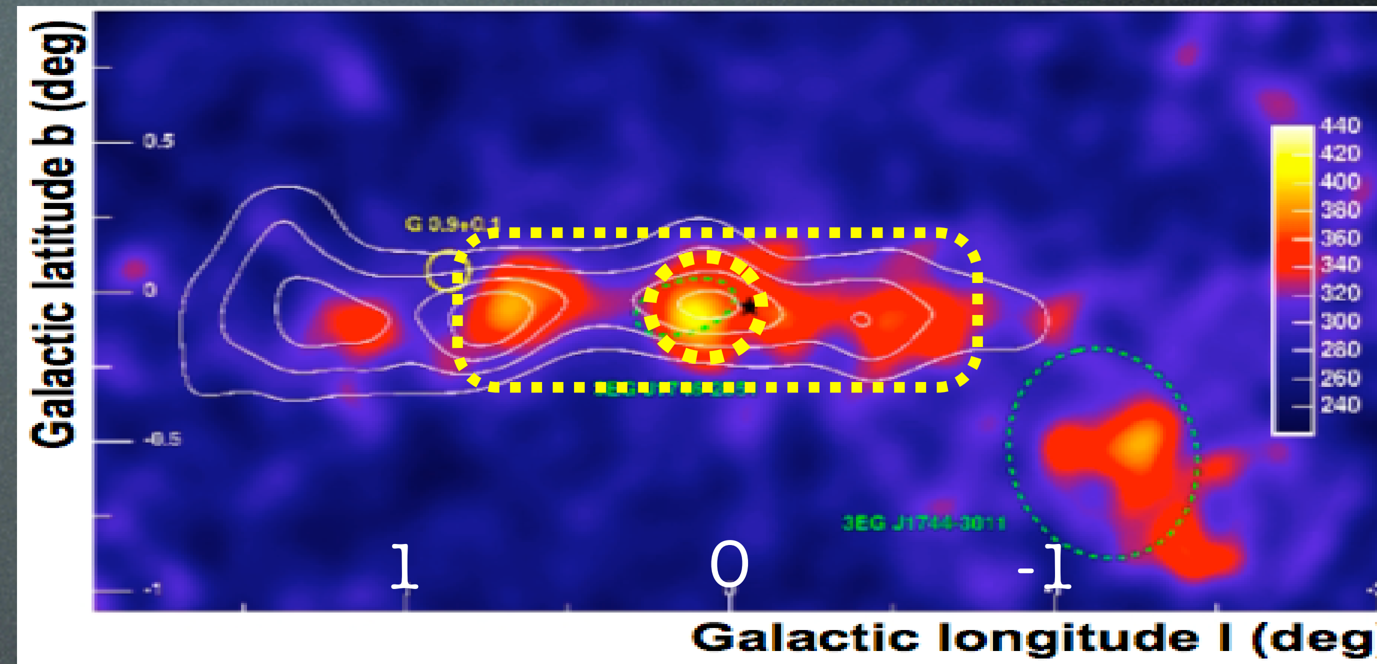

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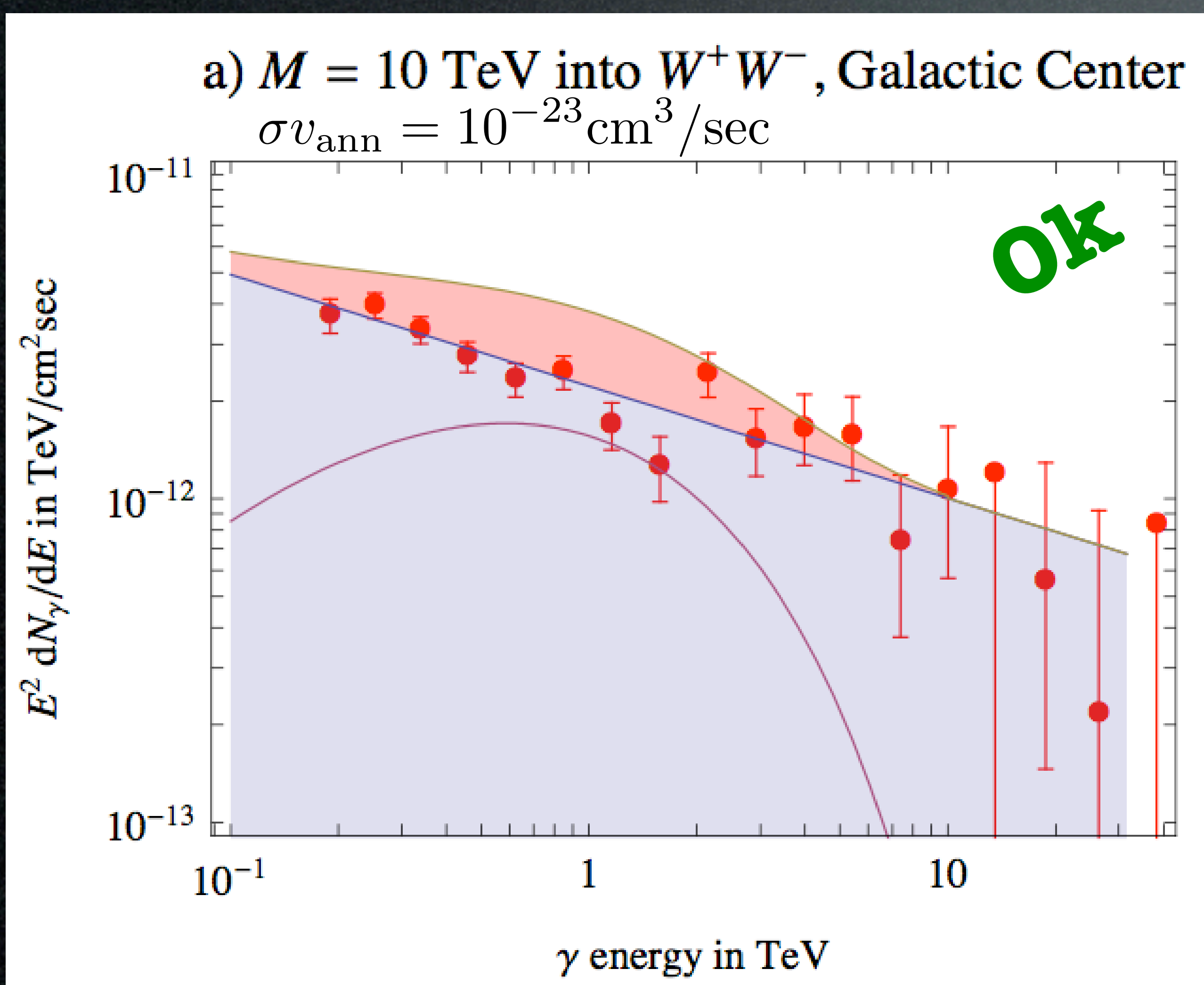
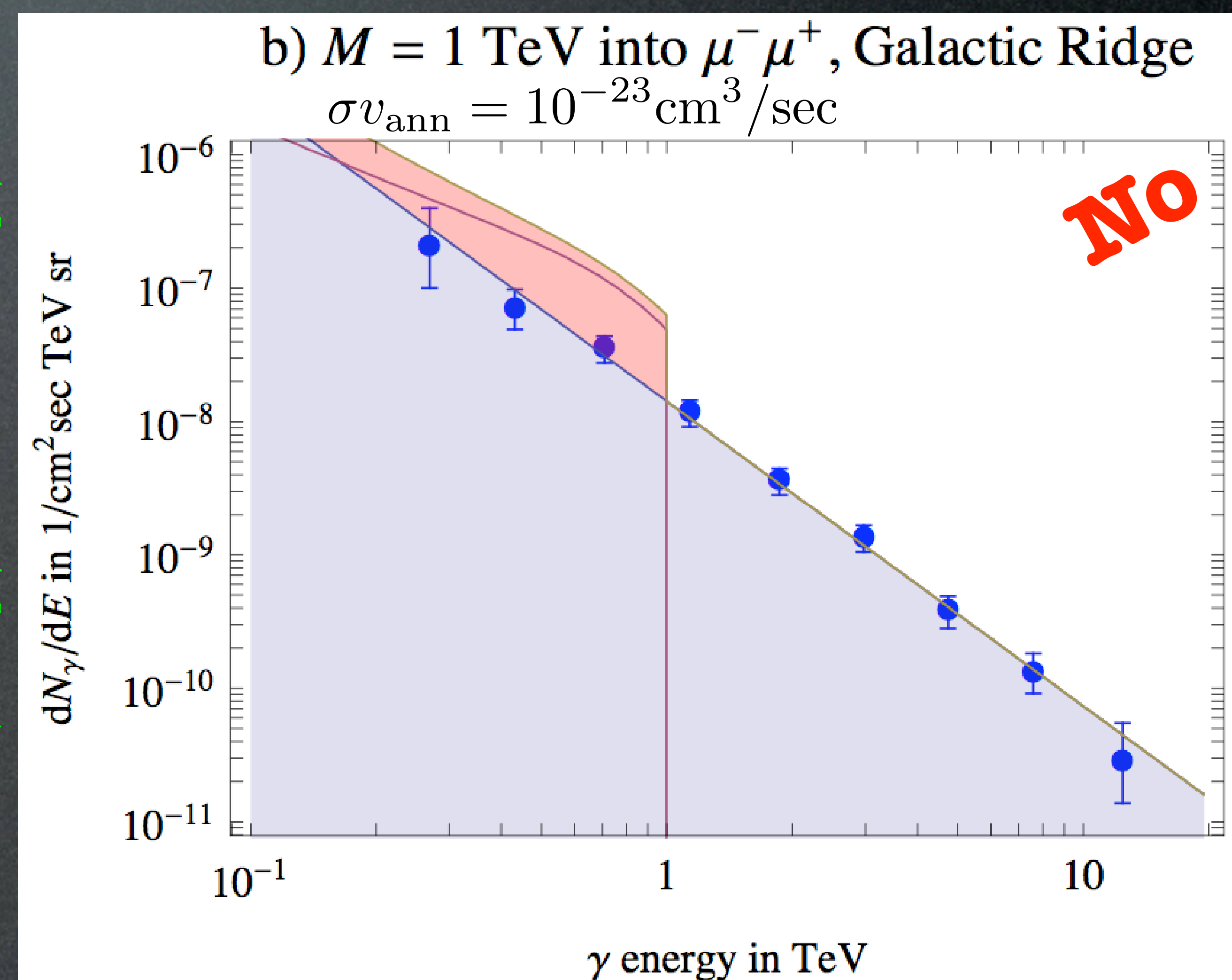


Data: HESS coll., astro-ph/0408145 and astro-ph/0610509



Data: HESS coll., astro-ph/0603021

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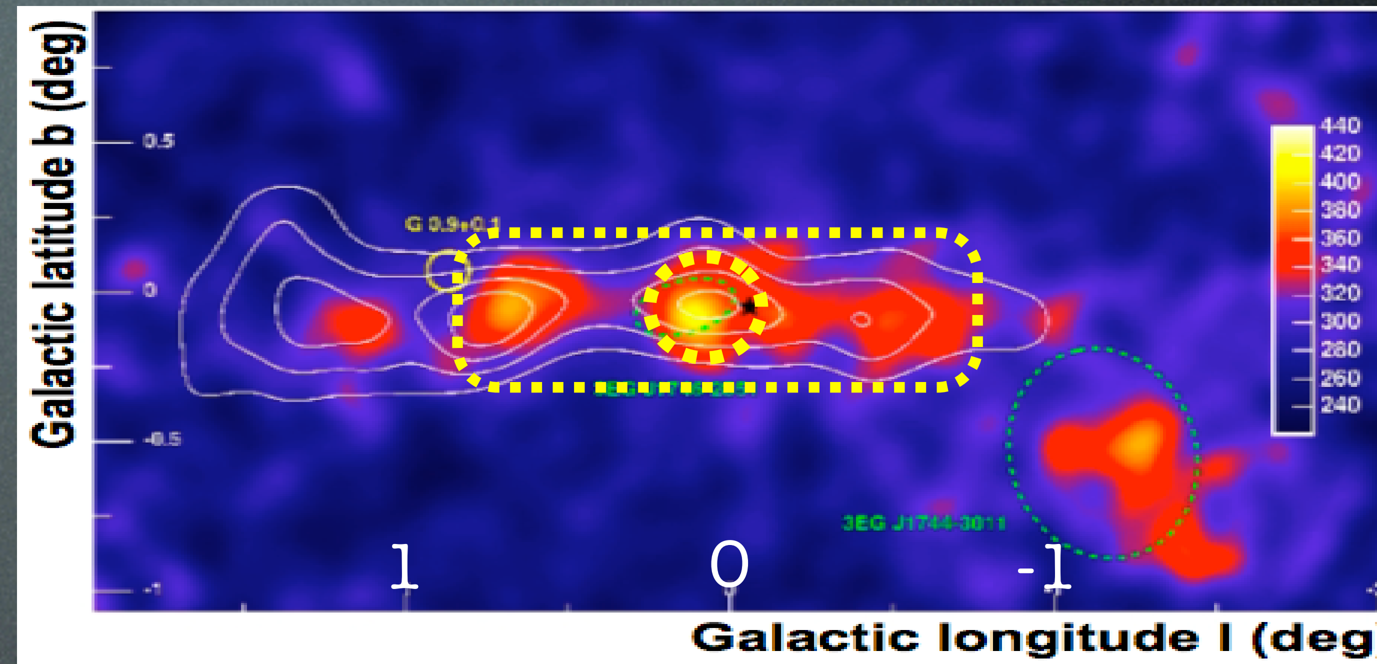
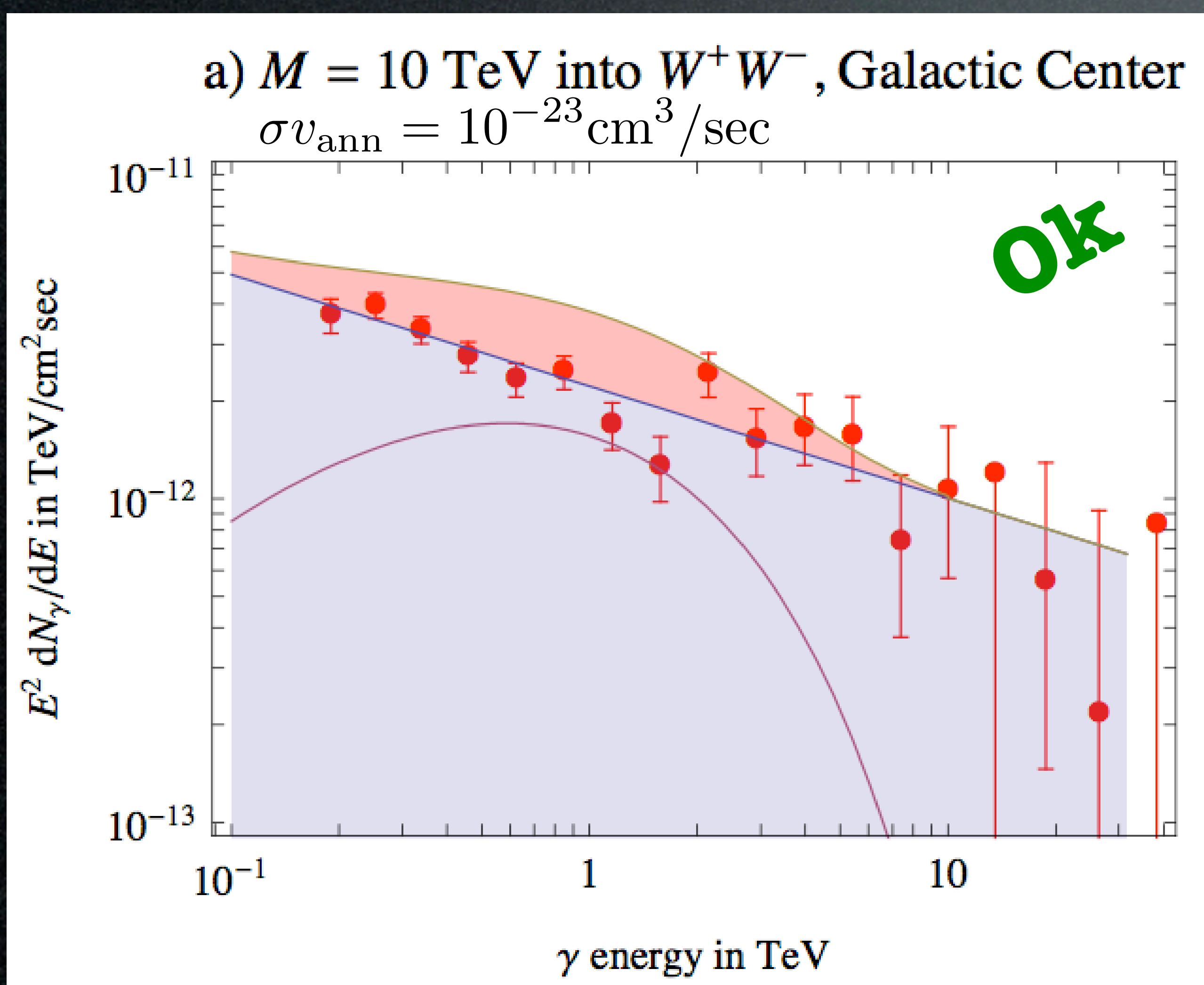
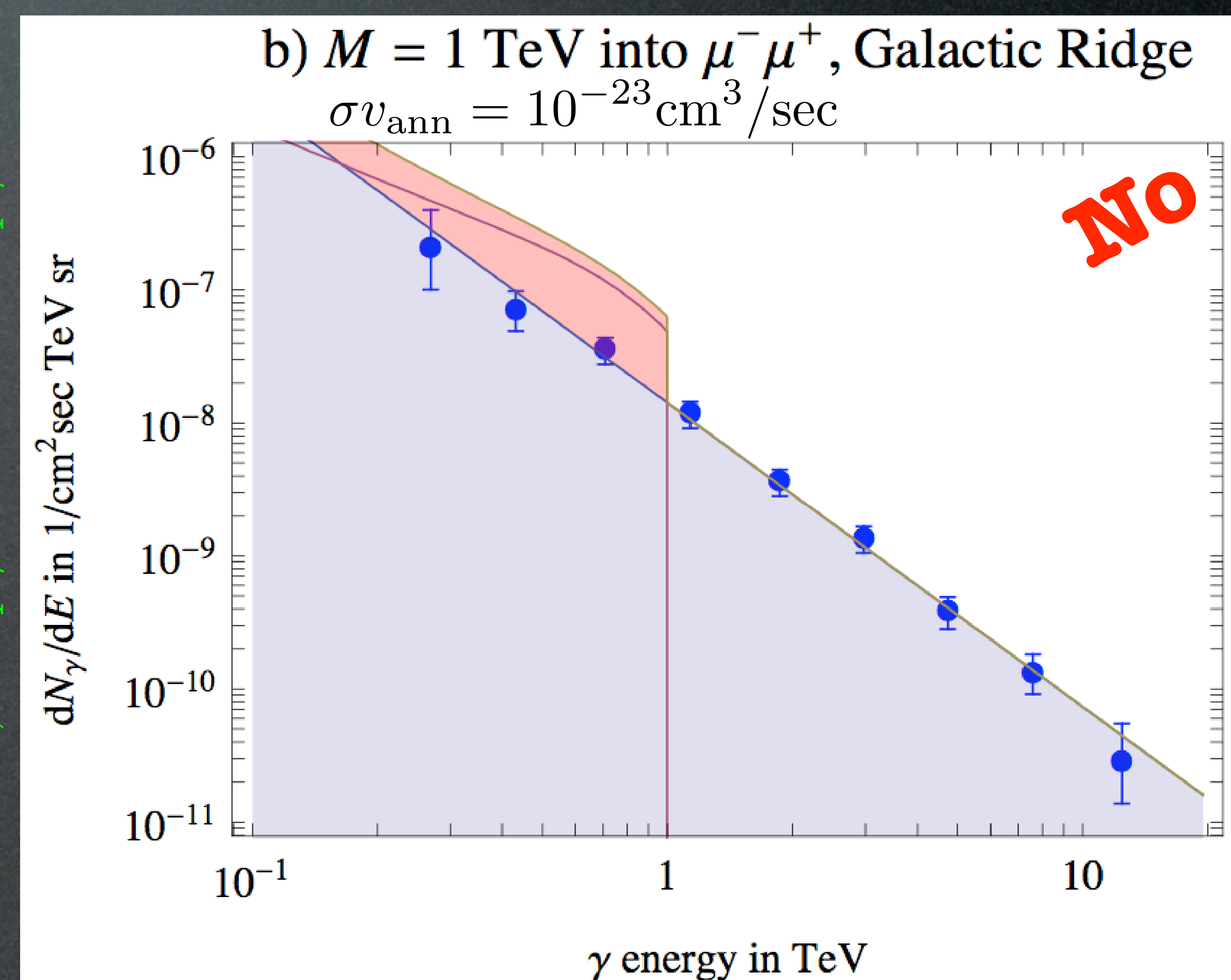
Moreover: no detection from Sgr dSph => upper bound.



HESS coll.



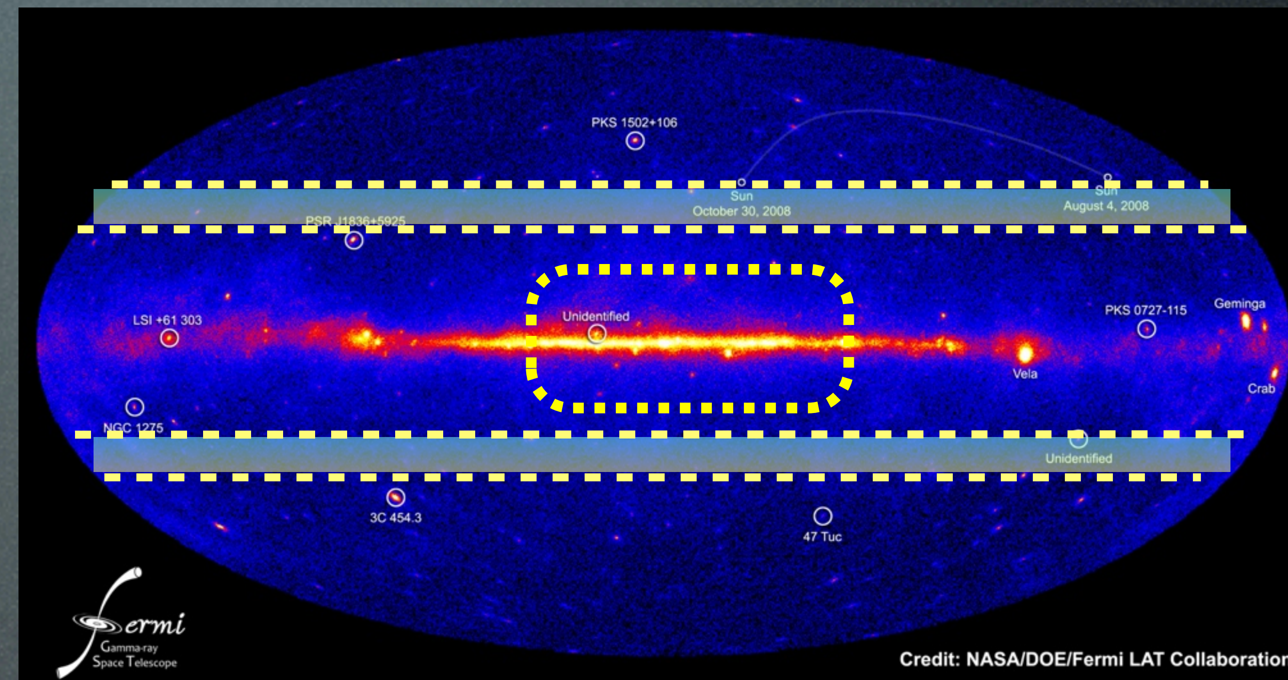
Data: HESS coll., astro-ph/0408145 and astro-ph/0610509



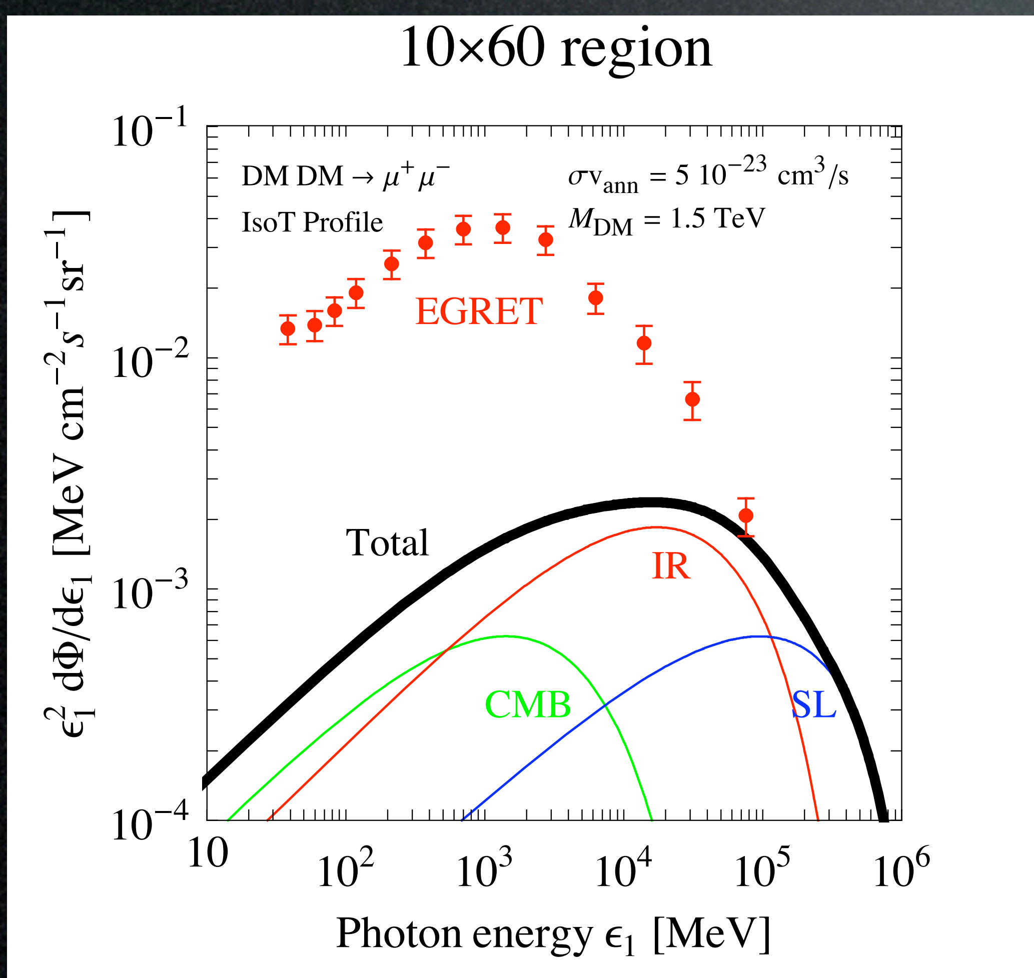
Data: HESS coll., astro-ph/0603021

Gamma constraints

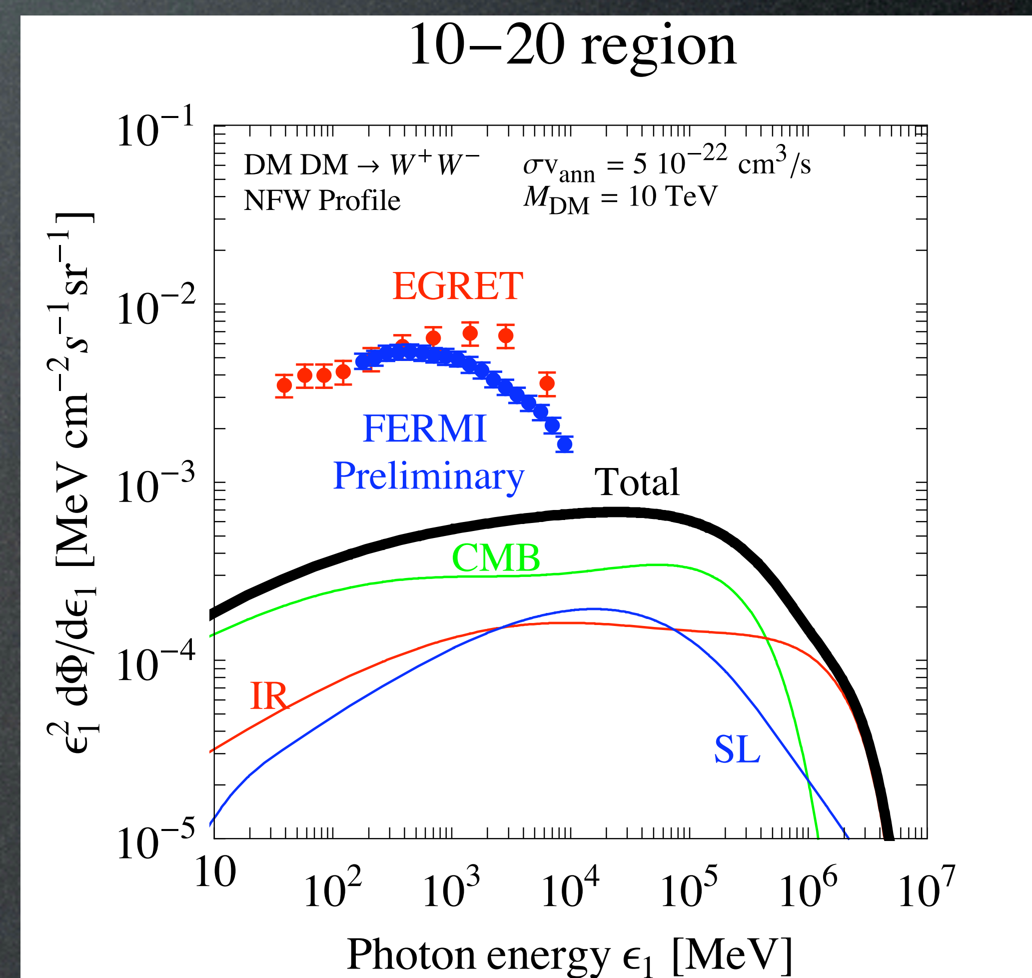
EGRET and FERMI have measured diffuse γ-ray emission. The DM signal must not excede that.



FERMI coll.

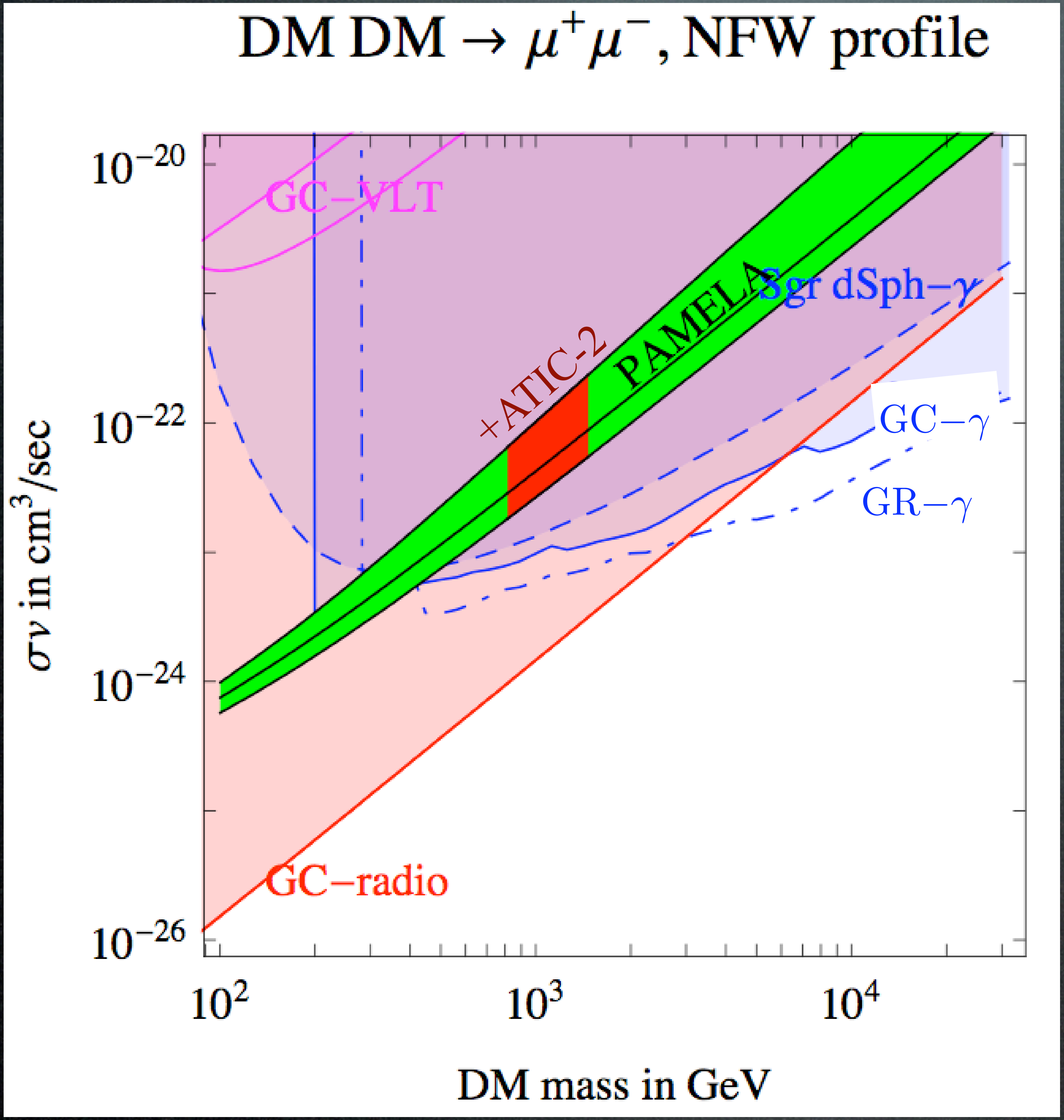


Data: EGRET coll.,Strong et al. astro-ph/0406254



Data: FERMI coll., several talks in 2009

Galactic Center γ constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

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

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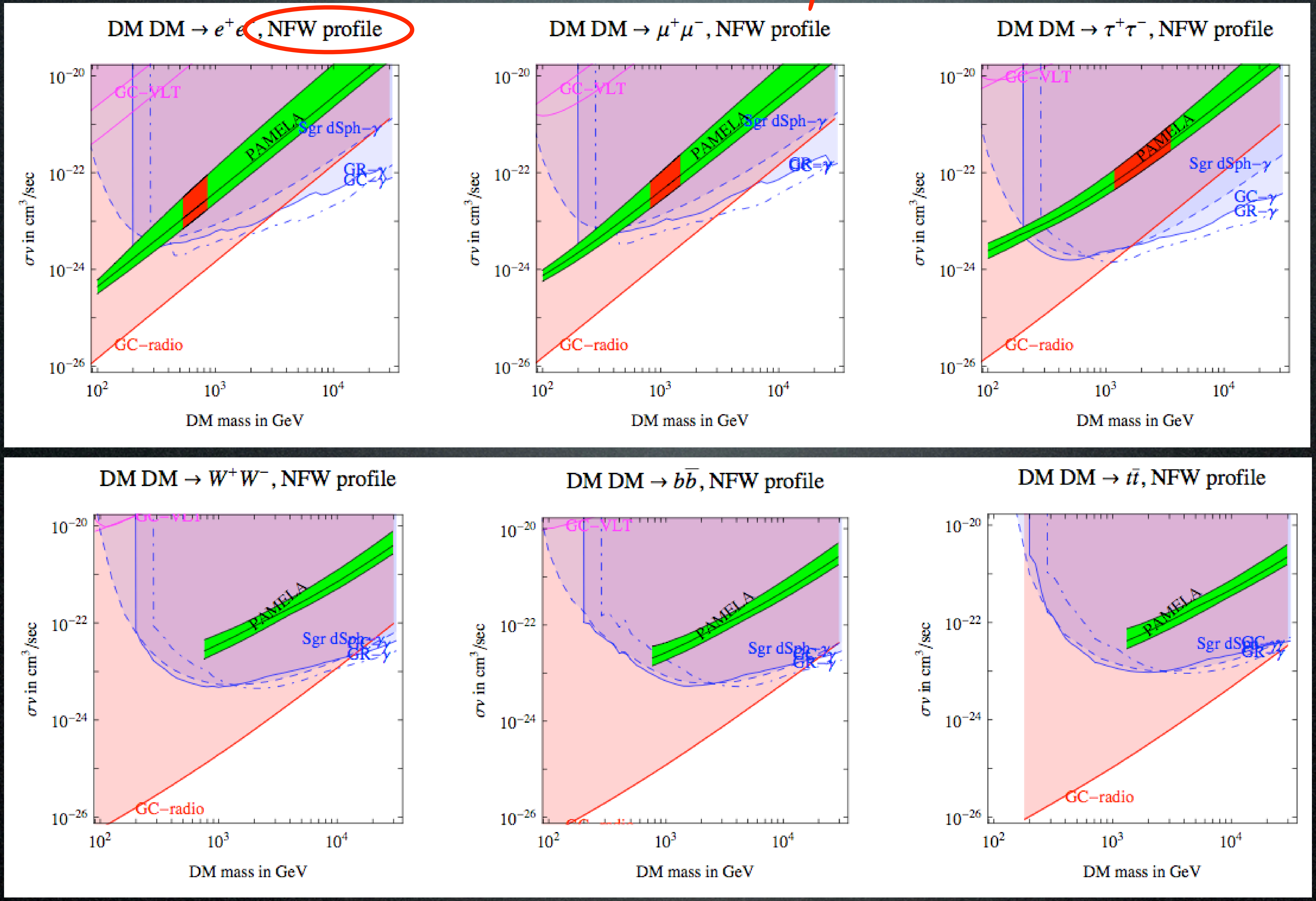
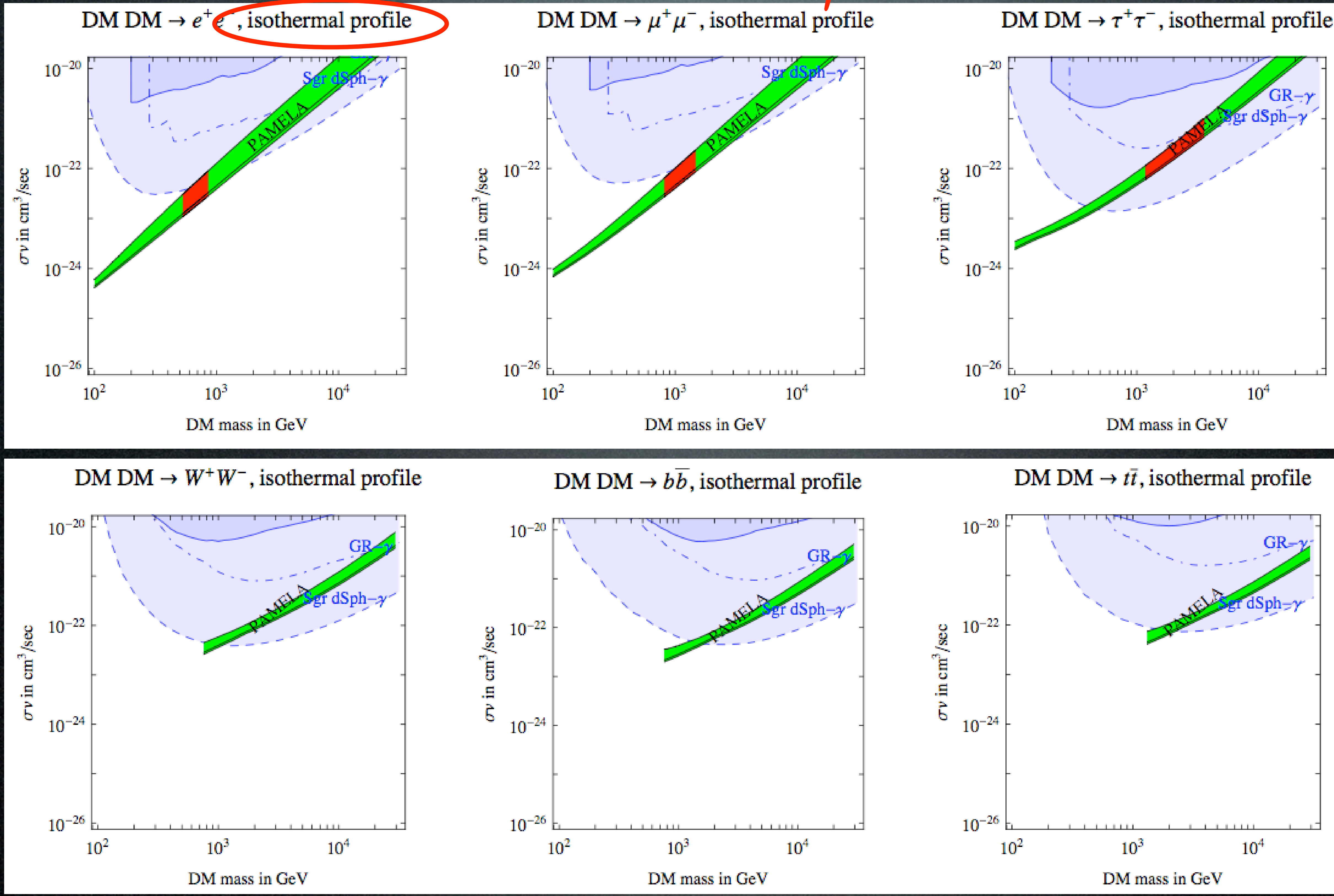


Bertone, Cirelli, Strumia, Taoso 0811.3744

see also: Bertone, Pieri, Pato today

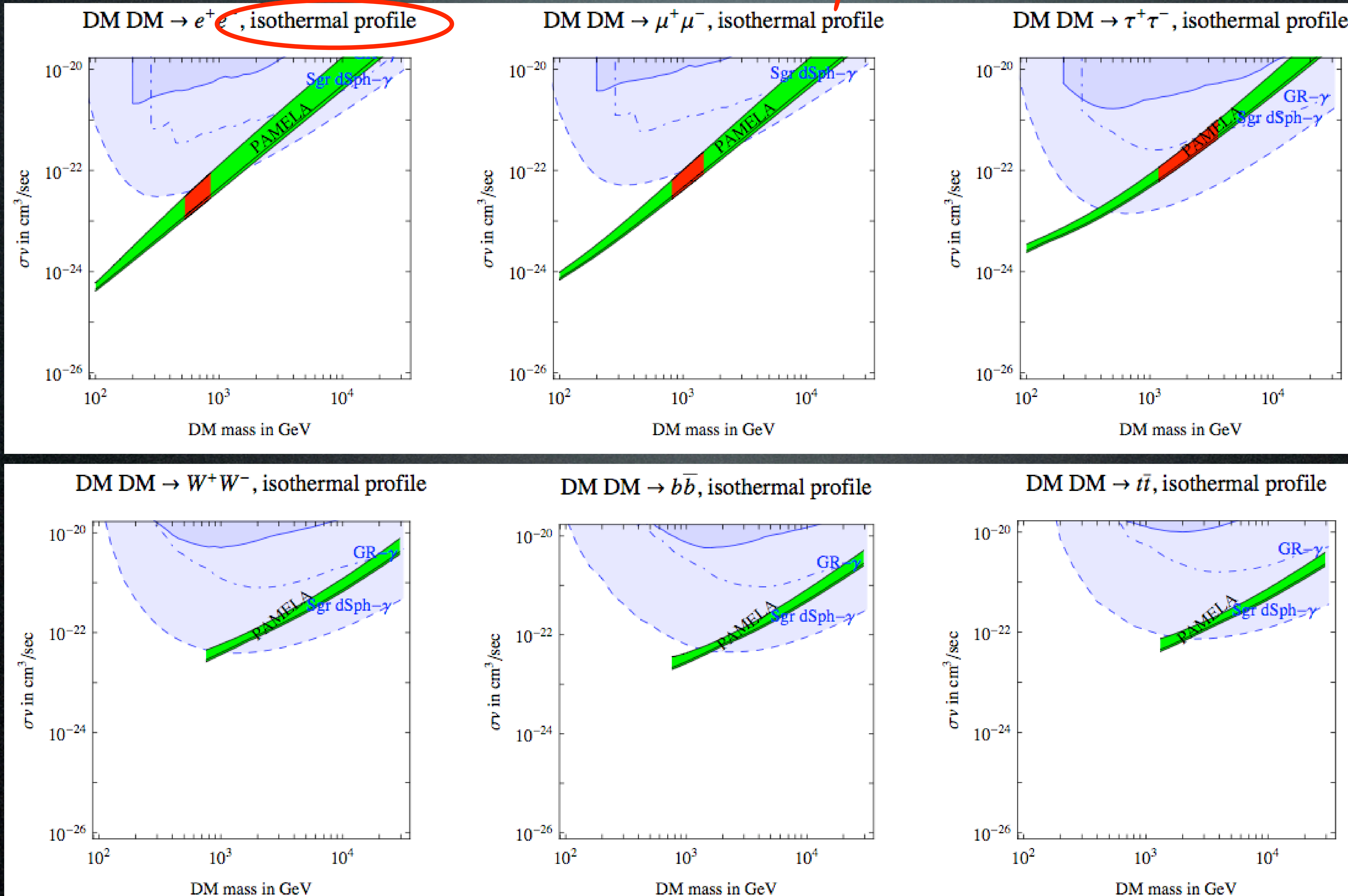
Galactic Center γ constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

Galactic Center γ constraints



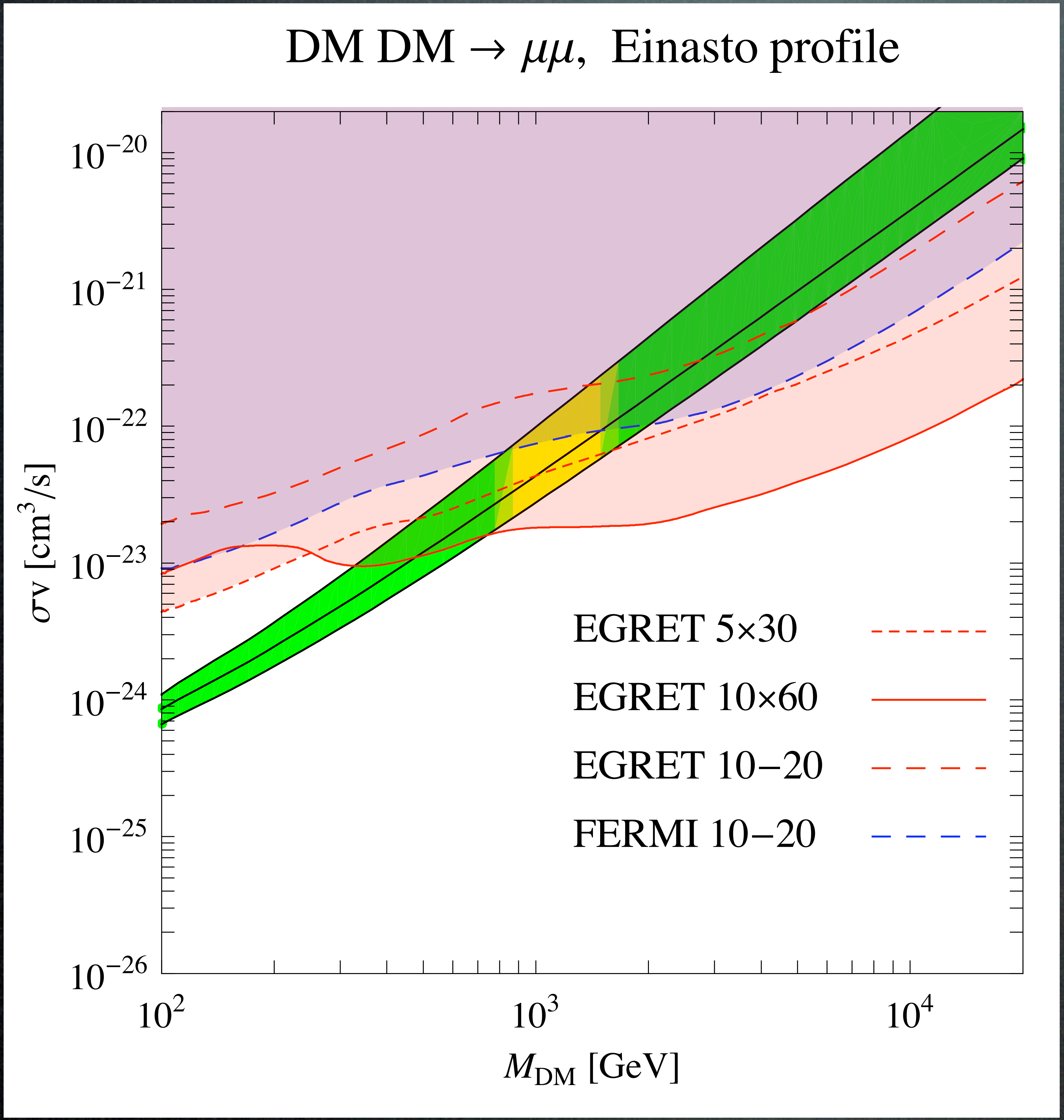
Bertone, Cirelli, Strumia, Taoso 0811.3744

...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).

Inverse Compton γ constraints



Cirelli, Panci 0904.3830

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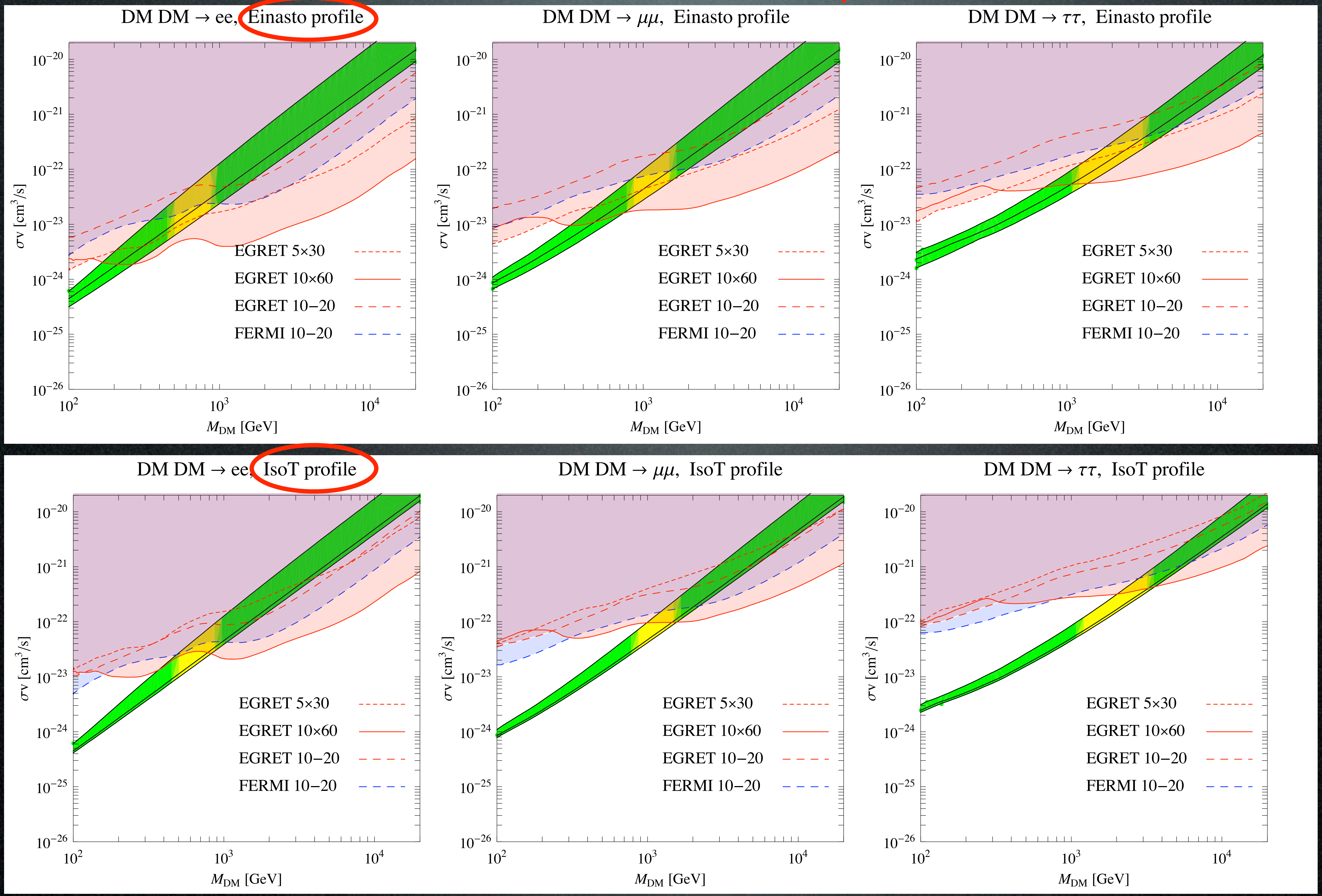


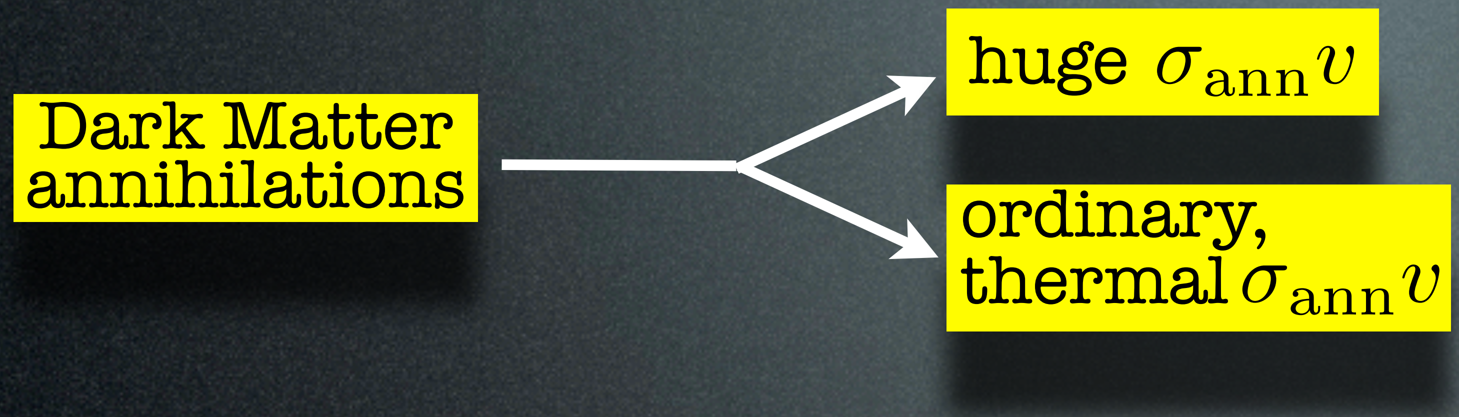
Cirelli, Panci 0904.3830

see also: Regis, Ullio 0904.4645

DM annihilations: the game

Dark Matter annihilations

DM annihilations: the game



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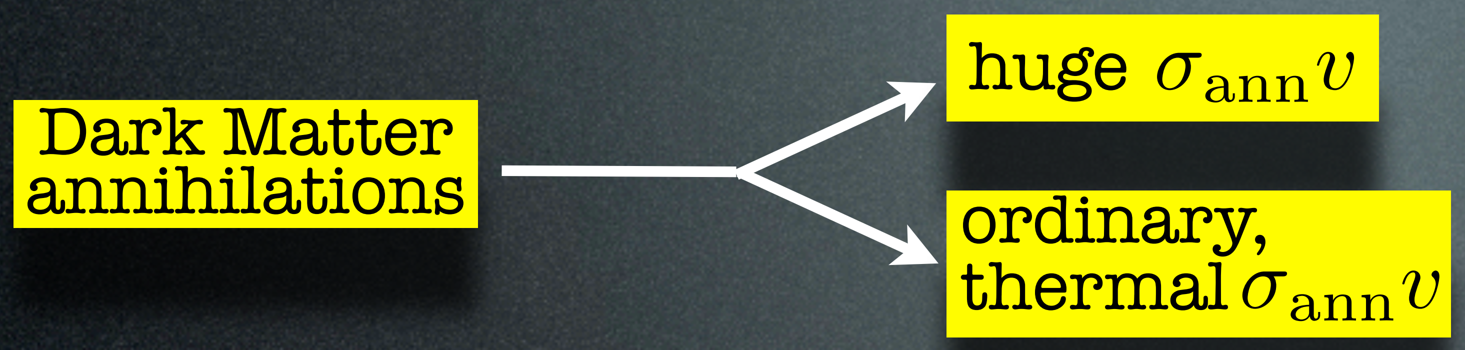

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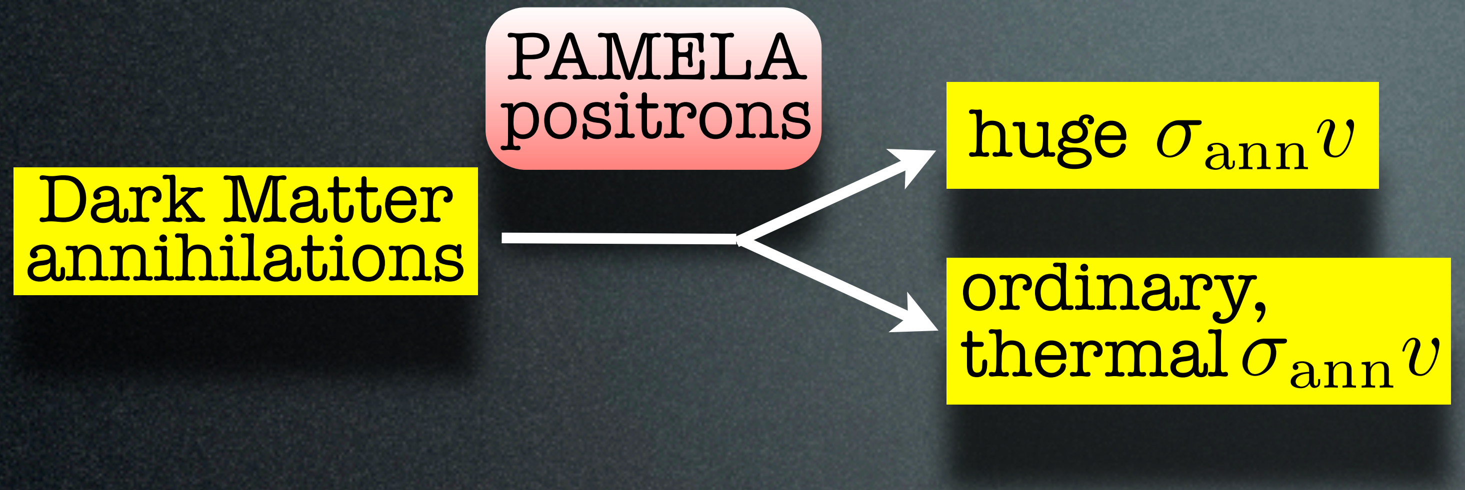

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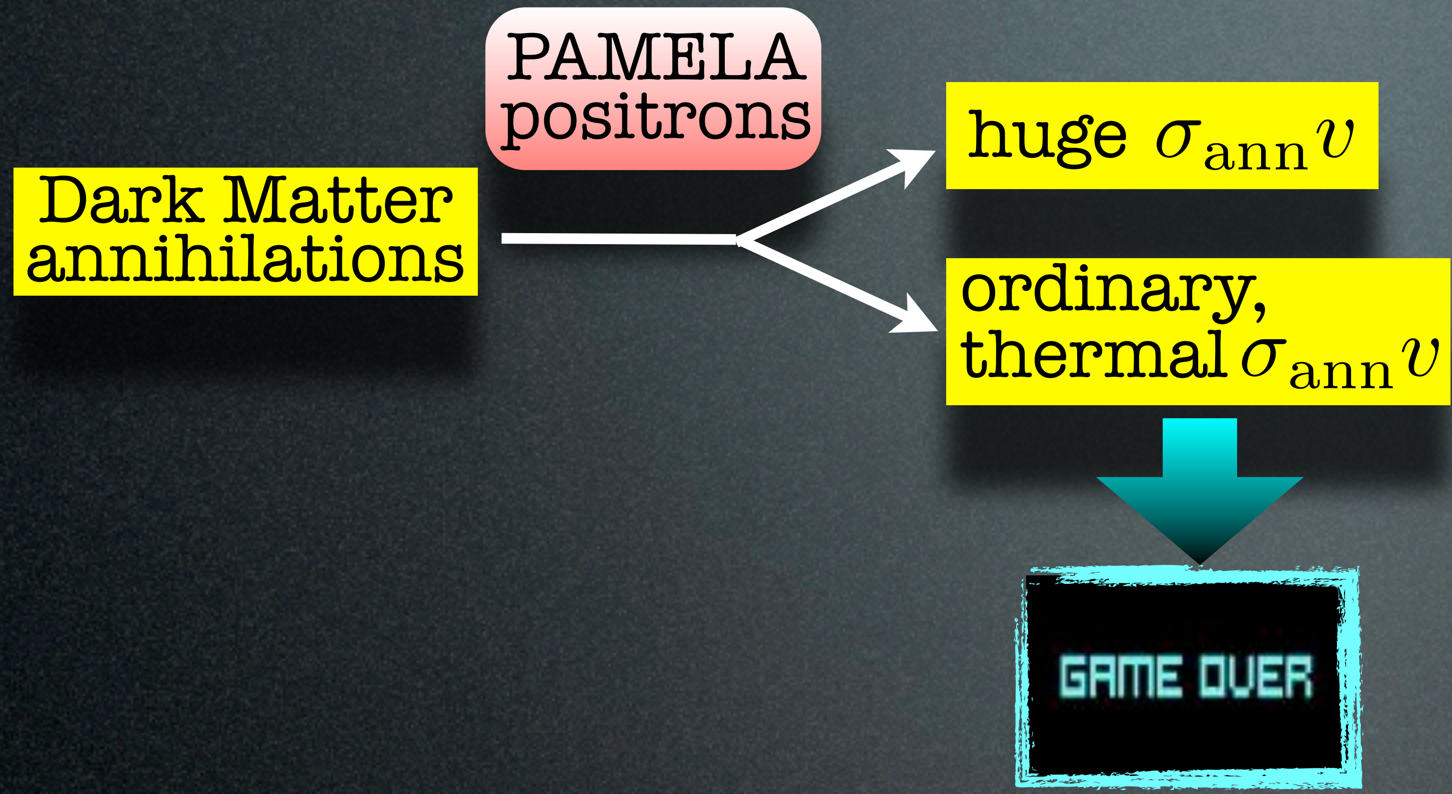

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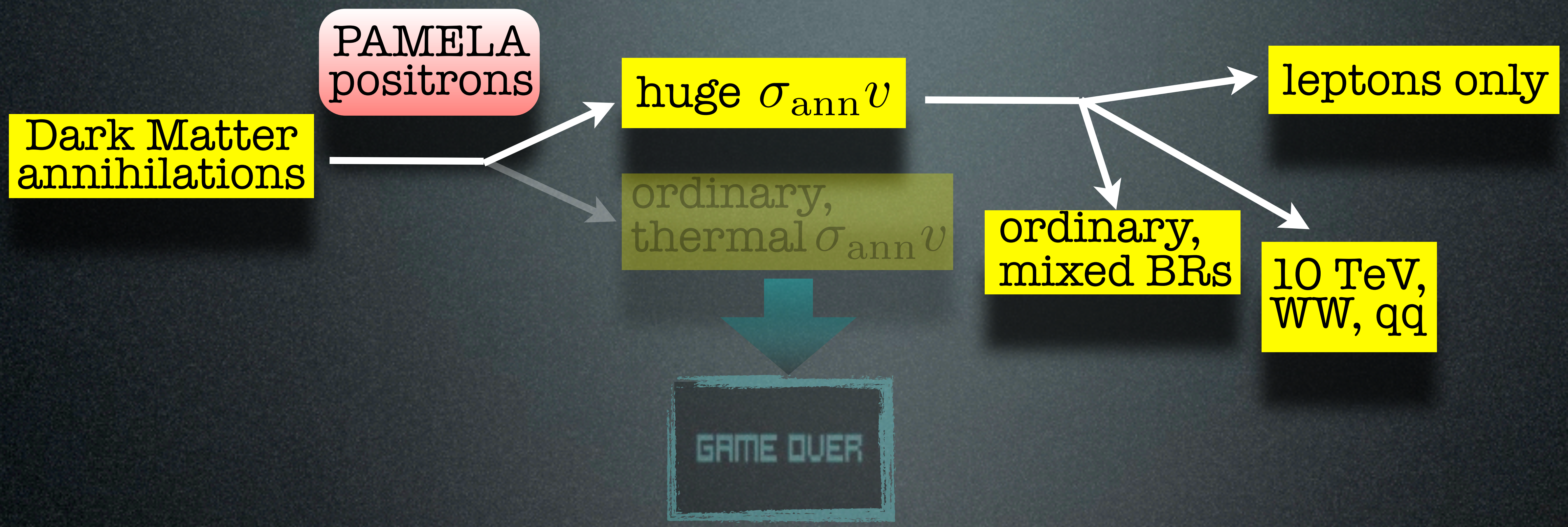

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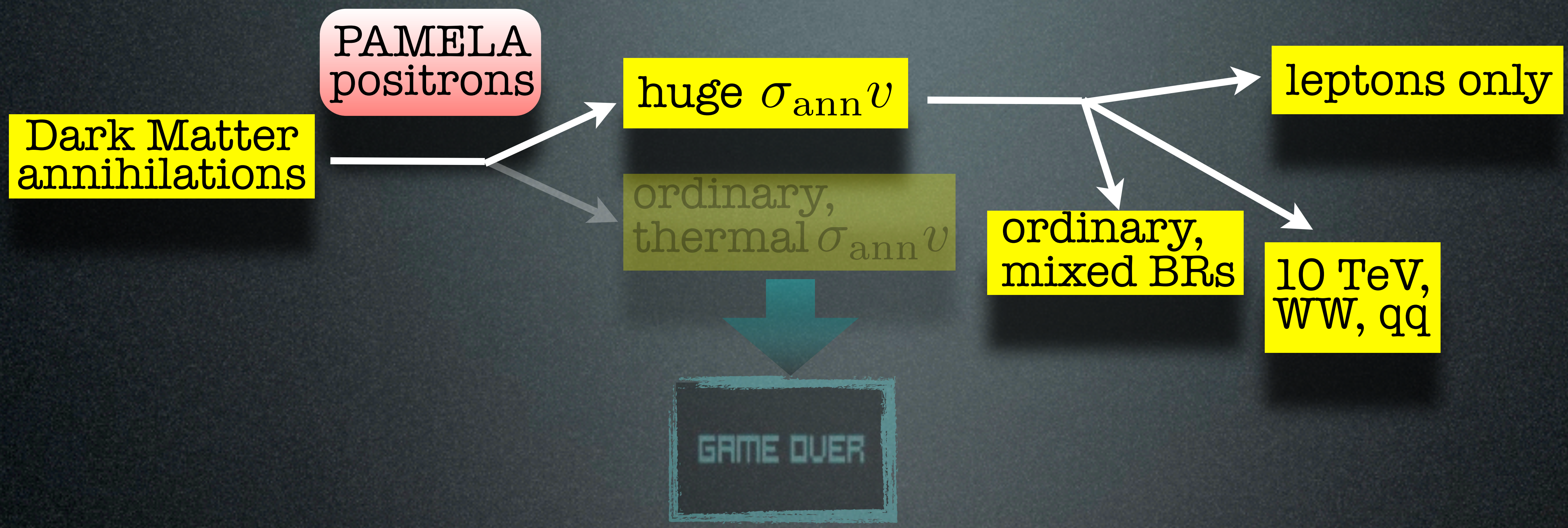

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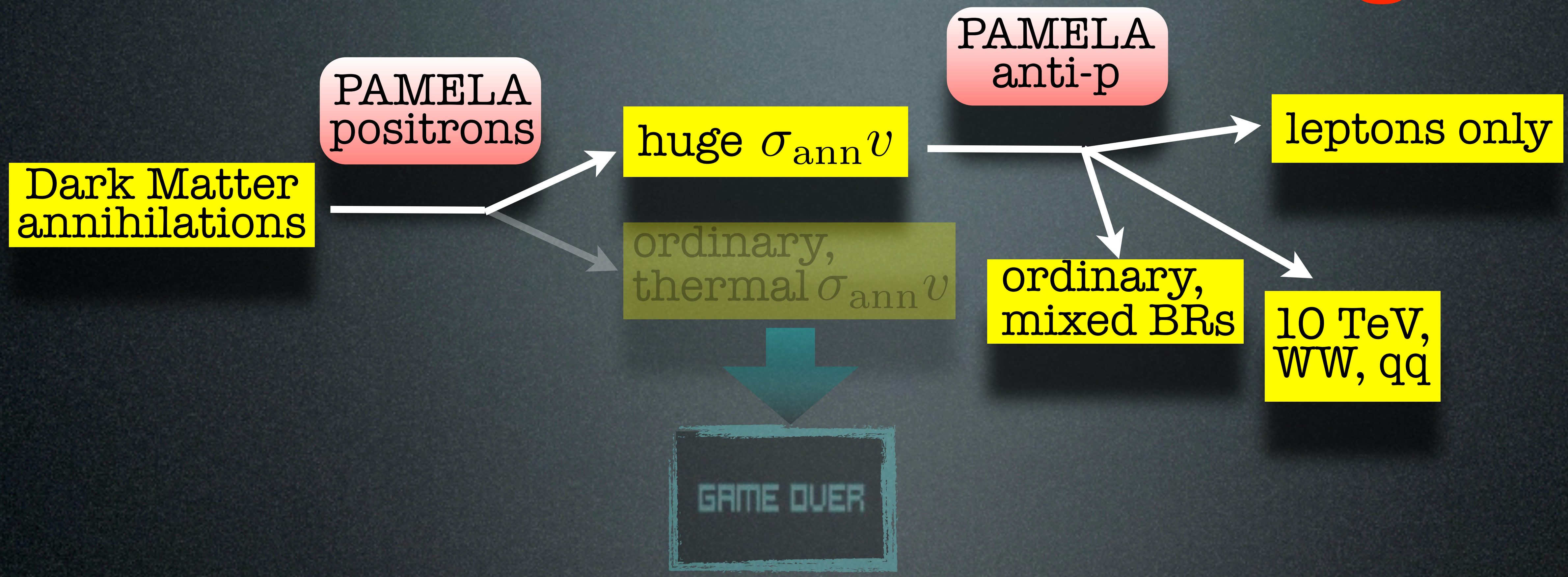

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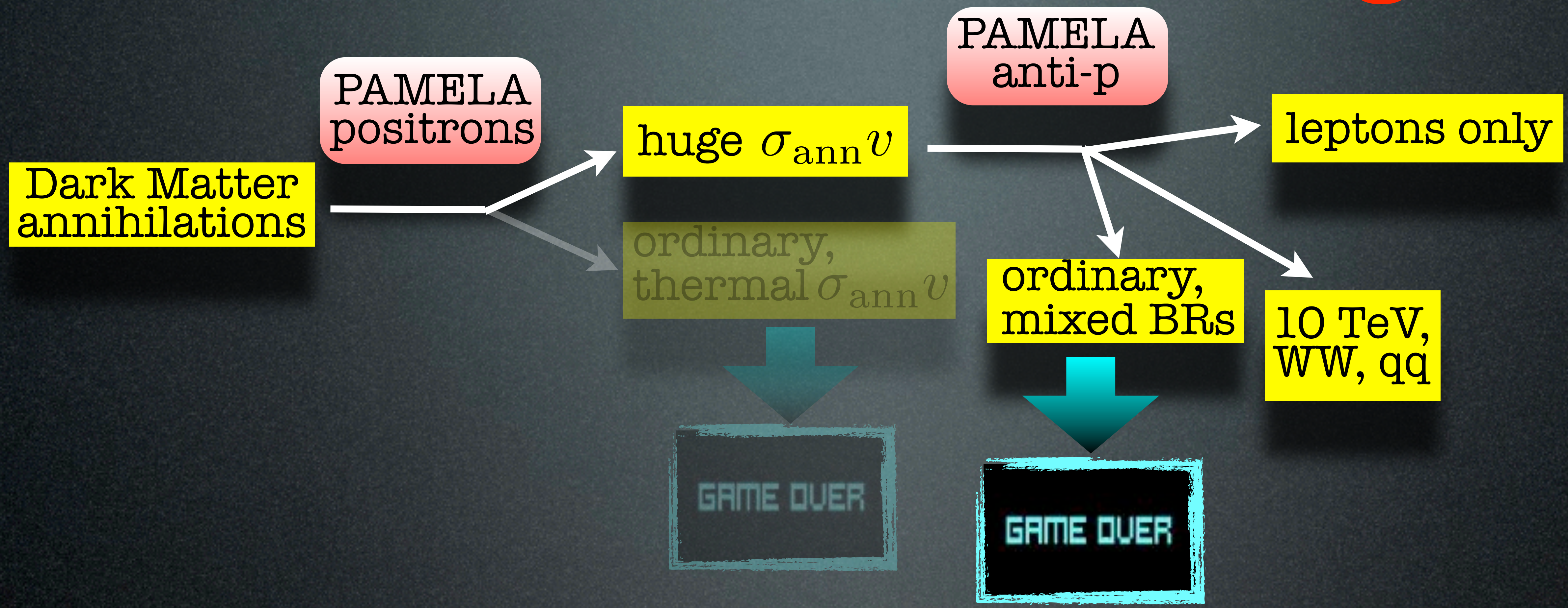

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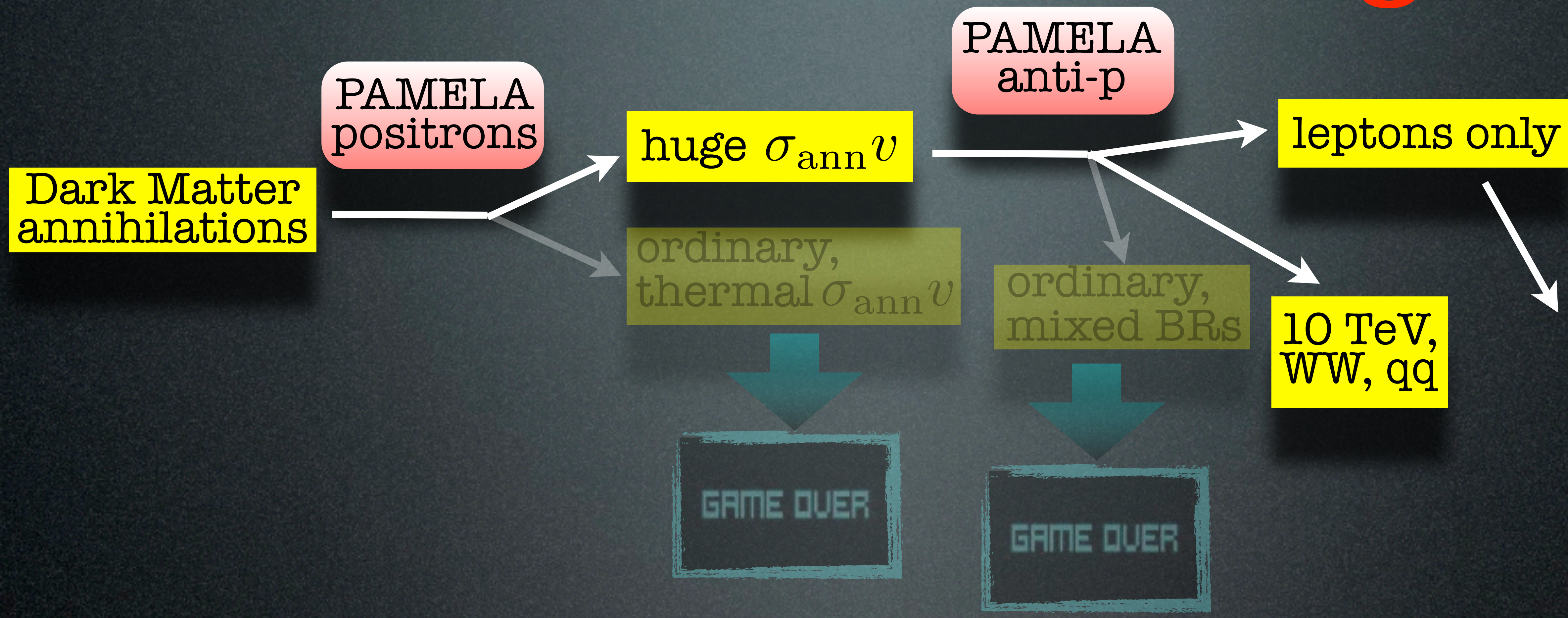

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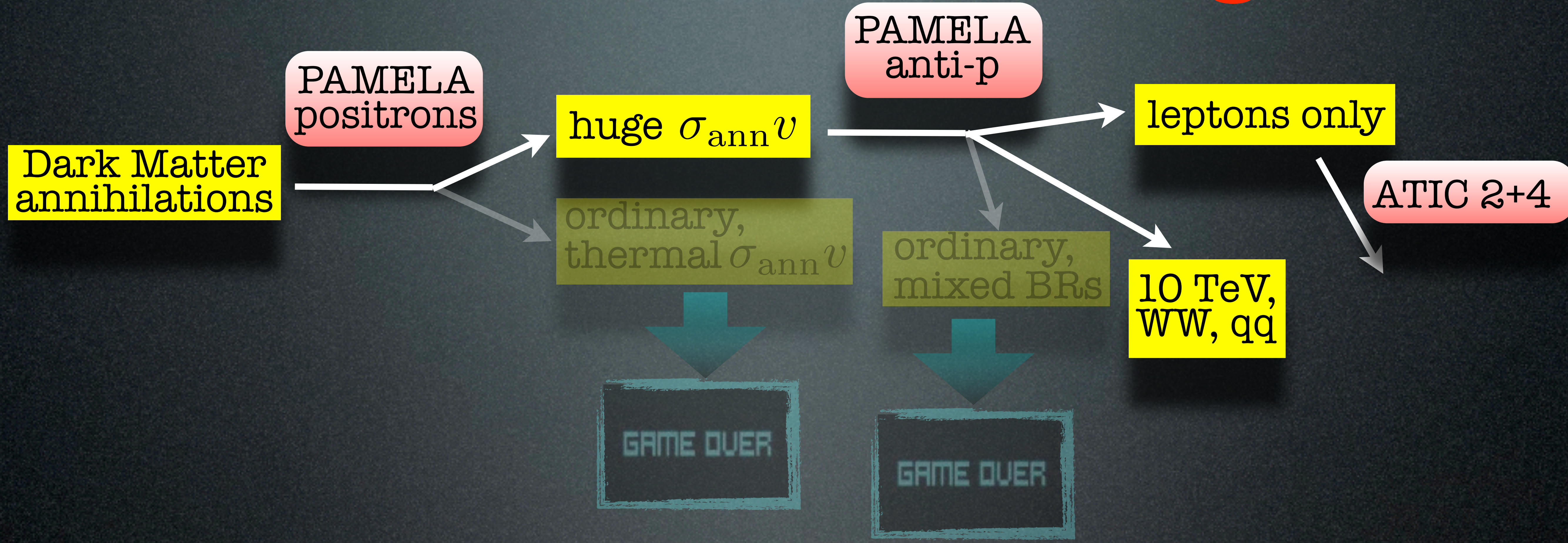

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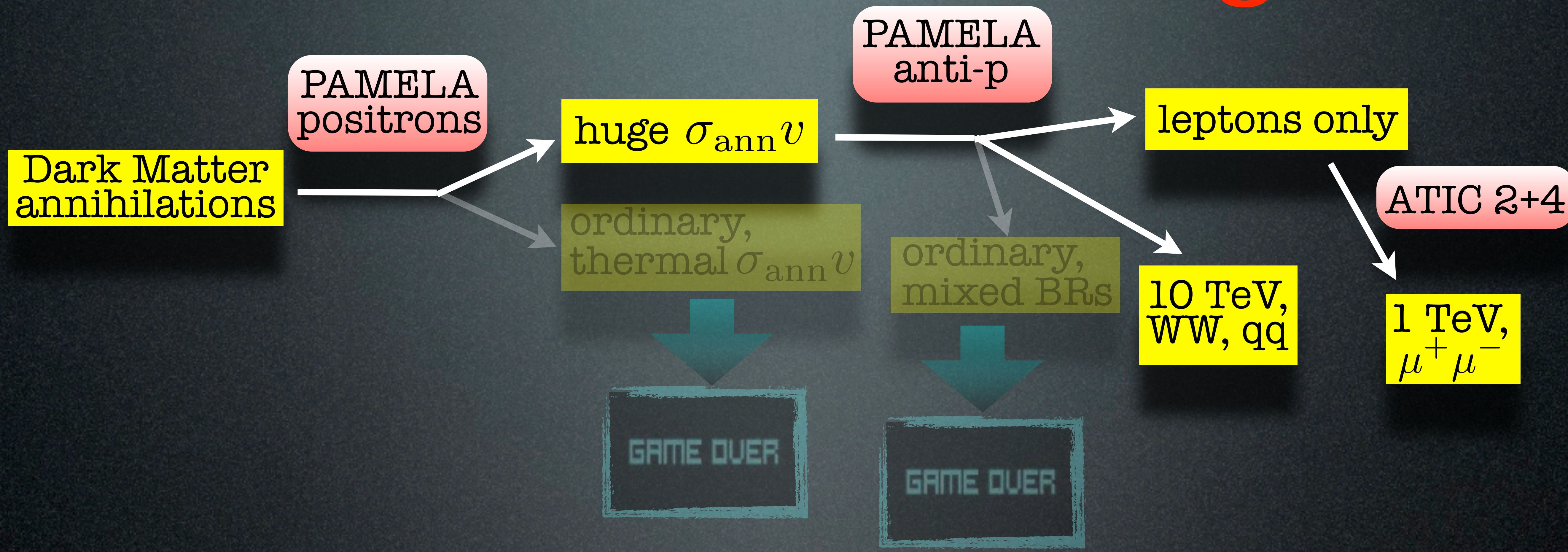

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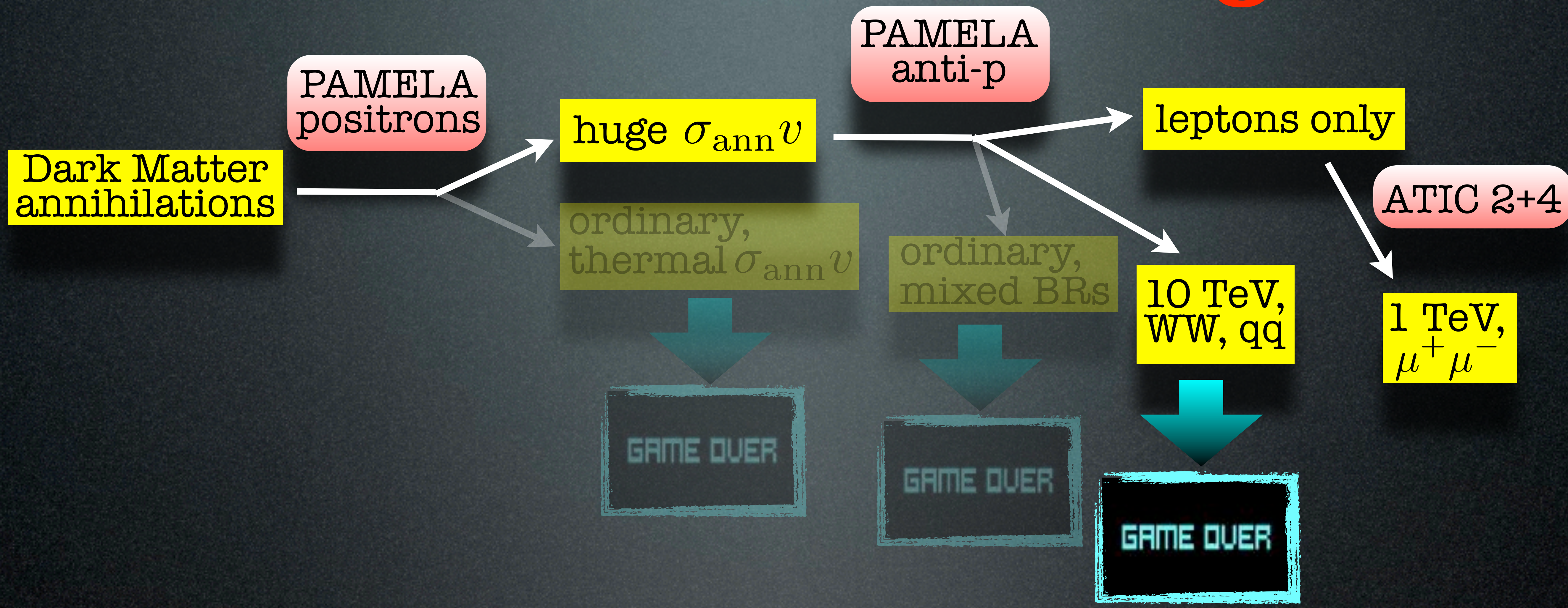

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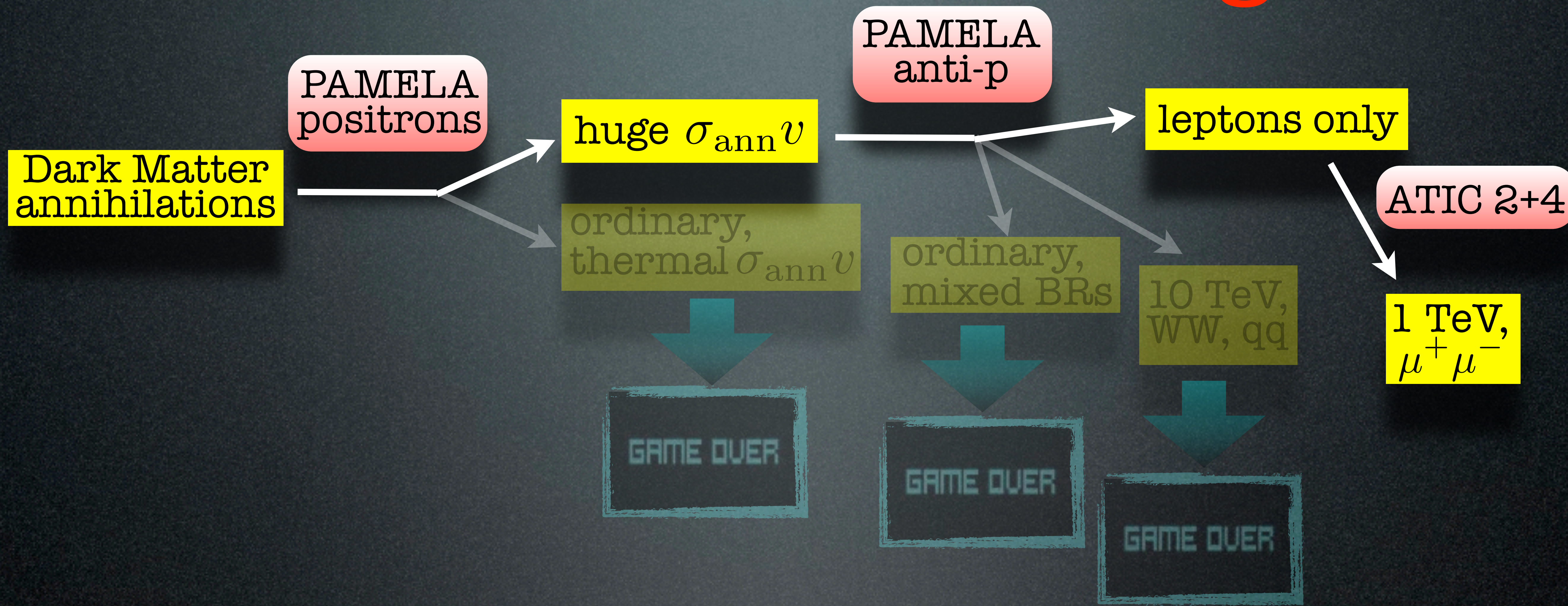

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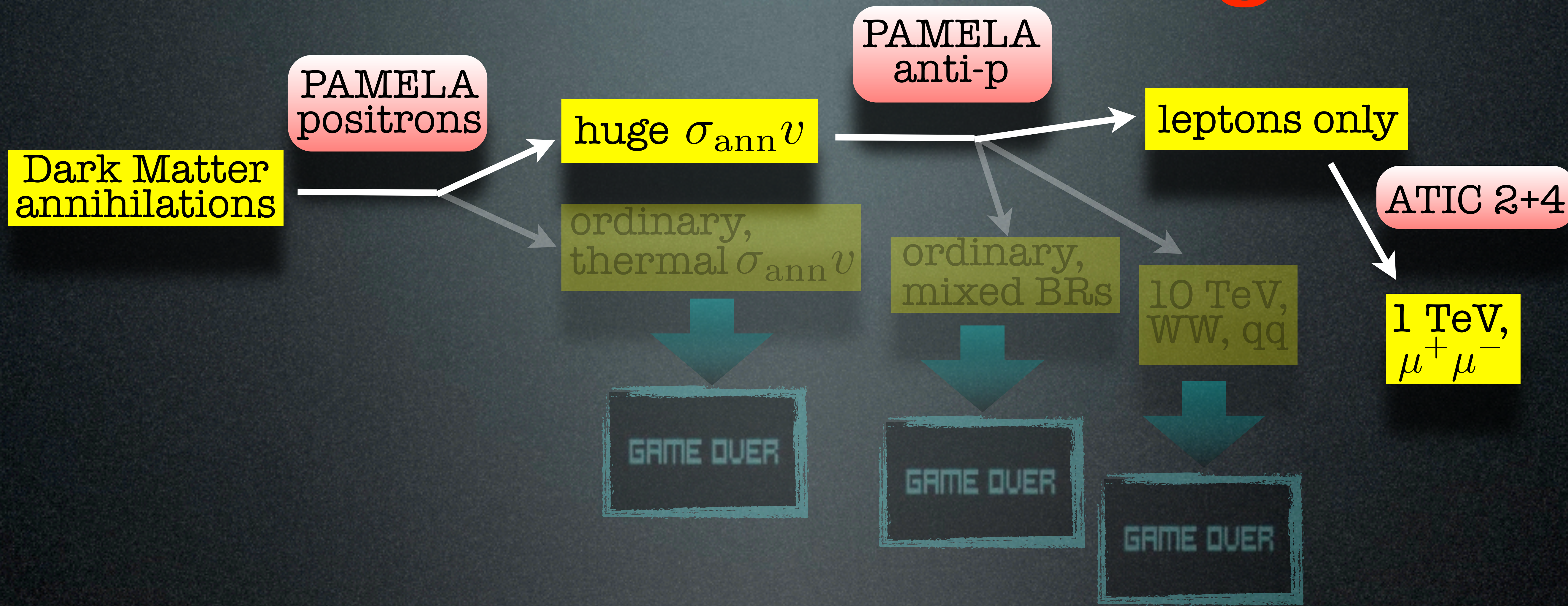

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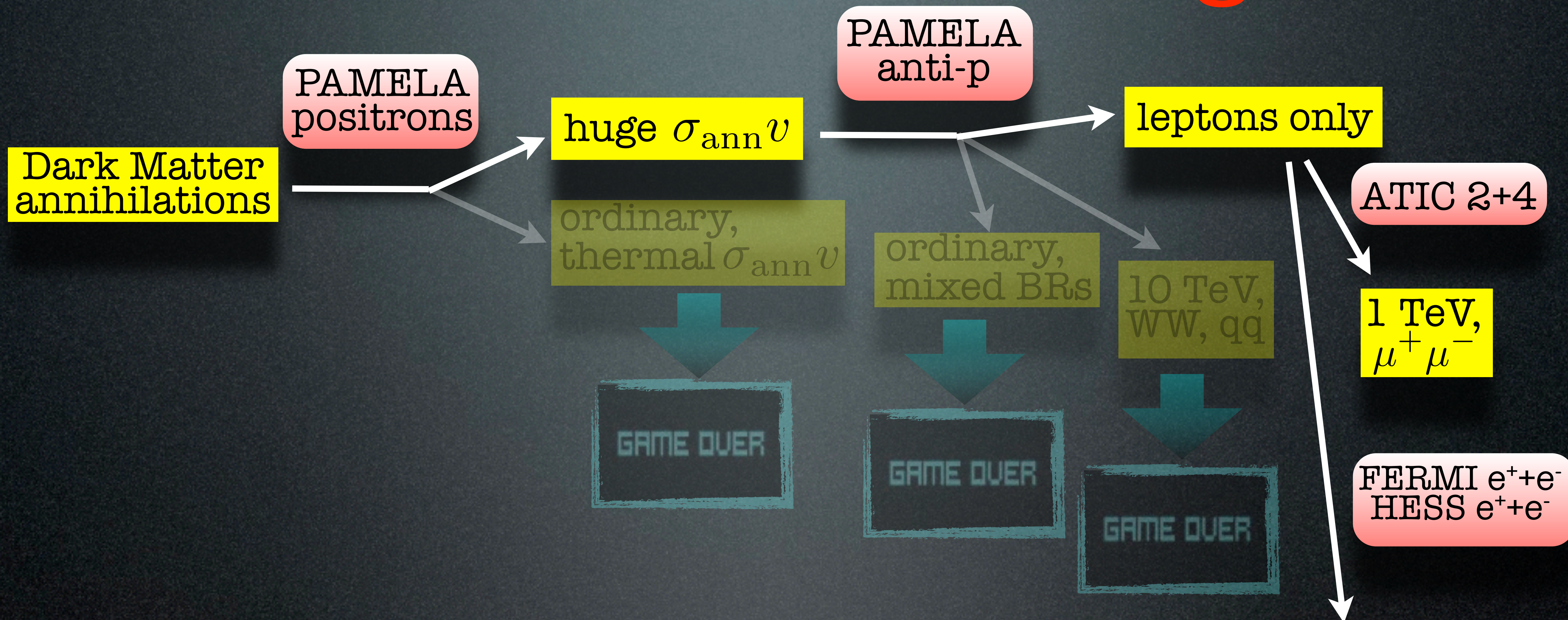

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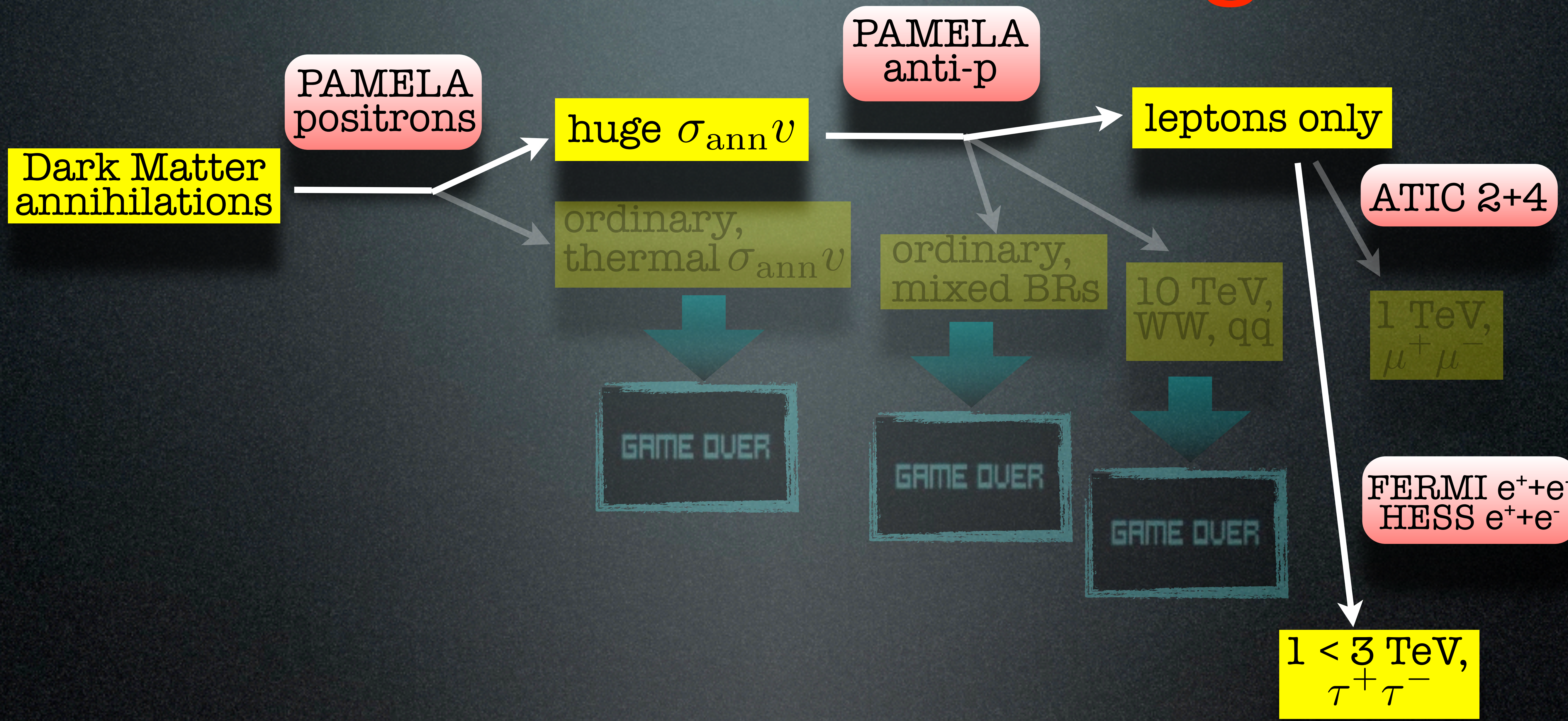

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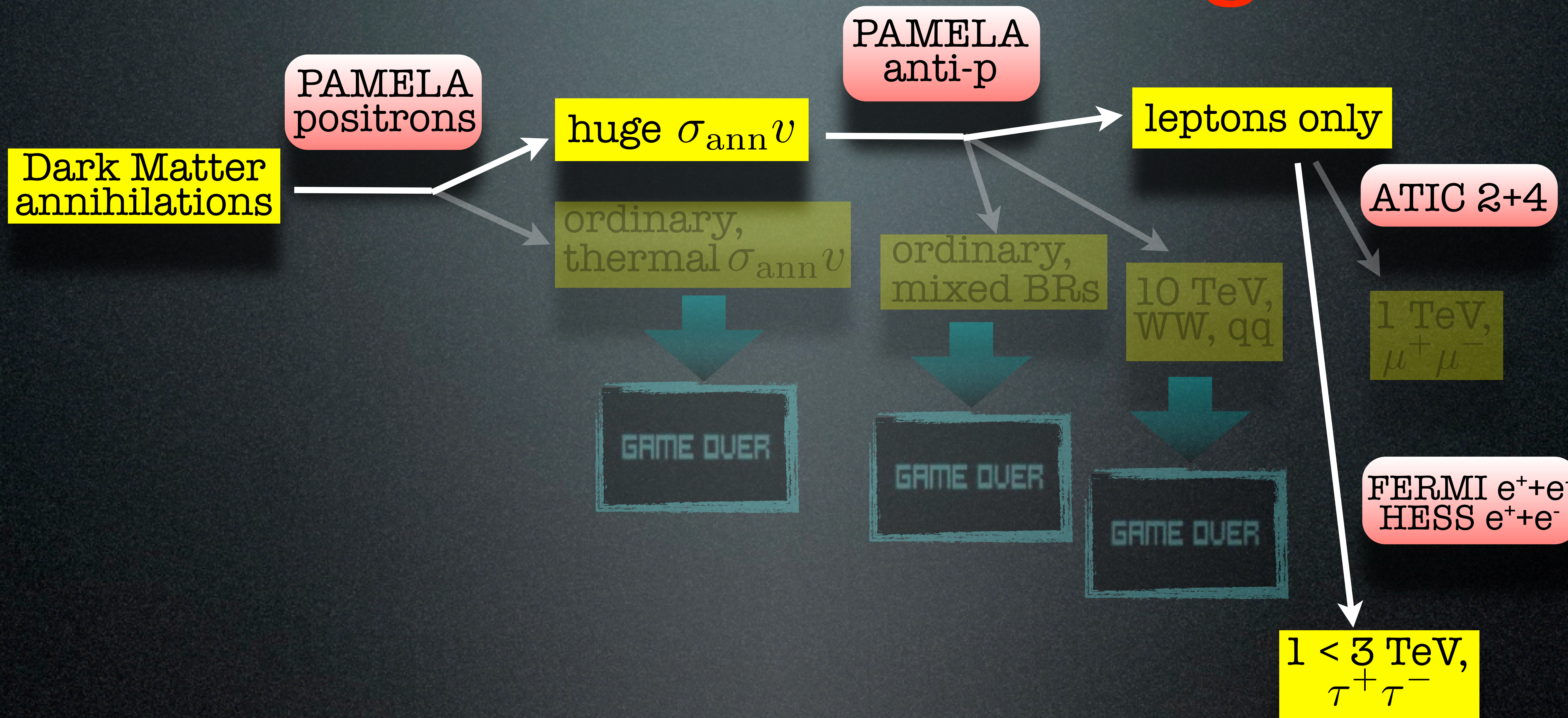

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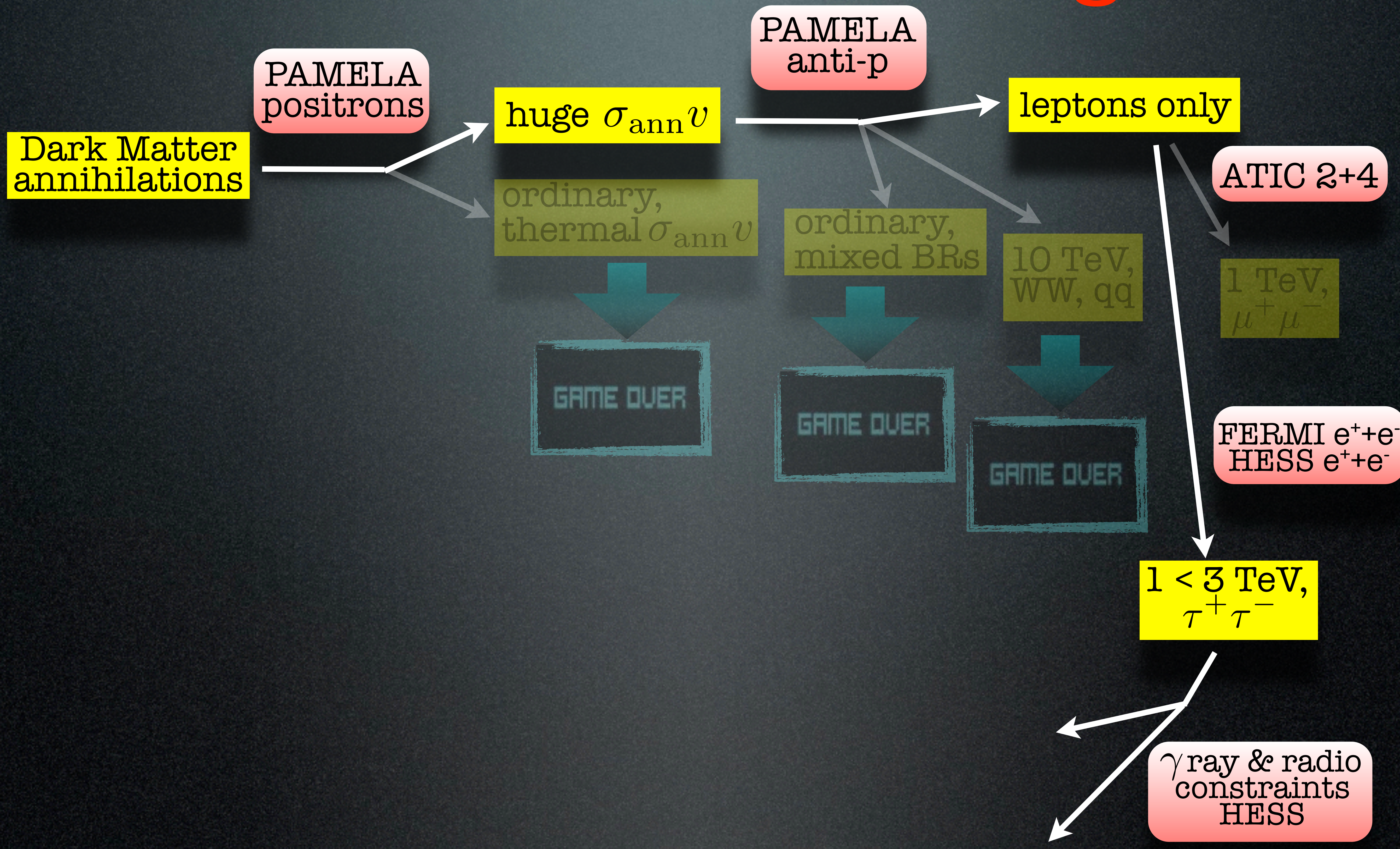

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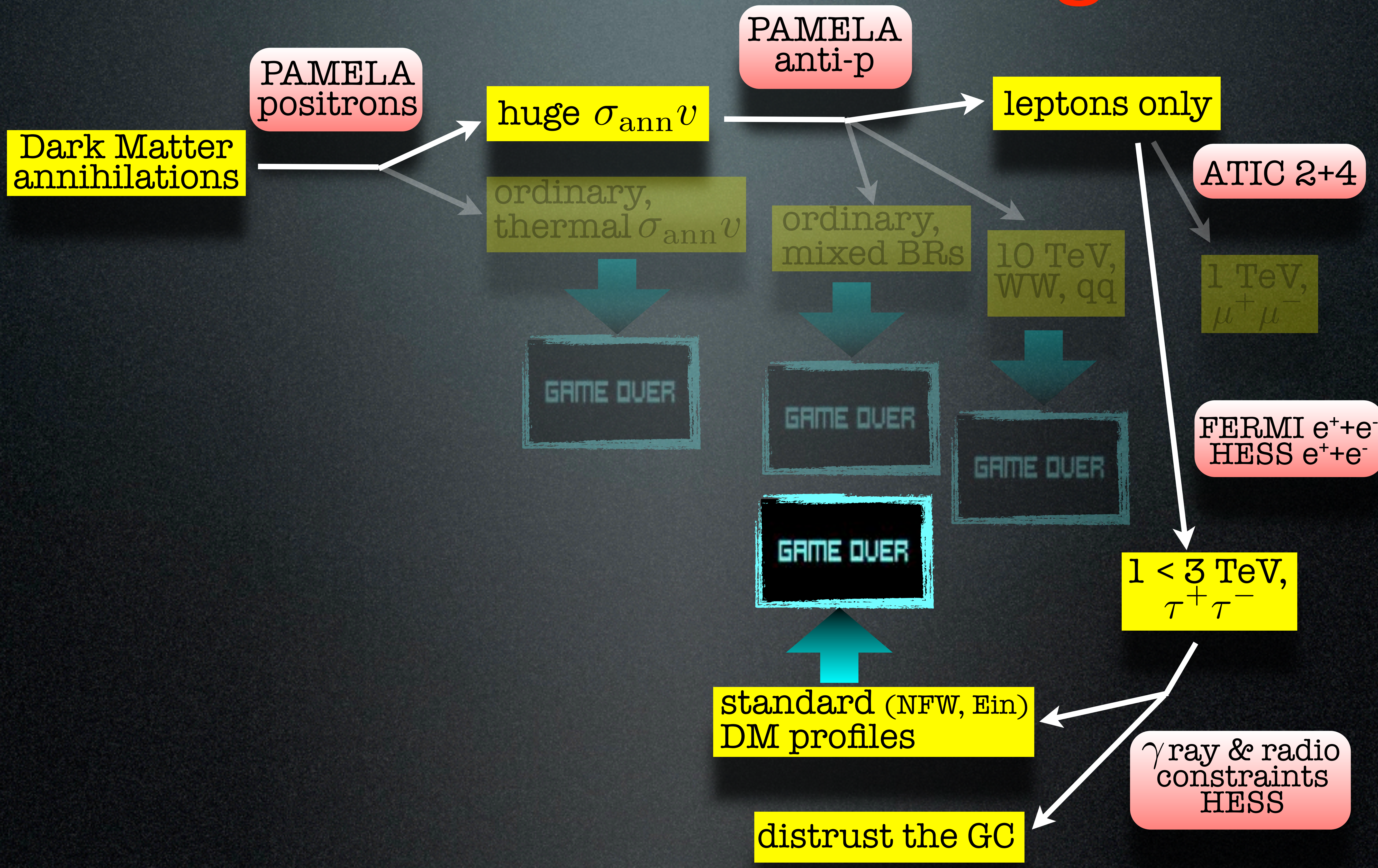

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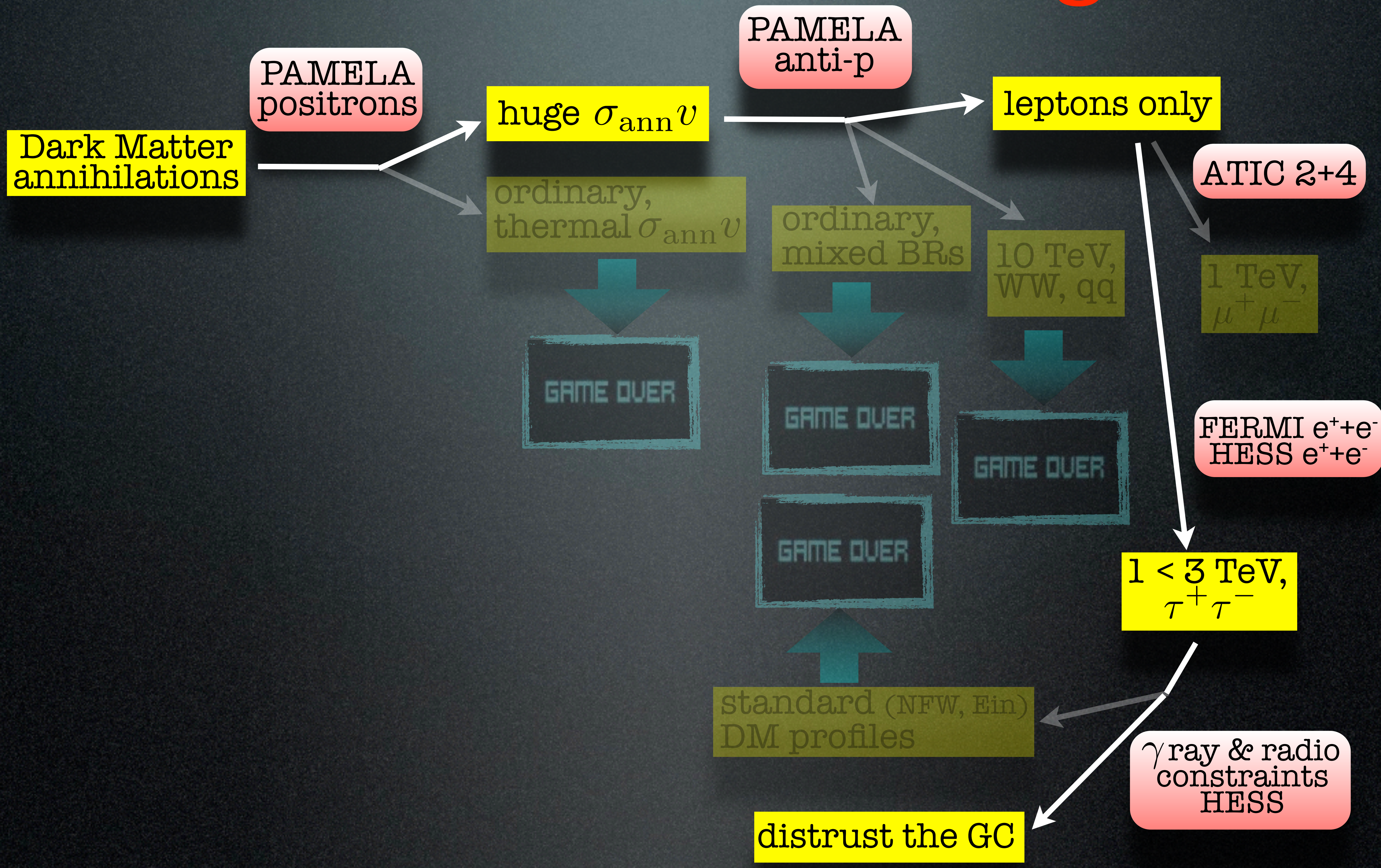

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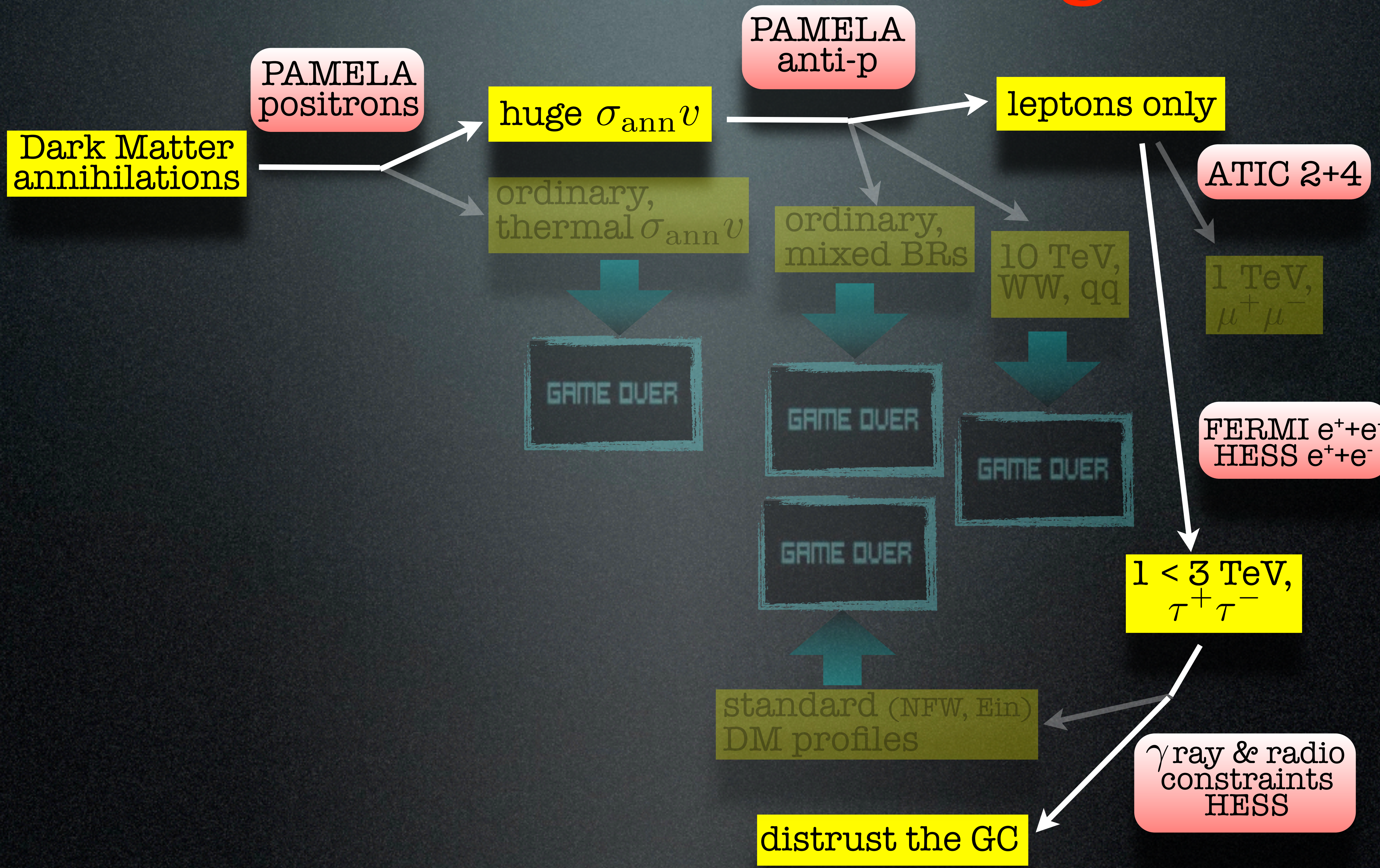

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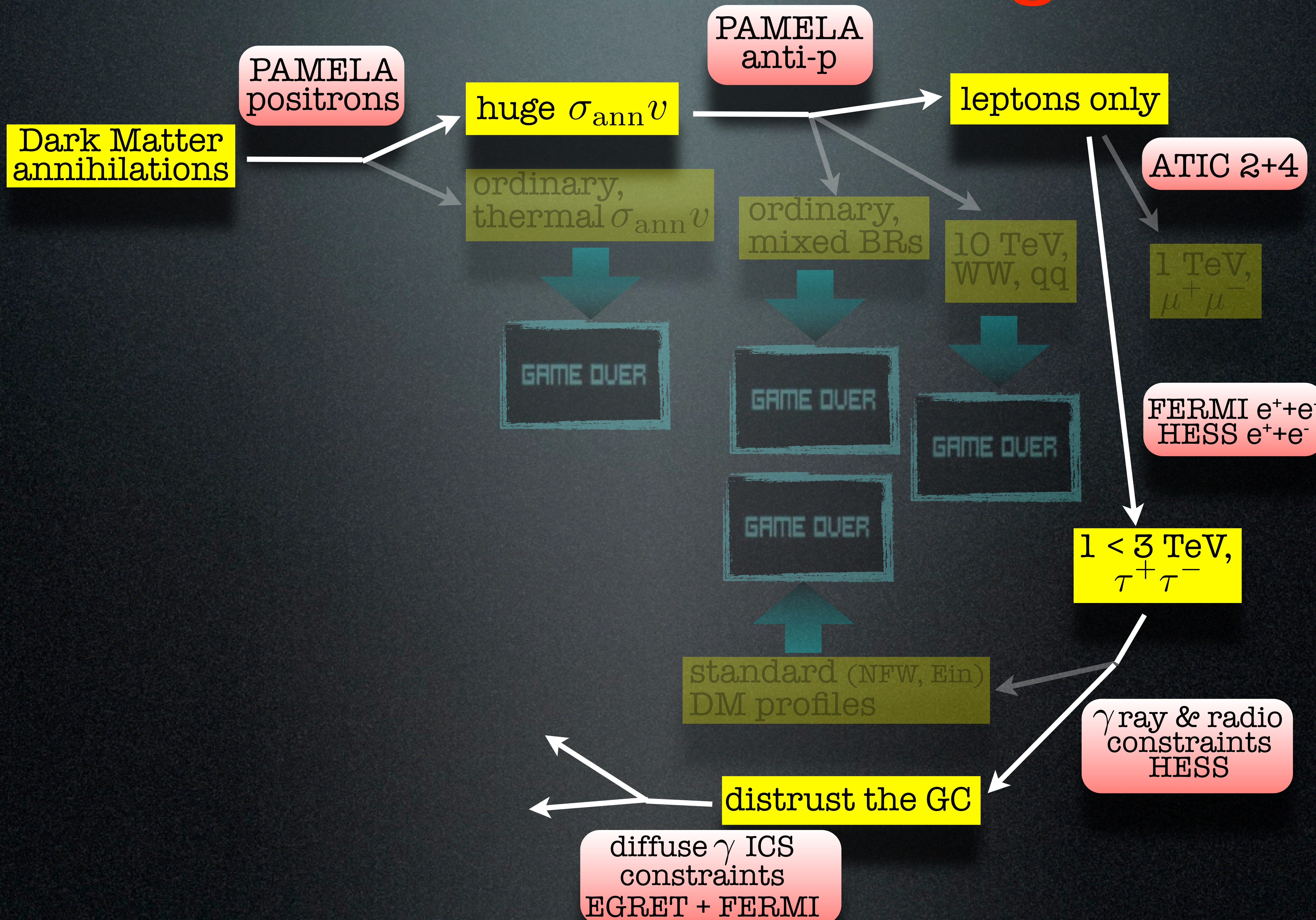

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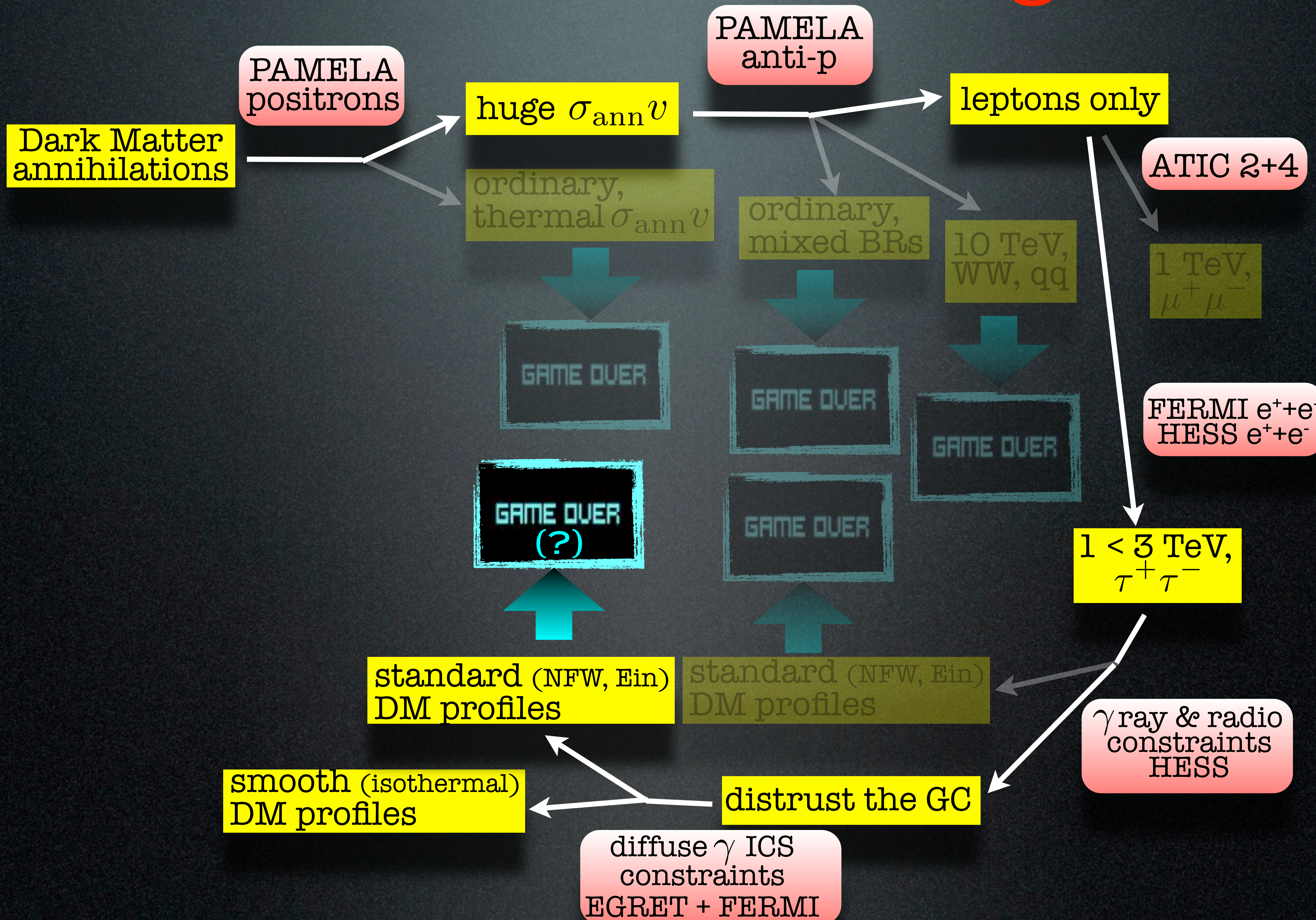

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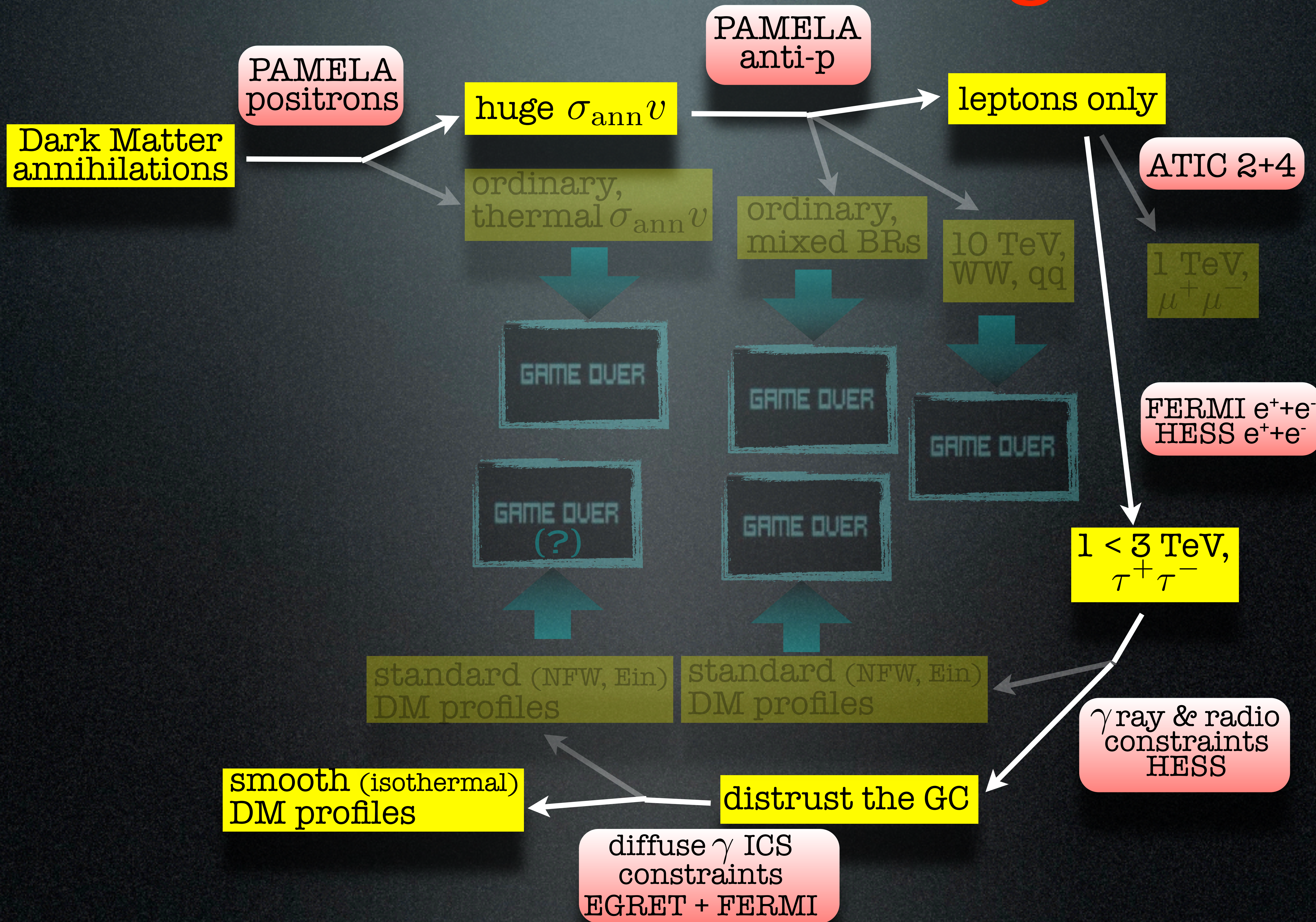

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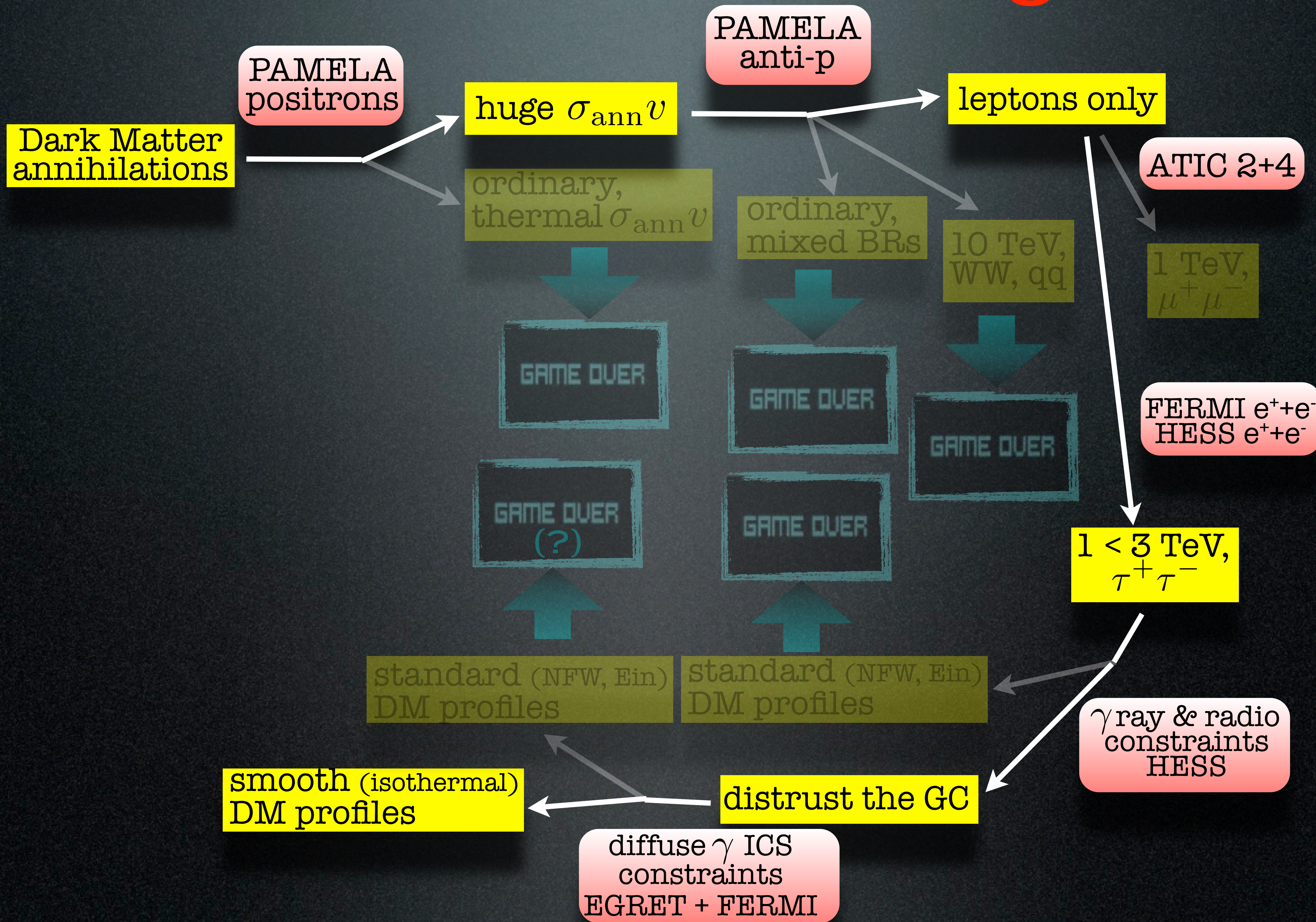

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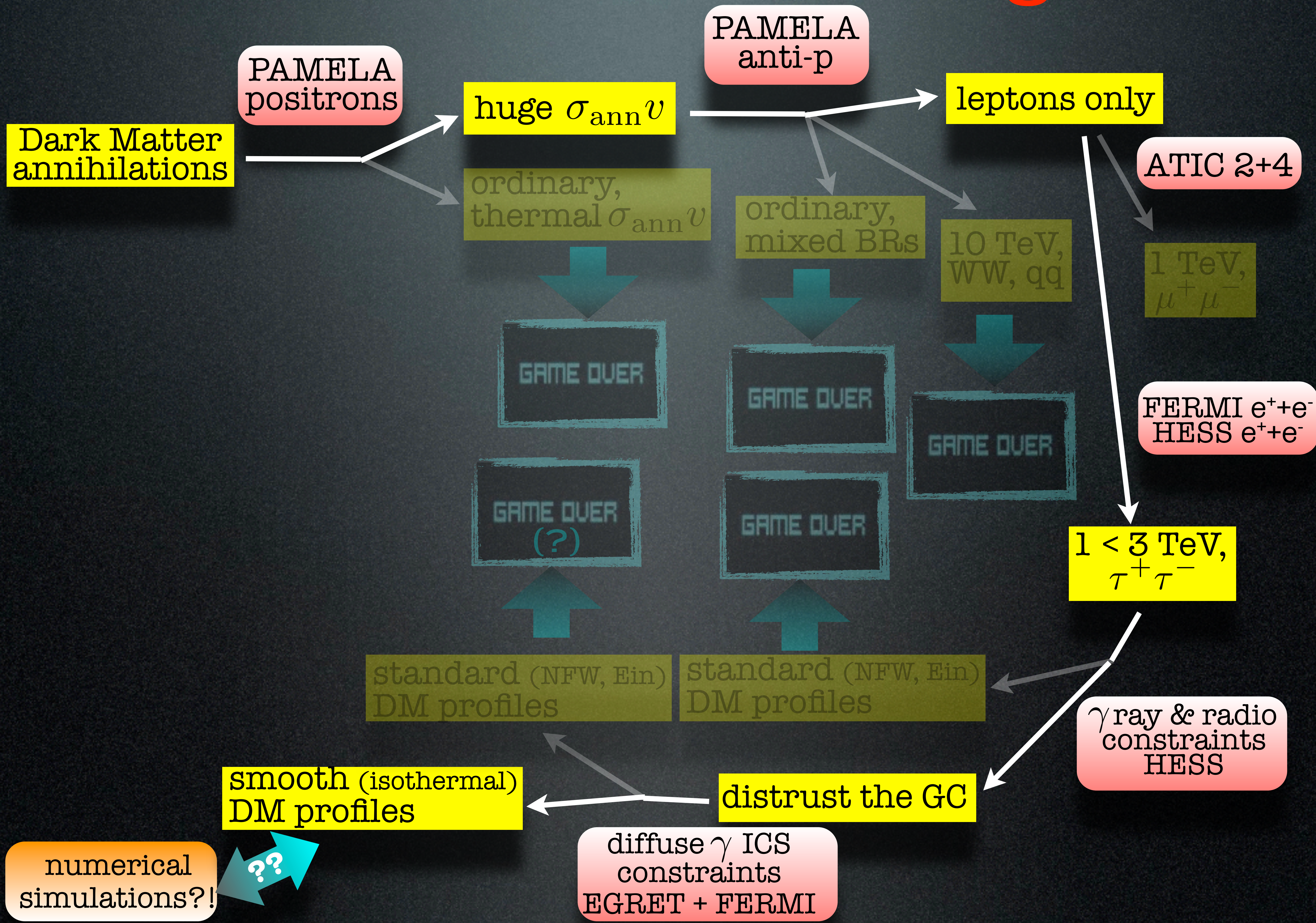

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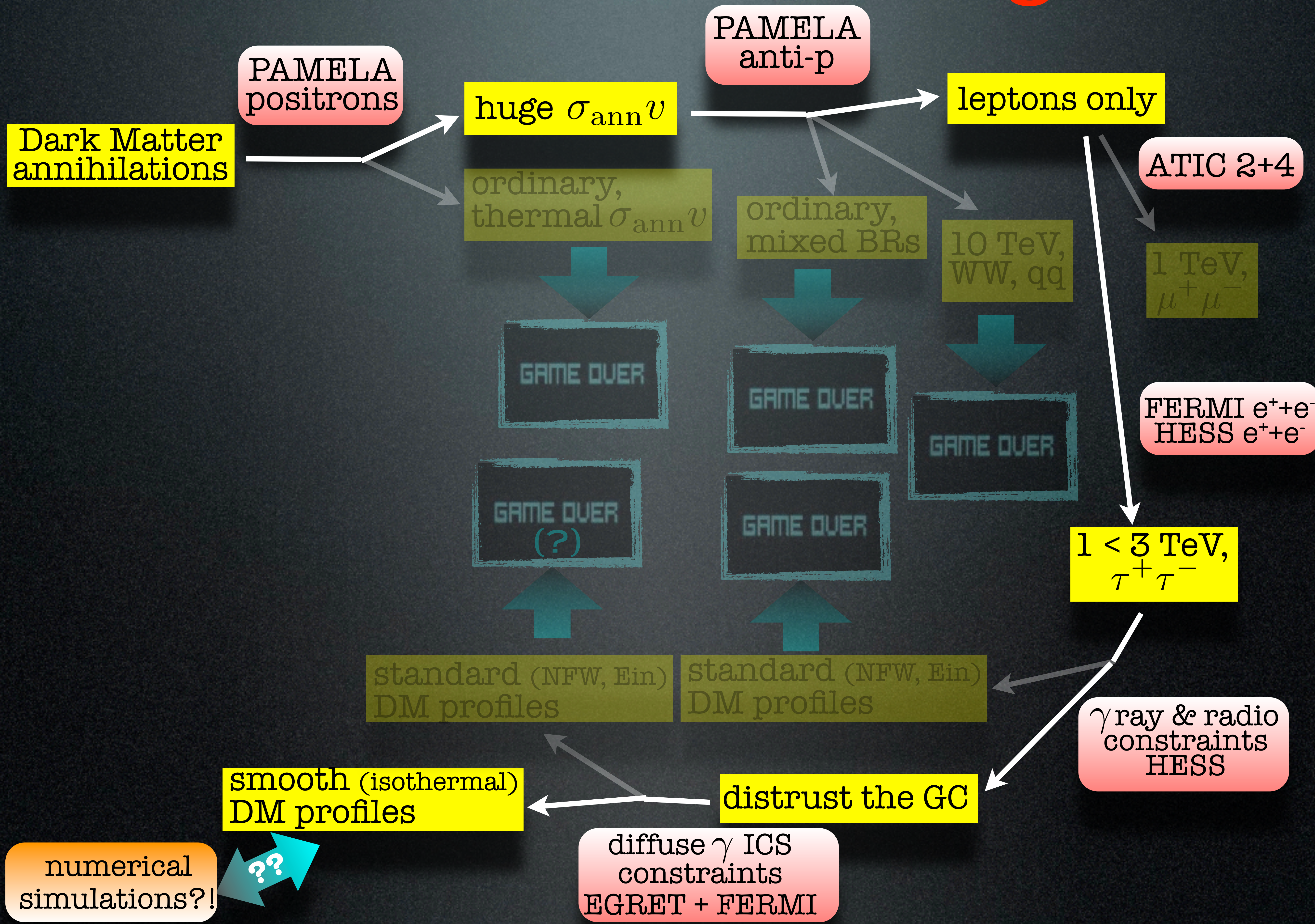

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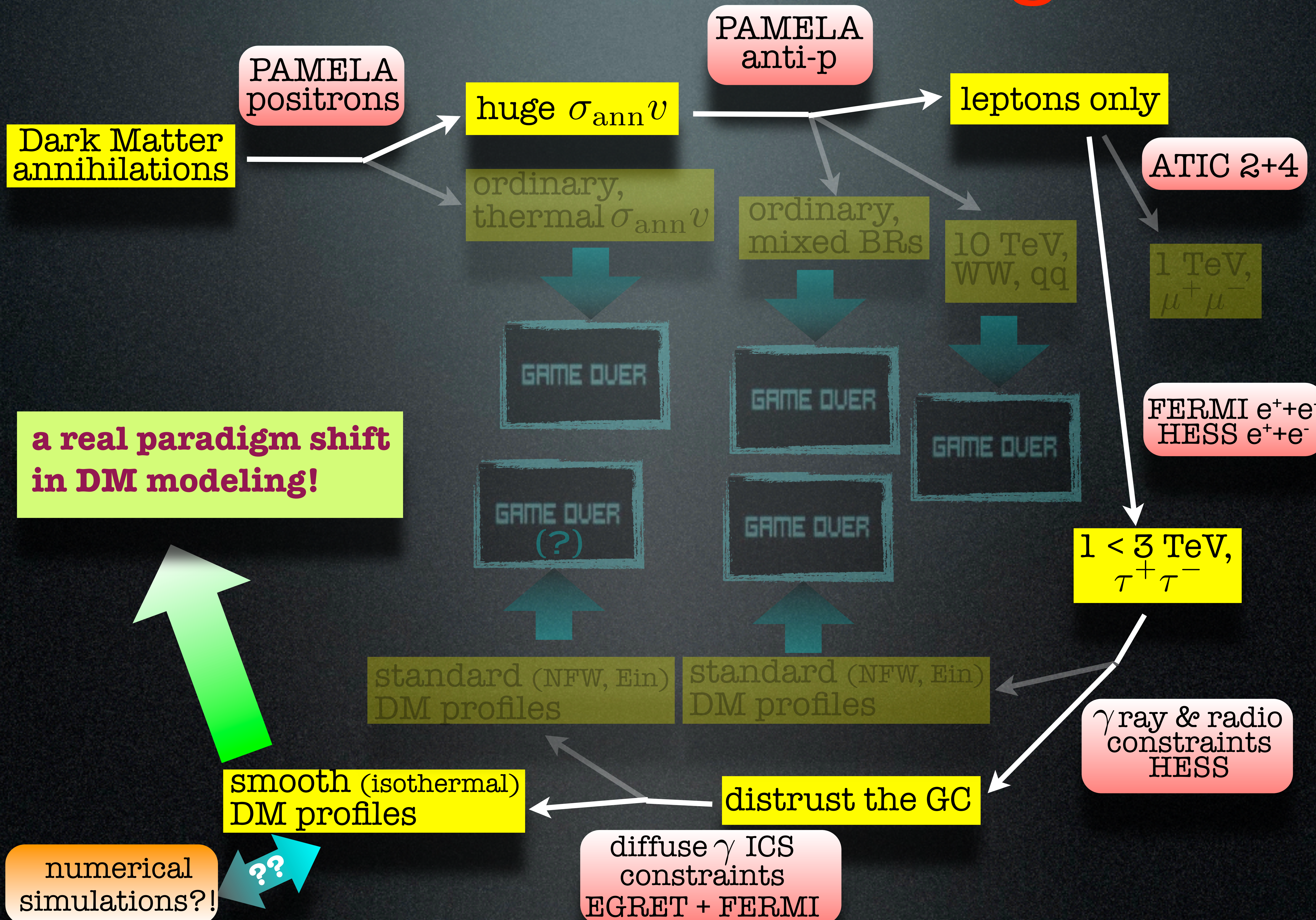

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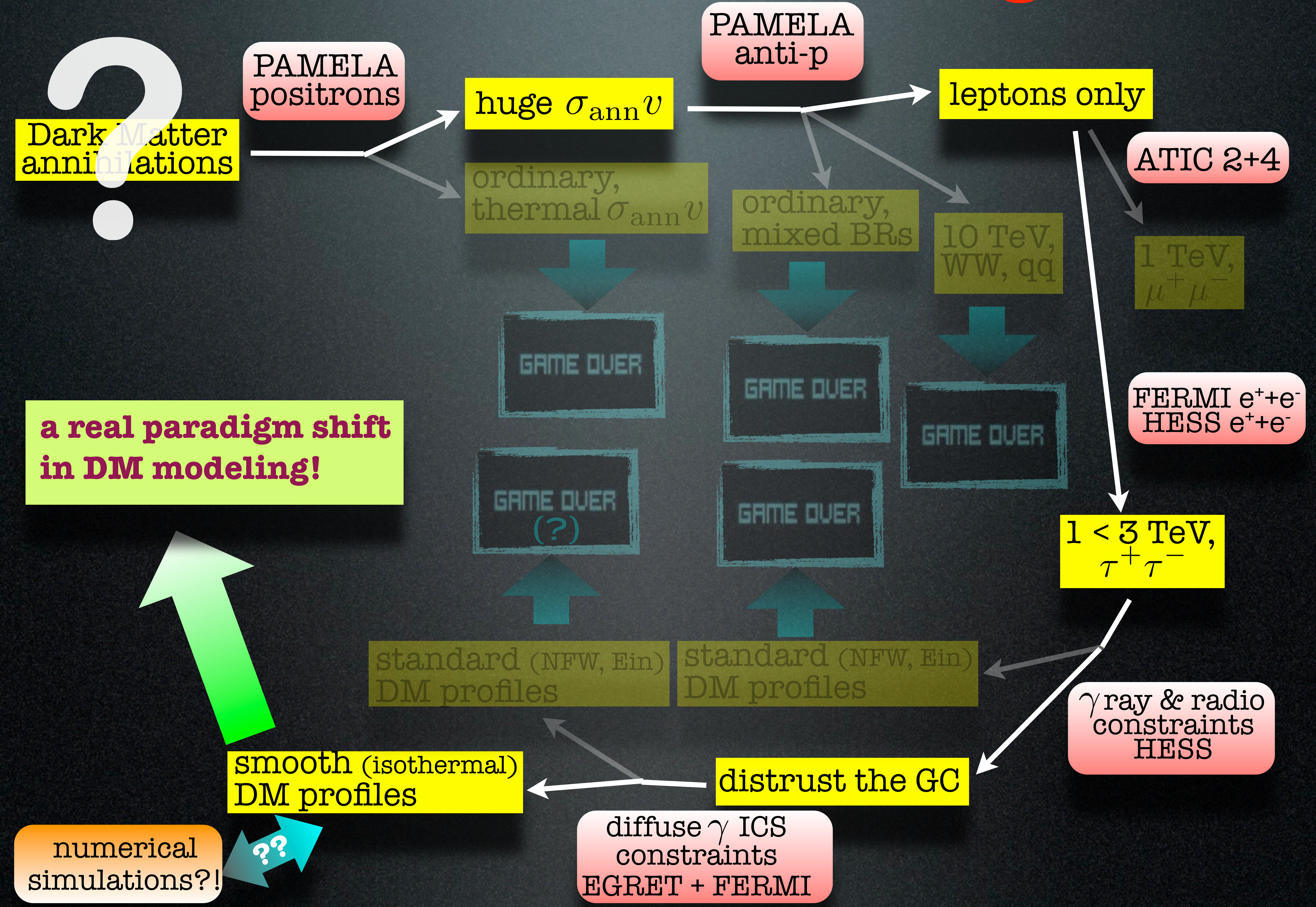

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Need a not-too-steep DM profile.

Future data (PAMELA, FERMI, AMS02...) will be crucial.
Will it be just some young, nearby pulsar?

Back up slides

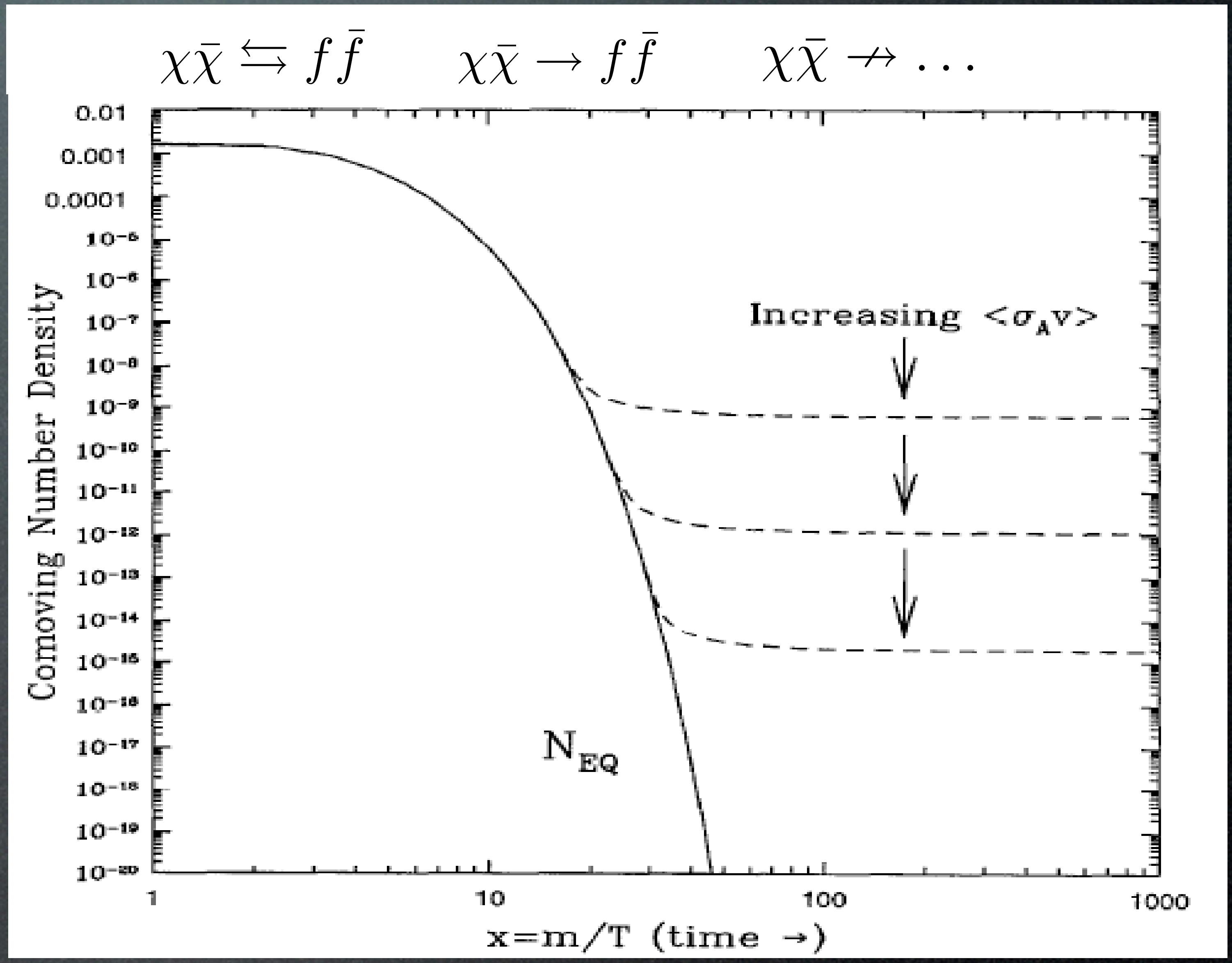
A thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\rm ann} v\rangle}$$

Relic $\Omega_{\rm DM} \simeq 0.23$ for

$$\langle\sigma_{\rm ann} v\rangle = 3\cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\rm ann} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

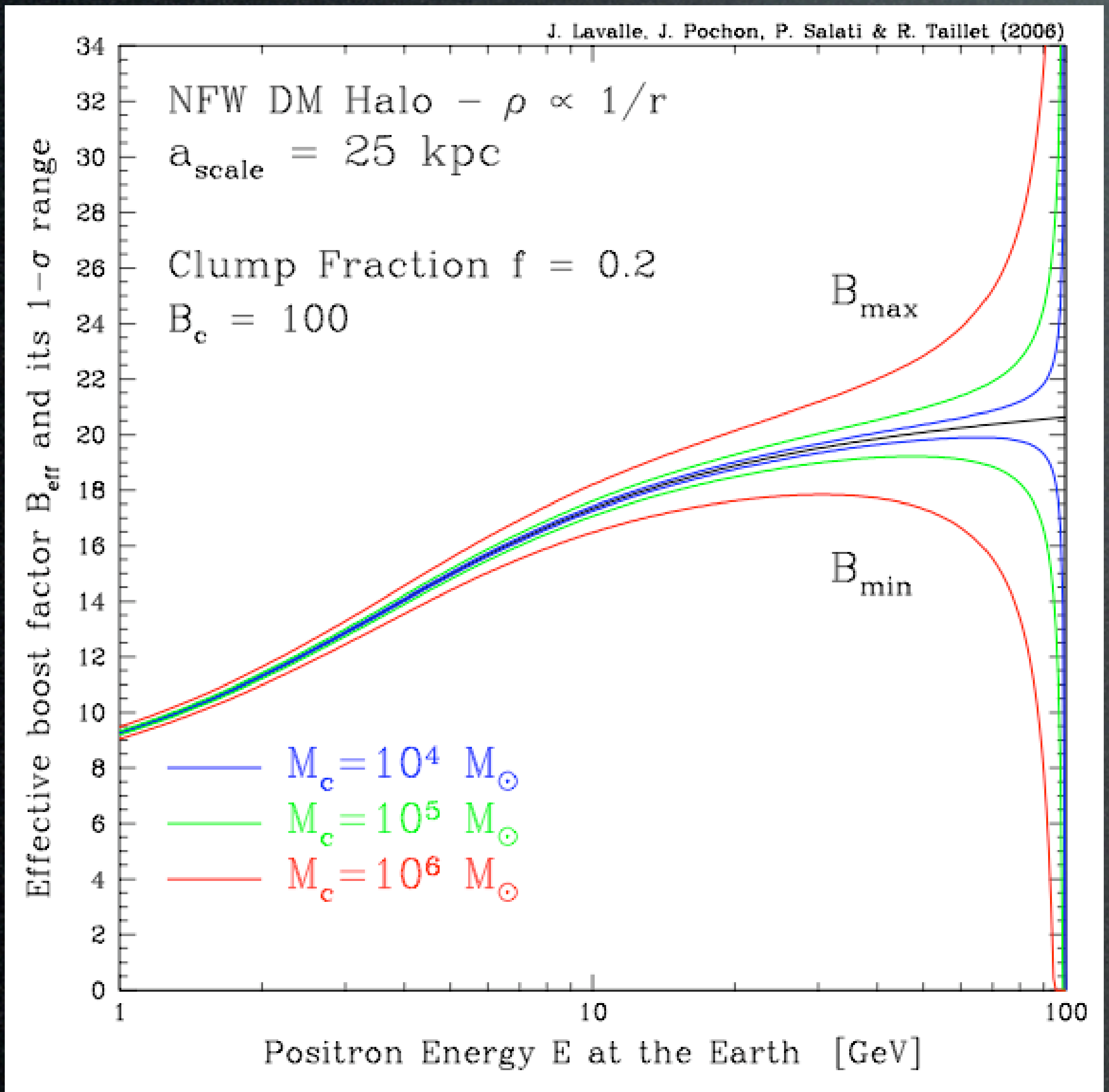
(WIMP)

Indirect Detection

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

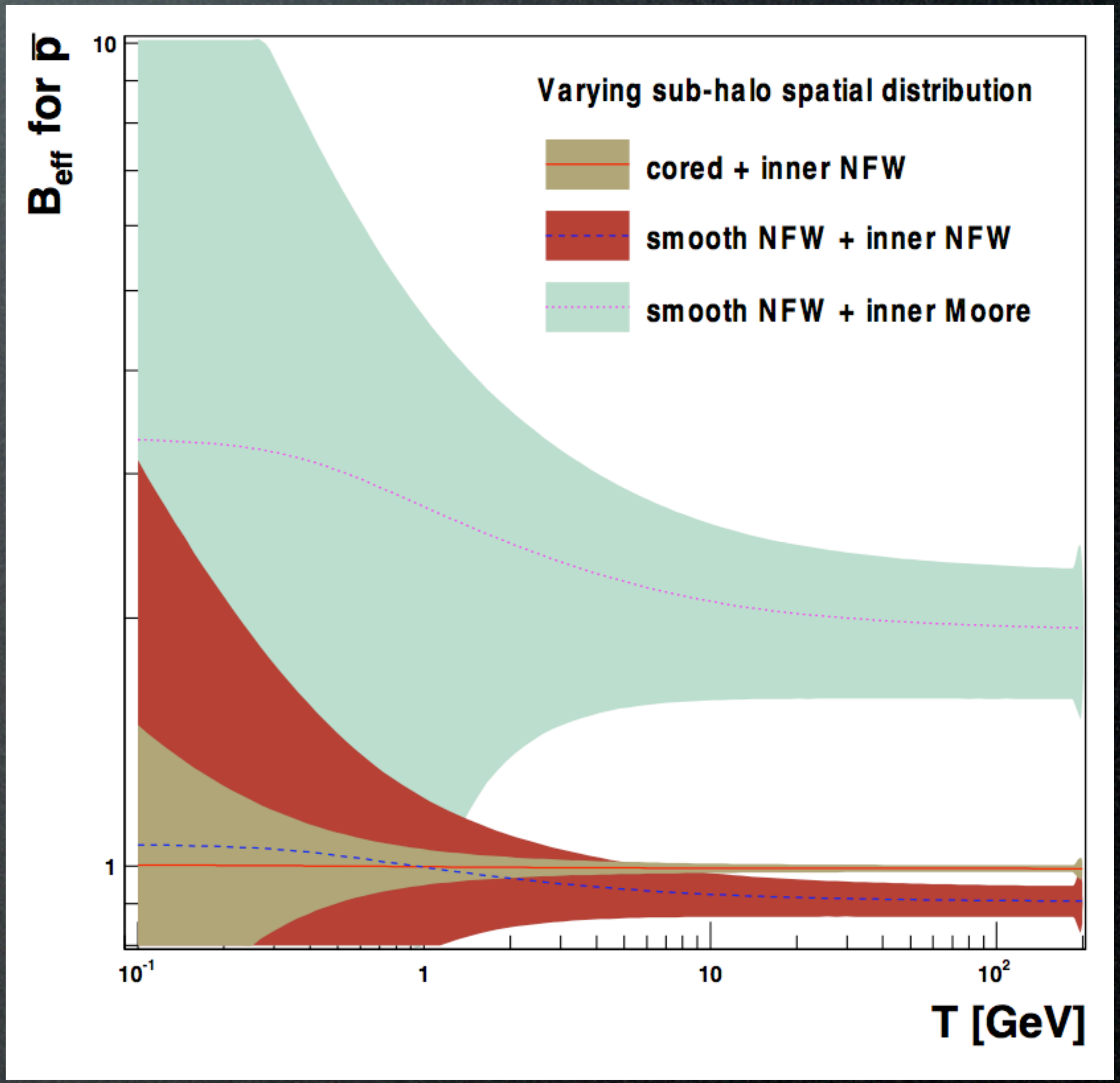
In principle, B is different for e^+, anti-p and gammas,
energy dependent,
dependent on many astro assumptions (inner density profile of clump, tidal disruptions and smoothing...),
with an energy dependent variance, at high energy for e^+, at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons

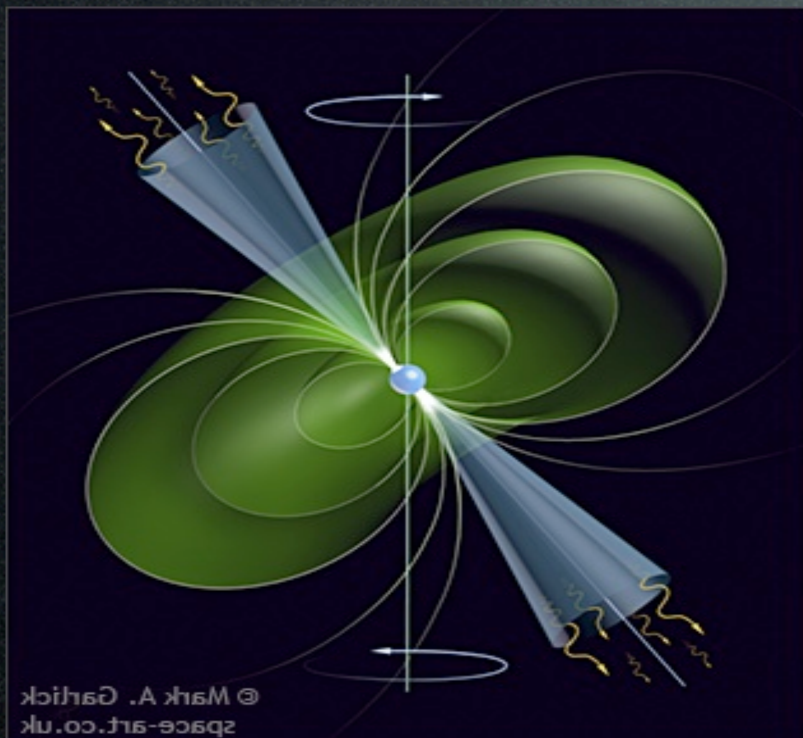


Lavalle et al. 2007

Astrophysical explanation?

[others?]

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



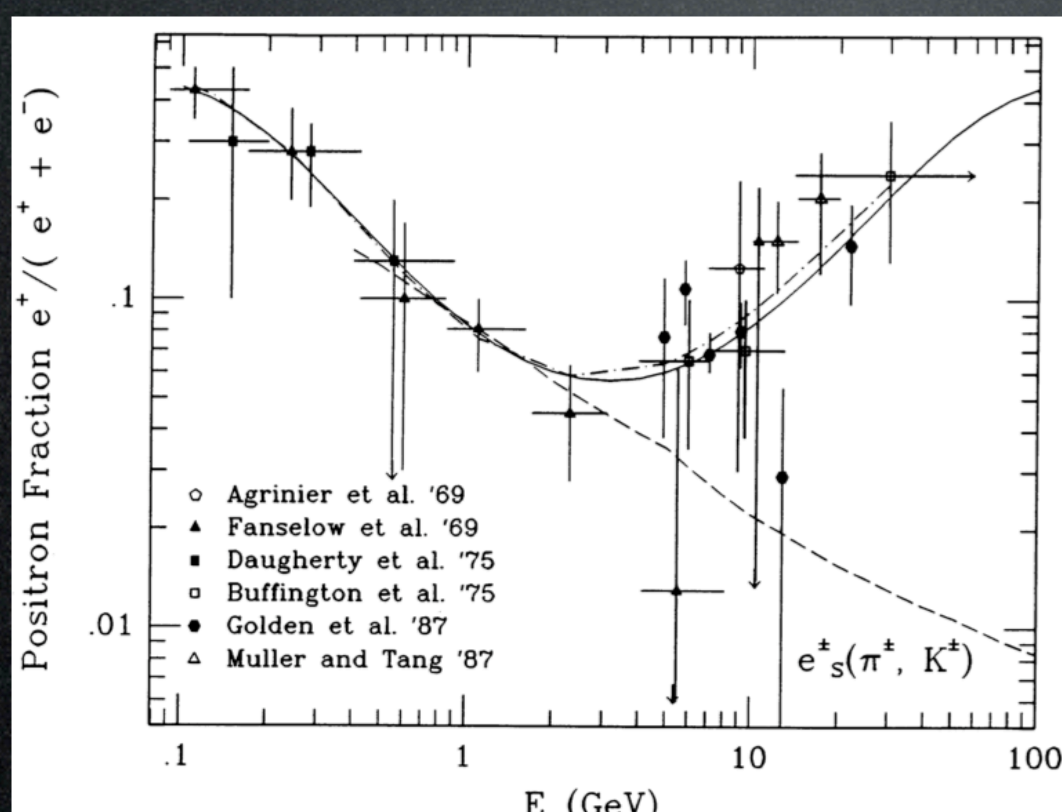
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \rightarrow 10^5$ yr (typical total energy output: 10^{46} erg).

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

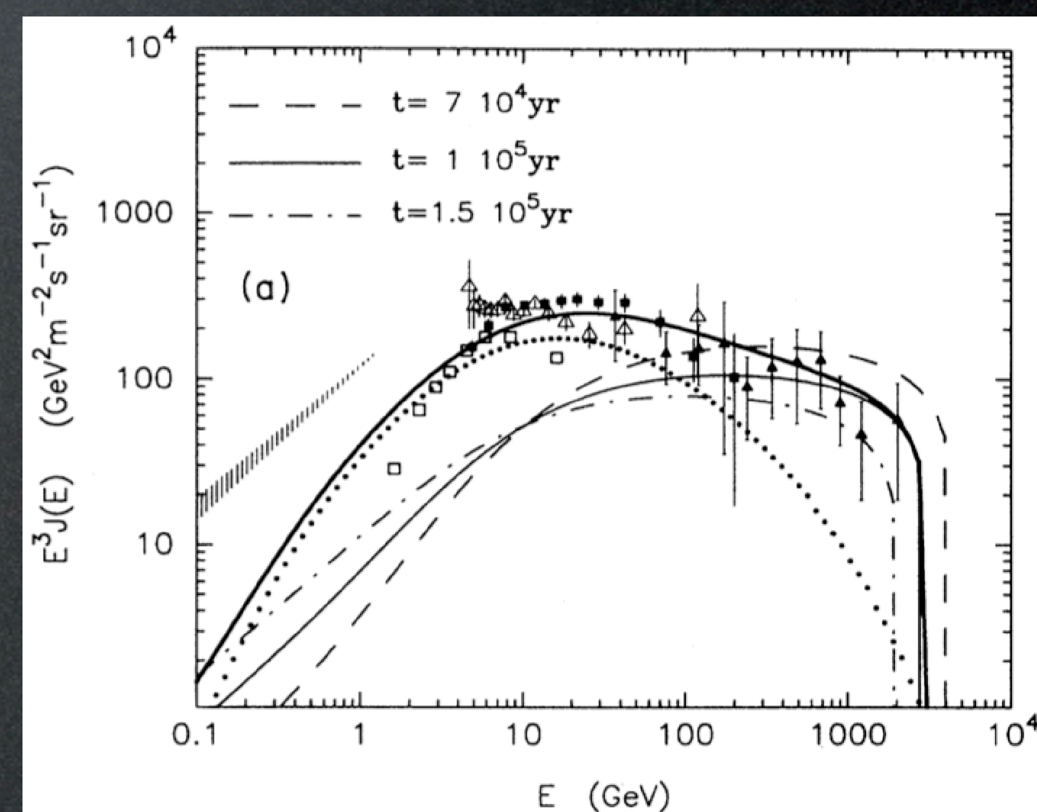
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

Not a new idea:



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



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

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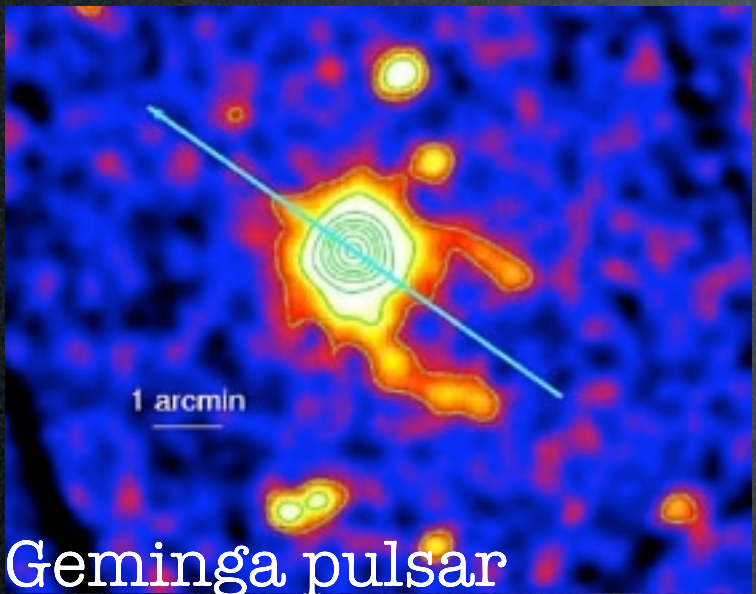

Geminga pulsar
(funny that it means:
"it is not there" in milanese)

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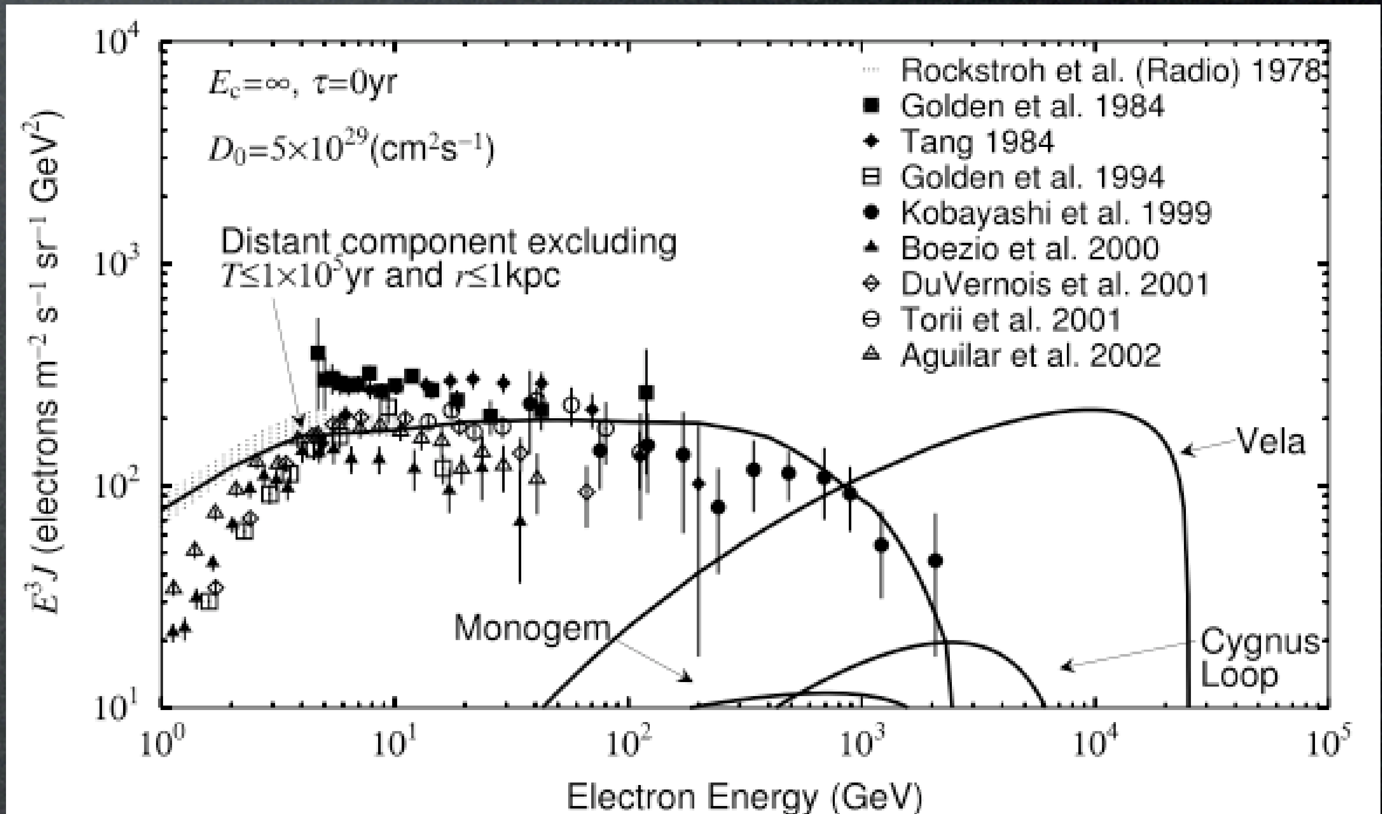
Try the fit with known nearby pulsars:

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

Kobayashi, Komori et al. 2004



Kobayashi, Komori et al. 2004

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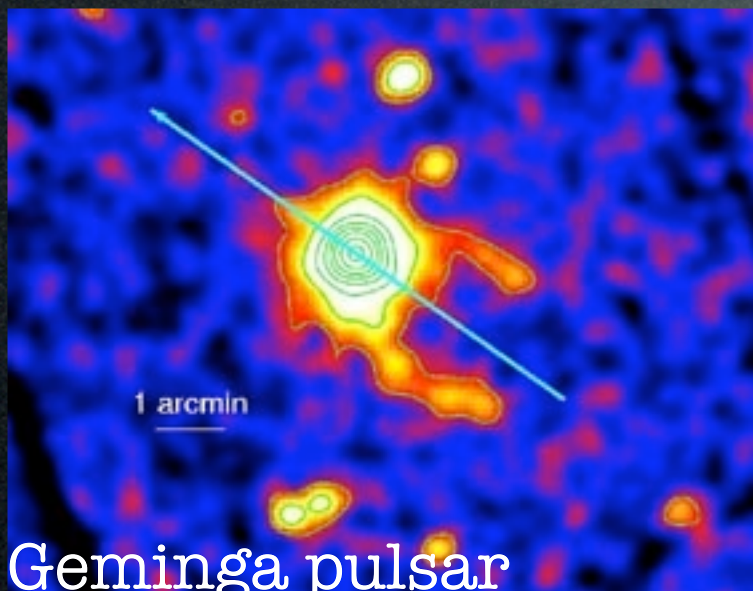

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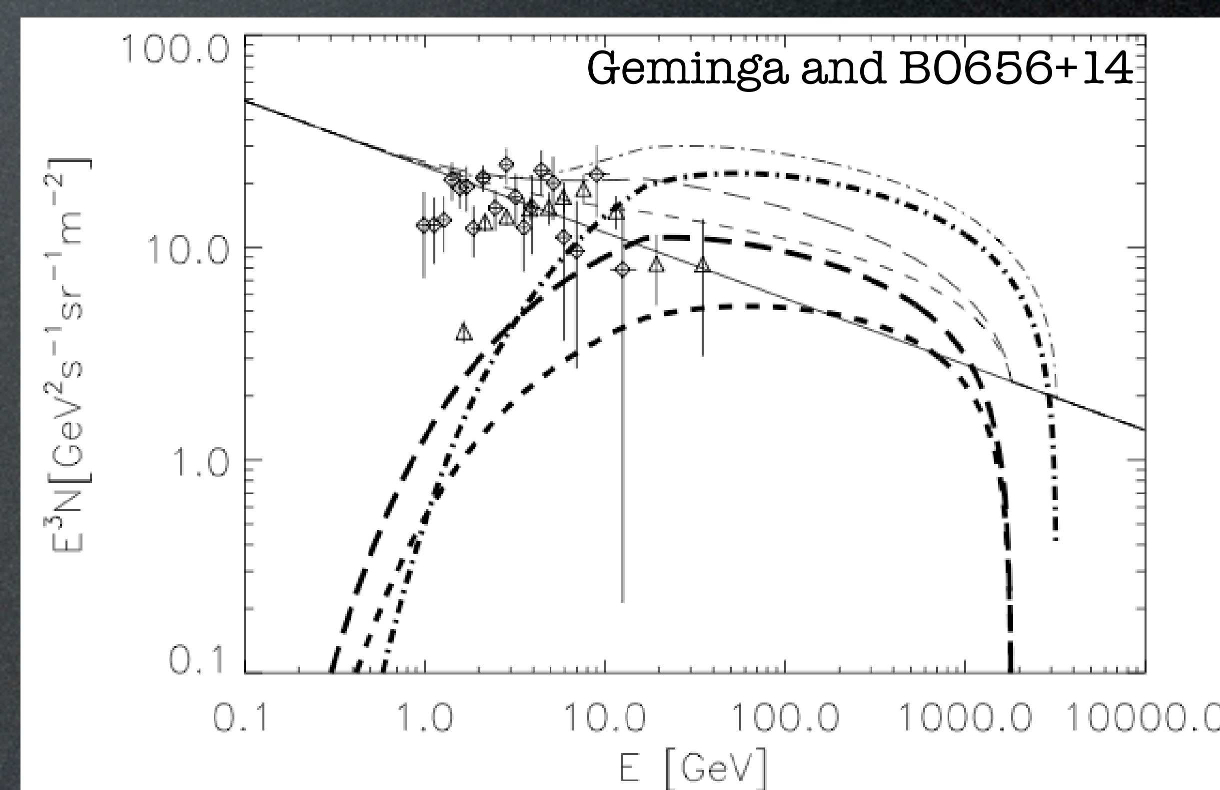
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

Try the fit with known nearby pulsars:

TABLE 1
LIST OF NEARBY SNRs

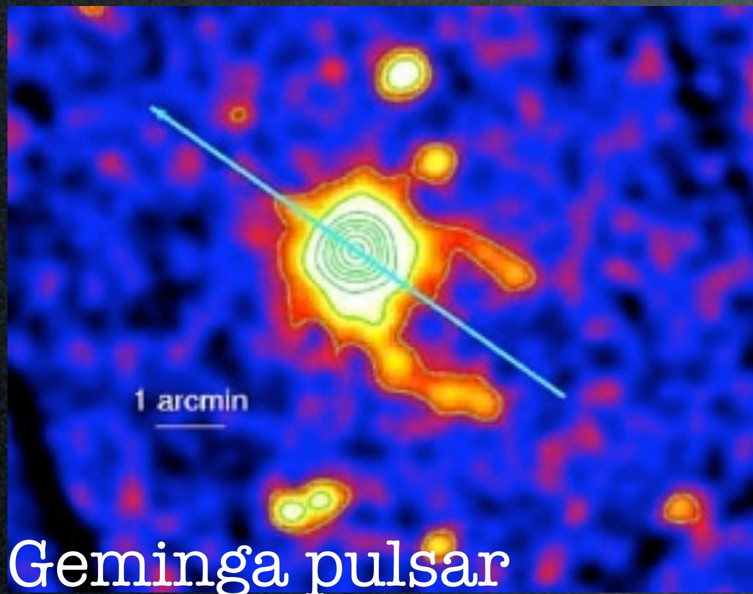
SNR	Distance (kpc)	Age (yr)	E_{max} [a] (TeV)
SN 185	0.95	1.8×10^3	1.7×10^2
S147	0.80	4.6×10^3	63
HB 21	0.80	1.9×10^4	14
G65.3+5.7	0.80	2.0×10^4	13
Cygnus Loop	0.44	2.0×10^4	13
Vela	0.30	1.1×10^4	25
Monogem	0.30	8.6×10^4	2.8
Loop1	0.17	2.0×10^5	1.2
Geminga	0.4	3.4×10^5	0.67



Büshing, de Jager et al. 0804.0220

Astrophysical explanation?

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.

Must be young (T < 10^5 yr) and nearby (< 1 kpc);
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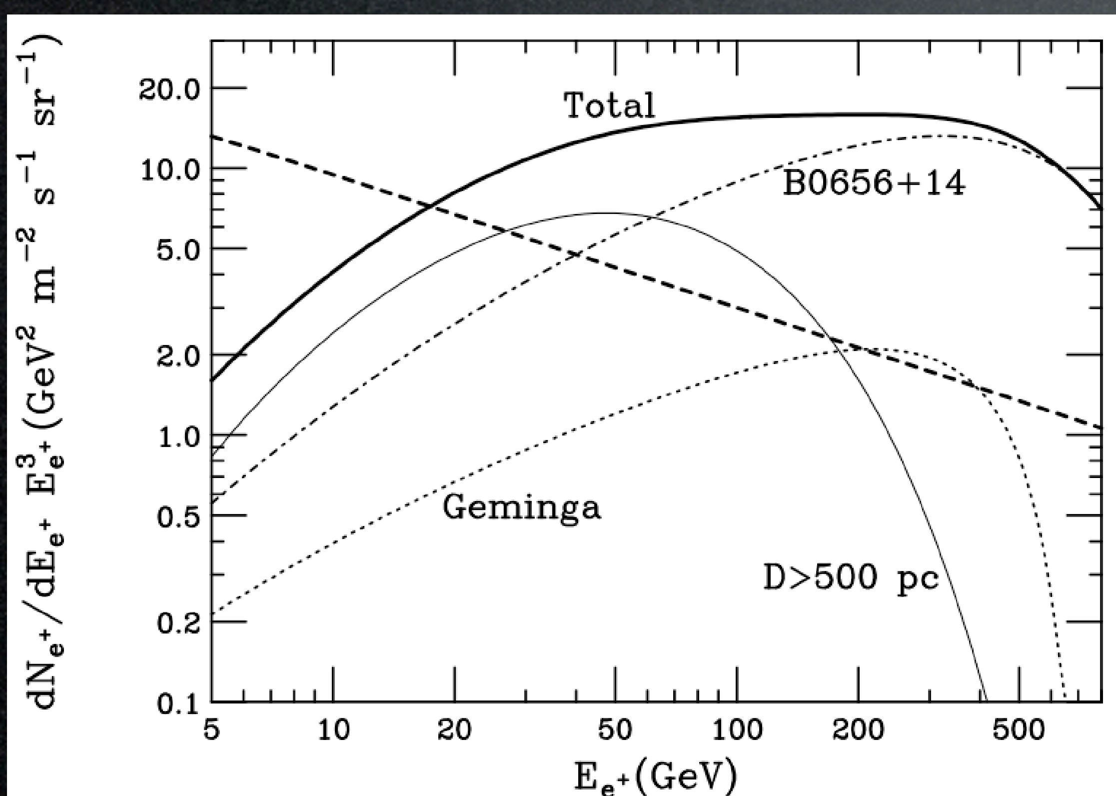
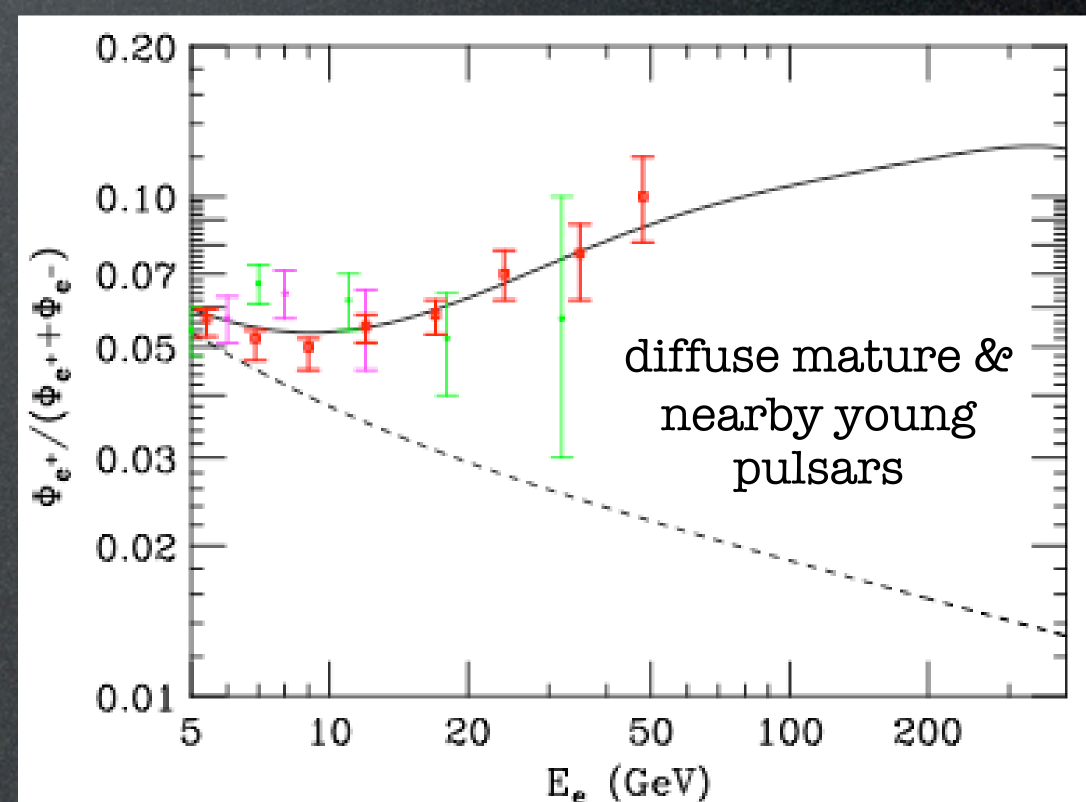
Predicted flux: $\Phi_{e^\pm} \approx E^{-p}\exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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





Hooper, Blasi, Serpico 2008

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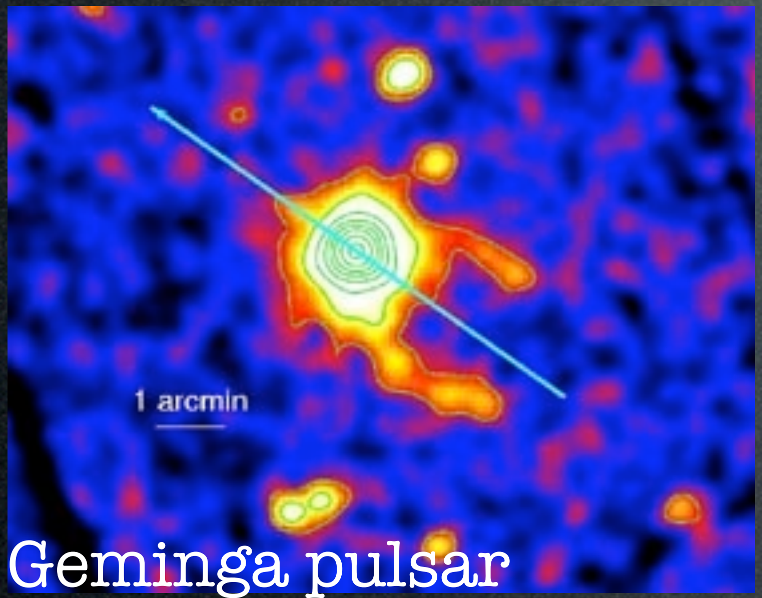

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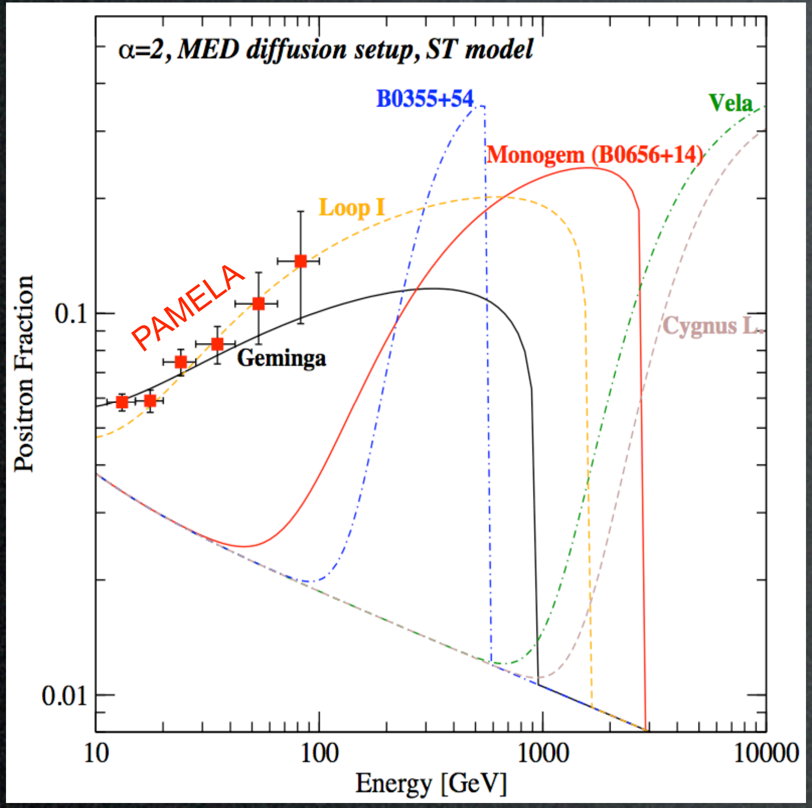
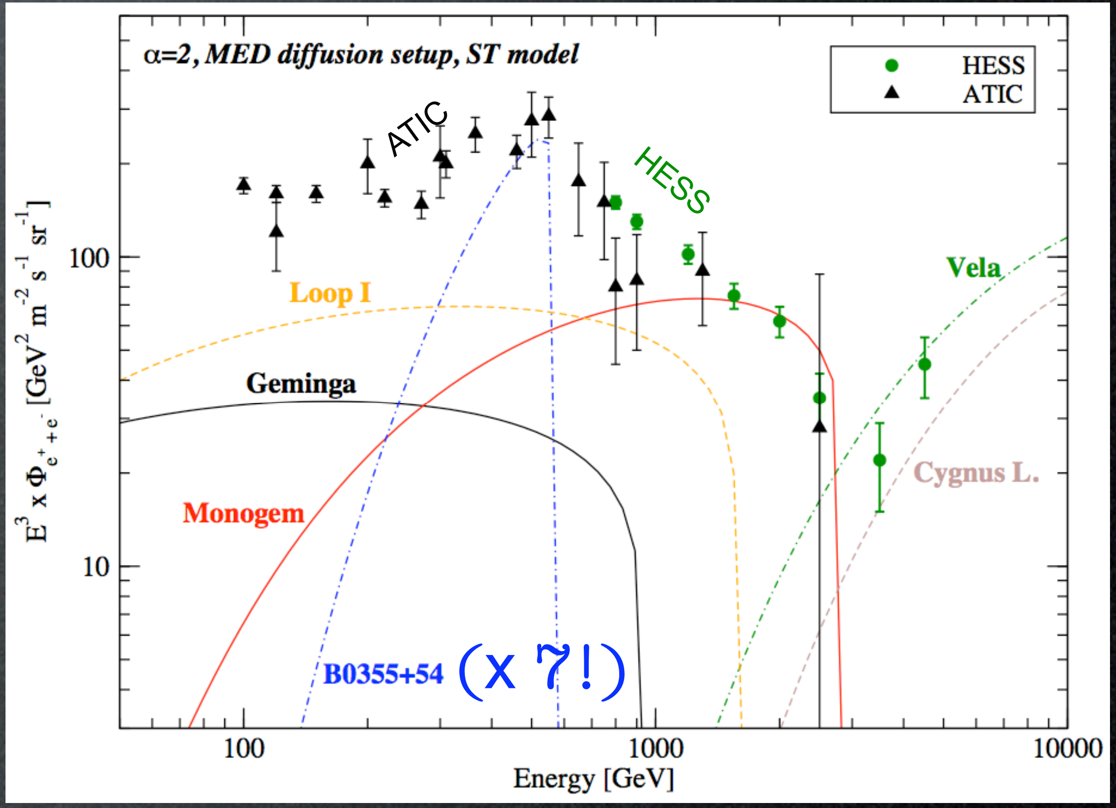
But ATIC needs a different (and very powerful) source:





Profumo 0812.4457

Astrophysical explanation?

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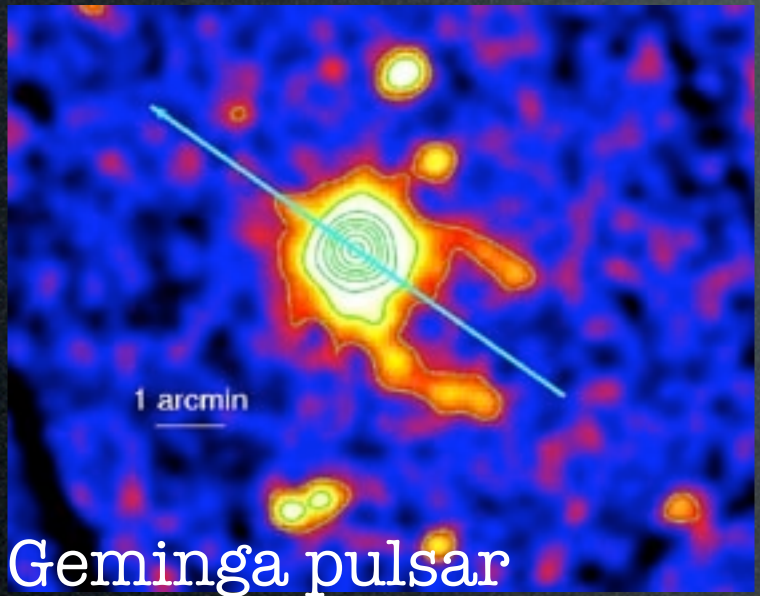


Geminga pulsar

'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.

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

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

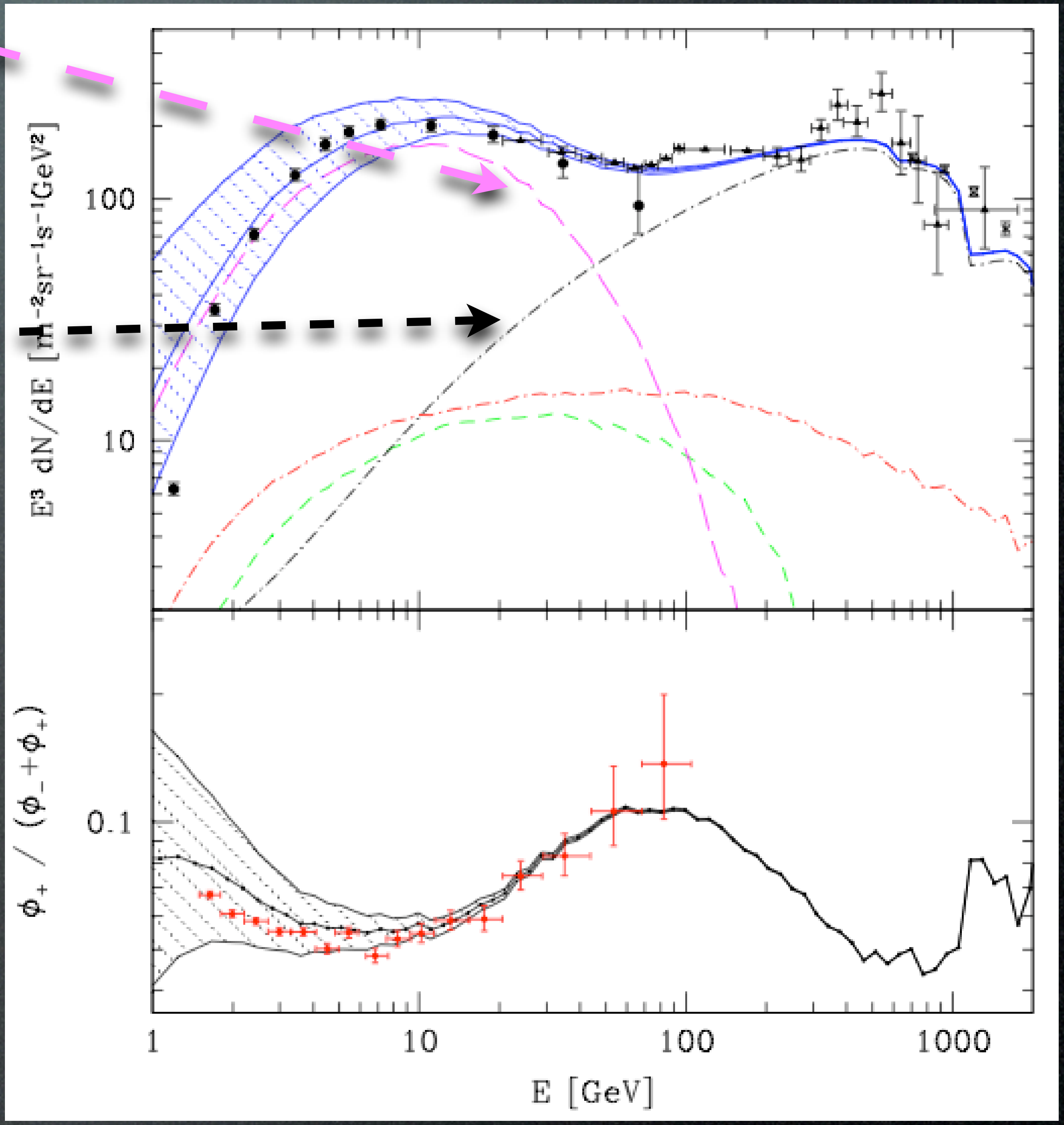
[back]

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

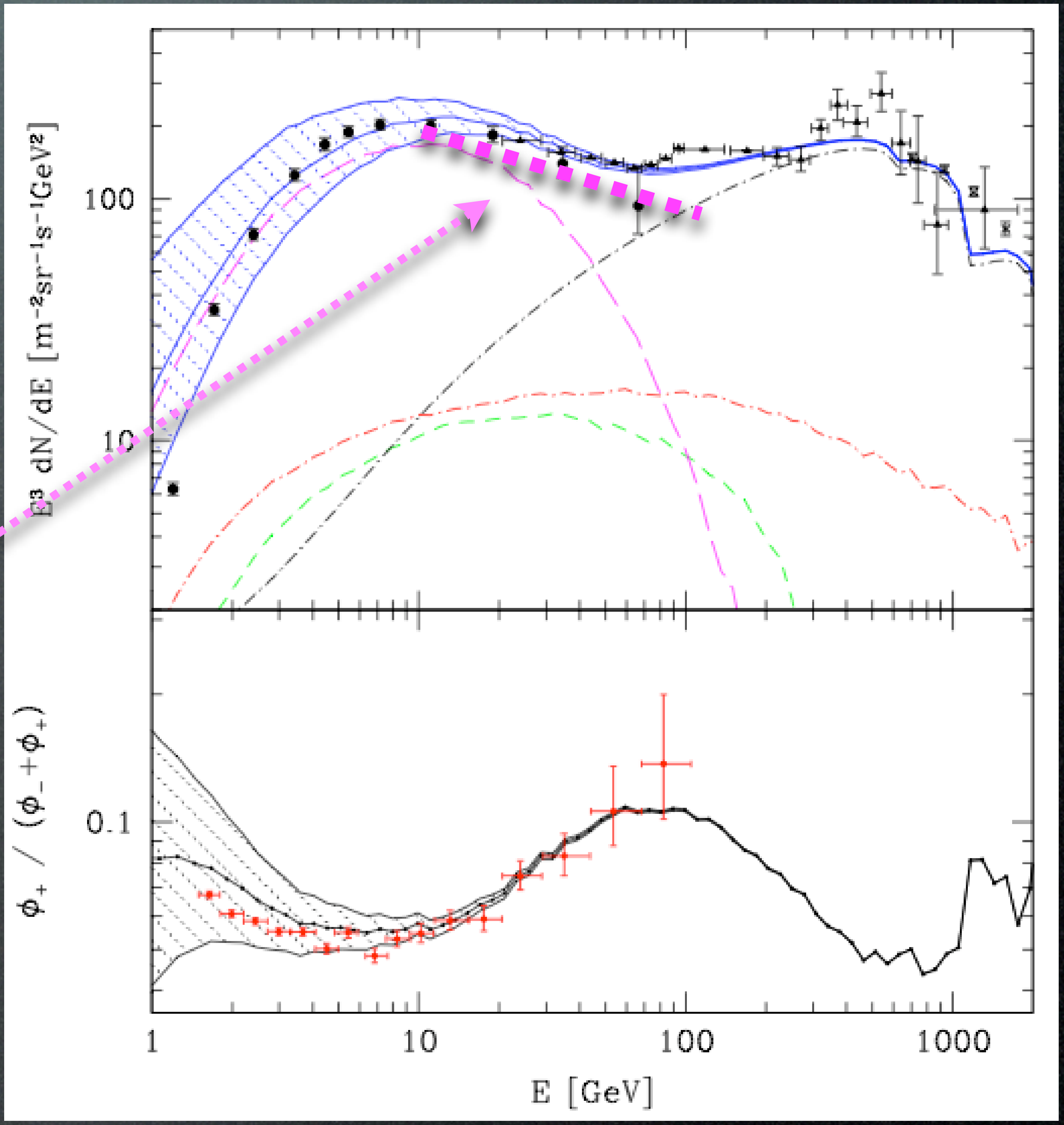
Indirect Detection

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]

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

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

Results

Which DM spectra can fit the data?

Ok, let's ***insist*** on Wino with: -mass $M_{\rm DM} = 200\,{\rm GeV}$

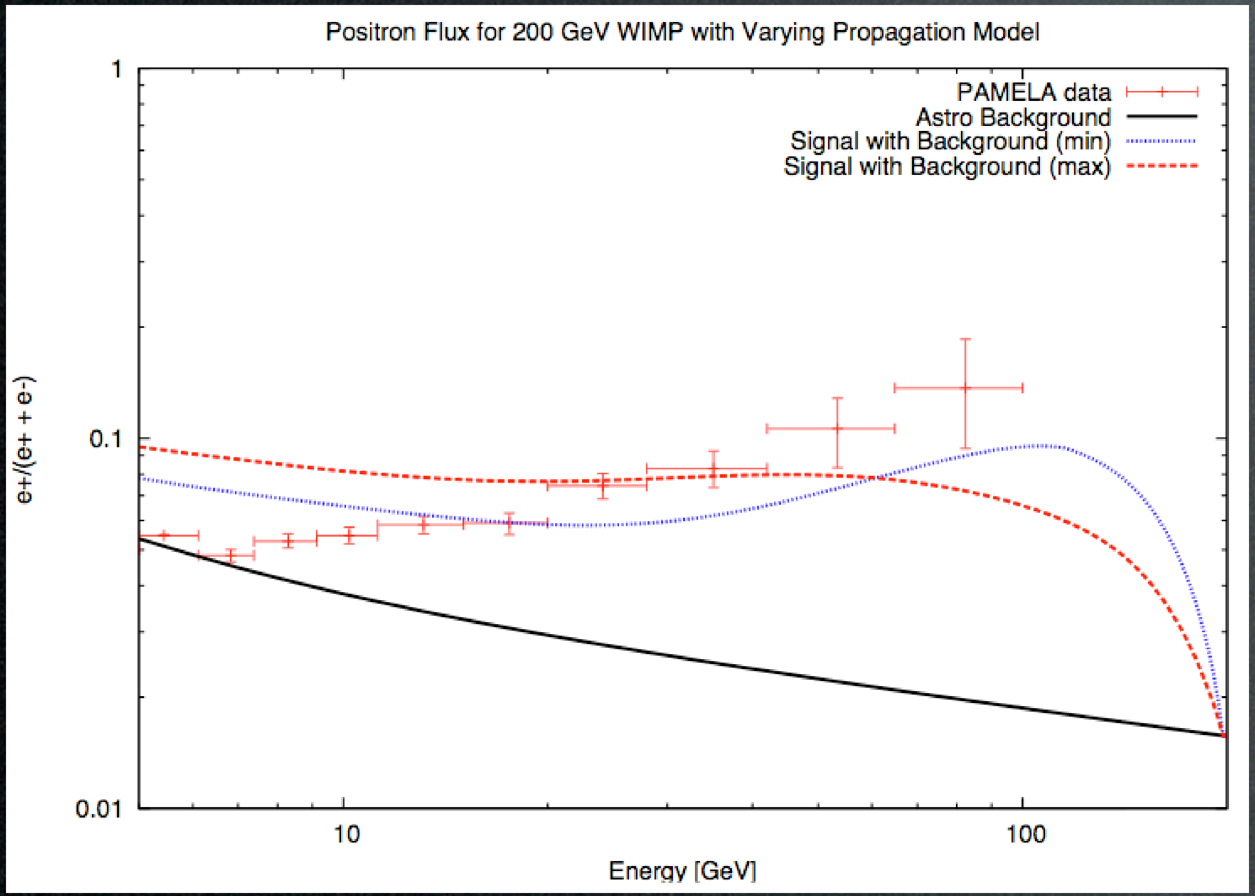
-annihilation $\rm DM\ DM \to W^+W^-$

If one: - assumes non-thermal production of DM

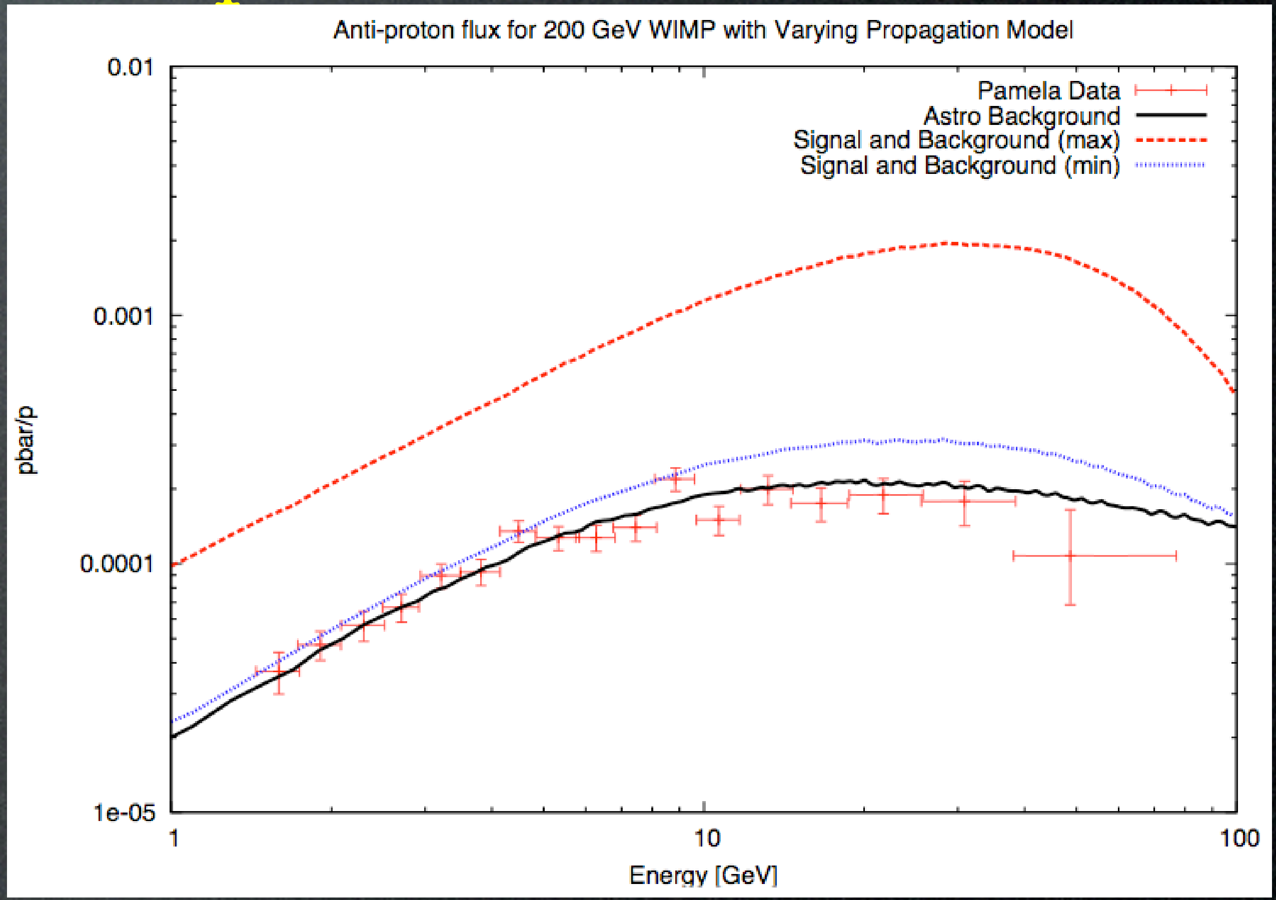
- takes positron energy loss 5 times larger than usual
- takes "min" propagation only
- gives up ATIC
- neglects conflict with EGRET bound (4 times too many gammas)

then:

Positrons:



Anti-protons:



G.Kane, A.Pierce, P.Grajek, D.Phalen, S.Watson 0812.4555

Results

Which DM spectra can fit the data?

Ok, let's ***insist*** on KK DM with:

-mass $M_{\rm DM} = 600 - 800\,{\rm GeV}$

-annihilation $\rm DM\ DM \rightarrow l^+ l^-\ (BR = 60\%)$

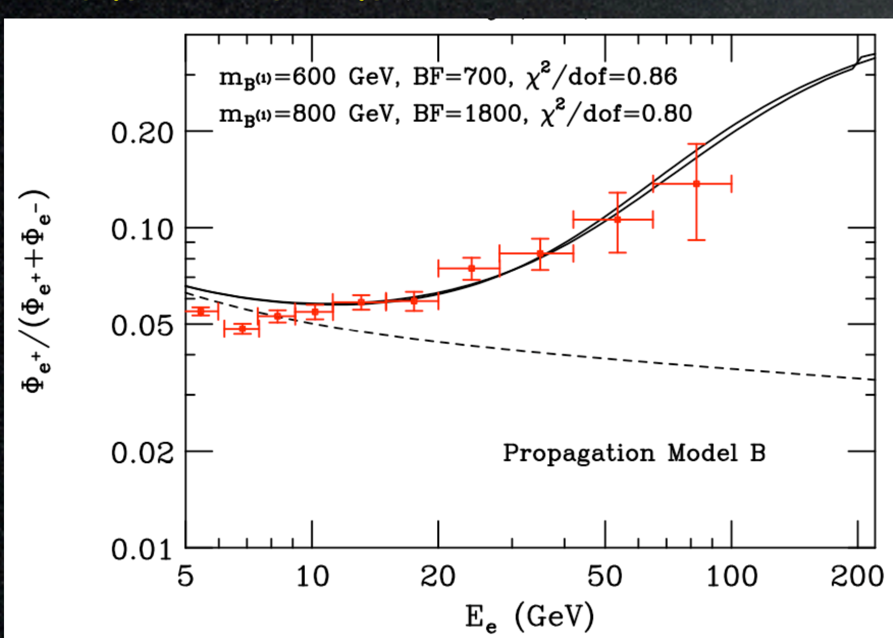
$\rm DM\ DM \rightarrow q\bar{q}\ (BR = 35\%)$

Good fit with: - boost $B = 1800$

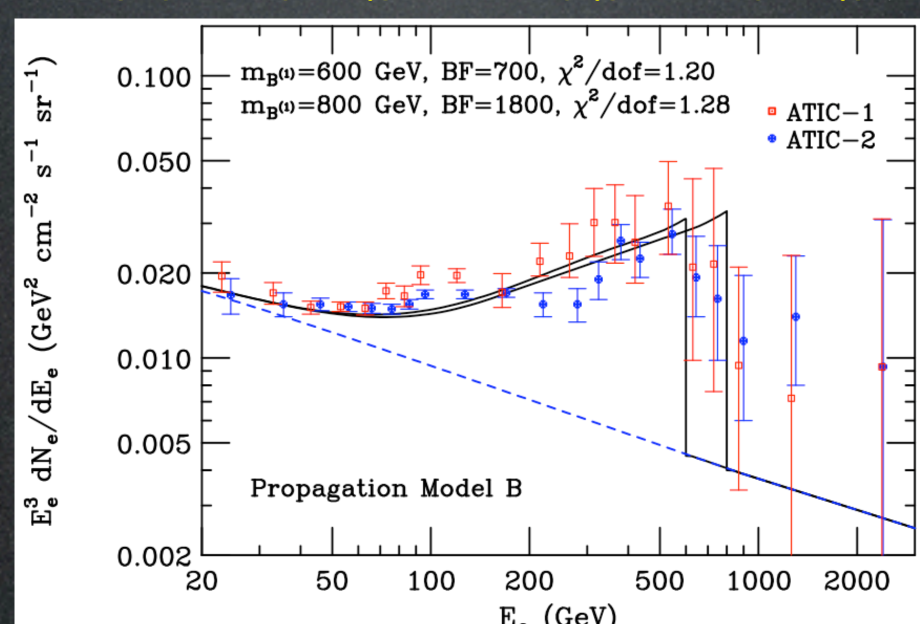
- propagation model B: $K(E_e) = 1.4 \times 10^{28}\,(E_e/4\,{\rm GeV})^{0.43}\,{\rm cm}^2/{\rm s}$, L=1 kpc

very large energy loss with very small L

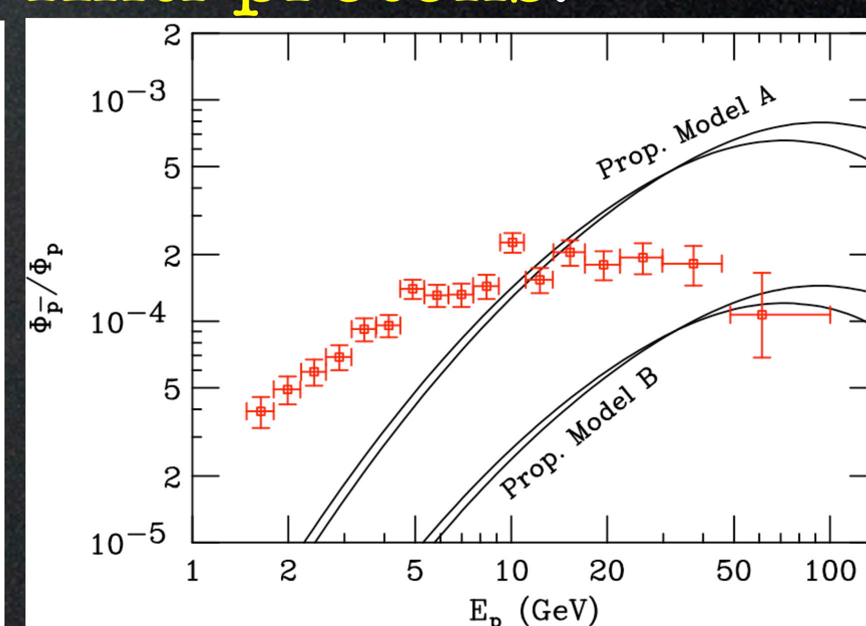
Positrons:



Electrons + Positrons:



Anti-protons:



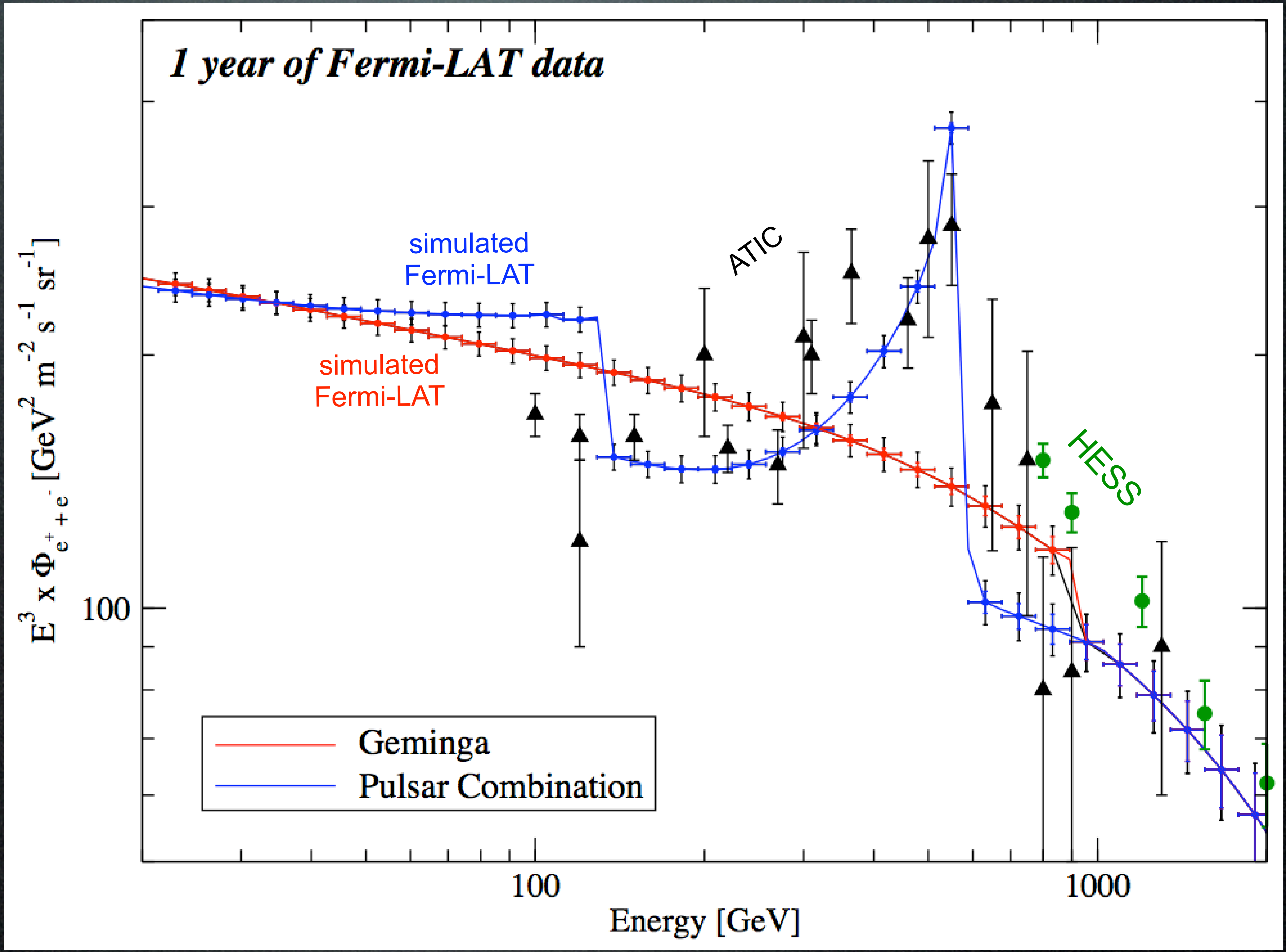
D.Hooper, K.Zurek 0902.0593

[where are the secondaries?]

Data sets

Electrons + positrons from Fermi-LAT:

Fermi detects gammas by pair production: it's inherently an e^+e^- detector



Profumo 0812.4457