18 may 2010
GGI Conference 'The Dark Matter Connection'

DM id: status and prespectives

Marco Cirelli
(CERN-TH & CNRS IPhT 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)
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)
JCAP 10 009 (2009)
0912.0663
and work in progress

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Questions

DM id has driven a volcanic activity in the field of DM theory and phenomenology in 2009.

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Why?

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DM id has driven a volcanic activity in the field of DM theory and phenomenology in 2009.

Why?

What has the eruption left?

DM detection

- direct detection
  Xenon, CDMS (Dama/Libra?)
- production at colliders
  LHC
- indirect
  - γ from annihil in galactic center or halo and from synchrotron emission
    Fermi, **HESS**, radio telescopes
  - e^+ from annihil in galactic halo or center
    PAMELA, **ATIC**, **Fermi**
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{D}$ from annihil in galactic halo or center
    GAPS
  - $\nu, \bar{\nu}$ from annihil in massive bodies
    Icecube, Km3Net

DM detection

- direct detection
- production at colliders
- indirect
  - γ from annihil in galactic center or halo and from synchrotron emission
    Fermi, HESS, radio telescopes
  - e^+ from annihil in galactic halo or center
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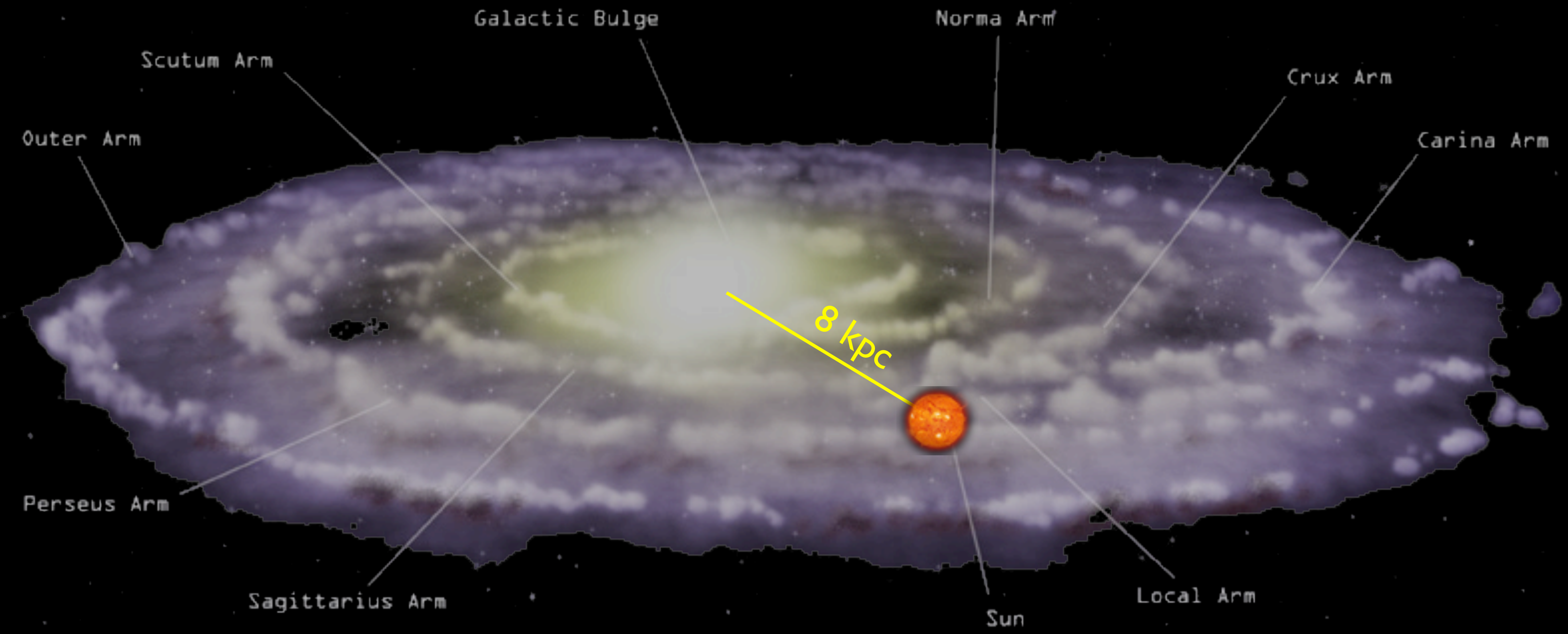
  - $\nu, \bar{\nu}$ from annihil in massive bodies

Indirect Detection

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



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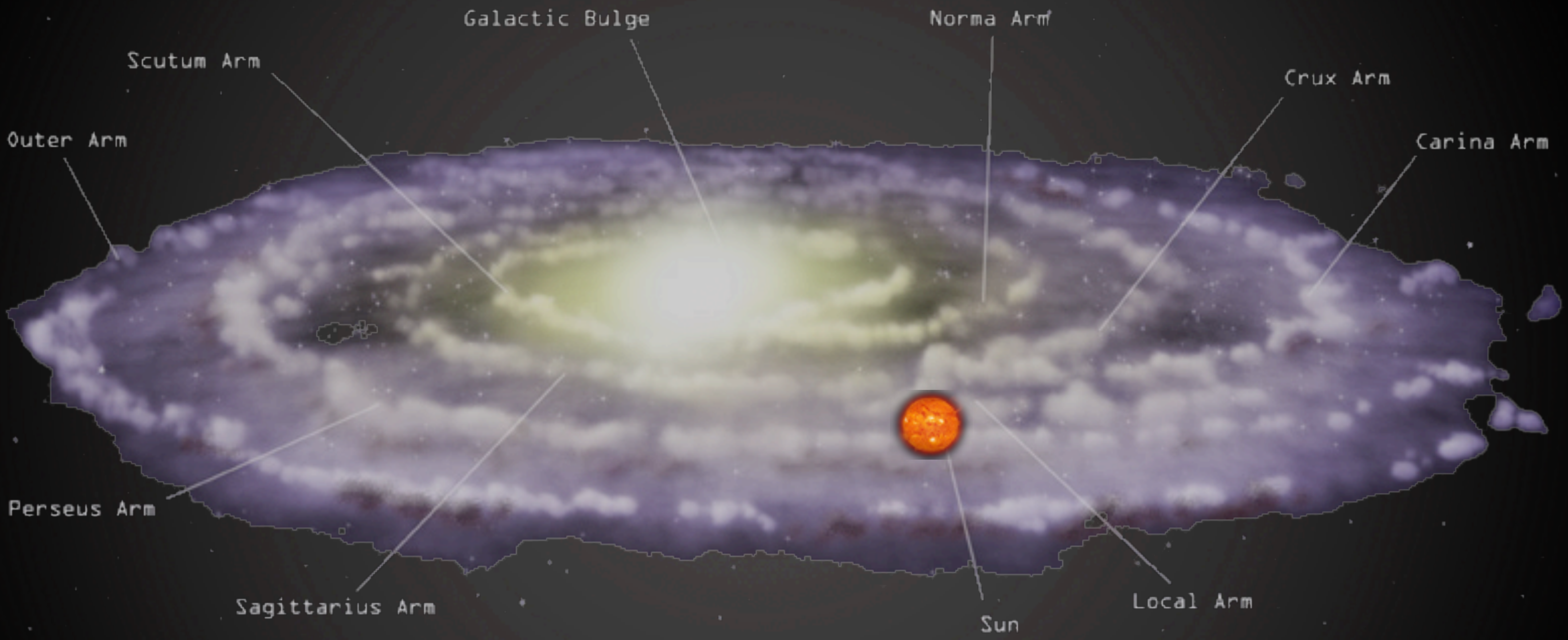

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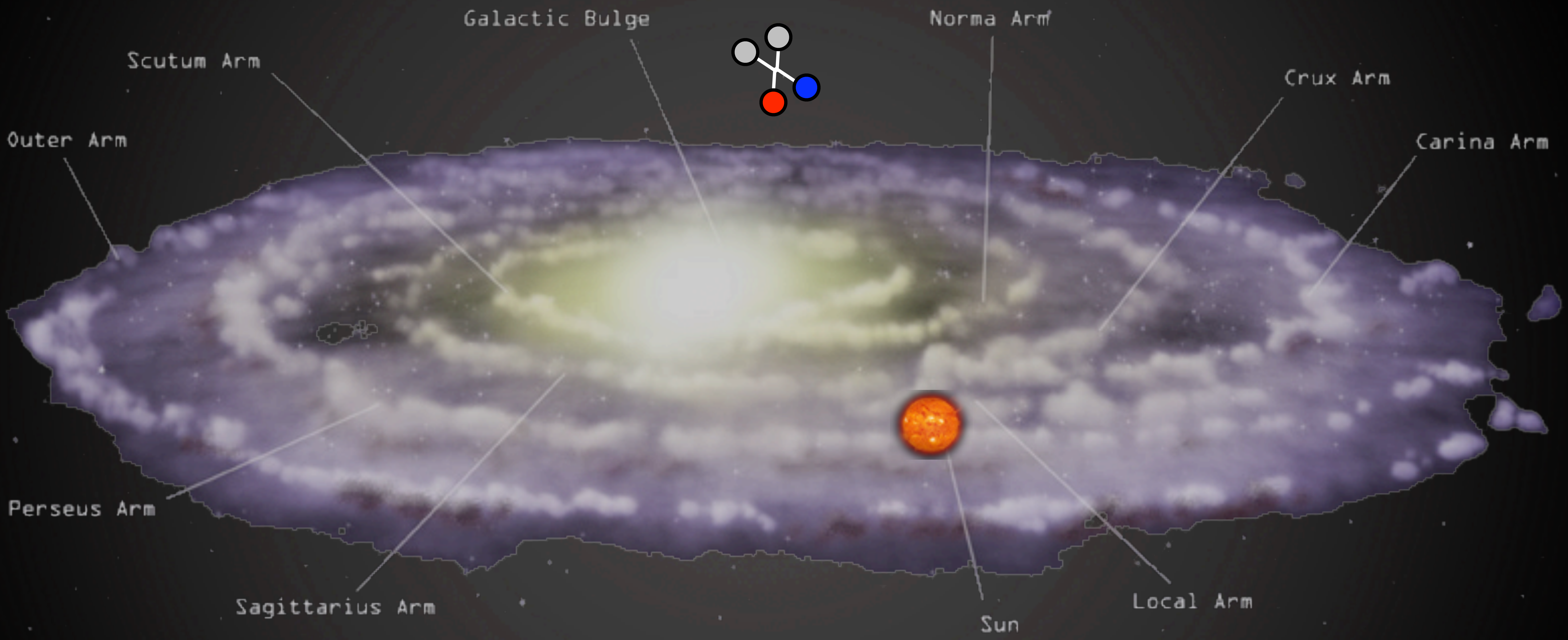

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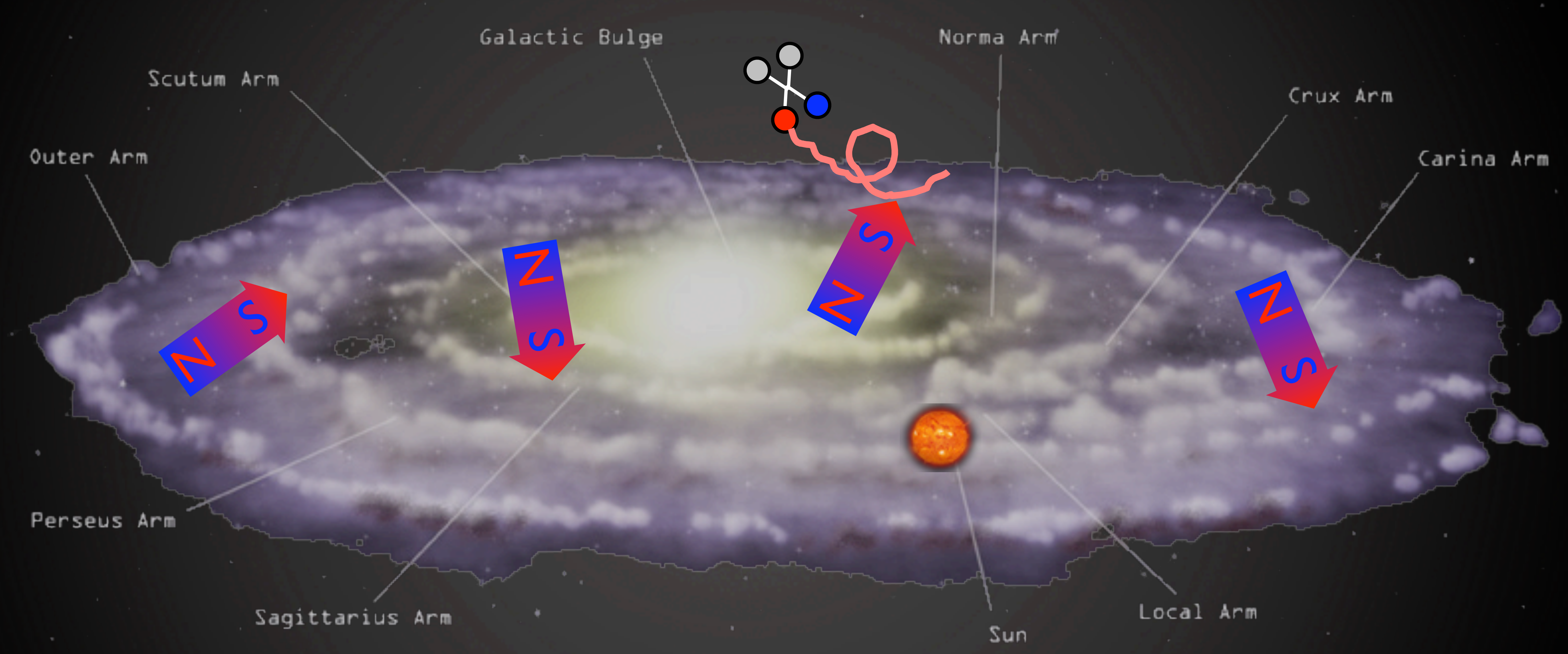

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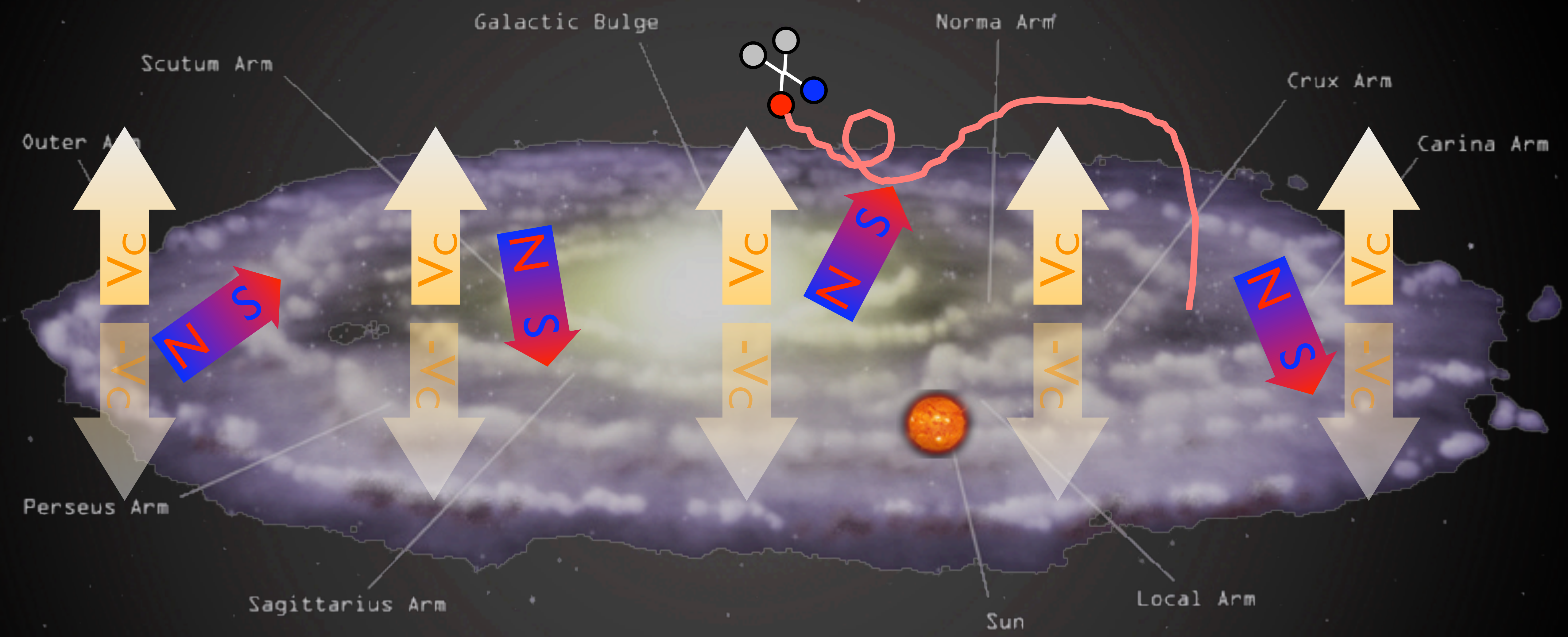

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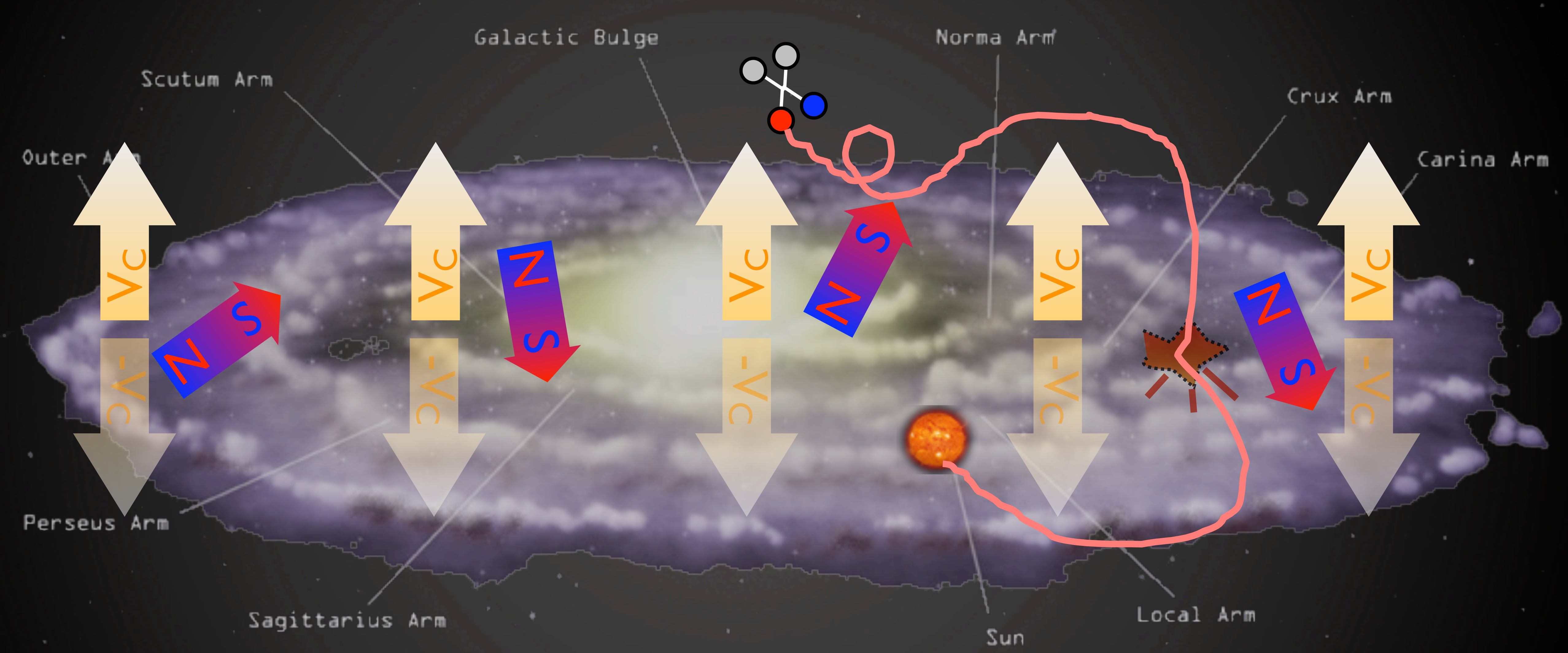

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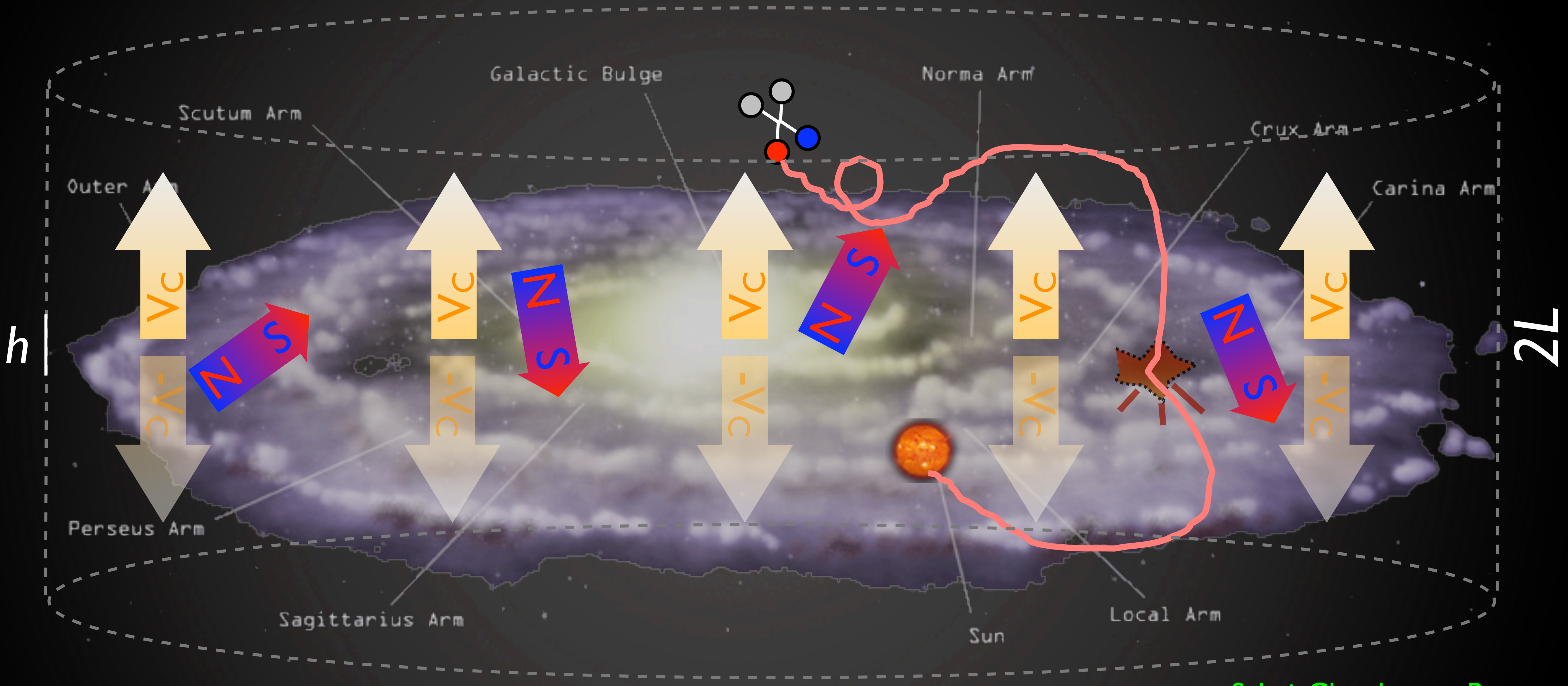


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

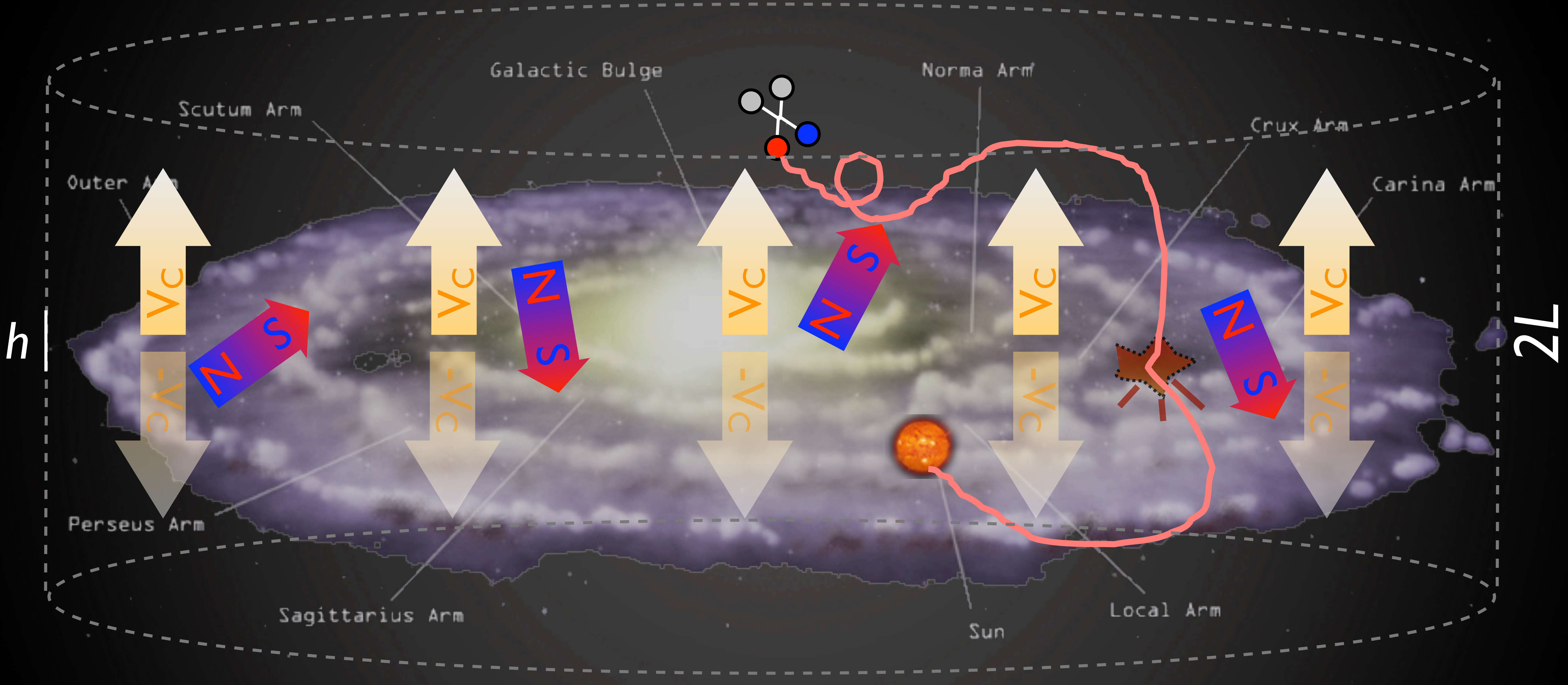
spectrum

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

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

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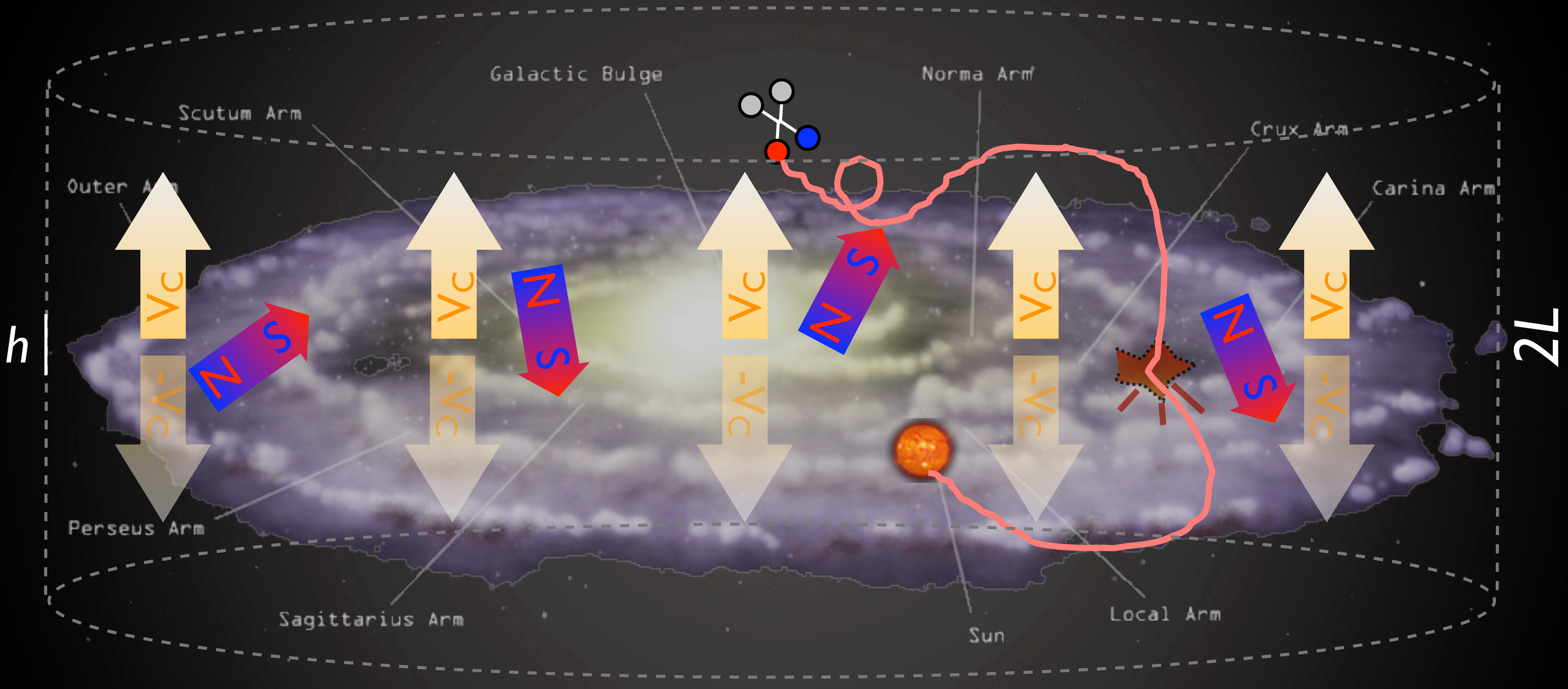

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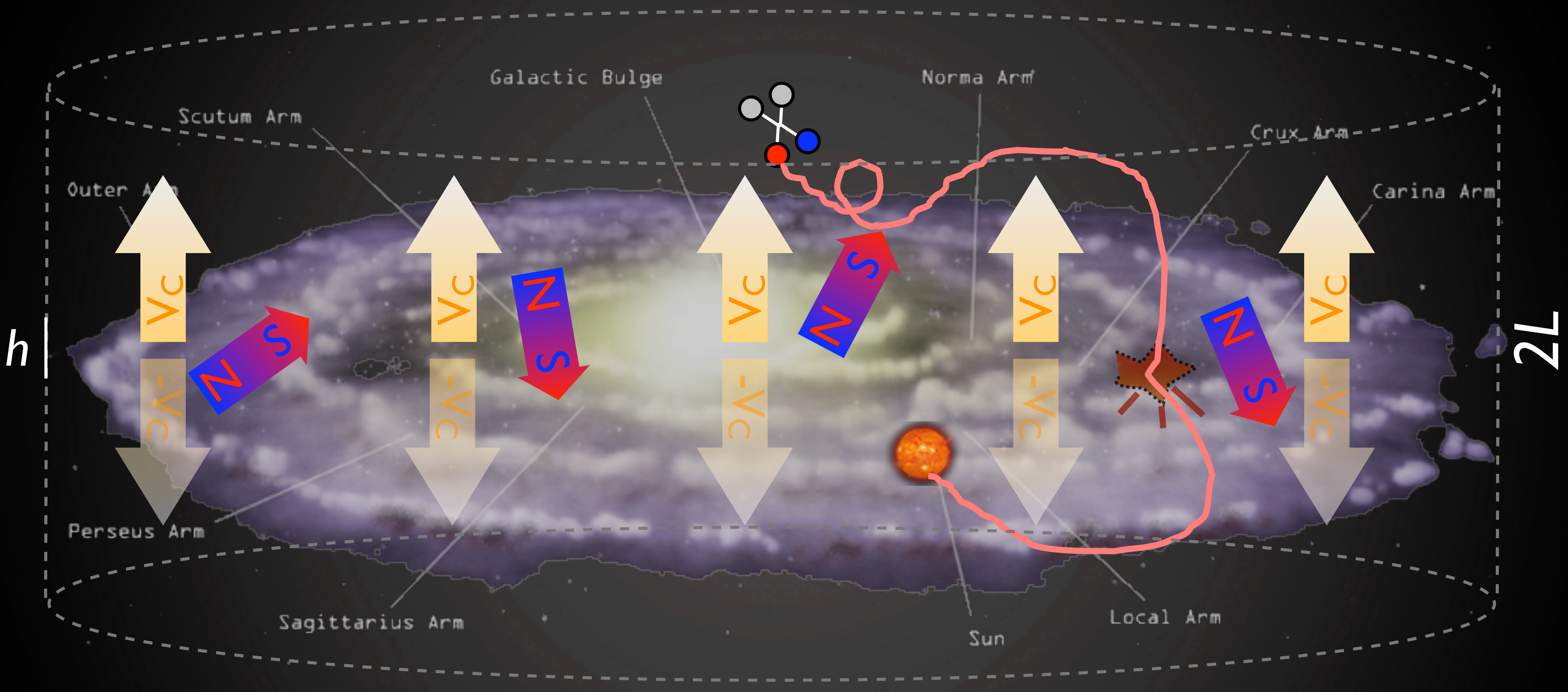
astro& cosmo

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:

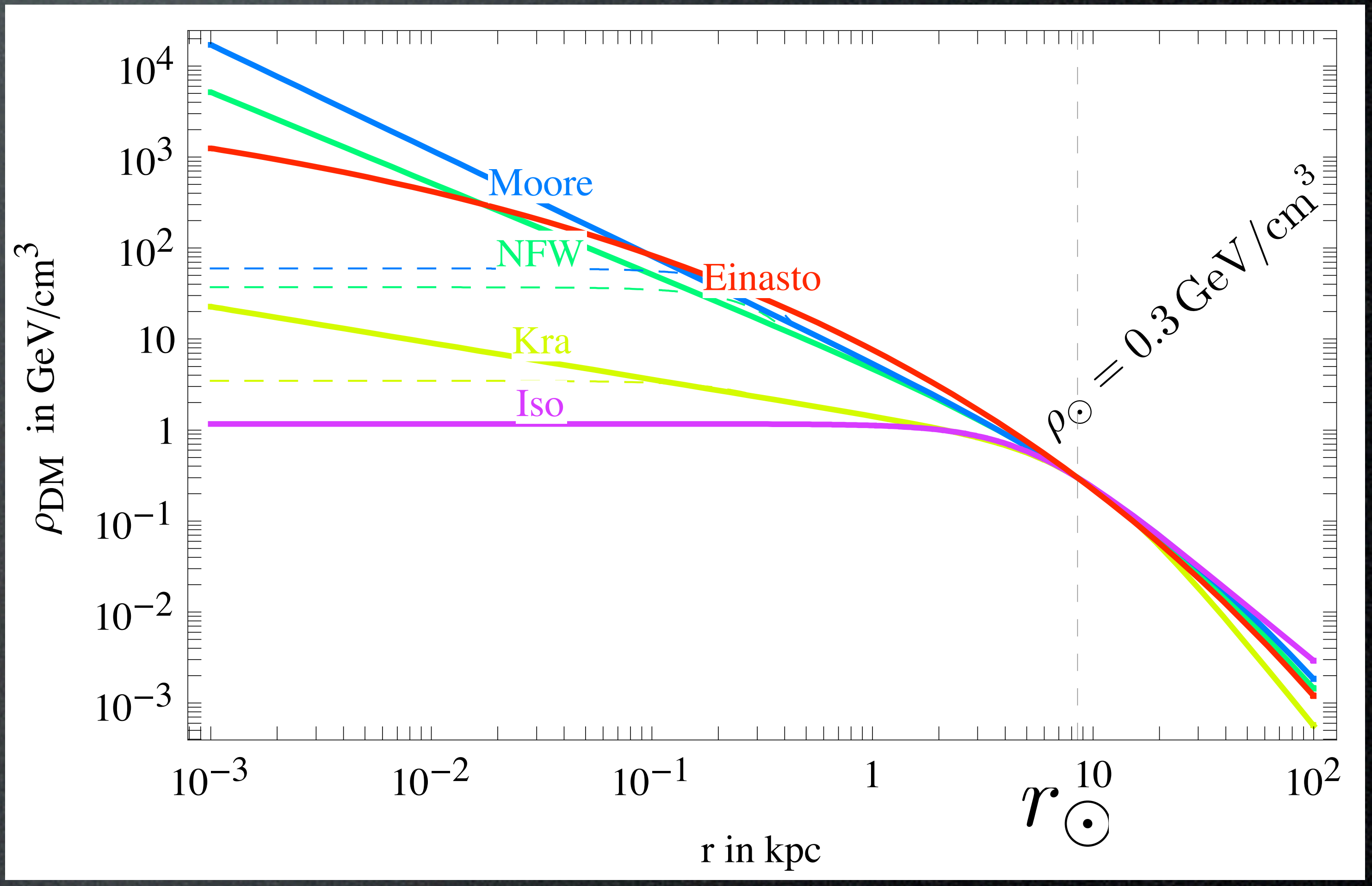
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

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

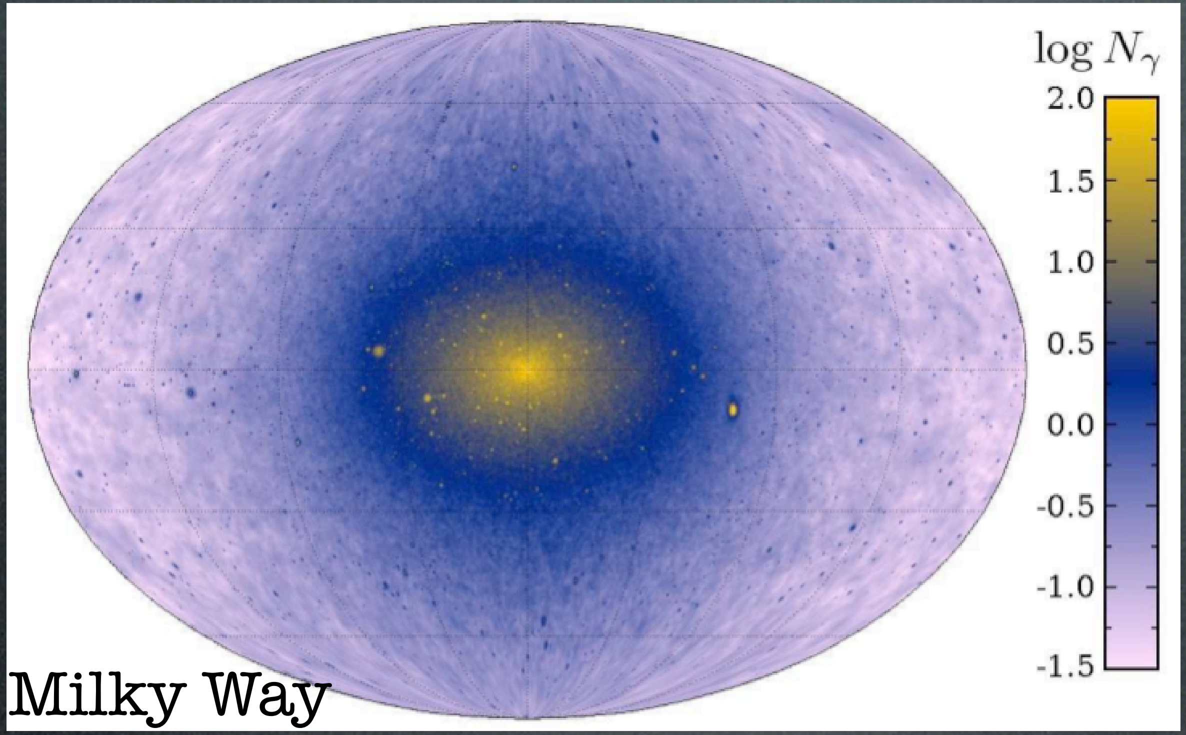
mild: Einasto

smooth: isothermal

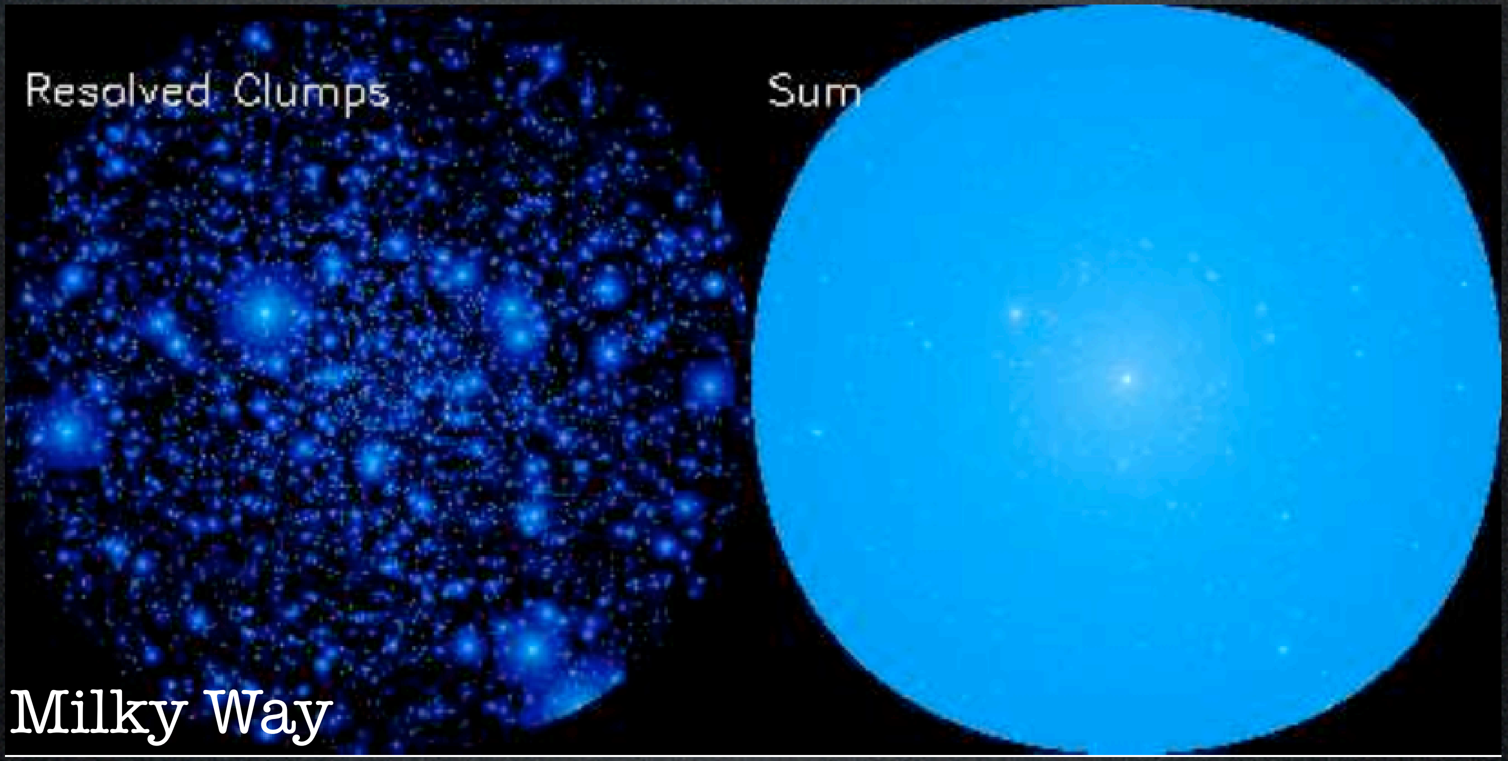
Indirect Detection

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

For illustration:



Kuhlen, Diemand, Madau 2007



Bertone, Branchini, Pieri 2007

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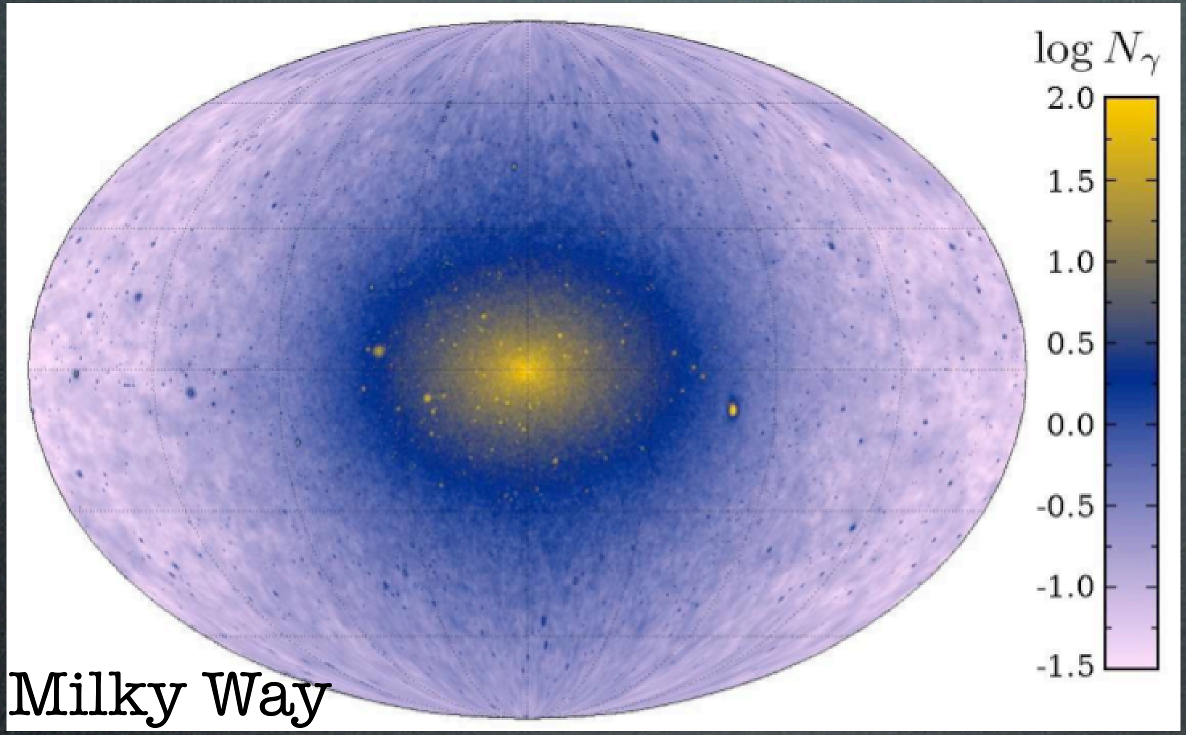
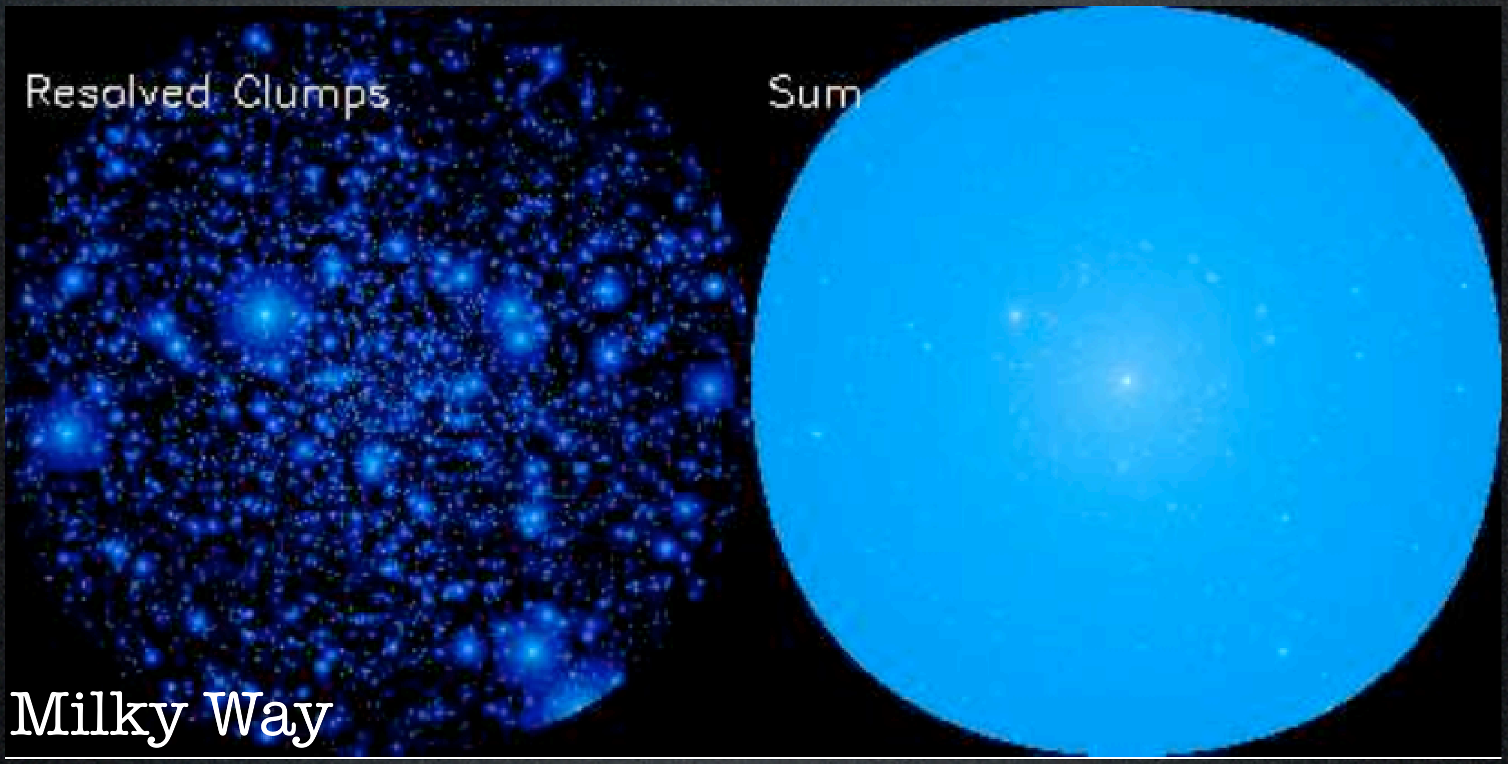


Kuhlen, Diemand, Madau 2007

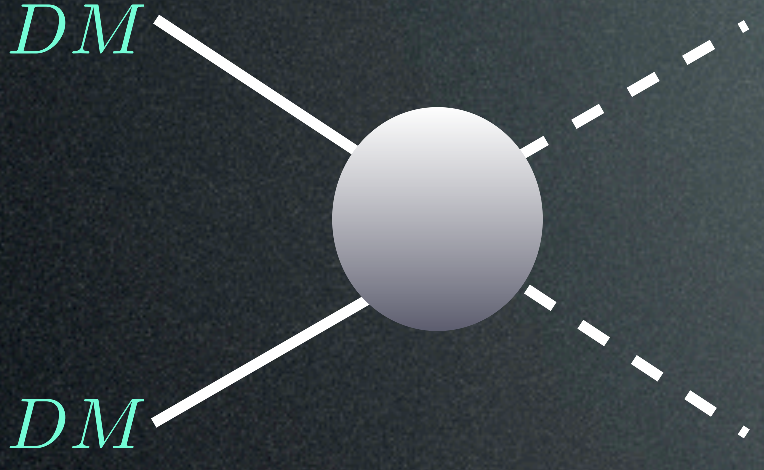
But: recent simulations seem to show almost no clumps in inner 10 kpc (tidal stripping).
[Millenium Simulation, Carlos Frenk]



Bertone, Branchini, Pieri 2007

Computing the theory predictions

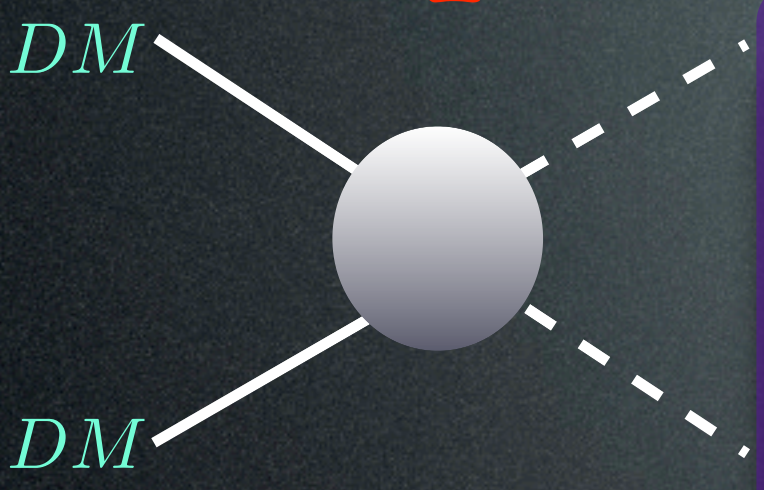
Spectra at production



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

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

Spectra at production

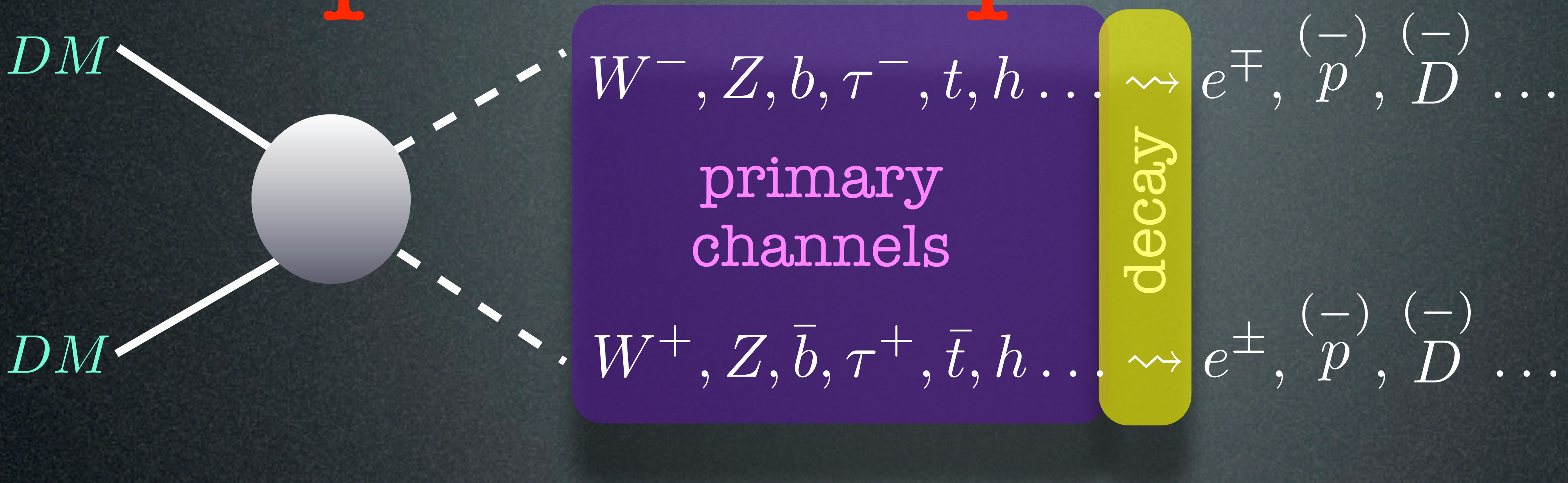


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary
channels

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

Spectra at production



DM

DM

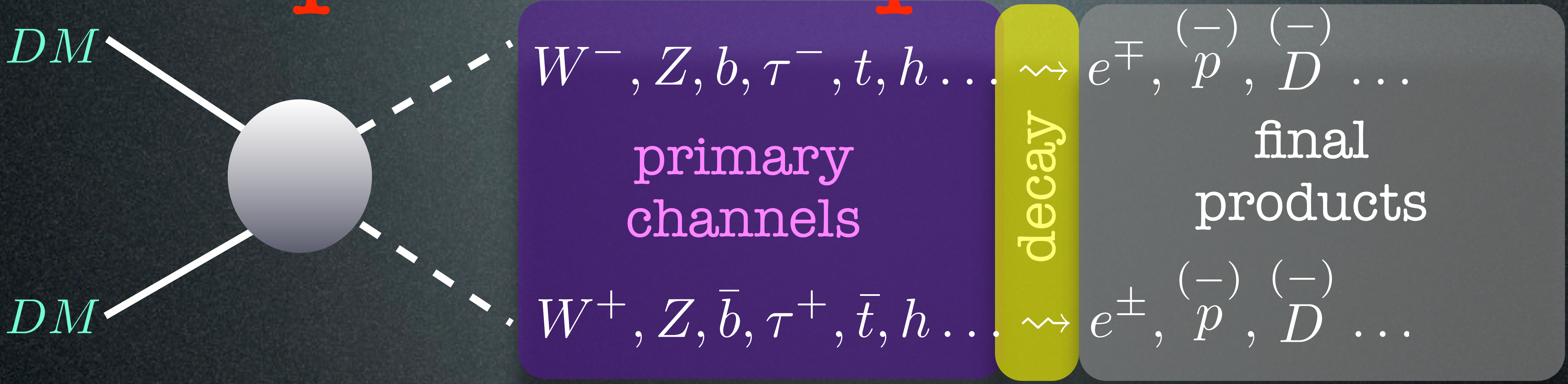
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary channels

decay

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

Spectra at production



DM

DM

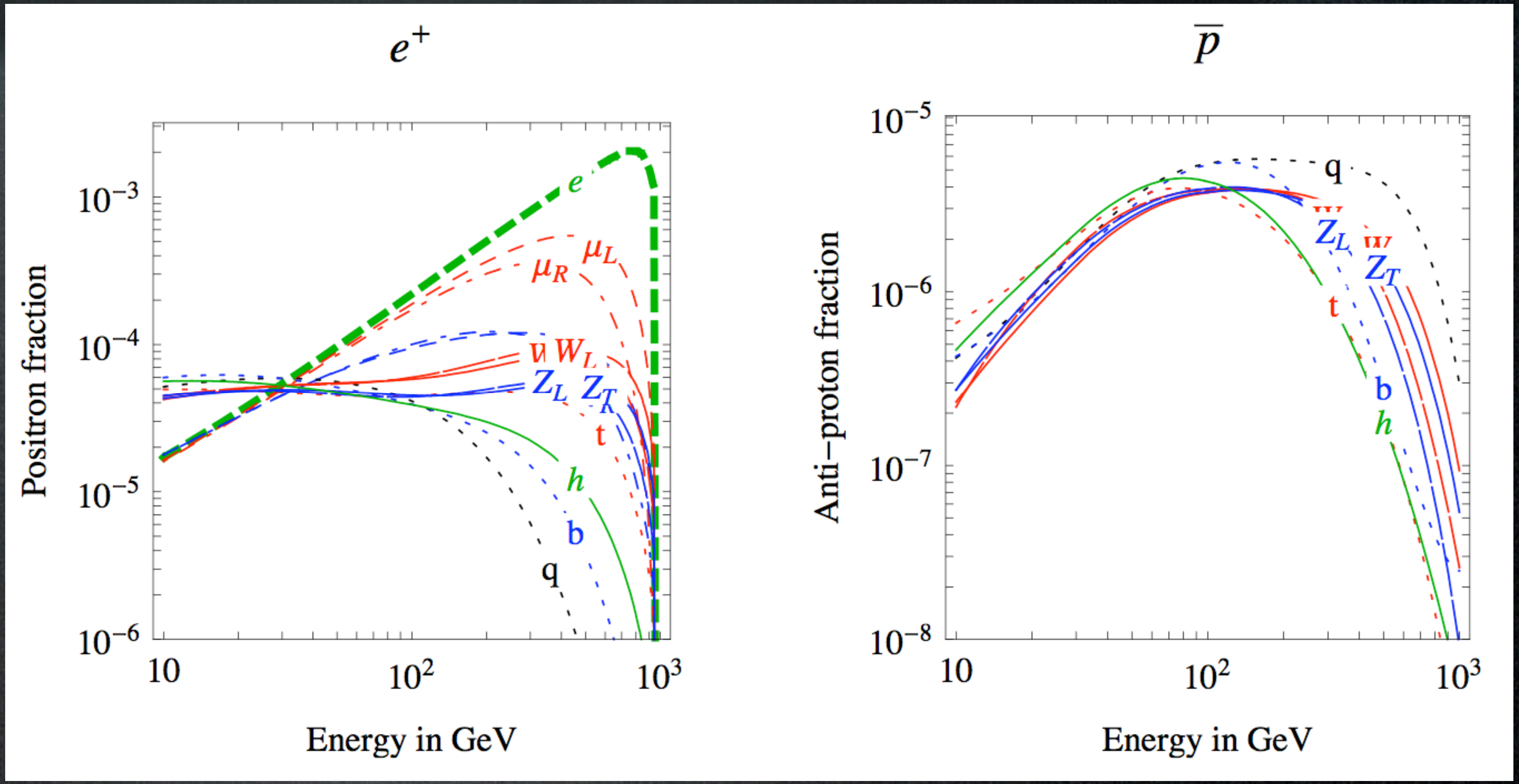
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

primary channels

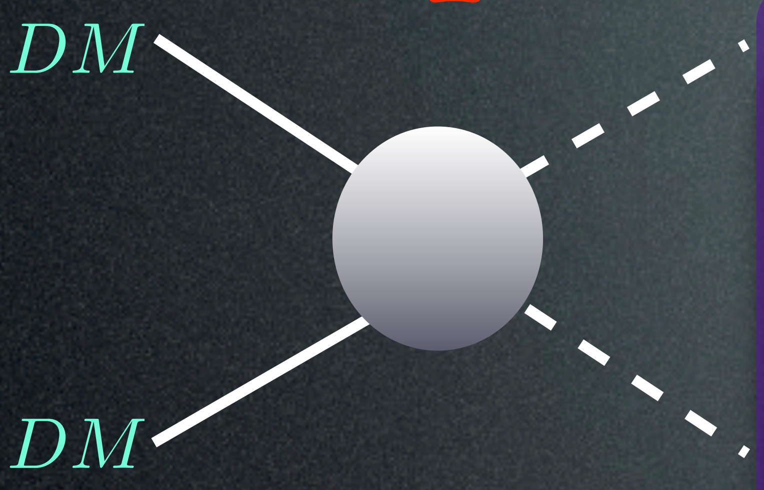
decay

final products

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



Spectra at production



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

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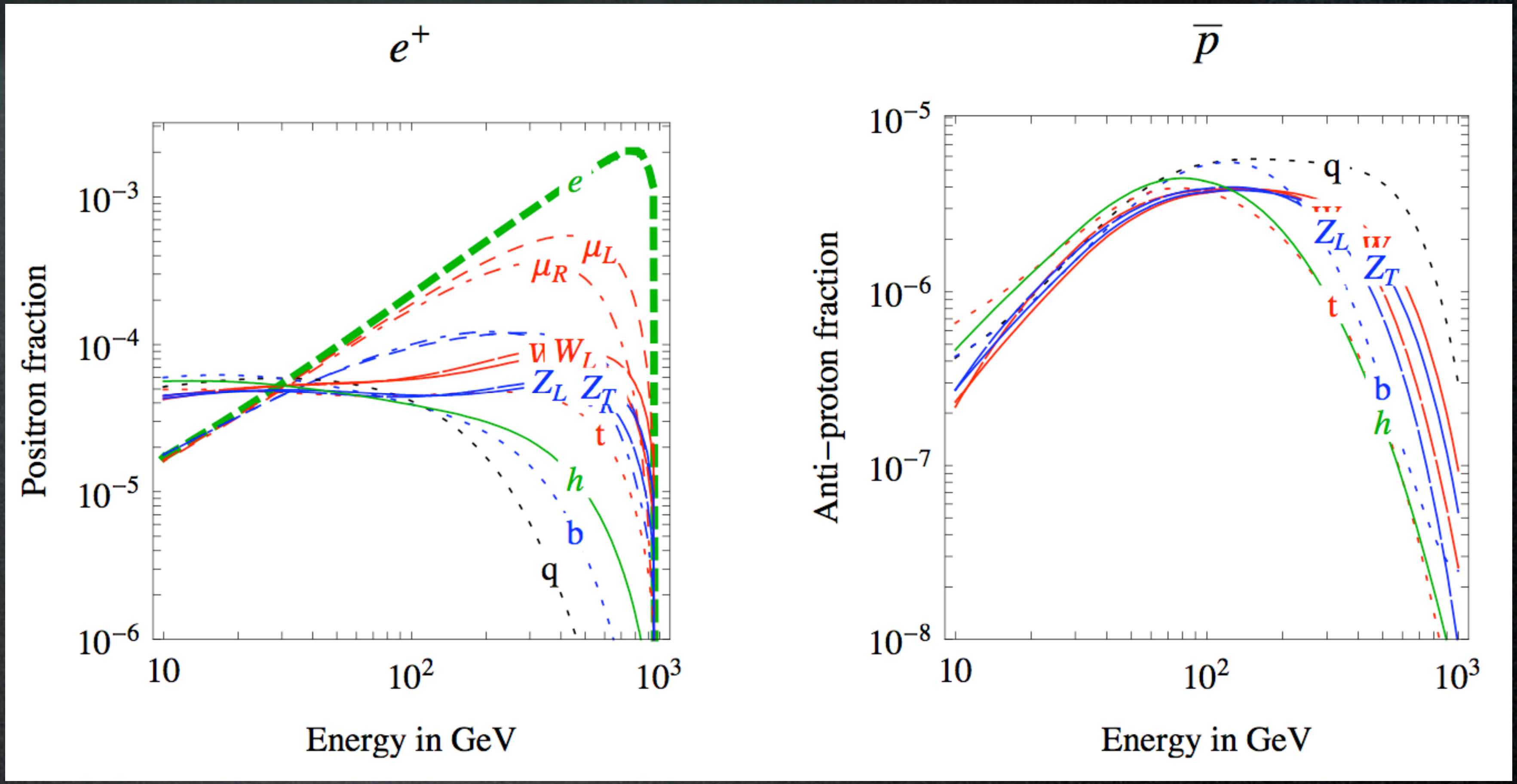


So what are the particle physics parameters?

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

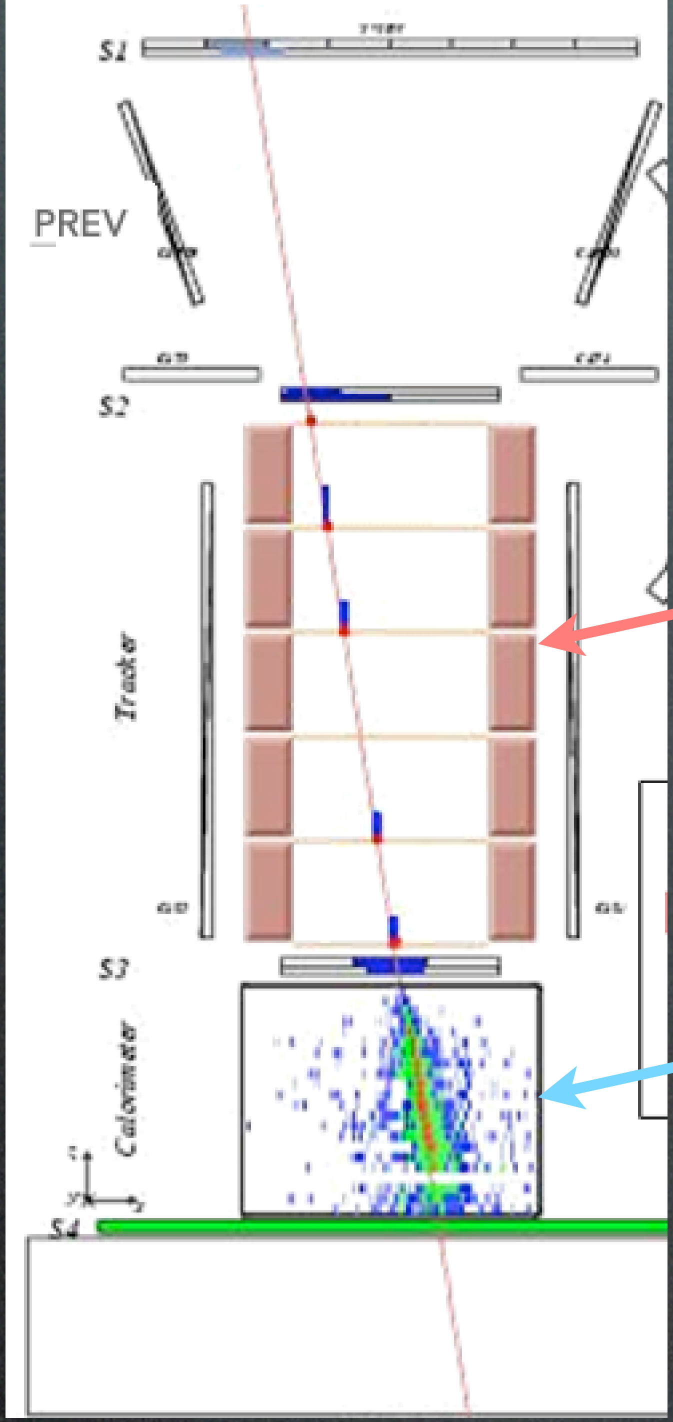
Comparing with data

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)

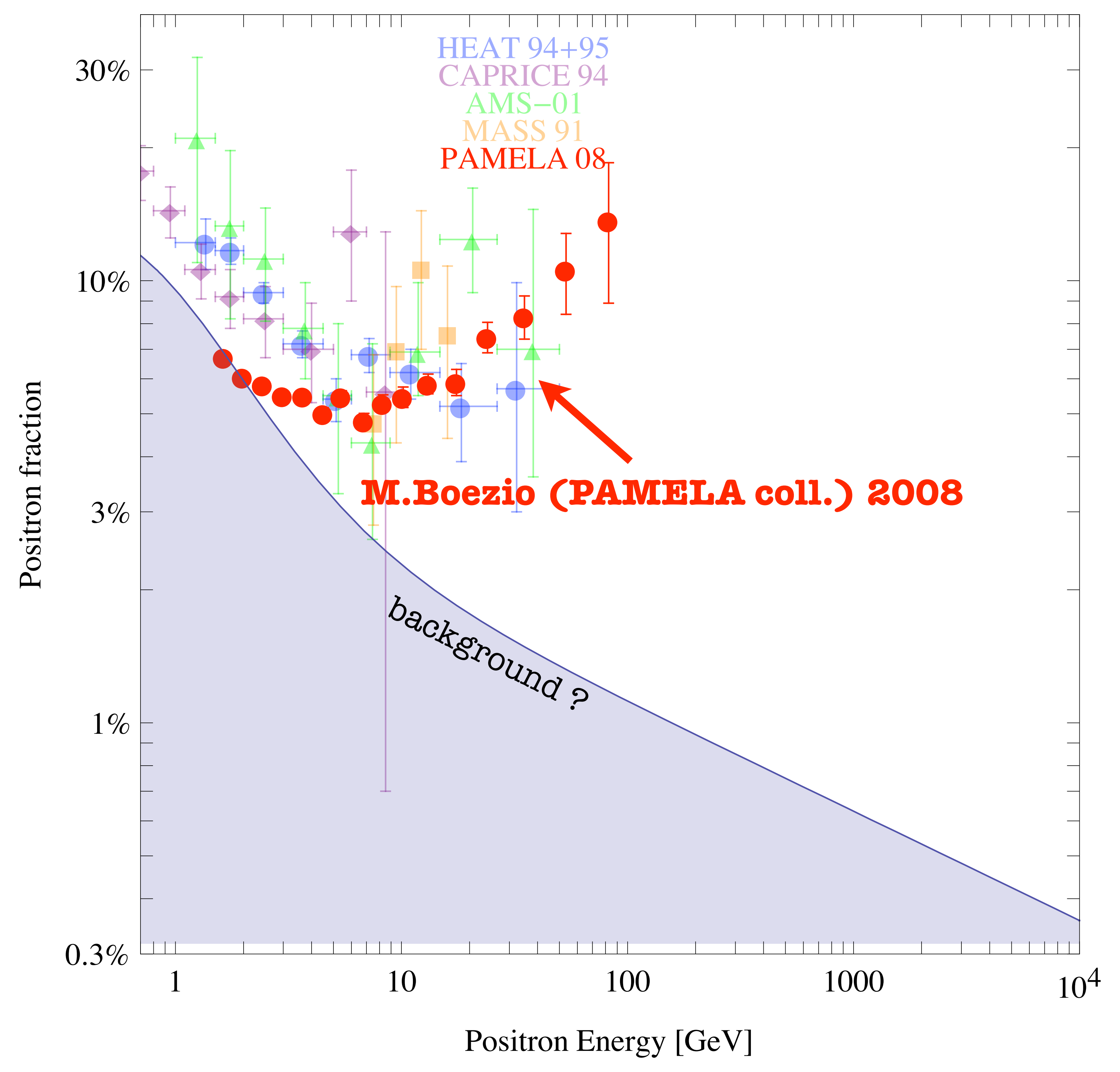
(swipe thru)

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: $\dfrac{e^+}{e^+ + e^-}$

(9430 e⁺ collected)

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

[backgnd]

Data sets

Positrons from PAMELA:

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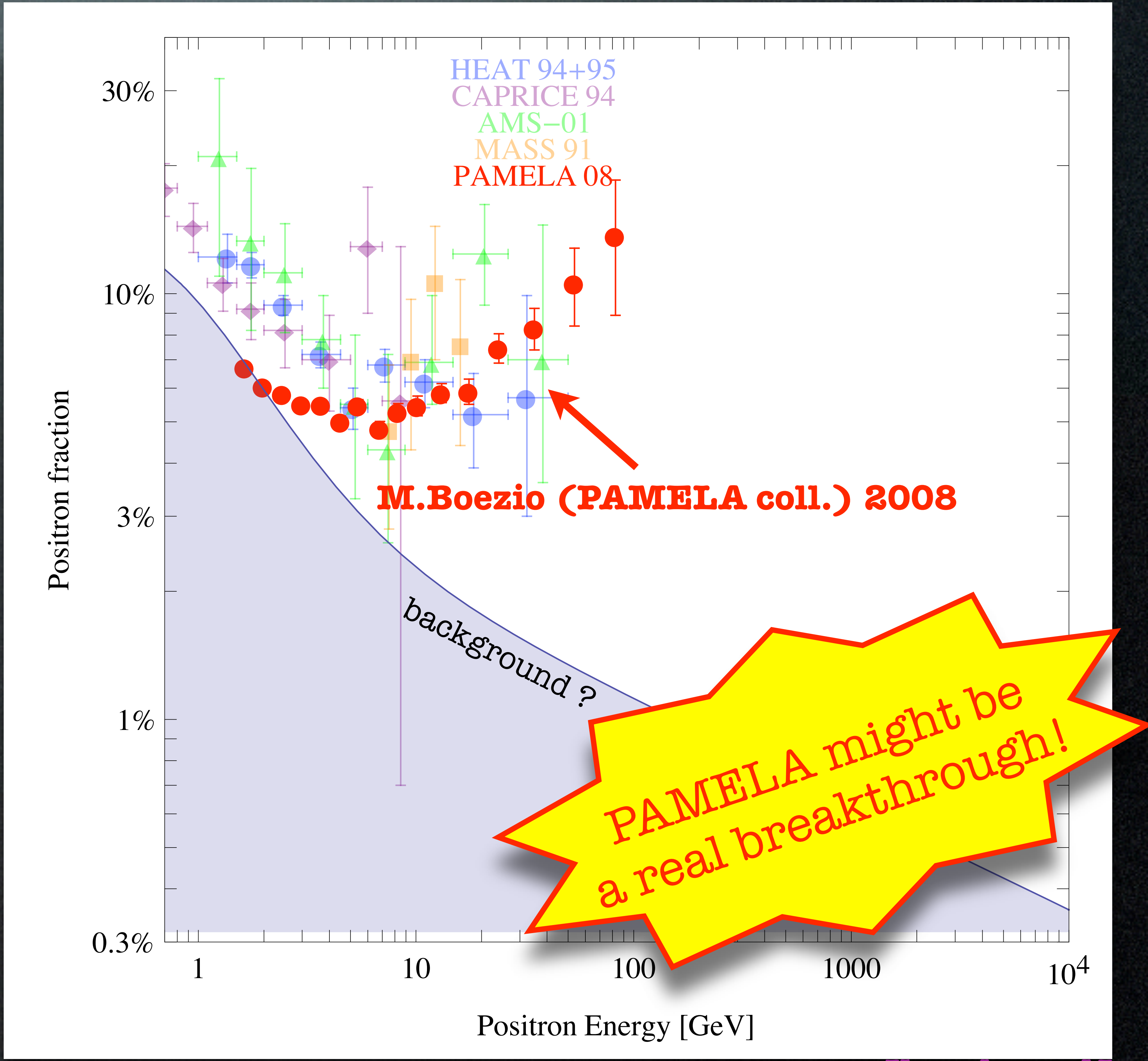
- very large flux!



M.Boezio (PAMELA coll.) 2008

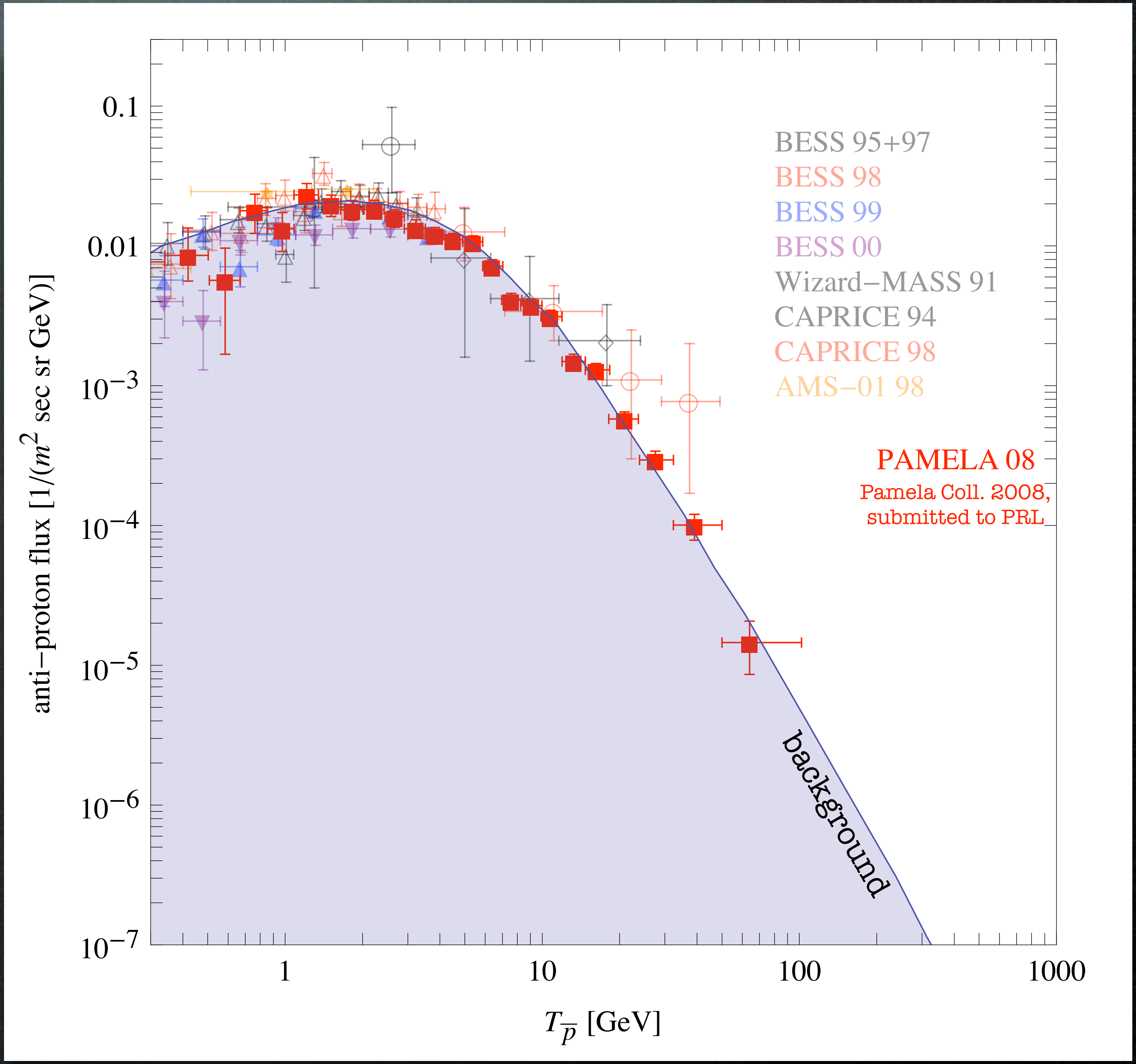
PAMELA might be a real breakthrough!

[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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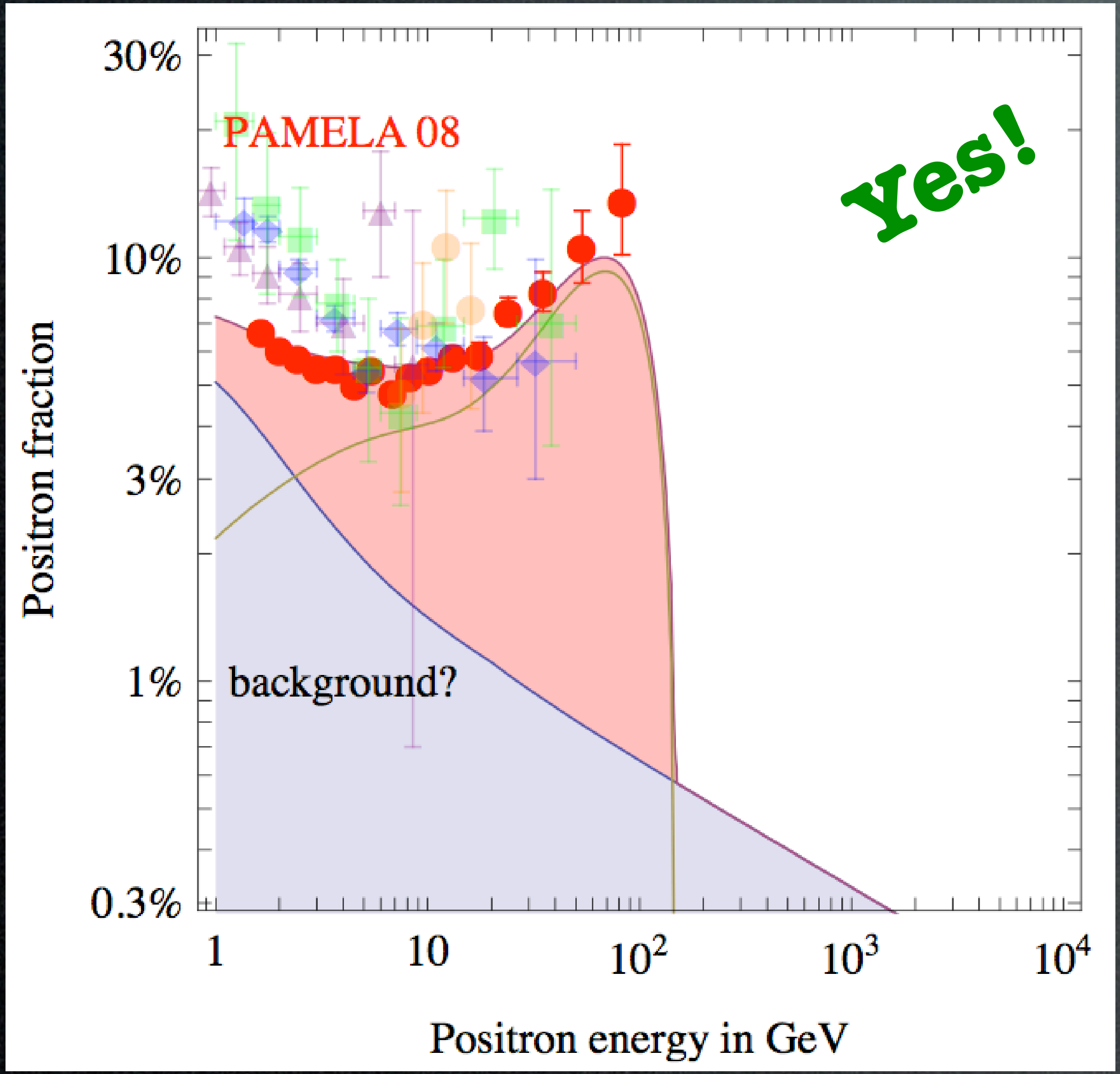
Which DM spectra can fit the data?

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

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

(a possible SuperSymmetric candidate: wino)

Positrons:



Results

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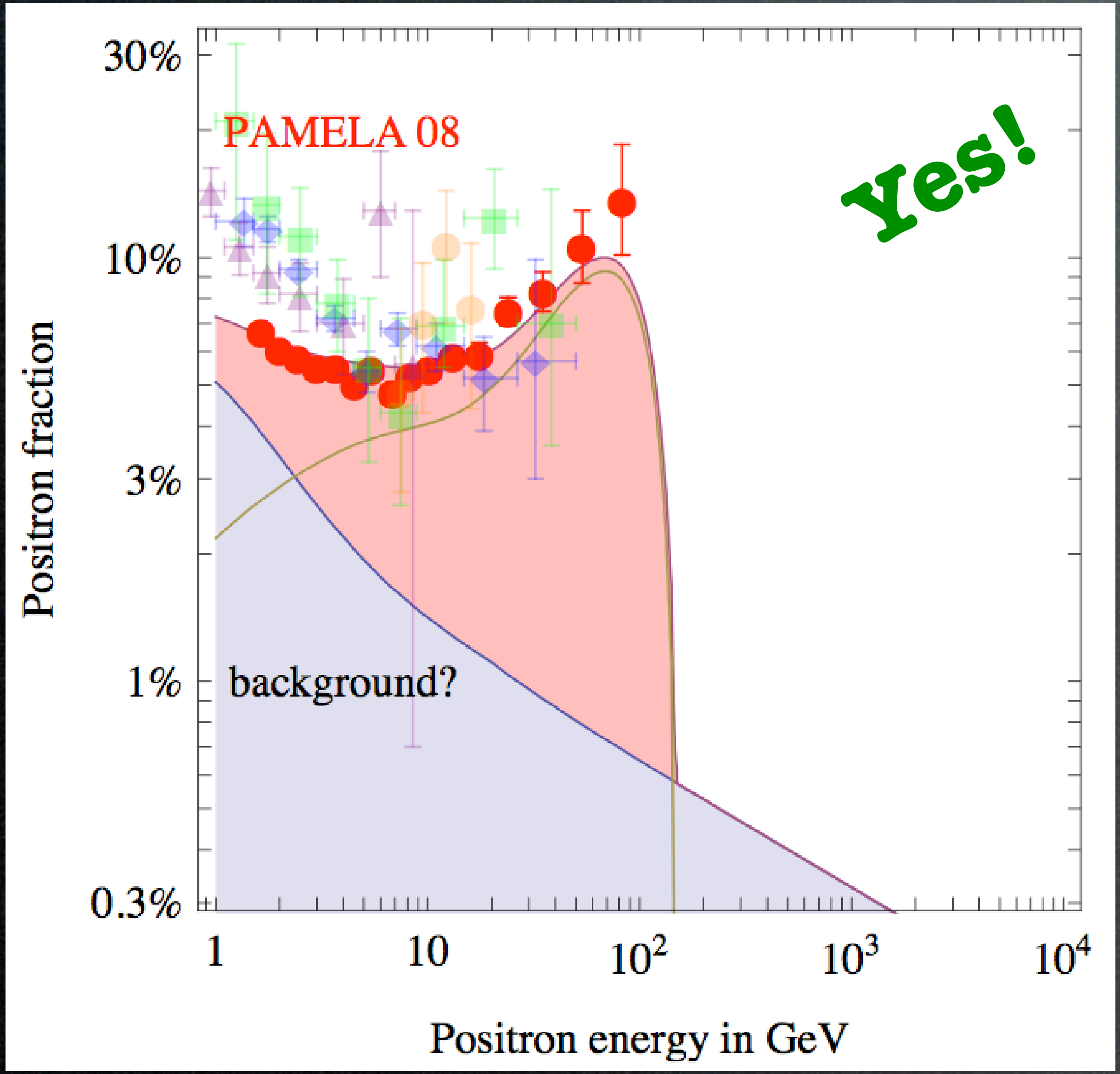
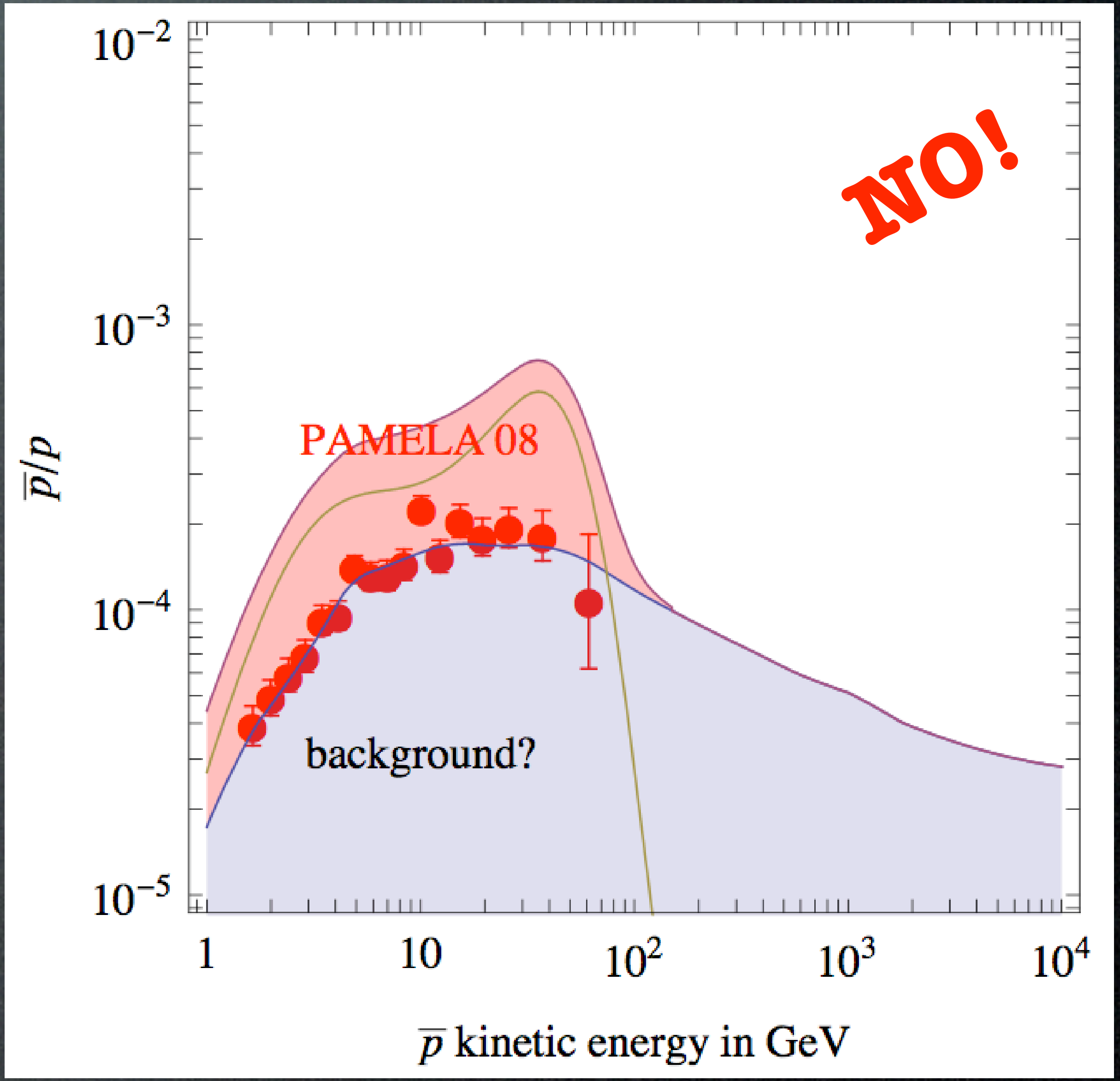


Anti-protons:



[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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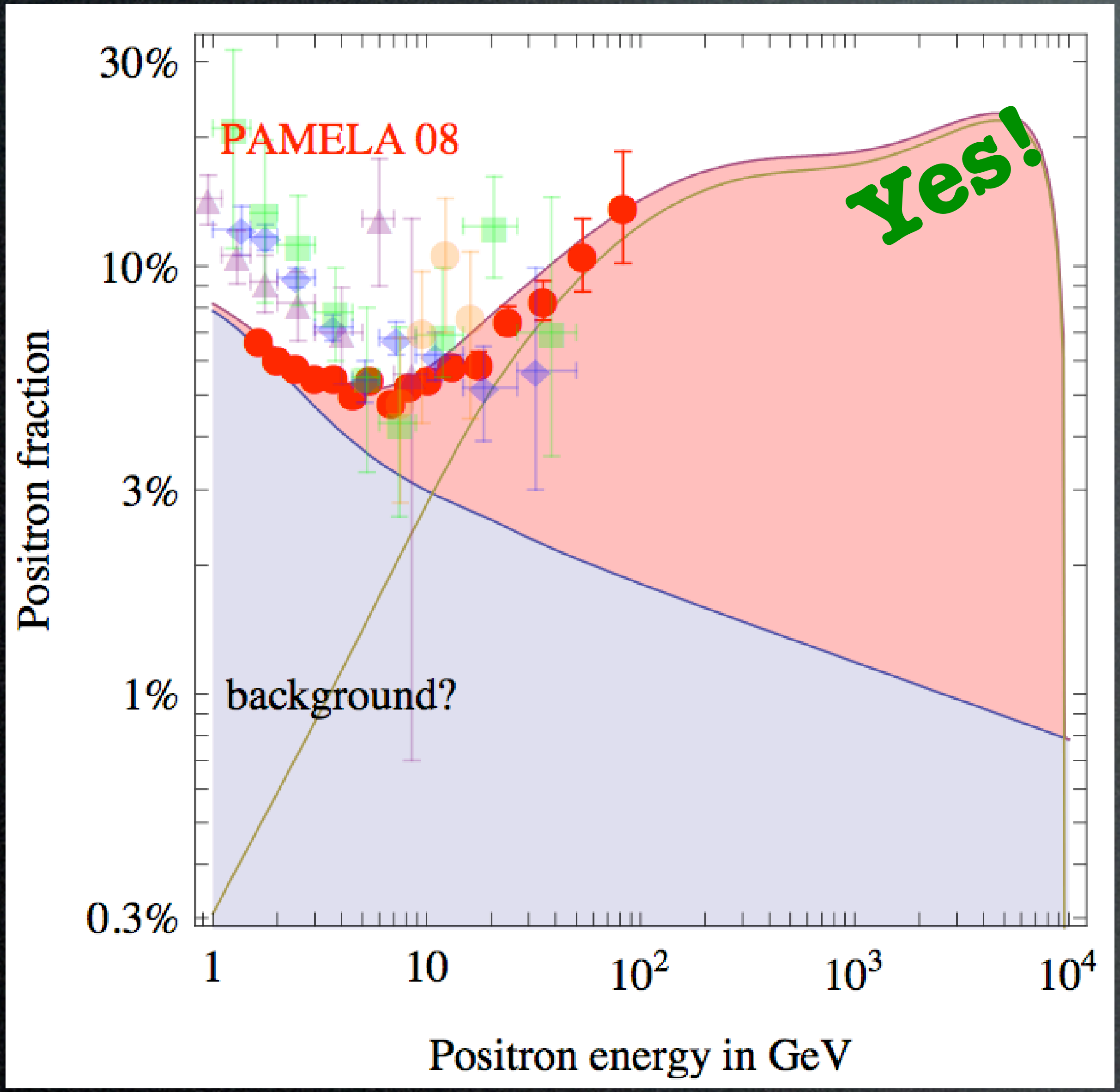
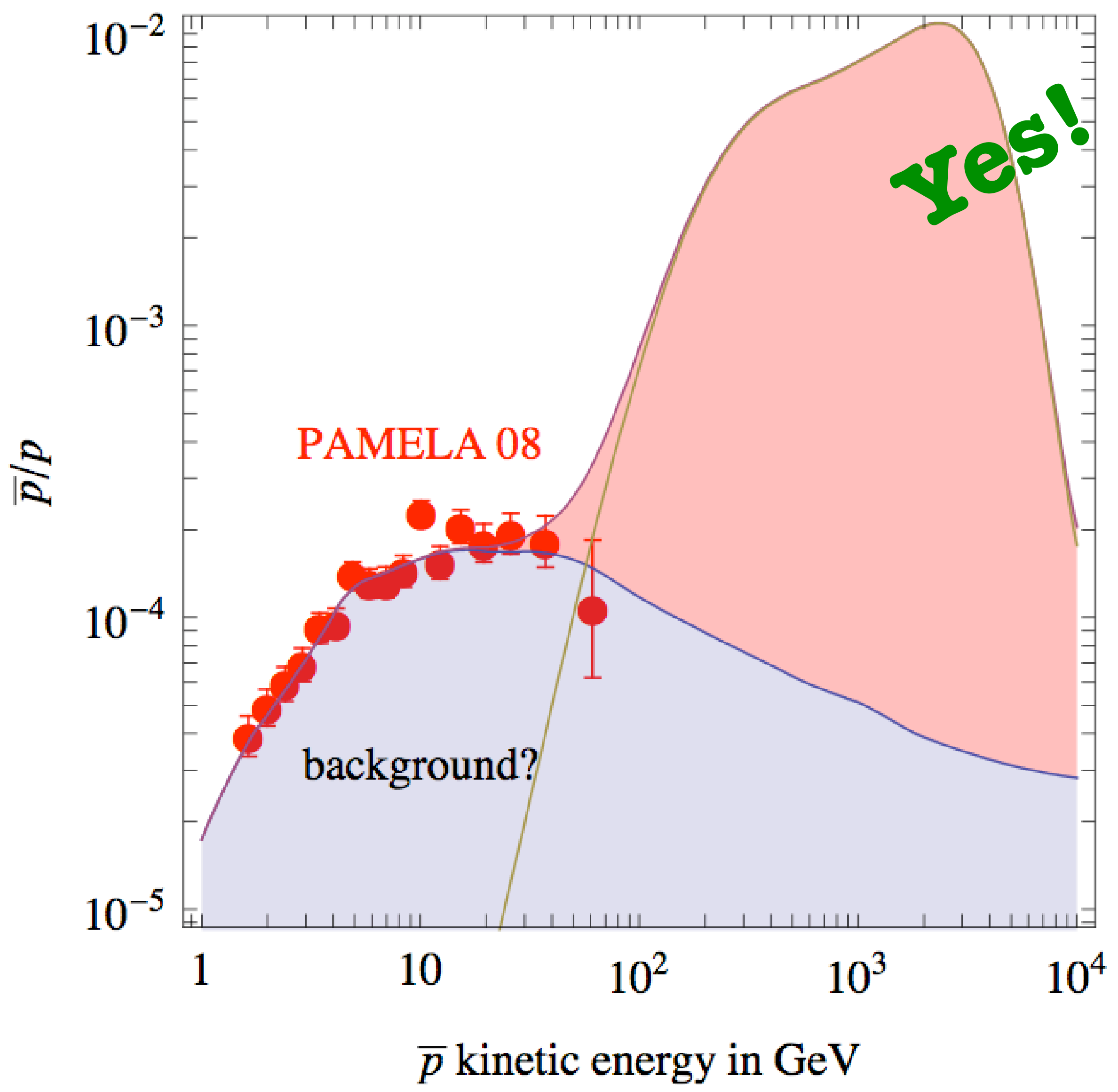


Anti-protons:



Results

Which DM spectra can fit the data?

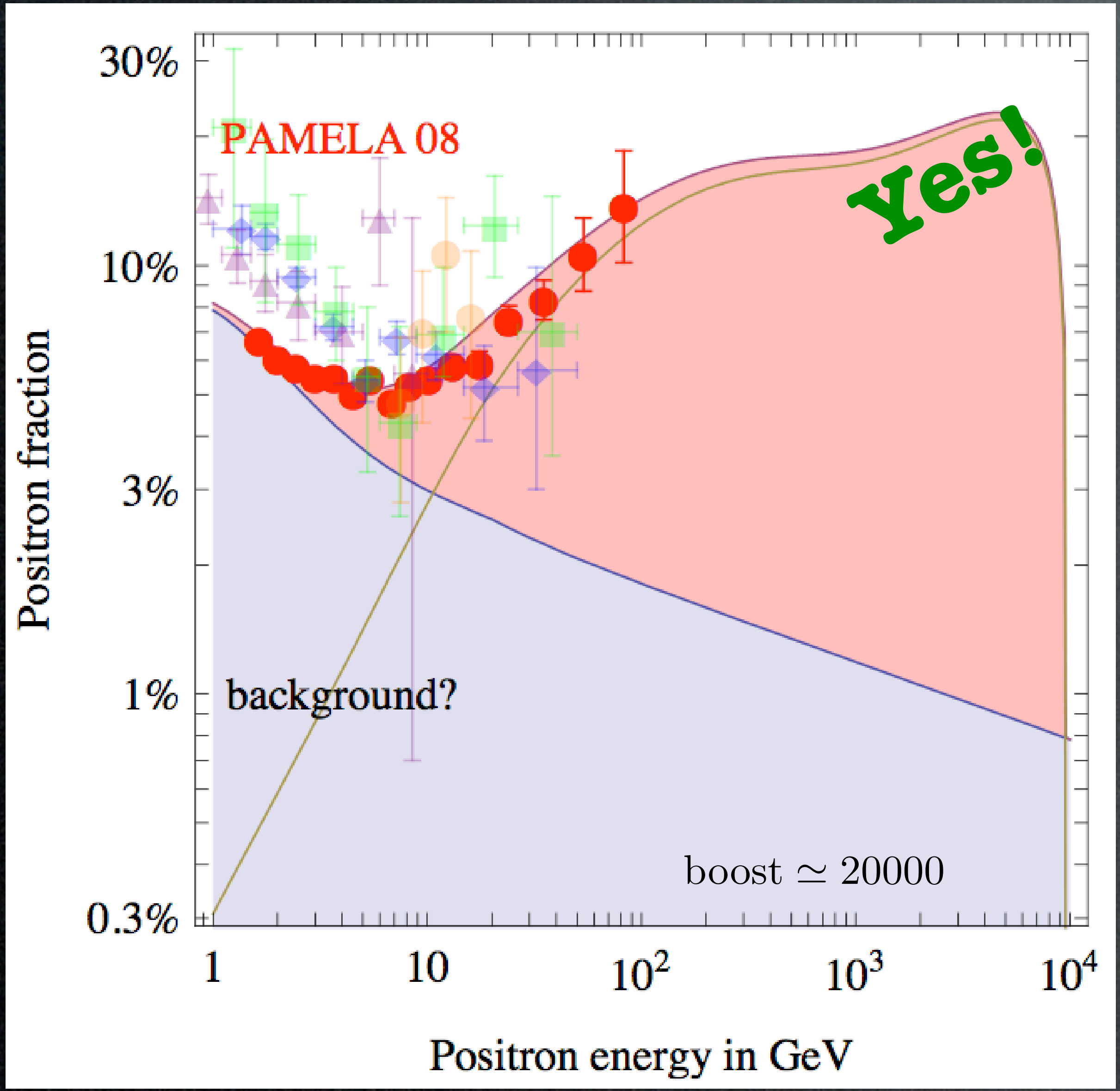
E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

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

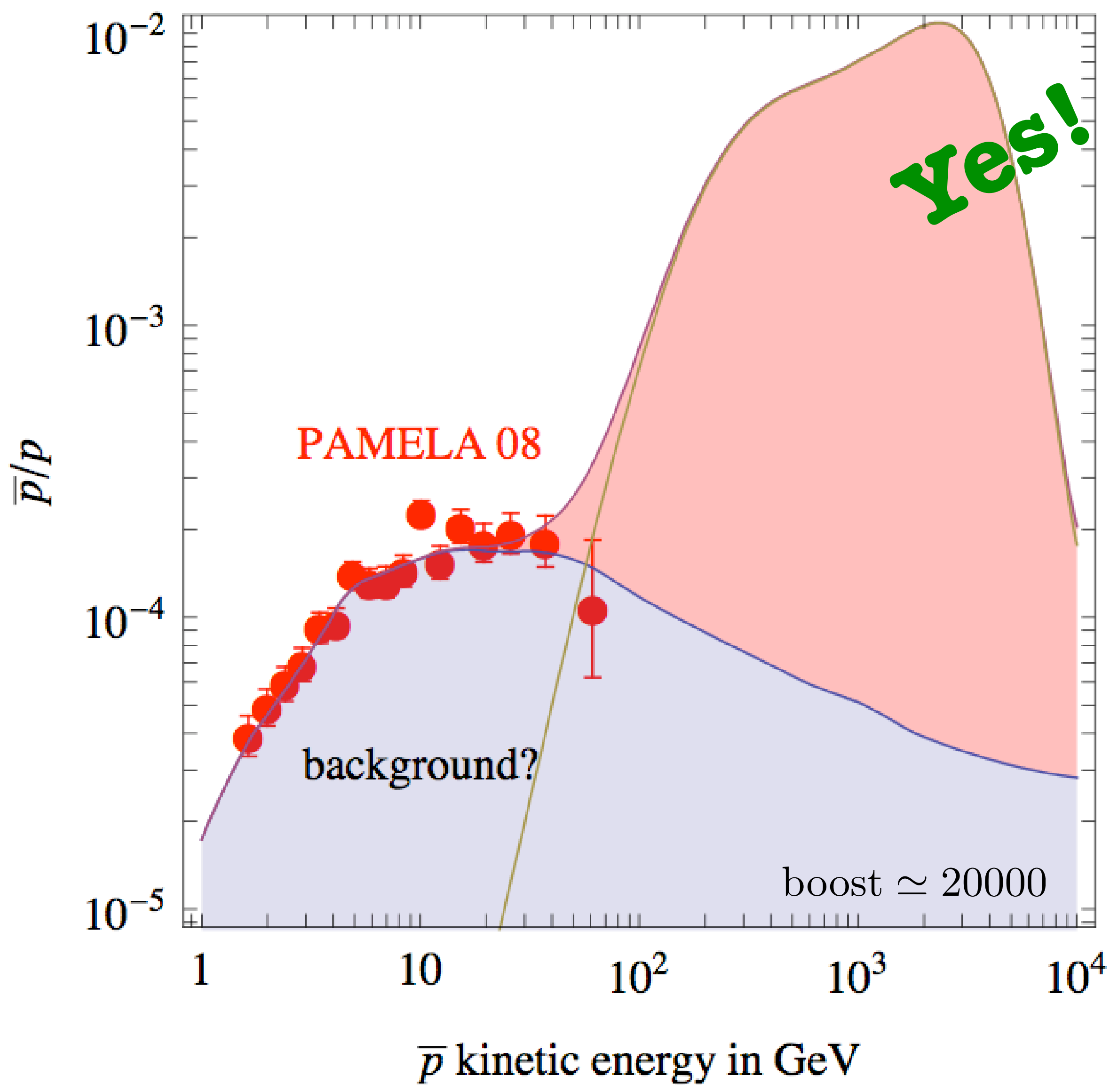
but...: -cross sec $\sigma_{\rm ann}v = 6 \cdot 10^{-22}{\rm cm}^3/{\rm sec}$

Mmm...

Positrons:



Anti-protons:

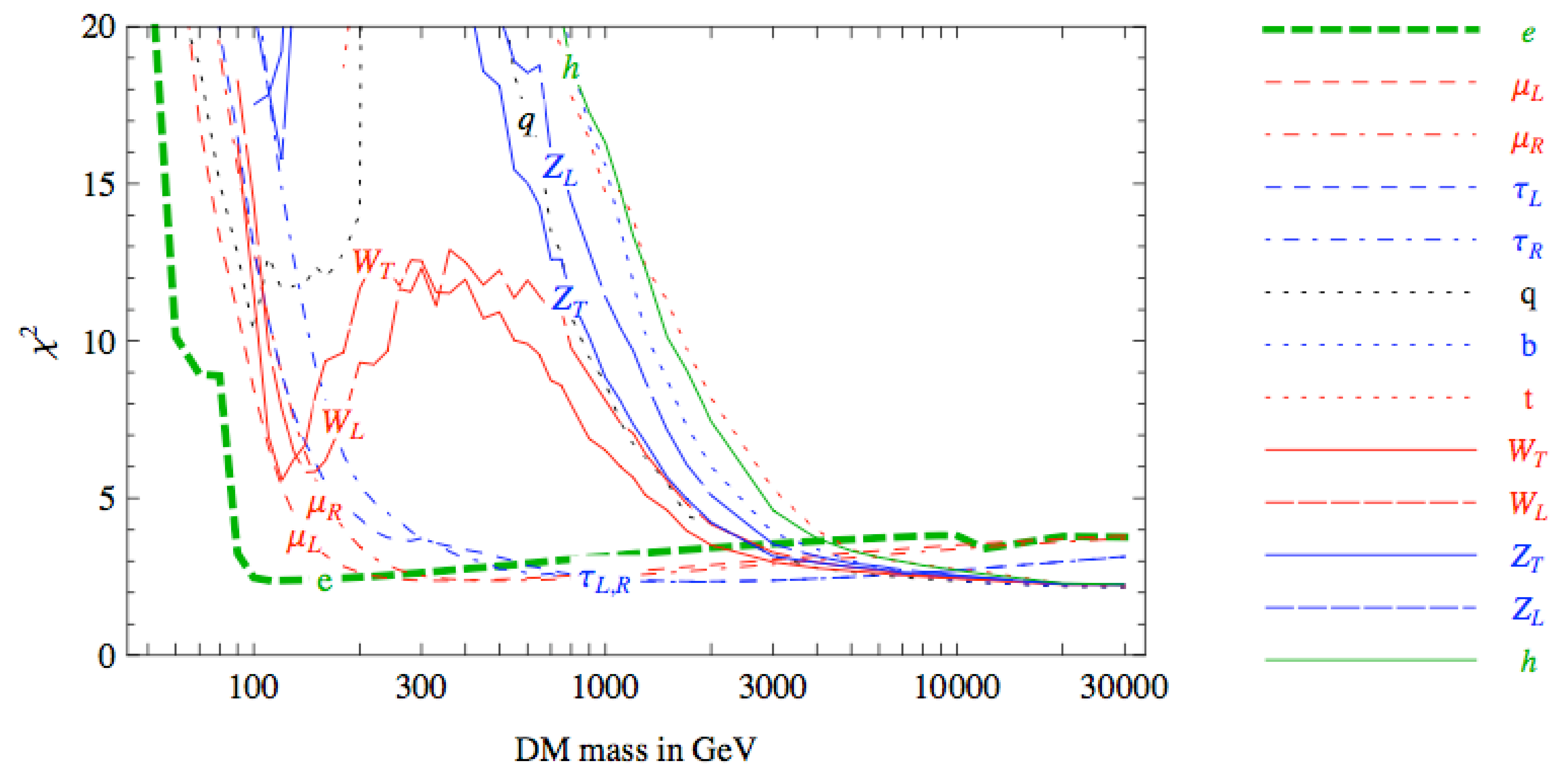


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons only

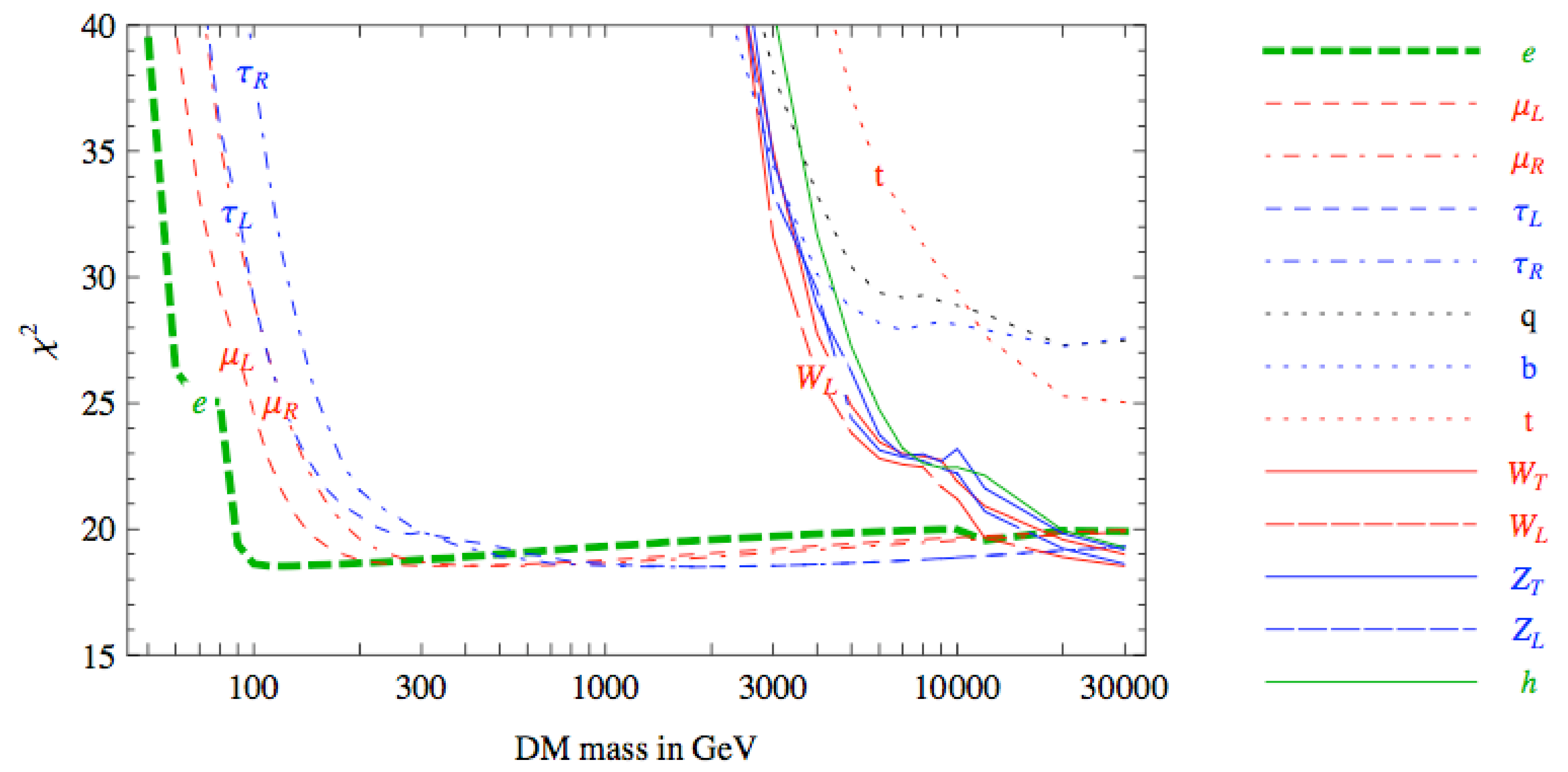


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons

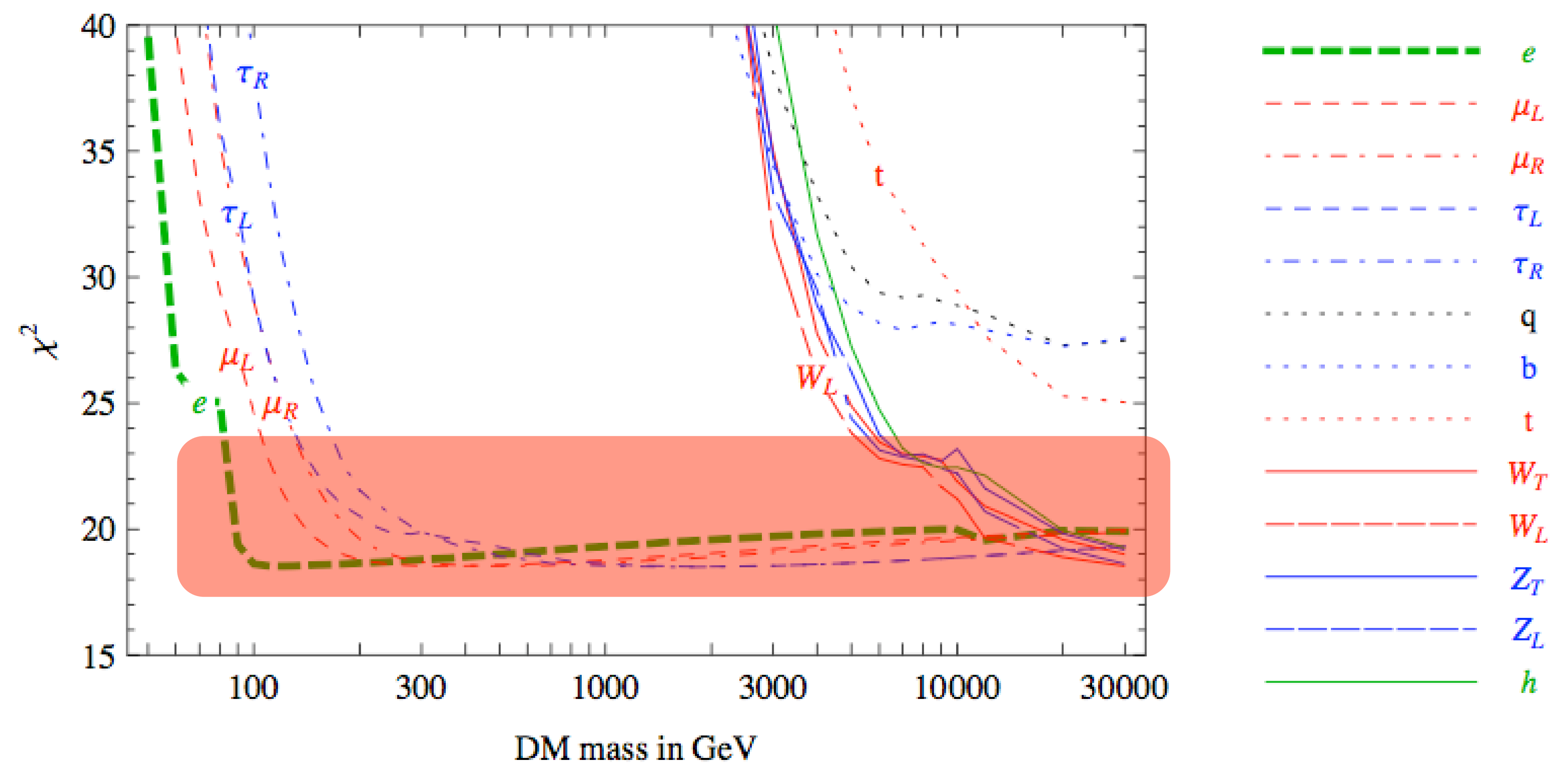


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



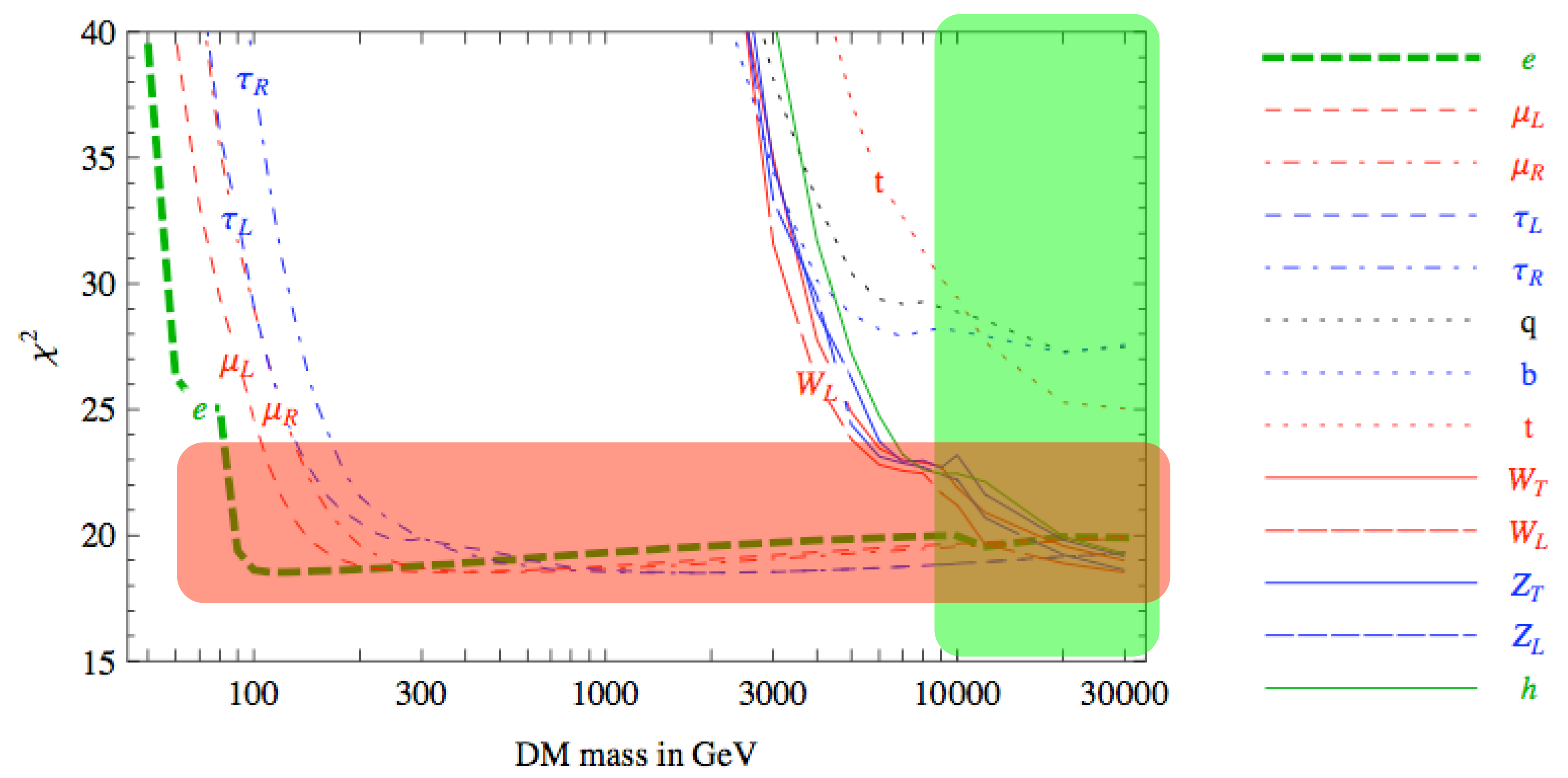
(1) annihilate into leptons (e.g. $\mu^+\mu^-$)

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



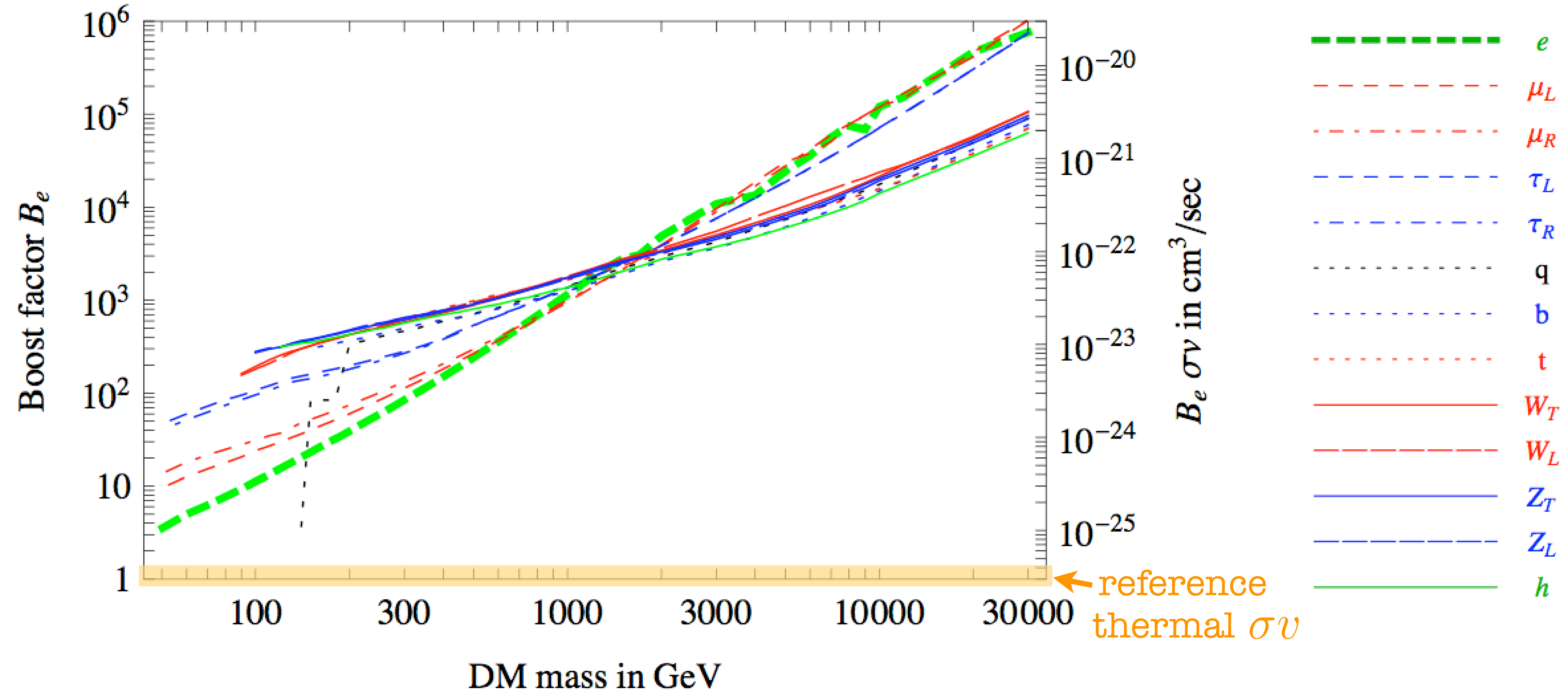
(1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

Results

Which DM spectra can fit the data?

Model-independent results:

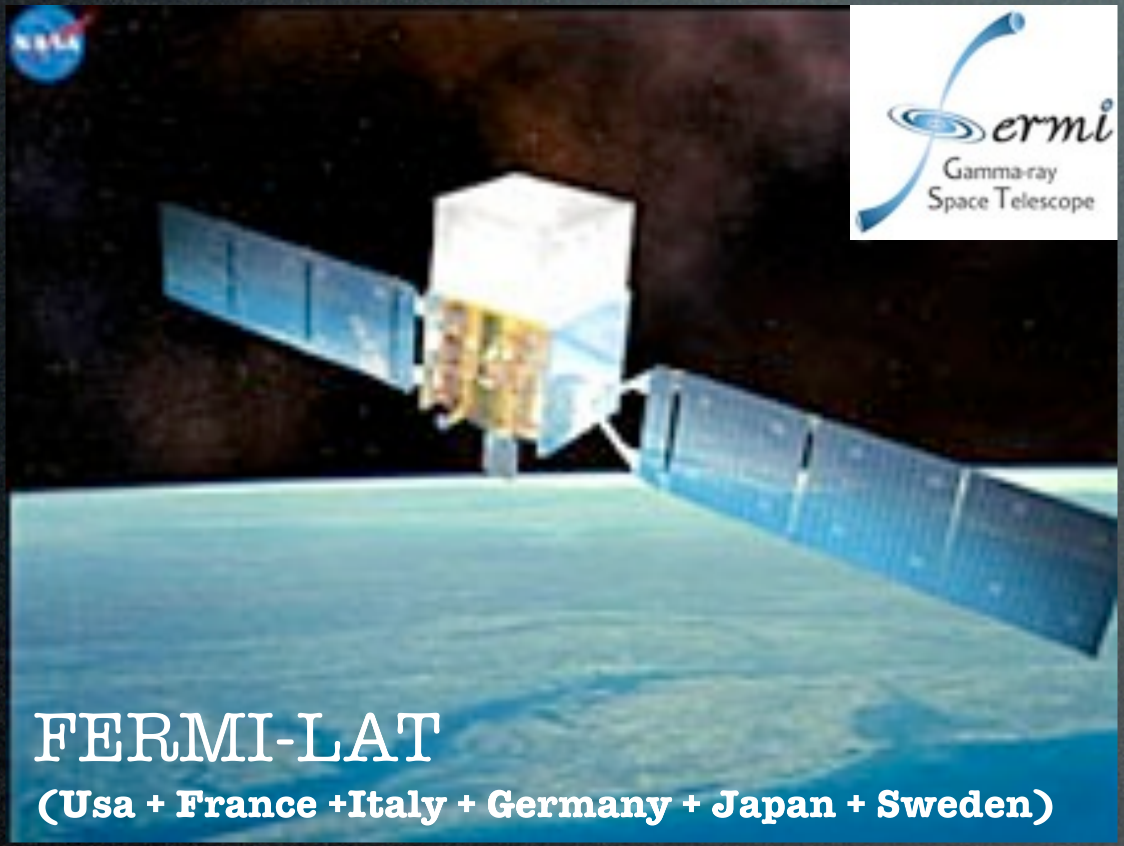
Cross section required by PAMELA

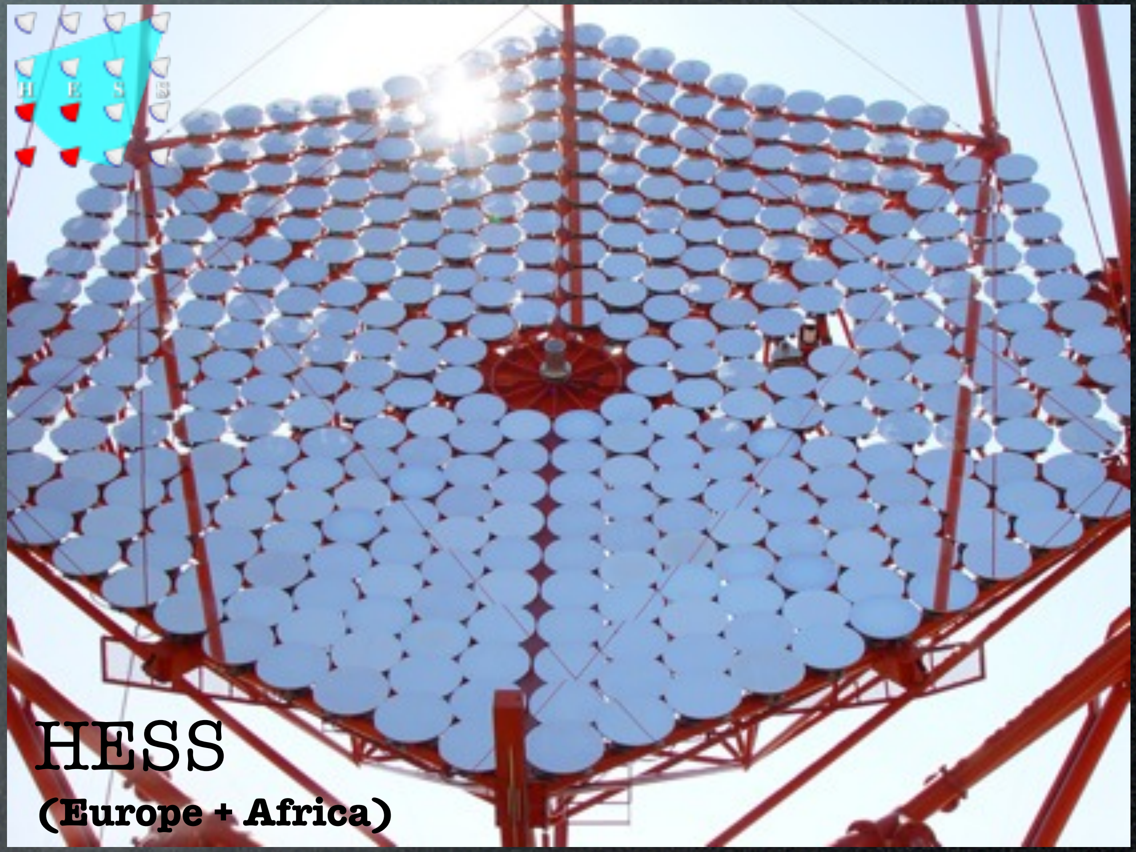


See also 1003.2808

Data sets

Electrons + positrons from FERMI and HESS:





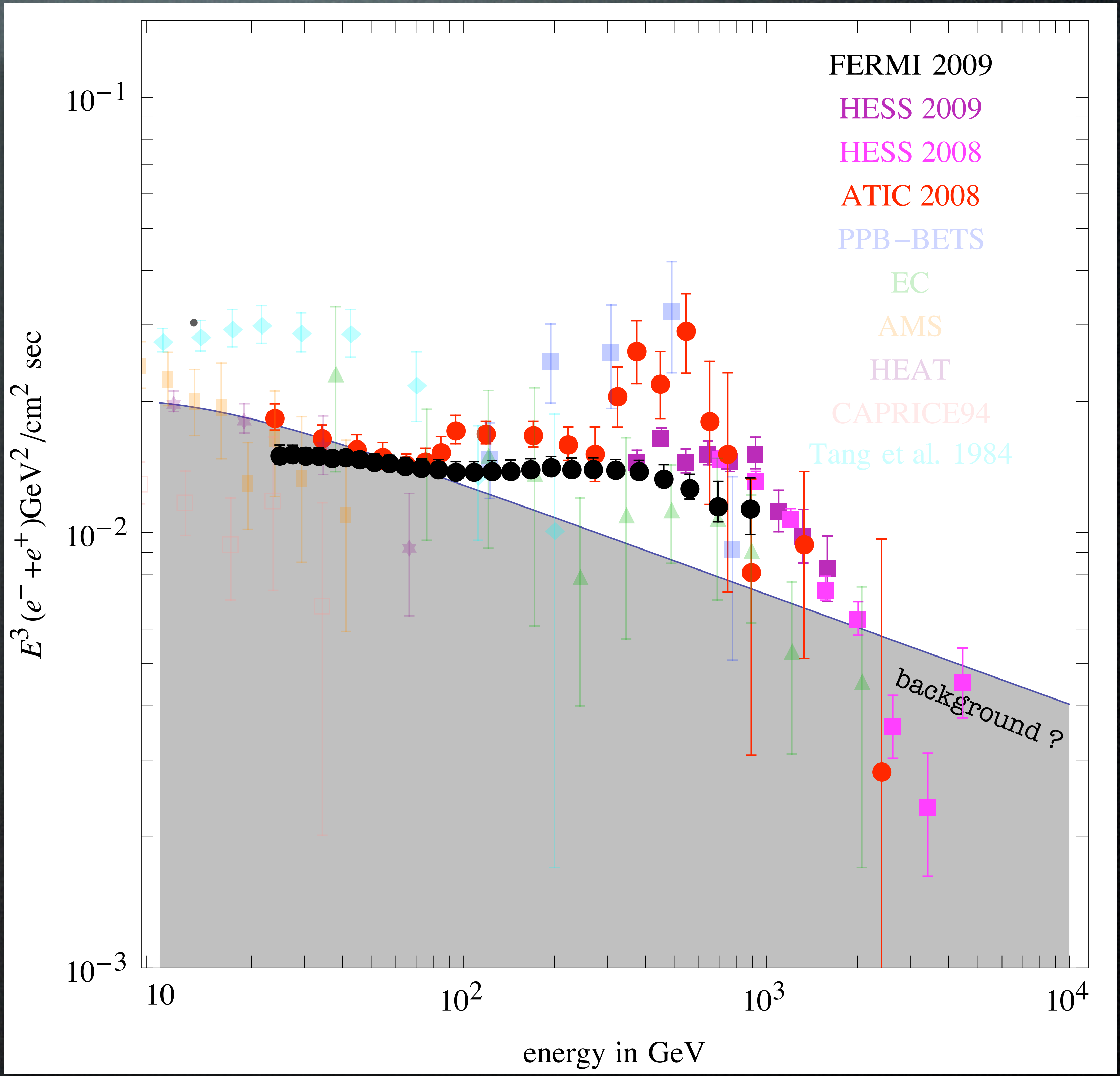
“Designed as a high-sensitivity
gamma-ray observatory,
the FERMI Large Area Telescope
is also an electron detector
with a large acceptance”

“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 $e^+ + e^-$ peak
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?



[formerly predicted GLAST sensitivity]

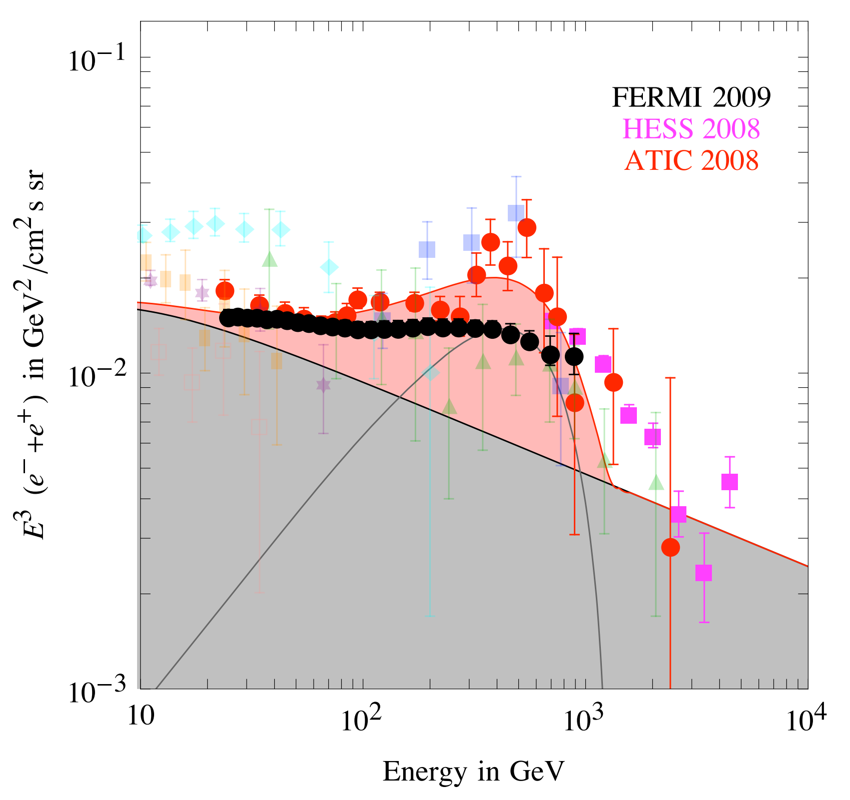
Results

Which DM spectra can fit the data?

Results

Which DM spectra can fit the data?

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



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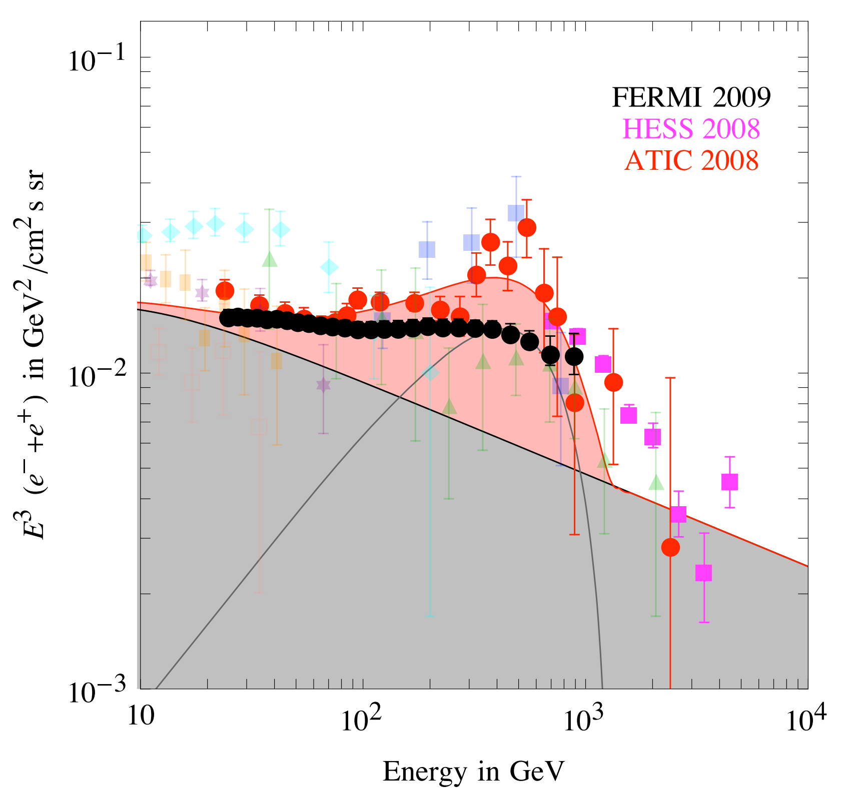
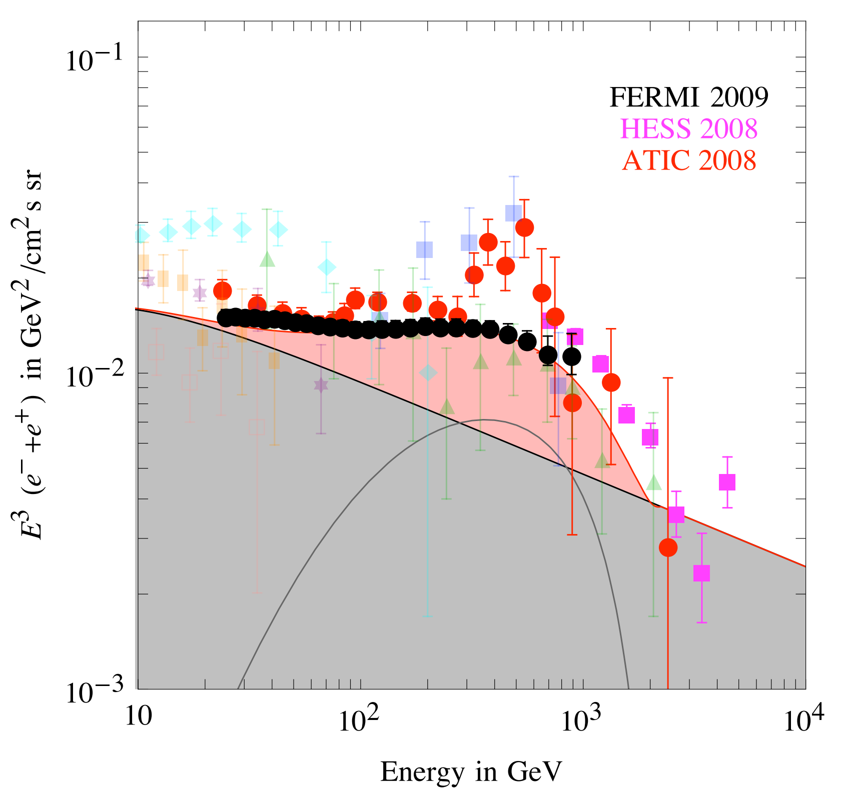


$\tau^+\tau^-, M_{\rm DM} \simeq 2\,{\rm TeV}$



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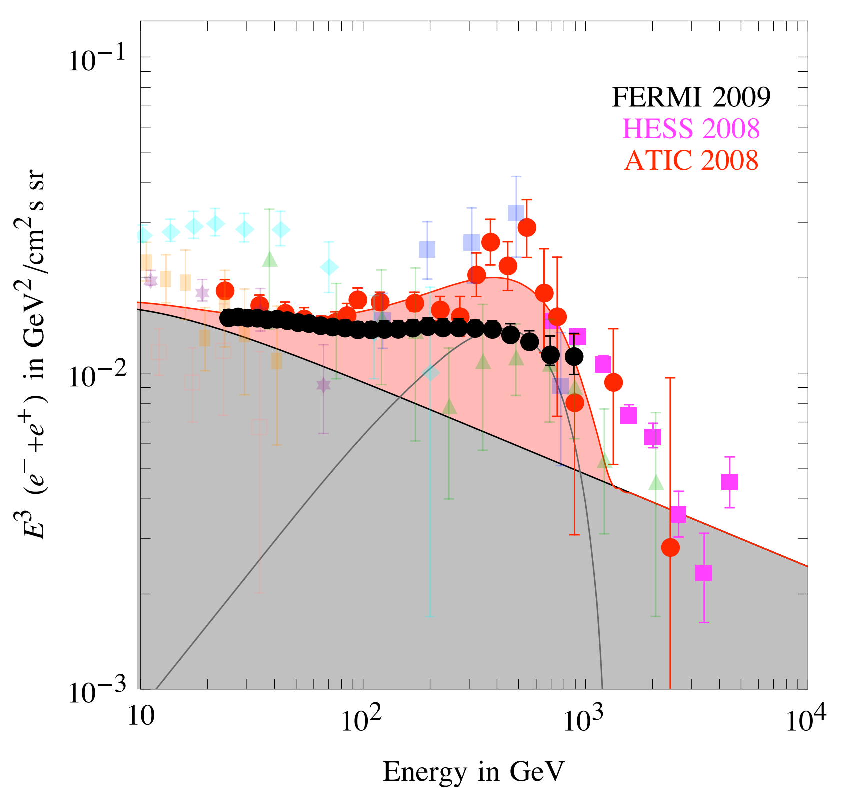
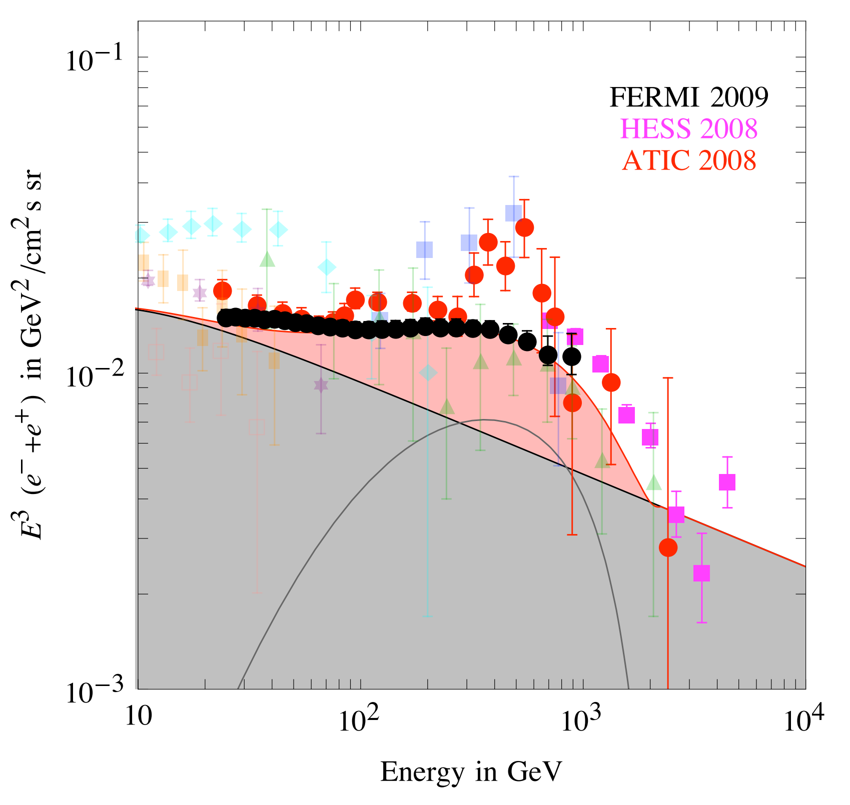
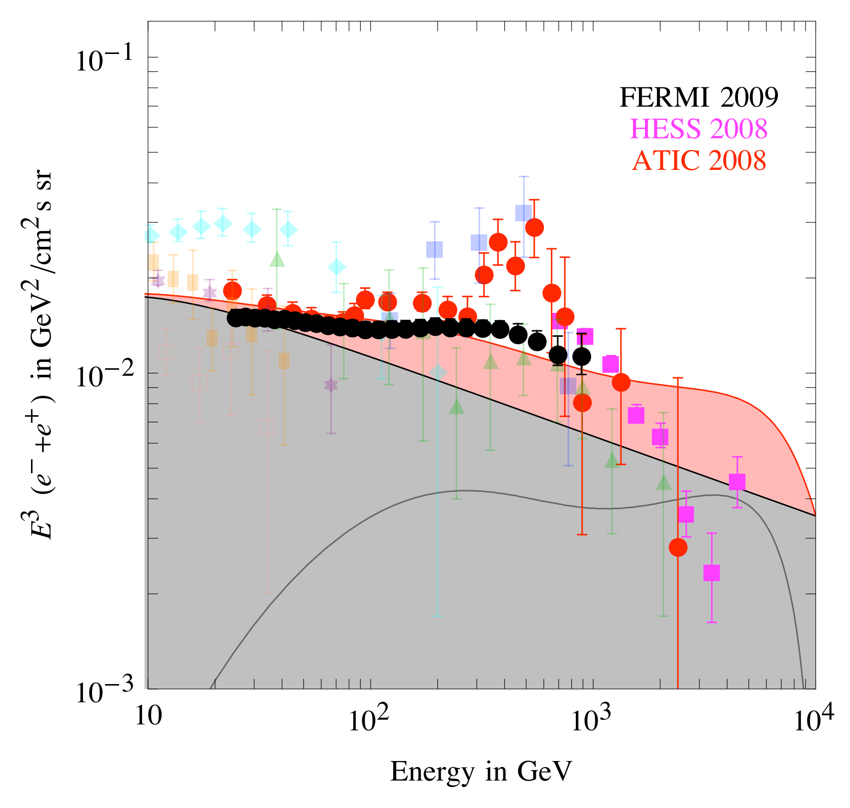


$\tau^+\tau^-, M_{\rm DM} \simeq 2\,\text{TeV}$



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



Results

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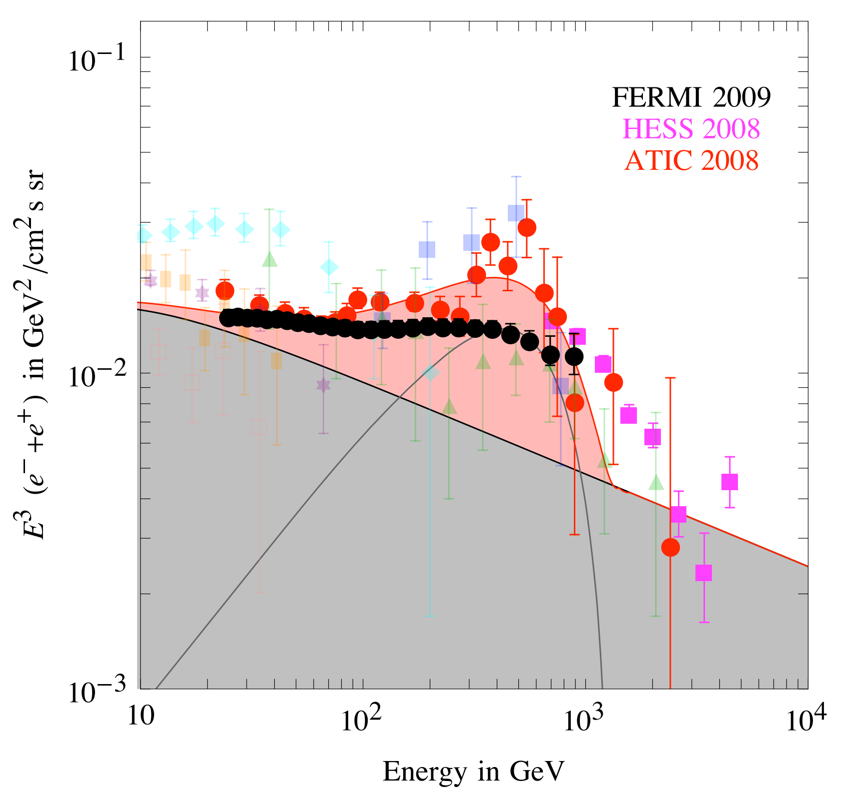
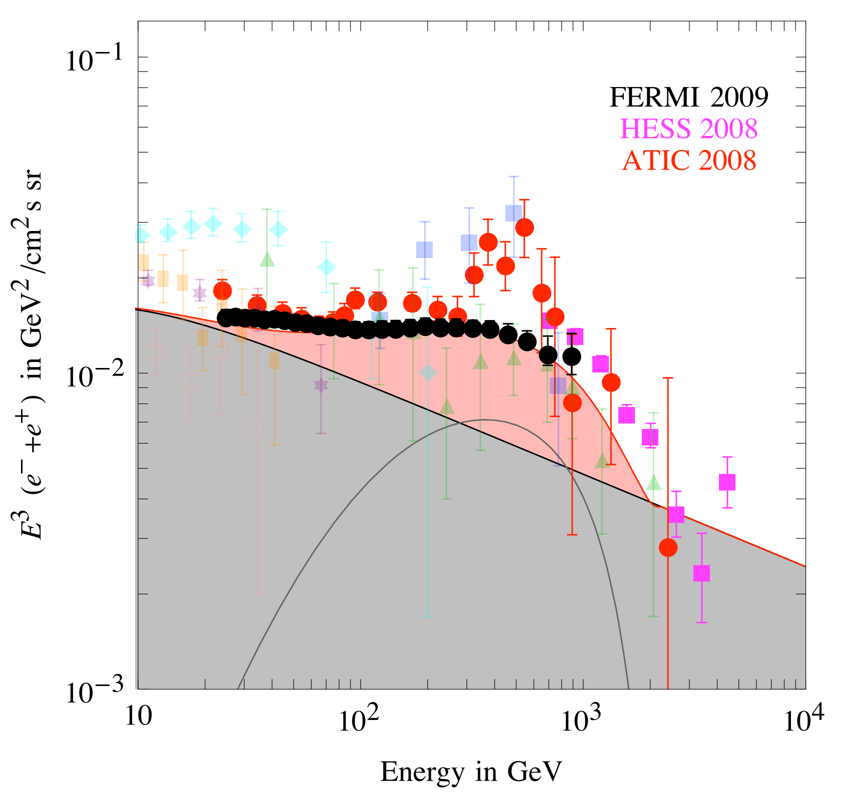


Notice:

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

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



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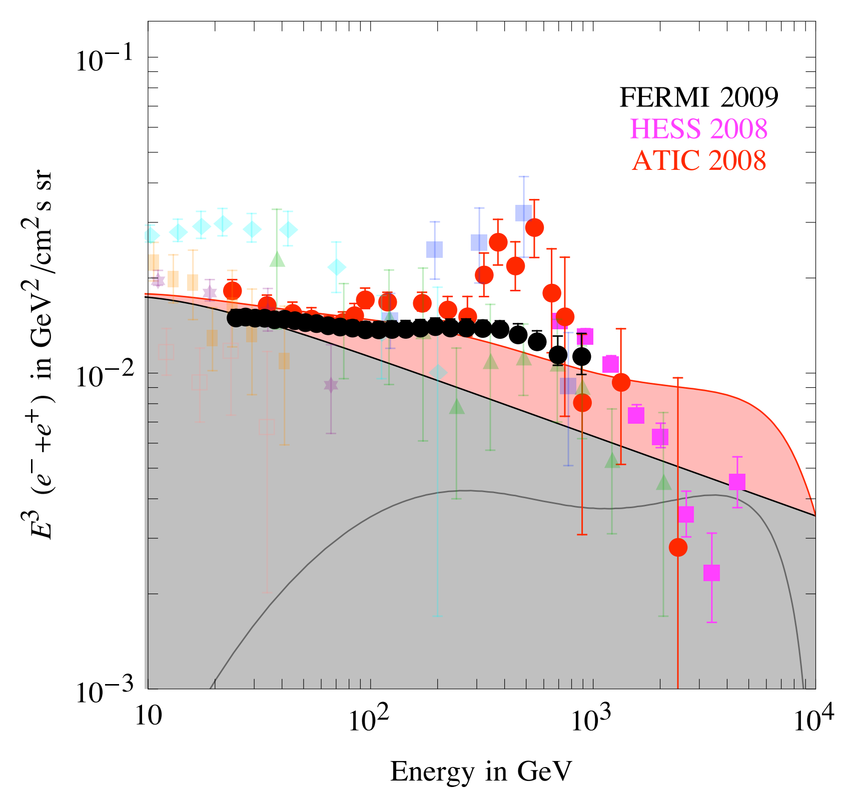

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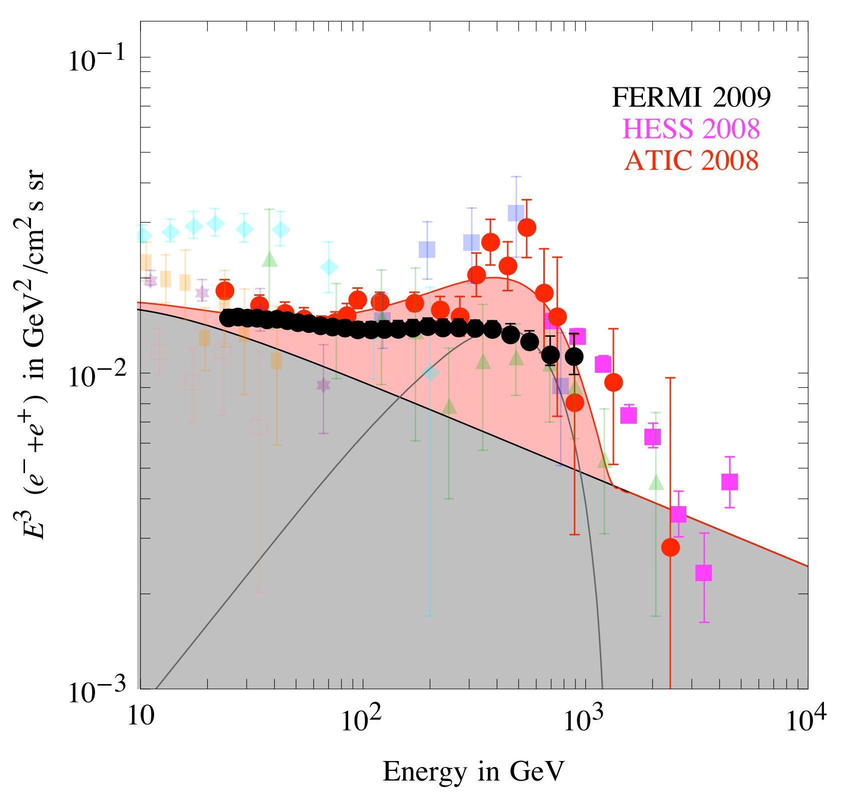

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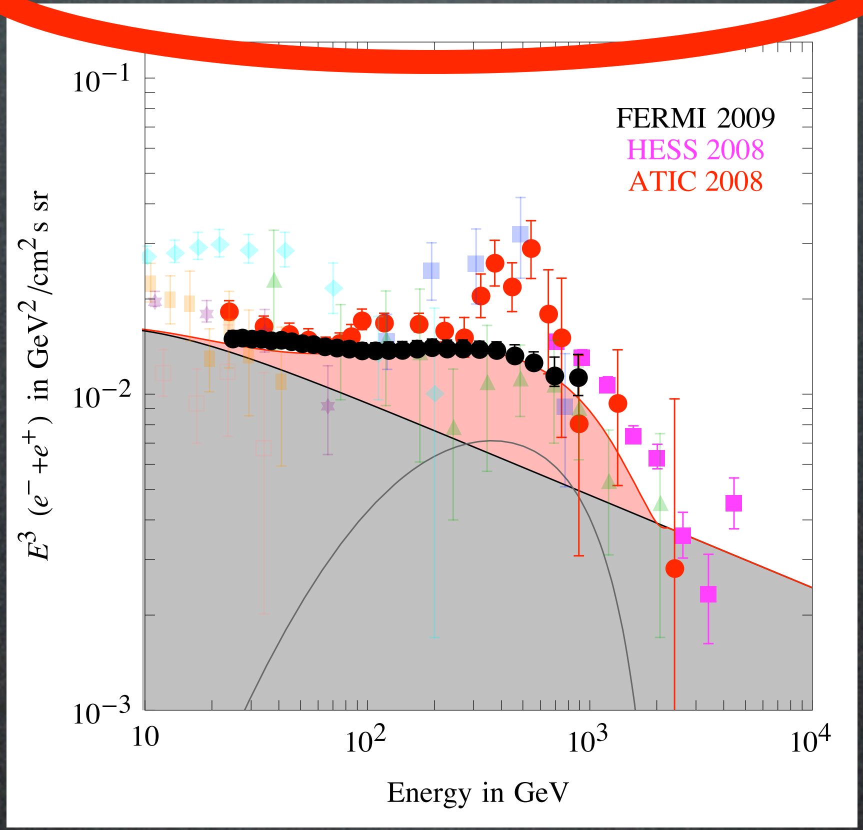

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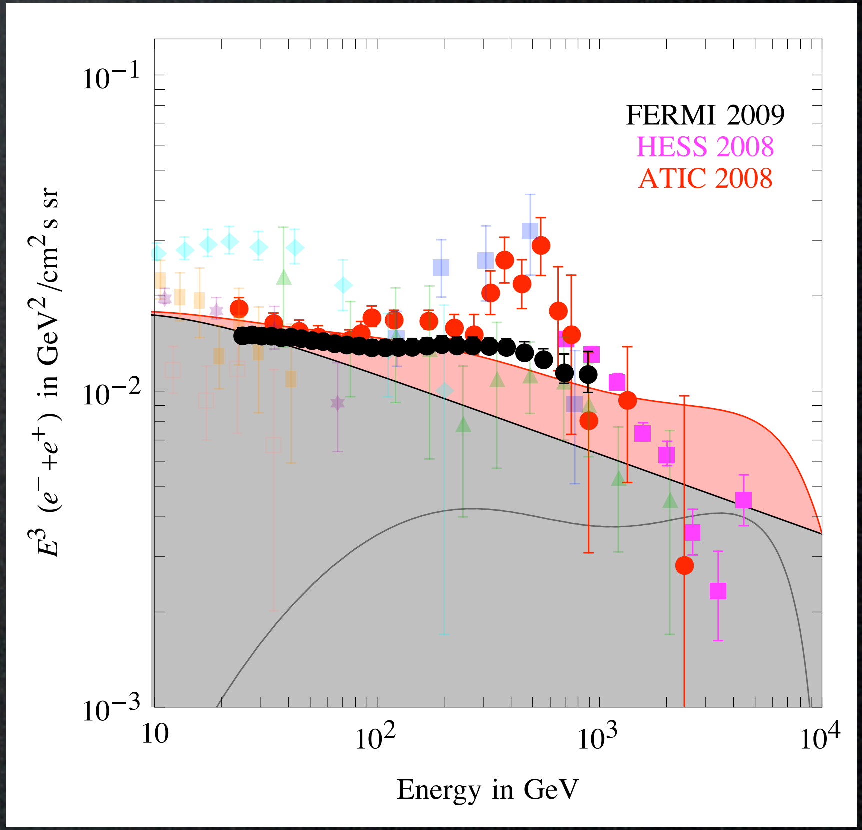


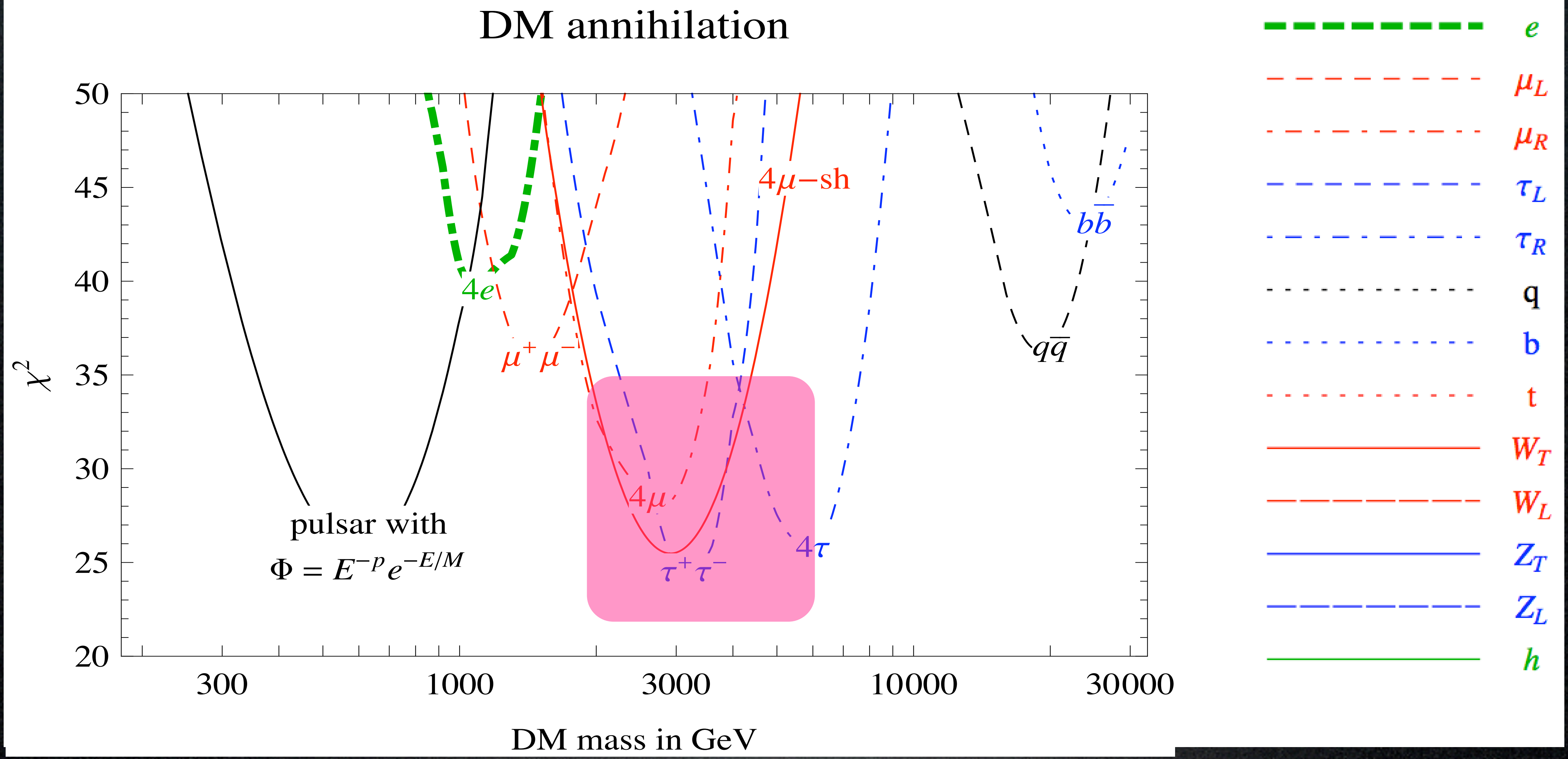
- no features in FERMI => $M_{\rm DM} > 1\ {\rm TeV}$
- a ‘cutoff’ in HESS => $M_{\rm DM} \lesssim 3\ {\rm TeV}$
- smooth lepton spectrum

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

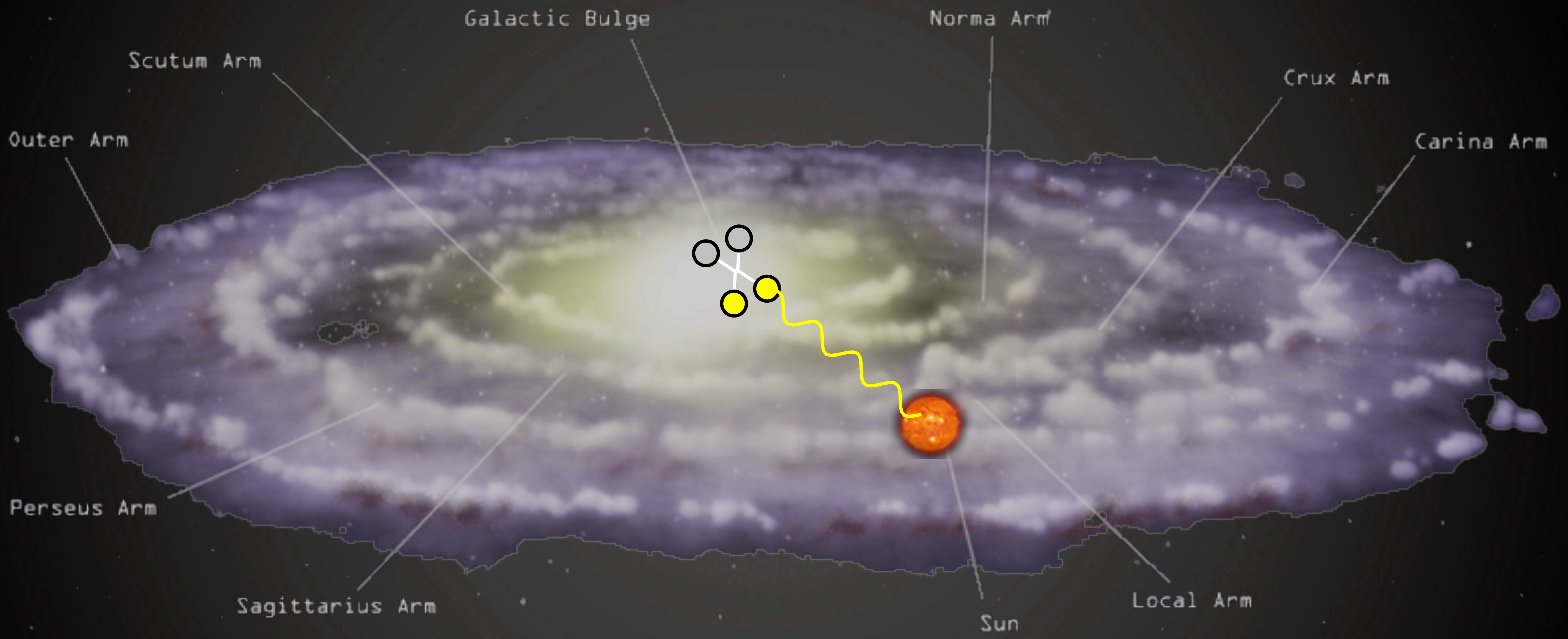
(1) annihilate into leptons (e.g. $\tau^+\tau^-$), mass ~3 TeV

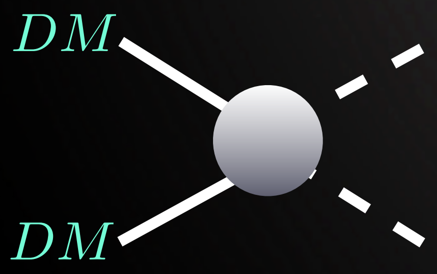
DM detection

- direct detection
- production at colliders
- indirect
  - γ from annihil in galactic center or halo and from synchrotron emission
    Fermi, **HESS**, radio telescopes
  - e^+ from annihil in galactic halo or center
    PAMELA, ATIC, Fermi
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{D}$ from annihil in galactic halo or center
  - $\nu, \bar{\nu}$ from annihil in massive bodies

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

Indirect Detection

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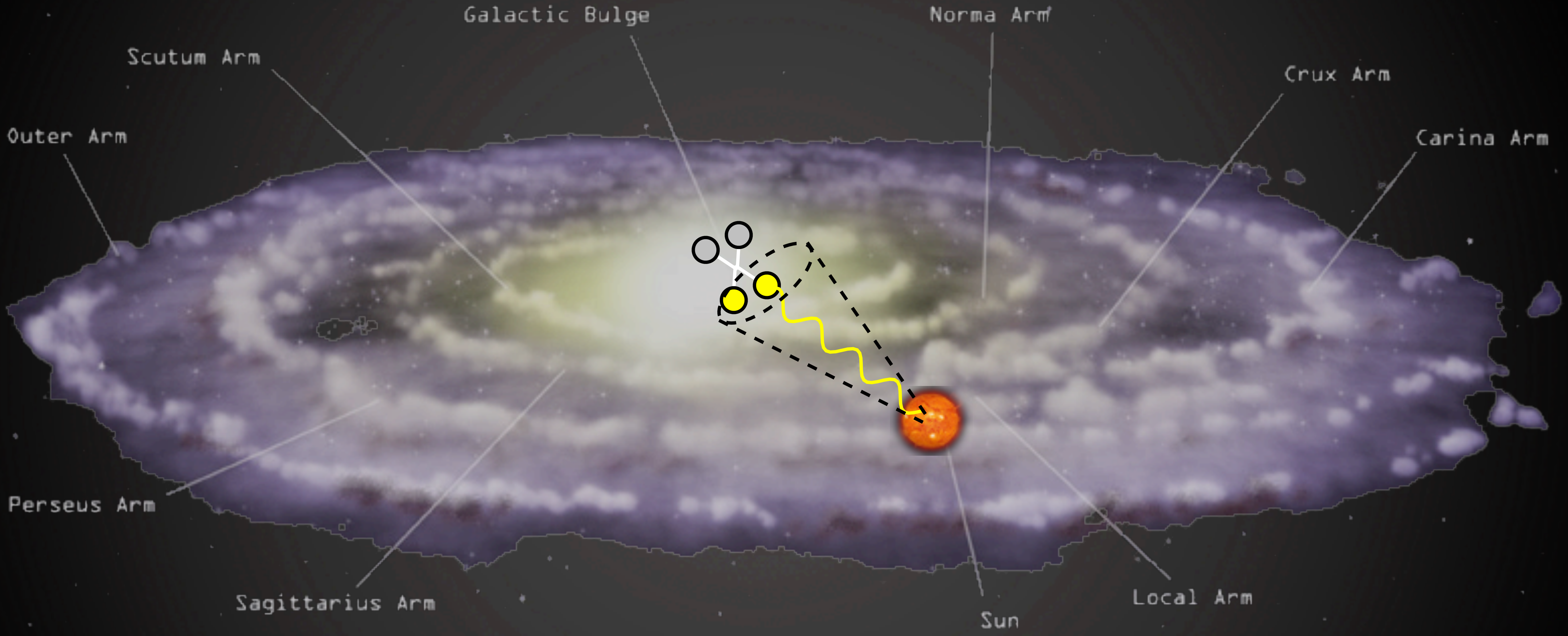
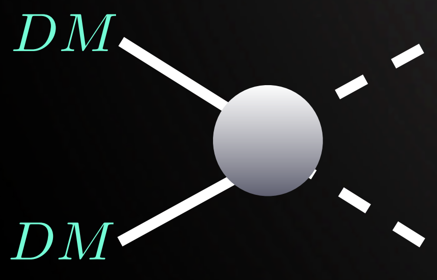


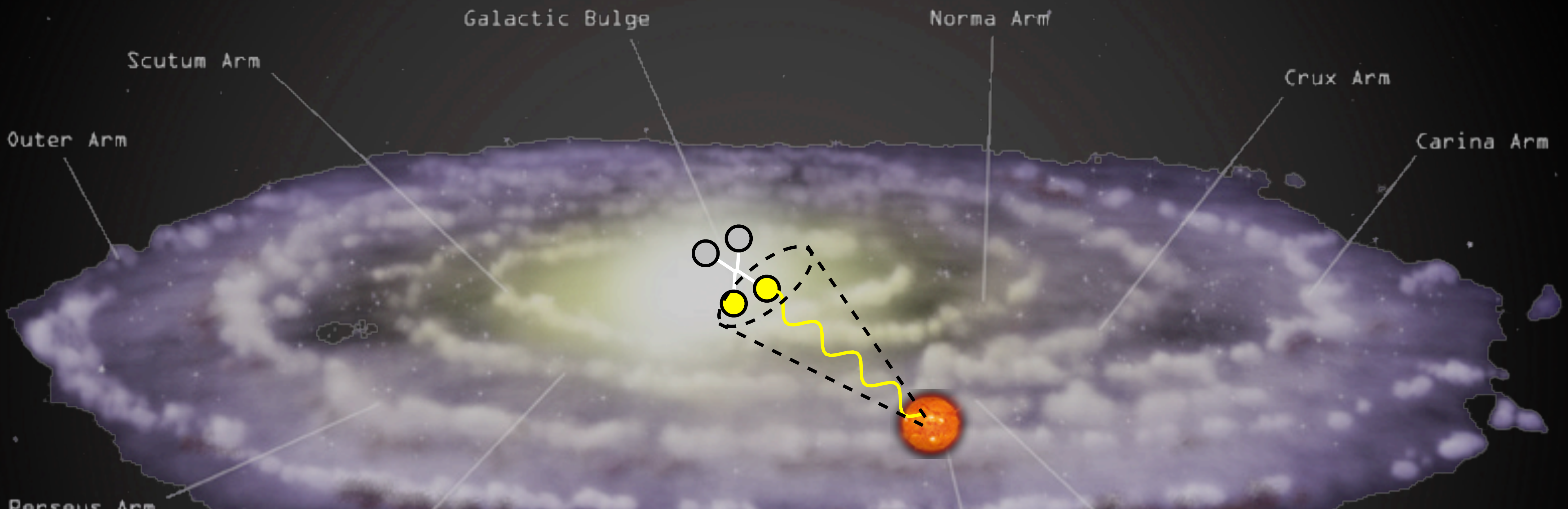


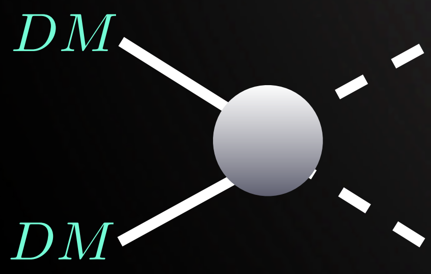
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \;\ldots \text{ and } \gamma$$

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

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

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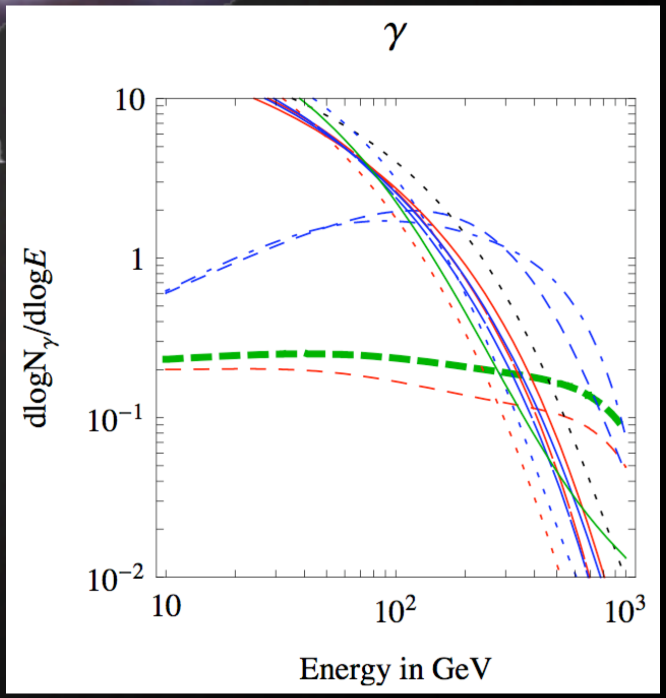
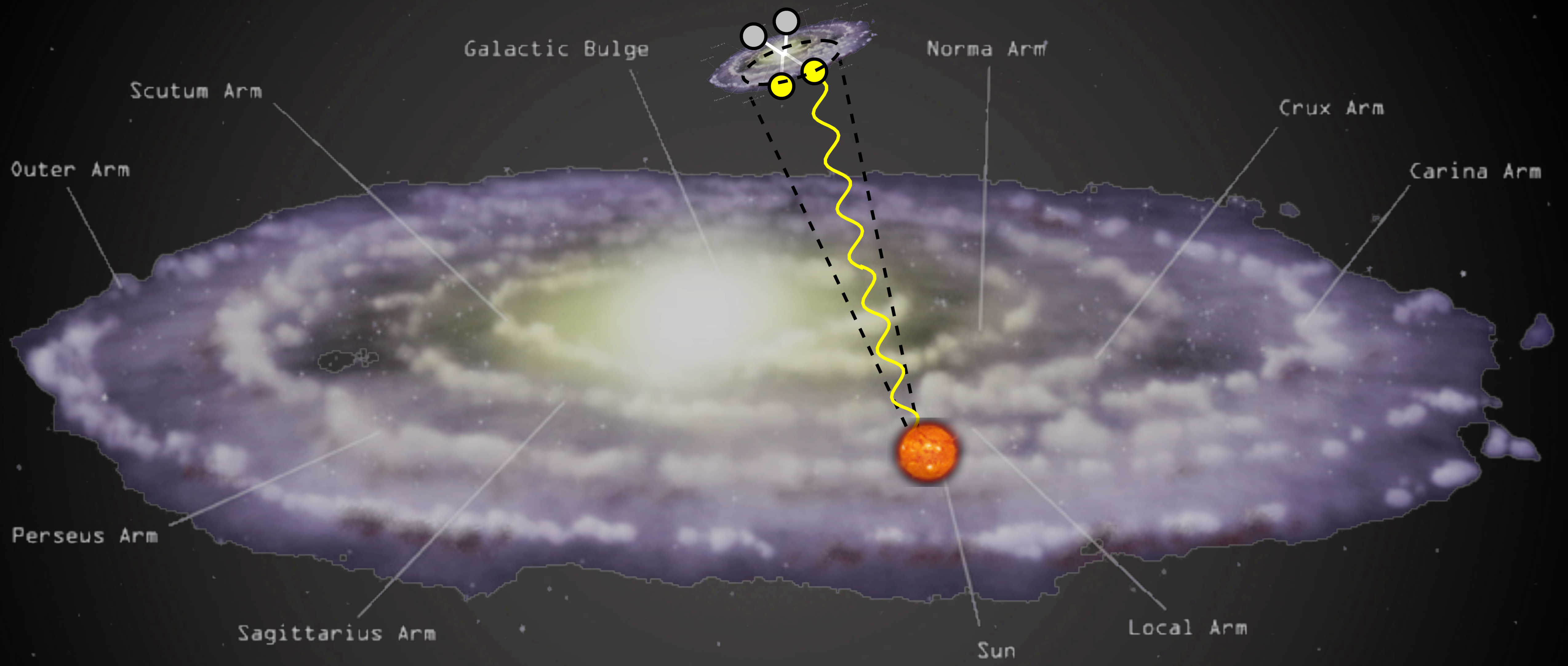
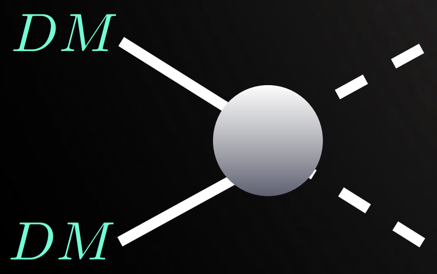


typically sub-TeV energies

Indirect Detection

γ from DM annihilations in Sagittarius Dwarf



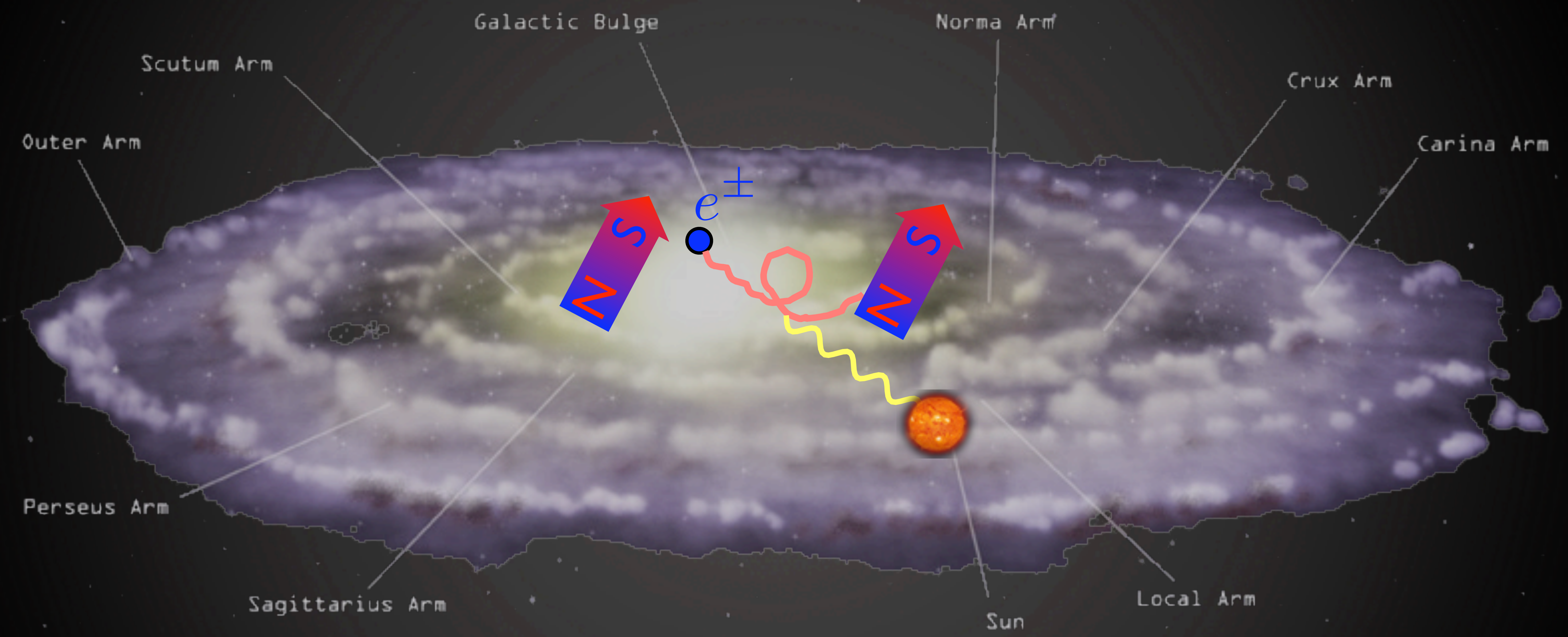


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and } \gamma$$

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

Indirect Detection

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



Indirect Detection

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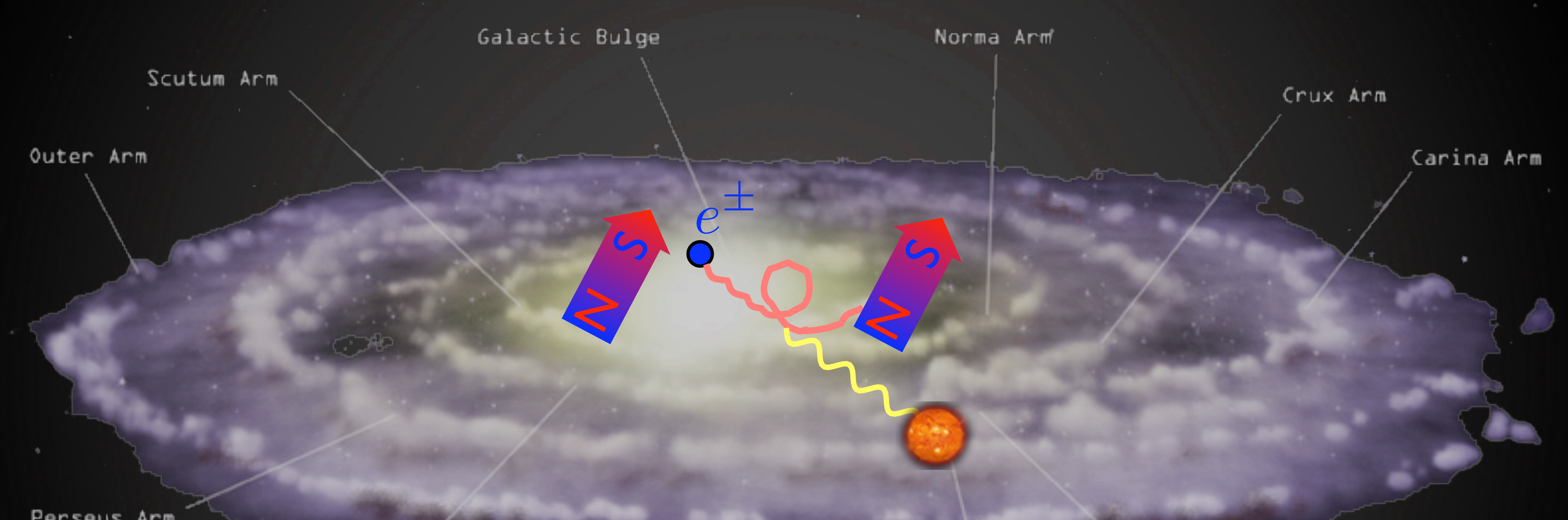
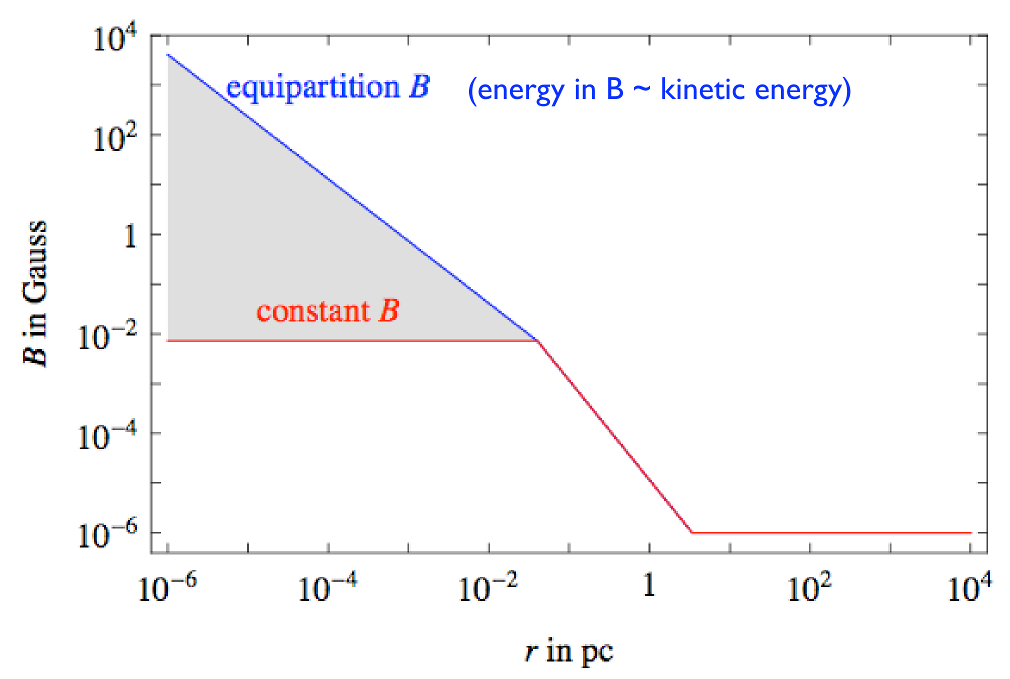


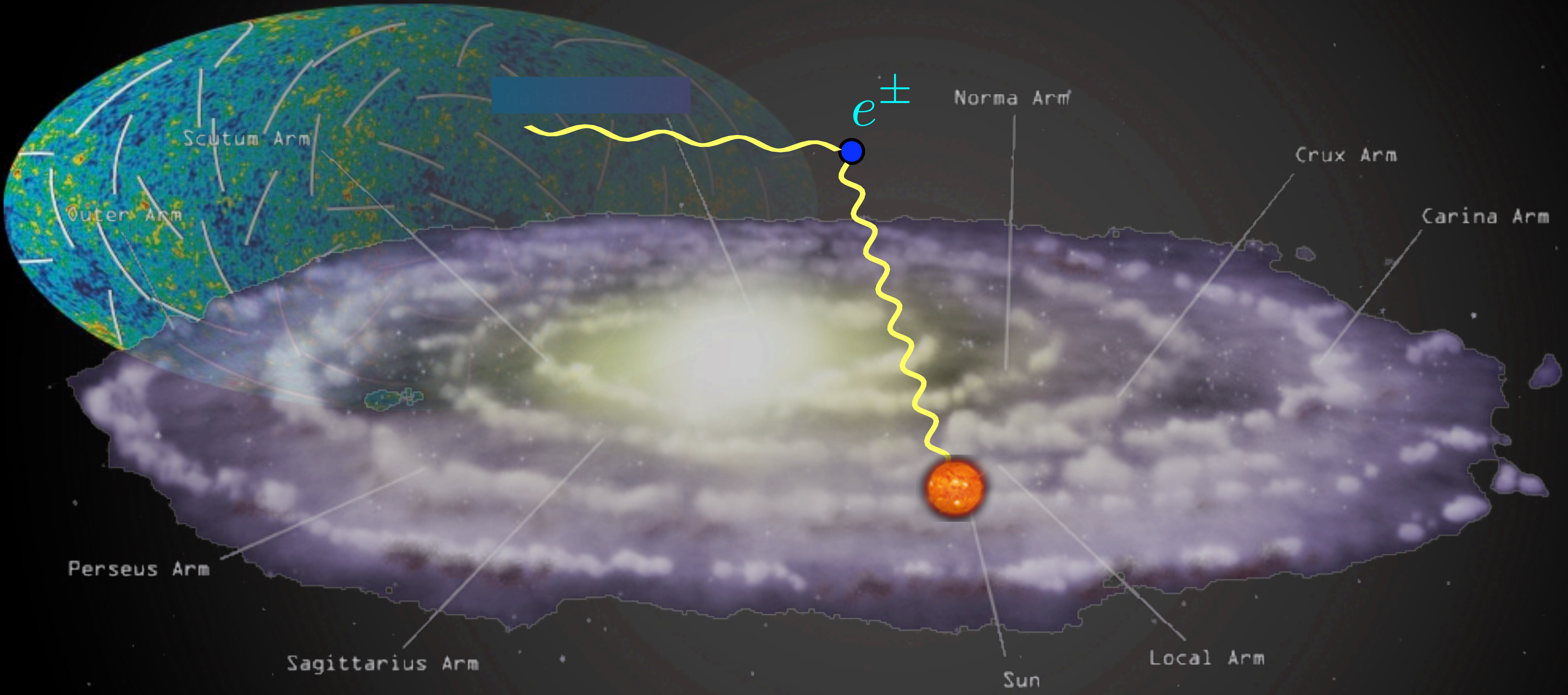


- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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

Indirect Detection

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

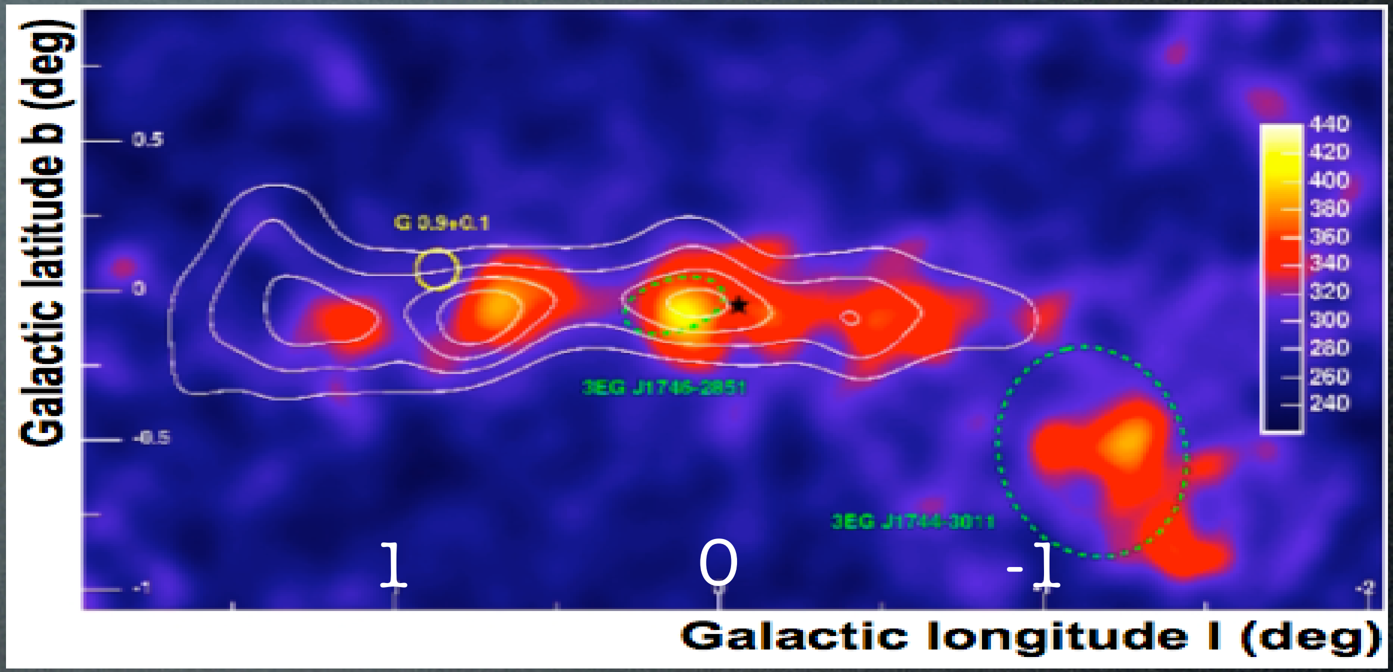


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

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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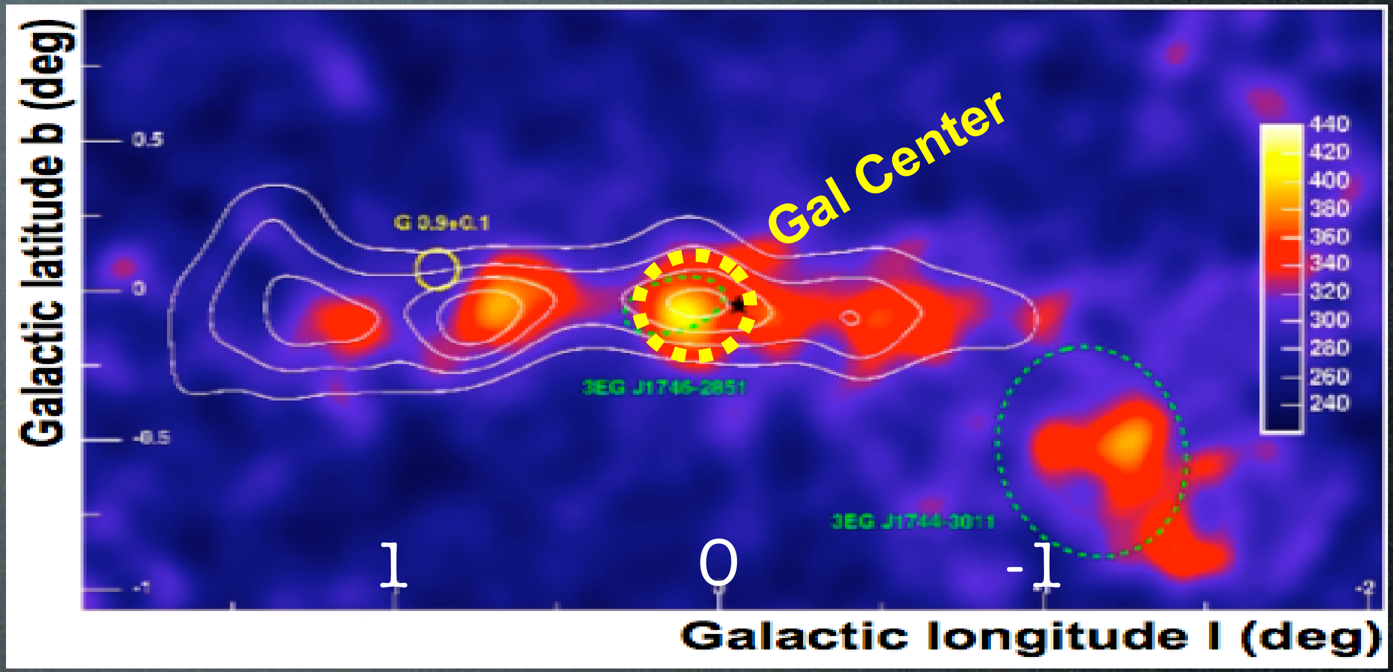

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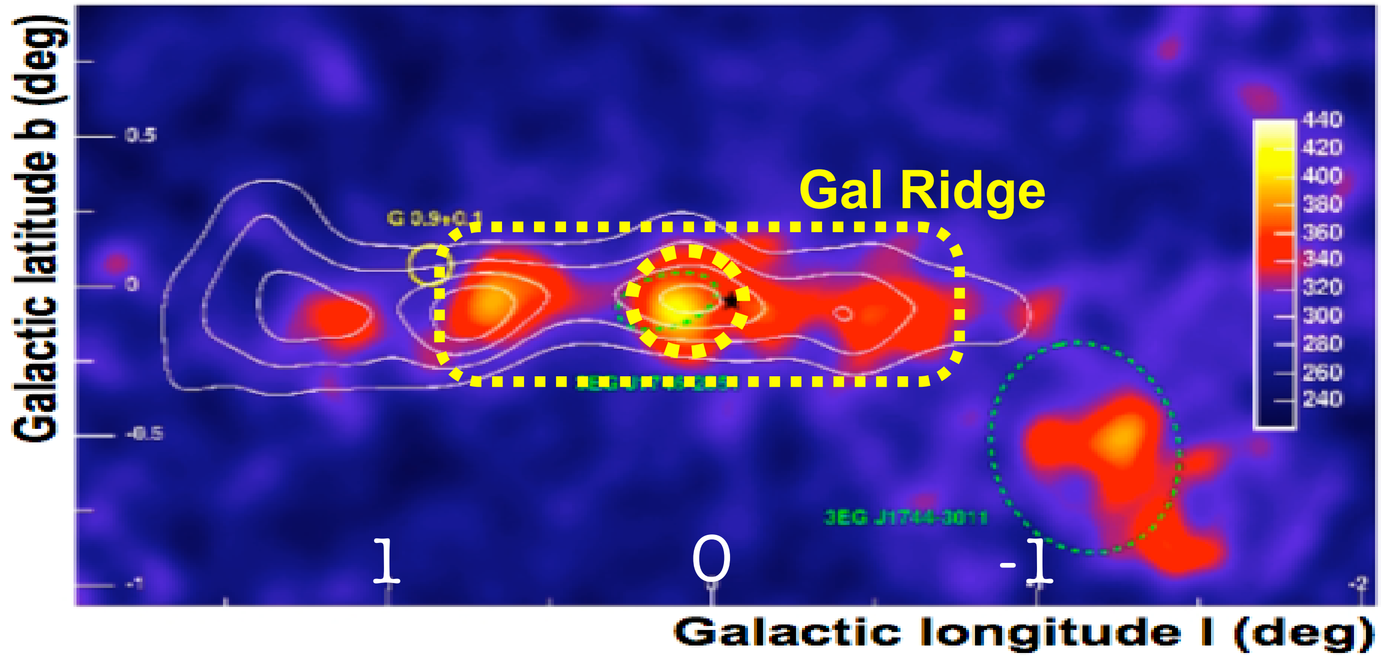

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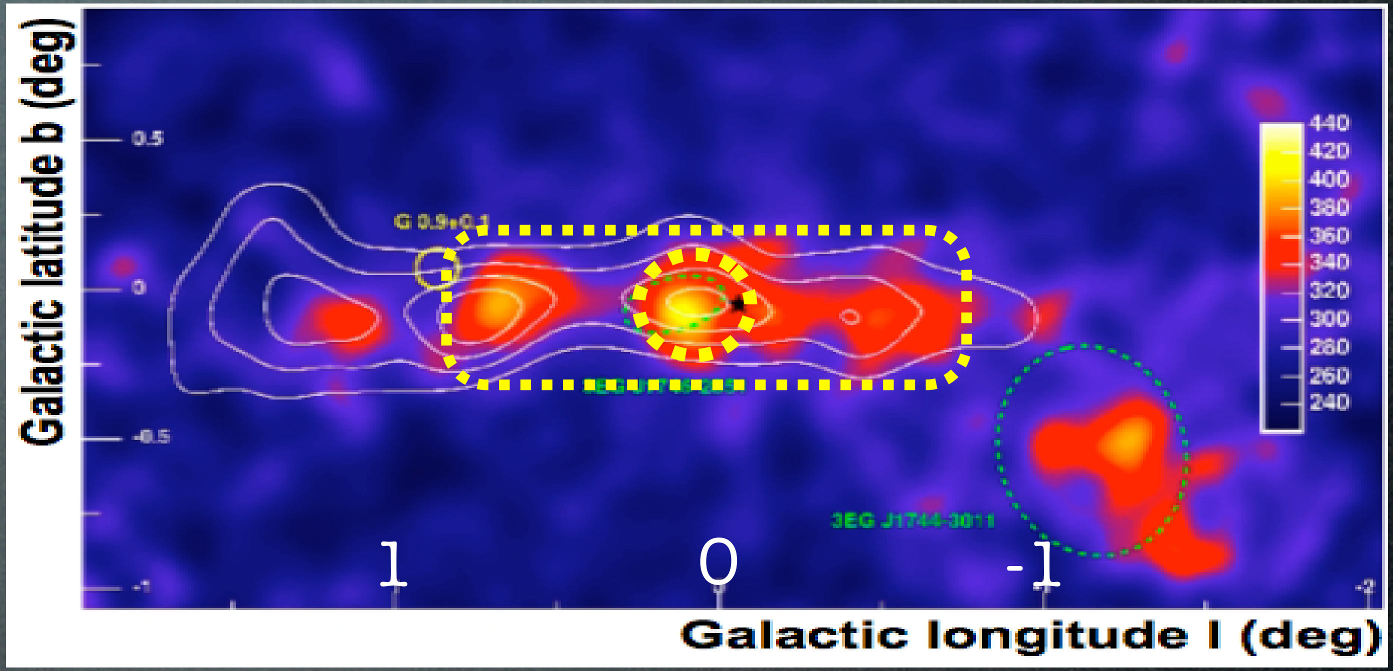
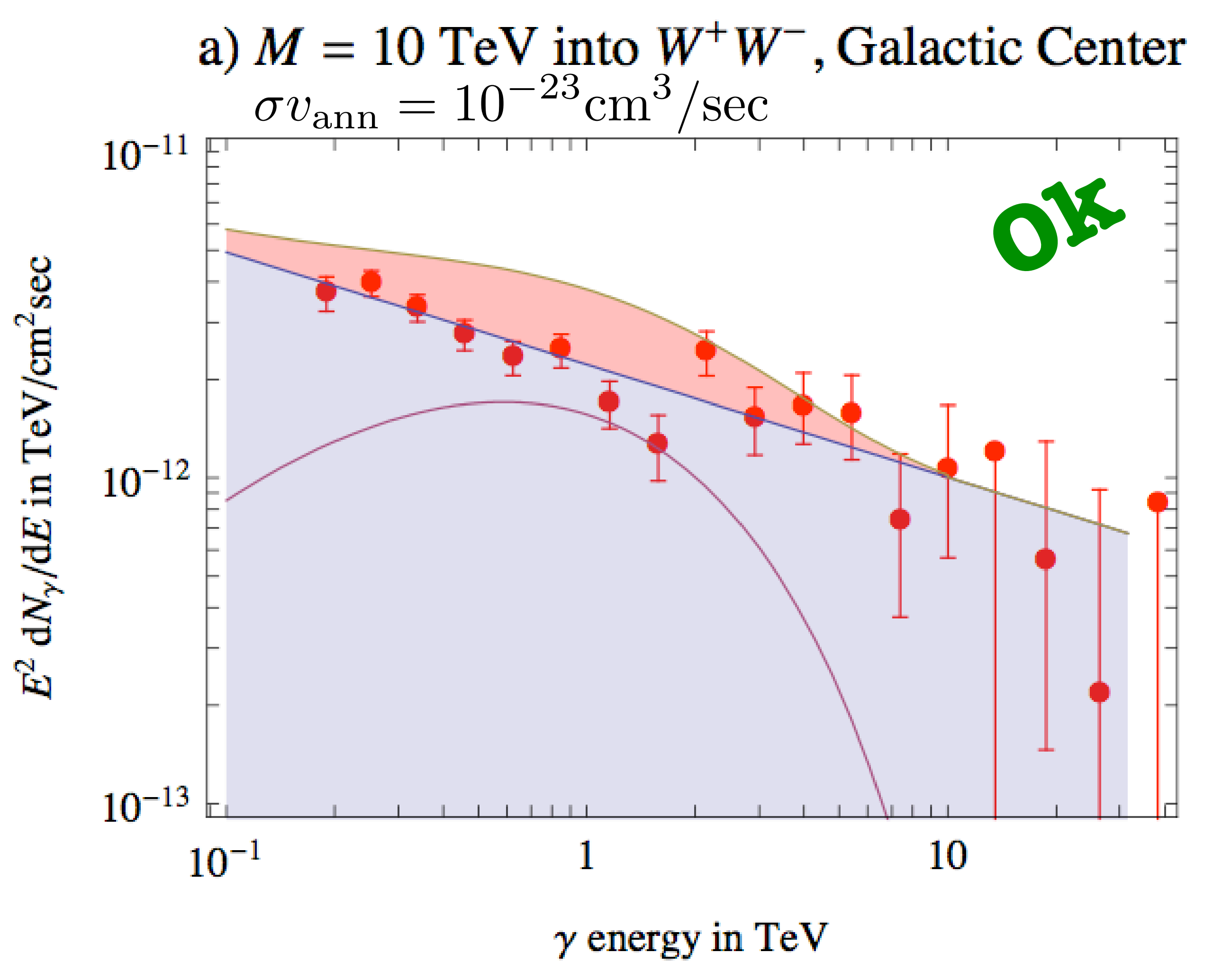


HESS coll.



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

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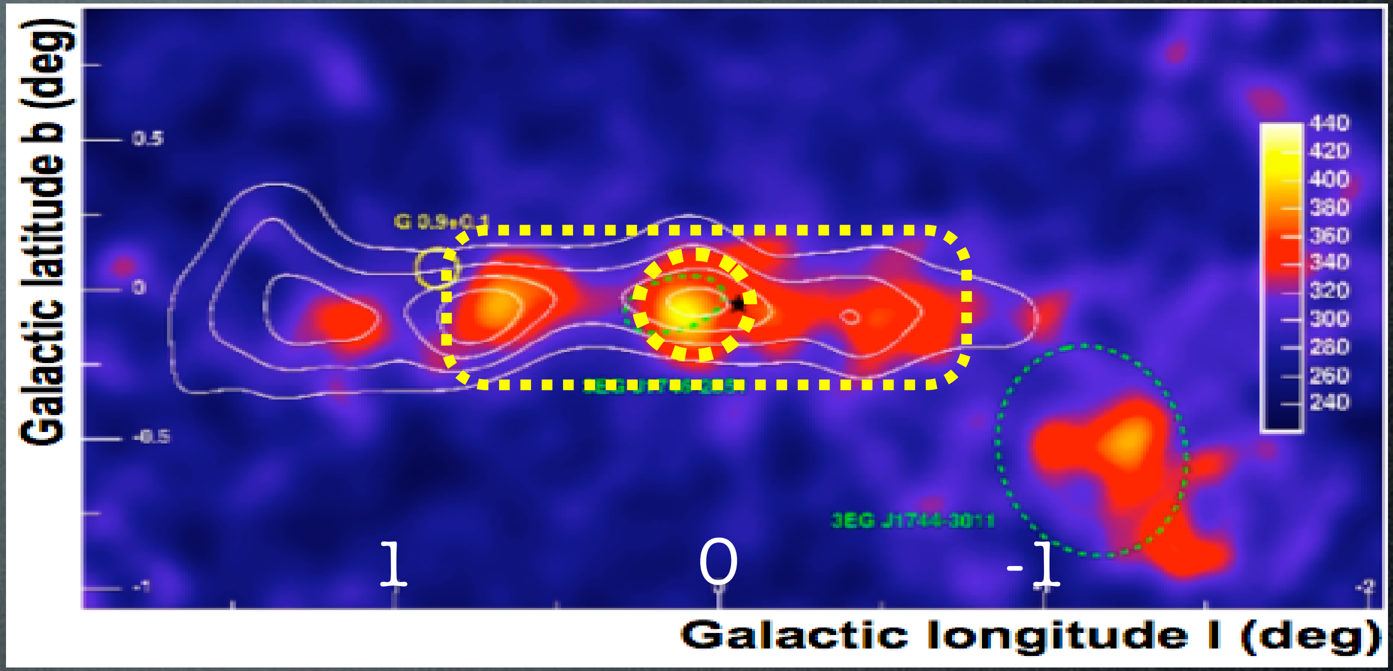
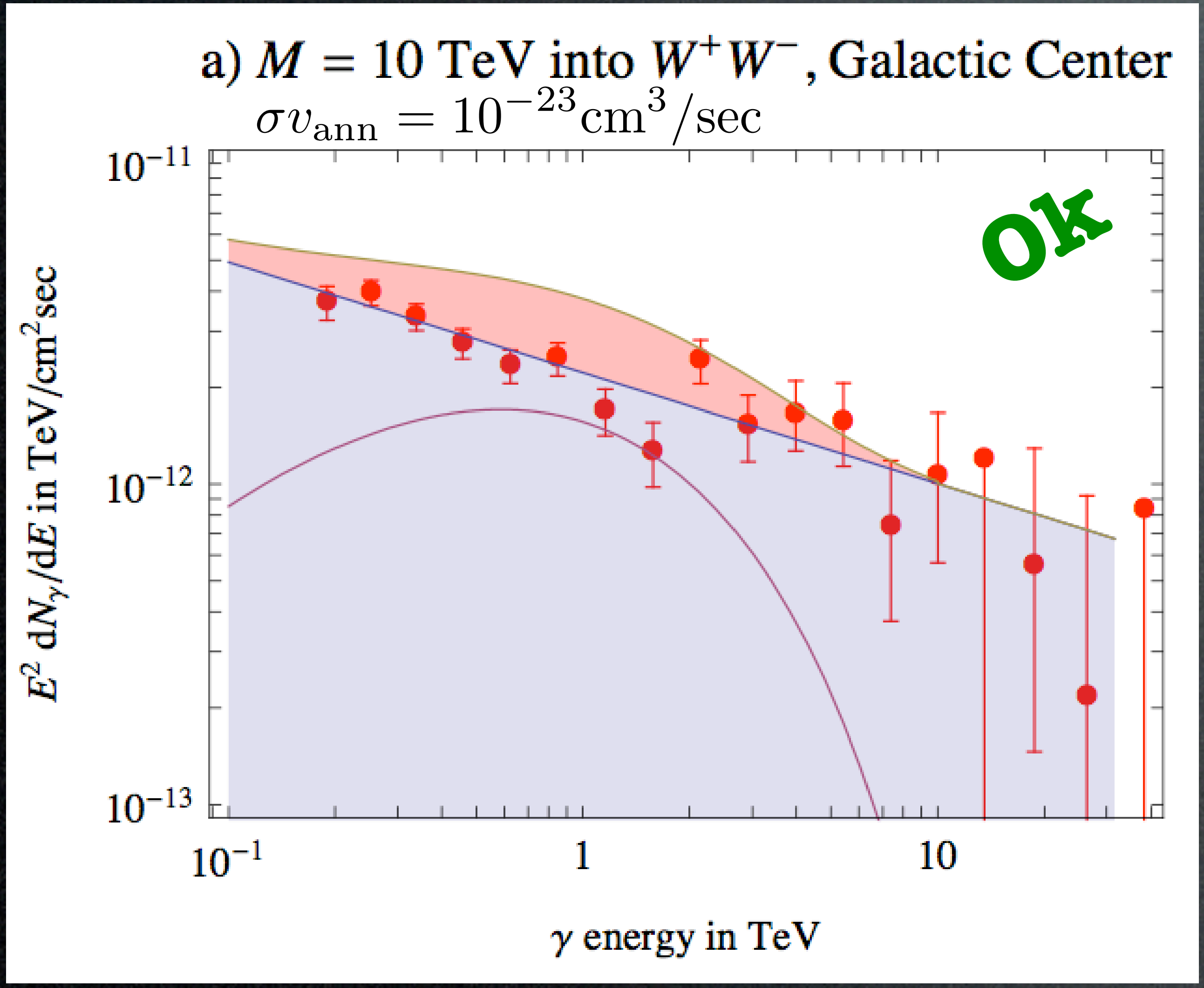


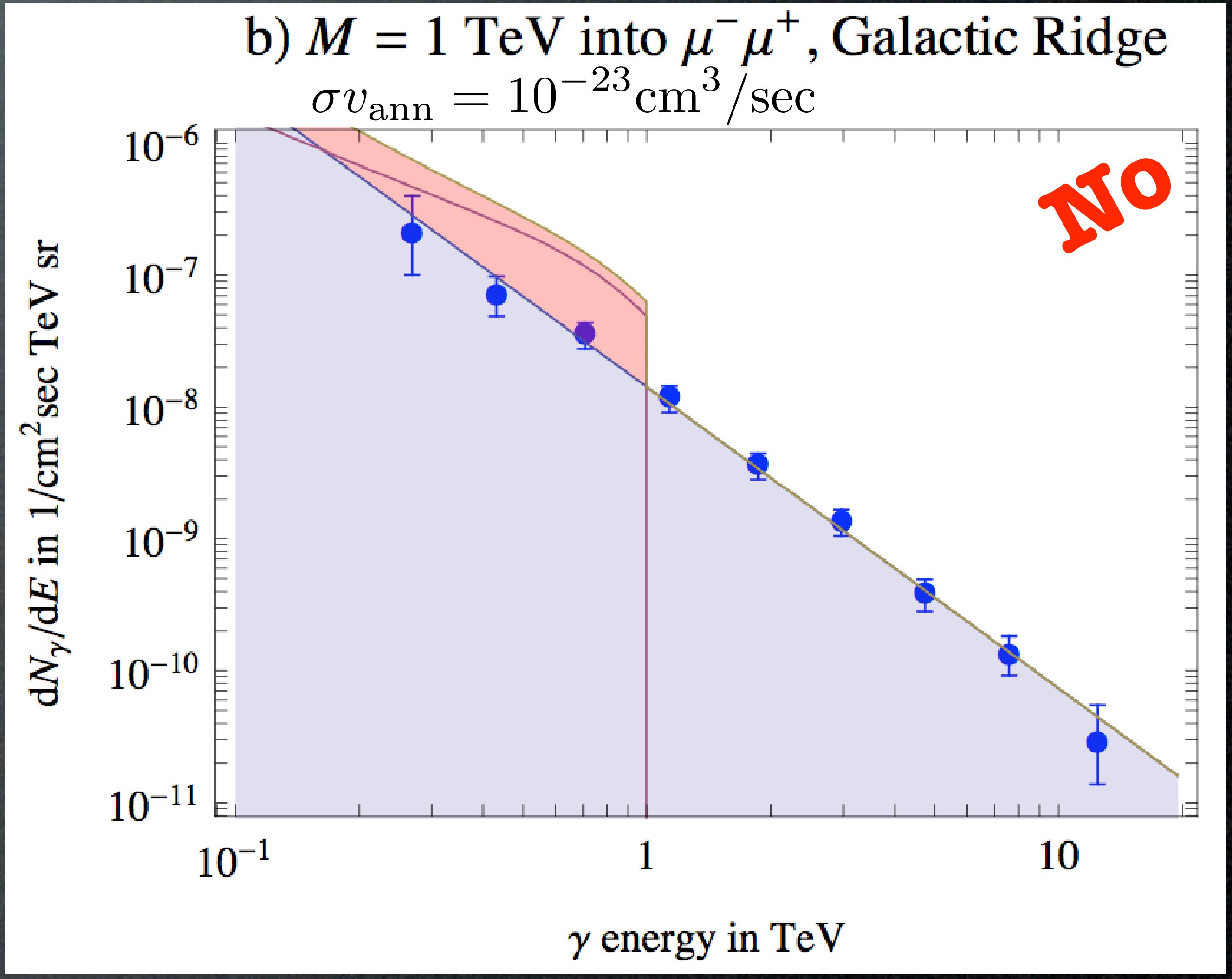
HESS coll.



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

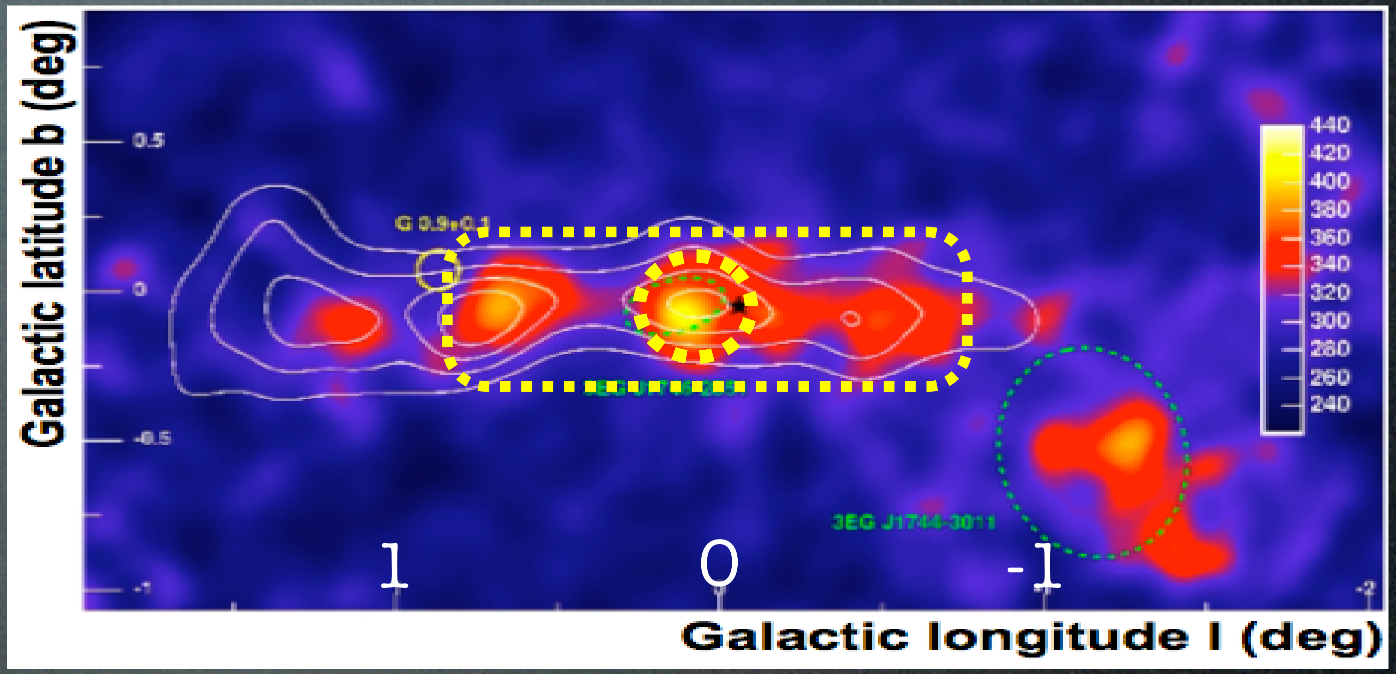
$\sigma v_{\rm ann} = 10^{-23}{\rm cm}^3/{\rm sec}$

Data: HESS coll., astro-ph/0603021

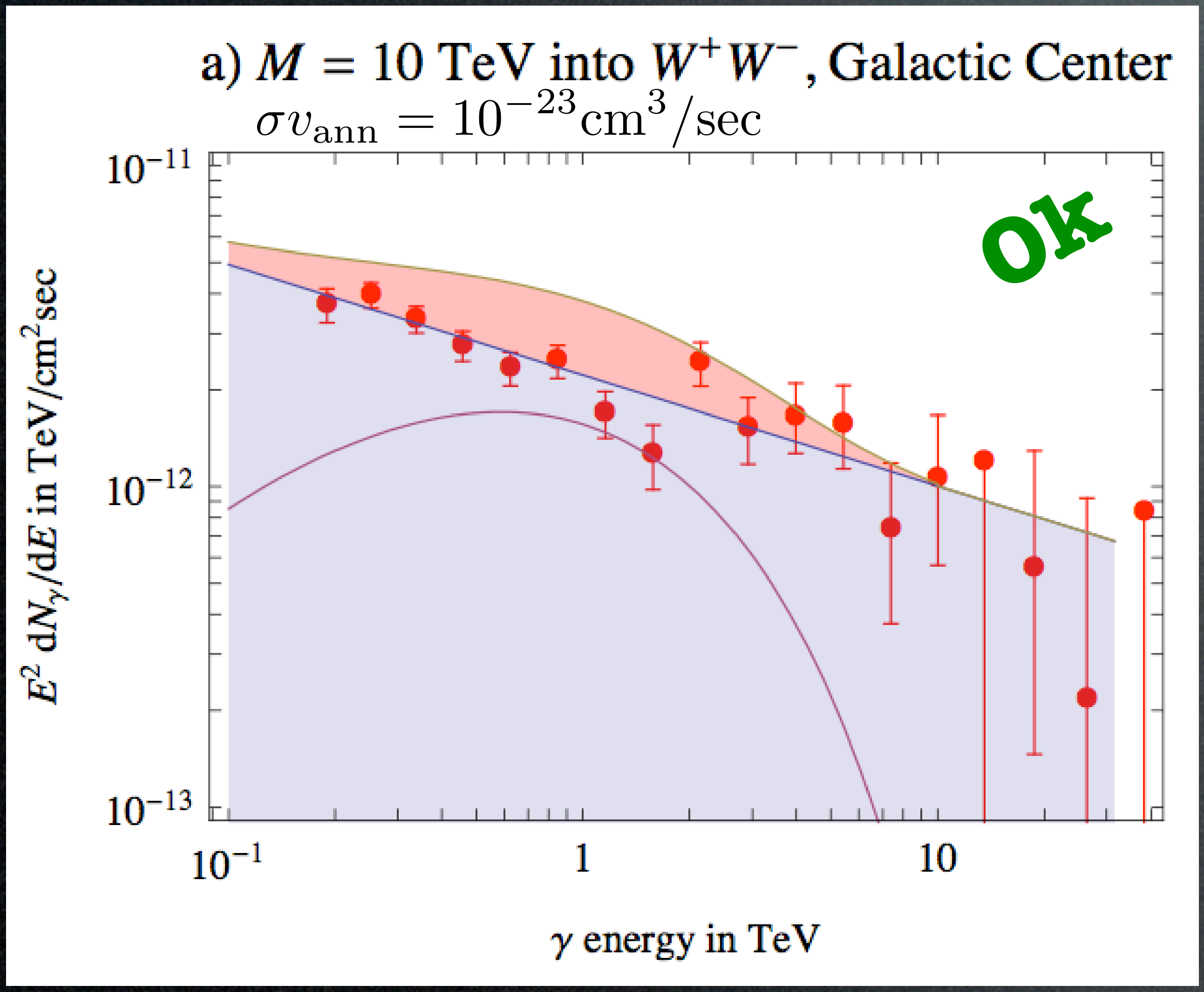
Gamma constraints

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.



HESS coll.

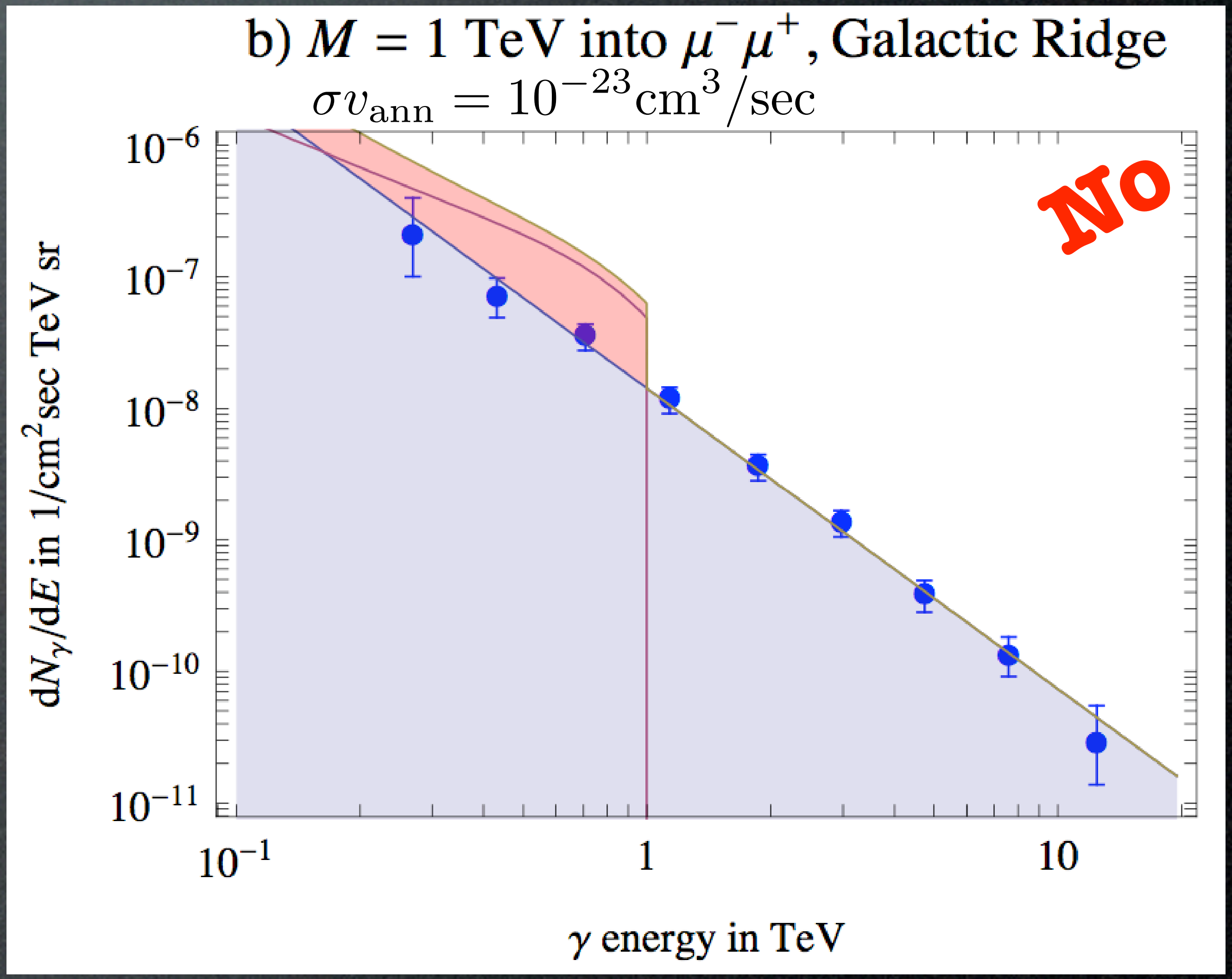


a) M = 10 TeV into W^+W^-, Galactic Center

$\sigma v_{\rm ann} = 10^{-23} \mathrm{cm}^3/\mathrm{sec}$

Ok

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



b) M = 1 TeV into $\mu^-\mu^+$, Galactic Ridge

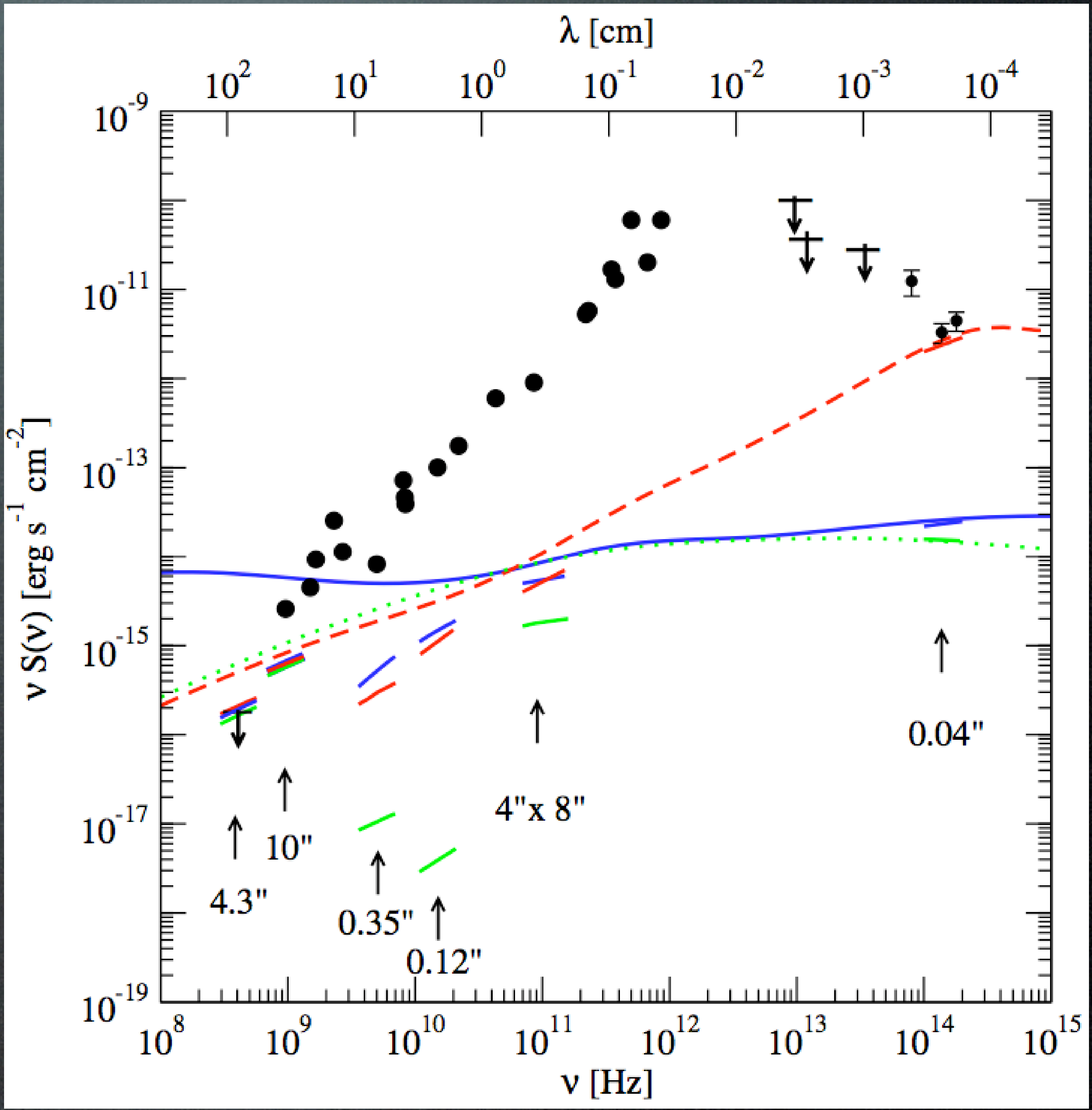
$\sigma v_{\rm ann} = 10^{-23} \mathrm{cm}^3/\mathrm{sec}$

No

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

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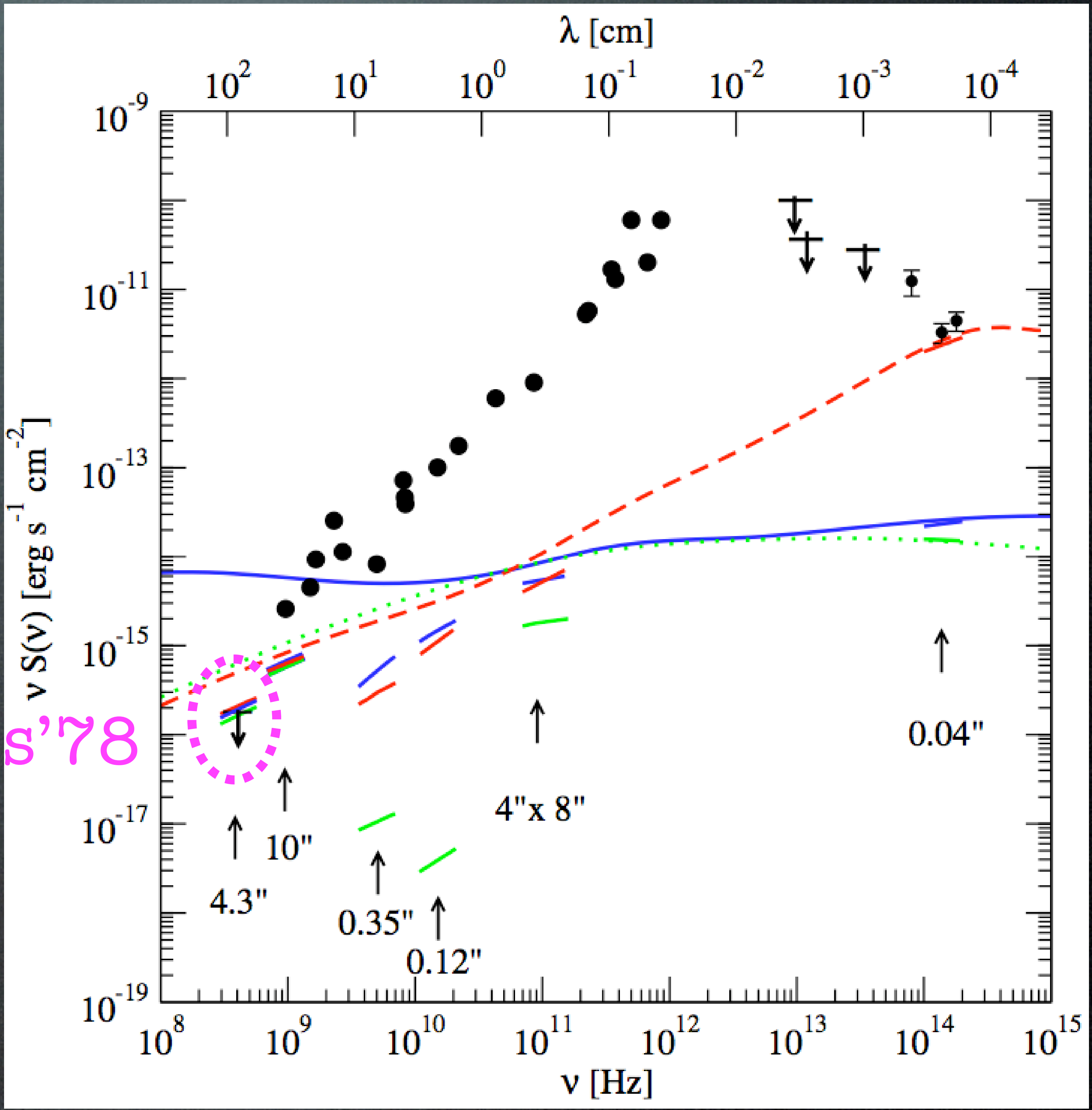
Davies 1978 upper bound at 408 MHz.



Davies'78

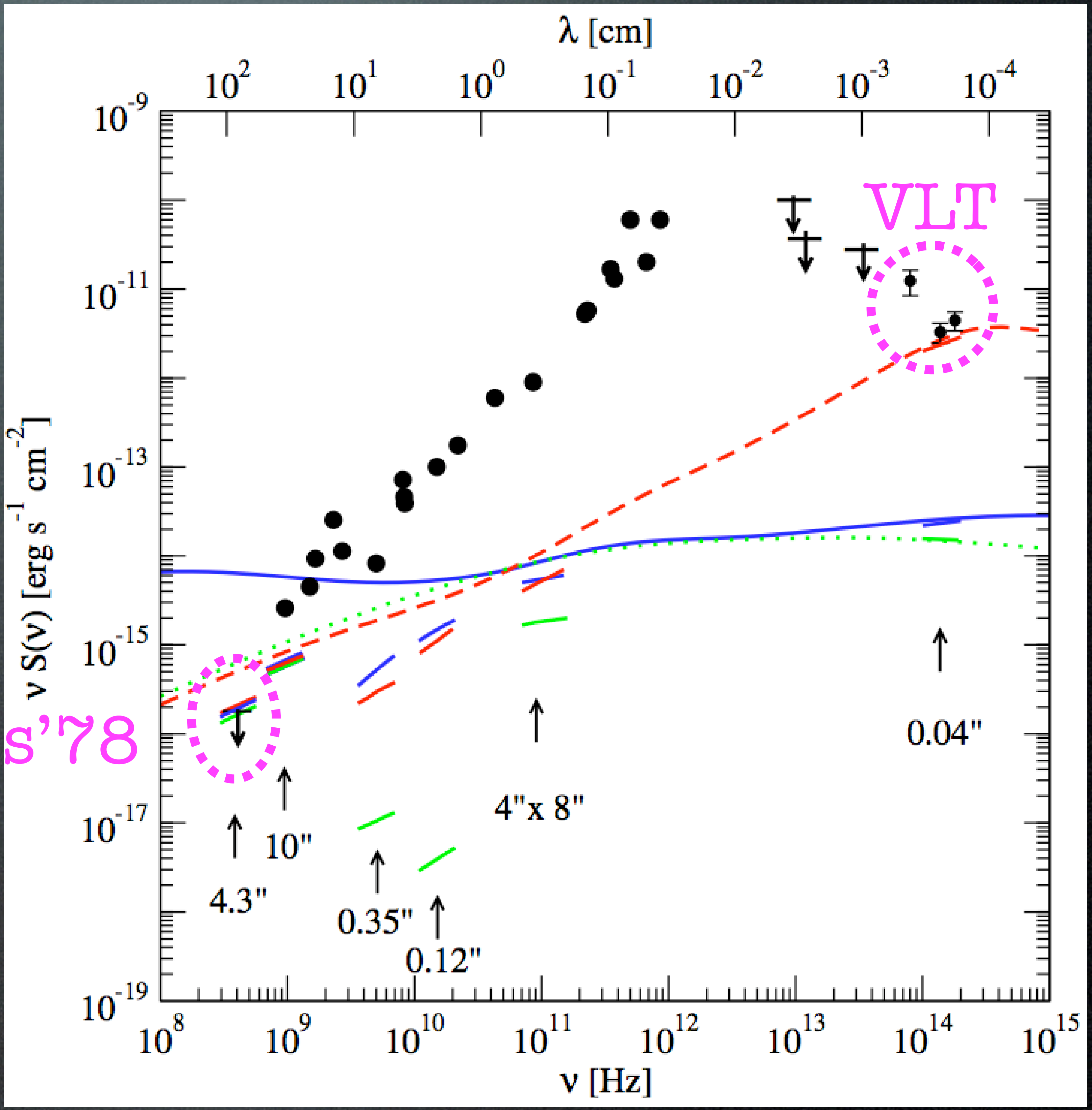
Regis, Ullio PRD 78 (2008)

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.

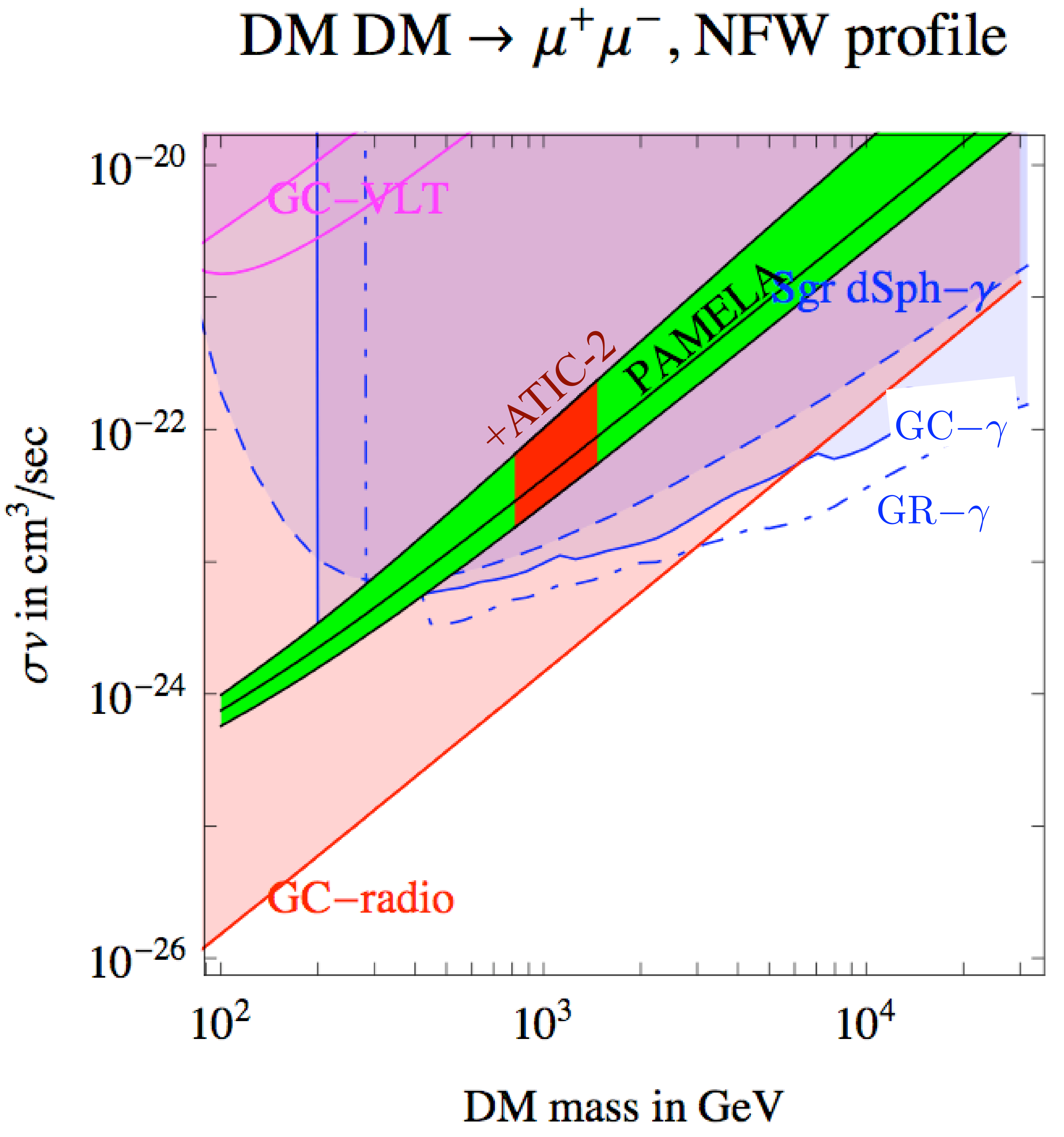
VLT 2003 emission at 10^{14} Hz.



Regis, Ullio PRD 78 (2008)

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

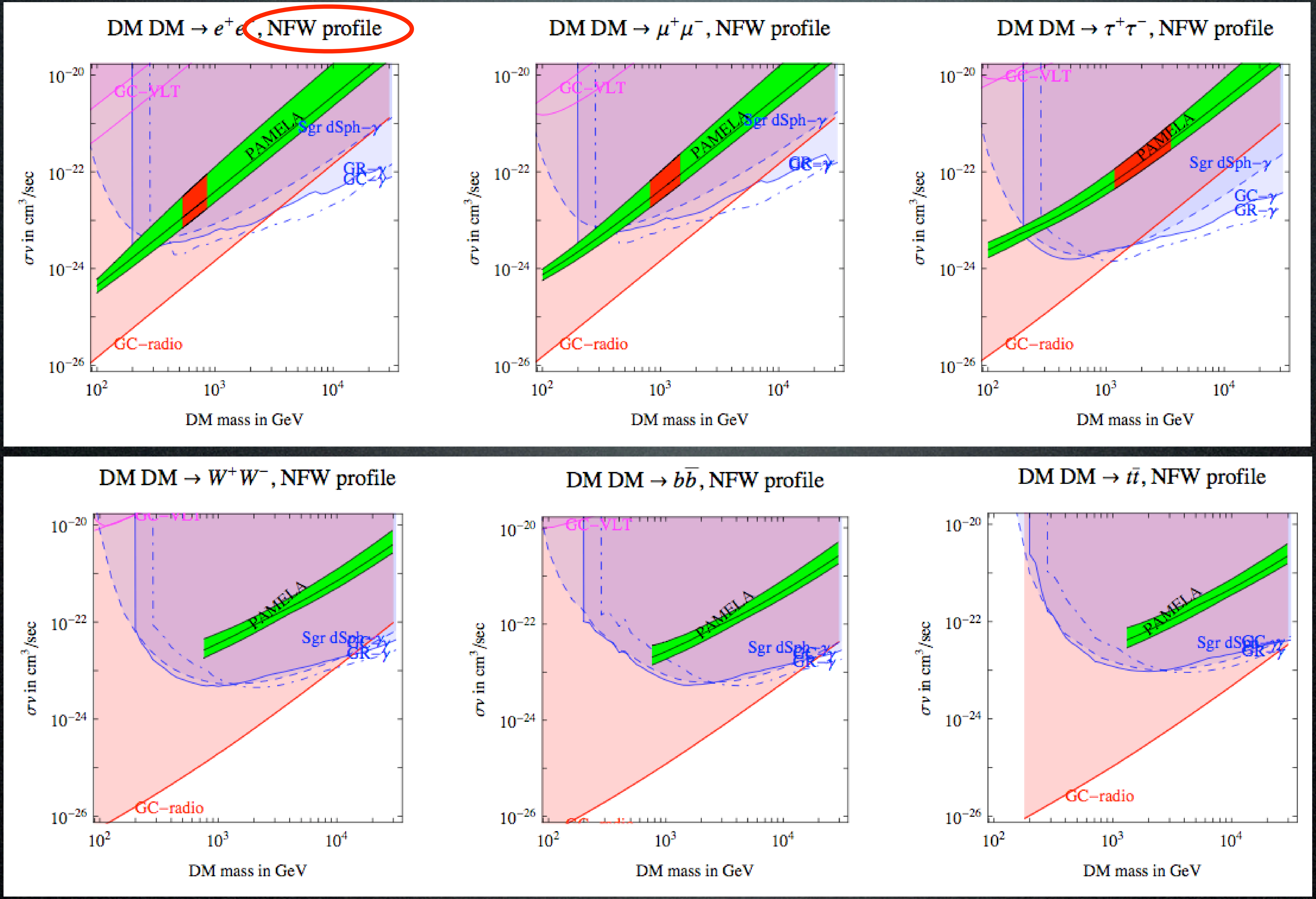
Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

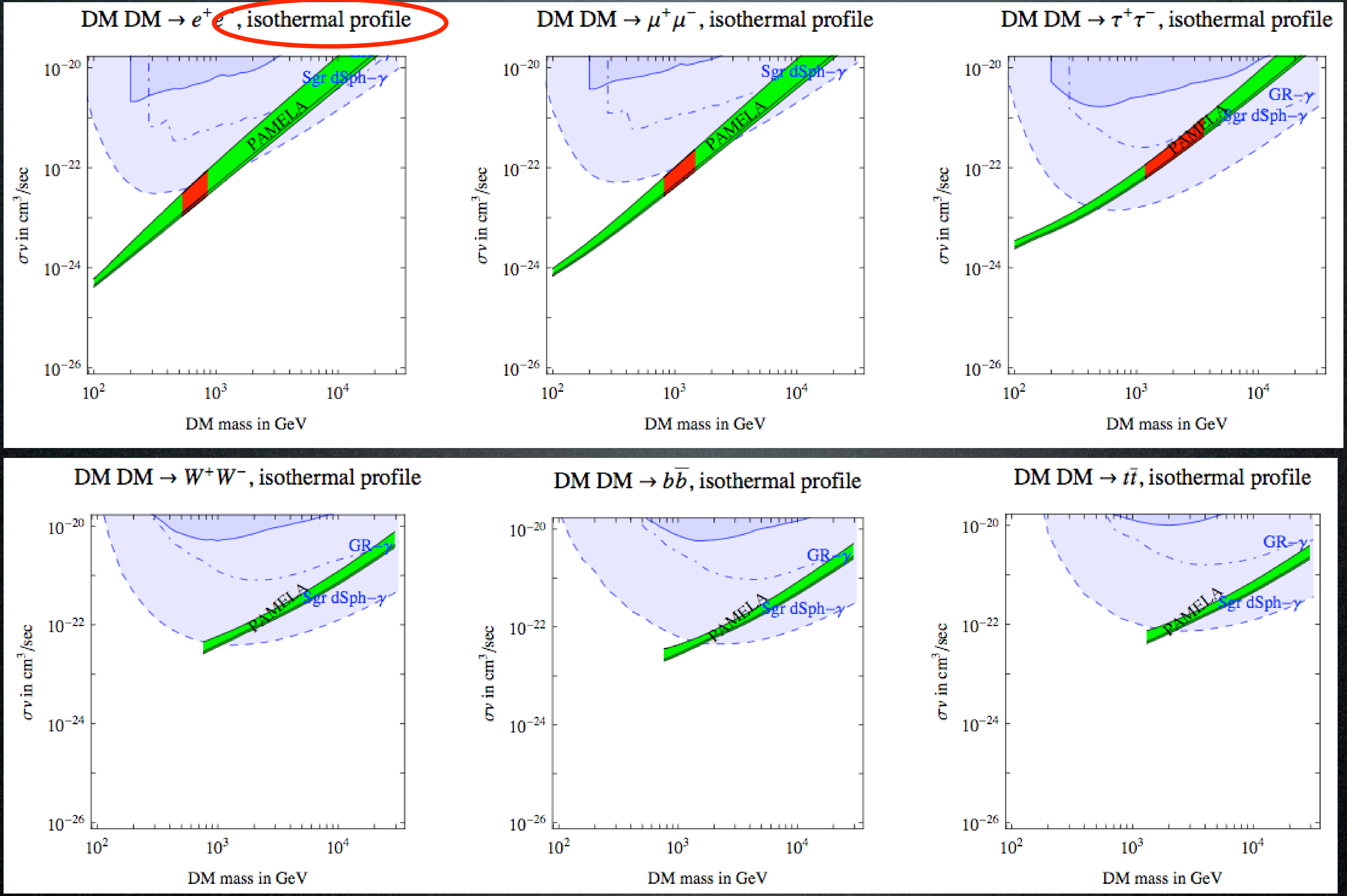
The PAMELA and ATIC regions are in conflict with gamma constraints, unless...

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

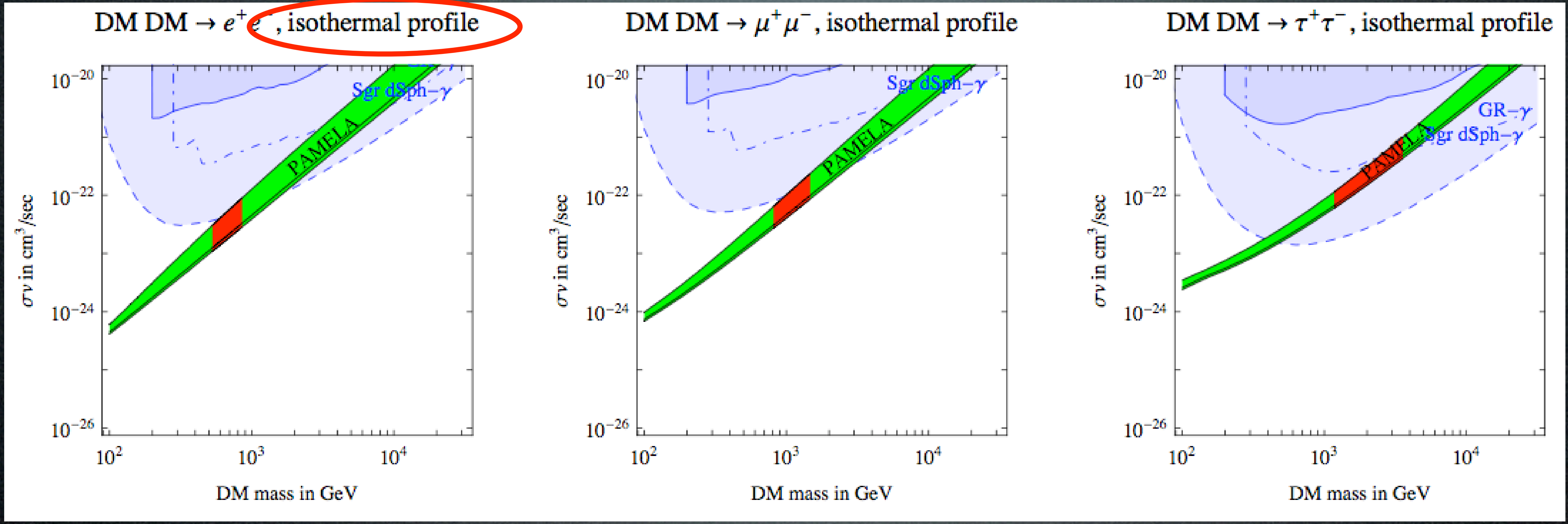
Gamma constraints

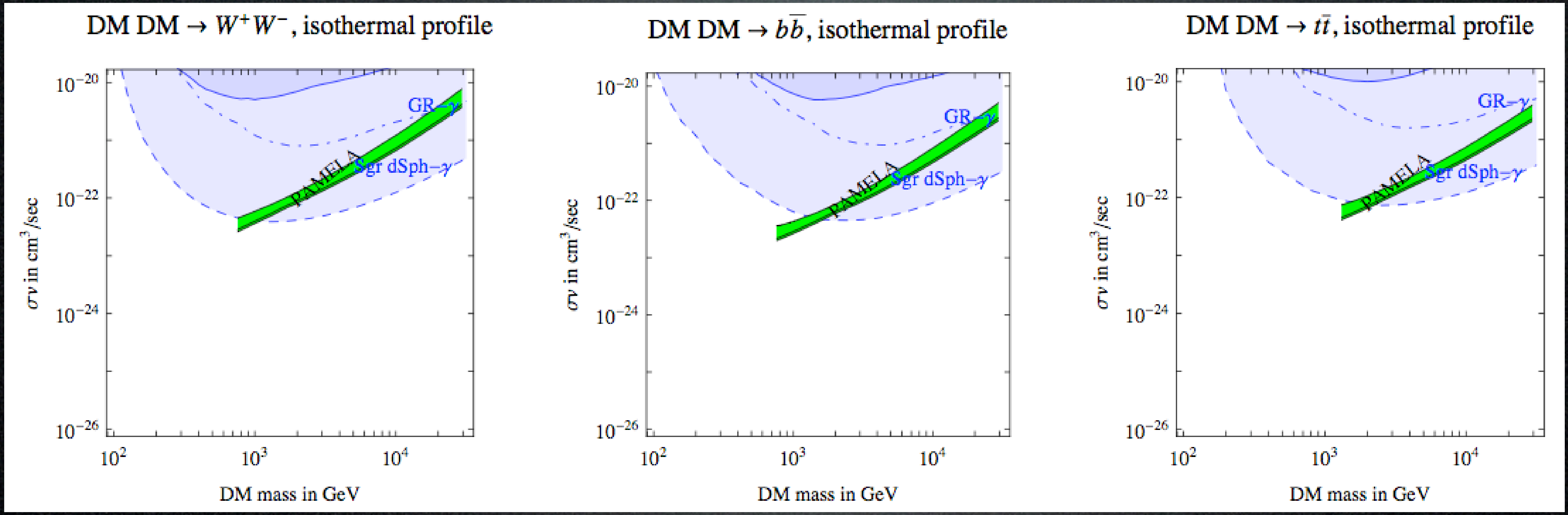


...not-too-steep profile needed.

Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints





Bertone, Cirelli, Strumia, Taoso 0811.3744

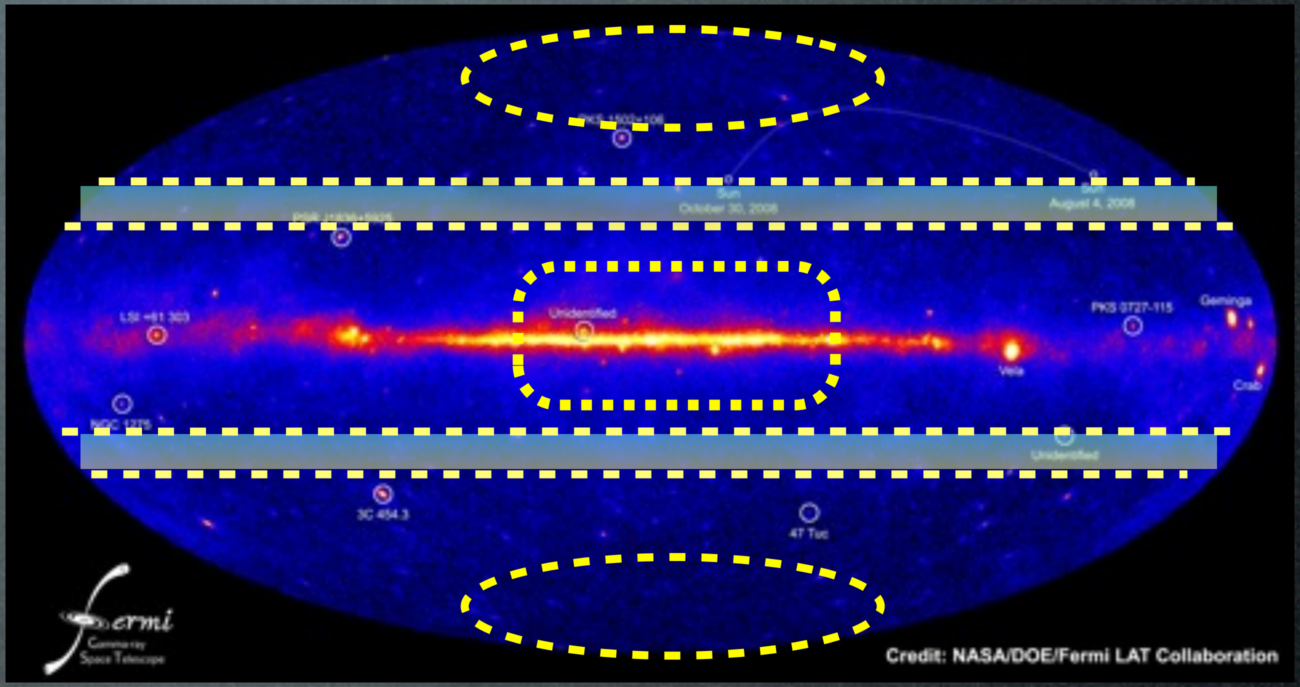
...not-too-steep profile needed.

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).

Gamma constraints

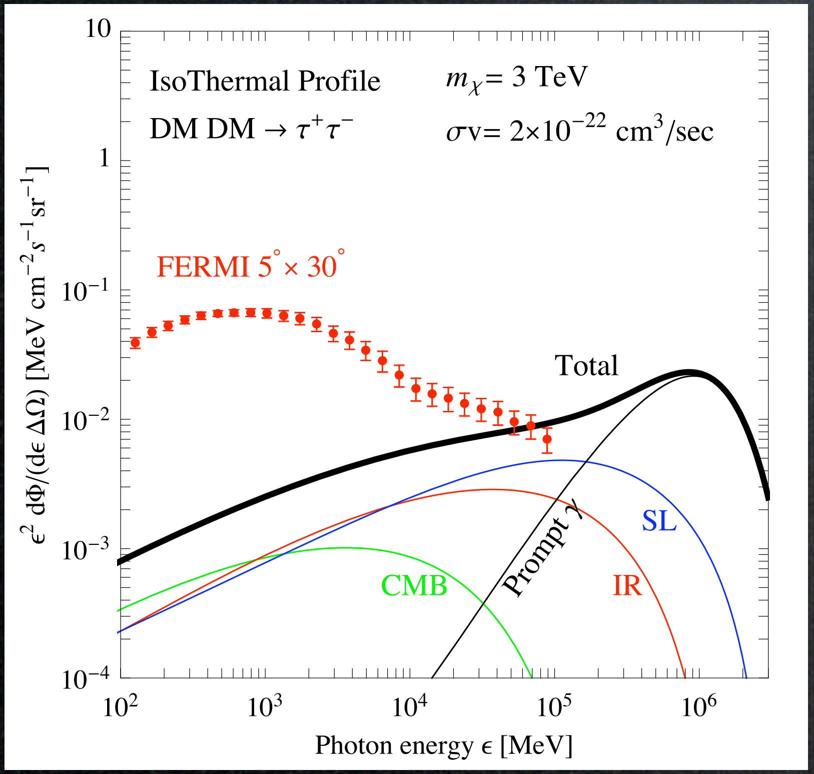
FERMI has measured diffuse γ-ray emission. The DM signal must not excede that.

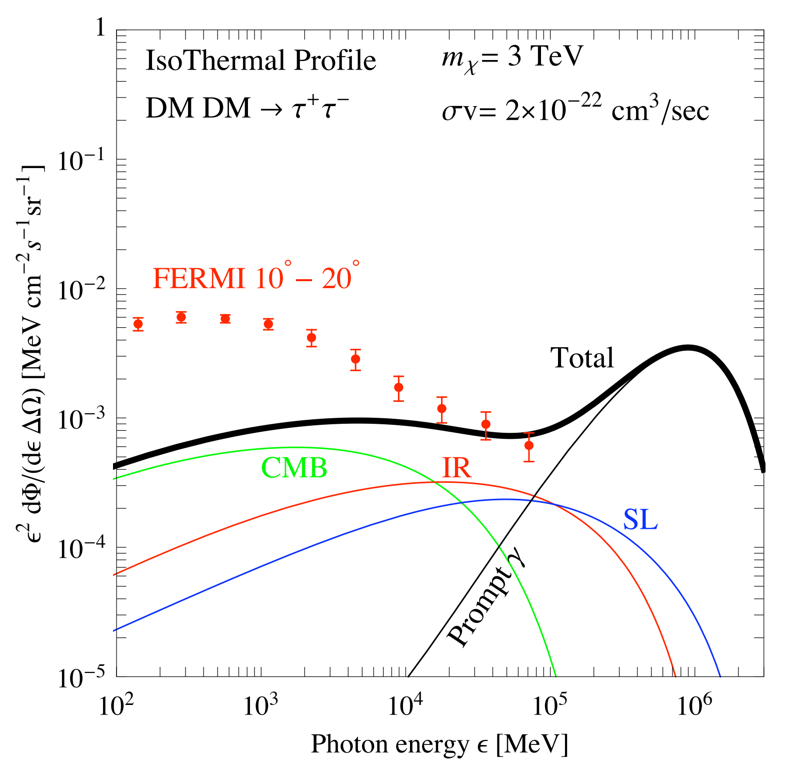


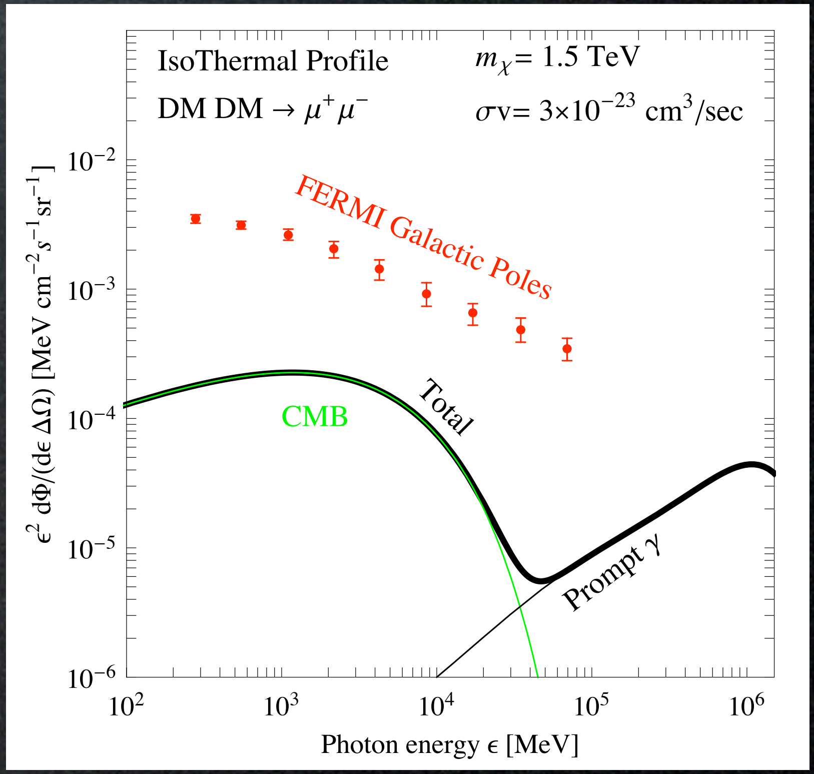
Credit: NASA/DOE/Fermi LAT Collaboration

FERMI coll.

Data: FERMI coll., several talks and papers

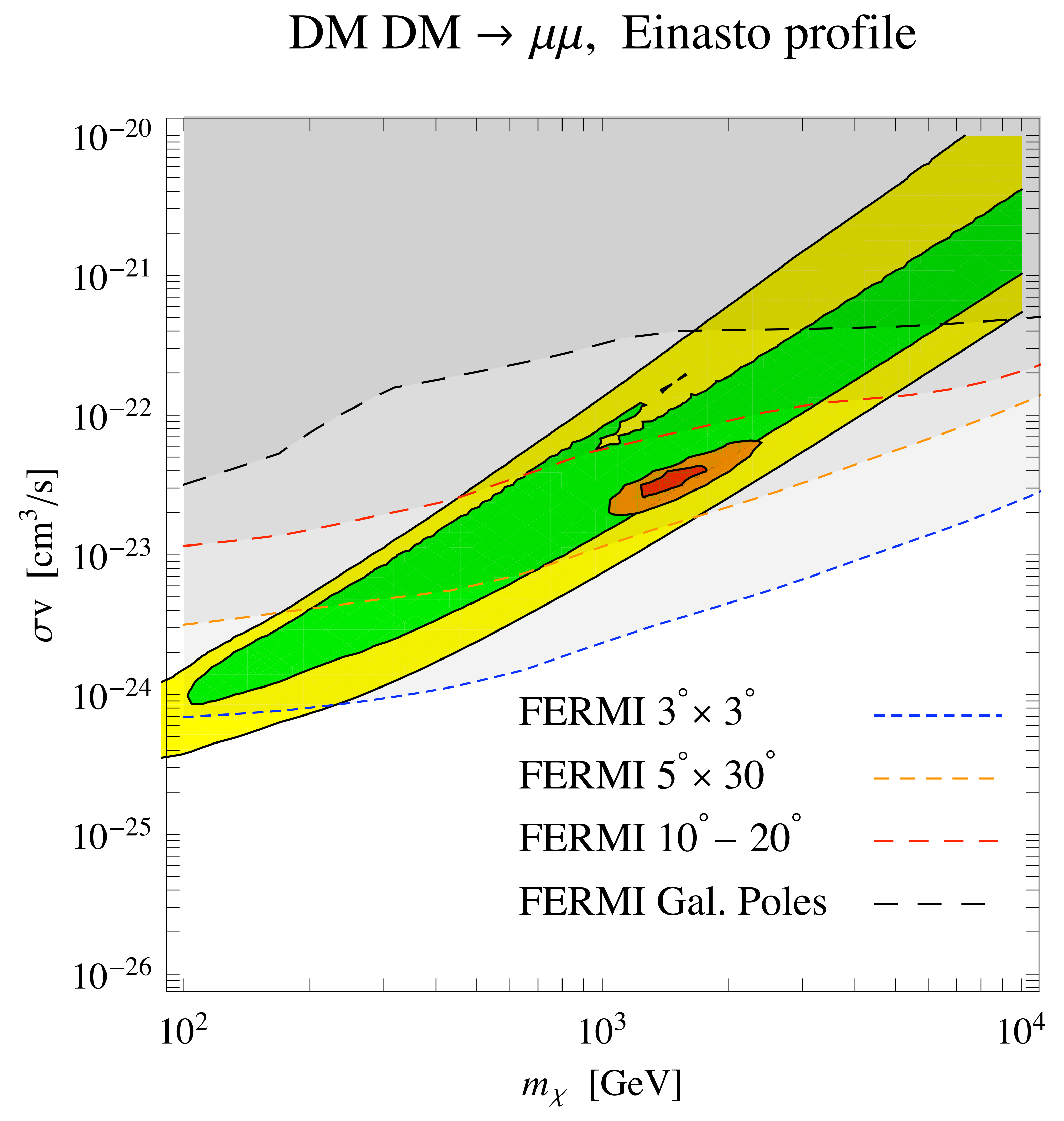






Cirelli, Panci, Serpico 0912.0663

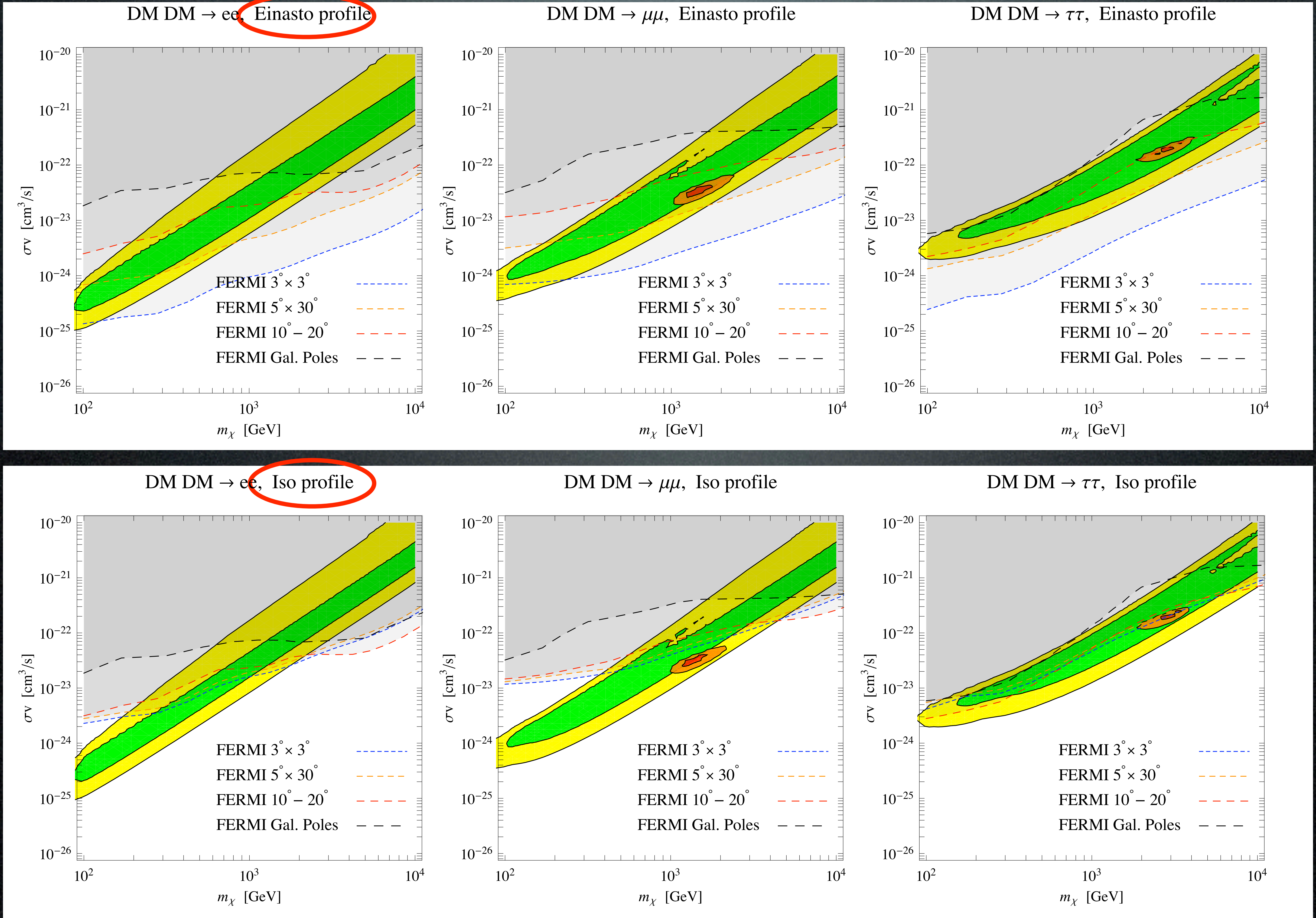
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

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

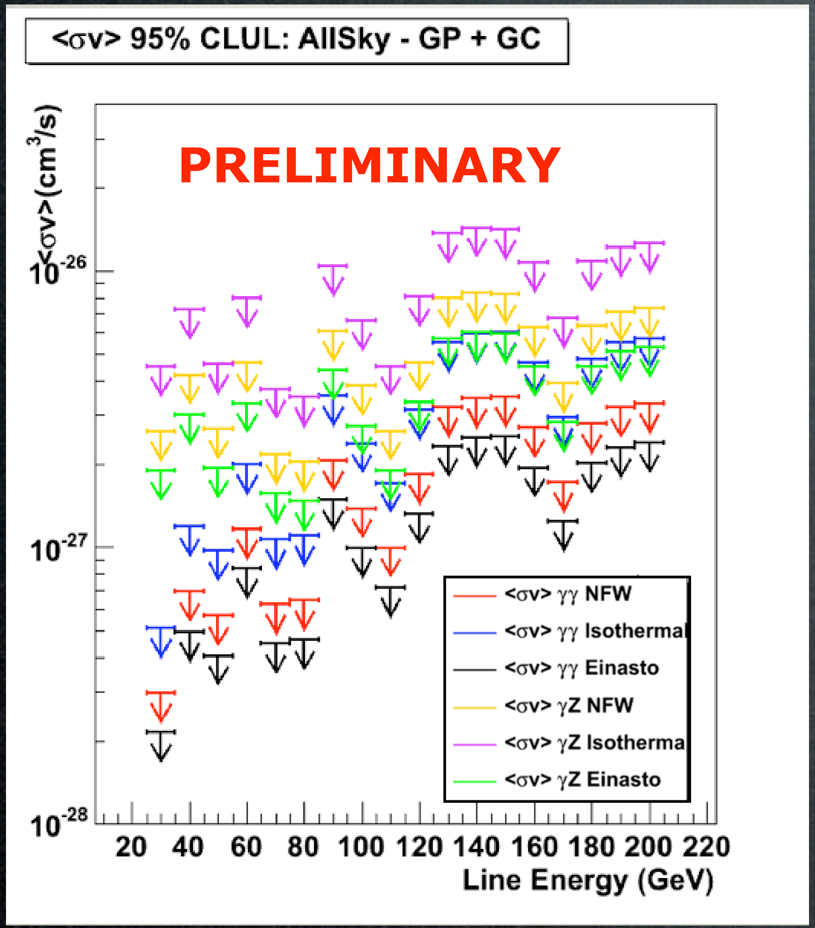
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

More FERMI γ constraints

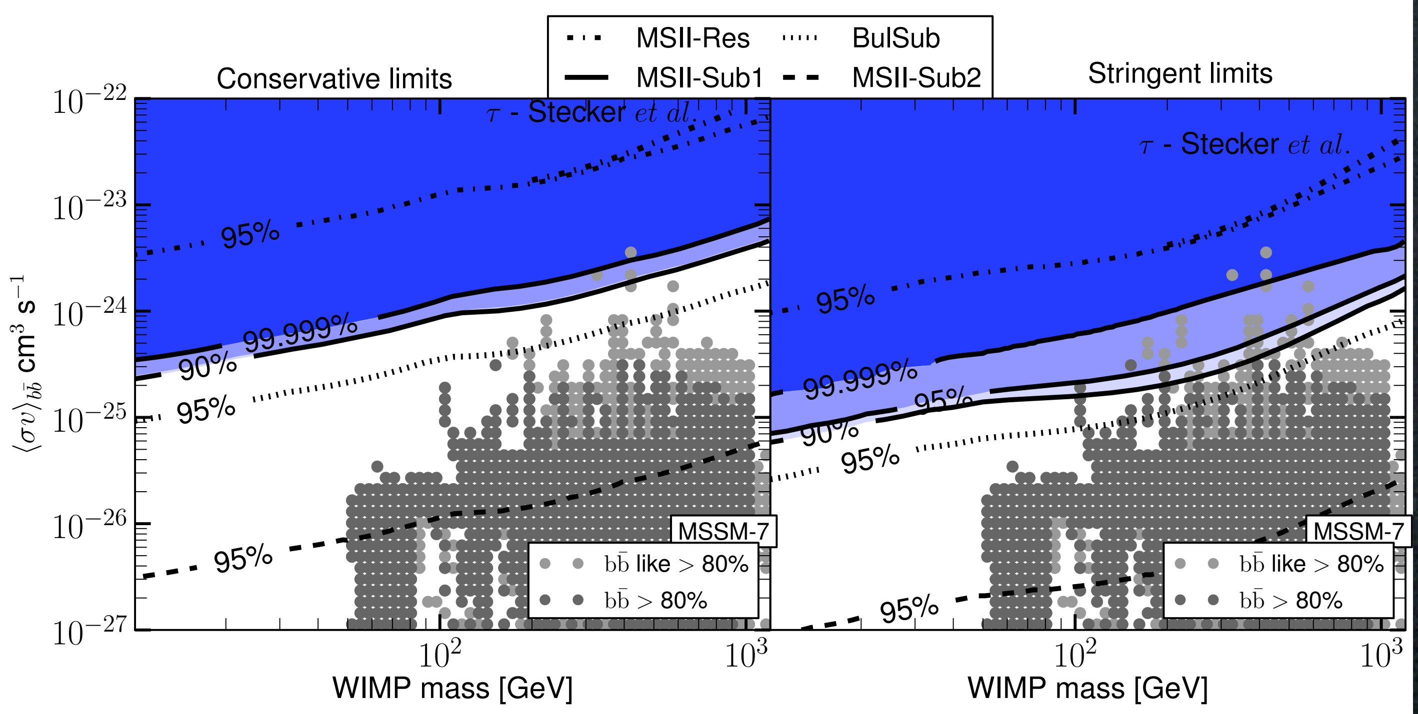
Gamma lines



FERMI Coll. 1001.4836

model dependent constraints, can be stringent

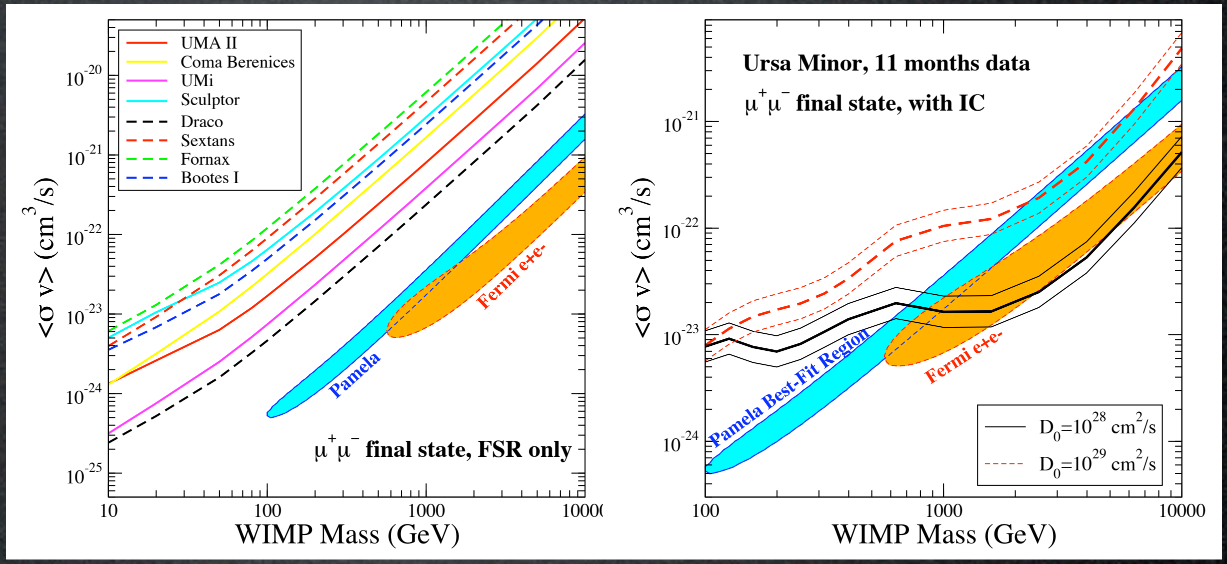
Isotropic gamma background



Conrad, Gustafsson, Sellerholm, Zaharijas, FERMI coll. JCAP 04 (2010) 014

bounds are typically very sensitive to the assumptions on the cosmological evolution of DM halos

dSph satellites



Competitive constraints (if ICS included)

Cohen-Tanugi, Farnier, Jeltema, Nuss, Profumo, 1001.4531

Gamma **fits**?

What if a signal of DM is *already* hidden in Fermi diffuse γ data?

10° 30°

$-15^\circ <$ $< 15^\circ$

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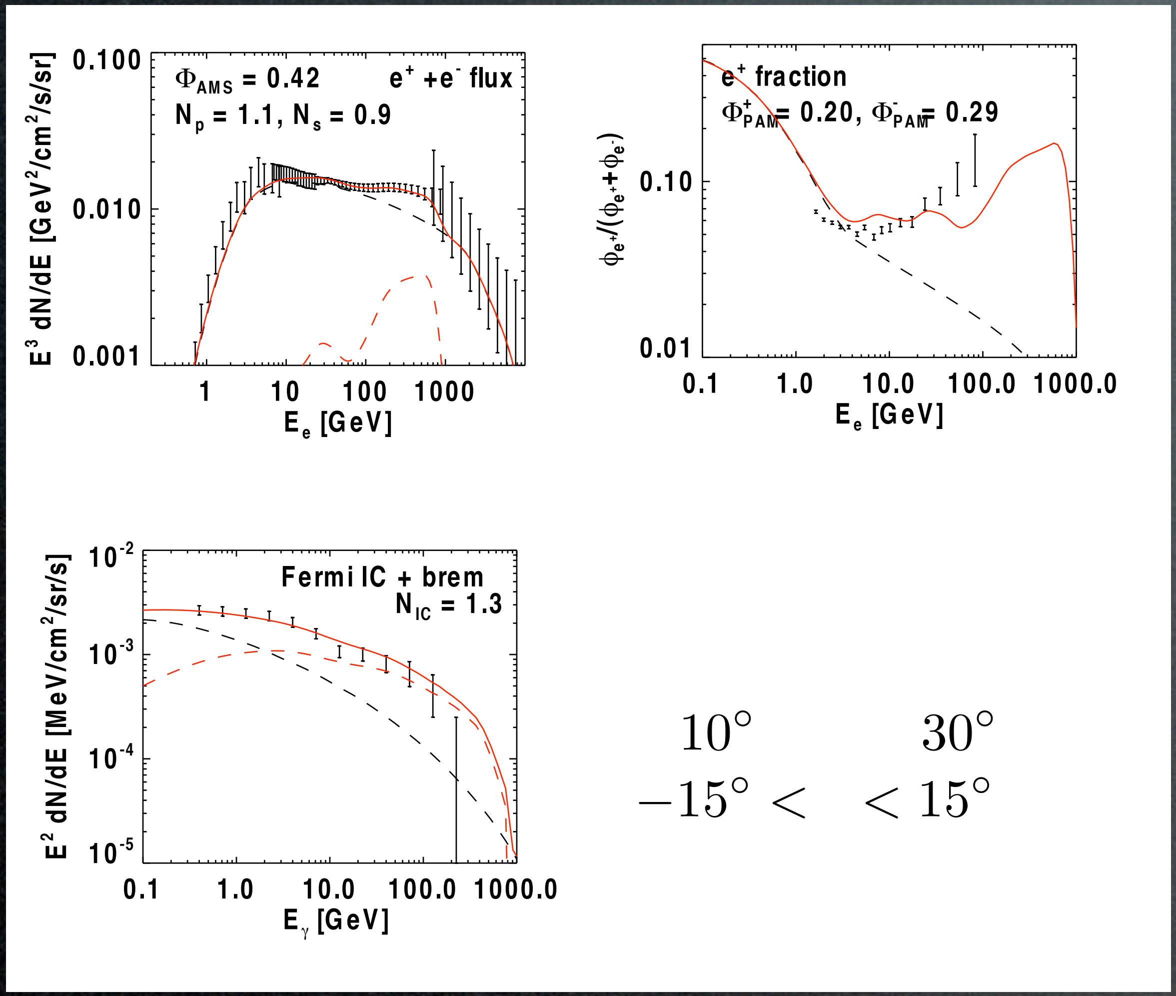
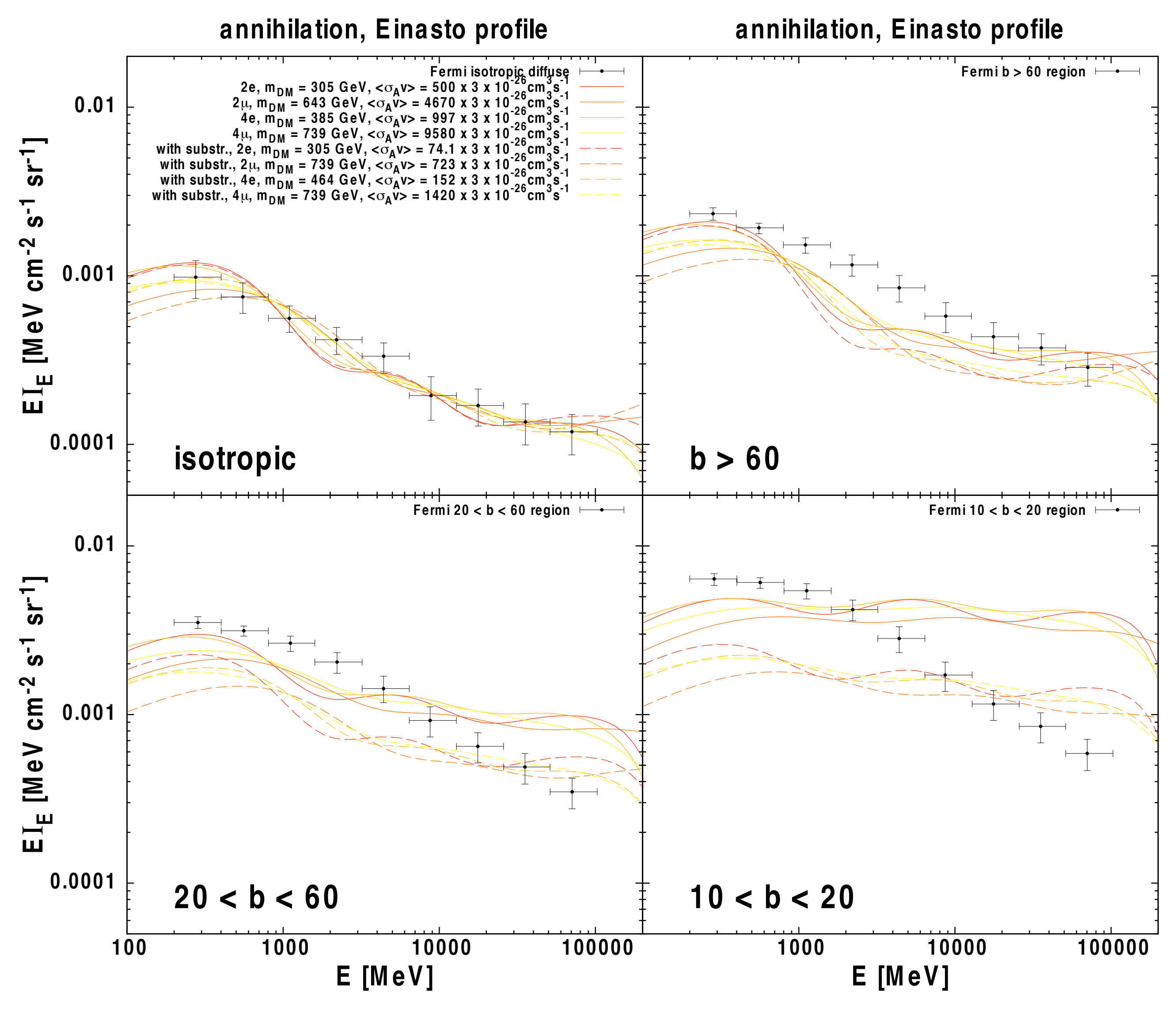


$10^\circ \qquad 30^\circ$

$-15^\circ < \quad < 15^\circ$

Lin, Finkbeiner, Dobler 1004.0989



Hutsi, Hektor, Raidal 1004.2036

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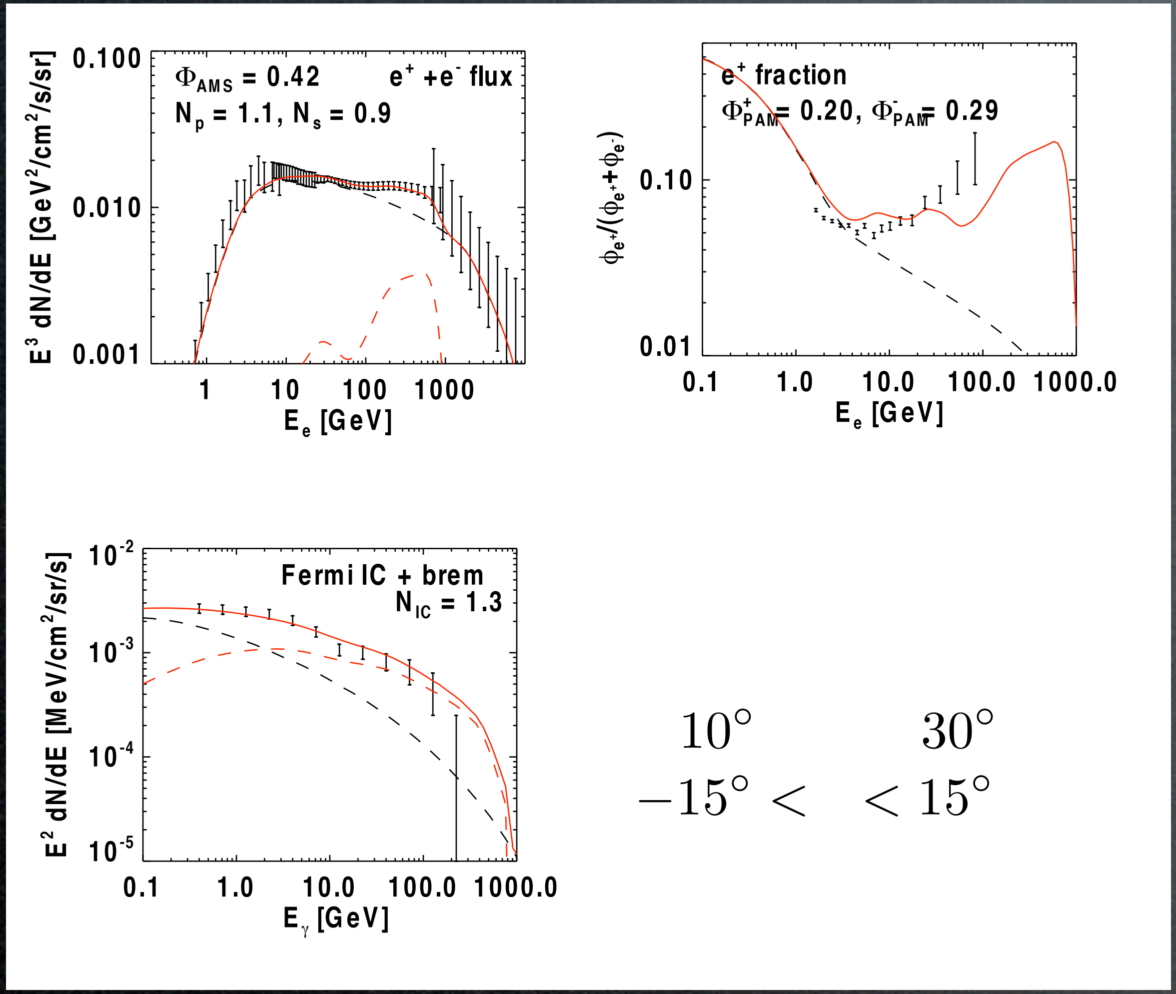
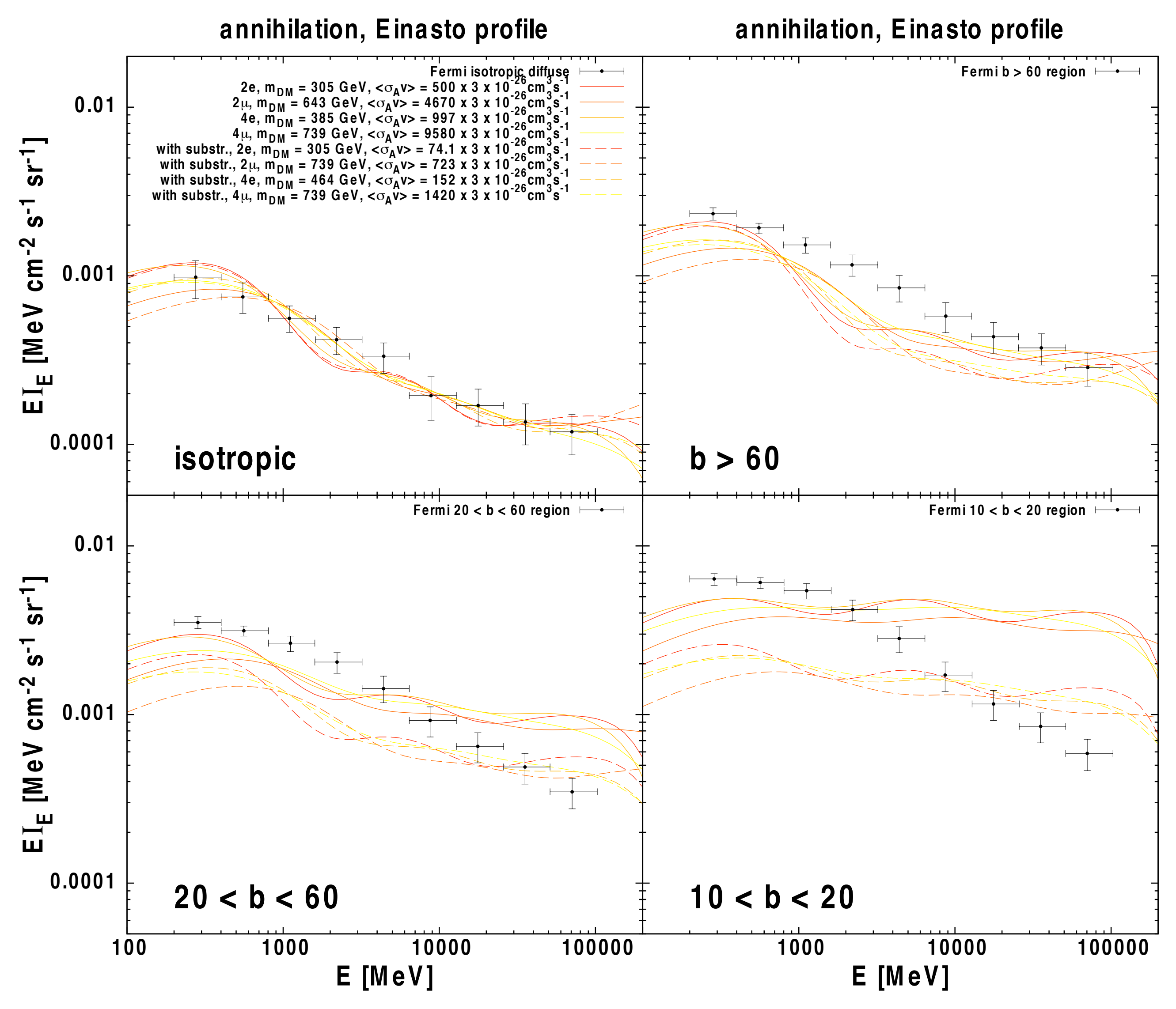


$$\begin{array}{cc} 10^\circ & 30^\circ \\ -15^\circ < & < 15^\circ \end{array}$$

Lin, Finkbeiner, Dobler 1004.0989



Hutsi, Hektor, Raidal 1004.2036

Mmm, a good fit requires fitting energy spectra + angular spectra + associated signals.

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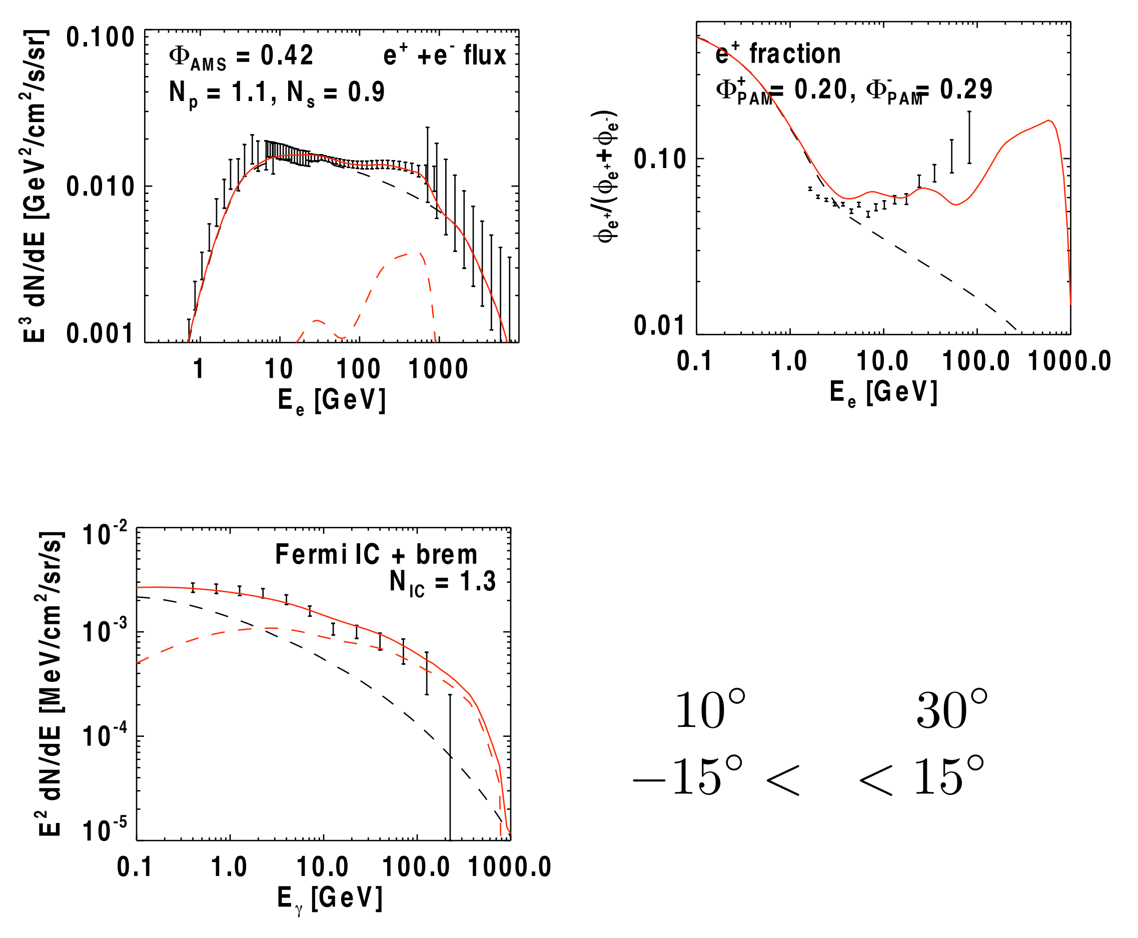
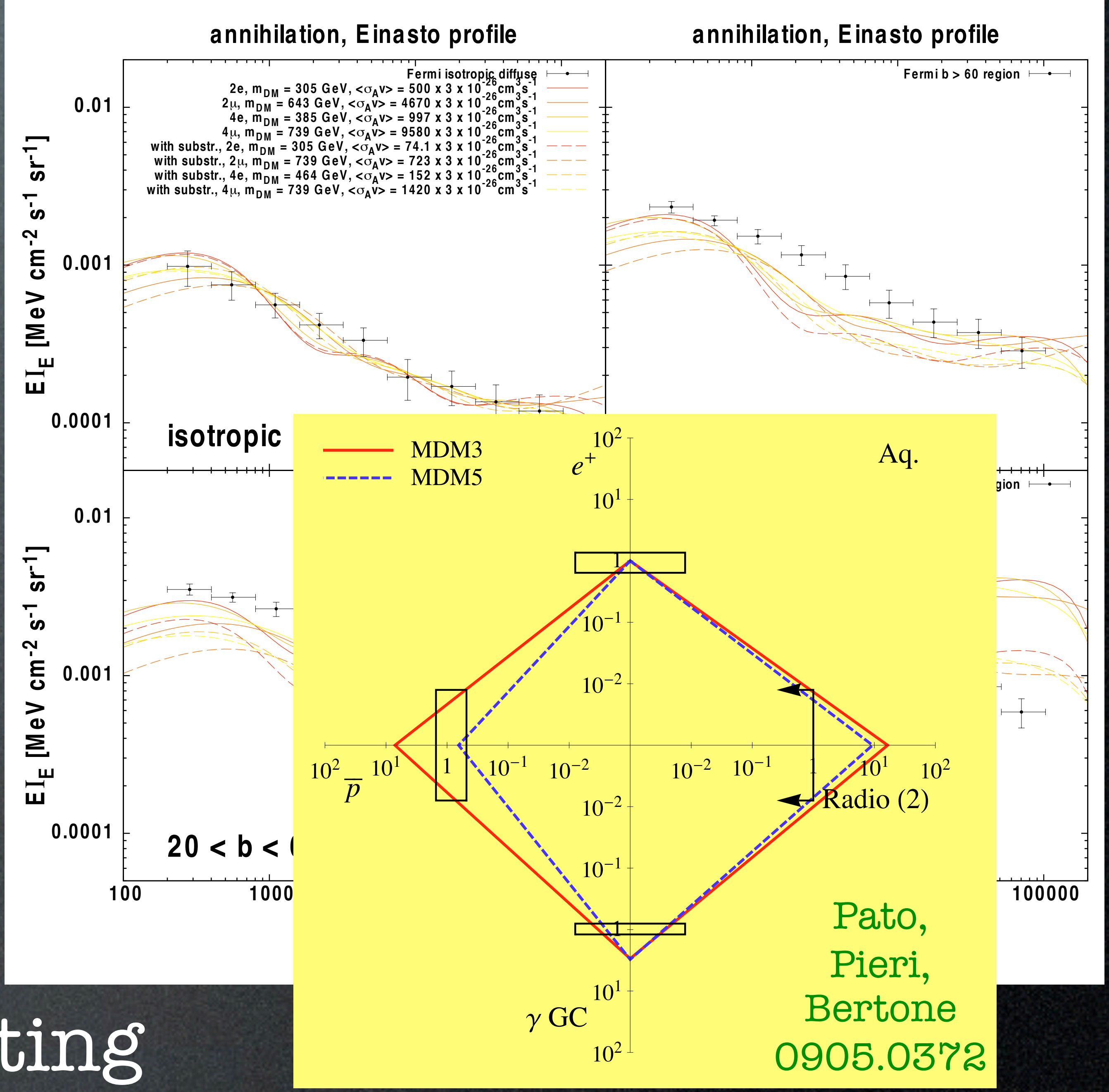


Lin, Finkbeiner, Dobler 1004.0989



Pato, Pieri, Bertone 0905.0372

Hutsi, Hektor, Raidal 1004.2036

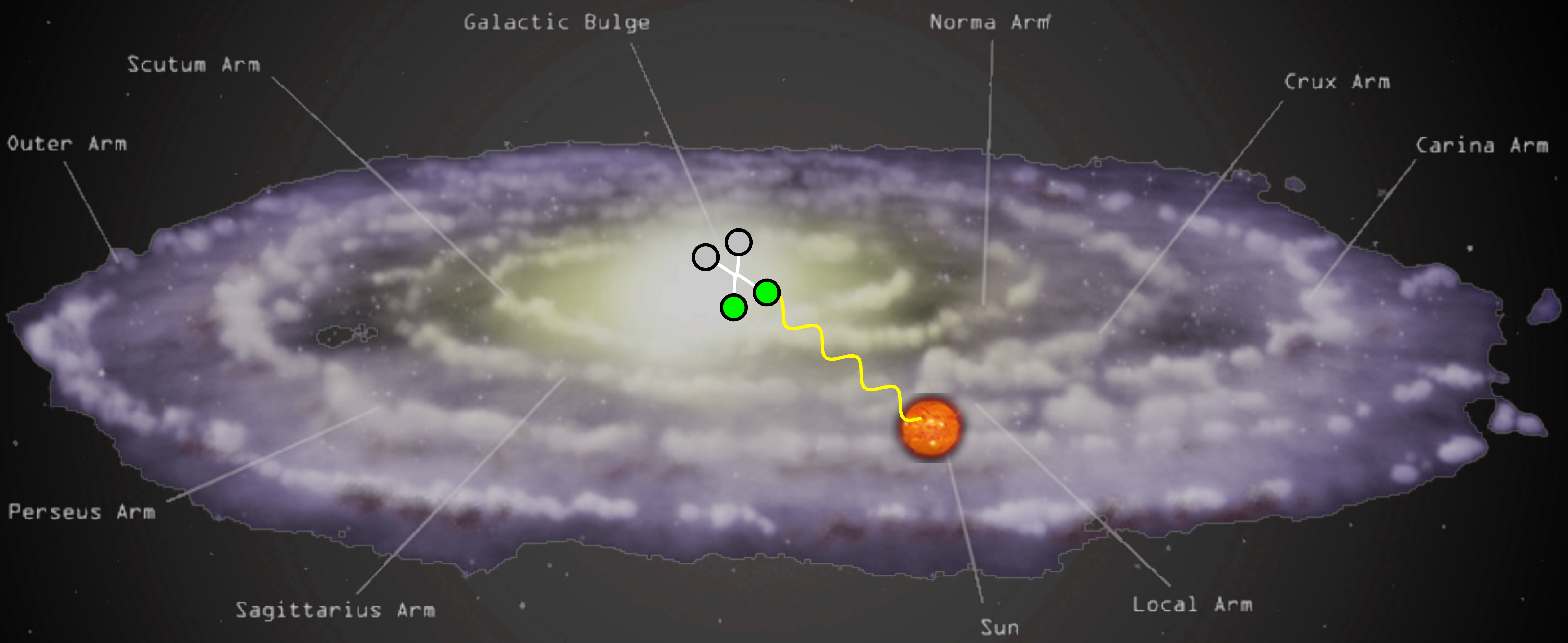
Mmm, a good fit requires fitting energy spectra + angular spectra + associated signals.

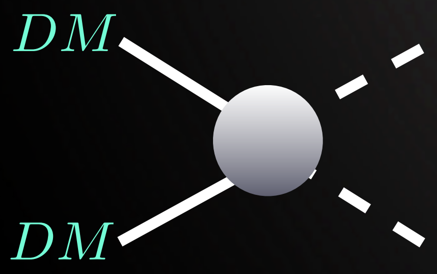
DM detection

- direct detection
- production at colliders
- indirect
  - γ from annihil in galactic center or halo and from synchrotron emission
    Fermi, HESS, radio telescopes
  - e^+ from annihil in galactic halo or center
    PAMELA, ATIC, Fermi
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{D}$ from annihil in galactic halo or center
  - $\nu, \bar{\nu}$ from annihil in galactic center

Indirect Detection

ν from DM annihilations in galactic center





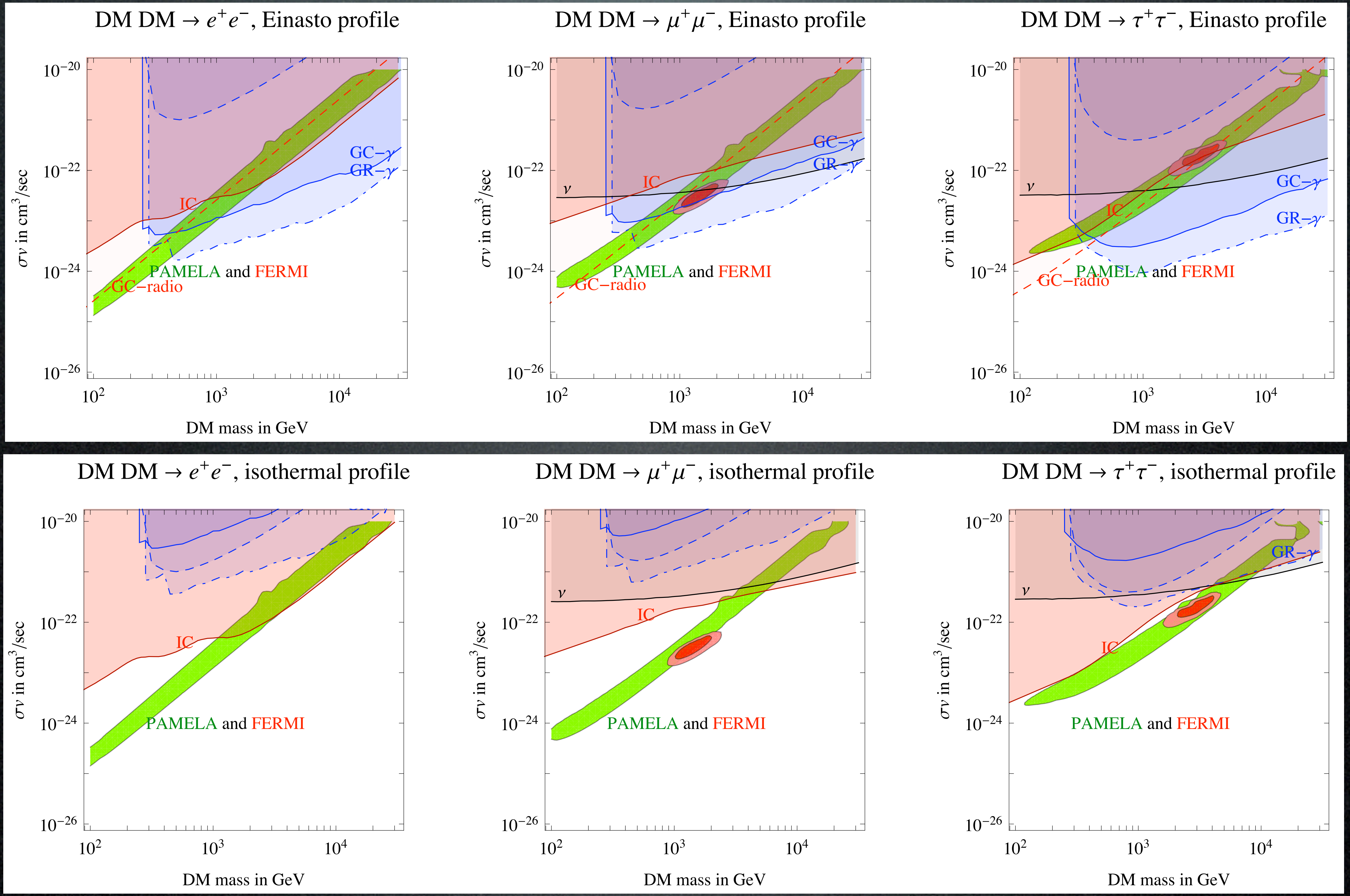
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and ν

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

Neutrino constraints

Comparing with SuperKamiokande data in 3° to 30°

- dependance on DM profile ‘similar’ to ICS gammas
- constraints large M_{DM} ($\sigma_{\nu N} \propto E_\nu$)



Strumia, Papucci et al. 0905.0480

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

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

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

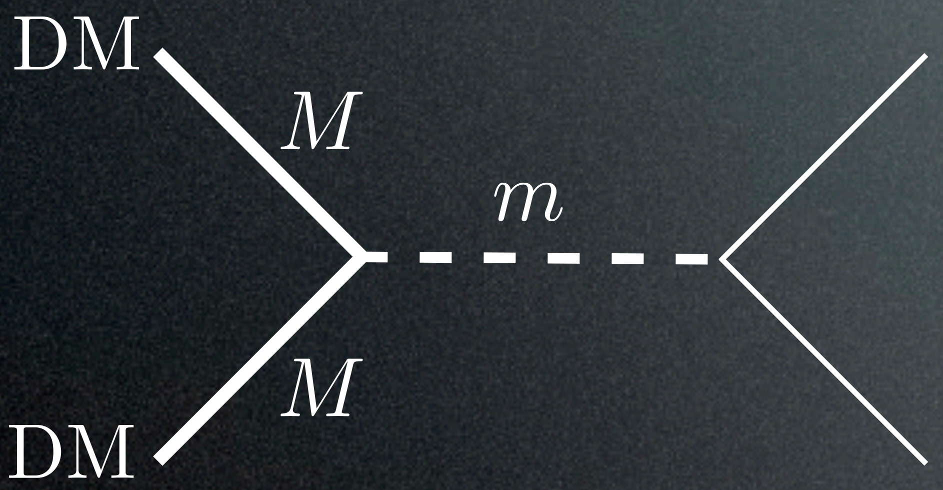
	at freeze-out	***today***
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$

\+ (Wimponium)

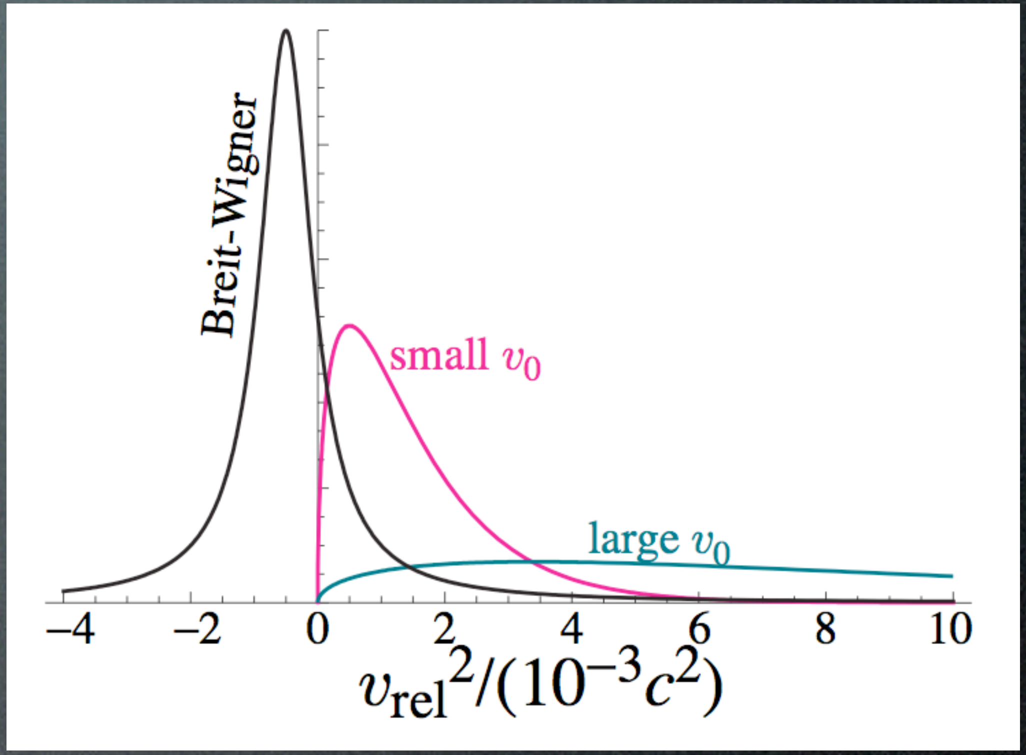
Resonance Enhancement

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

DM annihilation via a narrow resonance just below the threshold:



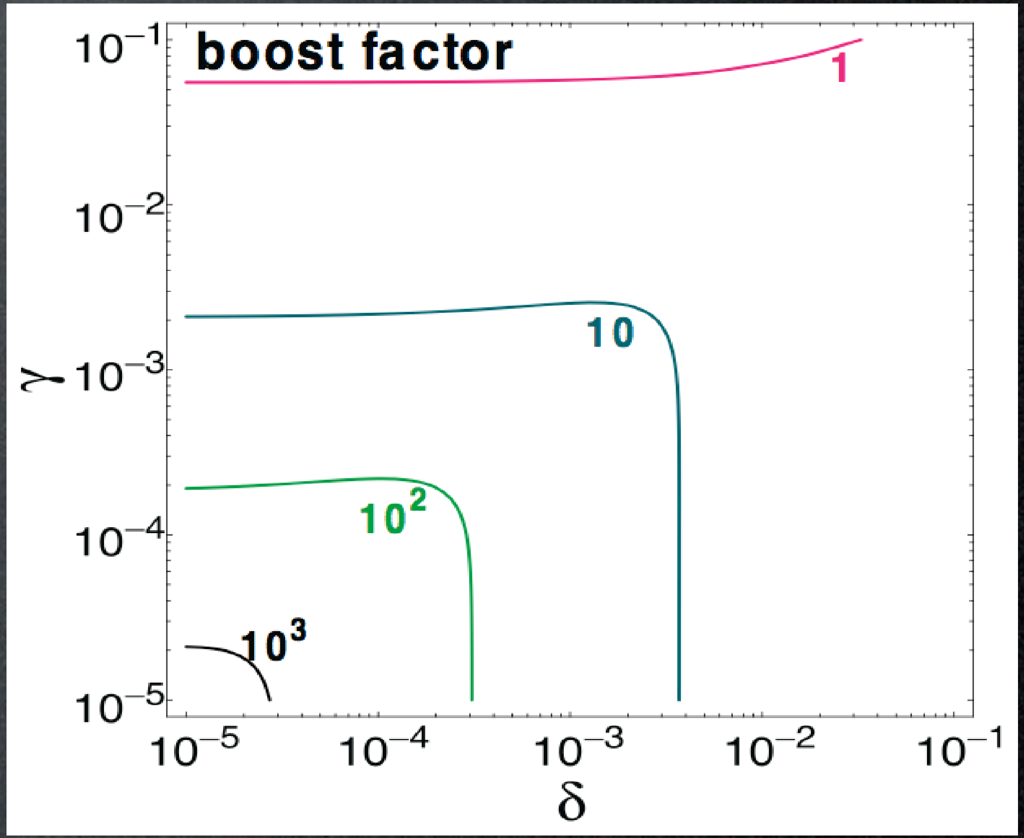
$m \lesssim 2M$



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

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

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



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

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A classical analogy:

Arkani-Hamed et al. 0810.0713

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

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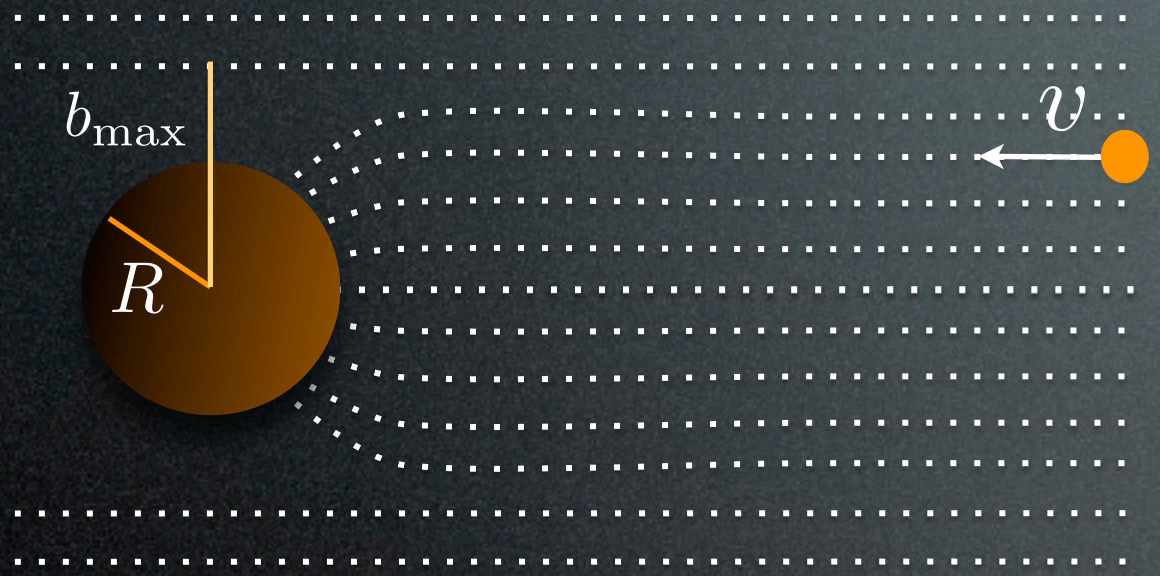
Arkani-Hamed et al. 0810.0713



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

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

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

For $v \gg v_{\text{esc}}$ then $\sigma \to \sigma_0$

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

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

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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

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

Sommerfeld enhancement:

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

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 $\left(\alpha=\frac{g^2}{4\pi}\approx\frac{1}{137}\right)$

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Cirelli, Strumia, Tamburini 0706.4071

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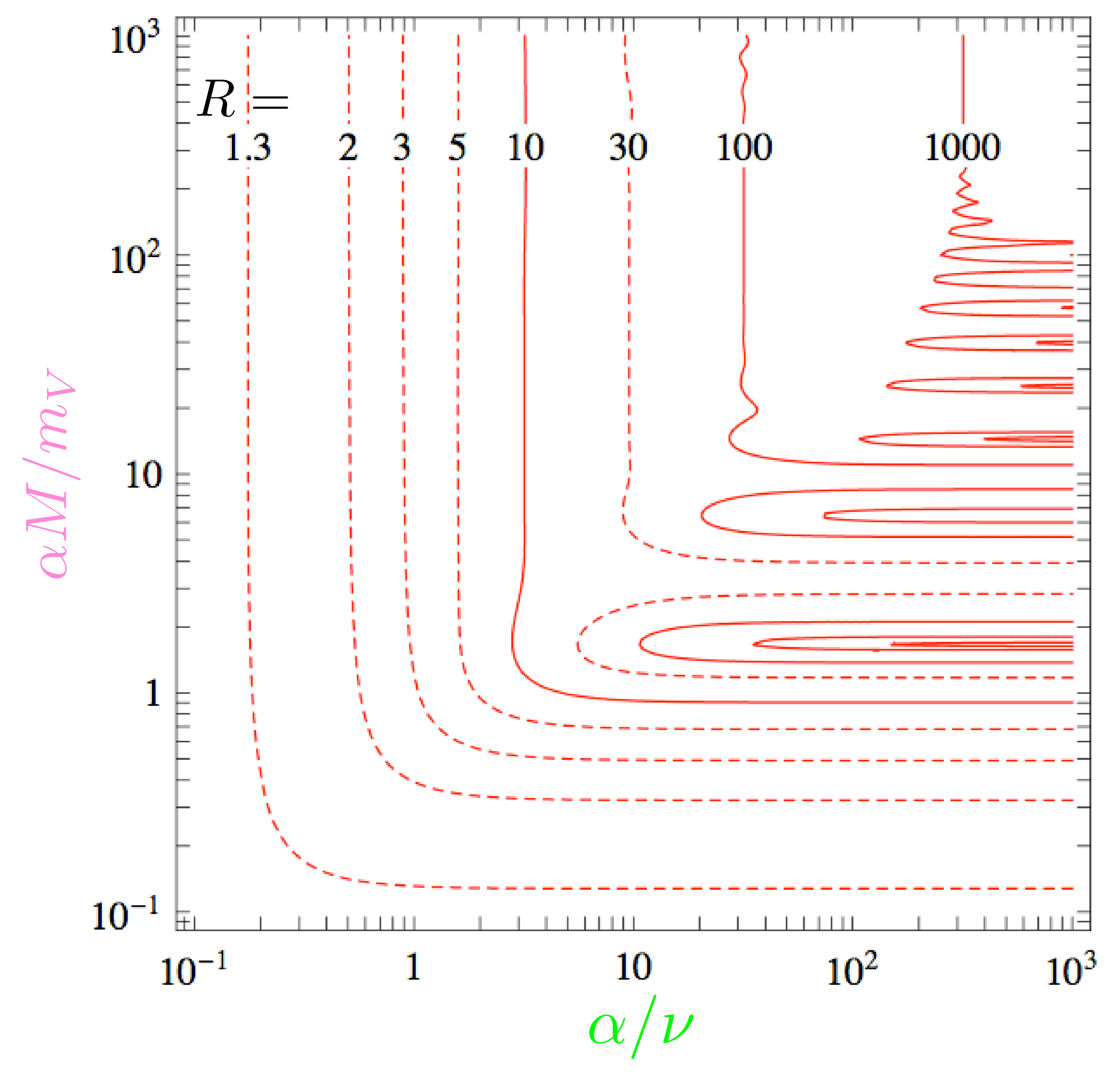
R depends on: α/ν and $\alpha M/m_V$



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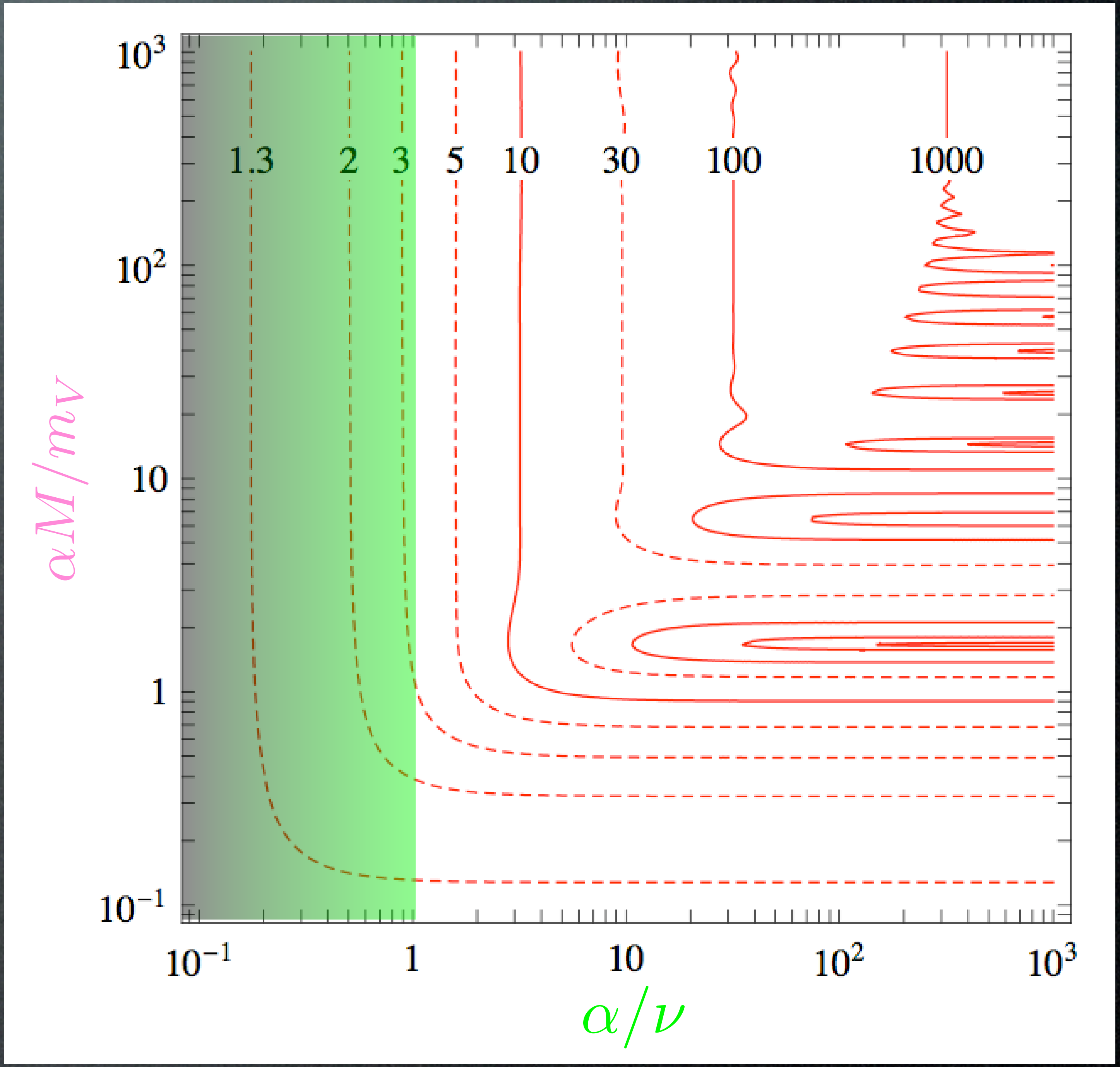
The effect is relevant for:

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

Cirelli, Strumia, Tamburini 0706.4071



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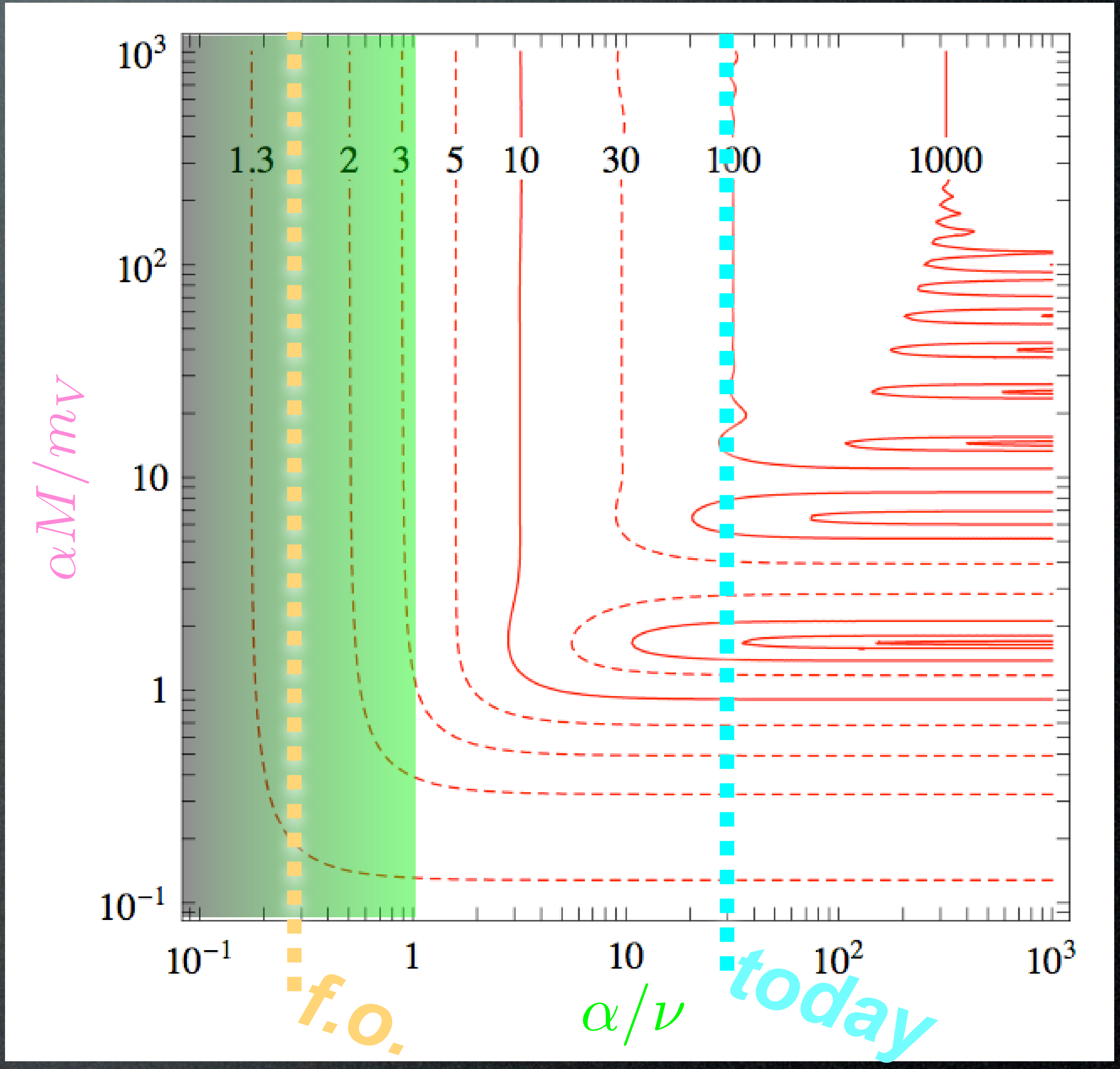

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Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378

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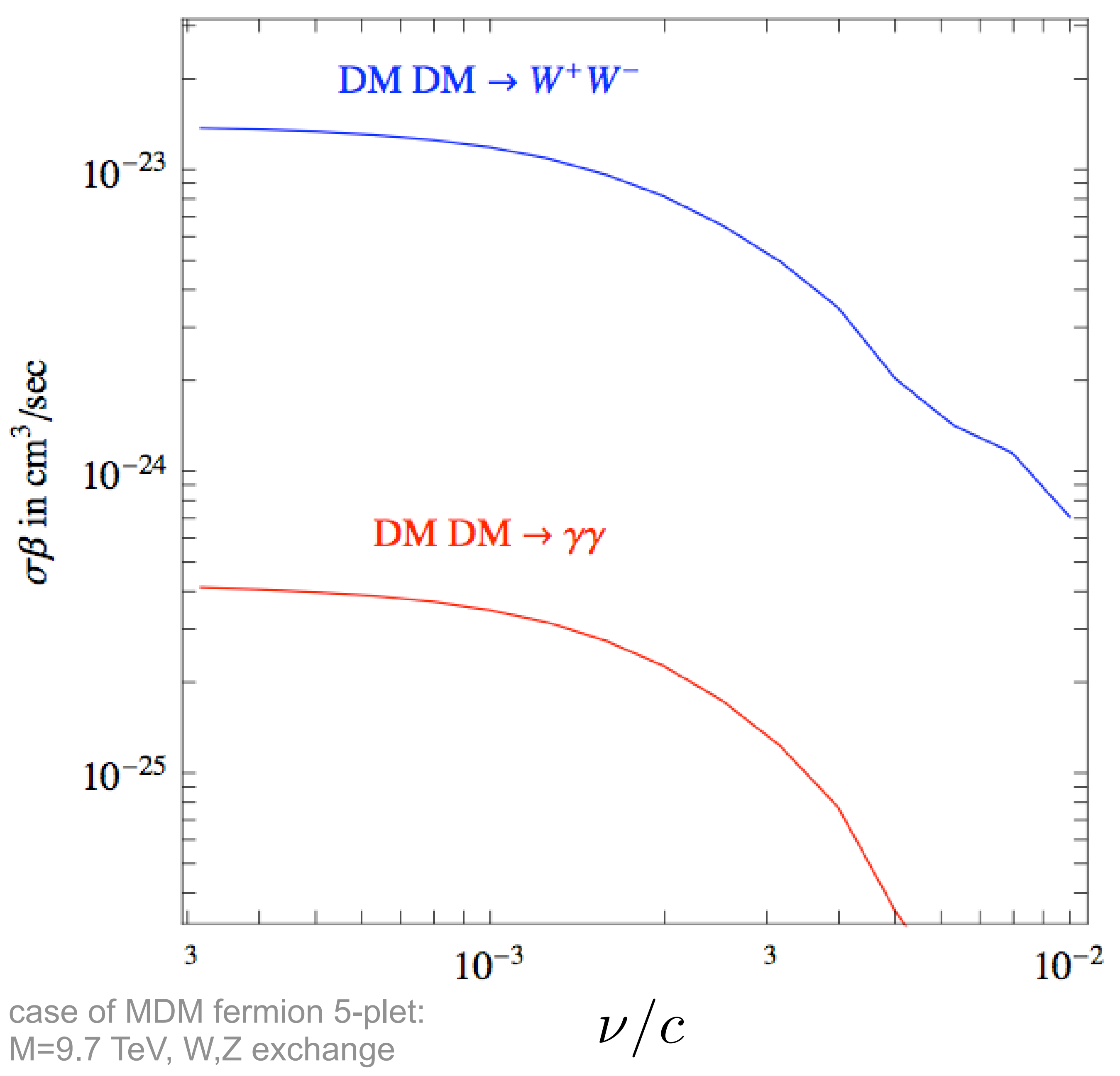

case of MDM fermion 5-plet:
M=9.7 TeV, W,Z exchange

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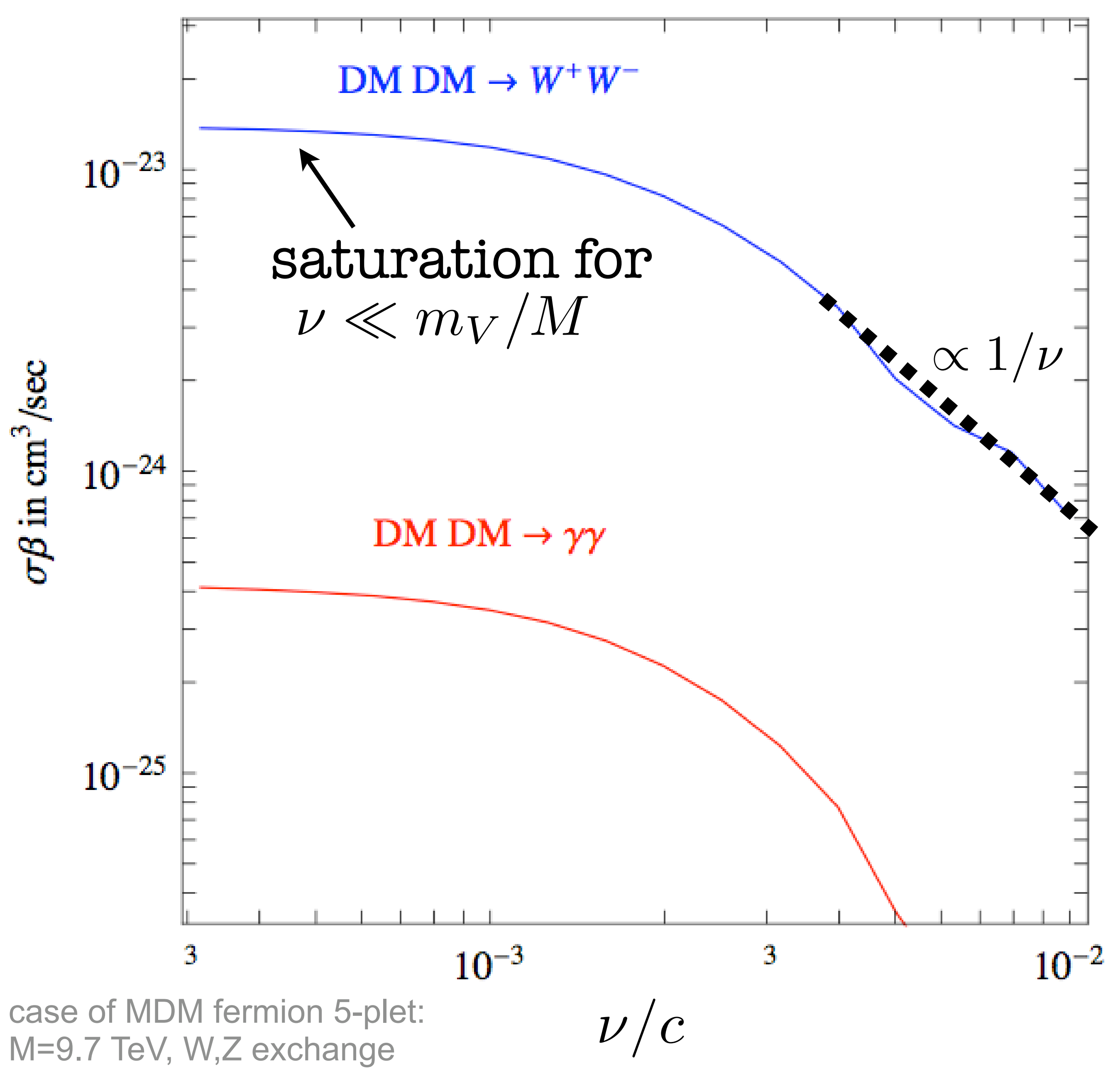
Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378



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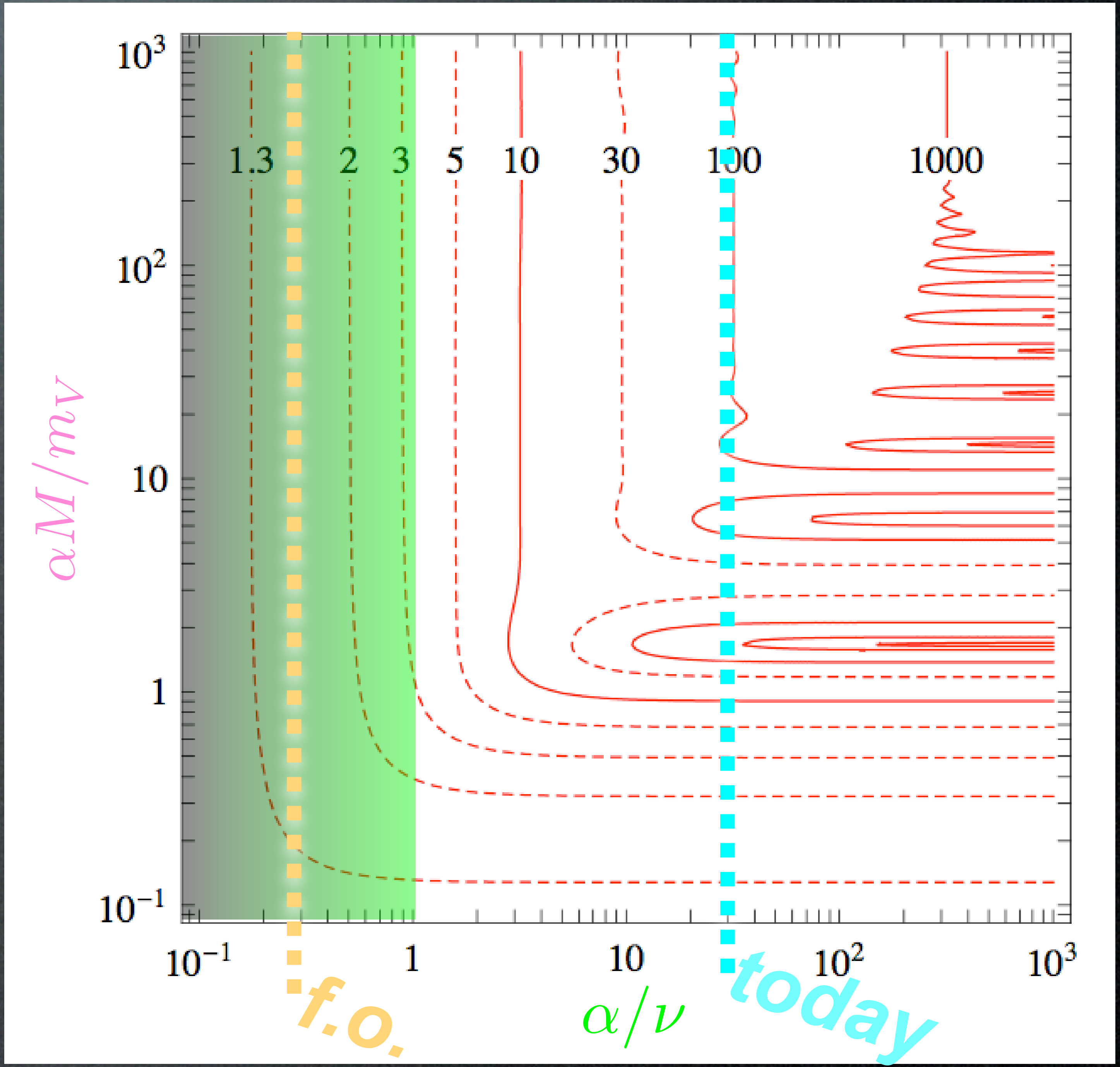

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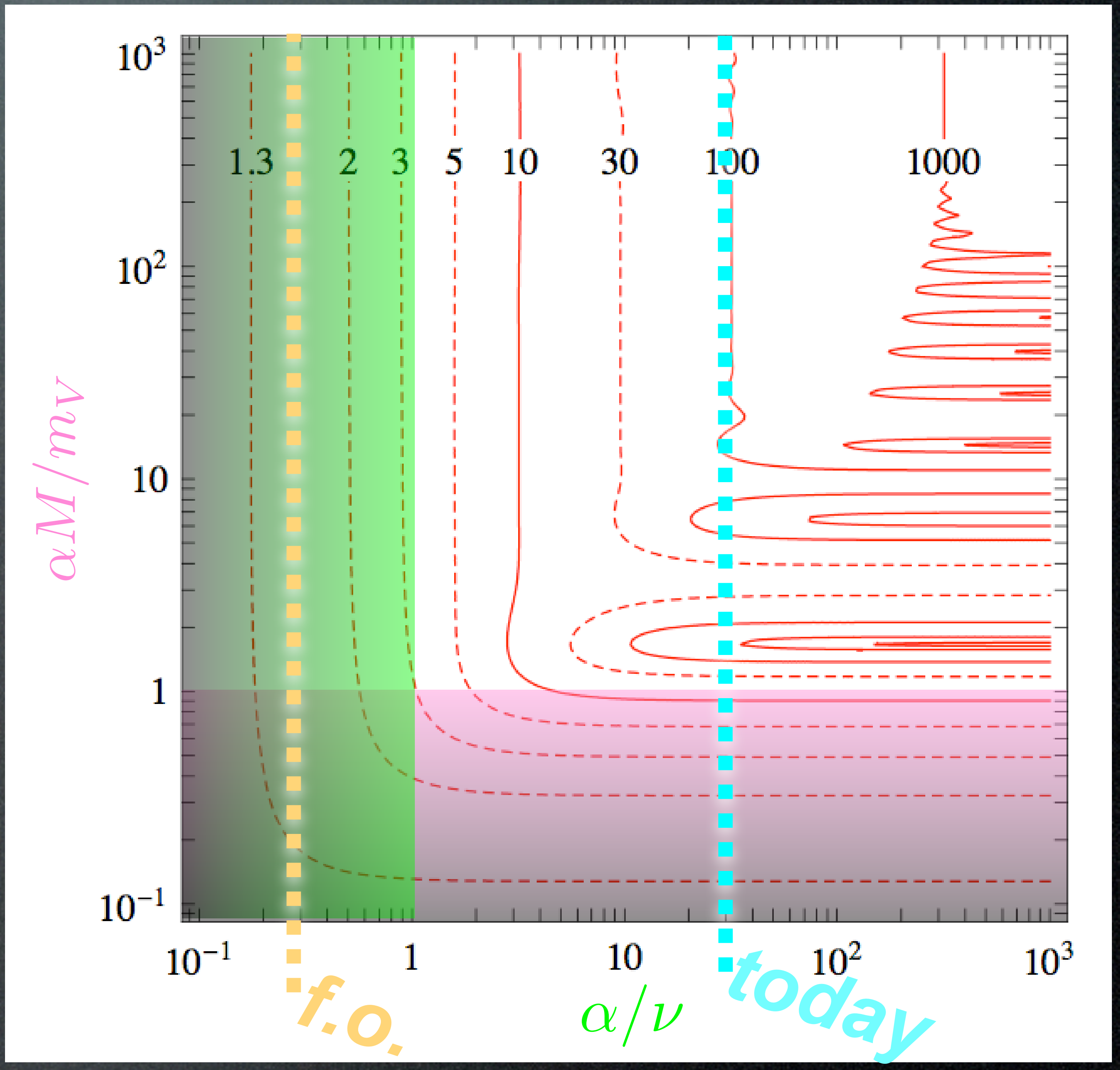
$\alpha M/m_V \gtrsim 1$ i.e. long range forces

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

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

Cirelli, Strumia, Tamburini 0706.4071



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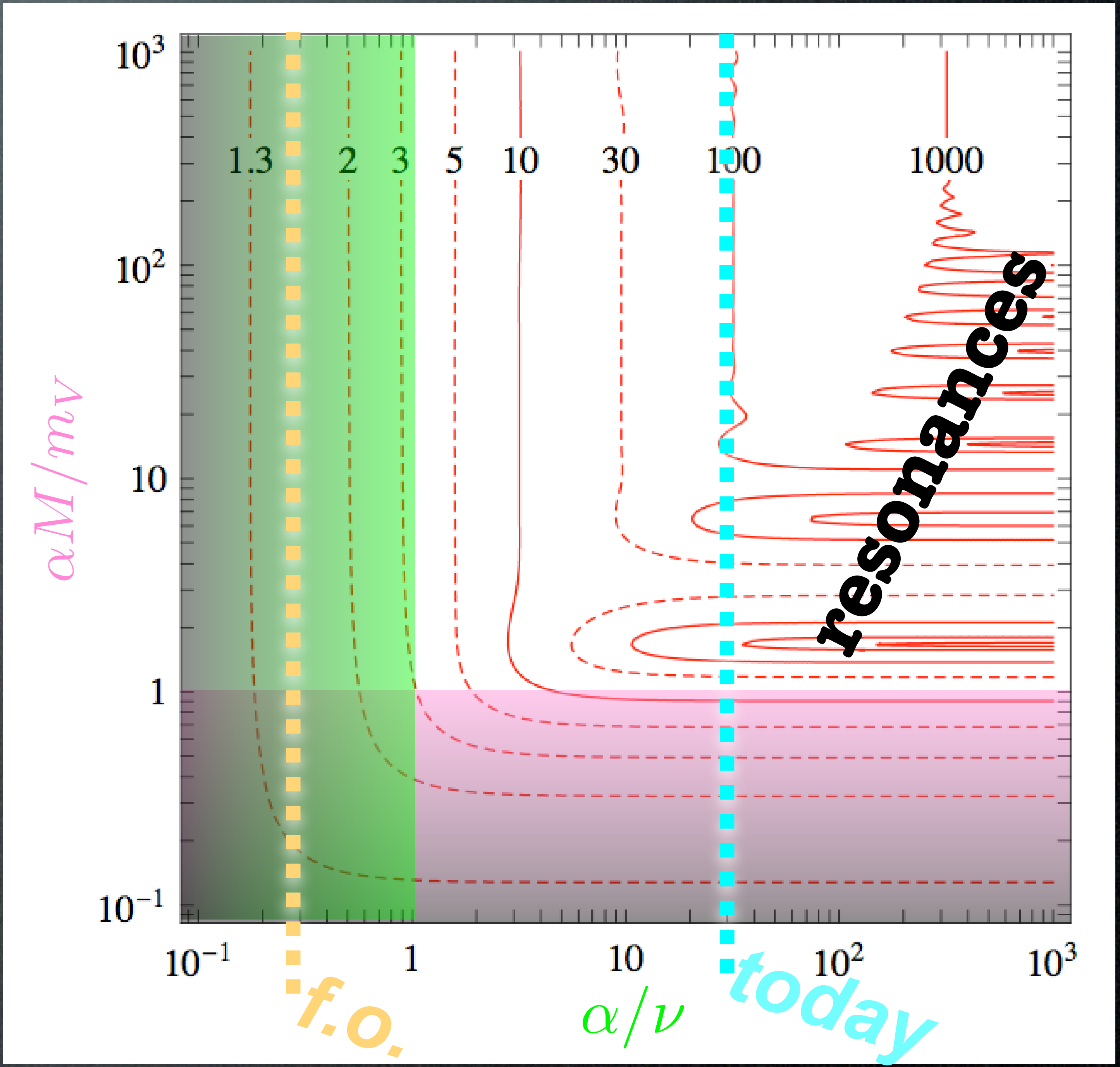

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Cirelli, Strumia, Tamburini 0706.4071
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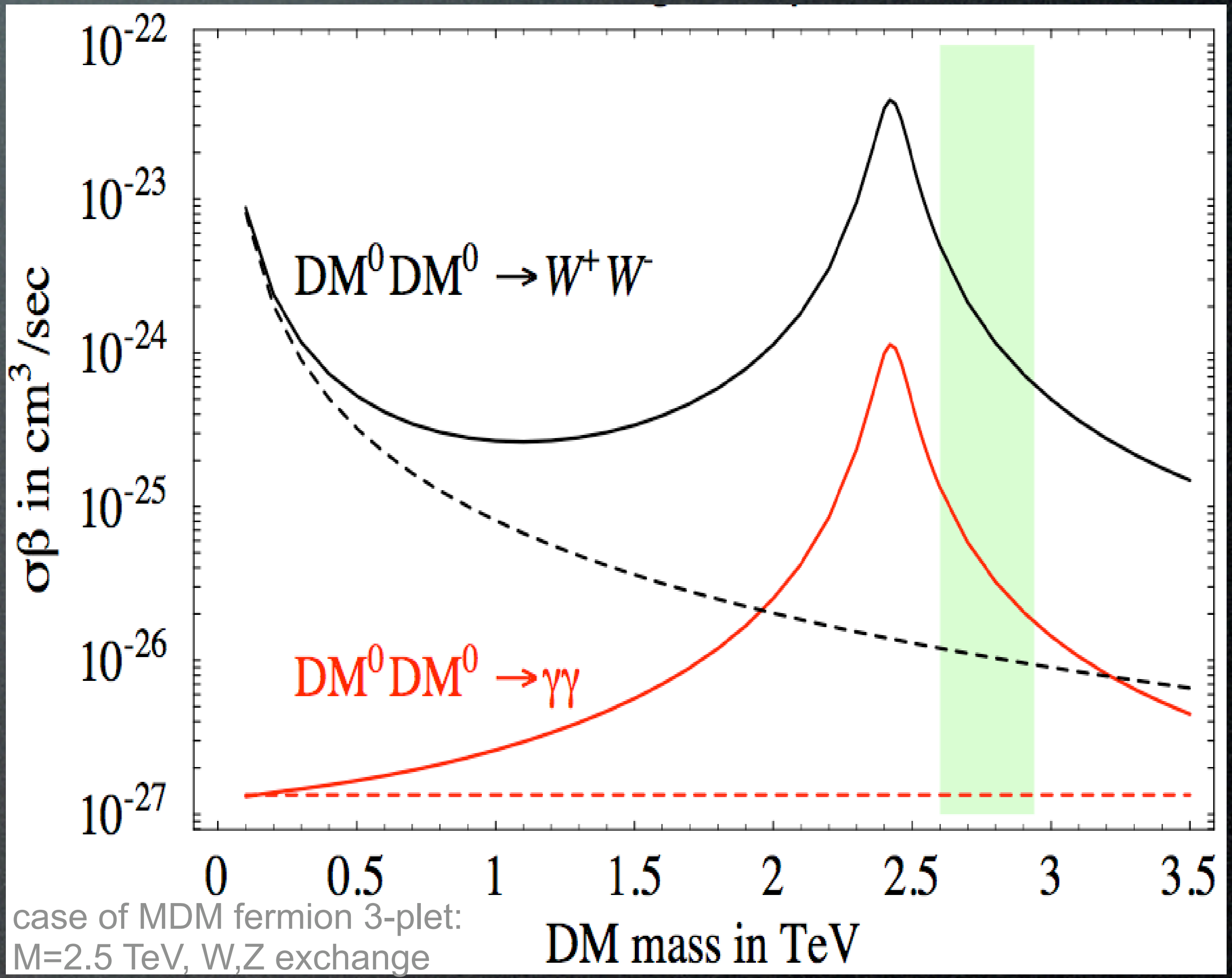

case of MDM fermion 3-plet:
M=2.5 TeV, W,Z exchange

Sommerfeld Enhancement

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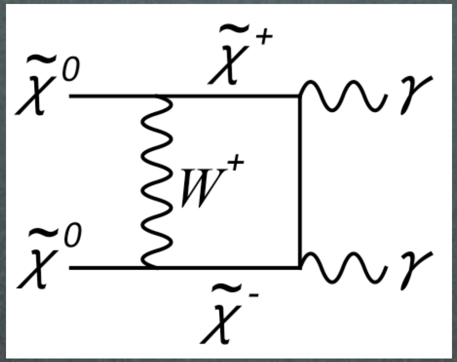
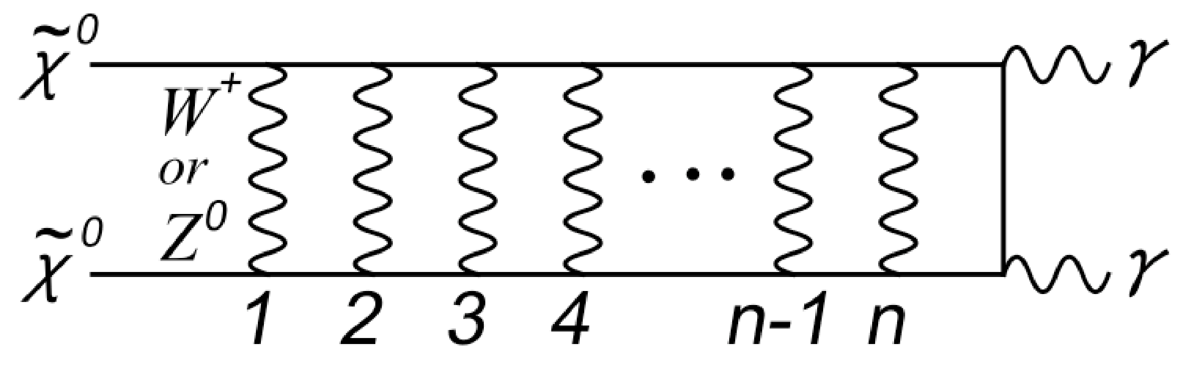
In terms of Feynman diagrams:

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

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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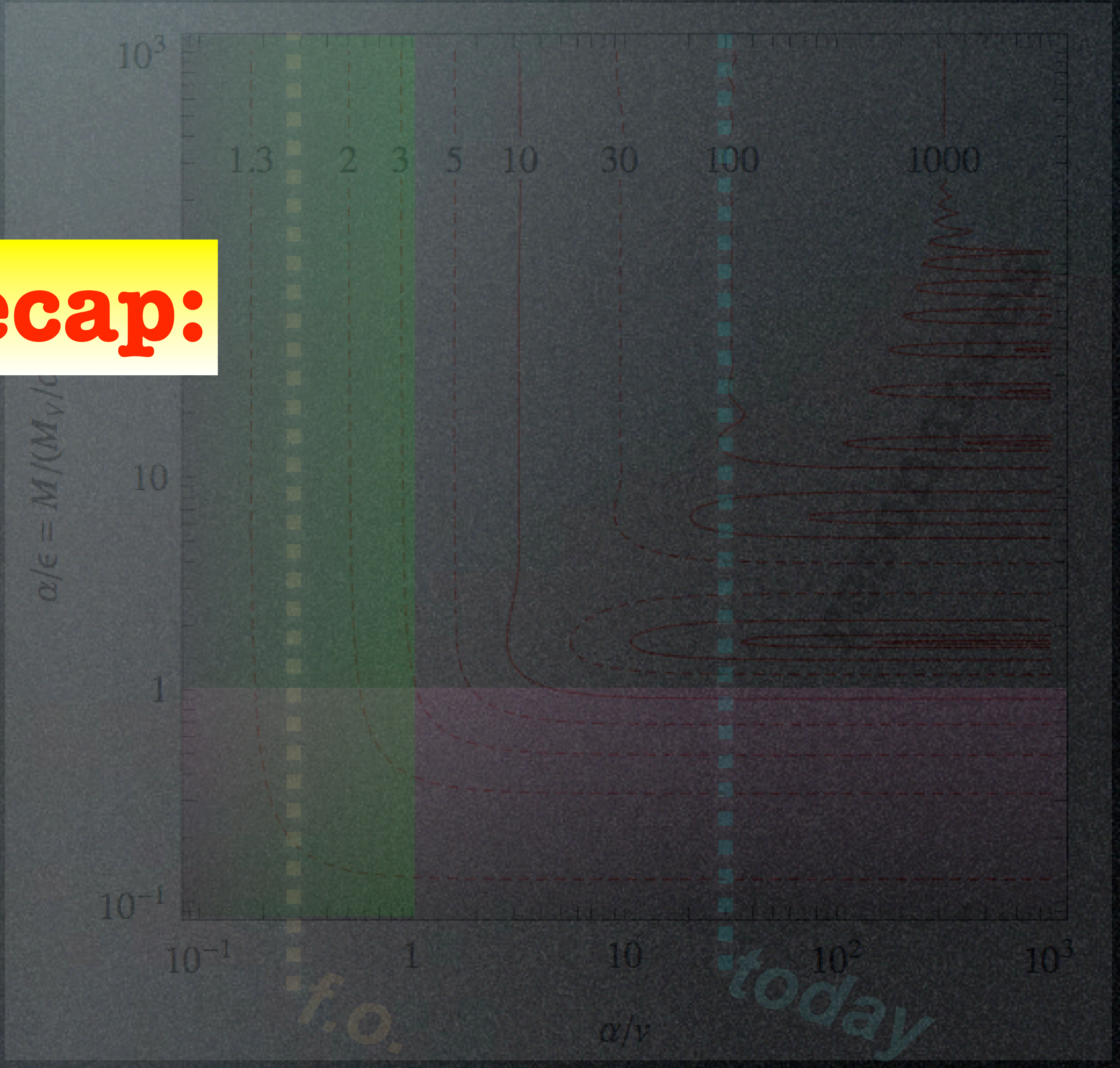
Recap:



Cirelli, Strumia, Tamburini 0706.4071

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$M \to \text{multi}-\text{TeV}$

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

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

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

- More drastic extensions:
  New models with a rich Dark sector

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - E.Ponton, L.Randall, 0811.1029: Singlet DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM - S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

- 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

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

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

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The "Theory of DM"

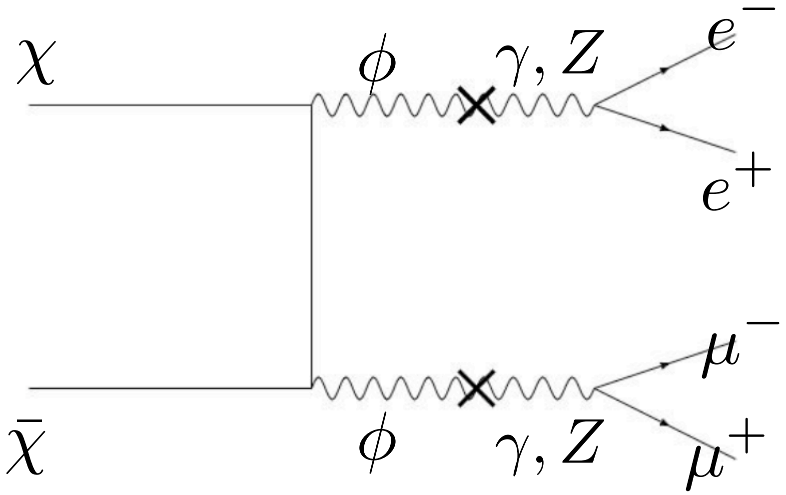
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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, $m_\phi \sim \mathrm{few\ GeV}$
- 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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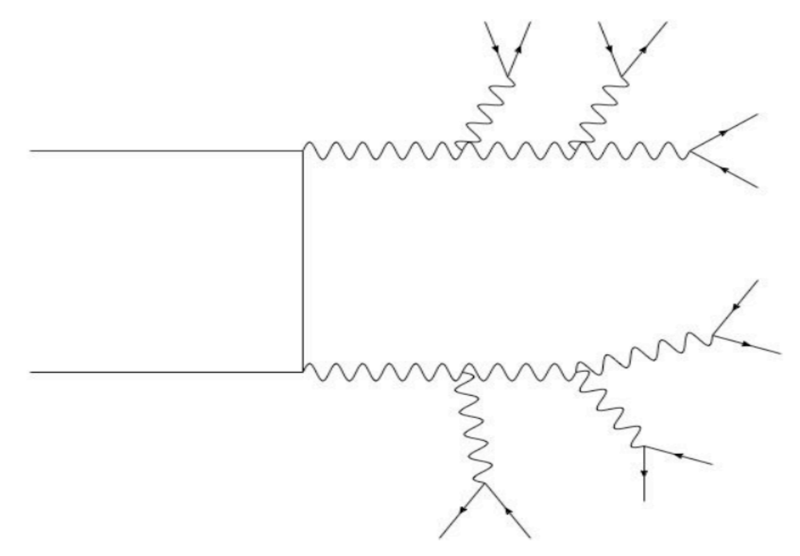


Extras:

χ is a multiplet of states and ϕ is non-abelian gauge boson:

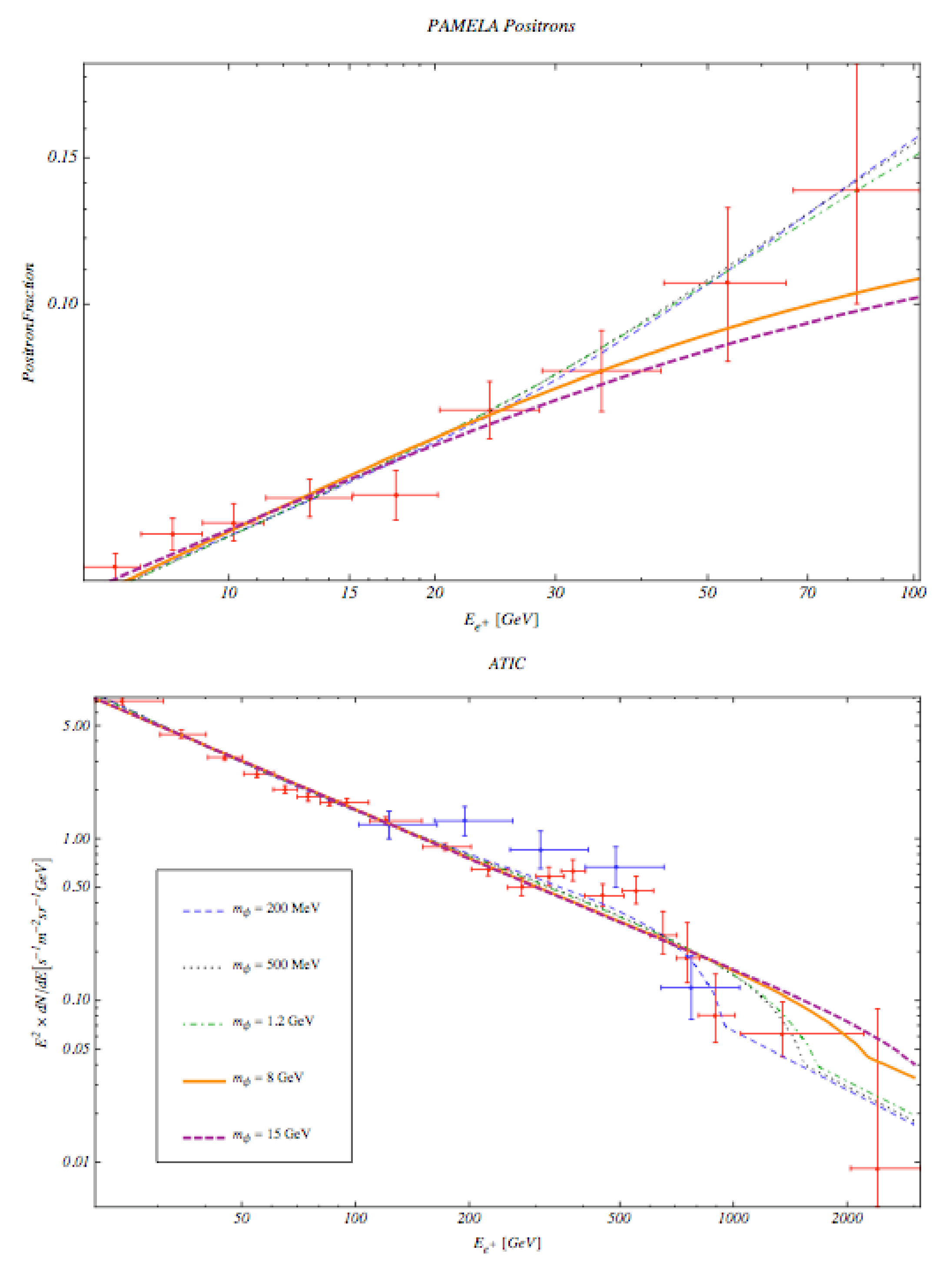
splitting $\delta M \sim 200\ \mathrm{KeV}$ (via loops of non-abelian bosons)

- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \rightarrow \chi\chi^*$ explains INTEGRAL

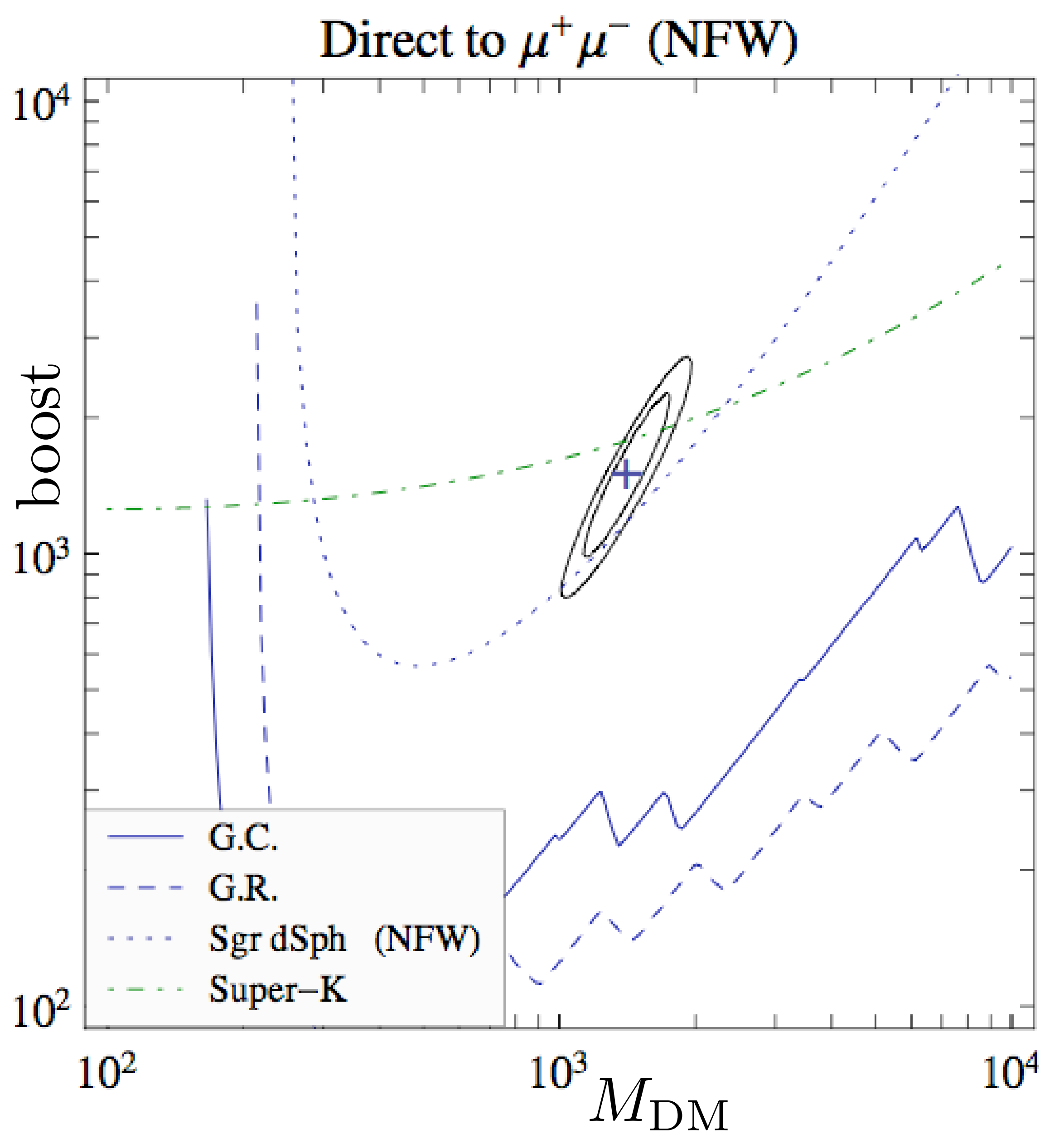
$\hookrightarrow e^+e^-$

The “Theory of DM”

Phenomenology:



Meade, Papucci, Volanski
0901.2925



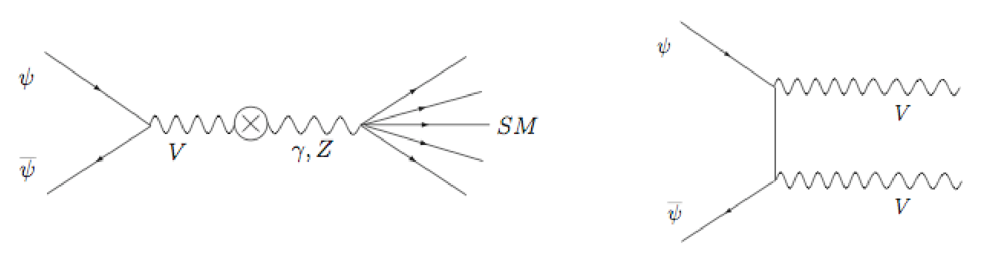
Mardon, Nomura, Stolarski,
Thaler 0901.2926

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

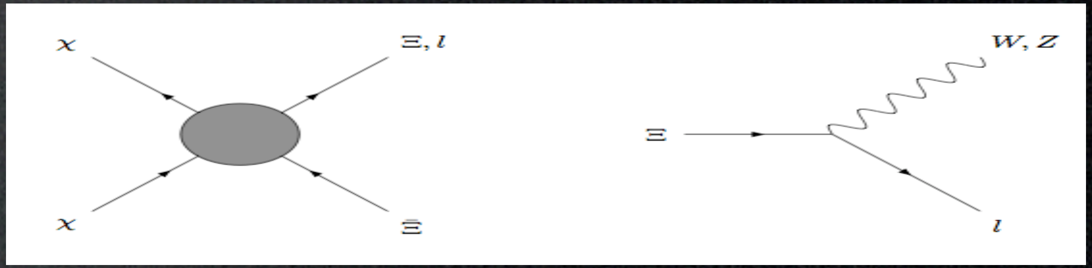
  Park, Shu 0901.0720

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

  Phalen, Pierce, Weiner 0901.3165



- ......

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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

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

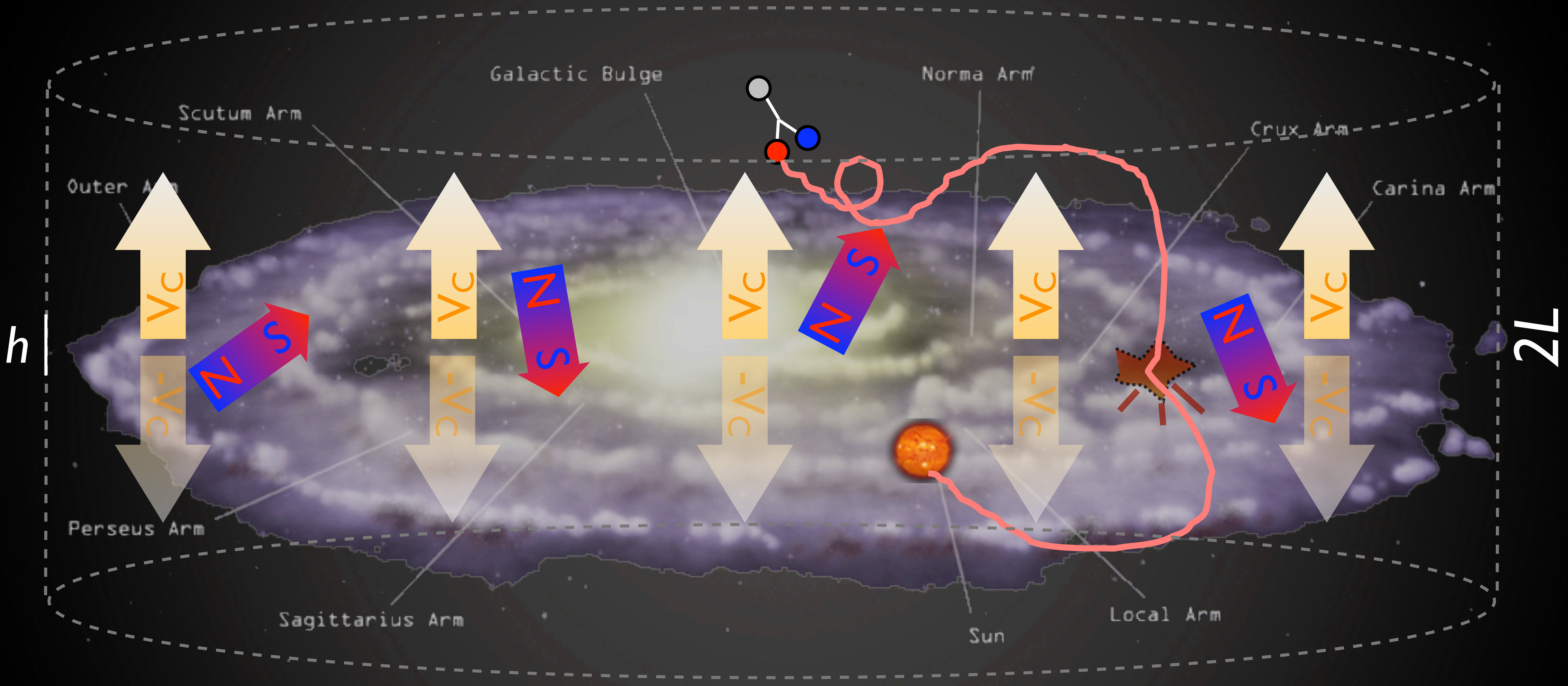
- or in TechniColor

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?

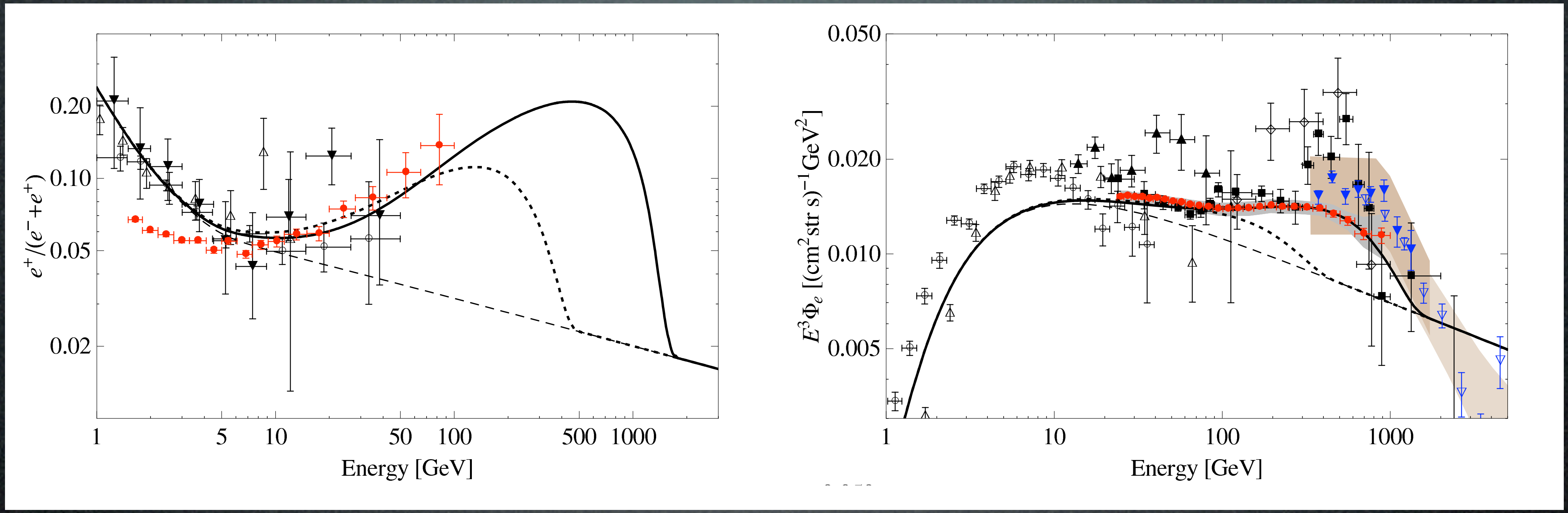
$$\text{flux} \propto n\,\Gamma_{\text{decay}}$$

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

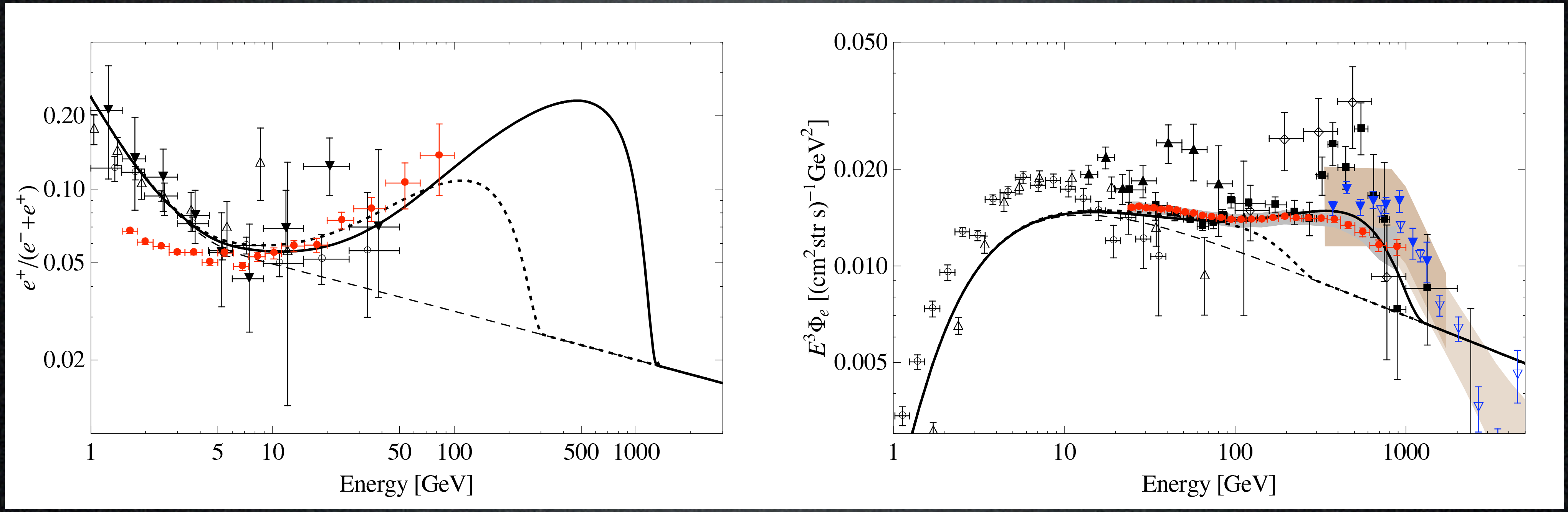
Decaying DM

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 $M_{\mathrm{DM}} = 2.5\,\mathrm{TeV}$:

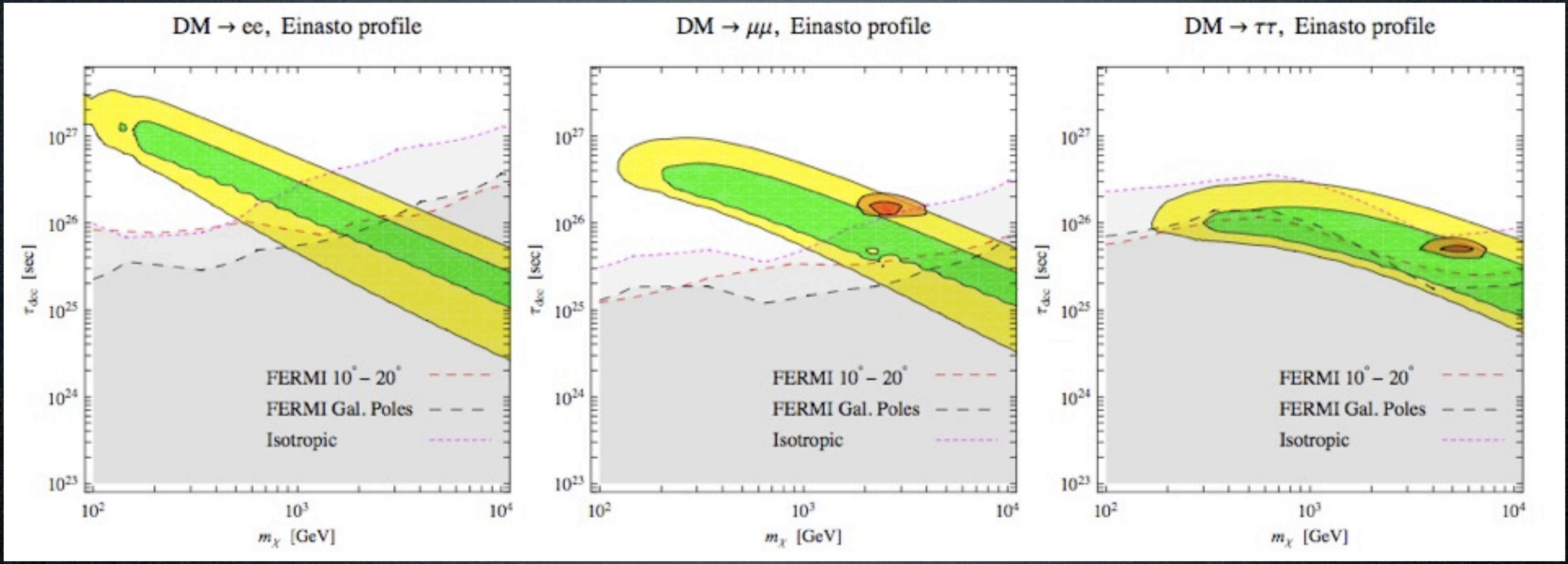


Ibarra, Tran, Weniger 2009

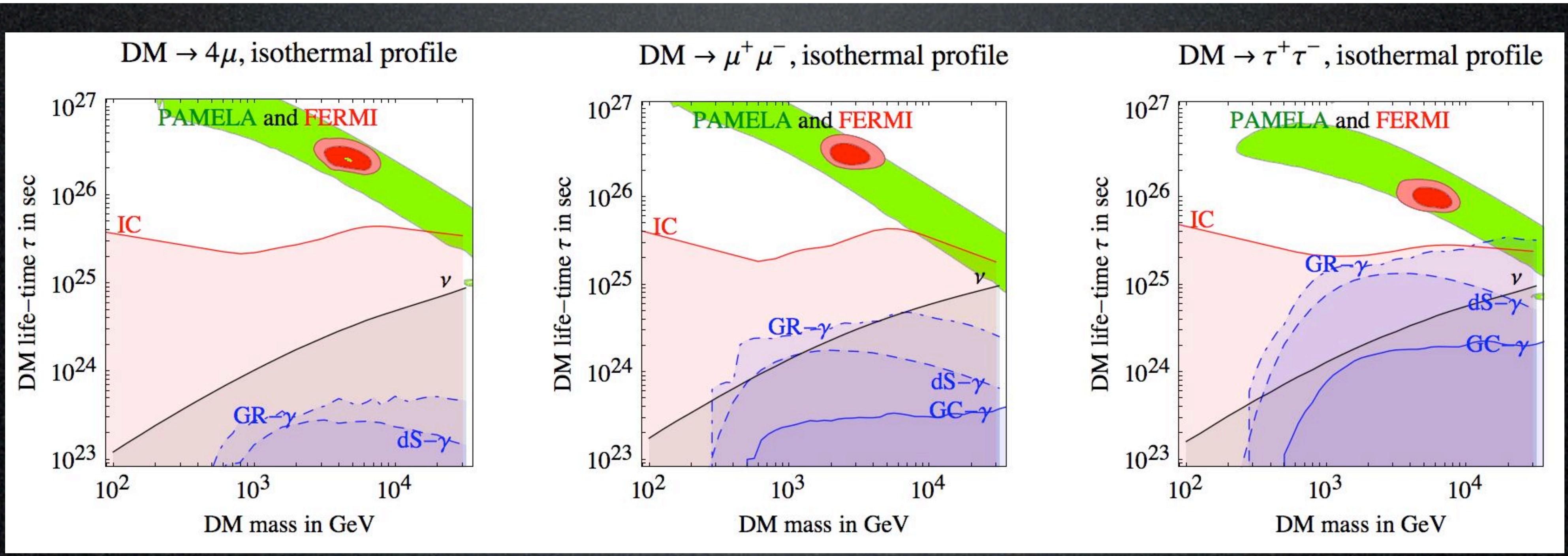
Decaying DM

Beware of gamma ray constraints

(but no radio, neutrino constraints)



Cirelli, Panci, Serpico 0912. 0663



Strumia, Papucci et al. 0905.0480

‘Answers’

DM id has driven a volcanic activity in the field of DM theory and phenomenology in 2009.

Why?

What has the eruption left?

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- 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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And open-mindedness.

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Did we find DM in CR???

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

Perspectives

Data: - AMS-02

- more FERMI!
- ACT
- GAPS?

Astro: - understand the “backgrounds” (pulsars, SNRs...)

- understand the propagation model

Theory: - keep an open mind

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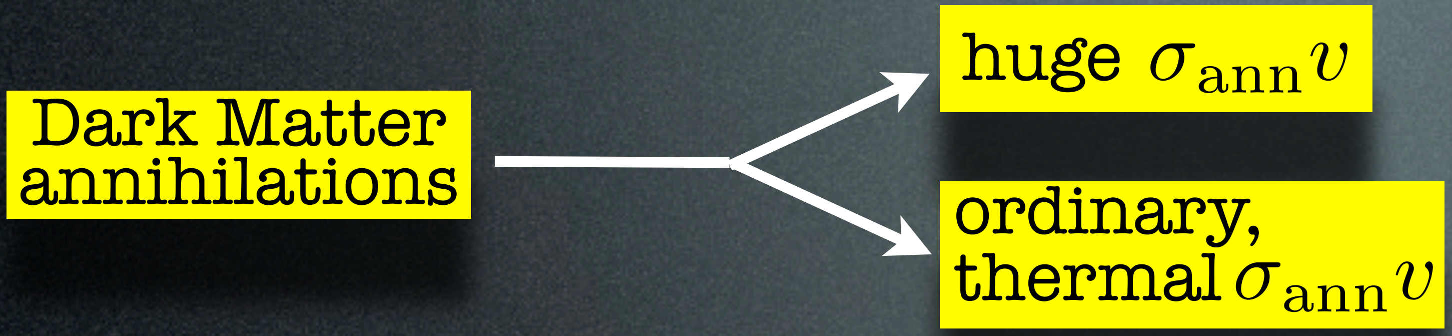
Back up slides

DM annihilations: the game

Dark Matter
annihilations

DM annihilations: the game

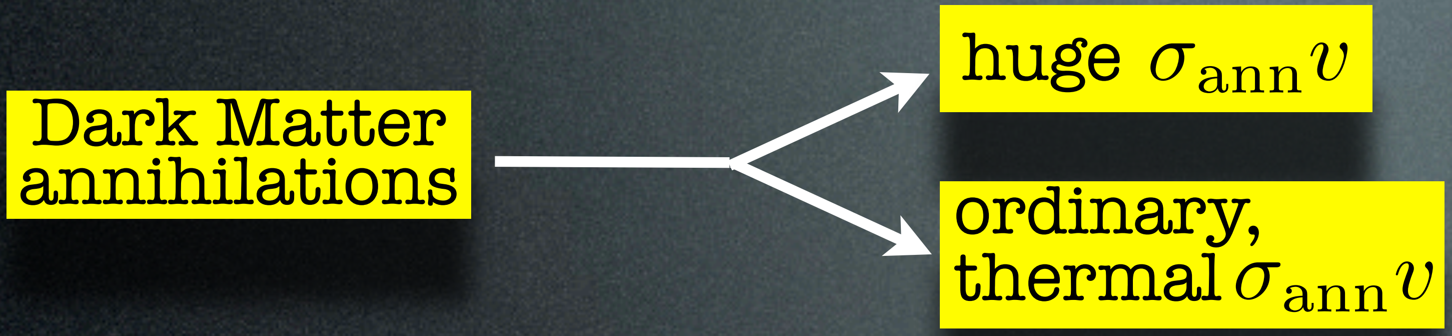


Dark Matter annihilations

huge $\sigma_{\rm ann} v$

ordinary, thermal $\sigma_{\rm ann} v$

DM annihilations: the game



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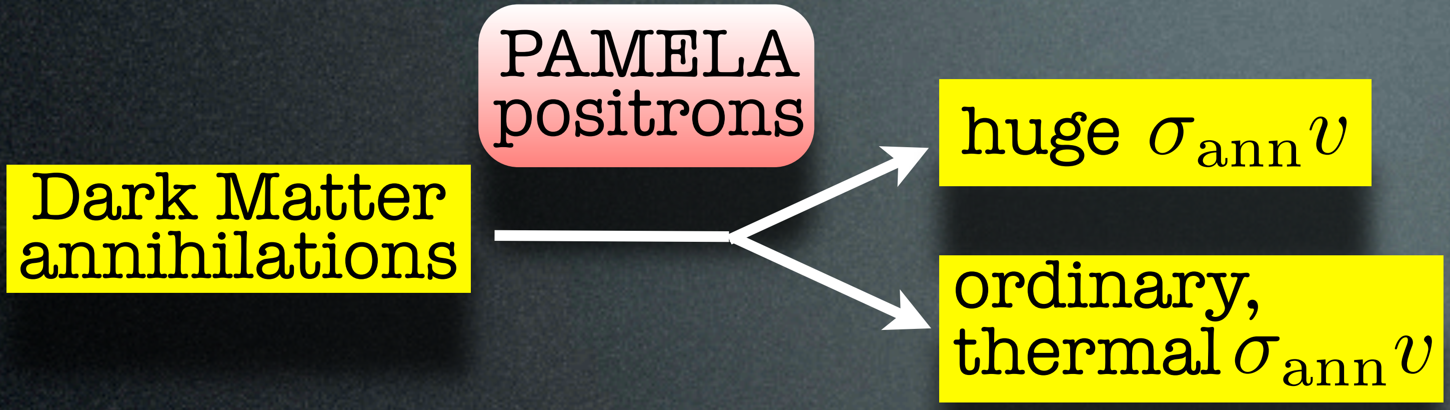

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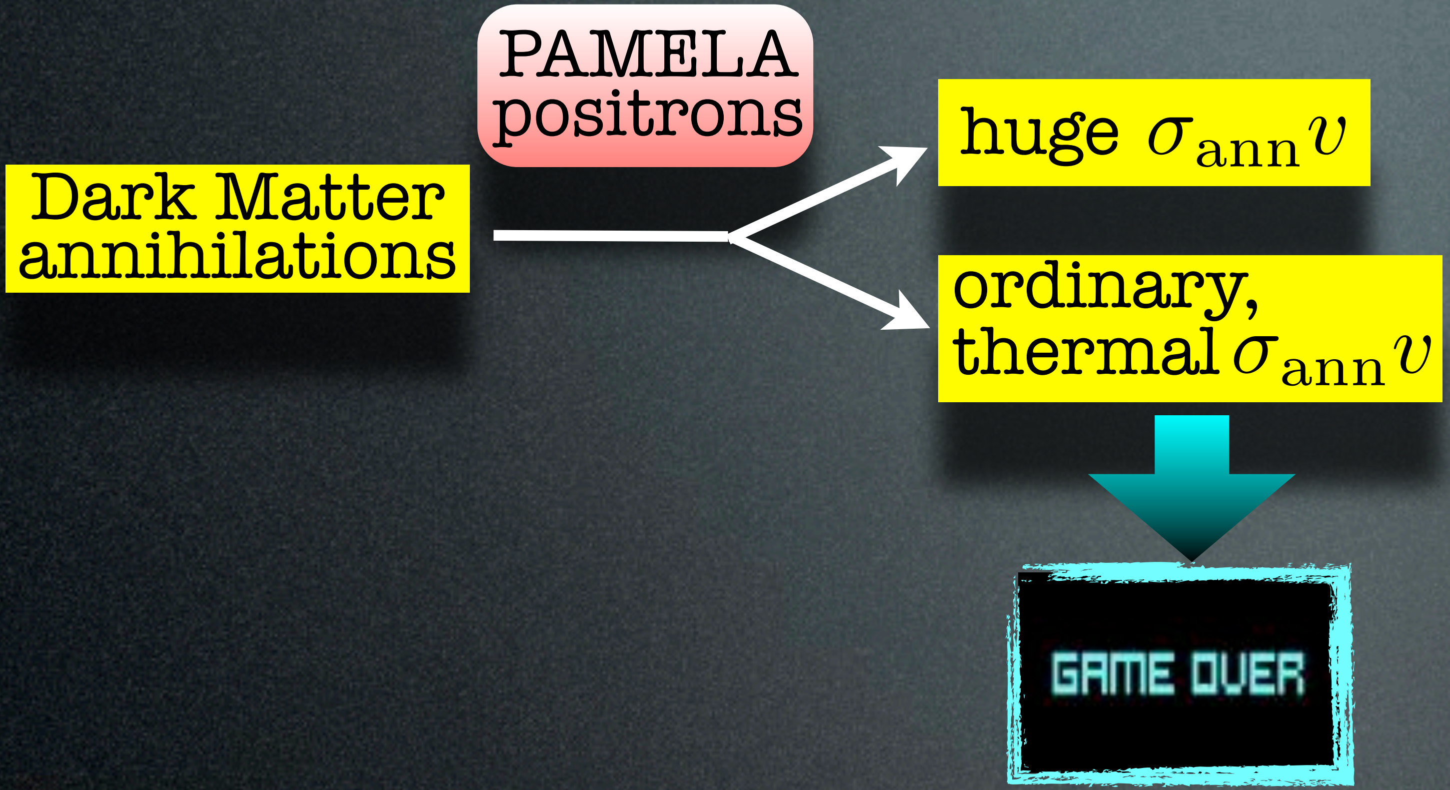

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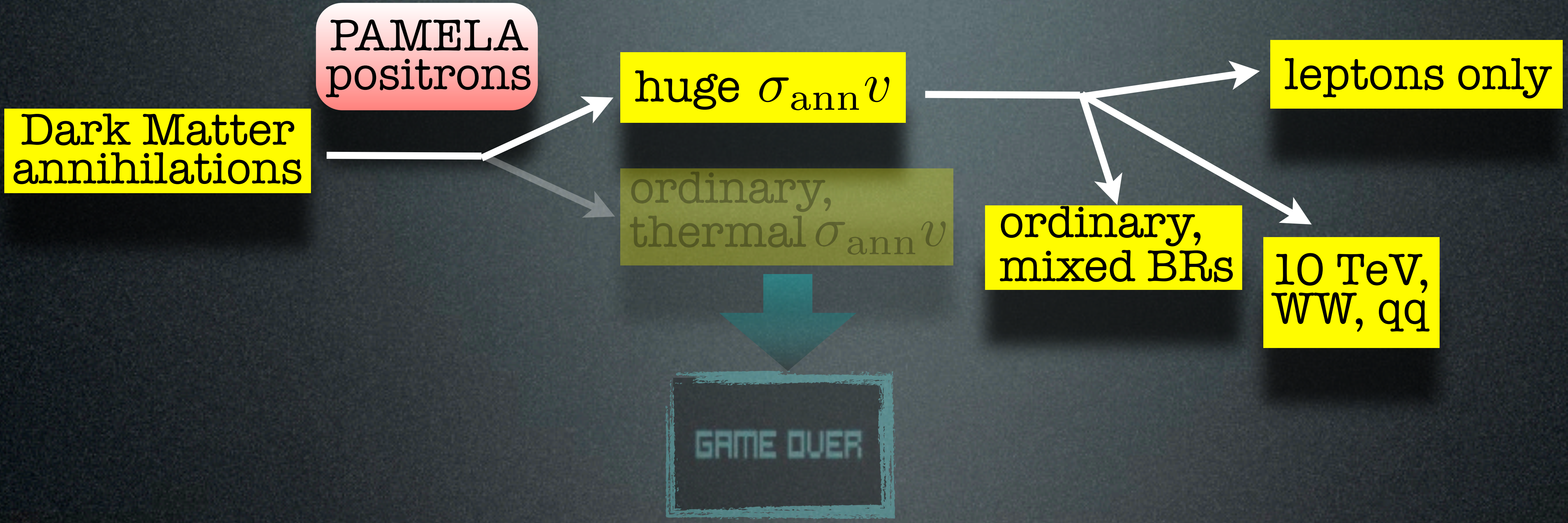

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10 TeV, WW, qq

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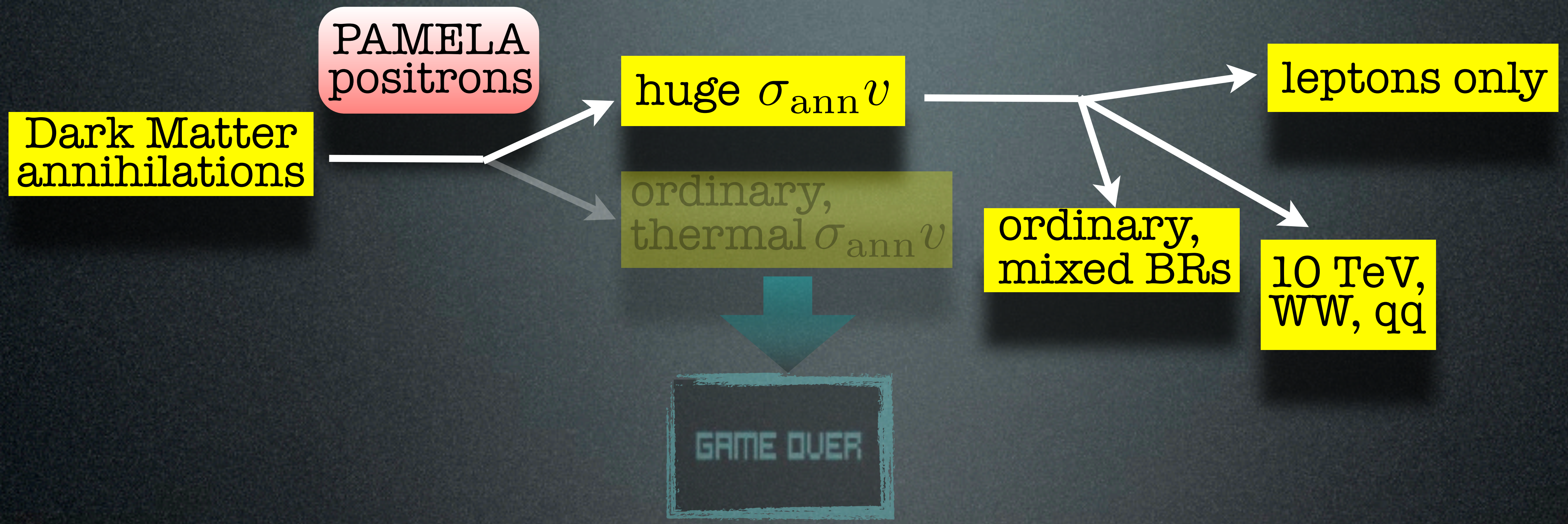

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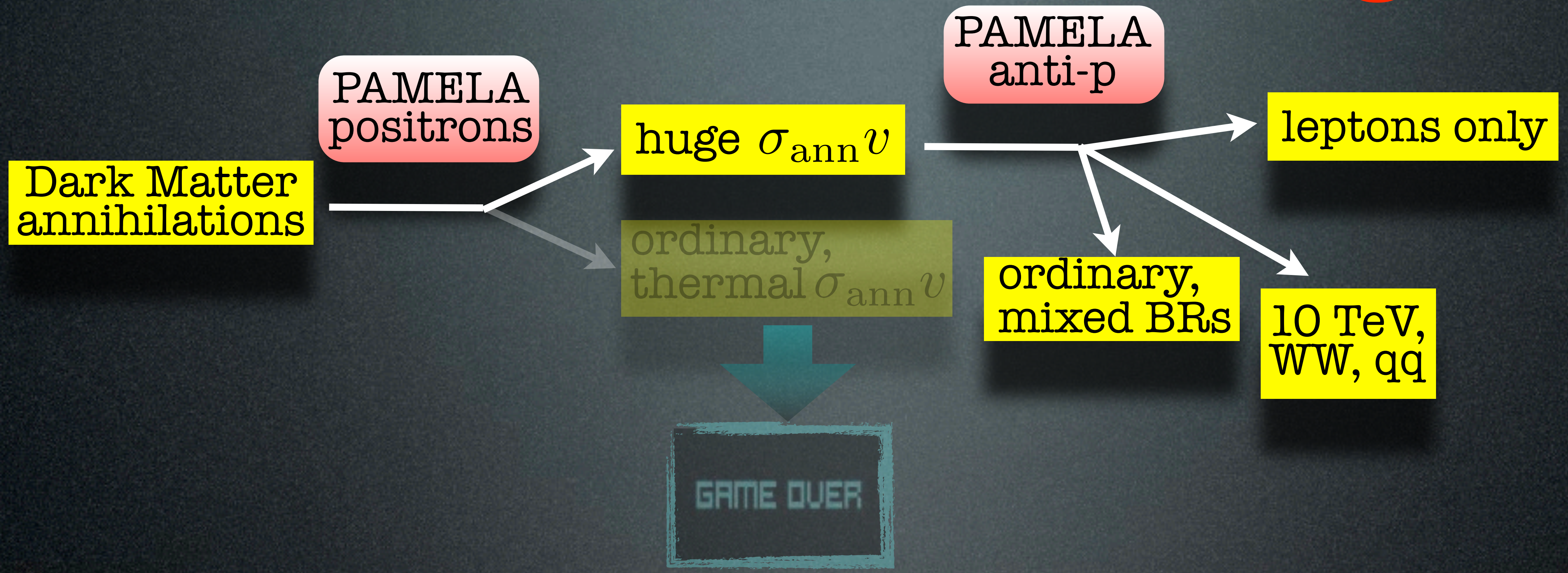

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GAME OVER

PAMELA anti-p

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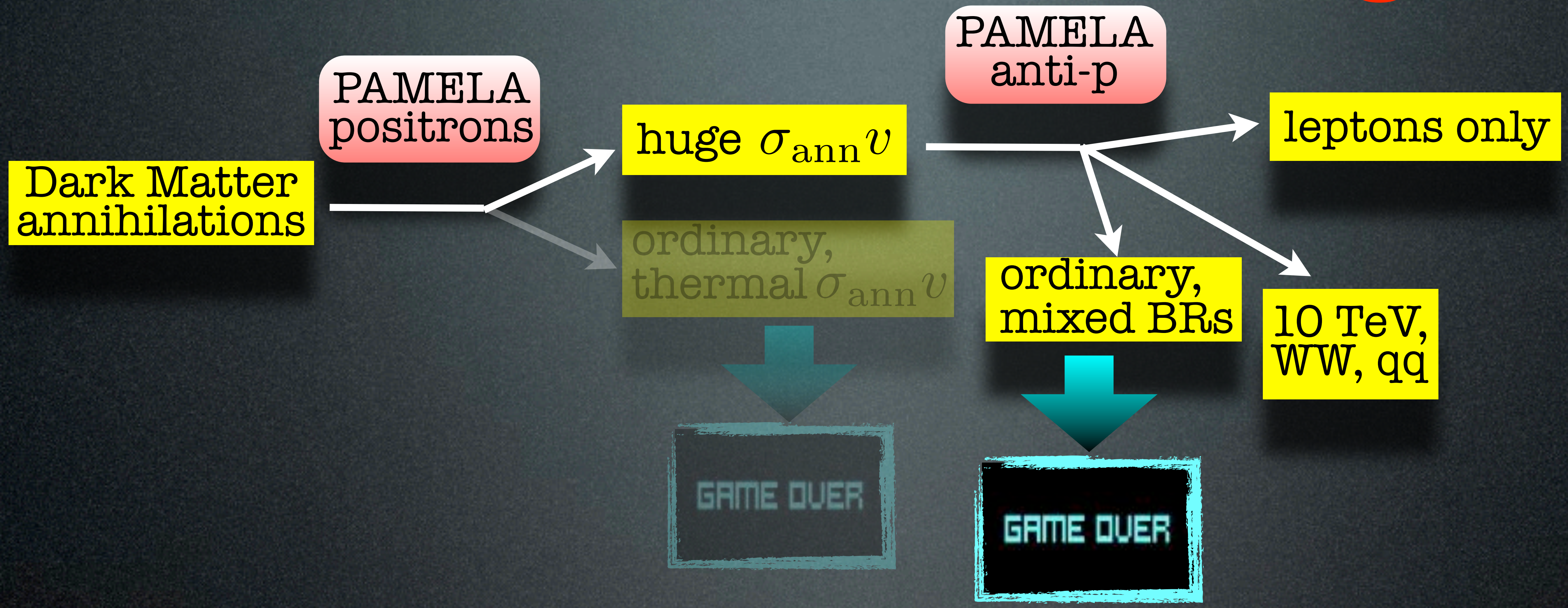

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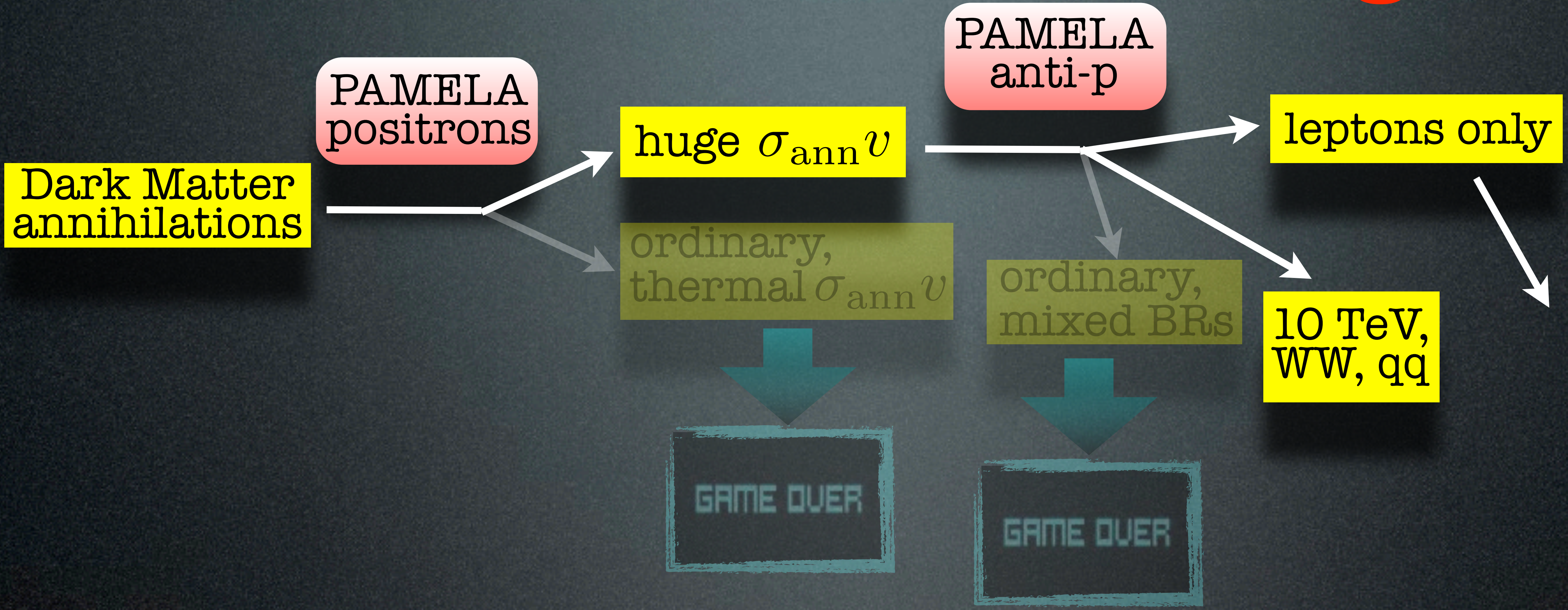

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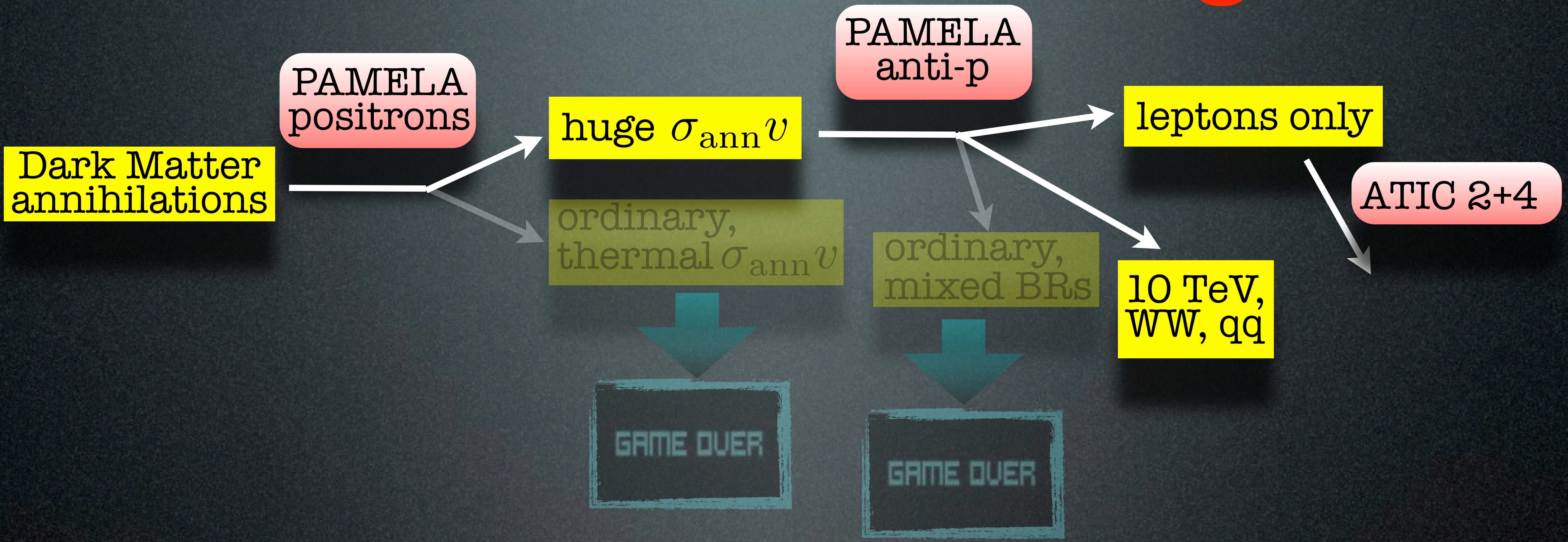

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ATIC 2+4

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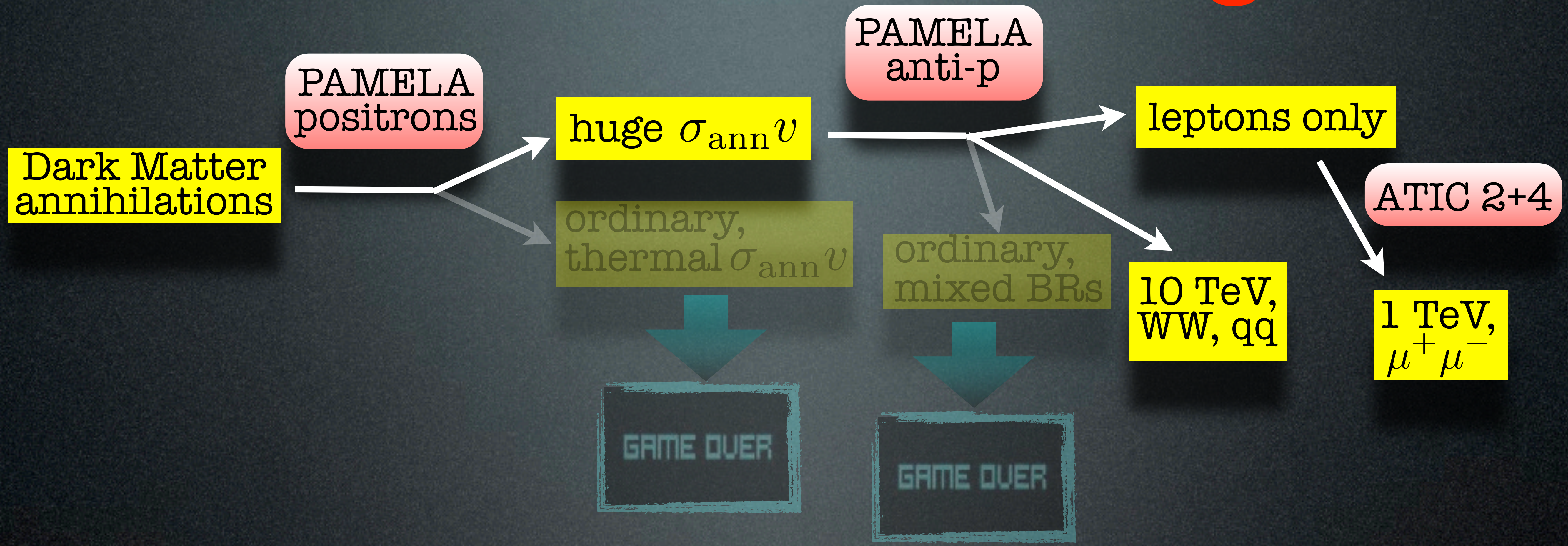

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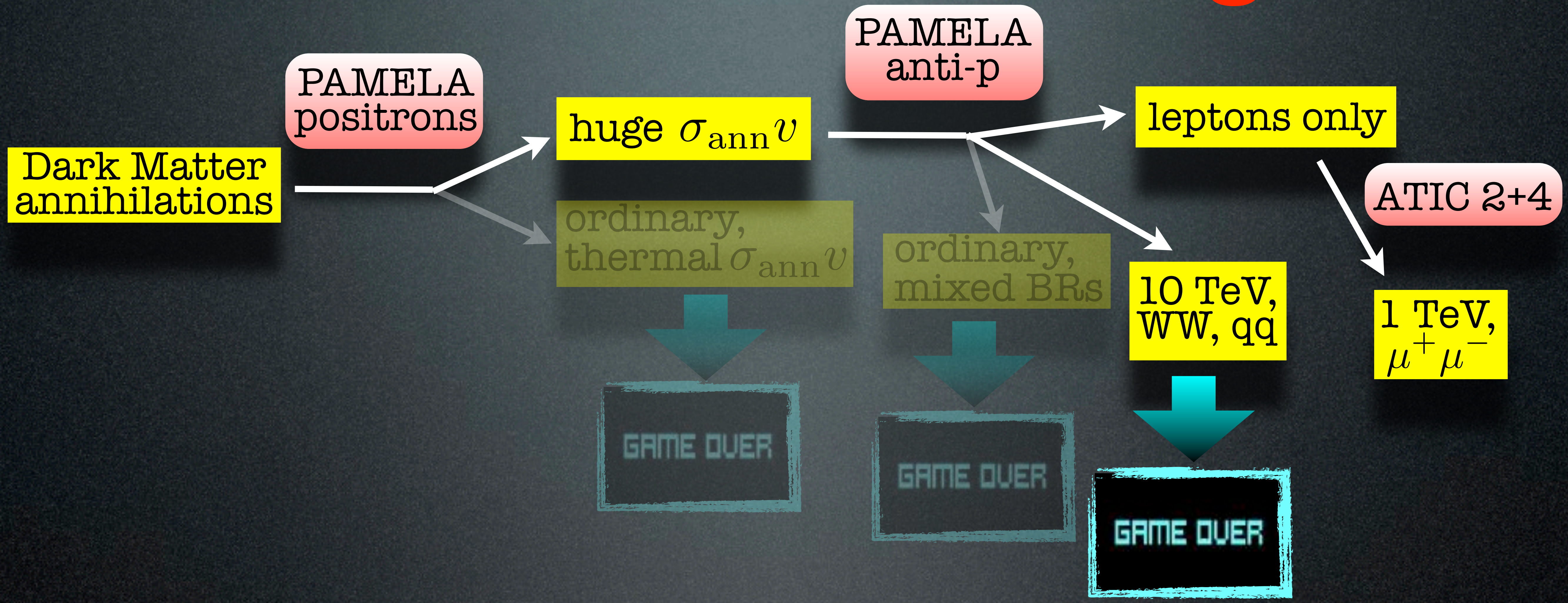

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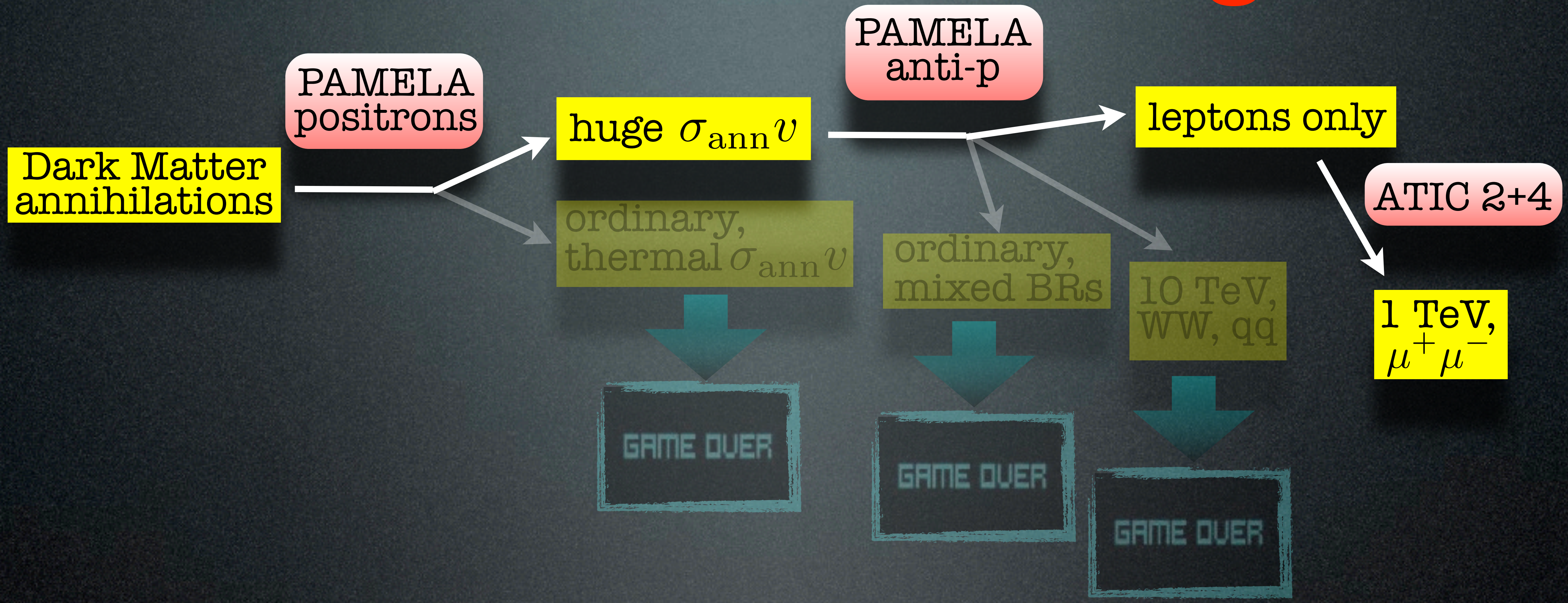

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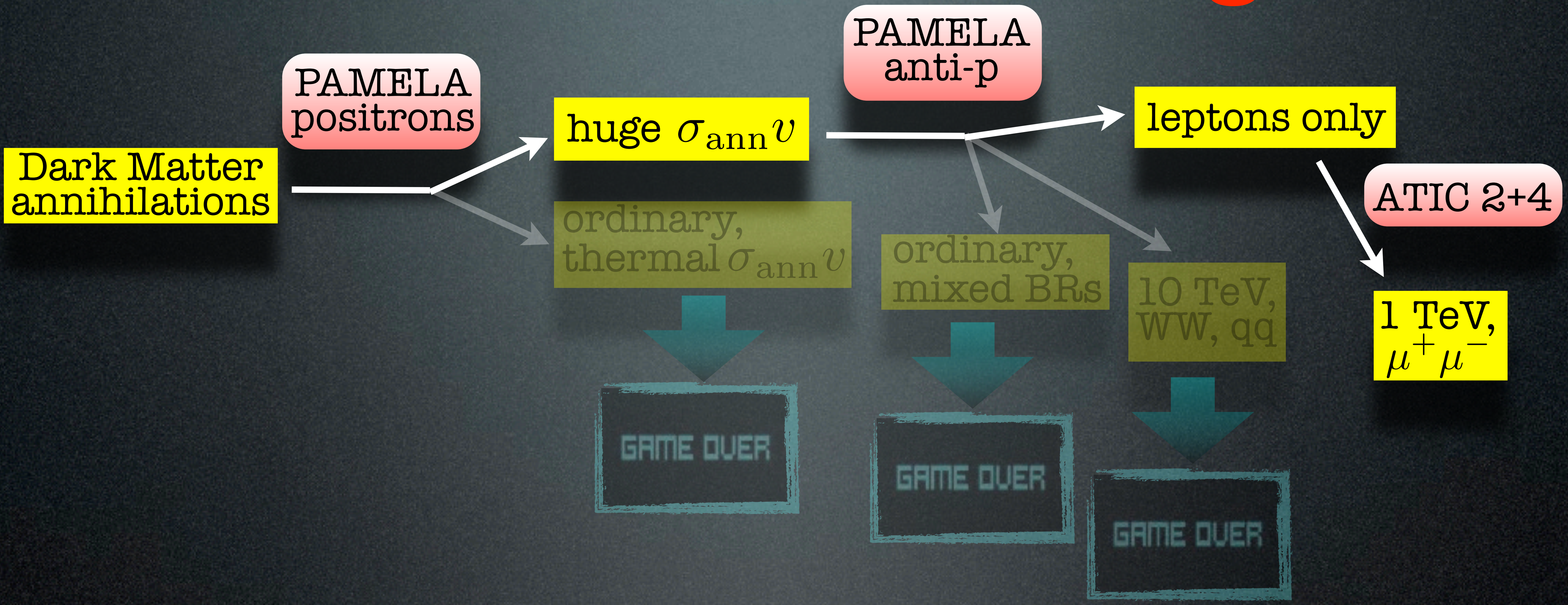

Dark Matter annihilations

PAMELA positrons

huge $\sigma_{\rm ann} v$

ordinary, thermal $\sigma_{\rm ann} v$

GAME OVER

PAMELA anti-p

leptons only

ordinary, mixed BRs

GAME OVER

10 TeV, WW, qq

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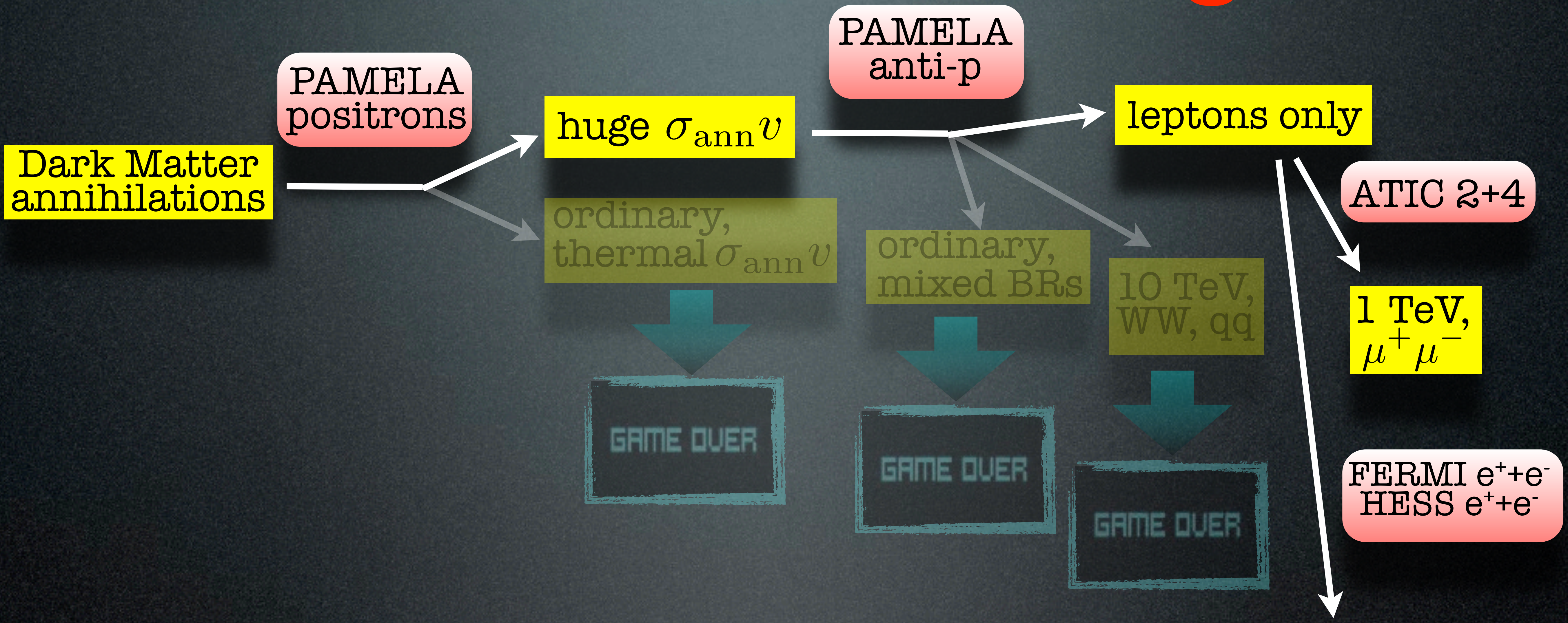

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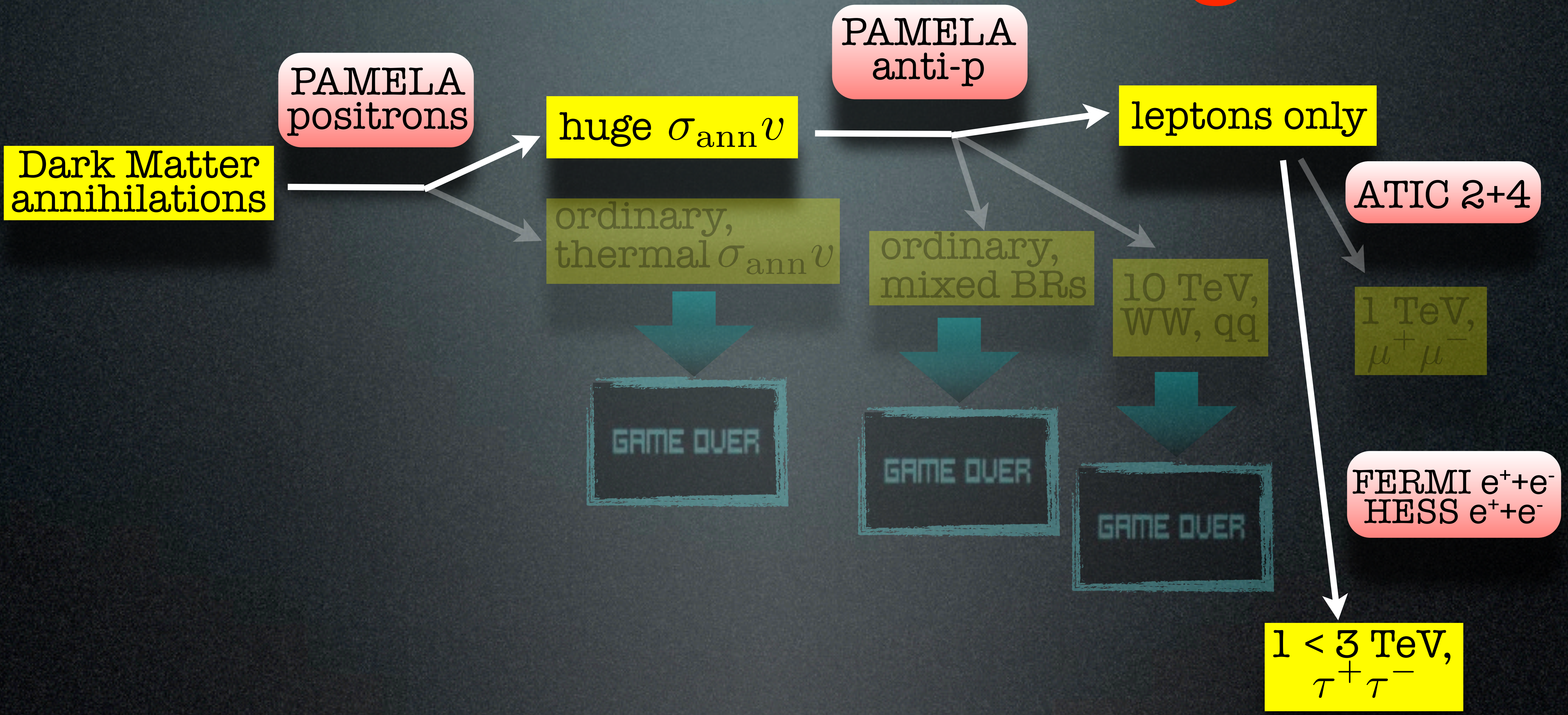

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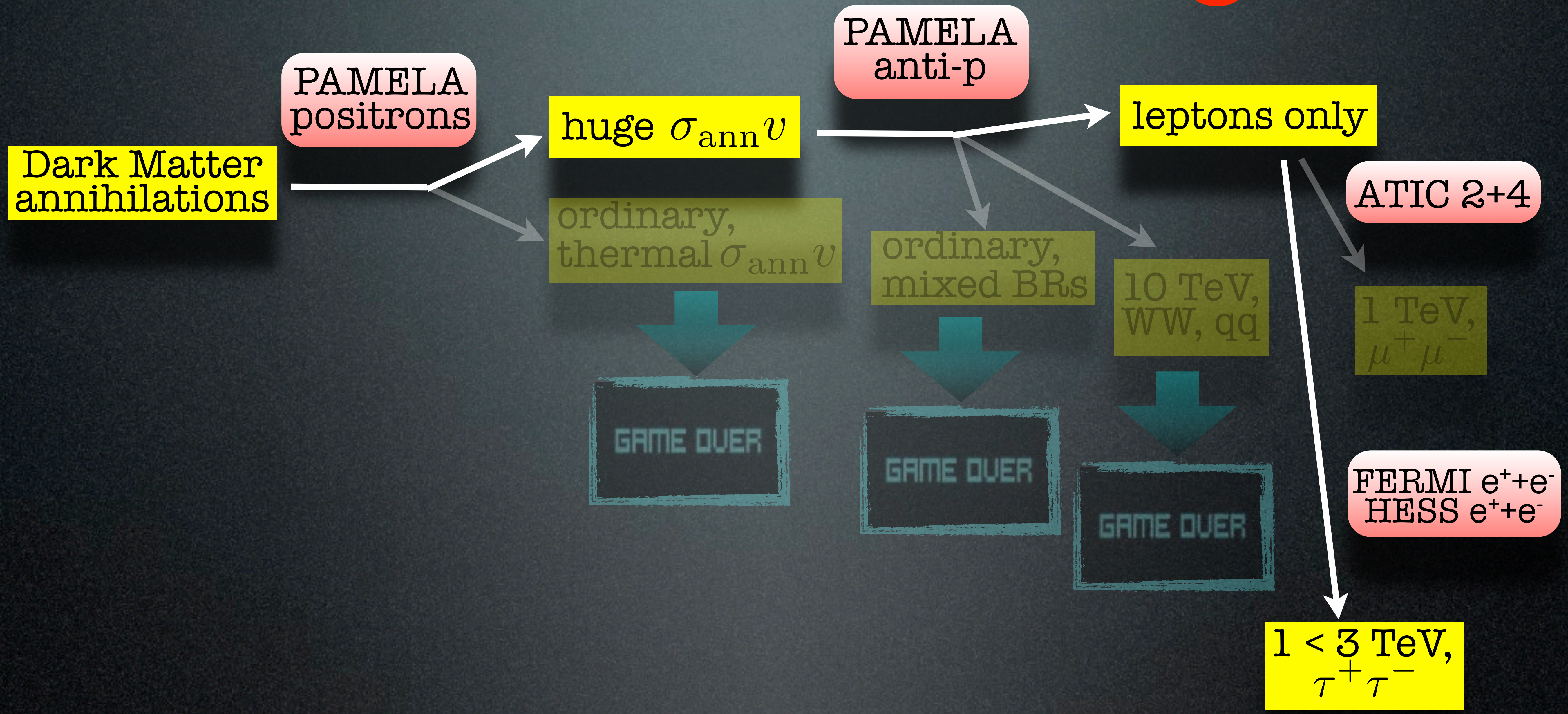

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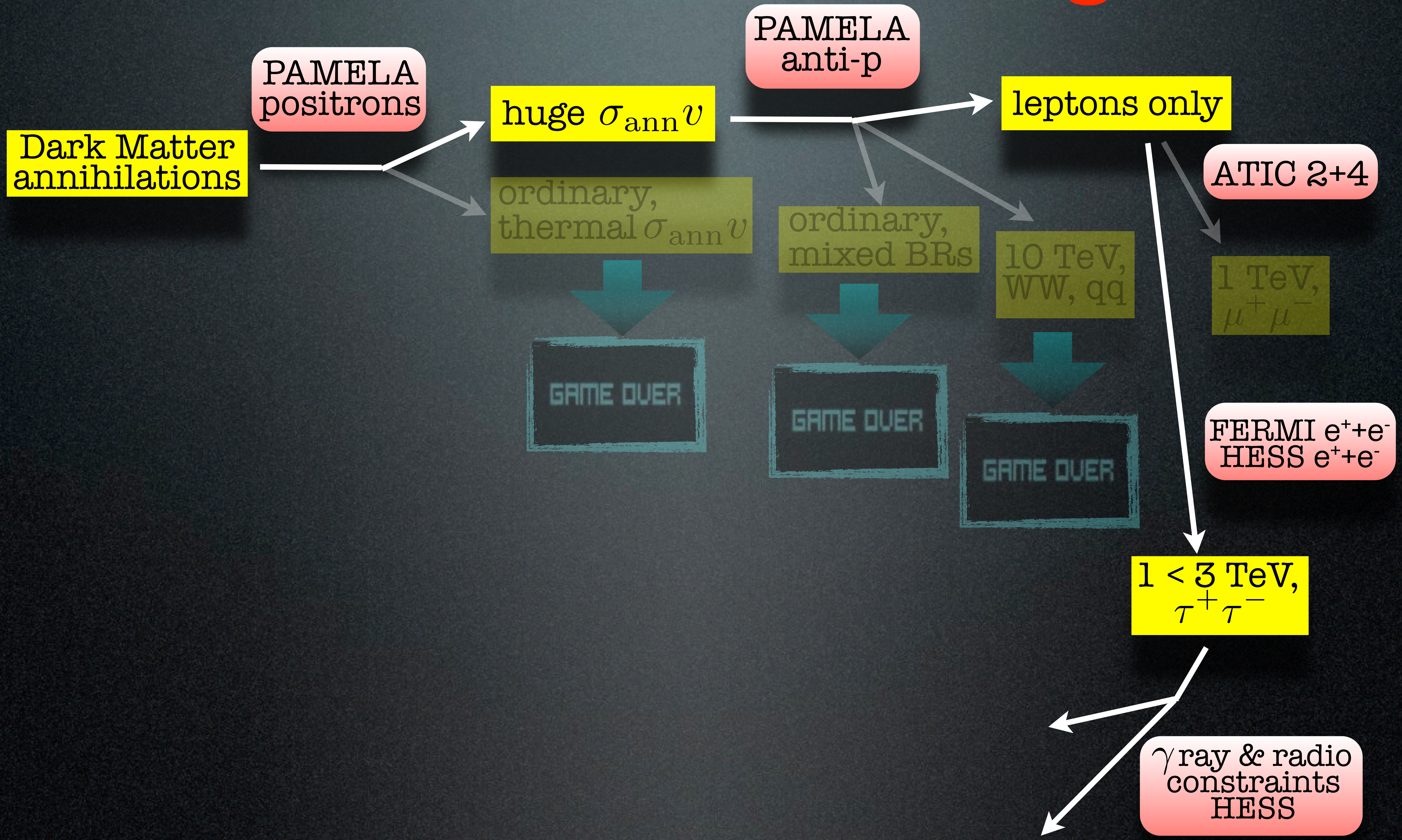

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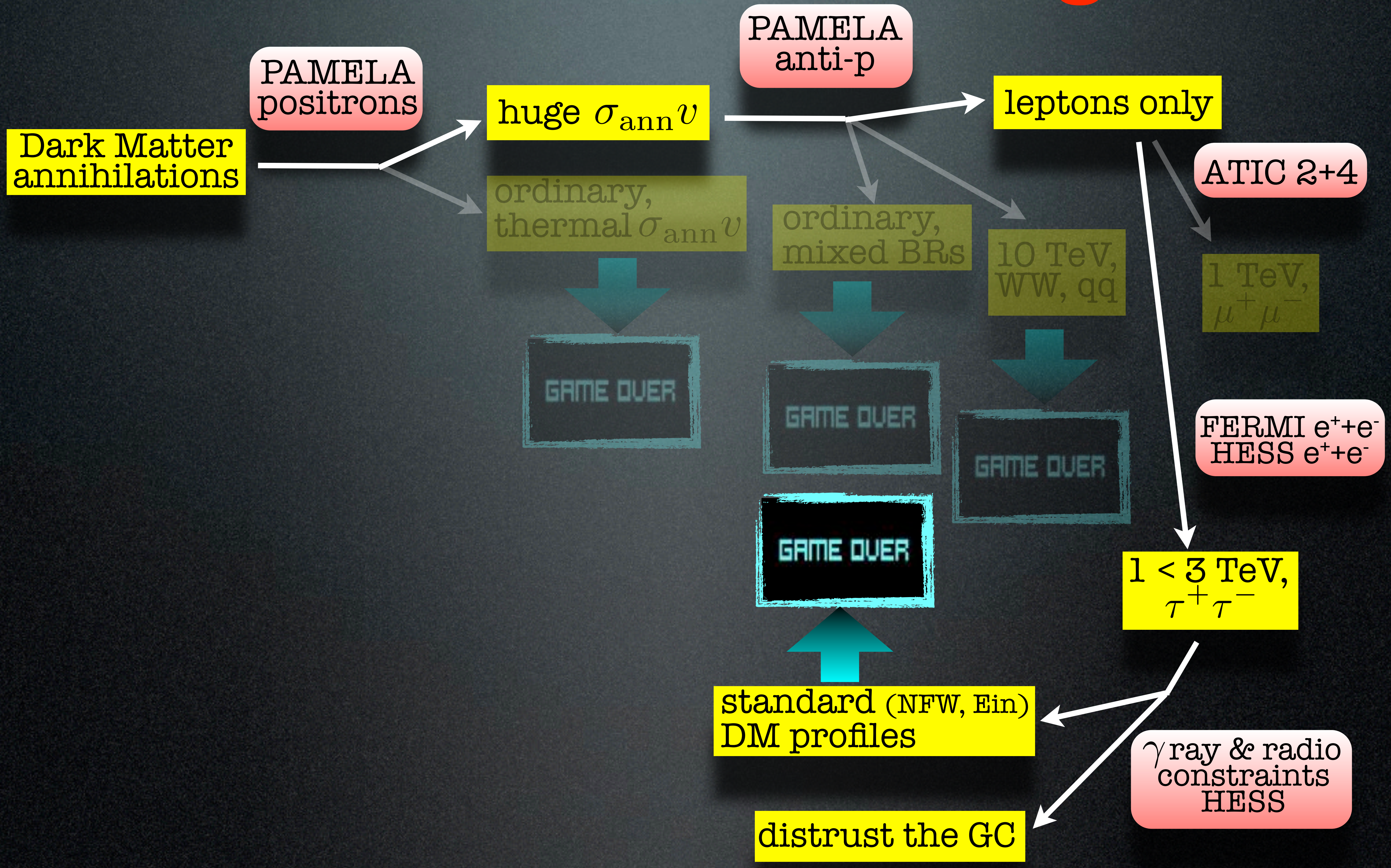

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GAME OVER

distrust the GC

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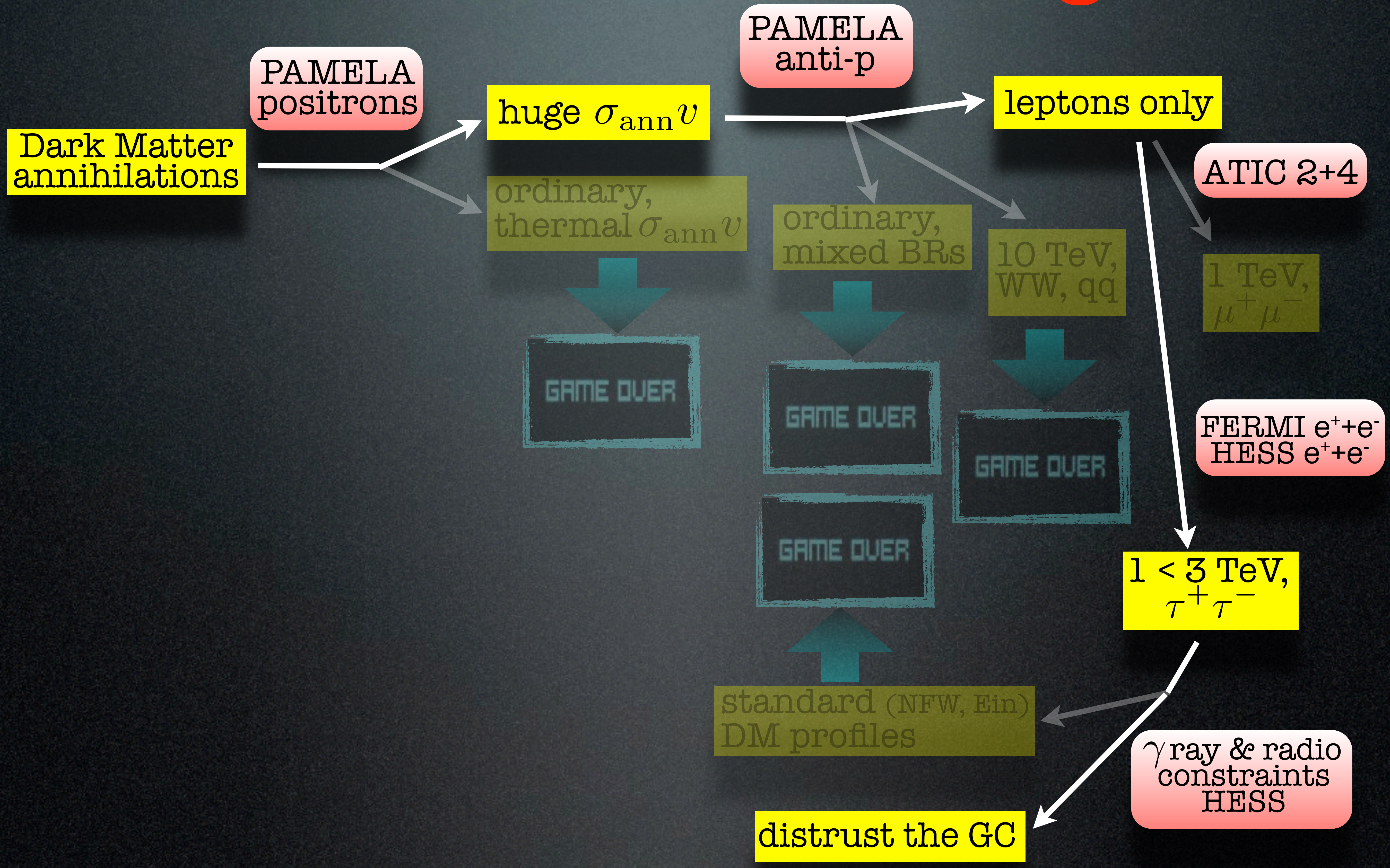

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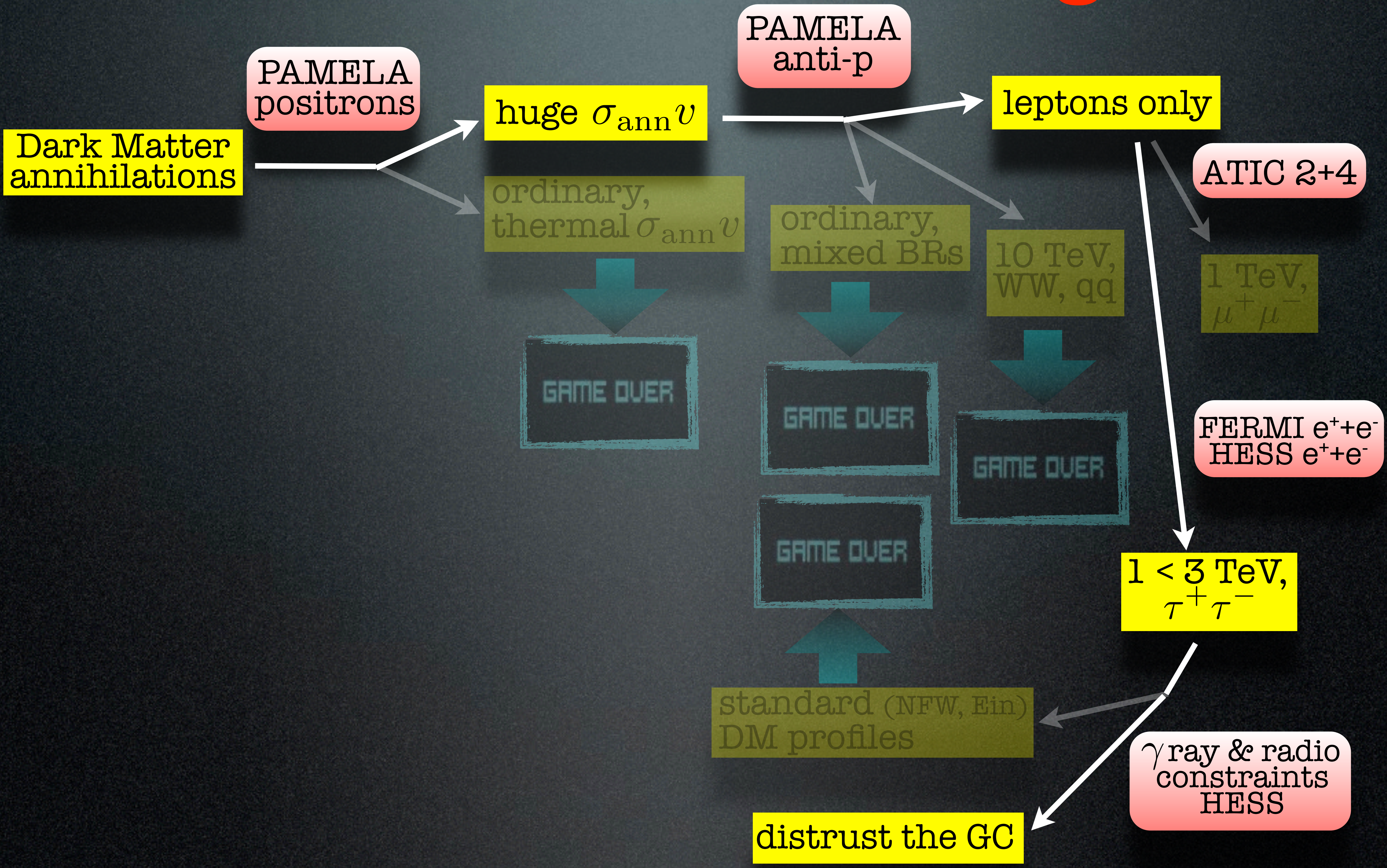

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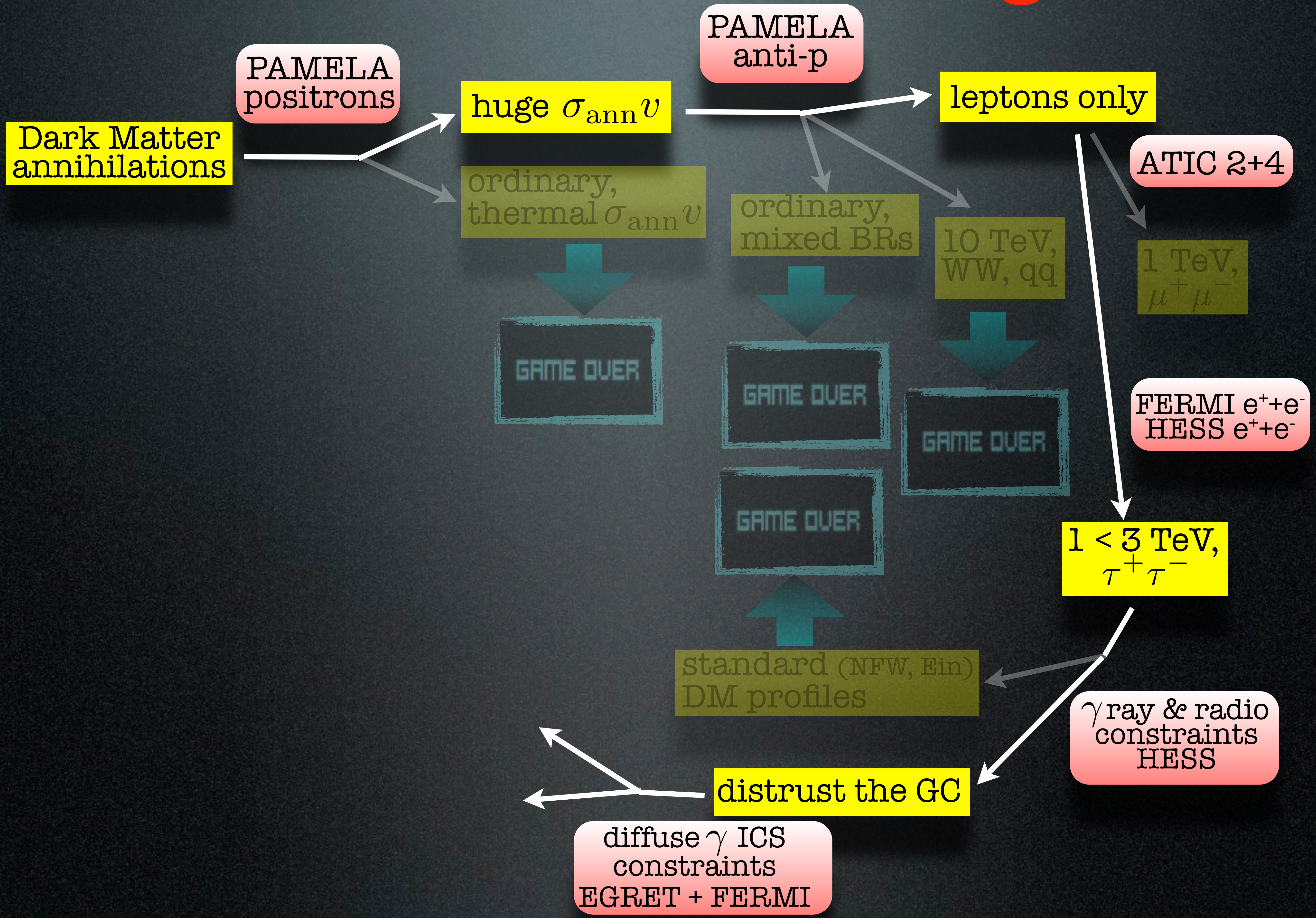

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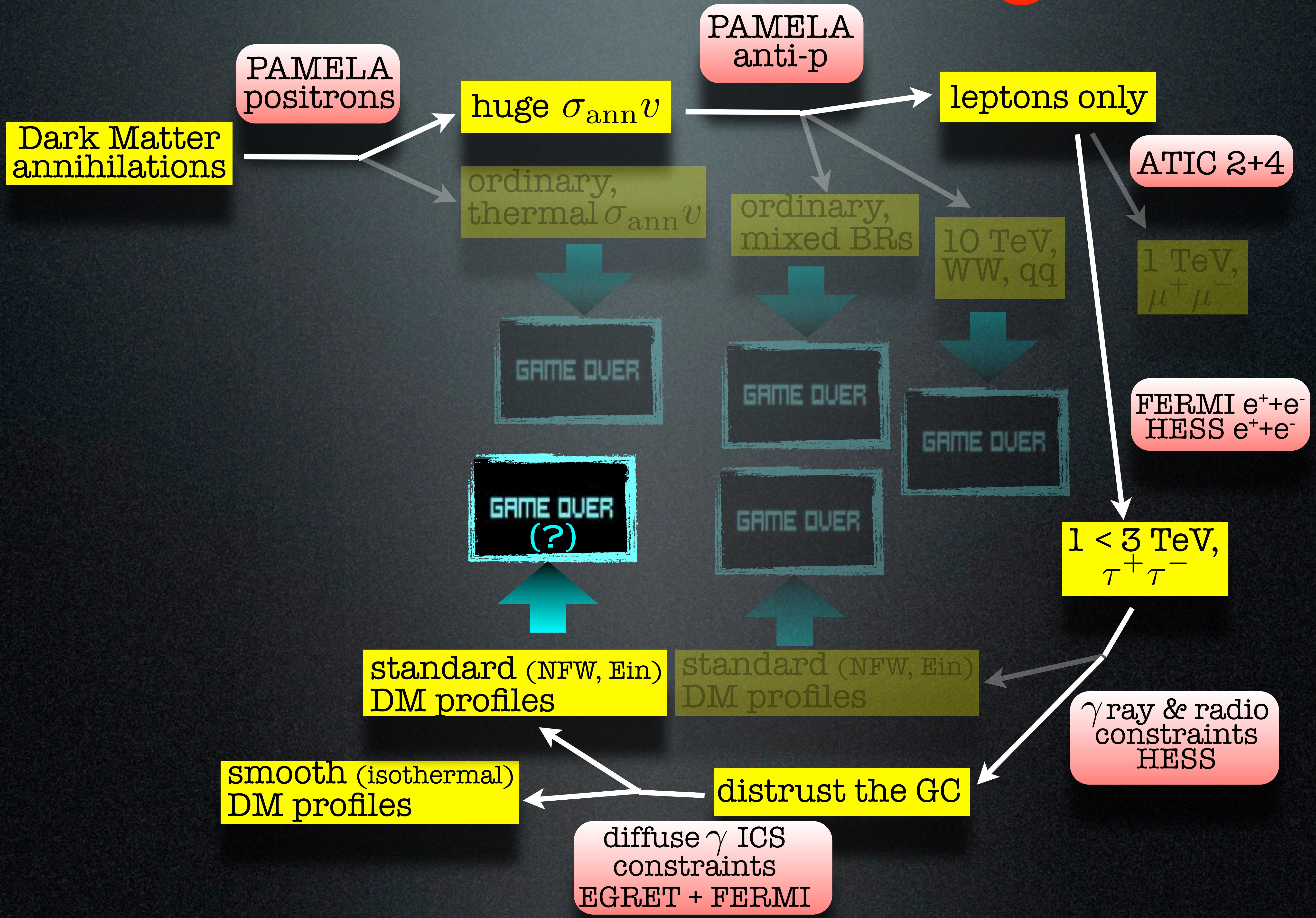

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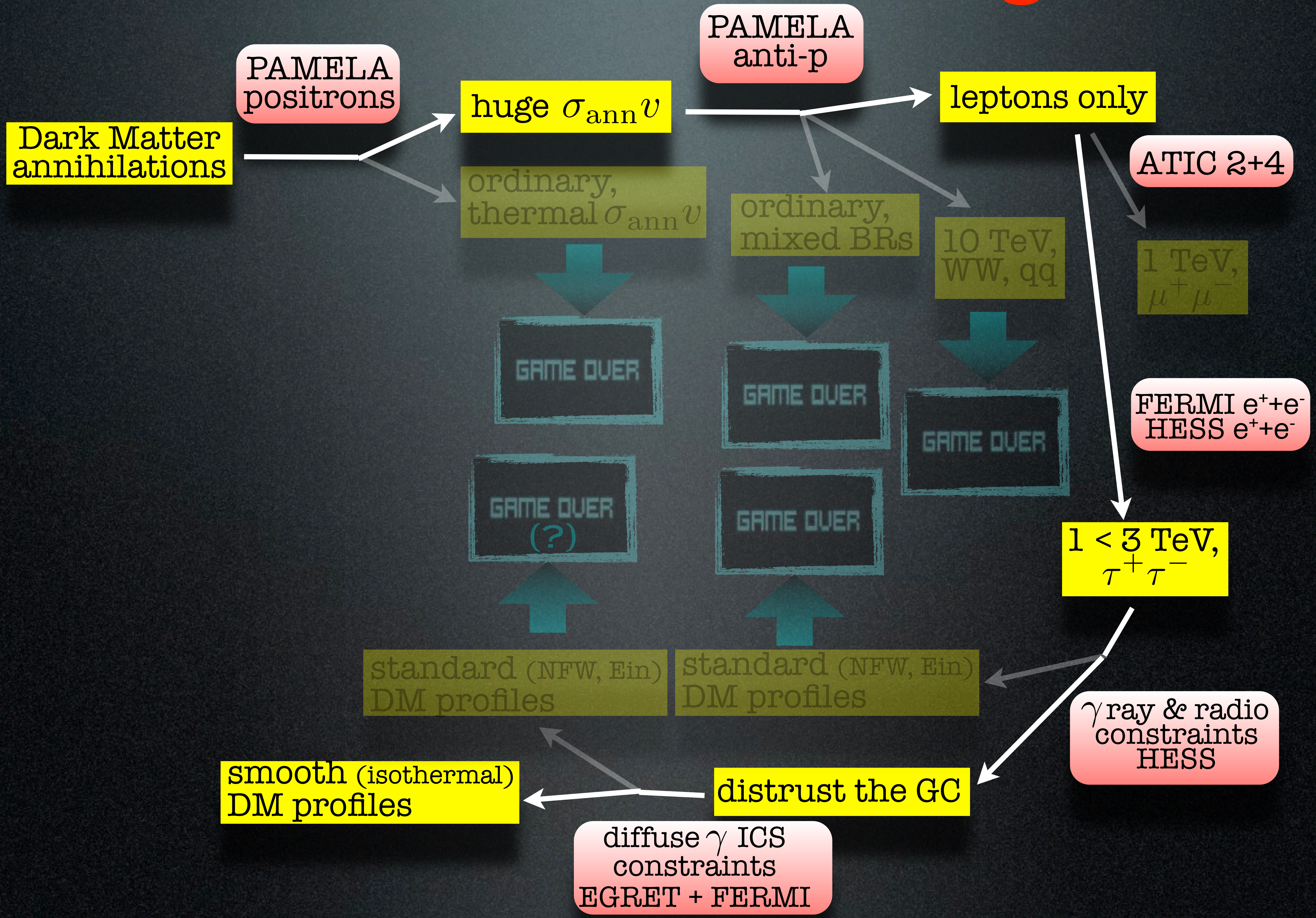

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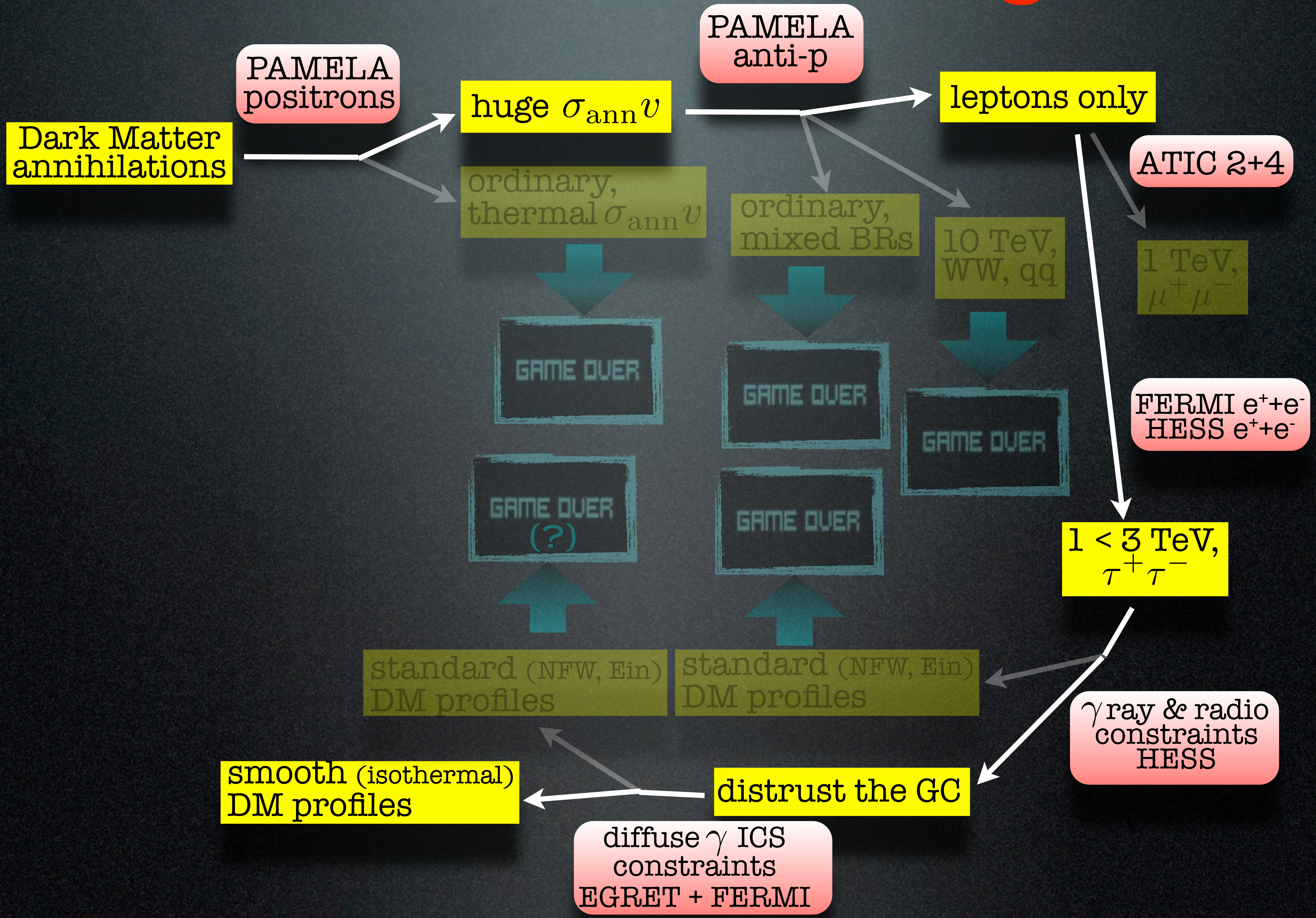

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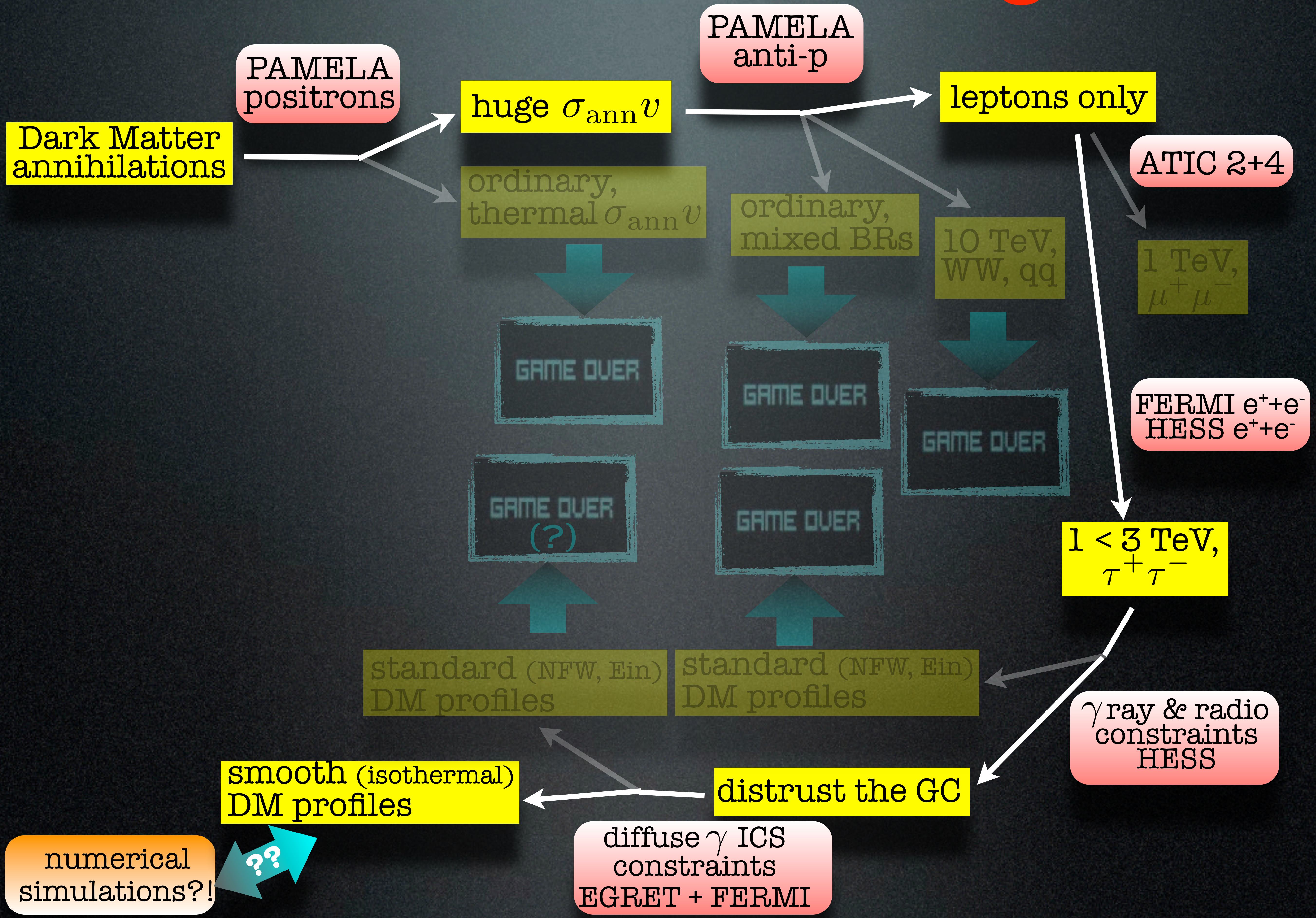

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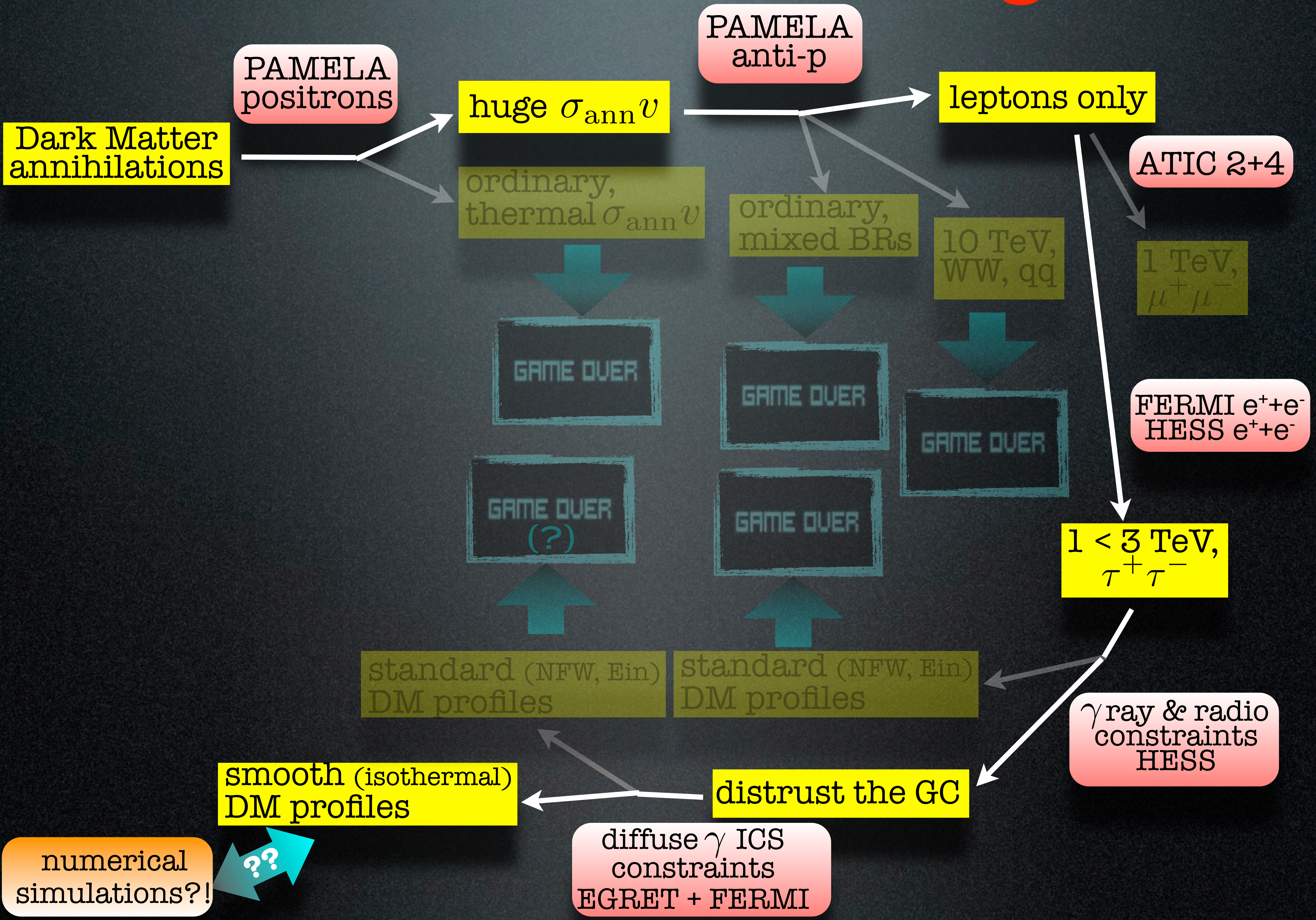

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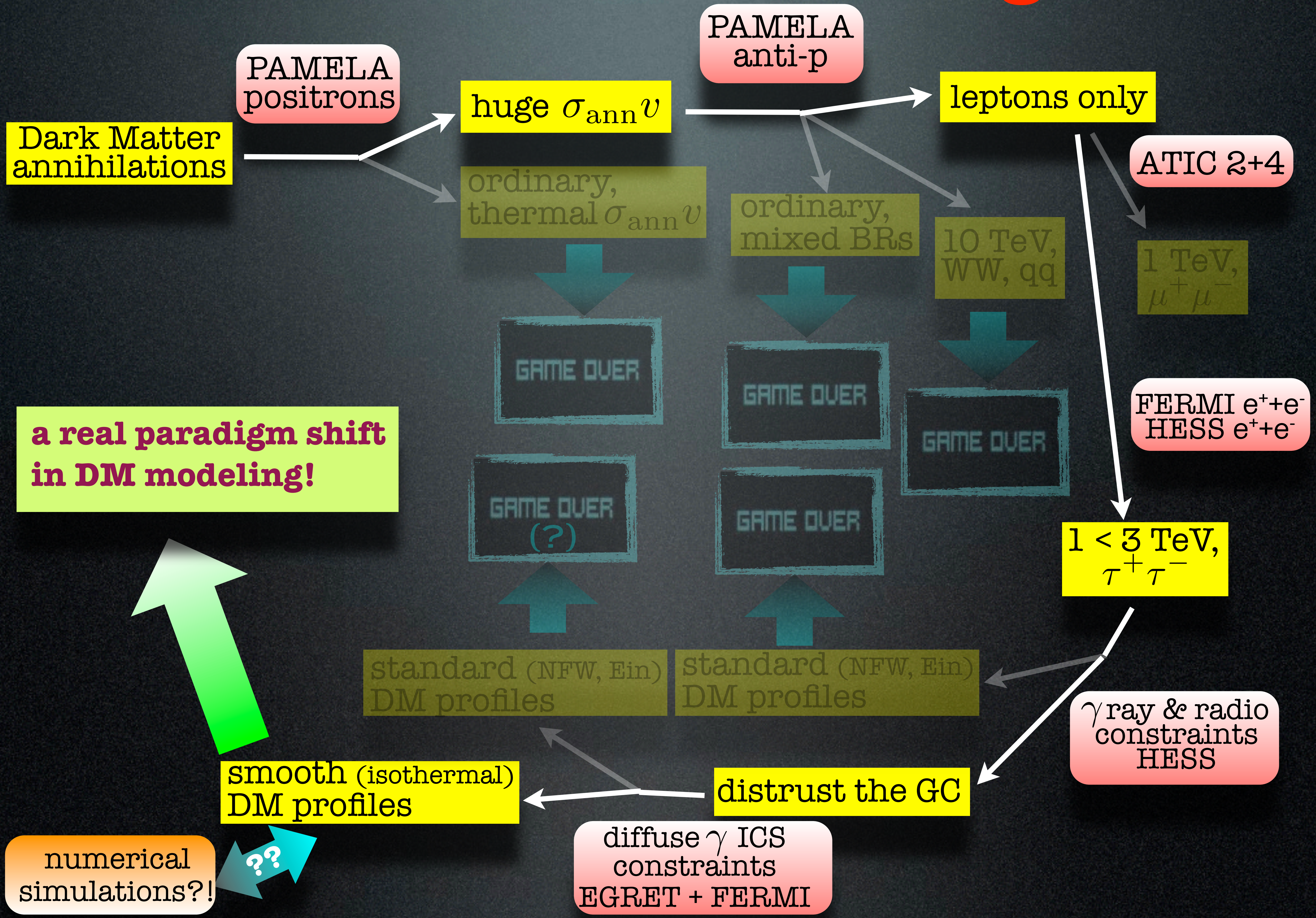

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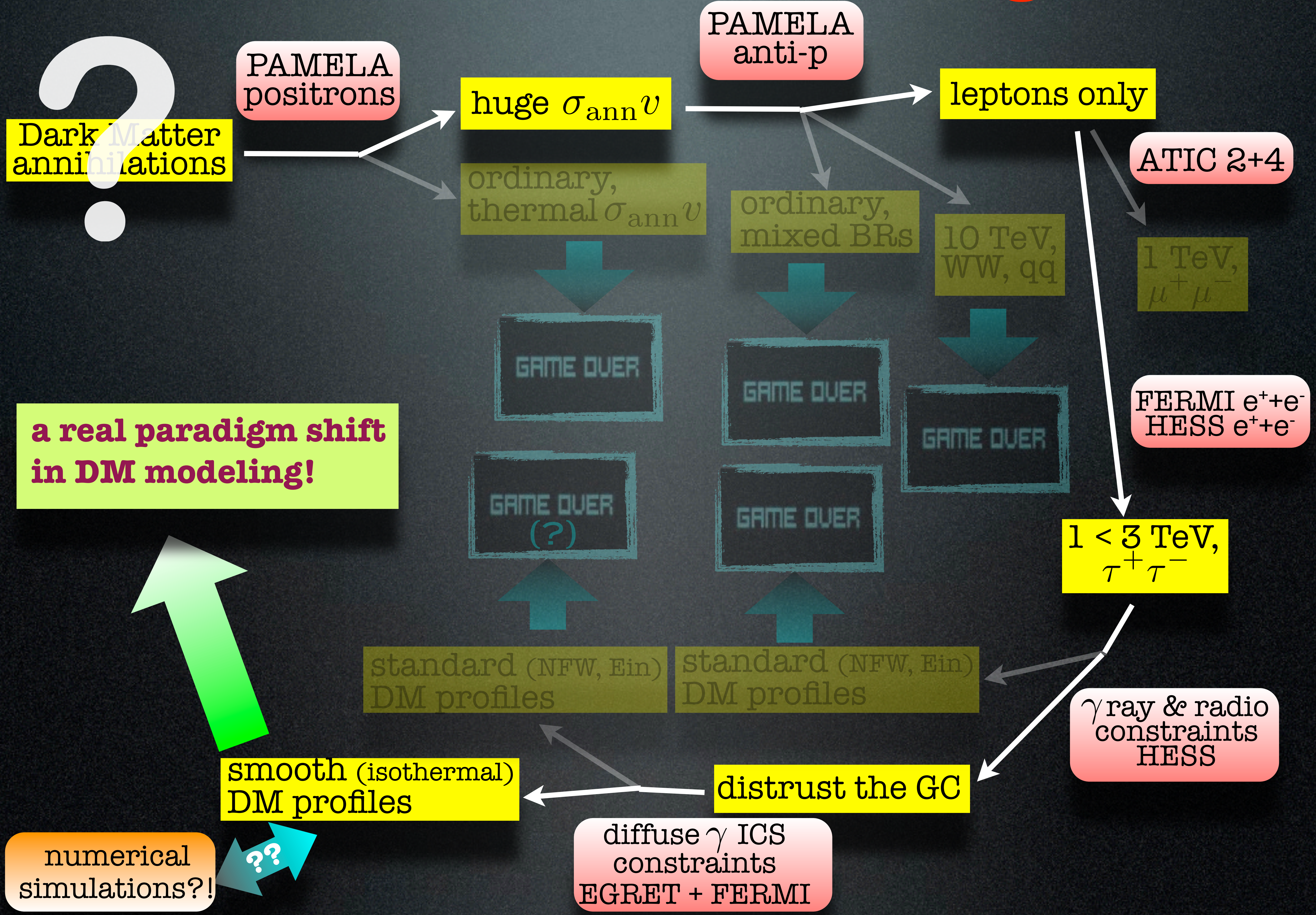

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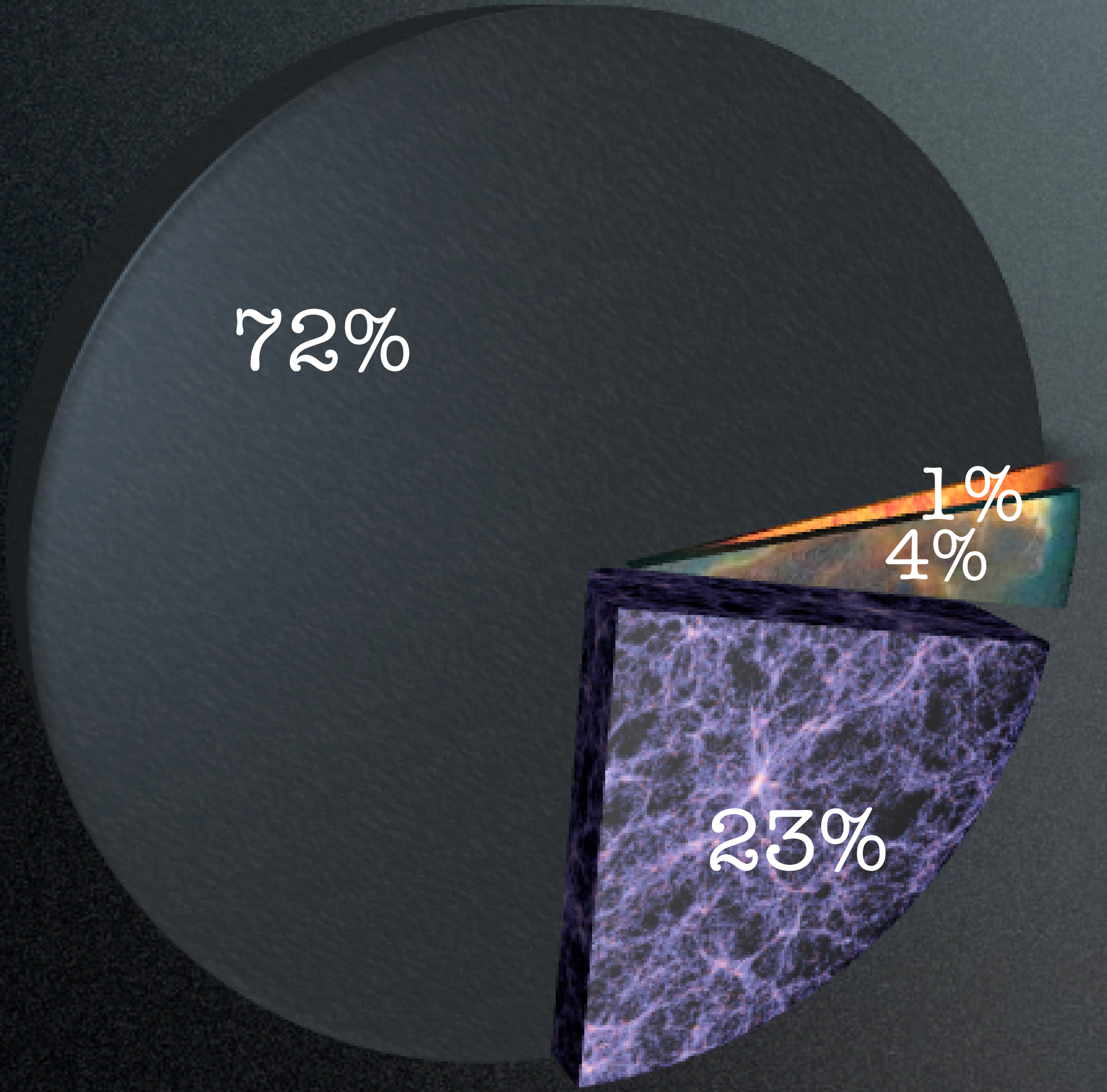
Future data (PAMELA, FERMI, AMS02...) will be crucial.
Will it be just some young, nearby pulsar?

The cosmic inventory

Most of the Universe is Dark.



FAvgQ: what's the difference between DM and DE?

DM behaves like matter

- overall it dilutes as volume expands
- clusters gravitationally on small scales
- $w = P/\rho = 0$ (NR matter)
  (radiation has $w = -1/3$)

DE behaves like a constant

- it does not dilute
- does not cluster, it is prob homogeneous
- $w = P/\rho \simeq -1$
- pulls the acceleration, FRW eq. $\frac{\ddot{a}}{a} = -\frac{4\pi G_{\mathrm{N}}}{3}(1-3w)\rho$

[back]

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

Andrey Kravtsov, cosmicweb.uchicago.edu

[back]

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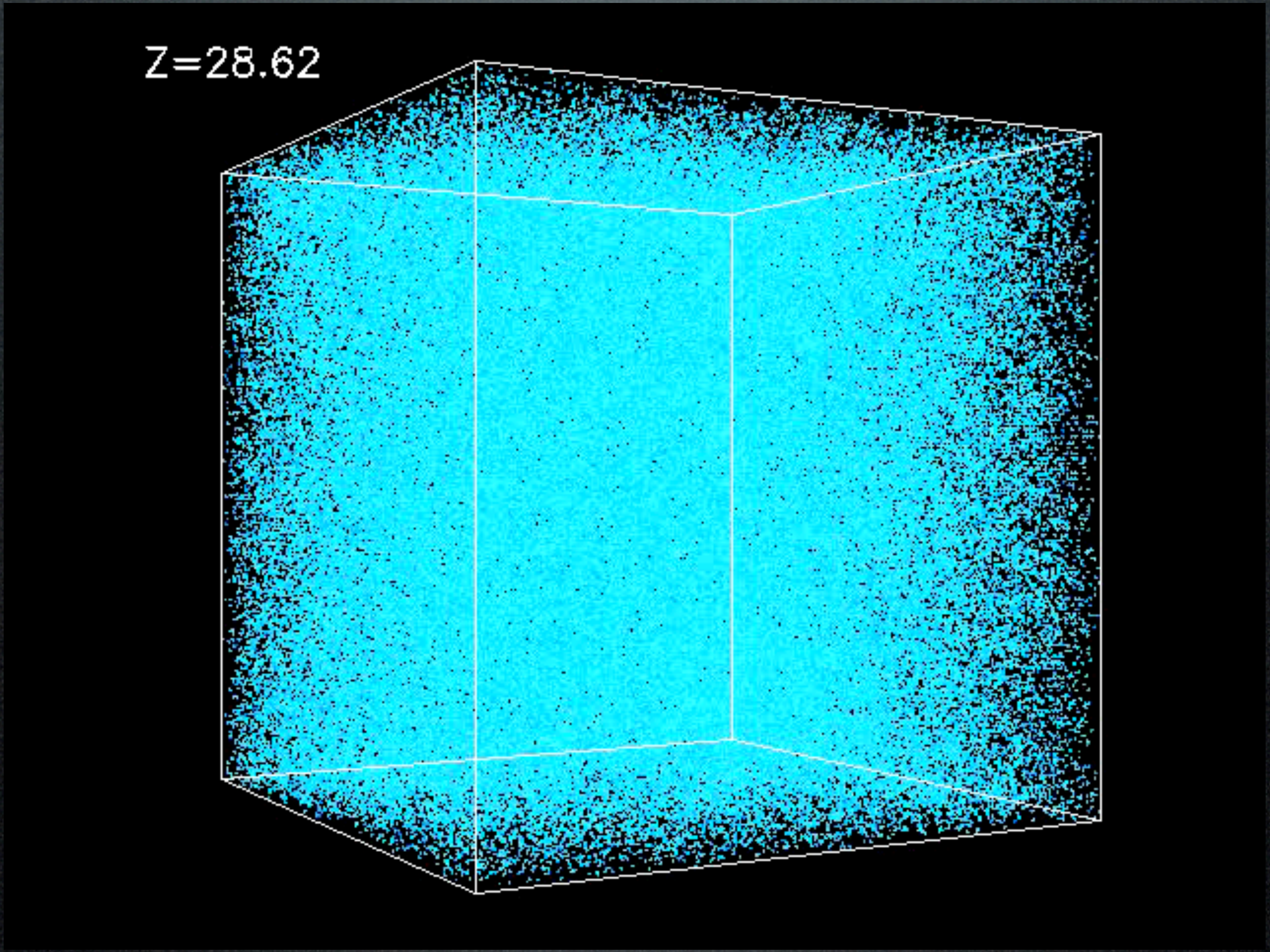

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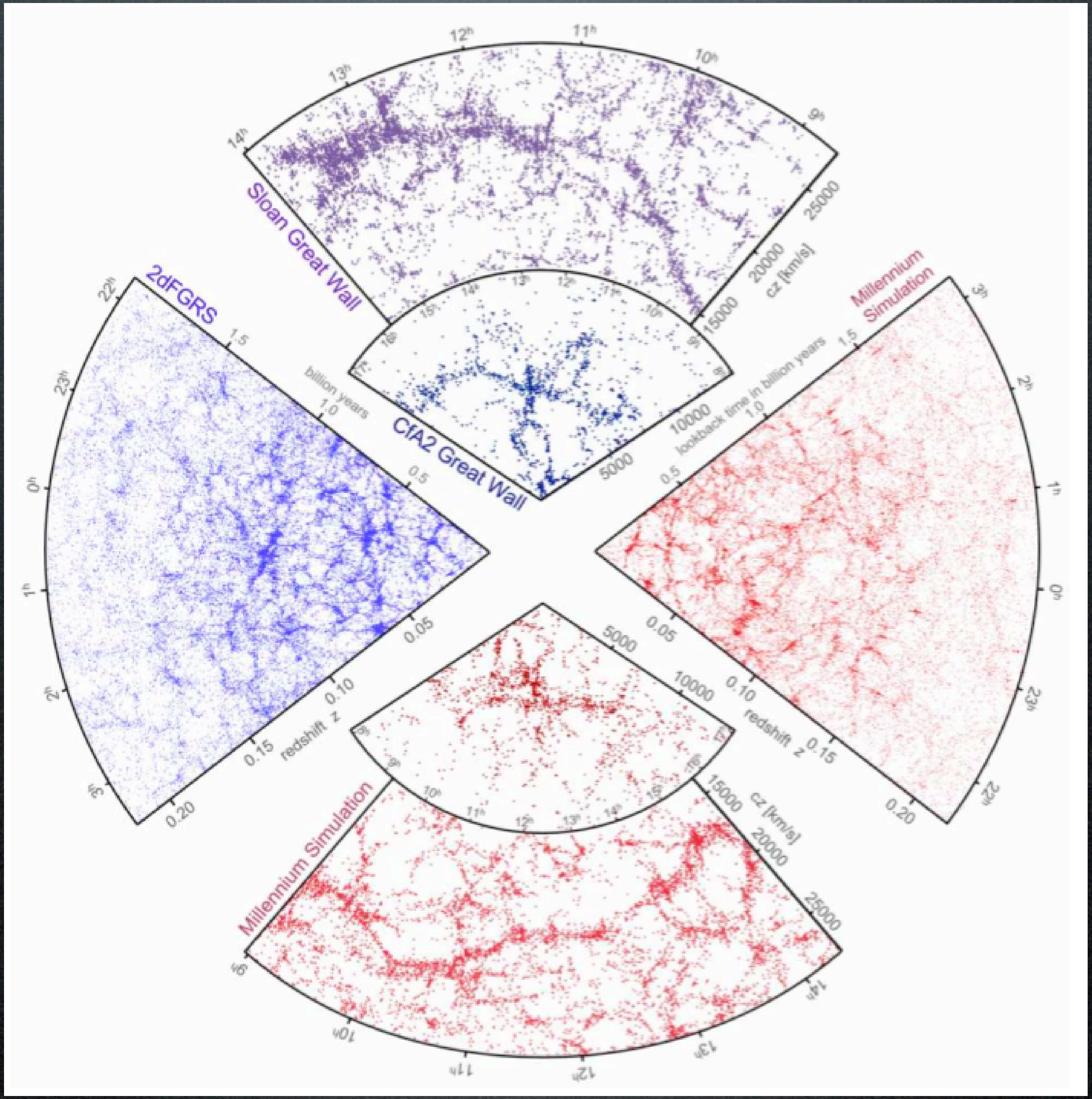
DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

Millennium:
10^{10} particles,
500 h^{-1} Mpc

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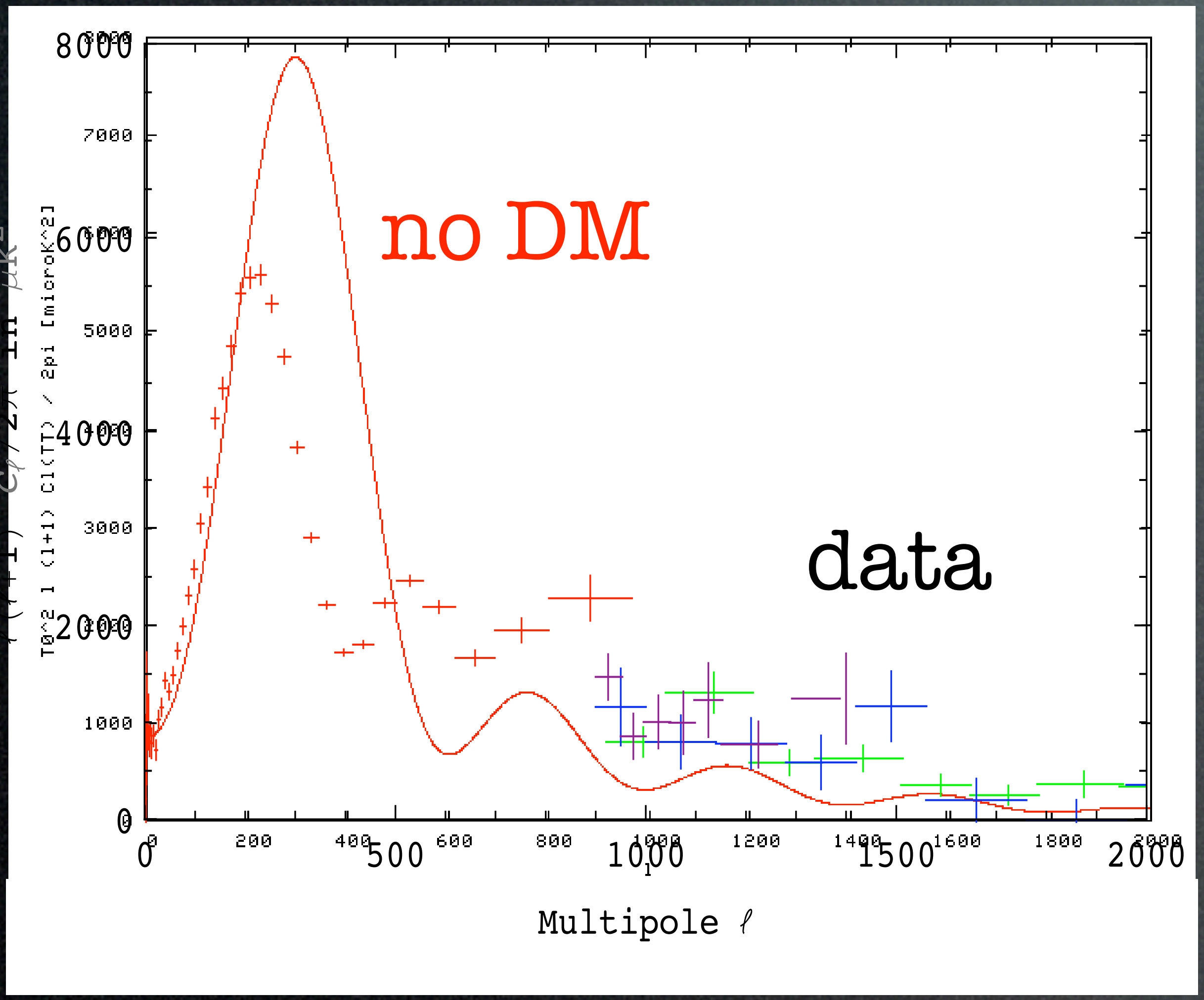
The Evidence for DM

How would the power spectra be without DM?
(and no other extra ingredient)

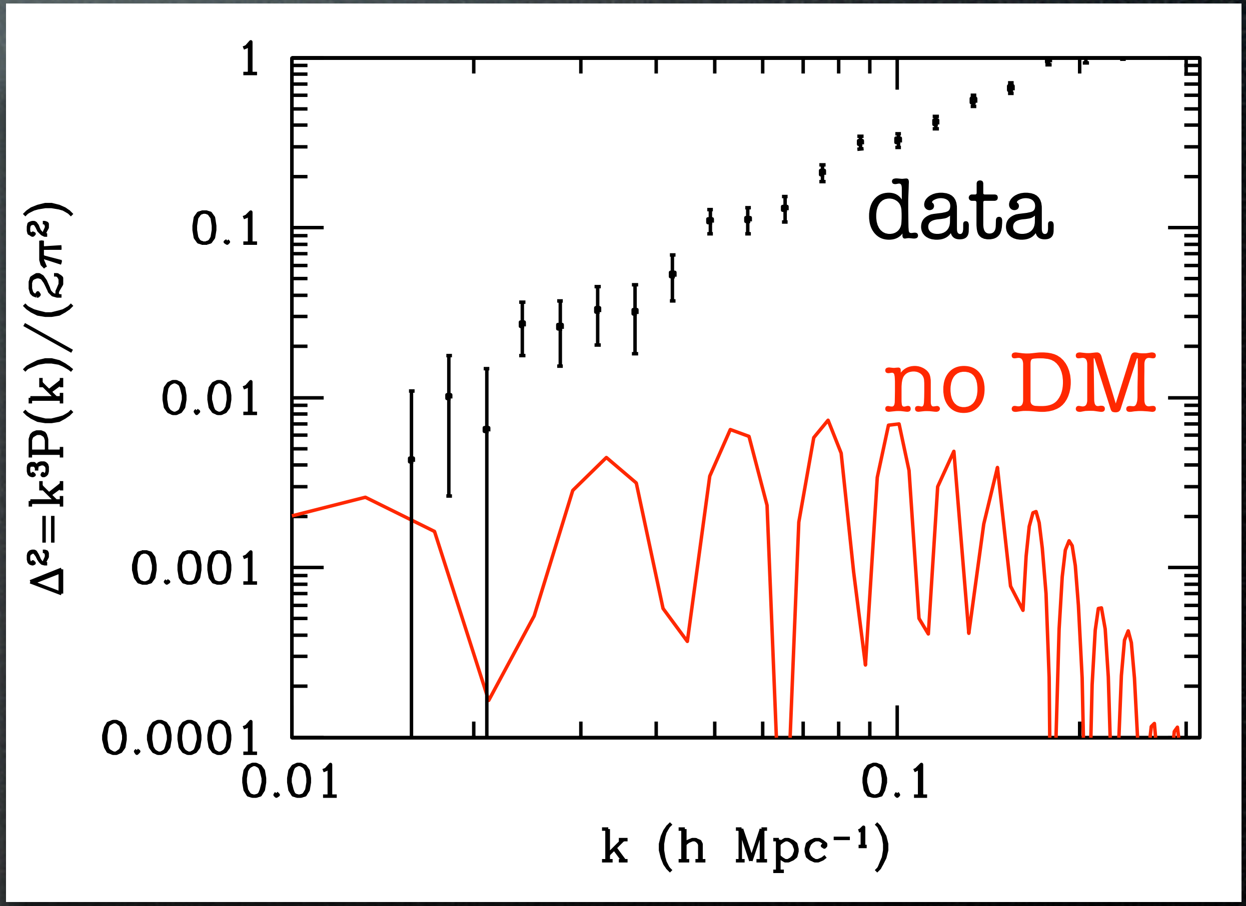
CMB



CAMB online

(in particular: no DM => no 3rd peak!)

LSS



Dodelson, Liguori 2006

(you need DM to gravitationally
“catalyse” structure formation)

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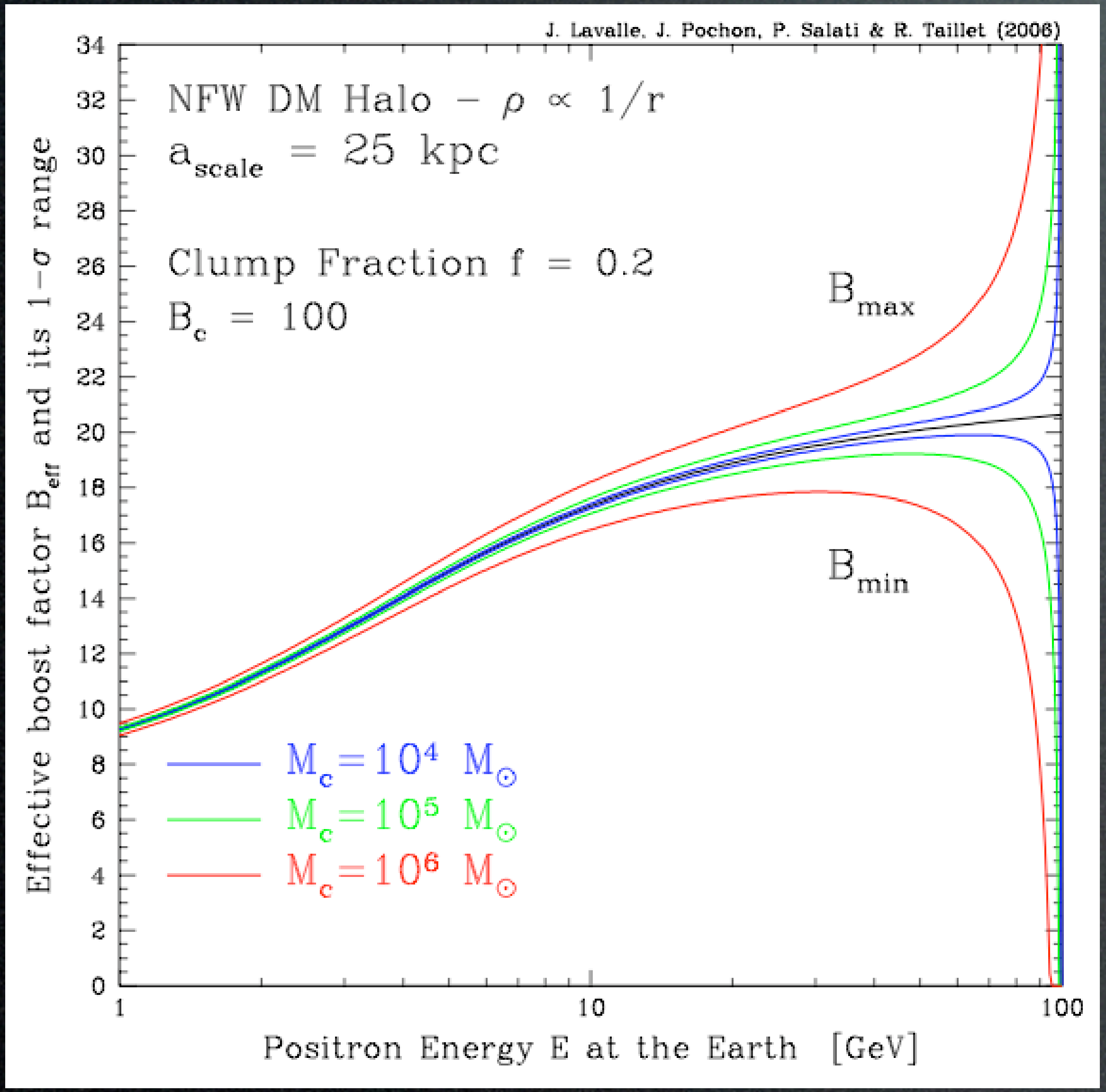
Indirect Detection

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

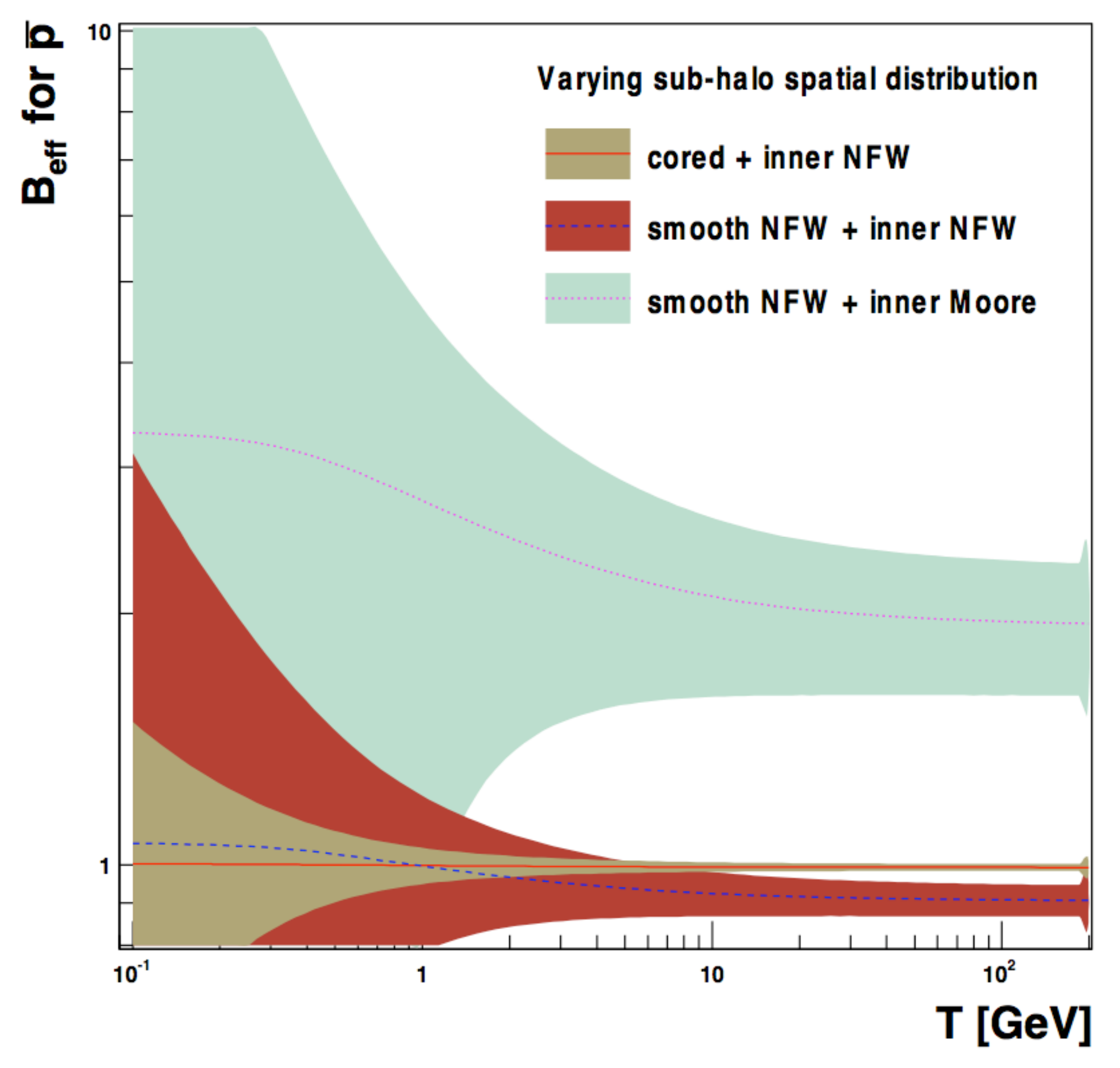
In principle, B is different for e^+, anti-p and gammas,
energy dependent,
dependent on many astro assumptions (inner density profile of clump, tidal disruptions and smoothing...),
with an energy dependent variance, at high energy for e^+, at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons



Lavalle et al. 2007

Indirect Detection

Propagation for positrons:

$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) = Q$$

diffusion

(in turbulent $\bar{B} \approx \mu\mathrm{G}$, assumed space indep.)

$$K(E) = K_0 (E/\mathrm{GeV})^{\delta}$$

energy loss

$$b(E) = (E/\mathrm{GeV})^2/\tau_E$$

$$\tau_E = 10^{16}\ \mathrm{s}$$

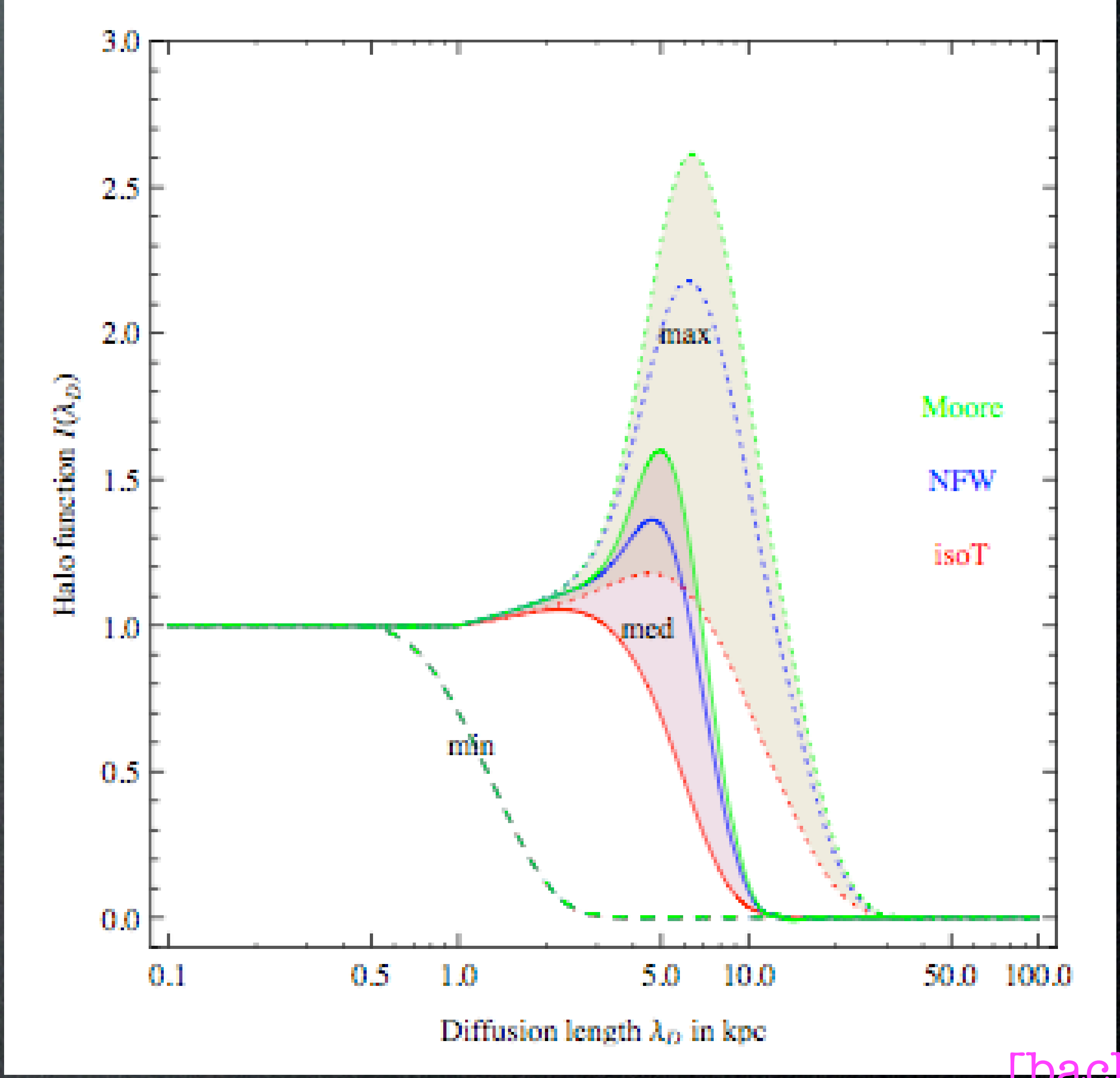
$$Q = \frac{1}{2}\left(\frac{\rho}{M_{\mathrm{DM}}}\right)^2 f_{\mathrm{inj}}, \qquad f_{\mathrm{inj}} = \sum_k \langle\sigma v\rangle_k \frac{dN^k_{e^+}}{dE}$$

Model	δ	K_0 in kpc^2/Myr	L in kpc
min (M2)	0.55	0.00595	1
med	0.70	0.0112	4
max (M1)	0.46	0.0765	15

Solution:

$$\Phi_{e^+}(E,\vec{r}_\odot) = B\frac{v_{e^+}}{4\pi}\frac{\tau_E}{E^2}\int_E^{M_{\mathrm{DM}}} dE'\ Q(E')\cdot I\left(\lambda_D(E,E')\right)$$

$$\lambda_D^2 = 4K_0\tau_E\left[\frac{(E/\mathrm{GeV})^{\delta-1} - (E'/\mathrm{GeV})^{\delta-1}}{\delta - 1}\right]$$



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Indirect Detection

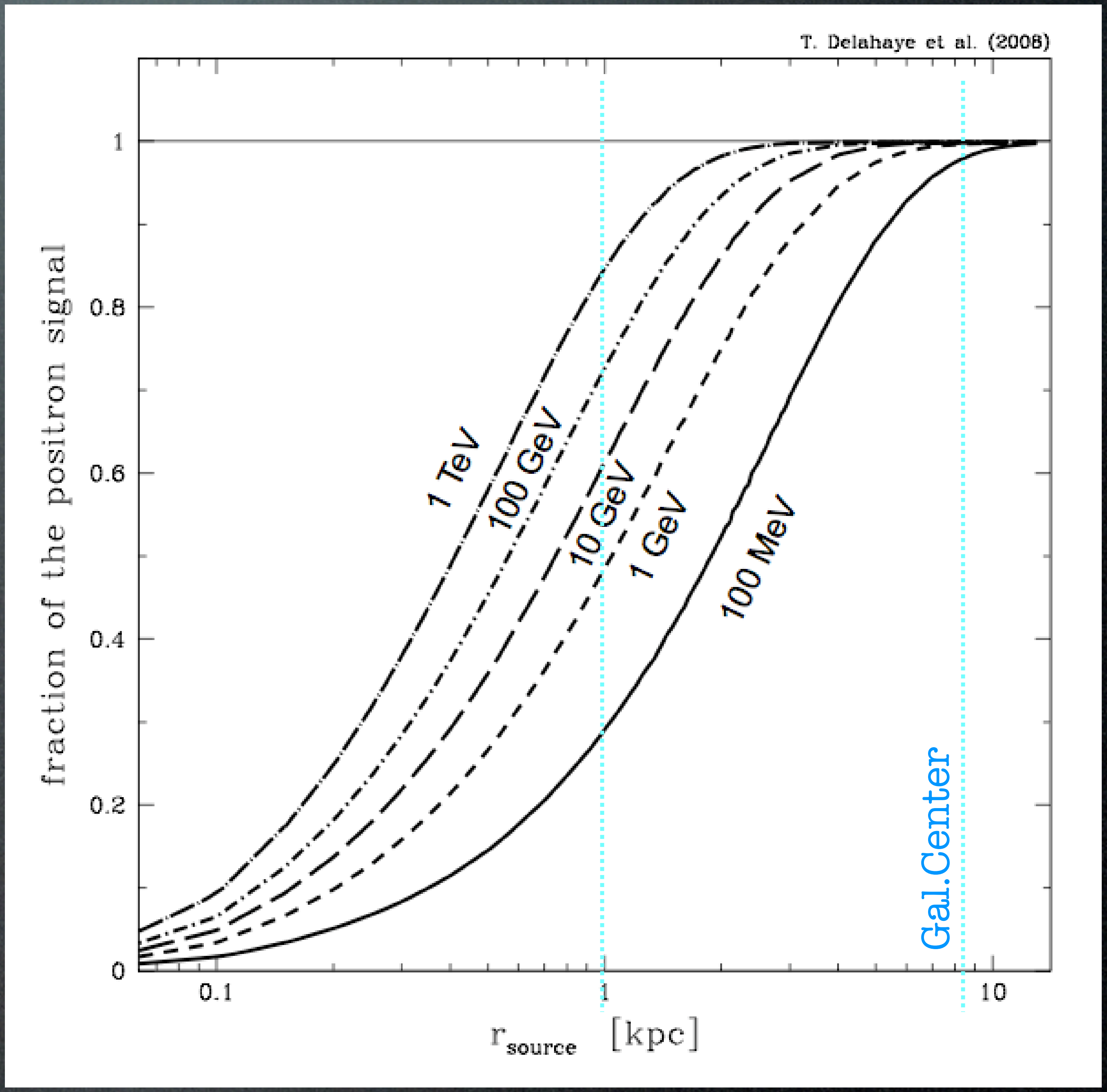
Where do positrons come from?

Mostly locally, within 1 kpc (more so at higher energy).

Typical lifetime (due to syn rad & IC):

$$\tau \approx 5 \cdot 10^5 \mathrm{yr} \frac{\mathrm{TeV}}{E} \frac{1}{\left(\frac{B}{5\mu\mathrm{G}}\right)^2 + 1.6 \frac{w}{\mathrm{eV/cm^3}}}$$

(w = density of IS photons)



T.Delahaye et al., 2008

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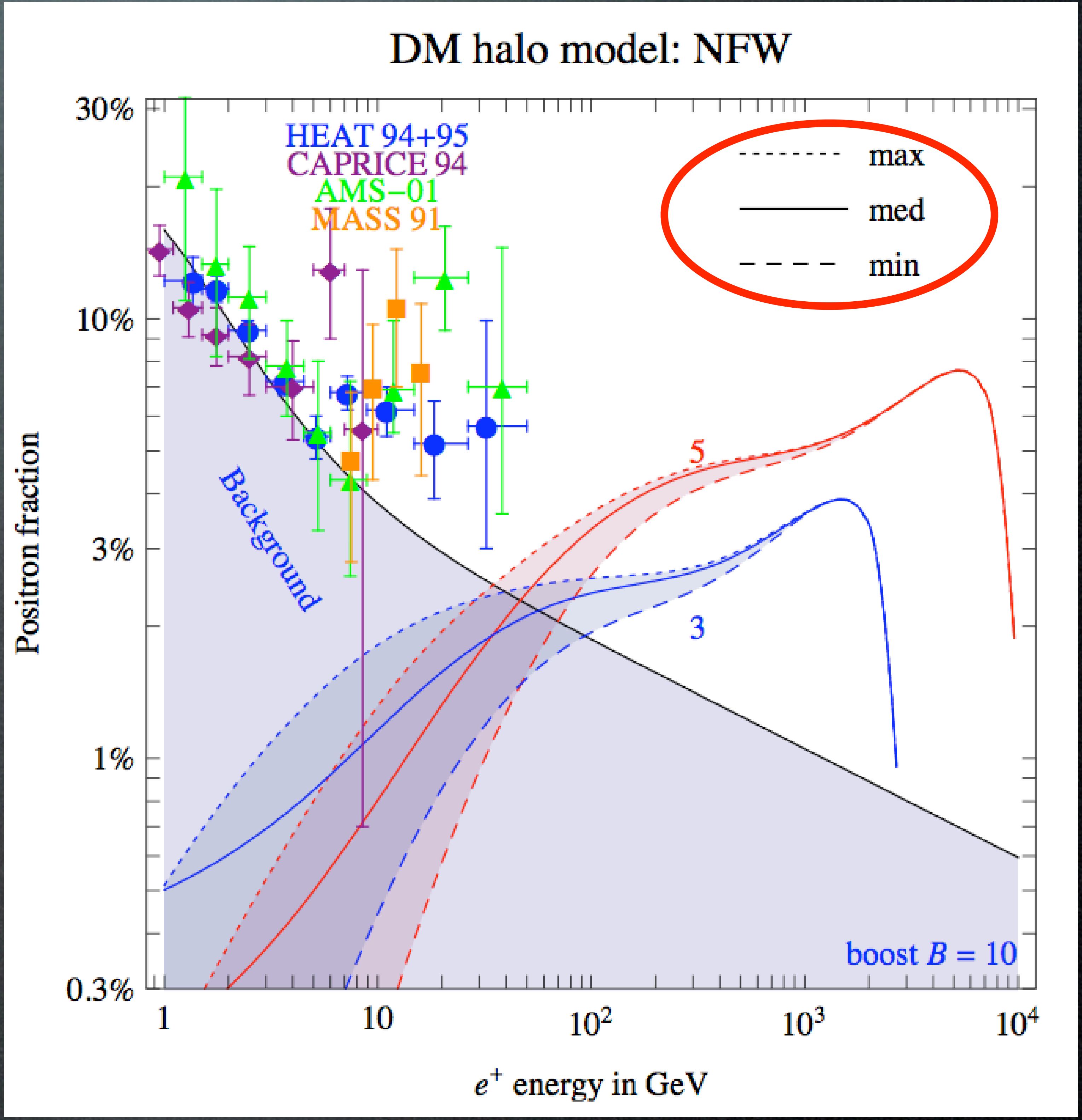
3. Indirect Detection

Results for positrons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



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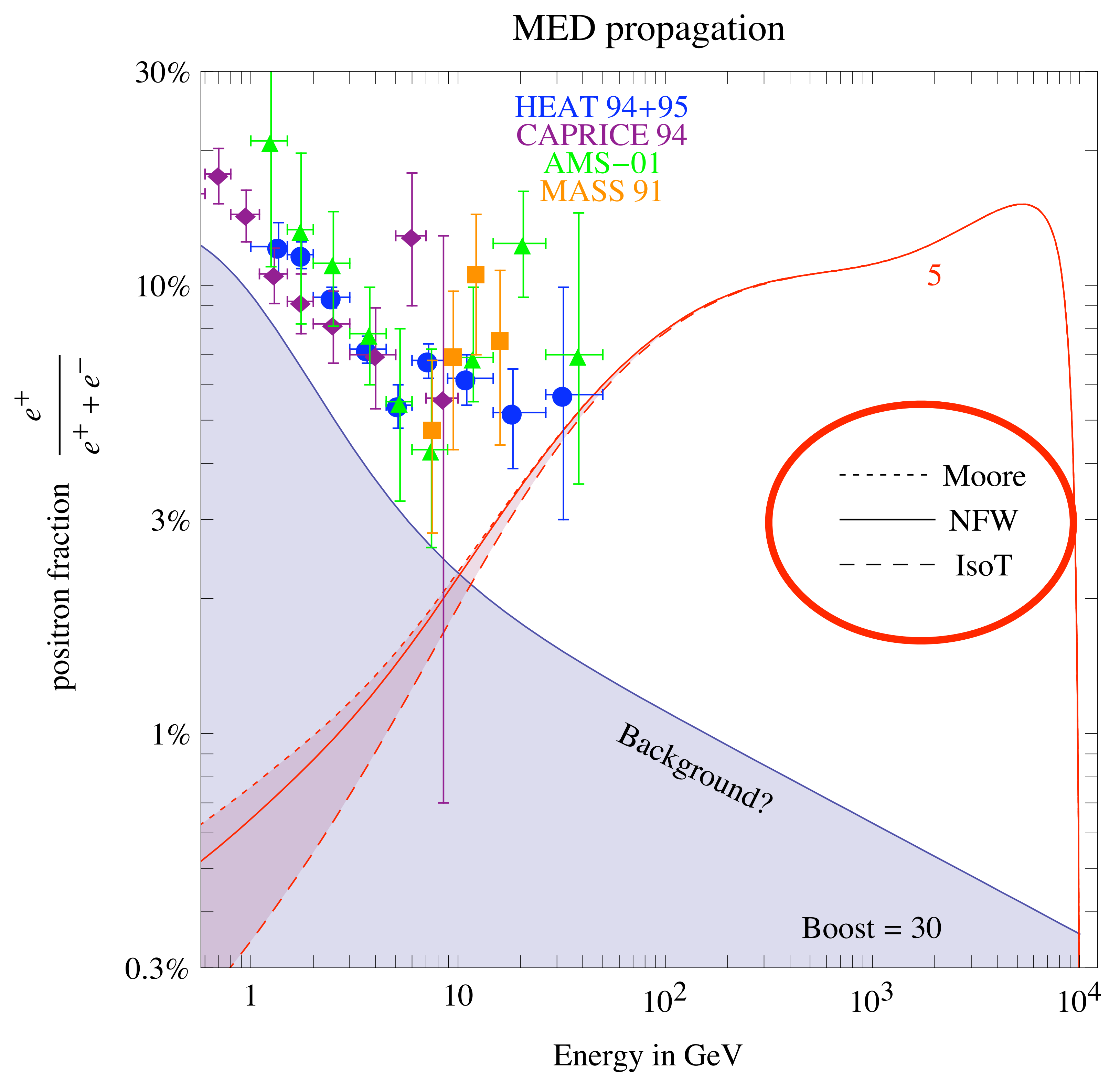

Distinctive signal, quite robust vs astro.

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3. Indirect Detection

Propagation for antiprotons:

$$\frac{\partial f}{\partial t} - K(T)\cdot\nabla^2 f + \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\, f\, V_{\mathrm{conv}}\right) = Q - 2h\,\delta(z)\,\Gamma_{\mathrm{ann}} f$$

diffusion

convective wind

spallations

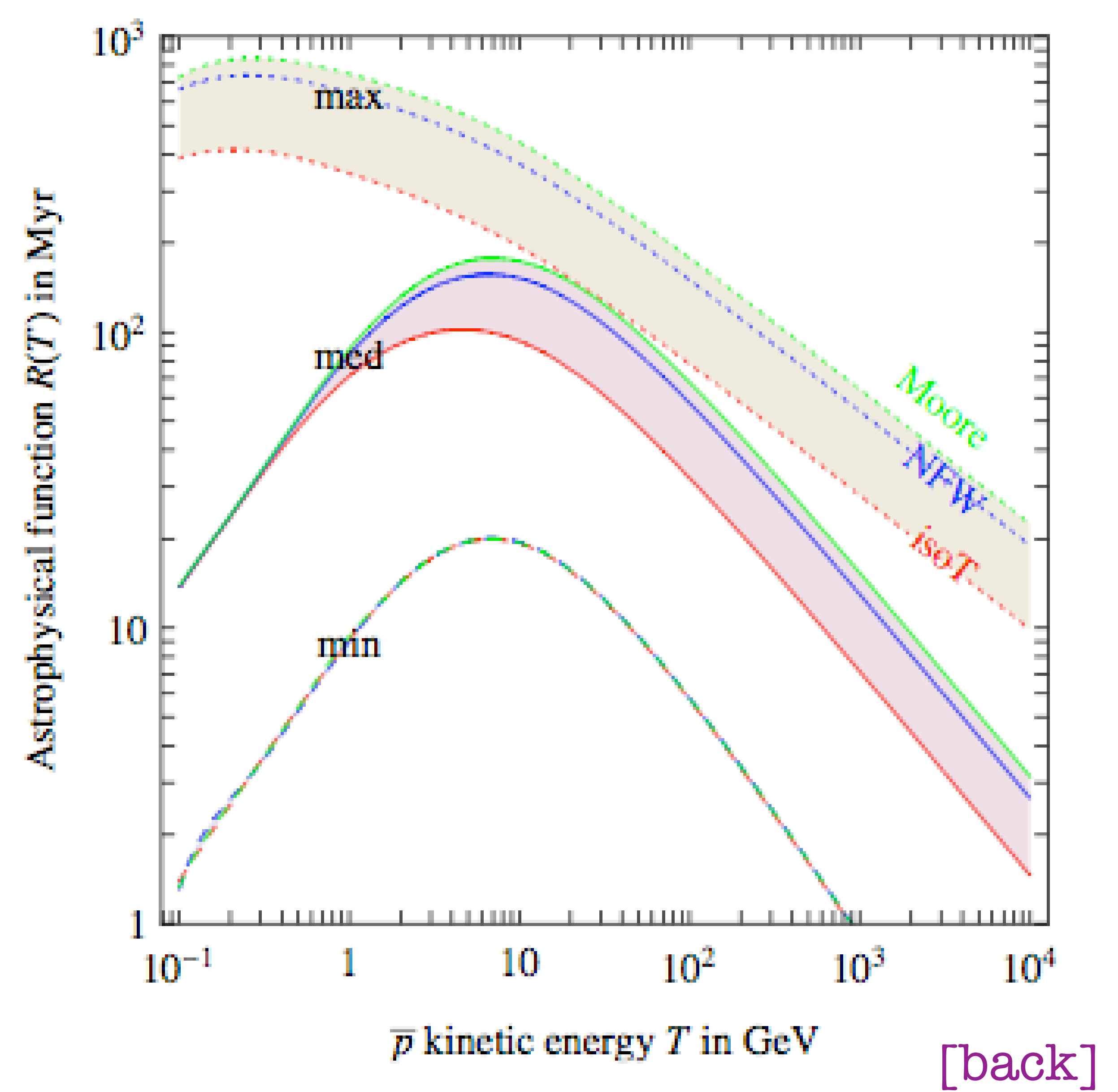
$K(T) = K_0 \beta\, (p/\mathrm{GeV})^\delta$

T kinetic energy

Model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5

Solution:

$$\Phi_{\bar{p}}(T, \vec{r}_\odot) = B\,\frac{v_{\bar{p}}}{4\pi}\left(\frac{\rho_\odot}{M_{\mathrm{DM}}}\right)^2 R(T) \sum_k \frac{1}{2}\langle\sigma v\rangle_k \frac{dN^k_{\bar{p}}}{dT}$$



[back]

Indirect Detection

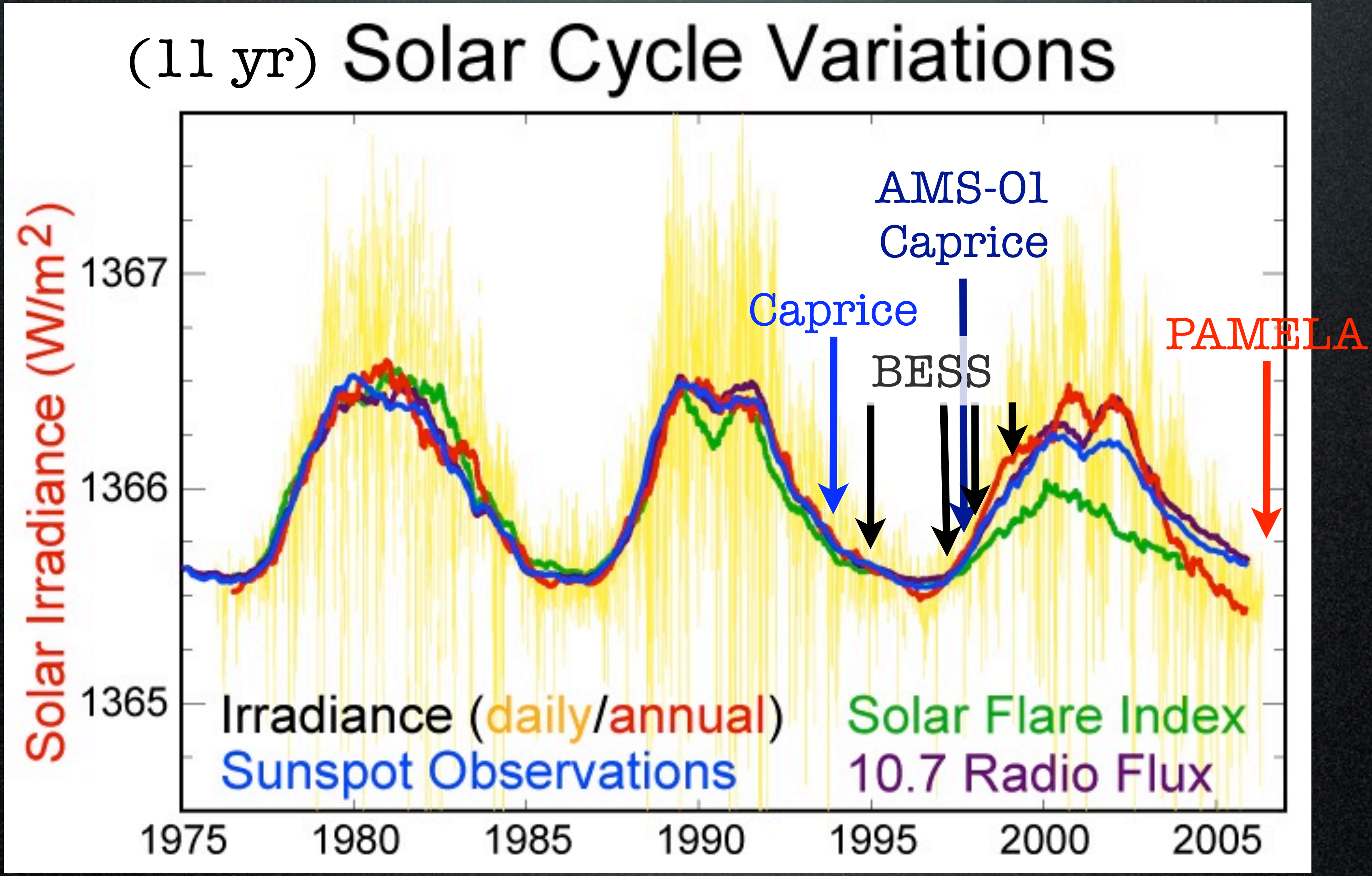
Solar wind Modulation of cosmic rays:

$$\frac{d\Phi_{\bar{p}\oplus}}{dT_\oplus} = \frac{p_\oplus^2}{p^2}\frac{d\Phi_{\bar{p}}}{dT}, \qquad T = T_\oplus + |Ze|\phi_F$$

spectrum at Earth

spectrum far from Earth

Fisk potential $\phi_F \simeq 500\ \text{MV}$

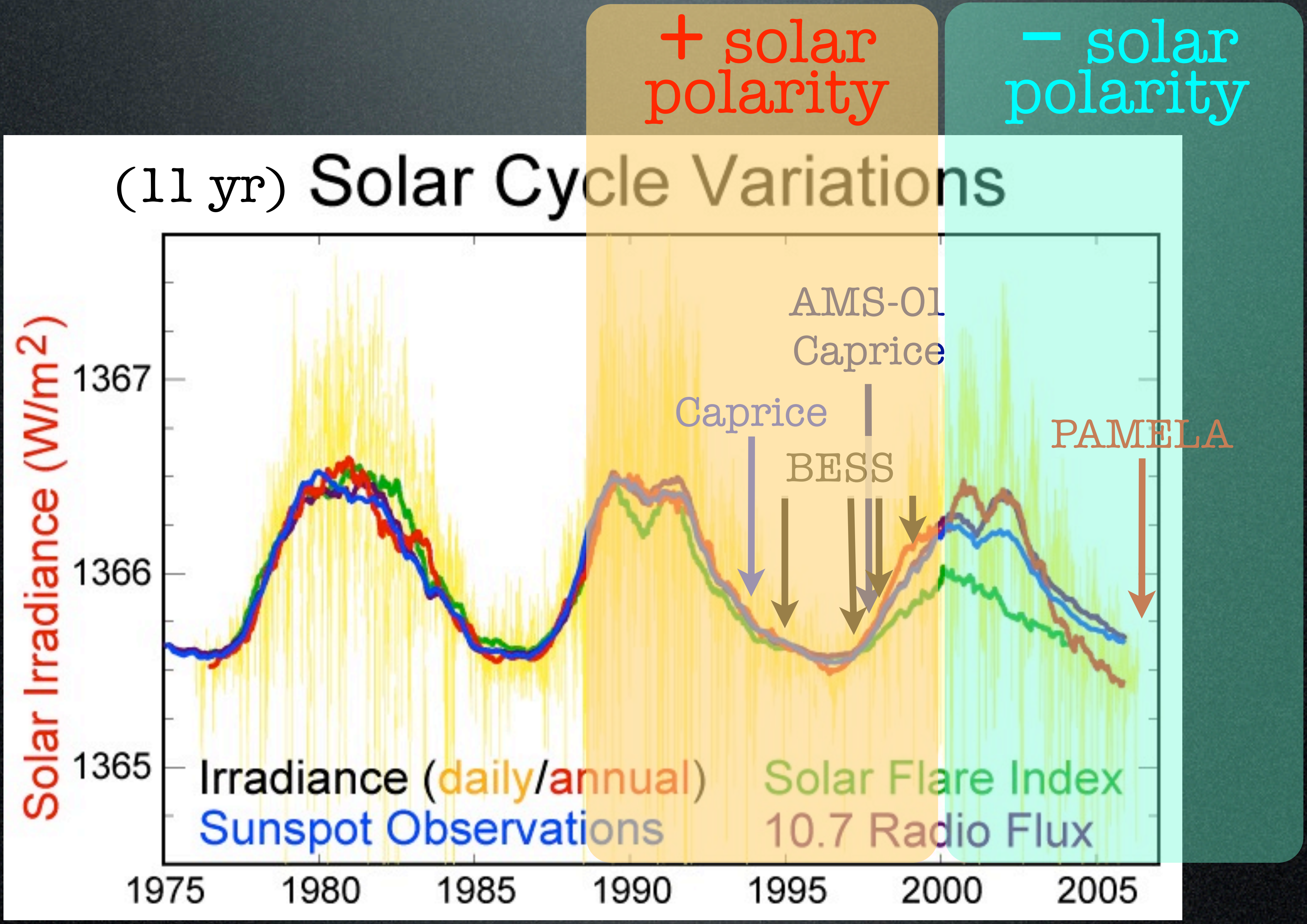


Indirect Detection

Solar polarity Modulation of cosmic rays:

solar magnetic polarity reverses at (the max of) each cycle;
during '– polarity' state, positive particles are more deflected away

+ = rotation parallel to magnetic field;
- = antiparallel



Indirect Detection

Background computations for positrons:

$$\Phi_{e^+}^{\rm bkg} = \frac{4.5\, E^{0.7}}{1 + 650\, E^{2.3} + 1500\, E^{4.2}}$$

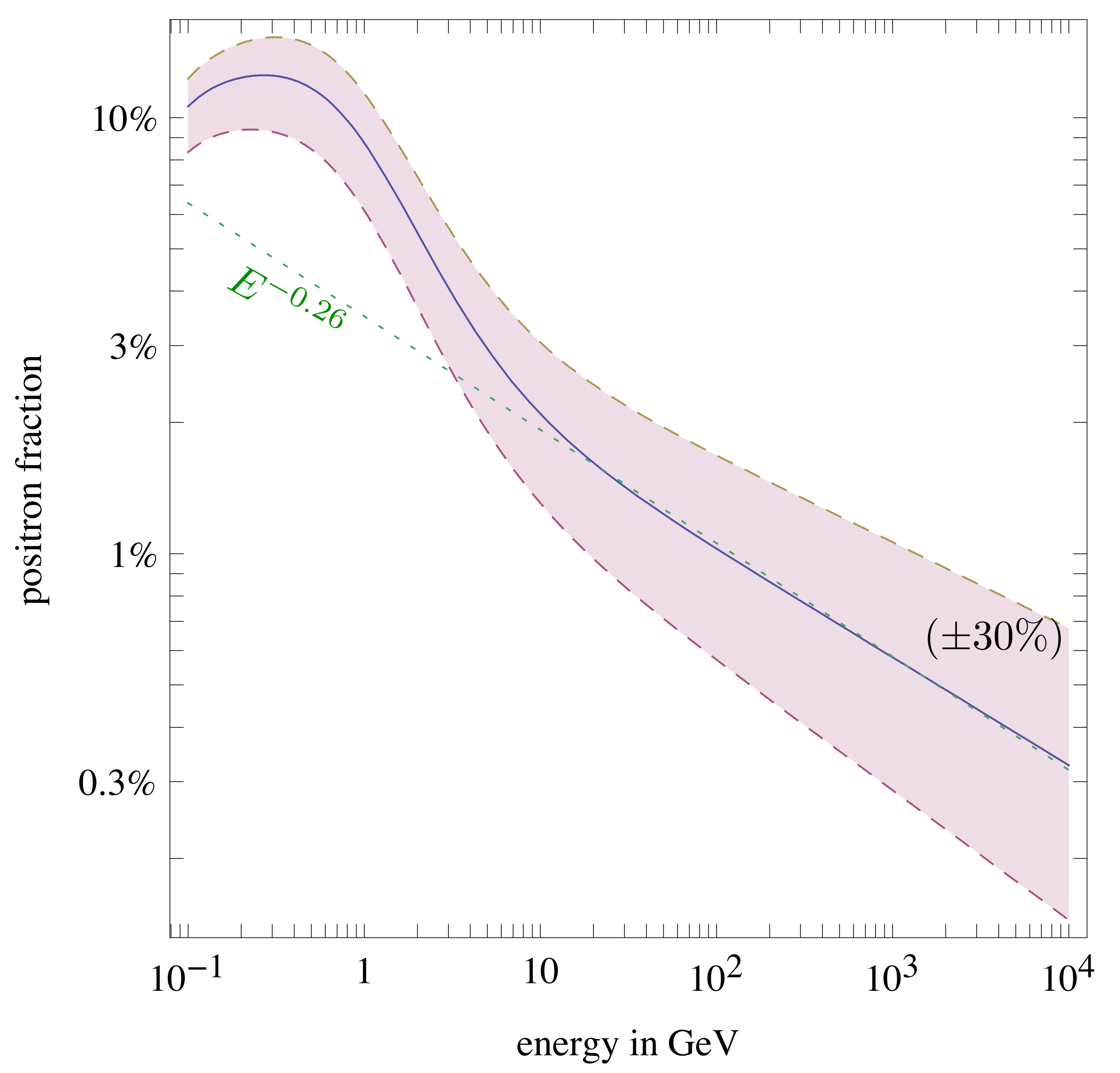
main source: CR nuclei spallating on IS gas

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

Baltz, Edsjo 1999

On the basis of CR simulations of Moskalenko, Strong 1998

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

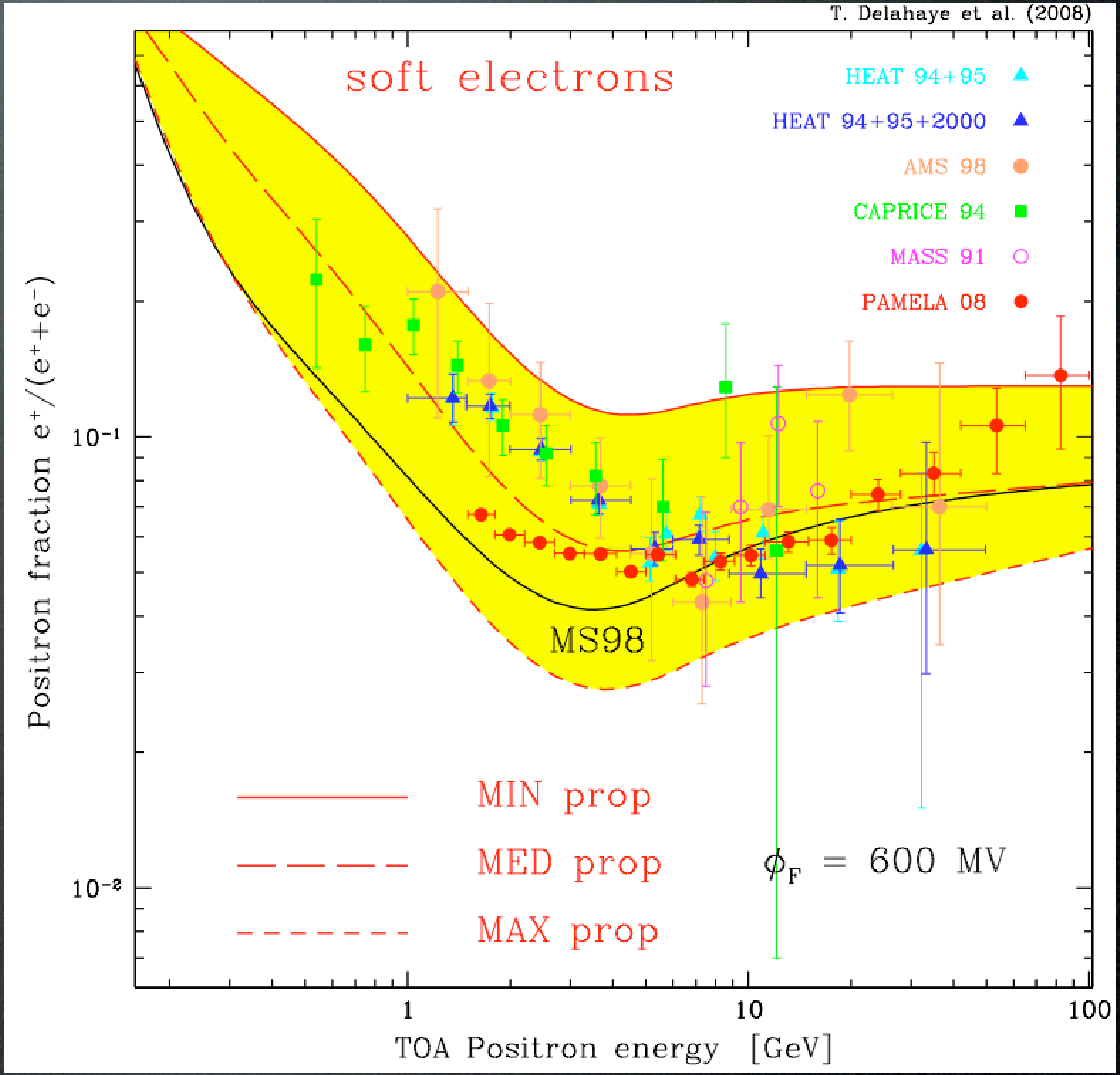


We marginalize w.r.t. the slope E^p, $\quad p = \pm 0.05$
and let normalization free.

[back]

Indirect Detection

Background estimation for positrons:



using new measuremens of electron fluxes

Casadei, Bindi 2004

T.Delahaye et al., 0809.5268

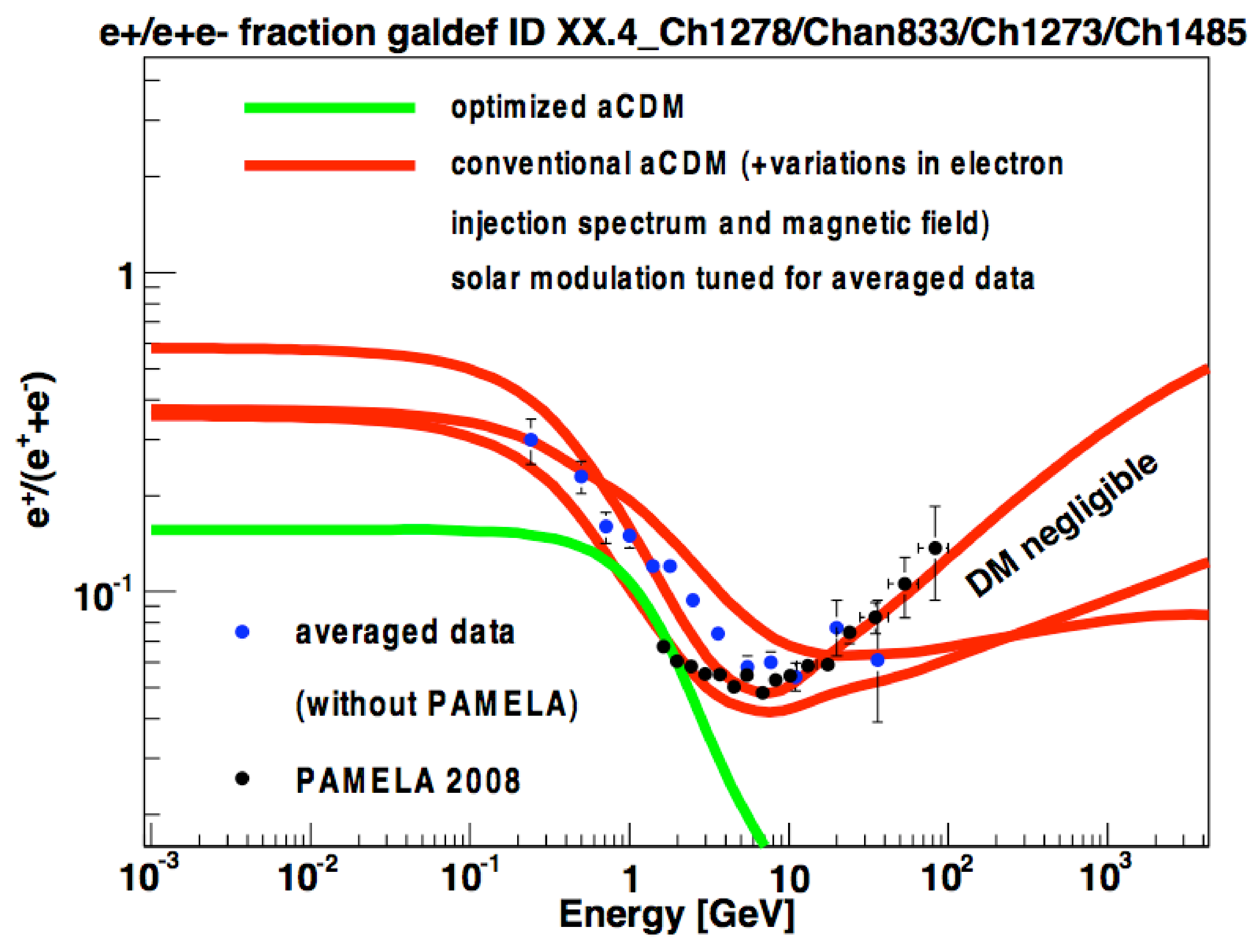
[back]

Indirect Detection

Background estimation for positrons:

relaxing the assumption of isotropy* in propagation model (aCDM = anisotropic convection driven transport model), allows to fit PAMELA with pure background

* (ROSAT X-ray satellite has seen fast, strong SN winds coming out from galaxy plane: not isotropic)



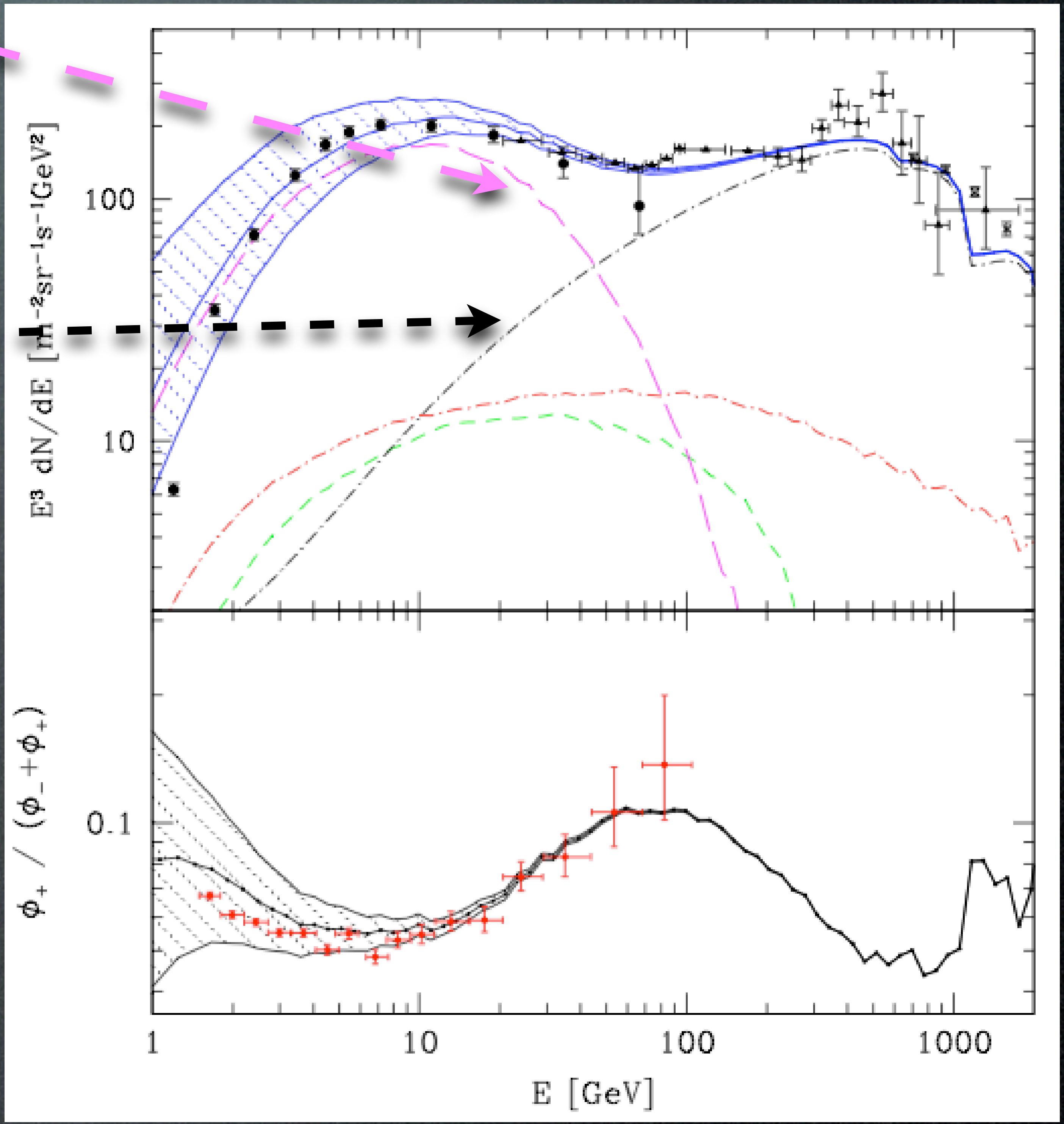
Gebauer 0811.2767

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

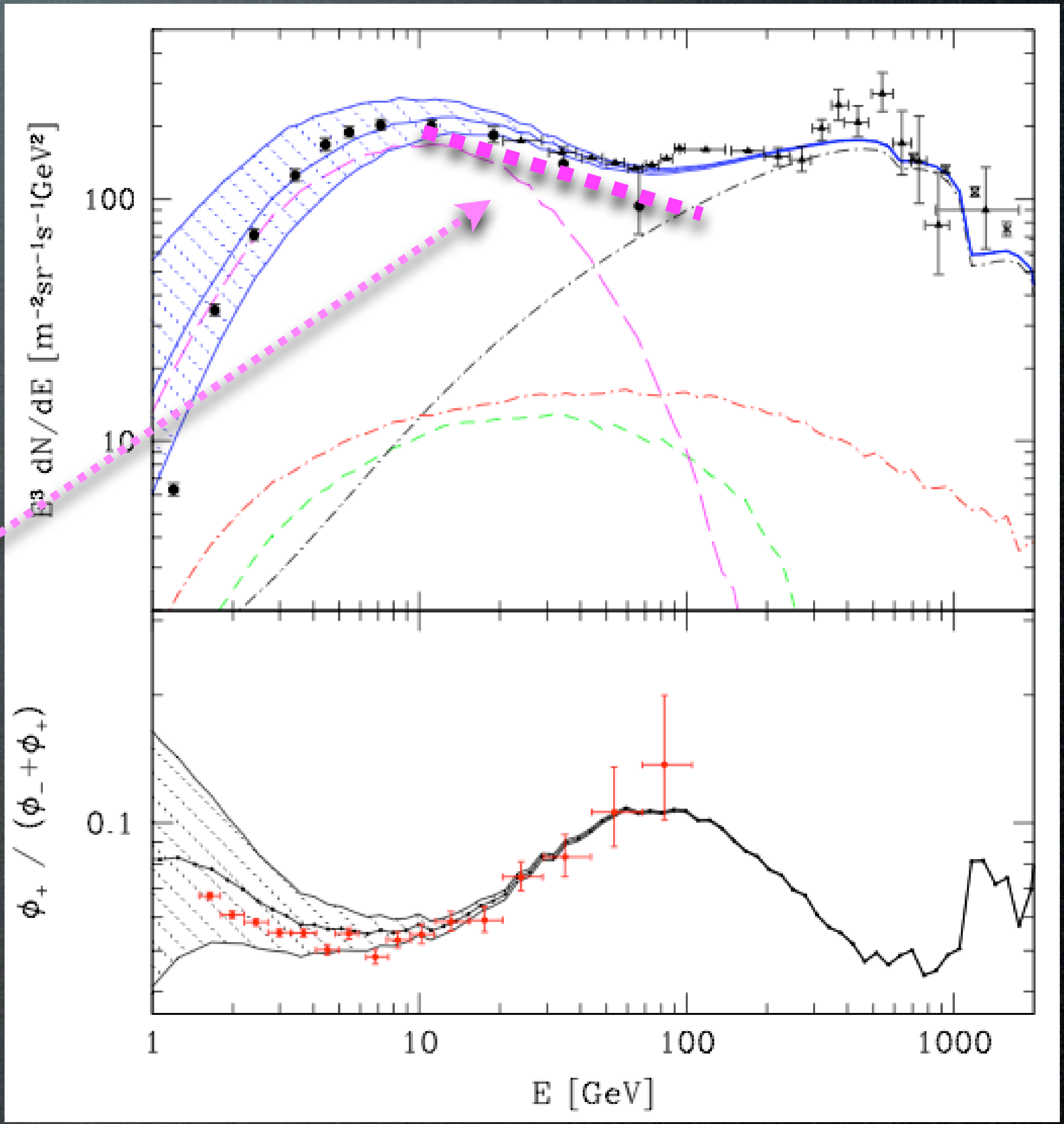
Indirect Detection

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...?



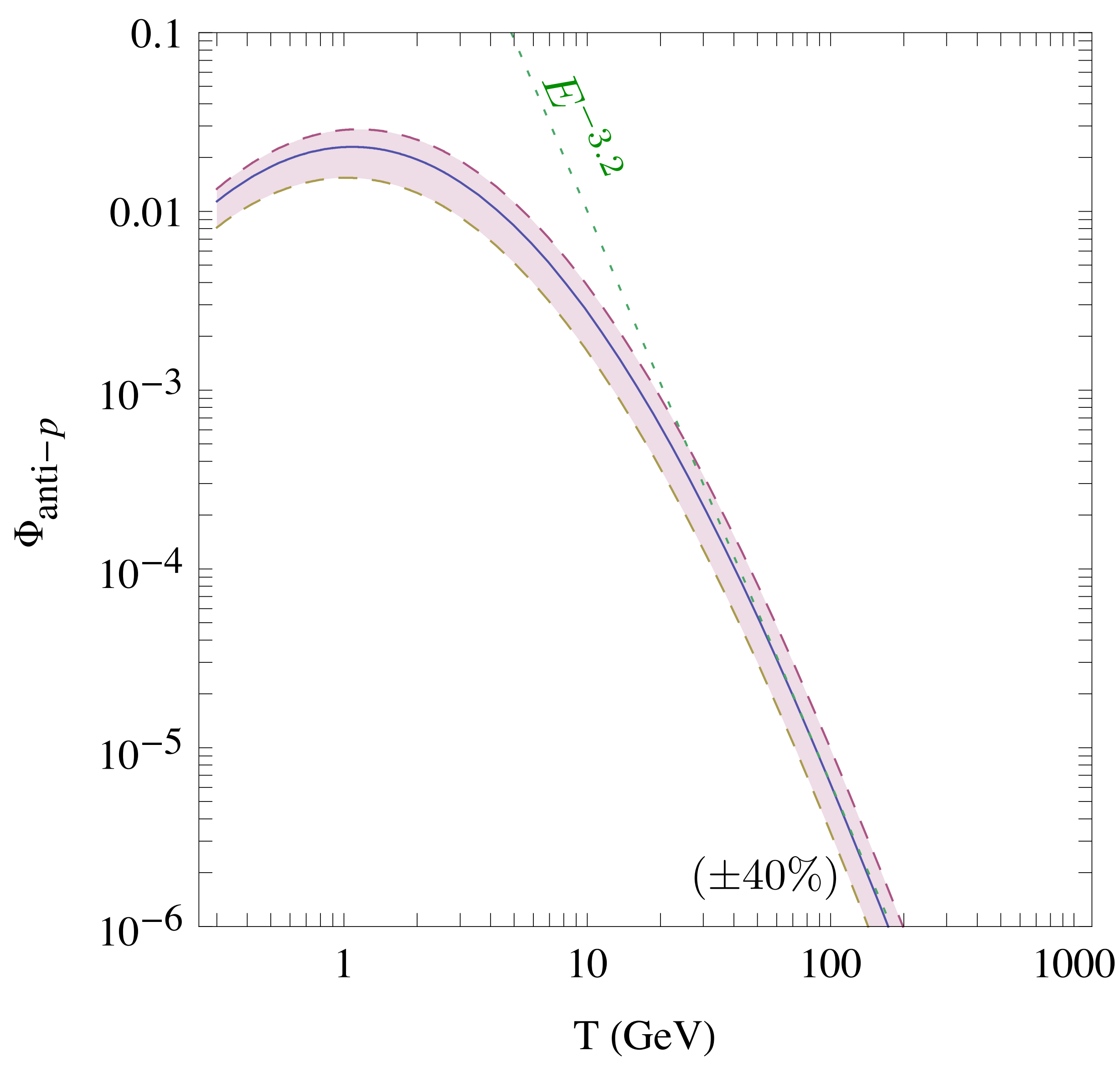
Tsvi Piran et al. 0902.0376

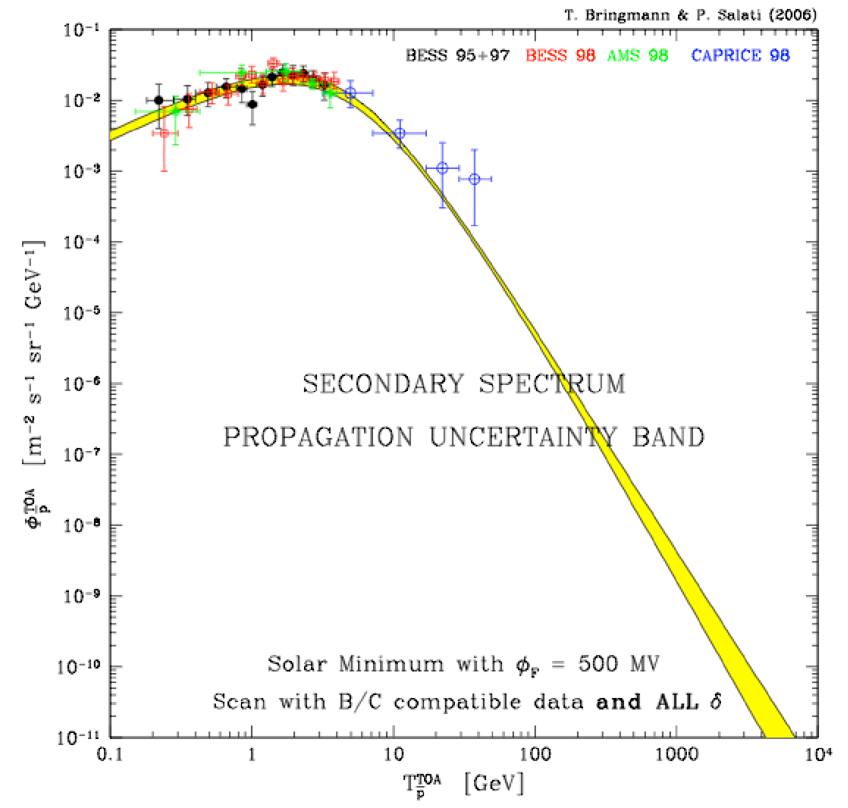
Indirect Detection

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





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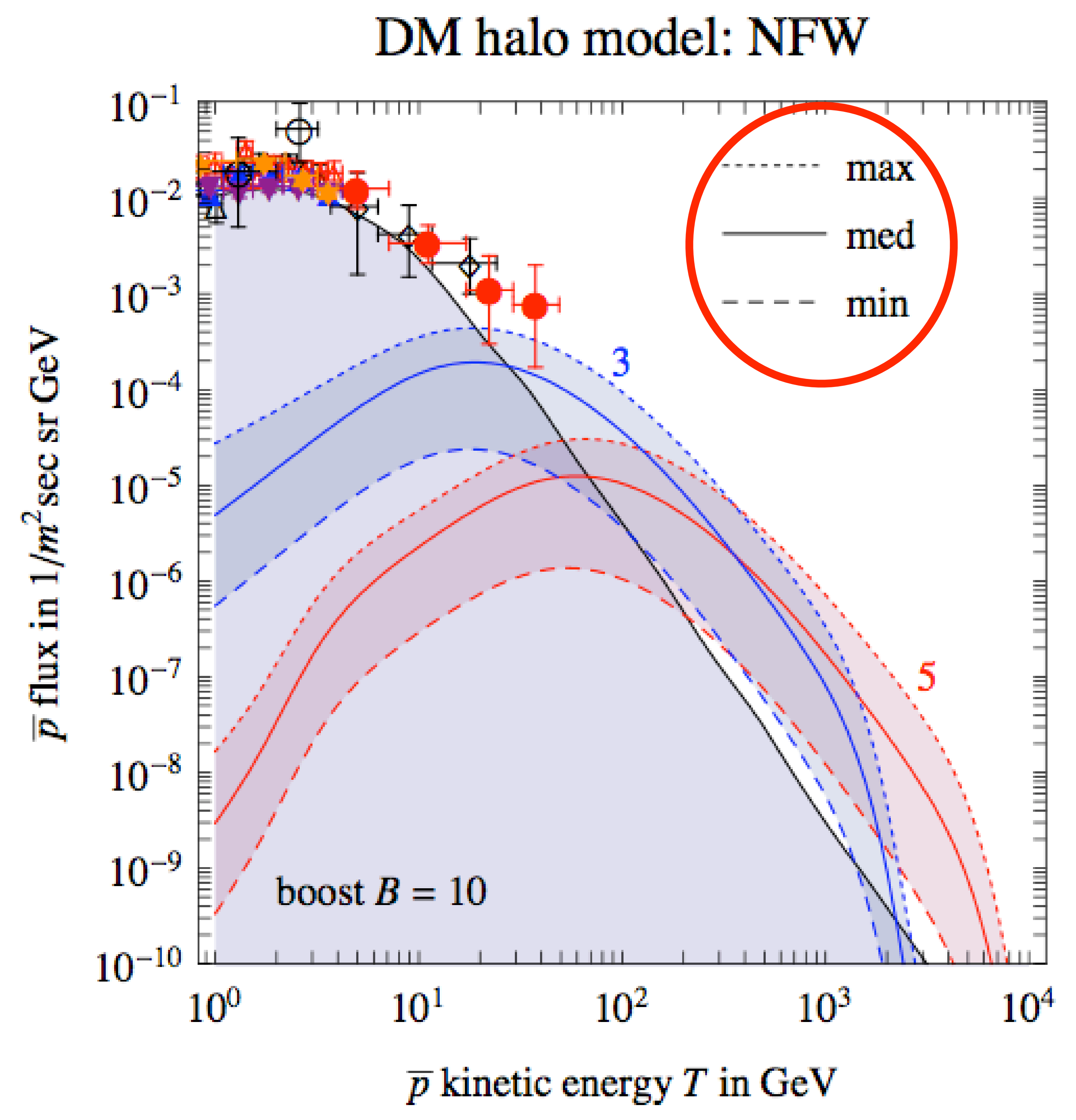
[back]

Indirect Detection

Results for anti-protons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



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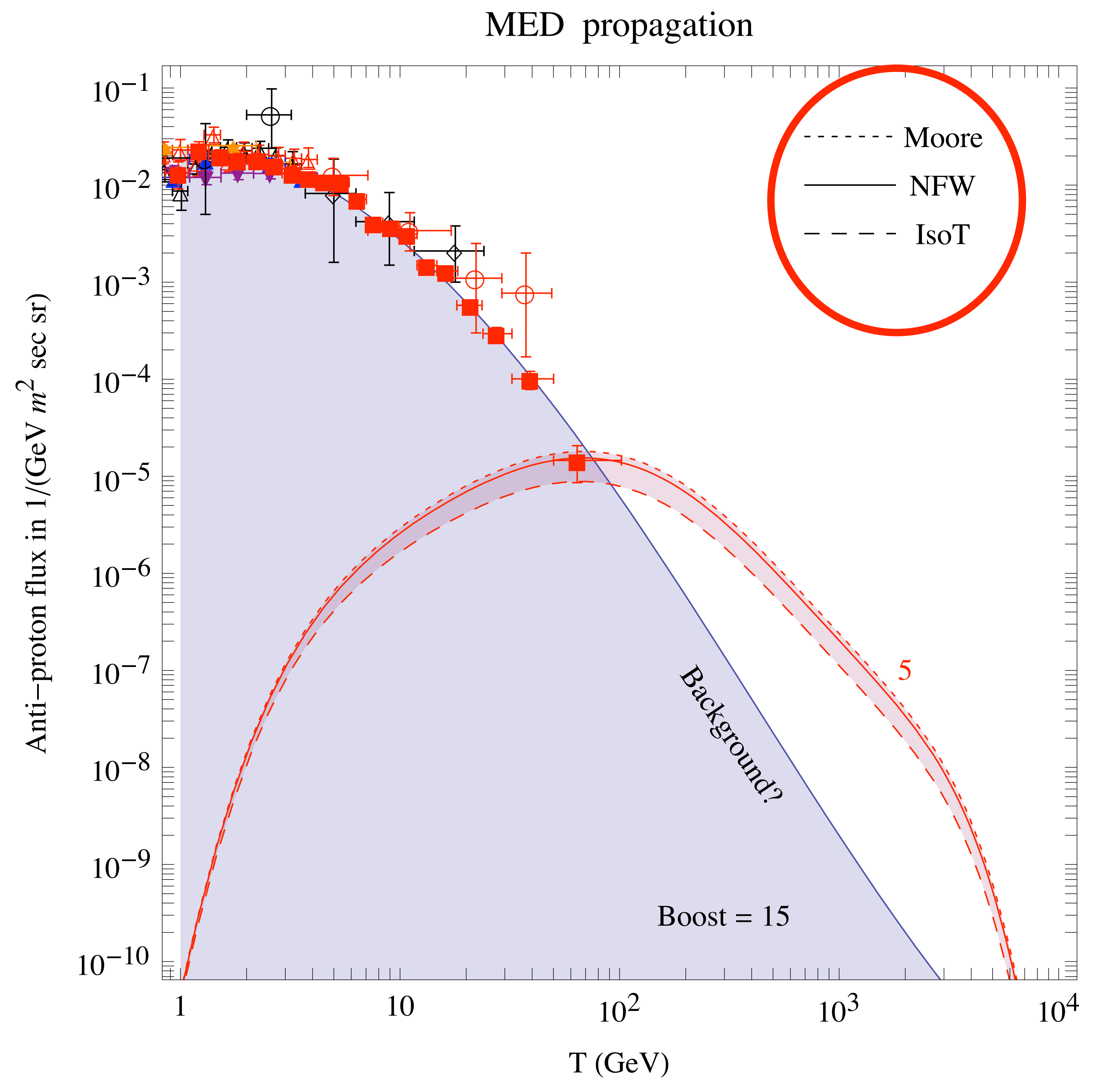


Challenges for the ‘conventional’ DM candidates

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

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

Results

Which DM spectra can fit the data?

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

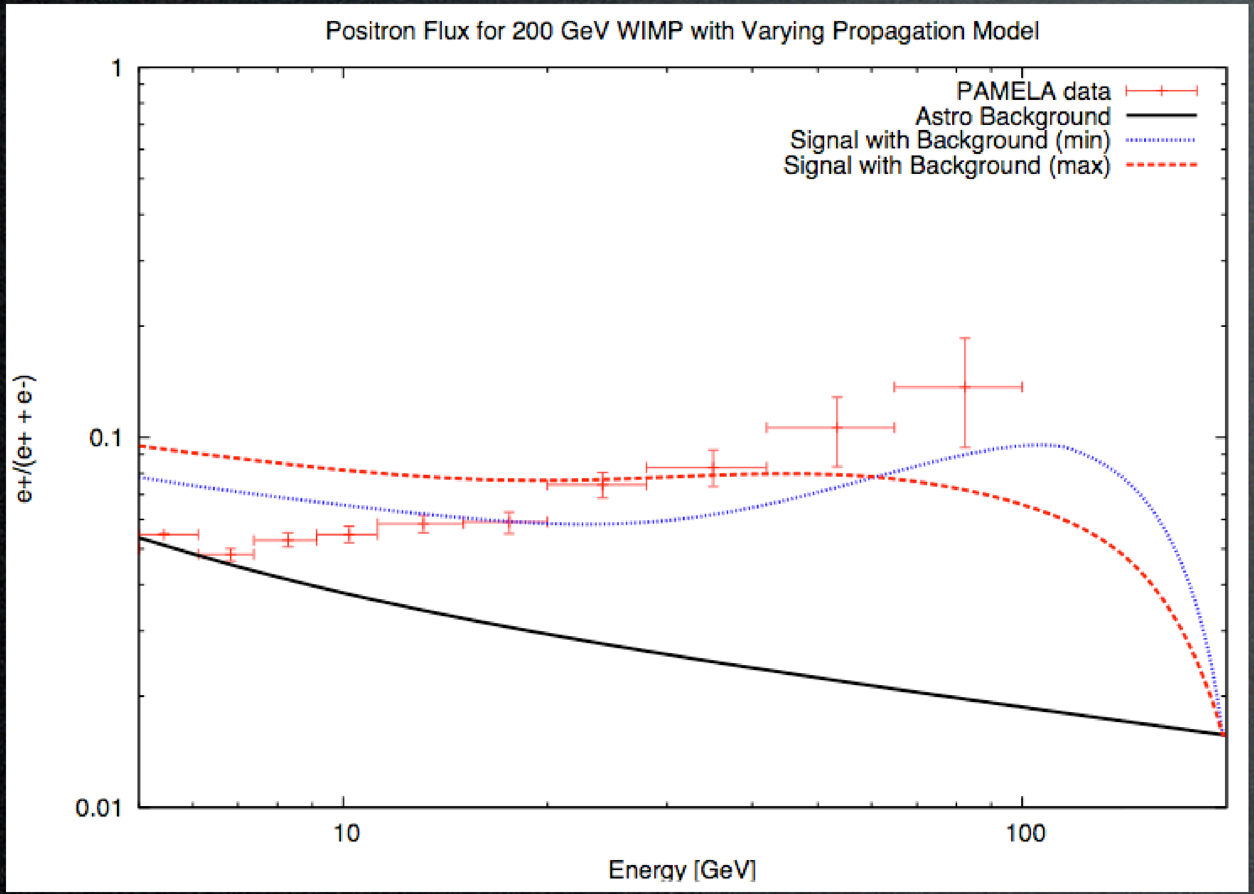
-annihilation $\mathrm{DM\,DM} \to W^+W^-$

If one: - assumes non-thermal production of DM

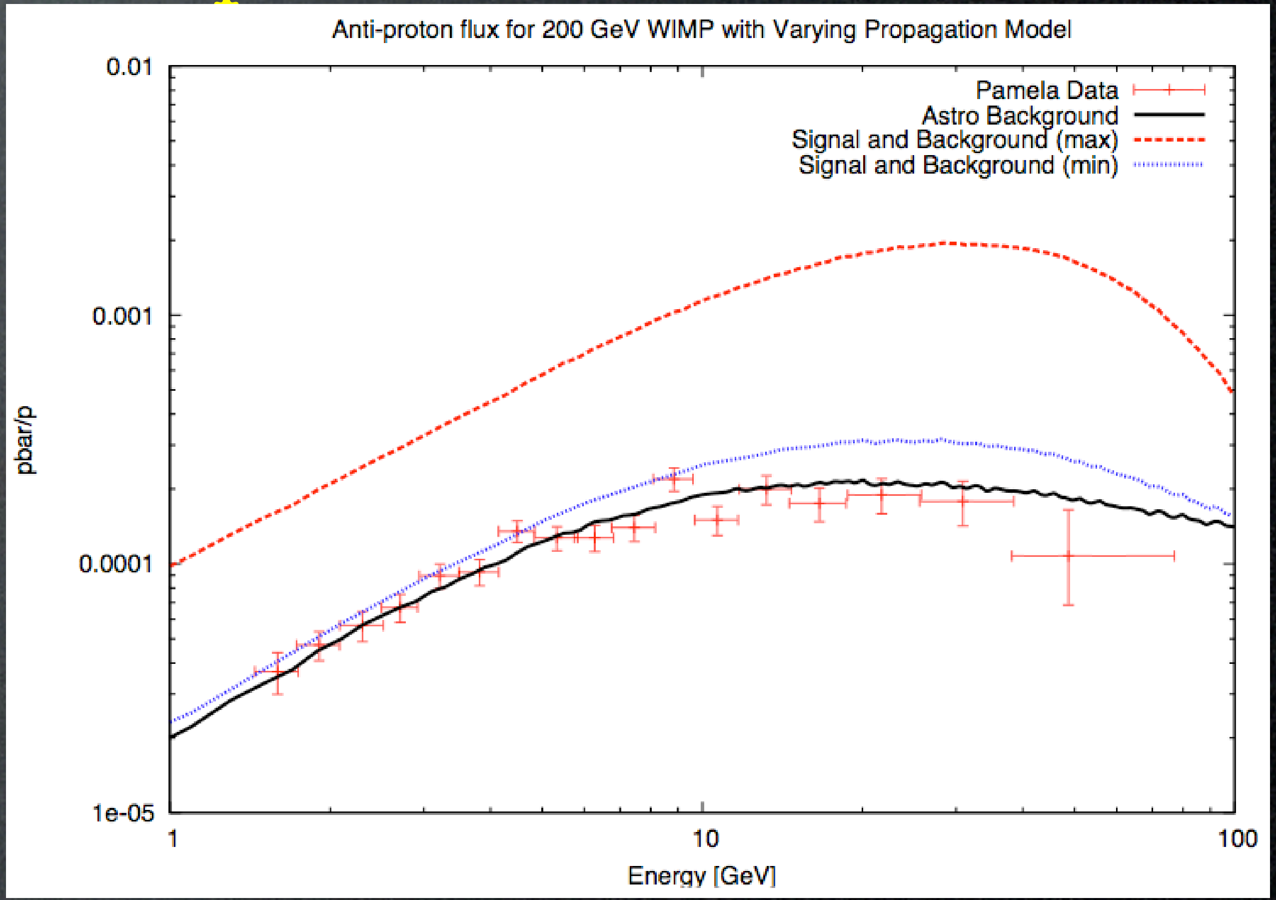
- takes positron energy loss 5 times larger than usual
- takes "min" propagation only
- gives up ATIC
- neglects conflict with EGRET bound (4 times too many gammas)

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 $\text{DM DM} \to l^+l^- \, (BR = 60\%)$

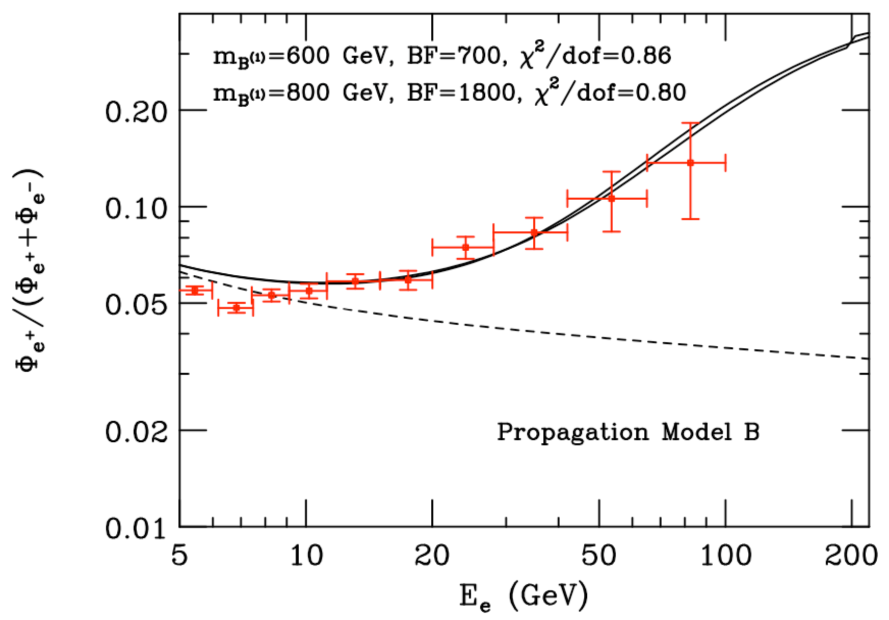
$\text{DM DM} \to q\bar{q} \, (BR = 35\%)$

Good fit with: - boost $B = 1800$

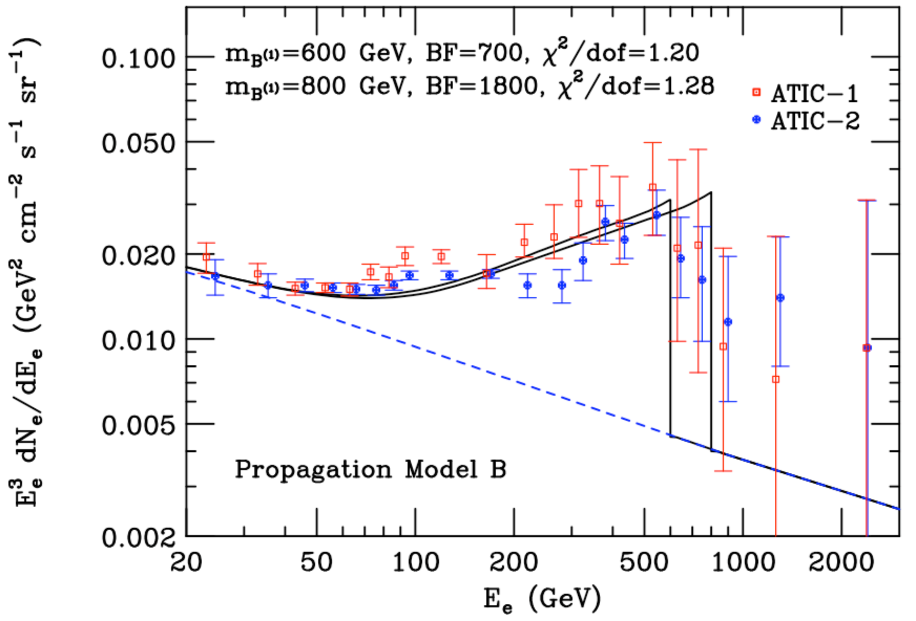
- propagation model B: $K(E_e) = 1.4 \times 10^{28}\, (E_e/4\,{\rm GeV})^{0.43}\,{\rm cm}^2/{\rm s}$, L=1 kpc

very large energy loss with very small L

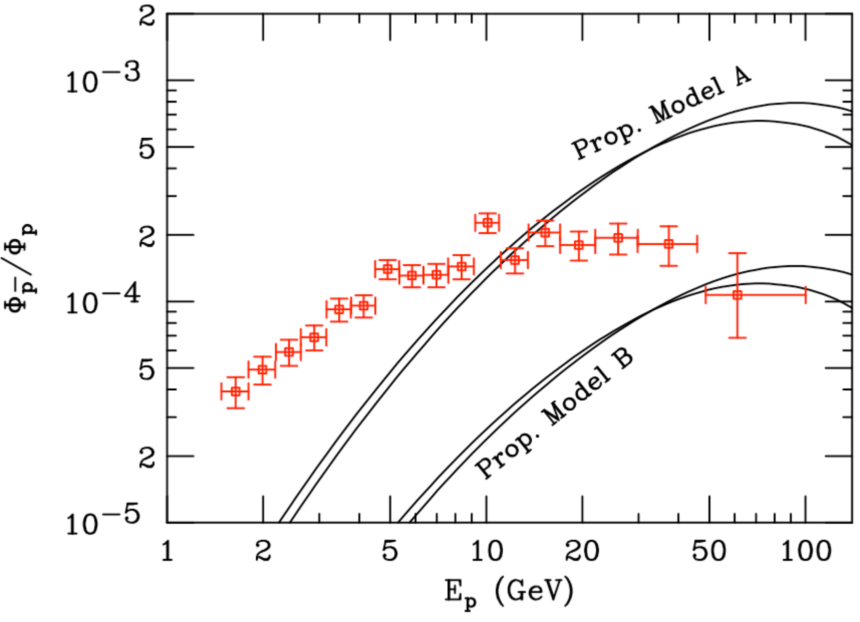
Positrons:



Electrons + Positrons:



Anti-protons:



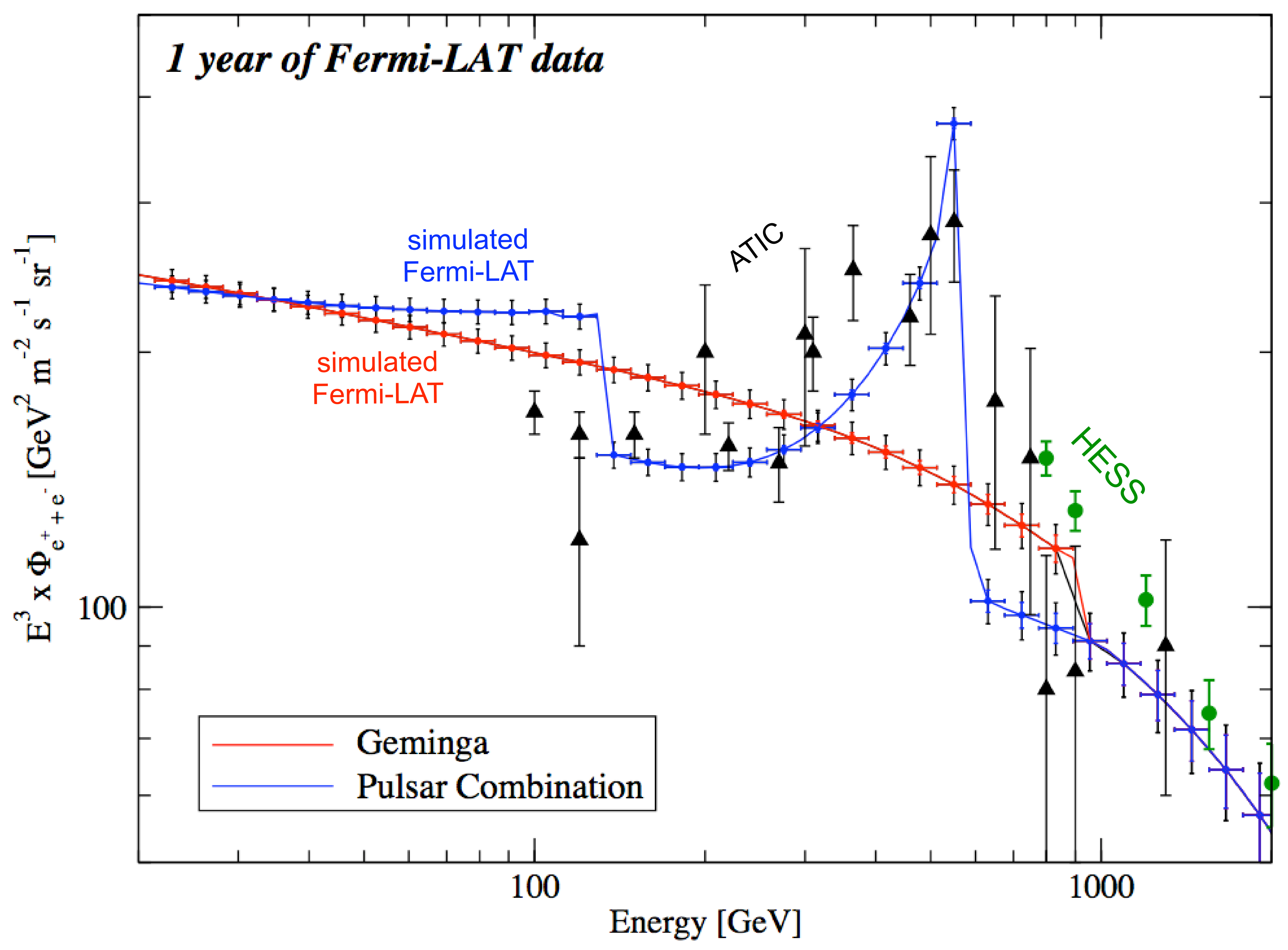
D.Hooper, K.Zurek 0902.0593

[where are the secondaries?]

Data sets

Electrons + positrons from Fermi-LAT:

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

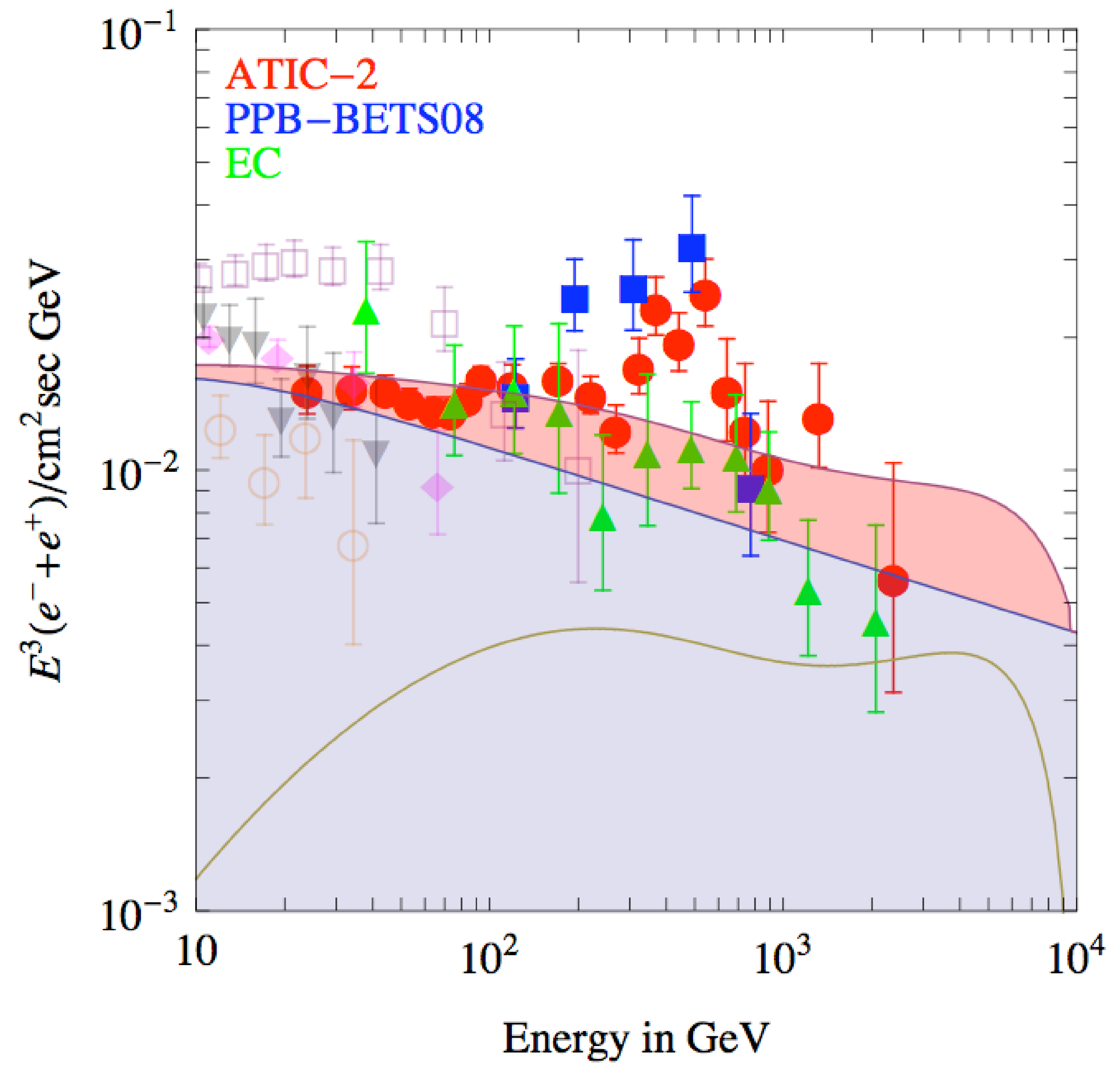


Profumo 0812.4457

[back]

Results

Which DM spectra can fit the data?



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]

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

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

- More drastic extensions:
  New models with a rich Dark sector

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - E.Ponton, L.Randall, 0811.1029: Singlet DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM - S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

- 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

Model building

- Minimal extensions of the SM:
    heavy WIMPS (Minimal DM, Inert Doublet)

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

- More drastic extensions:
    New models with a rich Dark sector
        - TeV mass DM
        - new forces (that Sommerfeld enhance)
        - leptophilic because: - kinematics (light mediator)
            - DM carries lepton #

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - E.Ponton, L.Randall, 0811.1029: Singlet DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.J.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM - S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shin, 0901.0720: split-UED DM - I.Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

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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 $M \sim 700+\ \mathrm{GeV}$

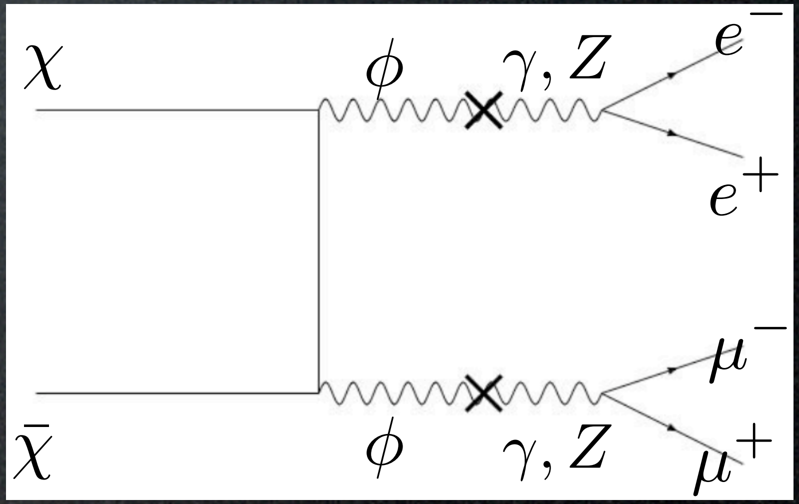
ϕ new gauge boson (“Dark photon”),

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

- 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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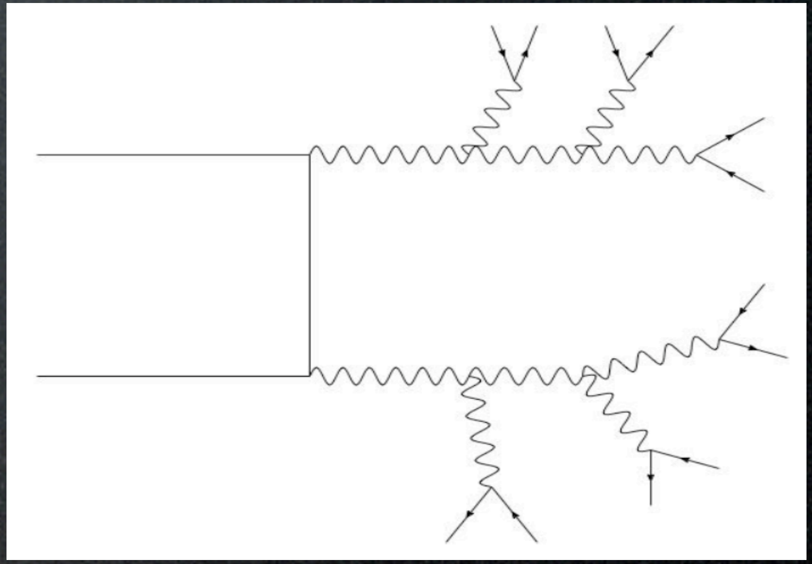
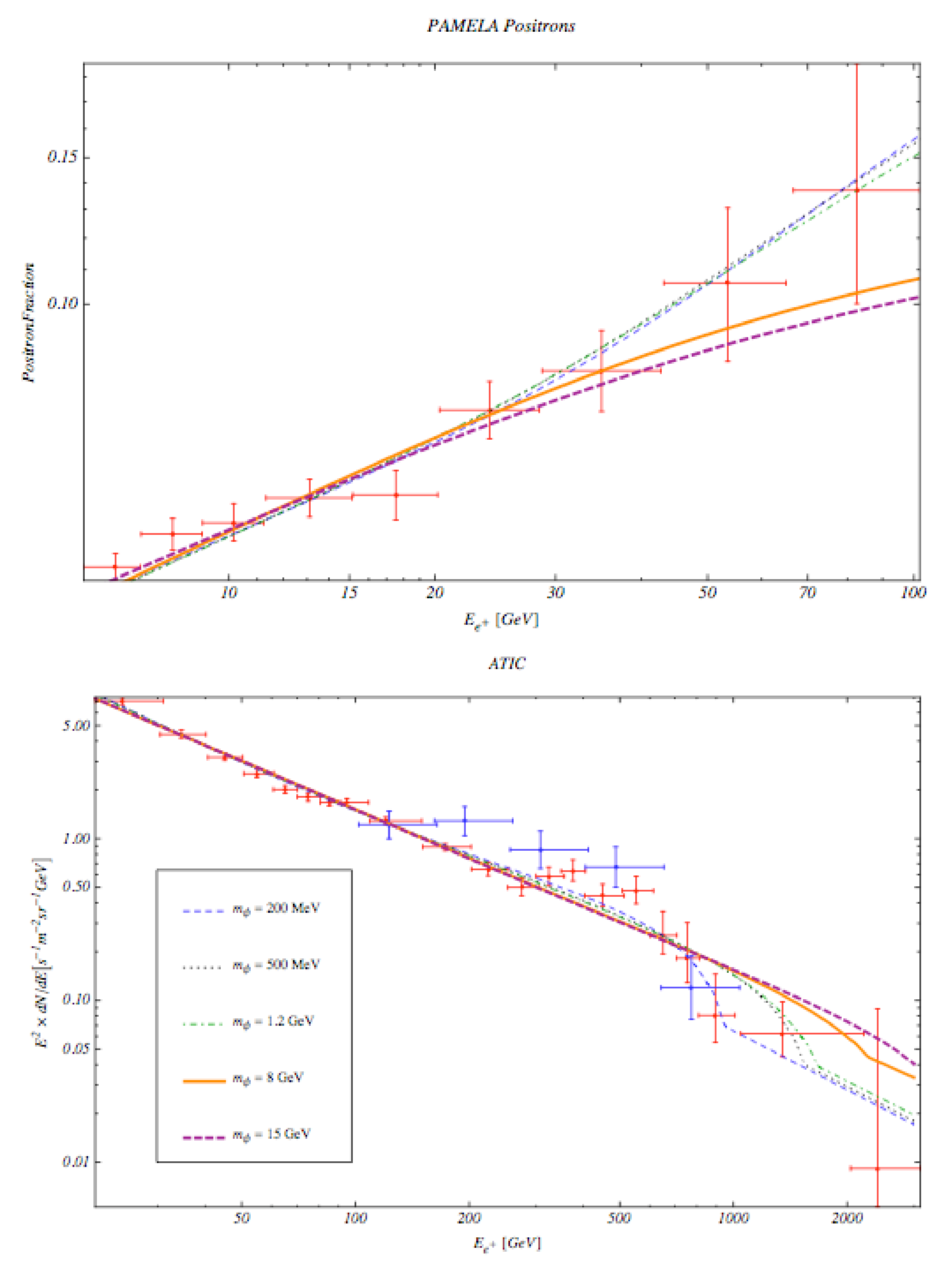


Extras:

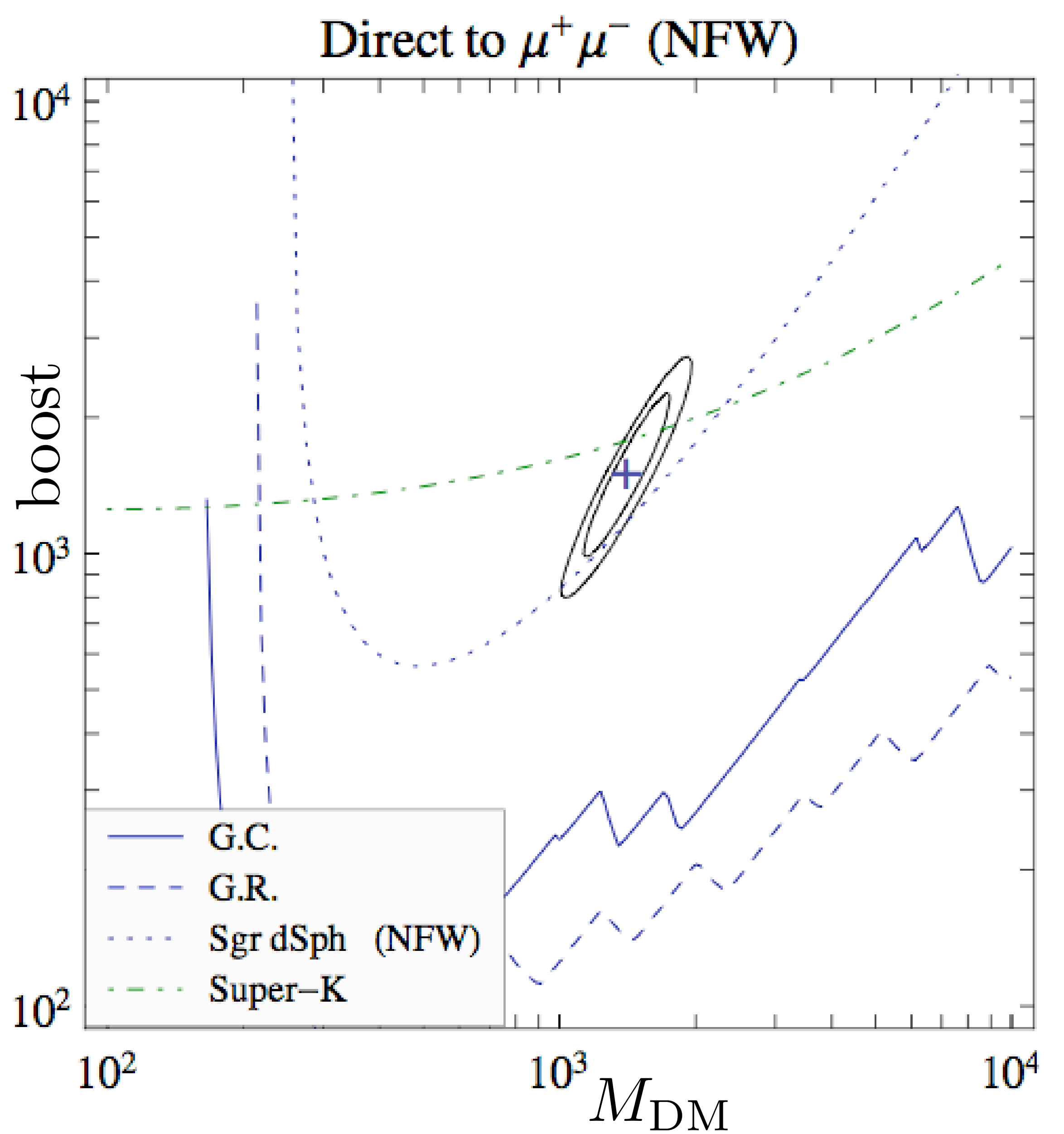
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200\ \mathrm{KeV}$ (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The "Theory of DM"

Phenomenology:



Meade, Papucci, Volanski
0901.2925



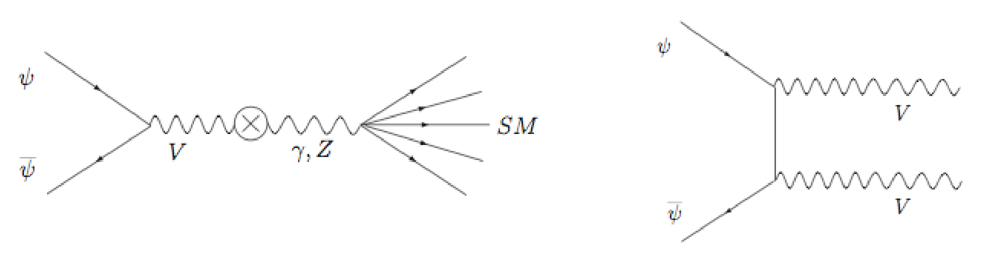
Mardon, Nomura, Stolarski,
Thaler 0901.2926

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

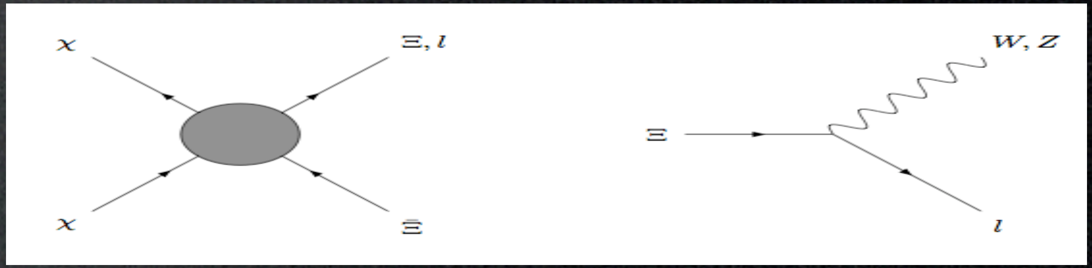
  Park, Shu 0901.0720

- 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 $(m_\phi \sim \text{tens GeV})$

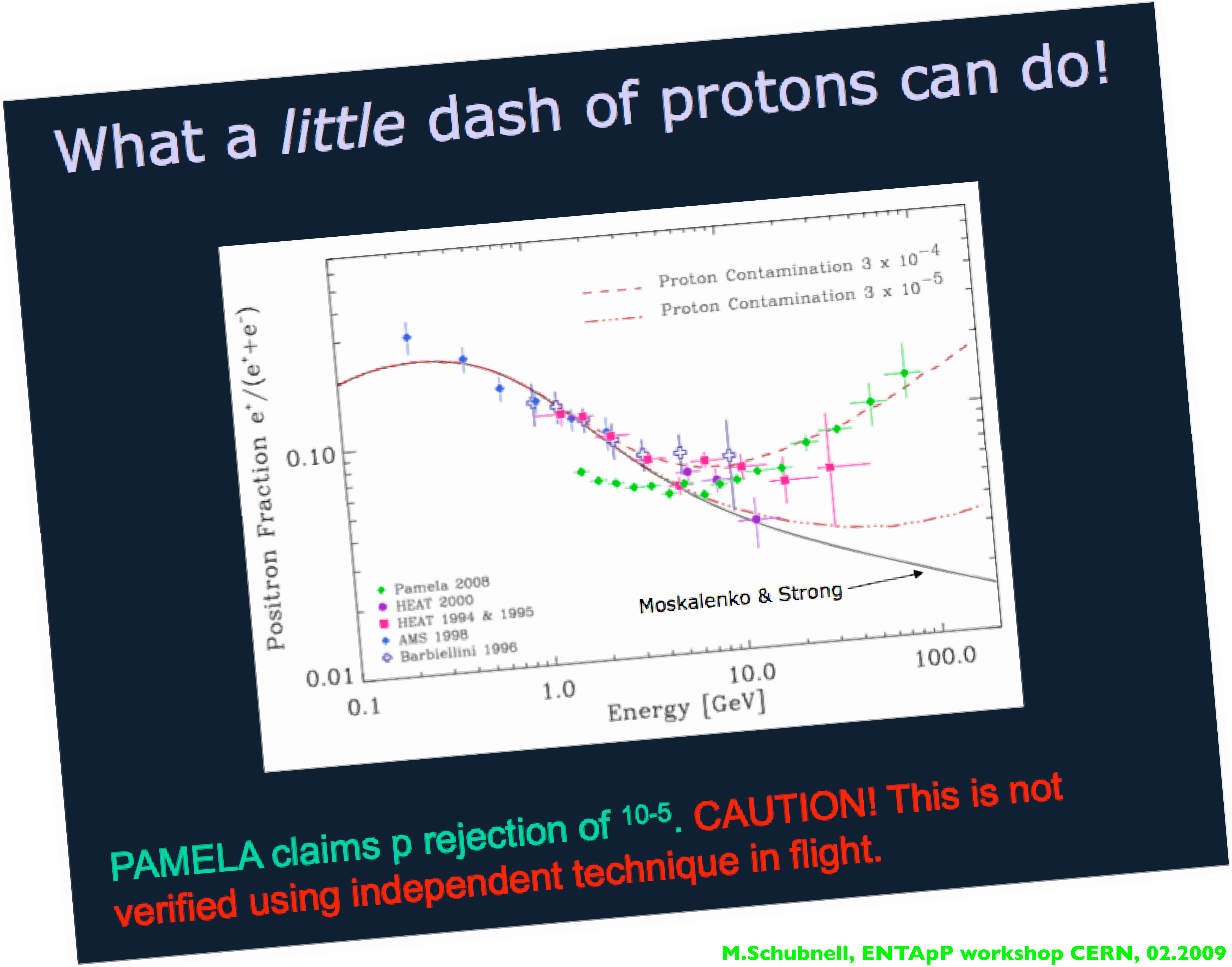
- New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly $(\sim \text{TeV})$ $(\sim 100\text{s GeV})$

  Phalen, Pierce, Weiner 0901.3165



- ……

“PAMELA did not do in-flight checks of the p rejection rate”



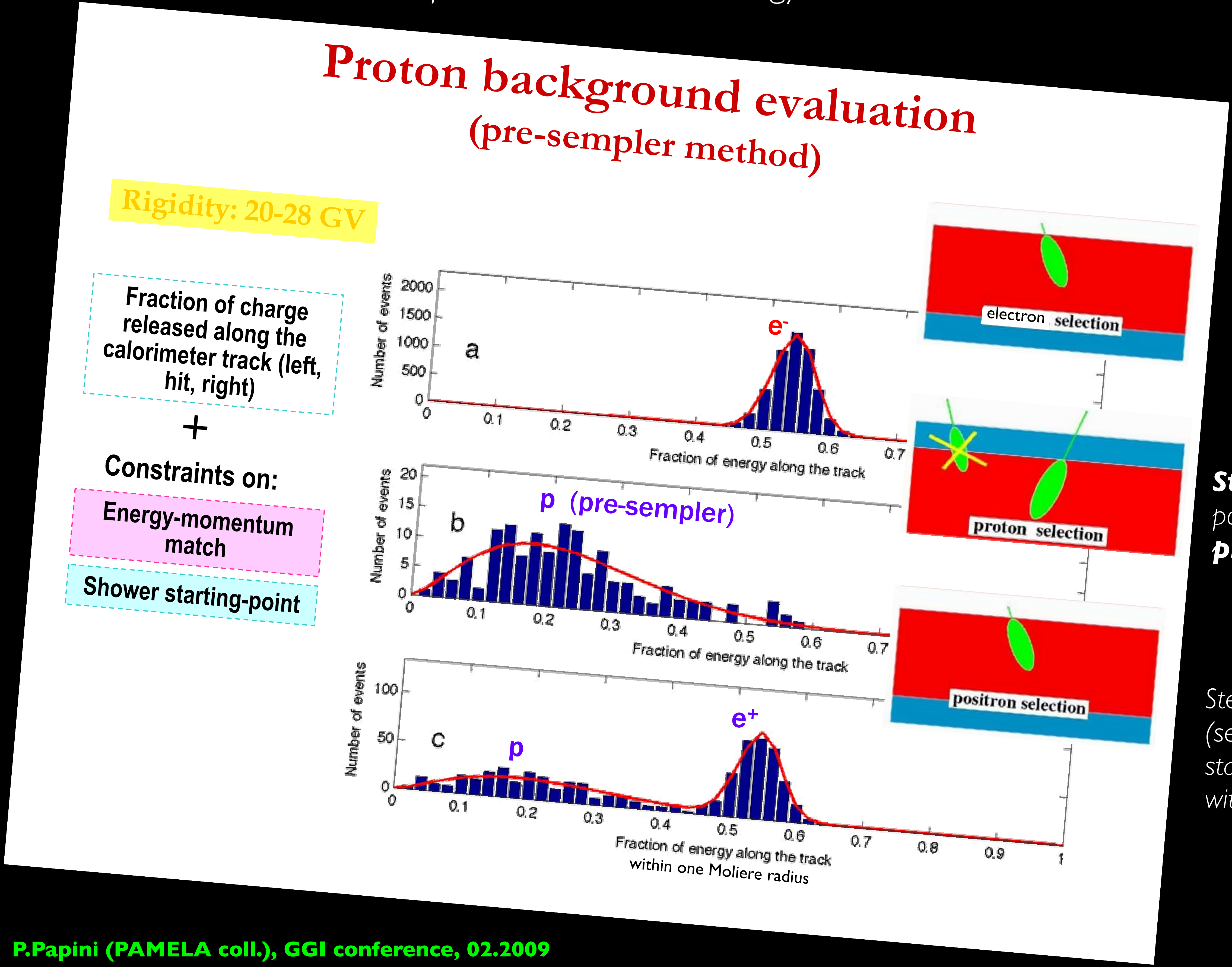
What a *little* dash of protons can do!

PAMELA claims p rejection of $^{10-5}$. CAUTION! This is not verified using independent technique in flight.

M.Schubnell, ENTApP workshop CERN, 02.2009

“PAMELA did do in-flight checks of the p rejection rate”

Method: in the calorimeter, leptons leave all their energy and on the top;
protons leave little energy and in the bottom.



Proton background evaluation
(pre-sempler method)

Rigidity: 20-28 GV

Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

Energy-momentum match

Shower starting-point

Step 1: use the upper portion of the calorimeter to select electrons only ($\bar{p}$ negligible)

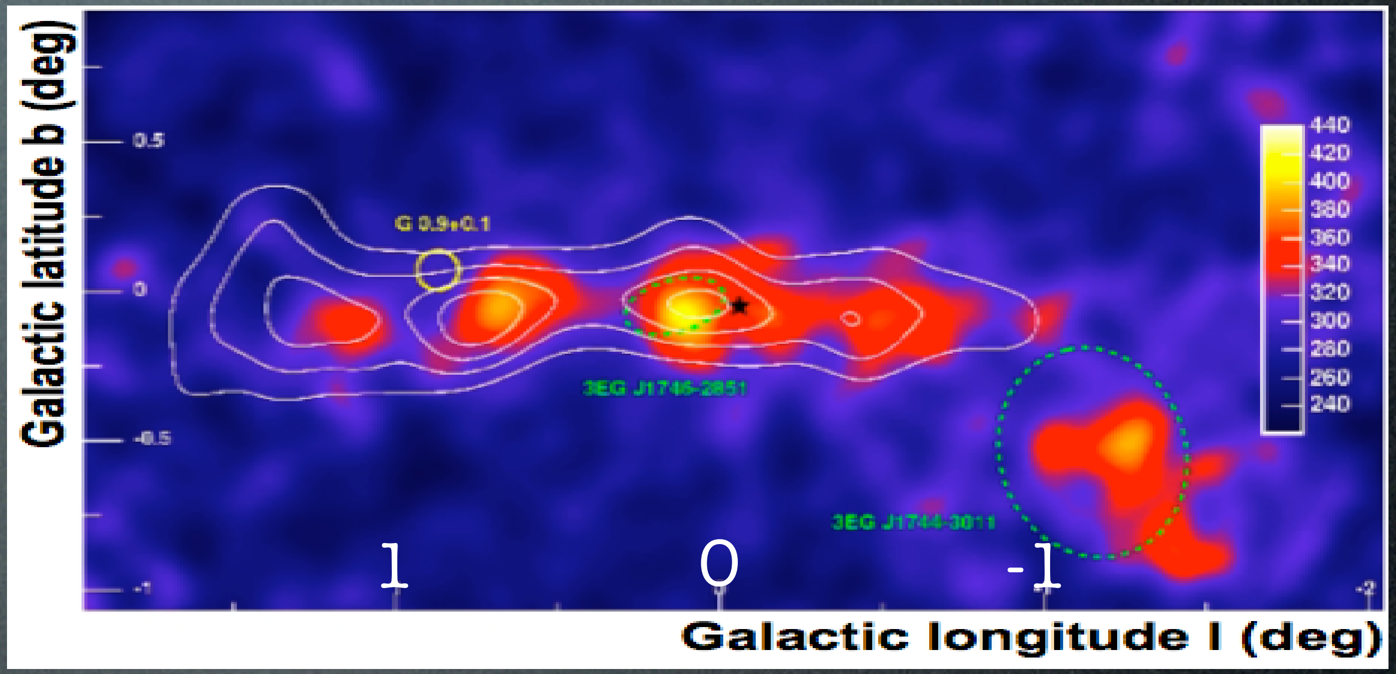
Step 2**: shower in lower portion selects **protons only

Step 3: full analysis (see that peak is statistically consistent with e^- peak of step 1)

P.Papini (PAMELA coll.), GGI conference, 02.2009

Gamma constraints

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



HESS coll.

Gamma constraints

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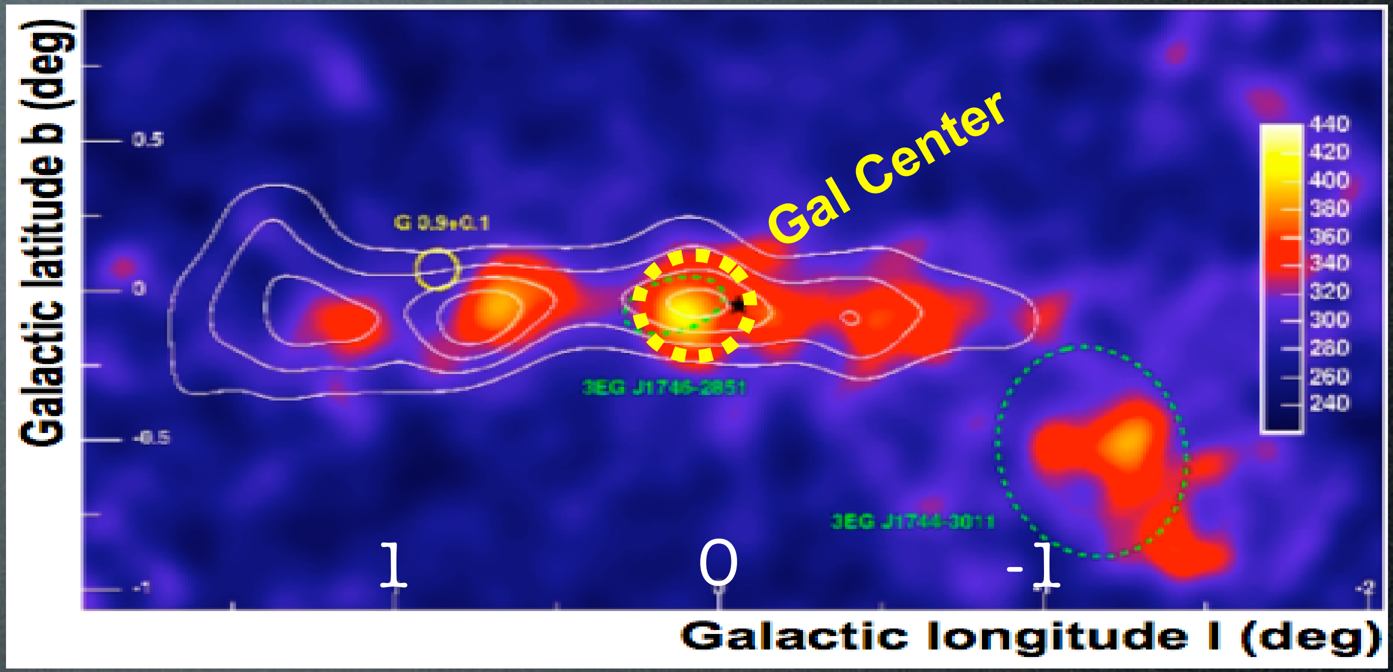

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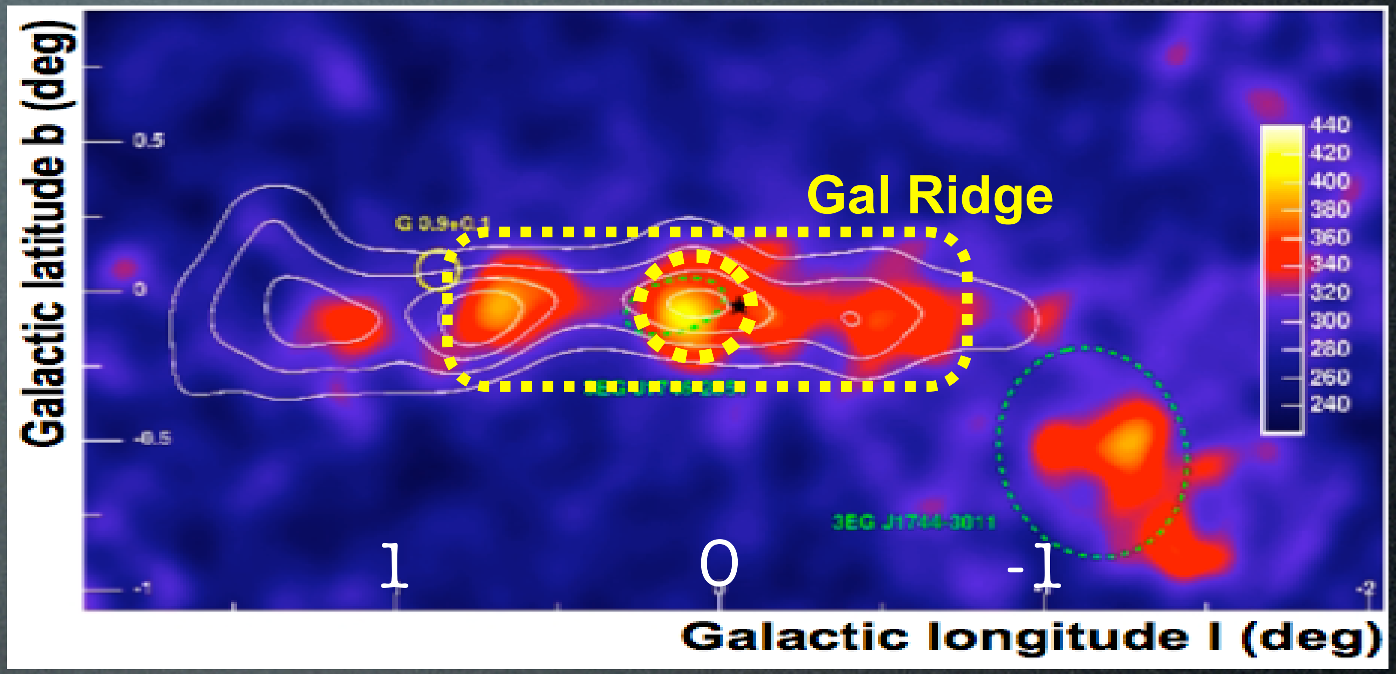

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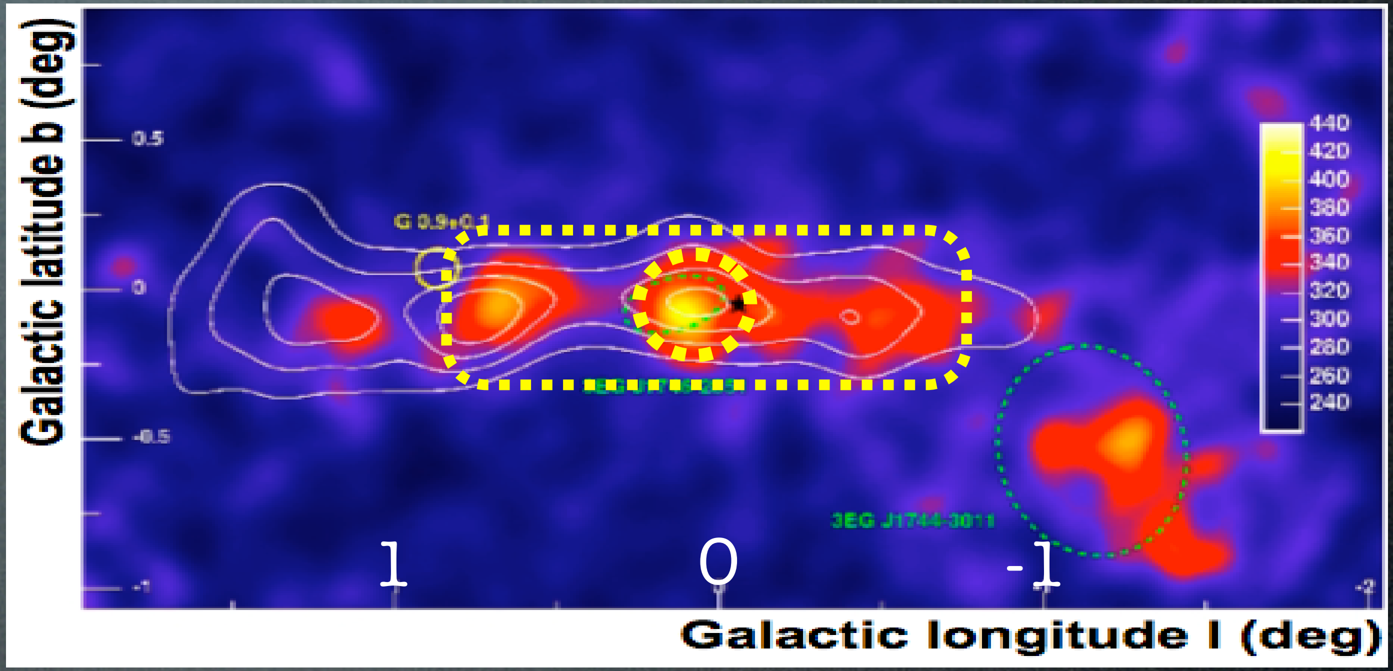
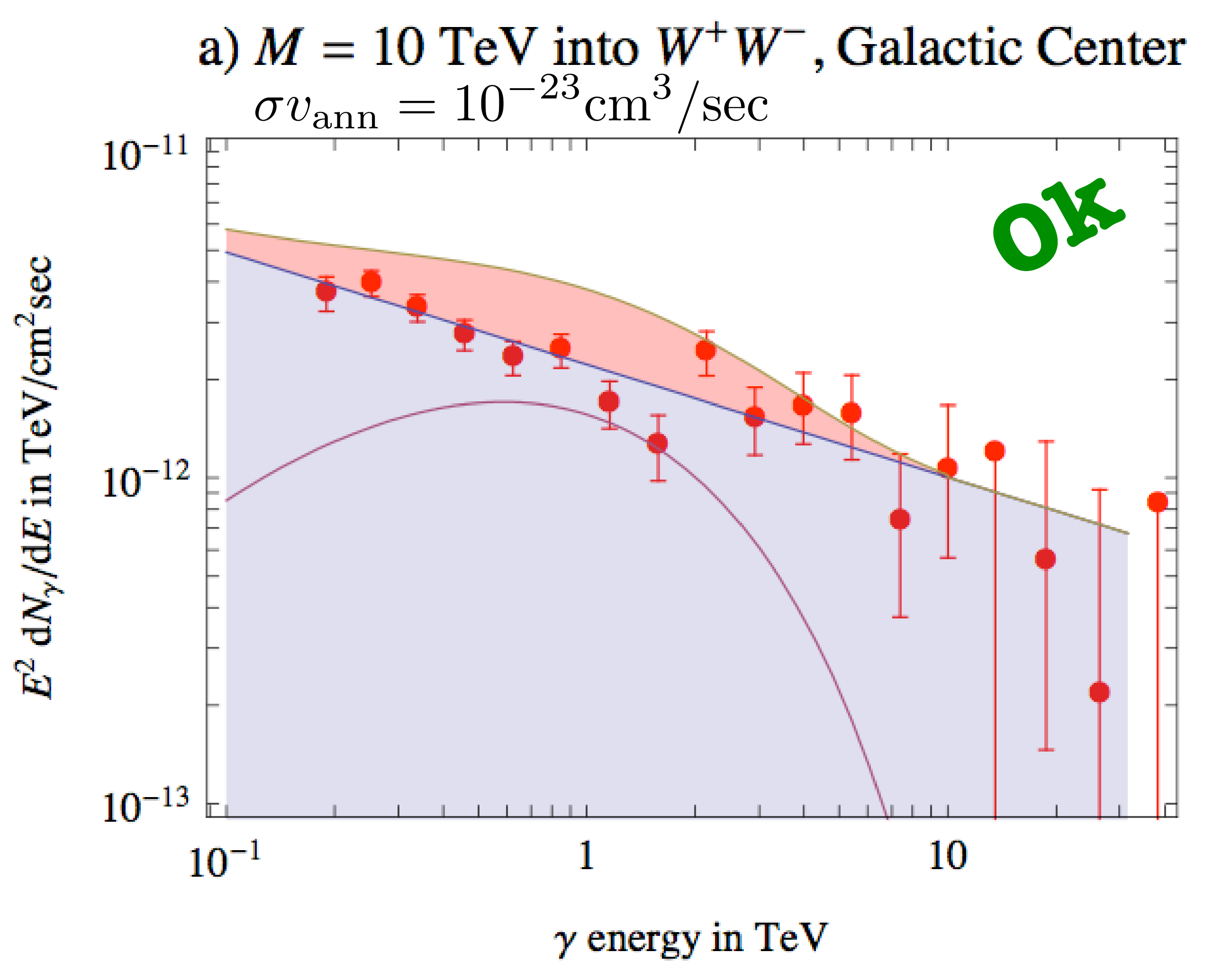


HESS coll.



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

Gamma constraints

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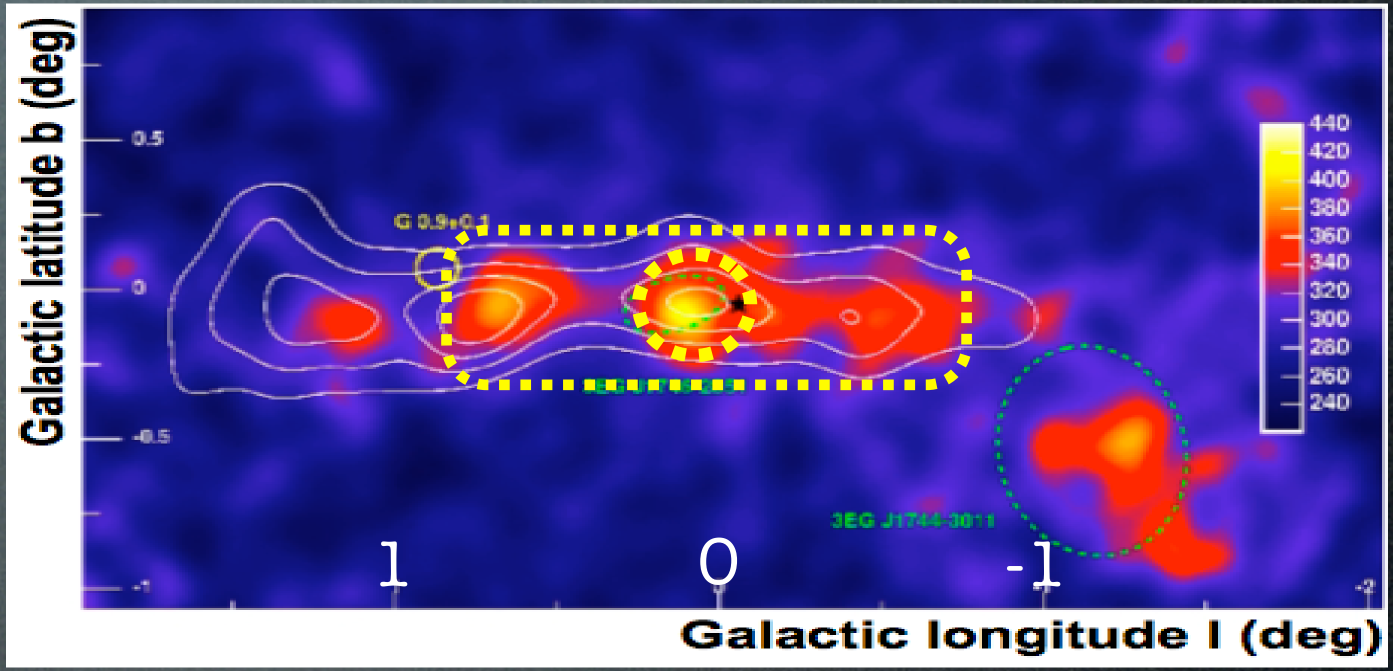
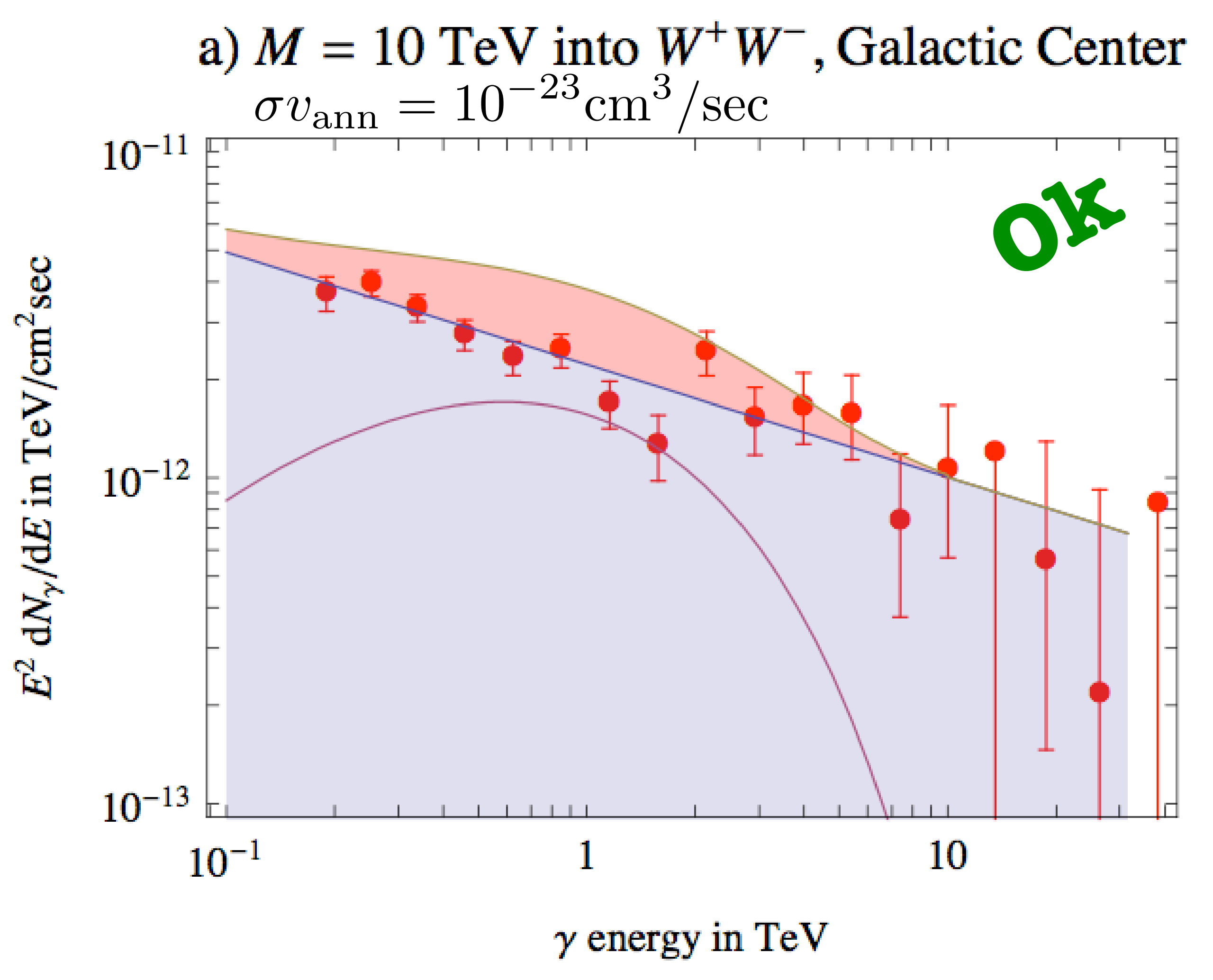


HESS coll.



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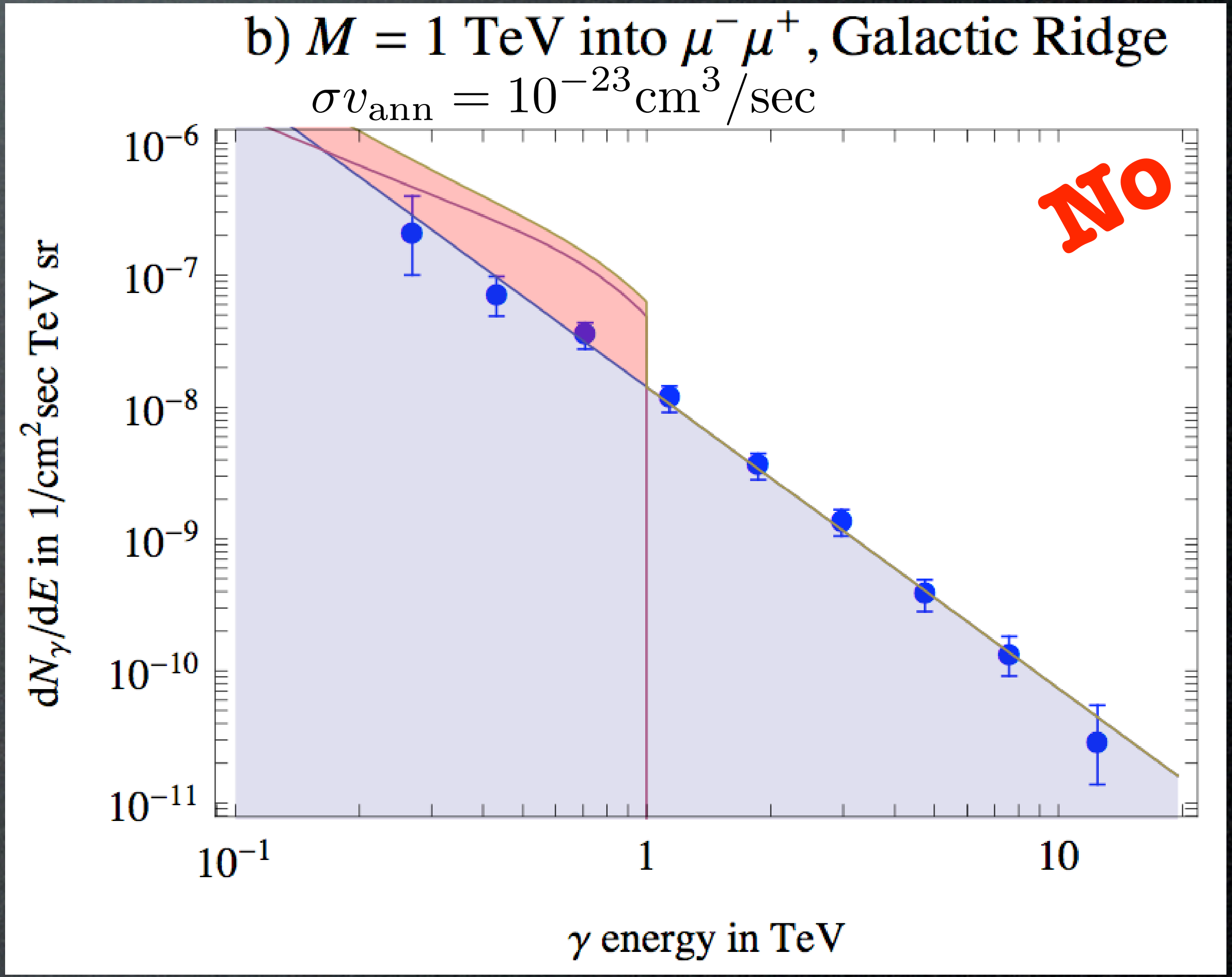
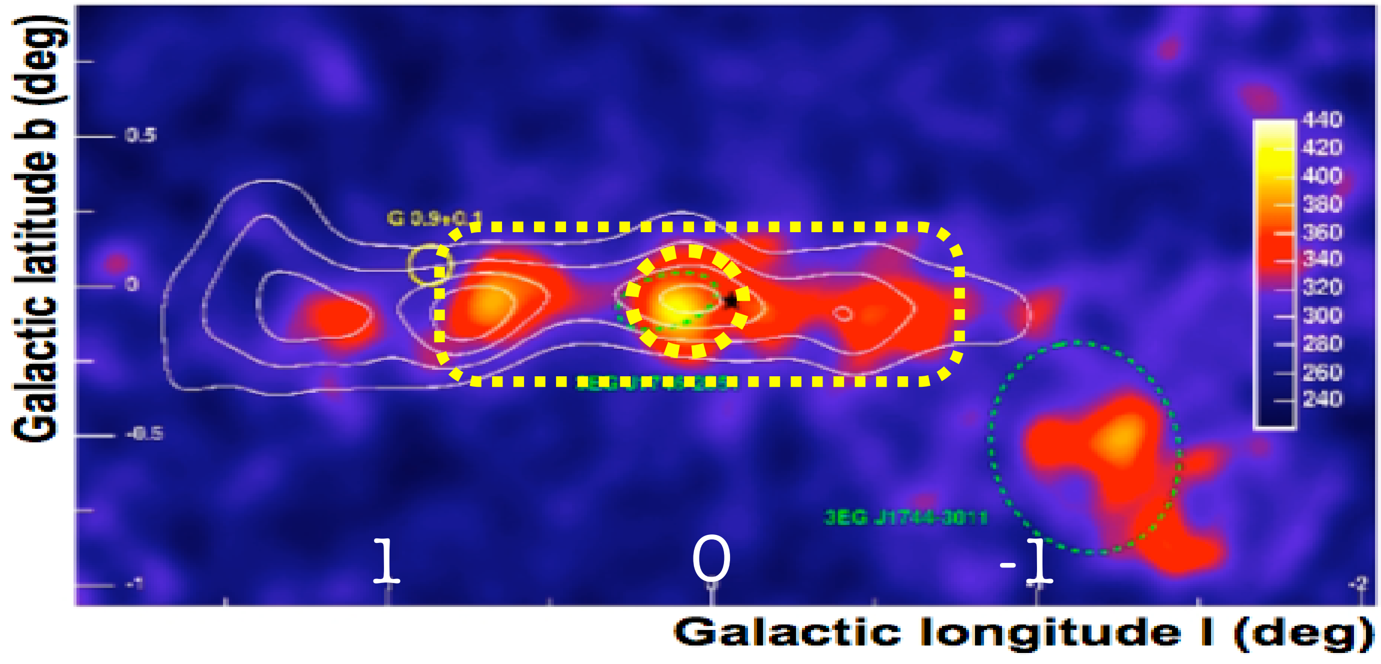


Data: HESS coll., astro-ph/0603021

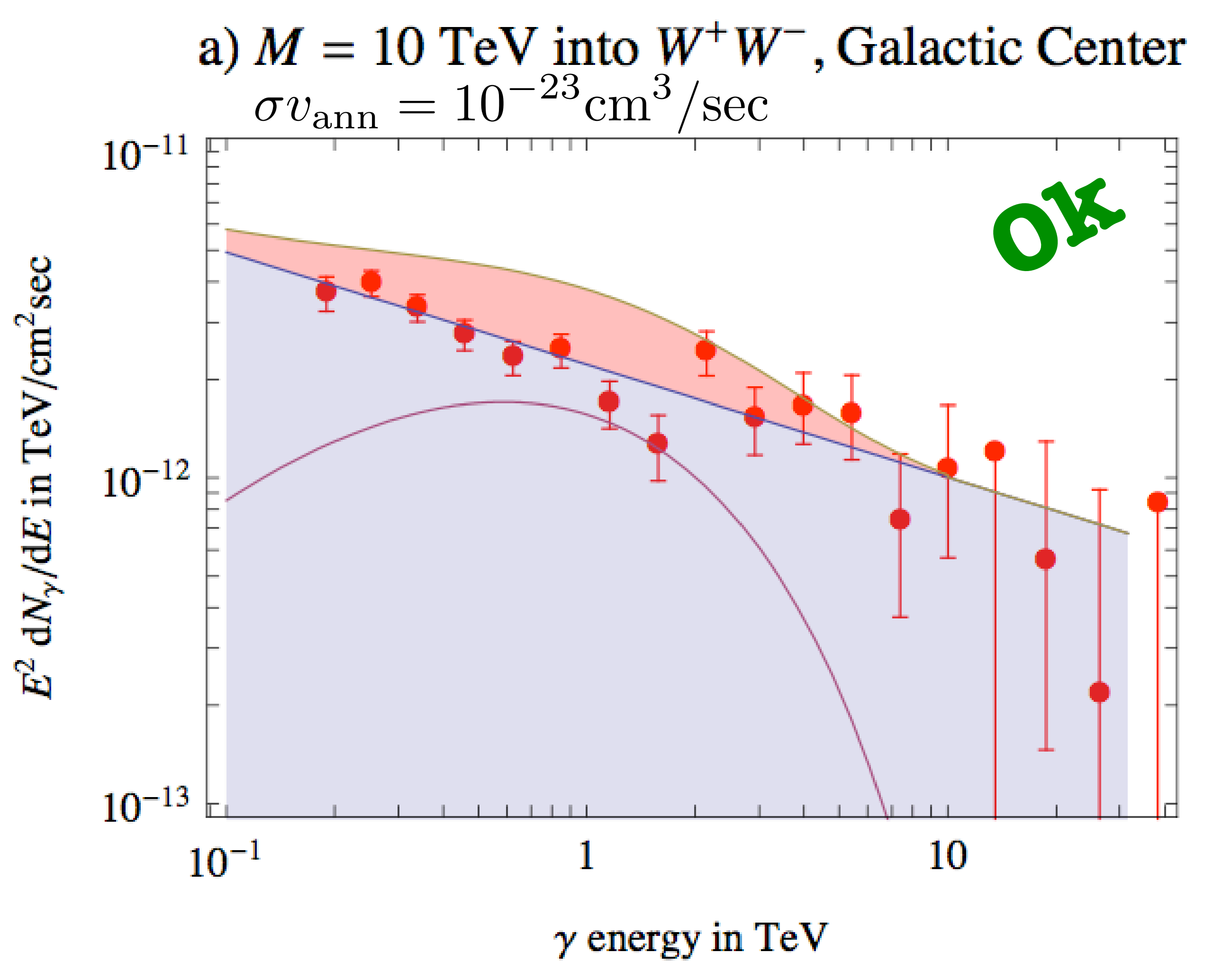
Gamma constraints

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.

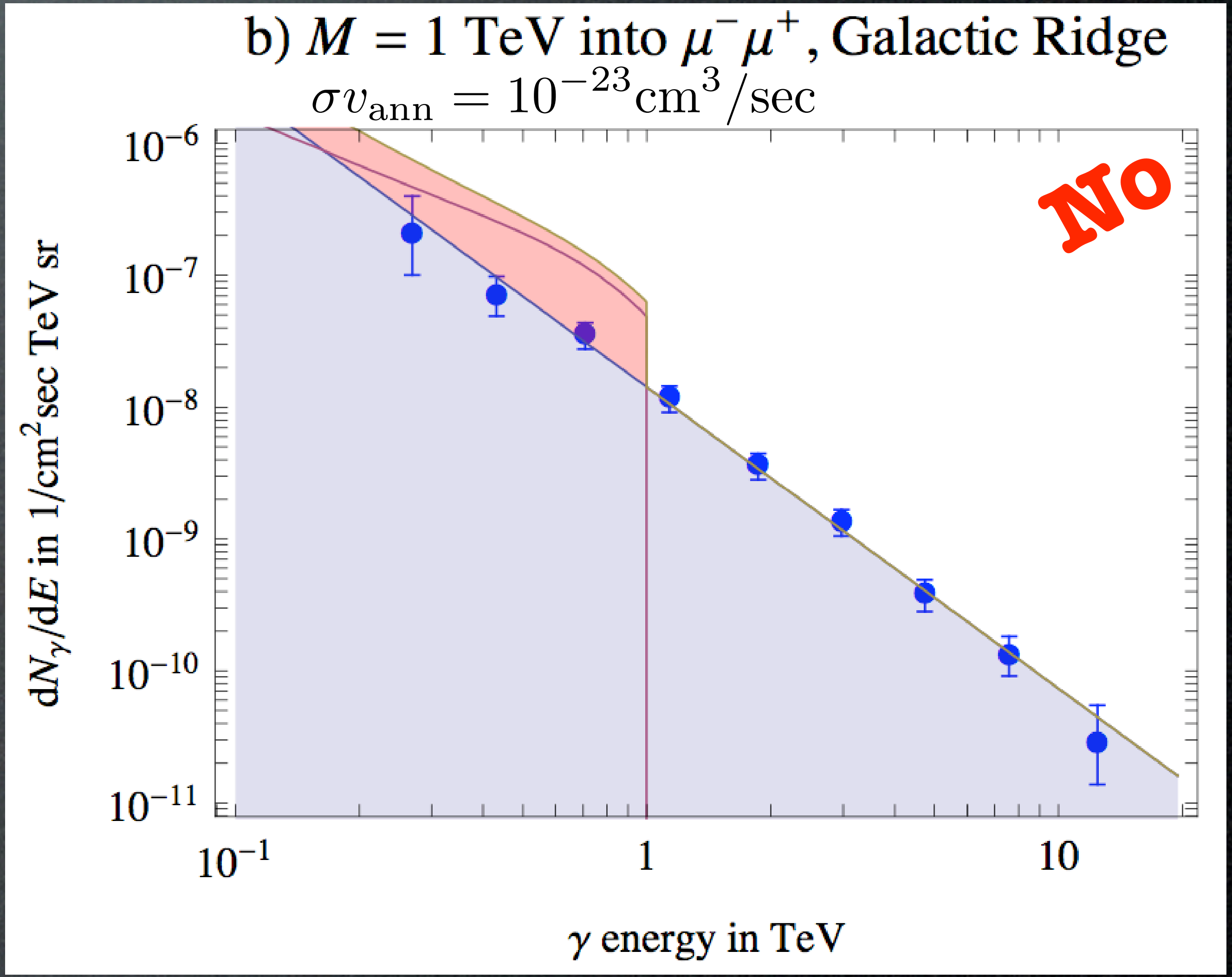


HESS coll.


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

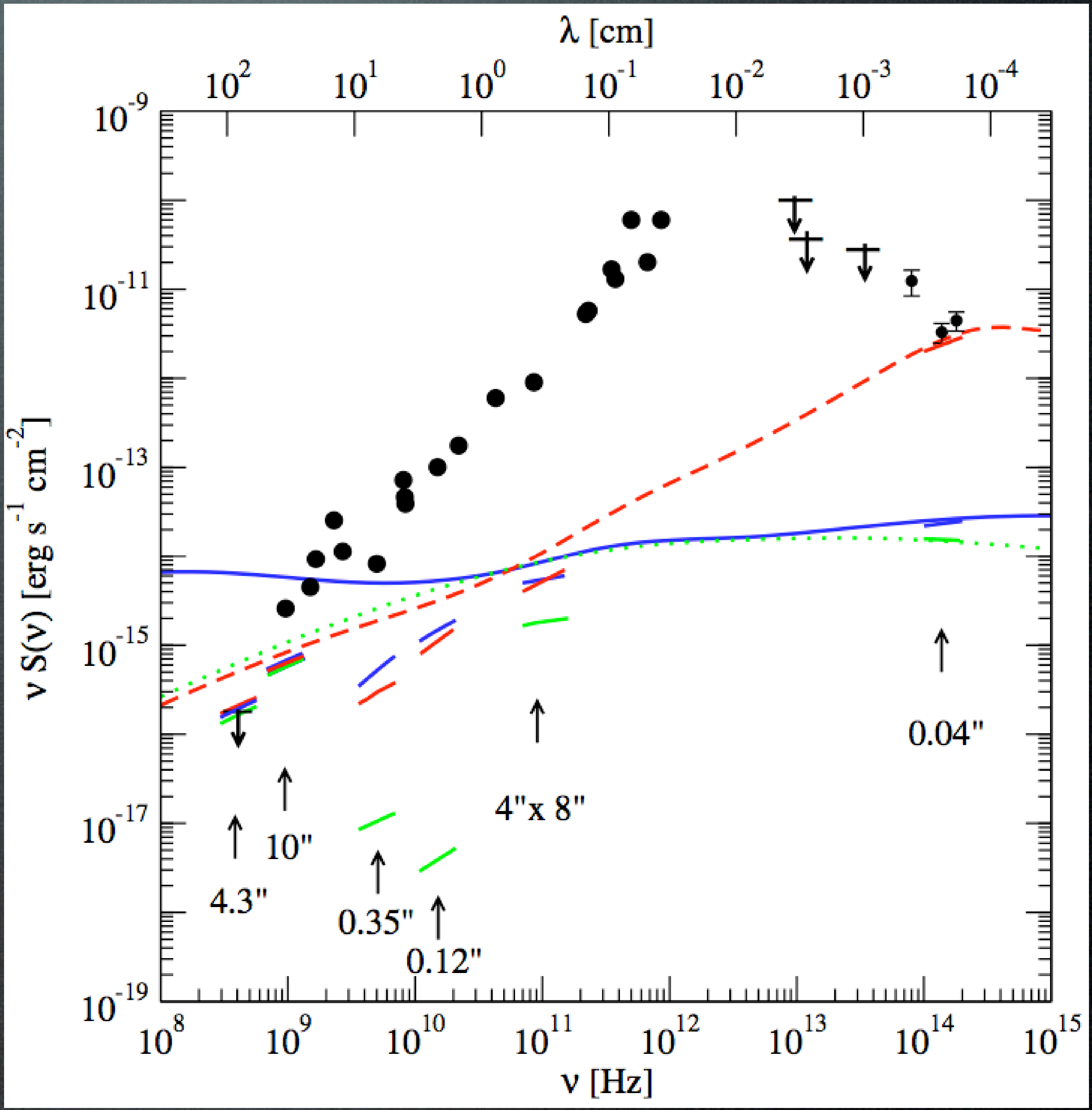

b) M = 1 TeV into $\mu^-\mu^+$, Galactic Ridge

$\sigma v_{\rm ann} = 10^{-23} {\rm cm}^3/{\rm sec}$

Data: HESS coll., astro-ph/0603021

Gamma constraints

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

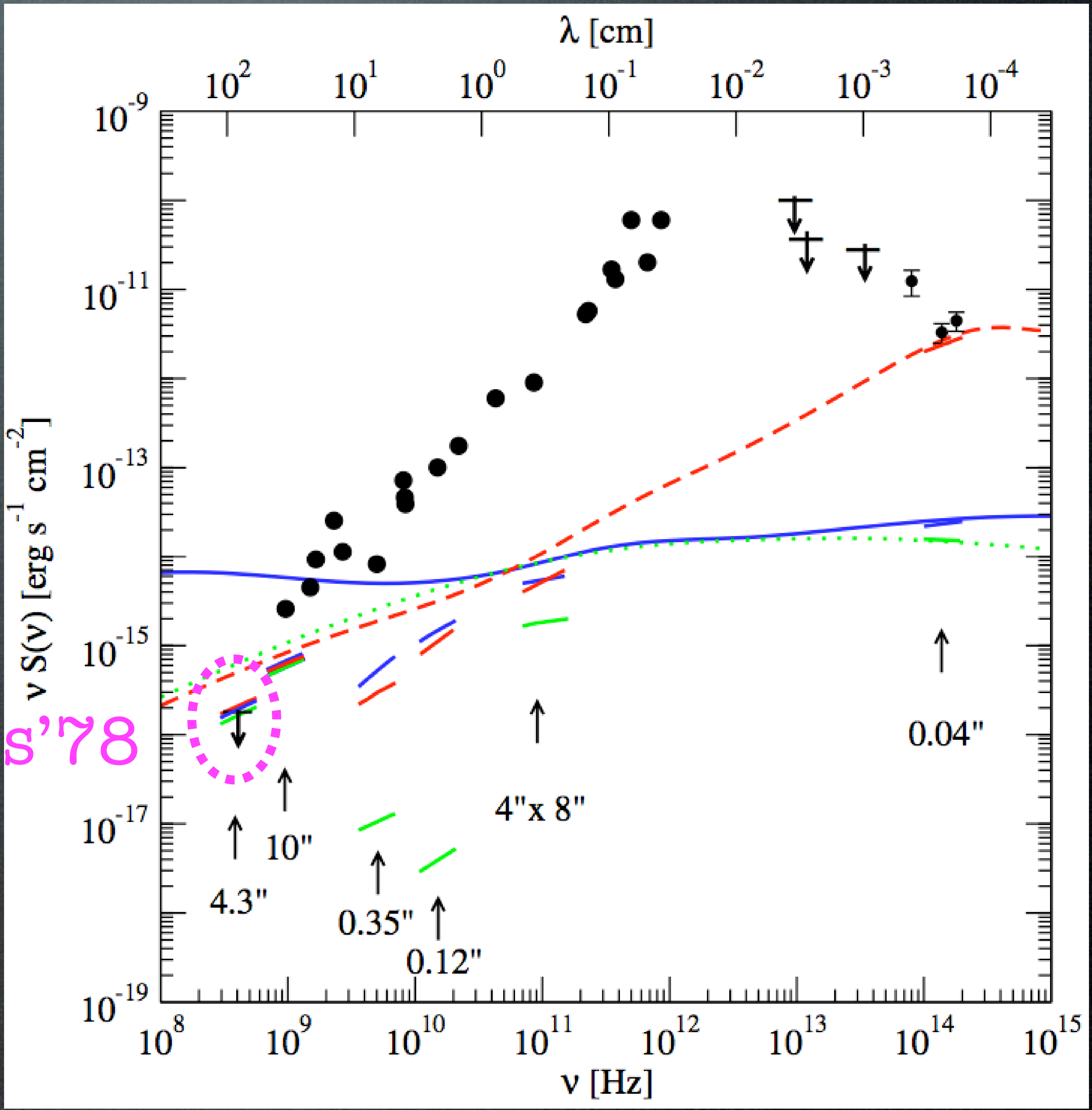


Regis, Ullio PRD 78 (2008)

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

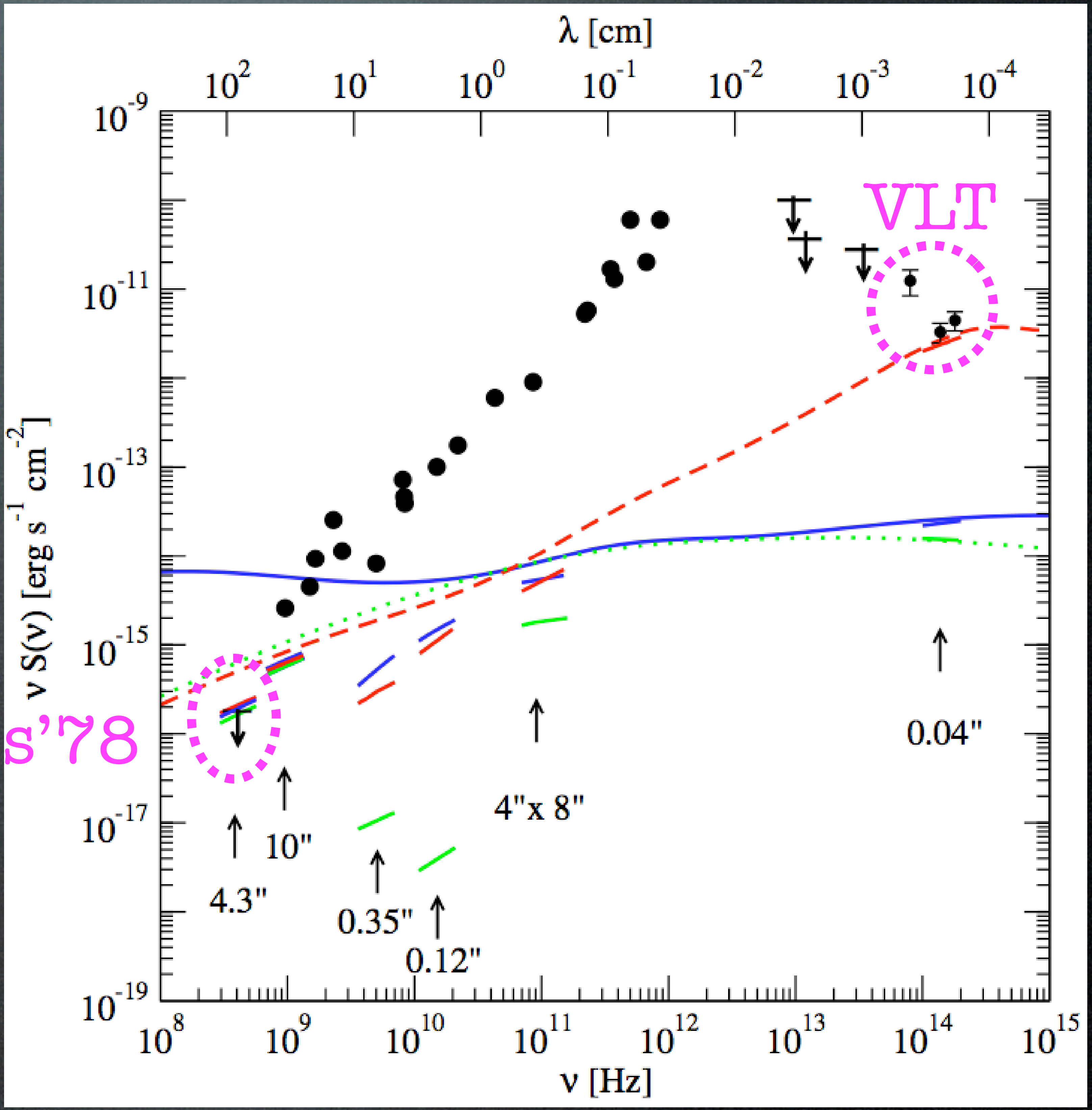
Regis, Ullio PRD 78 (2008)

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.



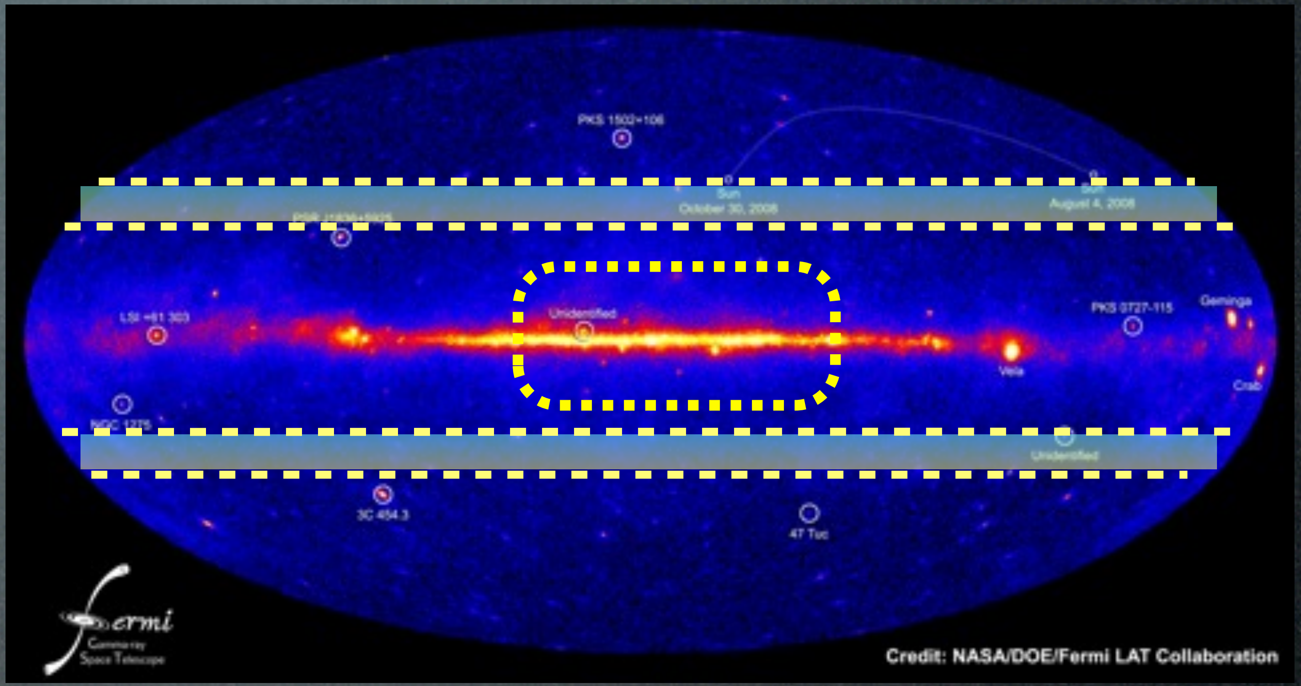
Davies'78

Regis, Ullio PRD '78 (2008)

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

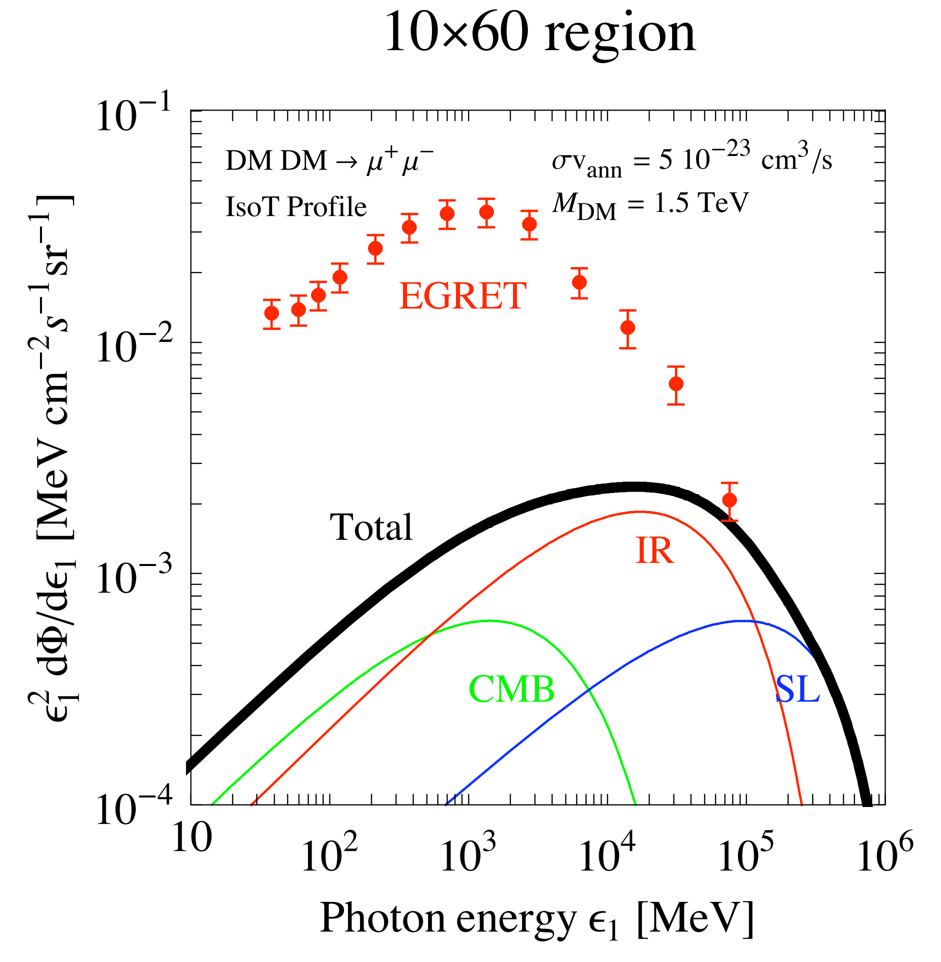
Gamma constraints

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

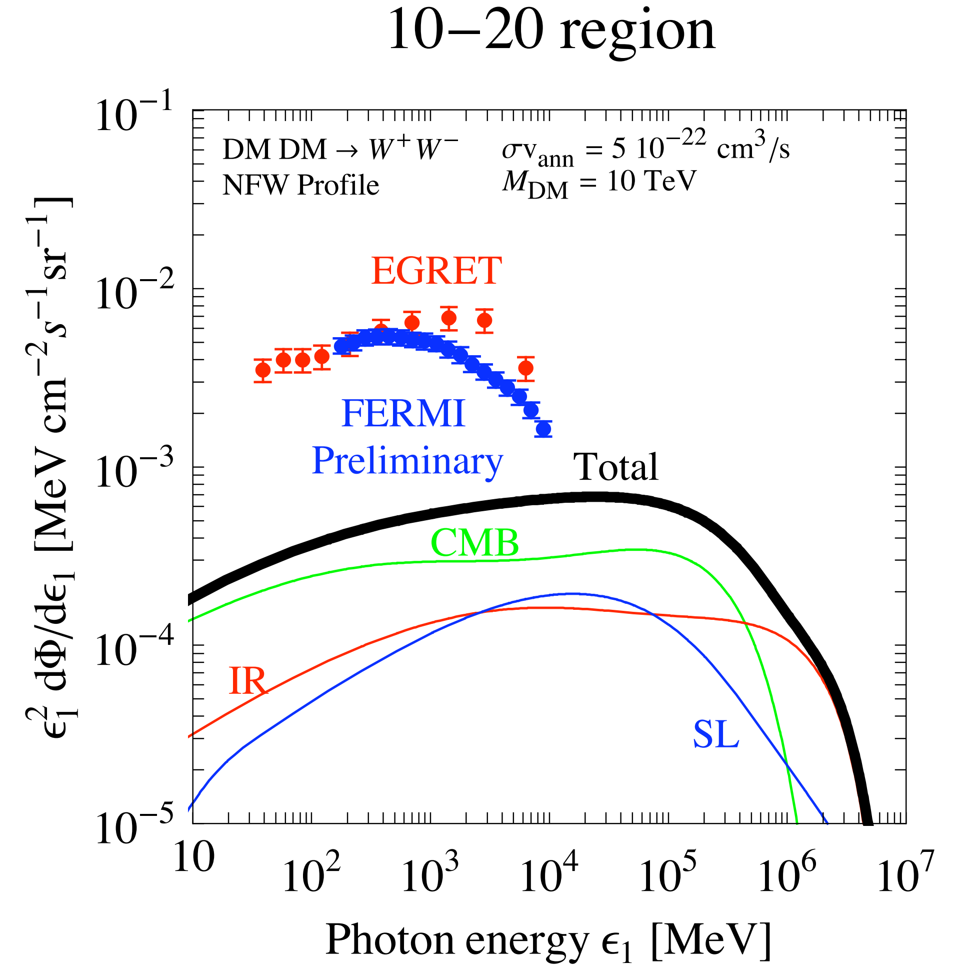


Credit: NASA/DOE/Fermi LAT Collaboration

FERMI coll.


10×60 region

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


10–20 region

Data: FERMI coll., several talks in 2009