

1 march 2010
Rencontres de La Thuile

Recent developments in theory and phenomenology of Dark Matter

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)
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0912.0663
and work in progress

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Questions

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

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Why?

Questions

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Why?

What has the eruption left?

DM detection

direct detection

Xenon, CDMS, Edelweiss, Dama/Libra?

production at colliders

LHC

indirect

γ from annihil in galactic halo or center
(line + continuum)

Fermi

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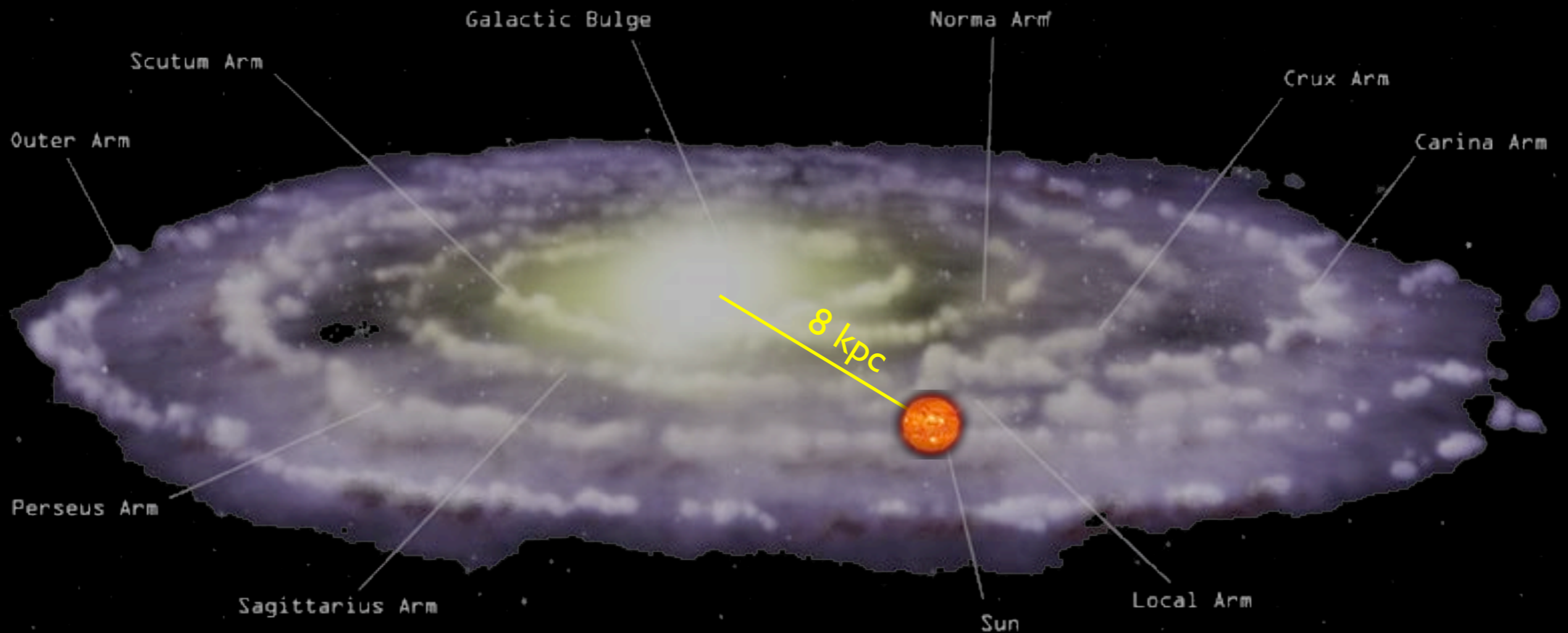
\bar{p} from annihil in galactic halo or center

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

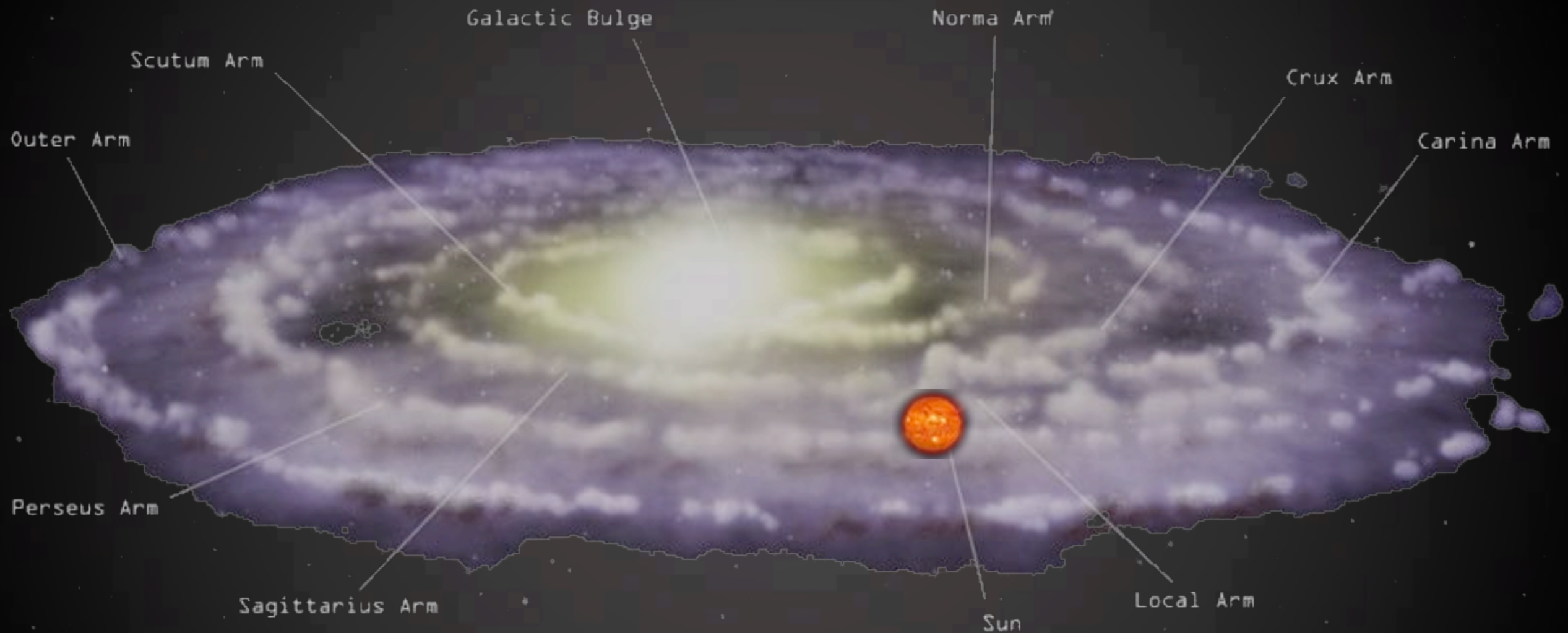
Indirect Detection

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



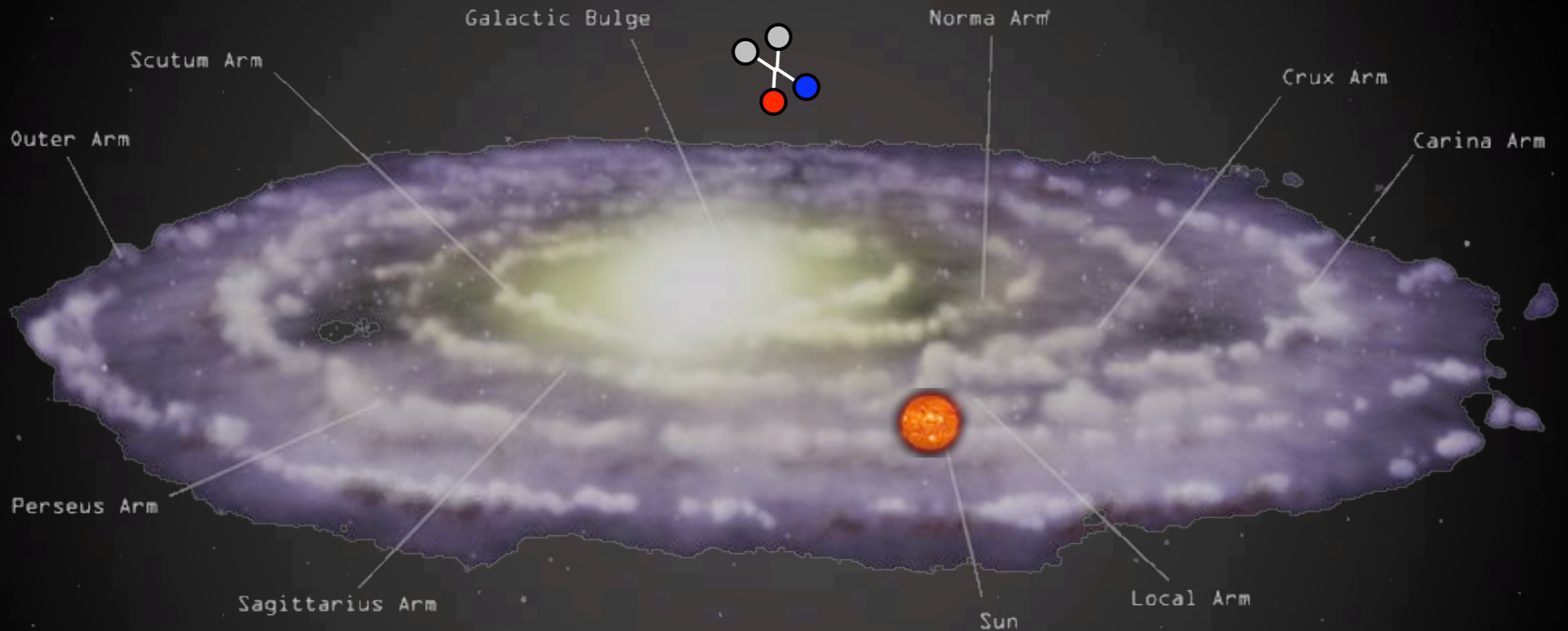
Indirect Detection

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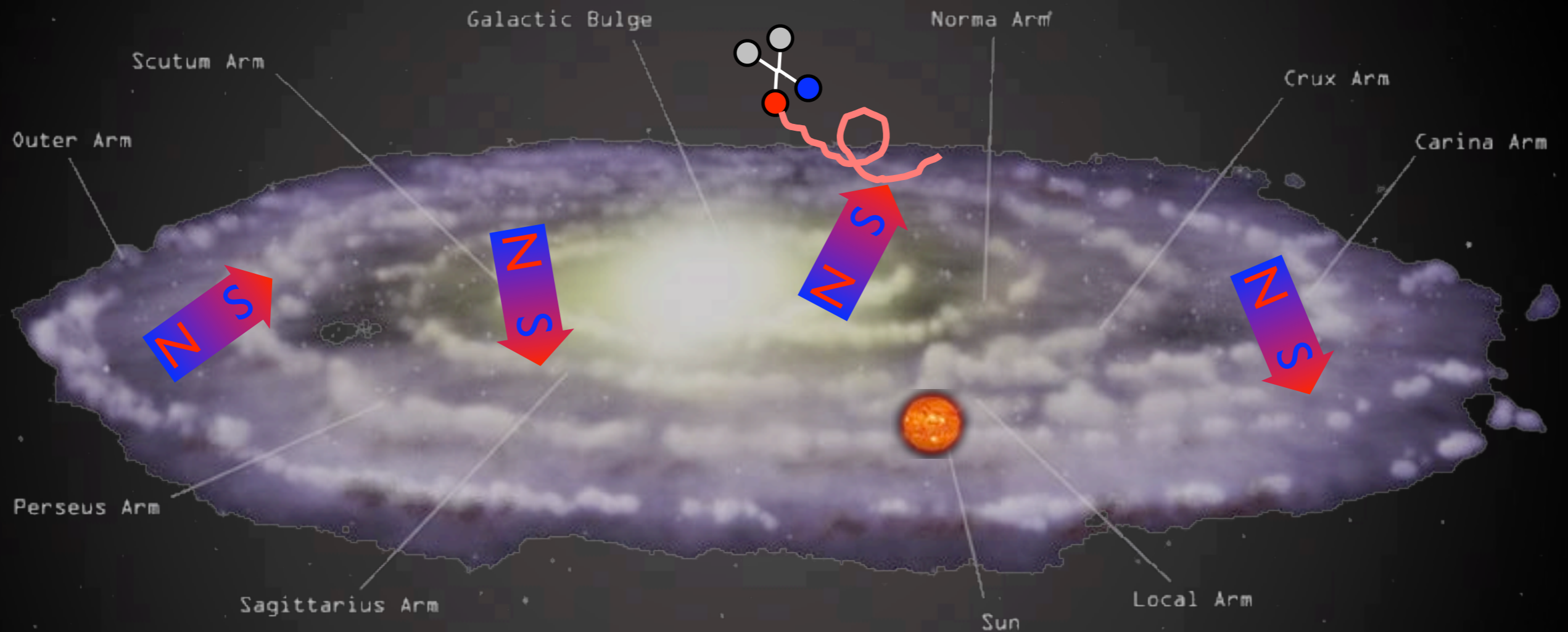
Indirect Detection

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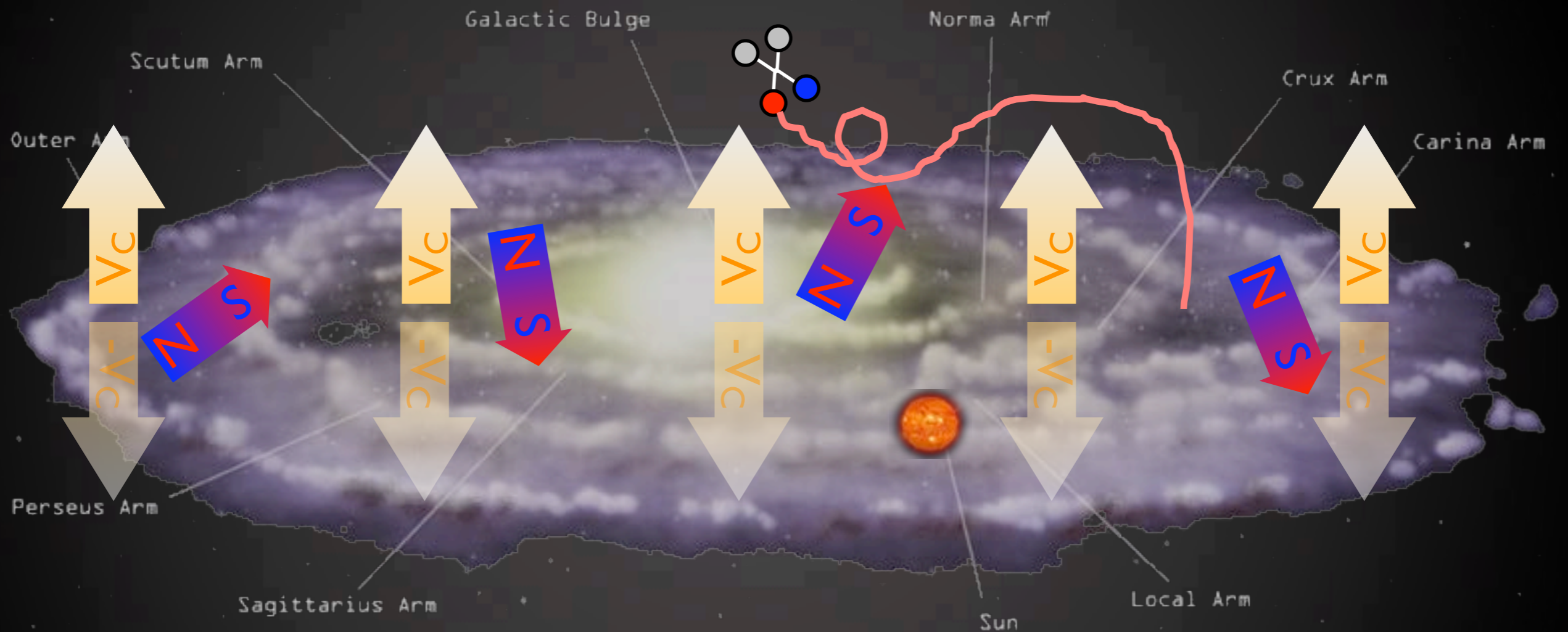
Indirect Detection

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



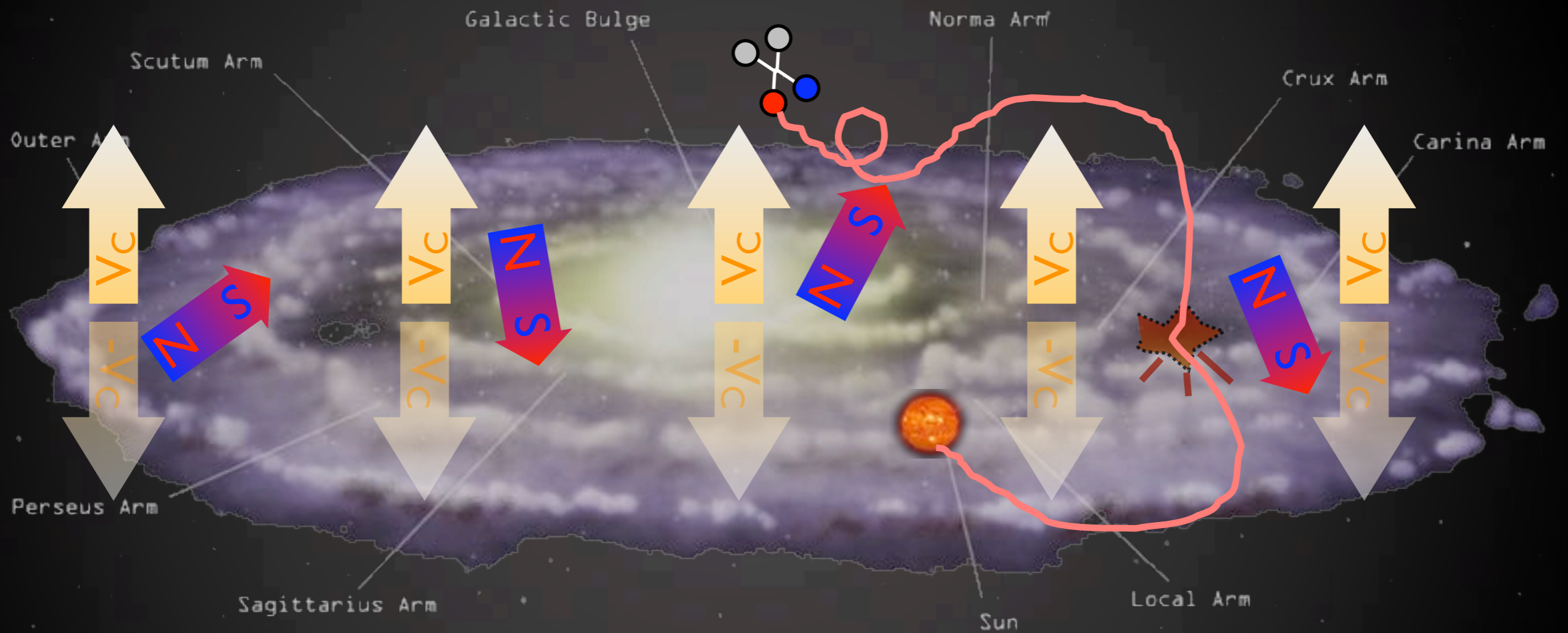
Indirect Detection

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



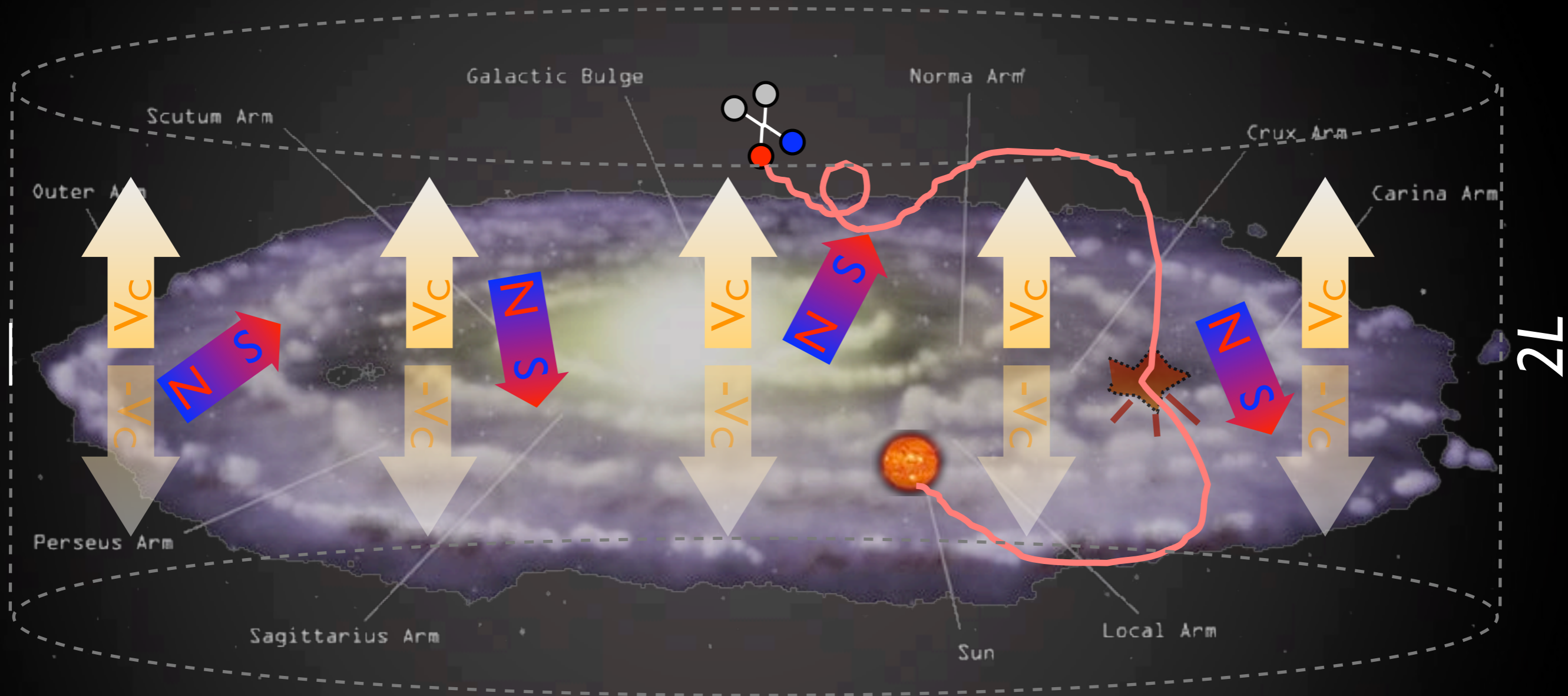
Indirect Detection

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



Indirect Detection

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



spectrum

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

diffusion

energy loss

convective wind

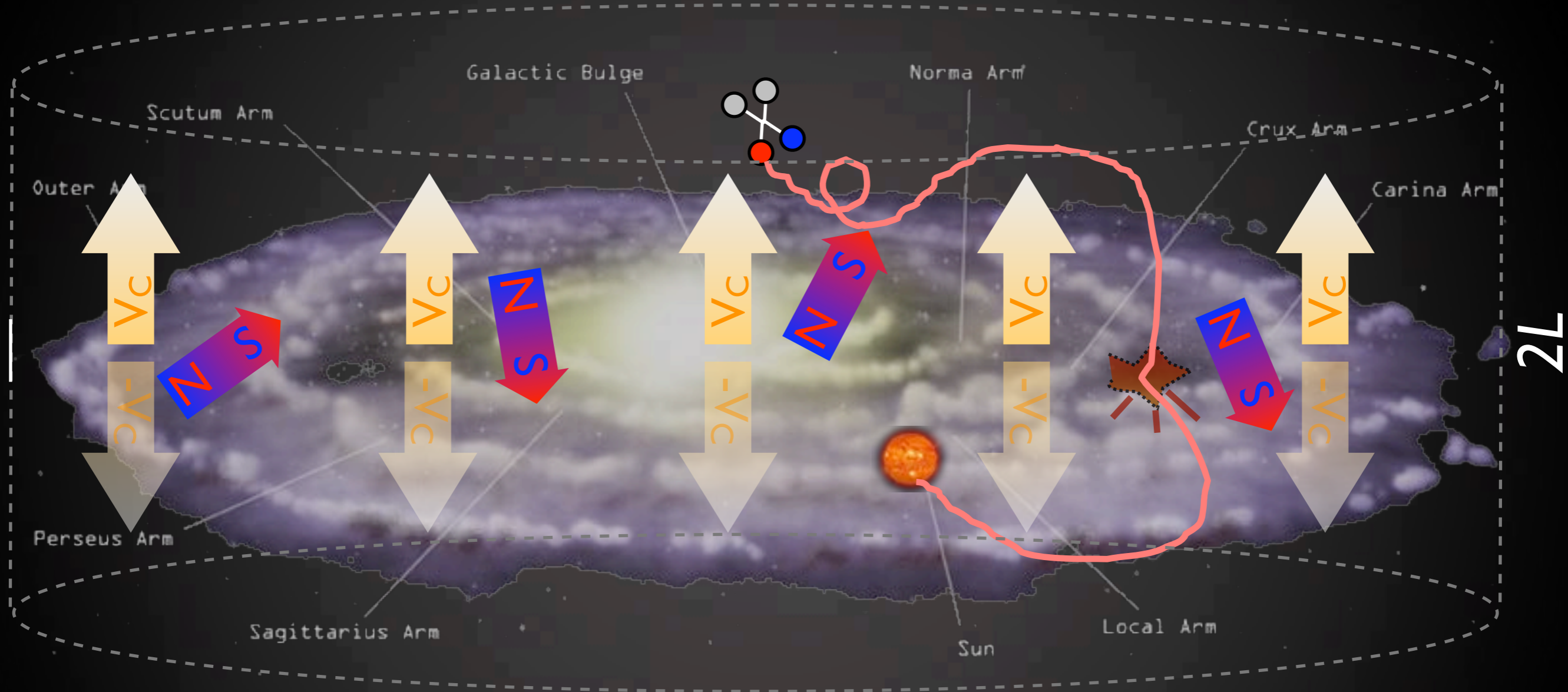
source

spallations

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

Indirect Detection

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

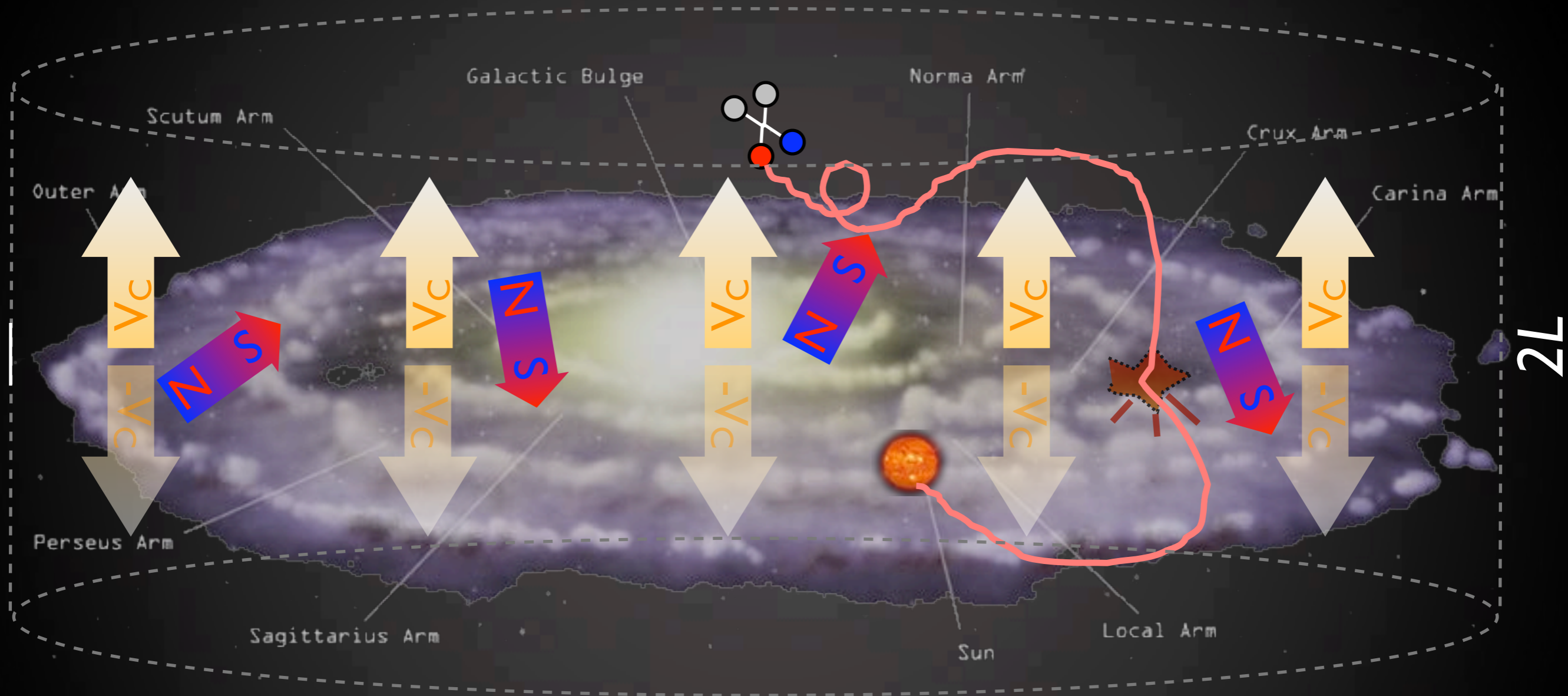


What sets the overall expected flux?

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

Indirect Detection

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



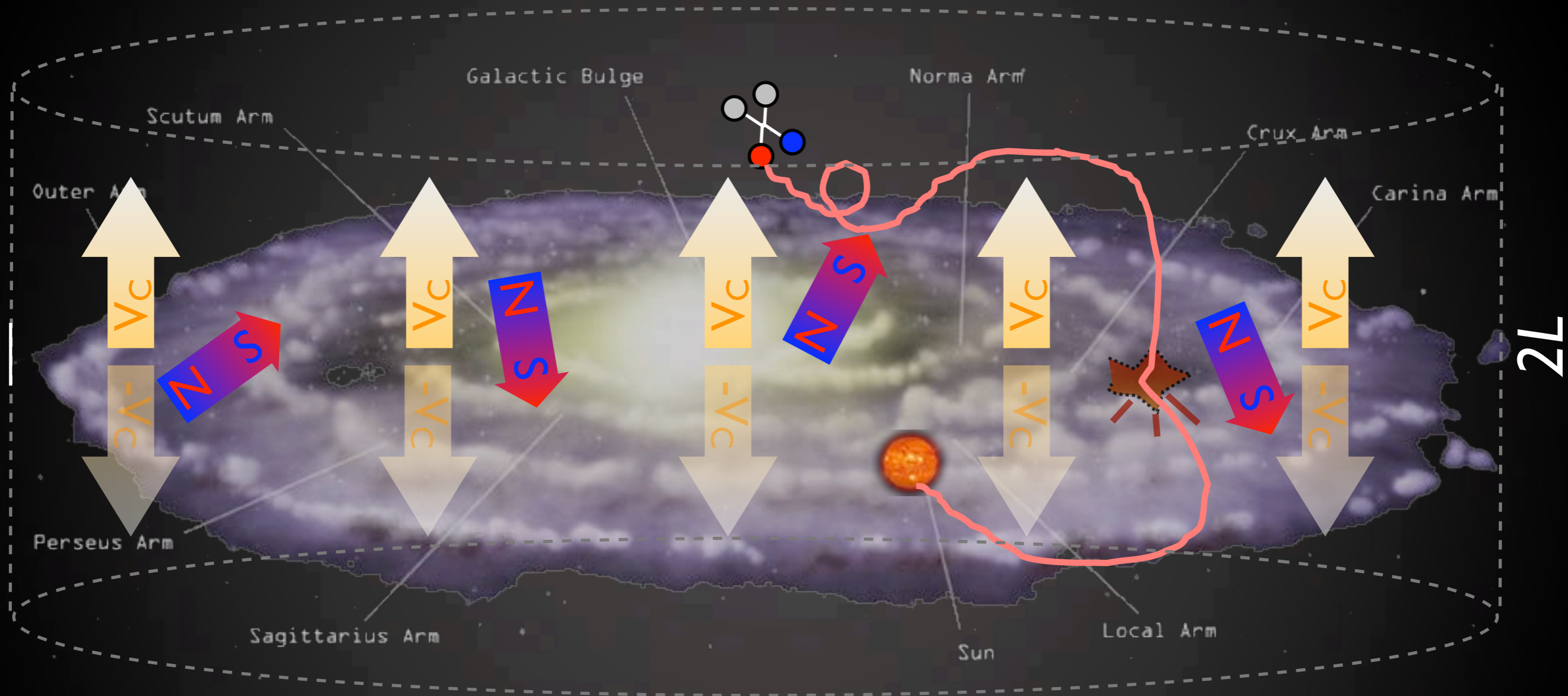
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astro & cosmo

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:

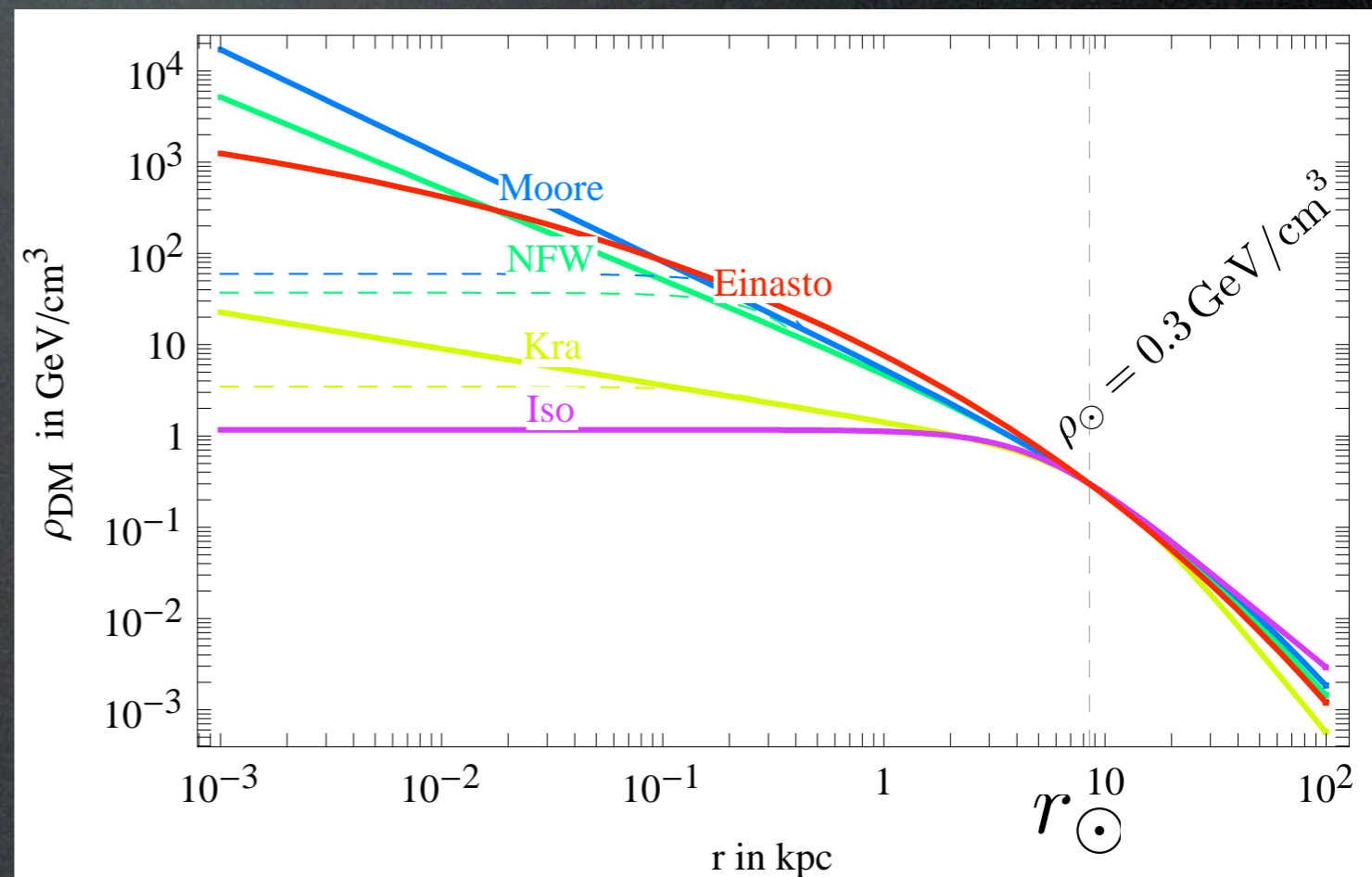
$$\rho(r) = \rho_{\odot} \left[\frac{r_{\odot}}{r} \right]^{\gamma} \left[\frac{1 + (r_{\odot}/r_s)^{\alpha}}{1 + (r/r_s)^{\alpha}} \right]^{(\beta-\gamma)/\alpha}$$

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 | $\alpha = 0.17$ $r_s = 20$ kpc $\rho_s = 0.06$ GeV/cm³



cuspy: **NFW**, **Moore**

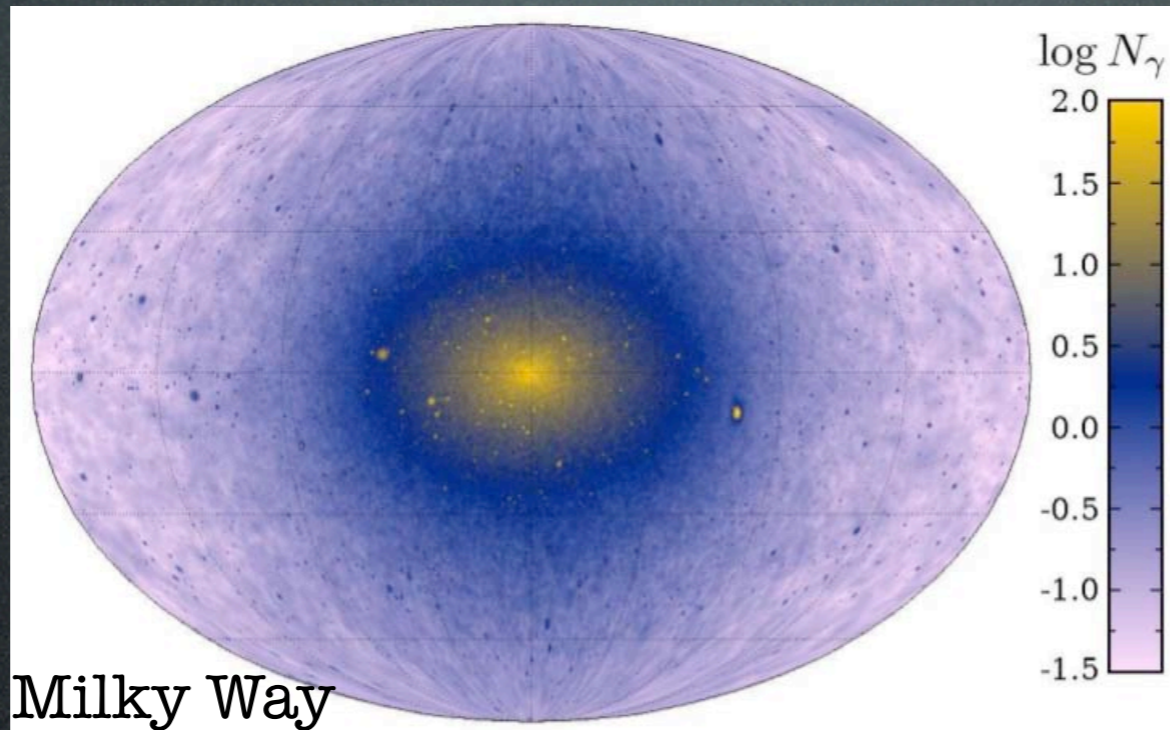
mild: **Einasto**

smooth: **isothermal**

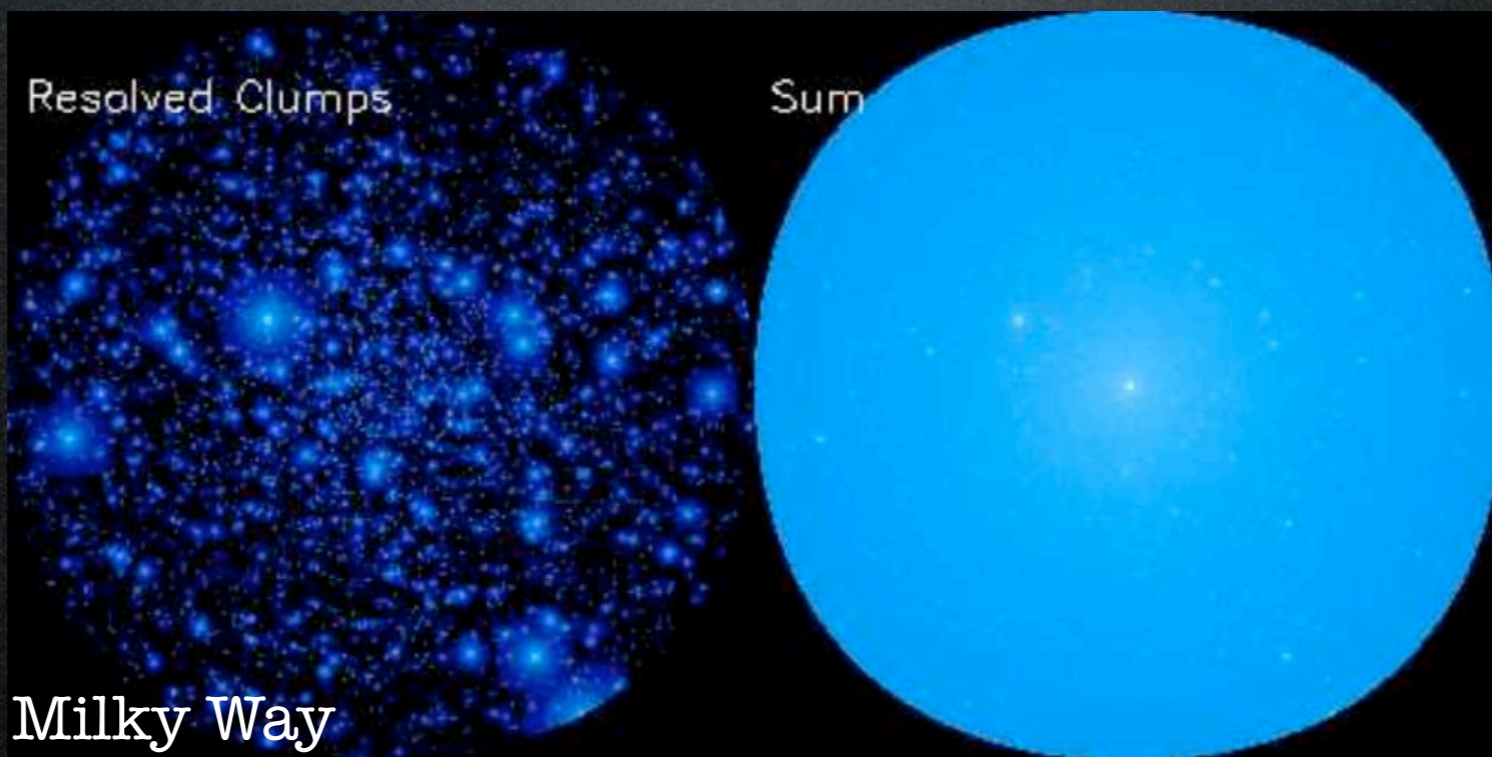
Indirect Detection

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

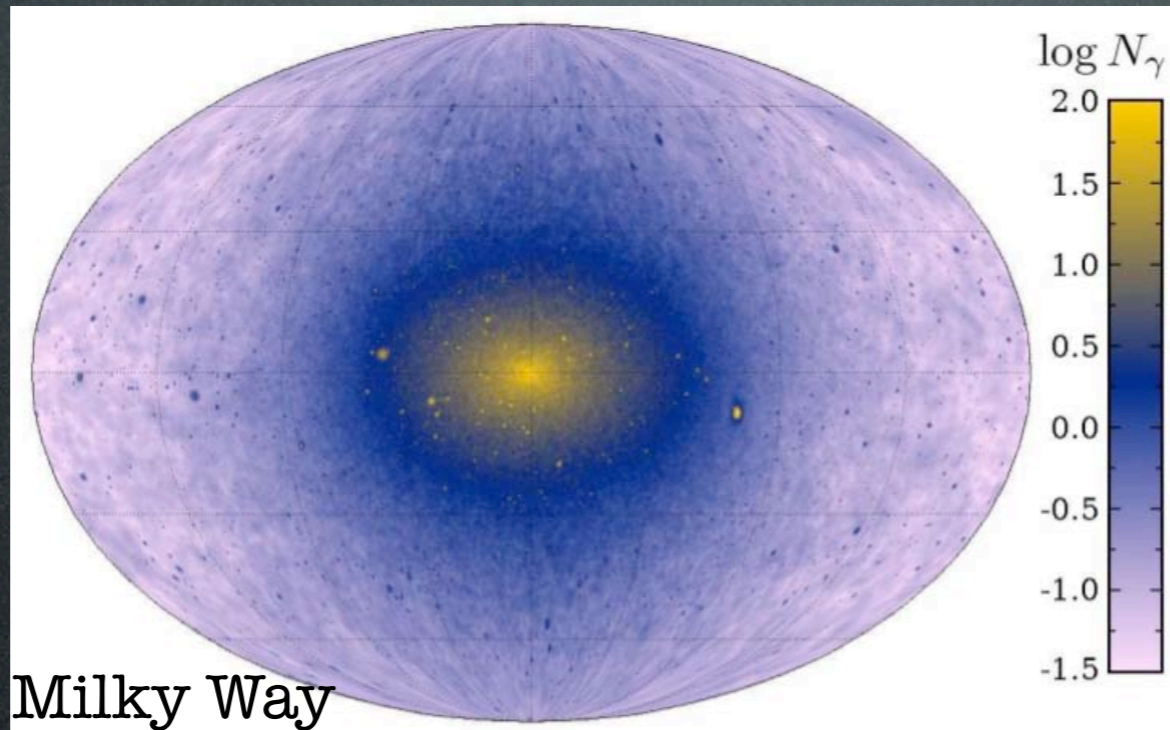


Bertone, Branchini, Pieri 2007

Indirect Detection

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

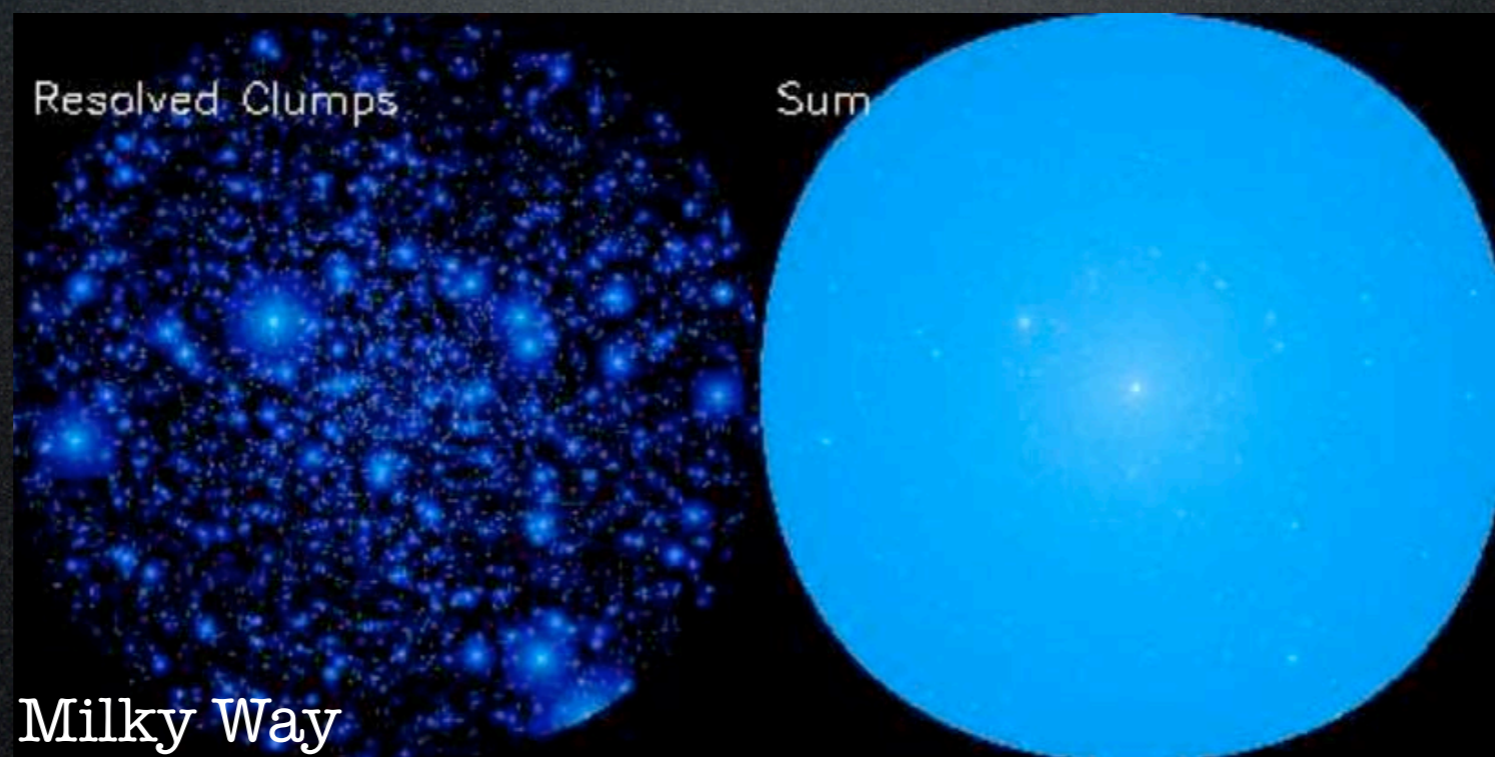
For illustration:



Kuhlen, Diemand, Madau 2007

But: recent simulations seem to show almost **no clumps** in inner 10 kpc (tidal stripping).

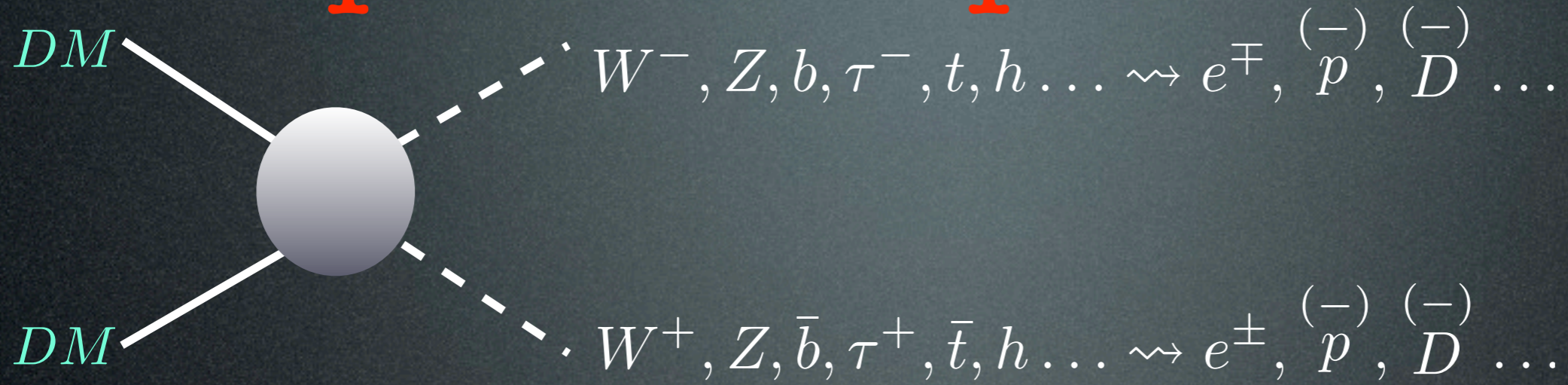
[Millenium Simulation, Carlos Frenk]



Bertone, Branchini, Pieri 2007

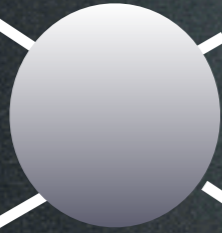
Computing the theory
predictions

Spectra at production



Spectra at production

DM



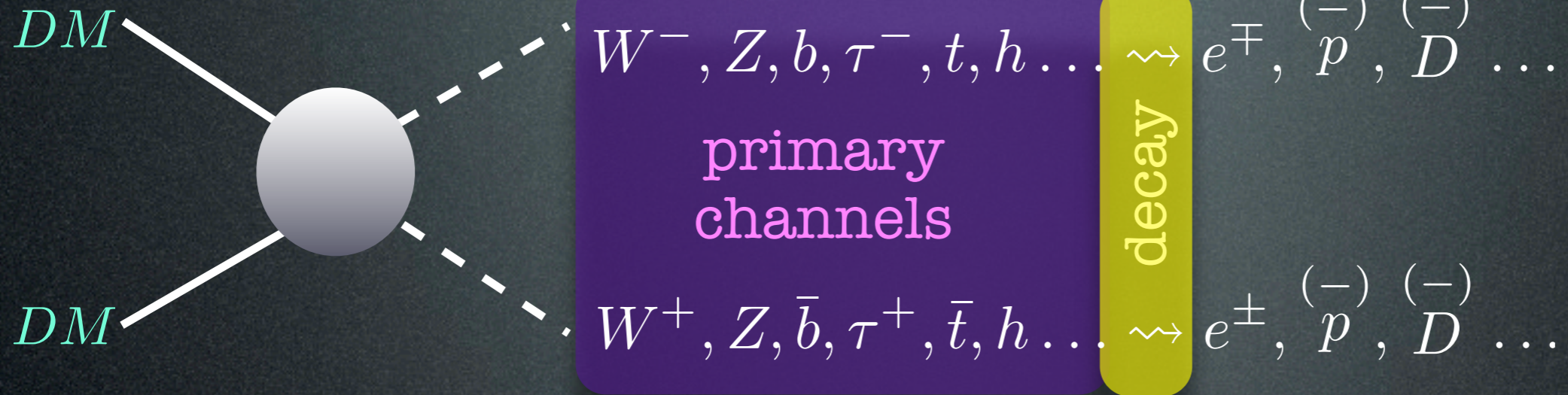
DM

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

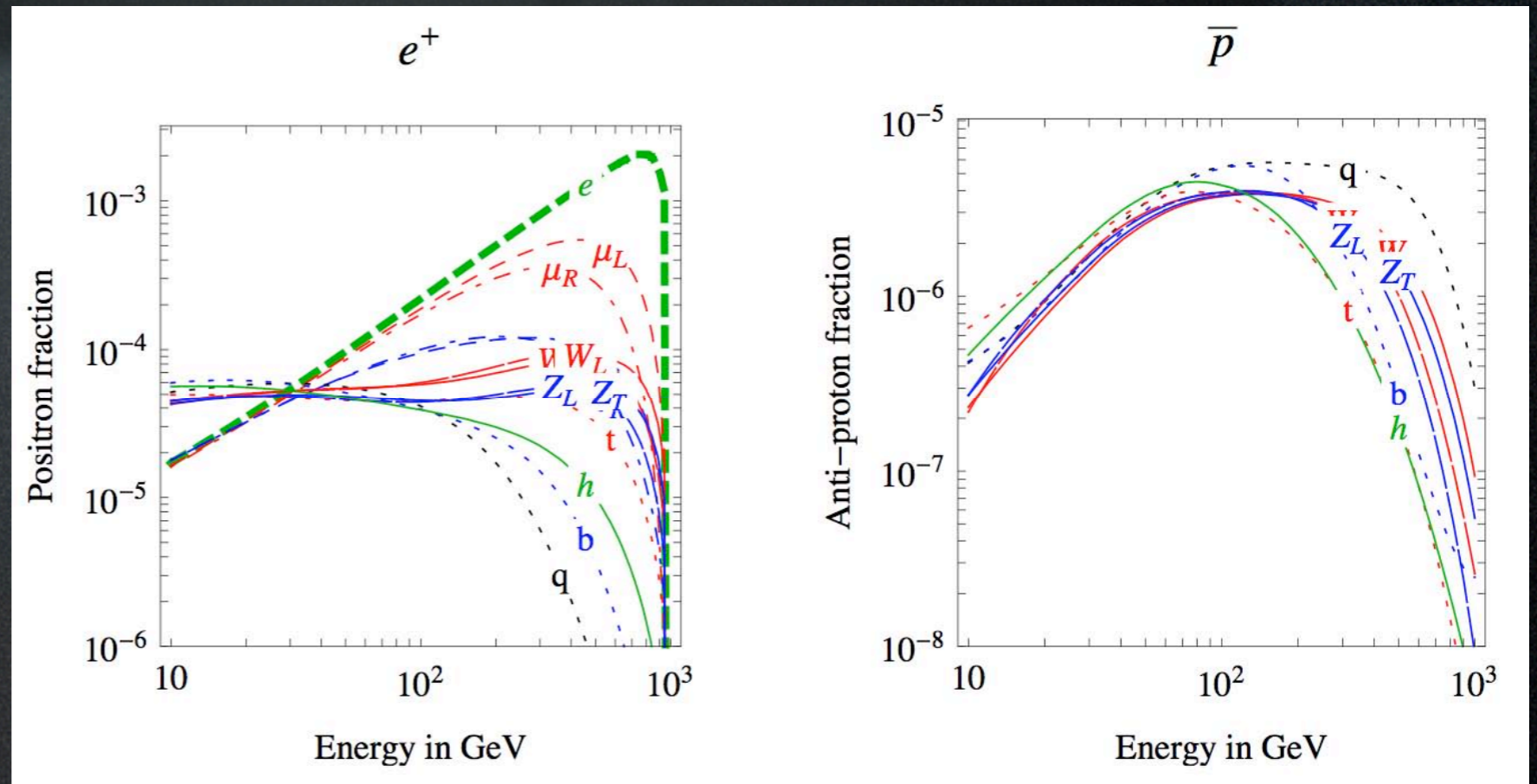
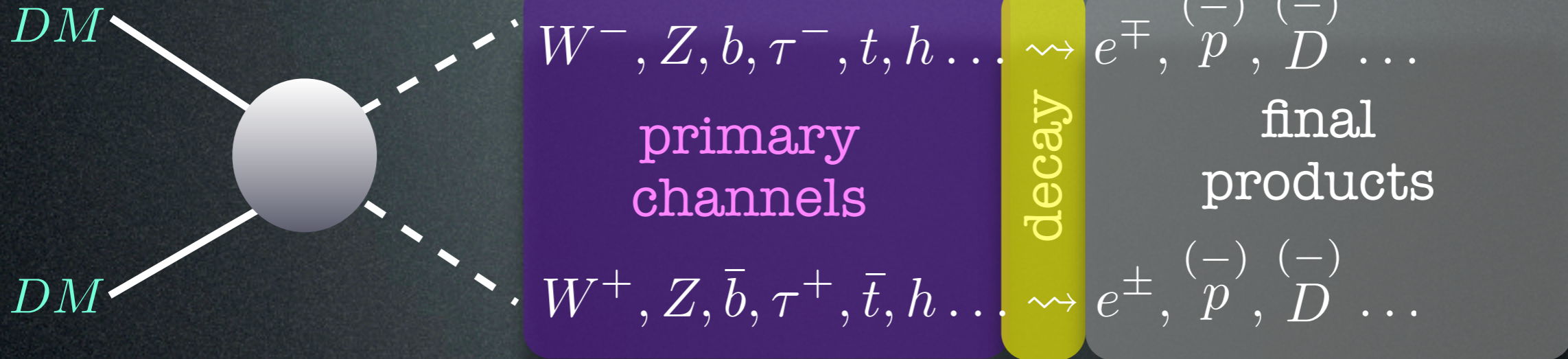
primary
channels

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

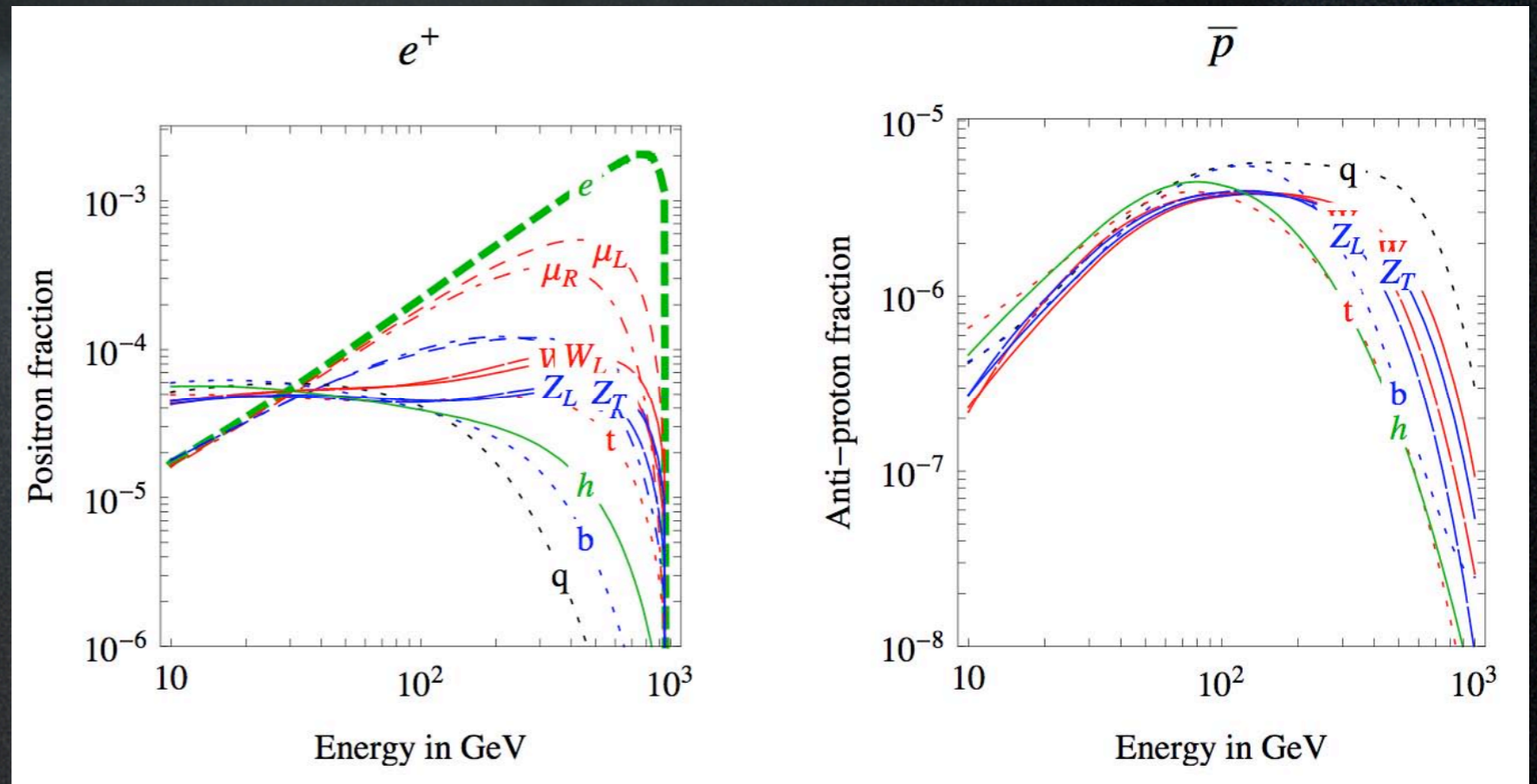
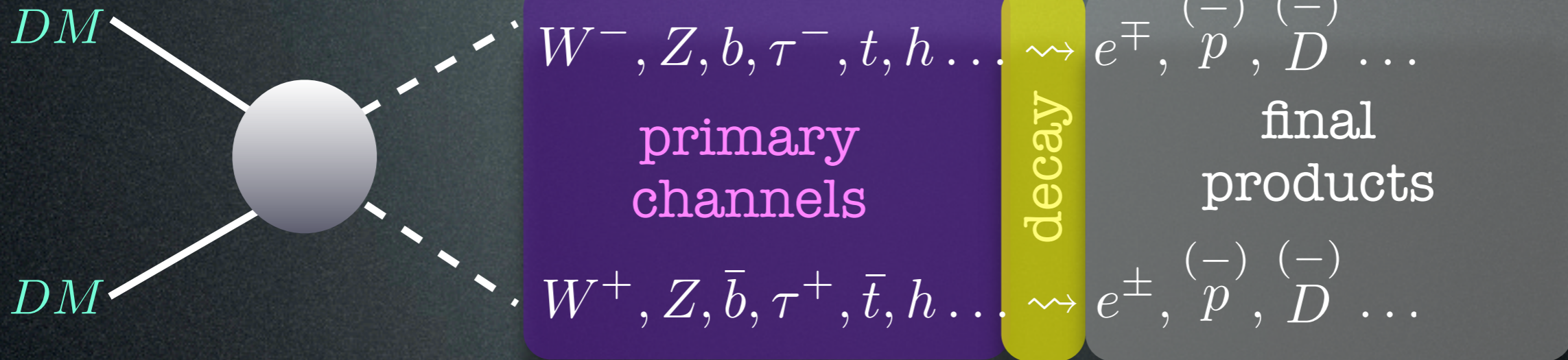
Spectra at production



Spectra at production



Spectra at production



So what are the particle physics parameters?

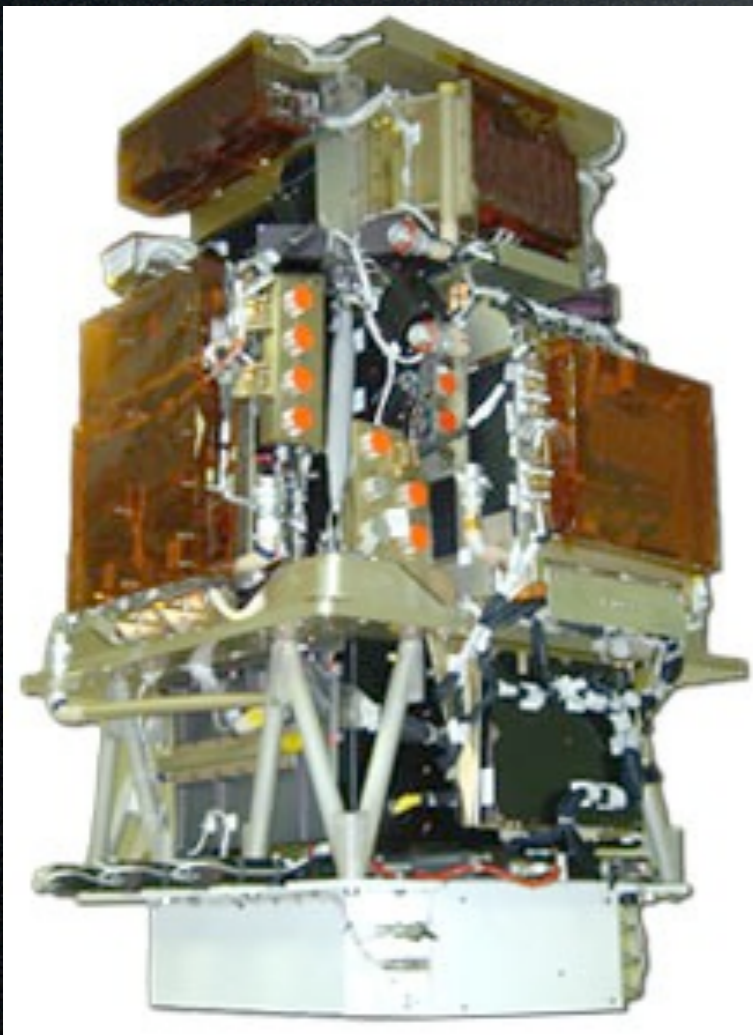
1. Dark Matter mass
2. primary channel(s)

Comparing with data

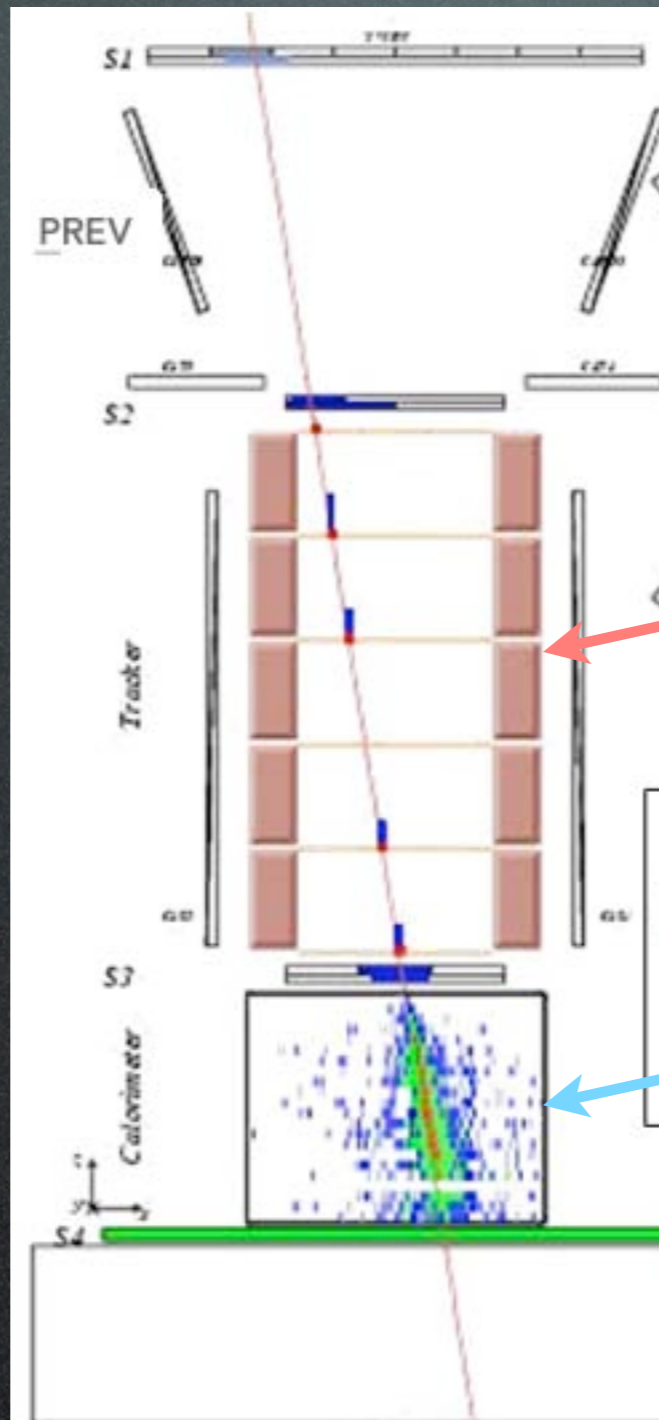
Data sets

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

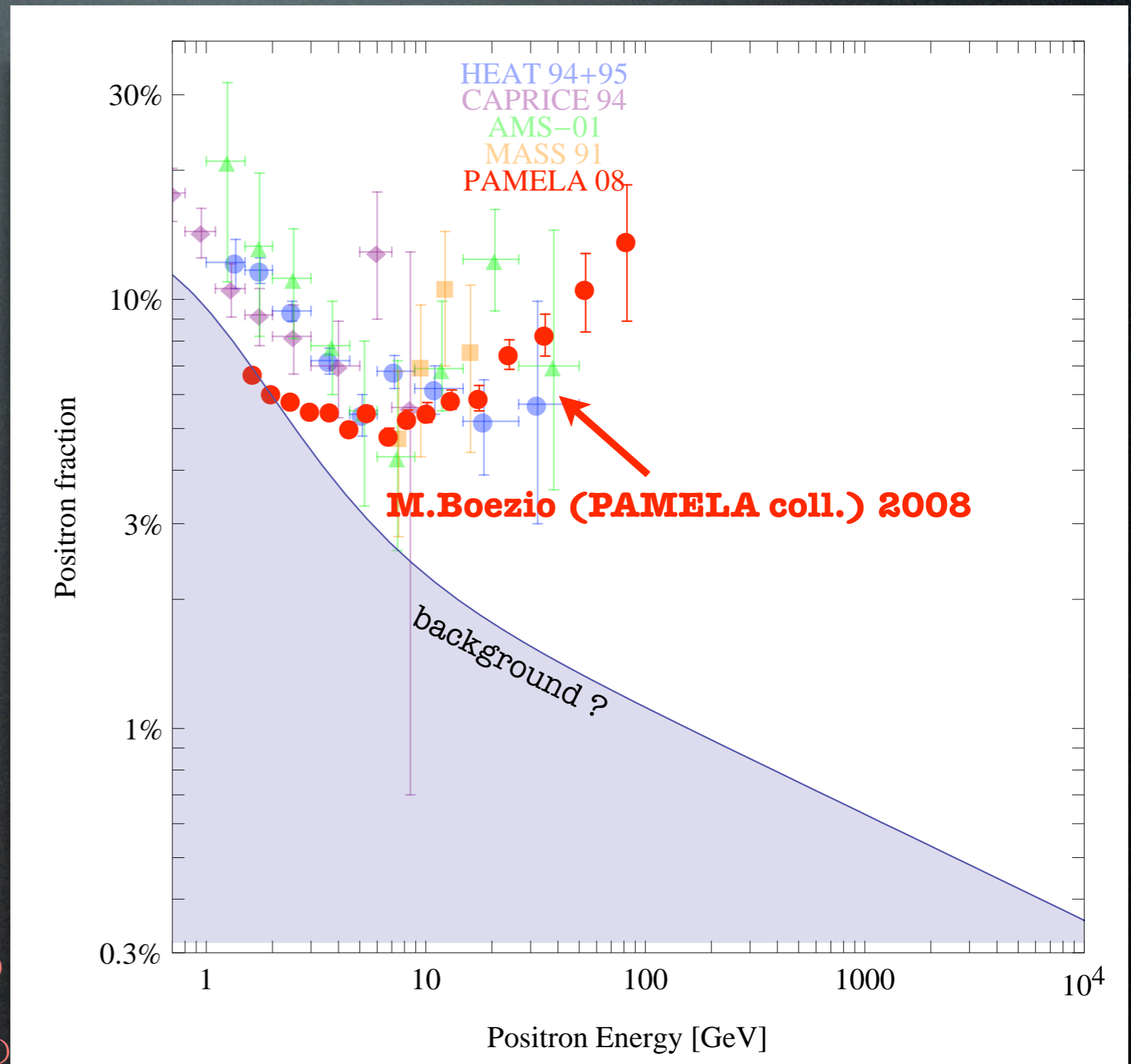
Positrons from PAMELA:

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

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

(9430 e^+ collected)

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

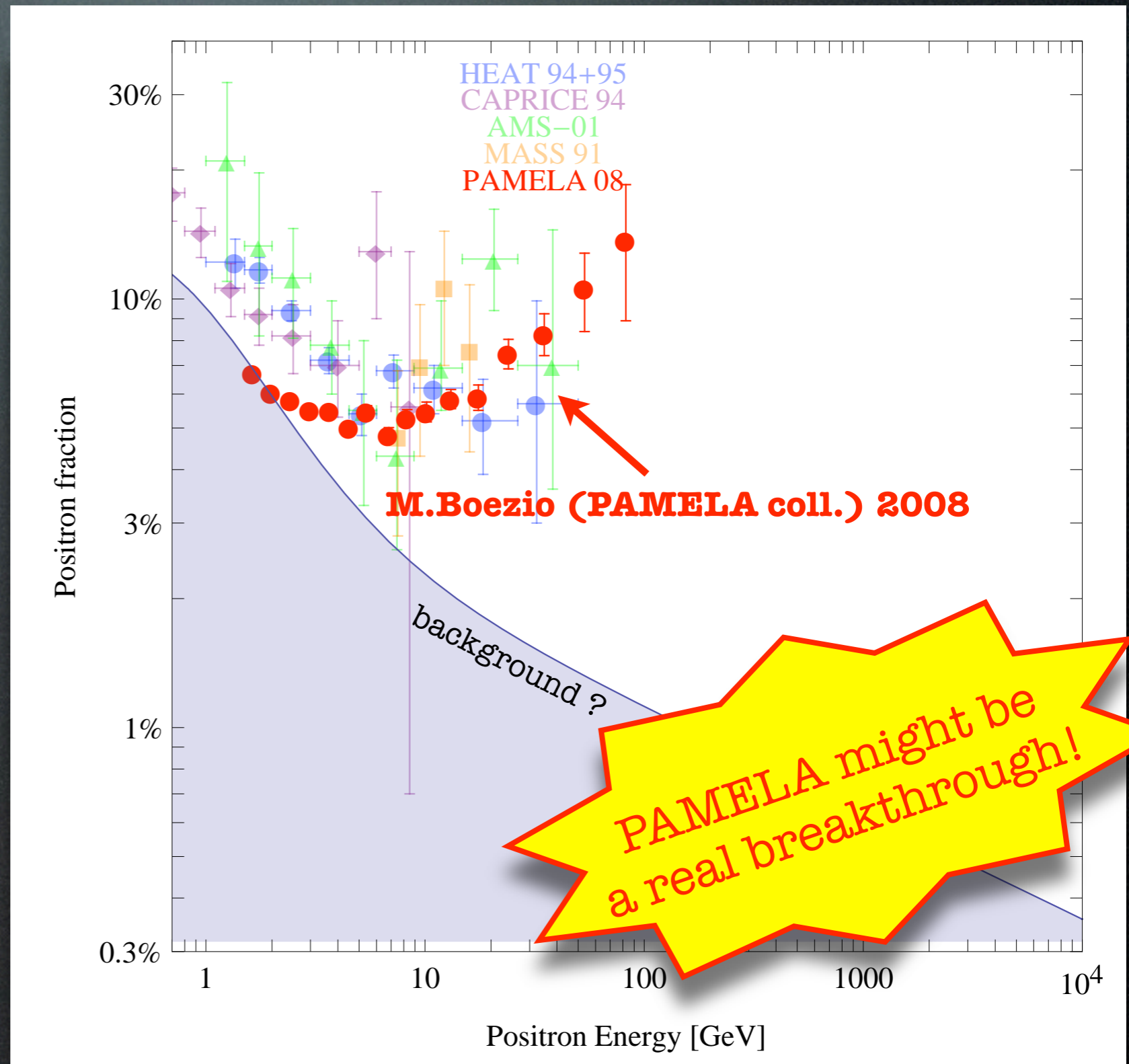


[backgnd]

Data sets

Positrons from PAMELA:

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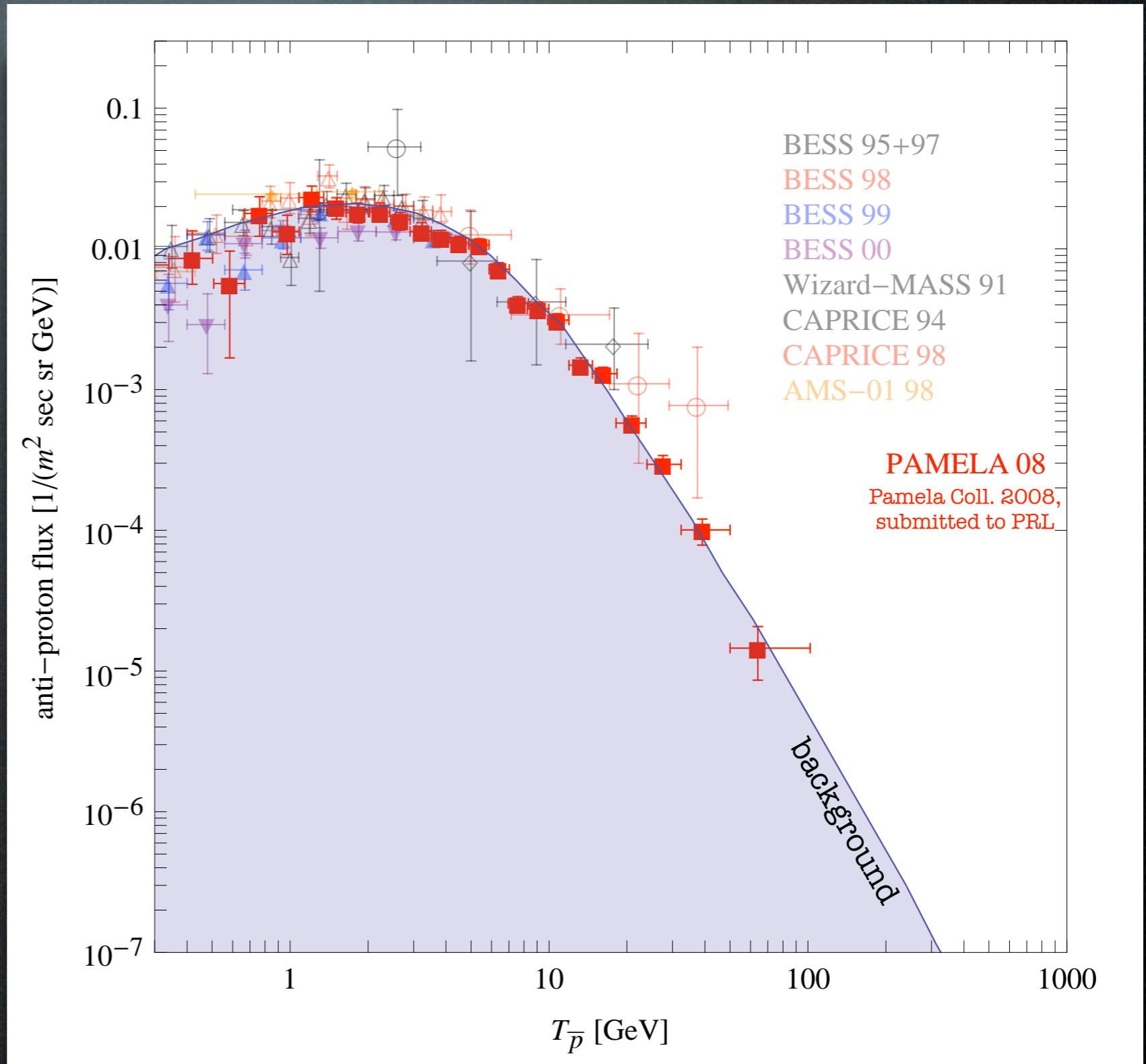


[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background



(about 1000 \bar{p} collected)

Results

Which DM spectra can fit the data?

Results

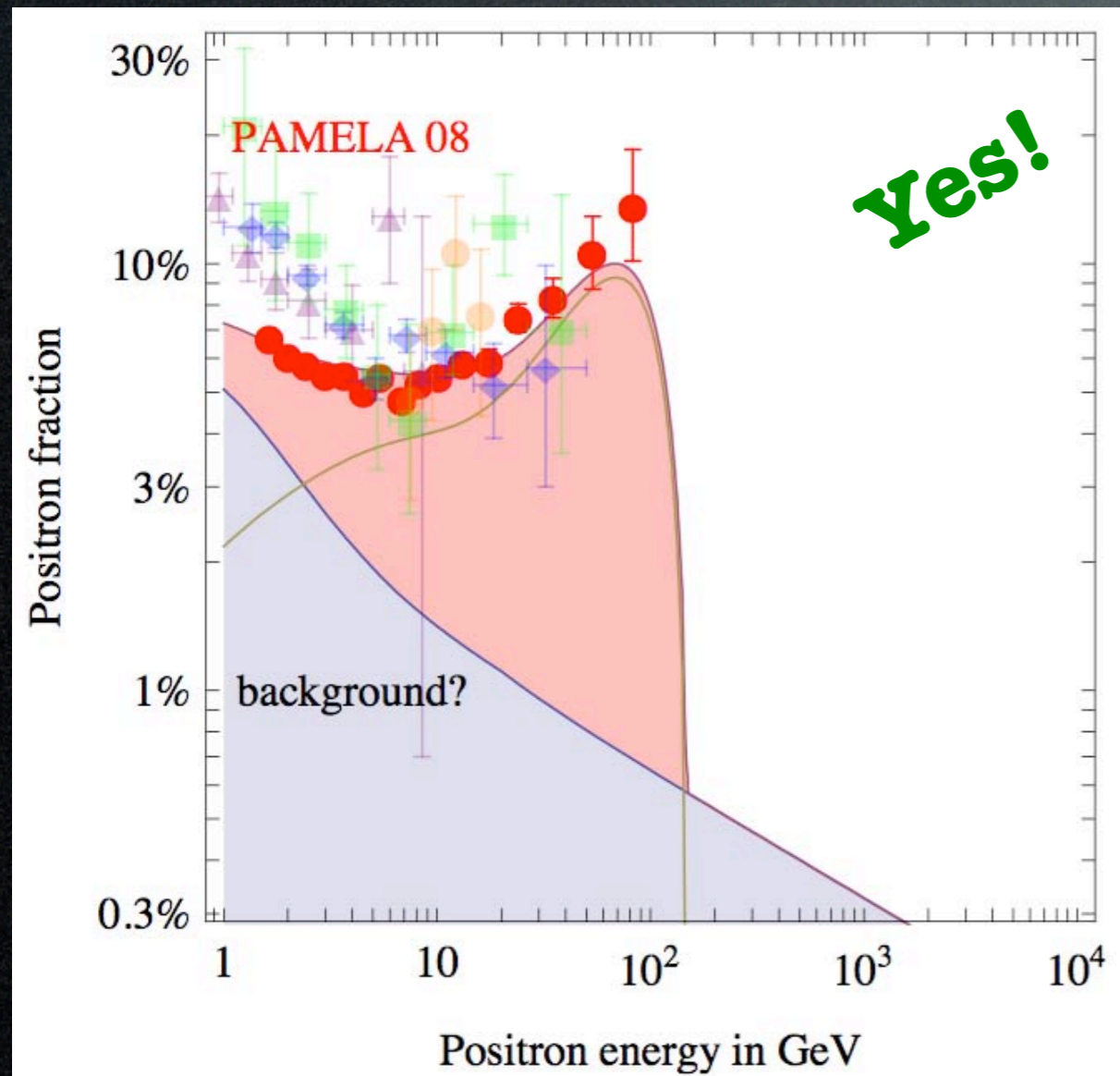
Which DM spectra can fit the data?

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

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

(a possible SuperSymmetric candidate: wino)

Positrons:



Results

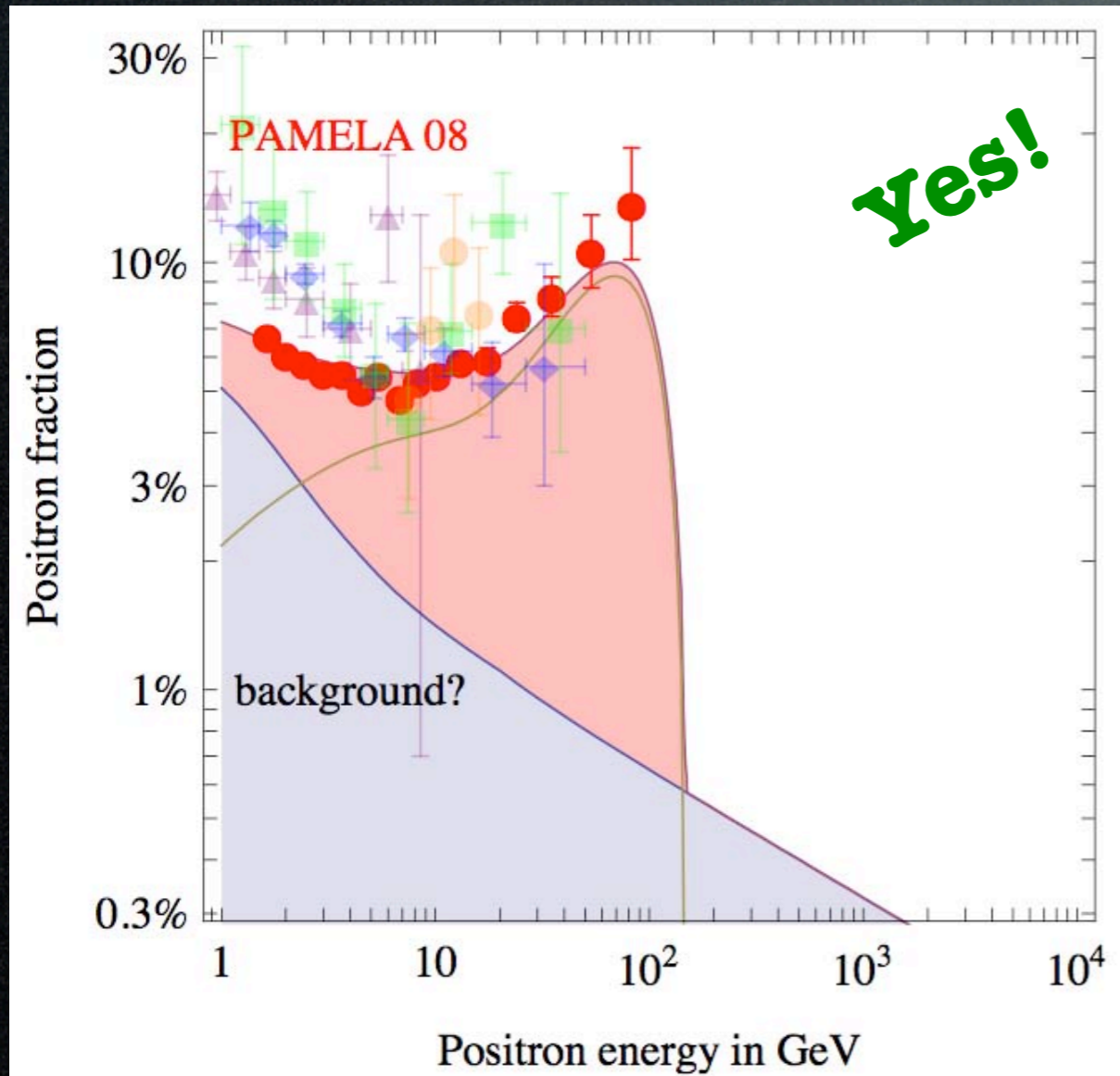
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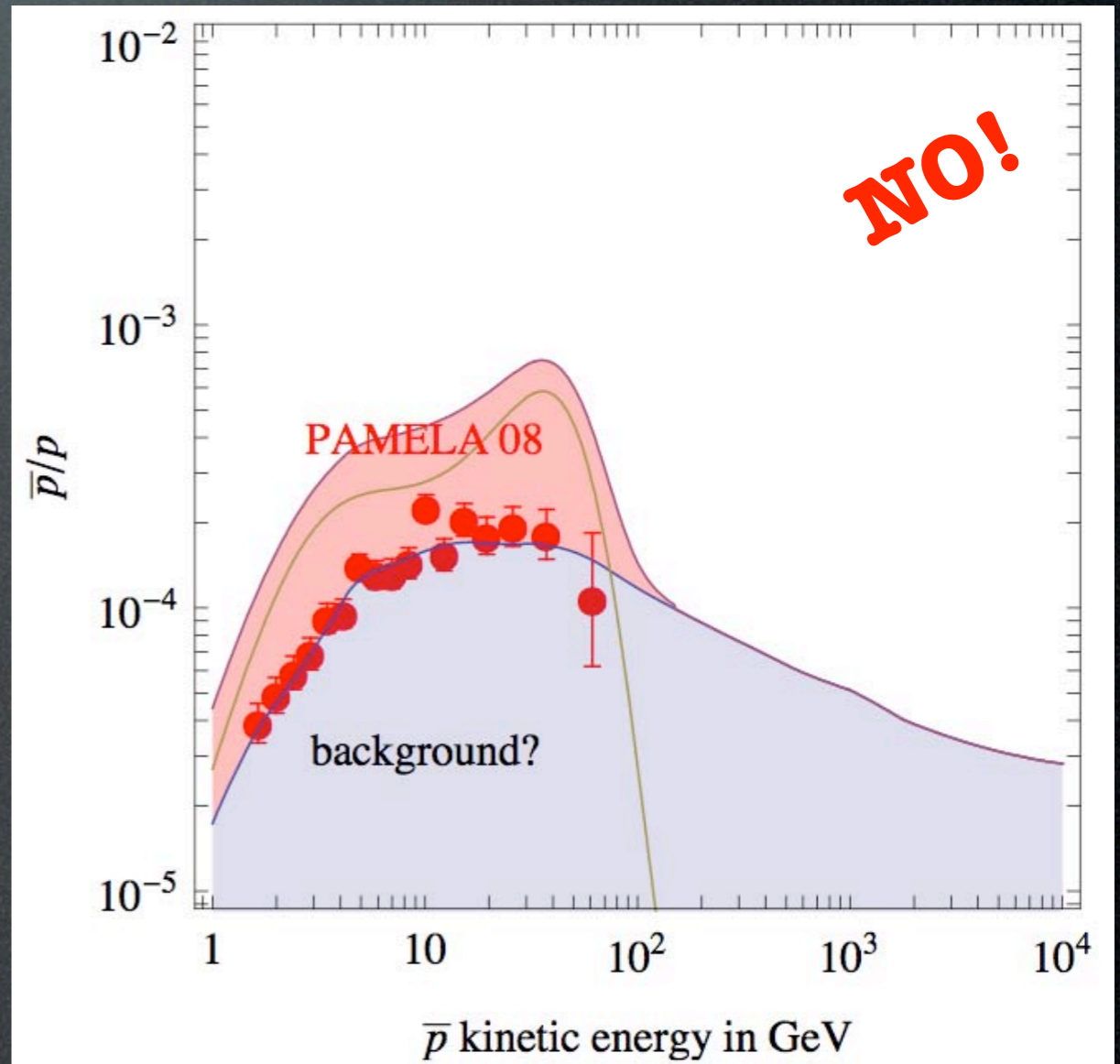
-annihilation $\text{DM DM} \rightarrow W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



[insisting on Winos]

Results

Which DM spectra can fit the data?

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

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

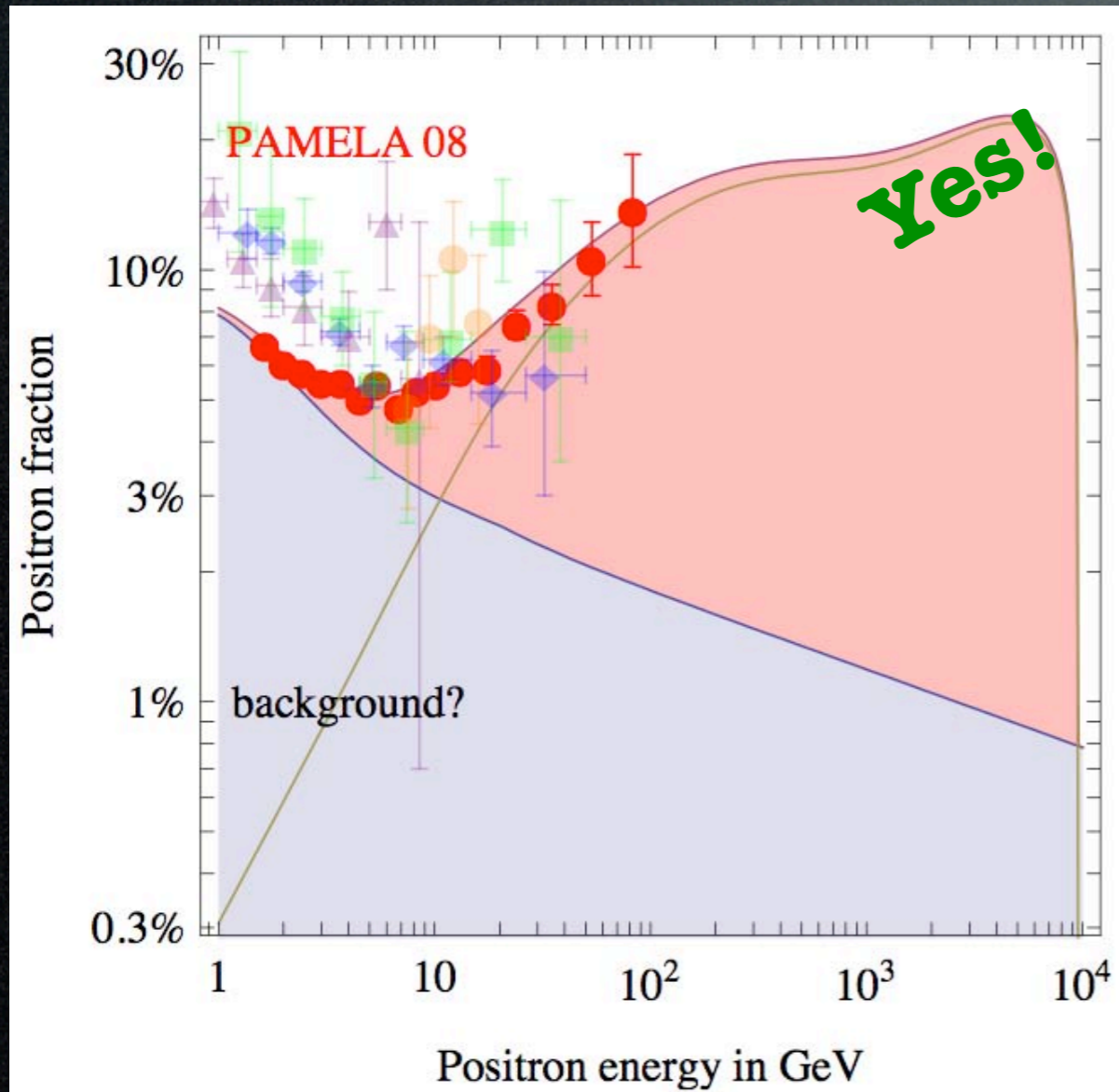
Results

Which DM spectra can fit the data?

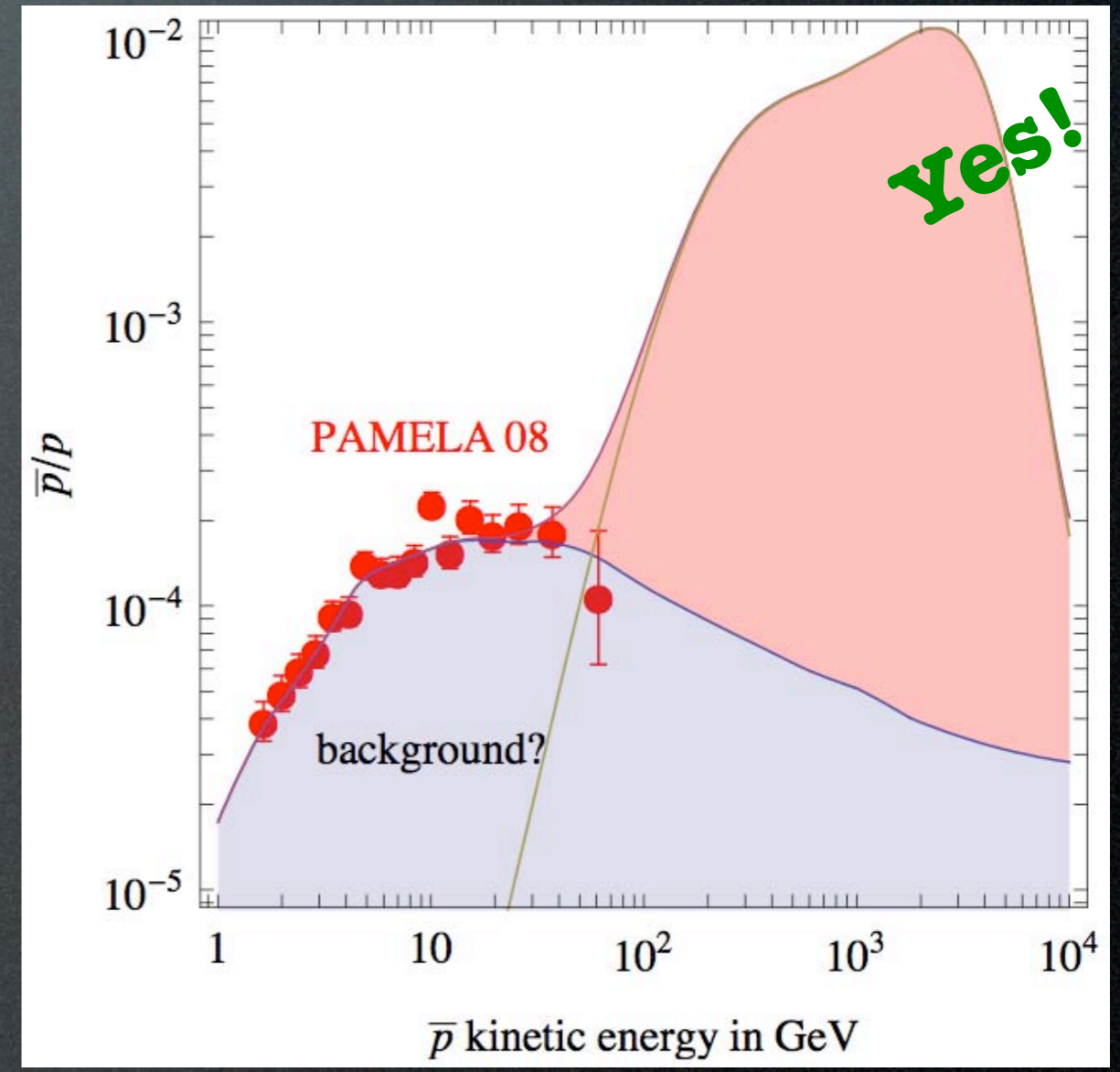
E.g. a DM with: -mass $M_{\text{DM}} = 10 \text{ TeV}$

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Positrons:



Anti-protons:



Results

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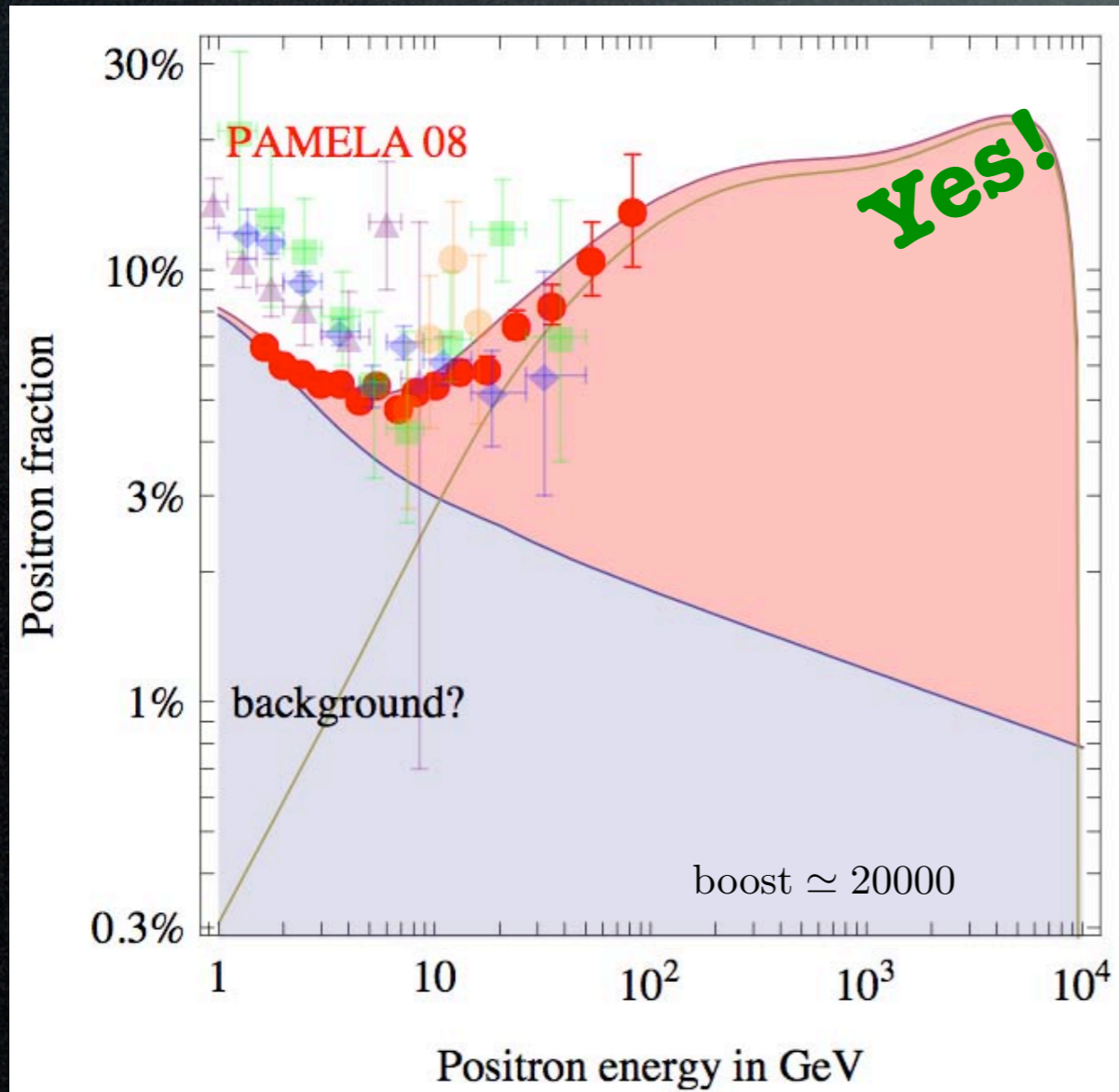
E.g. a DM with: -mass $M_{\text{DM}} = 10 \text{ TeV}$

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

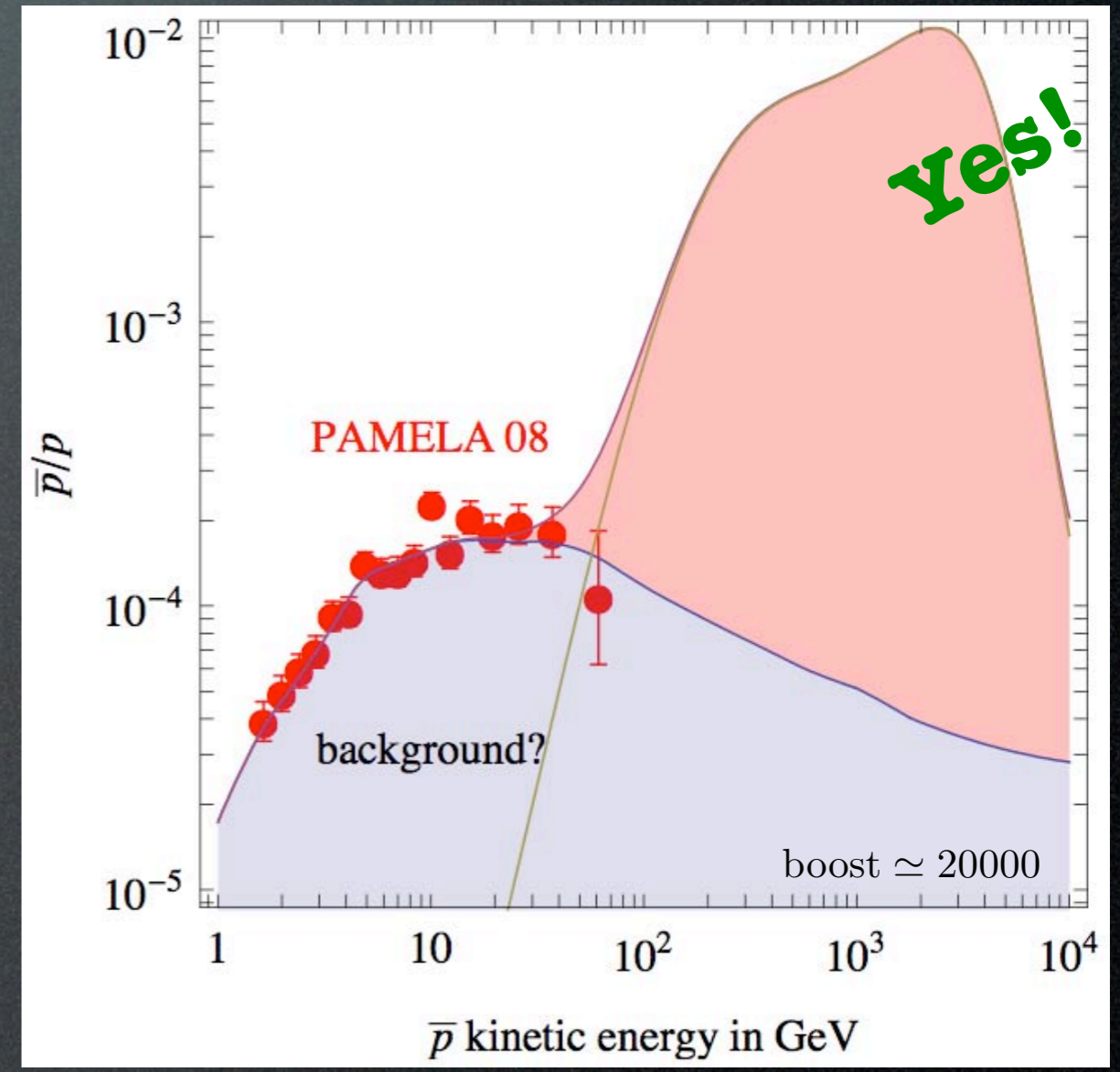
but...: -cross sec $\sigma_{\text{ann}} v = 6 \cdot 10^{-22} \text{ cm}^3/\text{sec}$

Mmm...

Positrons:



Anti-protons:

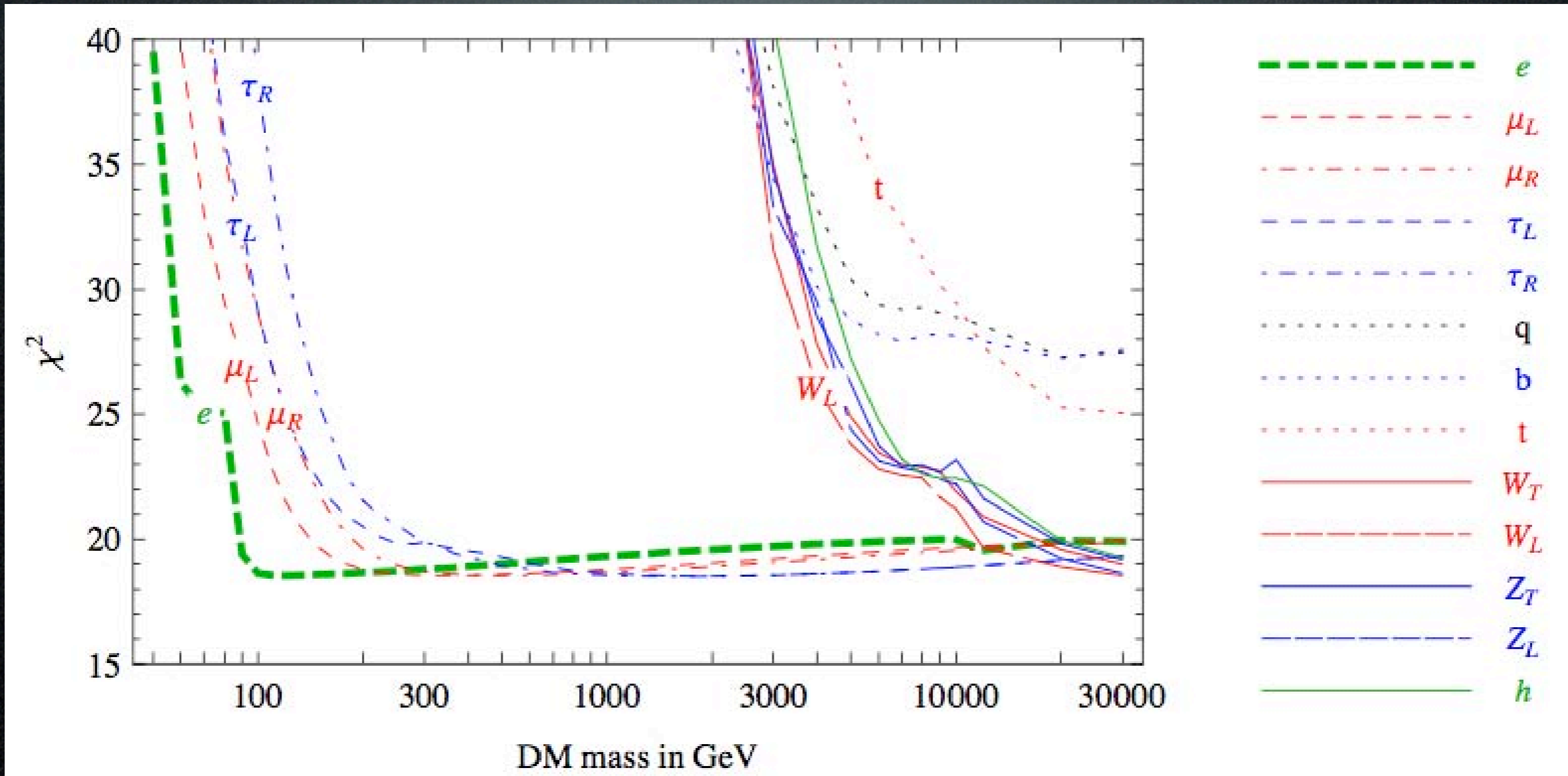


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons

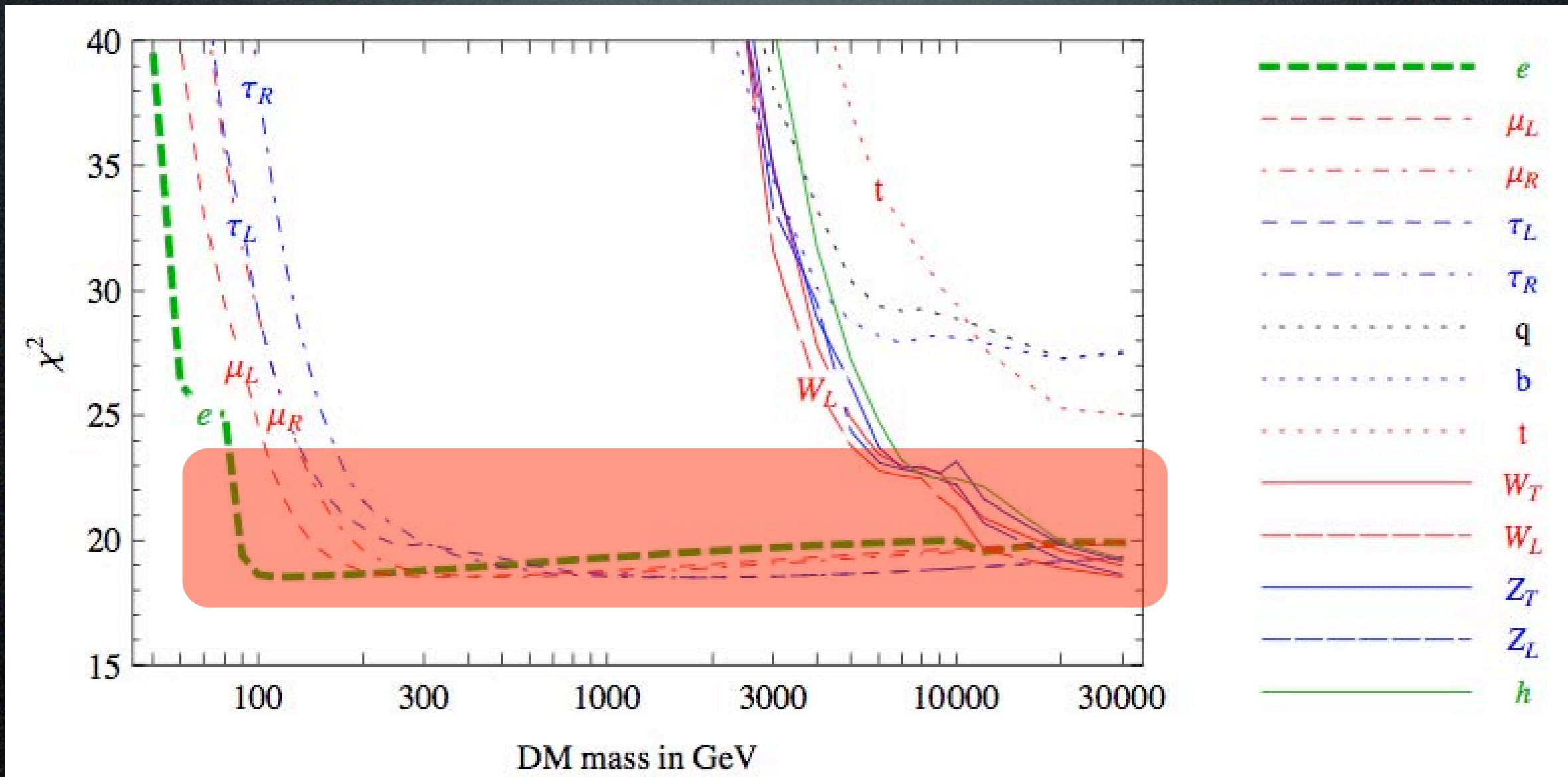


Results

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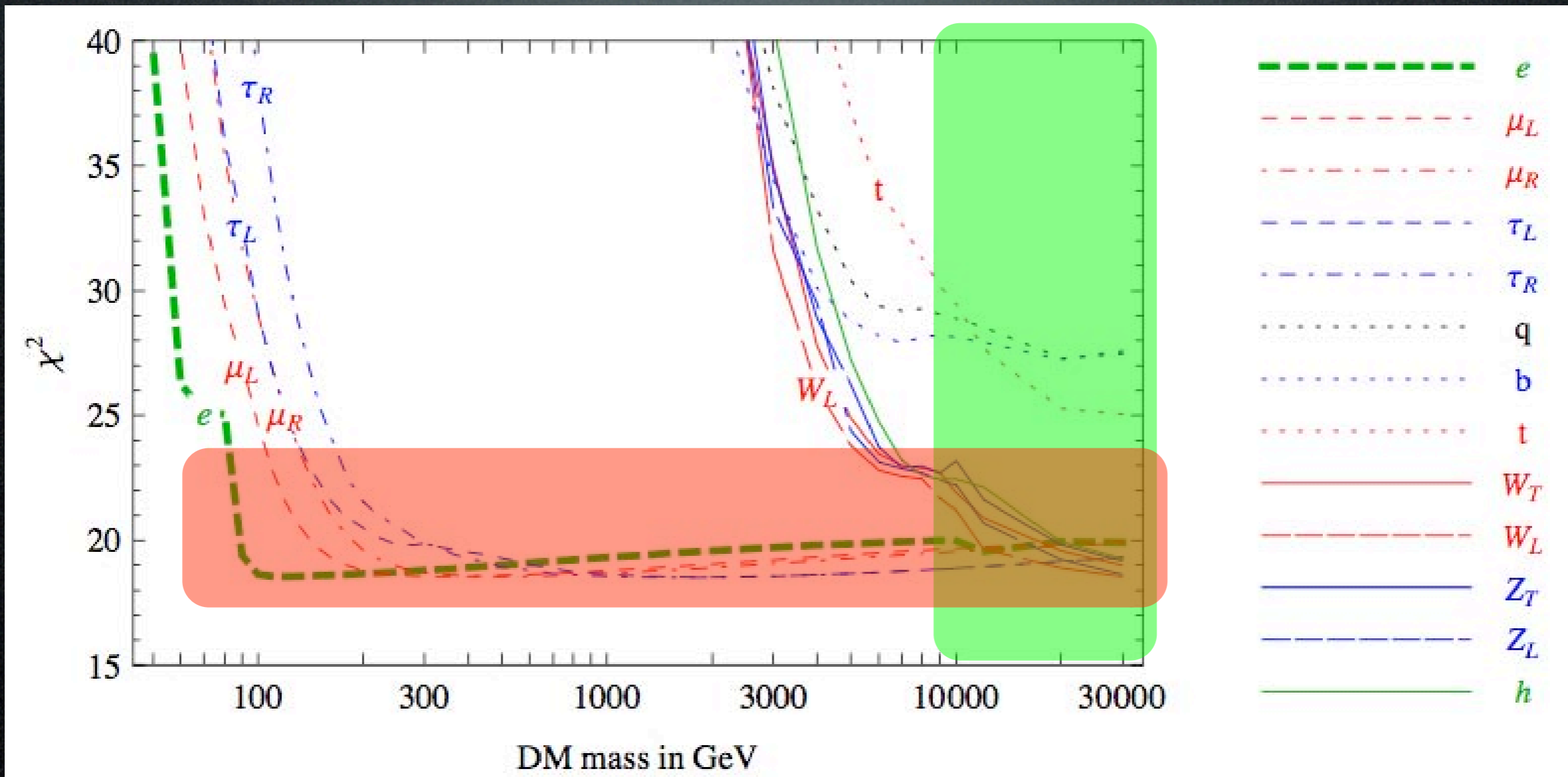
(1) annihilate into leptons (e.g. $\mu^+ \mu^-$)

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



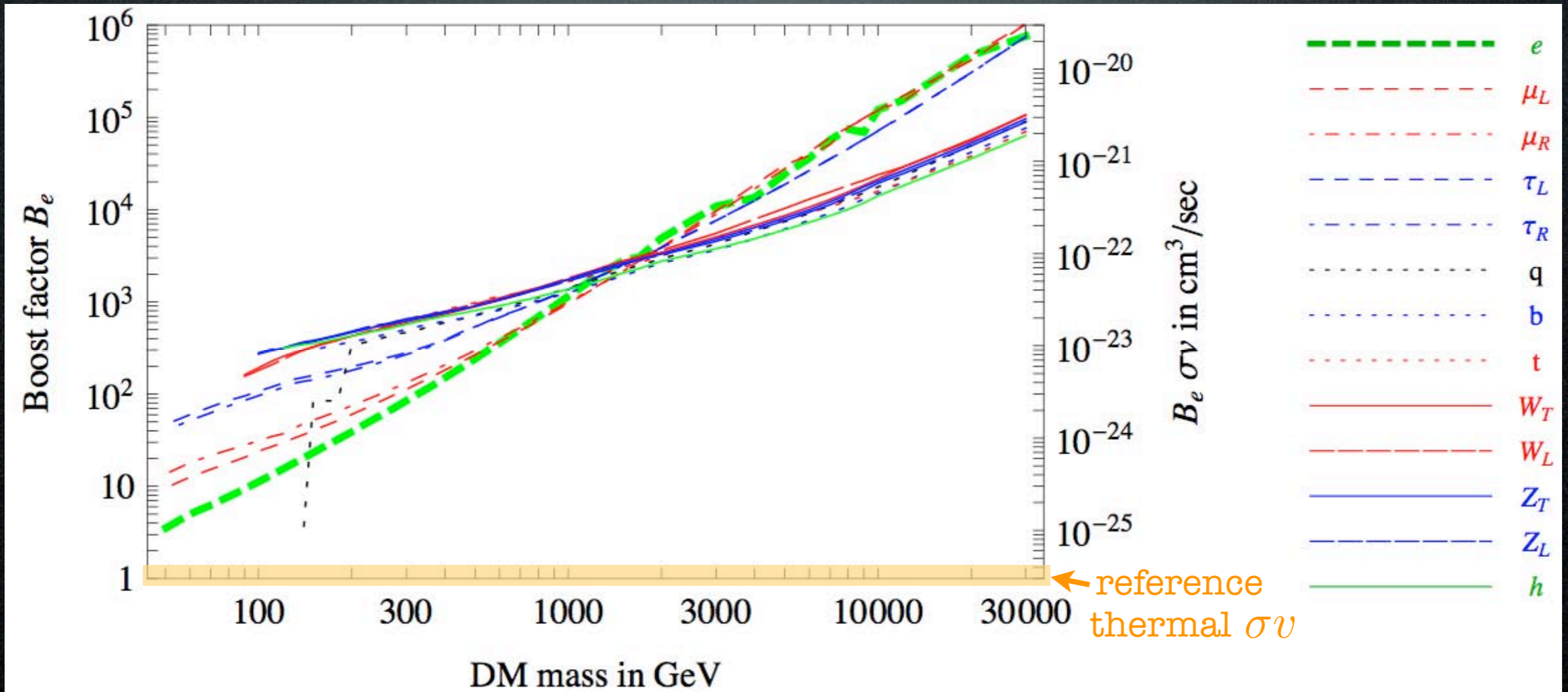
- (1) annihilate into leptons (e.g. $\mu^+ \mu^-$) or
- (2) annihilate into $W^+ W^-$ with mass $\gtrsim 10$ TeV

Results

Which DM spectra can fit the data?

Model-independent results:

Cross section required by PAMELA



Data sets

Electrons + positrons from **ATIC**, **PPB-BETS**:



PPB-BETS
(Japan)

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



ATIC (Usa + Germany, Russia, China)

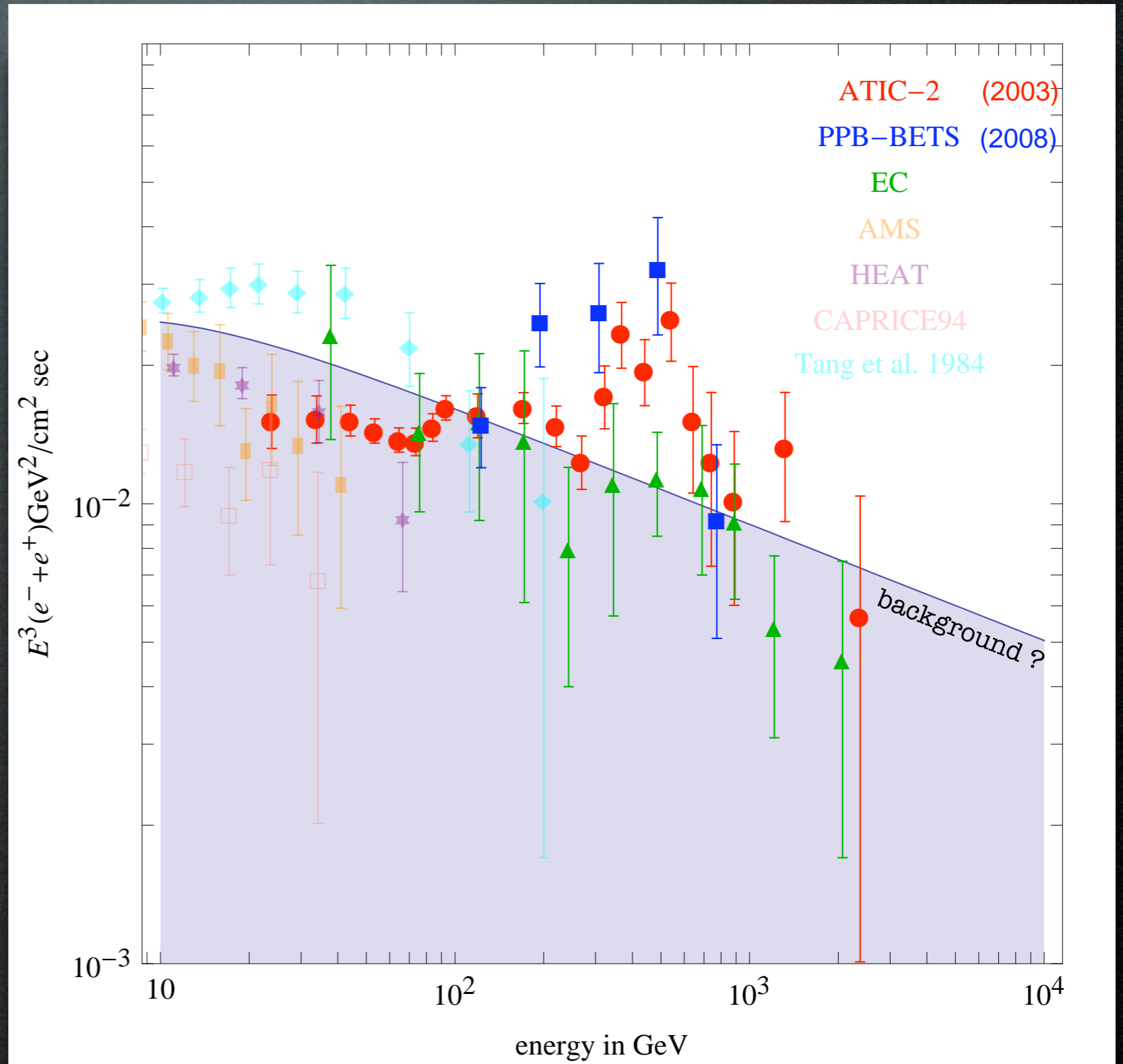
Advanced
Thin
Ionization
Calorimeter

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

Data sets

Electrons + positrons from ATIC, PPB-BETS:

- an $e^+ + e^-$ excess
at ~ 700 GeV??



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

Results

Which DM spectra can fit the data?

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

-annihilation $\text{DM DM} \rightarrow \mu^+ \mu^-$

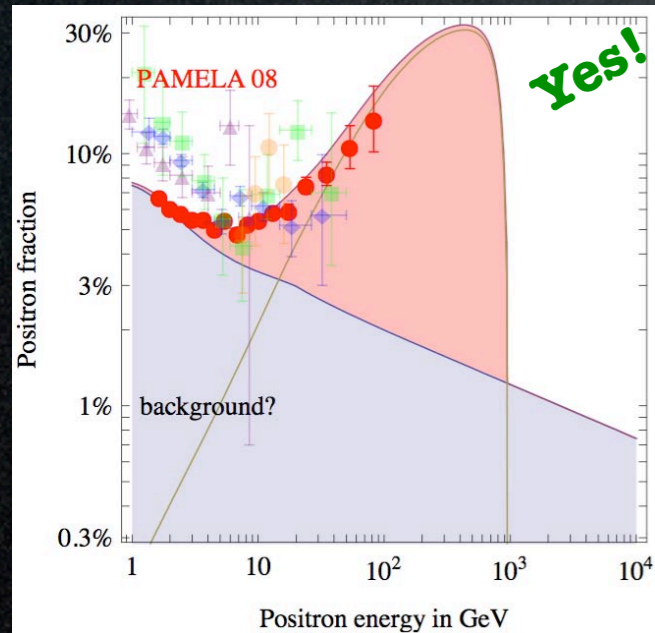
Results

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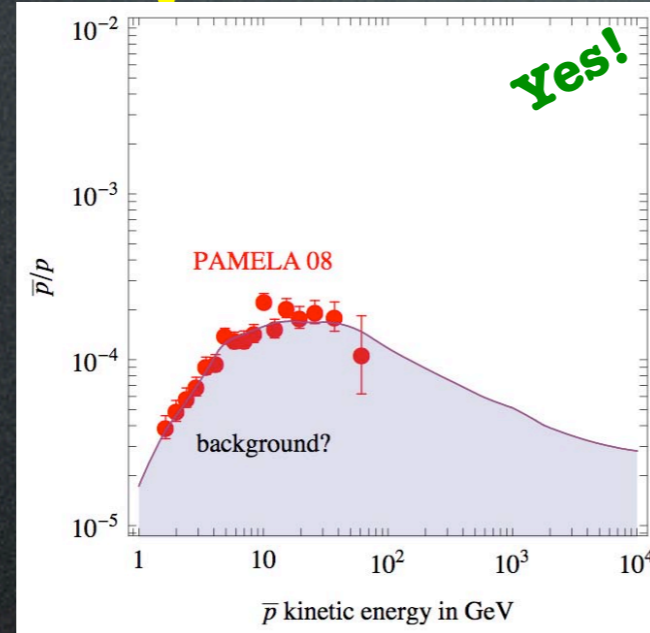
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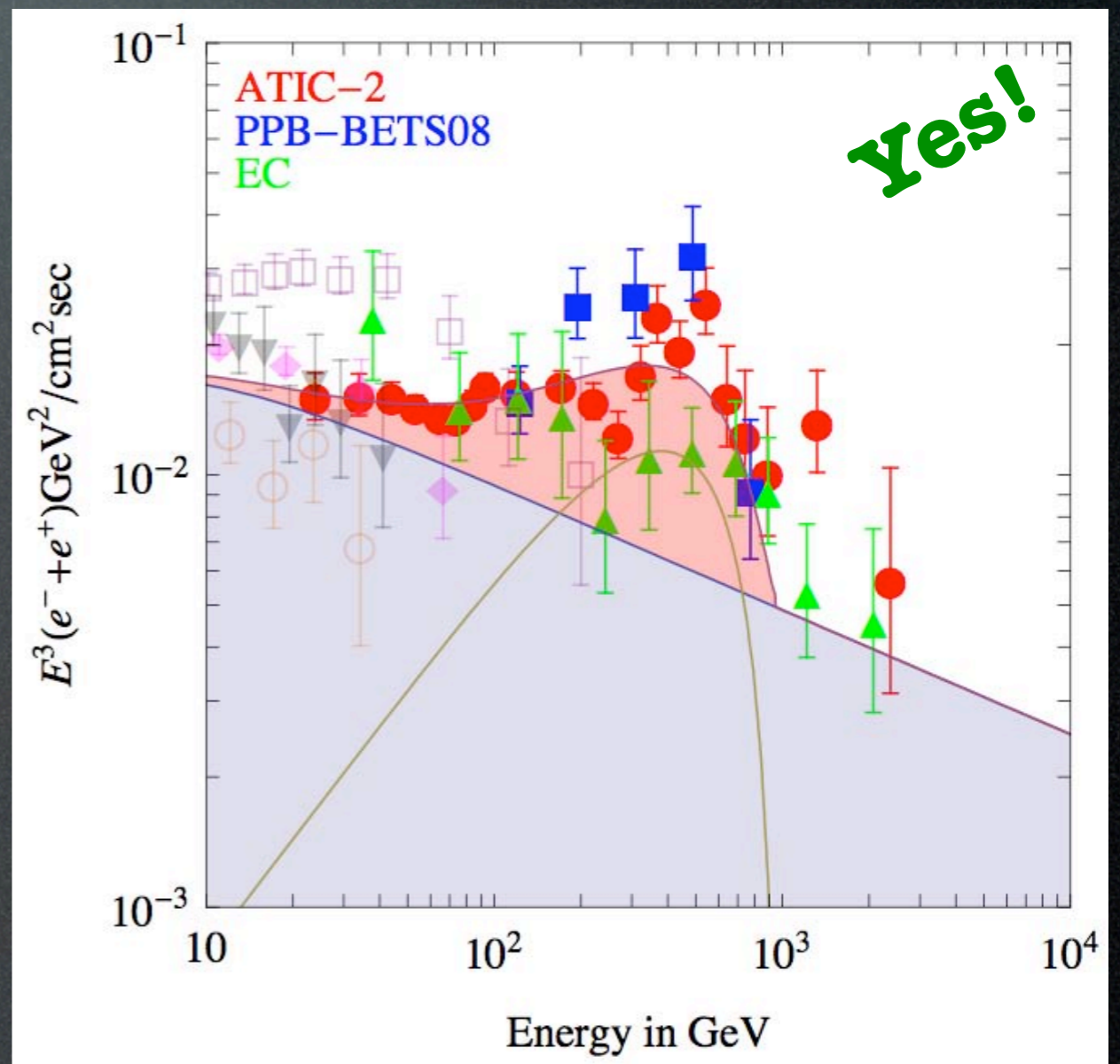
Positrons:



Anti-protons:



Electrons + Positrons:



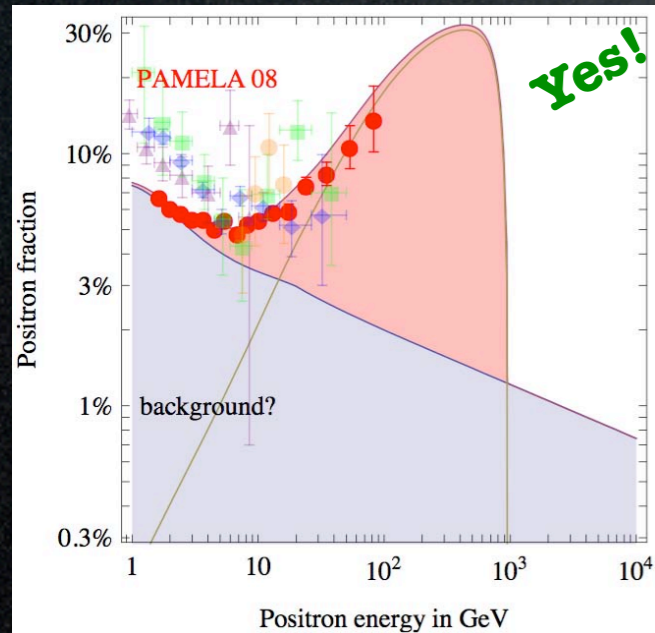
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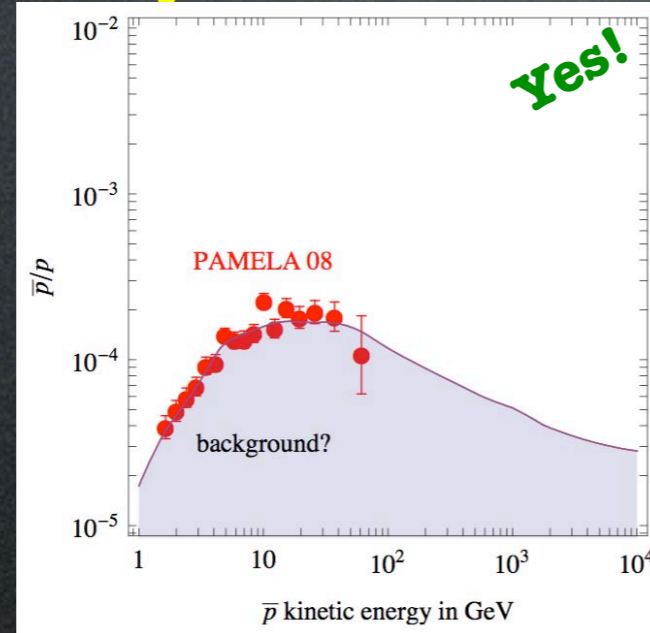
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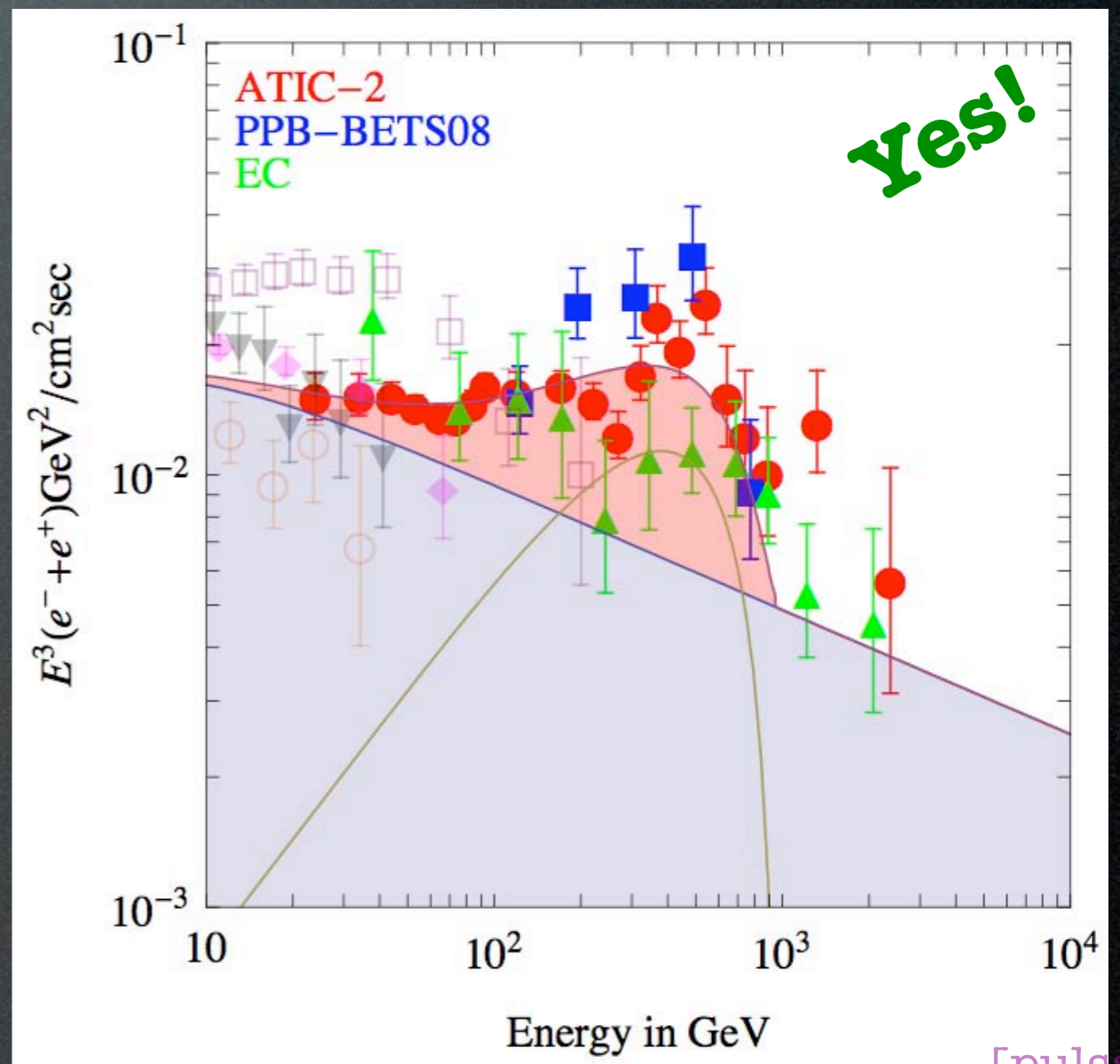
Positrons:



Anti-protons:



Electrons + Positrons:



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

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

Results

Which DM can fit the data?

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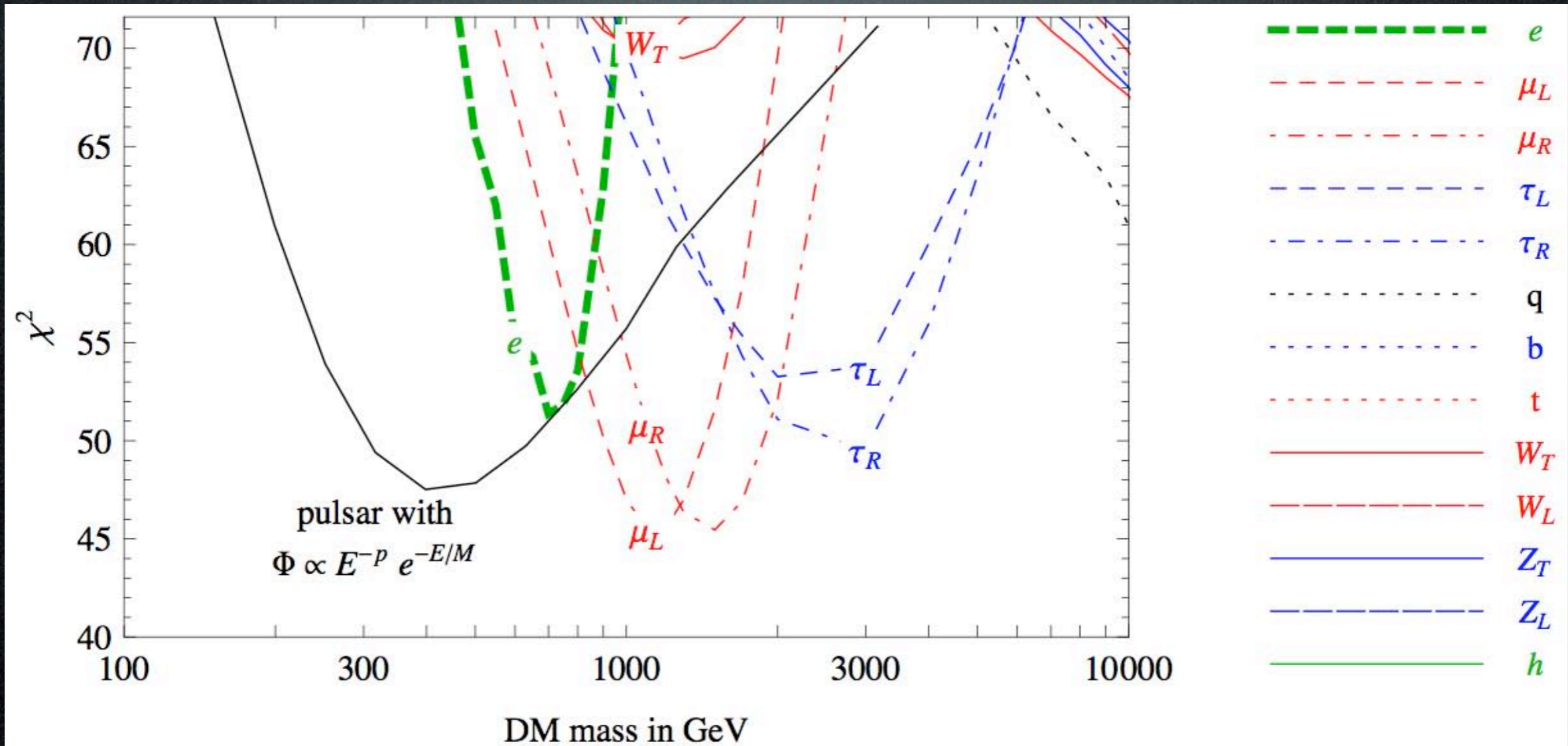
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Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons* + balloon experiments



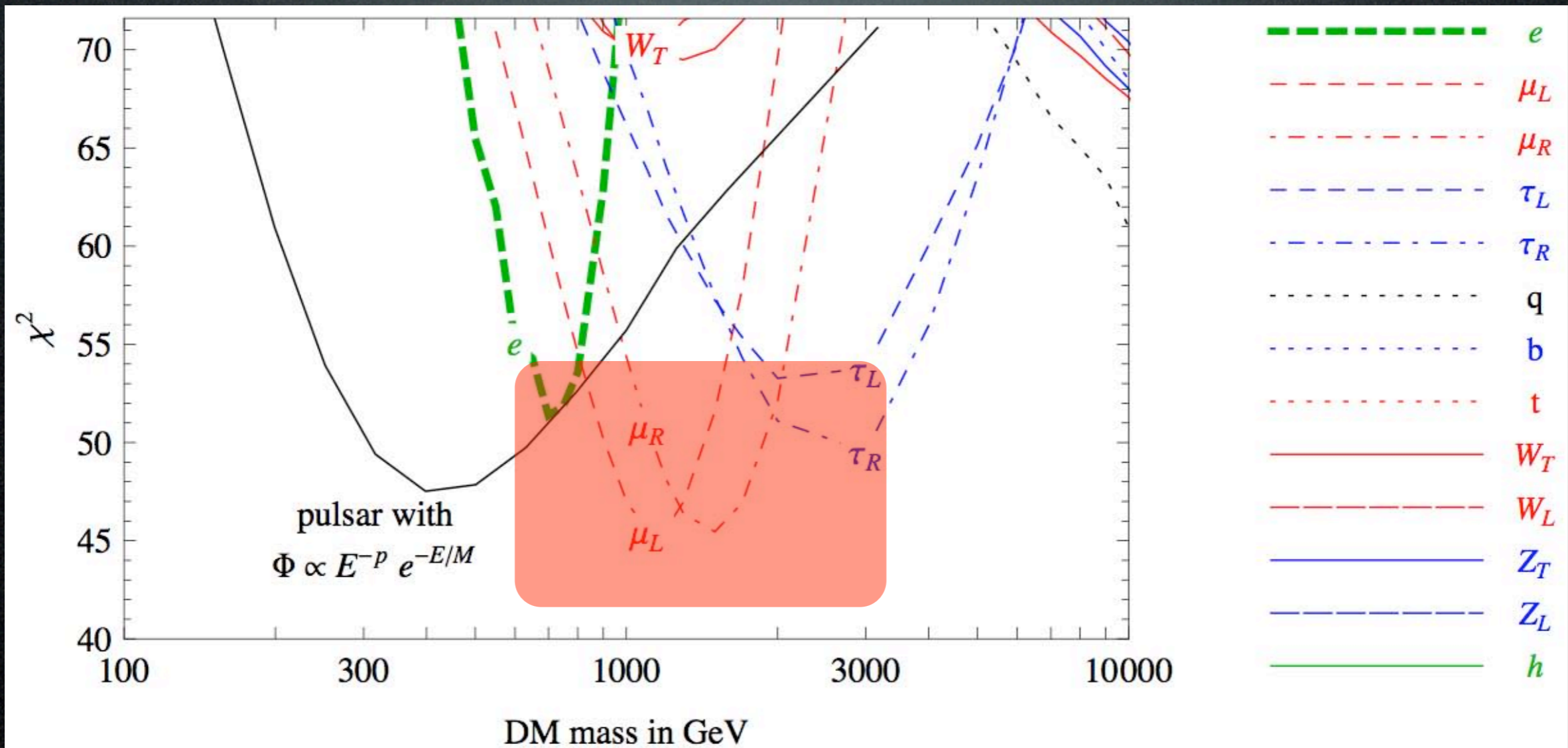
*adding anti-protons does not change much, non-leptonic channels give too smooth spectrum for balloons

Results

Which DM spectra can fit the data?

Model-independent results:

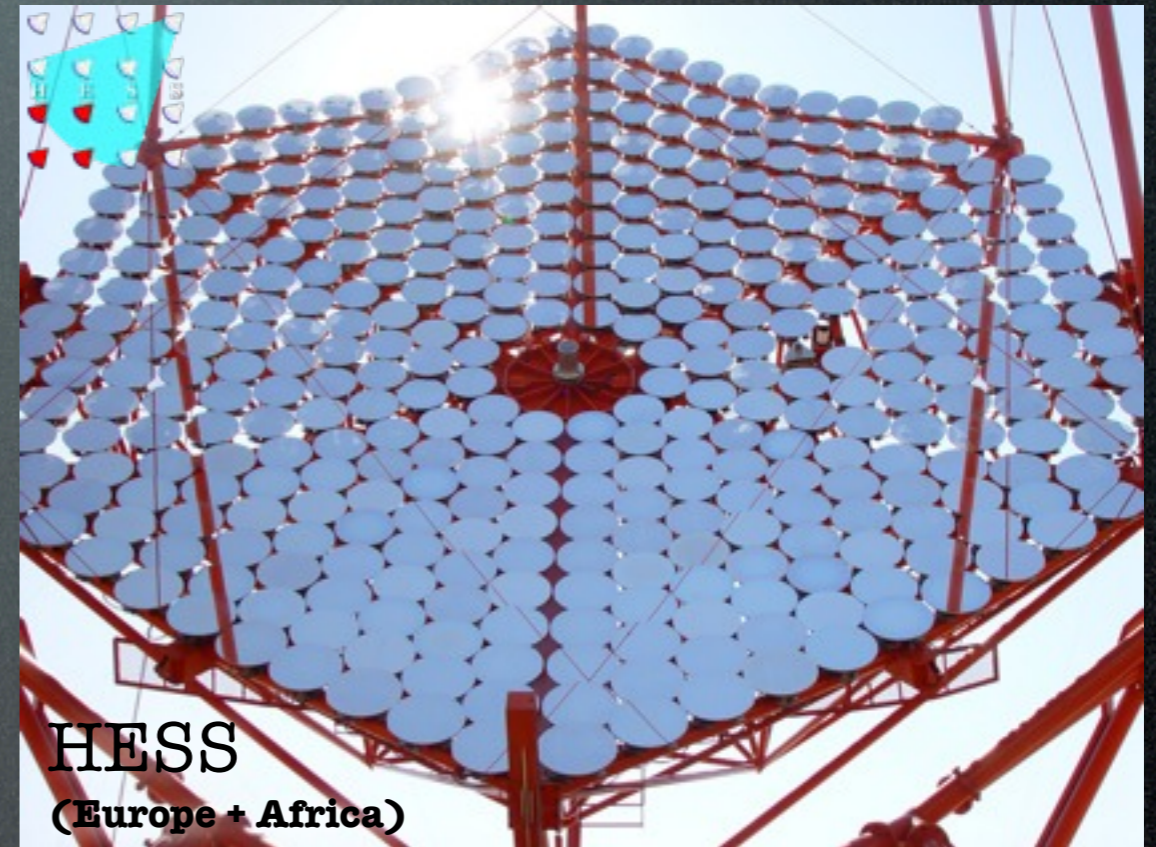
fit to PAMELA positrons* + balloon experiments



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

Data sets

Electrons + positrons from **FERMI** and **HESS**:



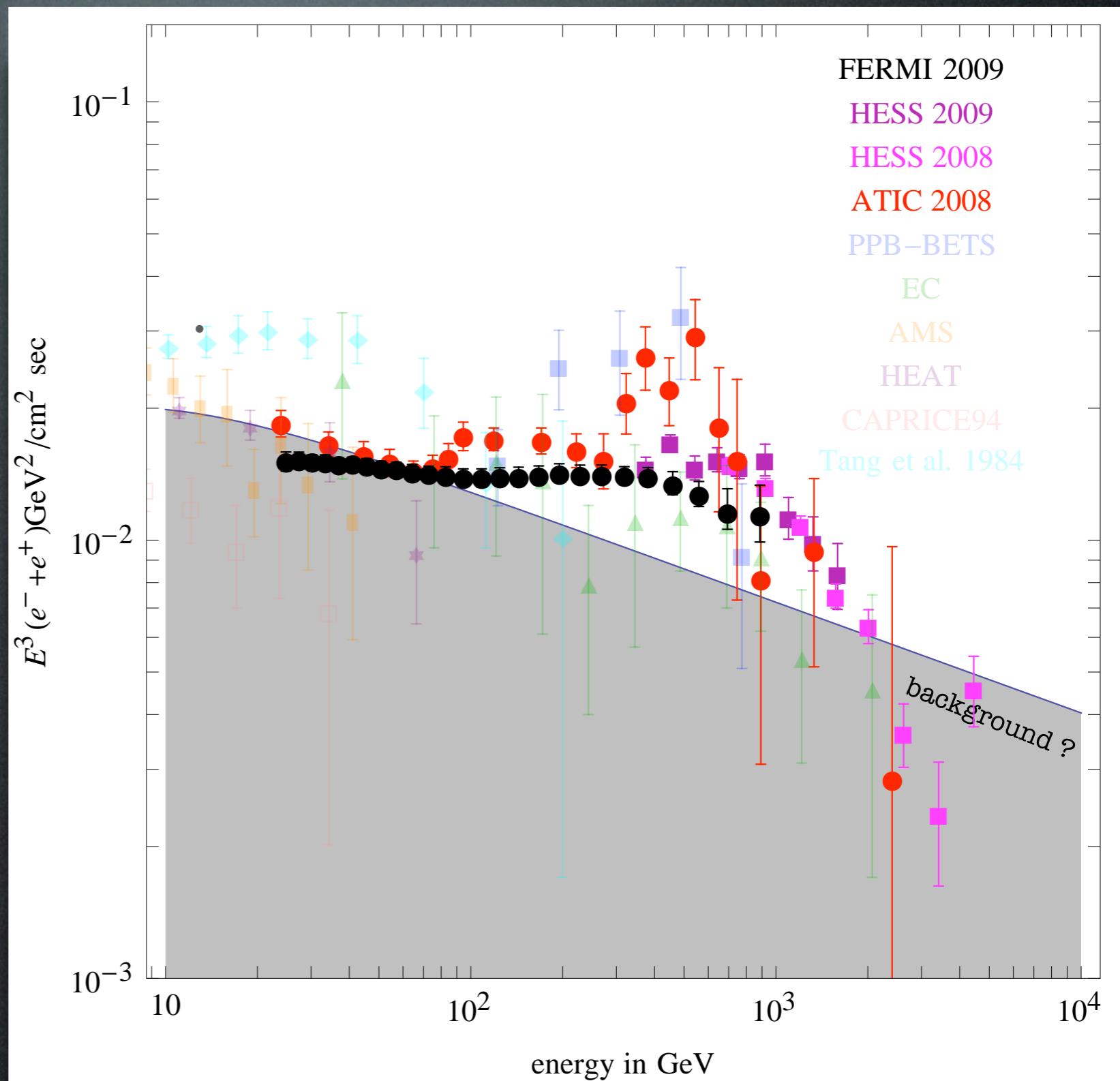
“Designed as a high-sensitivity gamma-ray observatory, the FERMI Large Area Telescope is also an electron detector with a large acceptance”

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

Data sets

Electrons + positrons adding FERMI and HESS:

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



[formerly predicted GLAST sensitivity]

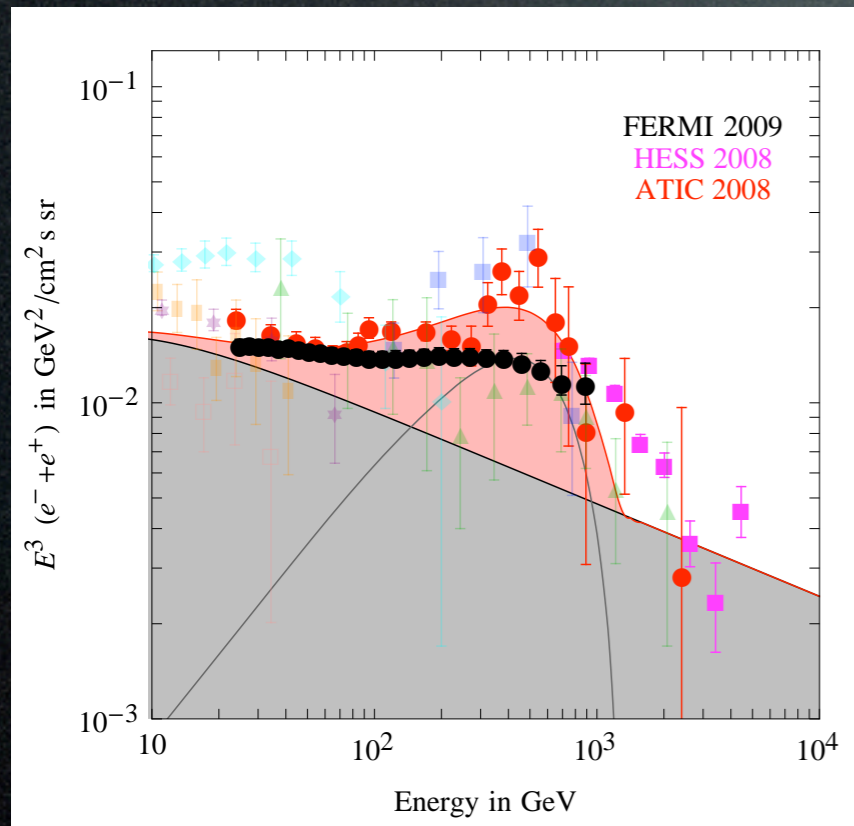
Results

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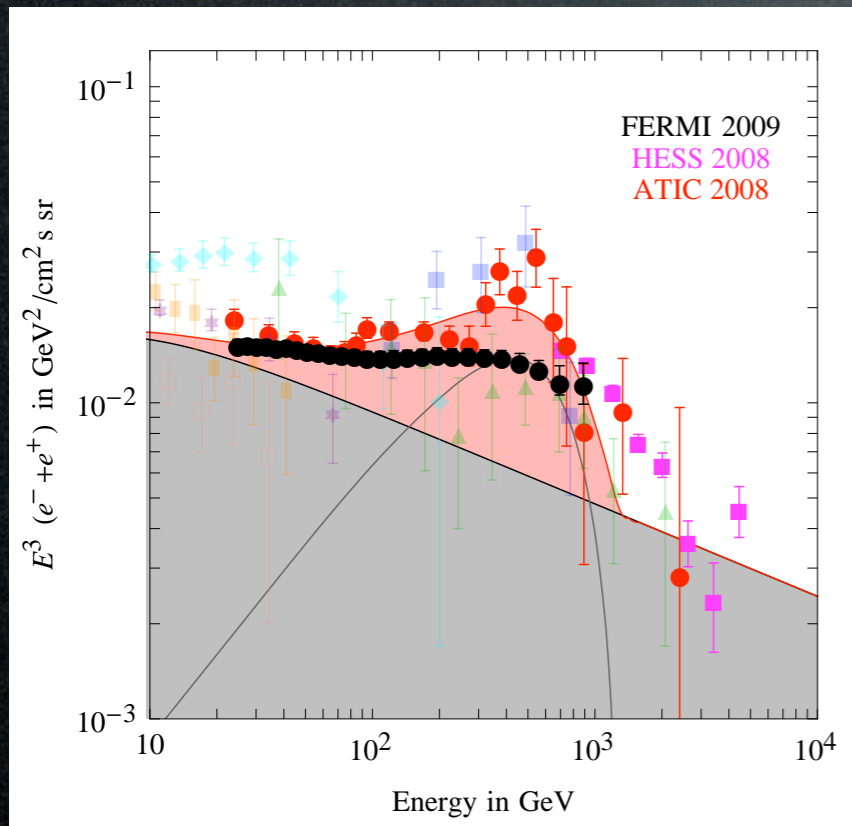
$\mu^+ \mu^-$, $M_{\text{DM}} \simeq 1 \text{ TeV}$



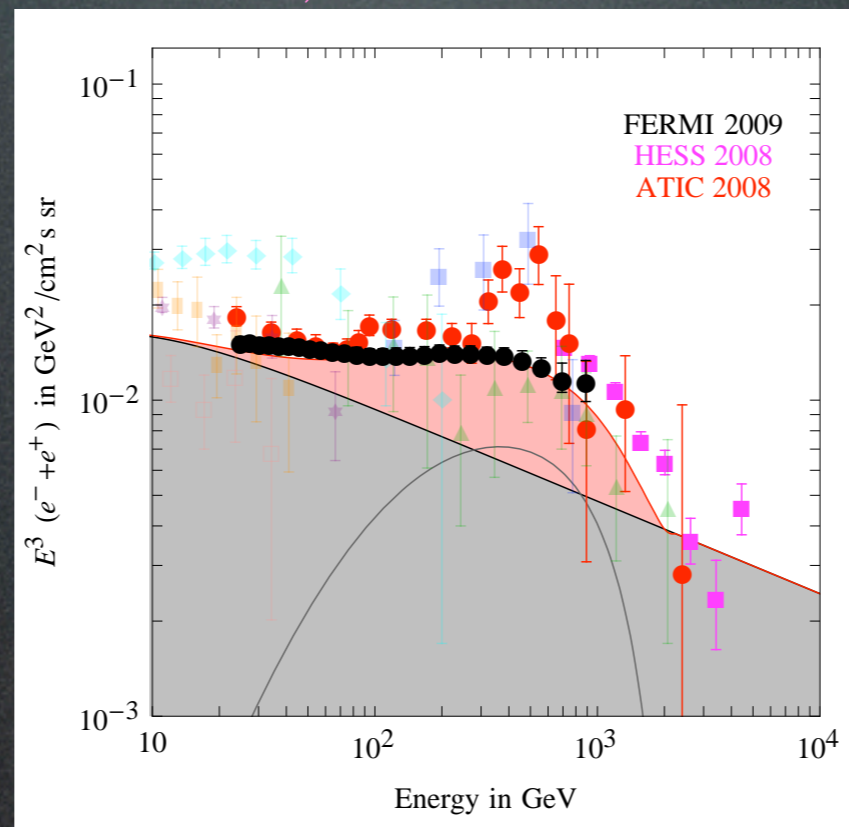
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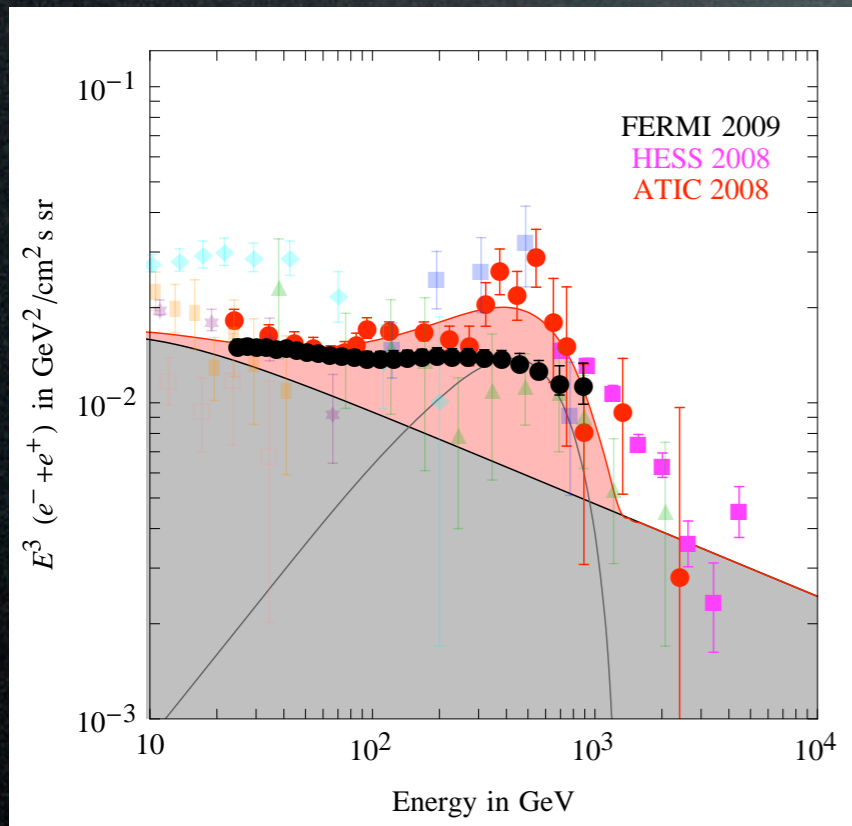
$\tau^+ \tau^-$, $M_{\text{DM}} \simeq 2 \text{ TeV}$



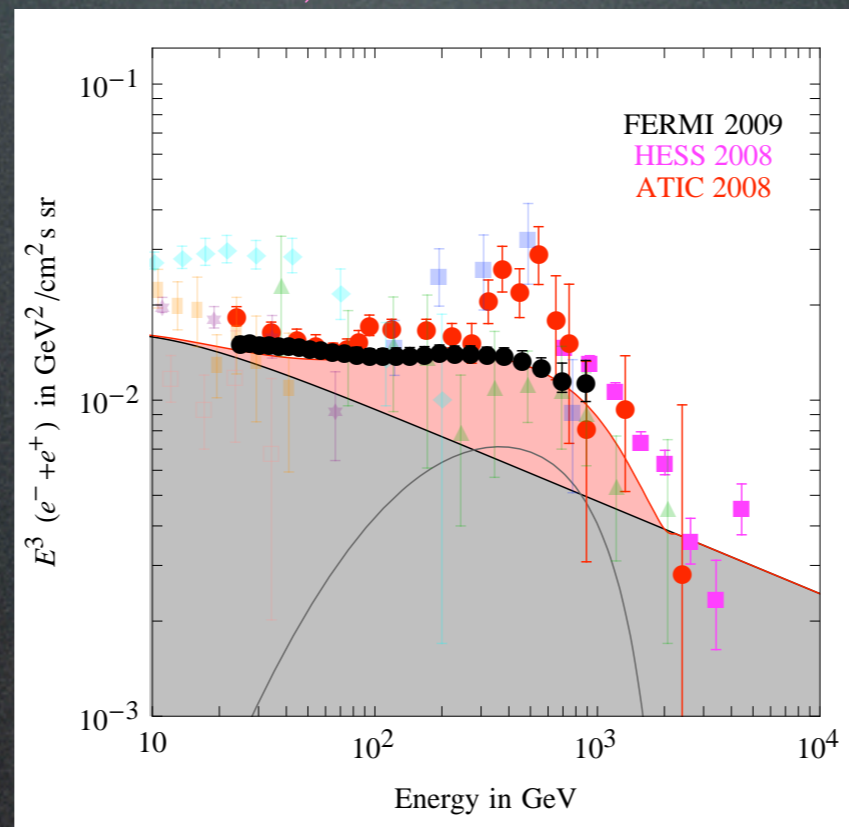
Results

Which DM spectra can fit the data?

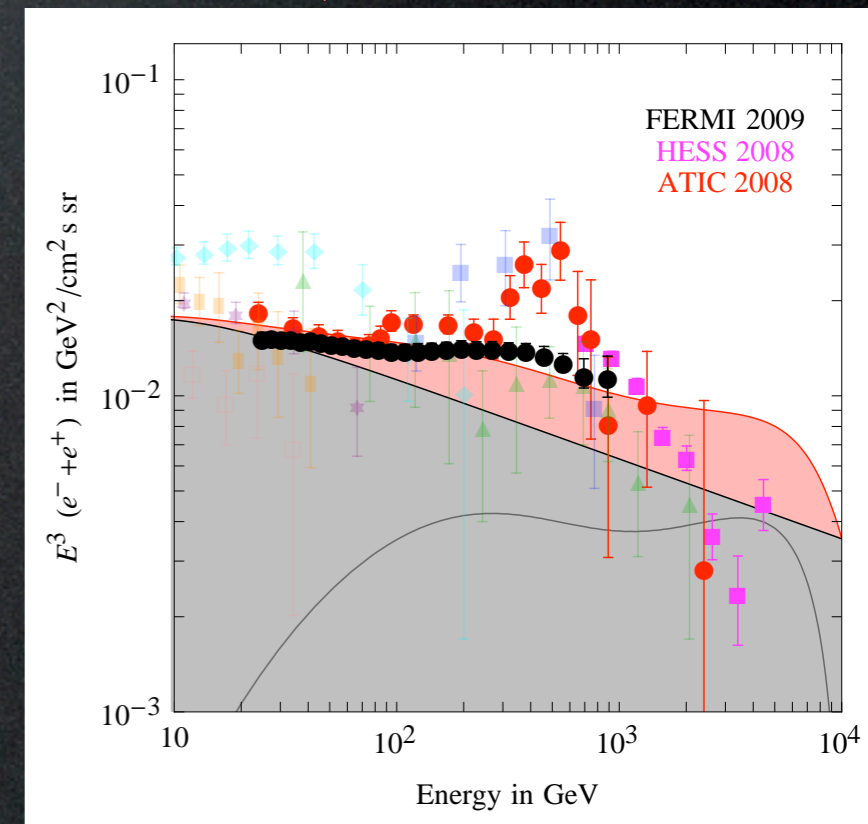
$\mu^+\mu^-$, $M_{\text{DM}} \simeq 1 \text{ TeV}$



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



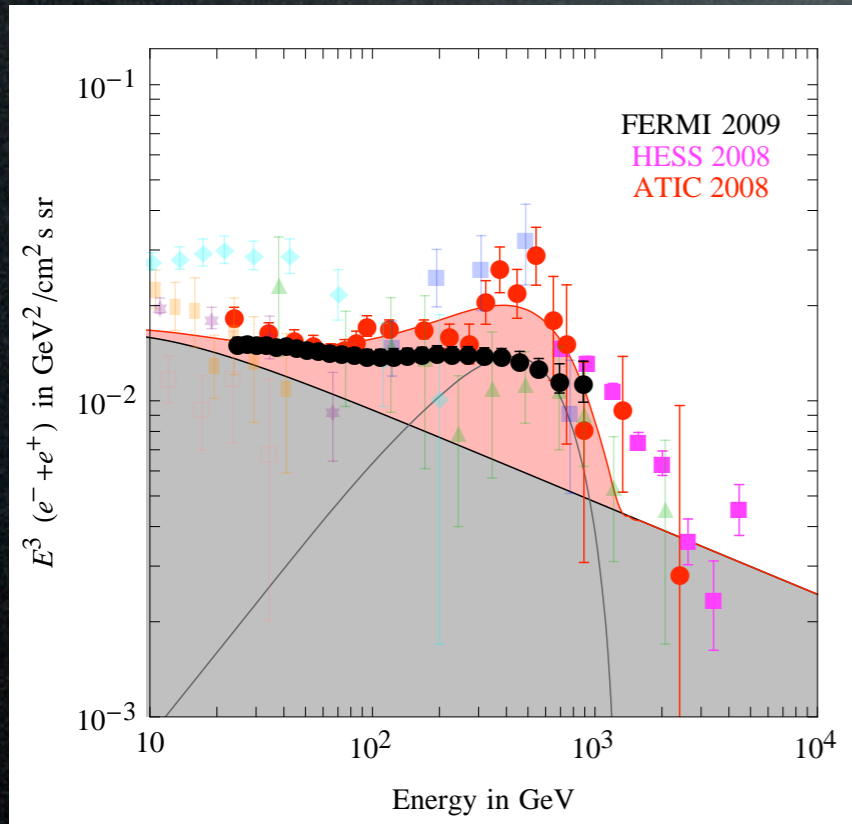
W^+W^- , $M_{\text{DM}} \simeq 10 \text{ TeV}$



Results

Which DM spectra can fit the data?

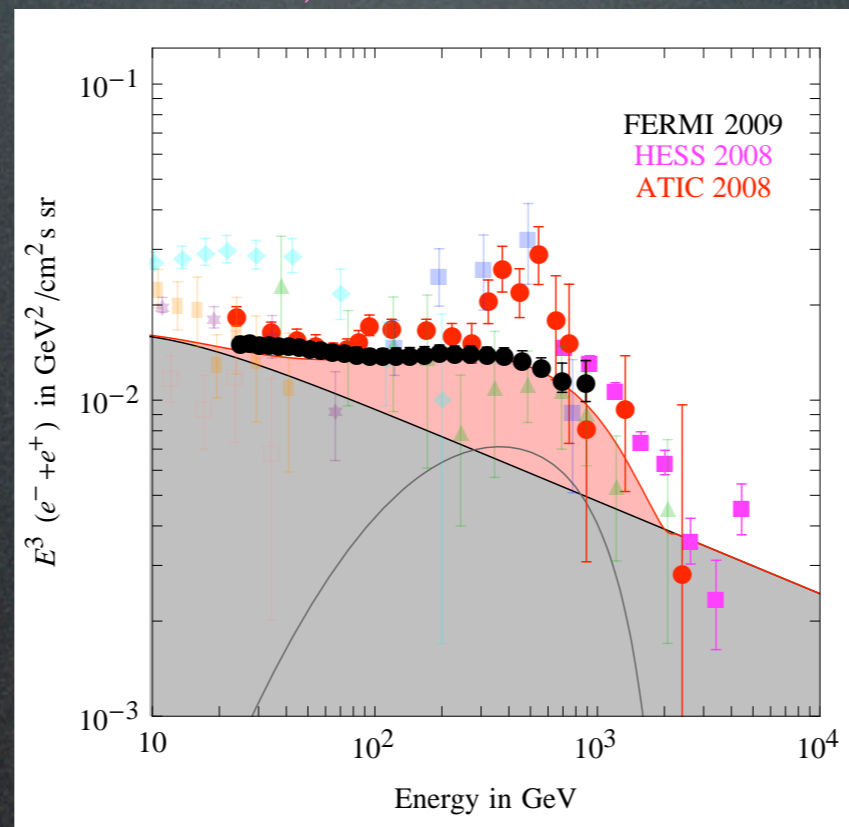
$\mu^+\mu^-, M_{\text{DM}} \simeq 1 \text{ TeV}$



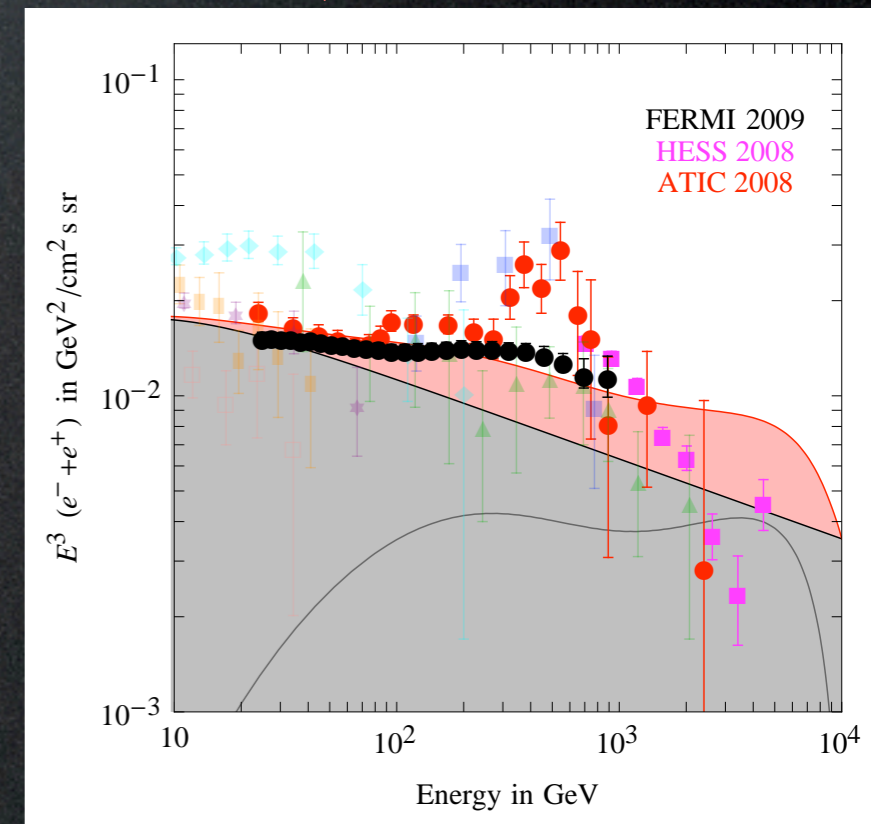
Notice:

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

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



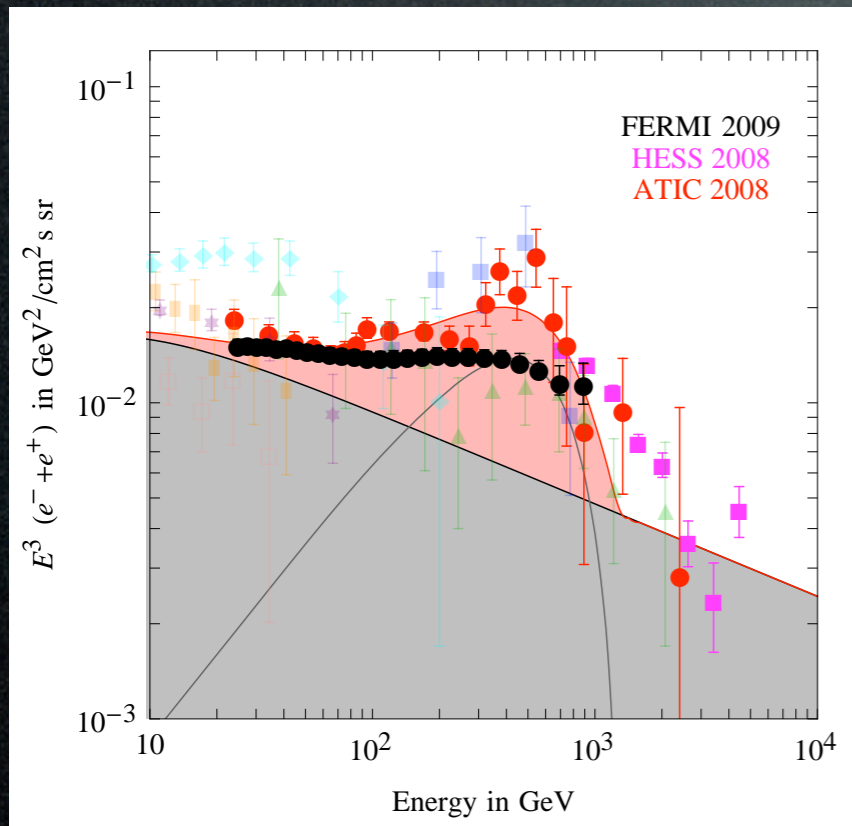
$W^+W^-, M_{\text{DM}} \simeq 10 \text{ TeV}$



Results

Which DM spectra can fit the data?

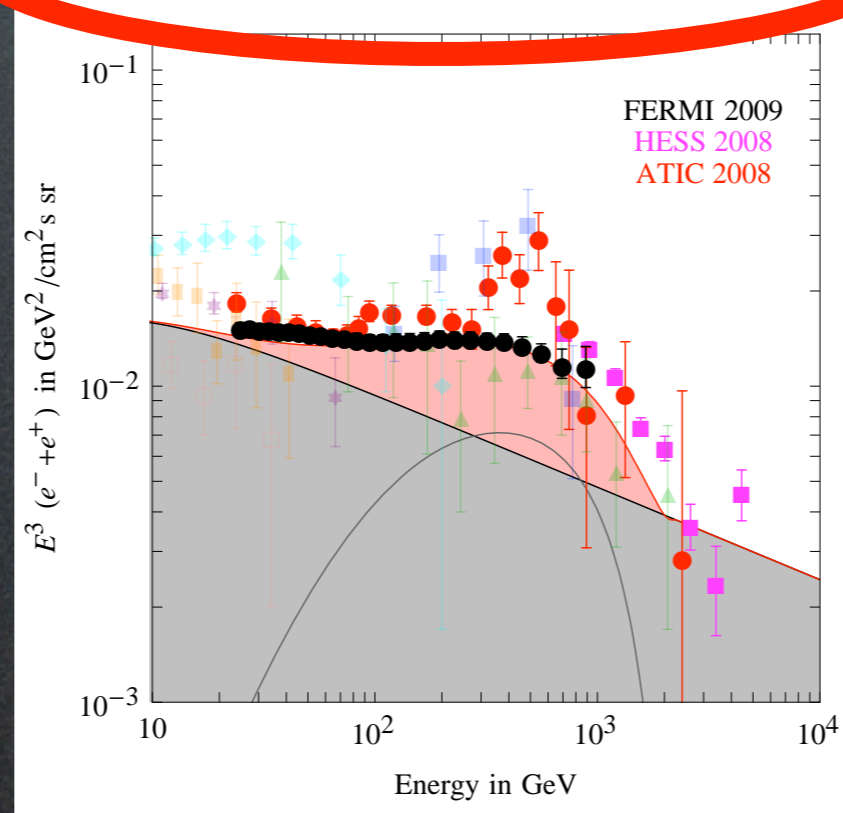
$\mu^+\mu^-$, $M_{\text{DM}} \simeq 1 \text{ TeV}$



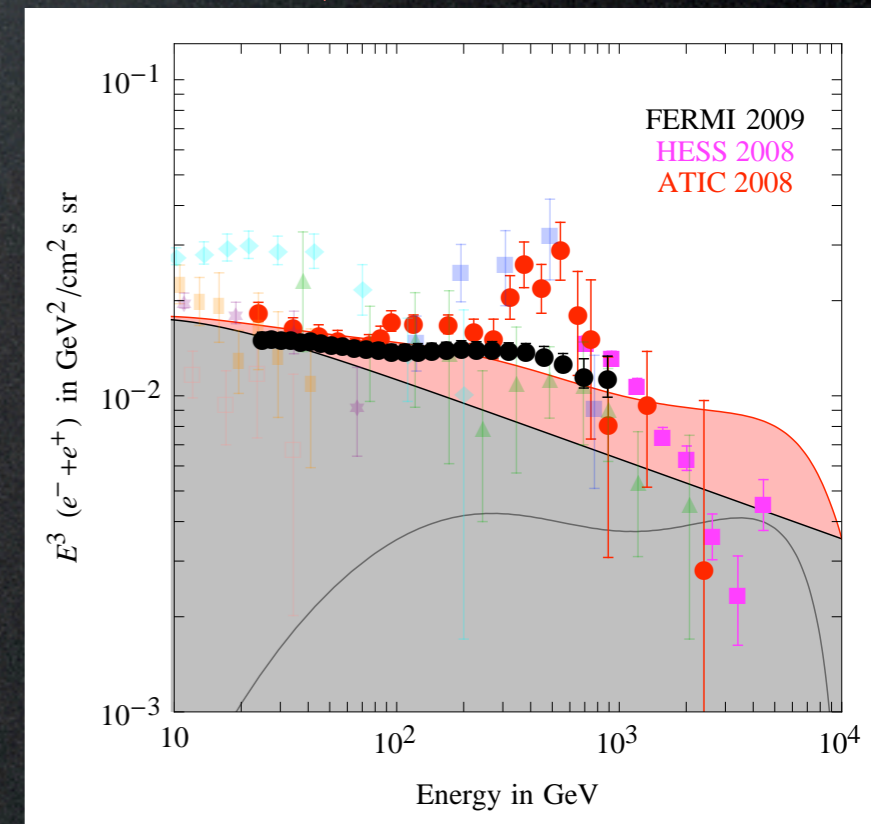
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W^+W^- , $M_{\text{DM}} \simeq 10 \text{ TeV}$



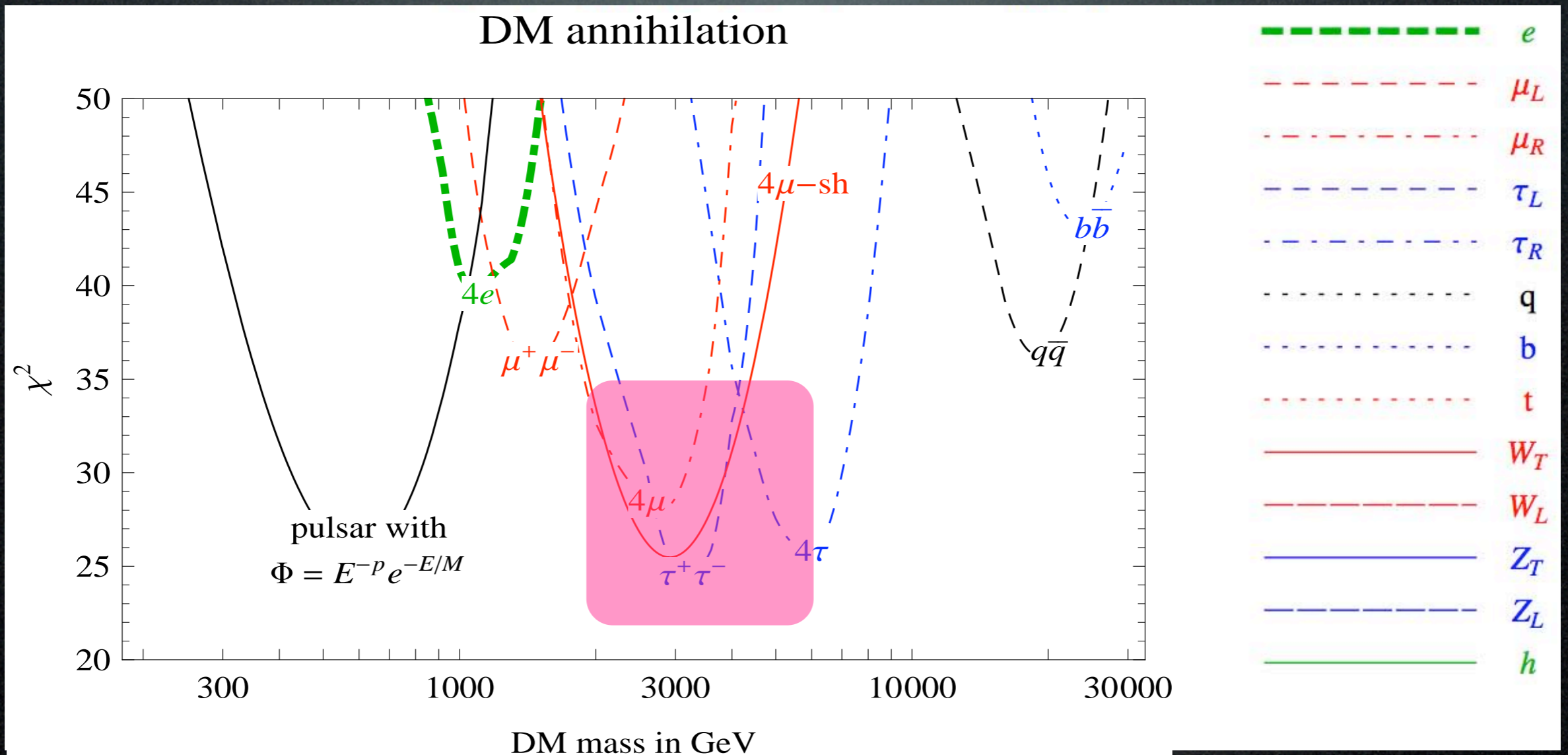
- no features in FERMI $\Rightarrow M_{\text{DM}} > 1 \text{ TeV}$
- a 'cutoff' in HESS $\Rightarrow M_{\text{DM}} \lesssim 3 \text{ TeV}$
- **smooth** lepton spectrum

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
and from synchrotron emission

HESS, FERMI, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

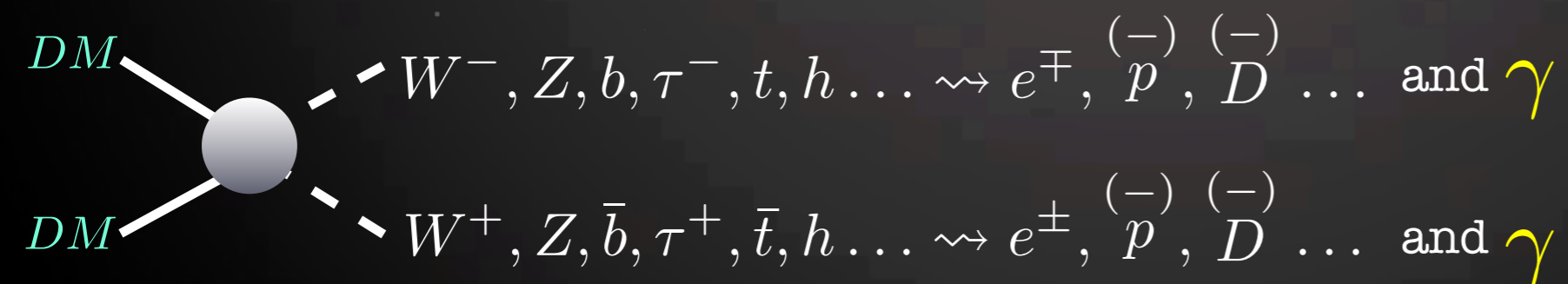
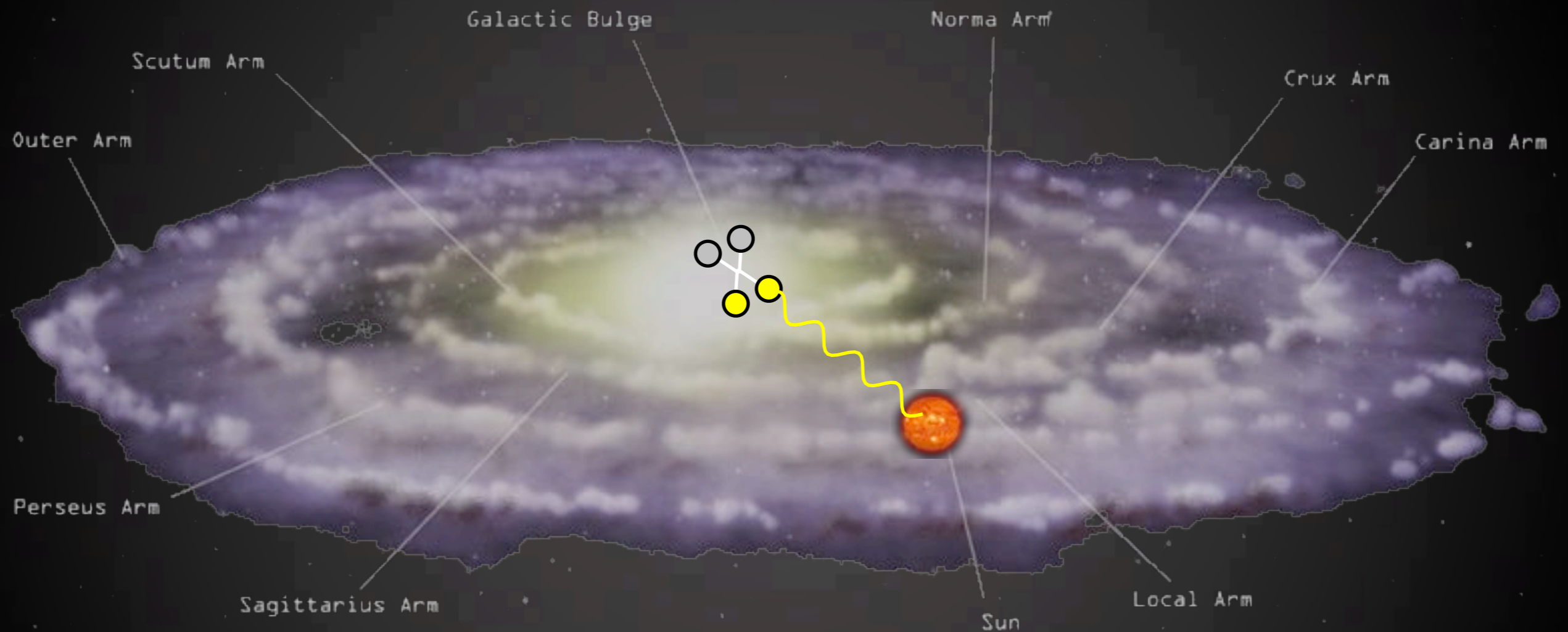
\bar{p} from annihil in galactic halo or center

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

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

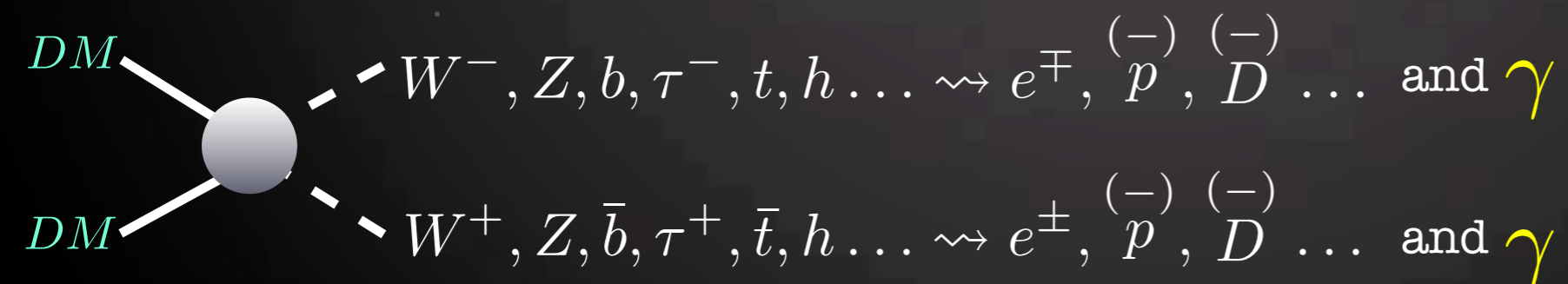
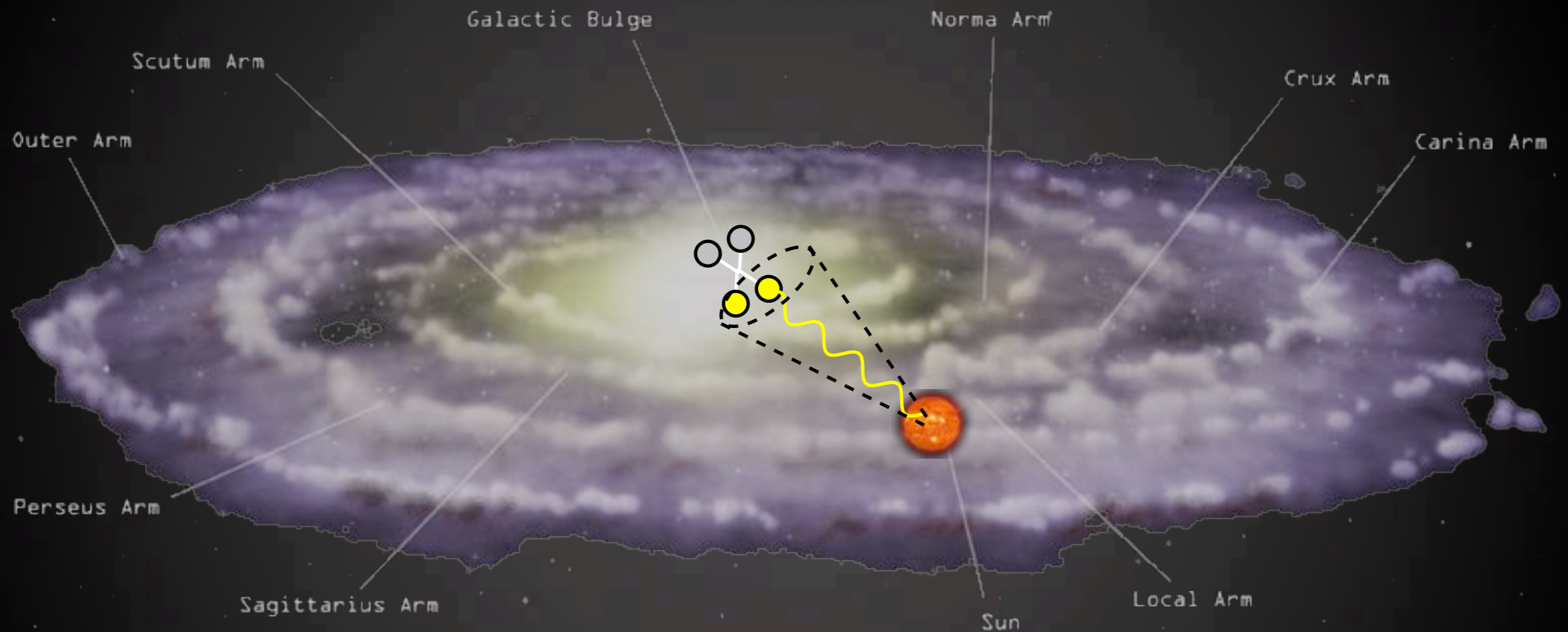
Indirect Detection

γ from DM annihilations in galactic center



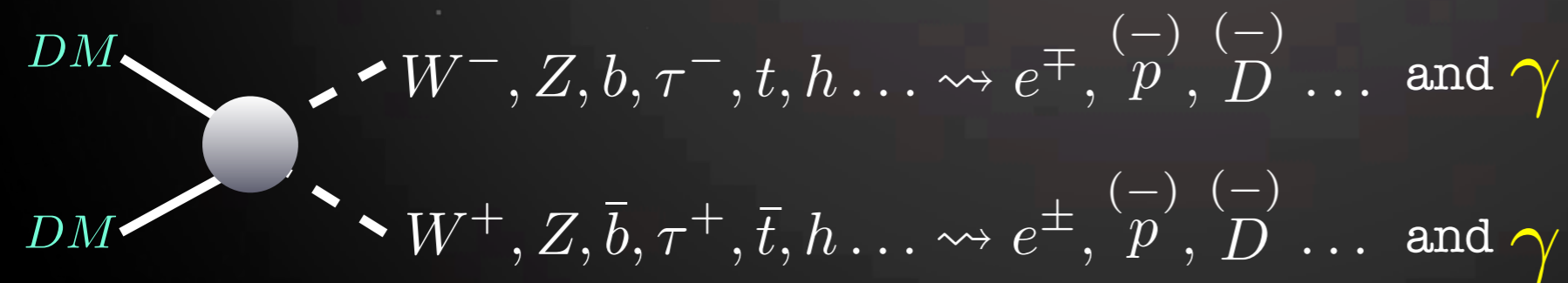
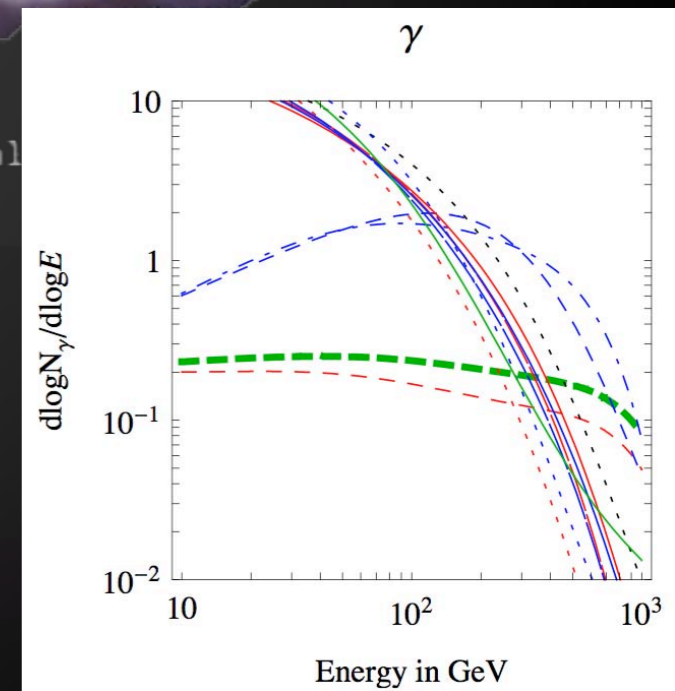
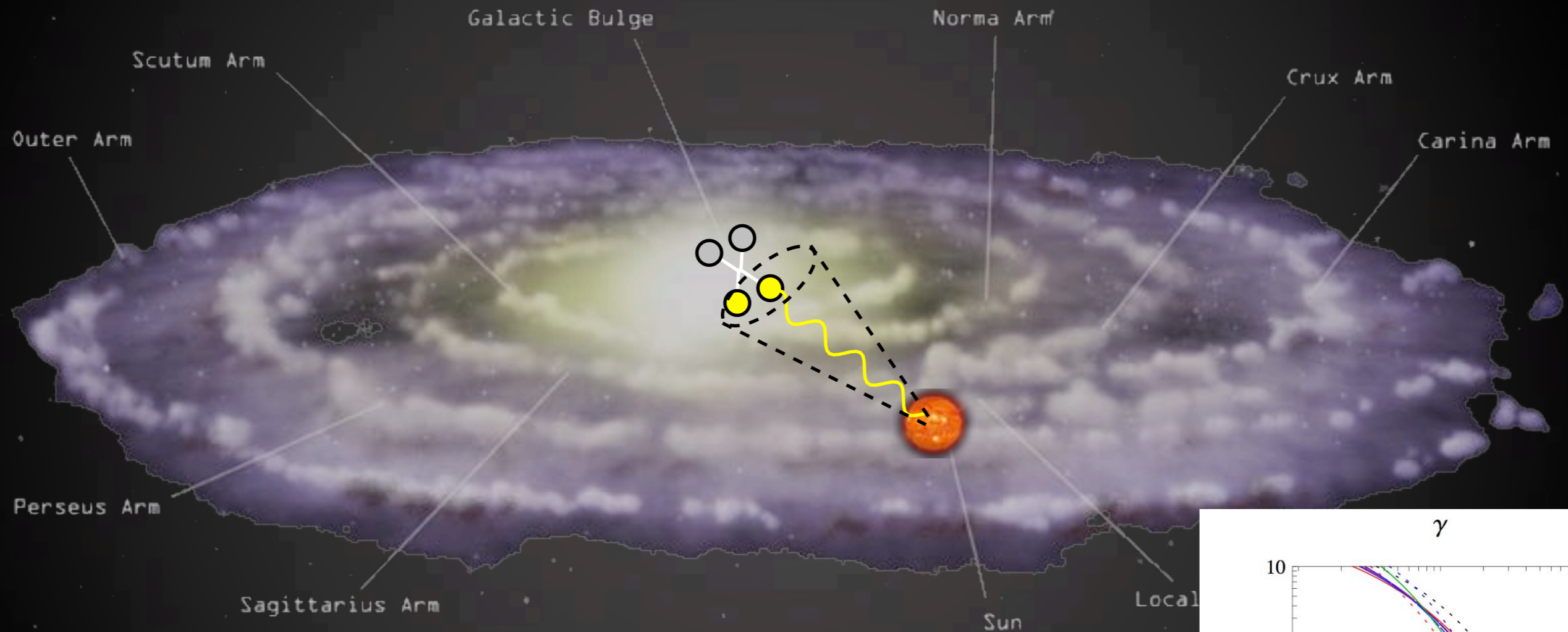
Indirect Detection

γ from DM annihilations in galactic center



Indirect Detection

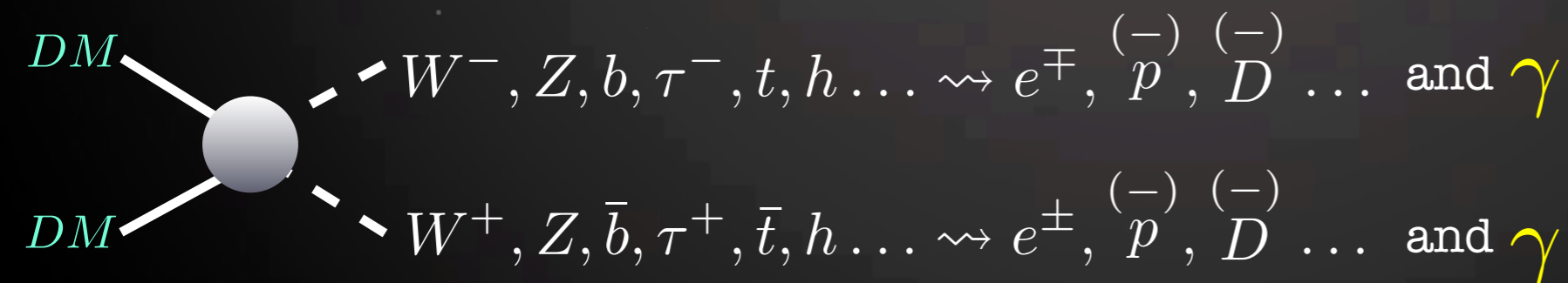
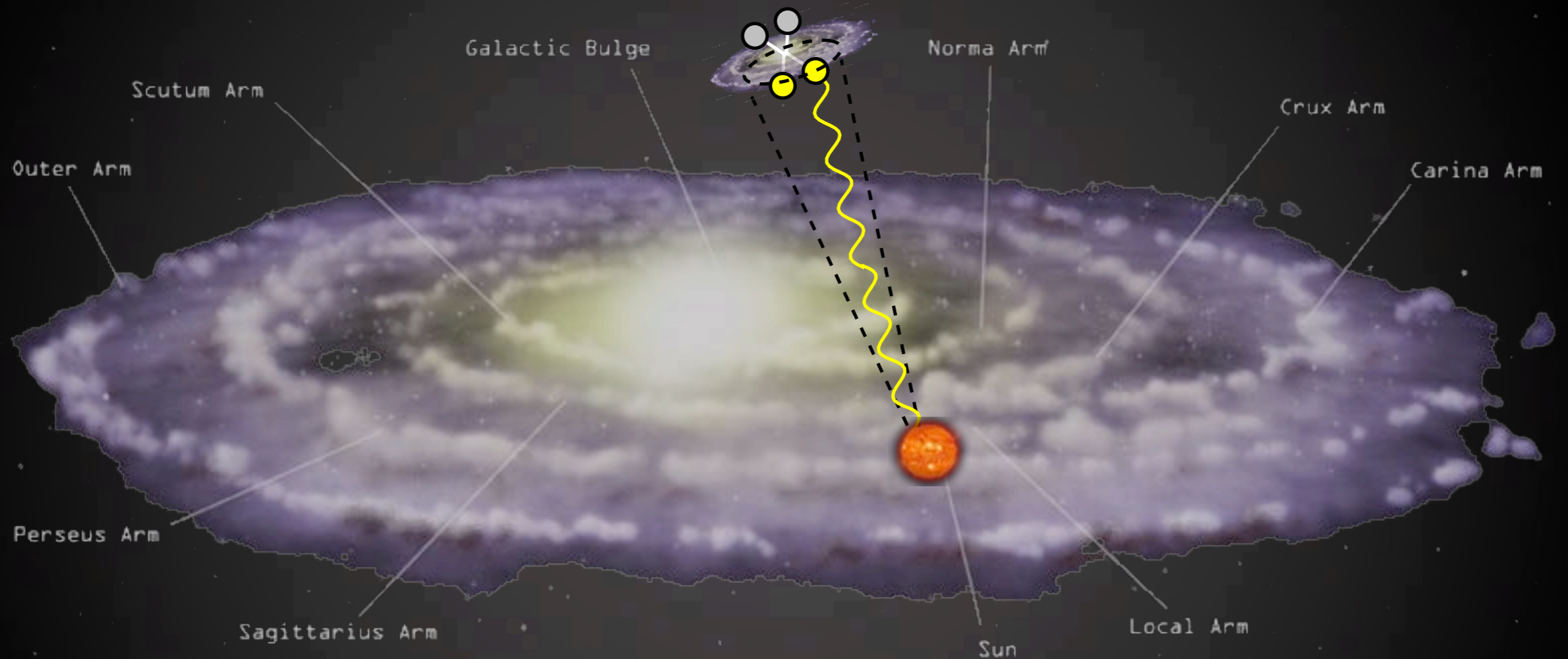
γ from DM annihilations in galactic center



typically sub-TeV energies

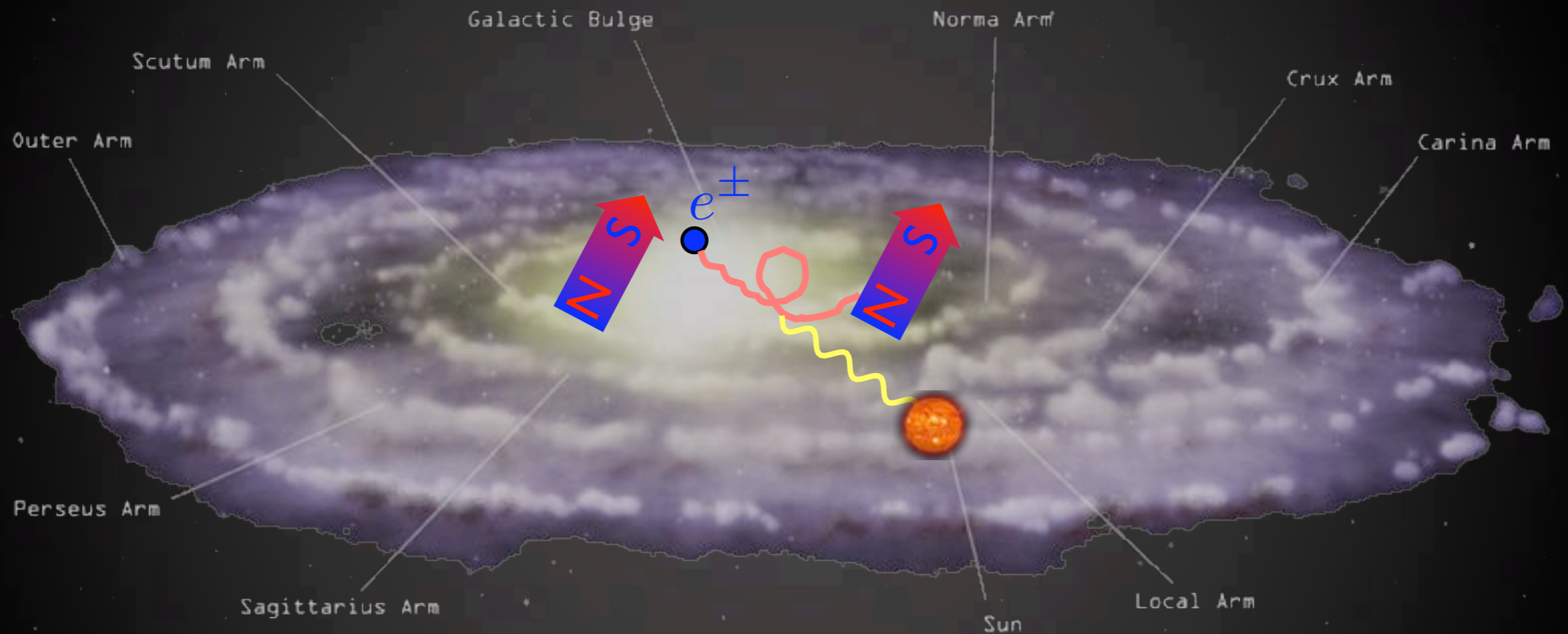
Indirect Detection

γ from DM annihilations in Sagittarius Dwarf



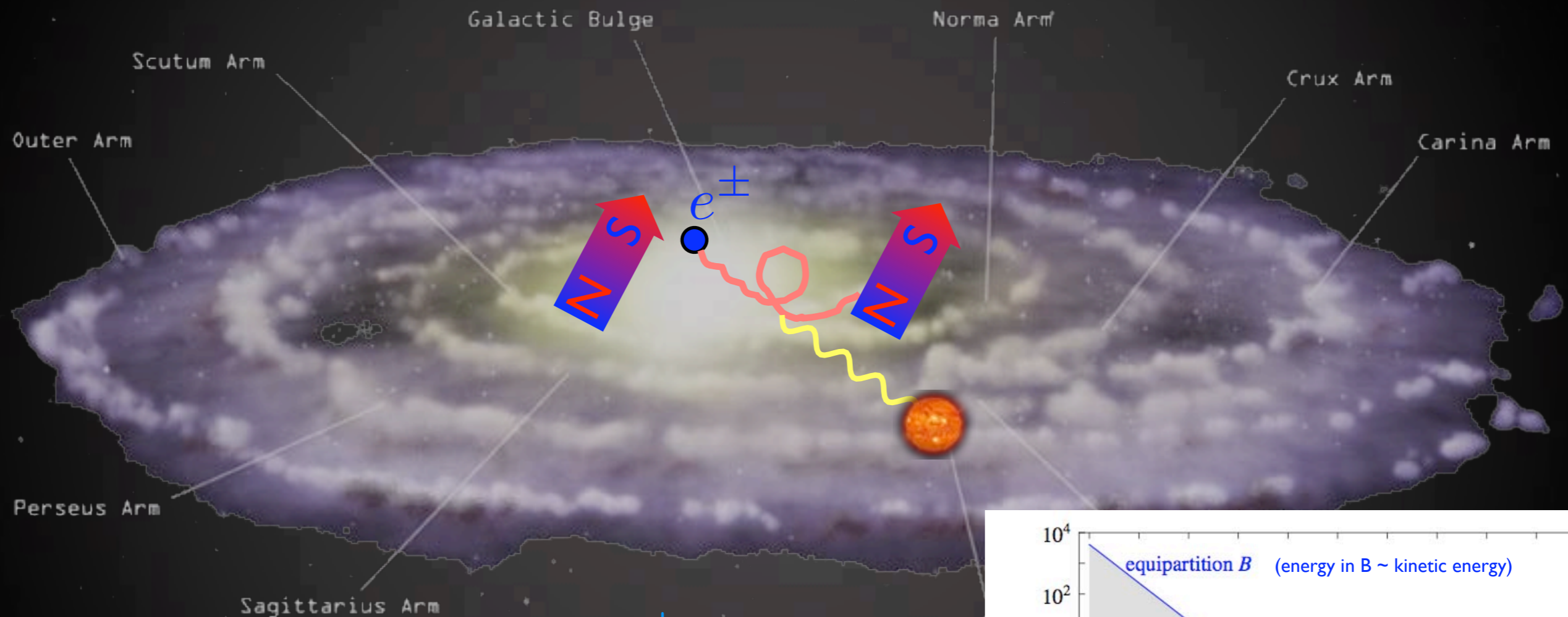
Indirect Detection

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



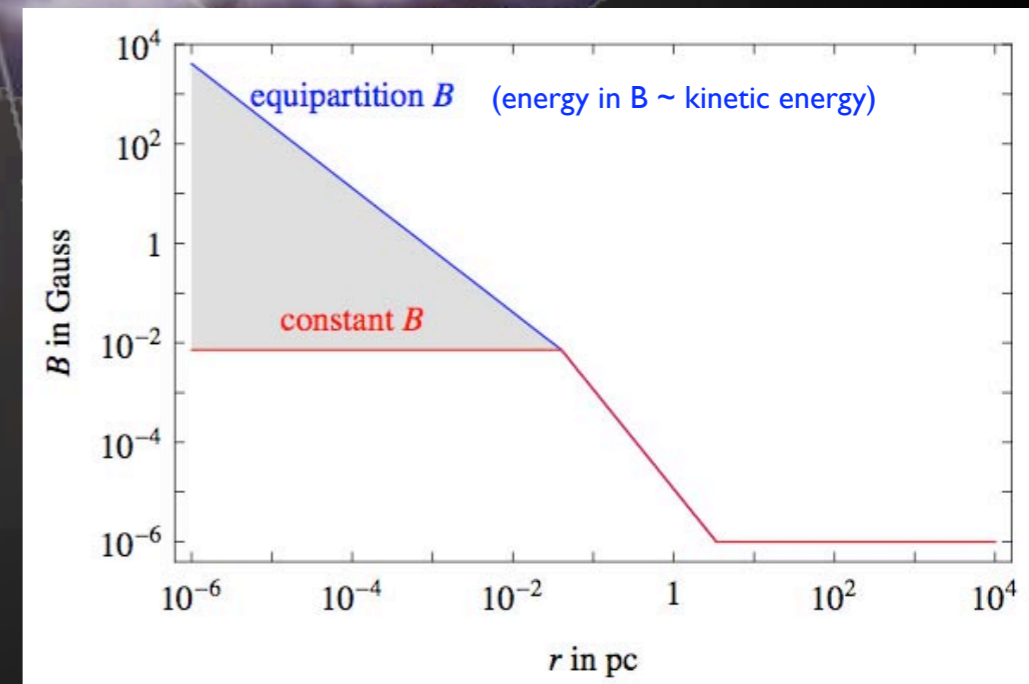
Indirect Detection

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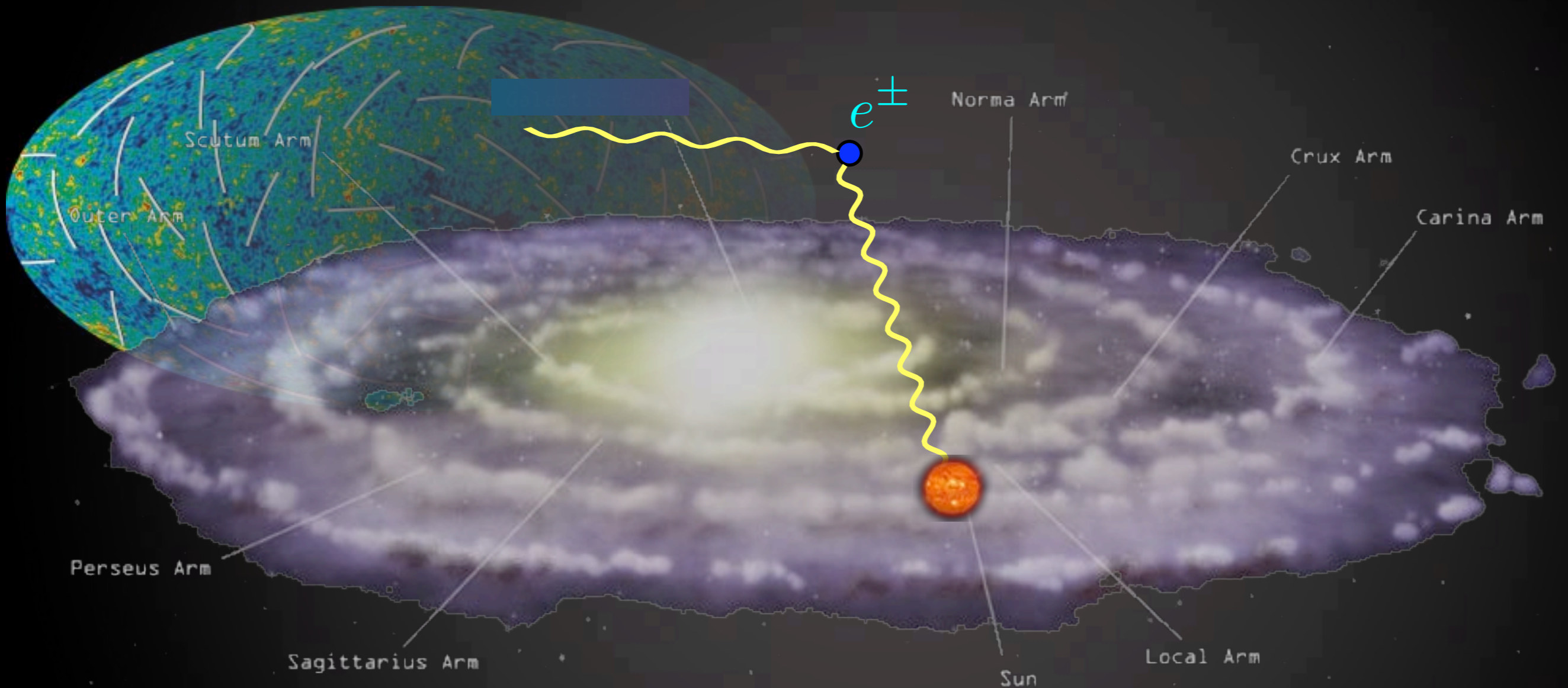
- compute the population of e^\pm from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic \vec{B}

(assuming 'scrambled' B ; in principle, directionality could focus emission, lift bounds by $O(\text{some})$)



Indirect Detection

γ from Inverse Compton on e^\pm in halo

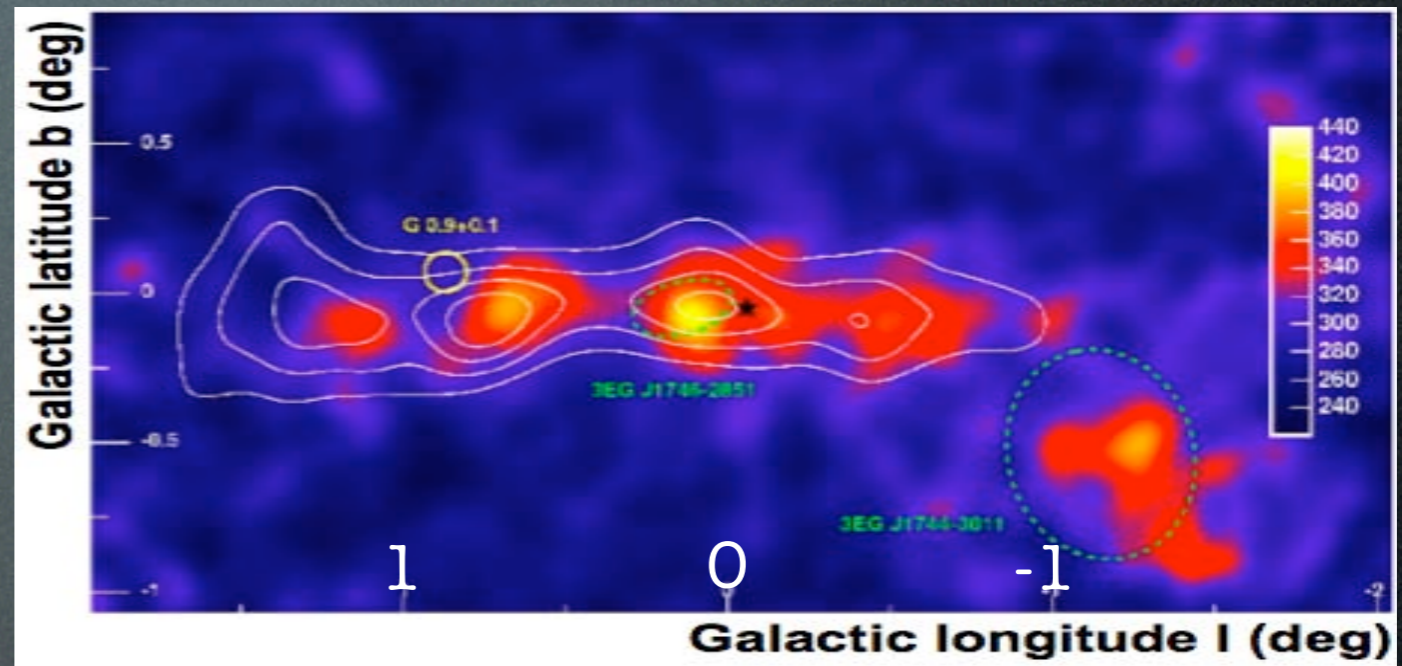


- upscatter of CMB, infrared and starlight photons on energetic e^\pm
- probes regions outside of Galactic Center

Comparing with data

Gamma constraints

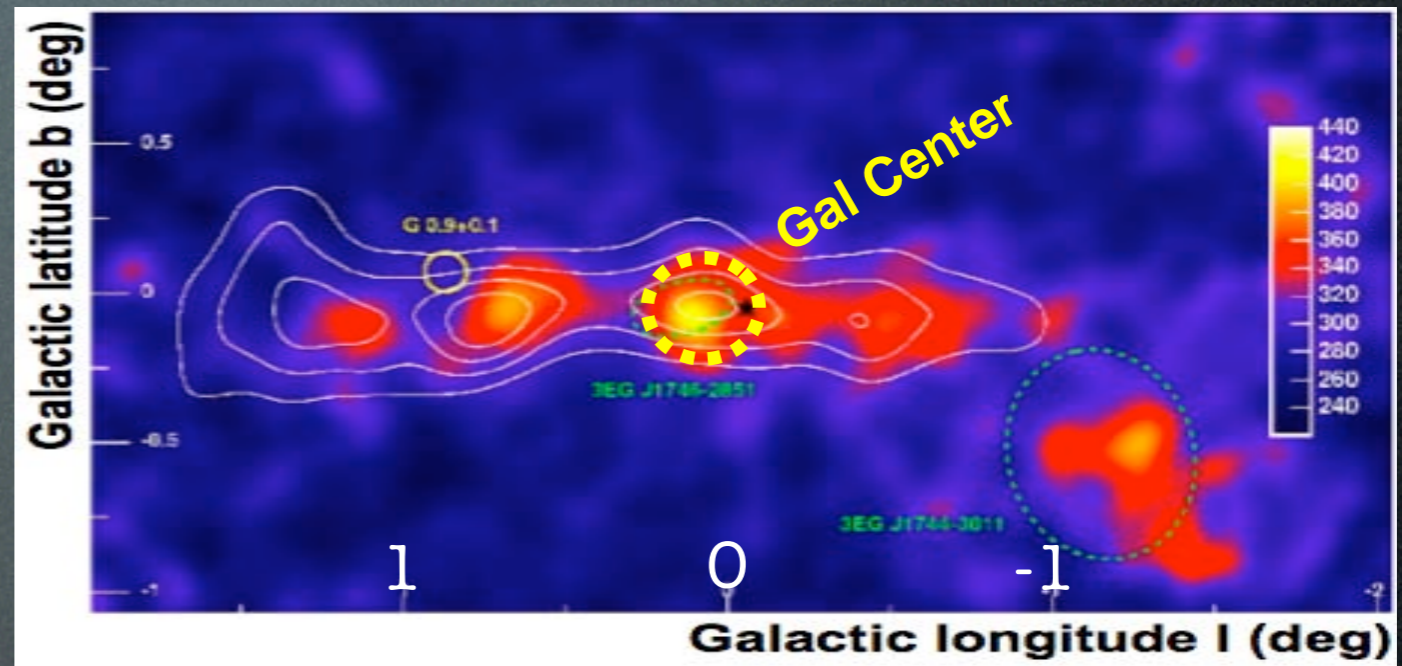
HESS has detected γ -ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.



HESS coll.

Gamma constraints

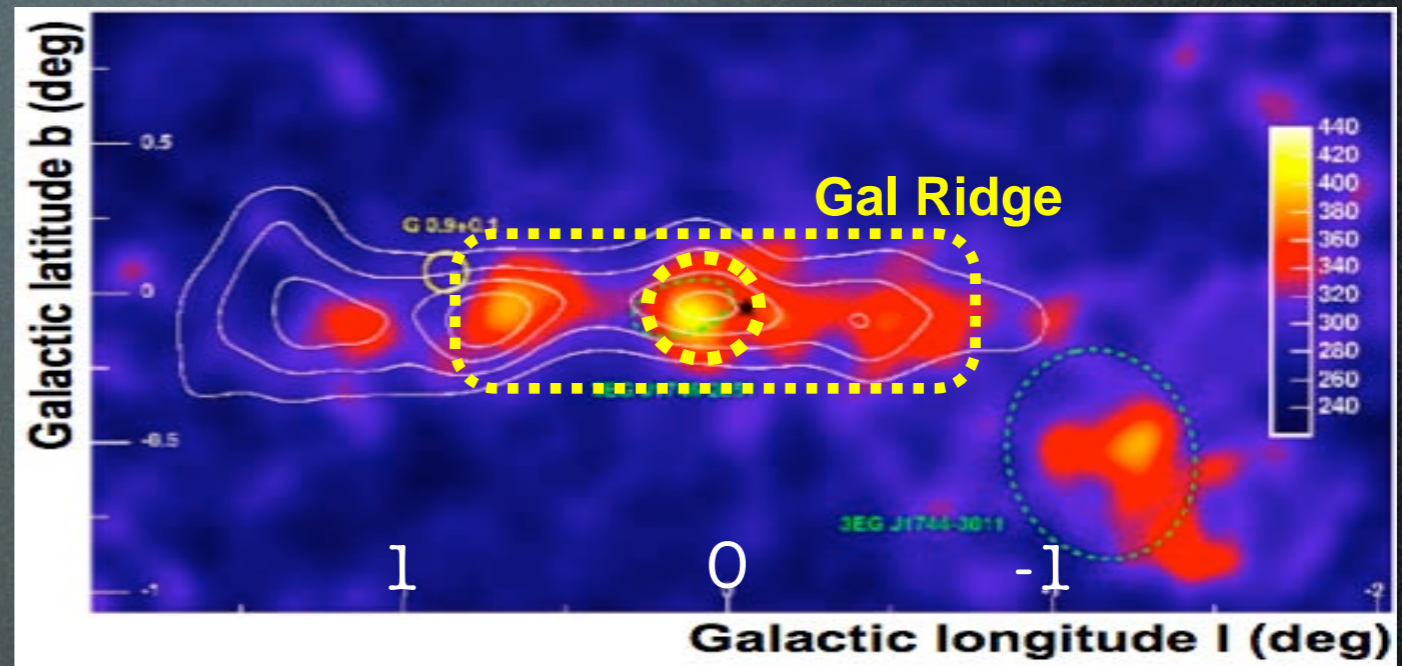
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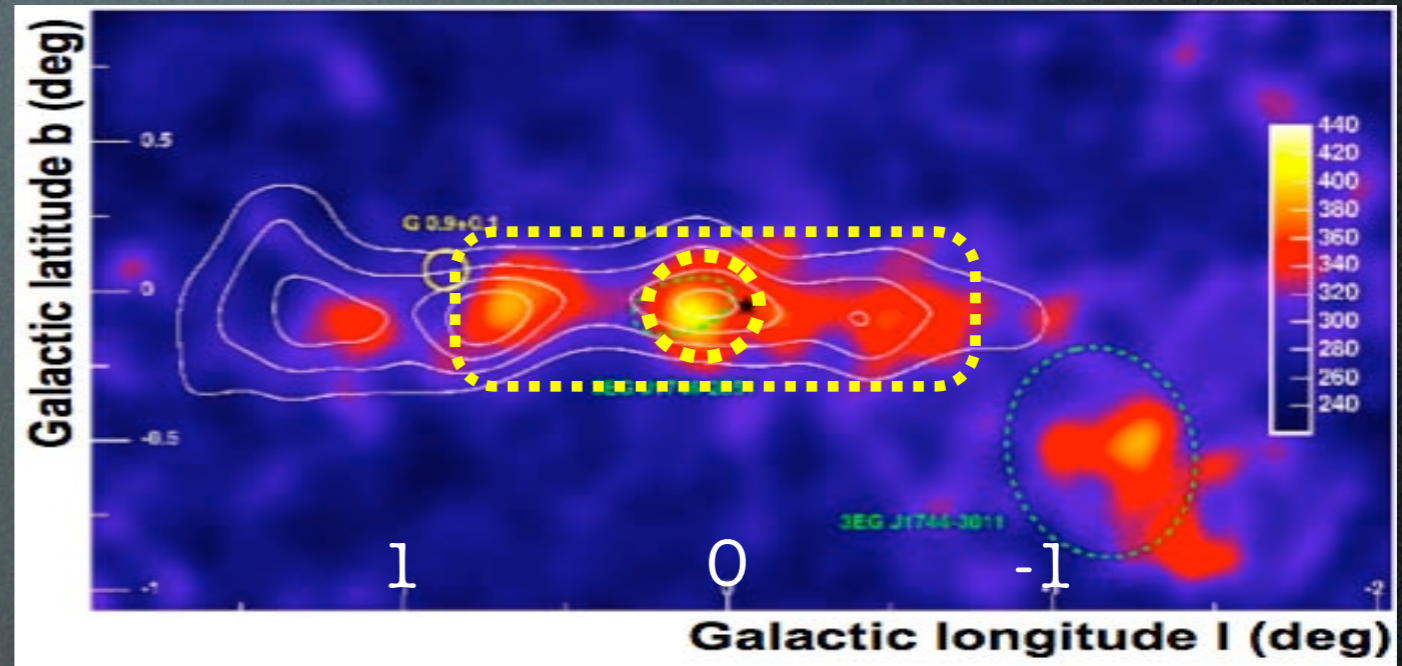
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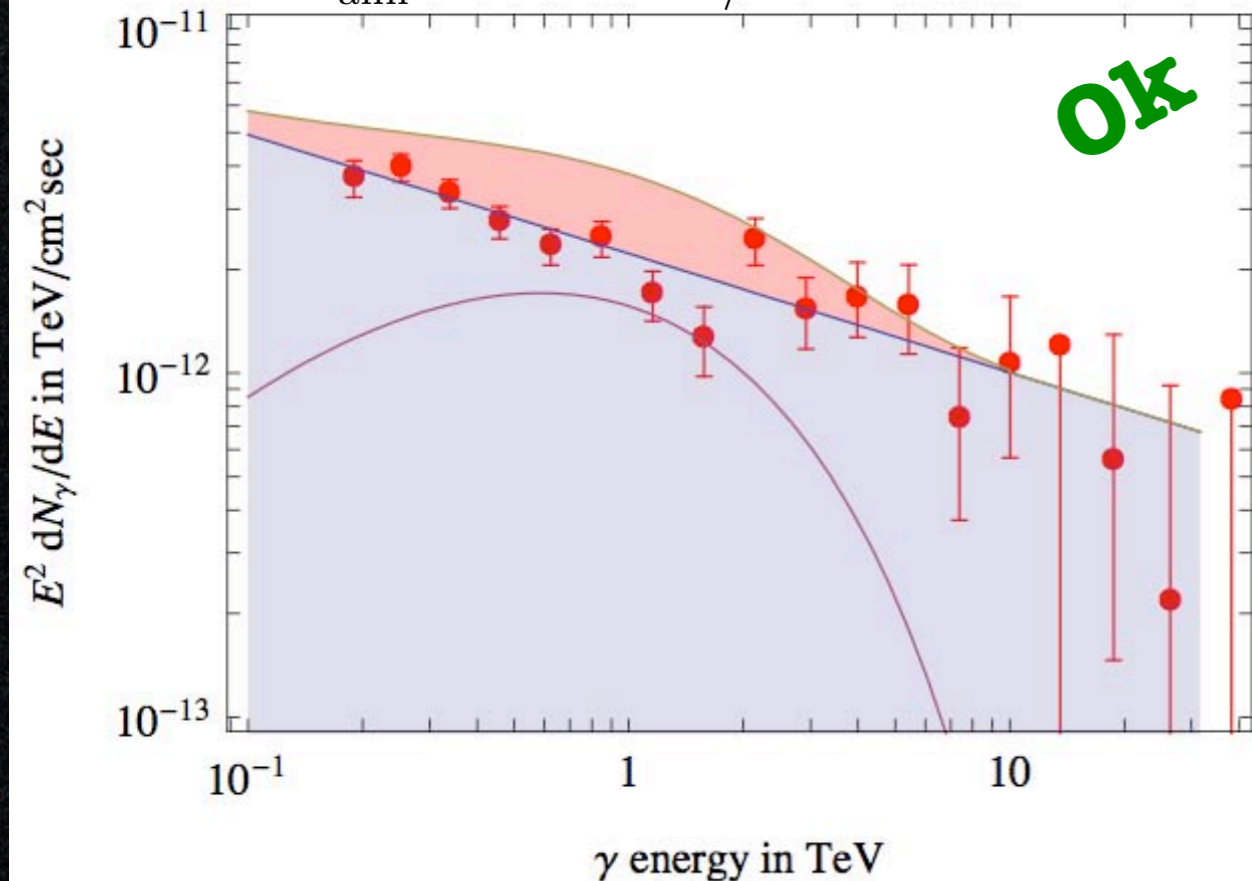
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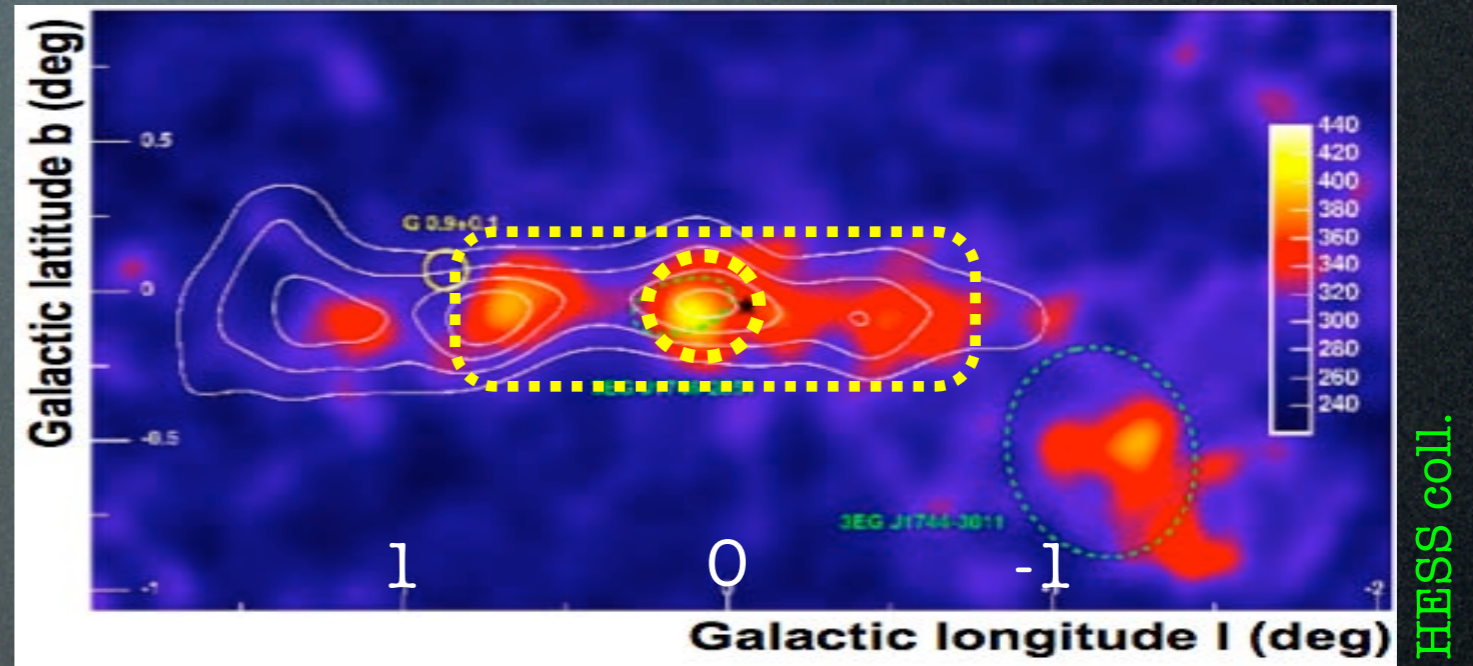
a) $M = 10$ TeV into W^+W^- , Galactic Center
 $\sigma v_{\text{ann}} = 10^{-23} \text{ cm}^3/\text{sec}$



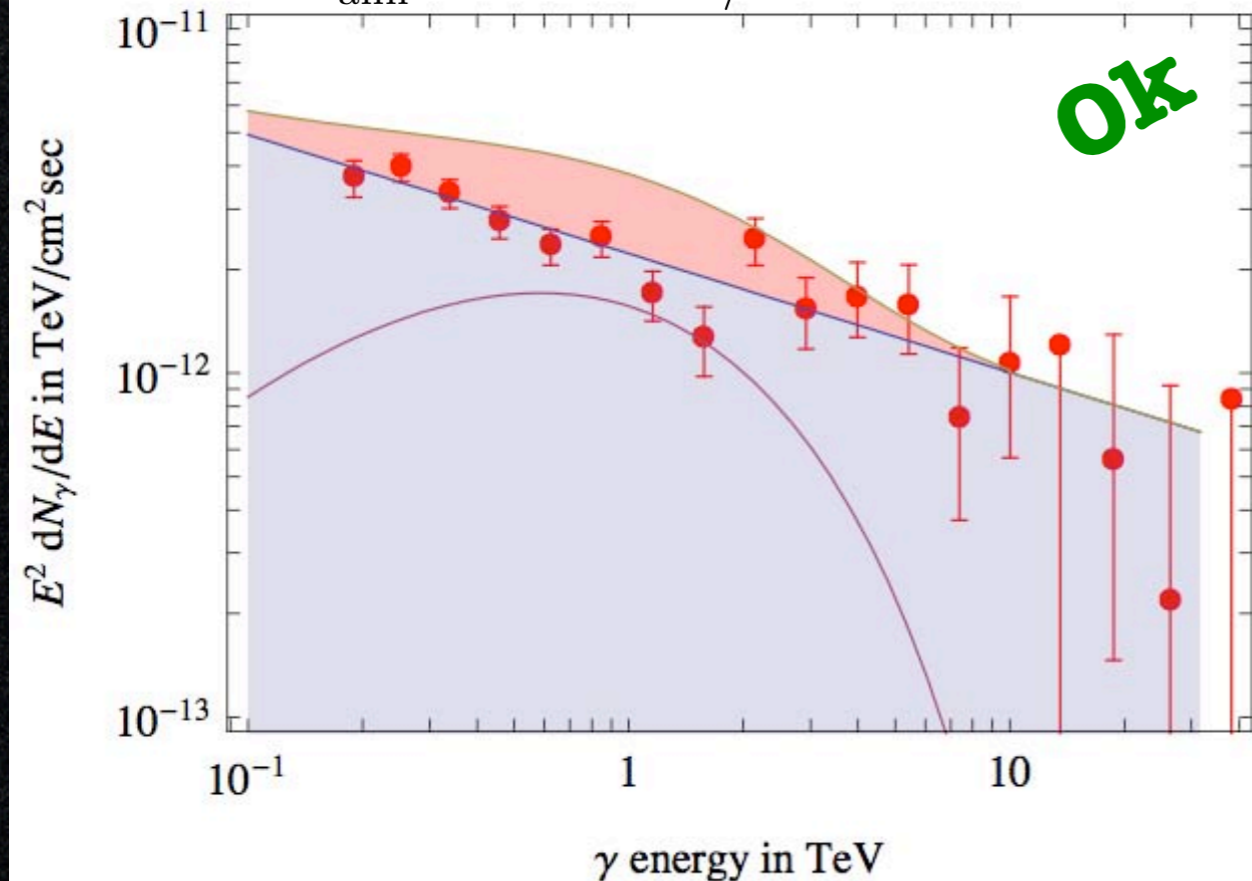
Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

Gamma constraints

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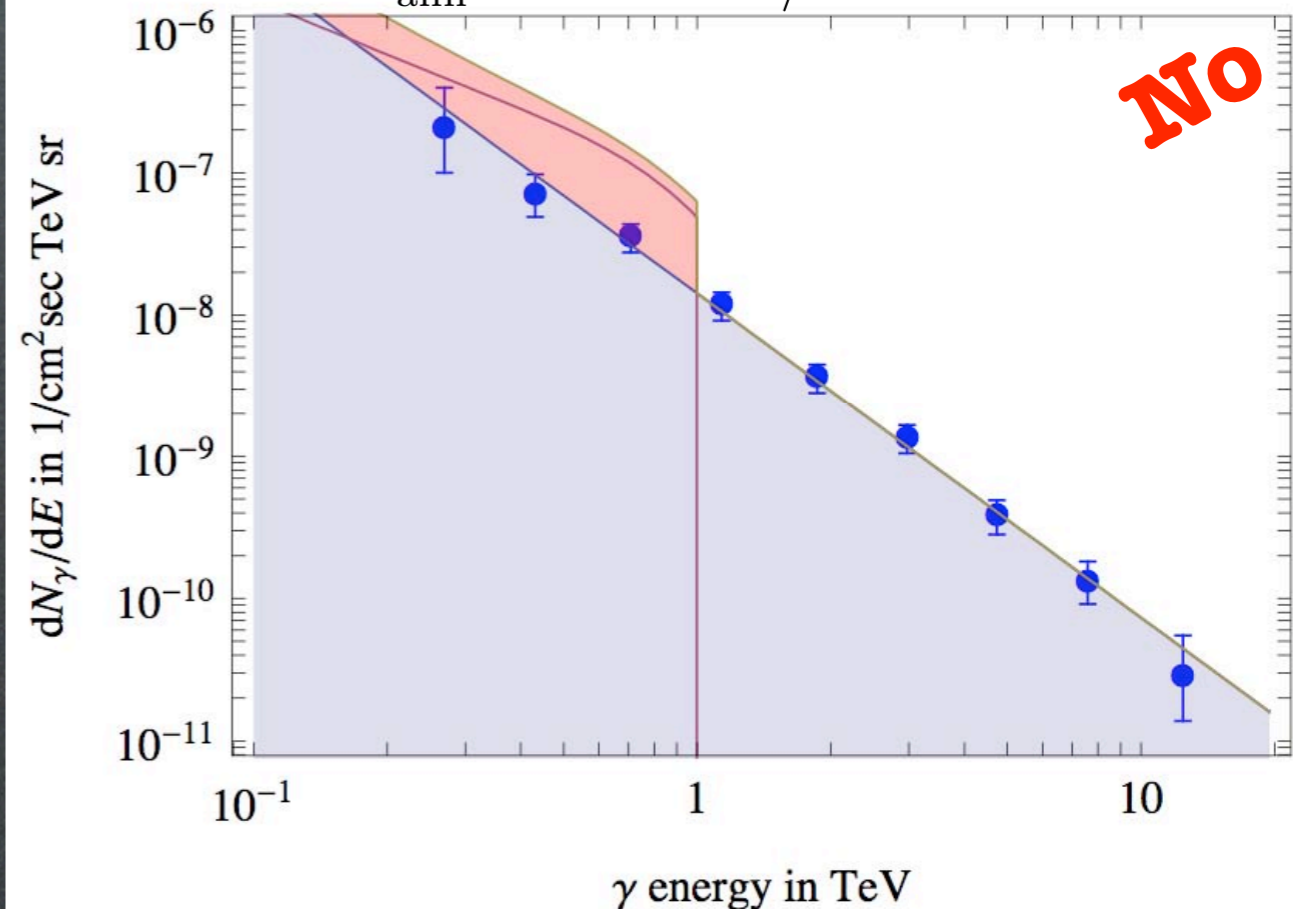


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 $\sigma v_{\text{ann}} = 10^{-23} \text{ cm}^3/\text{sec}$



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

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

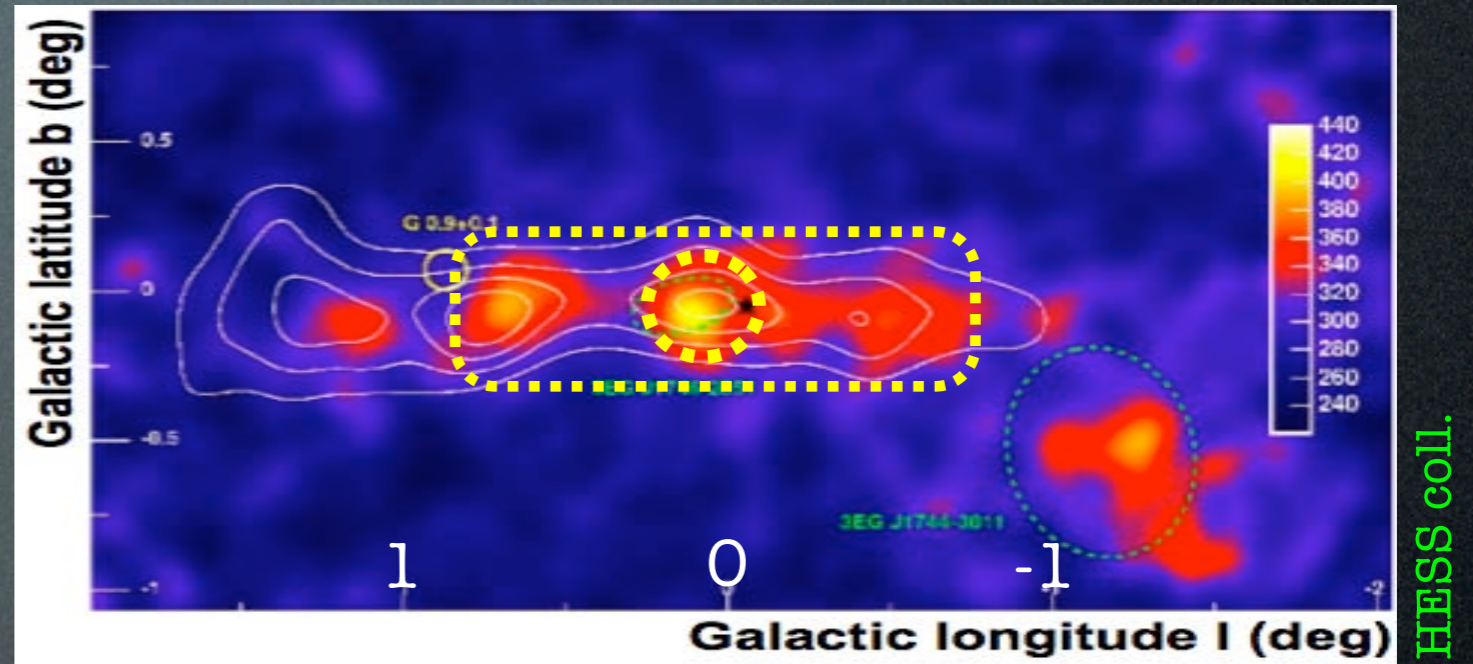


Data: HESS coll., astro-ph/0603021

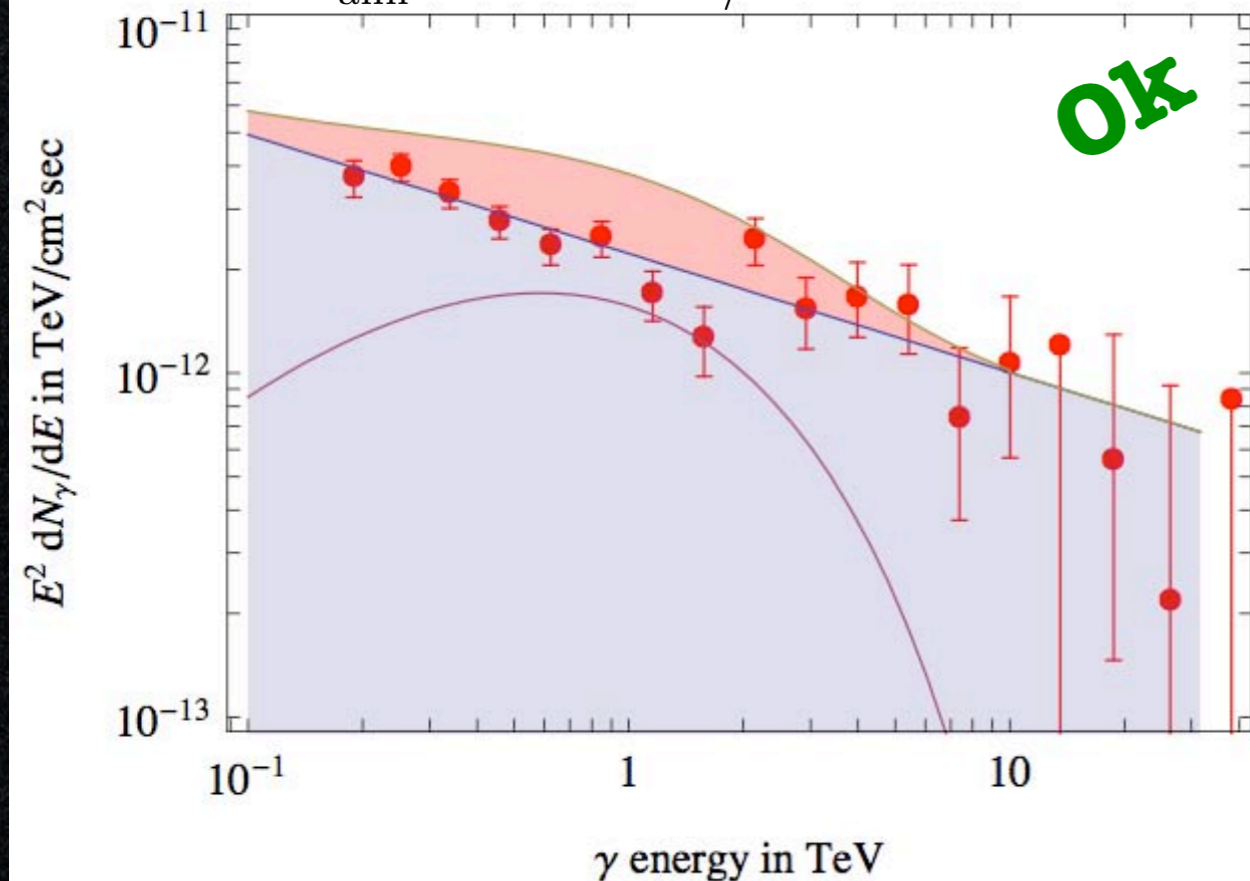
Gamma constraints

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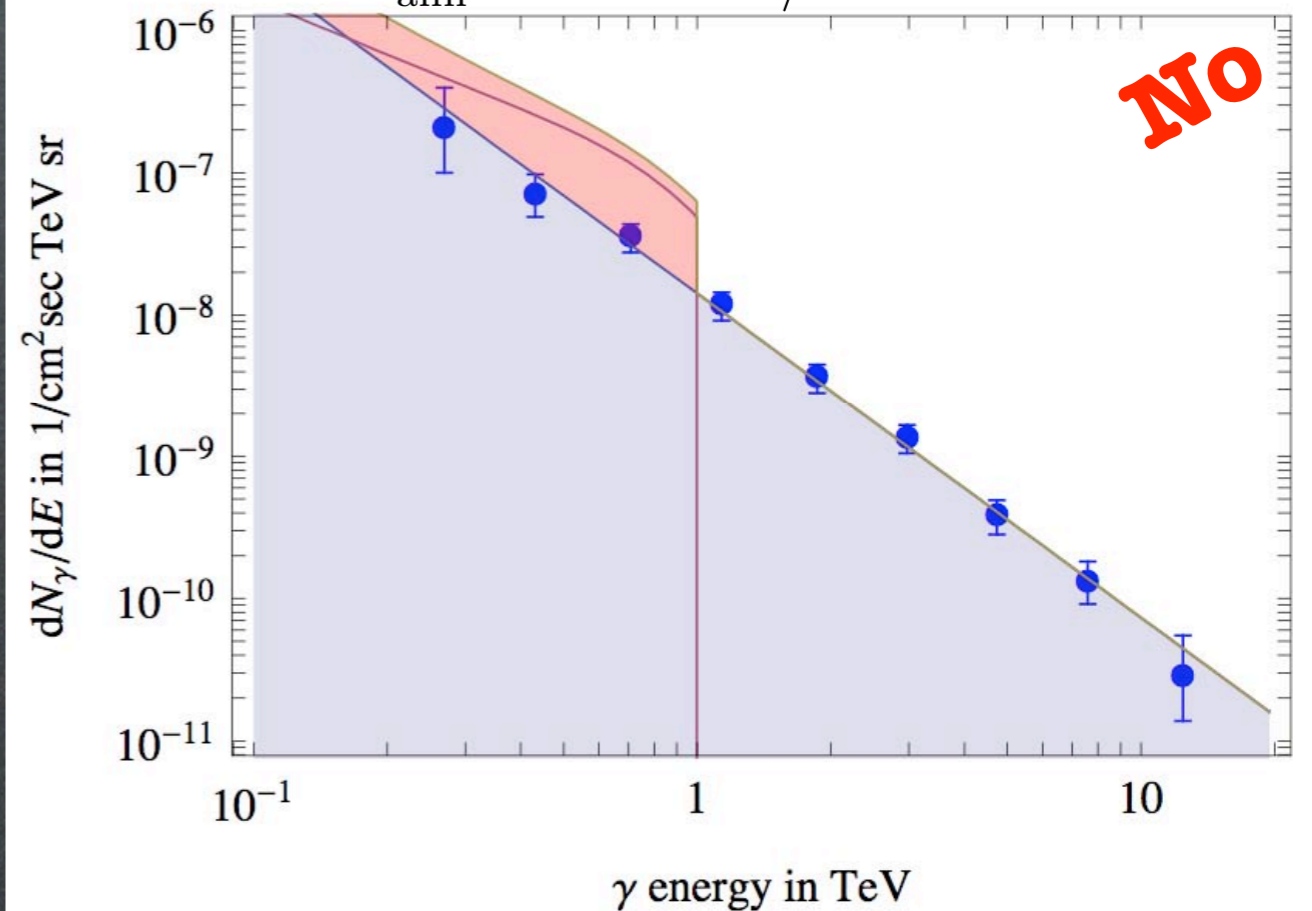
Moreover: no detection from Sgr dSph => upper bound.



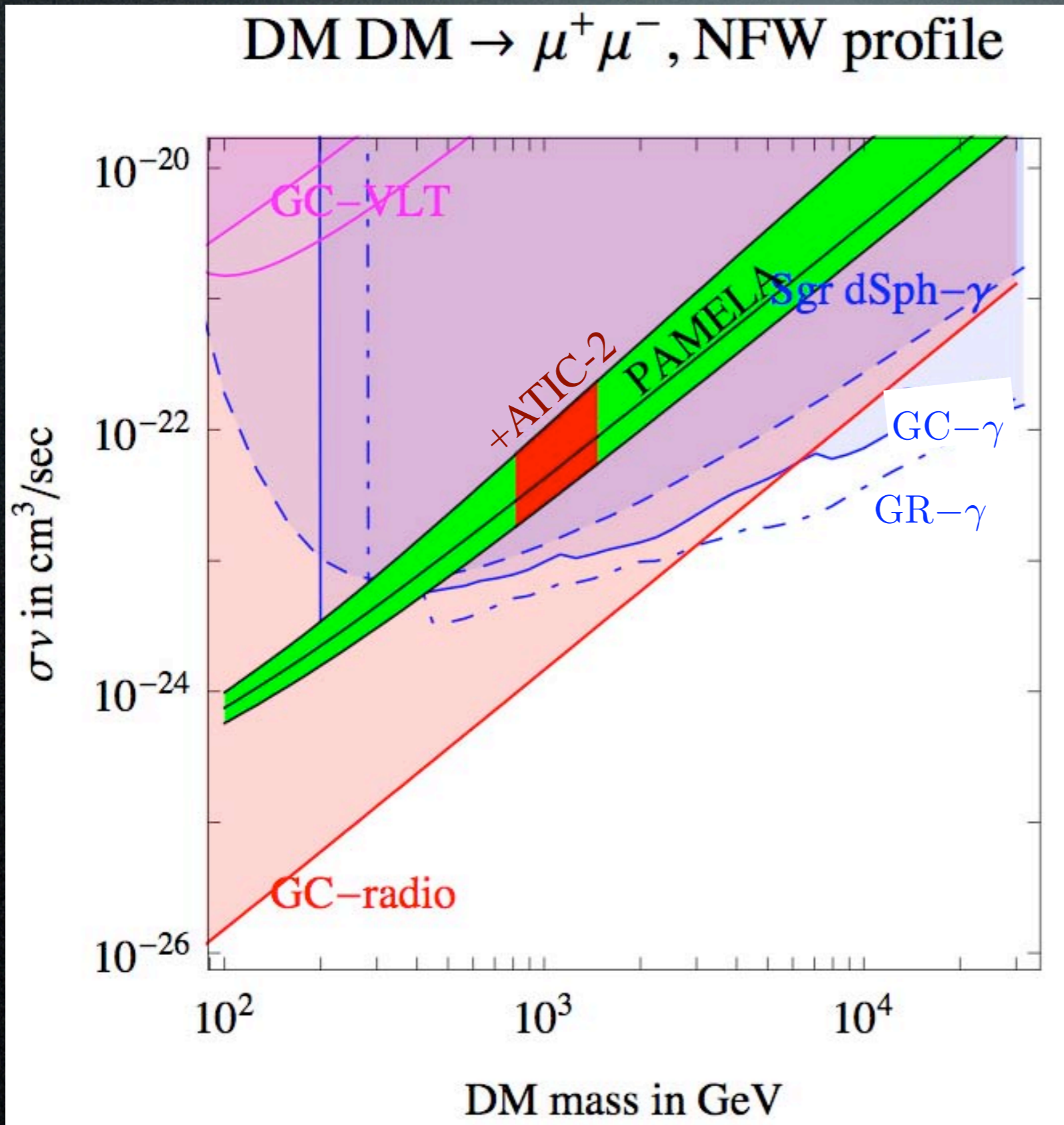
a) $M = 10$ TeV into W^+W^- , Galactic Center
 $\sigma v_{\text{ann}} = 10^{-23} \text{ cm}^3/\text{sec}$



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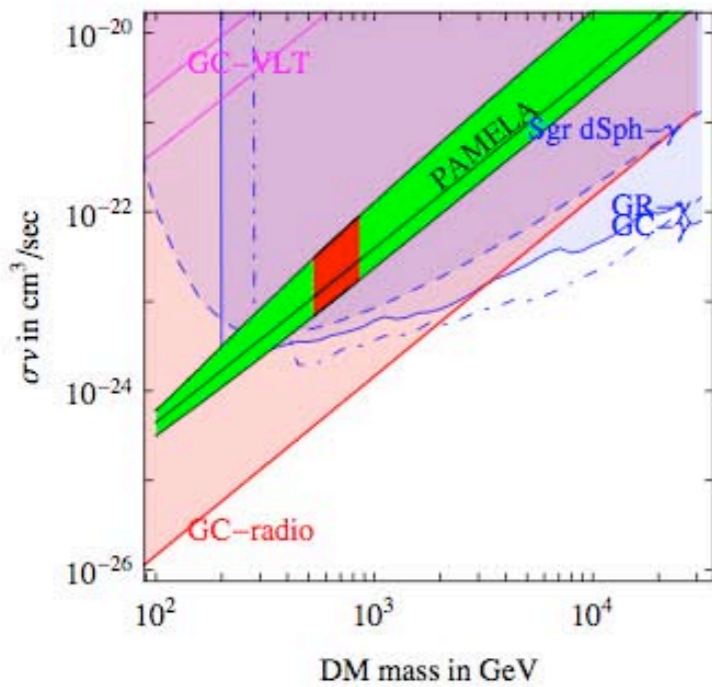
Gamma constraints



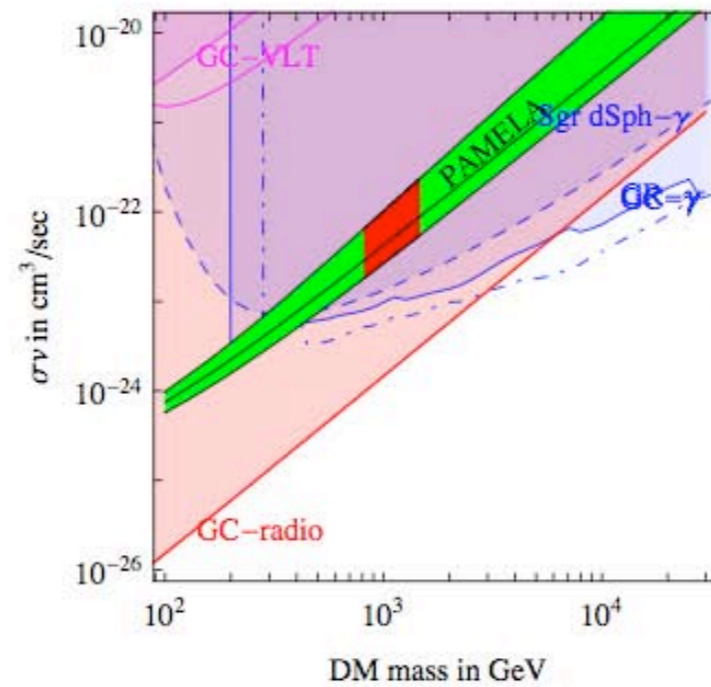
The PAMELA and ATIC regions are in **conflict** with gamma constraints, unless...

Gamma constraints

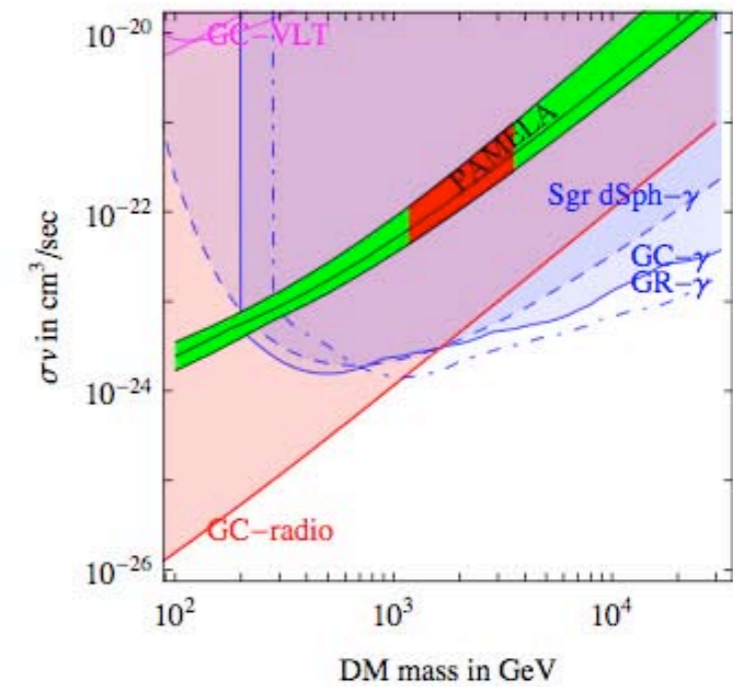
DM DM $\rightarrow e^+e^-$, NFW profile



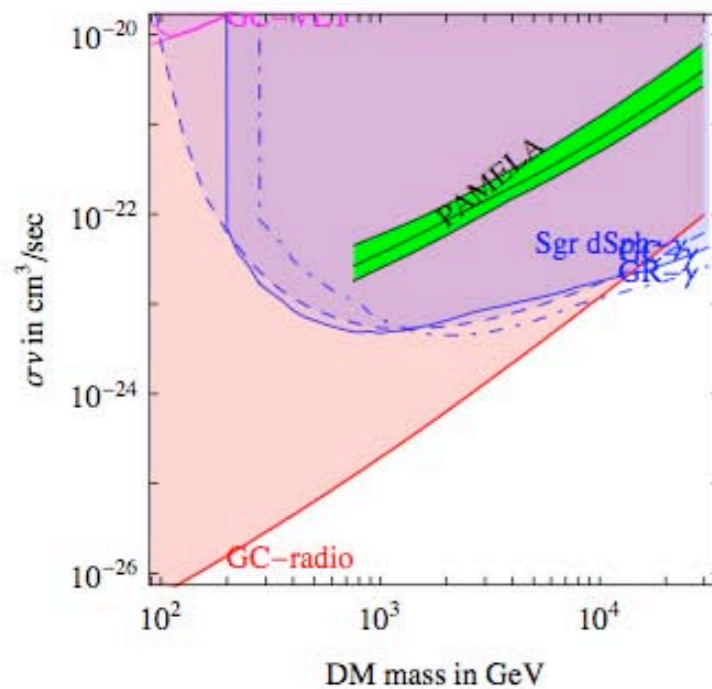
DM DM $\rightarrow \mu^+\mu^-$, NFW profile



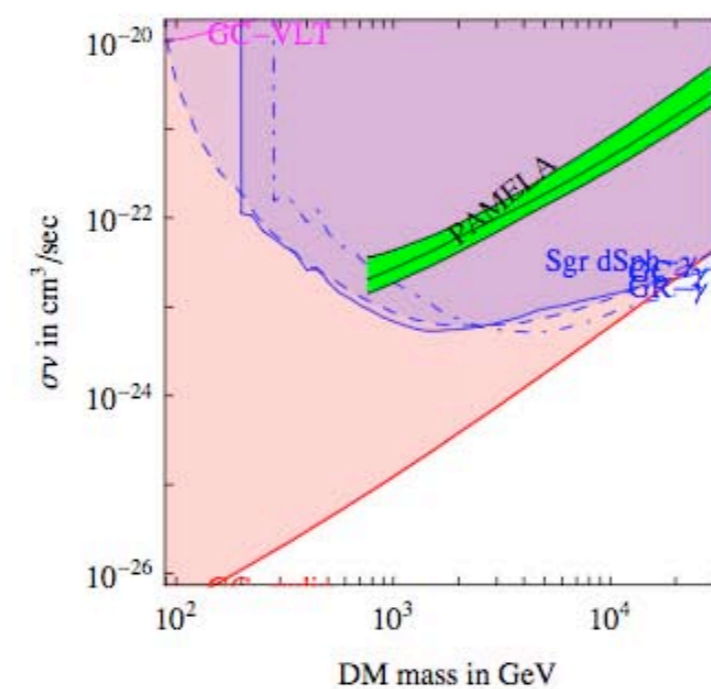
DM DM $\rightarrow \tau^+\tau^-$, NFW profile



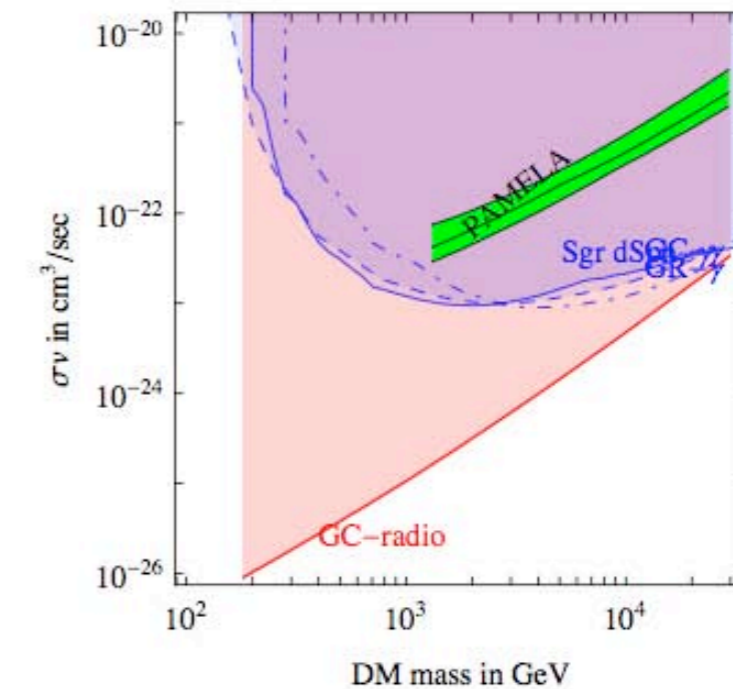
DM DM $\rightarrow W^+W^-$, NFW profile



DM DM $\rightarrow b\bar{b}$, NFW profile

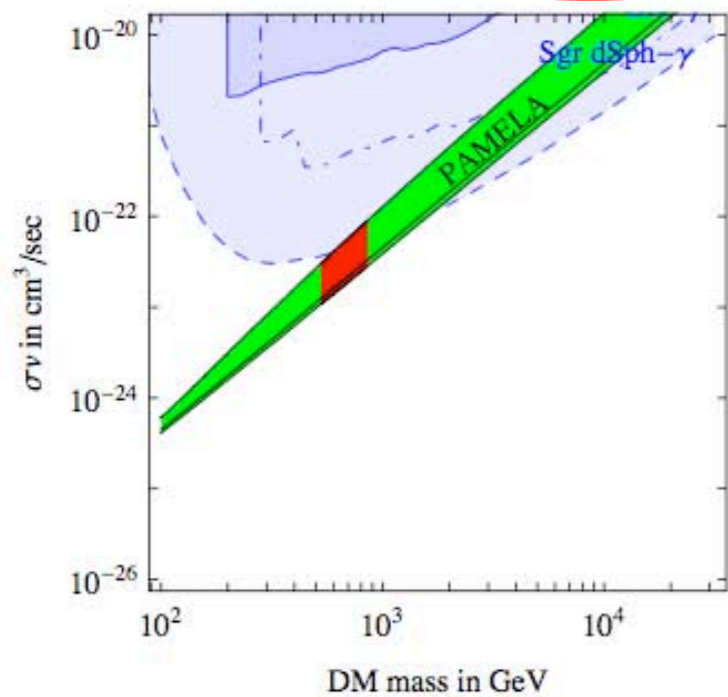


DM DM $\rightarrow t\bar{t}$, NFW profile

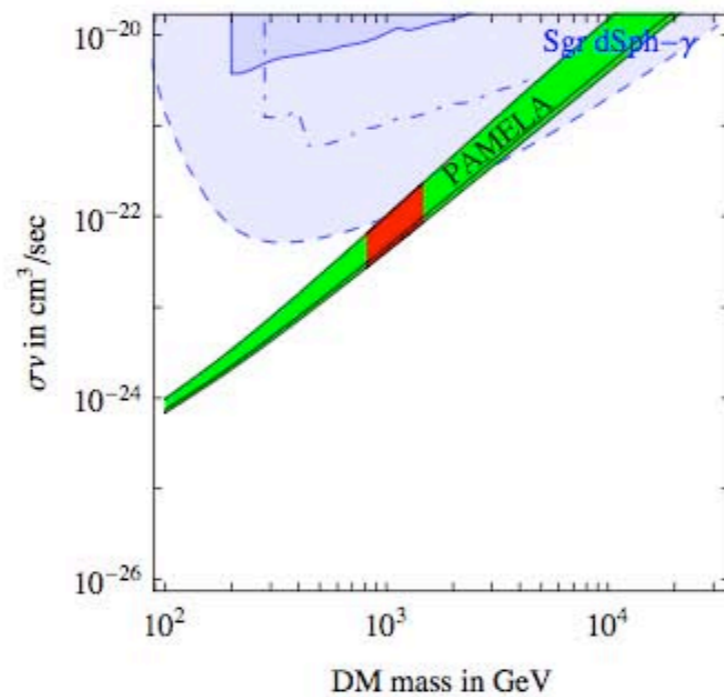


Gamma constraints

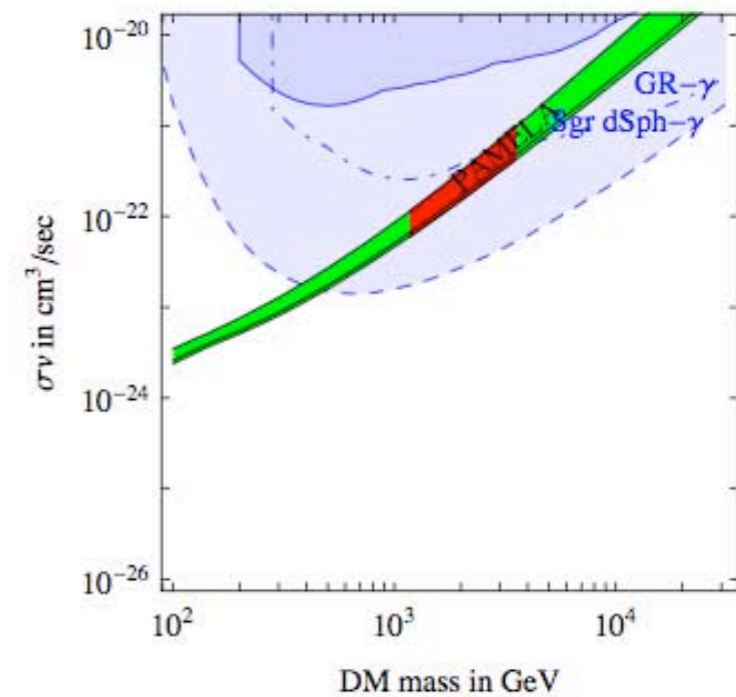
DM DM $\rightarrow e^+e^-$, isothermal profile



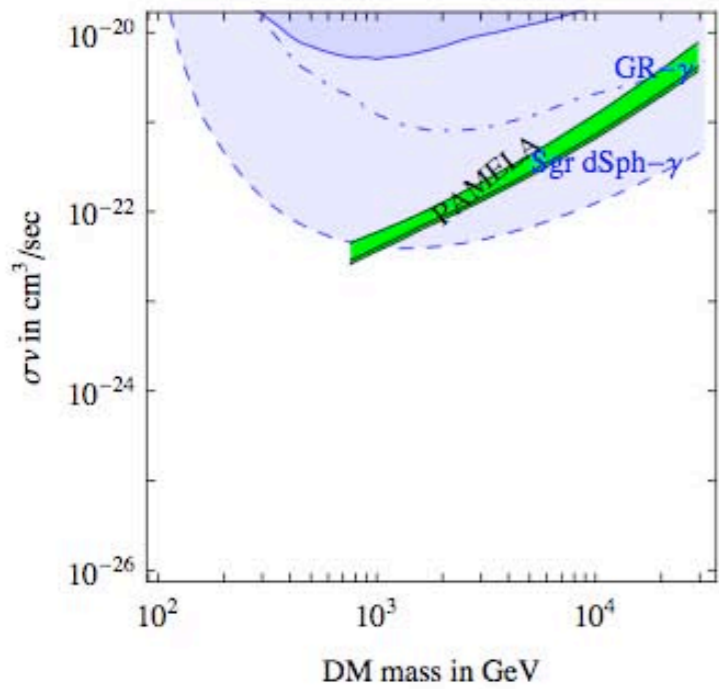
DM DM $\rightarrow \mu^+\mu^-$, isothermal profile



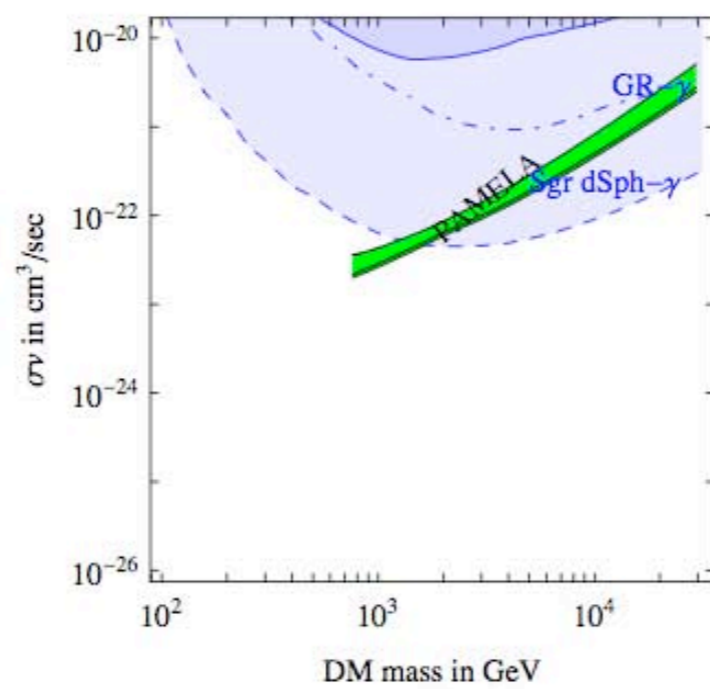
DM DM $\rightarrow \tau^+\tau^-$, isothermal profile



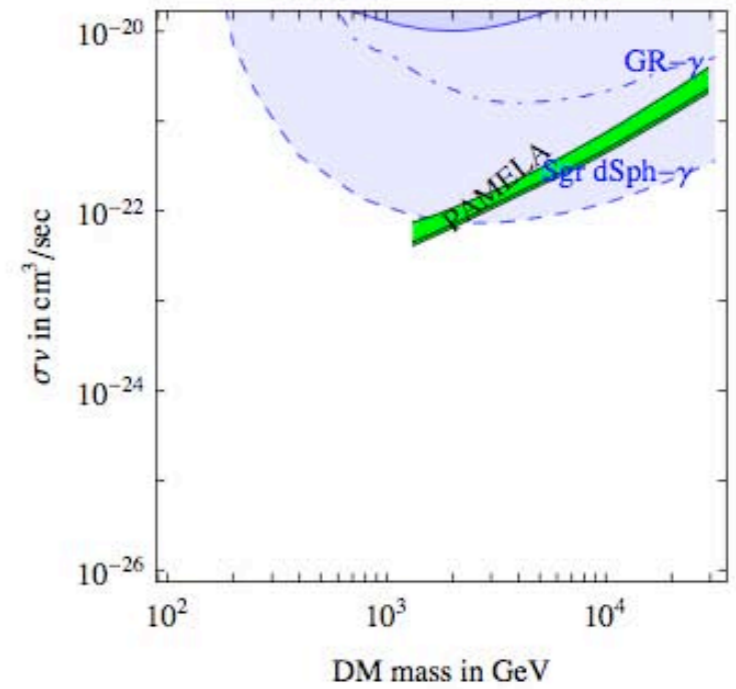
DM DM $\rightarrow W^+W^-$, isothermal profile



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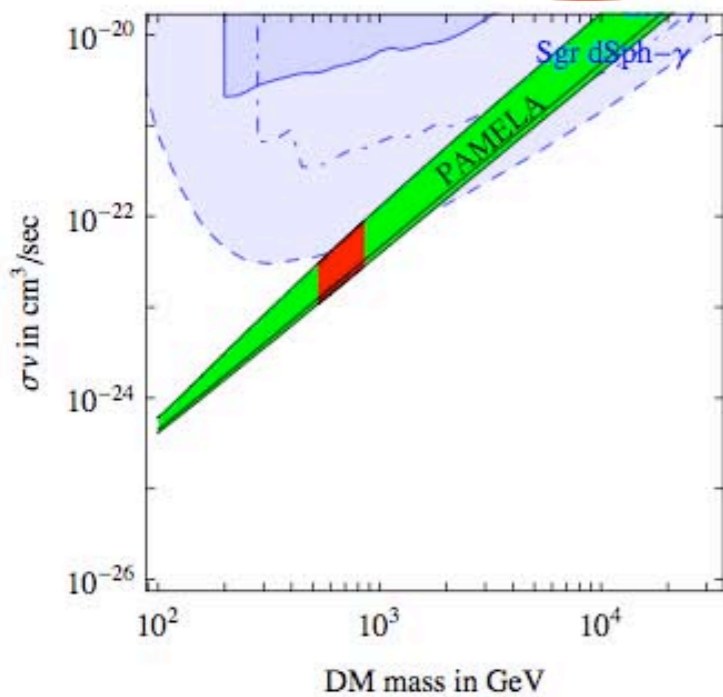
DM DM $\rightarrow t\bar{t}$, isothermal profile



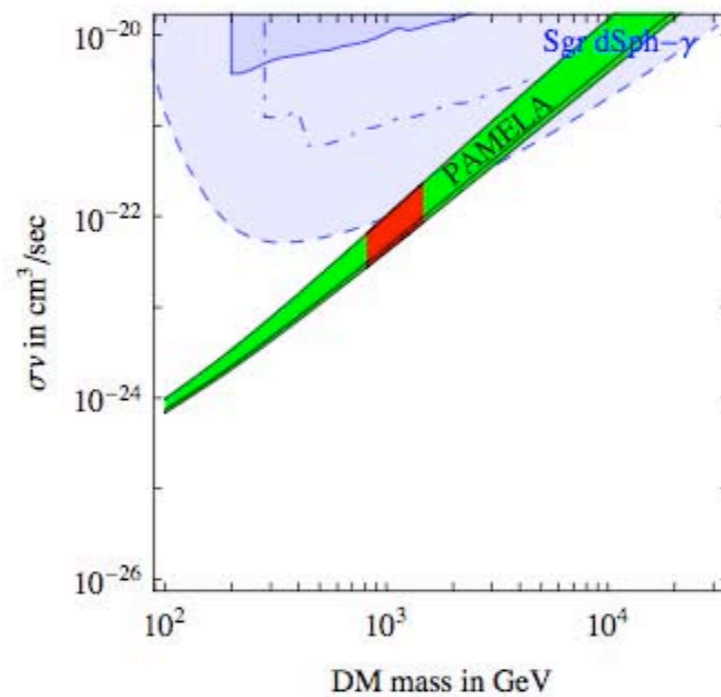
...not-too-steep profile needed.

Gamma constraints

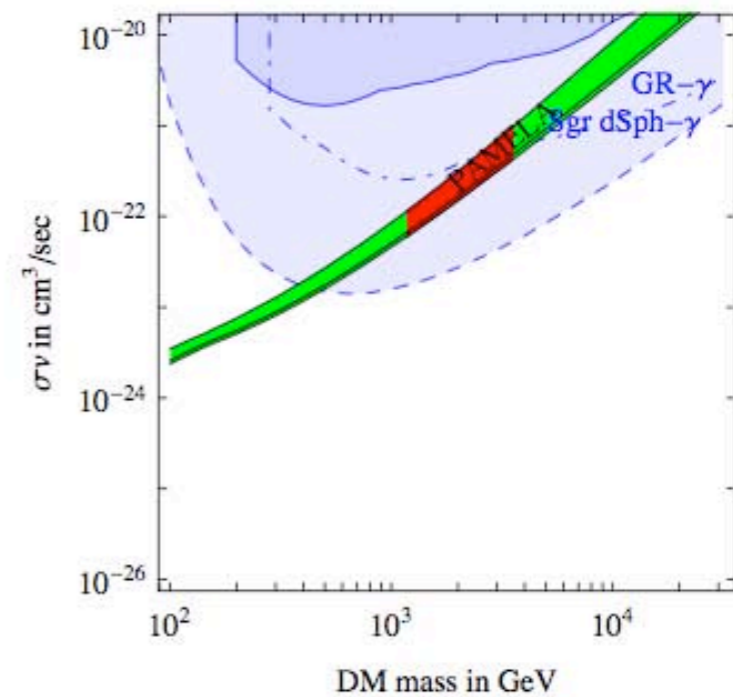
DM DM $\rightarrow e^+e^-$, isothermal profile



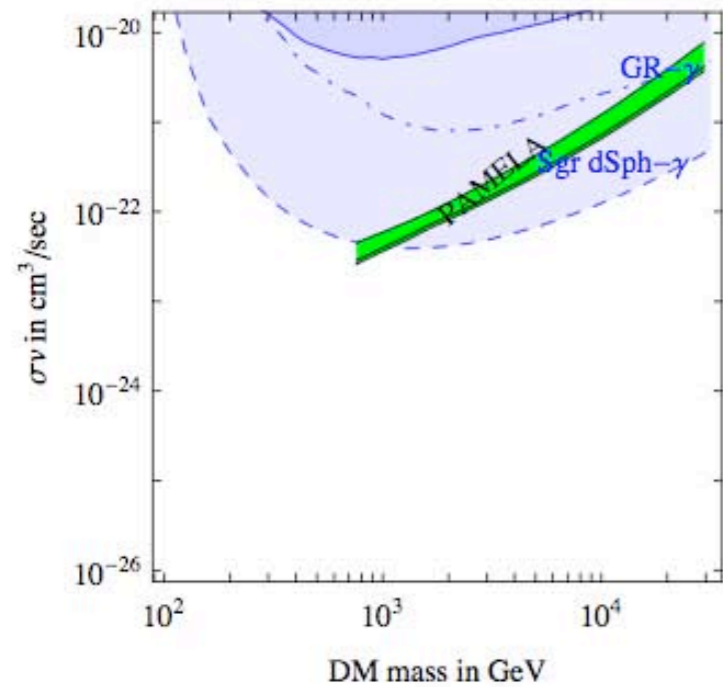
DM DM $\rightarrow \mu^+\mu^-$, isothermal profile



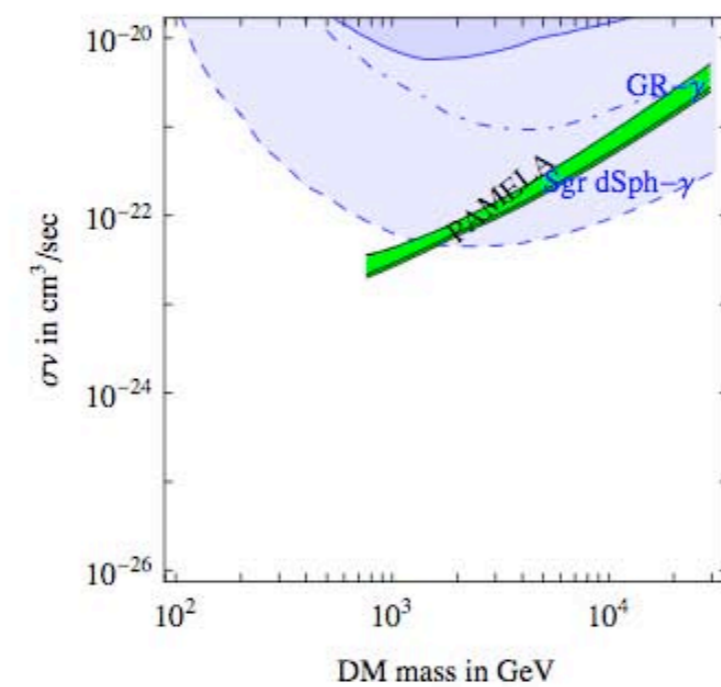
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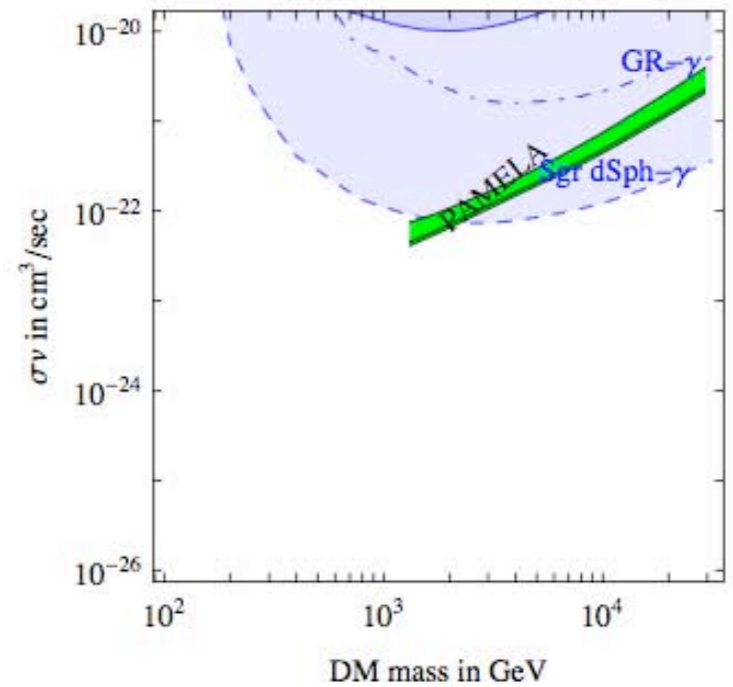
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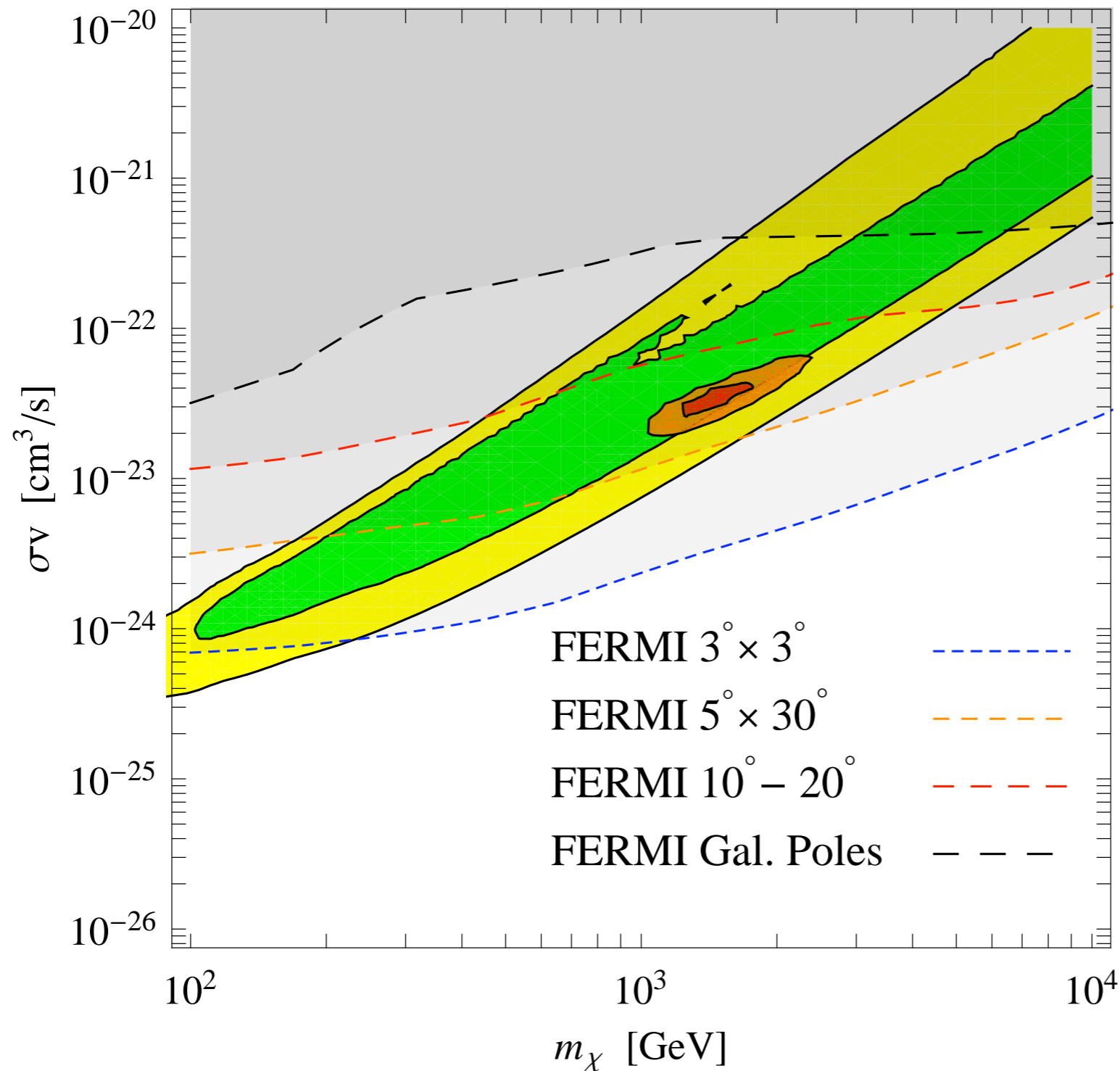
...not-too-steep profile needed.

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

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

Inverse Compton γ constraints

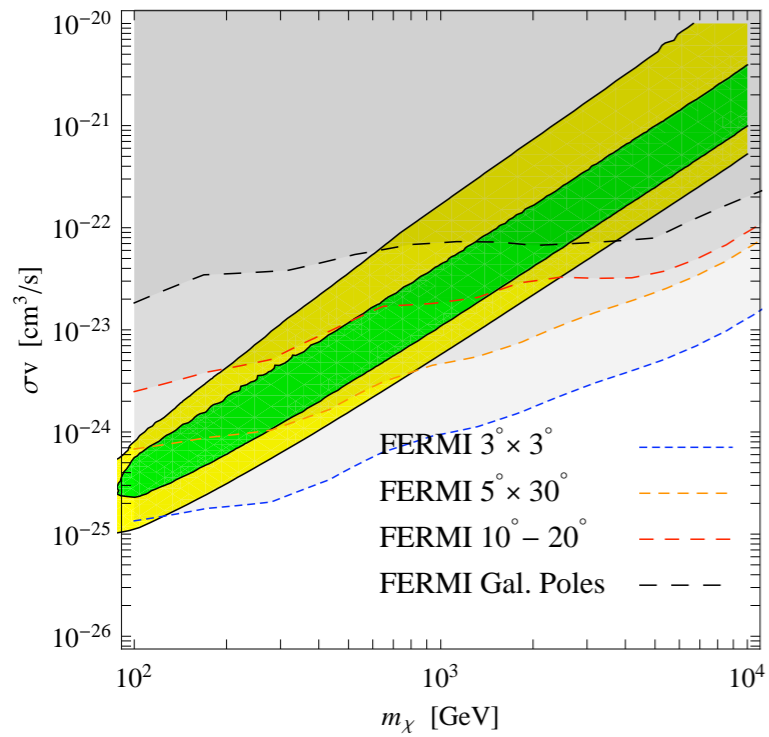
DM DM $\rightarrow \mu\mu$, Einasto profile



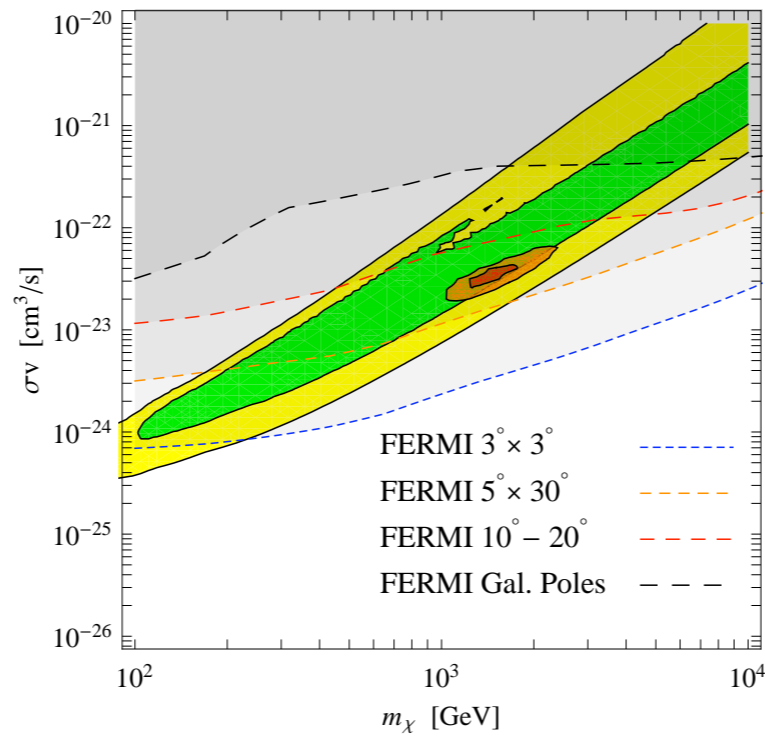
The PAMELA and ATIC regions are in **conflict** with these gamma constraints, and here...

Inverse Compton γ constraints

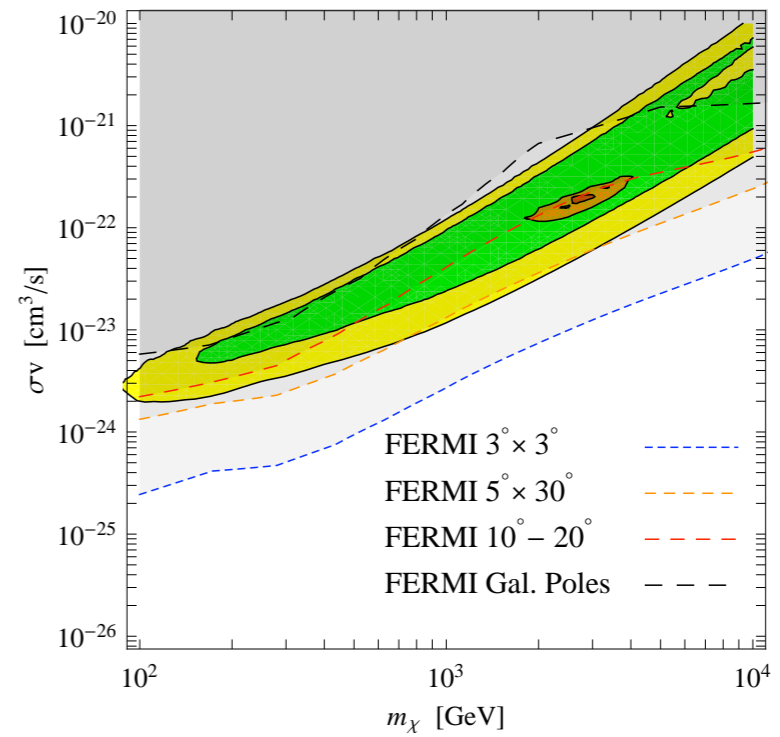
DM DM $\rightarrow e\bar{e}$, Einasto profile



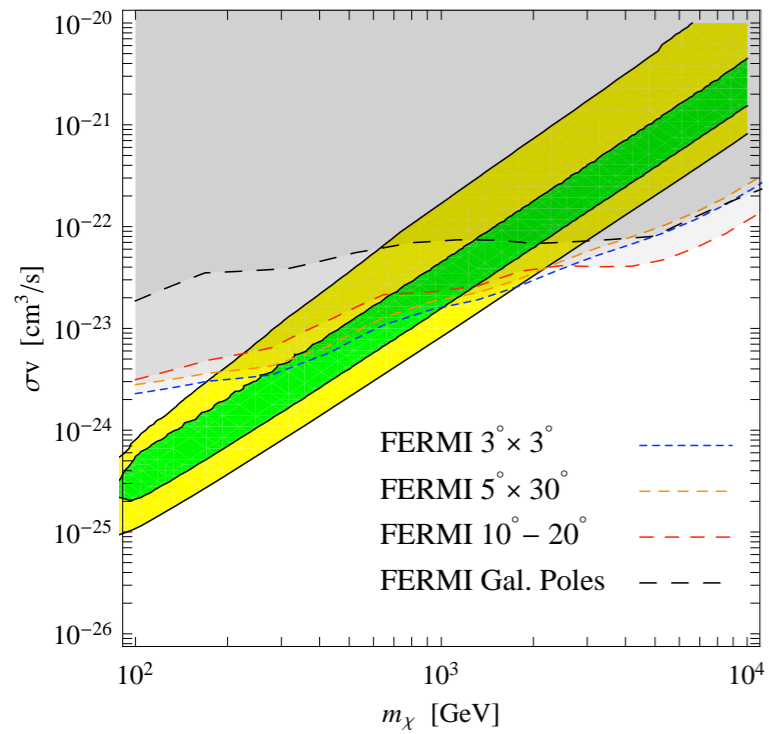
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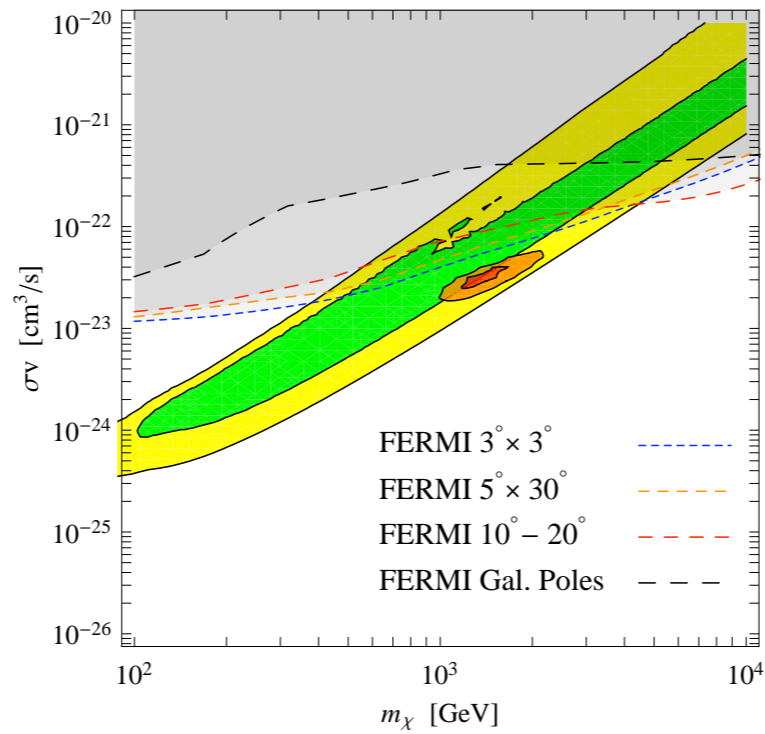
DM DM $\rightarrow \tau\tau$, Einasto profile



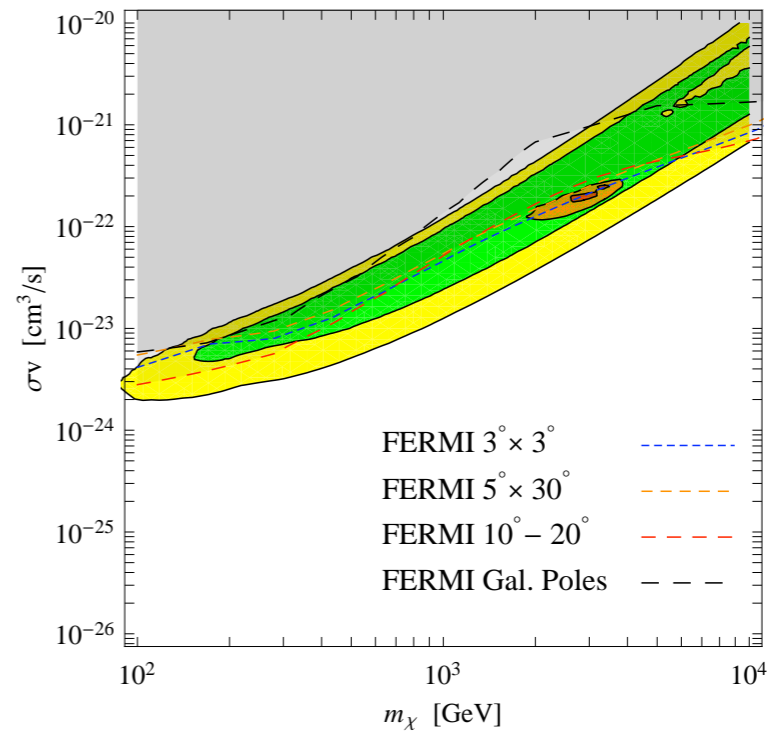
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Model building

- 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: Pyrra 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

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- TeV mass DM

- new forces (that Sommerfeld enhance)

- leptophilic because: - kinematics (light mediator)

- DM carries lepton #

- 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

The “Theory of DM”

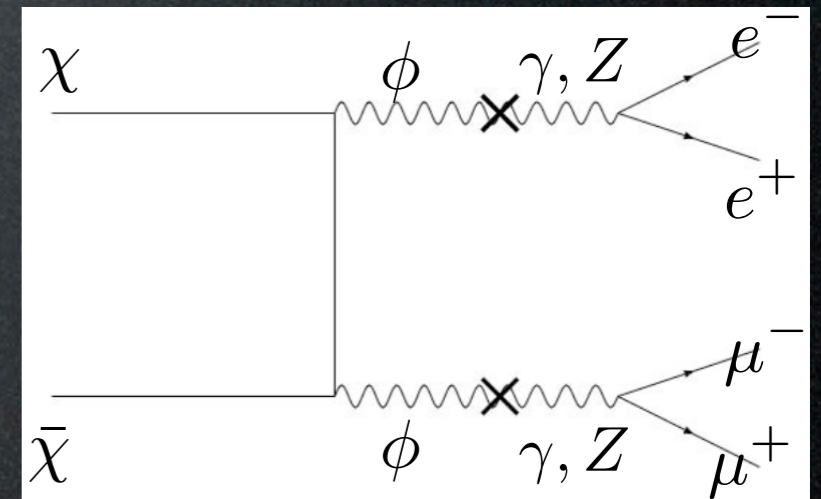
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

- χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV
- ϕ new gauge boson (“Dark photon”),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:

$$\alpha M/m_V \gtrsim 1 \quad \text{fulfilled}$$

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



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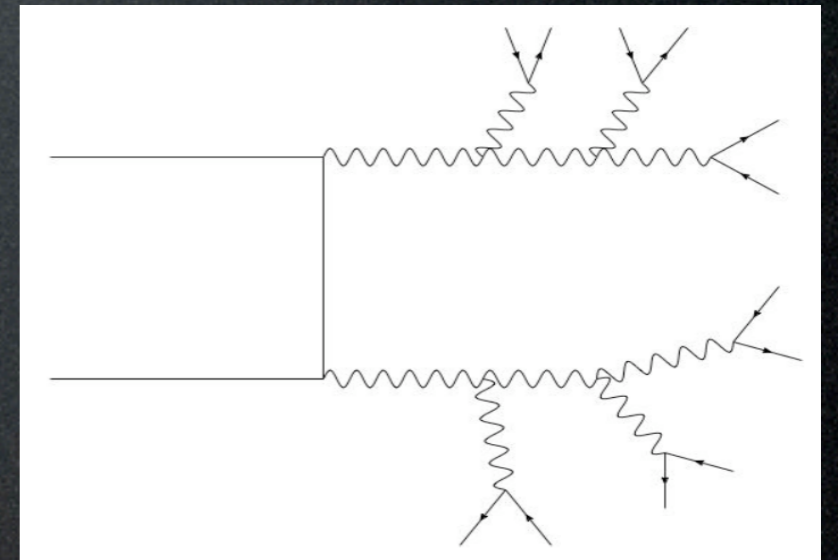
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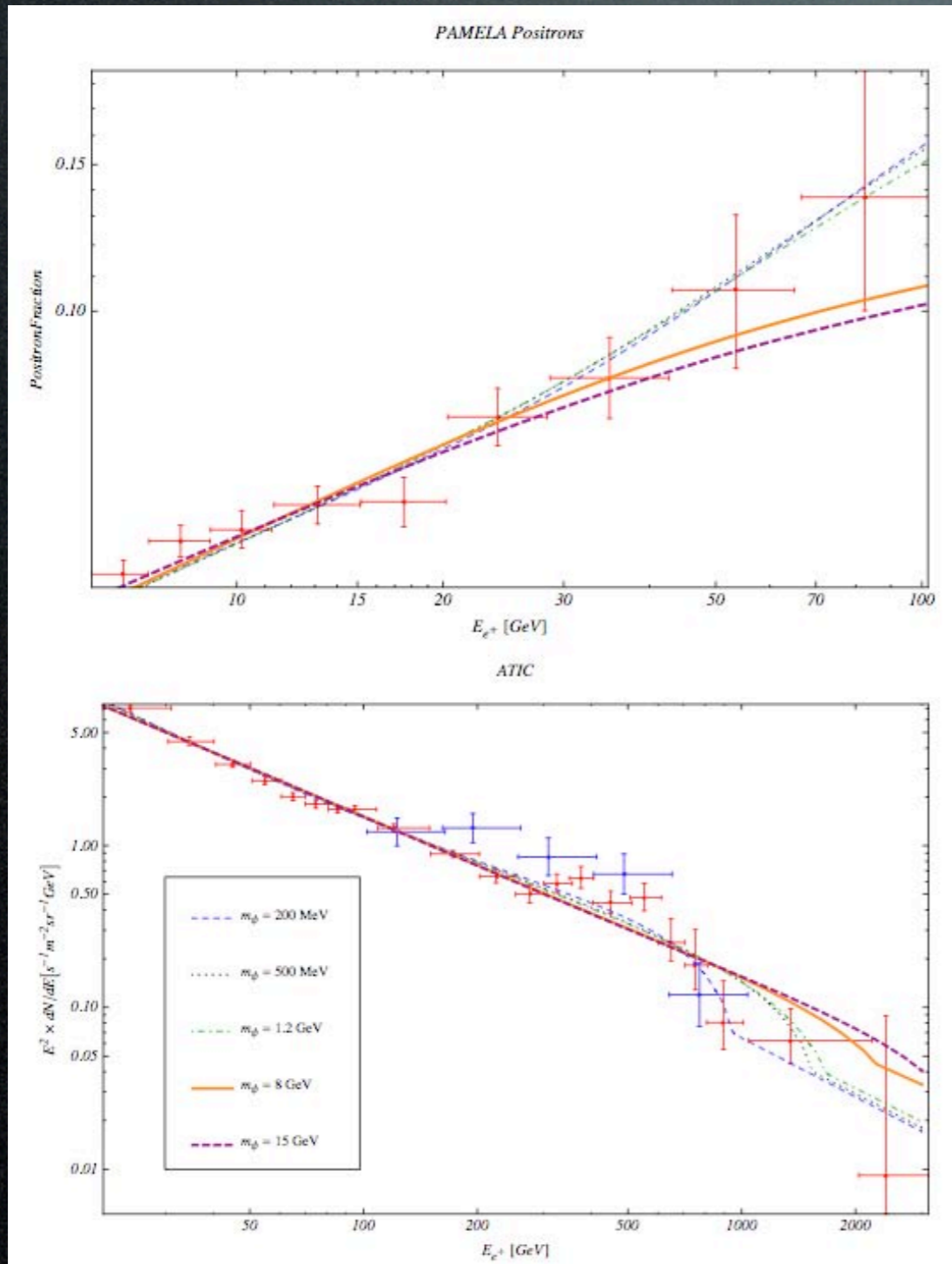


Extras:

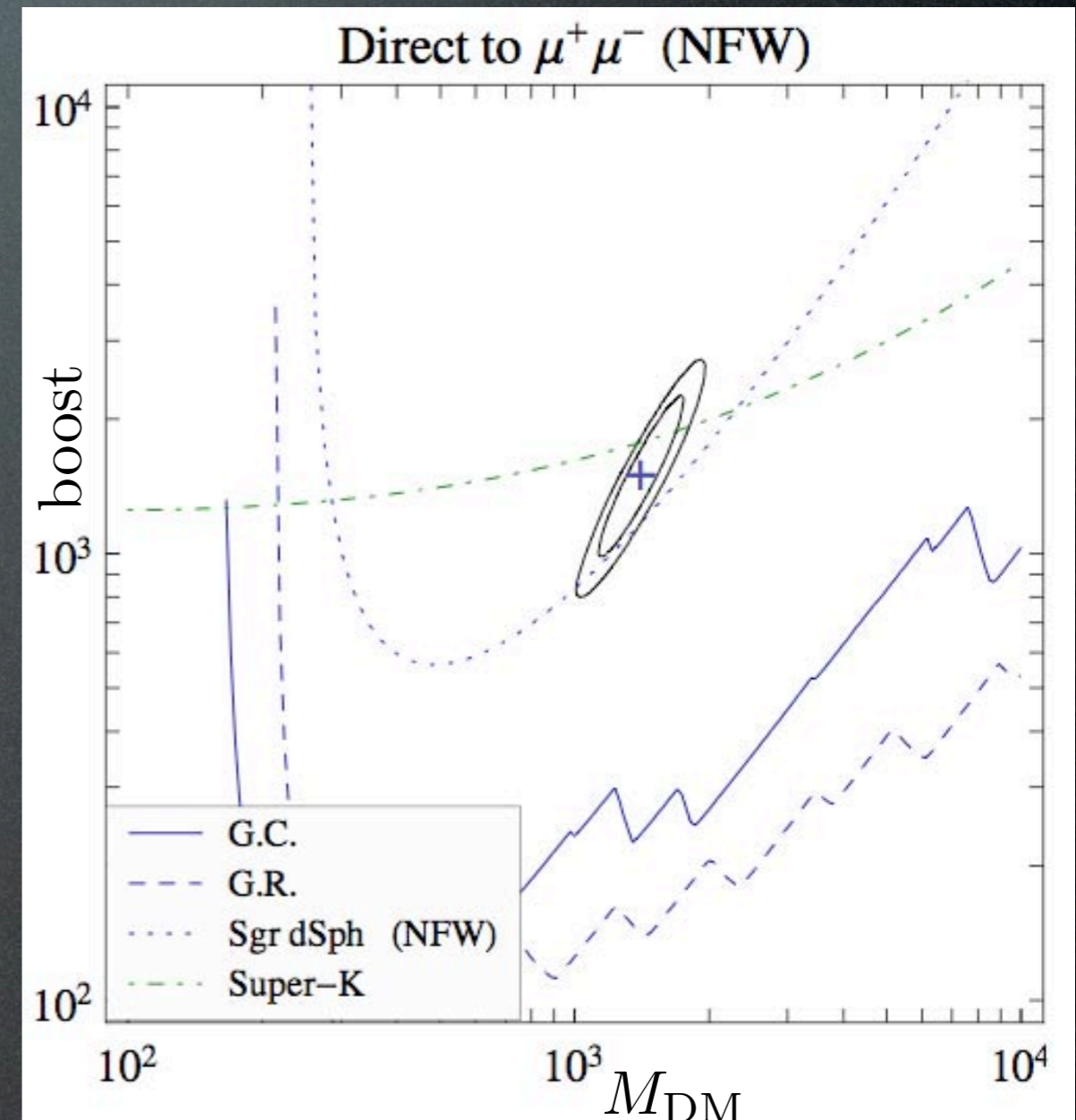
- χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- excited state decay $\chi\chi \rightarrow \chi\chi^* \hookrightarrow e^+e^-$ explains INTEGRAL

The “Theory of DM”

Phenomenology:



Meade, Papucci, Volanski
0901.2925



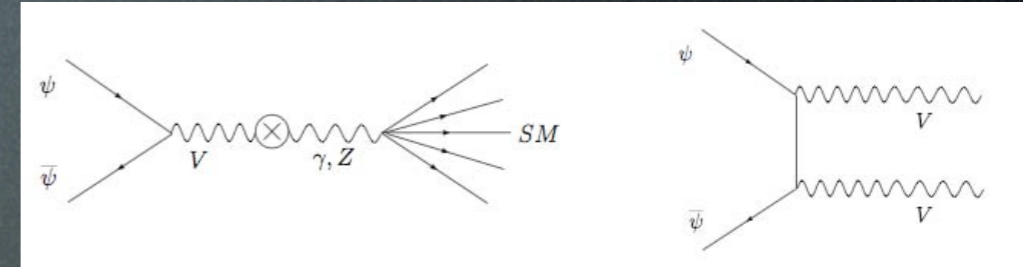
Mardon, Nomura, Stolarski,
Thaler 0901.2926

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

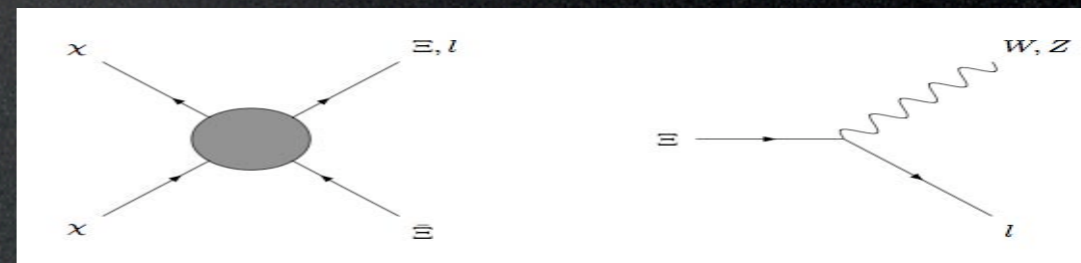
- ★ DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson ($m_\phi \sim$ tens GeV)

Cirelli, Kadastik, Raidal, Strumia 0809.2409

Fox, Poppitz 0811.0399

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

Phalen, Pierce, Weiner 0901.3165



- ★

DM detection

direct detection

Xenon, CDMS, Edelweiss, Dama/Libra?

production at colliders

LHC

indirect

γ from annihil in galactic halo or center
(line + continuum)

Fermi

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

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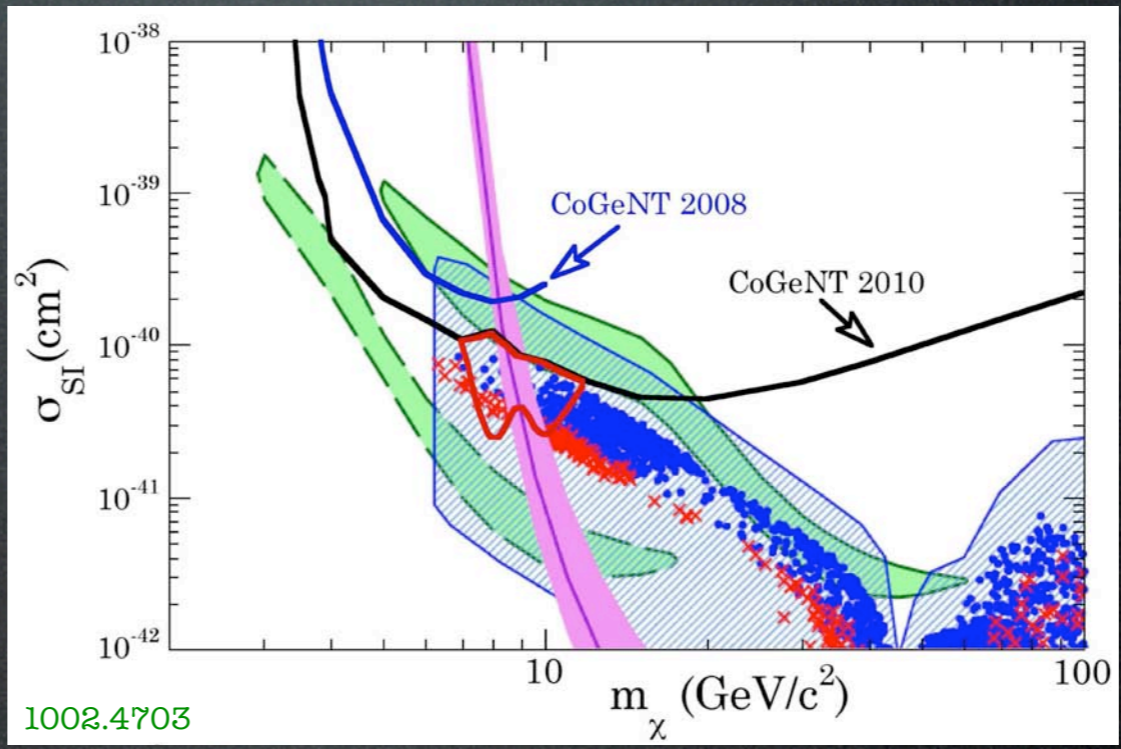
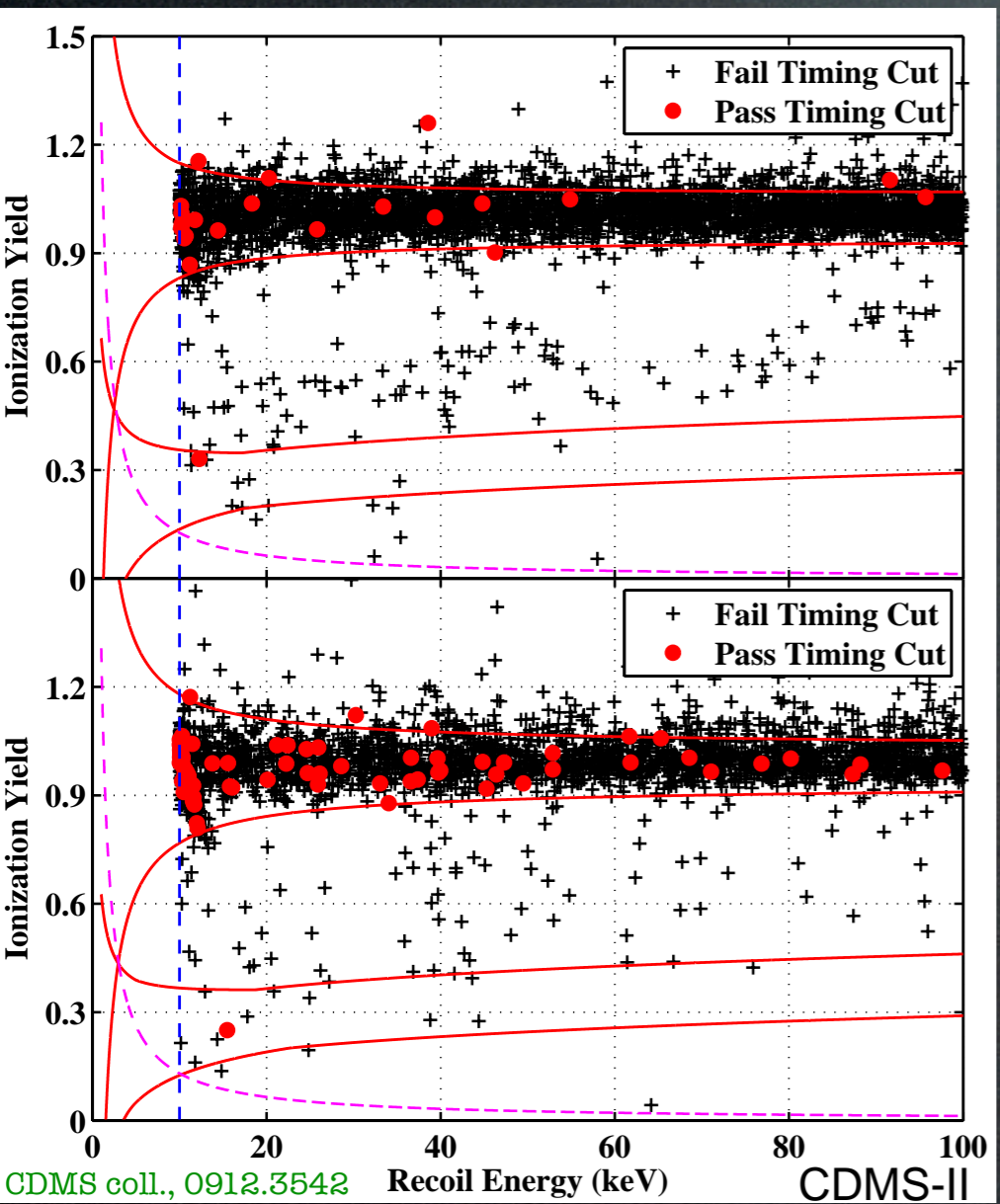
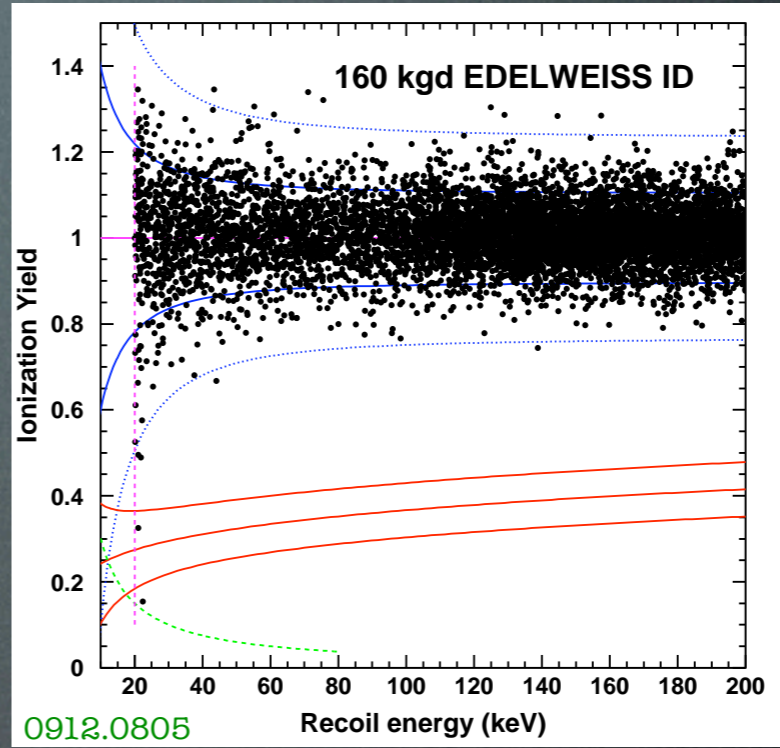
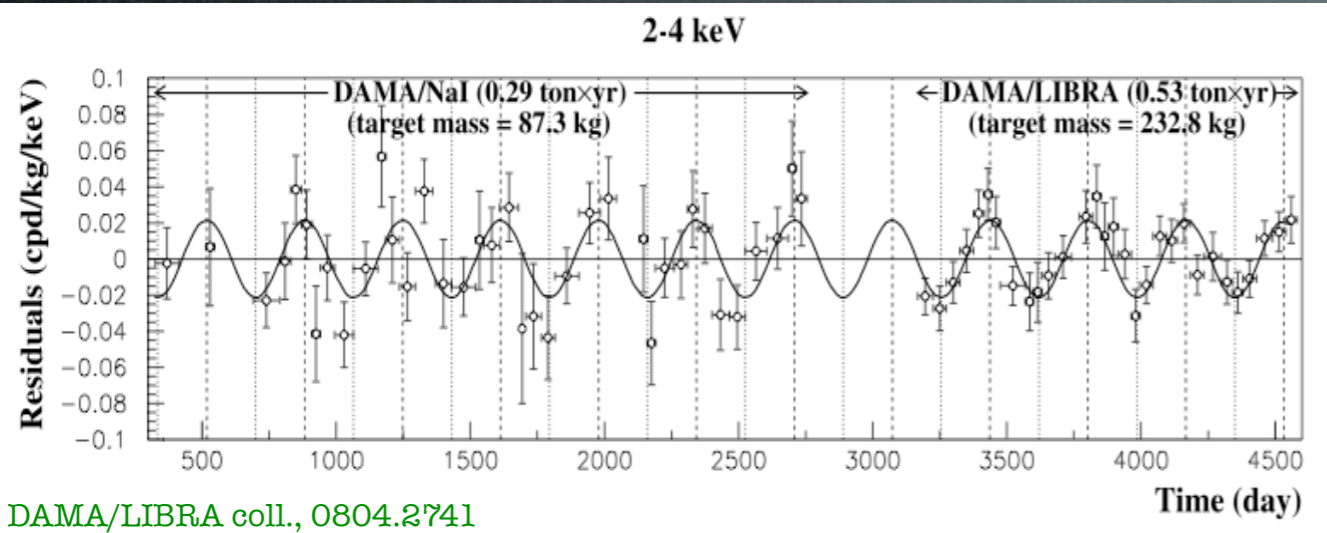
\bar{D} from annihil in galactic halo or center

GAPS

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

Icecube, Km³Net

DM direct detection?



We lack a satisfactory explanation [...]. It is tempting to consider a cosmological origin [...]. Prudence and past experience prompt us to continue work to exhaust less exotic possibilities.

CoGeNT coll., 1002.4703

'Answers'

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

Why?

What has the eruption left?

'Answers'

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Because the *data* (PAMELA, ATIC, HESS, FERMI, (CDMS?)...)

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- DM is very **heavy** (or very light?)
- annihilates **into leptons** and not anti-protons
- huge cross section (**boost? Sommerfeld?**)
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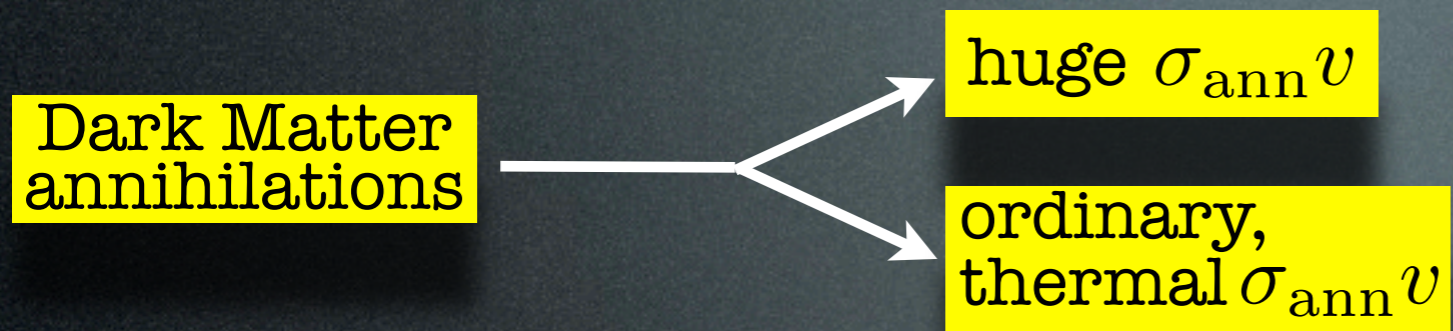
Hints.

And open-mindedness.

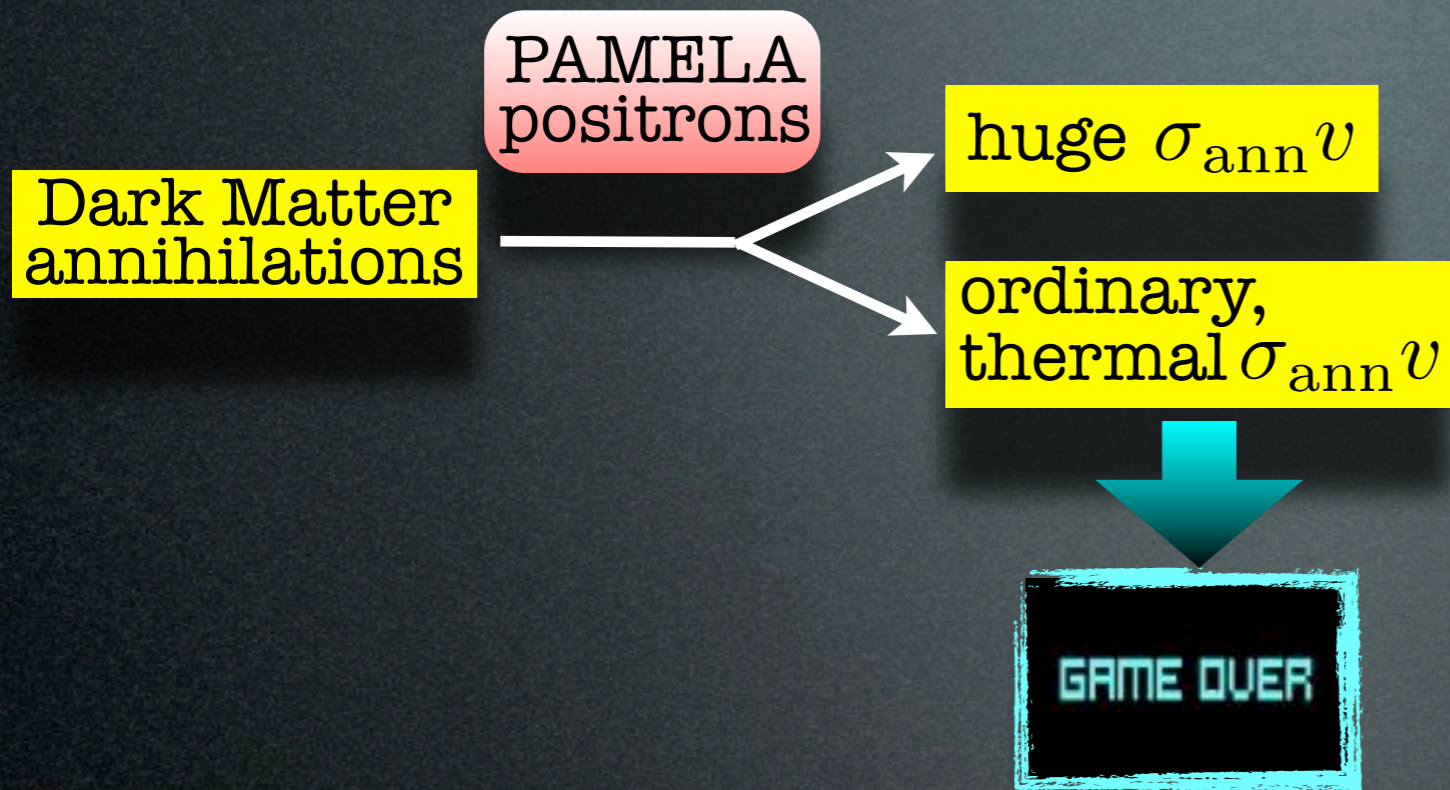
DM annihilations: the game

Dark Matter
annihilations

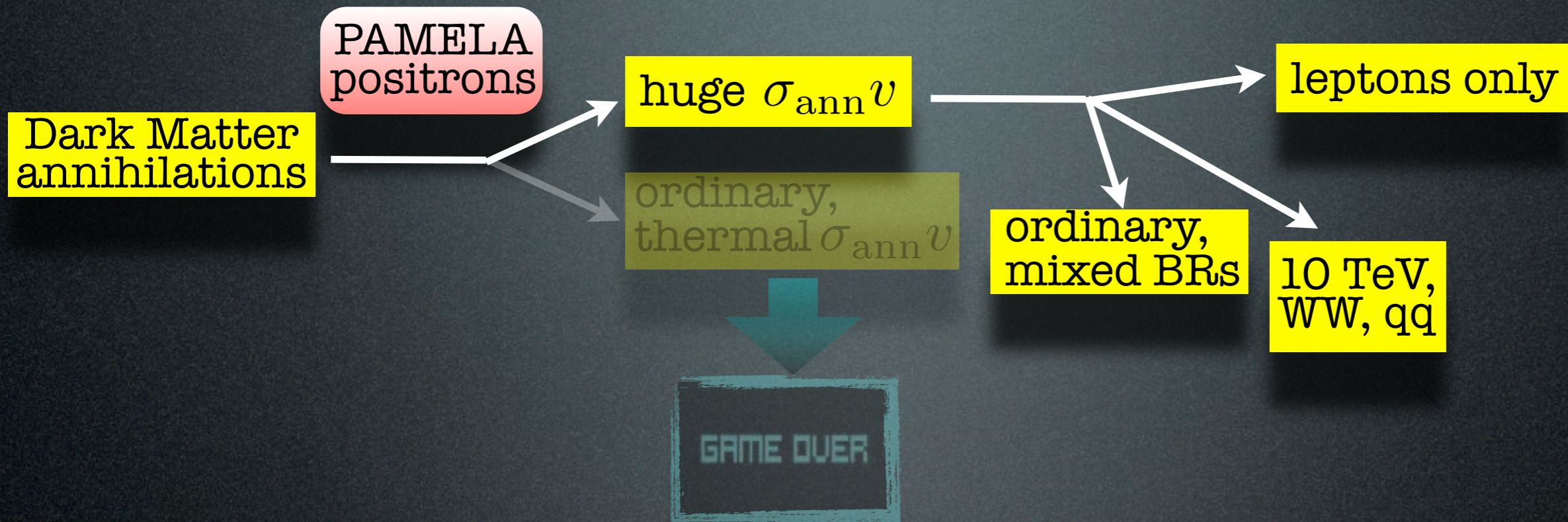
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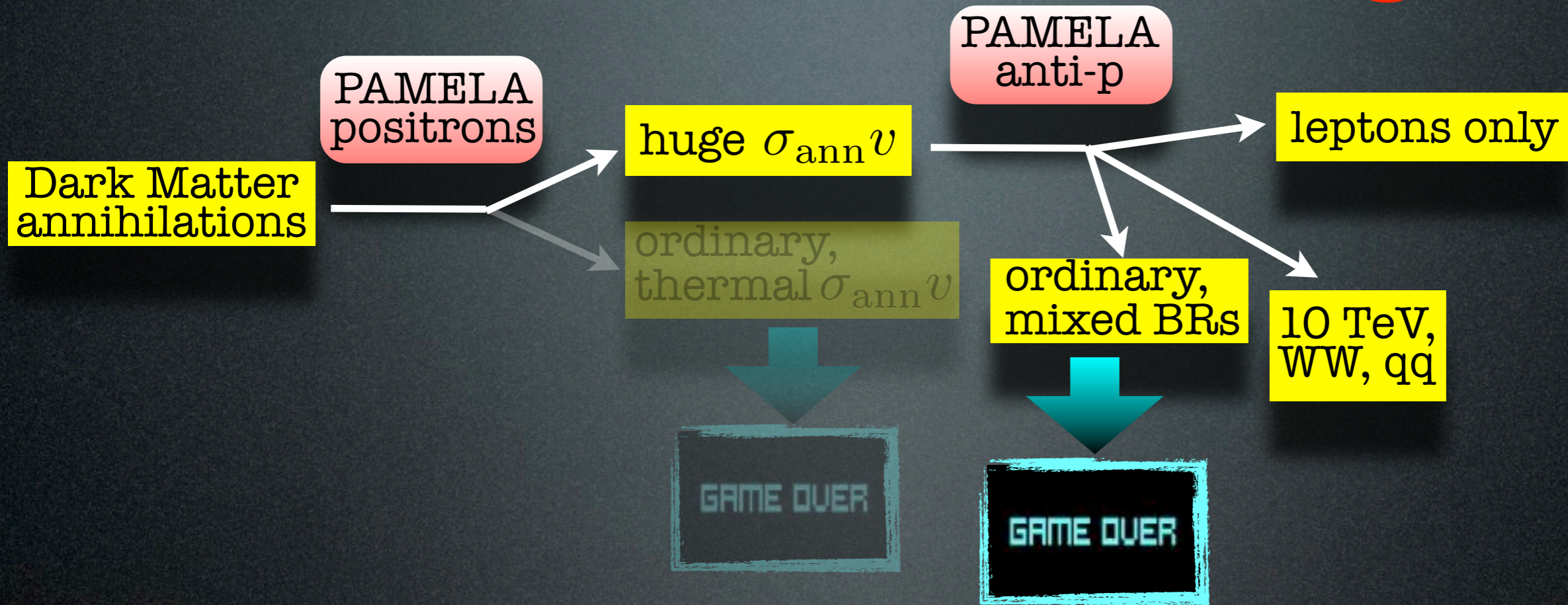
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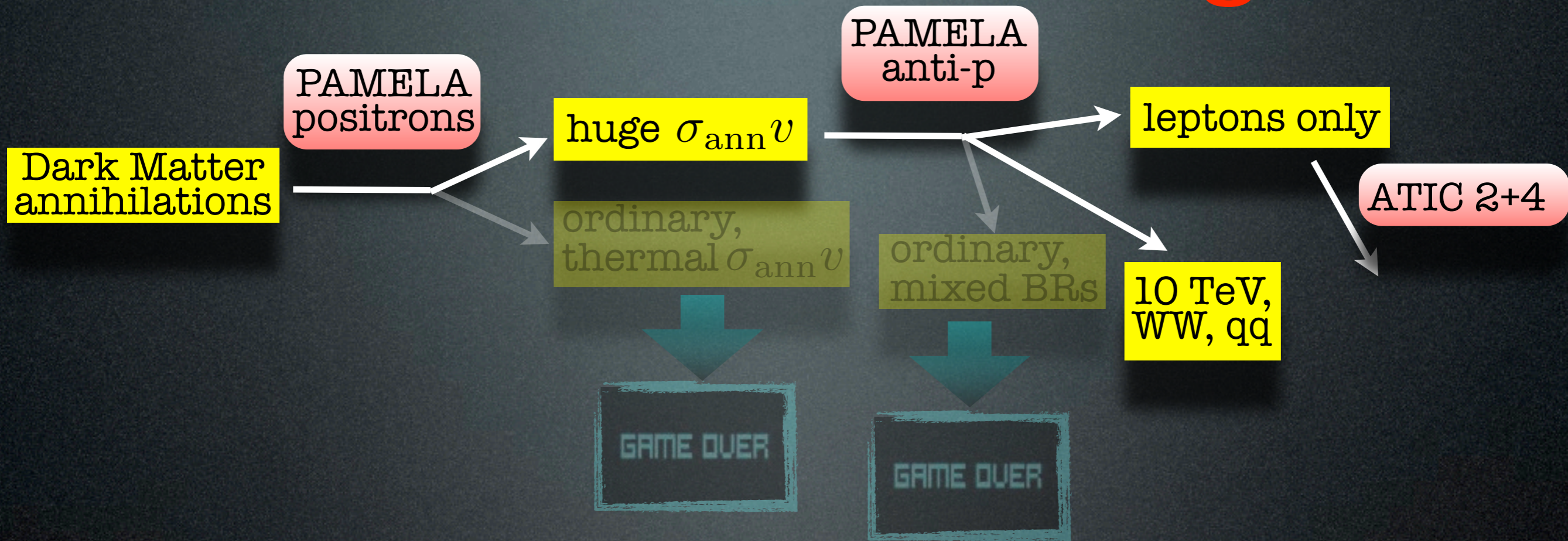
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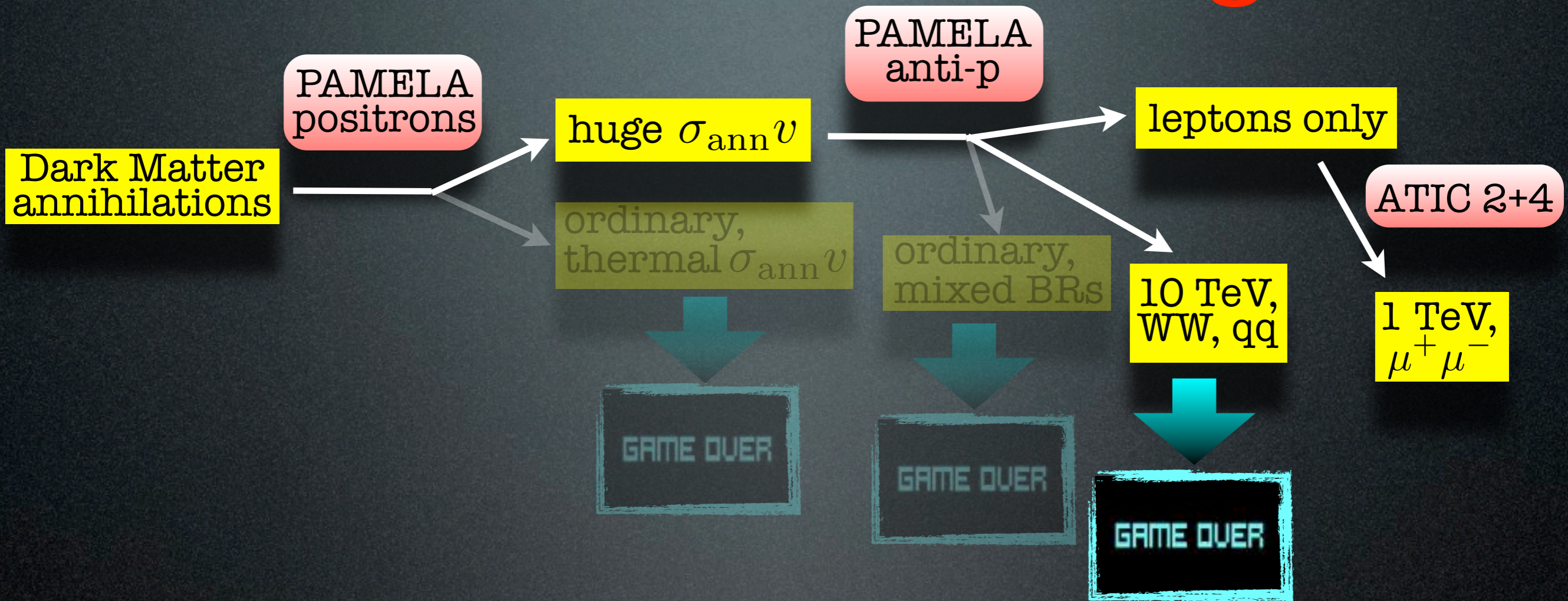
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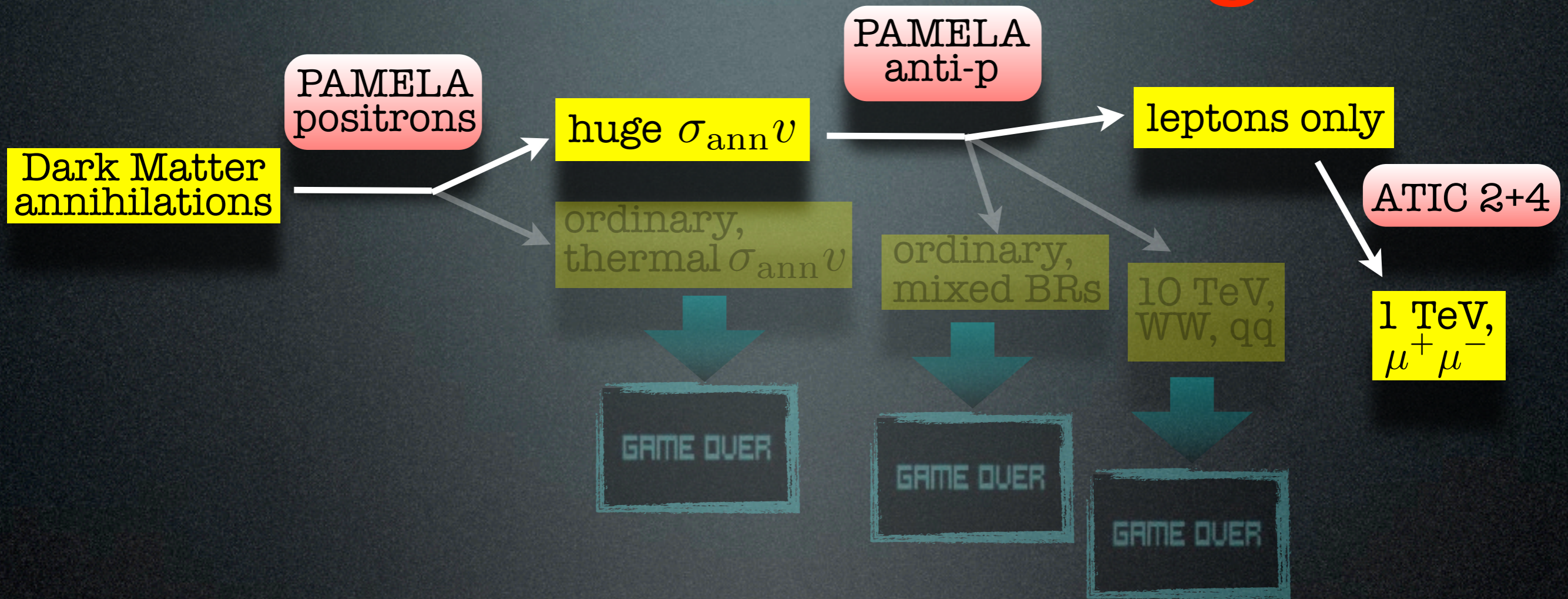
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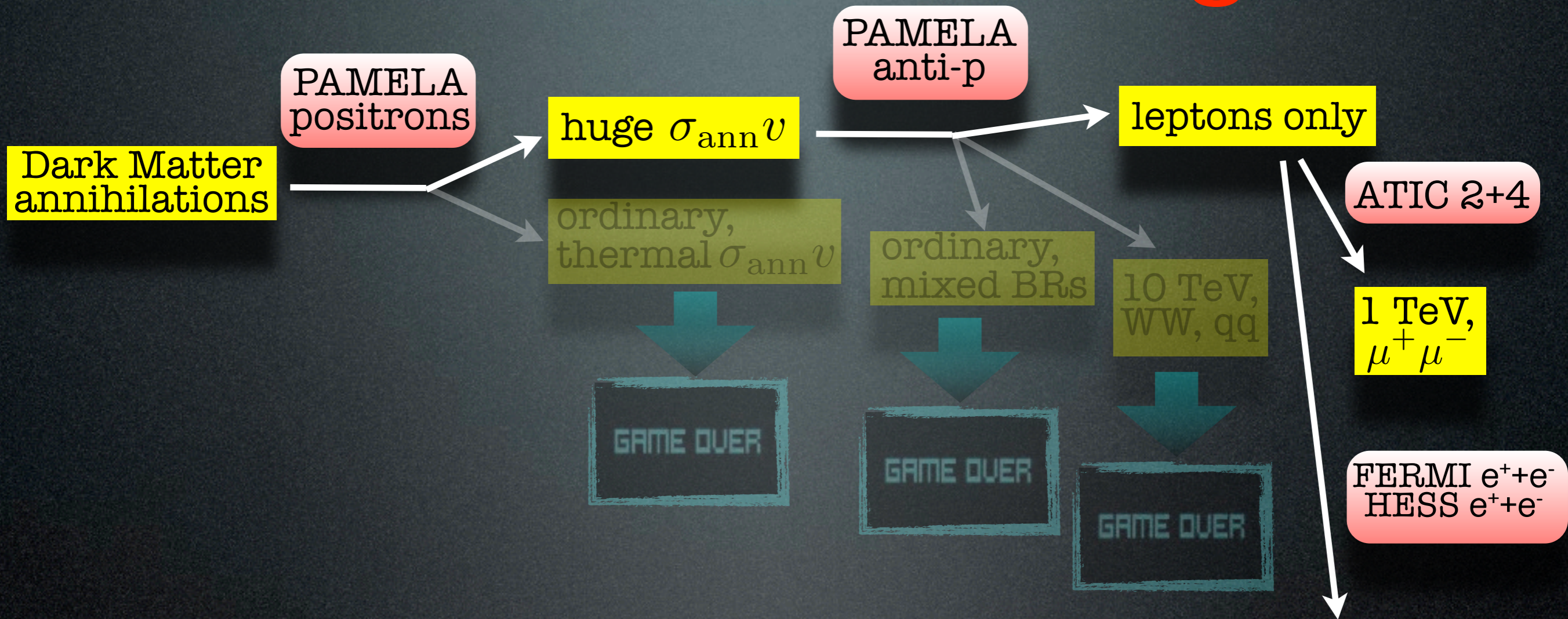
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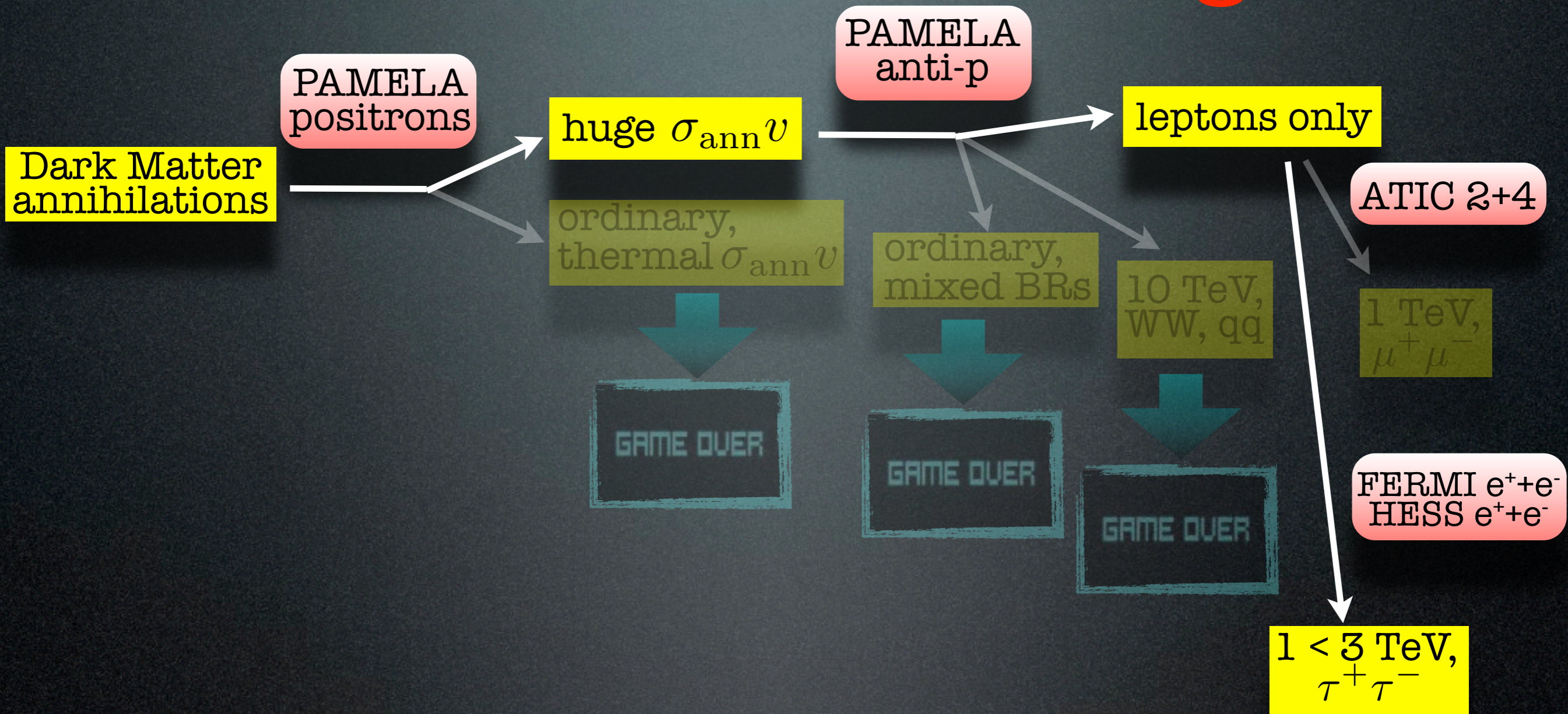
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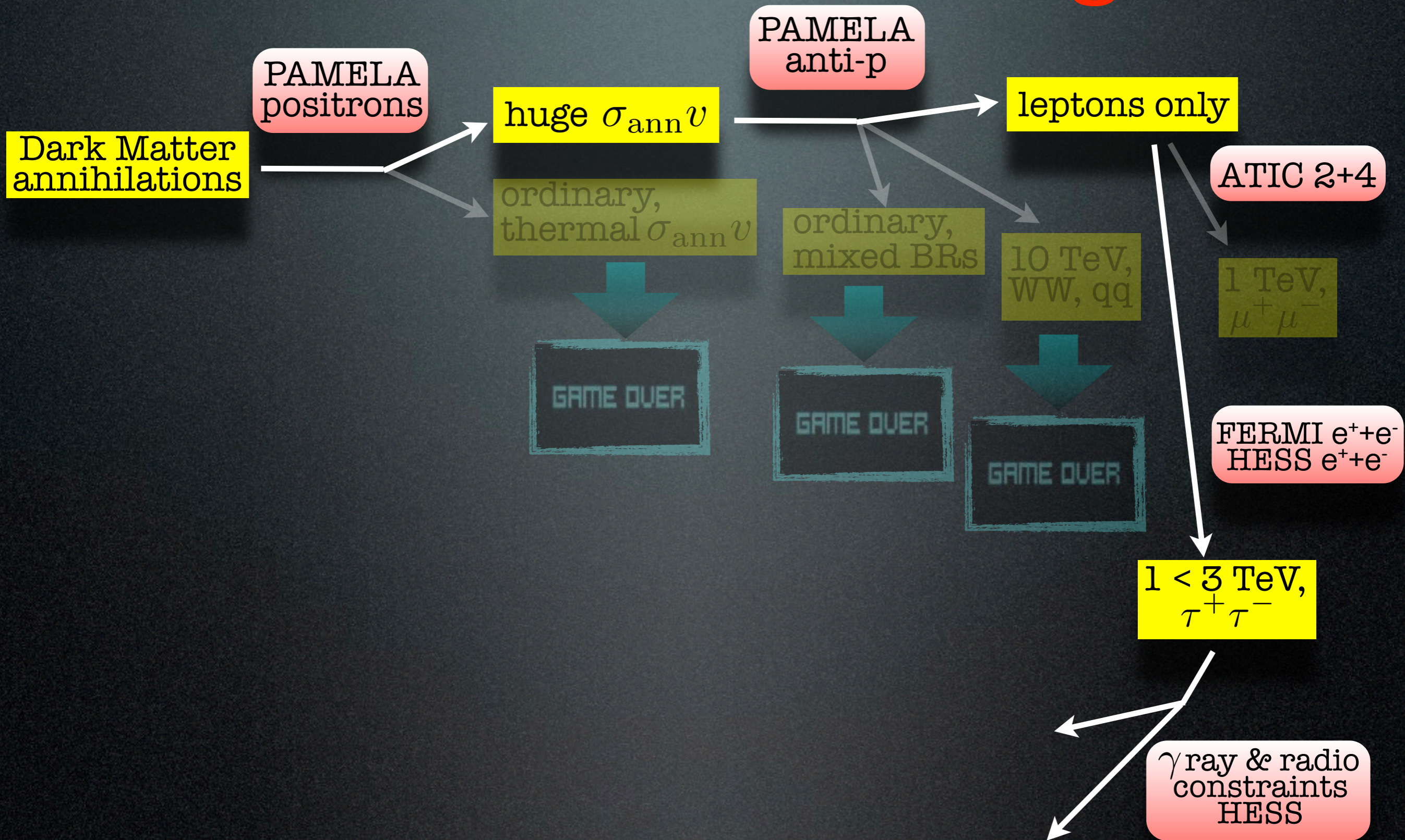
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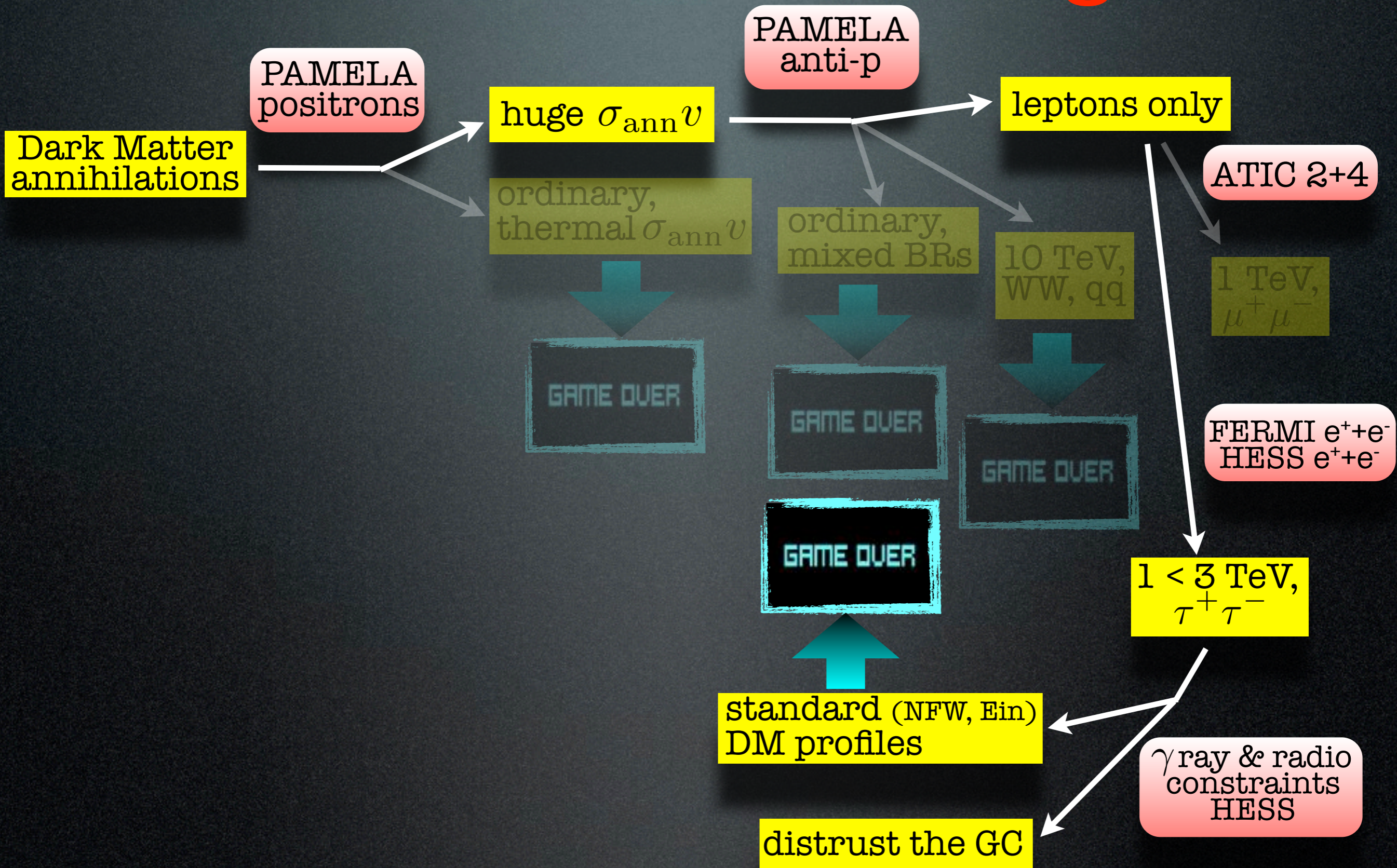
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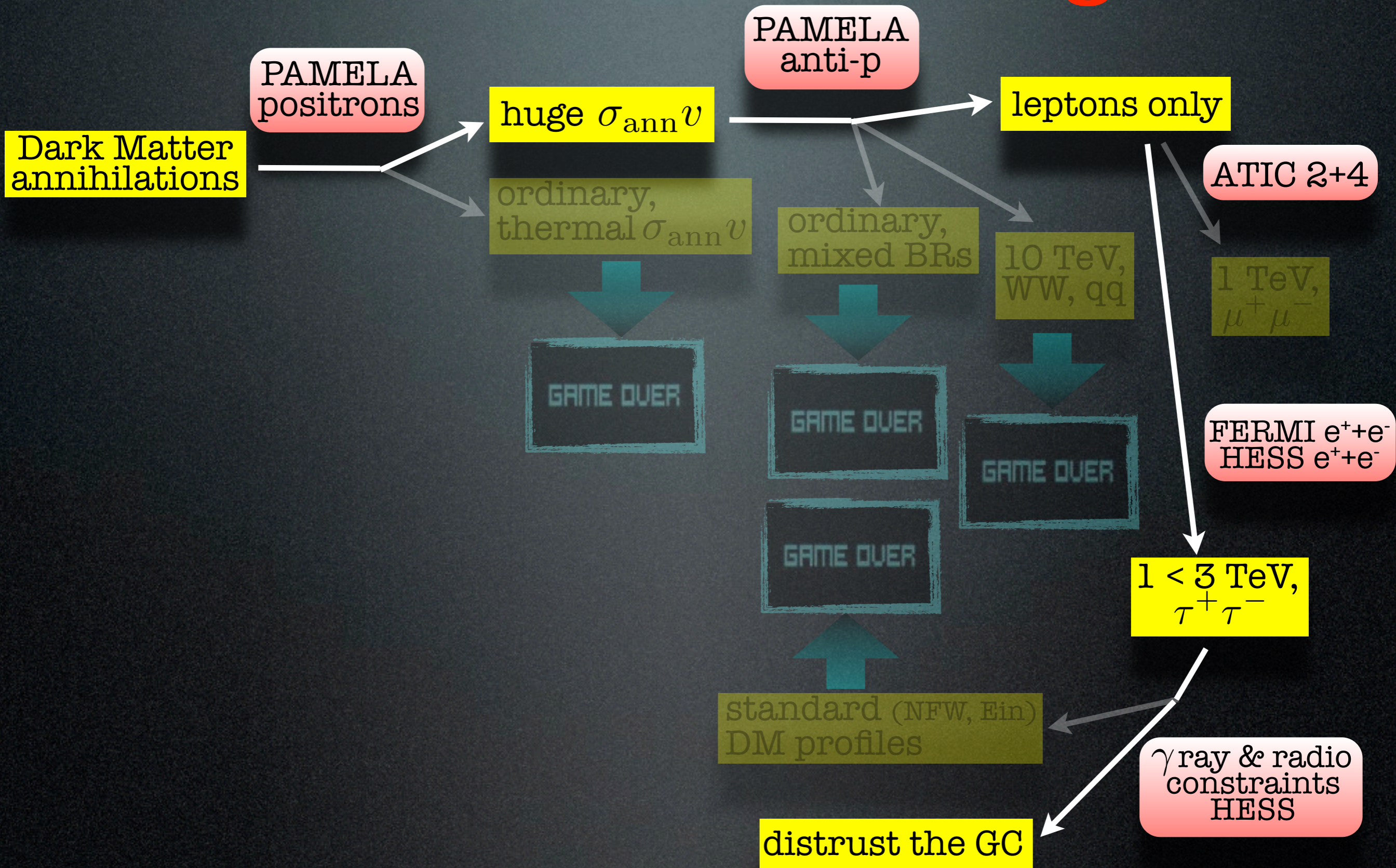
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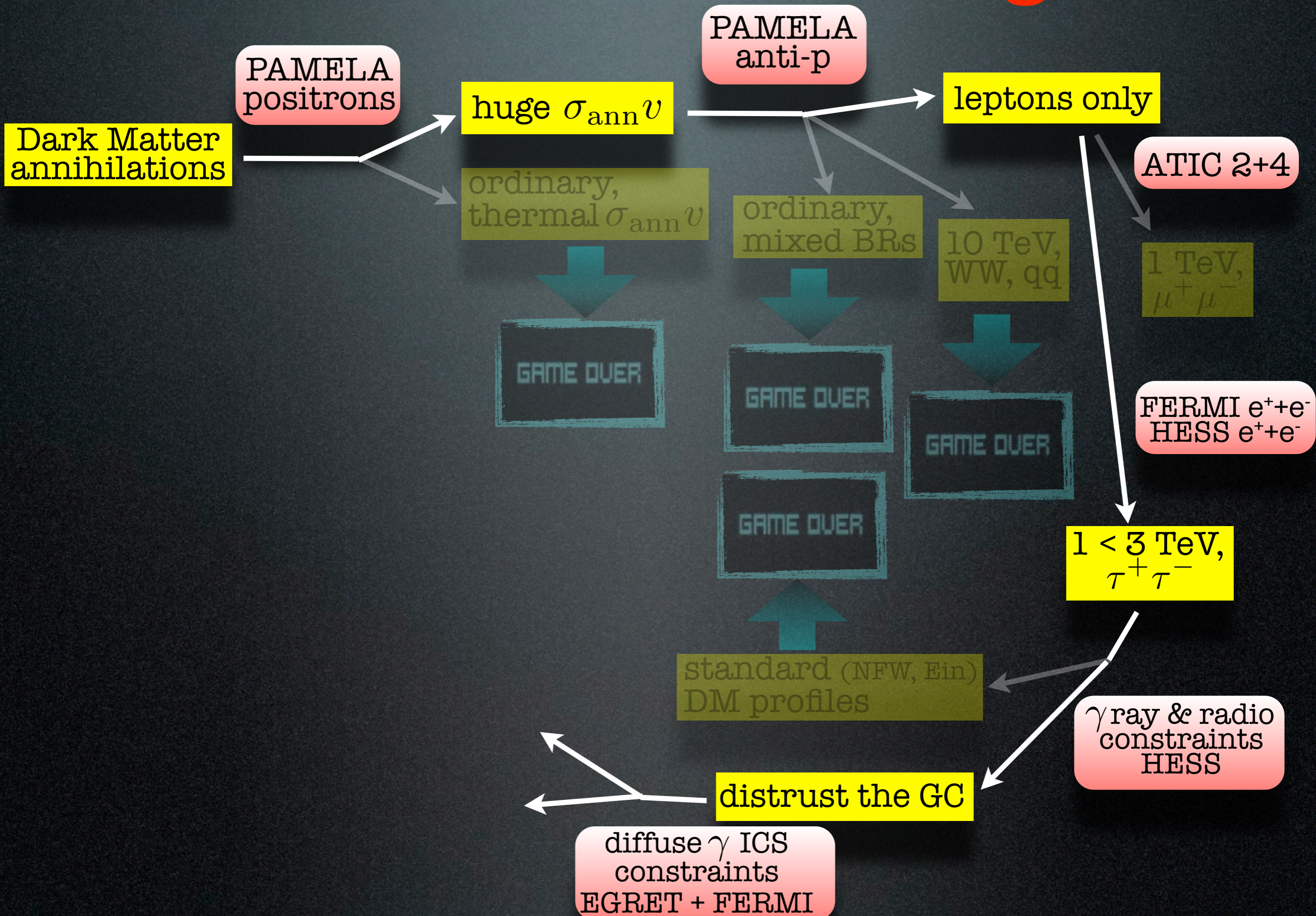
DM annihilations: the game



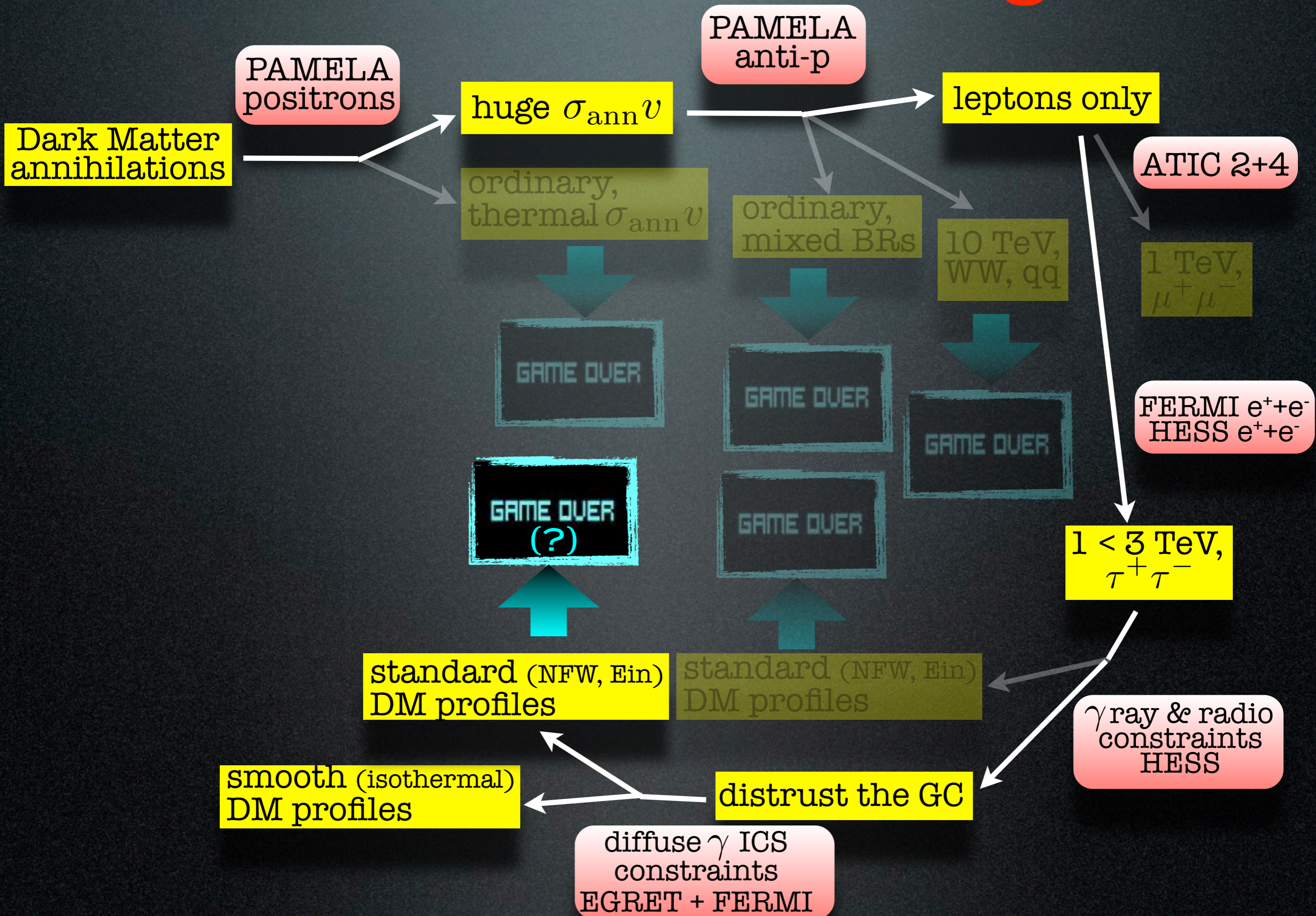
DM annihilations: the game



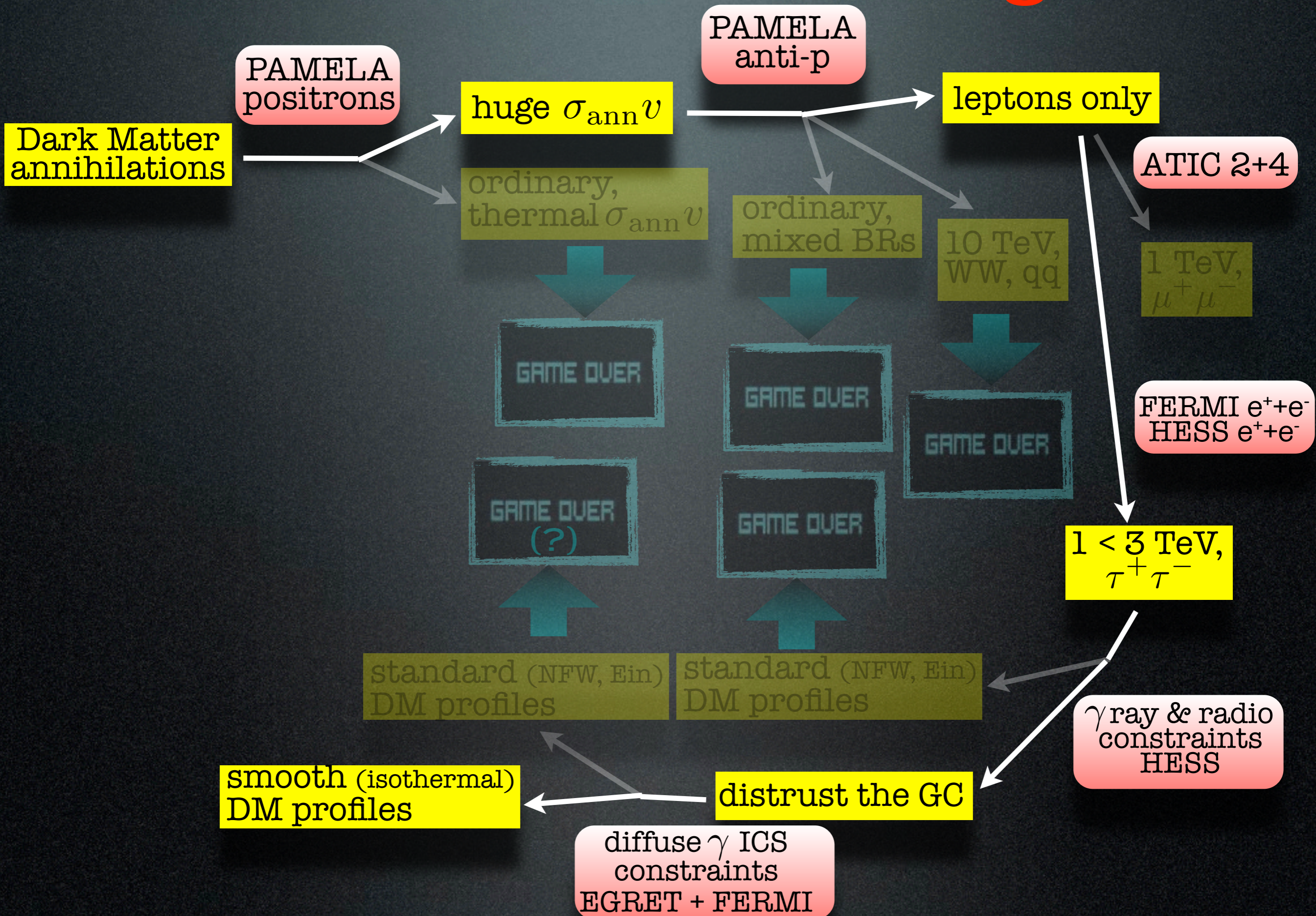
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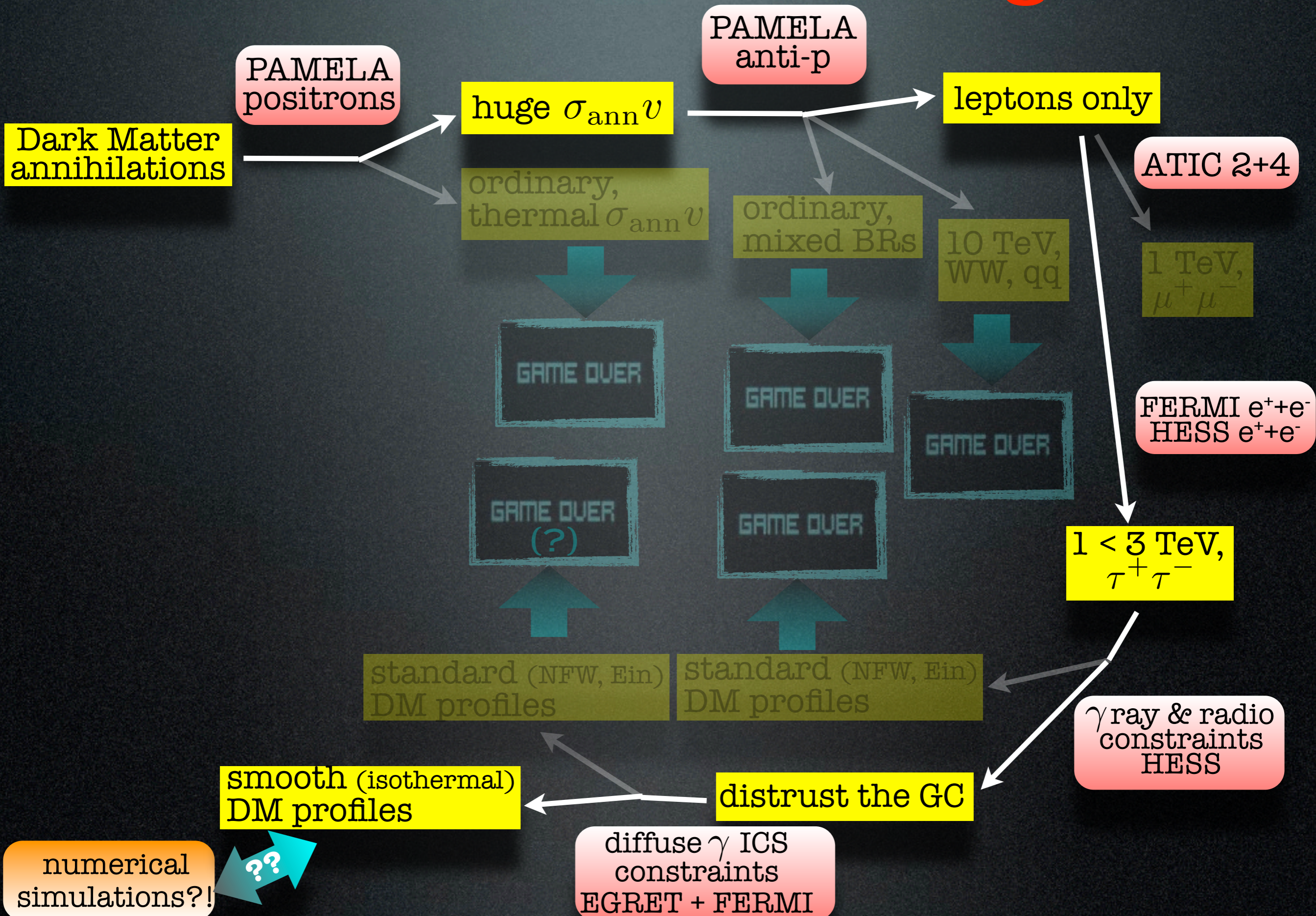
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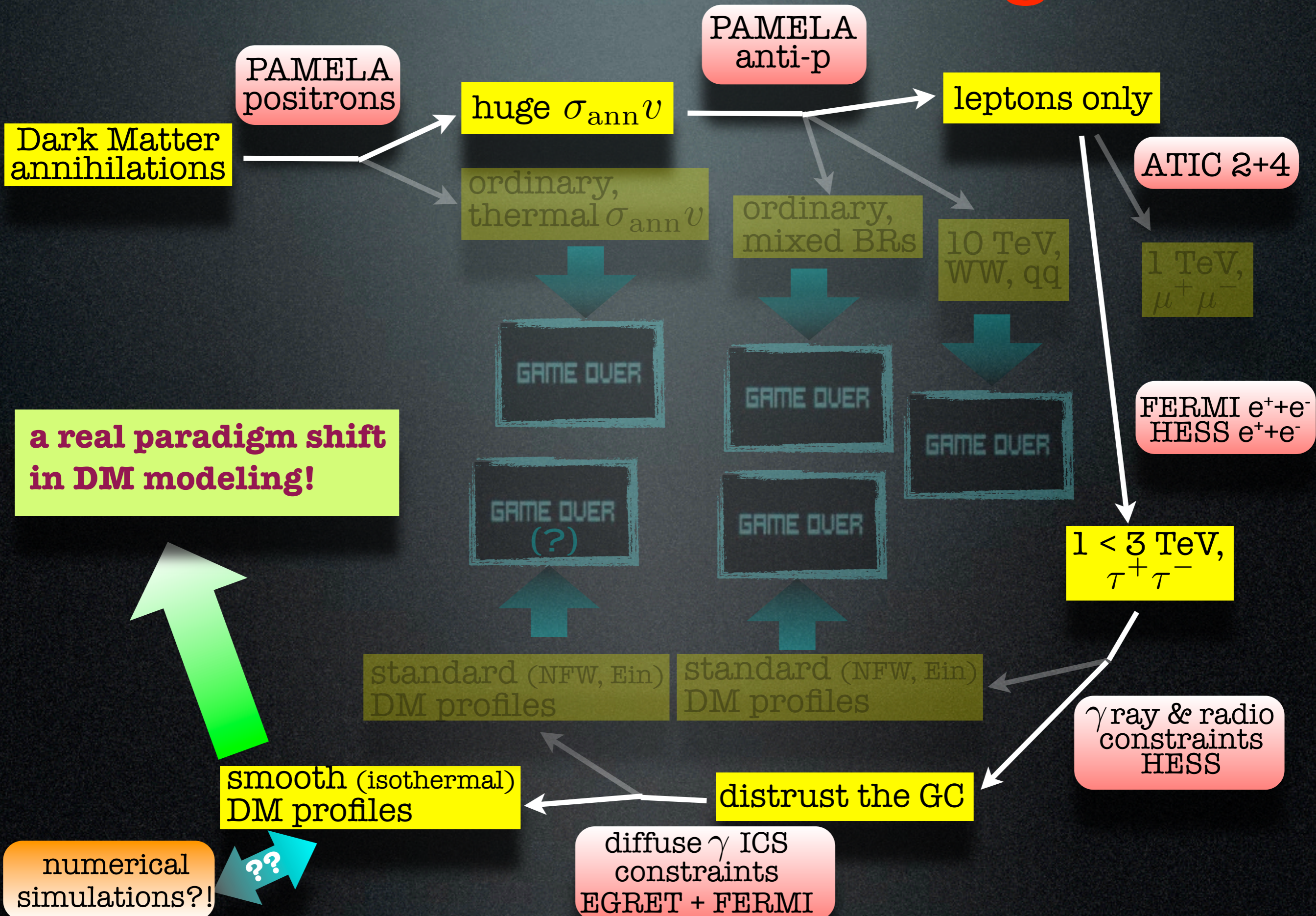
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Conclusions

Indirect DM searches are powerful and promising.

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excess in positrons, nothing in anti-protons.

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Need a **not-too-steep DM profile**.

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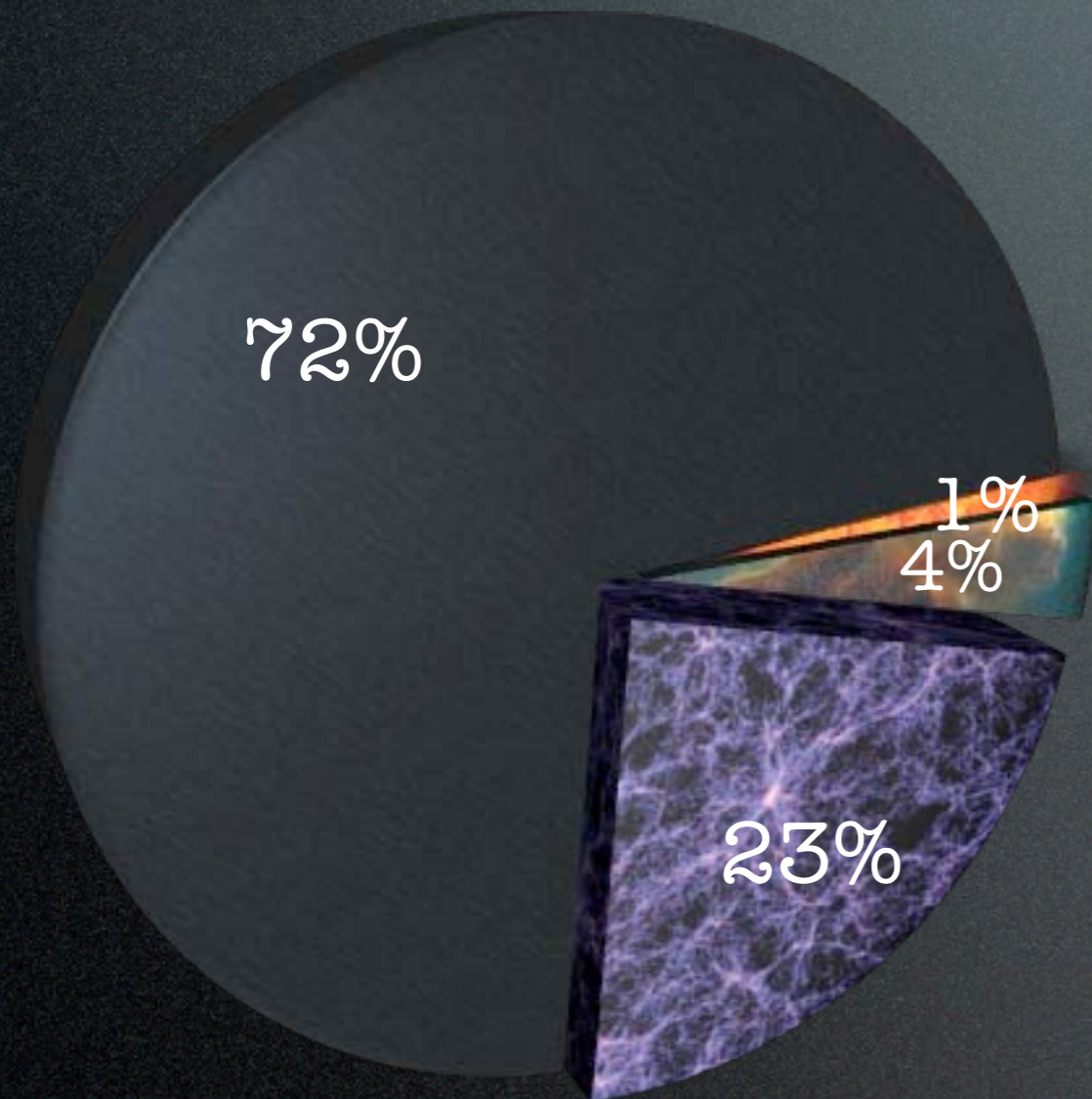
Need a **not-too-steep DM profile**.

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

Back up slides

The cosmic inventory

Most of the Universe is Dark.



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

DM behaves like **matter**

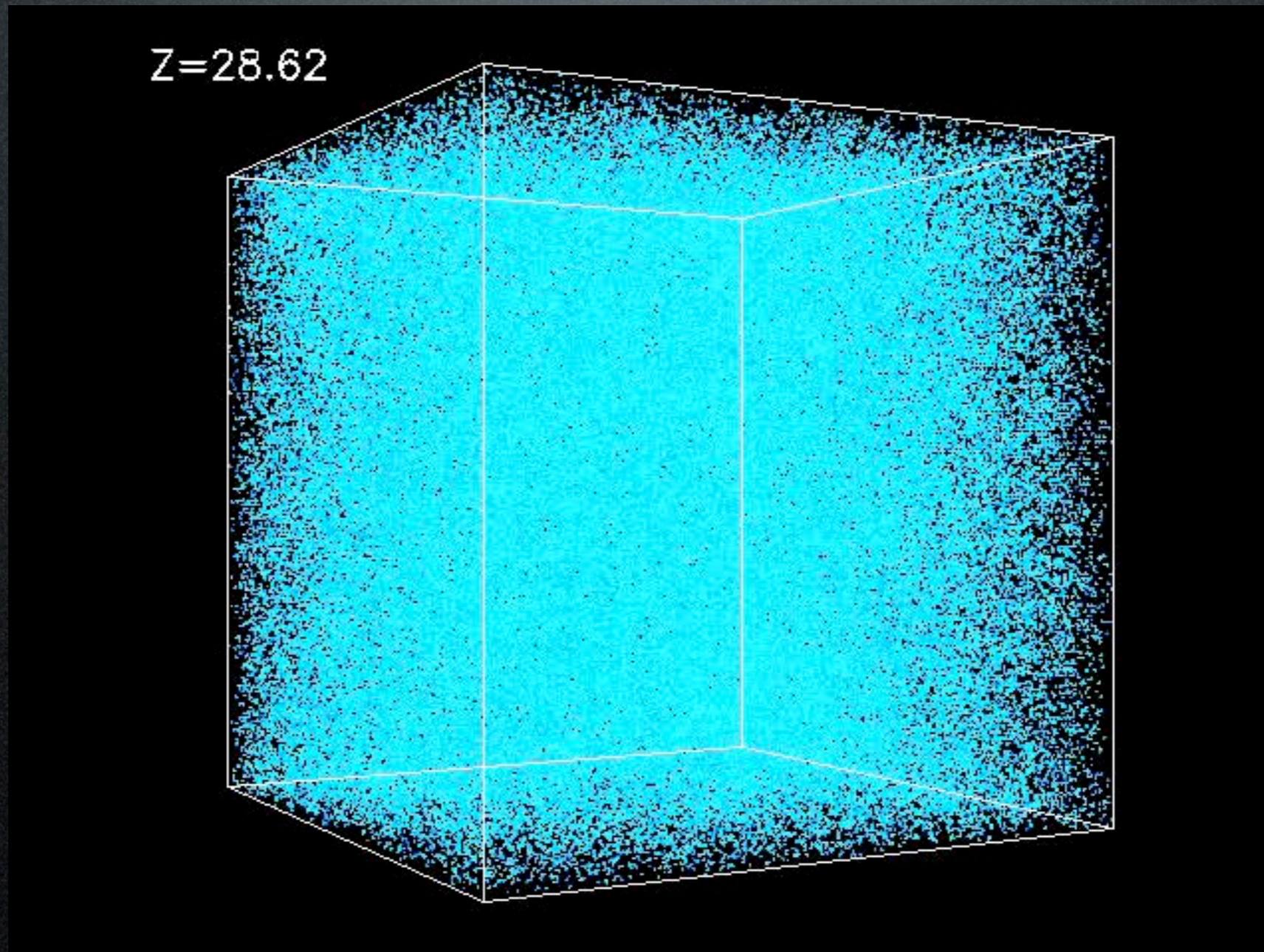
- overall it **dilutes** as volume expands
- **clusters** gravitationally on small scales
- $w = P/\rho = 0$ (NR matter)
(radiation has $w = -1/3$)

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. $\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(1 - 3w)\rho$

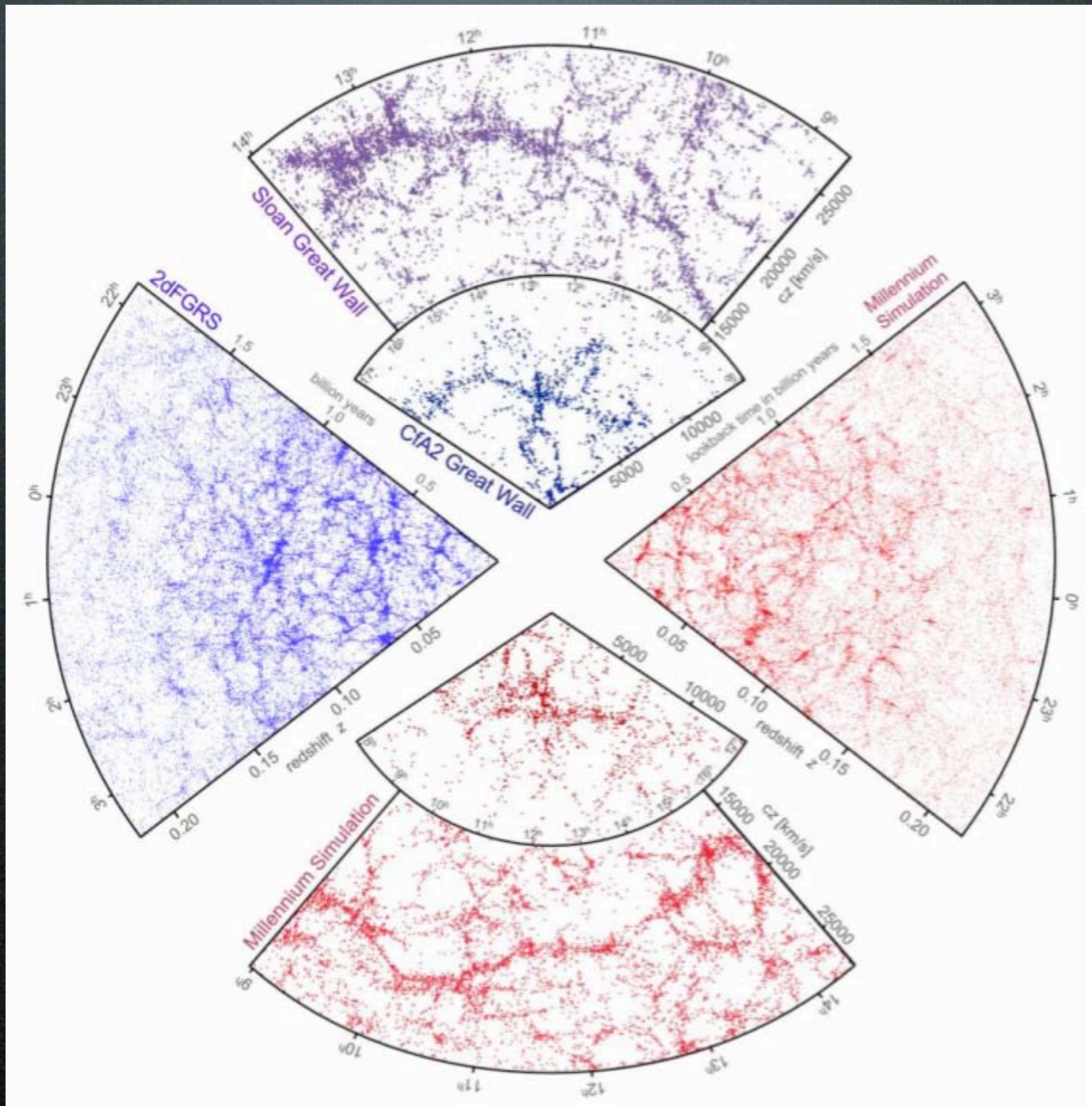
DM N-body simulations

2×10^6 CDM particles, 43 Mpc cubic box



DM N-body simulations

2dF: 2.2×10^5 galaxies
SDSS: 10^6 galaxies,
2 billion yr



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

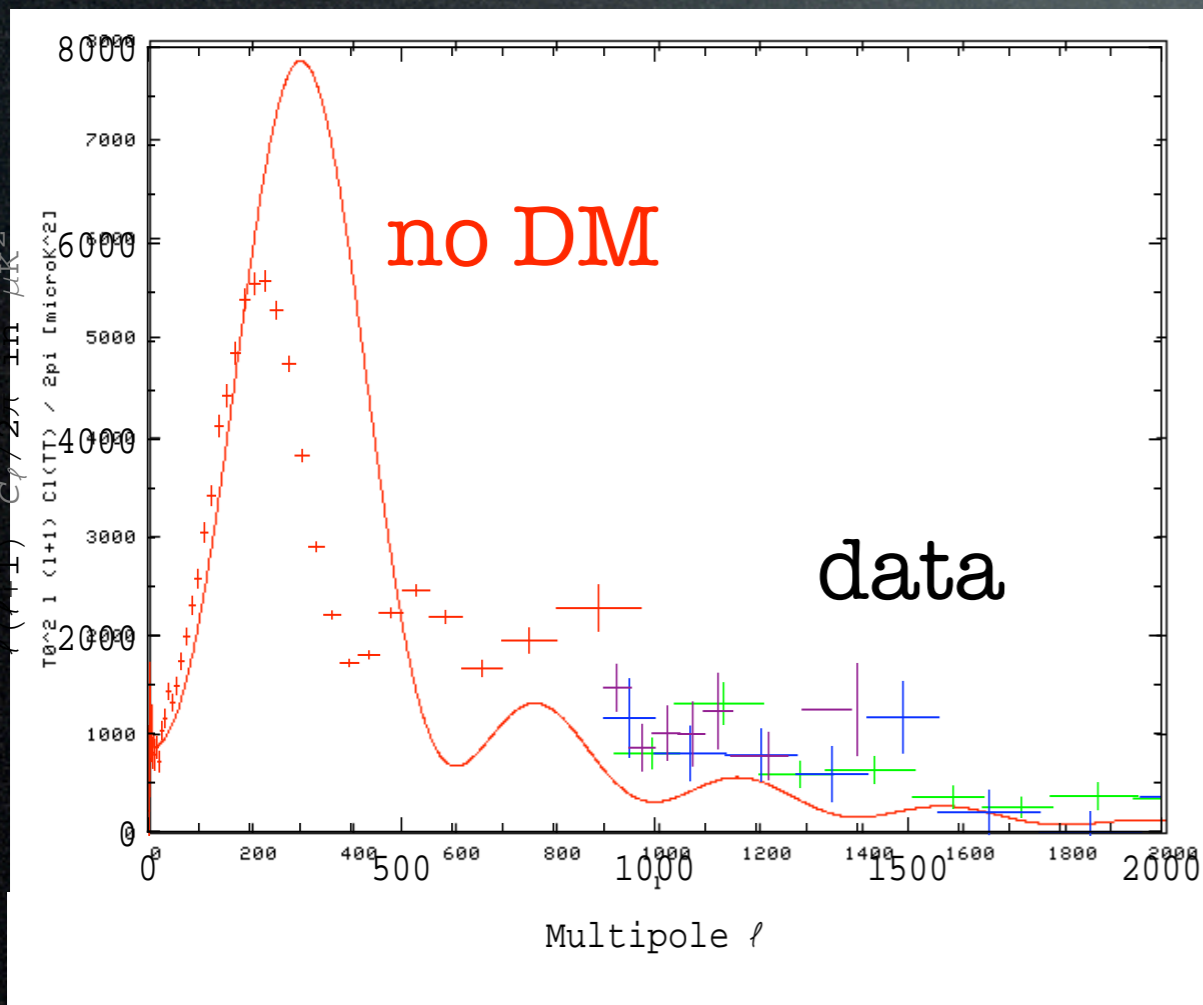
Springel, Frenk, White, Nature 440 (2006)

[back]

The Evidence for DM

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

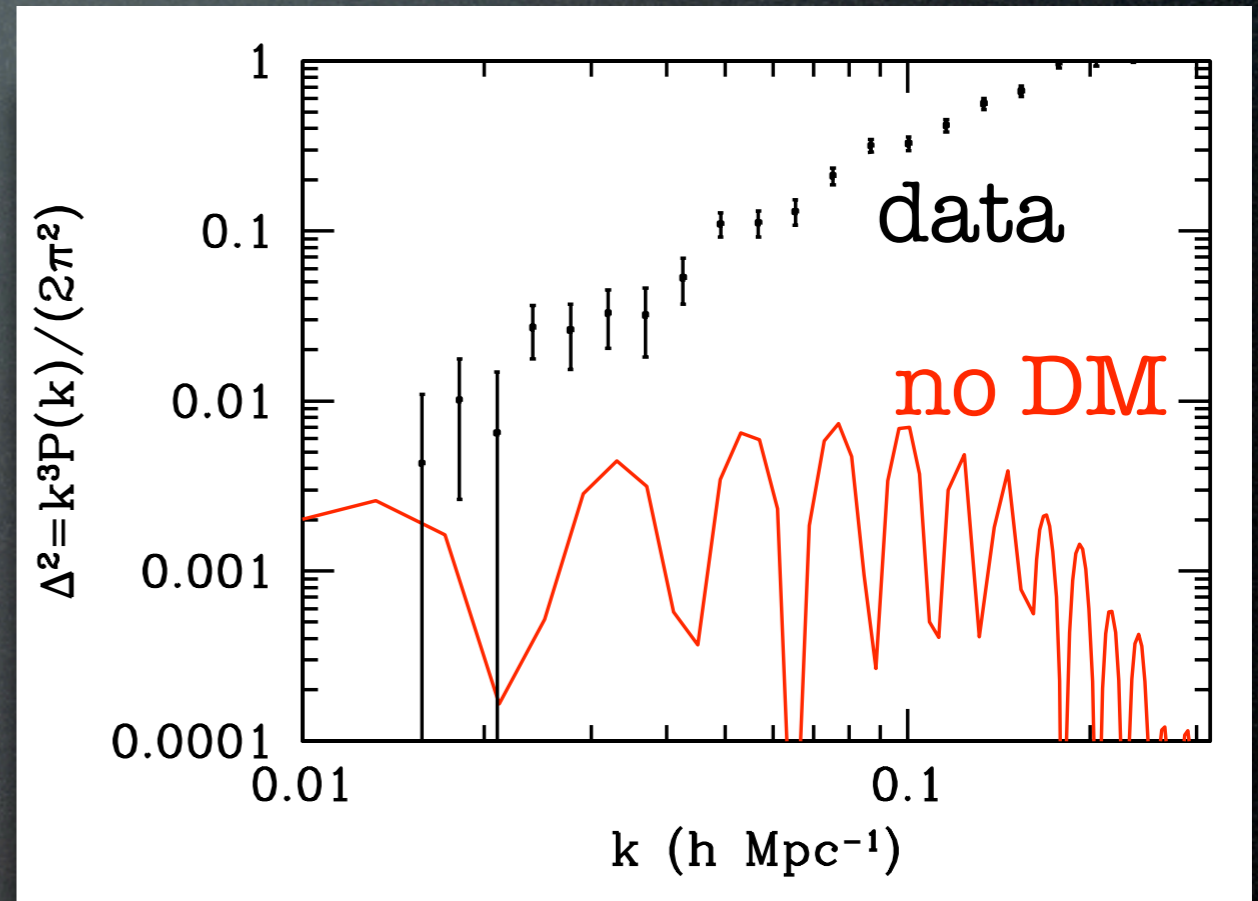
CMB



CAMB online

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

LSS



Dodelson, Liguori 2006

(you need DM to gravitationally
"catalyse" structure formation)

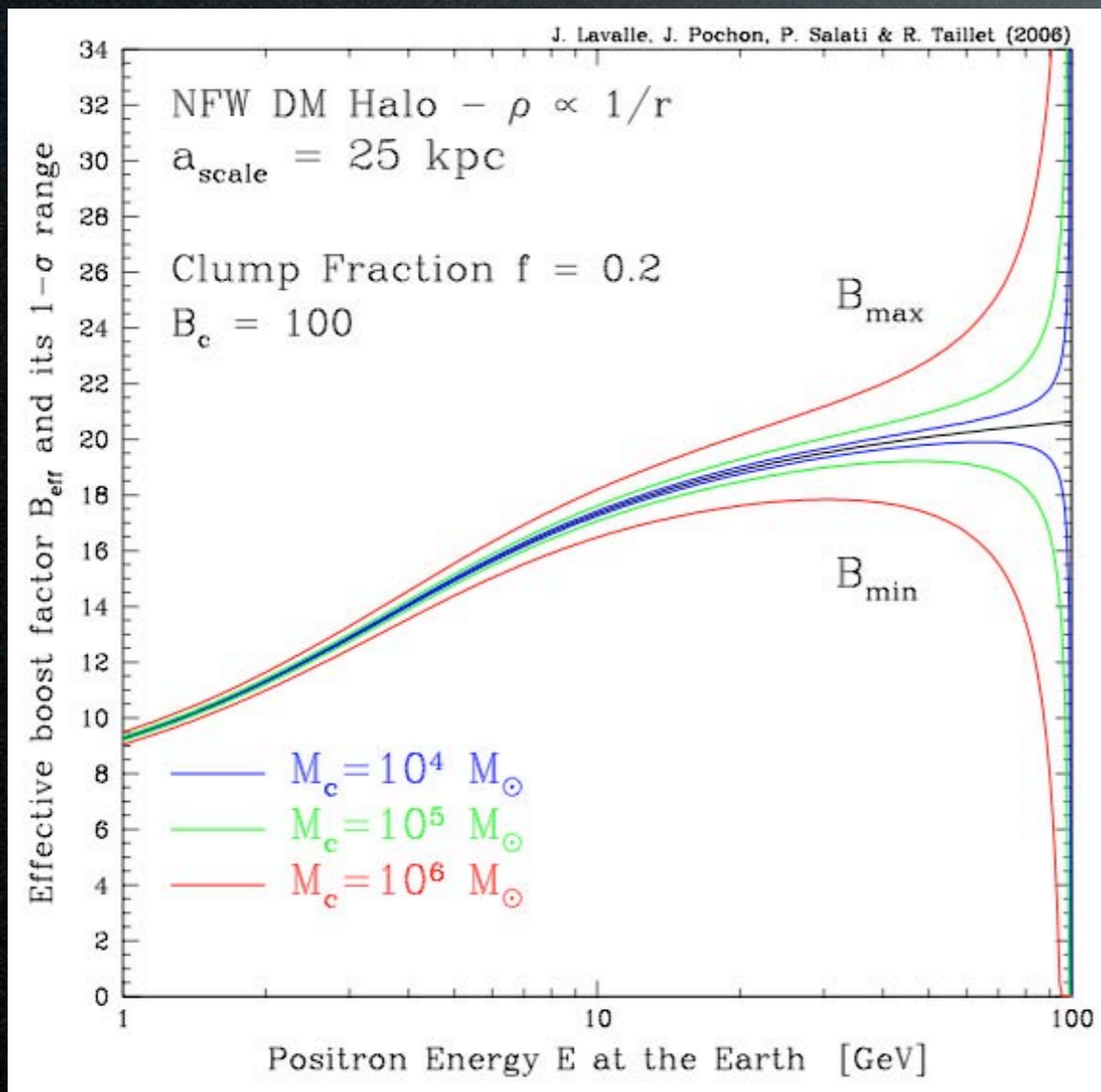
Indirect Detection

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

In principle, B is different for e^+ , anti-p and gammas, energy dependent,

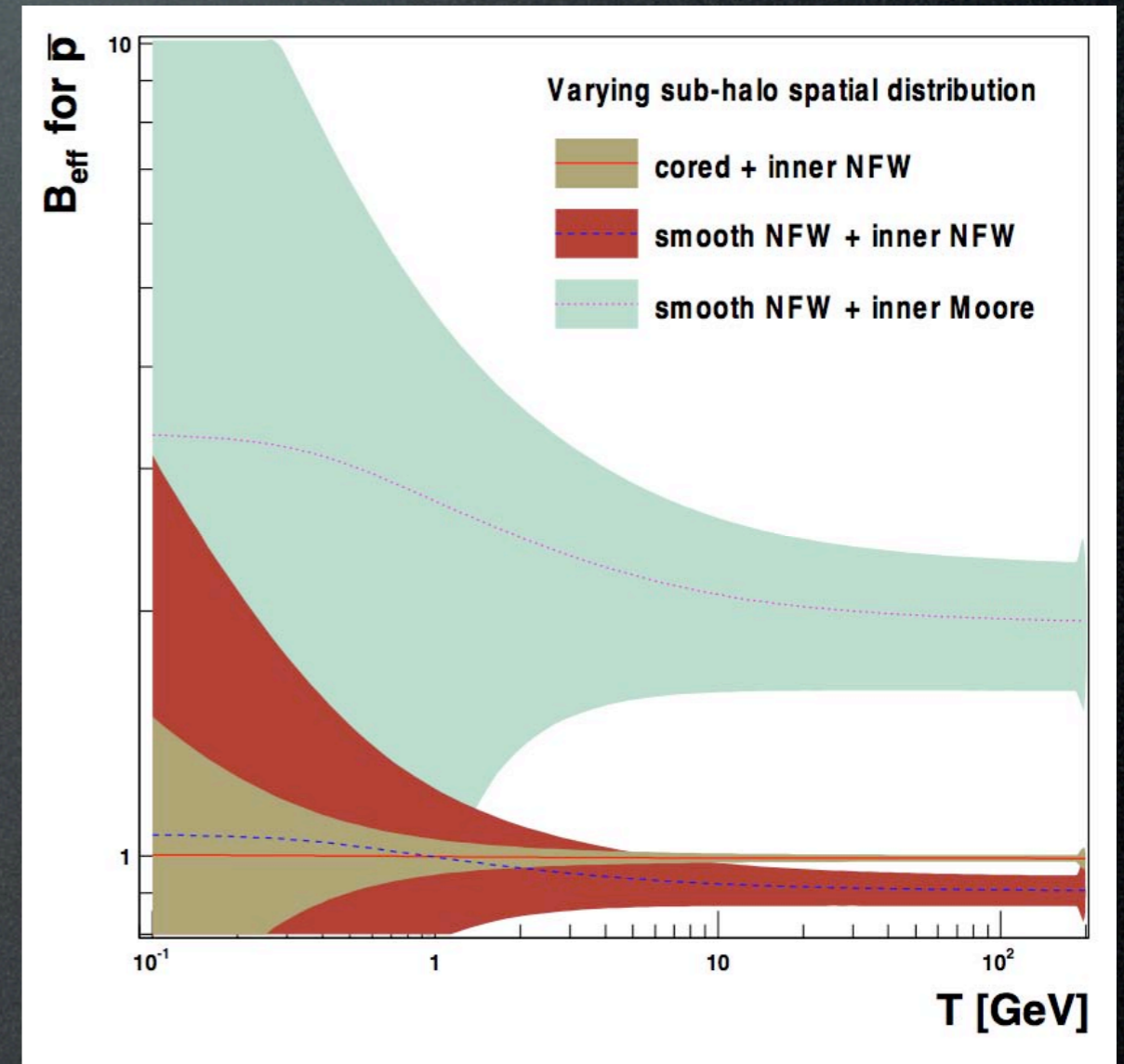
dependent on many astro assumptions (inner density profile of clump, tidal disruptions and smoothing...), with an energy dependent variance, at high energy for e^+ , at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons



Lavalle et al. 2007

Background



Background

Background computations for **positrons**:

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

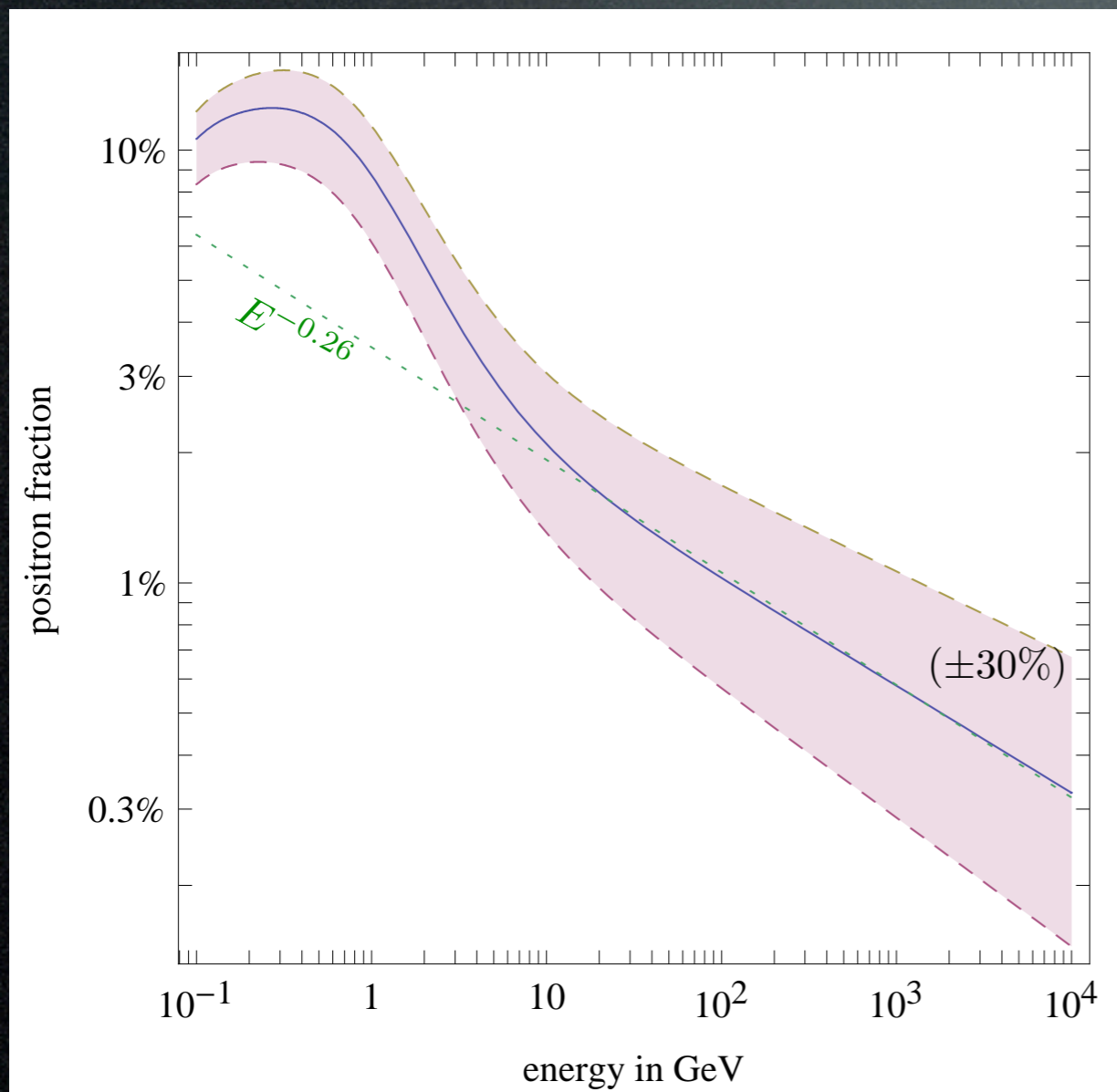
main source: CR nuclei
spallating on IS gas

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

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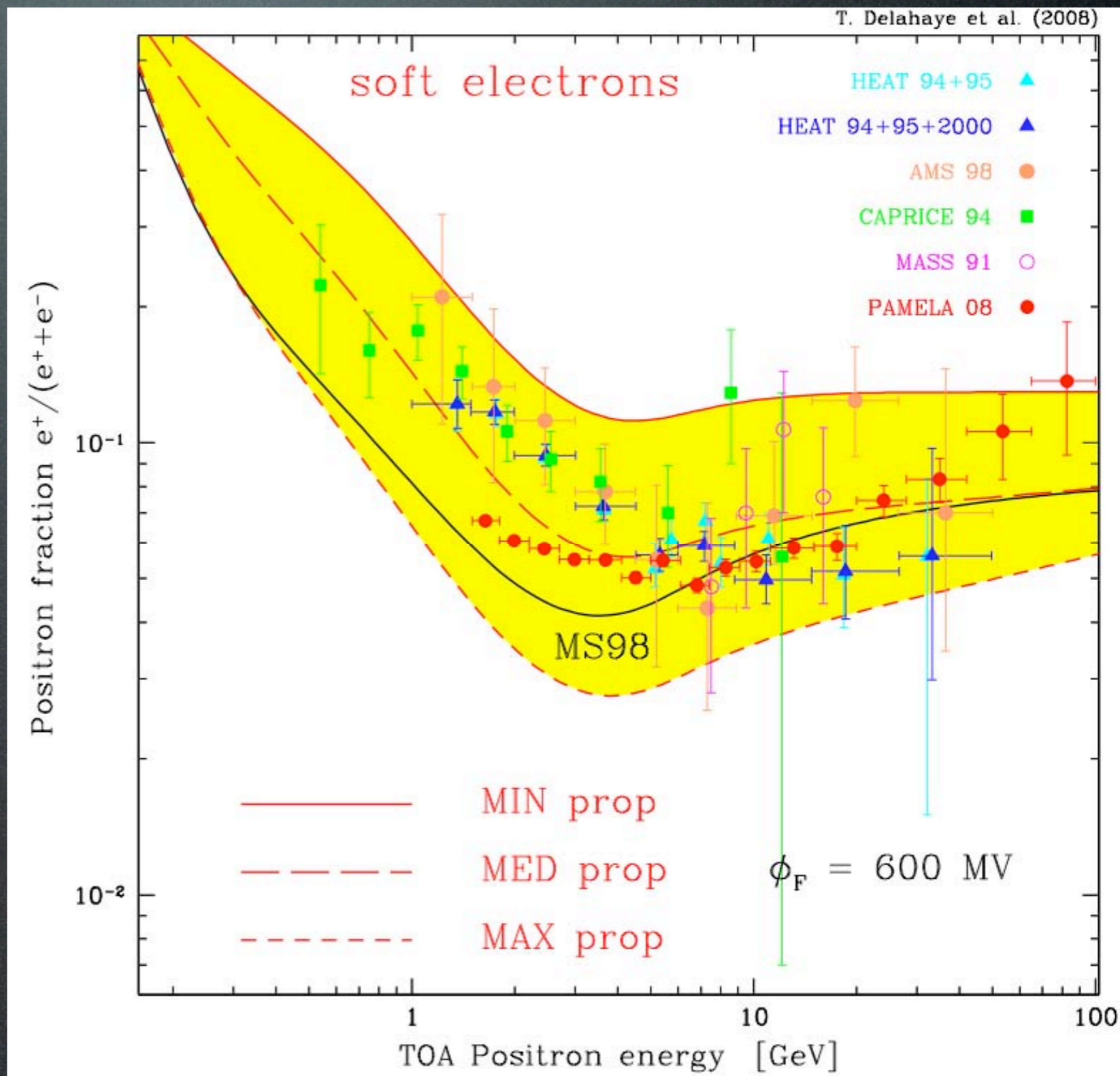


We marginalize w.r.t. the slope
 E^p , $p = \pm 0.05$
and let normalization free.

Background

Background estimation for positrons:

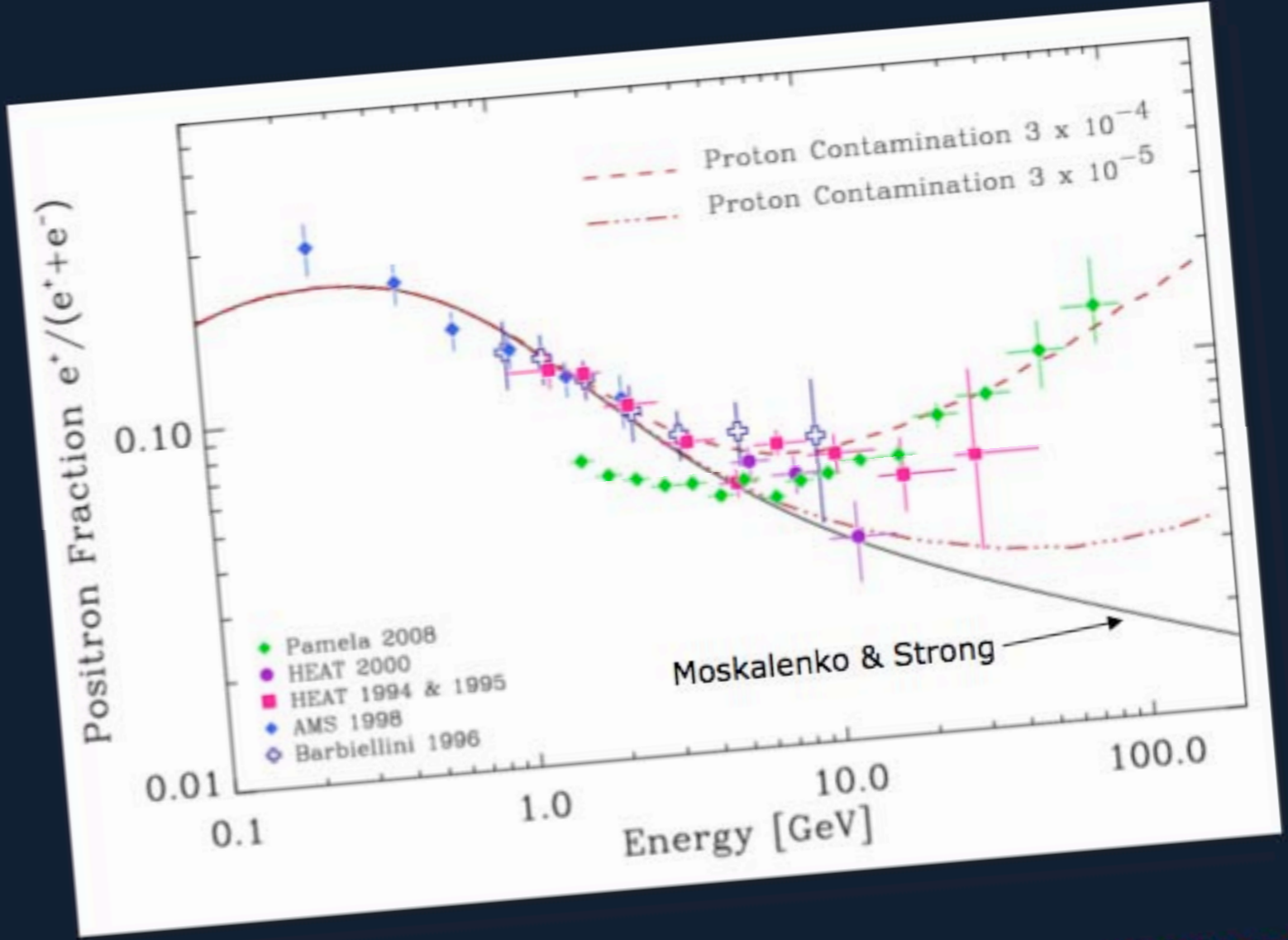
using new
measurements of
electron fluxes
Casadei, Bindi 2008



T.Delahaye et al., 09.2008

“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.

“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-sampler method)

Rigidity: 20-28 GV

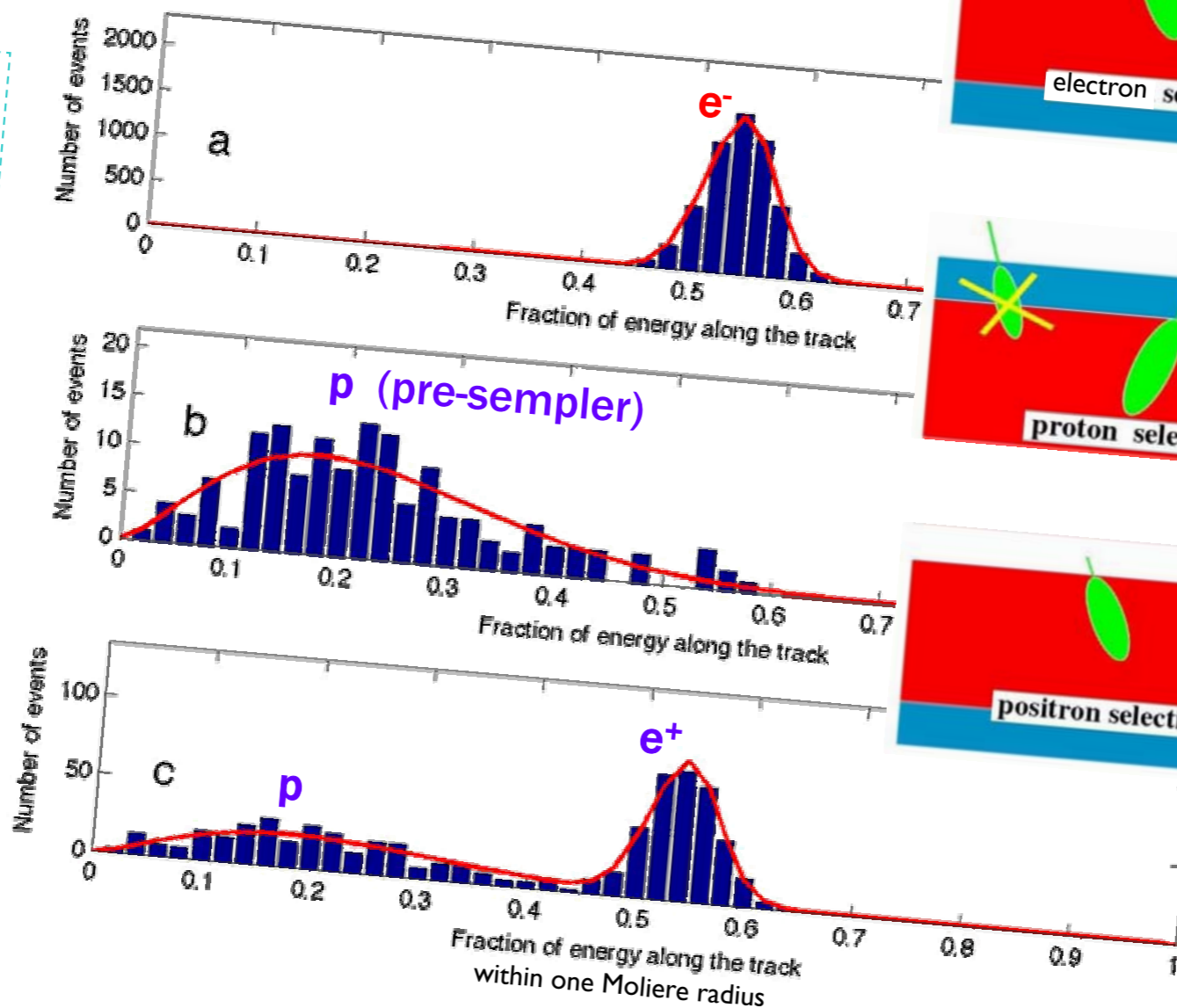
Fraction of charge released along the calorimeter track (left, hit, right)

+

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**

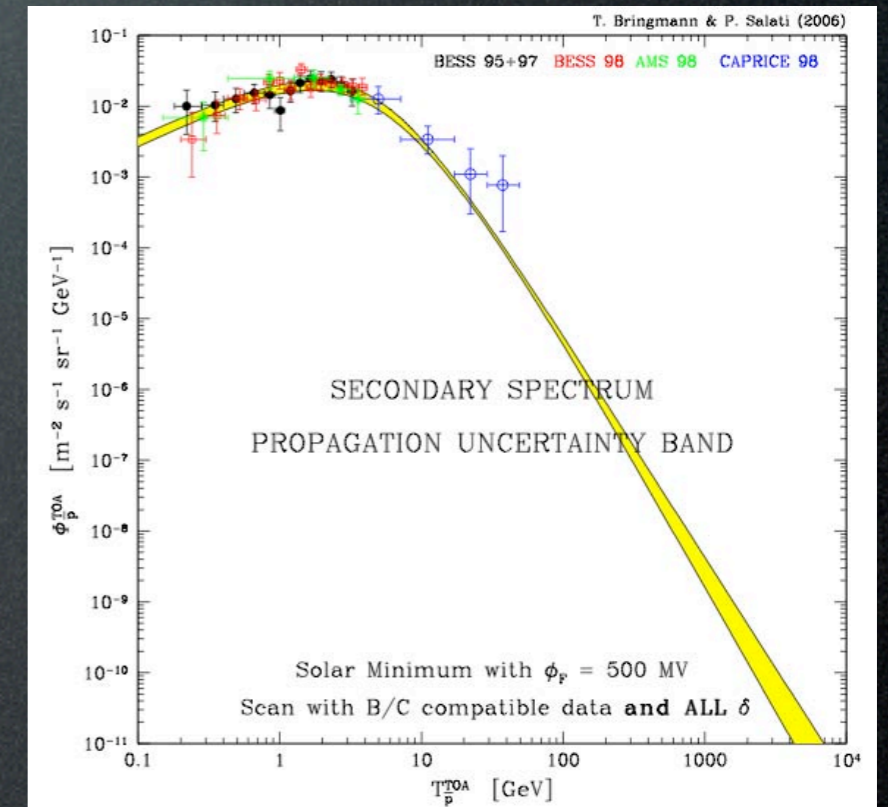
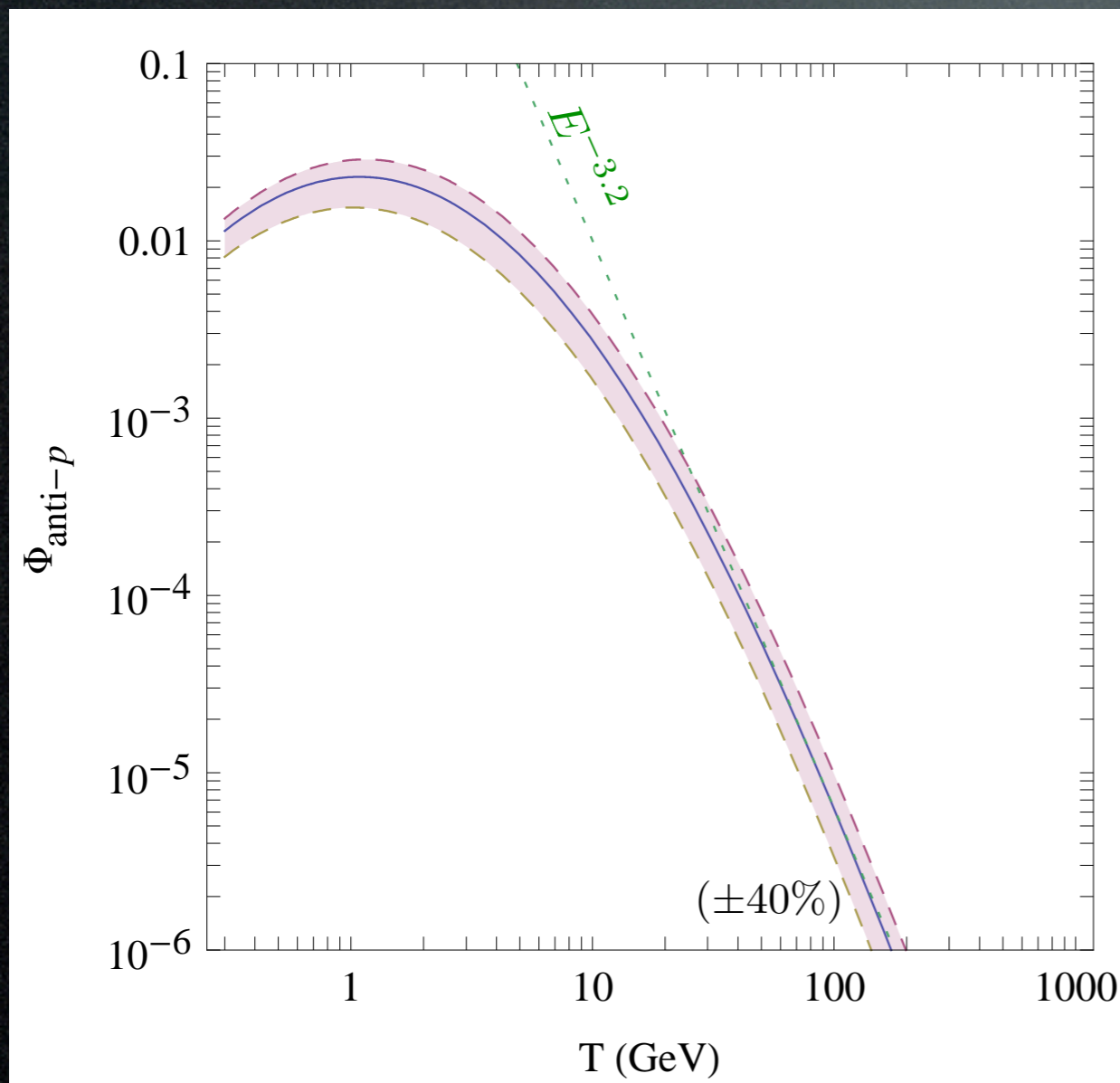
Step 3: full analysis (see that p peak is statistically consistent with e^- peak of step 1)

Background

Background computations for **antiprotons**:

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

Bringmann, Salati 2006



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

Background



Indirect Detection

Propagation for **positrons**:

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

diffusion

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

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

energy loss

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

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

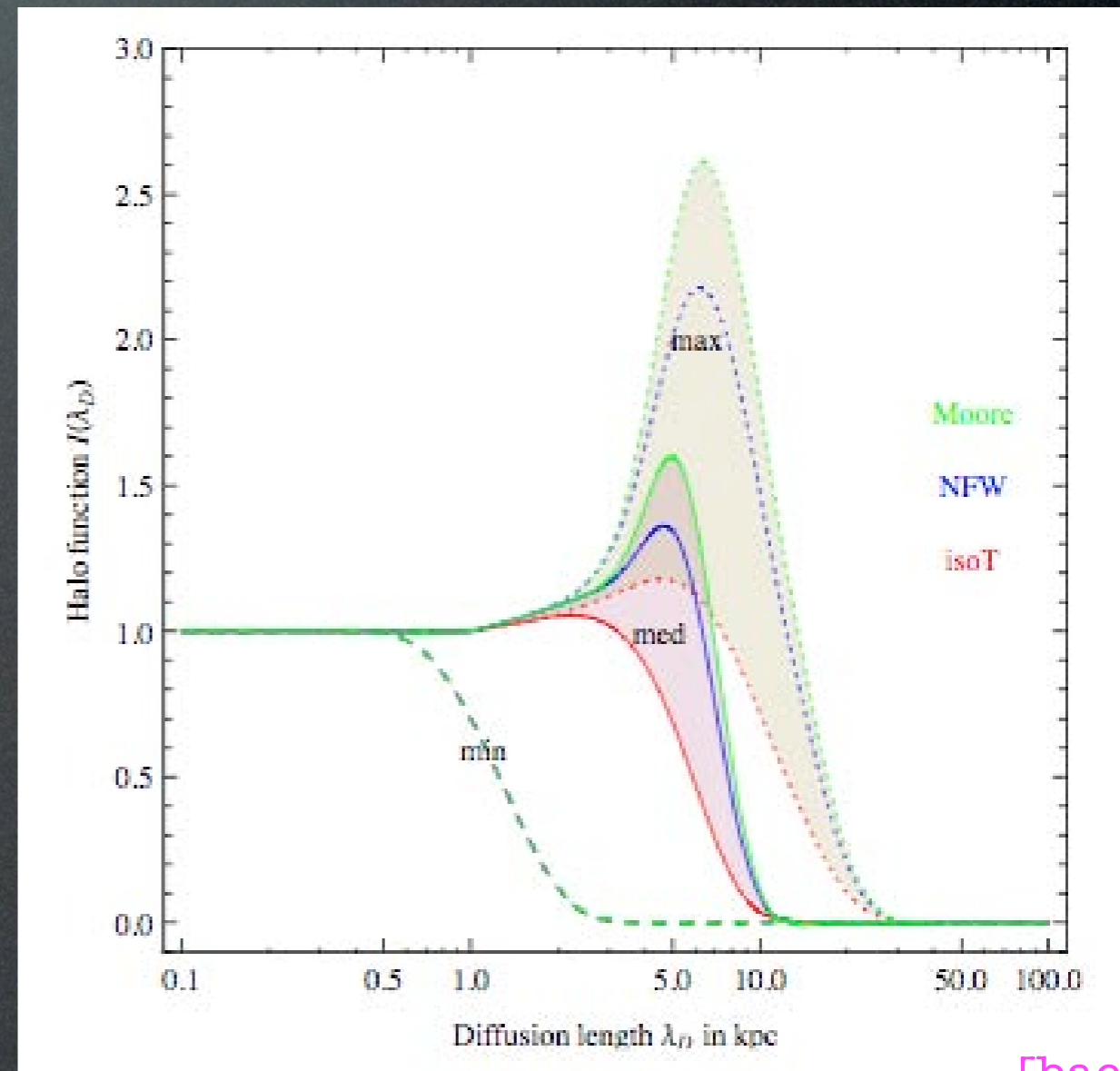
$$Q = \frac{1}{2} \left(\frac{\rho}{M_{\text{DM}}} \right)^2 f_{\text{inj}}, \quad f_{\text{inj}} = \sum_k \langle \sigma v \rangle_k \frac{dN_{e^+}^k}{dE}$$

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:

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

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



Indirect Detection

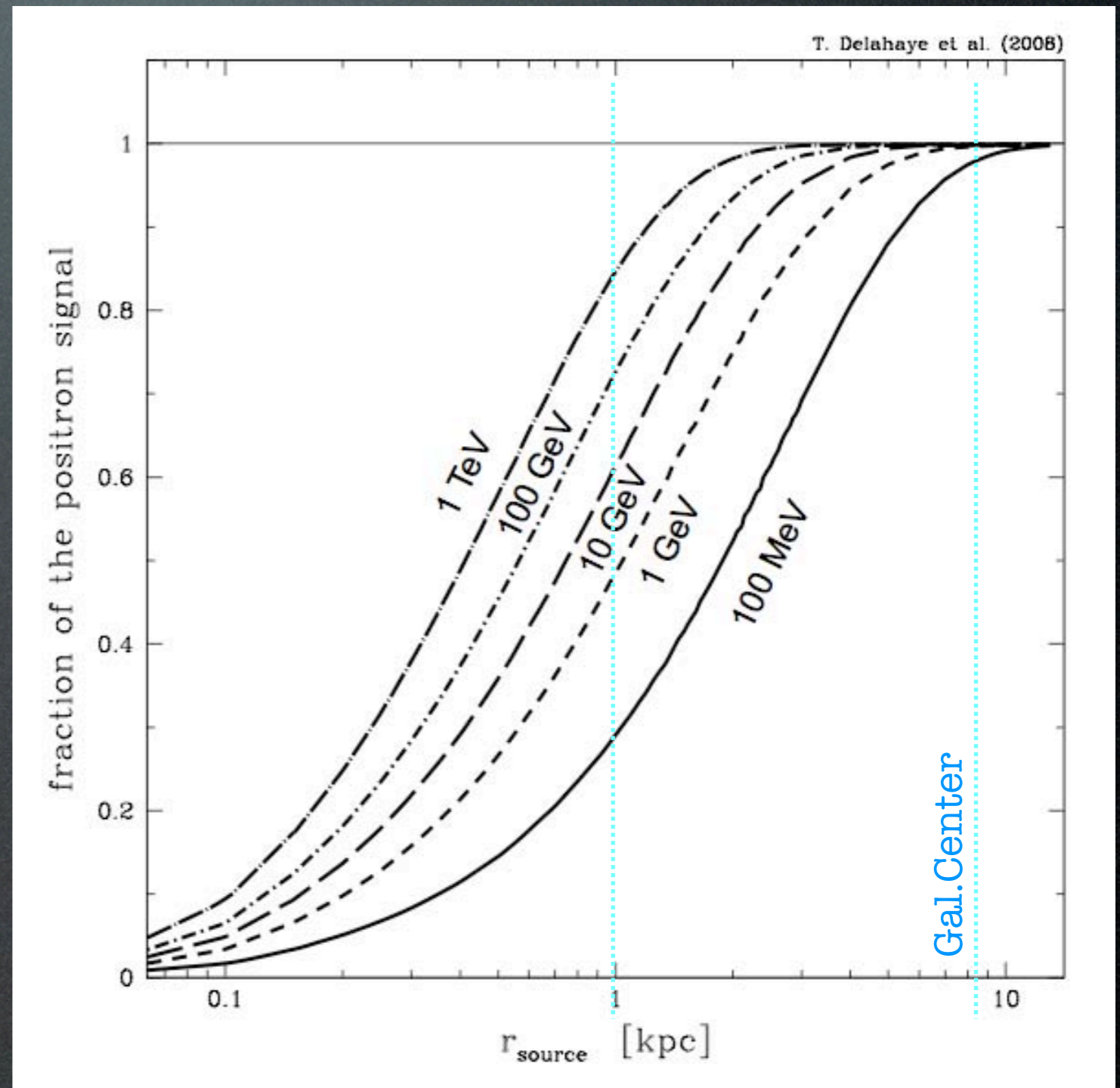
Where do **positrons** come from?

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

Typical lifetime (due to syn rad & IC):

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

(w = density of IS photons)

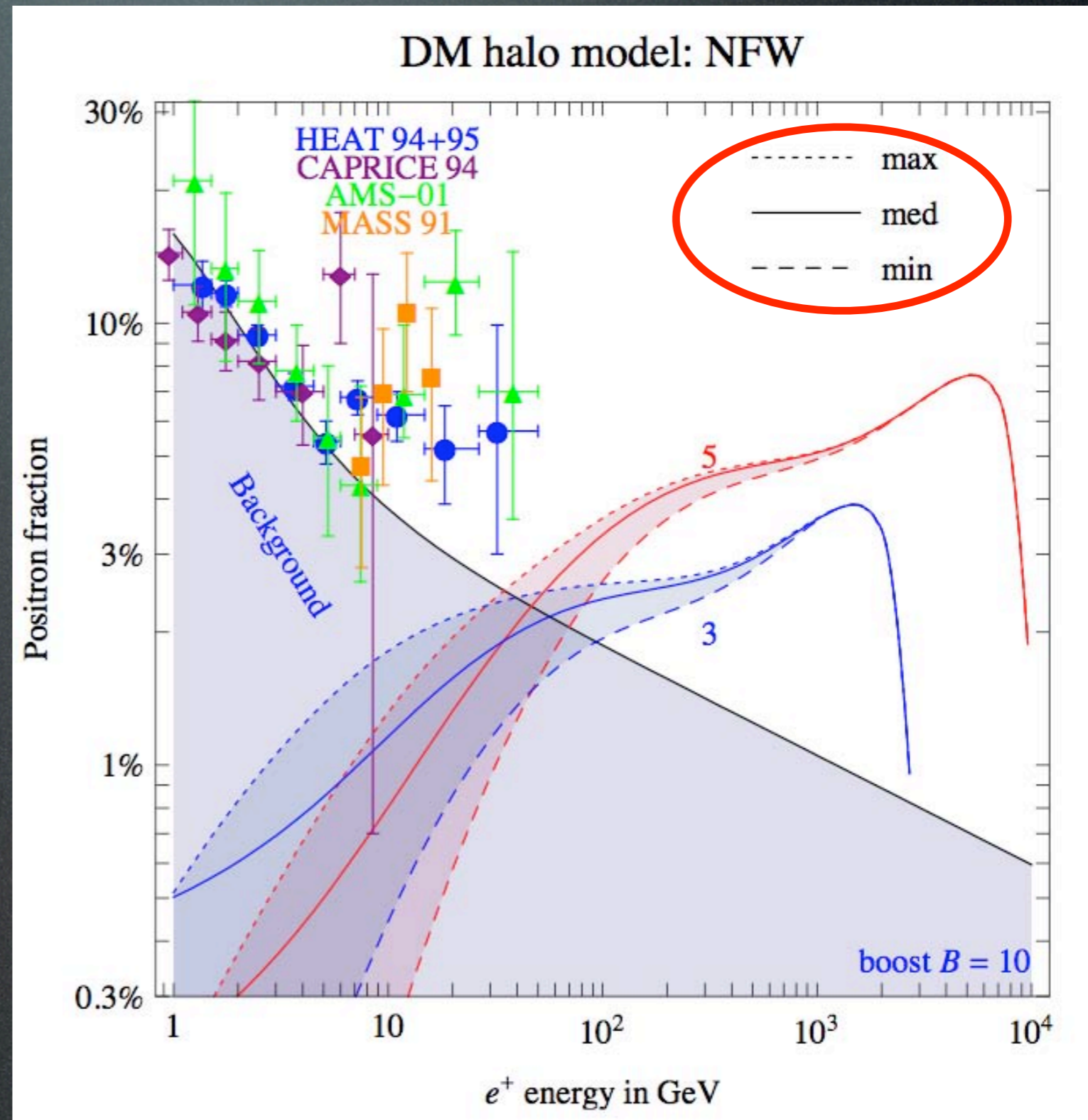


3. Indirect Detection

Results for **positrons**:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



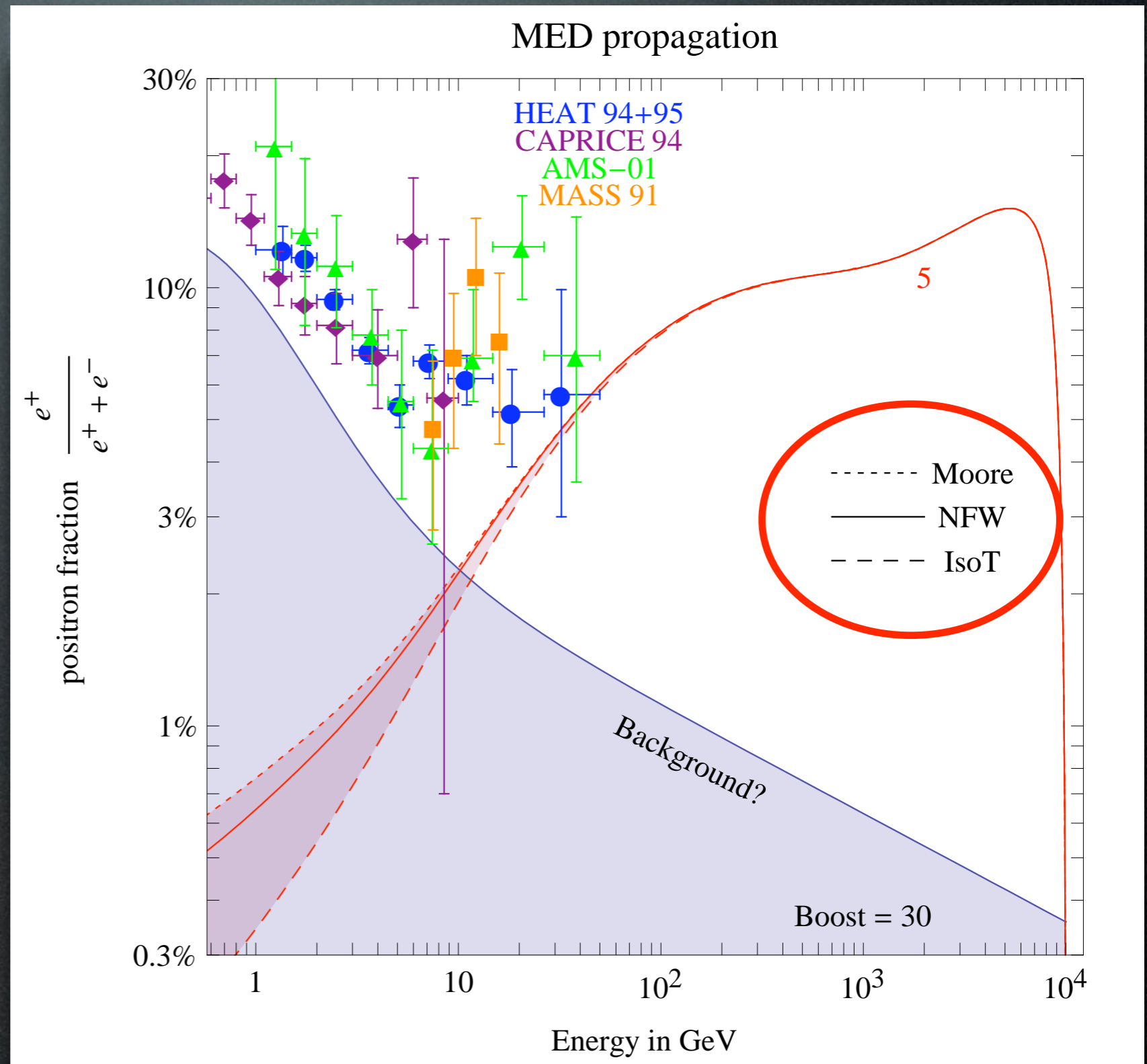
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Results for **positrons**:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B

Distinctive signal,
quite robust vs astro.



3. Indirect Detection

Propagation for **antiprotons**:

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

diffusion

convective wind

spallations

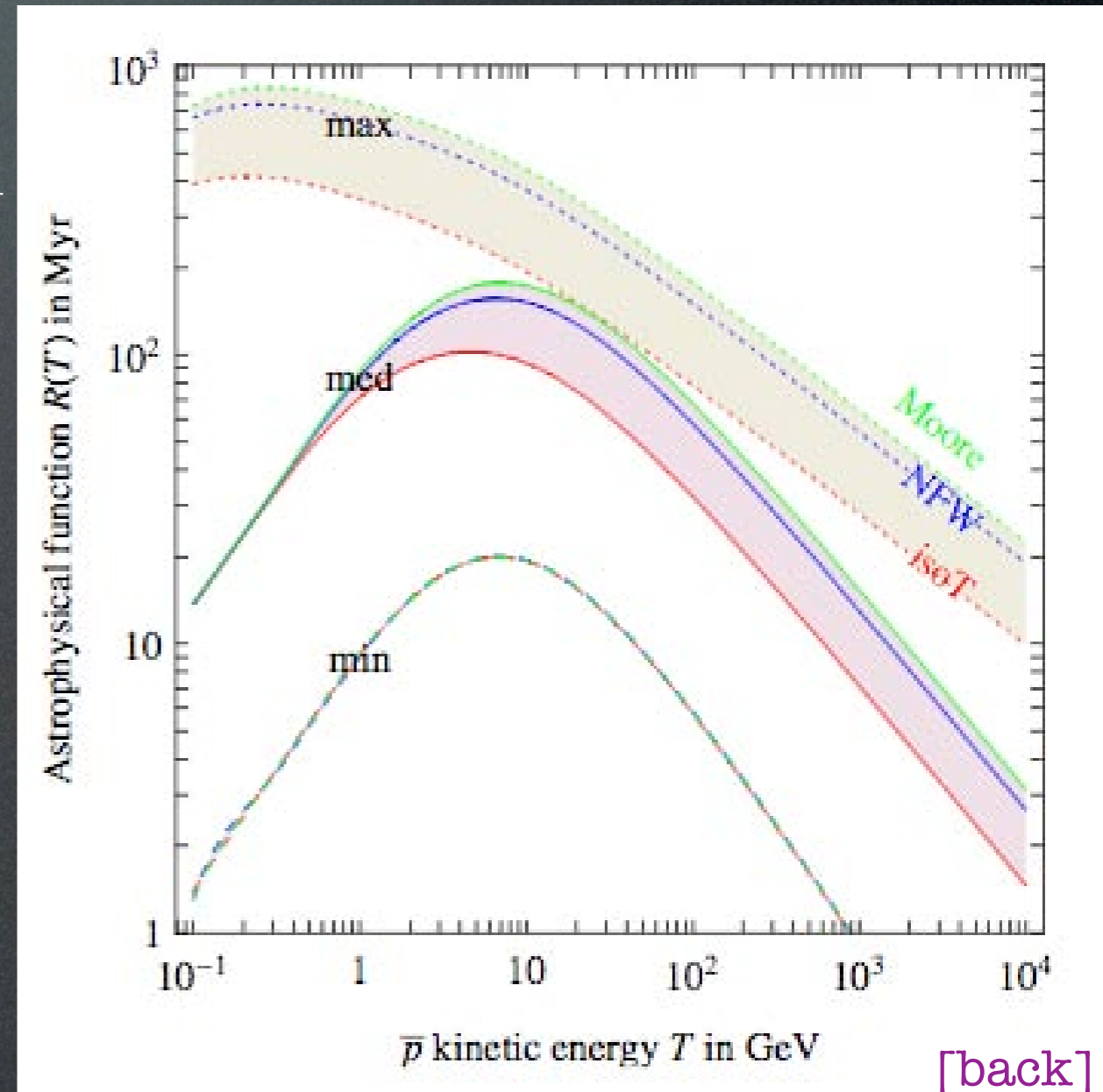
$$K(T) = K_0 \beta (p/\text{GeV})^\delta$$

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:

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



Indirect Detection

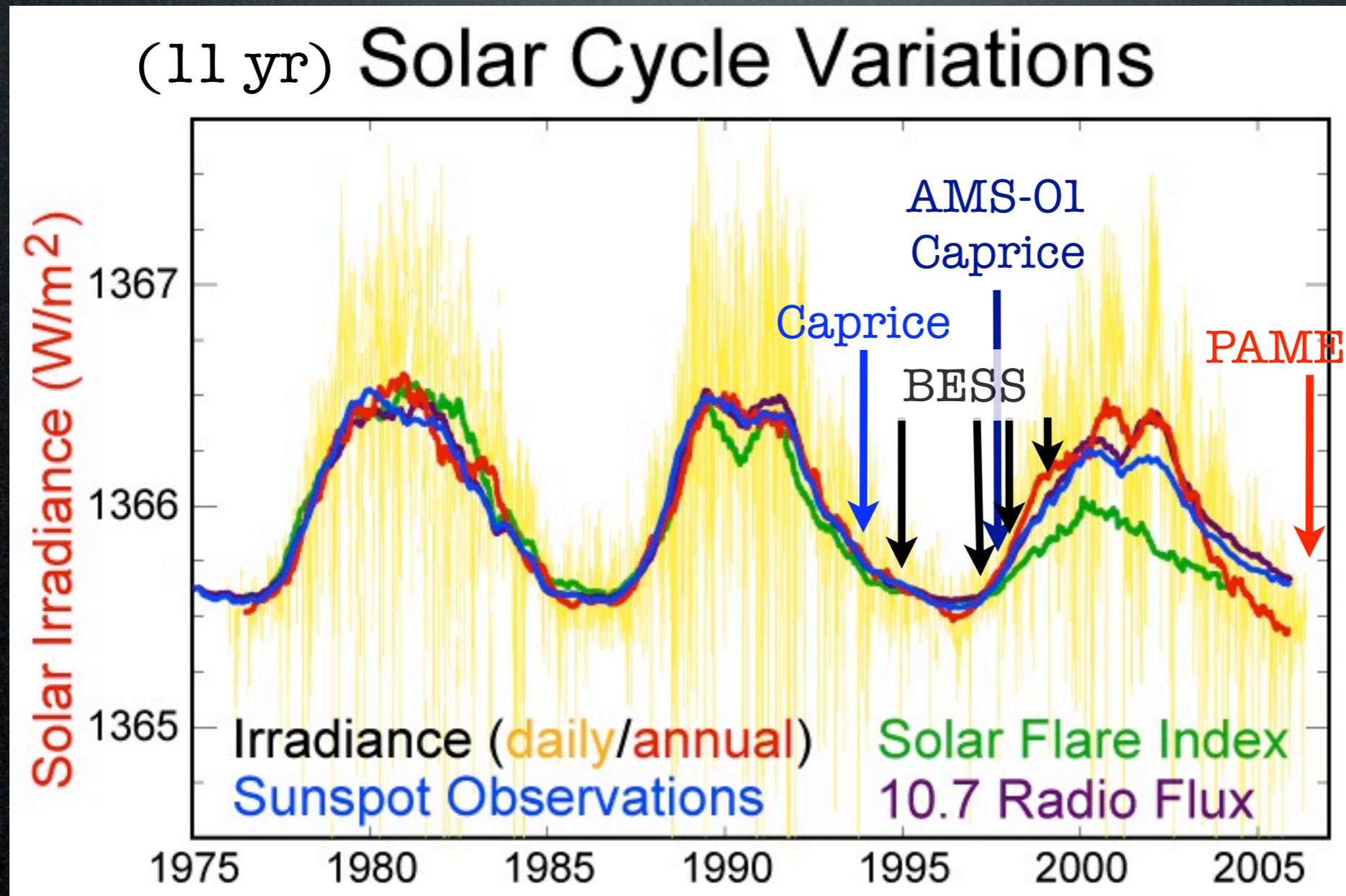
Solar wind Modulation of cosmic rays:

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

spectrum
at Earth

spectrum
far from Earth

Fisk
potential $\phi_F \simeq 500$ MV

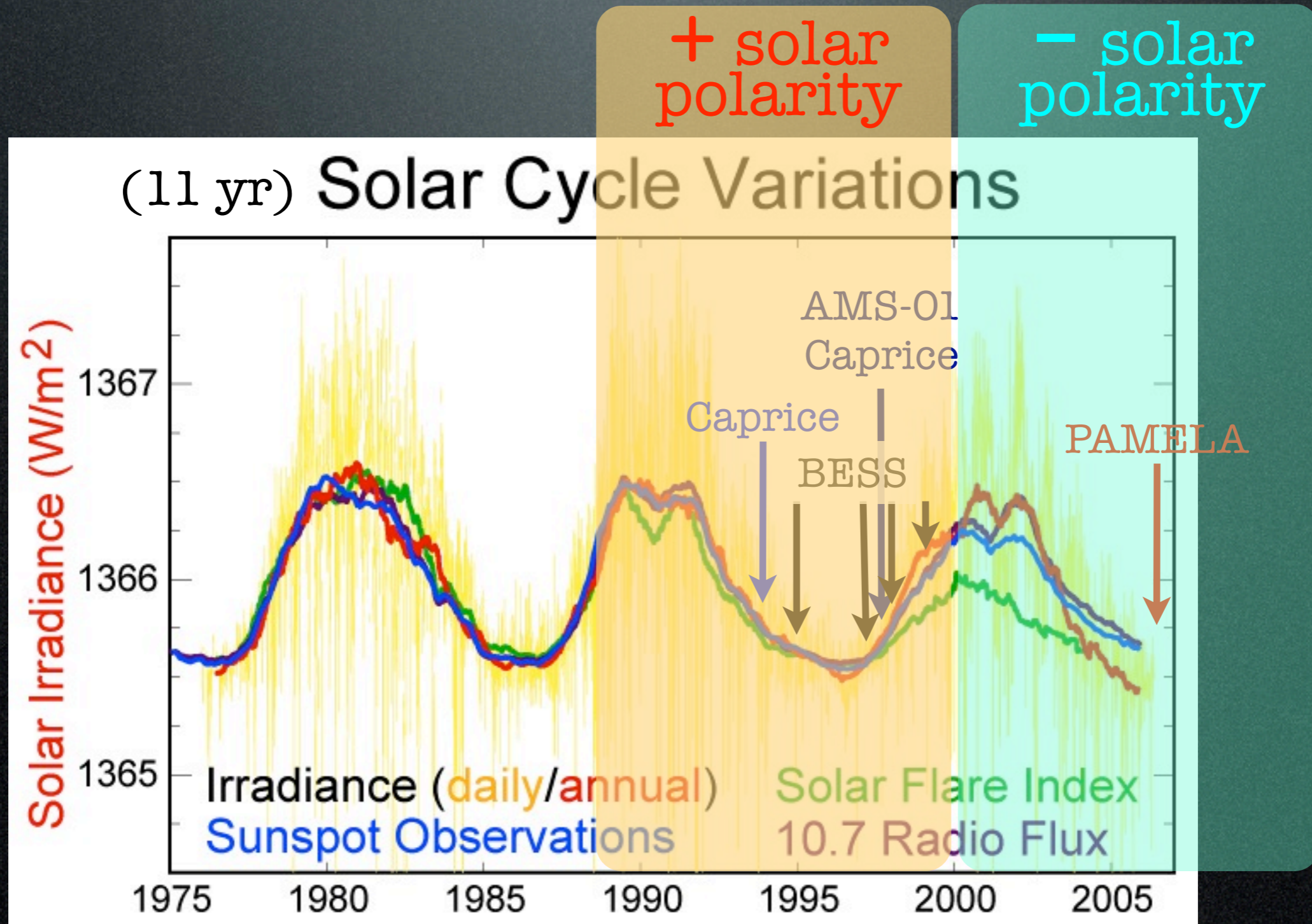


Indirect Detection

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



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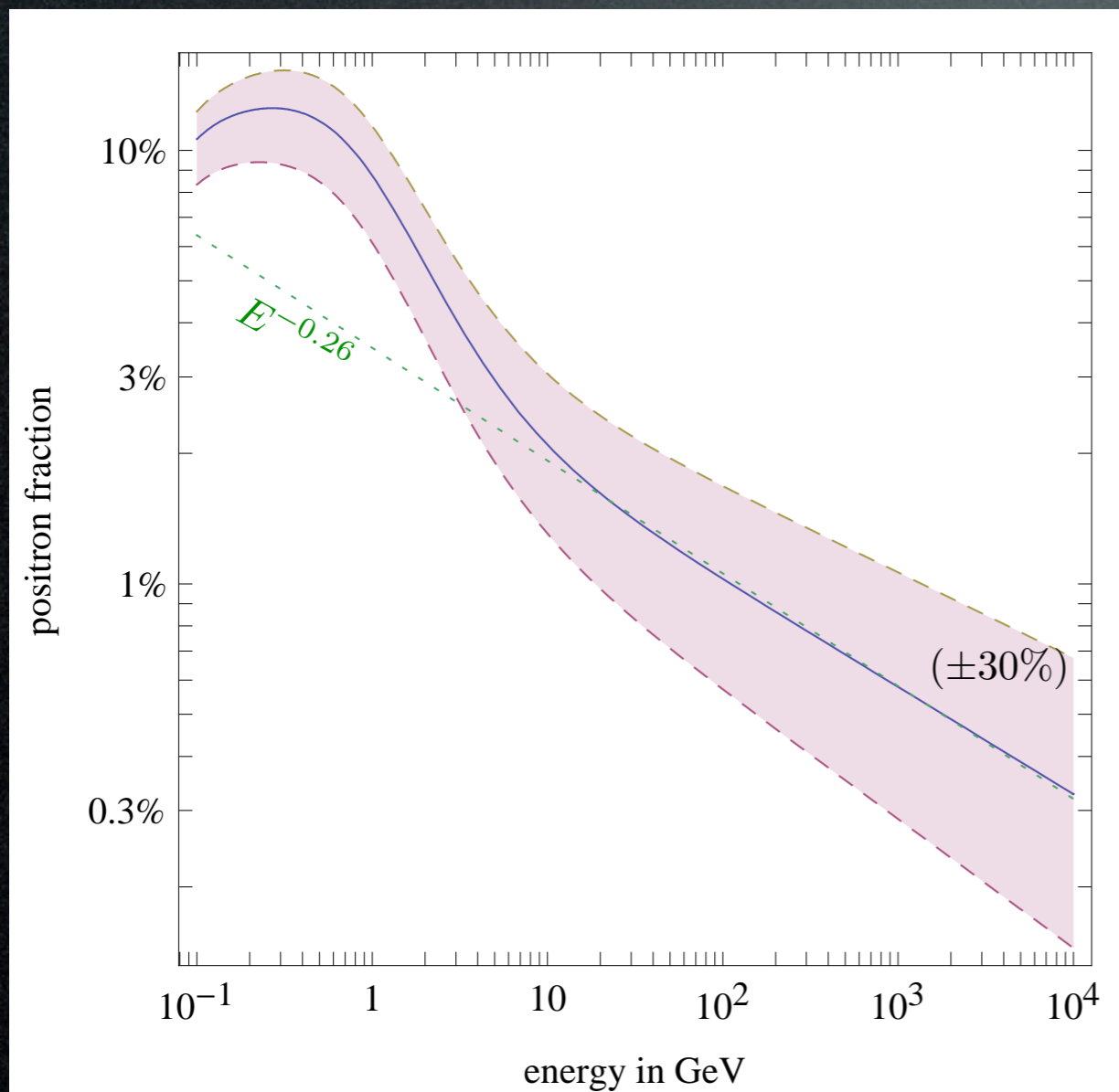
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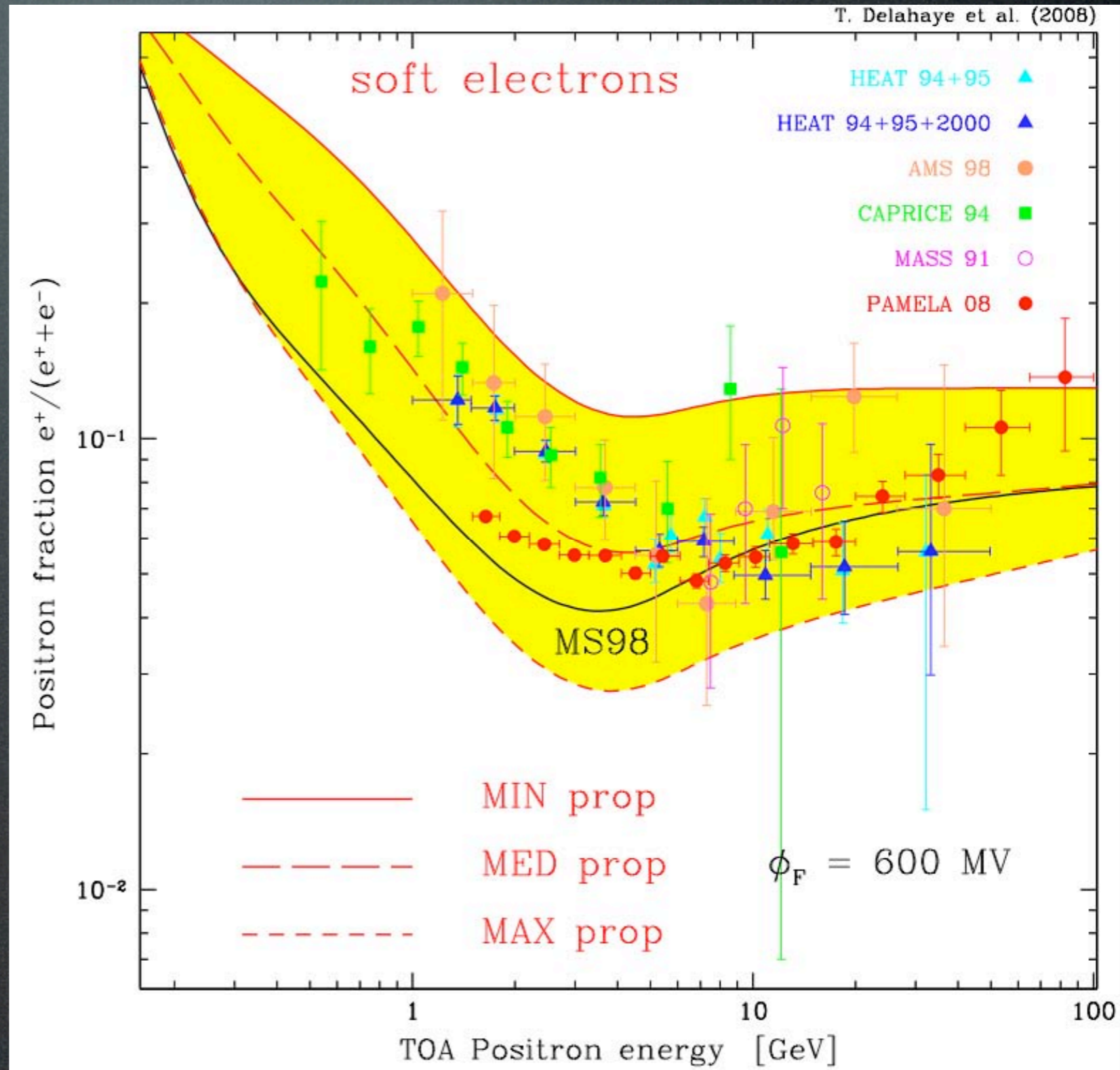
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and let normalization free.

[back]

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Background estimation for **positrons**:

using new
measurements of
electron fluxes
Casadei, Bindi 2004

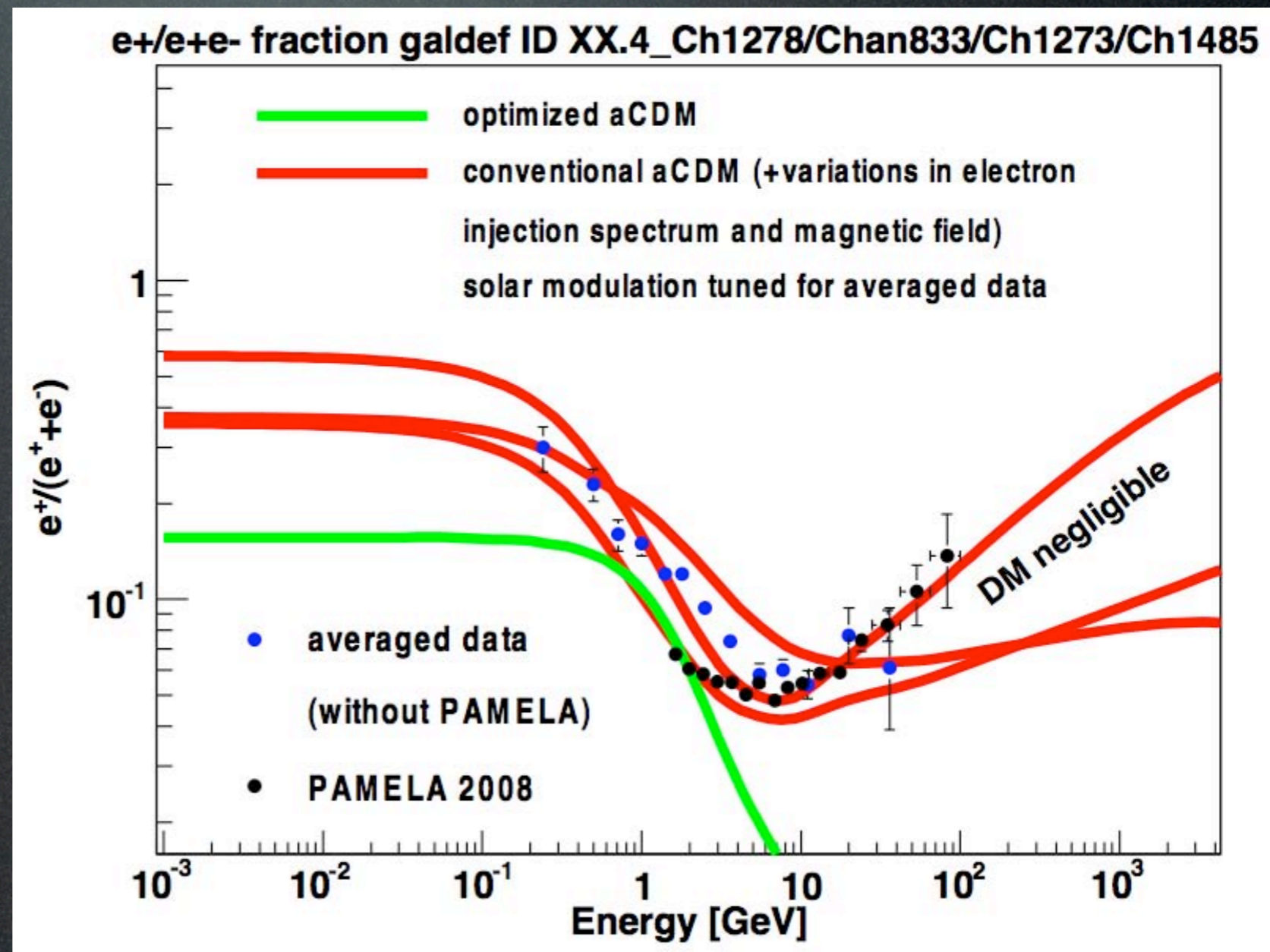


Indirect Detection

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)

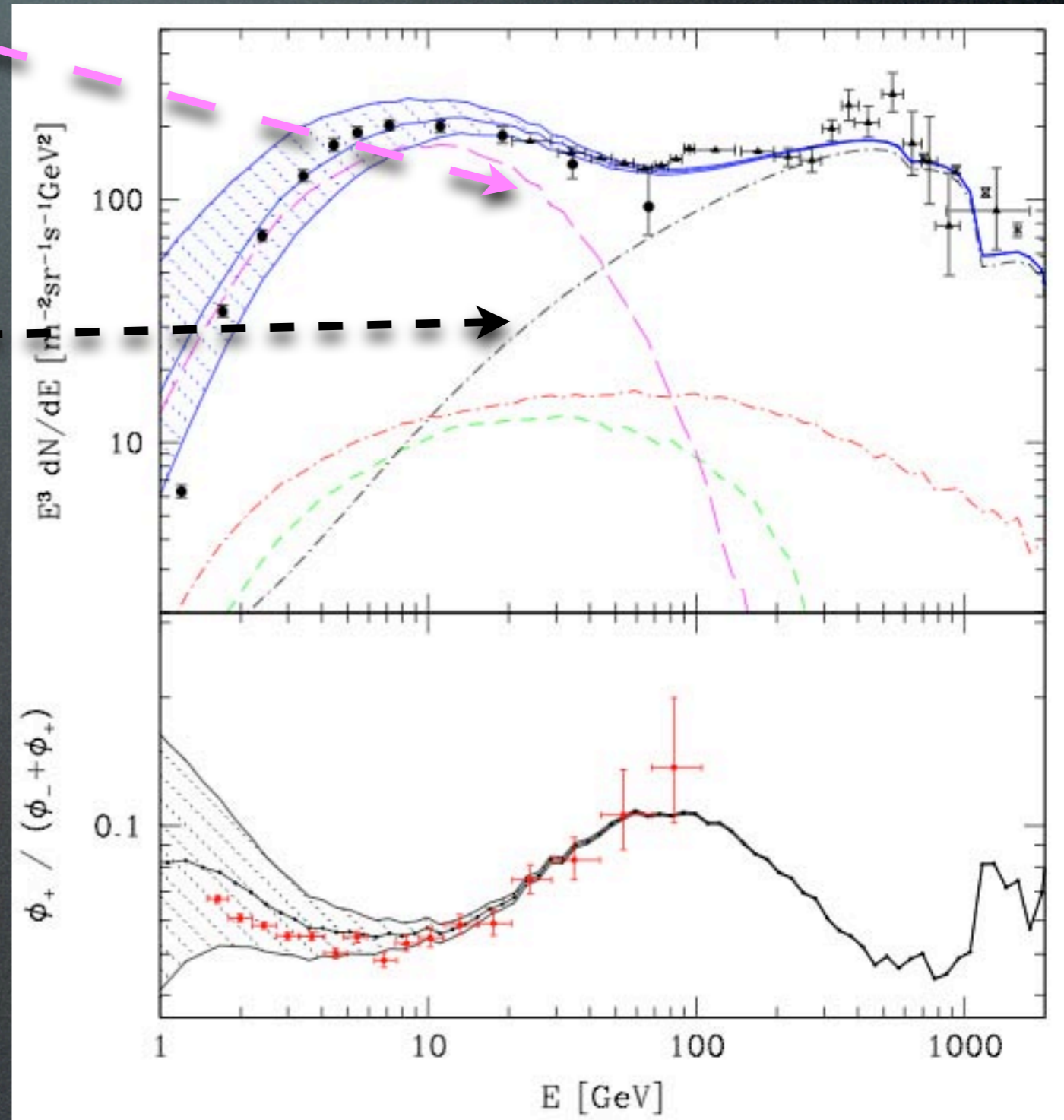


Indirect Detection

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



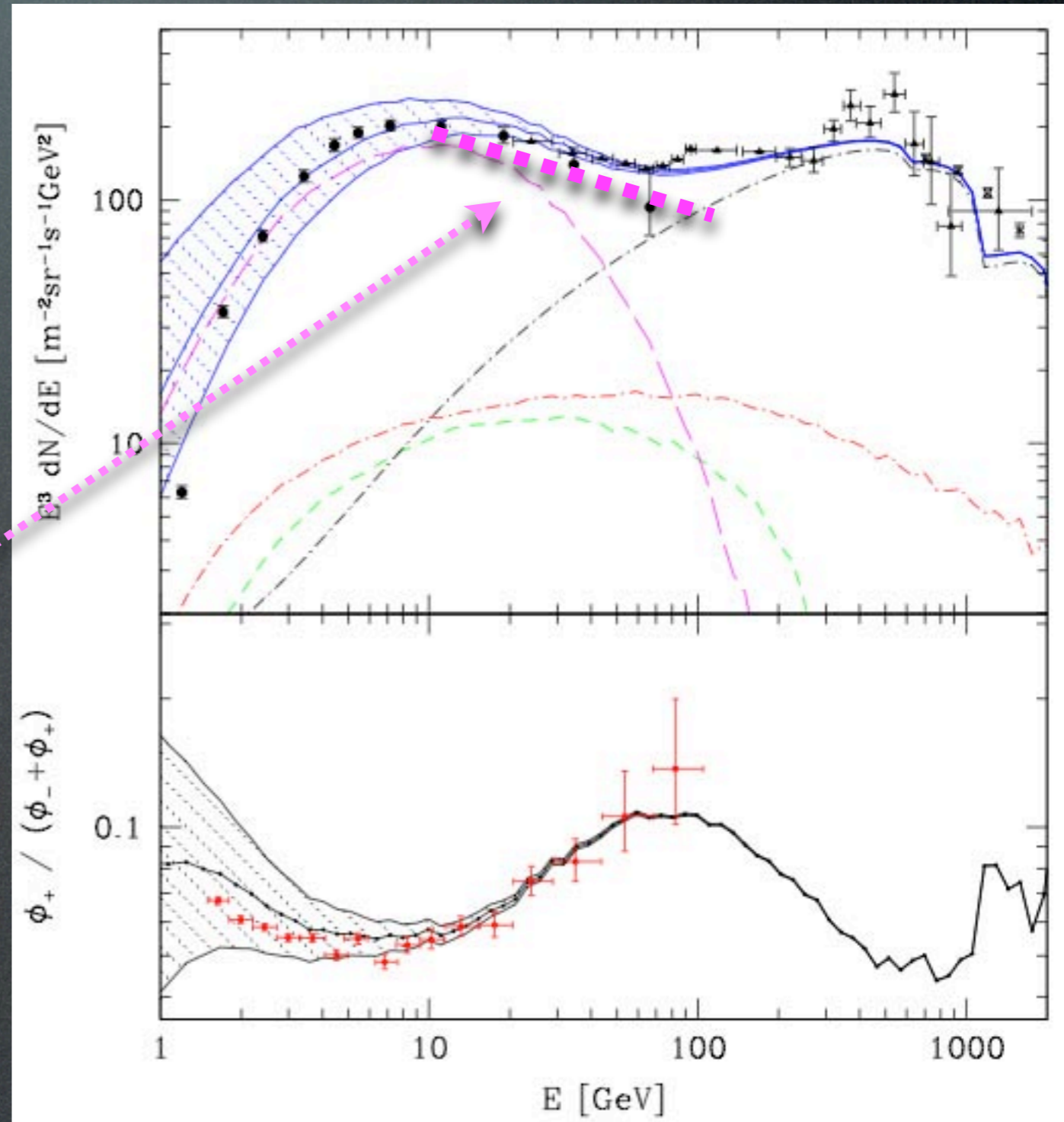
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But: preliminary PAMELA data on absolute e^- flux show harder spectrum ($E^{-3.33}$) than this prediction...; do nearby sources agree with B/C...?

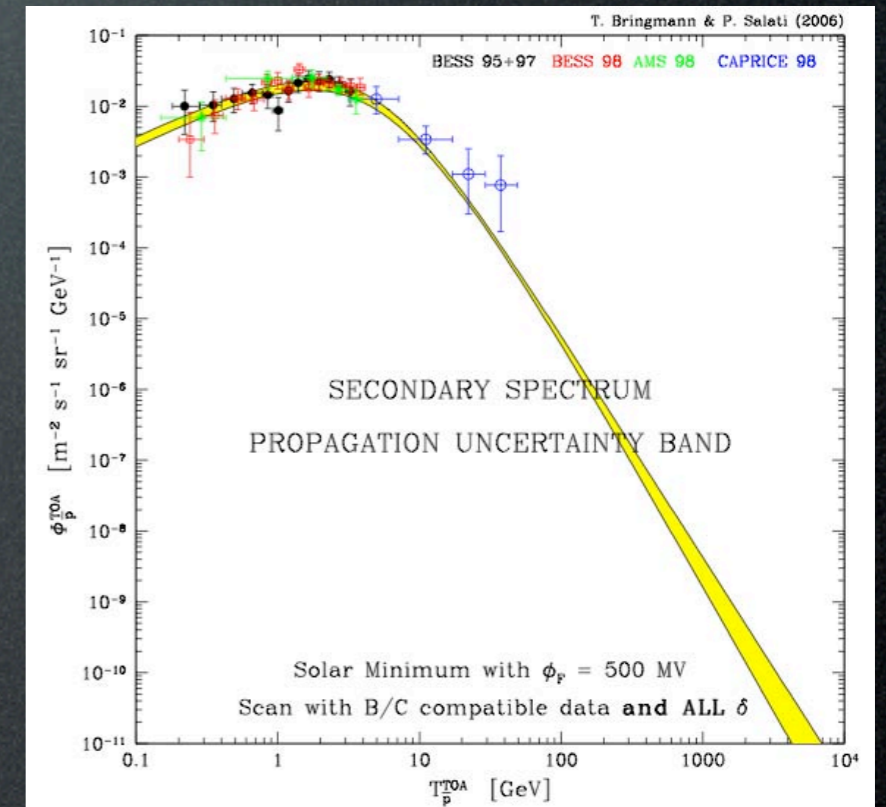
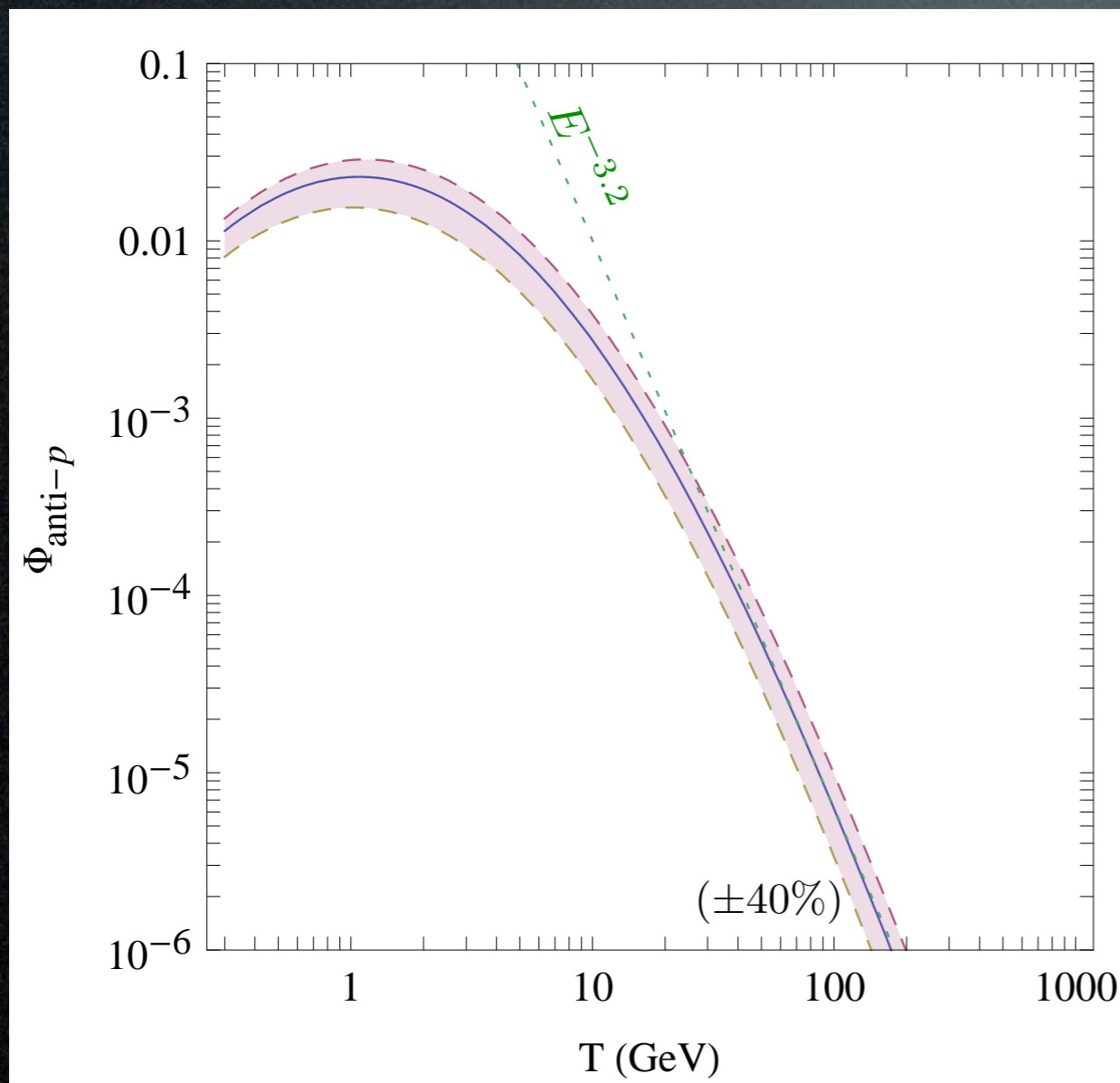


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Bringmann, Salati 2006



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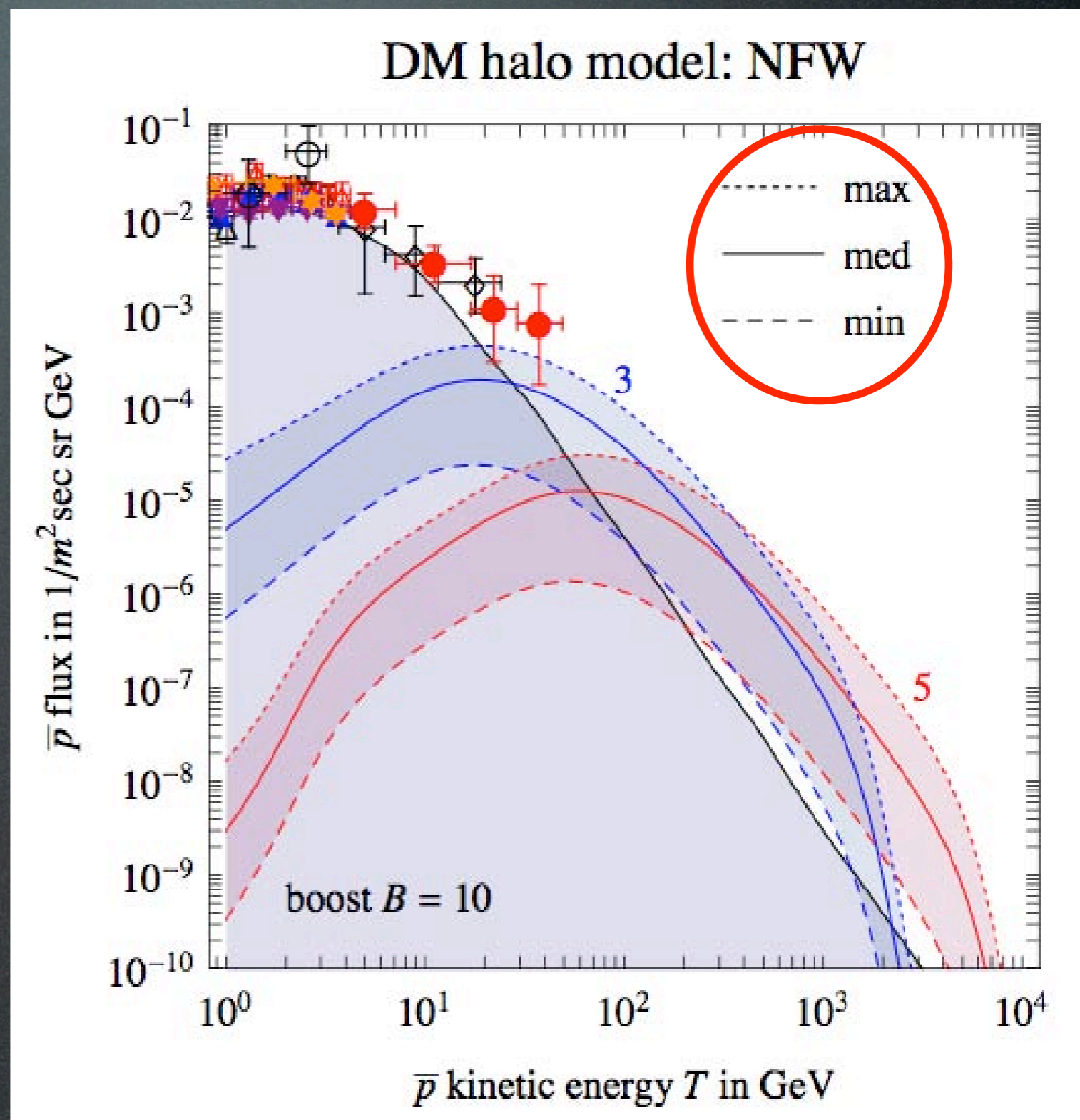
[back]

Indirect Detection

Results for **anti-protons**:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B

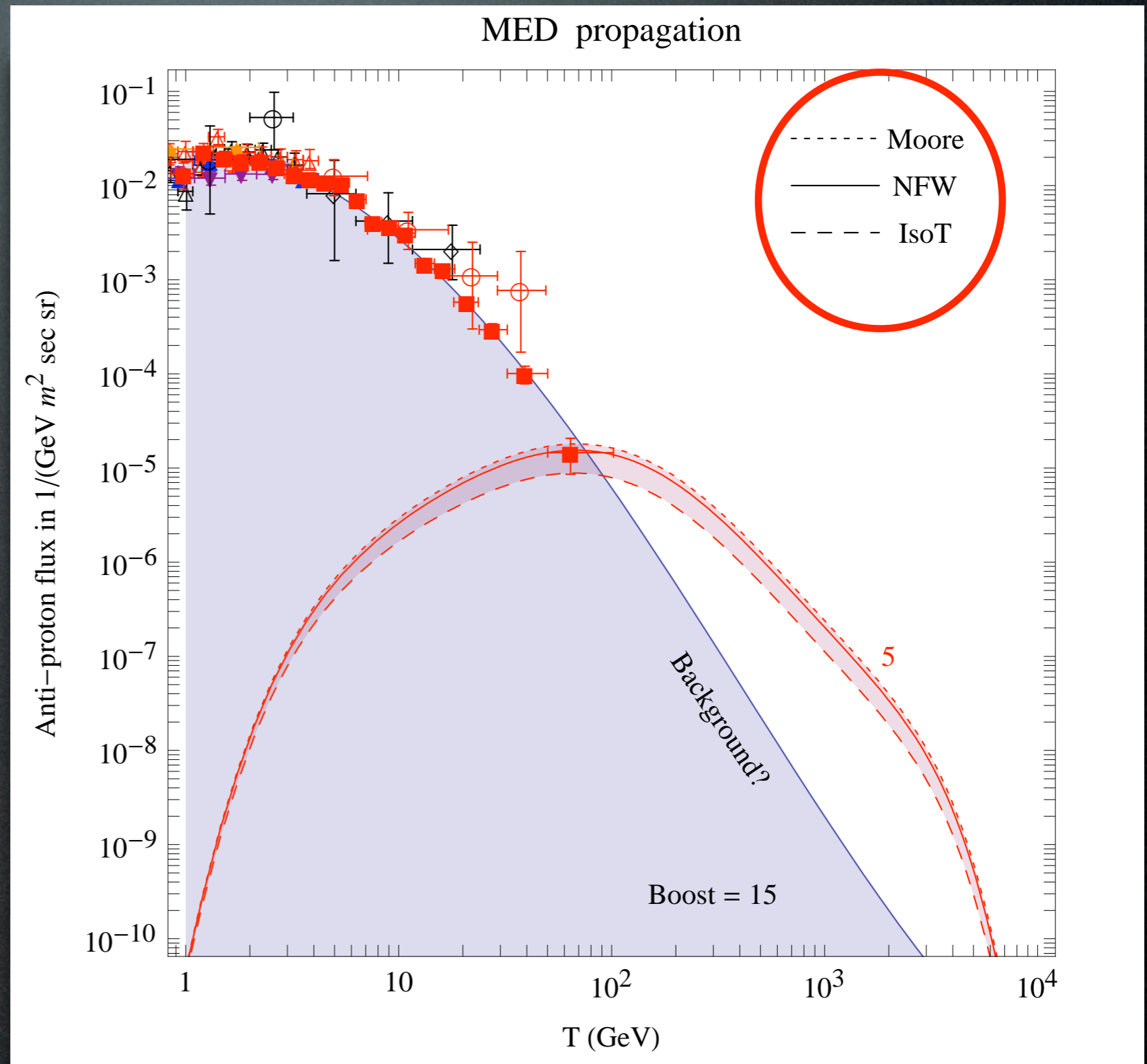


Indirect Detection

Results for **anti-protons**:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



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

$$\sigma_{\text{ann}}(\text{DM DM} \rightarrow f \bar{f}) \propto \left(\frac{m_f}{M_{\text{DM}}} \right)^2$$

Results

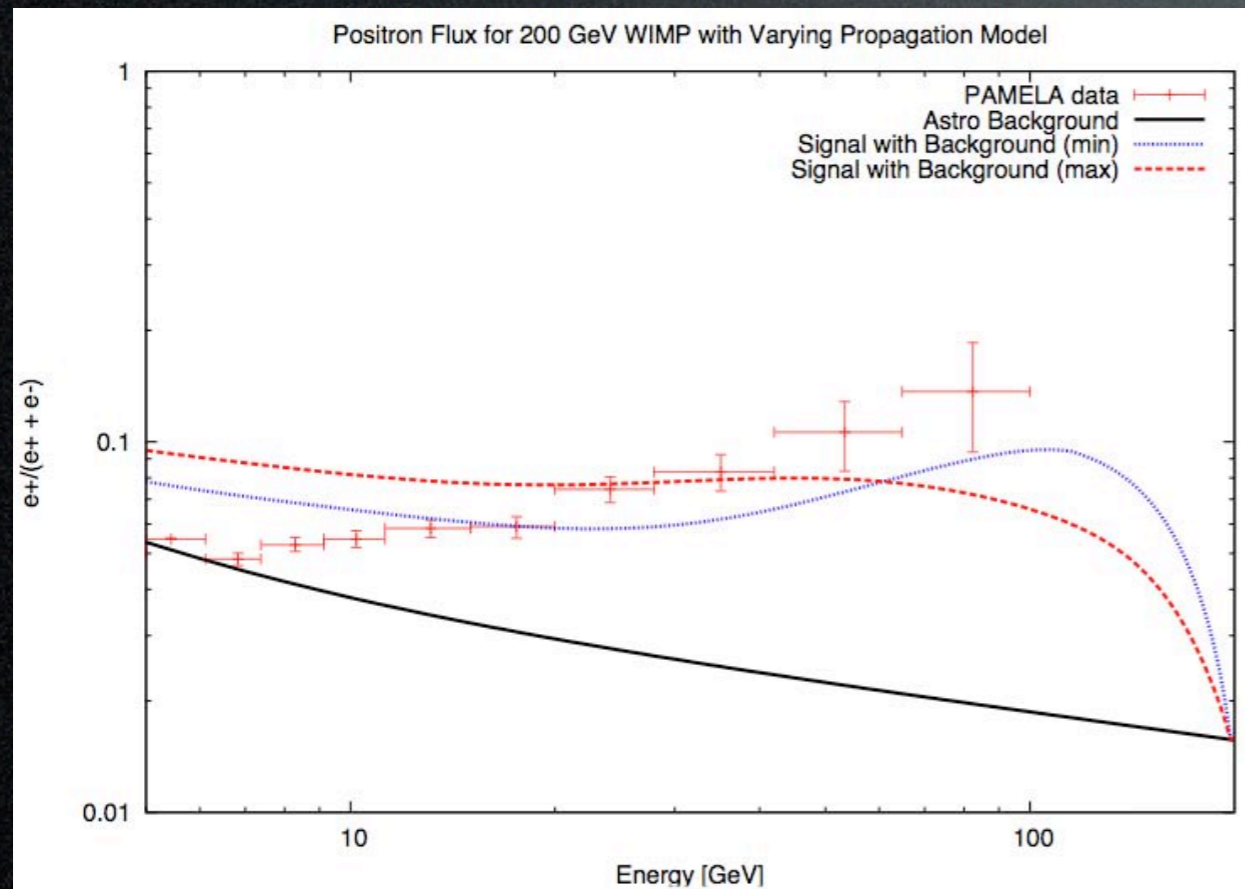
Which DM spectra can fit the data?

Ok, let's *insist* on Wino with: -mass $M_{\text{DM}} = 200 \text{ GeV}$
-annihilation $\text{DM DM} \rightarrow W^+ W^-$

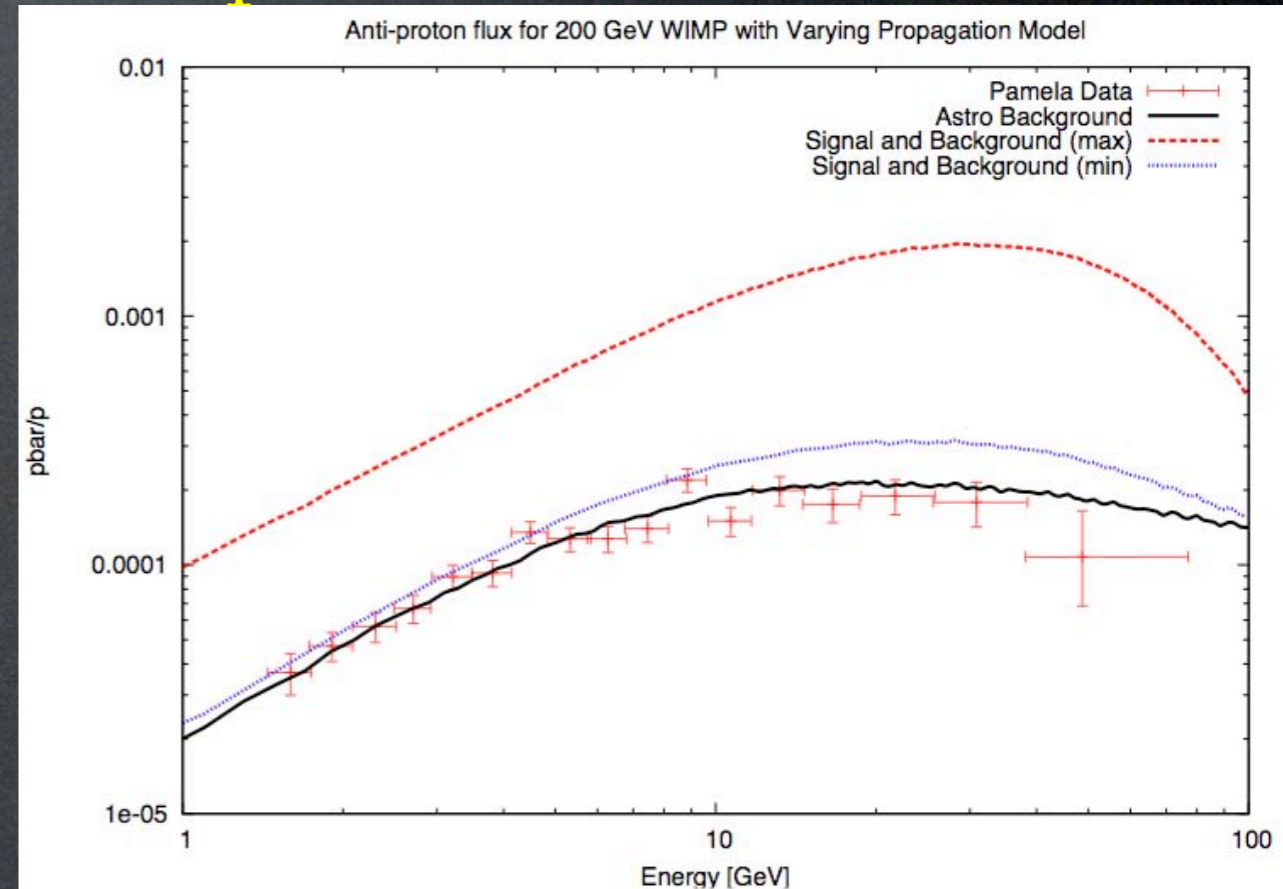
- If one:
- assumes non-thermal production of DM
 - takes positron energy loss 5 times larger than usual
 - takes “min” propagation only
 - gives up ATIC
 - neglects conflict with EGRET bound (4 times too many gammas)

then:

Positrons:



Anti-protons:



Results

Which DM spectra can fit the data?

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

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

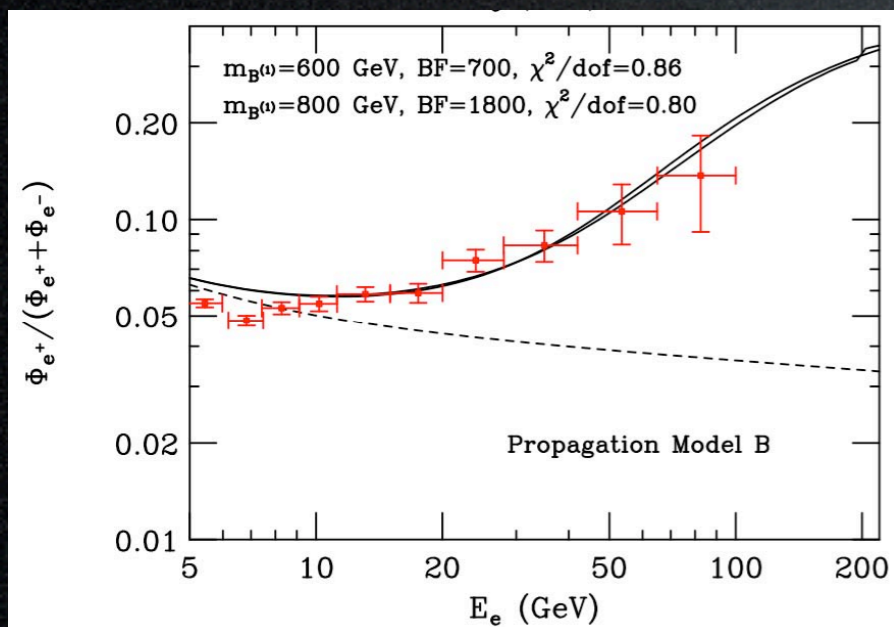
-annihilation $DM DM \rightarrow l^+ l^- (BR = 60\%)$
 $DM DM \rightarrow q\bar{q} (BR = 35\%)$

Good fit with: - boost $B = 1800$
 - propagation model

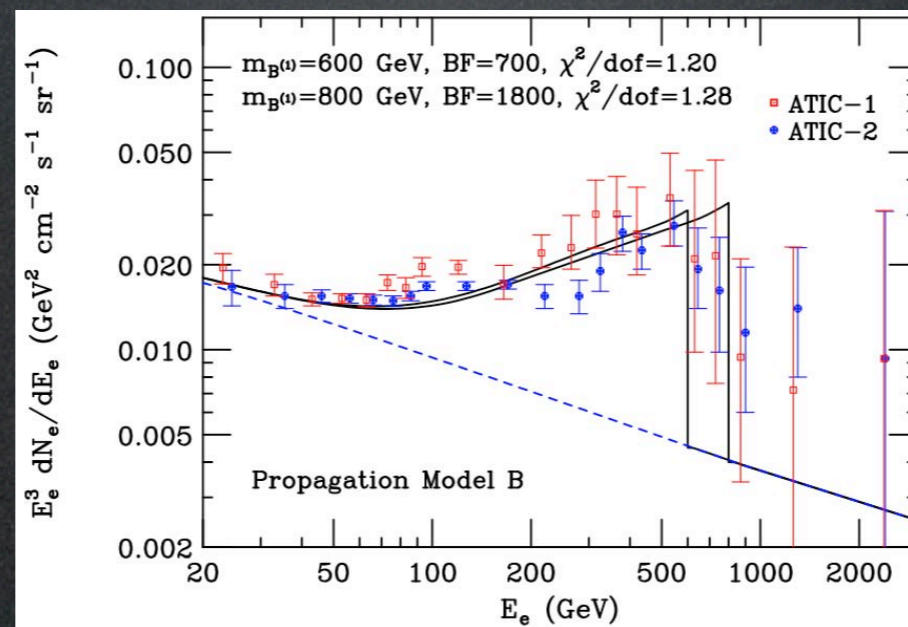
B: $K(E_e) = 1.4 \times 10^{28} (E_e/4 \text{ GeV})^{0.43} \text{ cm}^2/\text{s}, L=1 \text{ kpc}$

very large energy loss with very small L

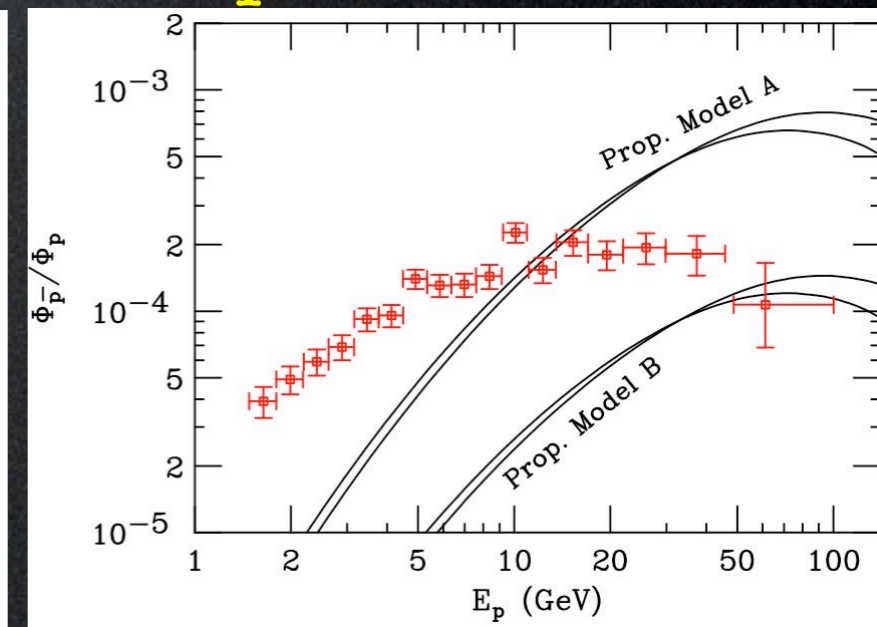
Positrons:



Electrons + Positrons:



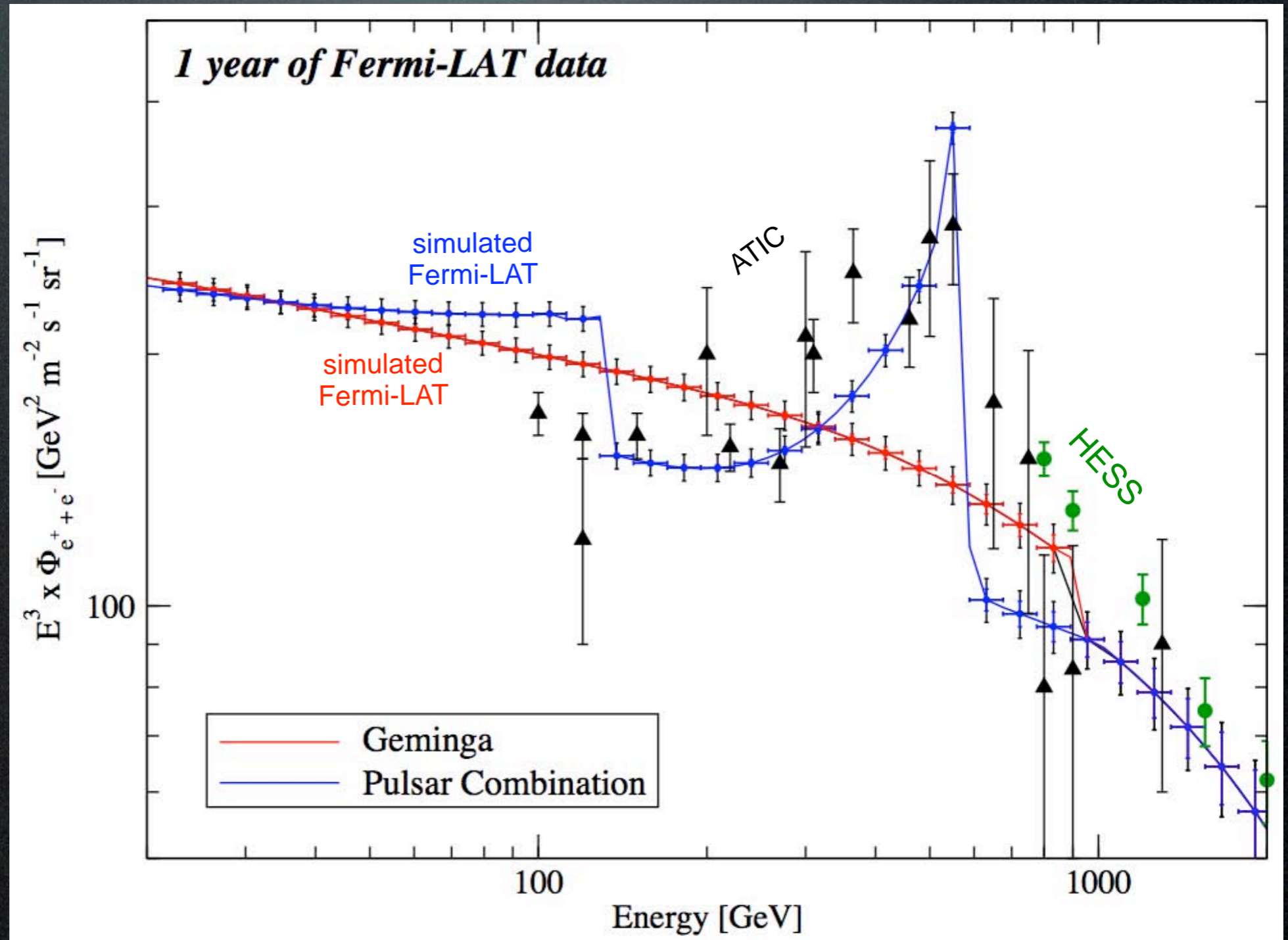
Anti-protons:



Data sets

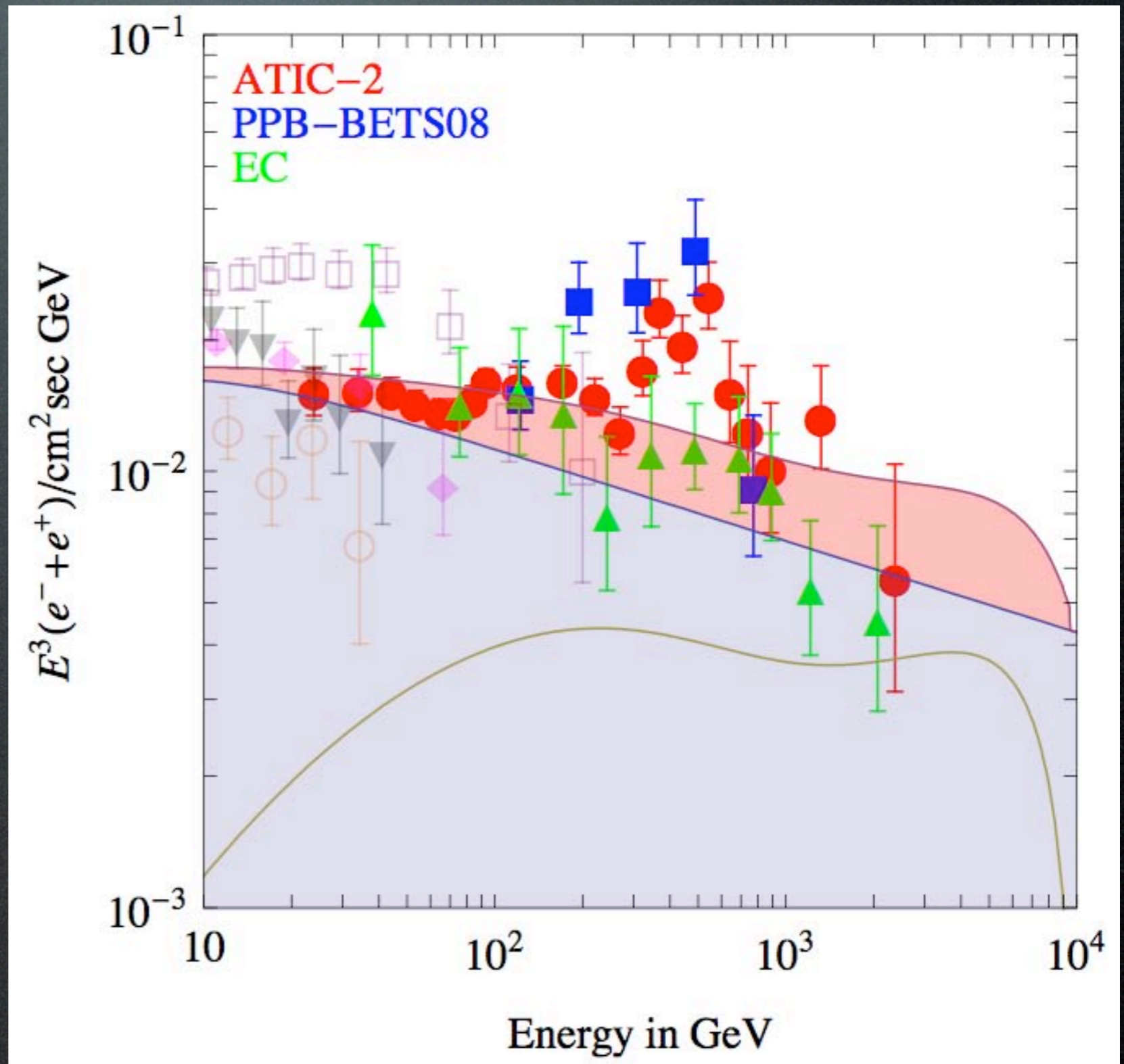
Electrons + positrons from Fermi-LAT:

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



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: Pyrra 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

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- TeV mass DM

- new forces (that Sommerfeld enhance)

- leptophilic because: - kinematics (light mediator)

- DM carries lepton #

- 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

The “Theory of DM”

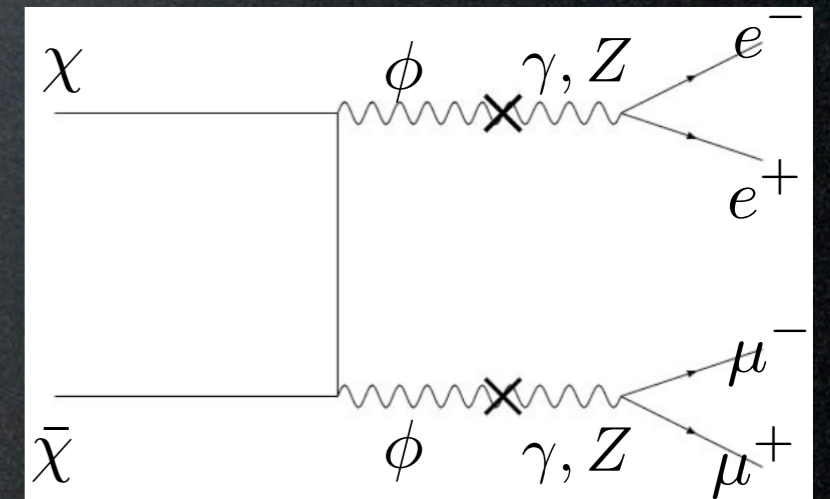
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

- χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV
- ϕ new gauge boson (“Dark photon”),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:

$$\alpha M/m_V \gtrsim 1 \quad \text{fulfilled}$$

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



The “Theory of DM”

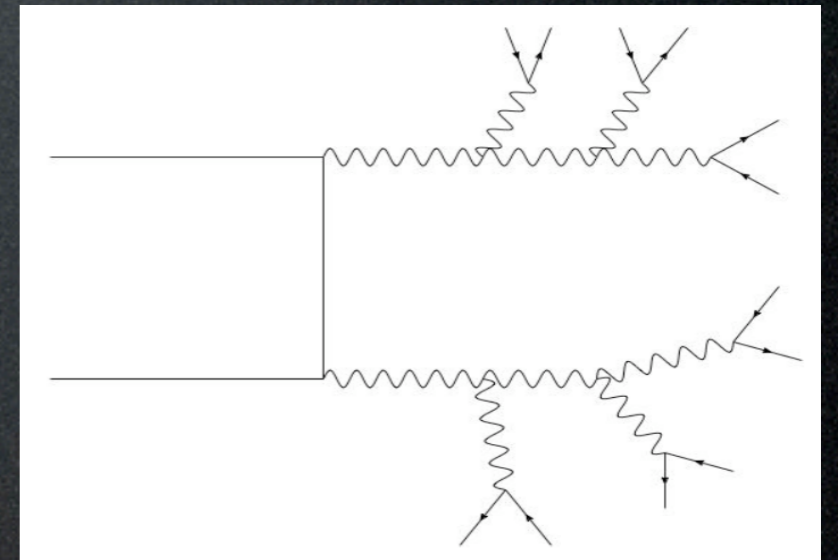
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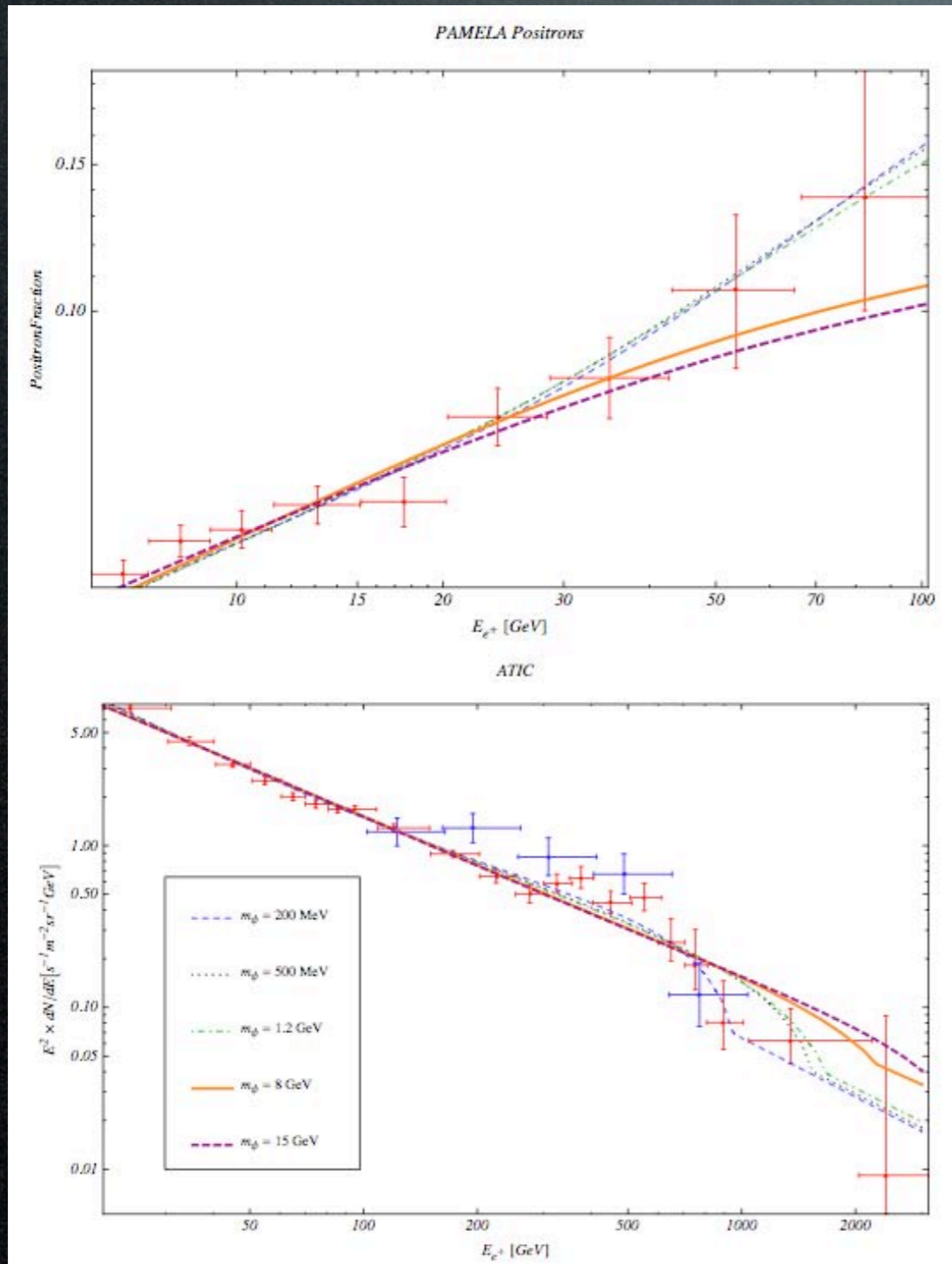


Extras:

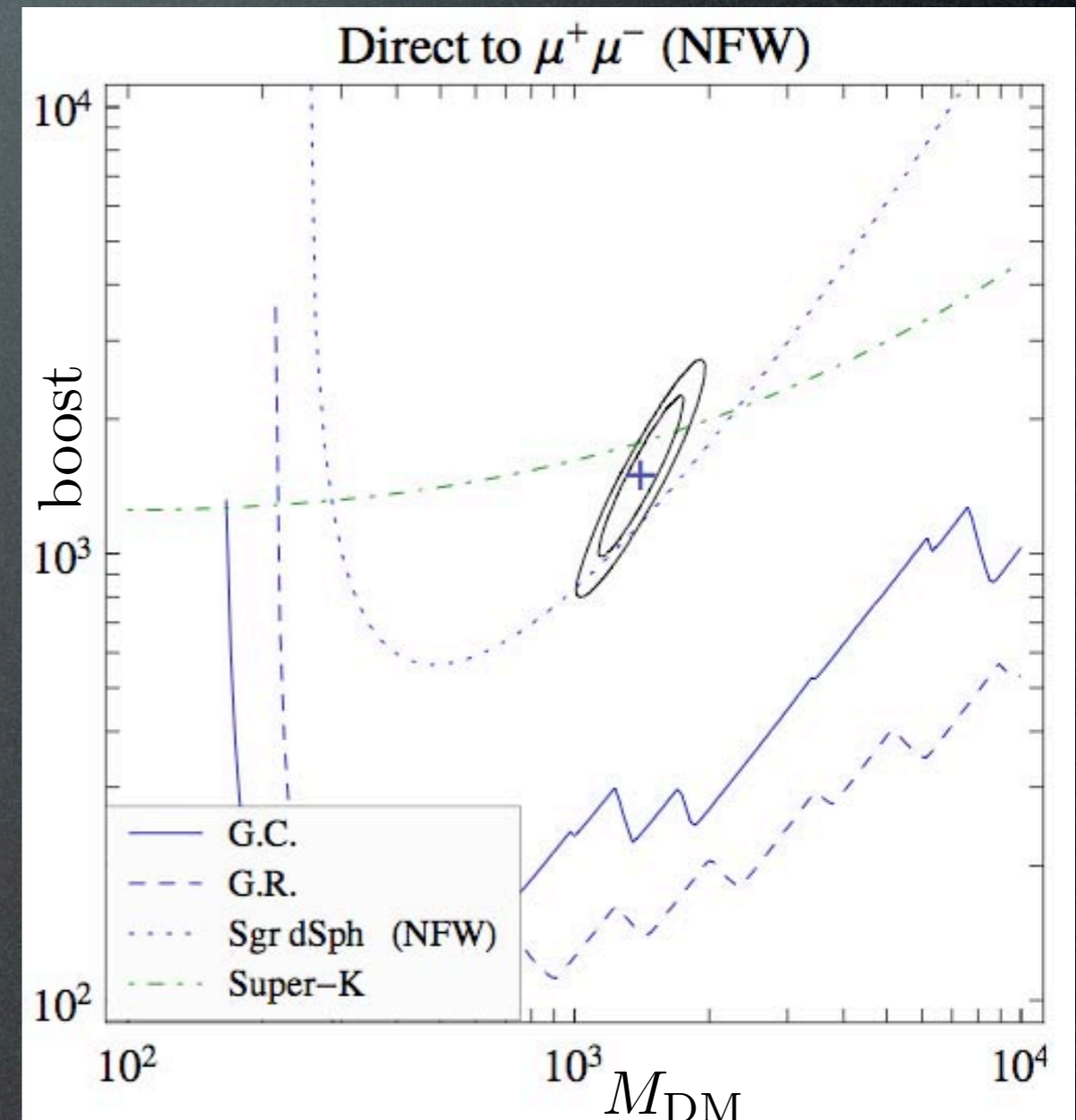
- χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- excited state decay $\chi\chi \rightarrow \chi\chi^* \hookrightarrow e^+e^-$ explains INTEGRAL

The “Theory of DM”

Phenomenology:



Meade, Papucci, Volanski
0901.2925



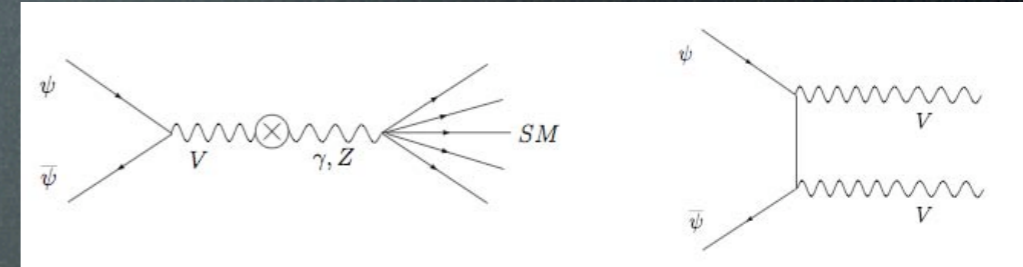
Mardon, Nomura, Stolarski,
Thaler 0901.2926

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

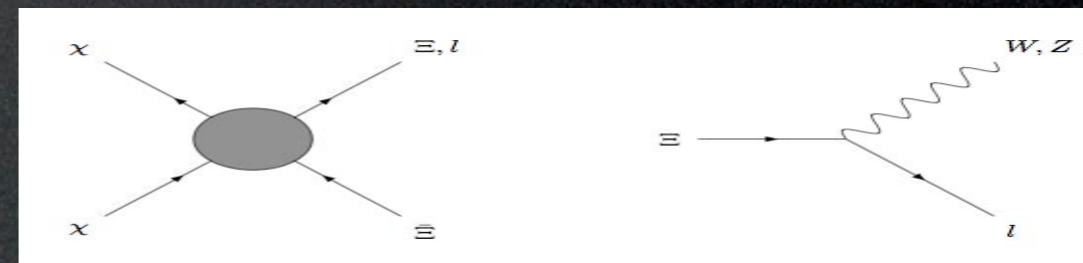
- ★ DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson ($m_\phi \sim$ tens GeV)

Cirelli, Kadastik, Raidal, Strumia 0809.2409

Fox, Poppitz 0811.0399

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

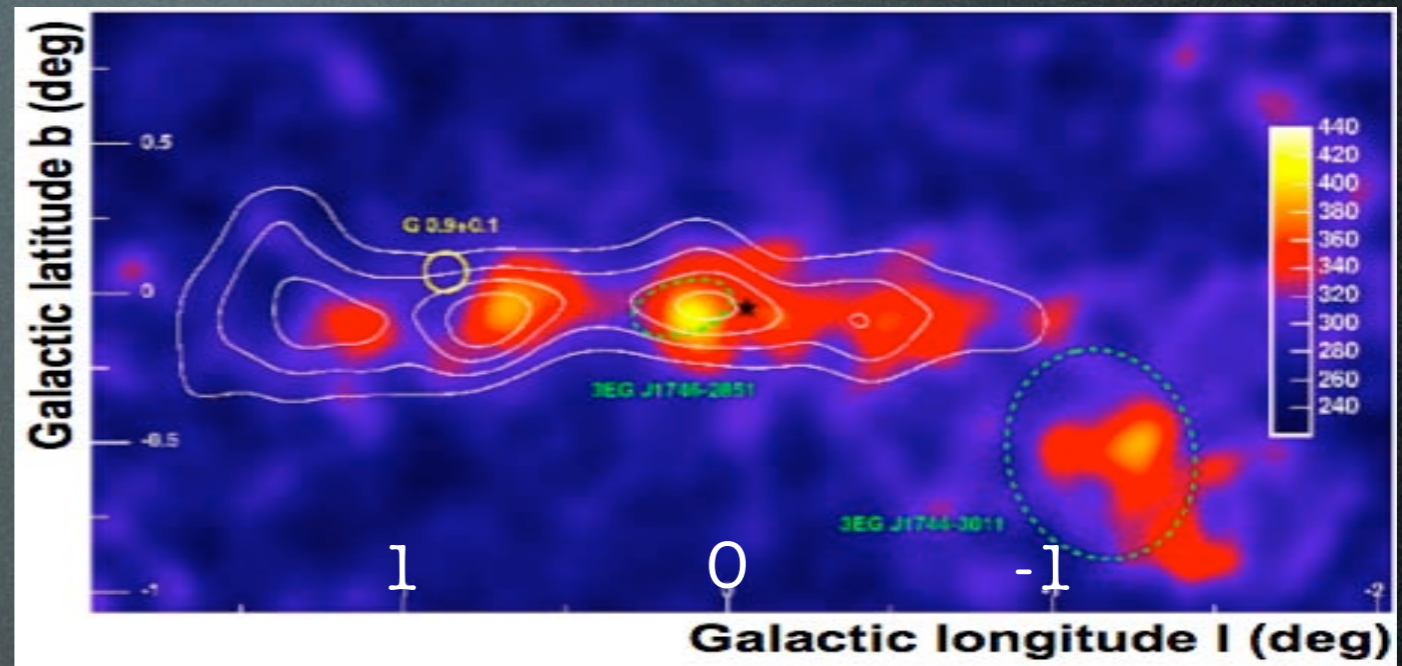
Phalen, Pierce, Weiner 0901.3165



- ★

Gamma constraints

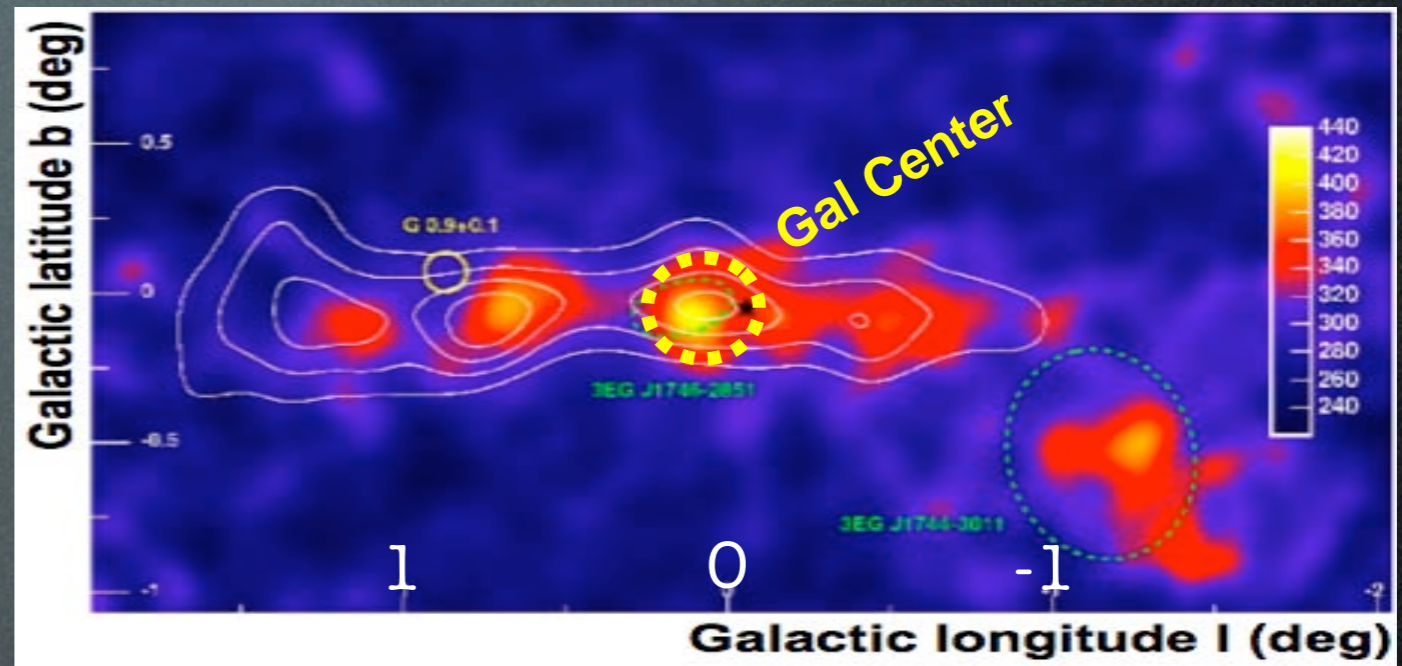
HESS has detected γ -ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.



HESS coll.

Gamma constraints

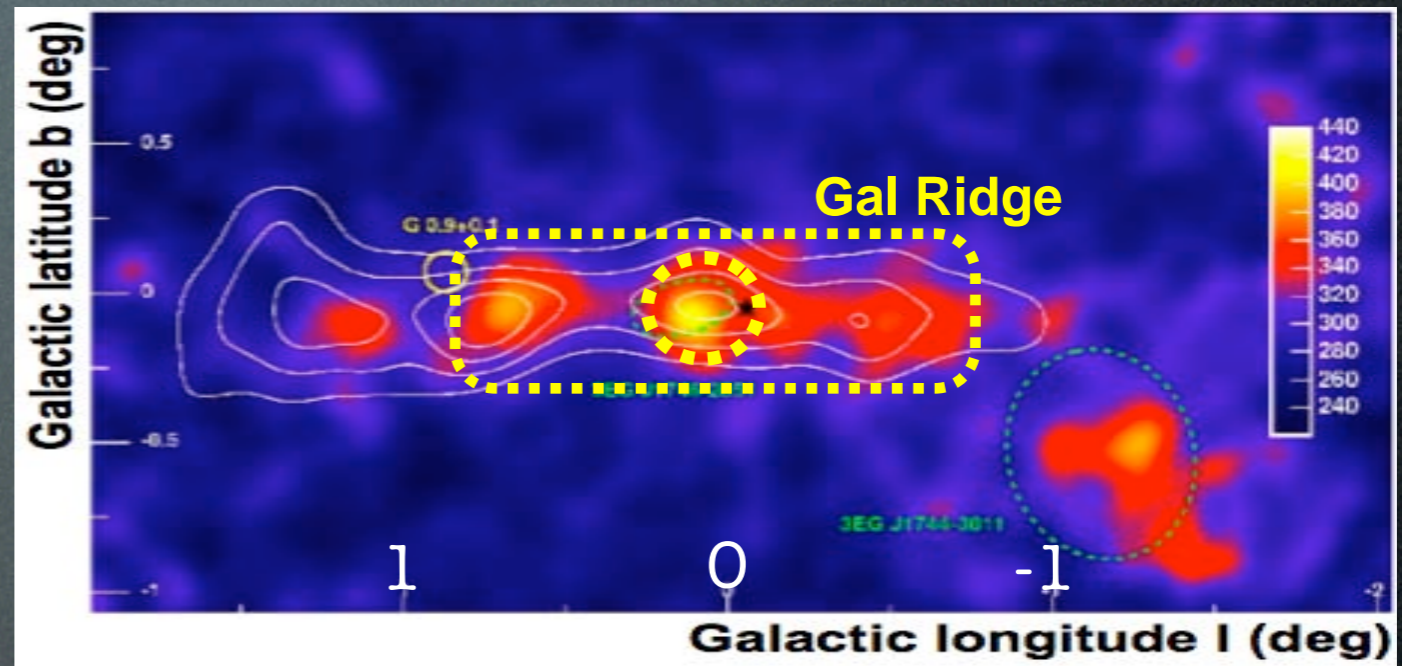
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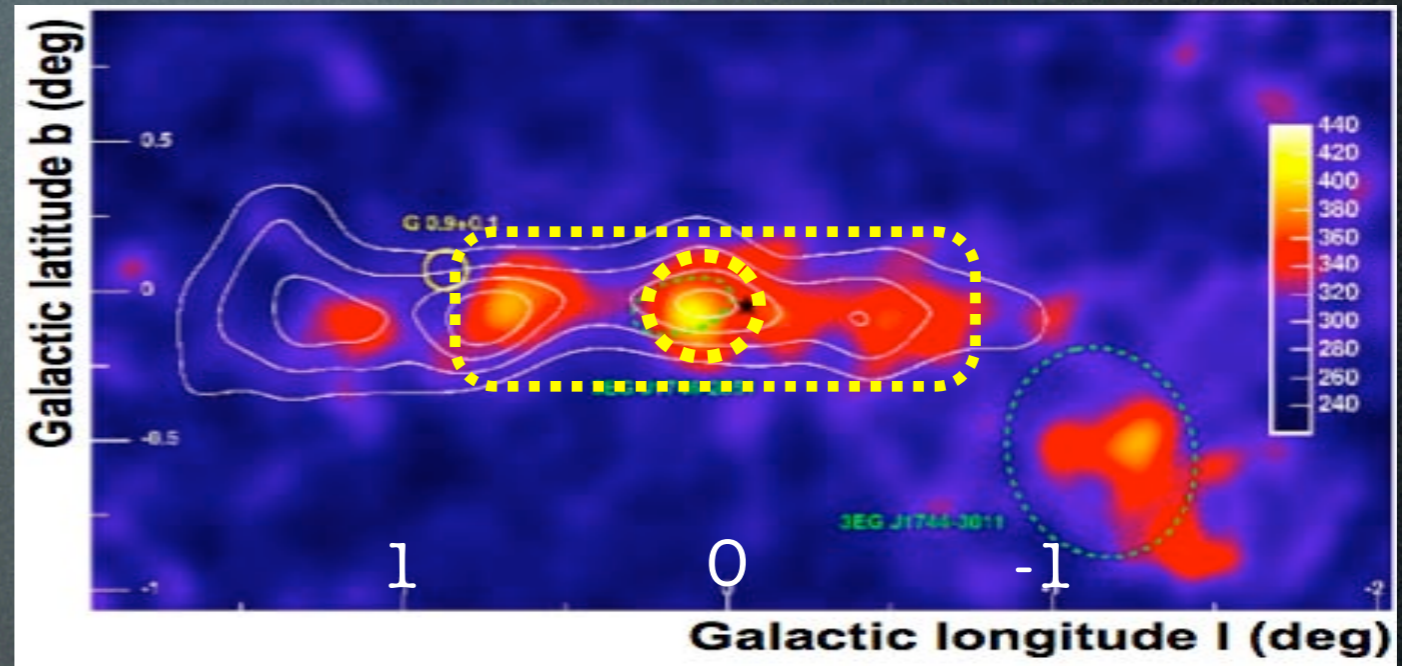
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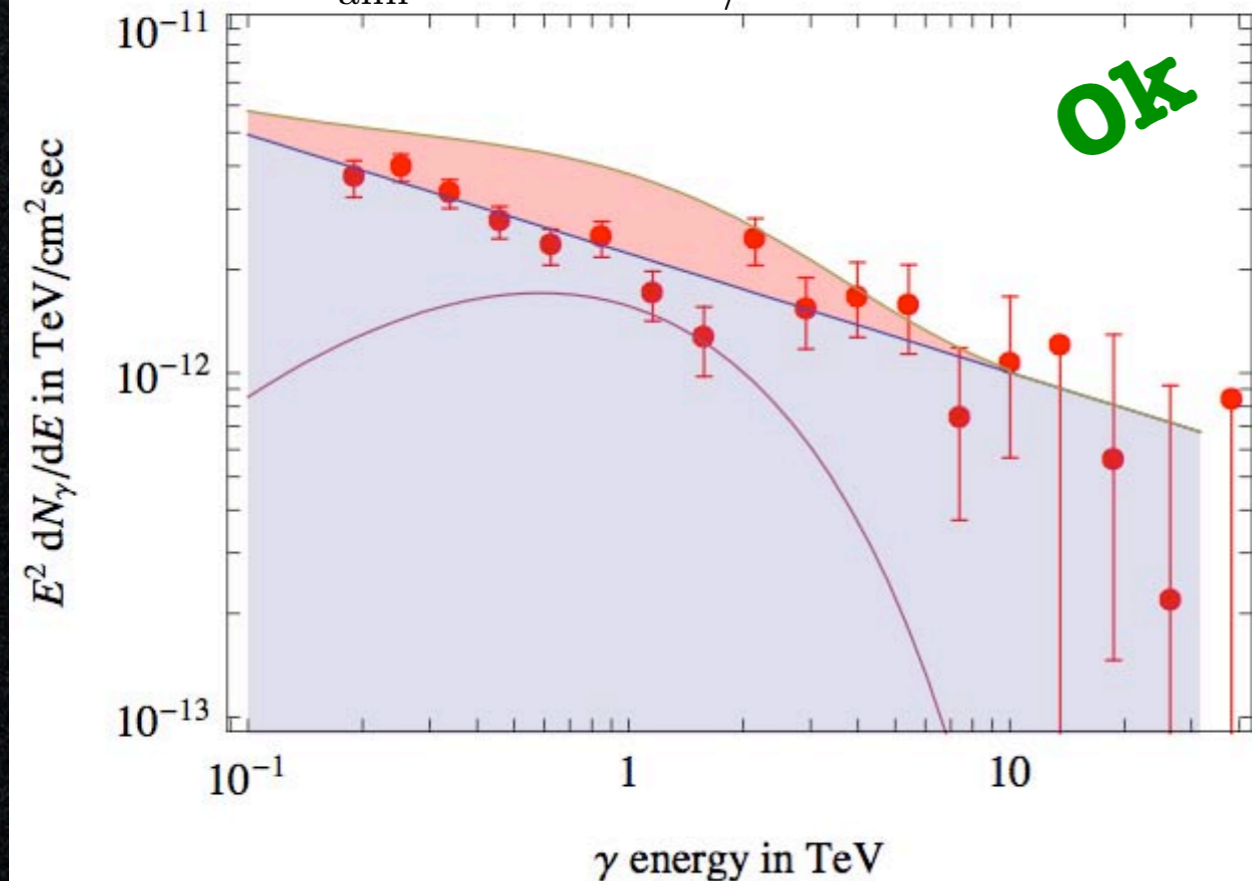
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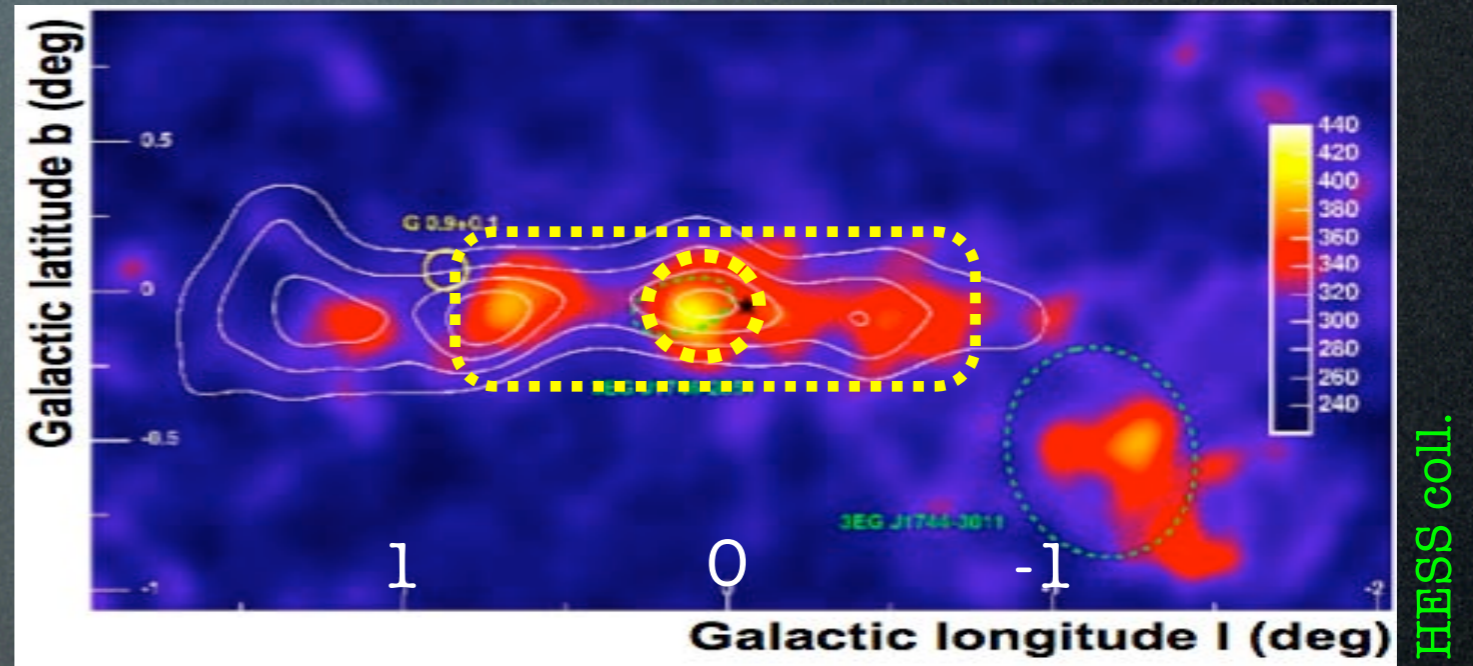
a) $M = 10$ TeV into W^+W^- , Galactic Center
 $\sigma v_{\text{ann}} = 10^{-23} \text{cm}^3/\text{sec}$



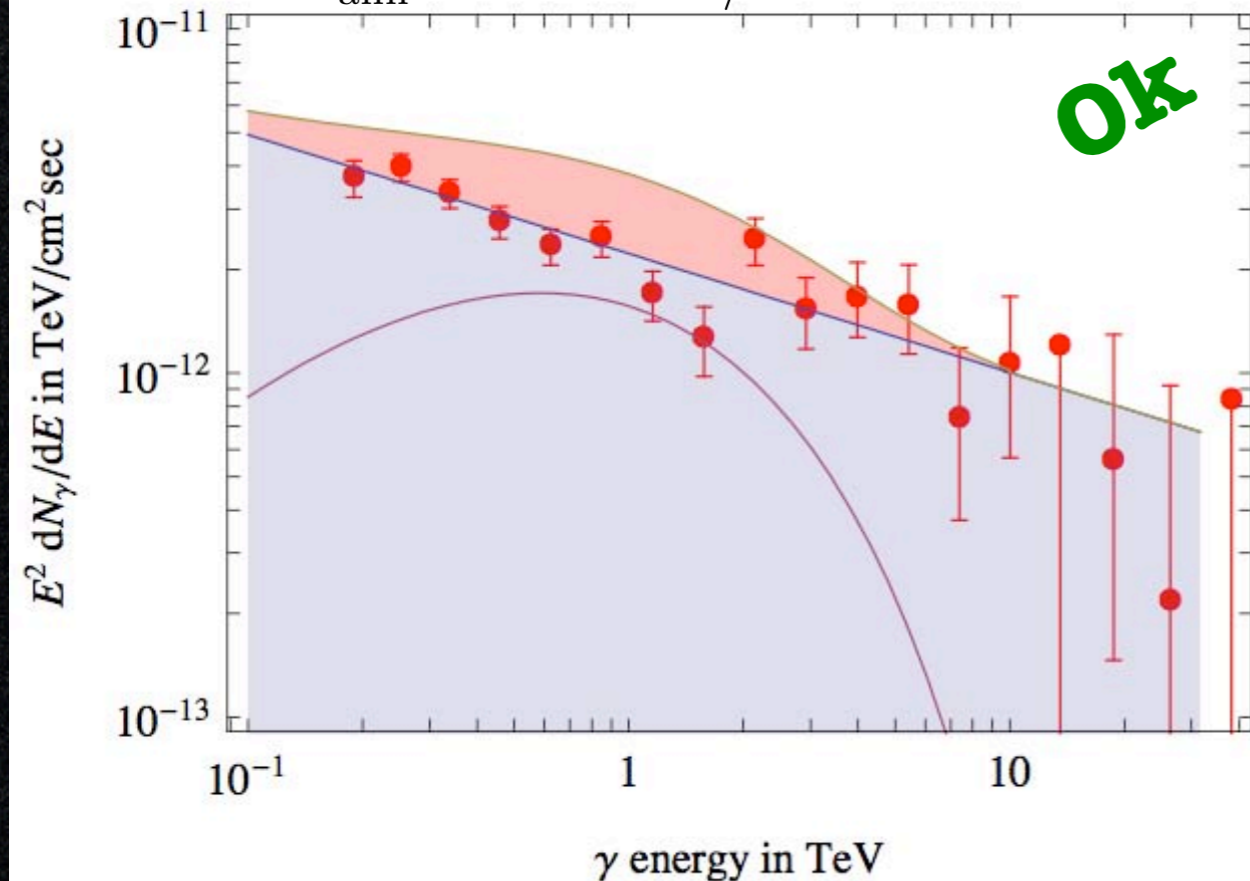
Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

Gamma constraints

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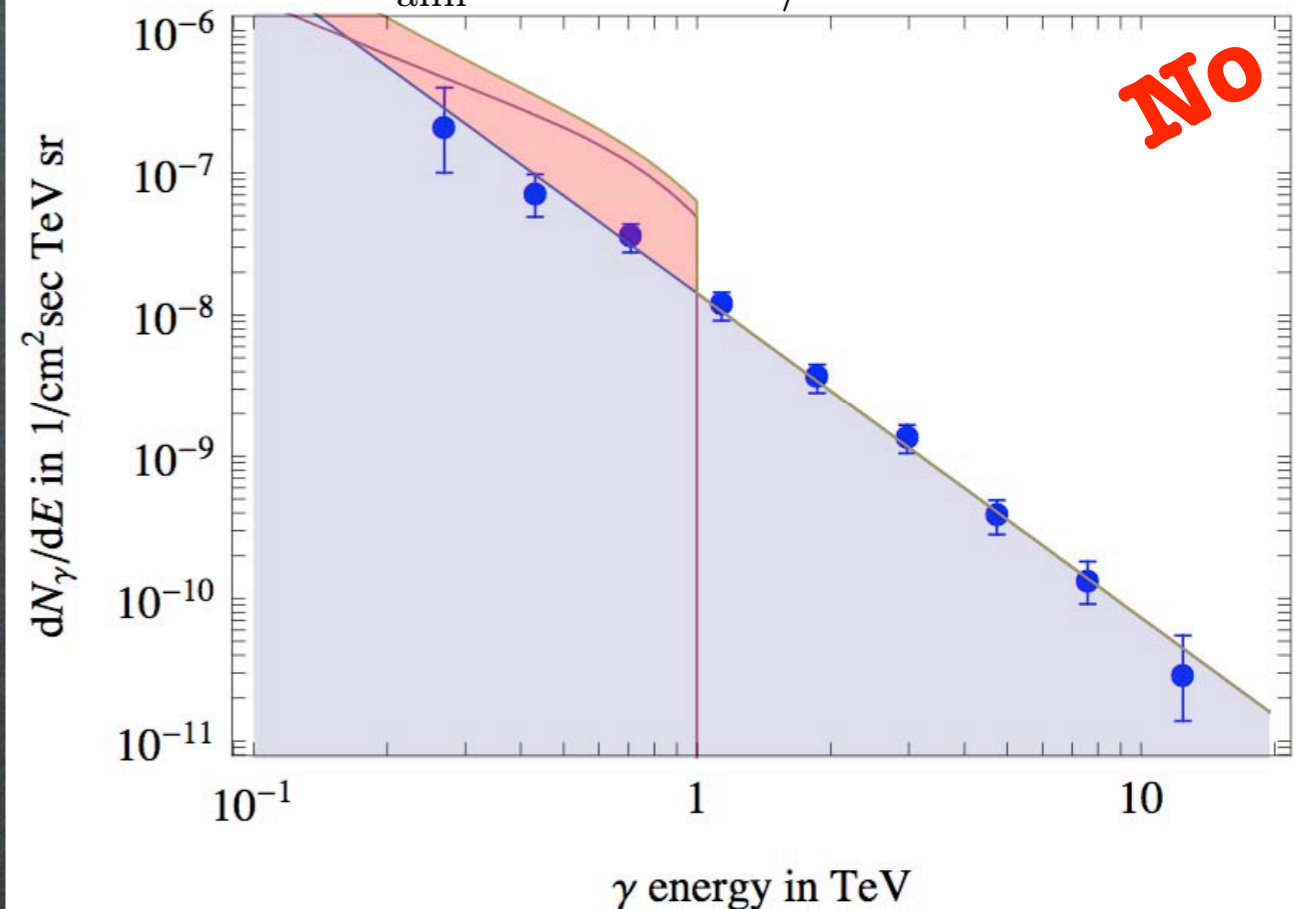


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b) $M = 1$ TeV into $\mu^-\mu^+$, Galactic Ridge
 $\sigma v_{\text{ann}} = 10^{-23} \text{ cm}^3/\text{sec}$

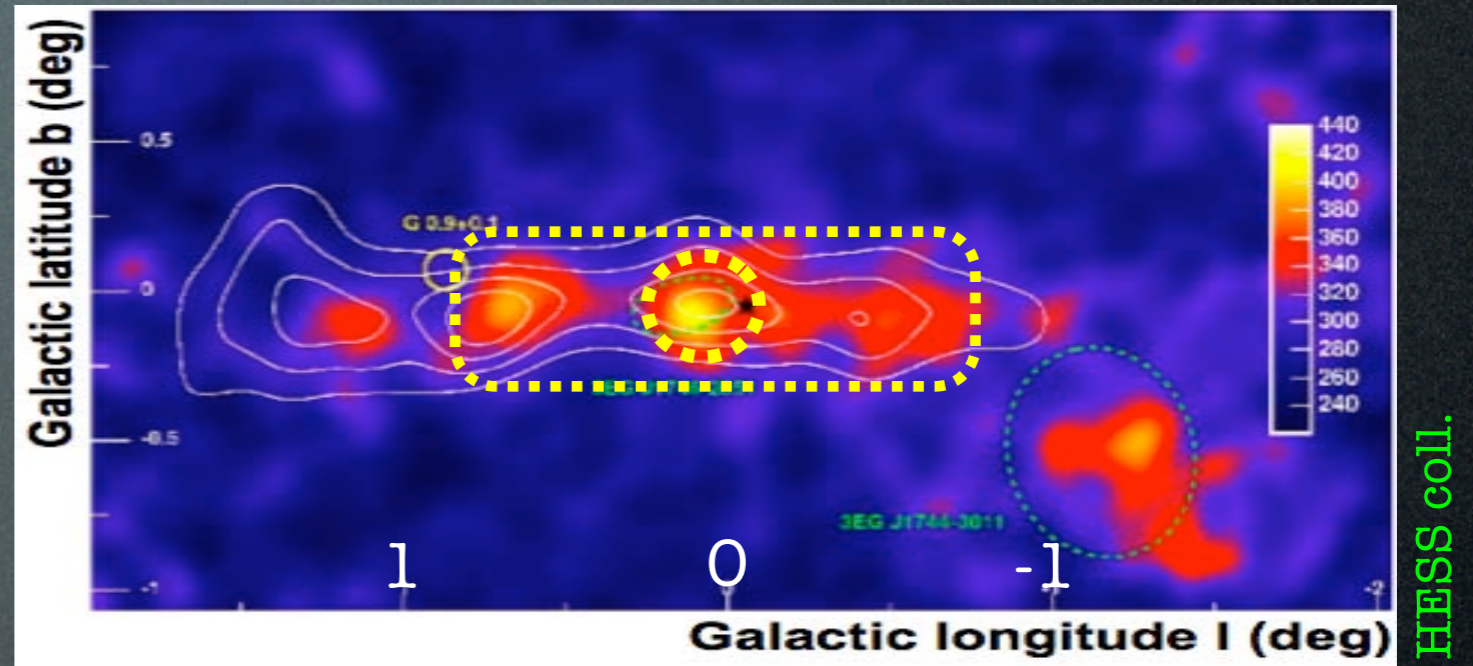


Data: HESS coll., astro-ph/0603021

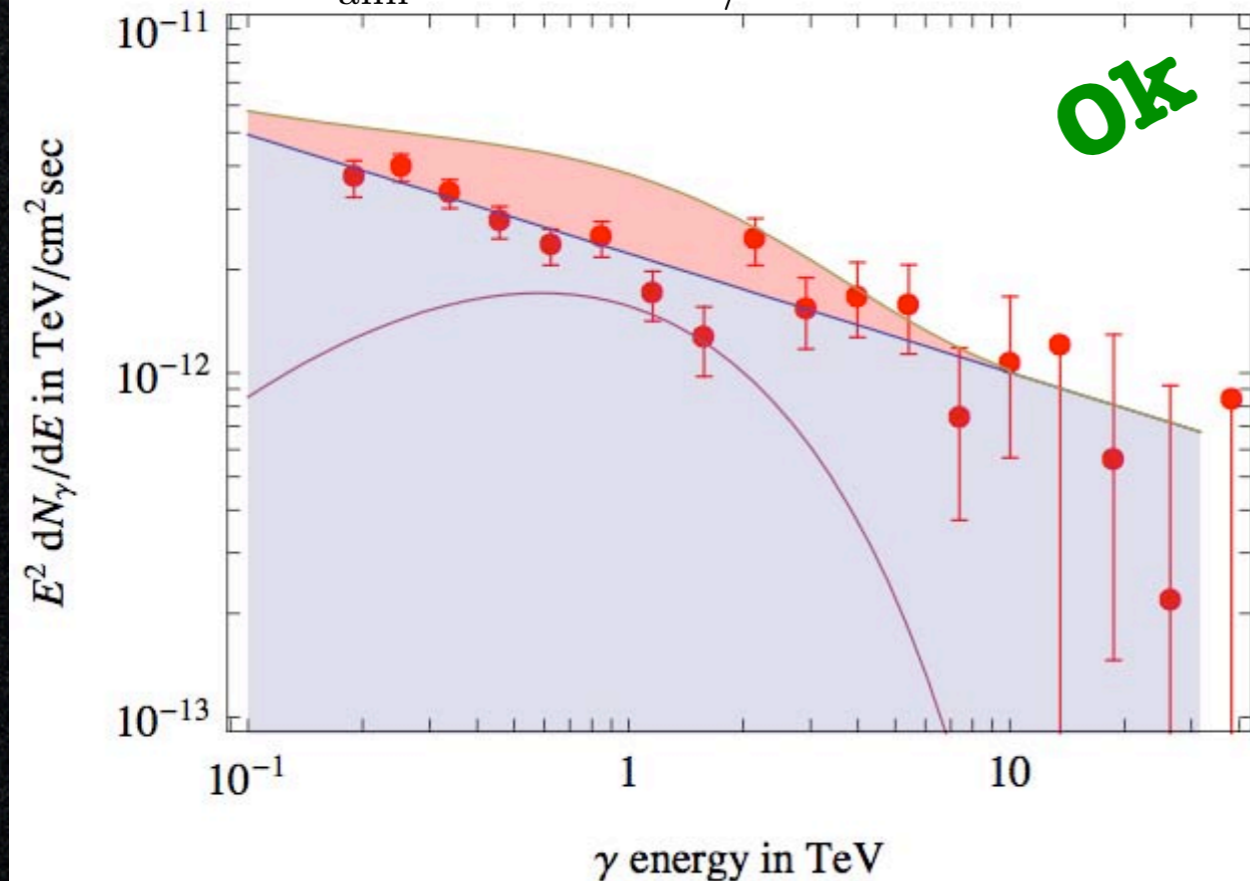
Gamma constraints

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

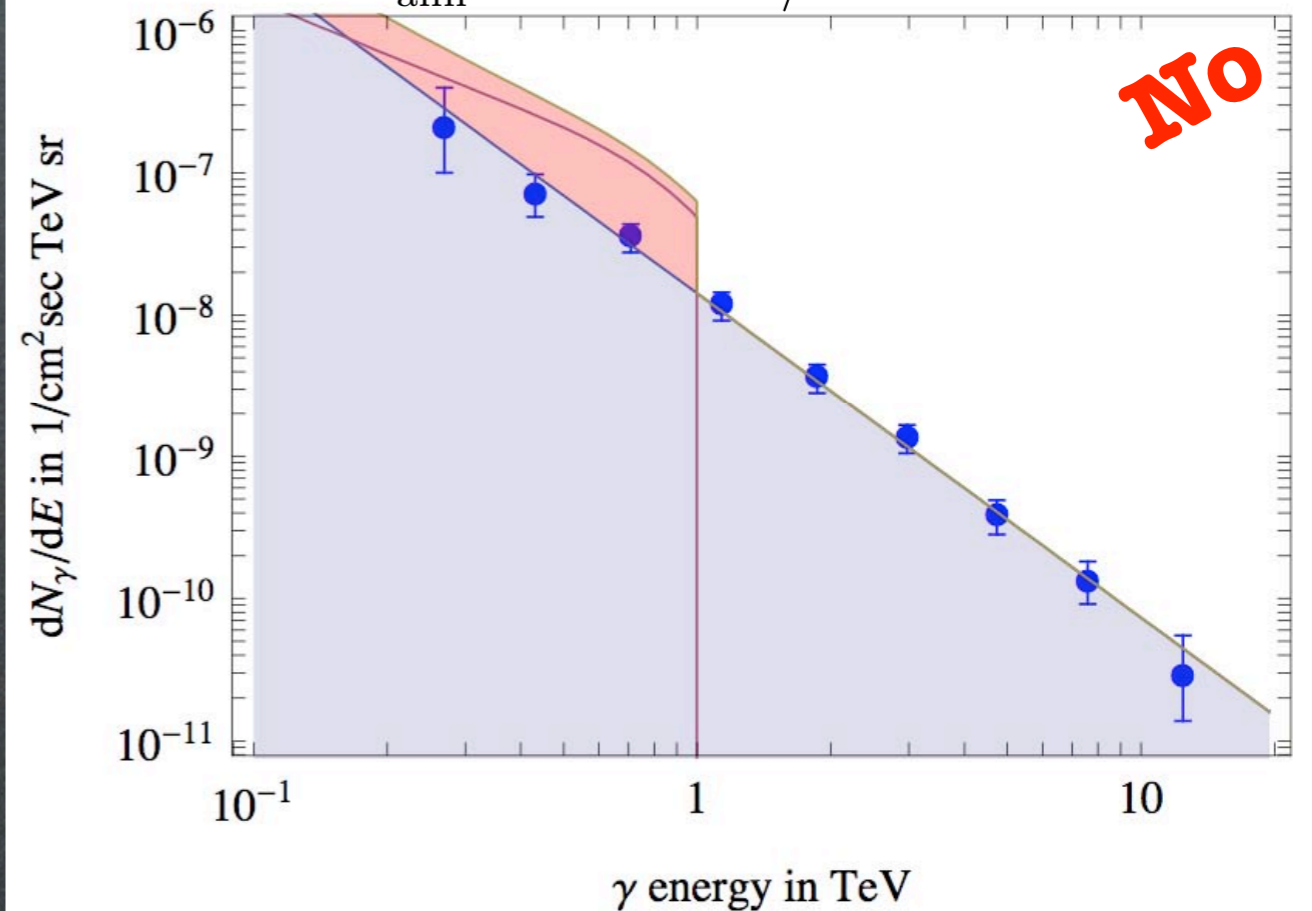
Moreover: no detection from Sgr dSph => upper bound.



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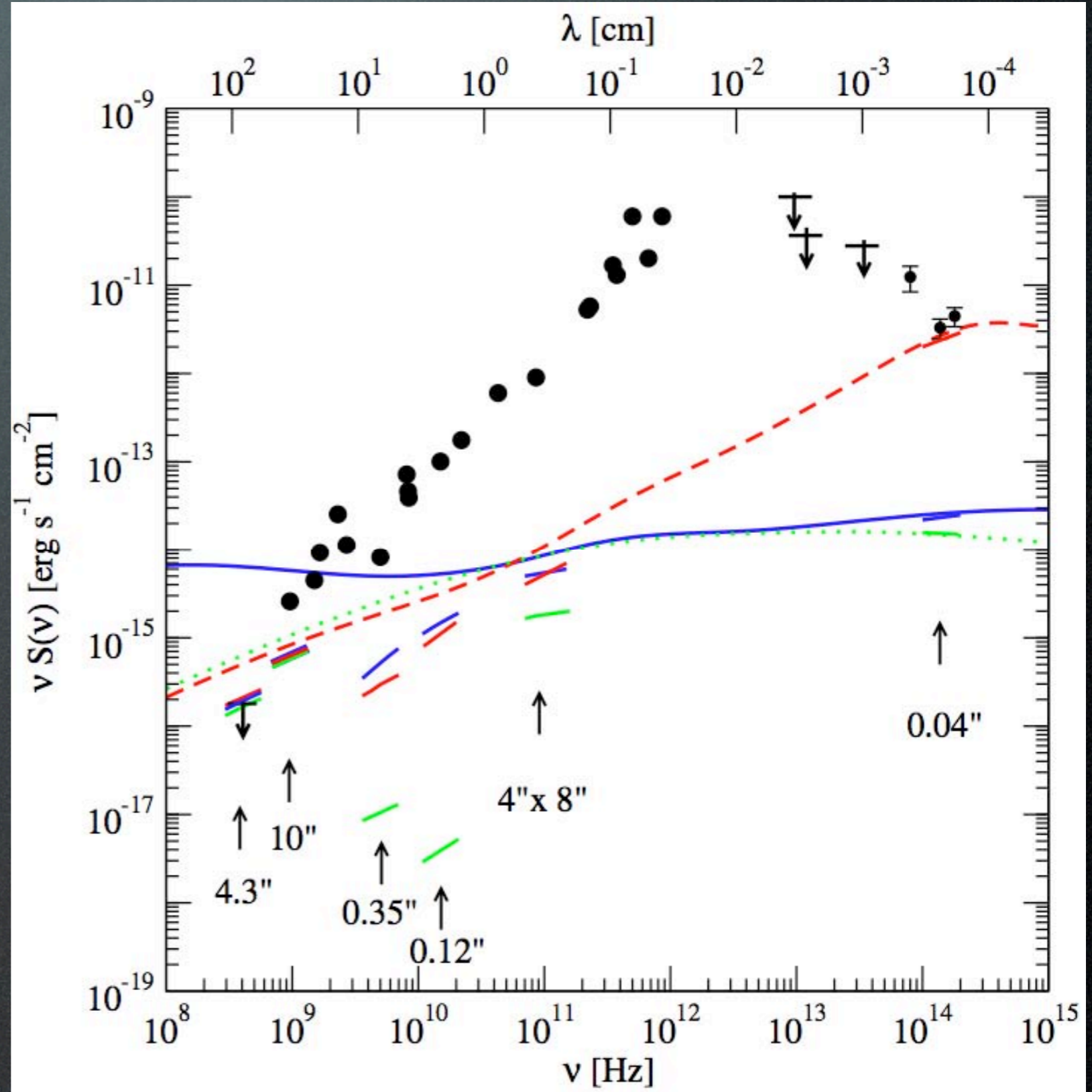


b) $M = 1$ TeV into $\mu^-\mu^+$, Galactic Ridge
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Gamma constraints

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

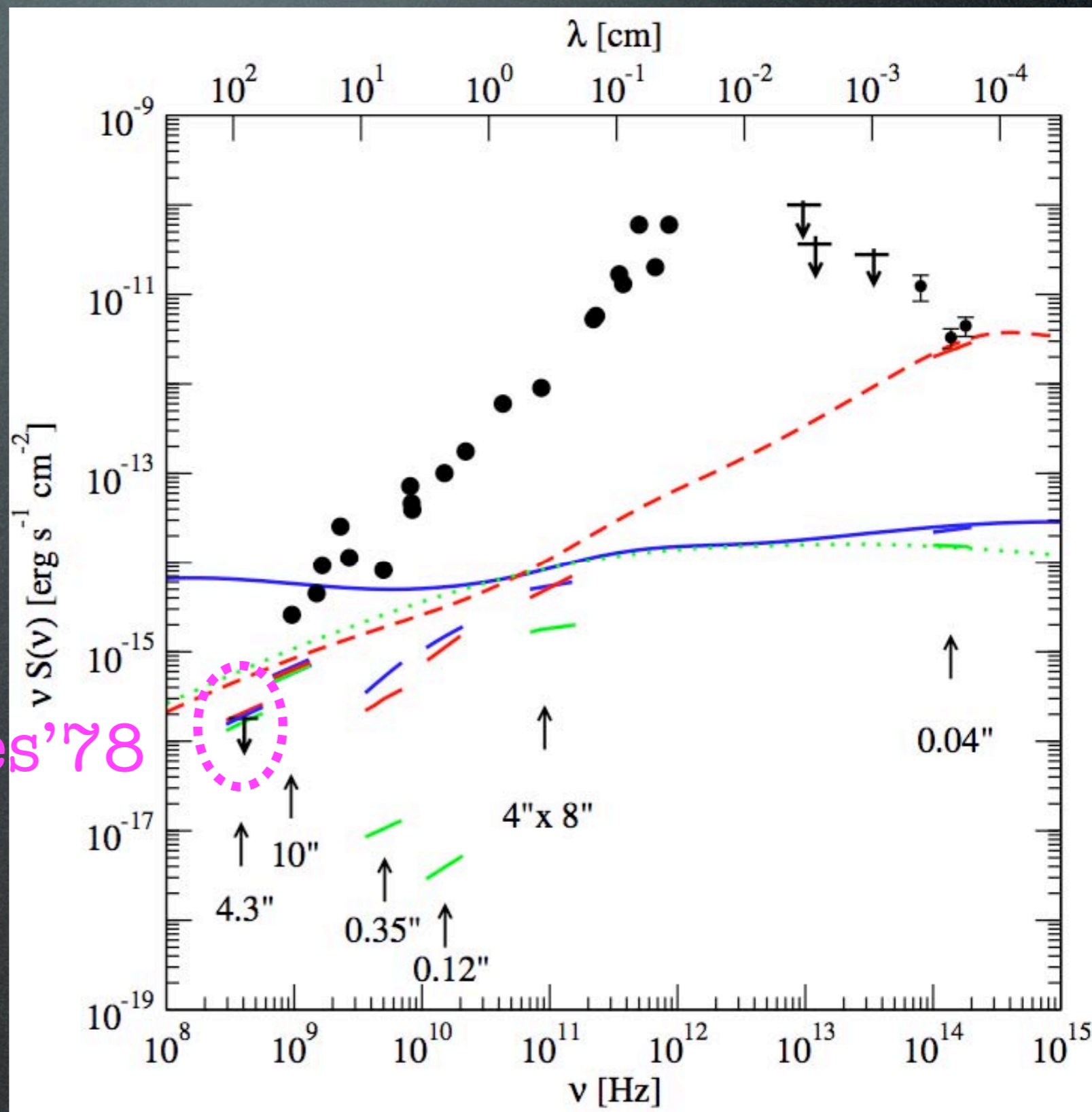


Gamma constraints

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

Davies 1978 upper bound at 408 MHz.

Davies'78



Gamma constraints

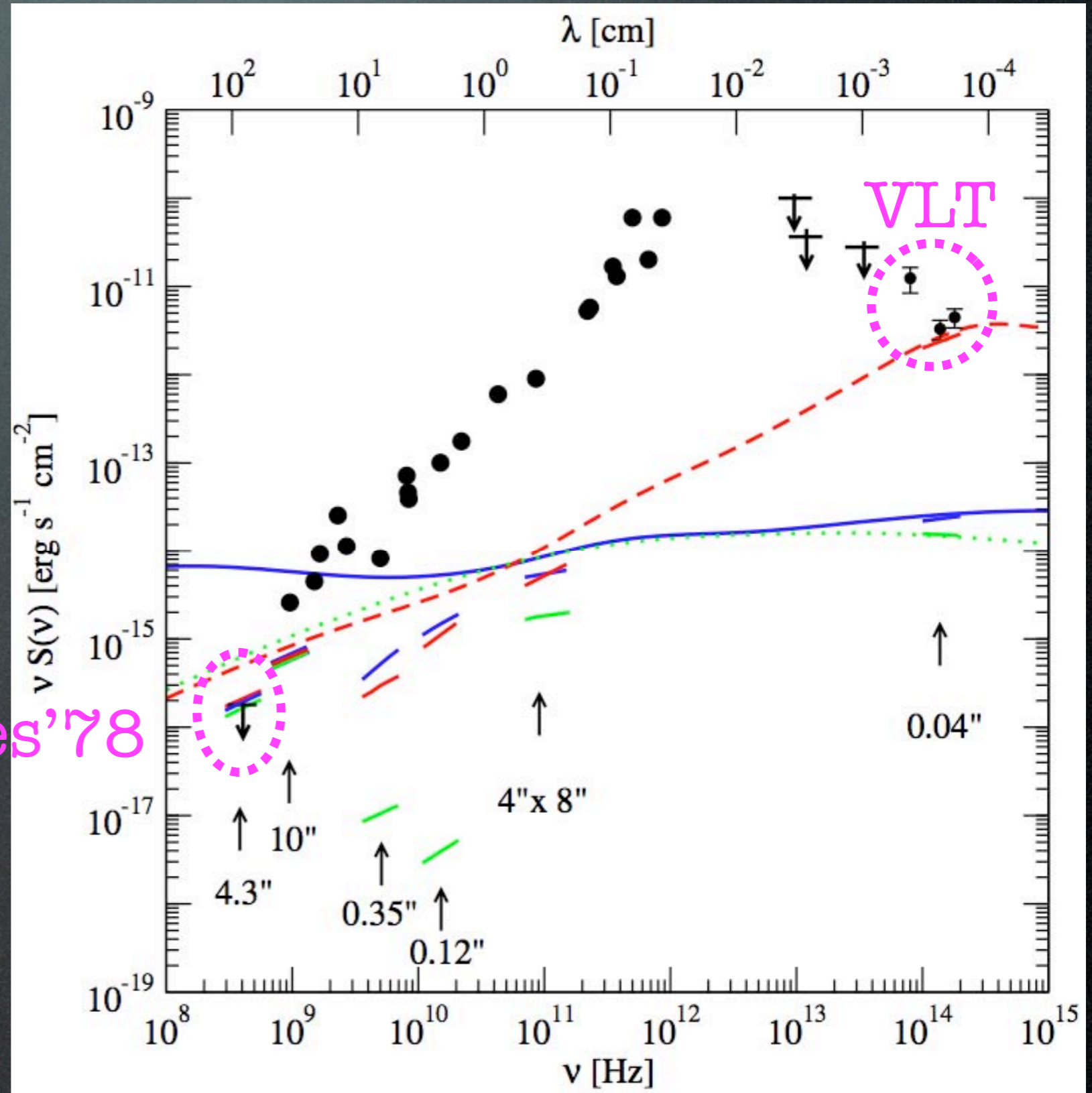
Several observations detected radio to IR emission from the Gal Center. The DM signal must not exceed that.

Davies 1978 upper bound at 408 MHz.

VLT 2003 emission at 10^{14} Hz.

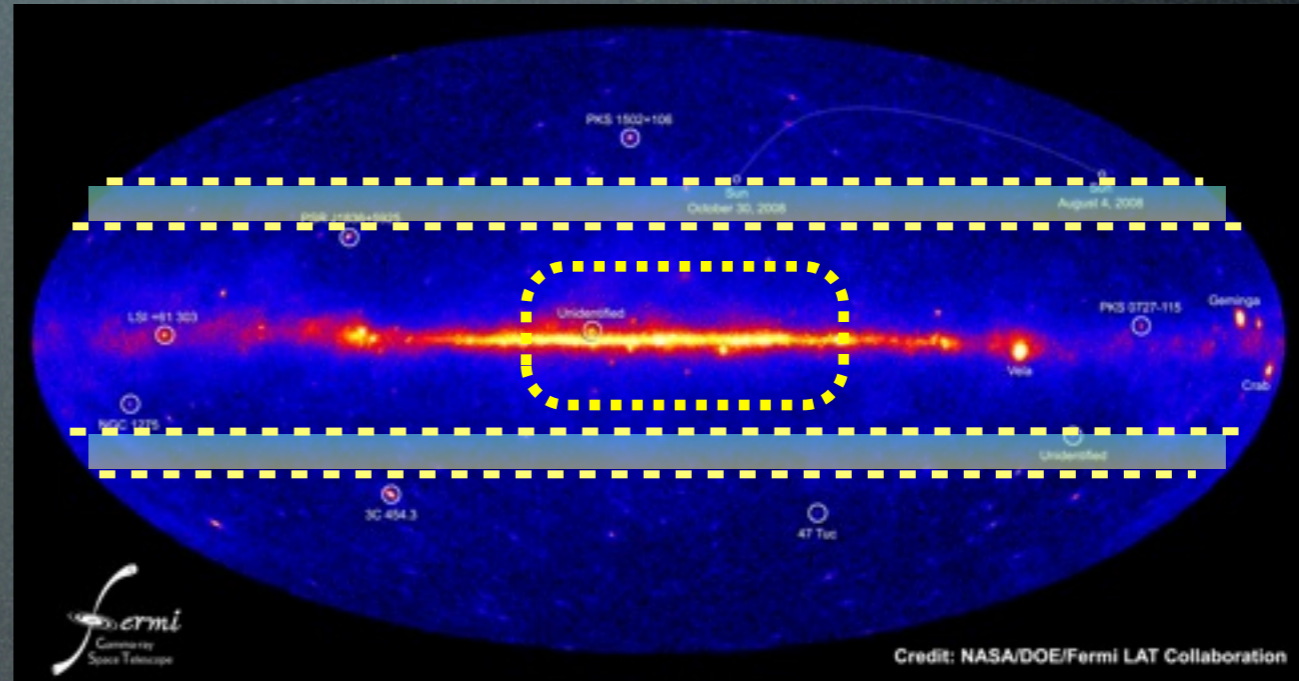
Davies'78

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

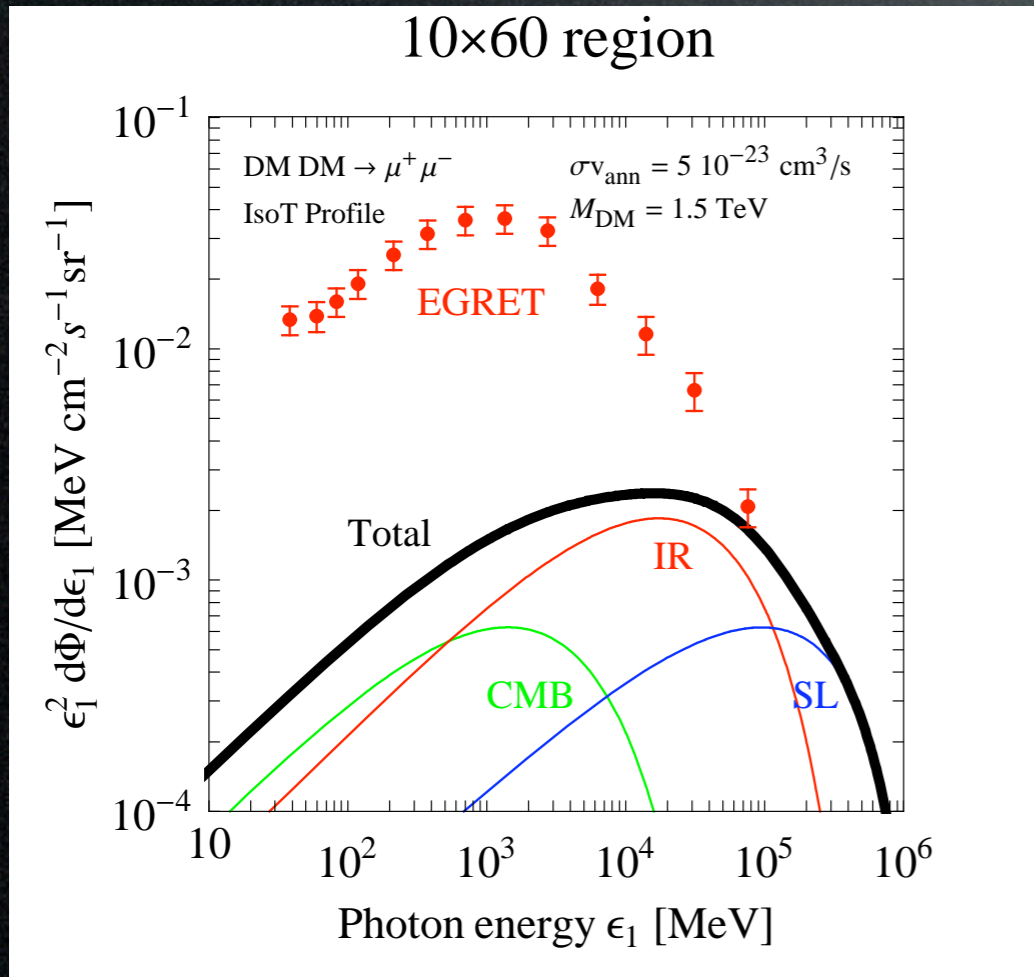


Gamma constraints

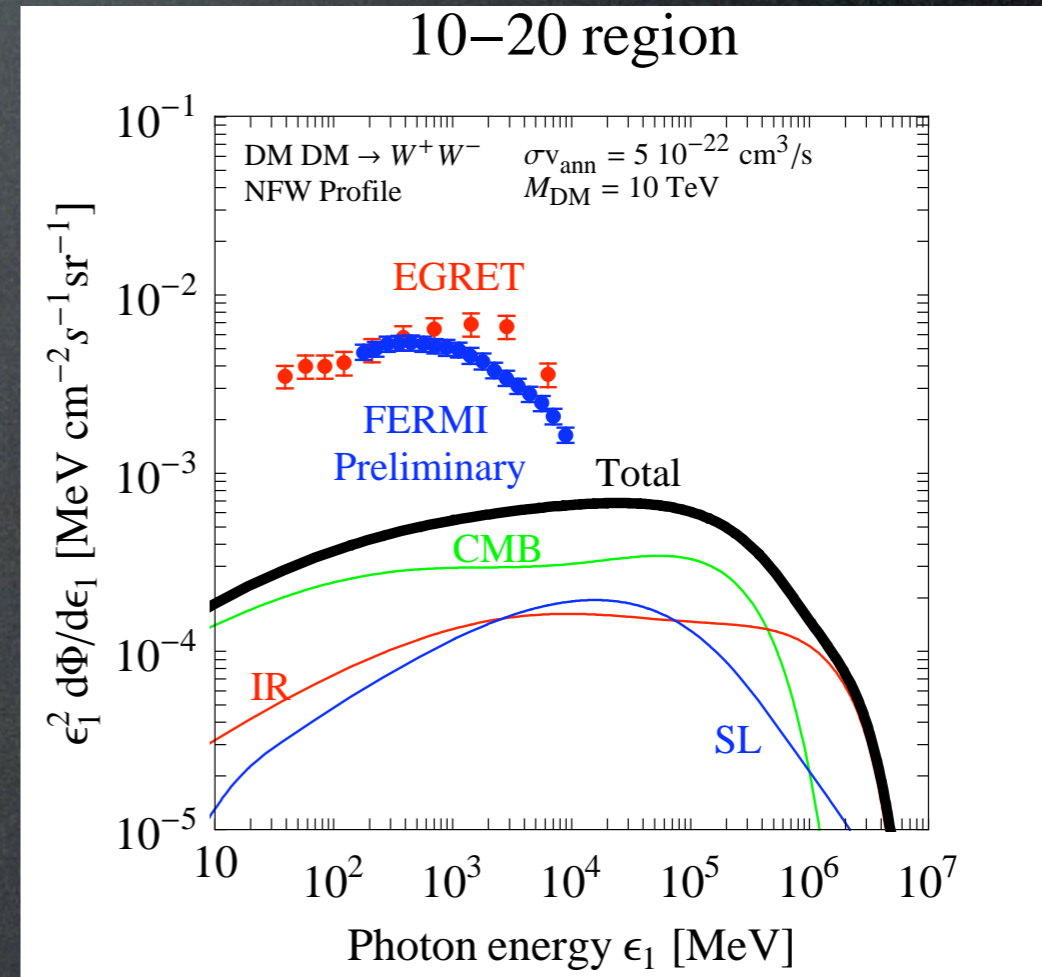
EGRET and FERMI have measured diffuse γ -ray emission. The DM signal must not exceed that.



FERMI coll.



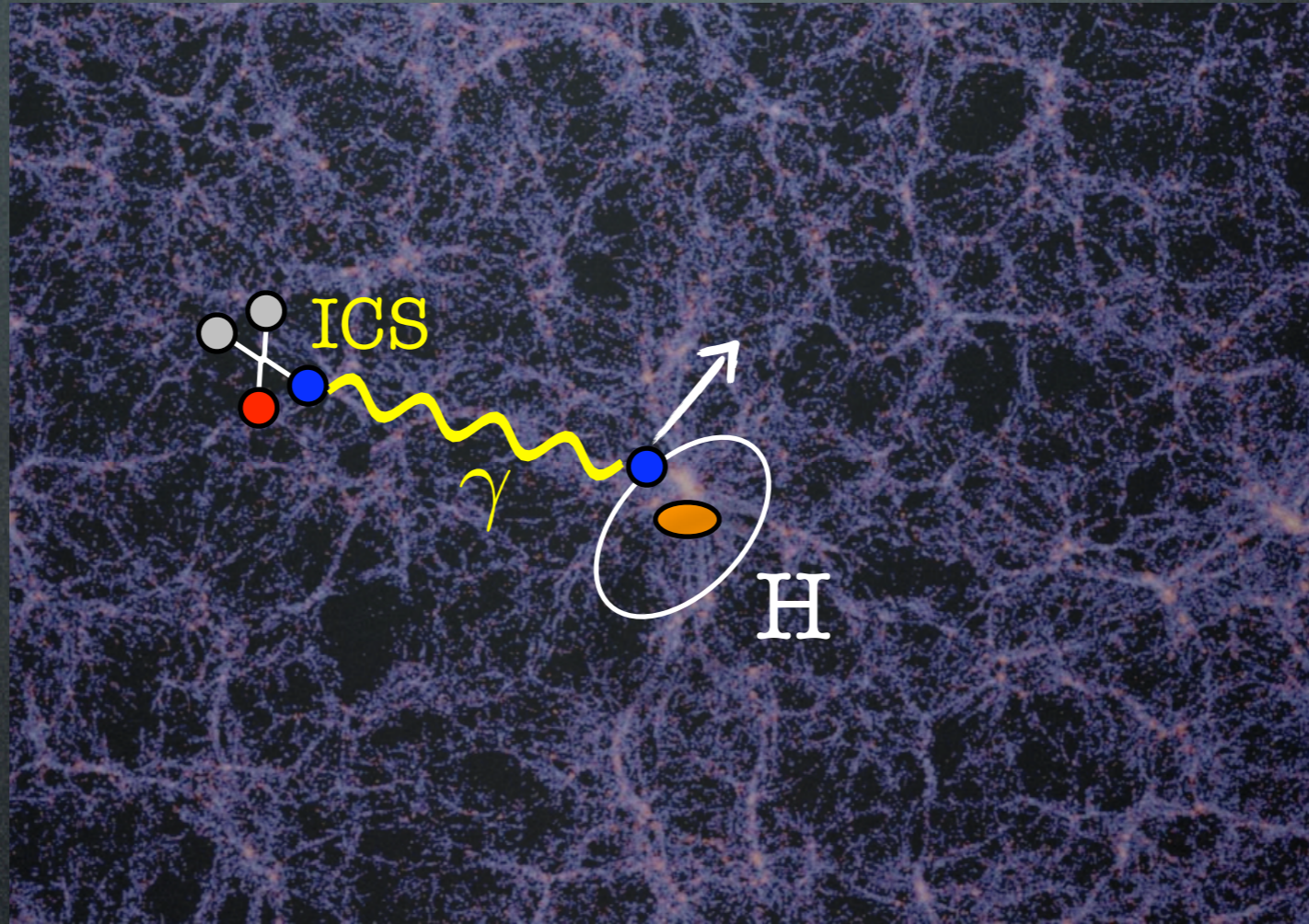
Data: EGRET coll., Strong et al. astro-ph/0406254



Data: FERMI coll., several talks in 2009

Cosmology: bounds from reionization

DM particle
annihilations
produce
free electrons



$$-n_A H_0 \sqrt{\Omega_M} (1+z)^{11/2} \frac{dx_{\text{ion}}(z)}{dz} = I(z) - R(z).$$

$$I(z) = \int_{e_i}^{m_x} dE_\gamma \frac{dn}{dE_\gamma}(z) \cdot P(E_\gamma, z) \cdot N_{\text{ion}}(E_\gamma)$$

$$P(E_\gamma, z) = n_A (1+z)^3 [1 - x_{\text{ion}}(z)] \cdot \sigma_{\text{tot}}(E_\gamma),$$

$$N_{\text{ion}}(E_\gamma) = \eta_{\text{ion}}(x_{\text{ion}}(z)) E_\gamma \left[\frac{n_H}{n_A} \frac{1}{e_{i,H}} + \frac{n_{\text{He}}}{n_A} \frac{1}{e_{i,\text{He}}} \right] = \eta_{\text{ion}}(x_{\text{ion}}(z)) \frac{E_\gamma}{\text{GeV}} \mu$$

$$\frac{dn}{dE_\gamma}(z) = \int_\infty^z dz' \frac{dt}{dz'} \frac{dN}{dE'_\gamma}(z') \frac{(1+z)^3}{(1+z')^3} \cdot A(z') \cdot \exp[\Upsilon(z, z', E'_\gamma)].$$

$$\Upsilon(z, z', E'_\gamma) \simeq - \int_{z'}^z dz'' \frac{dt}{dz''} n_A (1+z'')^3 \sigma_{\text{tot}}(E'_\gamma)$$

$$\frac{dT_{\text{igm}}(z)}{dz} = \frac{2T_{\text{igm}}(z)}{1+z}$$

$$- \frac{1}{H_0 \sqrt{\Omega_M} (1+z)^{5/2}} \left(\frac{x_{\text{ion}}(z)}{1+x_{\text{ion}}(z) + 0.073} \frac{T_{\text{CMB}}(z) - T_{\text{igm}}(z)}{t_c(z)} + \frac{2\eta_{\text{heat}}(x_{\text{ion}}(z)) \mathcal{E}(z)}{3n_A (1+z)^3} \right).$$

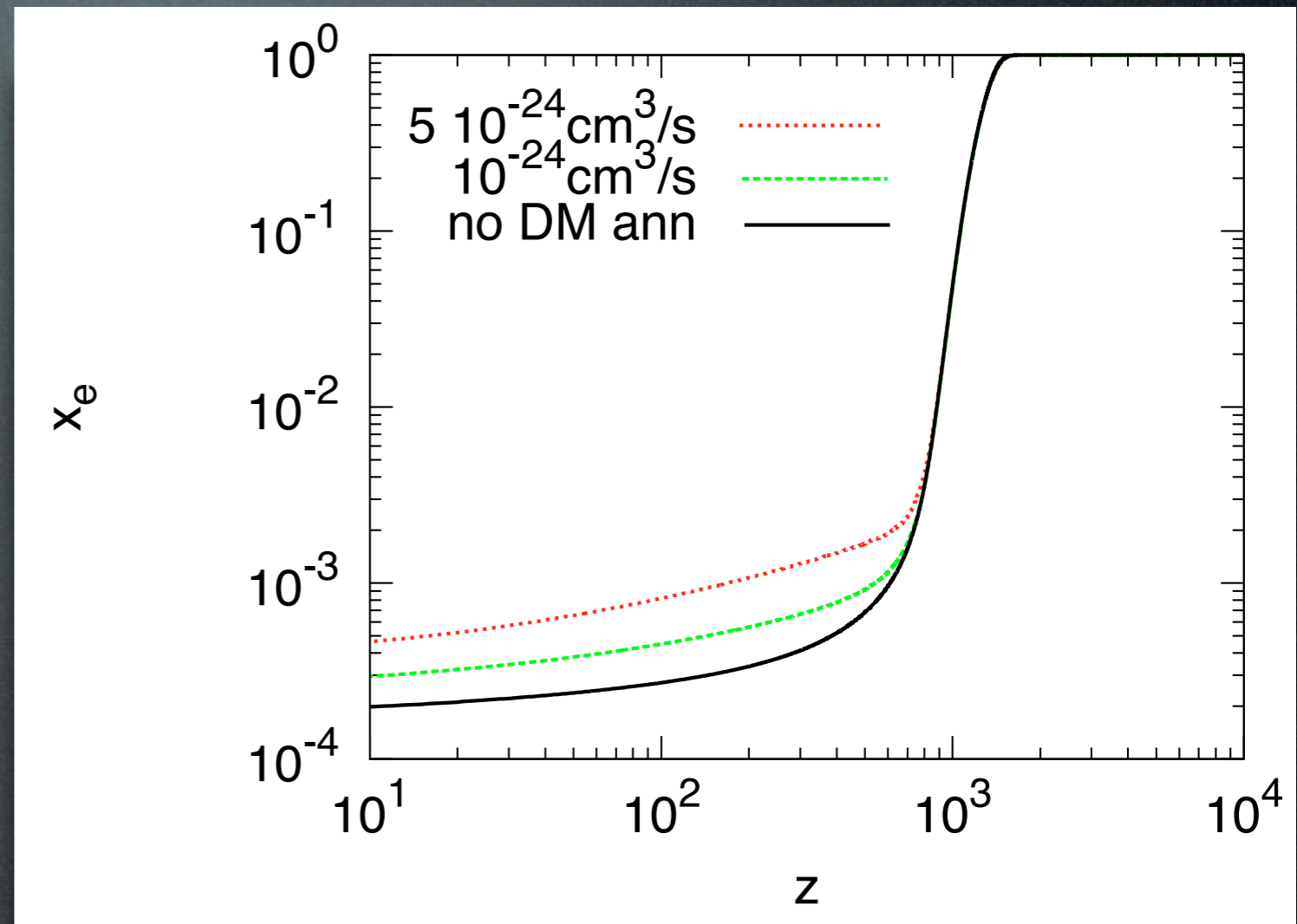
$$A(z) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \rho_{\text{DM},0}^2 (1+z)^6 (1 + \mathcal{B}_i(z)),$$

$$\mathcal{B}_i(z) = \frac{\Delta_{\text{vir}}(z)}{3\rho_c \Omega_M} \int_{M_{\text{min}}}^\infty dM M \frac{dn}{dM}(z, M) F_i(M, z),$$

$$\frac{dn}{dM}(M, z) = \sqrt{\frac{\pi}{2}} \frac{\rho_M}{M} \delta_c (1+z) \frac{d\sigma(R)}{dM} \frac{1}{\sigma^2(R)} \exp\left(-\frac{\delta_c^2 (1+z)^2}{2\sigma^2(R)}\right)$$

Cosmology: bounds from reionization

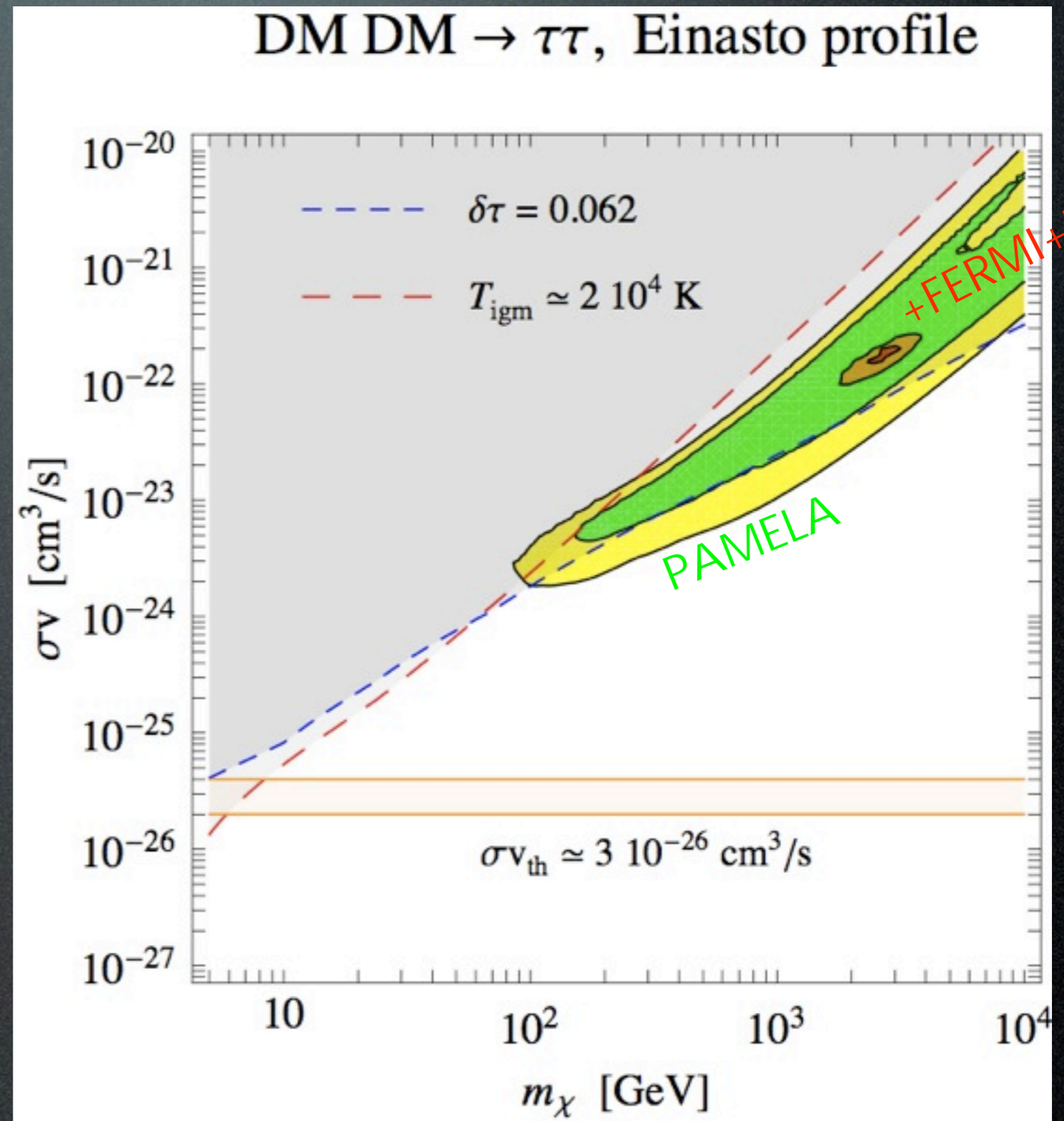
DM particles that fit
PAMELA+FERMI+HESS
produce
free electrons



Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

DM particles that fit
PAMELA+FERMI+HESS
produce **too many**
free electrons:
bounds on **optical depth**
of the Universe violated
 $\tau = 0.084 \pm 0.016$ (WMAP-5yr)



see also:

Huetsi, Hektor, Raidal 0906.4550
Kanzaki et al., 0907.3985

Cirelli, Iocco, Panci, JCAP 0910