11 may 2010
RWTH Aachen

Seeing Dark Matter in cosmic rays?!?

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 (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
  (line + continuum)
- e^+ from annihil in galactic halo or center
  PAMELA, ATIC, Fermi
- $\bar{p}$ from annihil in galactic halo or center
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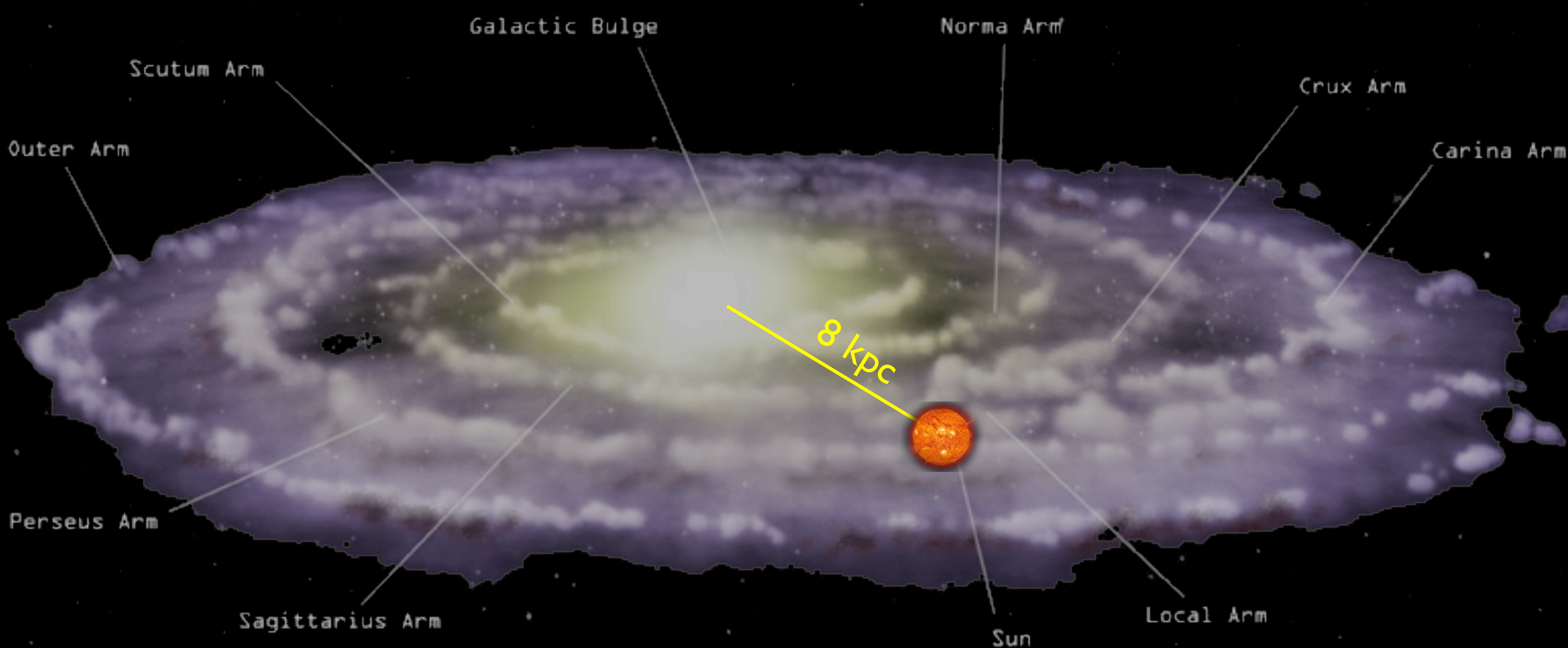
Indirect Detection

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



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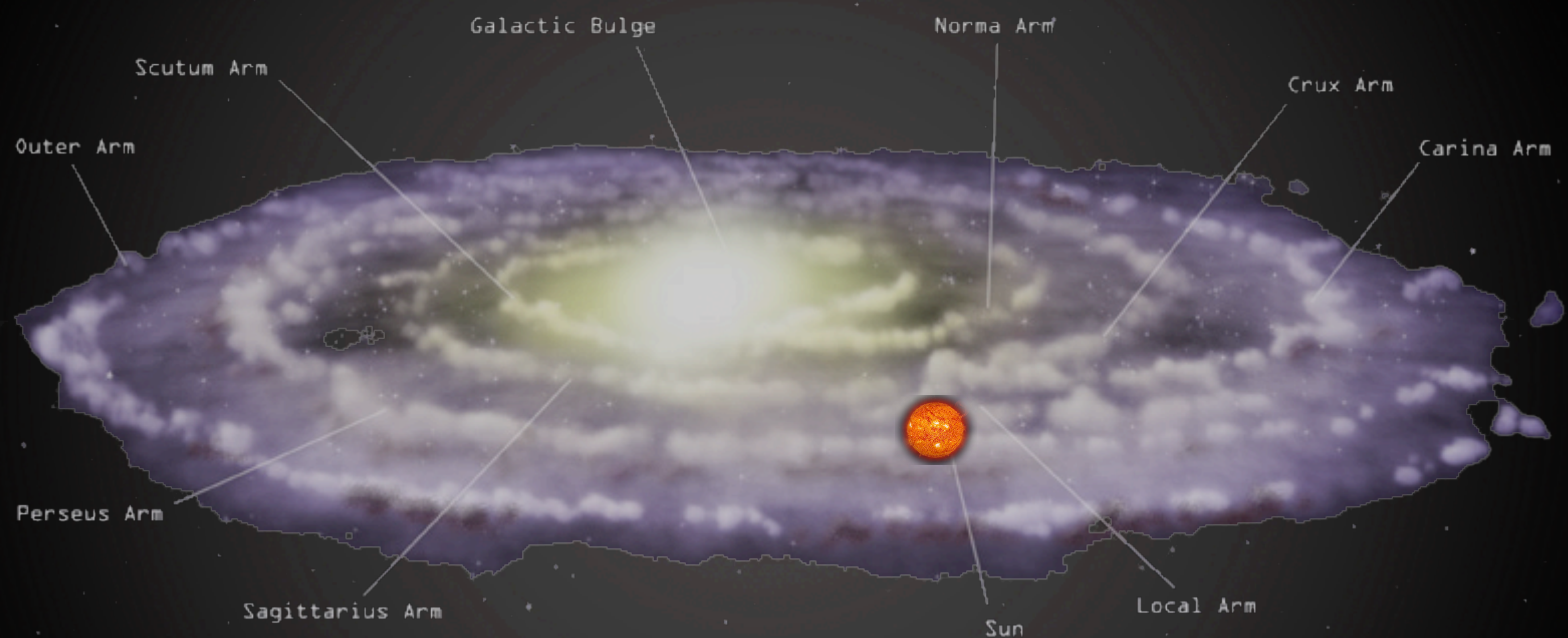

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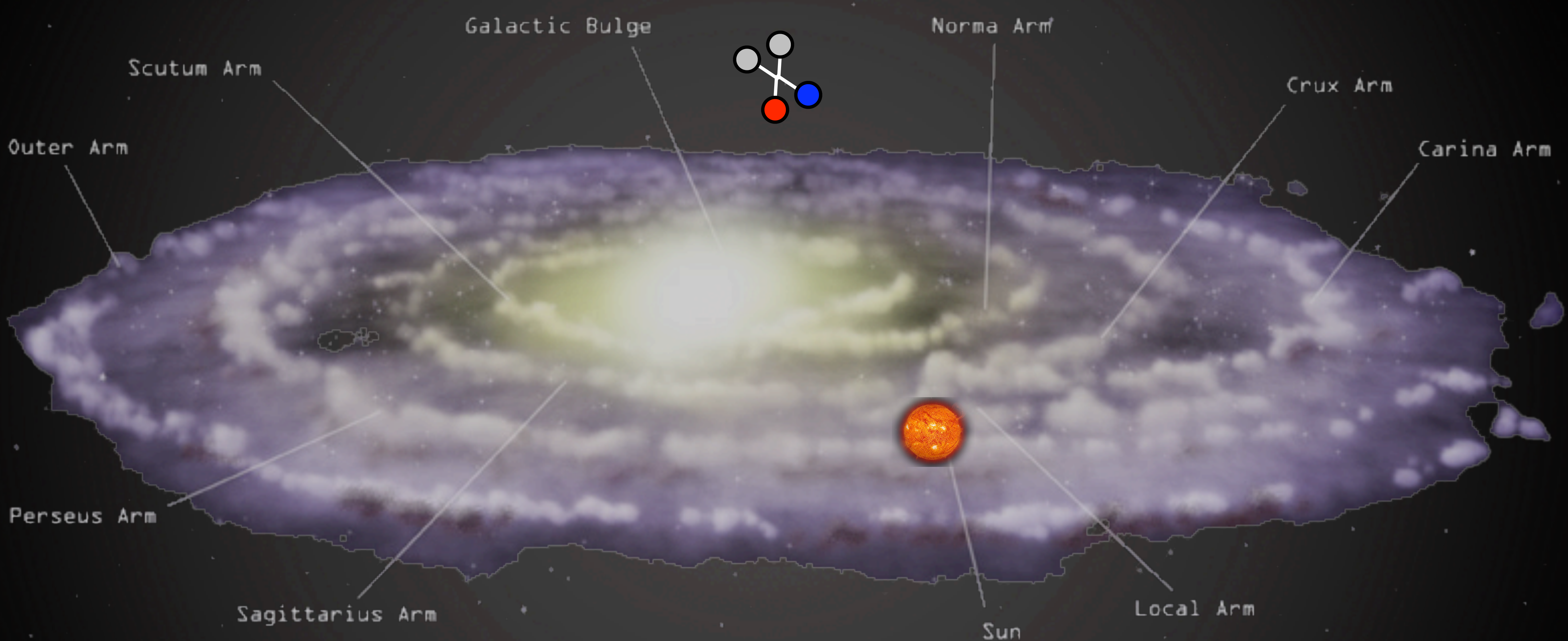

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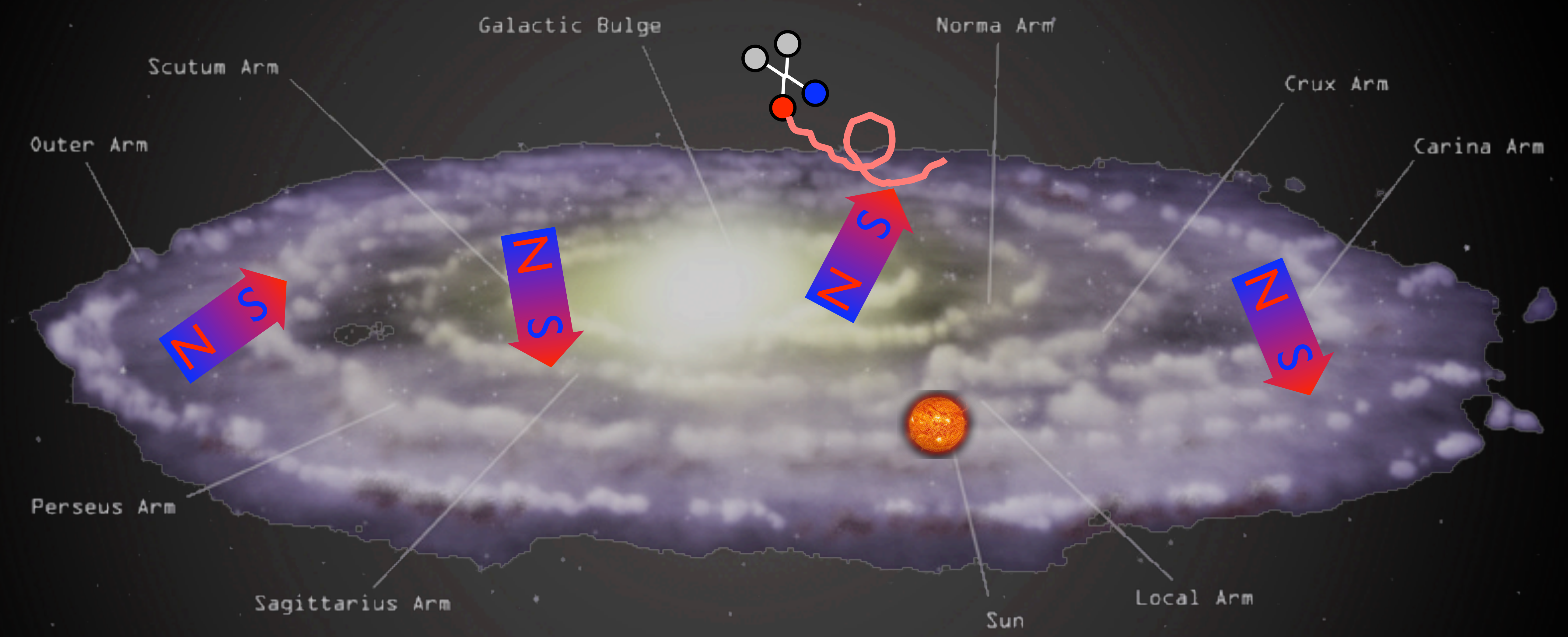

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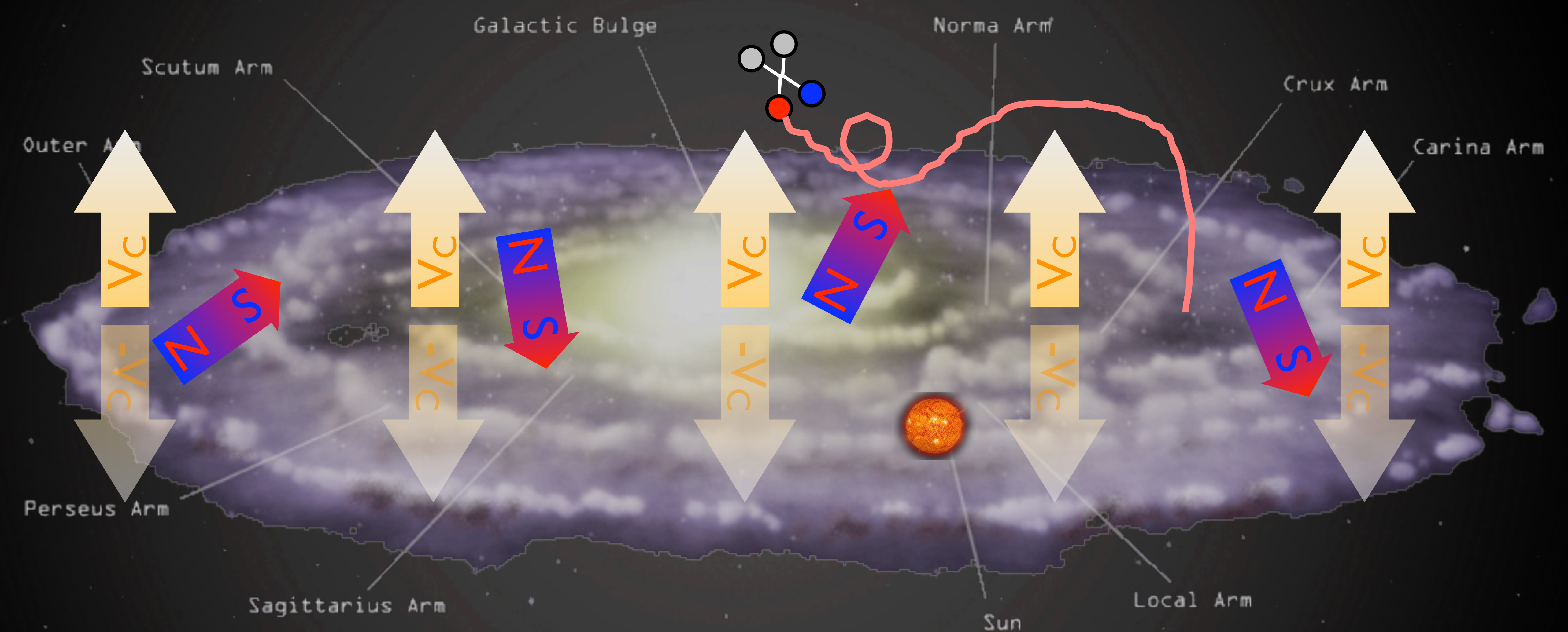
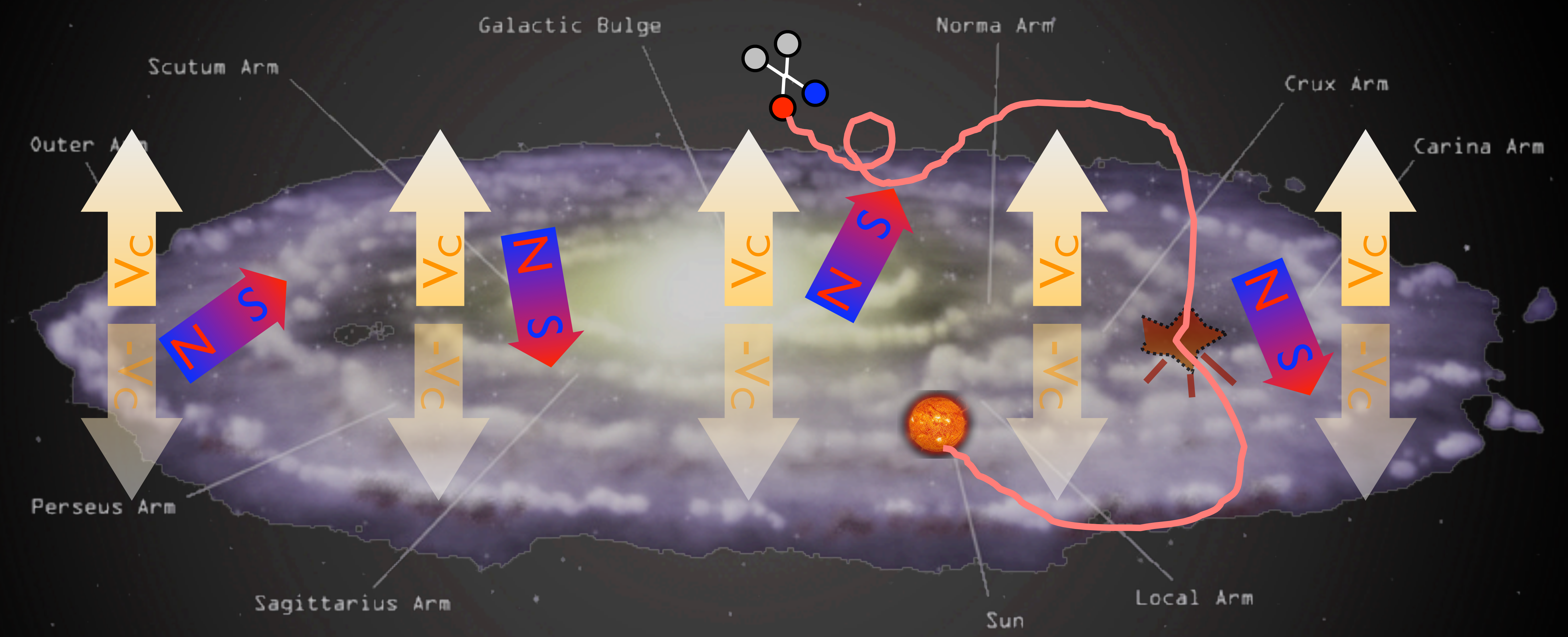


Indirect Detection

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



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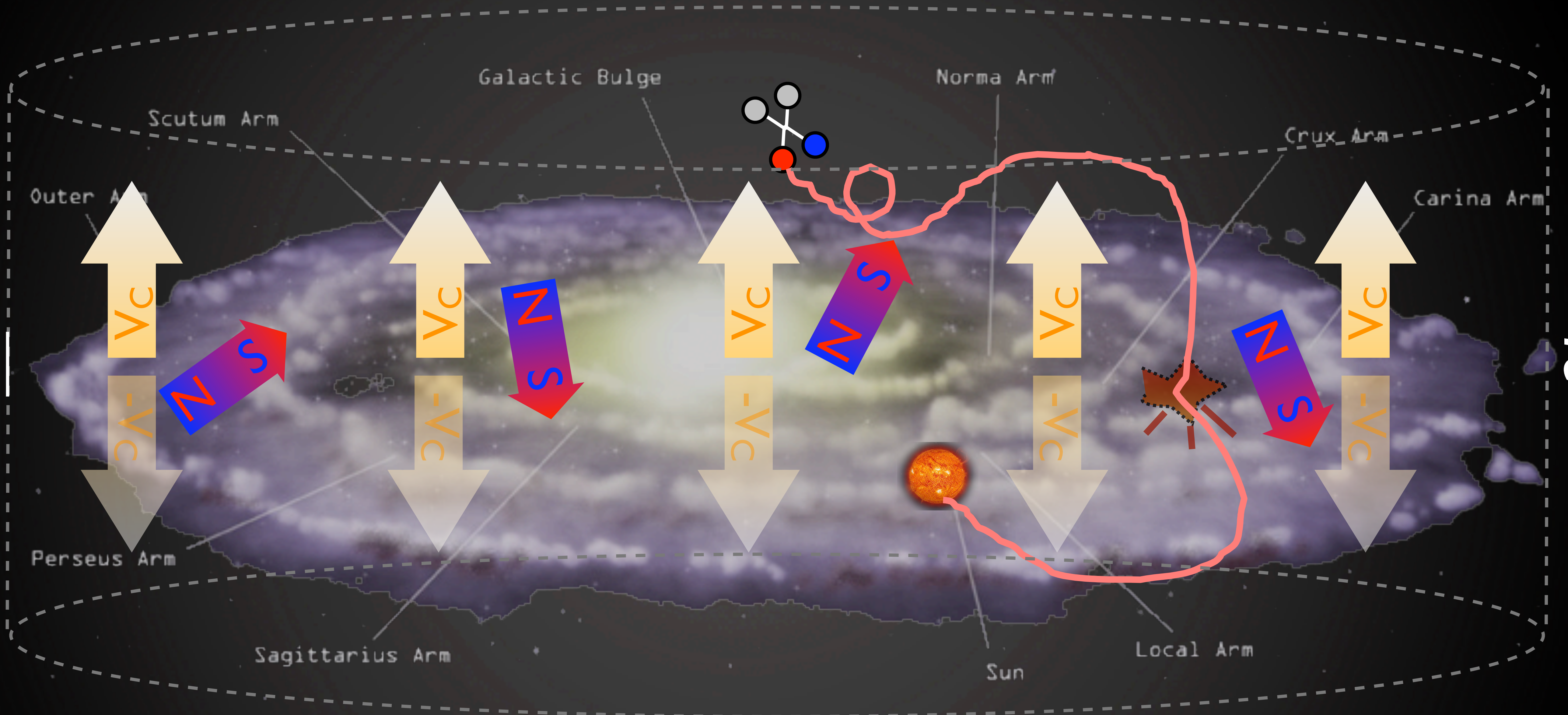


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

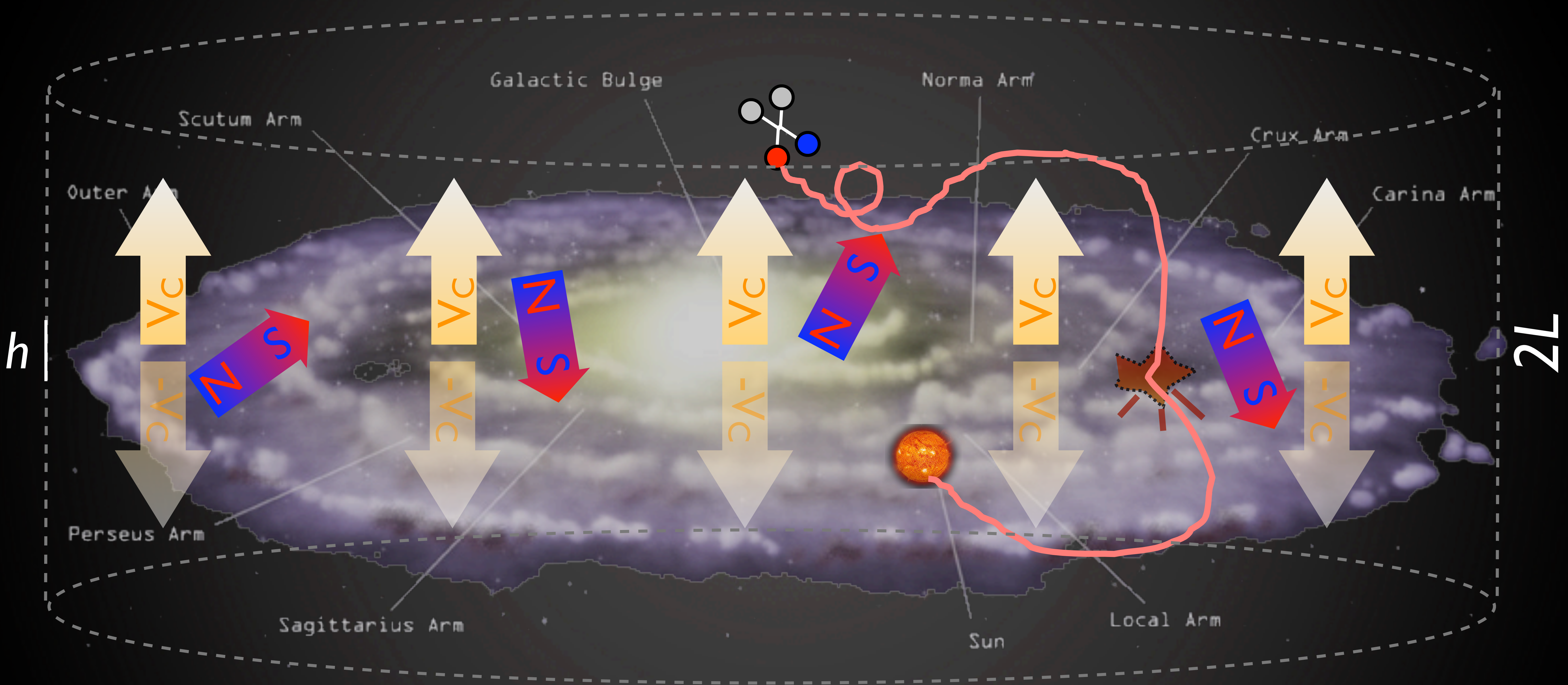
spectrum

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

diffusion   energy loss   convective wind   source   spallations

Indirect Detection

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

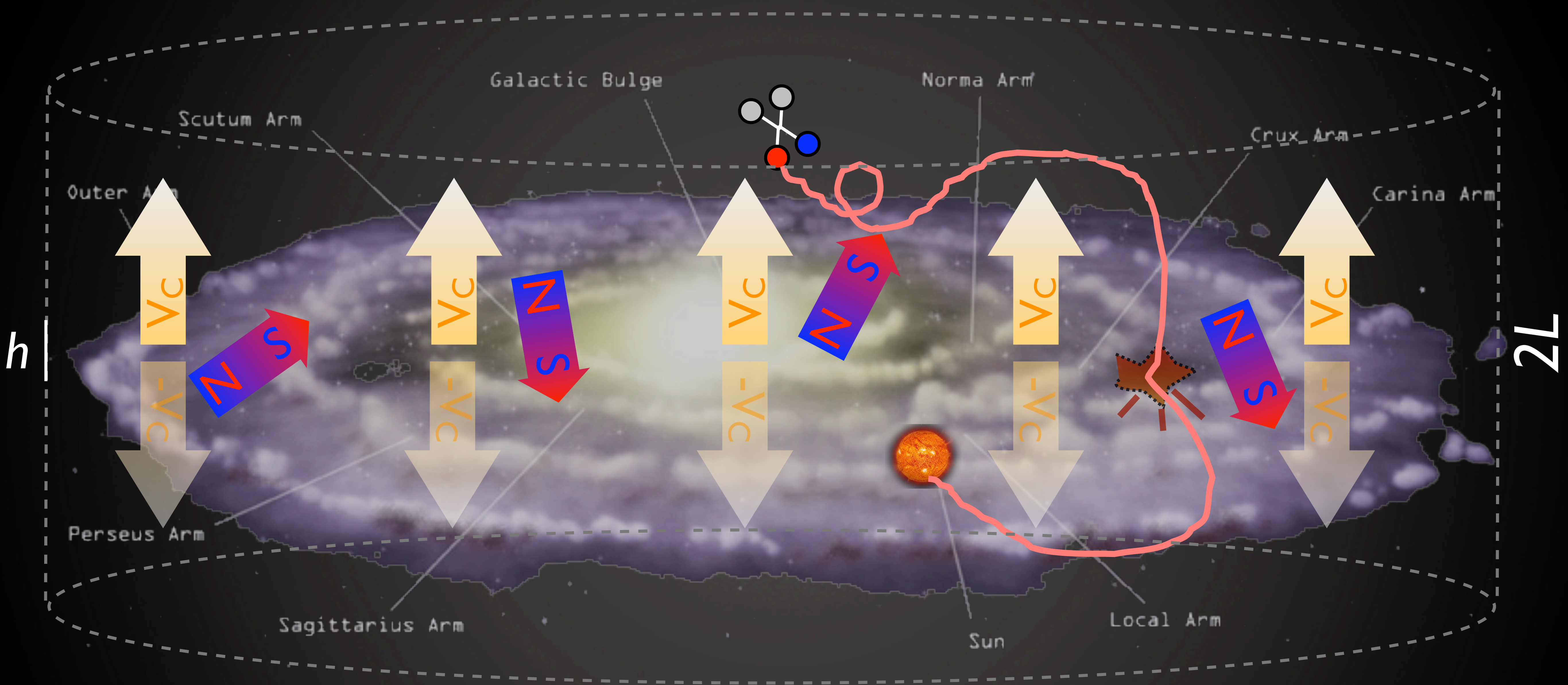


What sets the overall expected flux?

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

Indirect Detection

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



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astro& cosmo

particle

Indirect Detection

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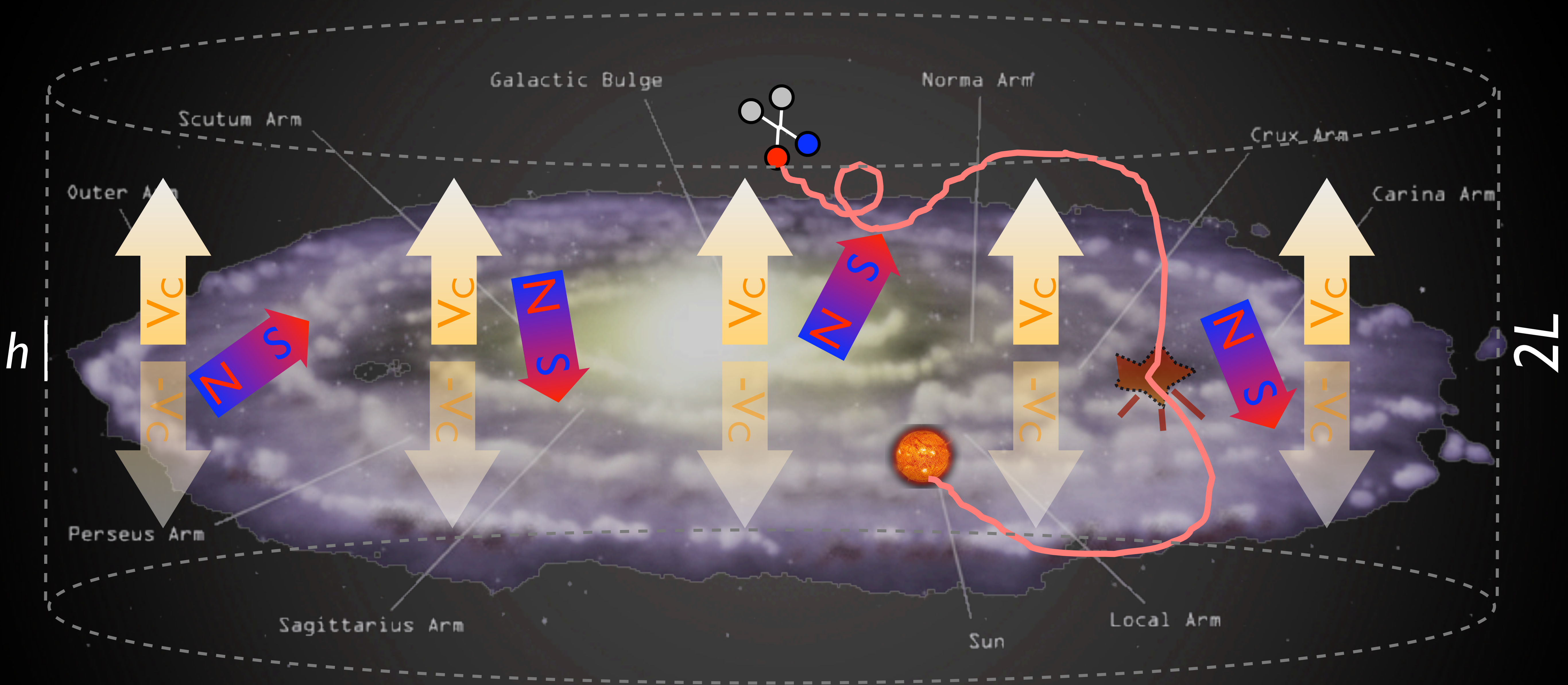

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$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

astro& cosmo

particle

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

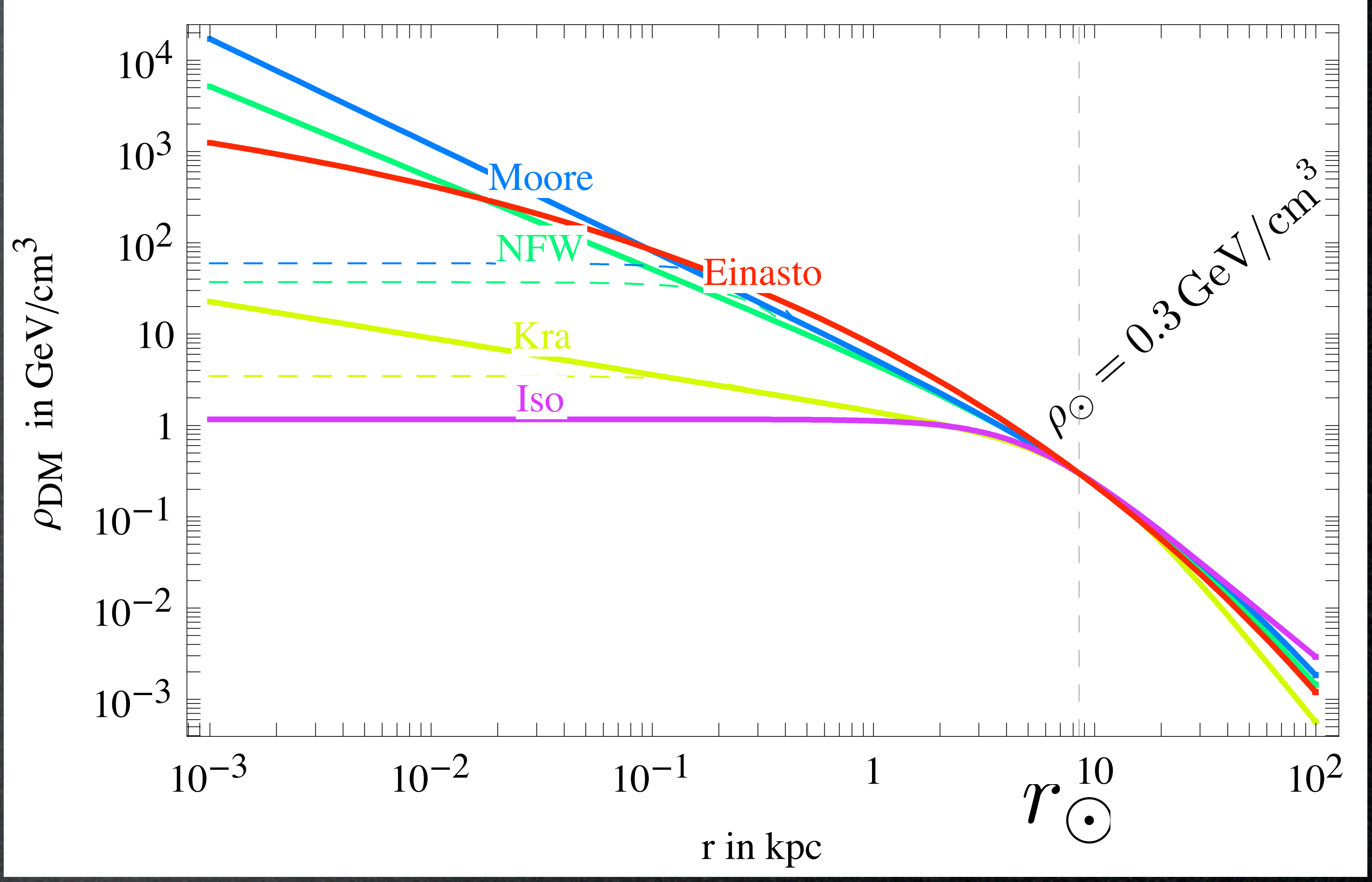
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

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

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

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

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

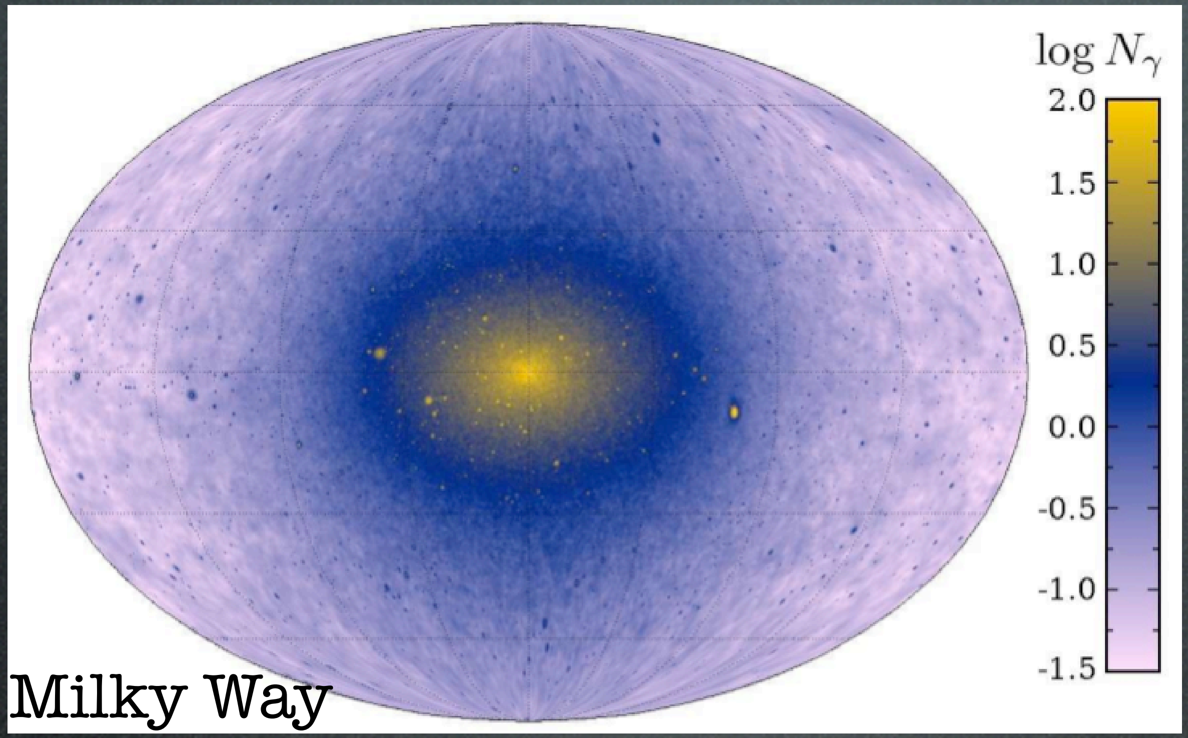


cuspy: NFW, Moore
mild: Einasto
smooth: isothermal

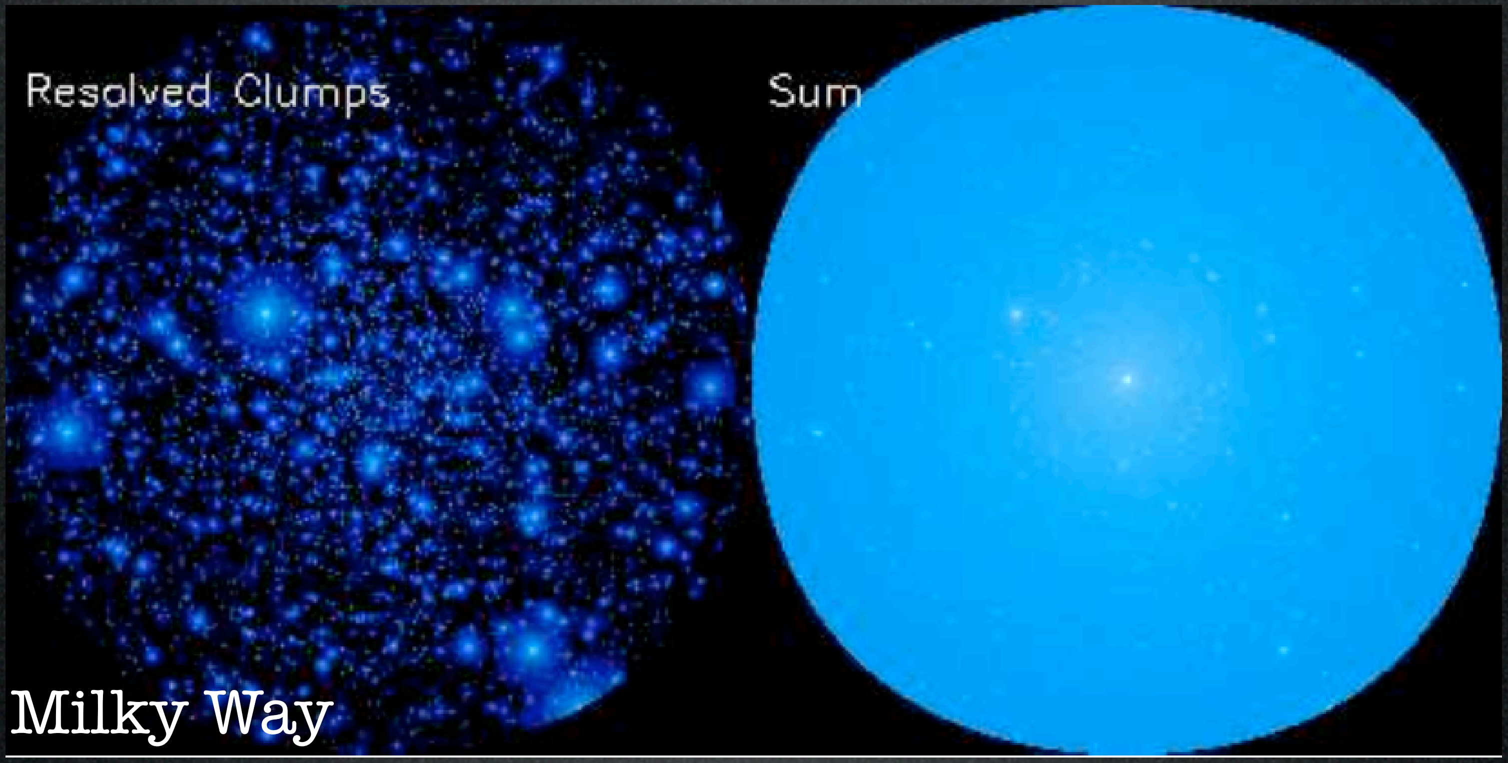
Indirect Detection

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

For illustration:



Kuhlen, Diemand, Madau 2007



Pieri, Bertone, Branchini, MNRAS 384 (2008), 0706.2101

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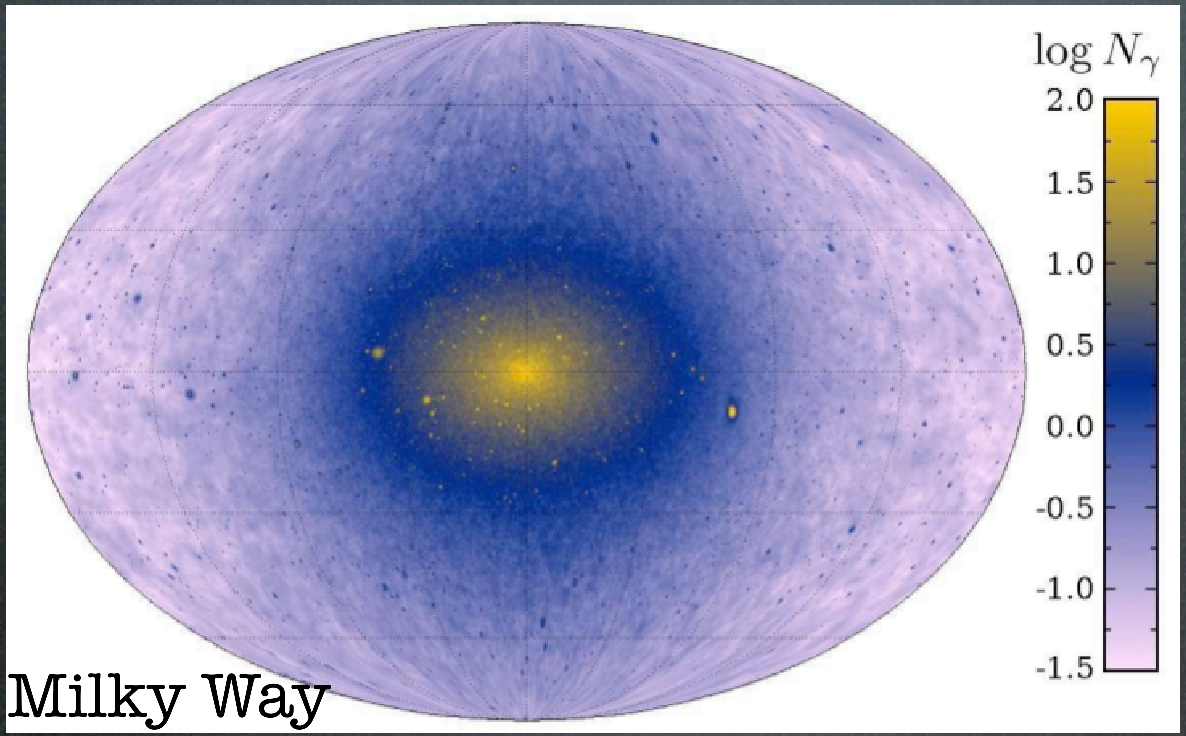
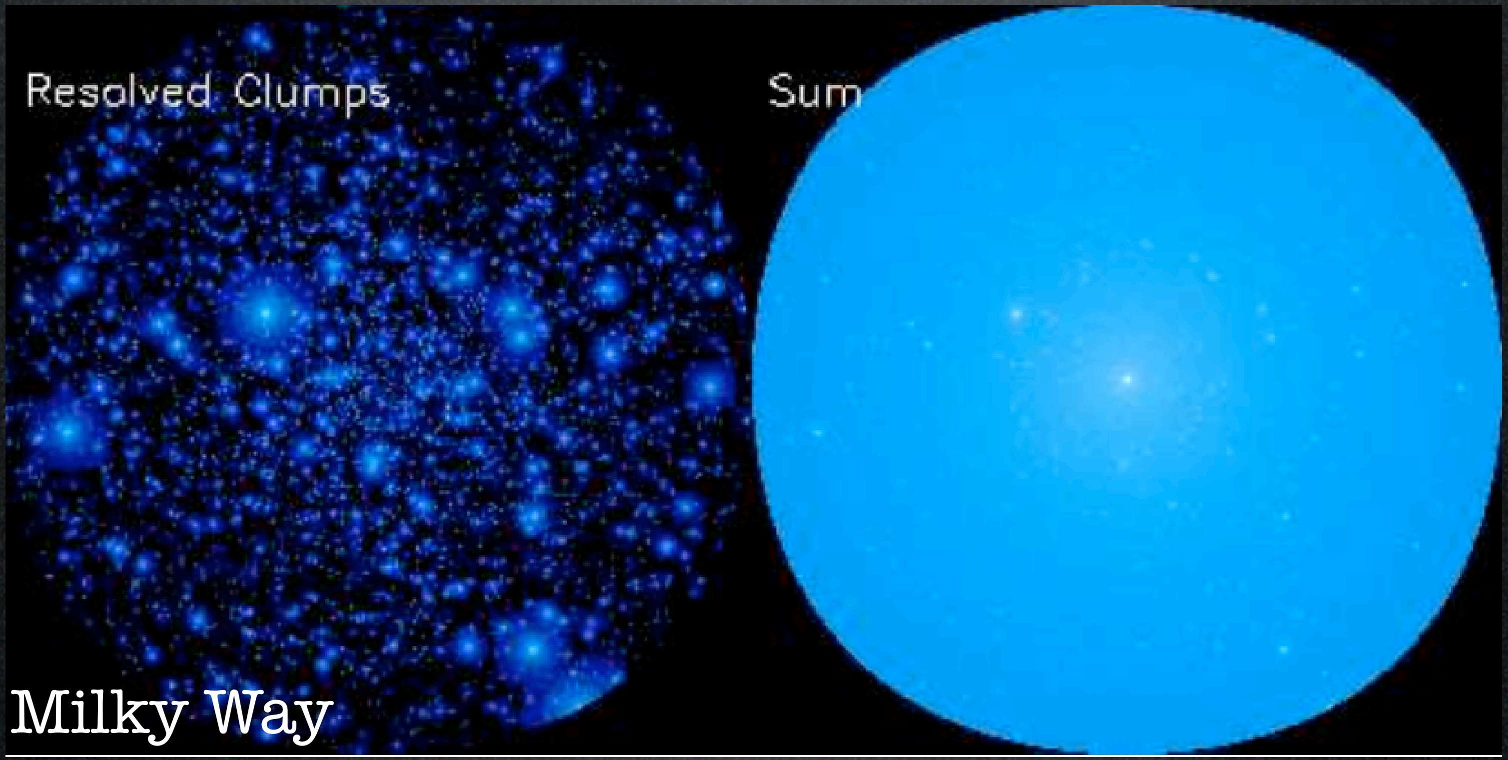


Kuhlen, Diemand, Madau 2007

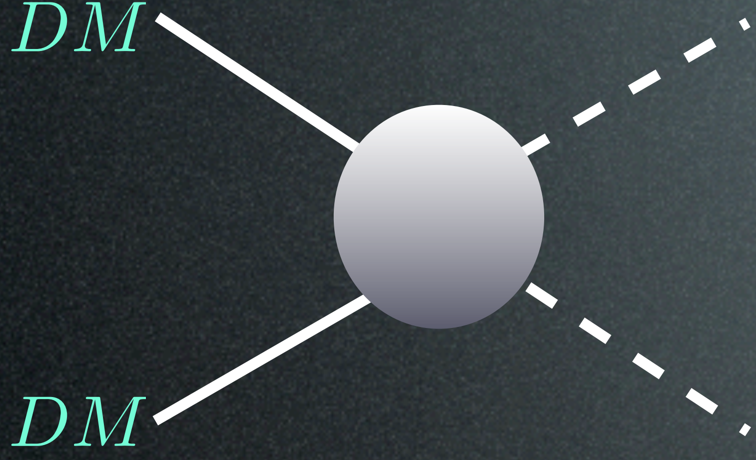
But: recent simulations seem to show almost no clumps in inner 10 kpc (tidal stripping).
[Millenium Simulation, Carlos Frenk]



Pieri, Bertone, Branchini, MNRAS 384 (2008), 0706.2101

Computing the theory predictions

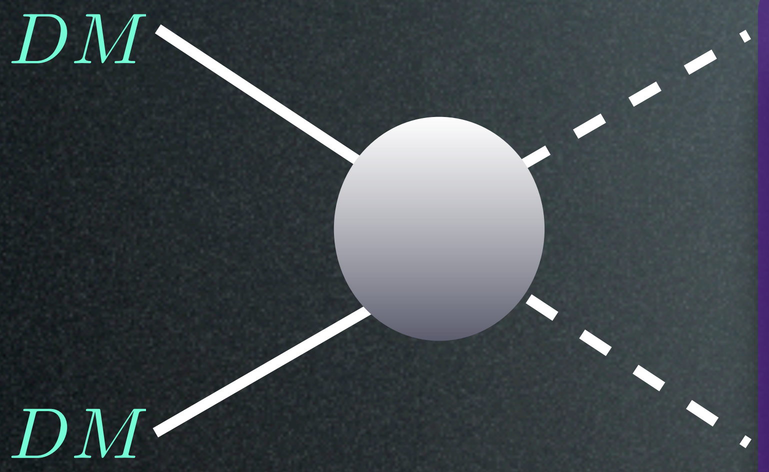
Spectra at production



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

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

Spectra at production

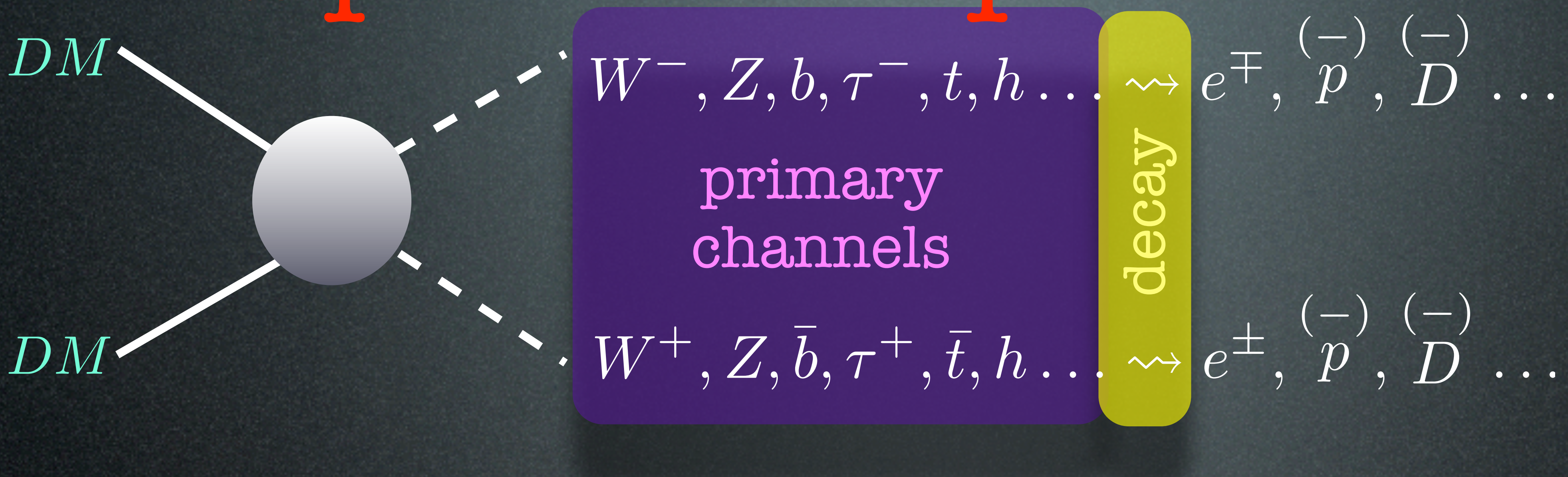


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

primary channels

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

Spectra at production



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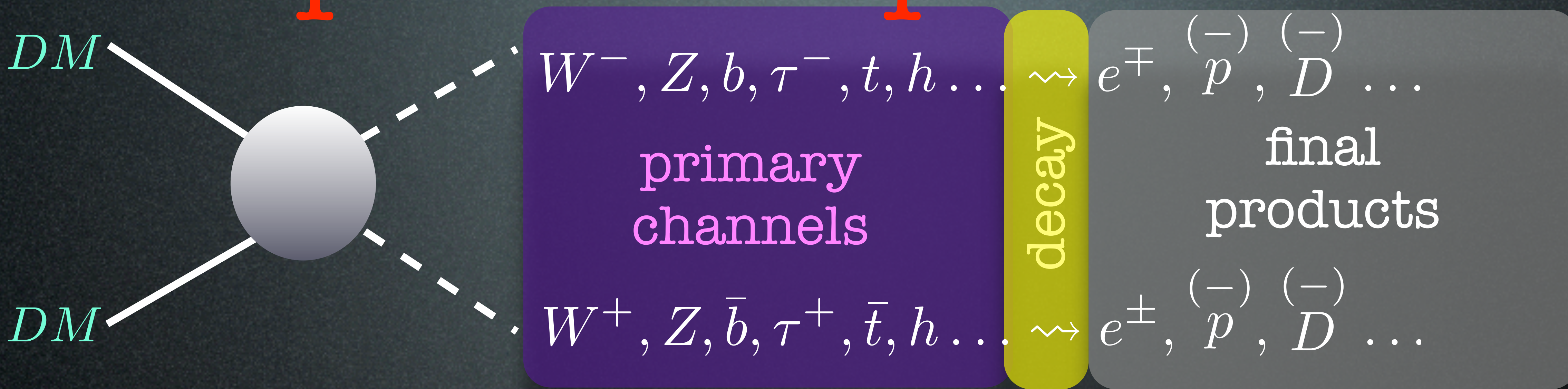

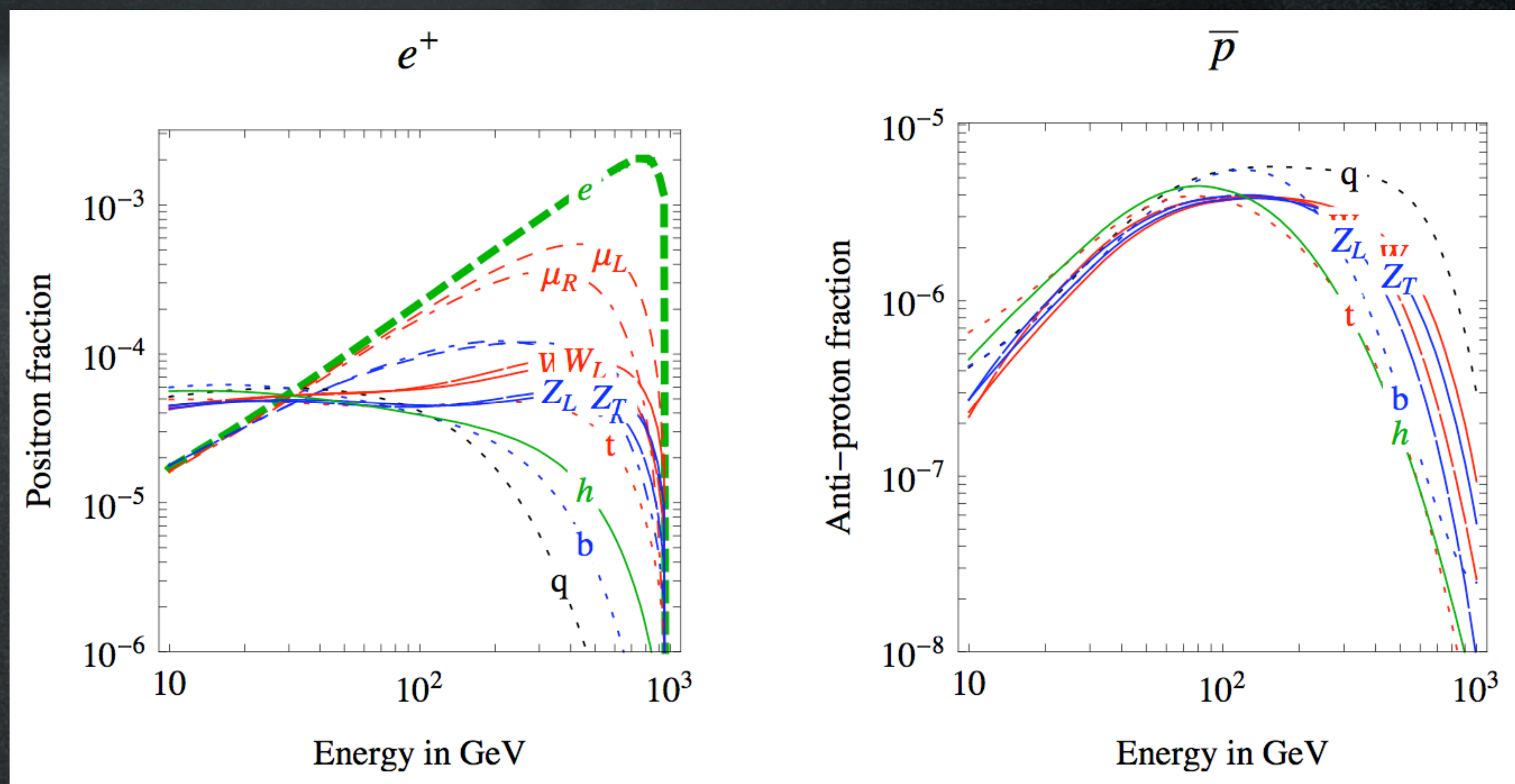

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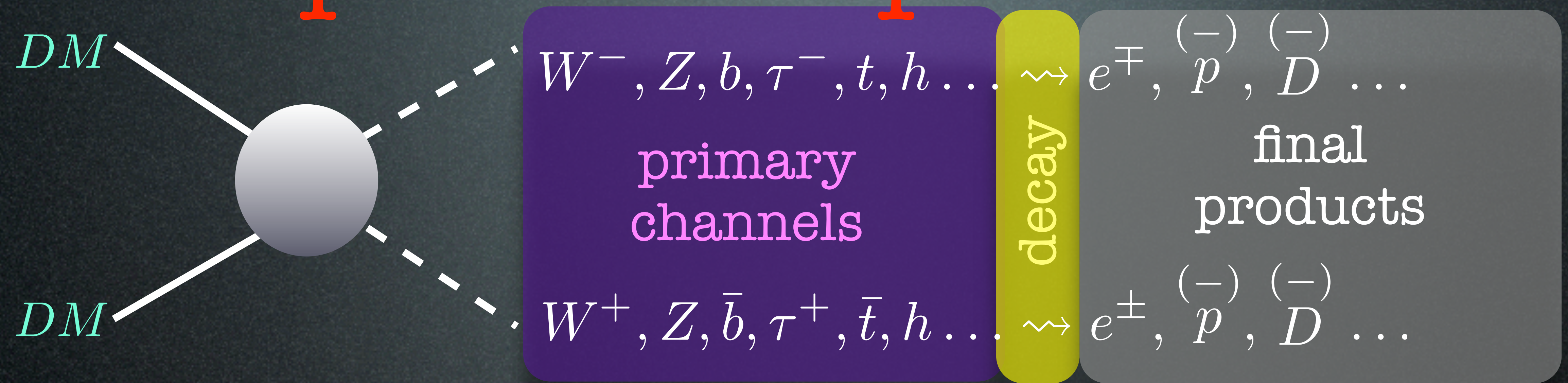
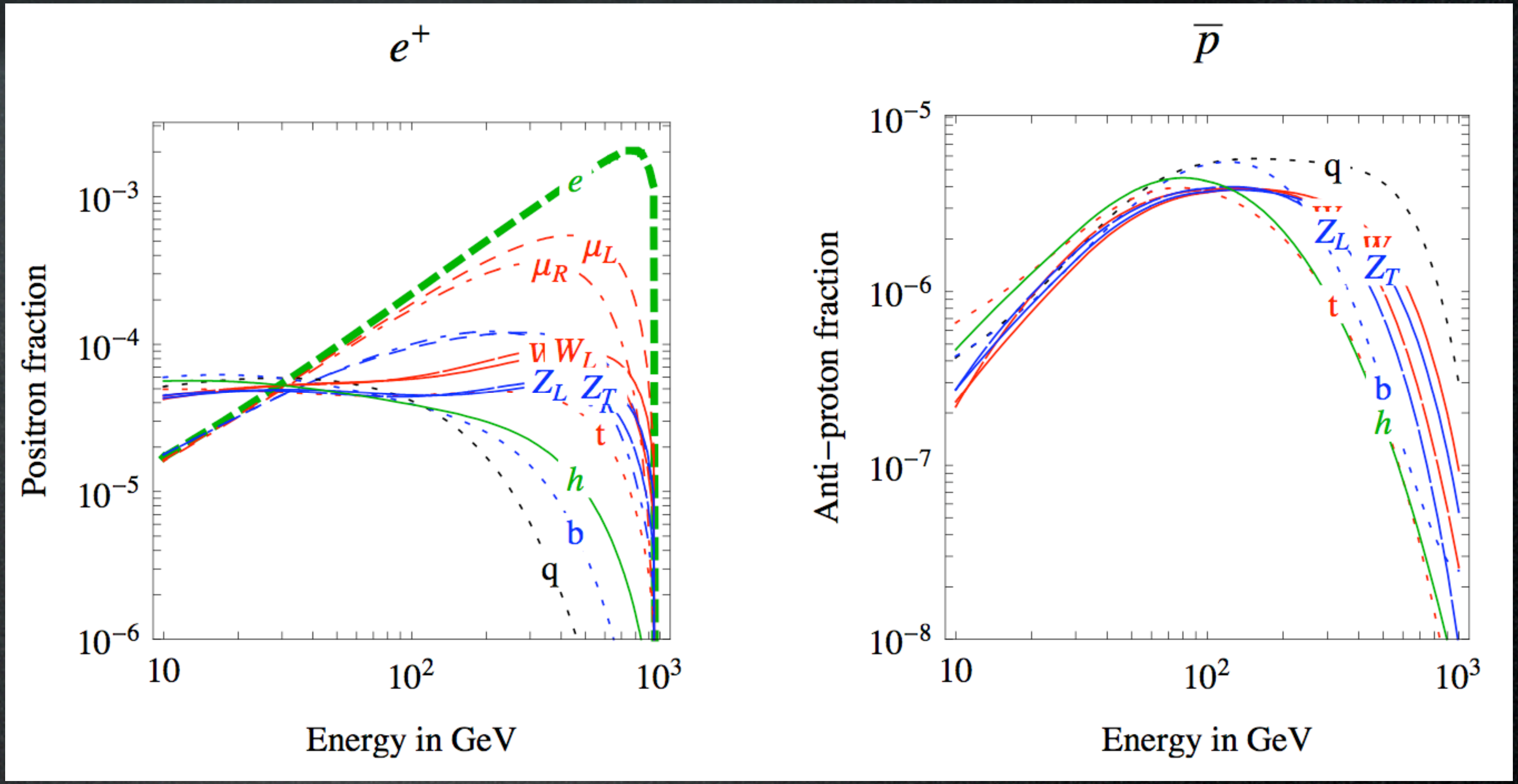




So what are the particle physics parameters?

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

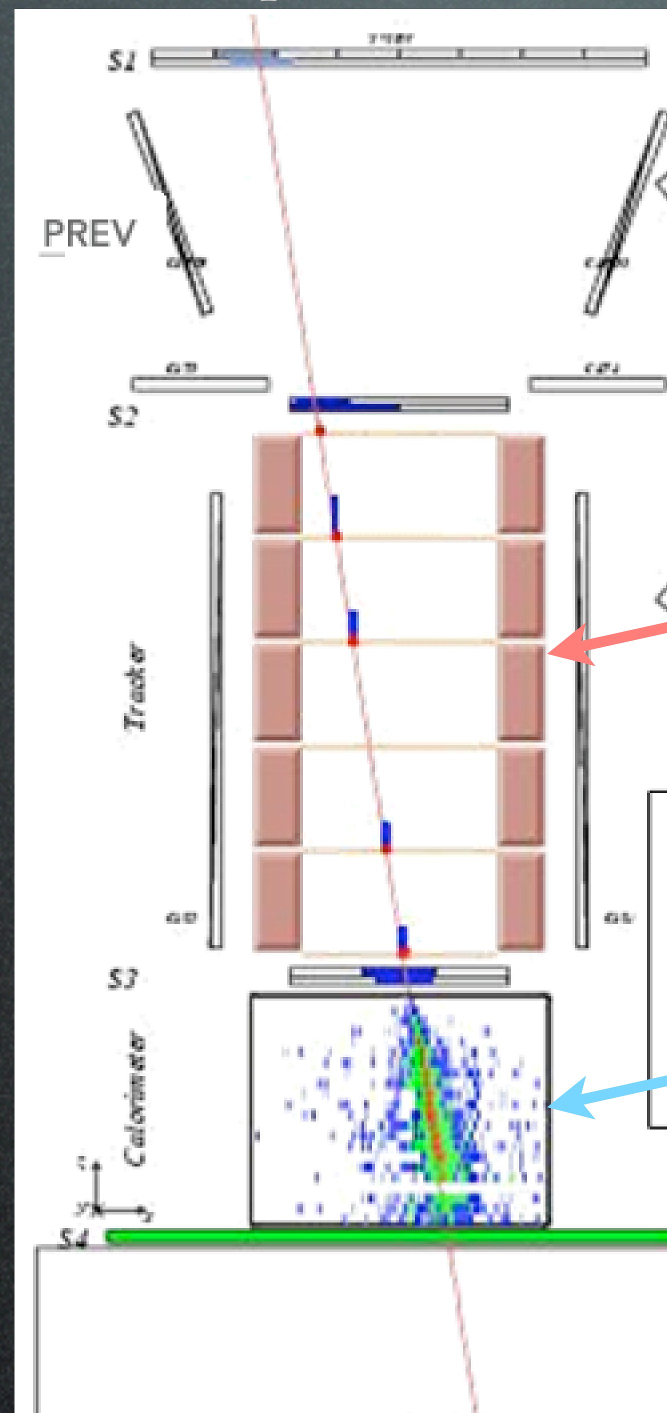
Comparing with data

Data sets

Positrons from PAMELA:

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

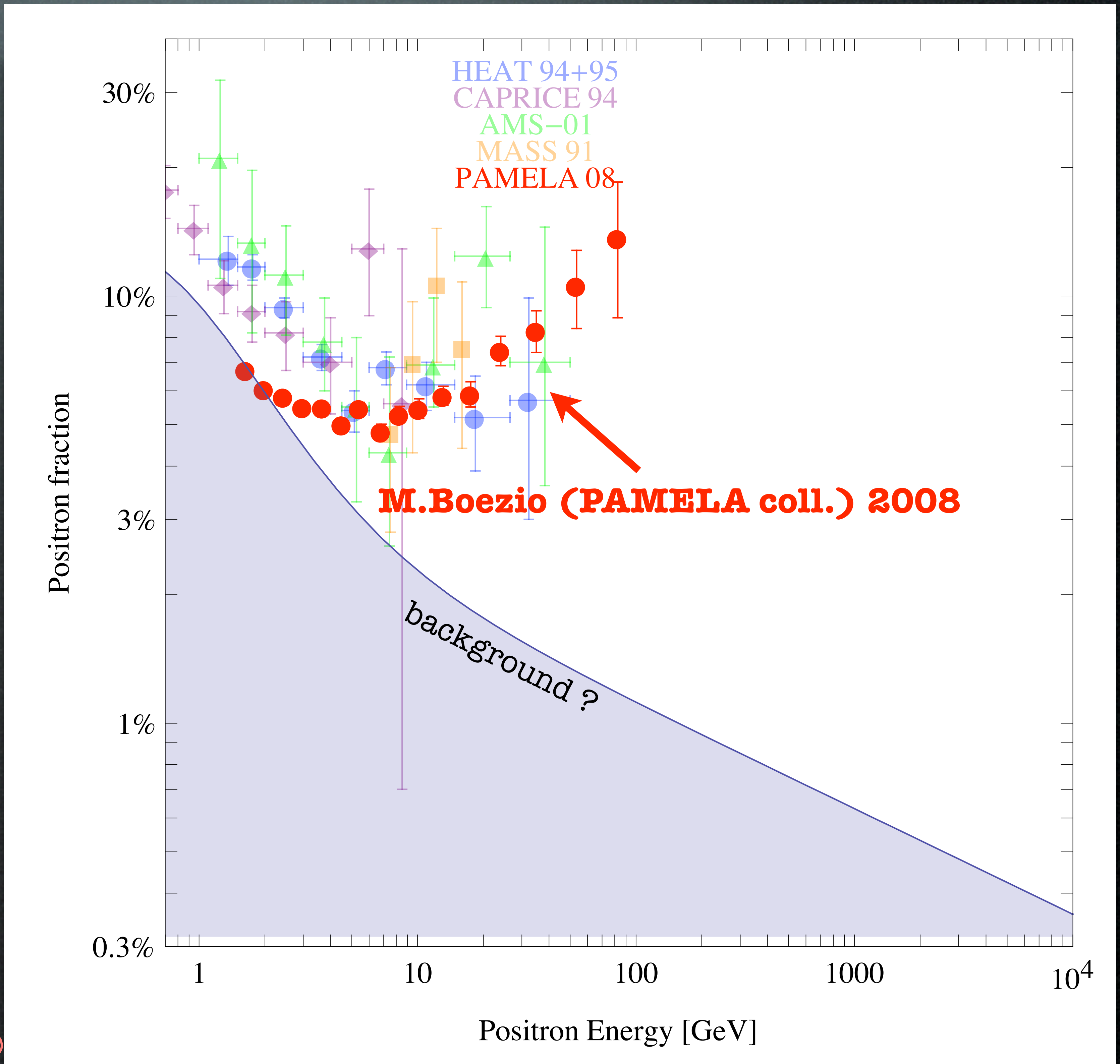
Positrons from PAMELA:

- 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

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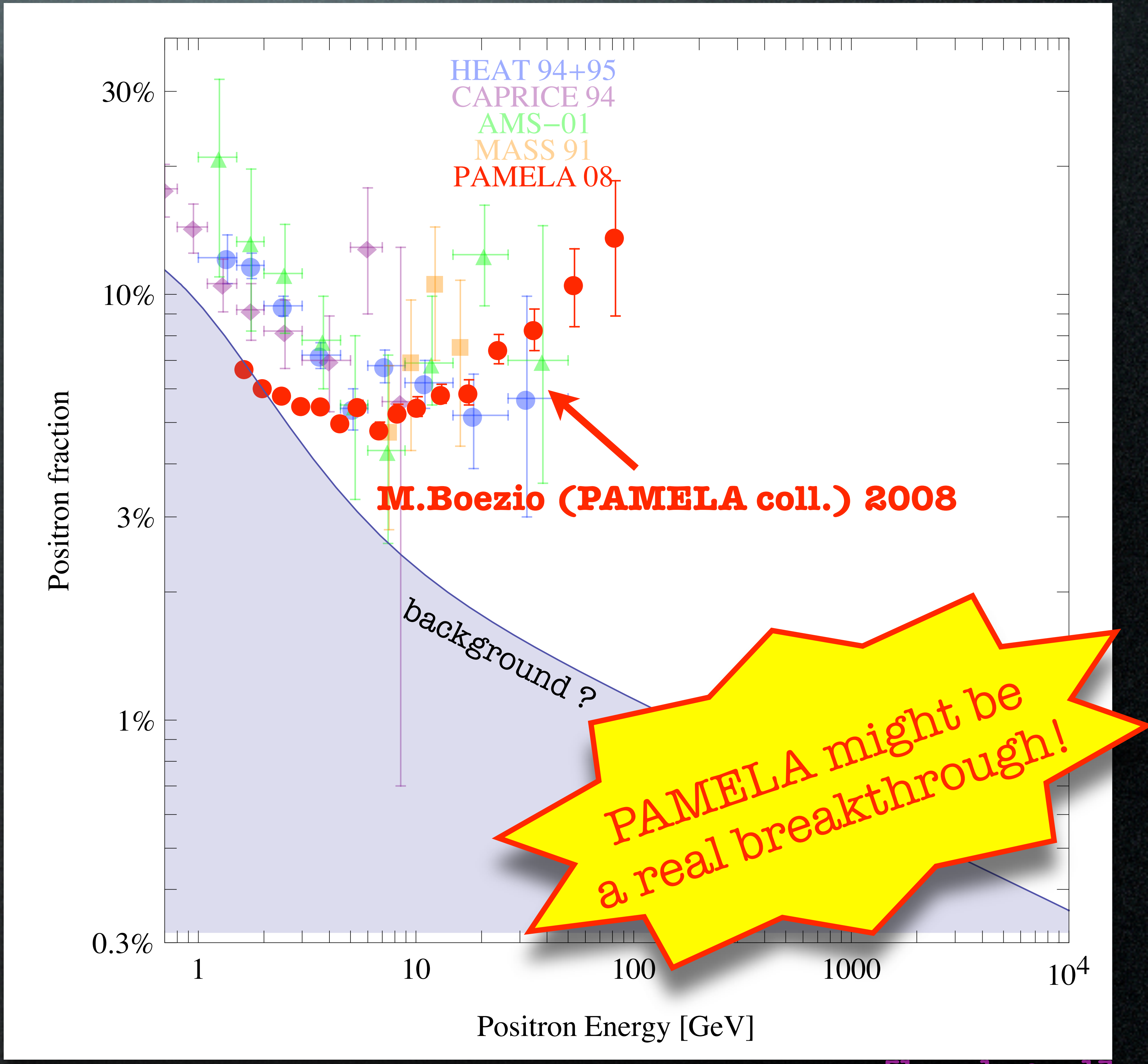
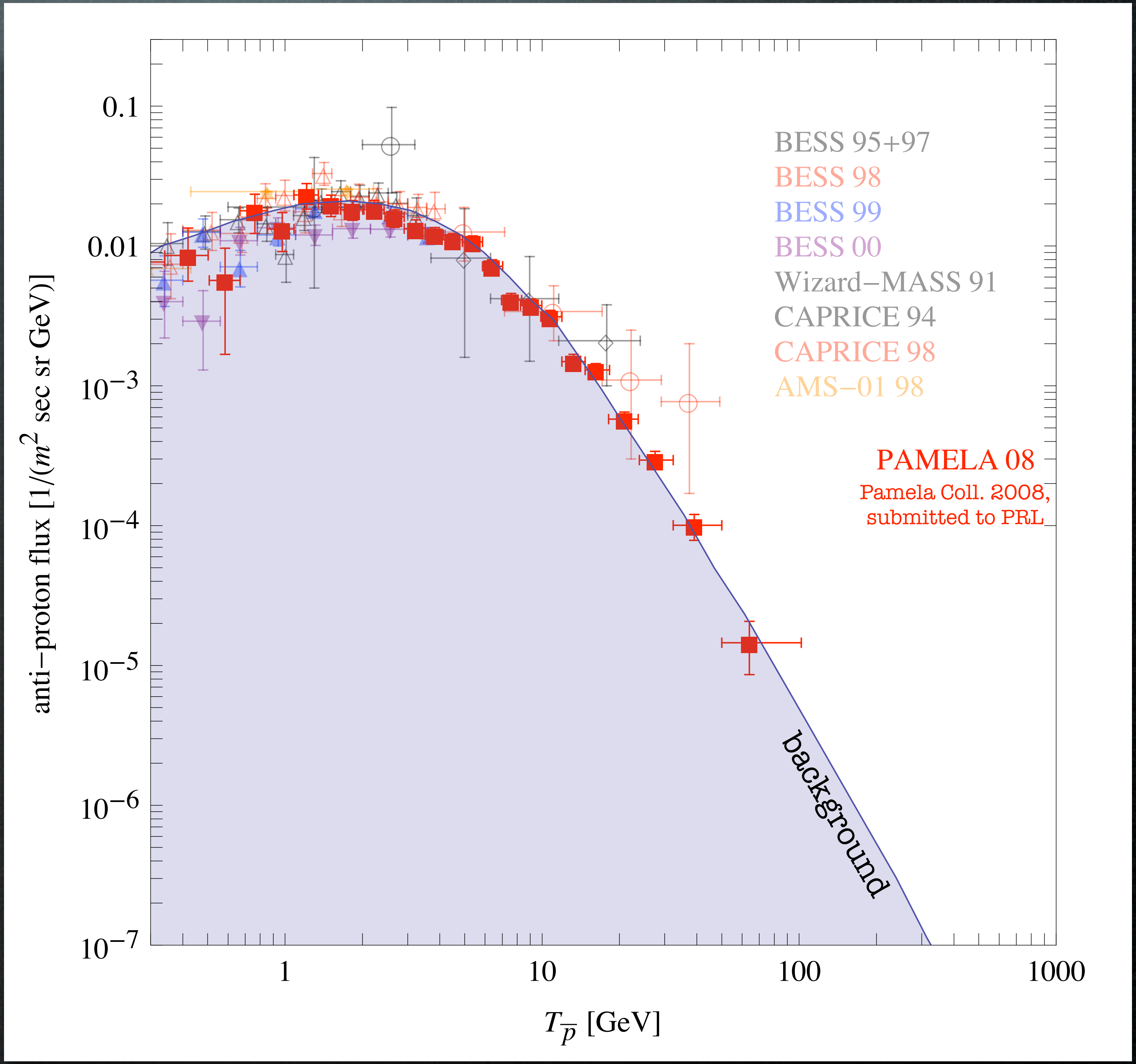


[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background



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

Background

(

Background

Background computations for positrons:

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

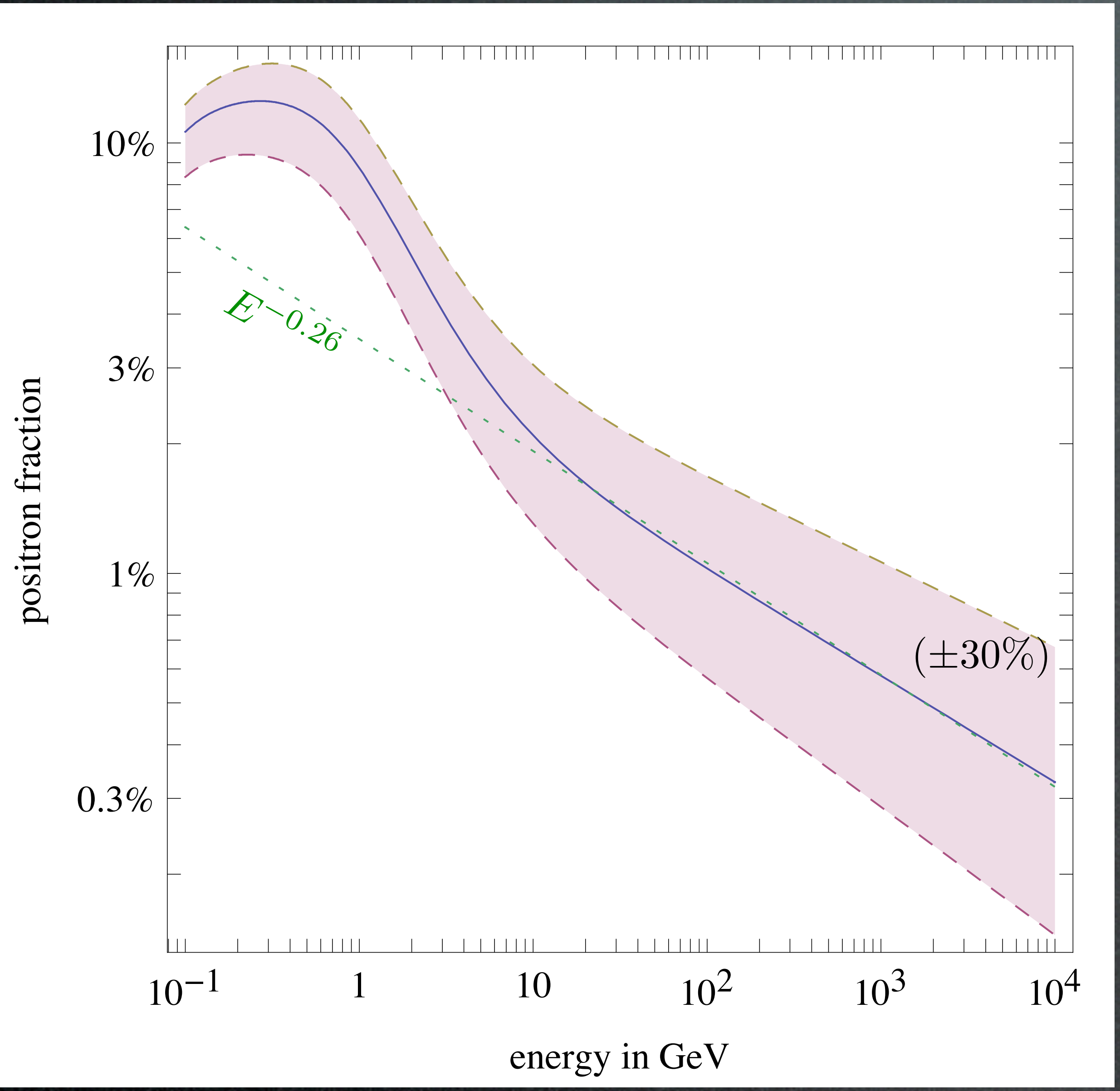
main source: CR nuclei spallating on IS gas

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

Baltz, Edsjo 1999

On the basis of CR simulations of Moskalenko, Strong 1998

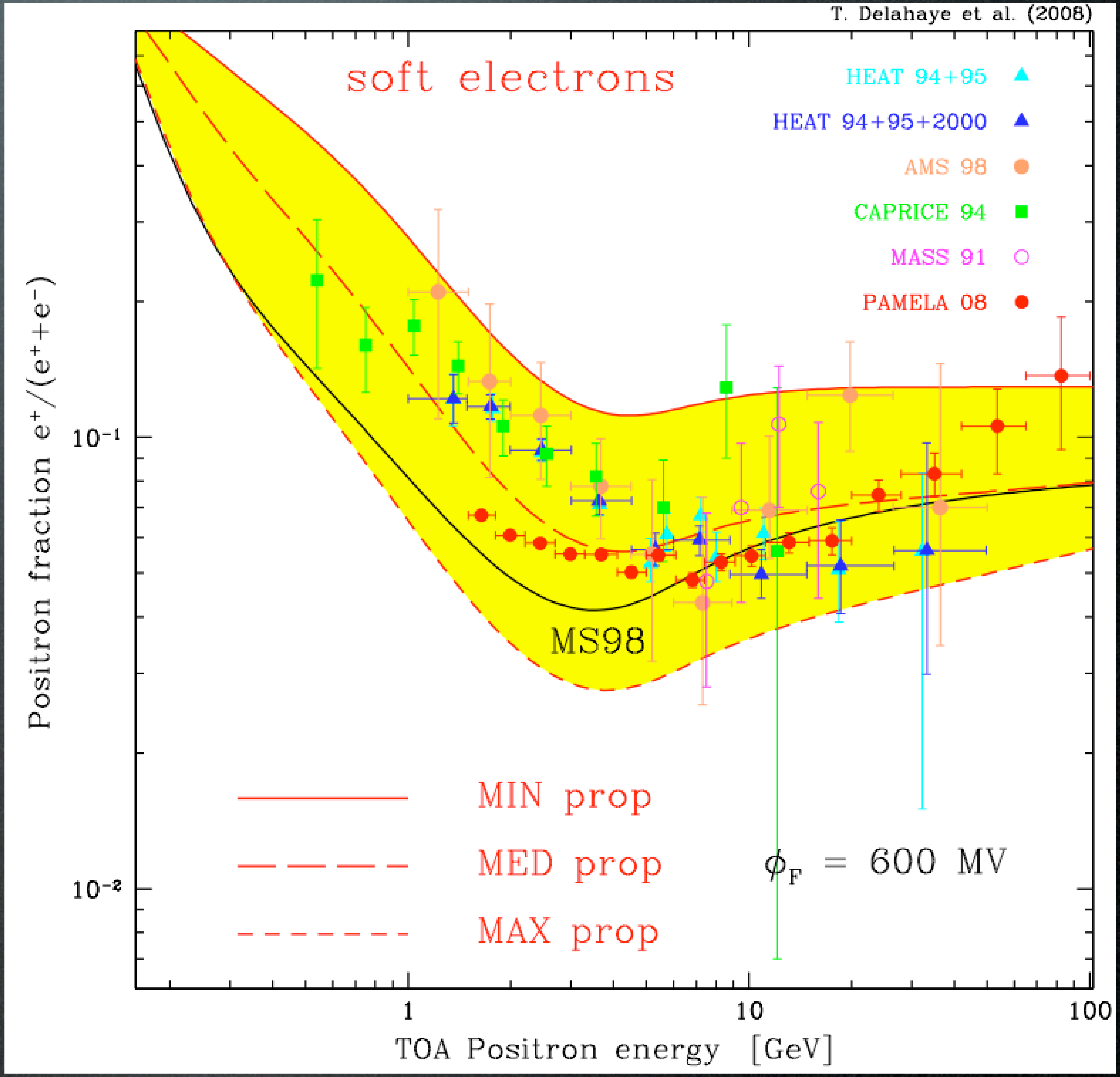
More recently:
Delahaye et al., 0809.5268
P.Salati, Cargese 2007



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

Background

Background estimation for positrons:



using new measuremens of electron fluxes
Casadei, Bindi 2008

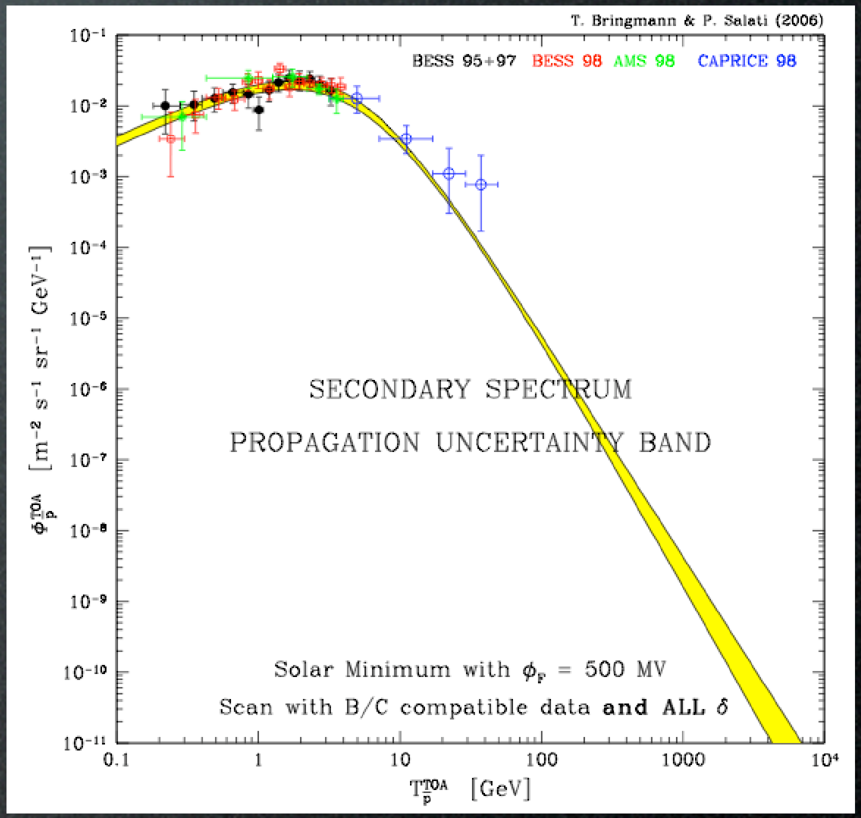
T.Delahaye et al., 09.2008

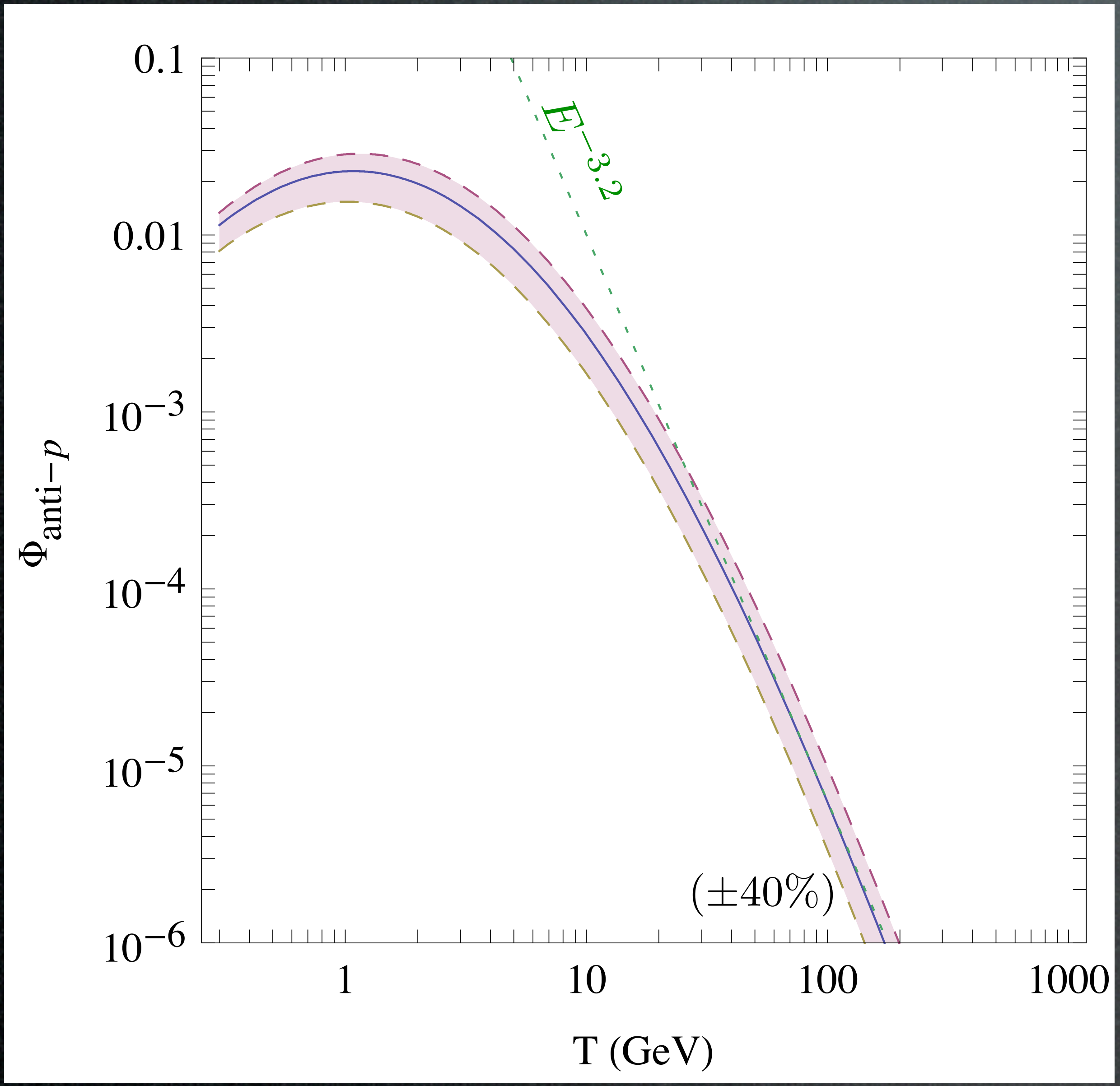
Background

Background computations for antiprotons:

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

Bringmann, Salati 2006





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$E^p, \quad p = \pm 0.05$
and let normalization free.

Background

Results

Which DM spectra can fit the data?

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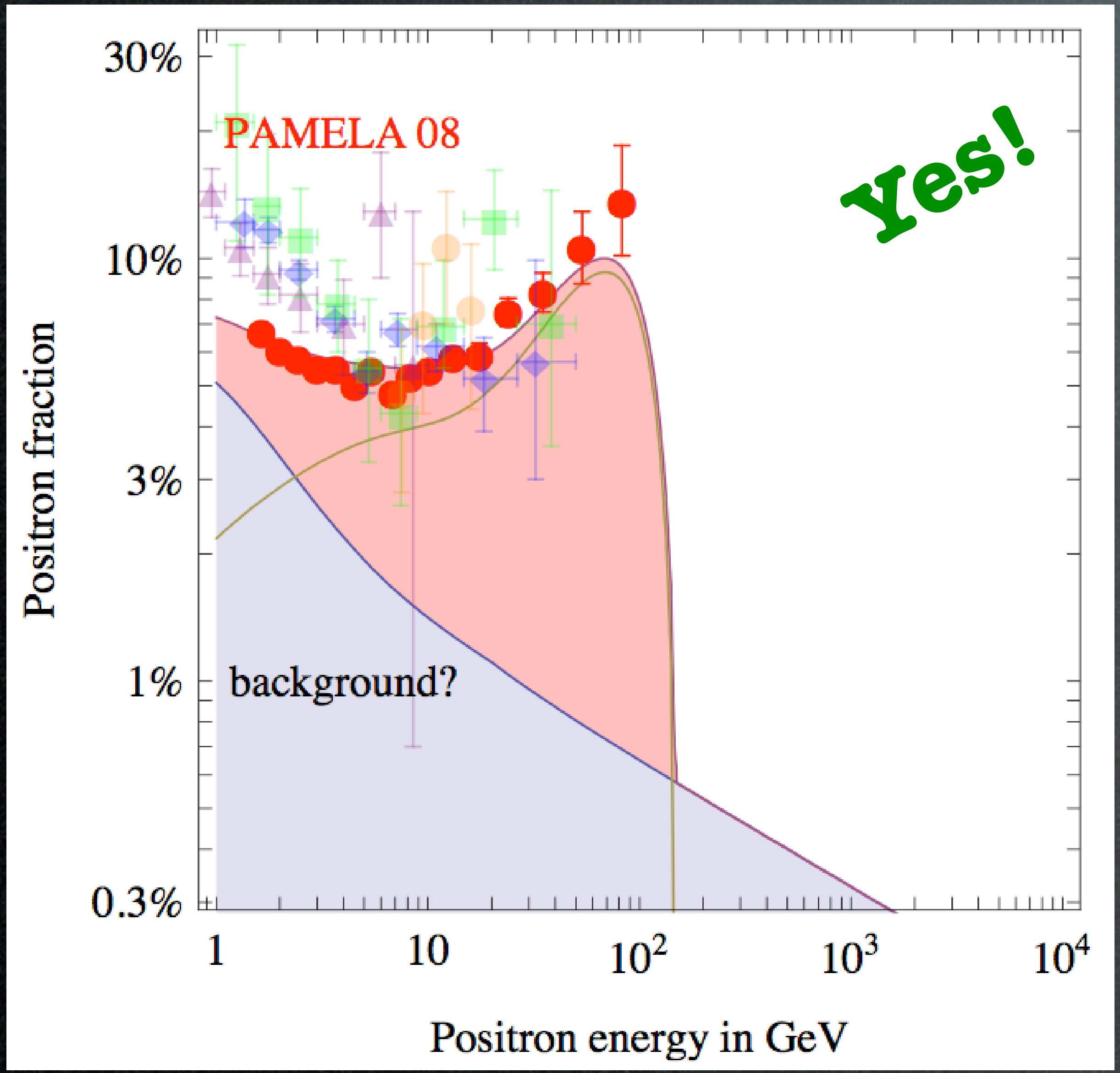
Which DM spectra can fit the data?

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

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

(a possible SuperSymmetric candidate: wino)

Positrons:



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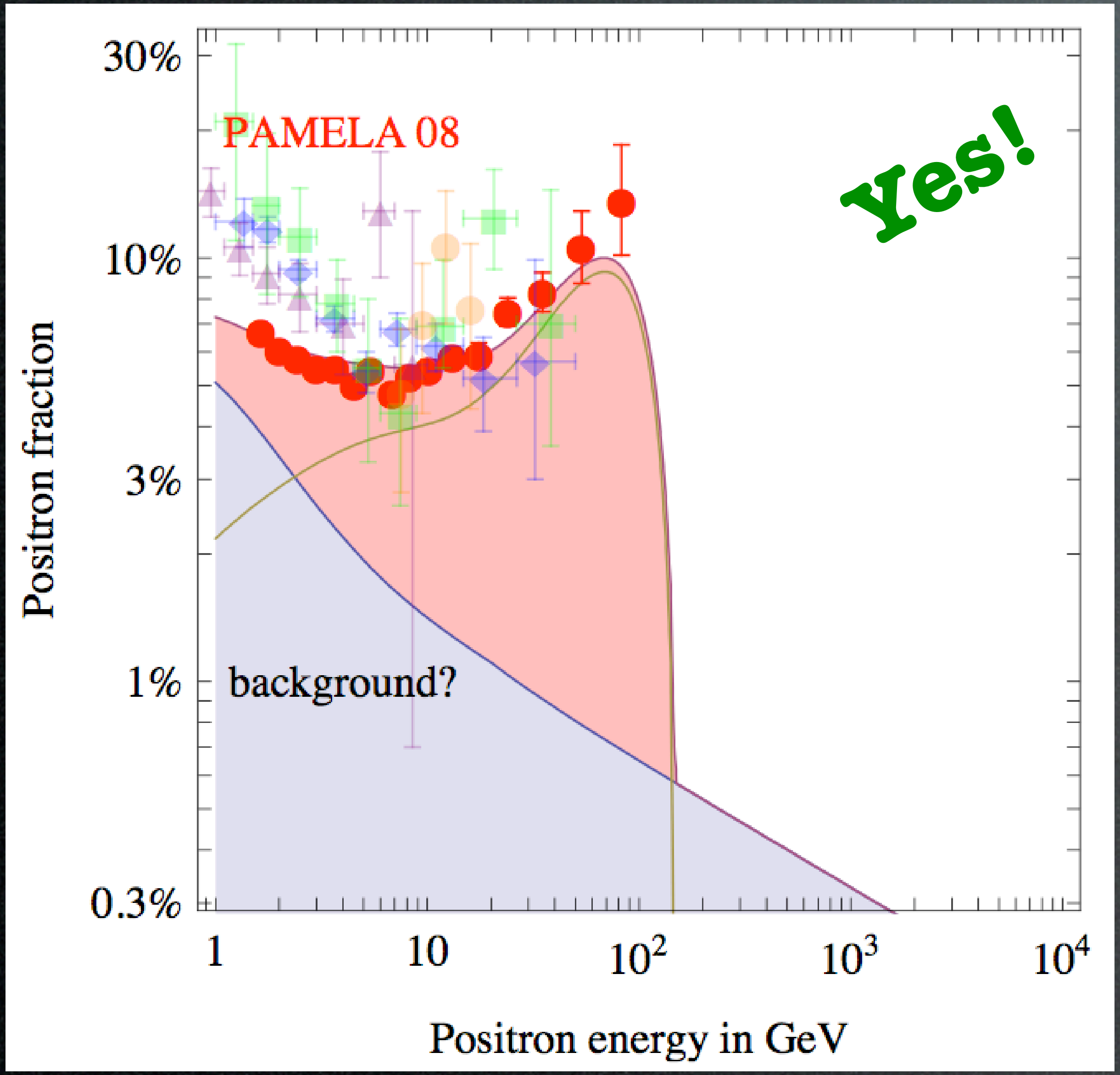
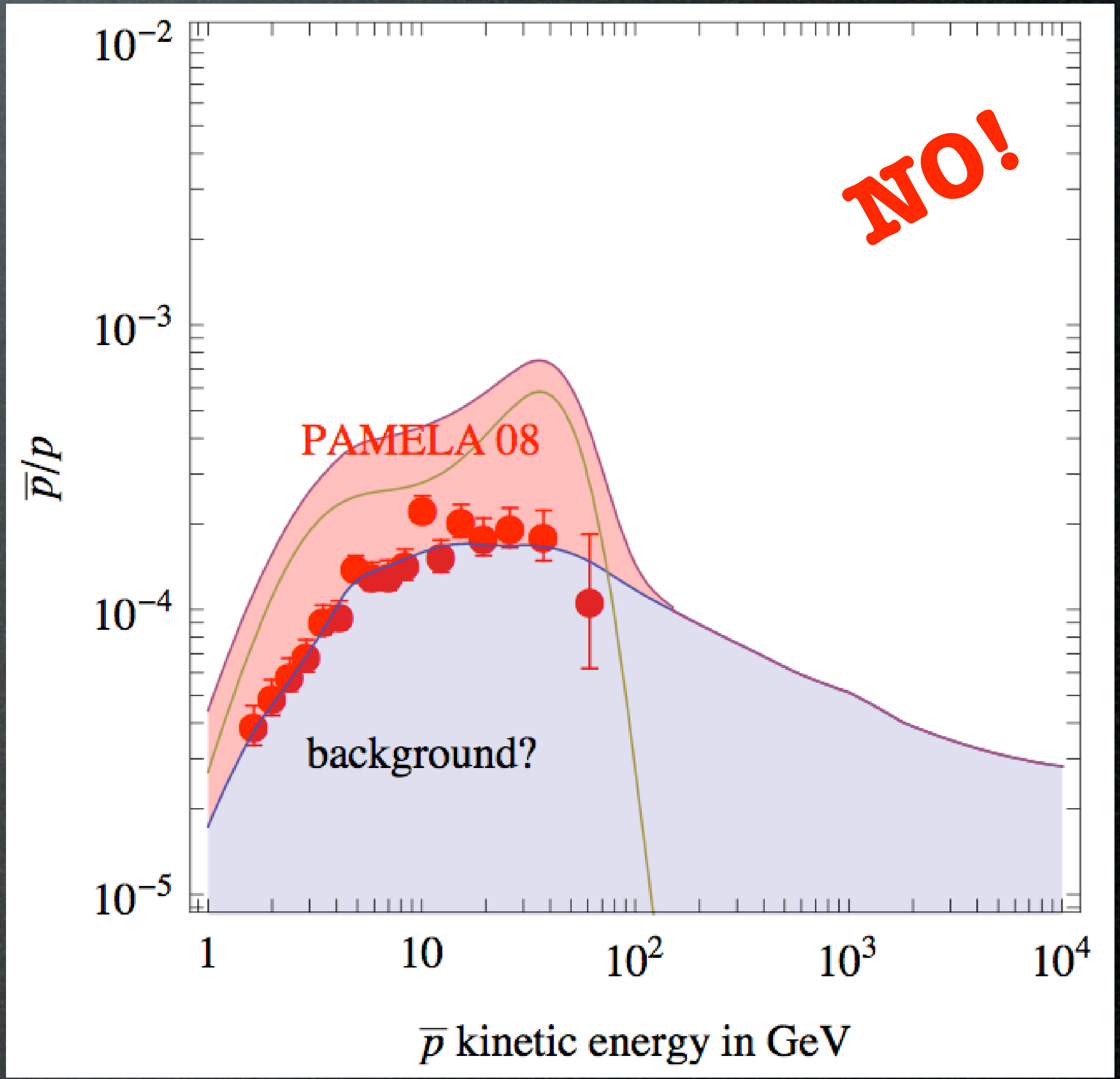


Anti-protons:



[insisting on Winos]

Results

Which DM spectra can fit the data?

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

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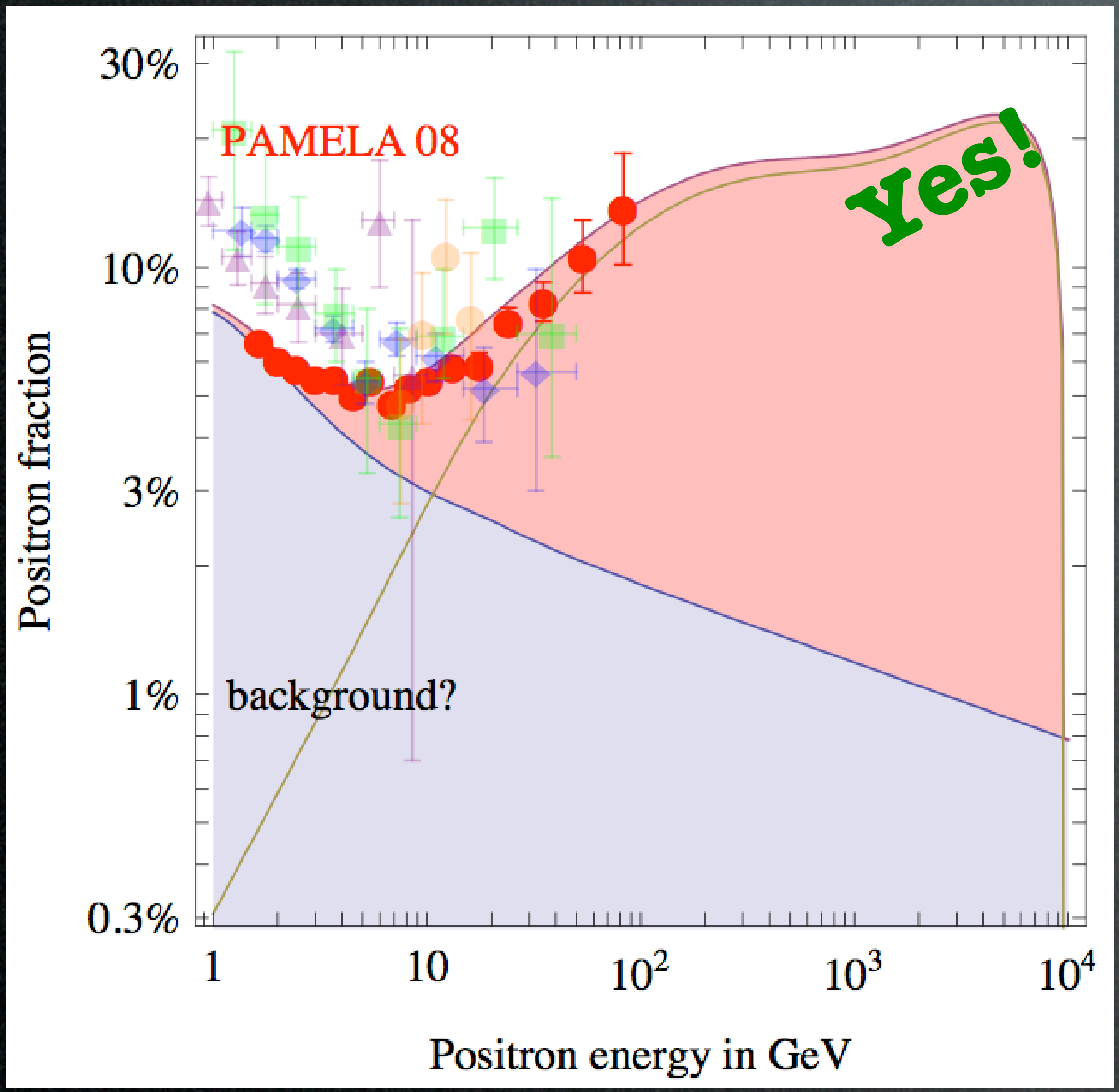

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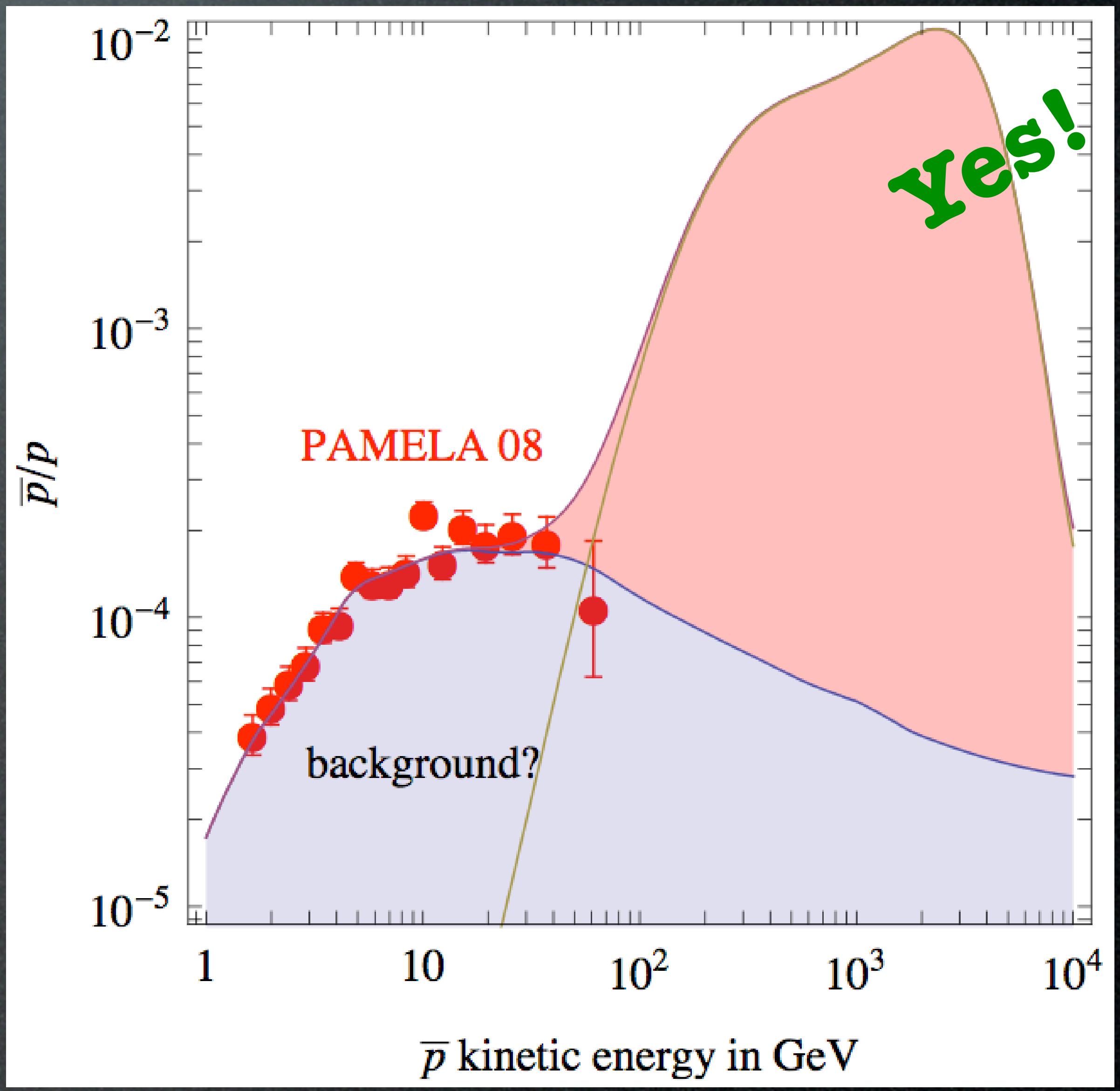


Results

Which DM spectra can fit the data?

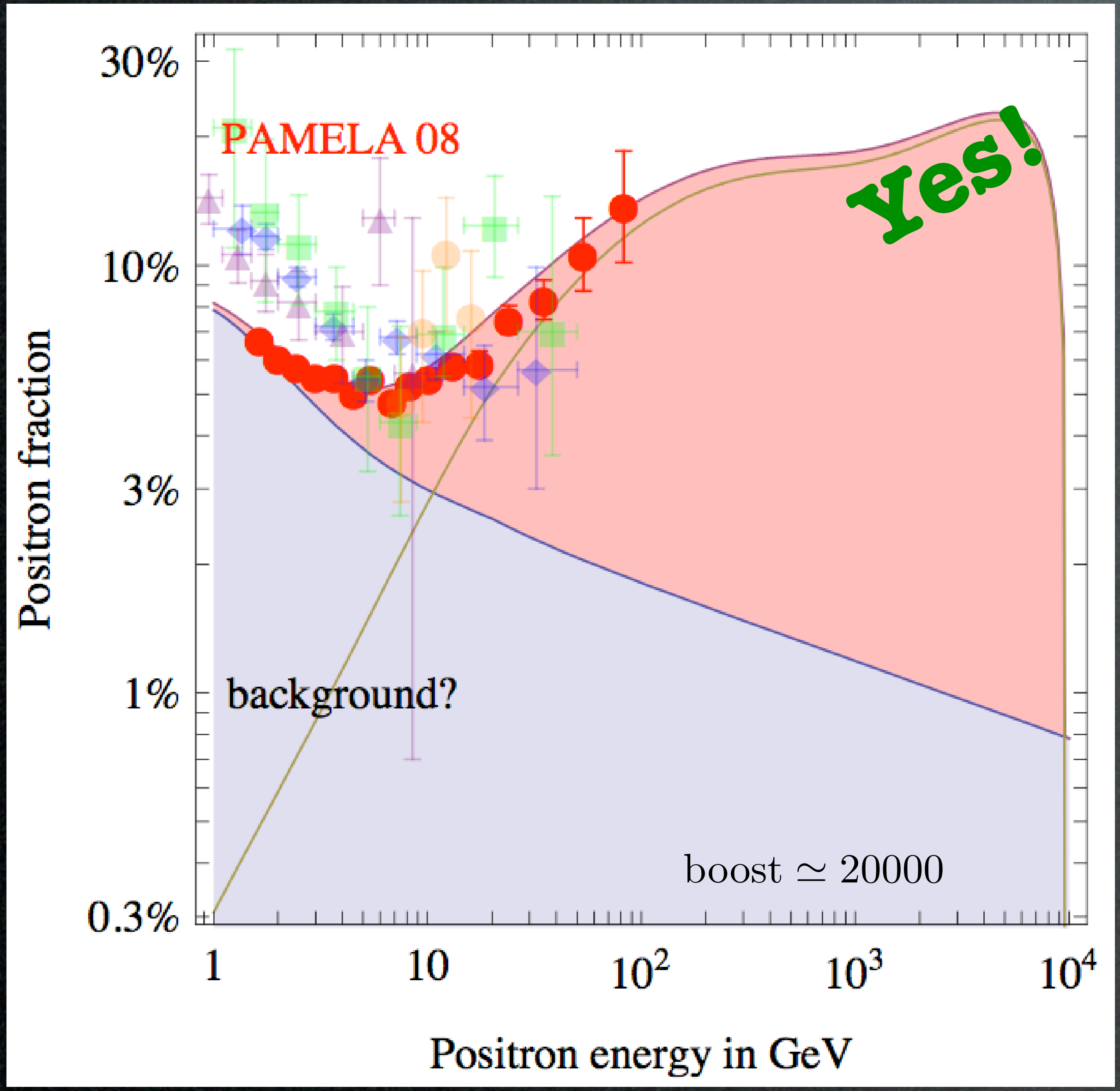
E.g. a DM with: -mass $M_{\rm DM} = 10\,\mathrm{TeV}$

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

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

Mmm...

Positrons:



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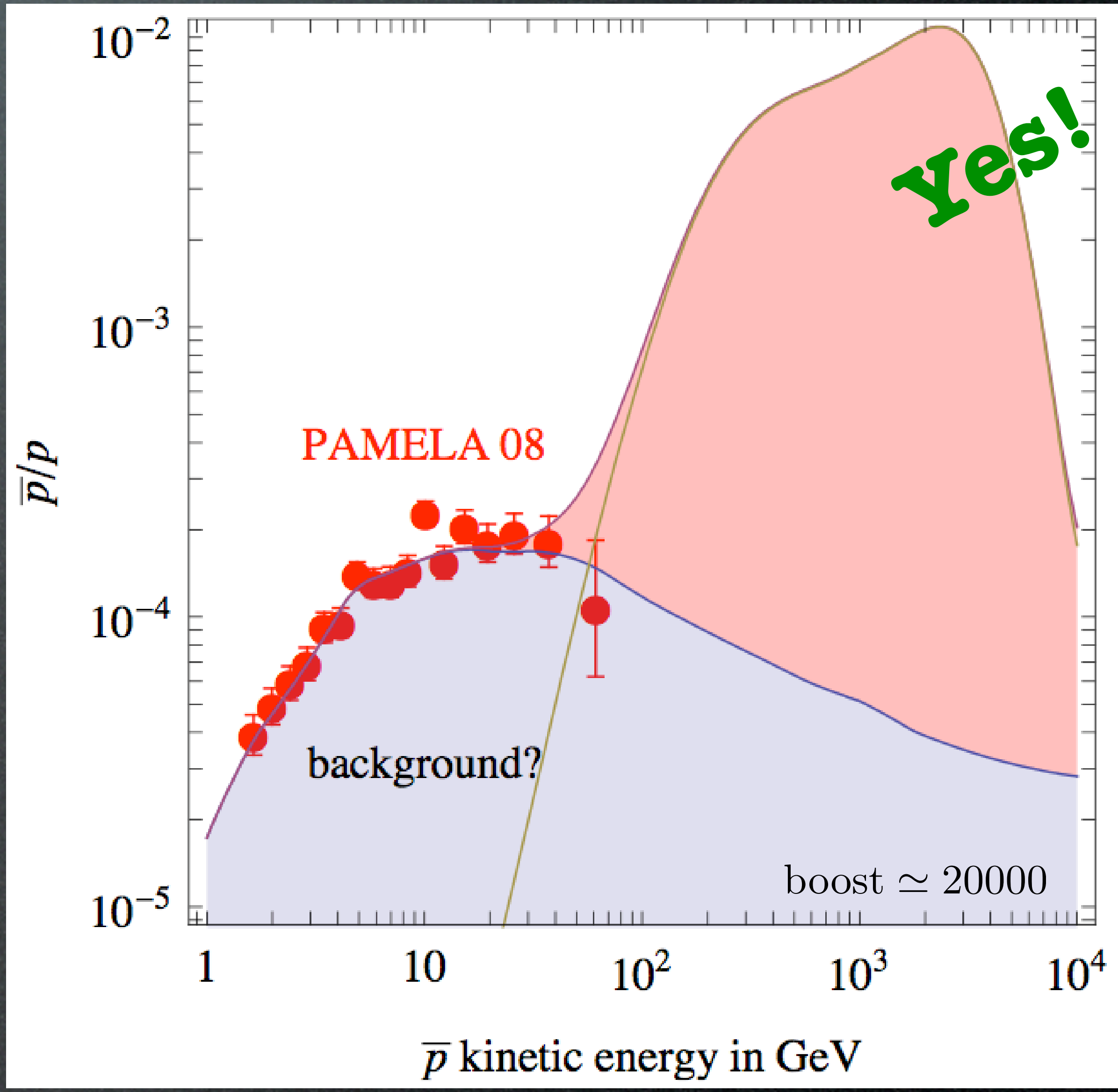
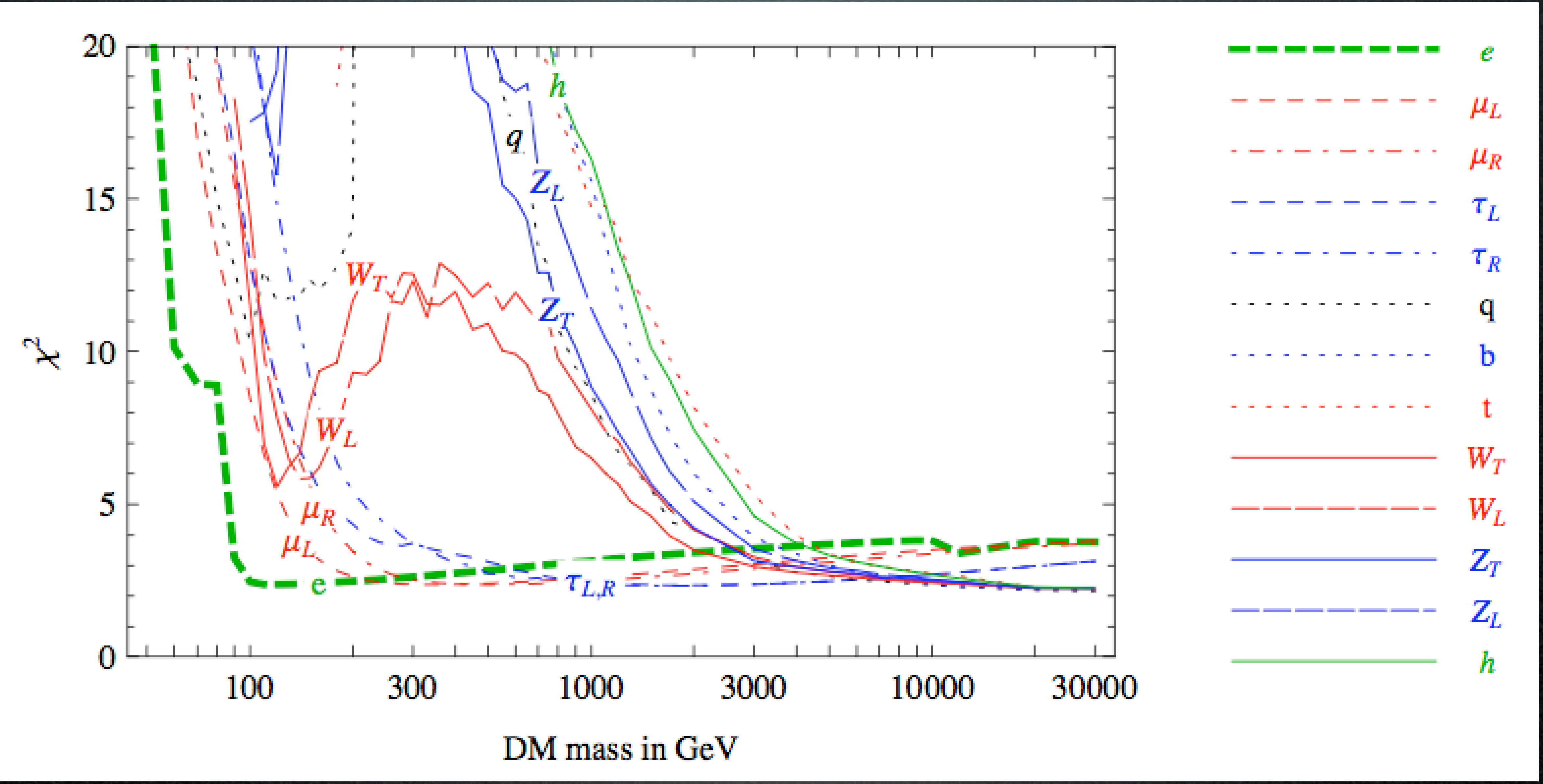


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons only

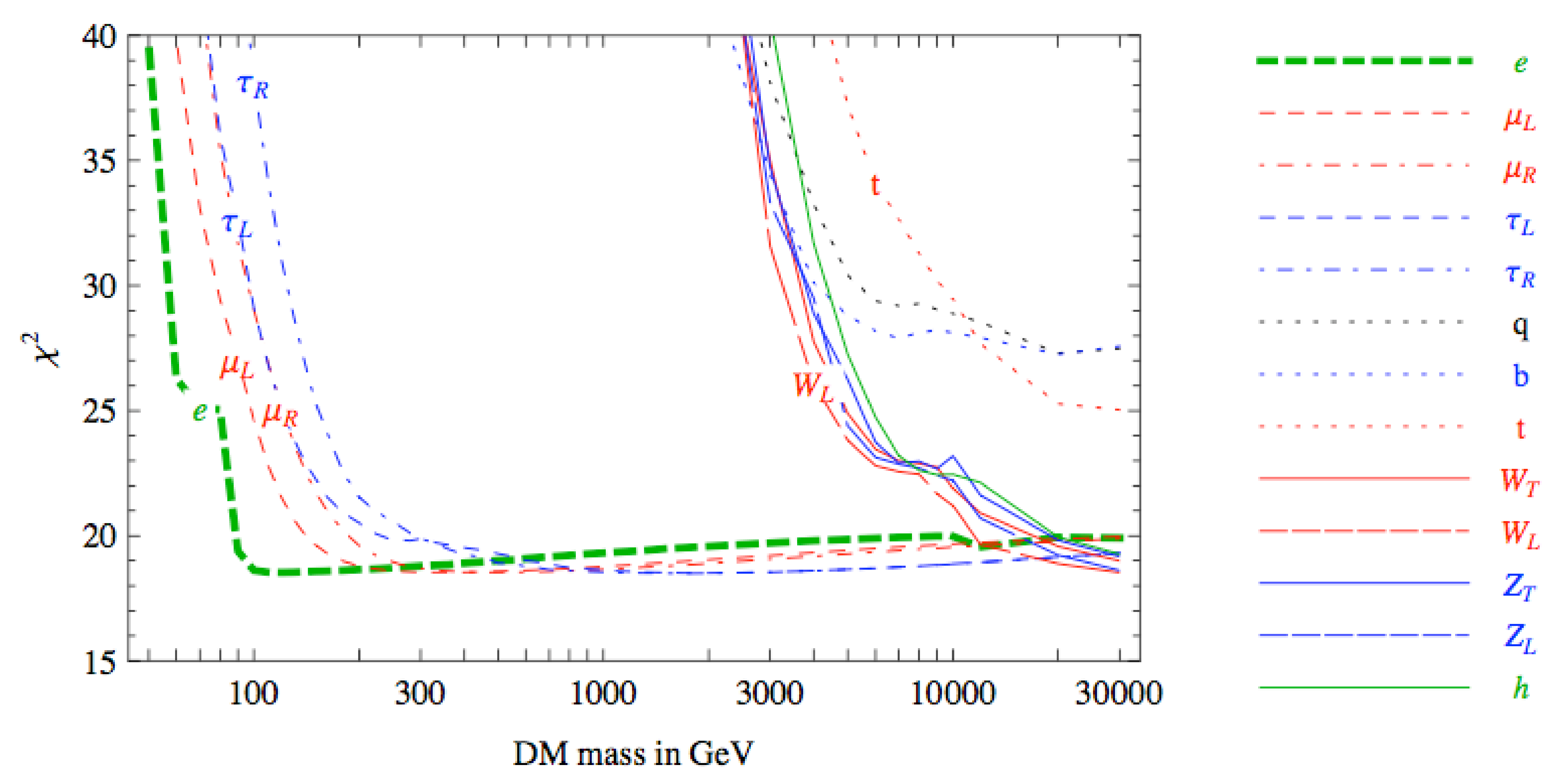


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



Results

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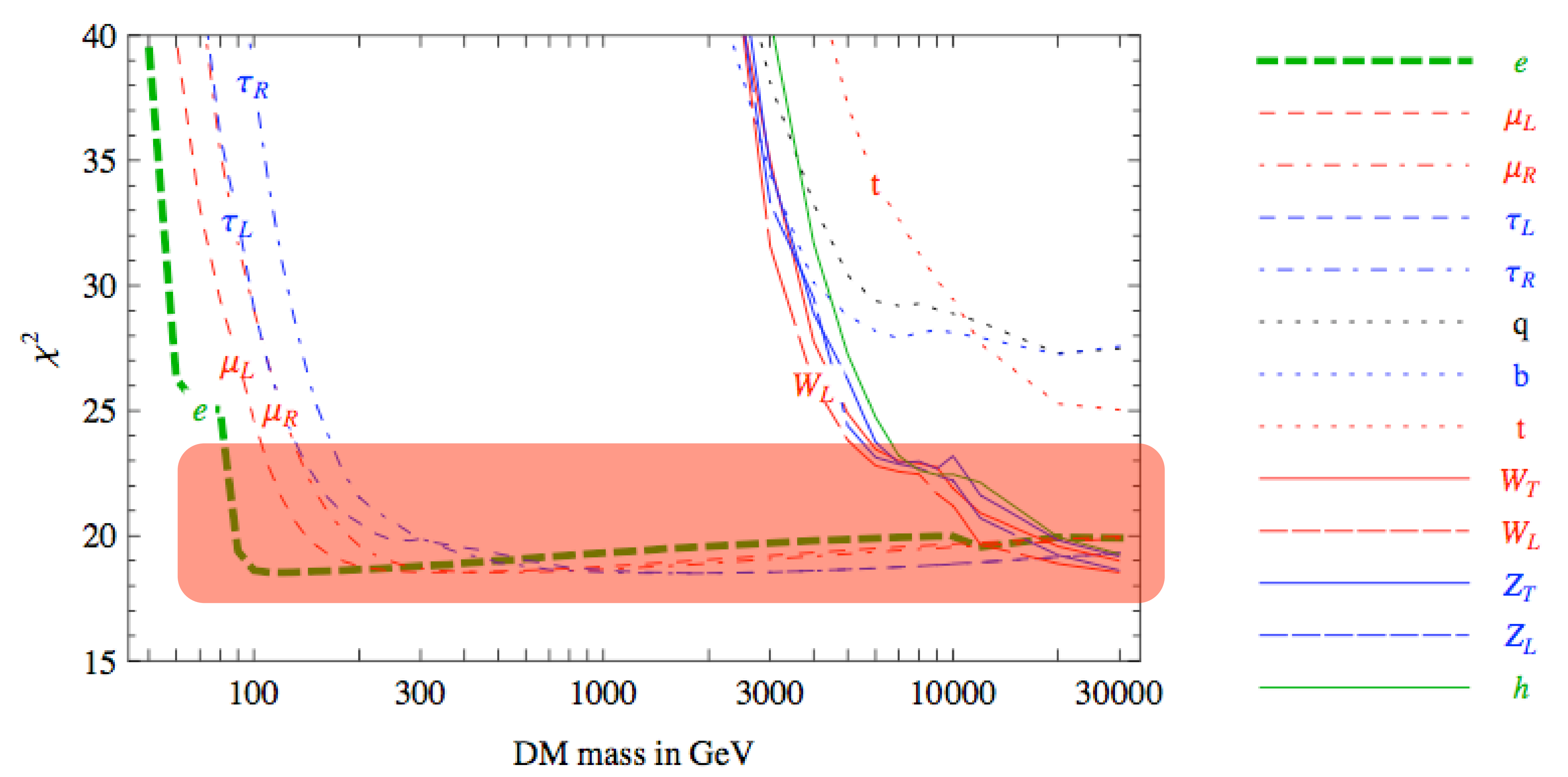


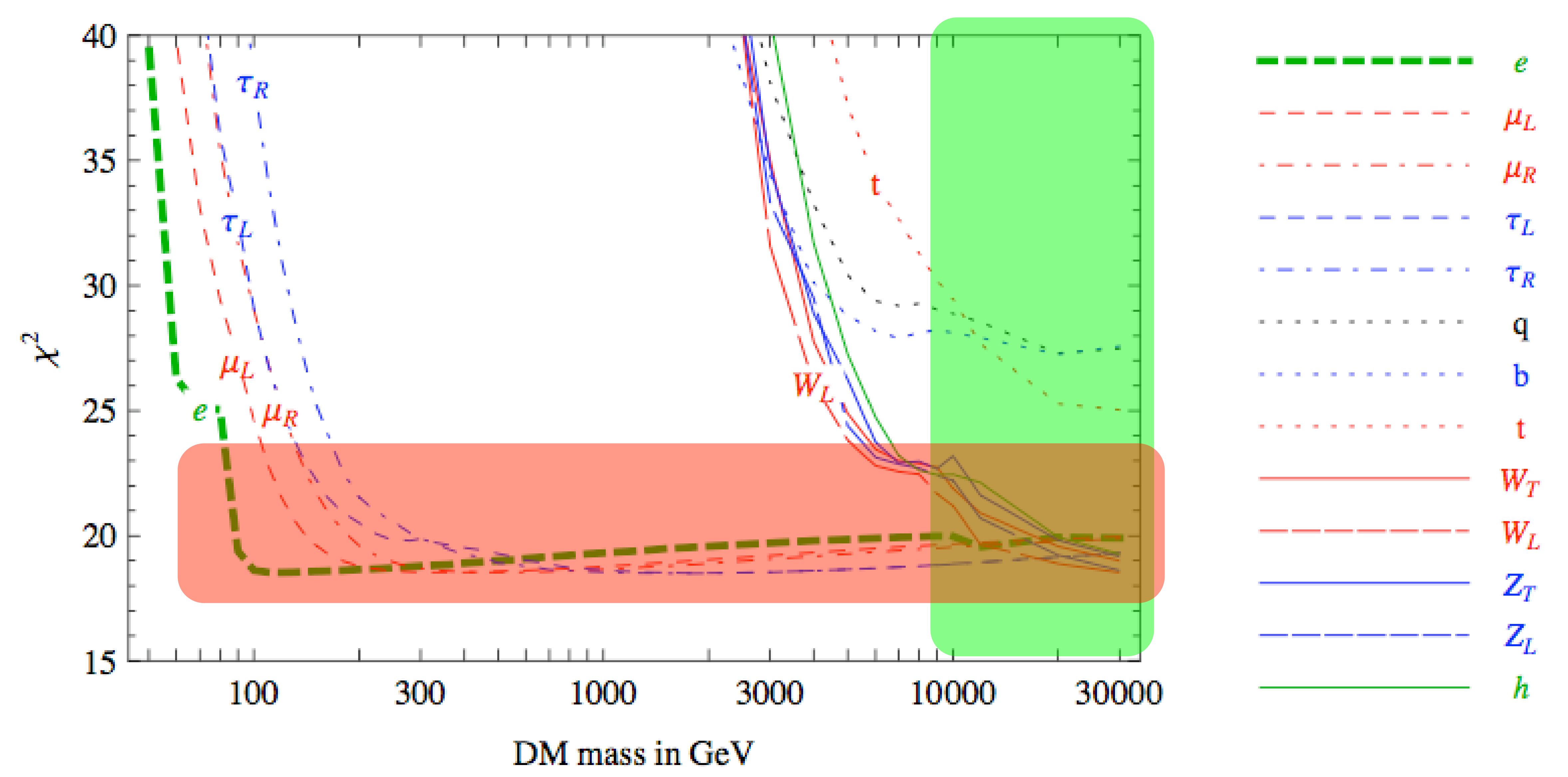
(1) annihilate into leptons (e.g. $\mu^+\mu^-$)

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

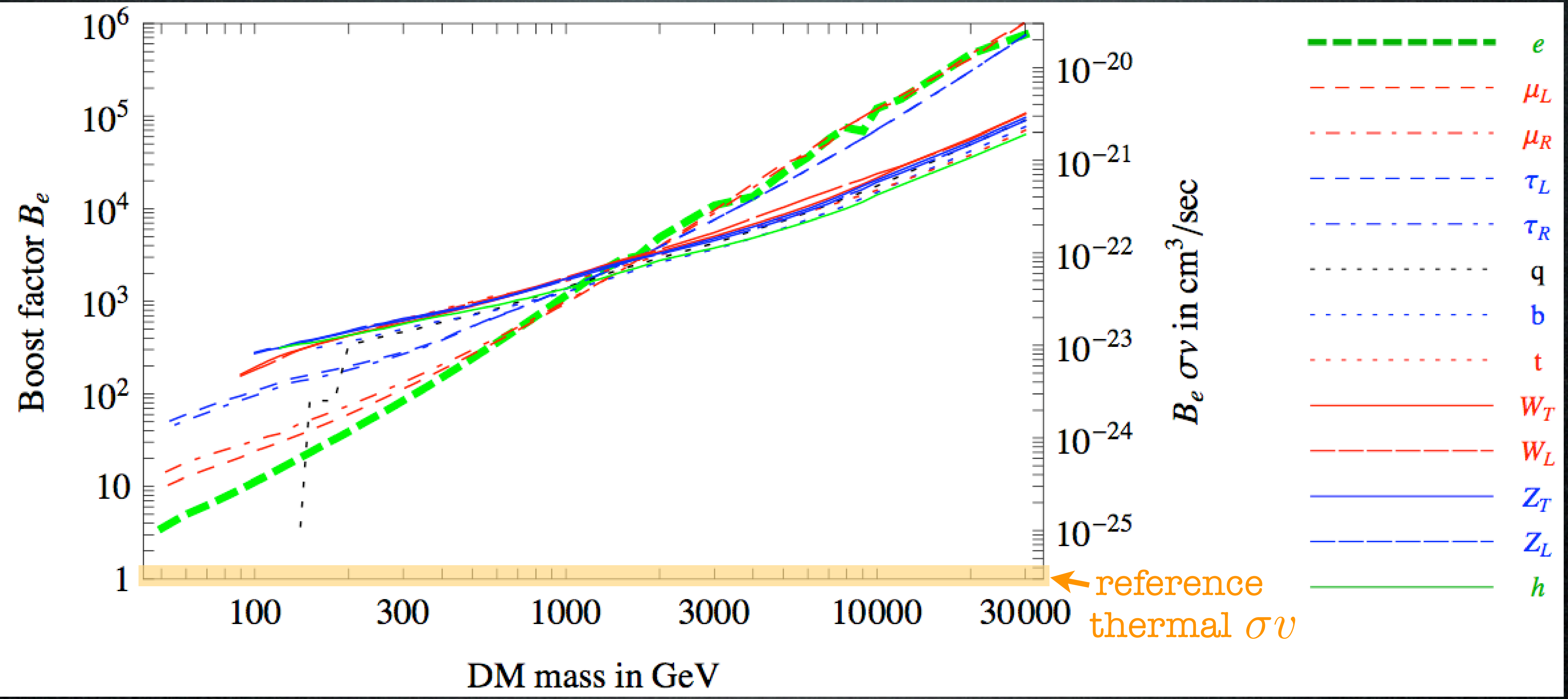
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

Results

Which DM spectra can fit the data?

Model-independent results:

Cross section required by PAMELA



Data sets

Electrons + positrons from ATIC, PPB-BETS:

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

Advanced
Thin
Ionization
Calorimeter

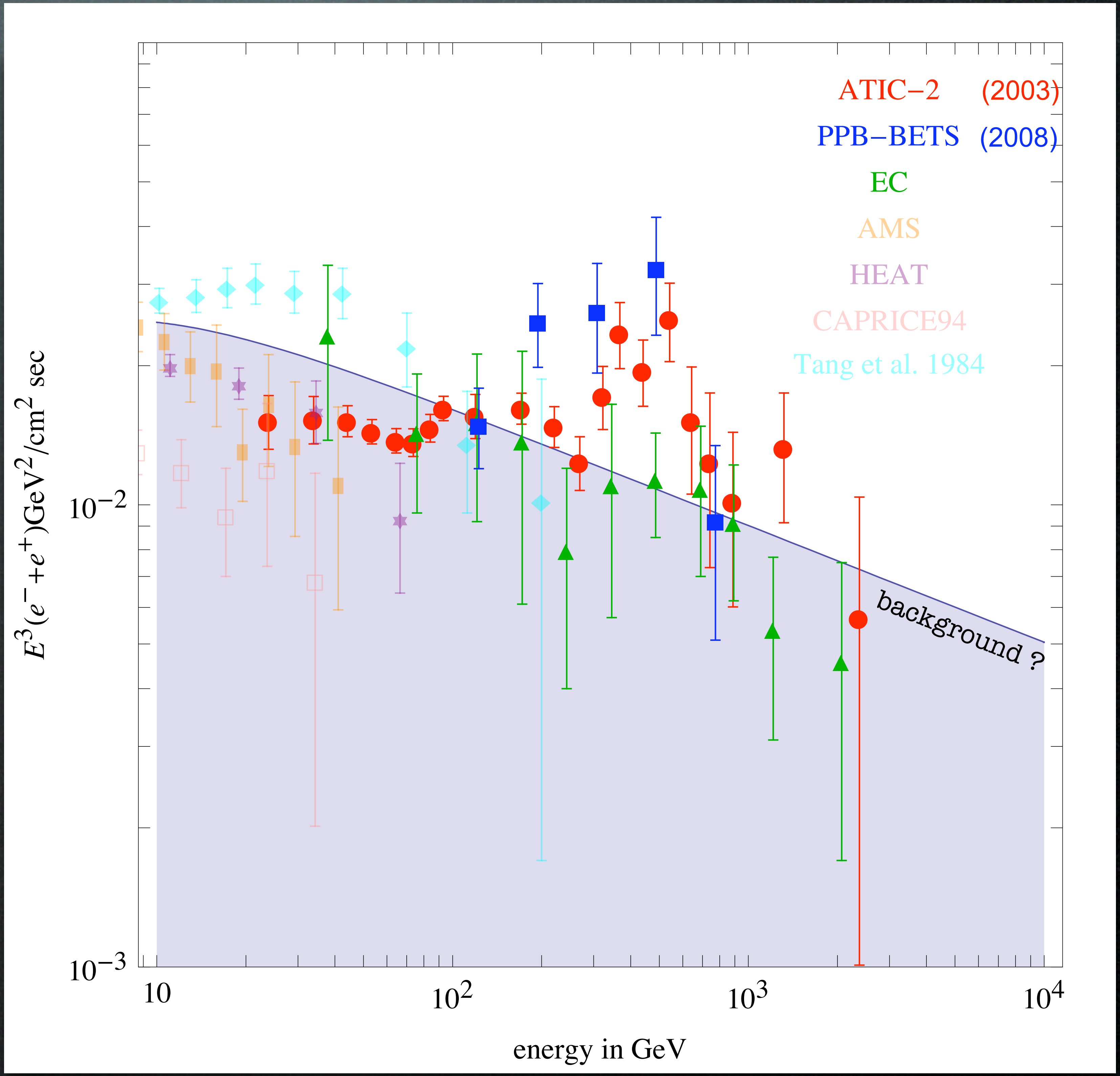
- bigger/denser: higher energy

- calorimeter only, no magnet: no charge discrimination

Data sets

Electrons + positrons from ATIC, PPB-BETS:

- an $e^+ + e^-$ excess at $\sim$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 $M_{\rm DM} = 1\,{\rm TeV}$

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

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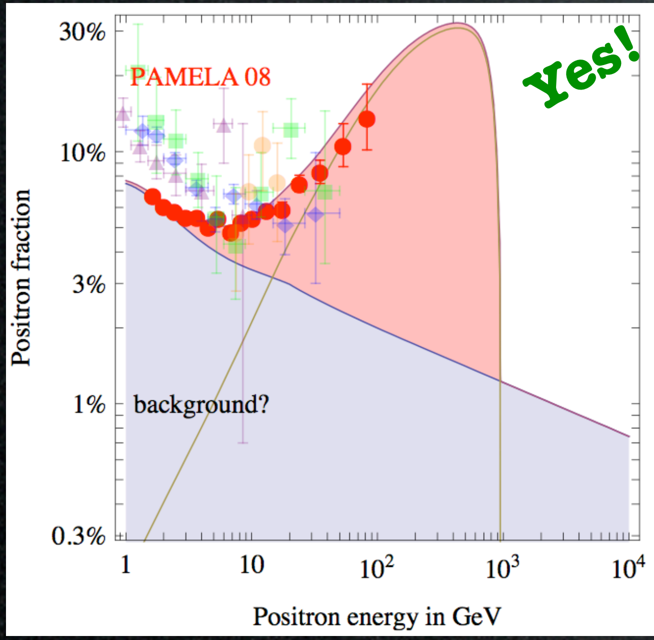
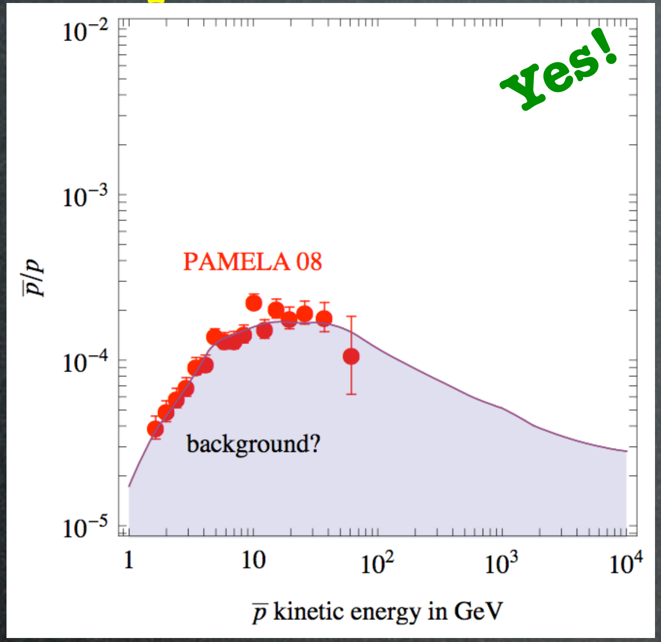
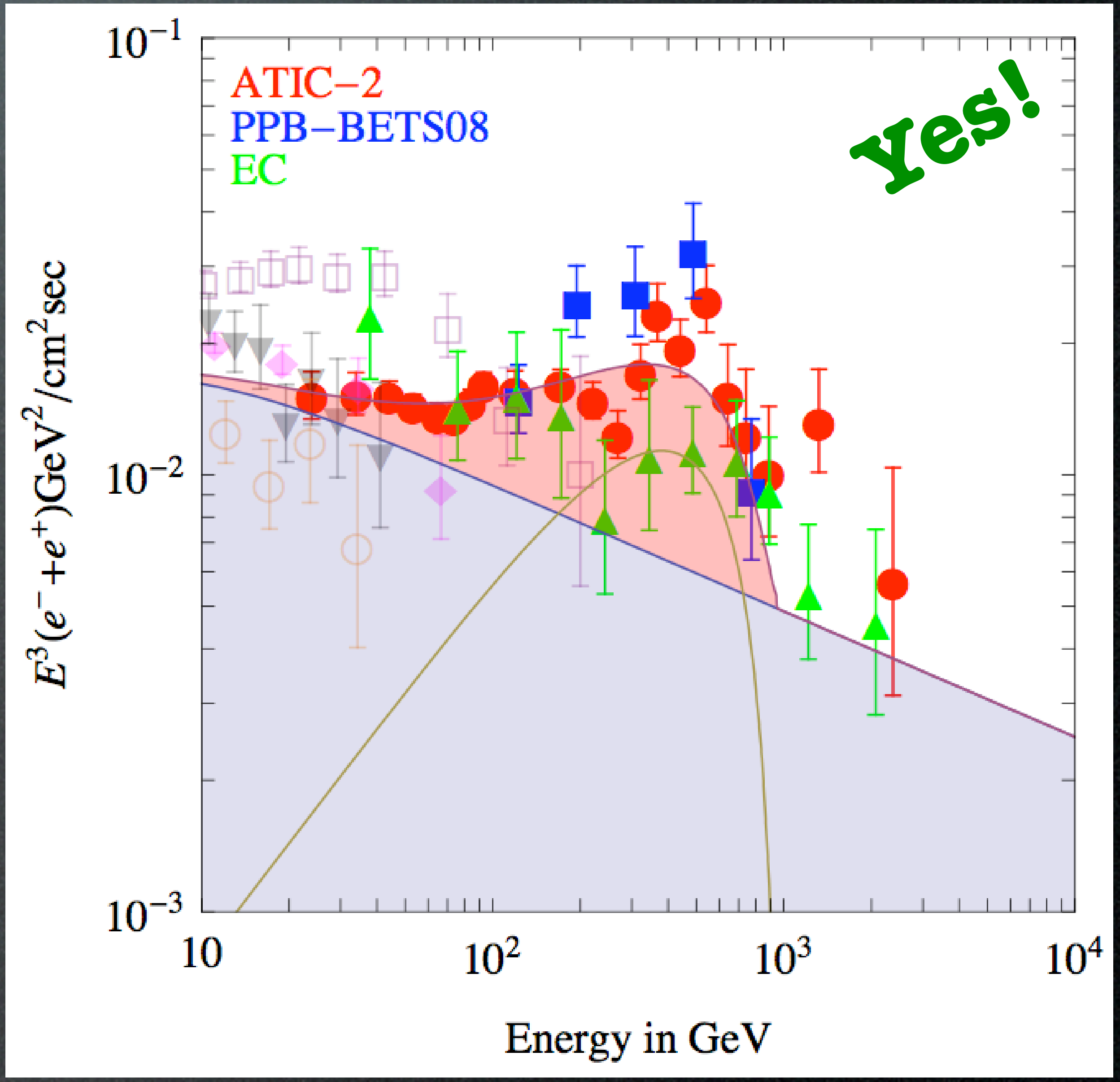


Anti-protons:



Electrons + Positrons:



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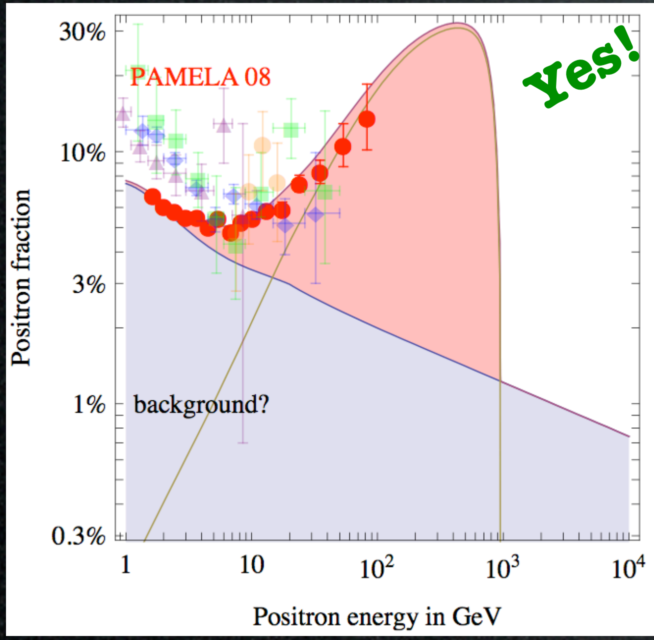

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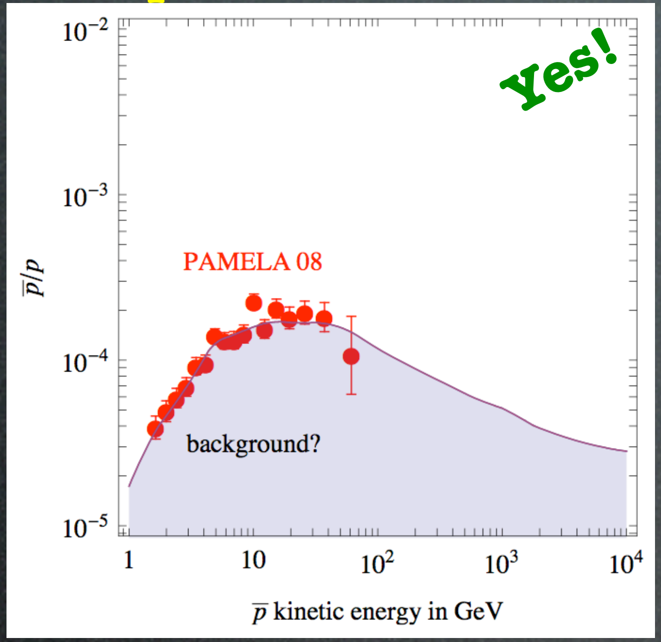

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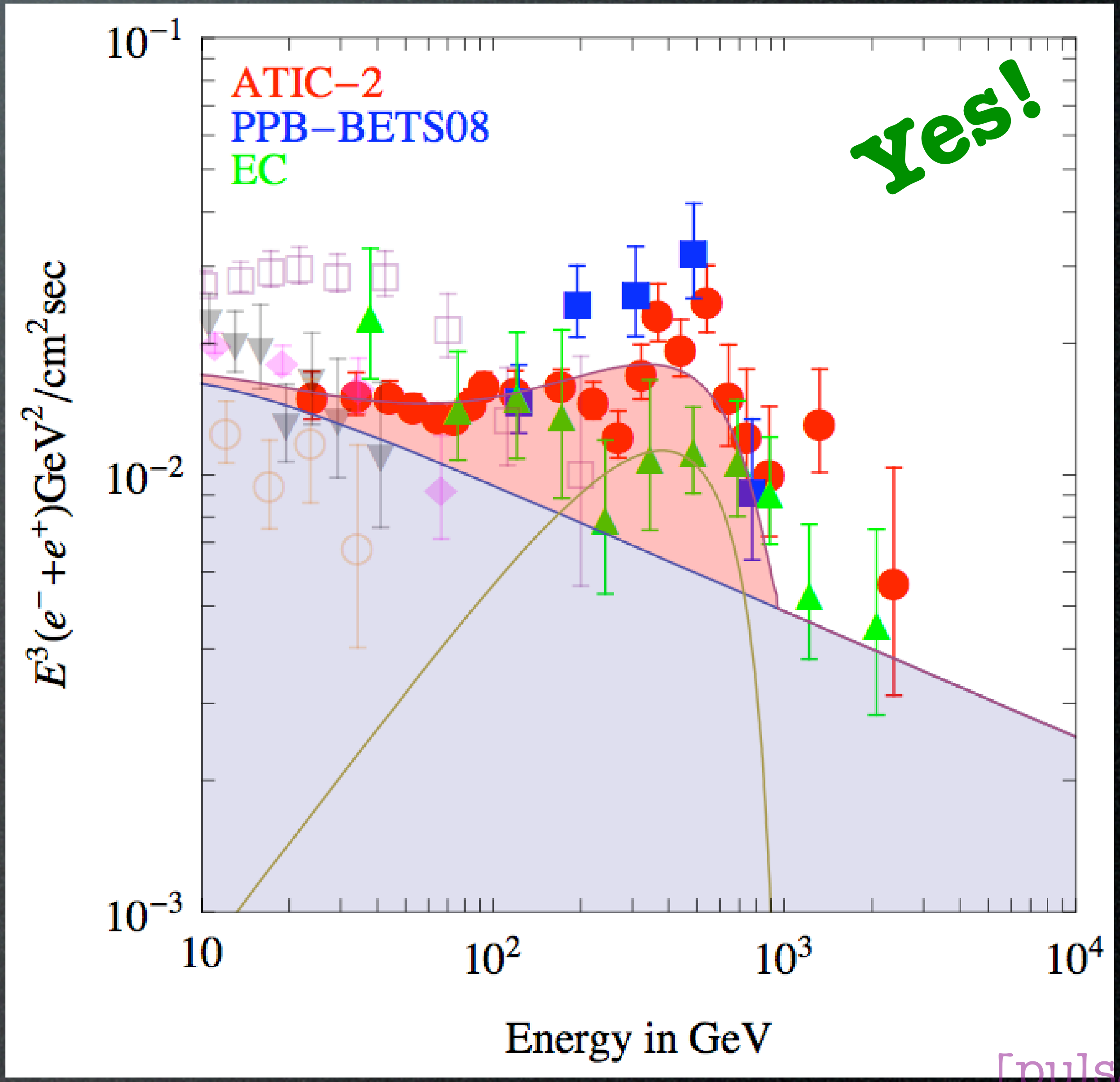

Have we identified the DM for the first time???

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

[pulsar]

Results

Which DM can fit the data?

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 - Yin, Yuan, Liu, Zhang, Bi, Zhu, 0811.0176: Leptonically decaying DM - 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 - K.Hamaguchi, E.Nakamura, S.Shirai, T.T.Yanagida, 0811.0737: Decaying DM in Composite Messenger - E.Ponton, L.Randall, 0811.1029: Singlet DM - A.Ibarra, D.Tran, 0811.1555: Decaying DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.3357: Decaying Hidden-Gauge-Boson DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - E.Nardi, F.Sannino, A.Strumia, 0811.4153: Decaying DM in TechniColor - 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 - A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075: Decaying DM in GUTs - 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 - C.-H.Chen, C.-Q.Geng, D.Zhuridov, 0901.2681: Fermionic decaying 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 - Goh, Hall, Kumar, 0902.0814: Leptonic Higgs - 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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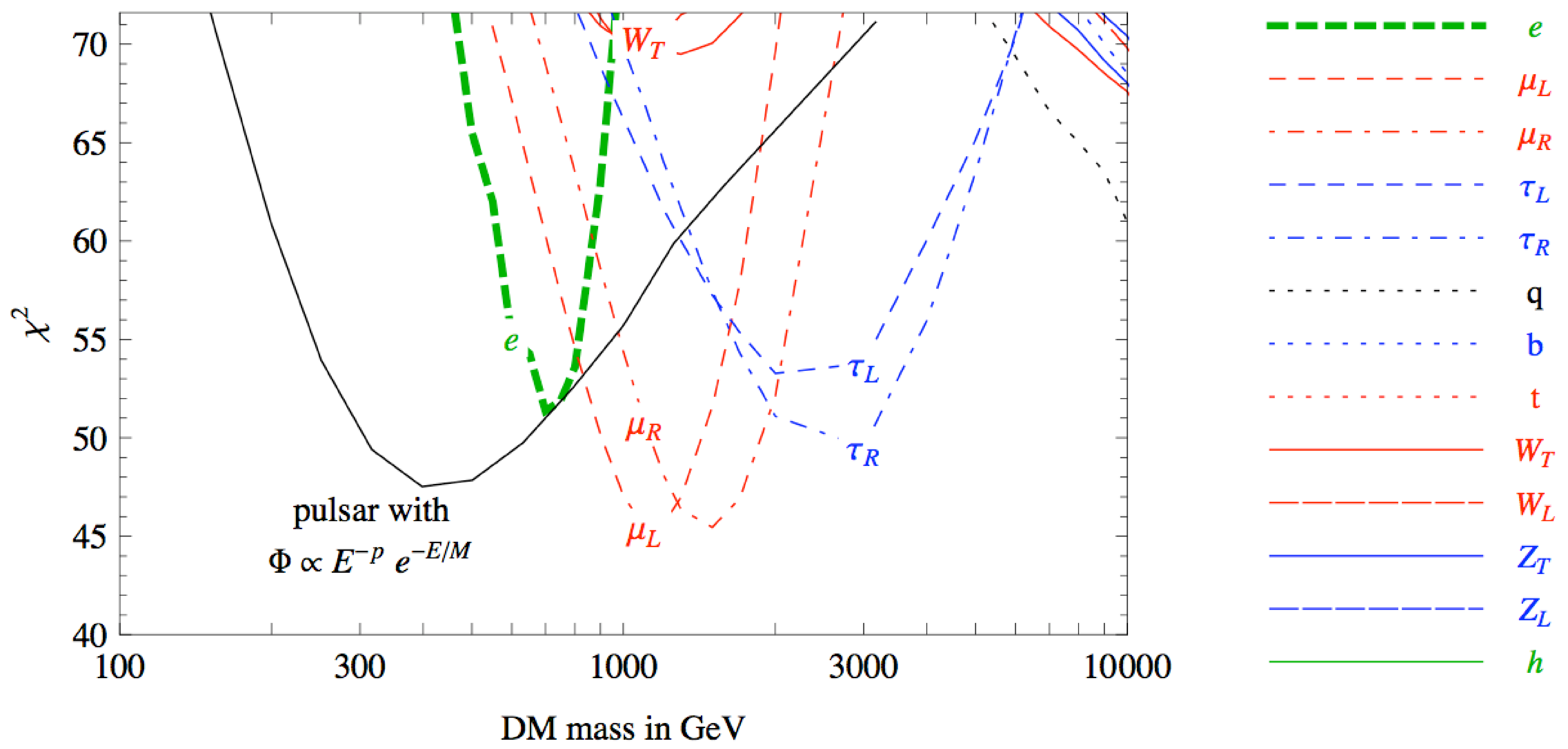
Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons* + balloon experiments



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

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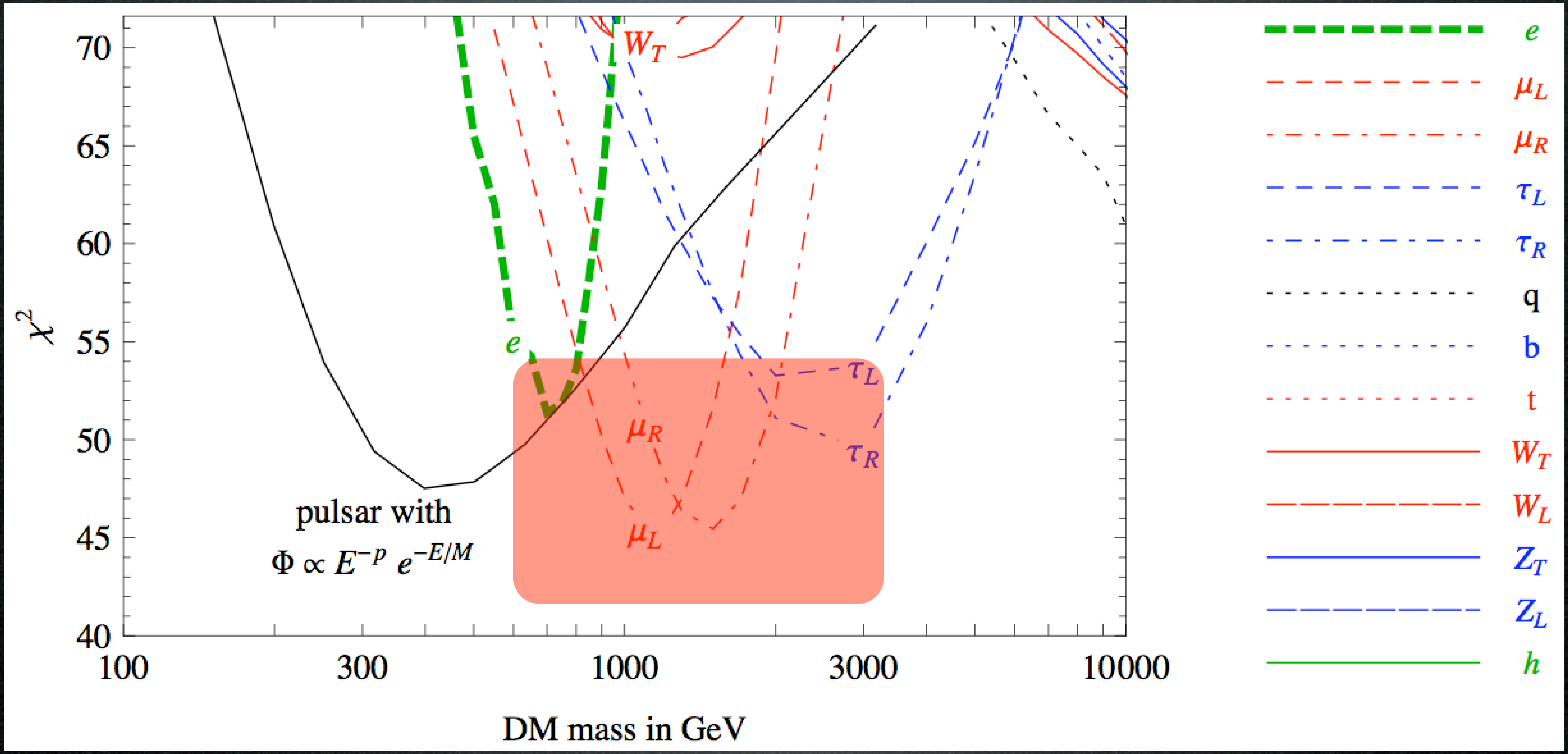
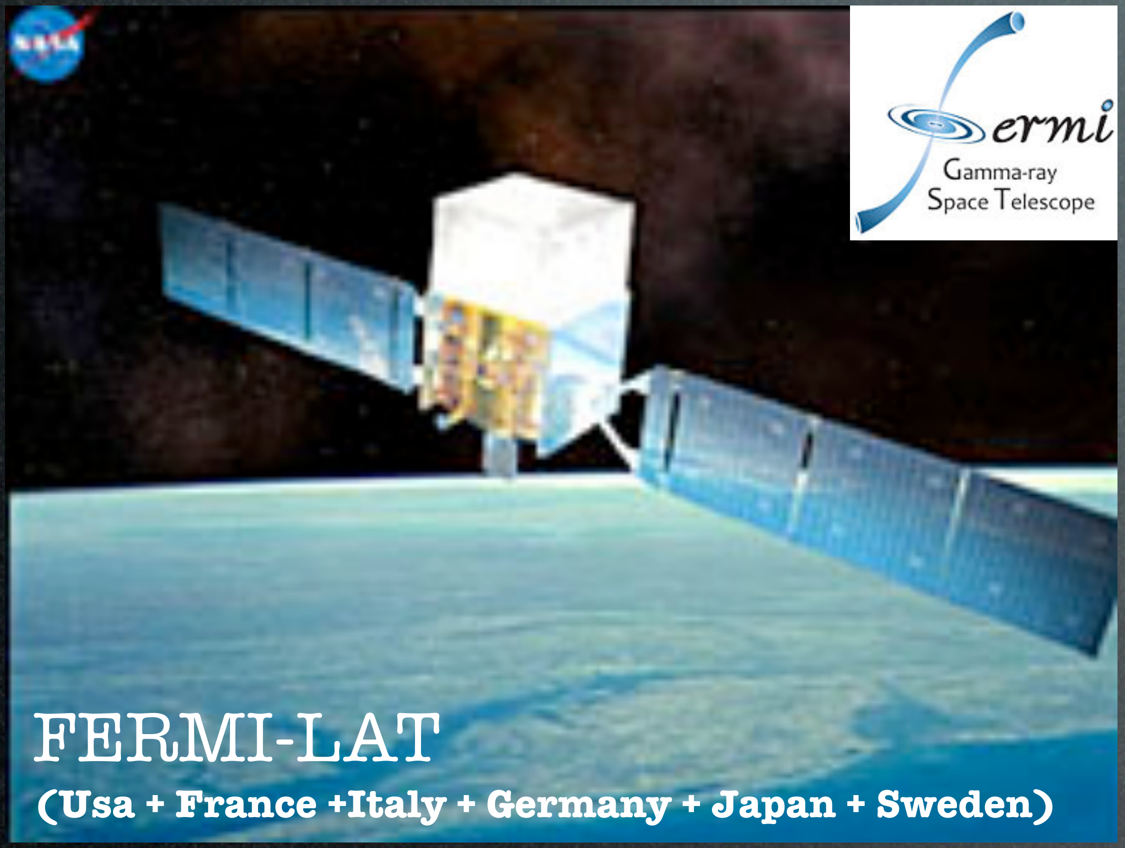
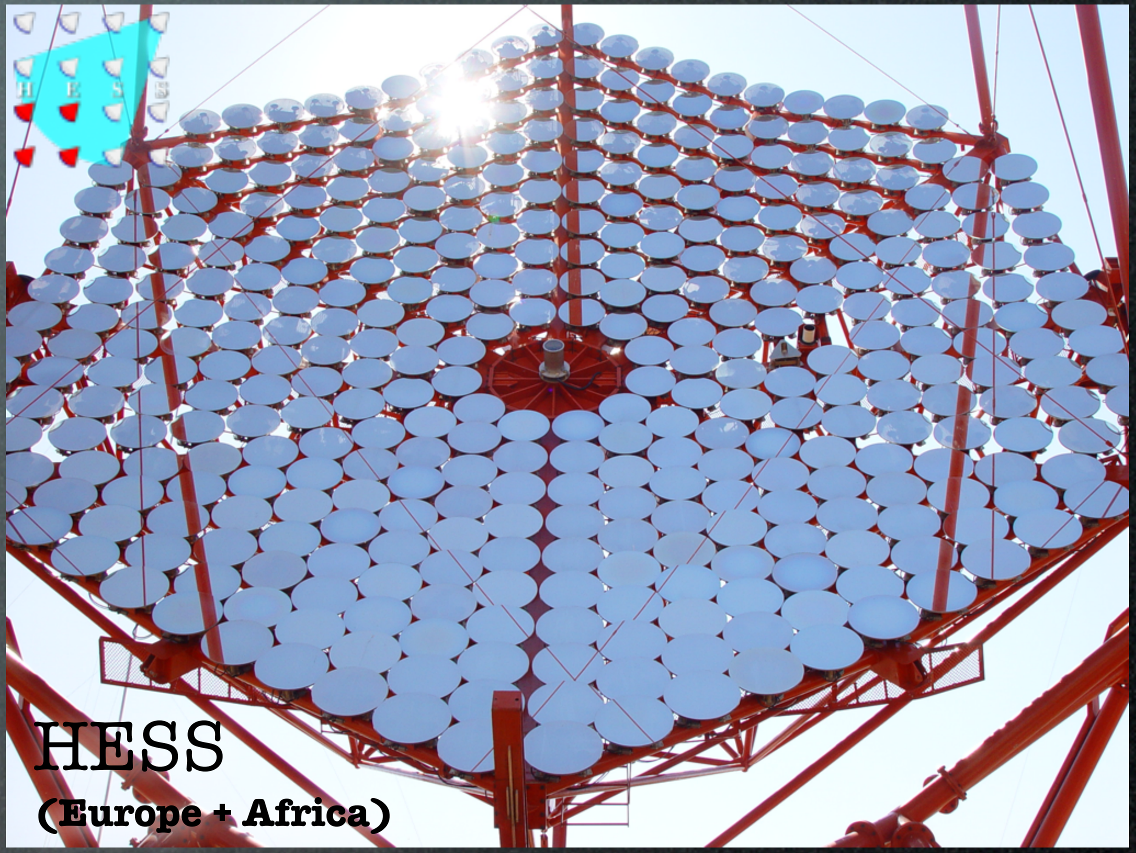


(1) annihilate into leptons (e.g. $\mu^+\mu^-$), mass ~1 TeV

Data sets

Electrons + positrons from FERMI and HESS:





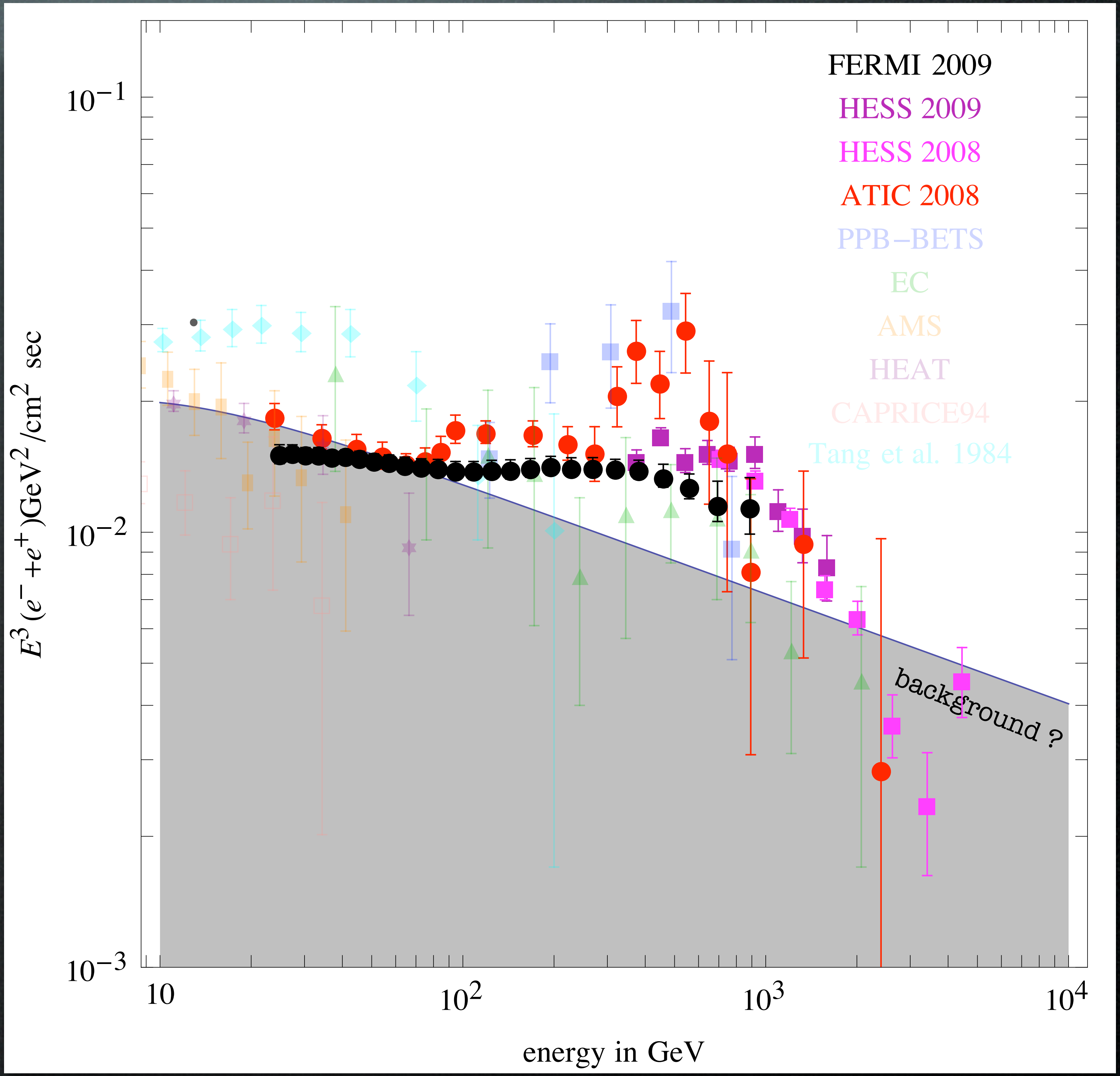
"Designed as a high-sensitivity gamma-ray observatory, the FERMI Large Area Telescope is also an electron detector with a large acceptance"

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

Data sets

Electrons + positrons adding FERMI and HESS:

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



[formerly predicted GLAST sensitivity]

Results

Which DM spectra can fit the data?

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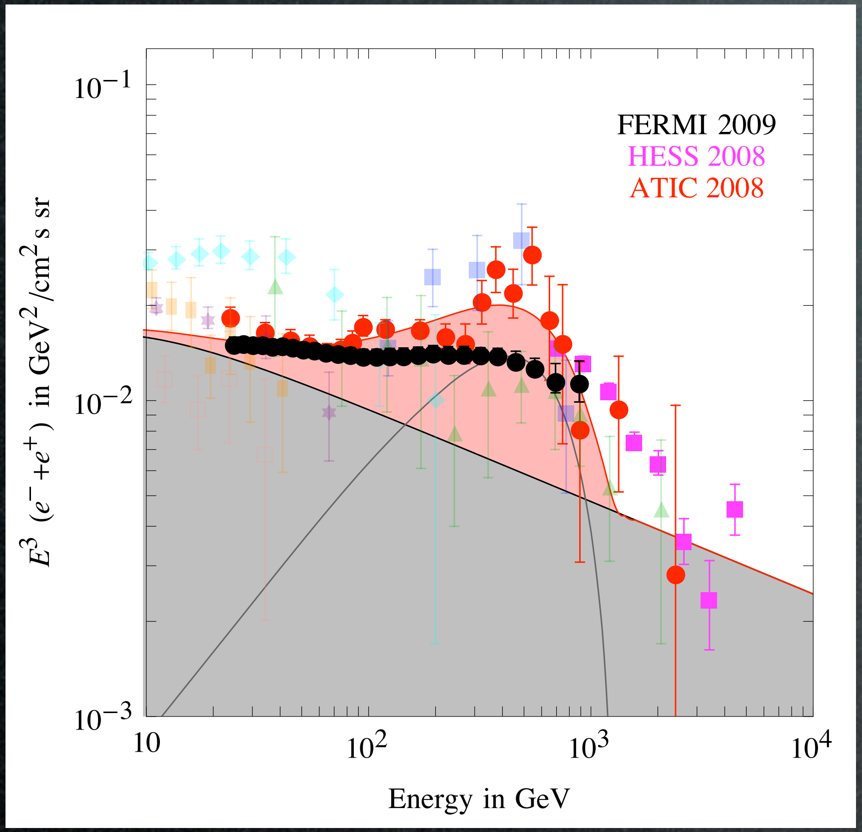
$\mu^+\mu^-, M_{\rm DM} \simeq 1\ \rm TeV$



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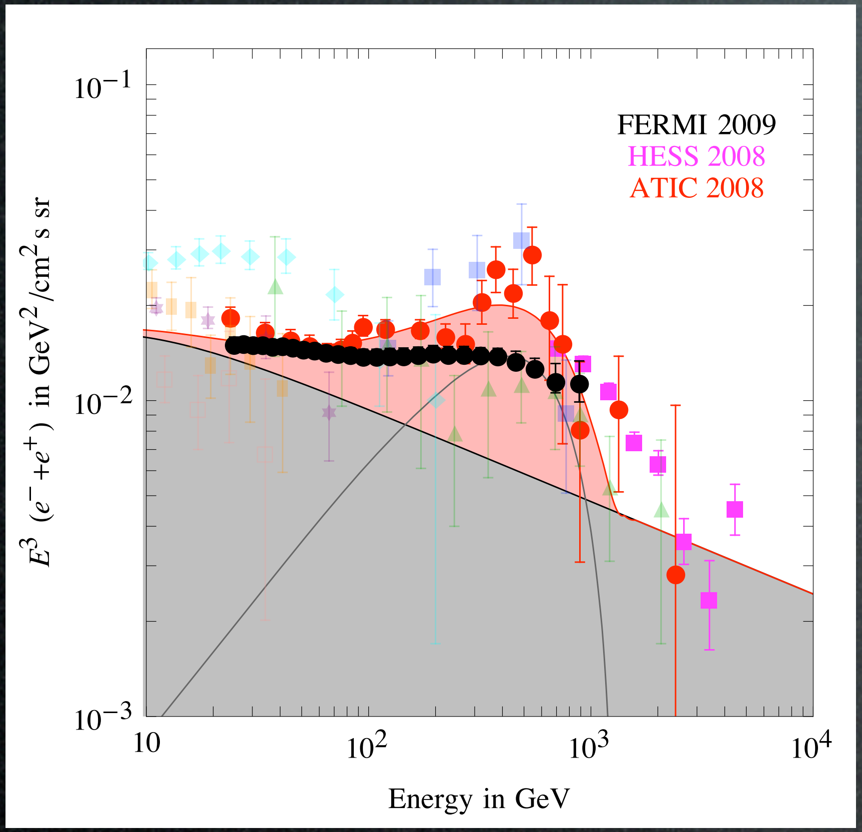
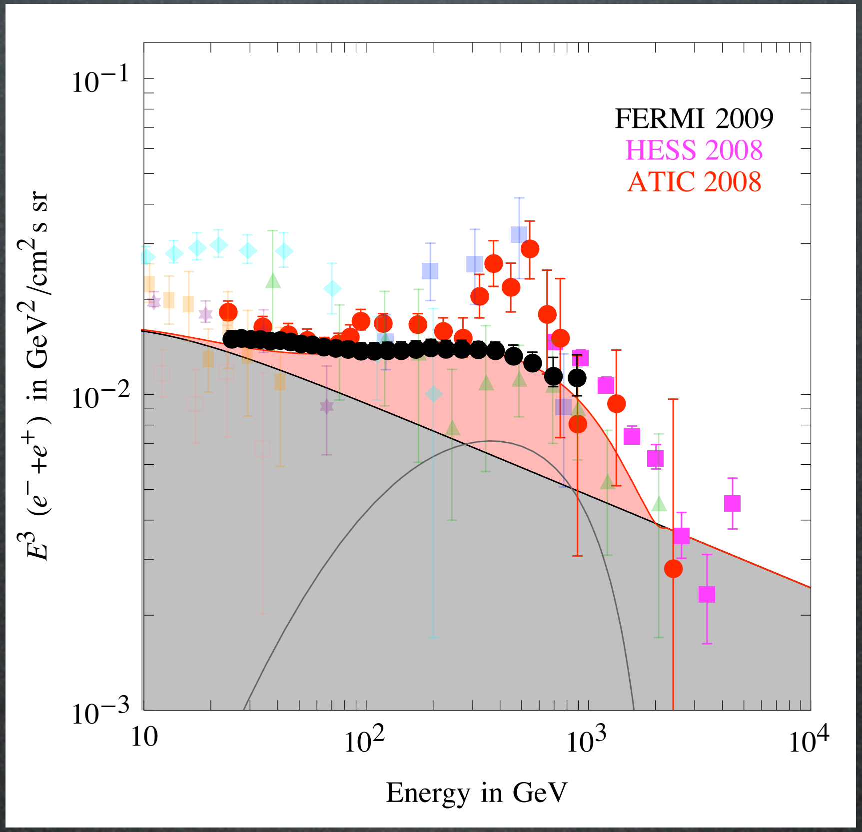


$\tau^+\tau^-, M_{\rm DM} \simeq 2$ TeV



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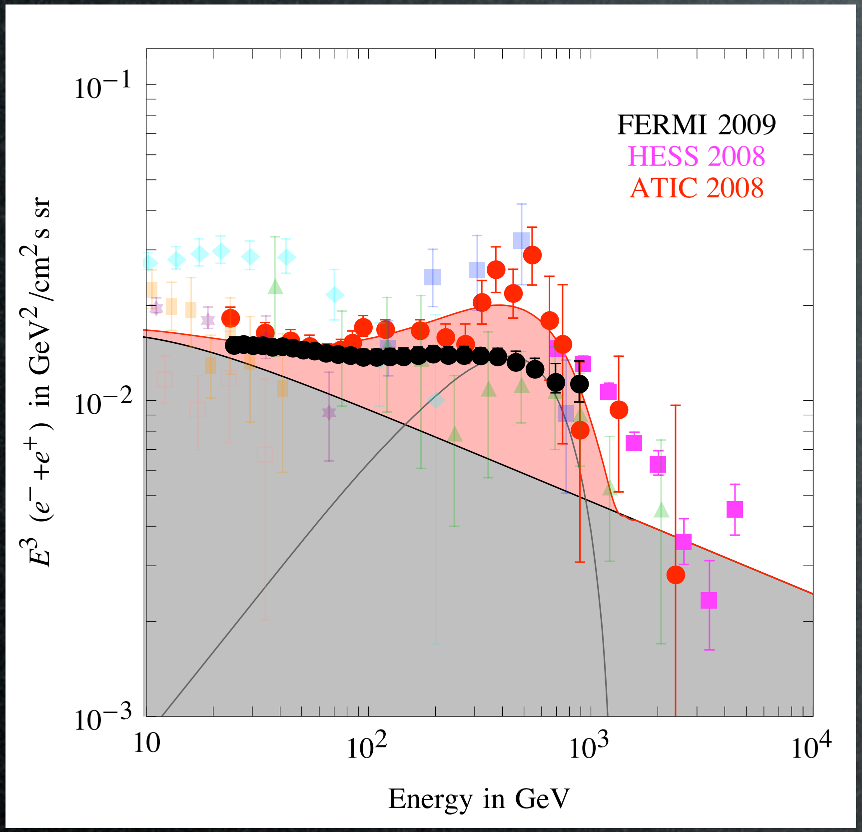

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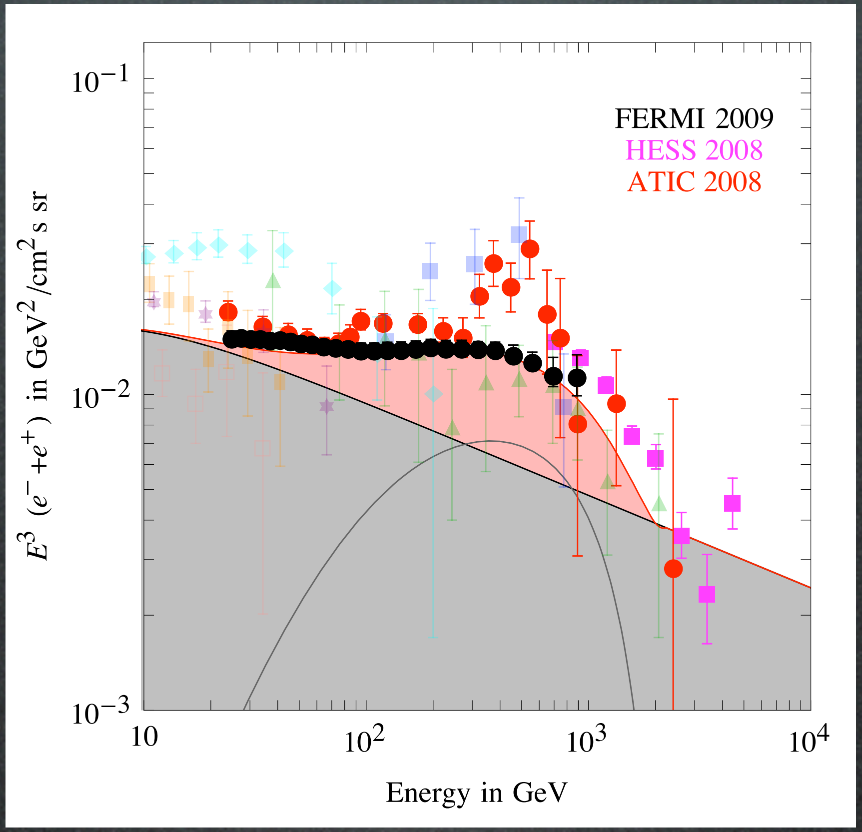
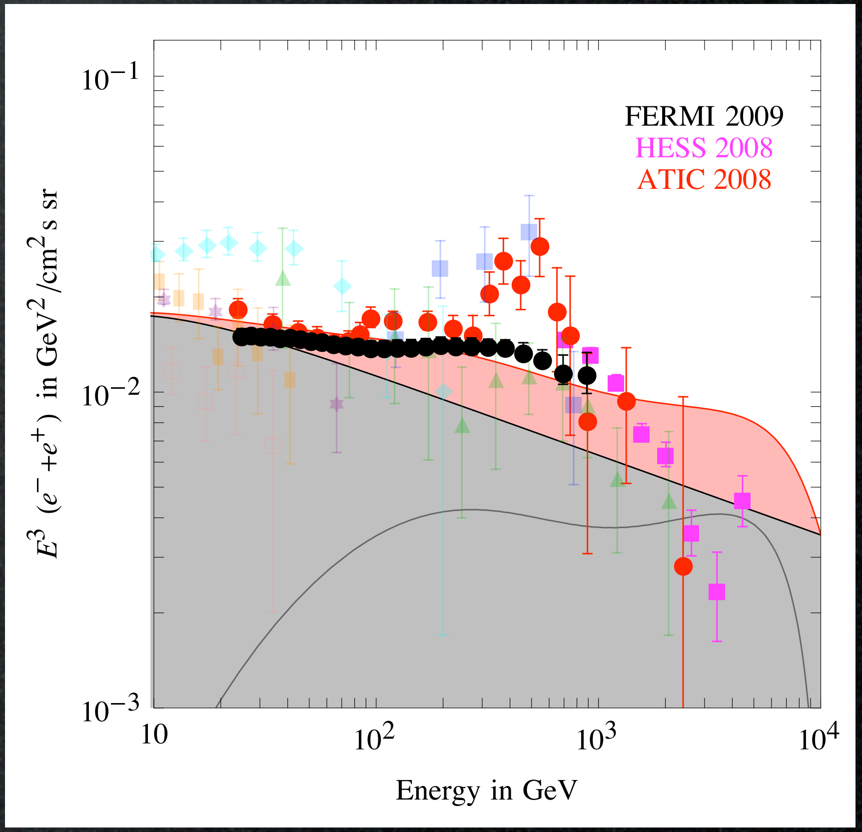


$W^+W^-, M_{\rm DM} \simeq 10\,{\rm TeV}$



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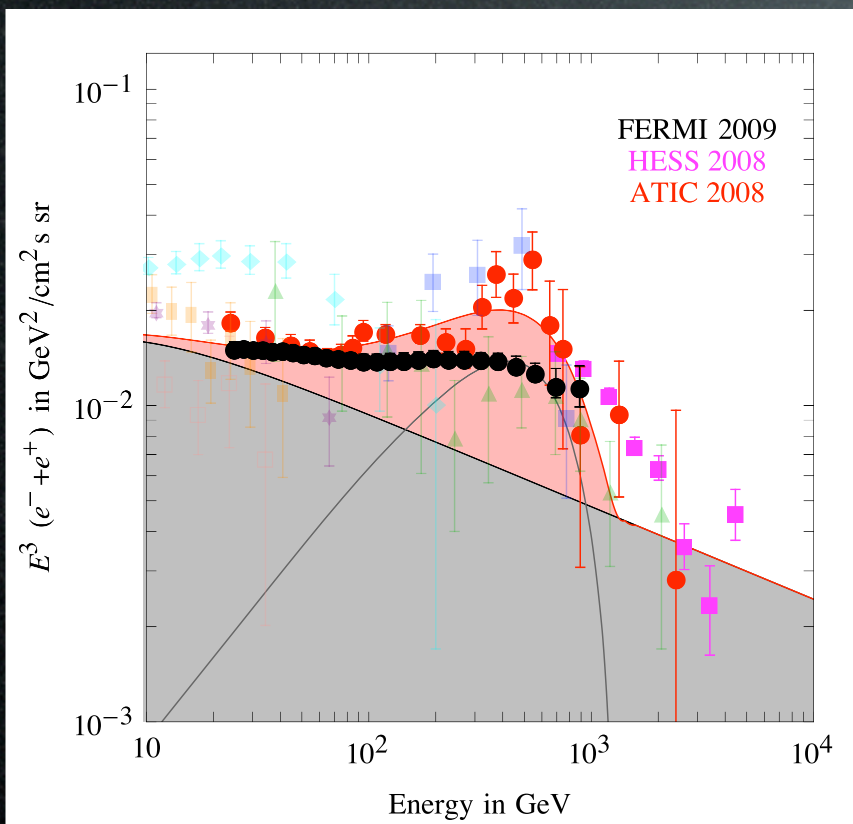

Notice:

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

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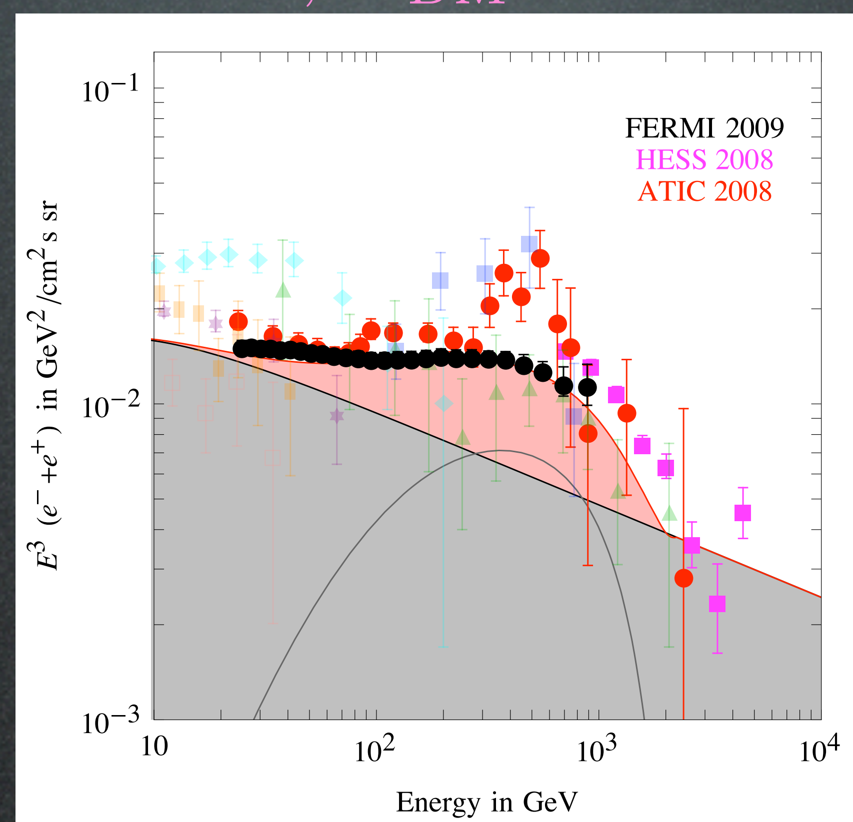

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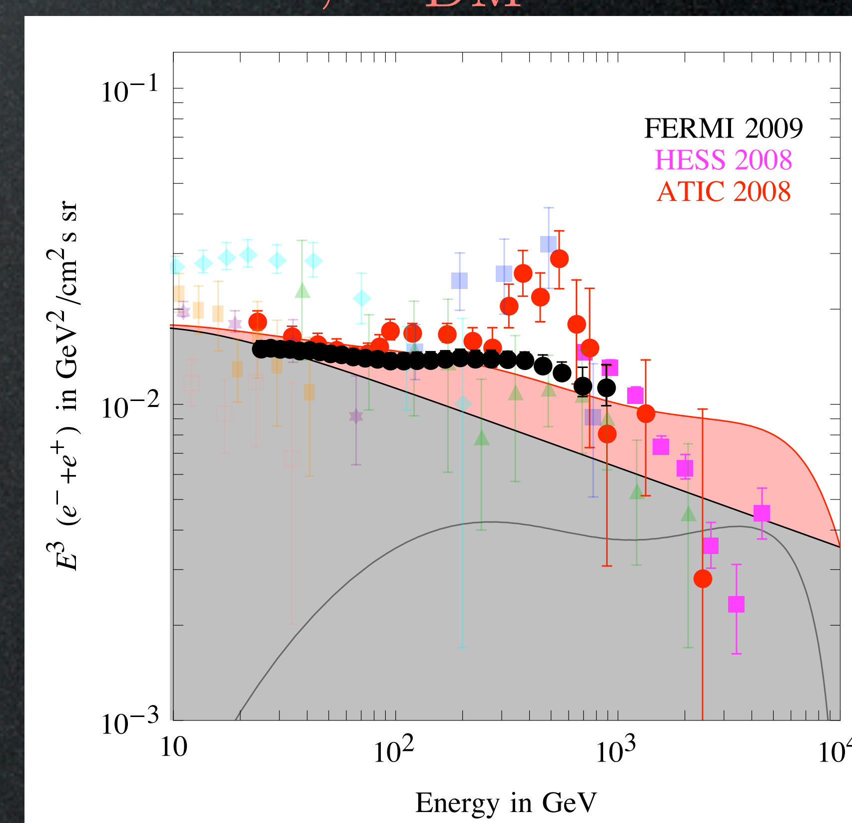

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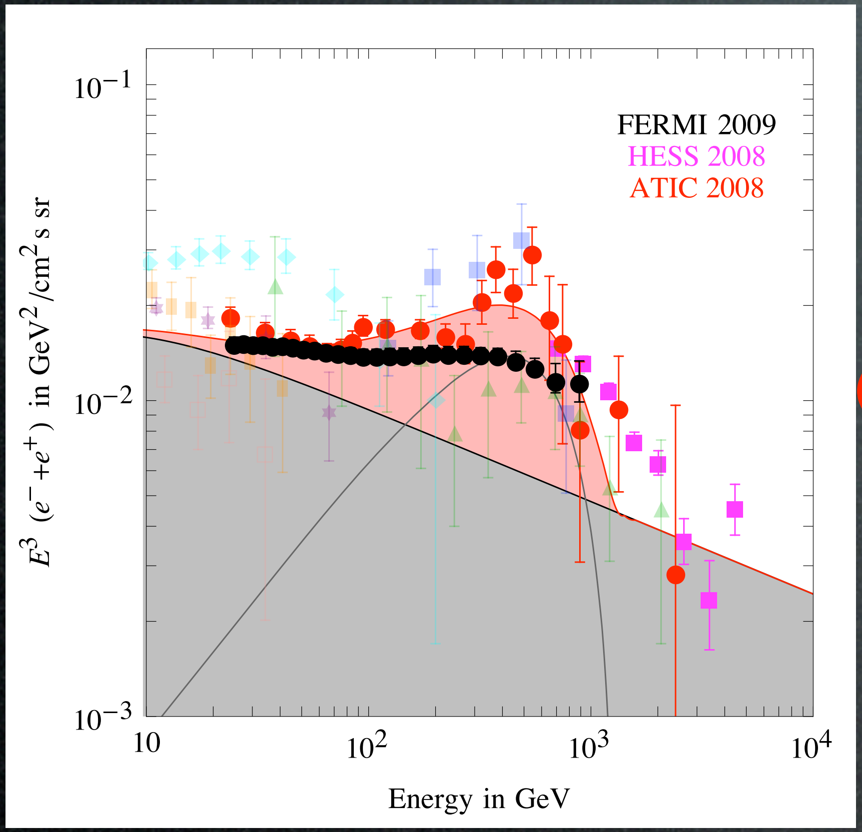

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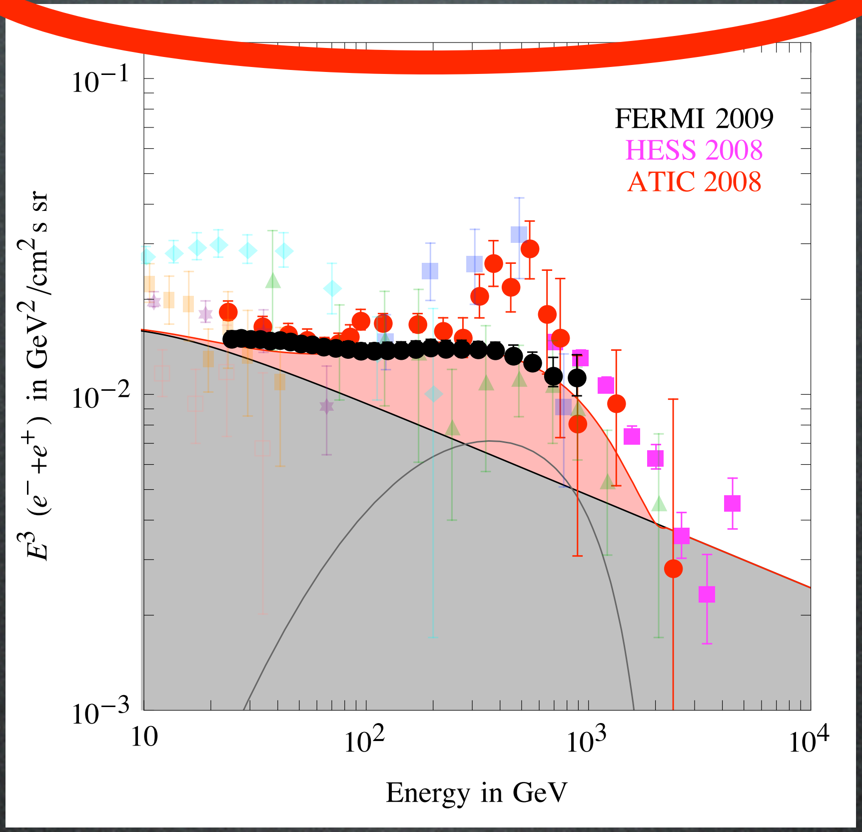

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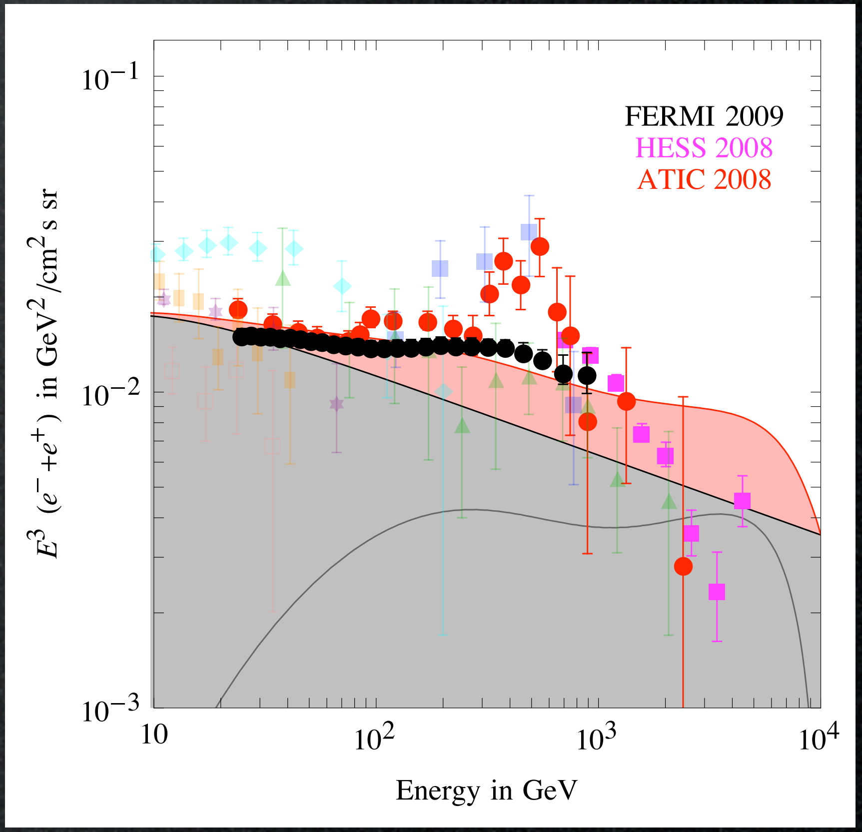


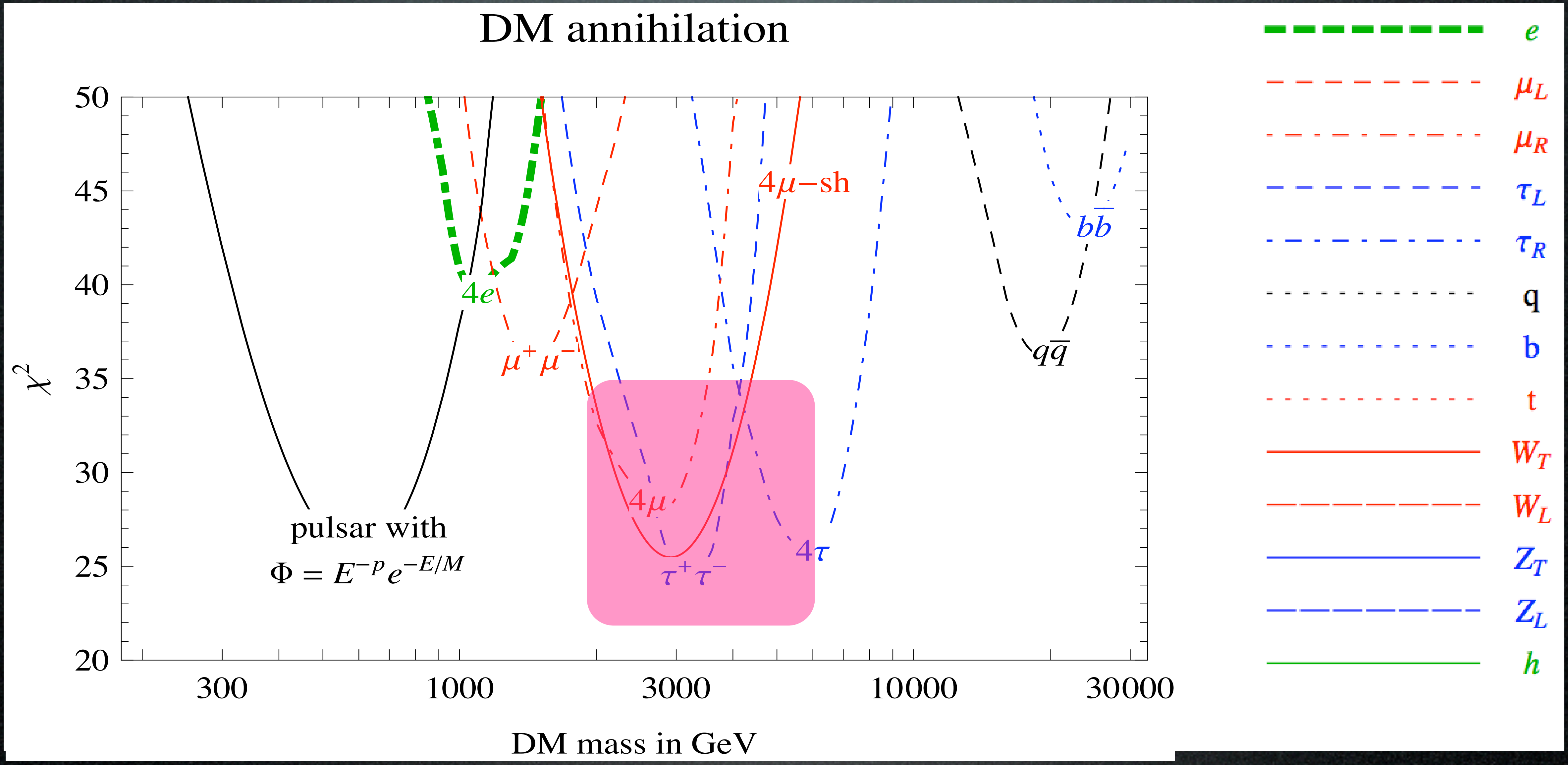
- no features in FERMI => $M_{\rm DM} > 1$ TeV
- a 'cutoff' in HESS => $M_{\rm DM} \lesssim 3$ TeV
- smooth lepton spectrum

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

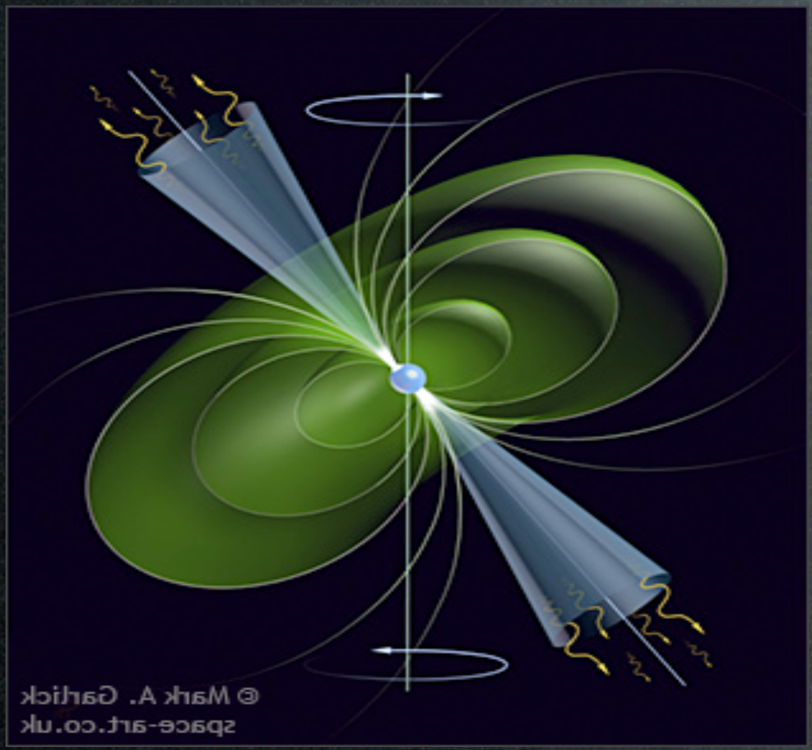
(1) annihilate into leptons (e.g. $\tau^+\tau^-$), mass $\sim$3 TeV

Astrophysical explanation?

Astrophysical explanation?

[others?]

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



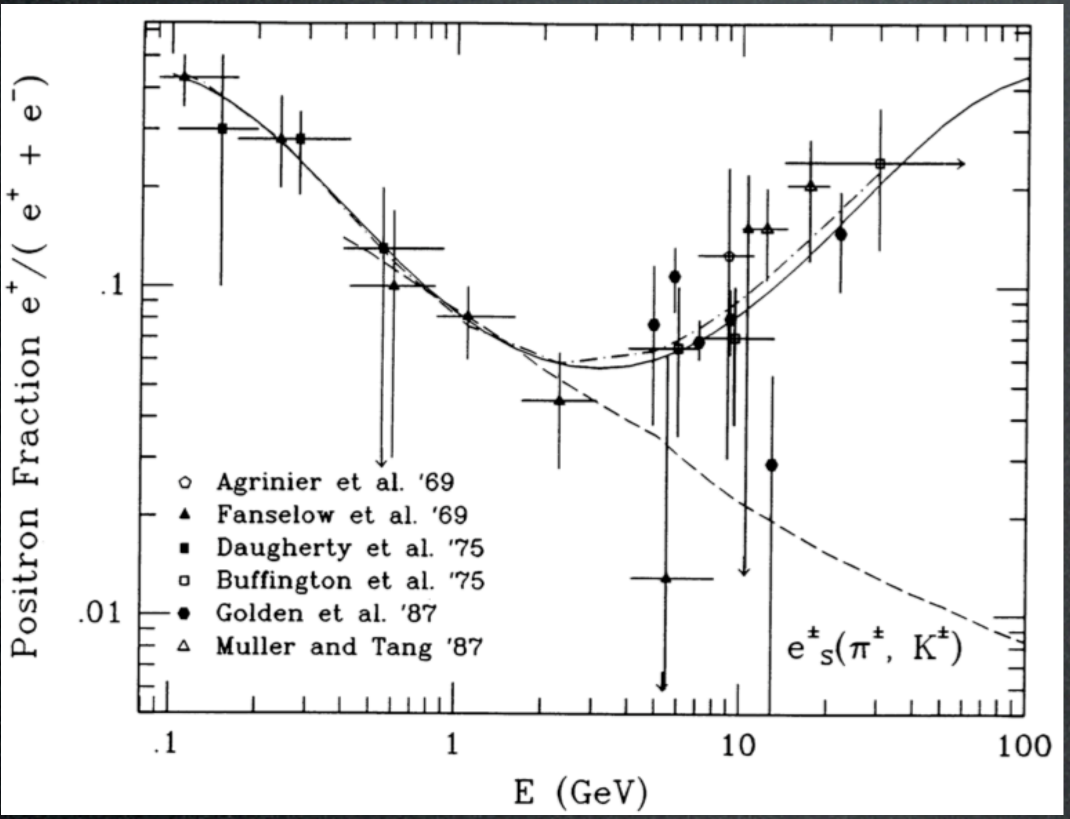
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \to 10^5$ yr (typical total energy output: 10^{46} erg).

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

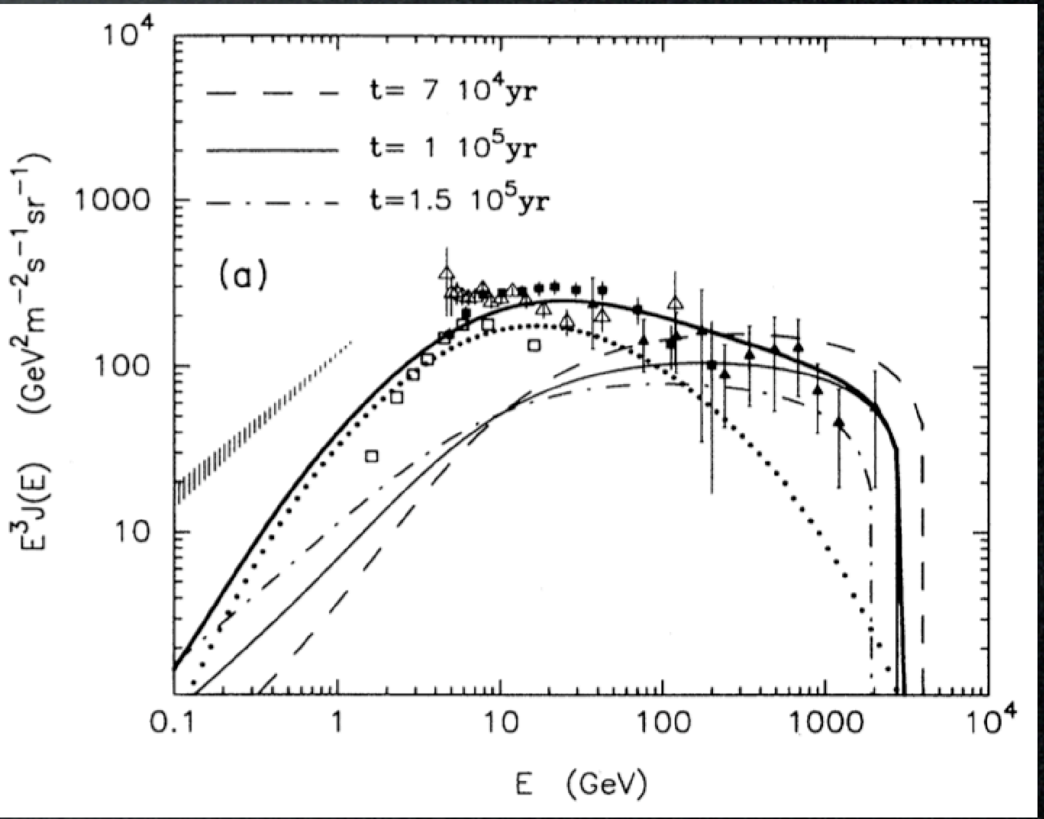
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

Not a new idea:



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



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

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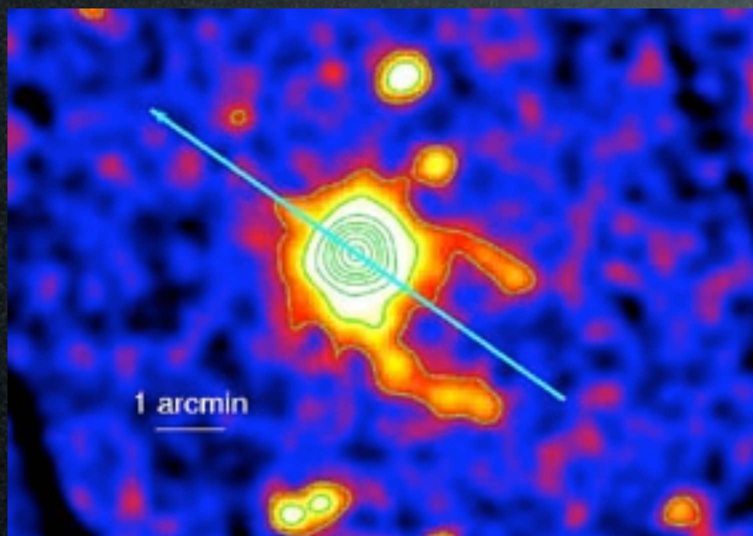

Geminga pulsar
(funny that it means:
"it is not there" in milanese)

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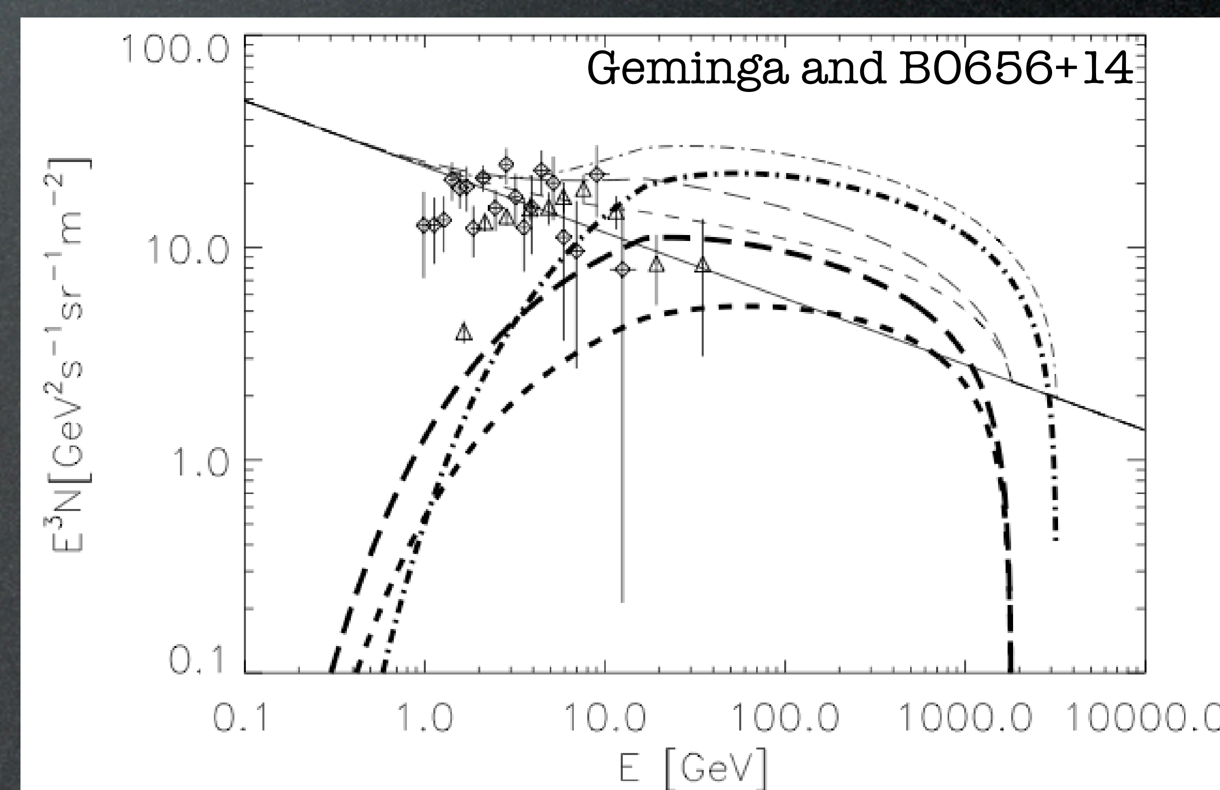
Try the fit with known nearby pulsars:

TABLE 1
LIST OF NEARBY SNRs

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



Büshing, de Jager et al. 0804.0220

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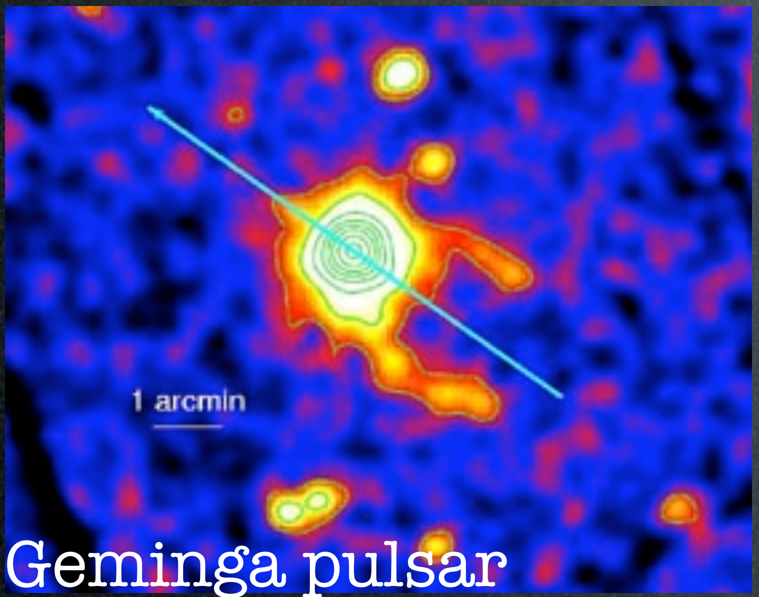

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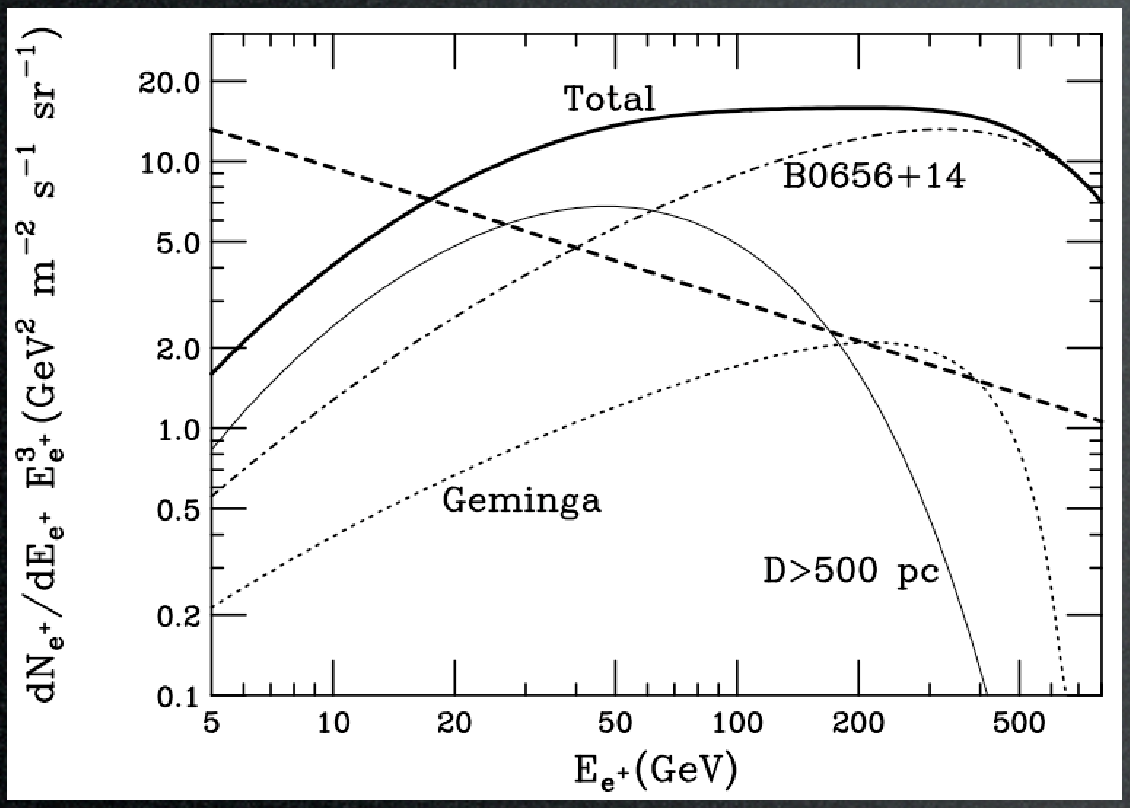
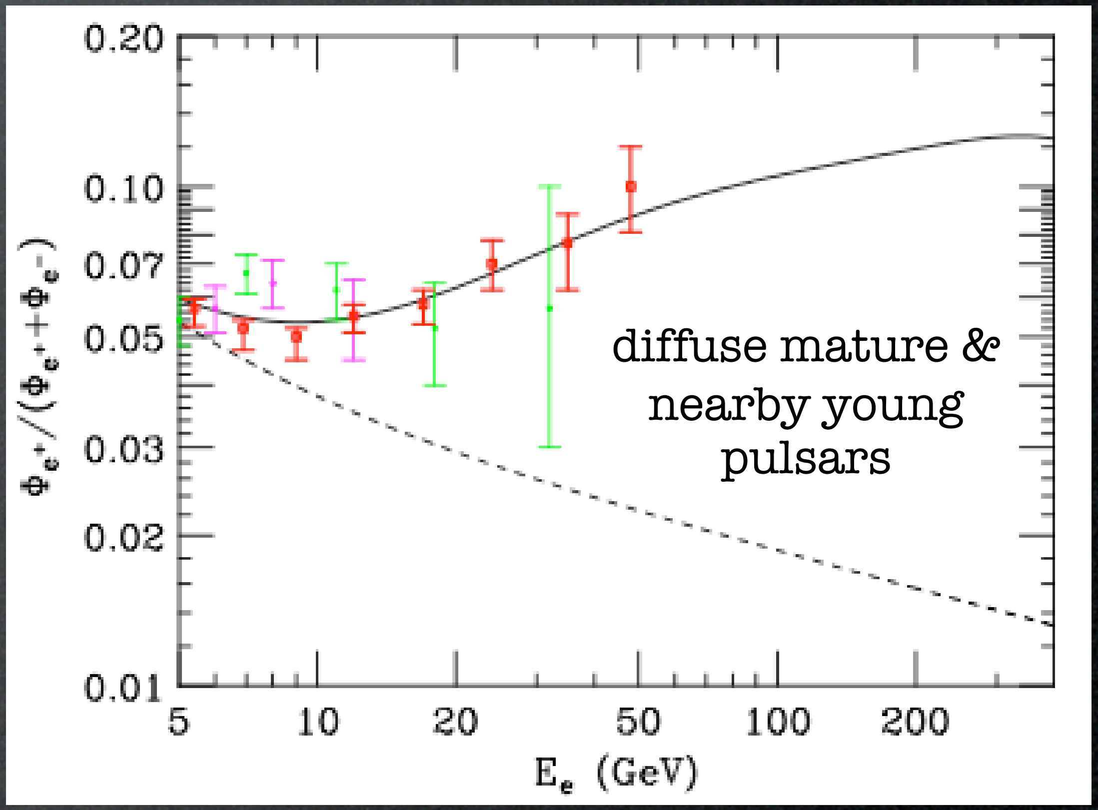
Try the fit with known nearby pulsars and diffuse mature pulsars:





Hooper, Blasi, Serpico 2008

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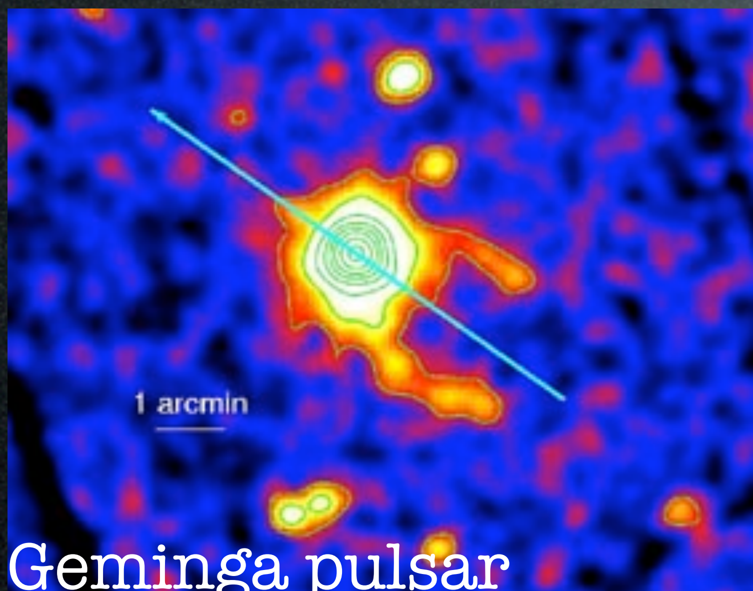

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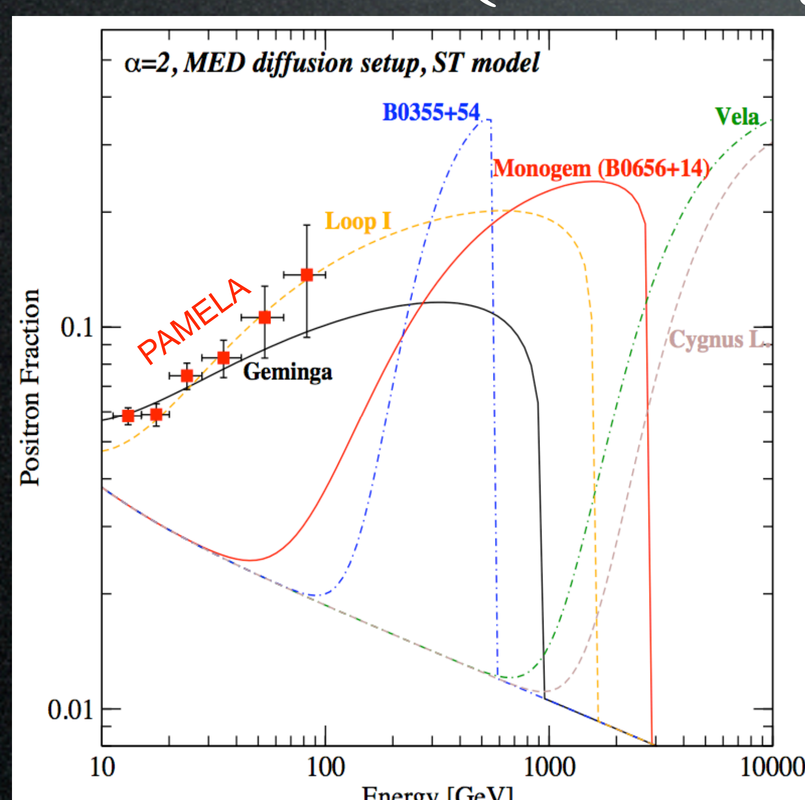
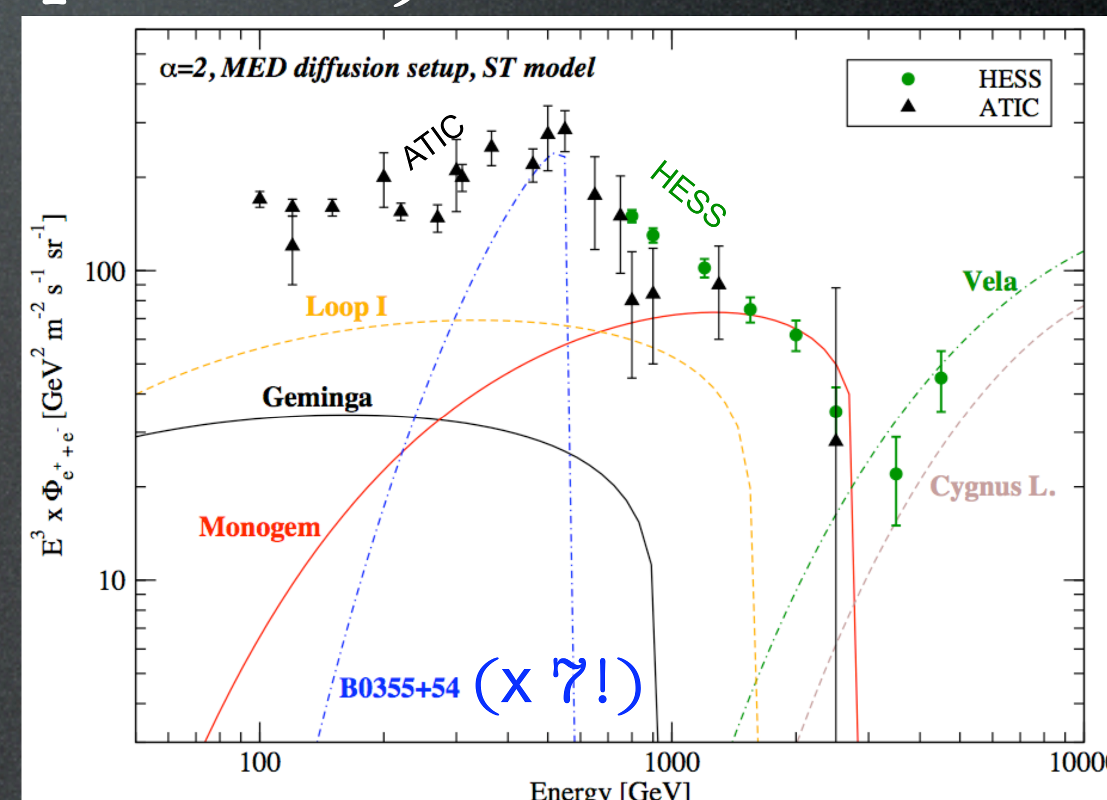
if not: too much diffusion, low energy, too low flux.

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

ATIC needs a different (and very powerful) source:

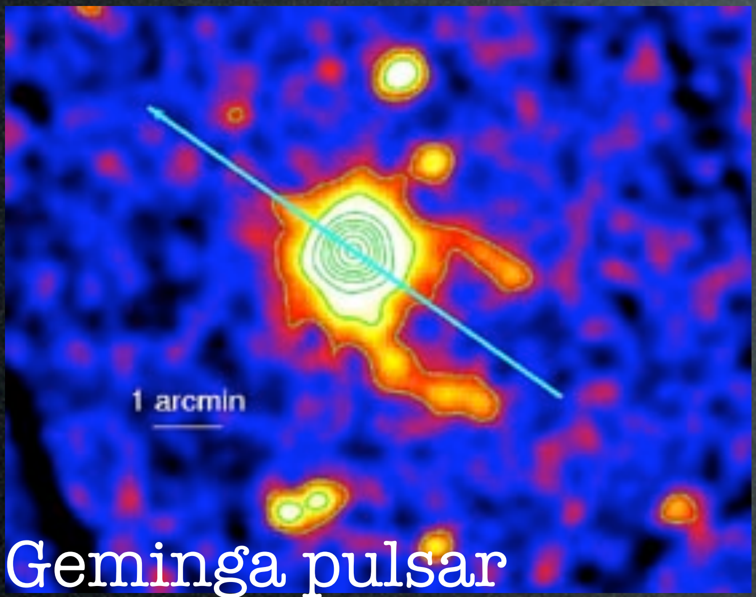




Profumo 0812.4457

Astrophysical explanation?

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

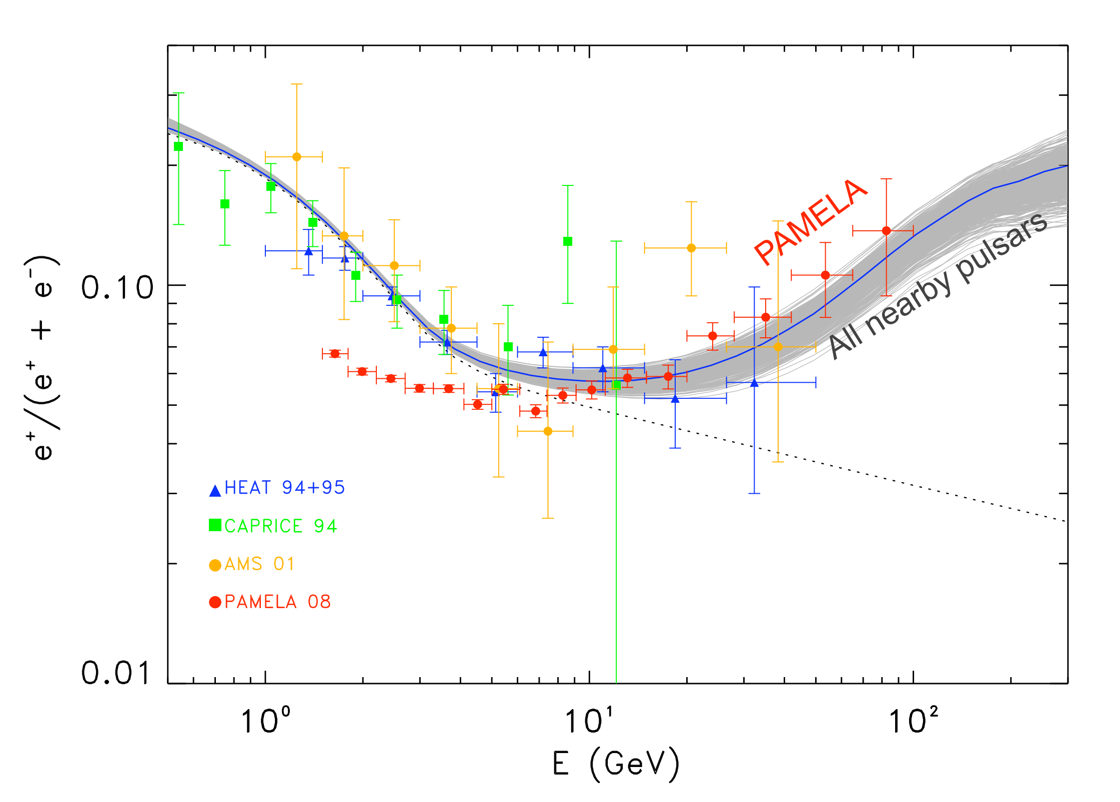


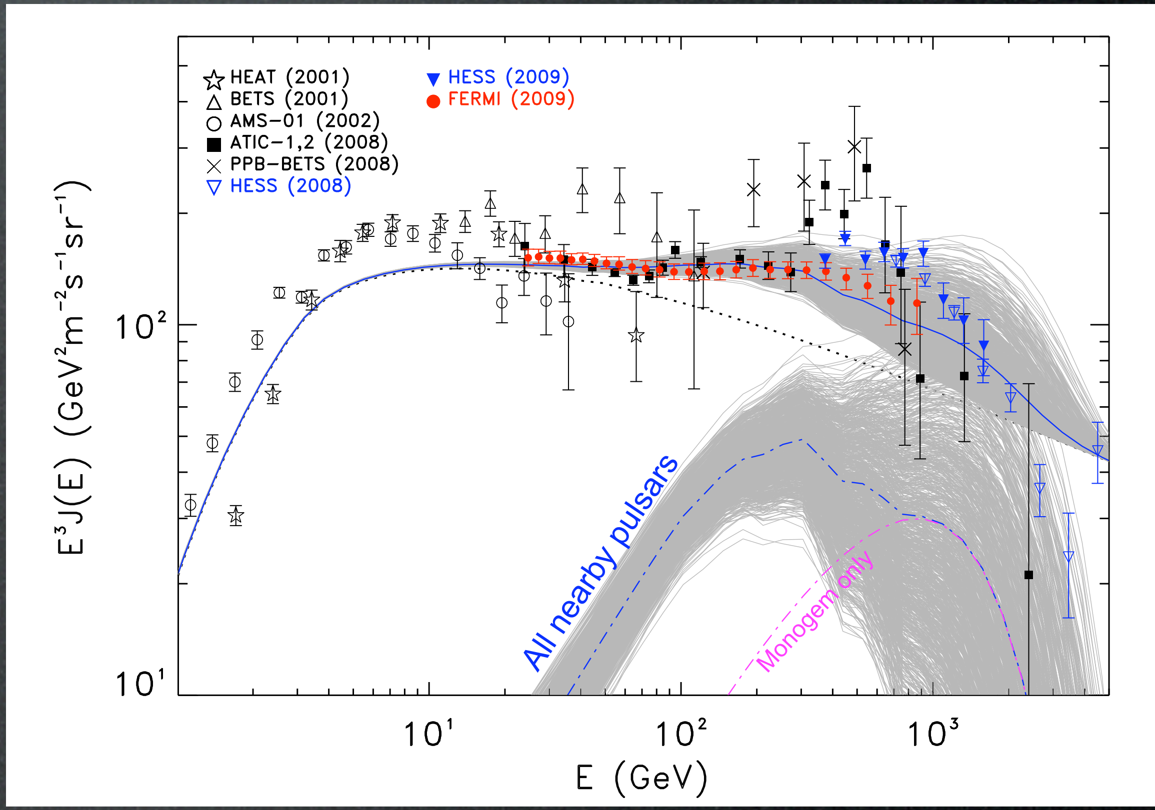
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \to 10^5$ yr.

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

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

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

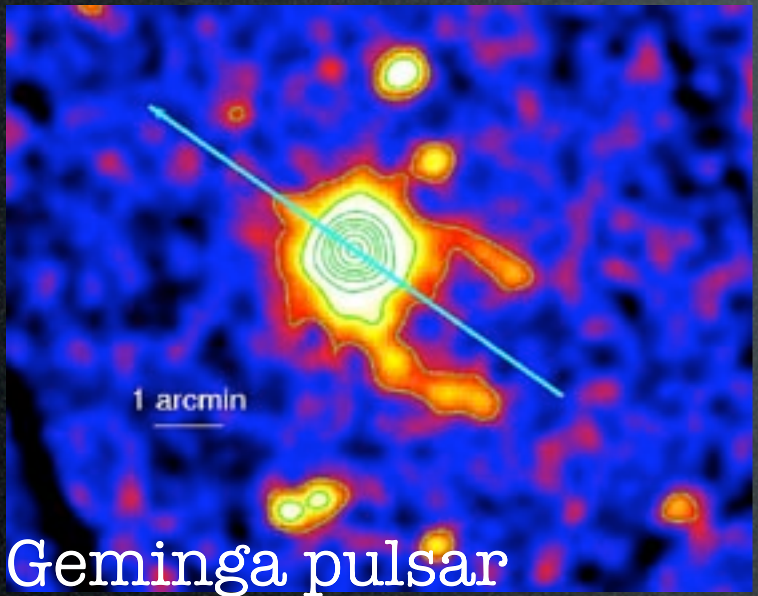




D.Grasso et al.
(sub-FERMI collab.)
0905.0636

Astrophysical explanation?

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



Geminga pulsar

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

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

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

Open issue.

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

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

[back]

DM detection

direct detection

production at colliders

indirect

γ from annihil in galactic center and from synchrotron emission

HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

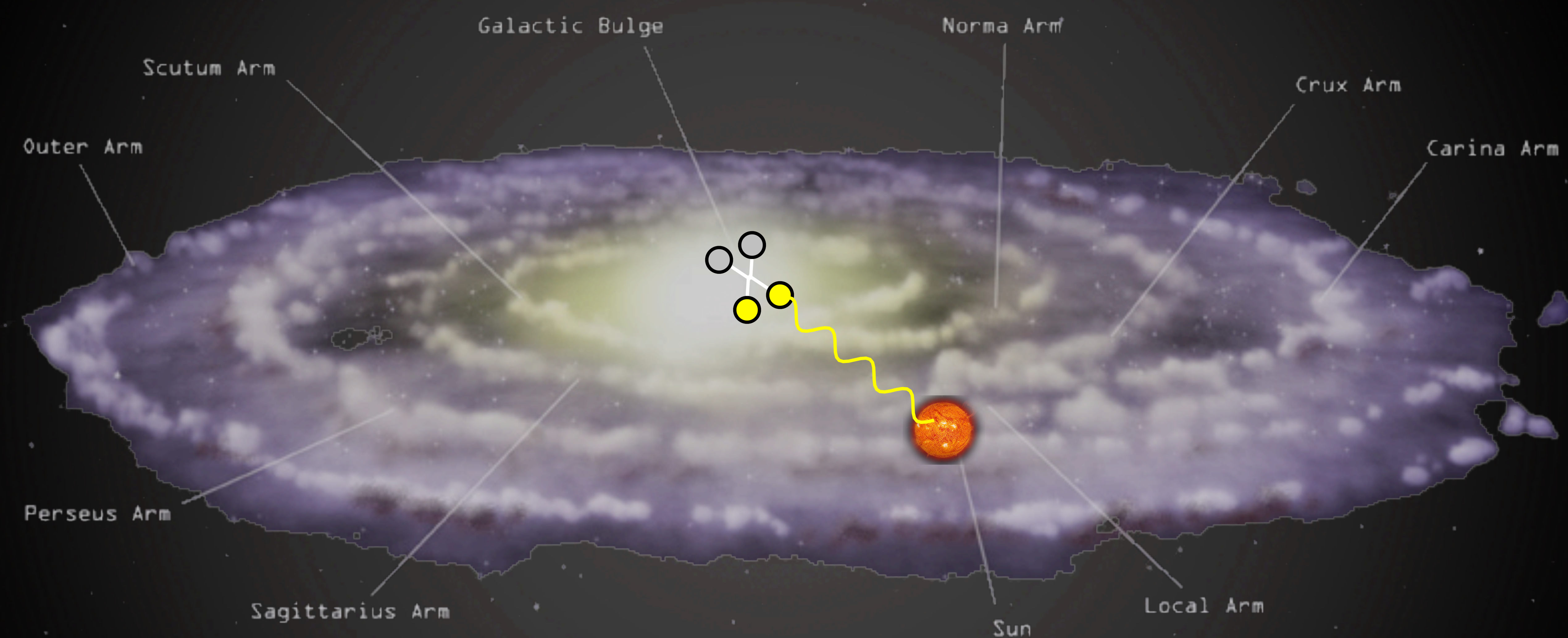
$\bar{p}$ from annihil in galactic halo or center

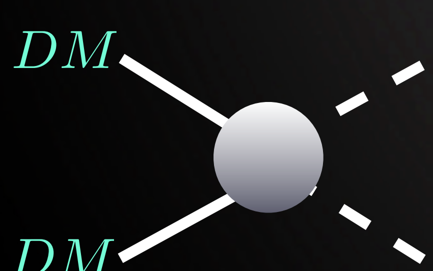
$\bar{D}$ from annihil in galactic halo or center

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

Indirect Detection

γ from DM annihilations in galactic center



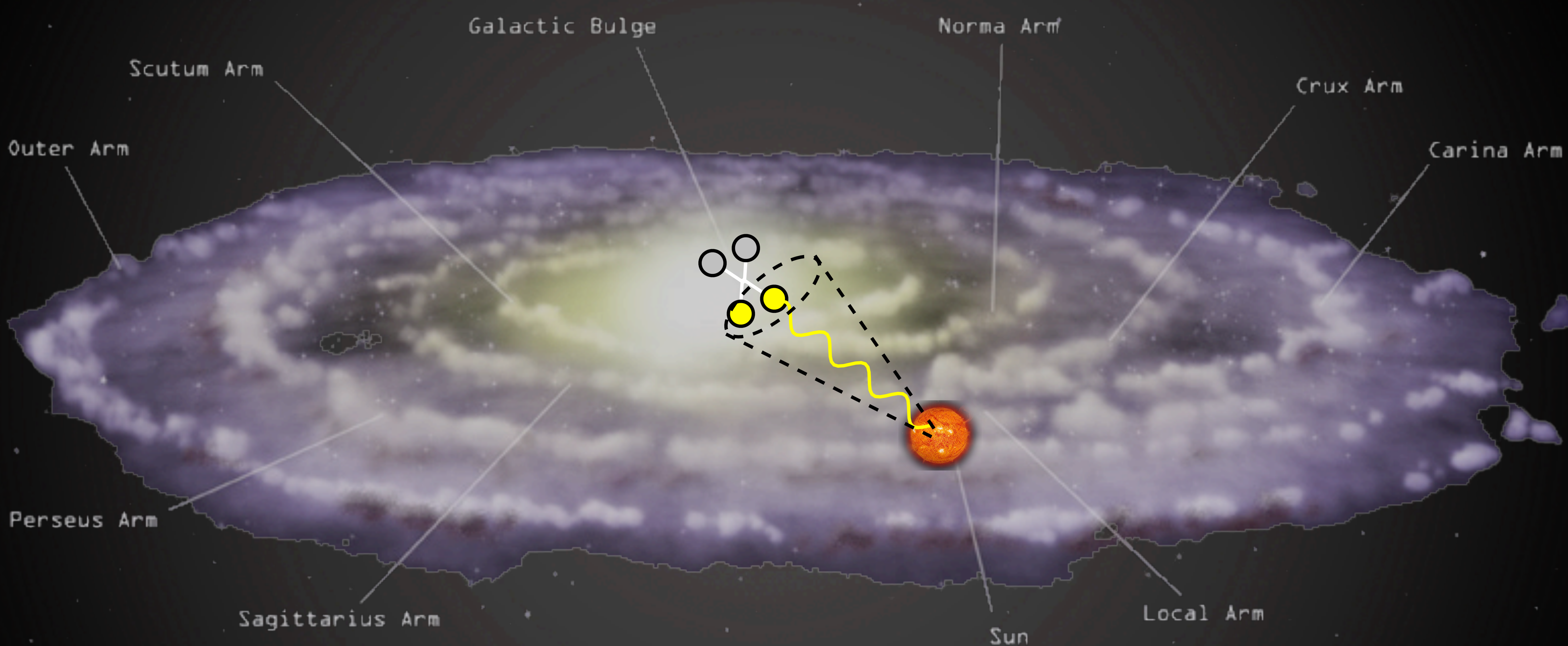


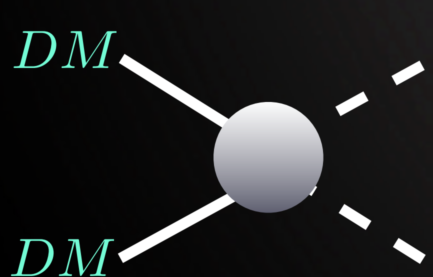
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

Indirect Detection

γ from DM annihilations in galactic center



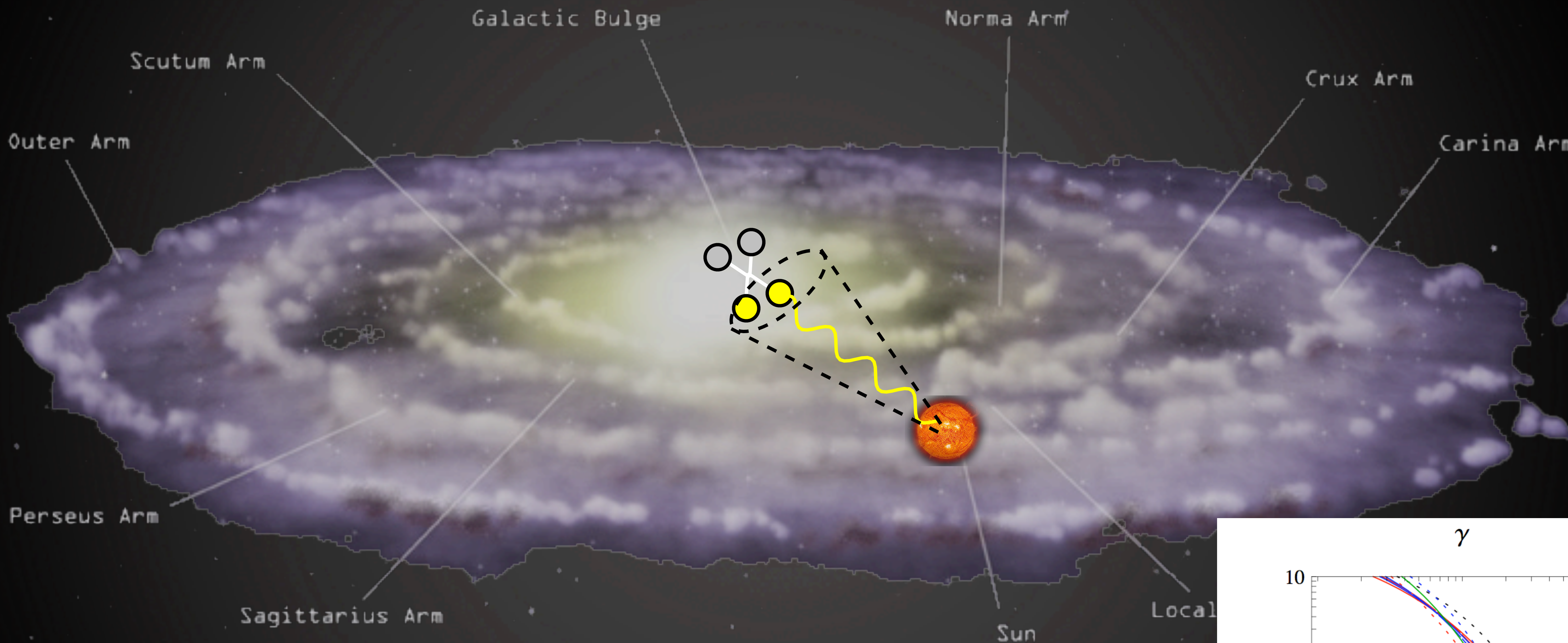


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

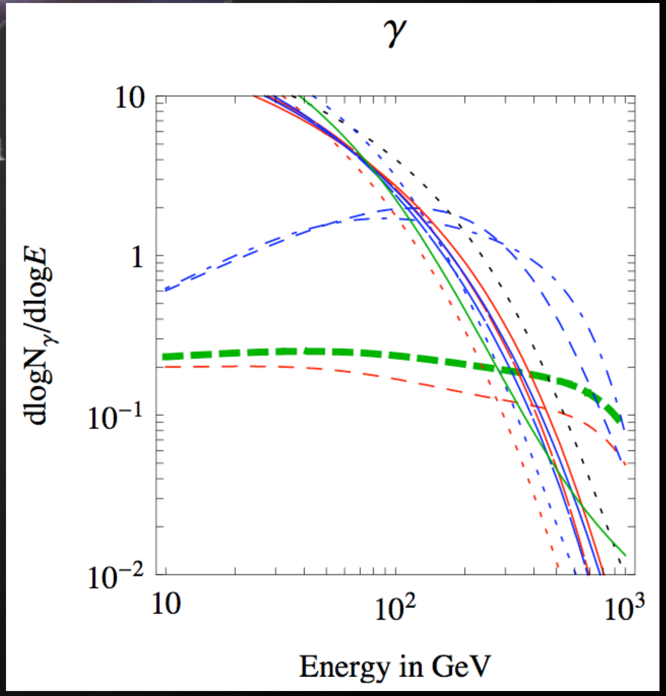
Indirect Detection

γ from DM annihilations in galactic center



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

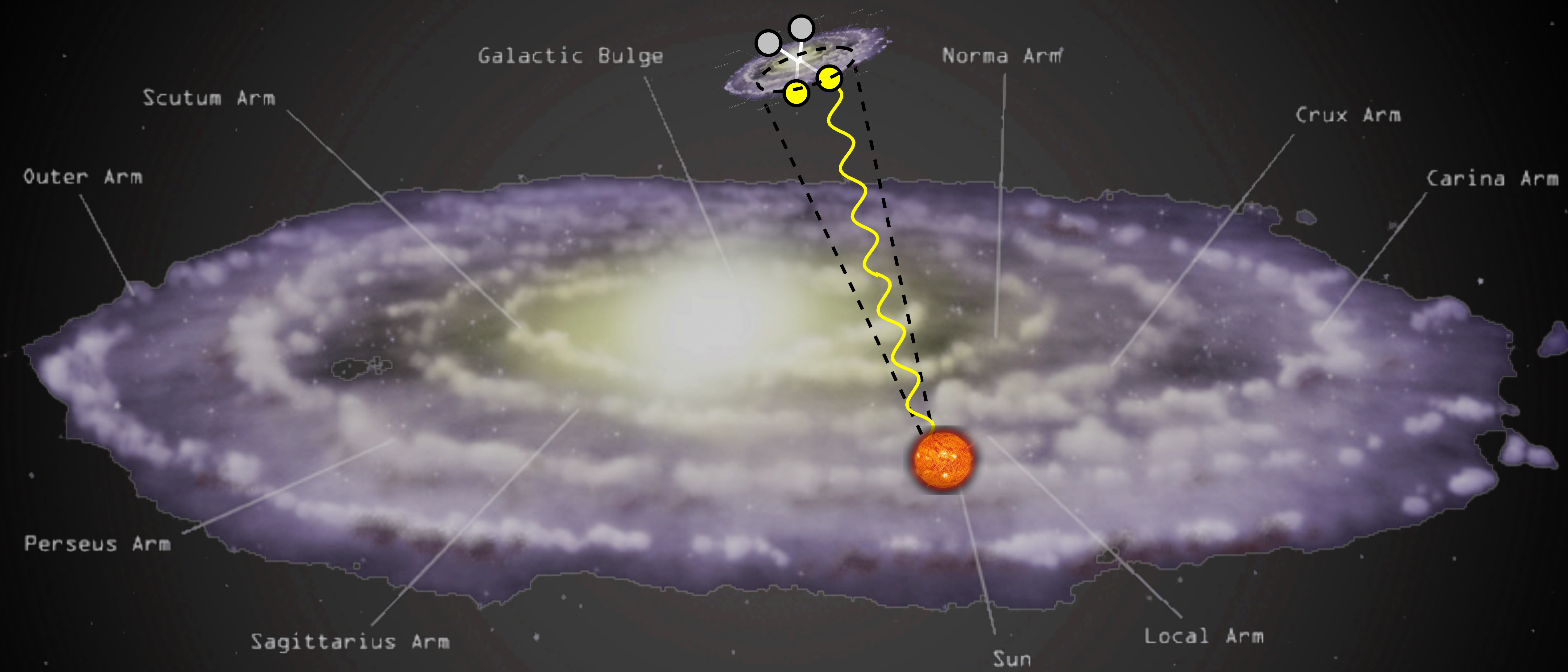
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

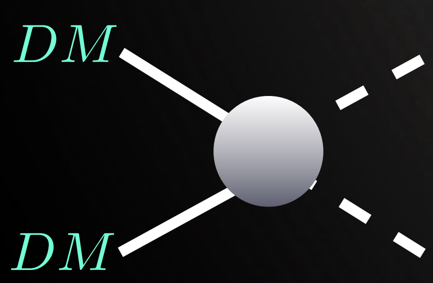


typically sub-TeV energies

Indirect Detection

γ from DM annihilations in Sagittarius Dwarf



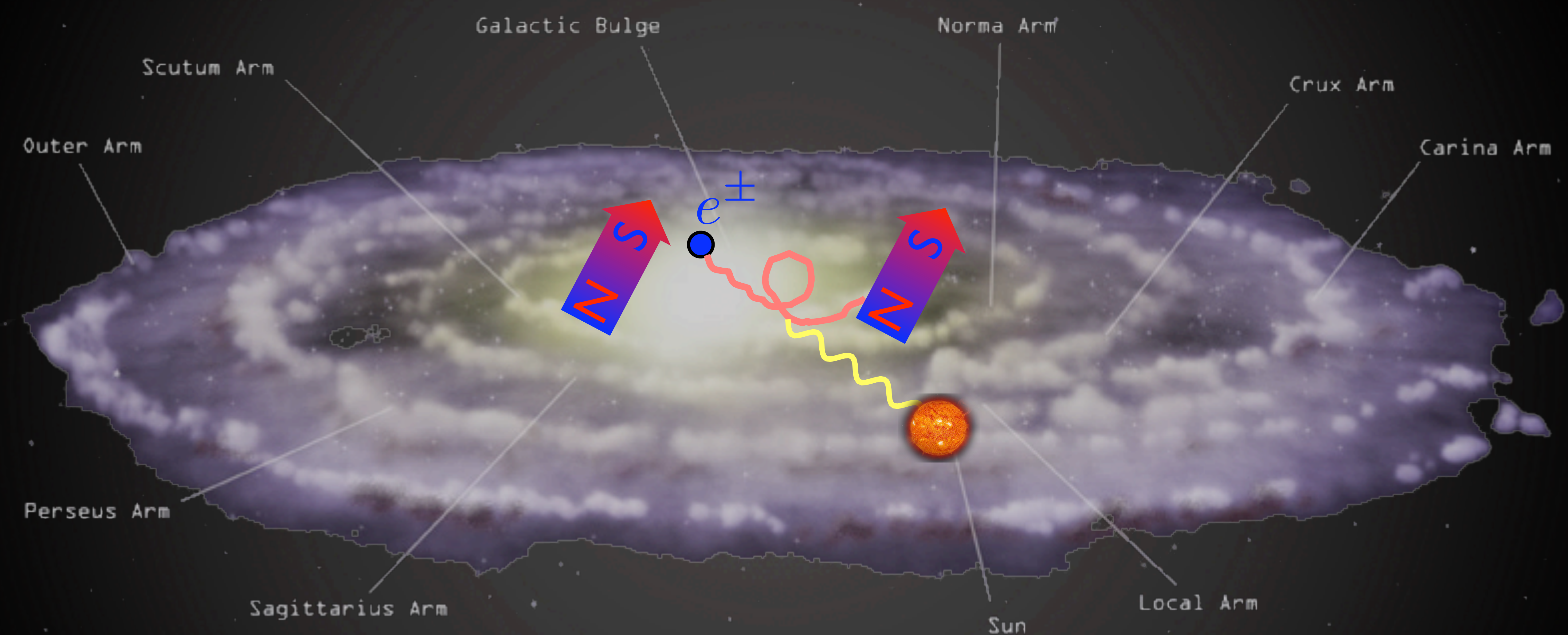


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

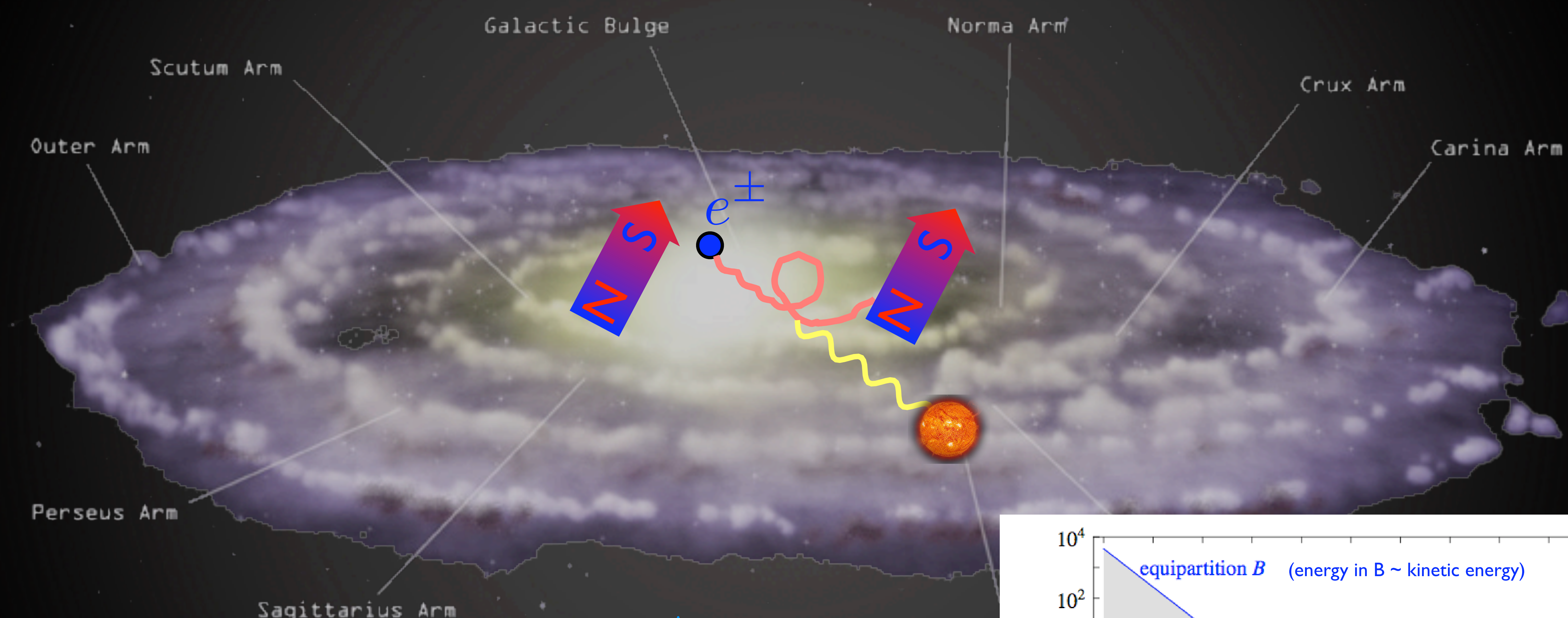
Indirect Detection

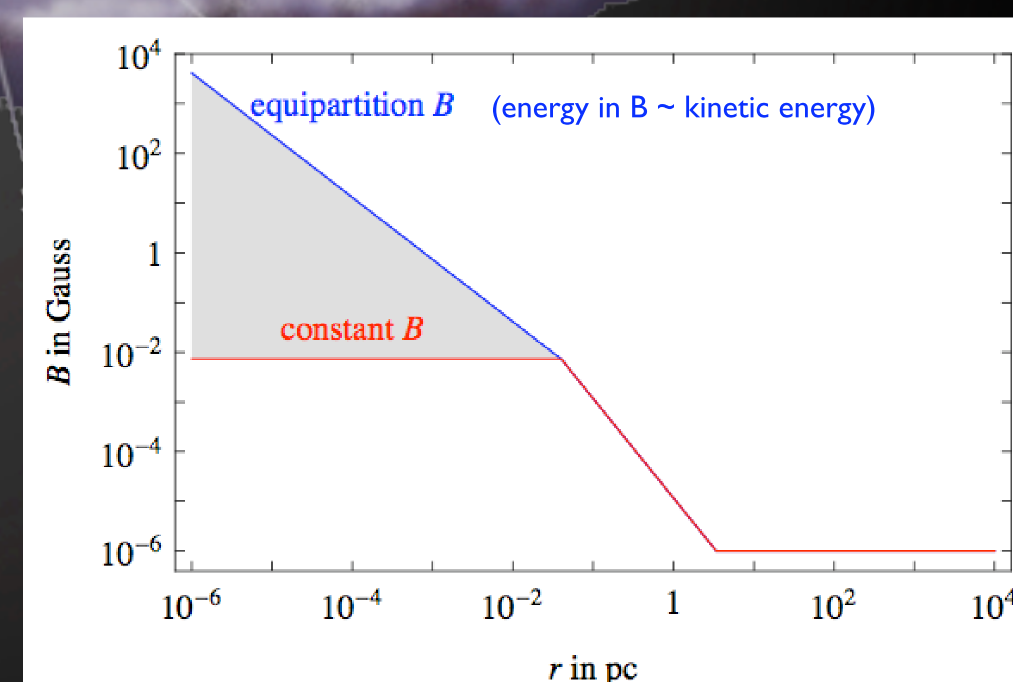
radio-waves from synchrotron radiation of $e^{\pm}$ in GC



Indirect Detection

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



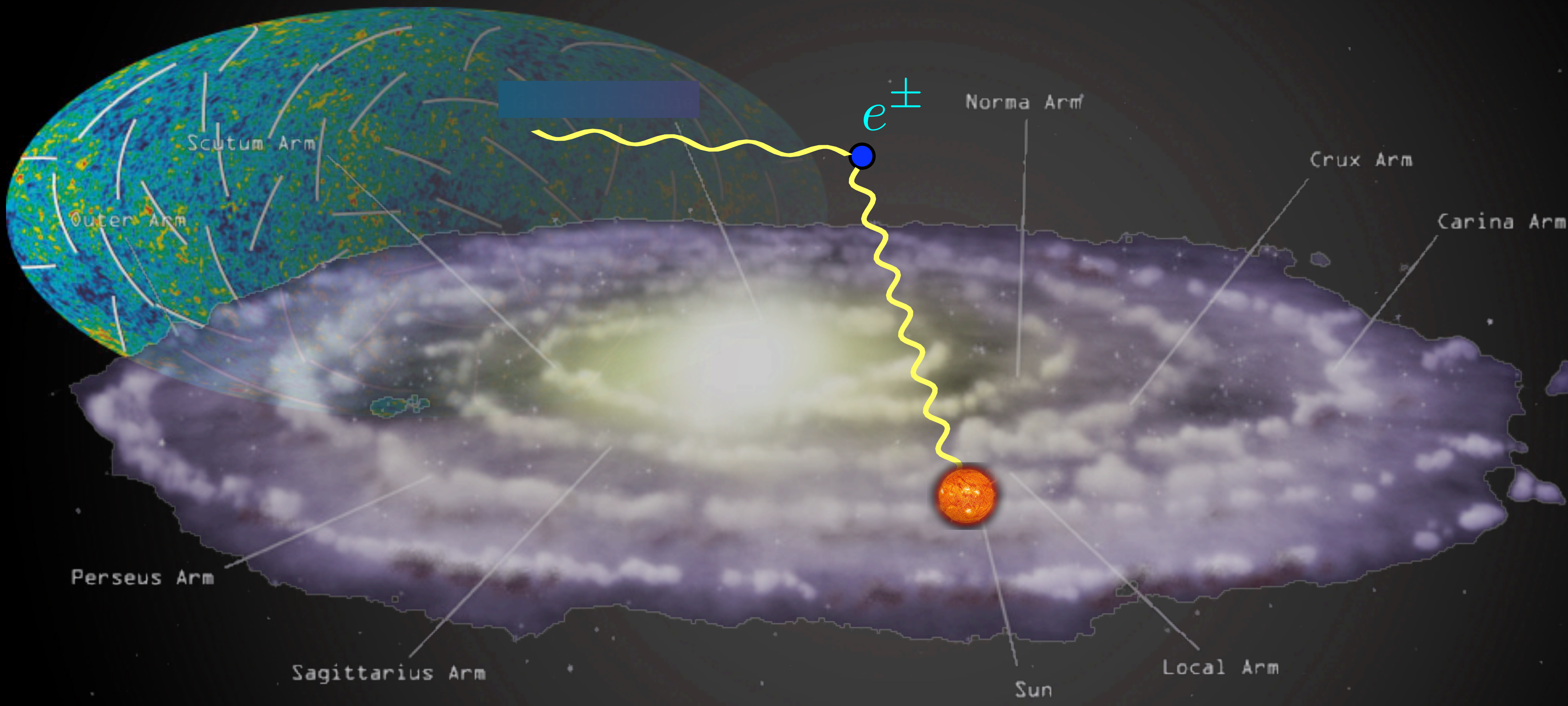


- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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

Indirect Detection

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

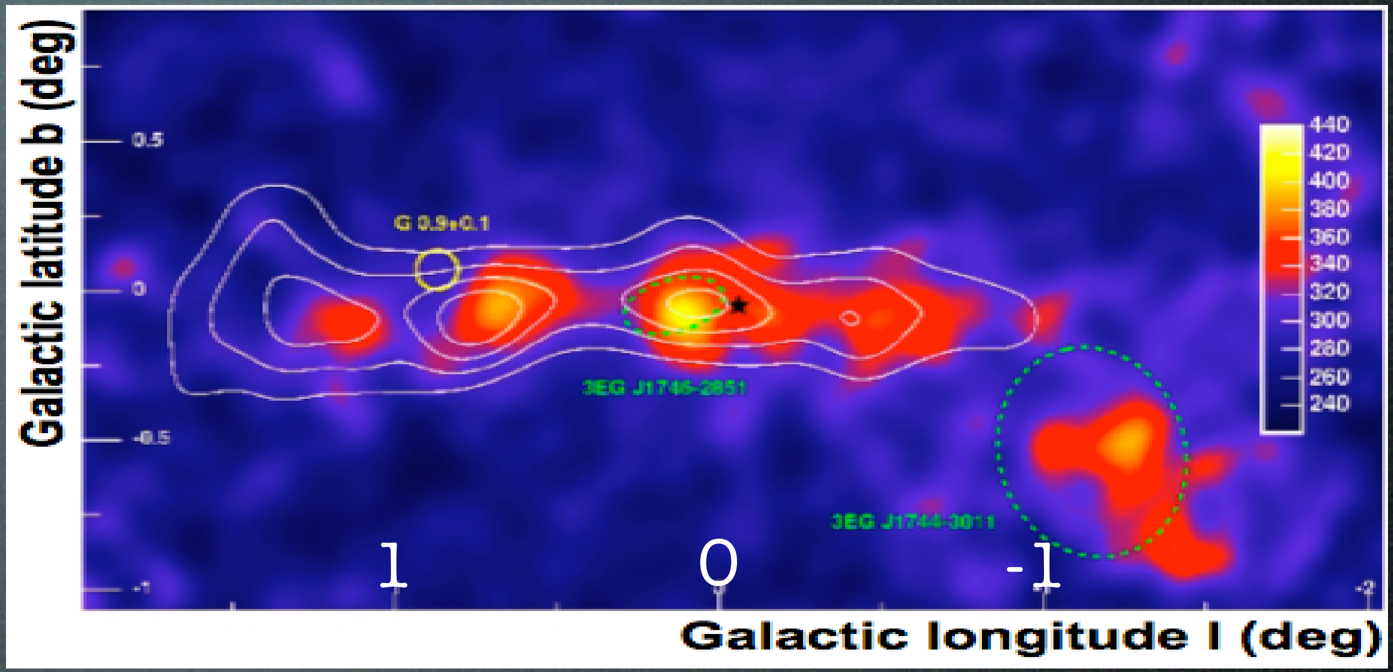


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Comparing with data

Gamma constraints

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



HESS coll.

Gamma constraints

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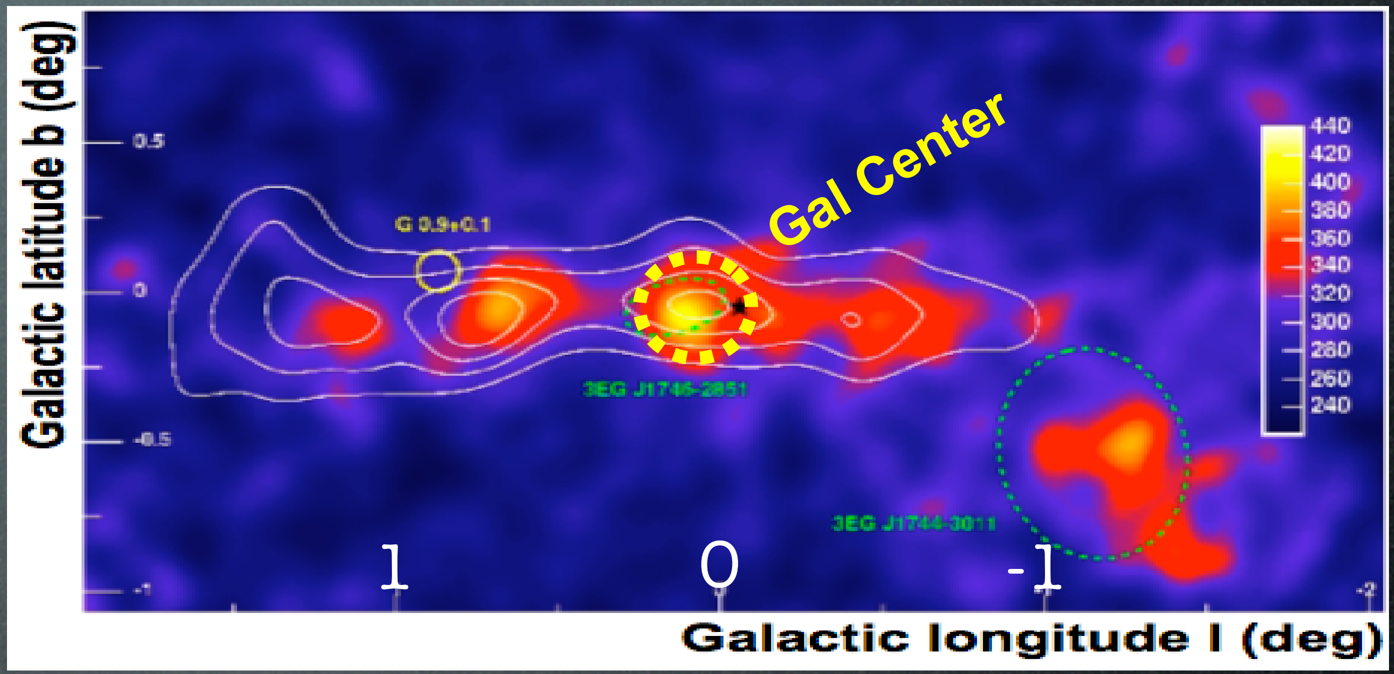

HESS coll.

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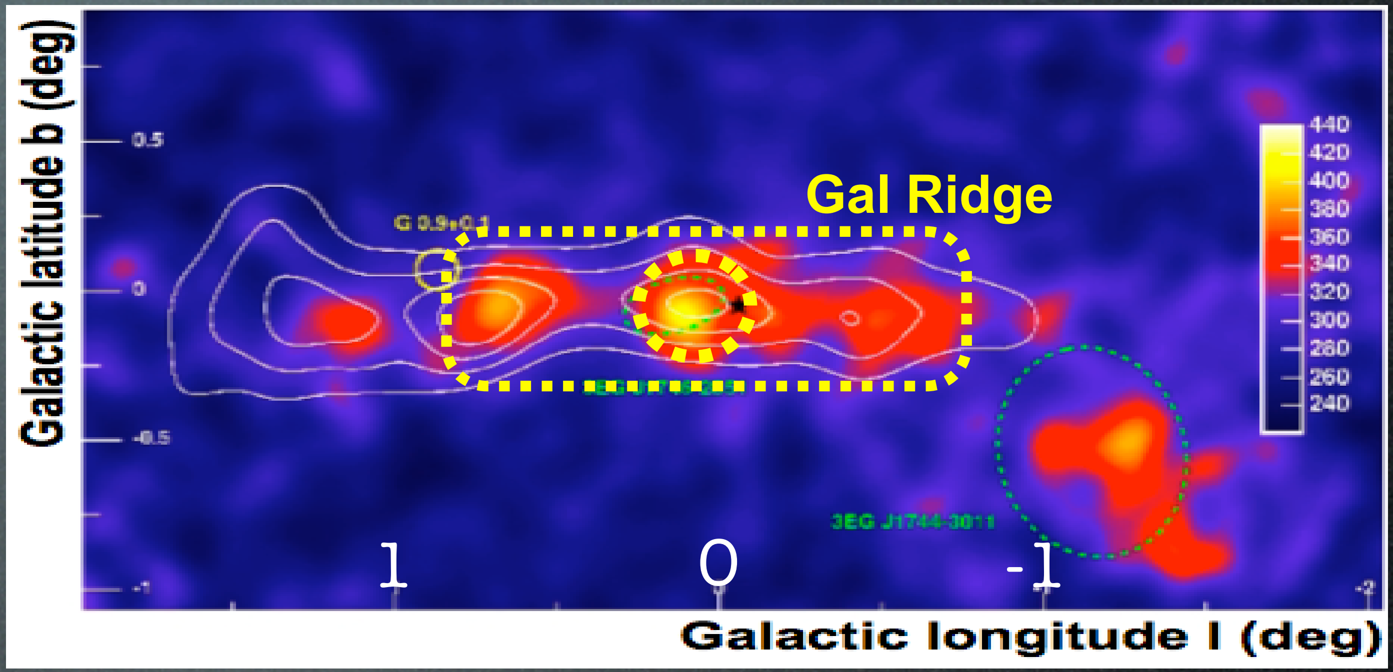

HESS coll.

Gamma constraints

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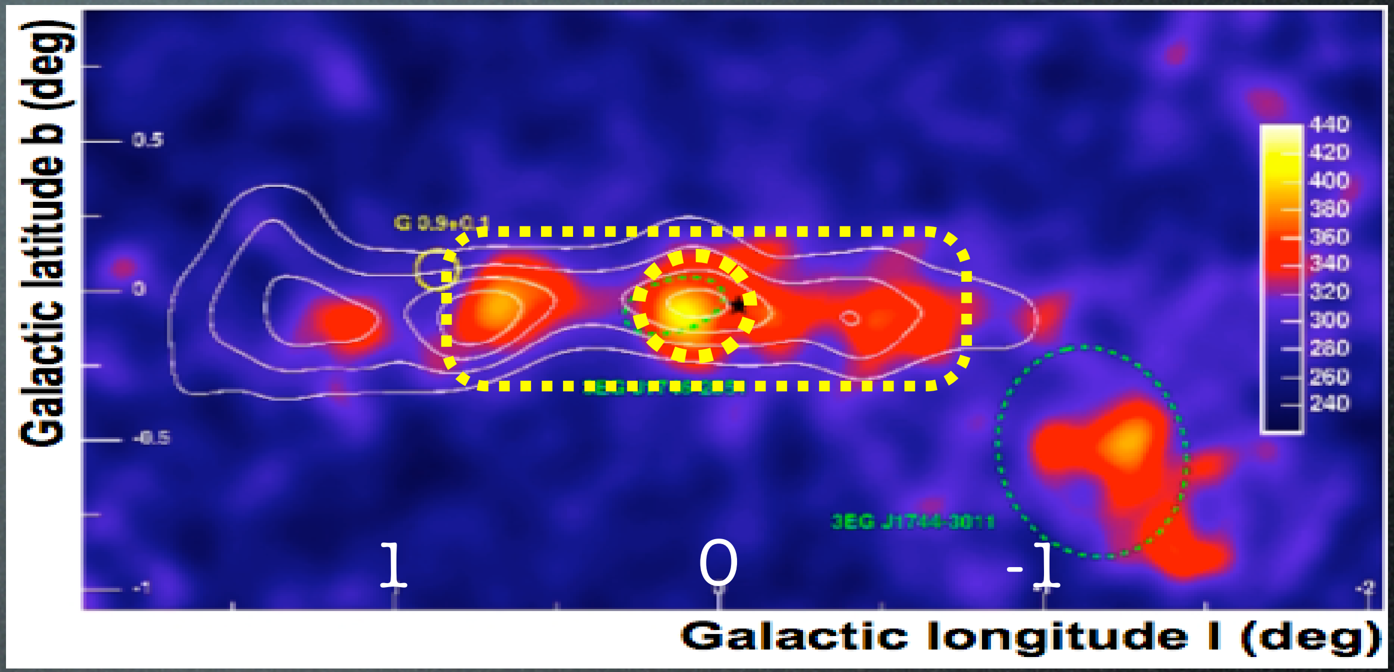
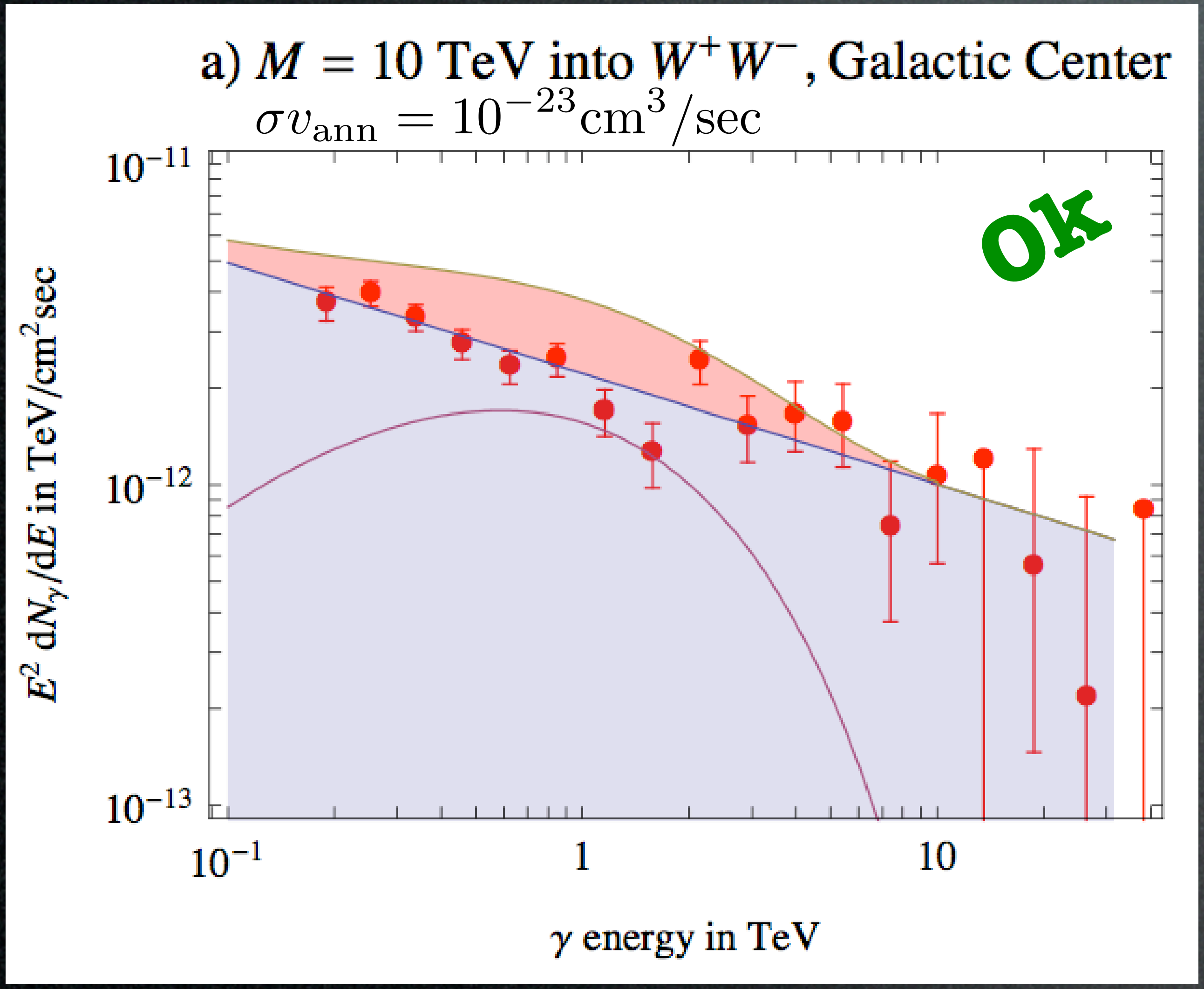


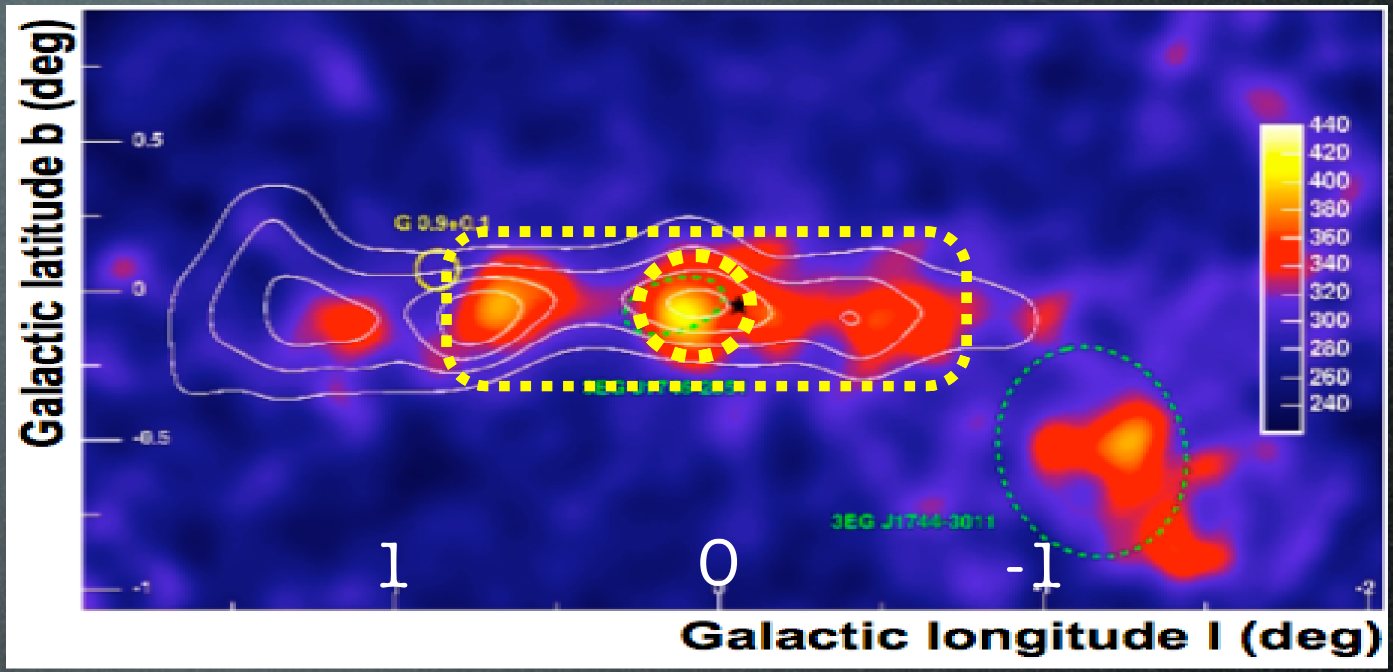
HESS coll.



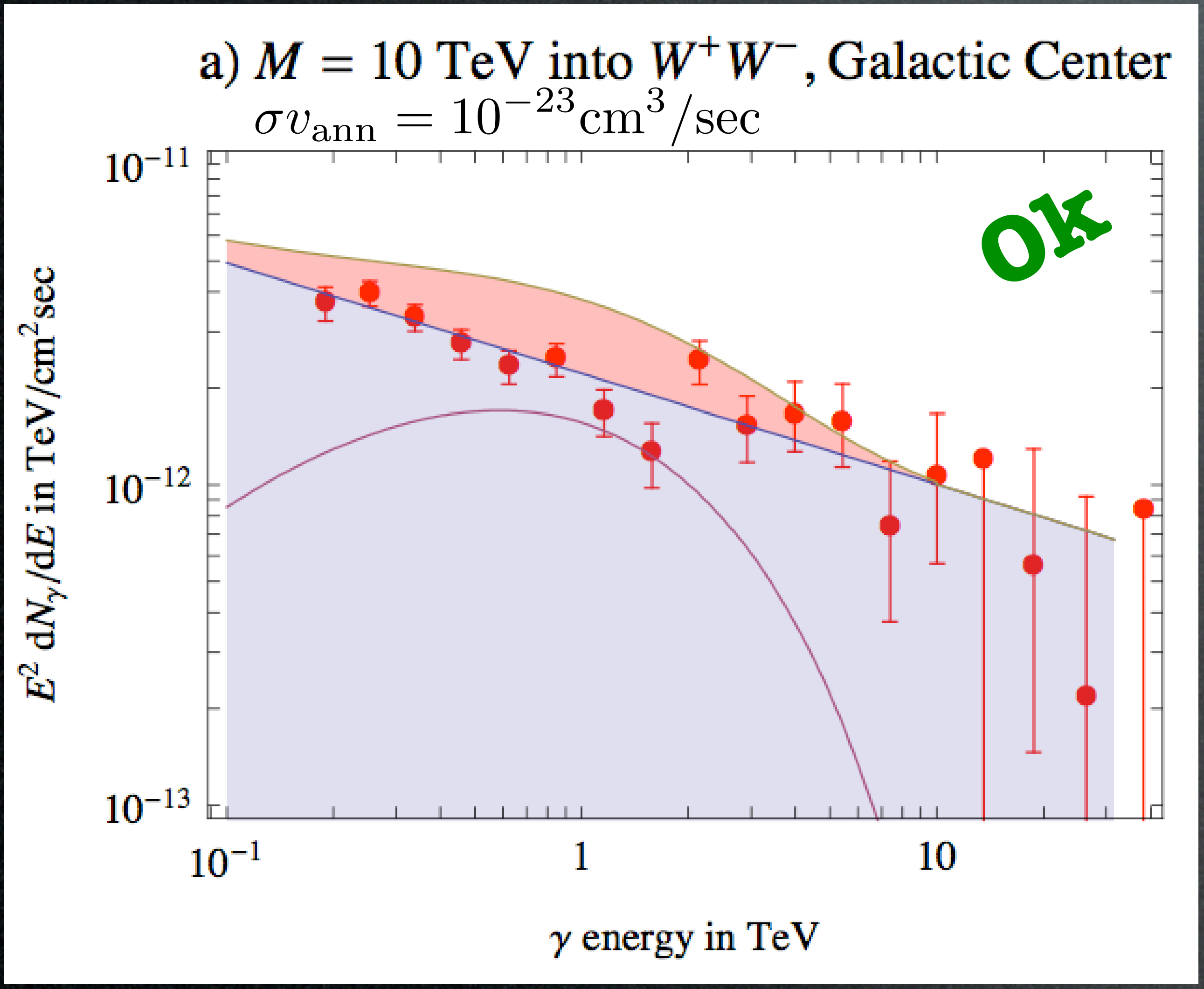
Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

Gamma constraints

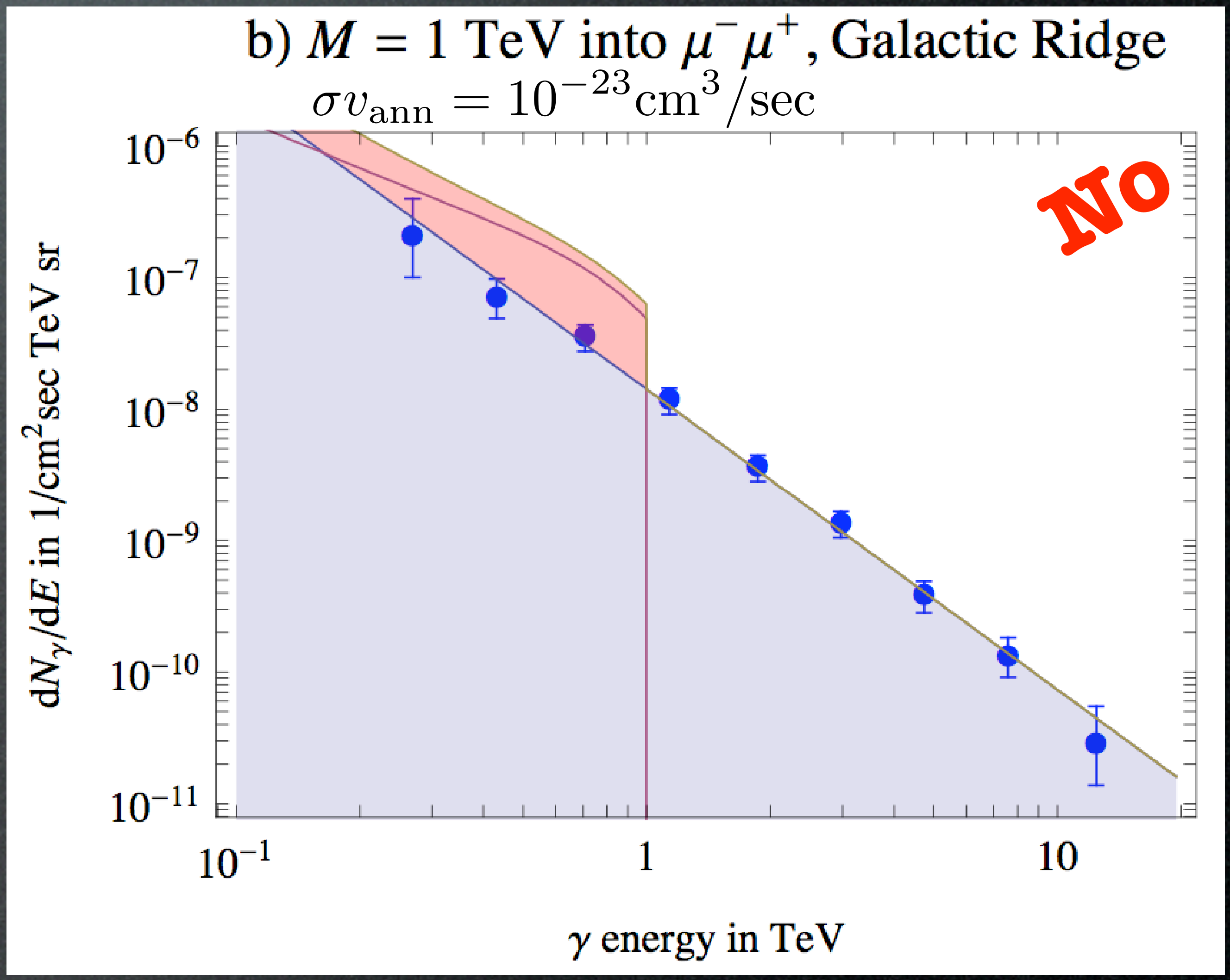
HESS has detected γ-ray emission from Gal Center and Gal Ridge. The DM signal must not excede that.



HESS coll.



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

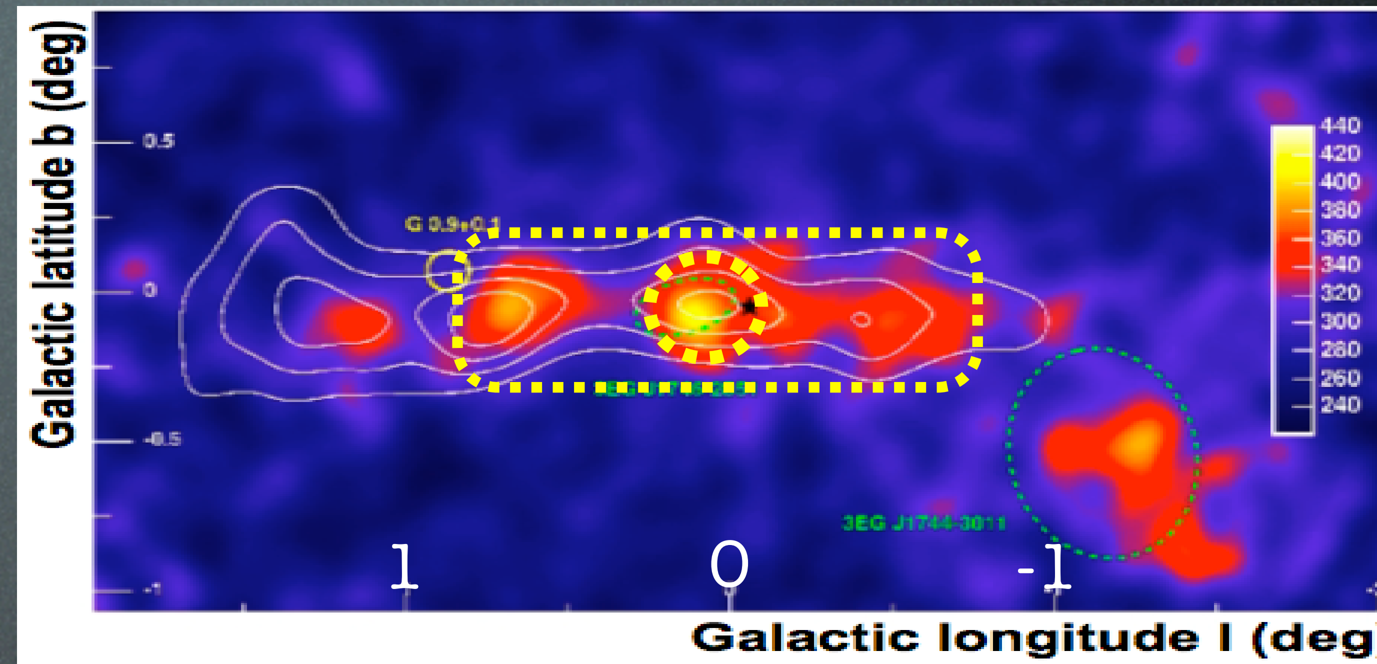


Data: HESS coll., astro-ph/0603021

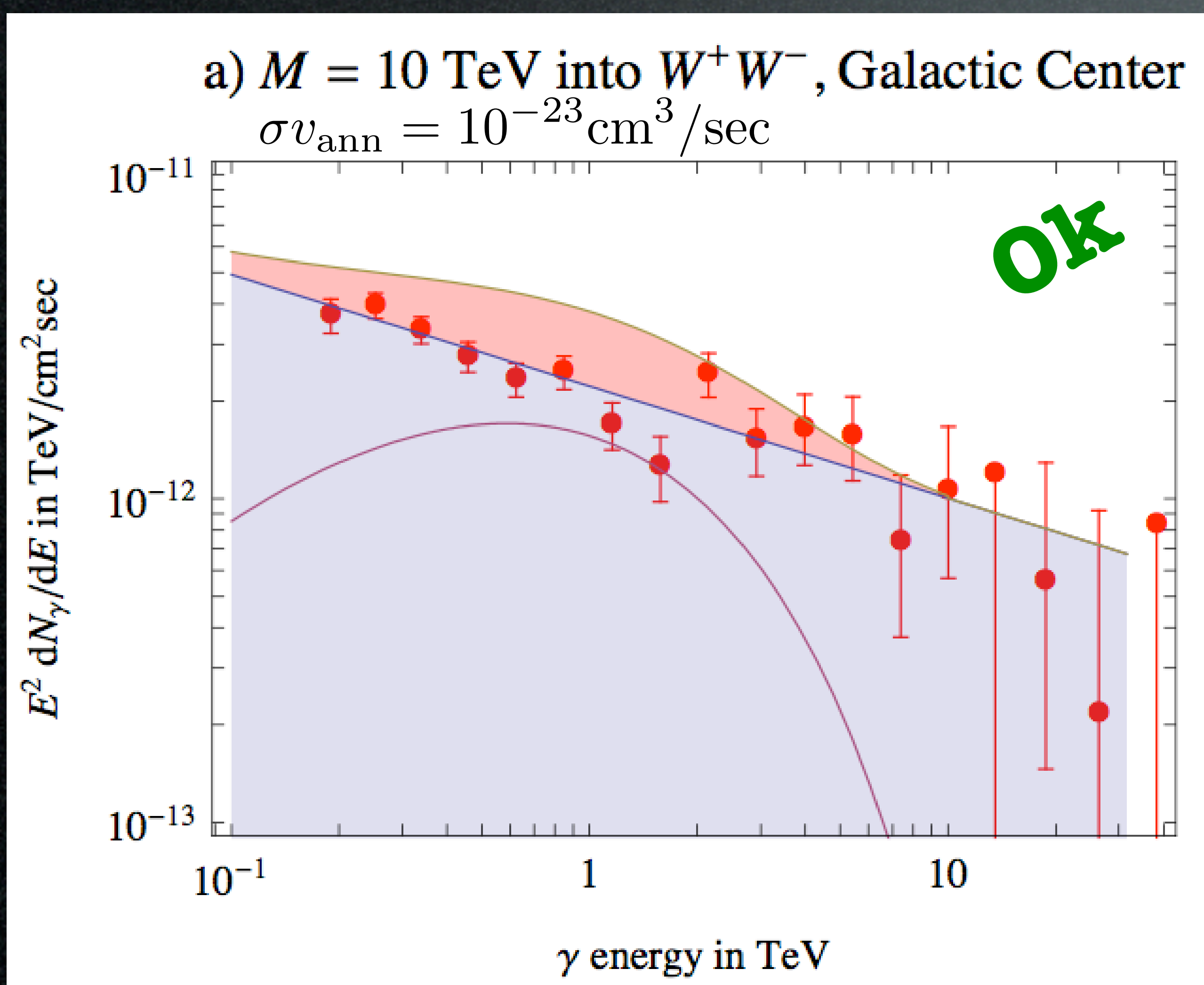
Gamma constraints

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

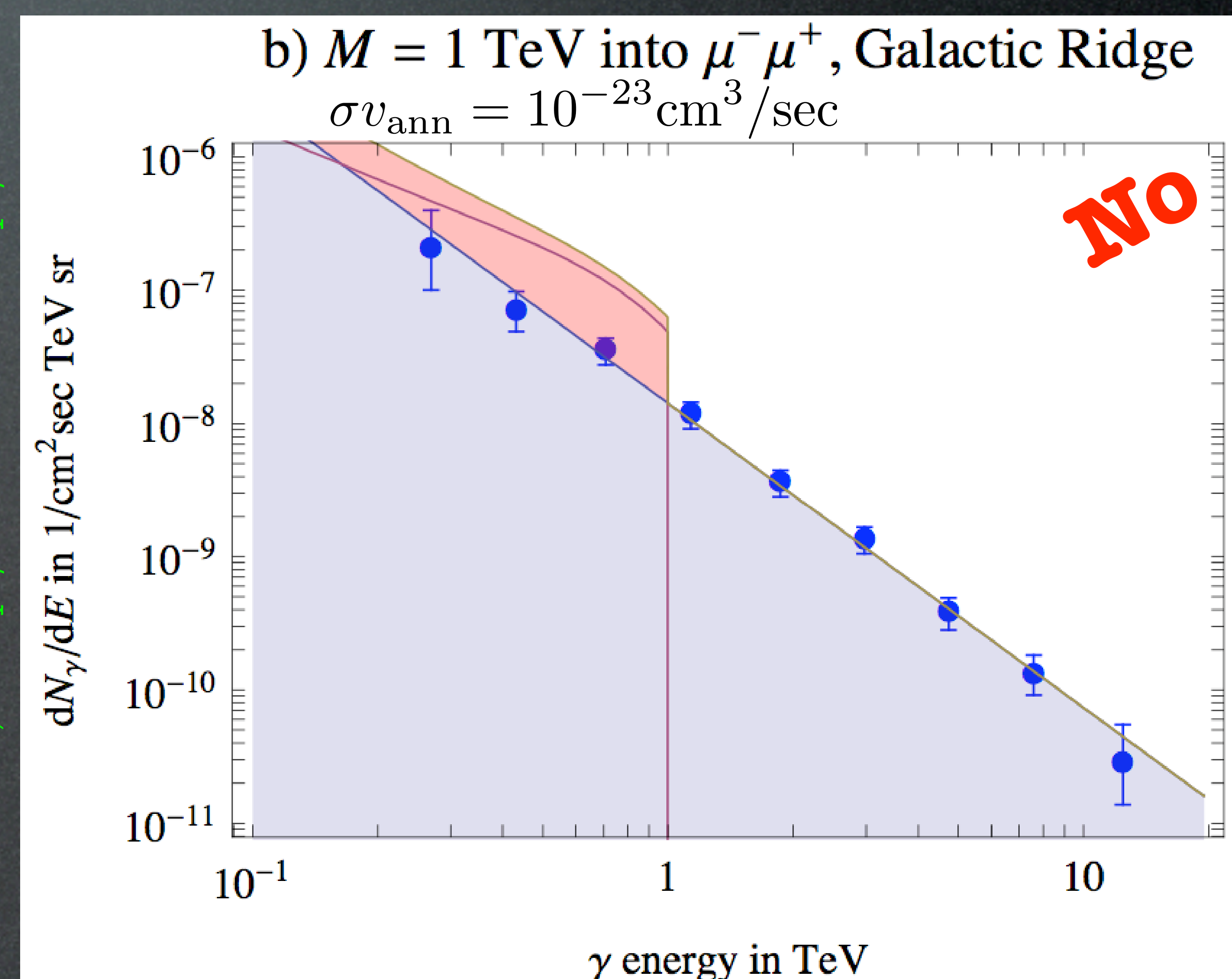
Moreover: no detection from Sgr dSph => upper bound.



HESS coll.



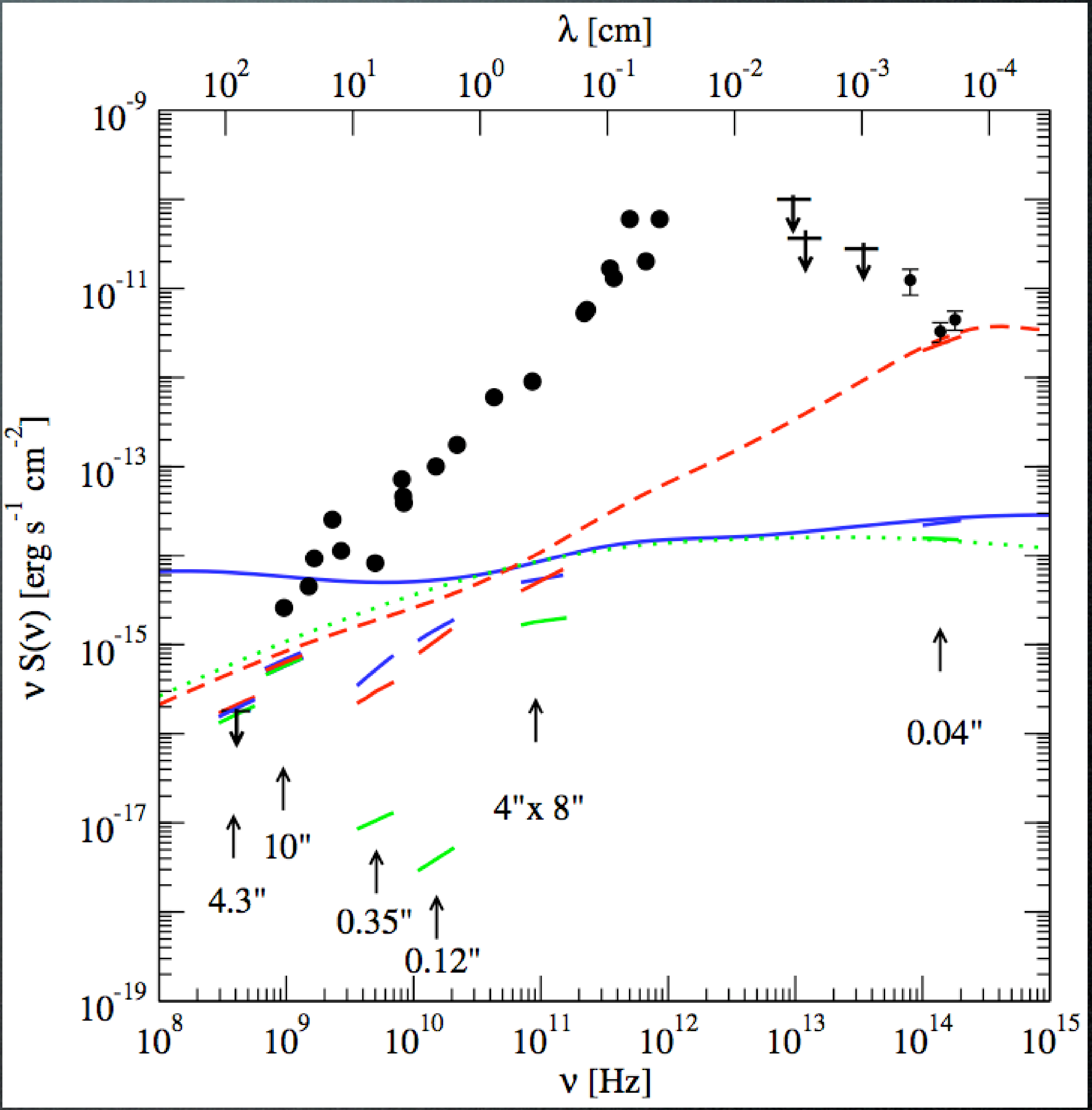
Data: HESS coll., astro-ph/0408145 and astro-ph/0610509



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.

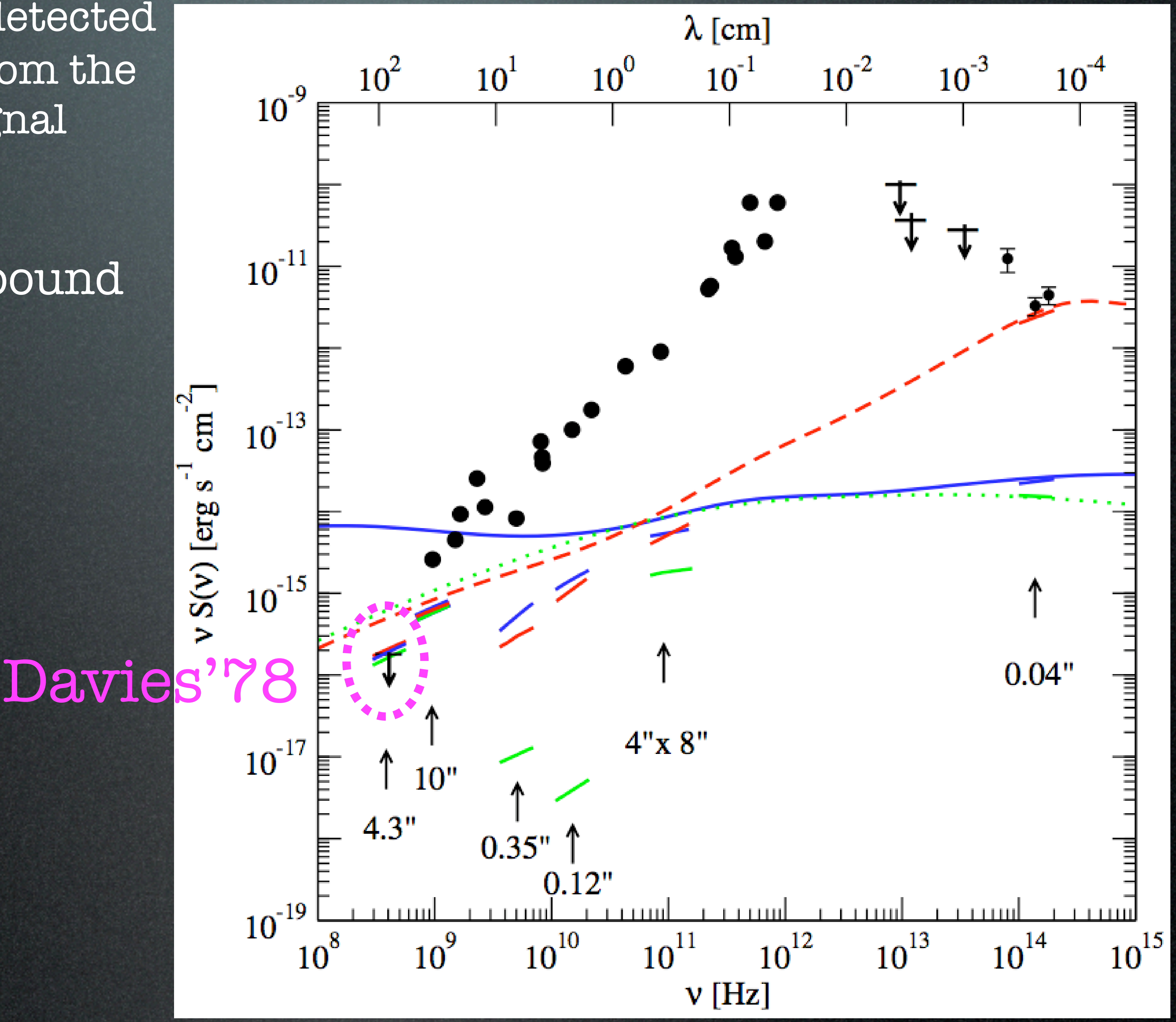


Regis, Ullio PRD 78 (2008)

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.



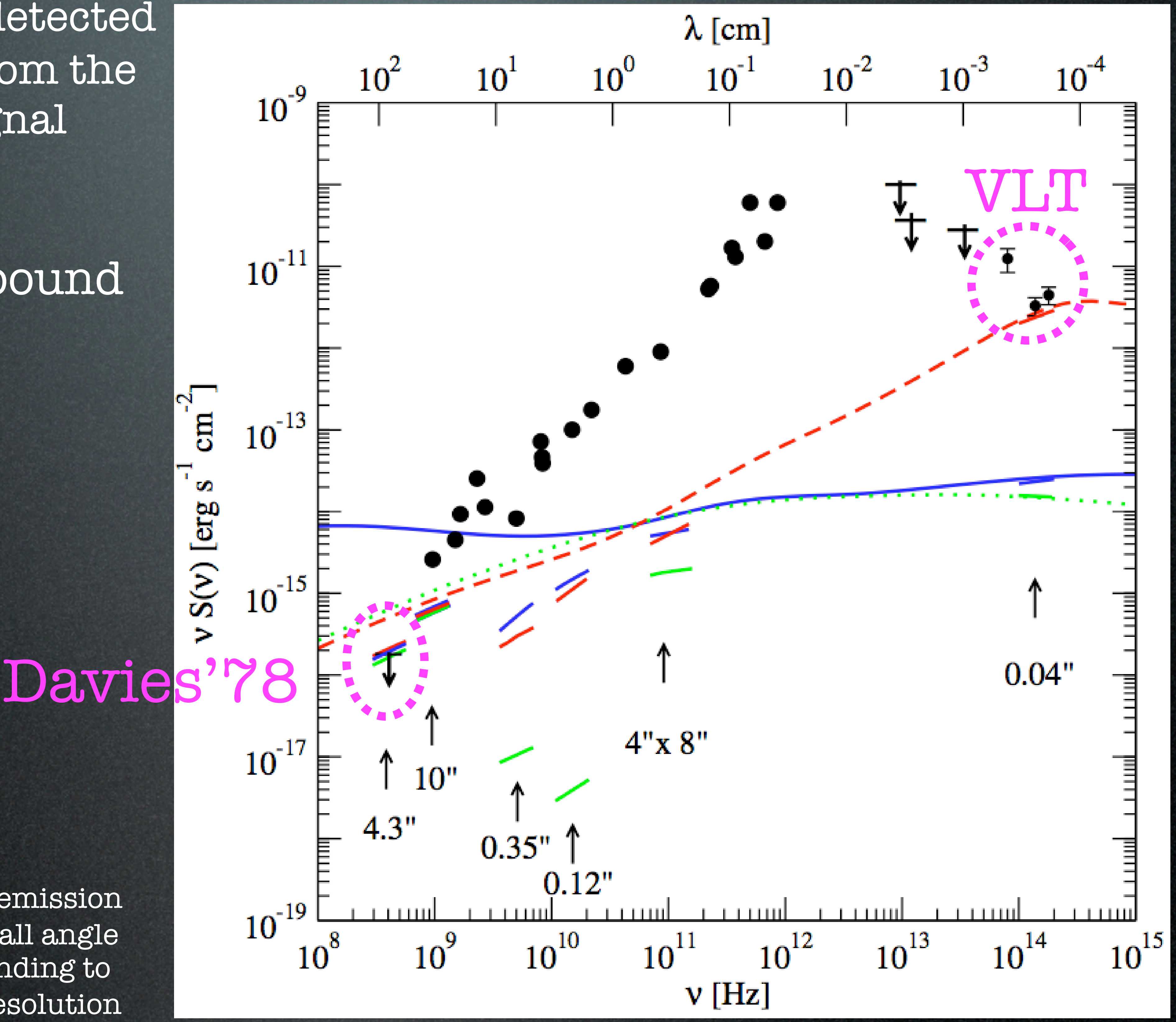
Regis, Ullio PRD 78 (2008)

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.

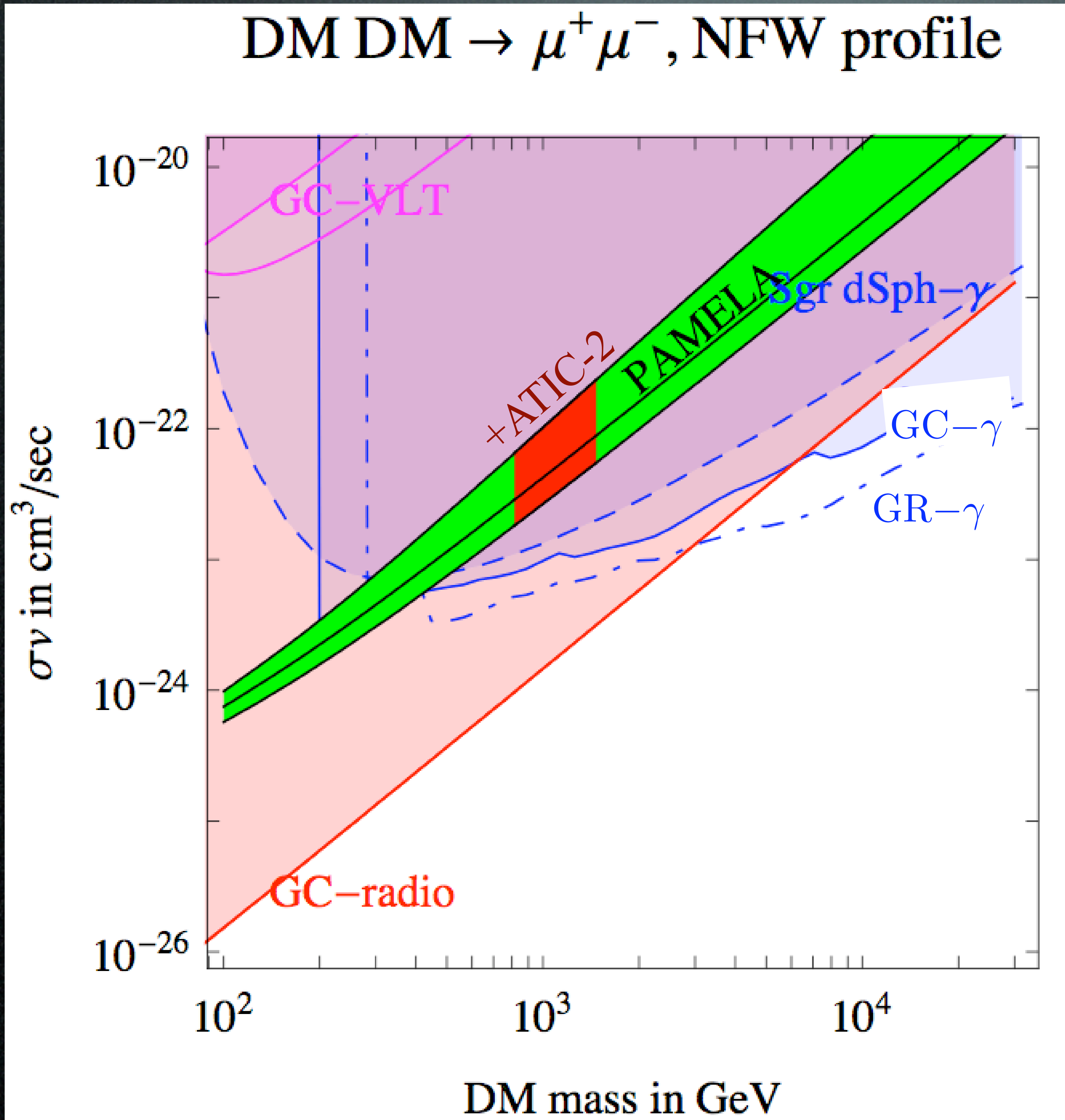
VLT 2003 emission at 10^{14} Hz.



Regis, Ullio PRD '78 (2008)

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

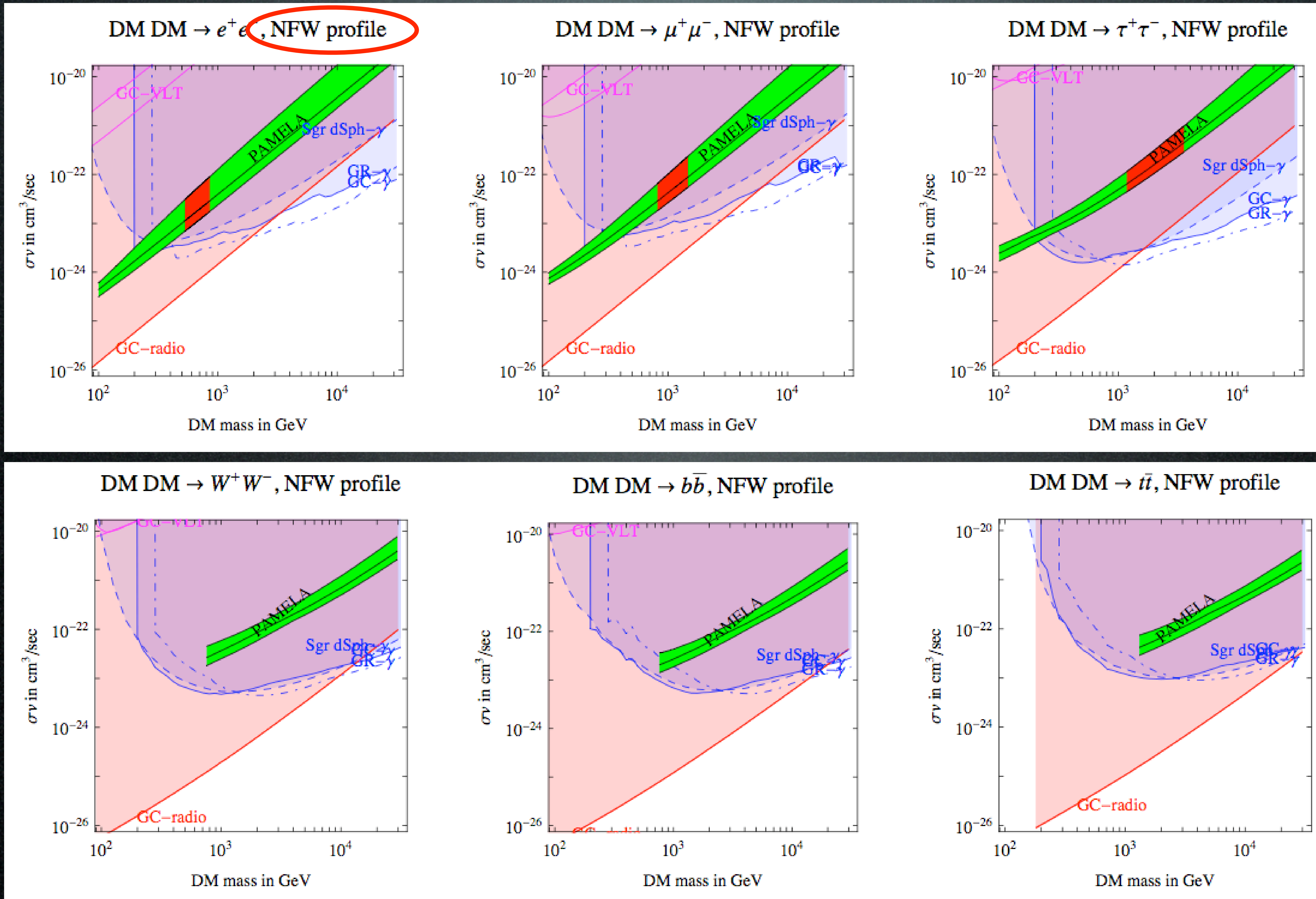
Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

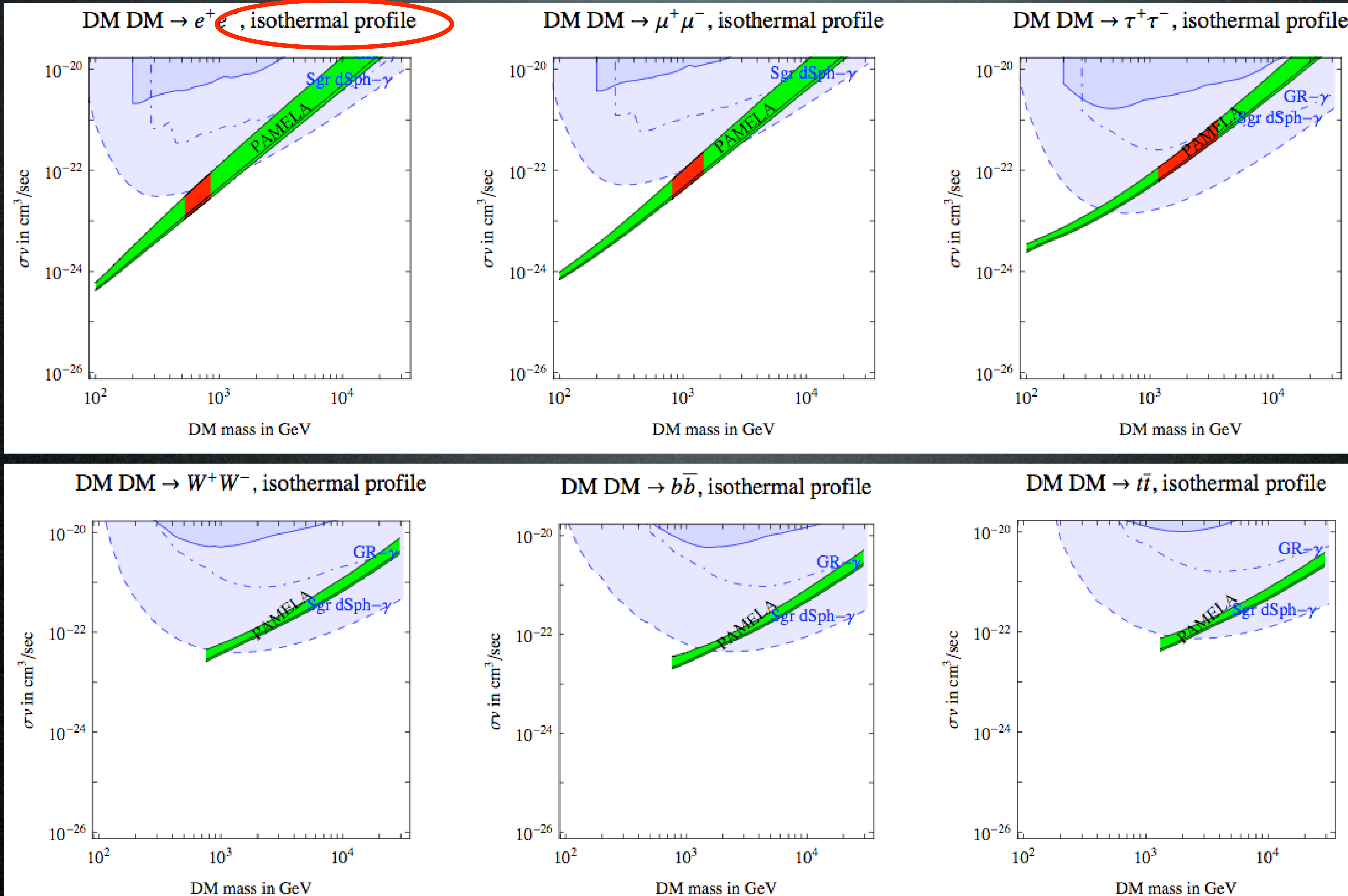
The PAMELA and ATIC regions are in conflict with gamma constraints, unless...

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

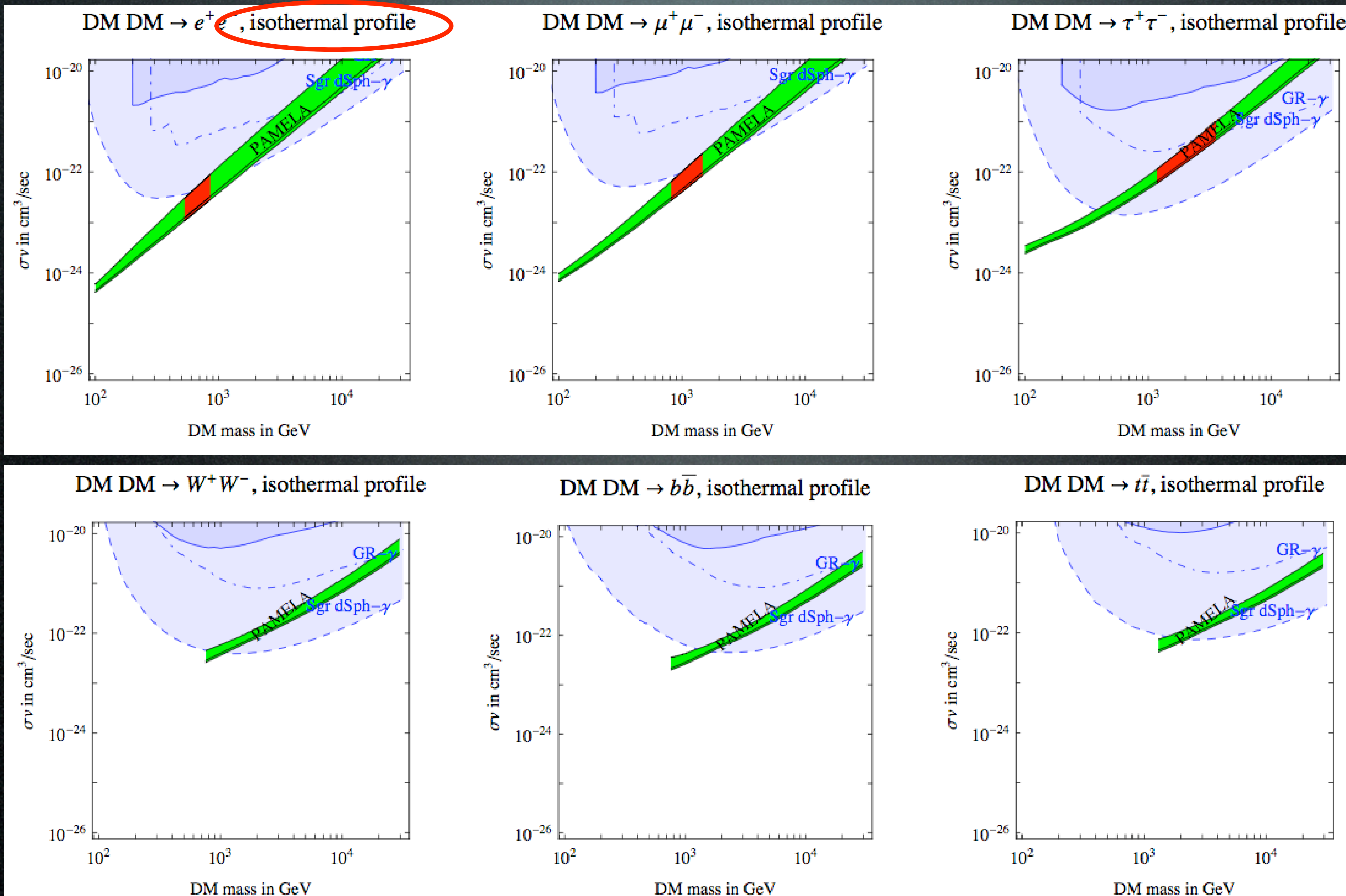
Gamma constraints



...not-too-steep profile needed.

Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

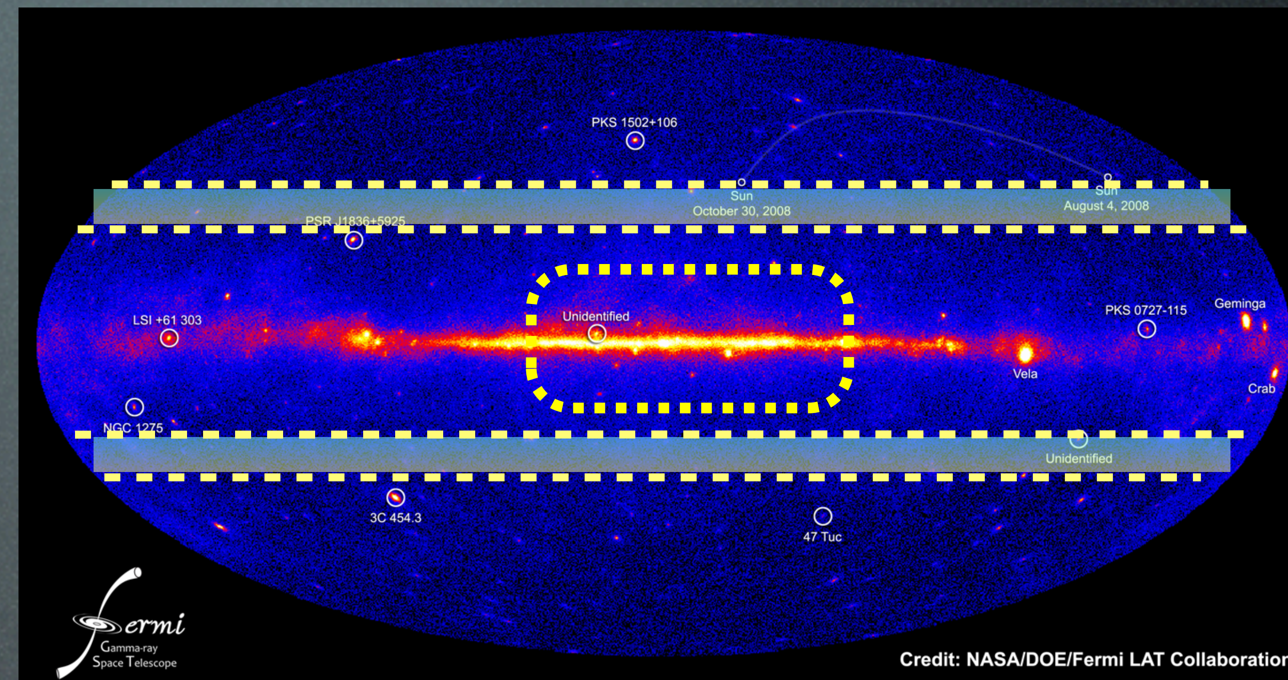
...not-too-steep profile needed.

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

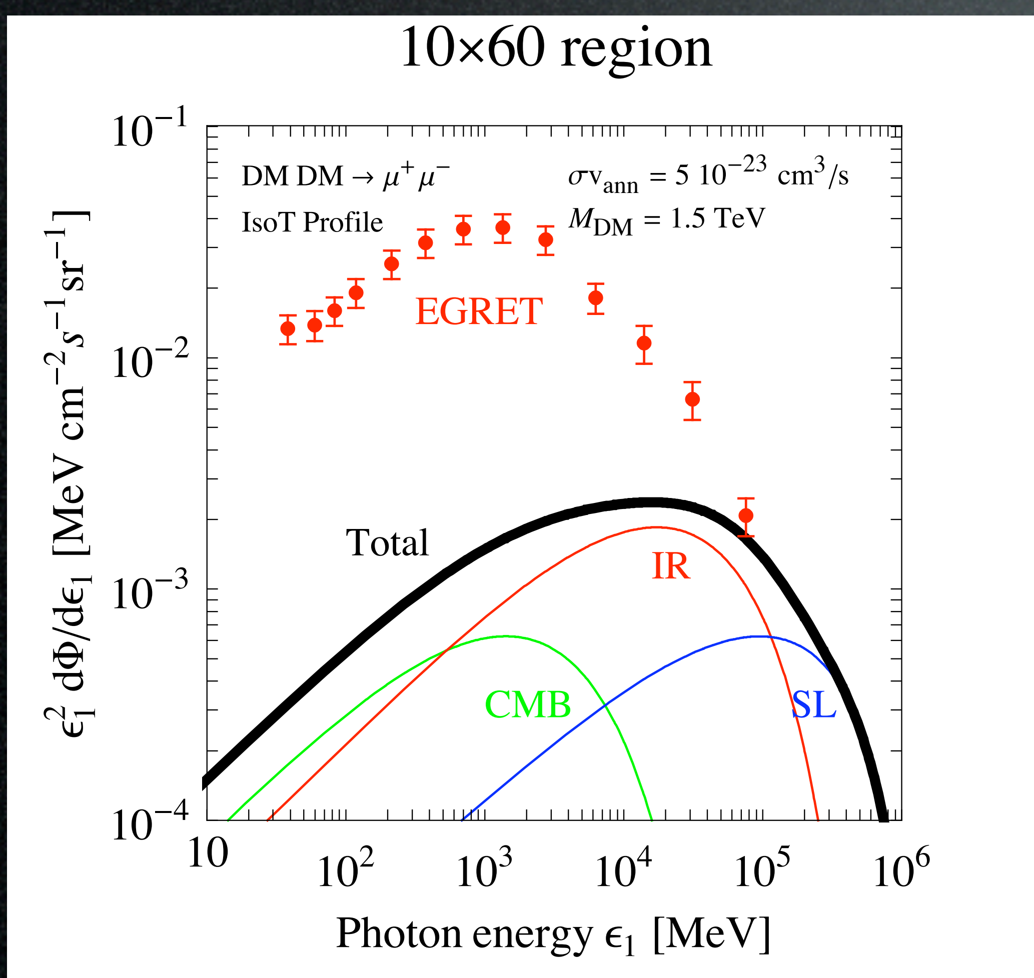
Or: take ad hoc DM profiles (truncated at 100 pc, with central void..., after all we don't know).

Gamma constraints

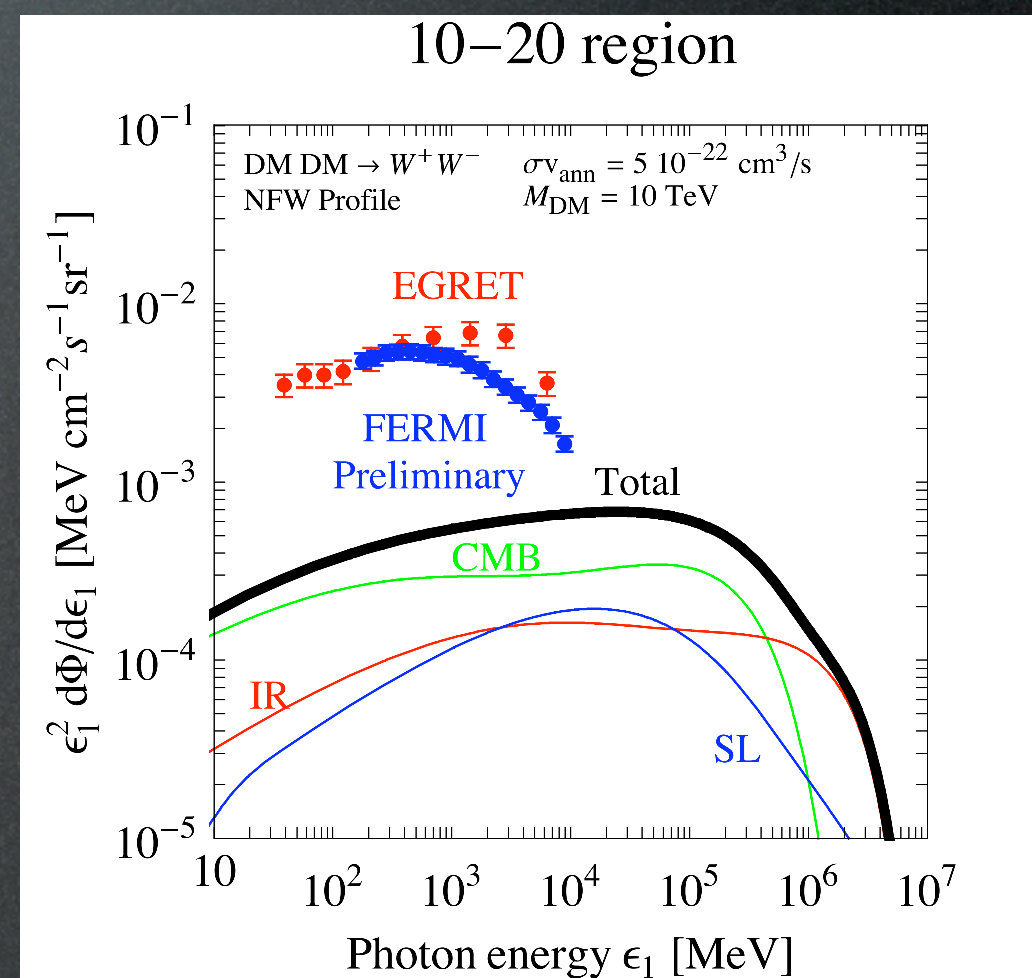
EGRET and FERMI have measured diffuse γ-ray emission. The DM signal must not excede that.



FERMI coll.

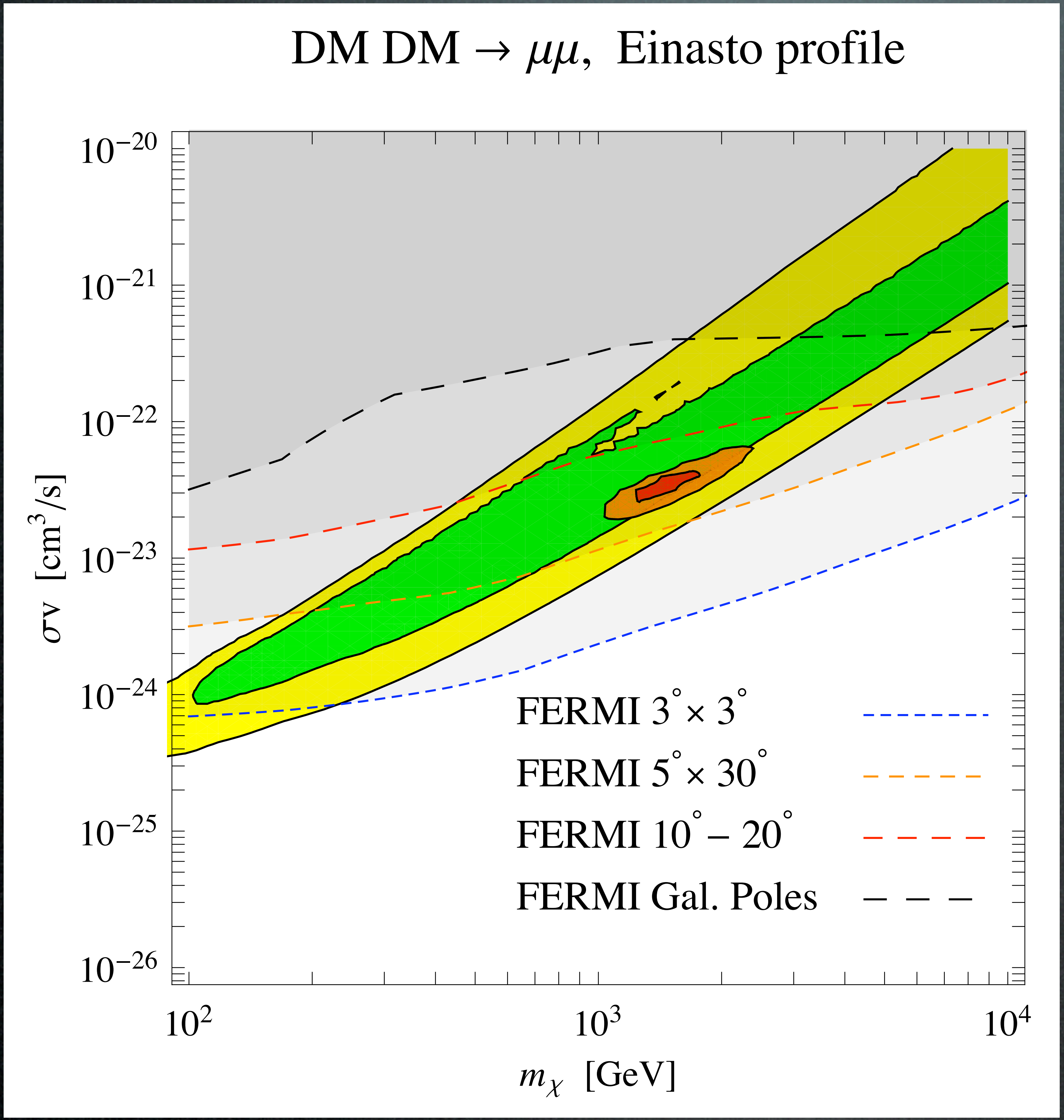


Data: EGRET coll.,Strong et al. astro-ph/0406254



Data: FERMI coll., several talks in 2009

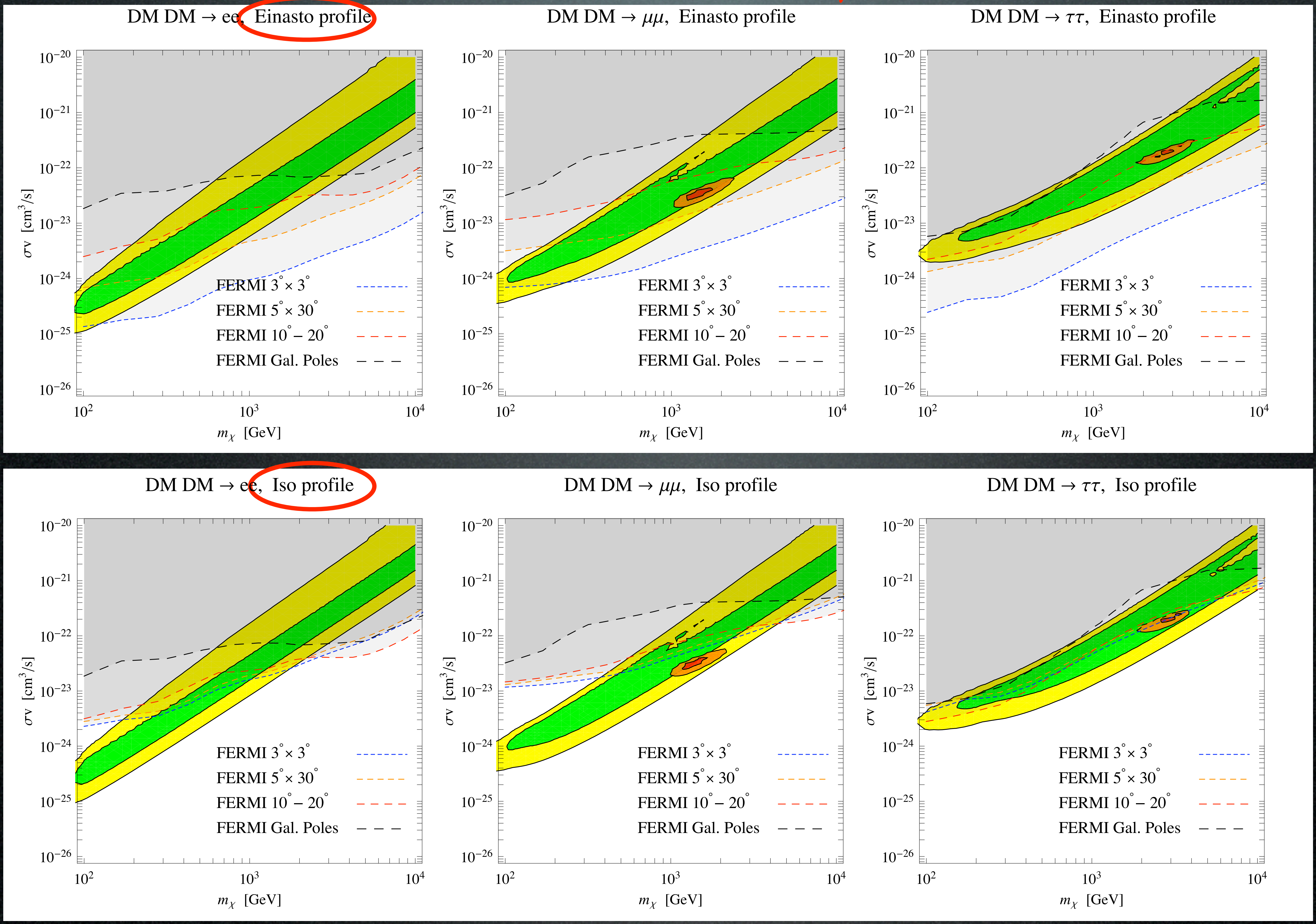
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

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

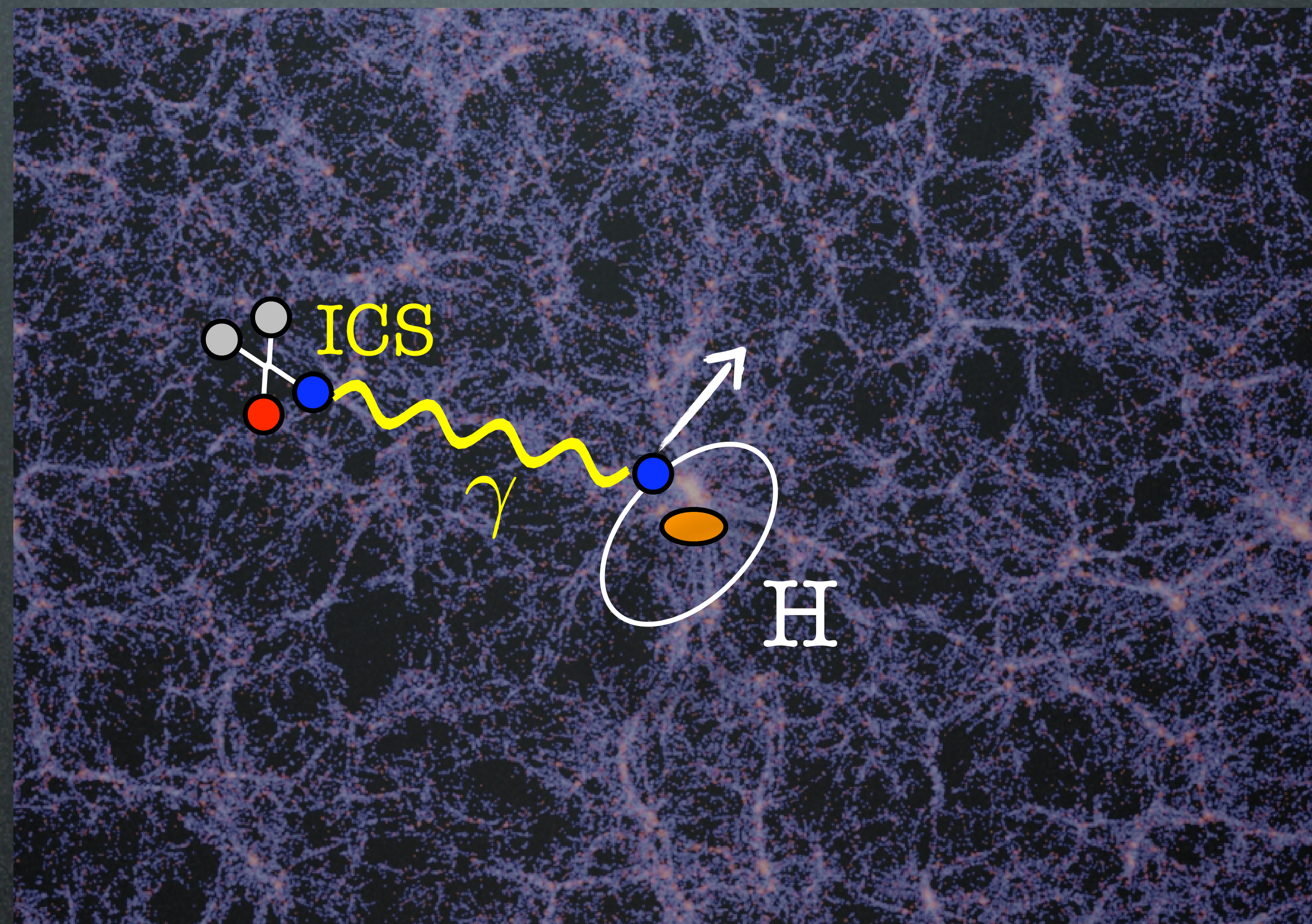
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

Cosmology: bounds from reionization

DM particle annihilations produce free electrons



$$-n_{\rm A} H_0 \sqrt{\Omega_{\rm M}}(1+z)^{11/2}\frac{dx_{\rm ion}(z)}{dz} = I(z) - R(z).$$

$$I(z) = \int_{e_{\rm i}}^{m_\chi} dE_\gamma\, \frac{dn}{dE_\gamma}(z)\cdot P(E_\gamma, z)\cdot N_{\rm ion}(E_\gamma)$$

$$P(E_\gamma, z) = n_{\rm A}(1+z)^3\left[1 - x_{\rm ion}(z)\right]\cdot \sigma_{\rm tot}(E_\gamma),$$

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

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

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

$$\frac{dT_{\rm igm}(z)}{dz} = \frac{2\,T_{\rm igm}(z)}{1+z} - \frac{1}{H_0\sqrt{\Omega_{\rm M}}\,(1+z)^{5/2}}\left(\frac{x_{\rm ion}(z)}{1+x_{\rm ion}(z)+0.073}\frac{T_{\rm CMB}(z)-T_{\rm igm}(z)}{t_{\rm c}(z)} + \frac{2\,\eta_{\rm heat}(x_{\rm ion}(z))\,\mathcal{E}(z)}{3\,n_{\rm A}(1+z)^3}\right).$$

$$A(z) = \frac{\langle\sigma v\rangle}{2\,m_\chi^2}\rho^2_{\rm DM,0}(1+z)^6\left(1+\mathcal{B}_i(z)\right),$$

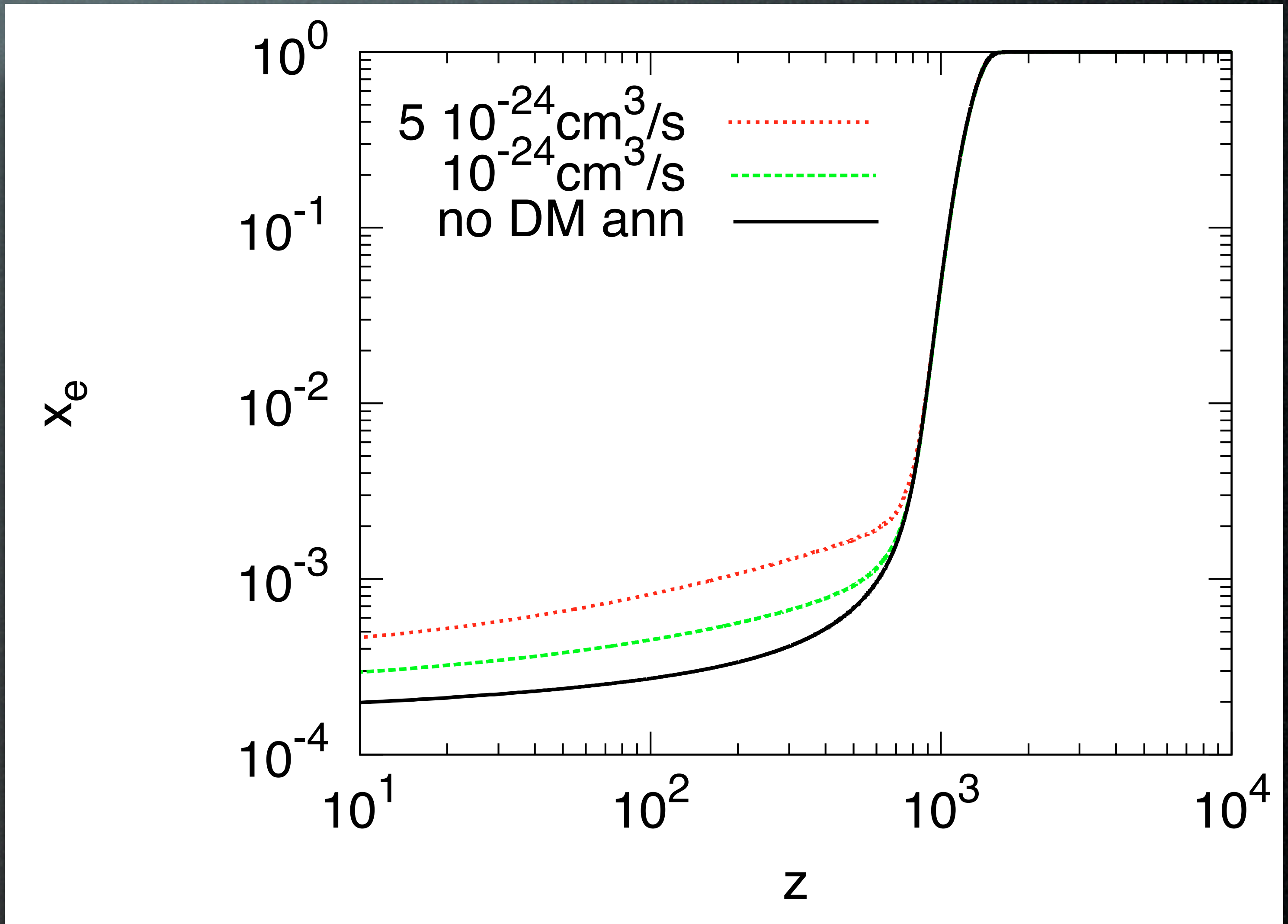
$$\mathcal{B}_i(z) = \frac{\Delta_{\rm vir}(z)}{3\,\rho_{\rm c}\Omega_{\rm M}}\int_{M_{\rm min}}^\infty dM\, M\frac{dn}{dM}(z,M)\,F_i(M,z),$$

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

Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

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

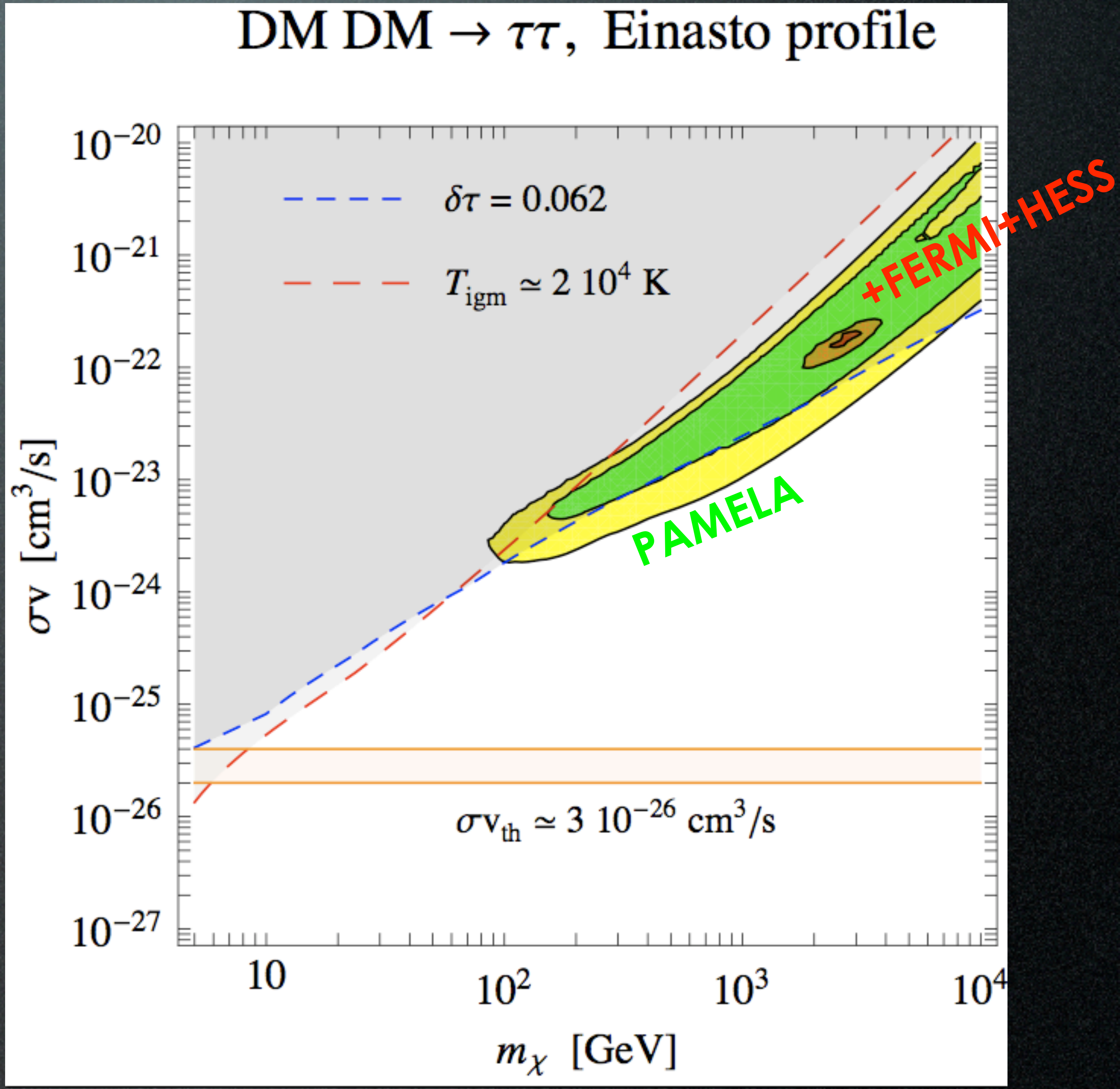


Kanzaki et al., 0907.3985

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)



Cirelli, Iocco, Panci, JCAP 0910

see also:
Huetsi, Hektor, Raidal 0906.4550
Kanzaki et al., 0907.3985

Challenges for the ‘conventional’ DM candidates

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

for any Majorana DM,
s-wave annihilation cross section

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

Results

Which DM spectra can fit the data?

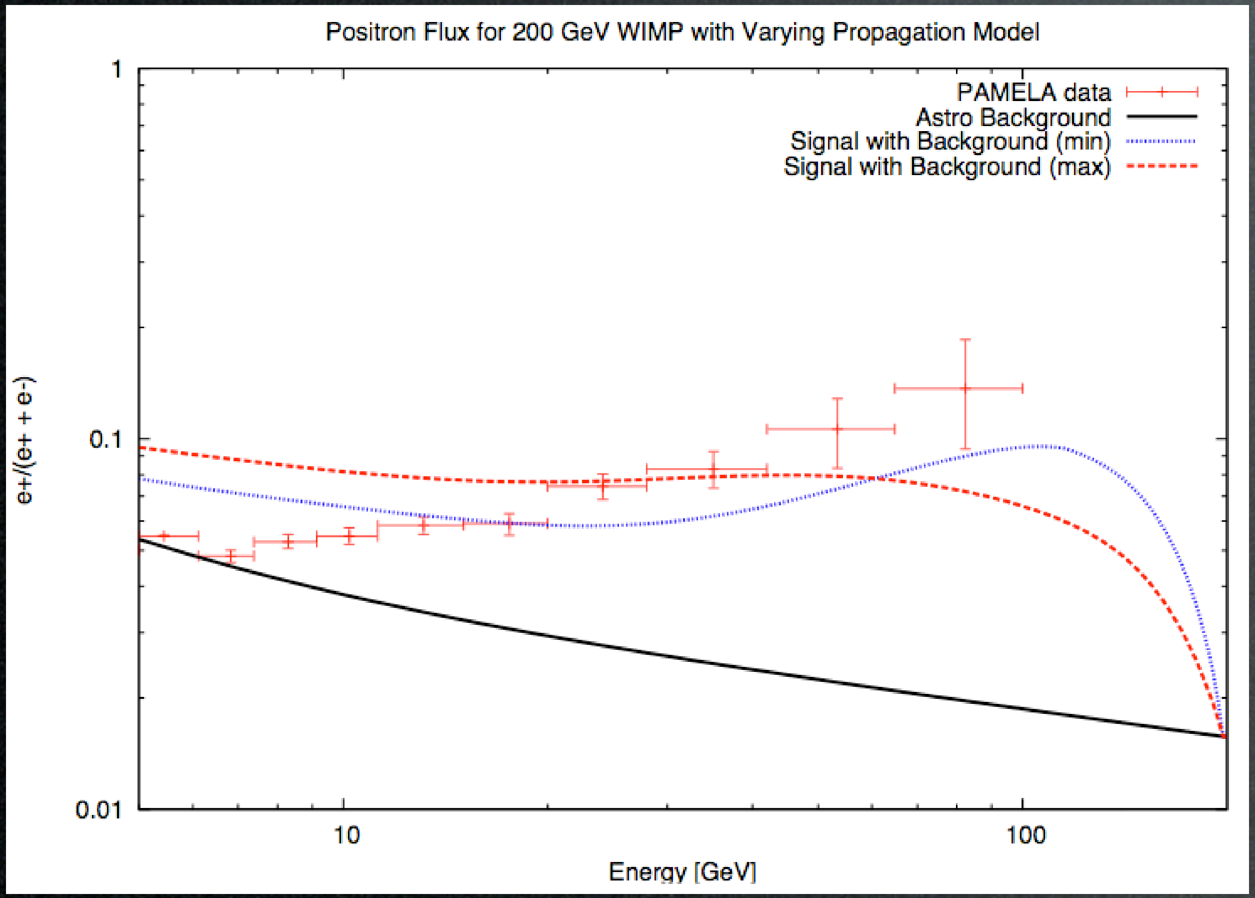
Ok, let's ***insist*** on Wino with: -mass $M_{\rm DM} = 200\,{\rm GeV}$

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

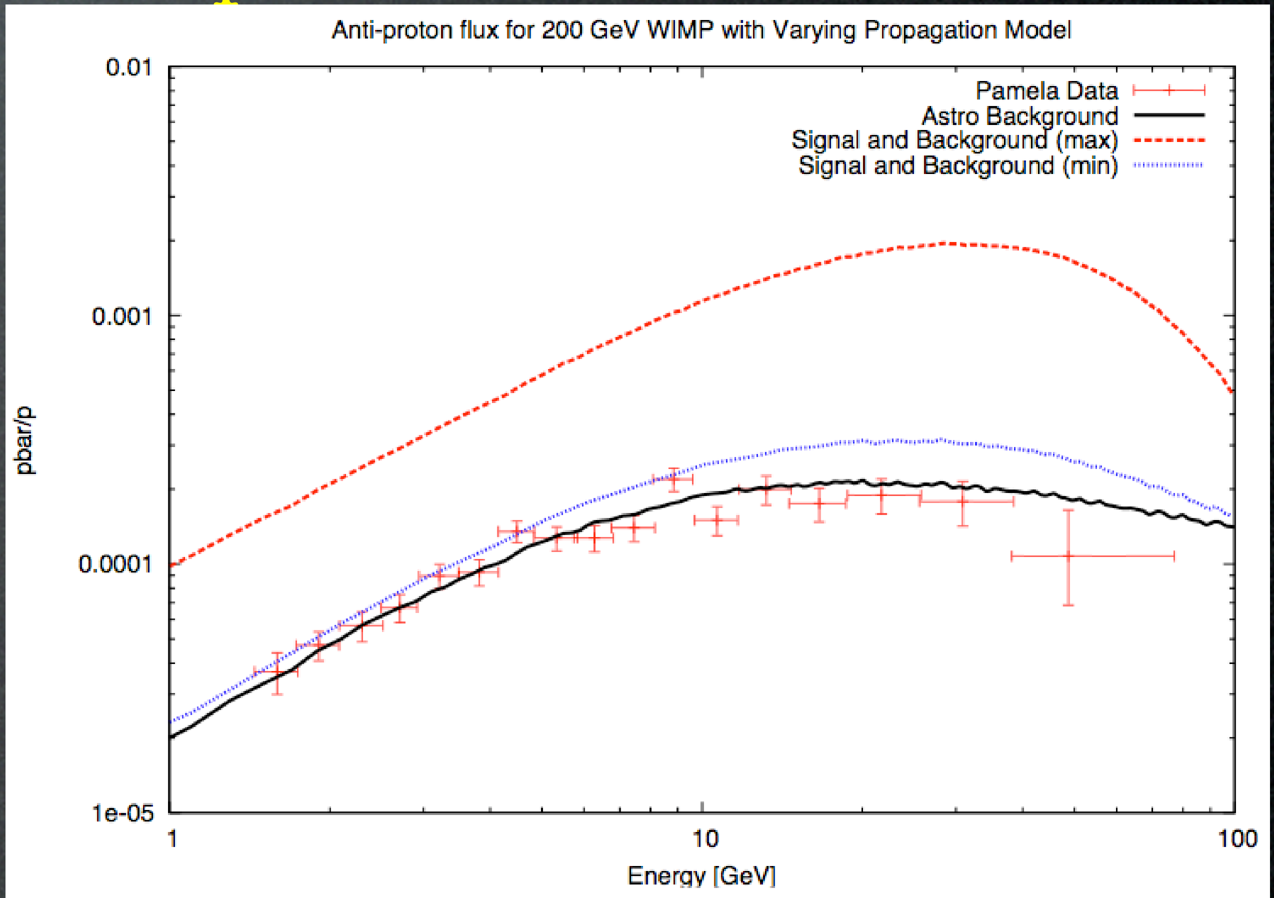
If one: - assumes non-thermal production of DM
- takes positron energy loss 5 times larger than usual
- takes "min" propagation only
- gives up ATIC
- neglects conflict with EGRET bound (4 times too many gammas)

then:

Positrons:



Anti-protons:



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

Results

Which DM spectra can fit the data?

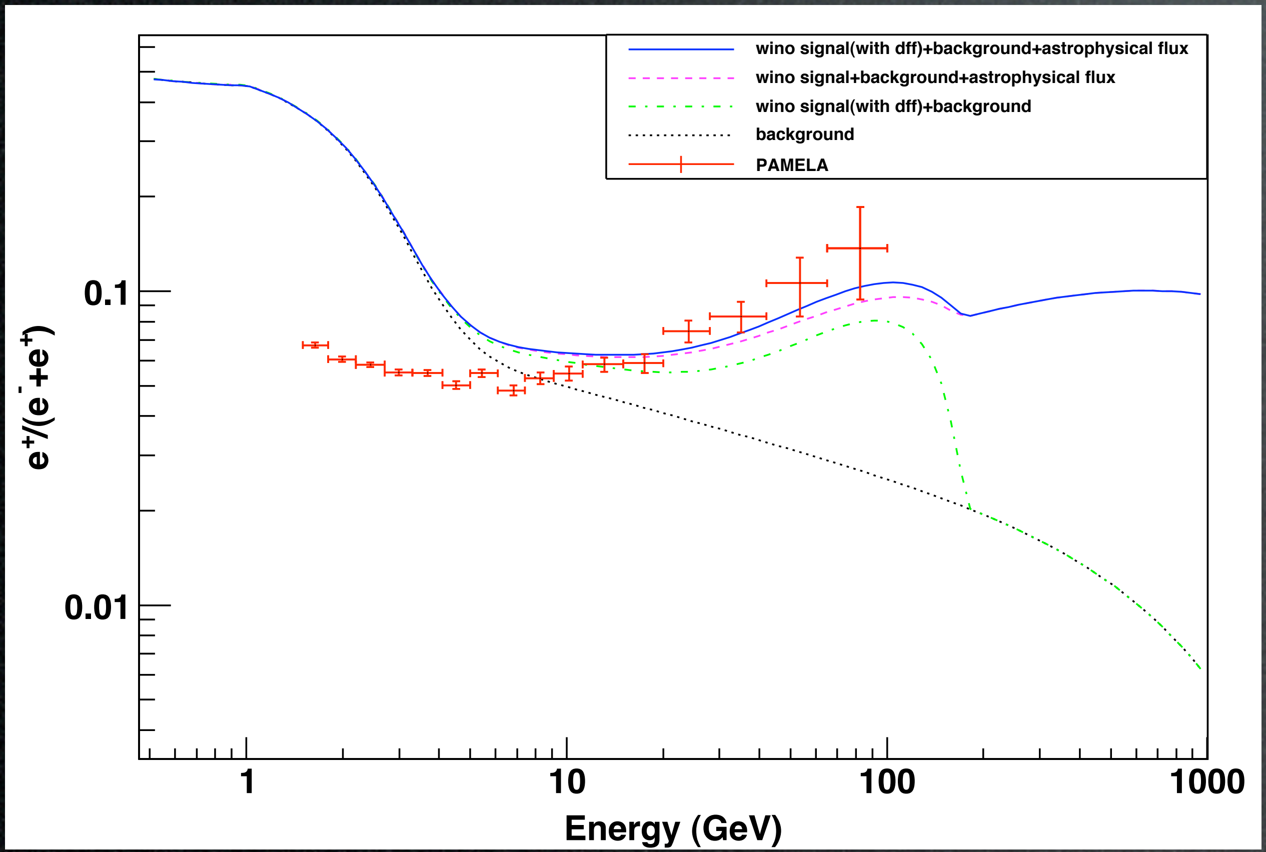
Ok, let's ***insist*** on Wino with: -mass $M_{\rm DM} = 180\,{\rm GeV}$

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

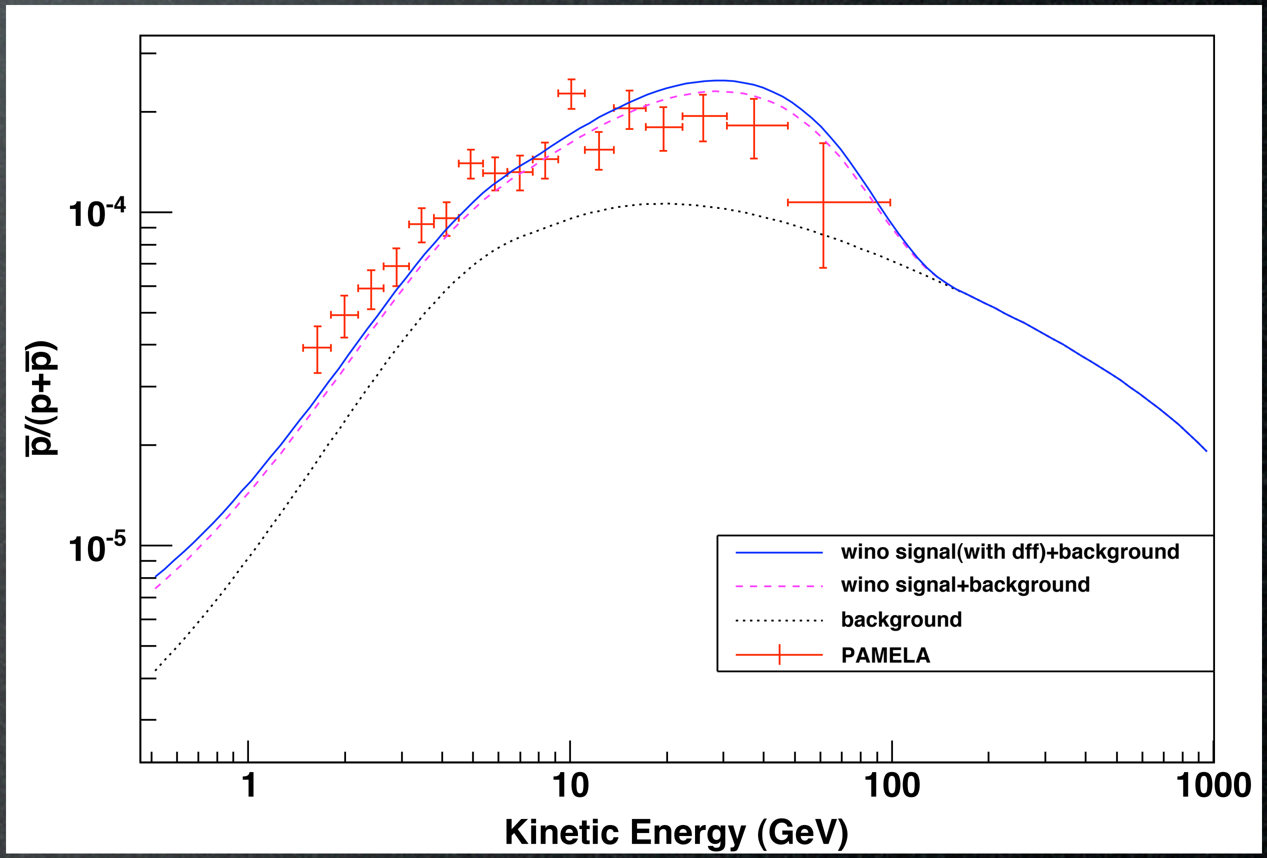
and - revise drastically the computation of the anti-proton background
- assume non-thermal production of DM
- assume other explanation for FERMI (astrophysics?)

then

Positrons:



Anti-protons:



G.Kane, R.Lu, S.Watson 0906.4765

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

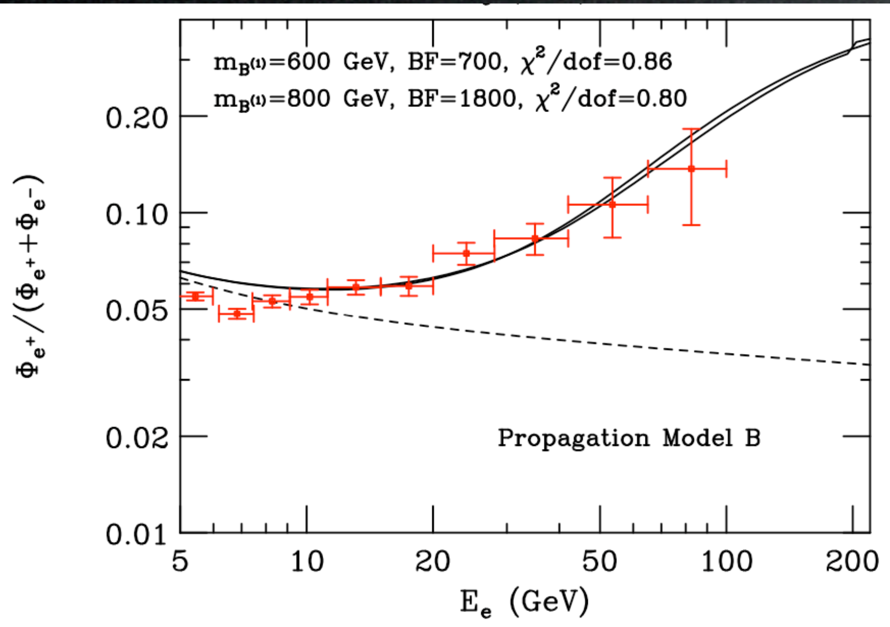
$\text{DM DM} \to q\bar{q}\,(BR = 35\%)$

Good fit with: - boost $B = 1800$

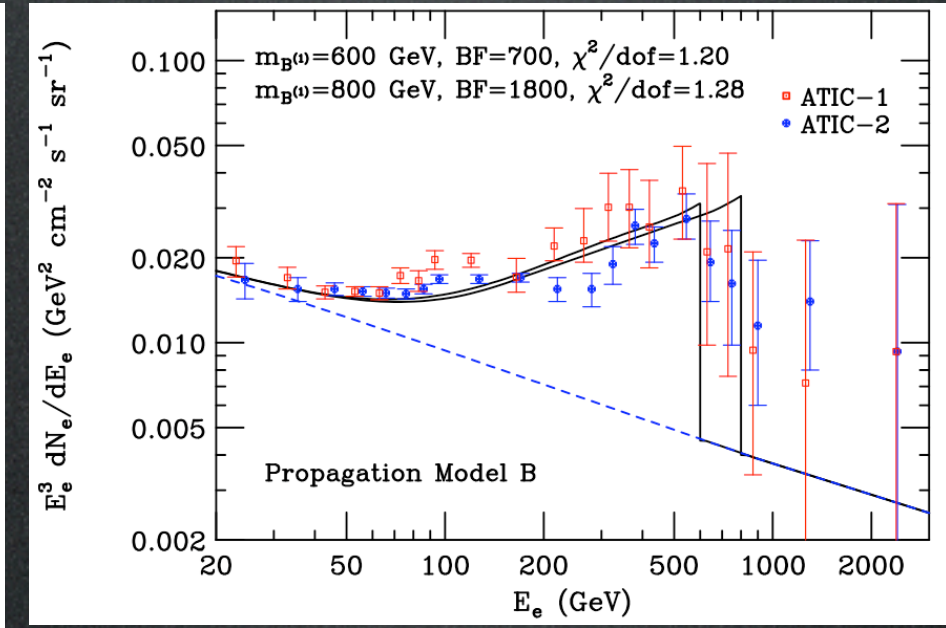
- propagation model $\text{B: } K(E_e) = 1.4\times 10^{28}\,(E_e/4\,{\rm GeV})^{0.43}\,{\rm cm}^2/{\rm s}, \text{L=1 kpc}$

very large energy loss with very small L

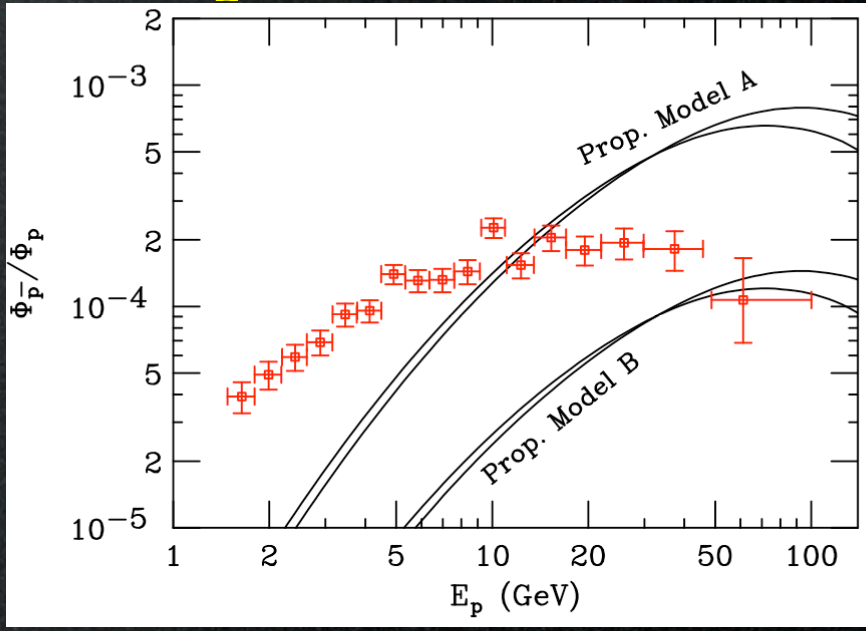
Positrons:



Electrons + Positrons:



Anti-protons:



D.Hooper, K.Zurek 0902.0593

[where are the secondaries?]

Enhancement

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

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

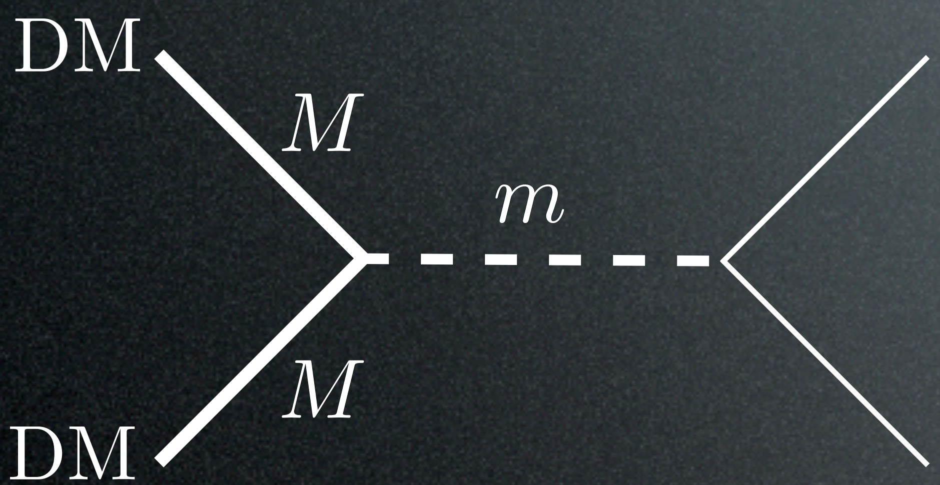
	at freeze-out	***today***
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$

+ (Wimponium)

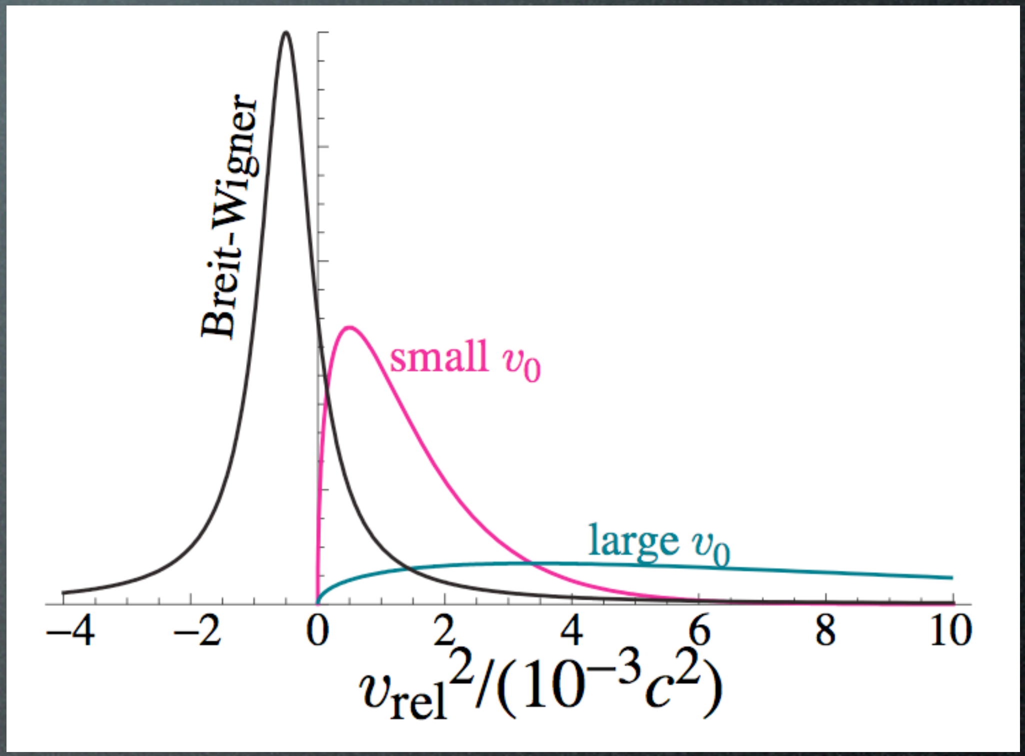
Resonance Enhancement

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

DM annihilation via a narrow resonance just below the threshold:



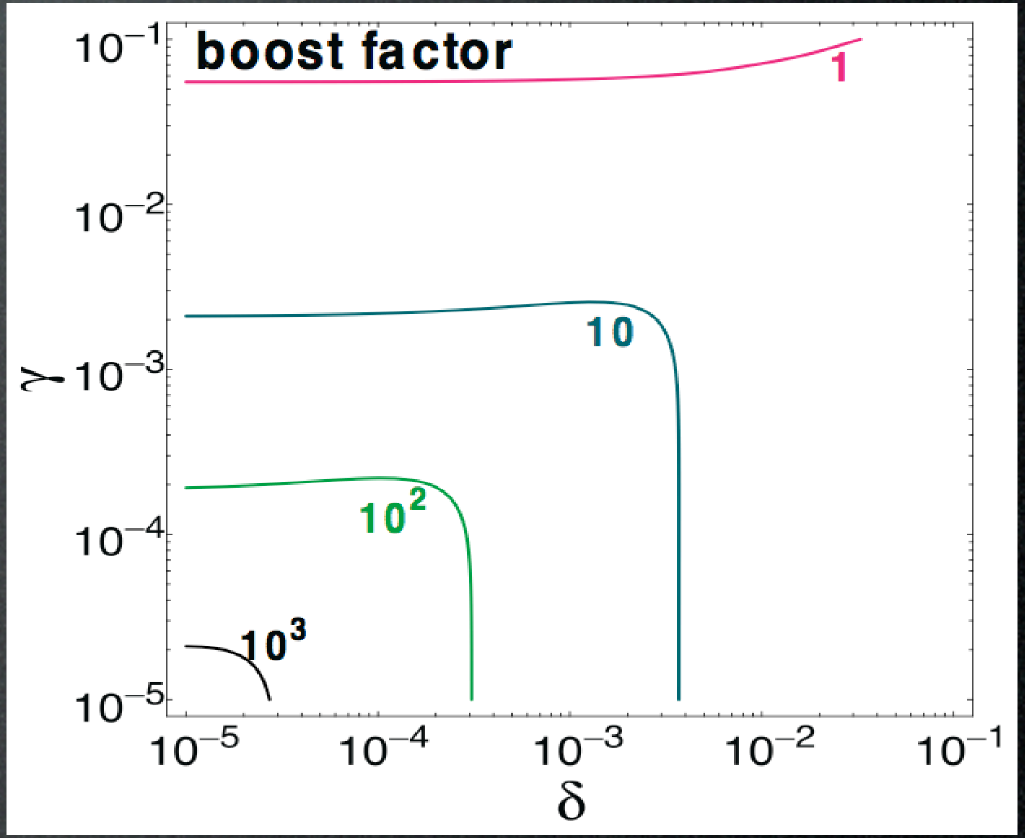
$m \lesssim 2M$



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

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

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



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

Sommerfeld Enhancement

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

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

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

Cirelli, Tamburini, Strumia 0706.4071

Arkani-Hamed et al., 0810.0713

Sommerfeld Enhancement

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

A classical analogy:

Arkani-Hamed et al. 0810.0713

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

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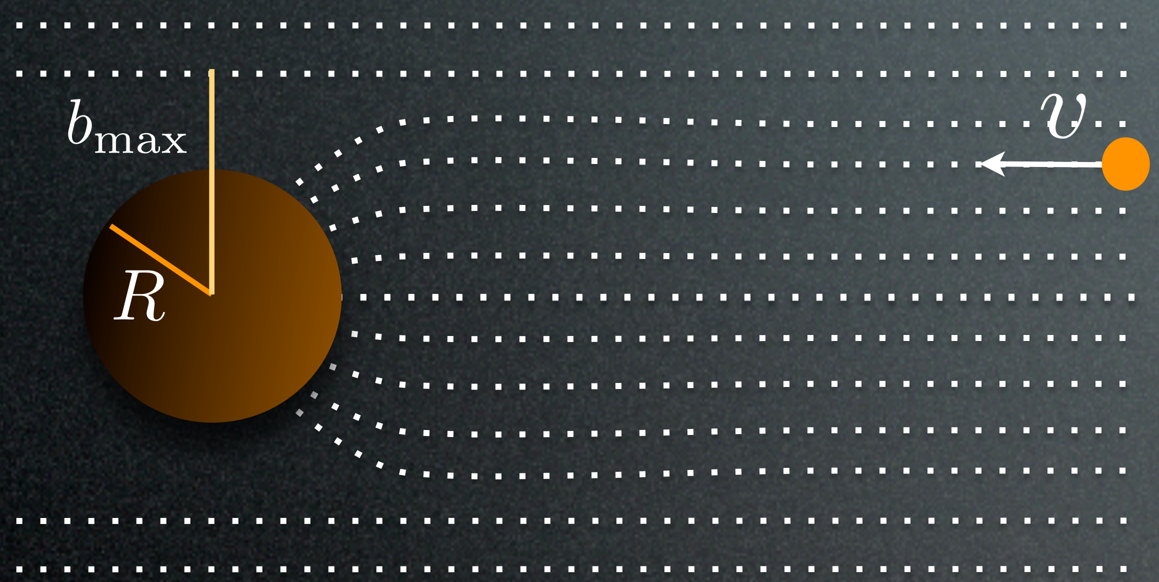
A classical analogy:

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

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

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

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

Sommerfeld Enhancement

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

Cirelli, Strumia, Tamburini 0706.4071

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

obeys (reduced) Schrödinger equation:

(V does not depend on time)

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

velocity

potential due to exchange of force carriers

At $r = 0$: annihilation

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

Sommerfeld enhancement:

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

unperturbed cross section

Sommerfeld Enhancement

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

Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071

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

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

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

Sommerfeld Enhancement

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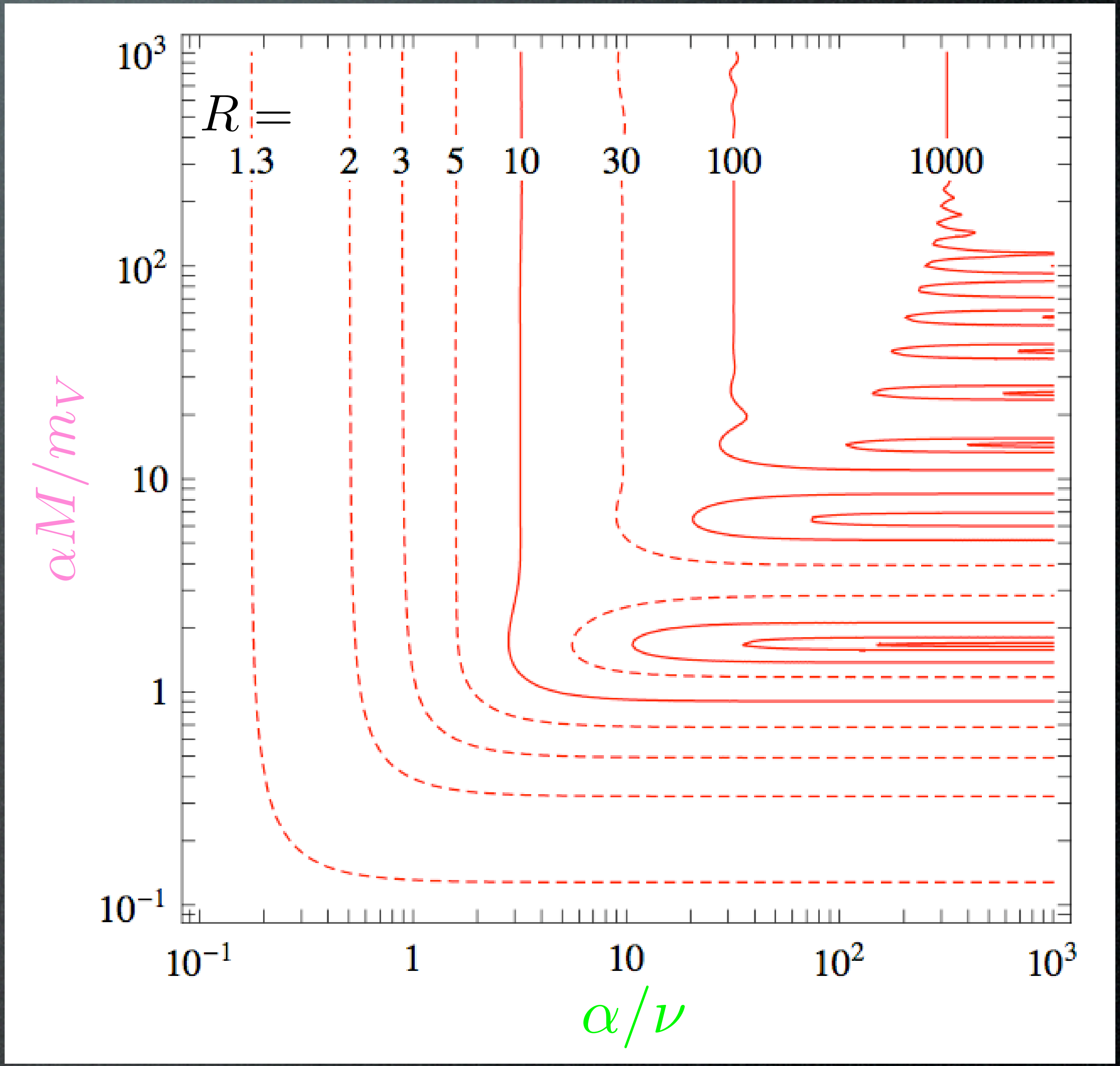
R depends on: α/ν and $\alpha M/m_V$



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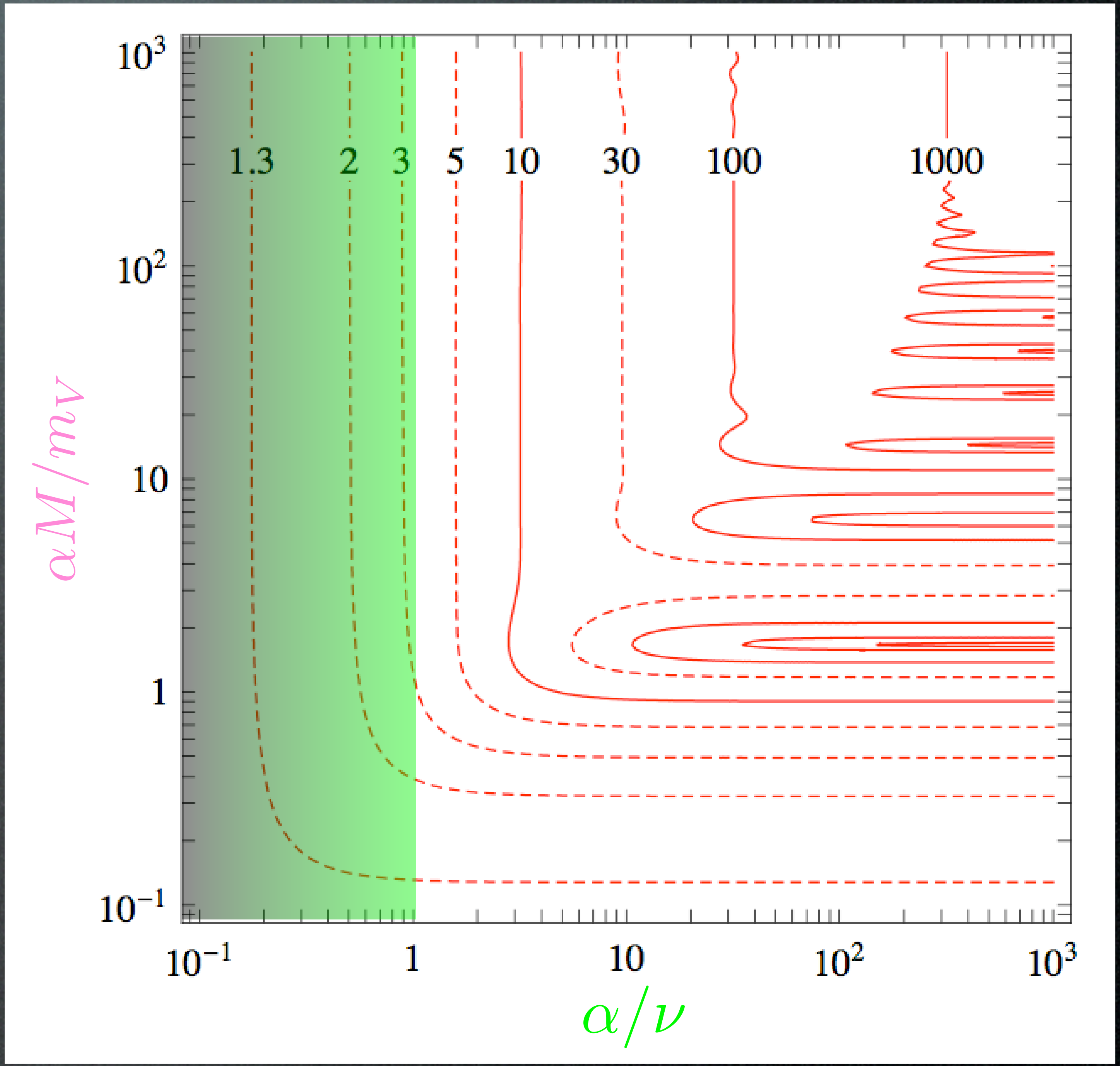
parameters are: α, ν, m_V, M

R depends on: α/ν and $\alpha M/m_V$

The effect is relevant for:

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



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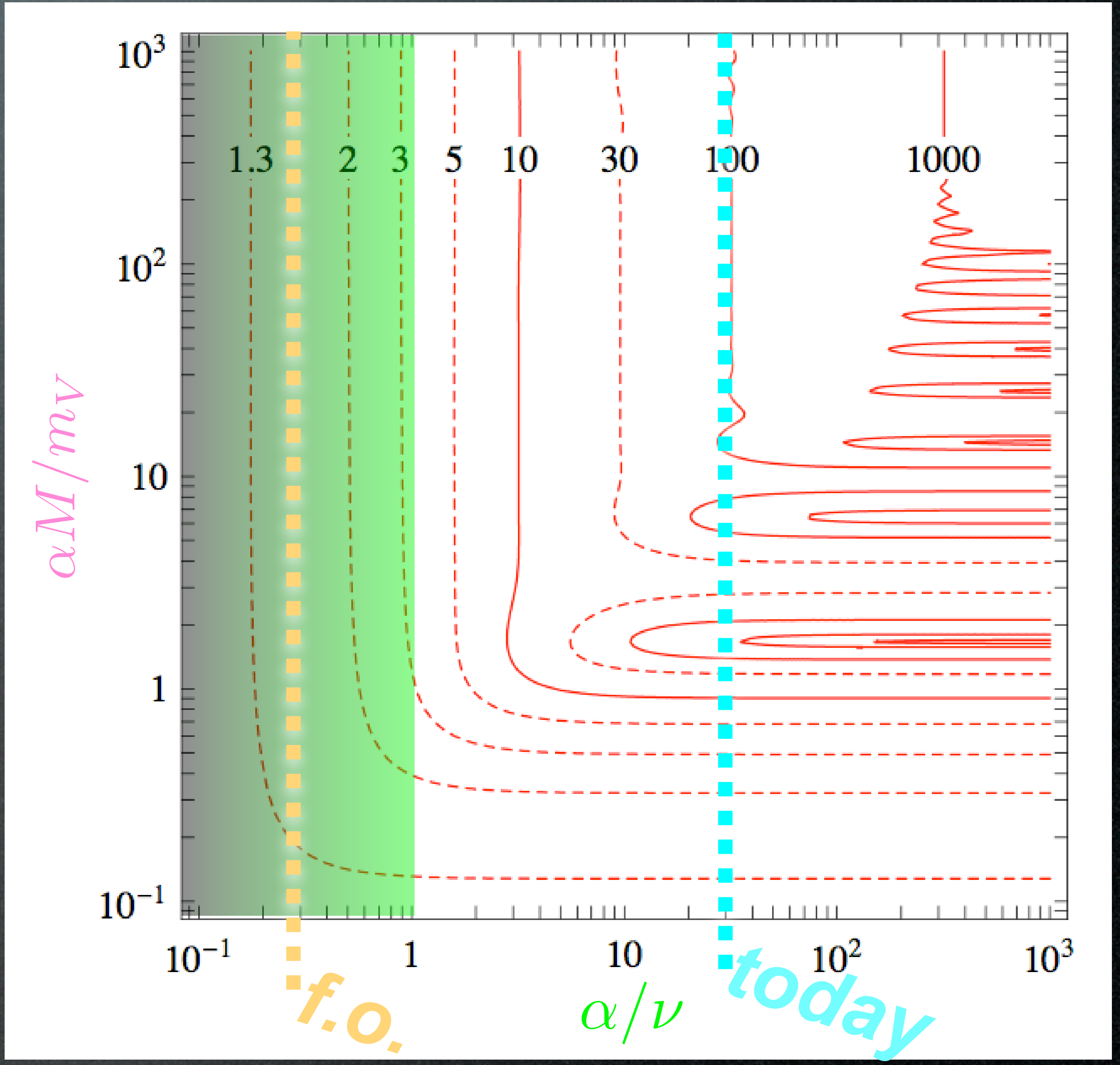

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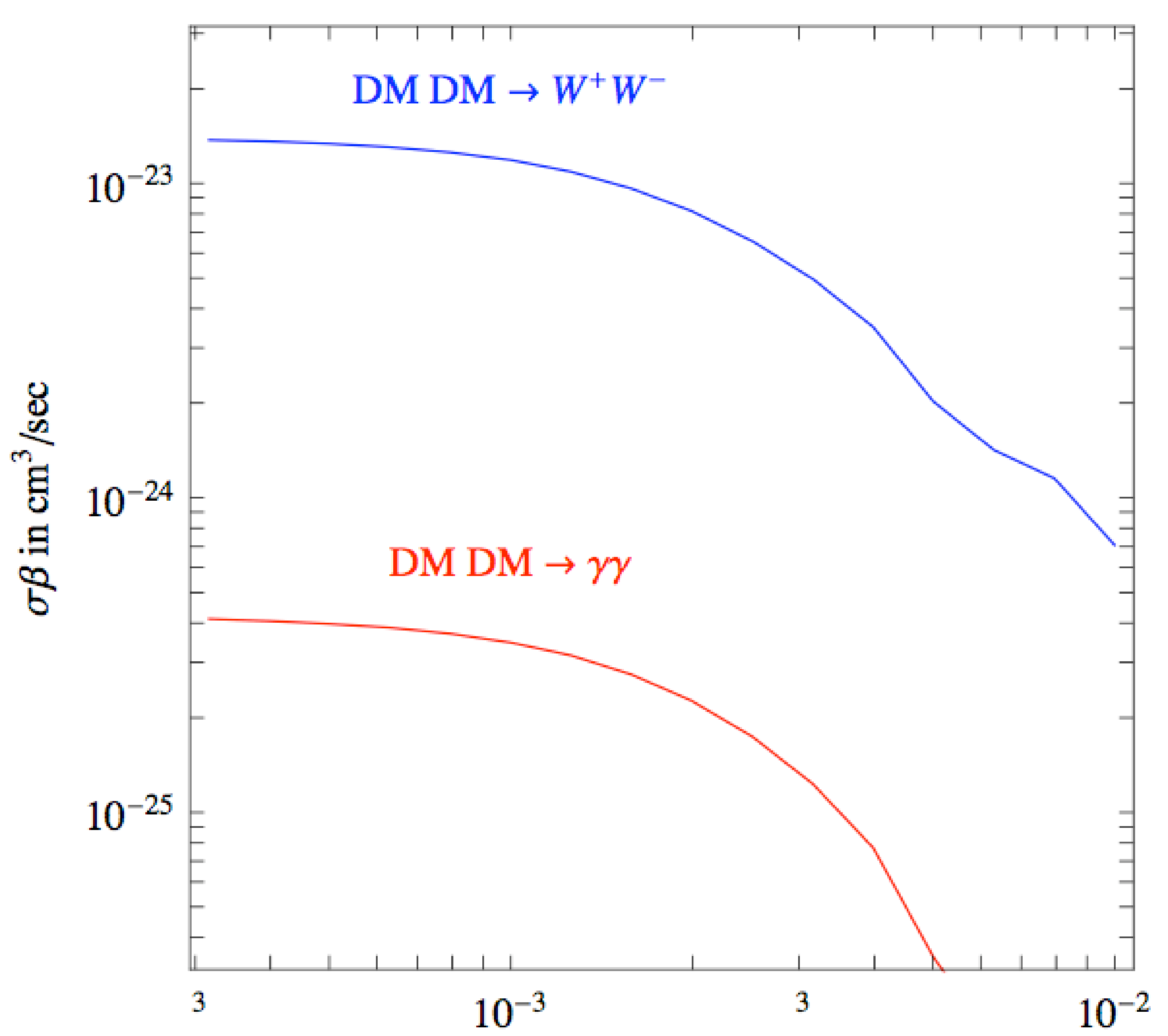
Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378



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

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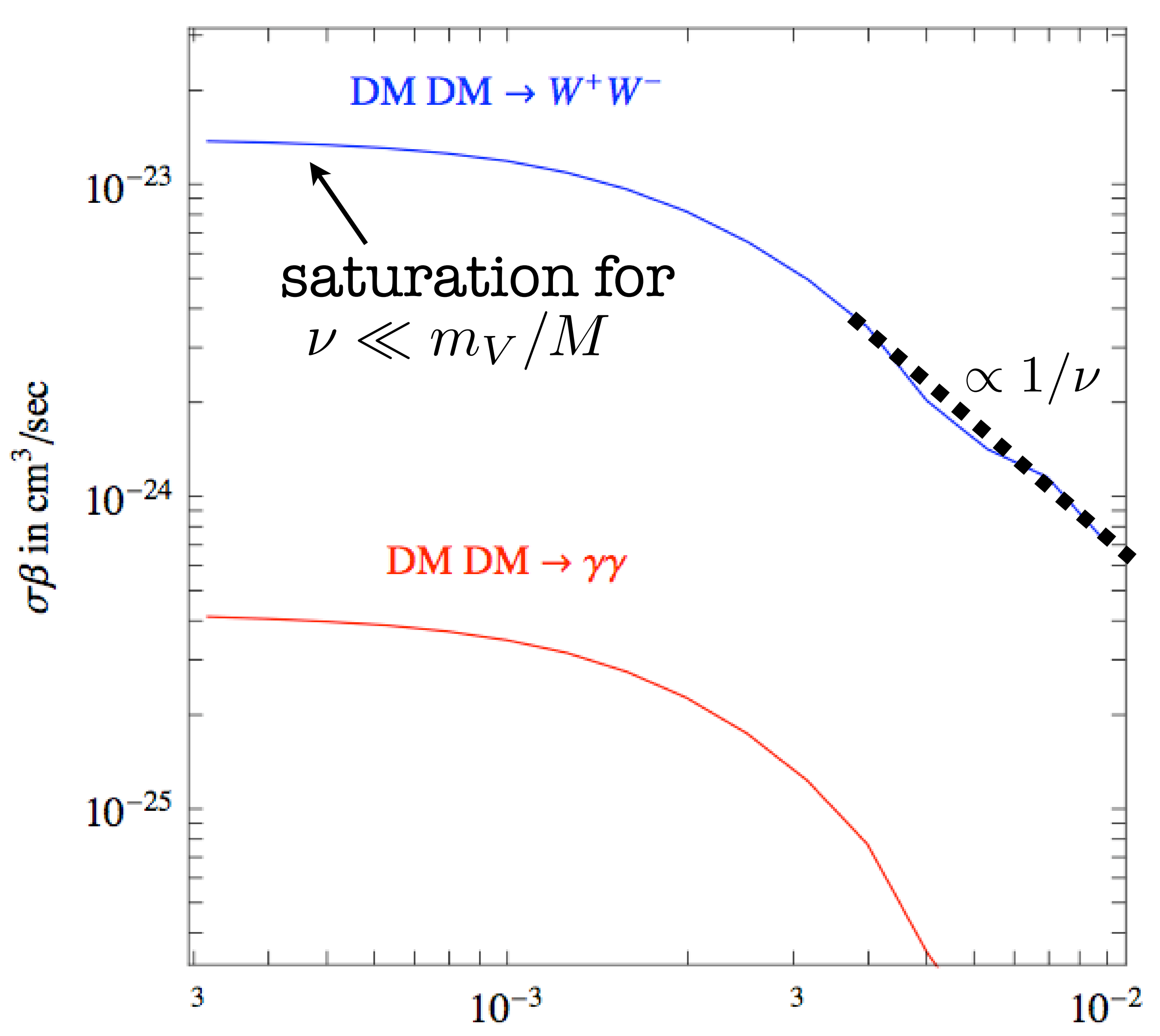

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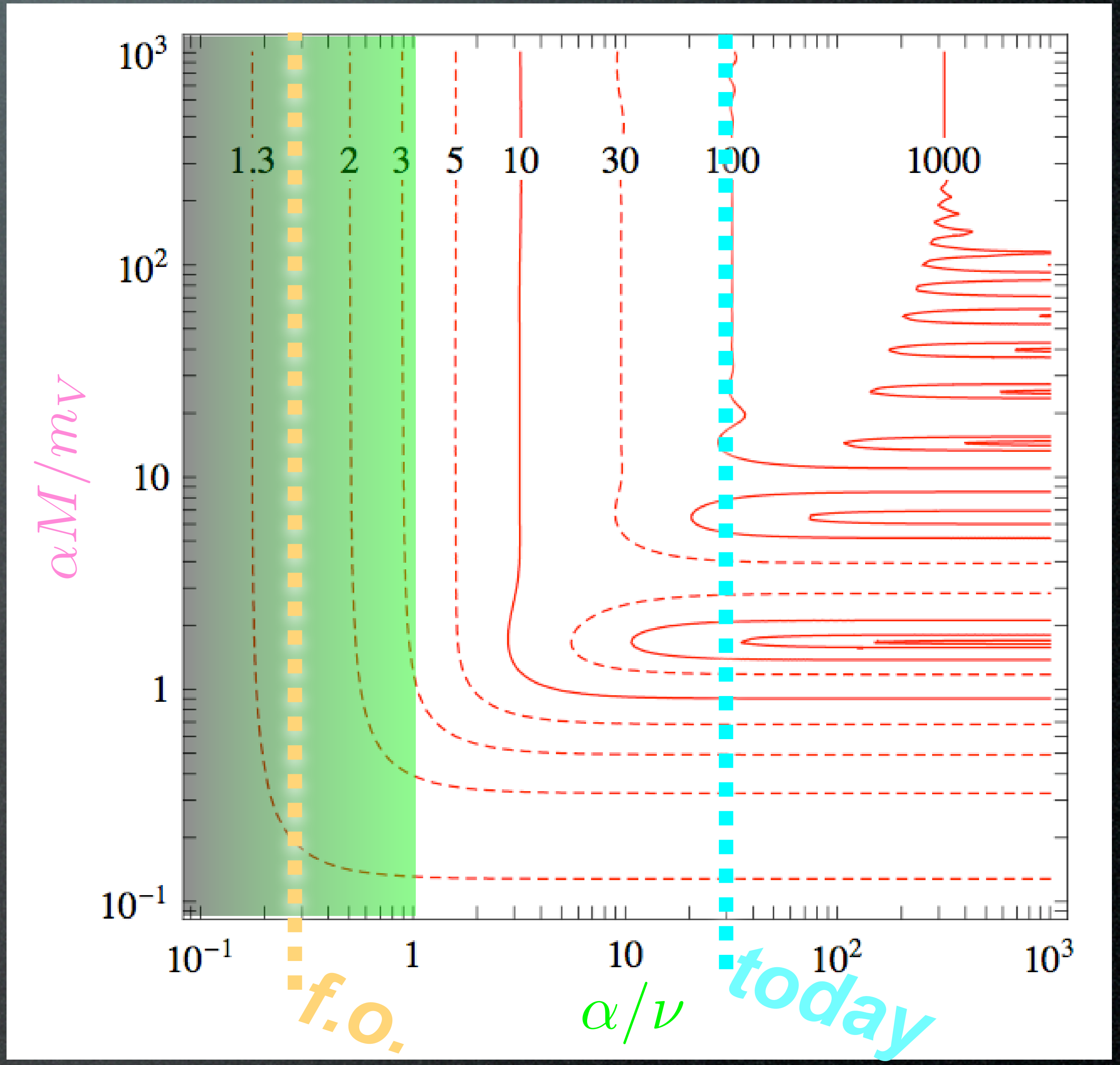

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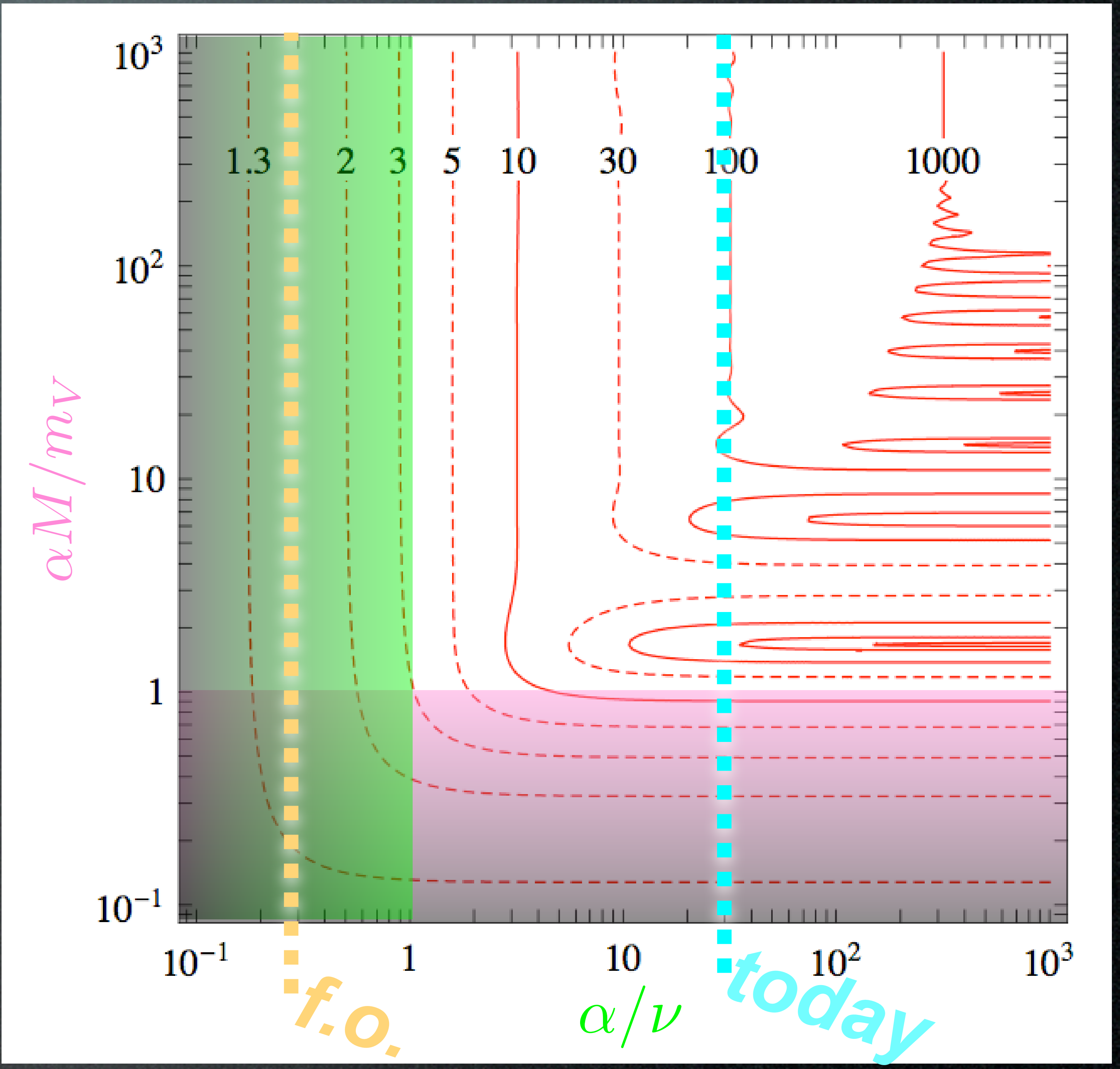
$\alpha M/m_V \gtrsim 1$ i.e. long range forces

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

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



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Cirelli, Strumia, Tamburini 0706.4071

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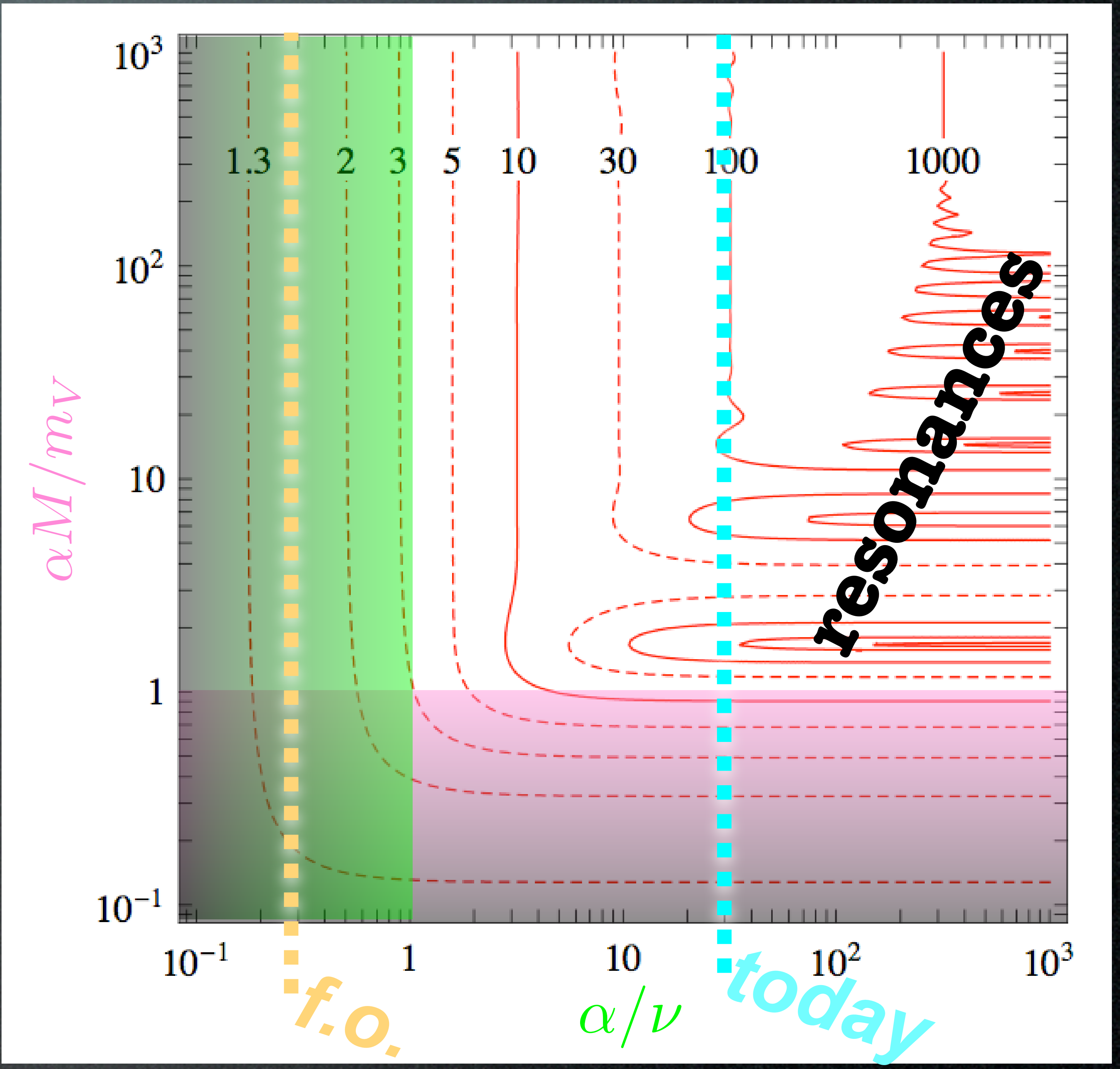

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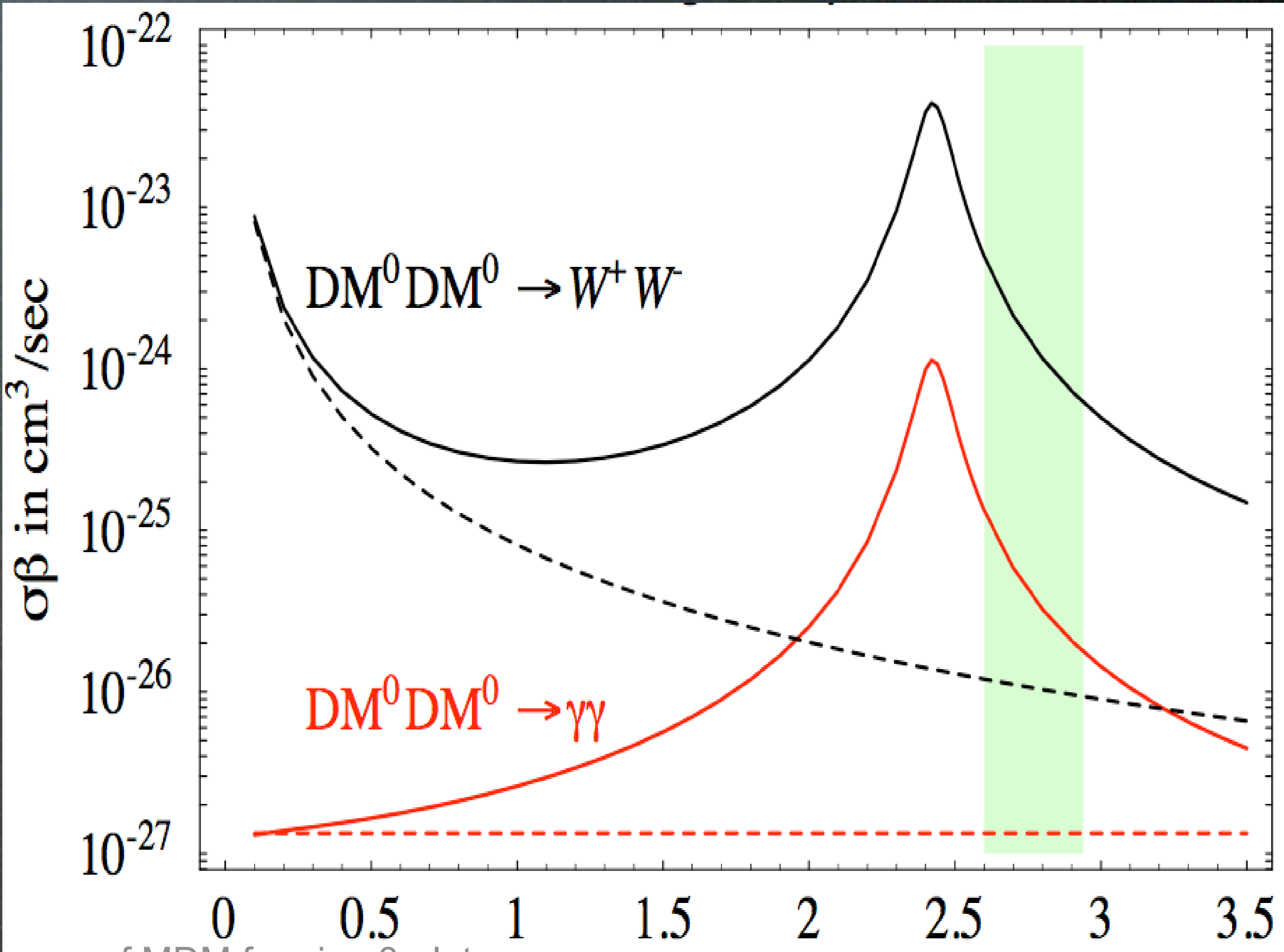


case of MDM fermion 3-plet:
M=2.5 TeV, W,Z exchange

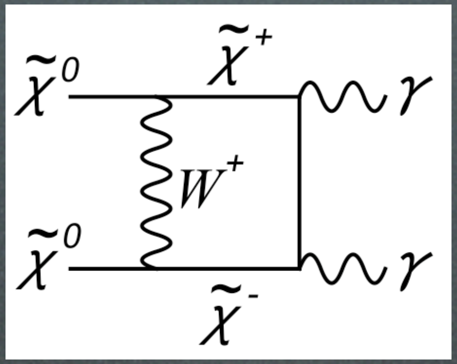
Sommerfeld Enhancement

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

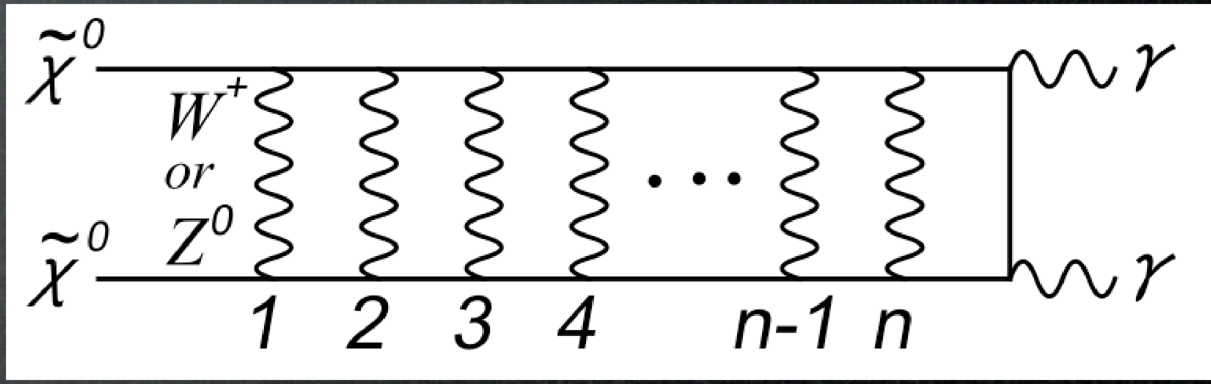
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



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



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

Sommerfeld Enhancement

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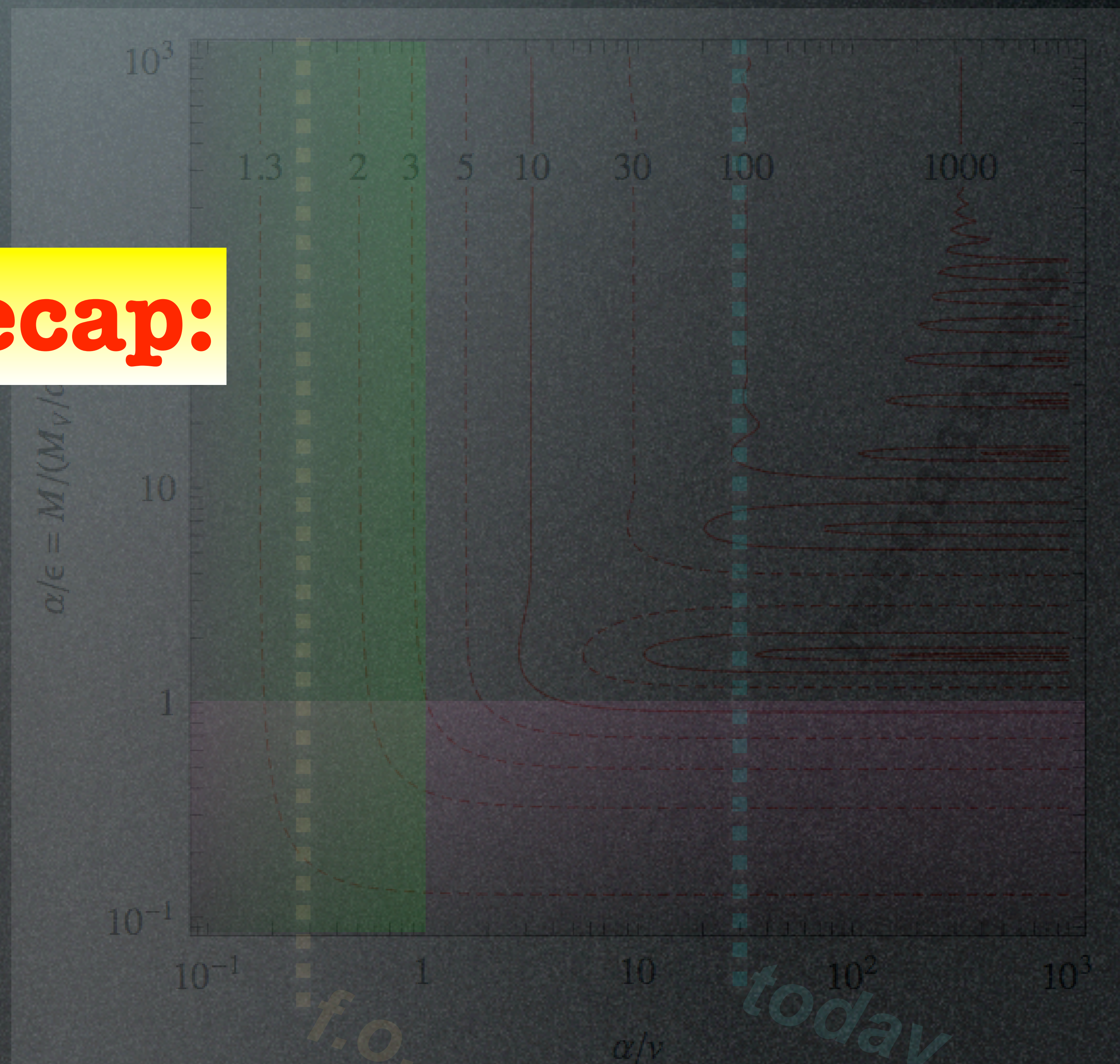
Recap:

Cirelli, Strumia, Tamburini 0706.4071



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

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:
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  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 - [illegible] G.Kribs, 0810.5557: [illegible] D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - K.Ishiwata, S.Matsumoto, T.[illegible] 0811.02[illegible] DM [illegible] 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 enhance[illegible] J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures [illegible] M.Pospelov, [illegible] 2.0522: 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.Richa[illegible] Hidden Fermion DM decays - D.Hooper, A.Stebbins, K.Z[illegible] 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.Thale[illegible] Cascade annihilations (li[illegible] non-abelian new boso[illegible]) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, [illegible] 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

The "Theory of DM"

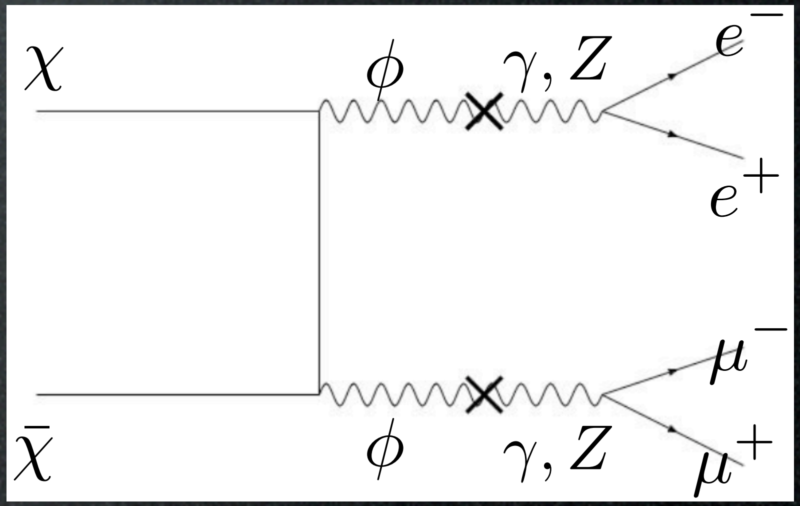
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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:
$\alpha M/m_V \gtrsim 1$ fulfilled

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



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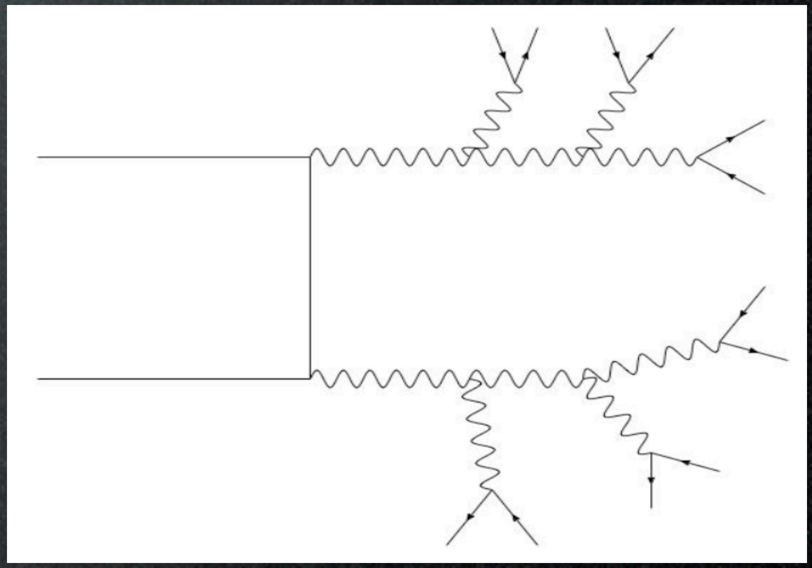
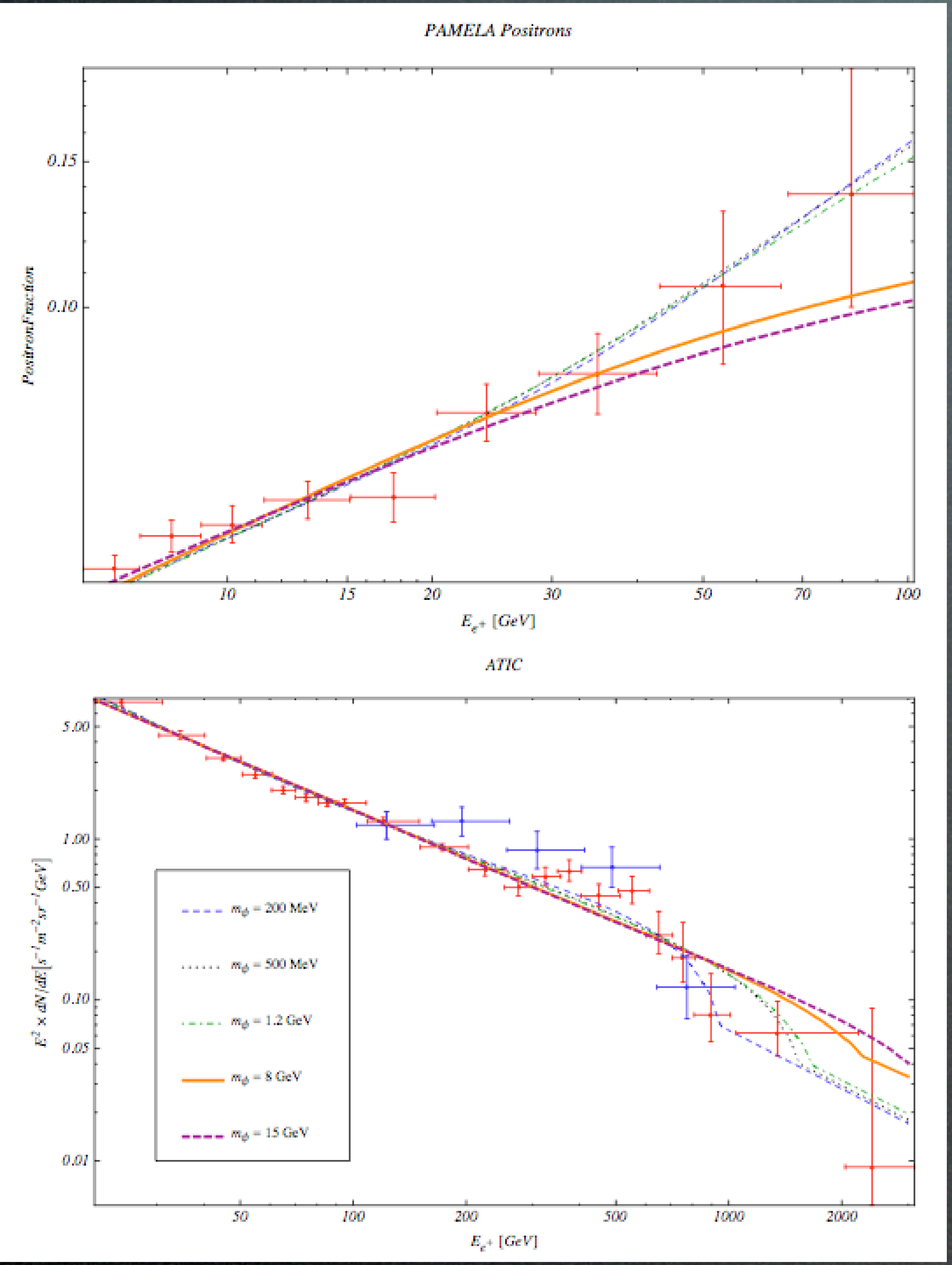


Extras:

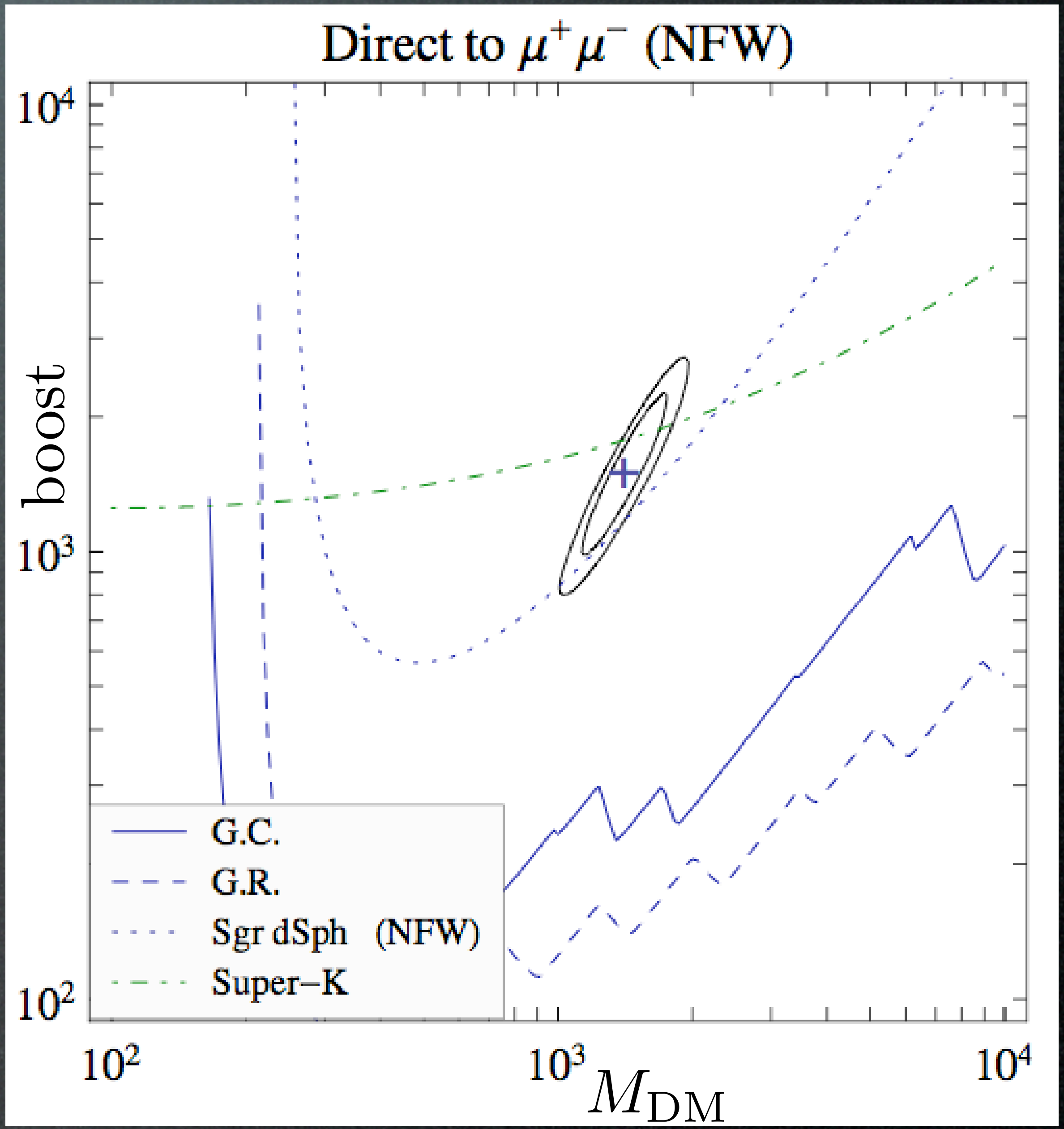
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The "Theory of DM"

Phenomenology:



Meade, Papucci, Volanski
0901.2925



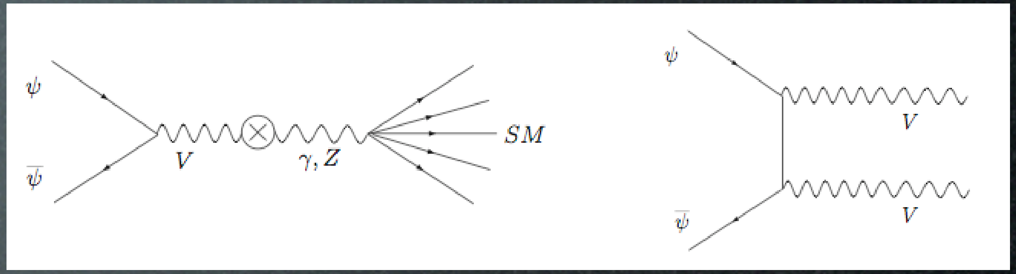
Mardon, Nomura, Stolarski,
Thaler 0901.2926

Variations

(selected)

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

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



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

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

  Bai, Han 0811.0387

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

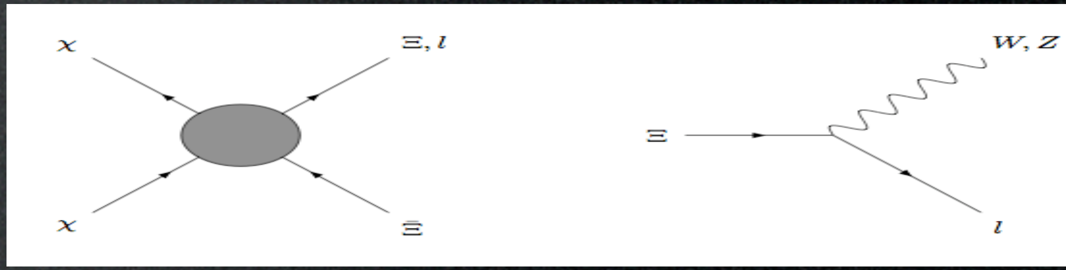
  Park, Shu 0901.0720

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

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

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

  Phalen, Pierce, Weiner 0901.3165



- ......

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 - [illegible] 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 - [illegible] 0812.0[illegible]: 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 - C.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

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?

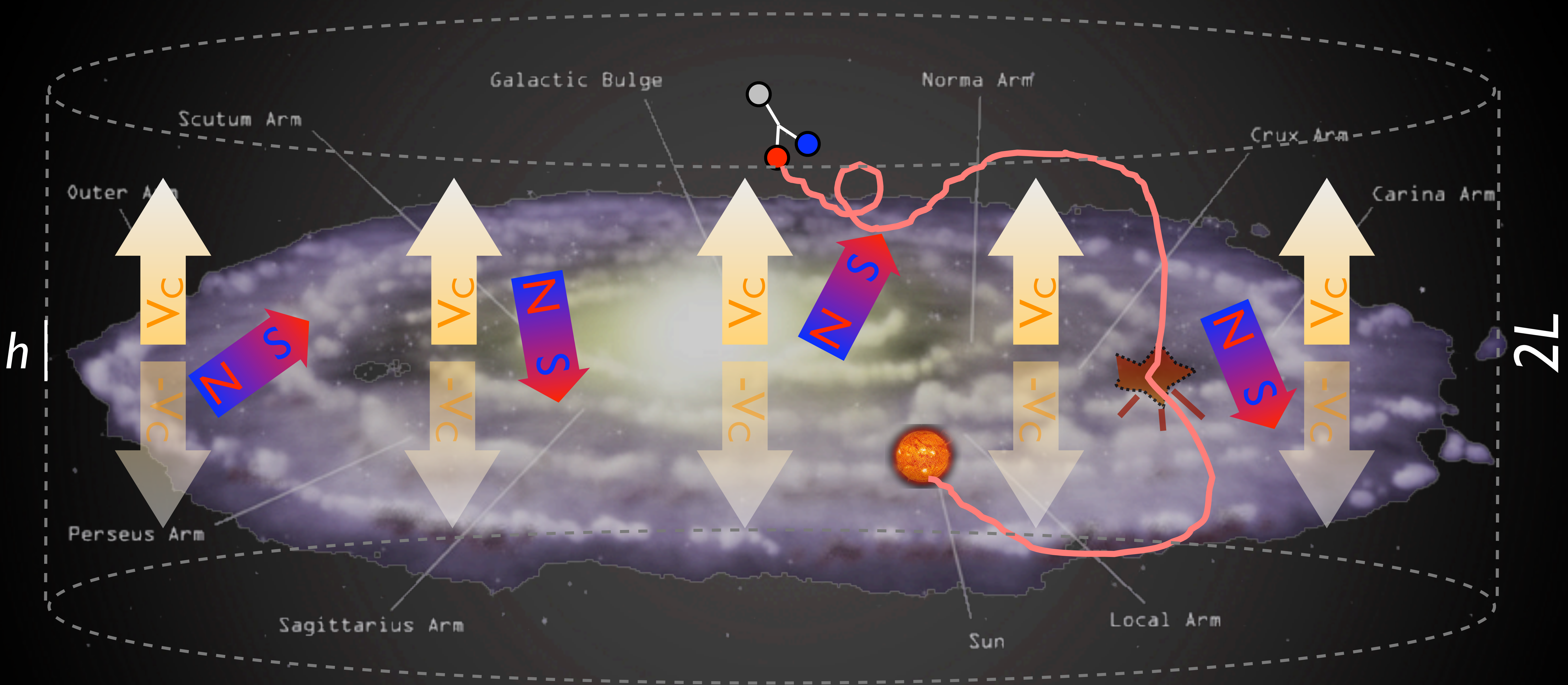
- dim 6 suppressed operator in GUT — Arvanitaki, Dimopoulos et al., 2008+09

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

- 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?

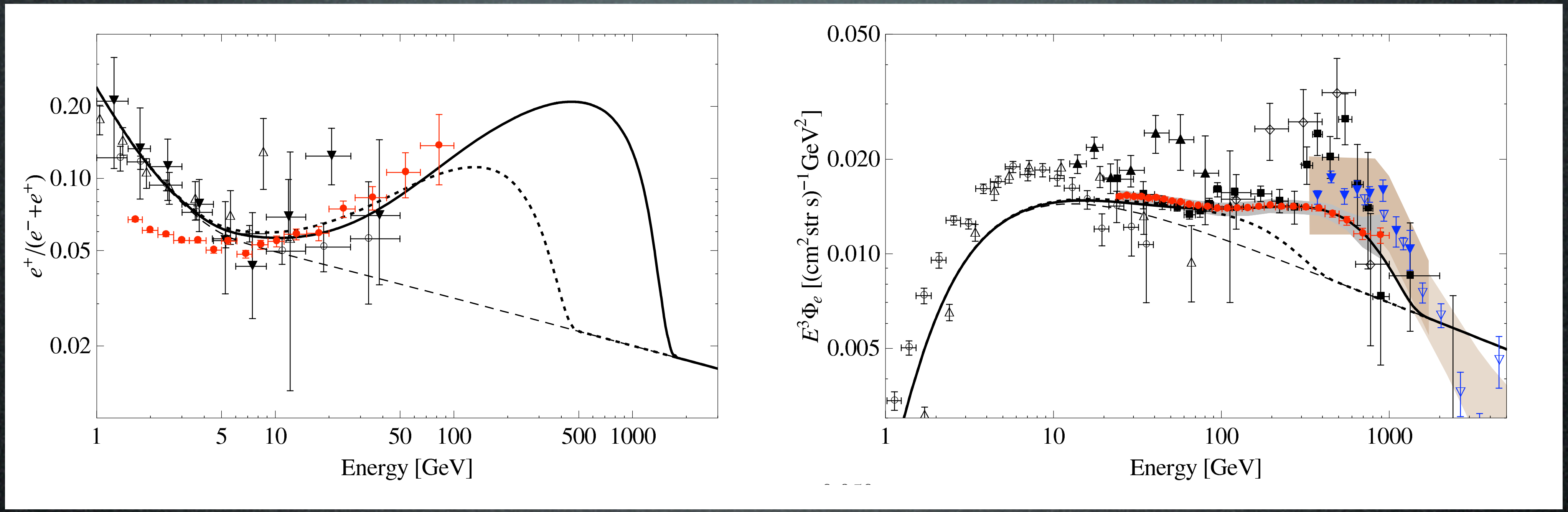
$$\text{flux} \propto n\, \Gamma_{\text{decay}}$$

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

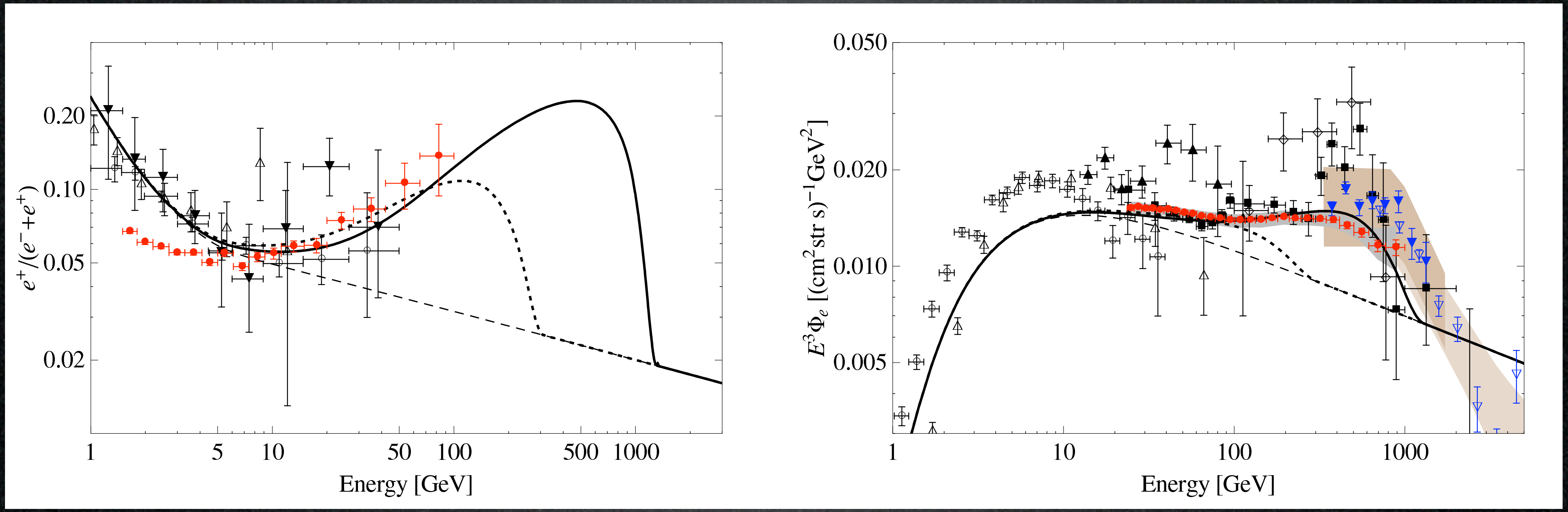
Decaying DM

Which DM spectra can fit the data?

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



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

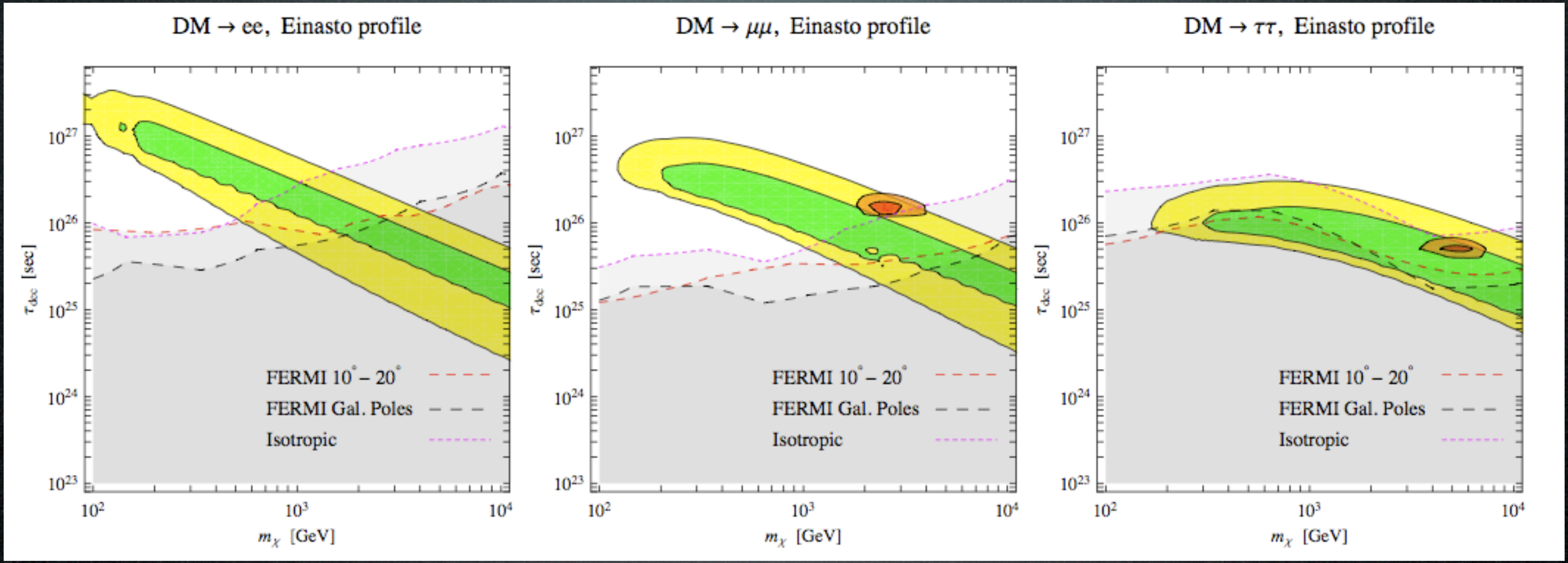


Ibarra, Tran, Weniger 2009

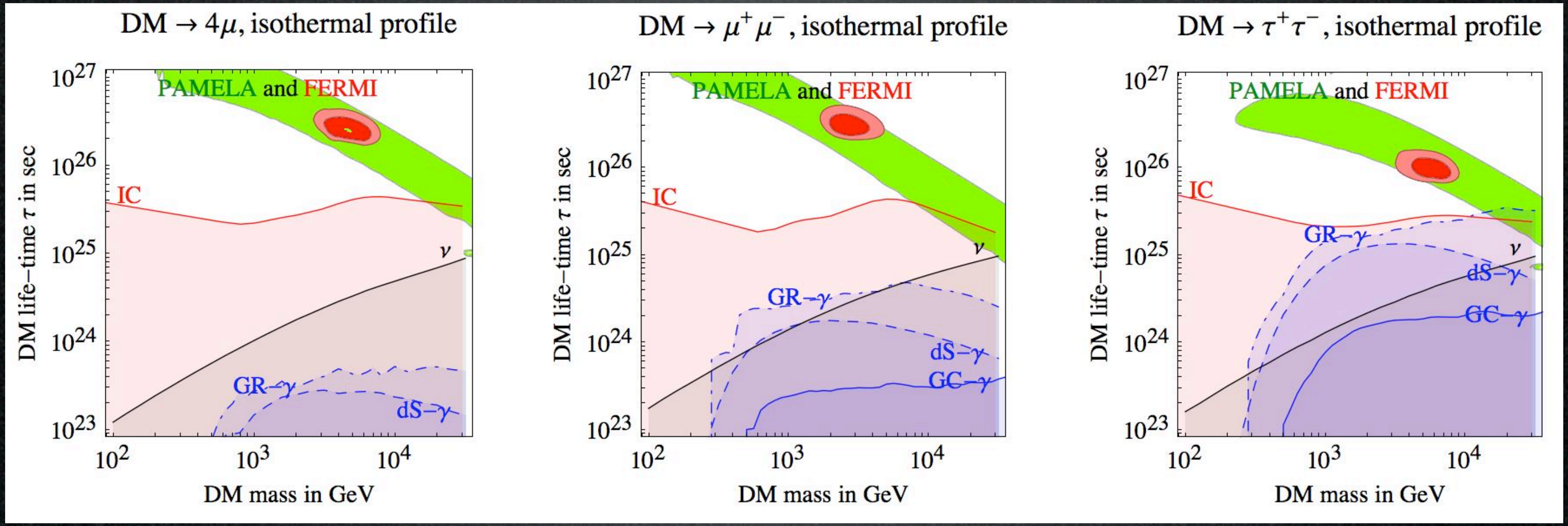
Decaying DM

Beware of gamma ray constraints

(but no radio, neutrino constraints)



Cirelli, Panci, Serpico 0912. 0663



Strumia, Papucci et al. 0905.0480

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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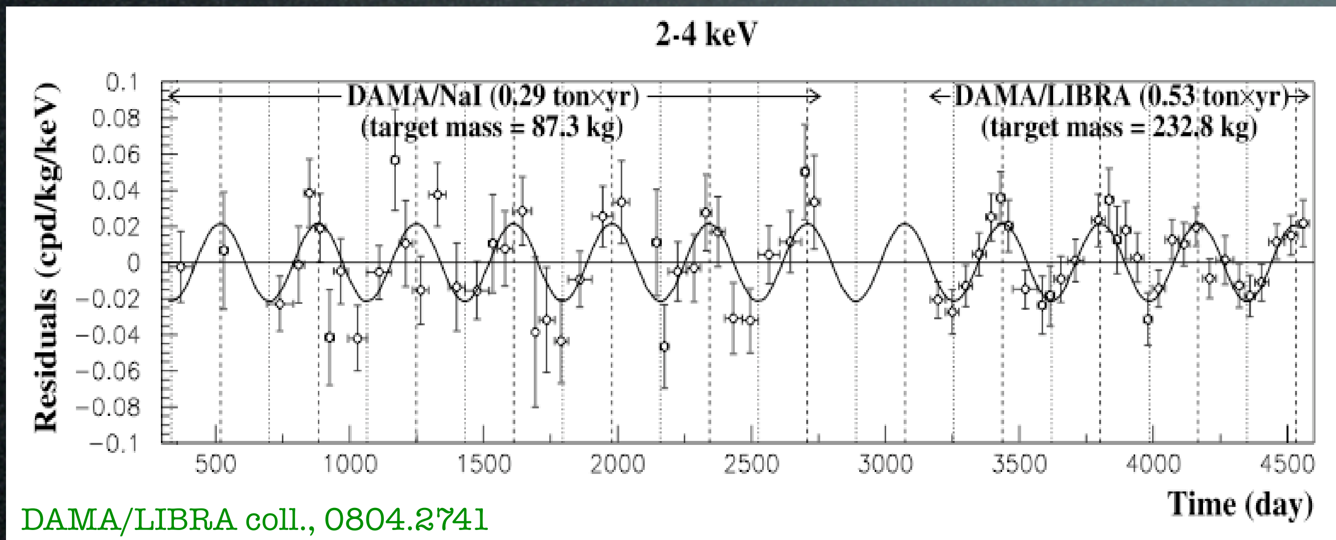
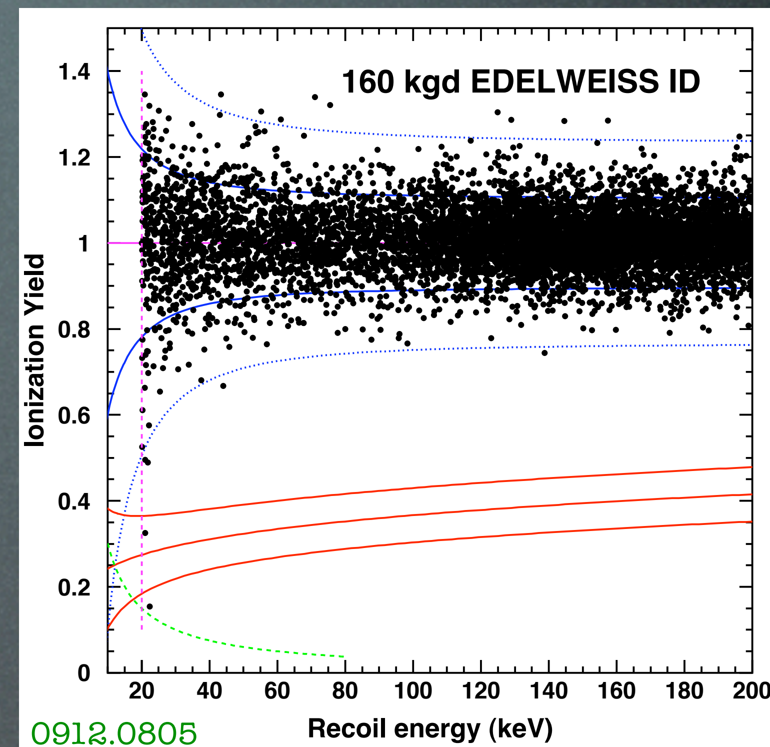
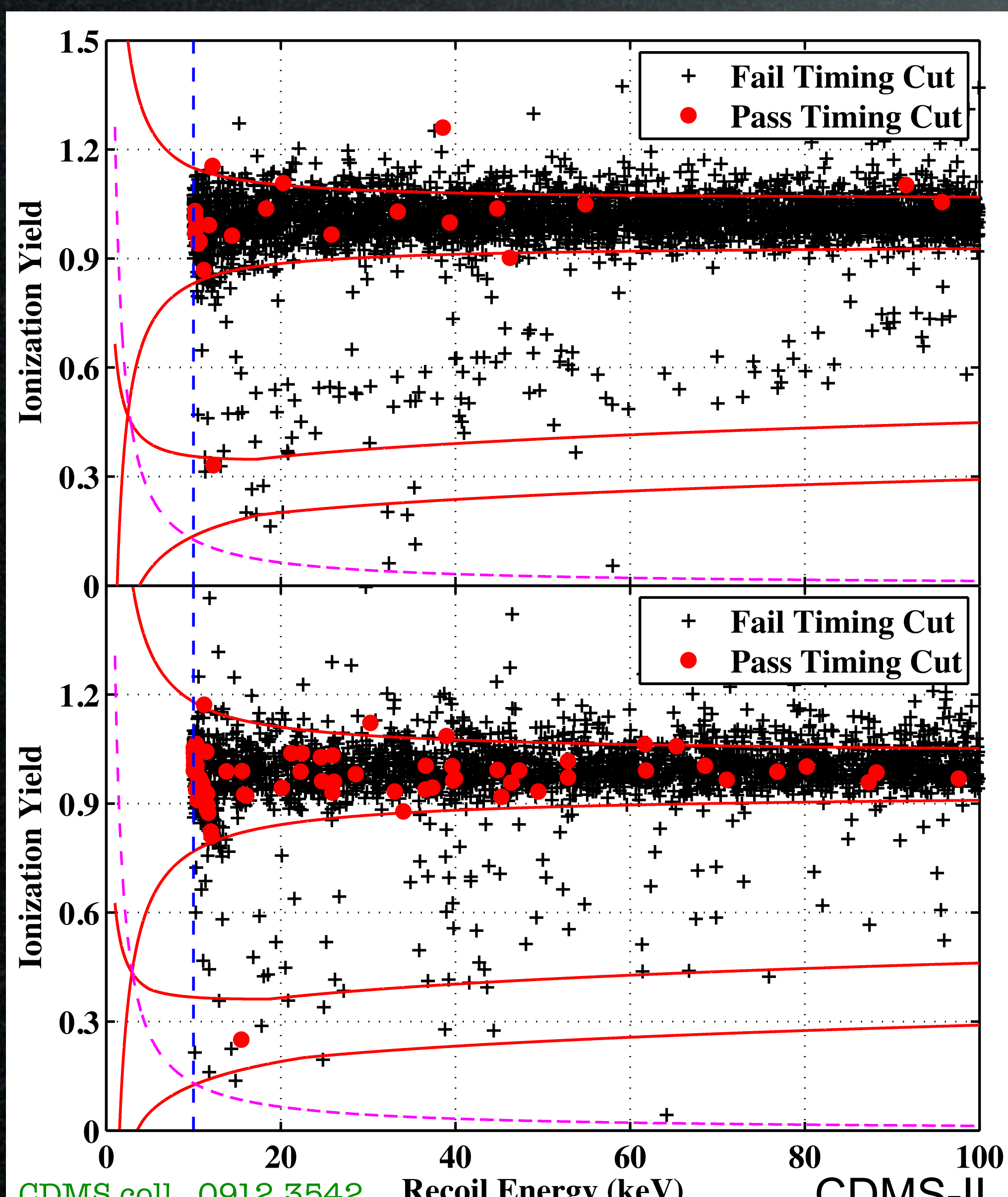
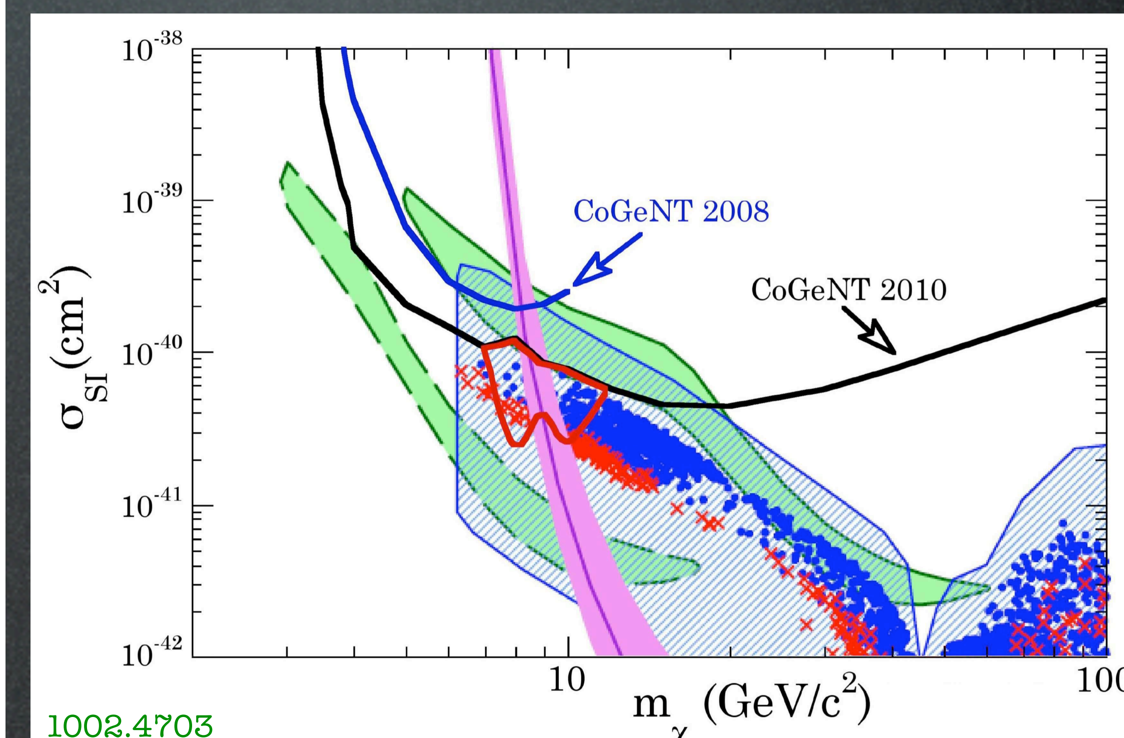
DM direct detection?









We lack a satisfactorily 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?

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Because the data (PAMELA, ATIC, HESS, FERMI, (CDMS?)...) point to a “weird” DM so theorists try to reinvent the field:

- DM is very heavy (or very light?)
- annihilates into leptons and not anti-protons
- huge cross section (boost? Sommerfeld?)
- must not produce too many gammas

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Hints.
And open-mindedness.

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Did we find DM in CR???

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Did we find DM in CR???

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

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

$$
\begin{tikzcd}[column sep=large]
 & \text{huge } \sigma_{\rm ann} v \\
\text{Dark Matter annihilations} \arrow[ur] \arrow[dr] & \\
 & \text{ordinary, thermal } \sigma_{\rm ann} v
\end{tikzcd}
$$

DM annihilations: the game

Dark Matter annihilations

PAMELA positrons

huge $\sigma_{\rm ann} v$

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

DM annihilations: the game

PAMELA positrons

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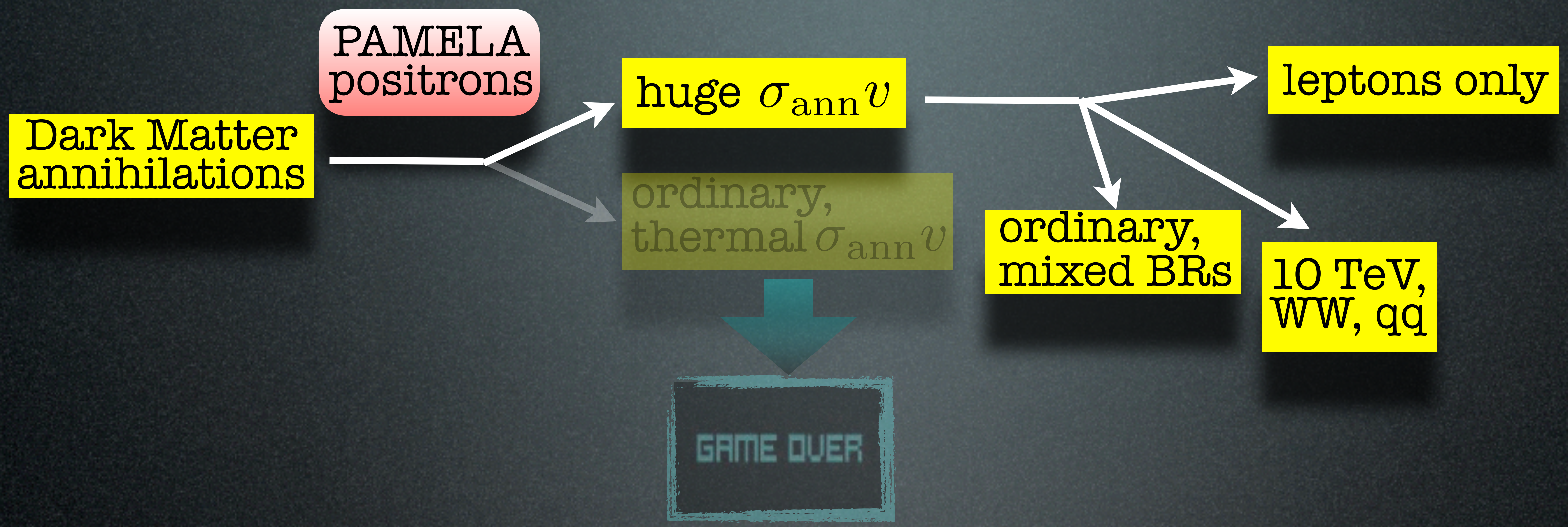

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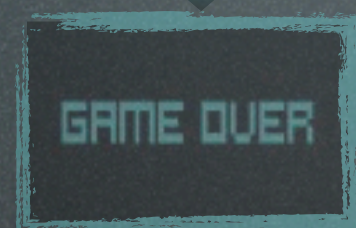


leptons only

ordinary, mixed BRs

10 TeV, WW, qq

DM annihilations: the game

Dark Matter annihilations

PAMELA positrons

huge $\sigma_{\rm ann} v$

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

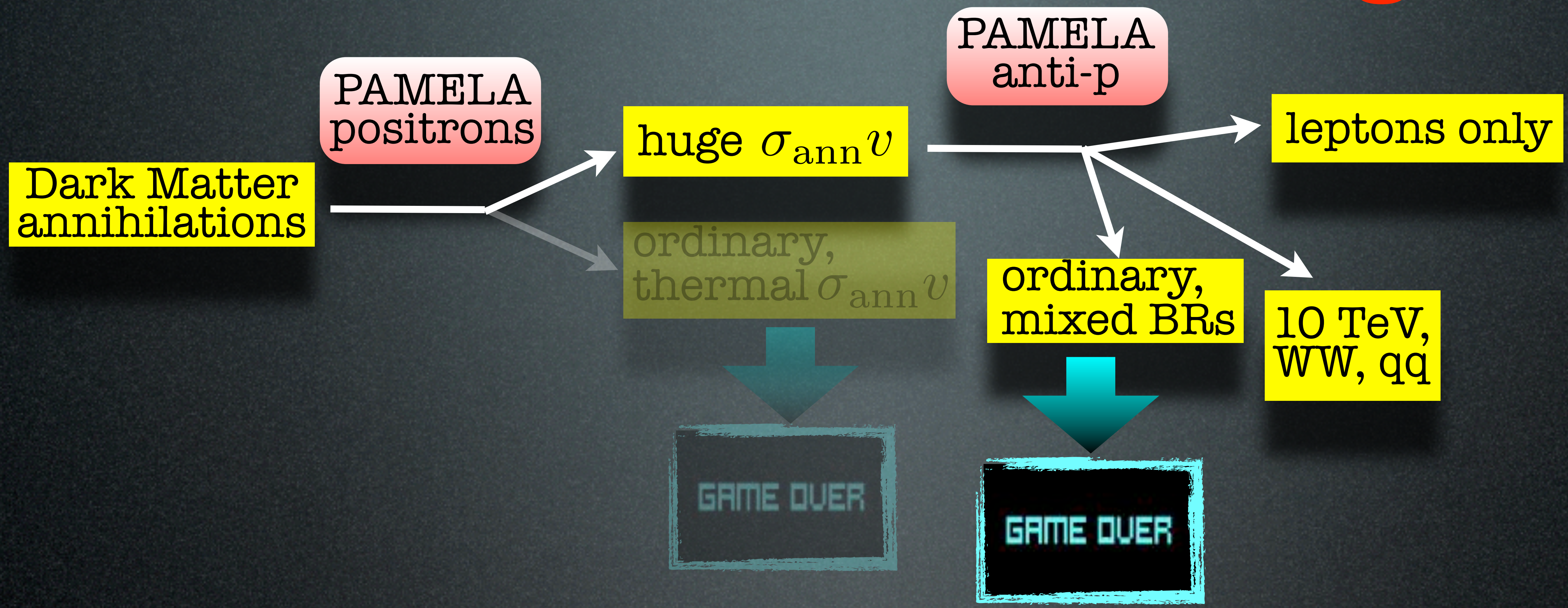
PAMELA anti-p

leptons only

ordinary, mixed BRs

10 TeV, WW, qq

DM annihilations: the game



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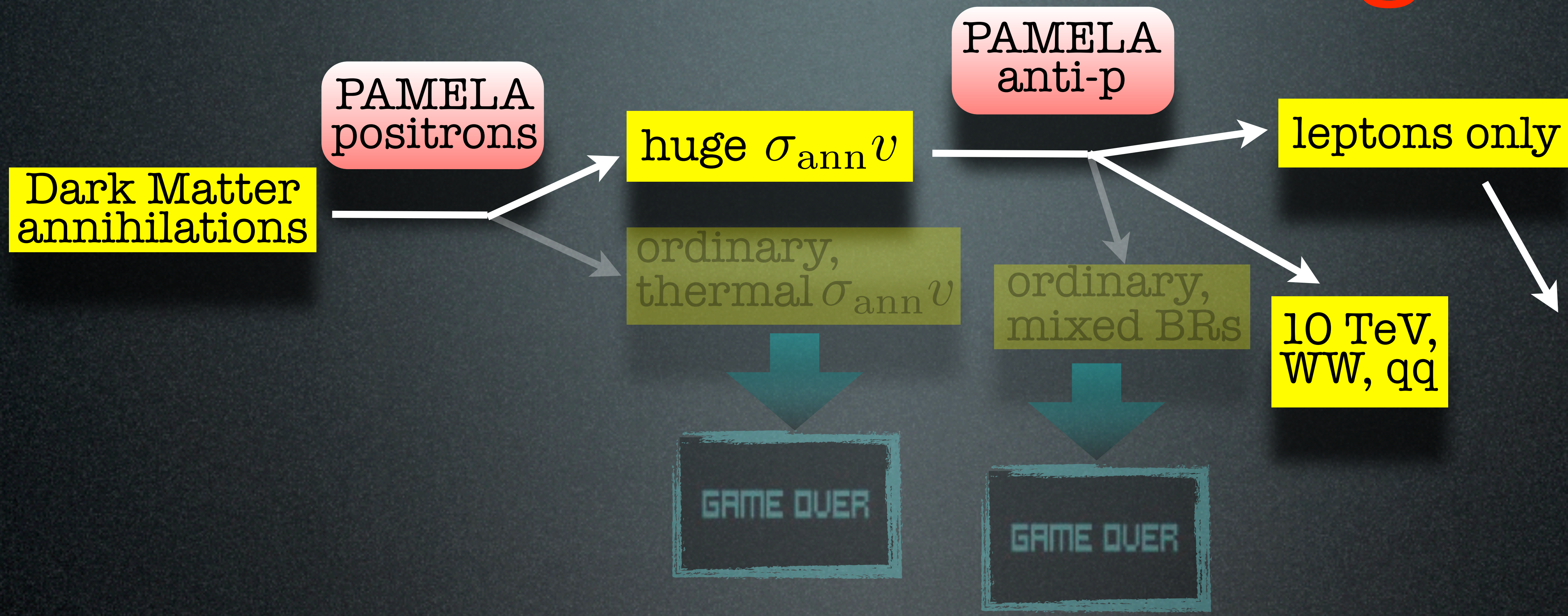

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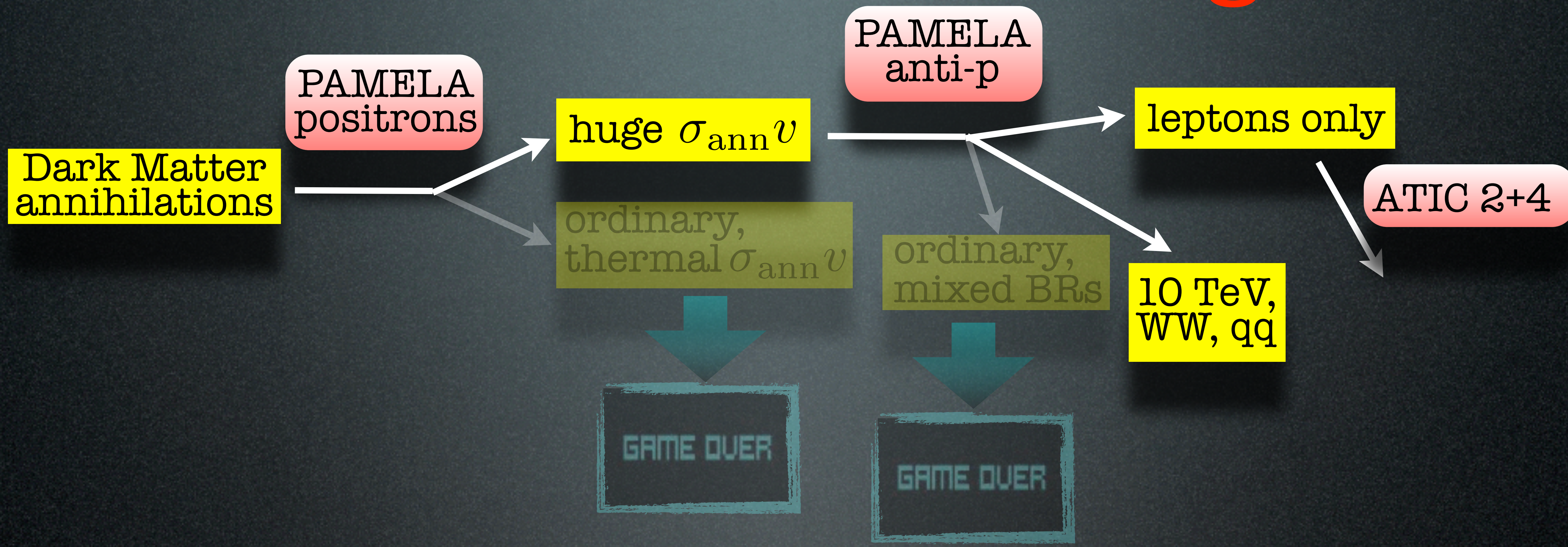
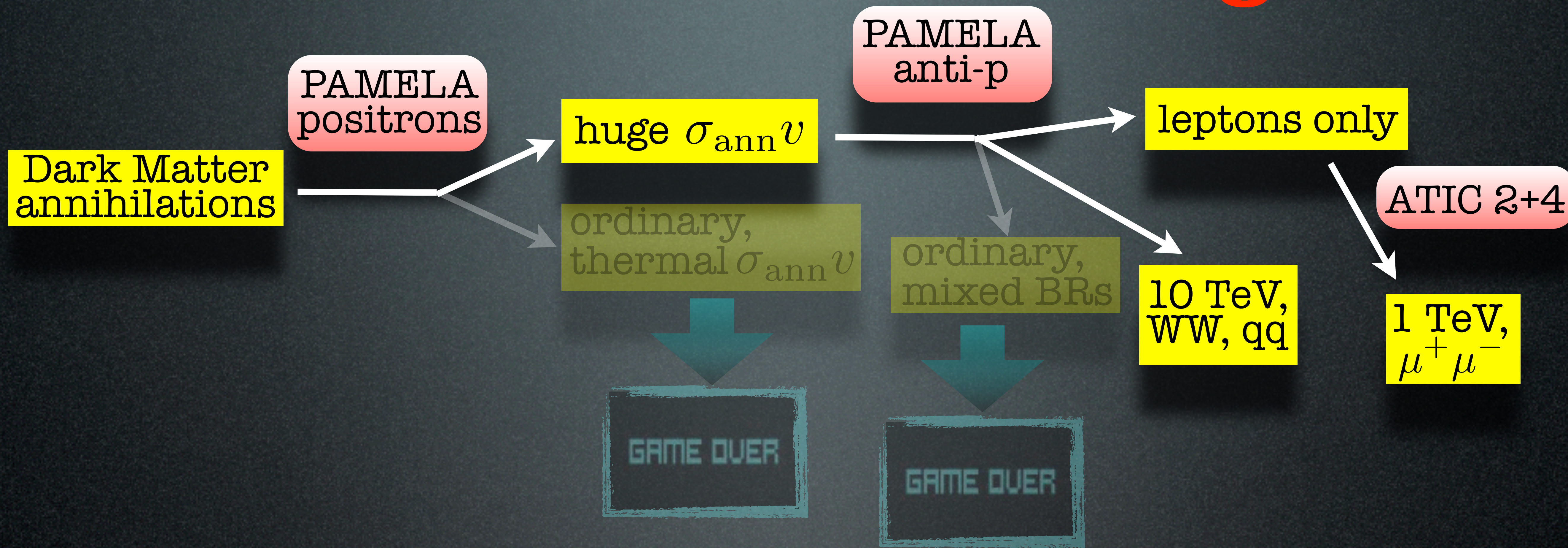


DM annihilations: the game



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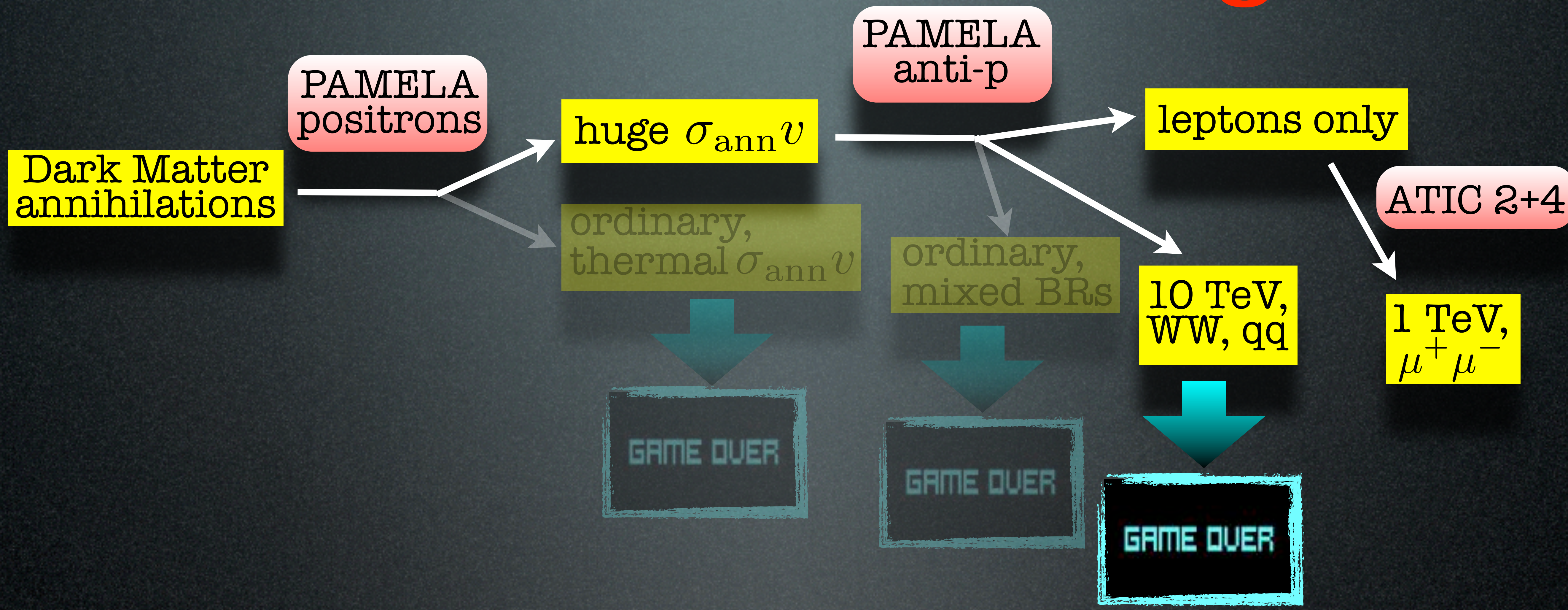

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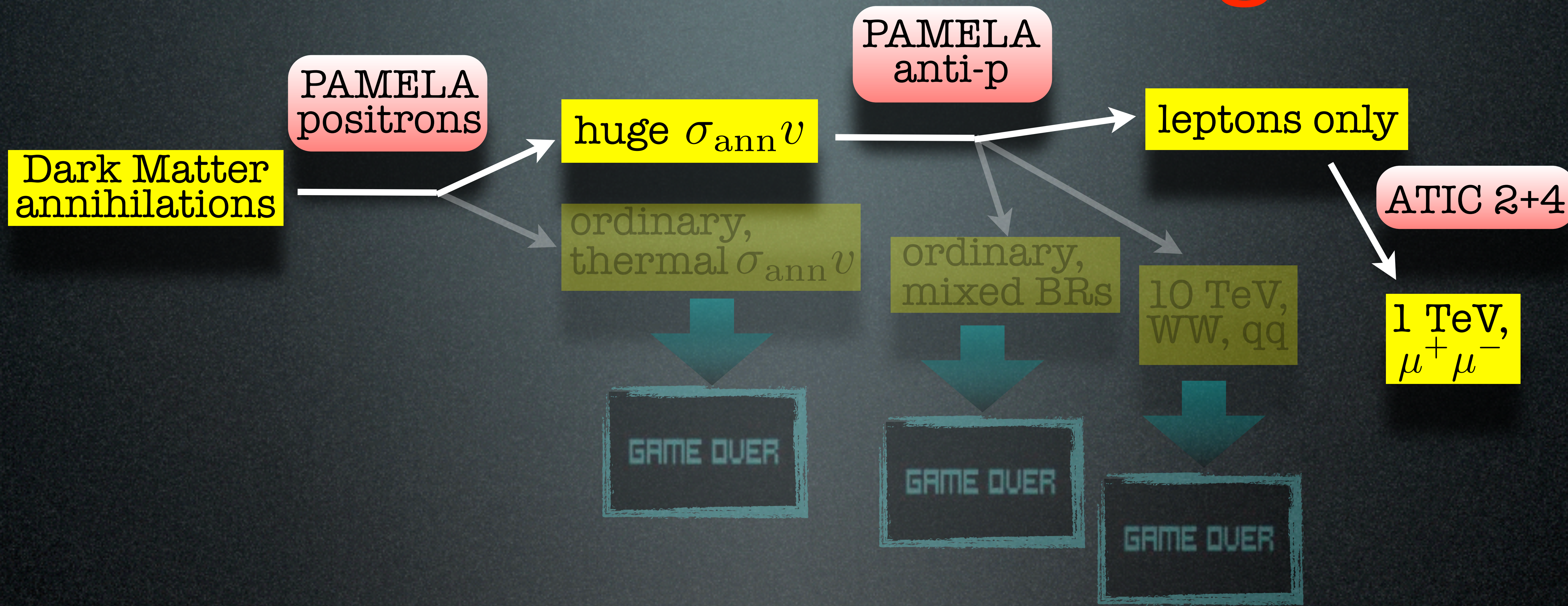

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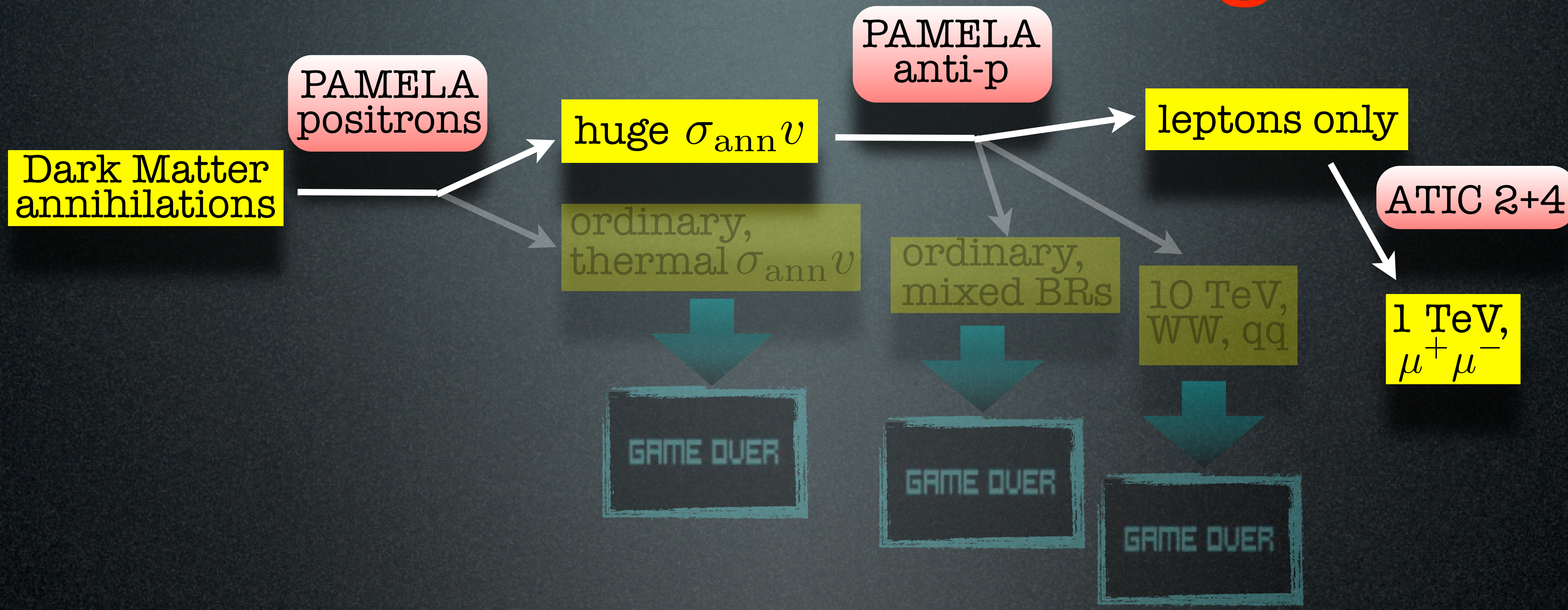

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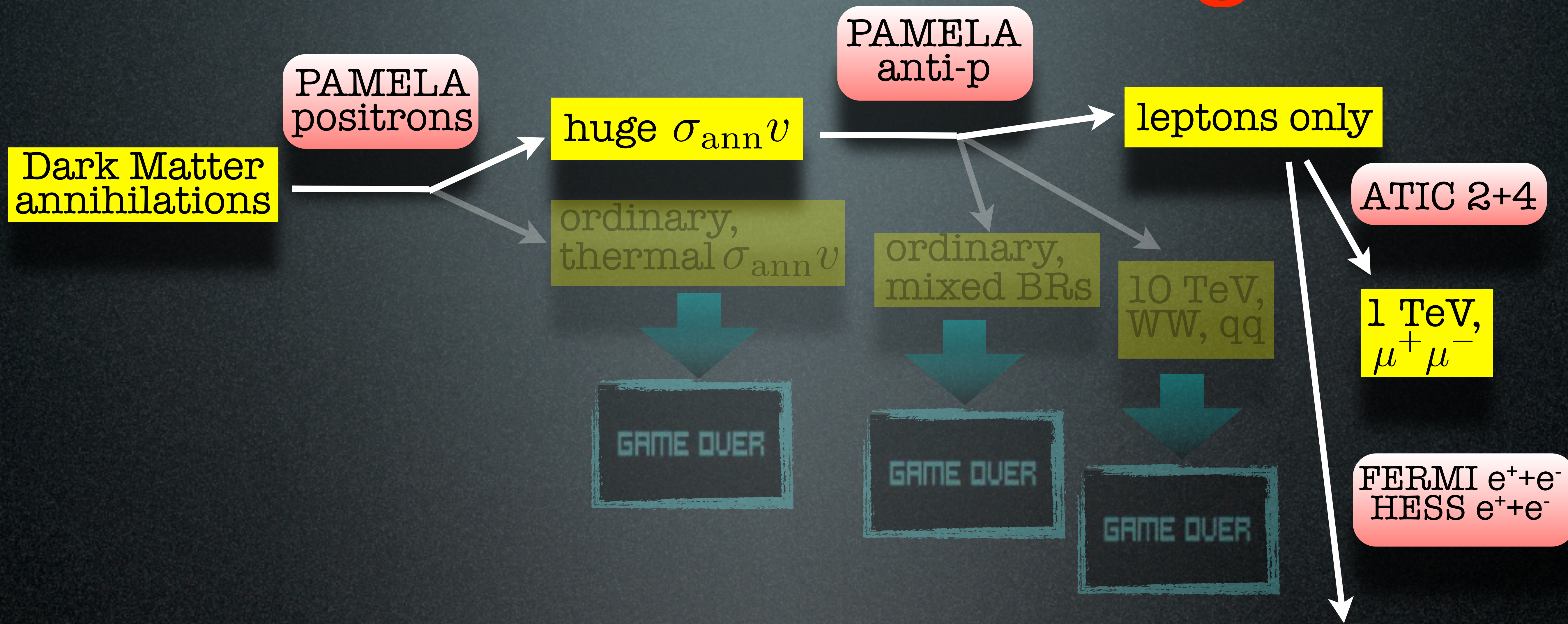

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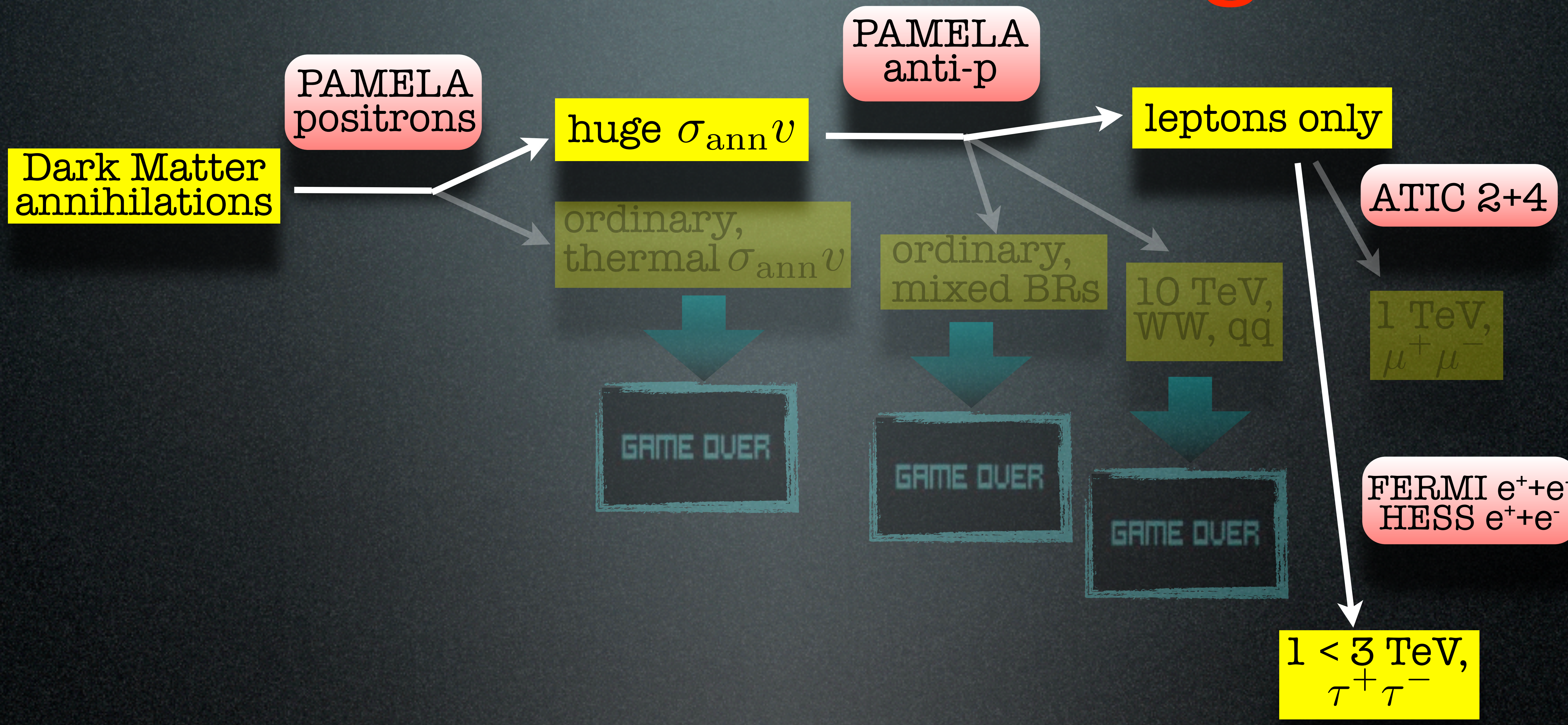

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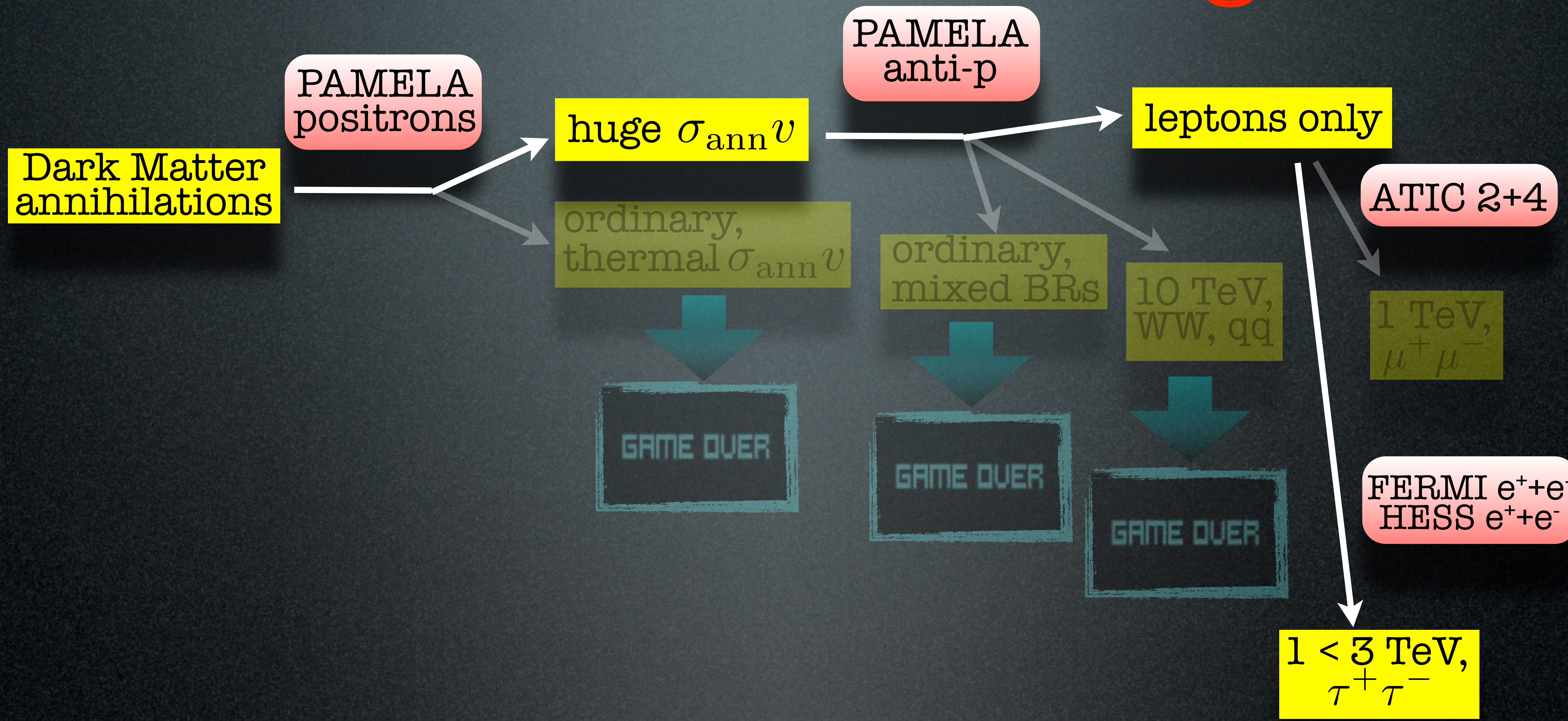

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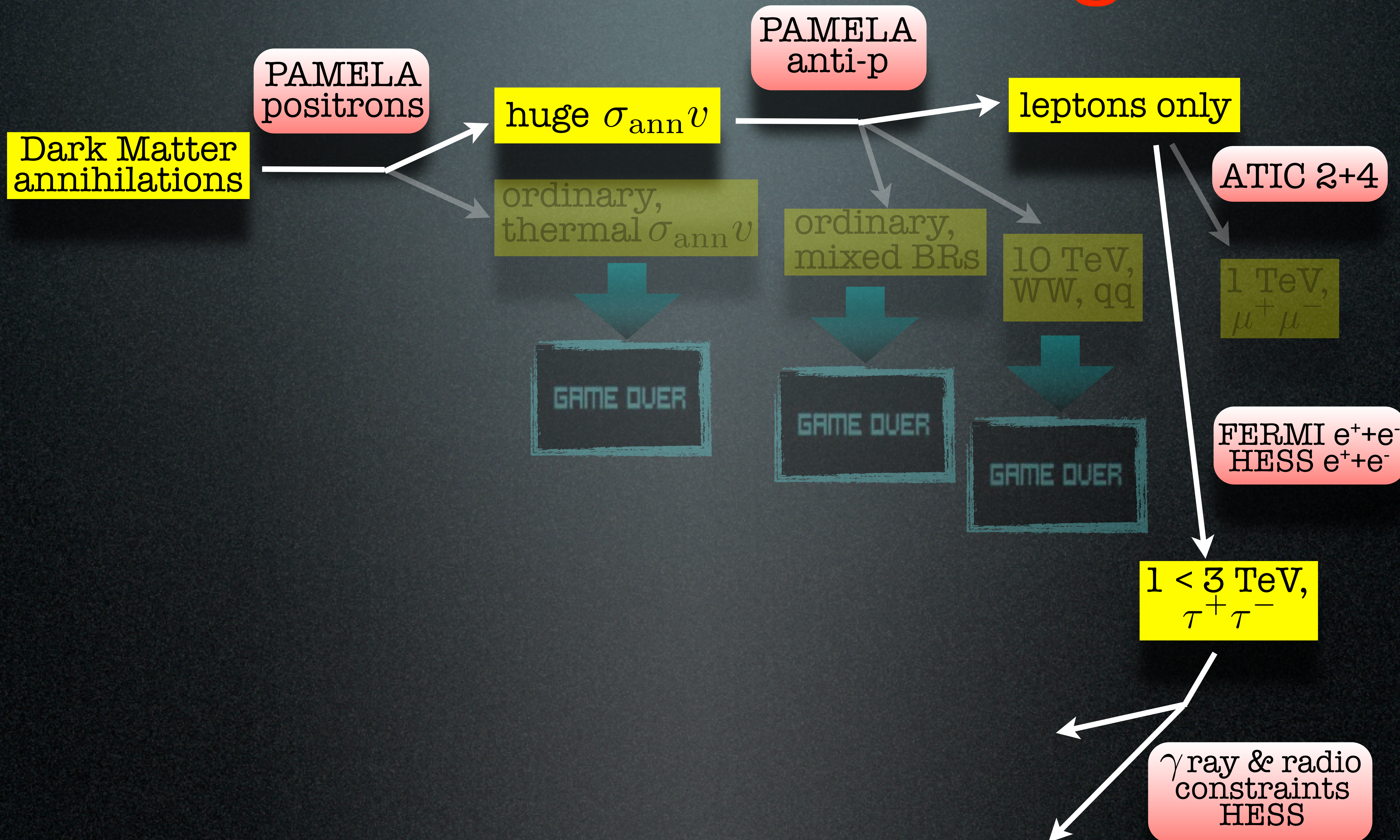

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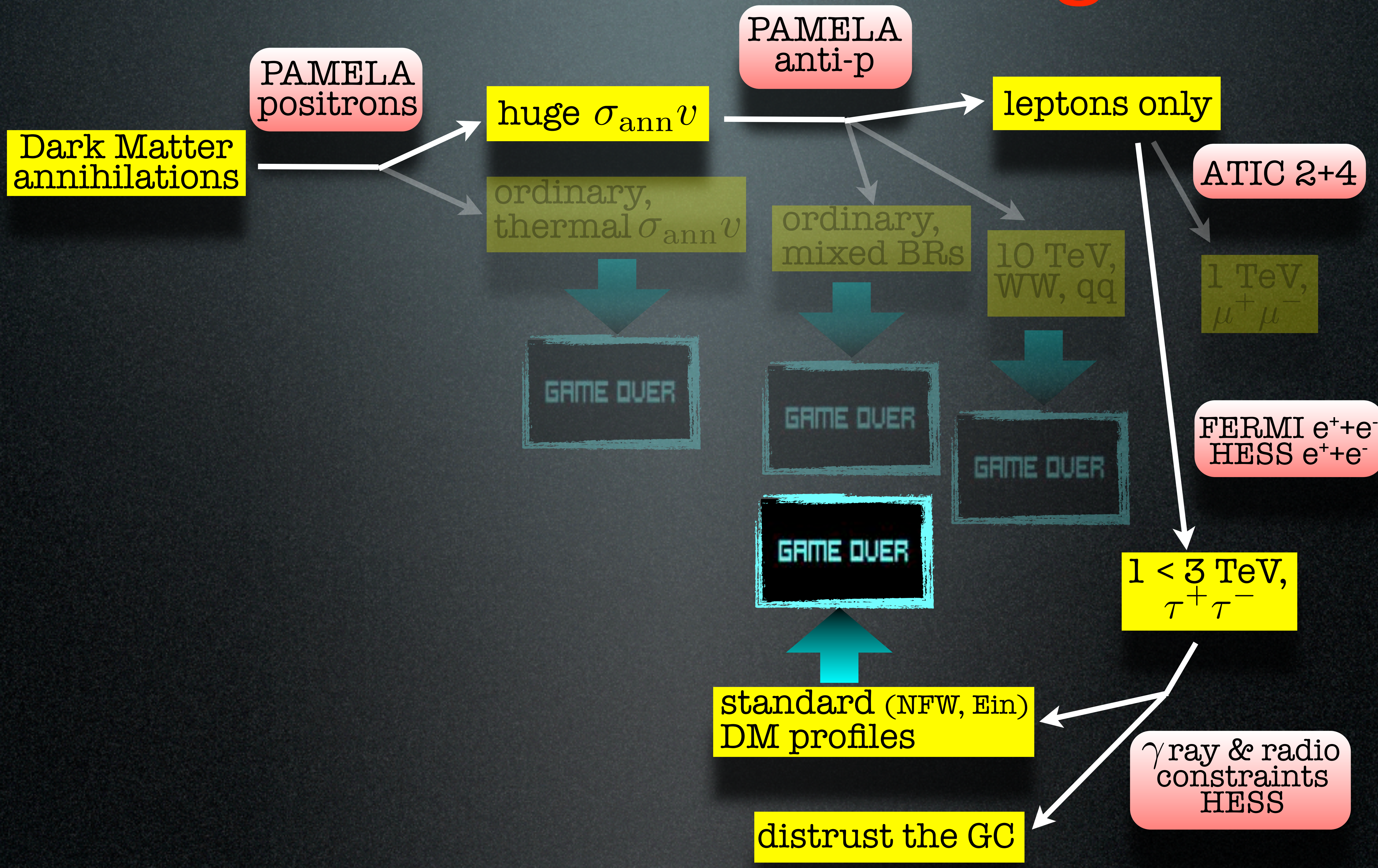

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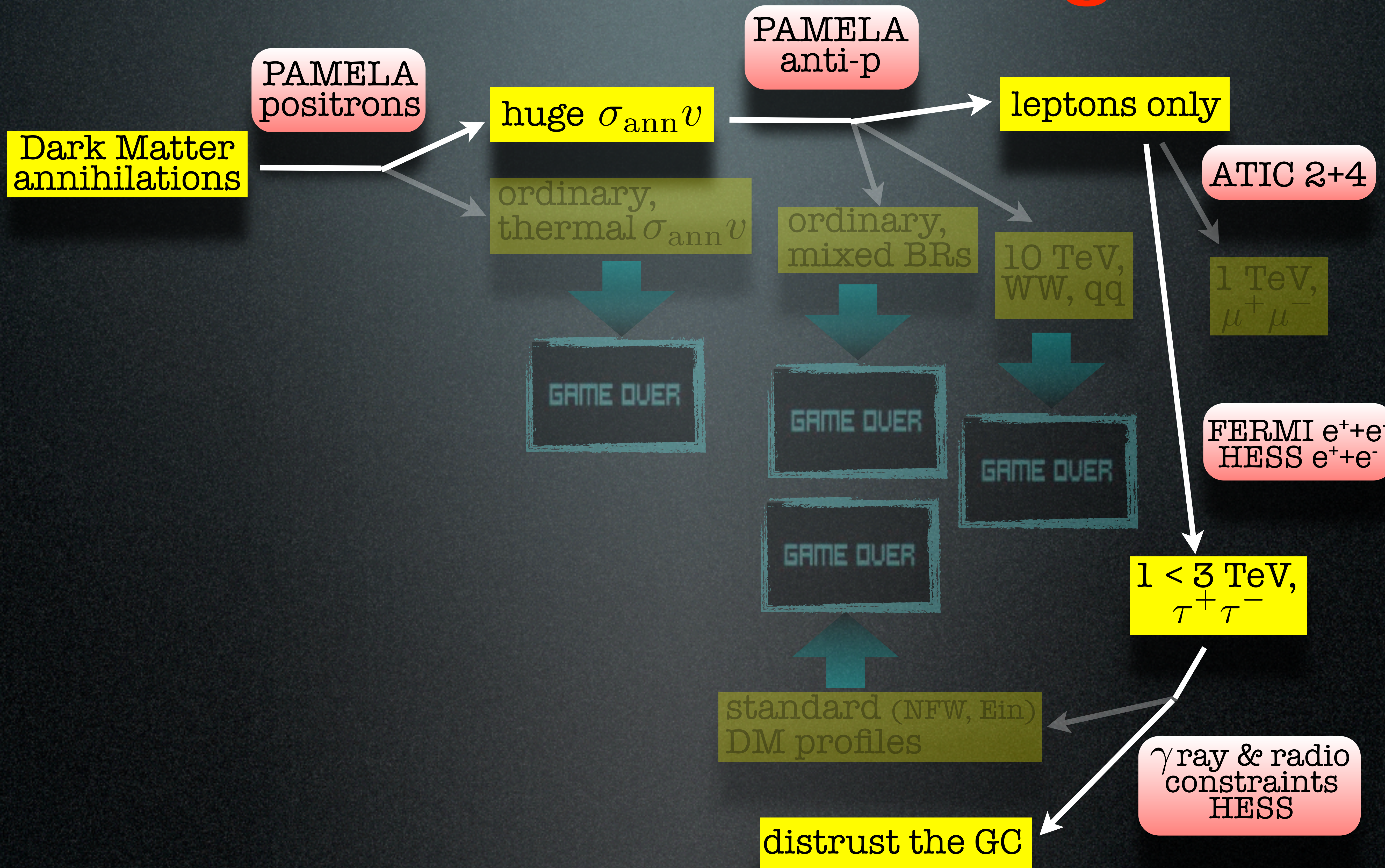

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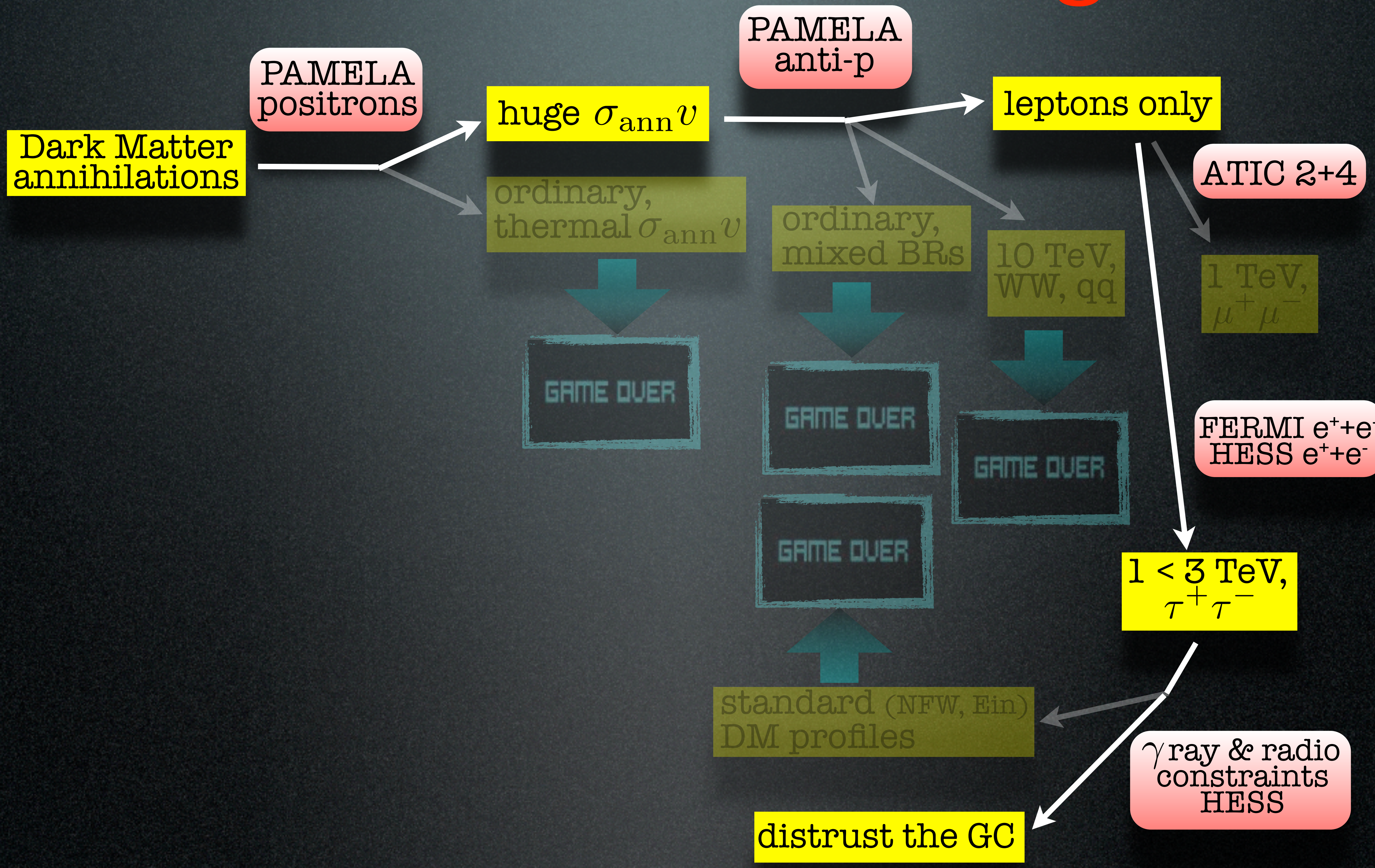
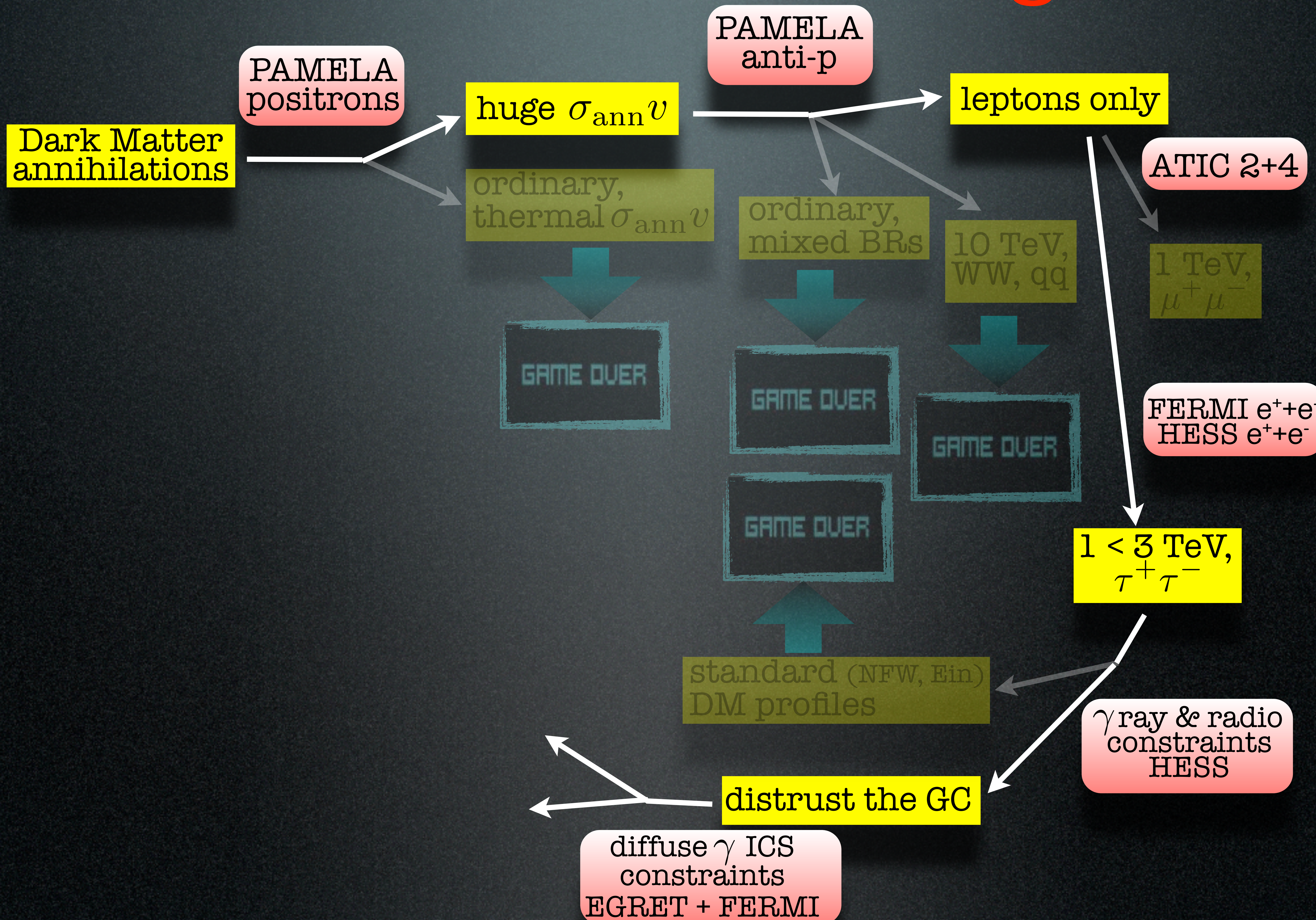
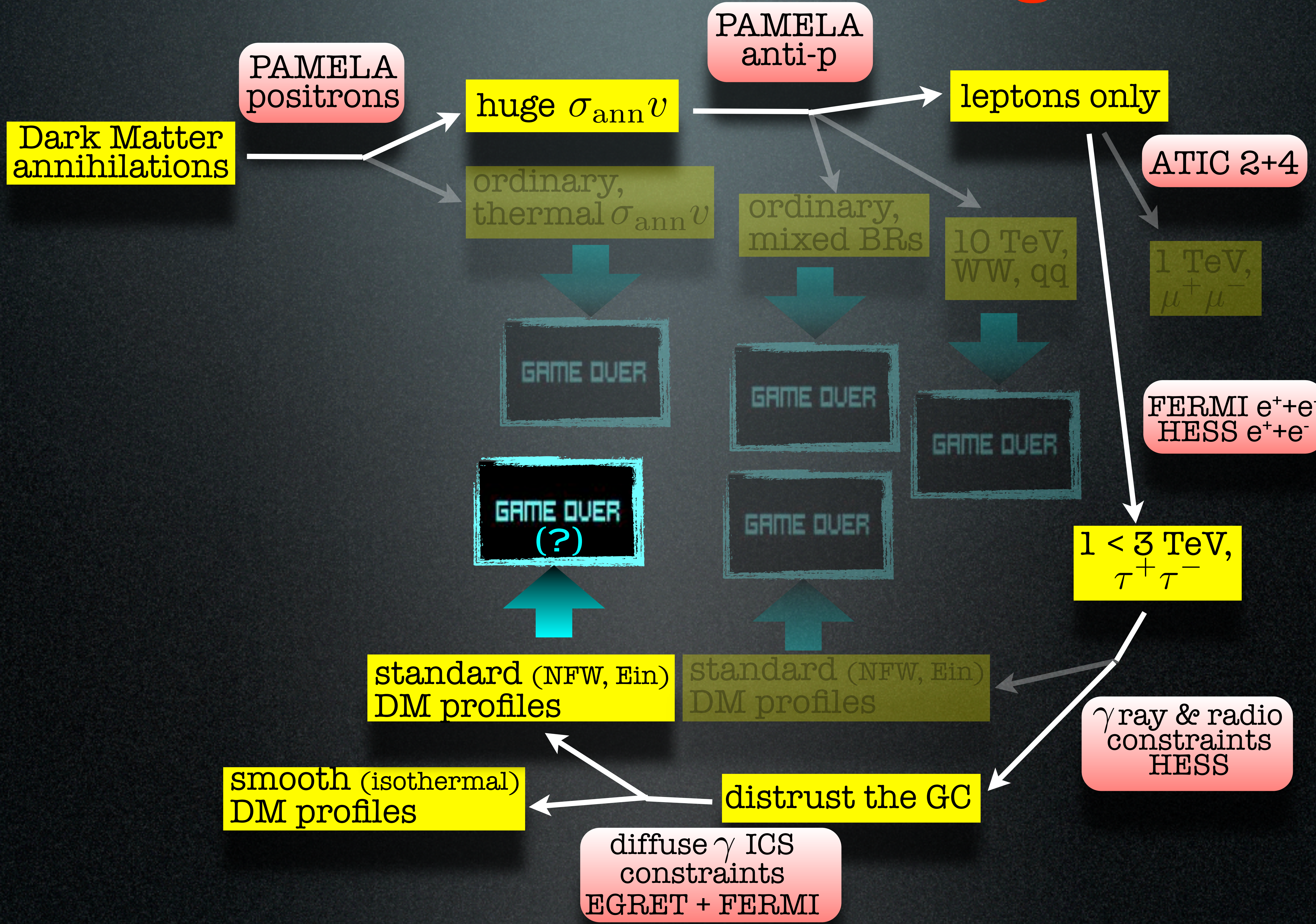


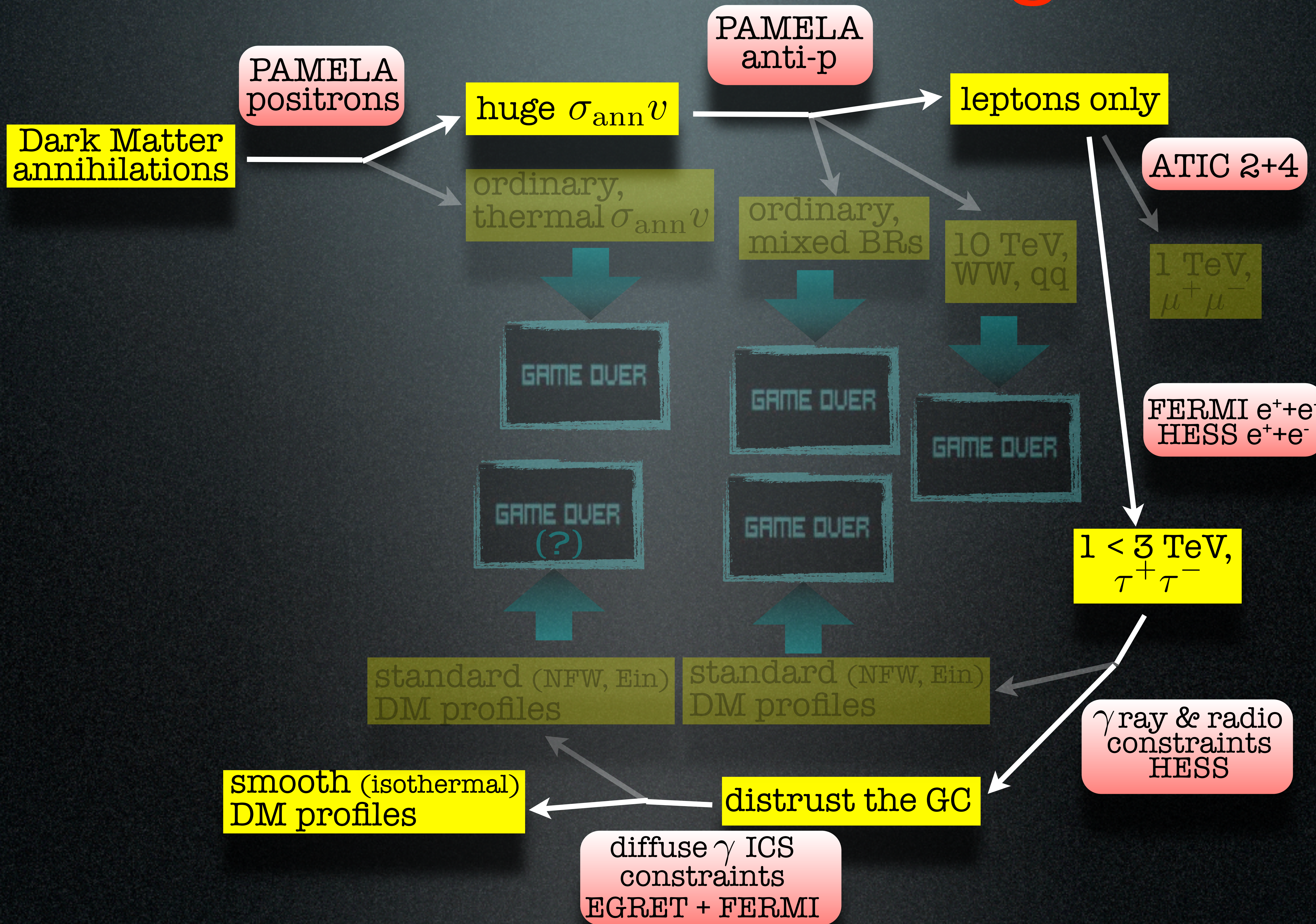
DM annihilations: the game



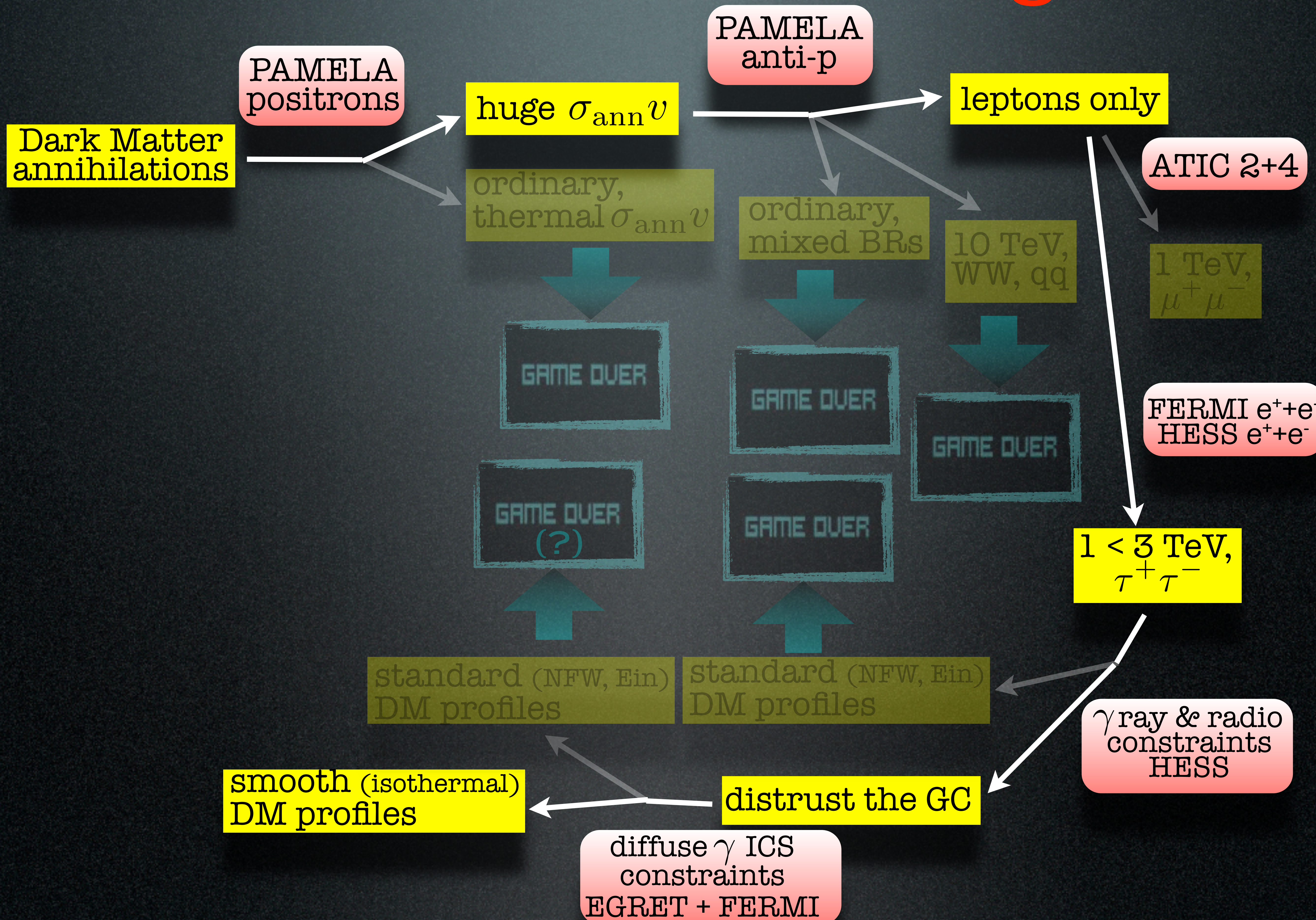
DM annihilations: the game



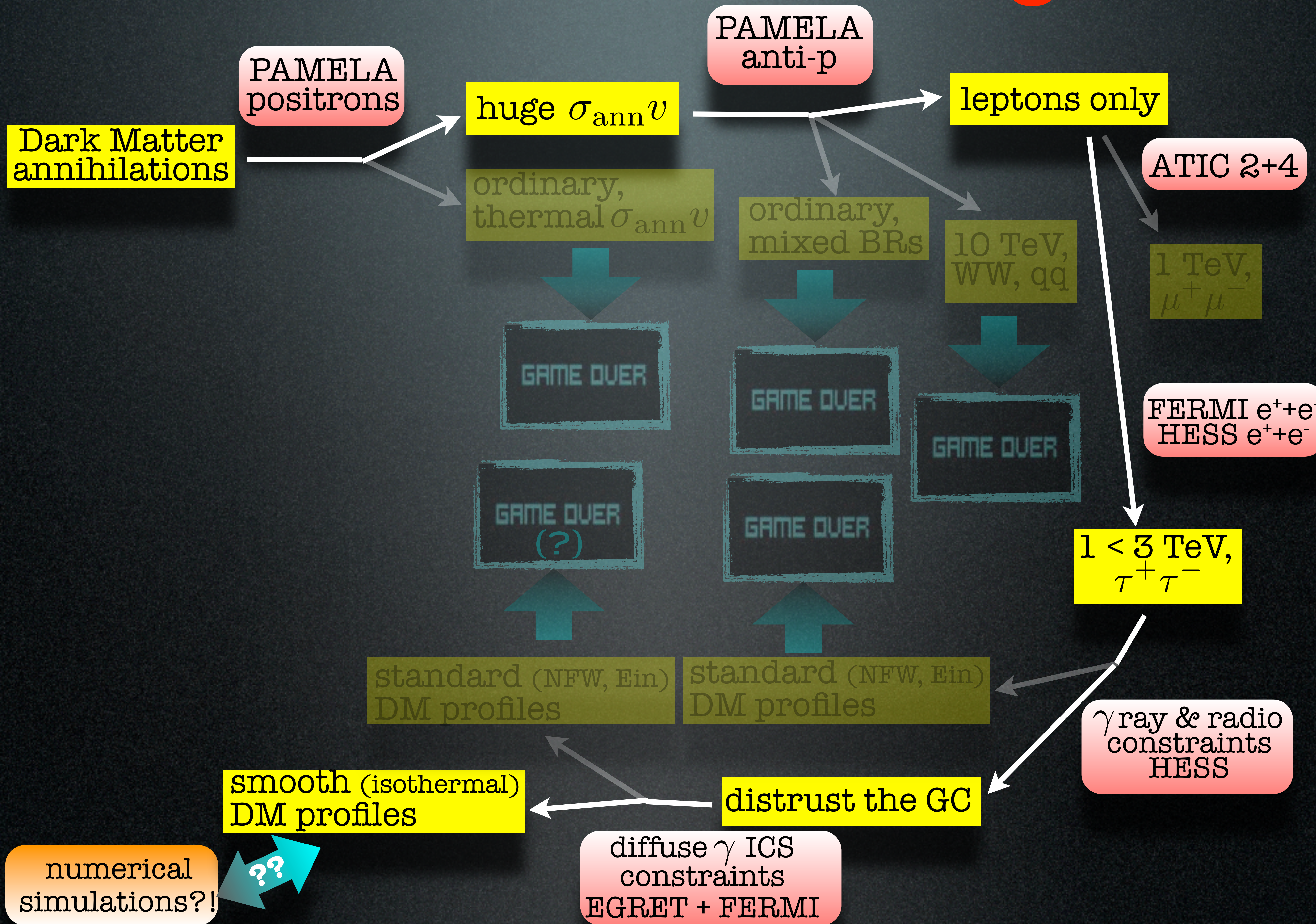
DM annihilations: the game



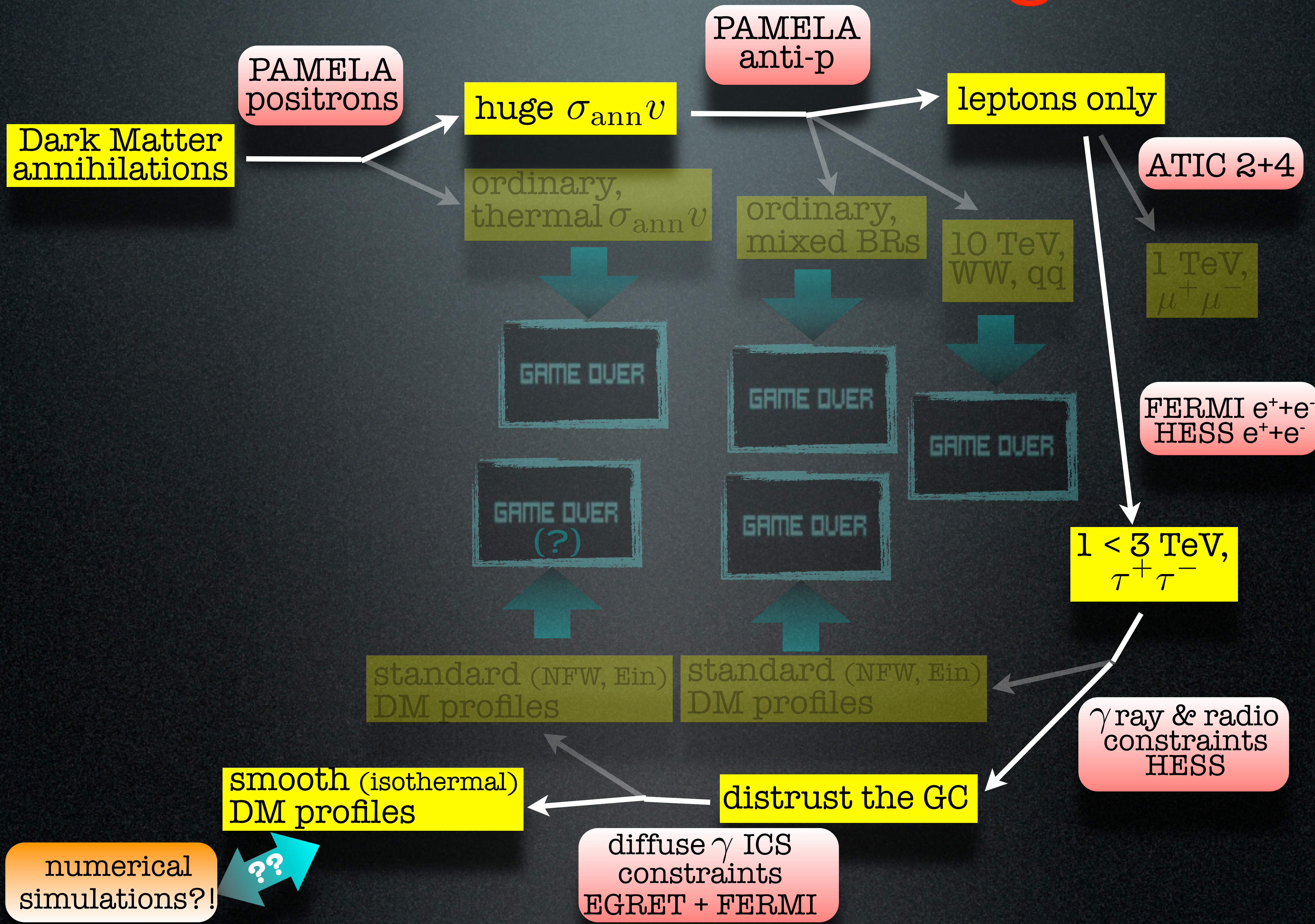
DM annihilations: the game



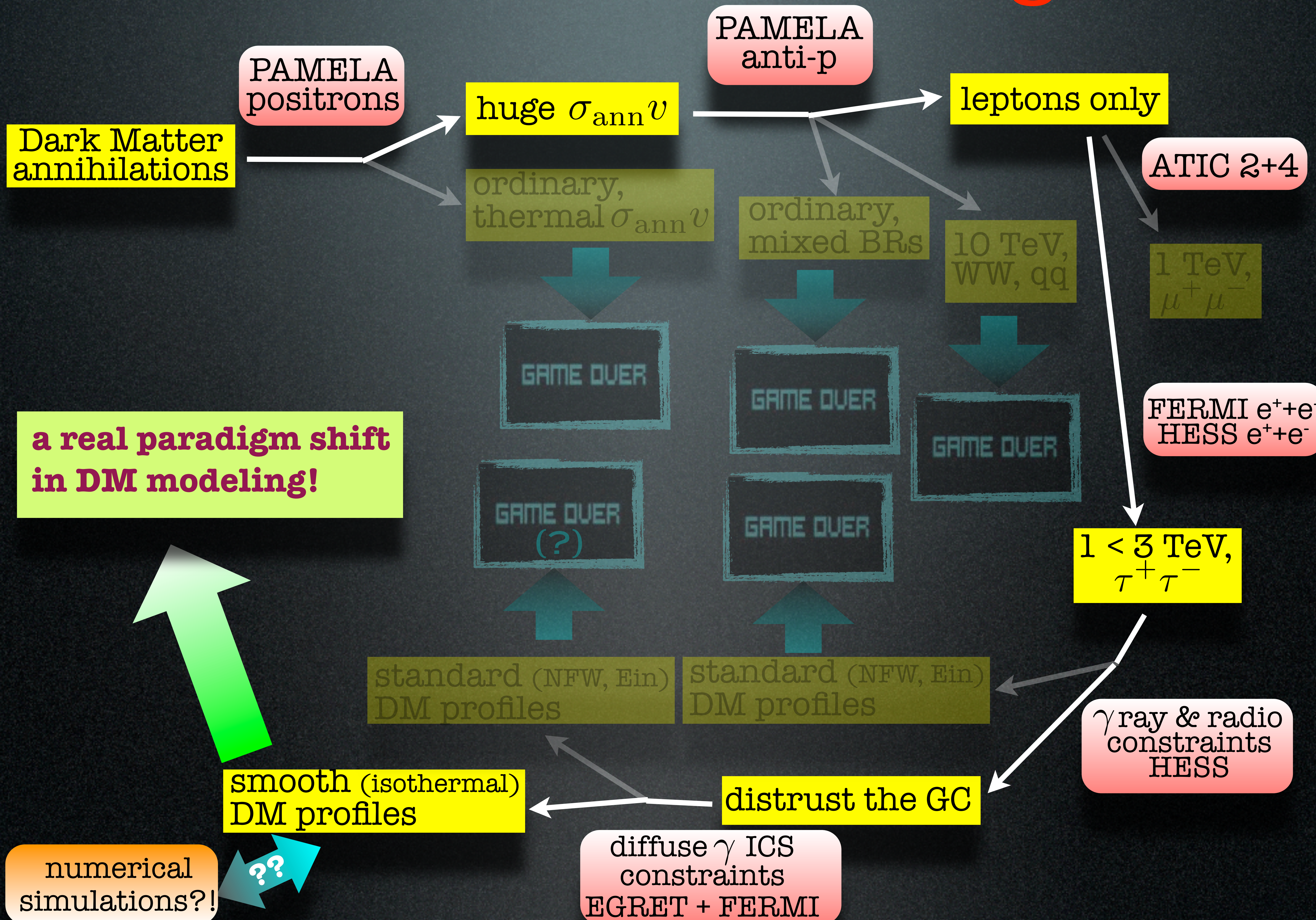
DM annihilations: the game



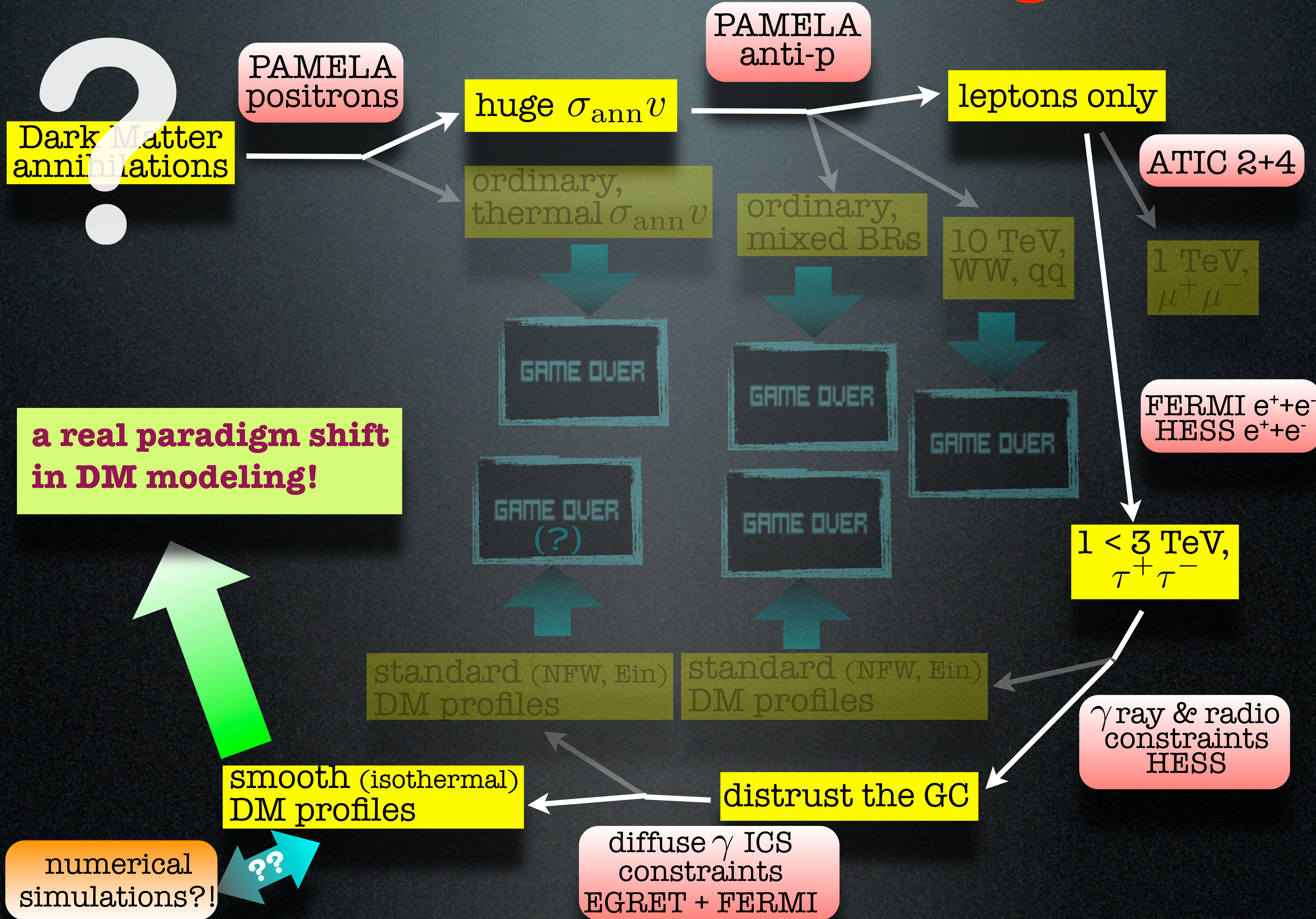
DM annihilations: the game



DM annihilations: the game

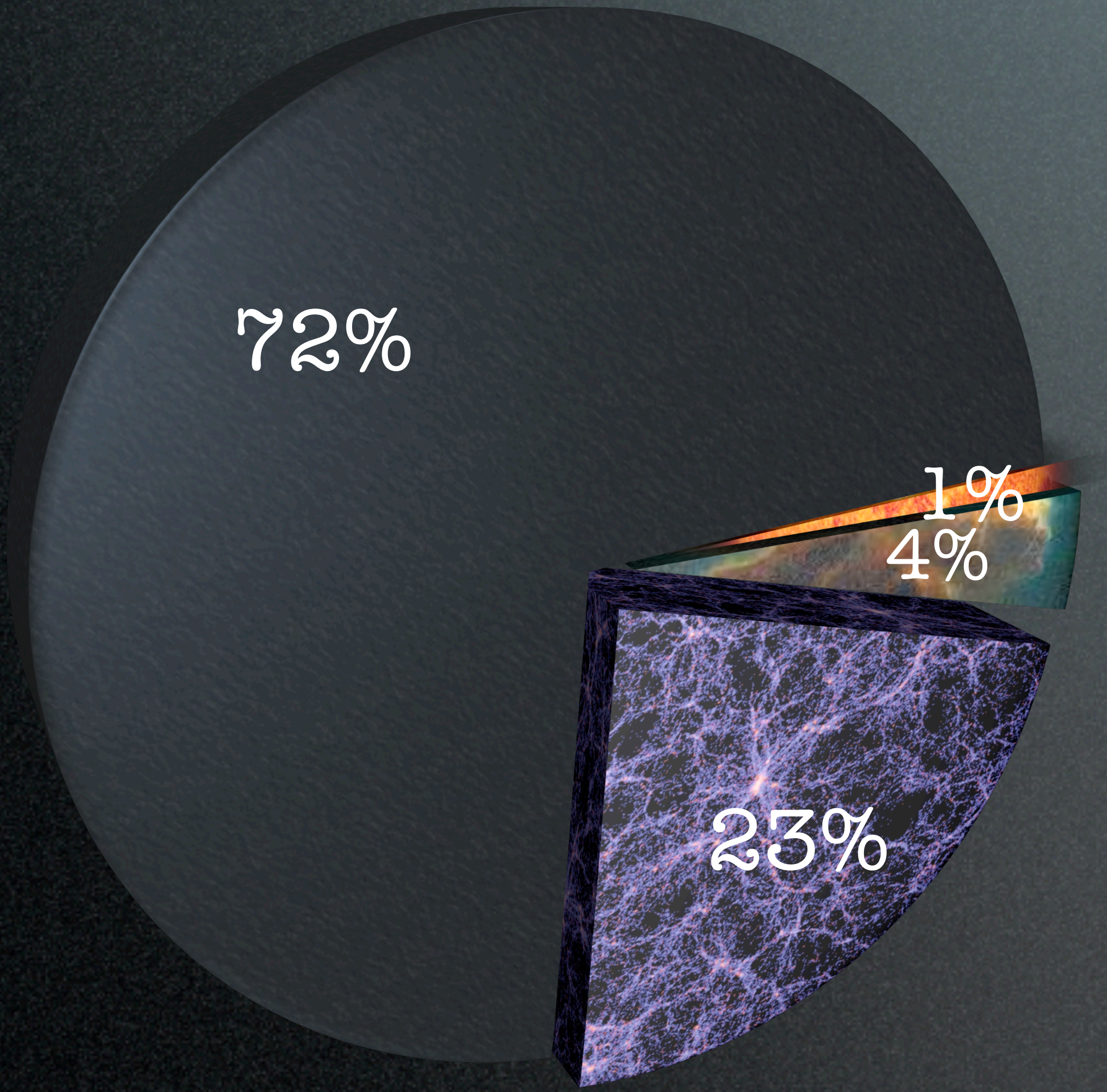


DM annihilations: the game



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

[back]

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

DM N-body simulations

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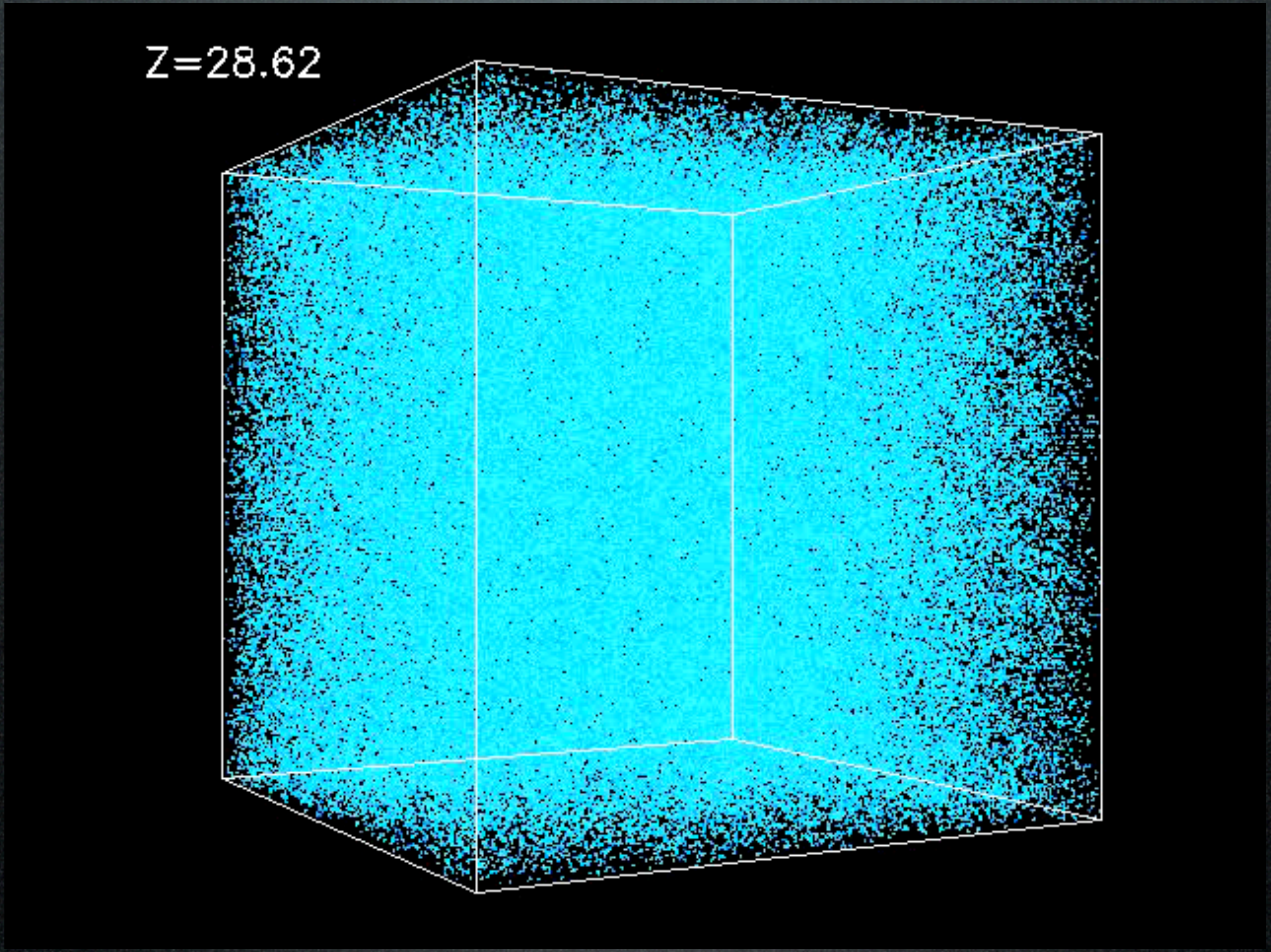

Andrey Kravtsov, cosmicweb.uchicago.edu

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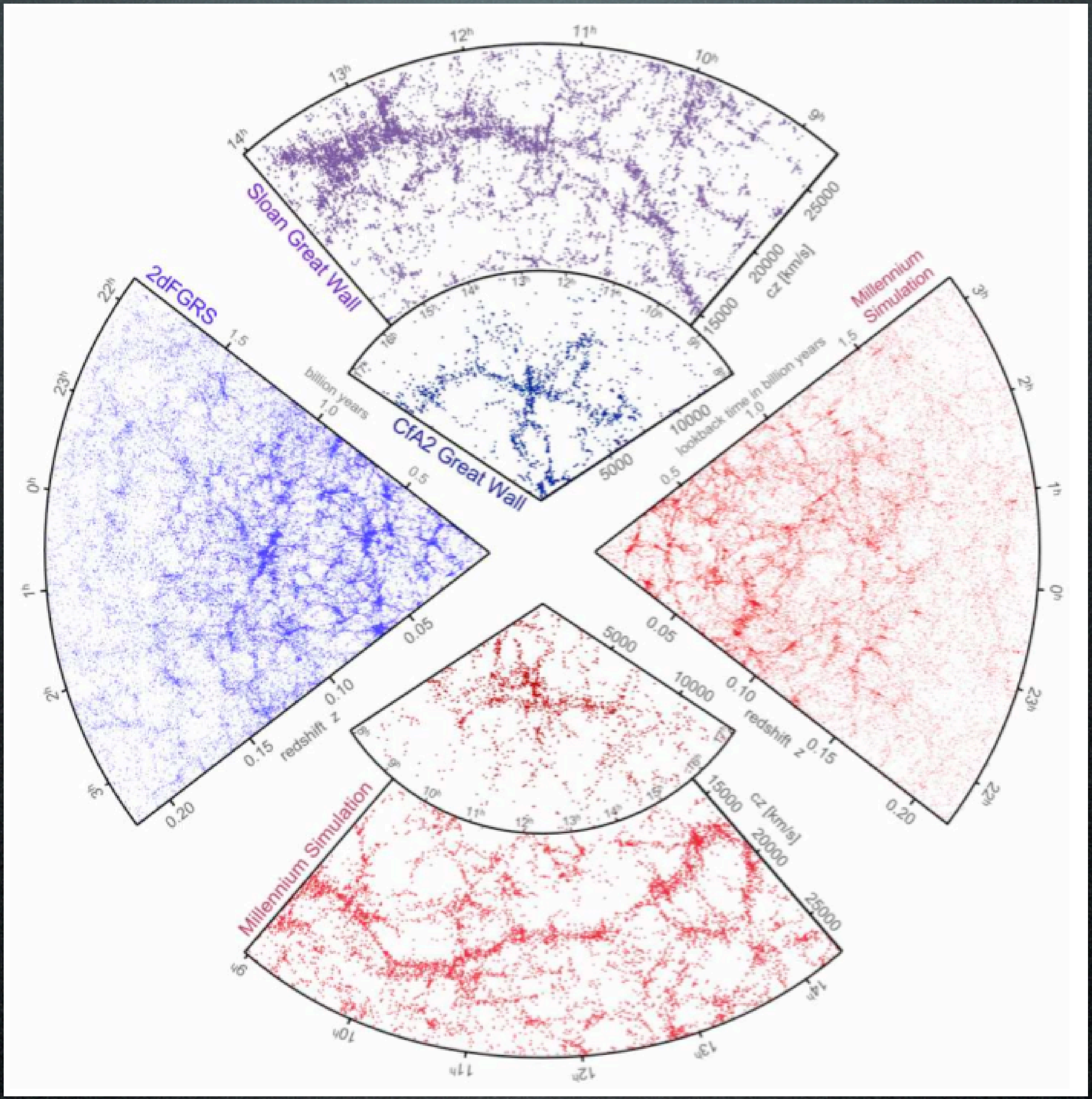
DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

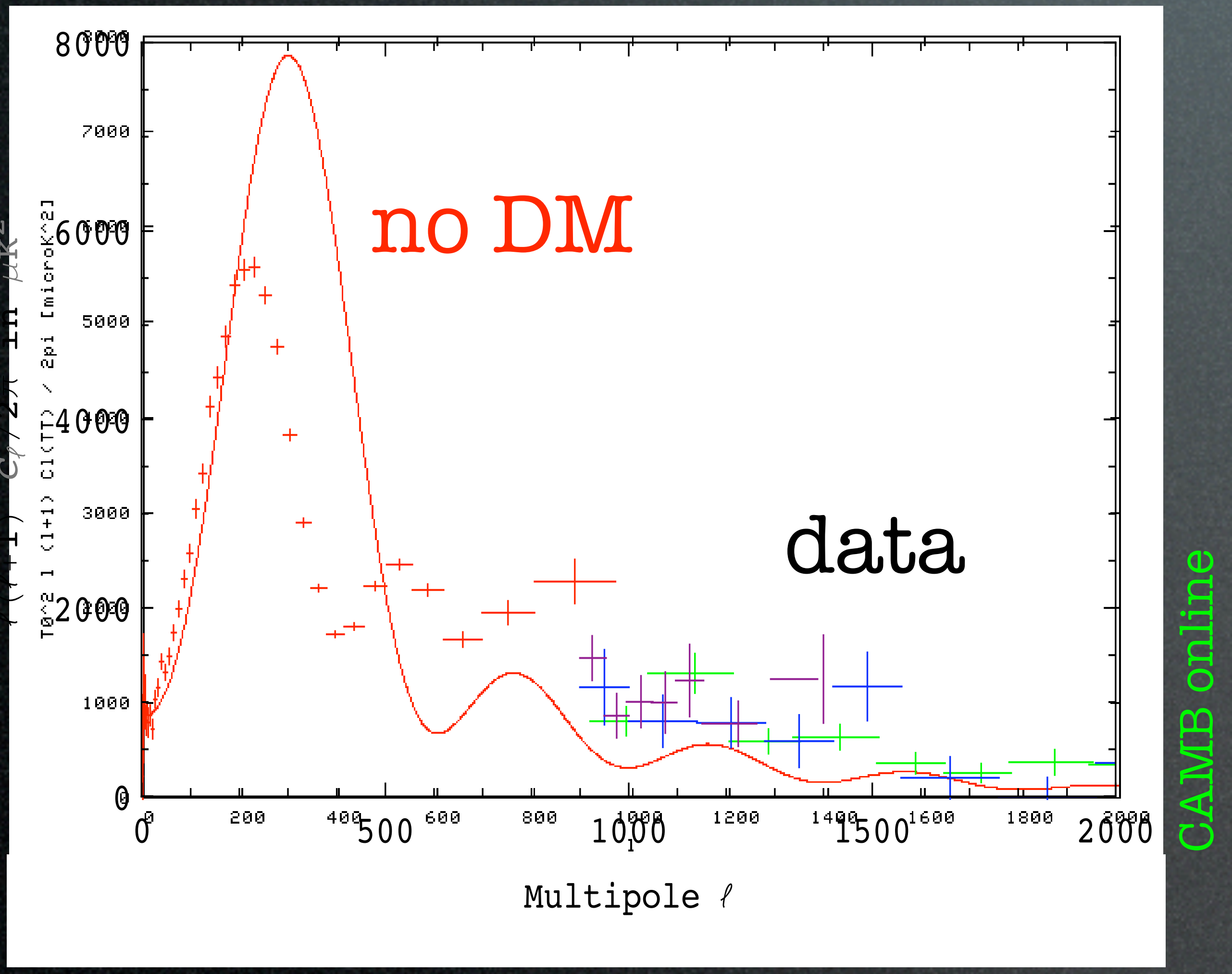
Millennium:
10^{10} particles,
500 h^{-1} Mpc

[back]

The Evidence for DM

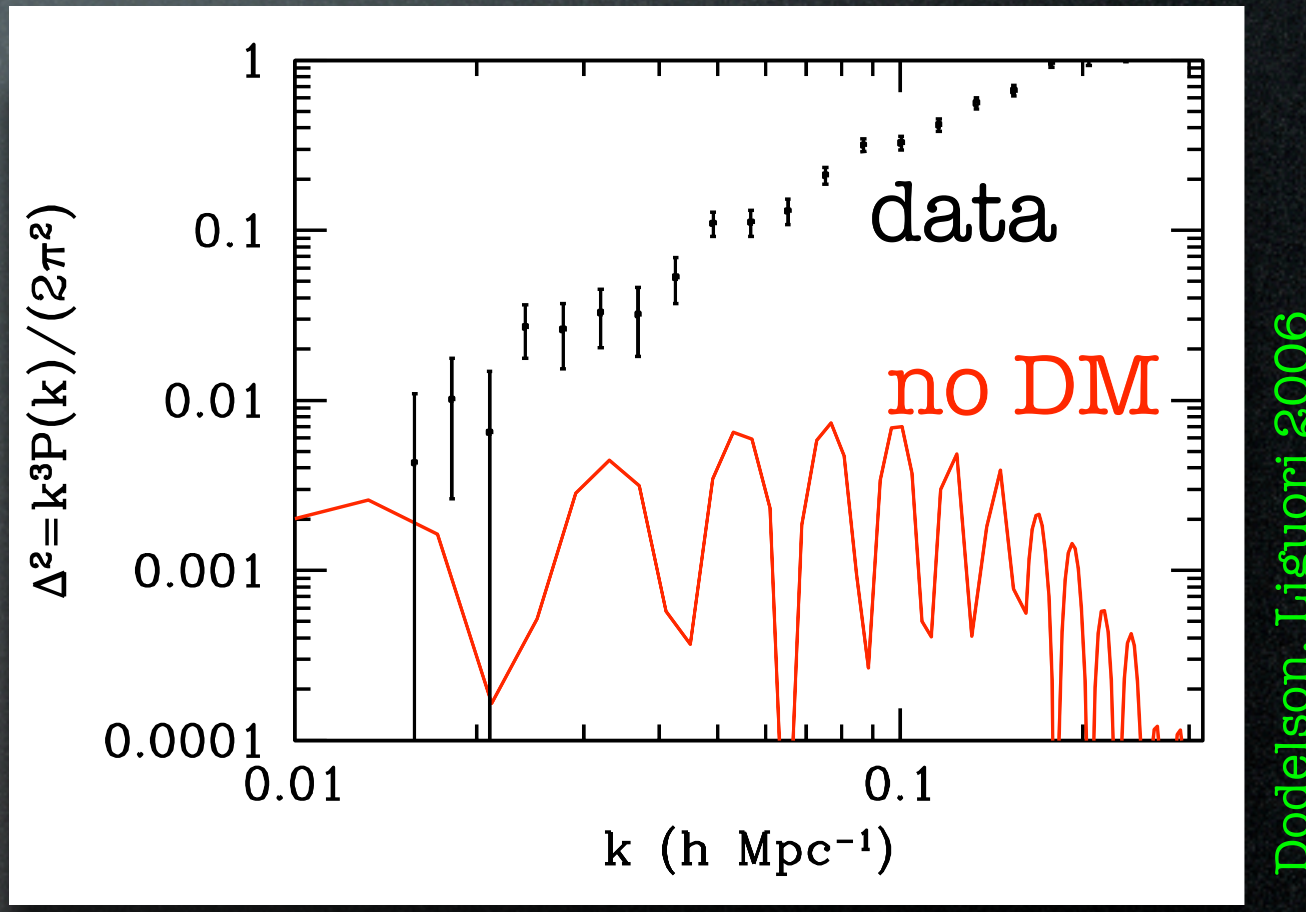
How would the power spectra be without DM?
(and no other extra ingredient)

CMB



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

LSS



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

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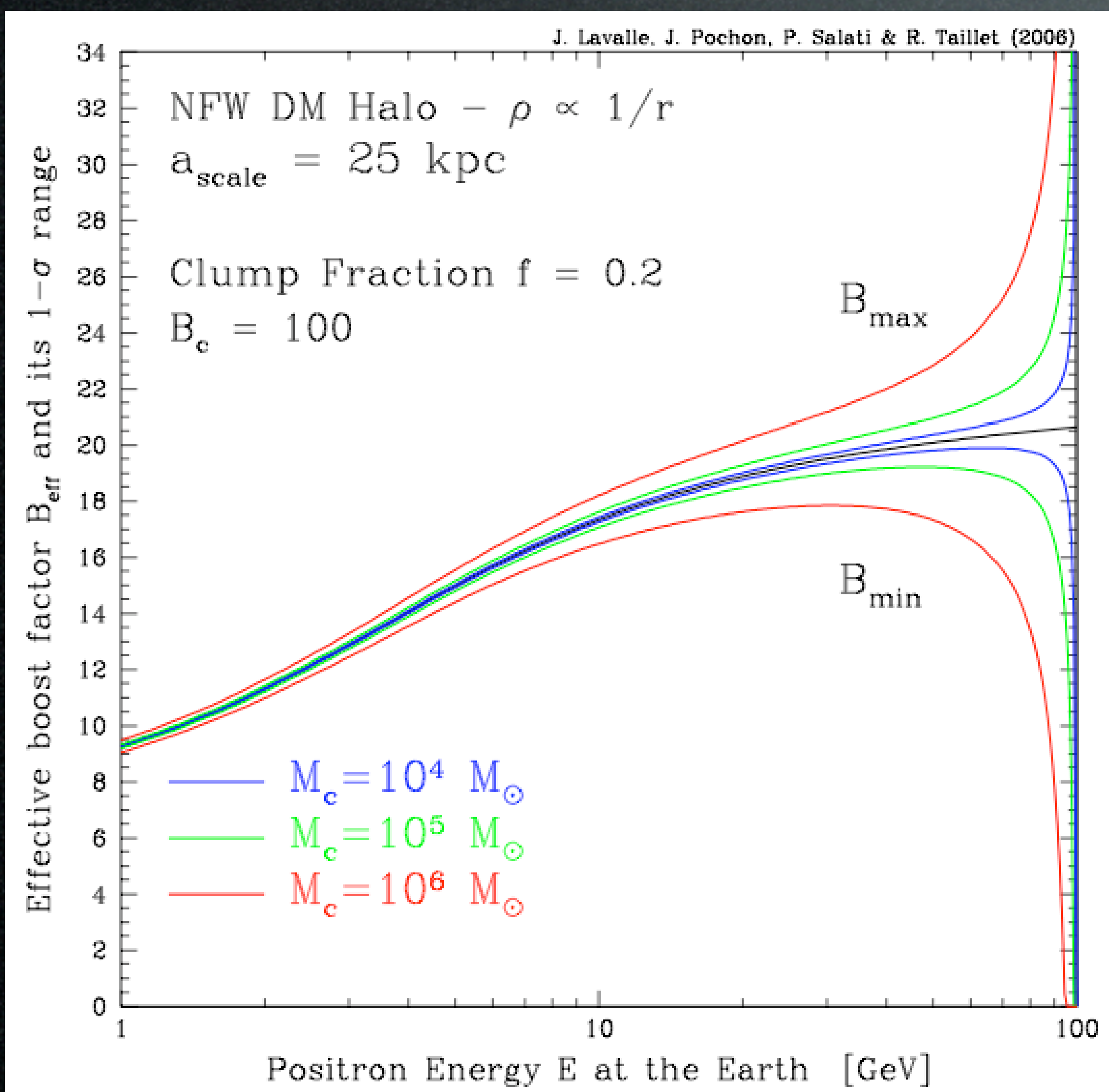
Indirect Detection

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

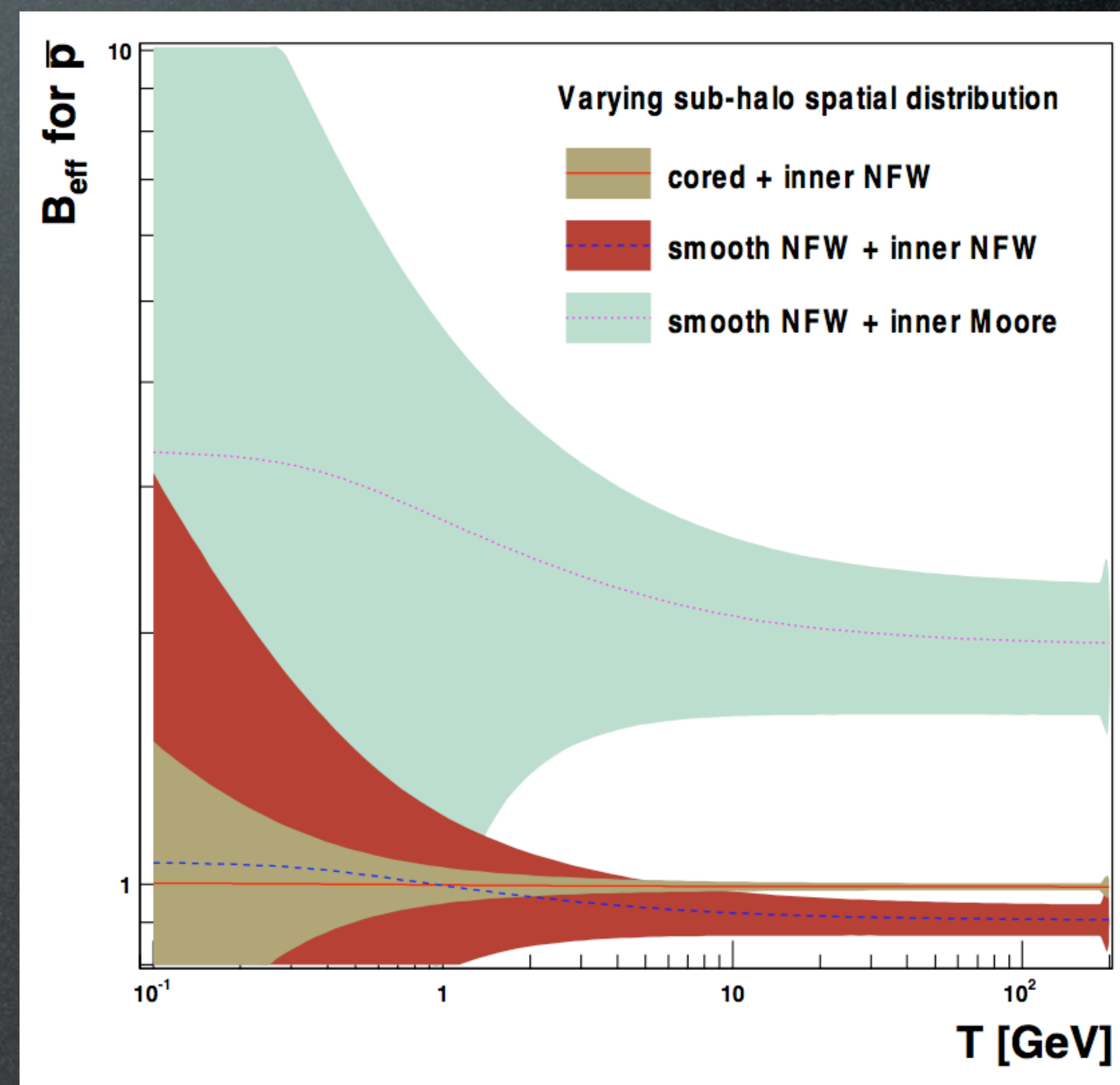
In principle, B is different for e^+, anti-p and gammas,
energy dependent,
dependent on many astro assumptions (inner density profile of clump, tidal disruptions and smoothing...),
with an energy dependent variance, at high energy for e^+, at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons



Lavalle et al. 2007

Indirect Detection

Propagation for positrons:

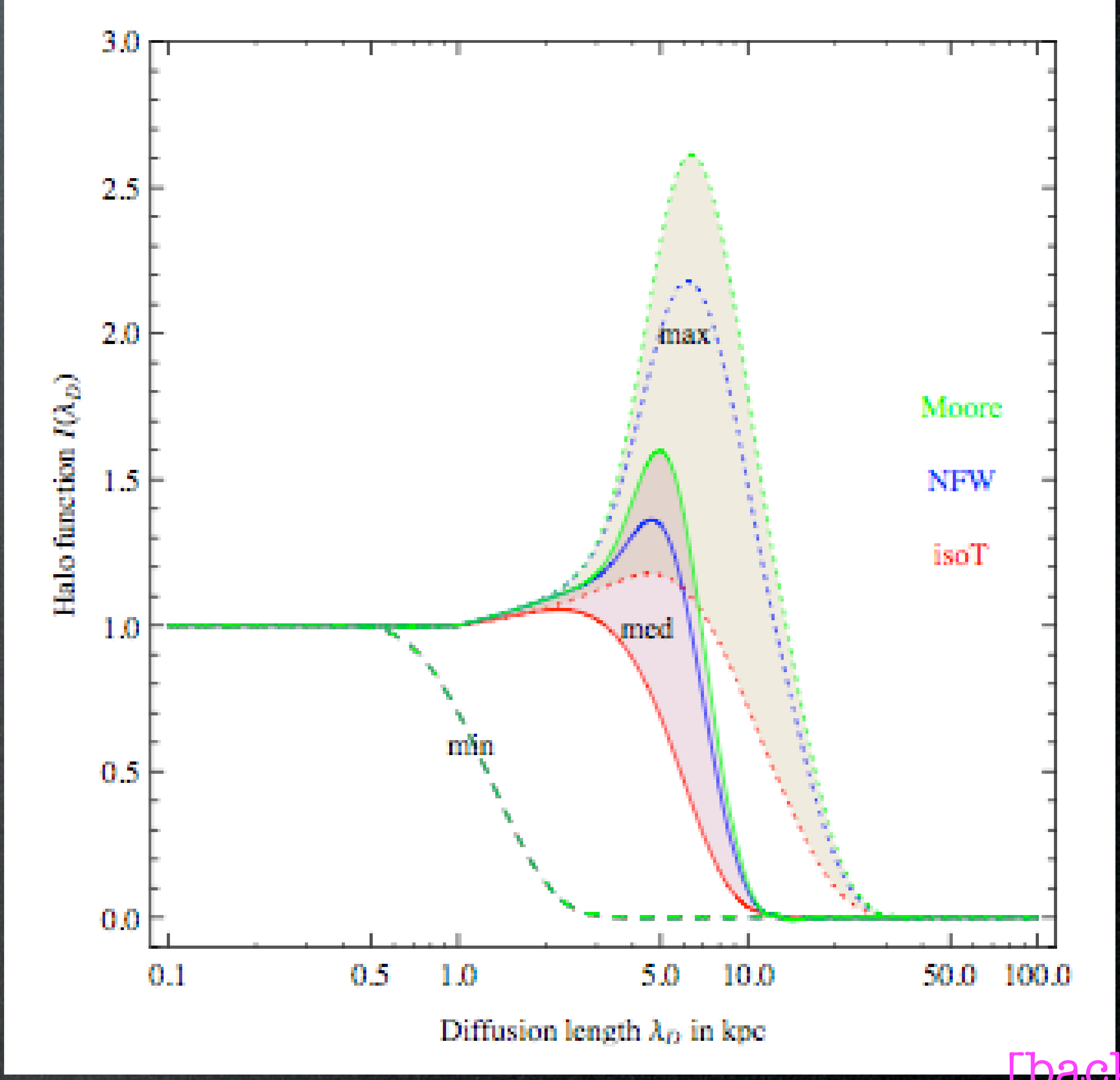
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) = Q$$

diffusion
(in turbulent $\bar{B} \approx \mu$G, assumed space indep.)
$K(E) = K_0(E/\mathrm{GeV})^\delta$

energy loss
$b(E) = (E/\mathrm{GeV})^2/\tau_E$
$\tau_E = 10^{16}$ s

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

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:

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

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

[back]

Indirect Detection

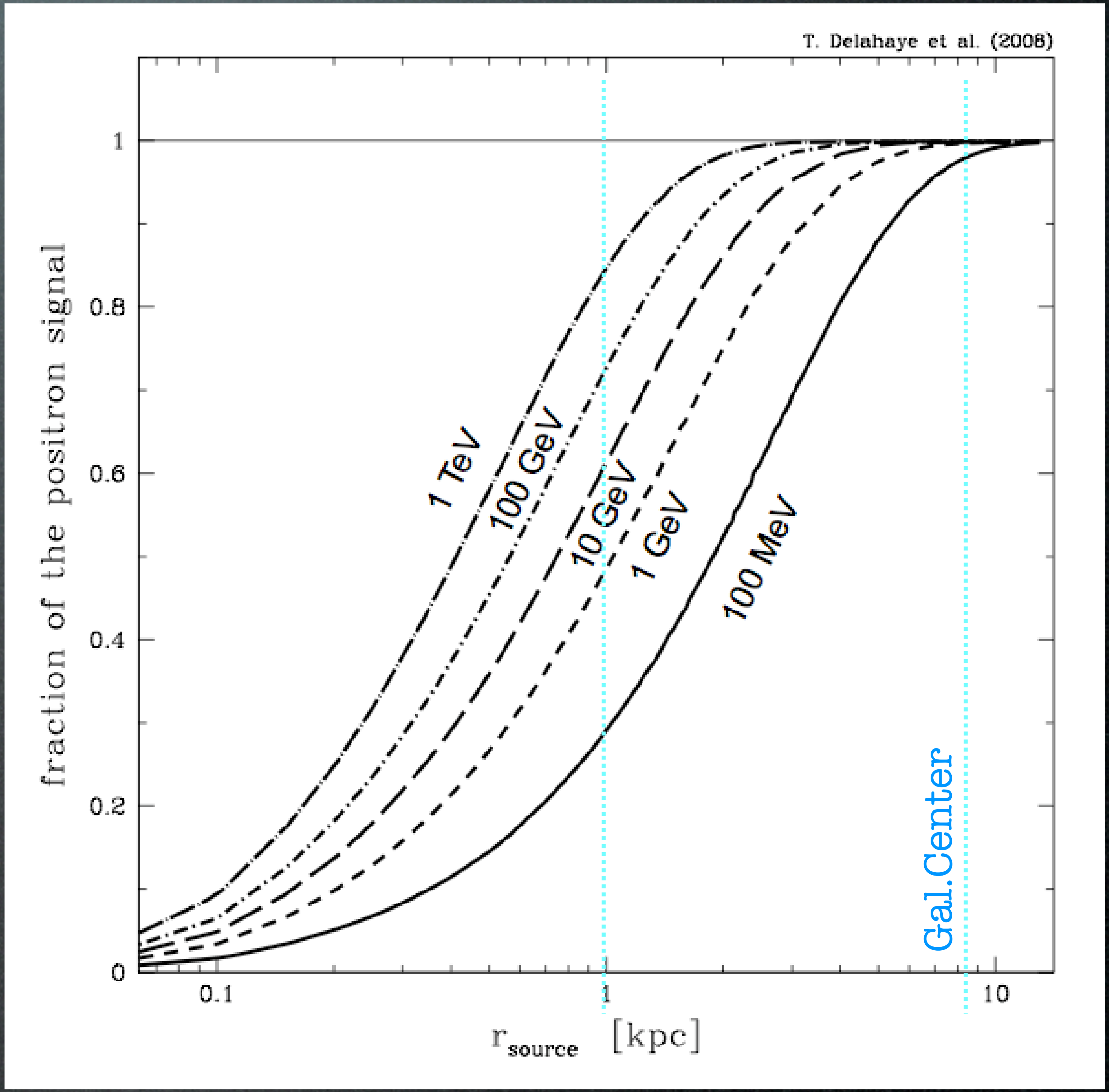
Where do positrons come from?

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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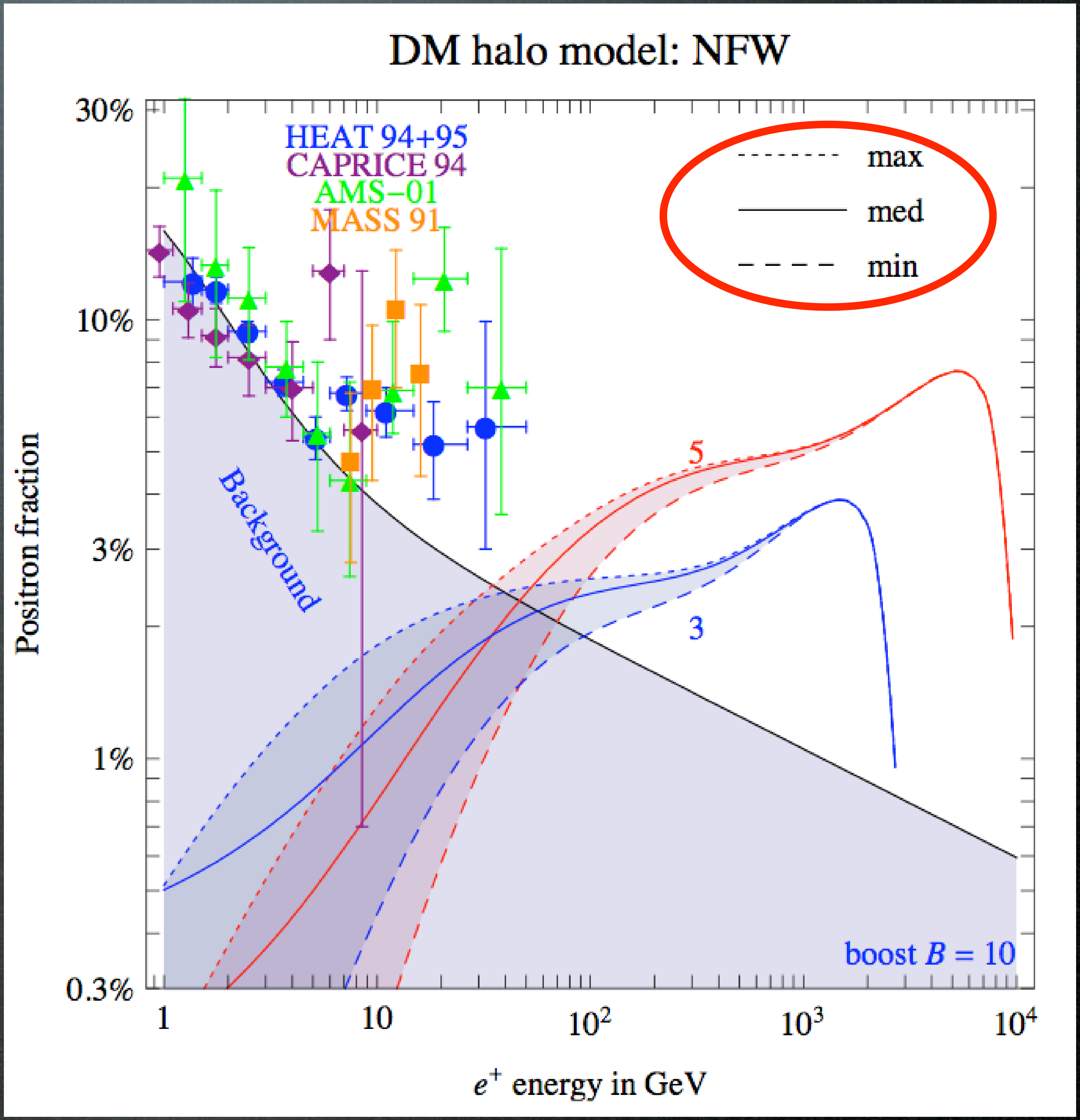
3. Indirect Detection

Results for positrons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



[back]

3. Indirect Detection

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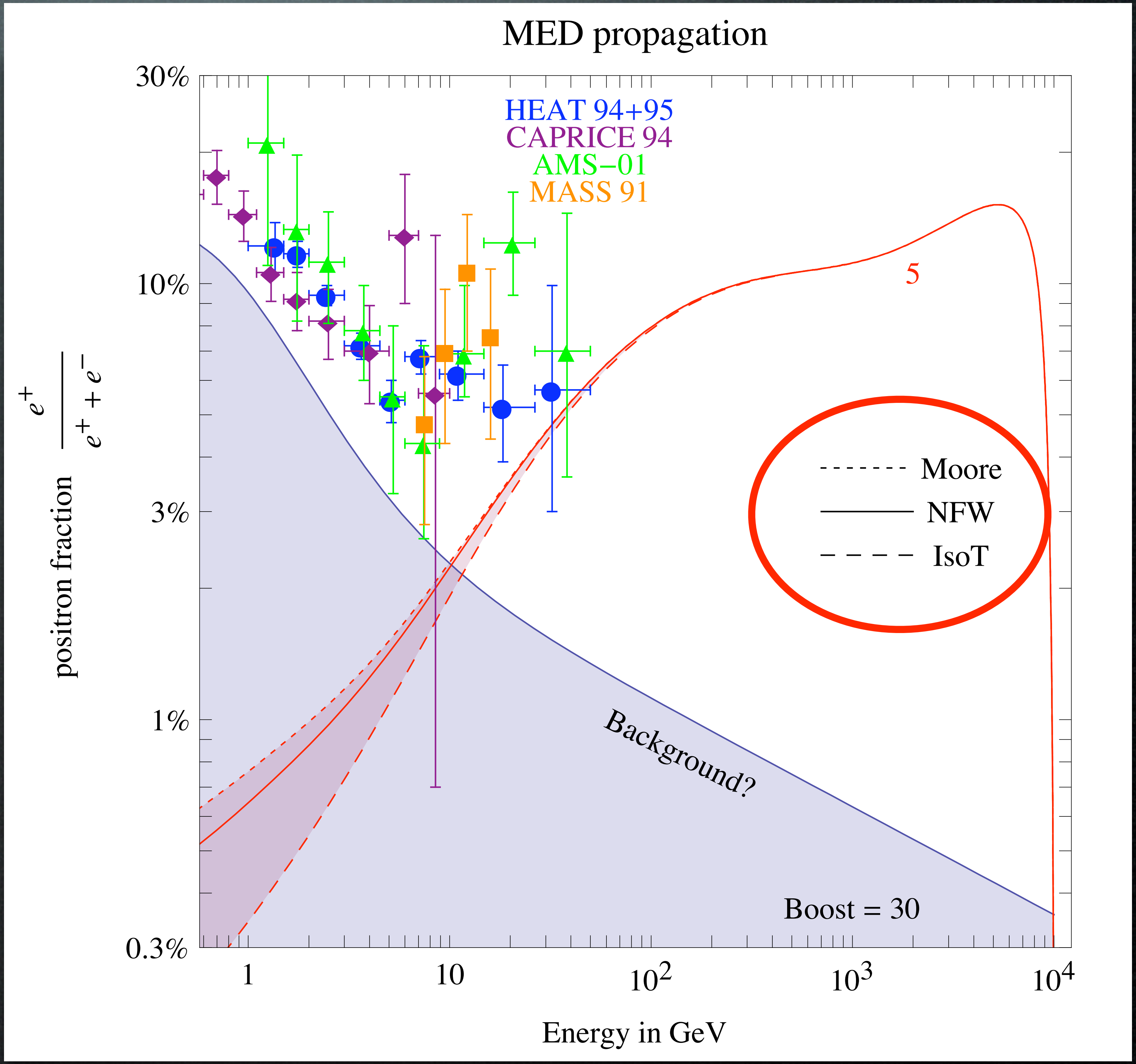


Distinctive signal,
quite robust vs astro.

[back]

3. Indirect Detection

Propagation for antiprotons:

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

diffusion — convective wind — spallations

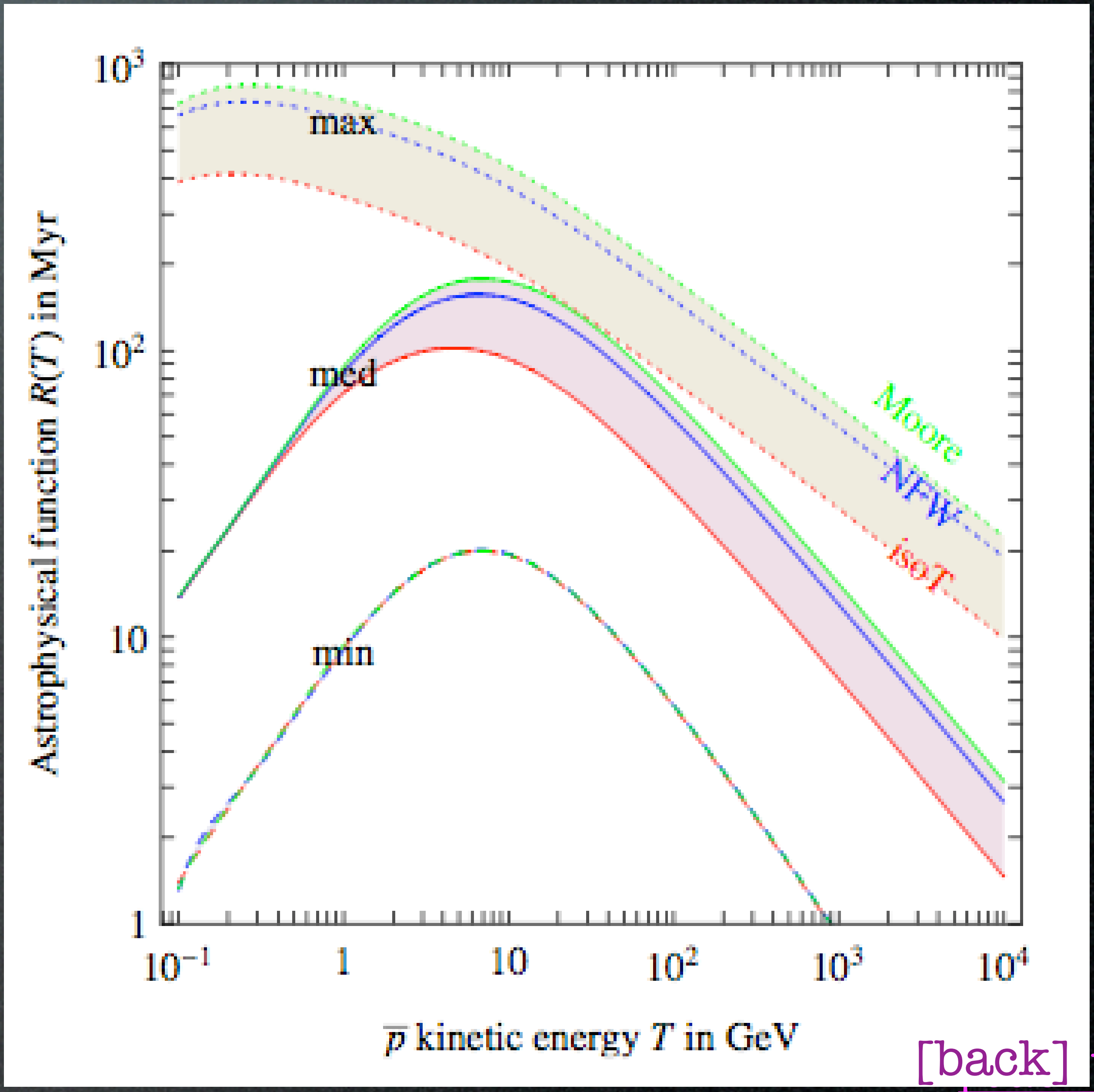
$K(T) = K_0 \beta\,(p/\mathrm{GeV})^{\delta}$

T kinetic energy

Model	δ	K_0 in $\mathrm{kpc}^2/\mathrm{Myr}$	L in kpc	$V_{\rm conv}$ 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:

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



[back]

Indirect Detection

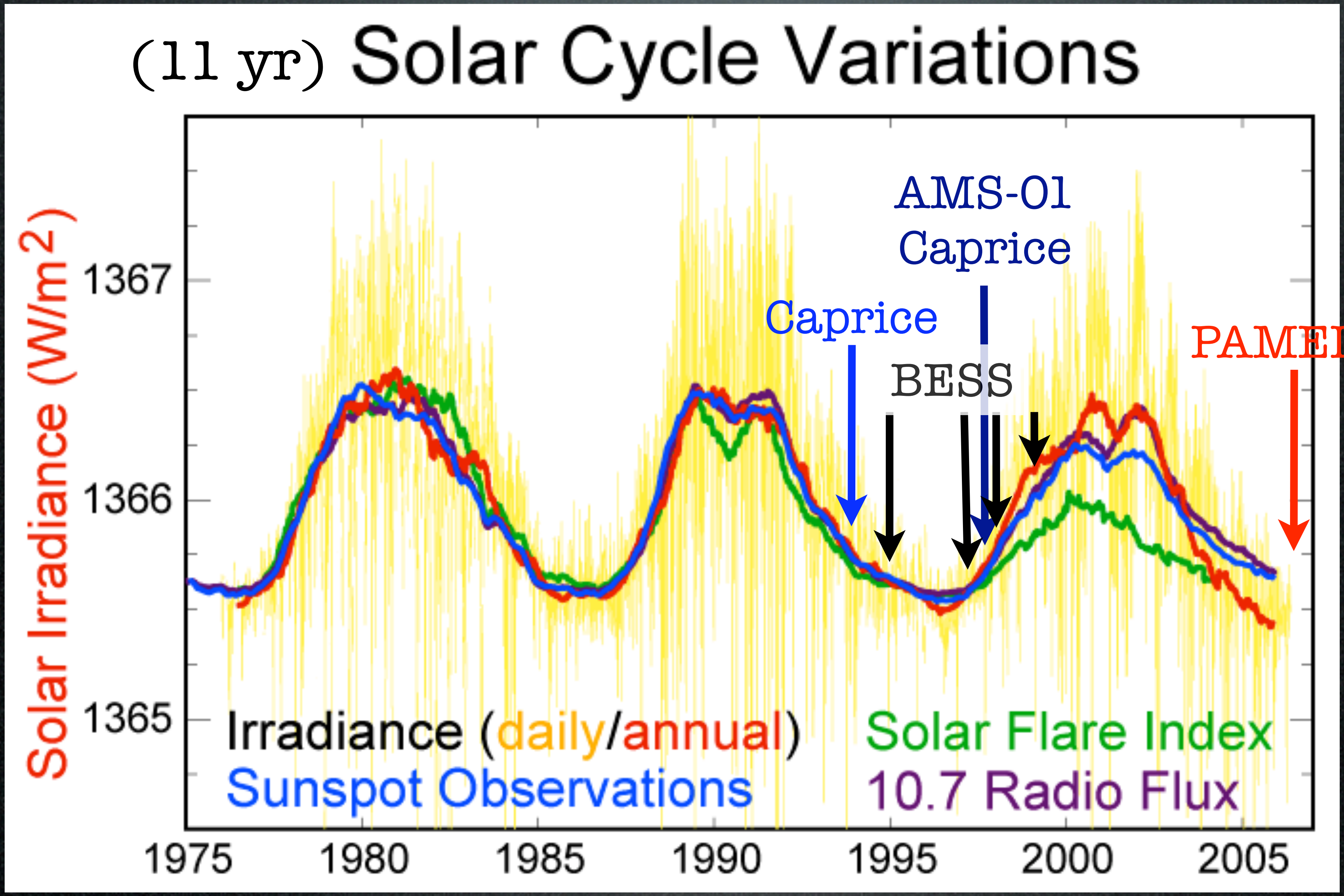
Solar wind Modulation of cosmic rays:

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

spectrum at Earth

spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV

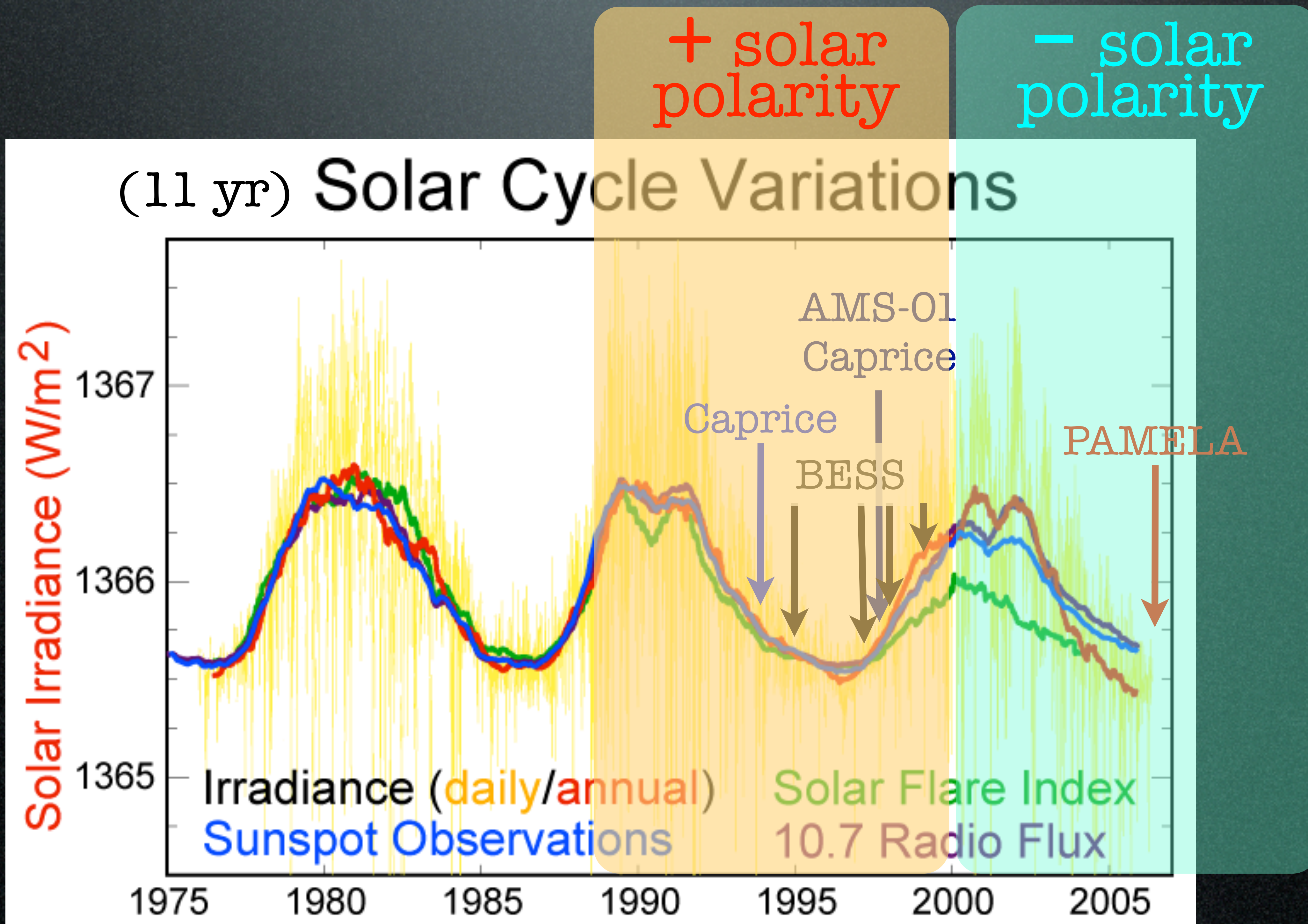


Indirect Detection

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:

main source: CR nuclei spallating on IS gas

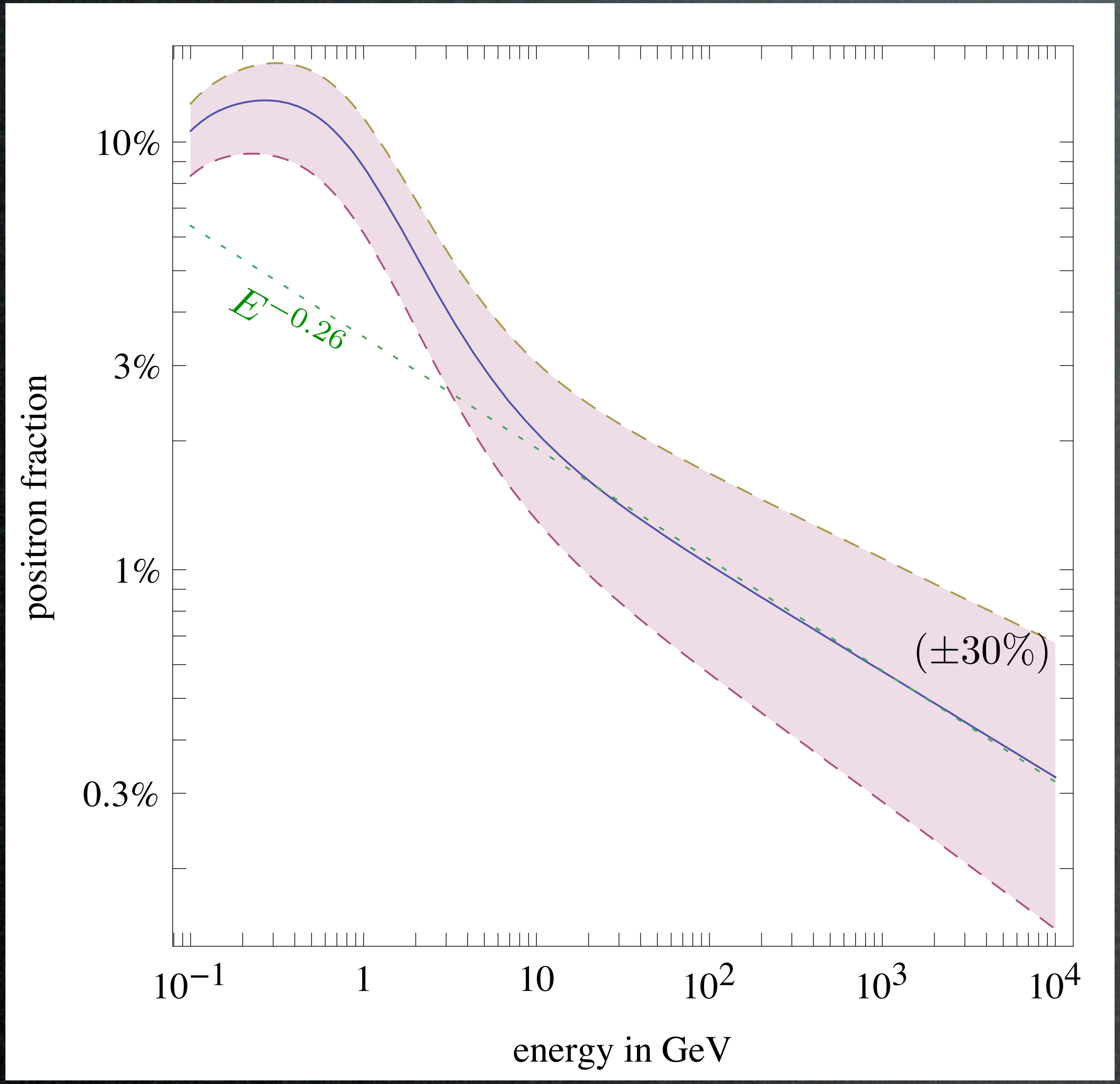
$$\Phi_{e^+}^{\rm bkg} = \frac{4.5\,E^{0.7}}{1+650\,E^{2.3}+1500\,E^{4.2}}$$

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

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.

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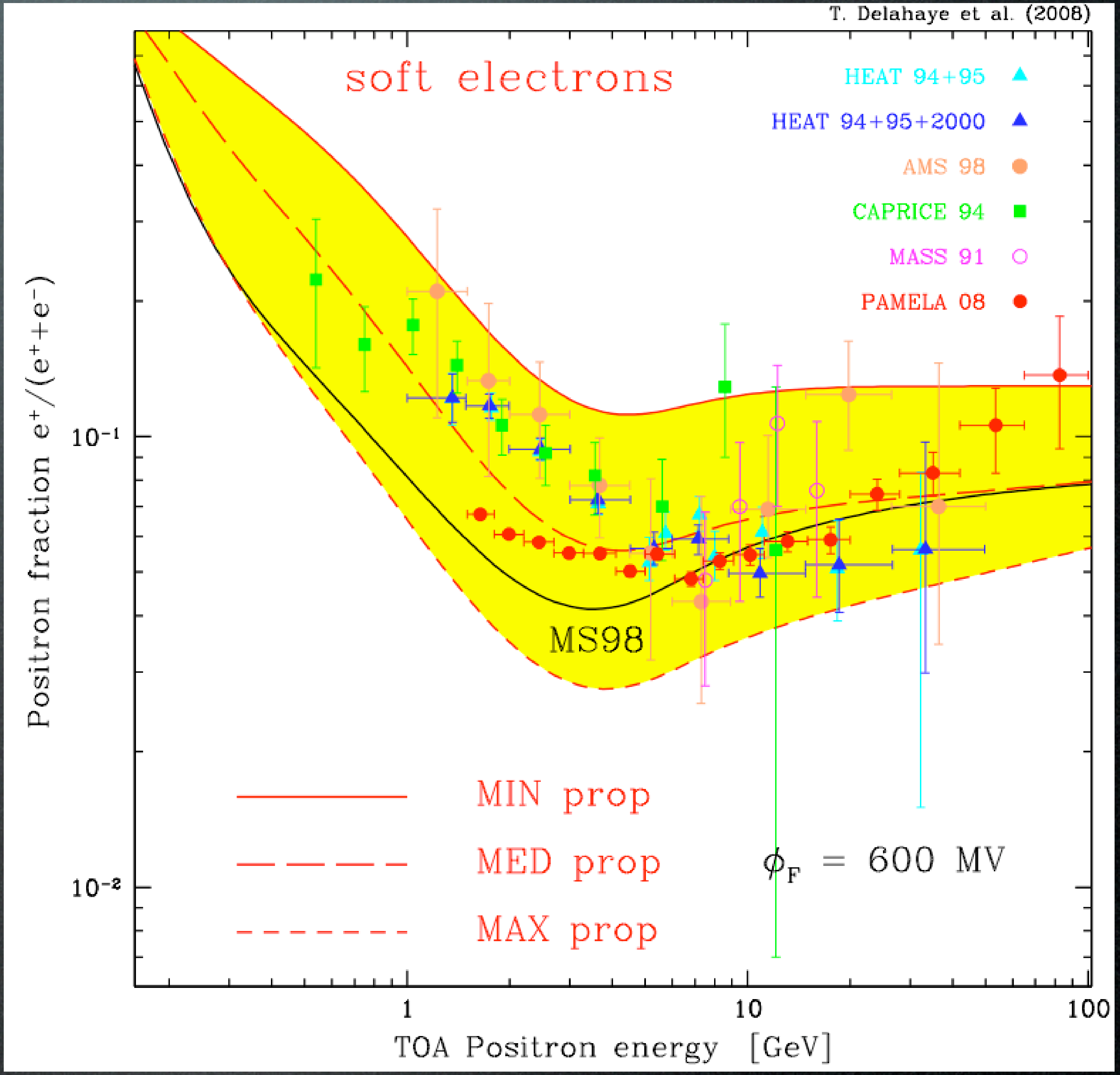
Indirect Detection

Background estimation for positrons:



using new measuremens of electron fluxes
Casadei, Bindi 2004

T.Delahaye et al., 0809.5268

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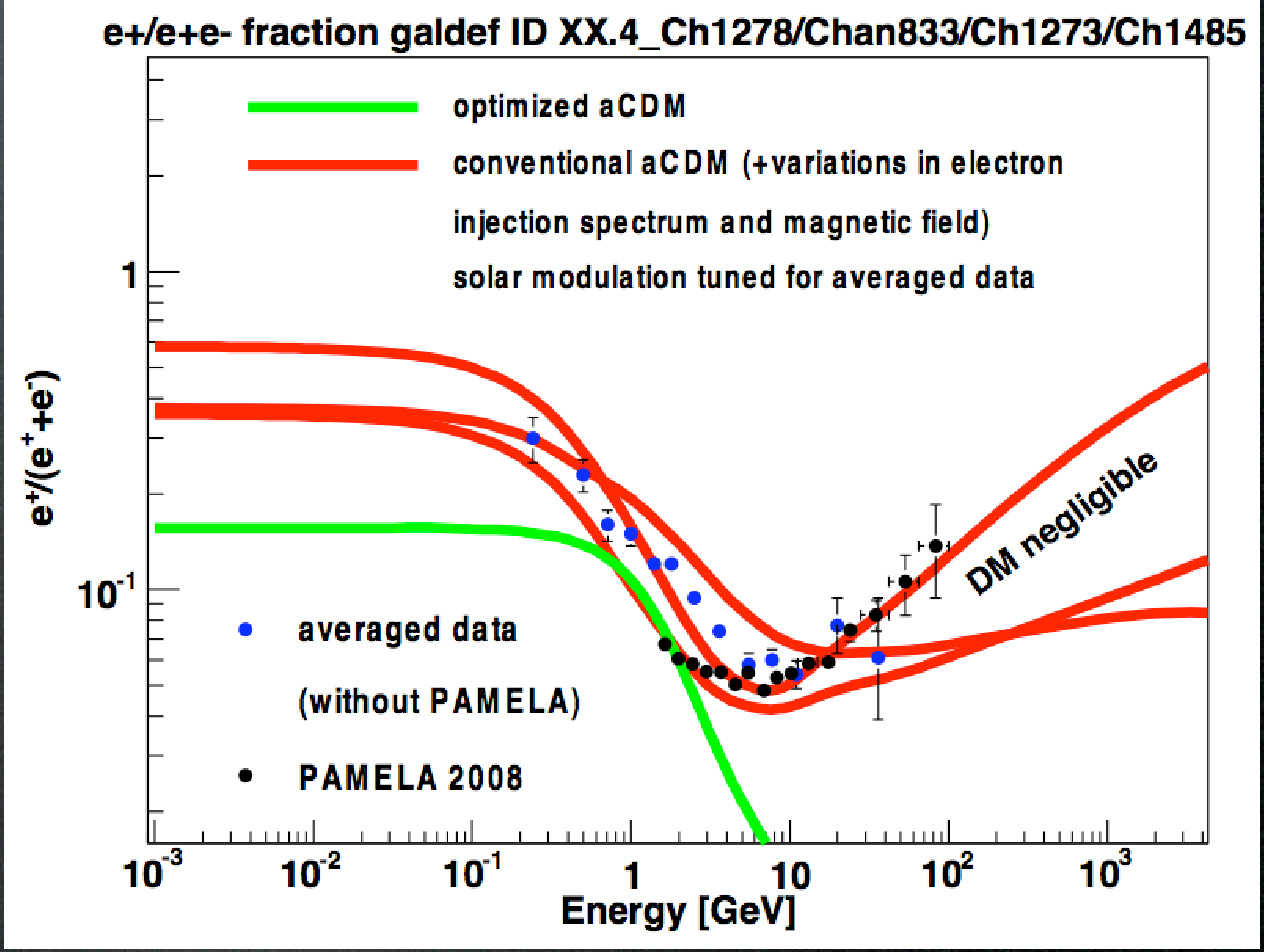
Indirect Detection

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)



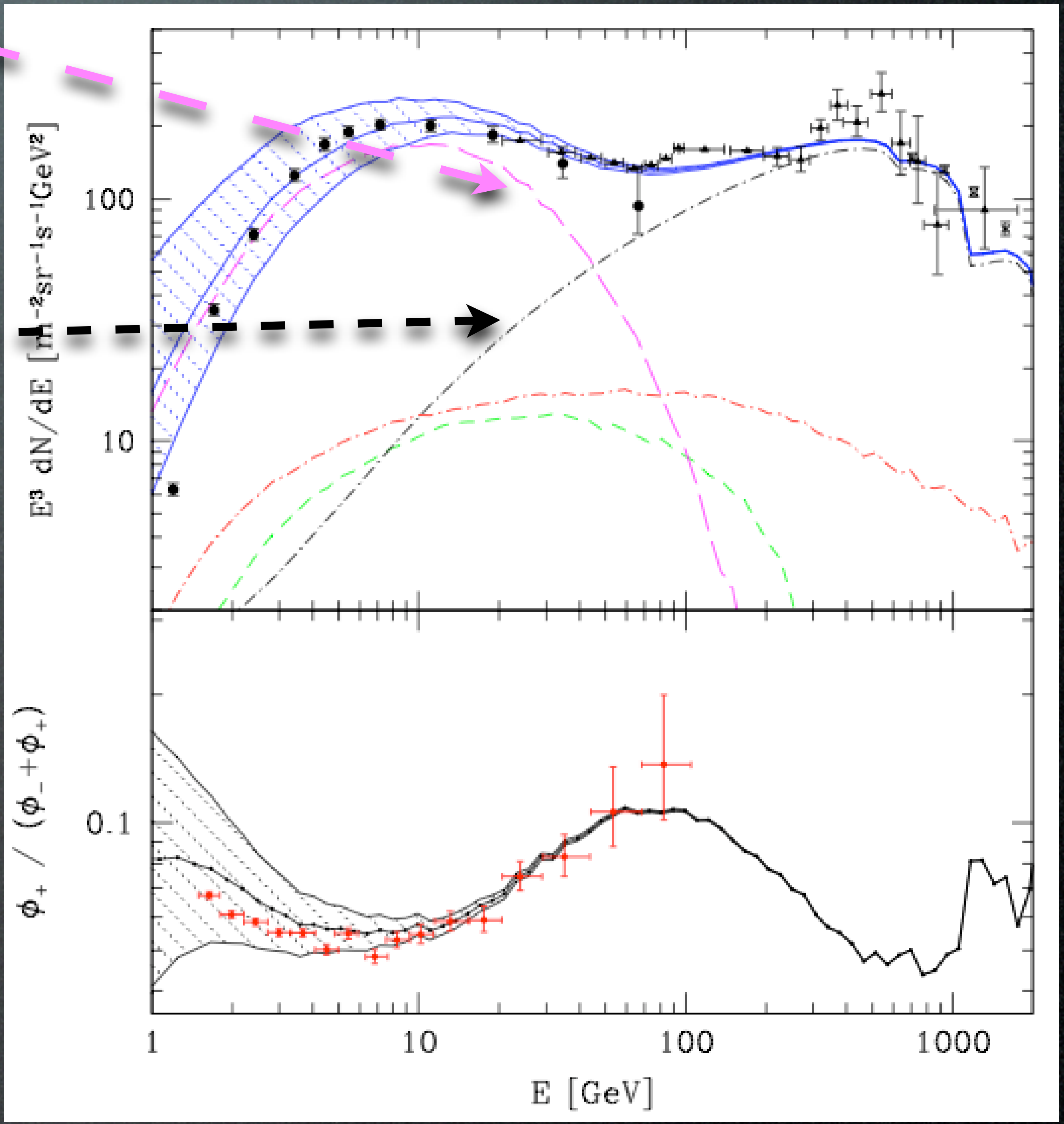
Gebauer 0811.2767

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

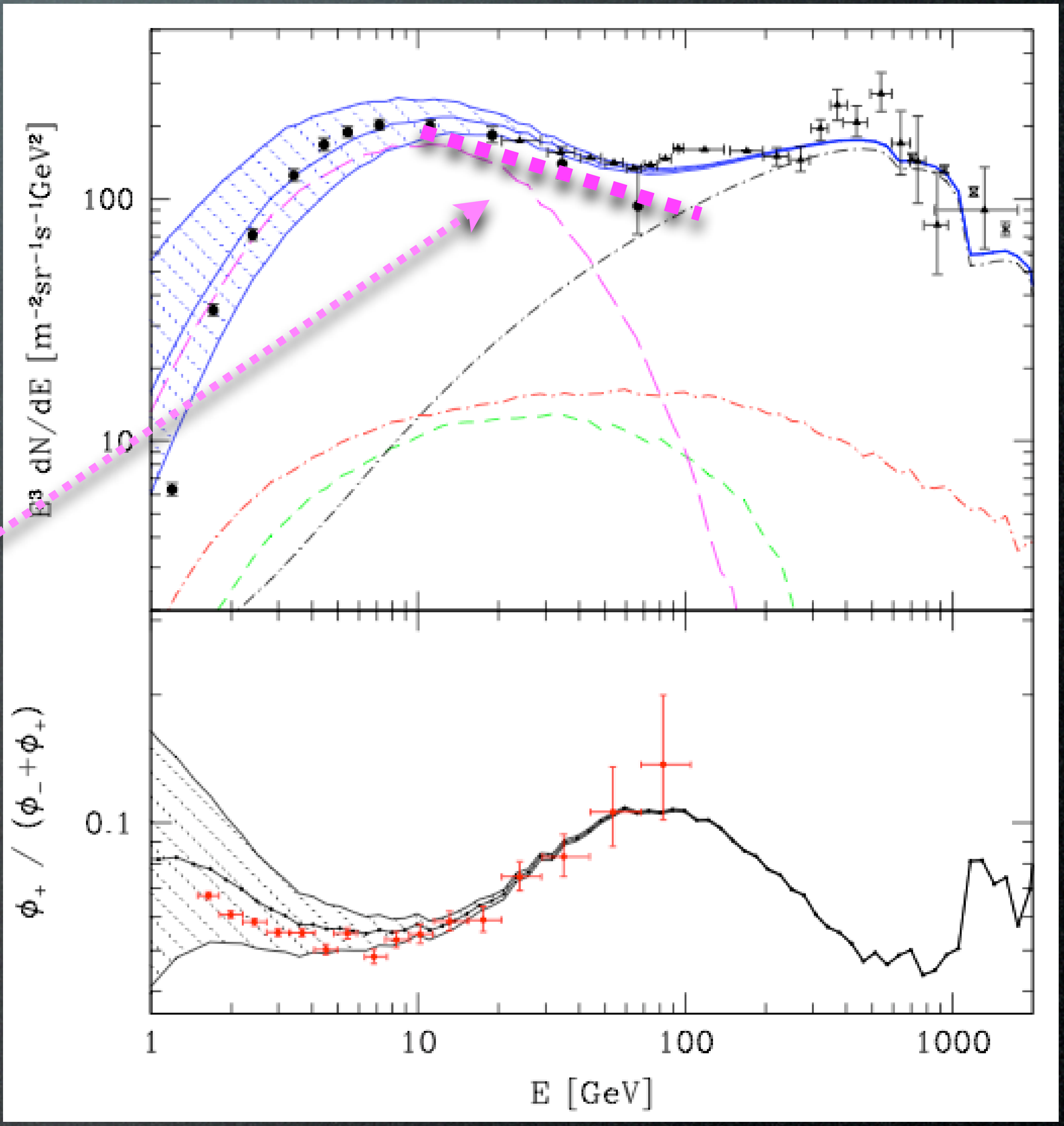
Indirect Detection

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...?



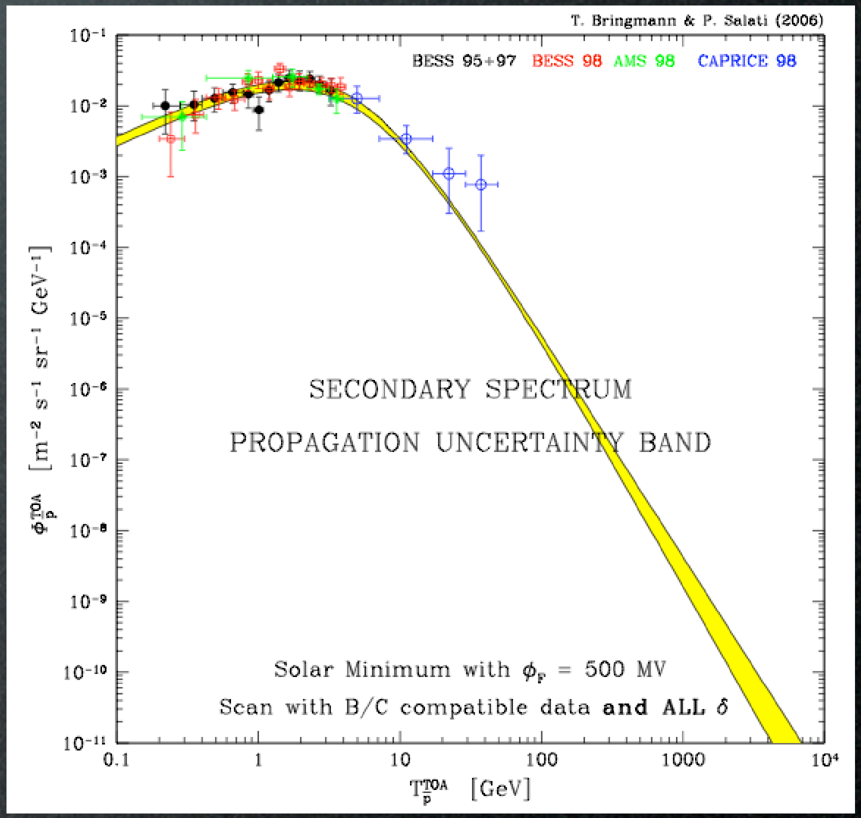
Tsvi Piran et al. 0902.0376

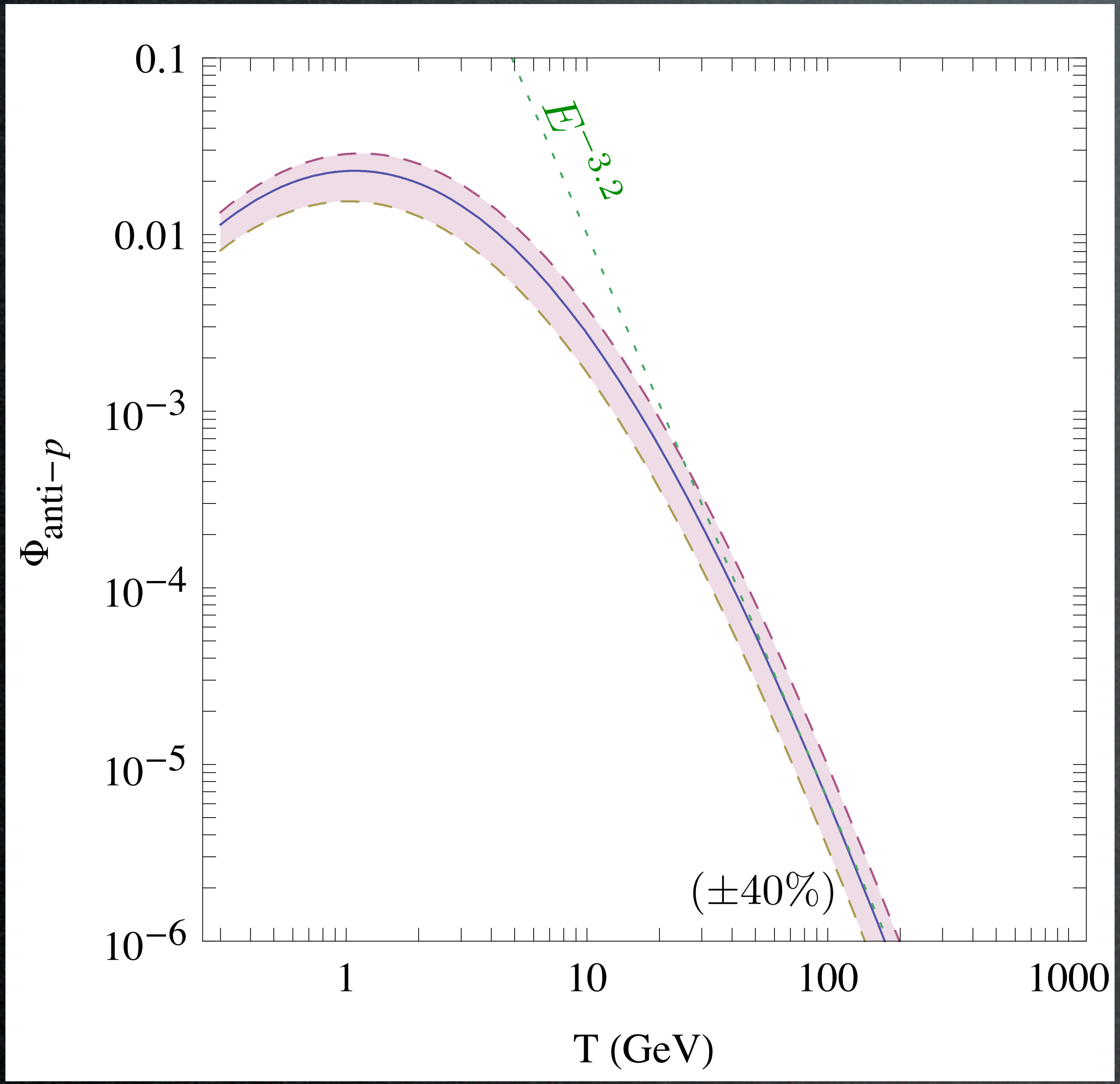
Indirect Detection

Background computations for antiprotons:

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

Bringmann, Salati 2006





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

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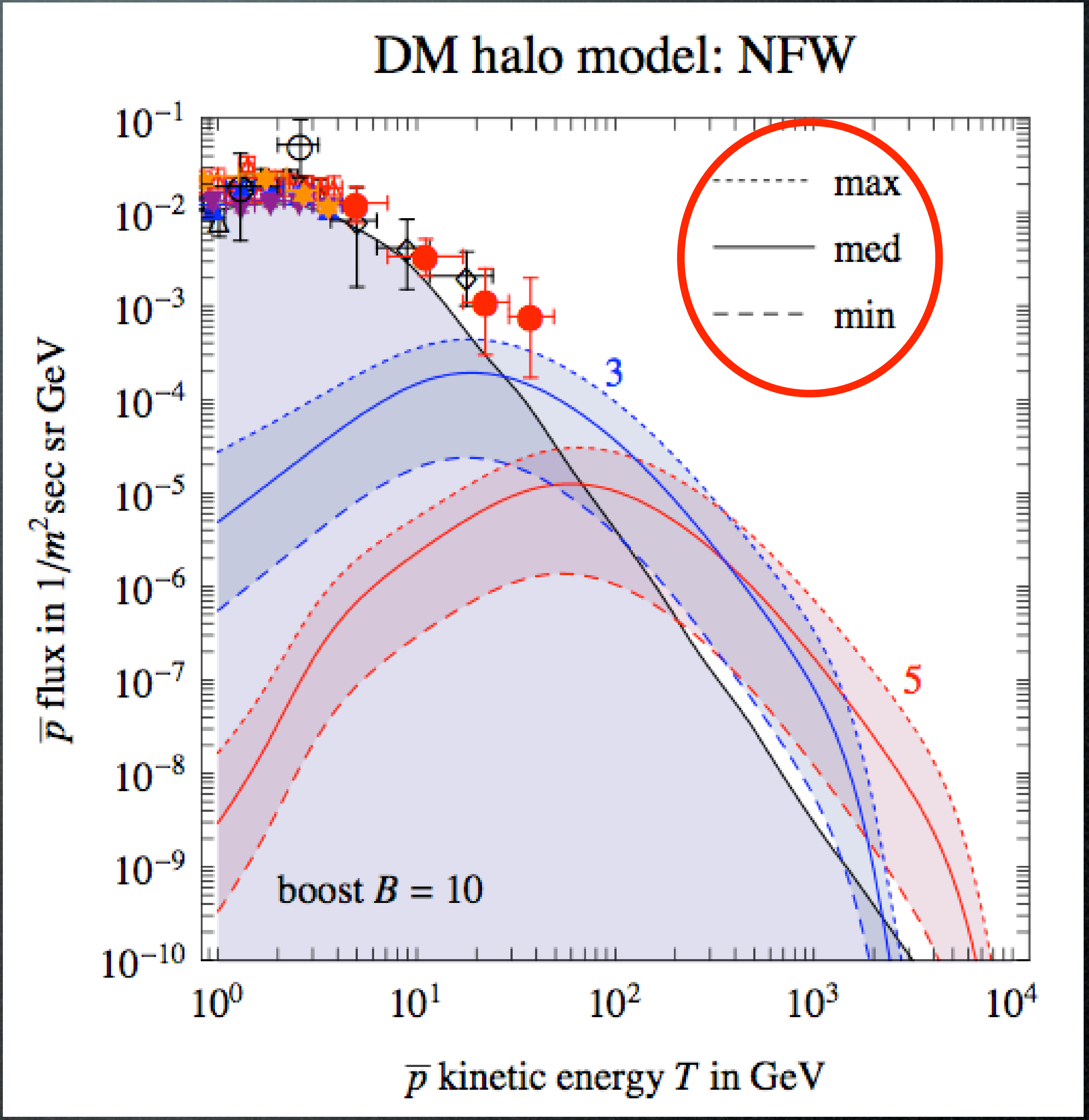
Indirect Detection

Results for anti-protons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



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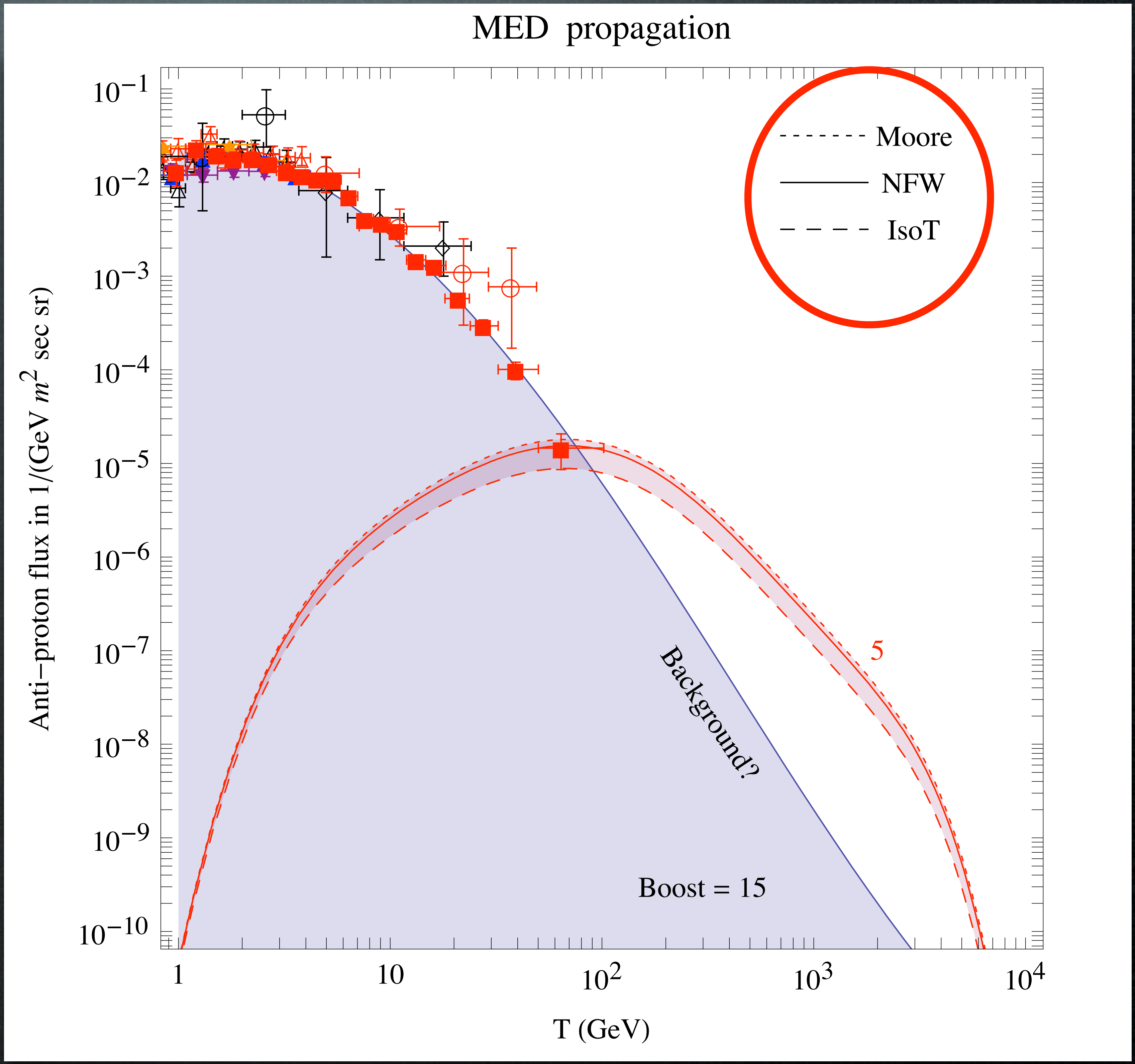
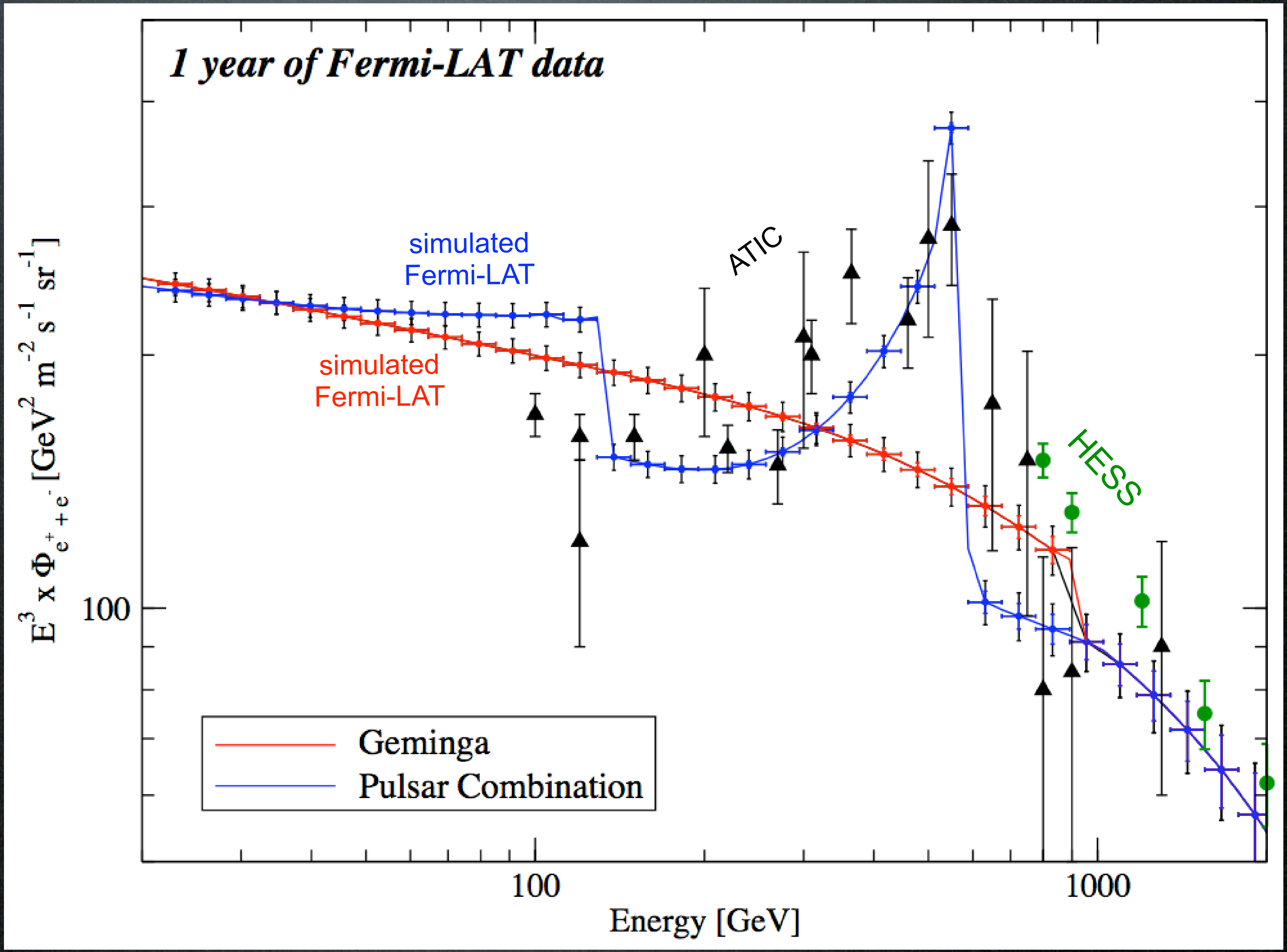


Data sets

Electrons + positrons from Fermi-LAT:

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



Profumo 0812.4457

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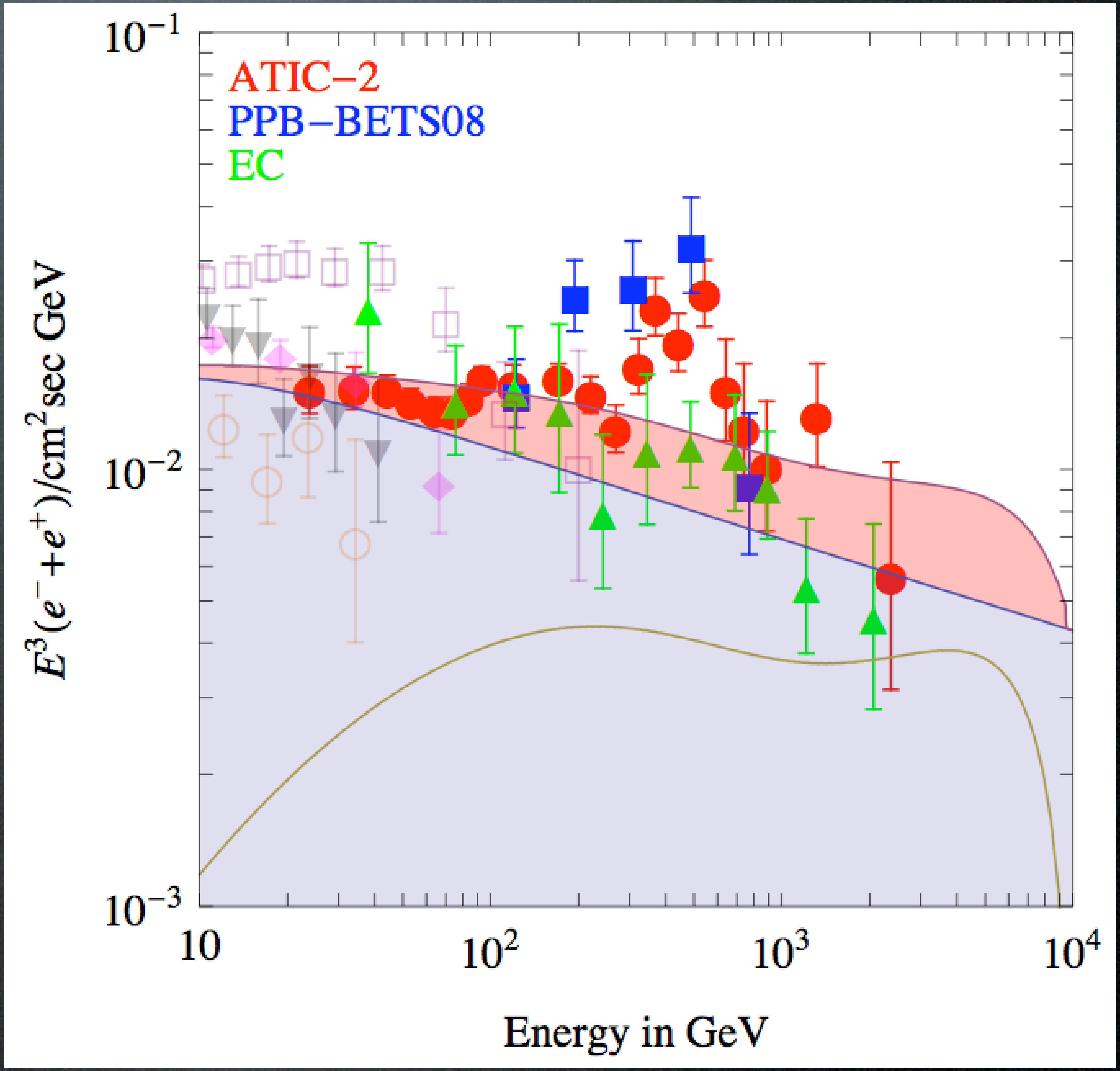
Results

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

...

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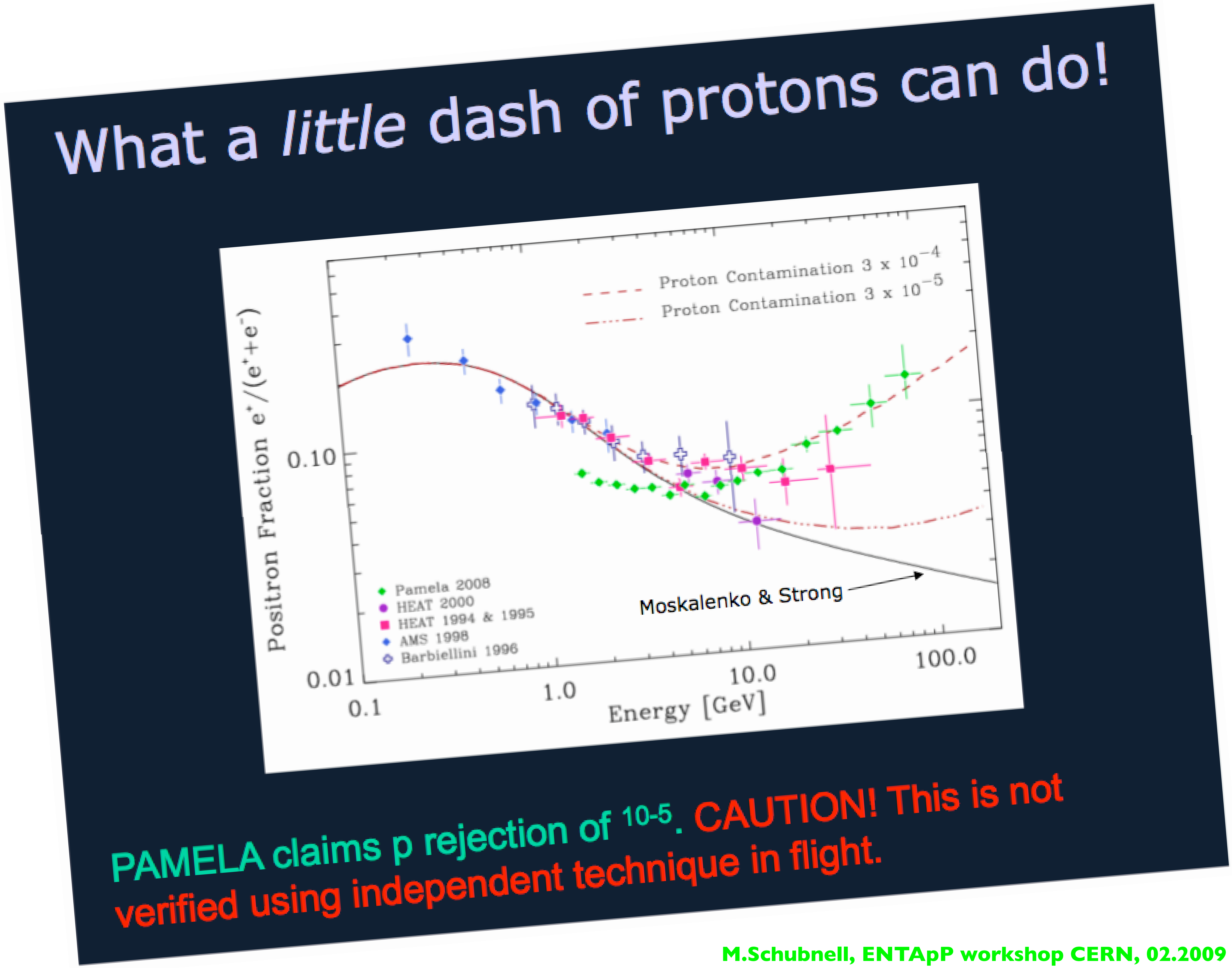
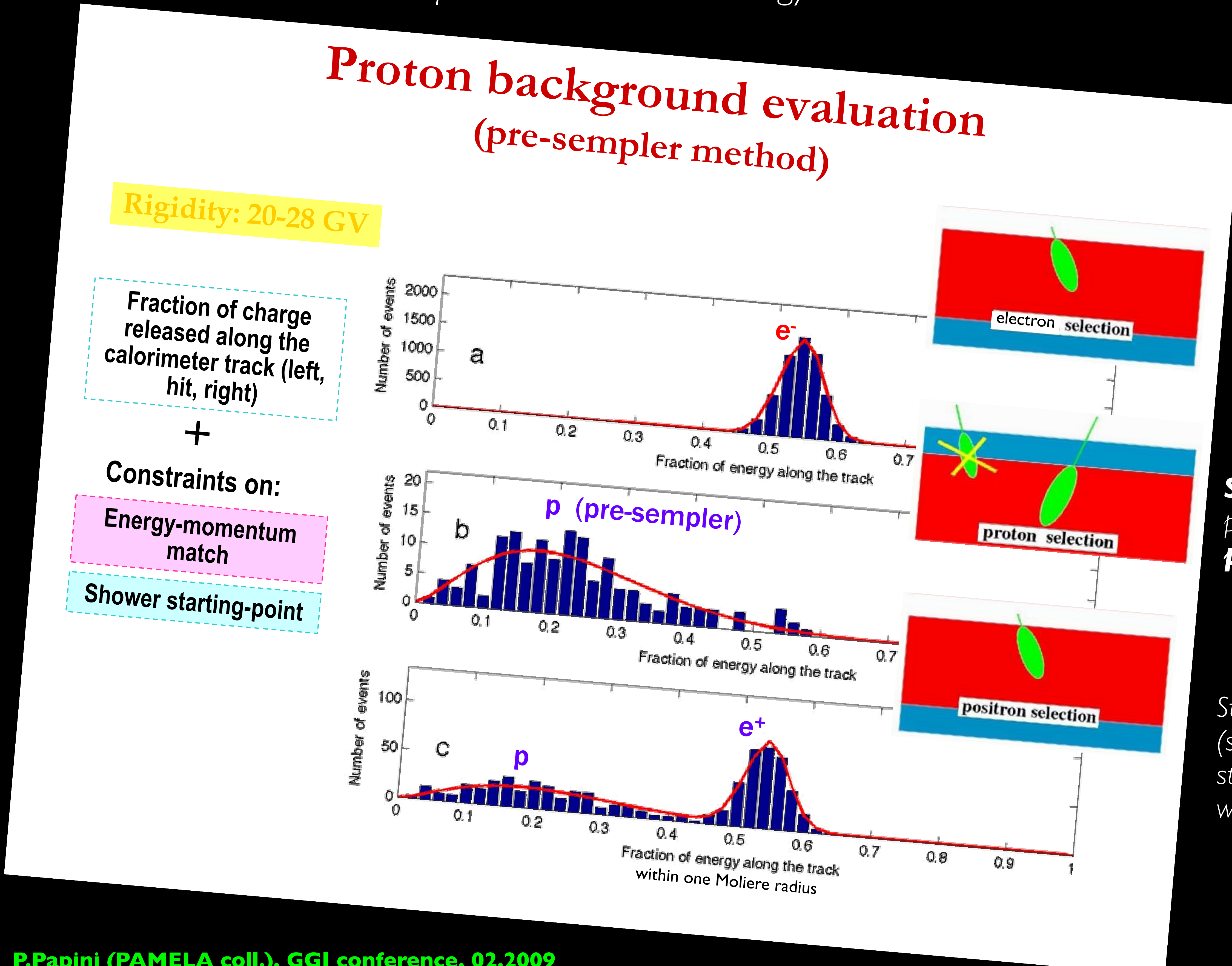
"PAMELA did not do in-flight checks of the p rejection rate"



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.



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