The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2045-7

Joint ICTP-INFN-SISSA Conference: Topical Issues in LHC Physics

29 June - 2 July, 2009

Dark Matter in Light of PAMELA and Fermi

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2 july 2009
Joint ICTP-INFN-SISSA Conference

Dark Matter in light of PAMELA and Fermi

Marco Cirelli
(CNRS, IPhT-CEA/Saclay)

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

Nuclear Physics B 753 (2006)
Nuclear Physics B 787 (2007)
Nuclear Physics B 800 (2008)
0808.3867 [astro-ph]
Nuclear Physics B 813 (2009)
JCAP03 009 (2009)
0904.1165
0904.3830
and work in progress

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Seeing Dark Matter in cosmic rays?!?

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and work in progress

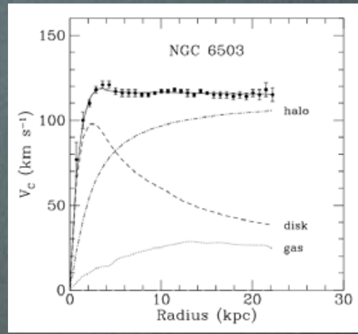
Questions

1. Are we seeing Dark Matter in cosmic rays?

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

The Evidence for DM

1) galaxy rotation curves

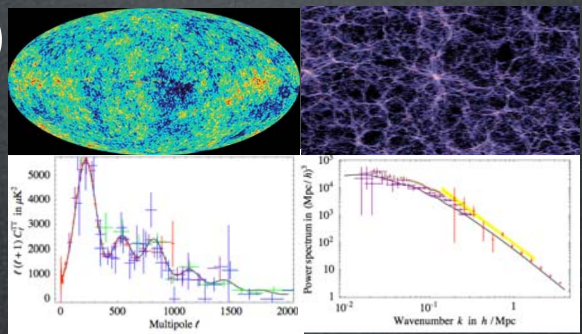


$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

$\Omega_M \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)



$\Omega_M \approx 0.26 \pm 0.05$

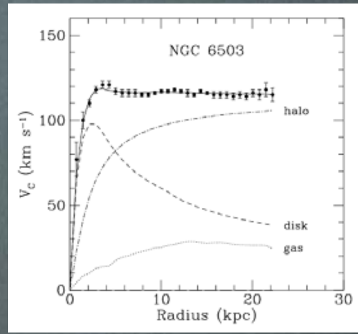
DM exists.

It consists of a particle.

Permeates galactic haloes.

The Evidence for DM

1) galaxy rotation curves



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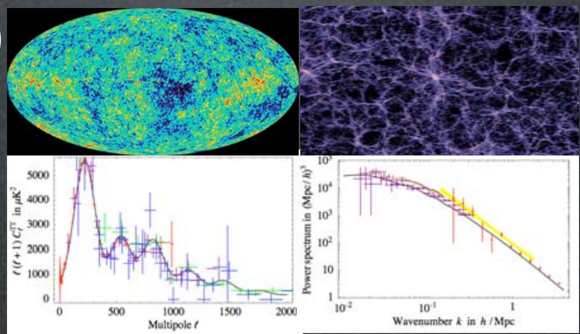


$\Omega_M \approx 0.26 \pm 0.05$

What is the DM??

It consists of a particle.

Permeates galactic haloes.

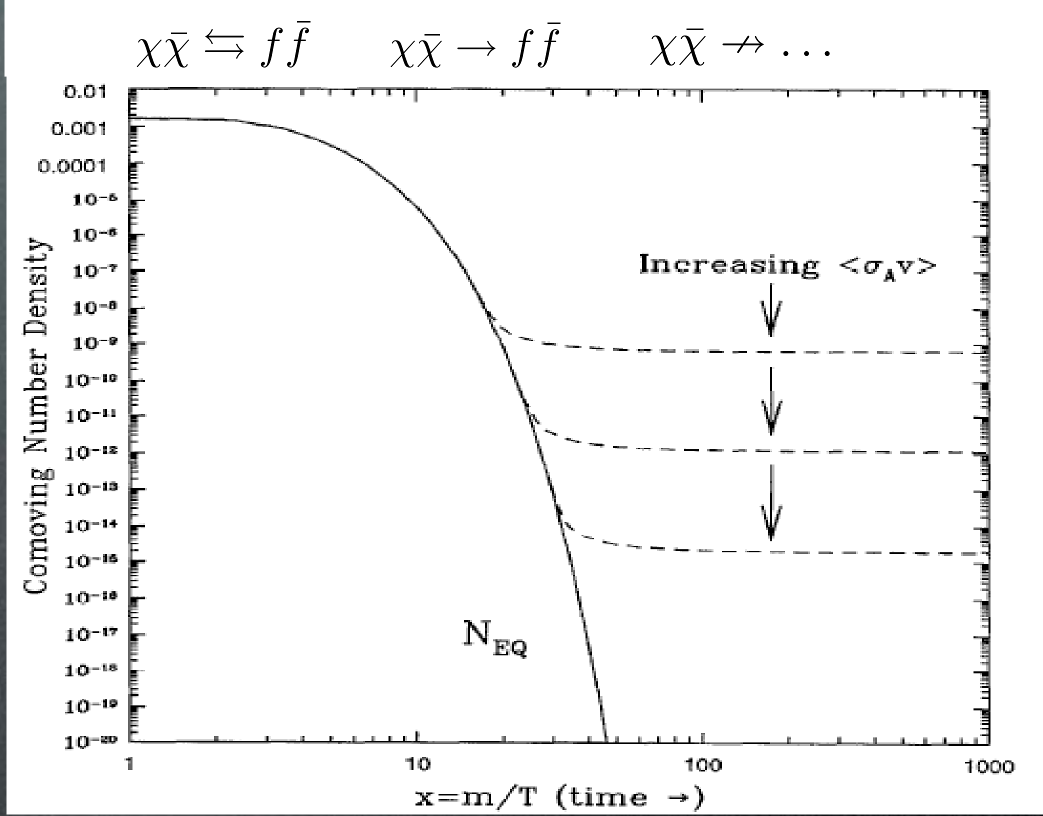
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

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

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

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



Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

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
  - $\bar{D}$ from annihil in galactic halo or center
  - $\nu, \bar{\nu}$ from annihil in massive bodies

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
- $\bar{D}$ from annihil in galactic halo or center
- $\nu, \bar{\nu}$ from annihil in massive bodies

DM detection

direct detection

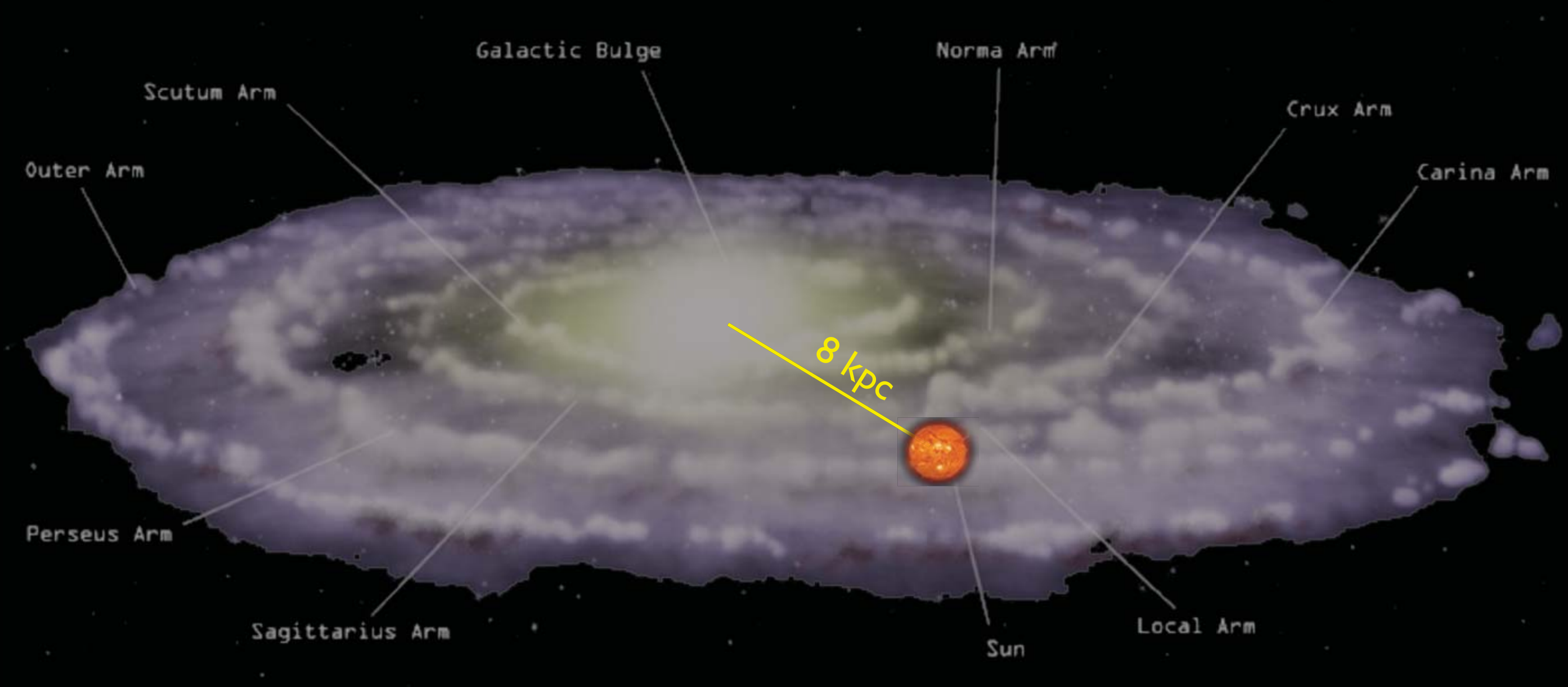
production at colliders

indirect

- γ from annihil in galactic halo or center (line + continuum)
- e^+ from annihil in galactic halo or center
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{D}$ from annihil in galactic halo or center
- $\nu, \bar{\nu}$ from annihil in massive bodies

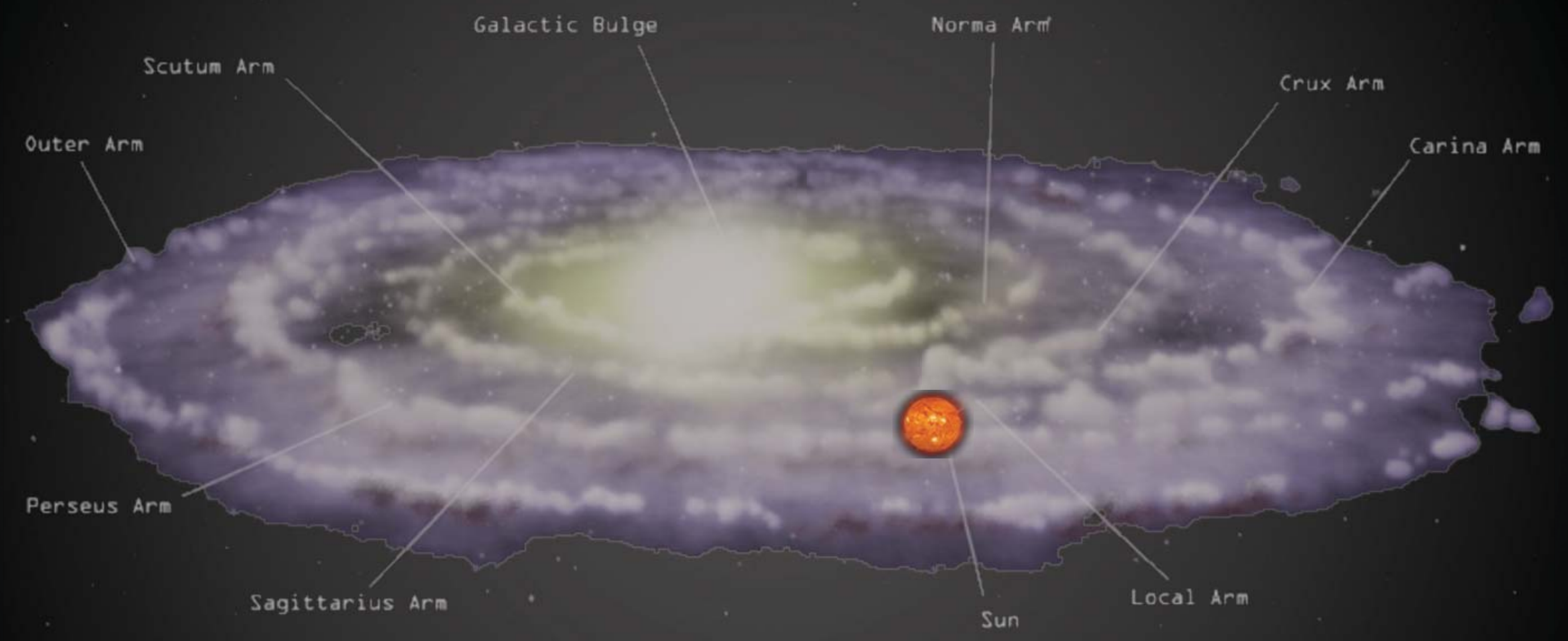
Indirect Detection

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



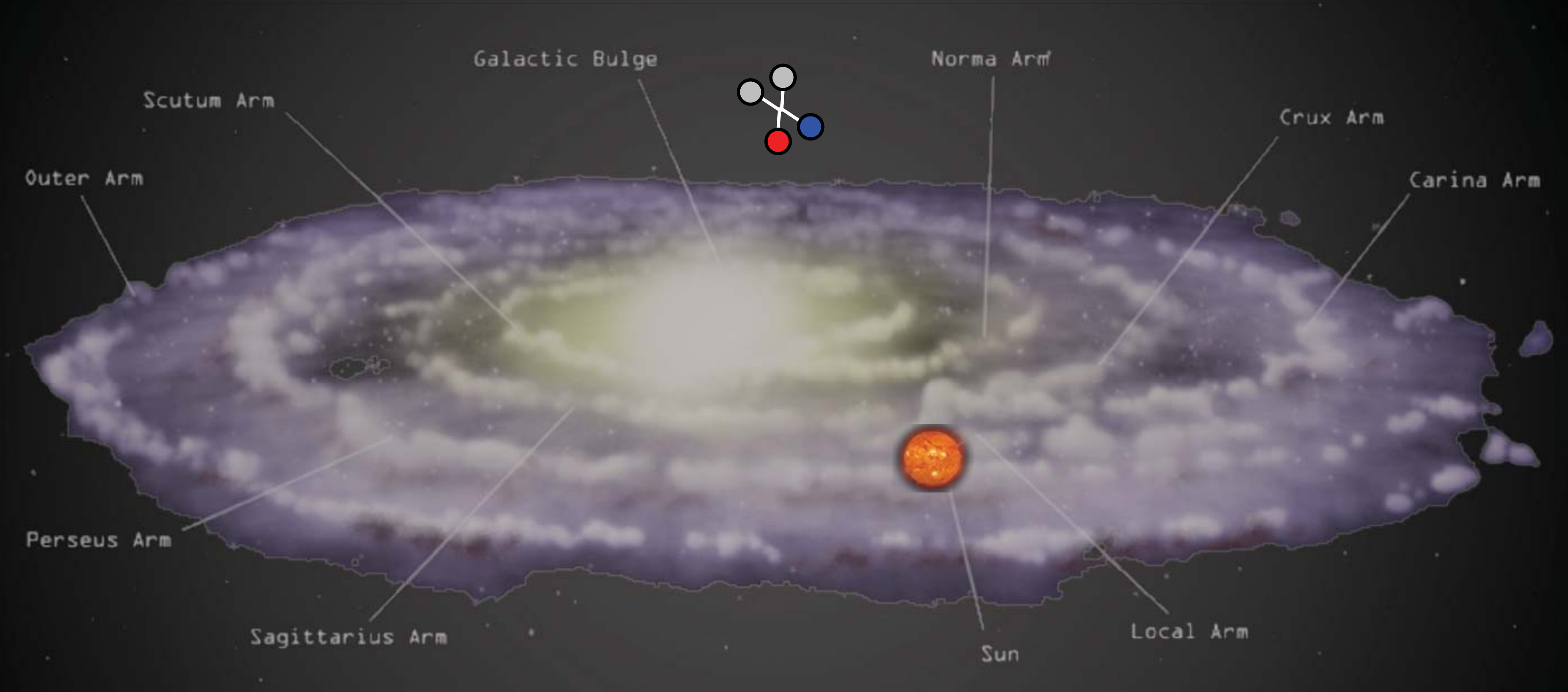
Indirect Detection

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



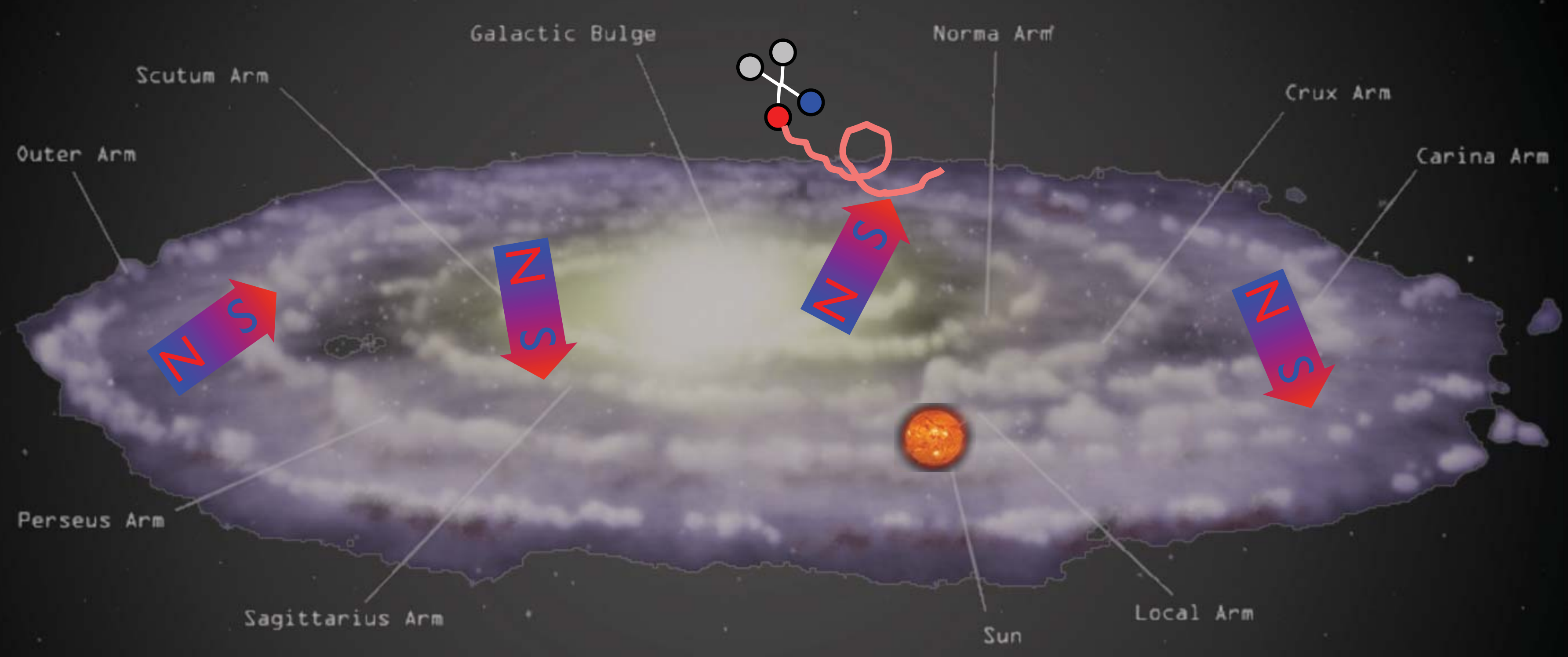
Indirect Detection

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



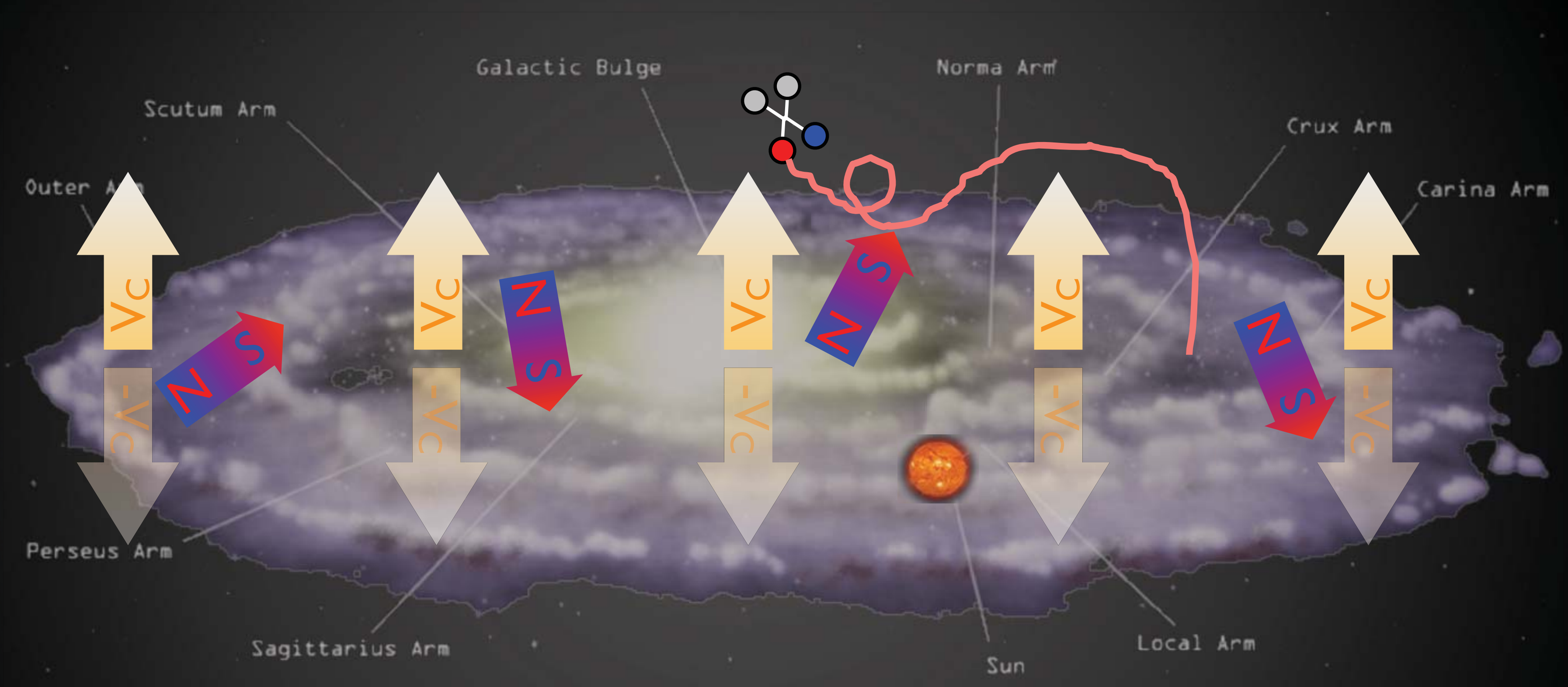
Indirect Detection

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



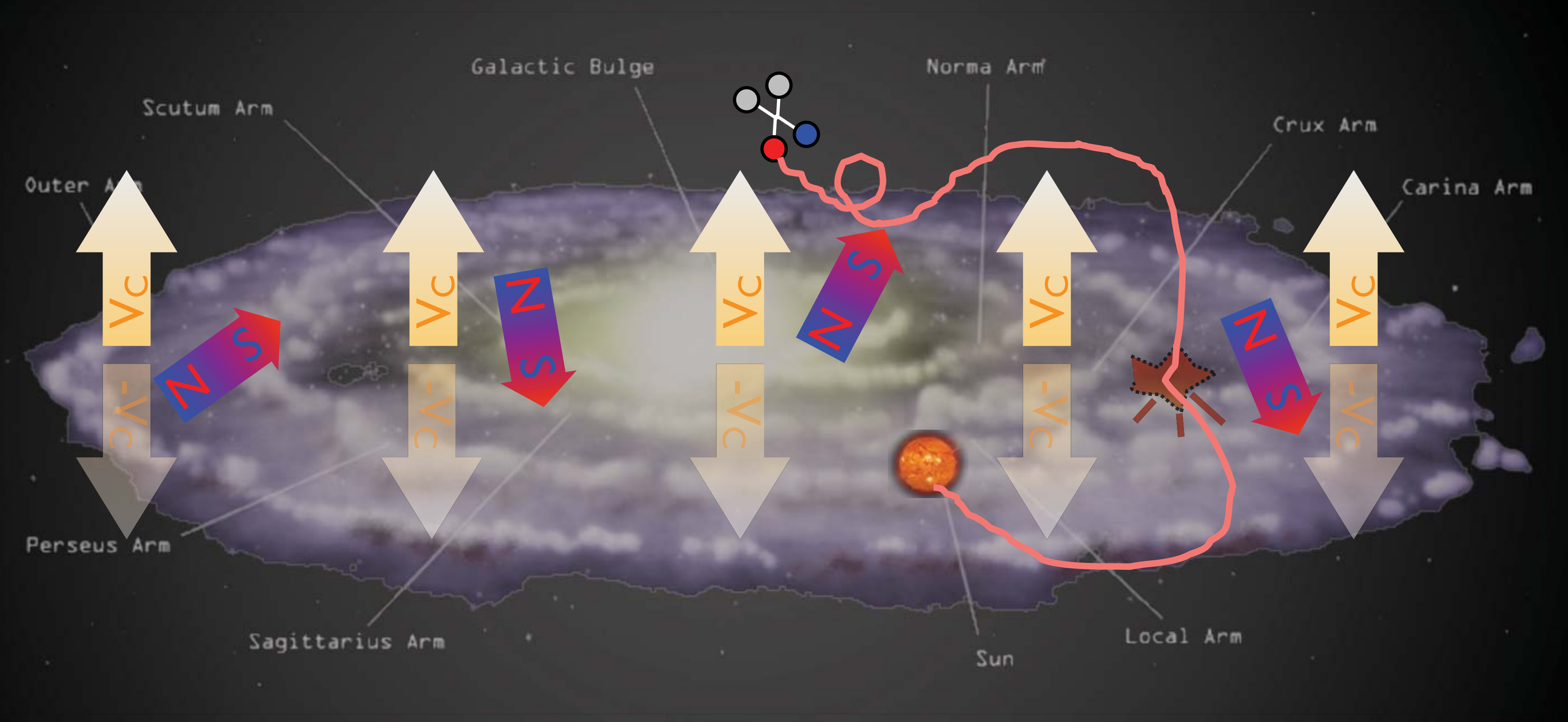
Indirect Detection

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



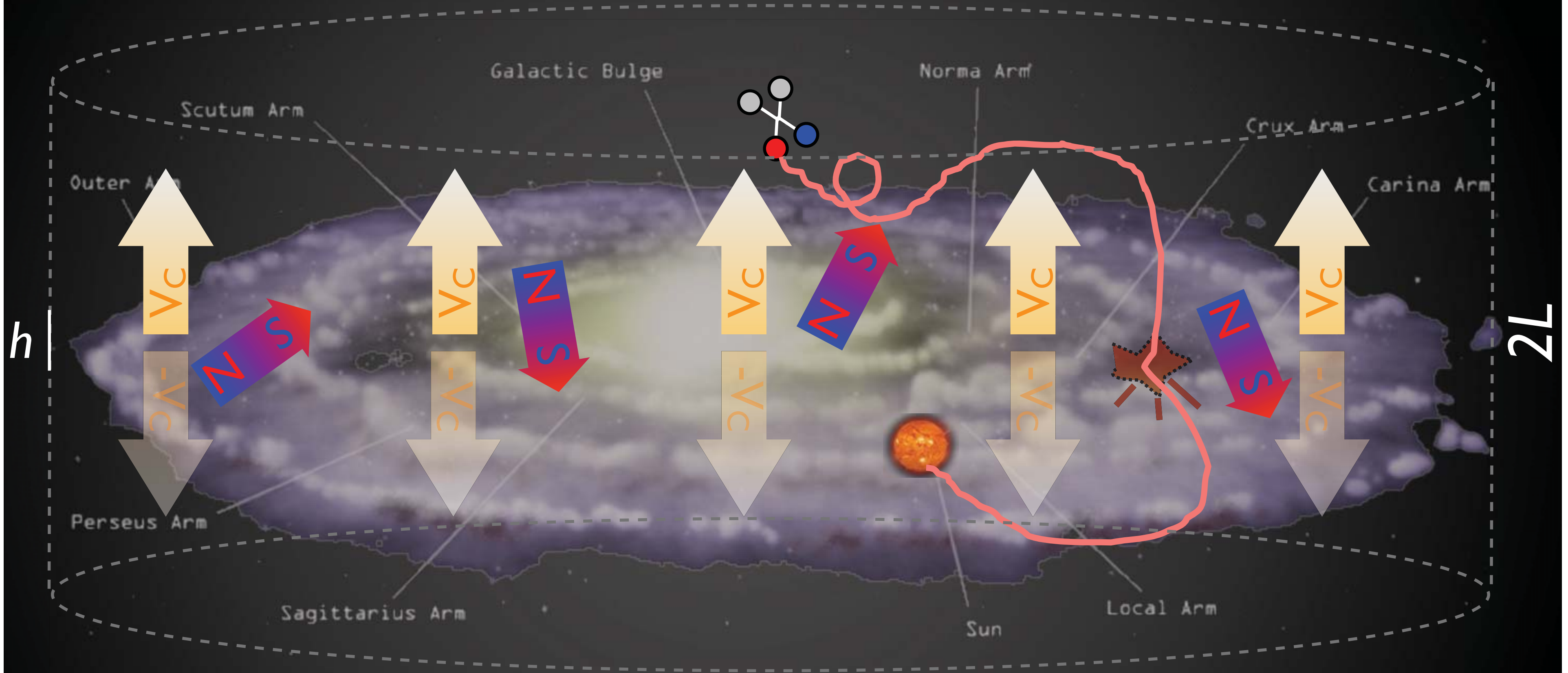
Indirect Detection

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



Indirect Detection

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



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

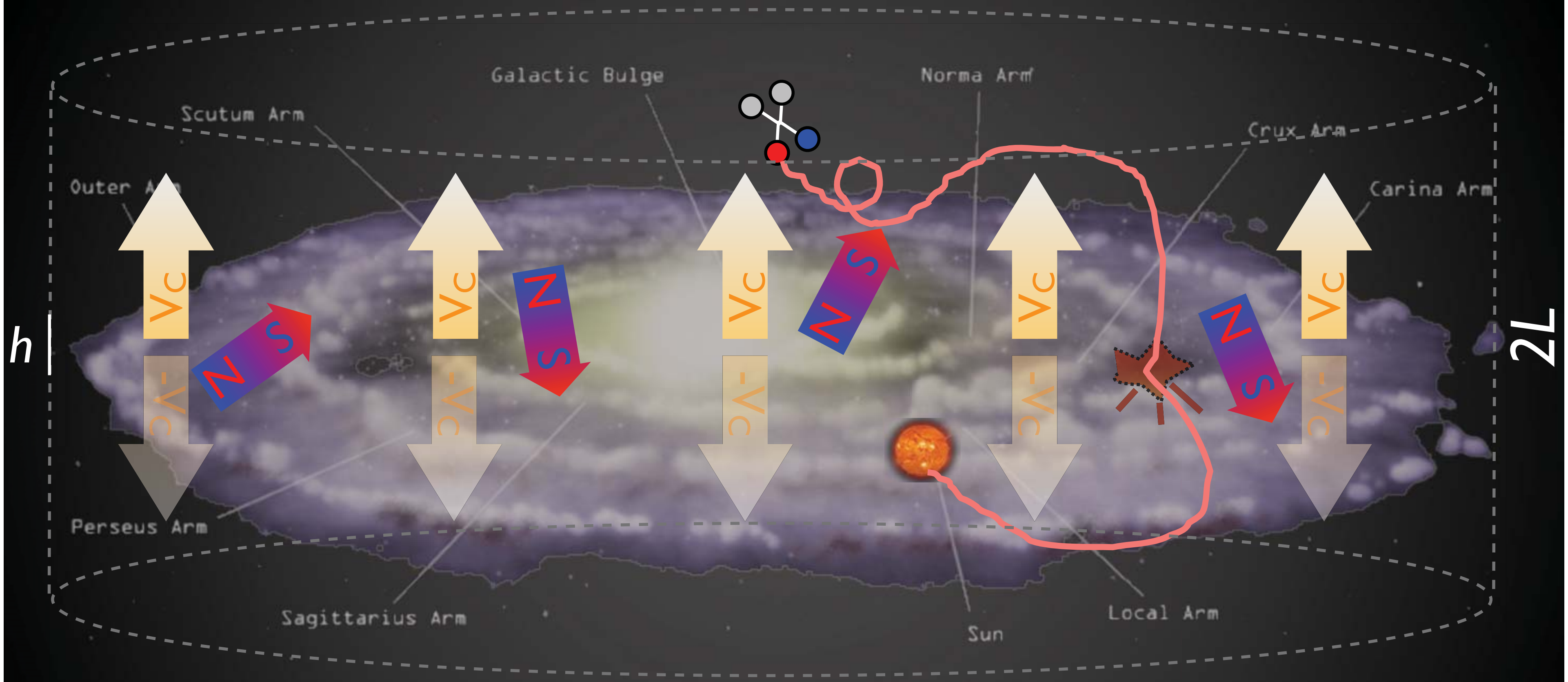
spectrum

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

diffusion energy loss convective wind source spallations

Indirect Detection

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



What sets the overall expected flux?

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

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:

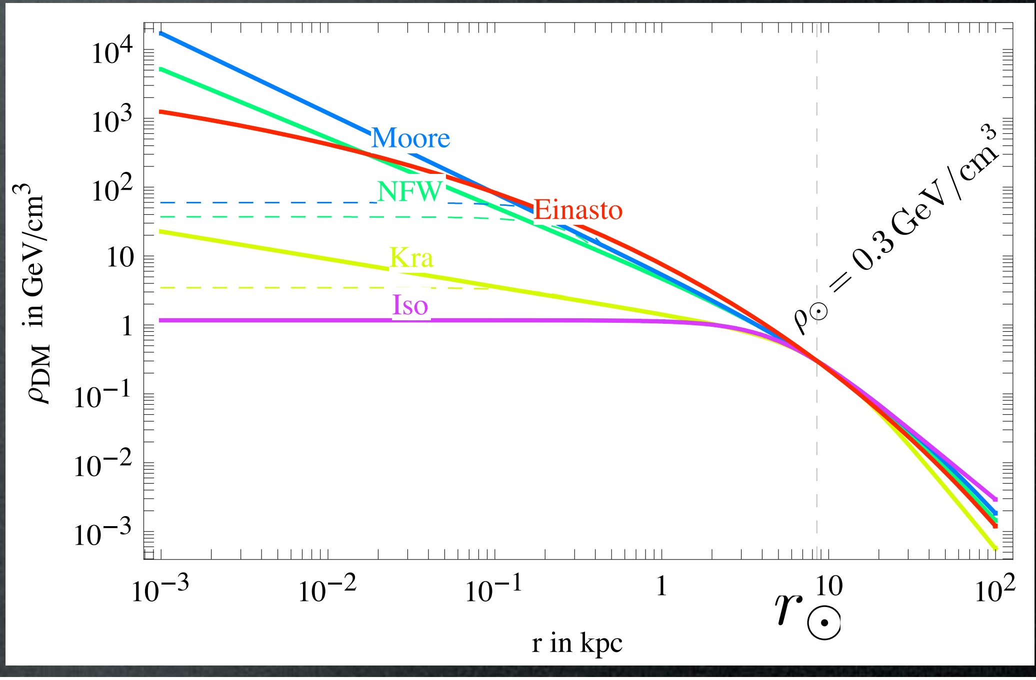
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

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

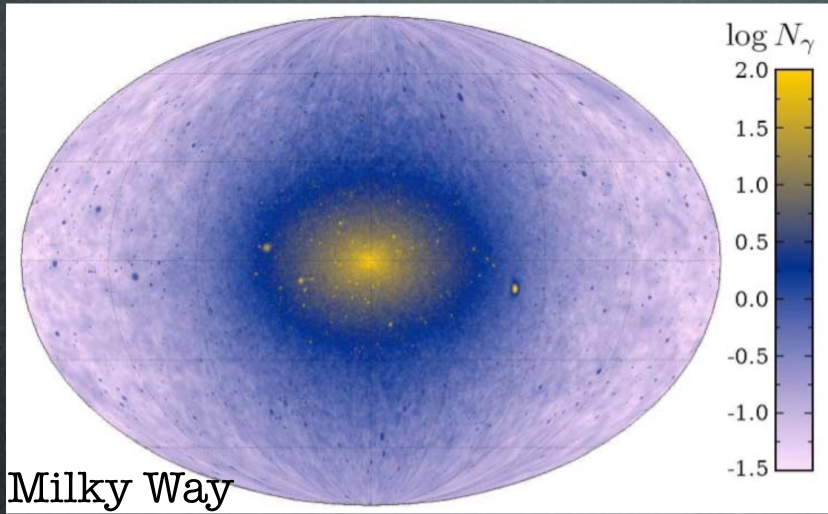


cuspy: NFW, Moore
mild: Einasto
smooth: isothermal

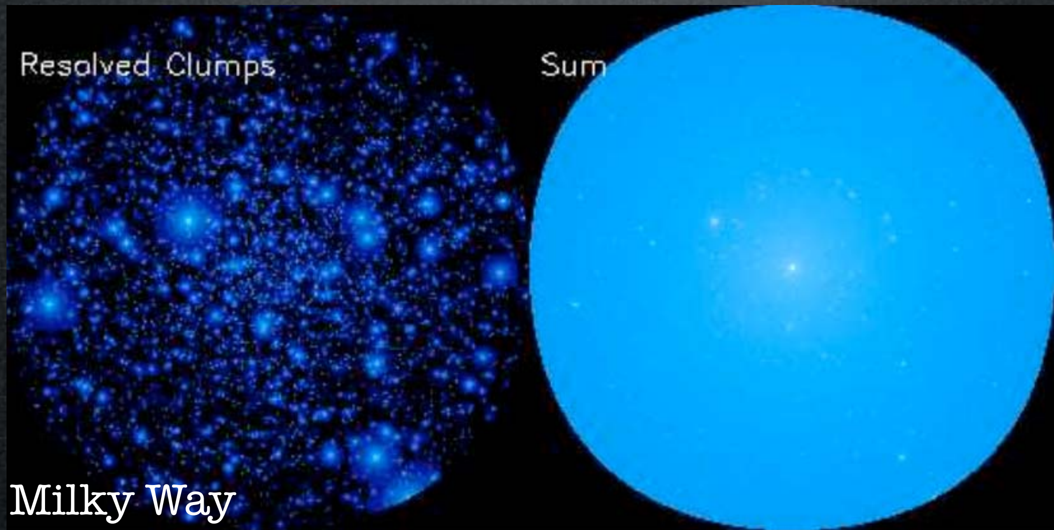
Indirect Detection

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

For illustration:



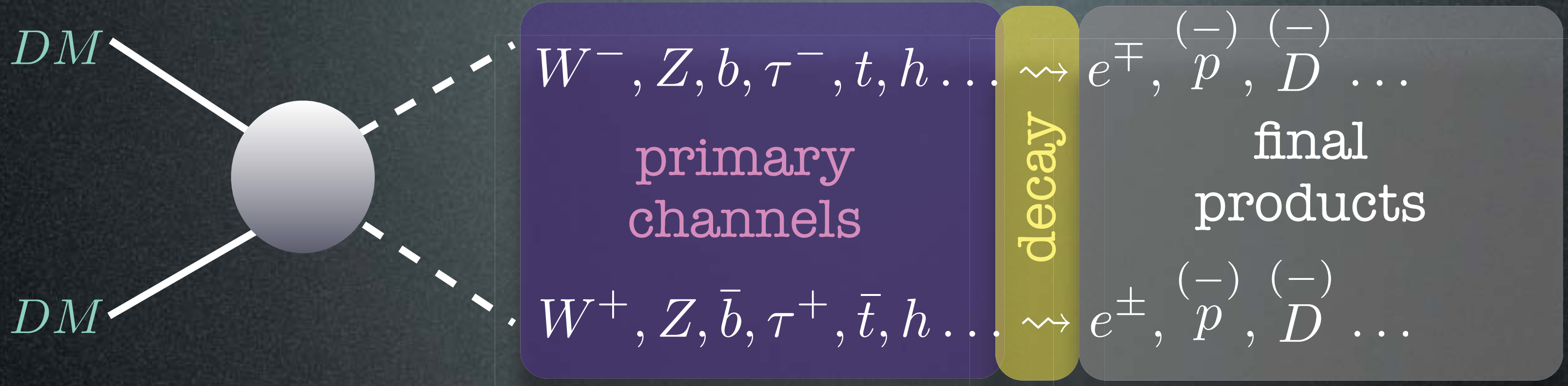
Kuhlen, Diemand, Madau 2007

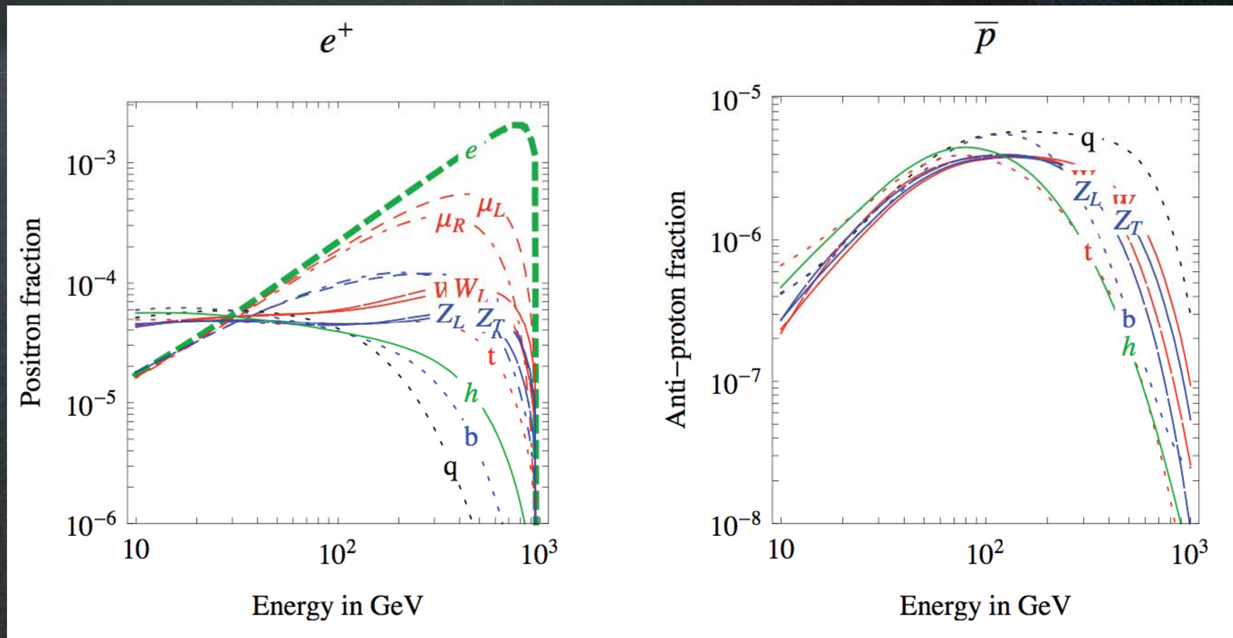


Bertone, Branchini, Pieri 2007

Computing the theory predictions

Spectra at production





So what are the particle physics parameters?

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

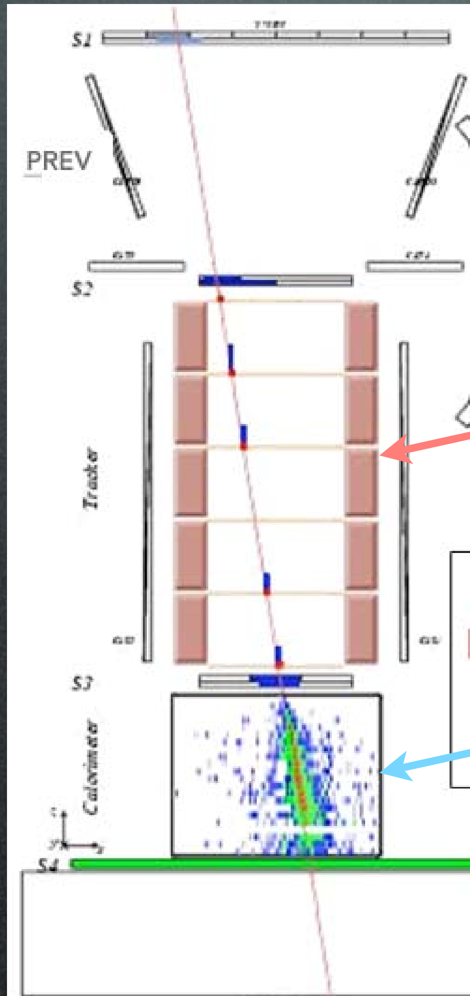
Comparing with data

Data sets

Positrons from PAMELA:

Payload for
Anti-
Matter
Exploration and
Light-nuclei
Astrophysics

92 GeV positron event



calibrated on accelerator fluxes

magnetic spectrometer:
charge and energy

calorimeter: $e^{\pm}$ vs $p/\bar{p}$

(make showers) (swipe thru)

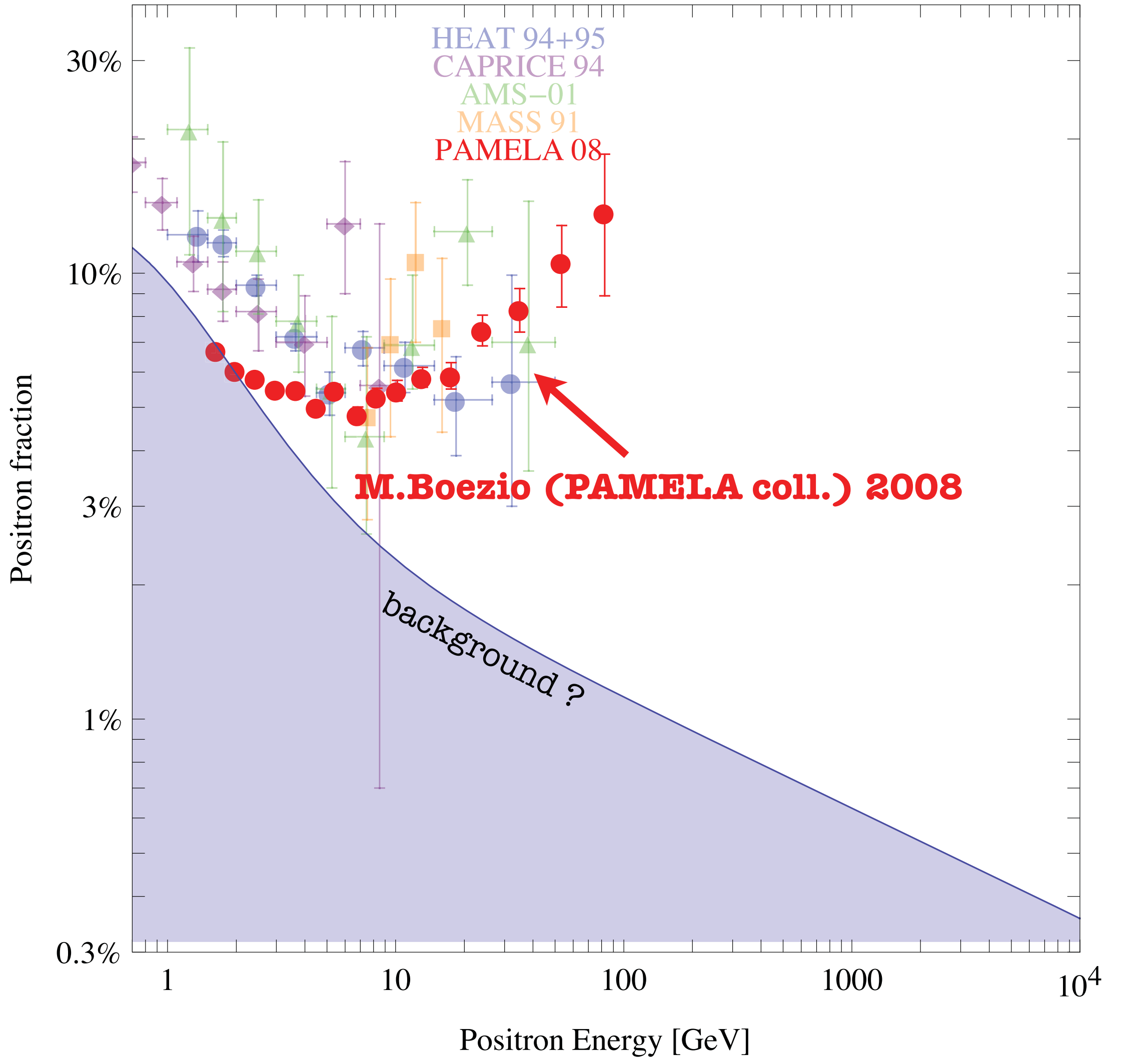
Big challenge: backgnd contamination
from p (10^4 more numerous at 100 GeV)

Data sets

Positrons from PAMELA:

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

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



(9430 e⁺ collected)

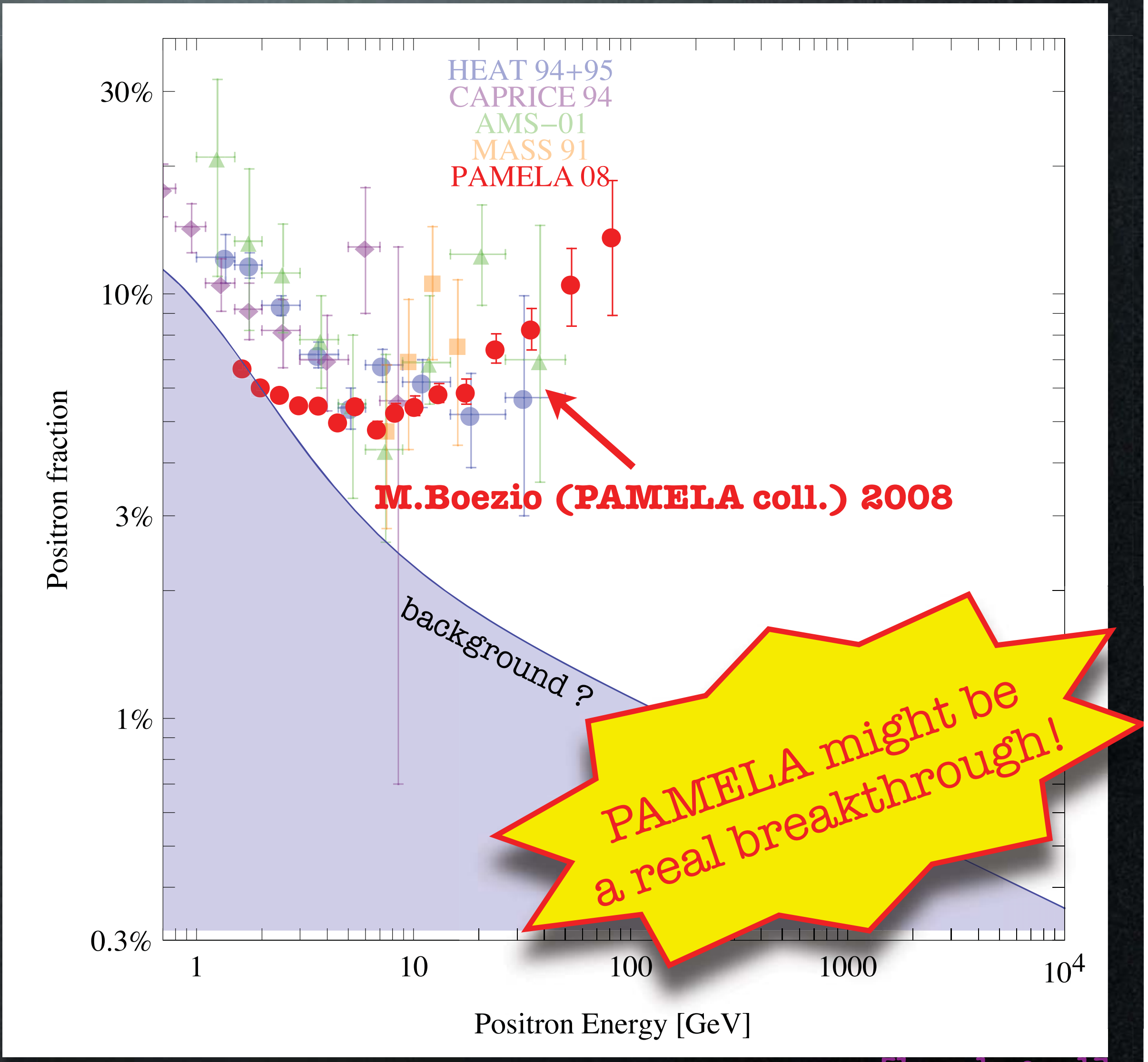
(errors statistical only, that's why larger at high energy)

[backgnd]

Data sets

Positrons from PAMELA:

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

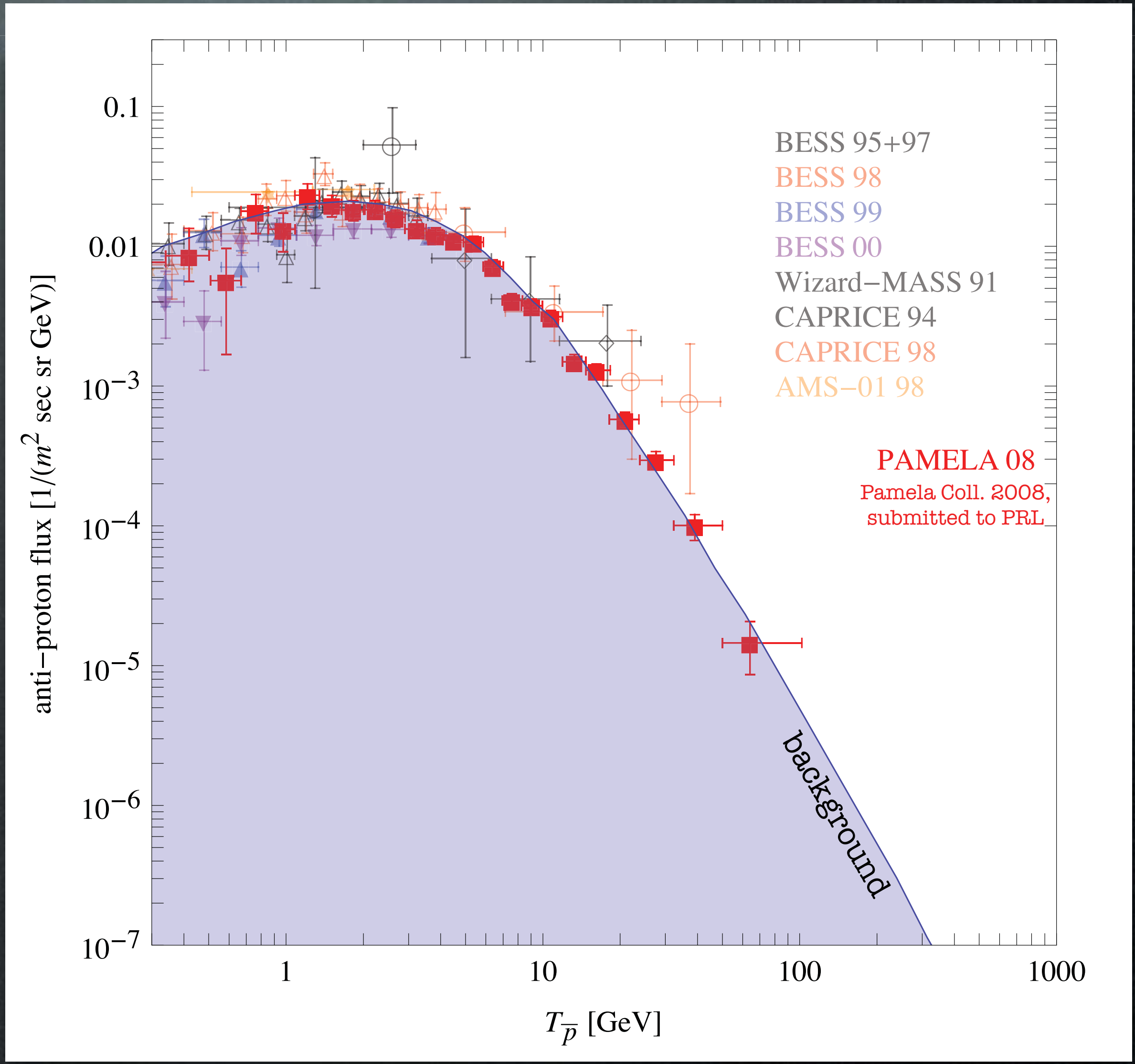


[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background



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

Results

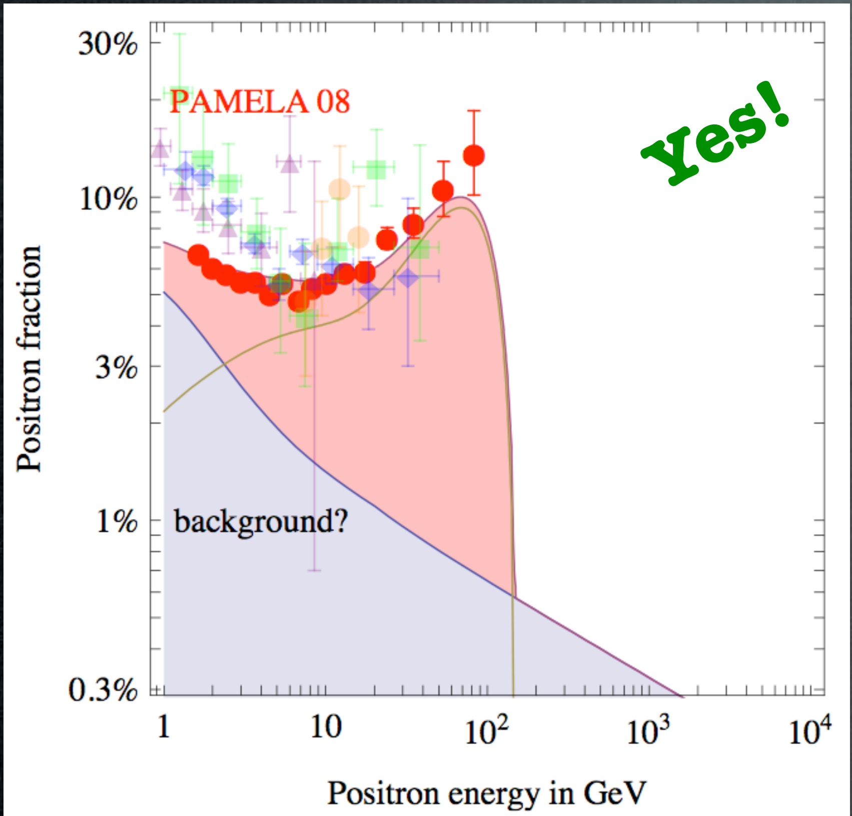
Which DM spectra can fit the data?

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

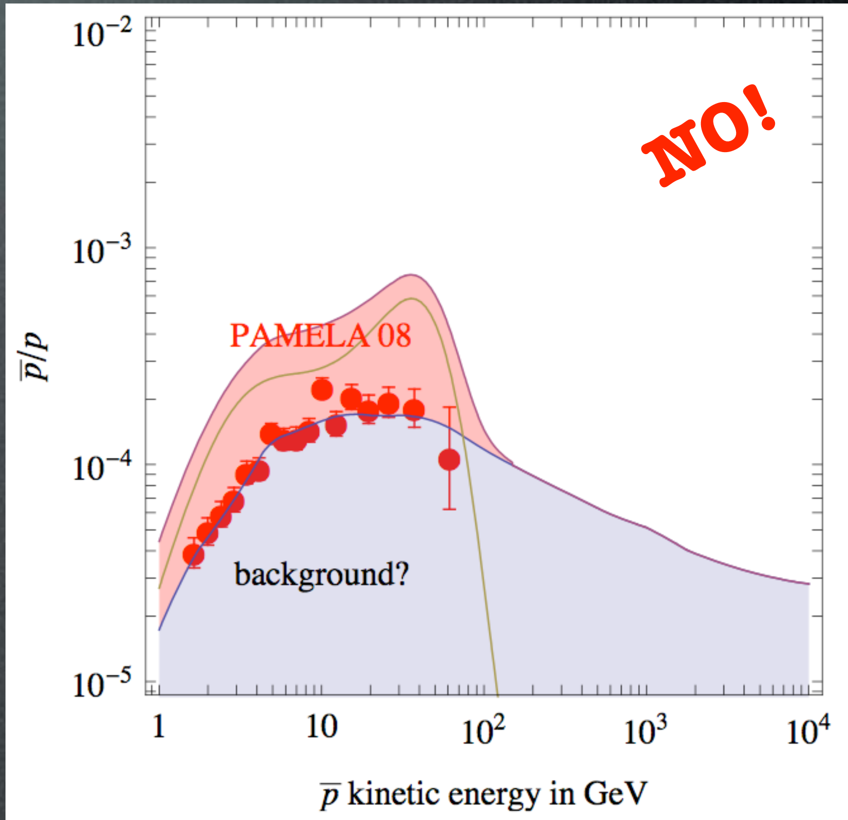
-annihilation $\rm DM\ DM \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



[insisting on Winos]

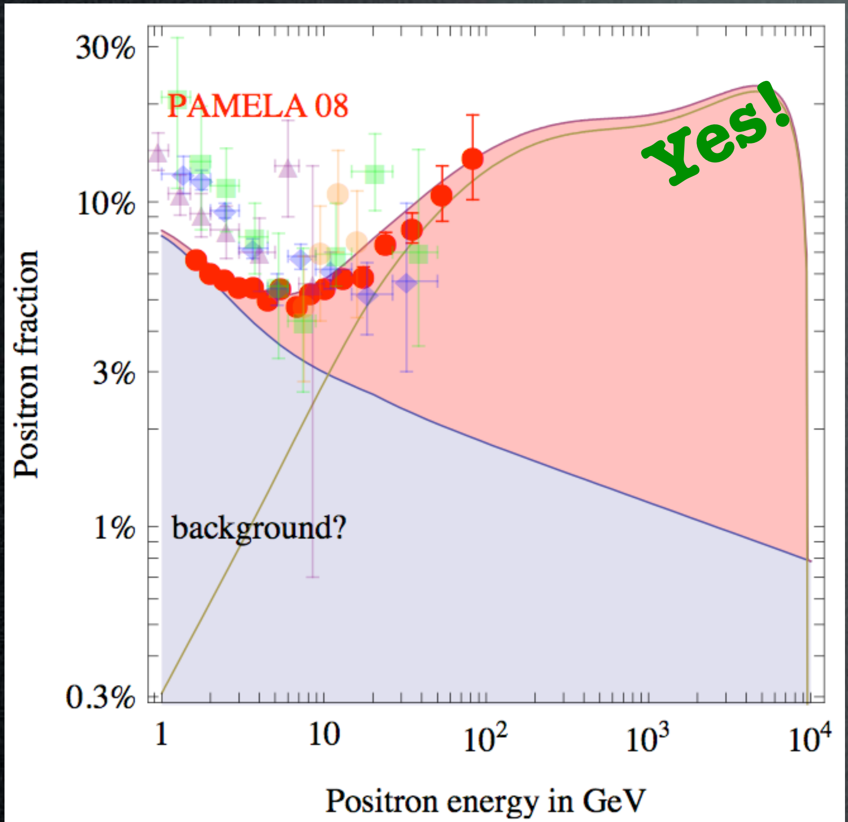
Results

Which DM spectra can fit the data?

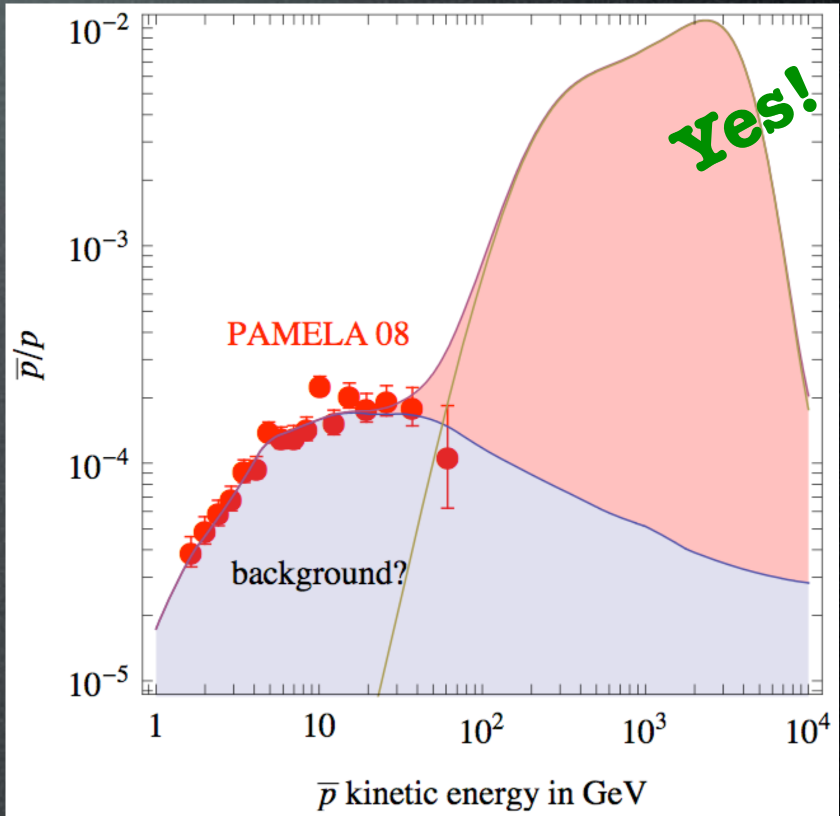
E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

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

Positrons:



Anti-protons:



Results

Which DM spectra can fit the data?

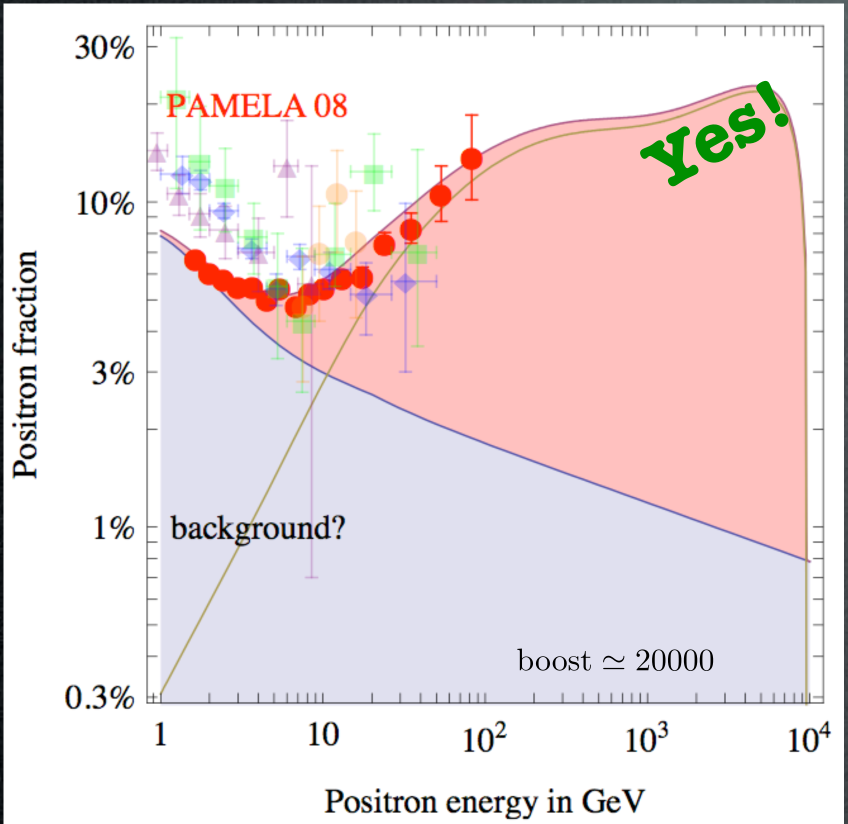
E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

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

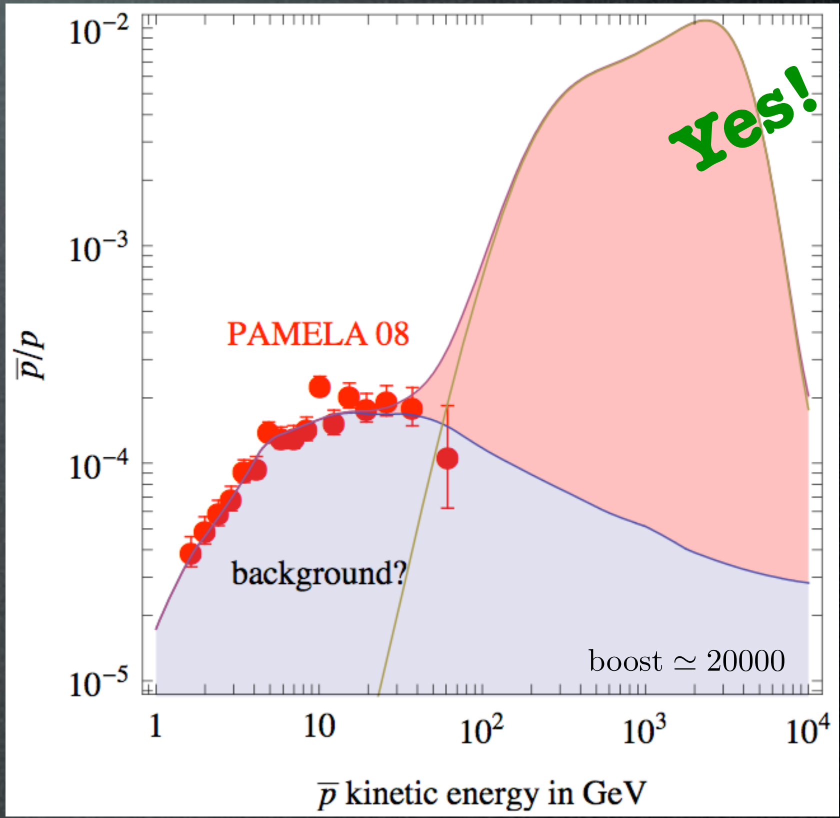
but...: -cross sec $\sigma_{\rm ann} v = 6 \cdot 10^{-22} {\rm cm}^3/{\rm sec}$

Mmm...

Positrons:



Anti-protons:

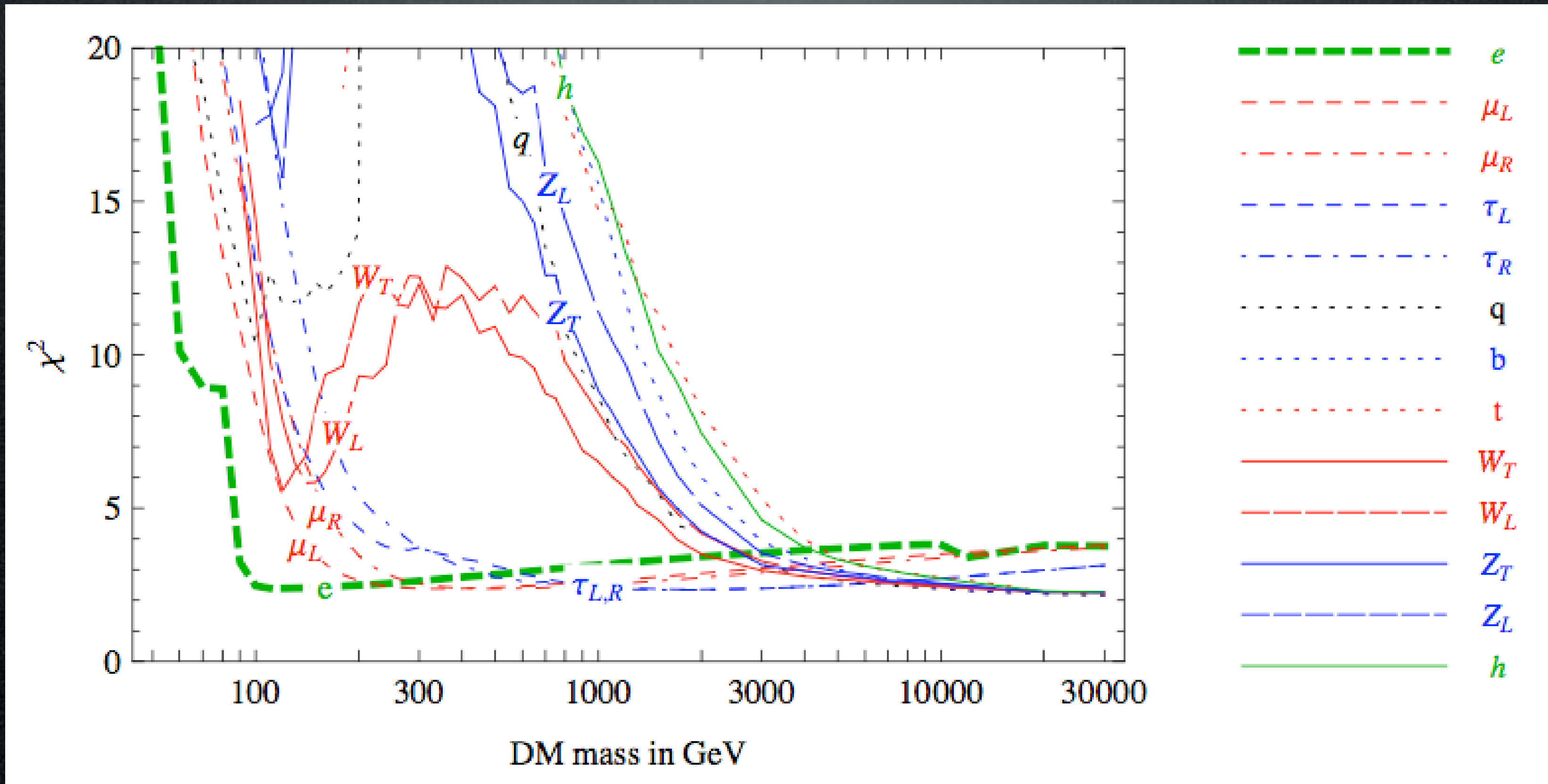


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons only

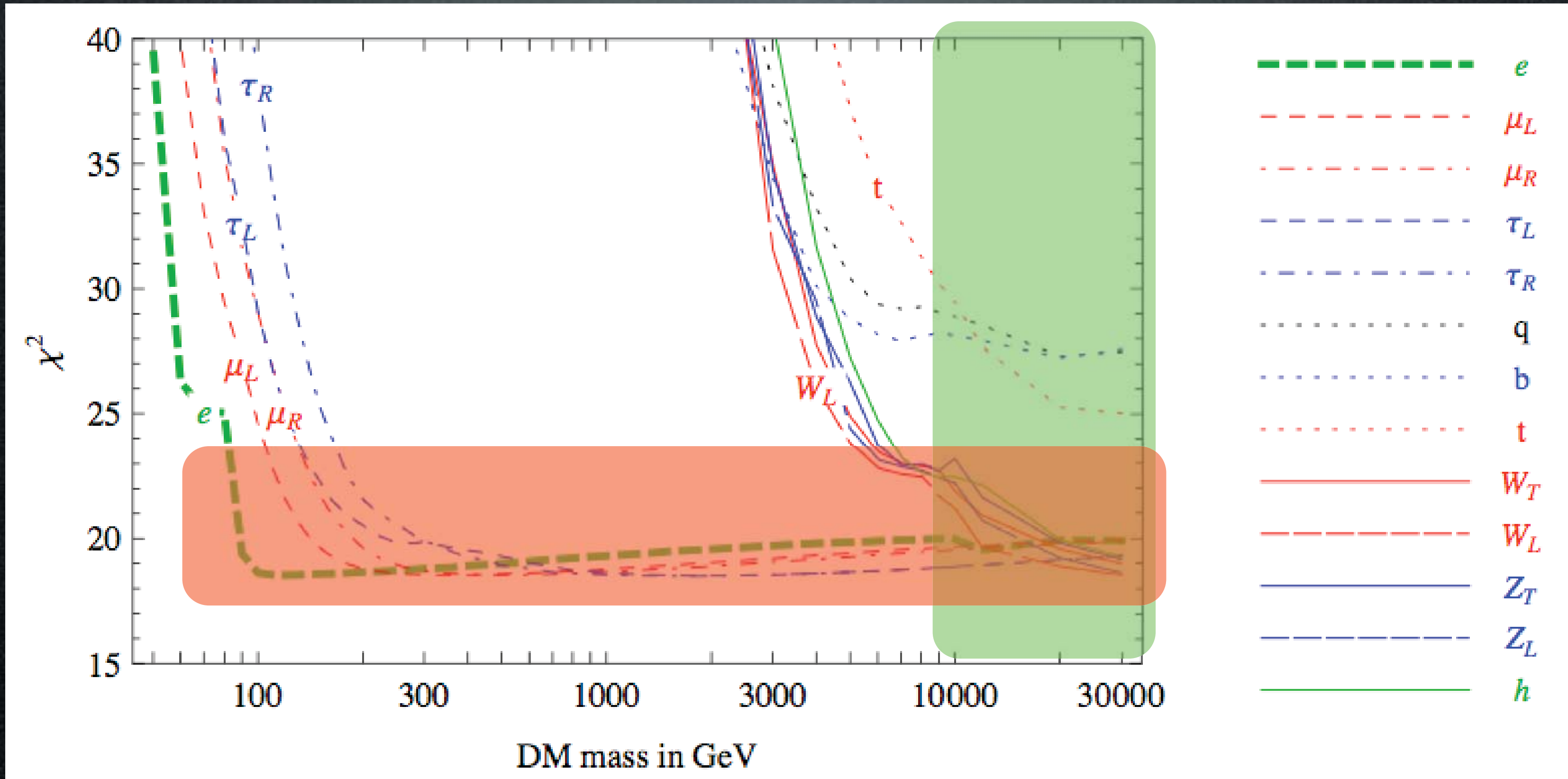


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



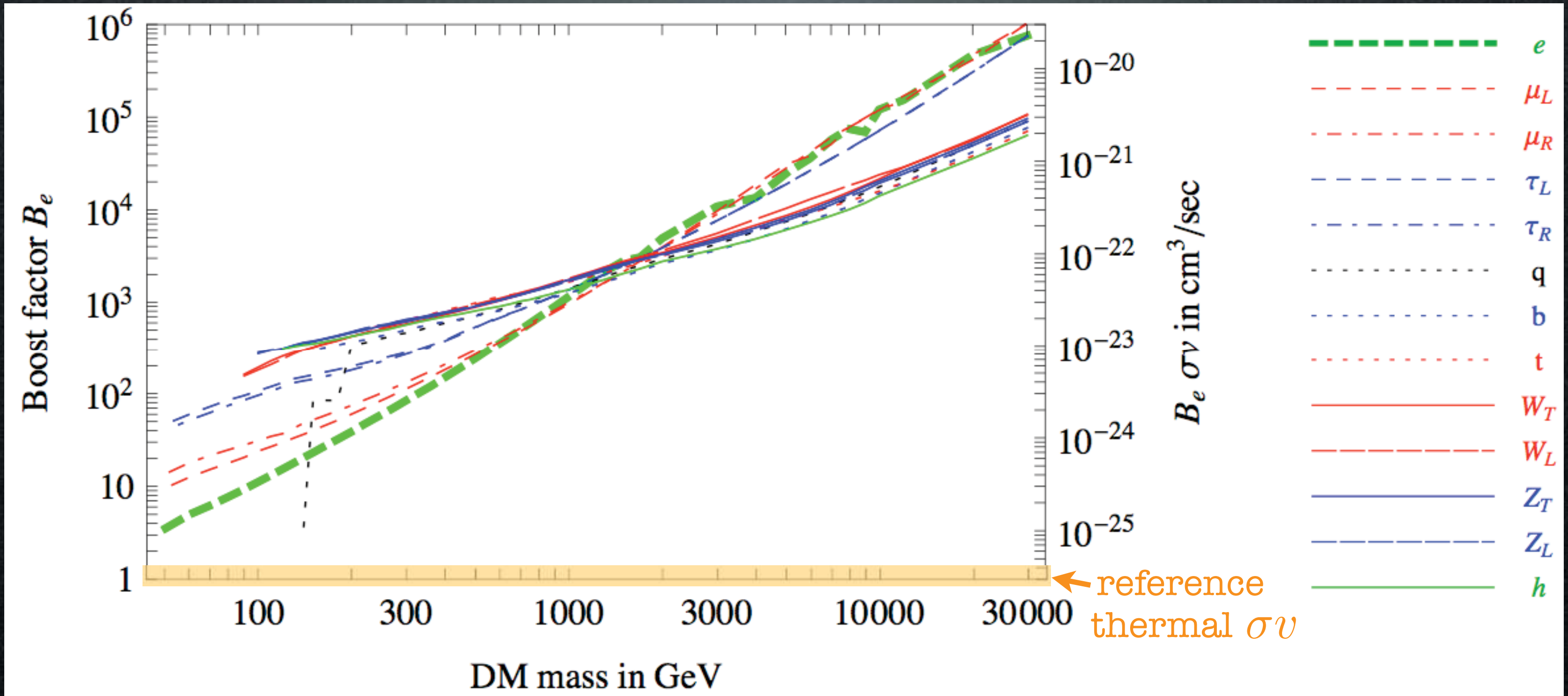
(1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

Results

Which DM spectra can fit the data?

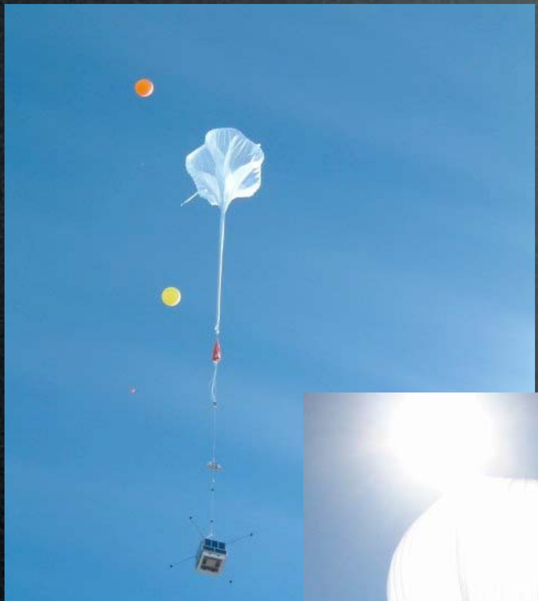
Model-independent results:

Cross section required by PAMELA



Data sets

Electrons + positrons from ATIC, PPB-BETS:



PPB-BETS
(Japan)

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

ATIC (Usa + Germany, Russia, China)

Advanced
Thin
Ionization
Calorimeter

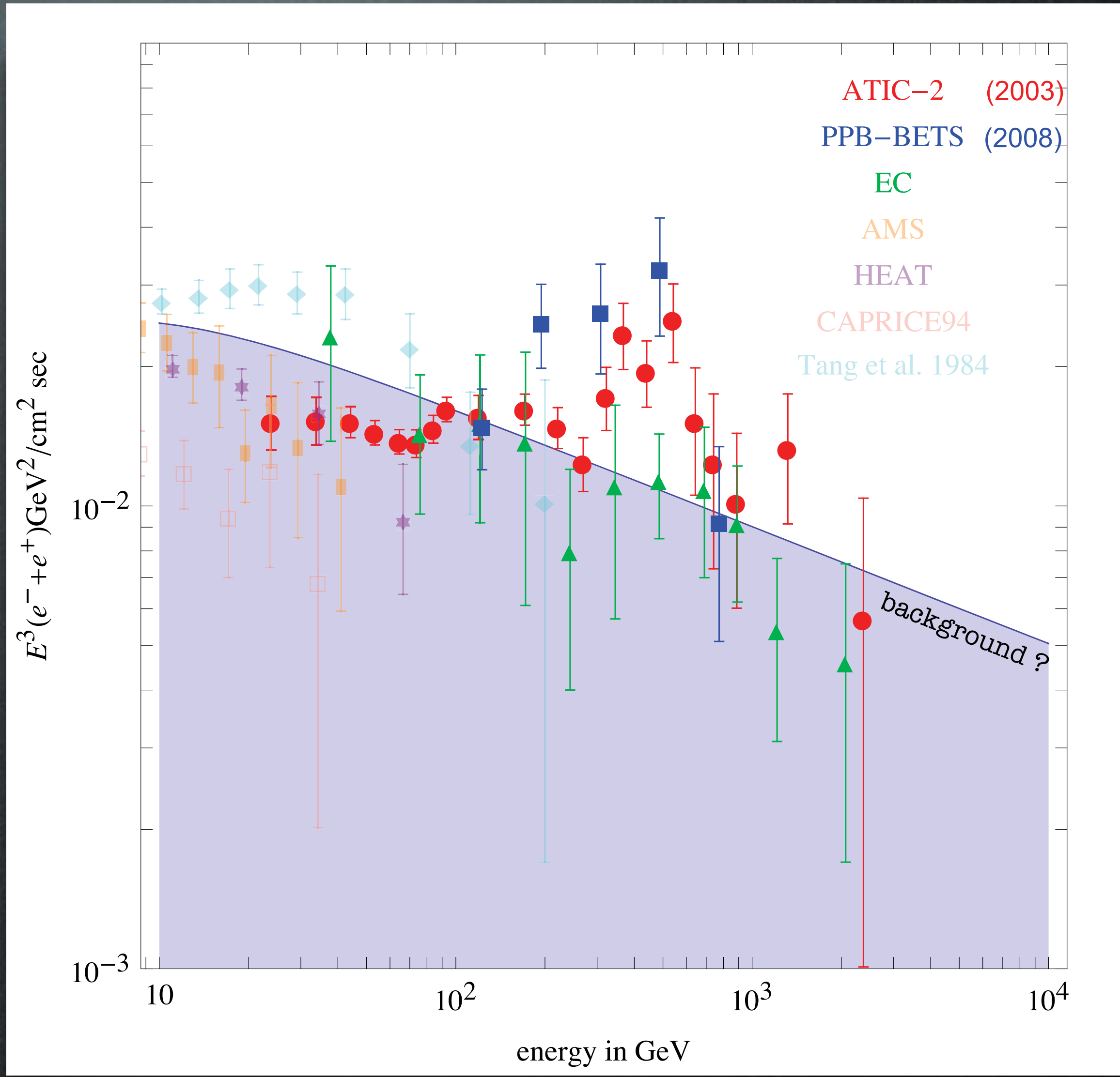
- bigger/denser: higher energy

- calorimeter only, no magnet:
  no charge discrimination

Data sets

Electrons + positrons from ATIC, PPB-BETS:

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



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

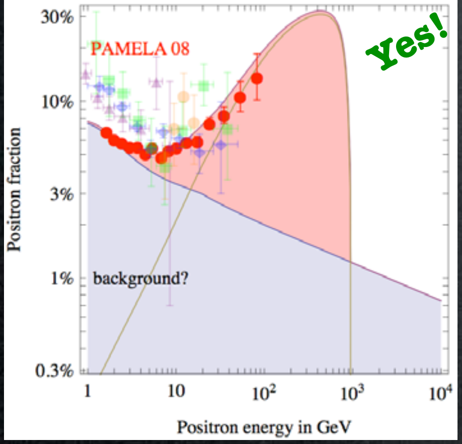
Results

Which DM spectra can fit the data?

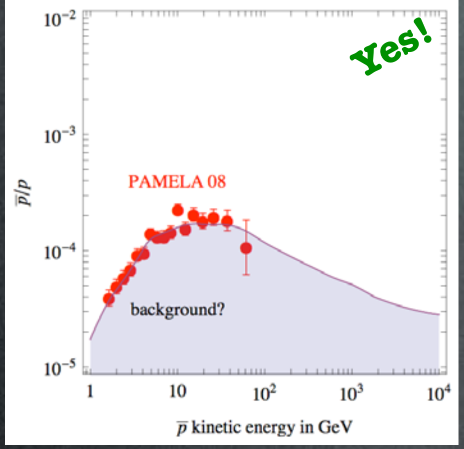
A DM with: -mass $M_{\rm DM} = 1\,{\rm TeV}$

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

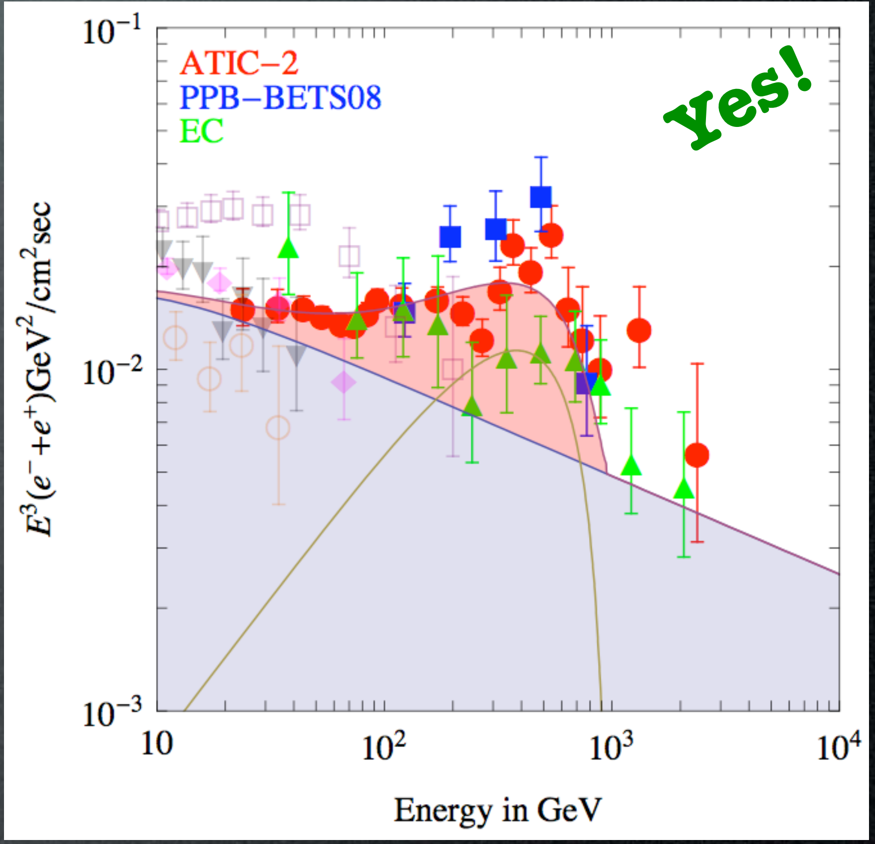
Positrons:



Anti-protons:



Electrons + Positrons:



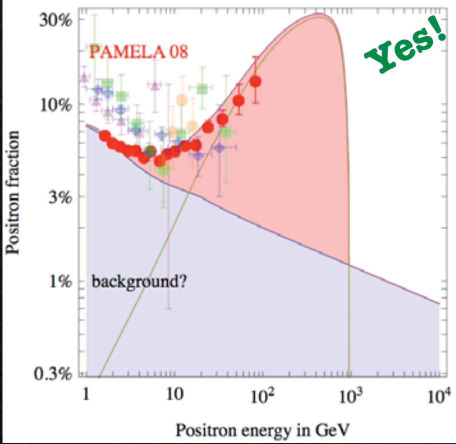
Results

Which DM spectra can fit the data?

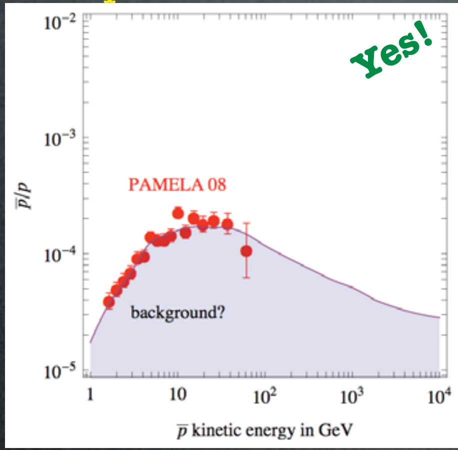
A DM with: -mass $M_{\rm DM} = 1\,{\rm TeV}$

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

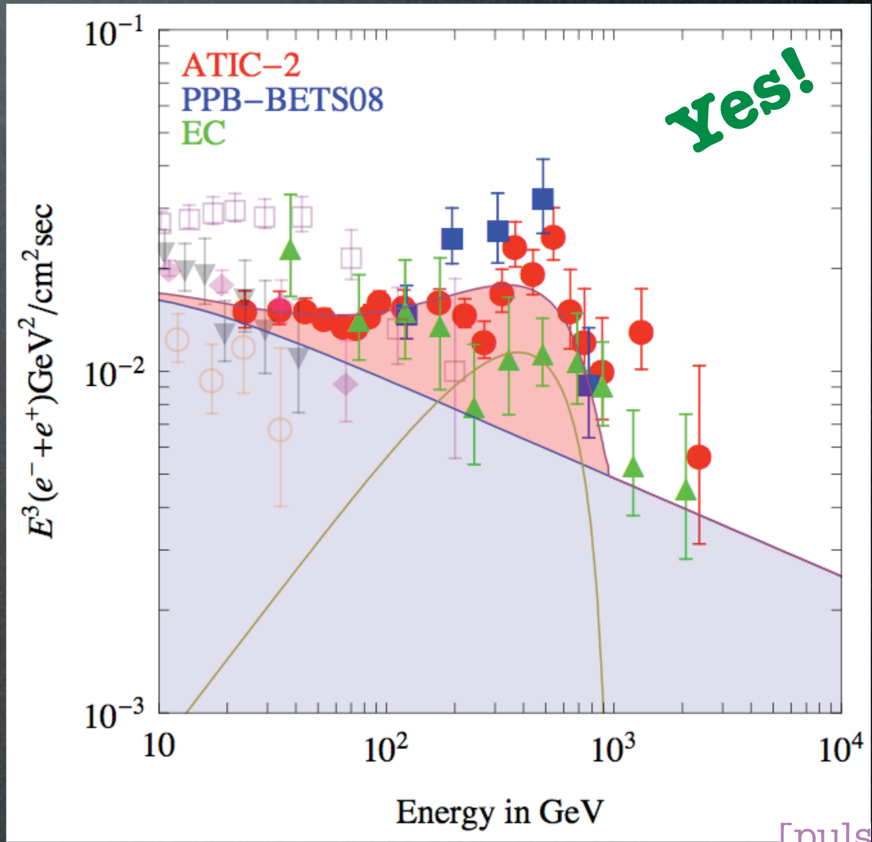
Positrons:



Anti-protons:



Electrons + Positrons:



[pulsar]

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

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

Results

Which DM can fit the data?

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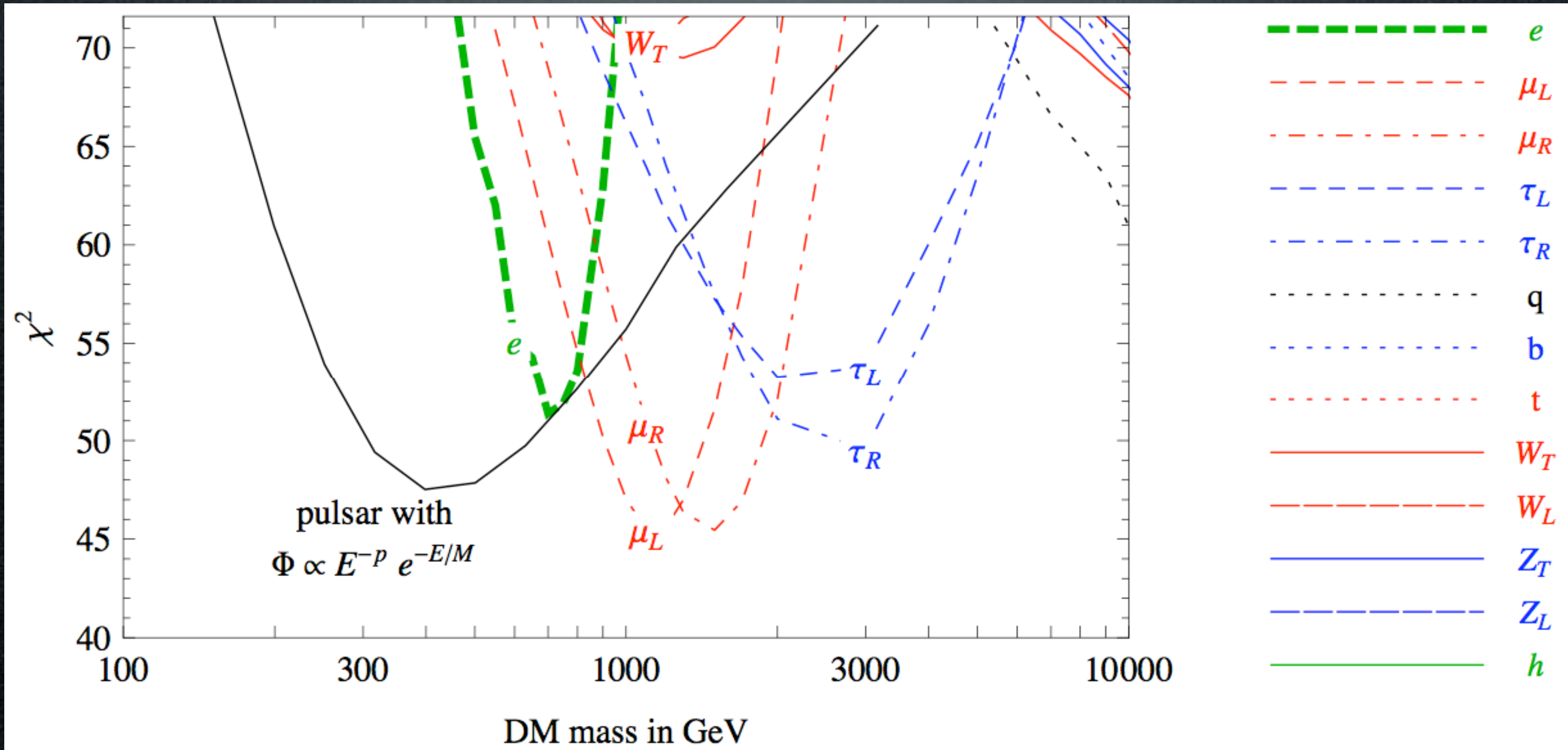
Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons* + balloon experiments



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

Results

Which DM spectra can fit the data?

Model-independent results:

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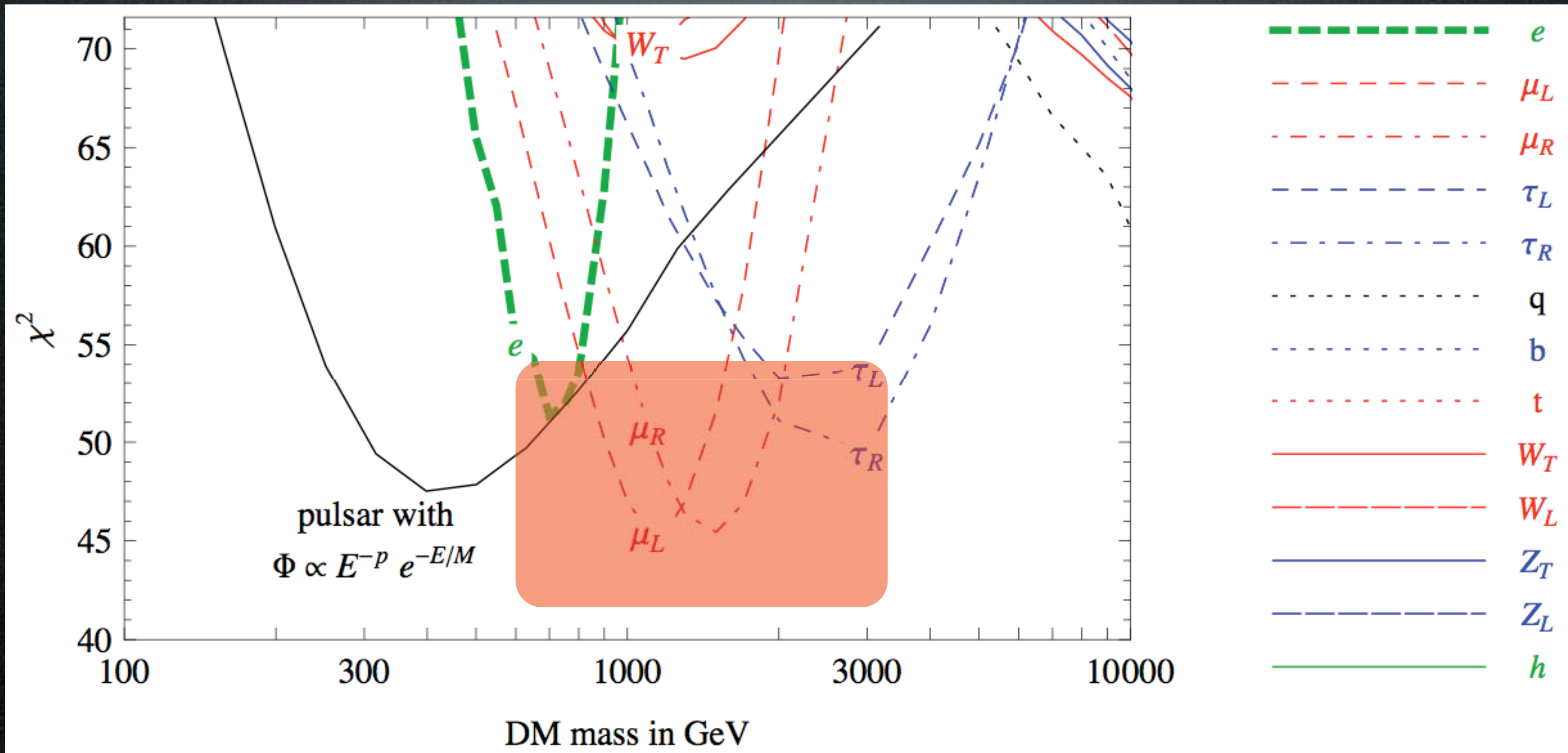
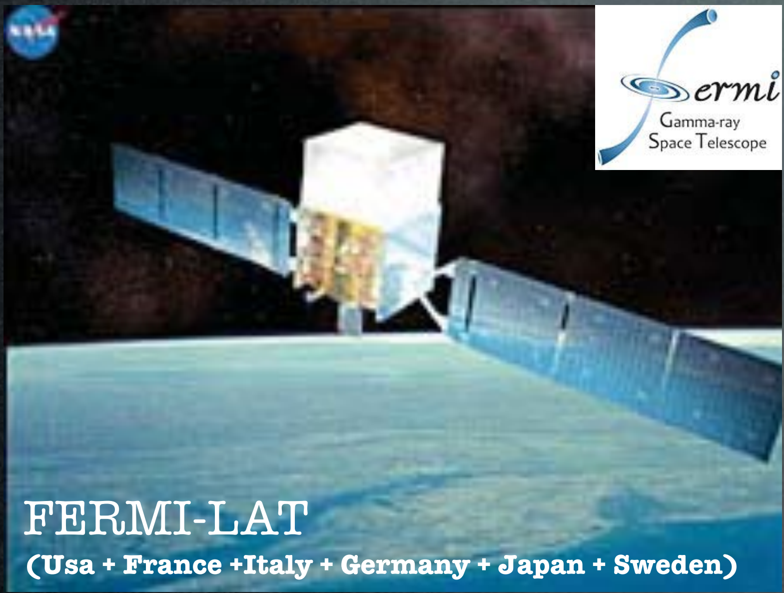
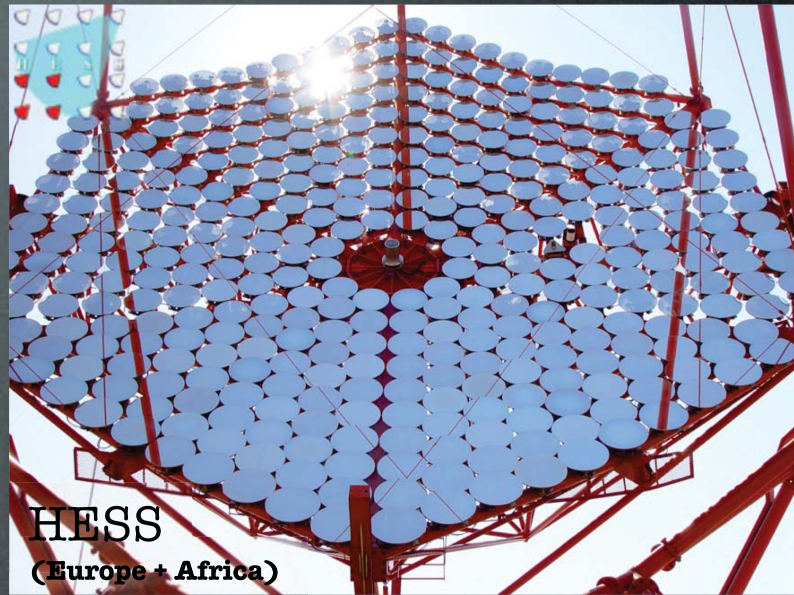


(1) annihilate into leptons (e.g. $\mu^+\mu^-$), mass $\sim$1 TeV

Data sets

Electrons + positrons from FERMI and HESS:





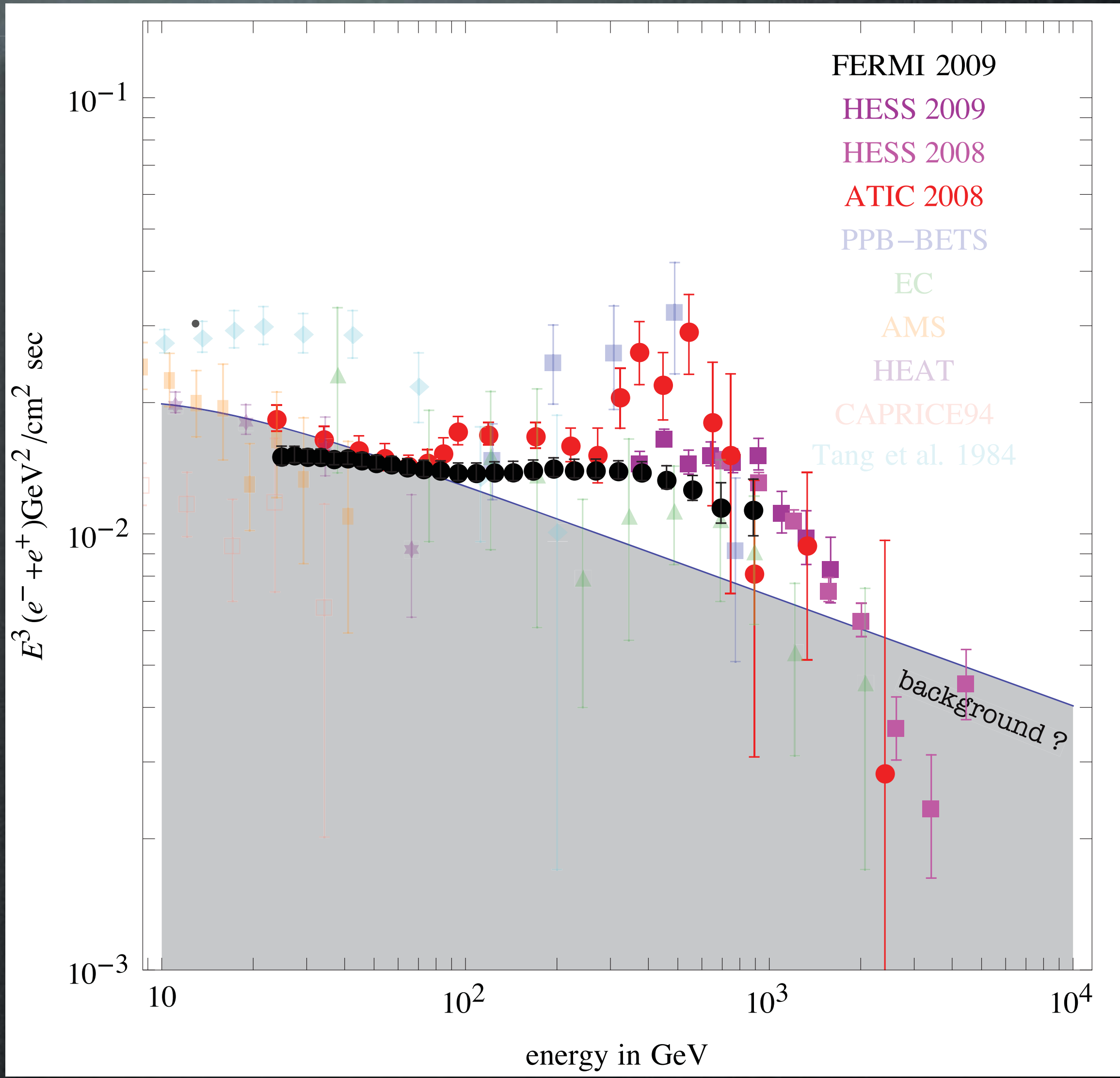
“Designed as a high-sensitivity gamma-ray observatory, the FERMI Large Area Telescope is also an electron detector with a large acceptance”

“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?

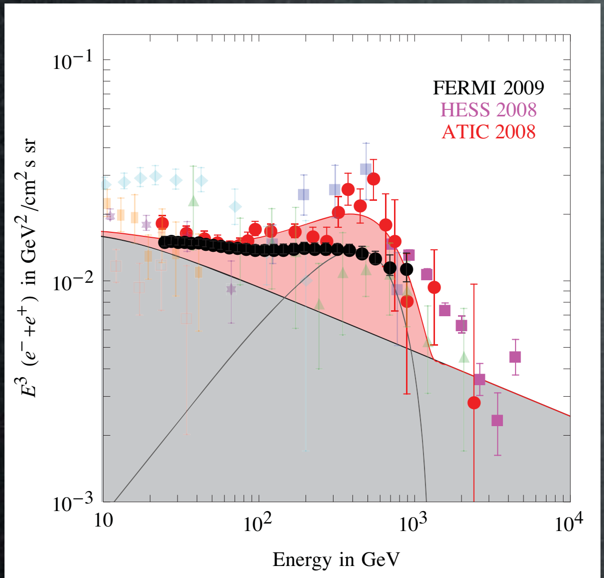


[formerly predicted GLAST sensitivity]

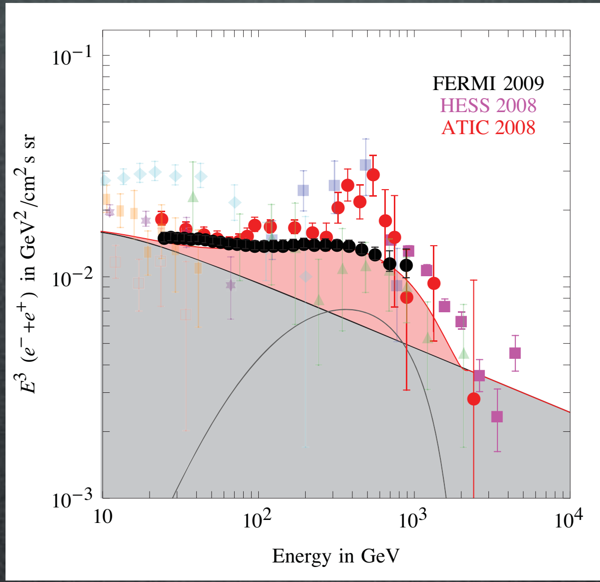
Results

Which DM spectra can fit the data?

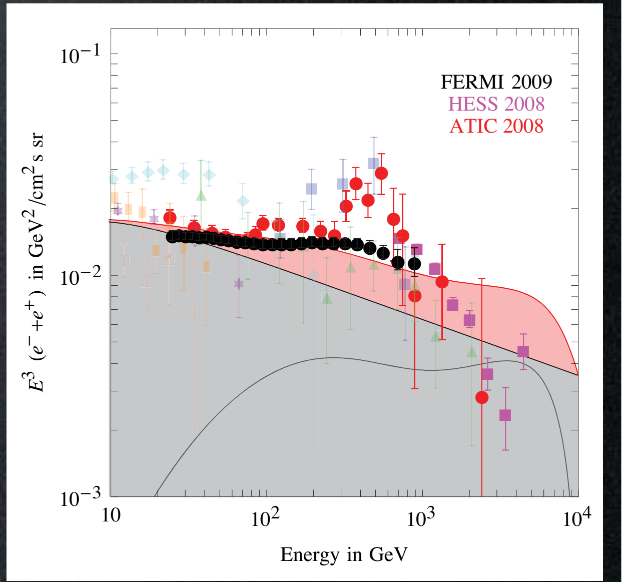
$\mu^+\mu^-, M_{\rm DM} \simeq 1\,{\rm TeV}$



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



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



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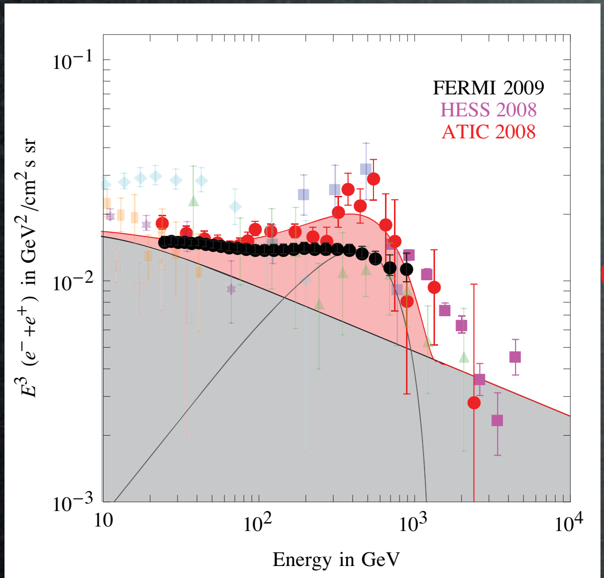
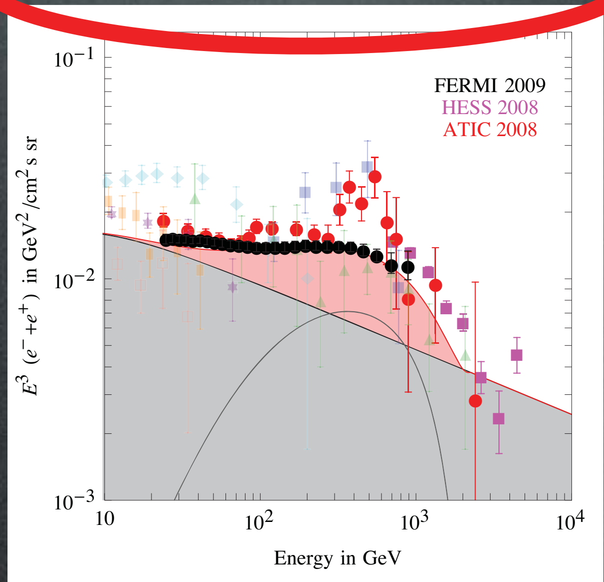


Notice:
- same spectra still fit PAMELA positron and anti-protons!

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



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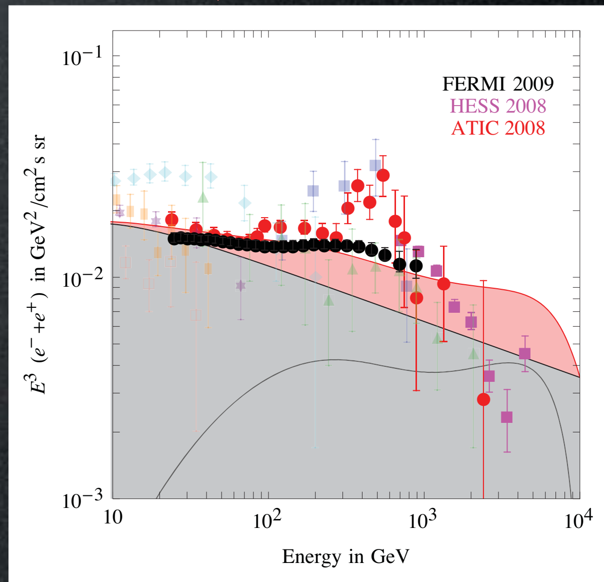


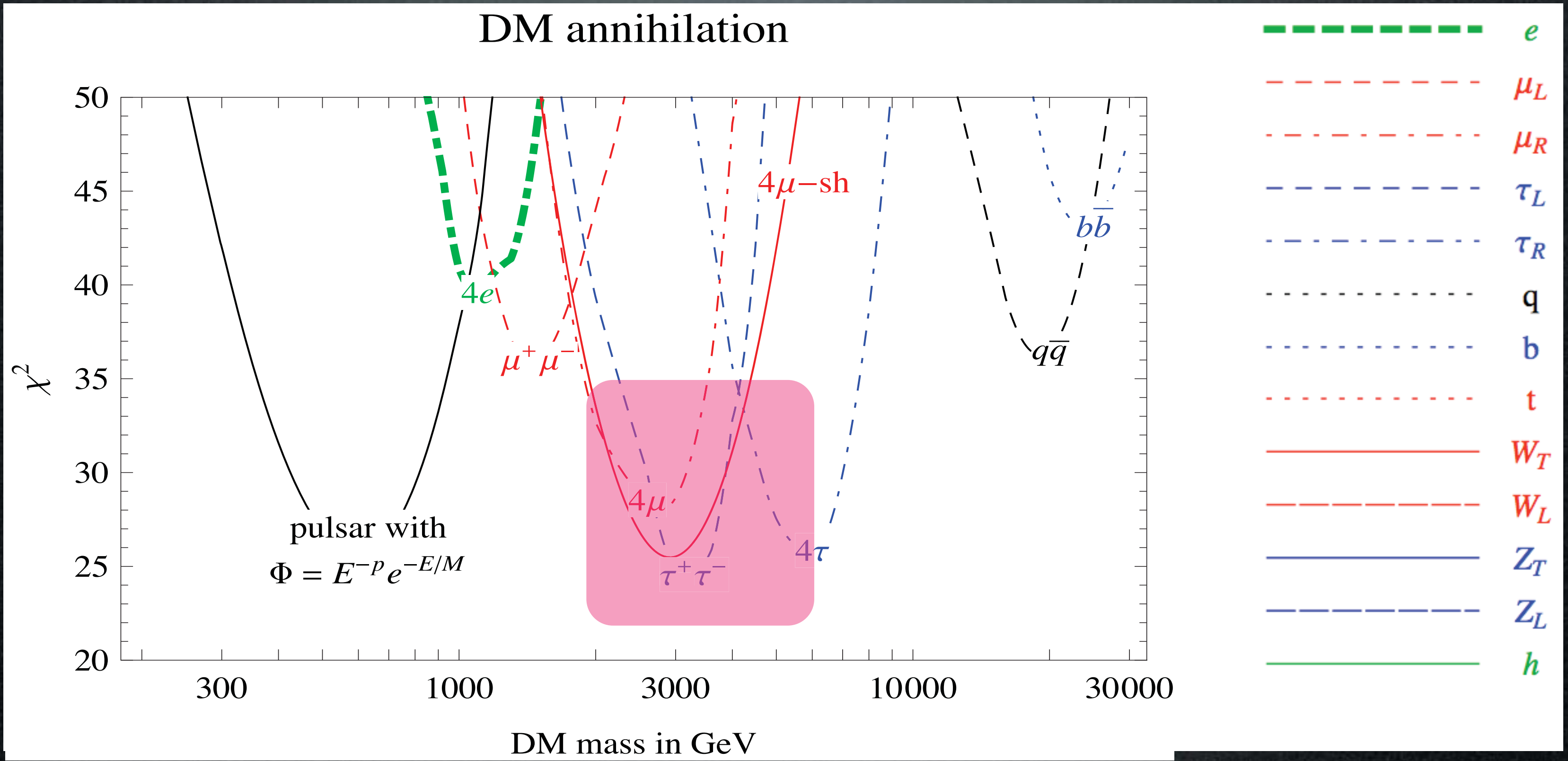
- no features in FERMI => $M_{\rm DM} > 1$ TeV
- a 'cutoff' in HESS => $M_{\rm DM} \lesssim 3$ TeV
- smooth lepton spectrum

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA + FERMI + HESS (no balloon):

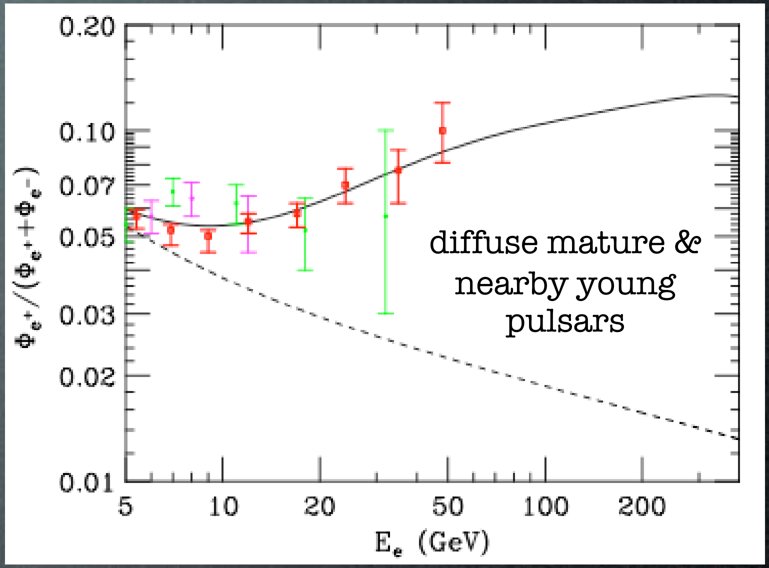


Strumia, Papucci et al. 0905.0480
see also: Bergstrom, Edsjo, Zaharijas 0905

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

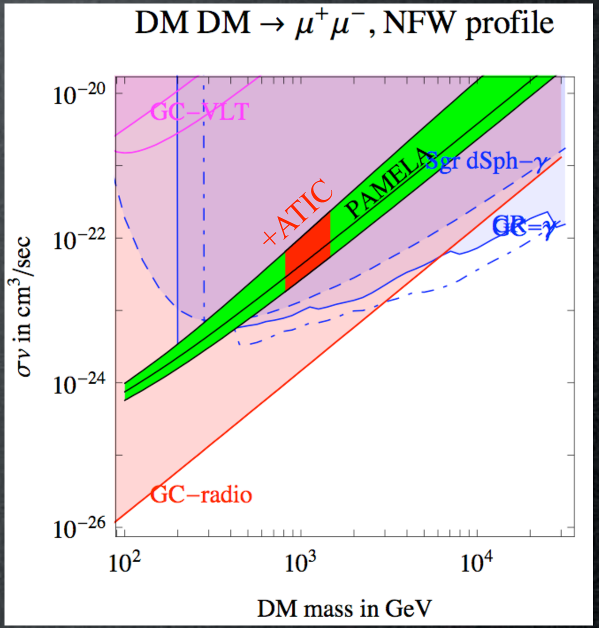
Two important remarks

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



Hooper, Blasi, Serpico 2008
Profumo 0812.4457

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



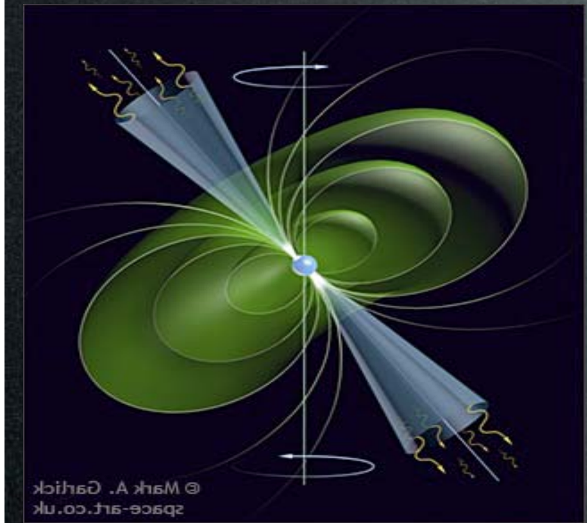
Bertone, Cirelli, Strumia, Taoso 0811.3744

[jump to conclusions]

Astrophysical explanation?

[others?]

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



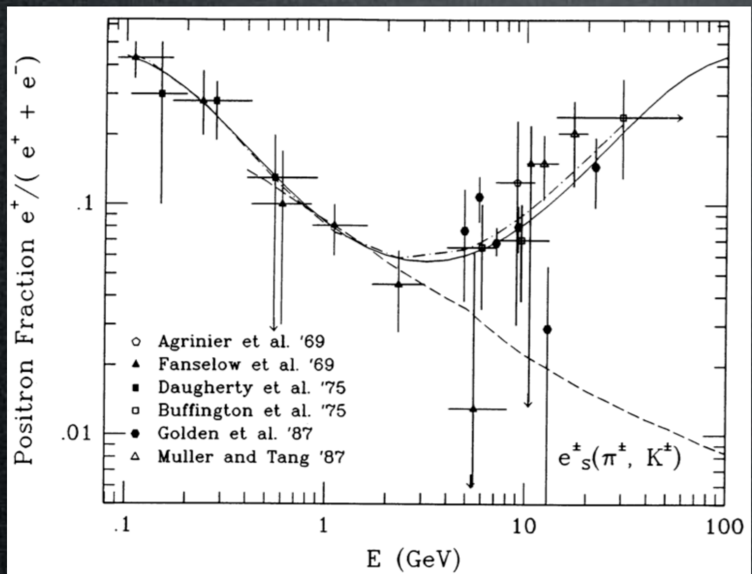
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \to 10^5$ yr (typical total energy output: 10^{46} erg).

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

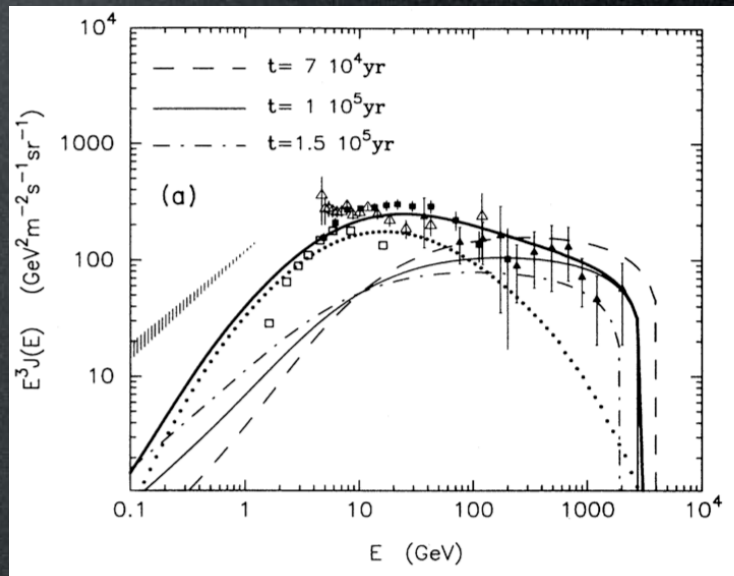
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

Not a new idea:



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



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

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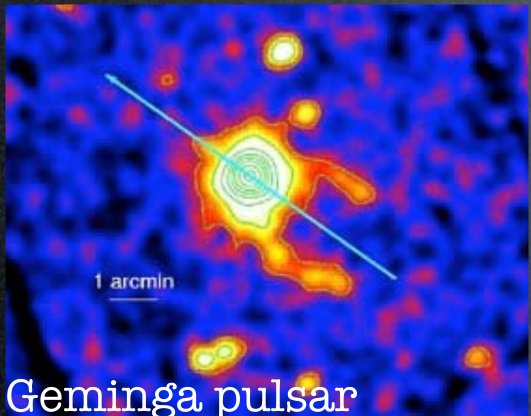

Geminga pulsar
(funny that it means:
"it is not there" in milanese)

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

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Try the fit with known nearby pulsars:

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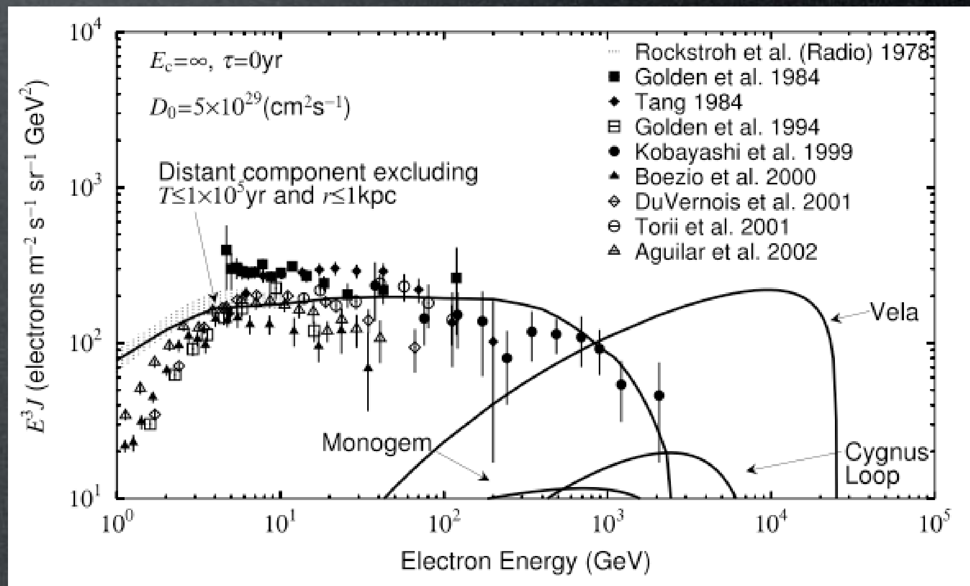
SNR	Distance (kpc)	Age (yr)	E_{max} [a] (TeV)
SN 185	0.95	1.8×10^3	1.7×10^2
S147	0.80	4.6×10^3	63
HB 21	0.80	1.9×10^4	14
G65.3+5.7	0.80	2.0×10^4	13
Cygnus Loop	0.44	2.0×10^4	13
Vela	0.30	1.1×10^4	25
Monogem	0.30	8.6×10^4	2.8
Loop1	0.17	2.0×10^5	1.2
Geminga	0.4	3.4×10^5	0.67

Kobayashi, Komori et al. 2004



Kobayashi, Komori et al. 2004

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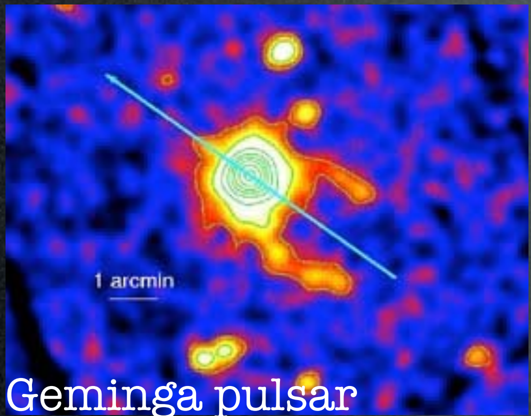

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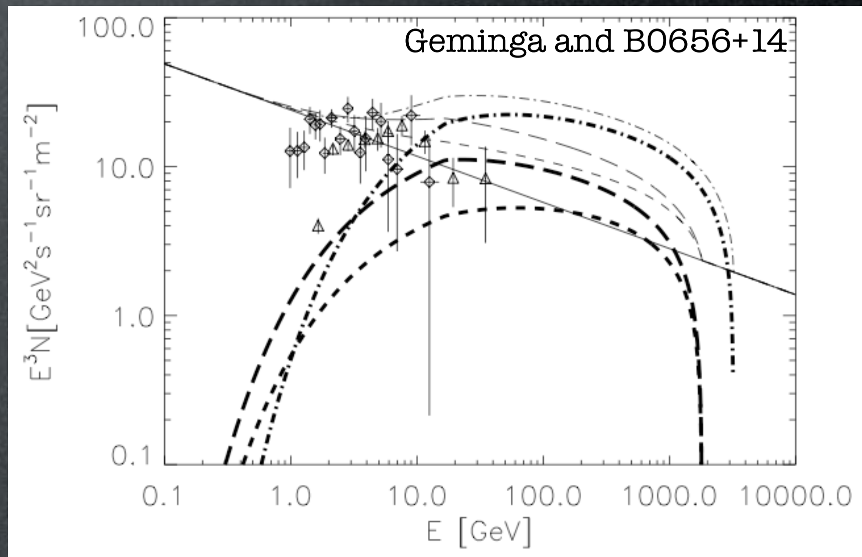

Büshing, de Jager et al. 0804.0220

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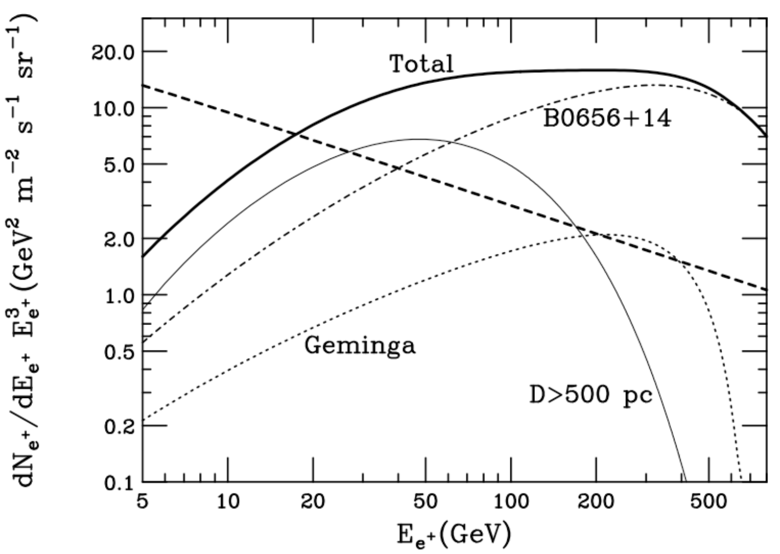
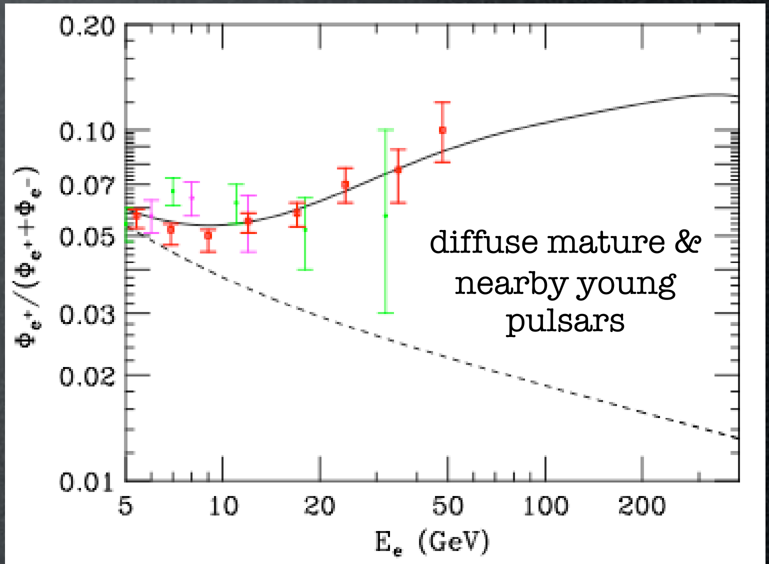
Try the fit with known nearby pulsars and diffuse mature pulsars:





Hooper, Blasi, Serpico 2008

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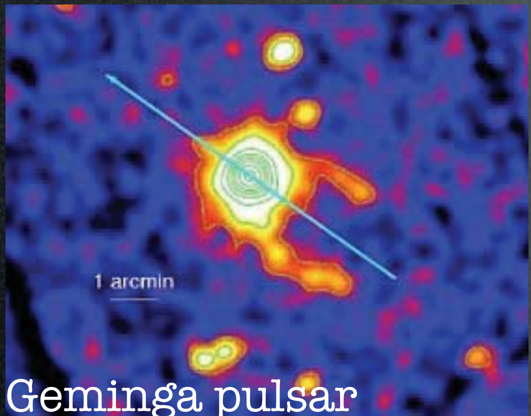

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Open issue.

(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]

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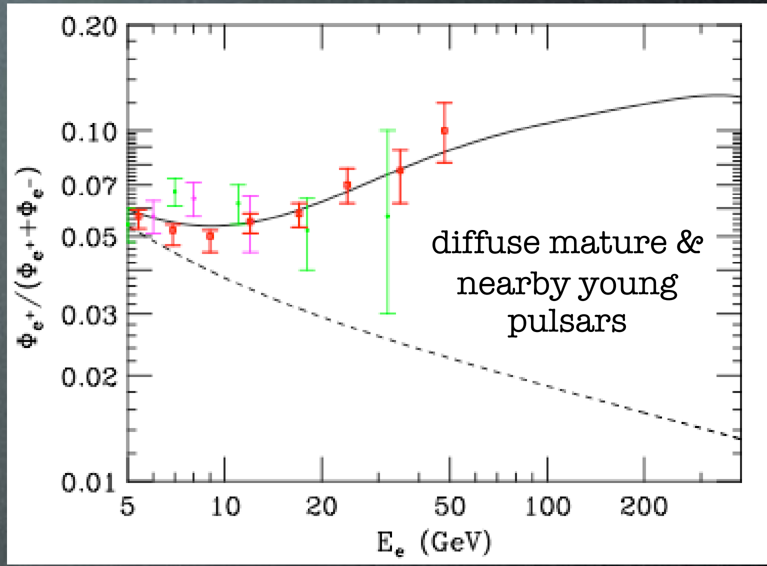
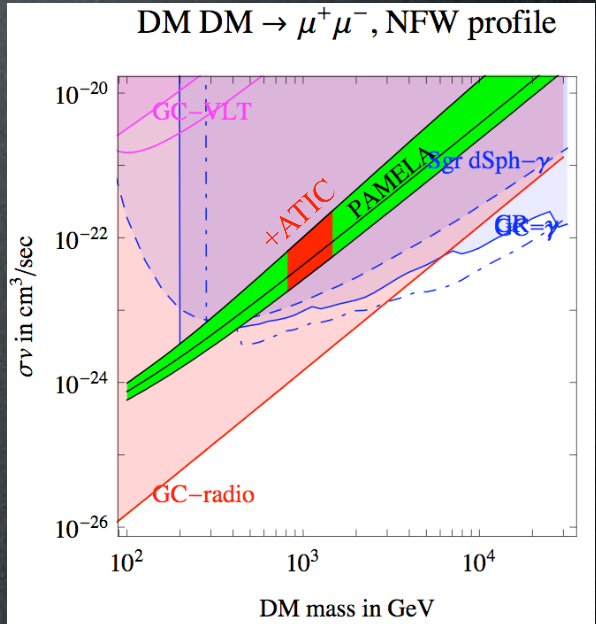


Hooper, Blasi, Serpico 2008
Profumo 0812.4457

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



Bertone, Cirelli, Strumia, Taoso 0811.3744

[jump to conclusions]

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

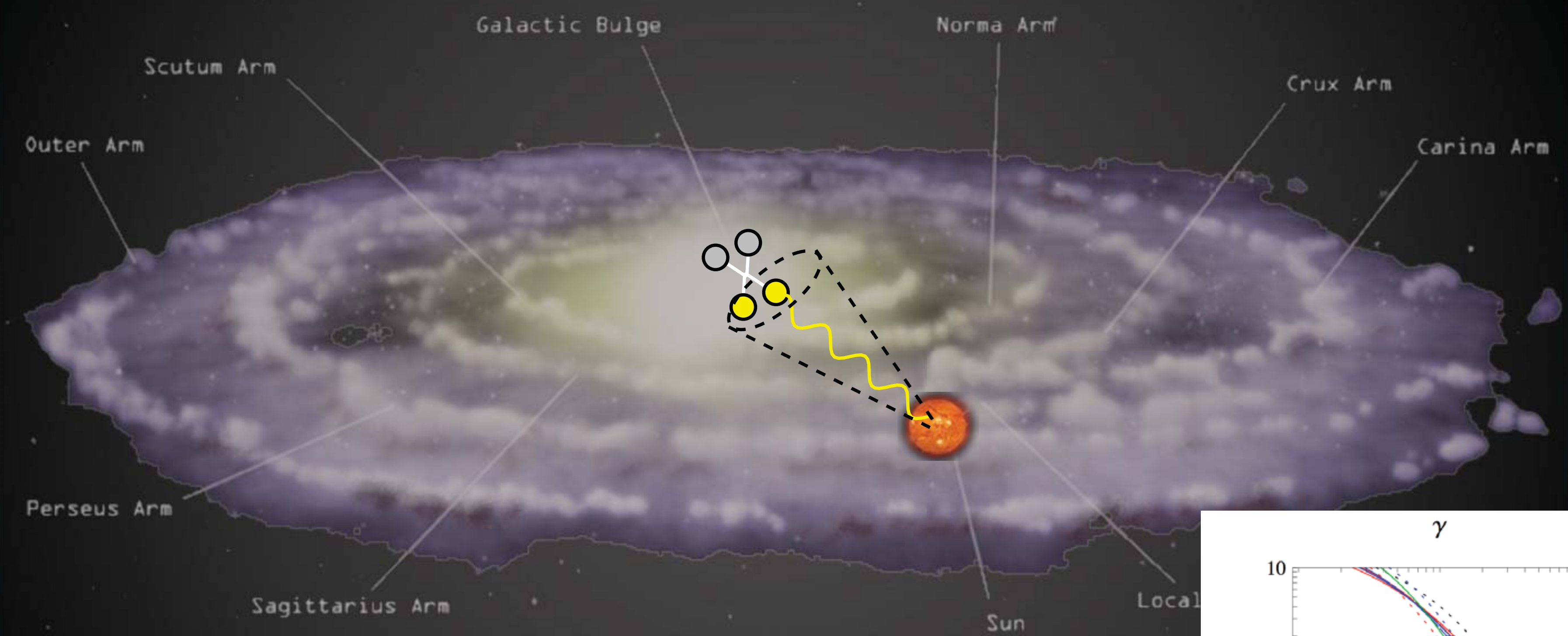
$\bar{p}$ from annihil in galactic halo or center

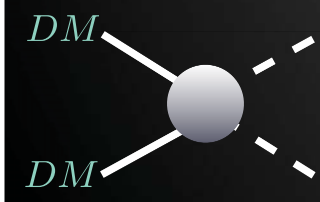
$\bar{D}$ from annihil in galactic halo or center

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

Indirect Detection

γ from DM annihilations in galactic center

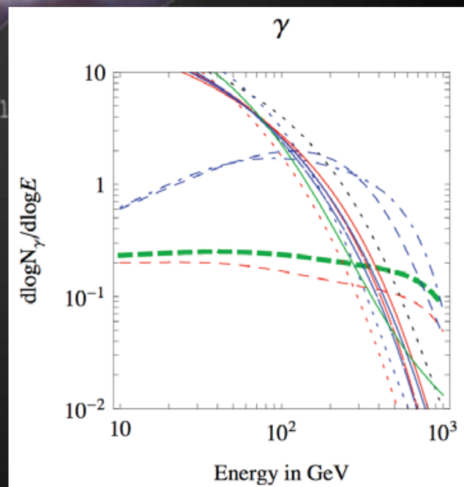




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and } \gamma$$

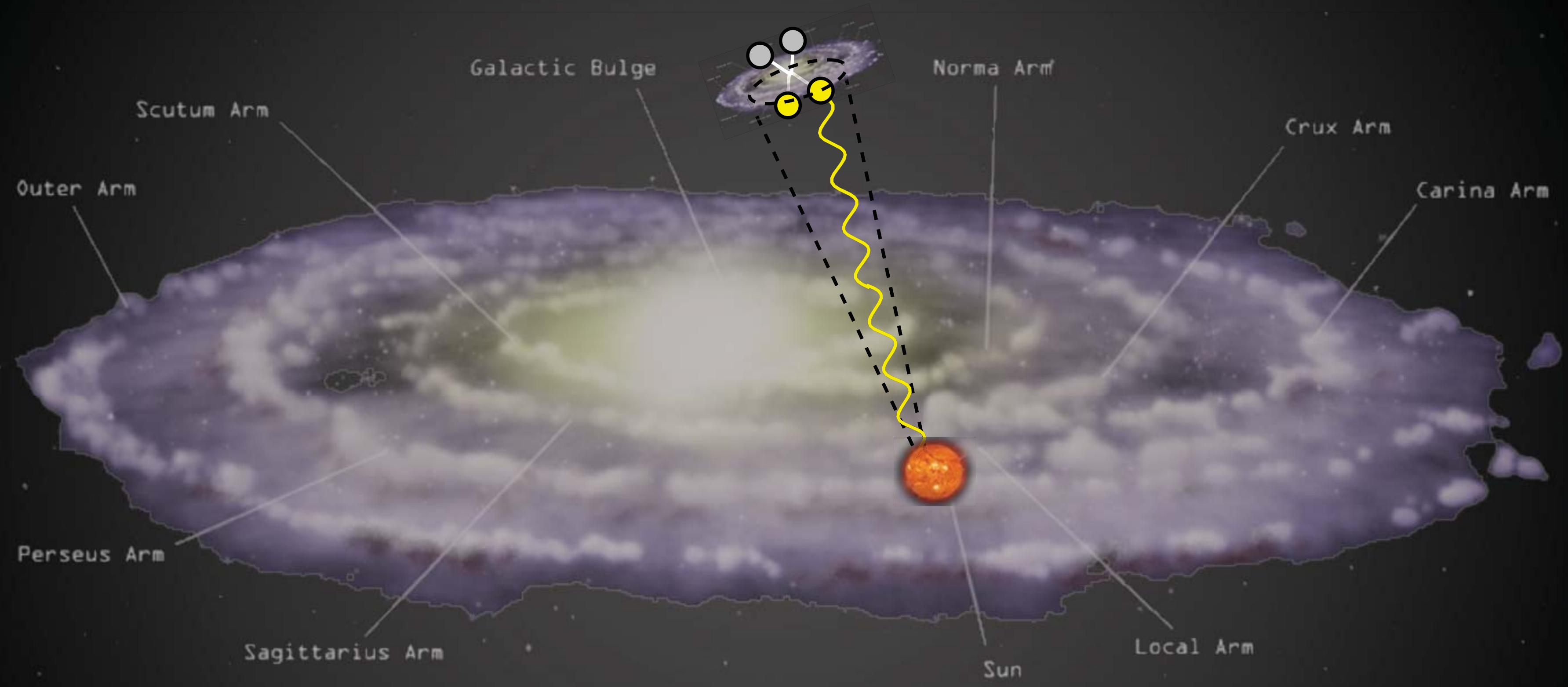
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and } \gamma$$

typically sub-TeV energies



Indirect Detection

γ from DM annihilations in Sagittarius Dwarf

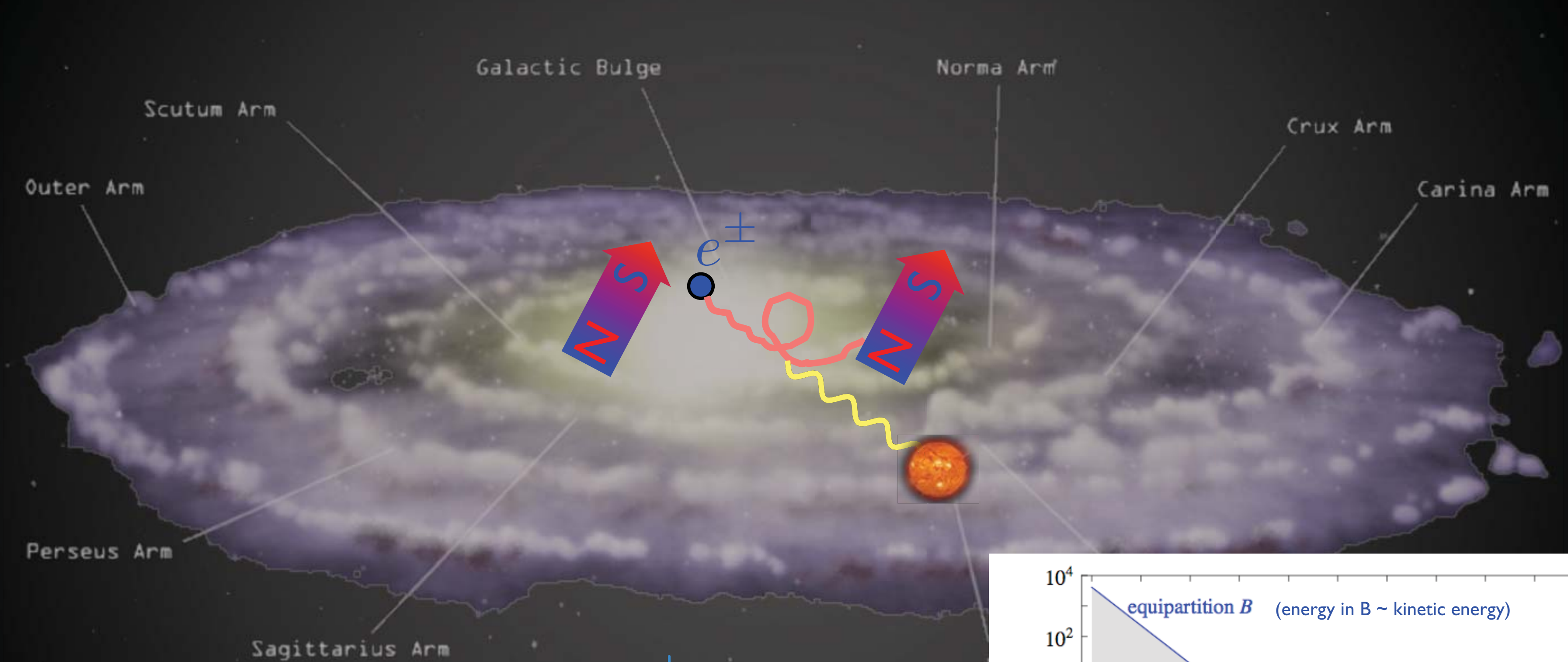


$$DM\,DM \to W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

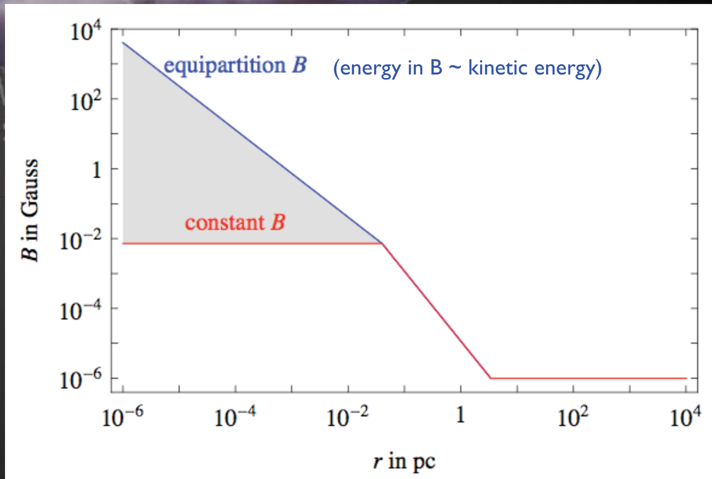
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

Indirect Detection

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



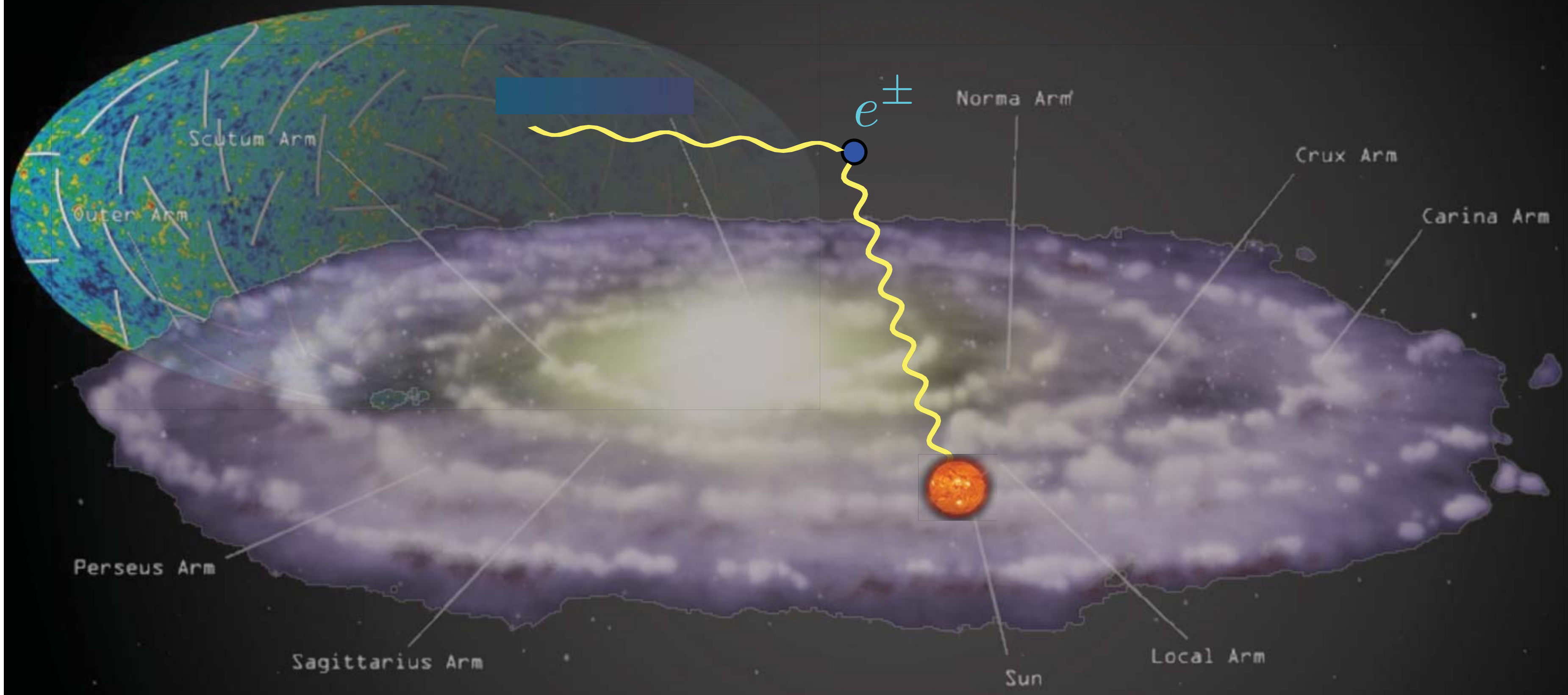
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$



(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

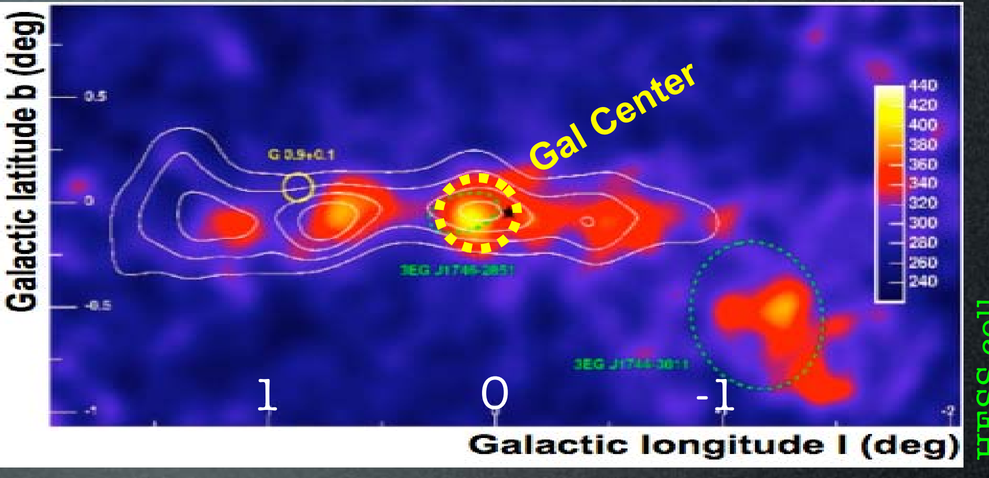


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

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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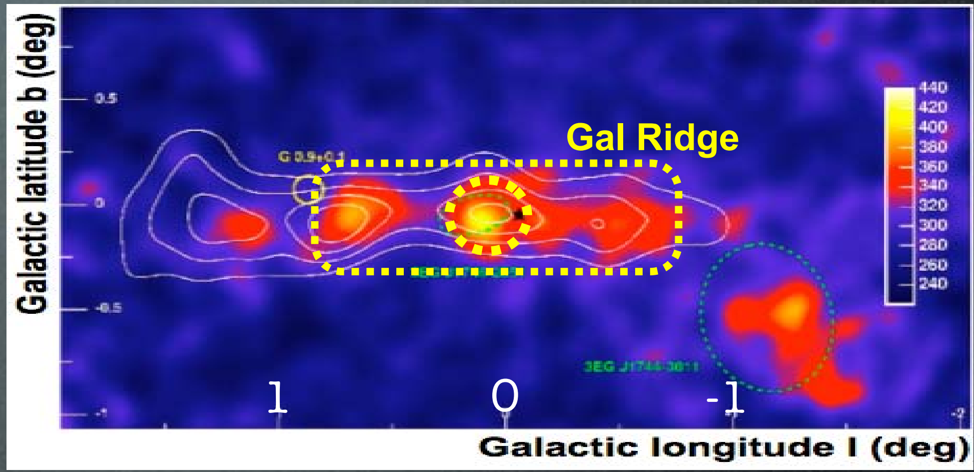
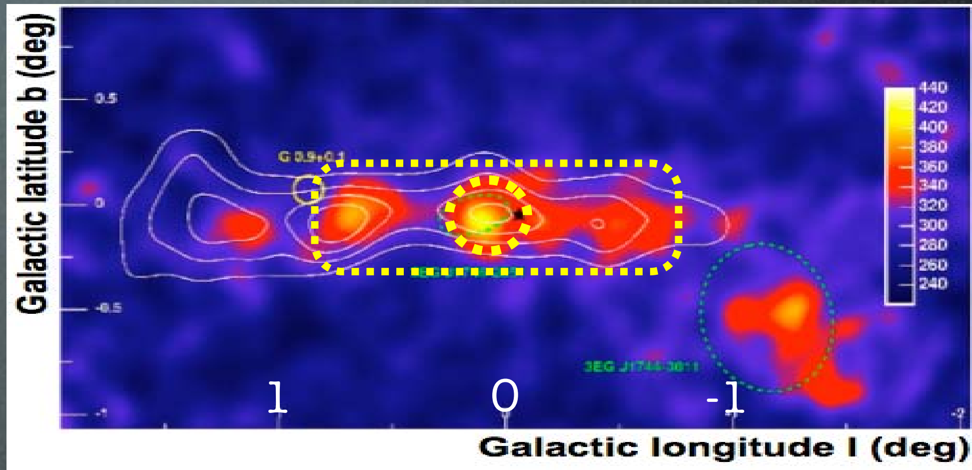


HESS coll.

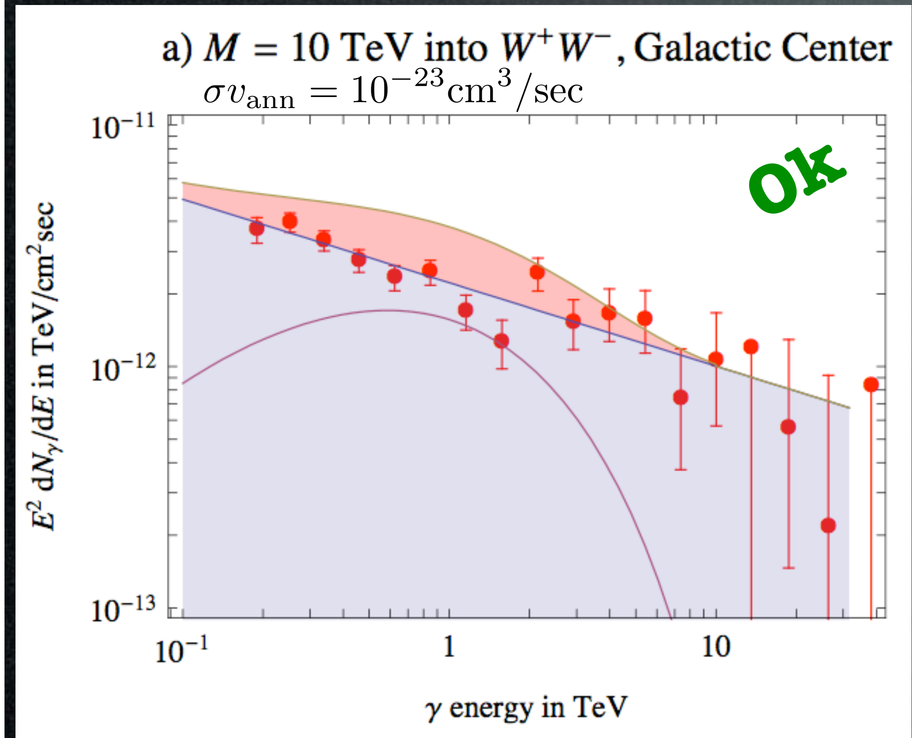
Gamma constraints

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

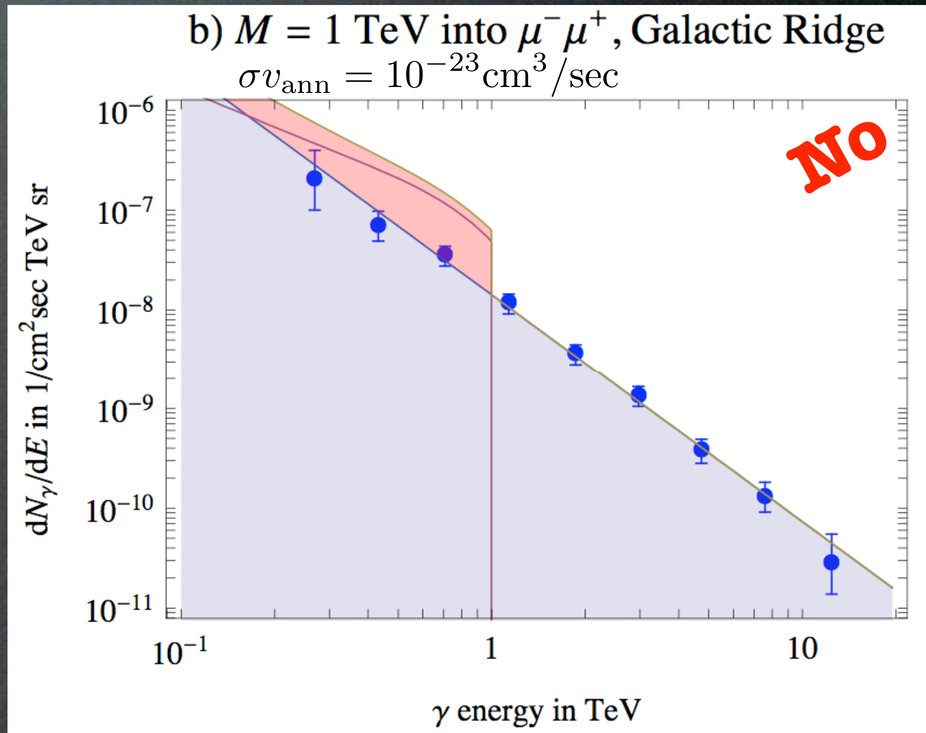
Moreover: no detection from Sgr dSph => upper bound.



HESS coll.



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

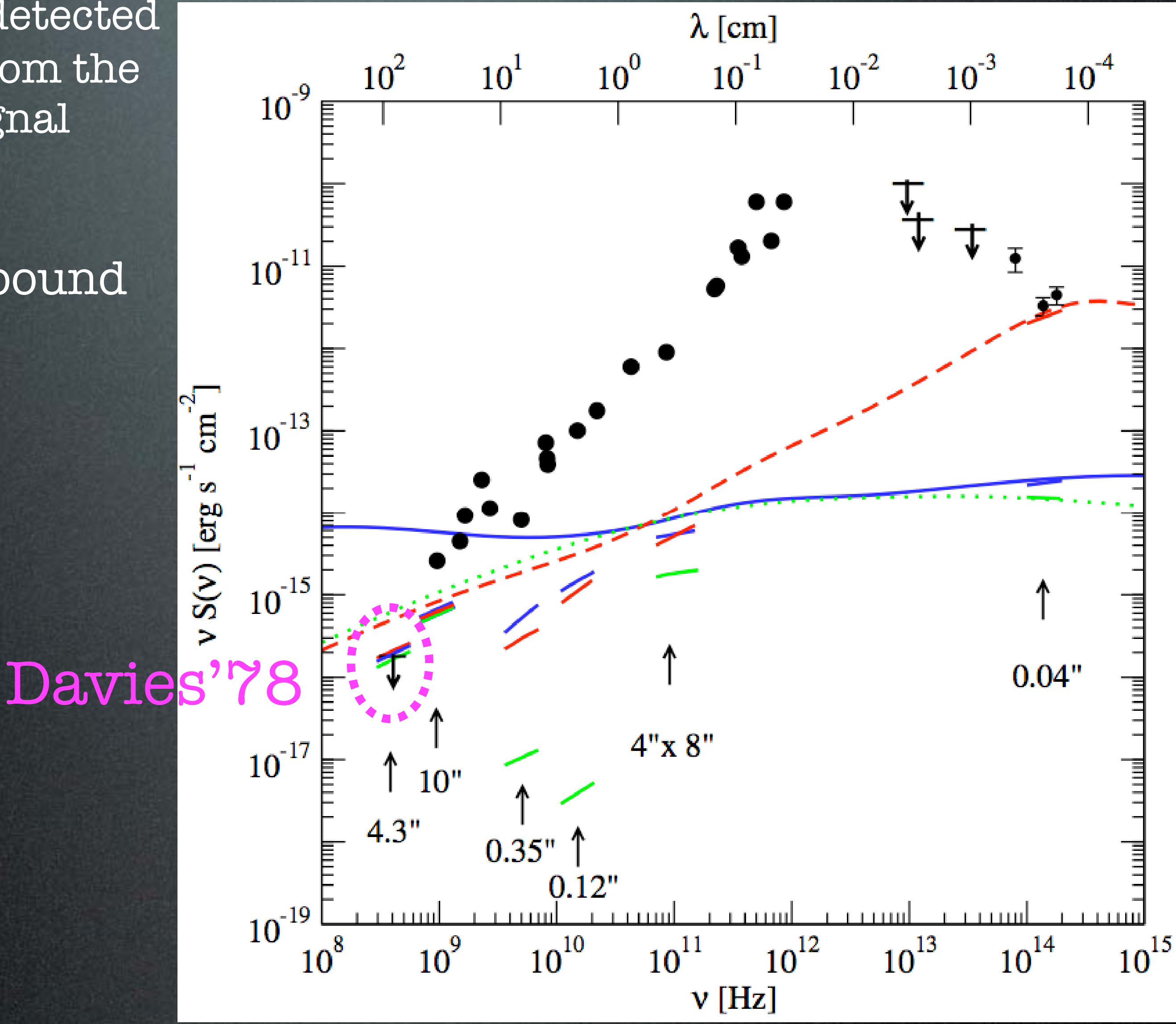


Data: HESS coll., astro-ph/0603021

Gamma constraints

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

Davies 1978 upper bound at 408 MHz.



Regis, Ullio PRD 78 (2008)

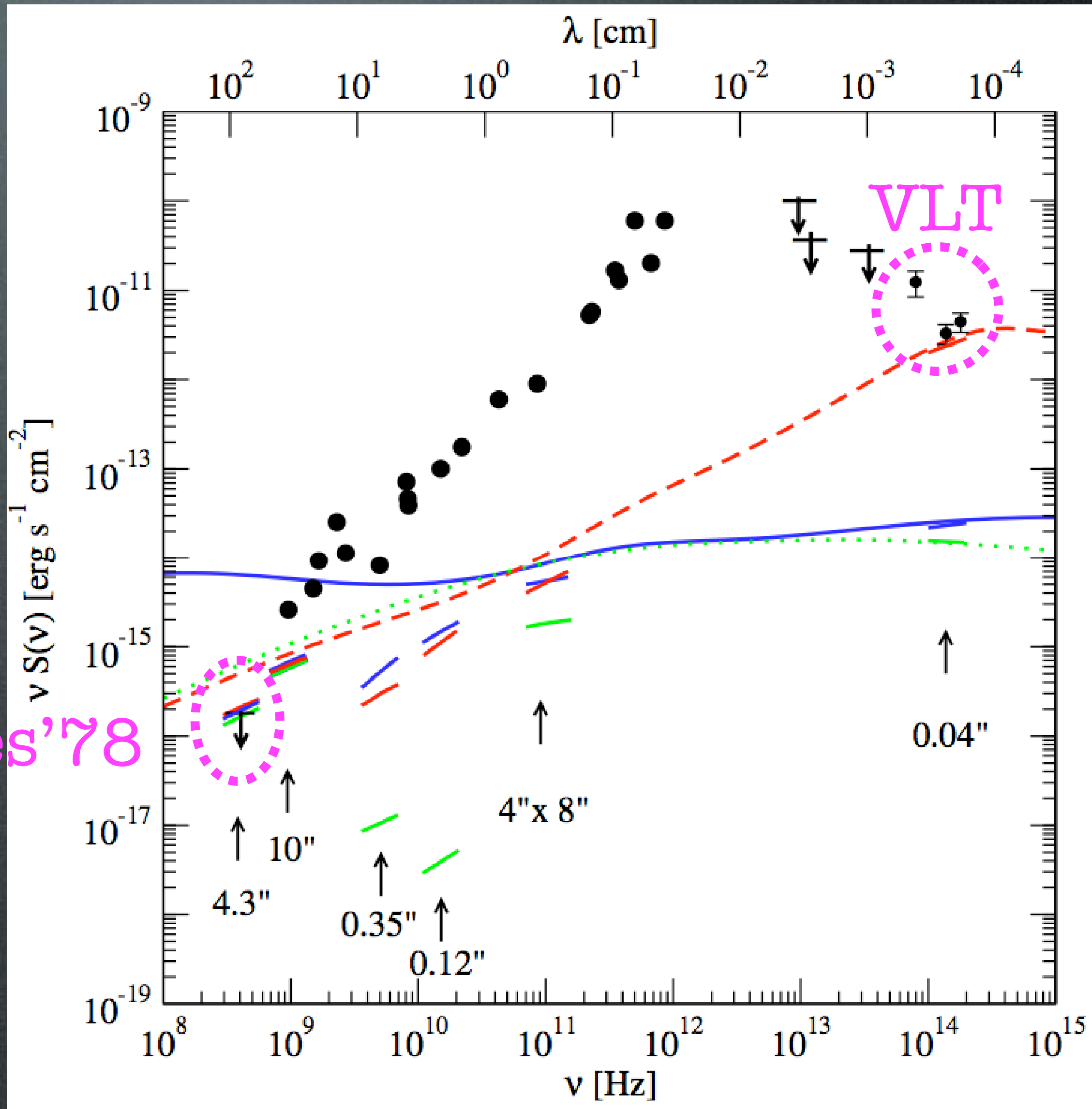
Gamma constraints

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.

Davies'78

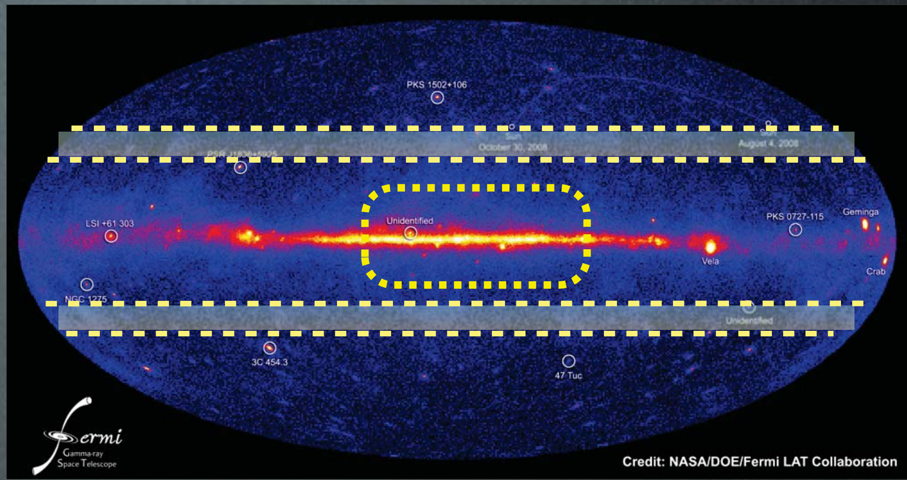


Regis, Ullio PRD '78 (2008)

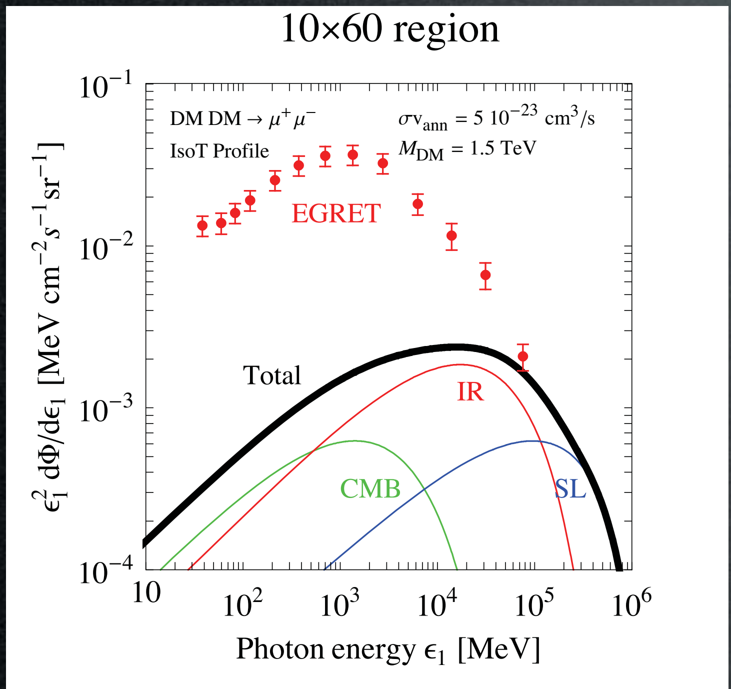
integrate emission over a small angle corresponding to angular resolution of instrument

Gamma constraints

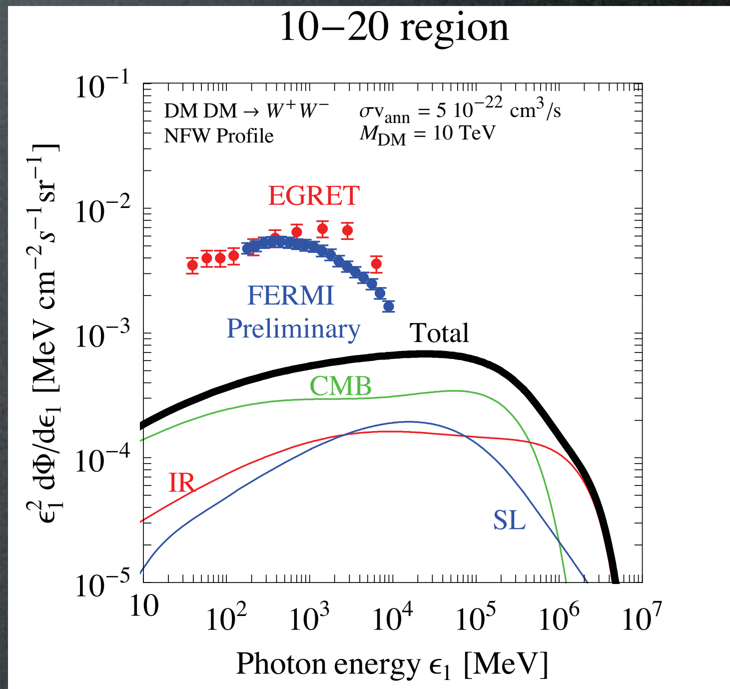
EGRET and FERMI have measured diffuse γ-ray emission. The DM signal must not excede that.



FERMI coll.

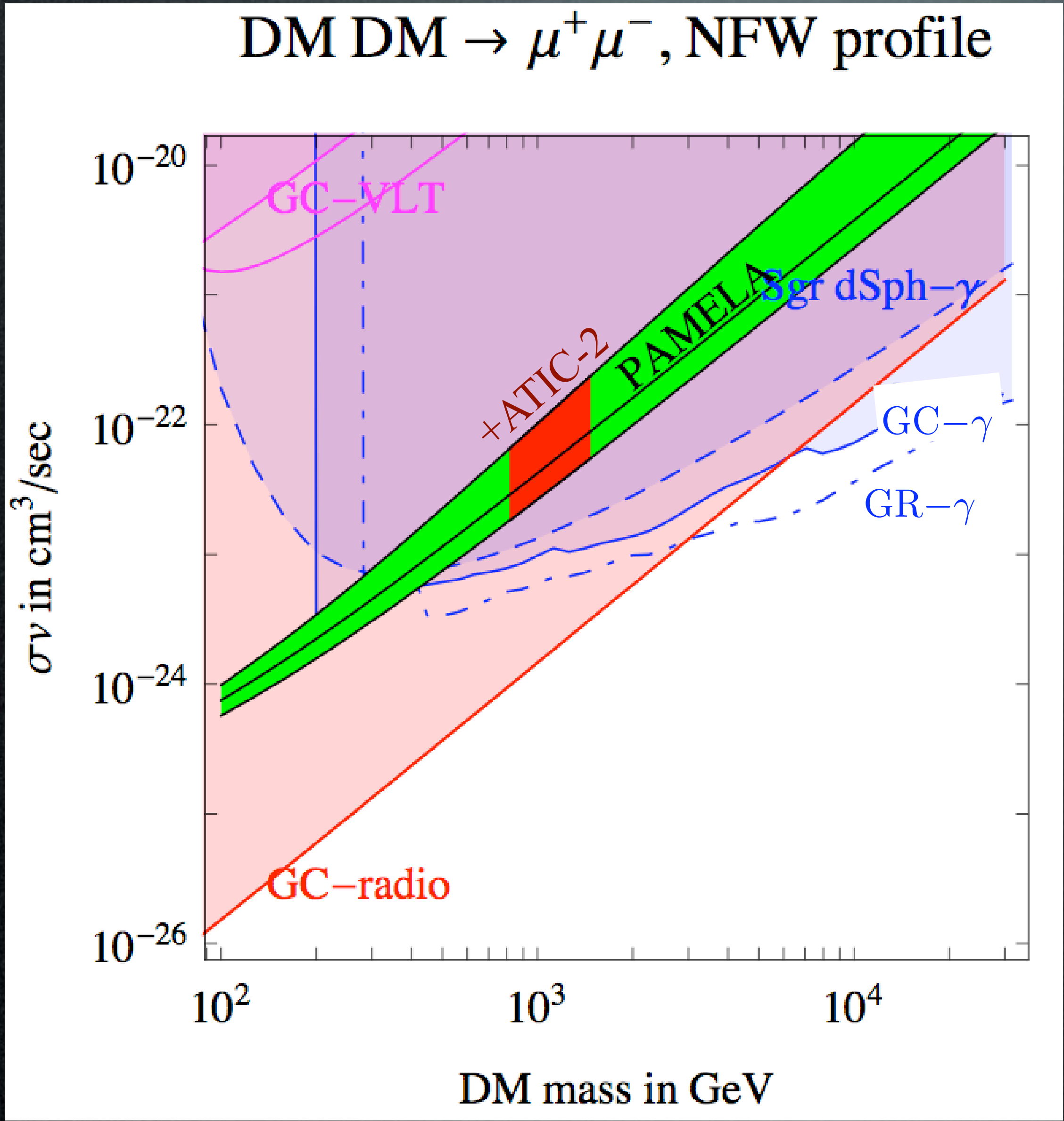


Data: EGRET coll.,Strong et al. astro-ph/0406254



Data: FERMI coll., several talks in 2009

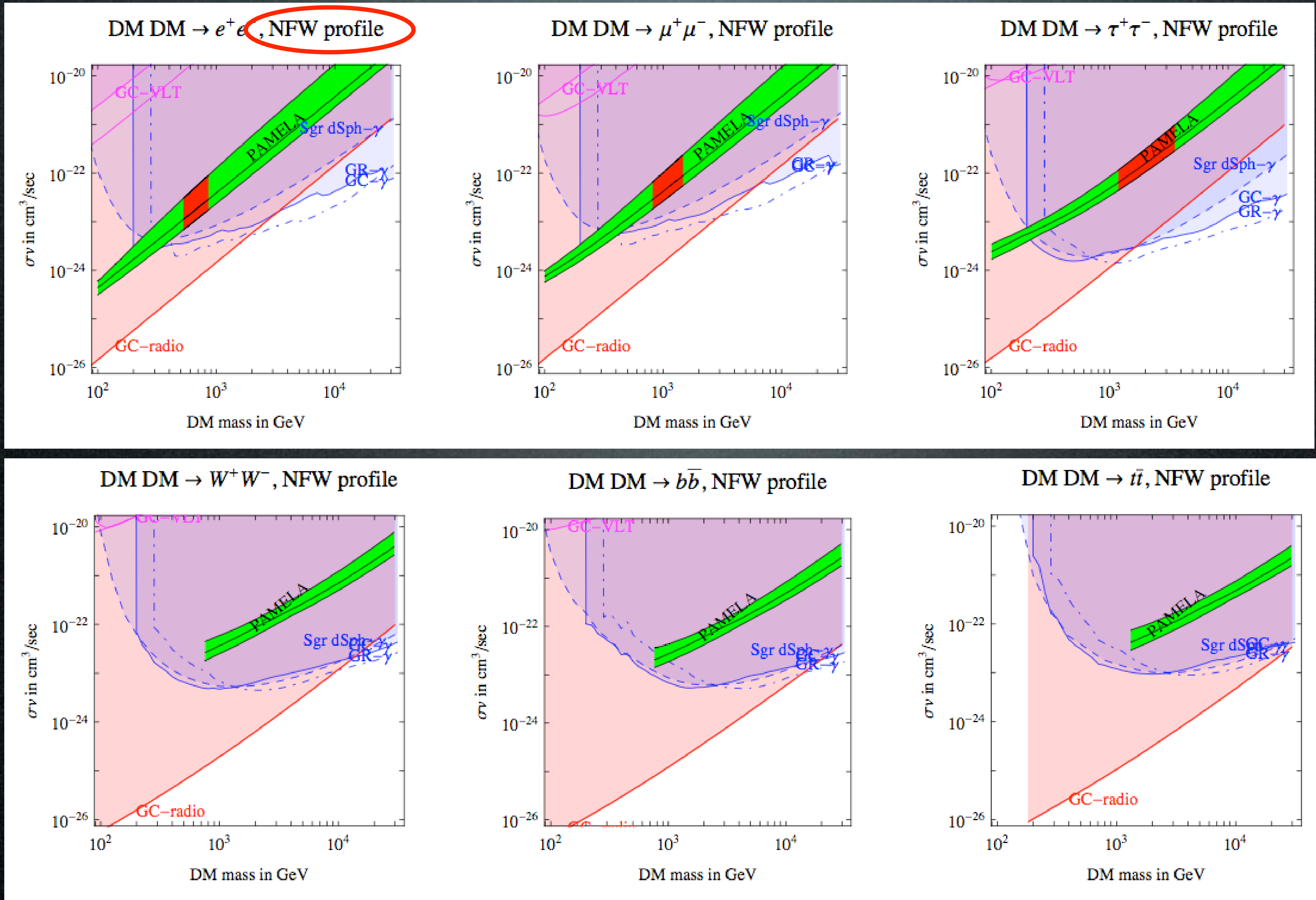
Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

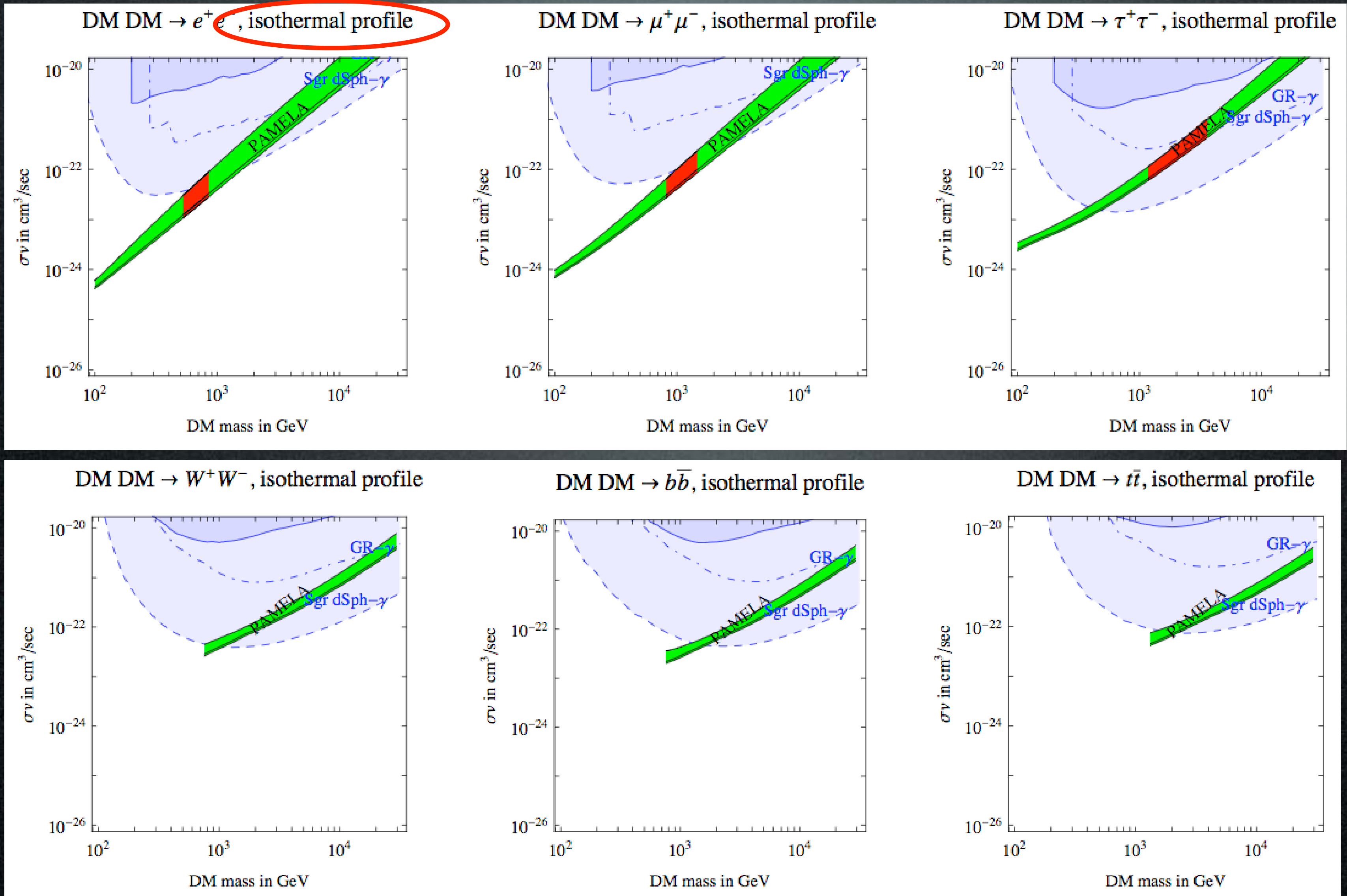
The PAMELA and ATIC regions are in conflict with gamma constraints, unless...

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints



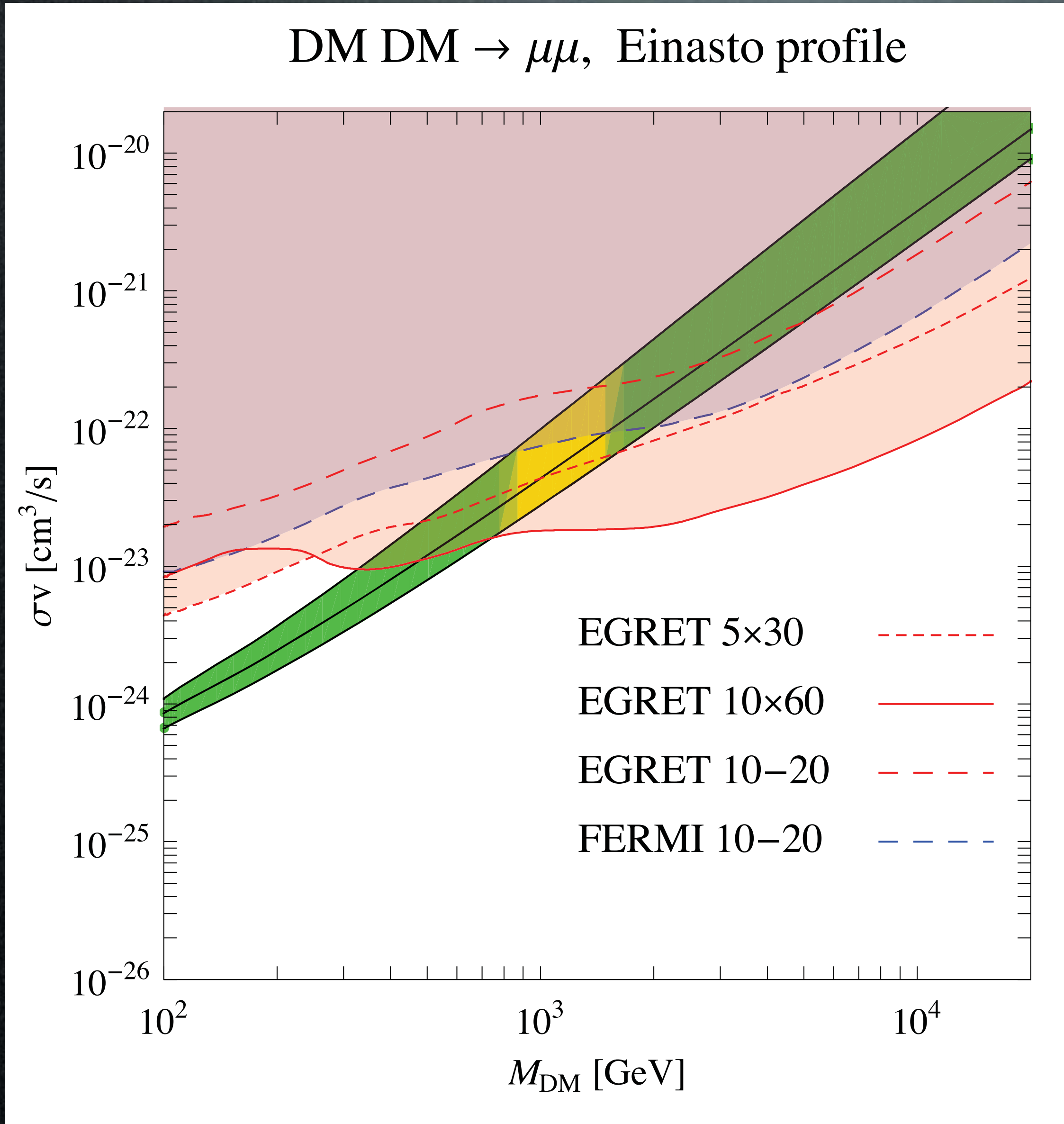
Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

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

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

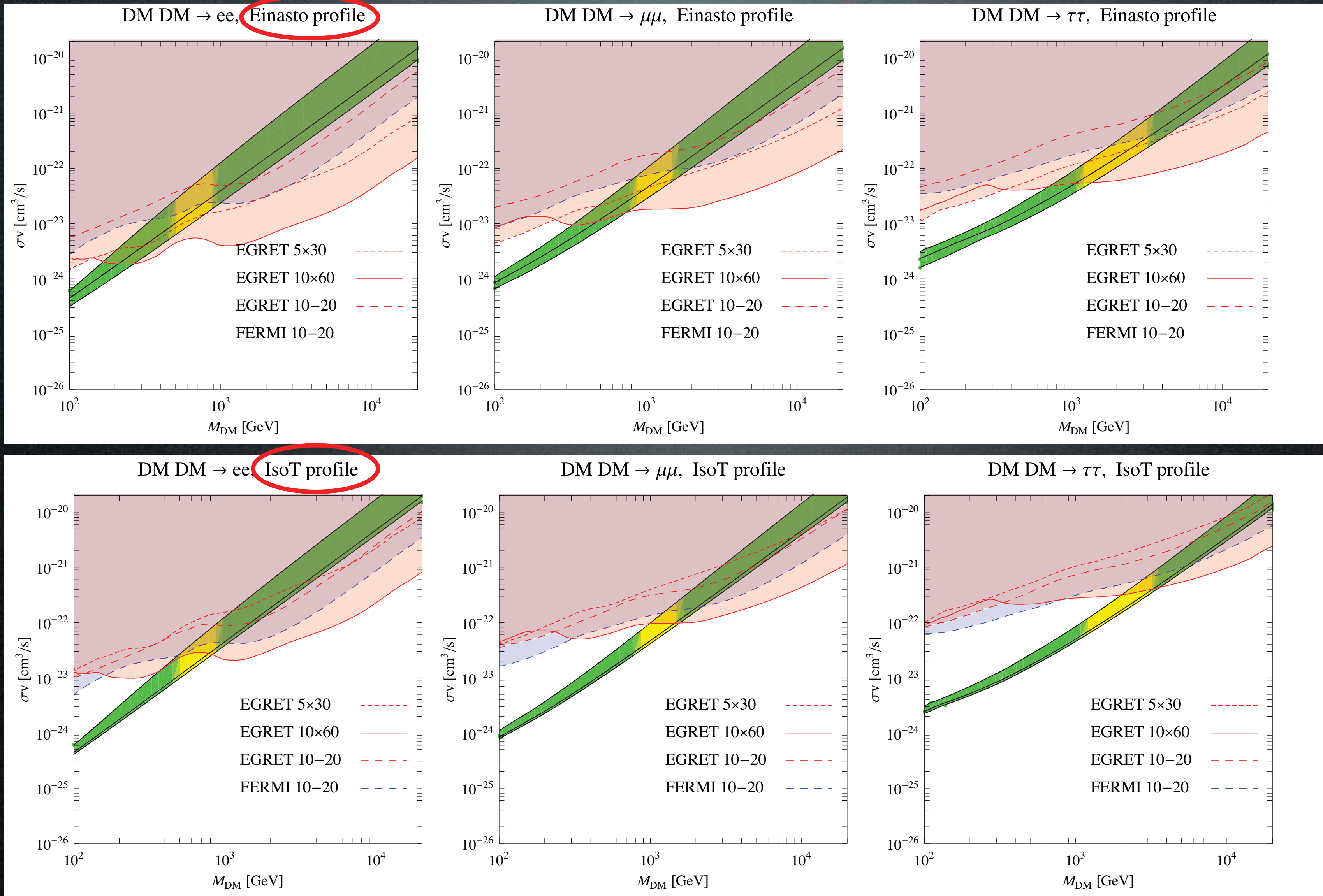
Inverse Compton γ constraints



Cirelli, Panci 0904.3830

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

Inverse Compton γ constraints



Cirelli, Panci 0904.3830

see also: Regis, Ullio 0904.4645

Answers

1. Are we seeing Dark Matter in cosmic rays?

I don't know, I fear it's unlikely, but maybe...
Maybe it's a pulsar.

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

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

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

Upcoming data: Fermi, ATIC-4, Pamela, HESS, AMS-02...

Answers

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DM annihilations: the game

Dark Matter annihilations

DM annihilations: the game

Dark Matter annihilations

huge $\sigma_{\text{ann}} v$

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

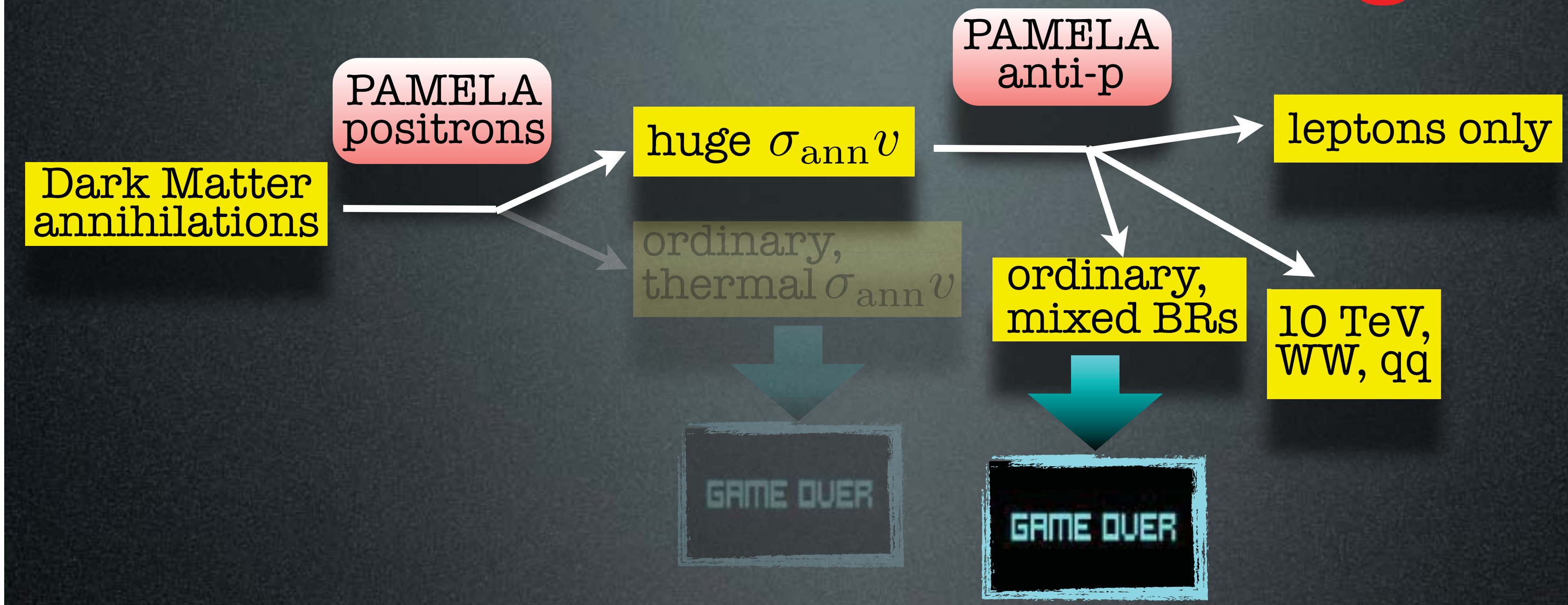
DM annihilations: the game

PAMELA positrons

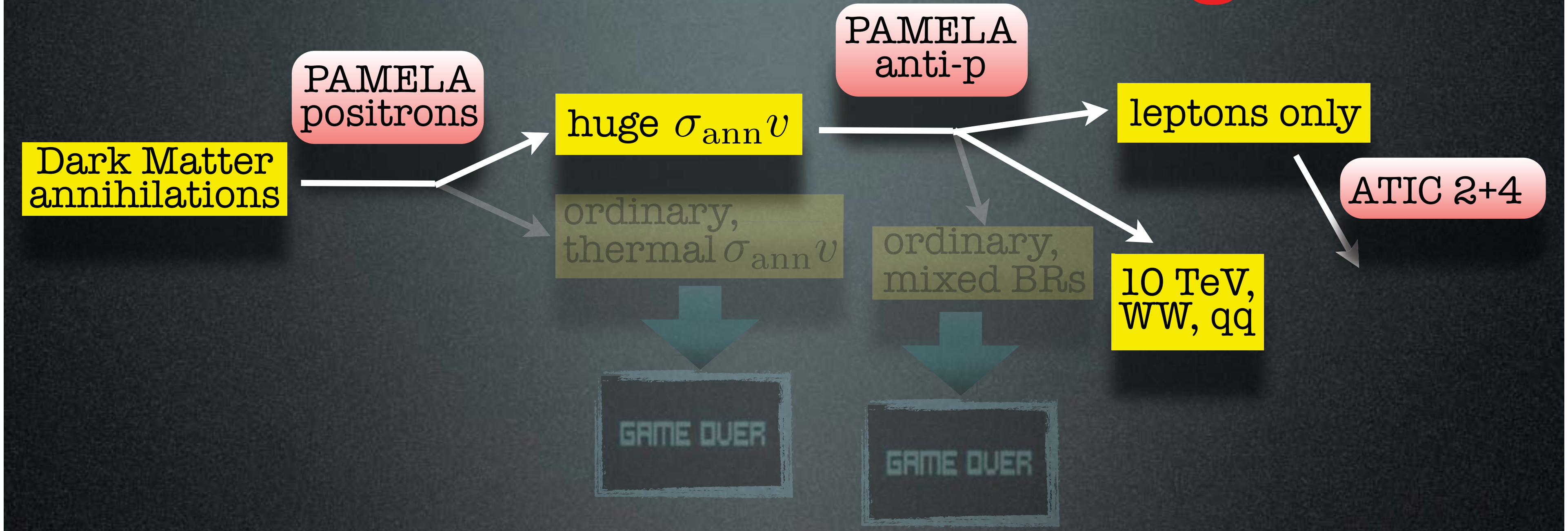
Dark Matter annihilations $\rightarrow$ huge $\sigma_{\rm ann} v$

Dark Matter annihilations $\rightarrow$ ordinary, thermal $\sigma_{\rm ann} v$

DM annihilations: the game



DM annihilations: the game



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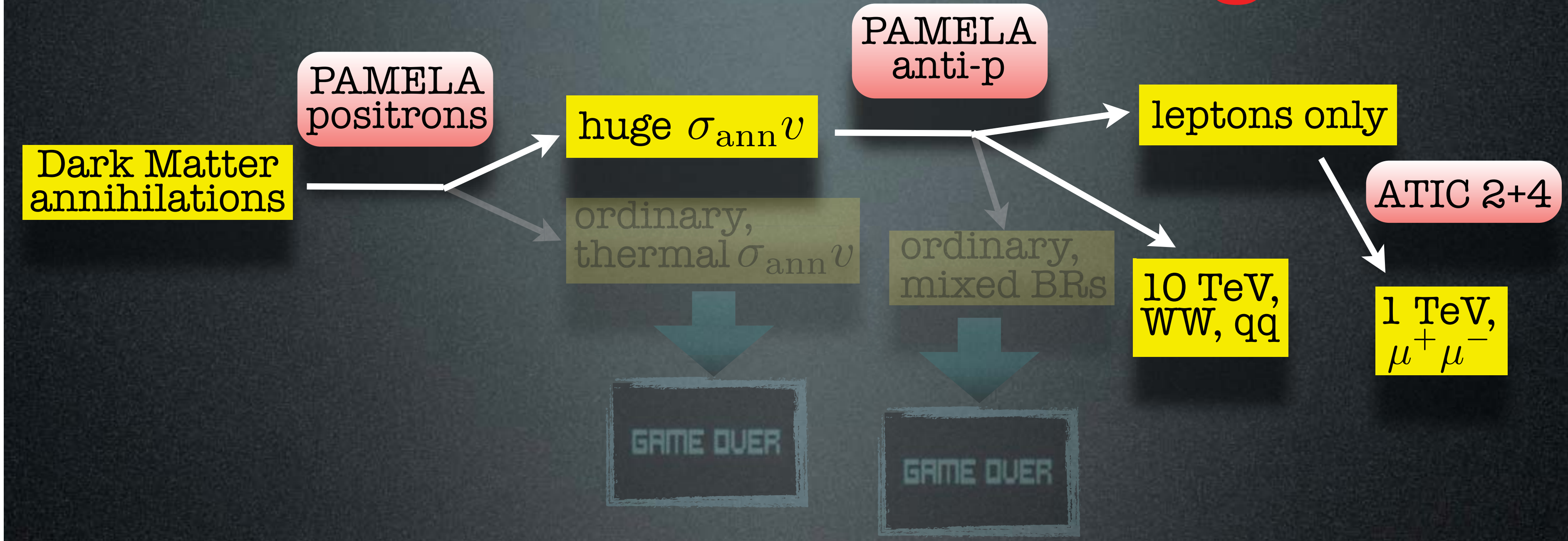
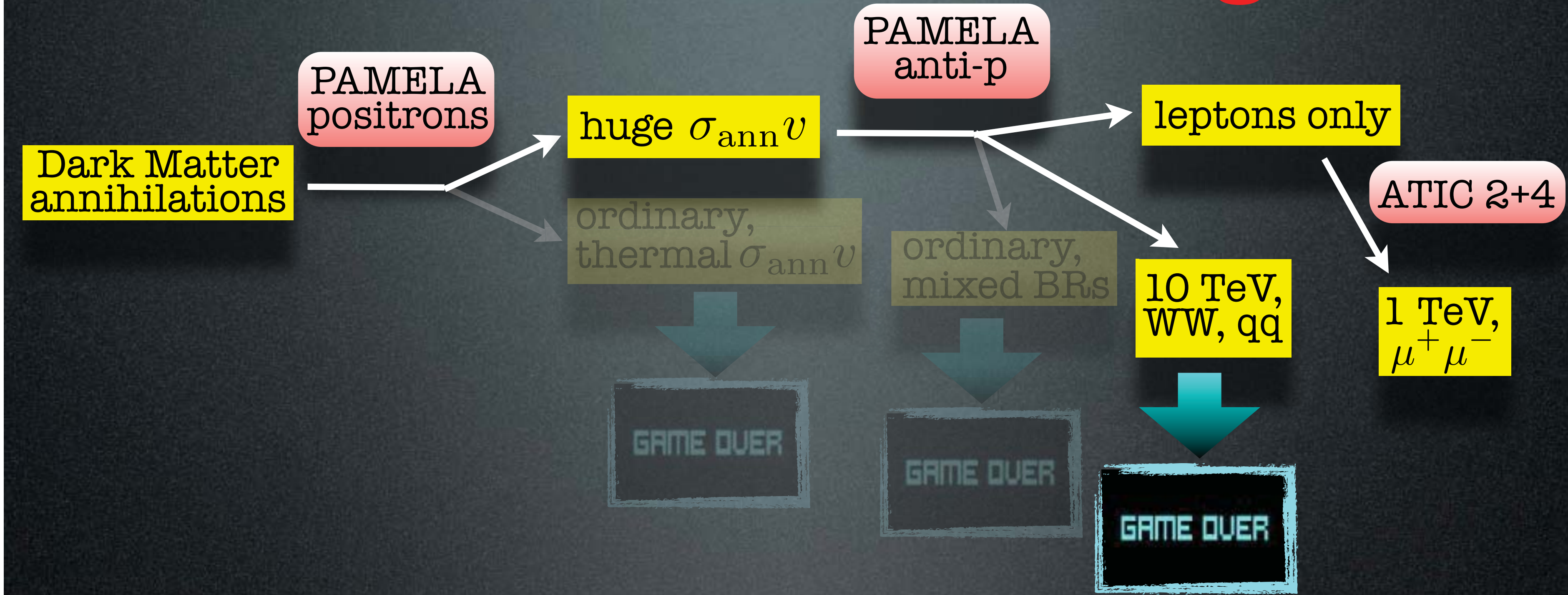


DM annihilations: the game



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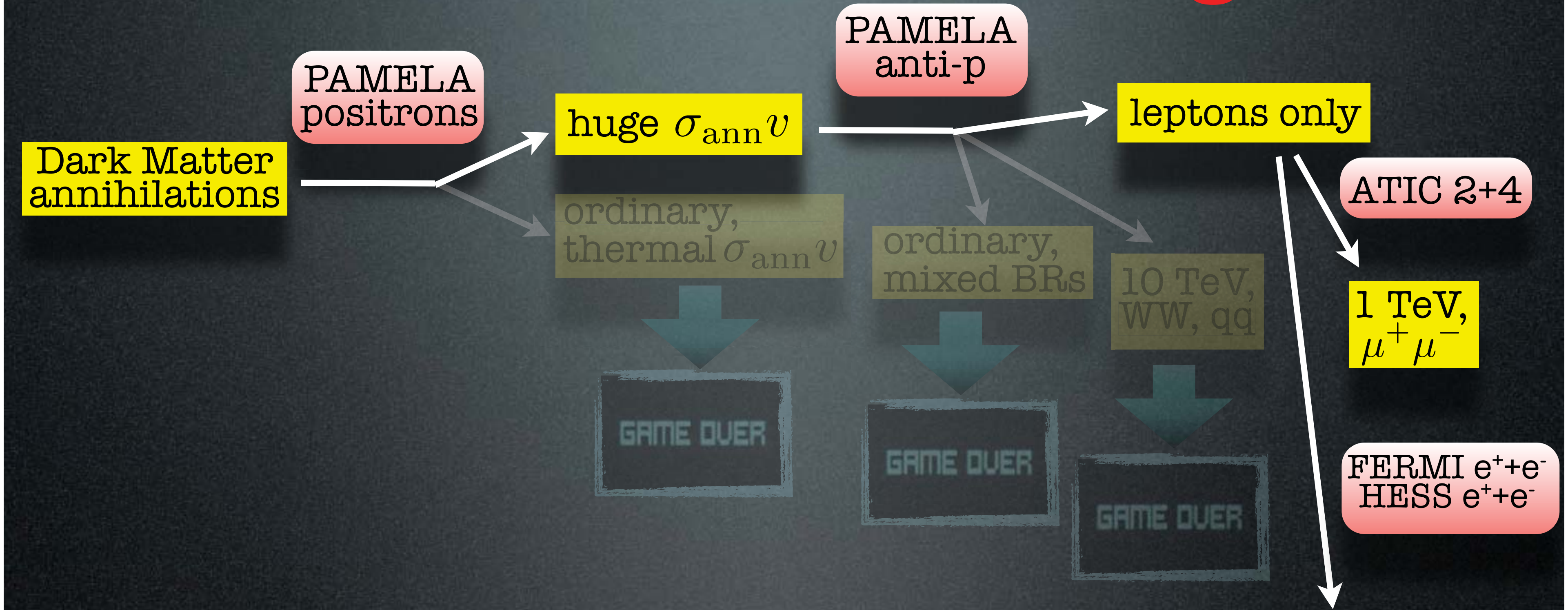
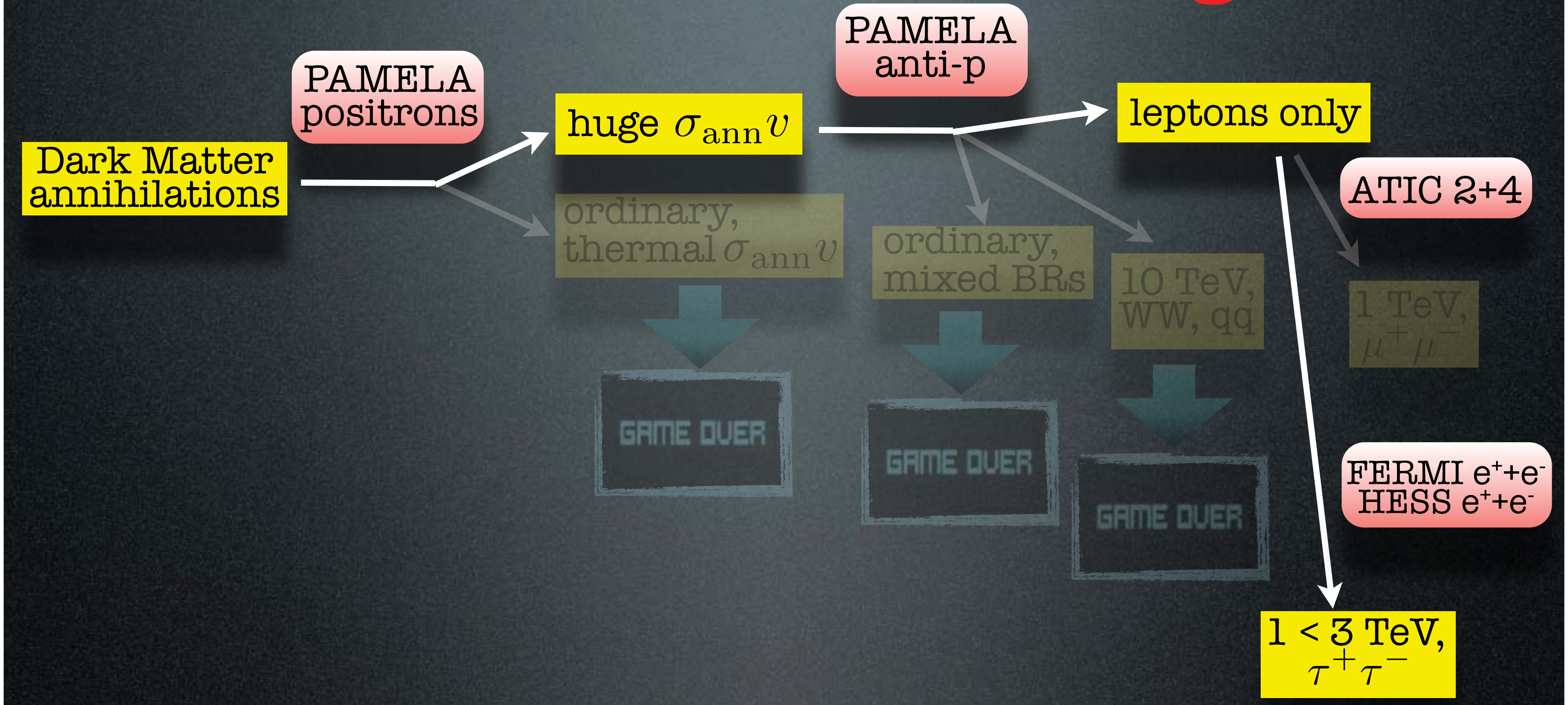
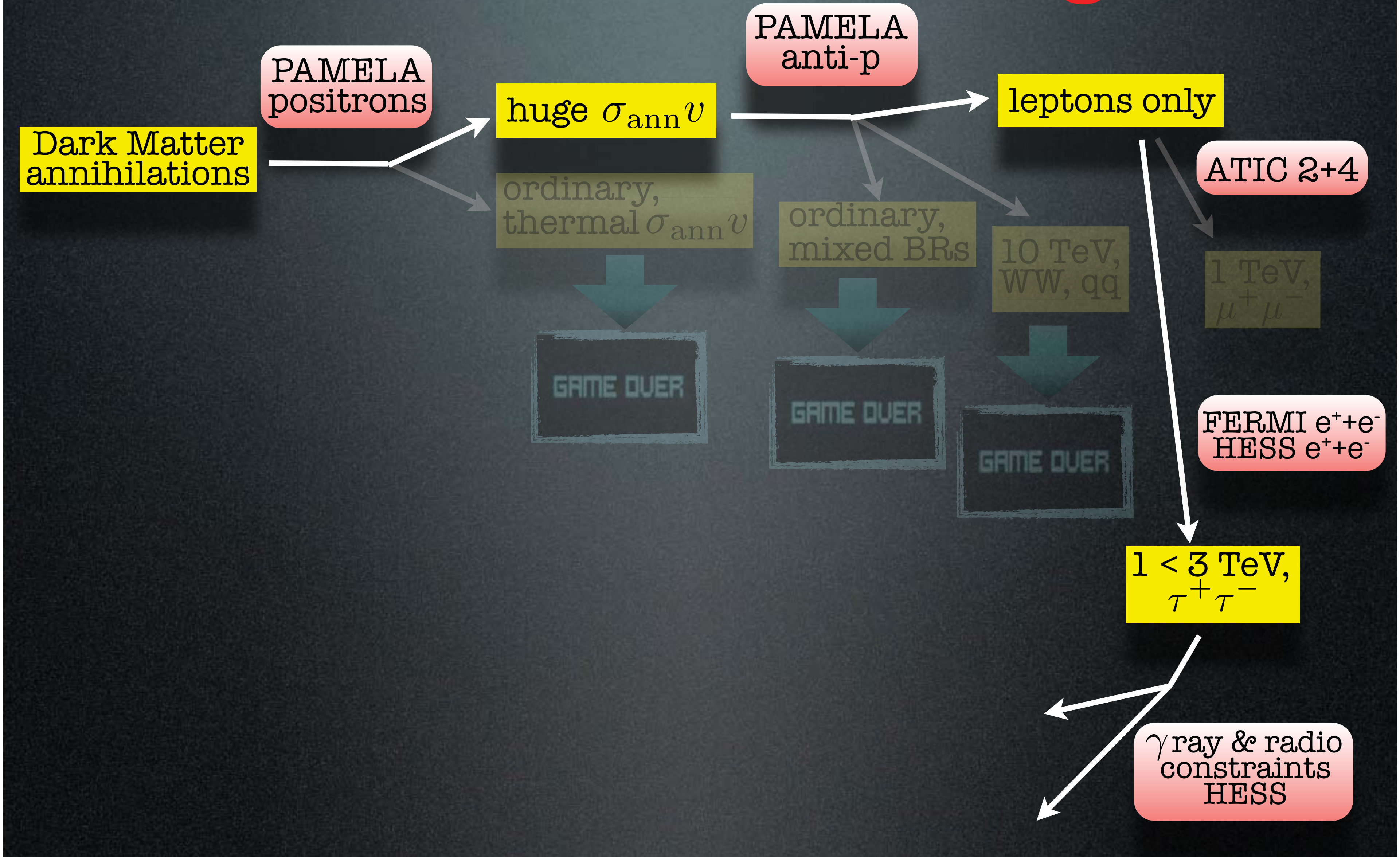


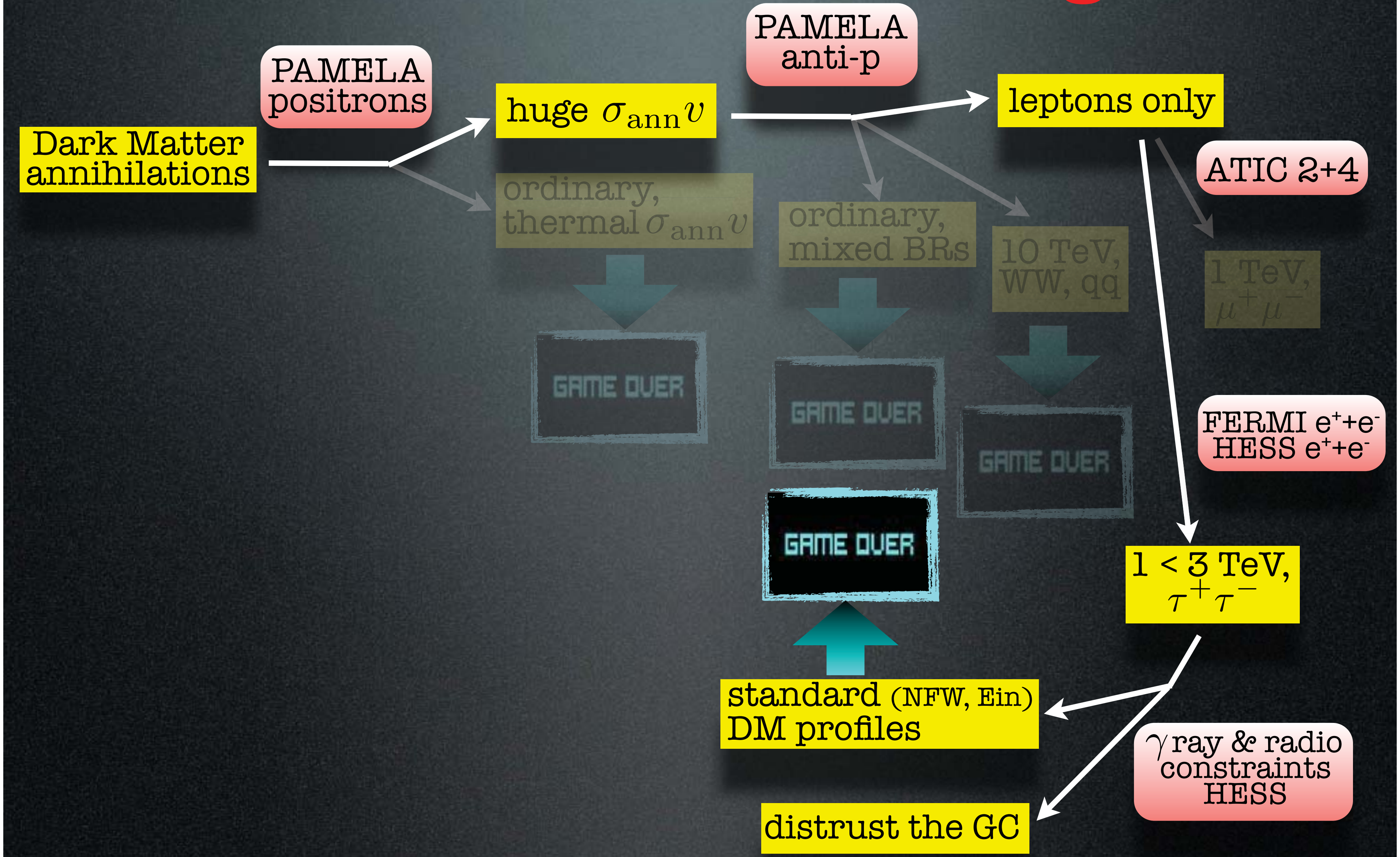
DM annihilations: the game



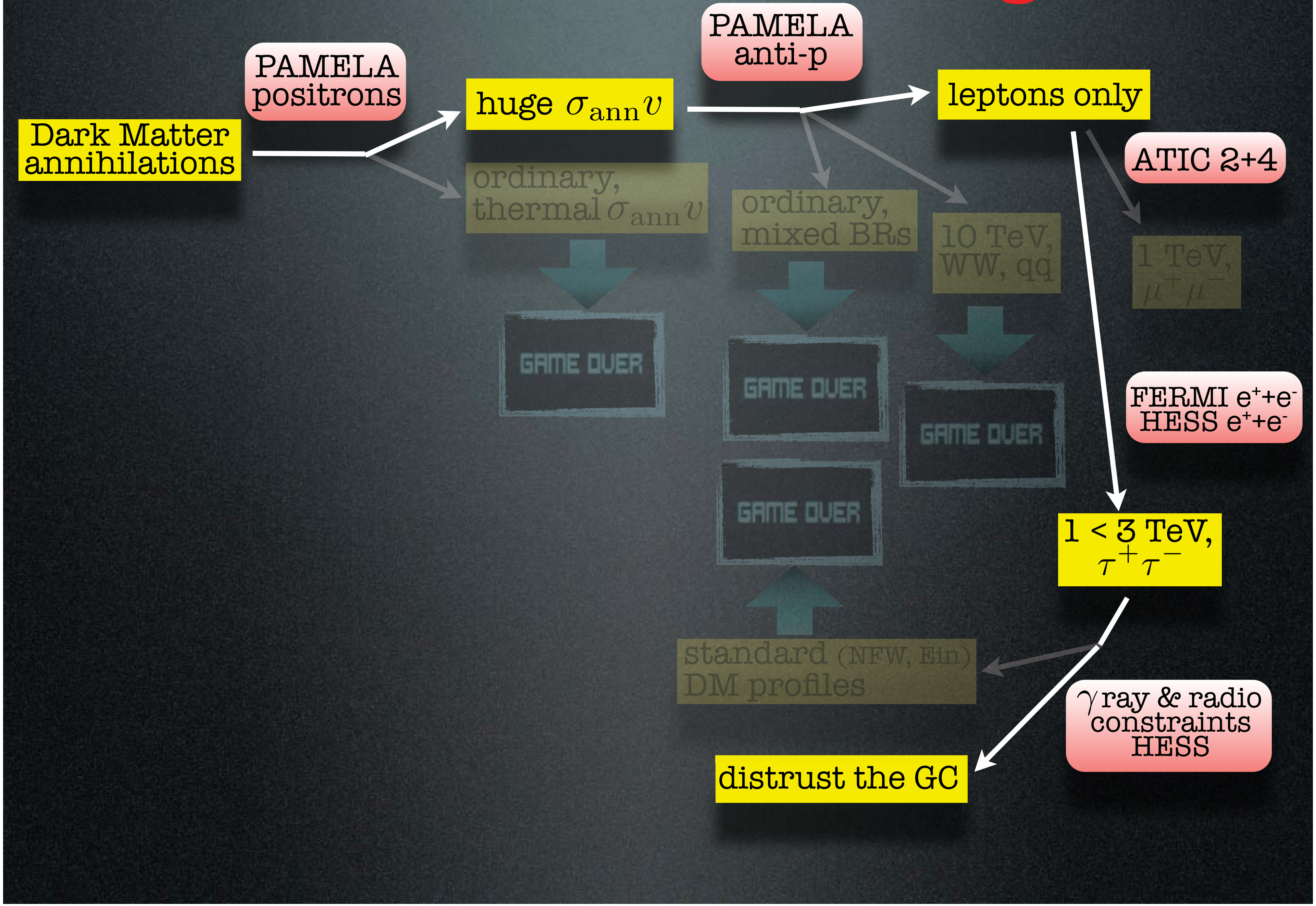
DM annihilations: the game



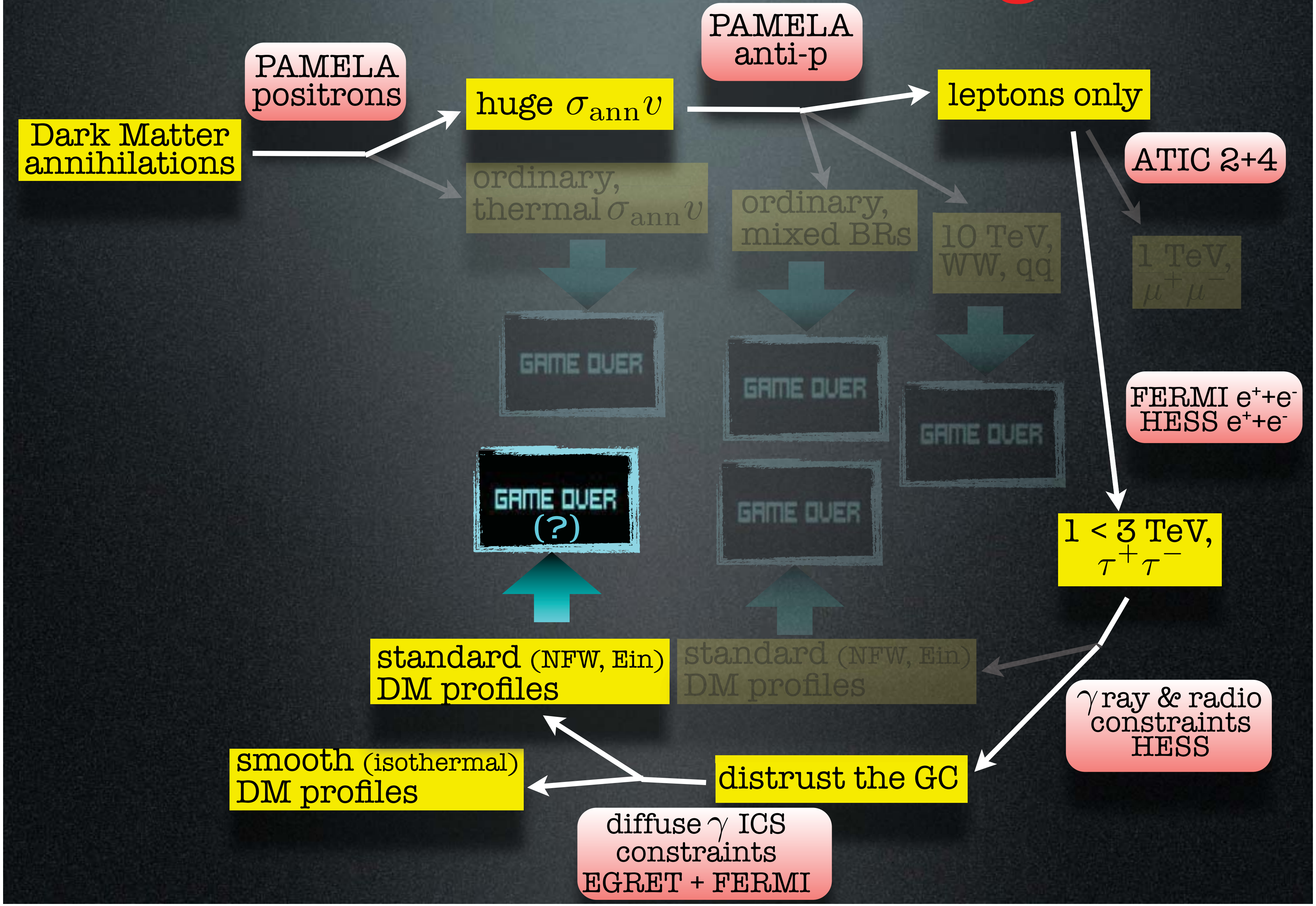
DM annihilations: the game



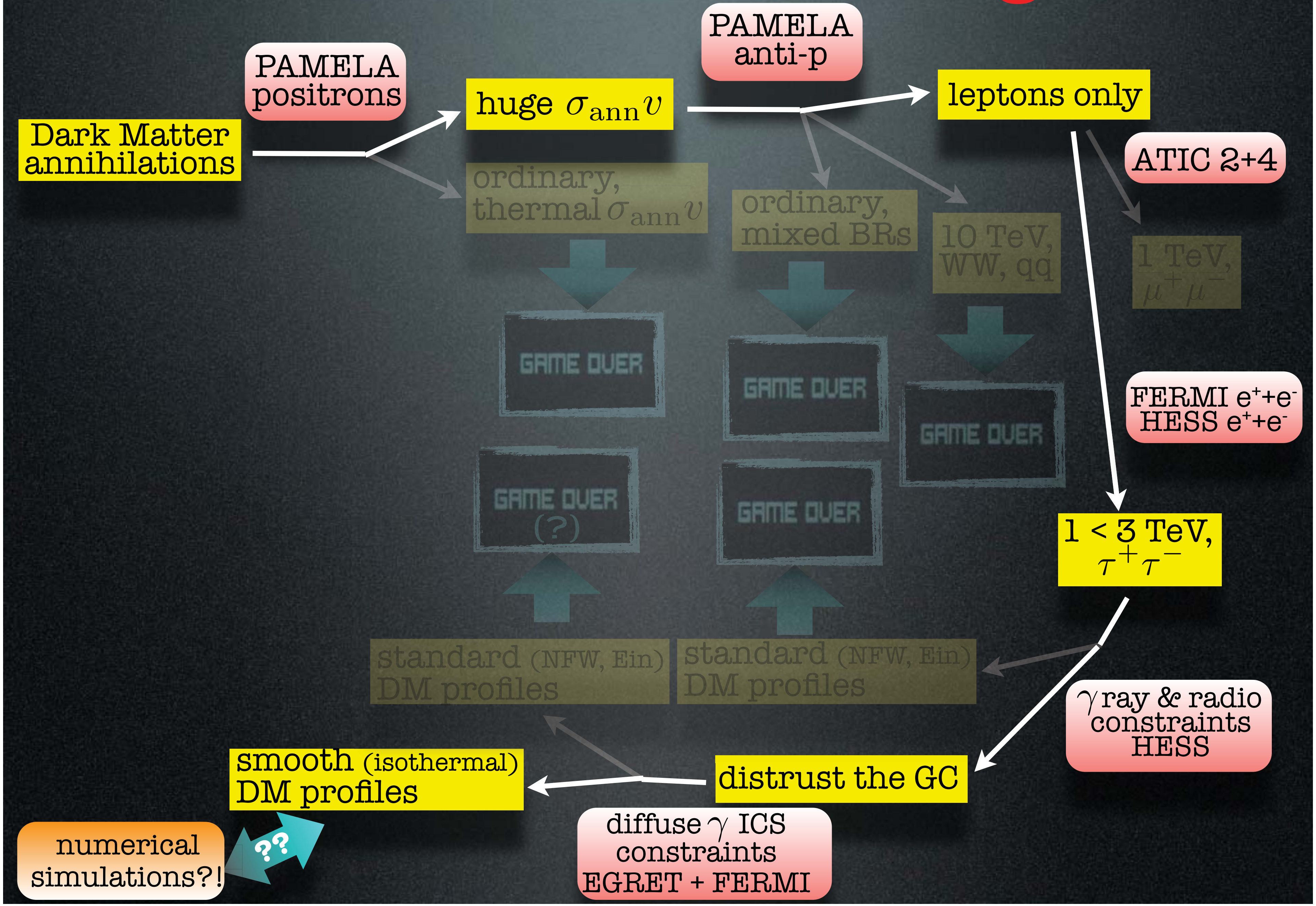
DM annihilations: the game

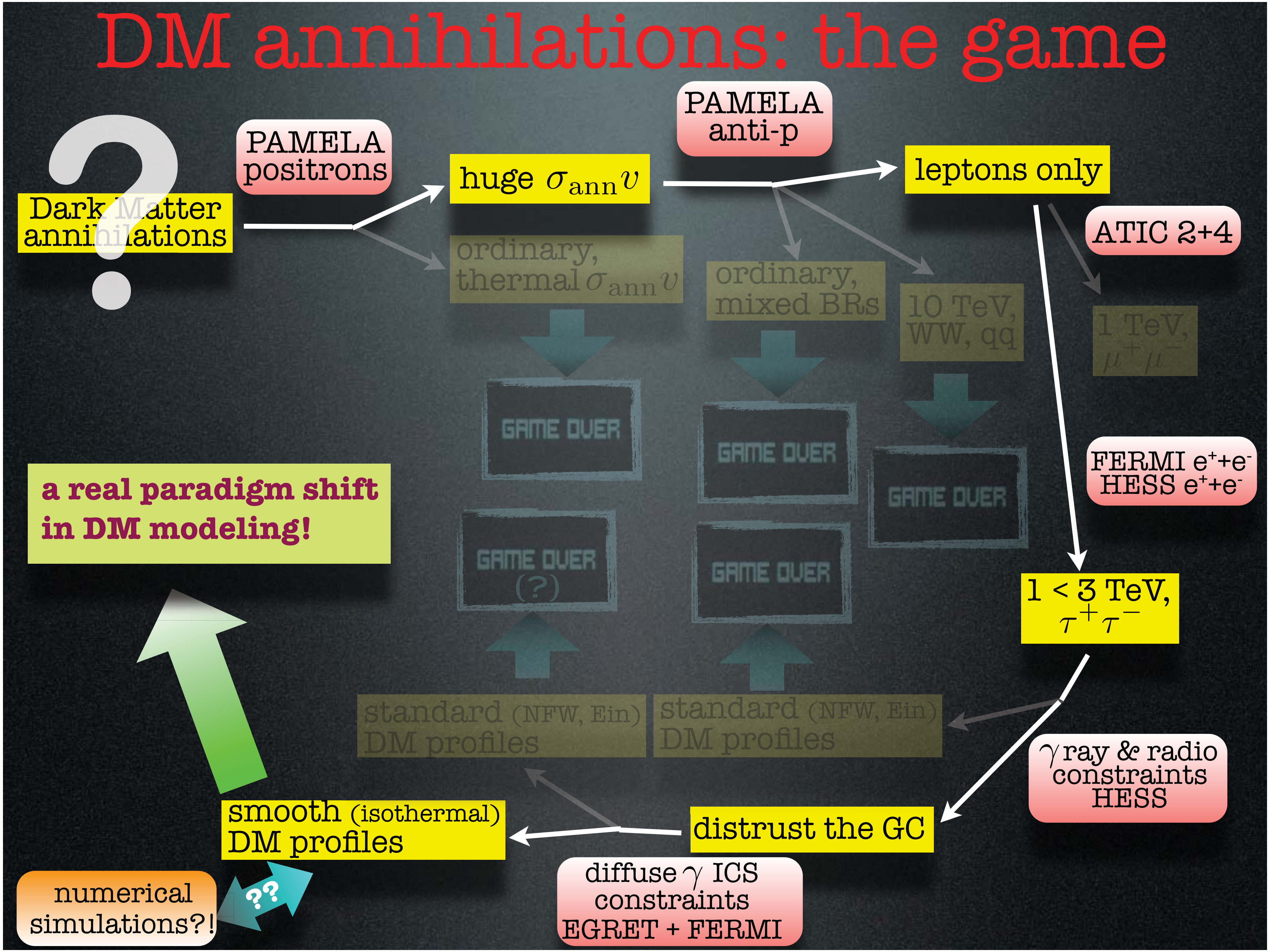


DM annihilations: the game



DM annihilations: the game




DM annihilations: the game
Dark Matter annihilations
PAMELA positrons
huge $\sigma_{\rm ann} v$
ordinary, thermal $\sigma_{\rm ann} v$
GAME OVER
GAME OVER (?)
PAMELA anti-p
leptons only
ordinary, mixed BRs
GAME OVER
GAME OVER
10 TeV, WW, qq
GAME OVER
ATIC 2+4
1 TeV, $\mu^+\mu^-$
FERMI $e^+ + e^-$
HESS $e^+ + e^-$
1 < 3 TeV, $\tau^+\tau^-$
γ ray & radio constraints HESS
standard (NFW, Ein) DM profiles
standard (NFW, Ein) DM profiles
distrust the GC
diffuse γ ICS constraints EGRET + FERMI
smooth (isothermal) DM profiles
a real paradigm shift in DM modeling!
numerical simulations?!
??

Conclusions

Indirect DM searches are powerful and promising.

The recent PAMELA results might be a breakthrough:
excess in positrons, nothing in anti-protons.

Would anything go with PAMELA? Not at all!
DM must - annihilate into leptons (e.g. $\mu^+\mu^-$) or
- annihilate into W^+W^- with mass $\gtrsim$ 10 TeV
and you need a huge flux.
Not your garden variety vanilla DM...

Adding balloon data (ATIC, PPB-BETS):
DM must annihilate into $\mu^+\mu^-$ and have $M_{\rm DM} \simeq 1\,{\rm TeV}$

Adding FERMI & HESS data:
DM must annihilate into $\tau^+\tau^-$ (?) and have $M_{\rm DM} \simeq 2 \div 3\ {\rm TeV}$

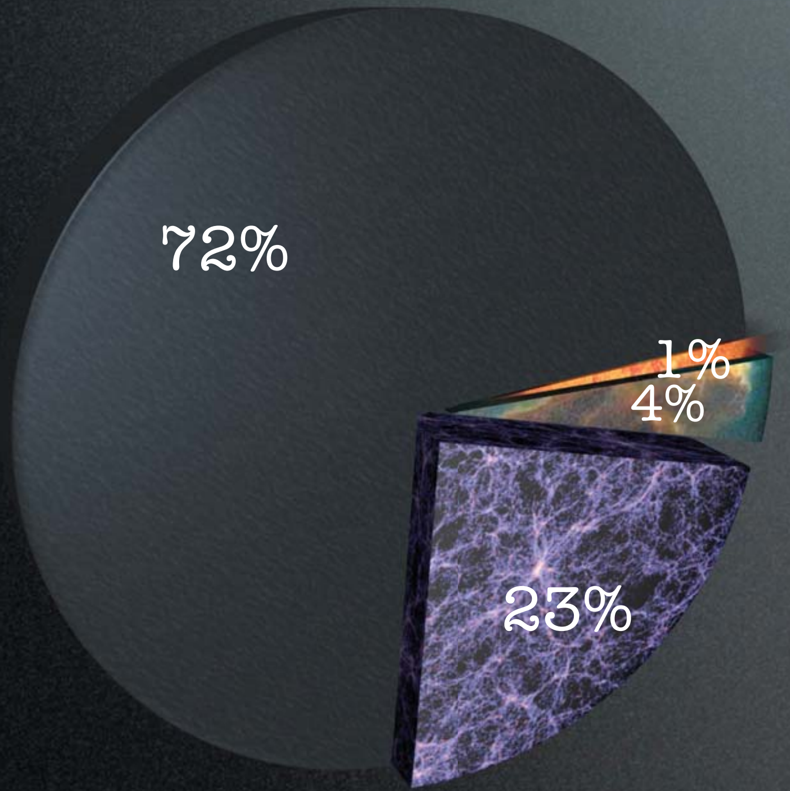
But: **gamma, synchrotron** and **ICS** constraints are severe!
Need a not-too-steep DM profile.

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

Back up slides

The cosmic inventory

Most of the Universe is Dark.



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

DM behaves like matter

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

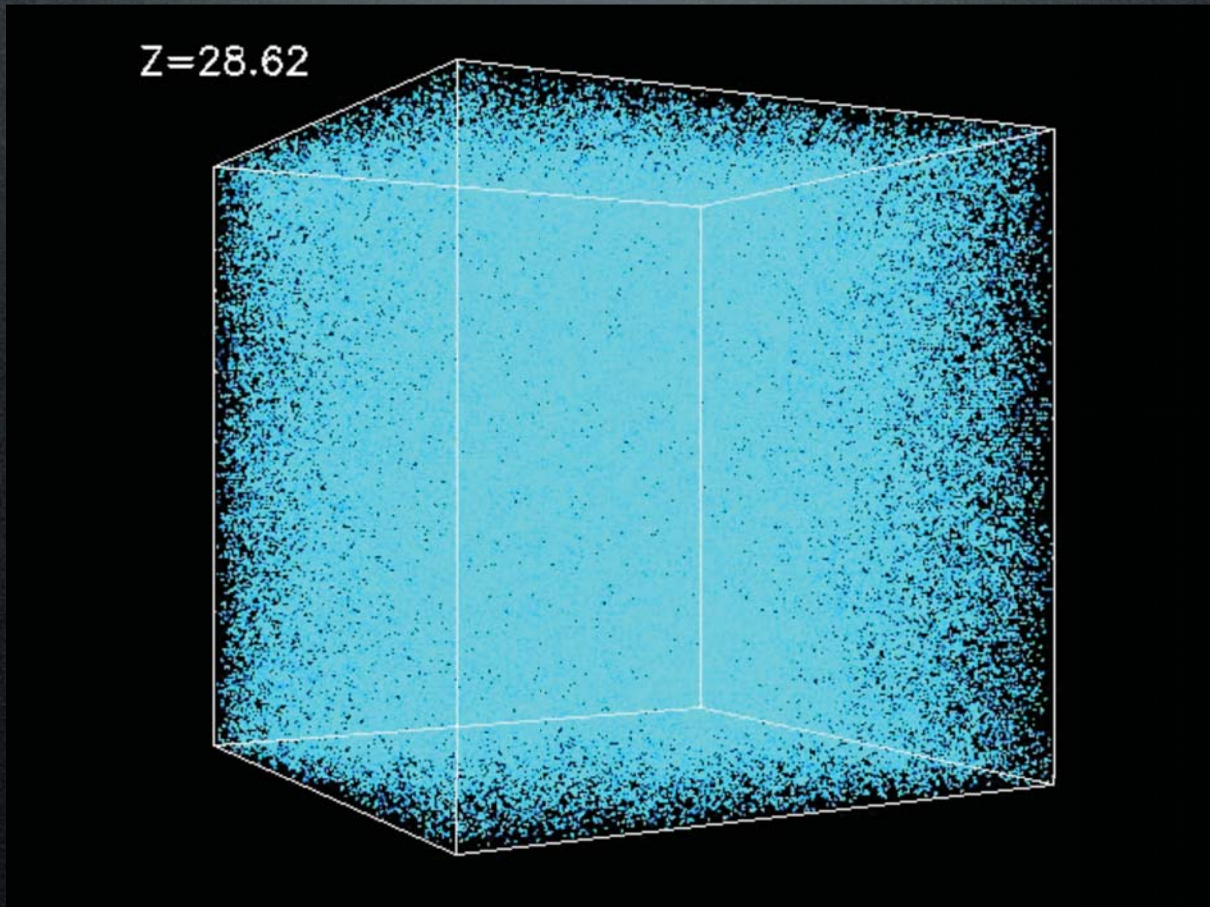
DE behaves like a constant

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

[back]

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box



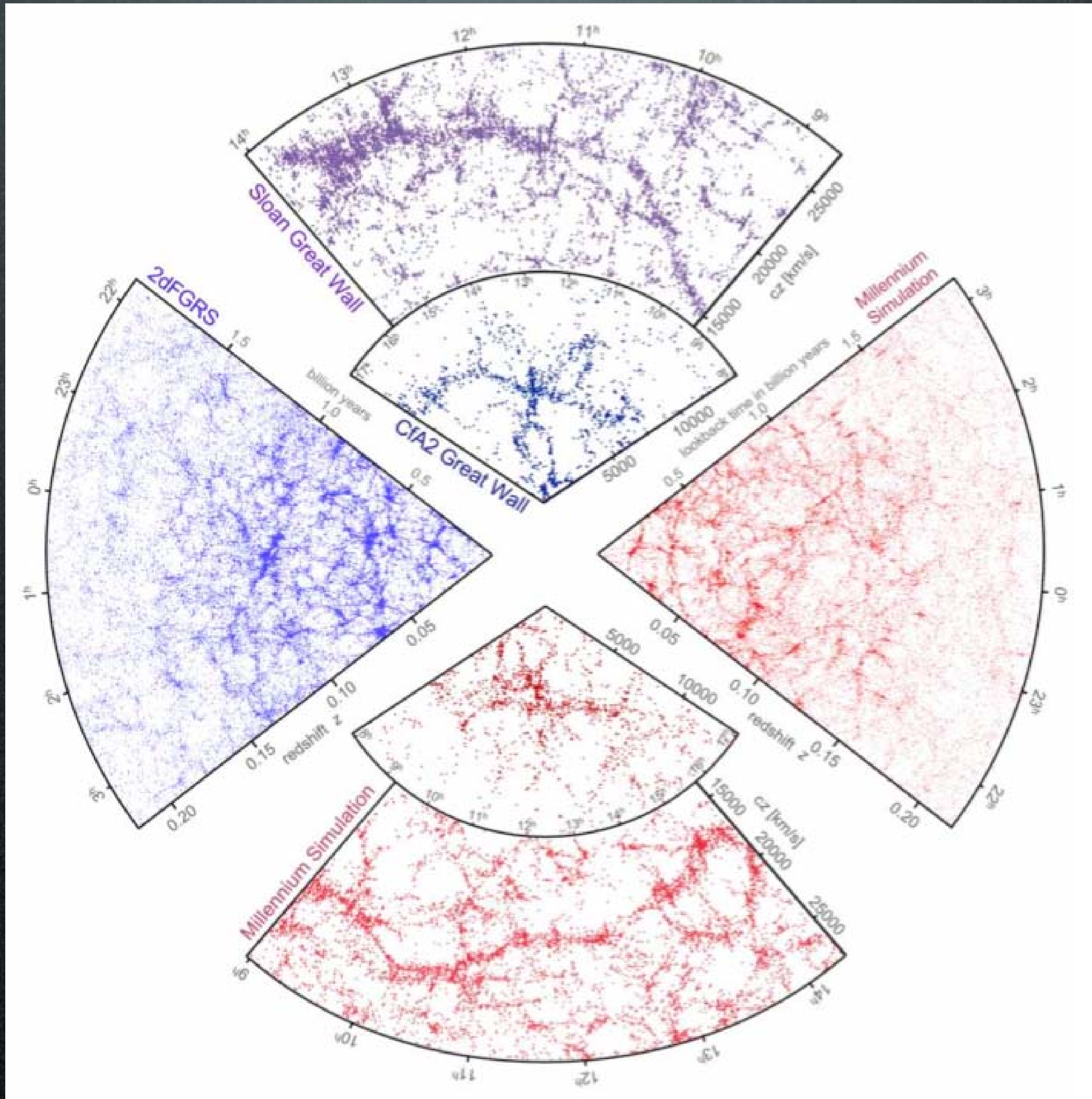
Andrey Kravtsov, cosmicweb.uchicago.edu

[back]

DM N-body simulations

2dF: $2.2\ 10^5$ galaxies

SDSS: 10^6 galaxies,
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

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

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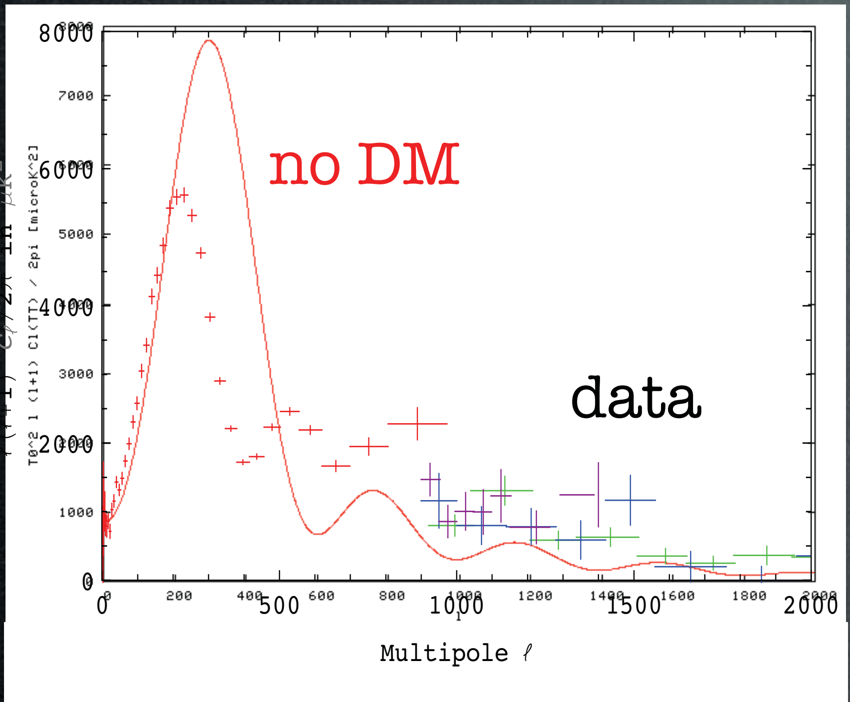
The Evidence for DM

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

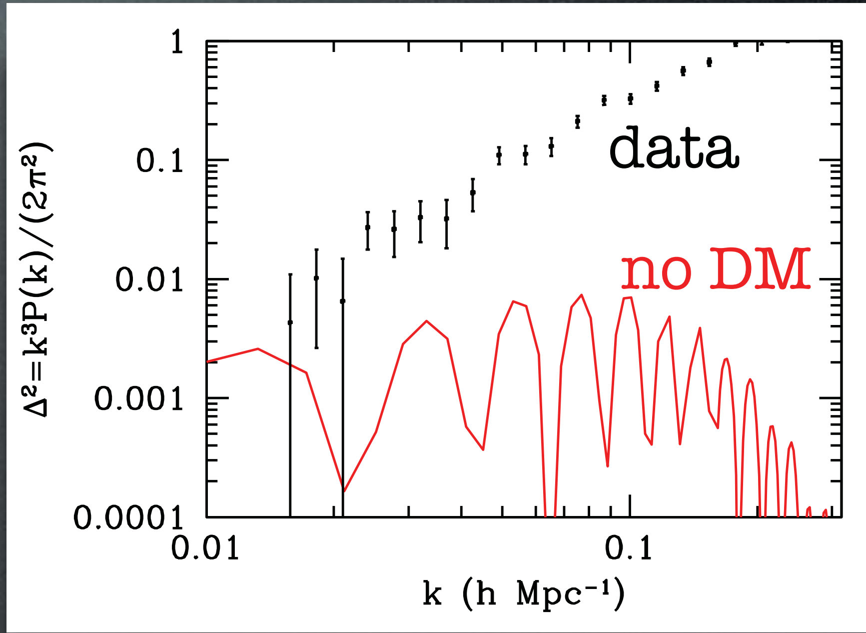
CMB



CAMB online

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

LSS



Dodelson, Liguori 2006

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

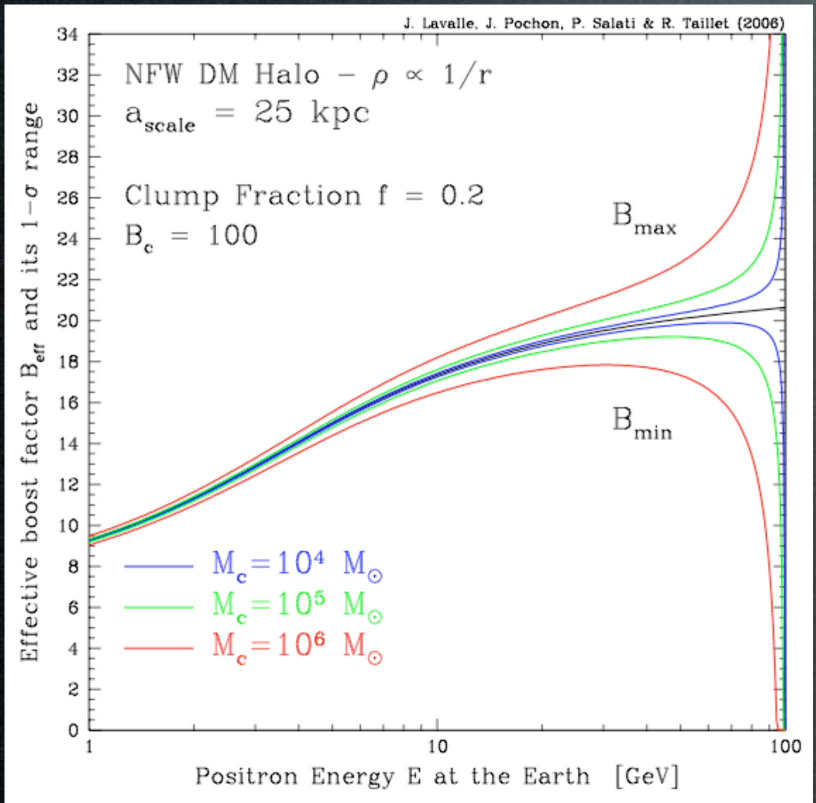
[back]

Indirect Detection

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

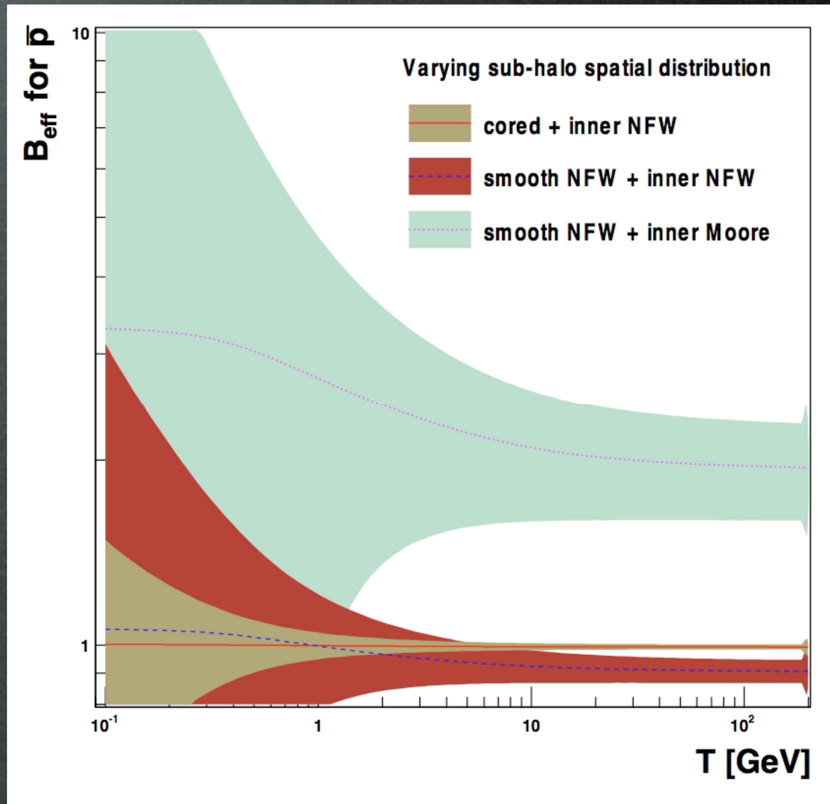
In principle, B is different for e^+, anti-p and gammas,
energy dependent,
dependent on many astro assumptions (inner density profile of clump, tidal disruptions and smoothing...),
with an energy dependent variance, at high energy for e^+, at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons



Lavalle et al. 2007

Indirect Detection

Propagation for positrons:

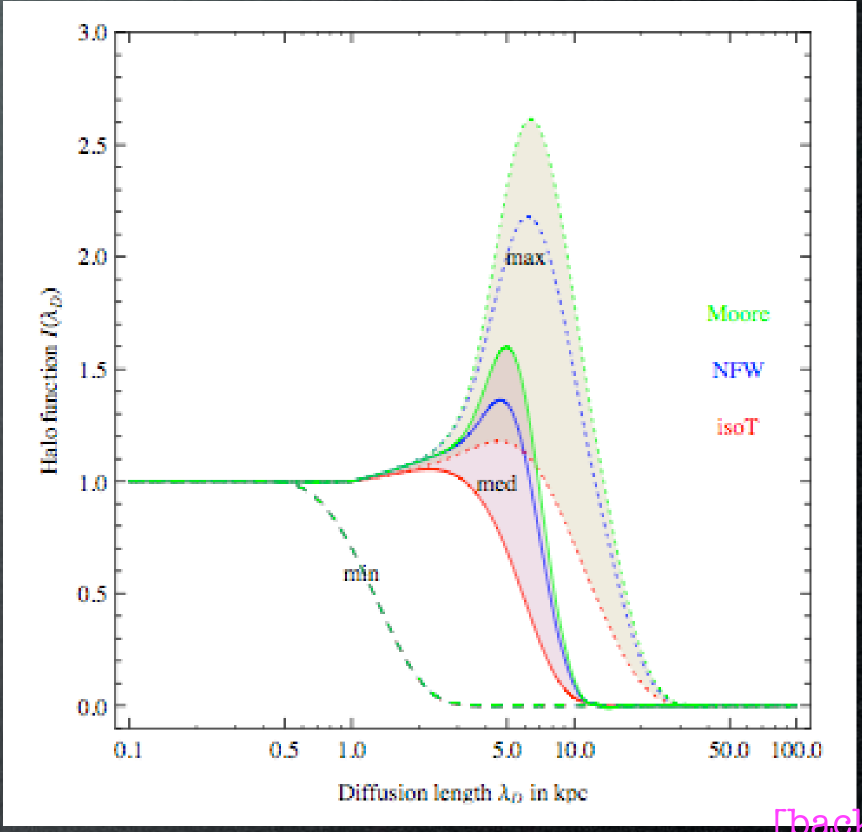
$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) = Q$$

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

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

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

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

[back]

Indirect Detection

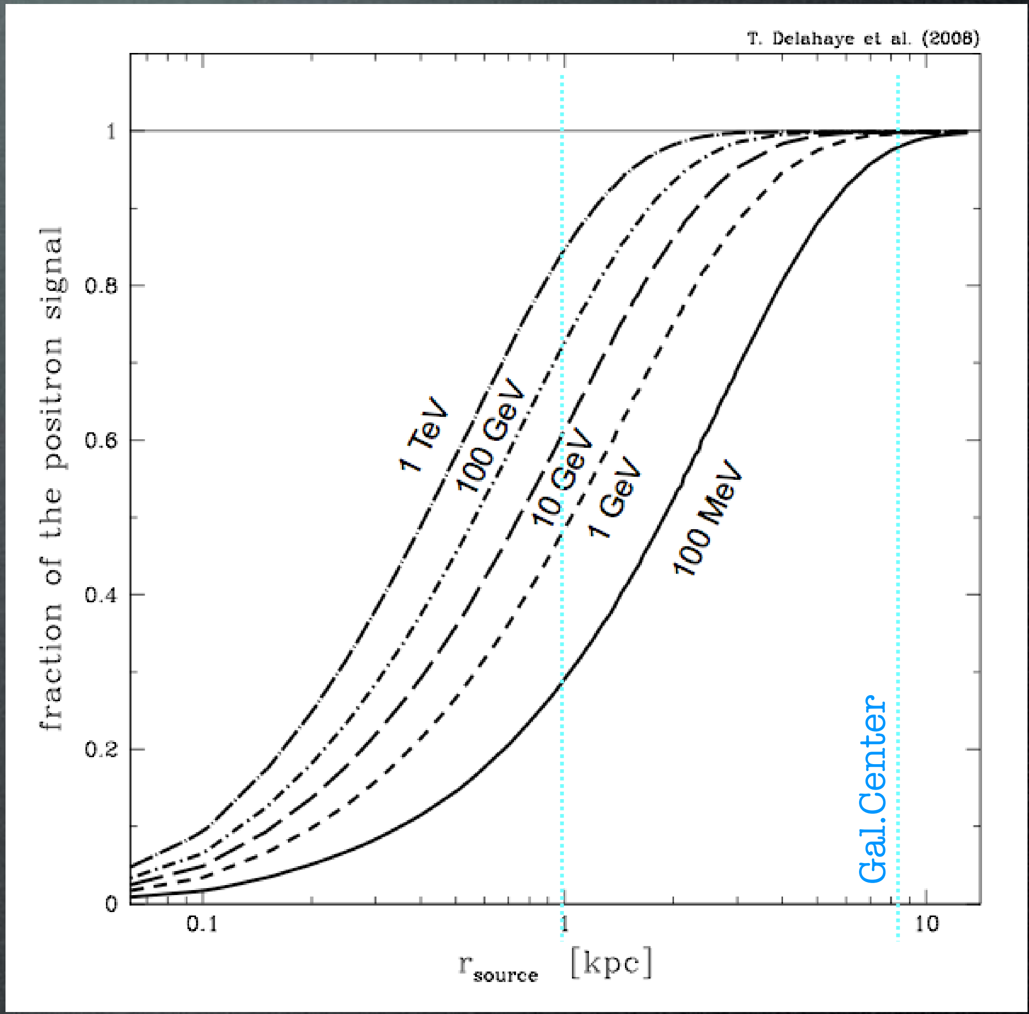
Where do positrons come from?

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

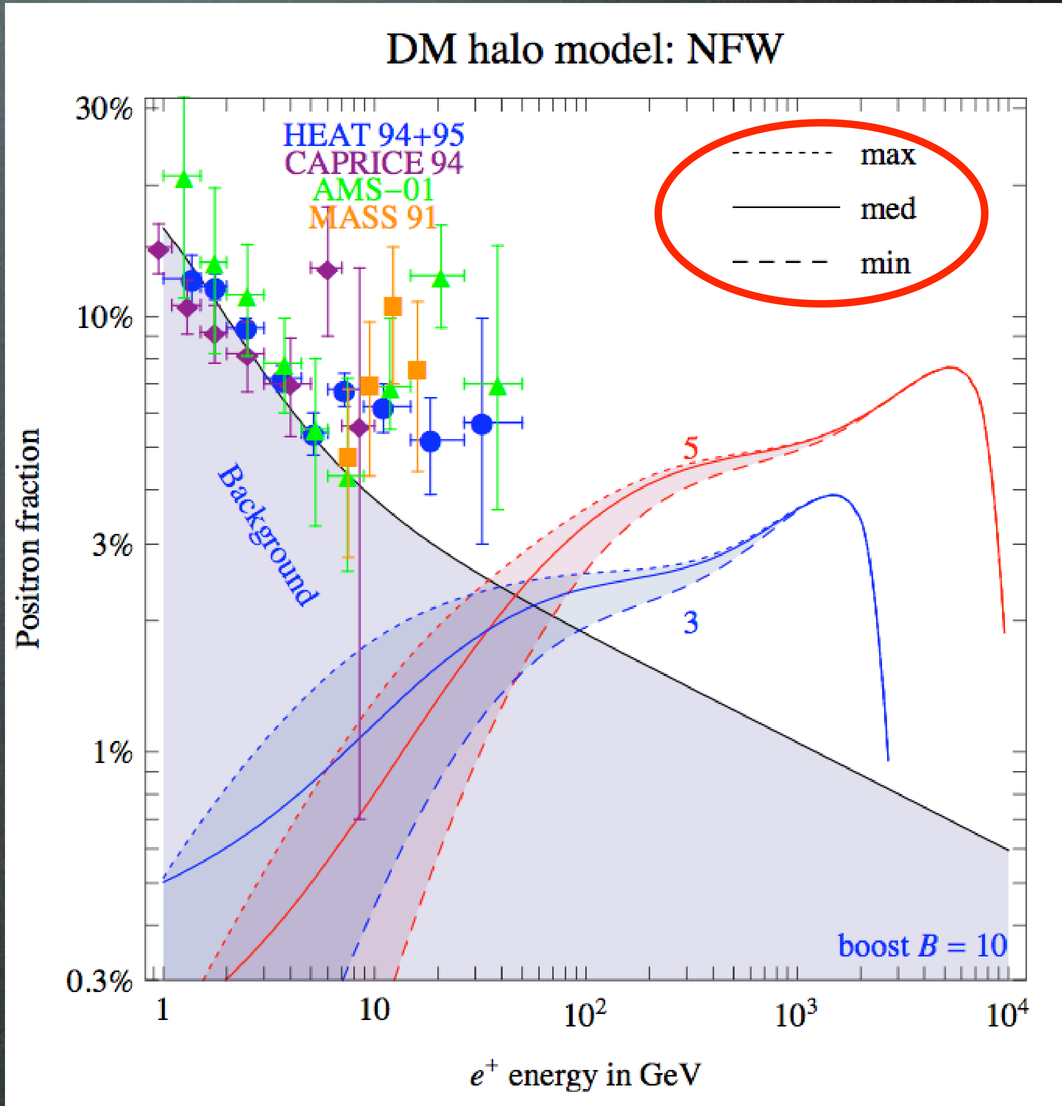
[back]

3. Indirect Detection

Results for positrons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



[back]

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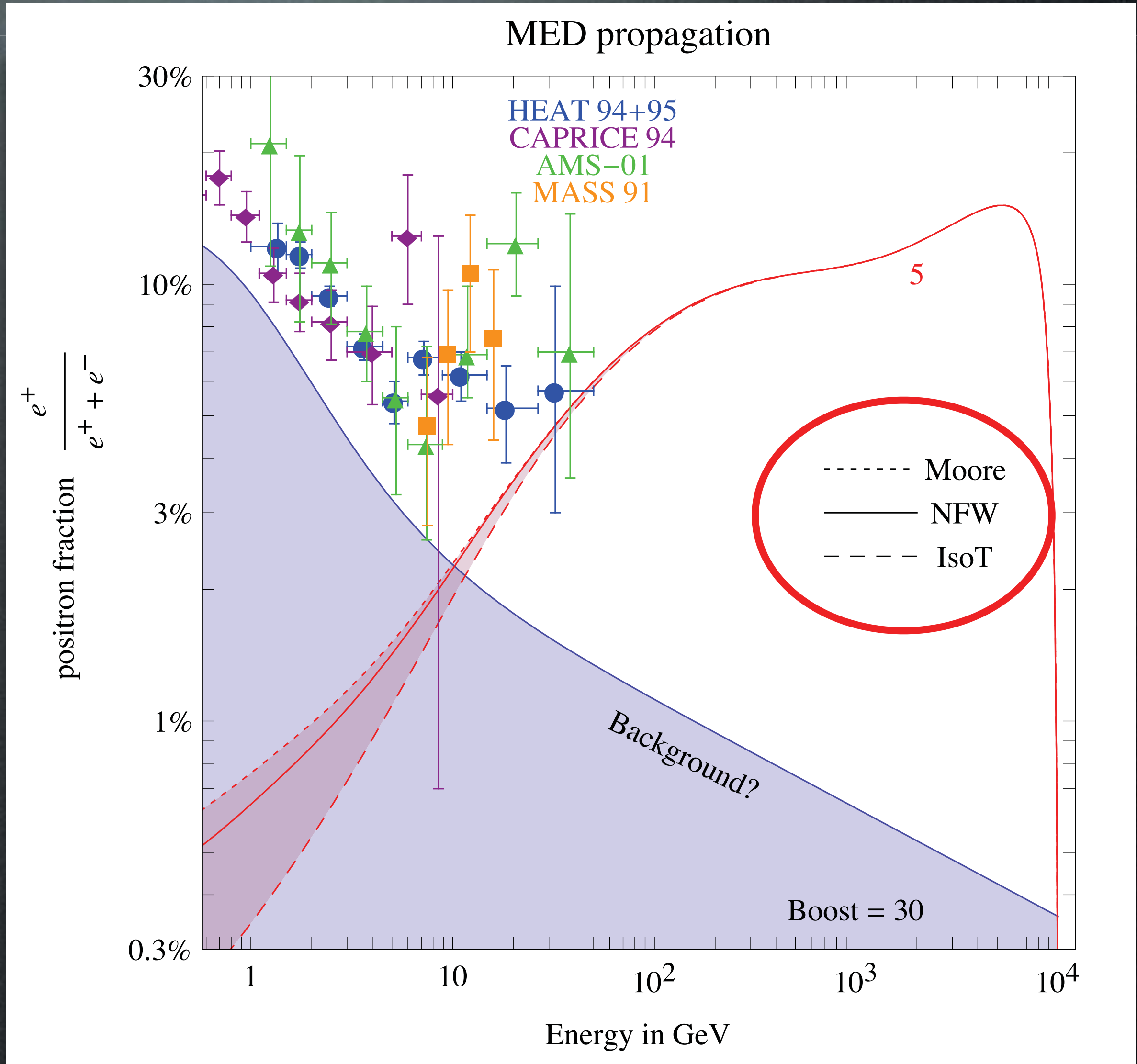


Distinctive signal,
quite robust vs astro.

[back]

3. Indirect Detection

Propagation for antiprotons:

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

diffusion — convective wind — spallations

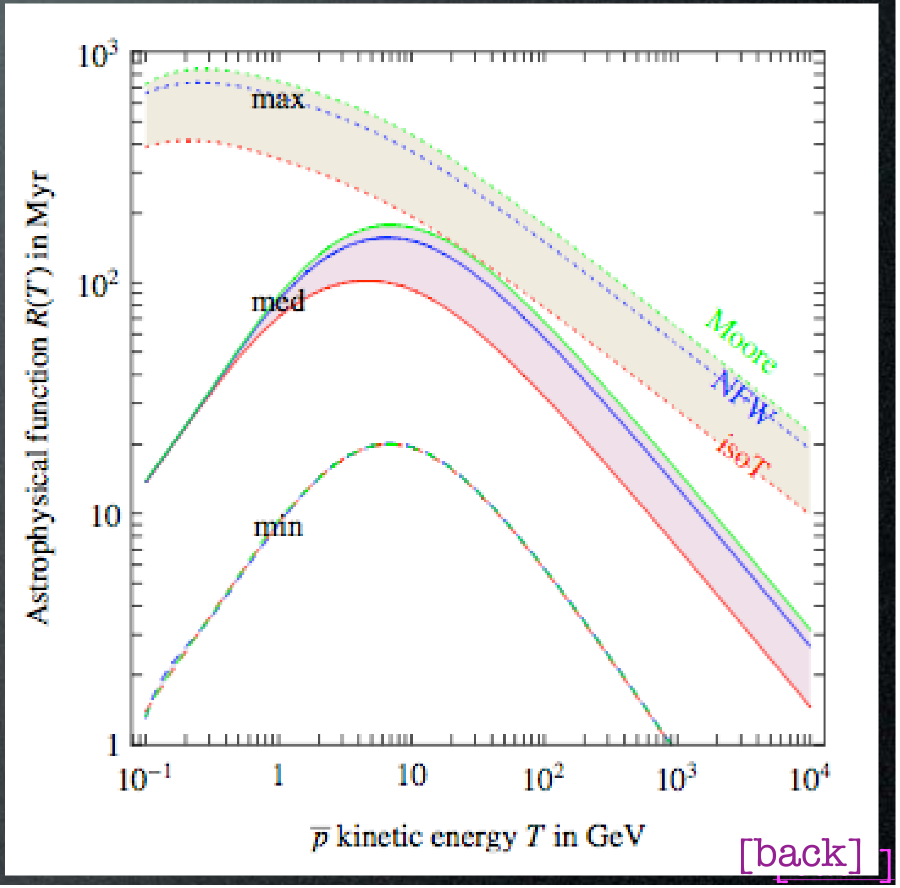
$K(T) = K_0 \beta\, (p/\mathrm{GeV})^{\delta}$

T kinetic energy

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

Solution:

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



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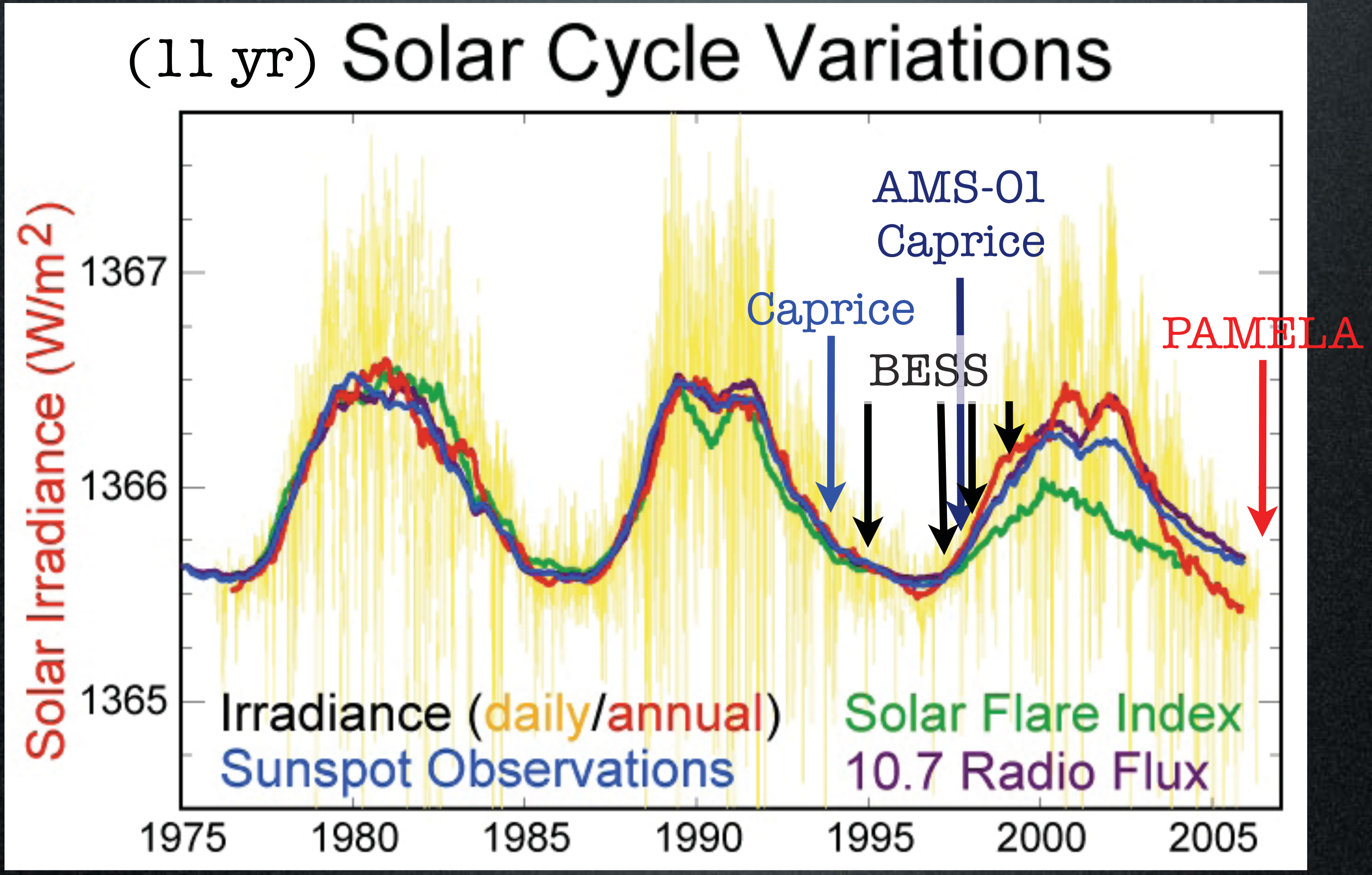
Indirect Detection

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 $\phi_F \simeq 500\ \mathrm{MV}$

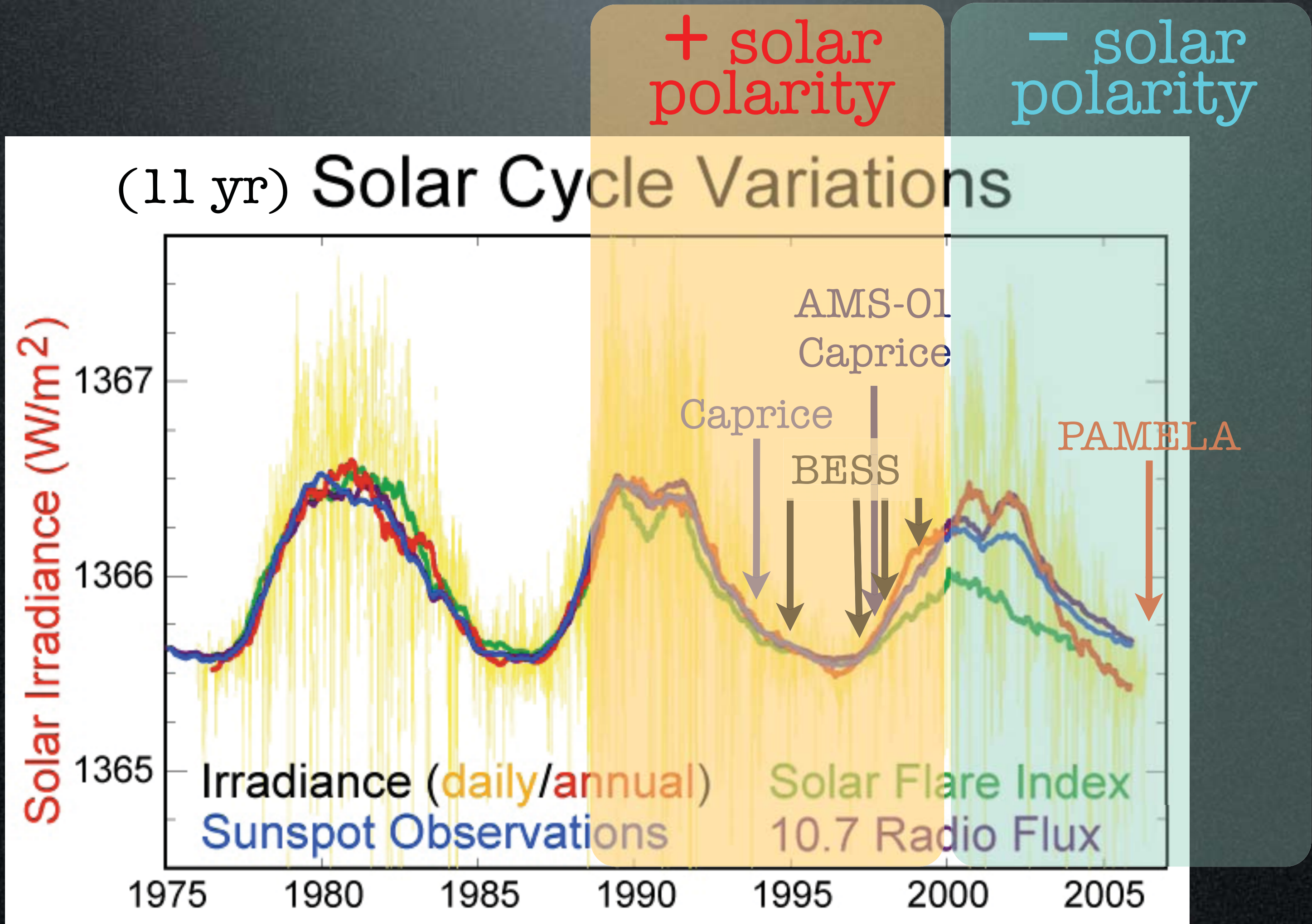


Indirect Detection

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

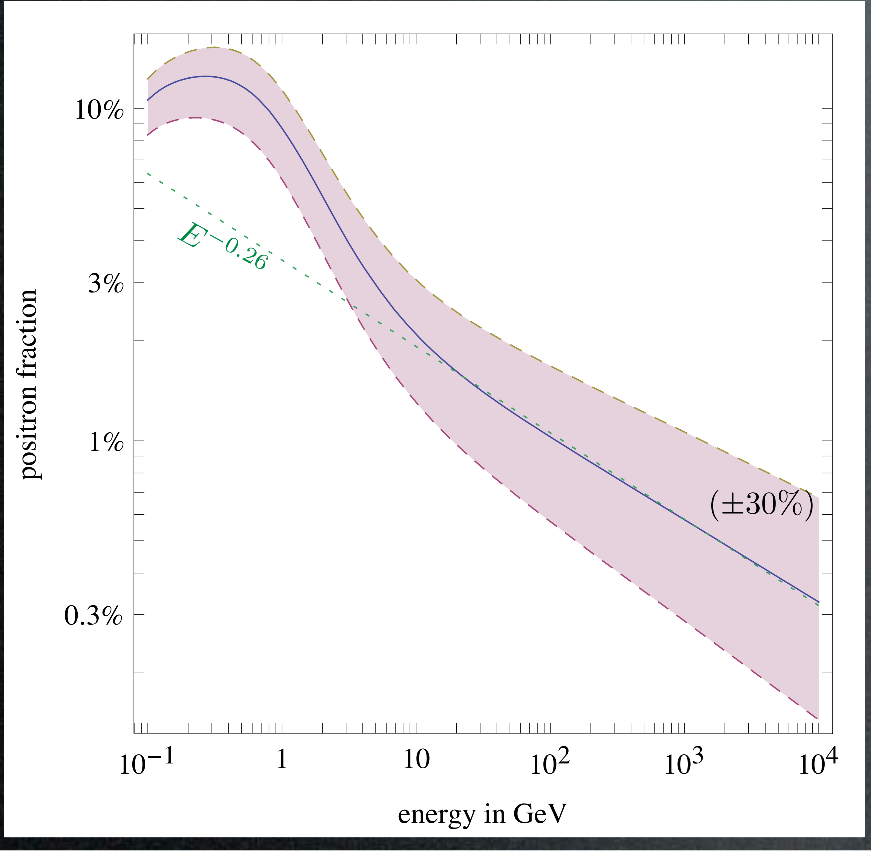
$$\Phi_{e^+}^{\rm bkg} = \frac{4.5\, E^{0.7}}{1 + 650\, E^{2.3} + 1500\, E^{4.2}}$$

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

Baltz, Edsjo 1999

On the basis of CR simulations of Moskalenko, Strong 1998

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

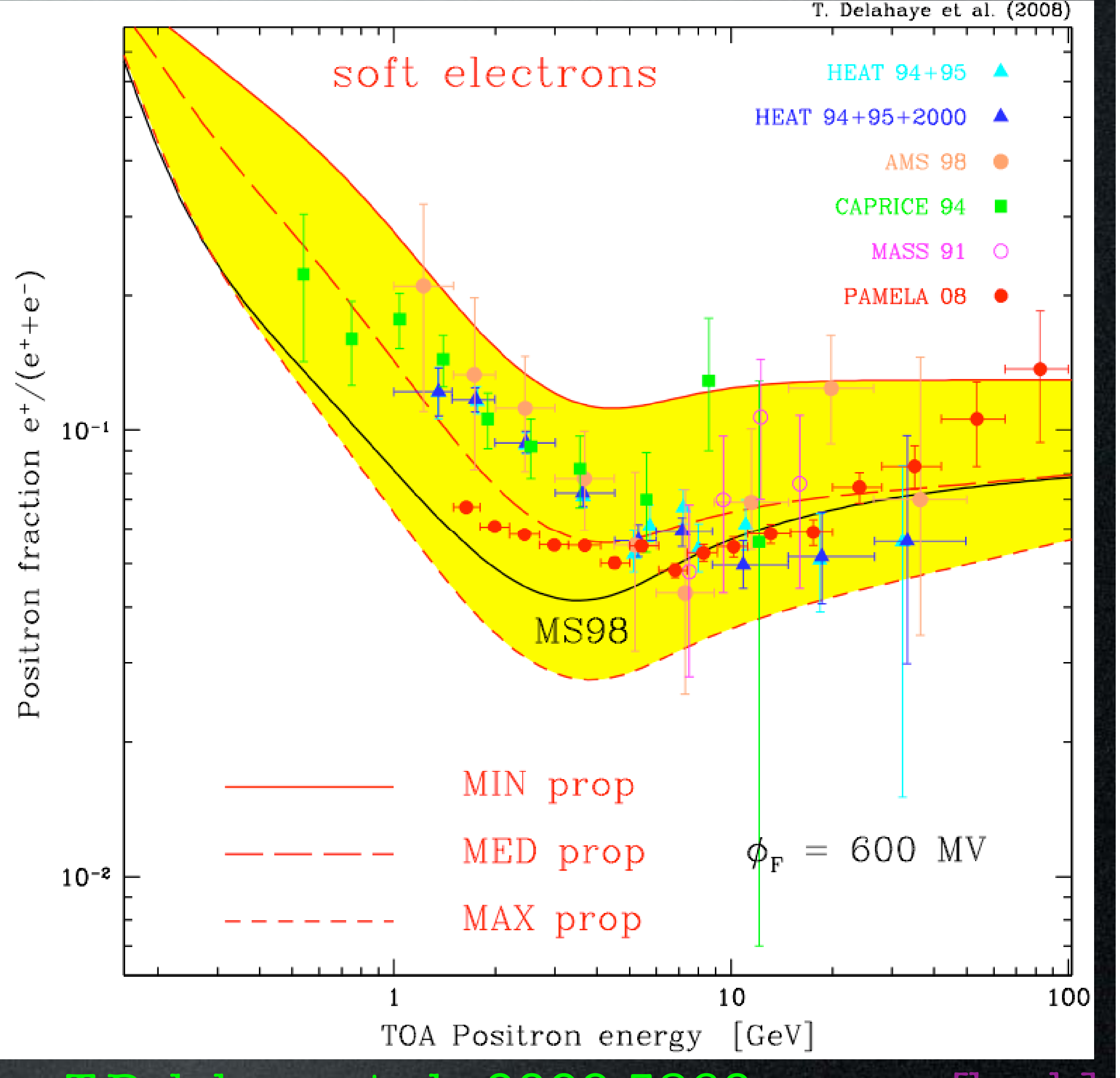


We marginalize w.r.t. the slope E^p, $\quad p = \pm 0.05$ and let normalization free.

[back]

Indirect Detection

Background estimation for positrons:



using new measuremens of electron fluxes

Casadei, Bindi 2004

T.Delahaye et al., 0809.5268

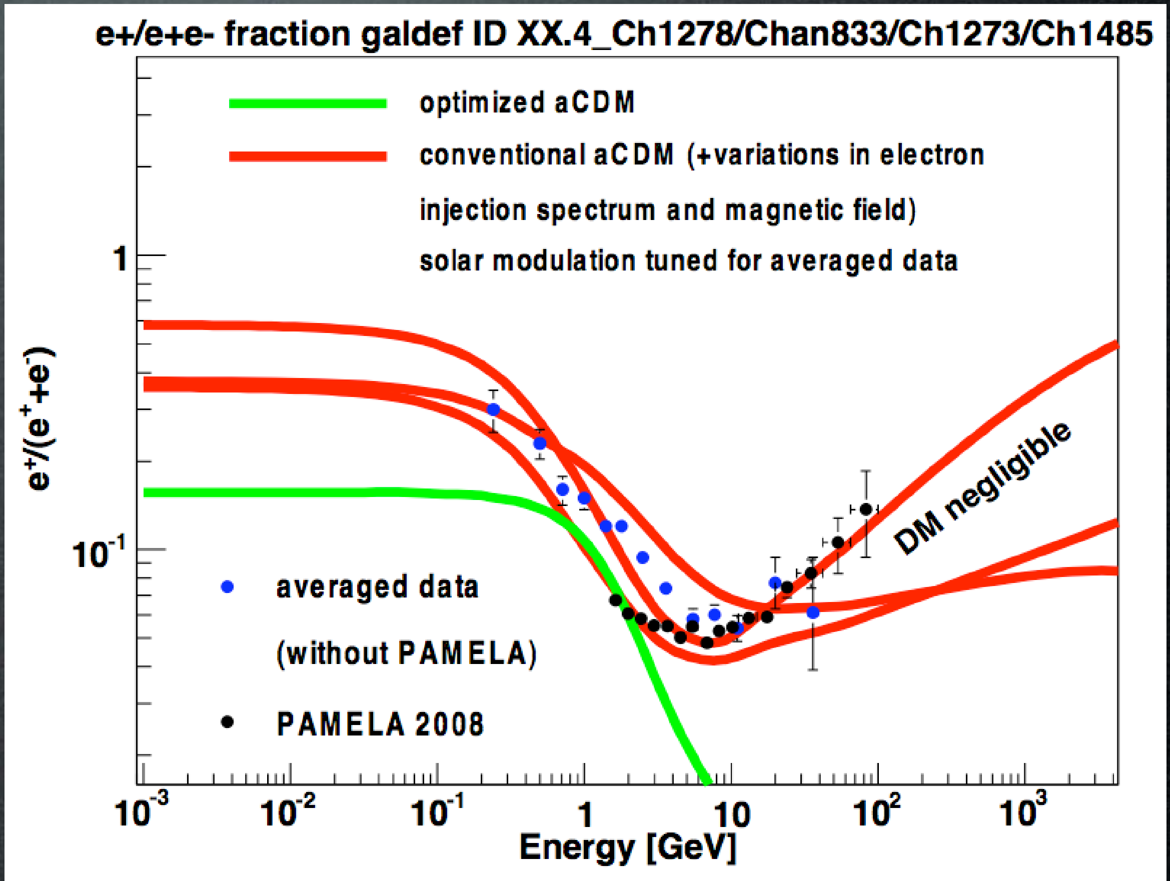
[back]

Indirect Detection

Background estimation for positrons:

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

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



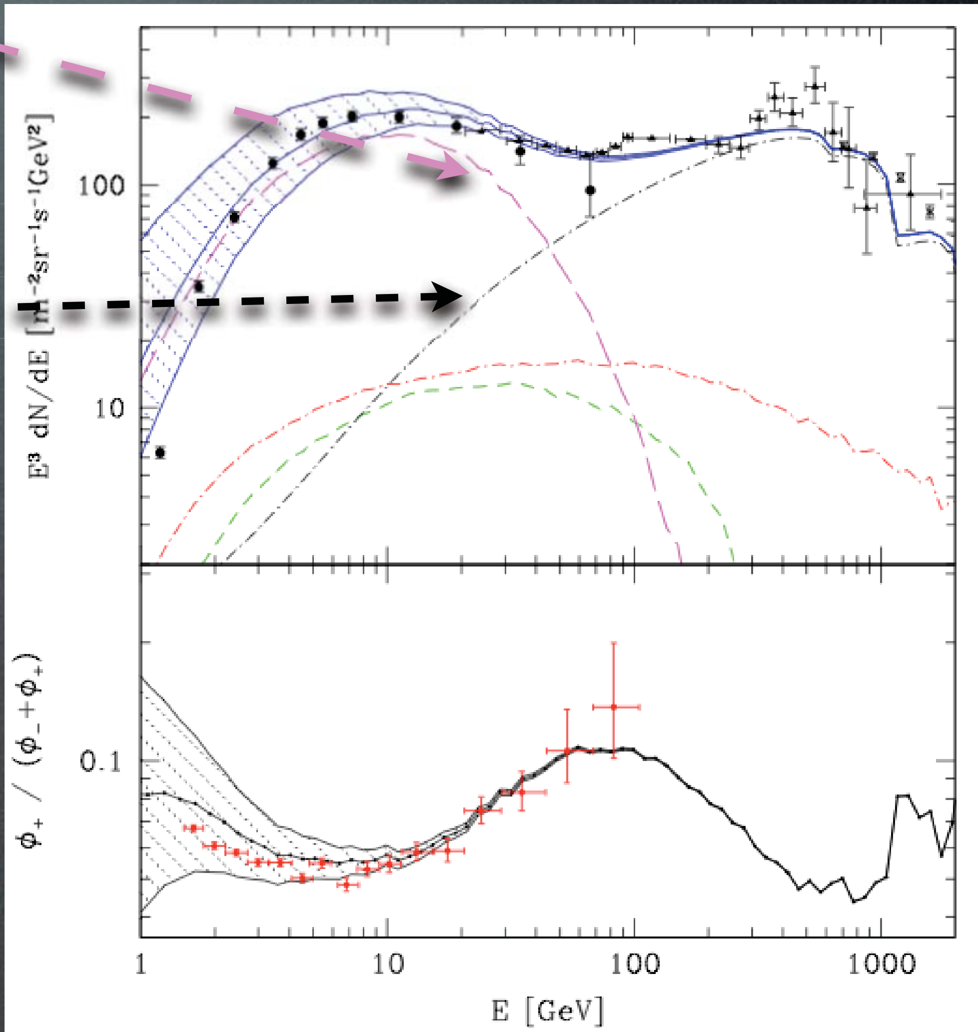
Gebauer 0811.2767

Indirect Detection

Background estimation for positrons:

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

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



Tsvi Piran et al. 0902.0376

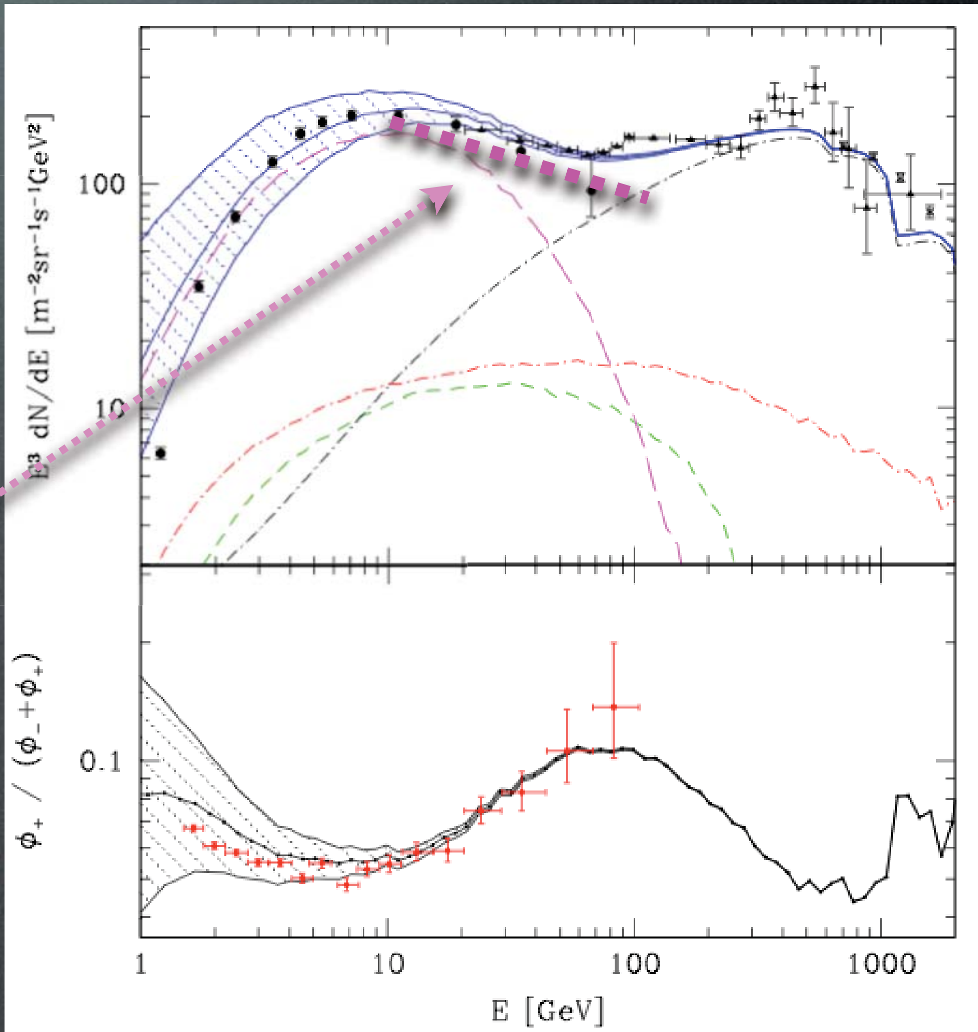
Indirect Detection

Background estimation for positrons:

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

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

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



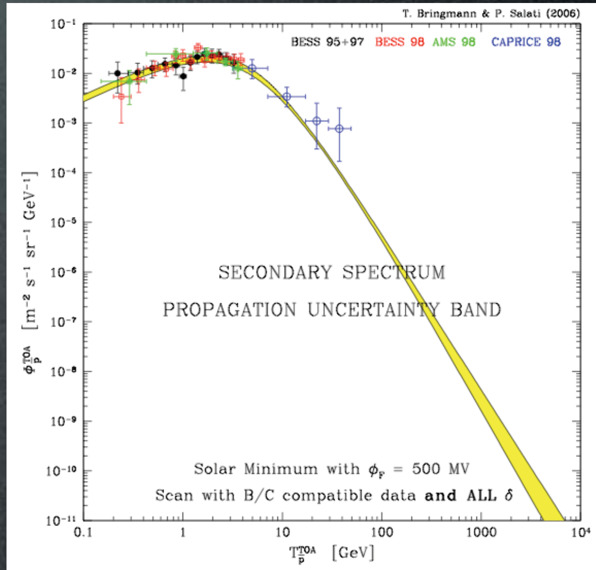
Tsvi Piran et al. 0902.0376

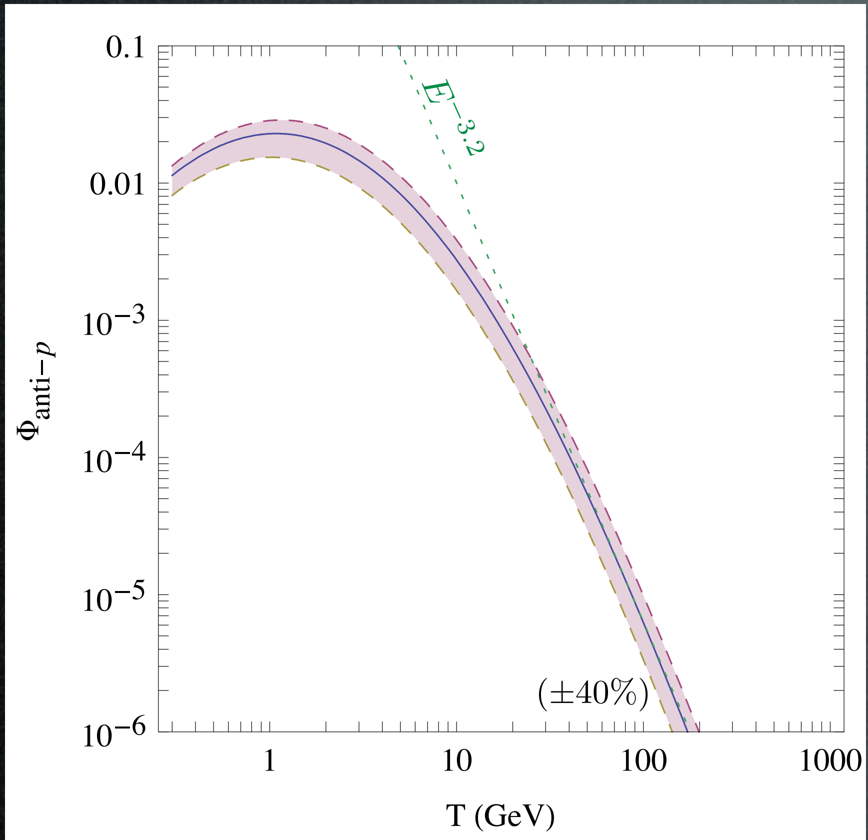
Indirect Detection

Background computations for antiprotons:

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

Bringmann, Salati 2006





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

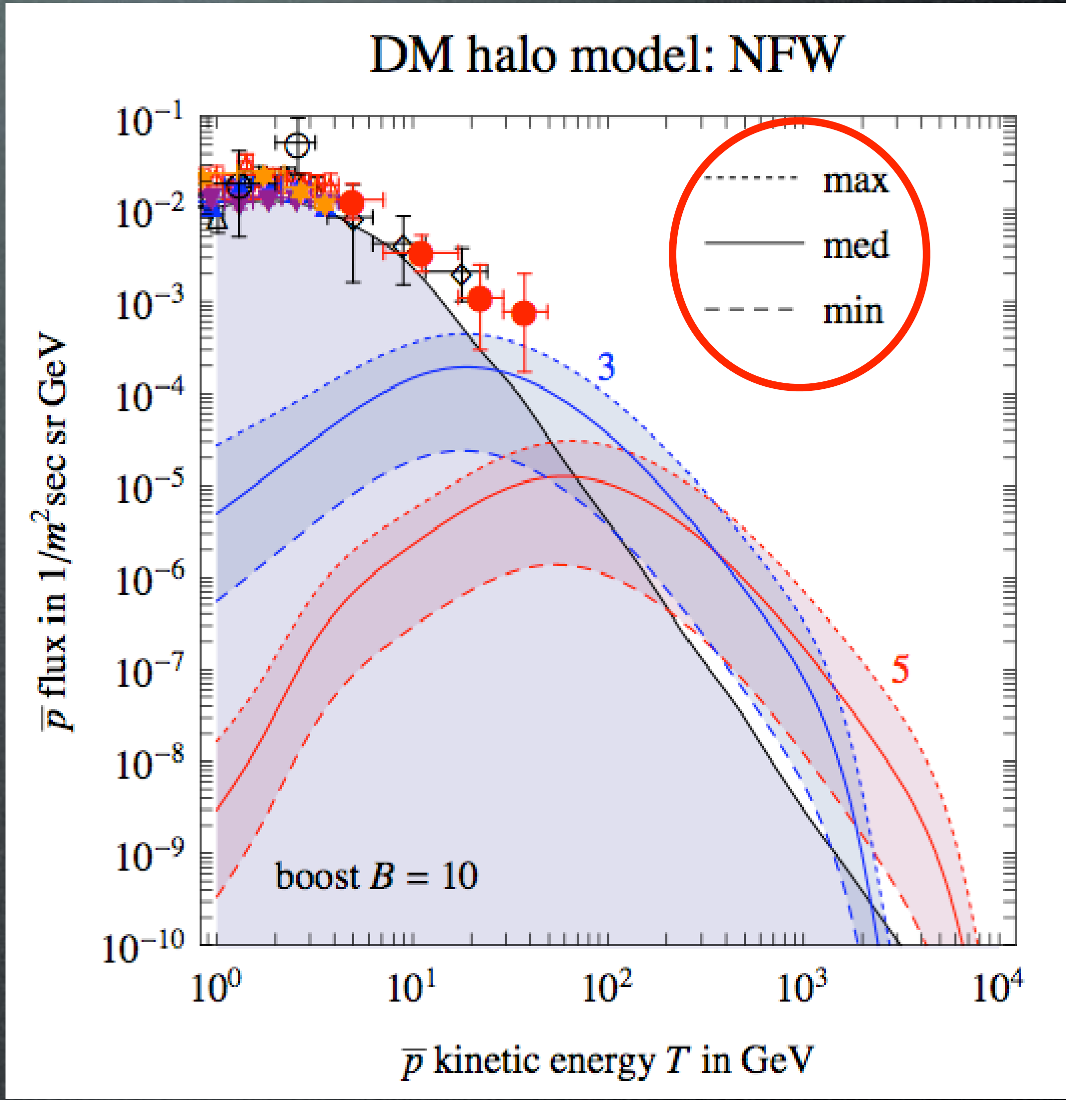
[back]

Indirect Detection

Results for anti-protons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



Indirect Detection

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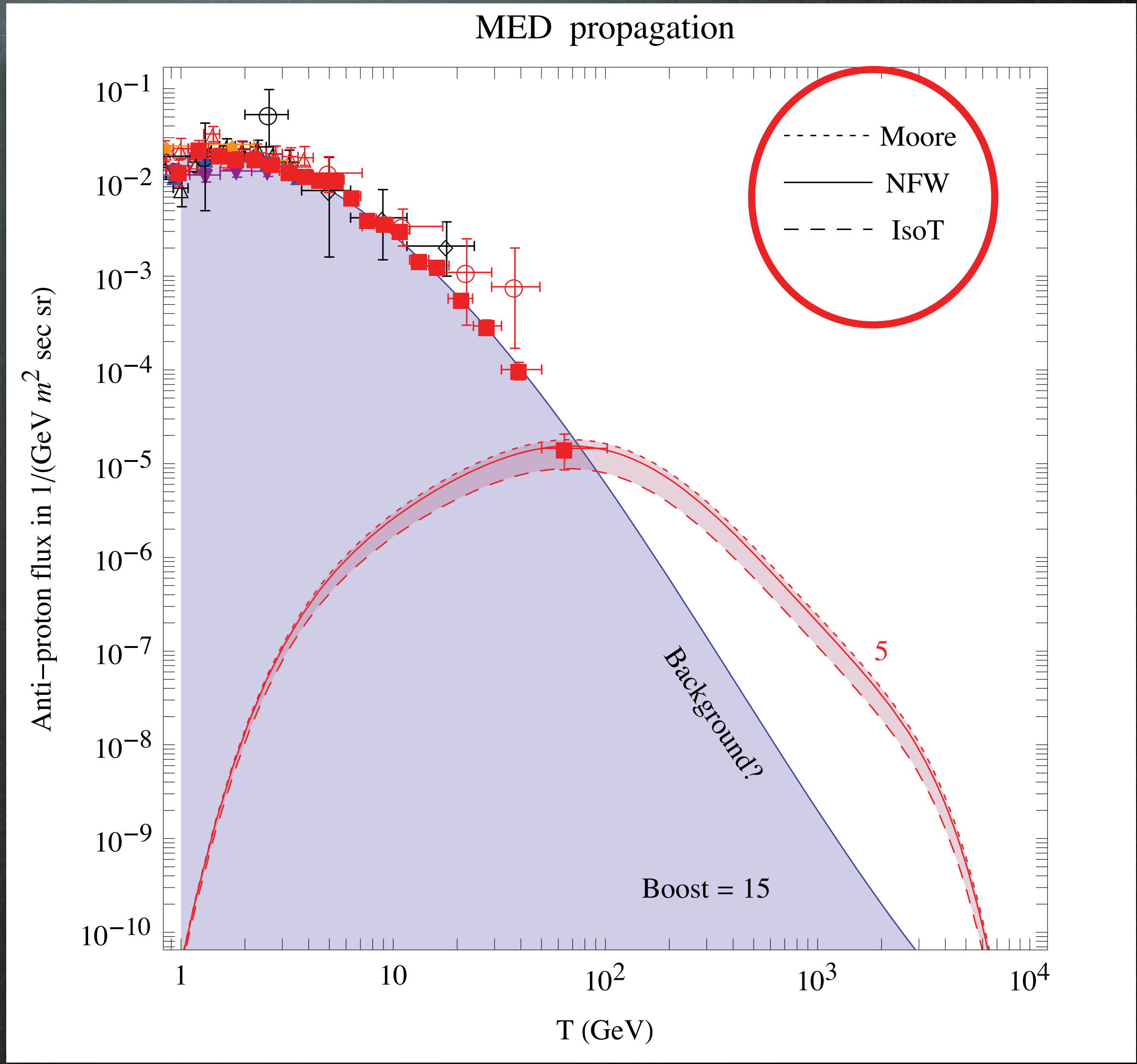


Challenges for the 'conventional' DM candidates

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

for any Majorana DM,
s-wave annihilation cross section

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

Results

Which DM spectra can fit the data?

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

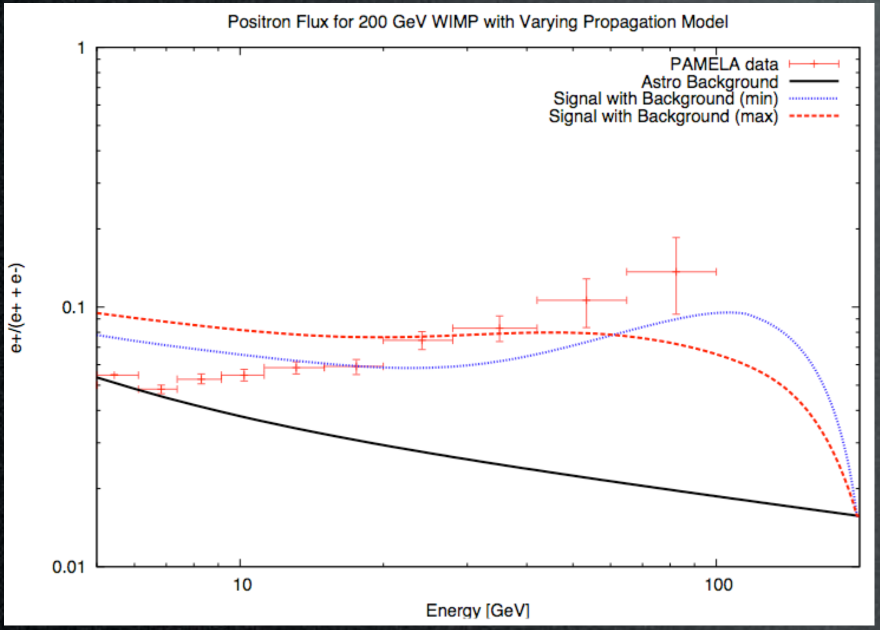
-annihilation $\rm DM\ DM \to W^+W^-$

If one: - assumes non-thermal production of DM

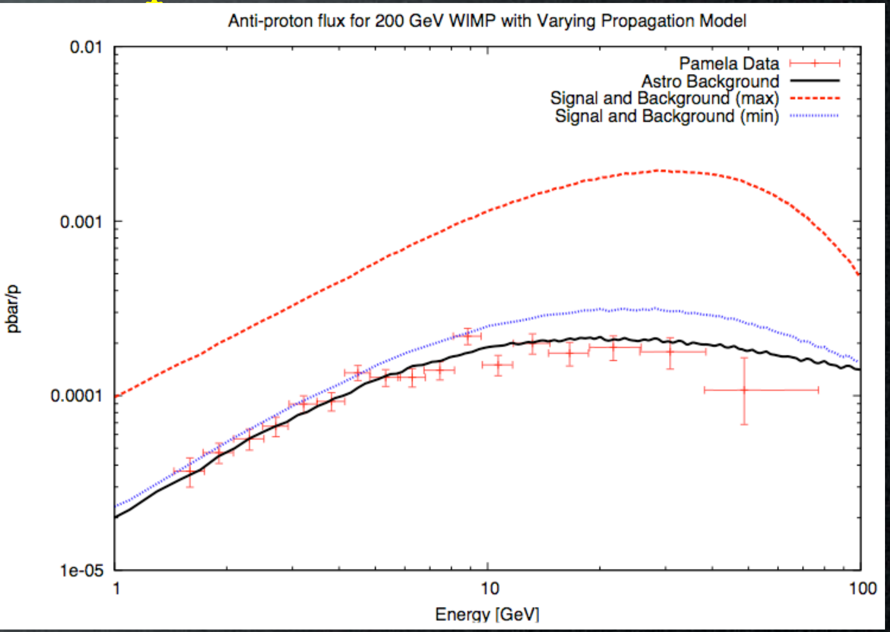
- takes positron energy loss 5 times larger than usual
- takes "min" propagation only
- gives up ATIC
- neglects conflict with EGRET bound (4 times too many gammas)

then:

Positrons:



Anti-protons:



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

Results

Which DM spectra can fit the data?

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

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

-annihilation $\mathrm{DM\ DM} \rightarrow l^+ l^- \,(BR = 60\%)$

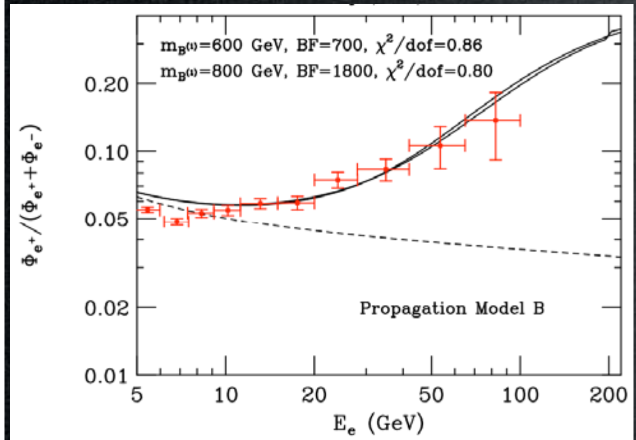
$\mathrm{DM\ DM} \rightarrow q\bar{q}\,(BR = 35\%)$

Good fit with: - boost $B = 1800$

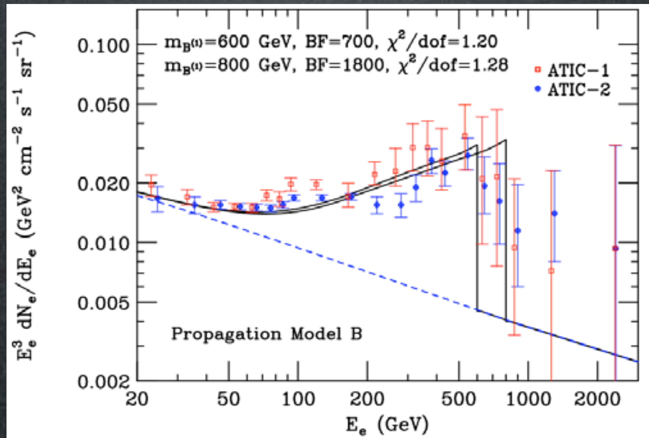
- propagation model $\mathrm{B{:}}\ K(E_e) = 1.4 \times 10^{28}\,(E_e/4\,\mathrm{GeV})^{0.43}\ \mathrm{cm^2/s,\ L{=}1\ kpc}$

very large energy loss with very small L

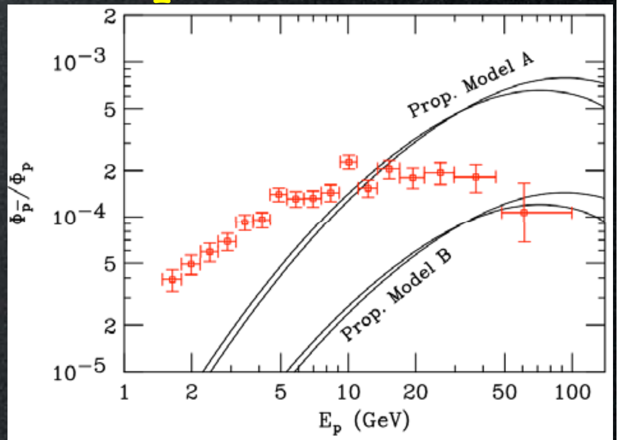
Positrons:



Electrons + Positrons:



Anti-protons:



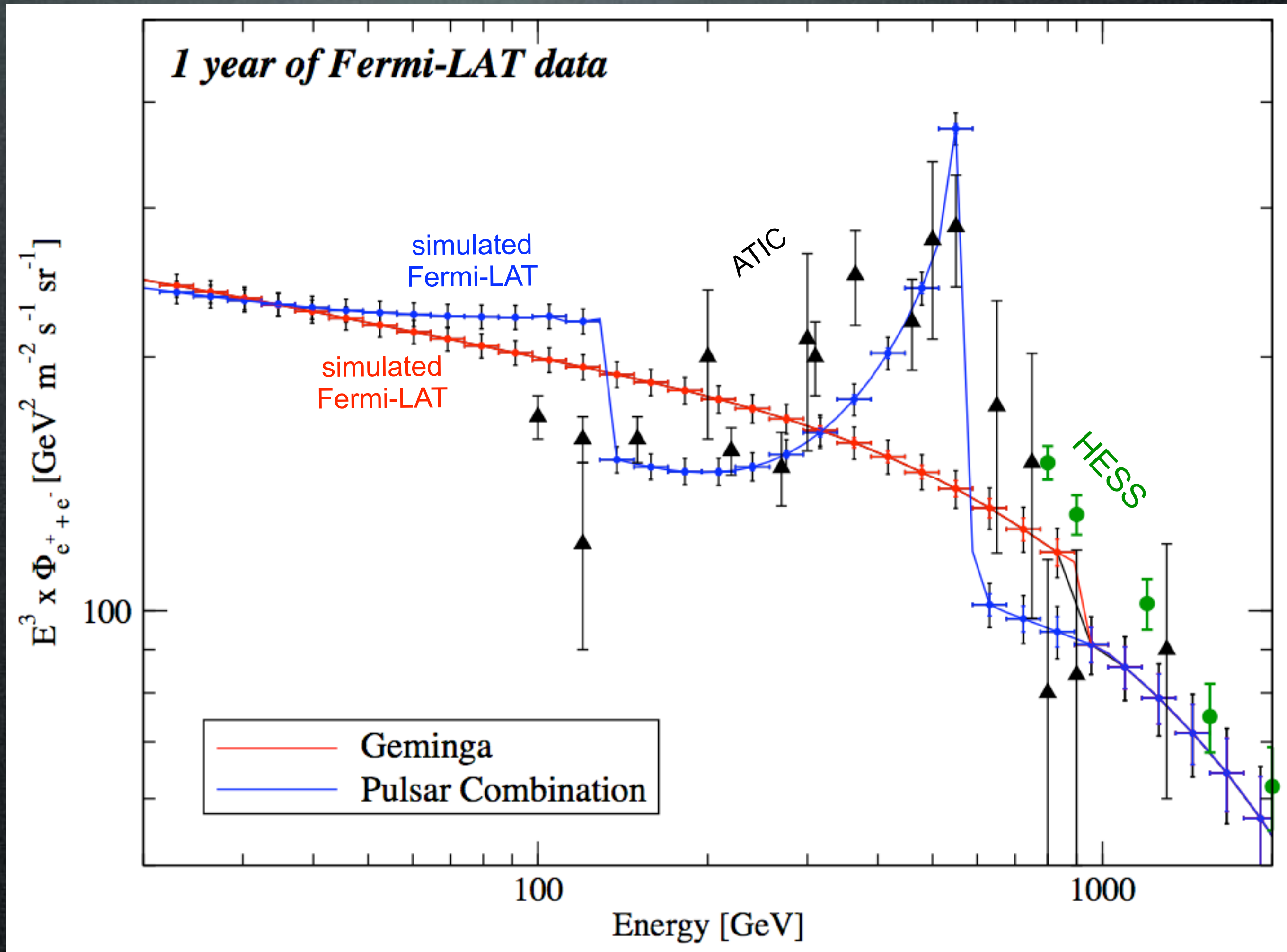
D.Hooper, K.Zurek 0902.0593

[where are the secondaries?]

Data sets

Electrons + positrons from Fermi-LAT:

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

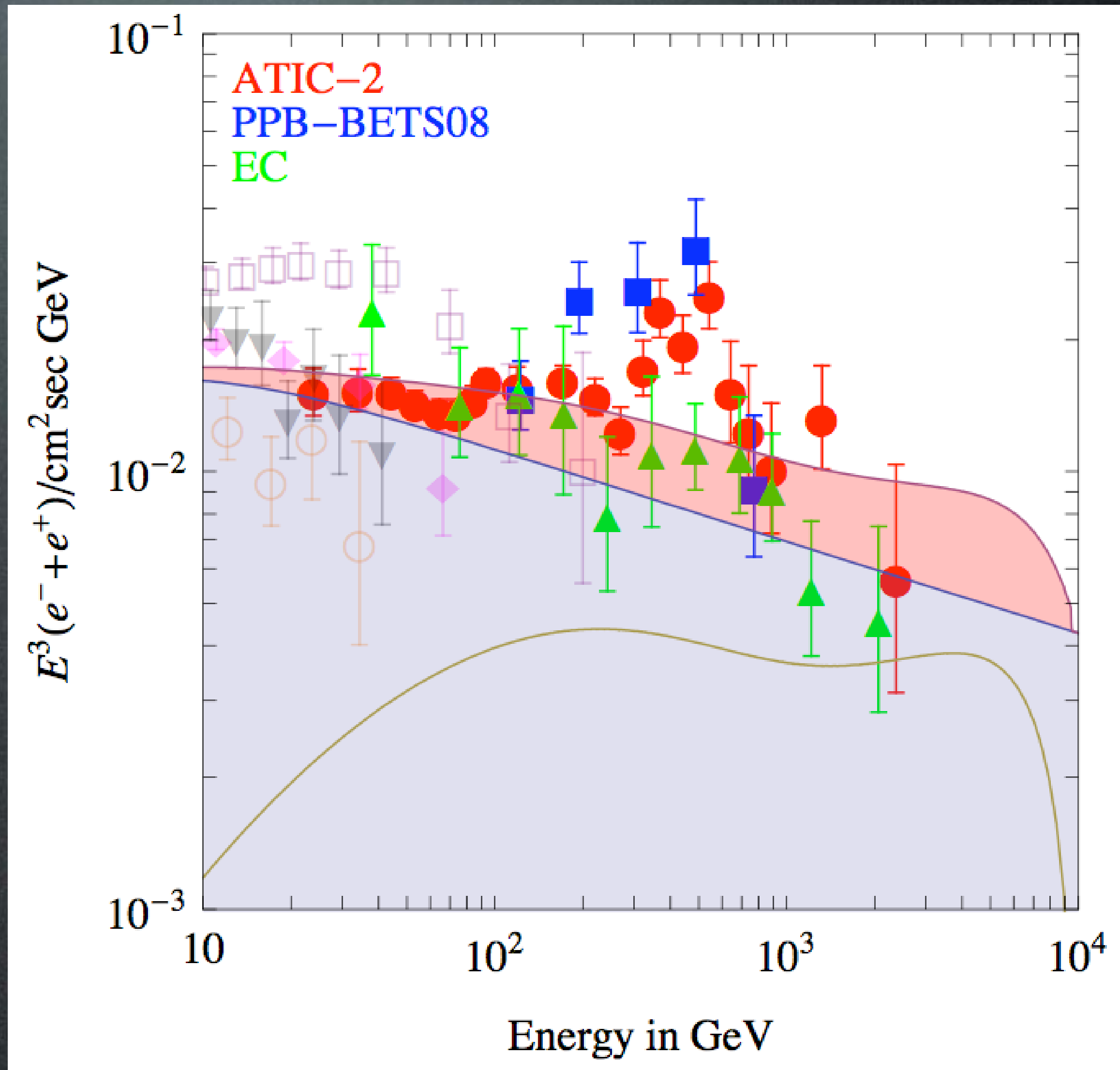


Profumo 0812.4457

[back]

Results

Which DM spectra can fit the data?



Astrophysical explanation?

see S.Profumo, 0812.4457

the electron spectrum has a steep deepening!

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

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

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

Dogiel, Sharov 1990

- does not work at E > 30 GeV

Coutu et al (HEAT), 1990

Gamma Ray Bursts produce e^+e^-!

Ioka 0812.4851

- maybe, constrained by gammas

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

ICRC 1990

- low energy and low flux

...

[back]

Model building

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

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

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

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

- Decaying DM

  Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

  A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

Model building

- Minimal extensions of the SM:
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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 #

- 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"

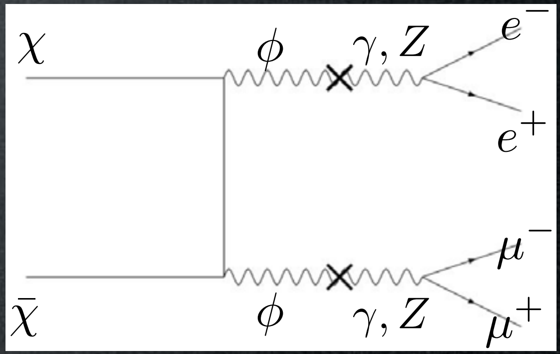
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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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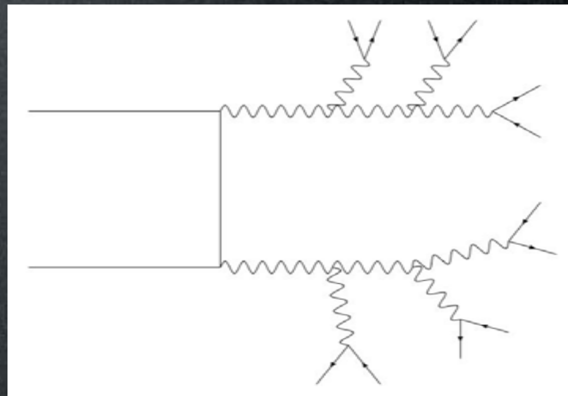
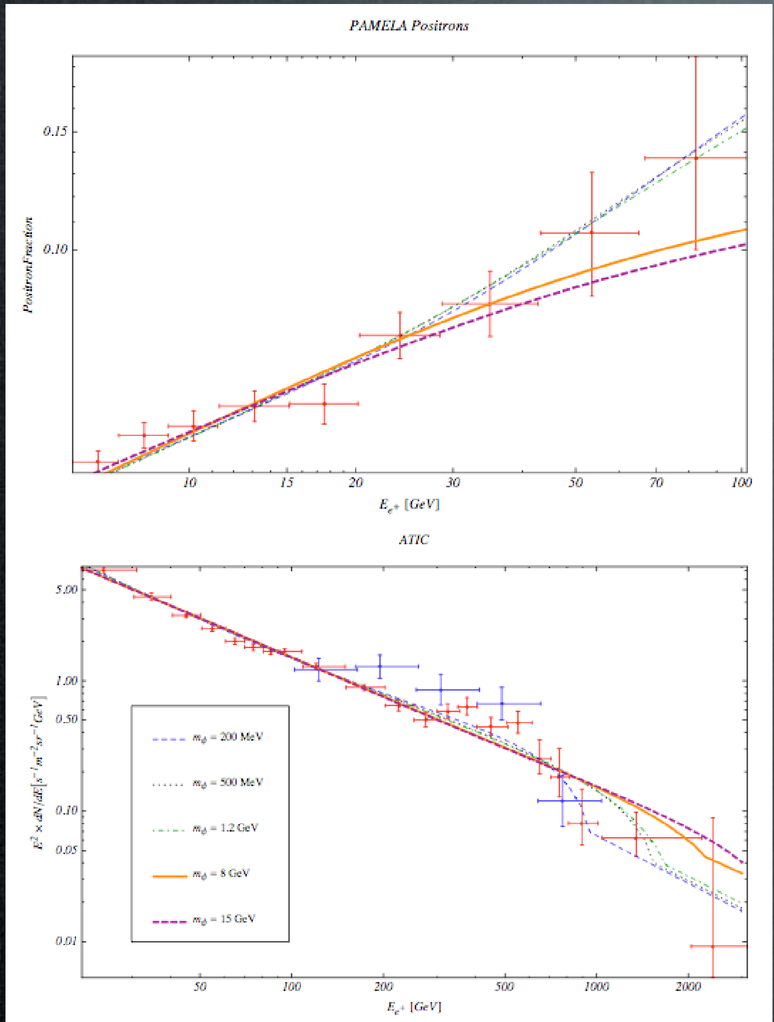


Extras:

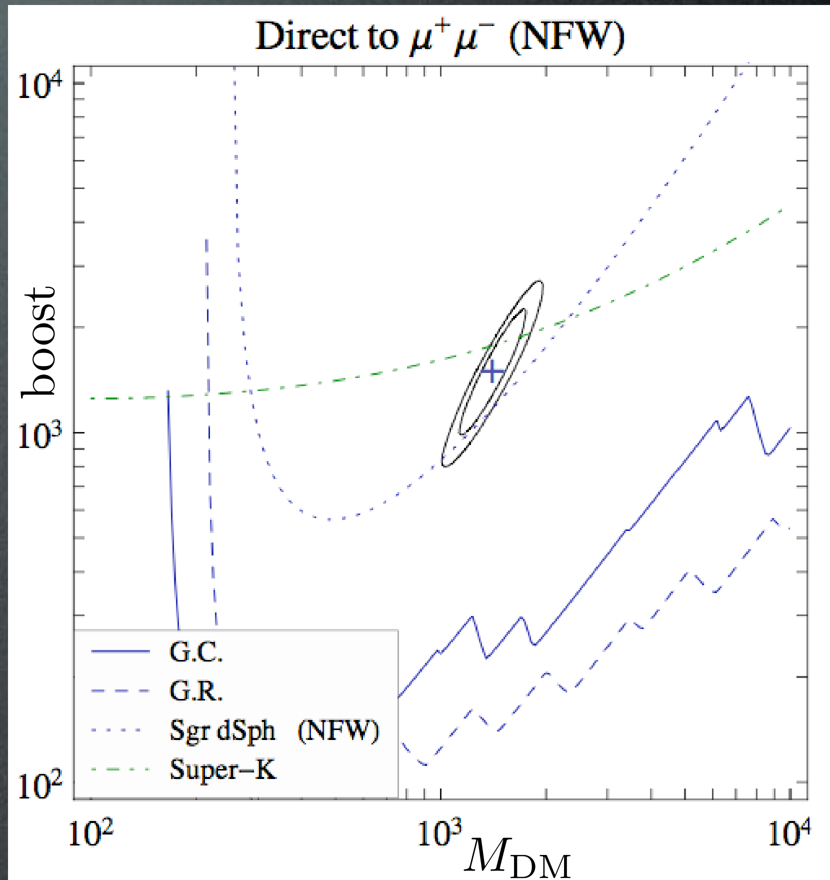
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200\ \mathrm{KeV}$ (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The “Theory of DM”

Phenomenology:



Meade, Papucci, Volanski
0901.2925



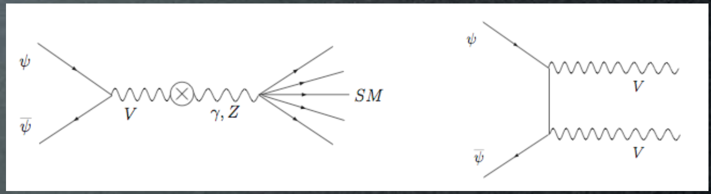
Mardon, Nomura, Stolarski,
Thaler 0901.2926

Variations

(selected)

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

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



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

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

  Bai, Han 0811.0387

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

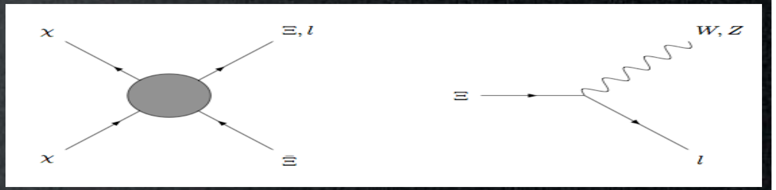
  Park, Shu 0901.0720

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

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

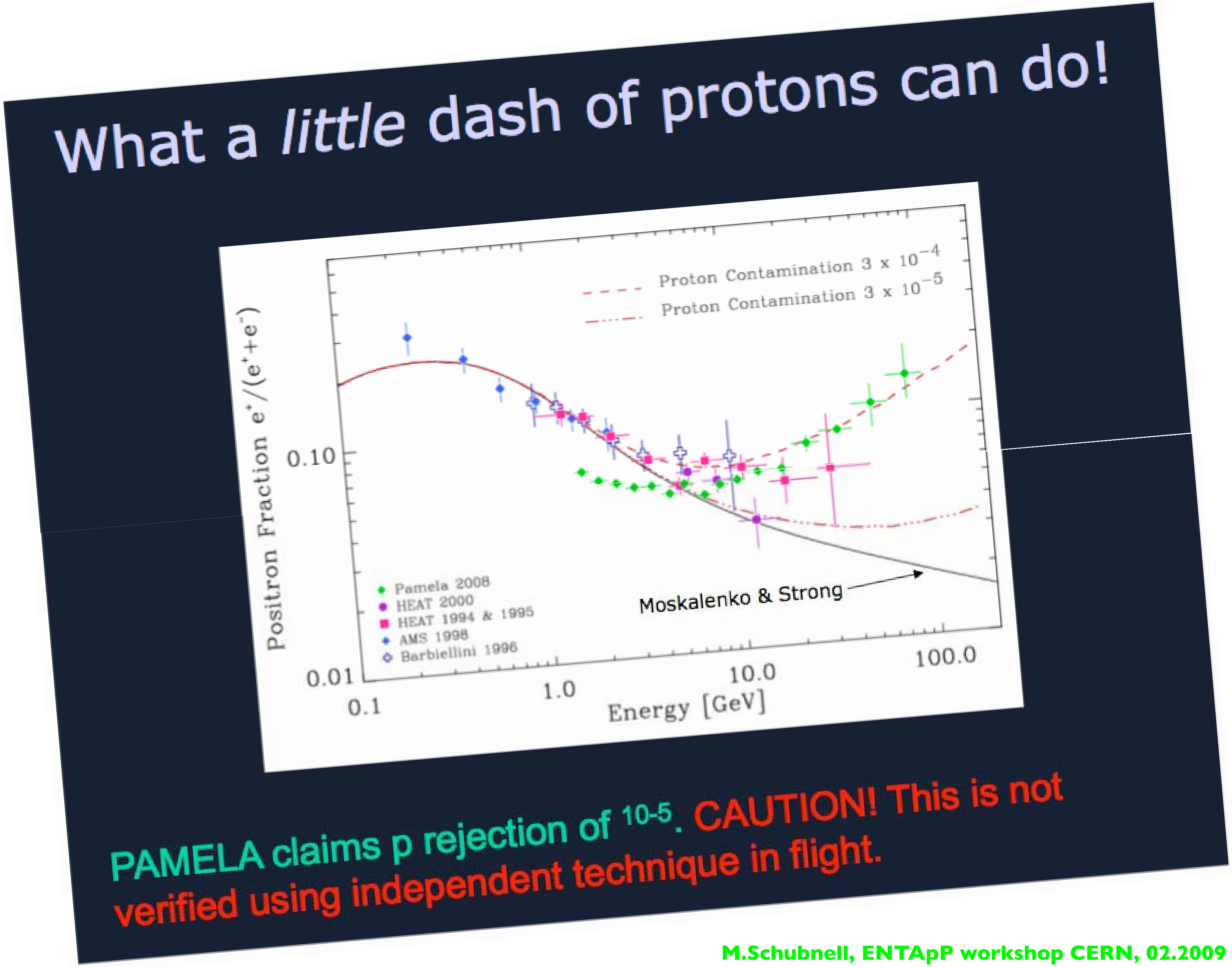
- New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly $(\sim \text{TeV})$ $(\sim \text{100s GeV})$

  Phalen, Pierce, Weiner 0901.3165



- ......

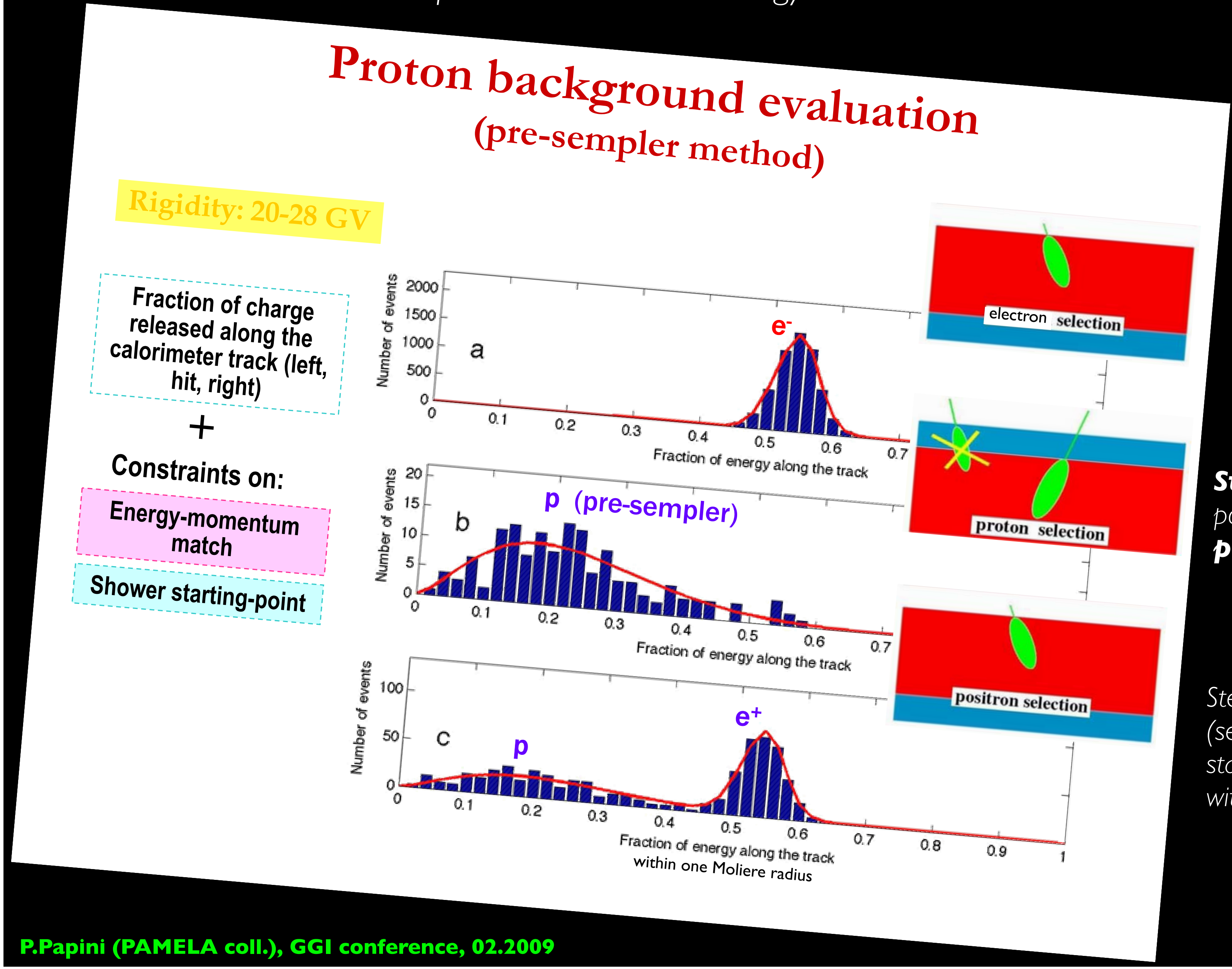
“PAMELA did not do in-flight checks of the p rejection rate”



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)

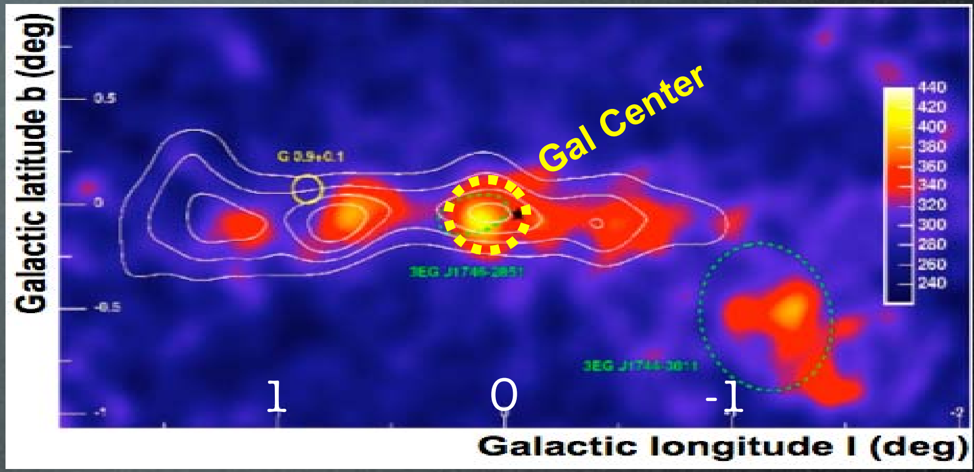
Step 2**: shower in lower portion selects **protons only

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

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

Gamma constraints

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



HESS coll.

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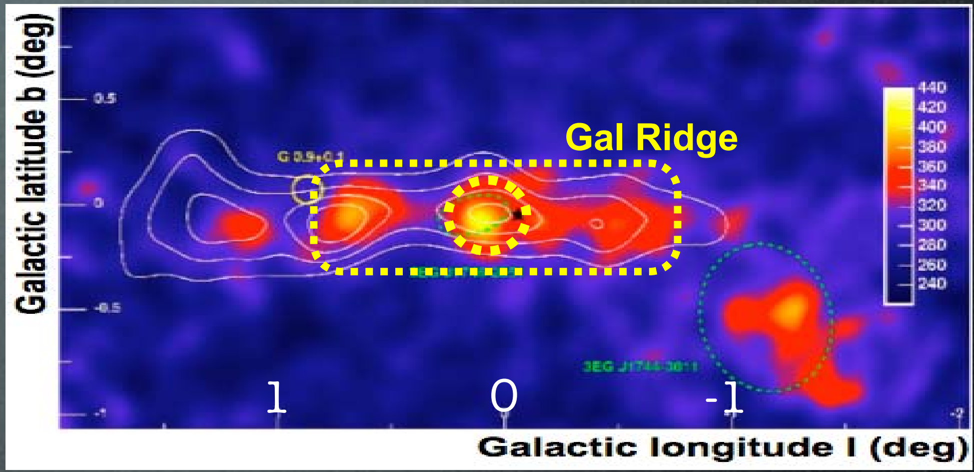
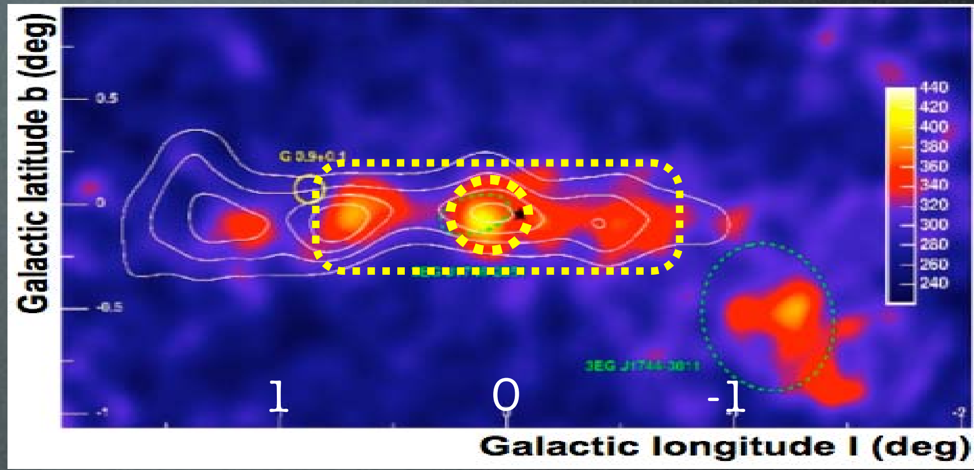


HESS coll.

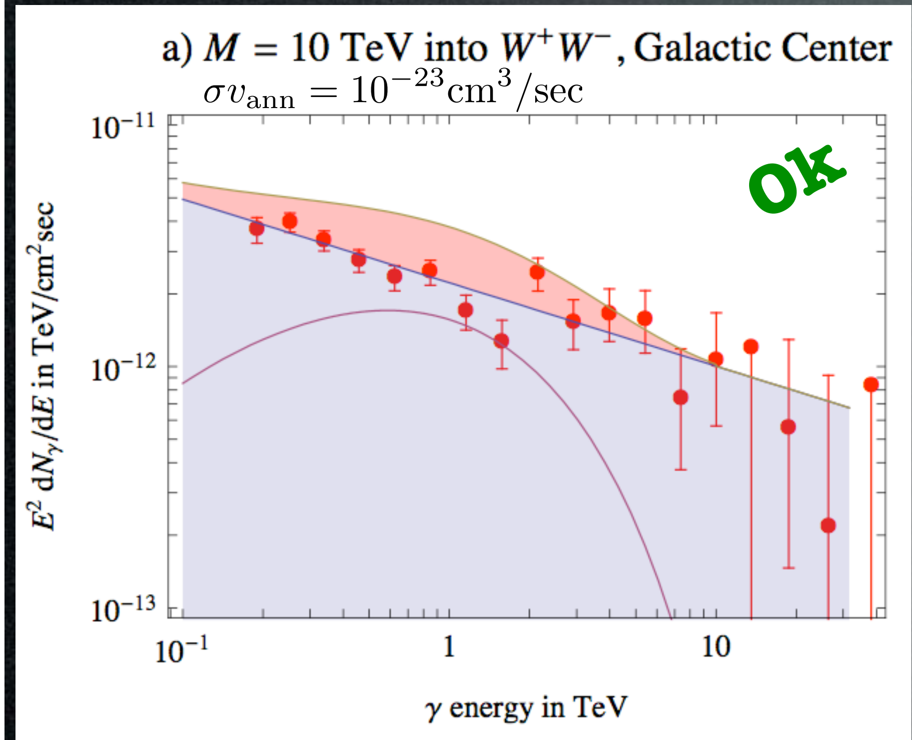
Gamma constraints

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

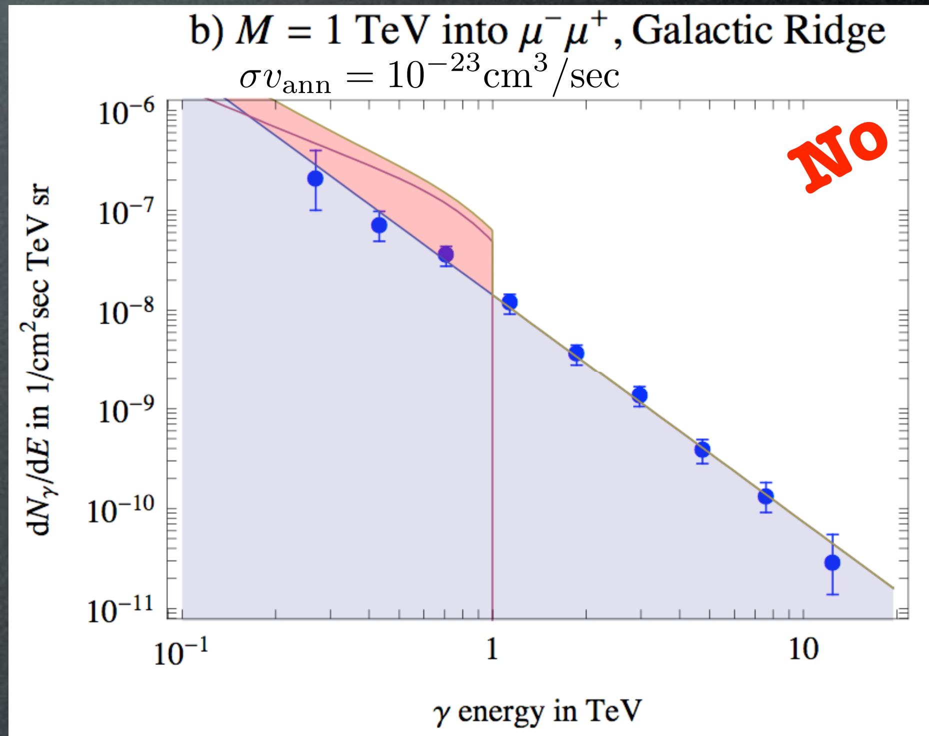
Moreover: no detection from Sgr dSph => upper bound.



HESS coll.



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

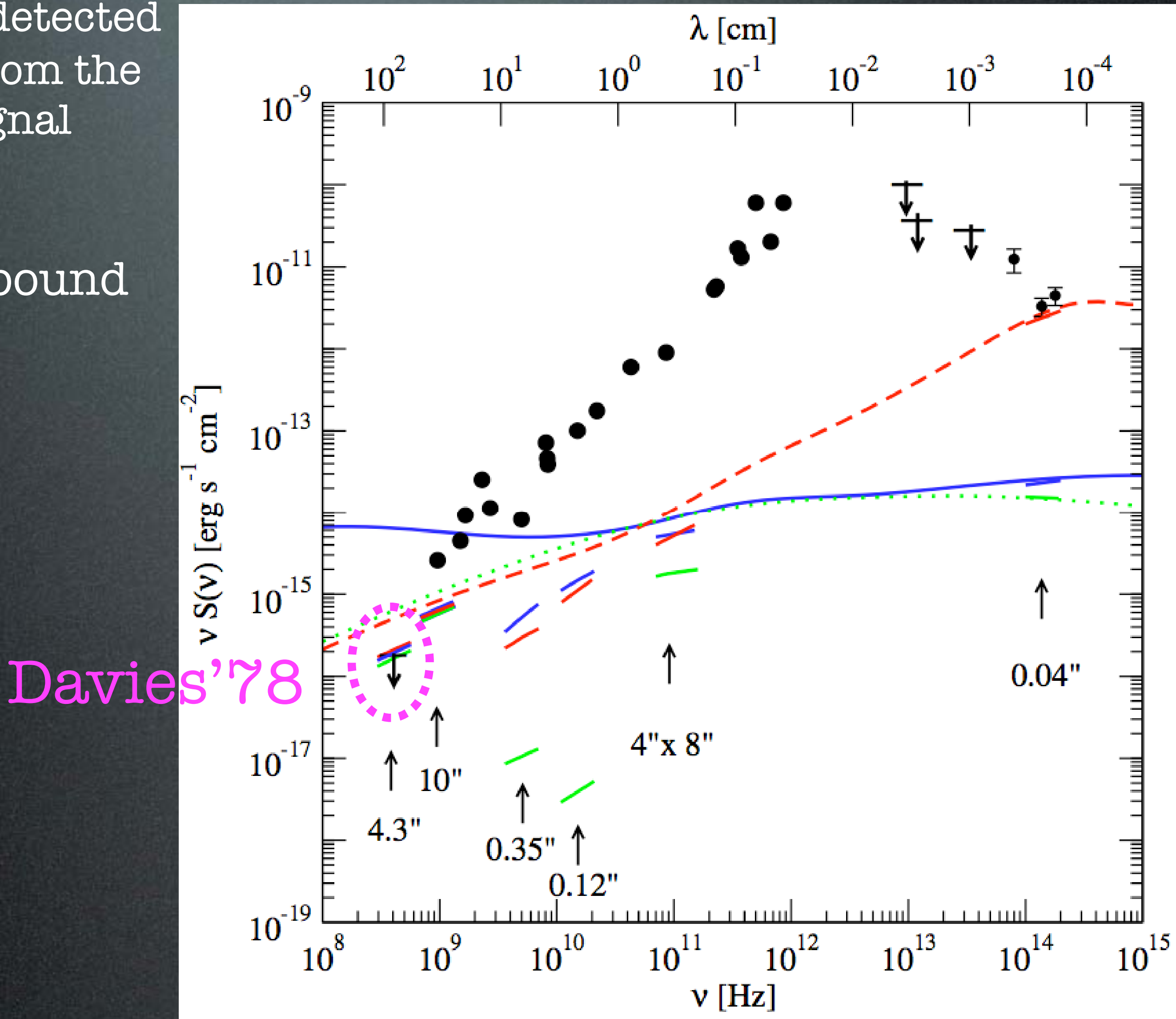


Data: HESS coll., astro-ph/0603021

Gamma constraints

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

Davies 1978 upper bound at 408 MHz.



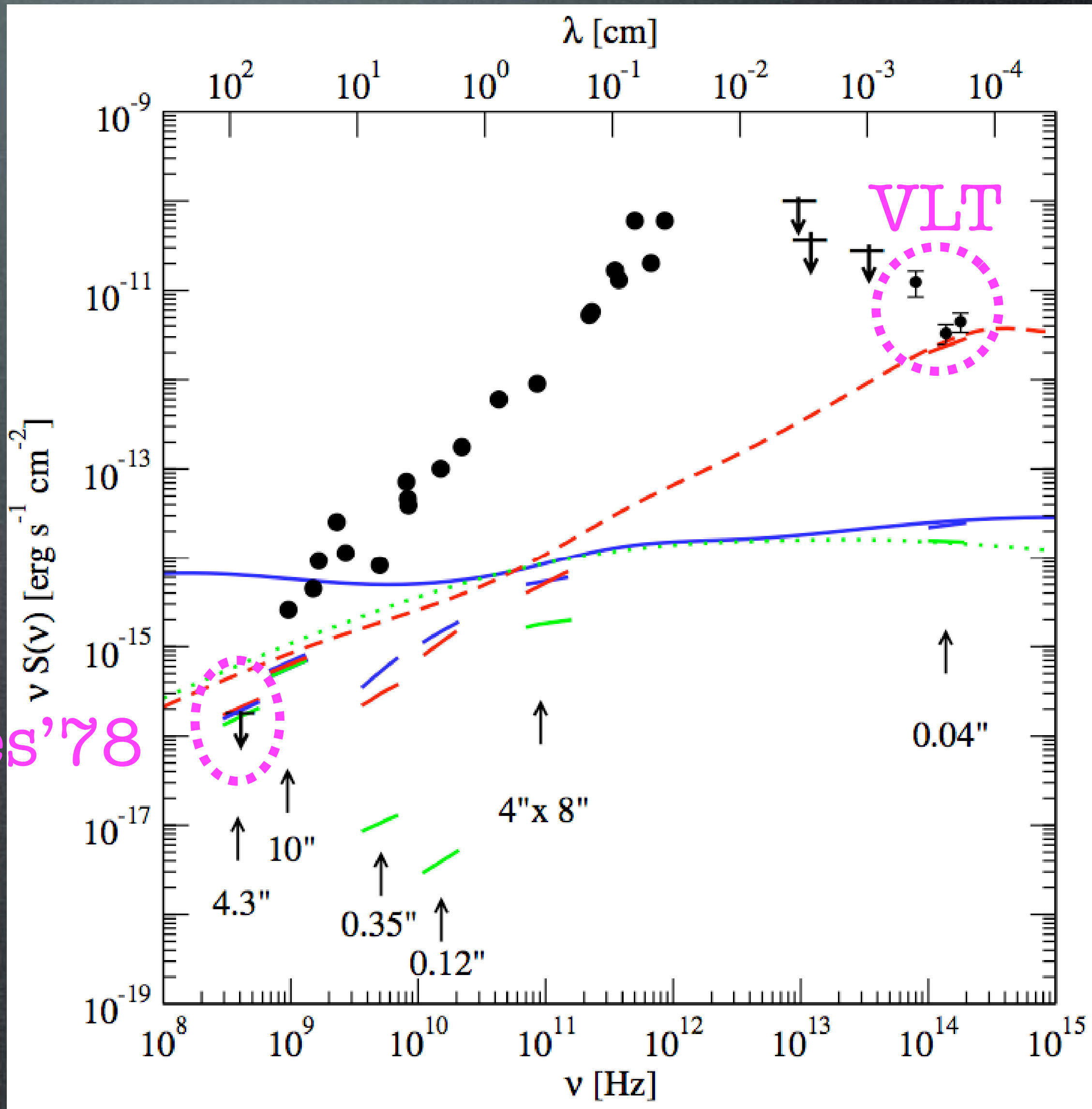
Regis, Ullio PRD '78 (2008)

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.

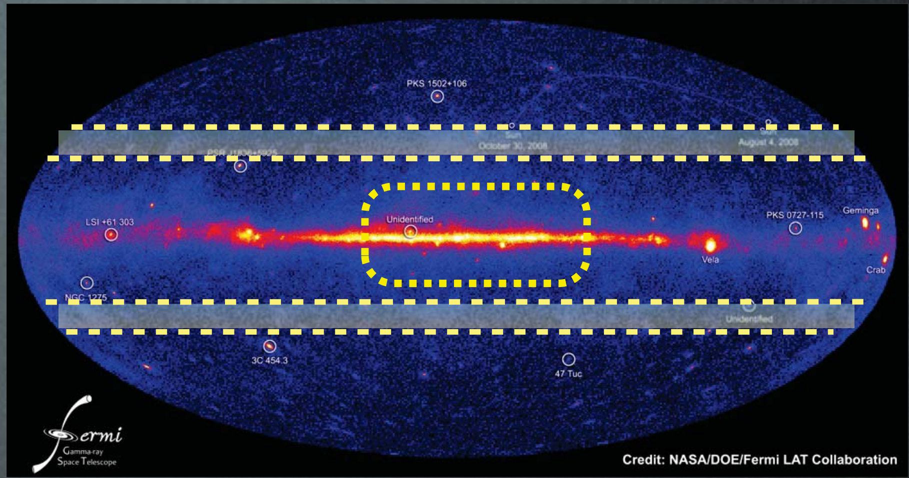


integrate emission over a small angle corresponding to angular resolution of instrument

Regis, Ullio PRD '78 (2008)

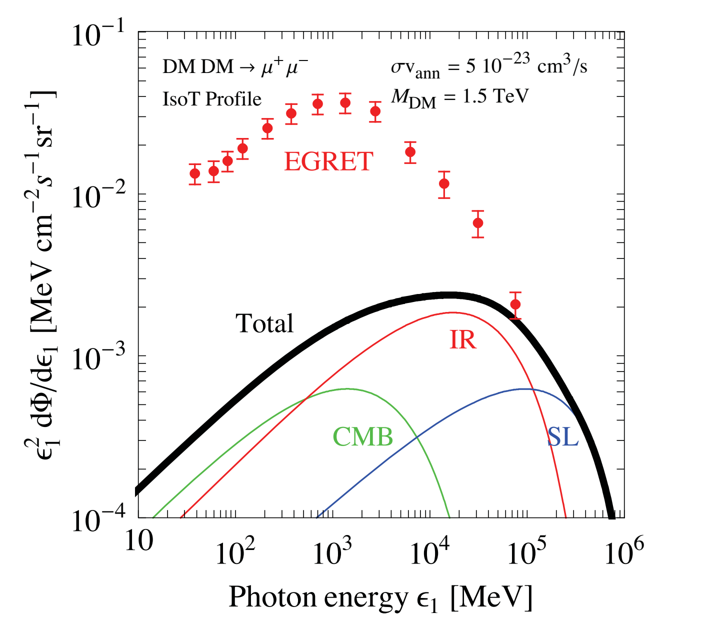
Gamma constraints

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



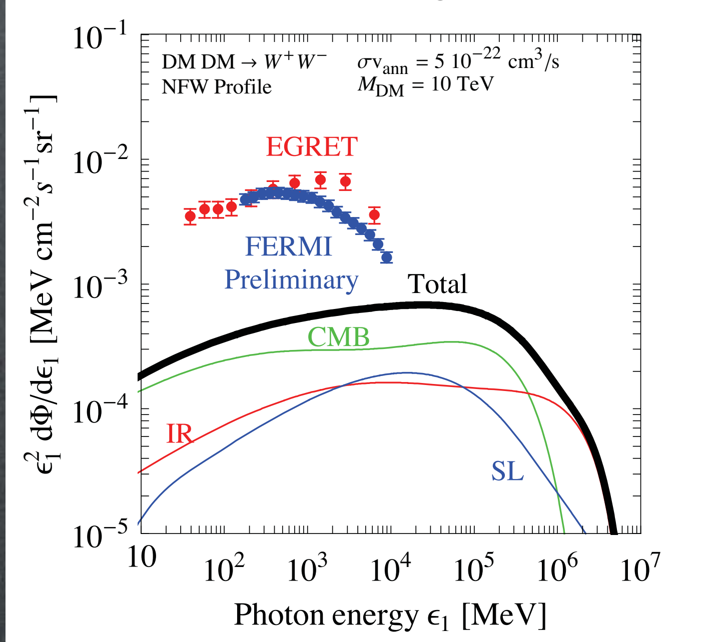
FERMI coll.

10×60 region



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

10–20 region



Data: FERMI coll., several talks in 2009