Title: Seeing Dark Matter in cosmic rays?

Date: Jun 11, 2009 11:20 AM

URL: http://pirsa.org/09060047

Abstract: Recent data from the PAMELA satellite and a number of balloon experiment have reported unexpected excesses in the measured fluxes of cosmic rays. Are these the first direct evidences for Dark Matter? If yes, which DM models and candidates can explain these anomalies and what do they imply for future searches?

11 june 2009

Workshop "New Lights on Dark Matter"

Seeing Dark Matter in cosmic rays?!?

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

11 june 2009
Workshop "New Lights on Dark Matter"

Model independent implications of the e^+, e^-, $\bar{p}$ cosmic ray spectra on Dark Matter properties and constraints from galactic gamma ray and radio waves

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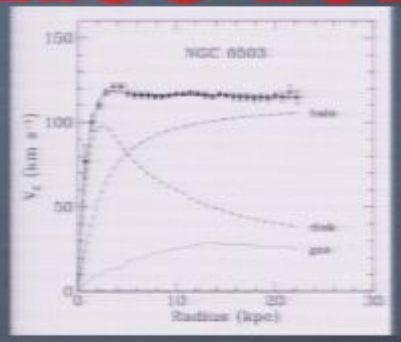
The Evidence for DM

1) galaxy rotation curves

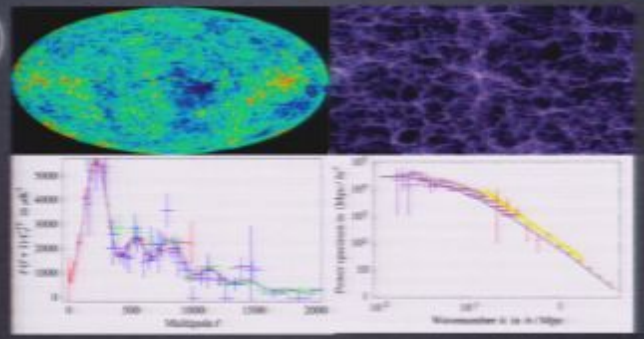


$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

$\Omega_M \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)



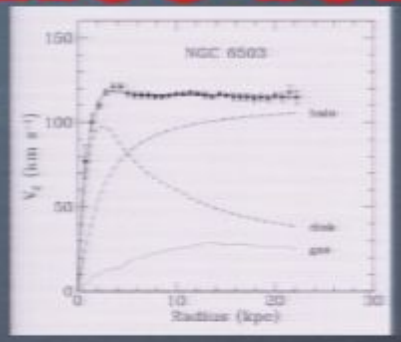
$\Omega_M \approx 0.26 \pm 0.05$

DM exists.

It consists of a particle.
Permeates galactic haloes.

The Evidence for DM

1) galaxy rotation curves



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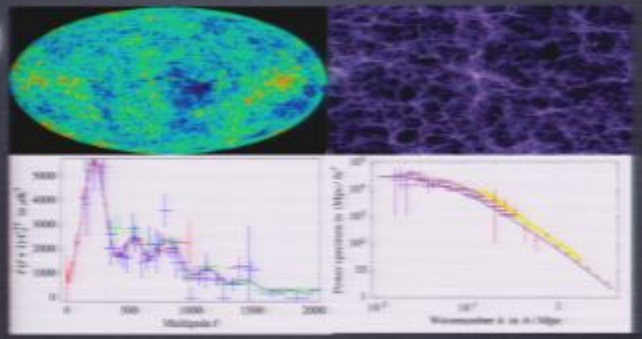


$\Omega_M \approx 0.26 \pm 0.05$

What is the DM??

It consists of a particle.
Permeates galactic haloes.

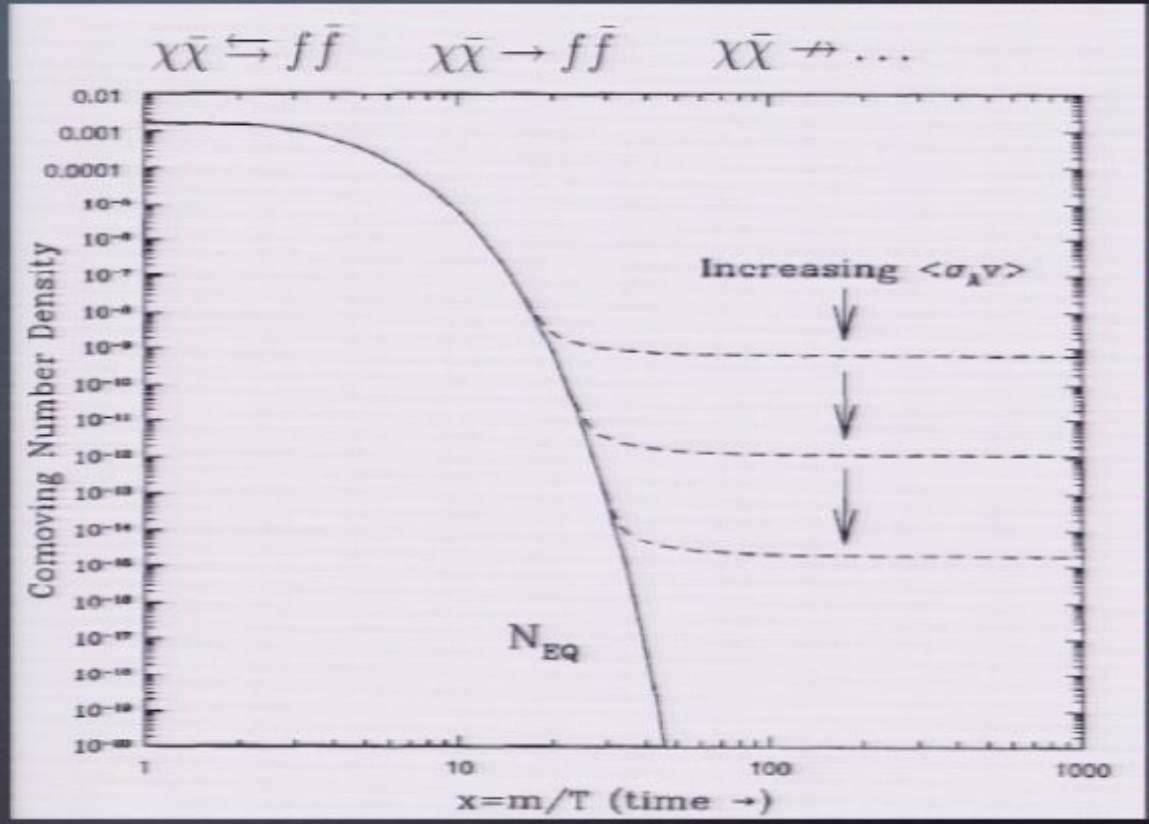
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

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

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

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



Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

DM detection

direct detection

Xenon, CDMS, Dama/Libra

production at colliders

LHC

indirect

- γ from annihil in galactic halo or center

  HESS, FERMI, radio telescopes
- e^+ from annihil in galactic halo or center

  PAMELA, **ATIC**, **Fermi**
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{D}$ from annihil in galactic halo or center

  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
- e^+ from annihil in galactic halo or center
  PAMELA, ATIC, Fermi
- $\bar{p}$ from annihil in galactic halo or center
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DM detection

direct detection

production at colliders

indirect

- γ from annihil in galactic halo or center
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DM detection

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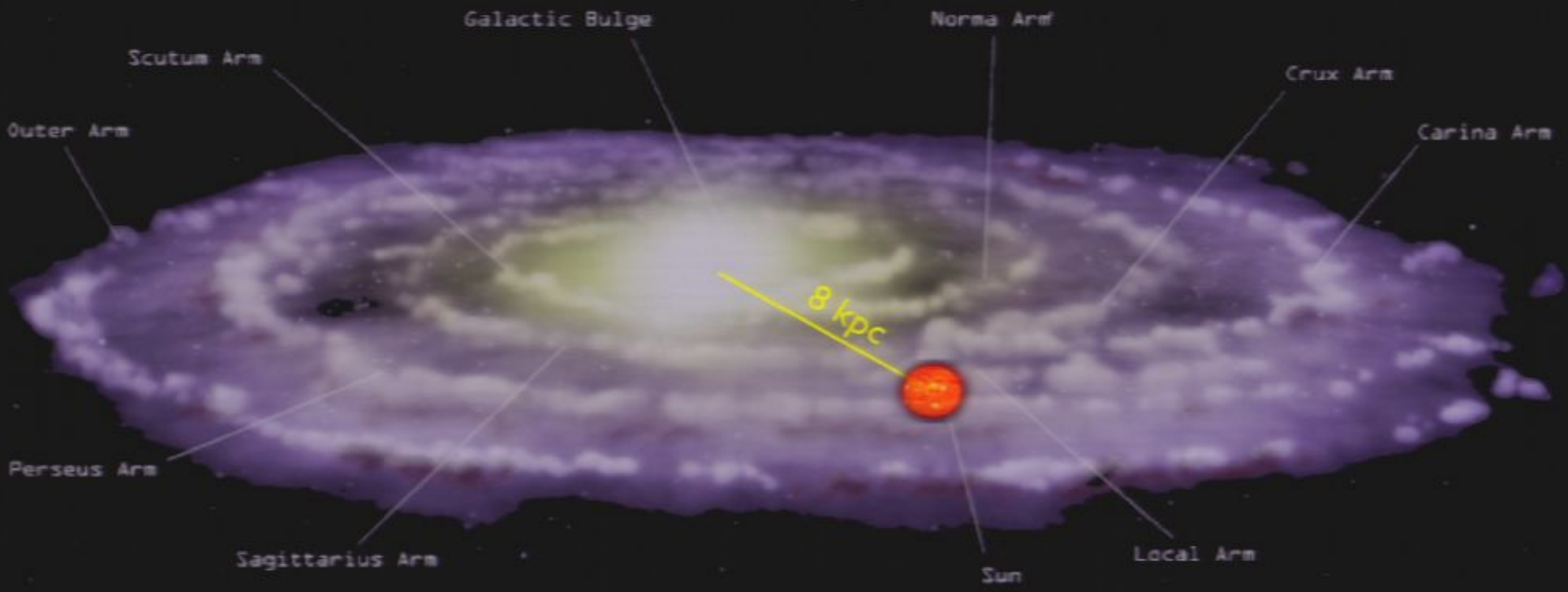
Indirect Detection

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



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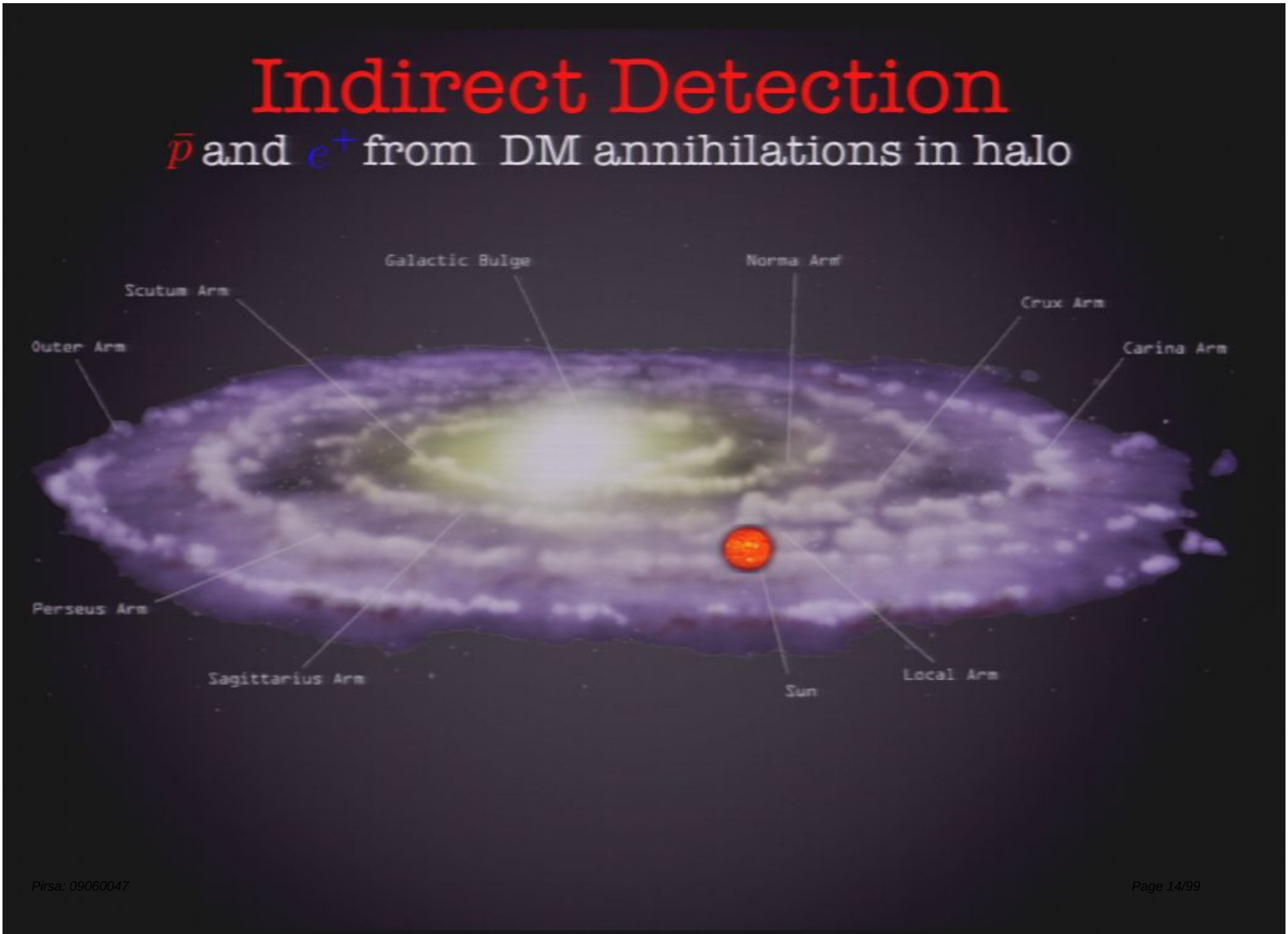

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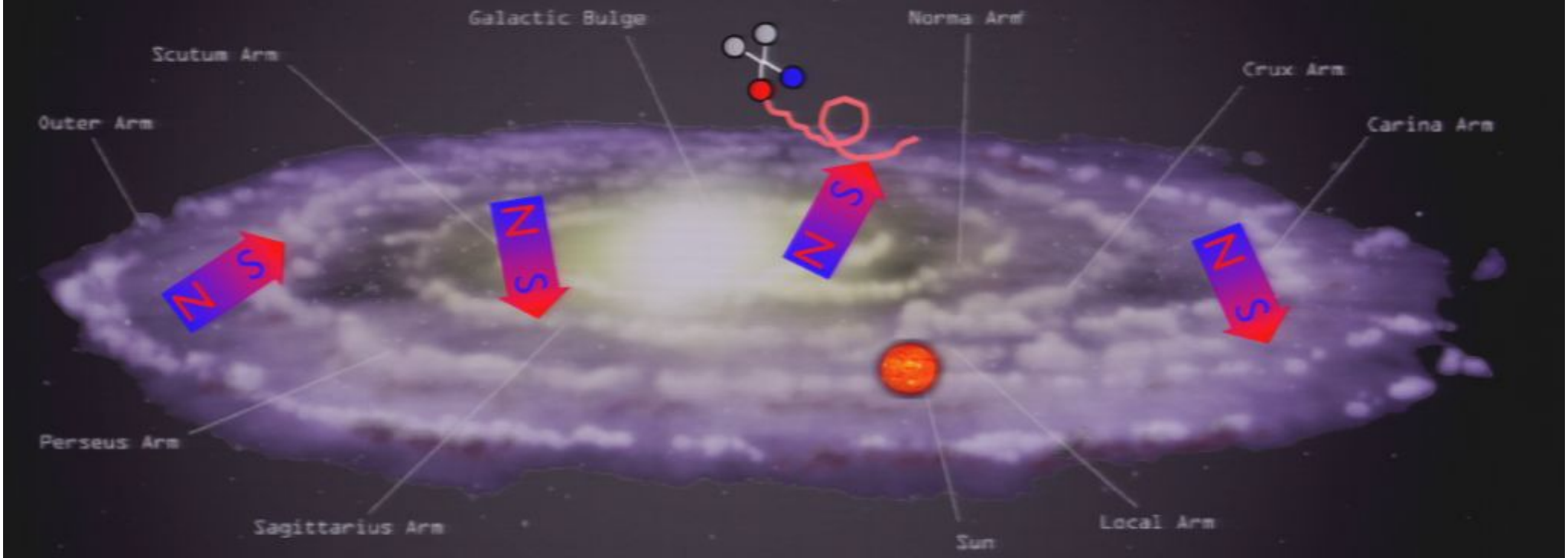

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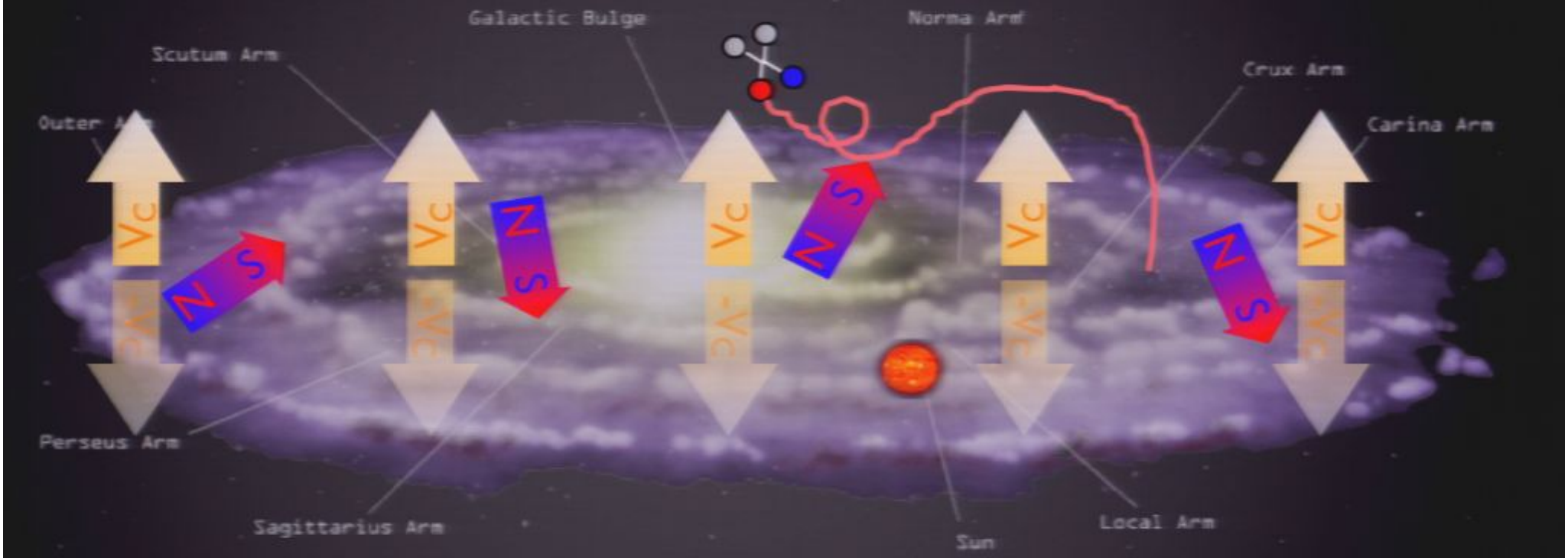

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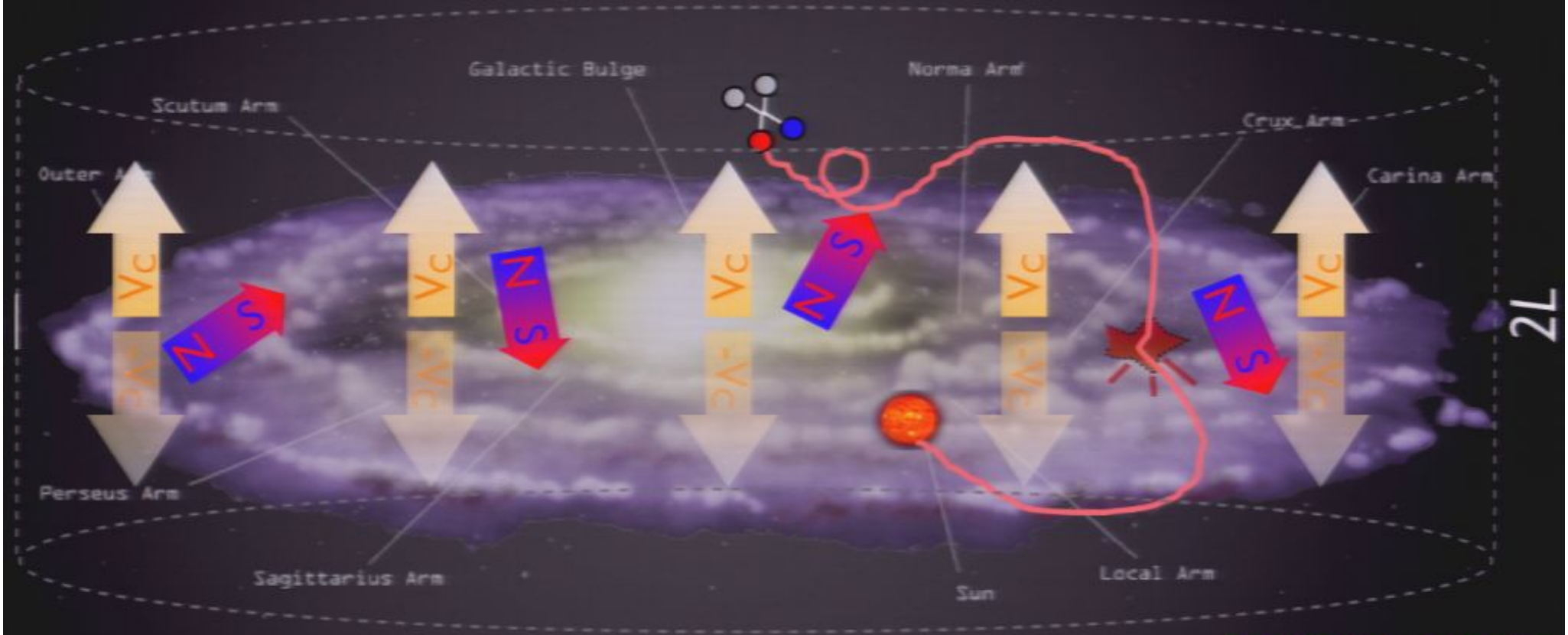


spectrum

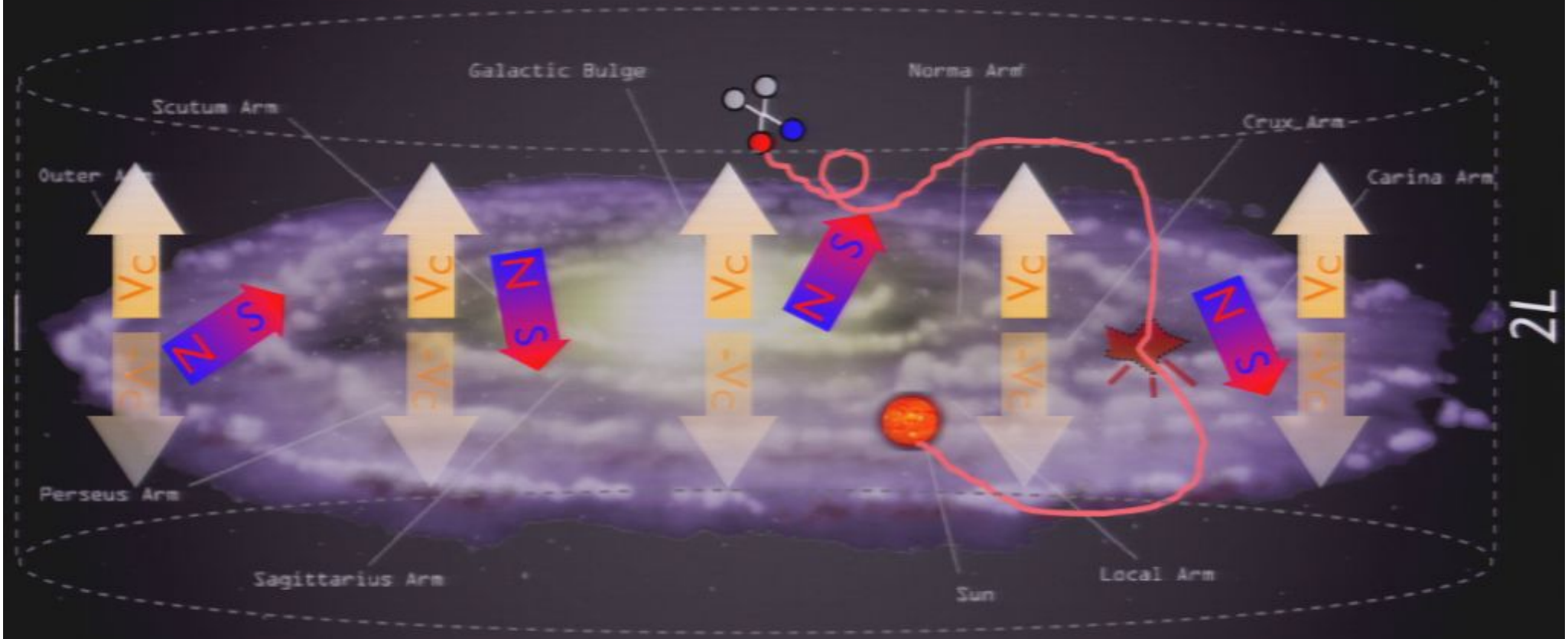
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion | energy loss | convective wind | source | spallations

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

Indirect Detection

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

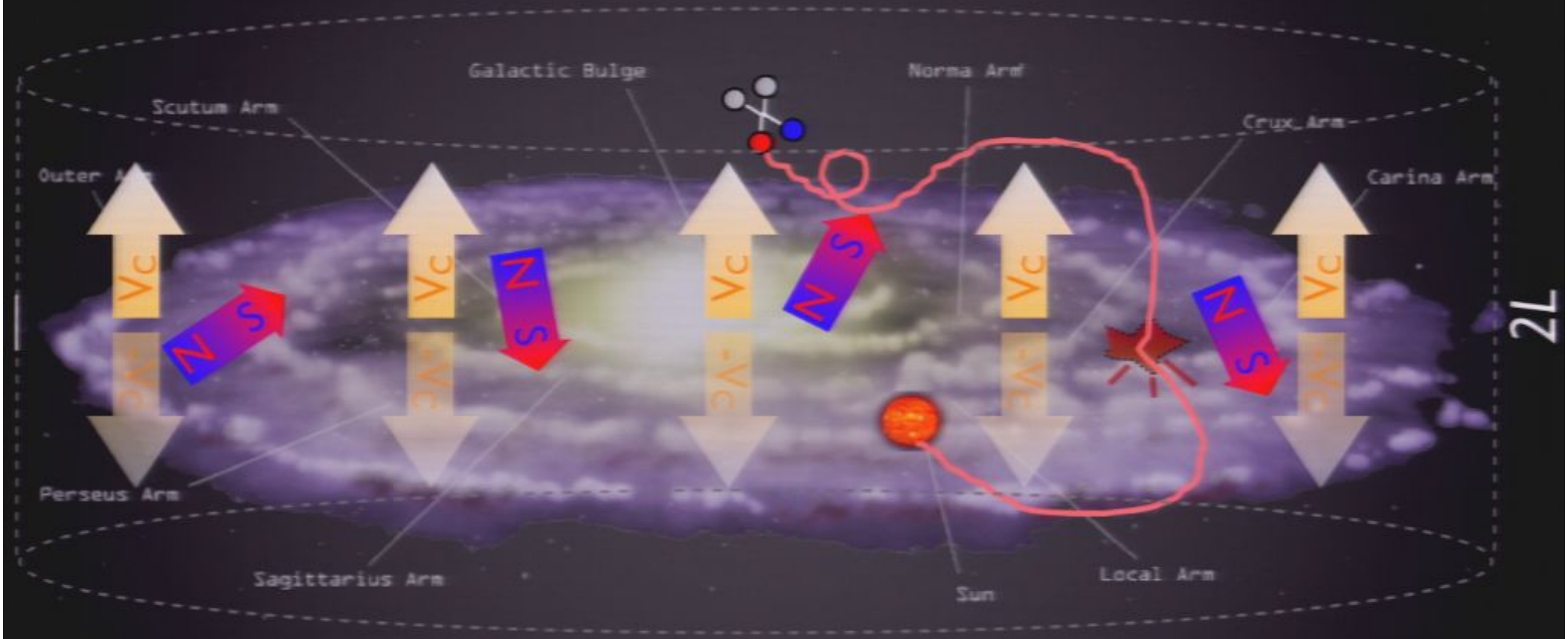


What sets the overall expected flux?

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

Indirect Detection

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



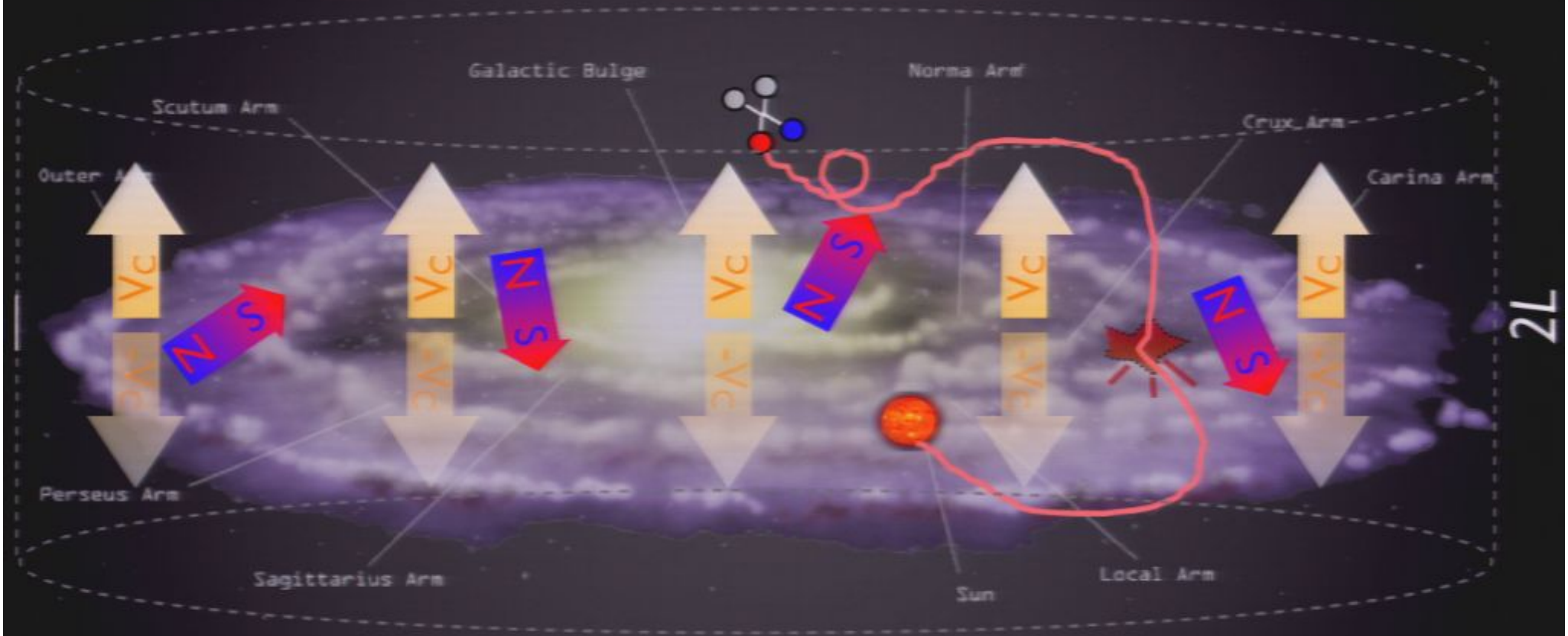
2L

What sets the overall expected flux?

$$\text{flux} \propto \underbrace{n^2}_{\text{astro\& cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

Indirect Detection

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



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$$\text{flux} \propto \underbrace{n^2}_{\text{astro\&cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

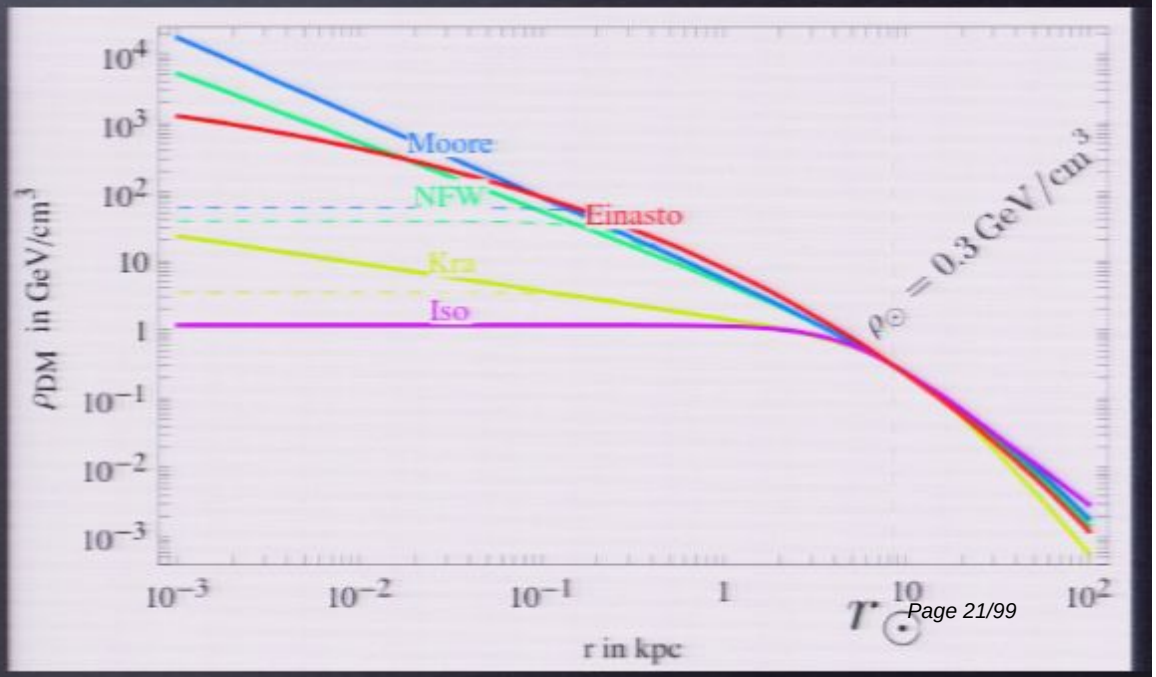
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

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

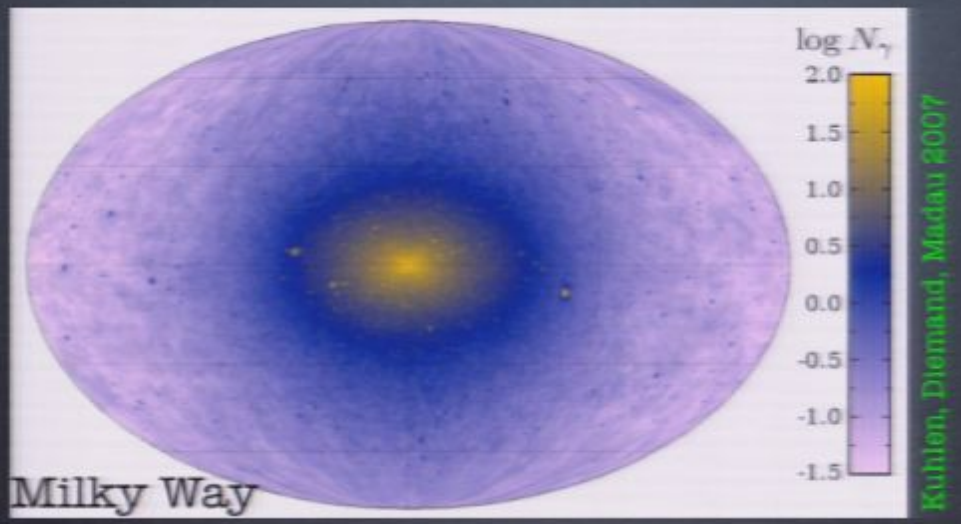
mild: Einasto

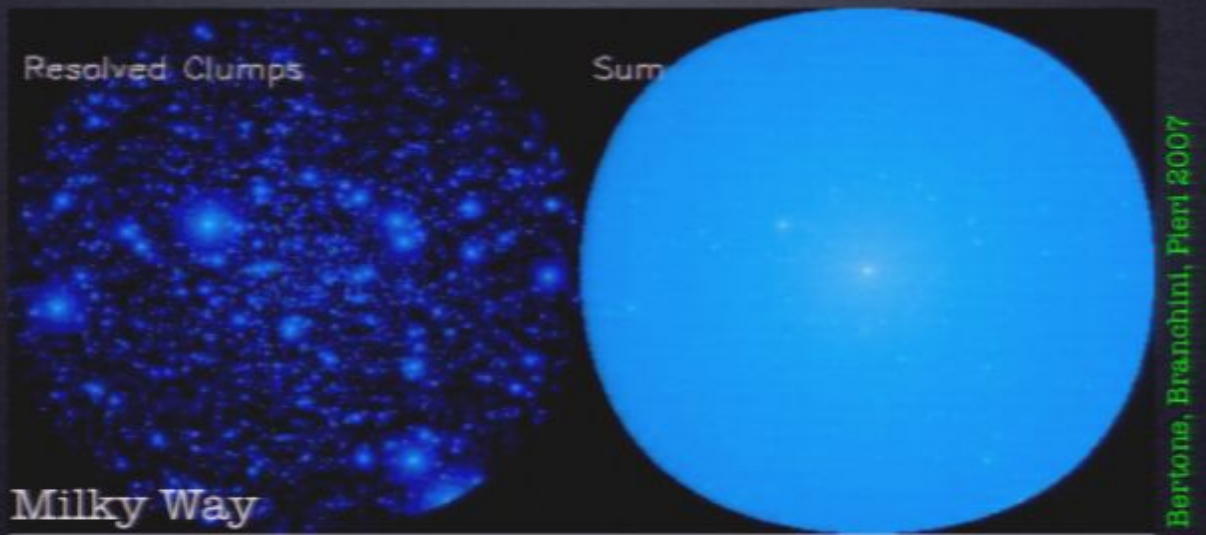
smooth: isothermal

Indirect Detection

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

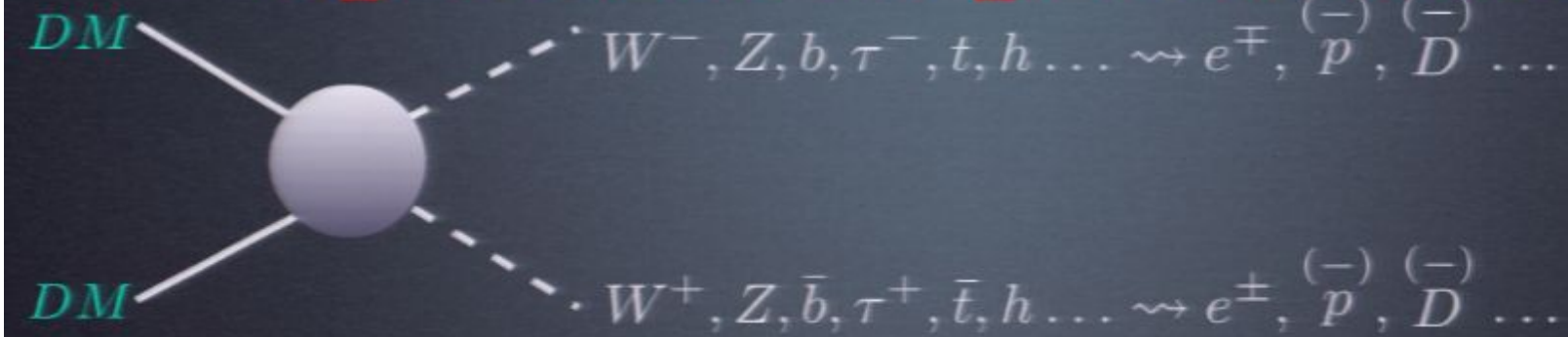
For illustration:





Computing the theory predictions

Spectra at production



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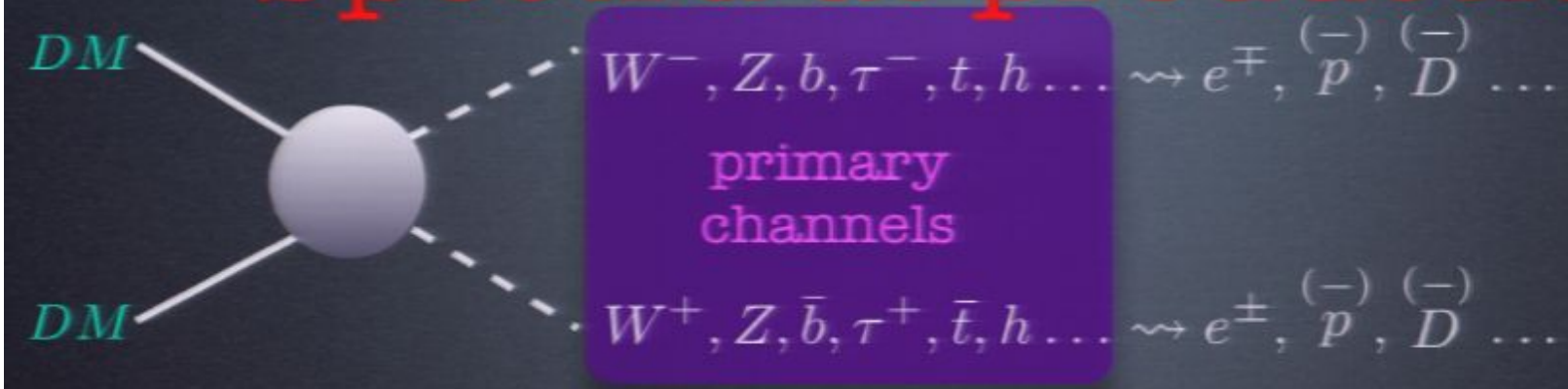

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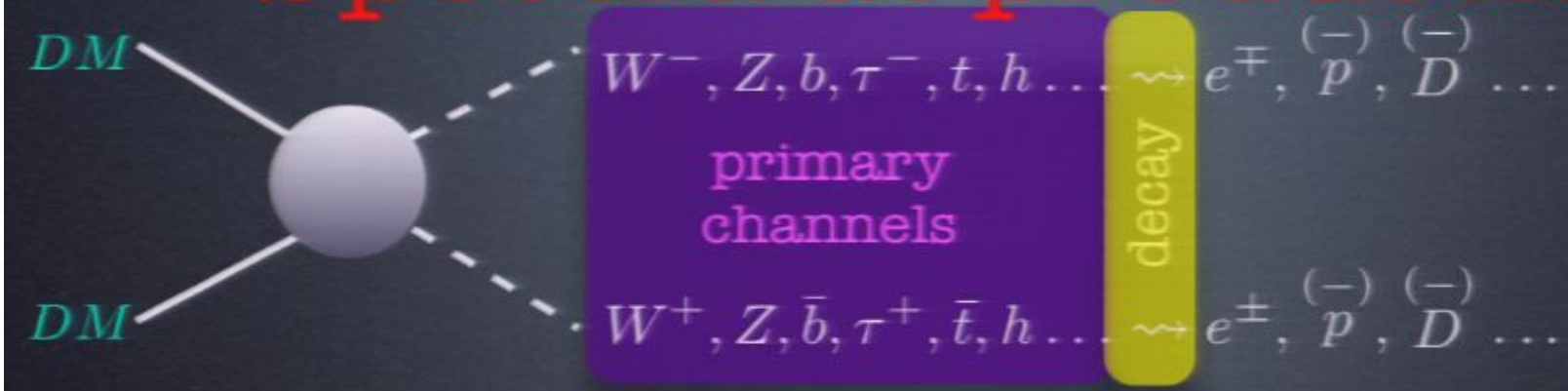
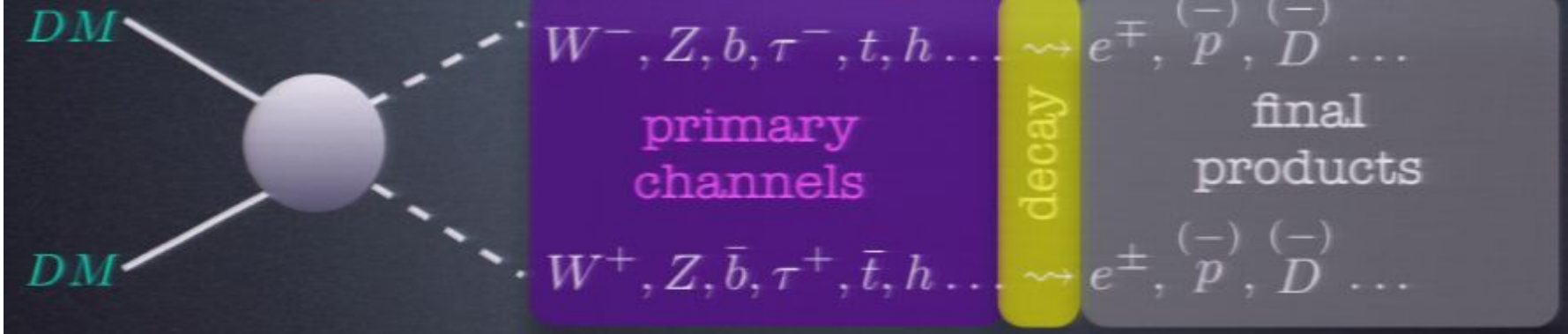
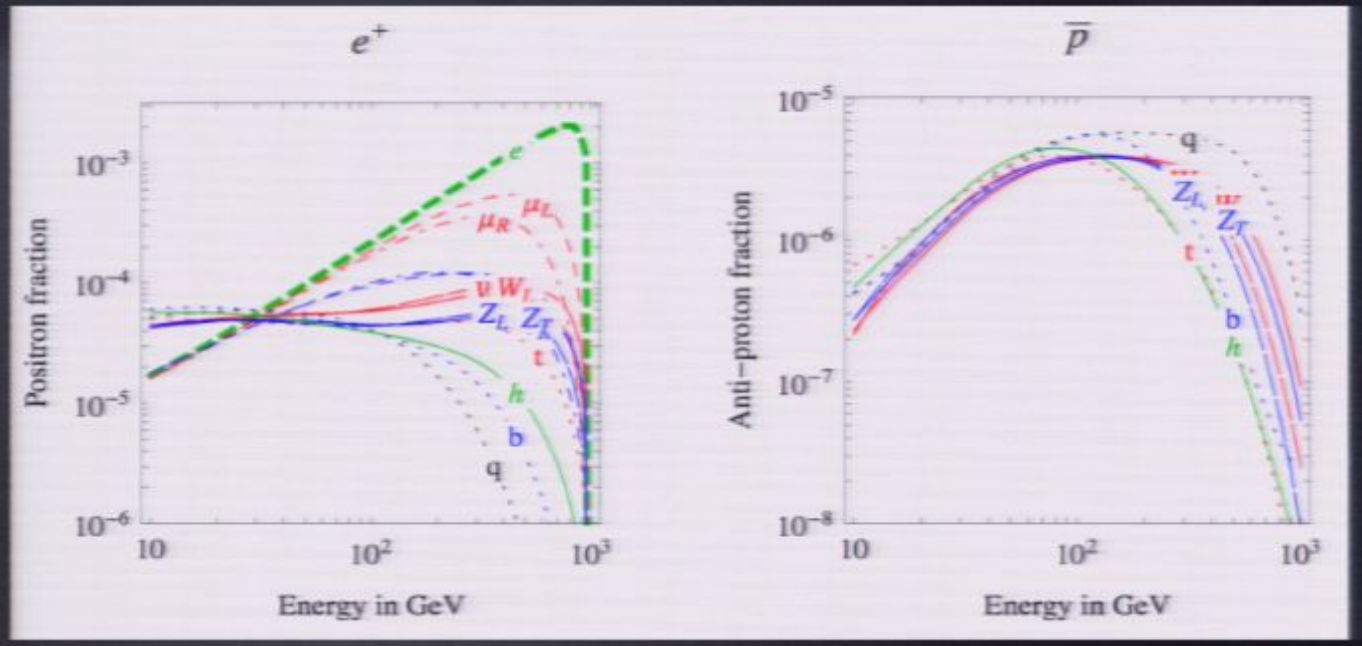


Spectra at production





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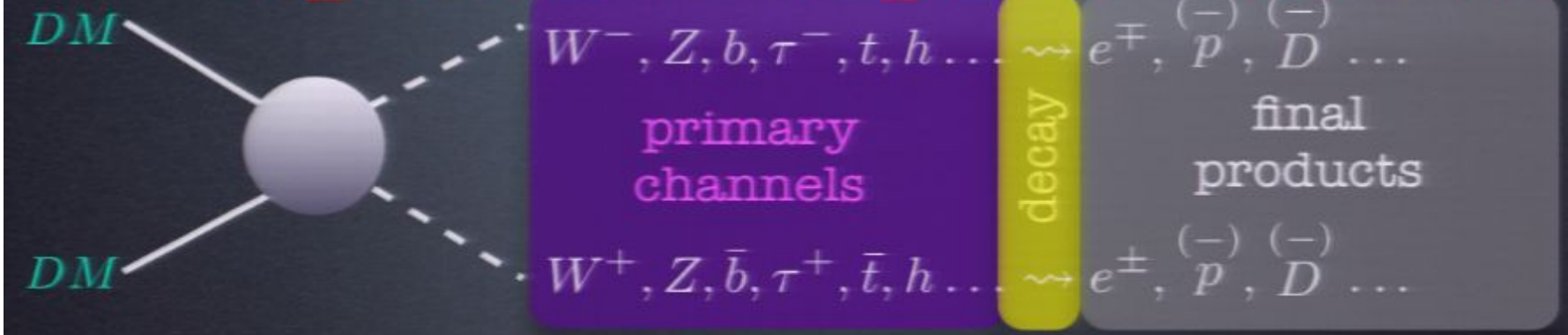
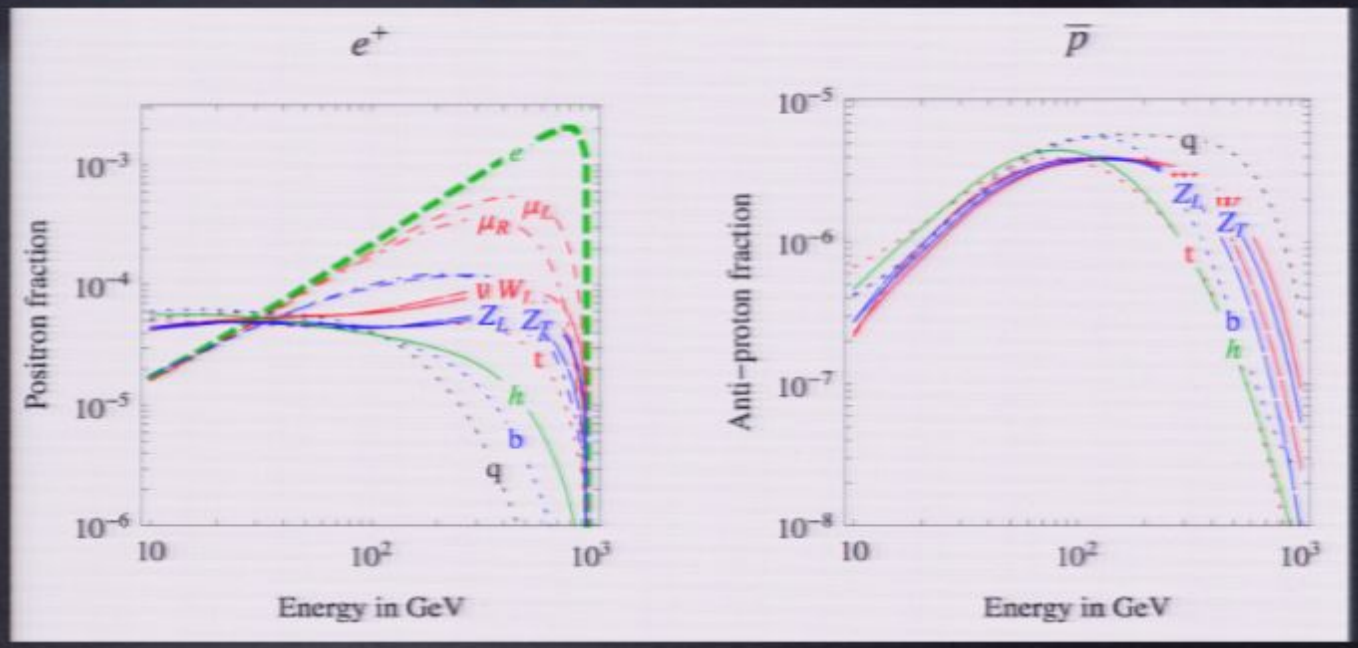




So what are the particle physics parameters?

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

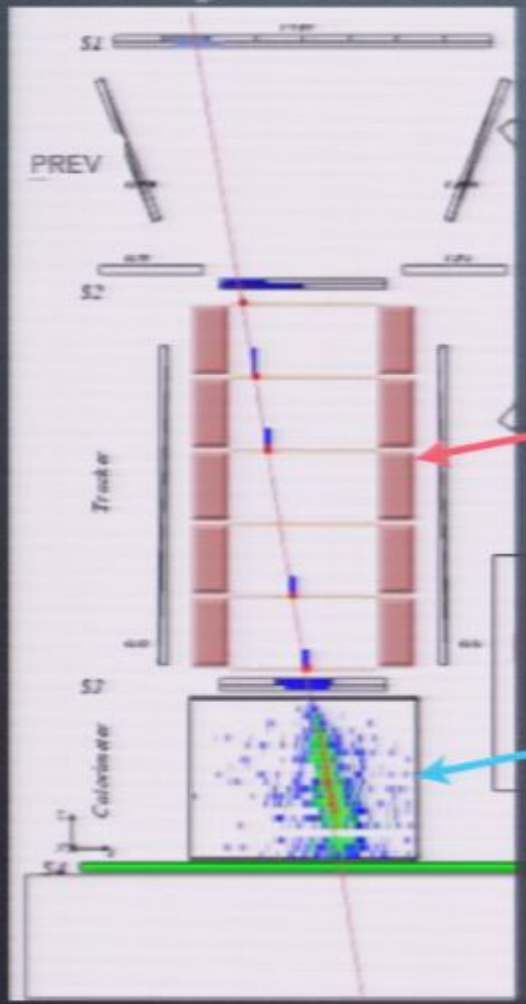
Comparing with data

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)

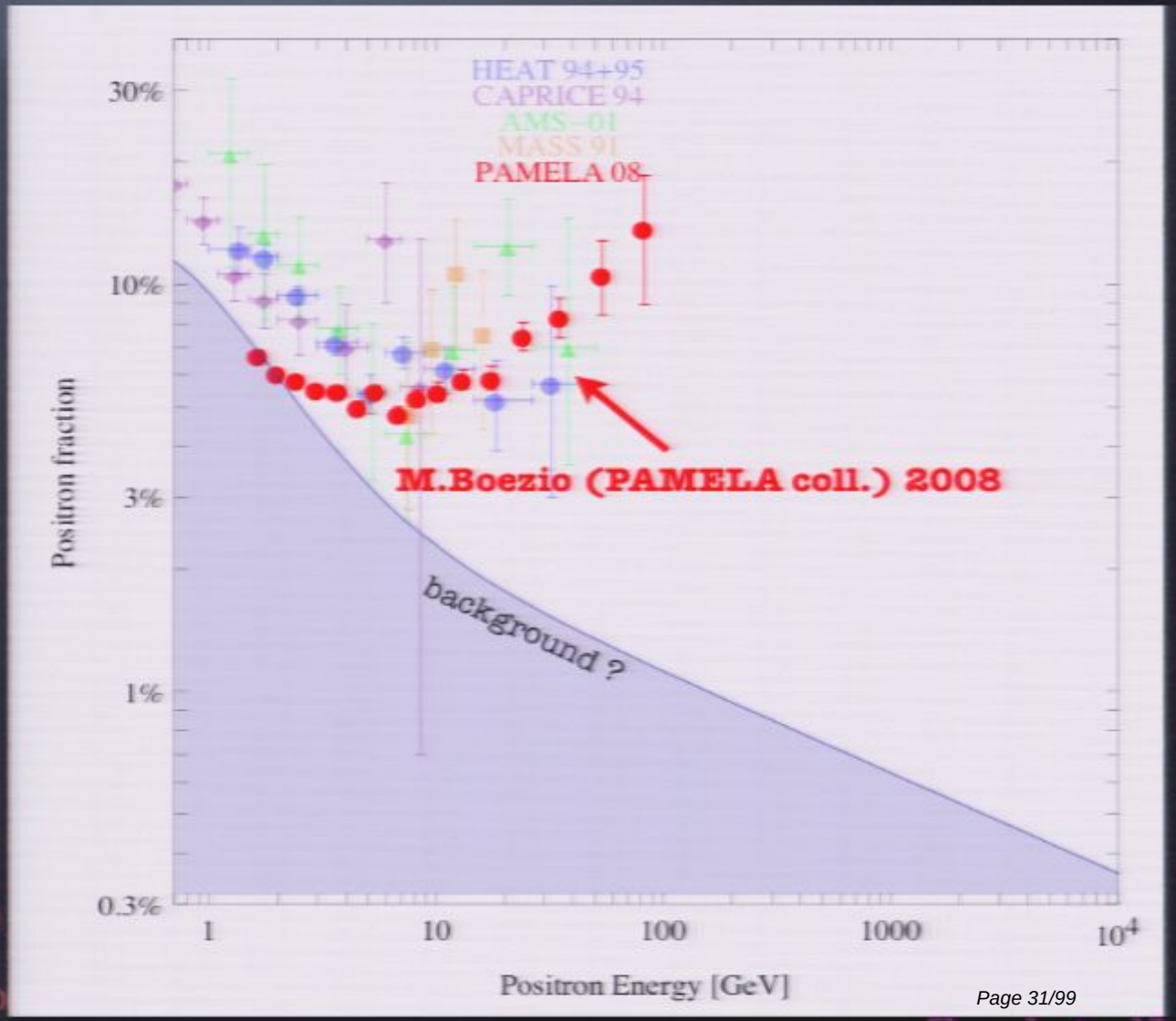
(swipe thru)

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

(9430 e^+ collected)

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

[backgnd]

Data sets

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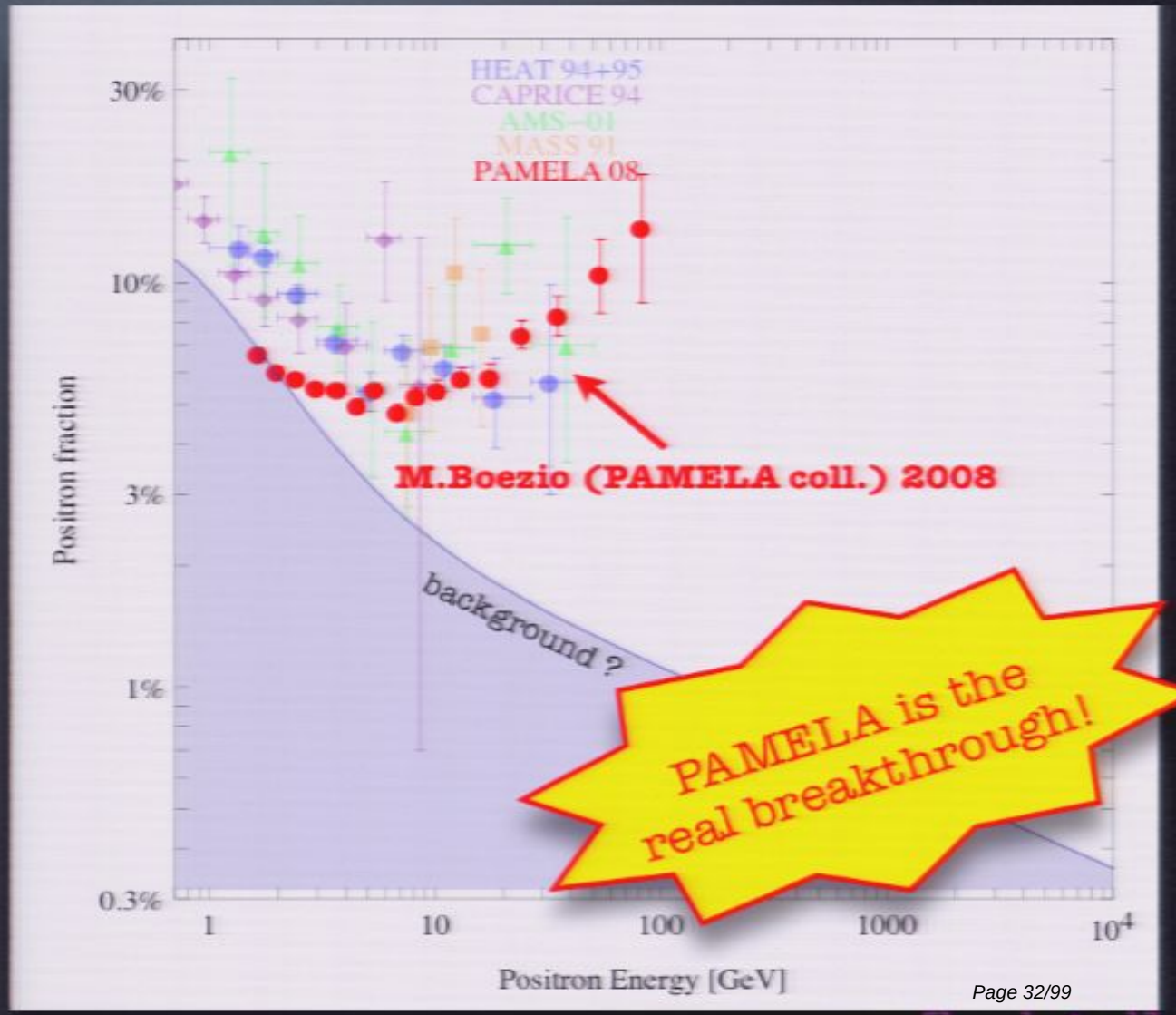
- very large flux!

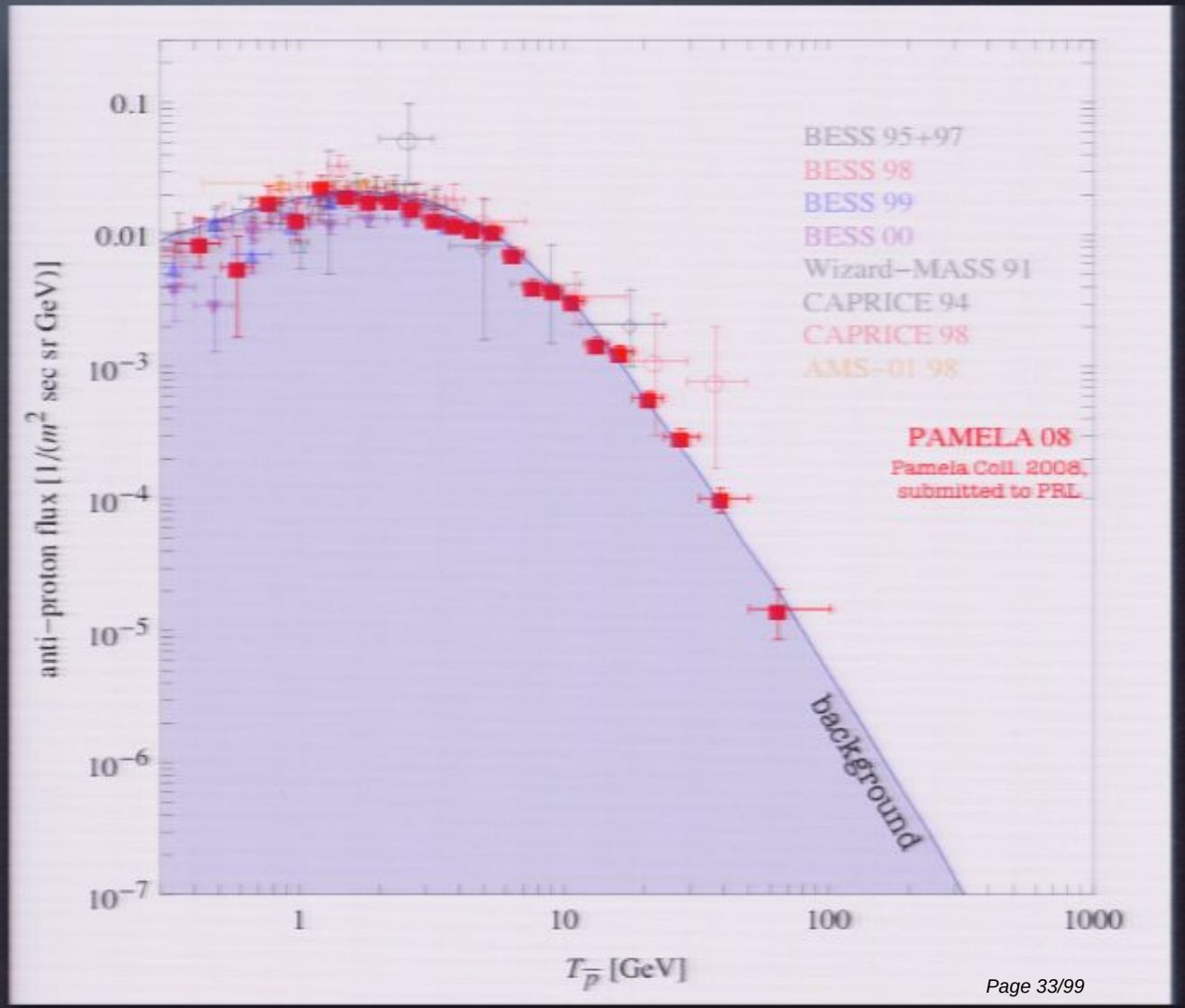


[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background



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

Results

Which DM spectra can fit the data?

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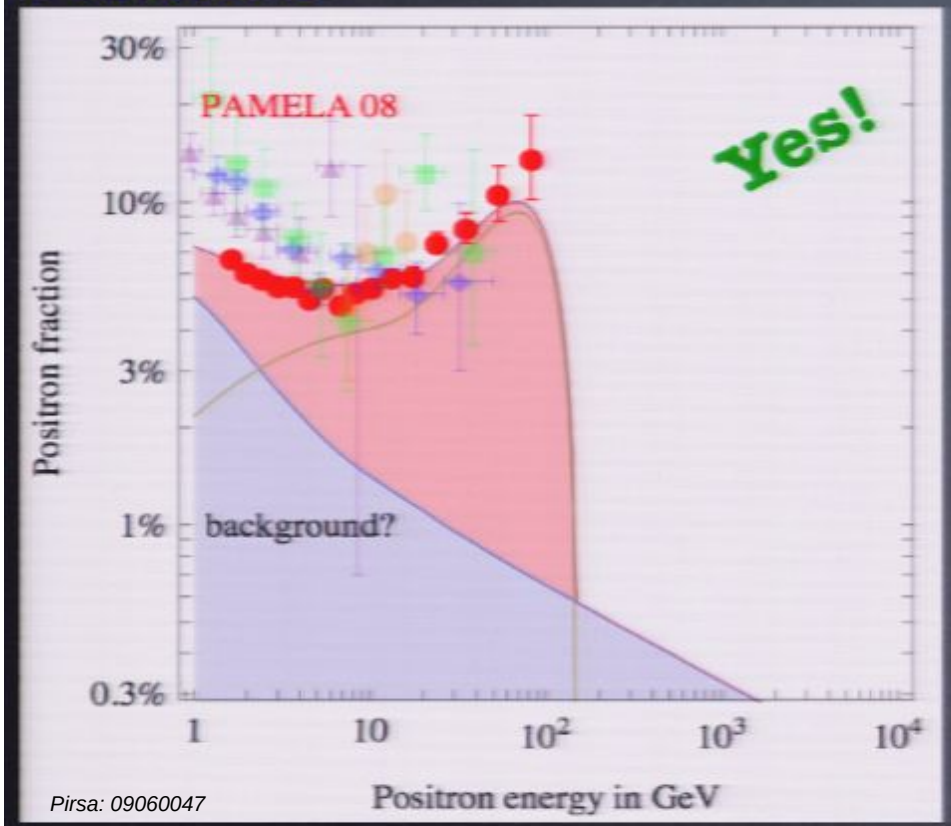
Which DM spectra can fit the data?

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

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

(a possible SuperSymmetric candidate: wino)

Positrons:



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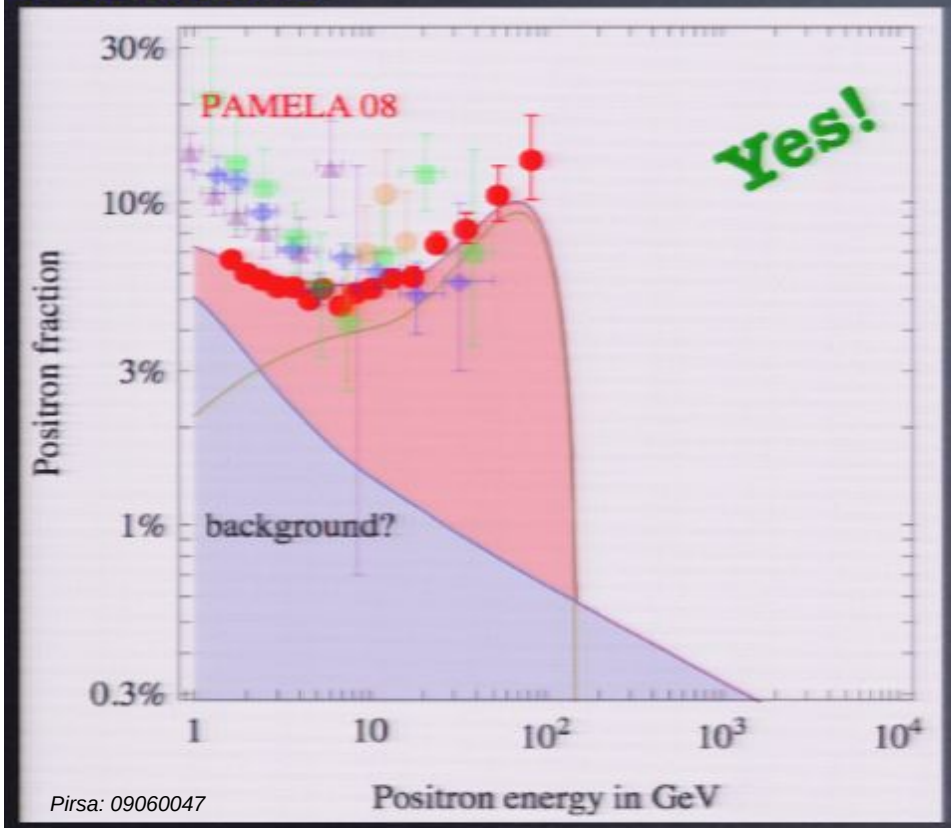
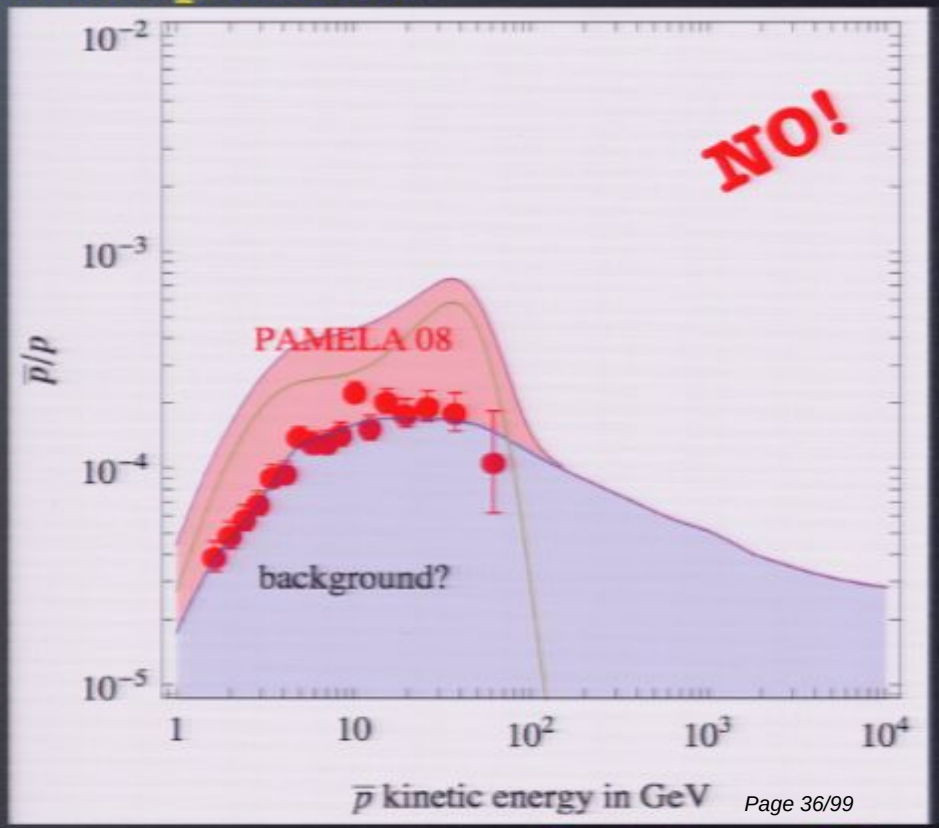


Anti-protons:



[insisting on Winos]

Results

Which DM spectra can fit the data?

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

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

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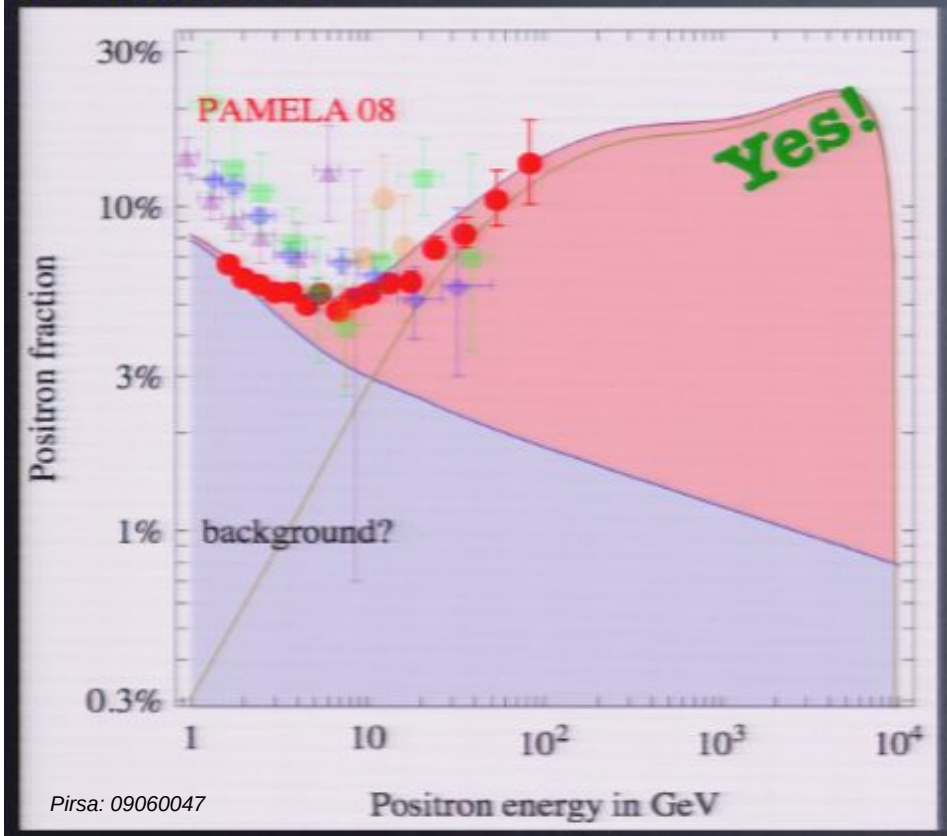
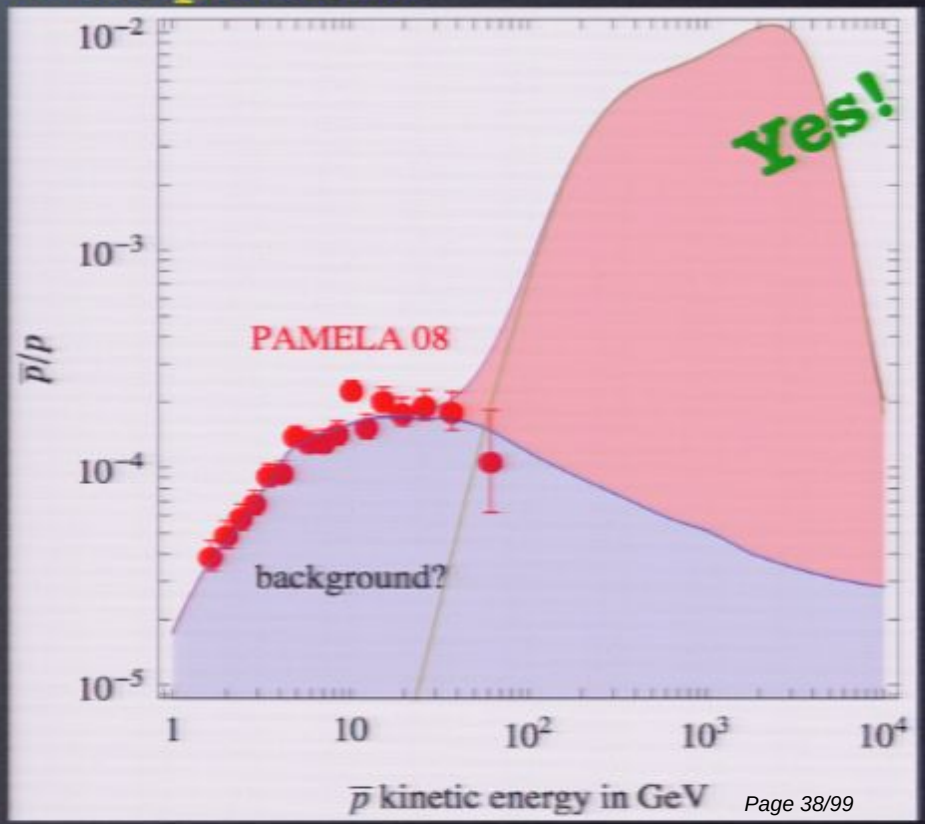


Anti-protons:



Results

Which DM spectra can fit the data?

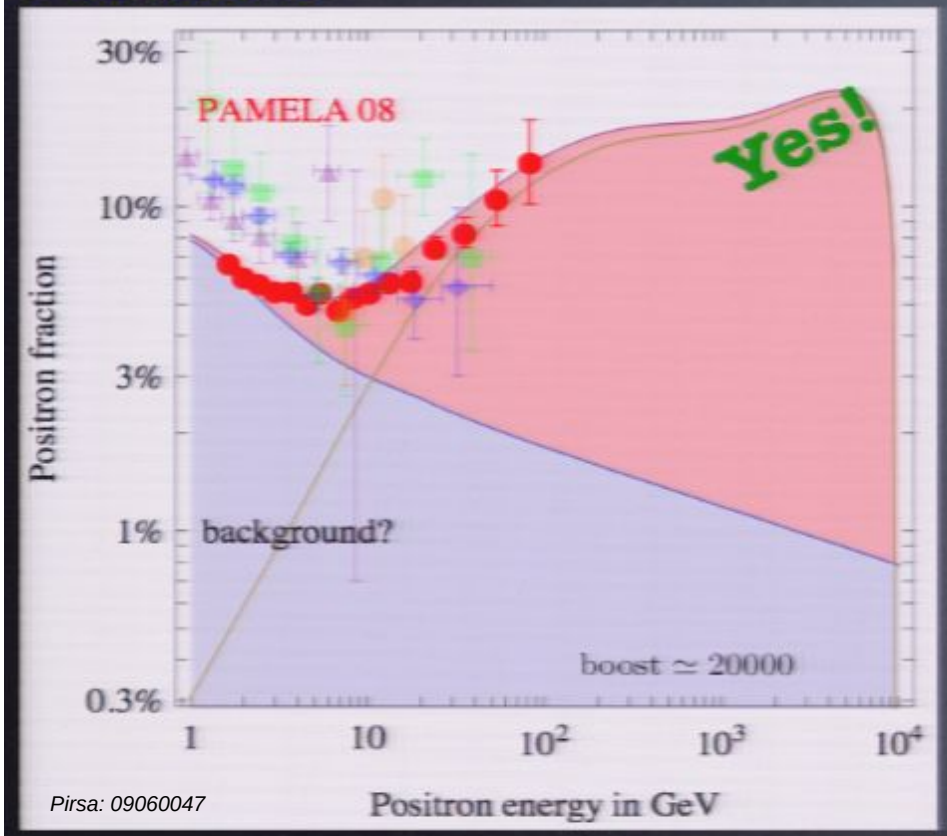
E.g. a DM with: -mass $M_{\rm DM} = 10\,{\rm TeV}$

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

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

Mmm...

Positrons:



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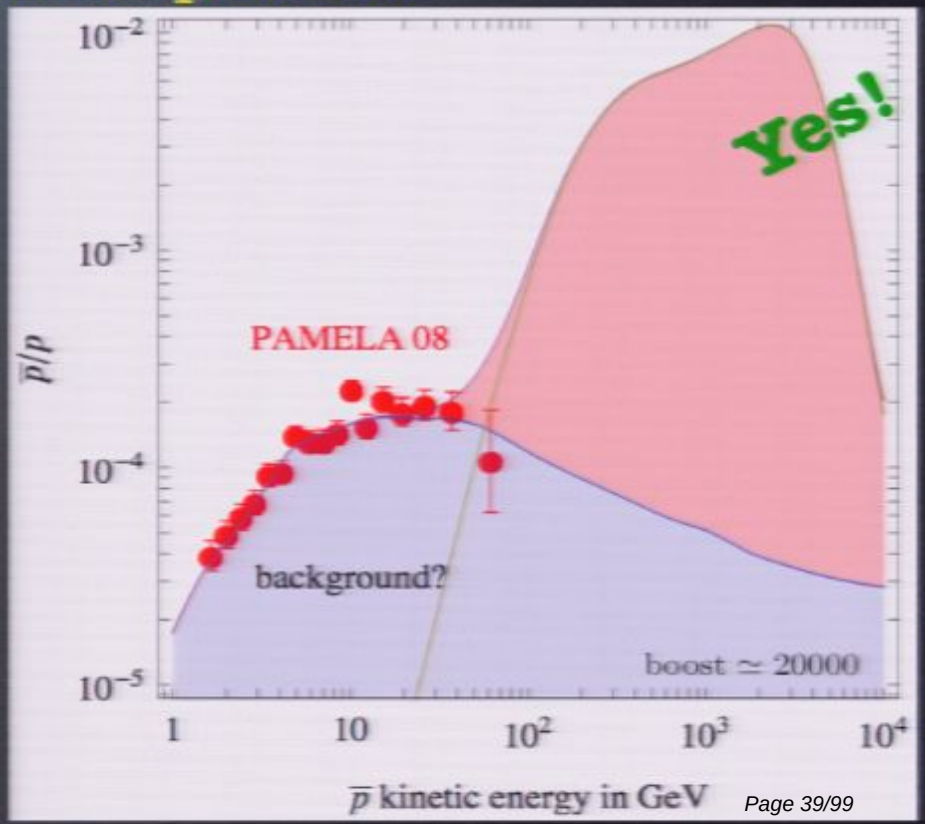
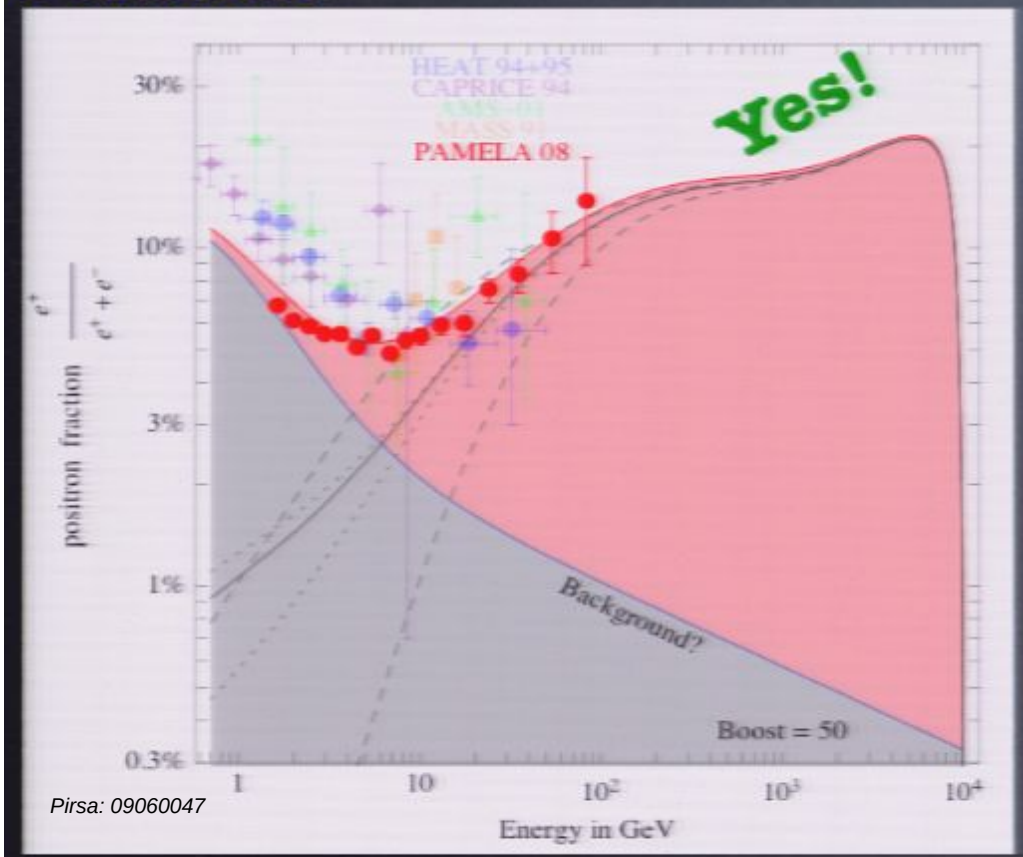


Results

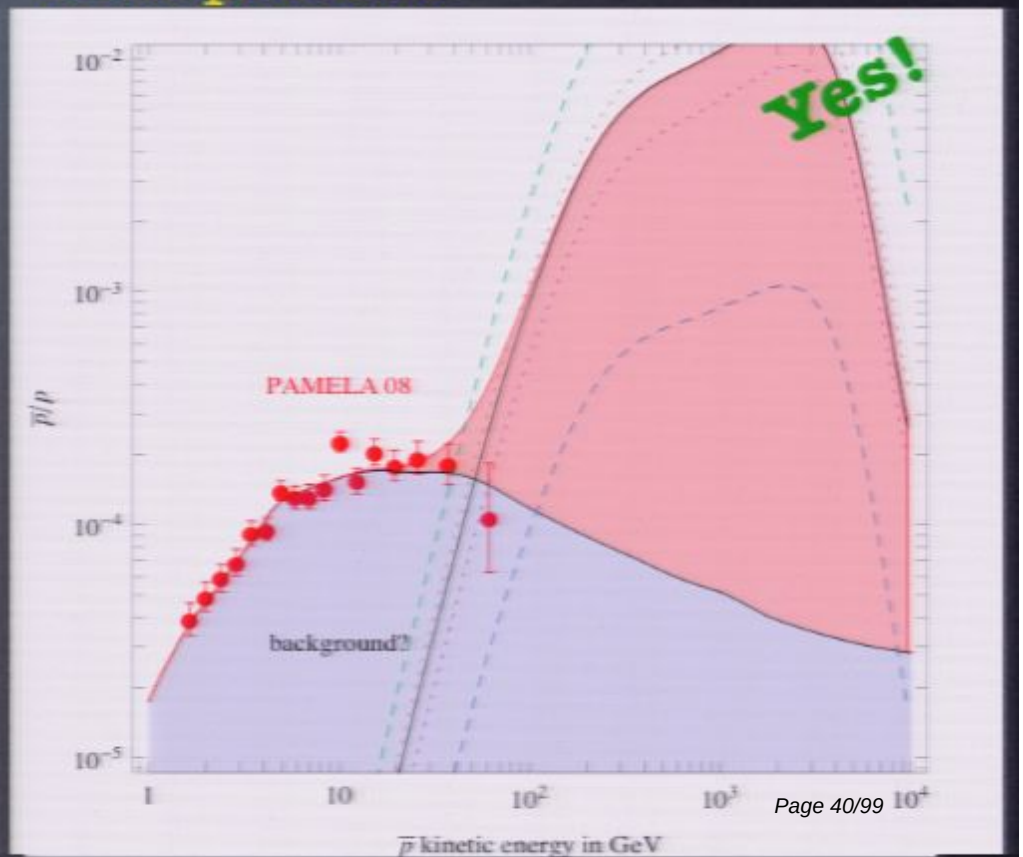
Which DM spectra can fit the data?

E.g. **Minimal DM**: -mass $M_{\rm DM} = 9.7\,{\rm TeV}$
[Cirelli, Strumia et al. 2006]
-annihilation $\mathrm{DM\,DM} \to W^+W^-$
-boost $B \simeq 30$ Yes!
[thanks to **Sommerfeld** enhancement]

Positrons:



Anti-protons:

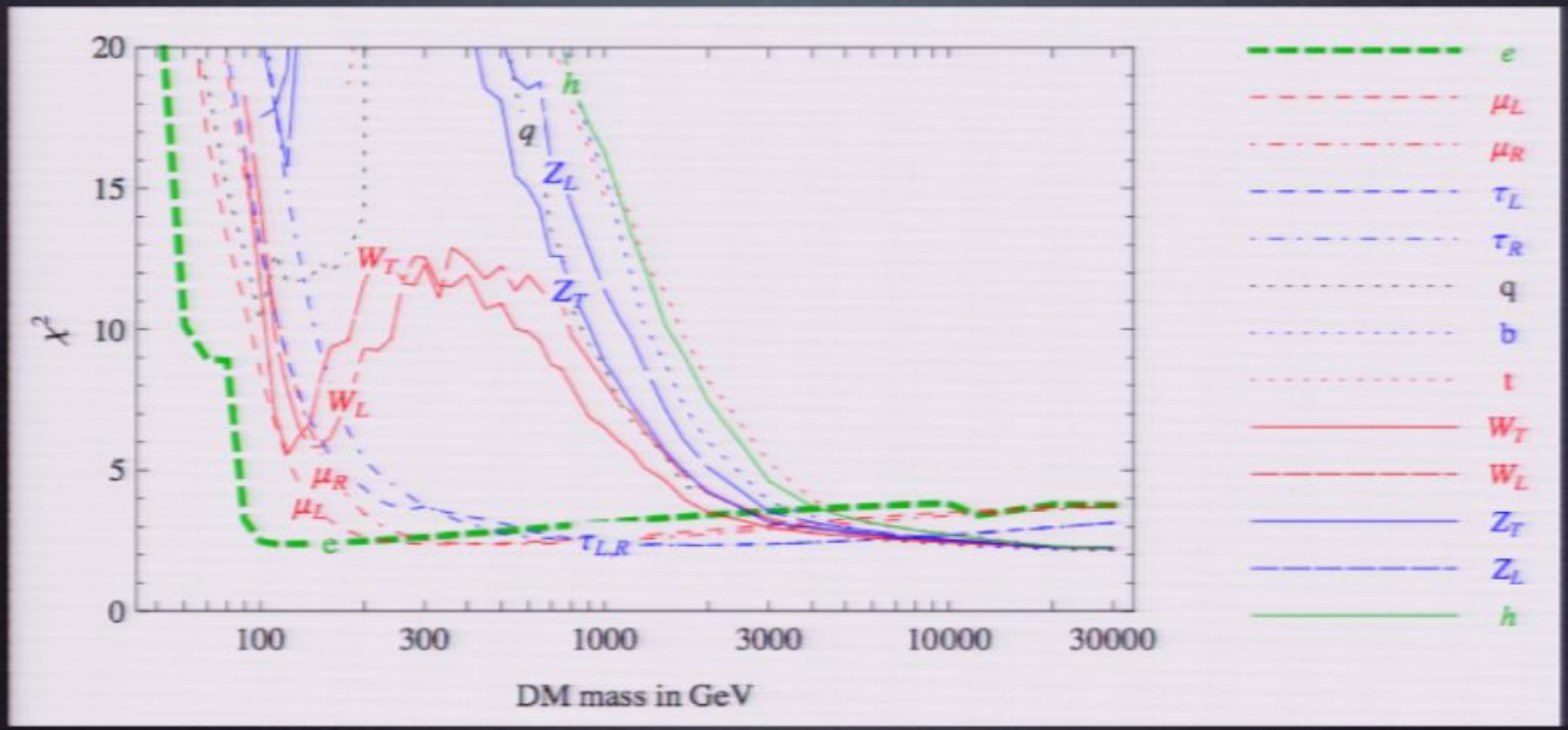


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons only

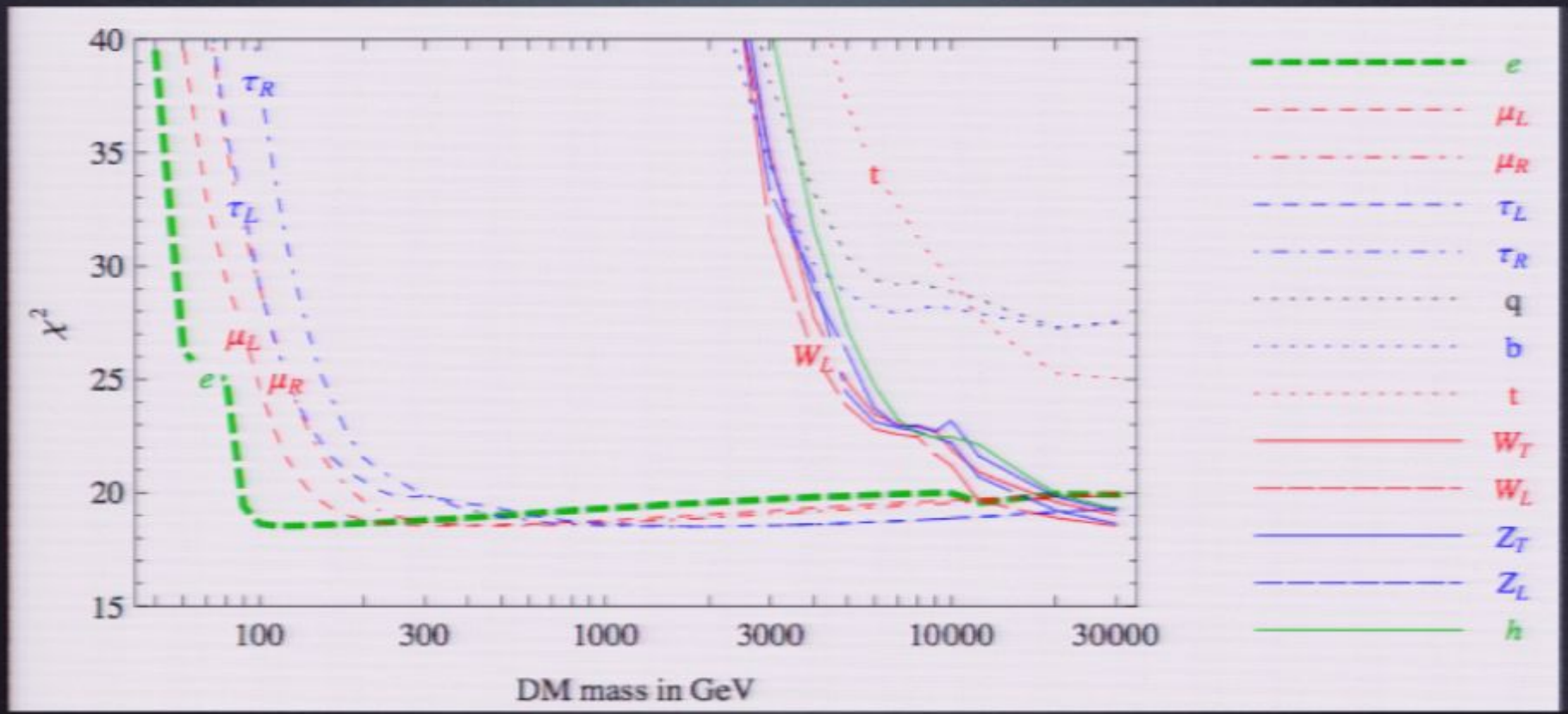


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons

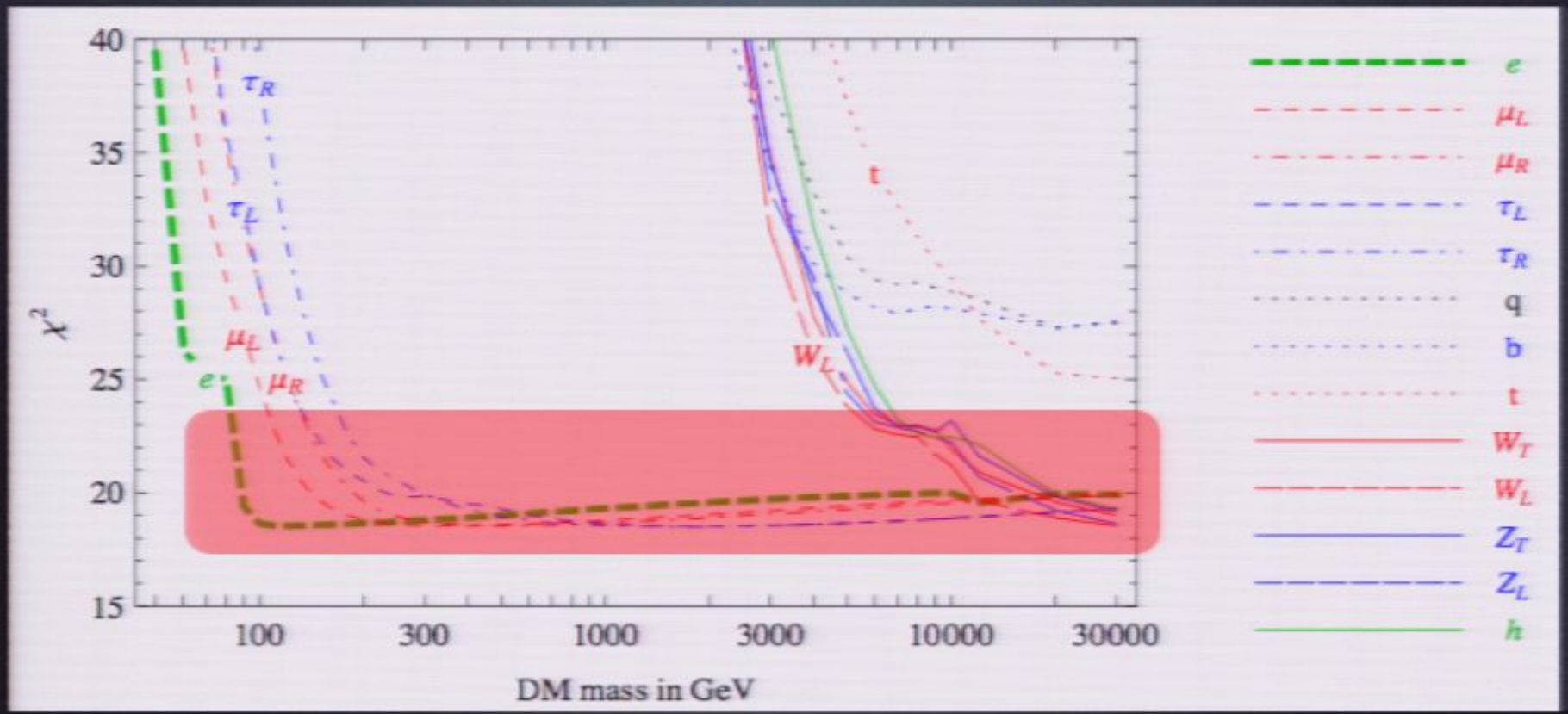


Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



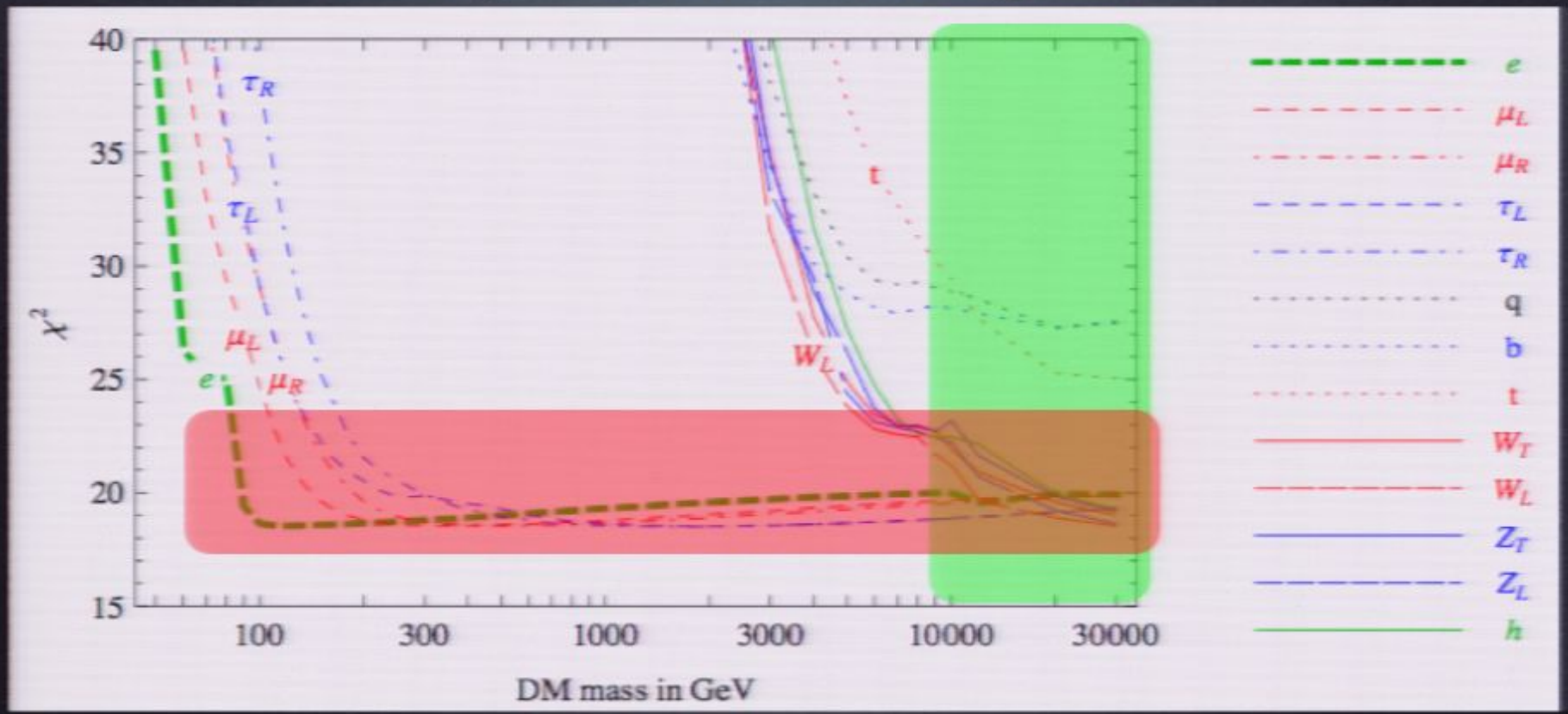
(1) annihilate into leptons (e.g. $\mu^+\mu^-$)

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons



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

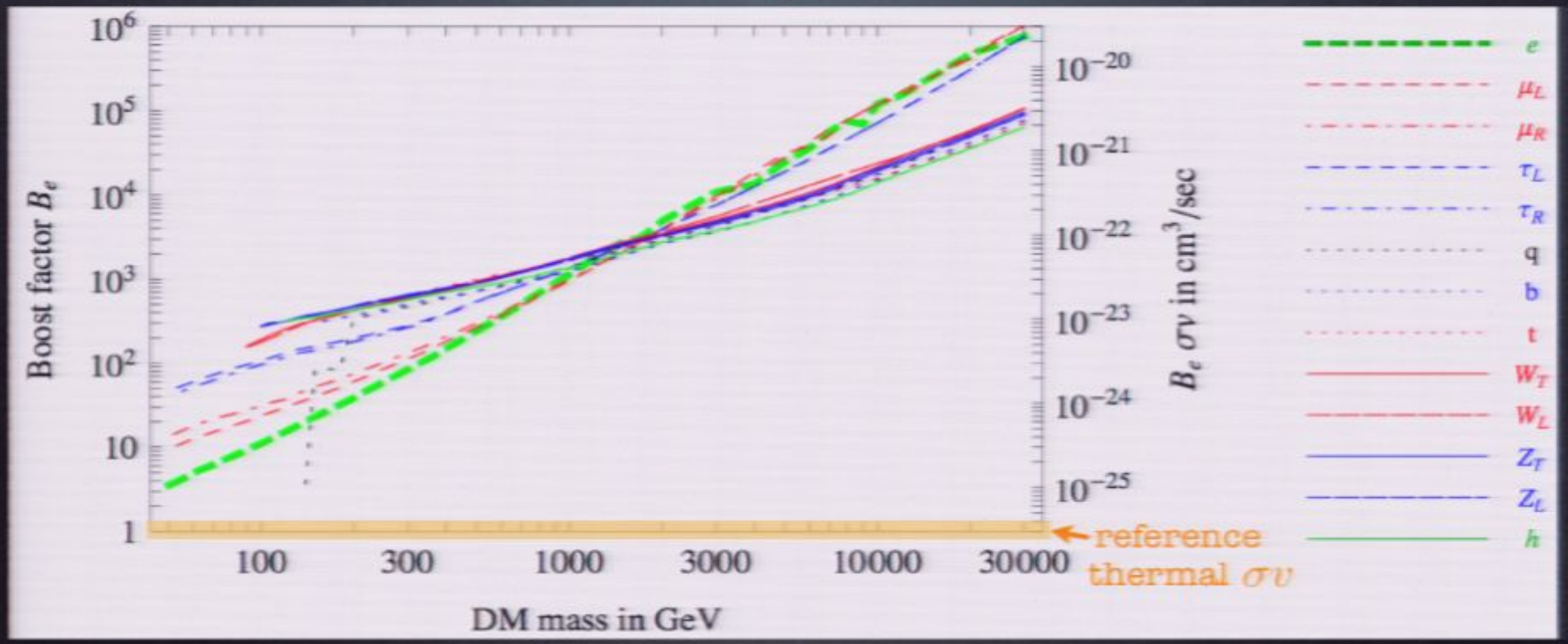
(2) annihilate into W^+W^- with mass $\gtrsim$ 10 TeV

Results

Which DM spectra can fit the data?

Model-independent results:

Cross-section required by PAMELA



Data sets

Electrons + positrons from ATIC, PPB-BETS:

PPB-BETS
(Japan)

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

ATIC (Usa + Germany, Russia, China)

Advanced
Thin
Ionization
Calorimeter

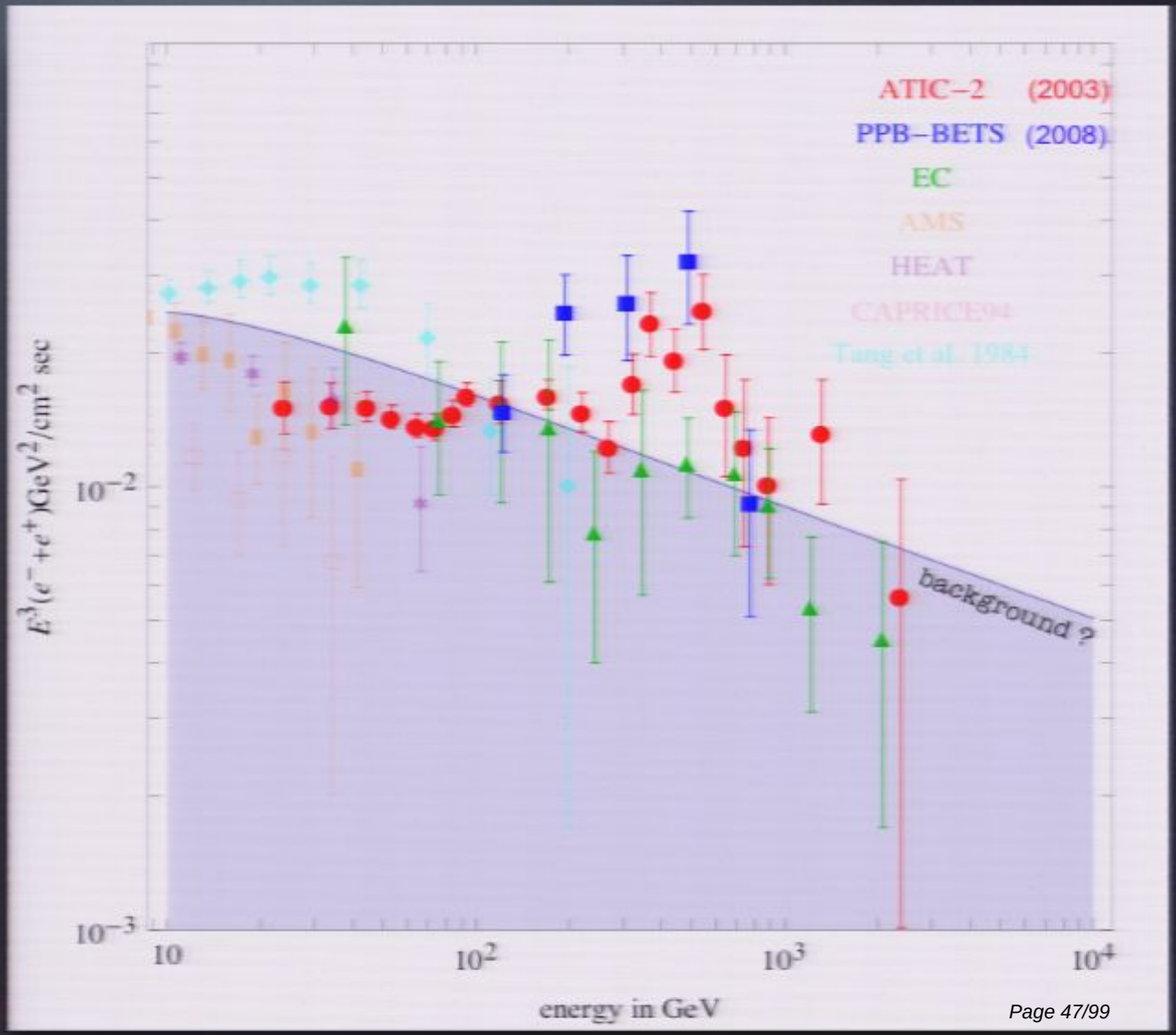
- bigger/denser: higher energy

- calorimeter only, no magnet:
no charge discrimination

Data sets

Electrons + positrons from ATIC, PPB-BETS:

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



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

Results

Which DM spectra can fit the data?

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

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

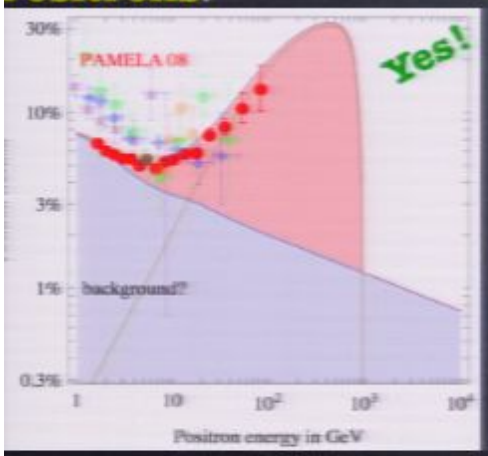
Results

Which DM spectra can fit the data?

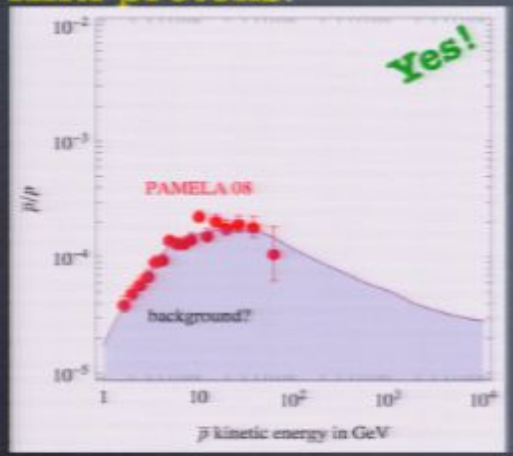
A DM with: -mass $M_{\rm DM} = 1\,{\rm TeV}$

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

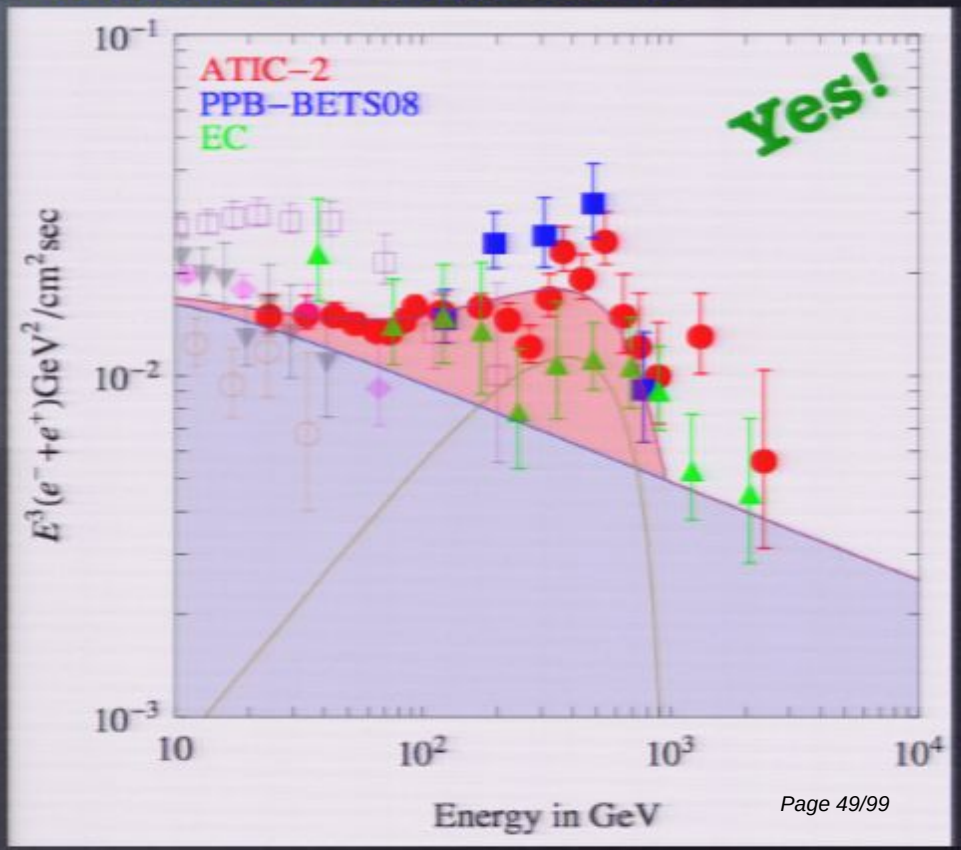
Positrons:



Anti-protons:



Electrons + Positrons:



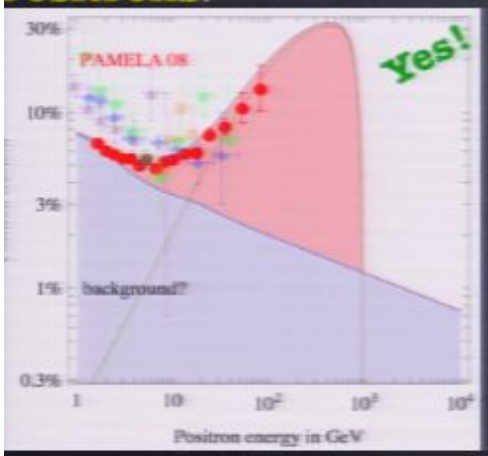
Results

Which DM spectra can fit the data?

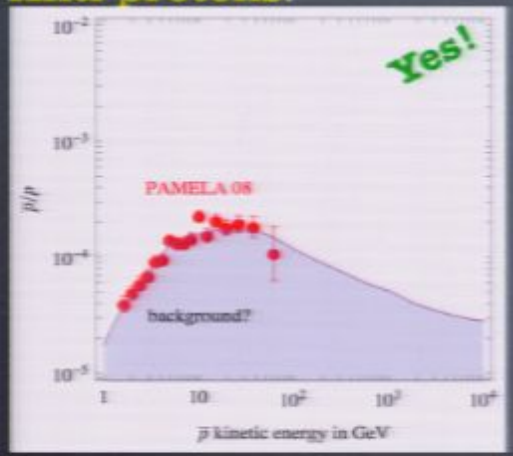
A DM with: -mass $M_{\rm DM} = 1\,{\rm TeV}$

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

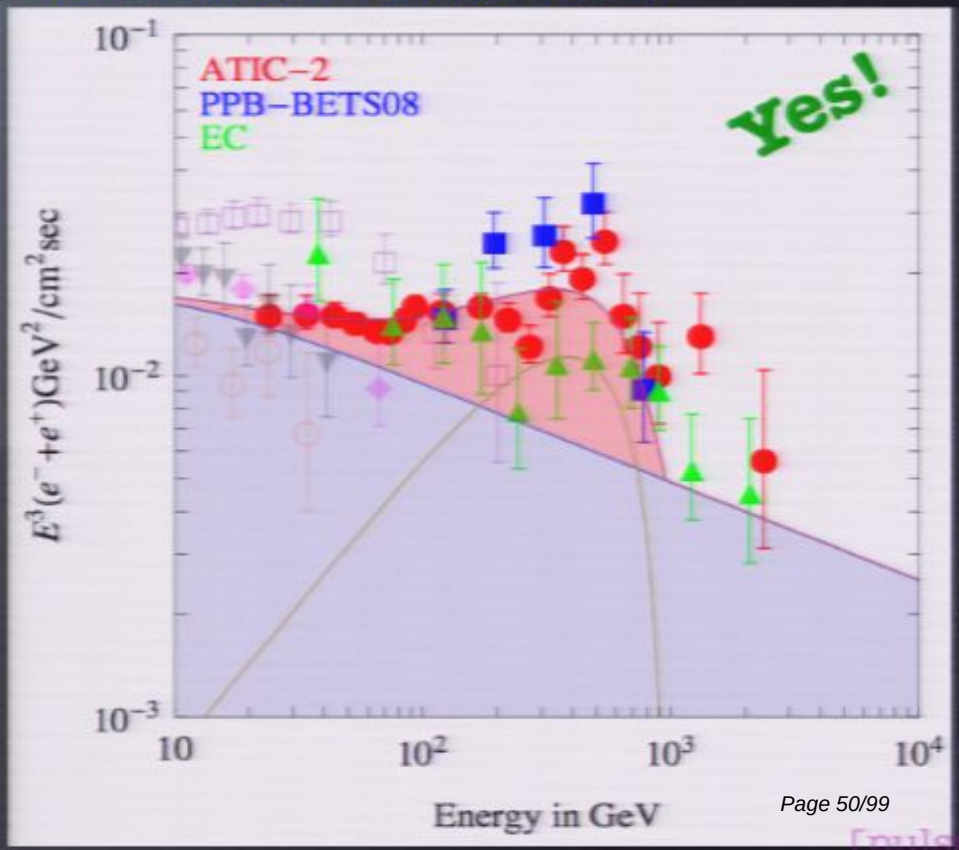
Positrons:



Anti-protons:



Electrons + Positrons:



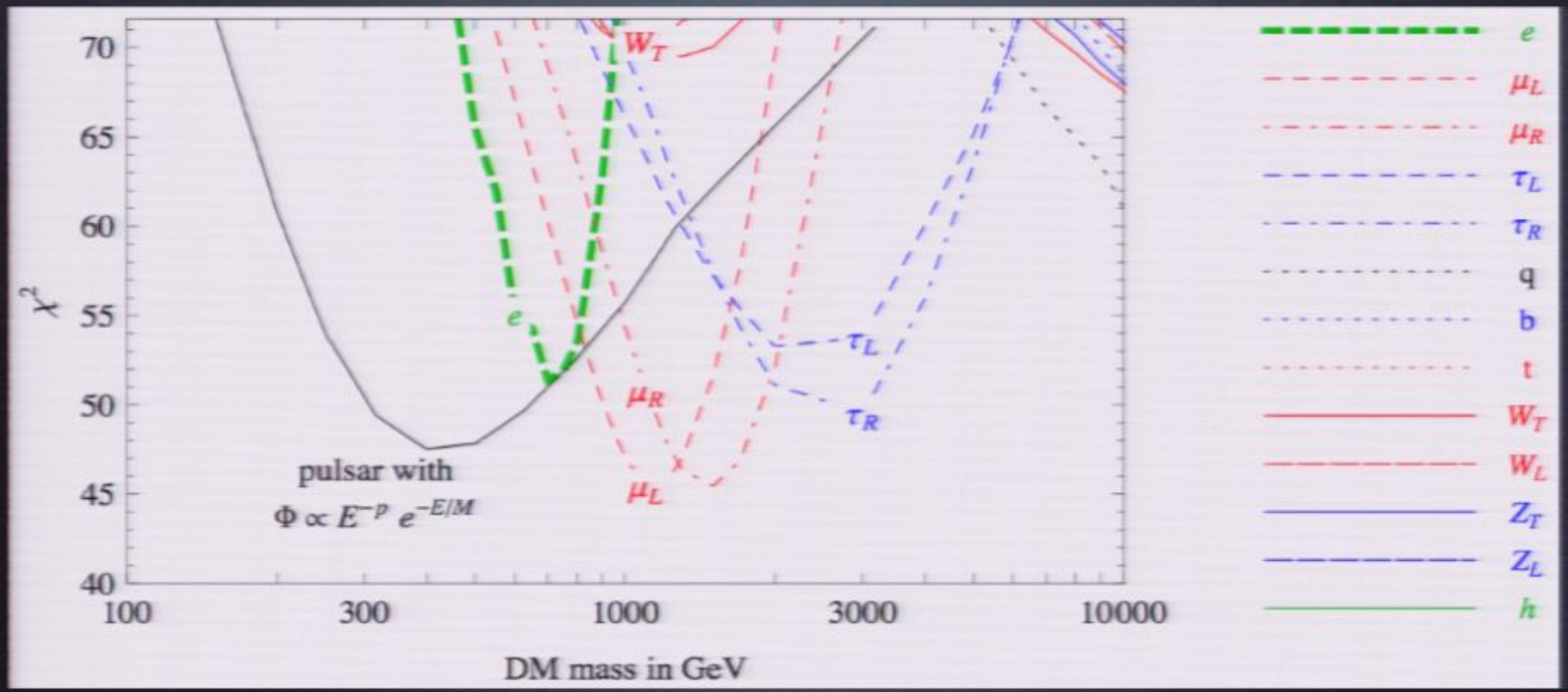
Have we identified the DM for the first time???

Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons* + balloon experiments



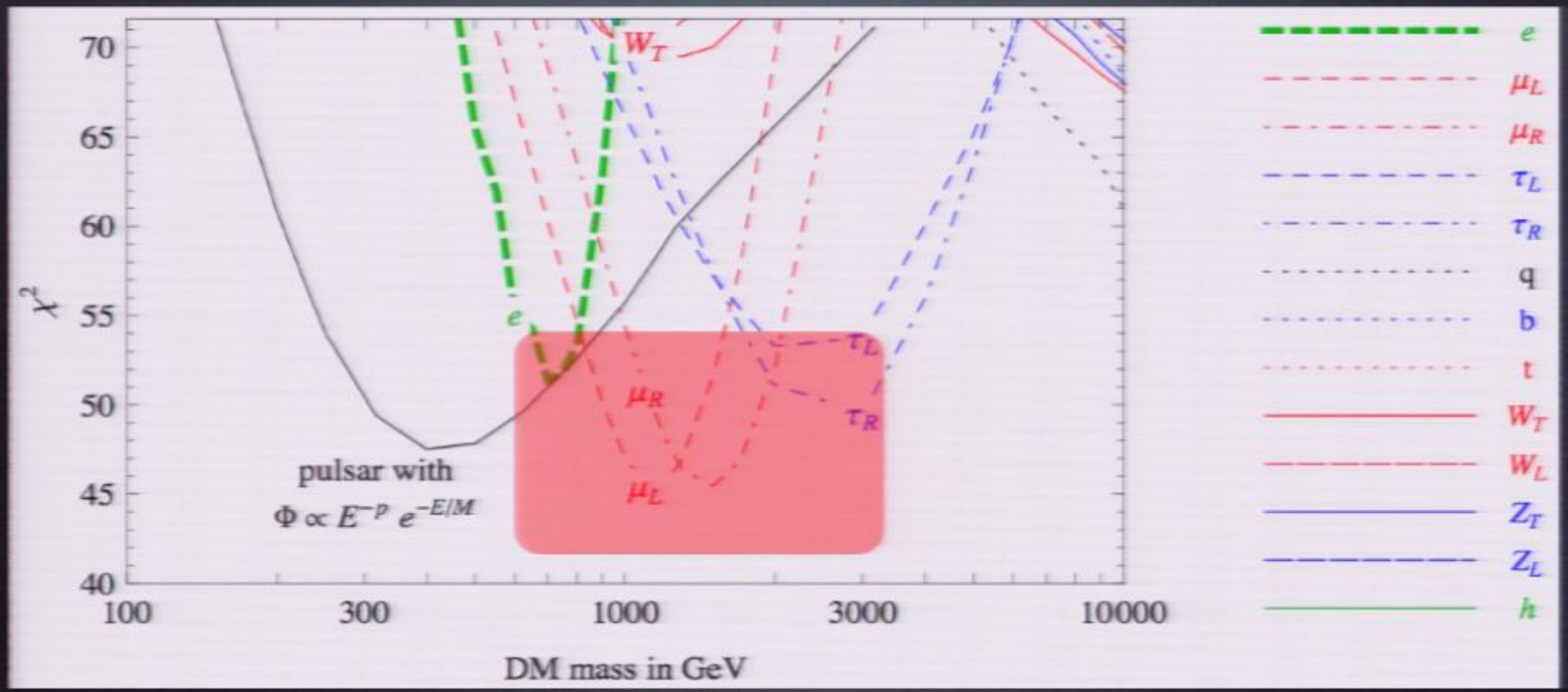
*adding anti-protons does not change much, non-leptonic channels give too smooth spectrum for balloons

Results

Which DM spectra can fit the data?

Model-independent results:

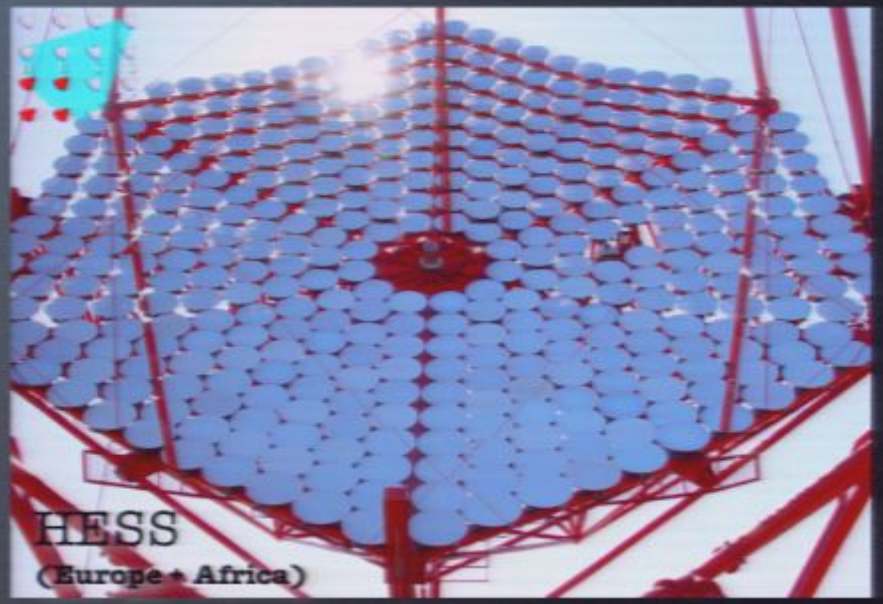
fit to PAMELA positrons* + balloon experiments



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

Data sets

Electrons + positrons from FERMI and HESS:

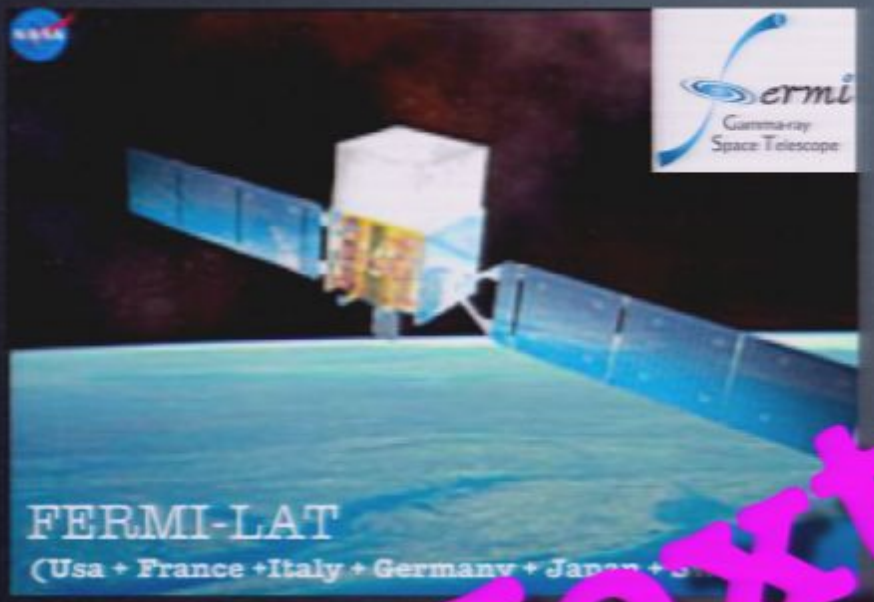


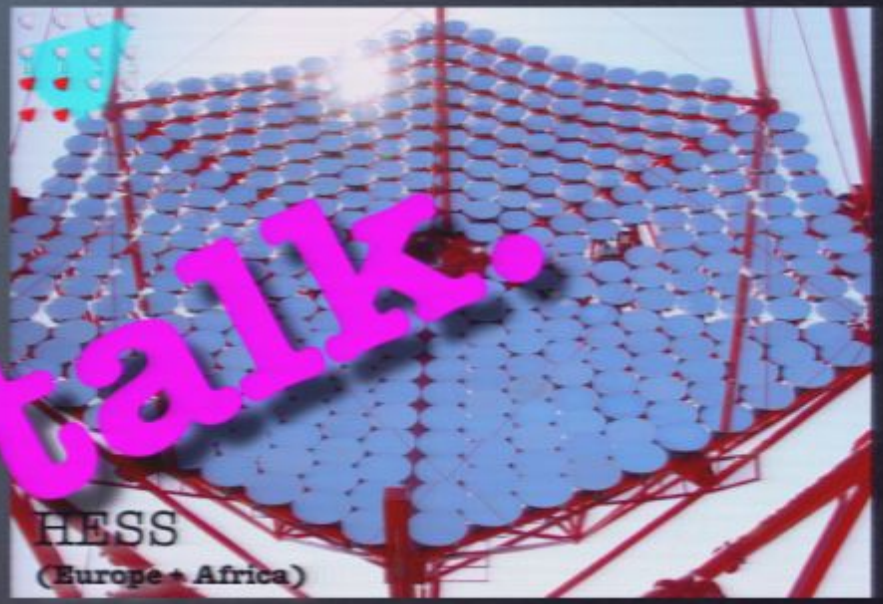
"Designed as a high-sensitivity gamma-ray observatory, the FERMI Large Area Telescope is also an electron detector with a large acceptance"

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

Data sets

Electrons + positrons from FERMI and HESS:





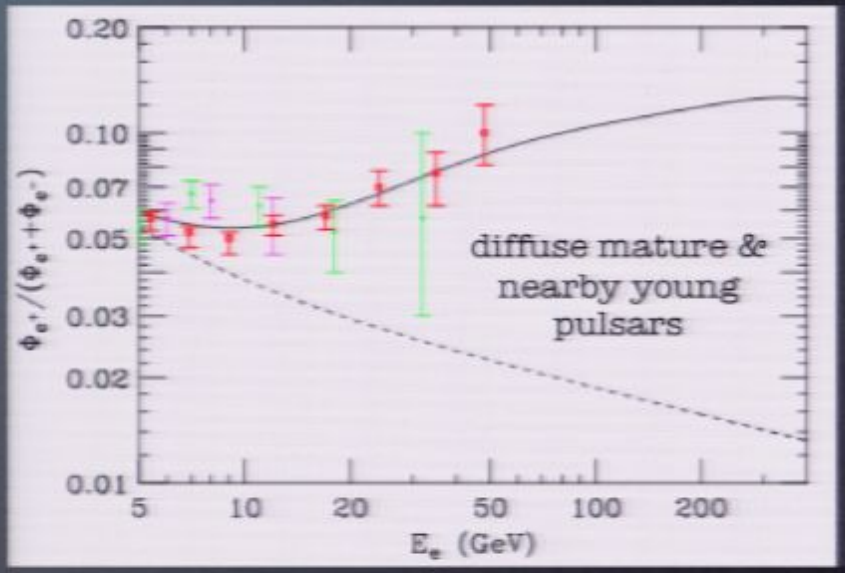
Next talk.

"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."

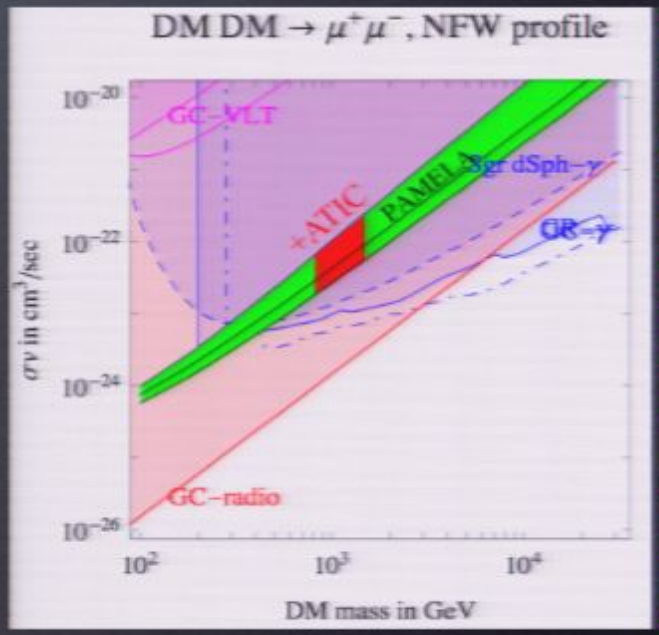
Two important remarks

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 and dwarf galaxies are severe



Bertone, Cirelli, Strumia, Taoso 0811.3744

[jump to conclusions]

DM detection

direct detection

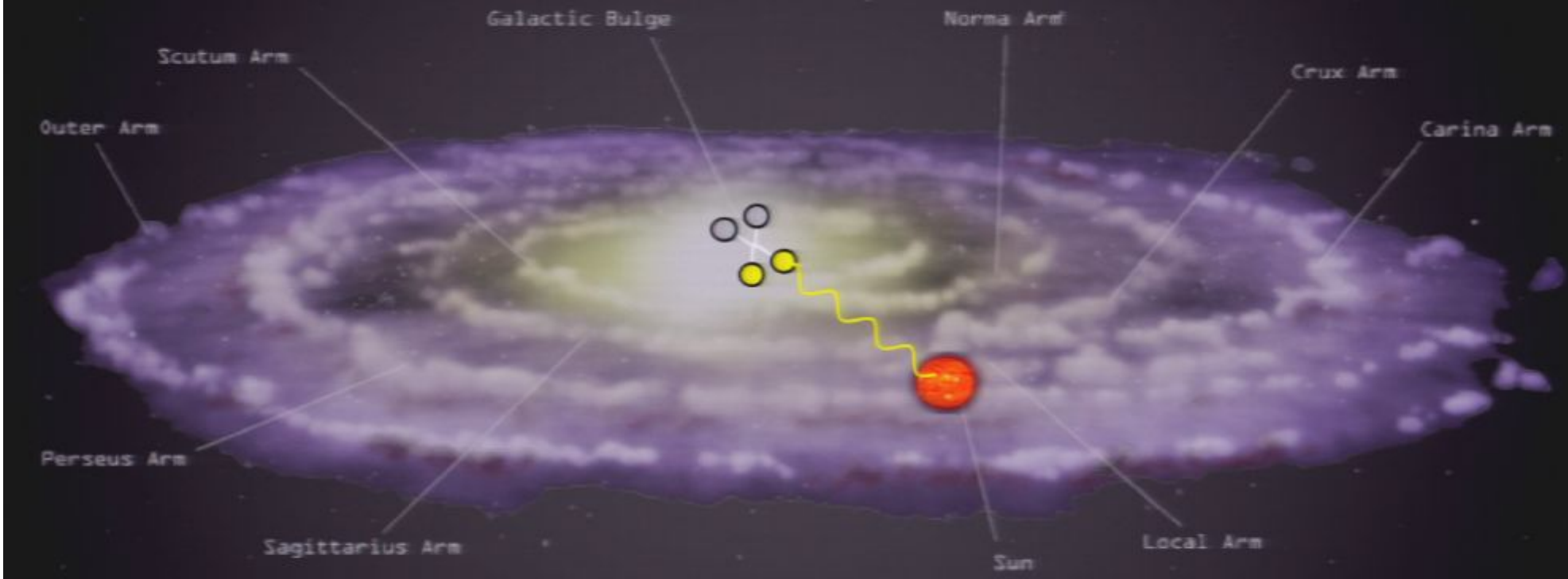
production at colliders

indirect

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

Indirect Detection

γ from DM annihilations in galactic center

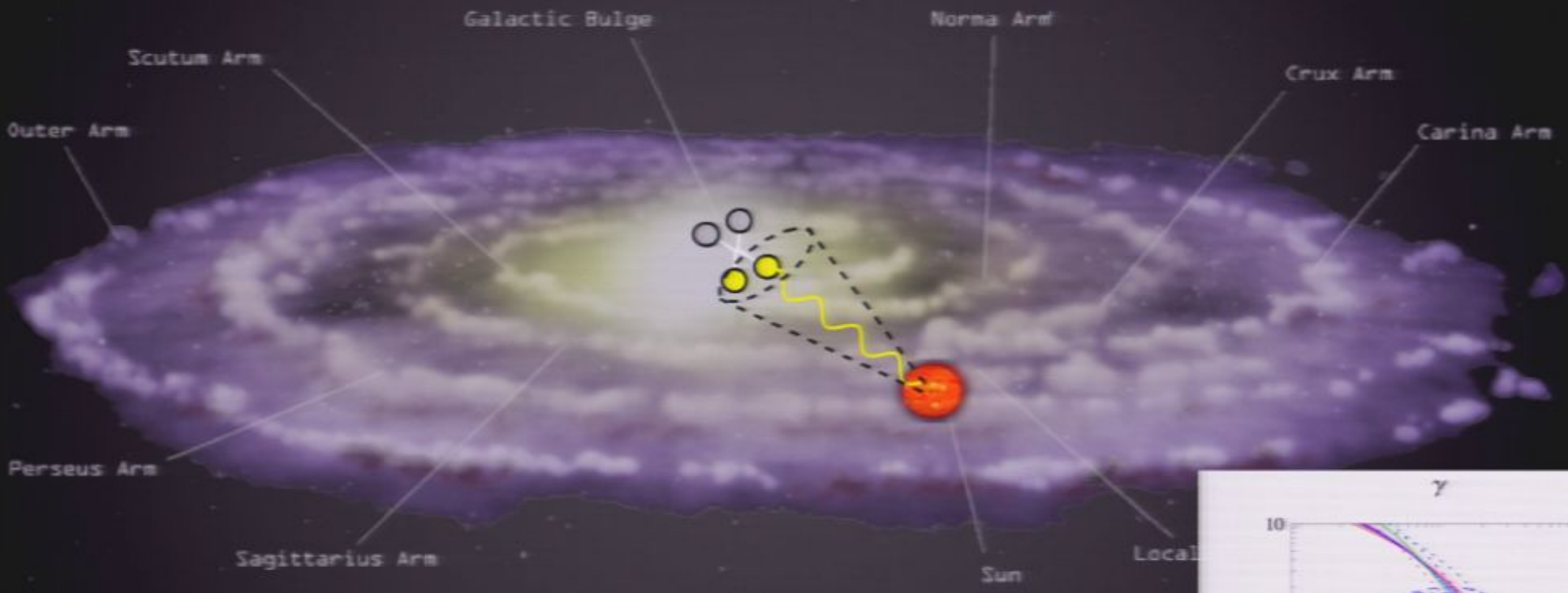


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

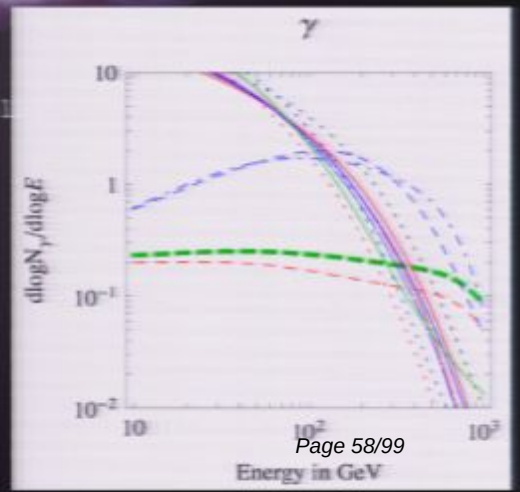
Indirect Detection

γ from DM annihilations in galactic center



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

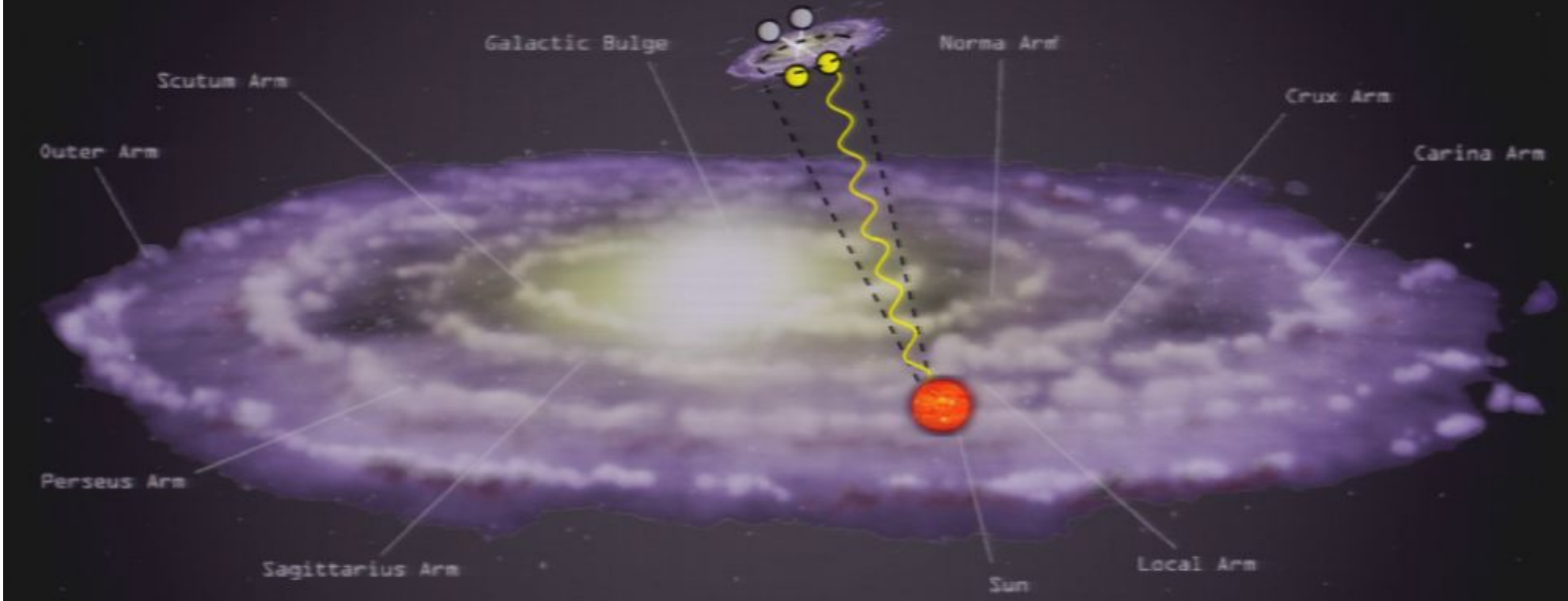
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

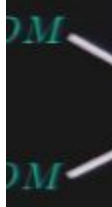


typically sub-TeV energies

Indirect Detection

γ from DM annihilations in Sagittarius Dwarf



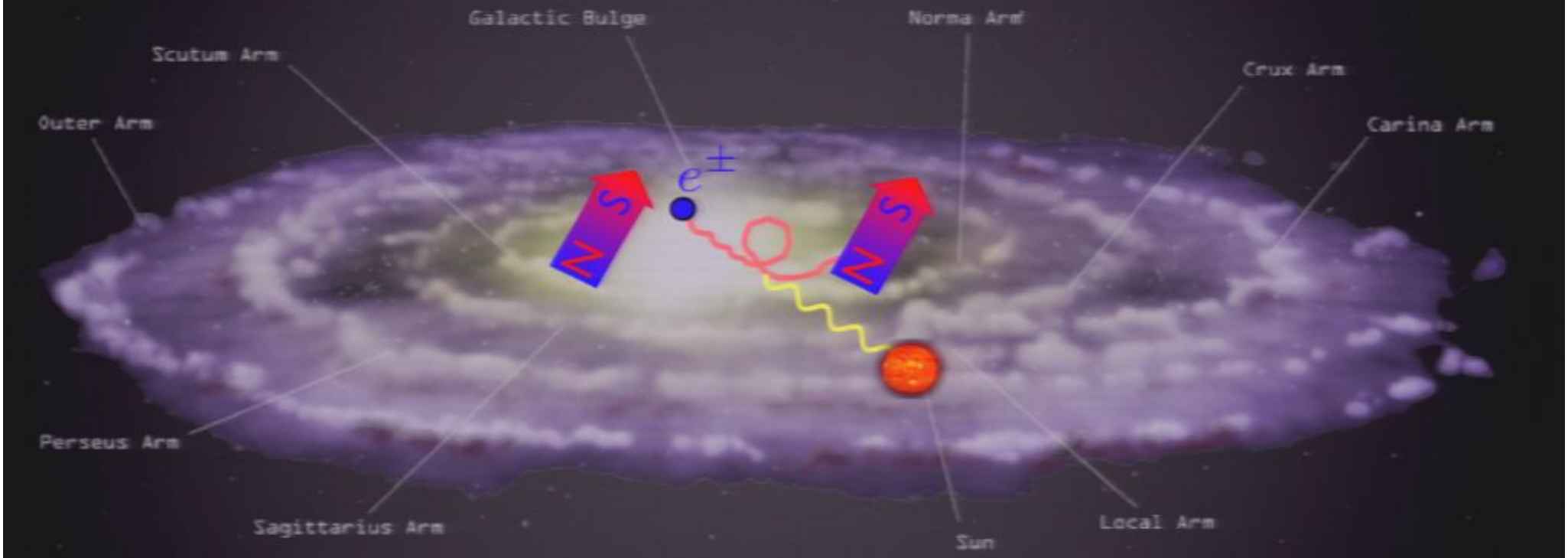


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

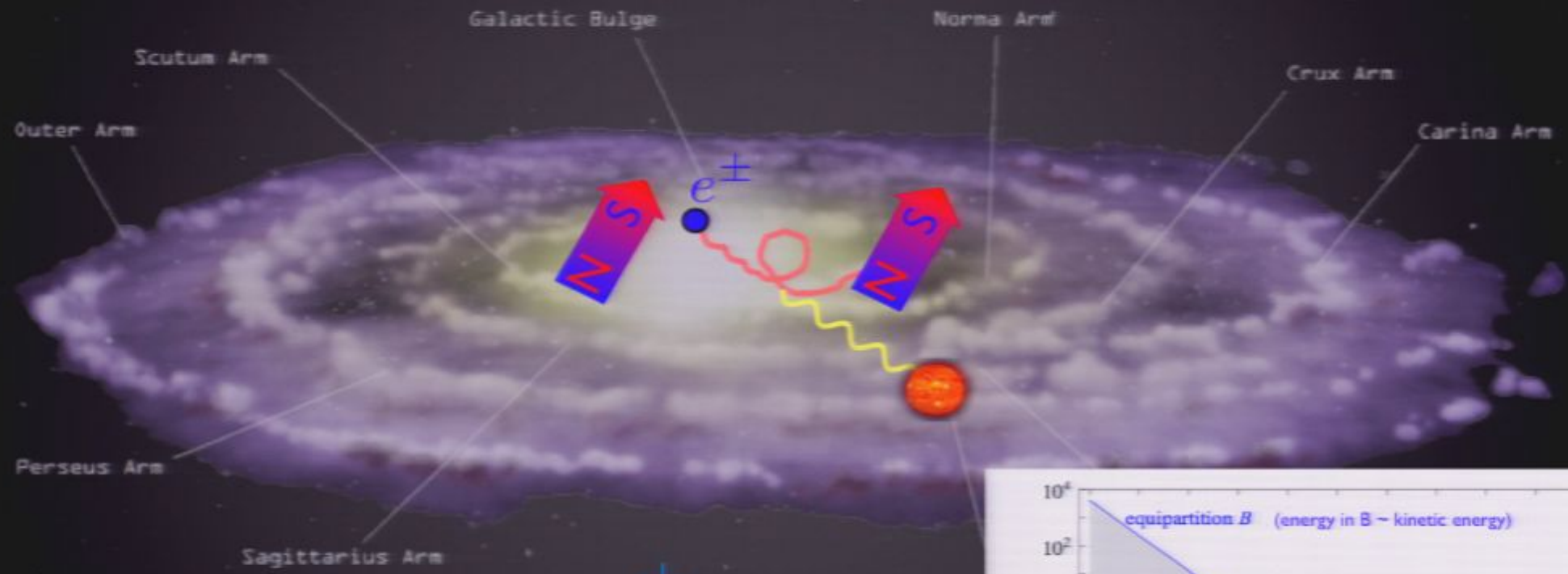
Indirect Detection

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



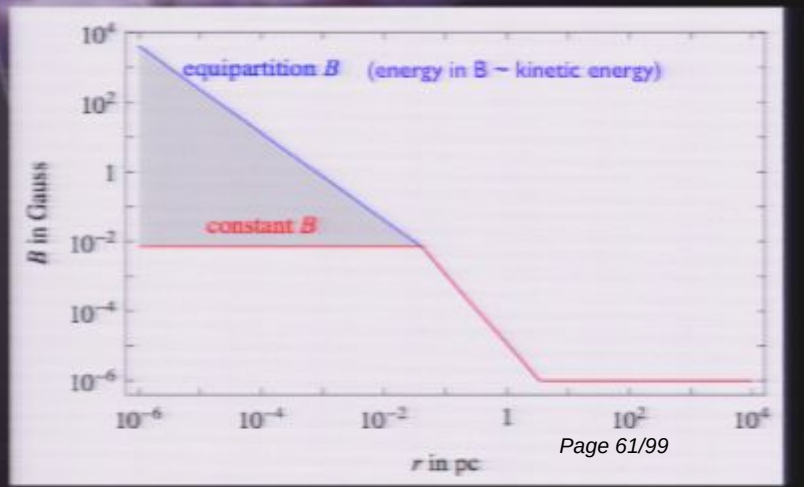
Indirect Detection

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



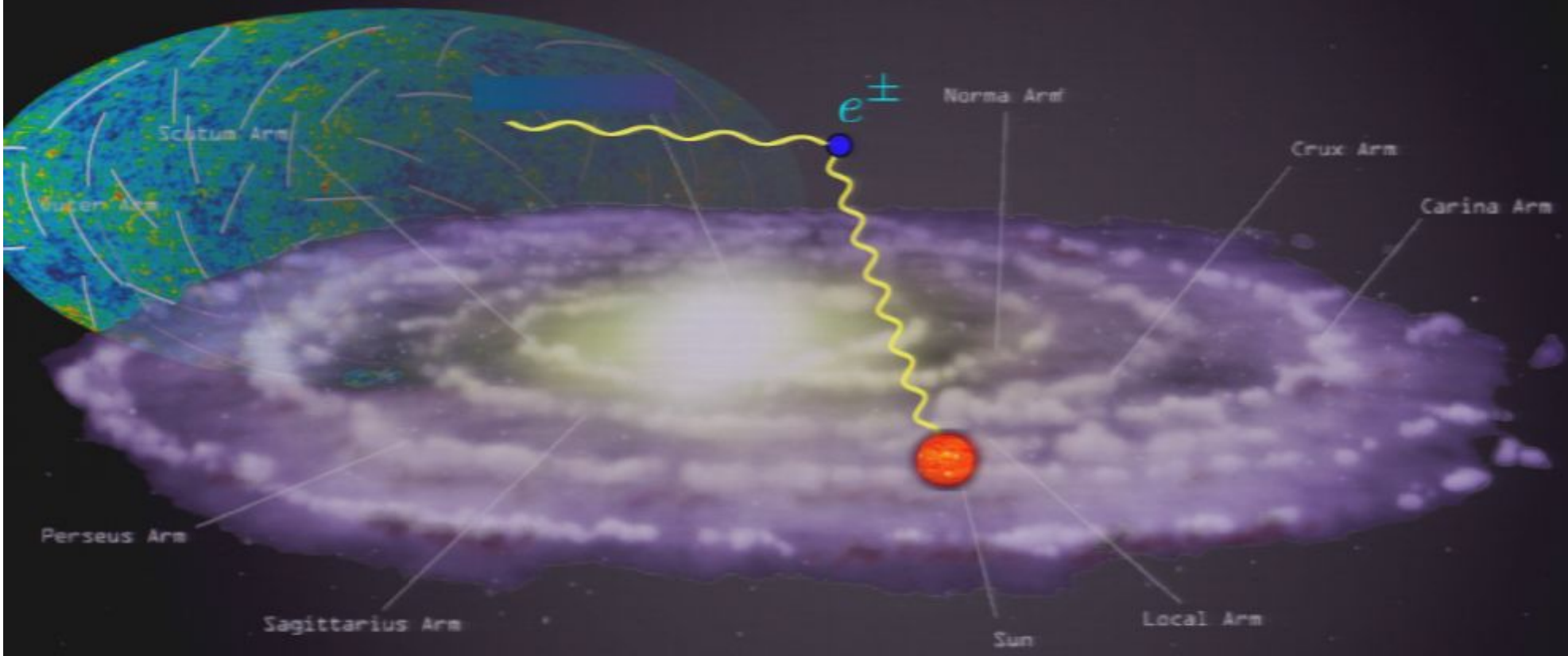
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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



Indirect Detection

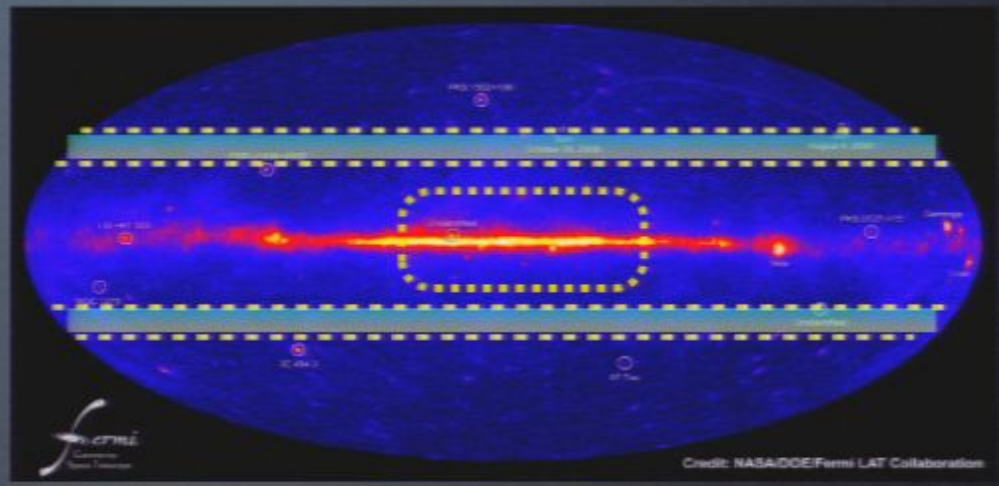
γ from Inverse Compton on $e^{\pm}$ in halo



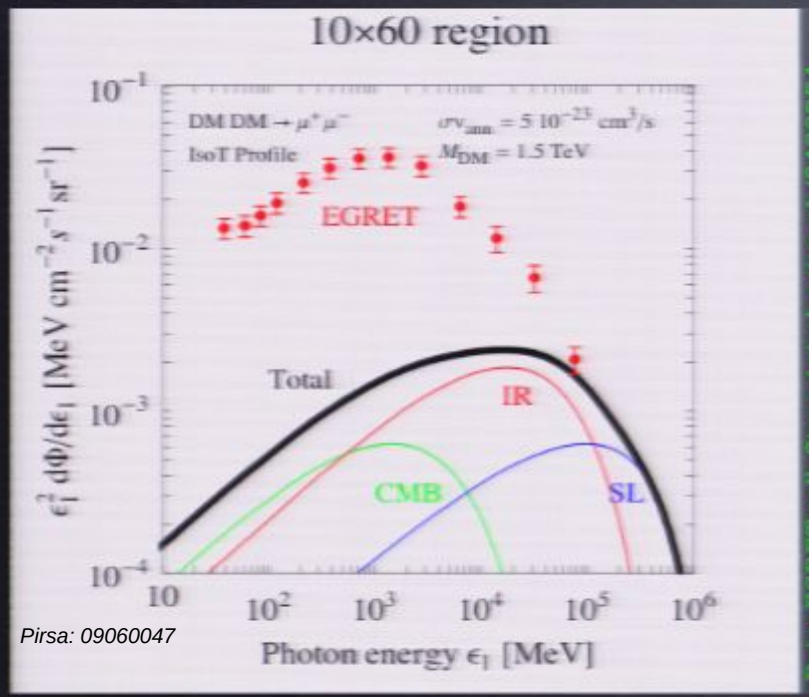
- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Gamma constraints

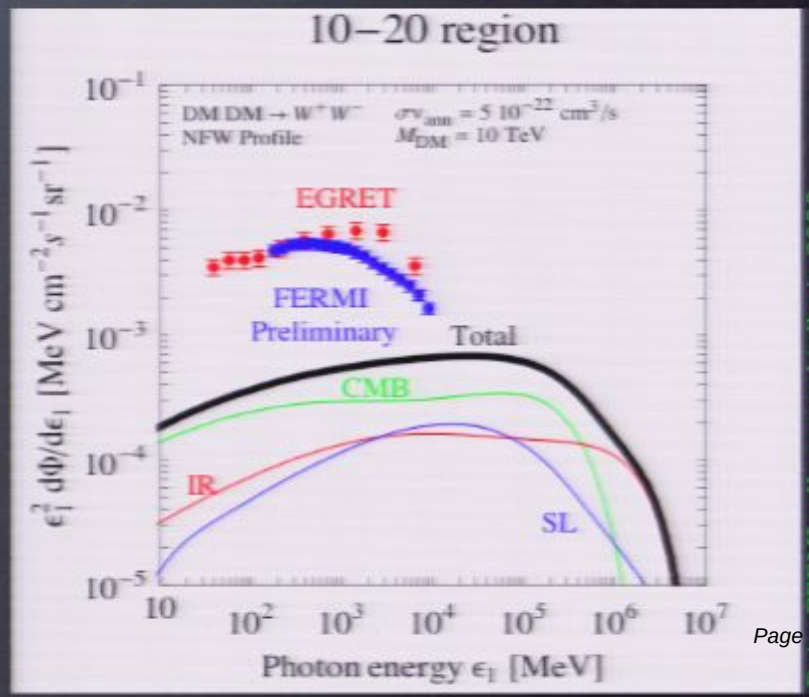
EGRET and FERMI have measured diffuse γ-ray emission. The DM signal must not excede that.



FERMI coll.



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



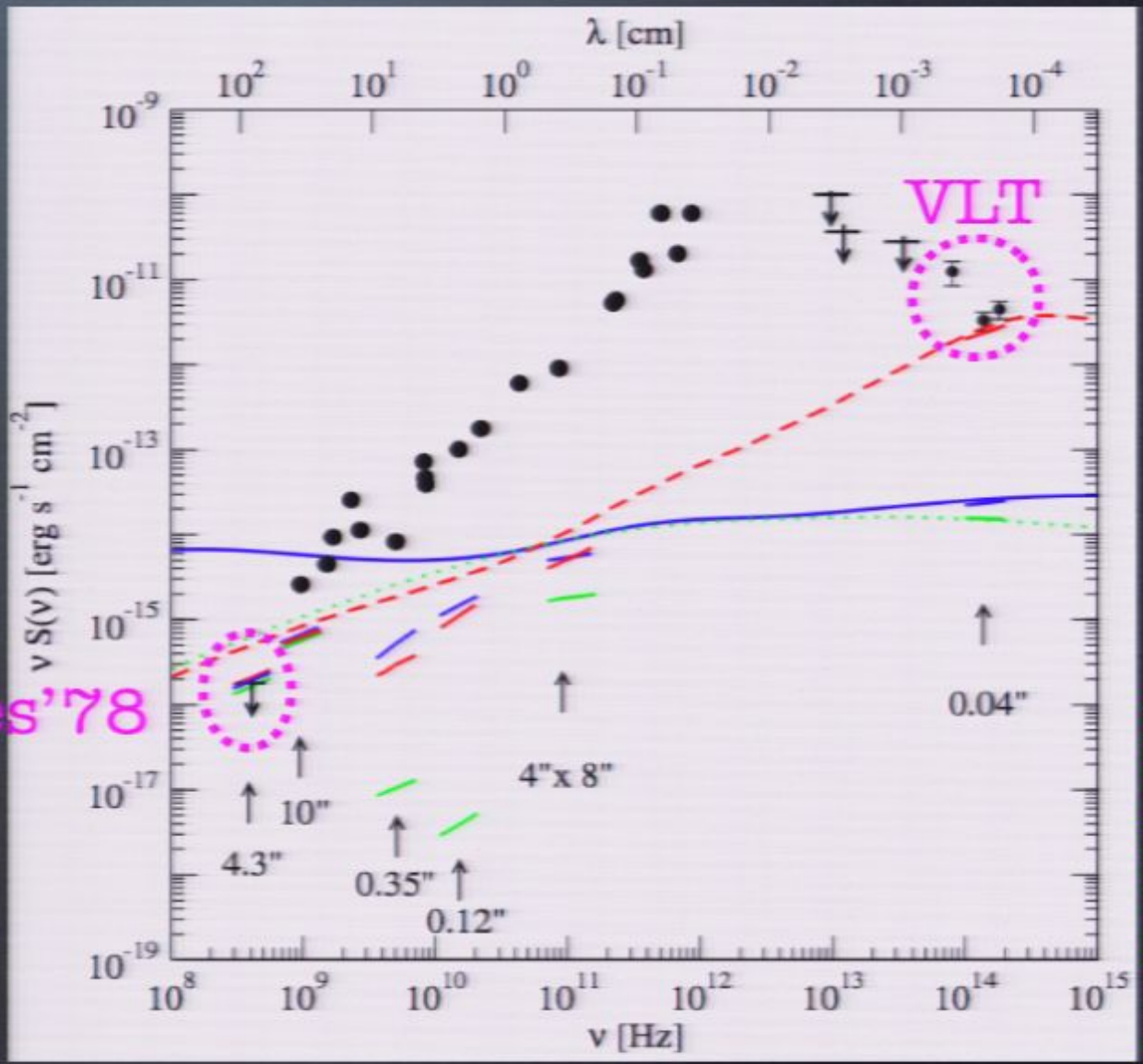
Data: FERMI coll., several talks in 2009

Gamma constraints

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.

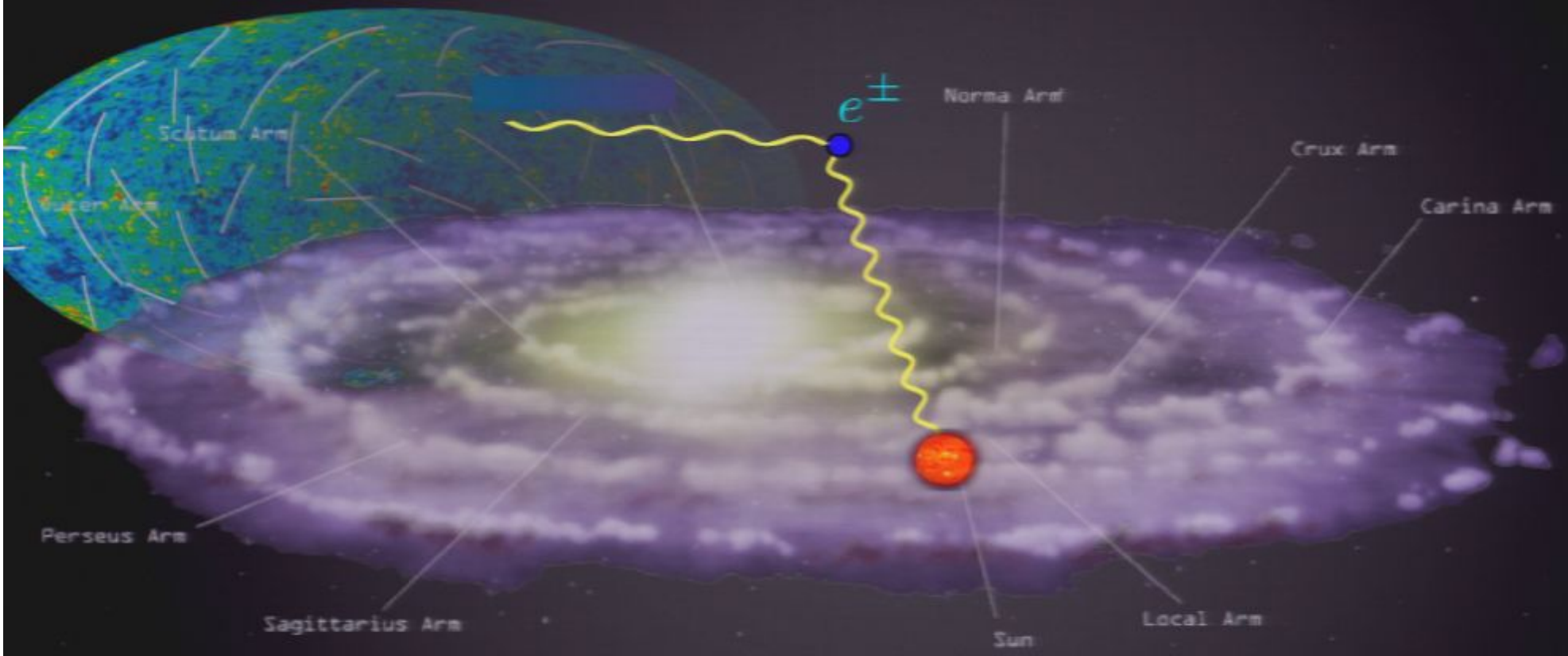
VLT 2003 emission at 10^{14} Hz.



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

Indirect Detection

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

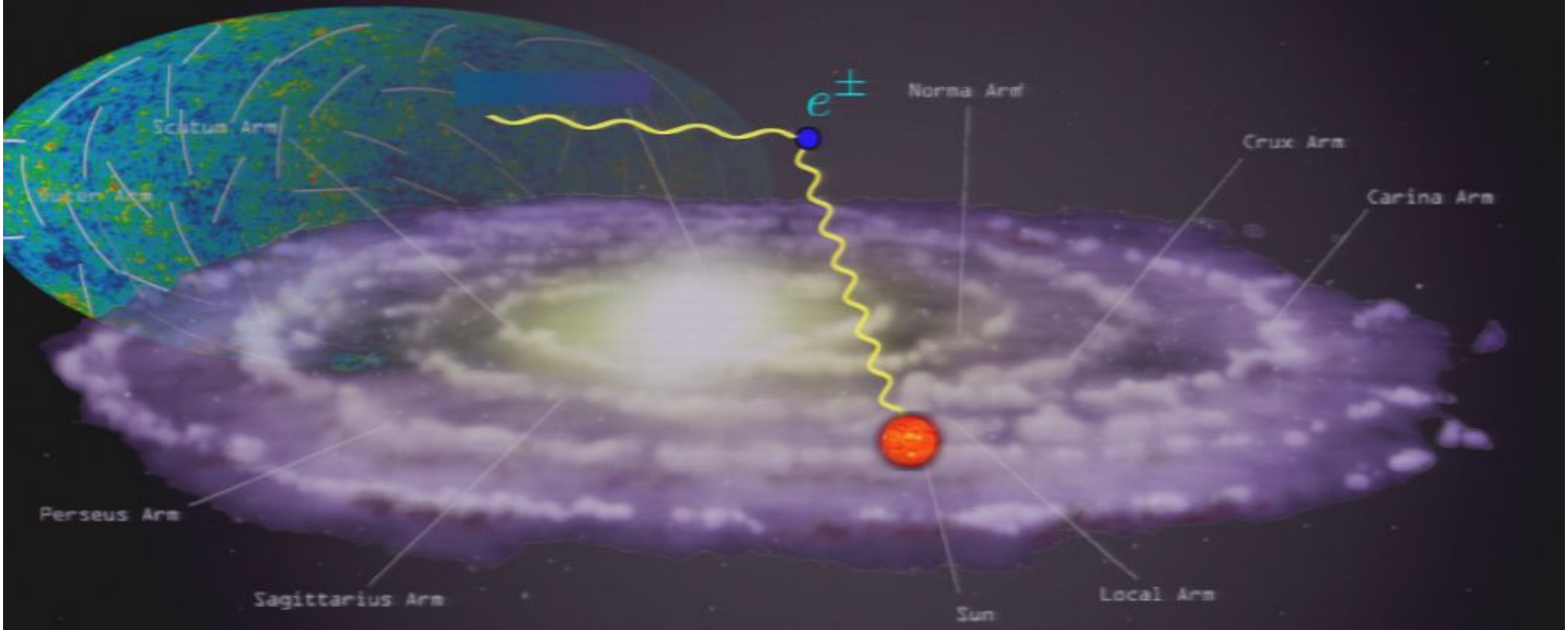


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Comparing with data

Indirect Detection

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

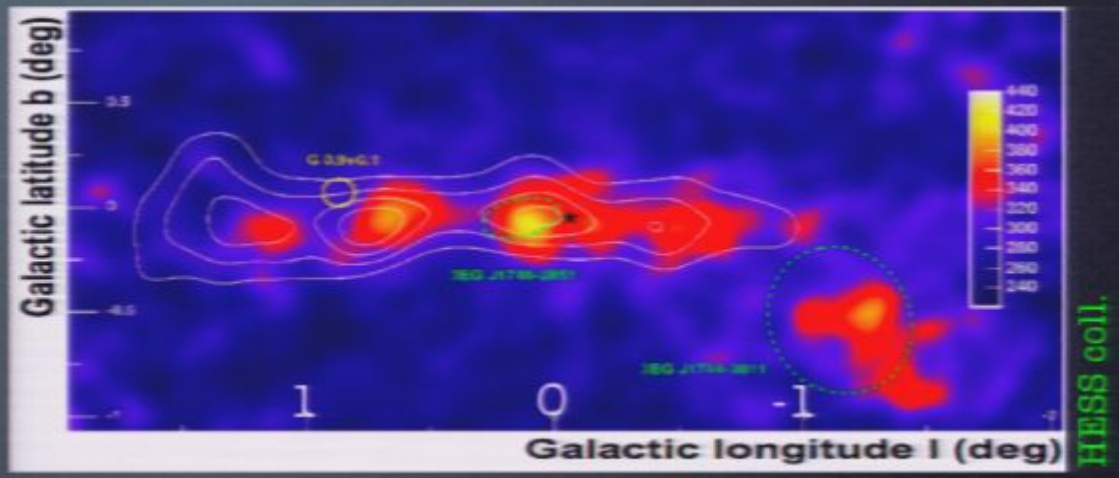


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Comparing with data

Gamma constraints

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



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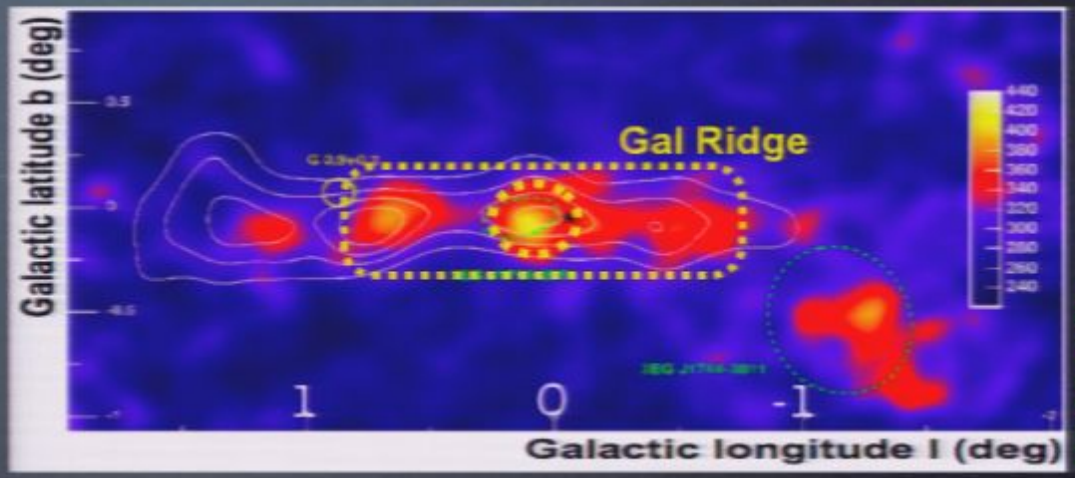

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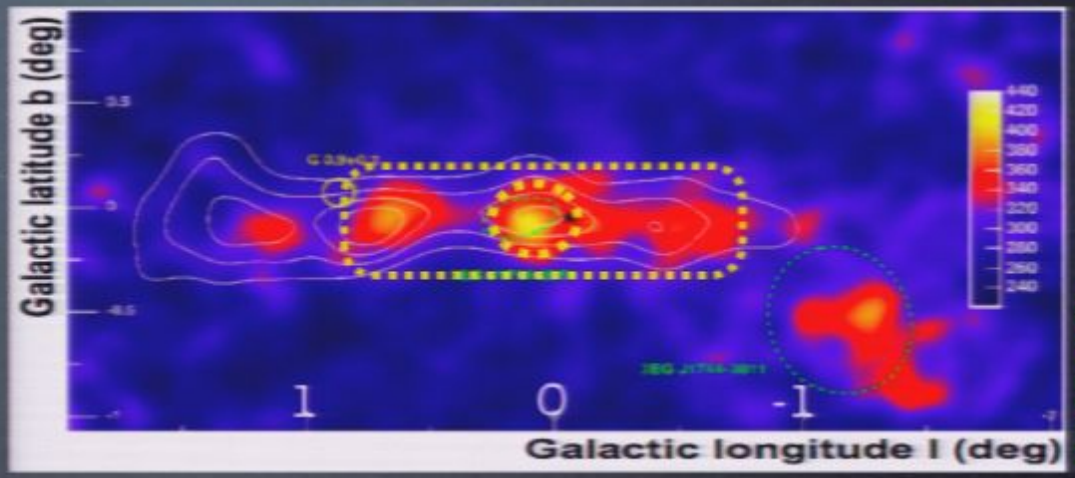
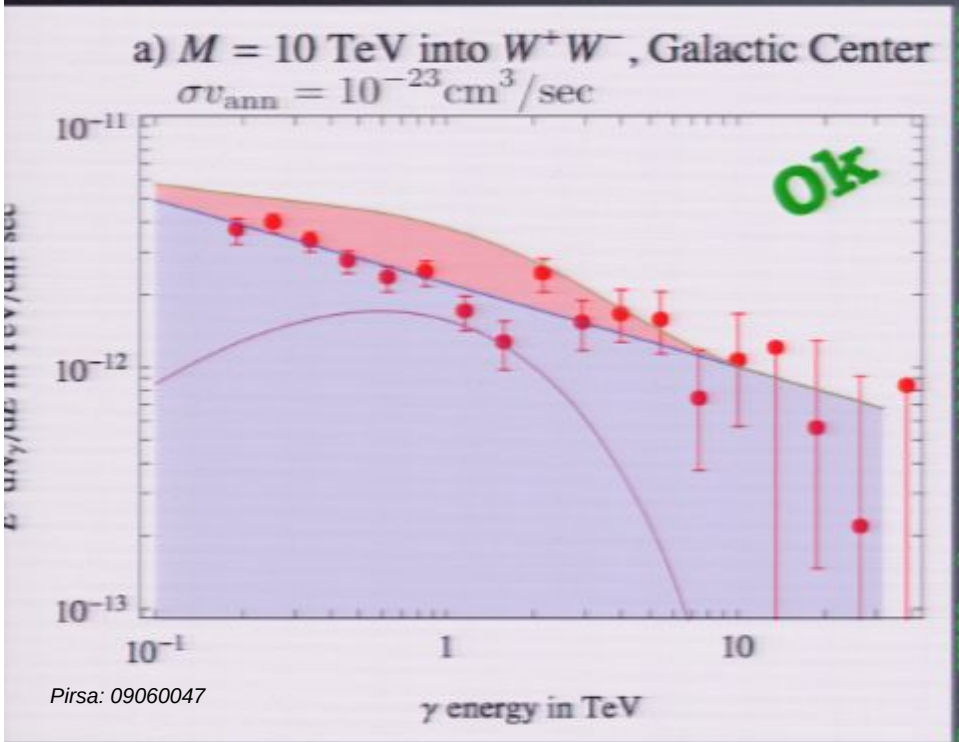


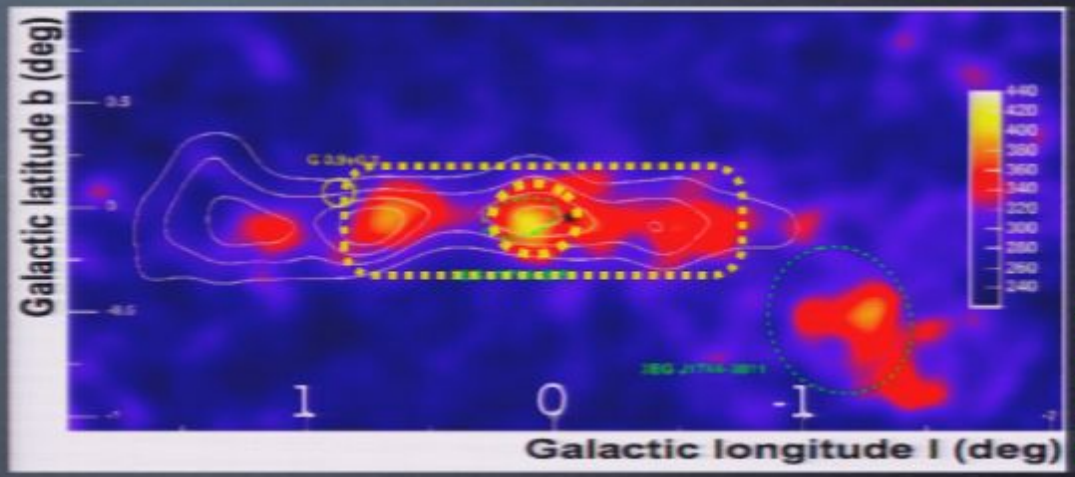
HESS coll.

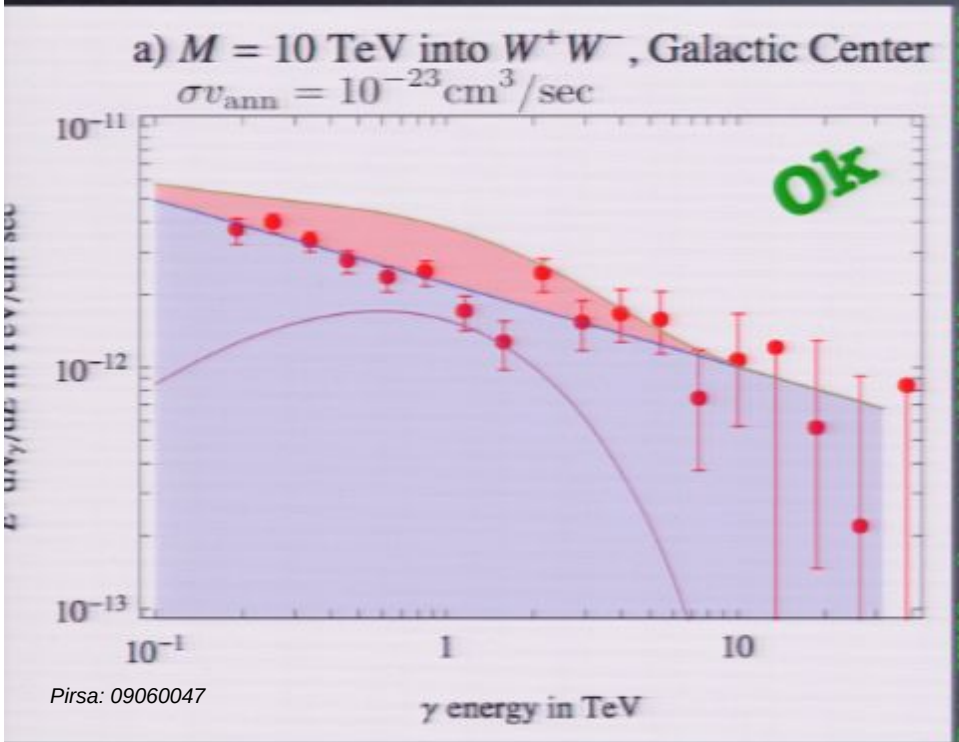


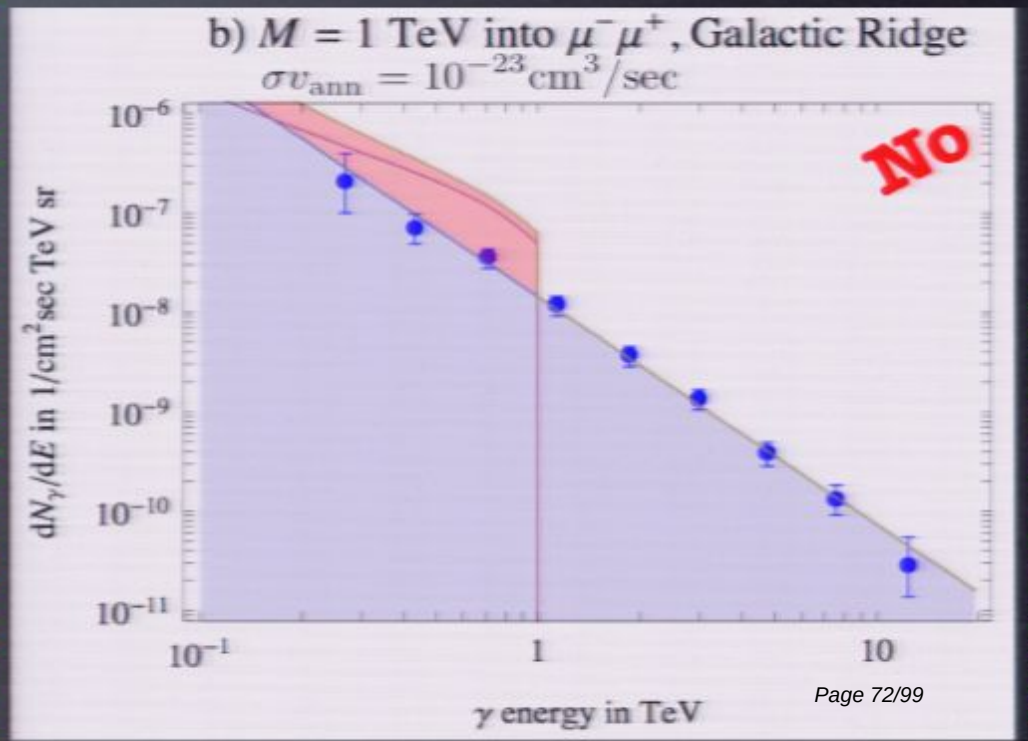
Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

Gamma constraints

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



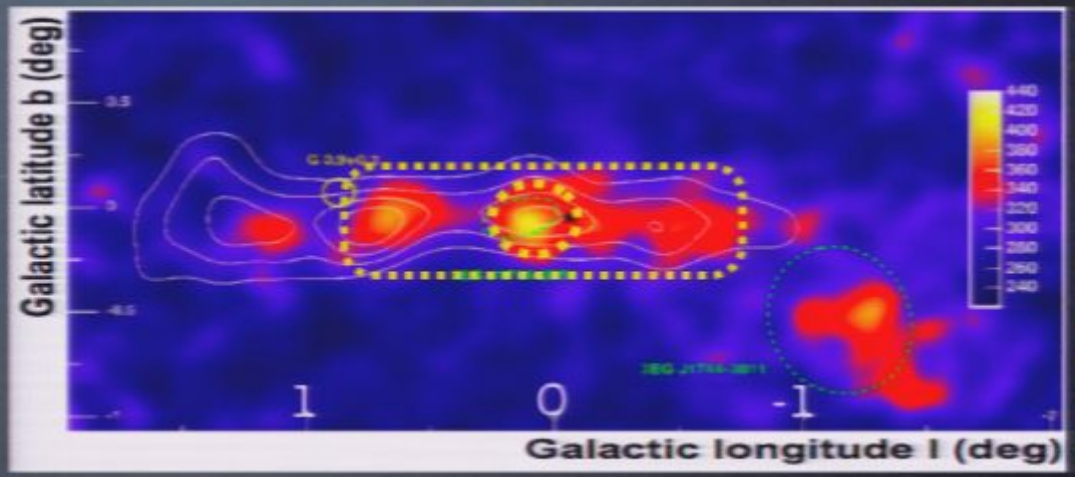


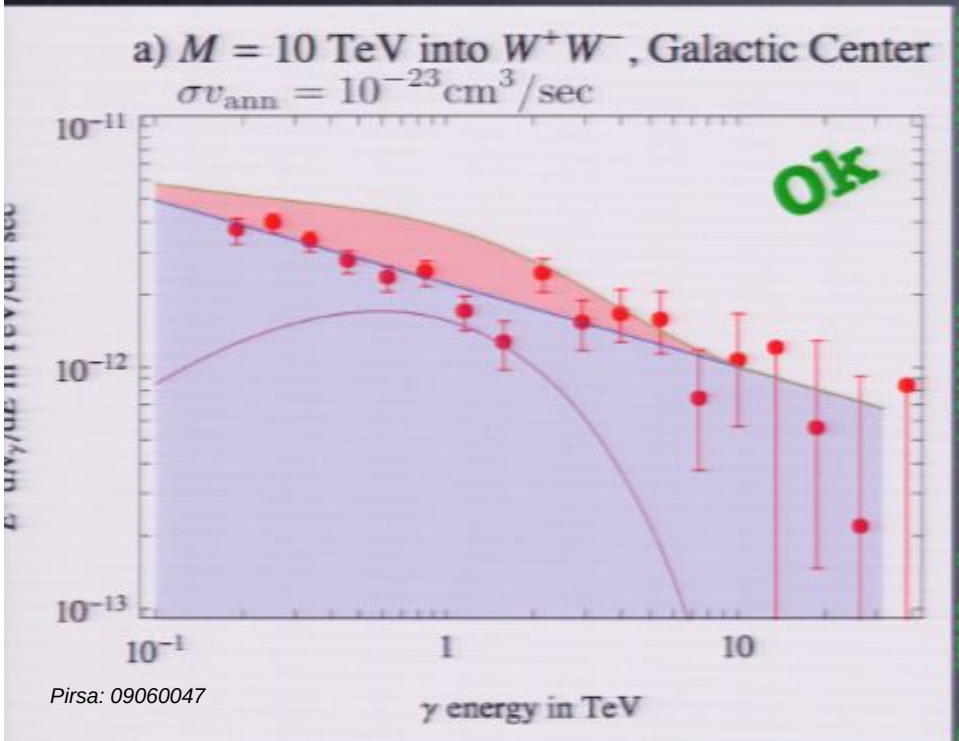


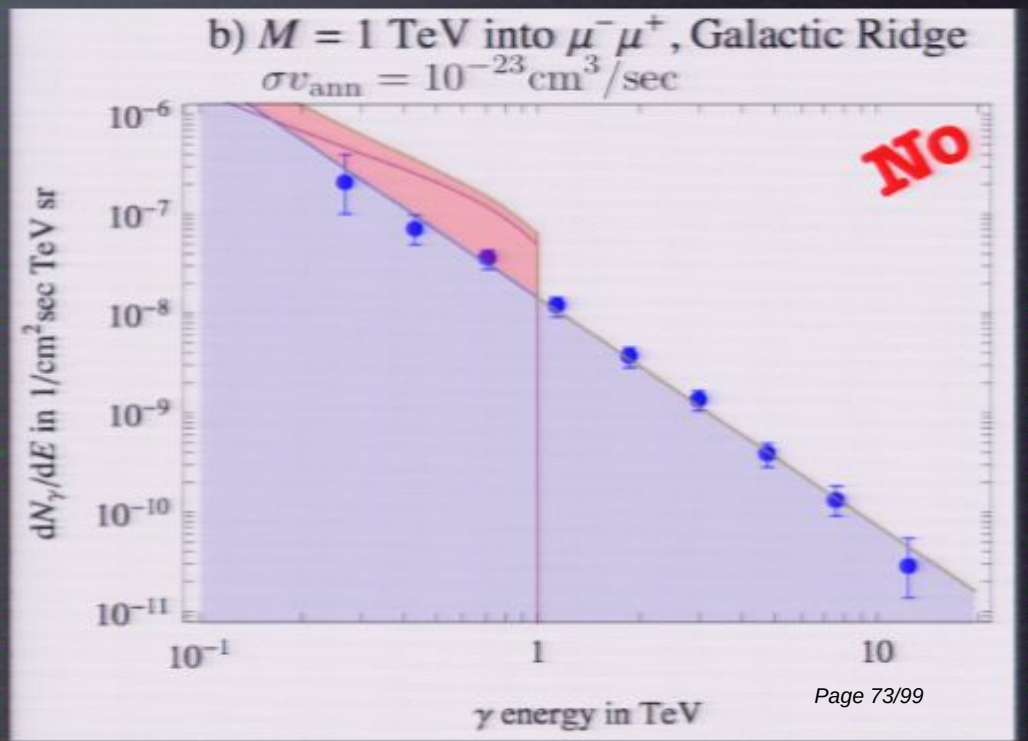
Gamma constraints

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.







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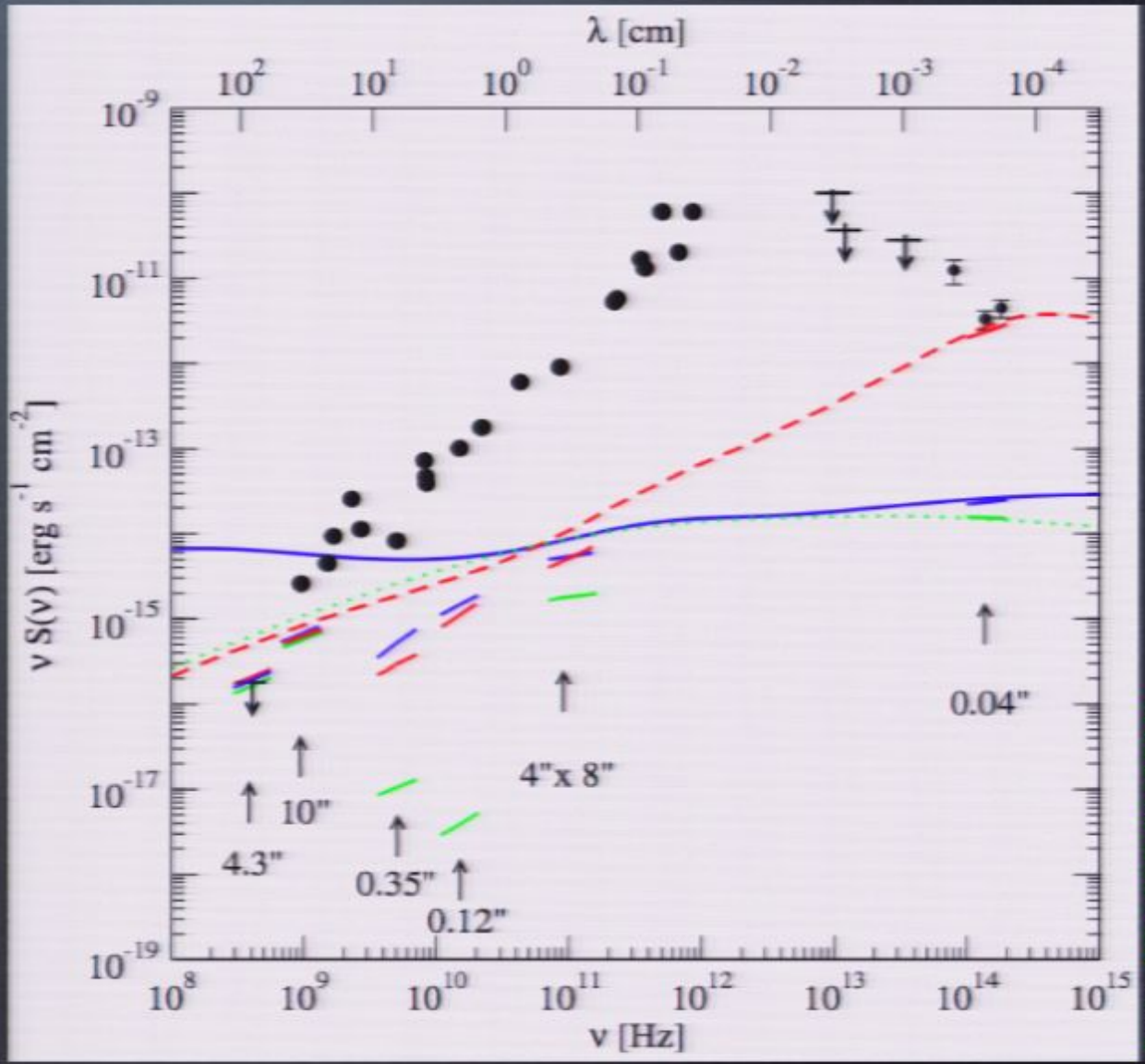

Regis, Ullio PRD 78 (2008)

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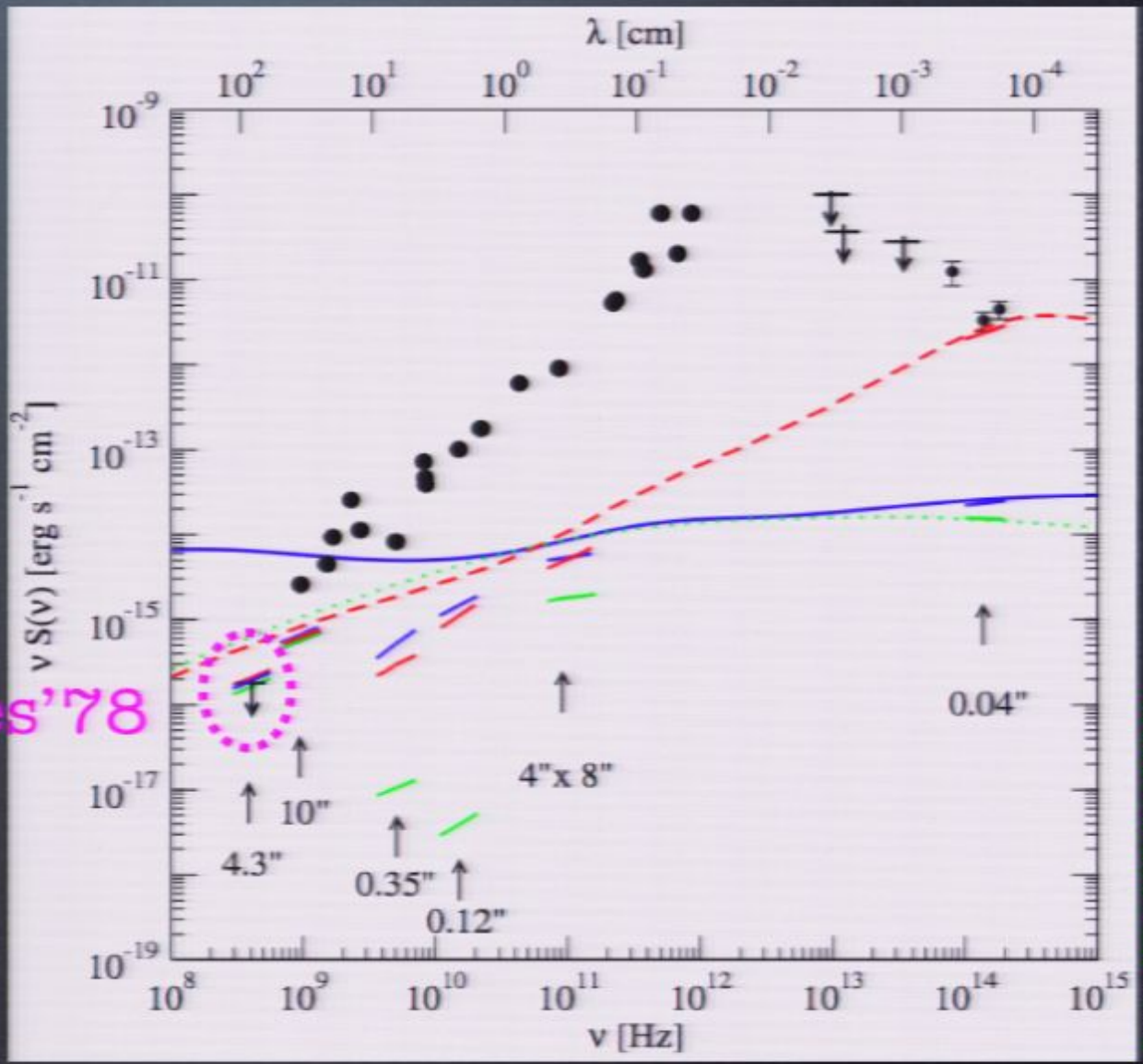

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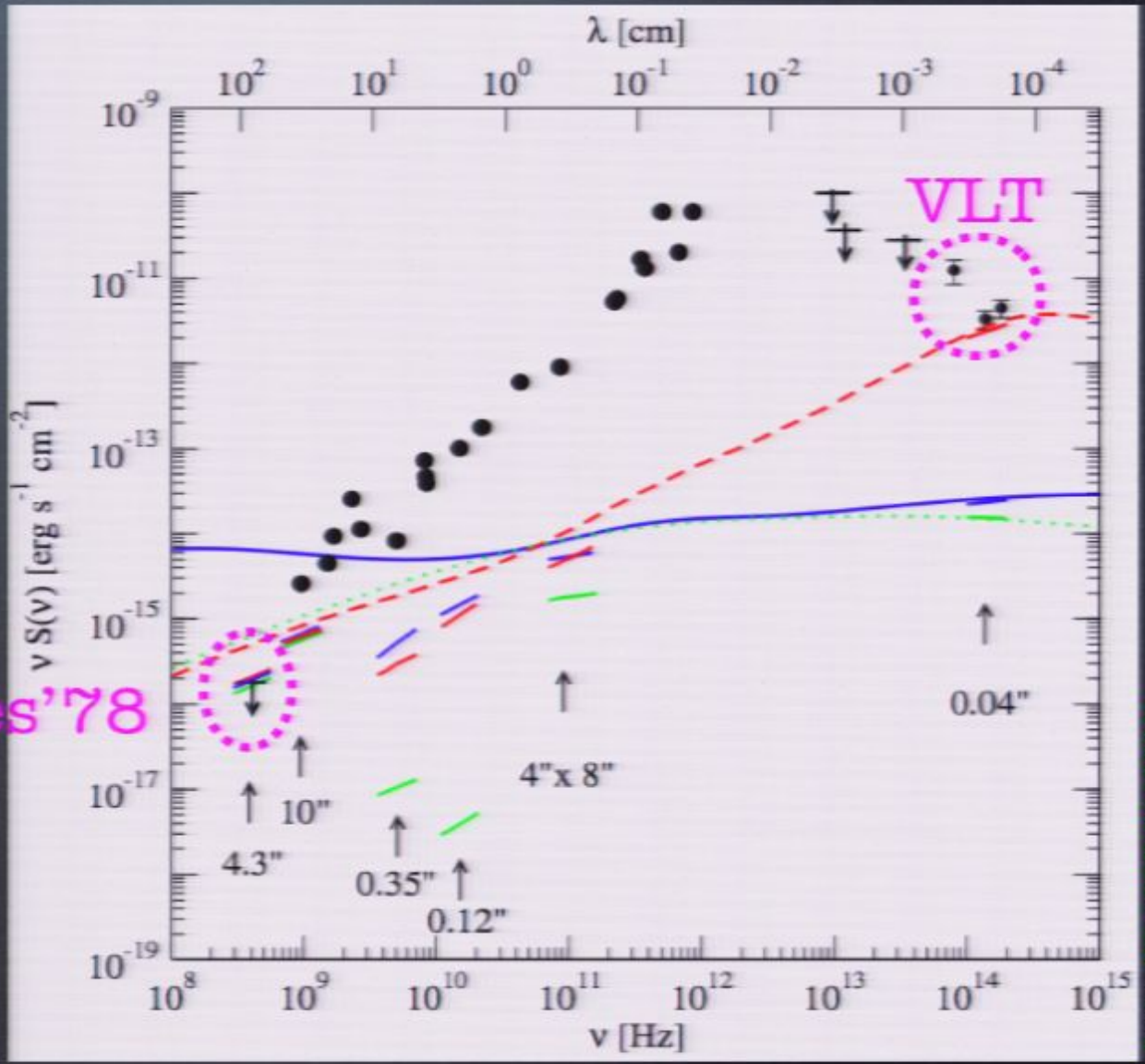

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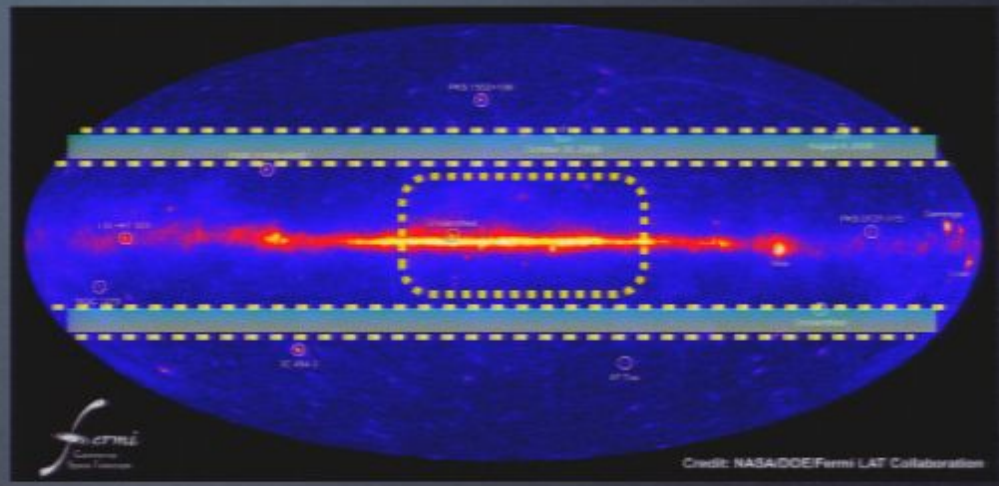
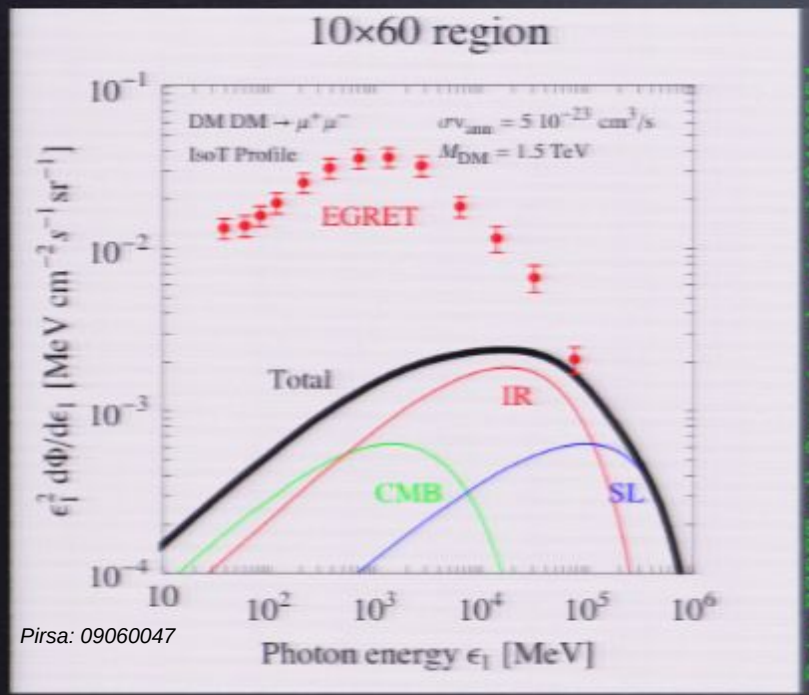
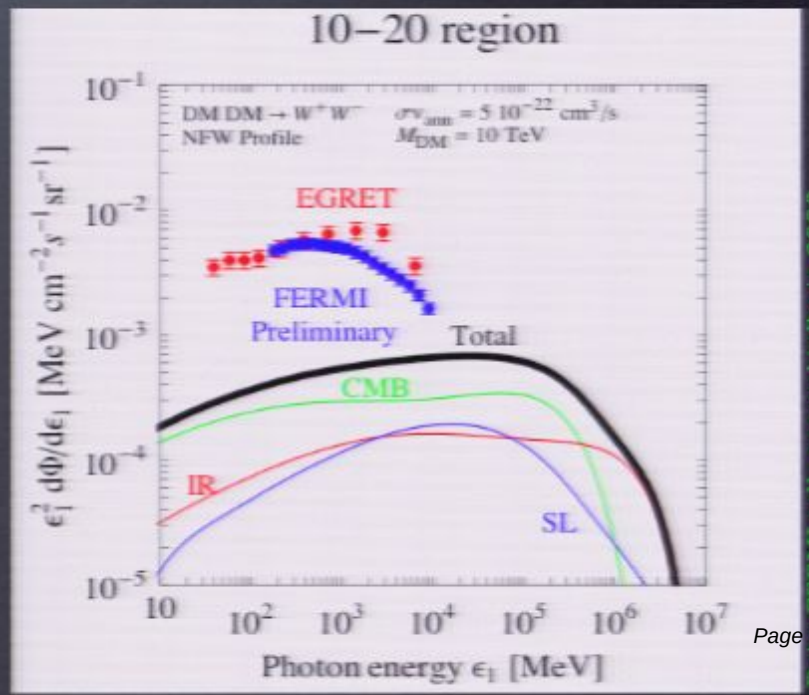


FERMI coll.

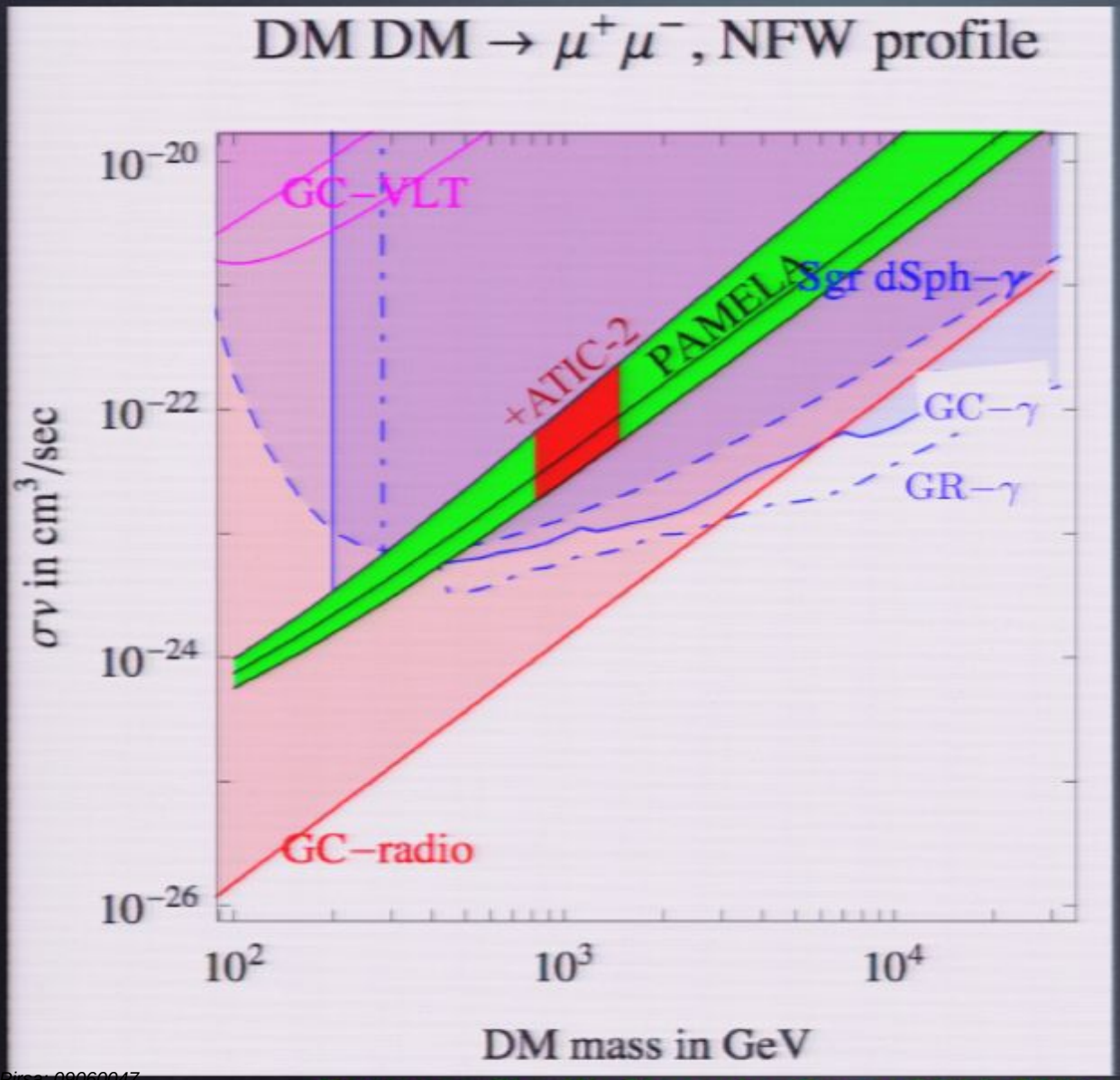


Data: EGRET coll.,Strong et al. astro-ph/0406254



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...

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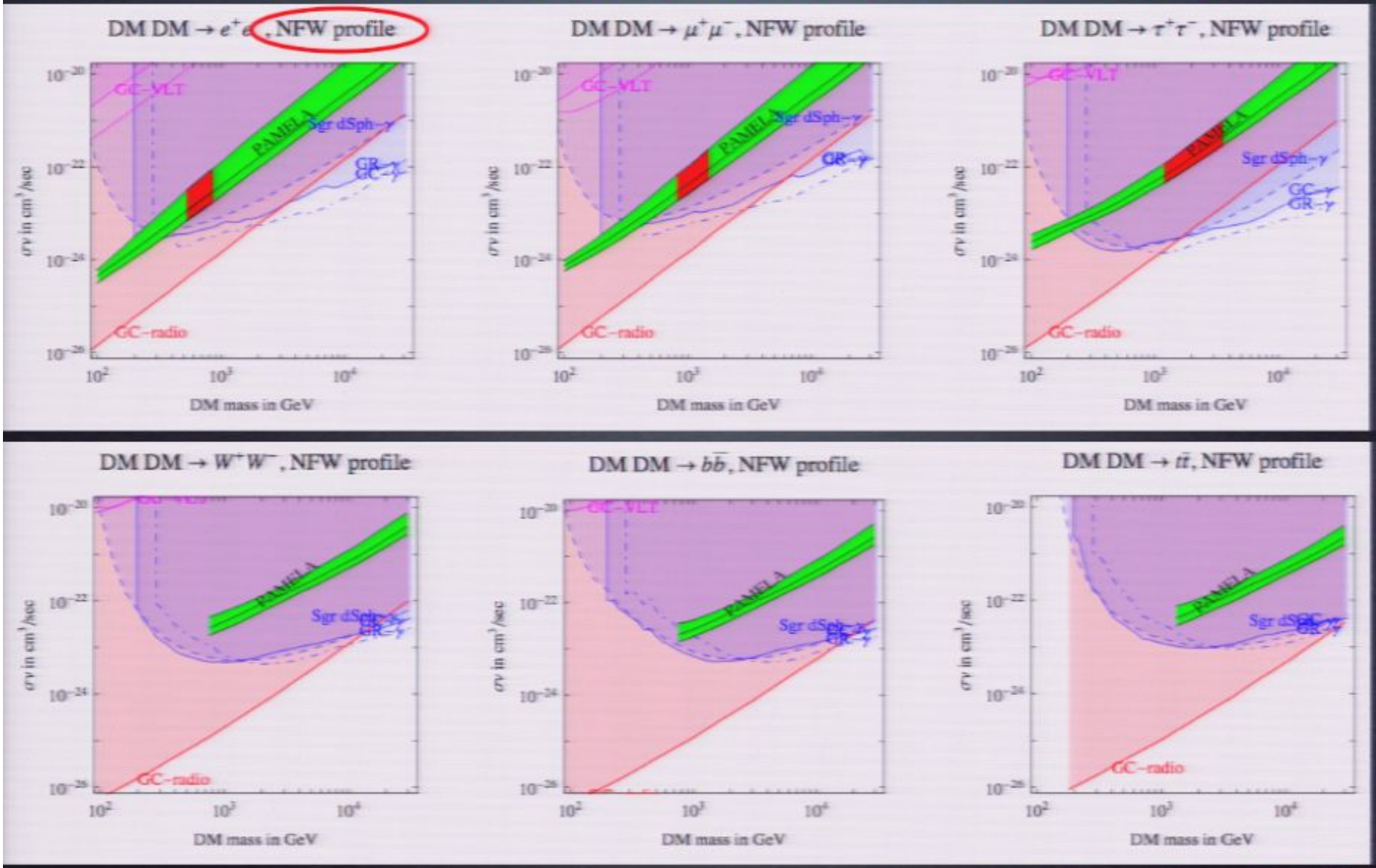

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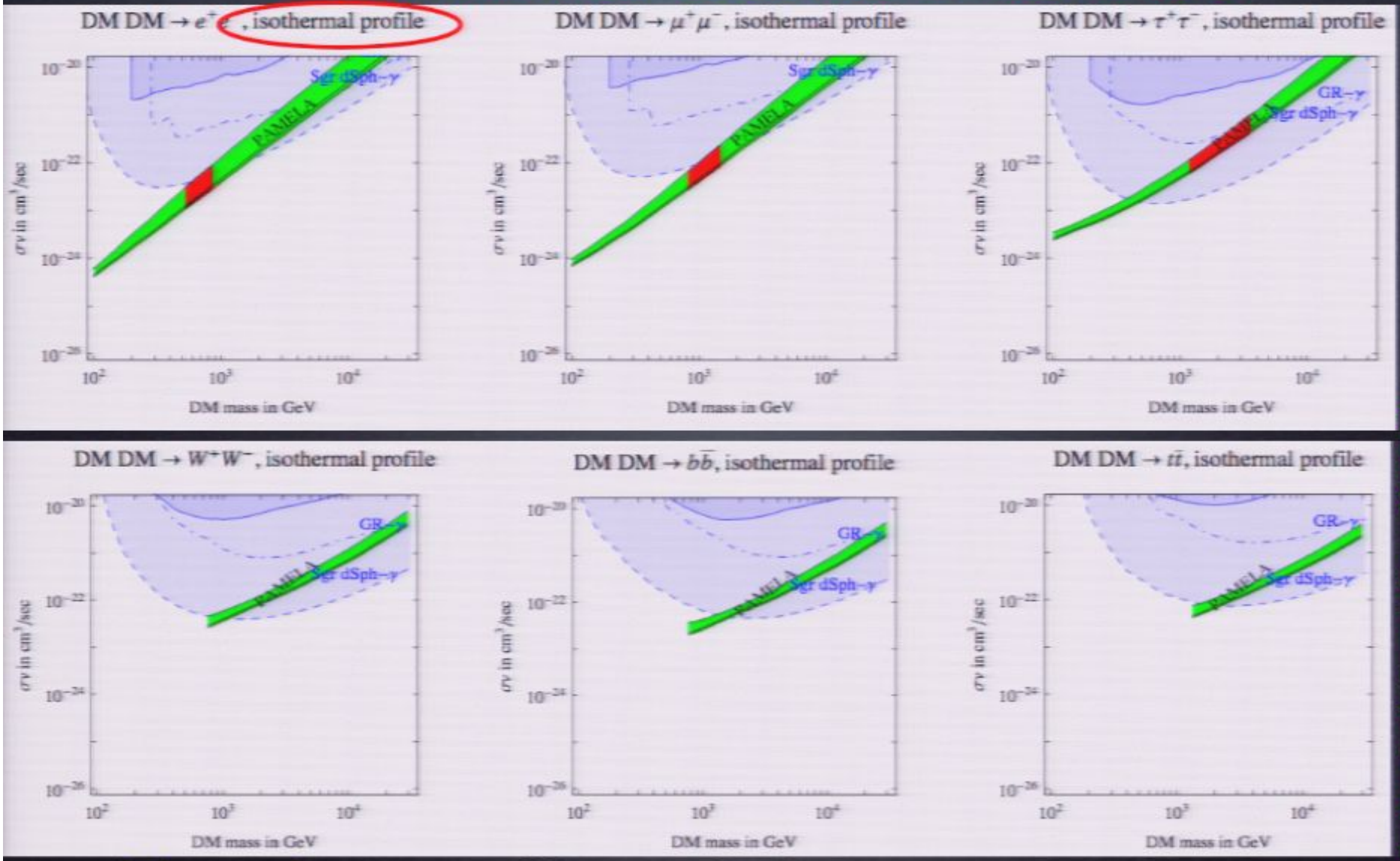

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...not-too-steep profile needed.

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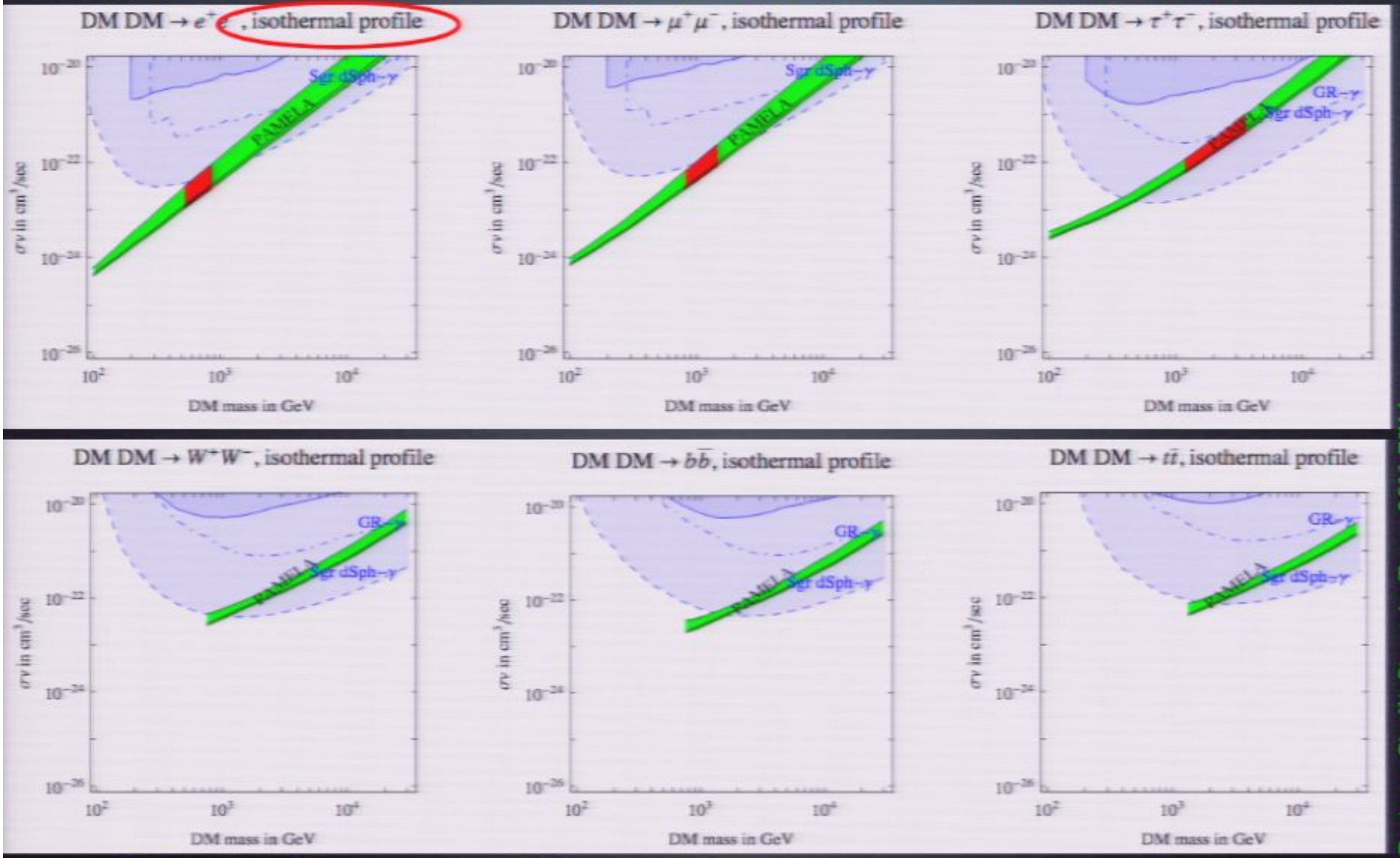

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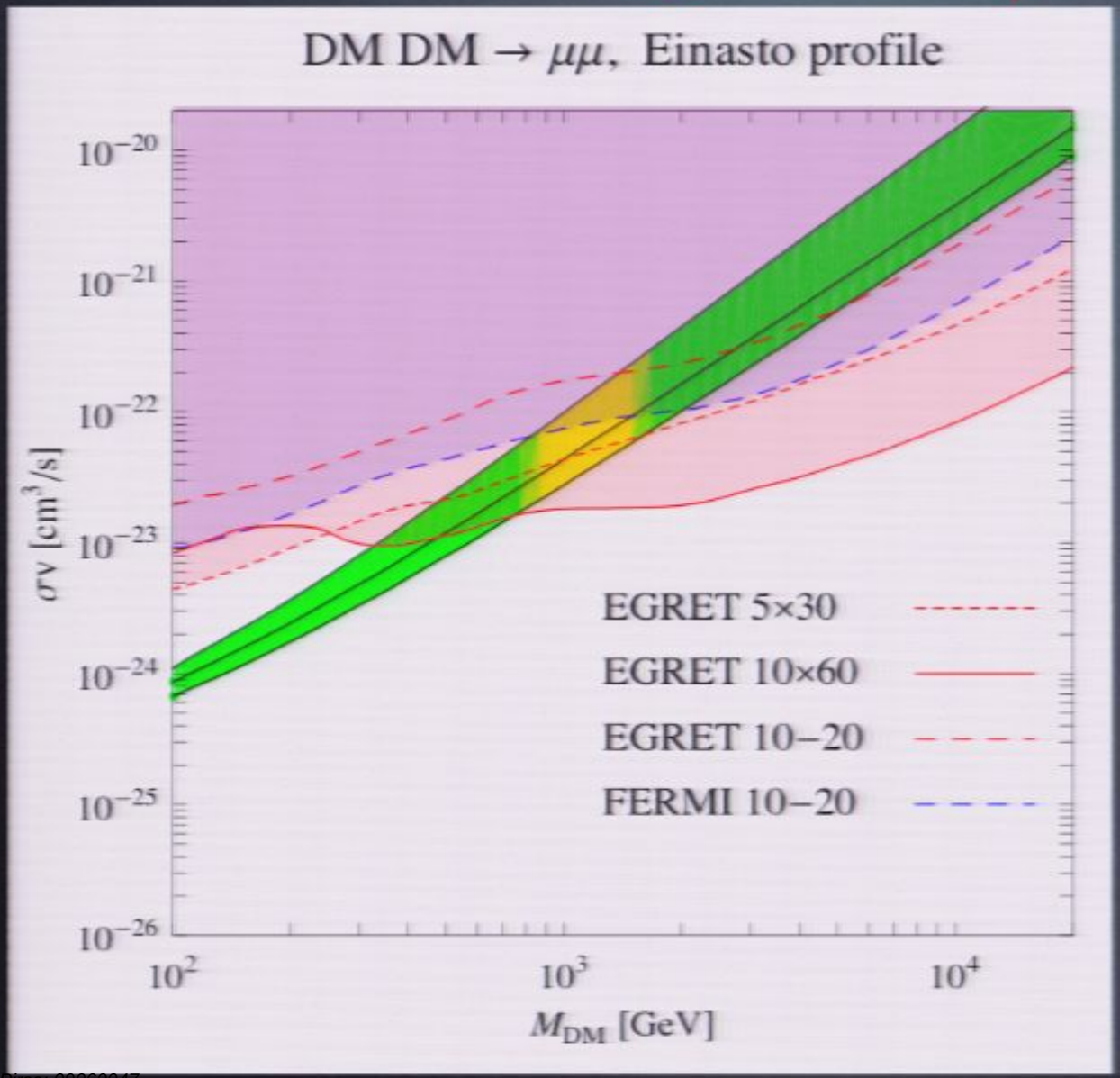
...not-too-steep profile needed.

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

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

Inverse Compton γ constraints



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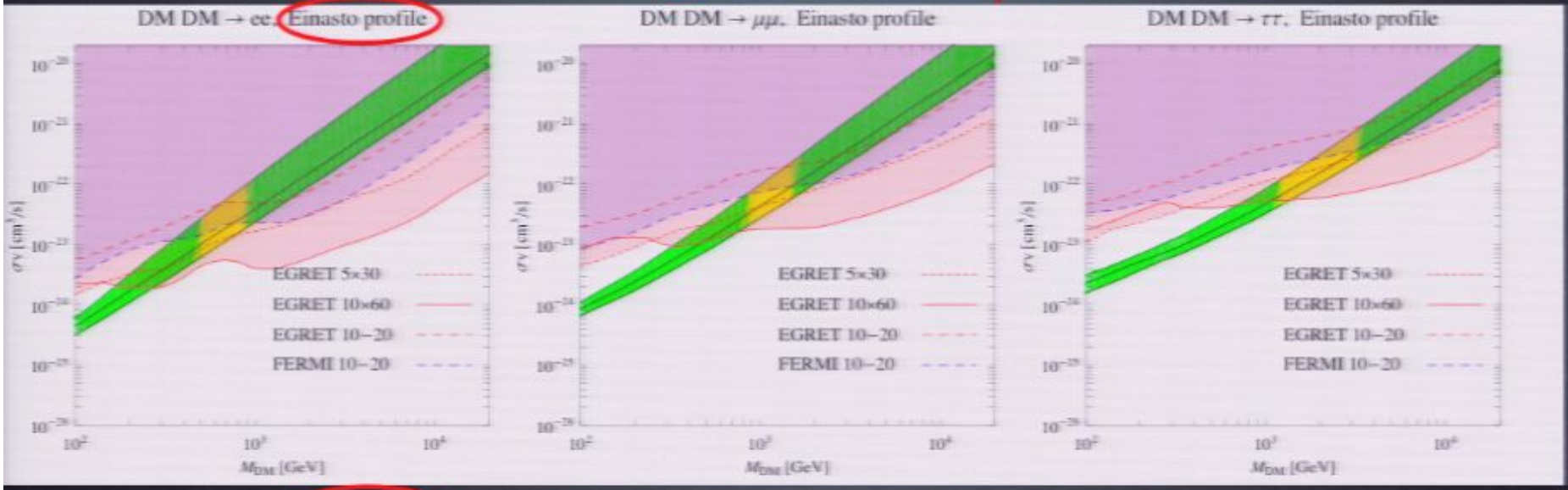

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see also: Regis, Ullio 0904.4645, Strumia, Papucci et al. 0905.0480

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

Topics not touched

- Implications of FERMI $e^+ + e^-$ data
- Neutrino bounds

- DM models with a richer dark sector
  (with light vectors and cascade annihilations)
- Decaying DM

- (Prospectives for anti-deuterium searches)

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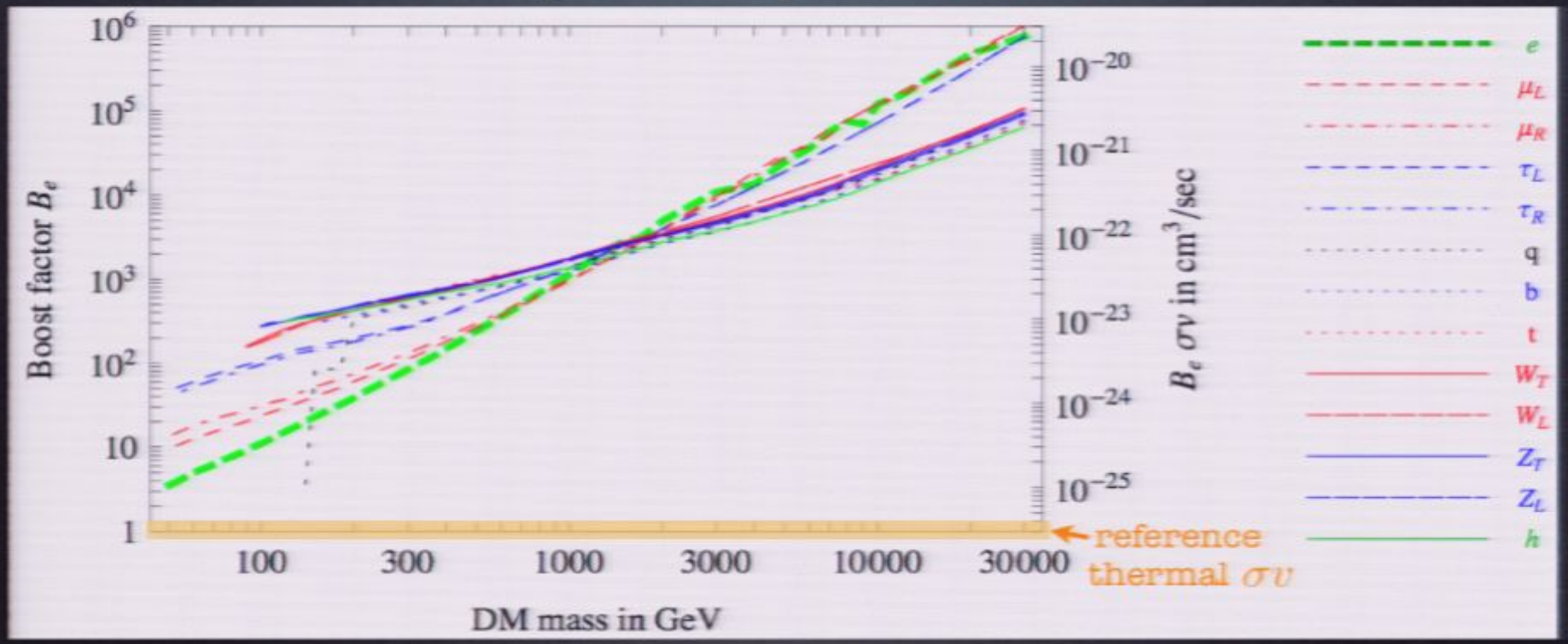
Results

Which DM spectra can fit the data?

Model-independent results:

Cross-section required by PAMELA



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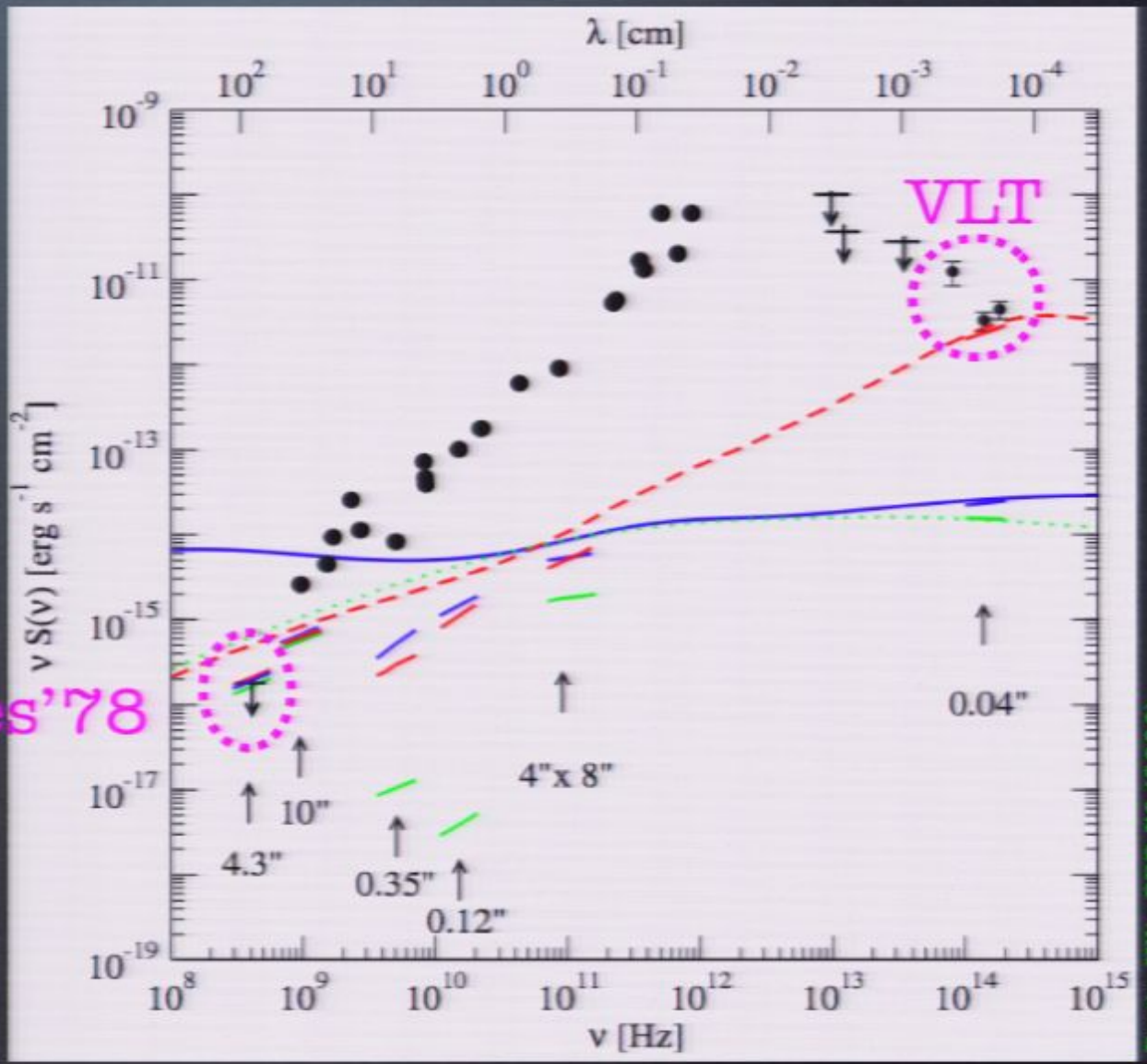

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Background computations for positrons:

main source: CR nuclei spallating on IS gas

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More recently:
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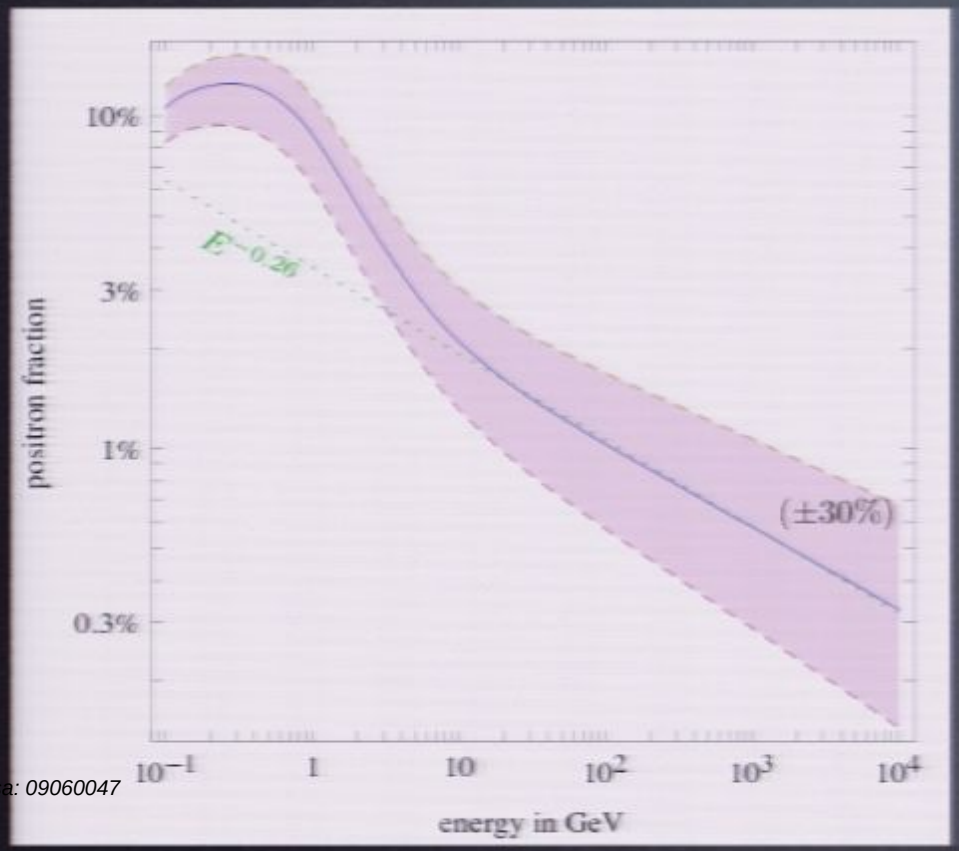

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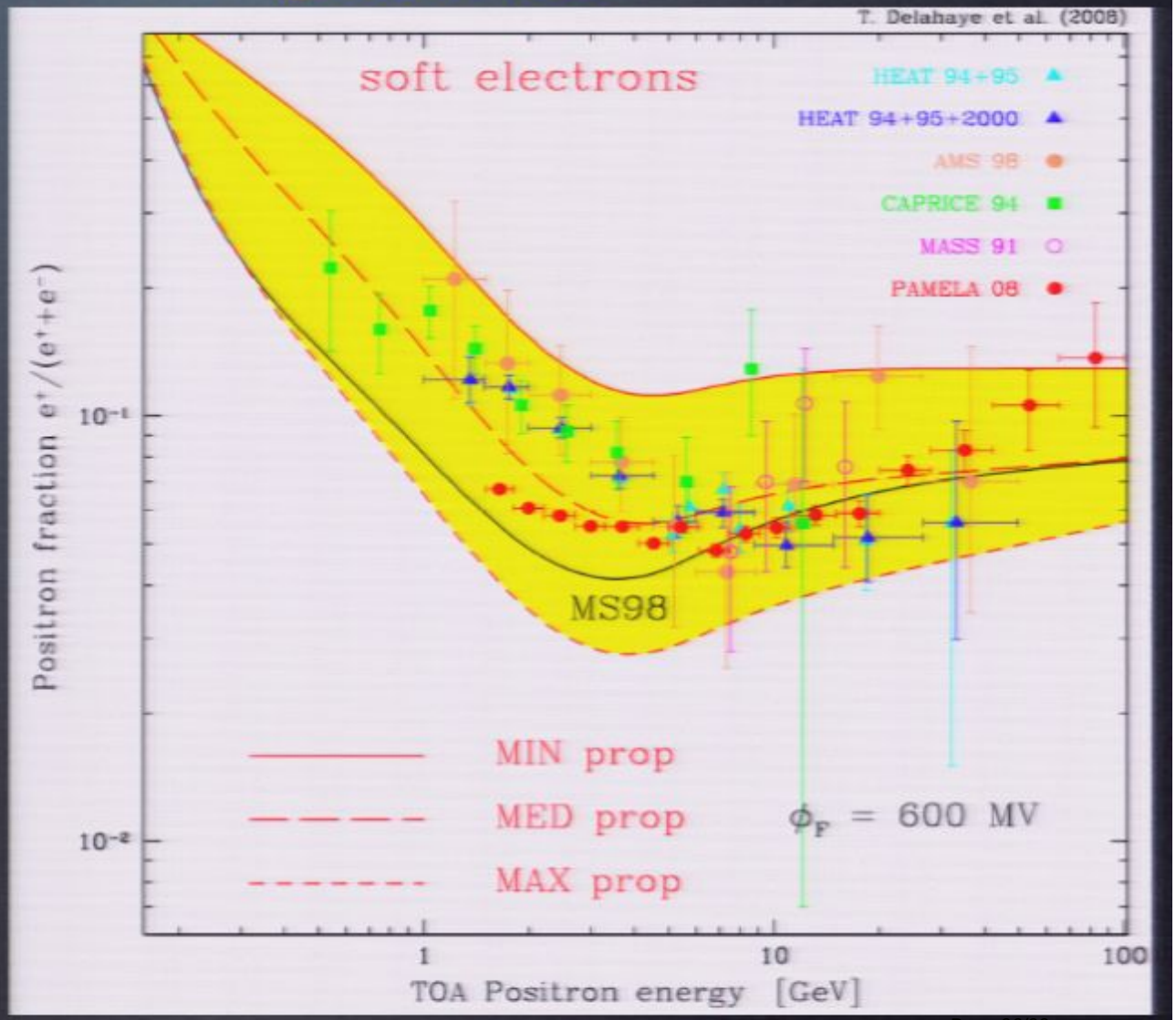

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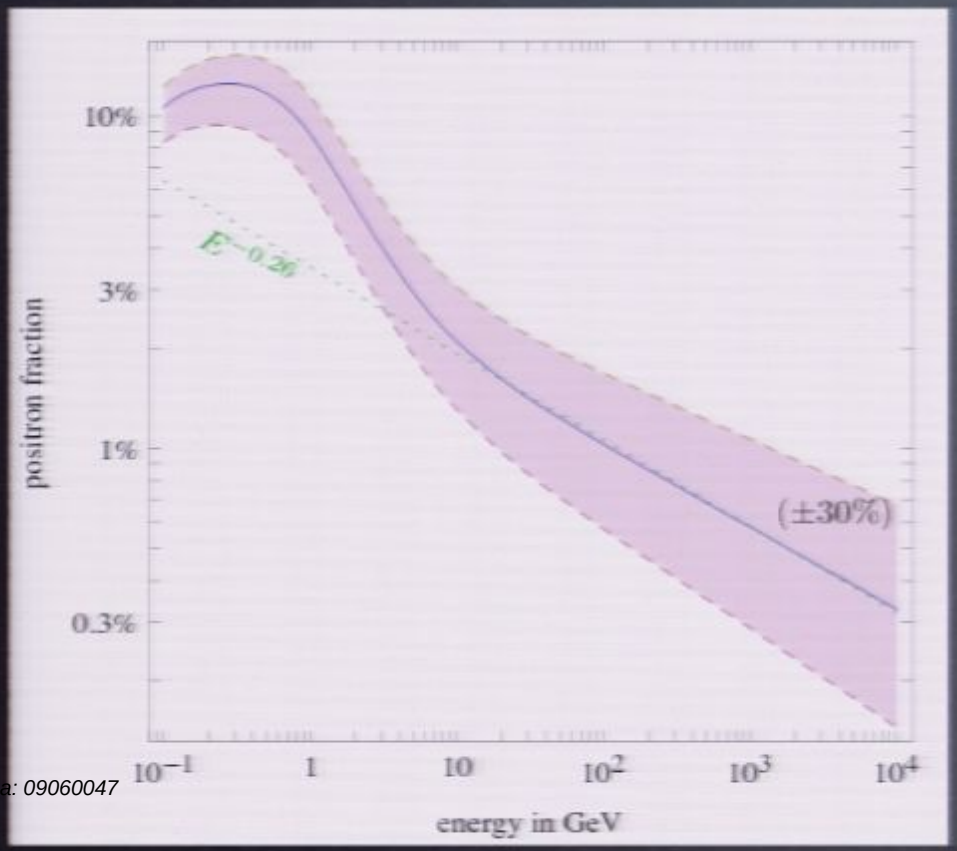

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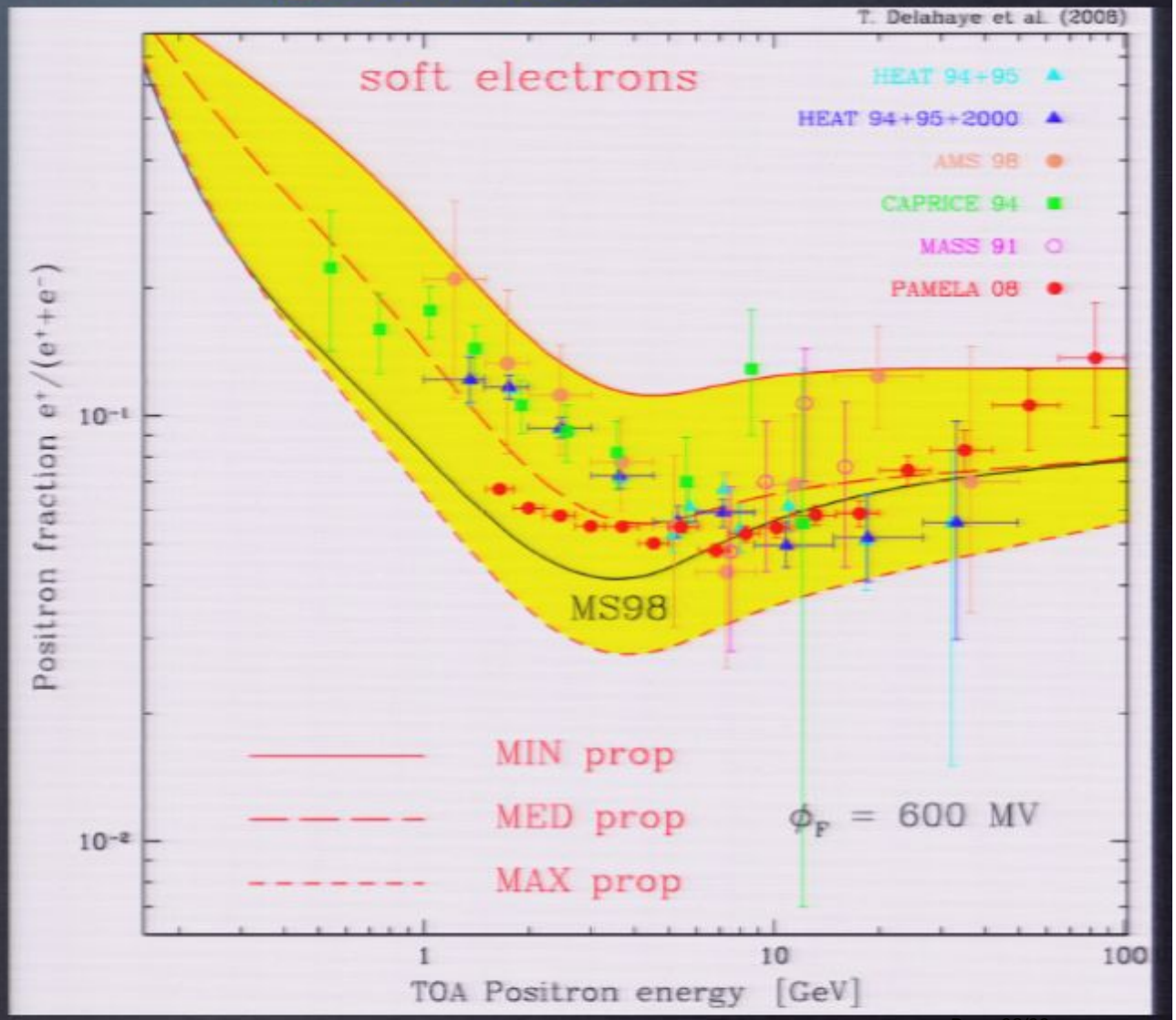

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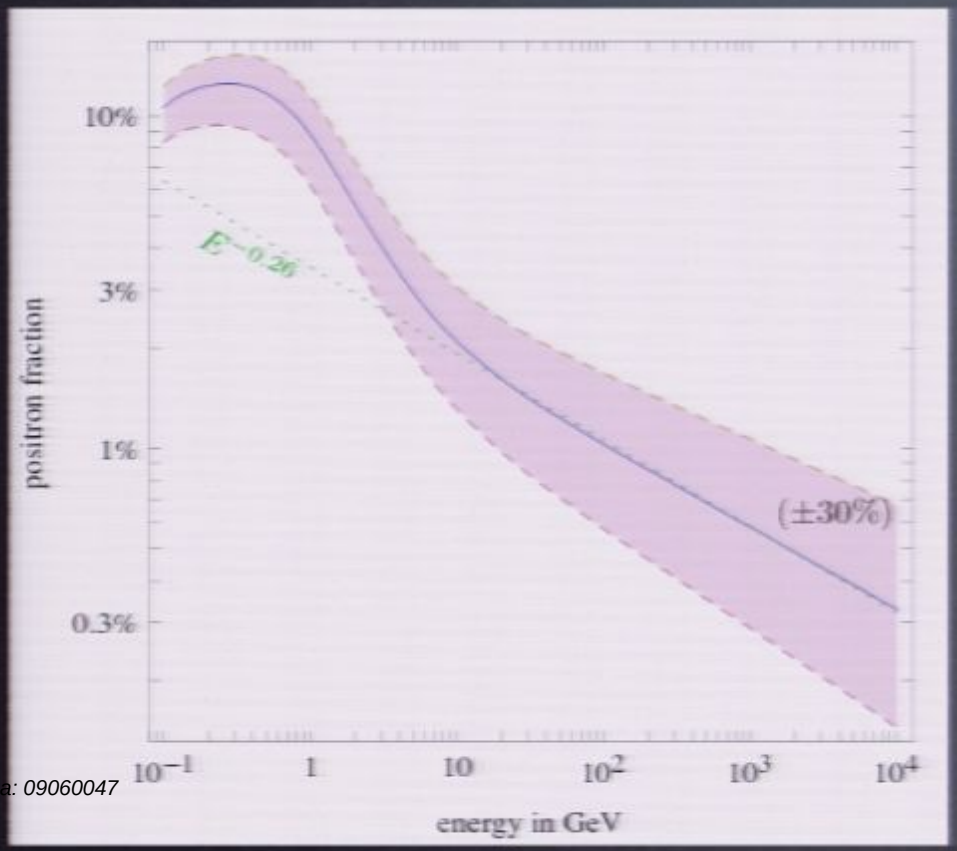

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