17 january 2011
Helmholtz Alliance national seminar, Bonn

Seeing signals of DM in cosmic rays?!?

Marco Cirelli
(CERN-TH & CNRS IPhT Saclay)

in collaboration mainly with:
A.Strumia (Pisa)
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M.Tamburini (Pisa)
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M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (Saclay)
F.Iocco (Saclay + IAP Paris)
P.Serpico (CERN)

0808.3867 [astro-ph]
Nuclear Physics B 813 (2009)
JCAP 03 009 (2009)
Physics Letters B 678 (2009)
Nuclear Physics B 821 (2009)
JCAP 10 009 (2009)
Nuclear Physics B 840 (2010)
1012.4515
and work in progress

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DM indirect detection: status circa 2011

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Annihilating DM indirect detection: my view of the status circa January 2011

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1012.4515
and work in progress

DM detection

direct detection

Xenon, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

- γ from annihil in galactic center or halo and from synchrotron emission

  Fermi, HESS, radio telescopes

- e^+ from annihil in galactic halo or center

  PAMELA, ATIC, Fermi

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

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

  GAPS

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

  Icecube, Km3Net

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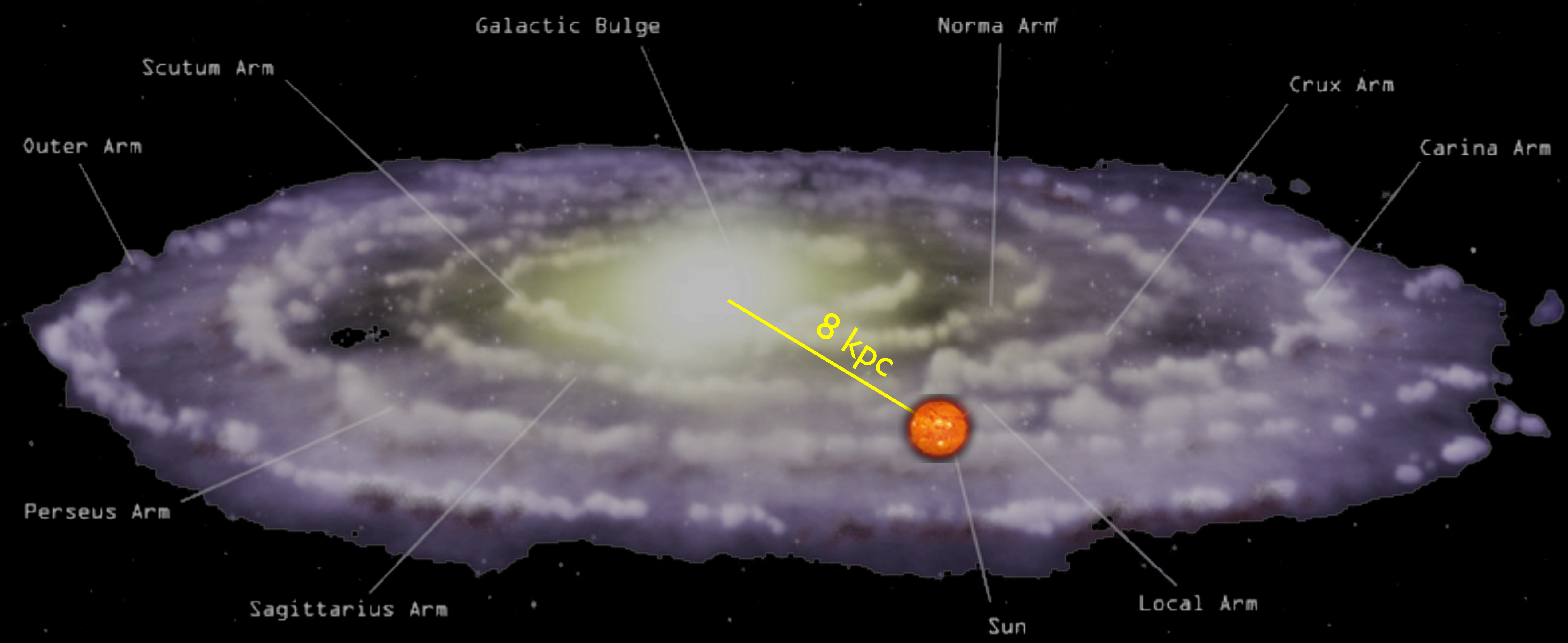
Indirect Detection

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



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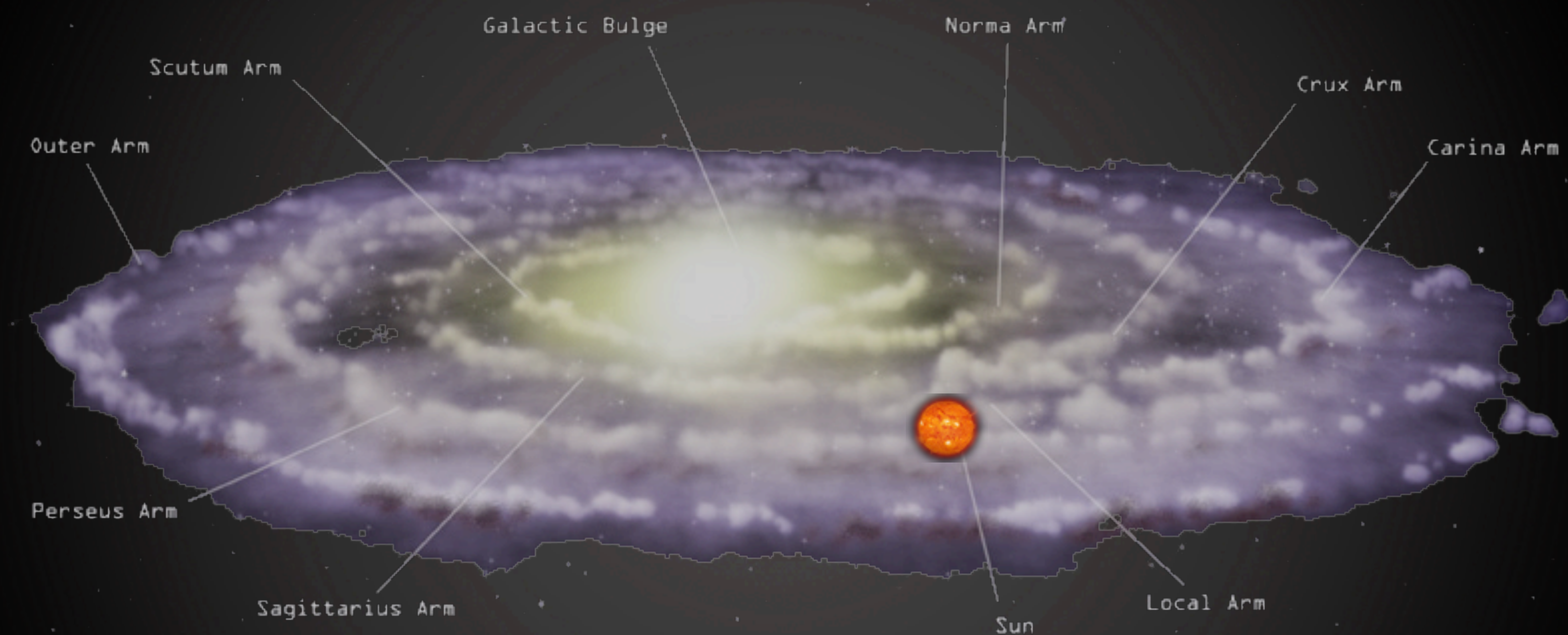

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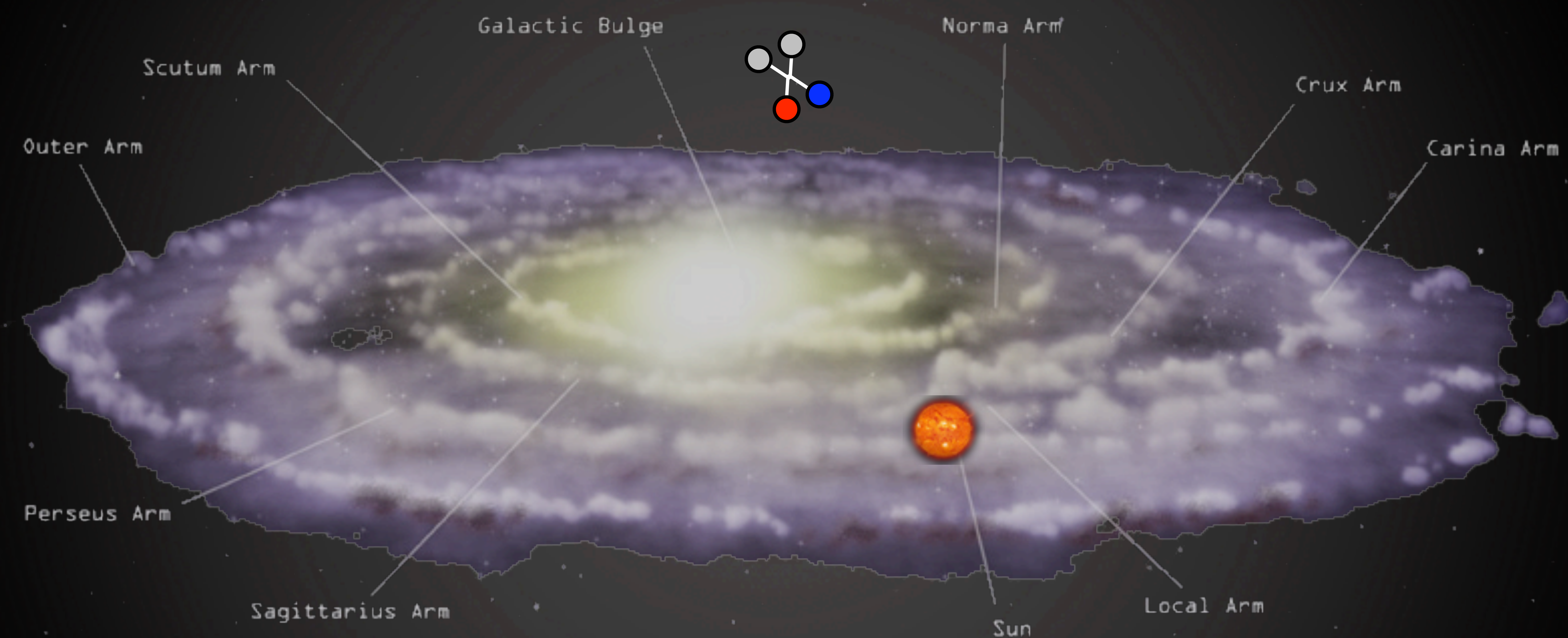

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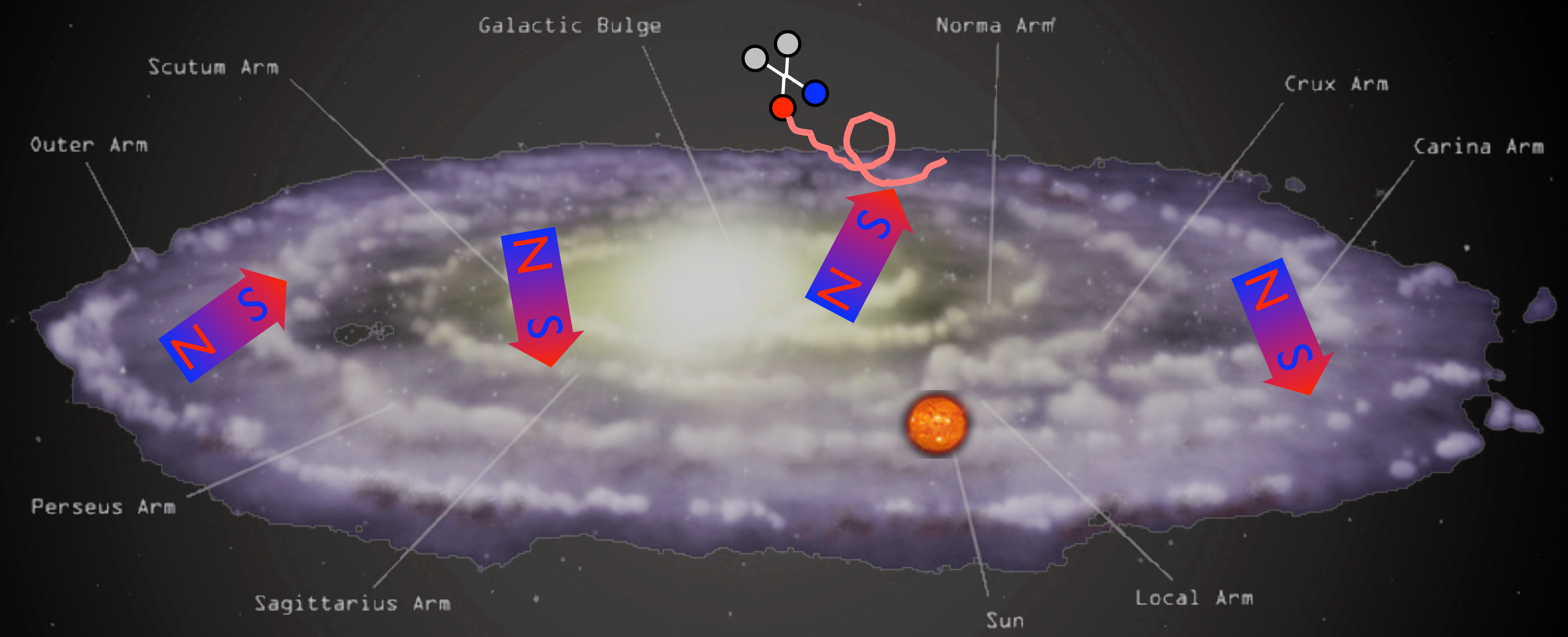

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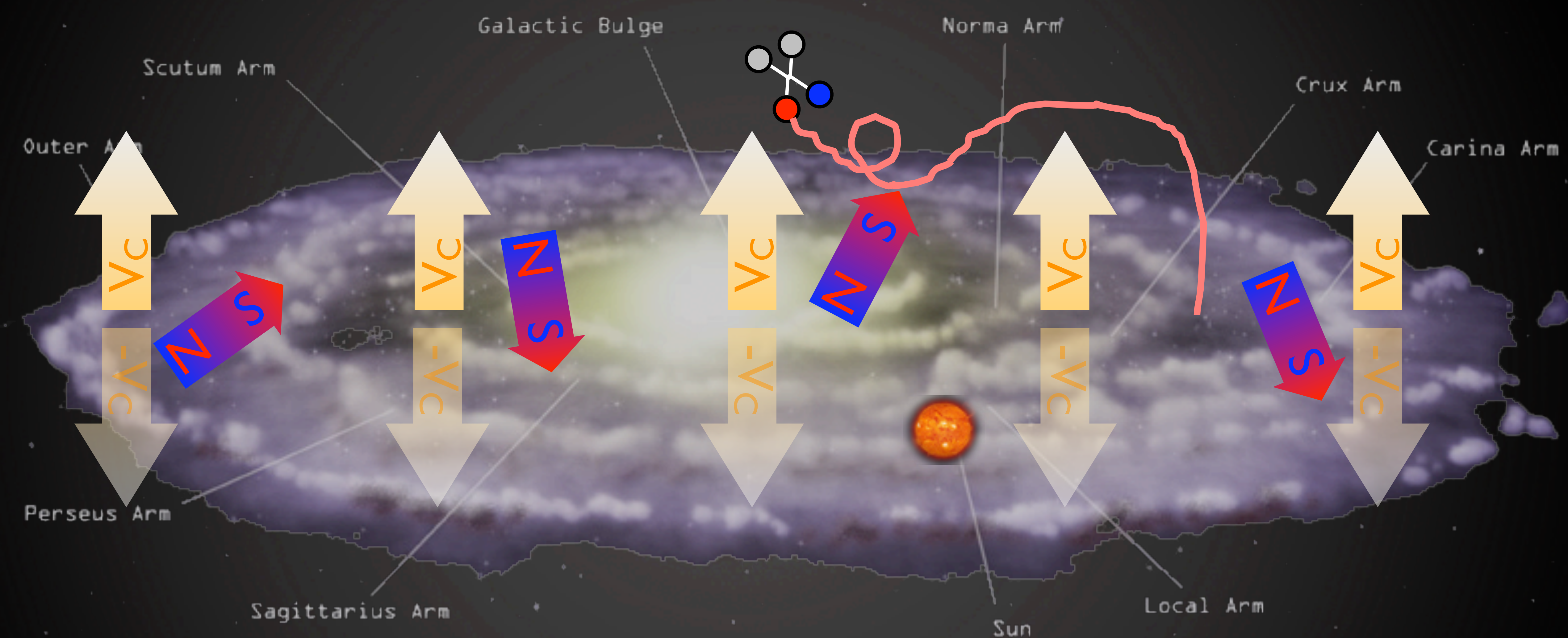

Indirect Detection

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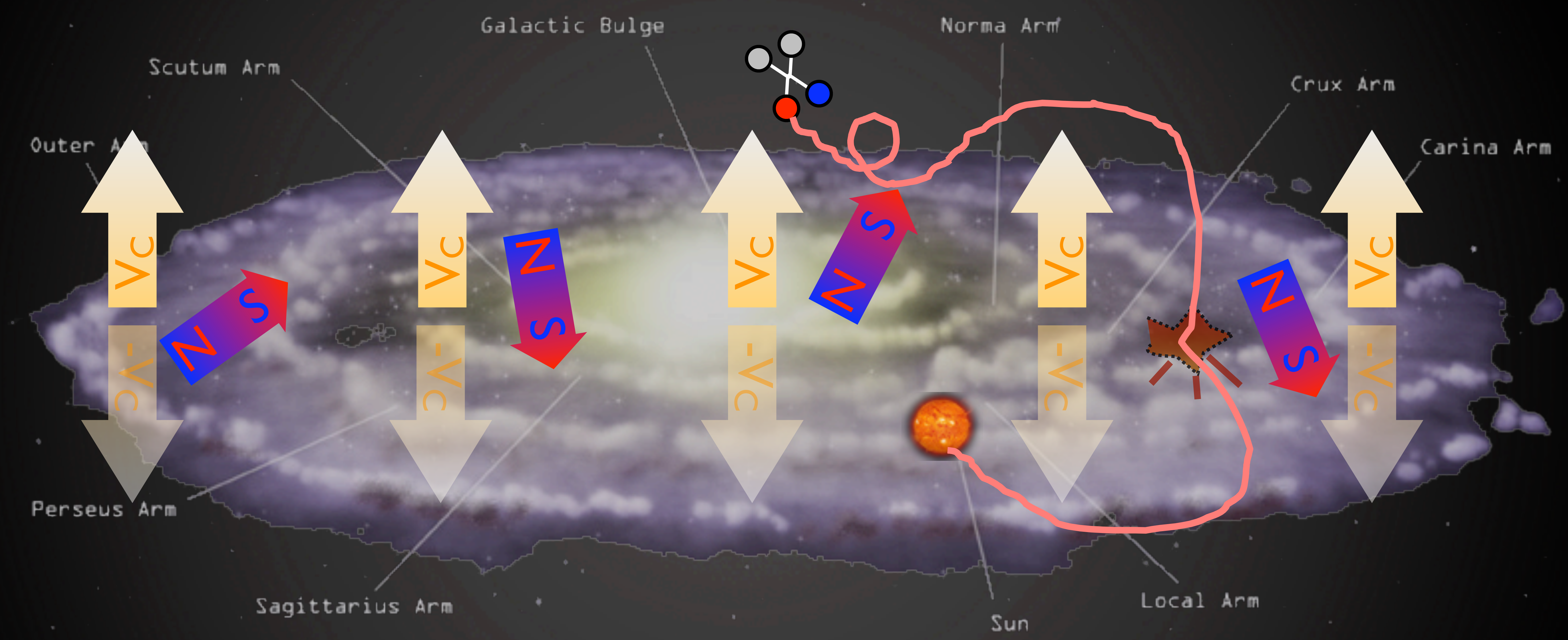

Indirect Detection

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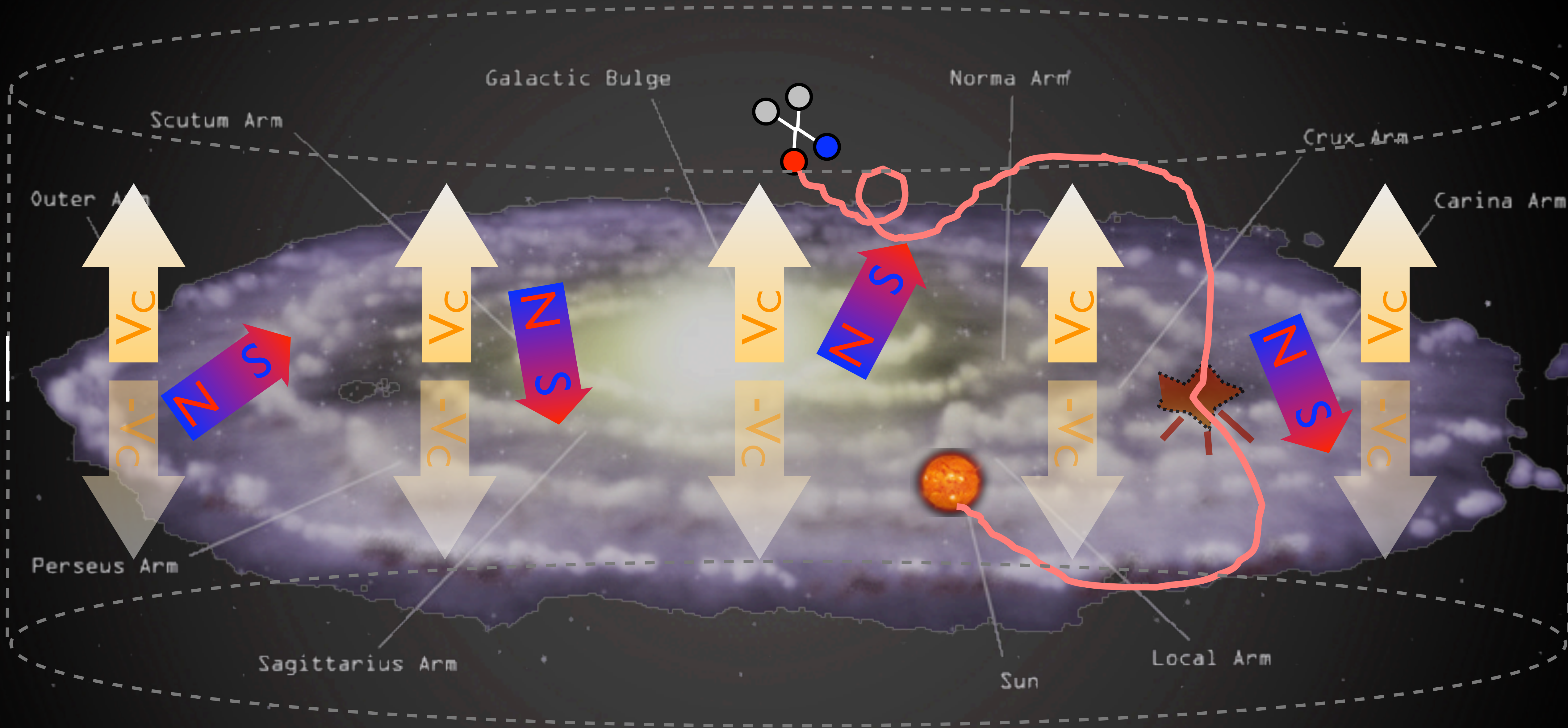


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

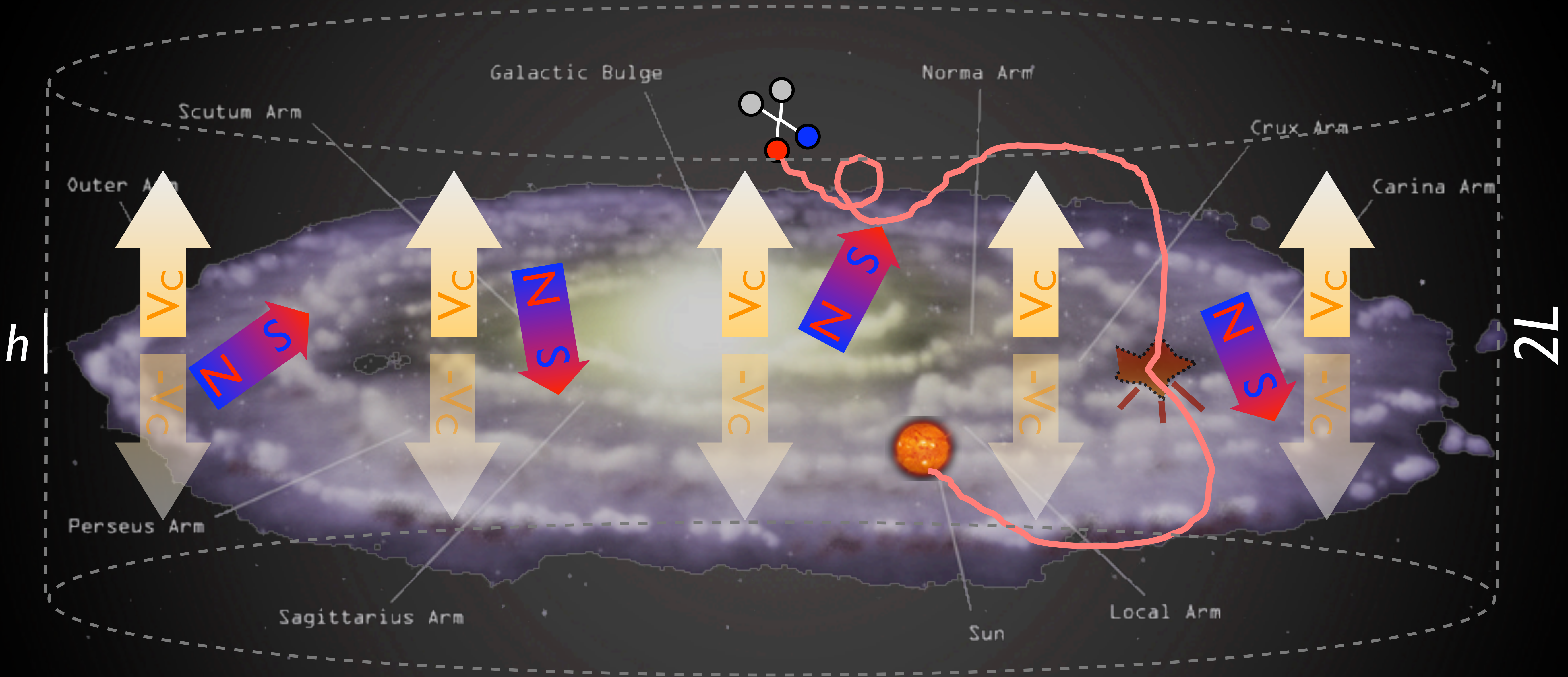
spectrum

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

diffusion — energy loss — convective wind — source — spallations

Indirect Detection

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

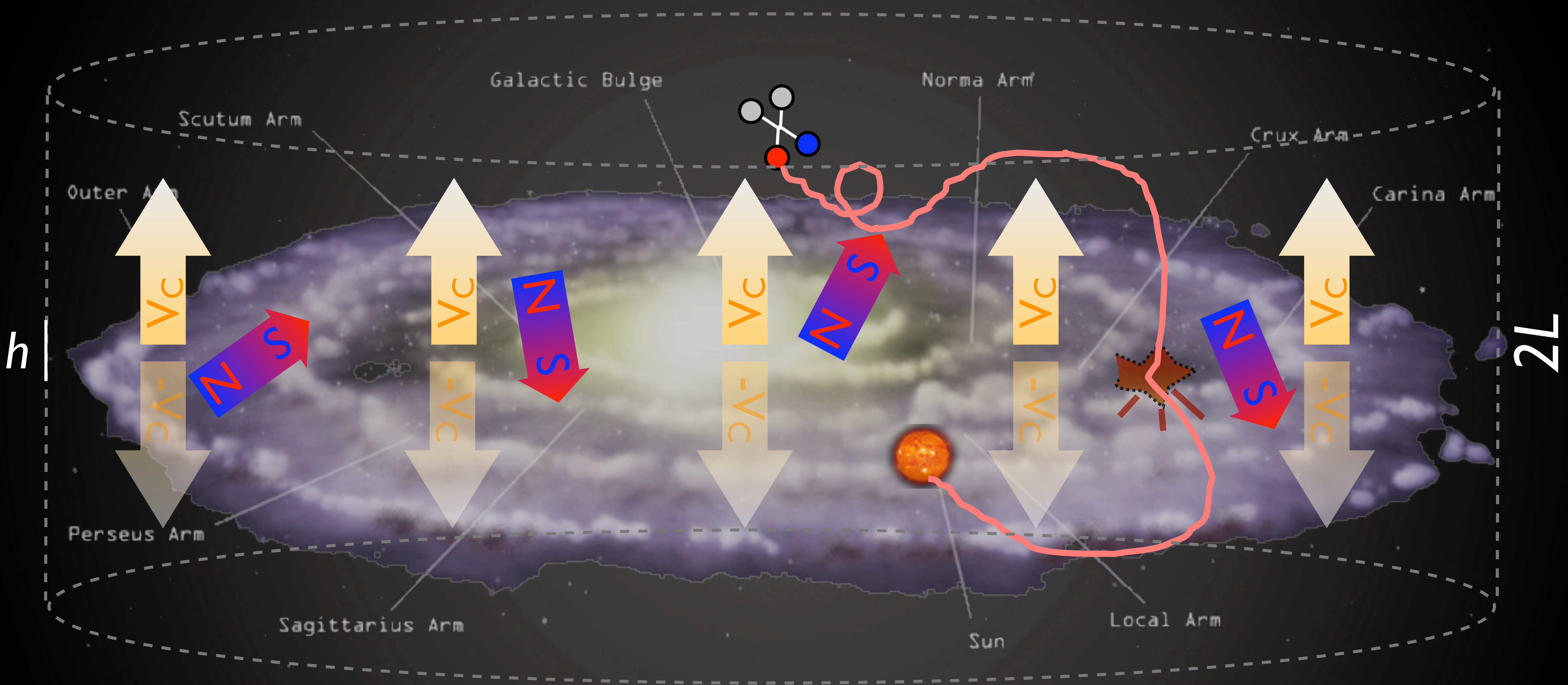


What sets the overall expected flux?

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

Indirect Detection

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



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astro& cosmo

particle

Indirect Detection

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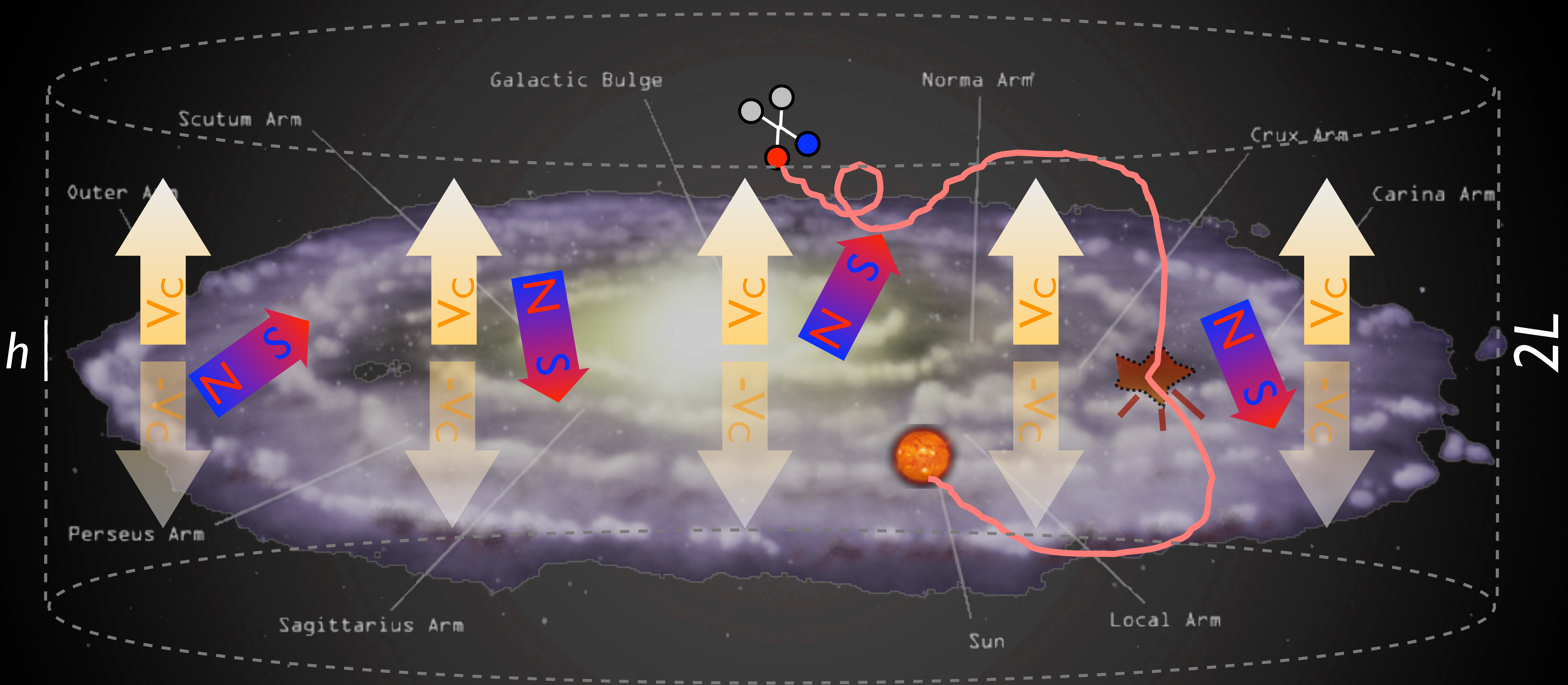


What sets the overall expected flux?

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

astro& cosmo

particle

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

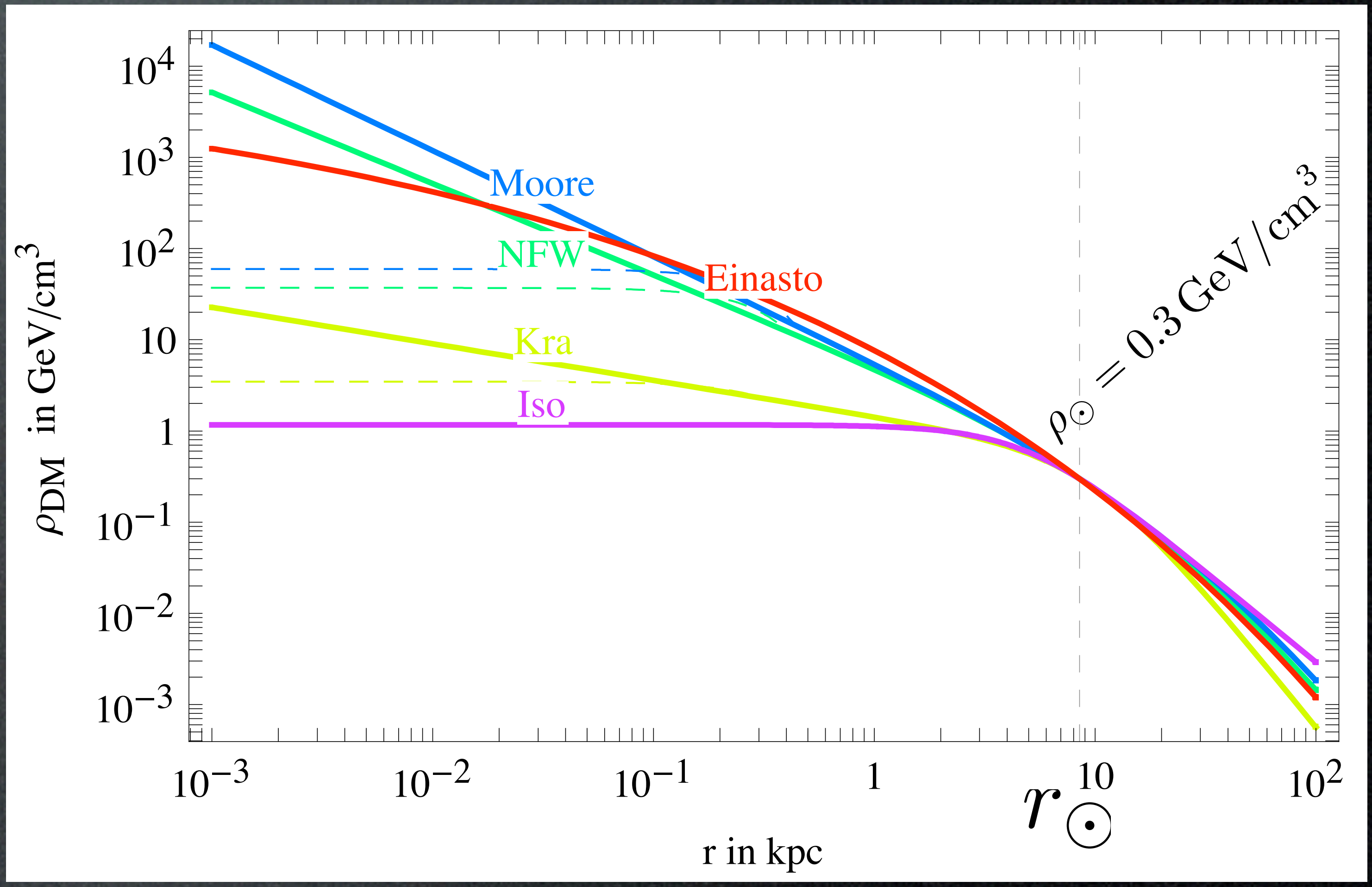
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

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

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

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

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

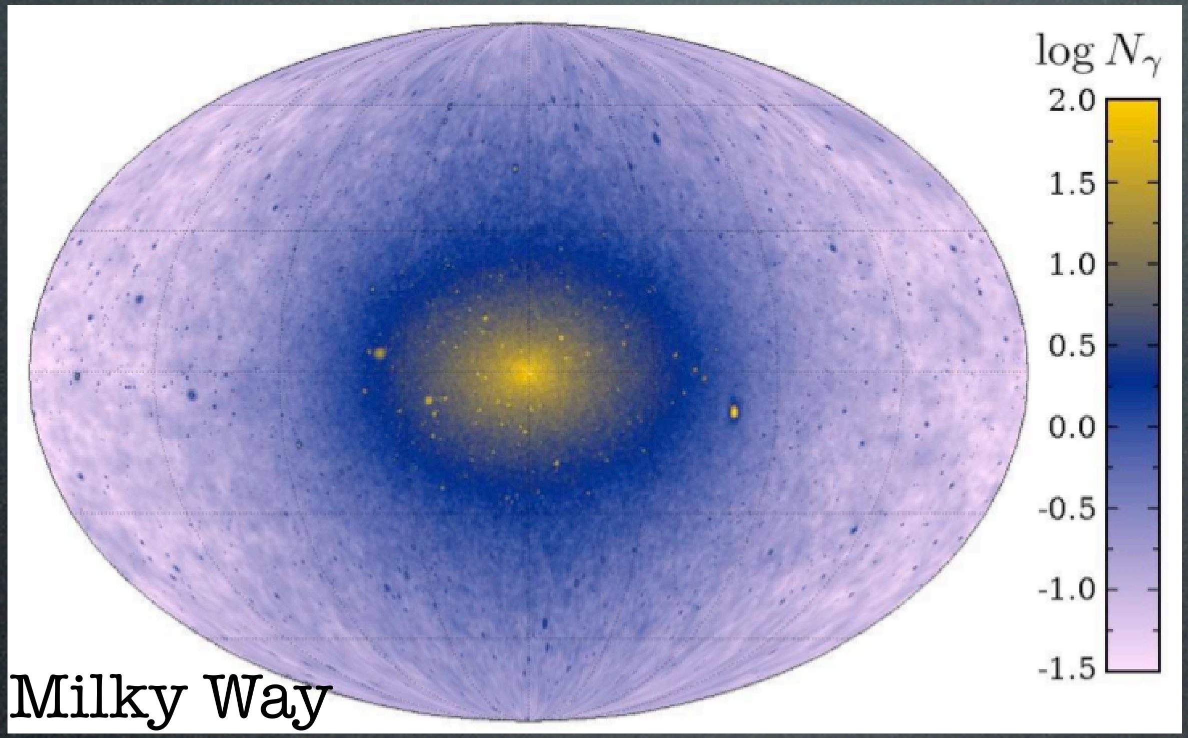


cuspy: NFW, Moore
mild: Einasto
smooth: isothermal

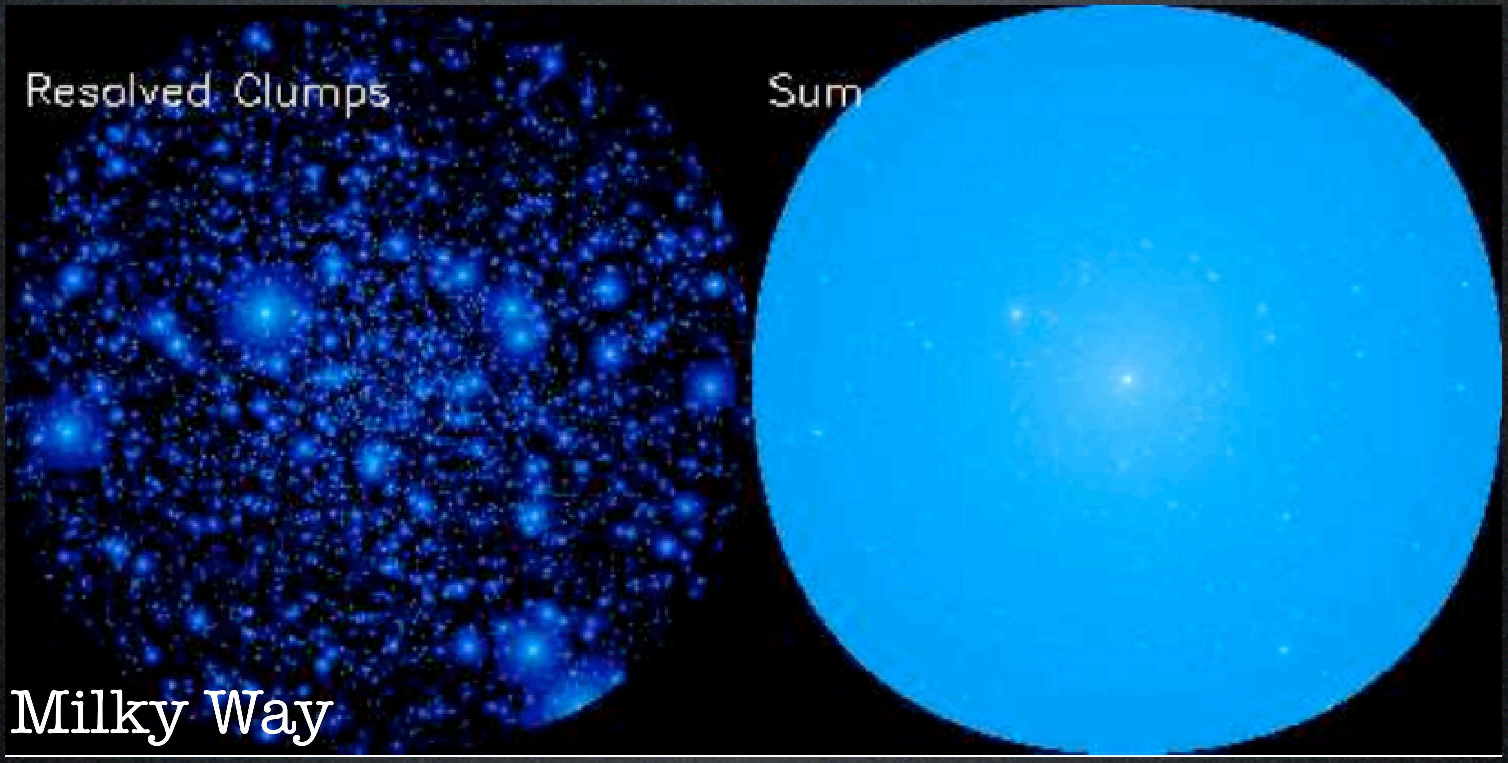
Indirect Detection

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

For illustration:



Kuhlen, Diemand, Madau 2007



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

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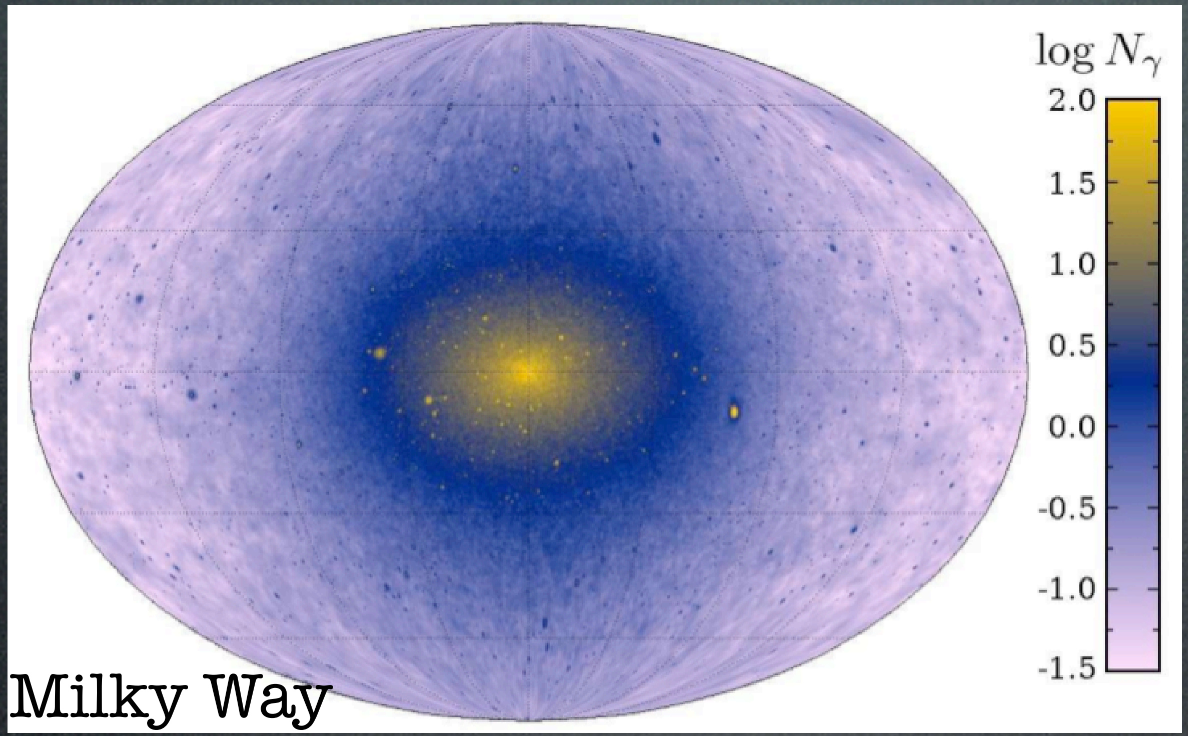
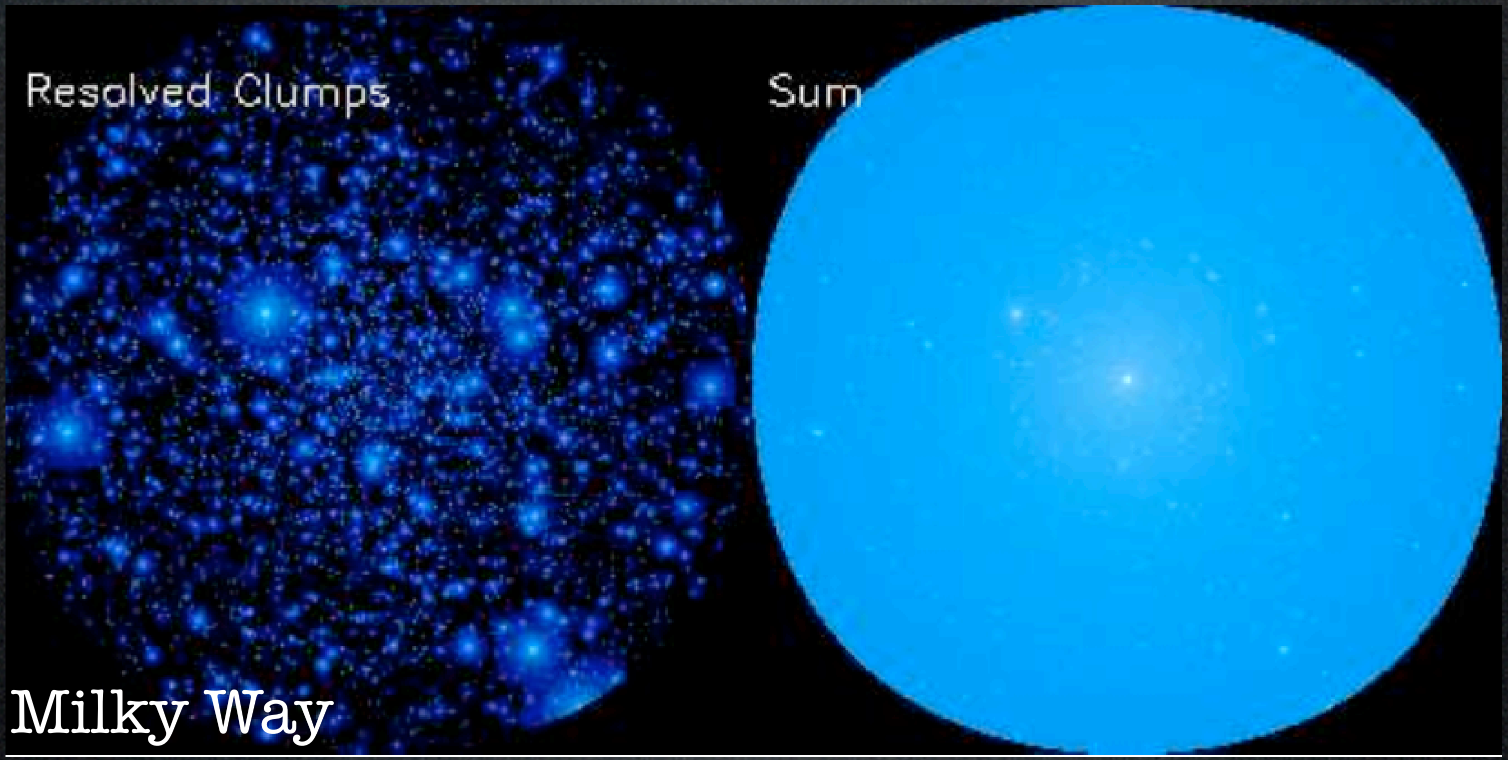


Kuhlen, Diemand, Madau 2007

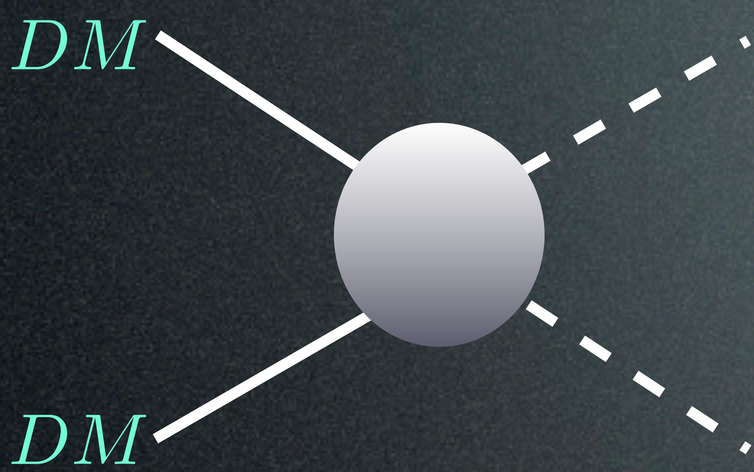
But: recent simulations seem to show almost no clumps in inner 10 kpc (tidal stripping).
[Millenium Simulation, Carlos Frenk]



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

Computing the theory predictions

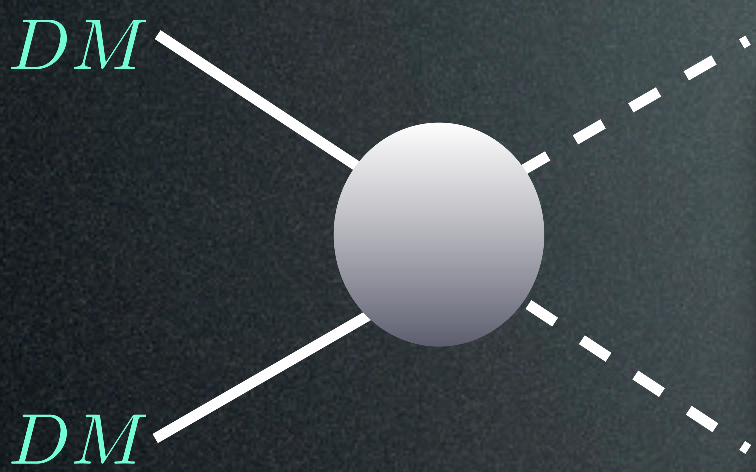
Spectra at production



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

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

Spectra at production

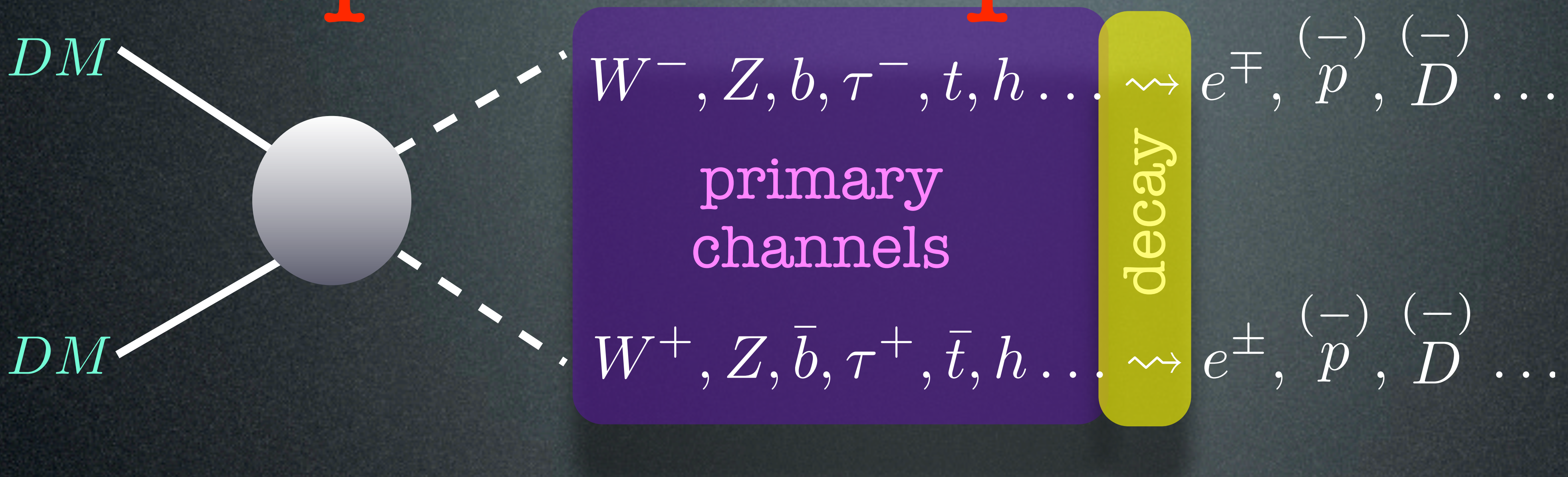


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

primary channels

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

Spectra at production



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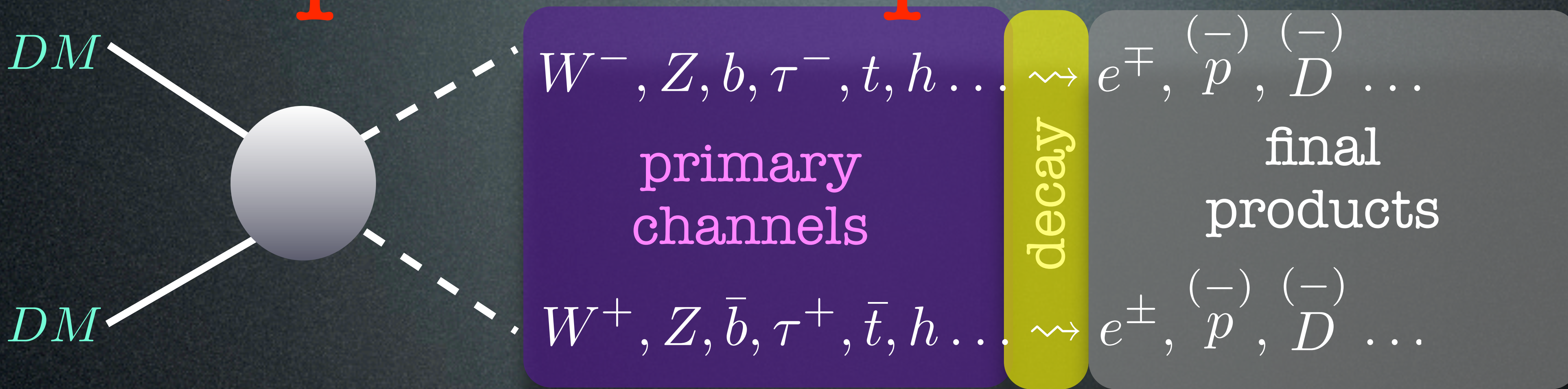
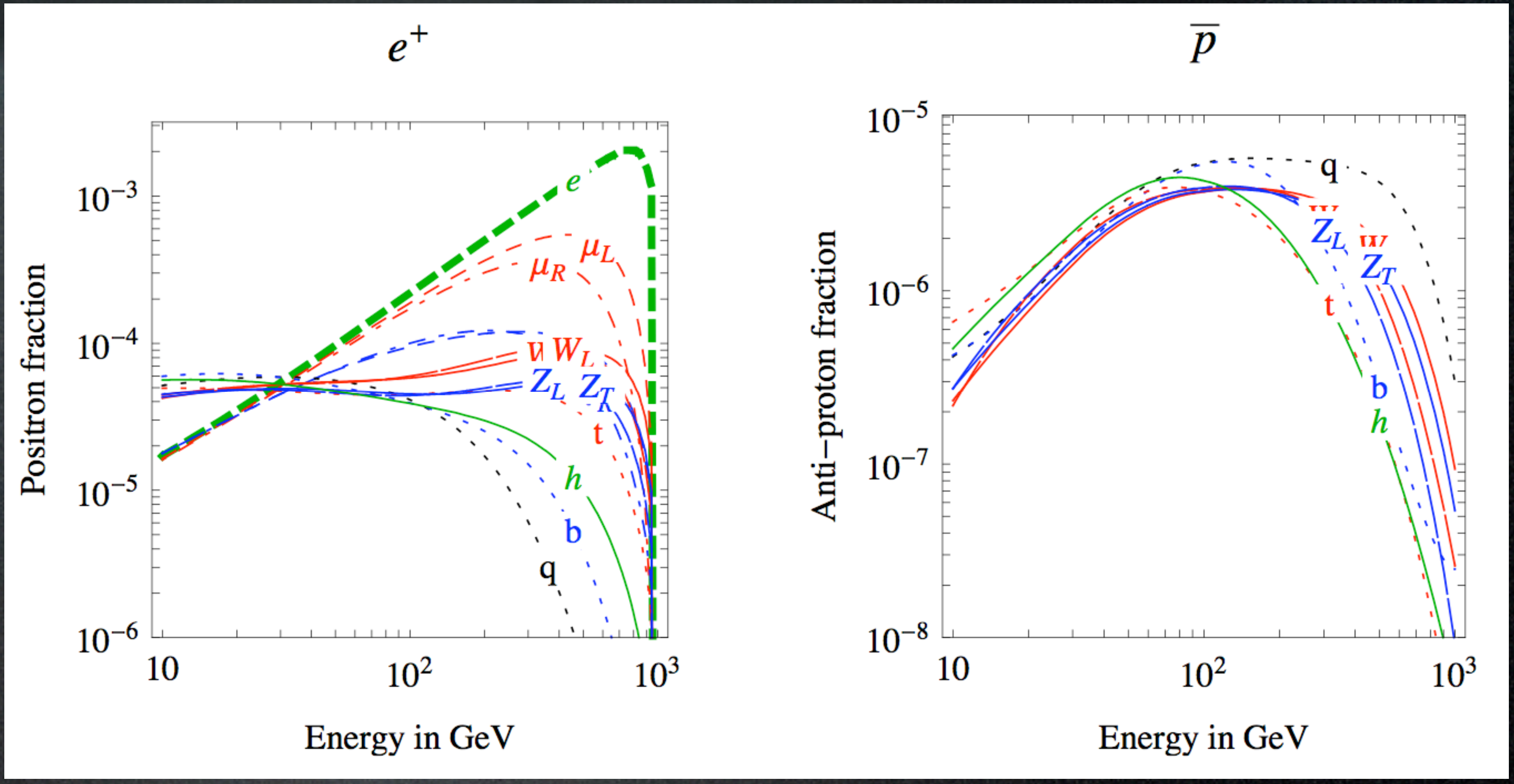
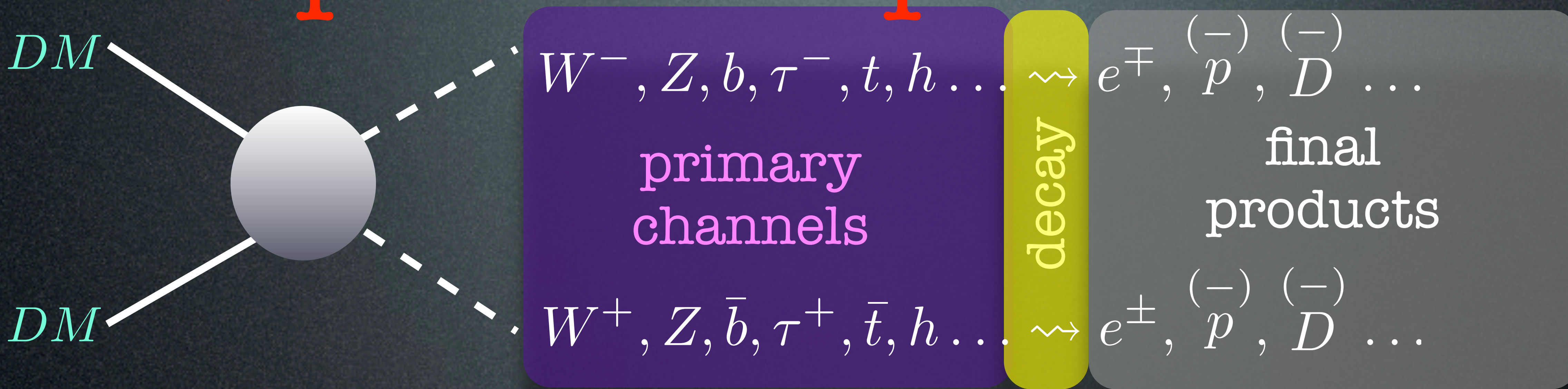
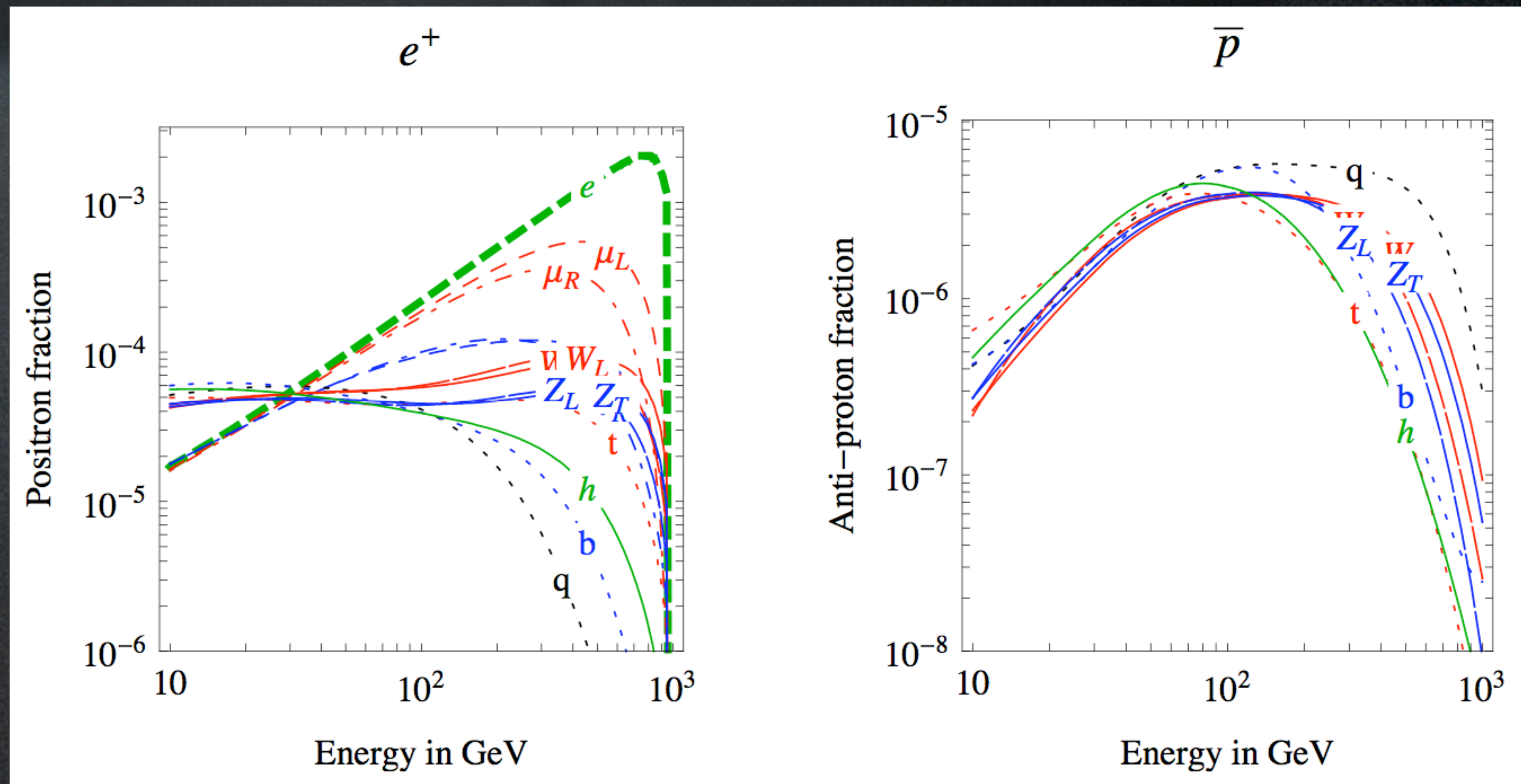




Spectra at production





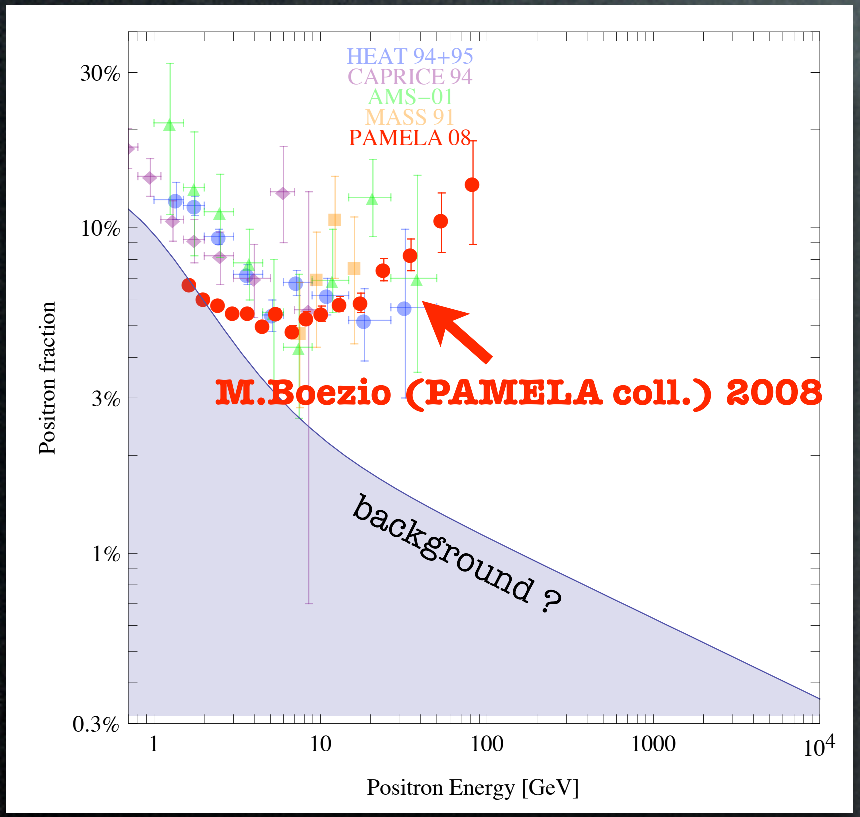
So what are the particle physics parameters?

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

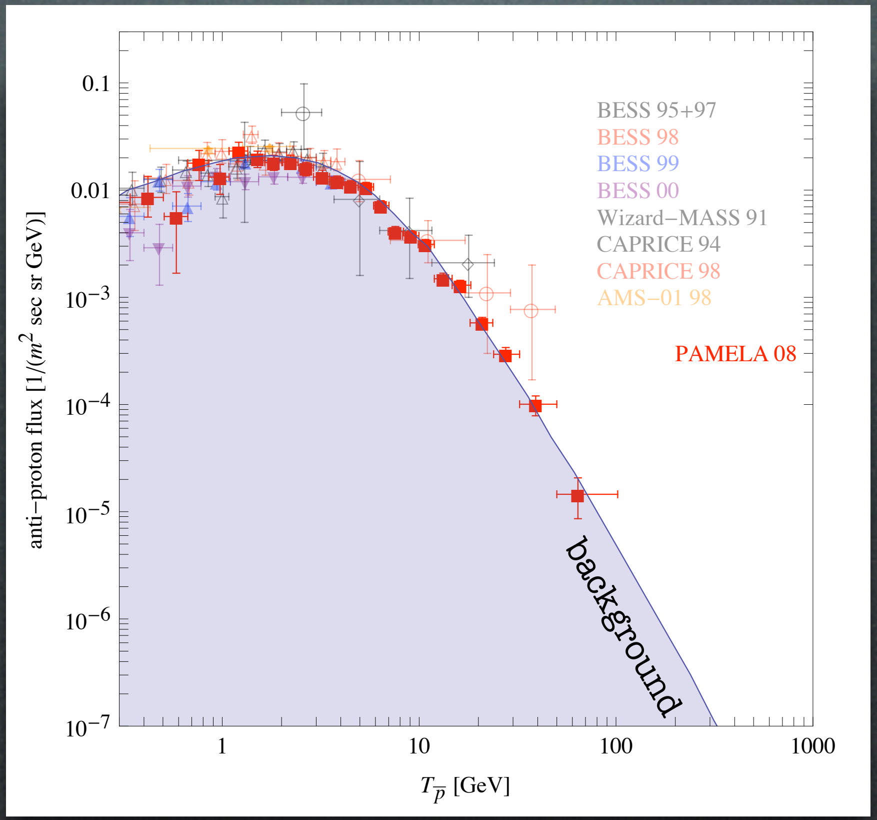
Comparing with data

Data

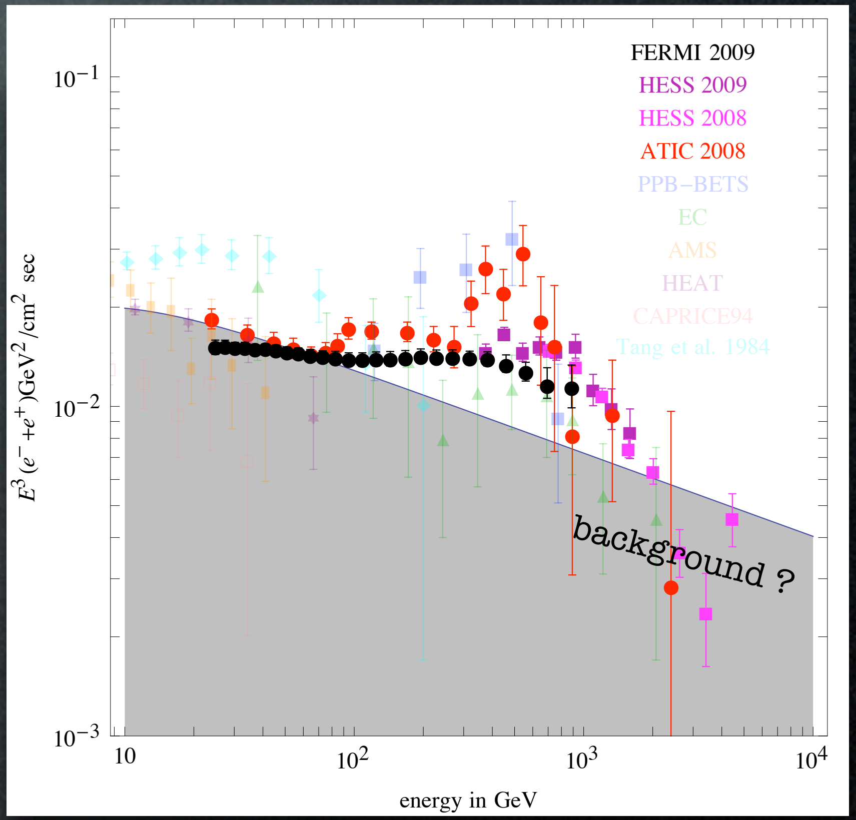
positron fraction



antiprotons



electrons + positrons

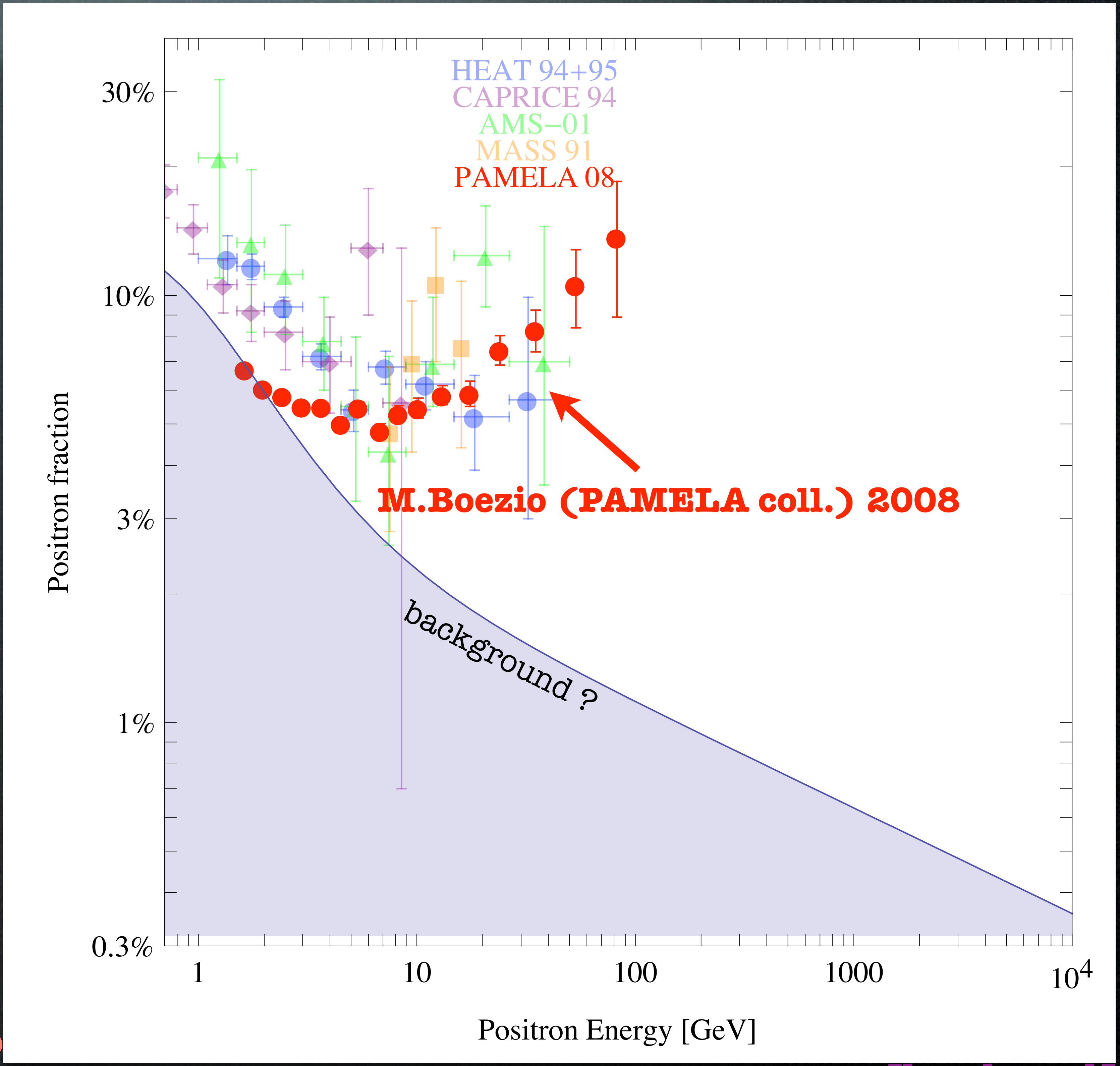


Data sets

Positrons from PAMELA:

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

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



(9430 e^+ collected)

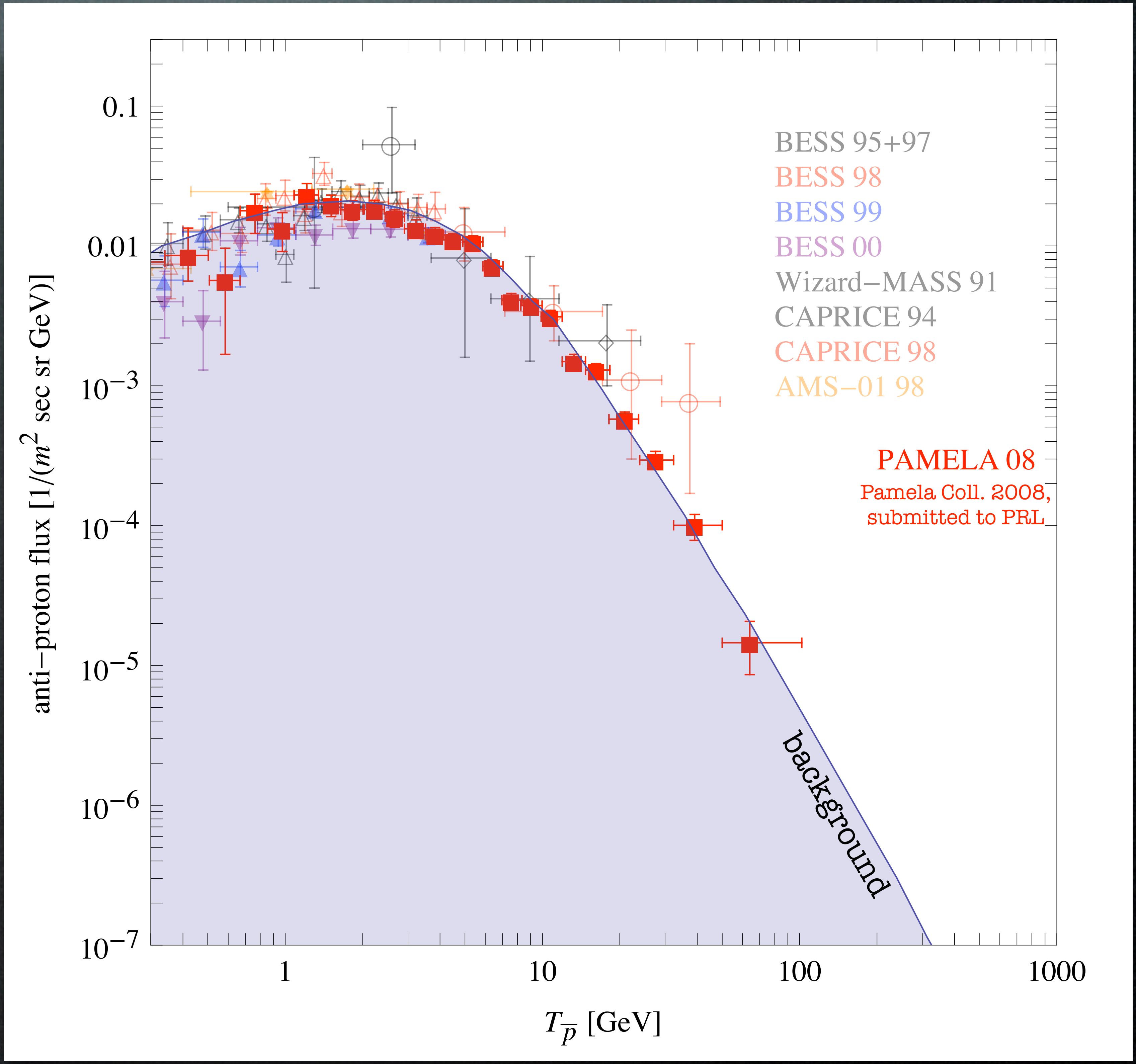
(errors statistical only, that's why larger at high energy)

[backgnd]

Data sets

Antiprotons from PAMELA:

- consistent with the background

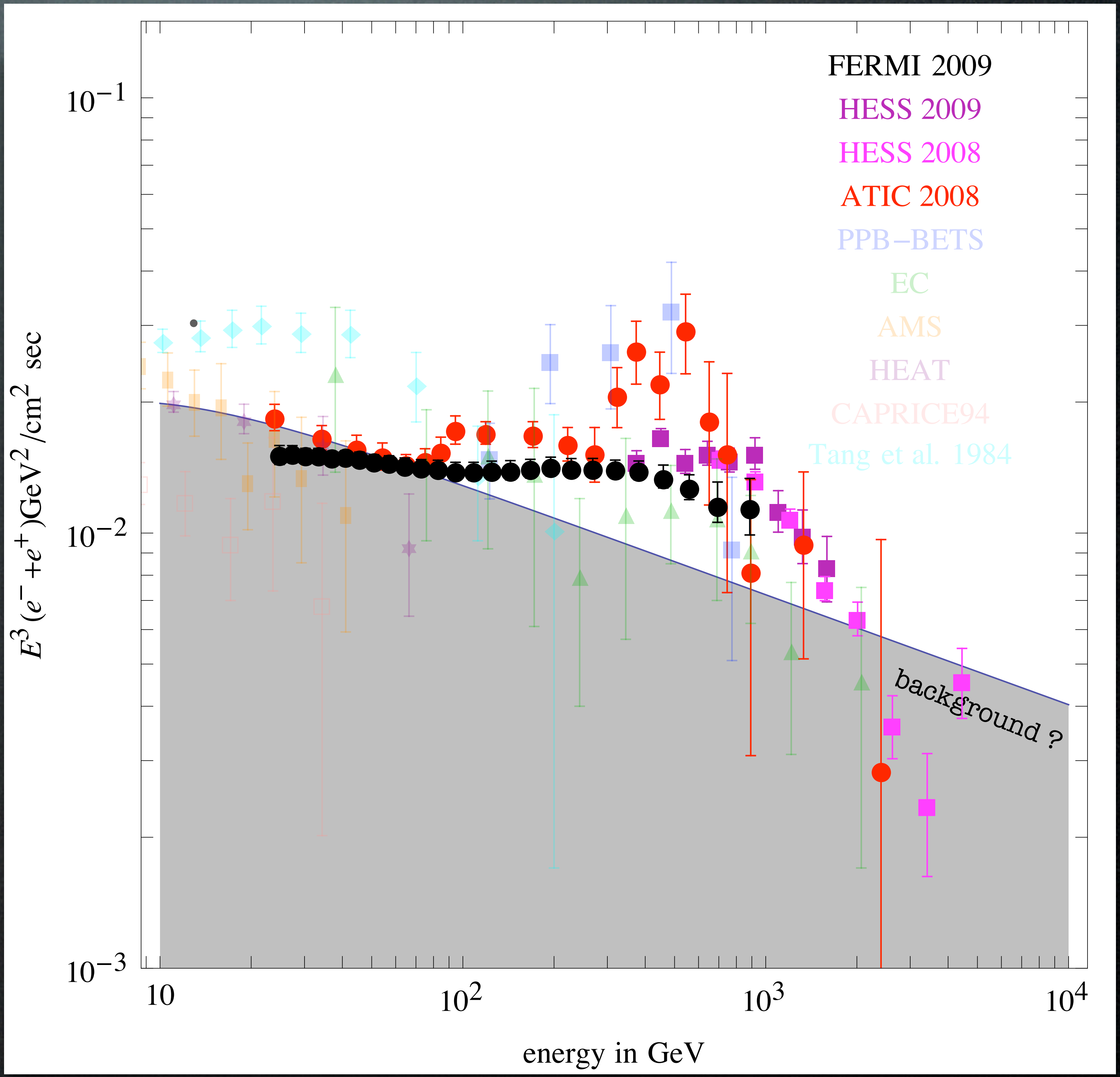


(about 1000 $\bar{p}$ collected)

Data sets

Electrons + positrons adding FERMI and HESS:

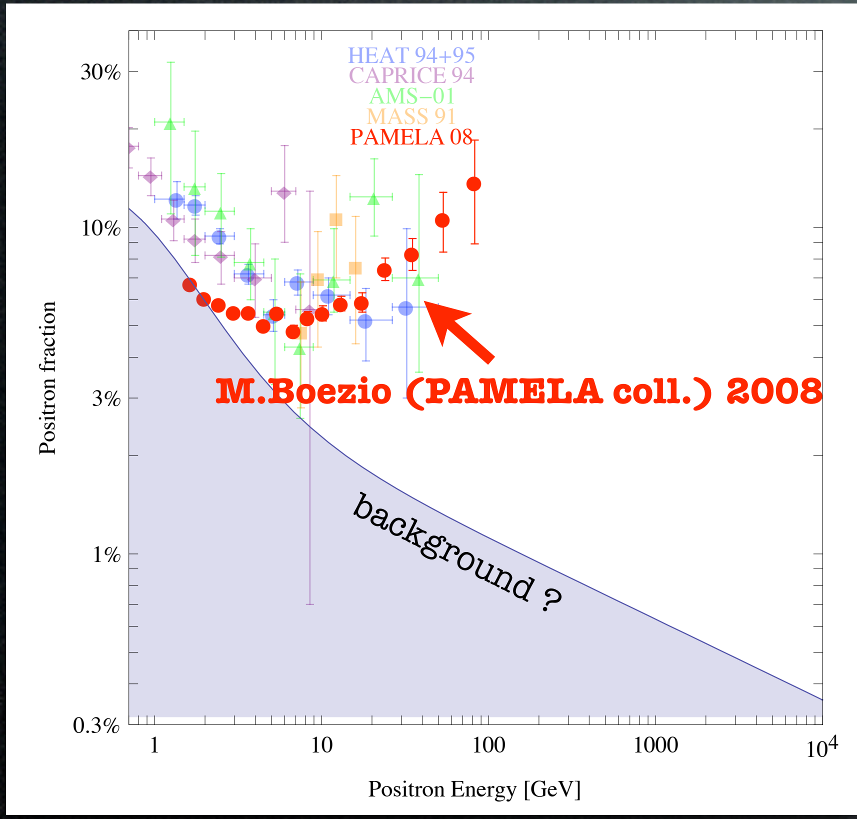
- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?



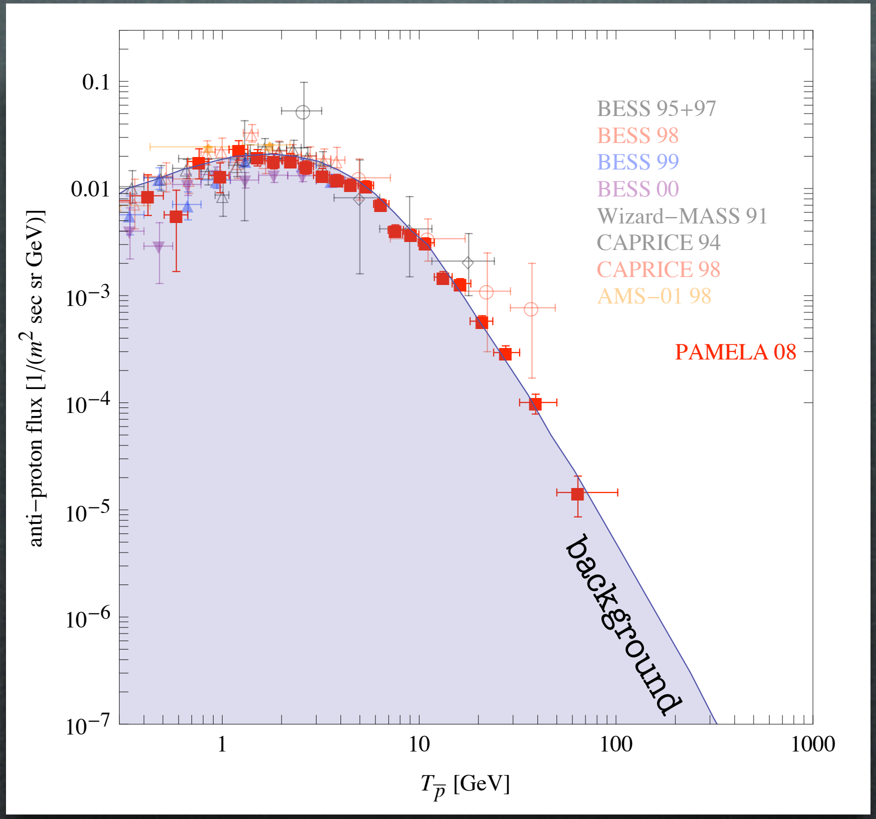
[formerly predicted GLAST sensitivity]

Data

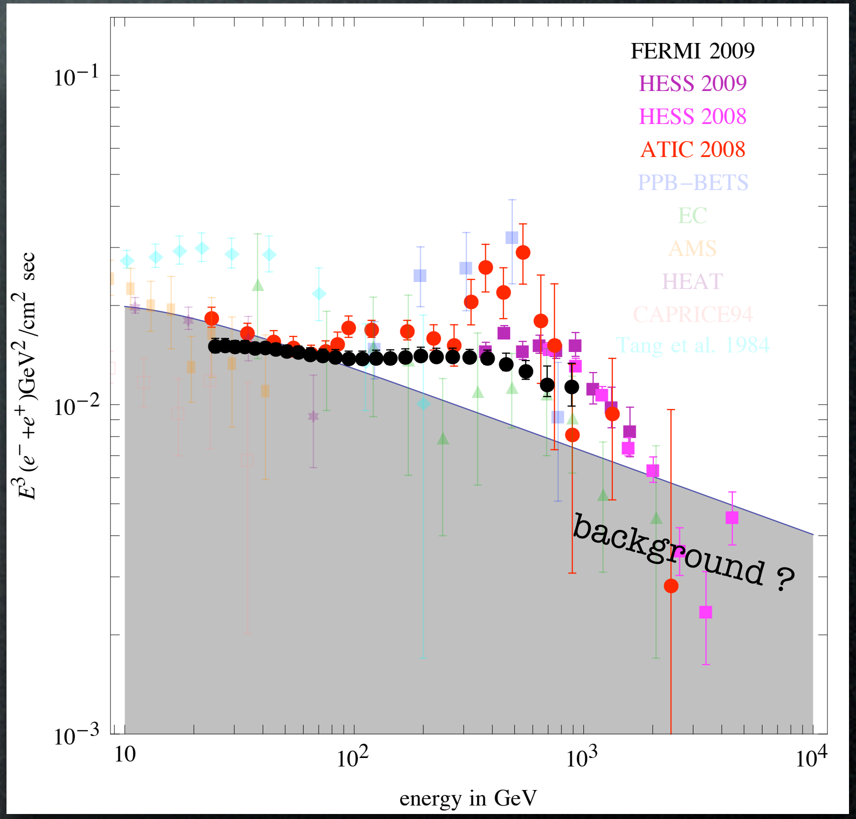
positron fraction



antiprotons



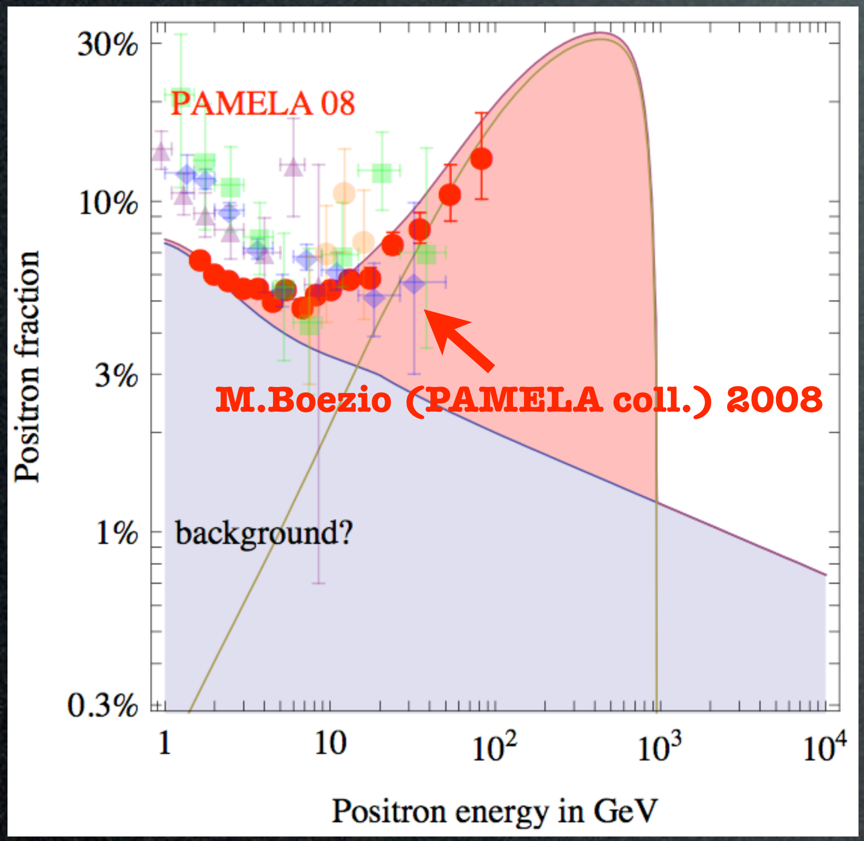
electrons + positrons



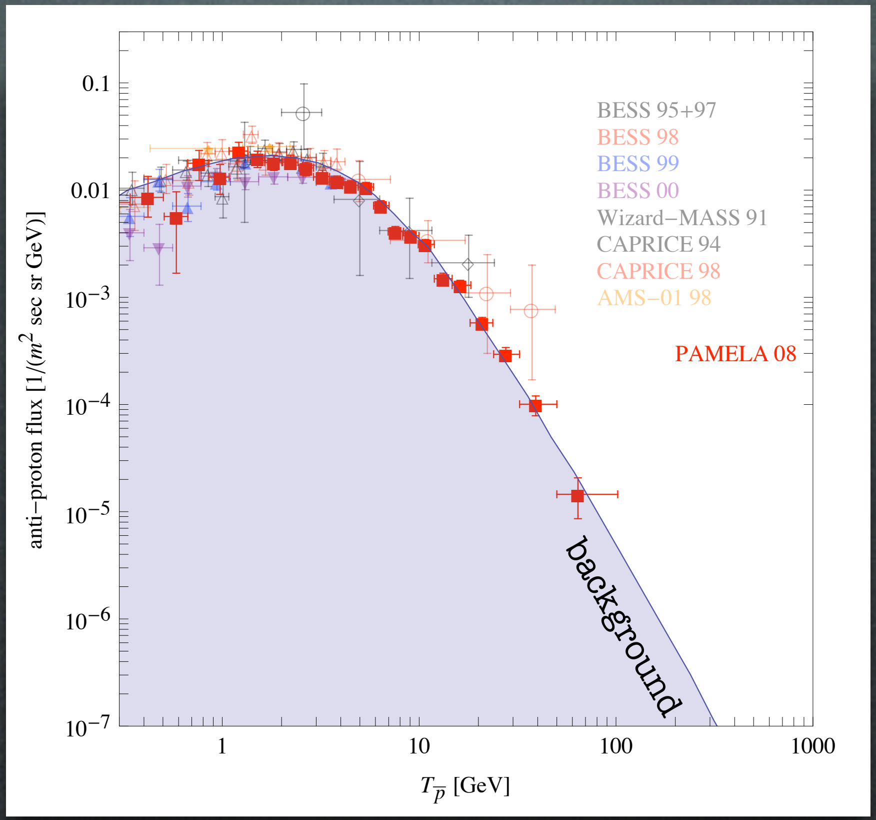
Are these signals of Dark Matter?

Data

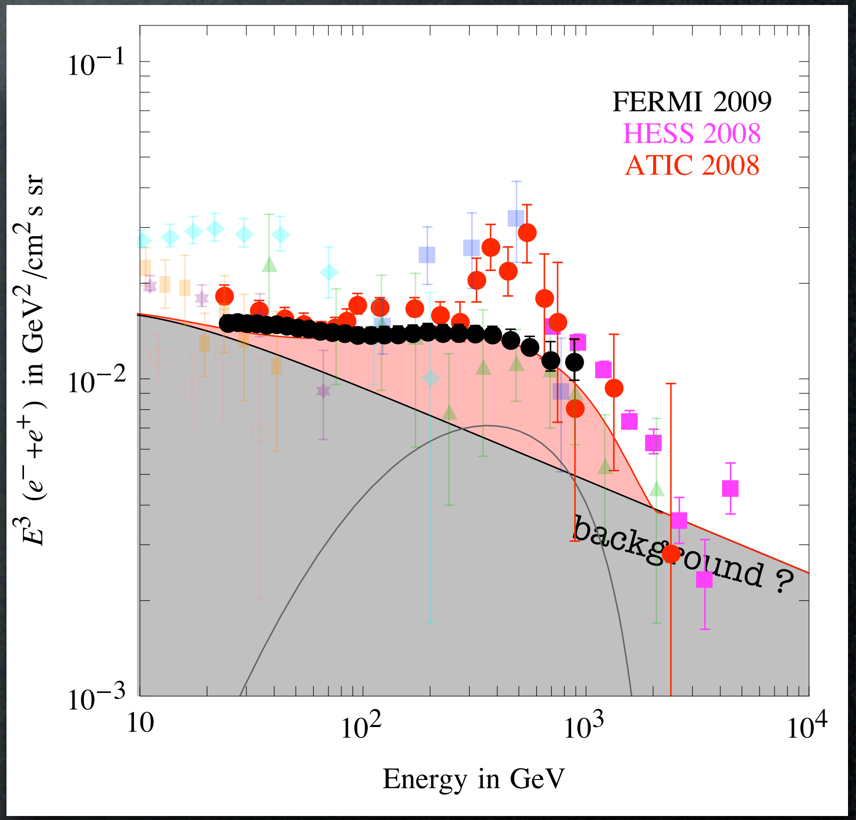
positron fraction



antiprotons



electrons + positrons

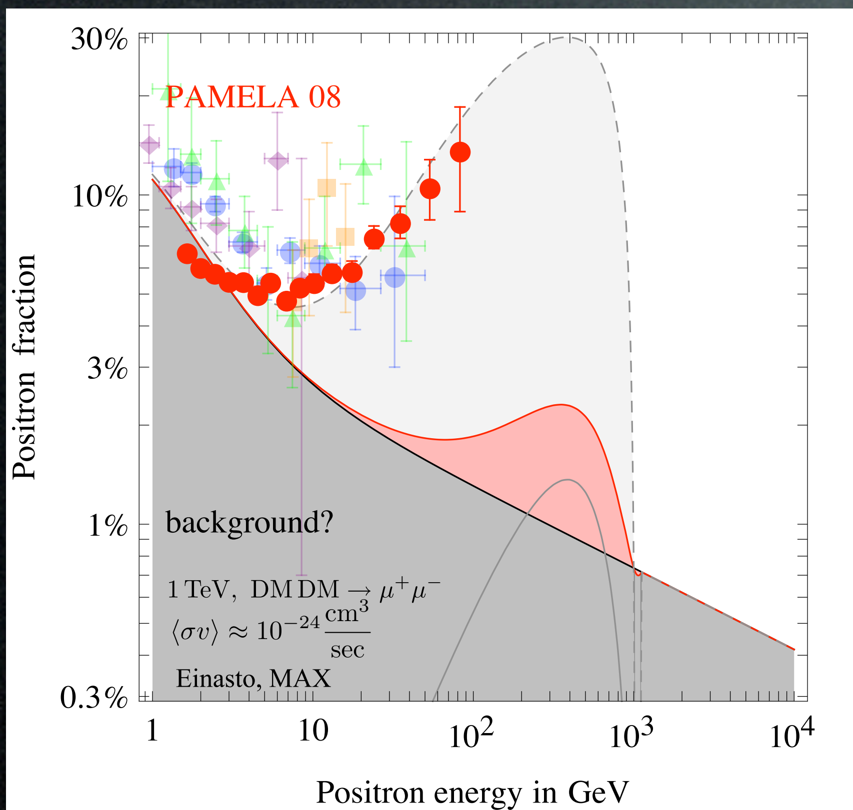


Are these signals of Dark Matter?

YES: few TeV, leptophilic DM
with huge $\langle\sigma v\rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

Data

positron fraction



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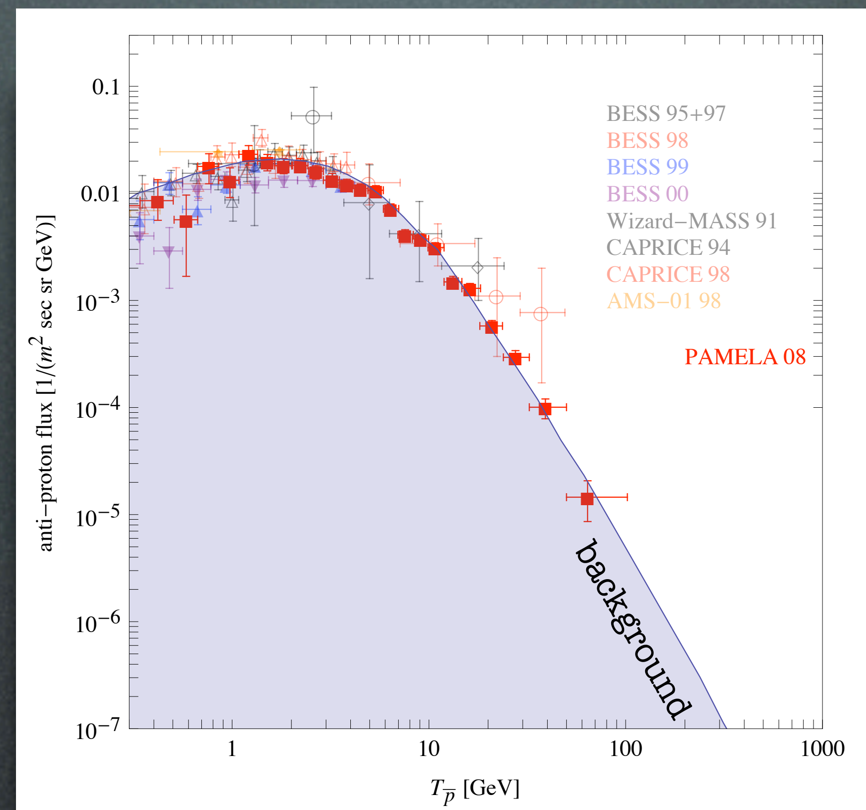
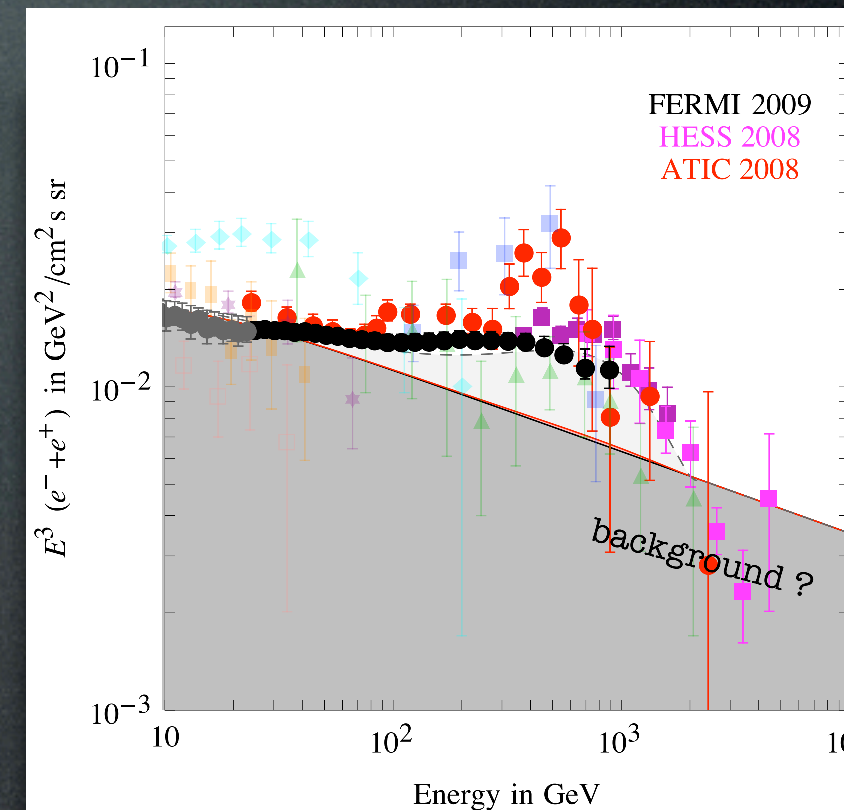


electrons + positrons



Are these signals of Dark Matter?

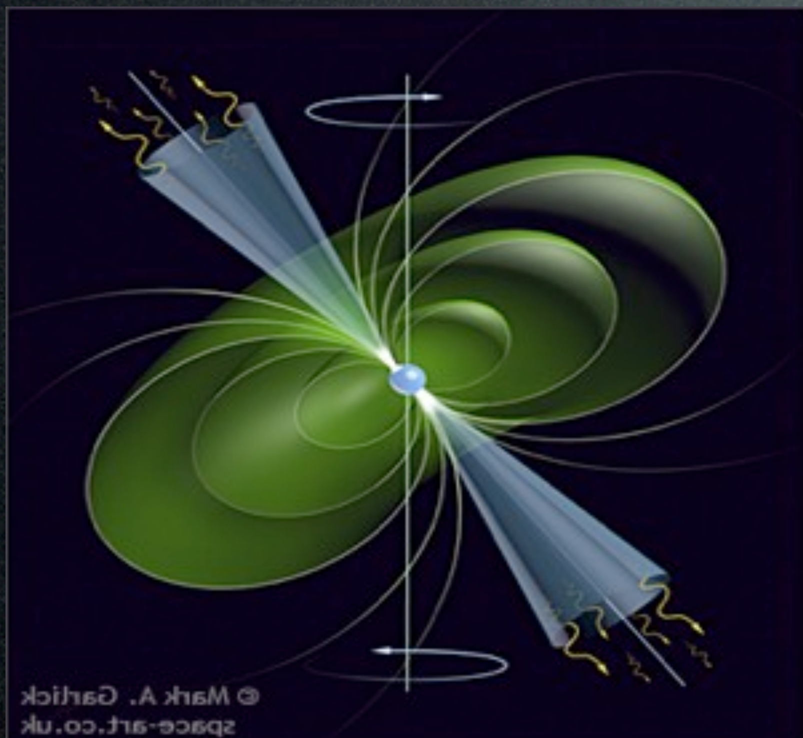
YES: few TeV, leptophilic DM
with huge $\langle\sigma v\rangle \approx 10^{-23}\,\text{cm}^3/\text{sec}$

NO: a formidable ‘background’ for future searches

Astrophysical explanation?

Astrophysical explanation?

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



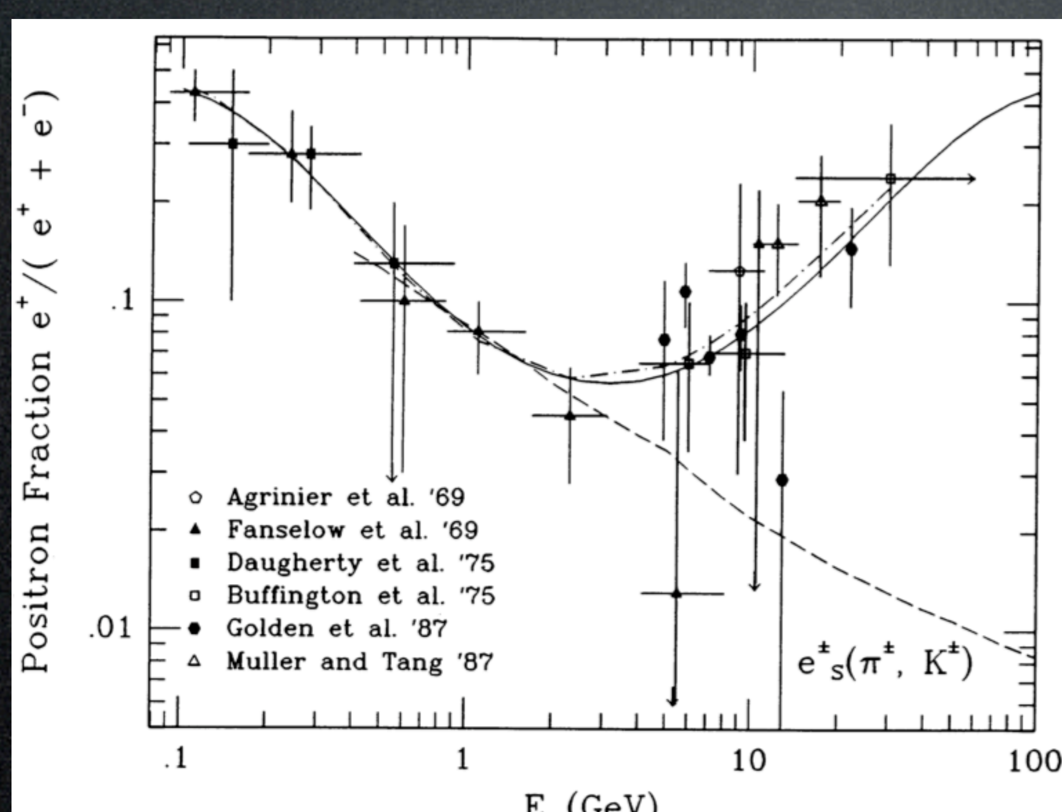
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \rightarrow 10^5$ yr (typical total energy output: 10^{46} erg).

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

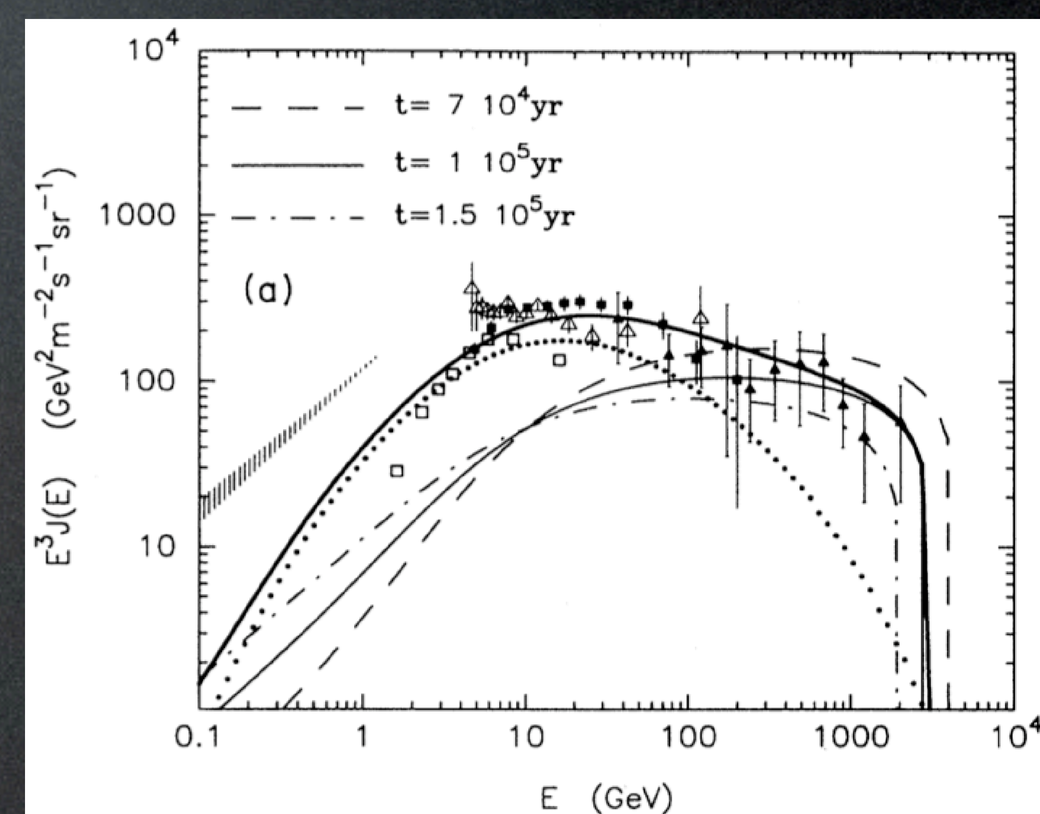
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

Not a new idea:



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



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

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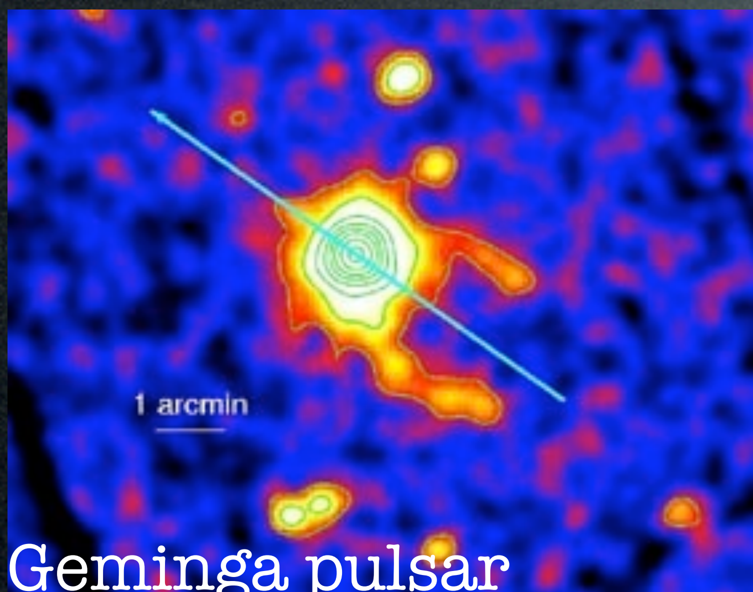

Geminga pulsar
(funny that it means:
"it is not there" in milanese)

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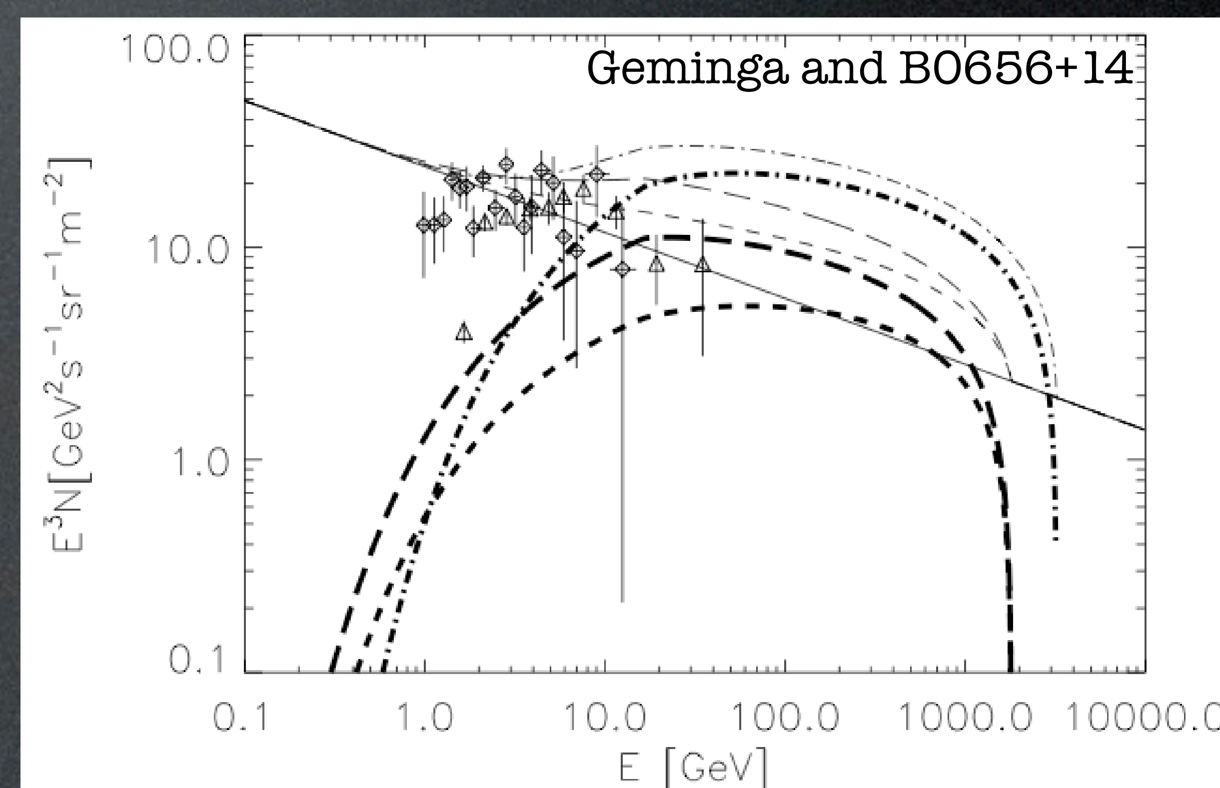
Try the fit with known nearby pulsars:

TABLE 1
List of Nearby SNRs

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



Büshing, de Jager et al. 0804.0220

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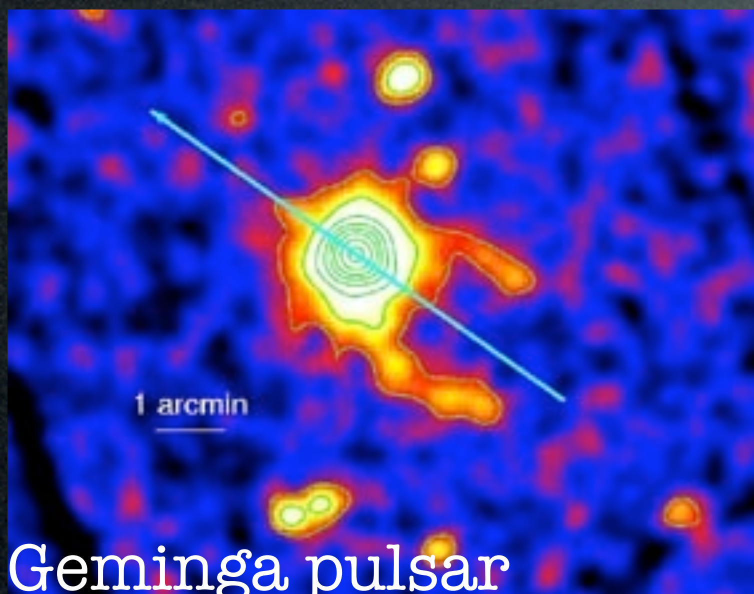


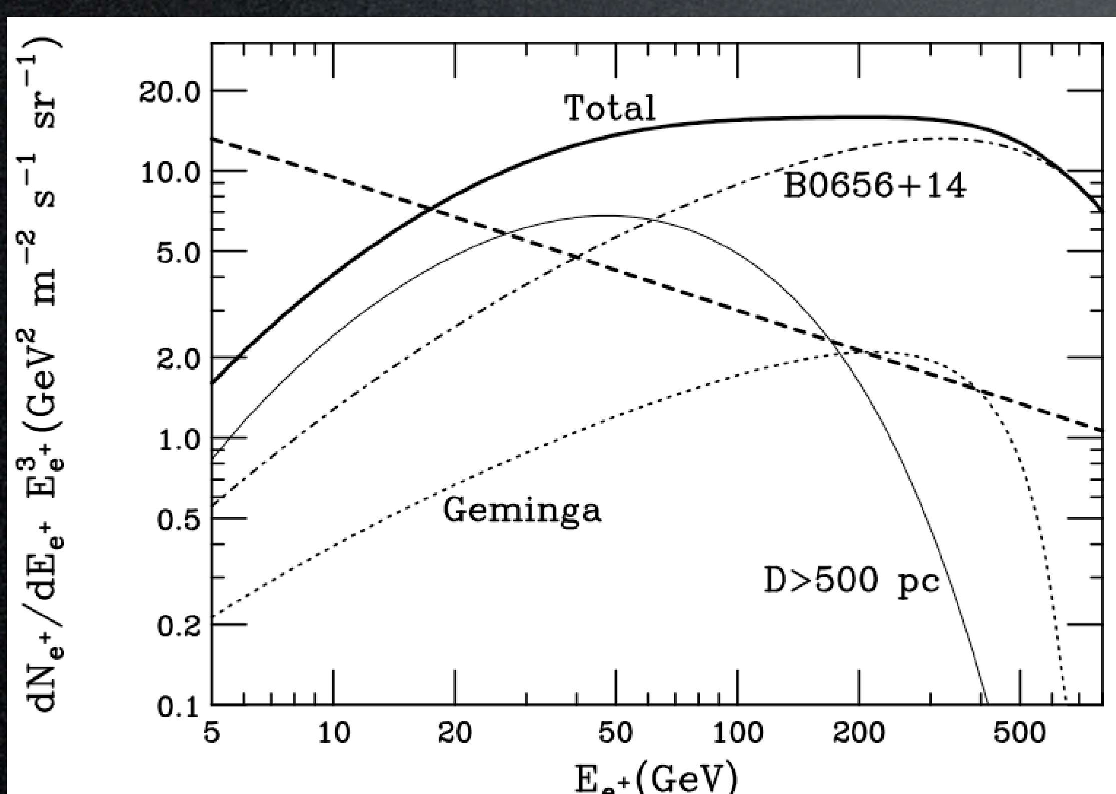
Geminga pulsar

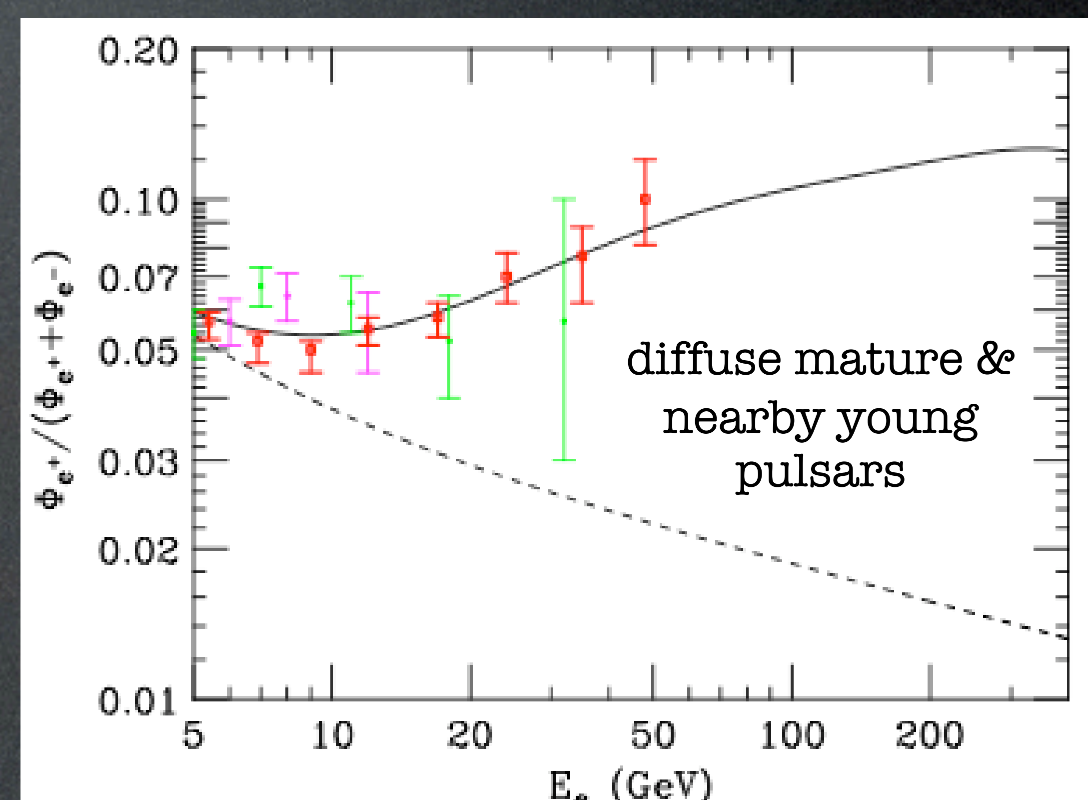
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \to 10^5$ yr.

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

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

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

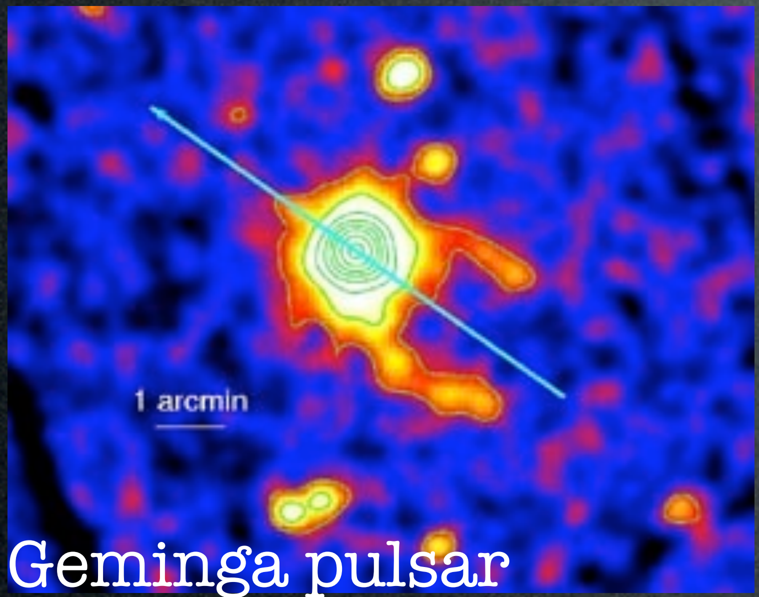




Hooper, Blasi, Serpico 2008

Astrophysical explanation?

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



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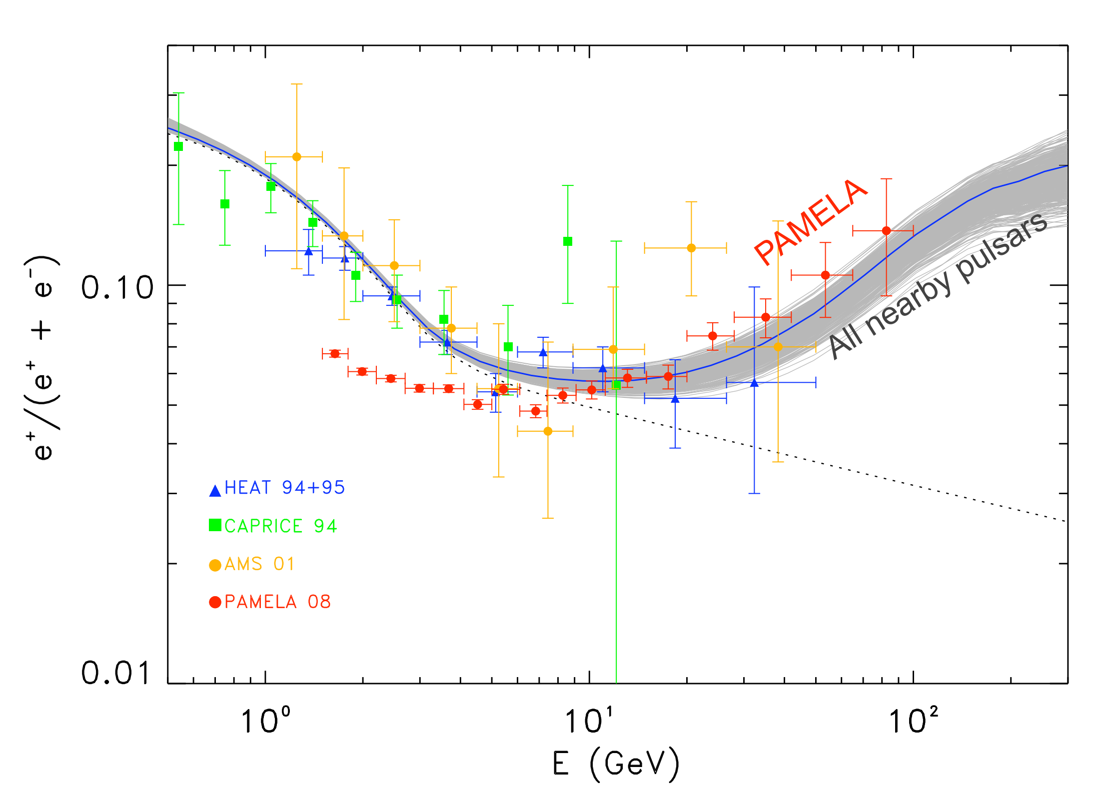
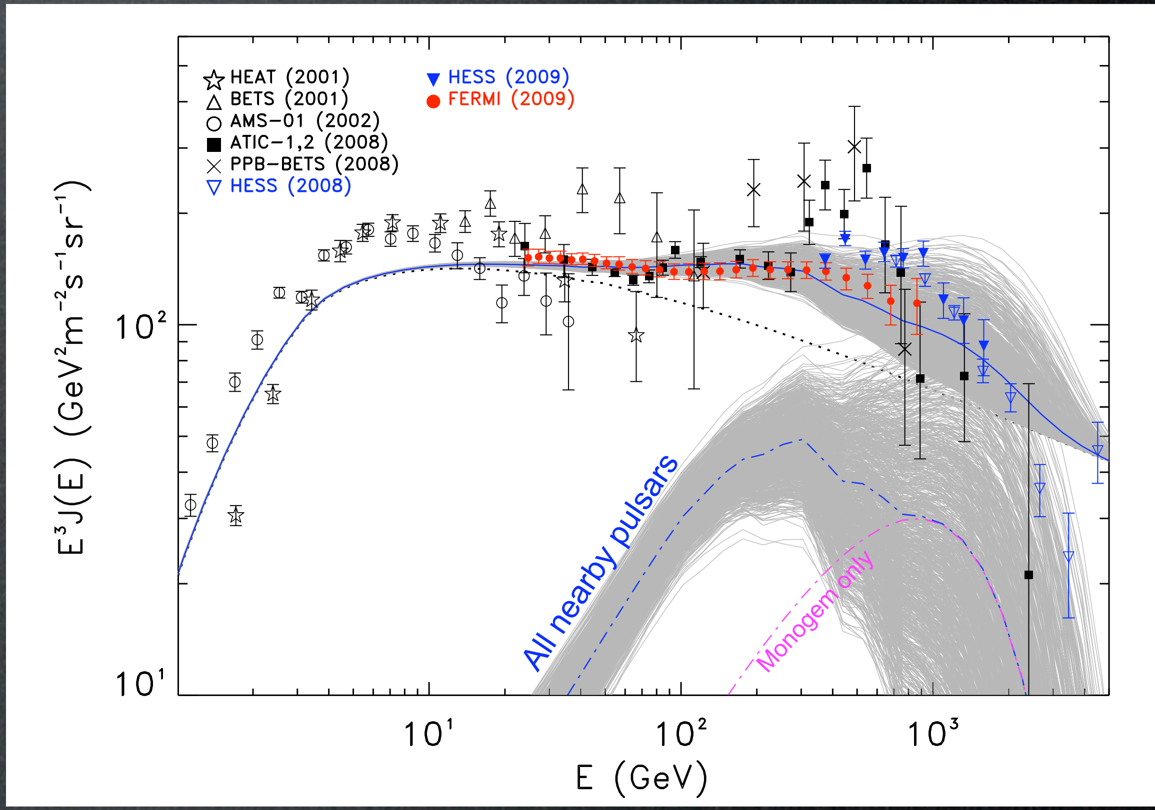
PAMELA + FERMI + HESS can be well fitted by pulsars:





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

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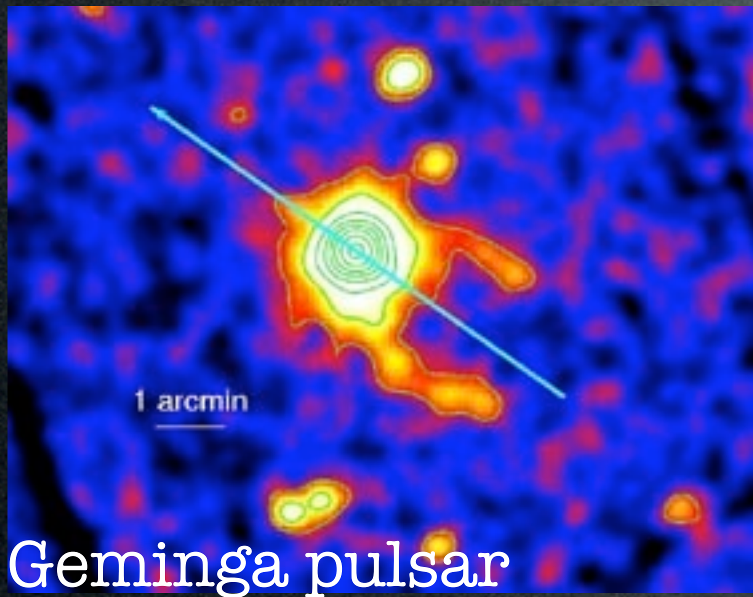

Geminga pulsar

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

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

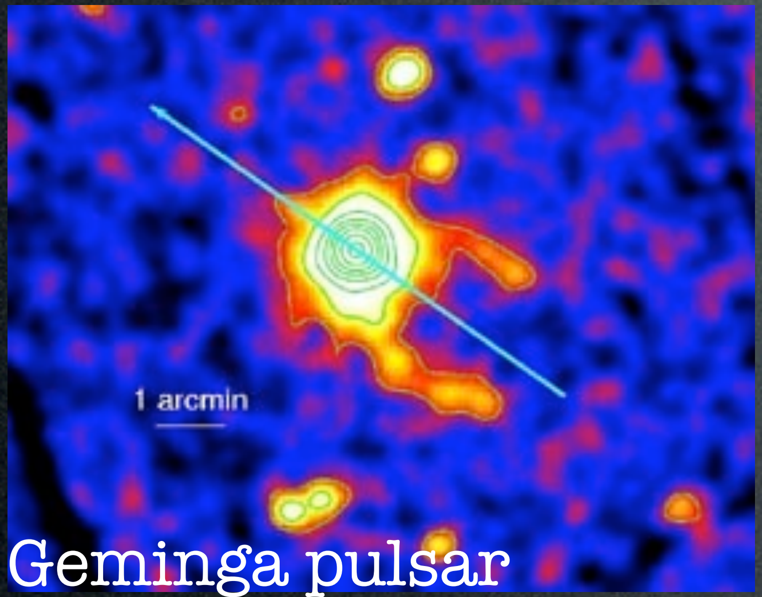
Open issue.

(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

Astrophysical explanation?

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



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Must be young (T < 10^5 yr) and nearby (< 1 kpc);
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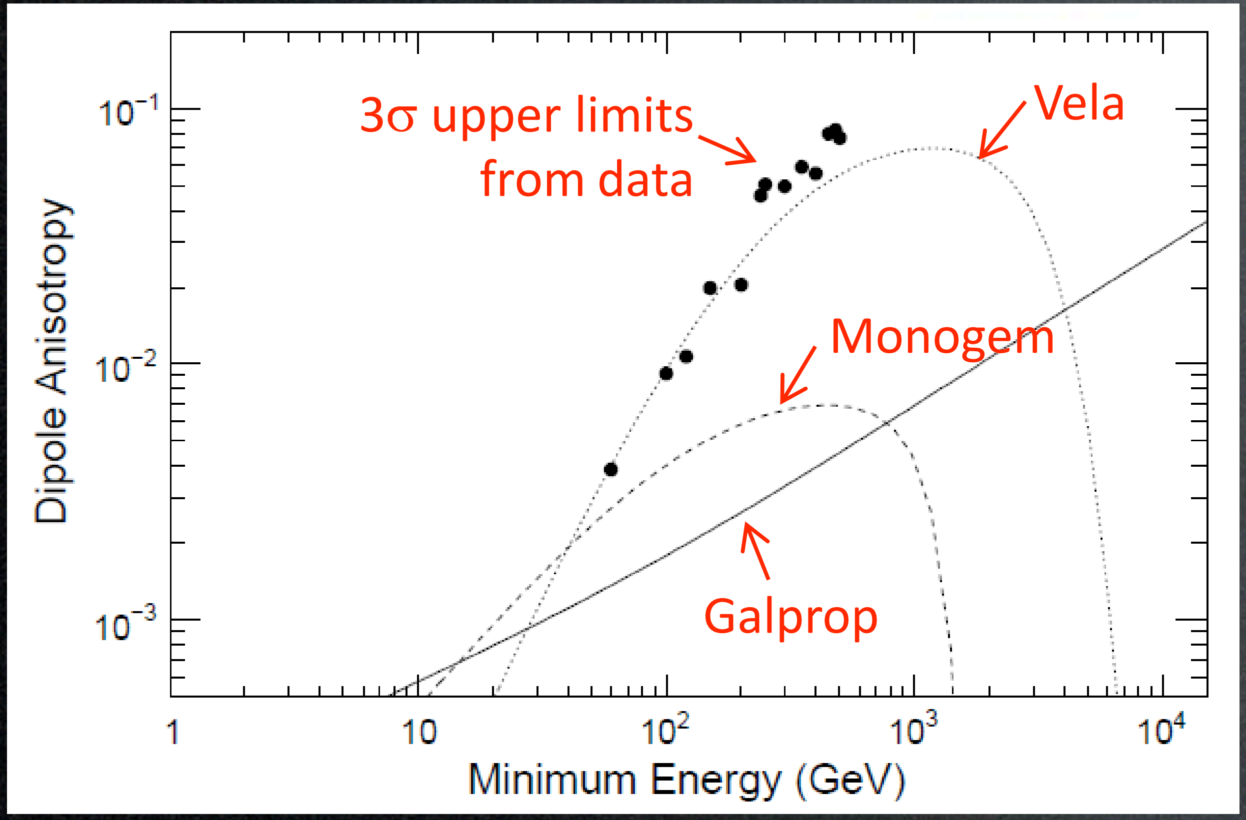
Fermi coll., 1008.5119



Rule out one single bright source.

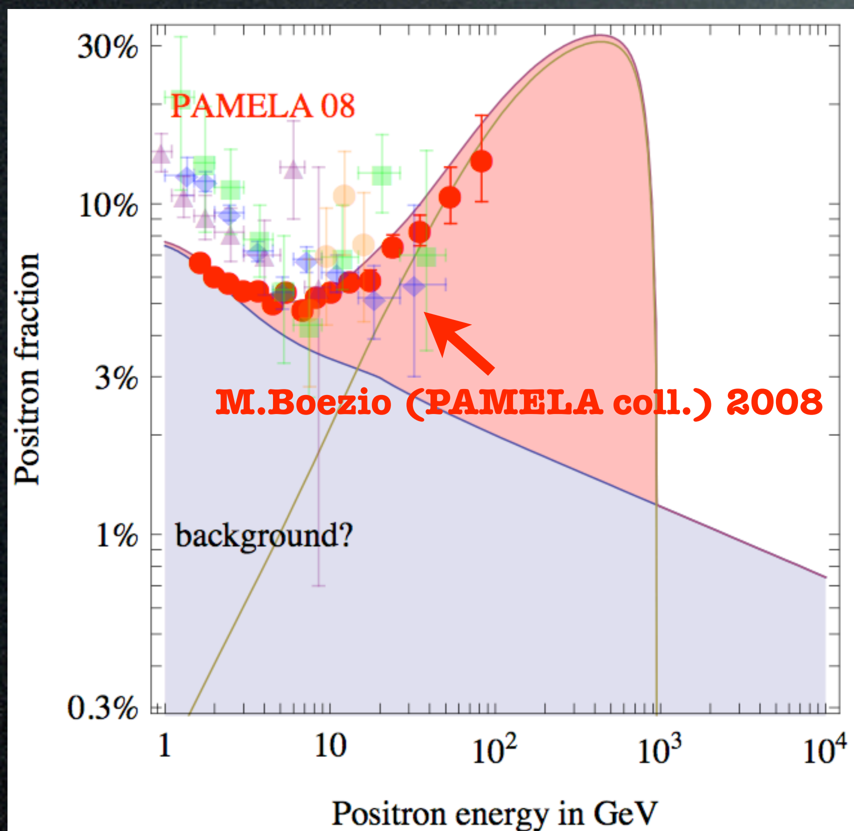
Open issue.

(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...)

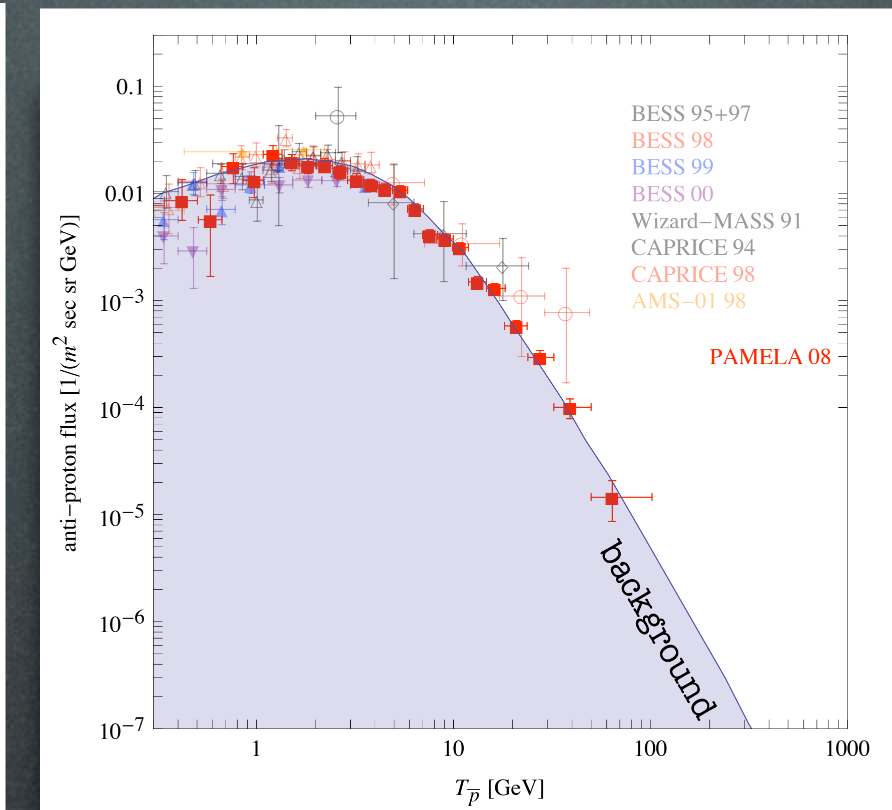
e.g. Yuksel, Kistler, Stanev 0810.2784
Hall, Hooper 0811.3362

Data

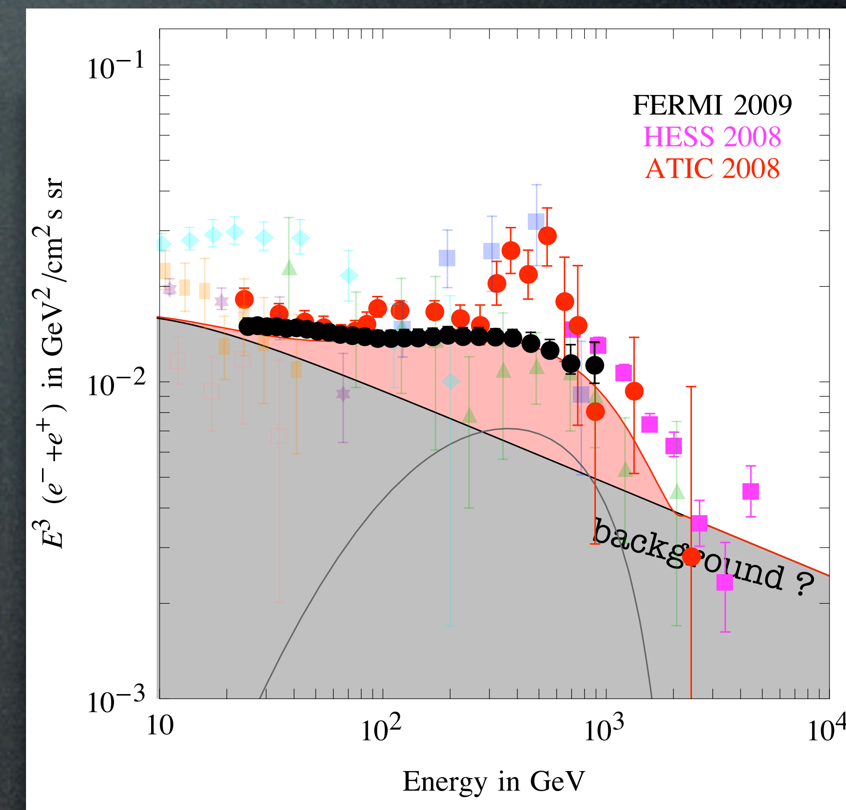
positron fraction



antiprotons



electrons + positrons



Are these signals of Dark Matter?

YES: few TeV, leptophilic DM
with huge $\langle\sigma v\rangle \approx 10^{-23}\,\text{cm}^3/\text{sec}$

NO: a formidable ‘background’ for future searches

DM detection

direct detection

production at colliders

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

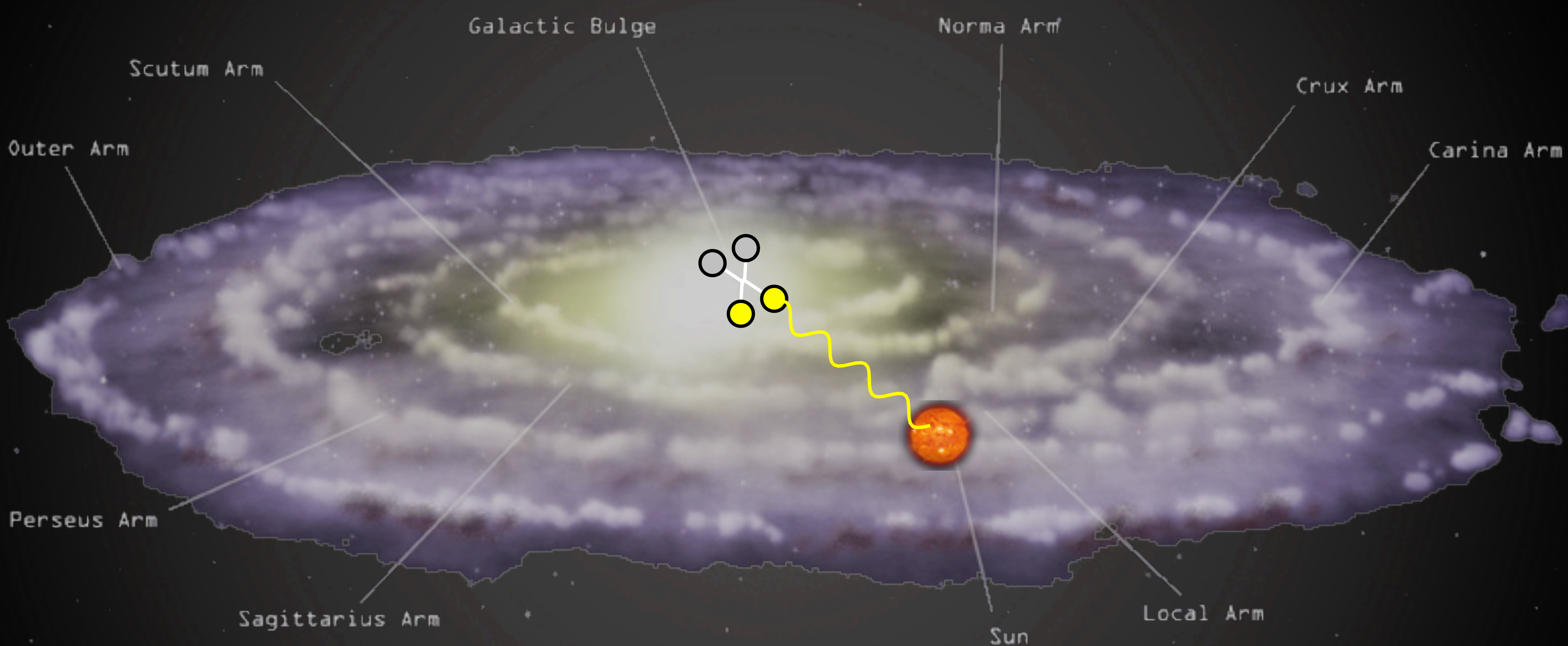
$\bar{p}$ from annihil in galactic halo or center

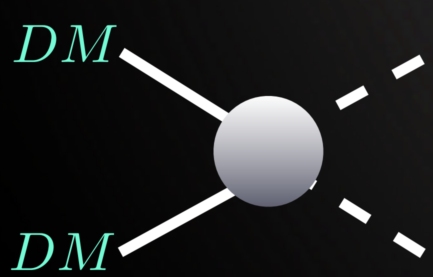
$\bar{D}$ from annihil in galactic halo or center

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

Indirect Detection

γ from DM annihilations in galactic center



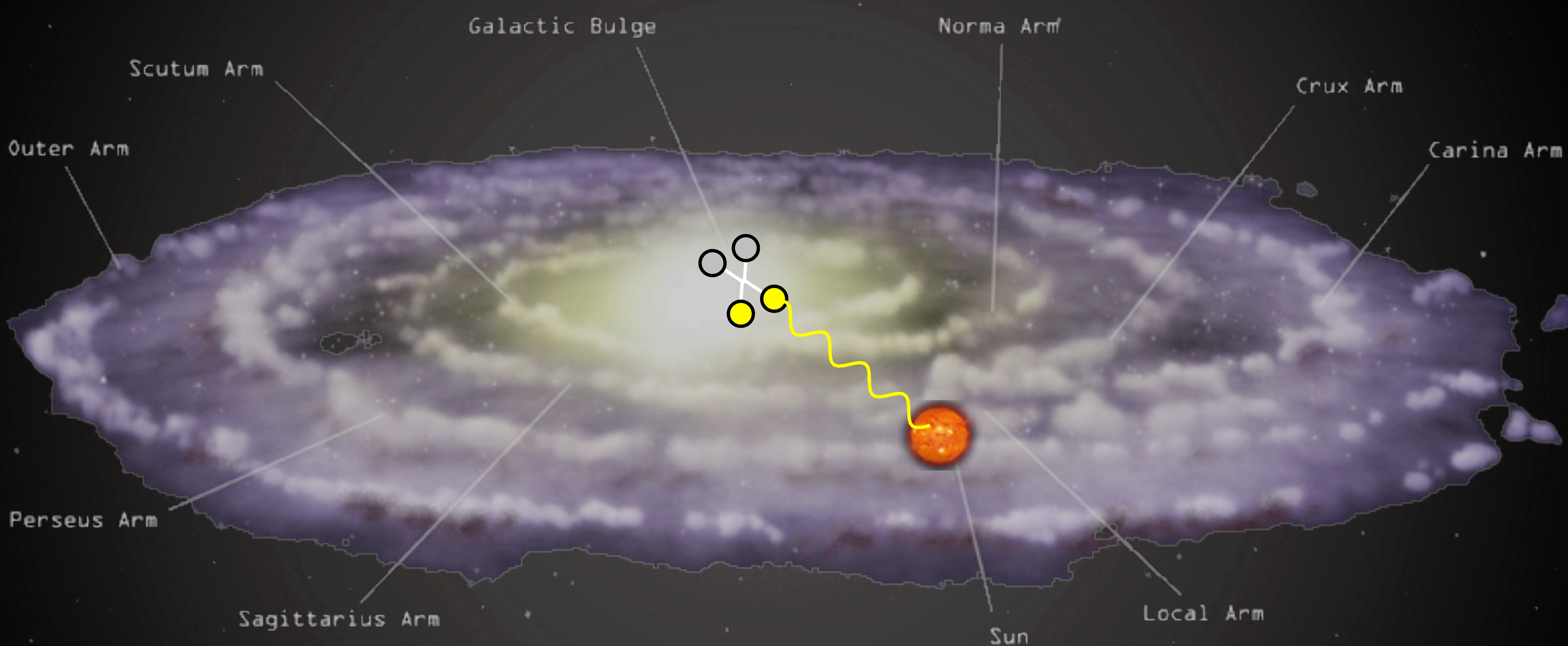


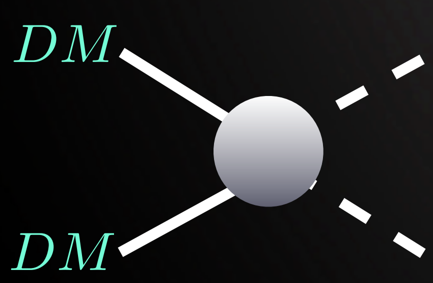
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

Indirect Detection

a. γ from DM annihilations in galactic center



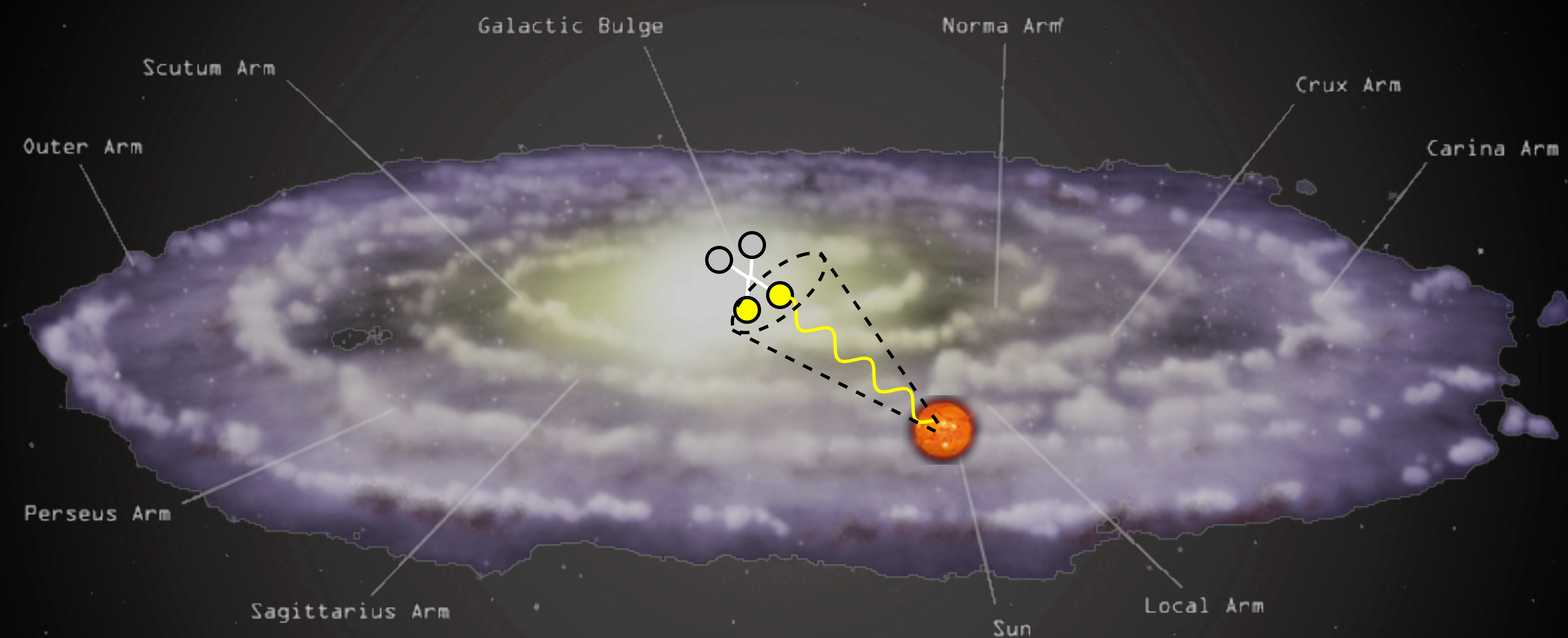


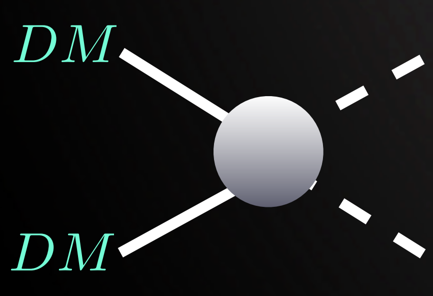
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and } \gamma$$

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

Indirect Detection

a. γ from DM annihilations in galactic center





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

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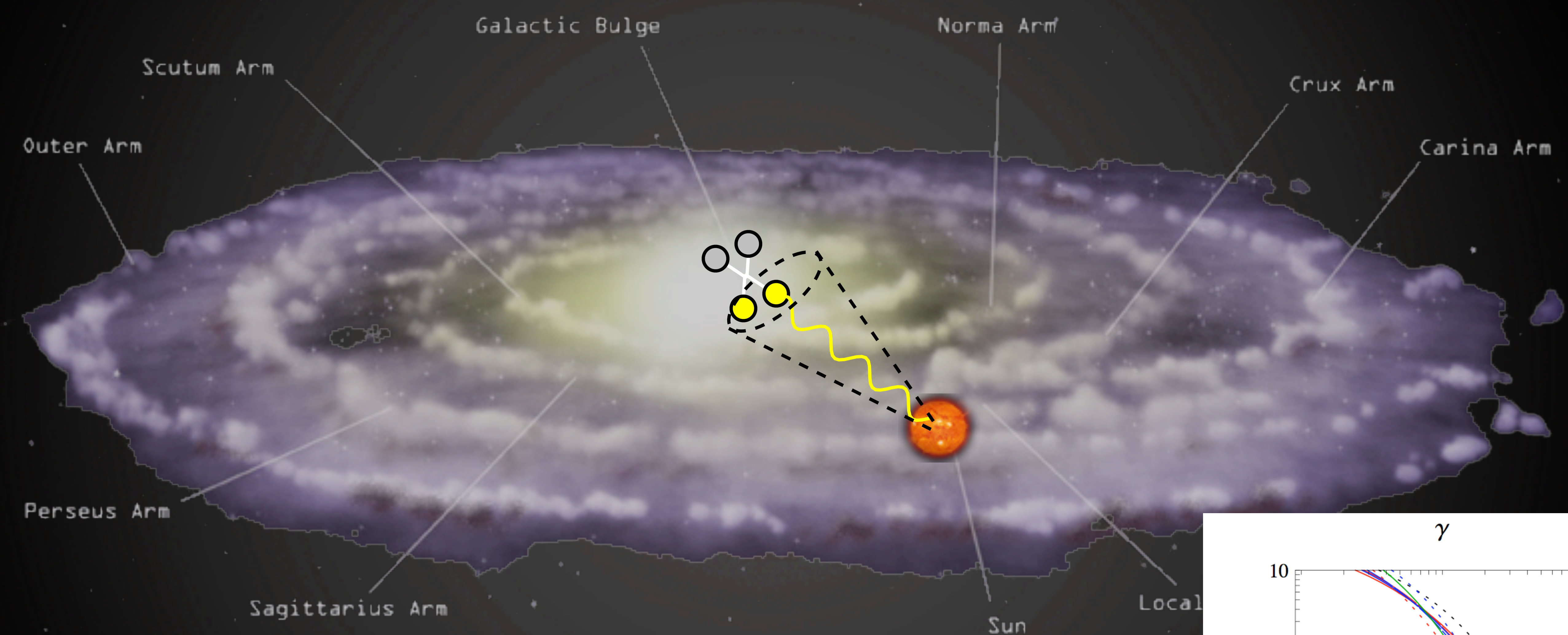
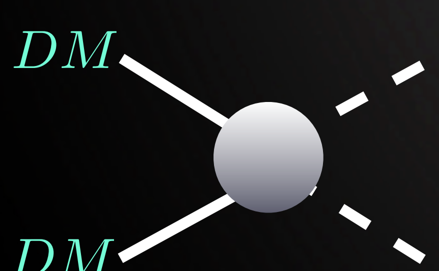
Indirect Detection

a. γ from DM annihilations in galactic center





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

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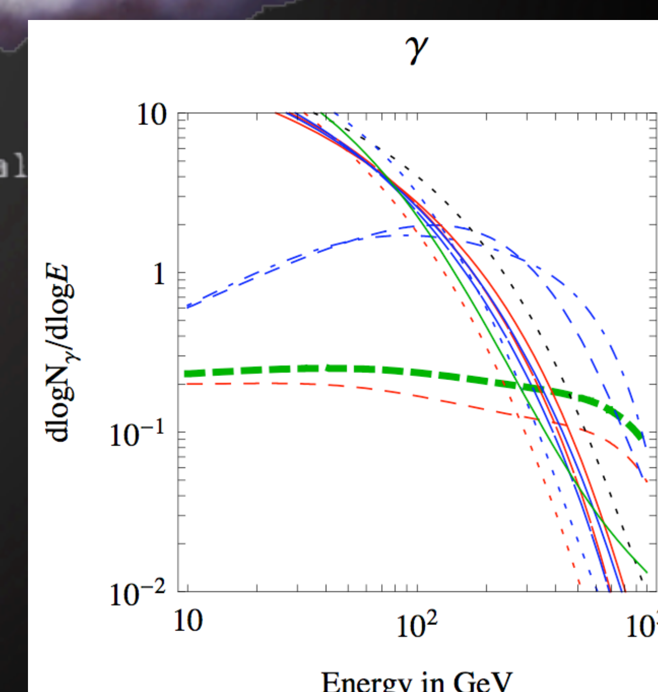
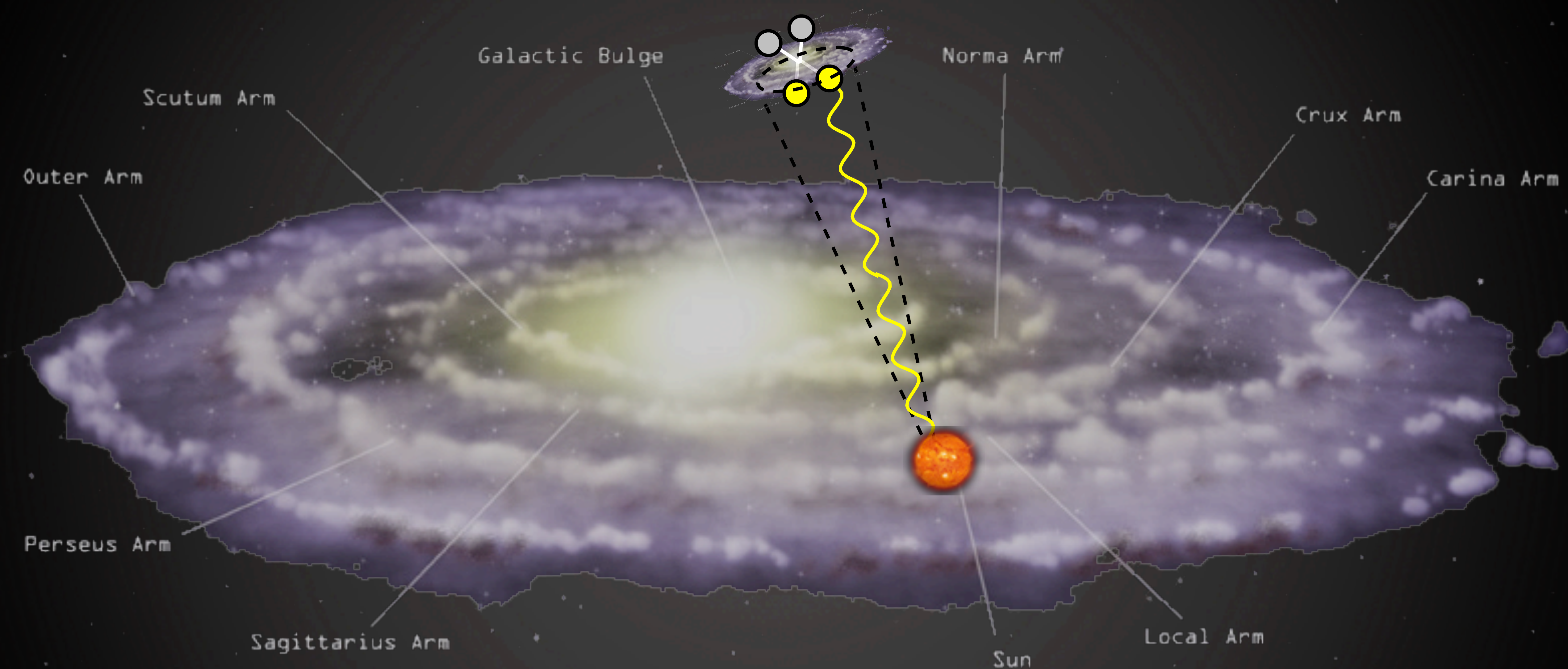
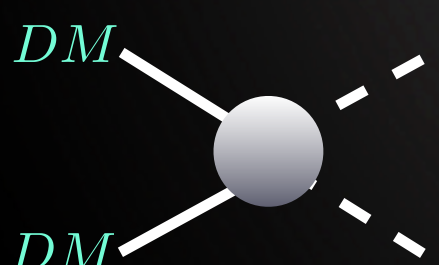


typically sub-TeV energies

Indirect Detection

b. γ from DM annihilations in Sagittarius Dwarf



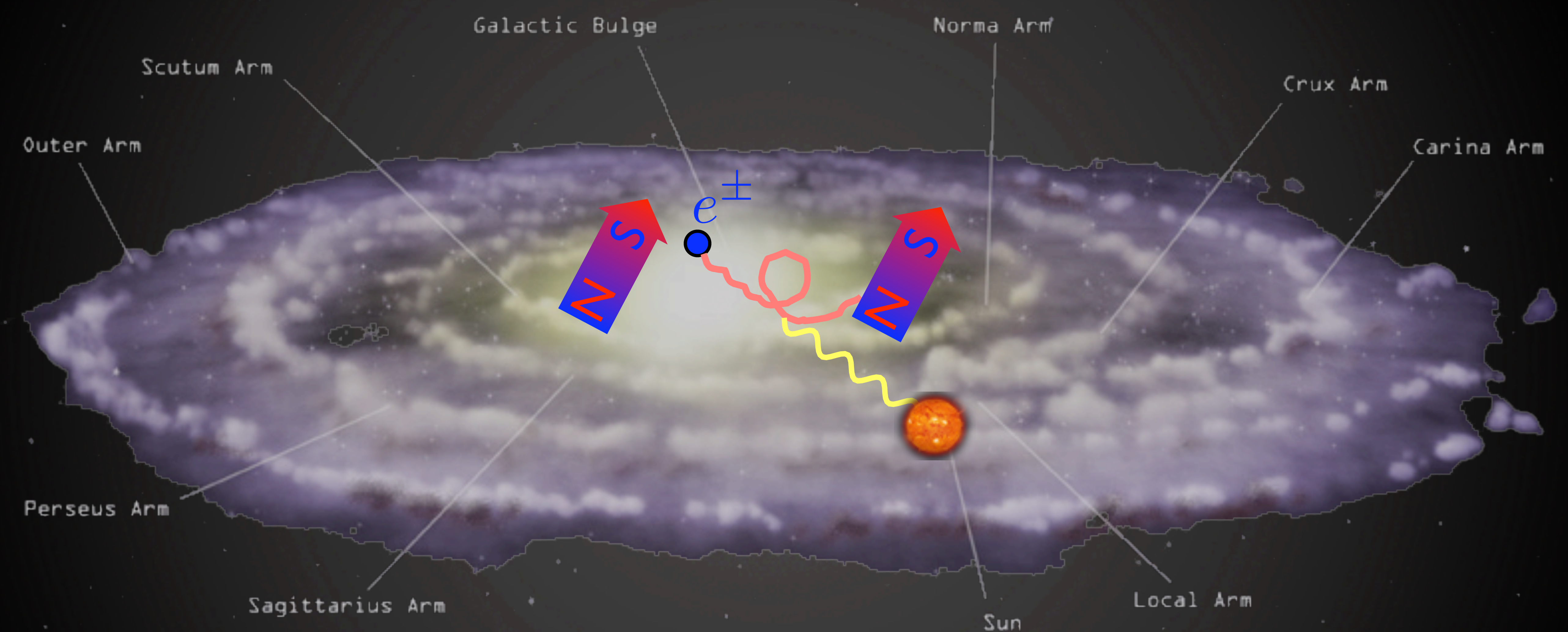


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

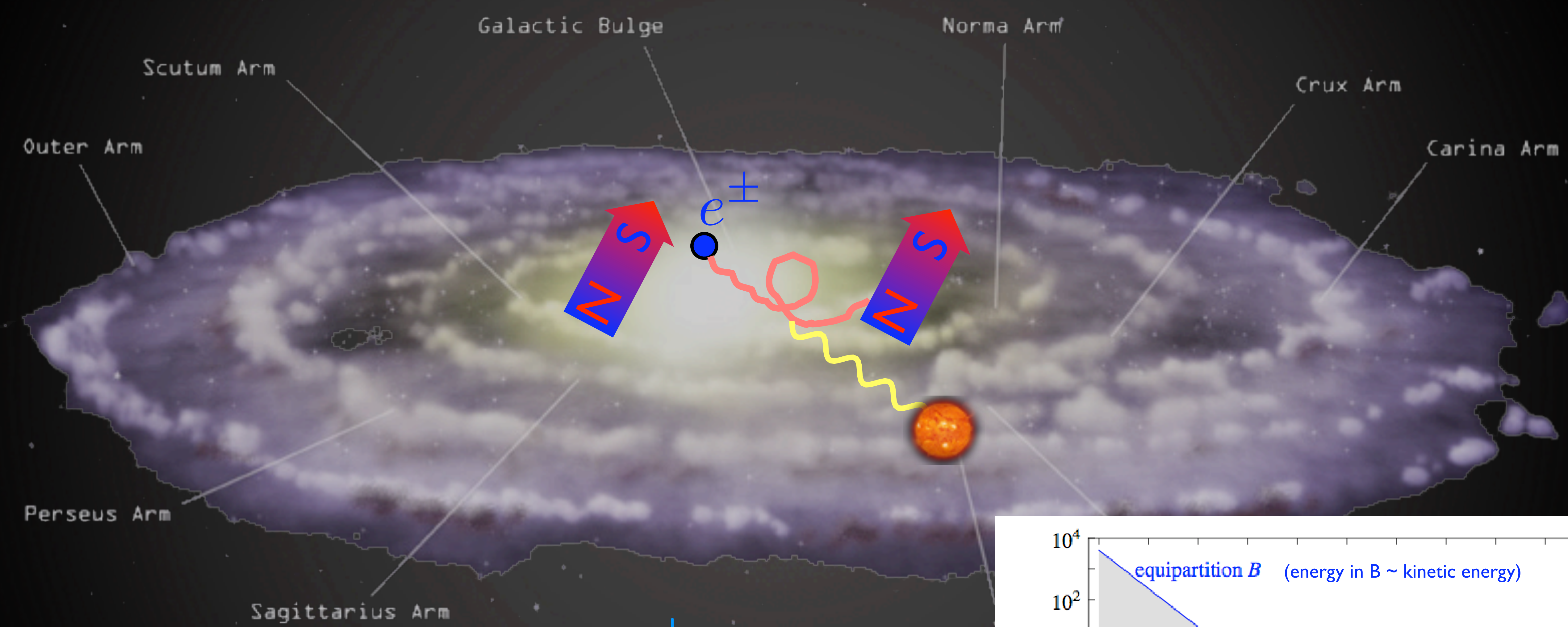
Indirect Detection

c. radio-waves from synchro radiation of $e^{\pm}$ in GC



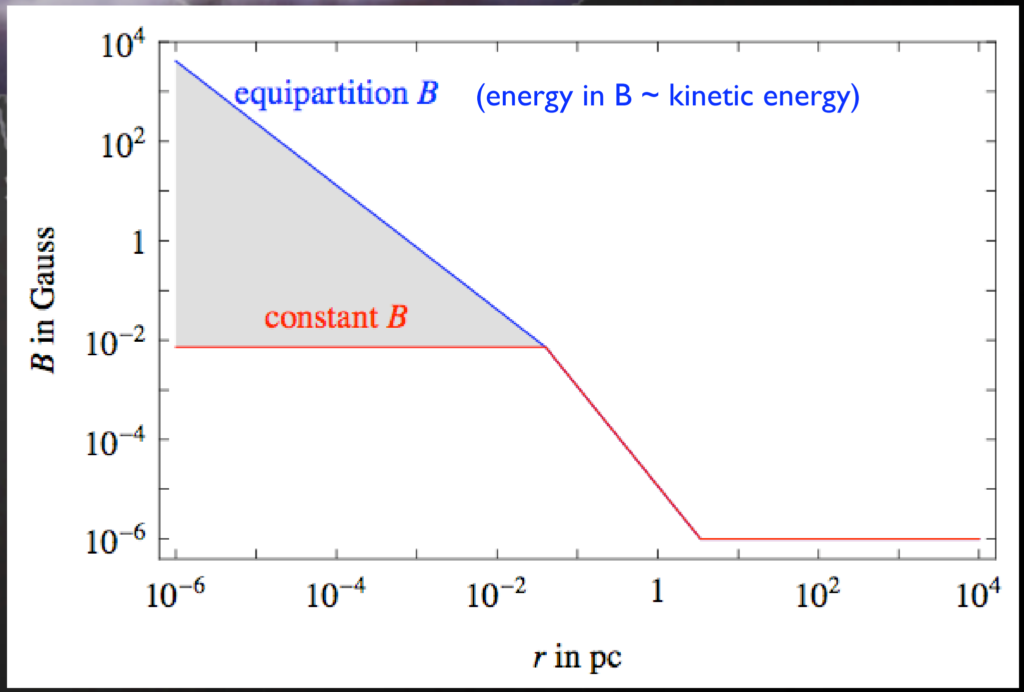
Indirect Detection

c. radio-waves from synchro radiation of $e^{\pm}$ in GC



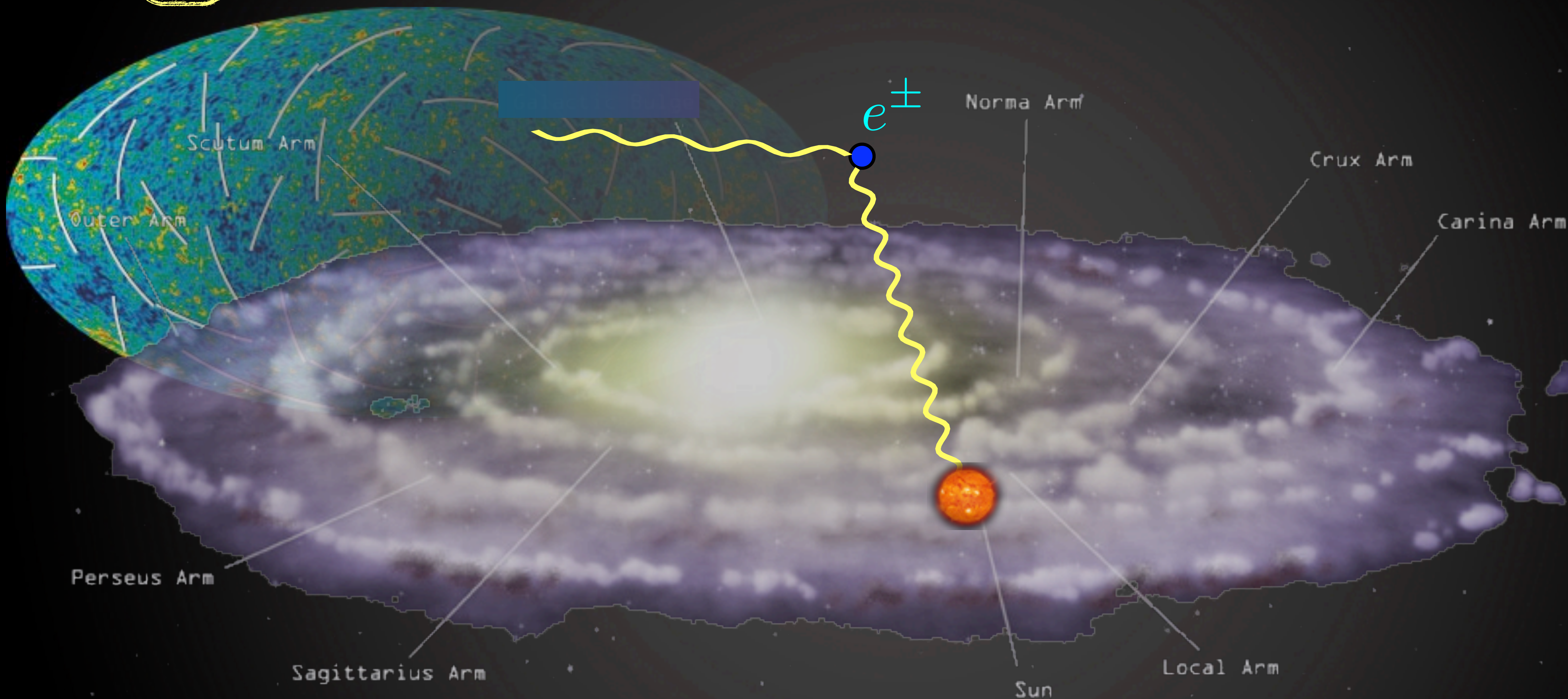
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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



Indirect Detection

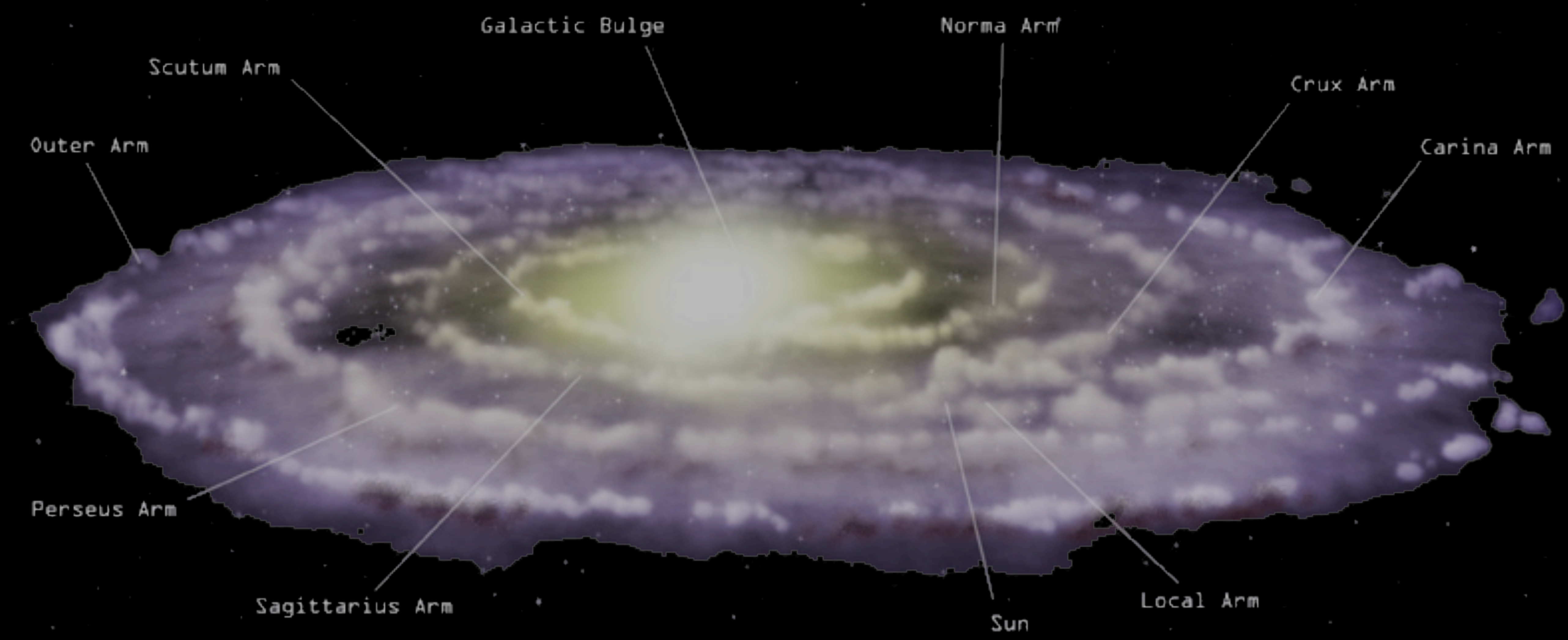
d. γ from Inverse Compton on $e^{\pm}$ in halo



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

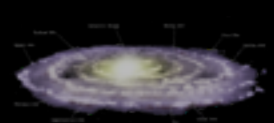
Indirect Detection

e. γ from outside the Galaxy



Indirect Detection

e. γ from outside the Galaxy

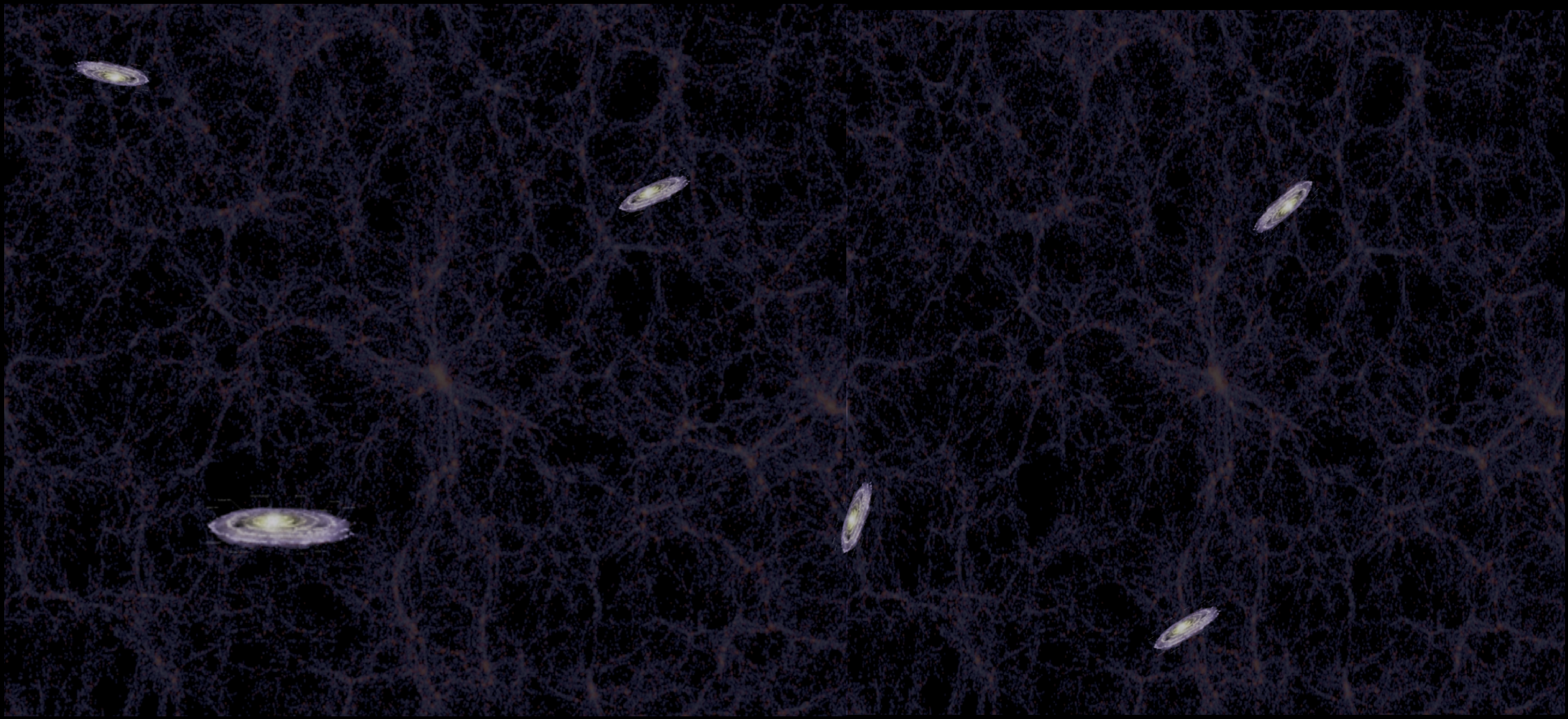


Indirect Detection

e. γ from outside the Galaxy

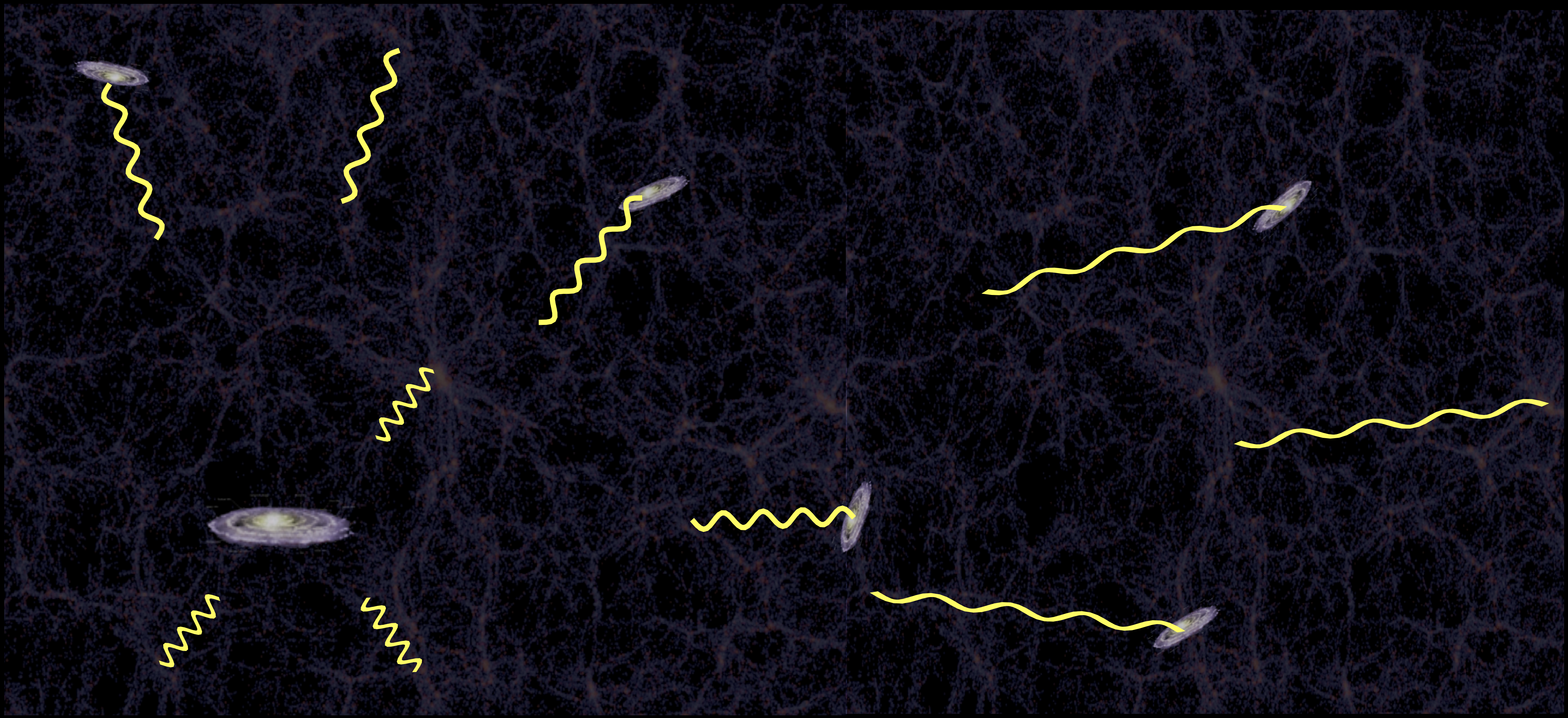
Indirect Detection

e. γ from outside the Galaxy



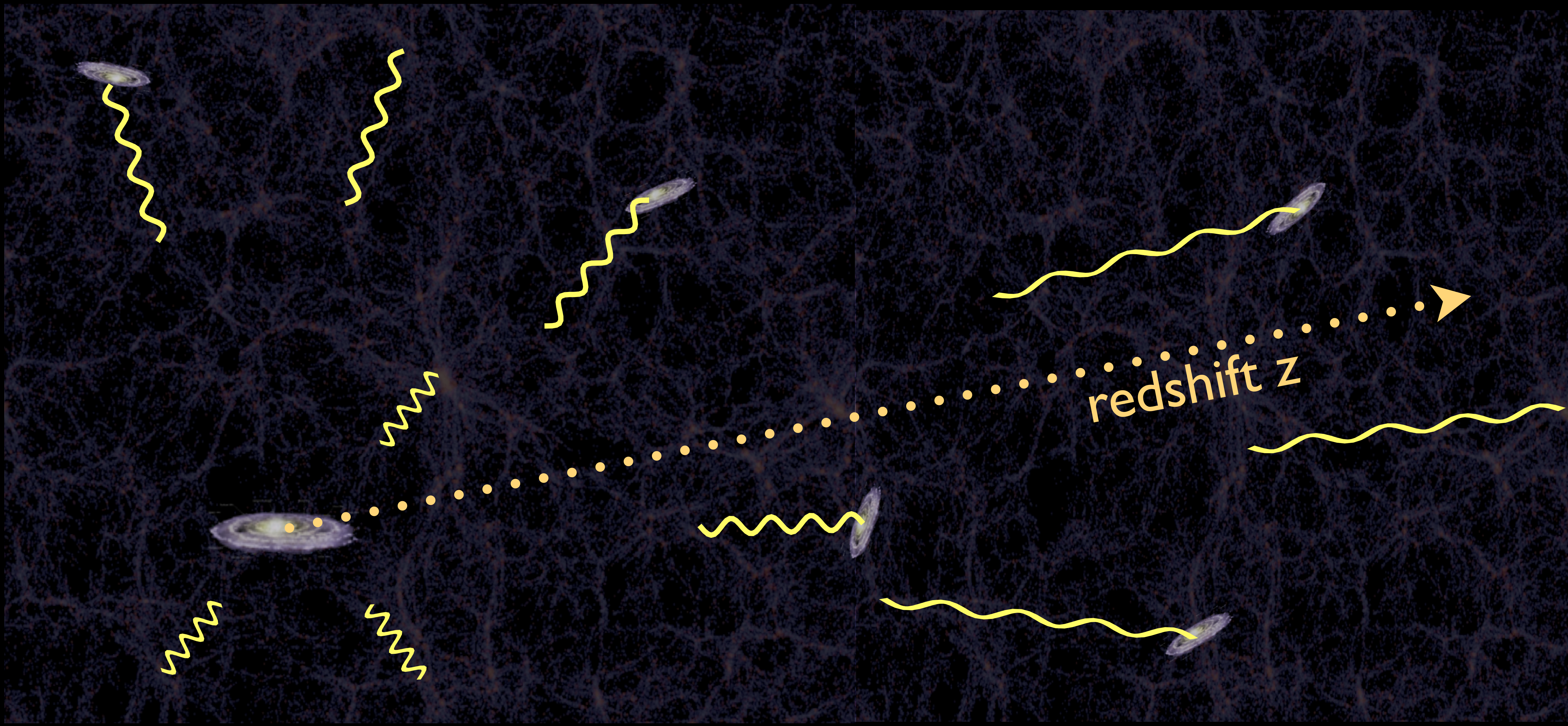
Indirect Detection

e. γ from outside the Galaxy



Indirect Detection

e. γ from outside the Galaxy

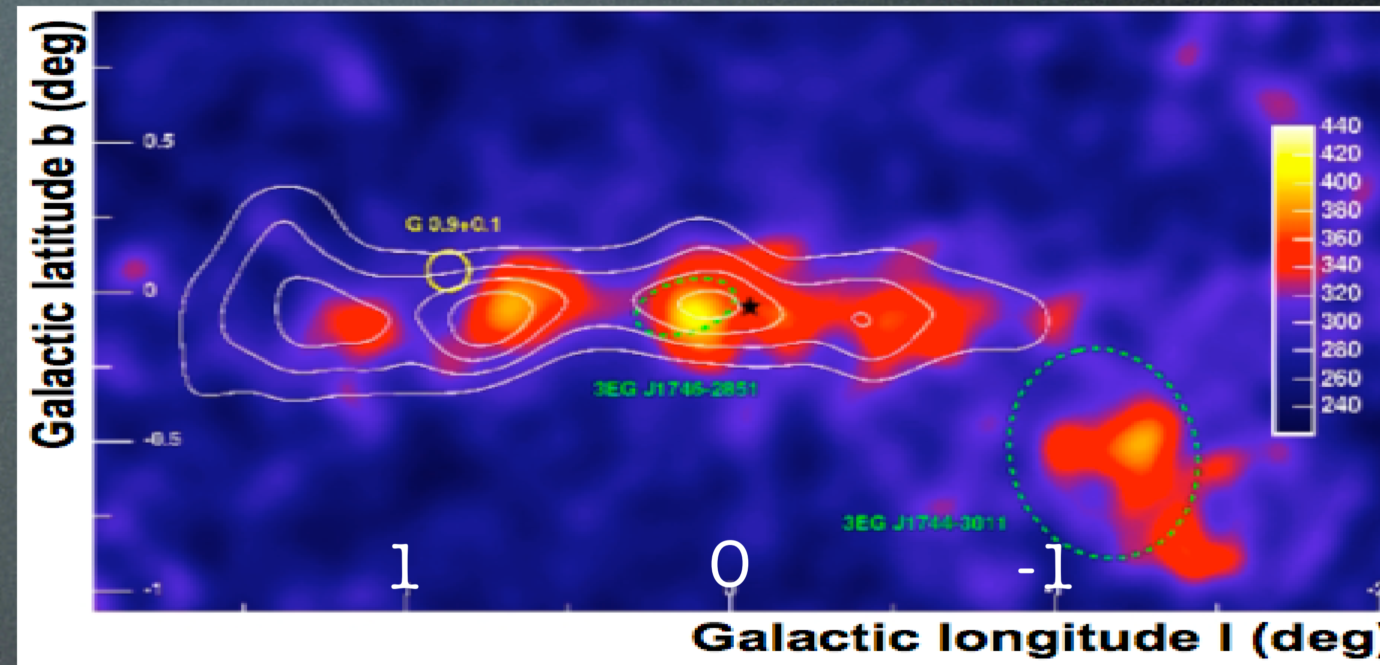


- isotropic flux of prompt and ICS gamma rays, integrated over z and r
- depends strongly on halo formation details and history

Comparing with data

Gamma constraints

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



a.

HESS coll.

Gamma constraints

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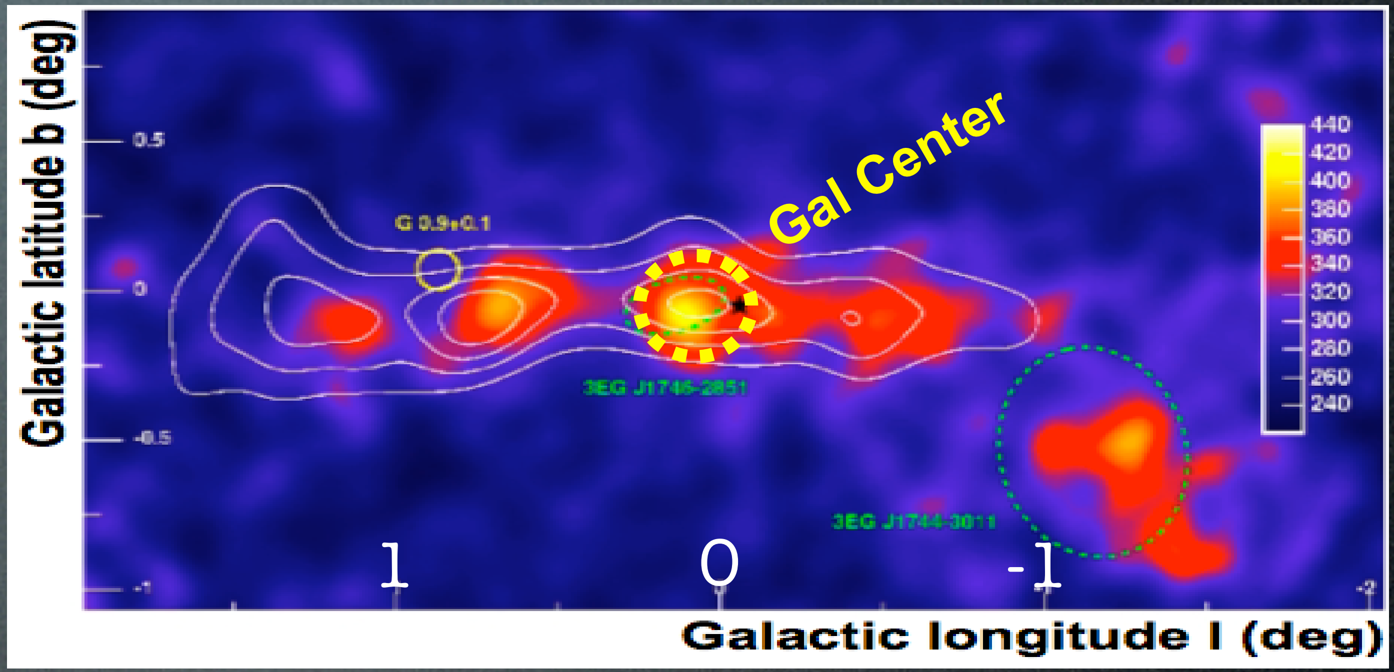

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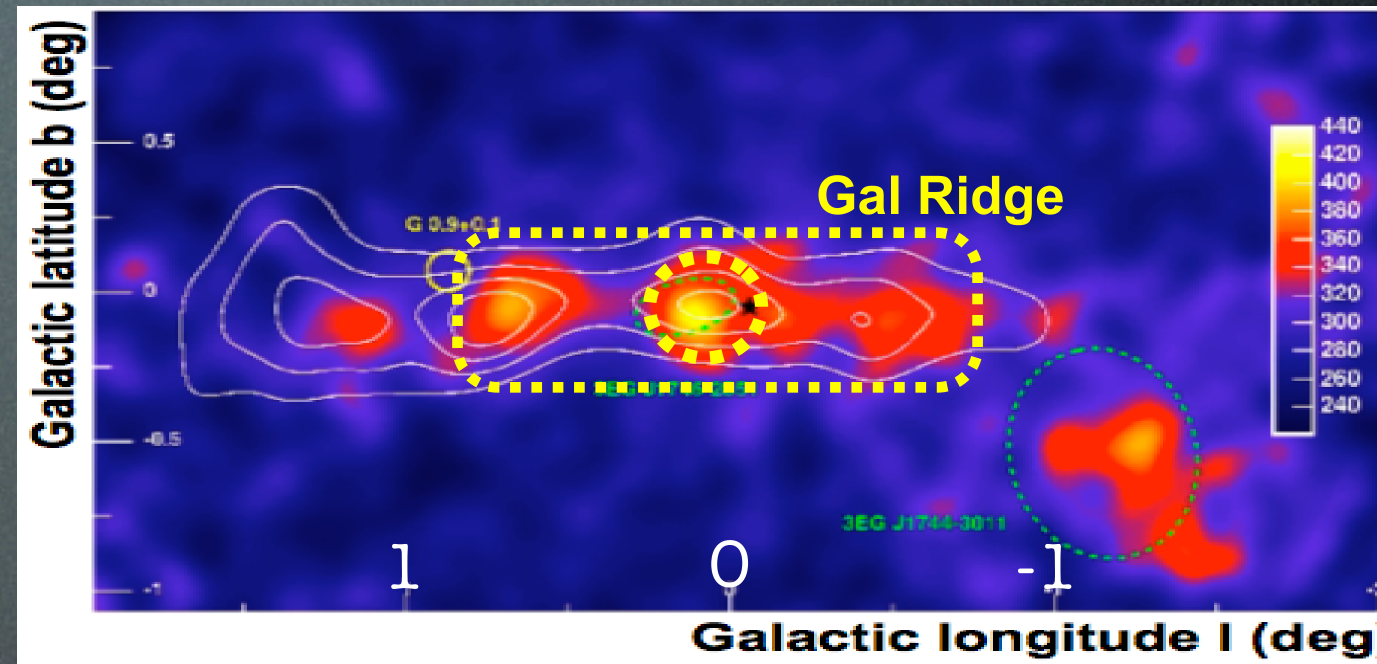

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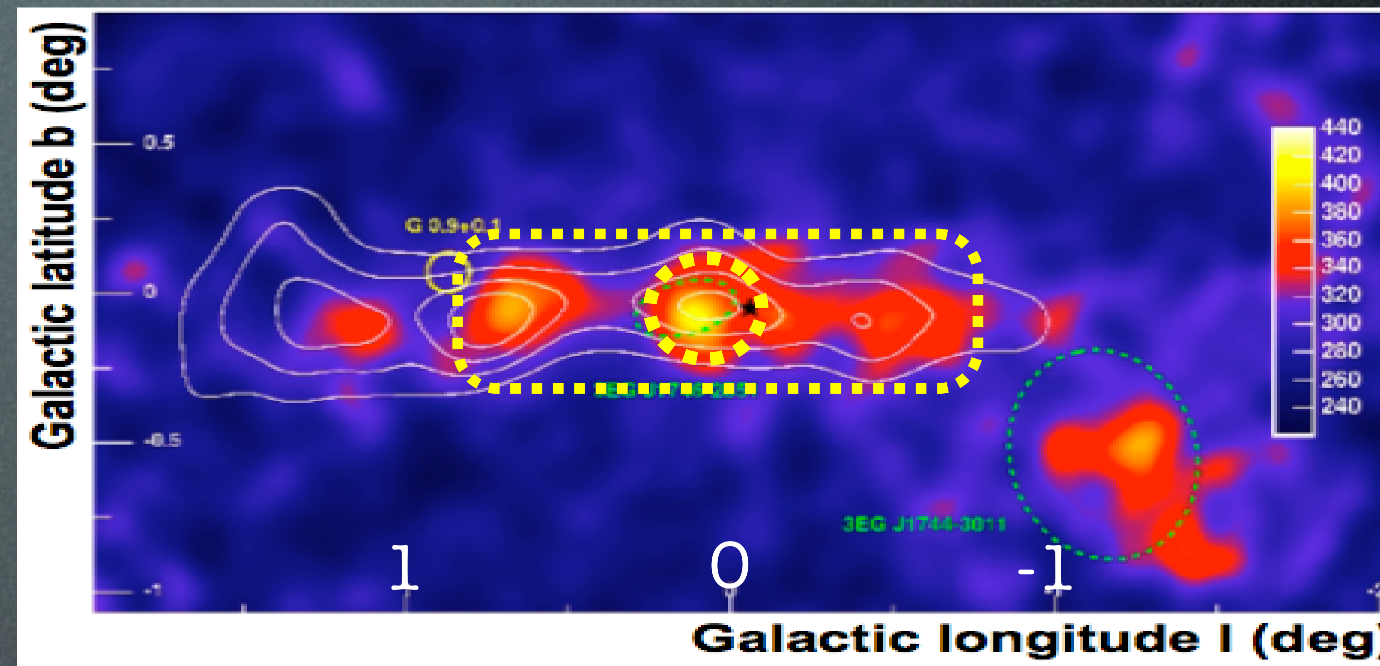
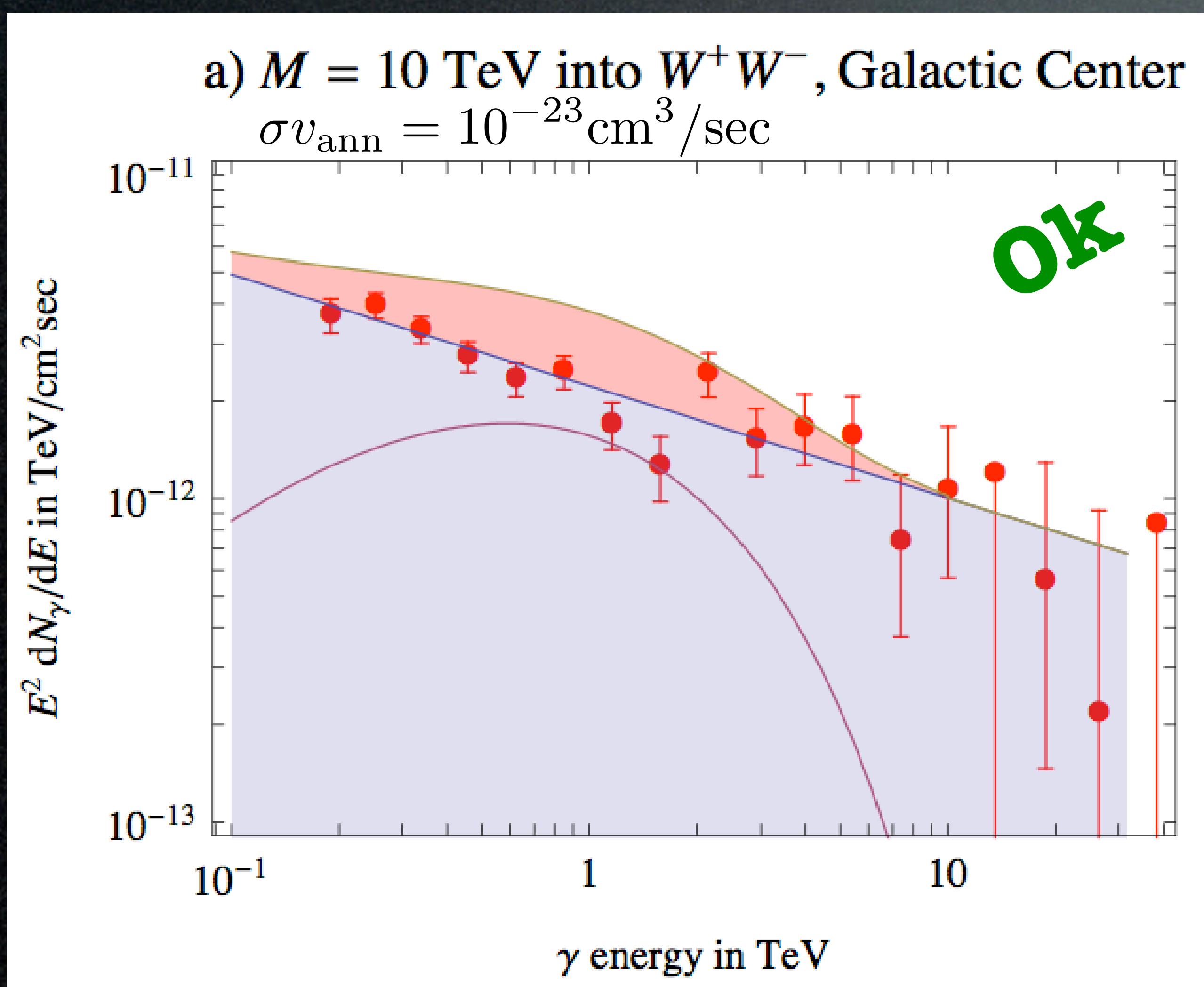


a.

HESS coll.



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

Gamma constraints

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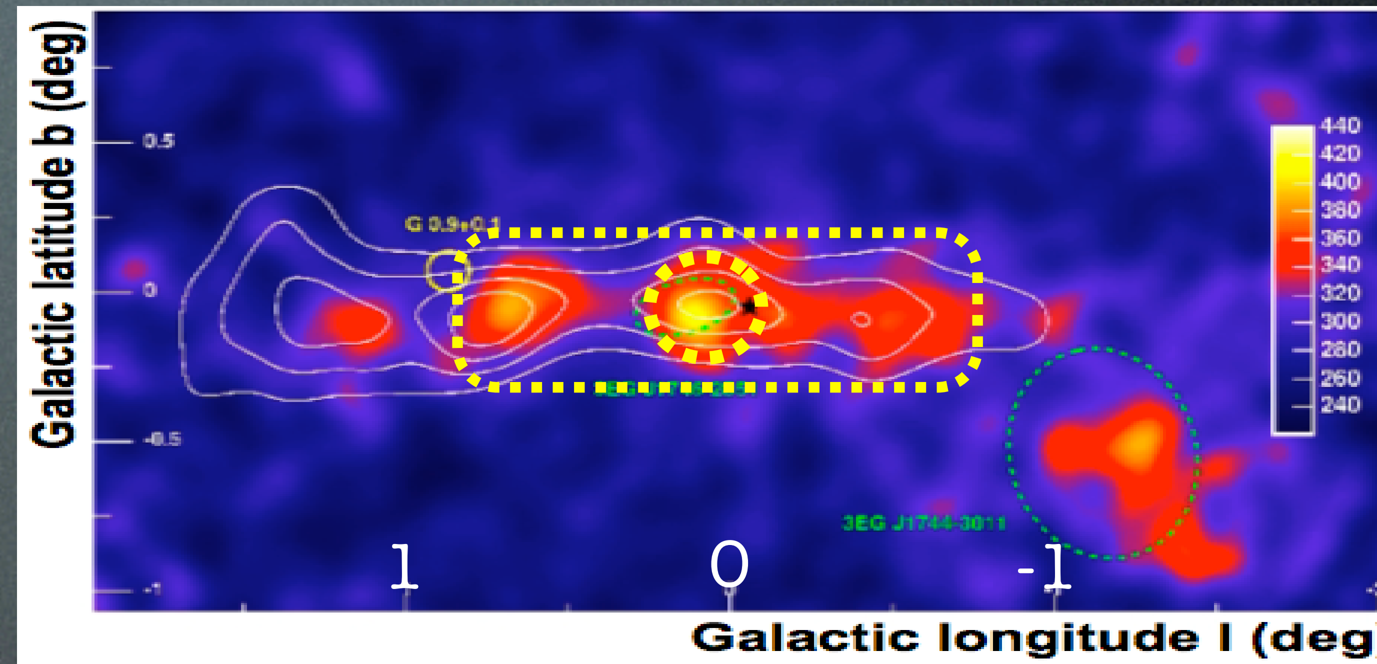
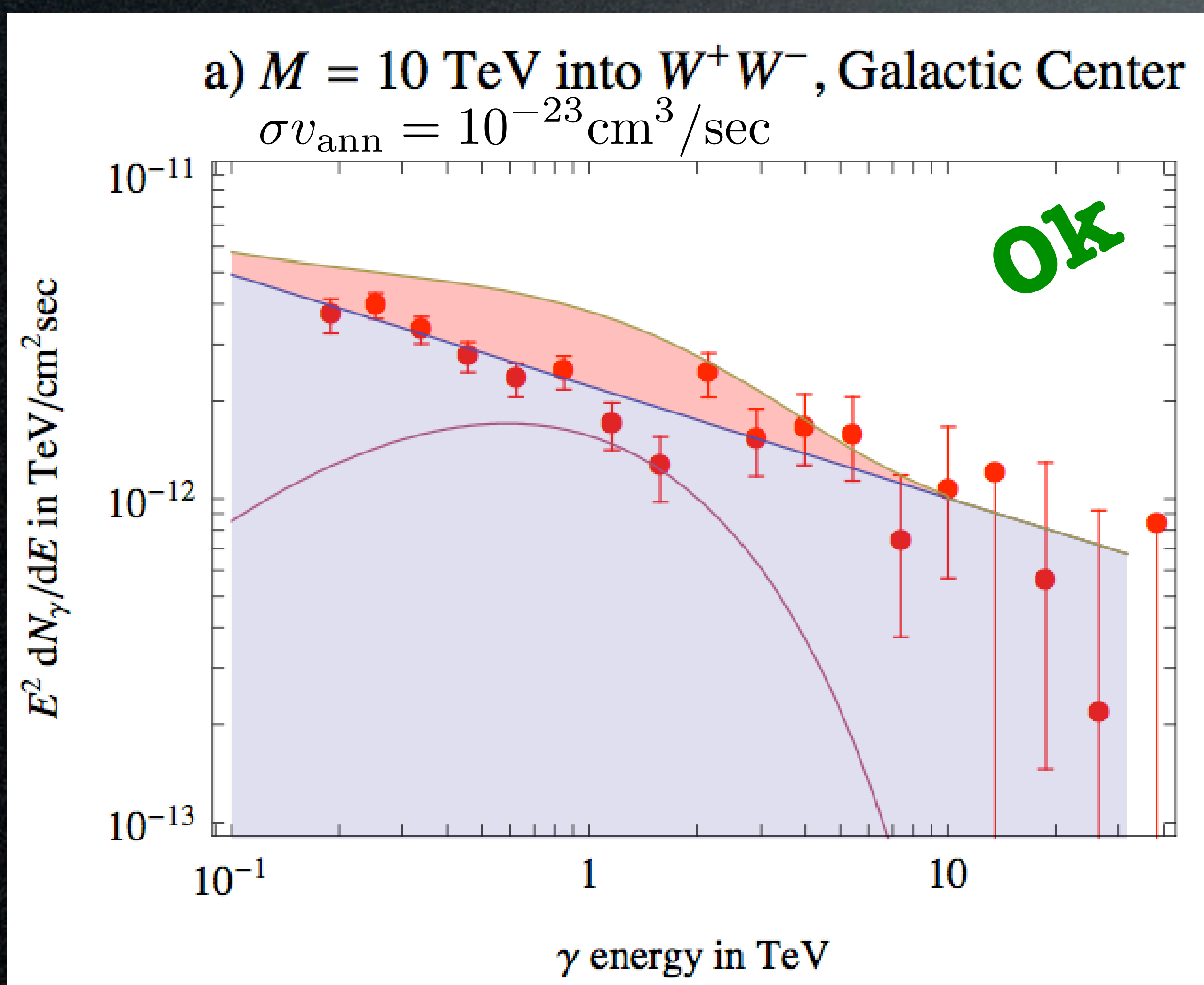


a.

HESS coll.



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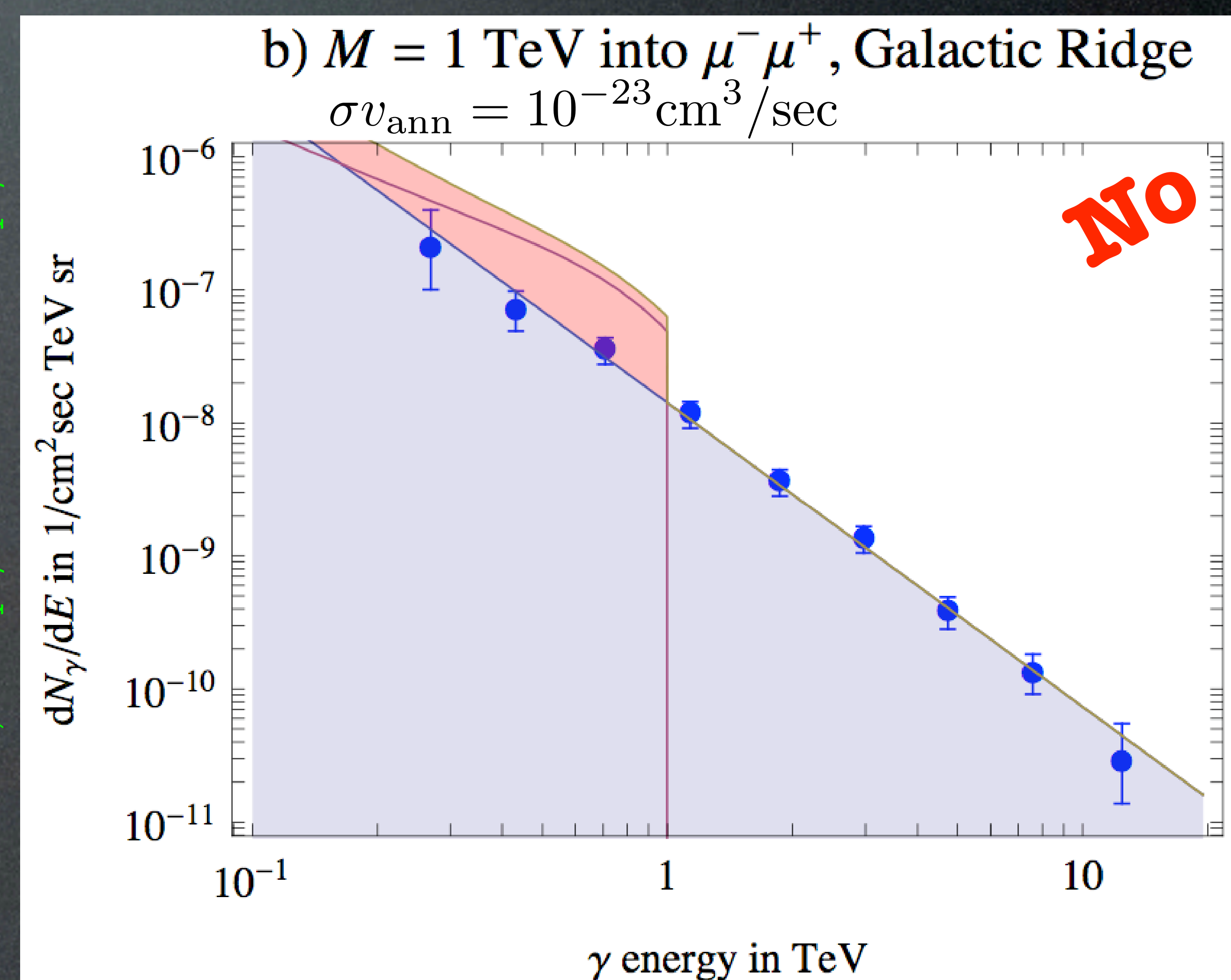
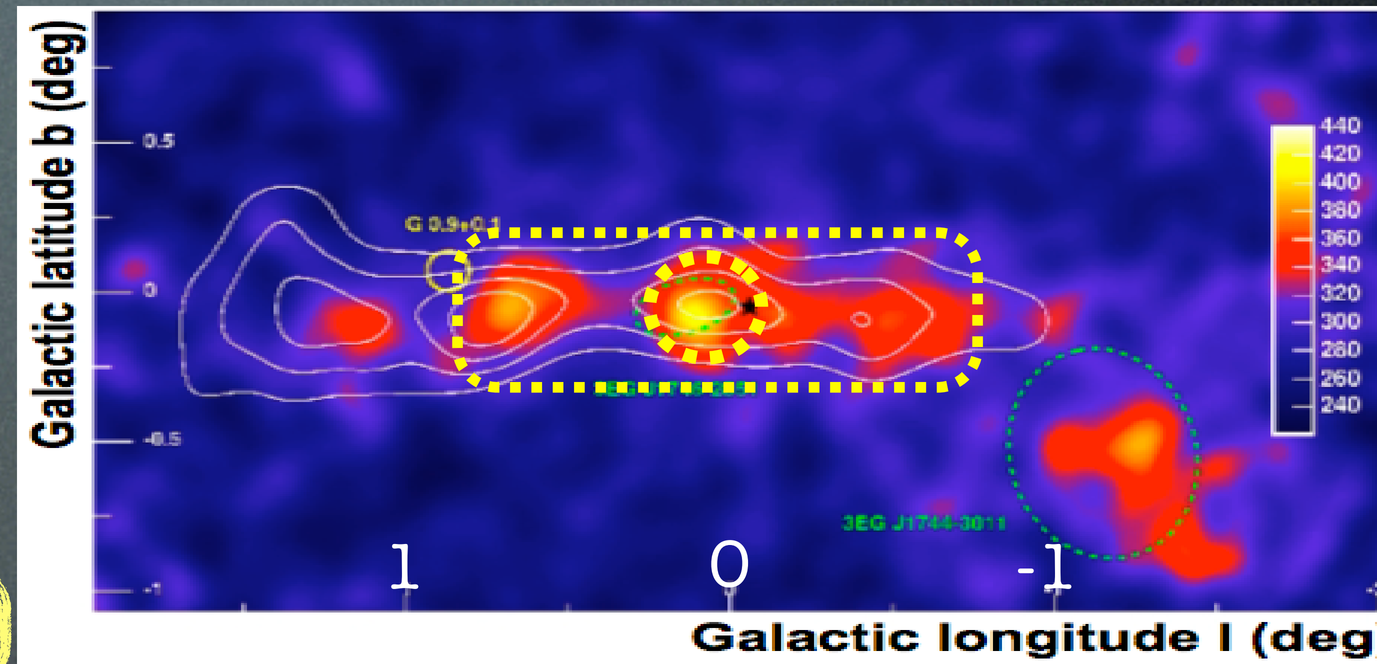


Data: HESS coll., astro-ph/0603021

Gamma constraints

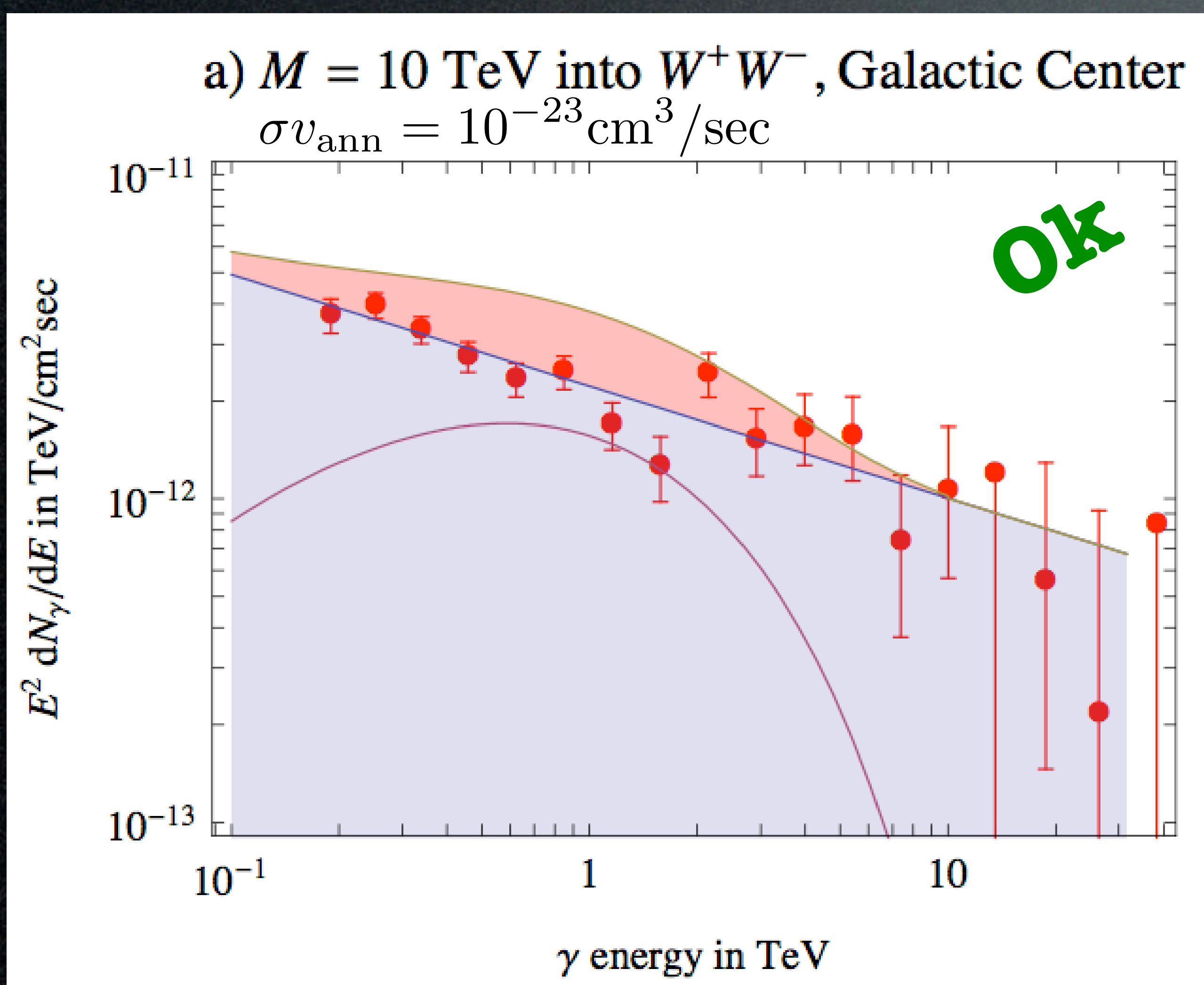
HESS has detected γ-ray emission from Gal Center and Gal Ridge. The DM signal must not excede that.

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

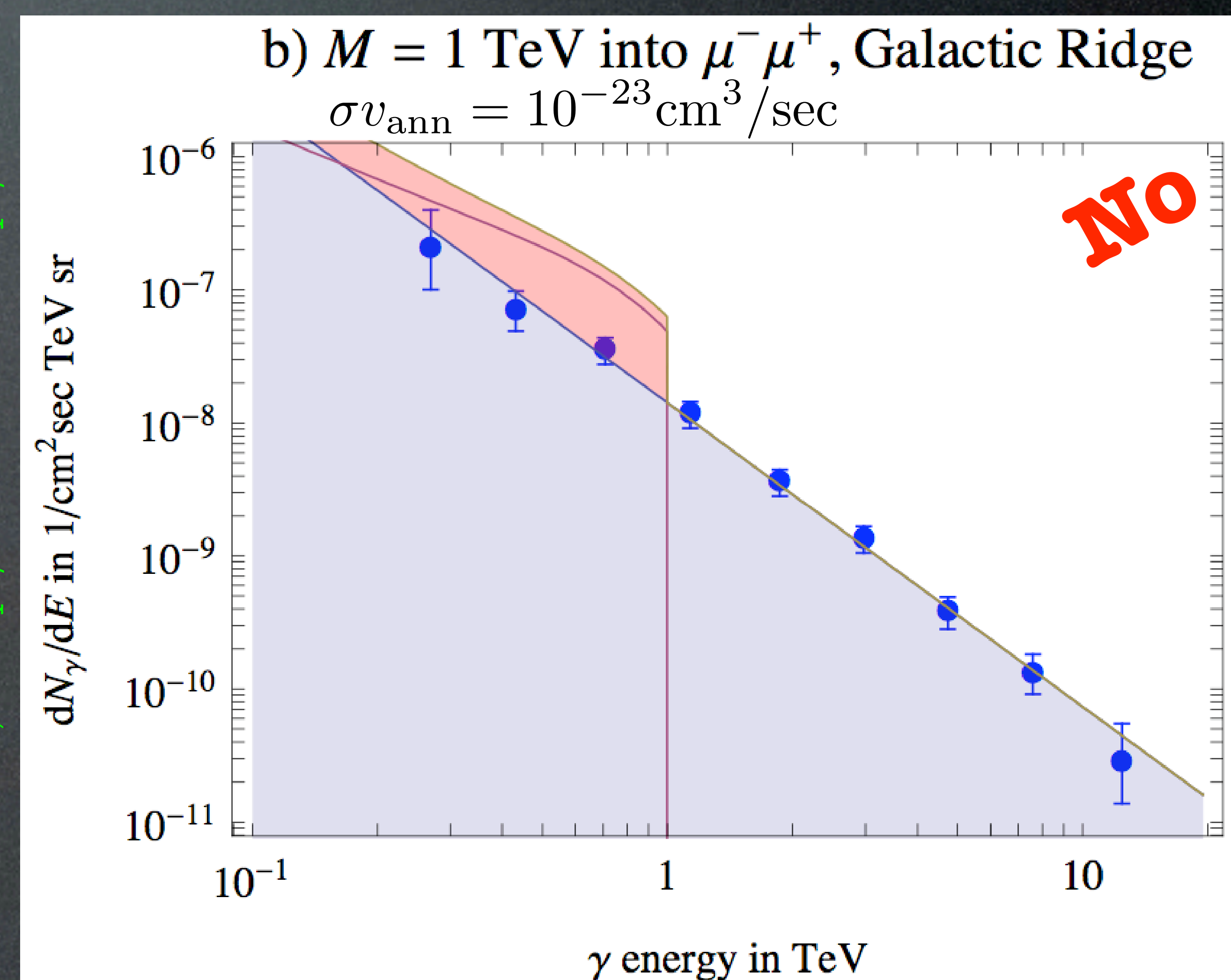


a.

HESS coll.



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



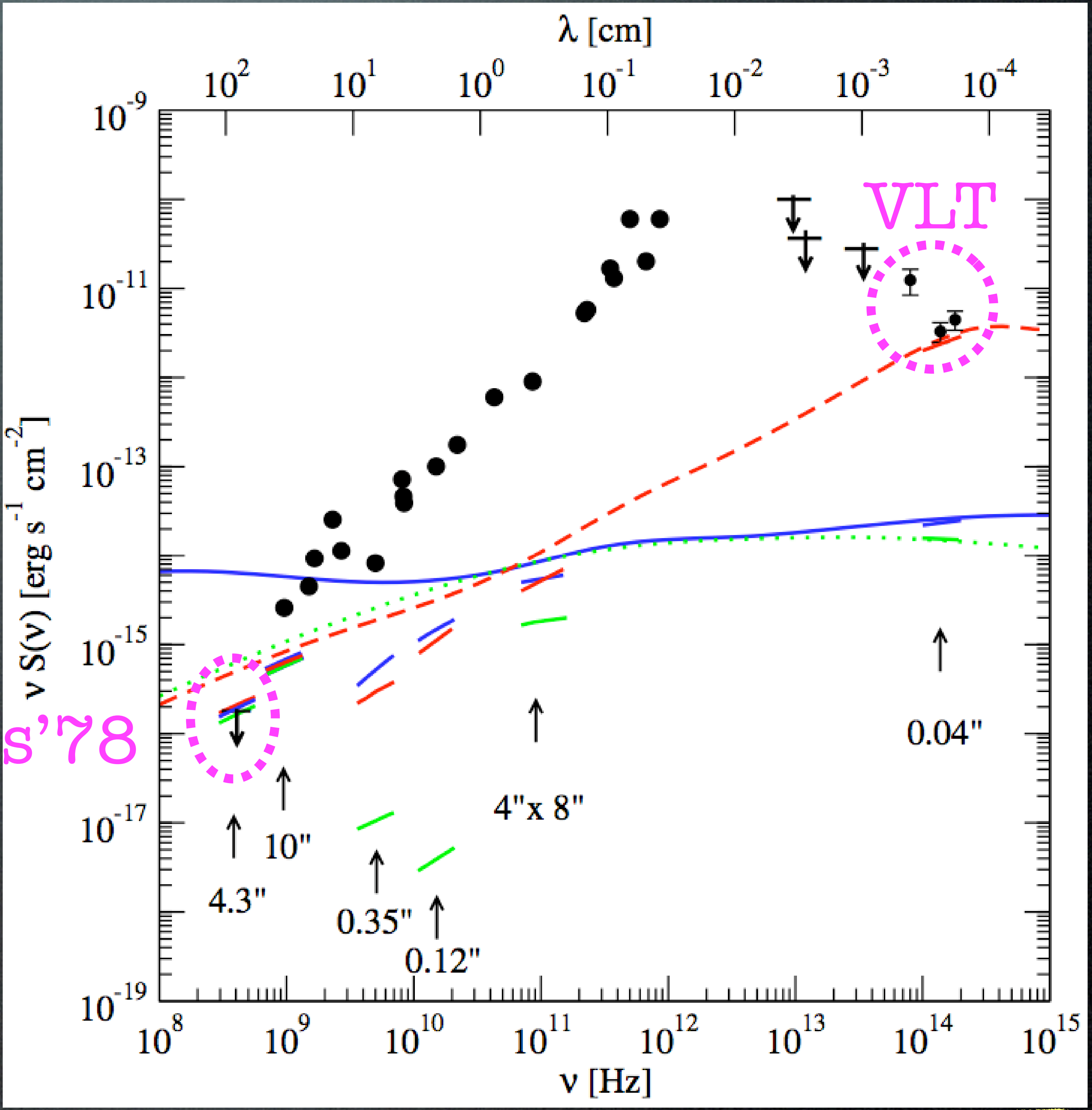
Data: HESS coll., astro-ph/0603021

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.

VLT 2003 emission at 10^{14} Hz.

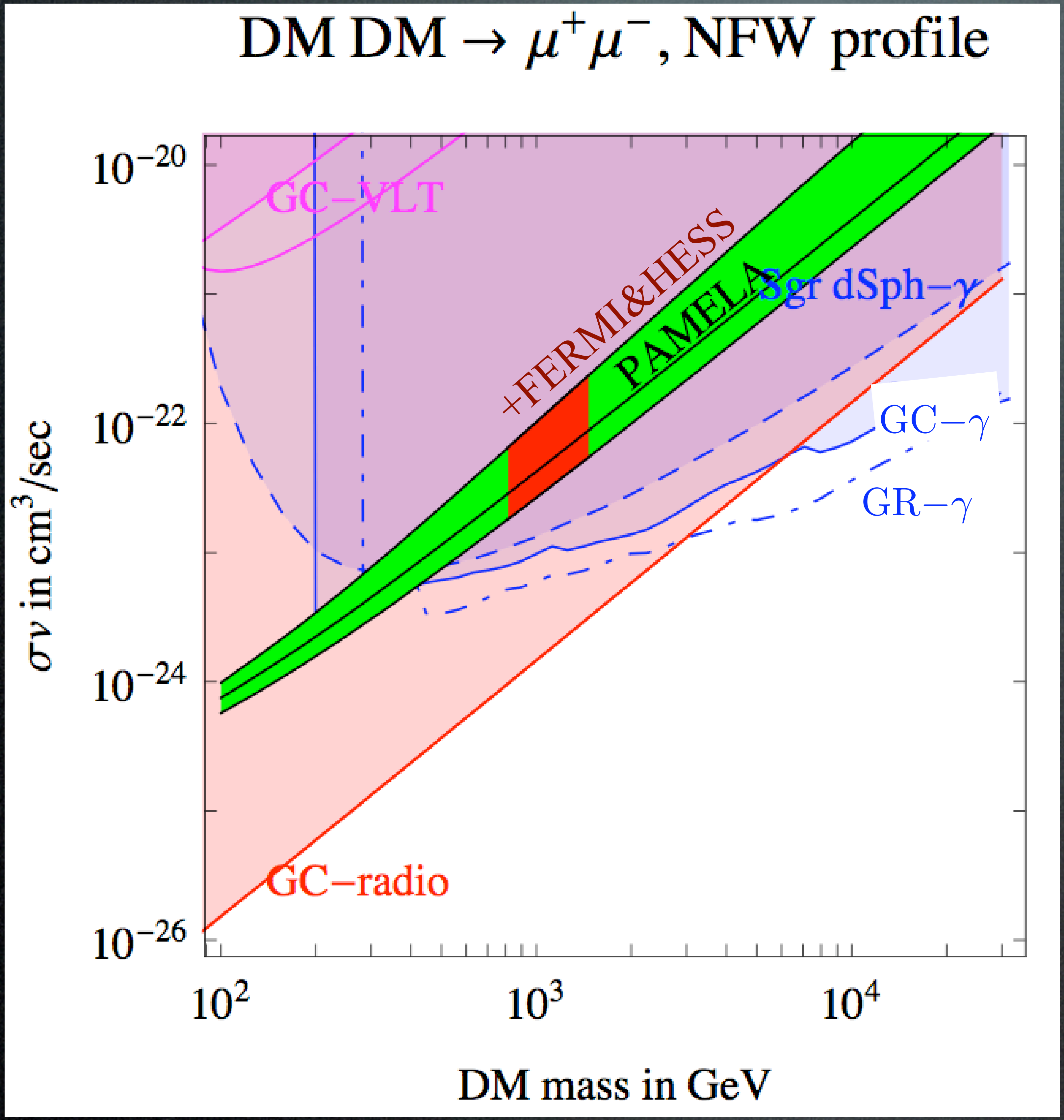


integrate emission over a small angle corresponding to angular resolution of instrument

Regis, Ullio PRD '78 (2008)

c.

Gamma constraints



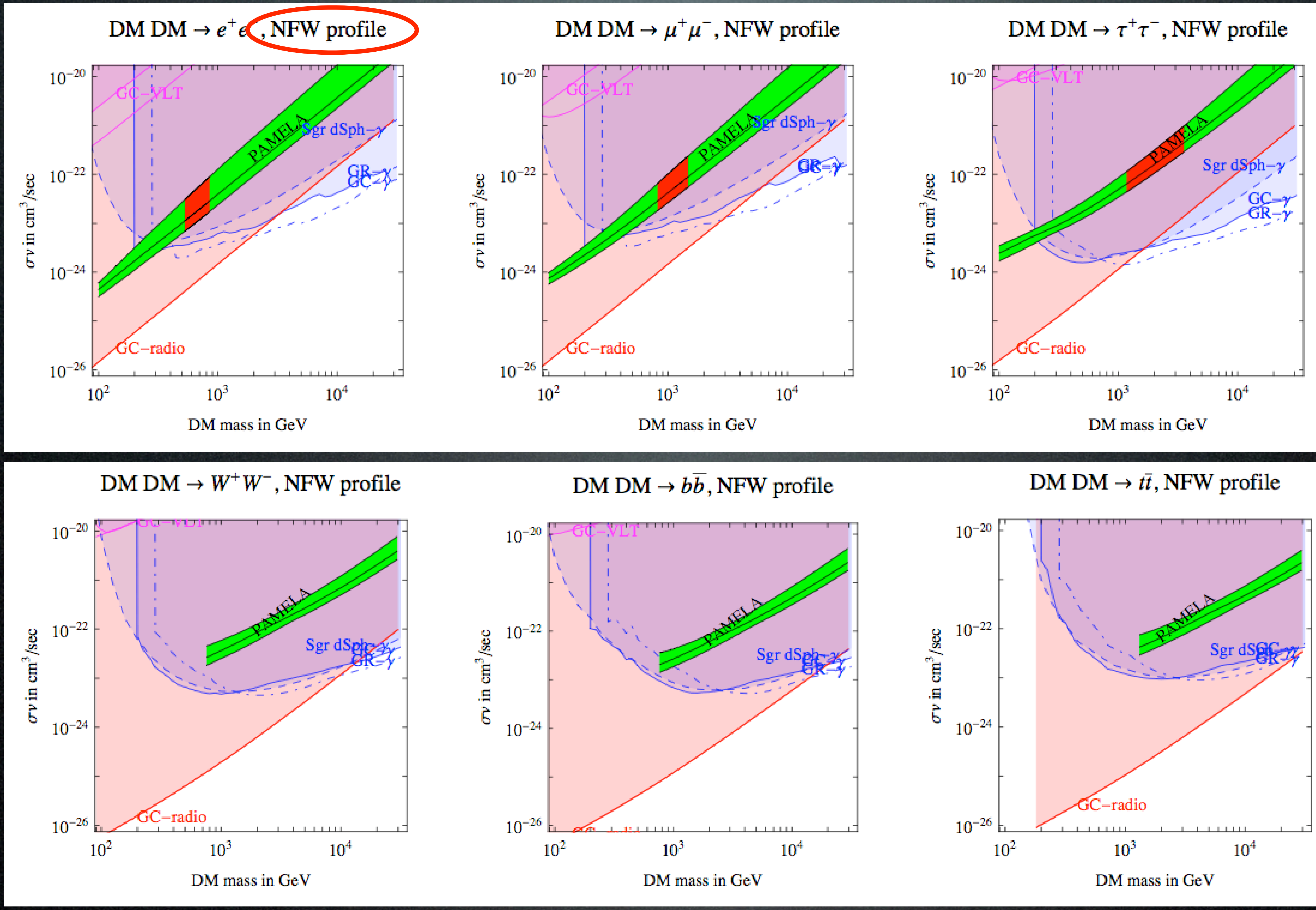
Bertone, Cirelli, Strumia, Taoso 0811.3744

a+b+c.

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

Gamma constraints

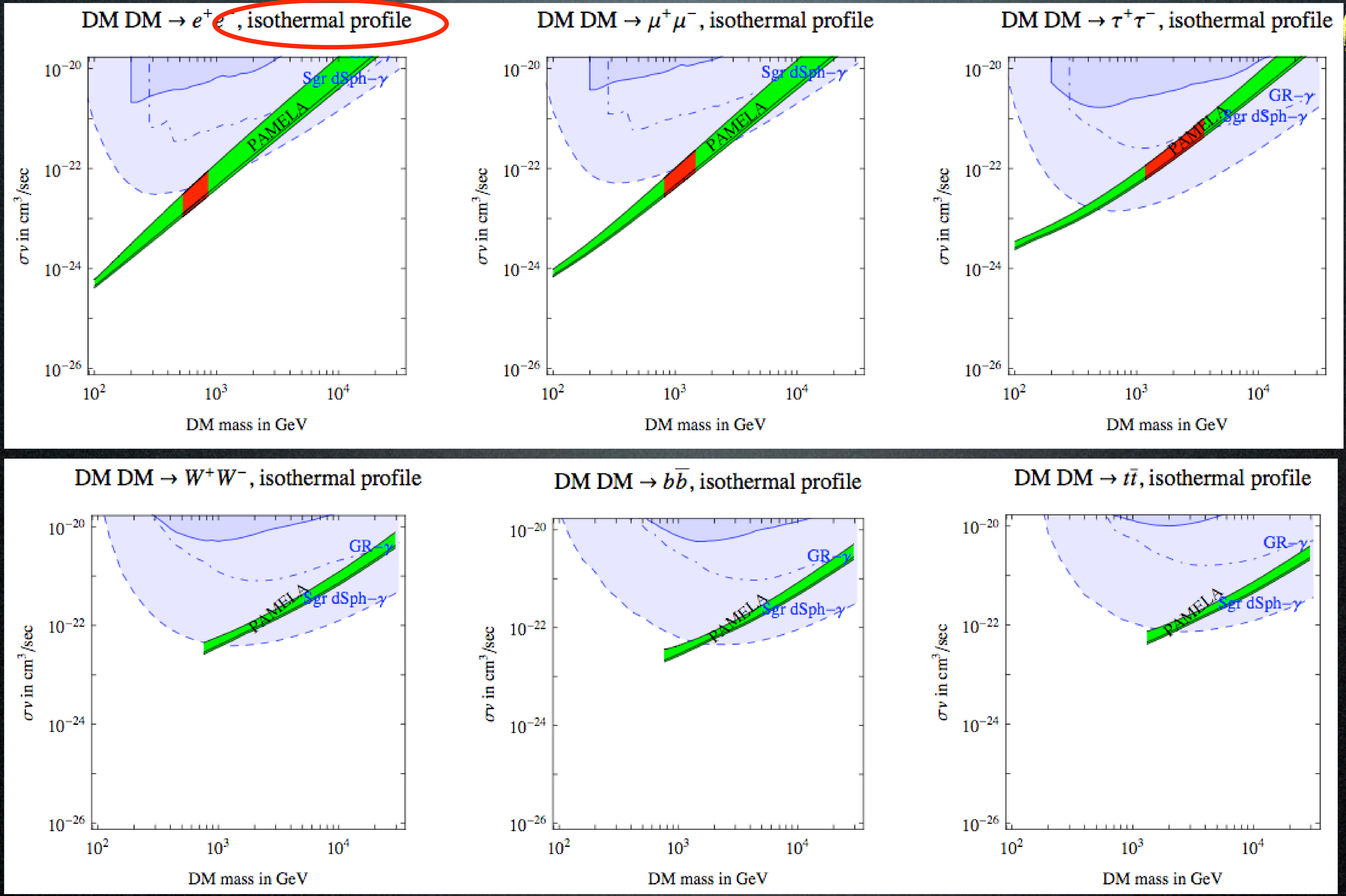
a+b+c.



Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints

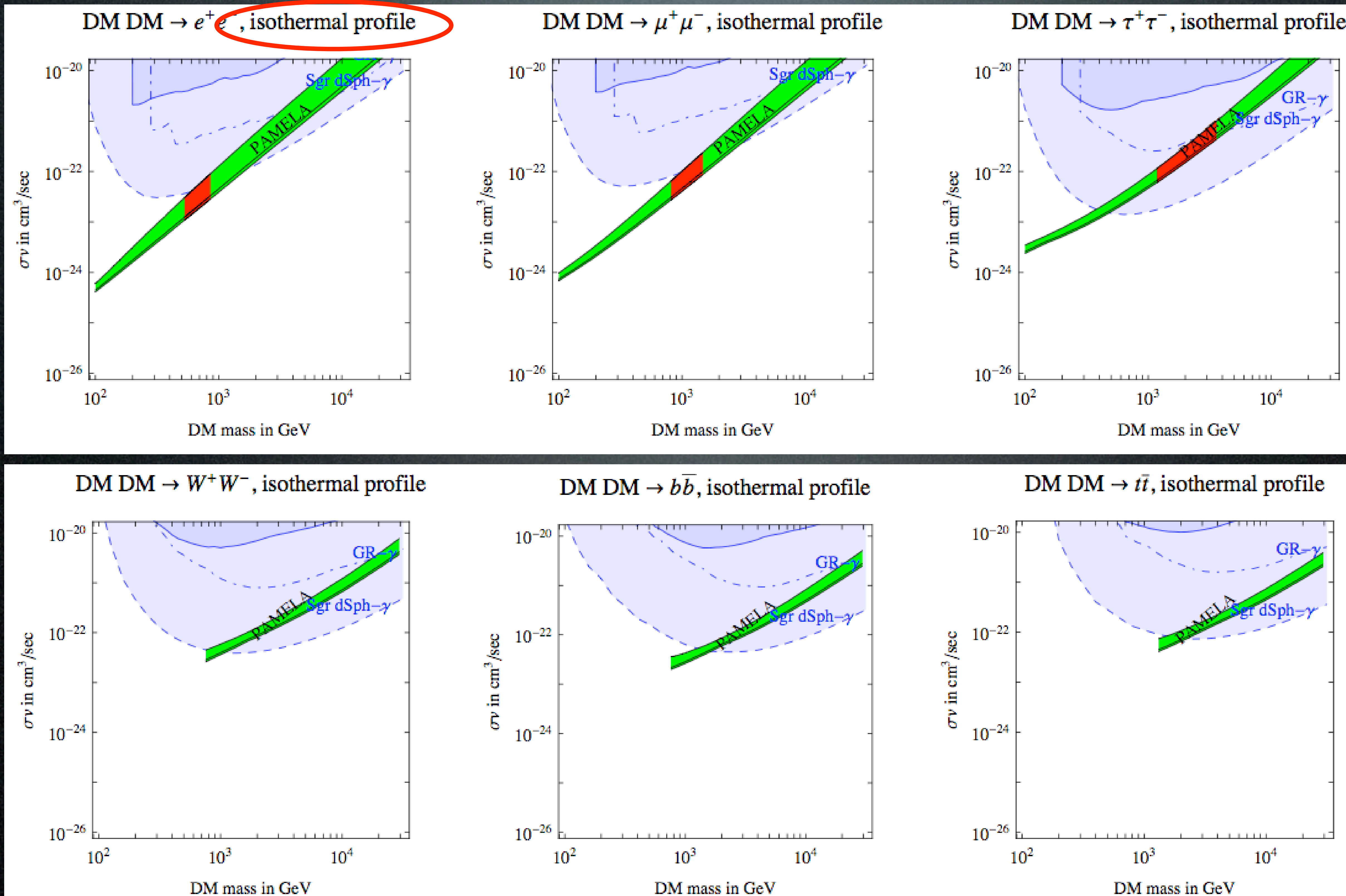
a+b+c.



Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

Gamma constraints



a+b+c.

Bertone, Cirelli, Strumia, Taoso 0811.3744

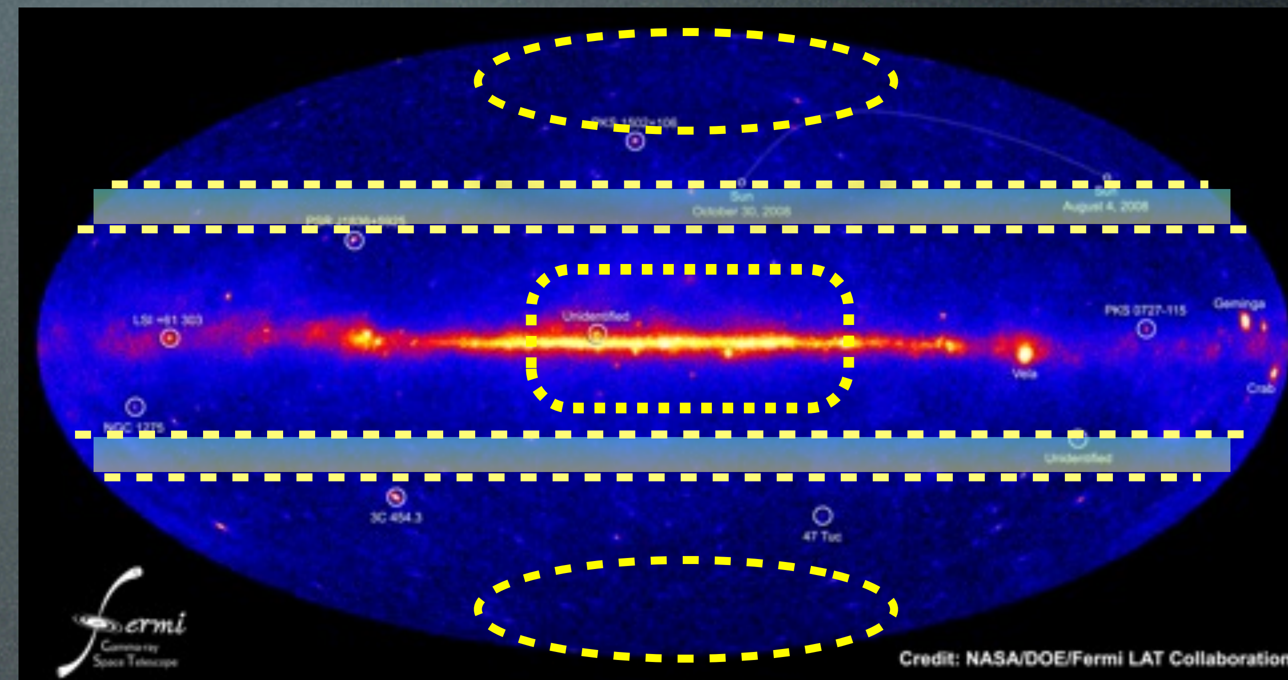
...not-too-steep profile needed.

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

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

Gamma constraints

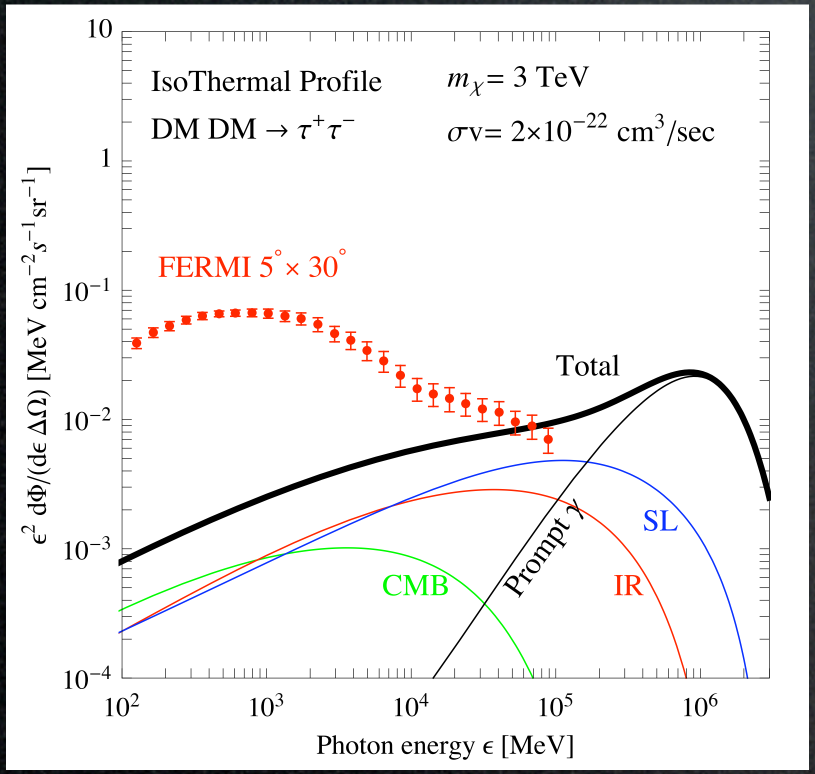
FERMI has measured diffuse γ-ray emission. The DM signal must not excede that.

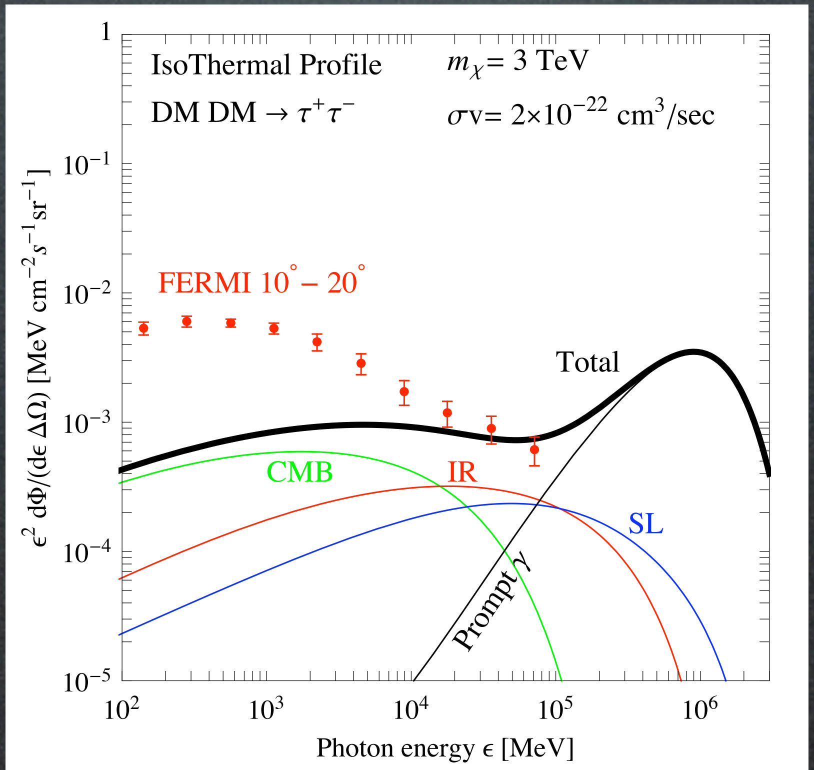


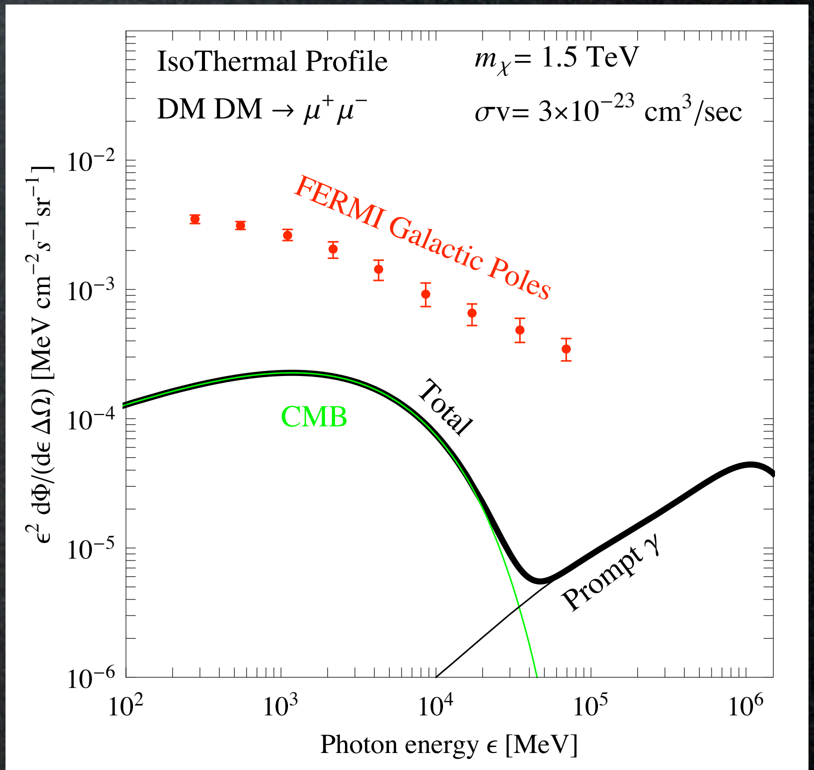
d.

FERMI coll.

Data: FERMI coll., several talks and papers



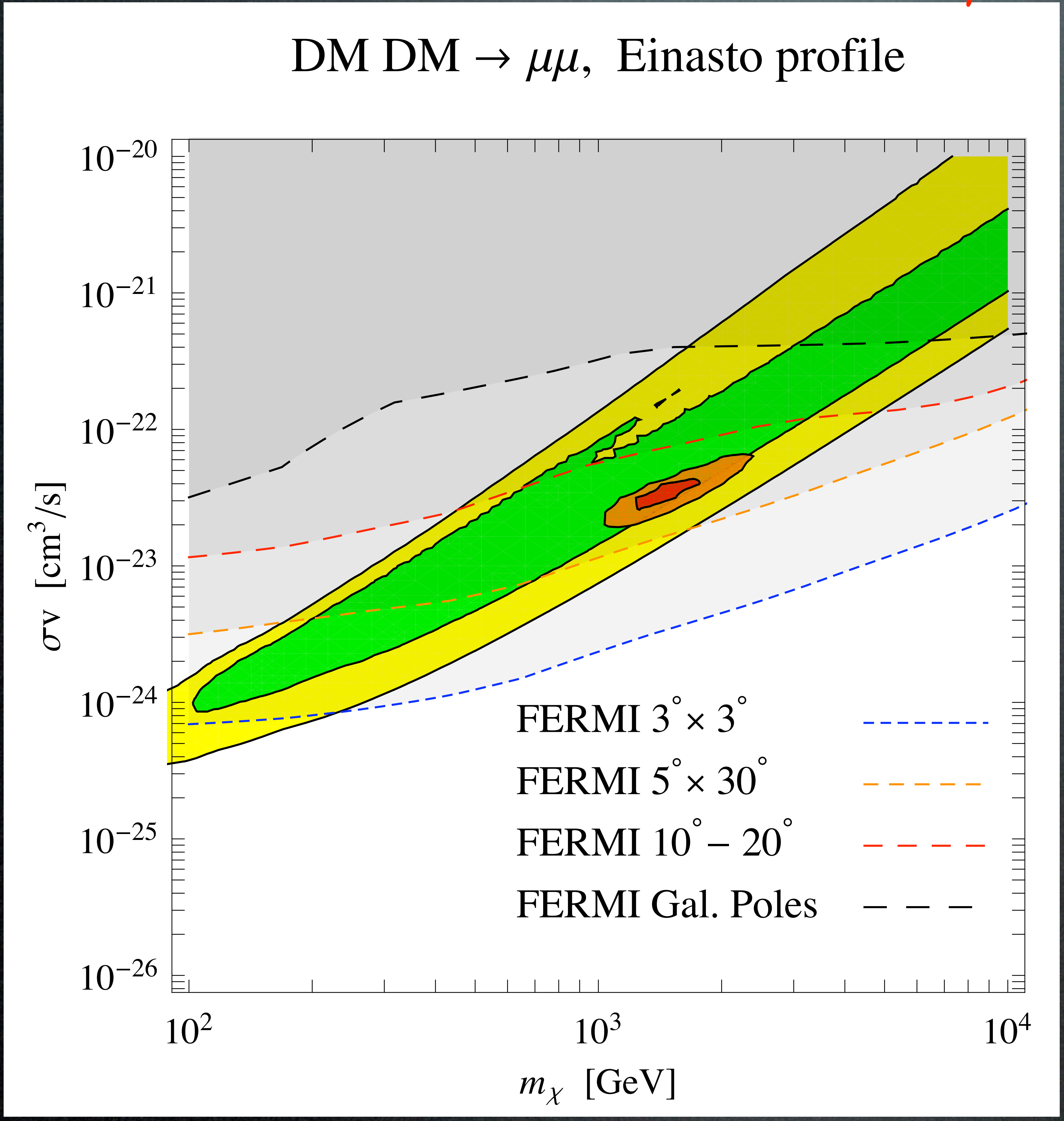




Cirelli, Panci, Serpico 0912.0663

Inverse Compton γ constraints

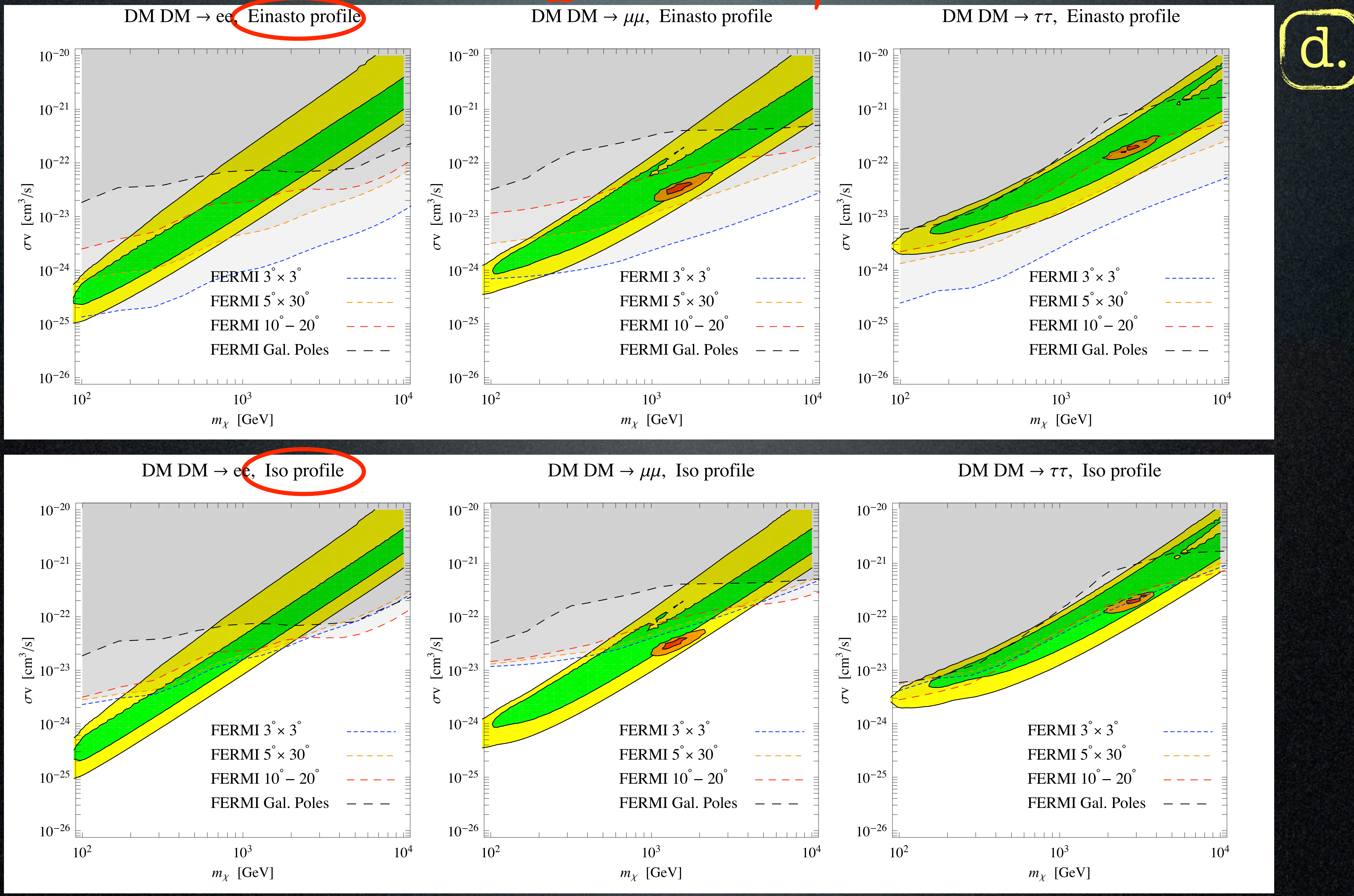
d.



Cirelli, Panci, Serpico 0912.0663

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

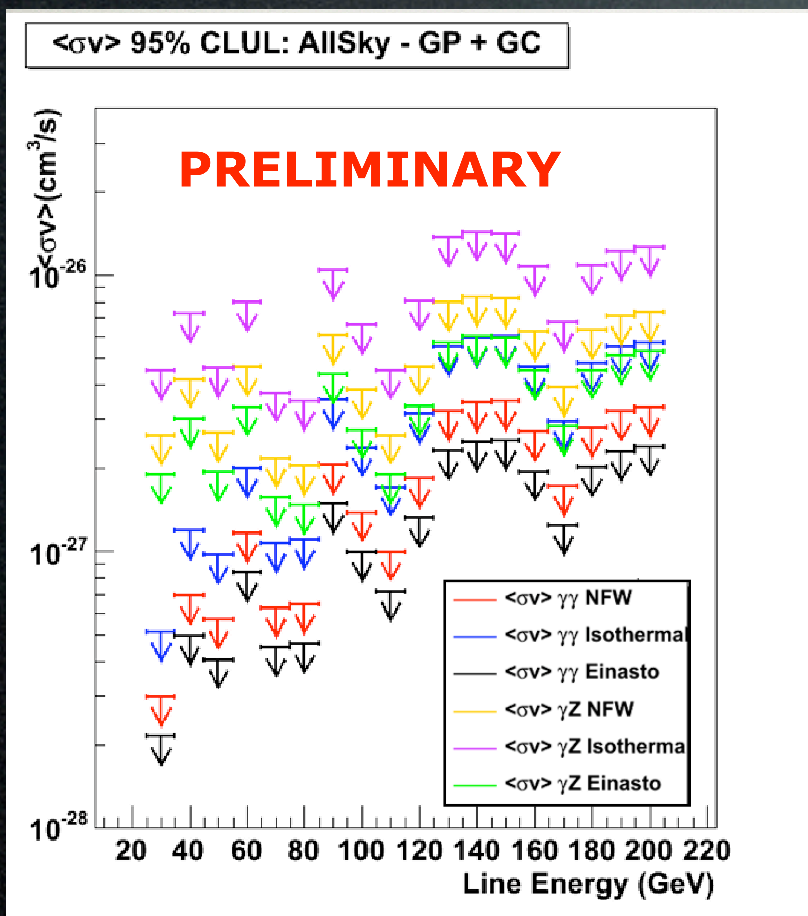
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

More FERMI γ constraints

Gamma lines

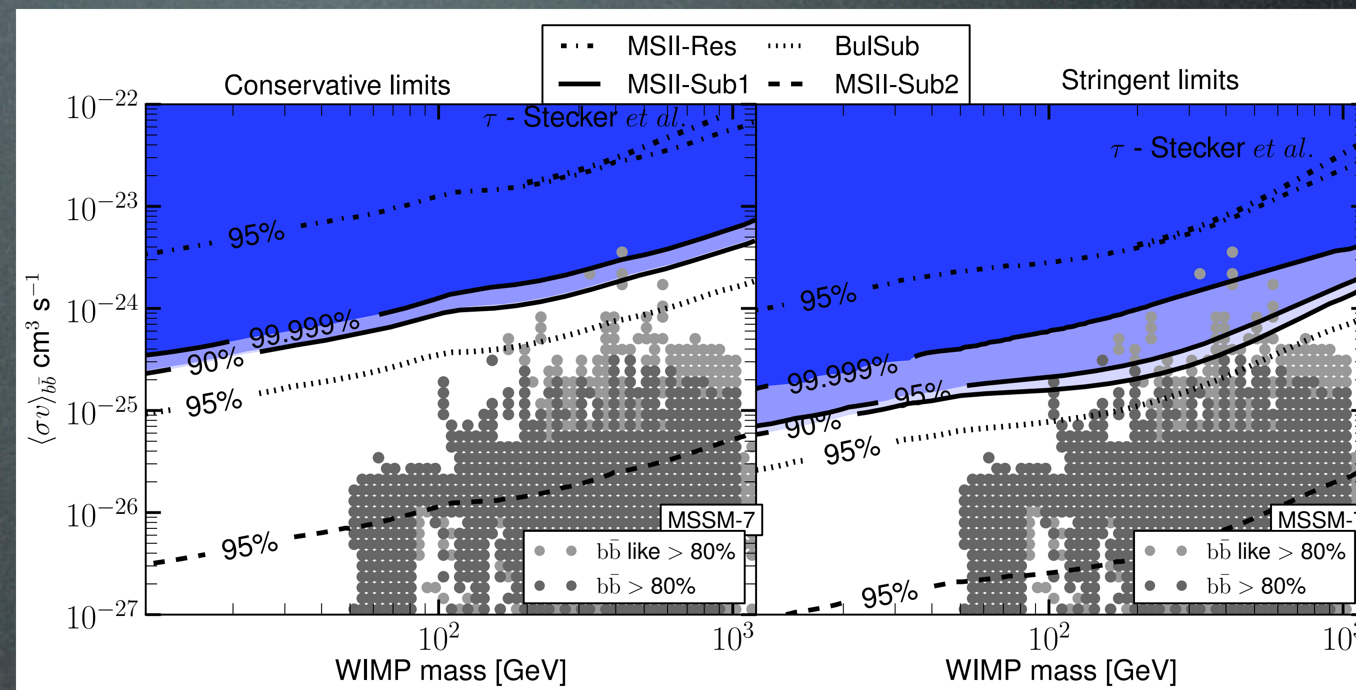


a.

FERMI Coll. 1001.4836

model dependent constraints, can be stringent

Isotropic gamma background

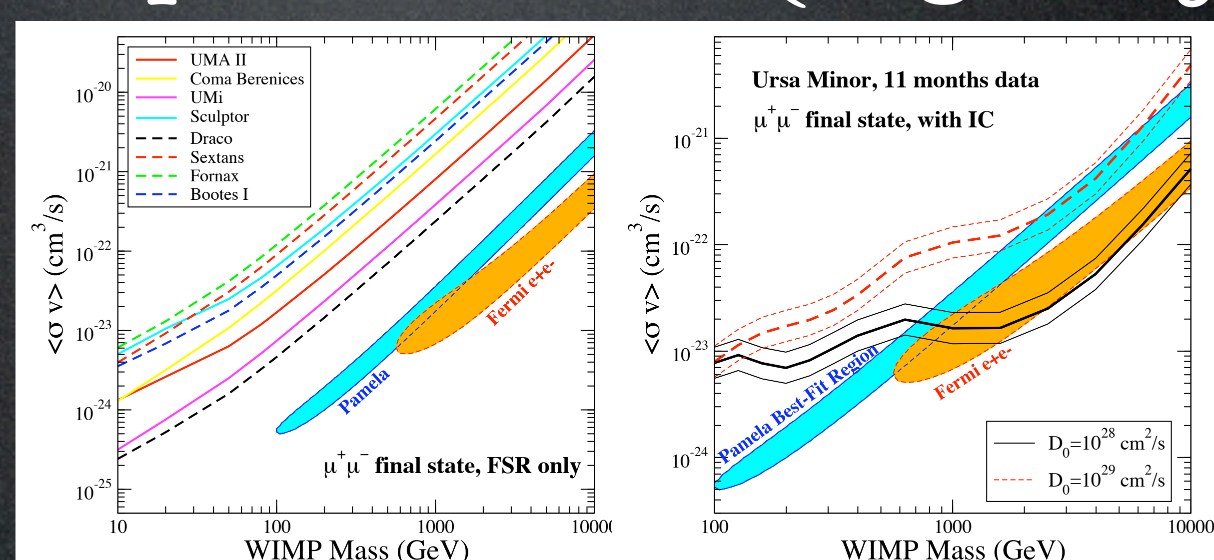


e.

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

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

dSph satellites (& galaxy clusters)



b.

Competitive constraints (if ICS included)

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

Gamma **fits**?

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

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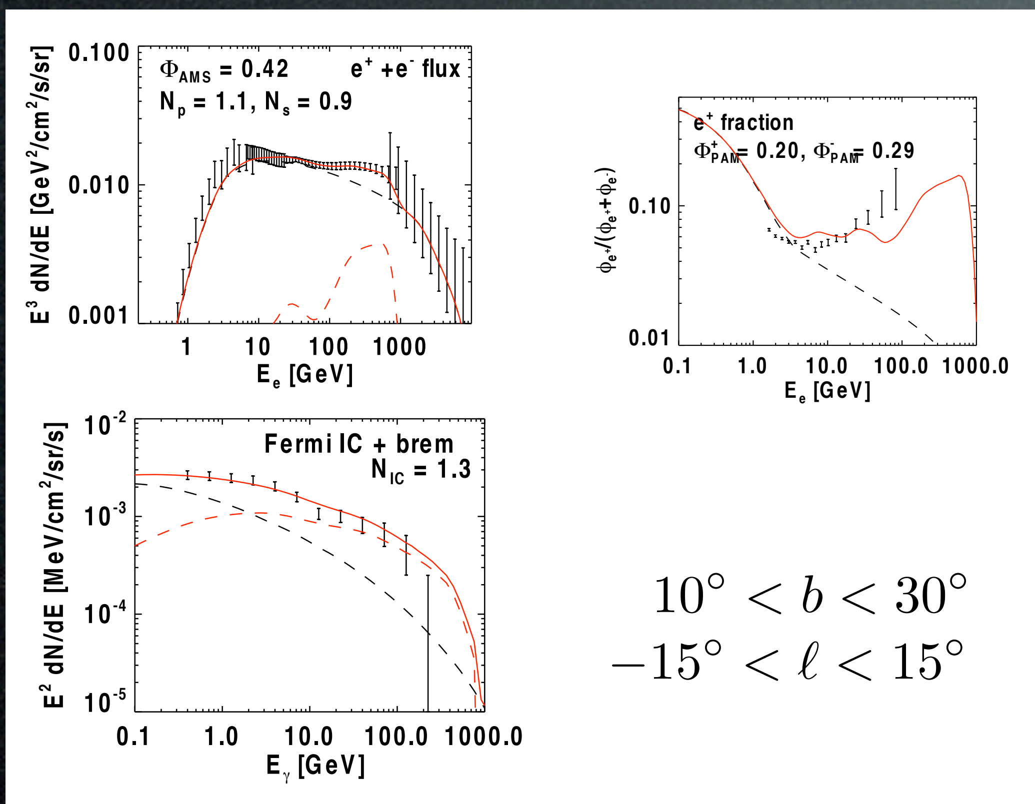
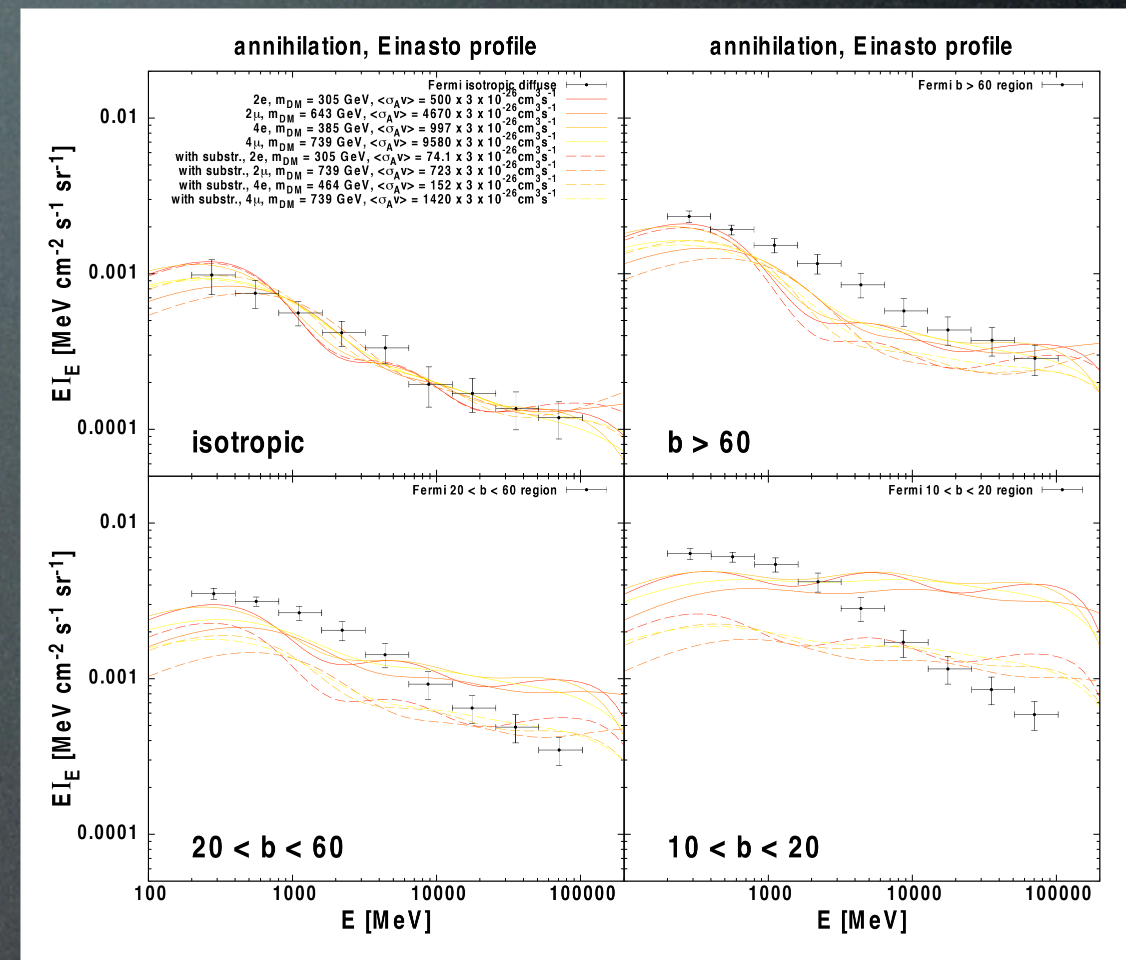
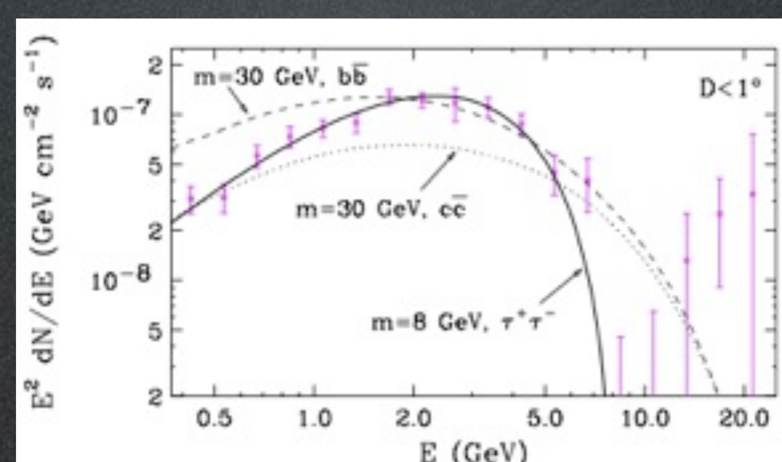


Lin, Finkbeiner, Dobler 1004.0989



Hutsi, Hektor, Raidal 1004.2036



Hooper, Goodenough 1010.2752

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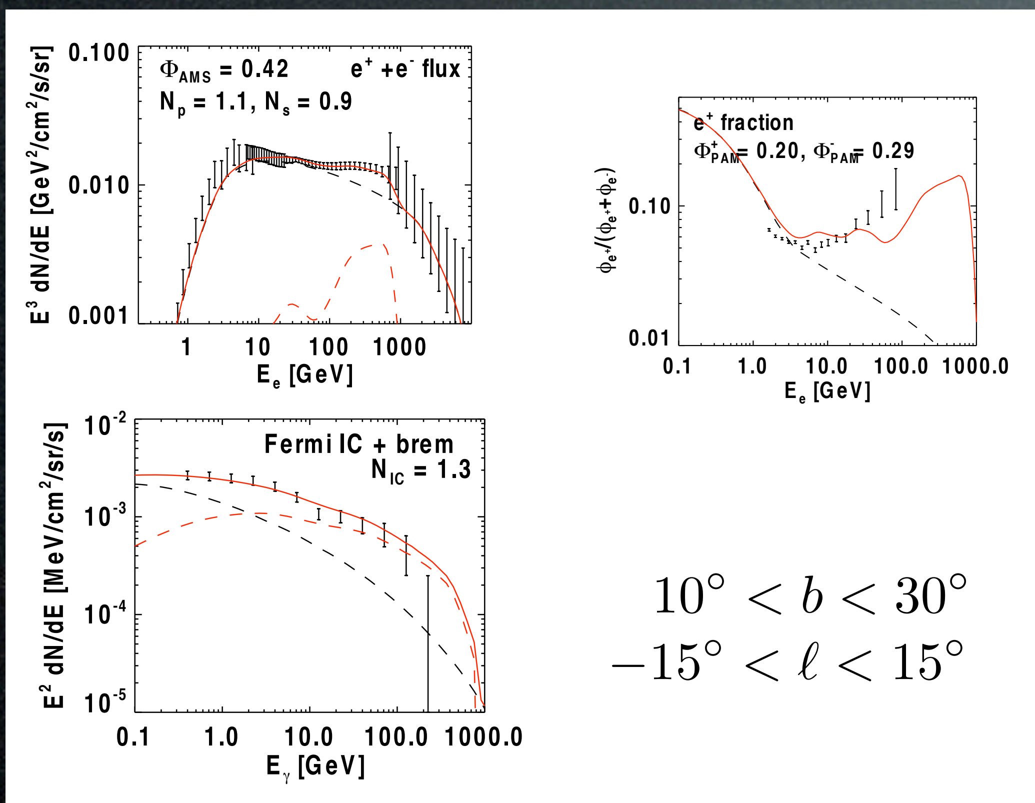
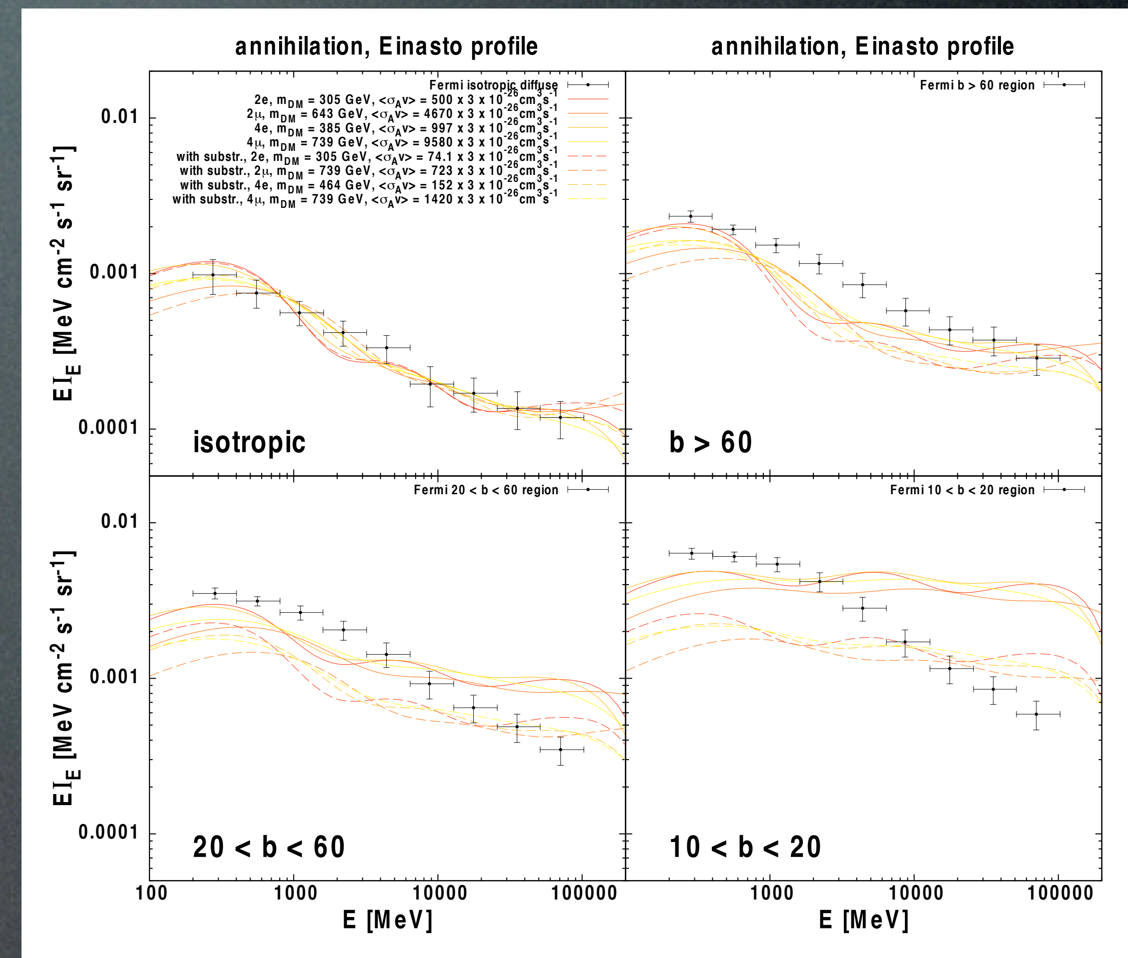
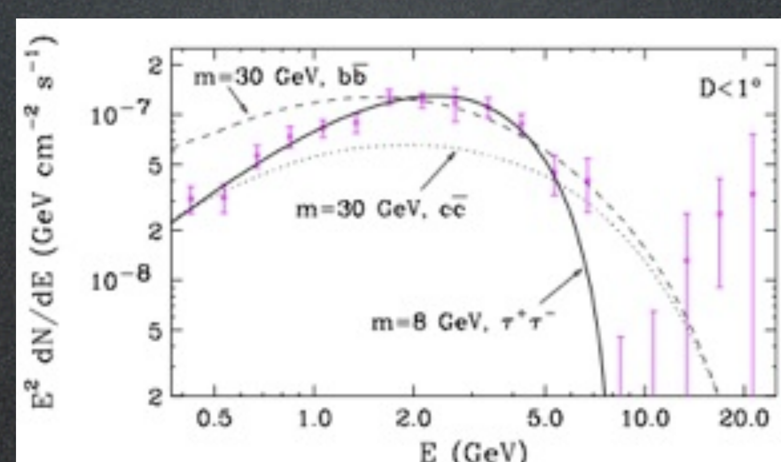


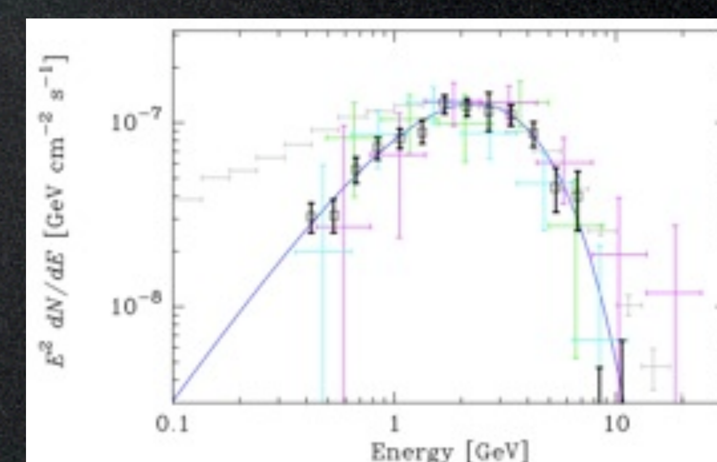
Lin, Finkbeiner, Dobler 1004.0989



Hutsi, Hektor, Raidal 1004.2036



Hooper, Goodenough 1010.2752



Abazajian 1011.4275

Mmm.... A good fit requires [1] careful bkgd subtraction & [2] fitting energy spectra + angular spectra + associated signals.

DM detection

direct detection

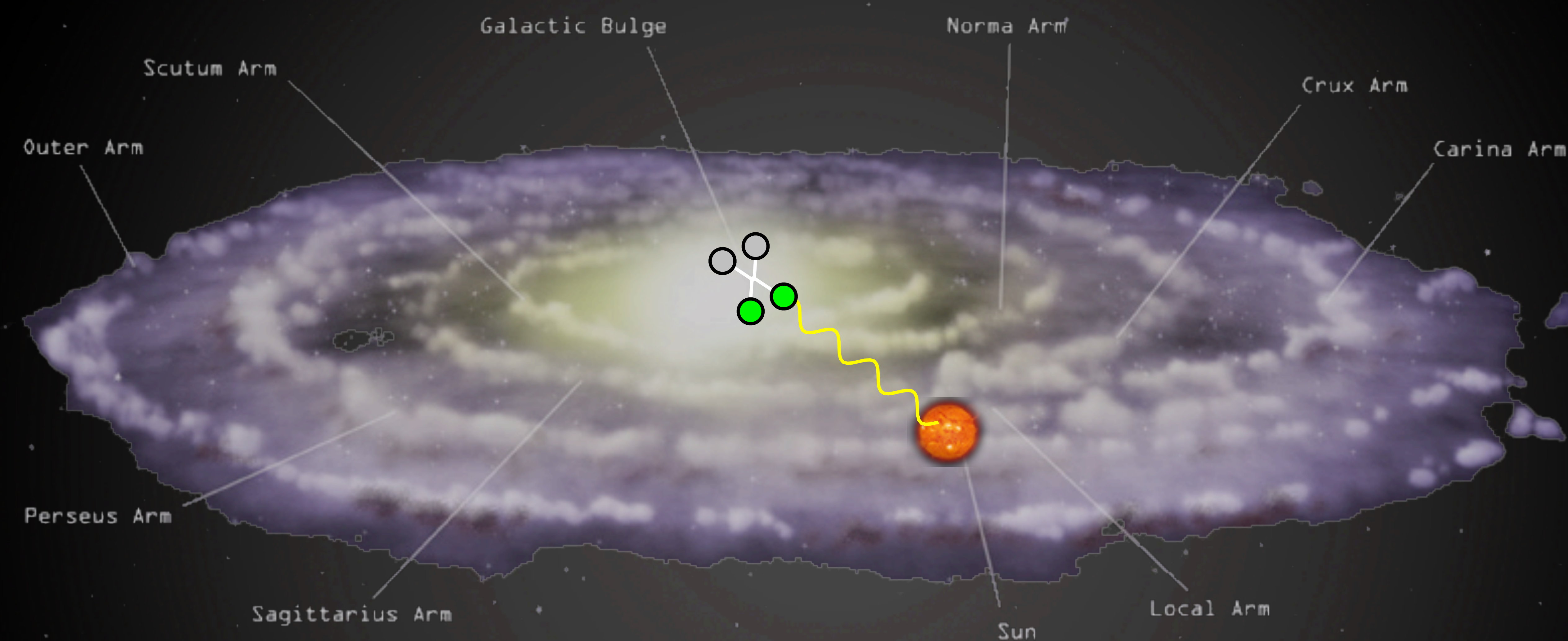
production at colliders

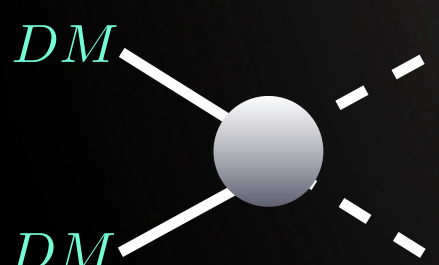
indirect

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

Indirect Detection

ν from DM annihilations in galactic center

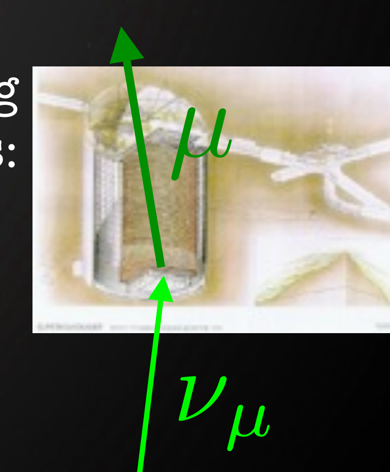




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \nu$$

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

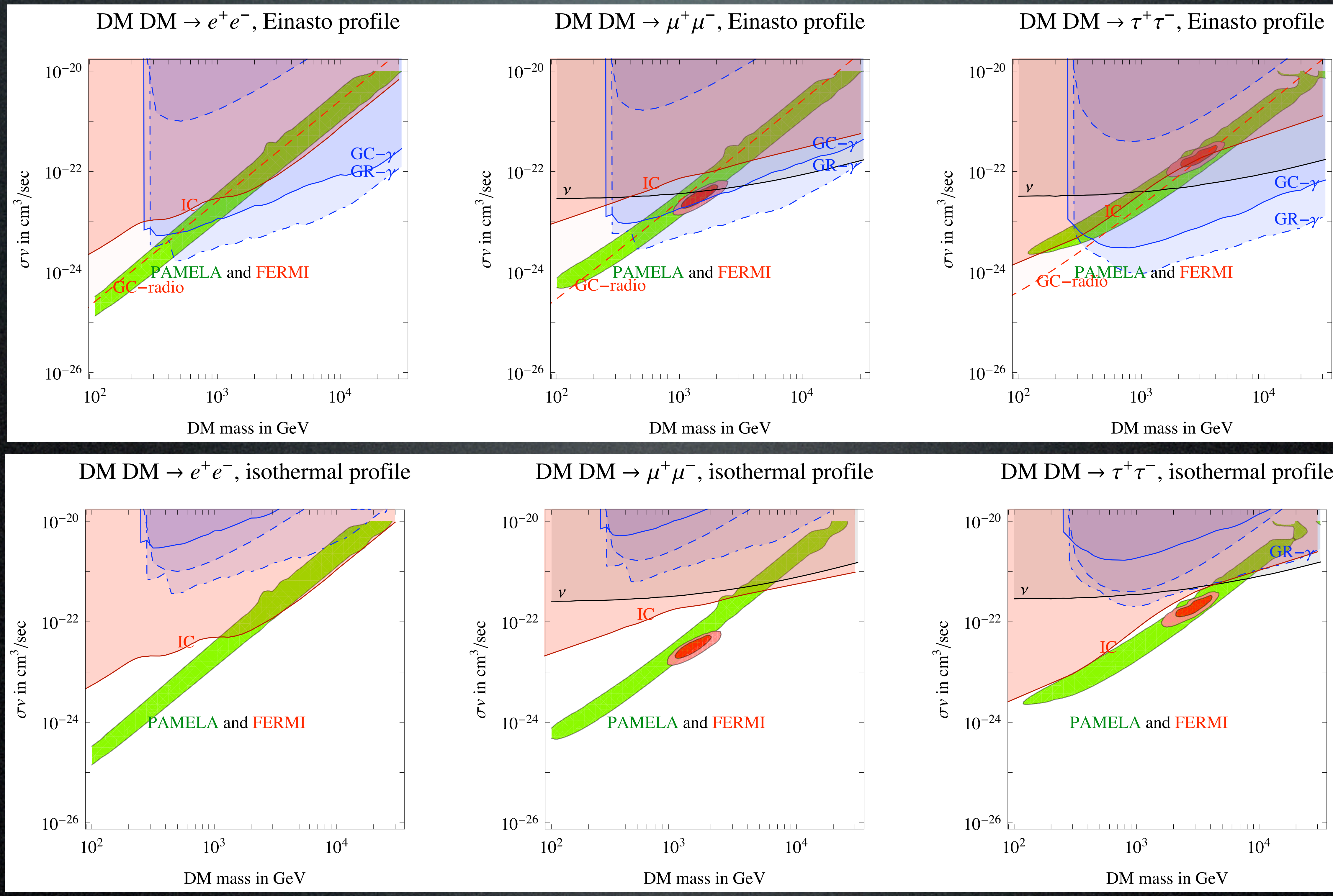
up-going muons:



Neutrino constraints

Comparing with SuperKamiokande data in 3° to 30°

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



Strumia, Papucci et al. 0905.0480

Advertisement

You need a quick **reference** for formulæ and methods to compute indirect detection signals?

You want to compute all **signatures** of your DM model in positrons, electrons, neutrinos, gamma rays...
but you don't want to mess around with astrophysics?

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'The Poor Particle Physicist Cookbook
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PPPC 4 DM ID

We provide ingredients and recipes for computing signals of TeV-scale
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Cirelli, Corcella, Hektor,
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Raidal, Sala, Strumia

1012.4515 [hep-ph]

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but you don't want to mess around with astrophysics?

Propagation functions for electrons and positrons everywhere in the Galaxy:

Energy loss coefficient function *b[E, r, z]* for electrons and positrons in the Galaxy: *Mathematica* function b.m, refer to the notebook Sample.nb for usage.

Annihilation

Positrons: The file ElectronHaloFunctGalaxyAnn.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy.
The notebook Sample.nb shows how to load and use it.

Decay

Positrons: The file ElectronHaloFunctGalaxyDec.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy
The notebook Sample.nb shows how to load and use it.

Propagation functions for charged cosmic rays at the location of the Earth:

Annihilation

Positrons: The file ElectronHaloFunctEarthAnn.m provides the halo functions $I(x,E_s,r_{Earth})$ at the location of the Earth.
The notebook Sample.nb shows how to load and use it.

Table of fit coefficients for the reduced halo function $I(\lambda)$ (in the approximated formalism - see paper).

Antiprotons: Table of fit coefficients for the propagation function R(T).

Antideuterons: Table of fit coefficients for the propagation function R(T).

Decay

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Antideuterons: Table of fit coefficients for the propagation function R(T).

Fluxes of charged cosmic rays at the Earth, after propagation:

Annihilation

Positrons: *Mathematica* function: the file ElectronFluxAnn.m provides the

Decay

Positrons: *Mathematica* function: the file ElectronFluxDec.m provides the

www.marcocirelli.net/PPPC4DMID.html

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direct detection

production at colliders

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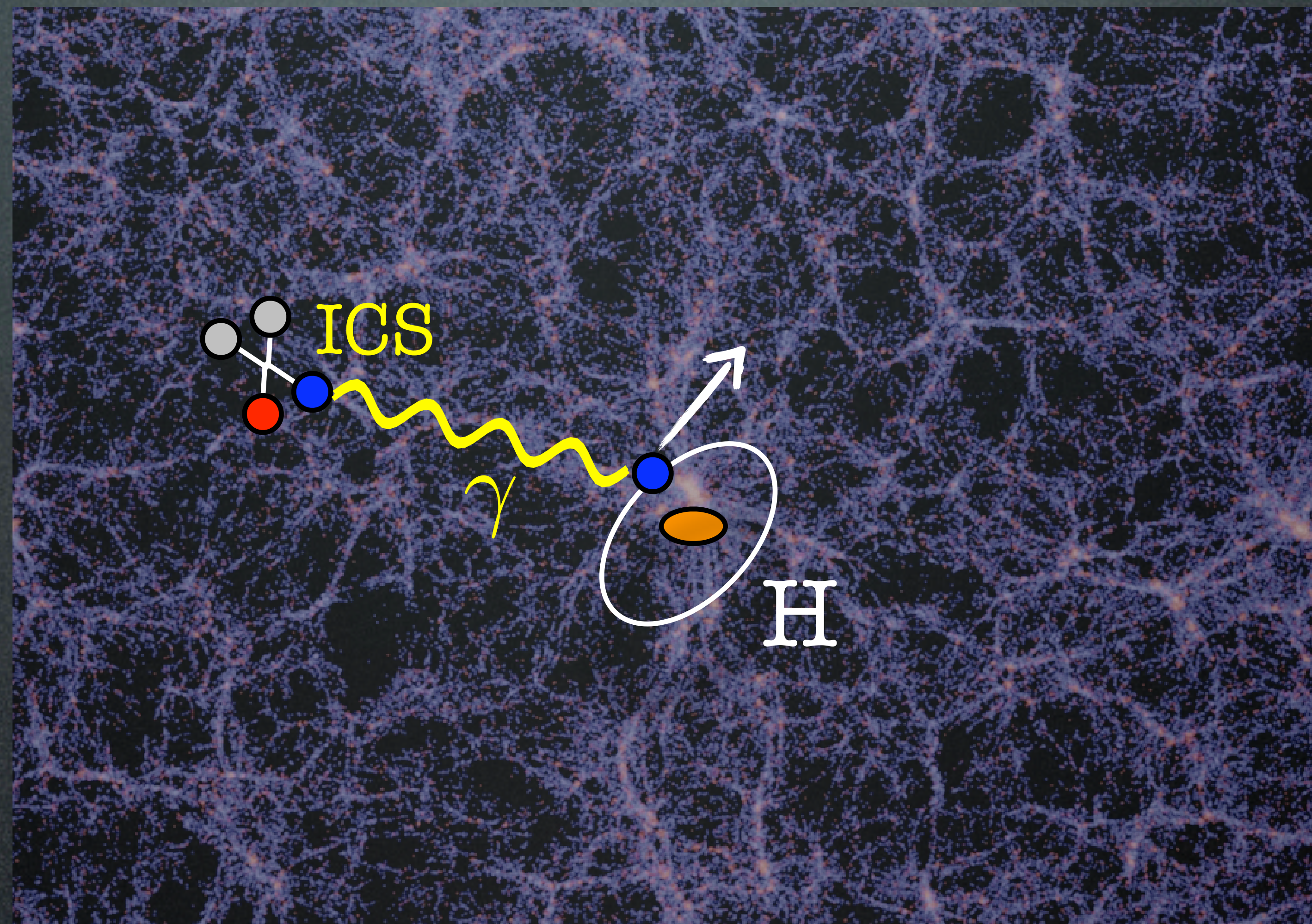
bonus track: cosmology

Cosmology: bounds from reionization

DM particle annihilations produce free electrons



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

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

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

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

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

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

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

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

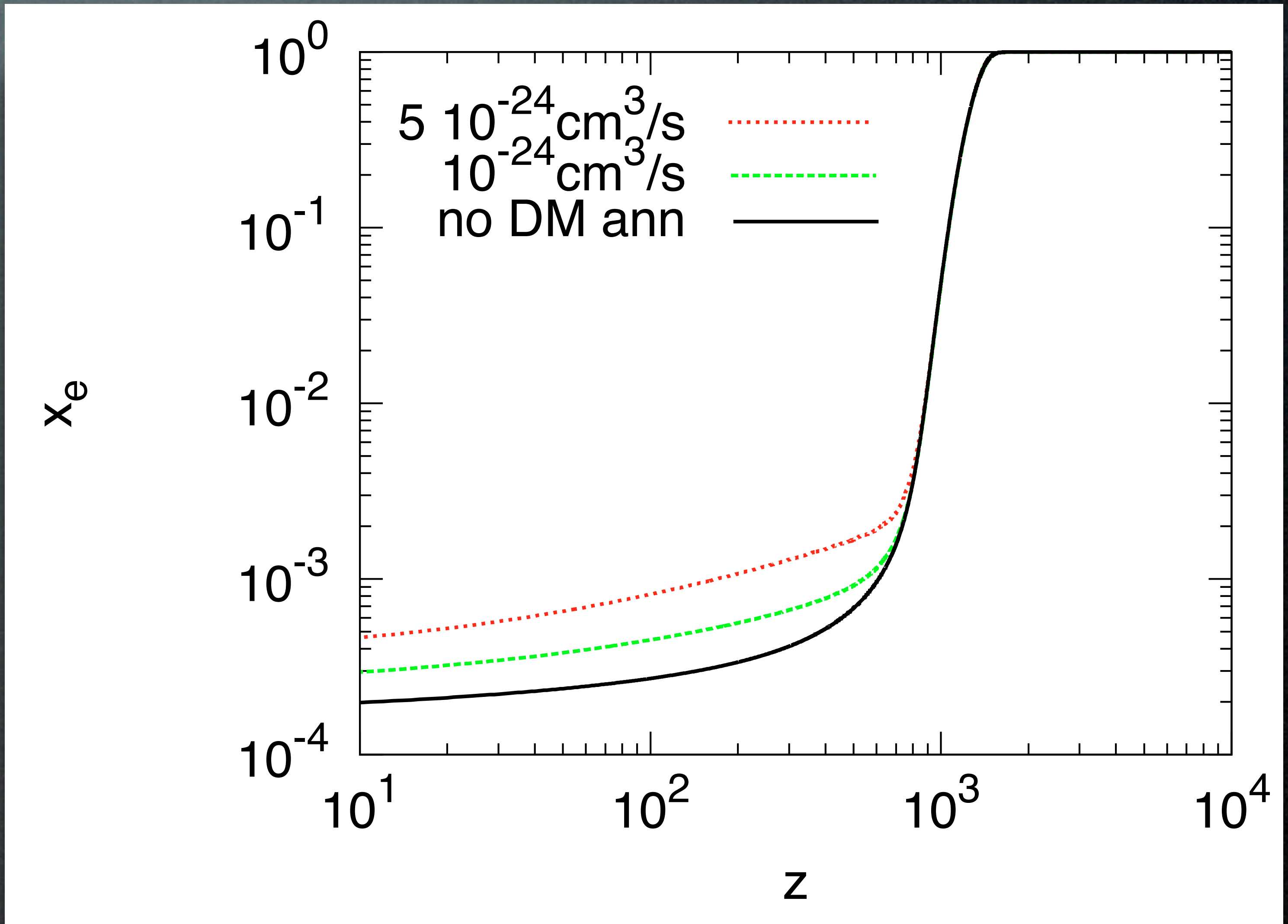
$$\mathcal{B}_i(z) = \frac{\Delta_{\rm vir}(z)}{3\,\rho_c\Omega_M}\int_{M_{\rm min}}^\infty dM\,M\frac{dn}{dM}(z,M)\,F_i(M,z),$$

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

Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

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

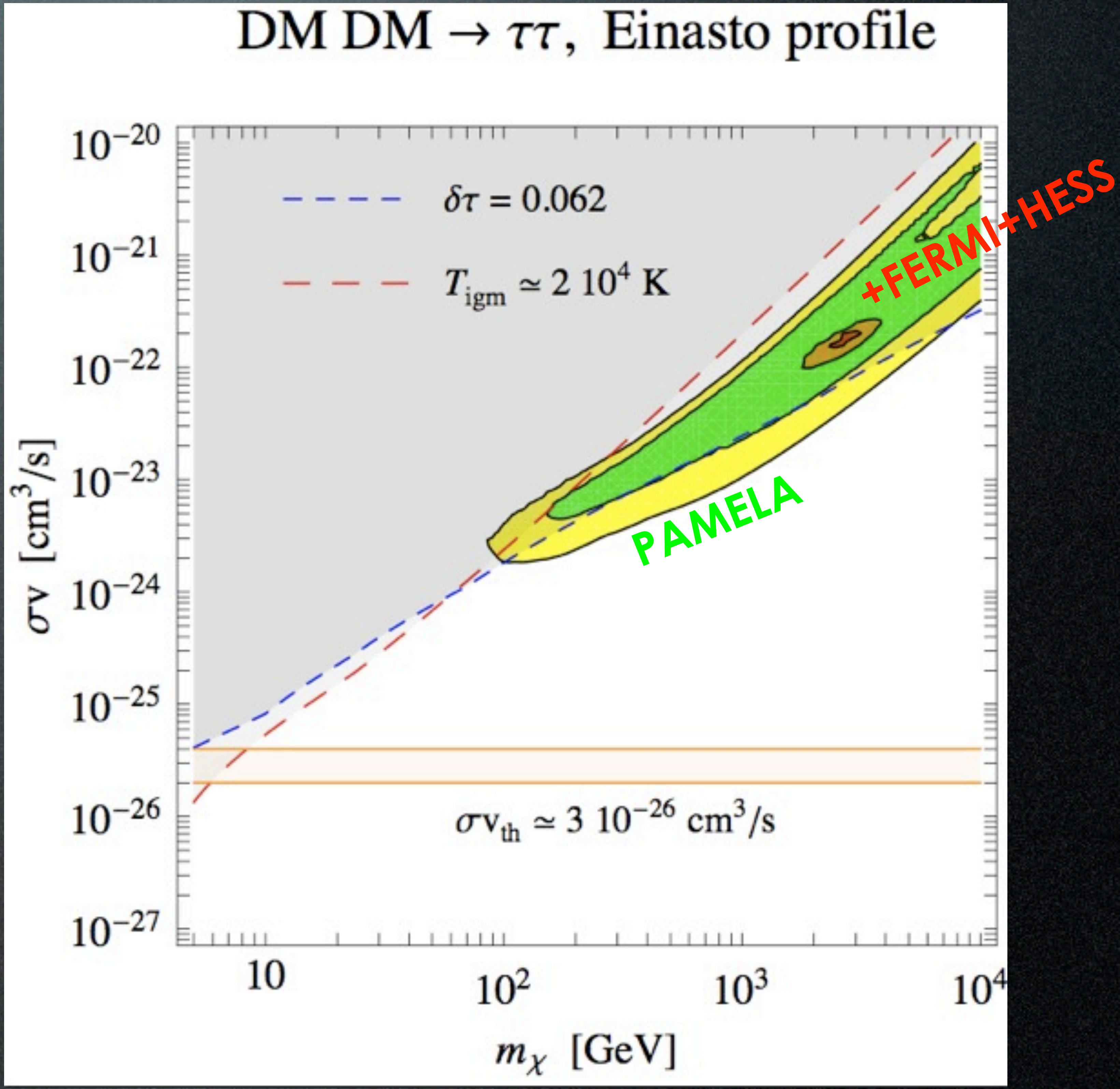


Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

DM particles that fit PAMELA+FERMI+HESS produce too many free electrons: bounds on optical depth of the Universe violated

$\tau = 0.084 \pm 0.016$ (WMAP-5yr)



Cirelli, Iocco, Panci, JCAP 0910

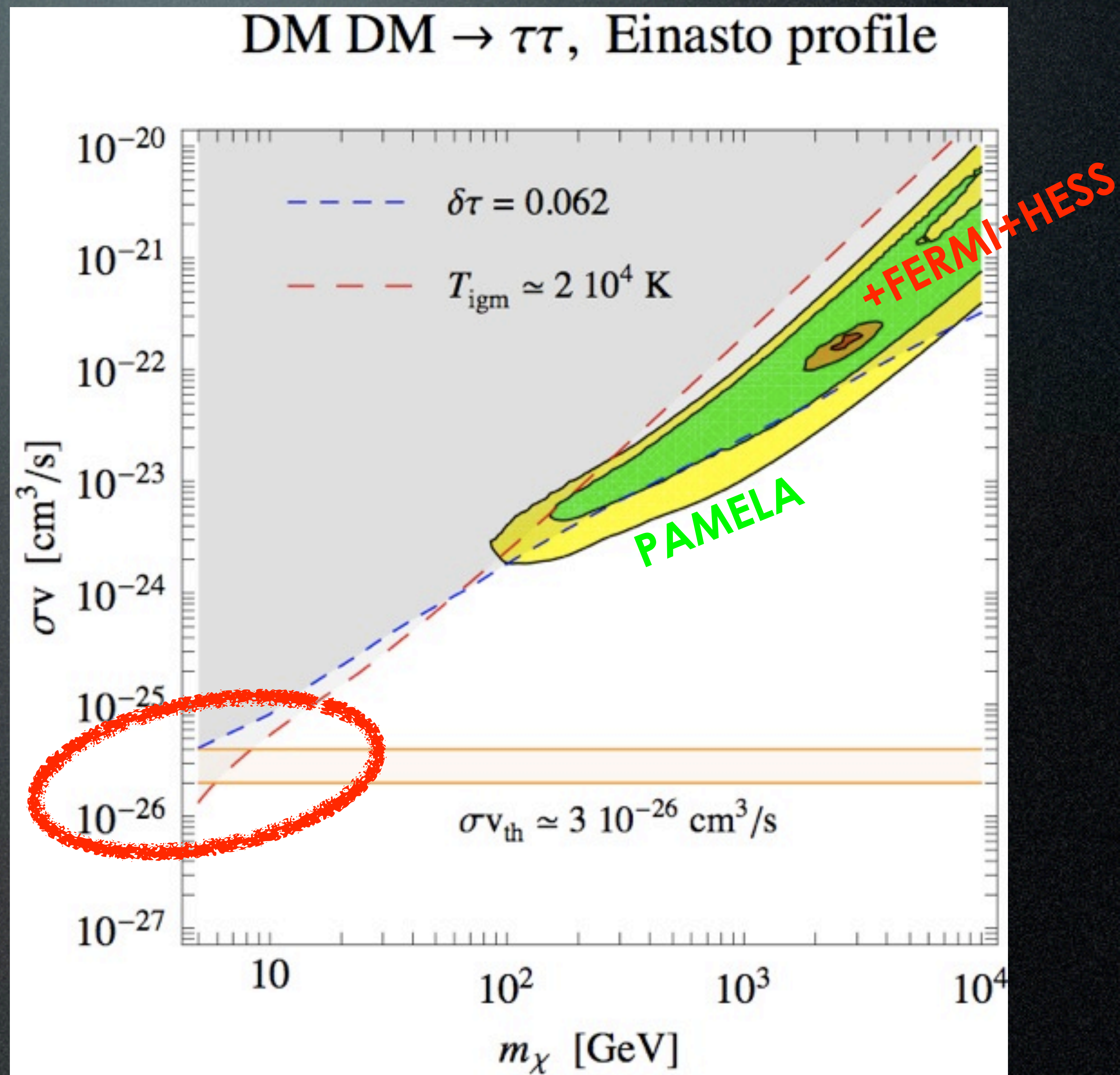
see also:
Huetsi, Hektor, Raidal 0906.4550
Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

DM particles that fit PAMELA+FERMI+HESS produce too many free electrons: bounds on optical depth of the Universe violated

$\tau = 0.084 \pm 0.016$ (WMAP-5yr)

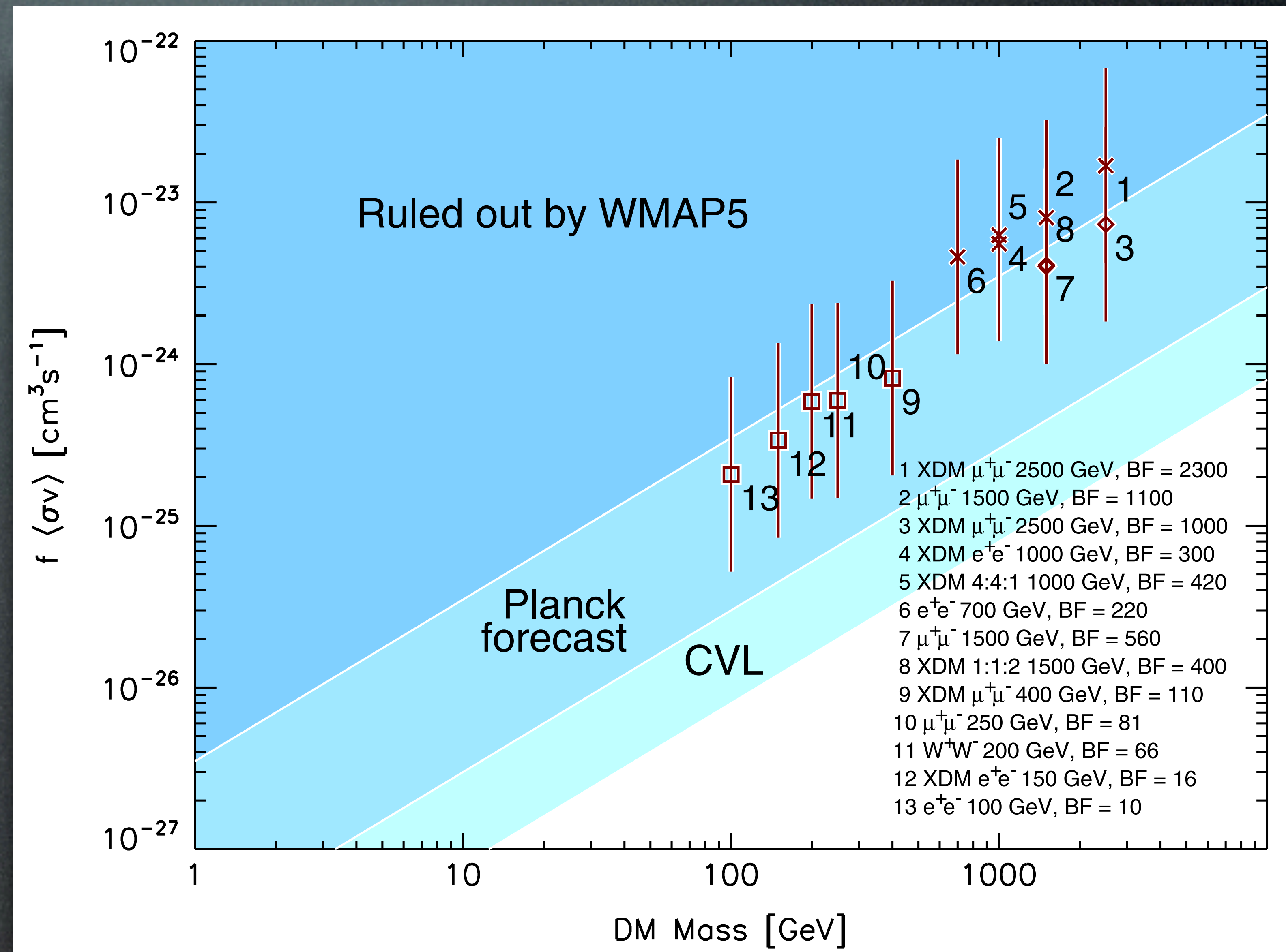
Starts constraining even thermal DM!



Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from CMB

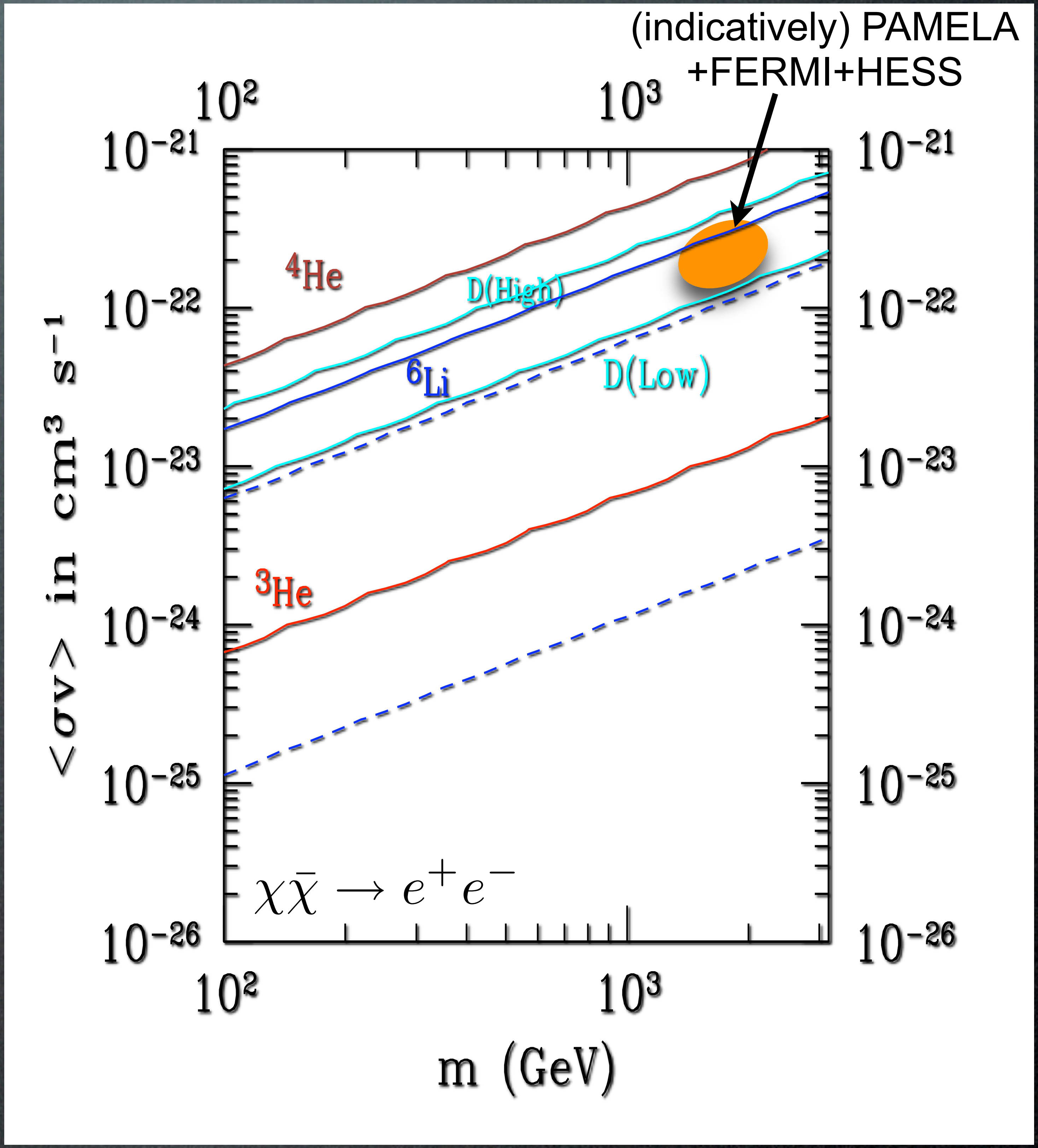
Similar conclusion from global CMB fits



Galli, Iocco, Bertone, Melchiorri, PRD 80 (2009)
Slatyer, Padmanabahn, Finkbeiner, PRD 80 (2009)

Cosmology: bounds from BBN

DM particles that fit PAMELA+FERMI+HESS inject too much energy that destroys forming nuclei: stringent bounds!



Hisano, Kohri et al., 0901.3582

Conclusions

2008-'10 has been crazy in the field of DM indirect detection.

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e^+/e^-	PAMELA, FERMI, HESS (ATIC, PPB-BETS)
$\bar{p}$	PAMELA
$\bar{d}$	GAPS?, AMS?
γ	FERMI, HESS
ν	SK, ICECUBE

Conclusions

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Status:

e^+/e^-	PAMELA, FERMI, HESS (ATIC, PPB-BETS)	something seen
$\bar{p}$	PAMELA	nothing strange
$\bar{d}$	GAPS?, AMS?	wait
γ	FERMI, HESS	plenty of data
ν	SK, ICECUBE	data

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			Is it DM?
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Did we find DM in CR???

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What has the crazyness left?

Hints.

And open-mindedness.

you can ask me about model building directions...

Did we find DM in CR???

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

Back up slides

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

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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 #

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- Decaying DM

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

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

Decaying DM

DM need not be absolutely stable,
just $\tau_{\rm DM} \gtrsim \tau_{\rm universe} \simeq 4.3\ 10^{17}{\rm sec}$.

The current CR anomalies can be due to decay with:

$$\tau_{\rm decay} \approx 10^{26}{\rm sec}$$

Motivations from theory?

- dim 6 suppressed operator in GUT

Arvanitaki, Dimopoulos et al., 2008+09

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

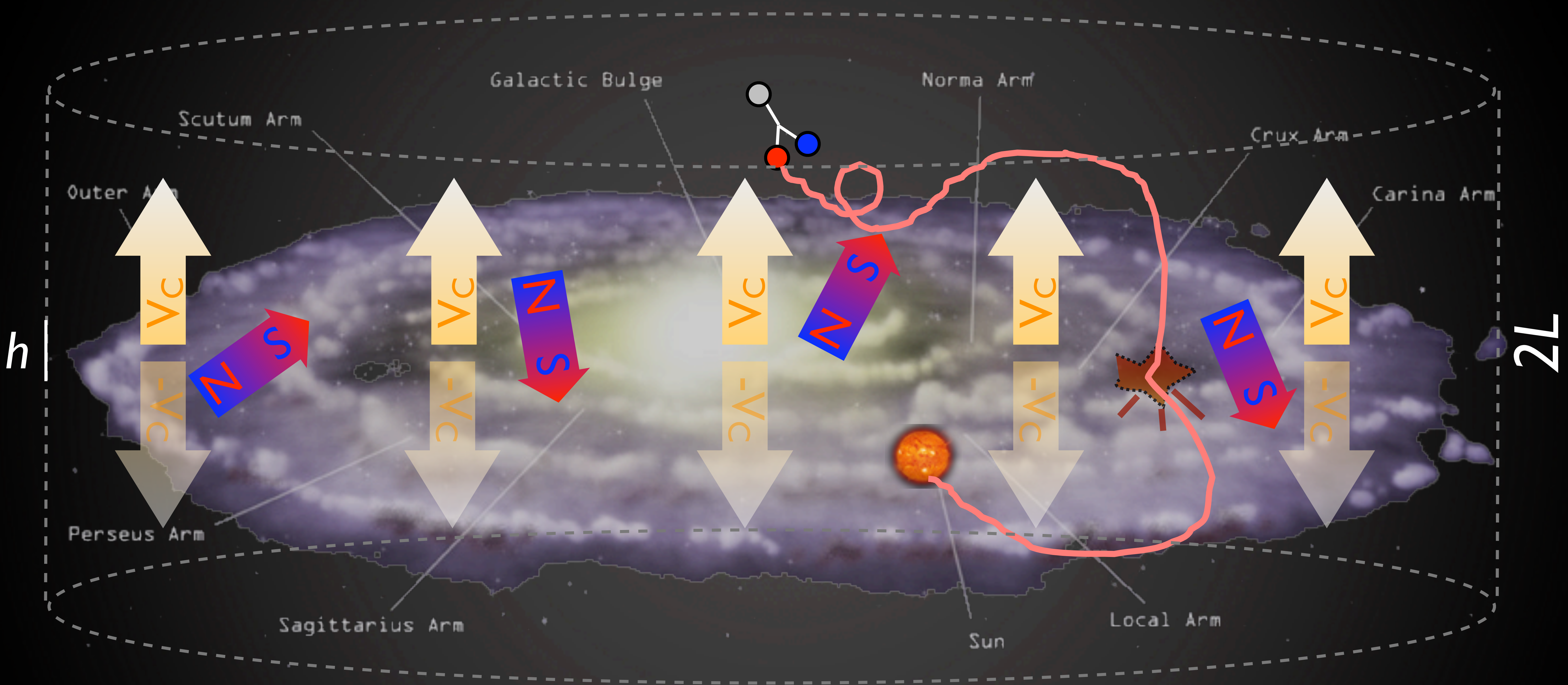
- or in TechniColor

Nardi, Sannino, Strumia 2008

- gravitino in SuSy with broken R-parity...

Indirect Detection

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



What sets the overall expected flux?

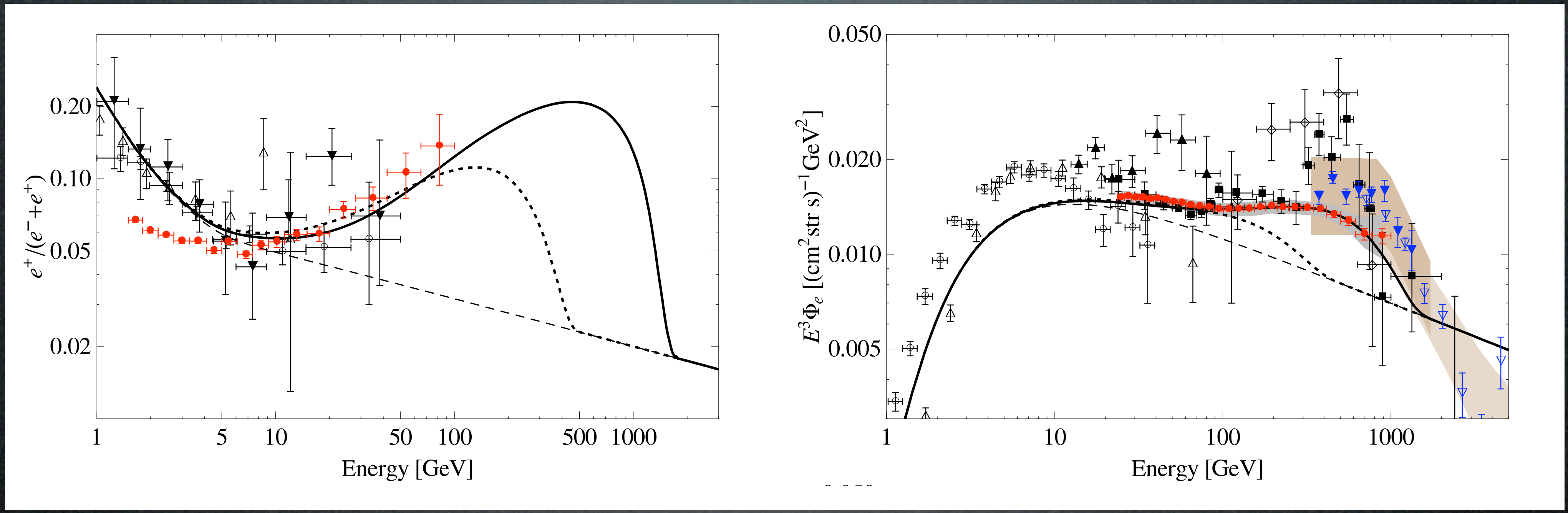
$$\text{flux} \propto n\, \Gamma_{\rm decay}$$

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

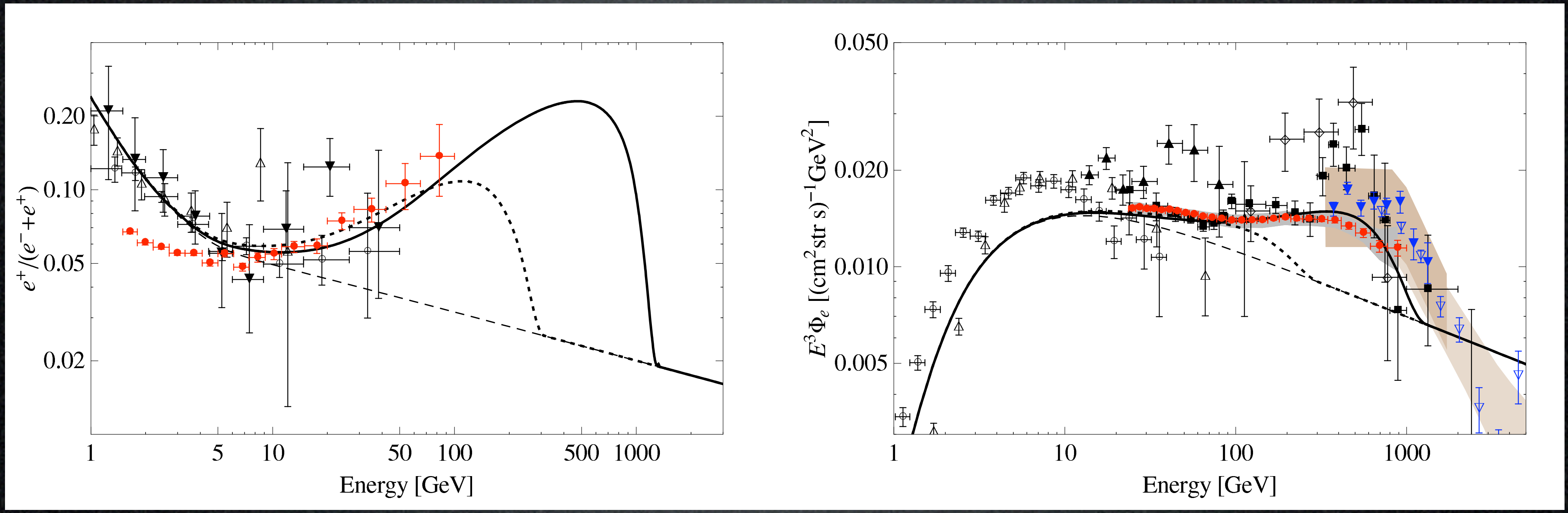
Decaying DM

Which DM spectra can fit the data?

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



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

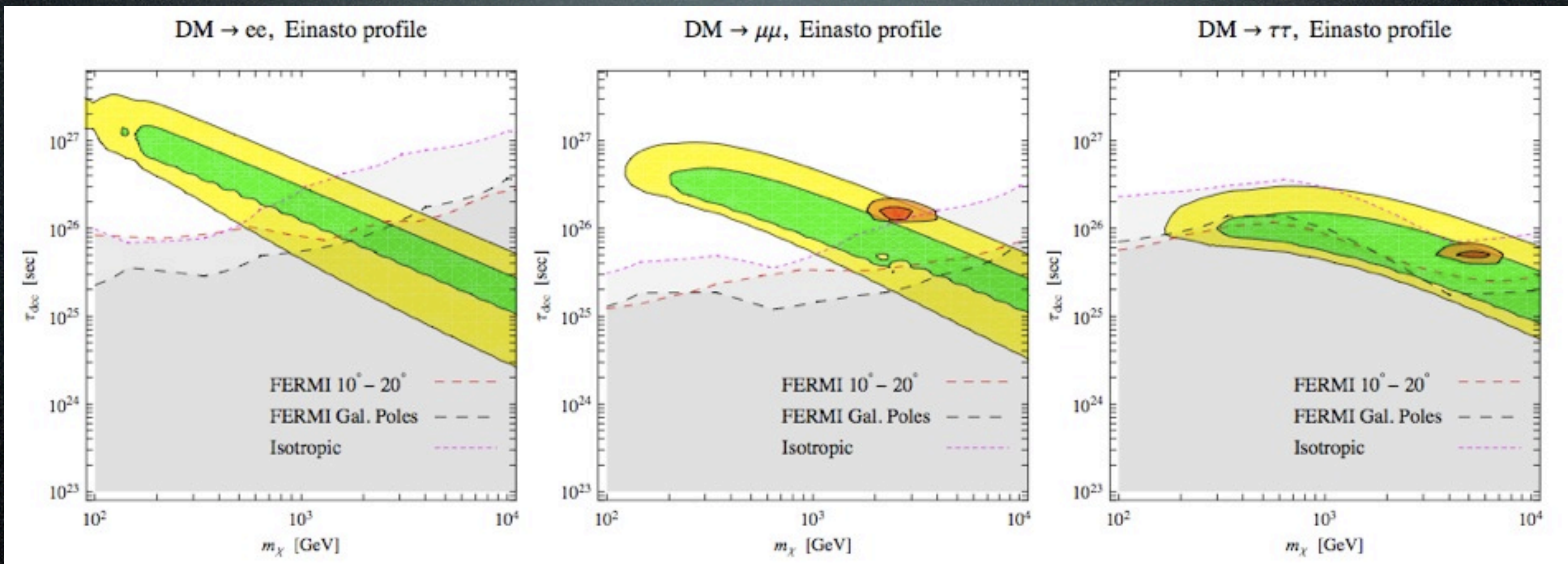


Ibarra, Tran, Weniger 2009

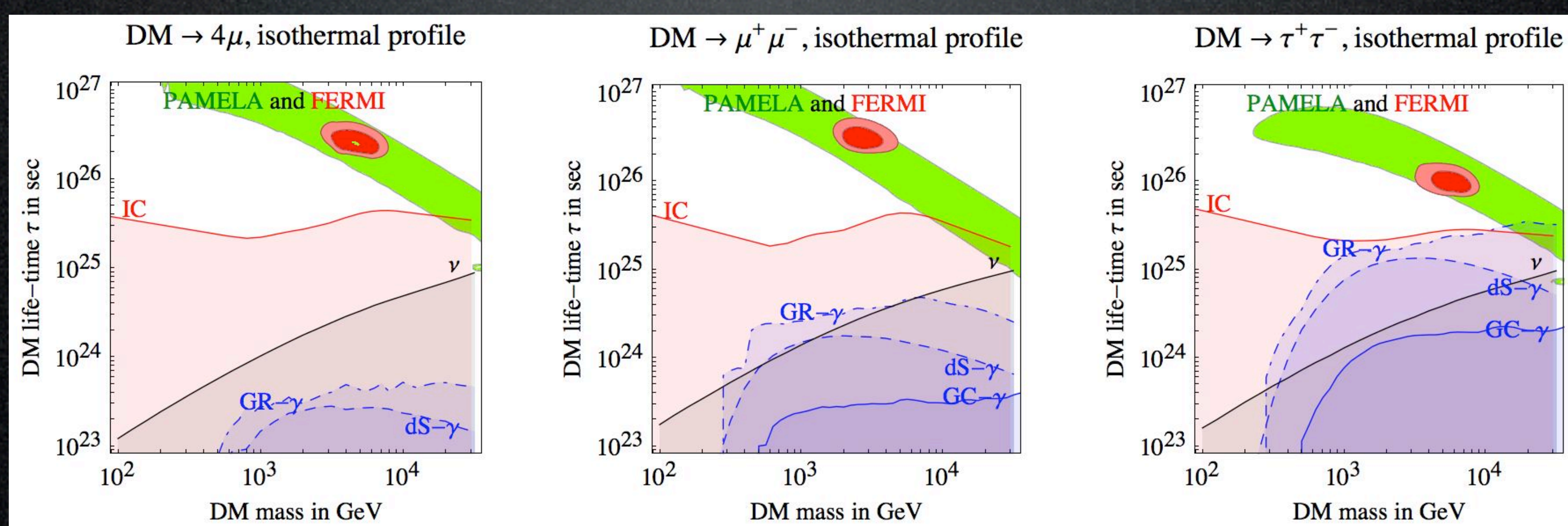
Decaying DM

Beware of gamma ray constraints

(but no radio, neutrino constraints)



Cirelli, Panci, Serpico 0912. 0663



Strumia, Papucci et al. 0905.0480

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

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

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

The "Theory of DM"

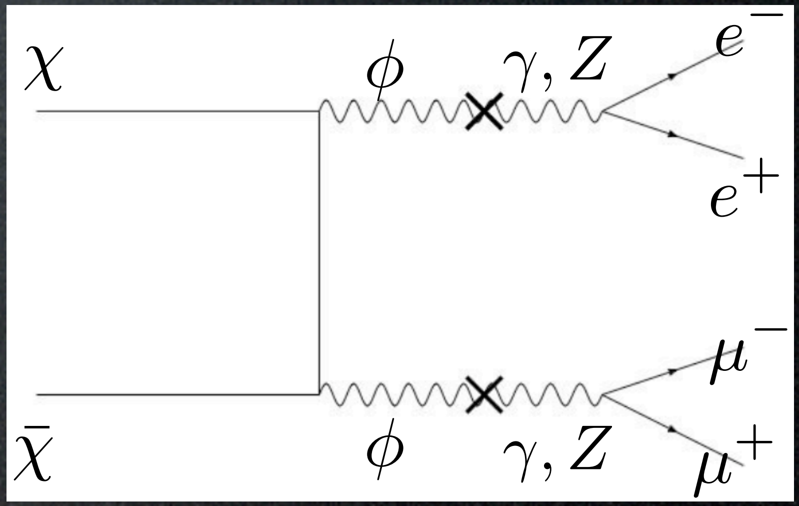
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+\ \mathrm{GeV}$

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim \mathrm{few\ GeV}$
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:
$\alpha M/m_V \gtrsim 1$ fulfilled

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



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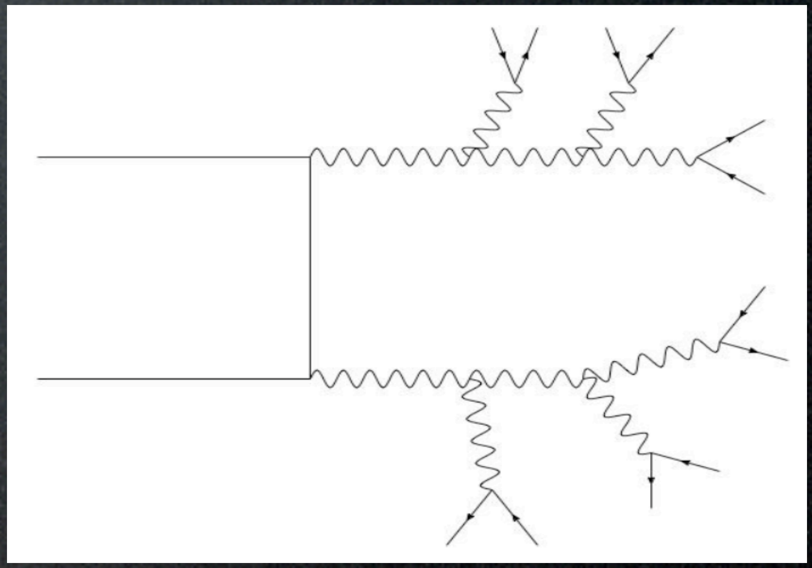
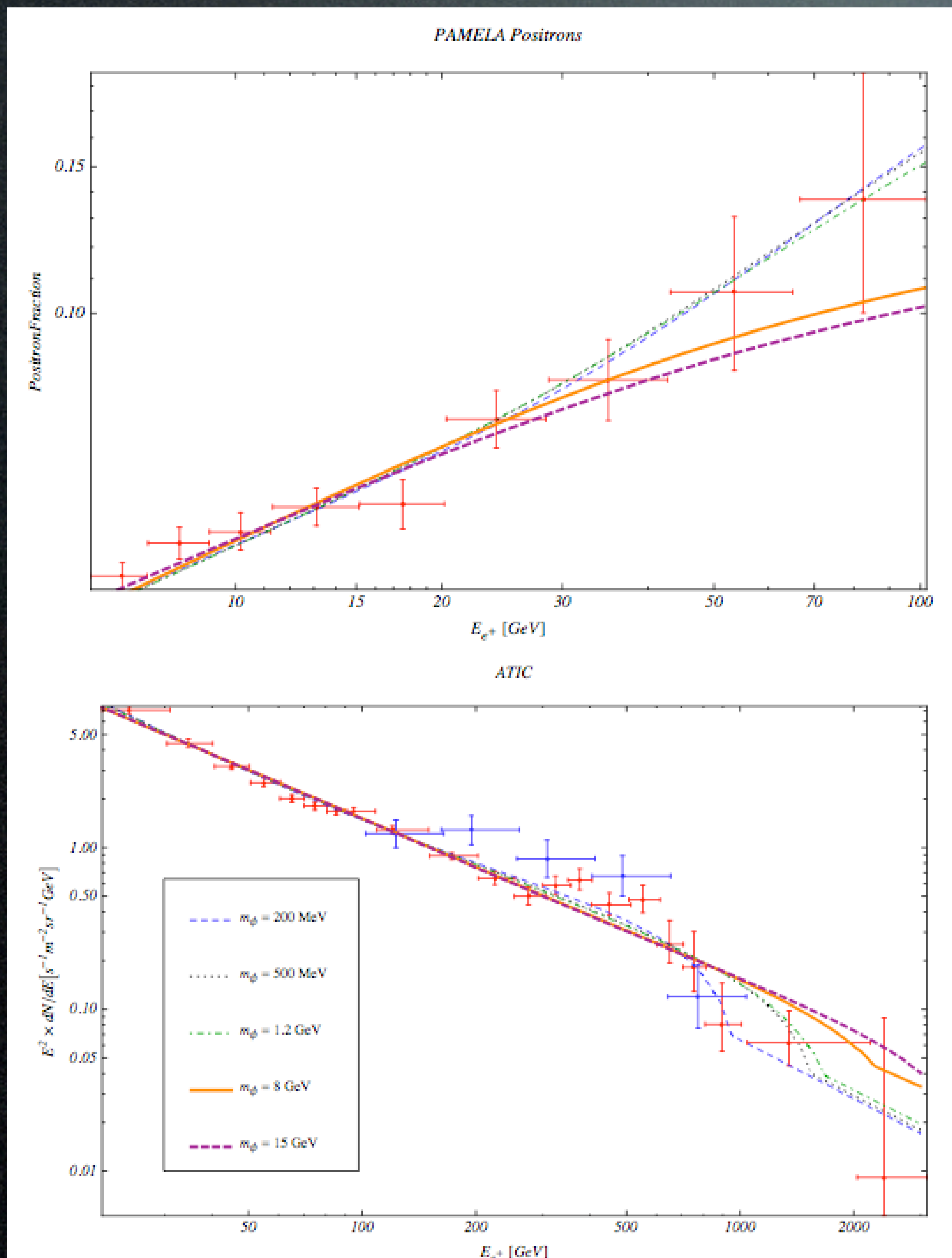


Extras:

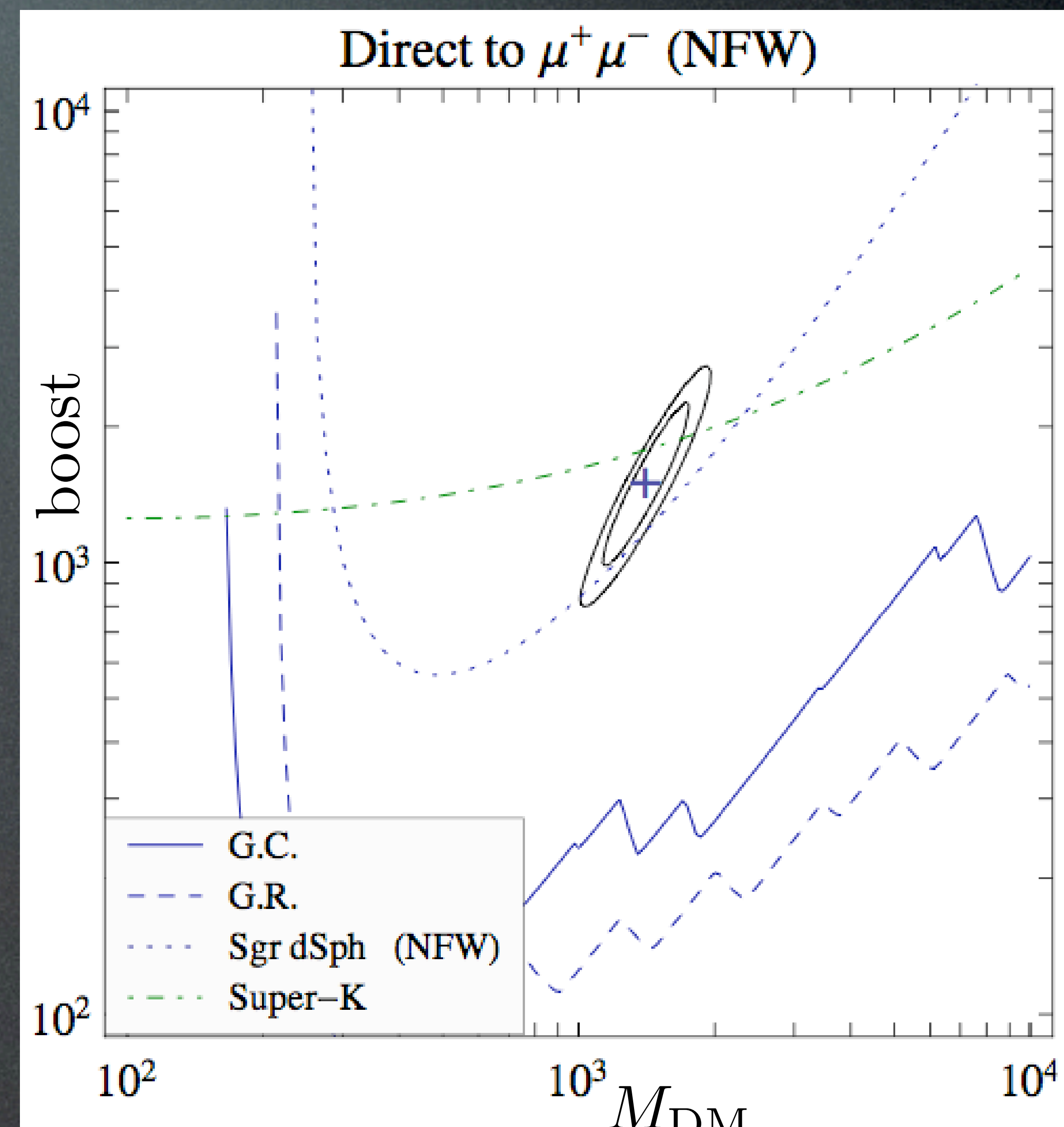
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200\ \mathrm{KeV}$ (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The "Theory of DM"

Phenomenology:



Meade, Papucci, Volanski
0901.2925



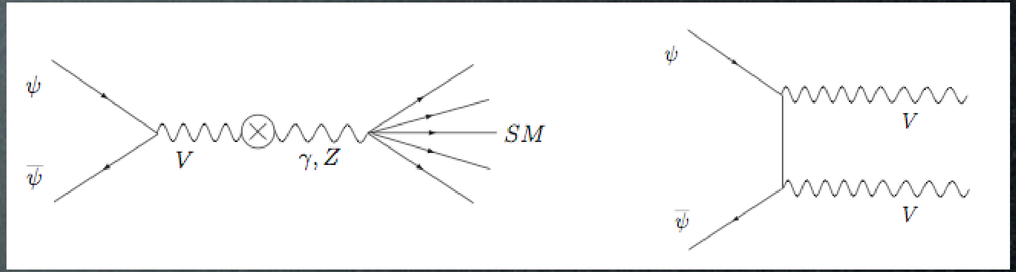
Mardon, Nomura, Stolarski,
Thaler 0901.2926

Variations

(selected)

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

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



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

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

  Bai, Han 0811.0387

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

  Park, Shu 0901.0720

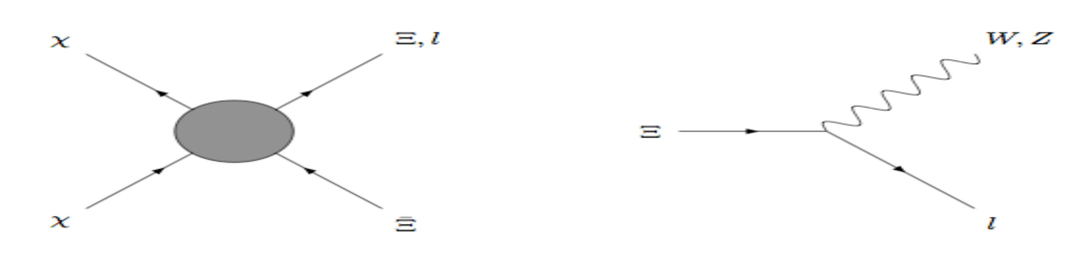
- DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson $(m_\phi \sim \text{tens GeV})$

  Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399

- New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly

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

  Phalen, Pierce, Weiner 0901.3165



- ......

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

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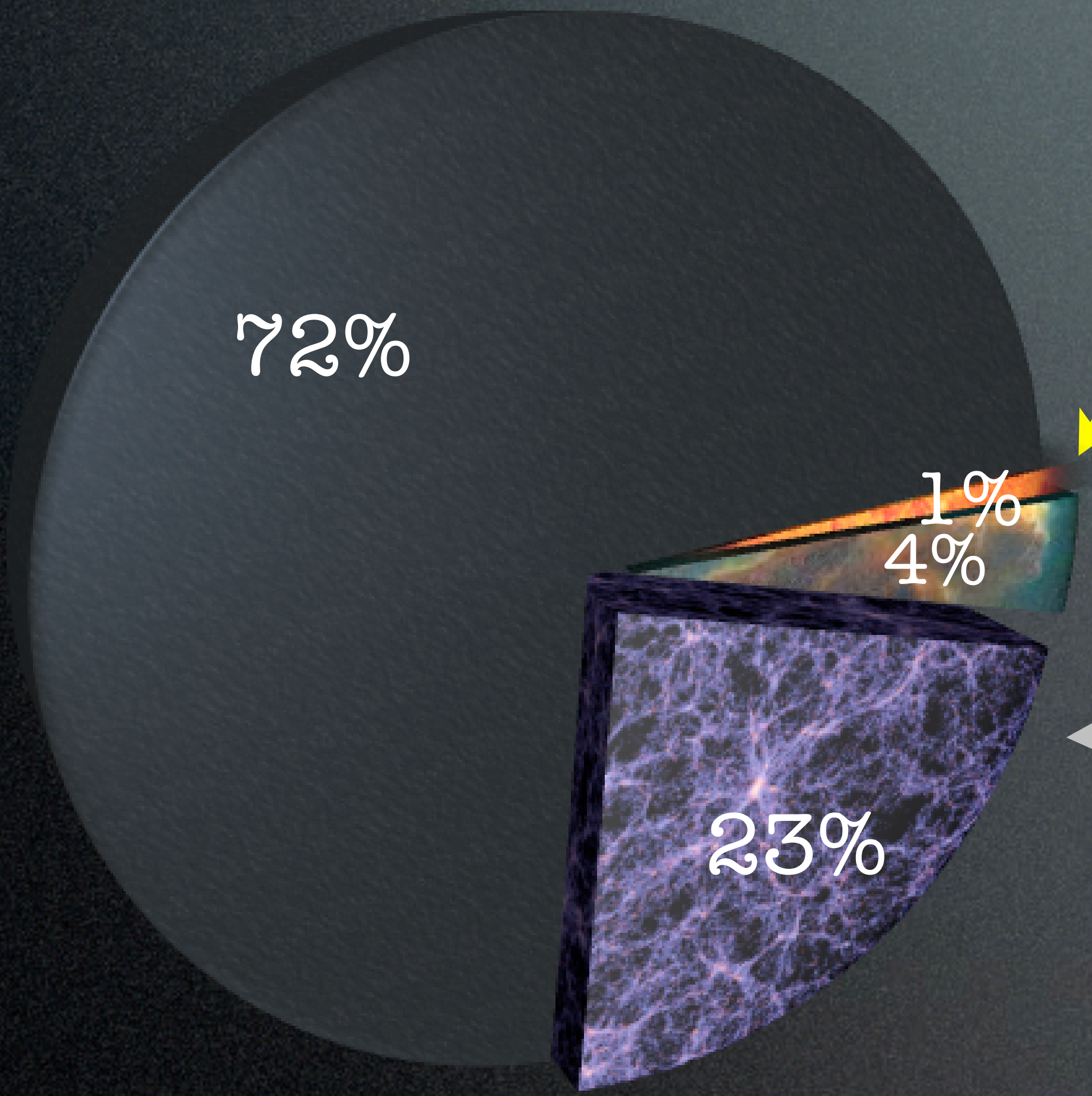
The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$ -BBN -CMB

$\Omega_{\rm DM} \sim 0.23$

$\Omega_{\rm de} \sim 0.72$

- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\rm tot} = 1 \text{ (flat)};\ \text{HST } h = 0.71 \pm 0.07 \right)$

what's the difference between DM and DE?

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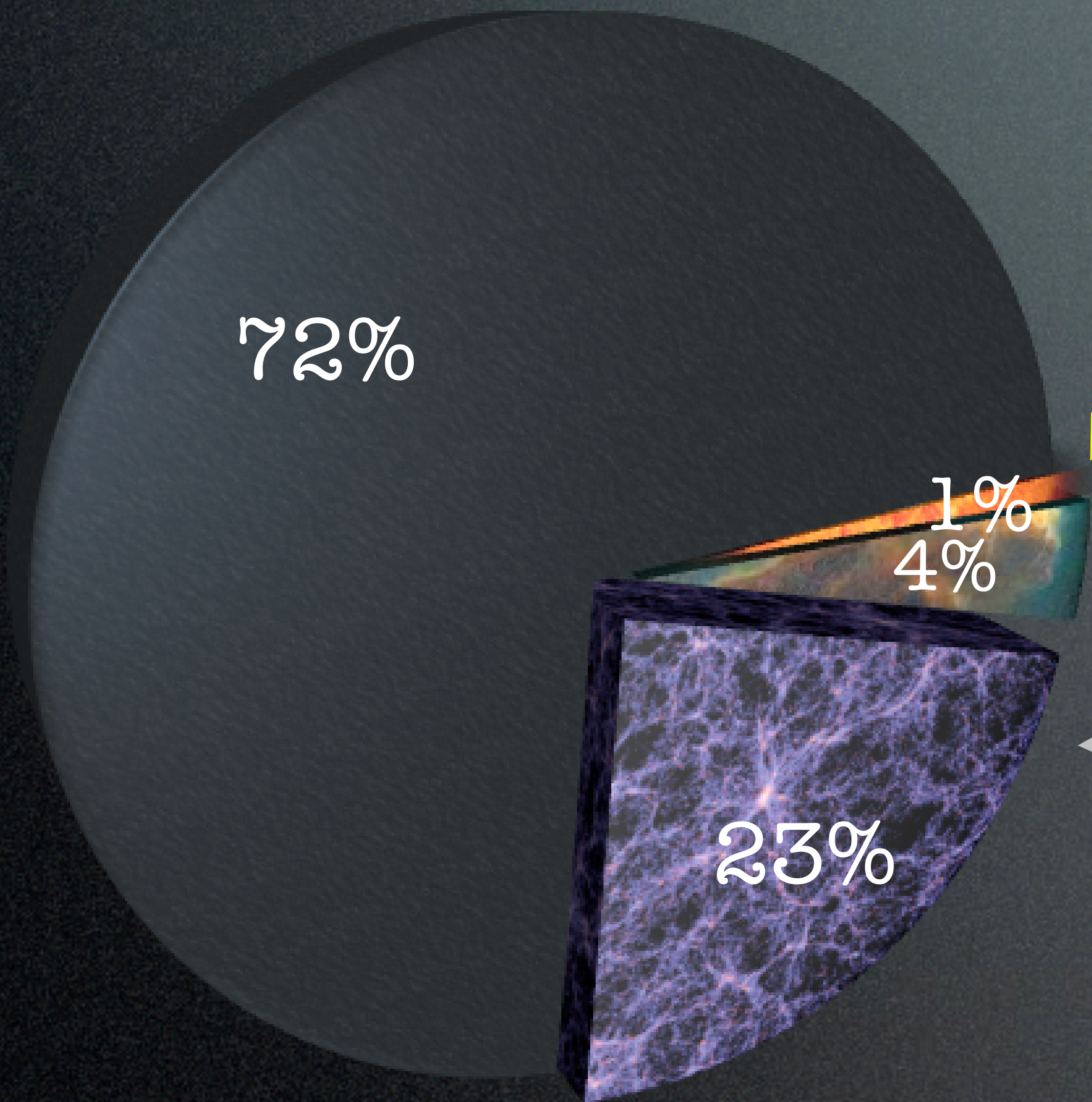

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what's the difference between DM and DE?

How do we know that Dark Matter is out there?

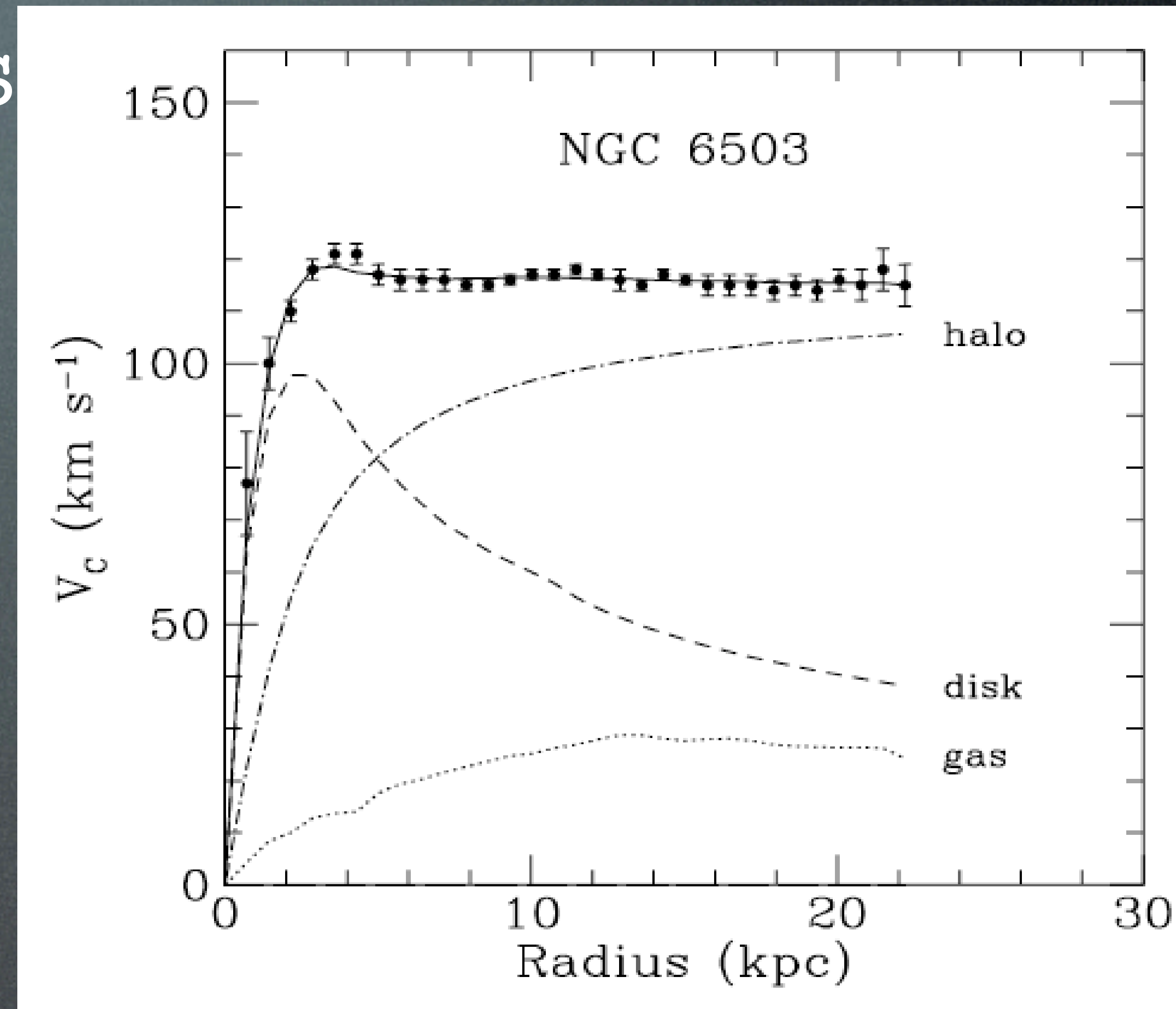
The Evidence for DM

1) galaxy rotation curves

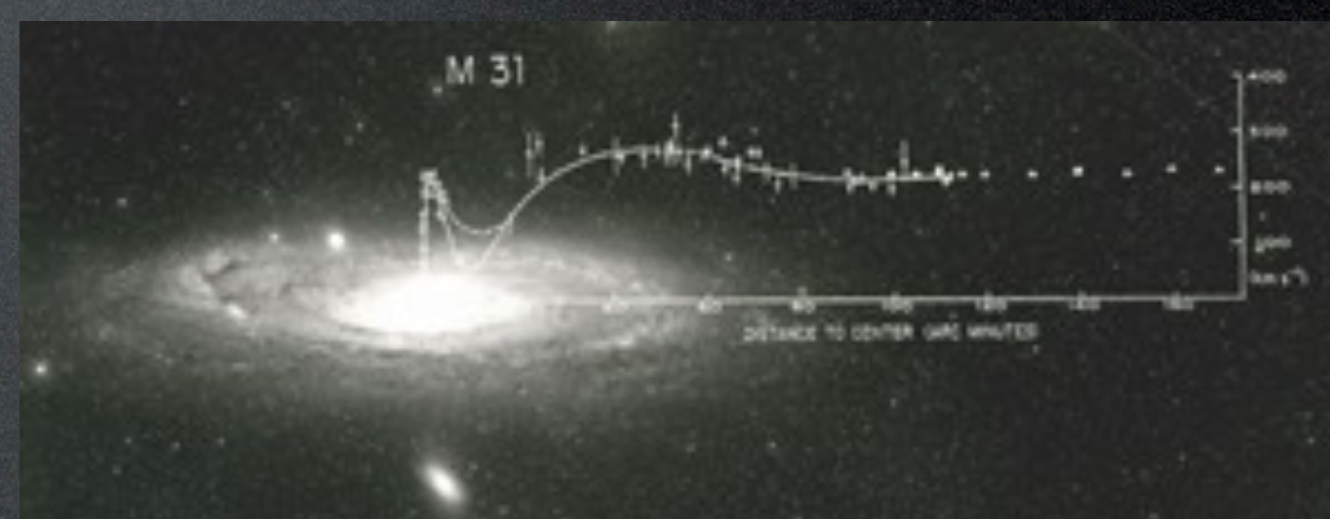
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_\mathrm{M} \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



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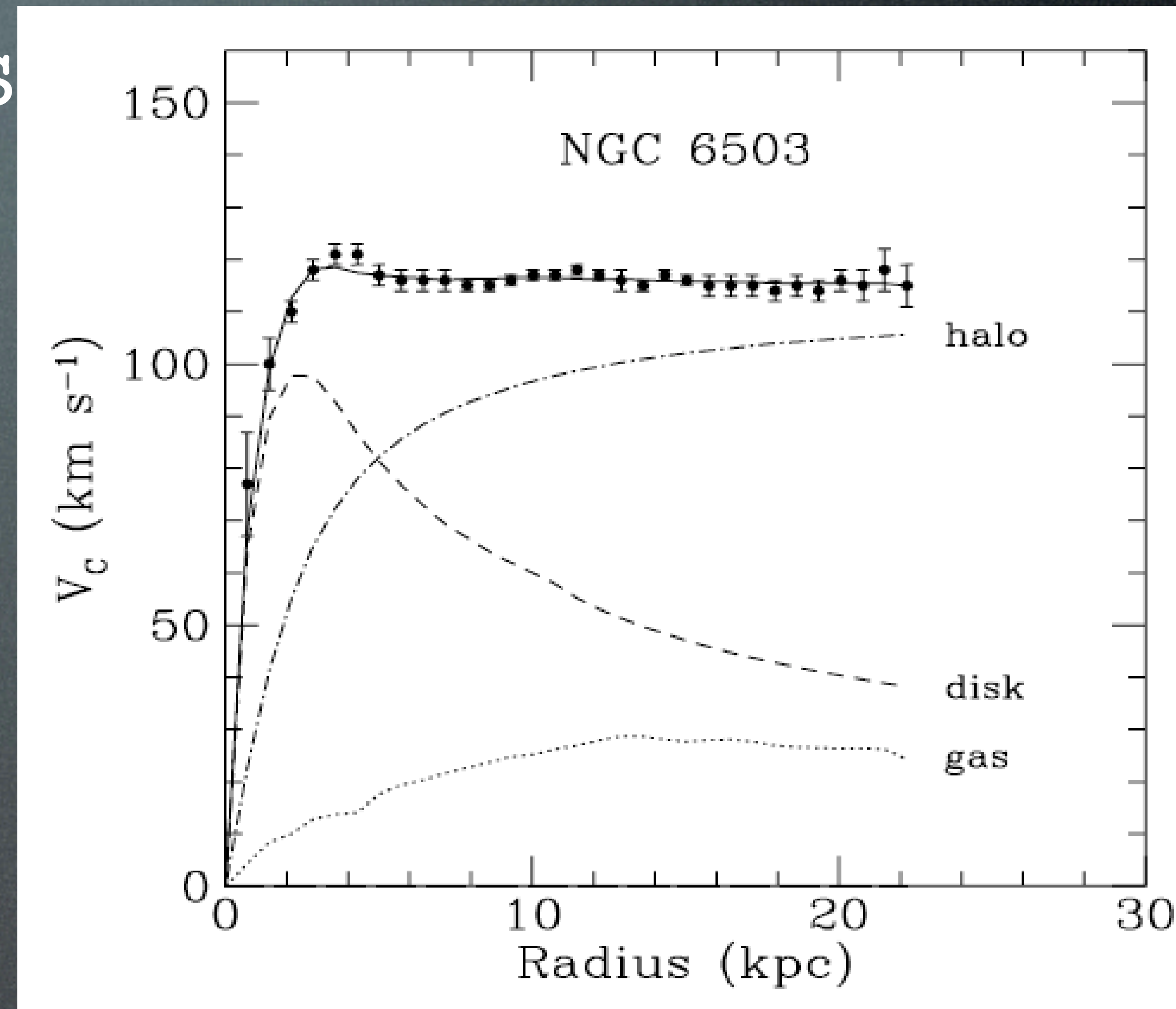

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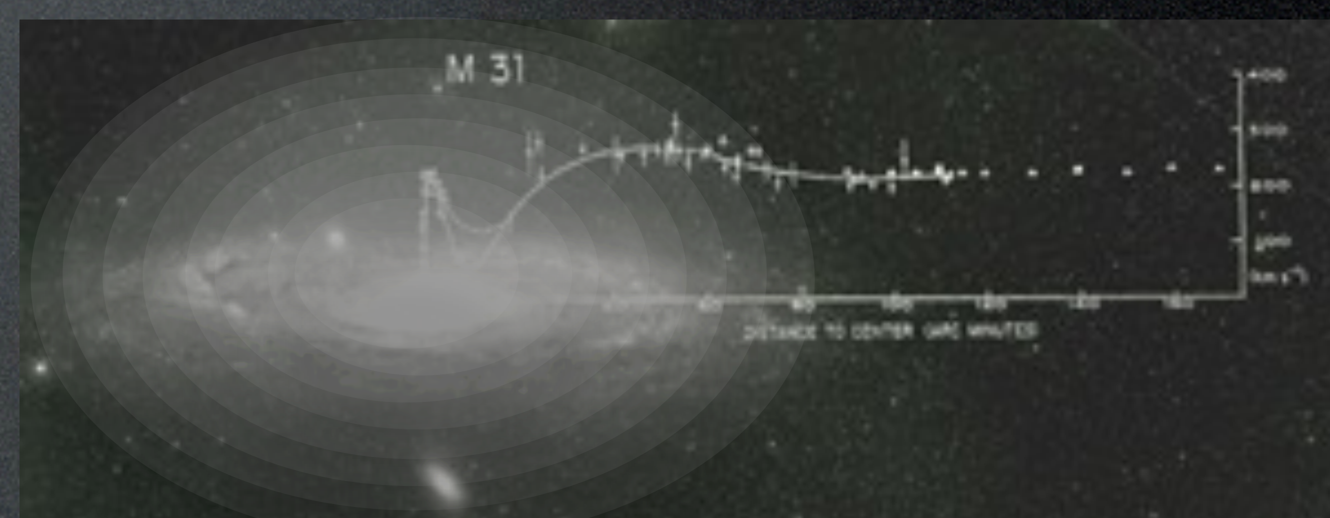

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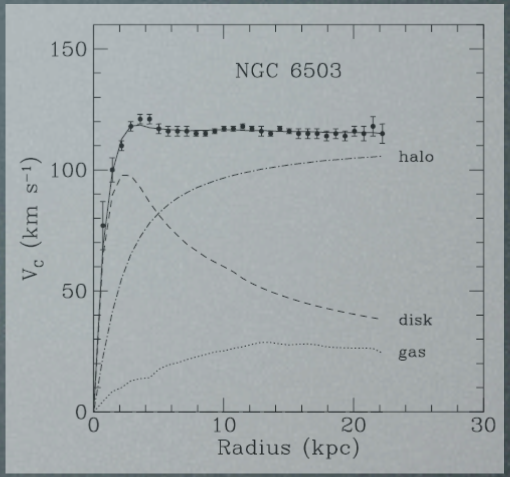

$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

$$\Omega_M \sim 0.2 \div 0.4$$

"bullet cluster" - NASA
astro-ph/0608247
[further developments]

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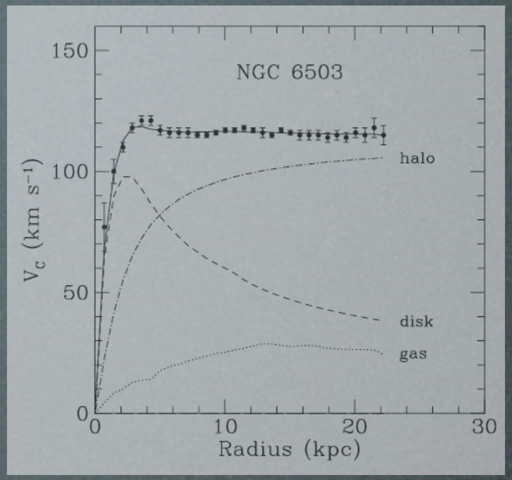

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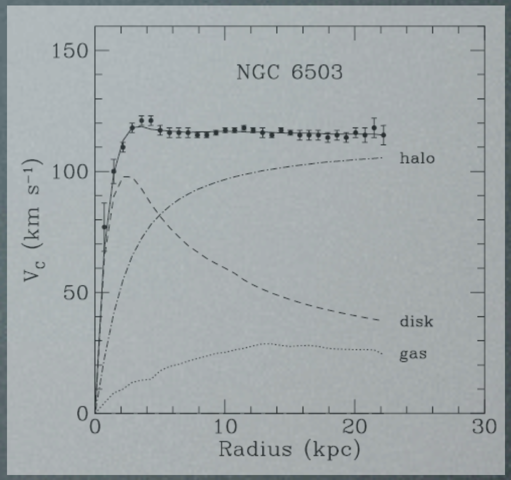

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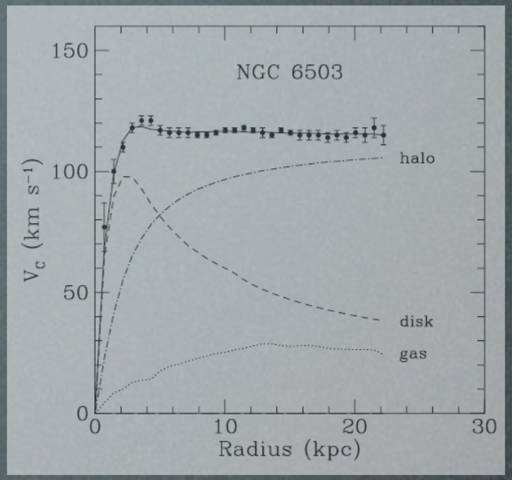

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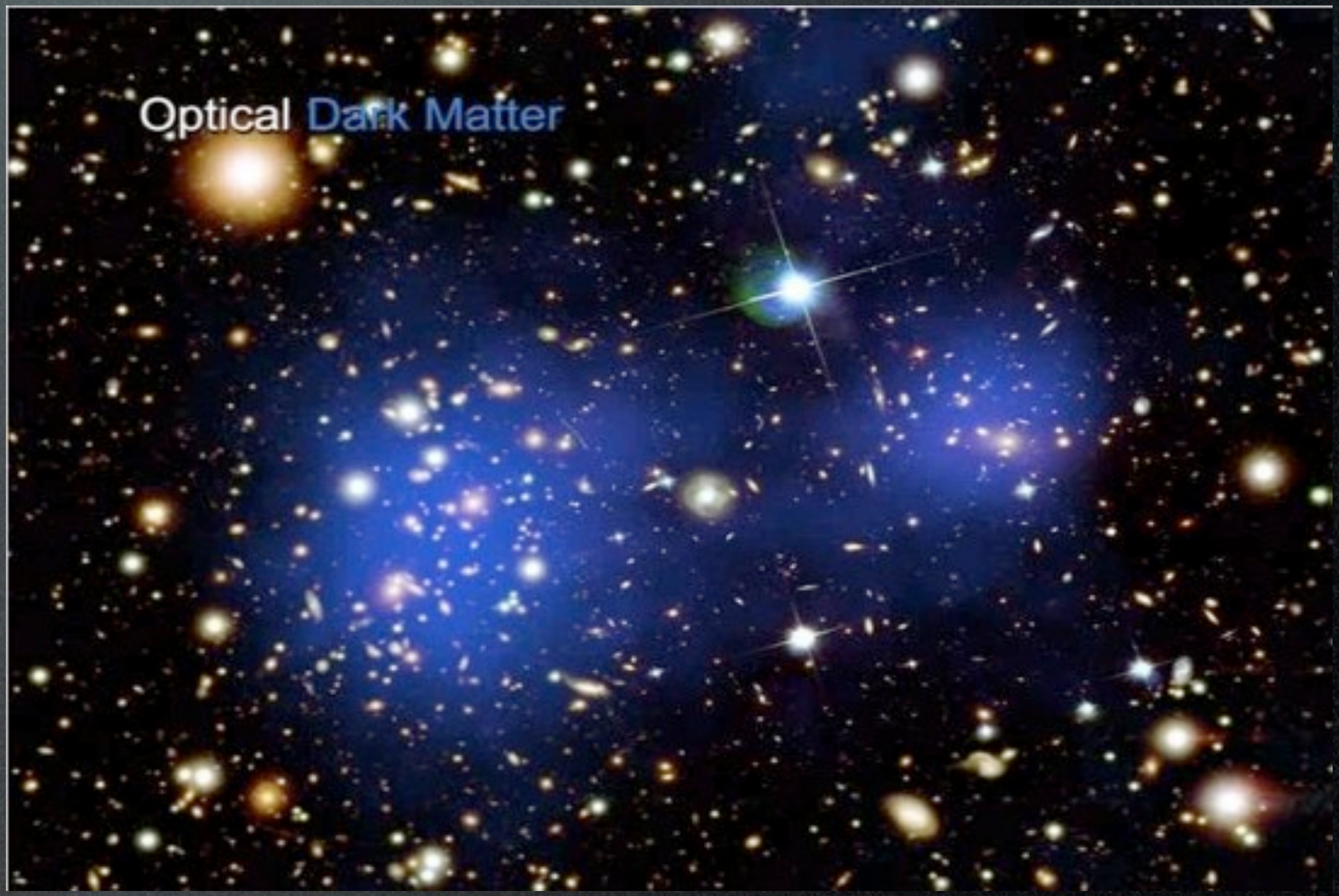

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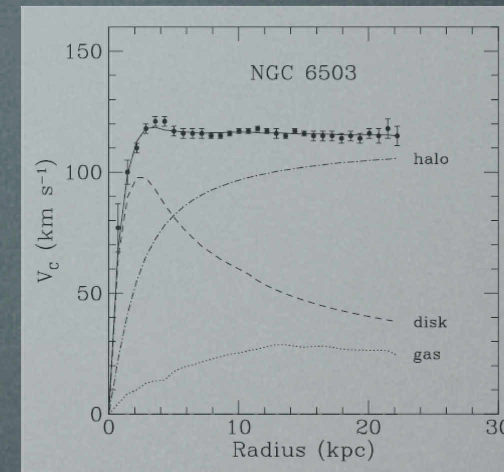

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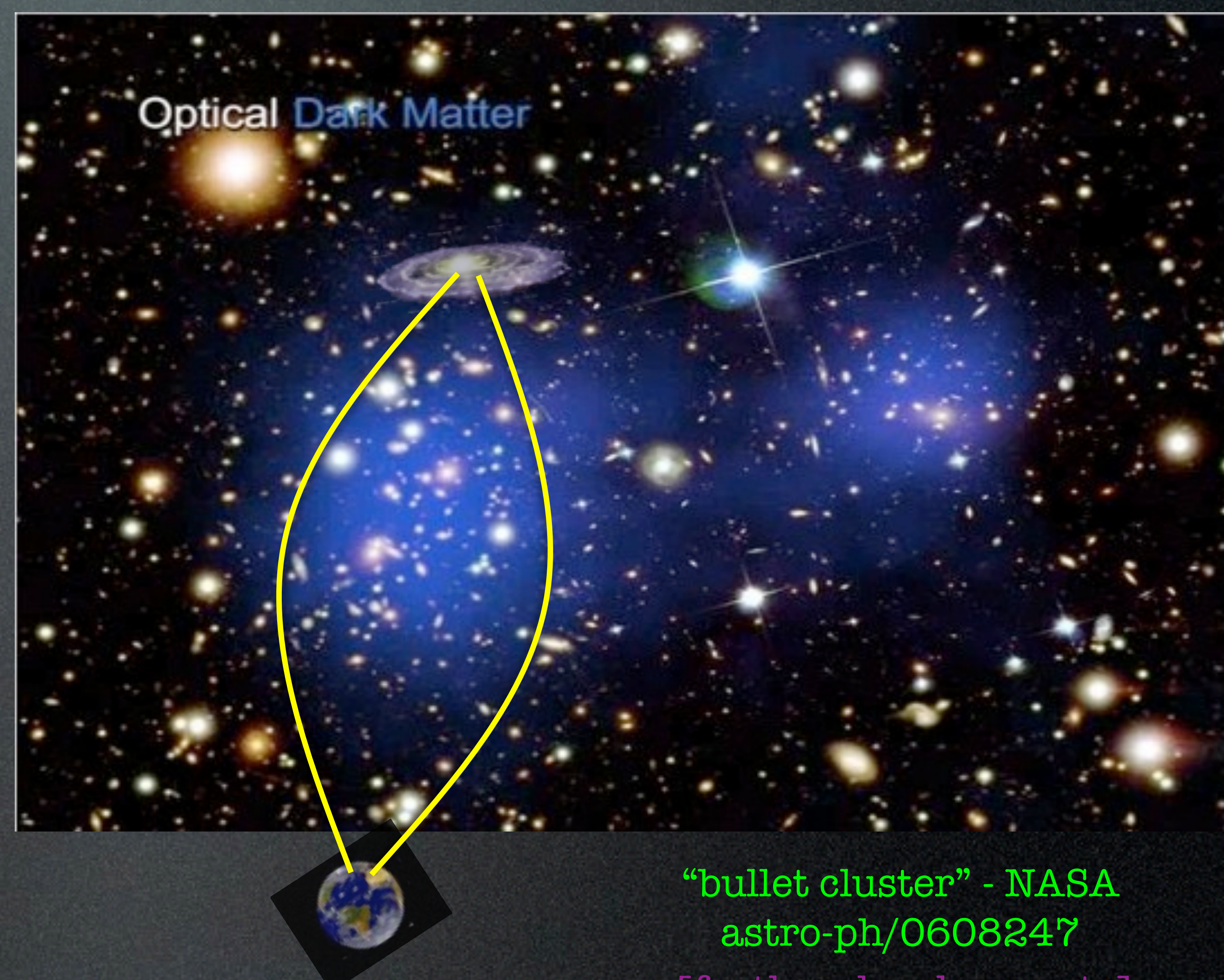

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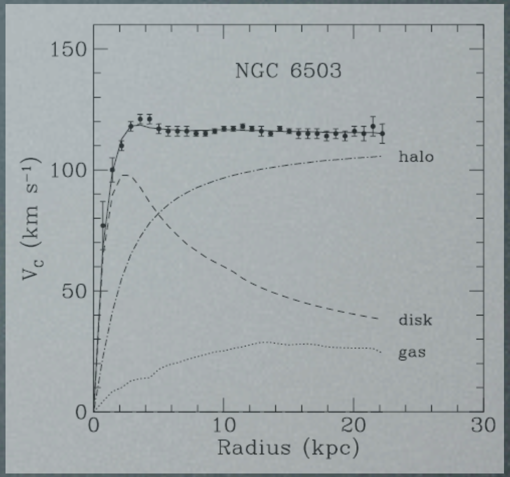

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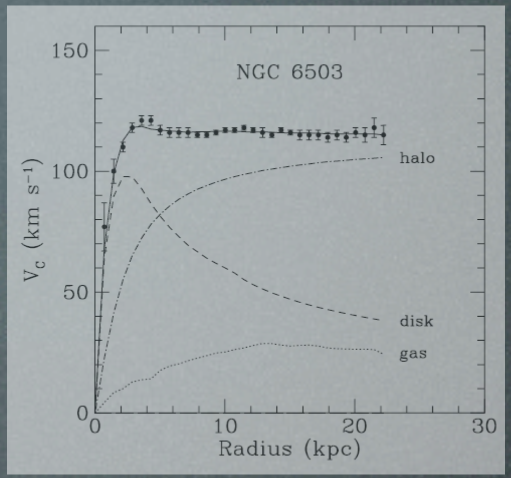

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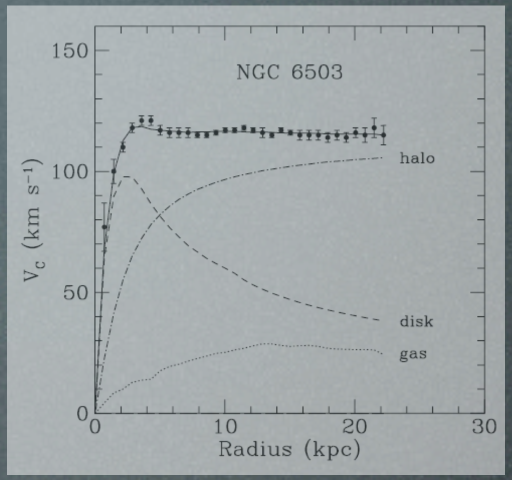

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- gravitation lensing

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ring of Dark Matter (2007)

The Evidence for DM

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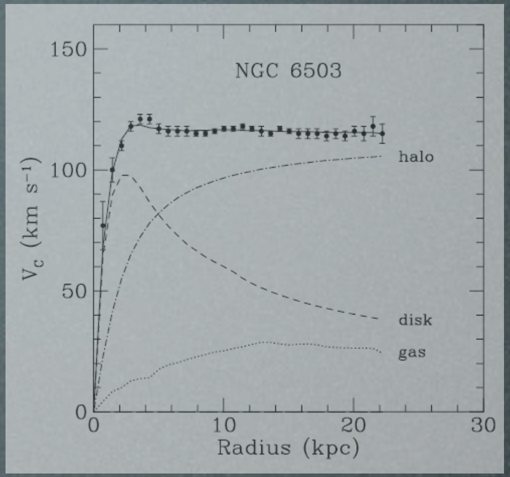

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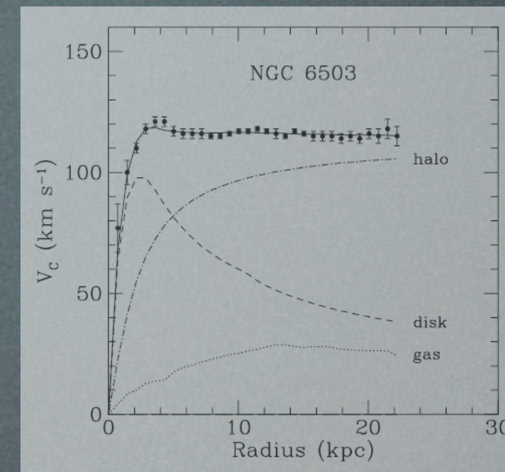

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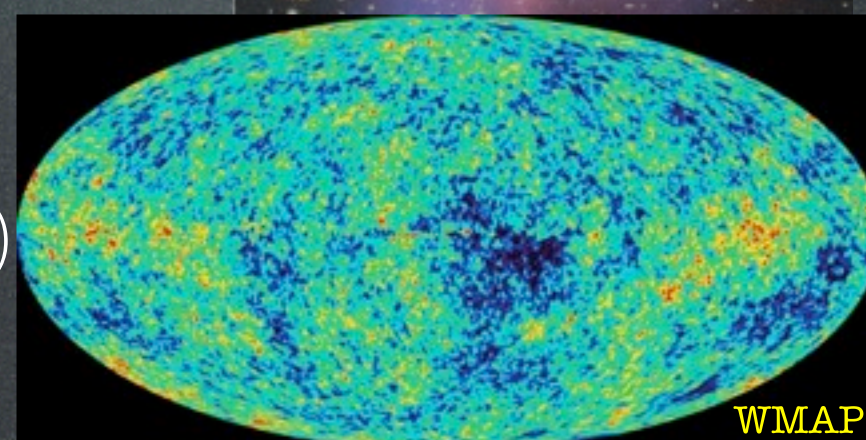

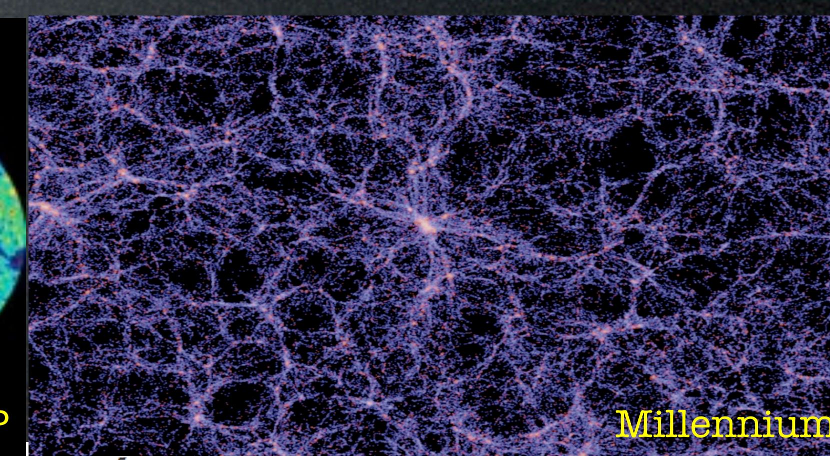

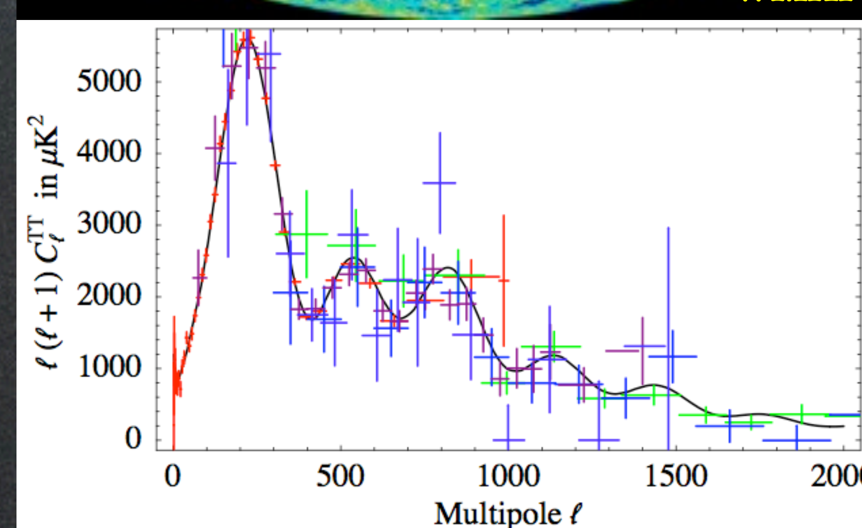

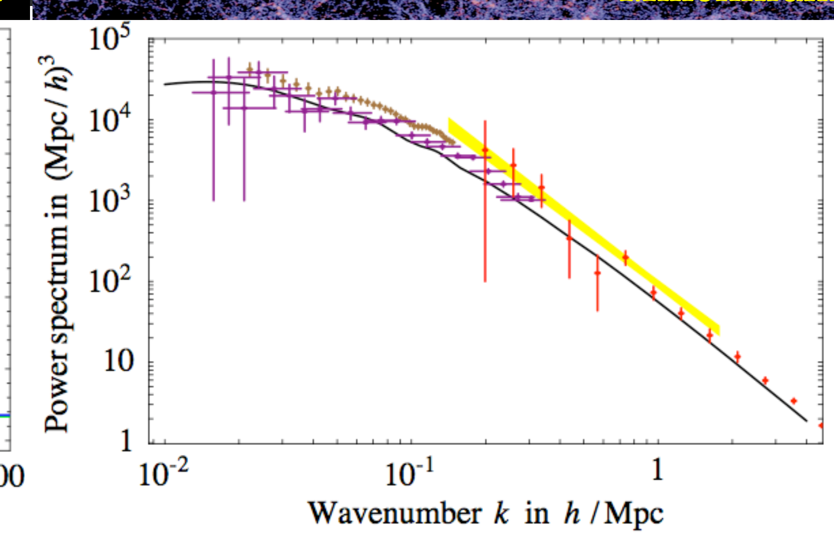

M.Cirelli and A.Strumia, astro-ph/0607086

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

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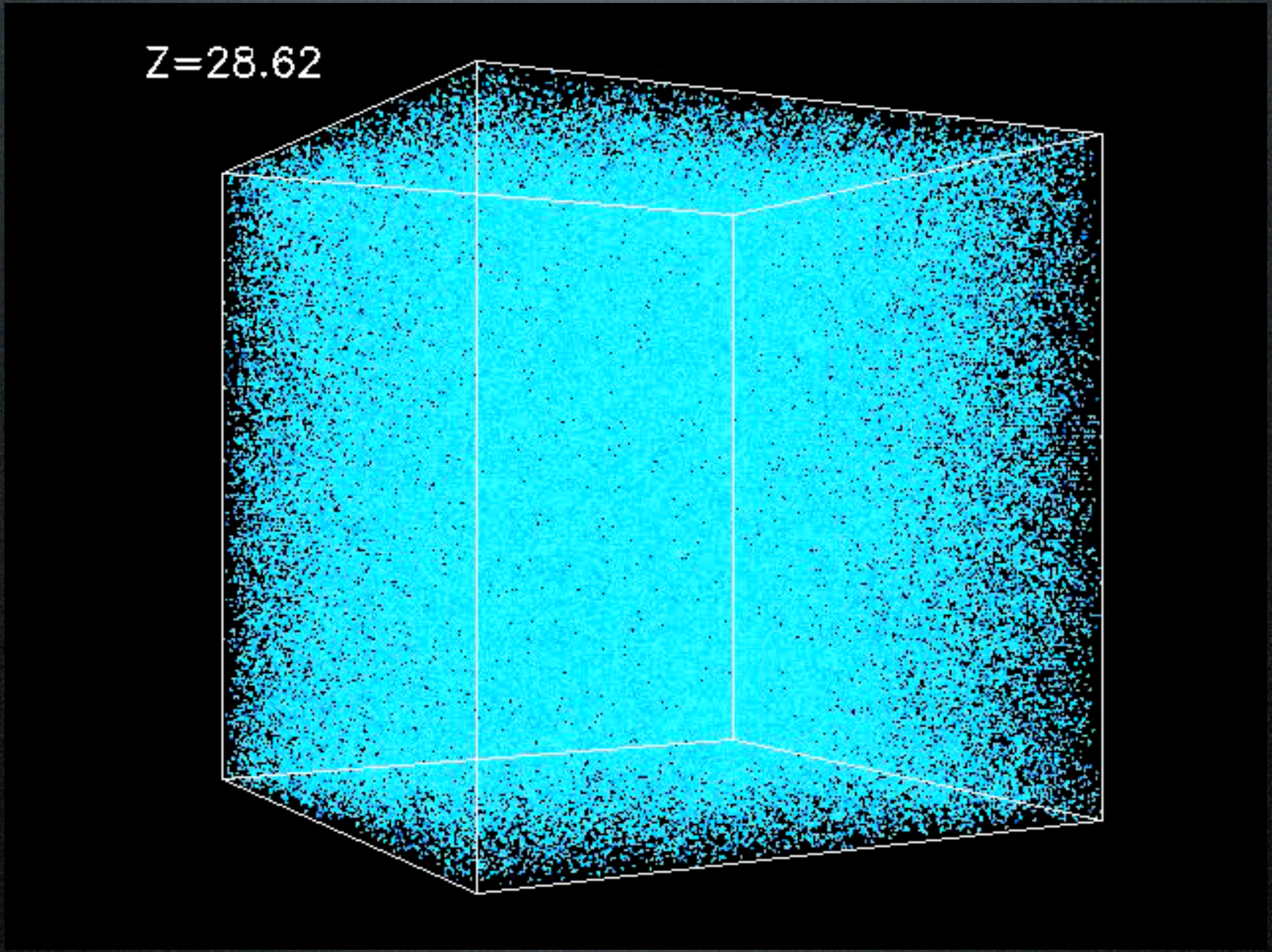


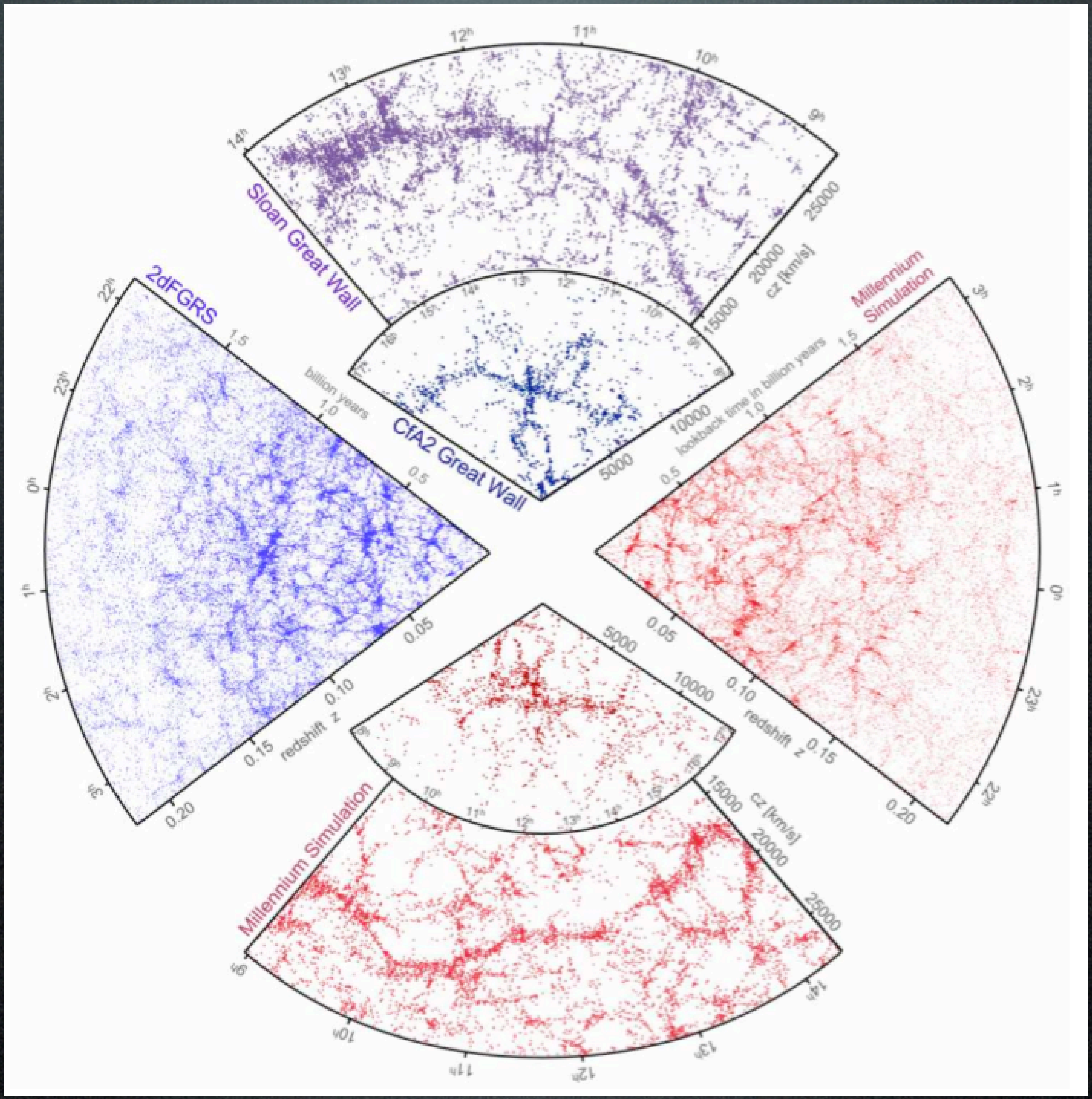
Andrey Kravtsov, cosmicweb.uchicago.edu

[back]

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



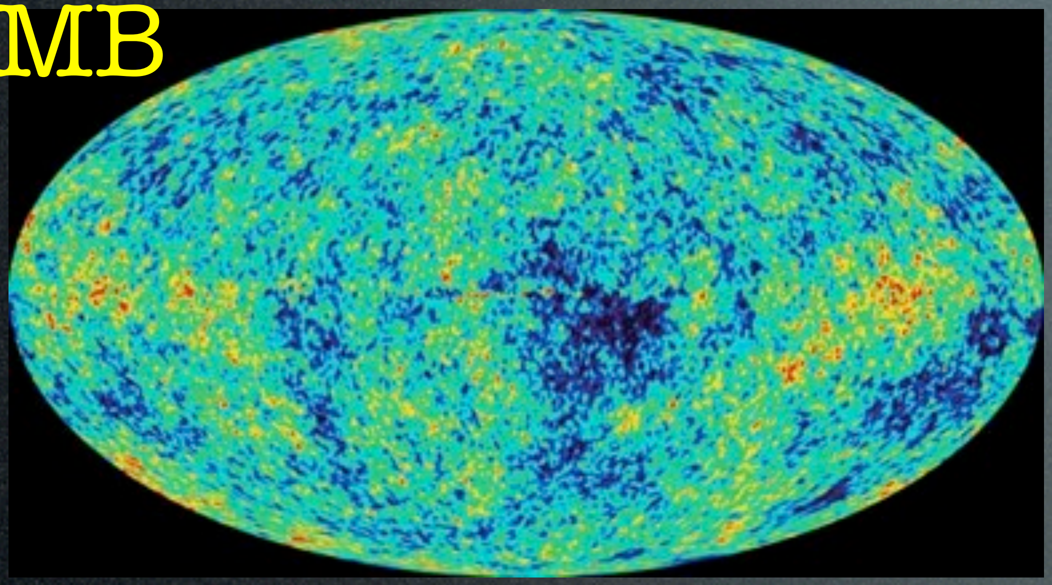
Springel, Frenk, White, Nature 440 (2006)

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

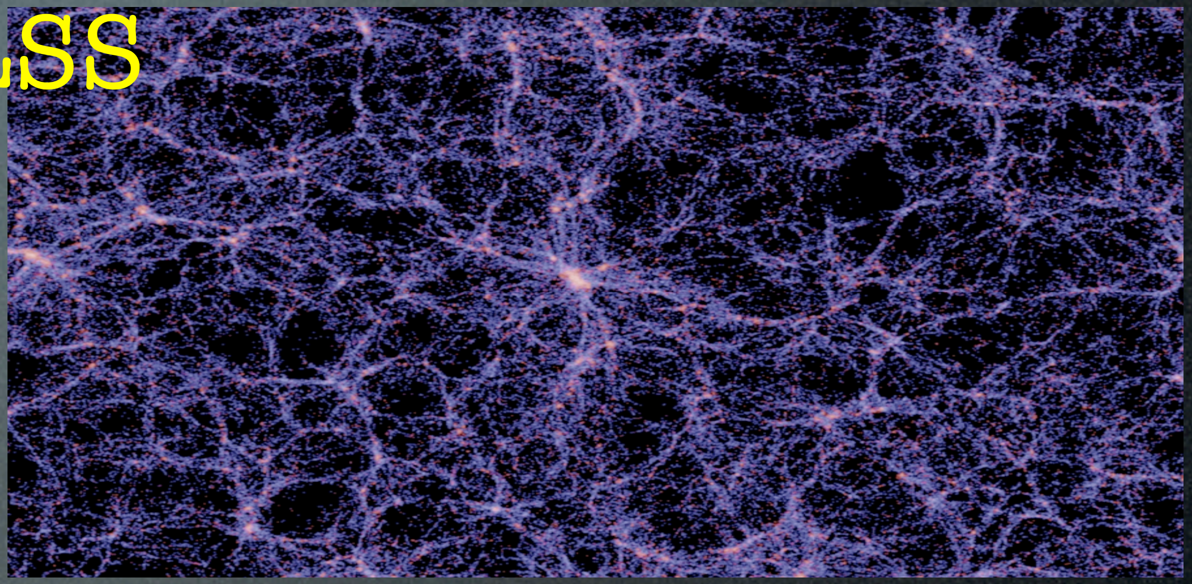
[back]

The Evidence for DM

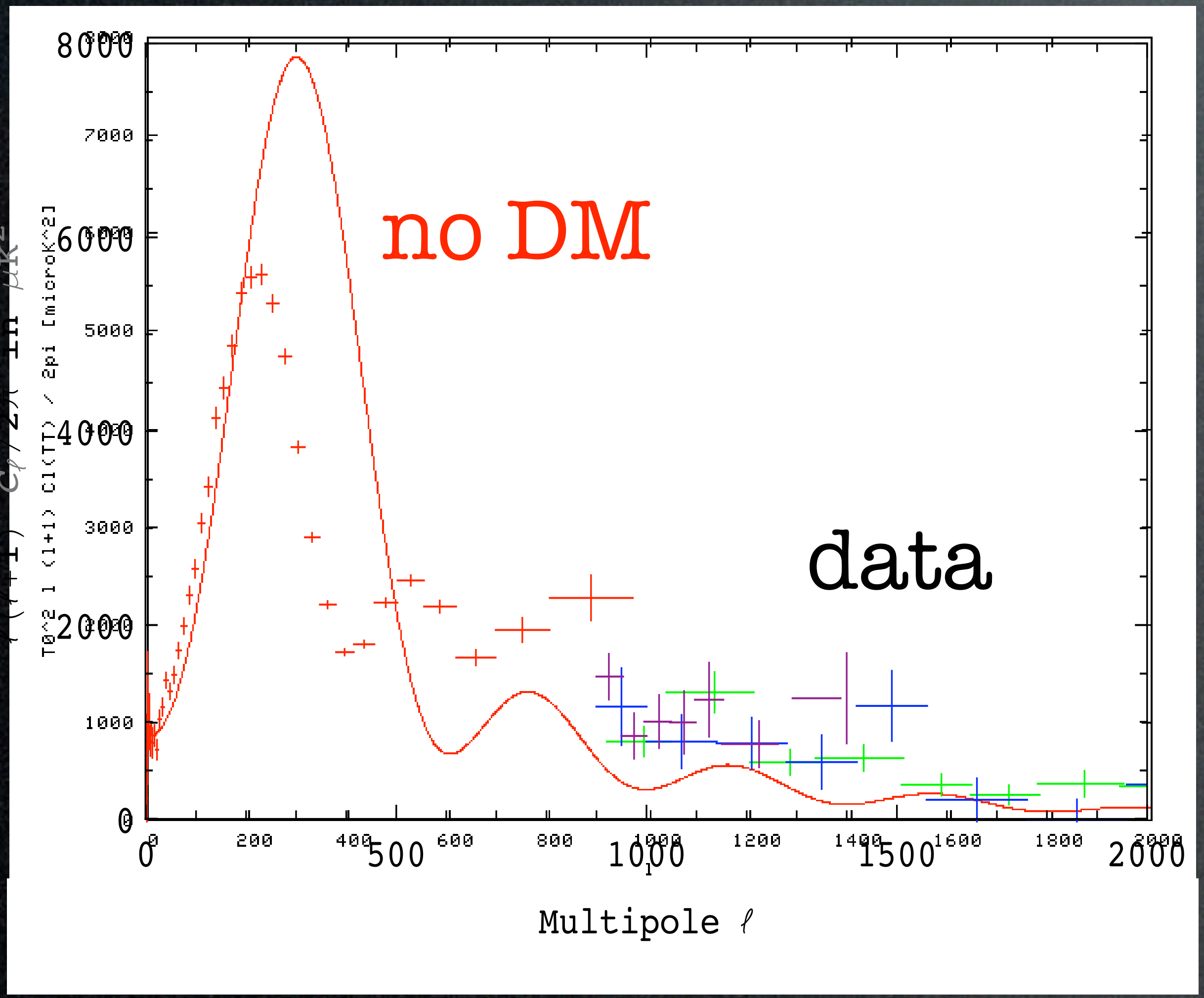
CMB



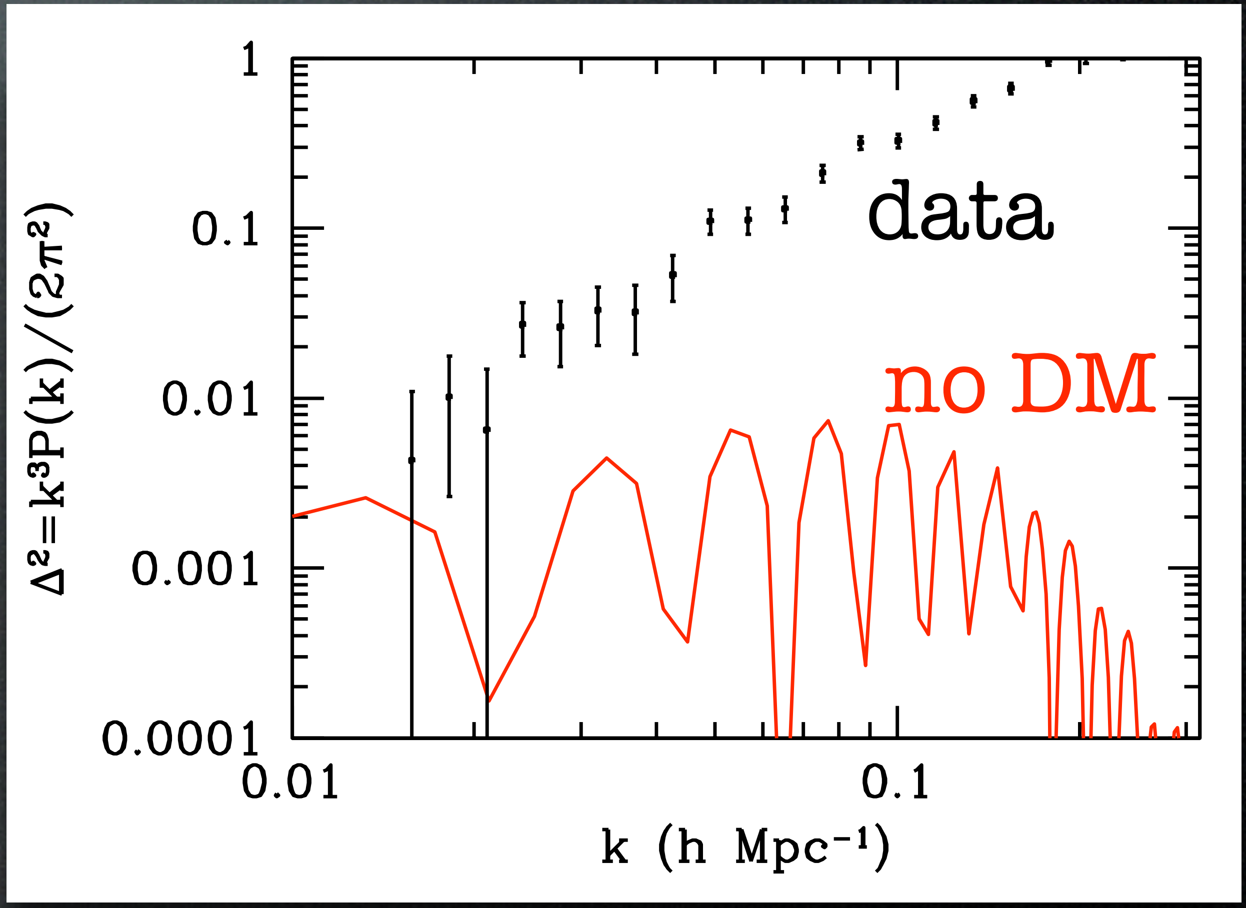
LSS



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



CAMB online



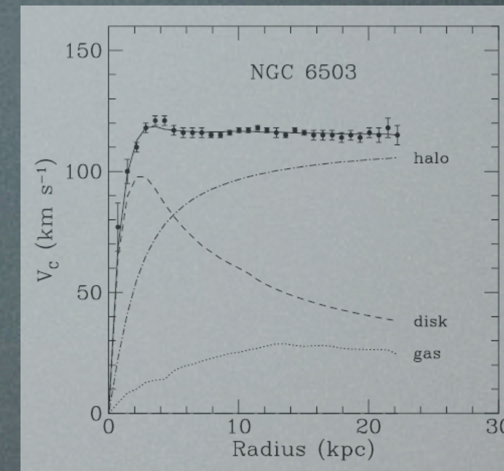
Dodelson, Liguori 2006

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

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

The Evidence for DM

1) galaxy rotation curves



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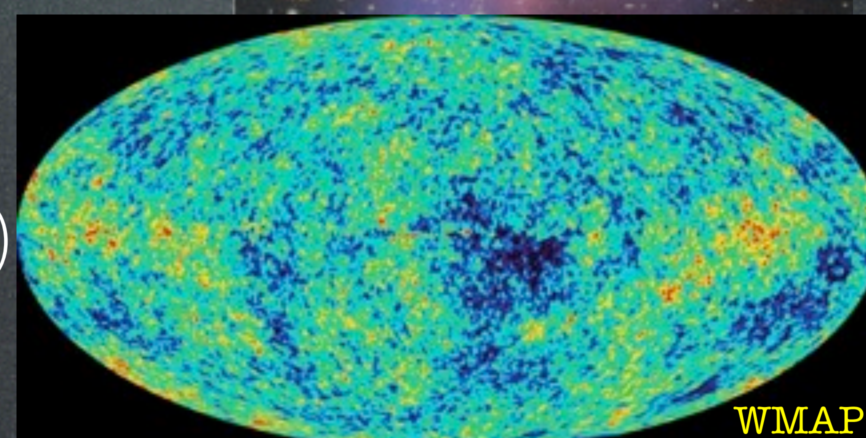
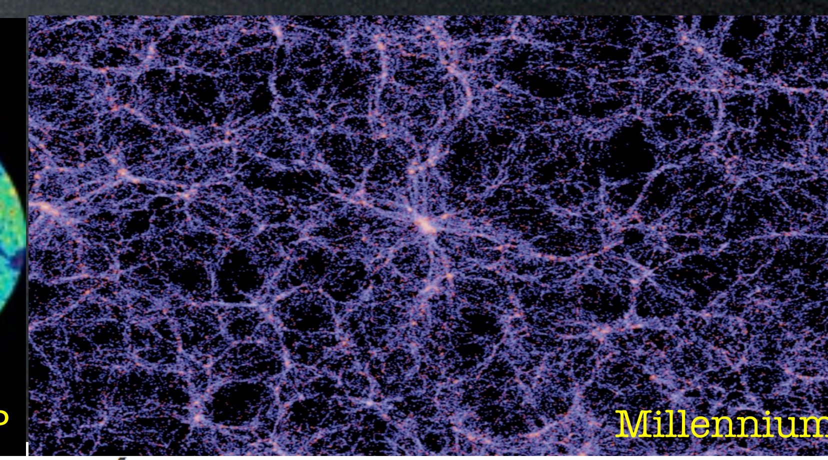
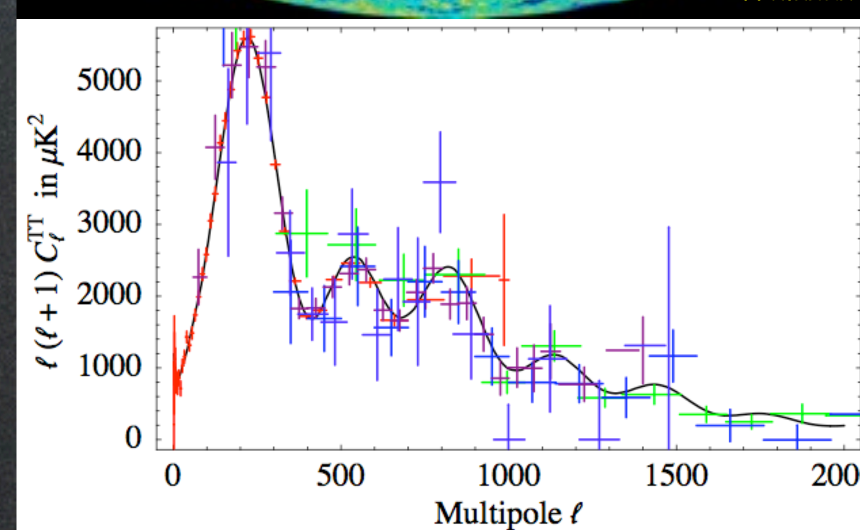
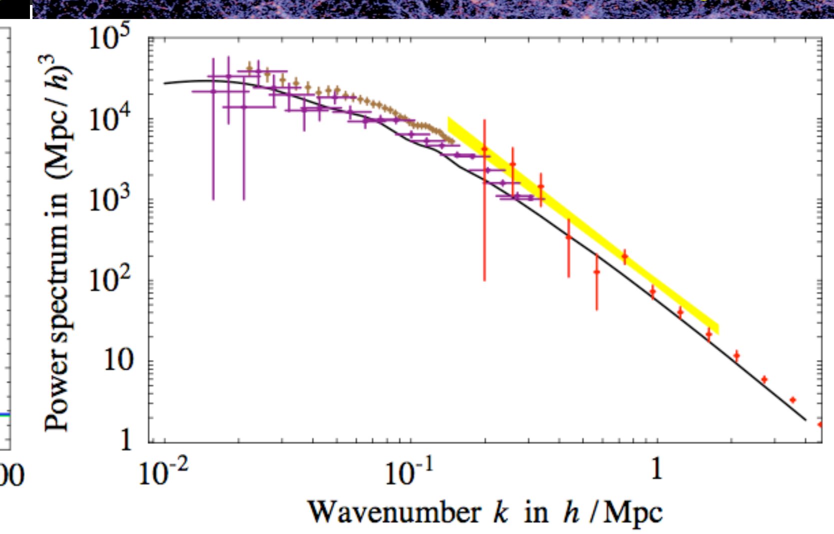




WMAP-3yr   Boomerang
ACbar   DASI
CBI   VSA

SDSS,   2dFRGS
LyA Forest Croft
LyA Forest SDSS





$\Omega_M \approx 0.26 \pm 0.05$

(spectra w/o DM)

M.Cirelli and A.Strumia, astro-ph/0607086

The Evidence for DM

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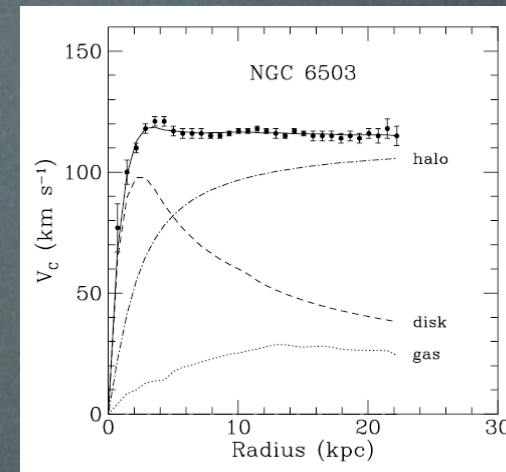

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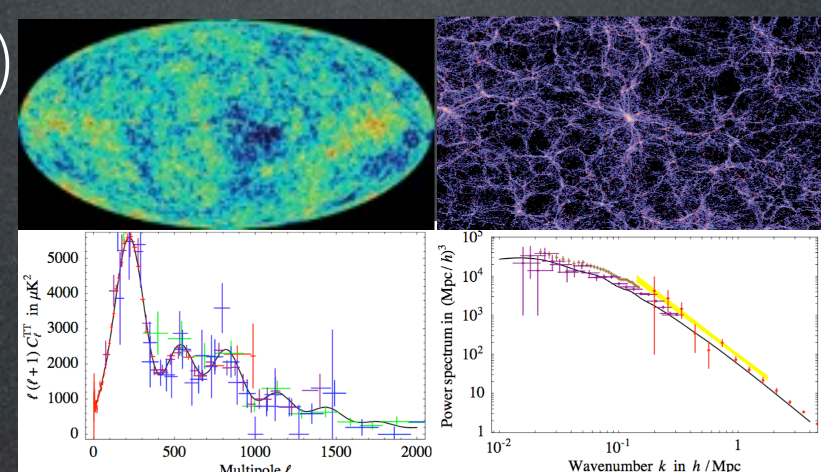

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What is DM?

What do we know of the particle physics properties of Dark Matter?

DM can **NOT** be:

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an astro *je ne sais pas quoi*:

DM can **NOT** be:

~~electrically charged~~ ~~short lived~~

an astro *je ne sais pas quoi*:

- neutrons

- gas

- Black Holes
- brown dwarves

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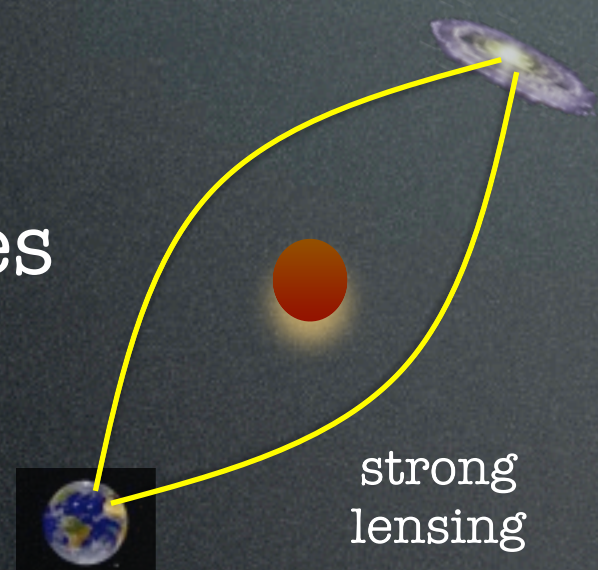

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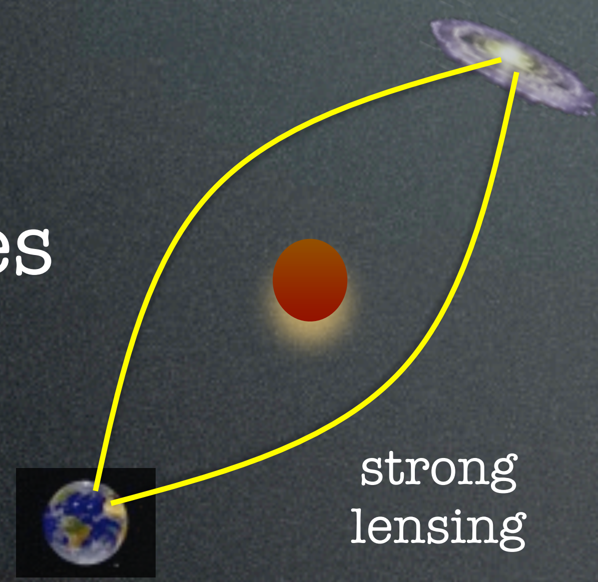

a baryon of the SM:

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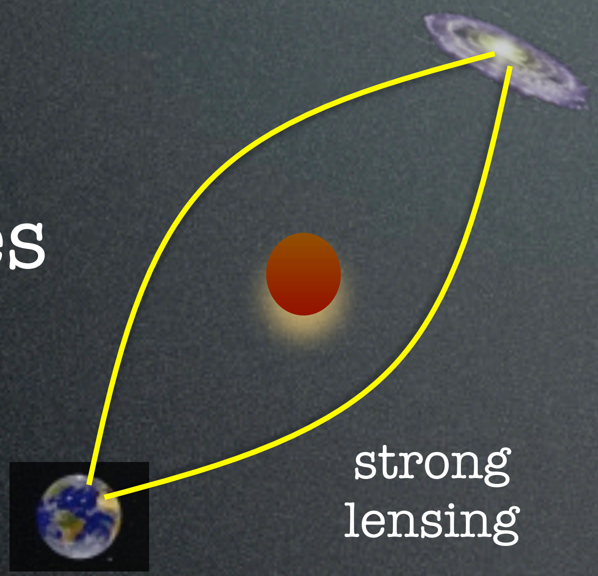

a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
- CMB says baryons are 4% max

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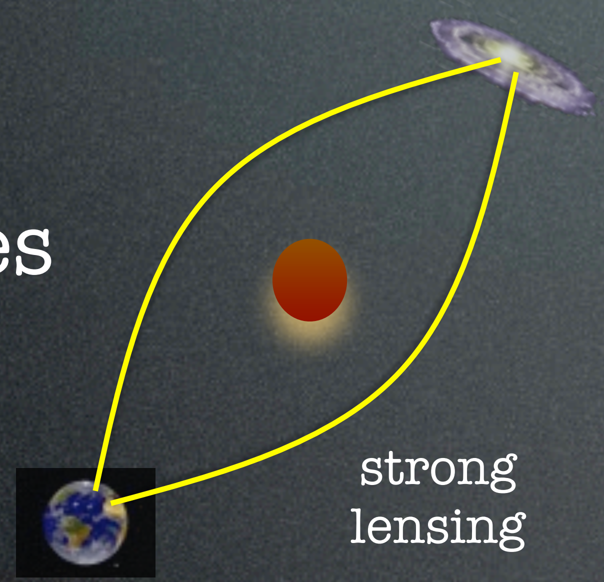

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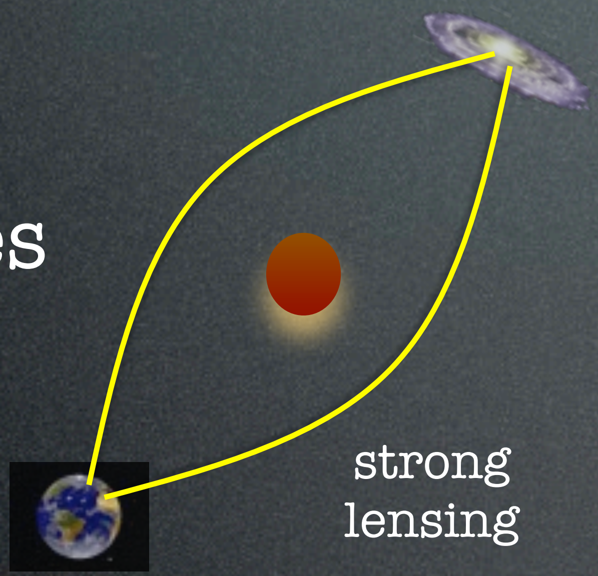

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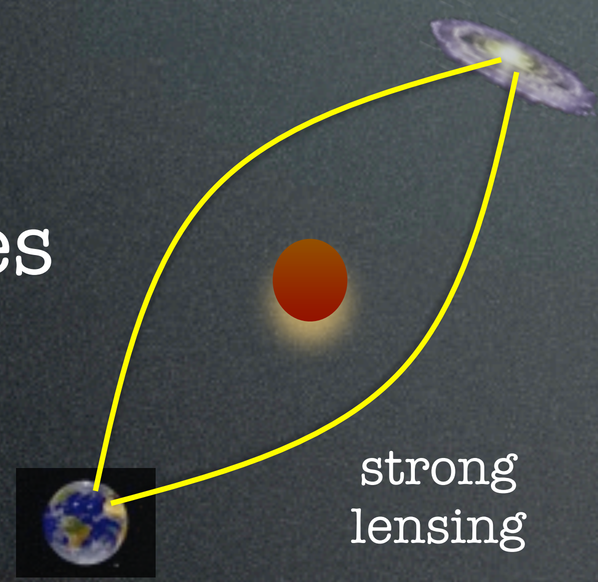

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What are the theoretical 'beliefs'?

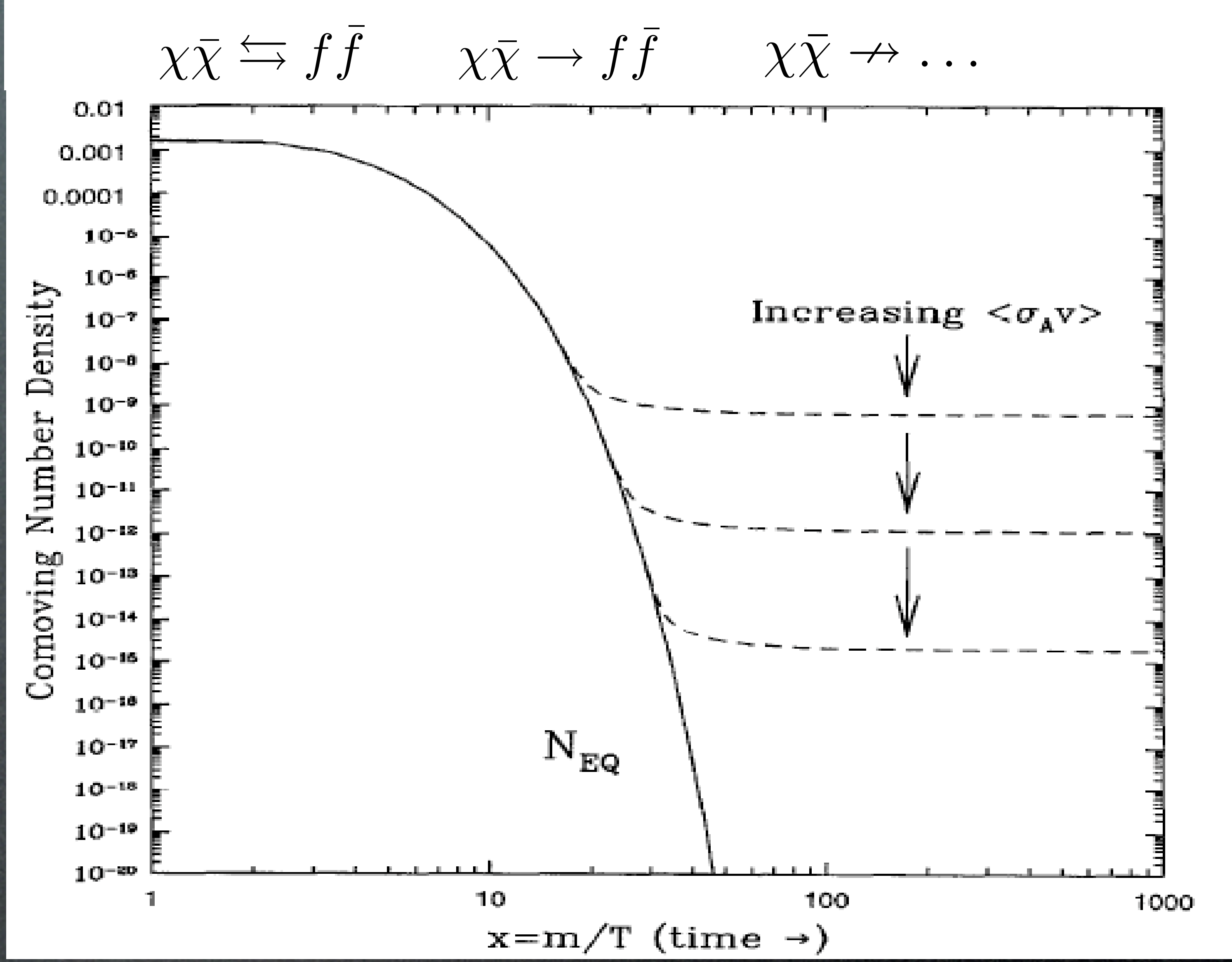
A thermal relic from the Early Universe

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:

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

(WIMP)

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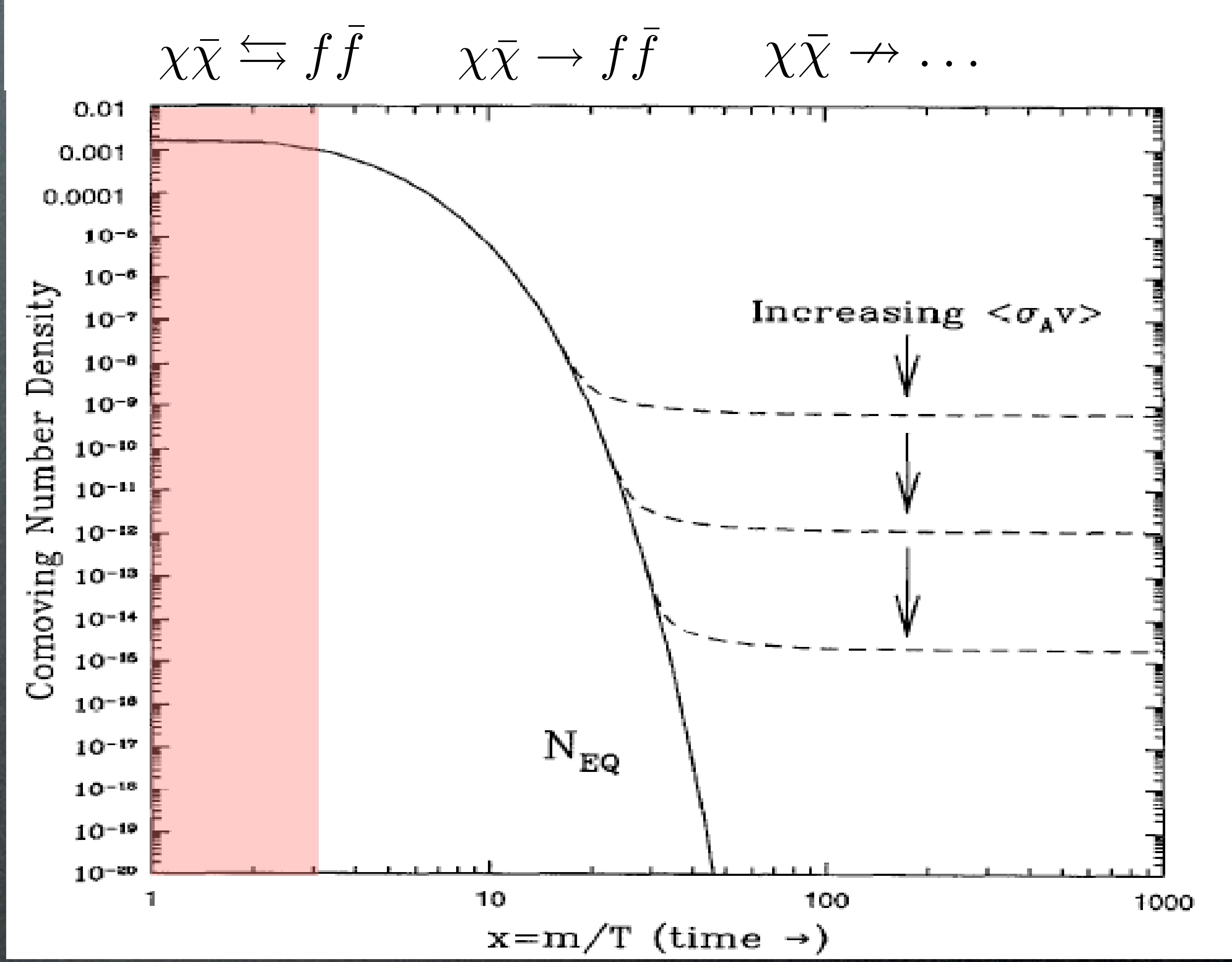

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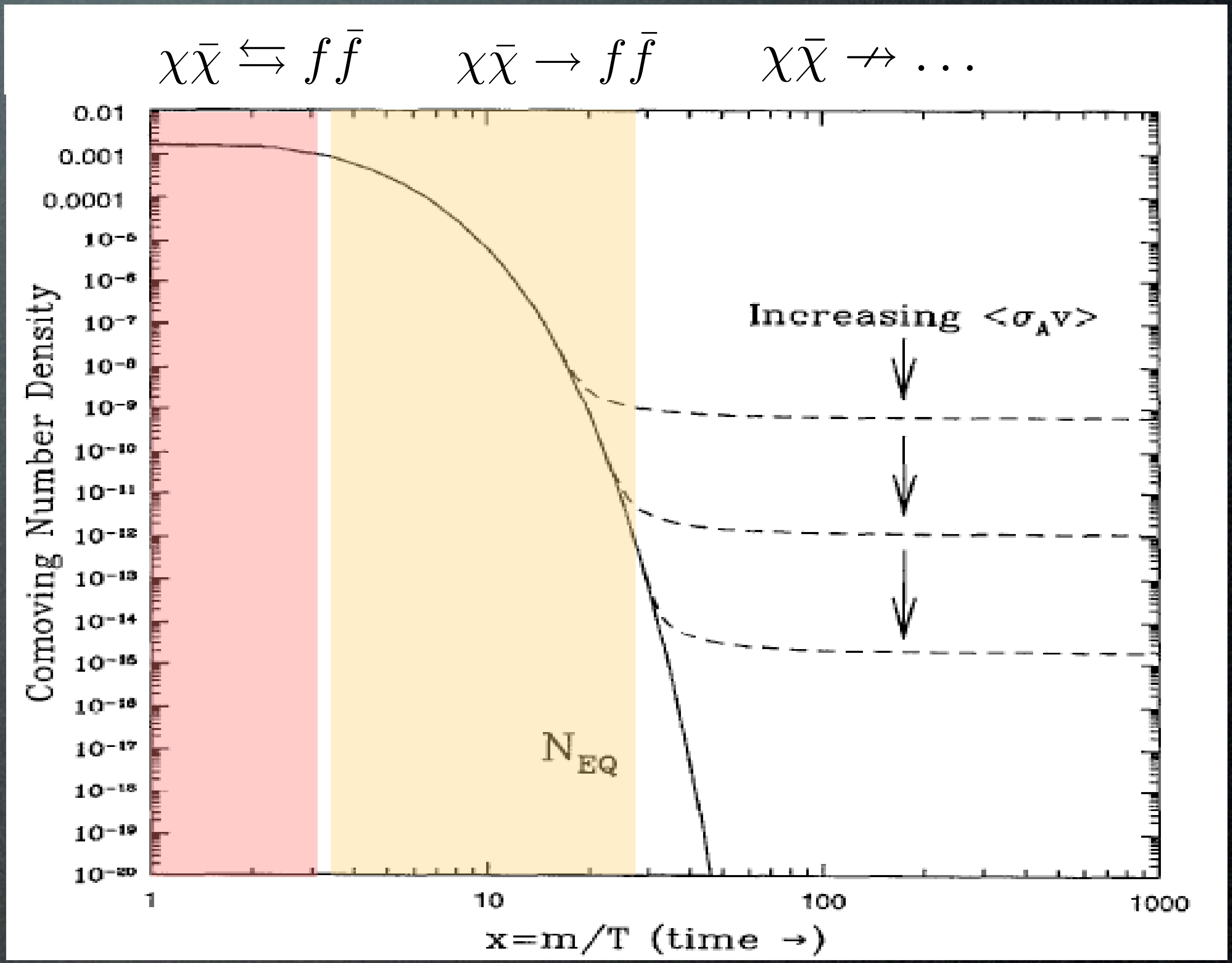

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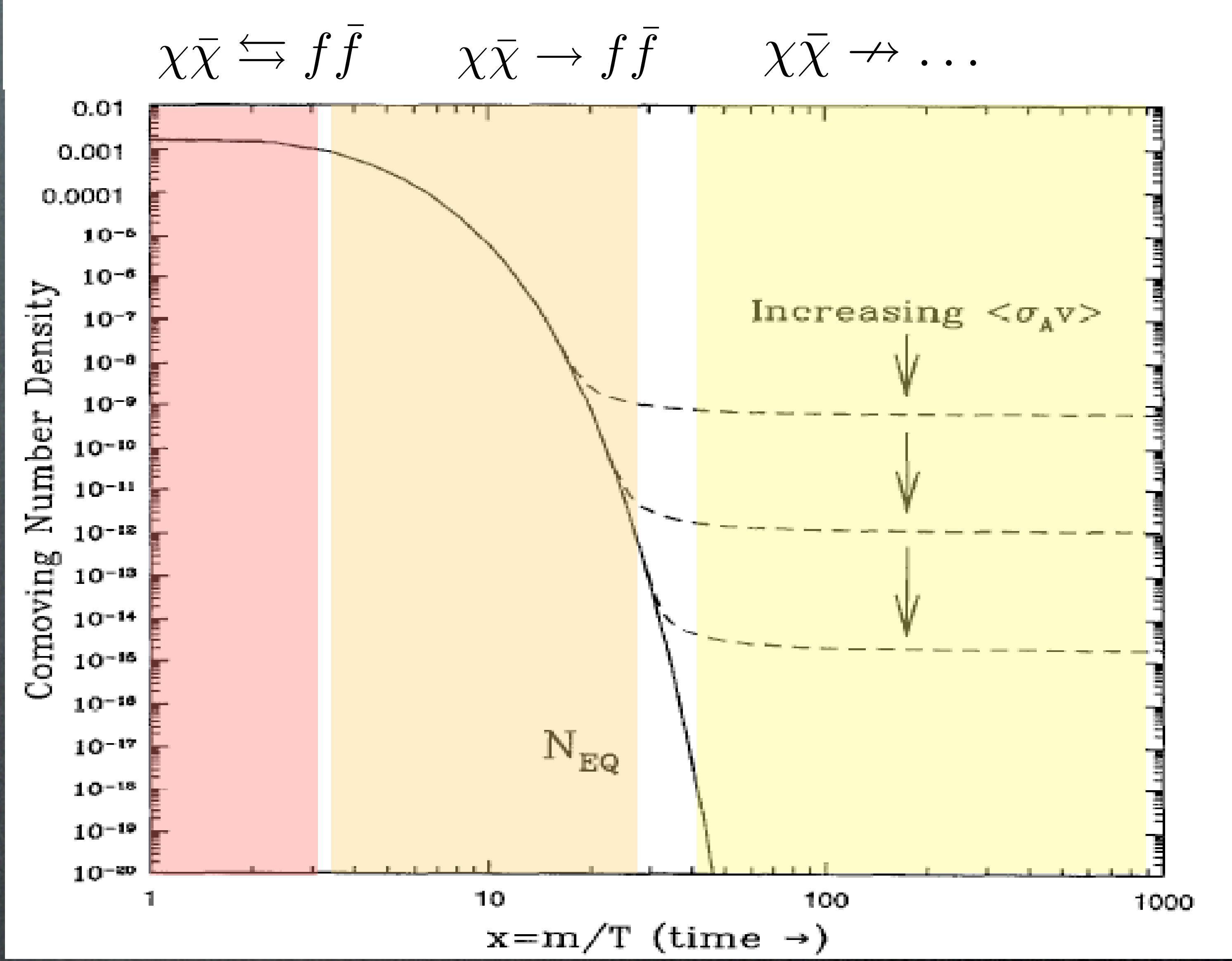

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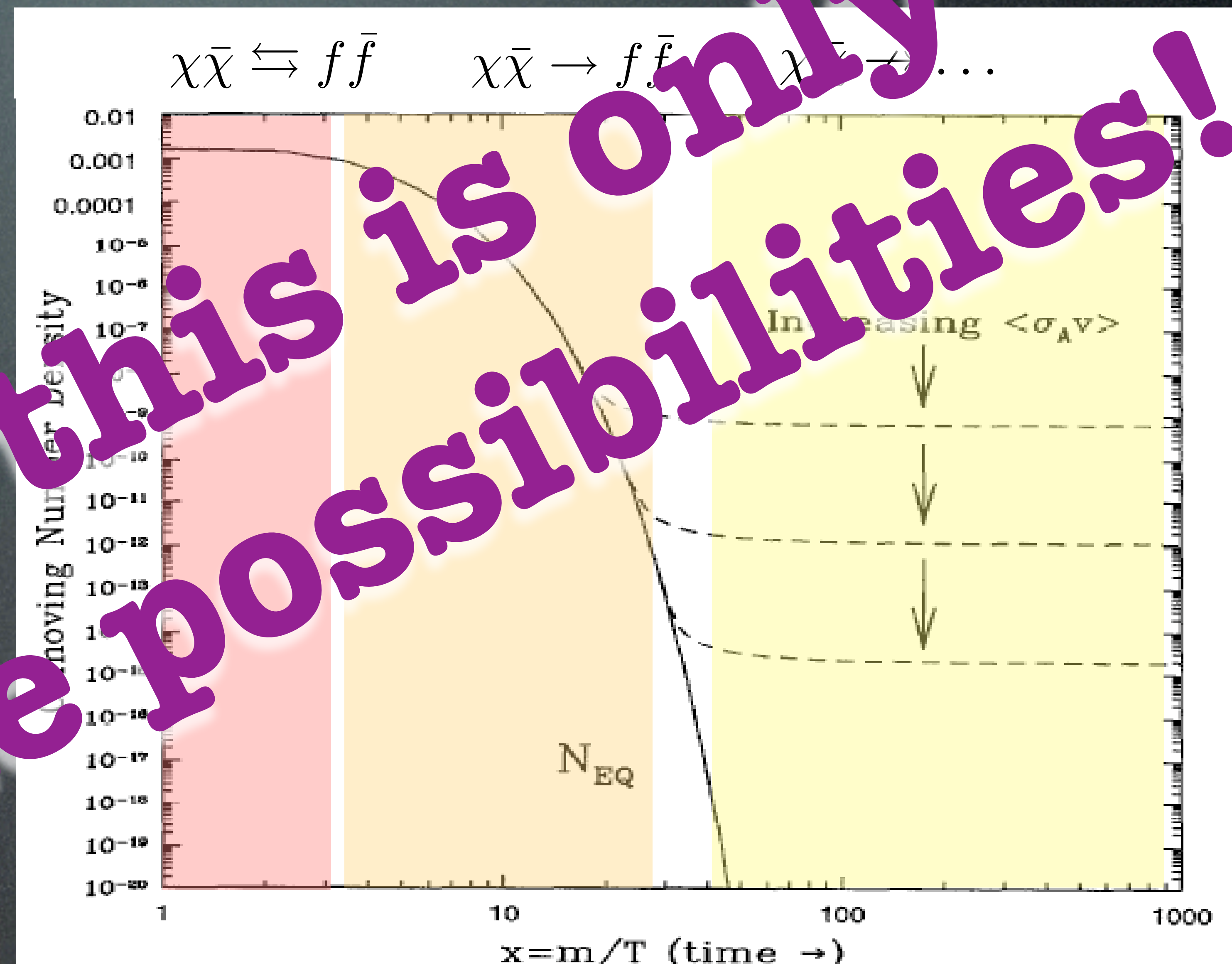

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Caveat: this is only one of the possibilities!

Weak cross section:

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(WIMP)

Indirect Detection

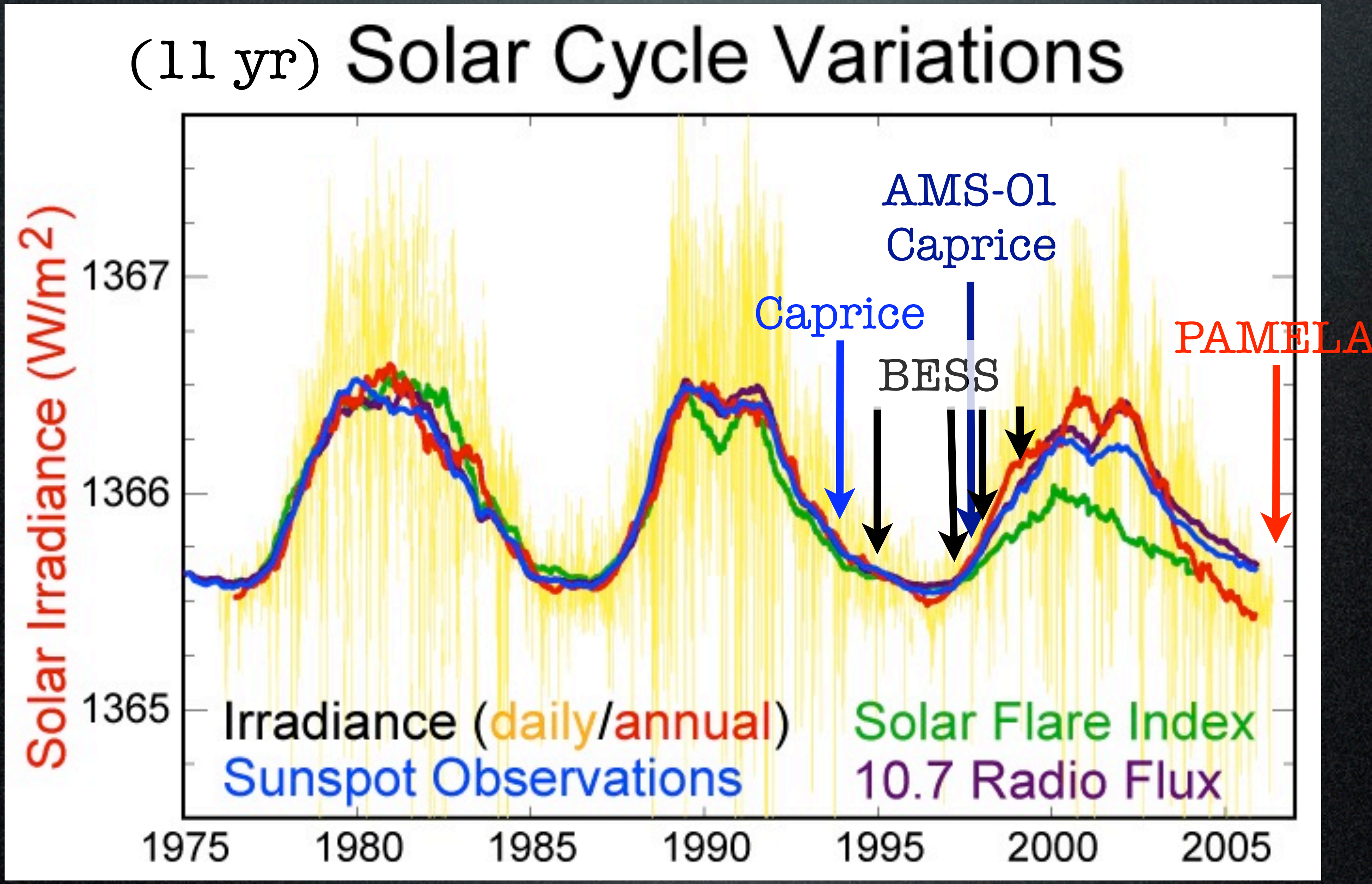
Solar wind Modulation of cosmic rays:

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

spectrum at Earth

spectrum far from Earth

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

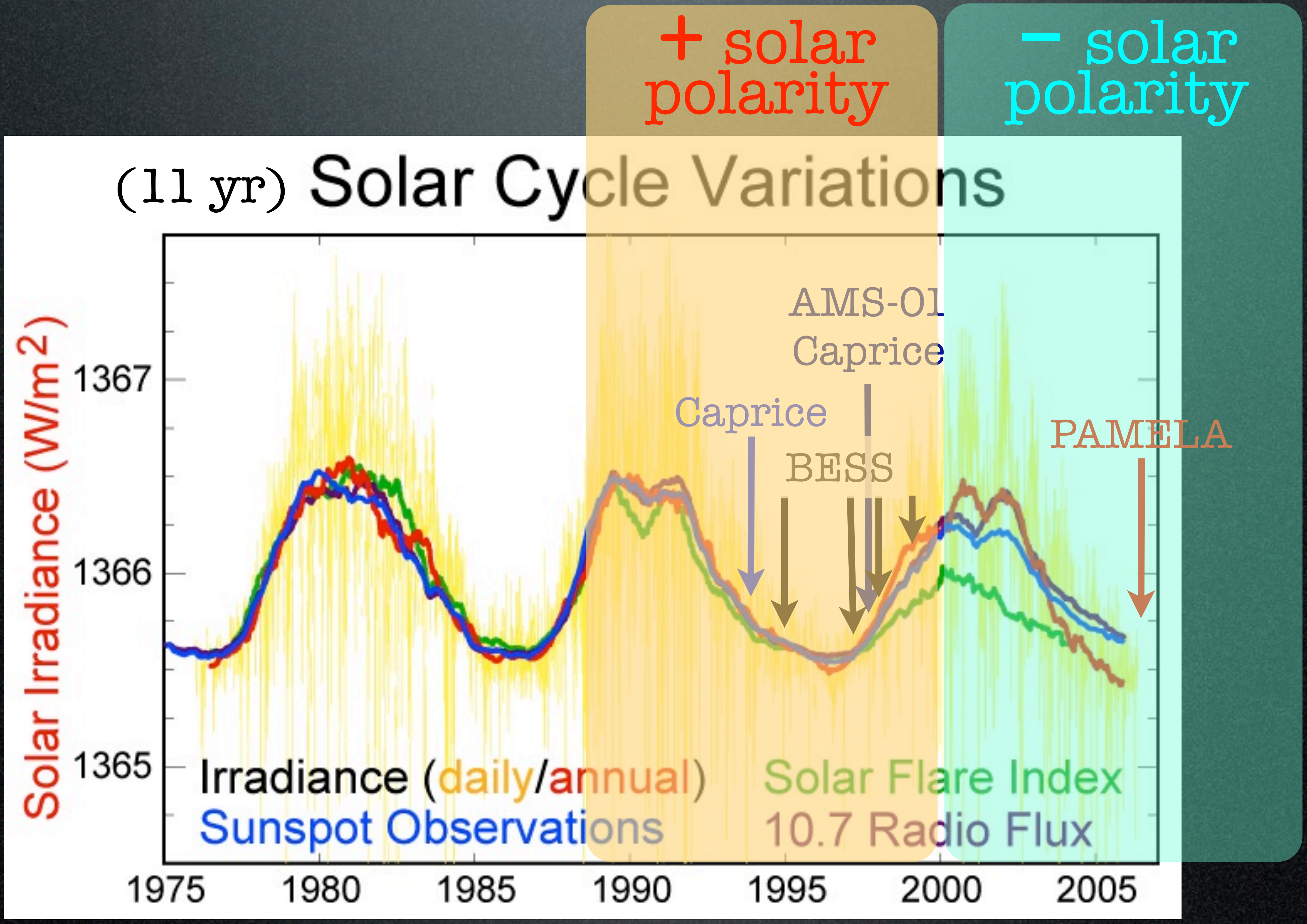


Indirect Detection

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



End