15 september 2010
UniverseNet School and Meeting - Lecce

DM indirect detection: status circa 2010

Marco Cirelli

(CERN-TH & CNRS IPhT Saclay)

in collaboration with:
A.Strumia (Pisa)
N.Fornengo (Torino)
M.Tamburini (Pisa)
R.Franceschini (Pisa)
M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (L'Aquila + Saclay + CERN)
F.Iocco (Saclay + IAP Paris)
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Reviews on Dark Matter:
Jungman, Kamionkowski, Griest, Phys.Rept. 267, 195-373, 1996
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Results covered here:
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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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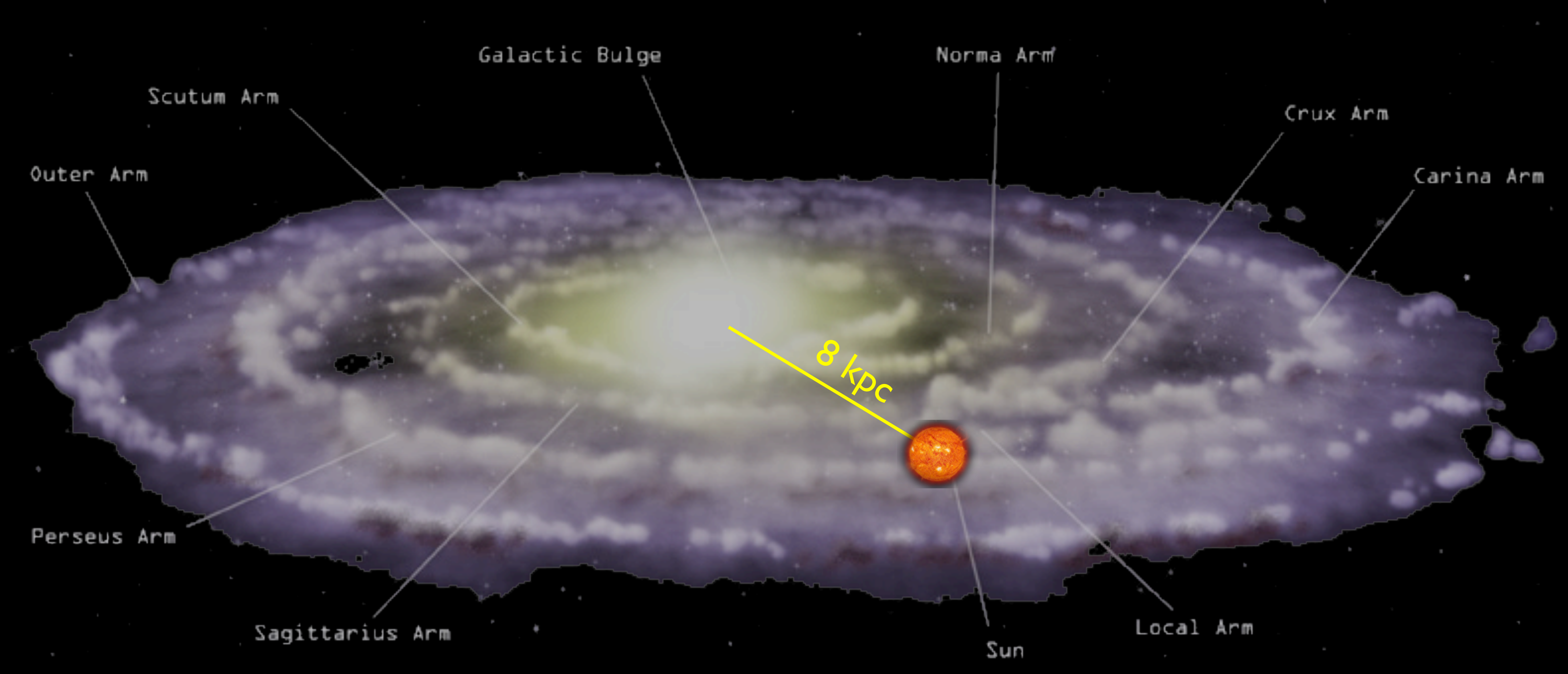
Indirect Detection

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



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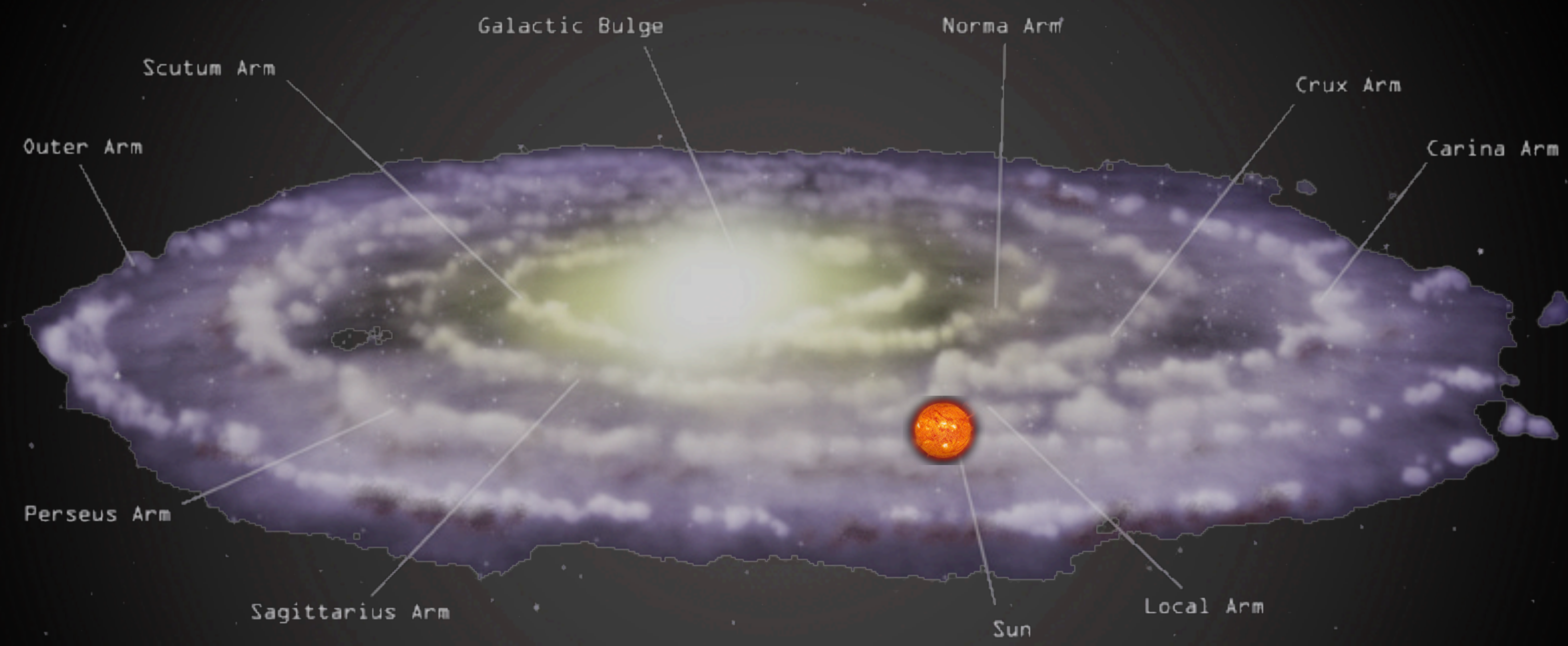

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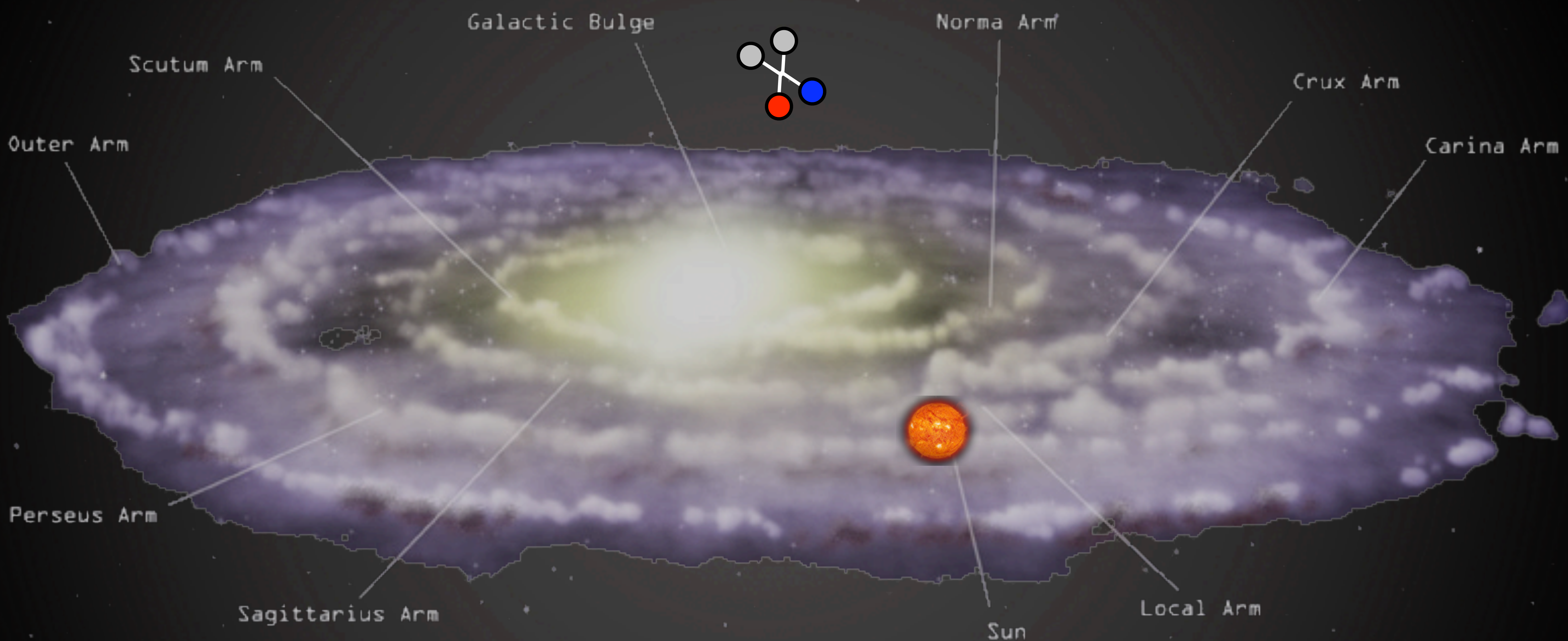

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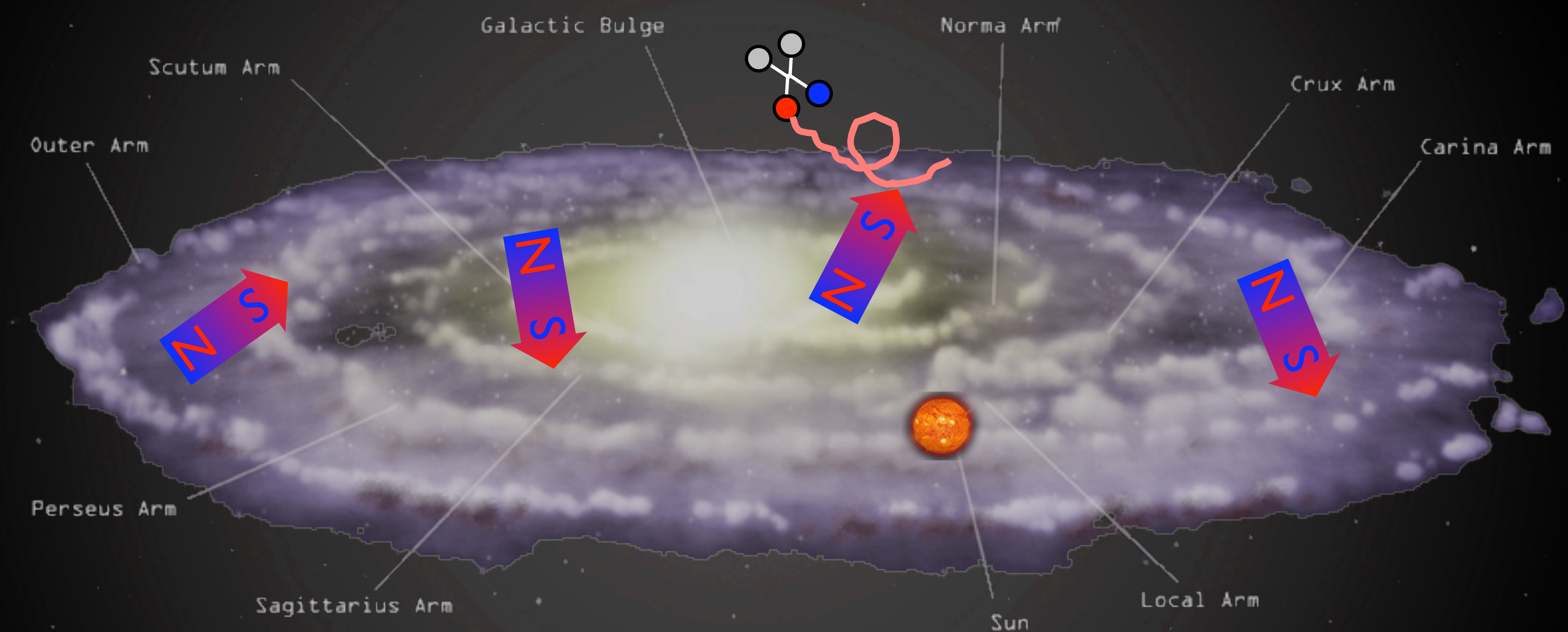

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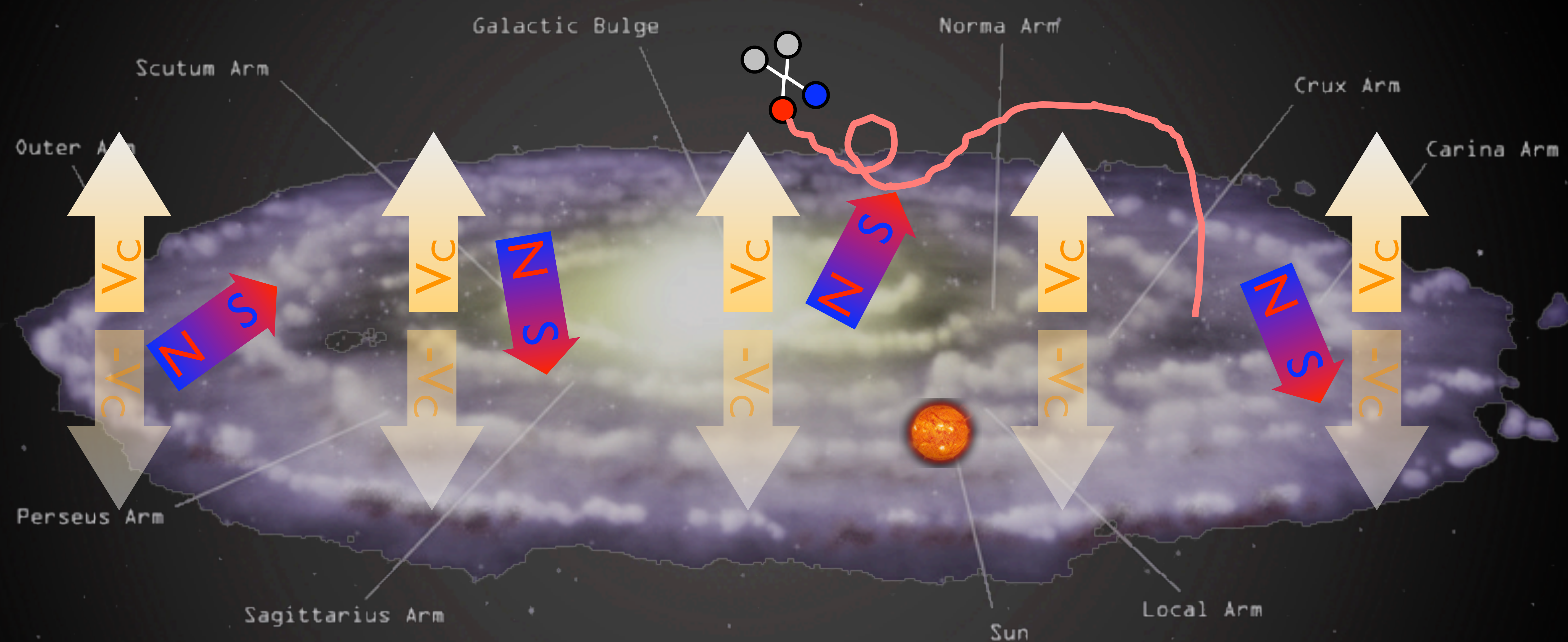

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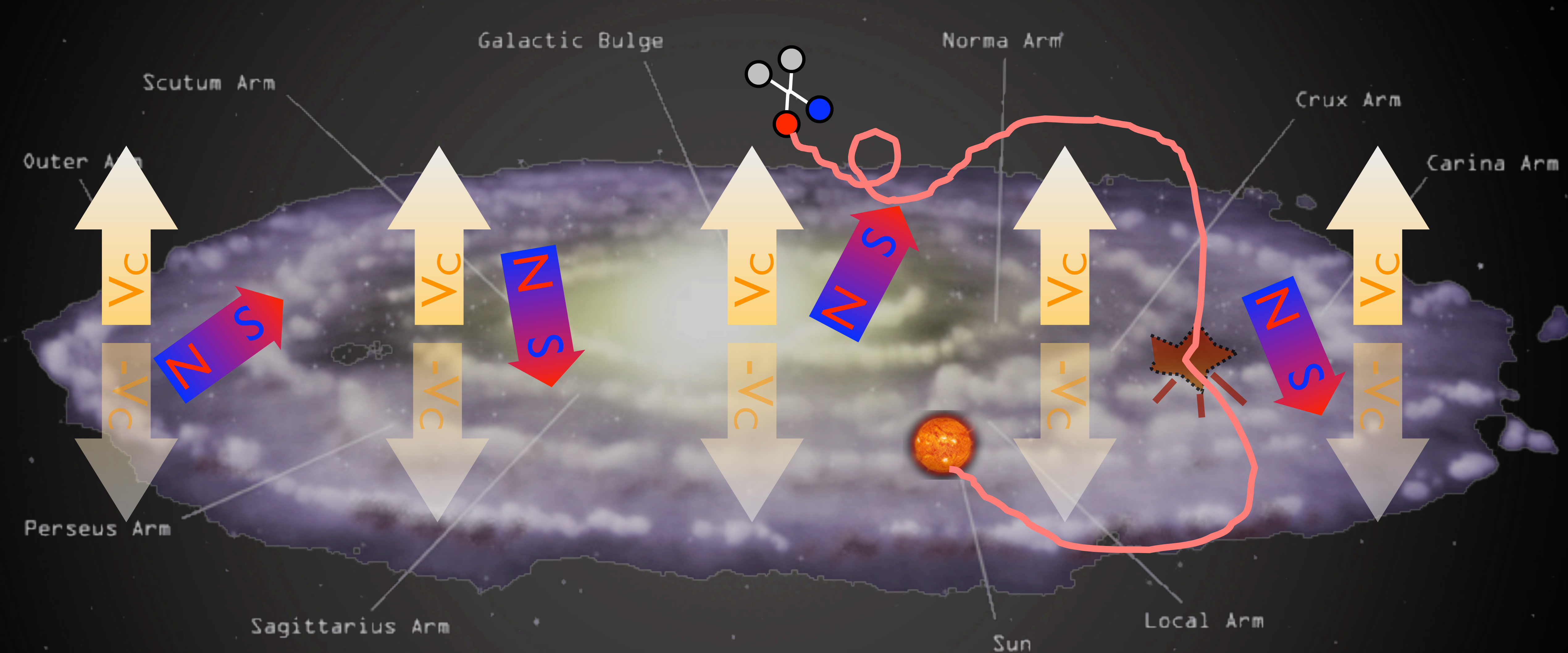

Indirect Detection

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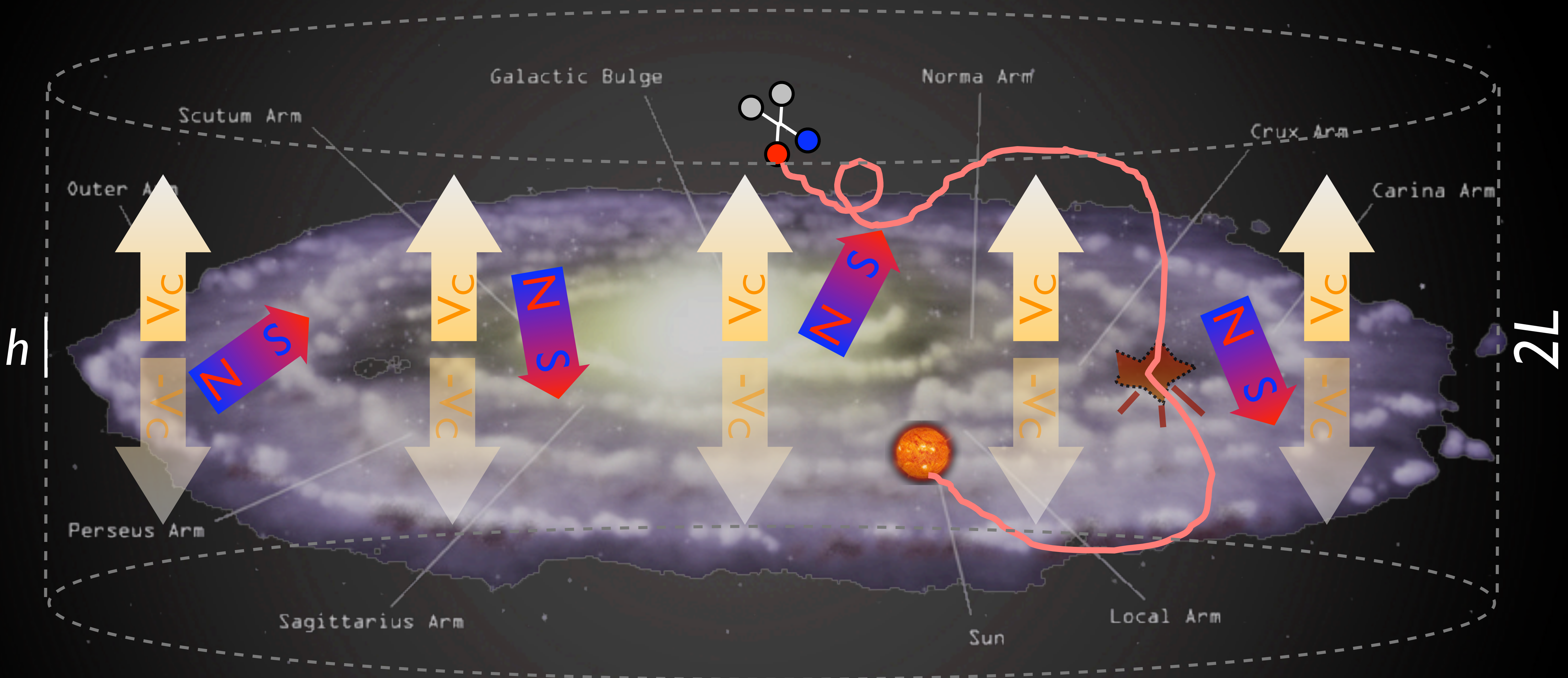


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

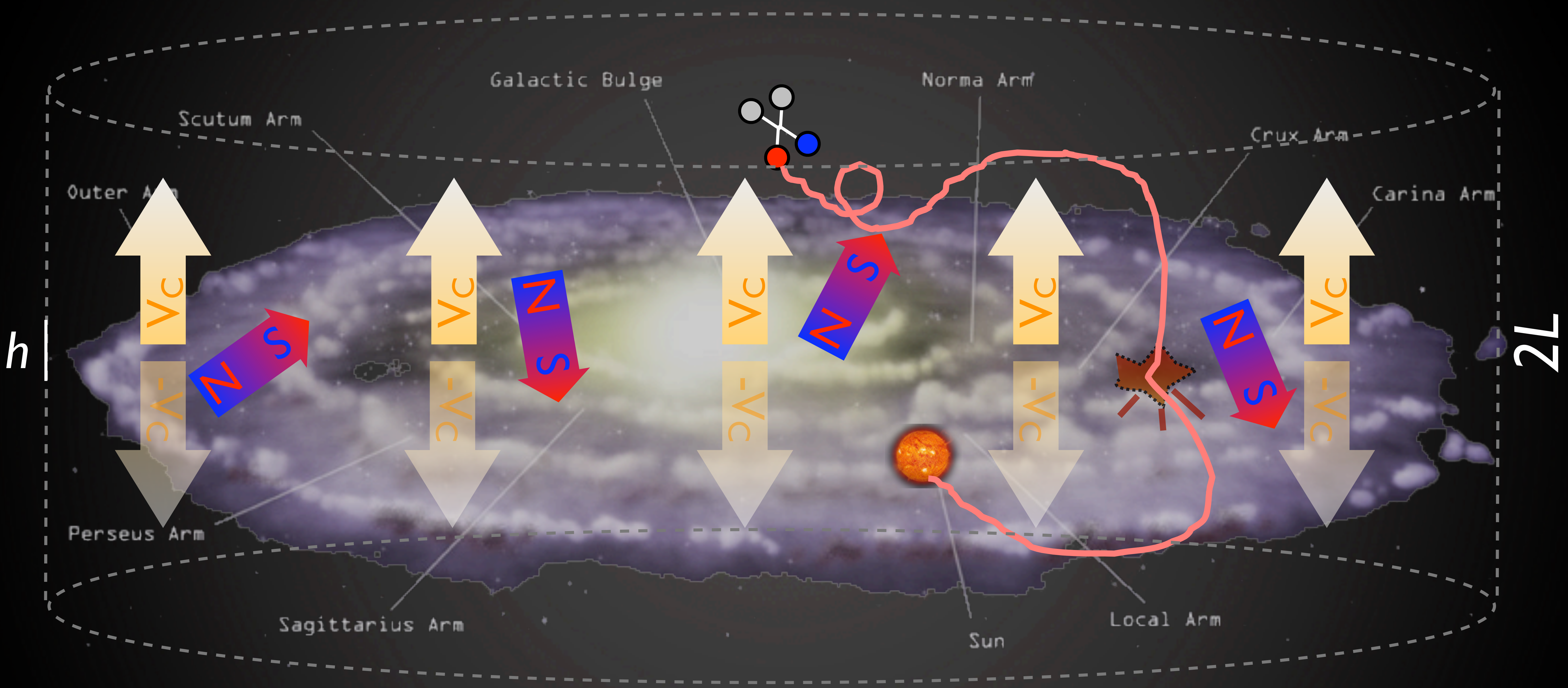
spectrum

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

diffusion   energy loss   convective wind   source   spallations

Indirect Detection

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



What sets the overall expected flux?

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

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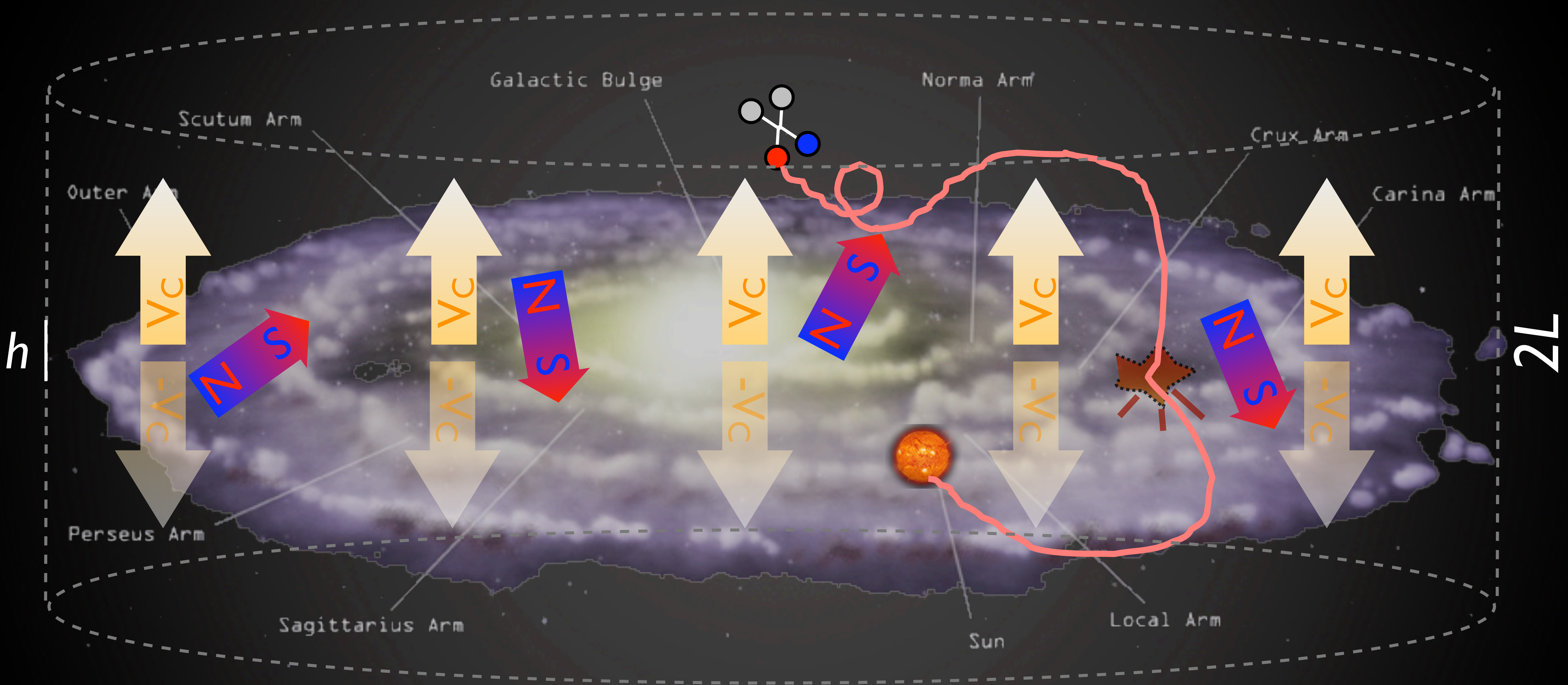

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astro& cosmo

particle

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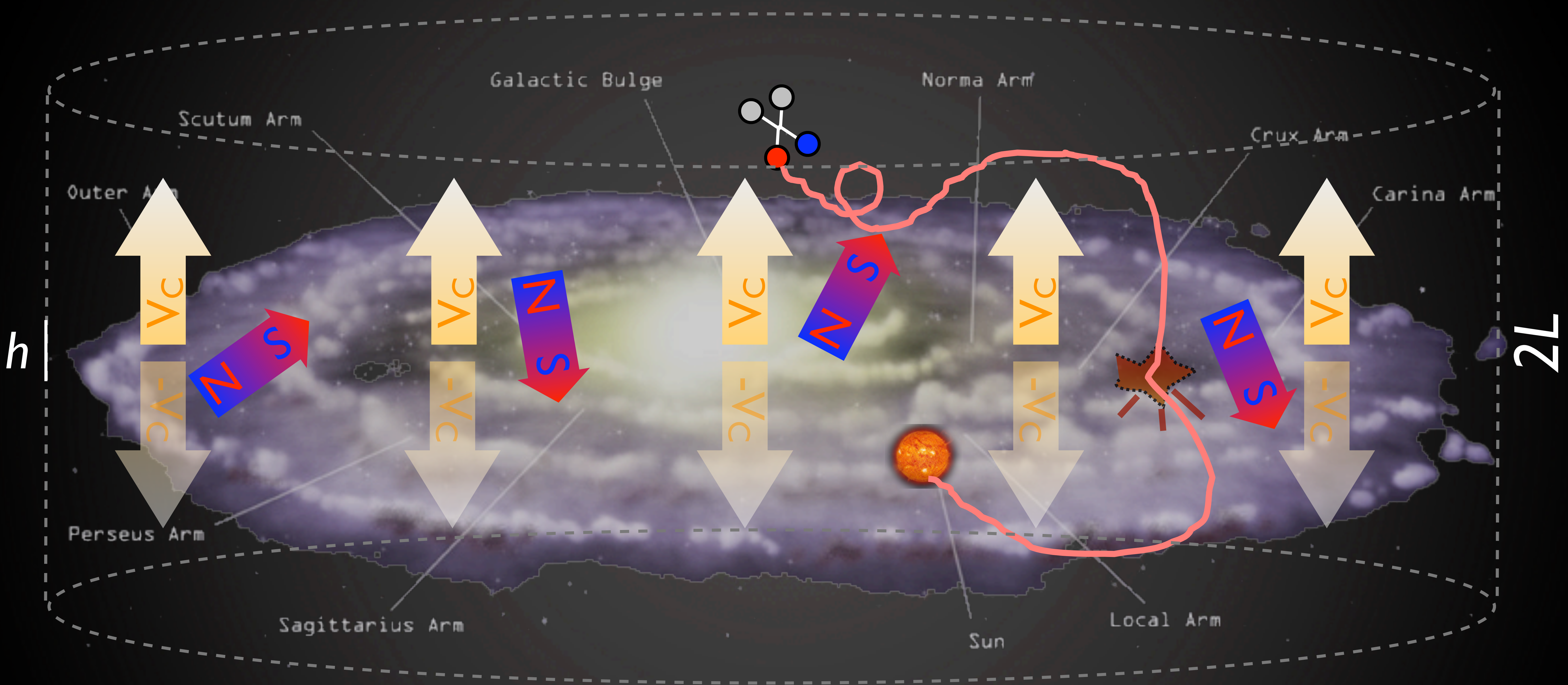

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reference cross section:

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

(

A thermal relic
from the Early Universe

(

A thermal relic from the Early Universe

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

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

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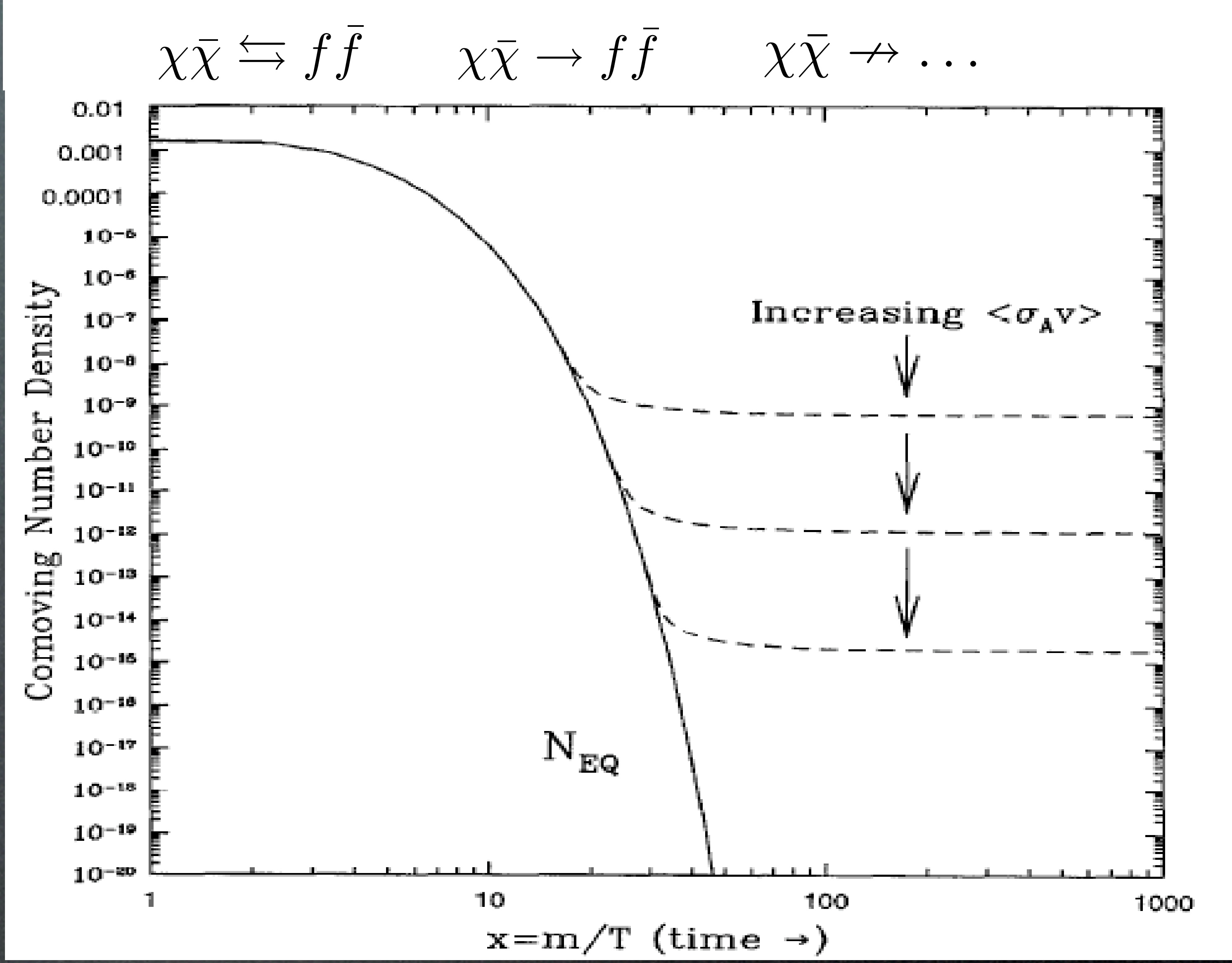

Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

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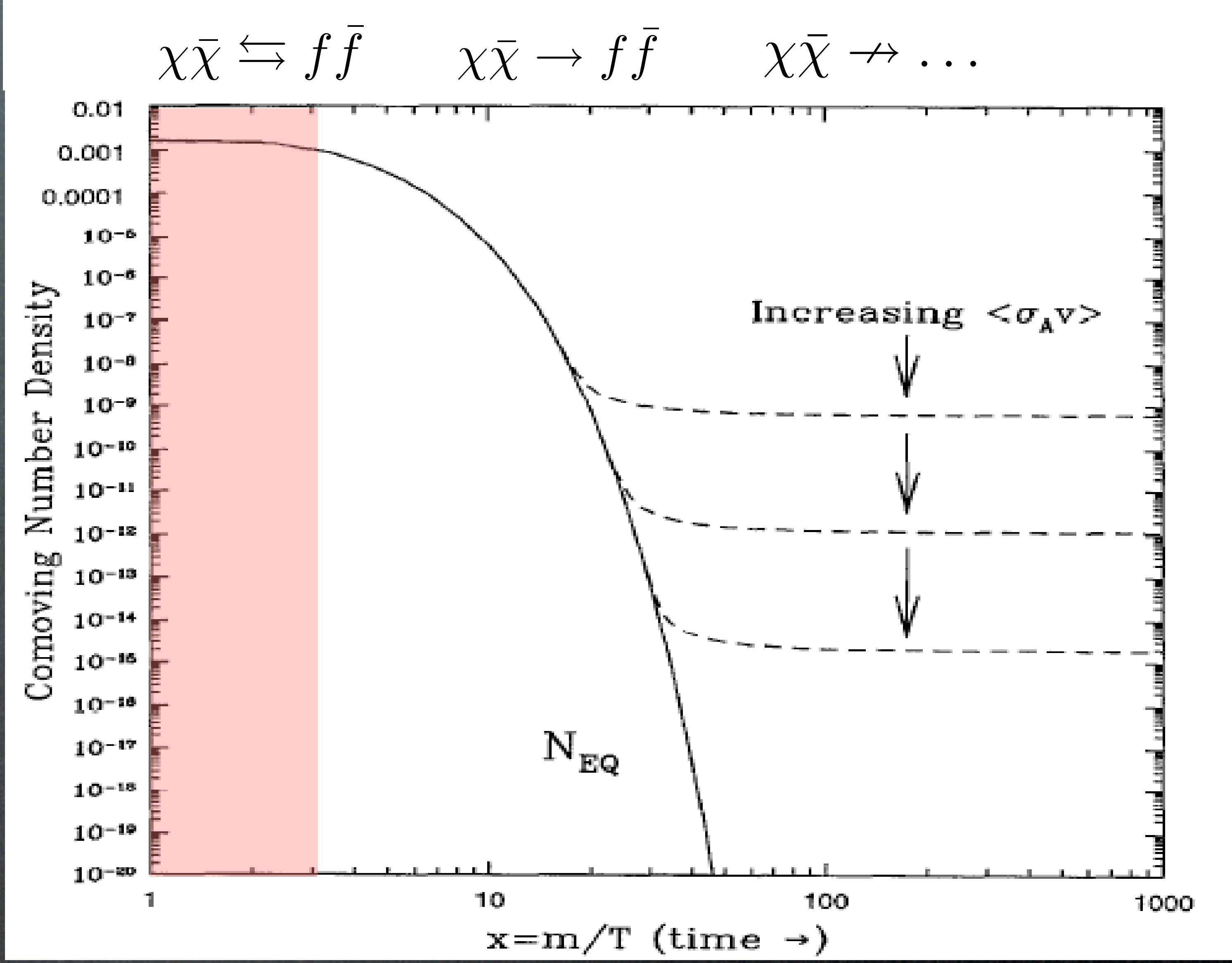

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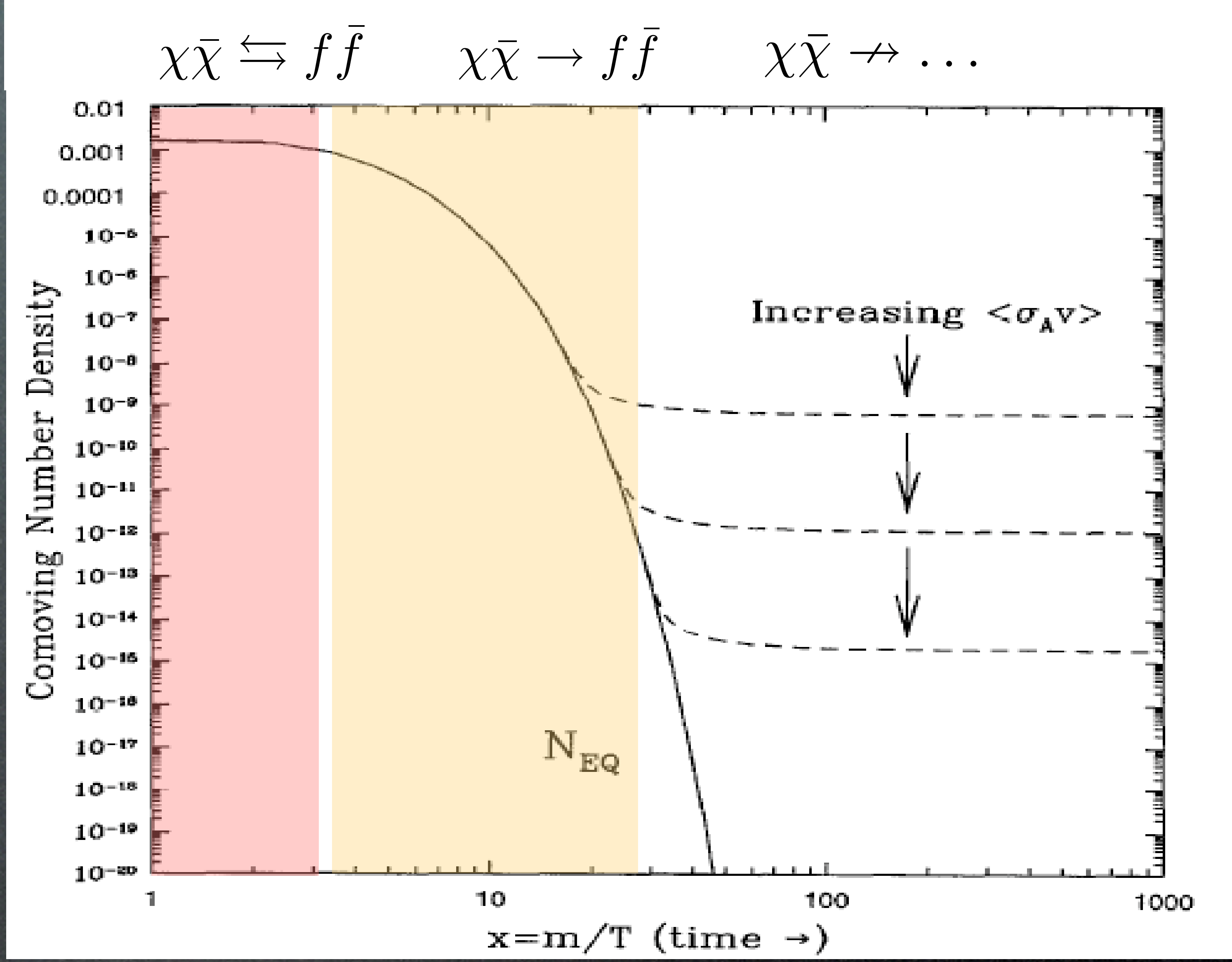

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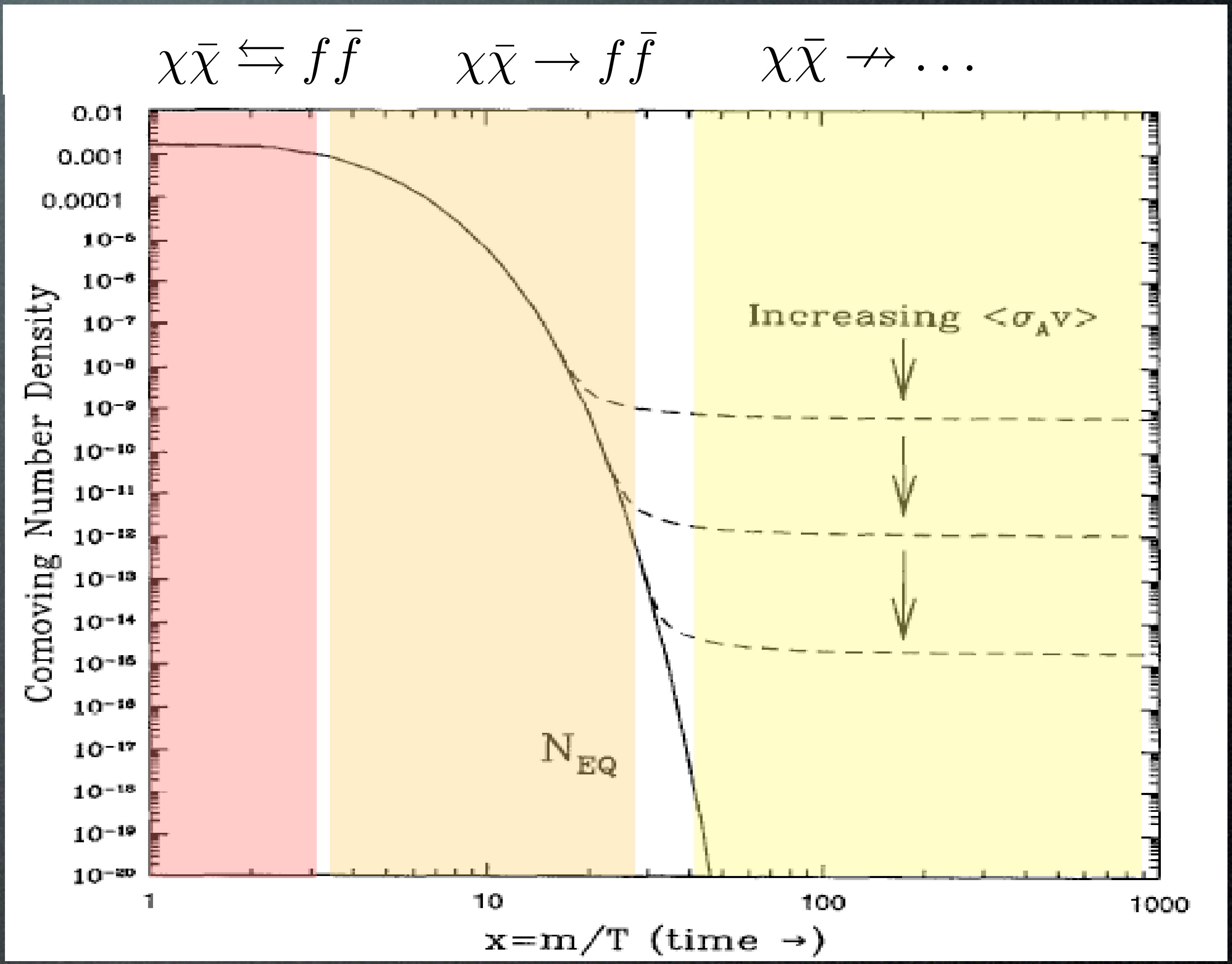

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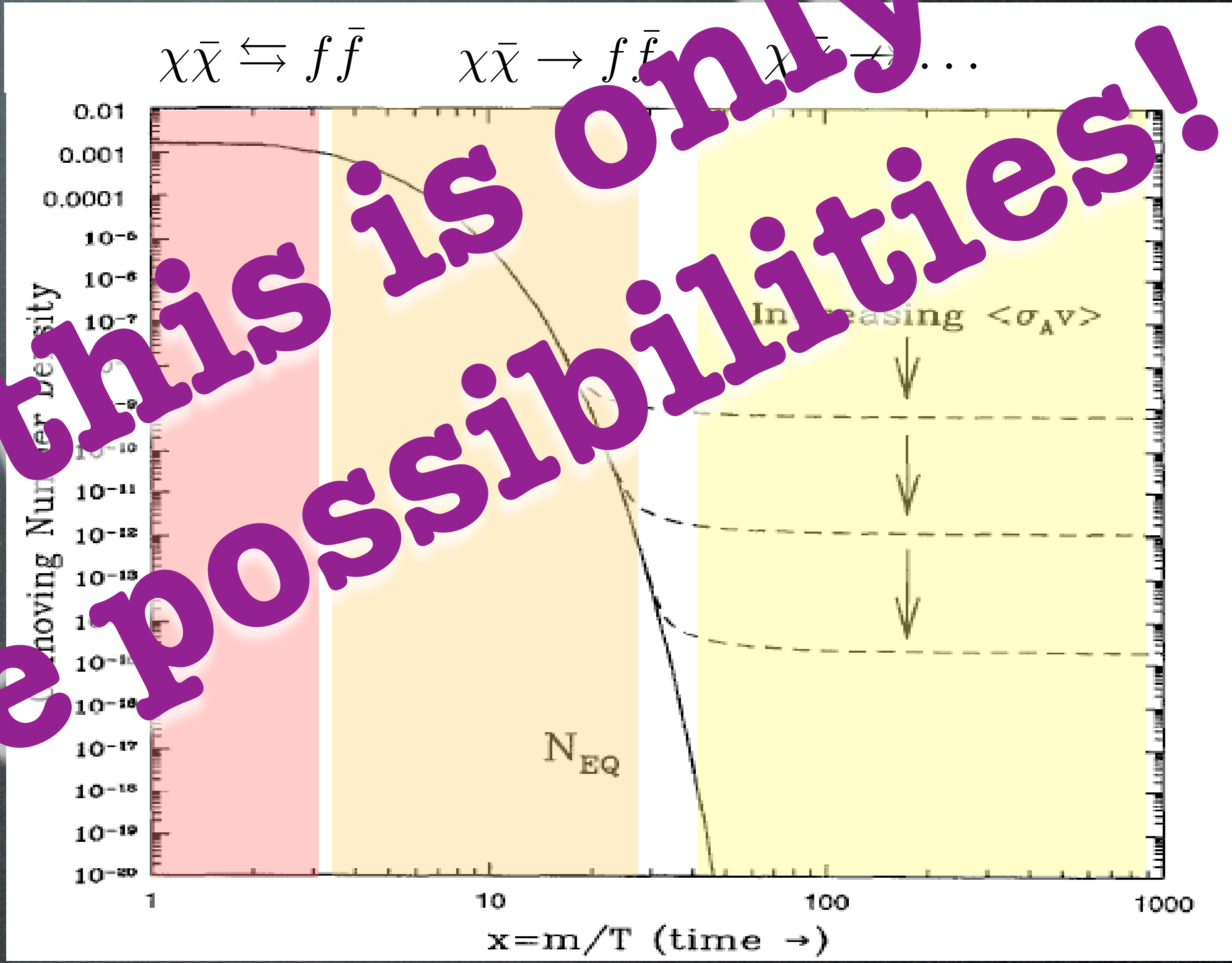

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Caveat: this is only one of the possibilities!

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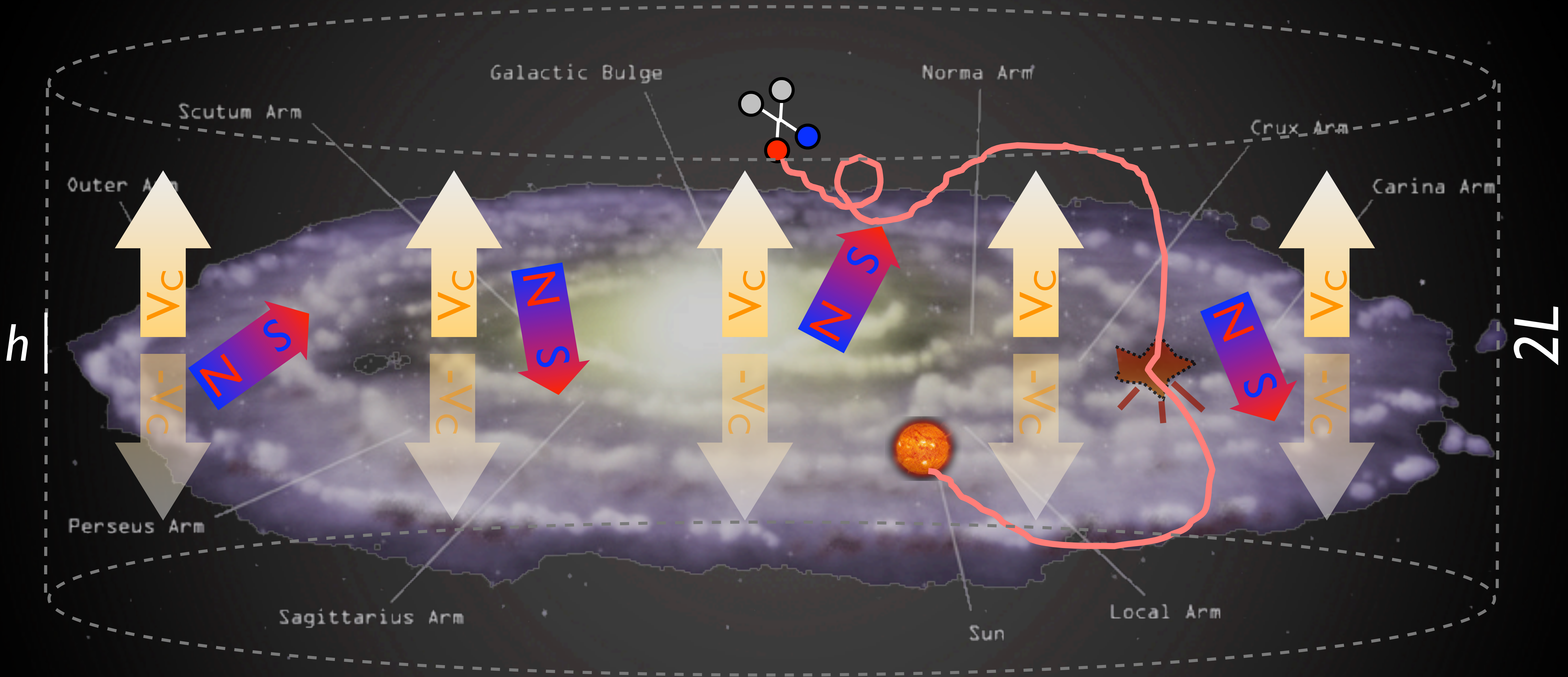

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astro& cosmo

particle

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DM halo profiles

From N-body numerical simulations:

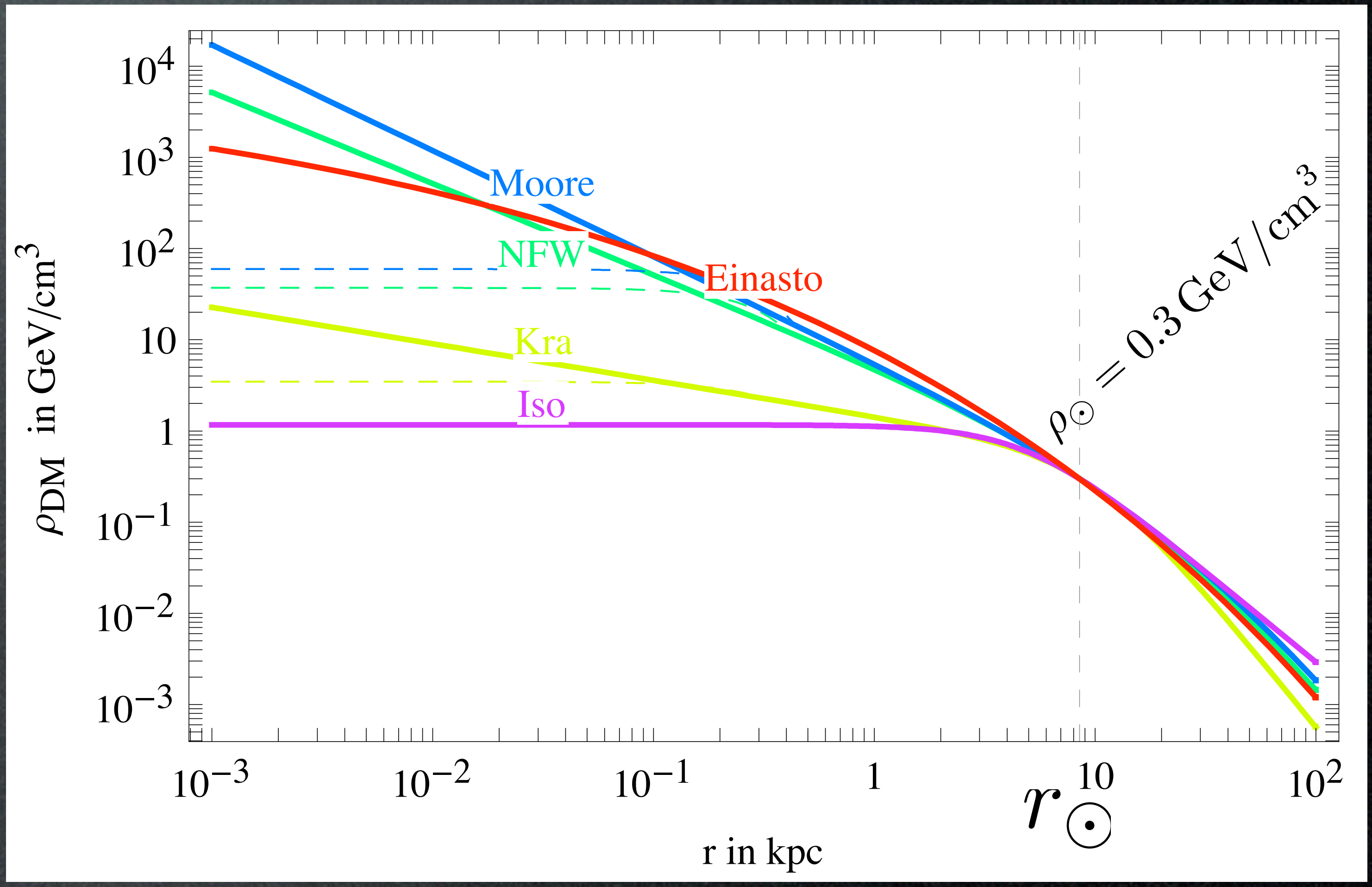
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

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

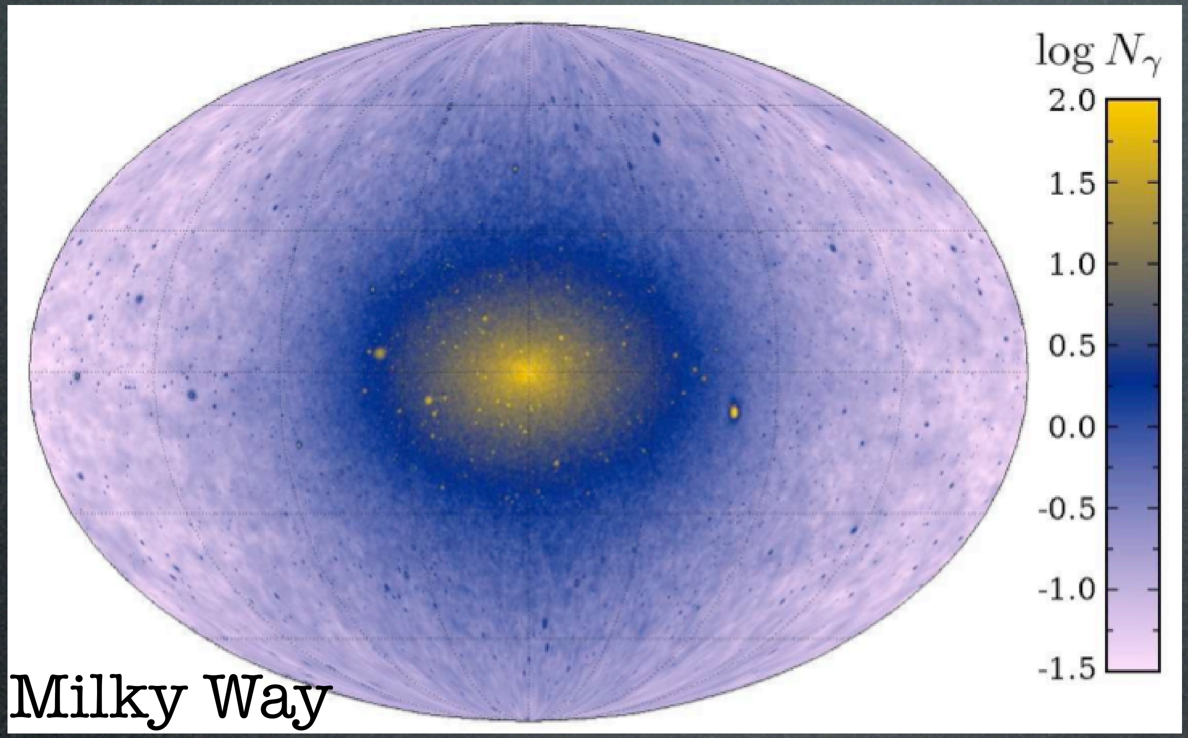


cuspy: NFW, Moore
mild: Einasto
smooth: isothermal

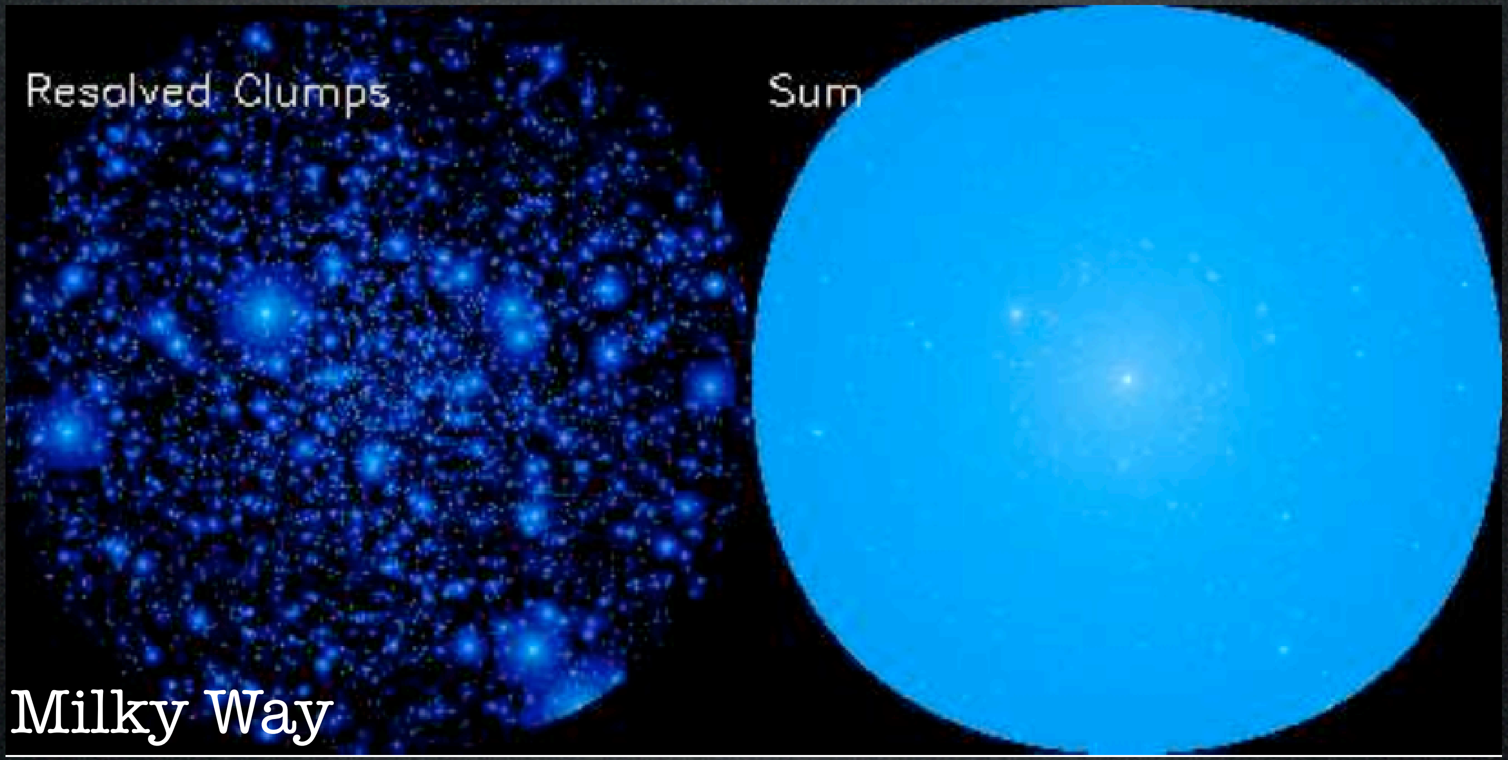
Indirect Detection

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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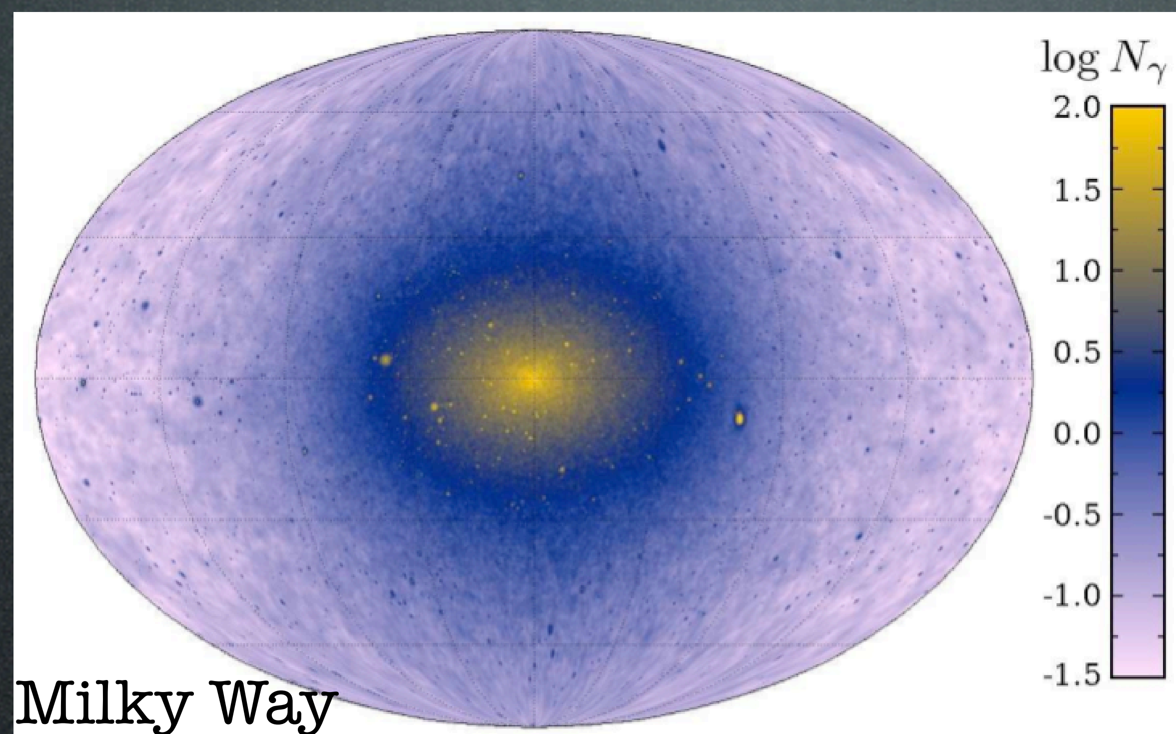
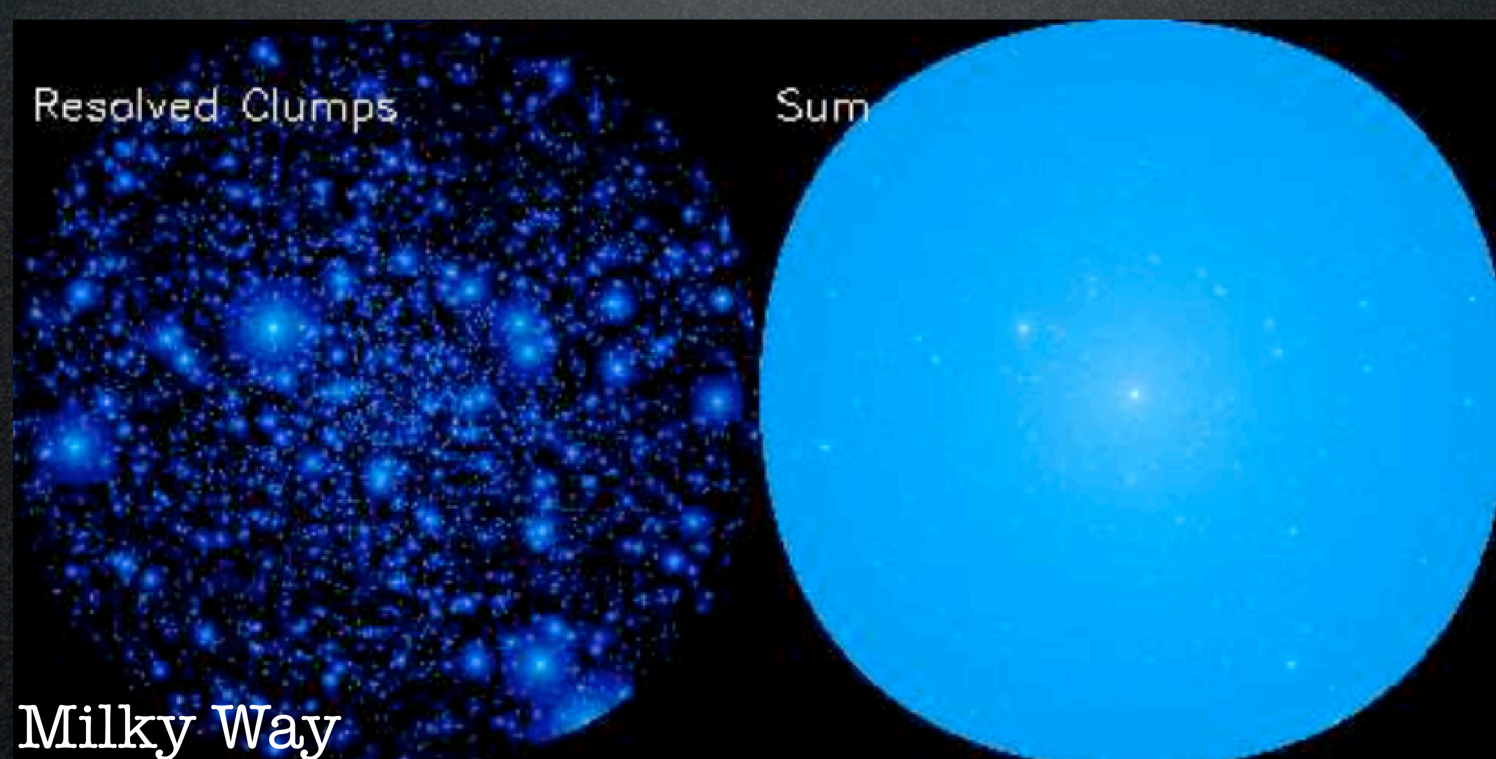


Kuhlen, Diemand, Madau 2007

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



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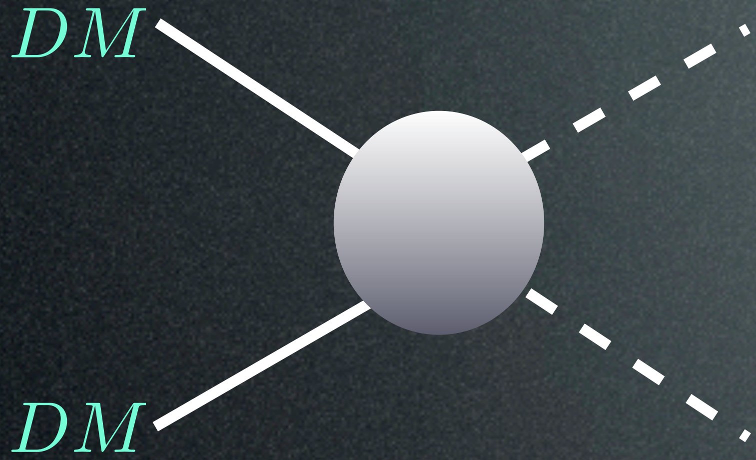
Computing the theory predictions

Spectra at production



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

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

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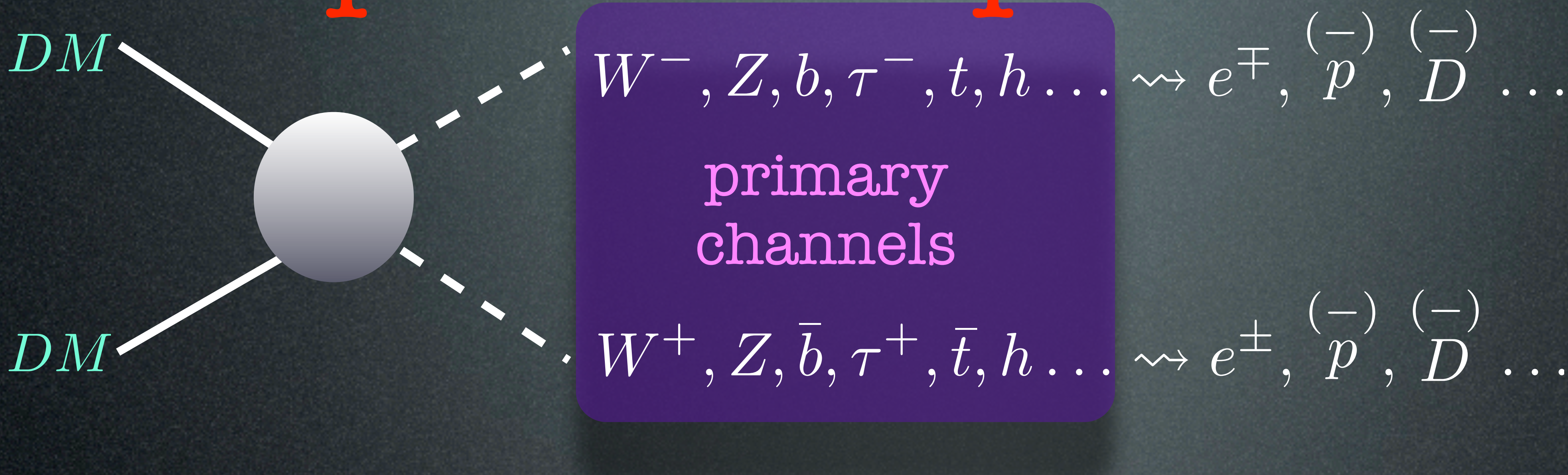

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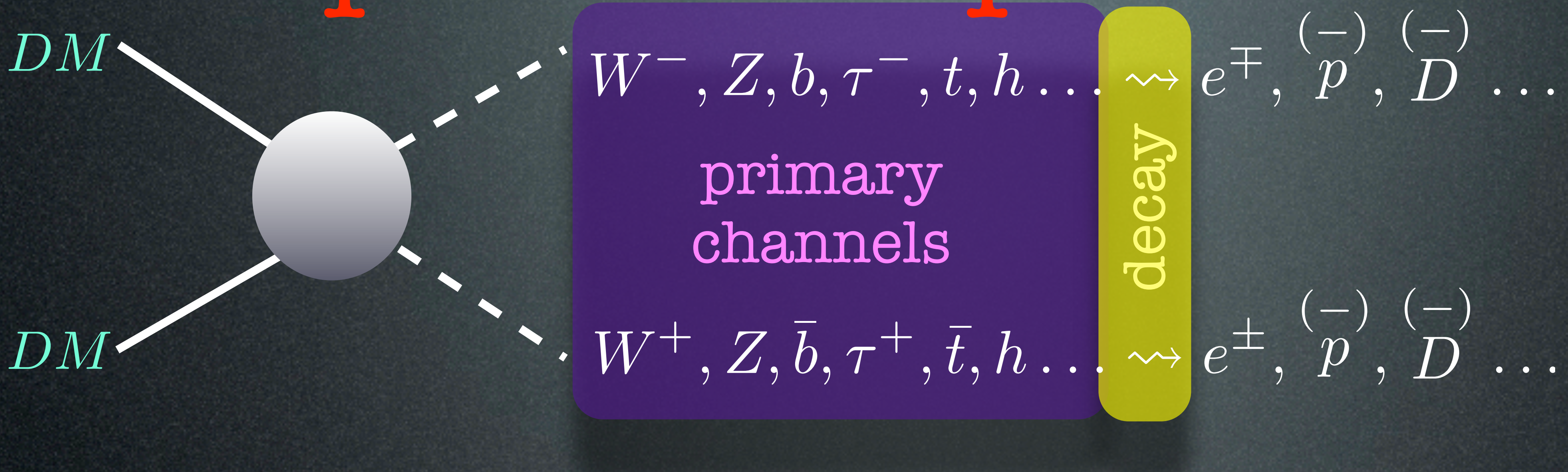

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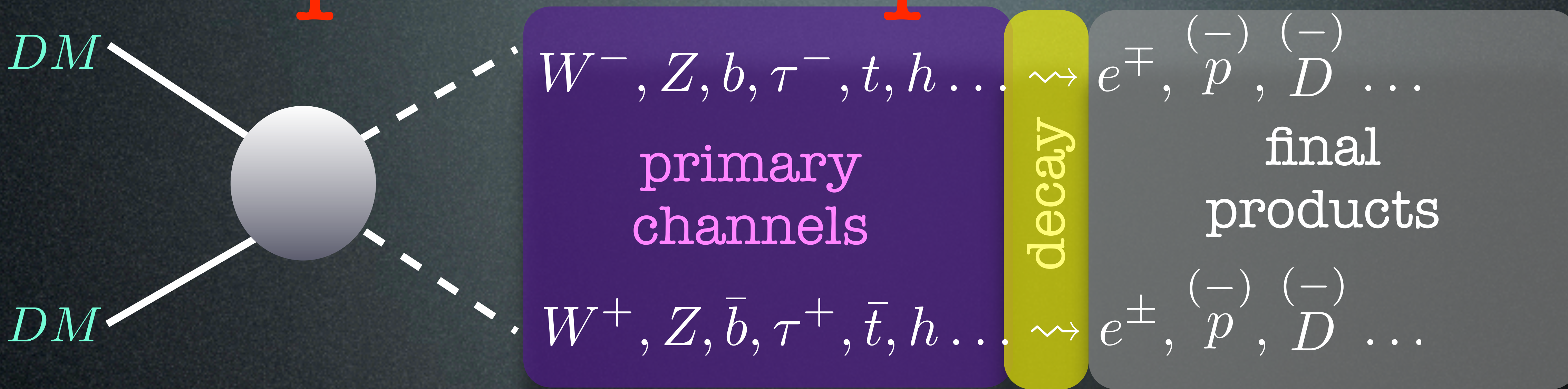

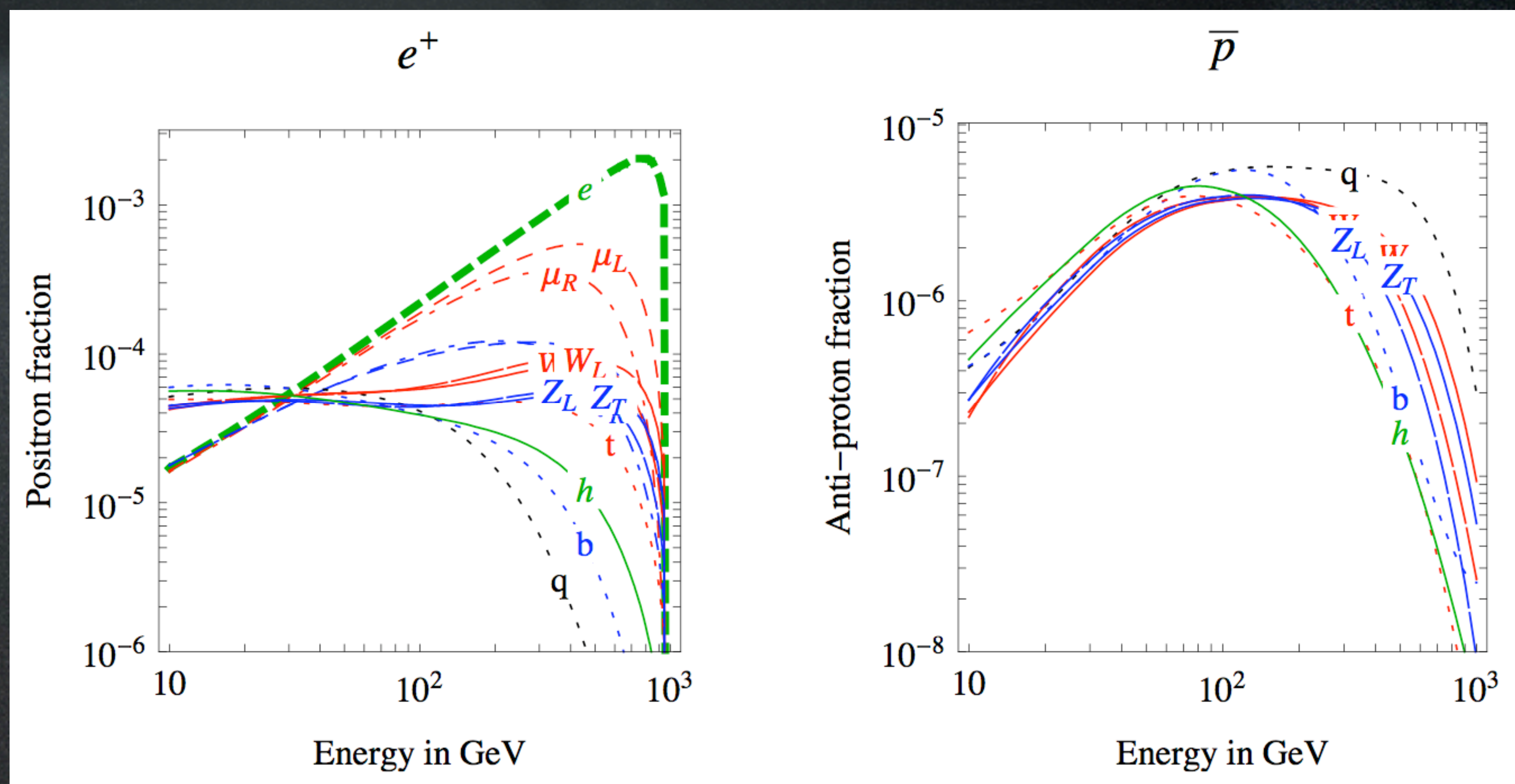

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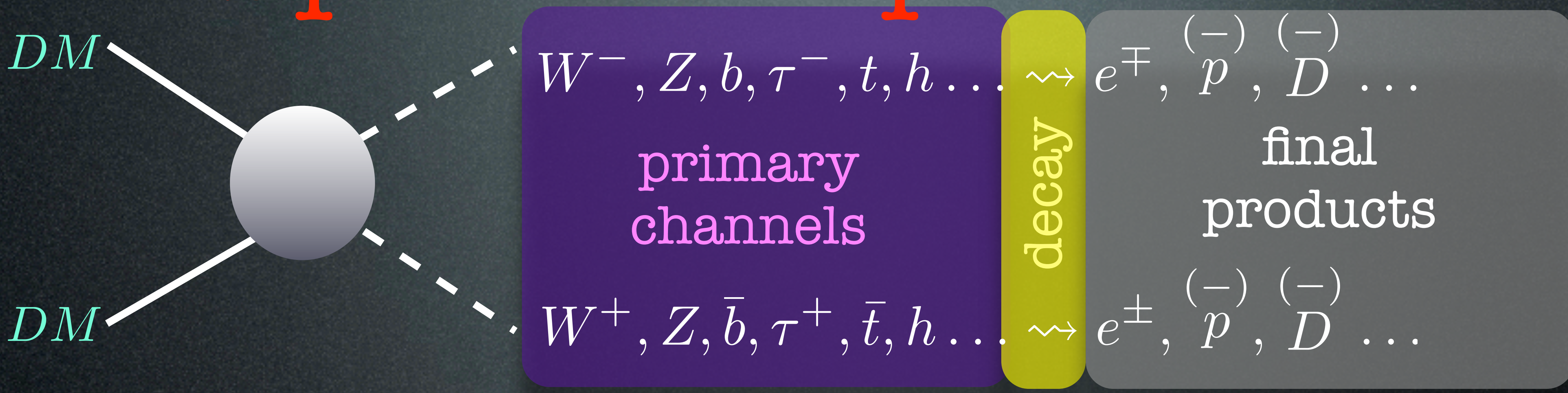
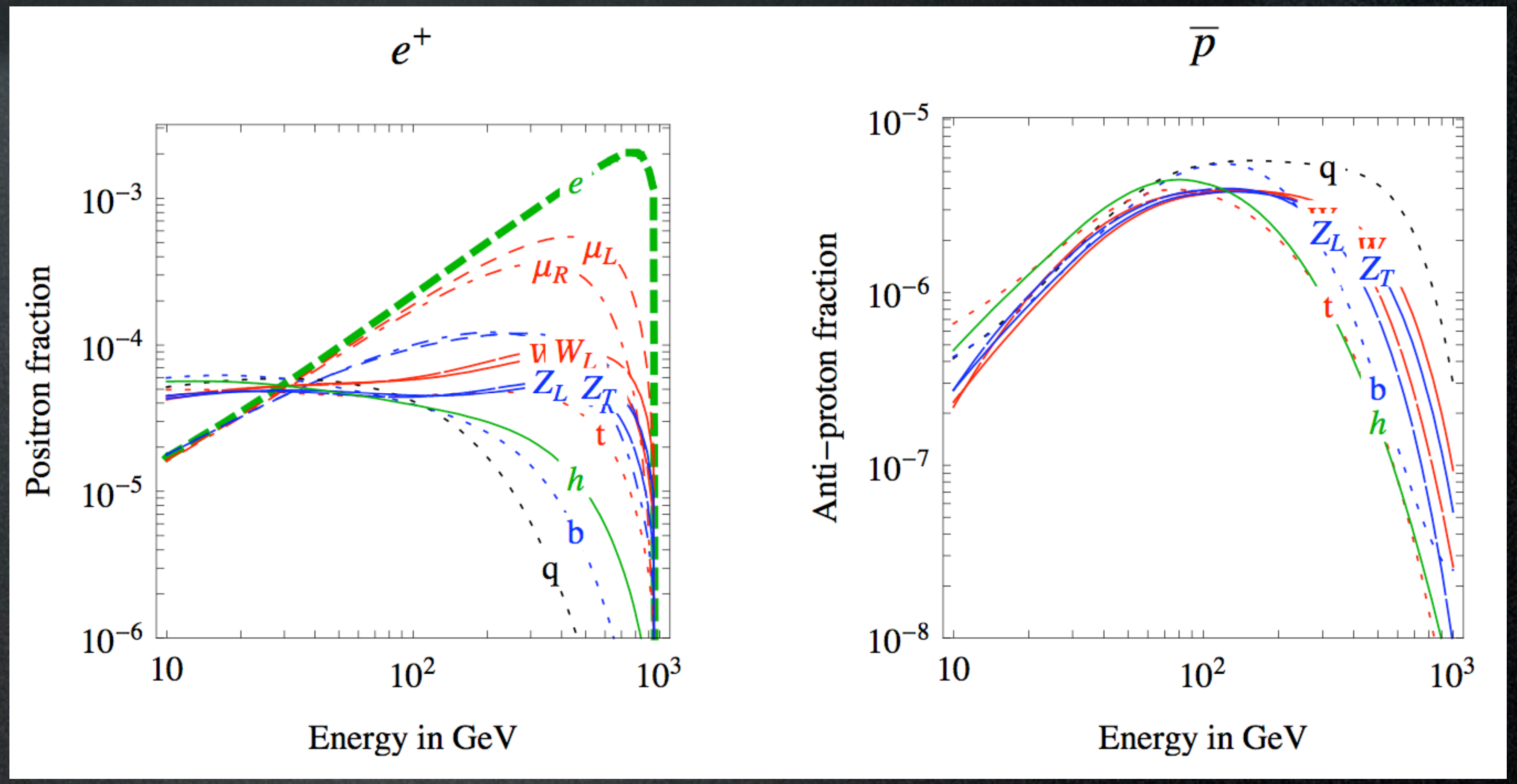




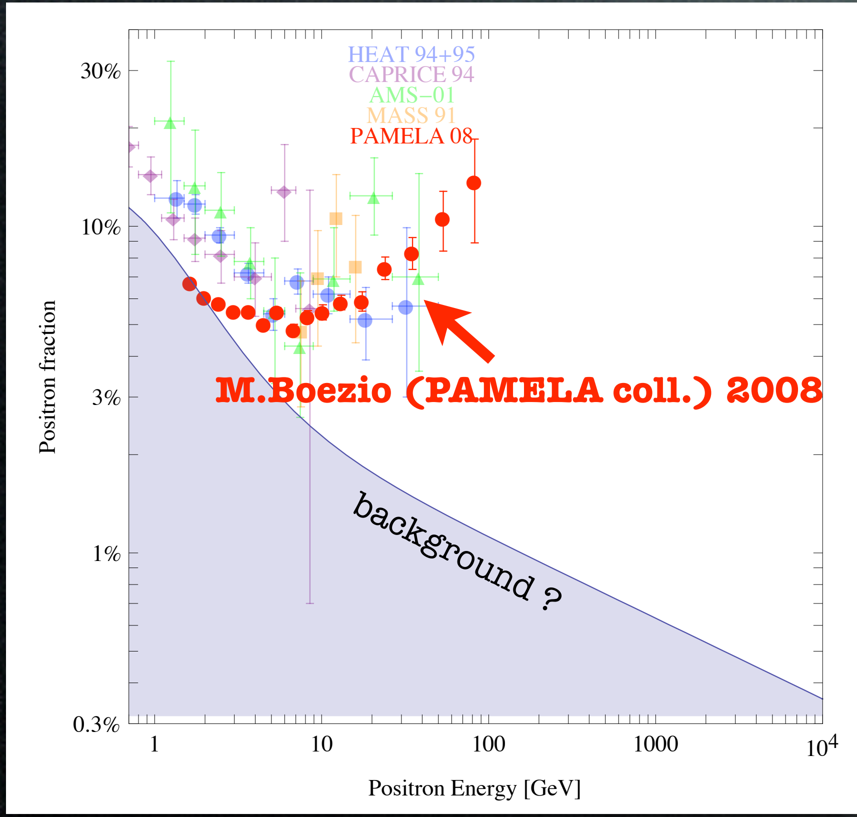
So what are the particle physics parameters?

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

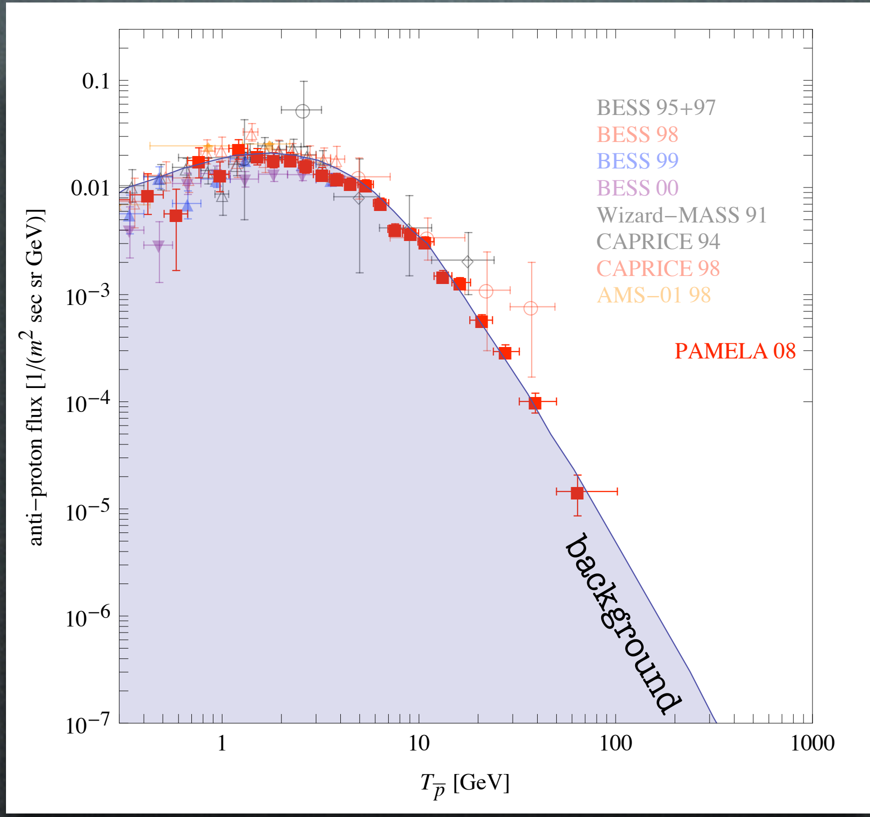
Comparing with data

Data

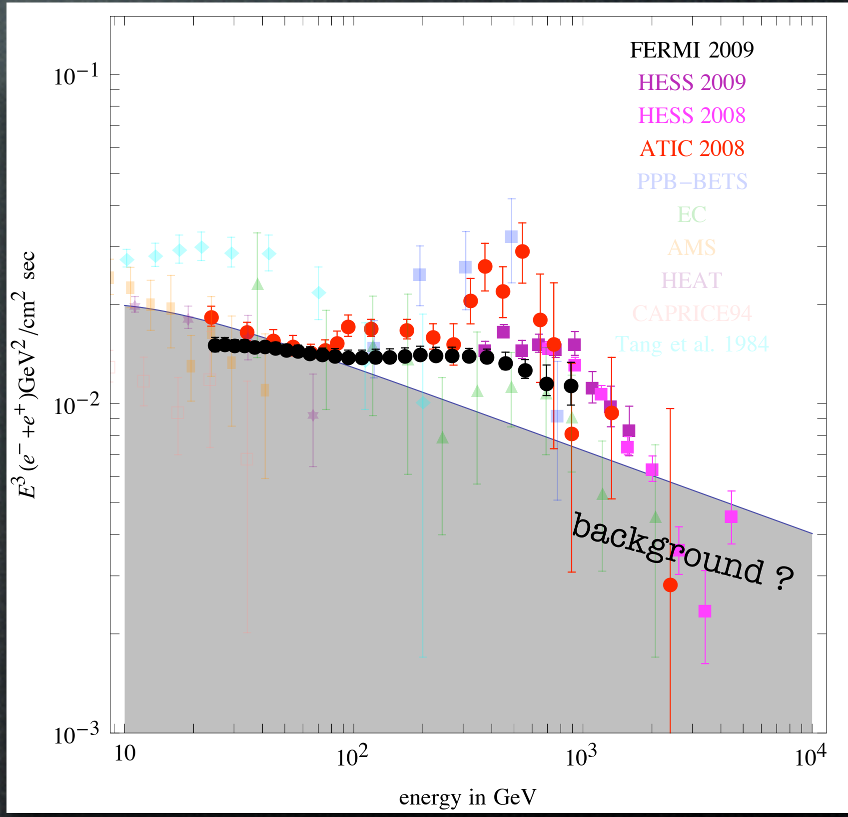
positron fraction



antiprotons



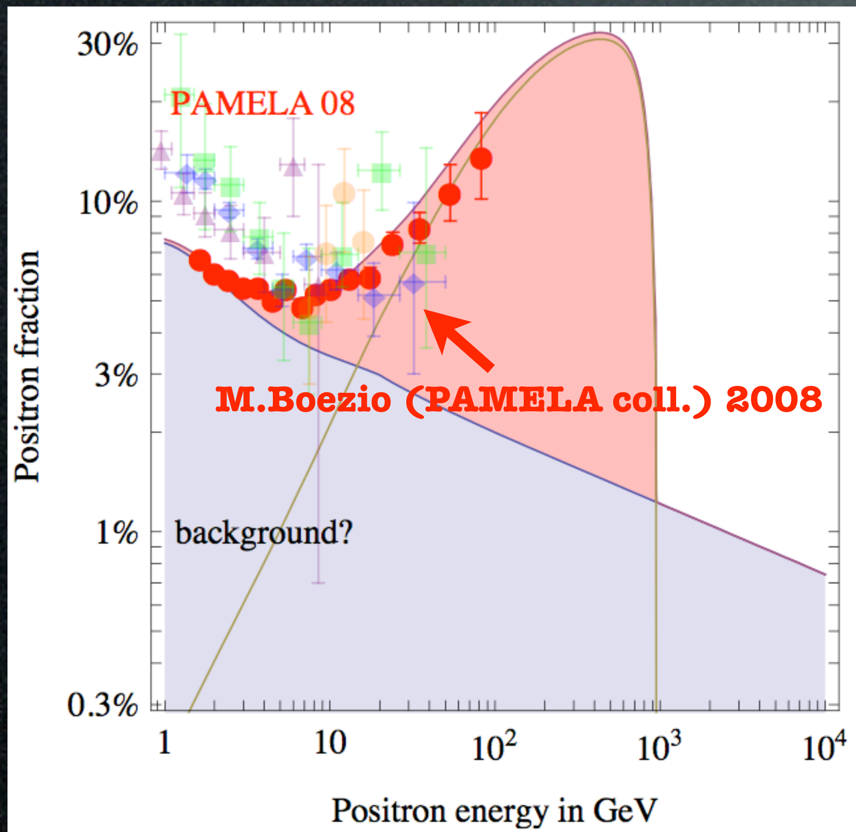
electrons + positrons



Are these signals of Dark Matter?

Data

positron fraction



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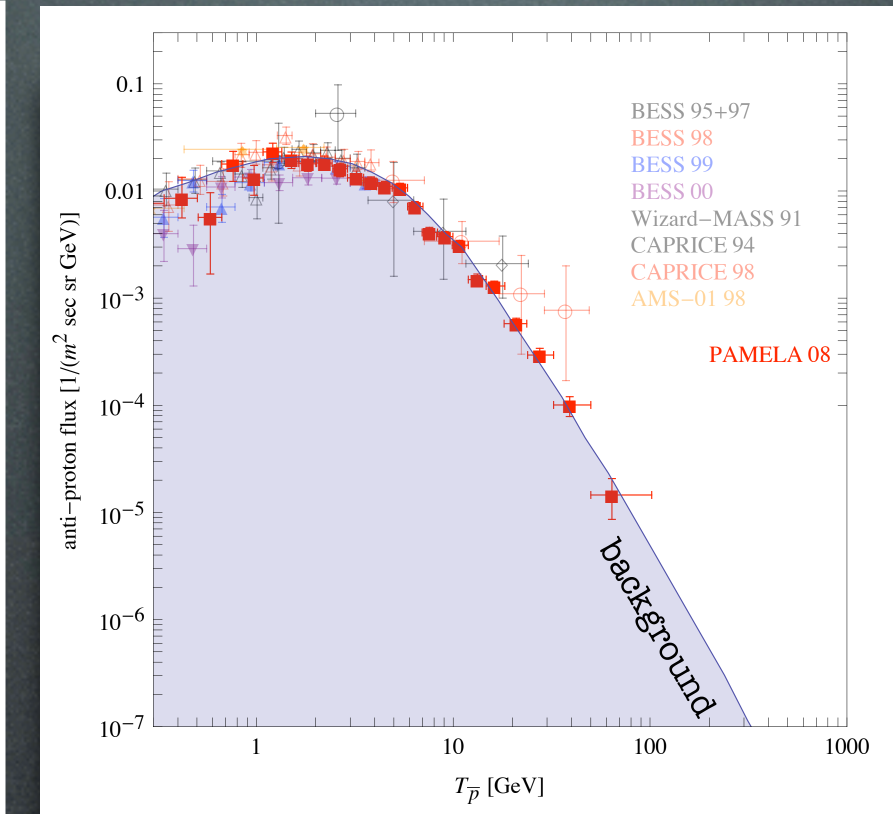

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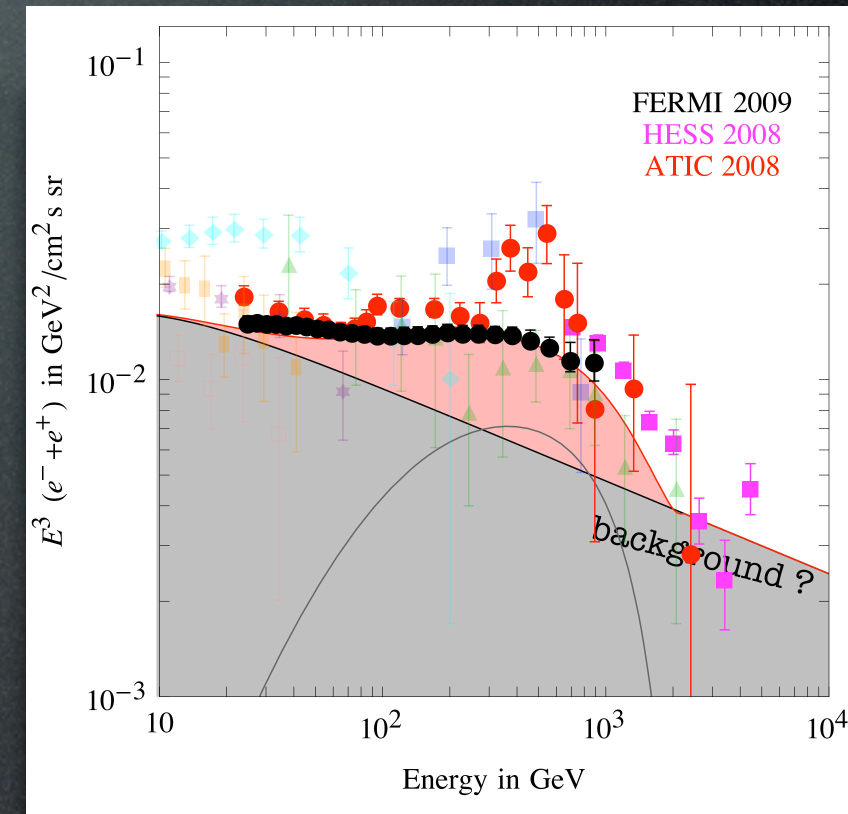

Are these signals of Dark Matter?

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

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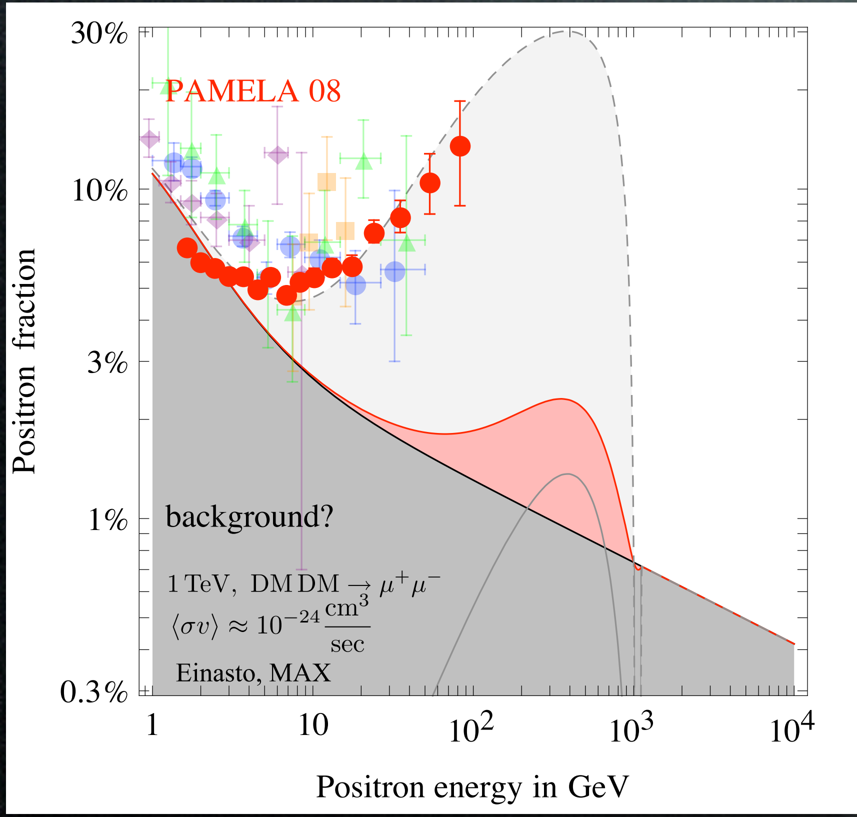

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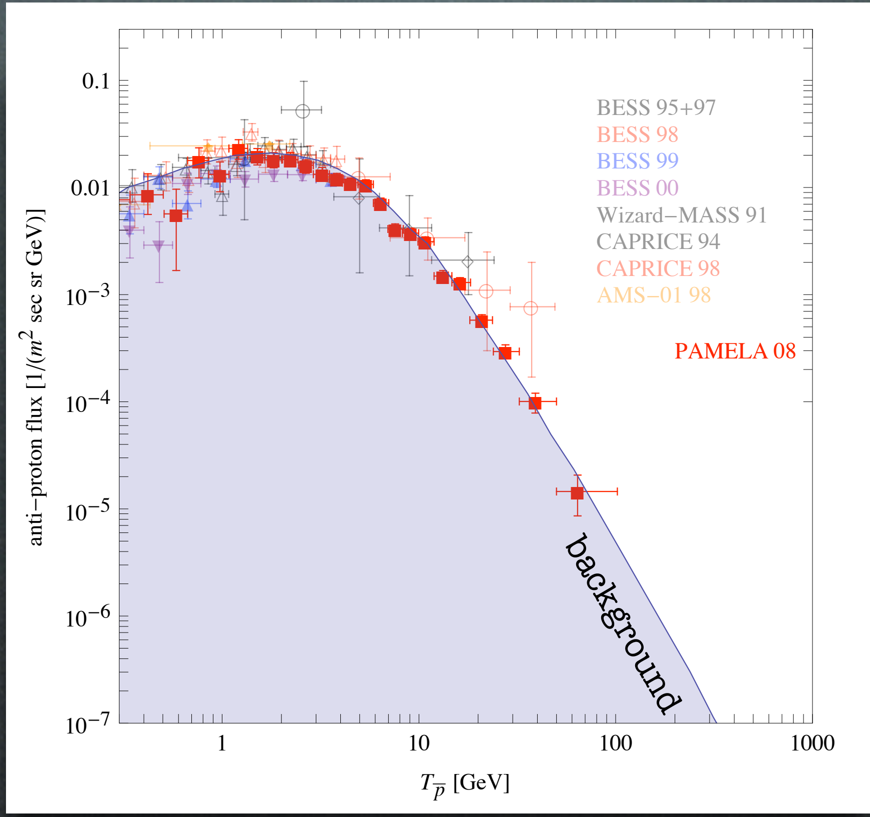

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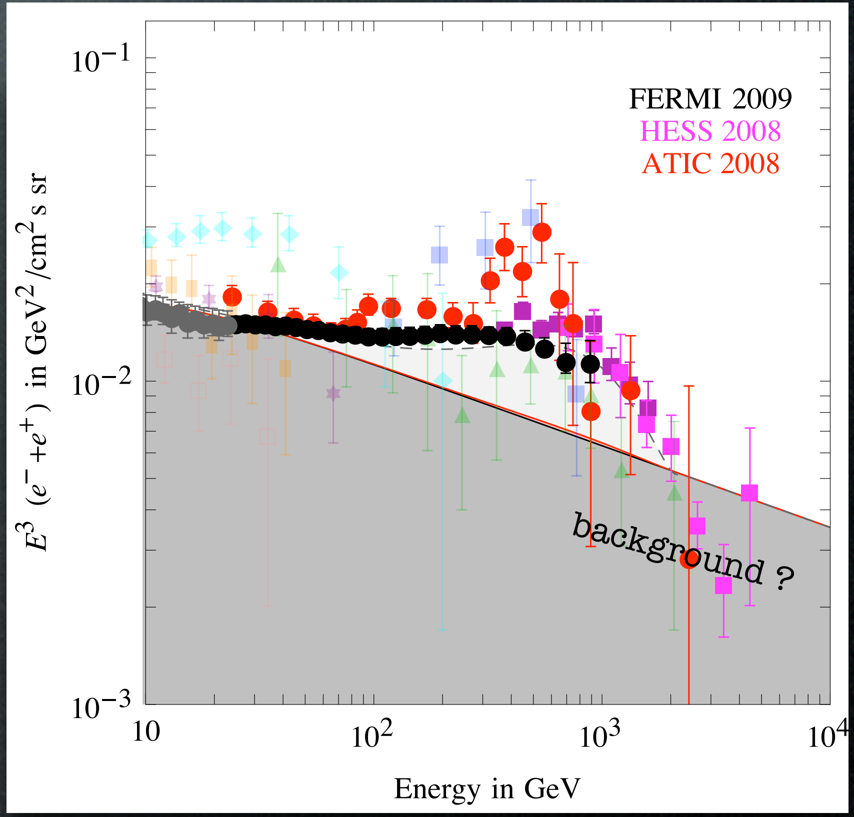

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NO: a formidable 'background' for future searches

Astrophysical explanation?

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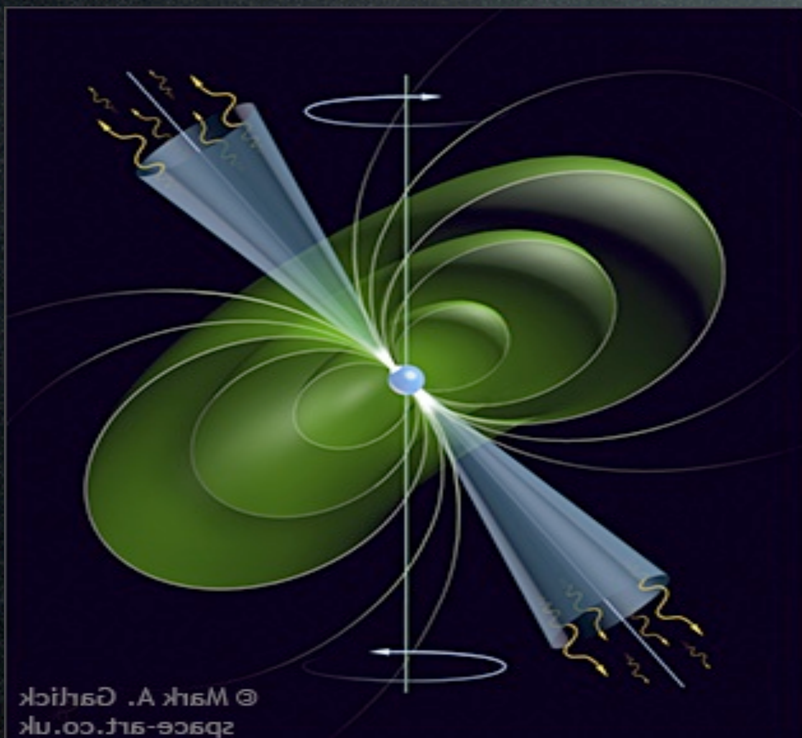
Or perhaps it's just a young, nearby pulsar...



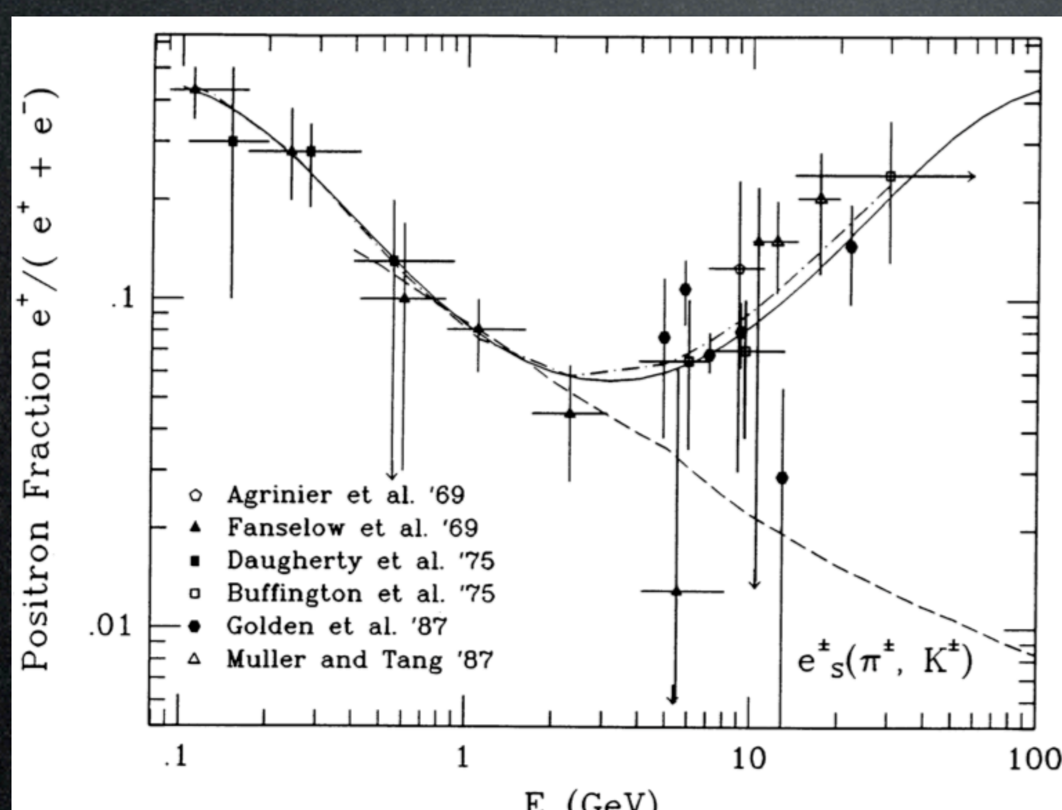
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \rightarrow 10^5$ yr (typical total energy output: 10^{46} erg).

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

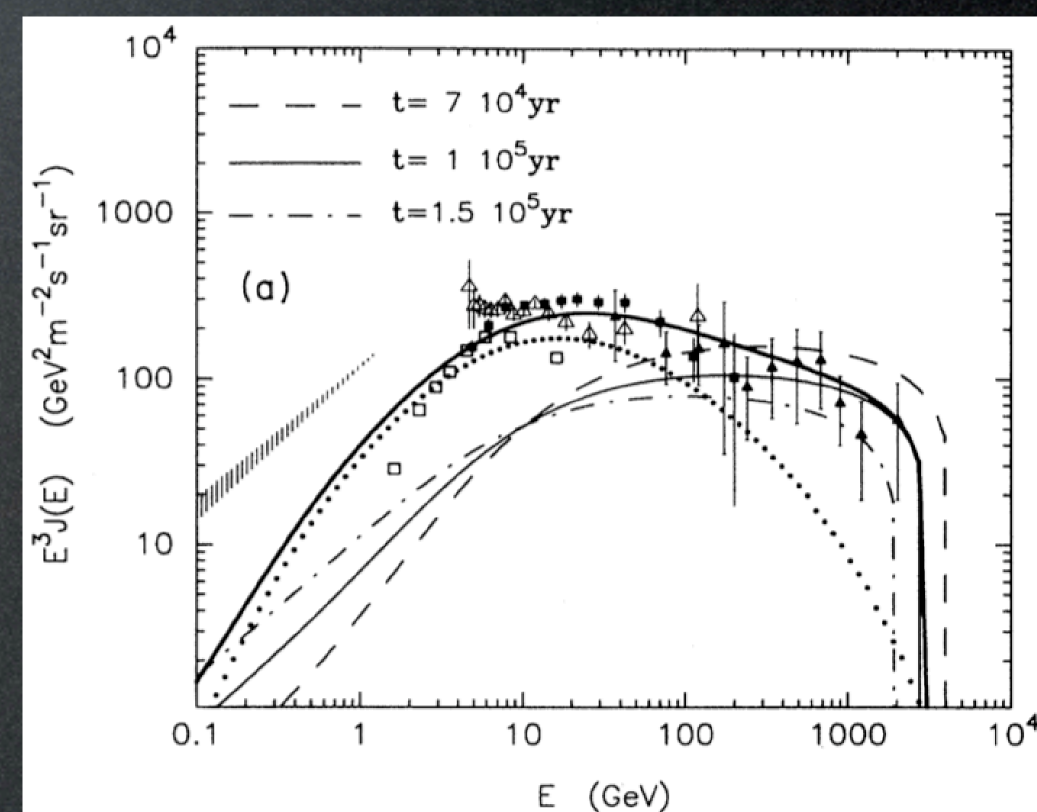
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

Not a new idea:



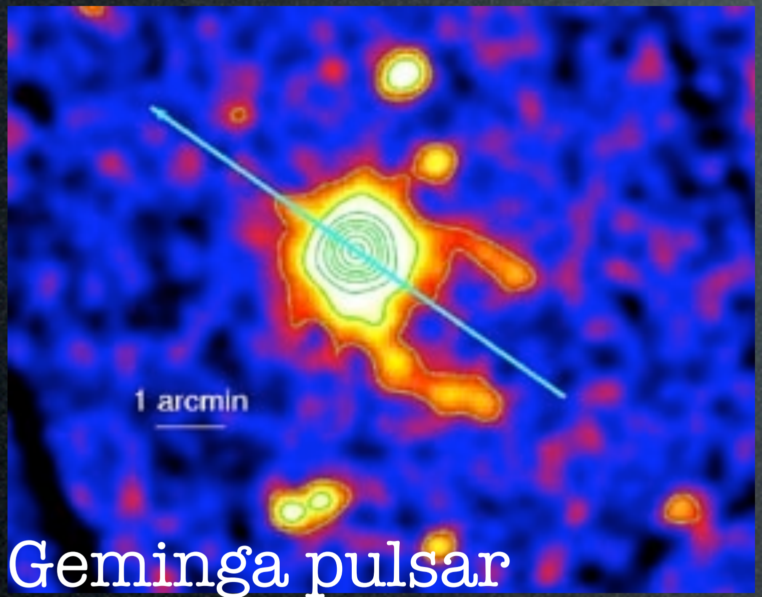
A.Boulares, APJ 342 (**1989**)



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

Astrophysical explanation?

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



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

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

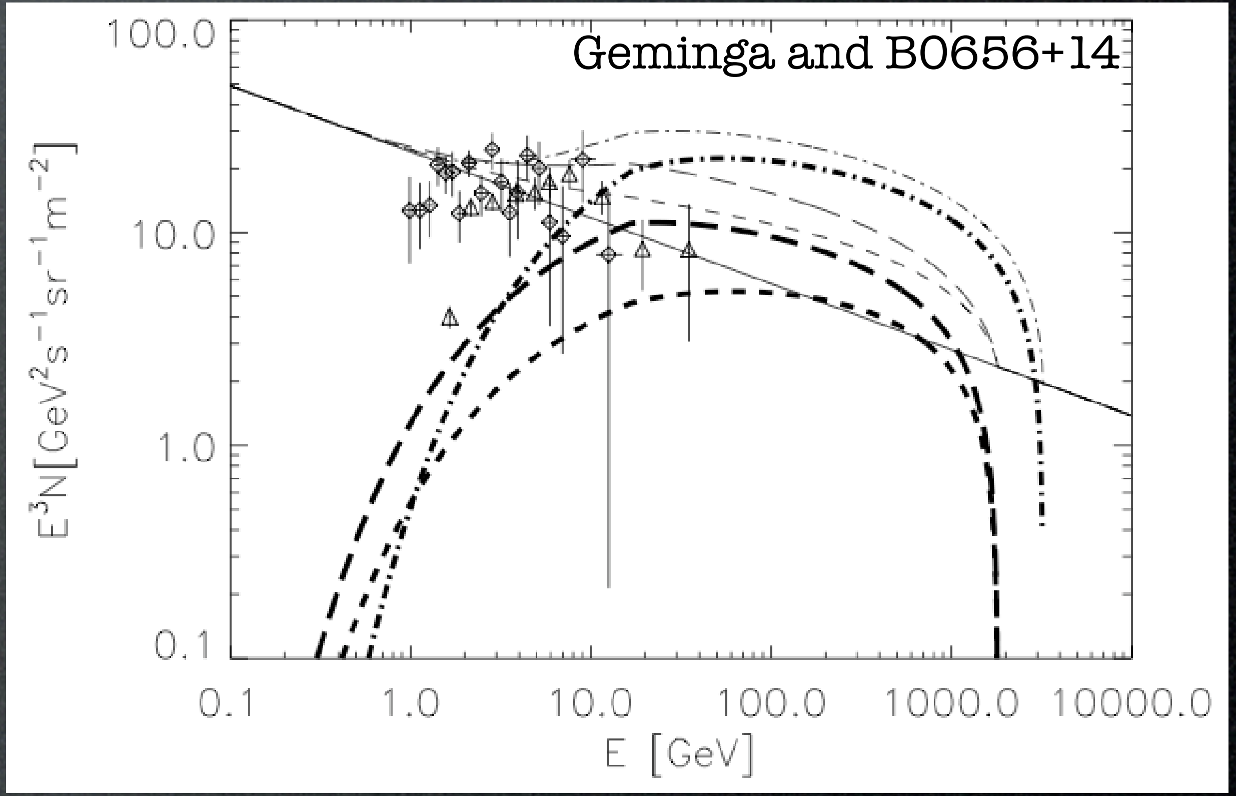
Must be young (T < 10^5 yr) and nearby (< 1 kpc);
if not: too much diffusion, low energy, too low flux.

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:

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

Astrophysical explanation?

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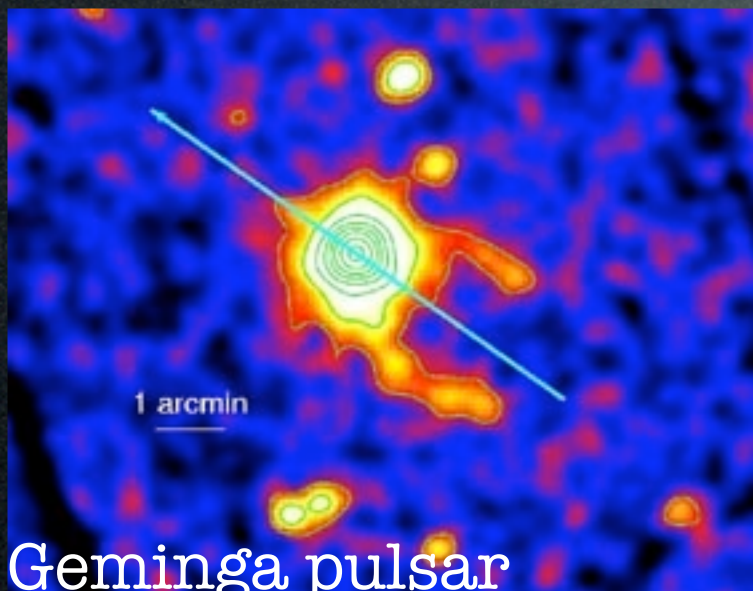

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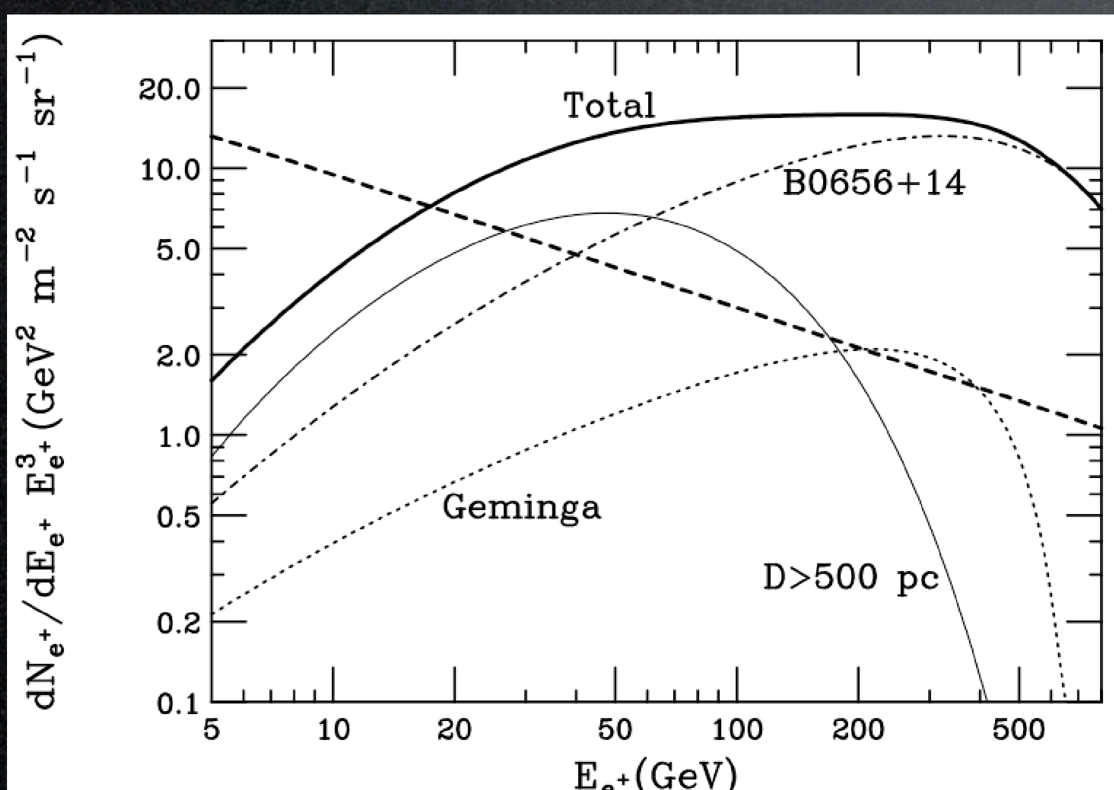
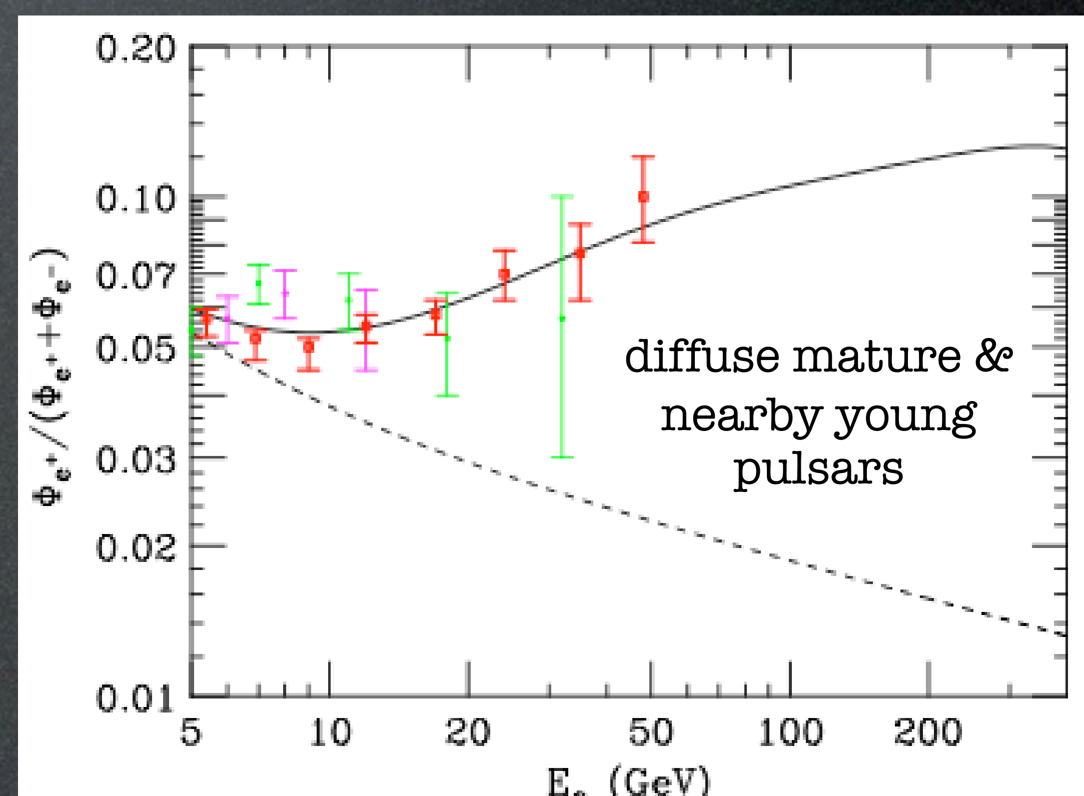
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

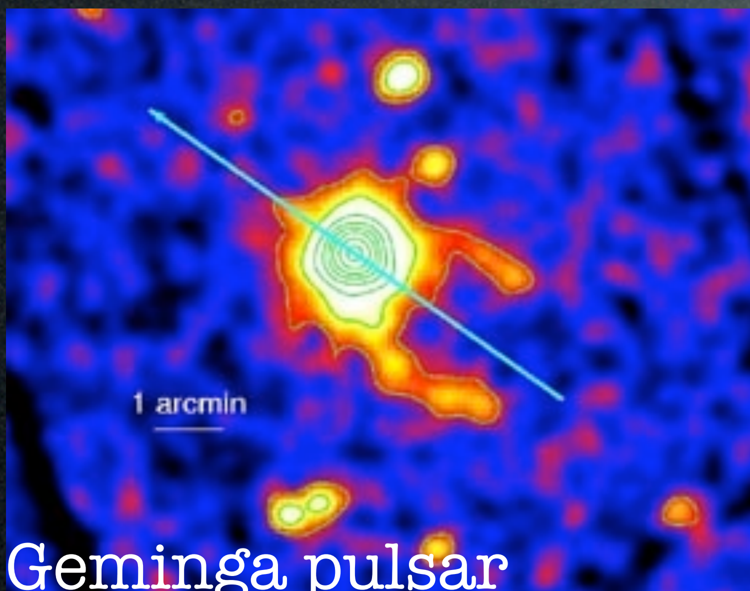




Hooper, Blasi, Serpico 2008

Astrophysical explanation?

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



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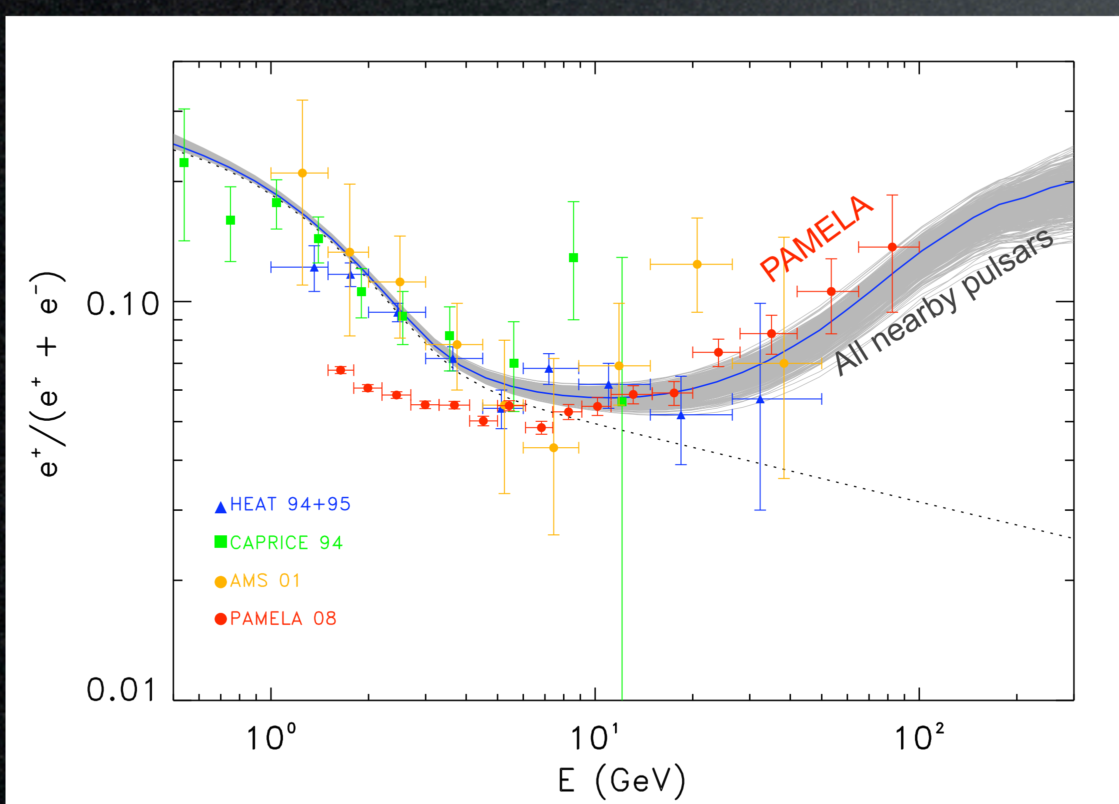
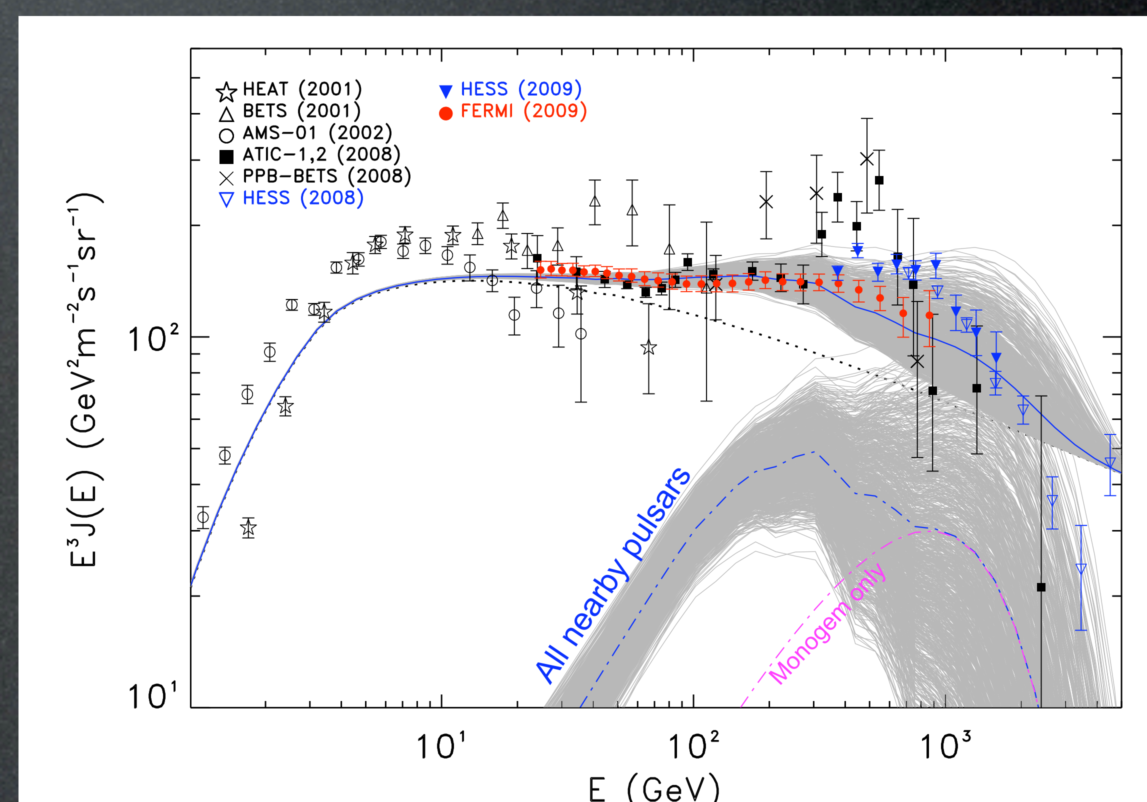
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

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

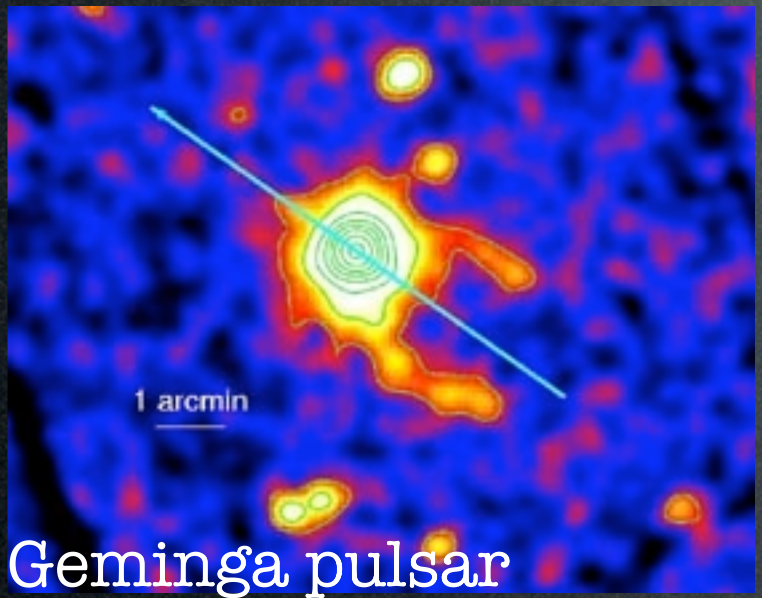




D.Grasso et al.
(sub-FERMI collab.)
0905.0636

Astrophysical explanation?

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



Geminga pulsar

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

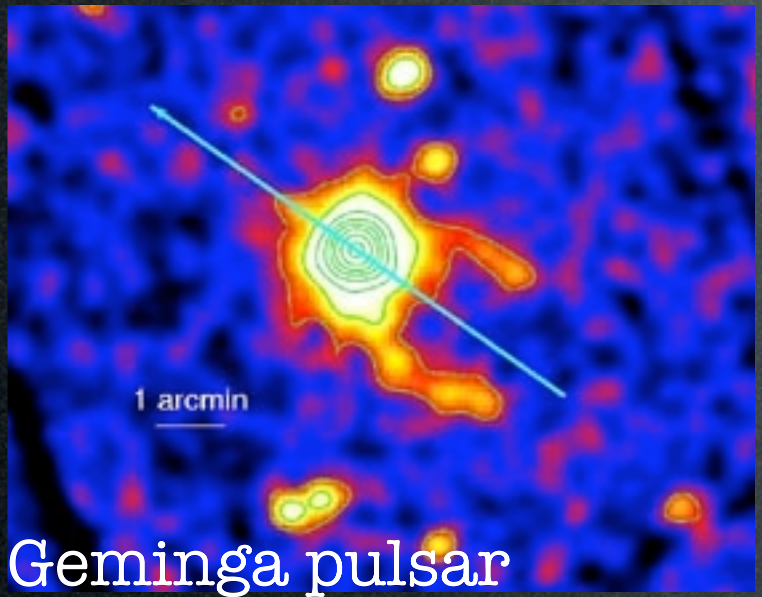
Open issue.

(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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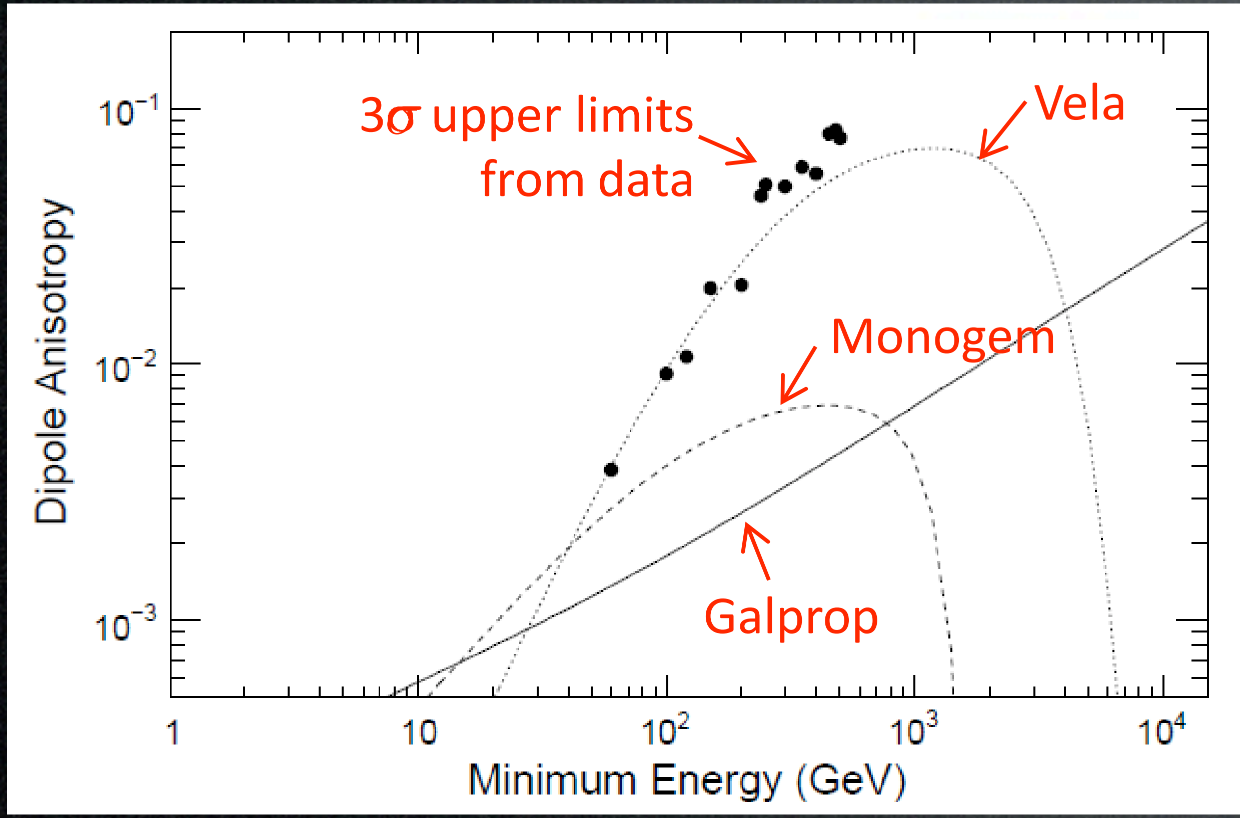
Fermi coll., 1008.5119



Rule out one single bright source.

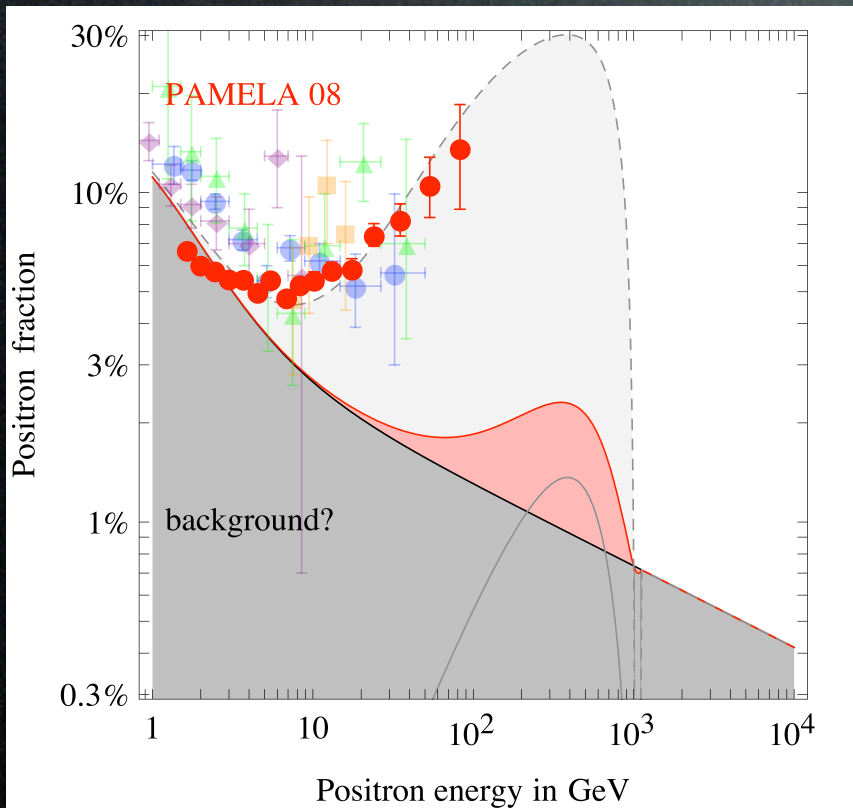
Open issue.

(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...)

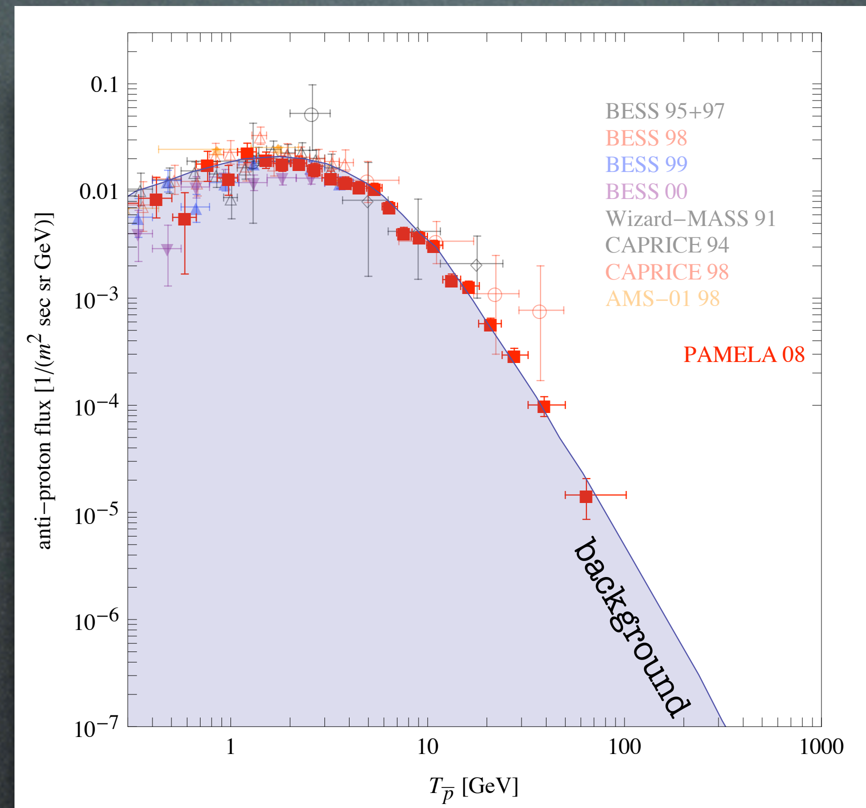
e.g. Yuksel, Kistler, Stanev 0810.2784
Hall, Hooper 0811.3362

Data

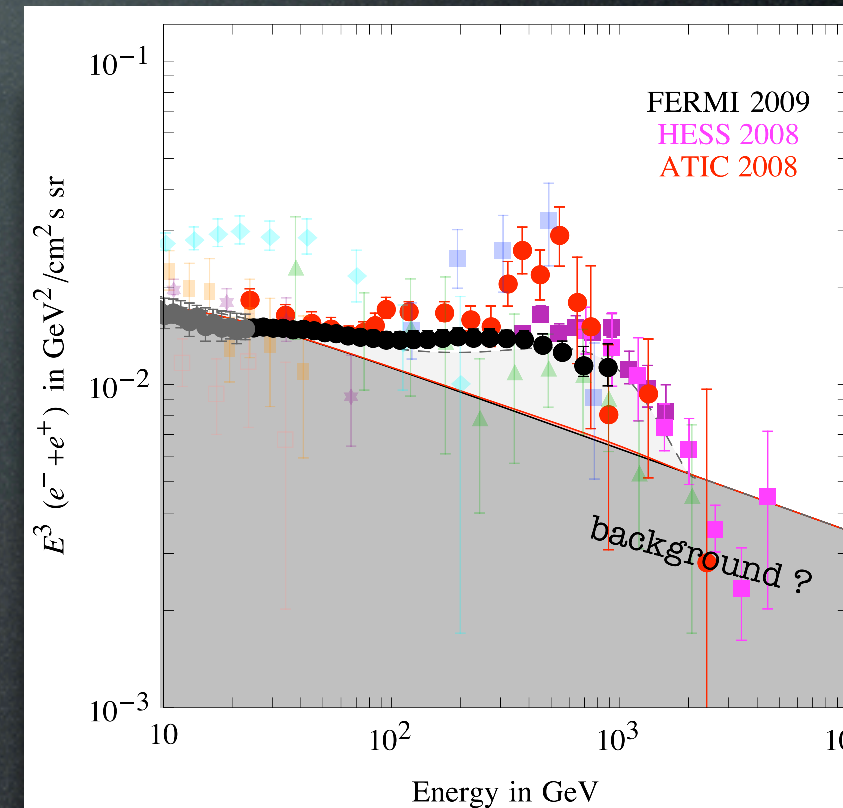
positron fraction



antiprotons



electrons + positrons



Are these signals of Dark Matter?

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

NO: a formidable ‘background’ for future searches

Enhancement

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

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

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

+ (Wimponium)

Enhancement

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

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	at freeze-out	*today*
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	**A.Hryczuk's talk**	

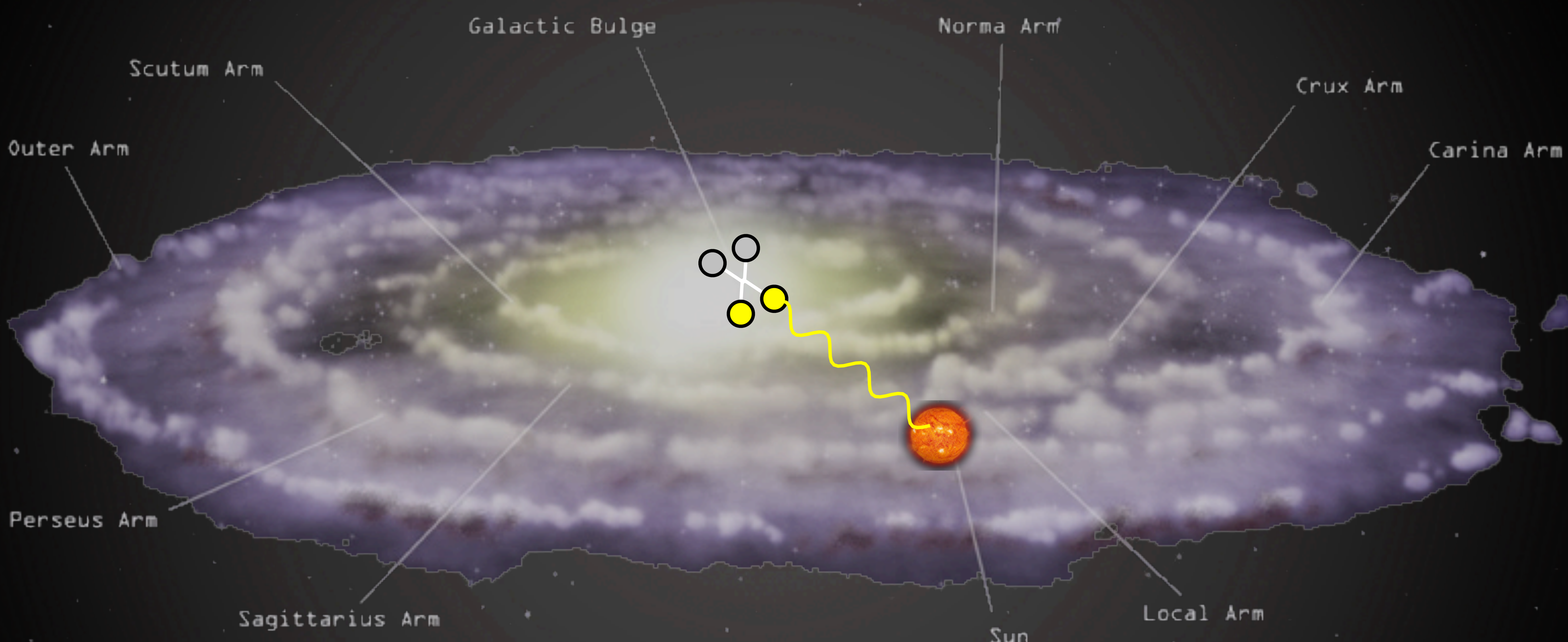
+ (Wimponium)

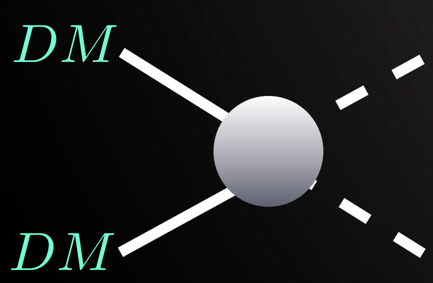
DM detection

- 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



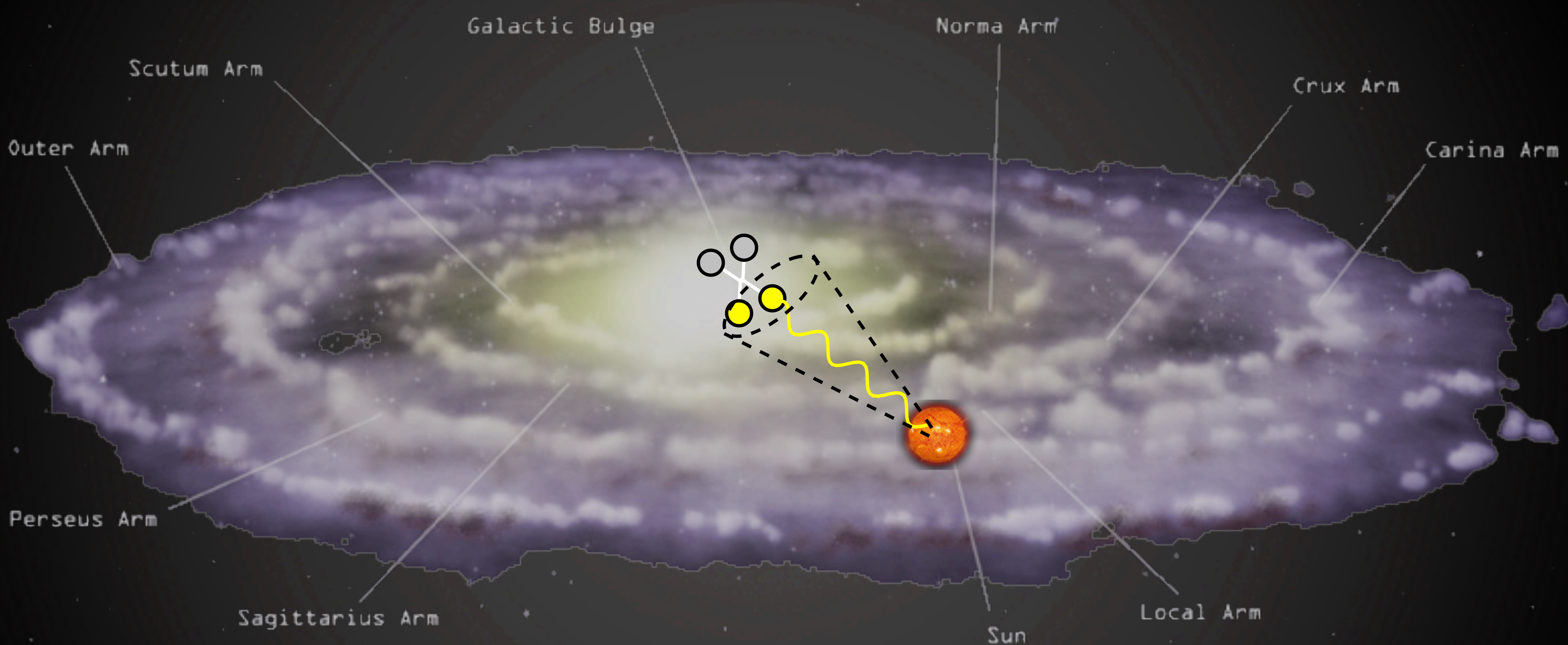


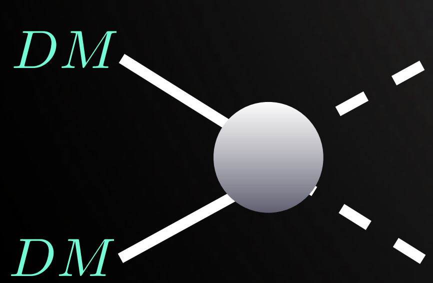
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

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

Indirect Detection

γ from DM annihilations in galactic center



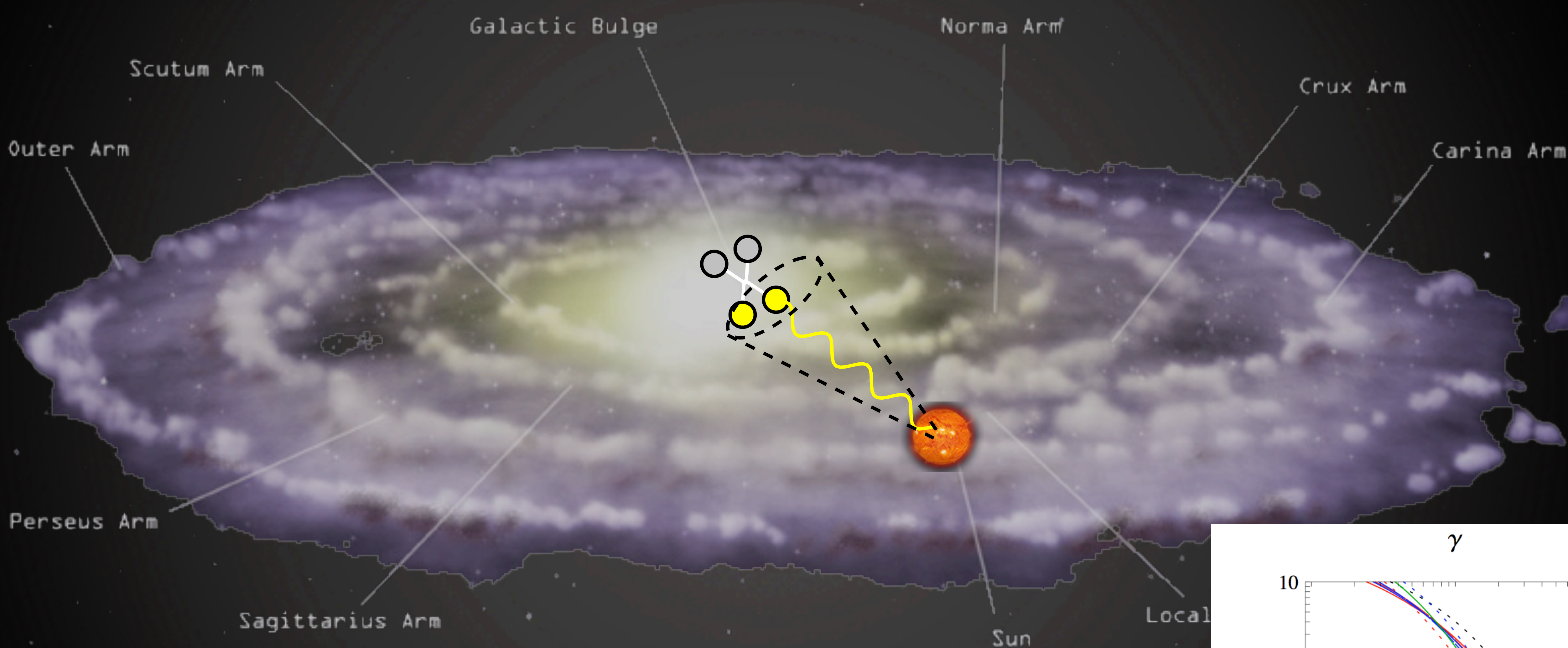


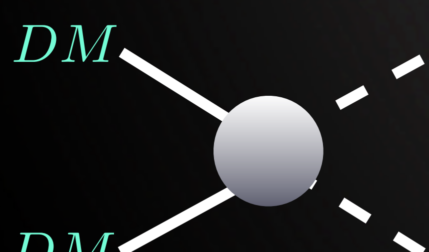
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

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

Indirect Detection

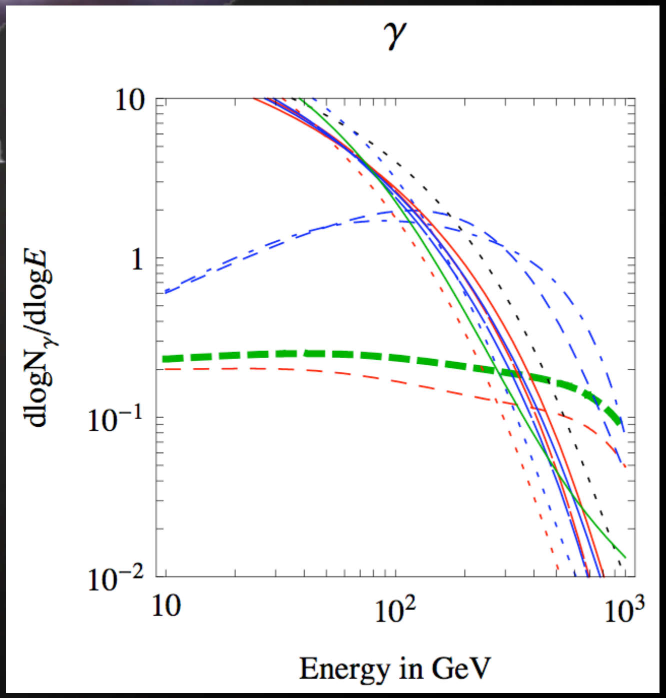
γ from DM annihilations in galactic center





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

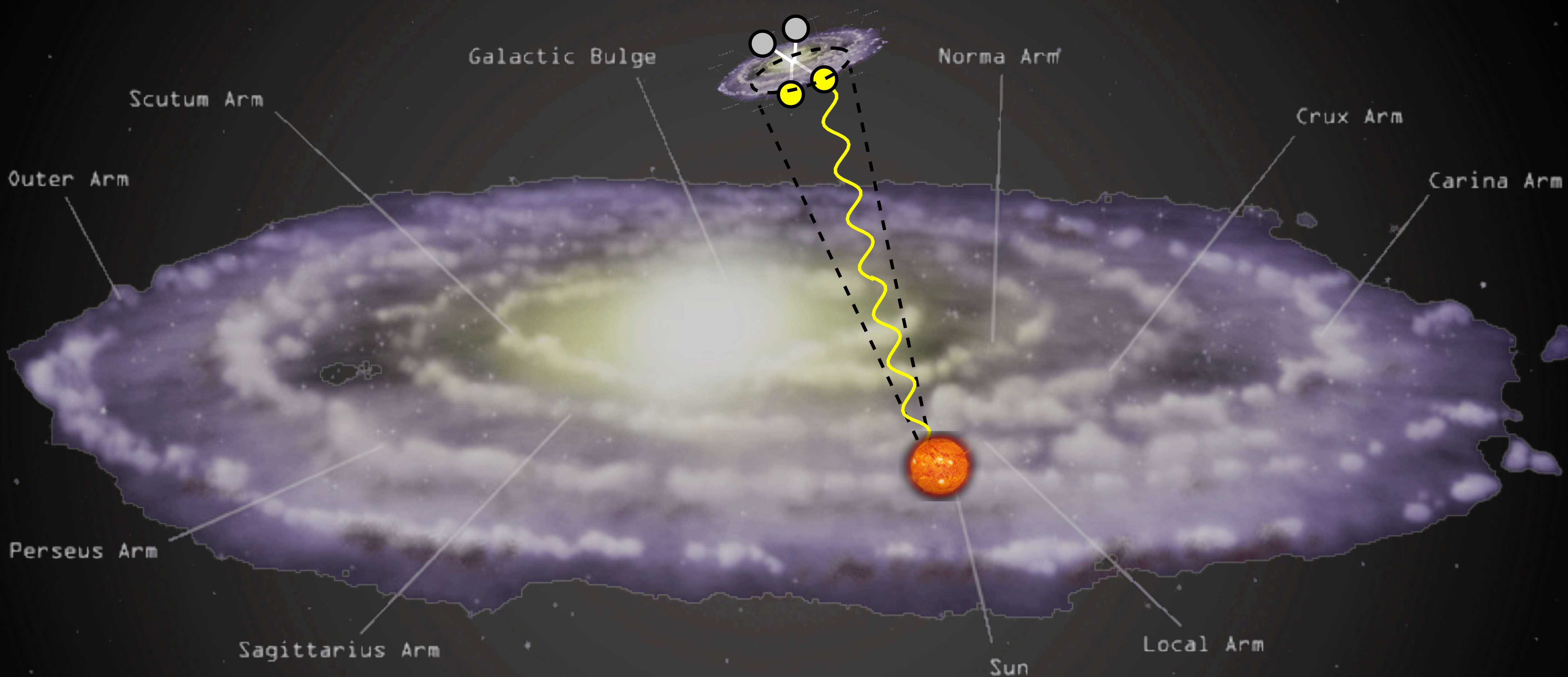
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

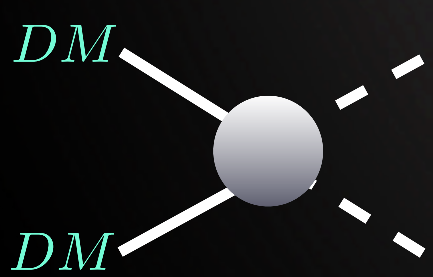


typically sub-TeV energies

Indirect Detection

γ from DM annihilations in Sagittarius Dwarf



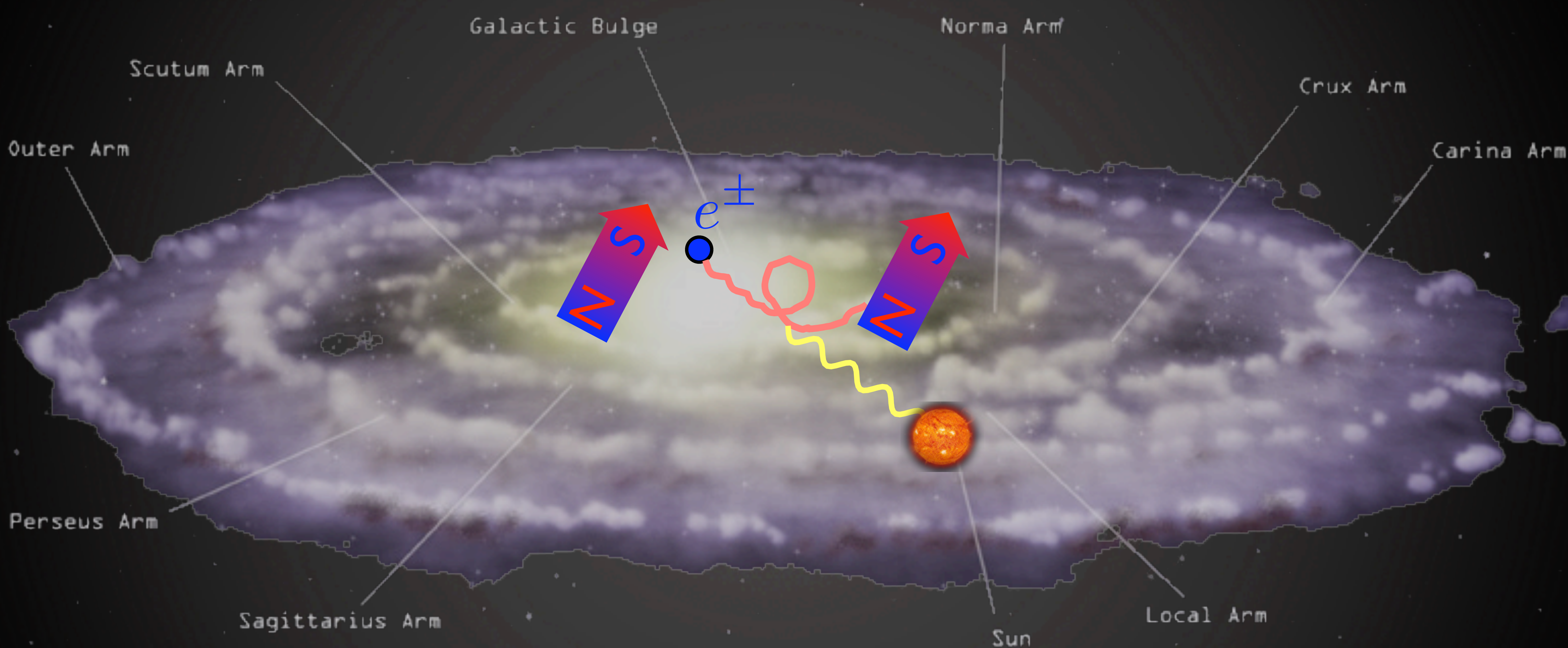


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

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

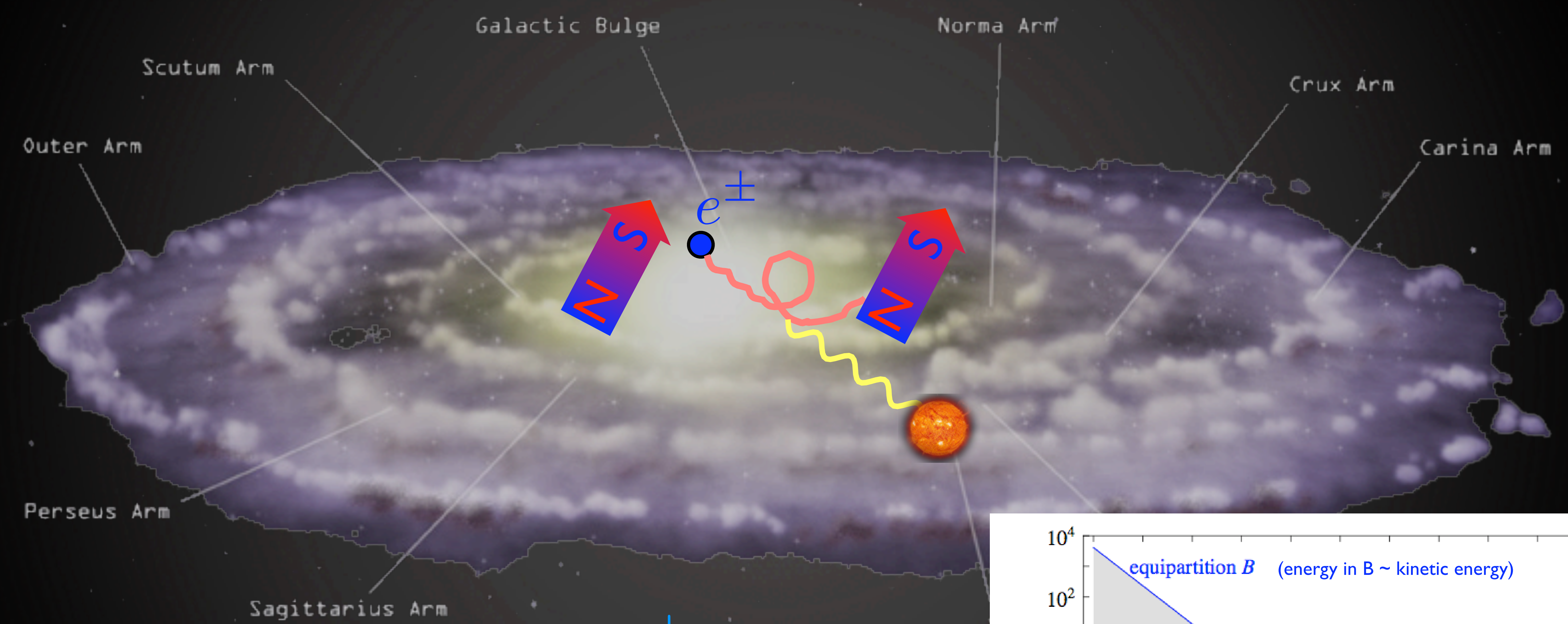
Indirect Detection

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



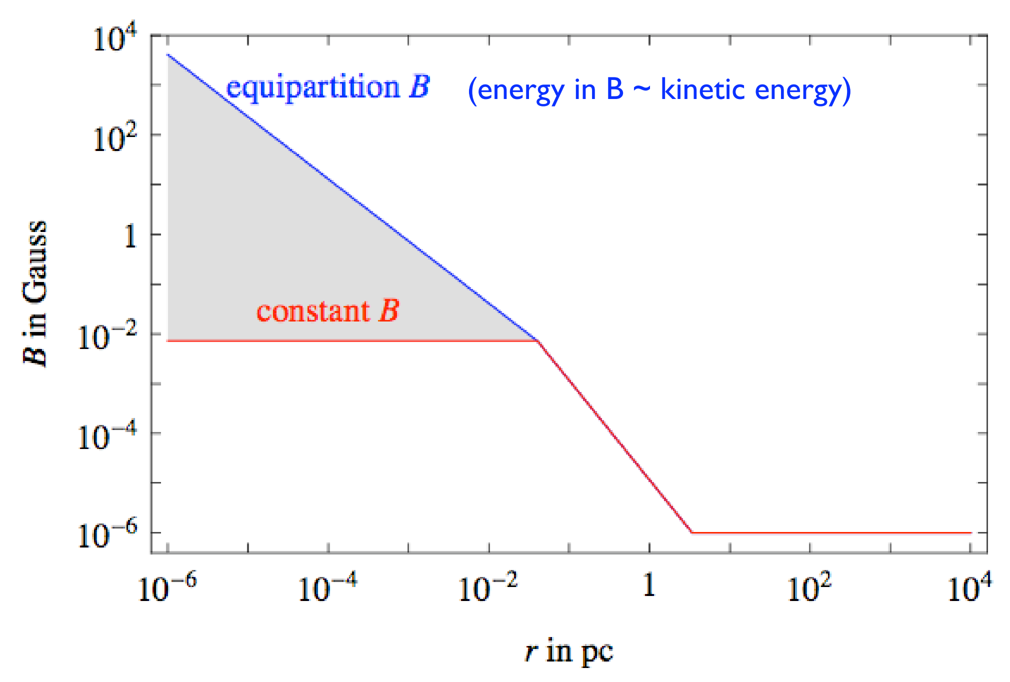
Indirect Detection

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



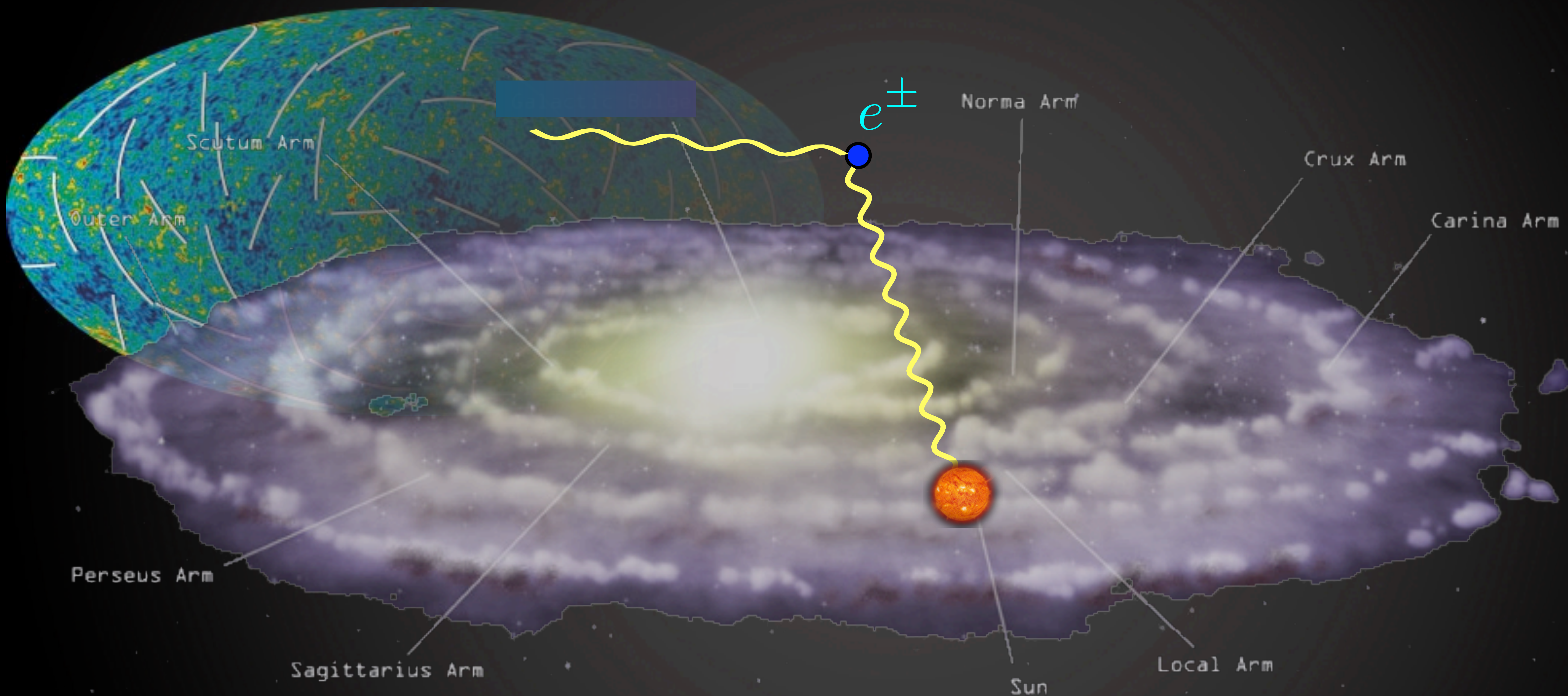
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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



Indirect Detection

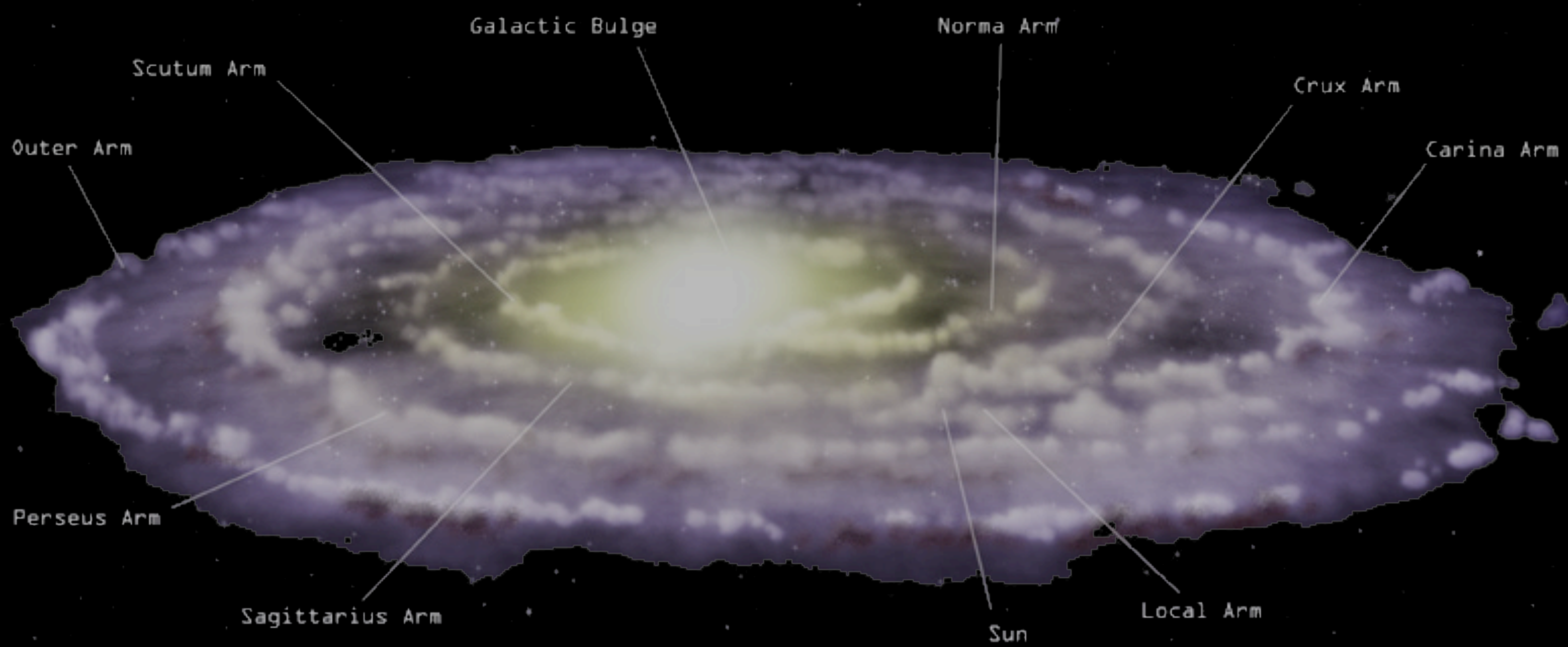
γ from Inverse Compton on $e^{\pm}$ in halo



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

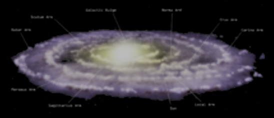
Indirect Detection

γ from outside the Galaxy



Indirect Detection

γ from outside the Galaxy

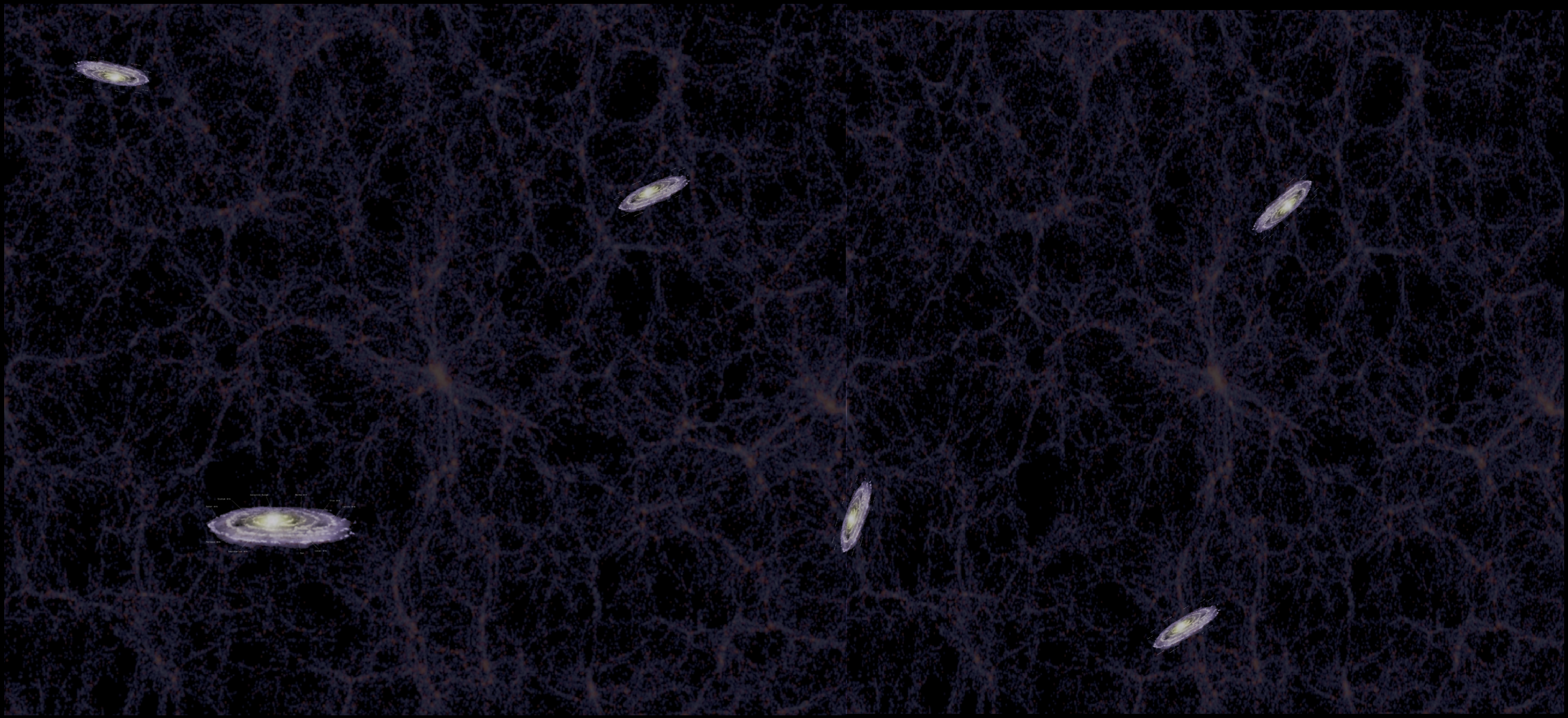


Indirect Detection

γ from outside the Galaxy

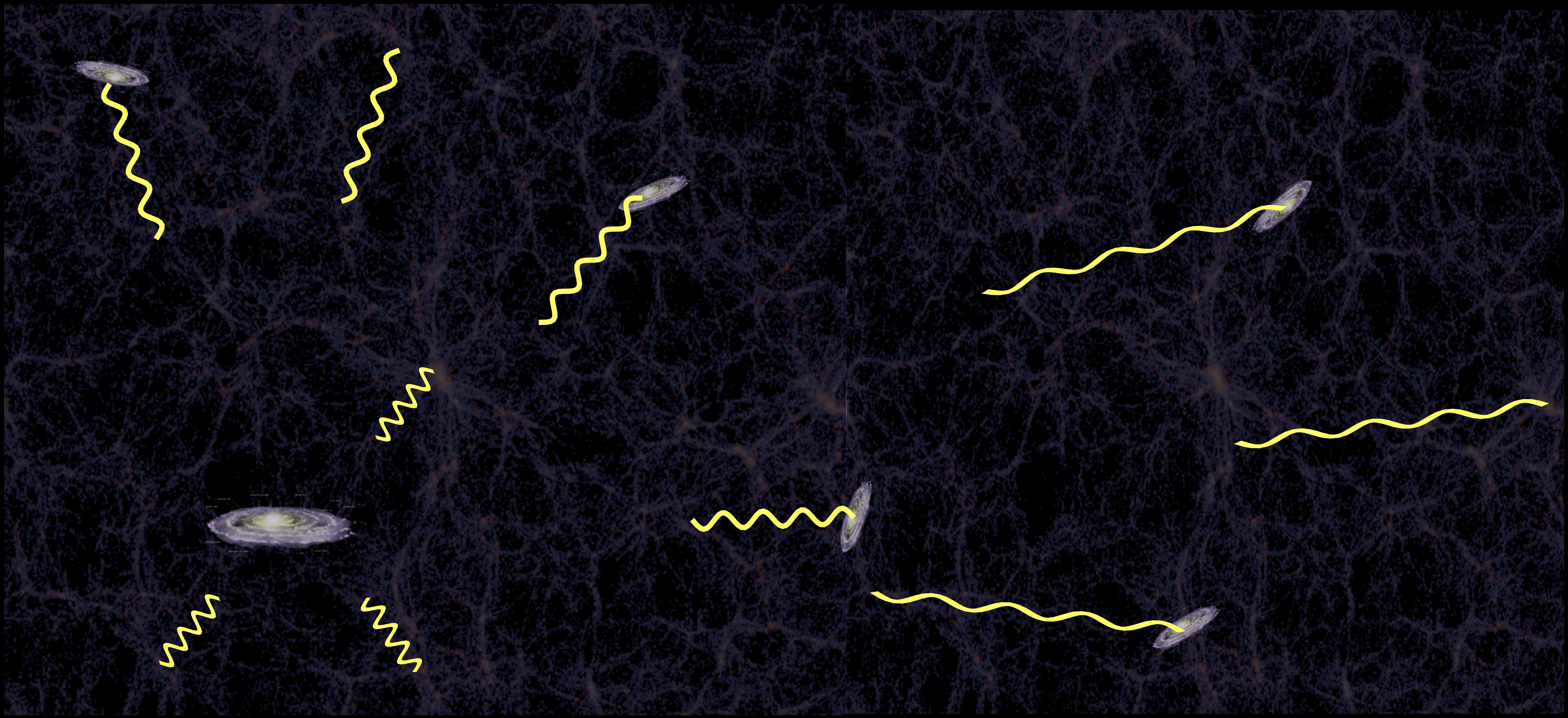
Indirect Detection

γ from outside the Galaxy



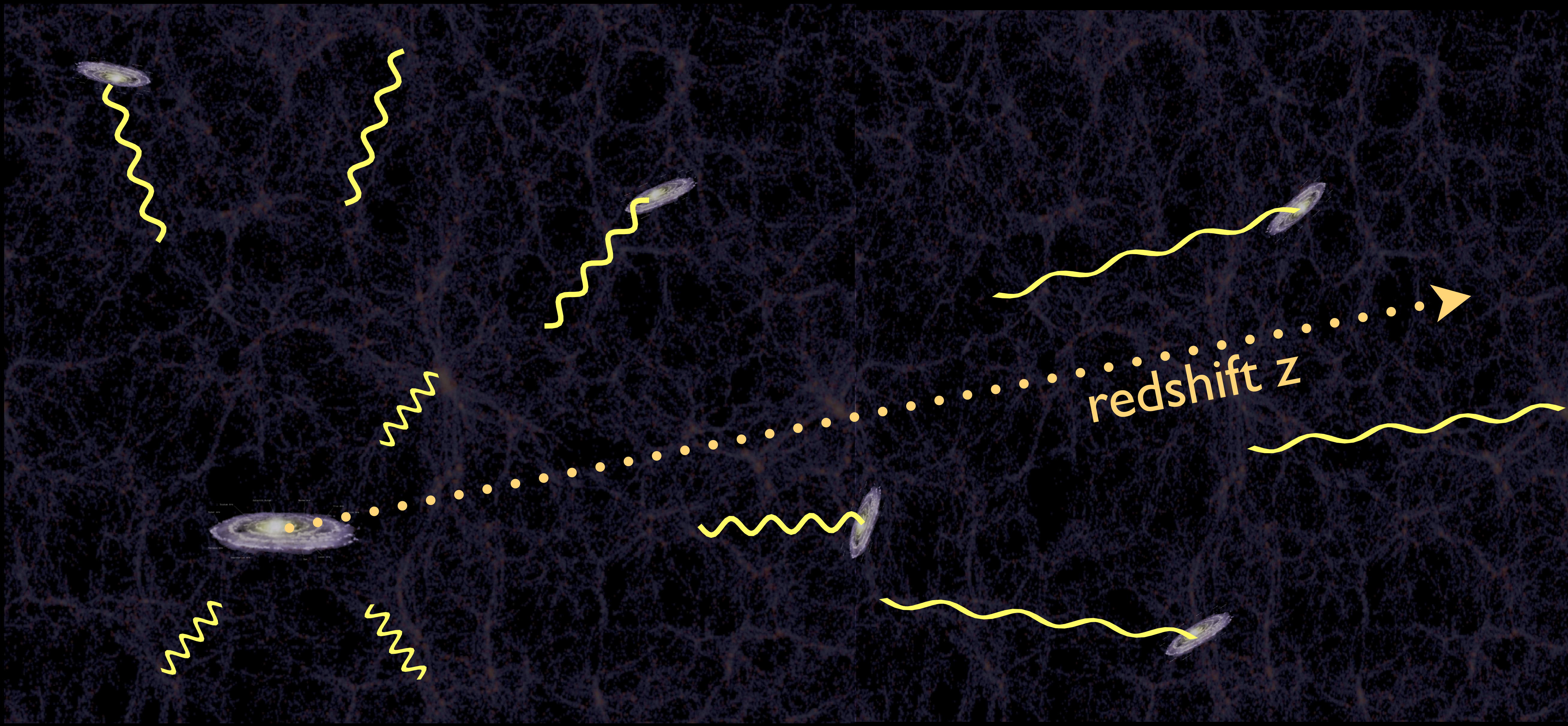
Indirect Detection

γ from outside the Galaxy



Indirect Detection

γ from outside the Galaxy

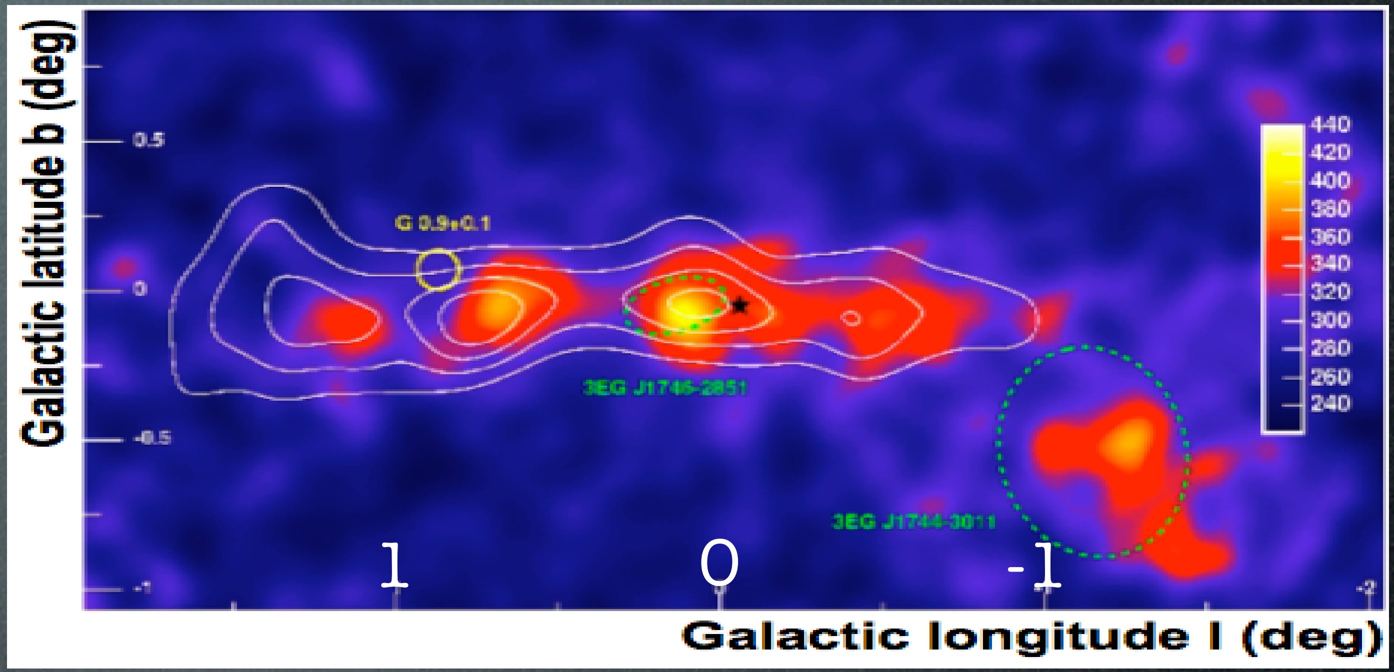


- isotropic flux of prompt and ICS gamma rays, integrated over z and r
- depends strongly on halo formation details and history

Comparing with data

Gamma constraints

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



HESS coll.

Gamma constraints

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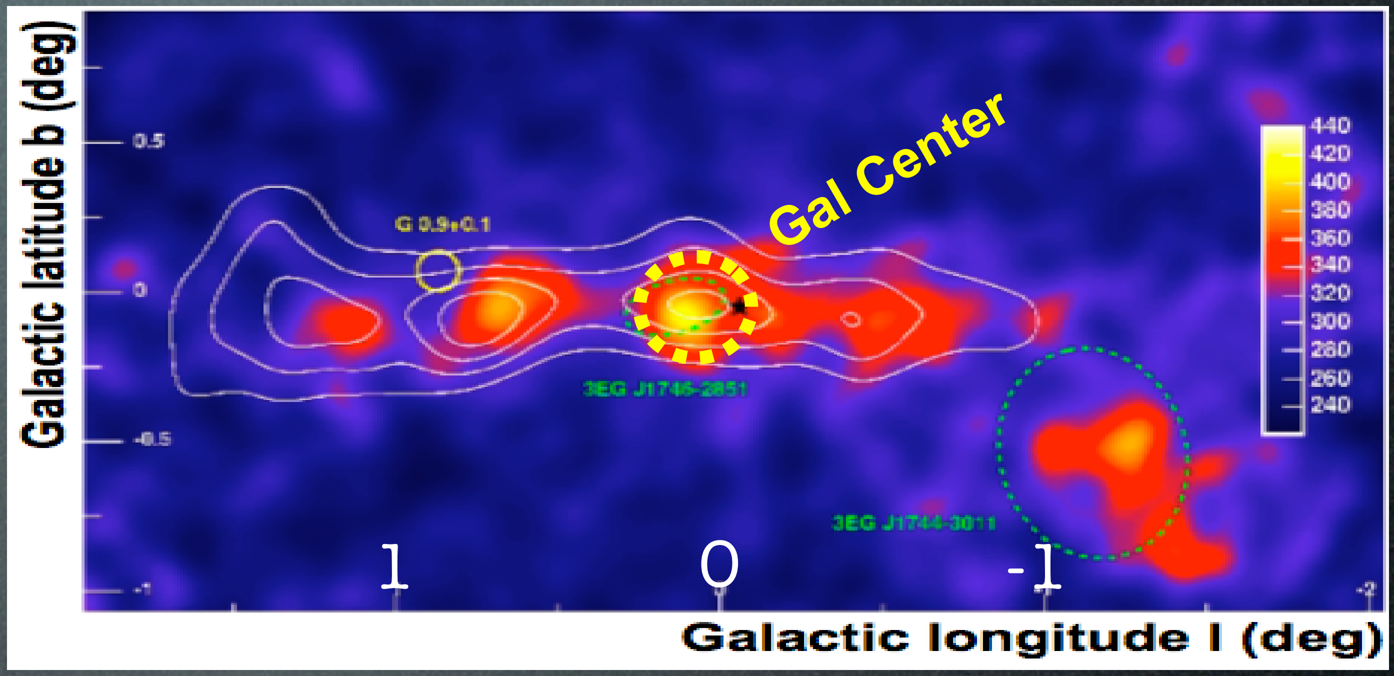

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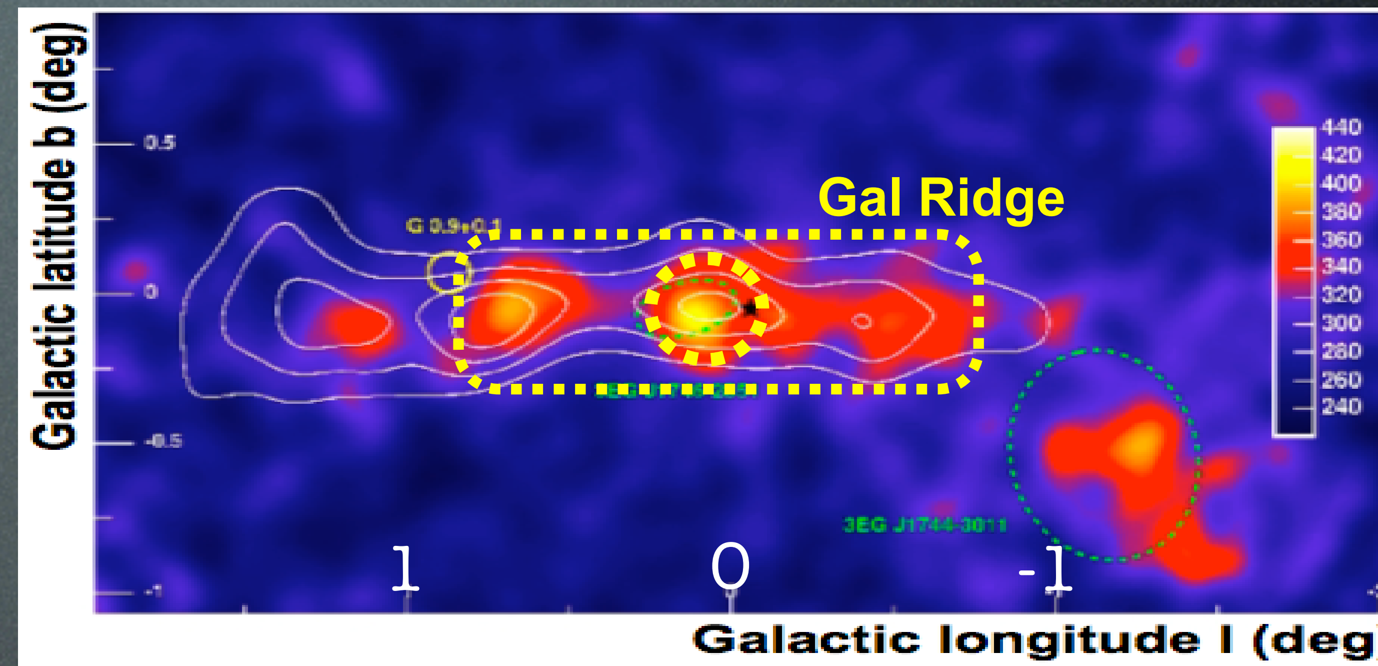

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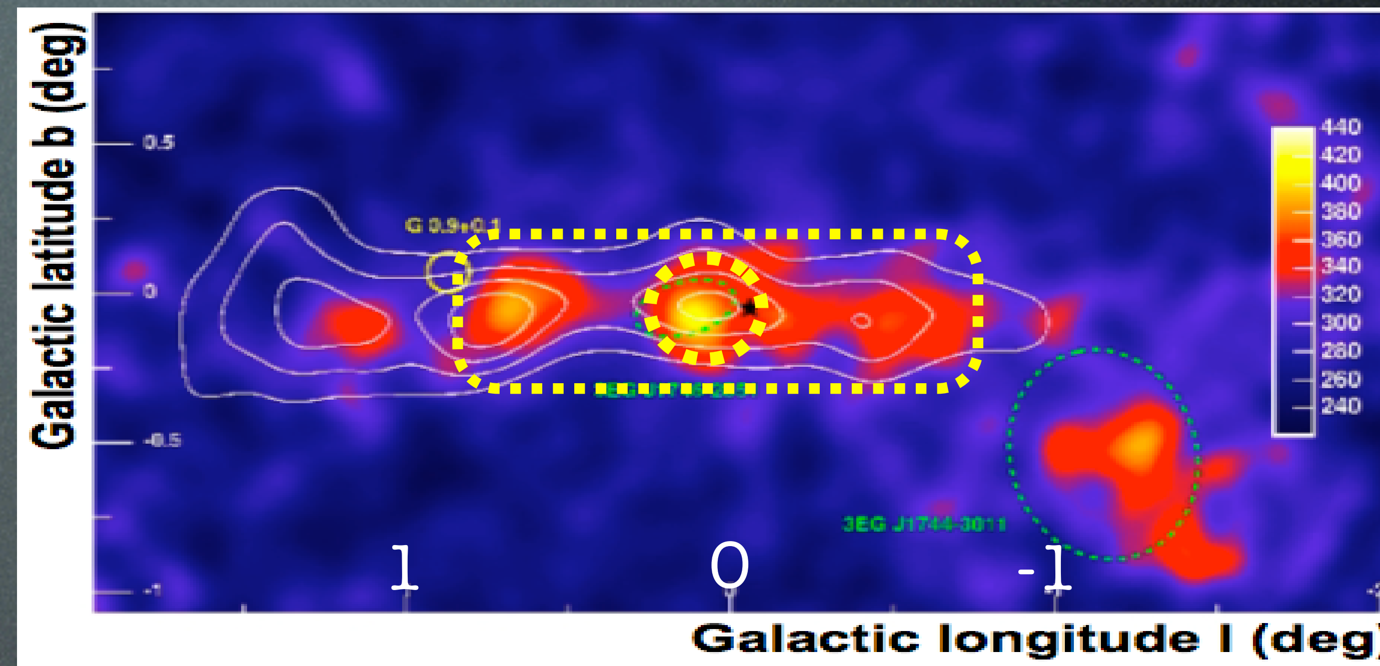
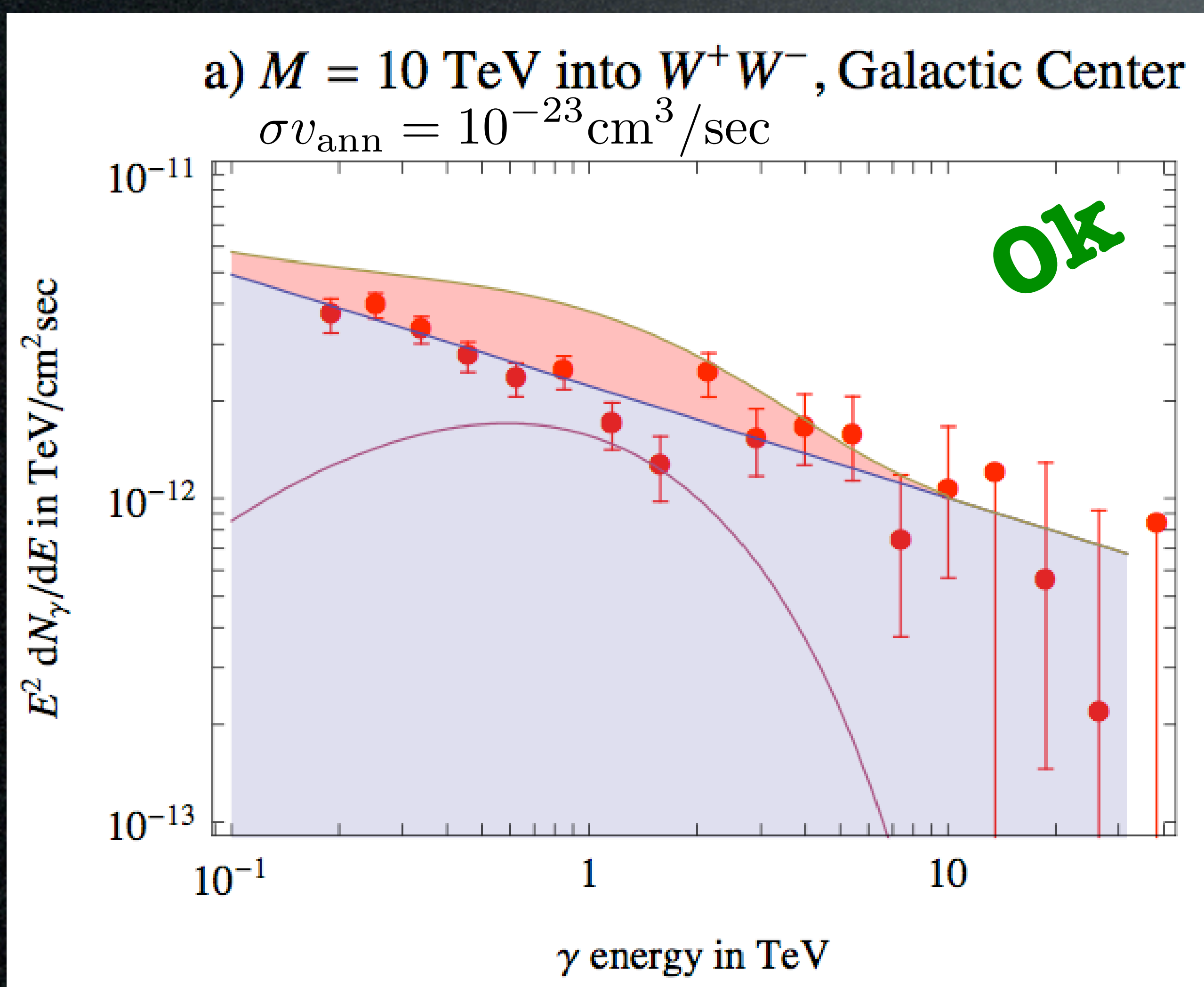


HESS coll.



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

Gamma constraints

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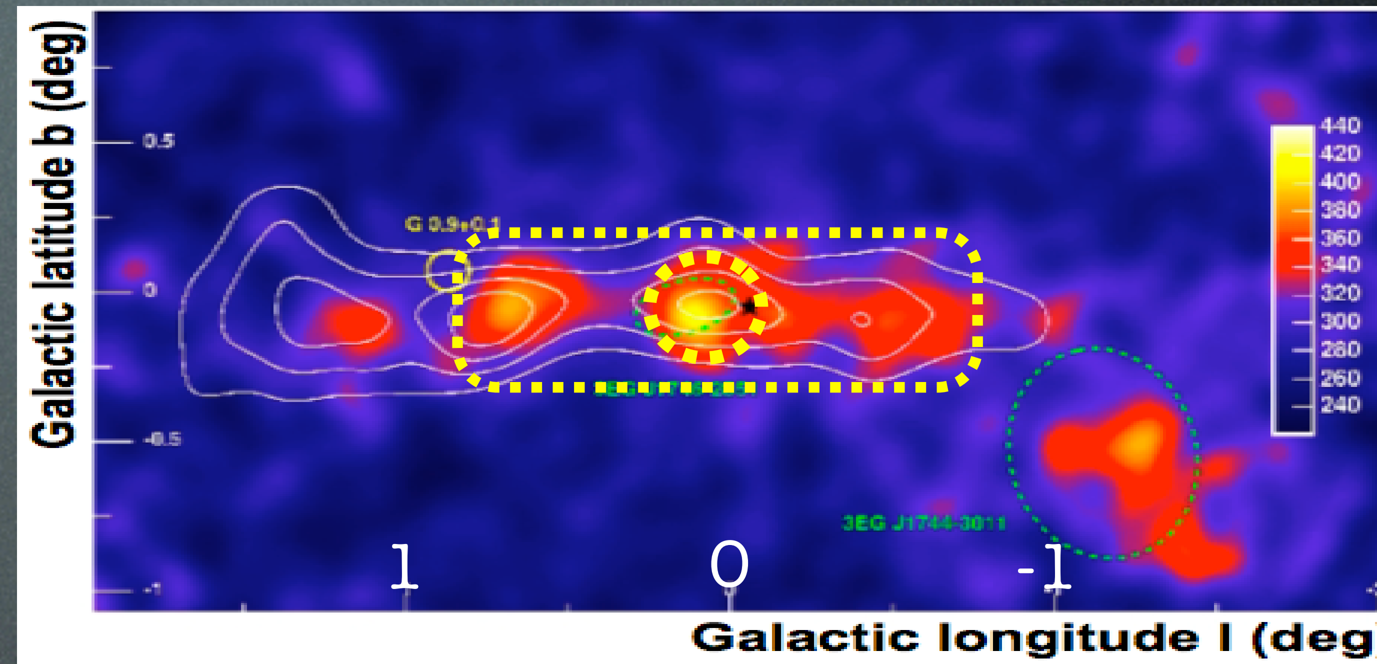
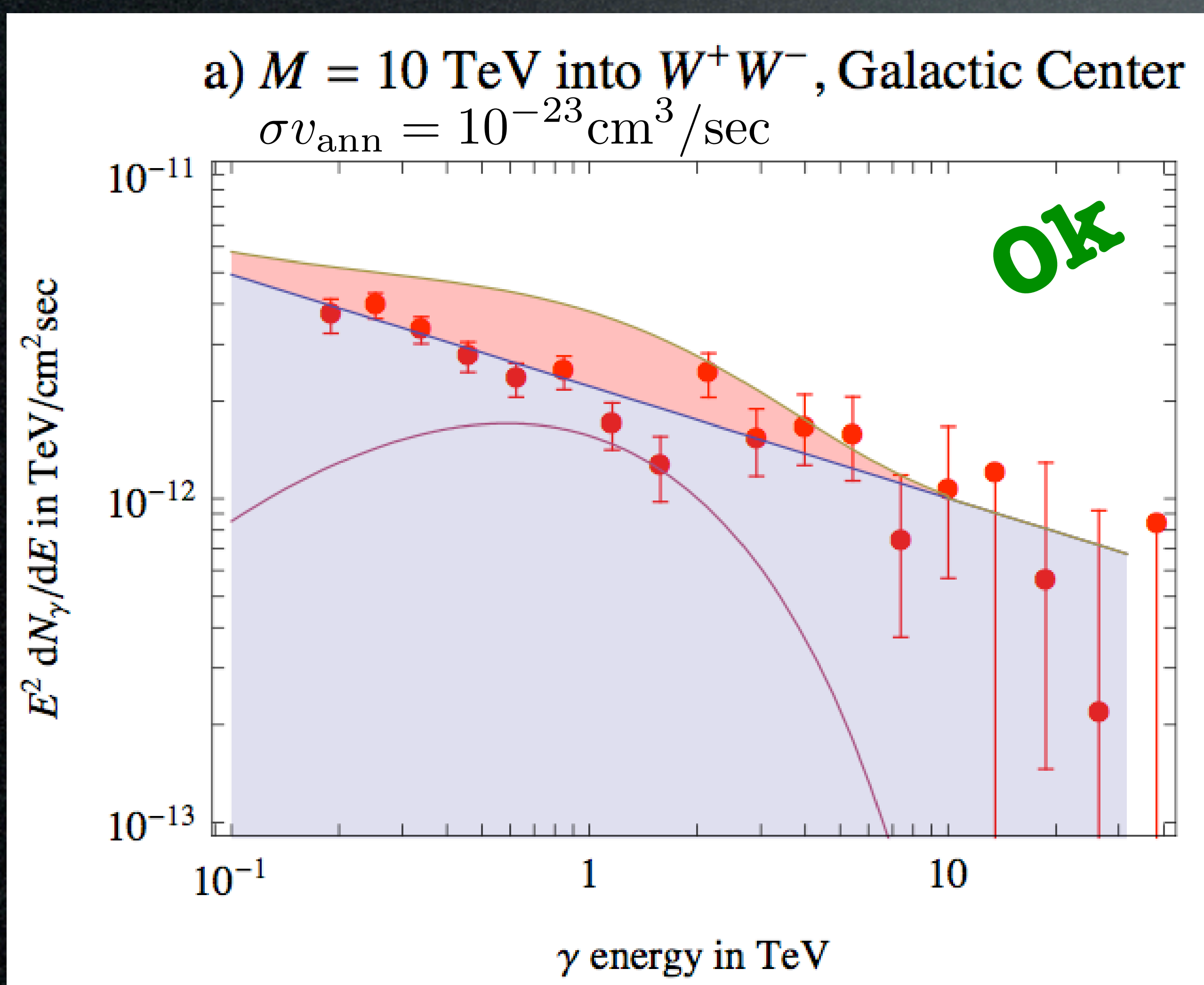


HESS coll.



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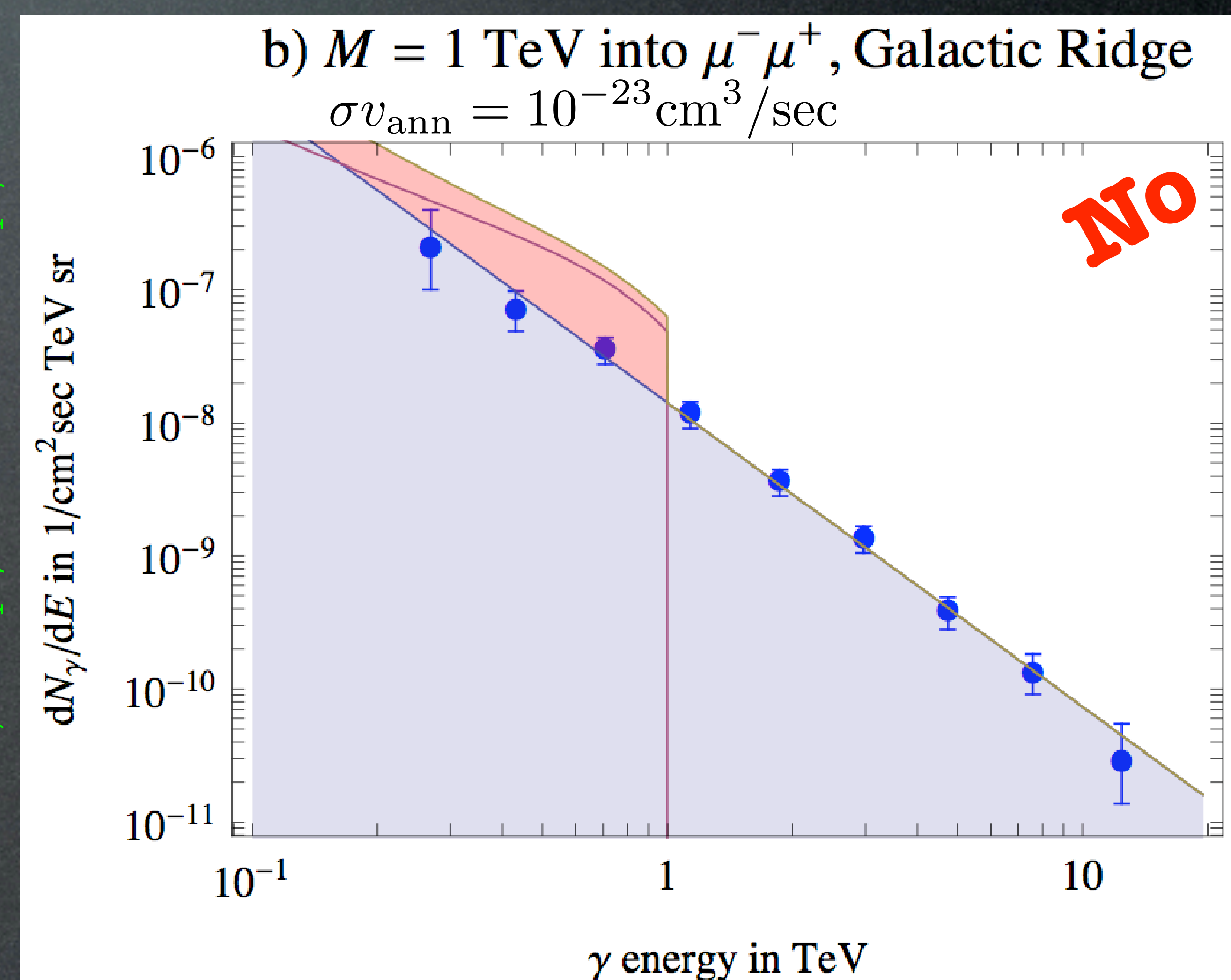
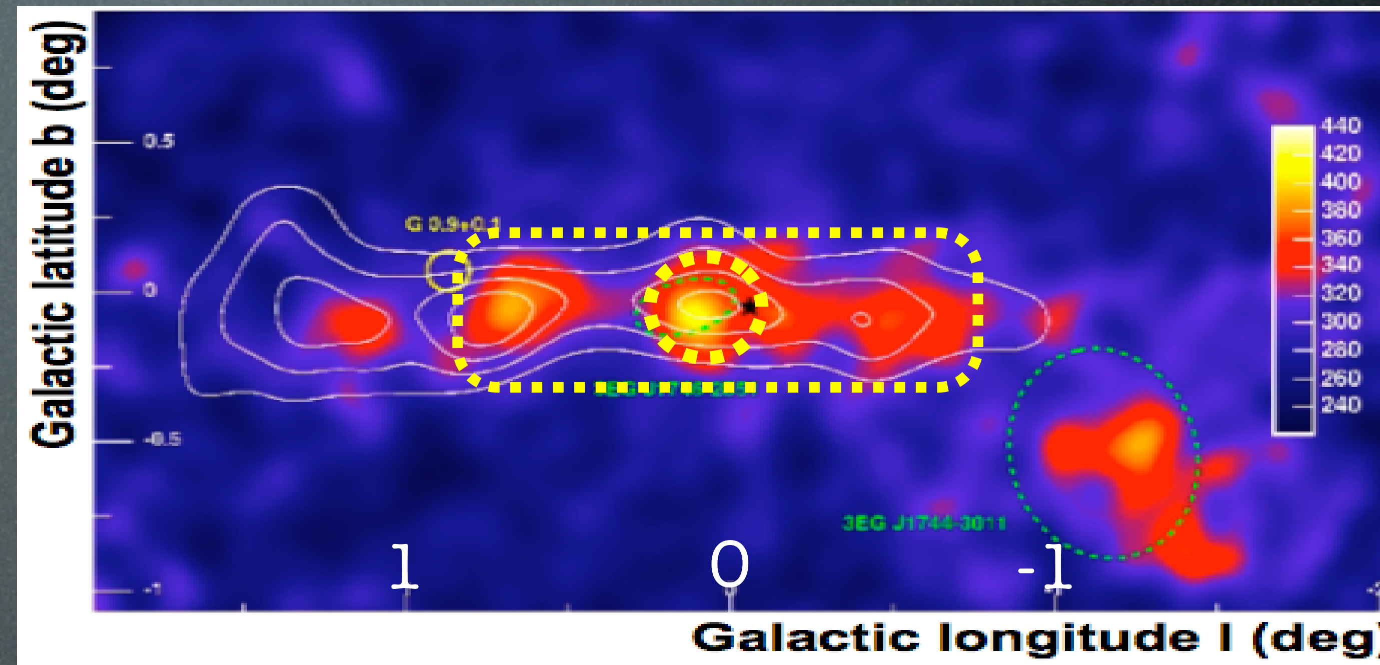


Data: HESS coll., astro-ph/0603021

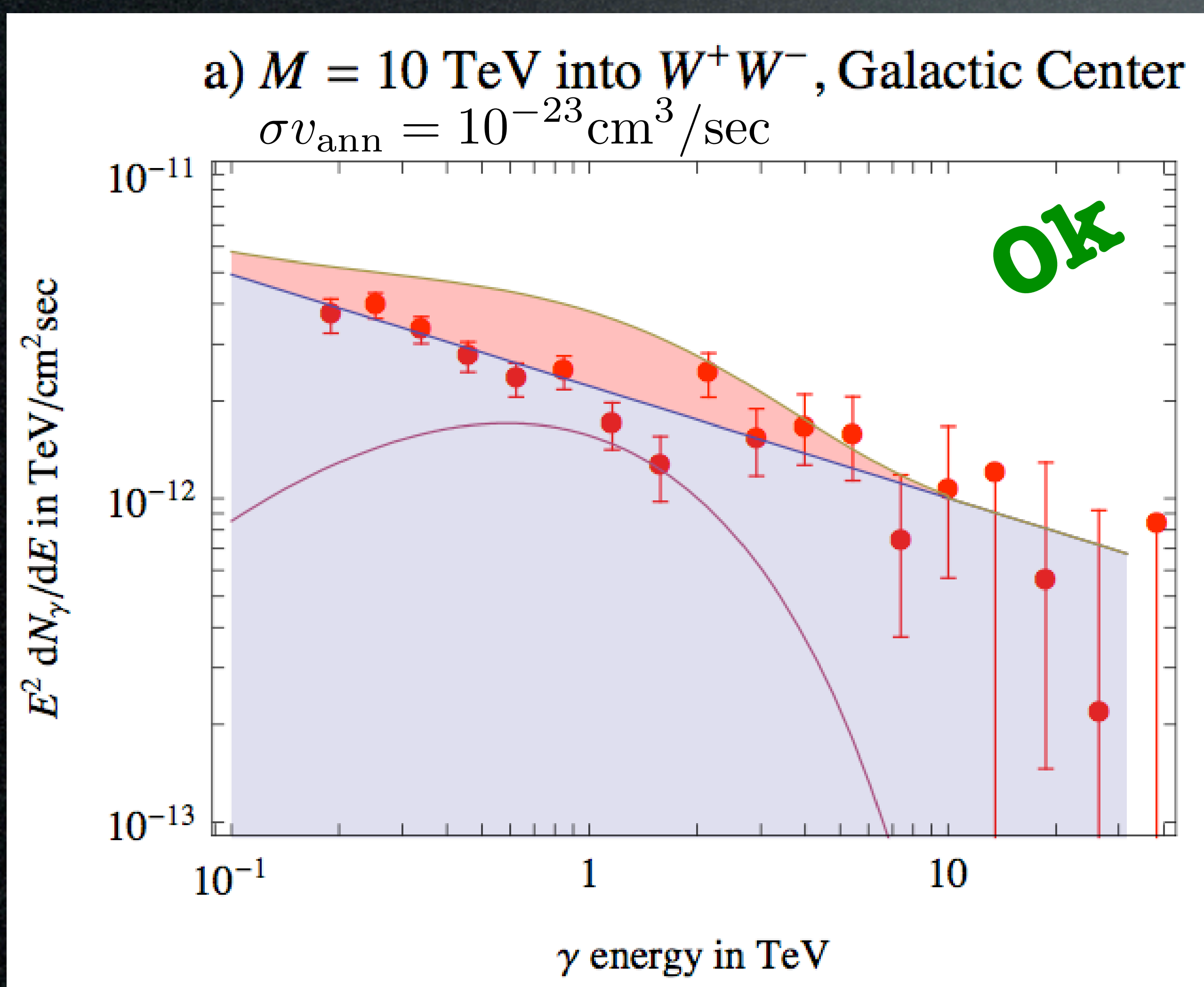
Gamma constraints

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

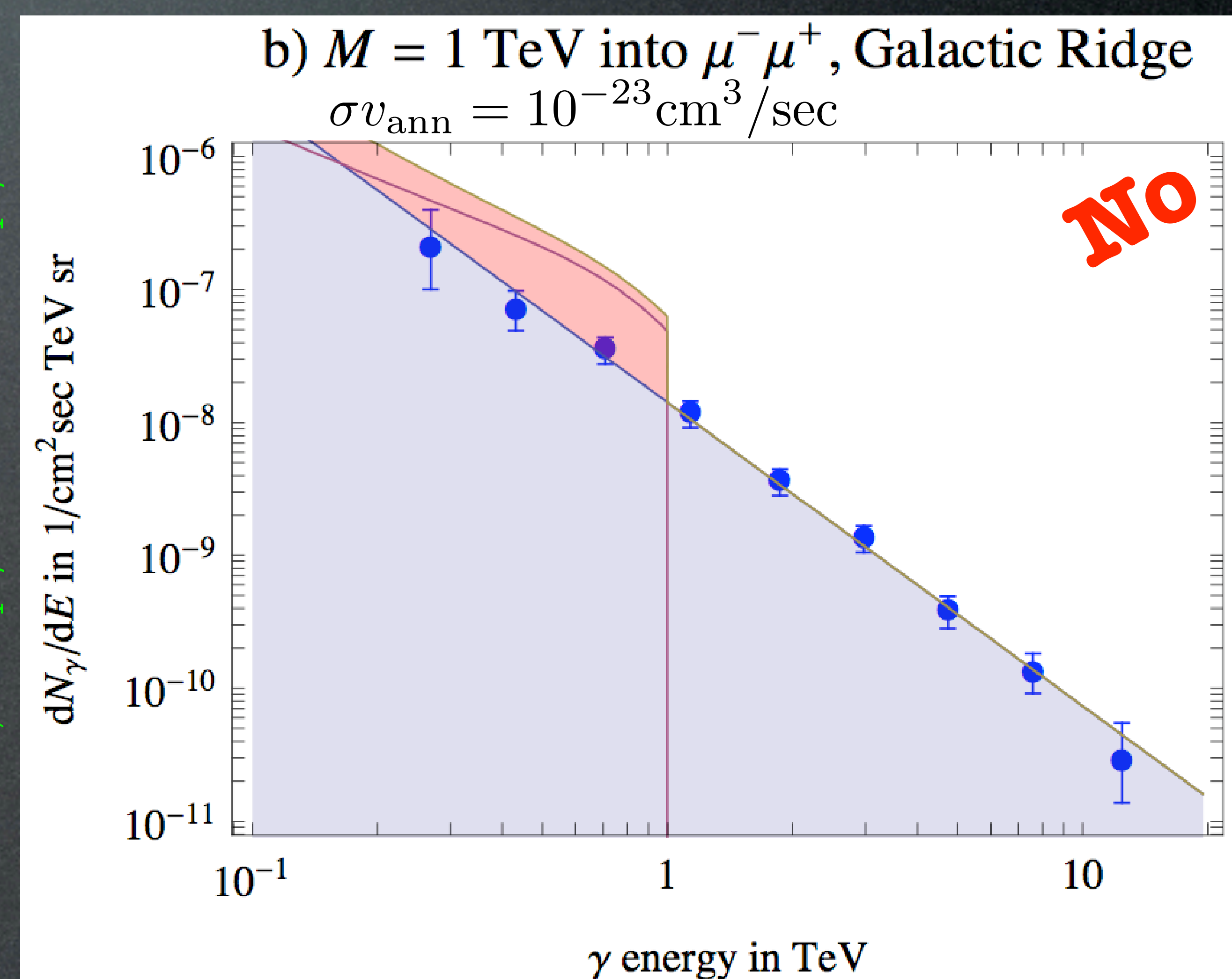
Moreover: no detection from Sgr dSph => upper bound.



HESS coll.

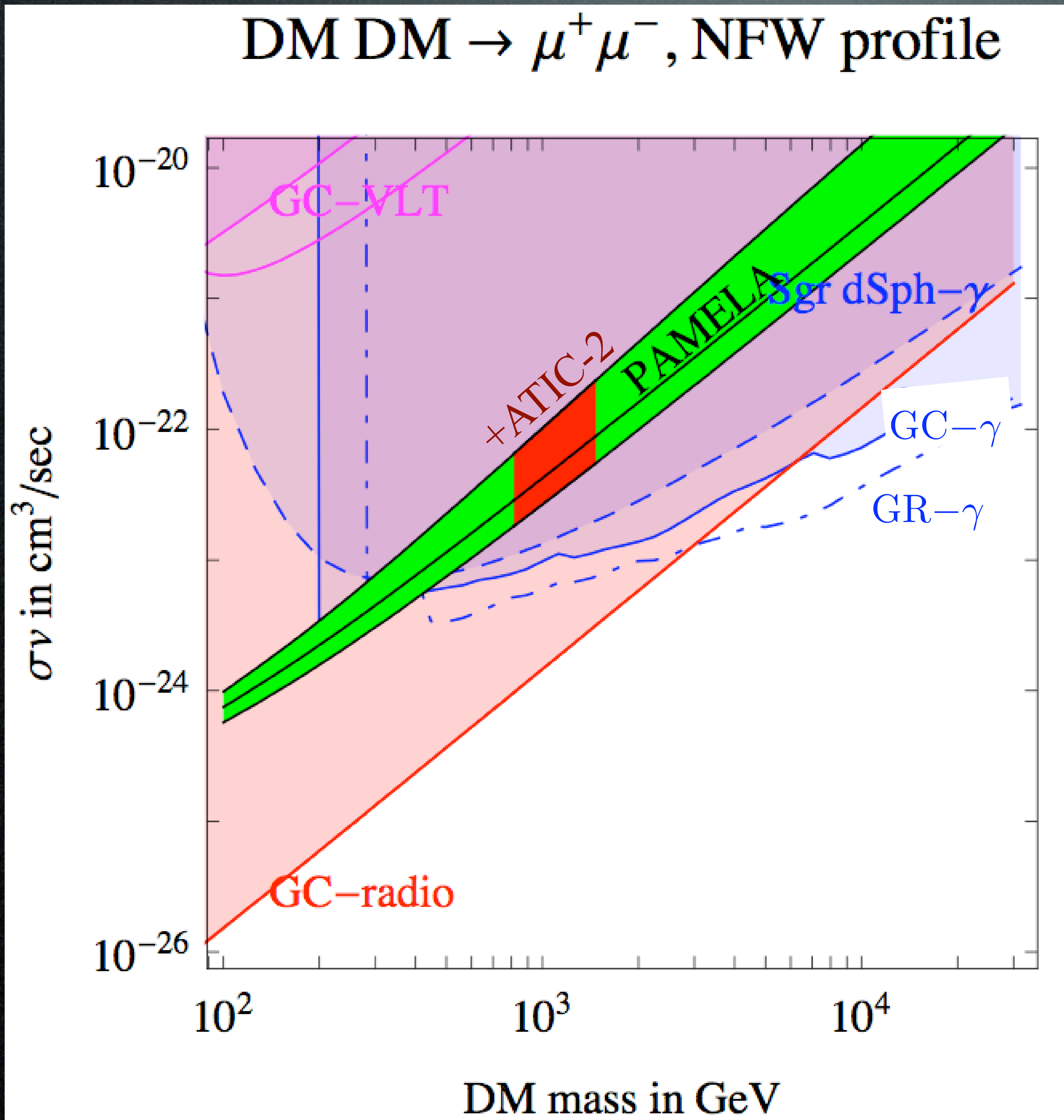


Data: HESS coll., astro-ph/0408145 and astro-ph/0610509



Data: HESS coll., astro-ph/0603021

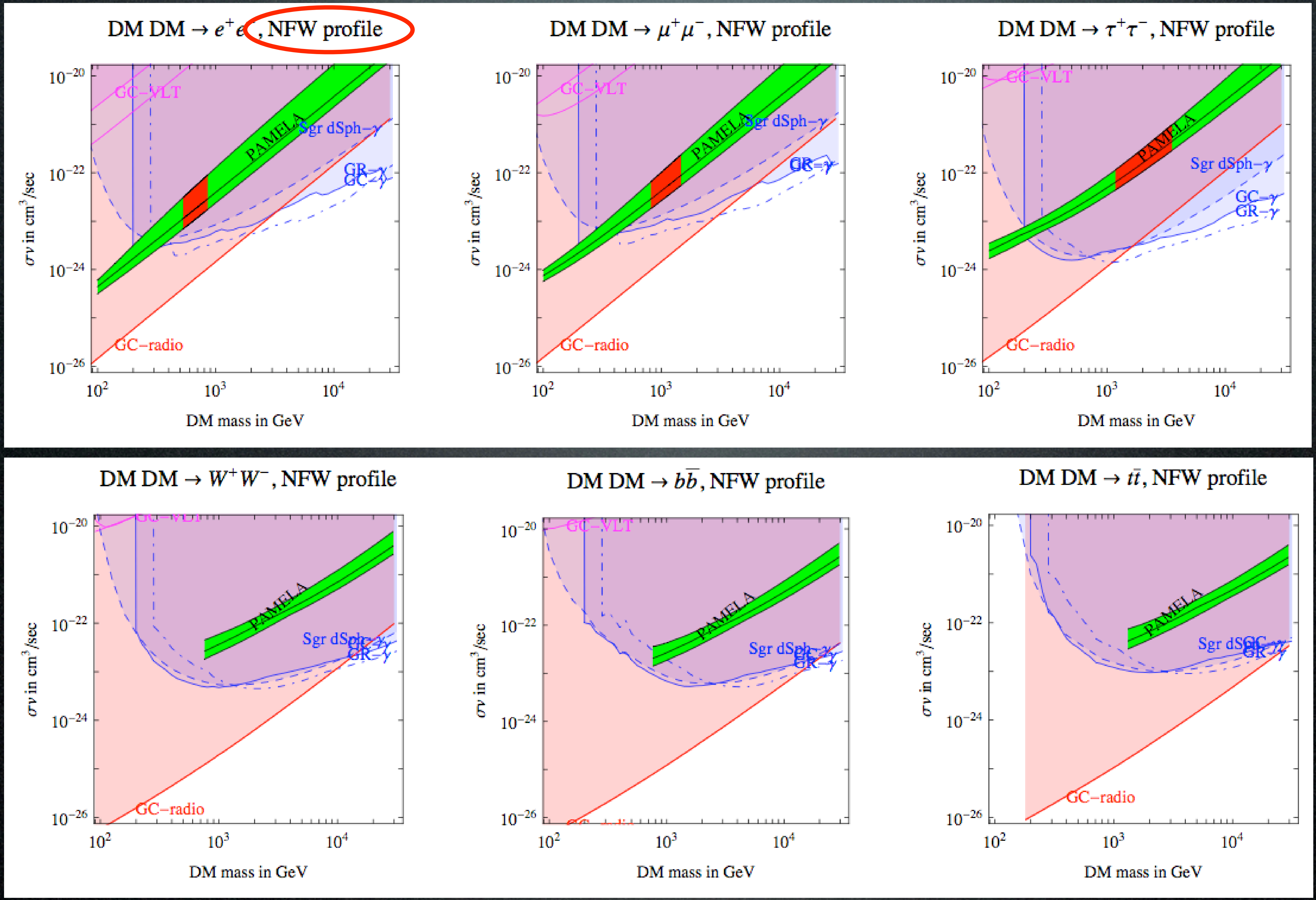
Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

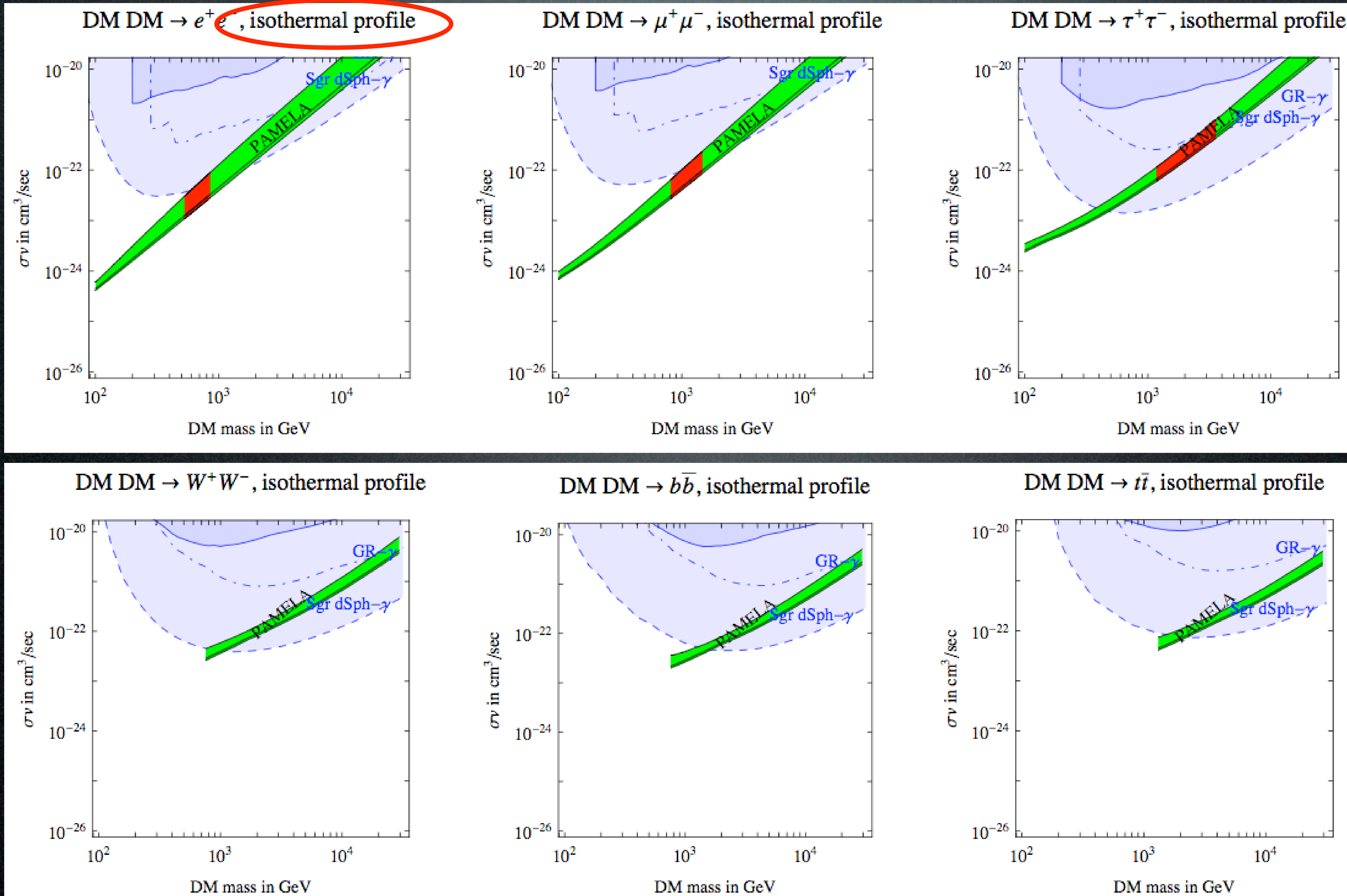
The PAMELA and ATIC/FERMI regions are in conflict with gamma constraints, unless...

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

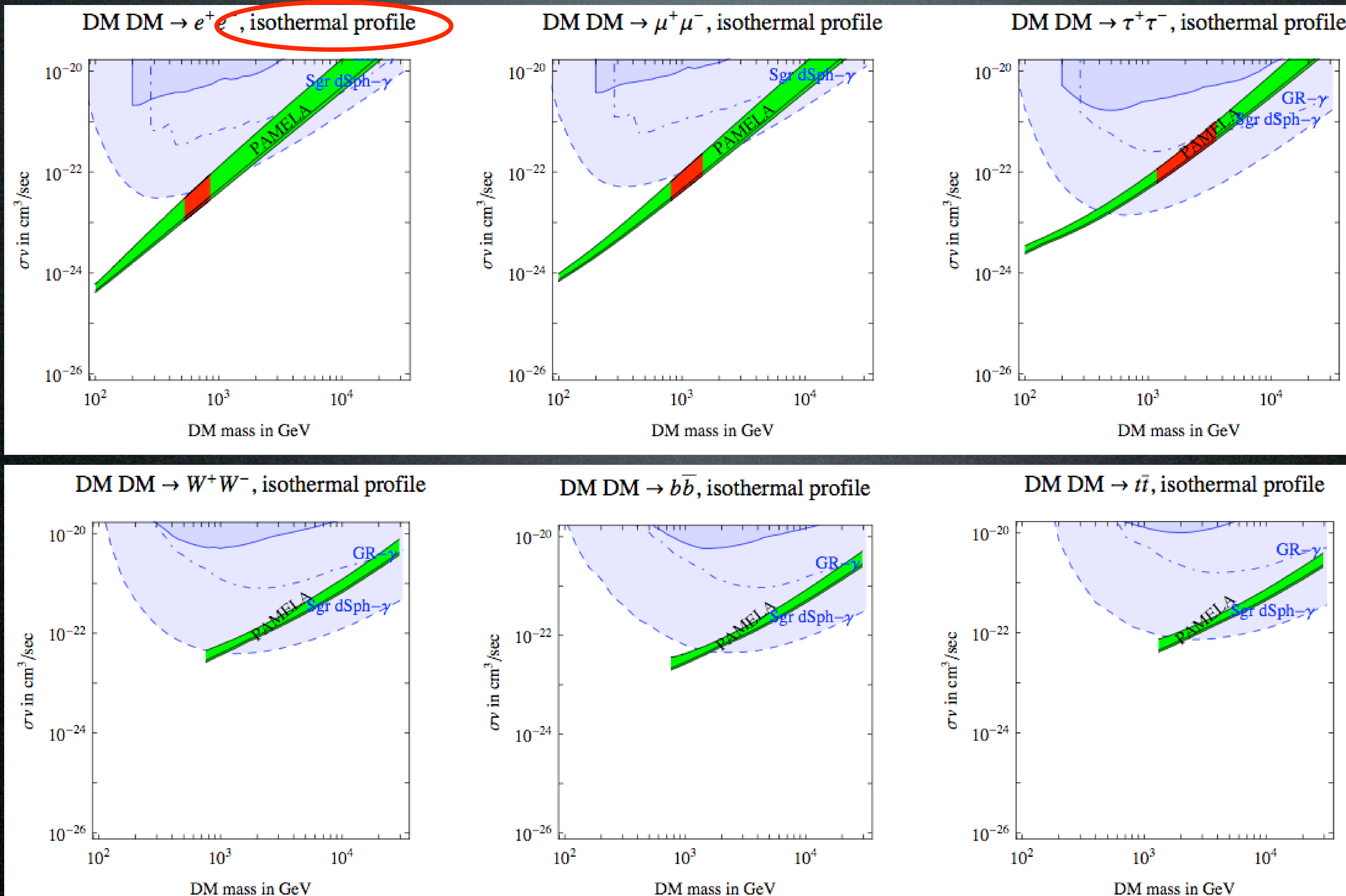
Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

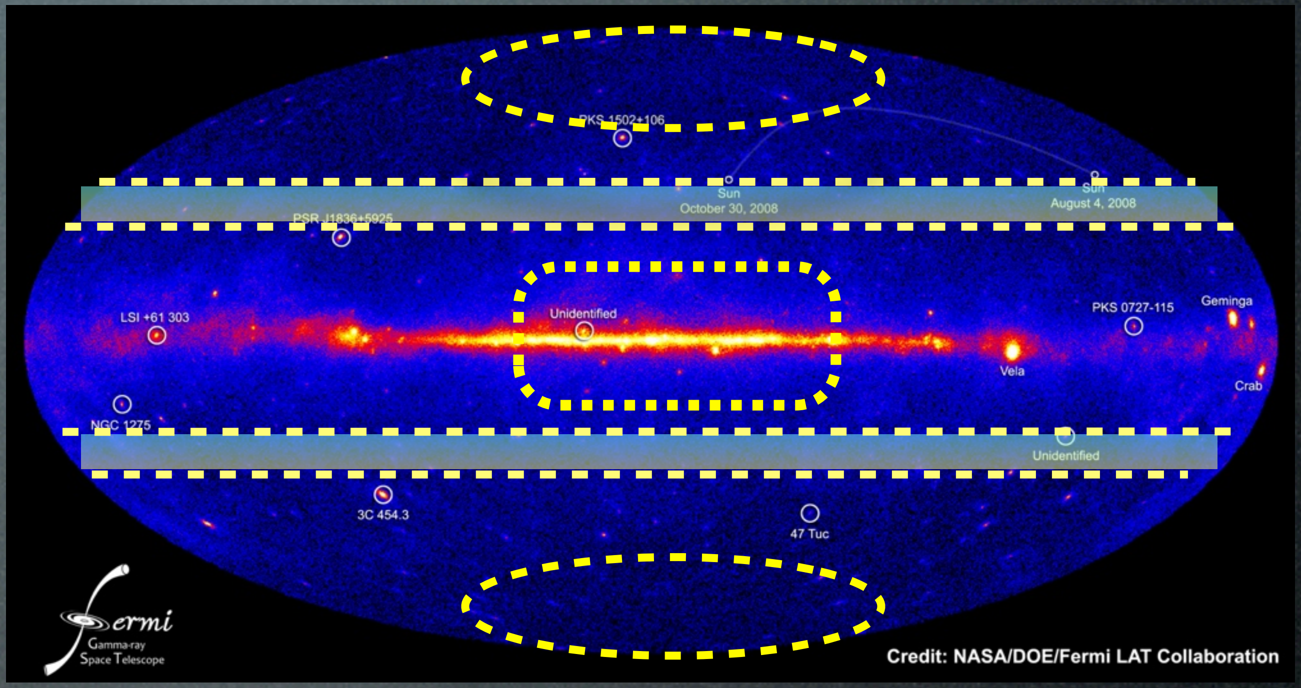
...not-too-steep profile needed.

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

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

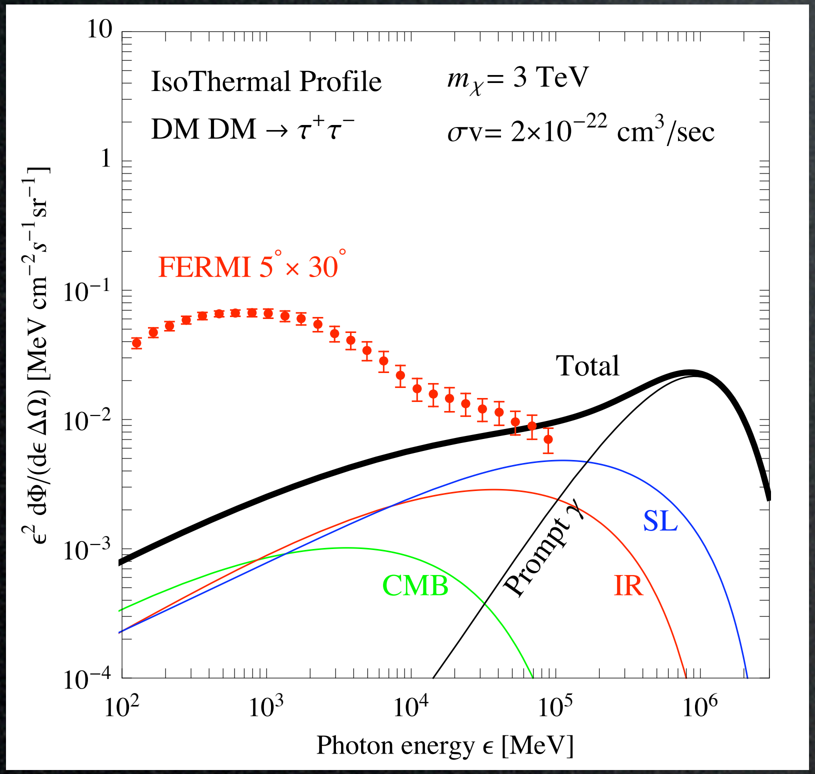
Gamma constraints

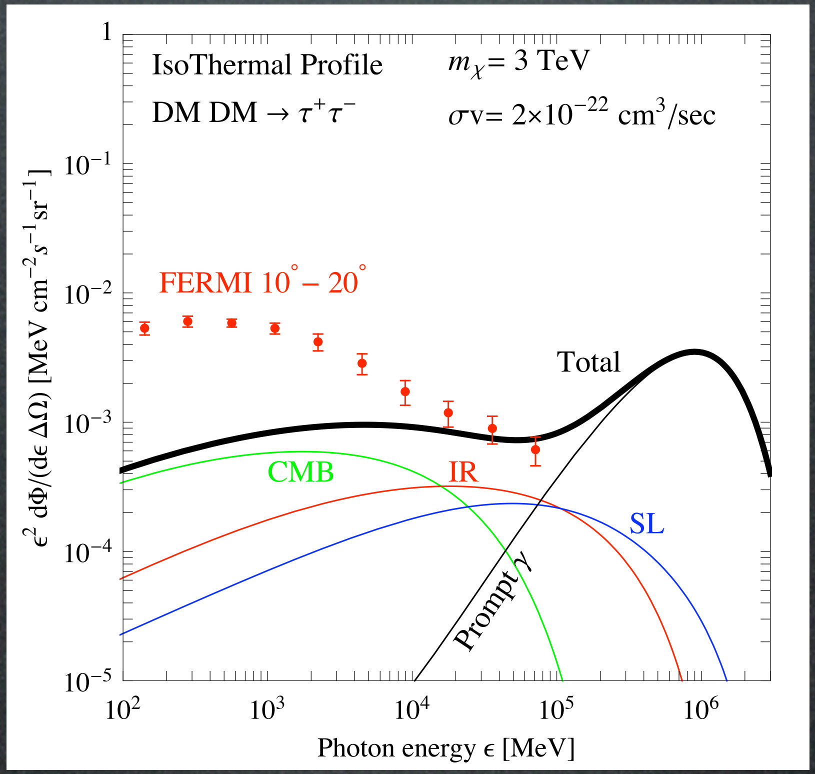
FERMI has measured diffuse γ-ray emission. The DM signal must not excede that.

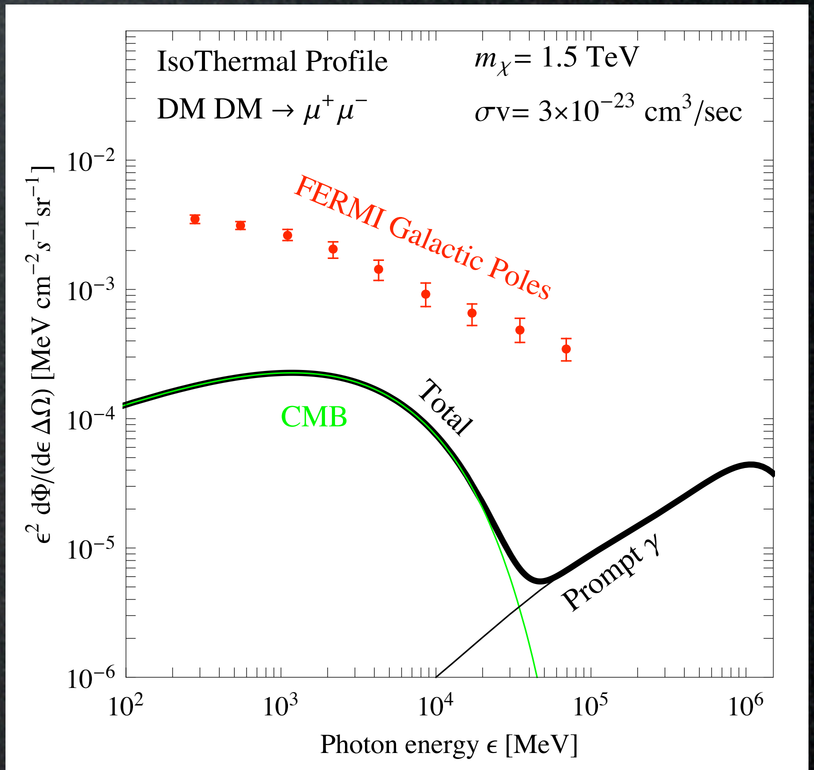


FERMI coll.

Data: FERMI coll., several talks and papers



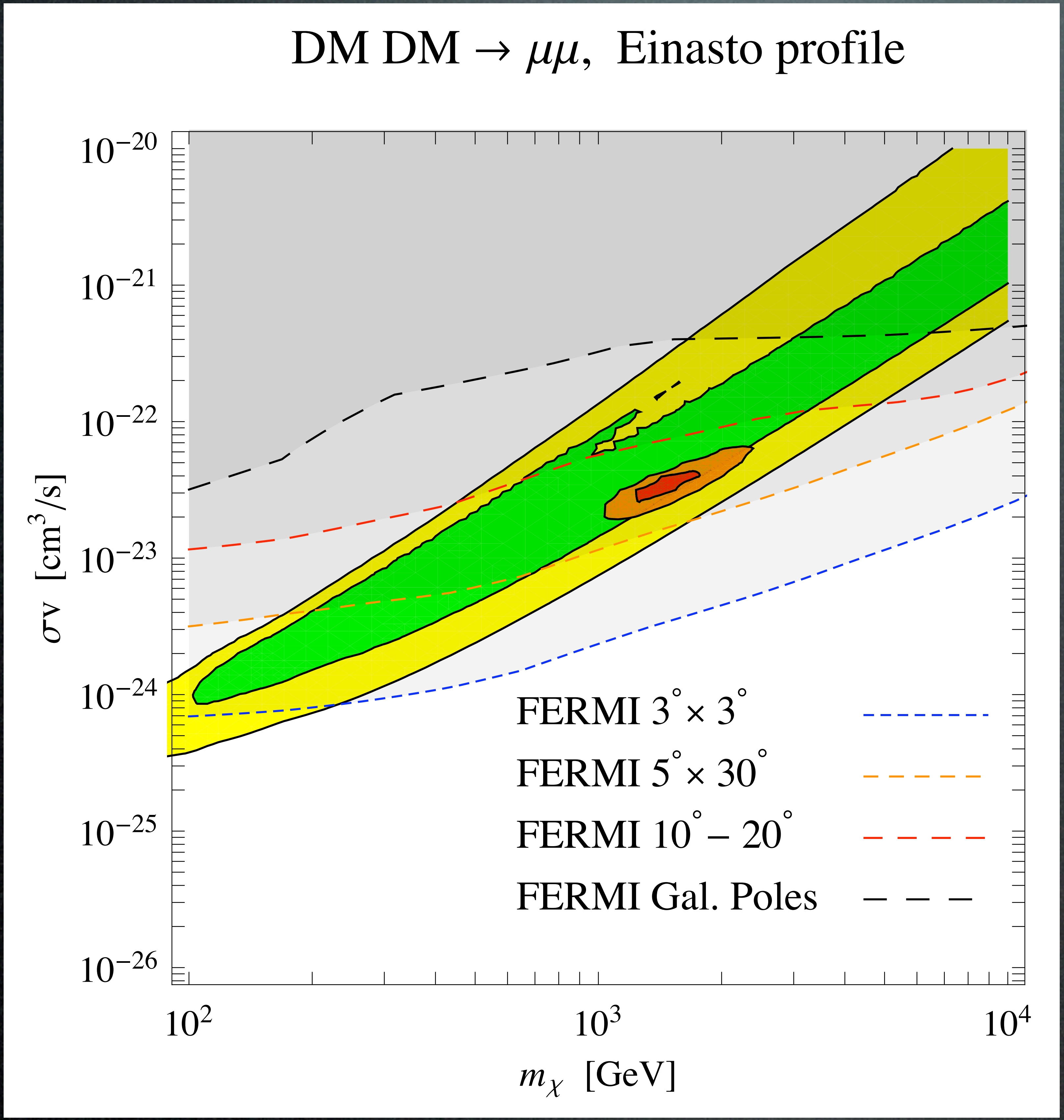




Cirelli, Panci, Serpico 0912.0663

P.Panci's talk

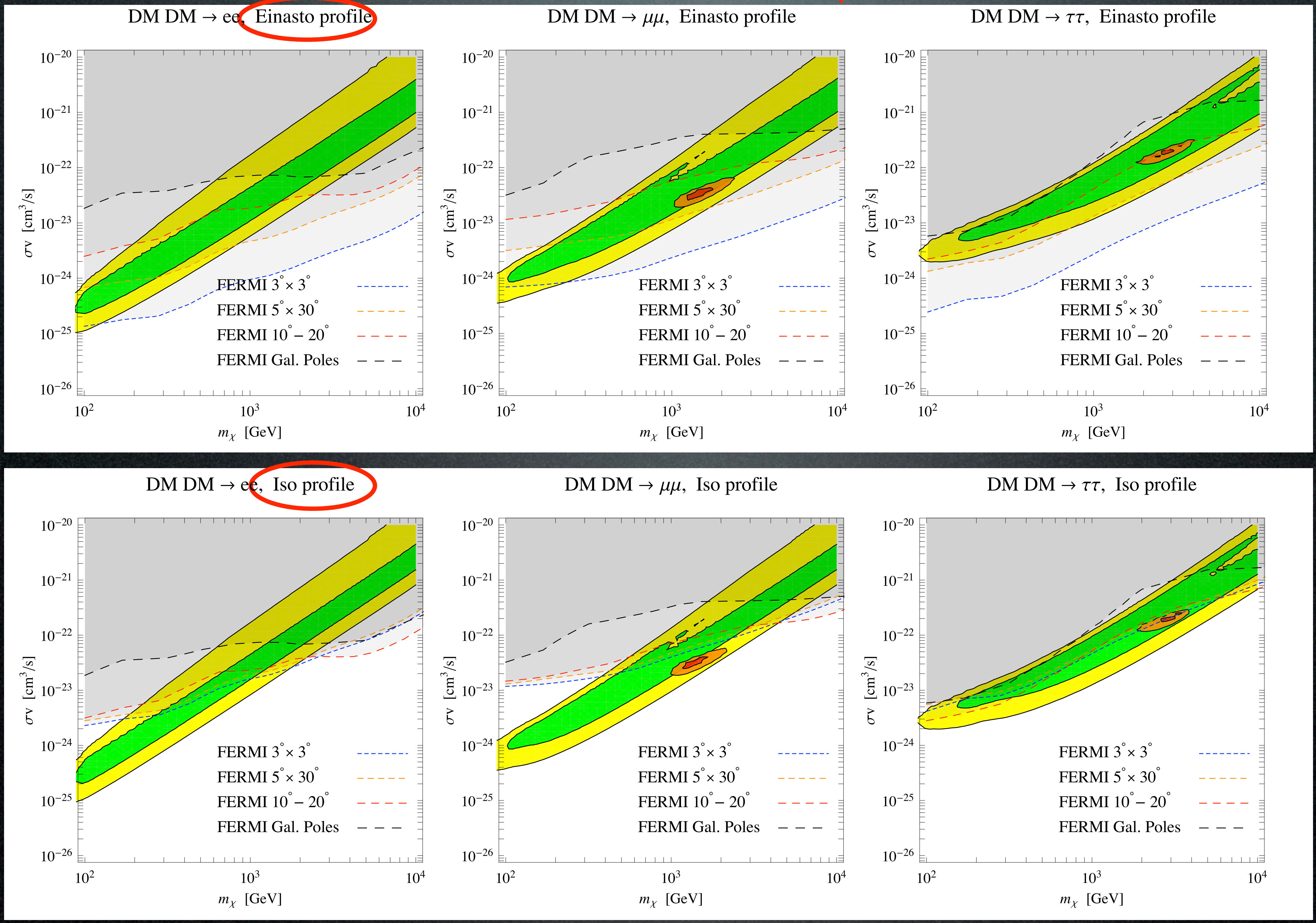
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

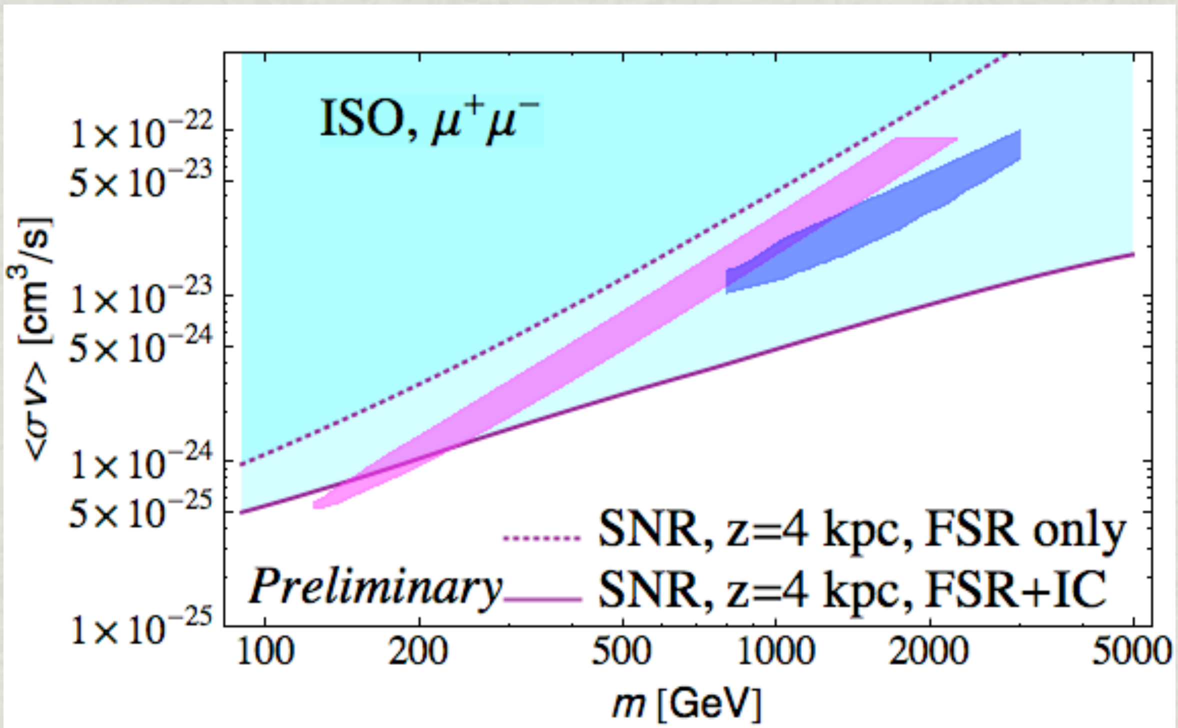
The PAMELA and ATIC/FERMI regions are in conflict with these gamma constraints, and here...

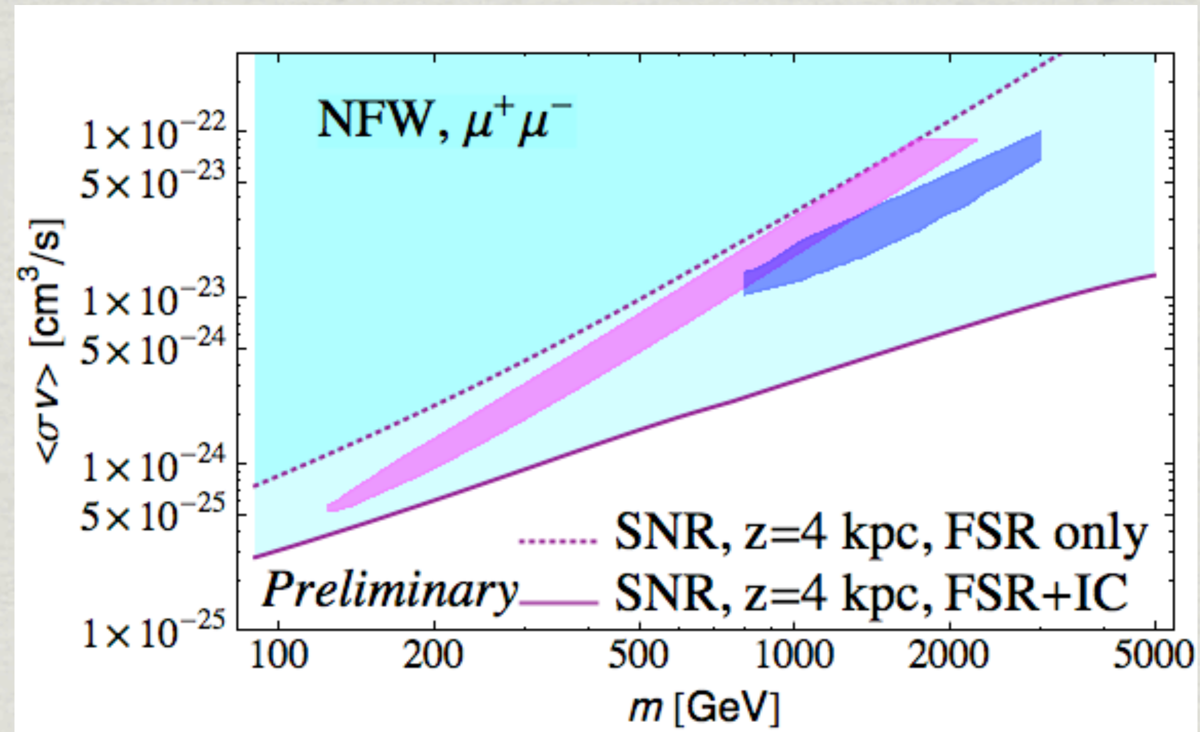
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

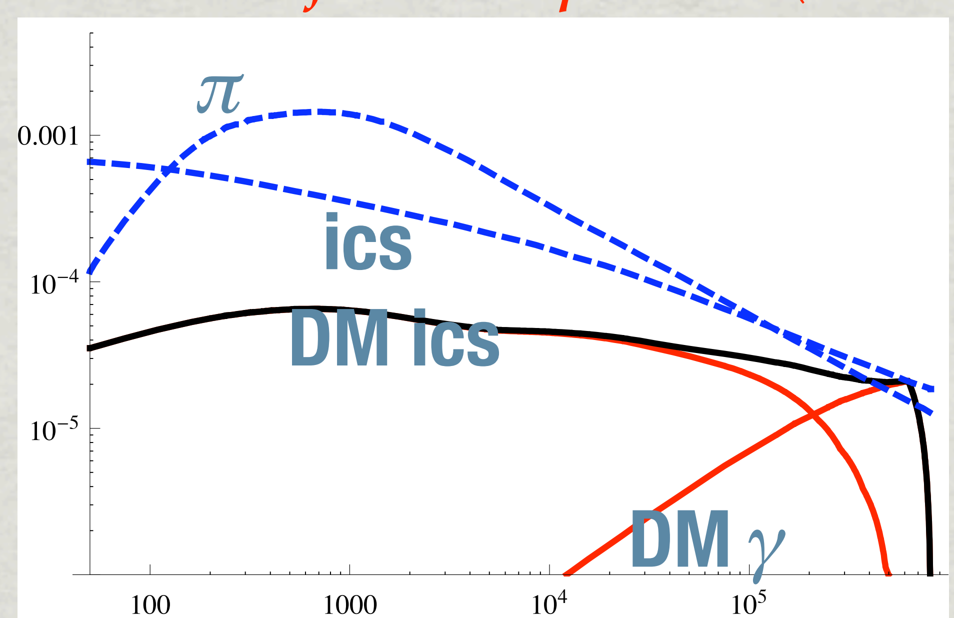
Exclusion plots, $\mu\mu$ channel





- *PAMELA (pink) and Fermi (Blue) regions are excluded when full DM spectrum (FSR+IC) is considered.*

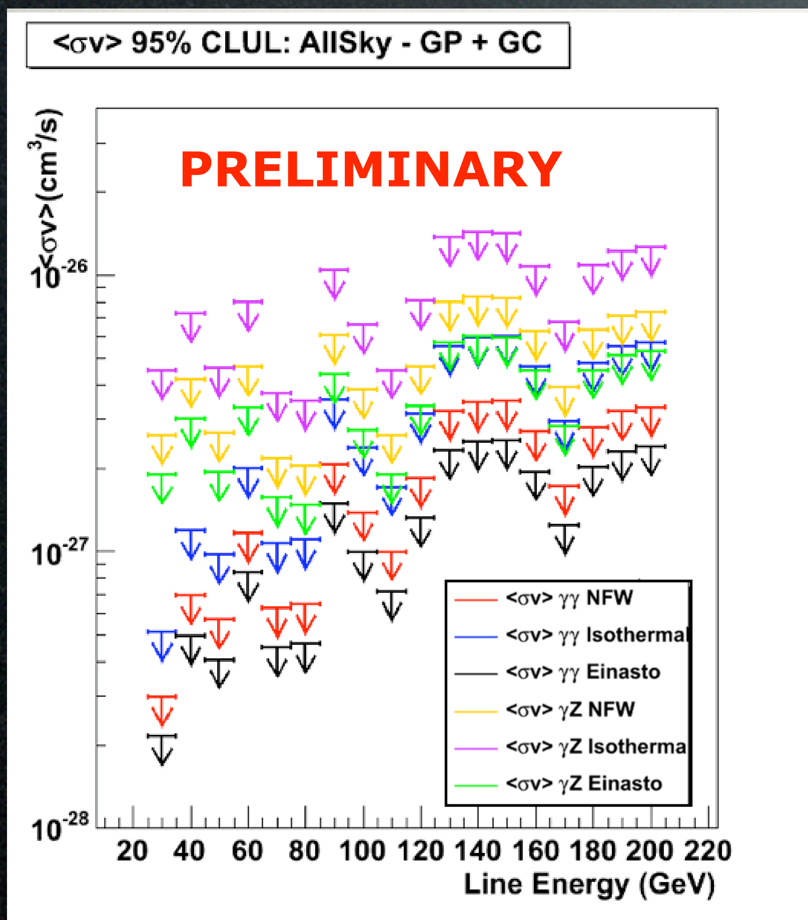
- *Note: FSR-only limits are weak since the data only up to 100 GeV has been used (will improve when/if <~300 GeV data set is used).*



M.Gustafsson's talk

More FERMI γ constraints

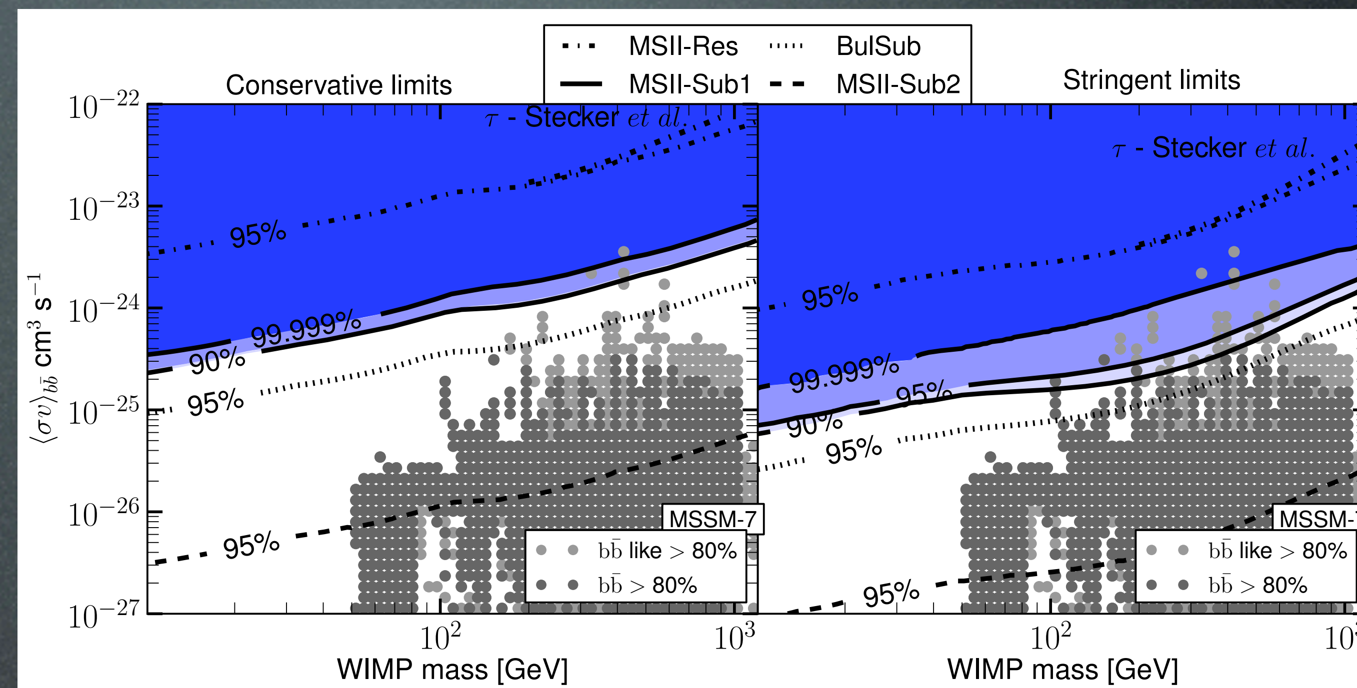
Gamma lines



FERMI Coll. 1001.4836

model dependent constraints, can be stringent

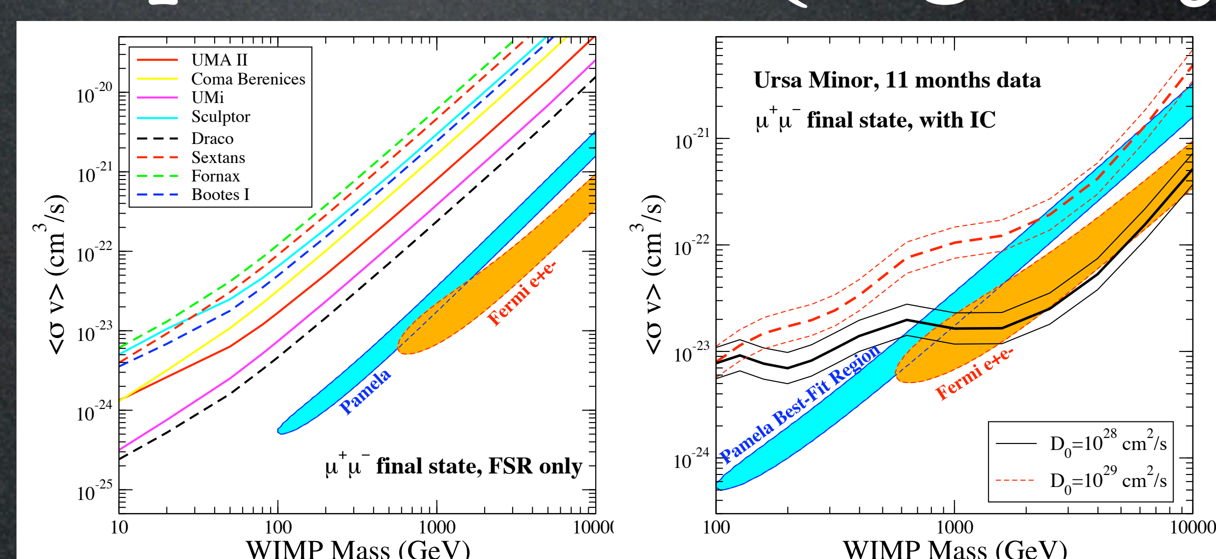
Isotropic gamma background



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

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

dSph satellites (& galaxy clusters)



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

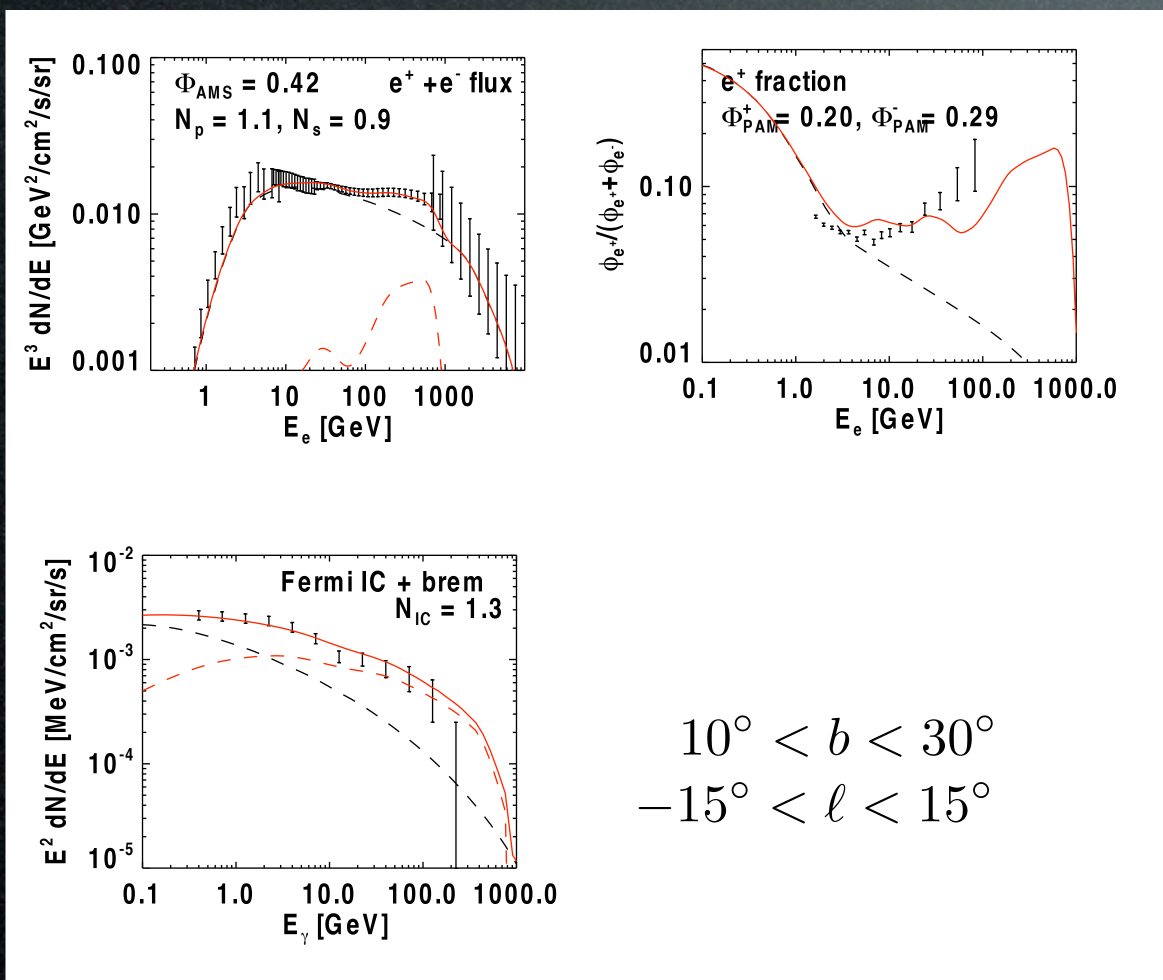
Competitive constraints (if ICS included)

Gamma **fits**?

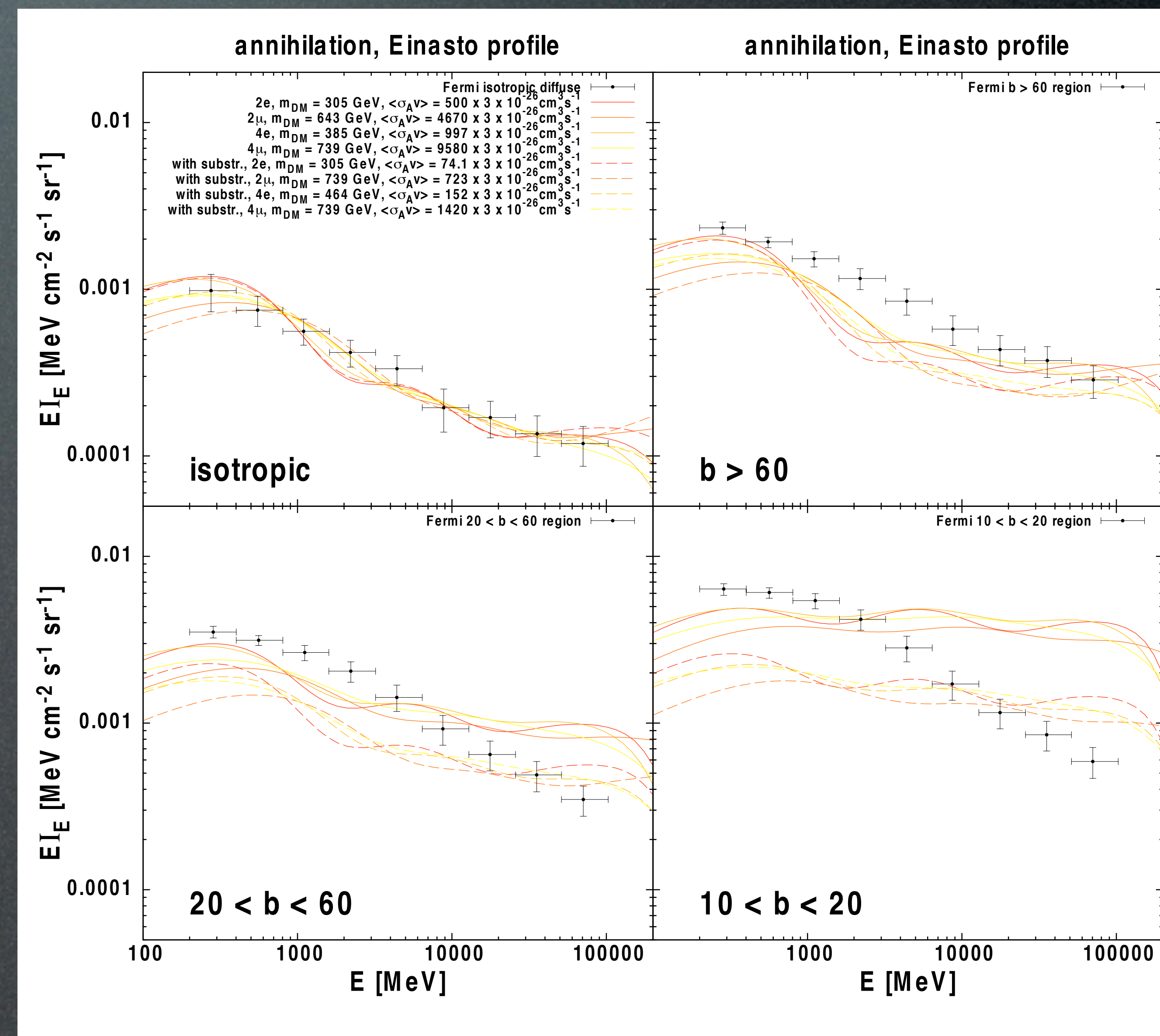
What if a signal of DM is *already* hidden in Fermi diffuse γ data?

Gamma **fits**?

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



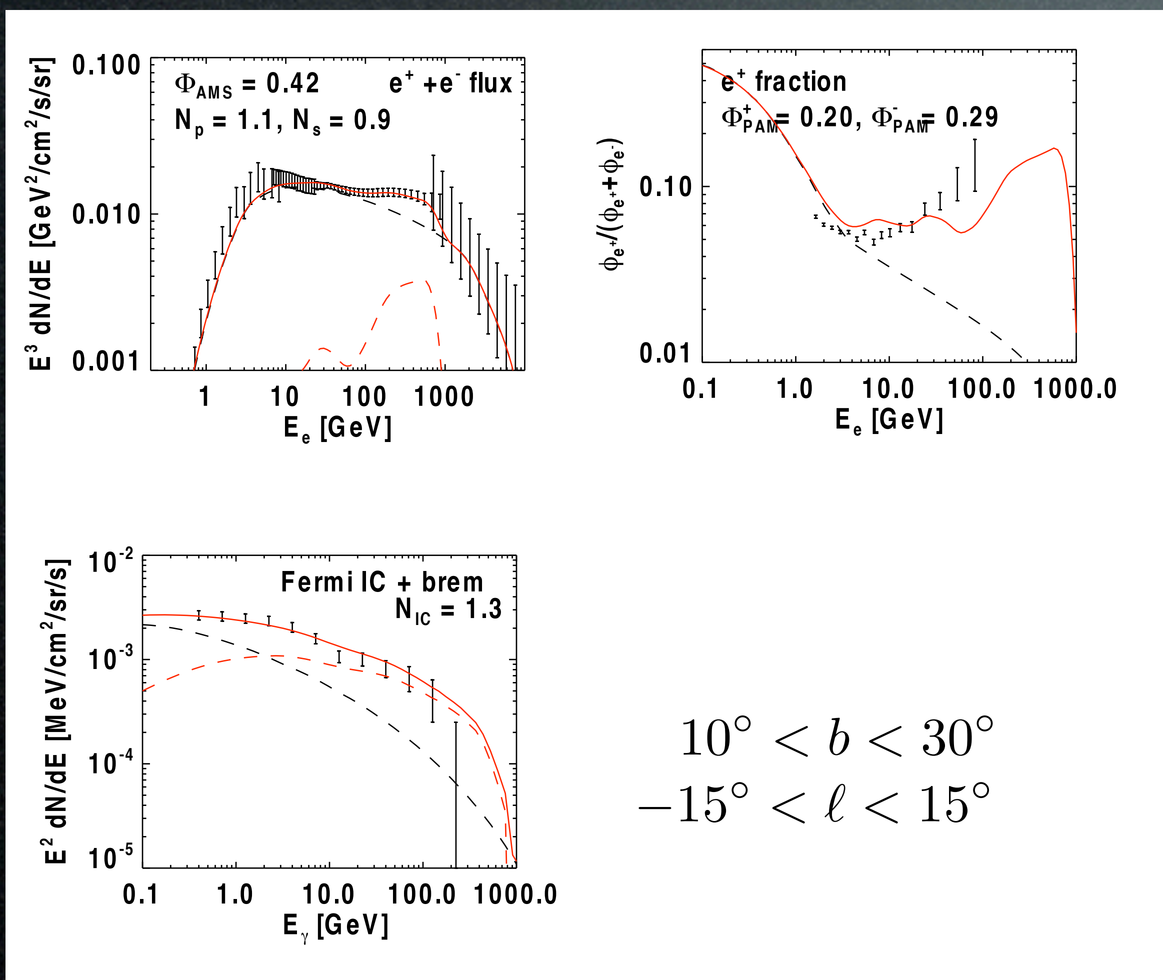
Lin, Finkbeiner, Dobler 1004.0989



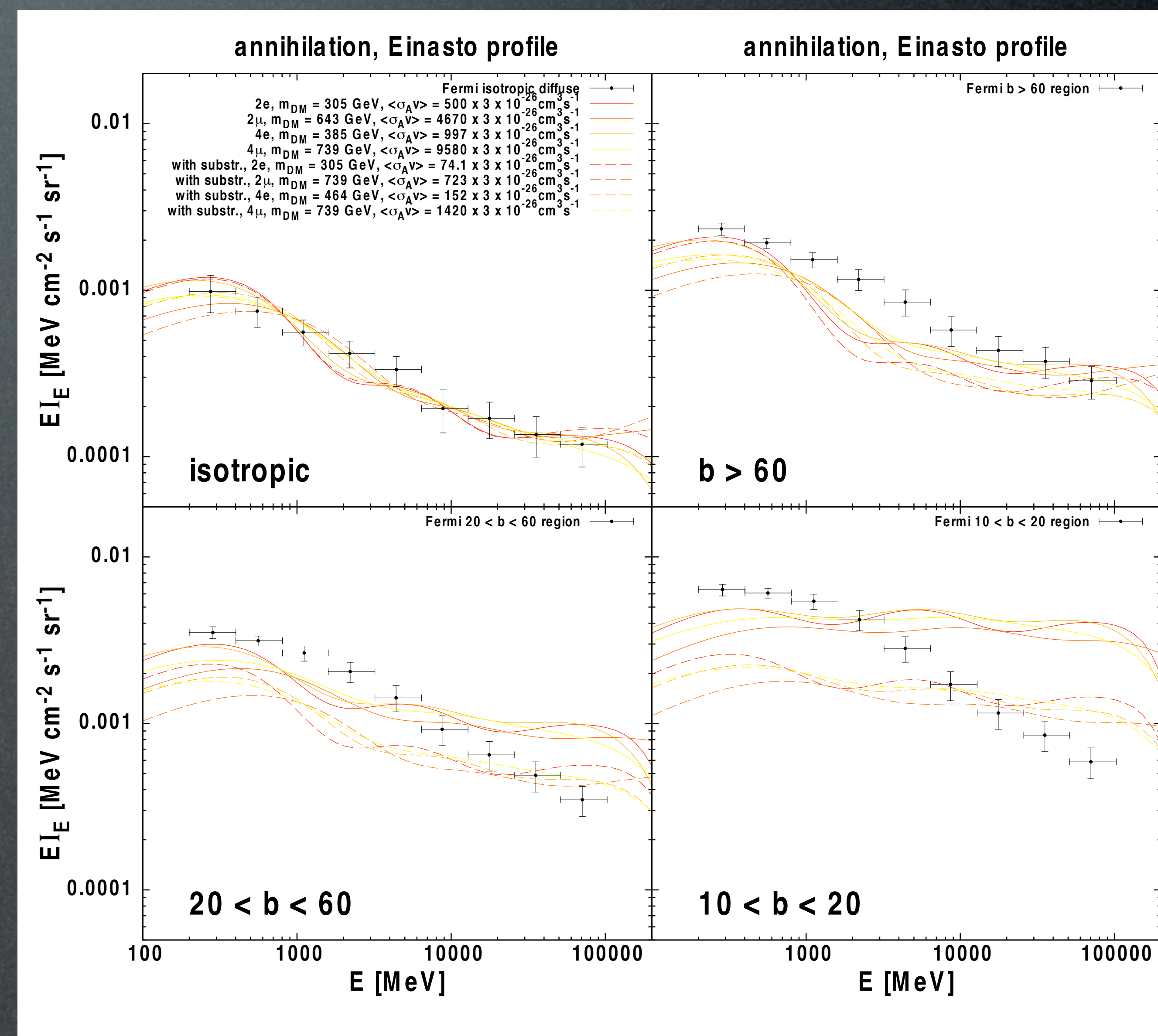
Hutsi, Hektor, Raidal 1004.2036

Gamma **fits**?

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



Lin, Finkbeiner, Dobler 1004.0989

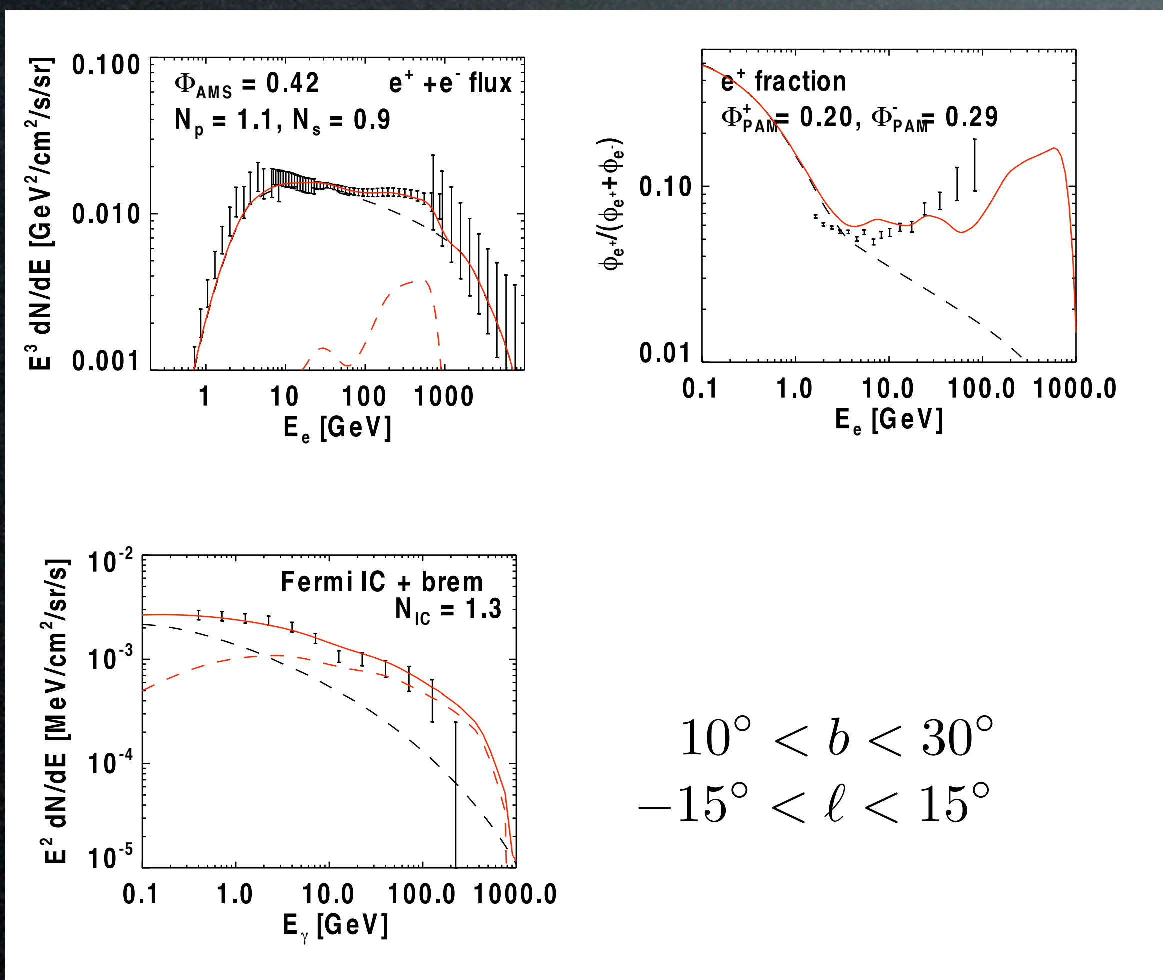


Hutsi, Hektor, Raidal 1004.2036

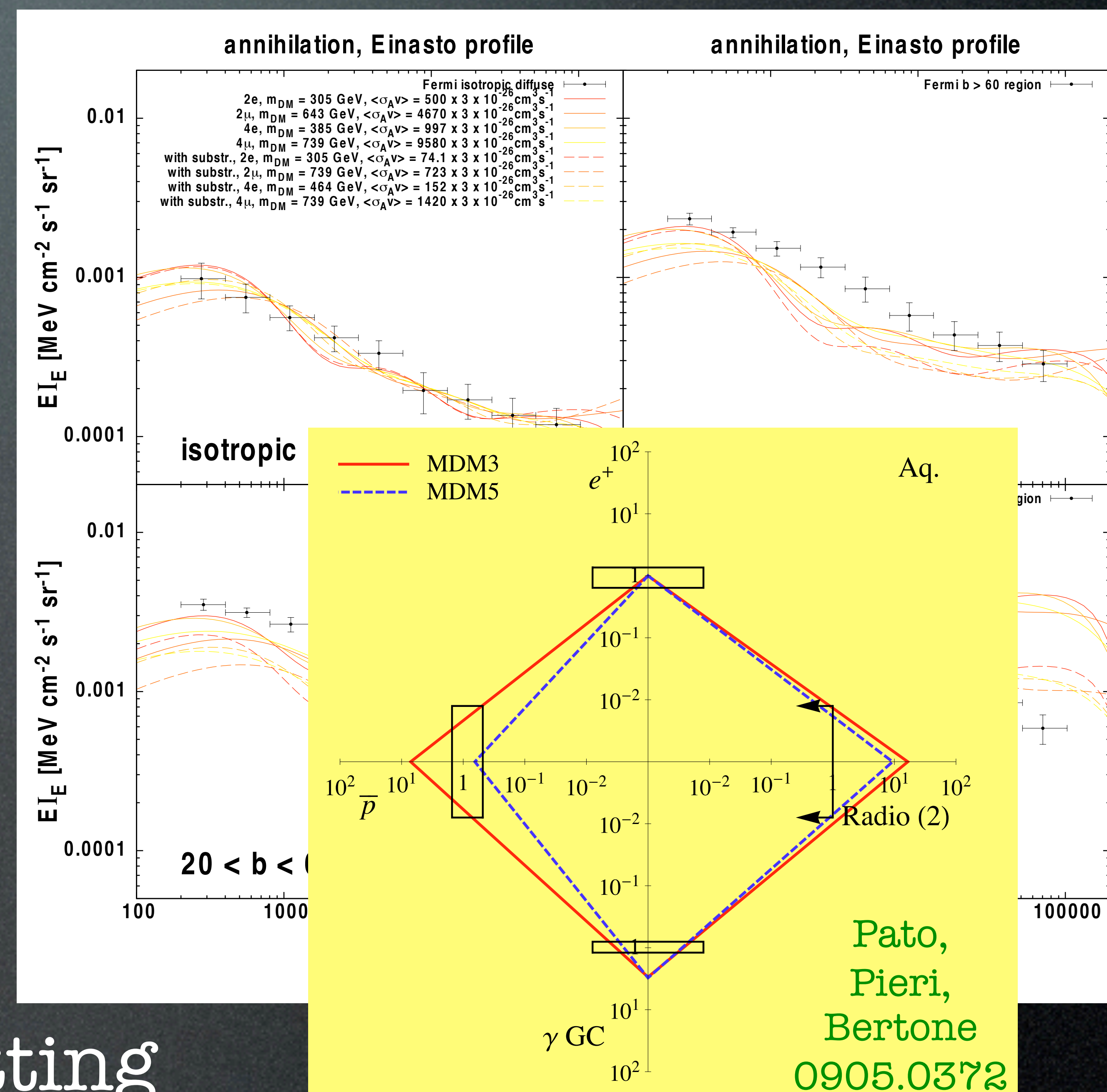
Mmm, a good fit requires fitting energy spectra + angular spectra + associated signals.

Gamma **fits**?

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



Lin, Finkbeiner, Dobler 1004.0989



Hutsi, Hektor, Raidal 1004.2036

Mmm, a good fit requires 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

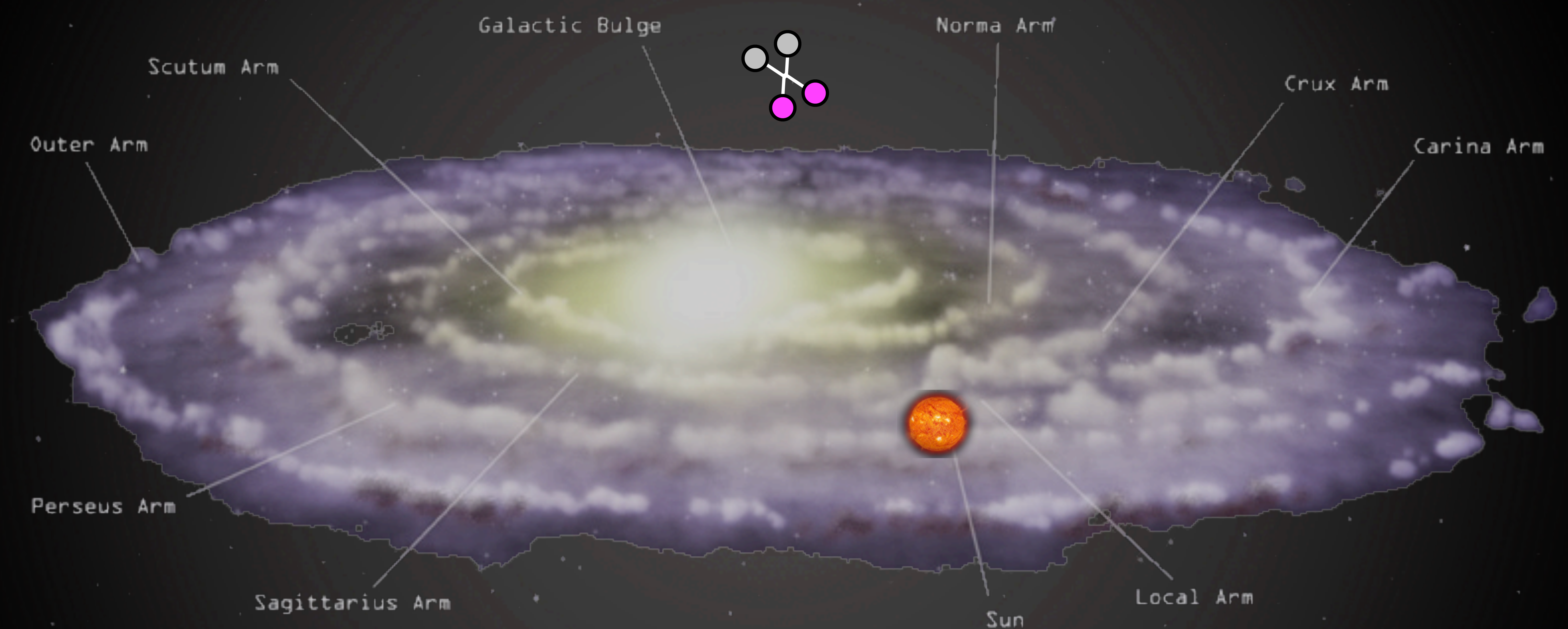
$\bar{p}$ from annihil in galactic halo or center

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

$\nu, \bar{\nu}$ from annihil in galactic center

Indirect Detection

$\bar{d}$ from DM annihilations in halo



Indirect Detection

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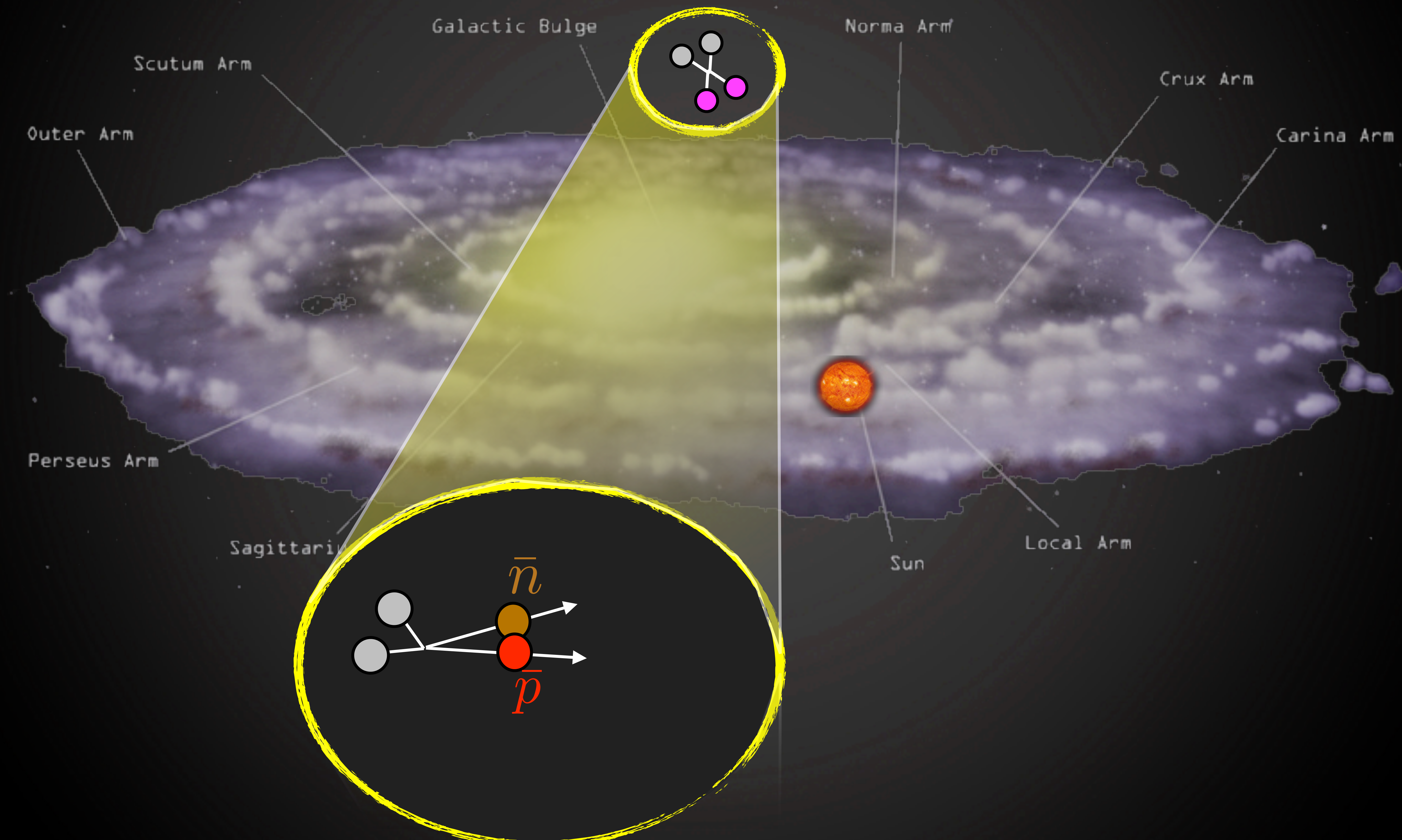
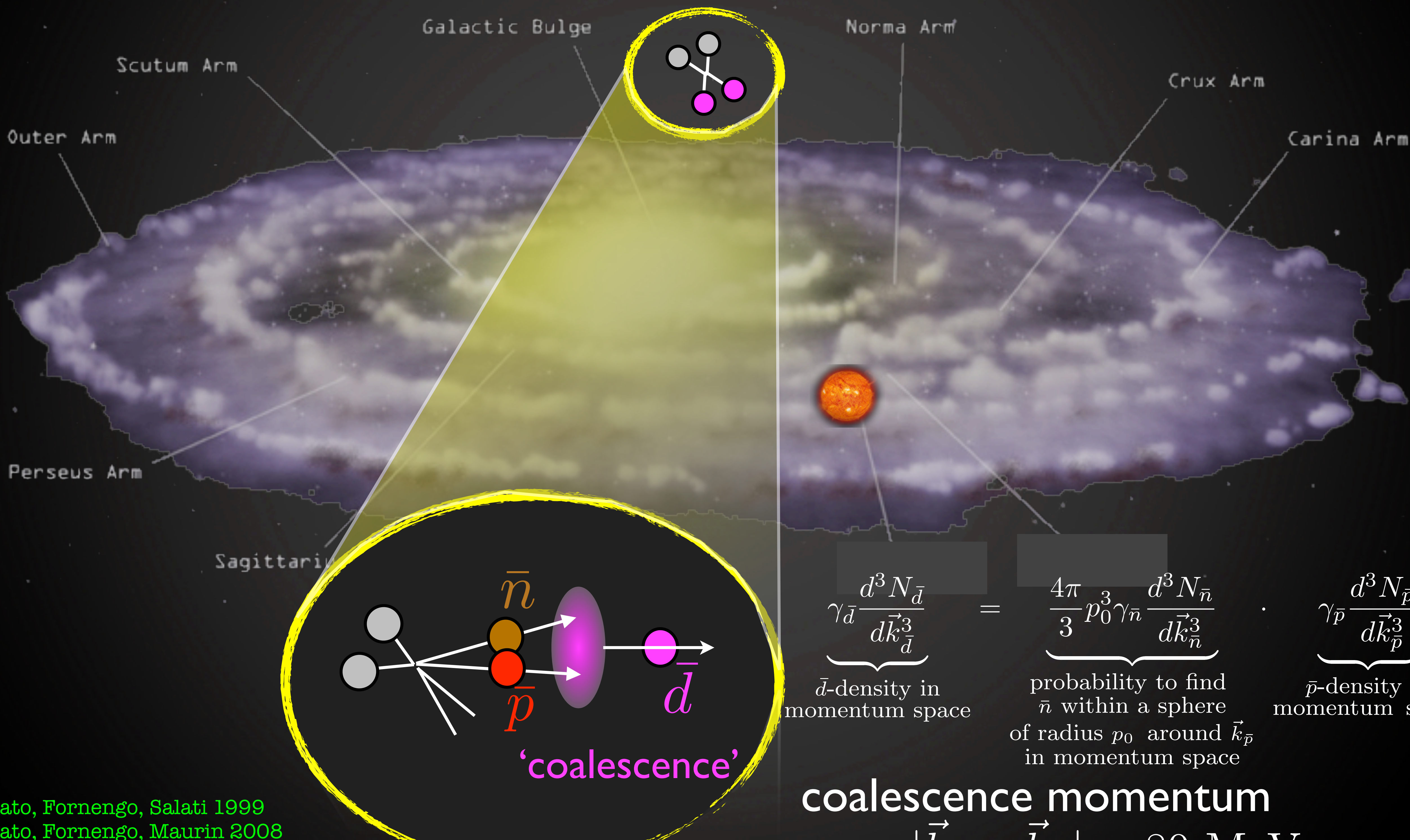


Indirect Detection

$\bar{d}$ from DM annihilations in halo



$$\underbrace{\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d\vec{k}^3_{\bar{d}}}}_{\bar{d}\text{-density in momentum space}} = \underbrace{\frac{4\pi}{3} p_0^3 \gamma_{\bar{n}} \frac{d^3 N_{\bar{n}}}{d\vec{k}^3_{\bar{n}}}}_{\text{probability to find } \bar{n} \text{ within a sphere of radius } p_0 \text{ around } \vec{k}_{\bar{p}} \text{ in momentum space}} \cdot \underbrace{\gamma_{\bar{p}} \frac{d^3 N_{\bar{p}}}{d\vec{k}^3_{\bar{p}}}}_{\bar{p}\text{-density in momentum space}}$$

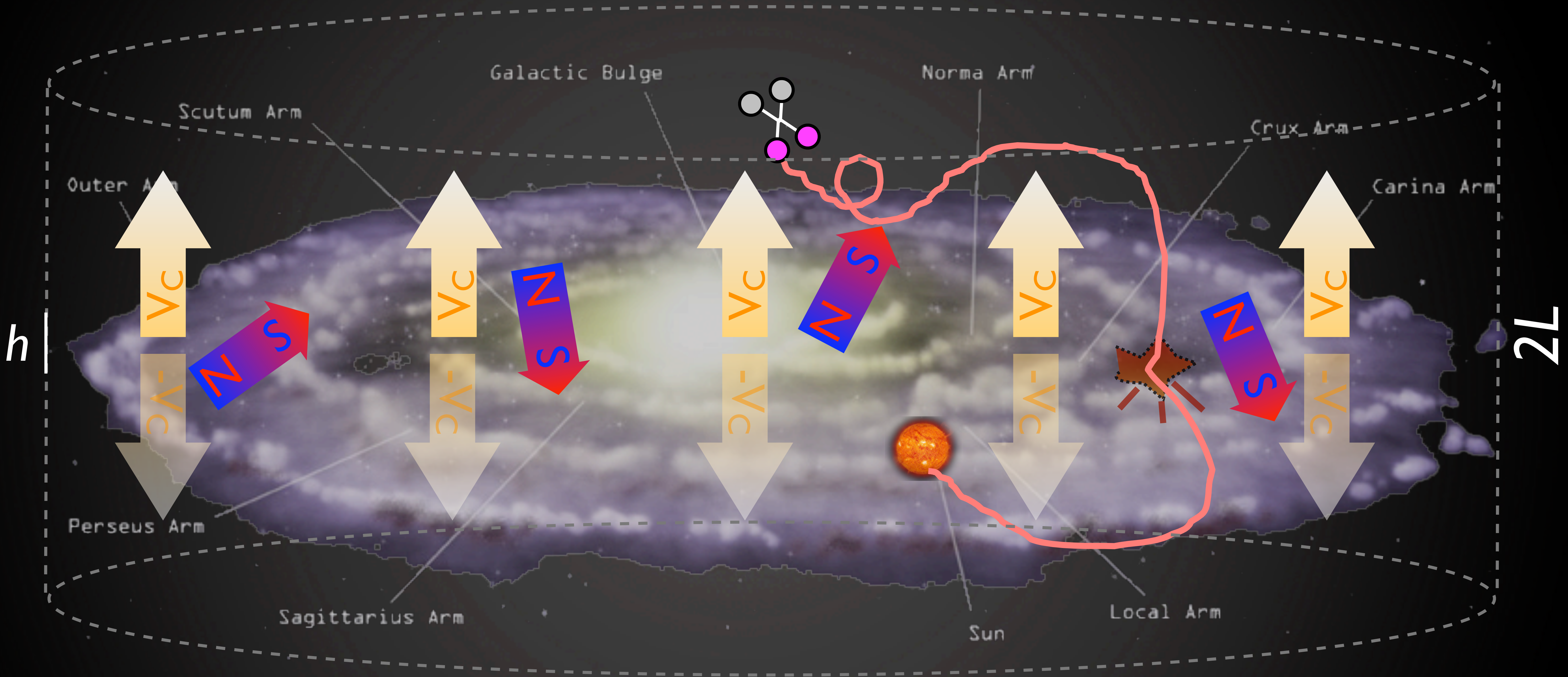
coalescence momentum

$$p_0 \simeq |\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}| \approx 80 \text{ MeV}$$

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Kadastik, Raidal, Strumia, 2009

Indirect Detection

$\bar{d}$ from DM annihilations in halo



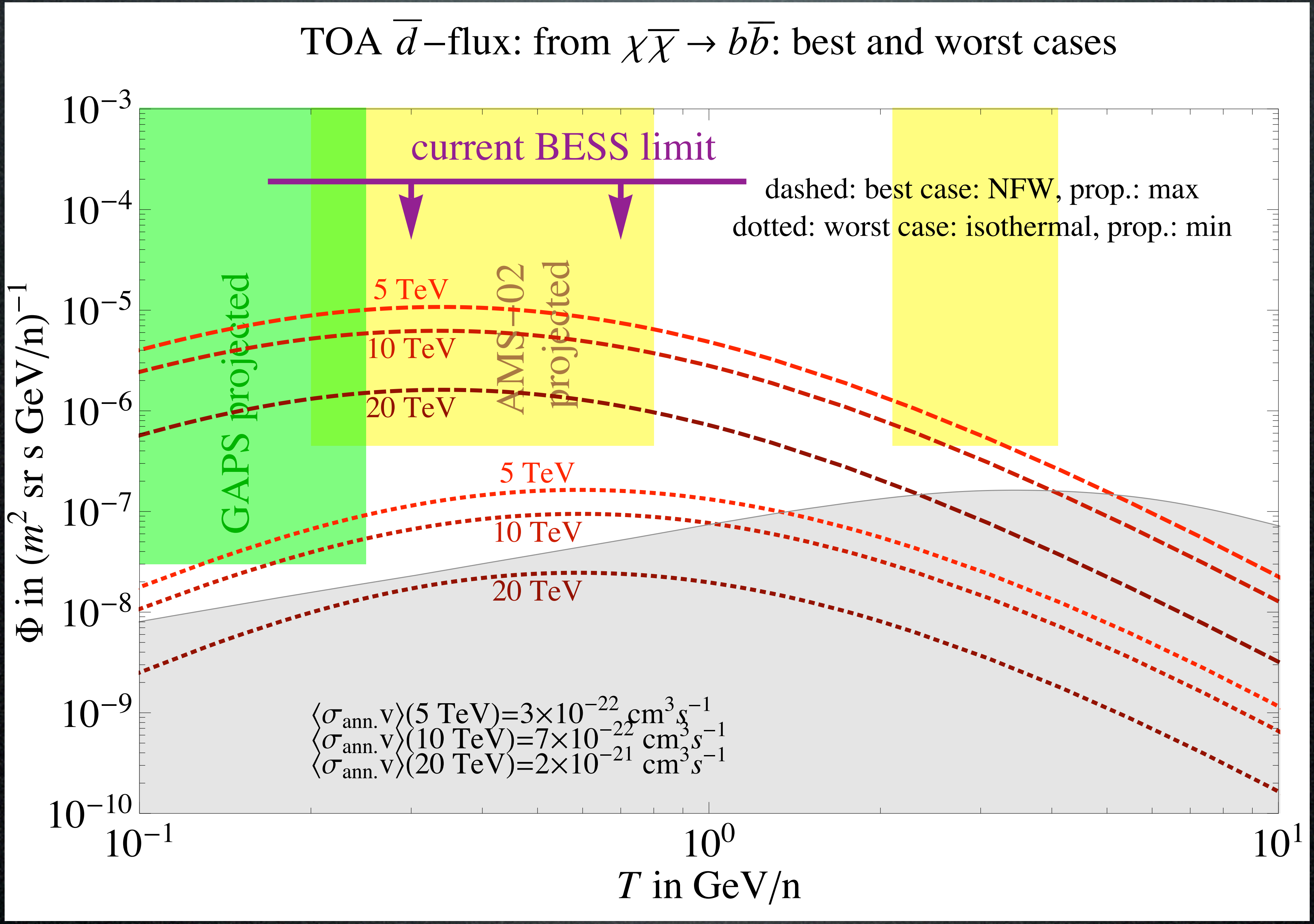
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}(b(E)f) + \frac{\partial}{\partial z}(V_c f) = Q_{\text{inj}} - 2h\delta(z)\Gamma_{\text{spall}} f$$

diffusion energy loss convective wind source spallations

Indirect Detection

$\bar{d}$ from DM annihilations in halo

The signals from heavy, non-leptons-only DM are interesting!

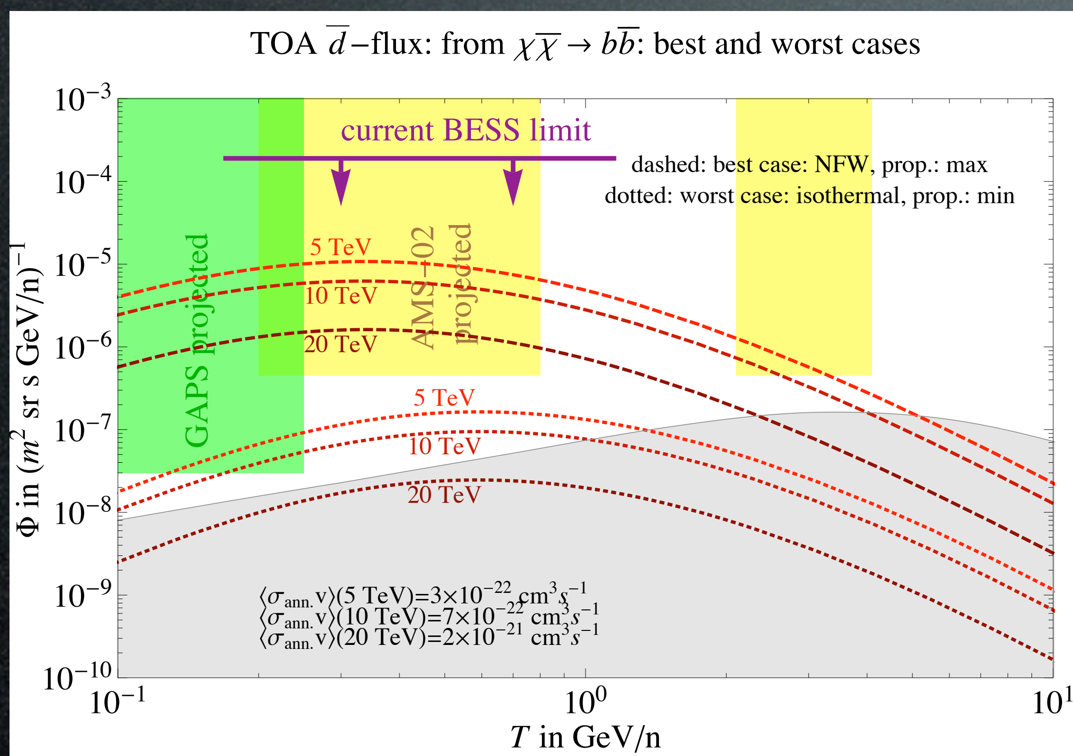


Bräuninger, Cirelli, 0904.1165

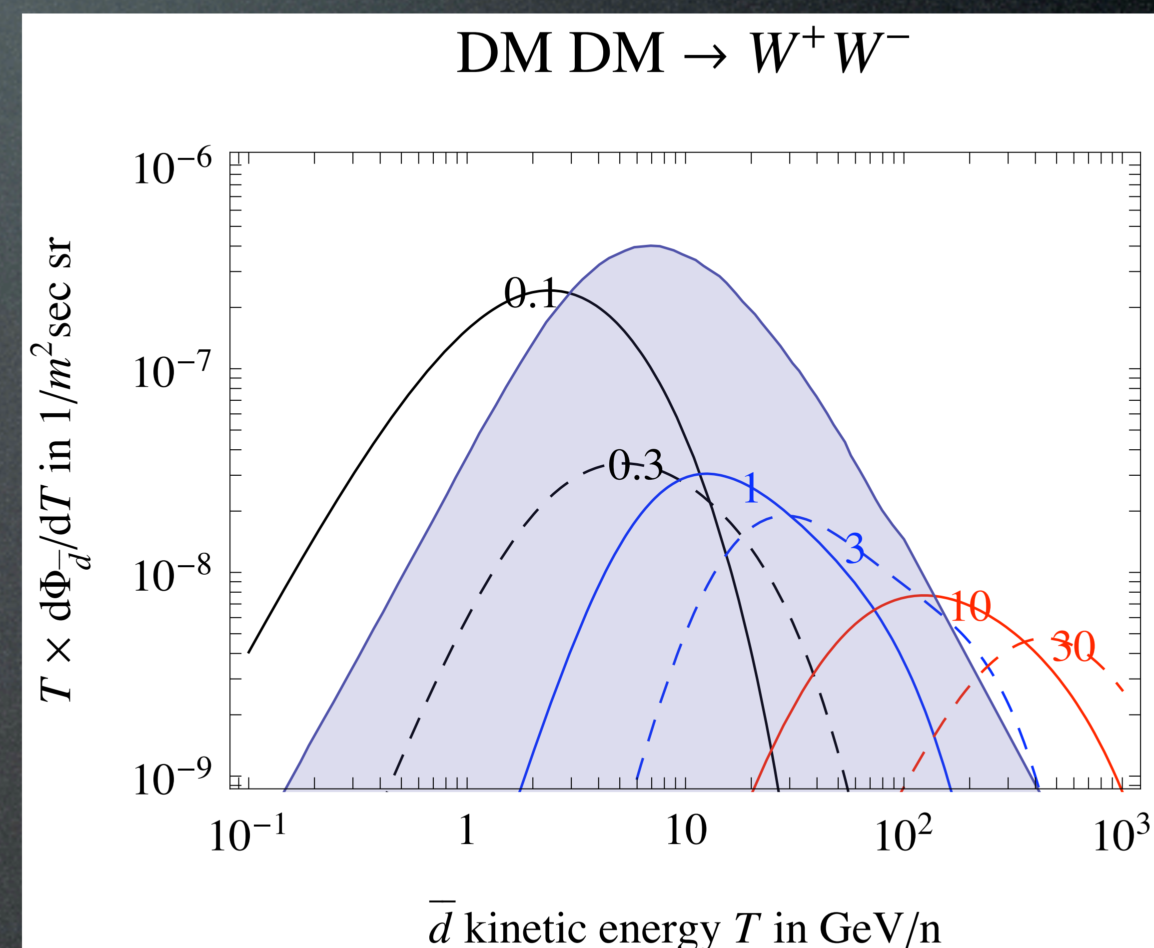
Indirect Detection

$\bar{d}$ from DM annihilations in halo

The signals from heavy, non-leptons-only DM are interesting!



Bräuninger, Cirelli, 0904.1165



Kadastik, Raidal, Strumia 0908.1578

Improved computation, including QCD jets.

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

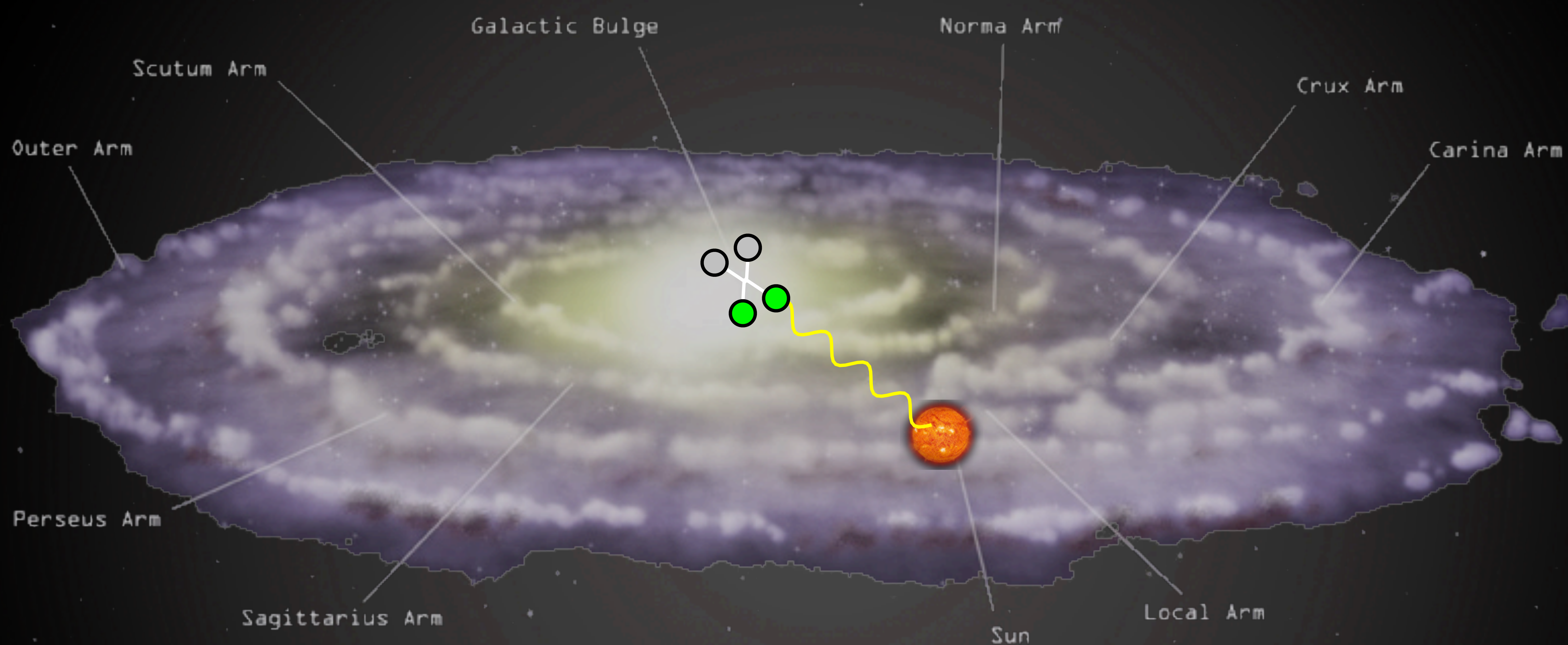
$\bar{p}$ from annihil in galactic halo or center

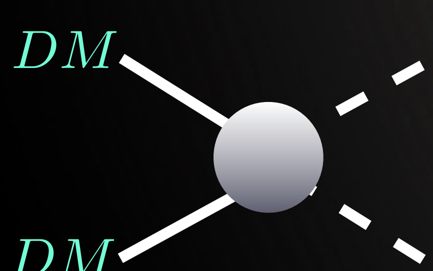
$\bar{d}$ from annihil in galactic halo or center

$\nu, \bar{\nu}$ from annihil in galactic center

Indirect Detection

ν from DM annihilations in galactic center

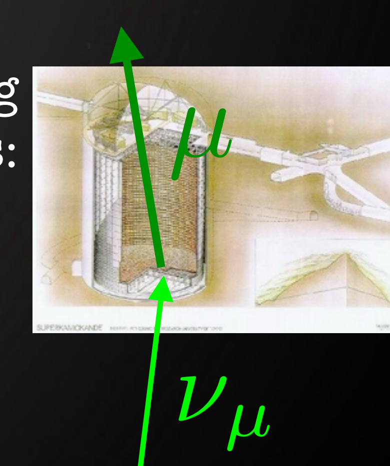




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \nu$$

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

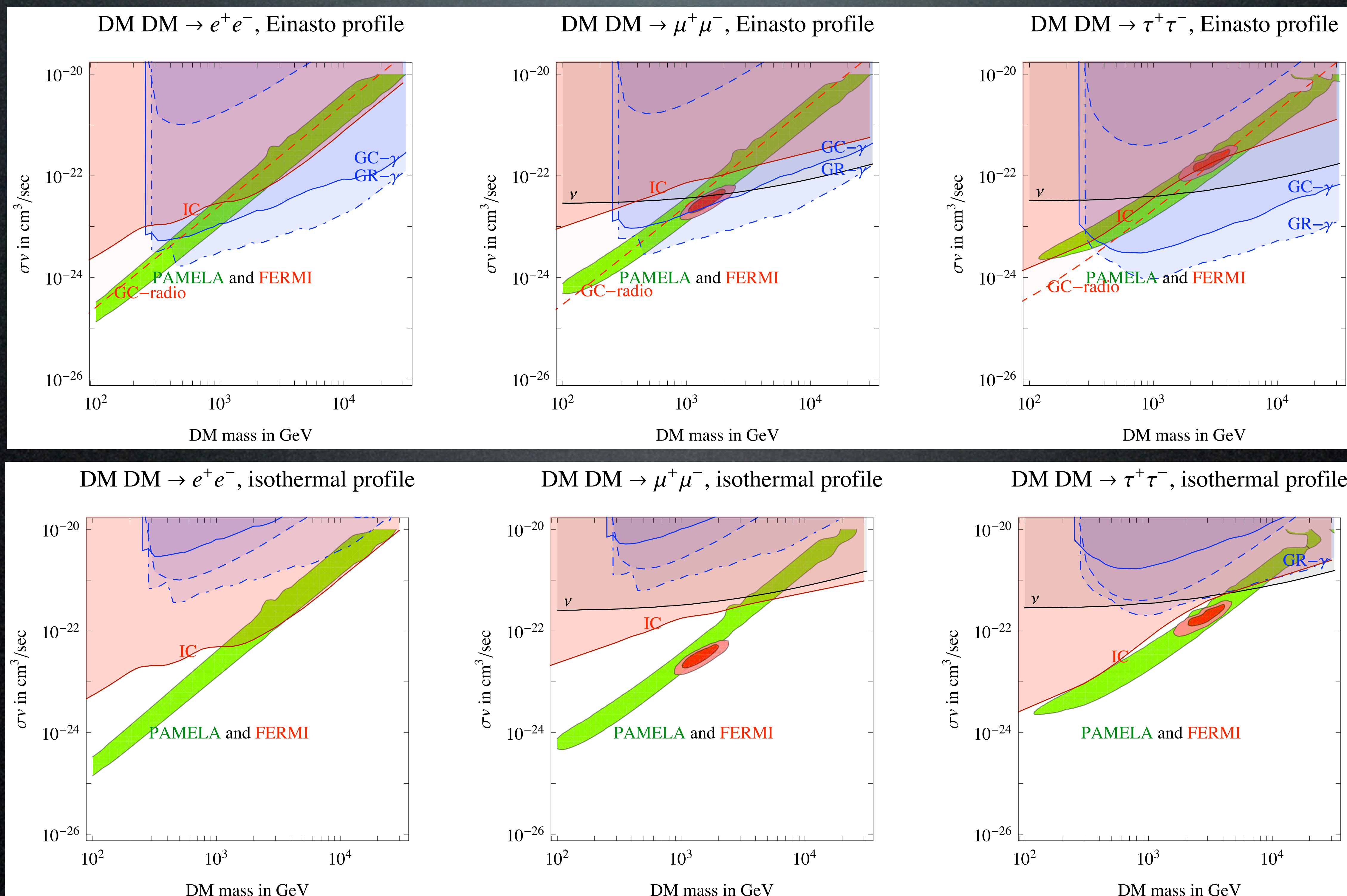
up-going muons:



Neutrino constraints

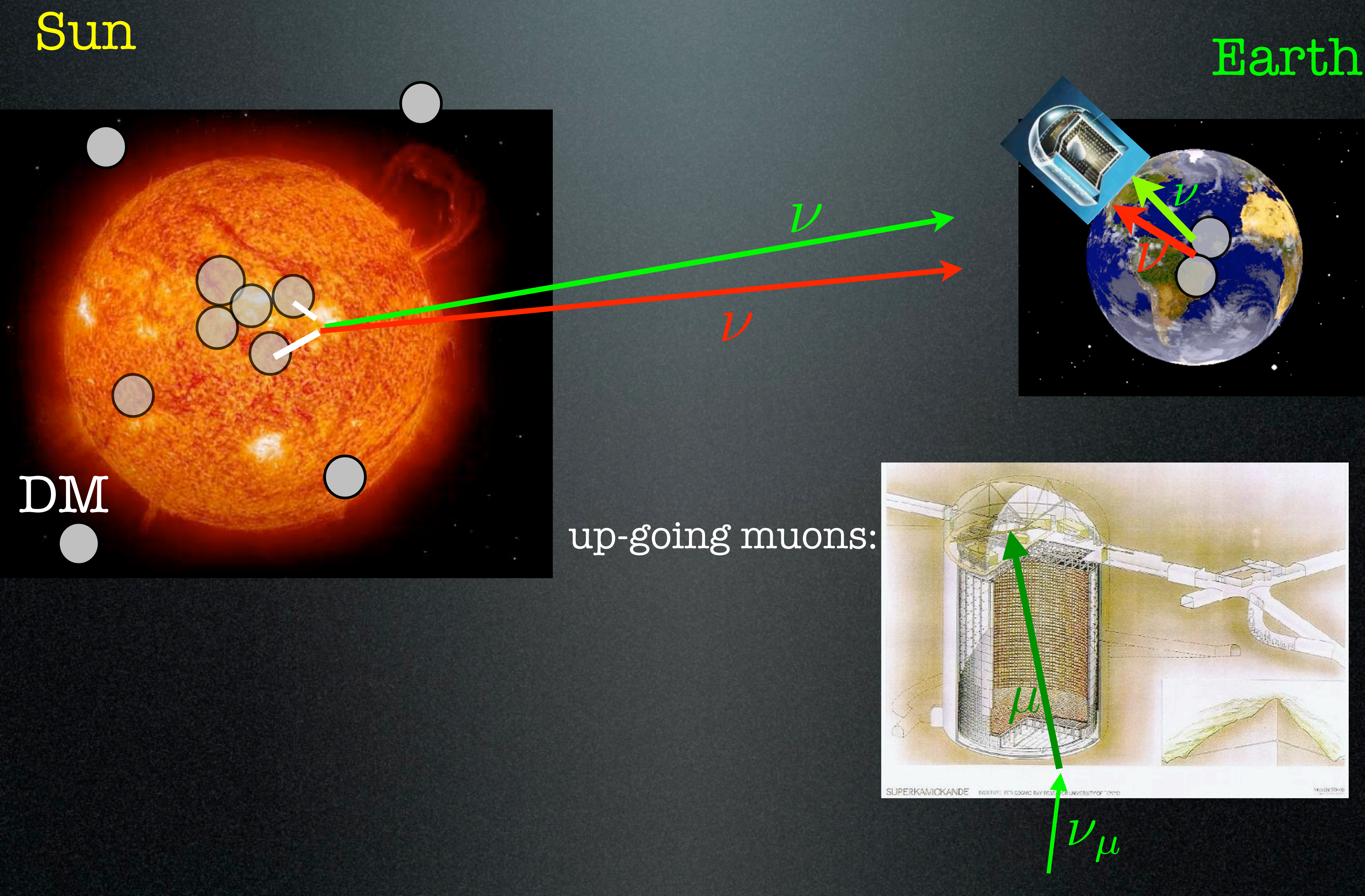
Comparing with SuperKamiokande data in 3° to 30°

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

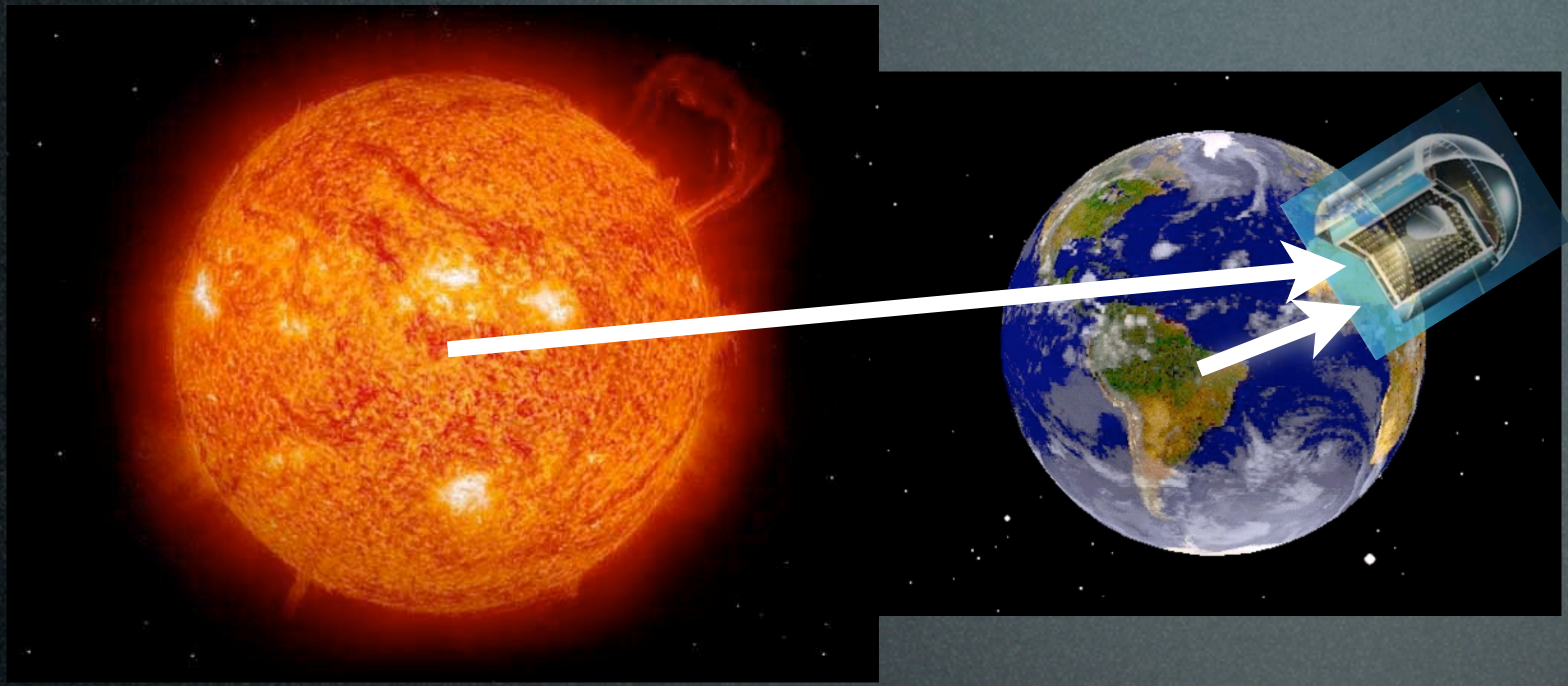


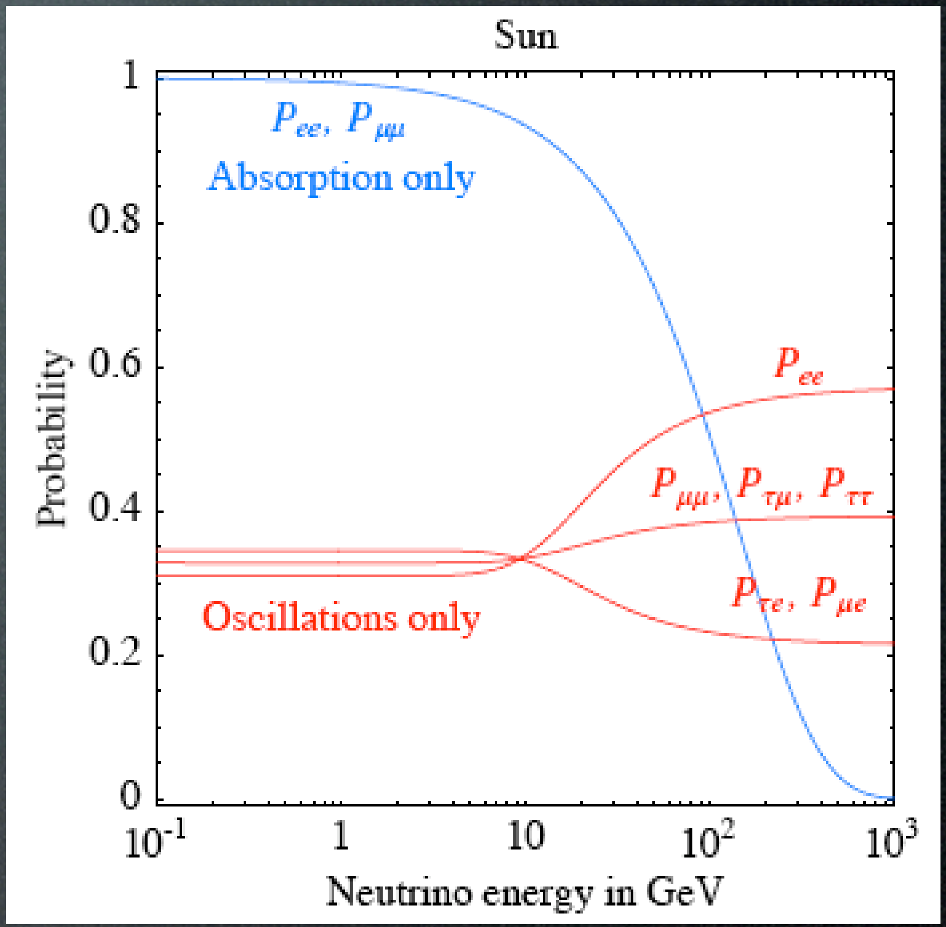
Strumia, Papucci et al. 0905.0480

Neutrinos from DM in the Sun



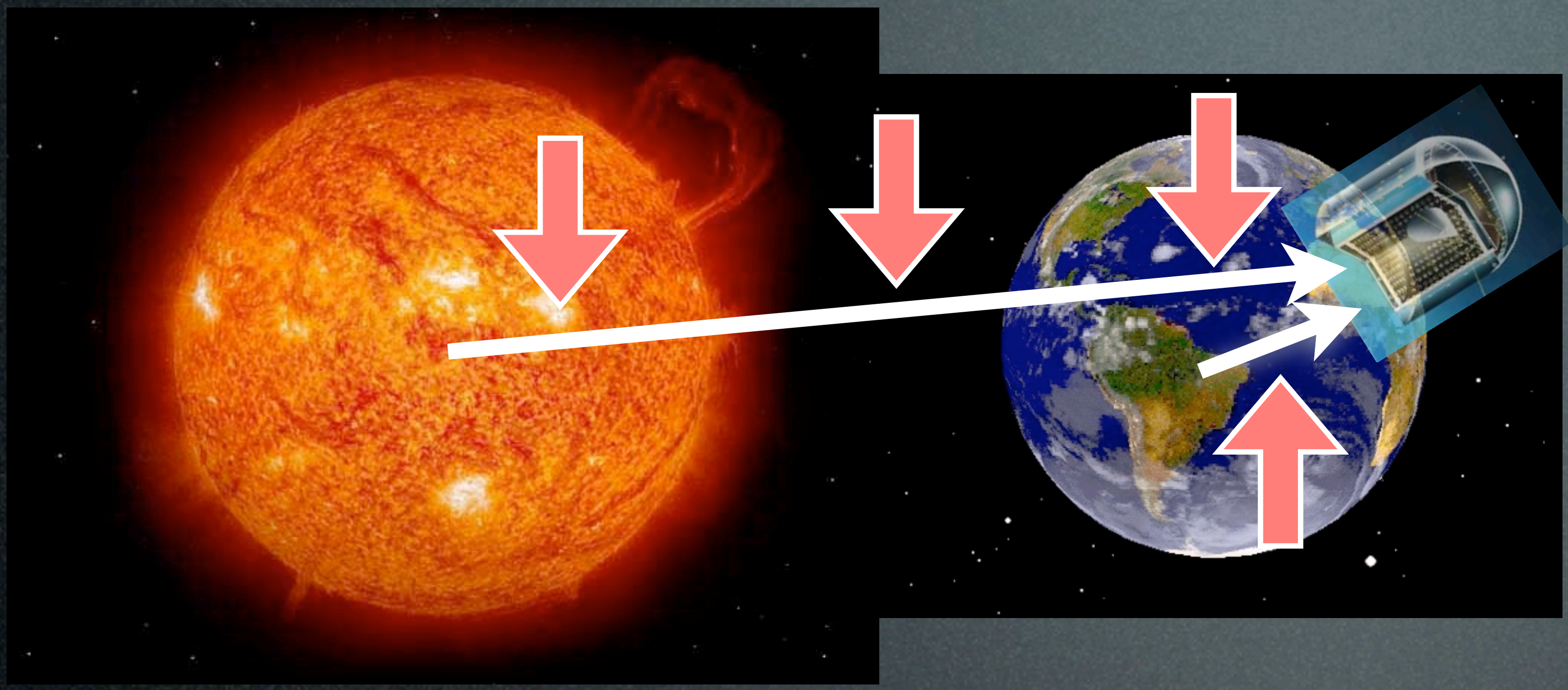
Propagation

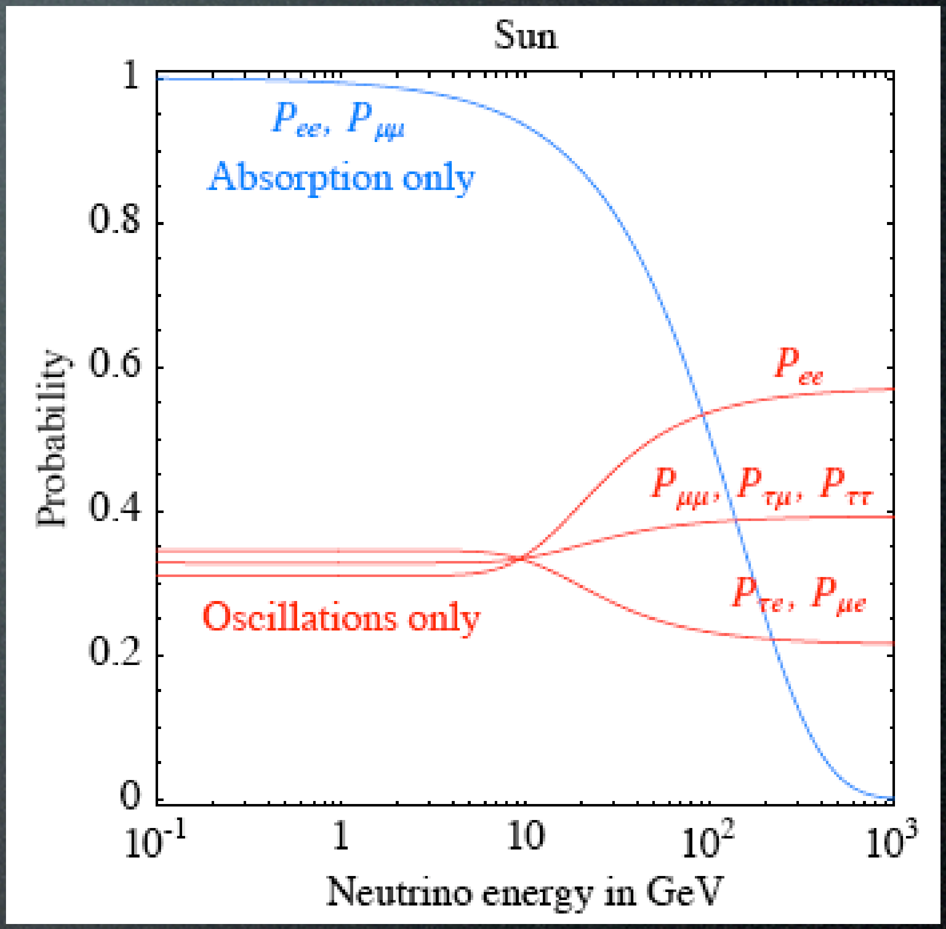




oscillations + interactions

Propagation





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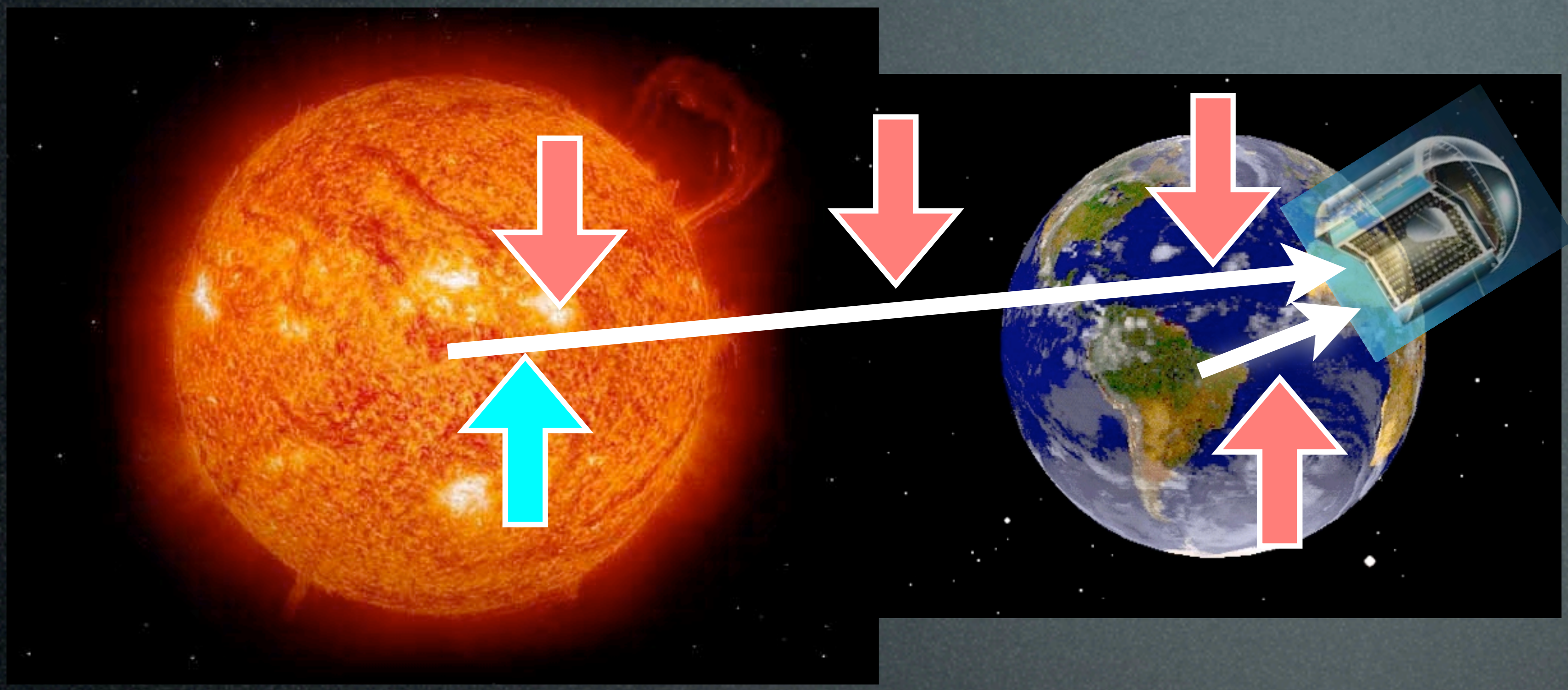
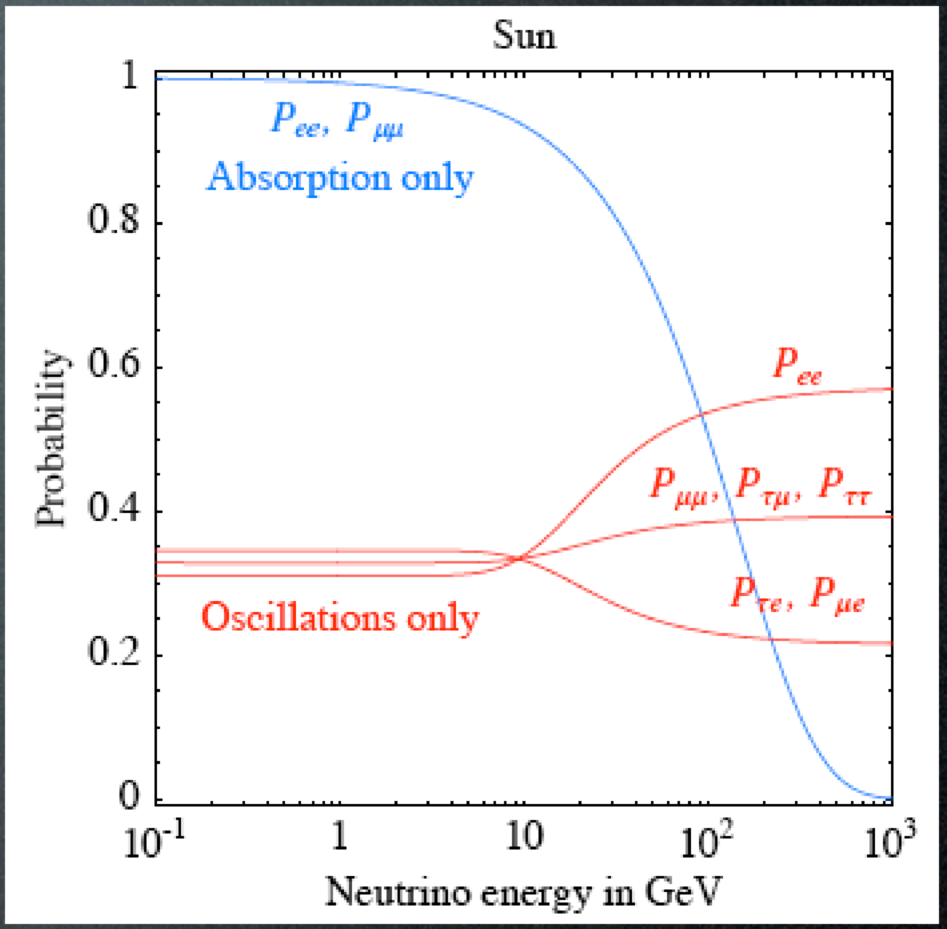
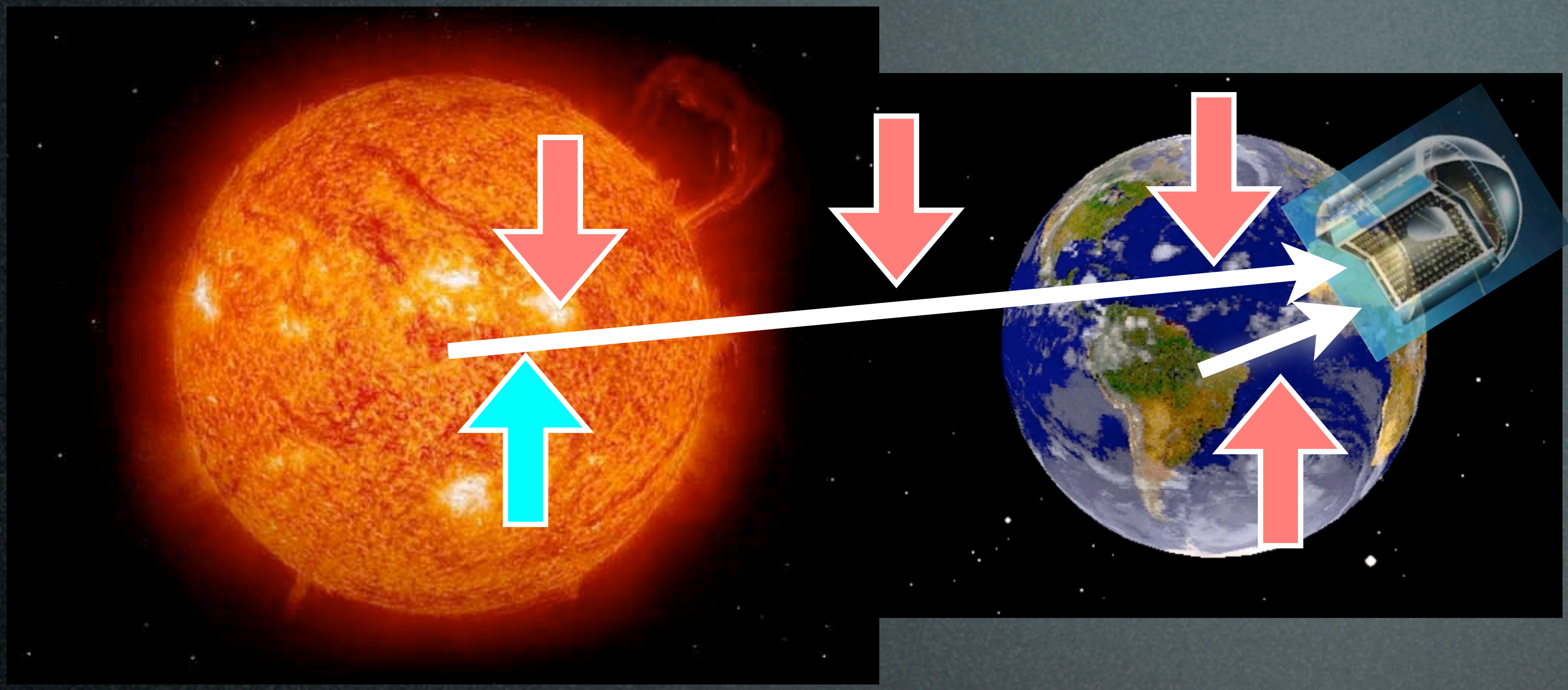
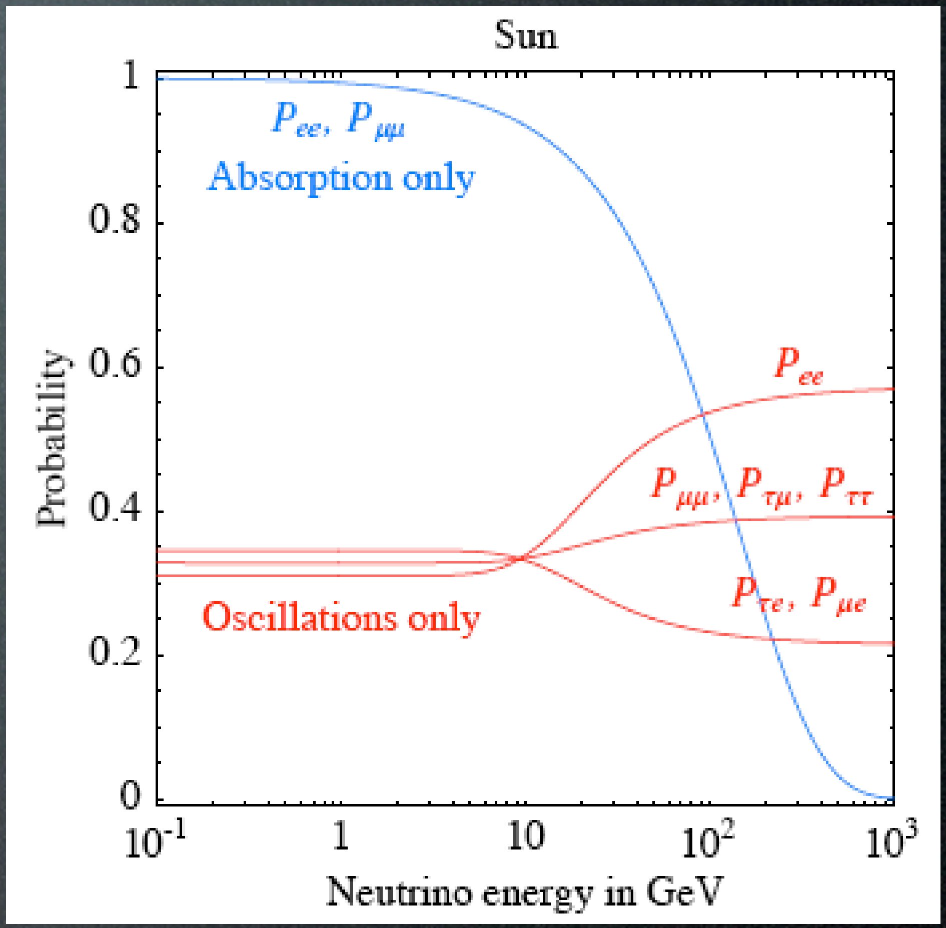




oscillations + interactions

Propagation

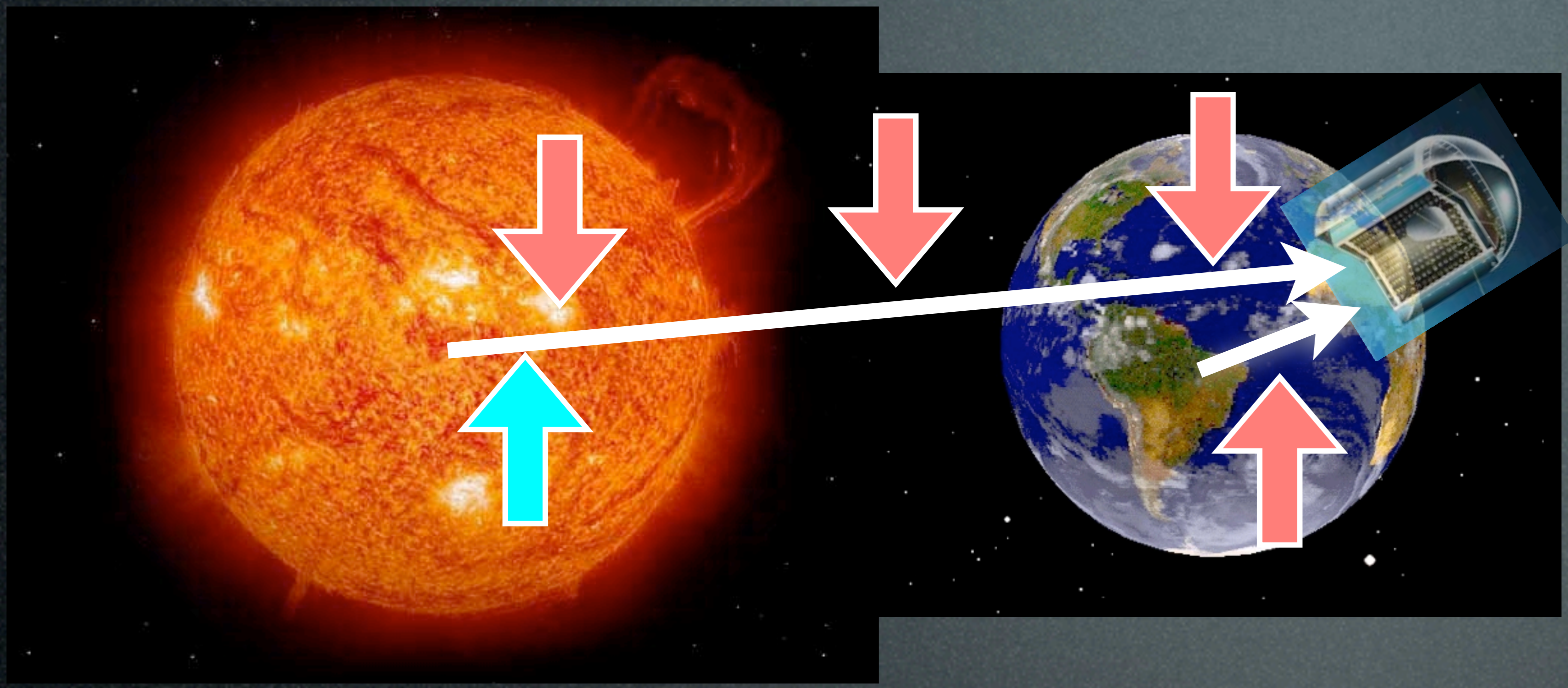


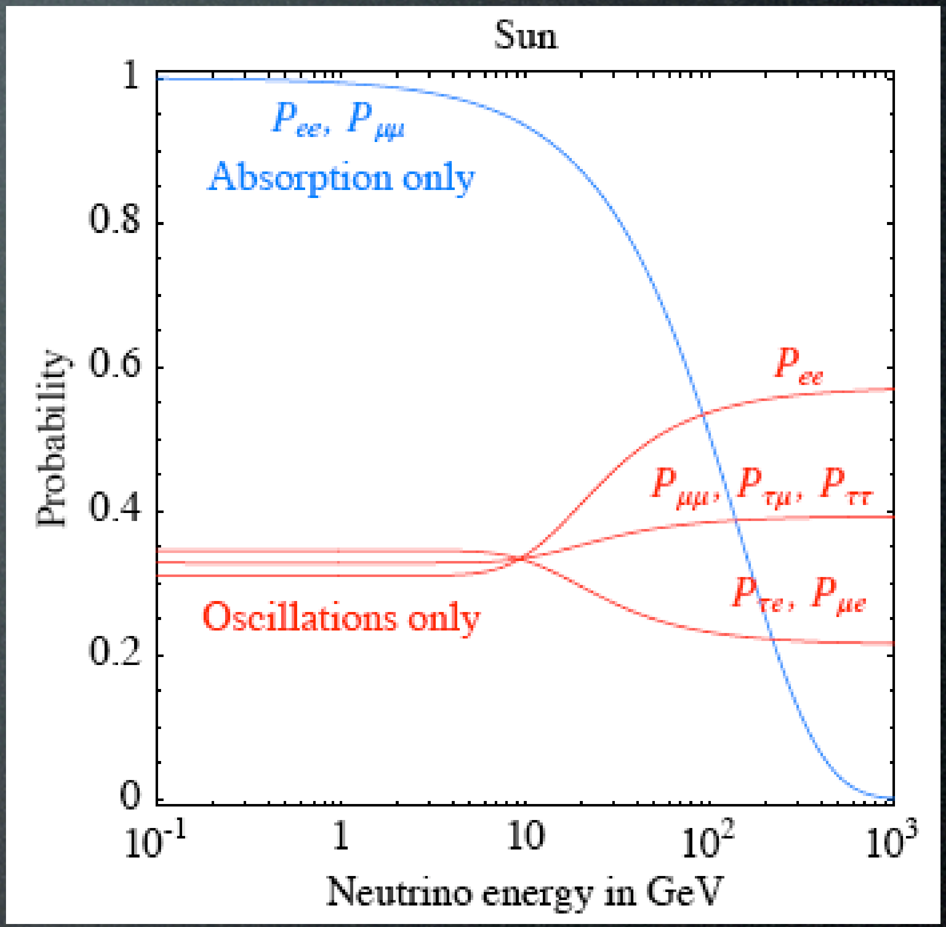


oscillations + interactions

$$\text{production} \longrightarrow \begin{pmatrix} \Phi_{\nu_e} & & \\ & \Phi_{\nu_\mu} & \\ & & \Phi_{\nu_\tau} \end{pmatrix} \longrightarrow \text{detection}$$

Propagation





oscillations + interactions

density matrix

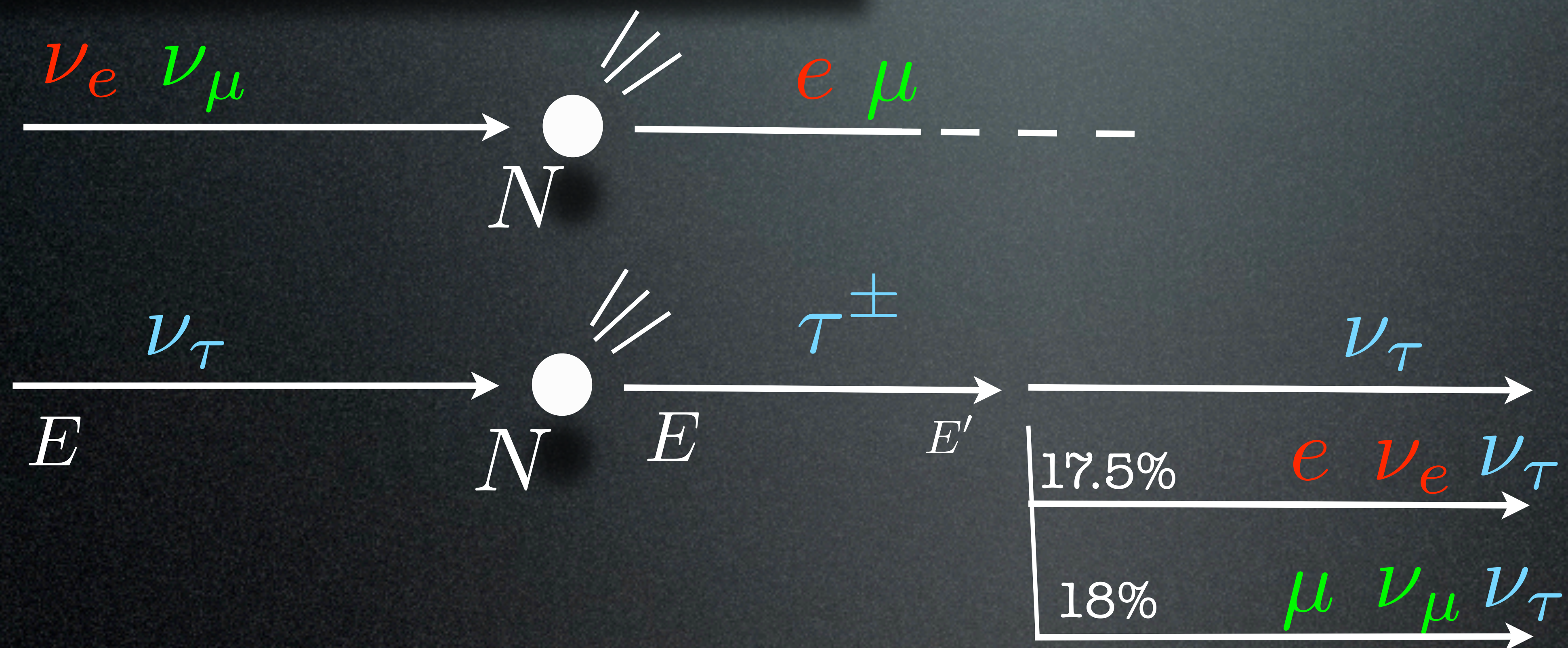
$$\boldsymbol{\rho} = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

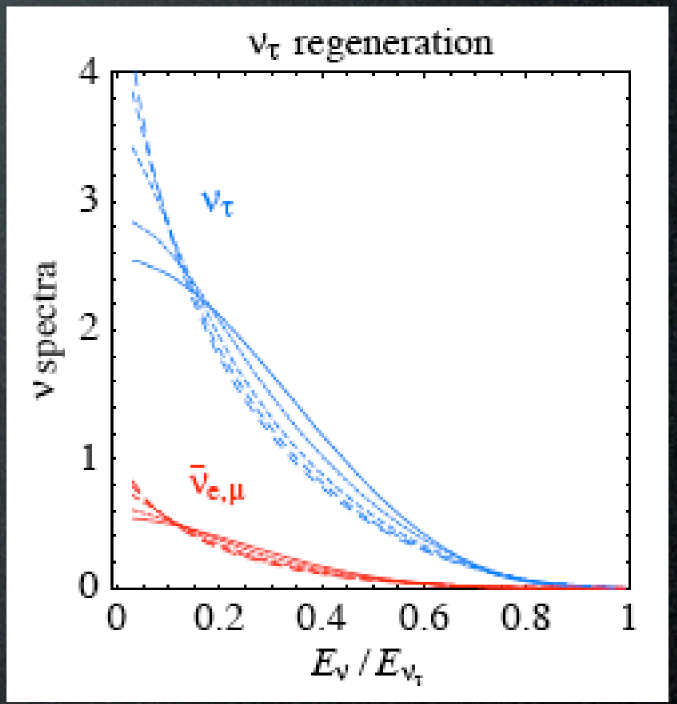
full evolution equation:

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{CC}} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{NC}} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{in}}$$

Propagation: CC absorption and tau regeneration

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC}$$





(re)generation

$$\left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} = -\frac{\{\boldsymbol{\Gamma}_{\rm CC}, \boldsymbol{\rho}\}}{2} + \int \frac{dE_\nu^{\rm in}}{E_\nu^{\rm in}} \Big[\boldsymbol{\Pi}_\tau \rho_{\tau\tau}(E_\nu^{\rm in}) \Gamma_{\rm CC}^\tau (E_\nu^{\rm in}) f_{\tau\to\tau}(E_\nu^{\rm in}, E_\nu)$$

$$+ \boldsymbol{\Pi}_{e,\mu} \bar{\rho}_{\tau\tau}(E_\nu^{\rm in}) \bar{\Gamma}_{\rm CC}^\tau (E_\nu^{\rm in}) f_{\bar{\tau}\to e,\mu}(E_\nu^{\rm in}, E_\nu) \Big]$$

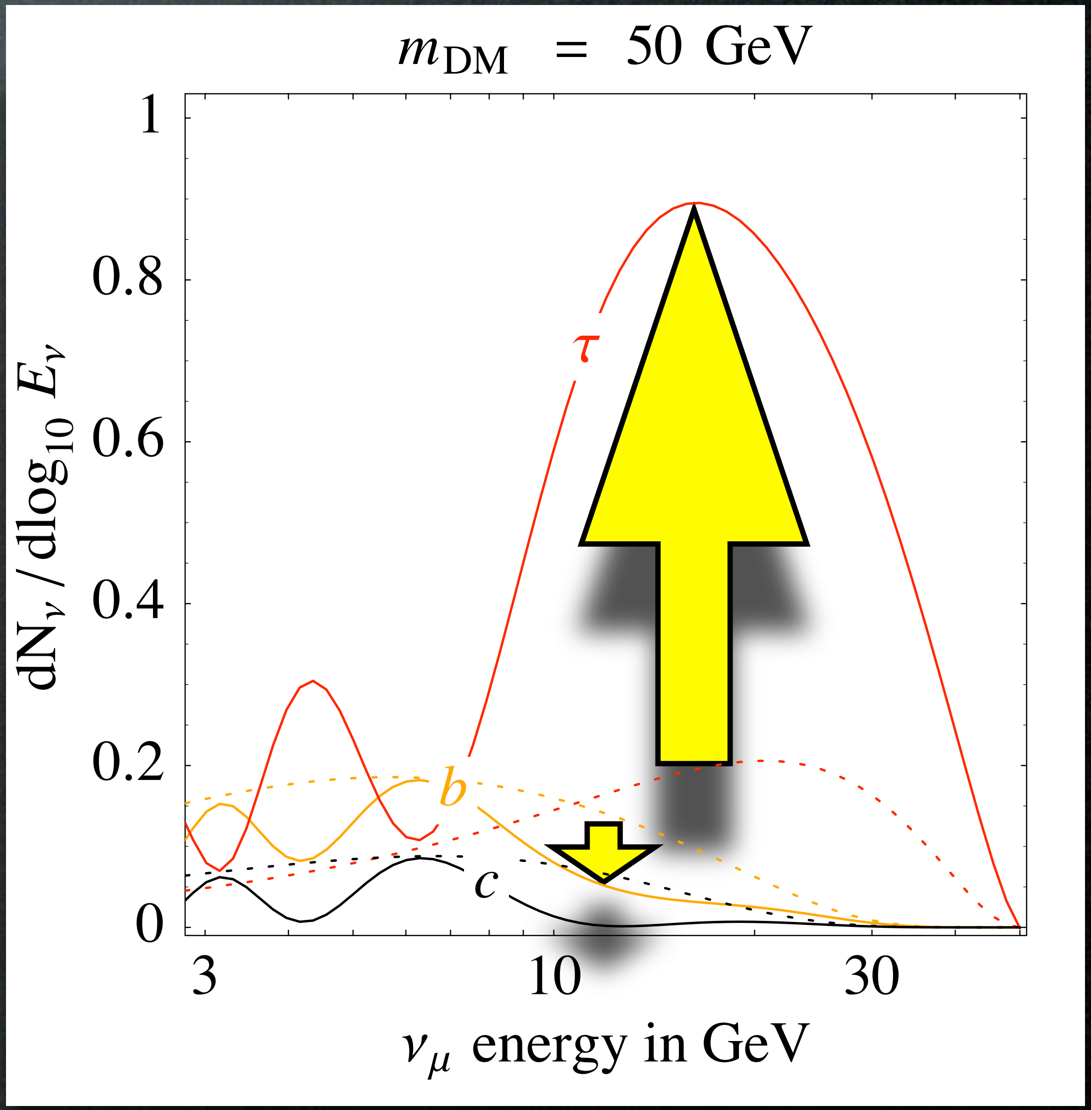
Propagation: summary

Effects of oscillations and interactions:

- reshuffle of the 3 flavors
  (oscillations and regeneration)

- attenuation of the fluxes

- degradation of energy
  (distortion of spectra)



700	0.12	0.608978	0.341566	0.288158	0.00732825	1.01016	0.329712	0.325684
700	0.13	0.549979	0.338742	0.261576	0.00587295	0.938862	0.306415	0.314678
700	0.14	0.497406	0.335783	0.237414	0.00472903	0.879793	0.28655	0.305119
700	0.15	0.45023	0.332688	0.215358	0.00380882	0.814194	0.269374	0.296714
700	0.16	0.407863	0.329461	0.195214	0.00307157	0.79659	0.254494	0.289315
700	0.17	0.369843	0.326101	0.176844	0.00248237	0.753636	0.24159	0.282798
700	0.18	0.335522	0.322618	0.160047	0.00200452	0.716648	0.230284	0.277002
700	0.19	0.304578	0.31901	0.14472	0.00162001	0.675494	0.220381	0.271845
700	0.2	0.276564	0.315279	0.130711	0.00130737	0.637912	0.211633	0.26723
700	0.21	0.251174	0.311436	0.117905	0.00105404	0.604016	0.203894	0.263081
700	0.22	0.228188	0.307472	0.10625	0.000849125	0.572074	0.19704	0.259361
700	0.23	0.207361	0.30339	0.0956315	0.000683914	0.540172	0.190963	0.25601
700	0.24	0.188471	0.299207	0.0859745	0.00055027	0.514165	0.185543	0.25298
700	0.25	0.171298	0.29493	0.0771891	0.000442236	0.490279	0.180708	0.250232
700	0.26	0.155638	0.290551	0.0691846	0.00035443	0.46804	0.176369	0.247734
700	0.27	0.141436	0.28608	0.0619432	0.000283948	0.449289	0.172486	0.245459
700	0.28	0.12846	0.281519	0.0553506	0.000226624	0.425593	0.168987	0.243375
700	0.29	0.116646	0.276873	0.0493849	0.00018028	0.402885	0.165838	0.241472
700	0.3	0.105937	0.272149	0.044022	0.000143647	0.385856	0.163012	0.239737
700	0.31	0.0961617	0.267351	0.0391701	0.00011413	0.370693	0.160458	0.238141
700	0.32	0.0872398	0.262489	0.0347864	0	0.356329	0.158152	0.236669
700	0.33	0.0791152	0.257559	0.0308456	0	0.342135	0.156067	0.235315
700	0.34	0.0716946	0.252566	0.0272953	0	0.327646	0.154173	0.234065
700	0.35	0.0649382	0.247521	0.0241132	0	0.313854	0.15246	0.232911
700	0.36	0.0587938	0.242423	0.0212697	0	0.302327	0.150908	0.231843
700	0.37	0.053184	0.237281	0.0187219	0	0.292082	0.149494	0.230853
700	0.38	0.0480605	0.232096	0.0164396	0	0.280878	0.148205	0.229935
700	0.39	0.0433863	0.226871	0.0144014	0	0.26817	0.14703	0.229083
700	0.4	0.0391341	0.221616	0.0125922	0	0.255281	0.145962	0.228293
700	0.41	0.0352722	0.216337	0.0109905	0	0.246658	0.144988	0.227559
700	0.42	0.0317531	0.211032	0.00956675	0	0.237501	0.1441	0.226875
700	0.43	0.0285549	0.205707	0.00830948	0	0.227852	0.143291	0.22624
700	0.44	0.0256505	0.200367	0.00720247	0	0.218472	0.142555	0.225648
700	0.45	0.0230042	0.195016	0.00622261	0	0.211149	0.14188	0.225094
700	0.46	0.0206088	0.189659	0.00536784	0	0.203462	0.141266	0.224579
700	0.47	0.0184371	0.184305	0.00461755	0	0.193263	0.140705	0.224098
700	0.48	0.0164685	0.178953	0.00395984	0	0.184528	0.140192	0.223651
700	0.49	0.0146954	0.173603	0.00339197	0	0.17742	0.139723	0.223235
700	0.5	0.0130821	0.168269	0.00289159	0	0.1702	0.139291	0.222845
700	0.51	0.0116199	0.162952	0.00245495	0	0.162878	0.138894	0.222479
700	0.52	0.0103006	0.157653	0.00207853	0	0.155461	0.138529	0.222137
700	0.53	0.0091172	0.152373	0.00175797	0	0.14865	0.138198	0.221818
700	0.54	0.00804896	0.147125	0.00147903	0	0.142326	0.137896	0.221523
700	0.55	0.00708584	0.141913	0.00123738	0	0.135811	0.137616	0.221247
700	0.56	0.00622815	0.136728	0.00103514	0	0.128866	0.13736	0.22099
700	0.57	0.00545587	0.131592	0.000859692	0	0.122174	0.137124	0.22075
700	0.58	0.00476481	0.126503	0.000709713	0	0.115727	0.136909	0.220526
700	0.59	0.00415106	0.121462	0.000583949	0	0.109512	0.136713	0.220318
700	0.6	0.00361091	0.116466	0.000481224	0	0.103521	0.136535	0.220125
700	0.61	0.00313234	0.111516	0.000395915	0	0.0987924	0.136371	0.219943
700	0.62	0.00270273	0.106636	0.000321888	0	0.0940419	0.136217	0.219773
700	0.63	0.00232052	0.101826	0.000258944	0	0.0888425	0.136075	0.219615
700	0.64	0.0019903	0.0970669	0.000209454	0	0.0824631	0.135944	0.219471
700	0.65	0.0016971	0.09239	0.000167397	0	0.0763778	0.135822	0.219336
700	0.66	0.00143827	0.0877947	0.00013201	0	0.0706895	0.13571	0.219209
700	0.67	0.00121235	0.0832786	0.000103	0	0.0653816	0.135606	0.219089
700	0.68	0.00101793	0.0788391	0	0	0.0604386	0.13551	0.218977
700	0.69	0.000853677	0.0744738	0	0	0.0558457	0.135423	0.218871

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1000	0.01	2.79247	0.366511	1.3968	0.457048	5.61005	1.82716	0.919742
1000	0.02	2.15668	0.365559	0.991901	0.204231	3.82578	1.28553	0.712858
1000	0.03	1.79387	0.363911	0.8028	0.114483	2.93931	1.00812	0.605074
1000	0.04	1.53776	0.361895	0.684616	0.072157	2.4272	0.829507	0.53499
1000	0.05	1.33956	0.359693	0.599003	0.0489113	2.03234	0.70252	0.484414
1000	0.06	1.17884	0.357397	0.531702	0.0349214	1.75792	0.607543	0.44582
1000	0.07	1.04477	0.355012	0.475982	0.0258933	1.53263	0.534022	0.415265
1000	0.08	0.930248	0.352551	0.428124	0.0196568	1.3774	0.475356	0.390323
1000	0.09	0.831432	0.350011	0.386264	0.0152195	1.24919	0.42789	0.369668
1000	0.1	0.745226	0.347383	0.349104	0.011944	1.13285	0.38883	0.352289
1000	0.11	0.669511	0.344657	0.315824	0.00946636	1.04641	0.356319	0.337515
1000	0.12	0.602507	0.341833	0.285792	0.00755059	1.0035	0.328926	0.324818
1000	0.13	0.543024	0.338898	0.25861	0.00605045	0.930891	0.305688	0.313837
1000	0.14	0.490023	0.335856	0.233942	0.00486824	0.869851	0.285842	0.304284
1000	0.15	0.442533	0.332695	0.211482	0.00391743	0.807676	0.268692	0.295895
1000	0.16	0.400033	0.329426	0.191078	0.00315756	0.790941	0.253876	0.288535
1000	0.17	0.36183	0.326042	0.172485	0.00254717	0.750797	0.240991	0.282023
1000	0.18	0.327358	0.322539	0.155526	0.00205104	0.711319	0.229683	0.276229
1000	0.19	0.296333	0.318929	0.14011	0.00165182	0.670335	0.219782	0.271073
1000	0.2	0.26834	0.315198	0.126087	0.00132906	0.633146	0.211067	0.266473
1000	0.21	0.243019	0.311357	0.113333	0.00106751	0.599613	0.203352	0.262345
1000	0.22	0.220099	0.307412	0.10174	0.000855653	0.567975	0.19651	0.258626
1000	0.23	0.19935	0.303359	0.0912182	0.00068483	0.536348	0.190429	0.255276
1000	0.24	0.18052	0.299203	0.081661	0.000546588	0.510498	0.185002	0.252245
1000	0.25	0.163438	0.29495	0.0730024	0.000435292	0.486773	0.180152	0.249489
1000	0.26	0.148007	0.290594	0.0651978	0.000346617	0.464841	0.175832	0.246999
1000	0.27	0.133941	0.286149	0.0581121	0.000274763	0.445278	0.17194	0.244725
1000	0.28	0.121202	0.281612	0.0517329	0.000217414	0.424888	0.168453	0.242649
1000	0.29	0.109634	0.276991	0.0459836	0.00017143	0.404331	0.165314	0.240749
1000	0.3	0.0990979	0.272294	0.0407912	0.00013467	0.384466	0.162474	0.239005
1000	0.31	0.0895467	0.26752	0.0361336	0.000105558	0.367805	0.159916	0.237409
1000	0.32	0.0808812	0.262672	0.0319576	0	0.354232	0.15761	0.235943
1000	0.33	0.0729865	0.257752	0.028202	0	0.340394	0.155516	0.234588
1000	0.34	0.0658381	0.252773	0.0248526	0	0.32613	0.153627	0.233339
1000	0.35	0.0593534	0.24774	0.0218644	0	0.312305	0.151917	0.232187
1000	0.36	0.0534345	0.242648	0.0191816	0	0.300595	0.15035	0.23112
1000	0.37	0.0480904	0.237508	0.0168079	0	0.290465	0.148936	0.23013
1000	0.38	0.043242	0.232323	0.0146969	0	0.279485	0.14765	0.229213
1000	0.39	0.0388436	0.227099	0.0128232	0	0.267057	0.14648	0.228365
1000	0.4	0.0348627	0.221838	0.0111693	0	0.254385	0.145416	0.227578
1000	0.41	0.0312476	0.216542	0.00970278	0	0.245628	0.144445	0.226843
1000	0.42	0.0279685	0.211219	0.00840448	0	0.236505	0.143556	0.226158
1000	0.43	0.025004	0.205876	0.00726341	0	0.227047	0.142747	0.225522
1000	0.44	0.022328	0.200516	0.00626447	0	0.217614	0.142008	0.22493
1000	0.45	0.0199072	0.195143	0.00538629	0	0.209036	0.141332	0.224375
1000	0.46	0.0177311	0.18976	0.00462535	0	0.200618	0.140716	0.223858
1000	0.47	0.0157624	0.184373	0.00395738	0	0.192007	0.140151	0.223377
1000	0.48	0.0139824	0.178988	0.00337234	0	0.18399	0.139633	0.222928
1000	0.49	0.0123819	0.173606	0.00286701	0	0.176558	0.139159	0.22251
1000	0.5	0.010941	0.168237	0.00242644	0	0.169532	0.138724	0.222119
1000	0.51	0.00965083	0.162883	0.00204701	0	0.162891	0.138325	0.221754
1000	0.52	0.00850324	0.157544	0.00172533	0	0.156615	0.13796	0.221413
1000	0.53	0.00748234	0.152221	0.00145363	0	0.150381	0.13763	0.221097
1000	0.54	0.00656094	0.146929	0.00121609	0	0.143788	0.137328	0.220802
1000	0.55	0.00573535	0.141673	0.00101126	0	0.136946	0.137048	0.220526
1000	0.56	0.00500765	0.136446	0.000841468	0	0.129317	0.136791	0.220267
1000	0.57	0.00435469	0.131266	0.000694397	0	0.122395	0.136553	0.220025
1000	0.58	0.00377281	0.126133	0.000568917	0	0.116143	0.136336	0.2198

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M. Cirelli, N. Fornengo, T. Montaruli, I. Sokalski, A. Strumia and F. Vissani, hep-ph/0506298

http://www.marcocirelli.net/DMnu.html

700	0.12	0.608978	0.341566	0.288158	0.00732825	1.01016	0.329712	0.325684
700	0.13	0.549979	0.338742	0.261576	0.00587295	0.938862	0.306415	0.314678
700	0.14	0.497406	0.335783	0.237414	0.00472903	0.879793	0.28655	0.305119
700	0.15	0.45023	0.332688	0.215358	0.00380882	0.814194	0.269374	0.296714
700	0.16	0.407863	0.329461	0.195214	0.00307157	0.79659	0.254494	0.289315
700	0.17	0.369843	0.326101	0.176844	0.00248237	0.753636	0.24159	0.282798
700	0.18	0.335522	0.322618	0.160047	0.00200452	0.716648	0.230284	0.277002
700	0.19	0.304578	0.31901	0.14472	0.00162001	0.675494	0.220381	0.271845
700	0.2	0.276564	0.315279	0.130711	0.00130737	0.637912	0.211633	0.26723
700	0.21	0.251174	0.311436	0.117905	0.00105404	0.604016	0.203894	0.263081
700	0.22	0.228188	0.307472	0.10625	0.000849125	0.572074	0.19704	0.259361
700	0.23	0.207361	0.30339	0.0956315	0.000683914	0.540172	0.190963	0.25601
700	0.24	0.188471	0.299207	0.0859745	0.00055027	0.514165	0.185543	0.25298
700	0.25	0.171298	0.29493	0.0771891	0.000442236	0.490279	0.180708	0.250232
700	0.26	0.155638	0.290551	0.0691846	0.00035443	0.46804	0.176369	0.247734
700	0.27	0.141436	0.28608	0.0619432	0.000283948	0.449289	0.172486	0.245459
700	0.28	0.12846	0.281519	0.0553506	0.000226624	0.425593	0.168987	0.243375
700	0.29	0.116646	0.276873	0.0493849	0.00018028	0.402885	0.165838	0.241472
700	0.3	0.105937	0.272149	0.044022	0.000143647	0.385856	0.163012	0.239737
700	0.31	0.0961617	0.267351	0.0391701	0.00011413	0.370693	0.160458	0.238141
700	0.32	0.0872398	0.262489	0.0347864	0	0.356329	0.158152	0.236669
700	0.33	0.0791152	0.257559	0.0308456	0	0.342135	0.156067	0.235315
700	0.34	0.0716946	0.252566	0.0272953	0	0.327646	0.154173	0.234065
700	0.35	0.0649382	0.247521	0.0241132	0	0.313854	0.15246	0.232911
700	0.36	0.0587938	0.242423	0.0212697	0	0.302327	0.150908	0.231843
700	0.37	0.053184	0.237281	0.0187219	0	0.292082	0.149494	0.230853
700	0.38	0.0480605	0.232096	0.0164396	0	0.280878	0.148205	0.229935
700	0.39	0.0433863	0.226871	0.0144014	0	0.26817	0.14703	0.229083
700	0.4	0.0391341	0.221616	0.0125922	0	0.255281	0.145962	0.228293
700	0.41	0.0352722	0.216337	0.0109905	0	0.246658	0.144988	0.227559
700	0.42	0.0317531	0.211032	0.00956675	0	0.237501	0.1441	0.226875
700	0.43	0.0285549	0.205707	0.00830948	0	0.227852	0.143291	0.22624
700	0.44	0.0256505	0.200367	0.00720247	0	0.218472	0.142555	0.225648
700	0.45	0.0230042	0.195016	0.00622261	0	0.211149	0.14188	0.225094
700	0.46	0.0206088	0.189659	0.00536784	0	0.203462	0.141266	0.224579
700	0.47	0.0184371	0.184305	0.00461755	0	0.193263	0.140705	0.224098
700	0.48	0.0164685	0.178953	0.00395984	0	0.184528	0.140192	0.223651
700	0.49	0.0146954	0.173603	0.00339197	0	0.17742	0.139723	0.223235
700	0.5	0.0130821	0.168269	0.00289159	0	0.1702	0.139291	0.222845
700	0.51	0.0116199	0.162952	0.00245495	0	0.162878	0.138894	0.222479
700	0.52	0.0103006	0.157653	0.00207853	0	0.155461	0.138529	0.222137
700	0.53	0.0091172	0.152373	0.00175797	0	0.14865	0.138198	0.221818
700	0.54	0.00804896	0.147125	0.00147903	0	0.142326	0.137896	0.221523
700	0.55	0.00708584	0.141913	0.00123738	0	0.135811	0.137616	0.221247
700	0.56	0.00622815	0.136728	0.00103514	0	0.128866	0.13736	0.22099
700	0.57	0.00545587	0.131592	0.000859692	0	0.122174	0.137124	0.22075
700	0.58	0.00476481	0.126503	0.000709713	0	0.115727	0.136909	0.220526
700	0.59	0.00415106	0.121462	0.000583949	0	0.109512	0.136713	0.220318
700	0.6	0.00361091	0.116466	0.000481224	0	0.103521	0.136535	0.220125
700	0.61	0.00313234	0.111516	0.000395915	0	0.0987924	0.136371	0.219943
700	0.62	0.00270273	0.106636	0.000321888	0	0.0940419	0.136217	0.219773
700	0.63	0.00232052	0.101826	0.000258944	0	0.0888425	0.136075	0.219615
700	0.64	0.0019903	0.0970669	0.000209454	0	0.0824631	0.135944	0.219471
700	0.65	0.0016971	0.09239	0.000167397	0	0.0763778	0.135822	0.219336
700	0.66	0.00143827	0.0877947	0.00013201	0	0.0706895	0.13571	0.219209
700	0.67	0.00121235	0.0832786	0.000103	0	0.0653816	0.135606	0.219089
700	0.68	0.00101793	0.0788391	0	0	0.0604386	0.13551	0.218977
700	0.69	0.000853677	0.0744738	0	0	0.0558457	0.135423	0.218871

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1000	0.01	2.79247	0.366511	1.3968	0.457048	5.61005	1.82716	0.919742
1000	0.02	2.15668	0.365559	0.991901	0.204231	3.82578	1.28553	0.712858
1000	0.03	1.79387	0.363911	0.8028	0.114483	2.93931	1.00812	0.605074
1000	0.04	1.53776	0.361895	0.684616	0.072157	2.4272	0.829507	0.53499
1000	0.05	1.33956	0.359693	0.599003	0.0489113	2.03234	0.70252	0.484414
1000	0.06	1.17884	0.357397	0.531702	0.0349214	1.75792	0.607543	0.44582
1000	0.07	1.04477	0.355012	0.475982	0.0258933	1.53263	0.534022	0.415265
1000	0.08	0.930248	0.352551	0.428124	0.0196568	1.3774	0.475356	0.390323
1000	0.09	0.831432	0.350011	0.386264	0.0152195	1.24919	0.42789	0.369668
1000	0.1	0.745226	0.347383	0.349104	0.011944	1.13285	0.38883	0.352289
1000	0.11	0.669511	0.344657	0.315824	0.00946636	1.04641	0.356319	0.337515
1000	0.12	0.602507	0.341833	0.285792	0.00755059	1.0035	0.328926	0.324818
1000	0.13	0.543024	0.338898	0.25861	0.00605045	0.930891	0.305688	0.313837
1000	0.14	0.490023	0.335856	0.233942	0.00486824	0.869851	0.285842	0.304284
1000	0.15	0.442533	0.332695	0.211482	0.00391743	0.807676	0.268692	0.295895
1000	0.16	0.400033	0.329426	0.191078	0.00315756	0.790941	0.253876	0.288535
1000	0.17	0.36183	0.326042	0.172485	0.00254717	0.750797	0.240991	0.282023
1000	0.18	0.327358	0.322539	0.155526	0.00205104	0.711319	0.229683	0.276229
1000	0.19	0.296333	0.318929	0.14011	0.00165182	0.670335	0.219782	0.271073
1000	0.2	0.26834	0.315198	0.126087	0.00132906	0.633146	0.211067	0.266473
1000	0.21	0.243019	0.311357	0.113333	0.00106751	0.599613	0.203352	0.262345
1000	0.22	0.220099	0.307412	0.10174	0.000855653	0.567975	0.19651	0.258626
1000	0.23	0.19935	0.303359	0.0912182	0.00068483	0.536348	0.190429	0.255276
1000	0.24	0.18052	0.299203	0.081661	0.000546588	0.510498	0.185002	0.252245
1000	0.25	0.163438	0.29495	0.0730024	0.000435292	0.486773	0.180152	0.249489
1000	0.26	0.148007	0.290594	0.0651978	0.000346617	0.464841	0.175832	0.246999
1000	0.27	0.133941	0.286149	0.0581121	0.000274763	0.445278	0.17194	0.244725
1000	0.28	0.121202	0.281612	0.0517329	0.000217414	0.424888	0.168453	0.242649
1000	0.29	0.109634	0.276991	0.0459836	0.00017143	0.404331	0.165314	0.240749
1000	0.3	0.0990979	0.272294	0.0407912	0.00013467	0.384466	0.162474	0.239005
1000	0.31	0.0895467	0.26752	0.0361336	0.000105558	0.367805	0.159916	0.237409
1000	0.32	0.0808812	0.262672	0.0319576	0	0.354232	0.15761	0.235943
1000	0.33	0.0729865	0.257752	0.028202	0	0.340394	0.155516	0.234588
1000	0.34	0.0658381	0.252773	0.0248526	0	0.32613	0.153627	0.233339
1000	0.35	0.0593534	0.24774	0.0218644	0	0.312305	0.151917	0.232187
1000	0.36	0.0534345	0.242648	0.0191816	0	0.300595	0.15035	0.23112
1000	0.37	0.0480904	0.237508	0.0168079	0	0.290465	0.148936	0.23013
1000	0.38	0.043242	0.232323	0.0146969	0	0.279485	0.14765	0.229213
1000	0.39	0.0388436	0.227099	0.0128232	0	0.267057	0.14648	0.228365
1000	0.4	0.0348627	0.221838	0.0111693	0	0.254385	0.145416	0.227578
1000	0.41	0.0312476	0.216542	0.00970278	0	0.245628	0.144445	0.226843
1000	0.42	0.0279685	0.211219	0.00840448	0	0.236505	0.143556	0.226158
1000	0.43	0.025004	0.205876	0.00726341	0	0.227047	0.142747	0.225522
1000	0.44	0.022328	0.200516	0.00626447	0	0.217614	0.142008	0.22493
1000	0.45	0.0199072	0.195143	0.00538629	0	0.209036	0.141332	0.224375
1000	0.46	0.0177311	0.18976	0.00462535	0	0.200618	0.140716	0.223858
1000	0.47	0.0157624	0.184373	0.00395738	0	0.192007	0.140151	0.223377
1000	0.48	0.0139824	0.178988	0.00337234	0	0.18399	0.139633	0.222928
1000	0.49	0.0123819	0.173606	0.00286701	0	0.176558	0.139159	0.22251
1000	0.5	0.010941	0.168237	0.00242644	0	0.169532	0.138724	0.222119
1000	0.51	0.00965083	0.162883	0.00204701	0	0.162891	0.138325	0.221754
1000	0.52	0.00850324	0.157544	0.00172533	0	0.156615	0.13796	0.221413
1000	0.53	0.00748234	0.152221	0.00145363	0	0.150381	0.13763	0.221097
1000	0.54	0.00656094	0.146929	0.00121609	0	0.143788	0.137328	0.220802
1000	0.55	0.00573535	0.141673	0.00101126	0	0.136946	0.137048	0.220526
1000	0.56	0.00500765	0.136446	0.000841468	0	0.129317	0.136791	0.220267
1000	0.57	0.00435469	0.131266	0.000694397	0	0.122395	0.136553	0.220025
1000	0.58	0.00377281	0.126133	0.000568917	0	0.116143	0.136336	0.2198

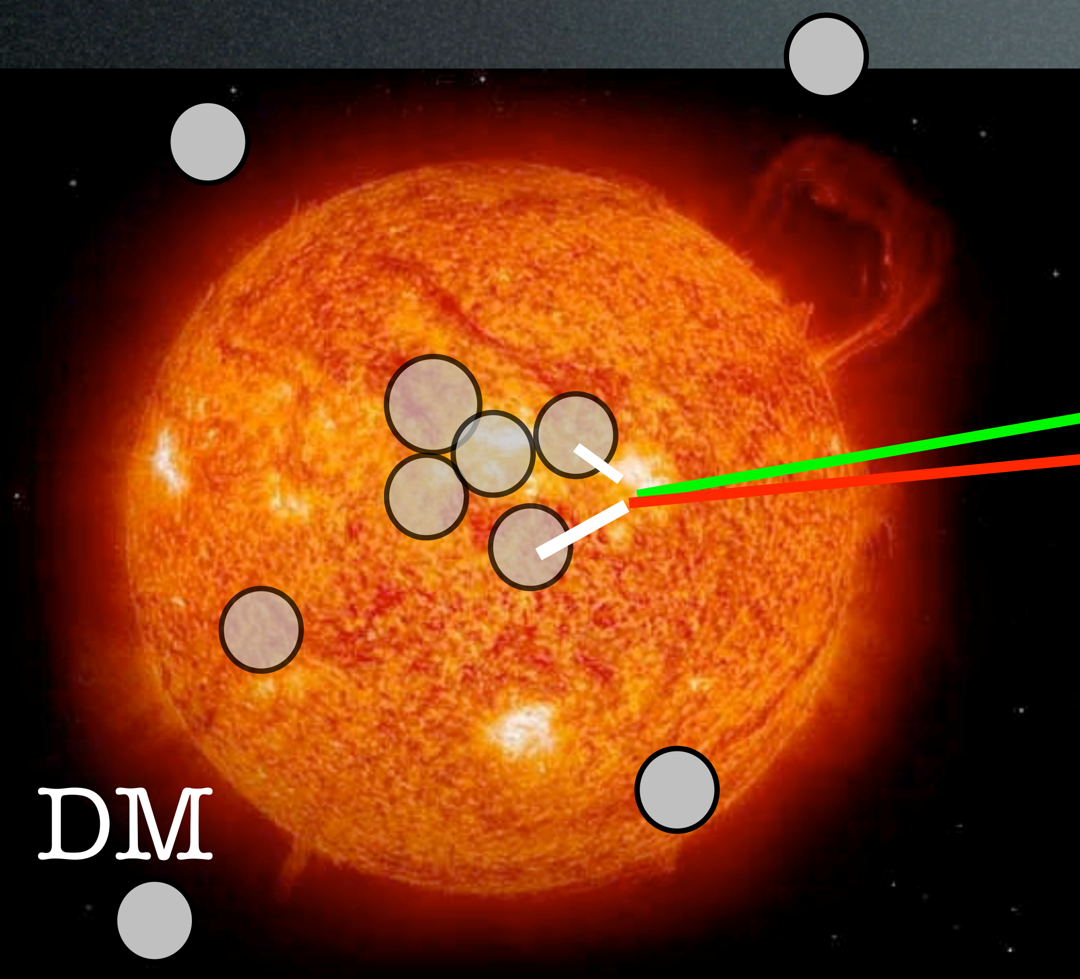
....

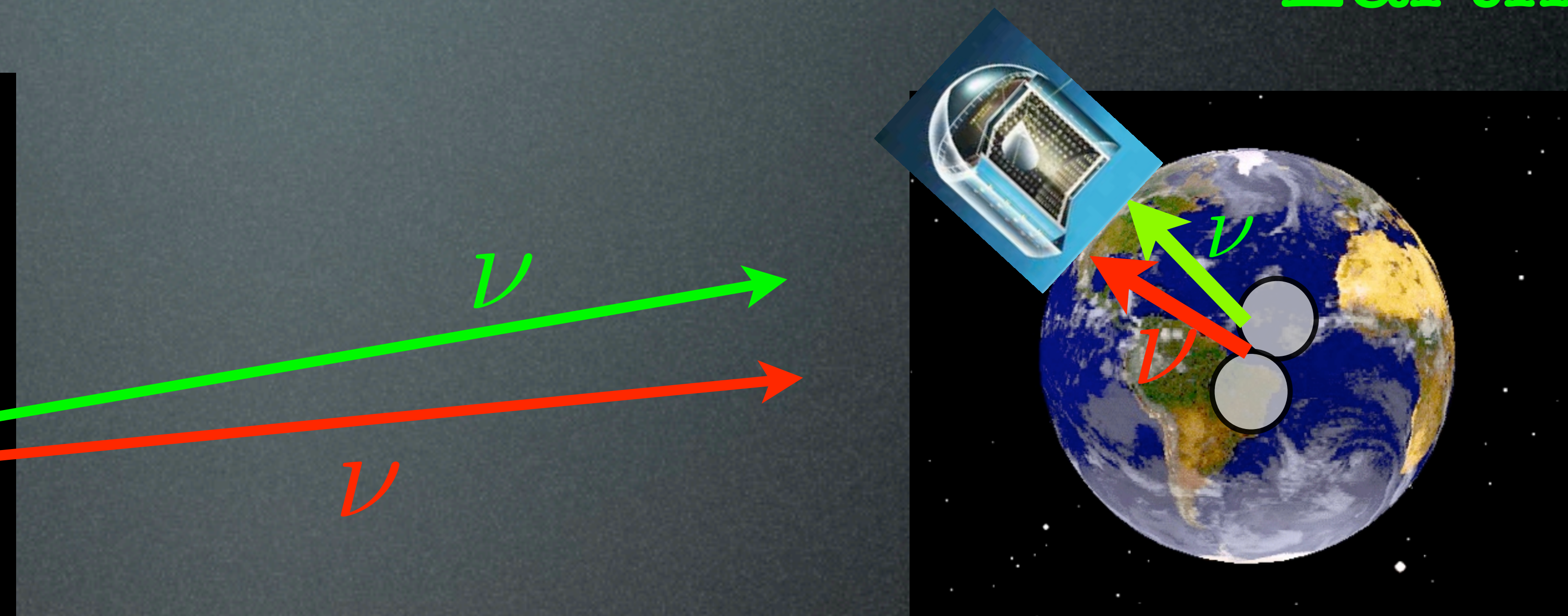
http://www.marcocirelli.net/**PPPC4DMID.html**

Neutrinos from DM in the Sun

Sun

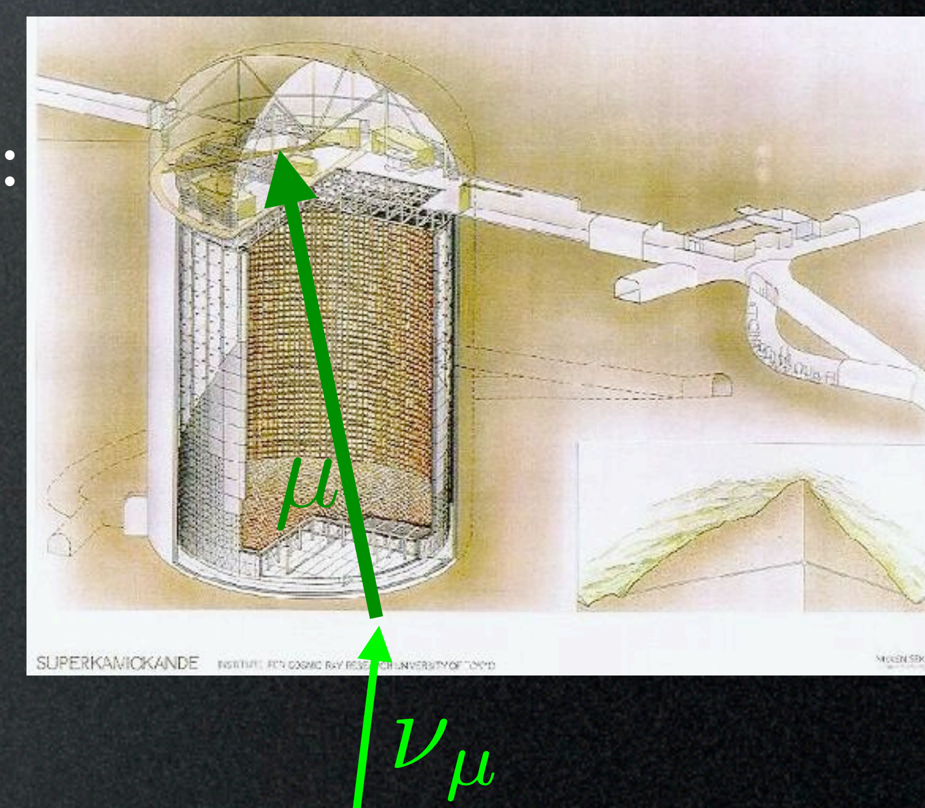
Earth





DM

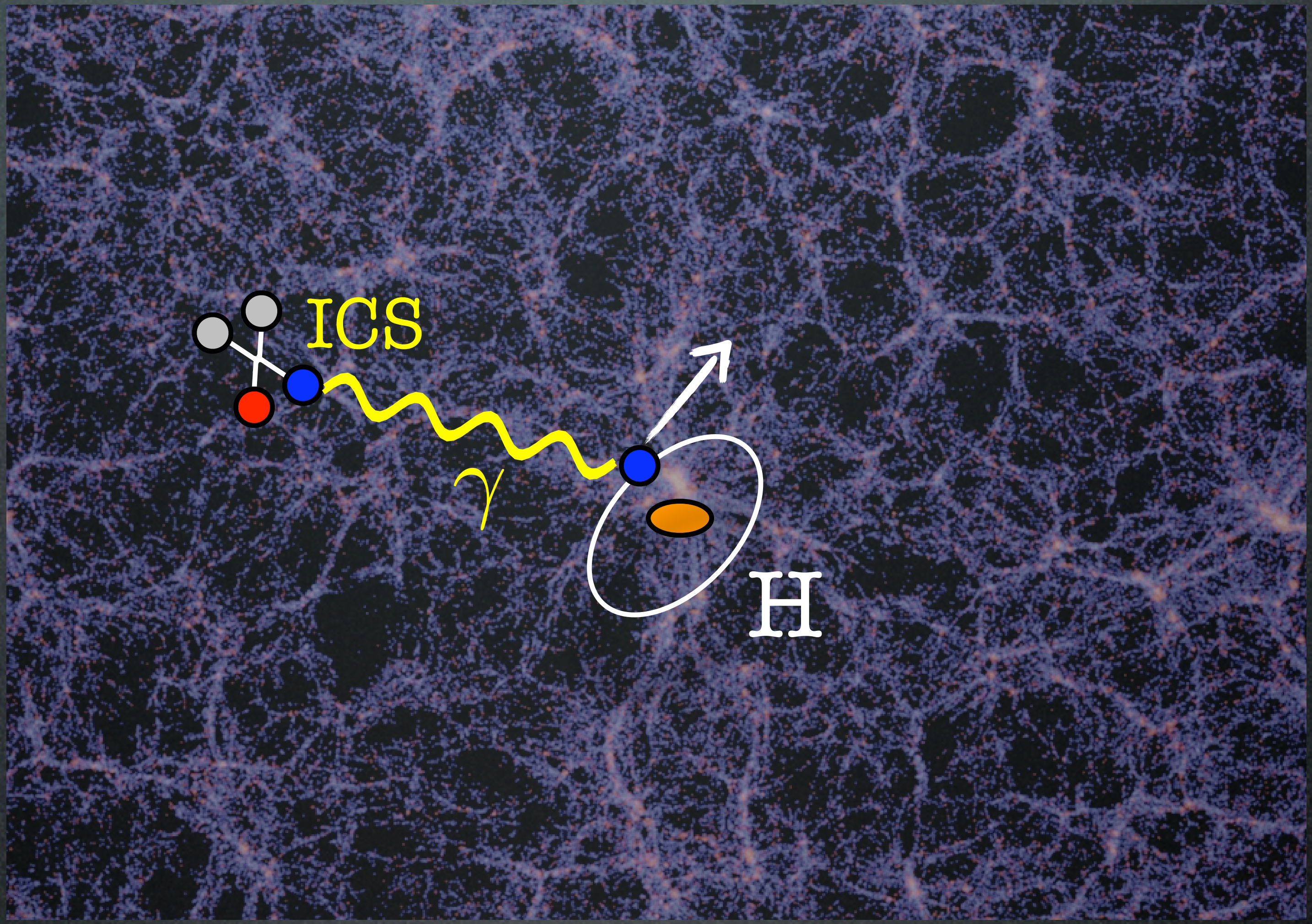
up-going muons:



Not very promising
if DM is heavy
and leptophilic.

Cosmology: bounds from reionization

DM particle annihilations produce free electrons



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

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

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

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

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

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

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

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

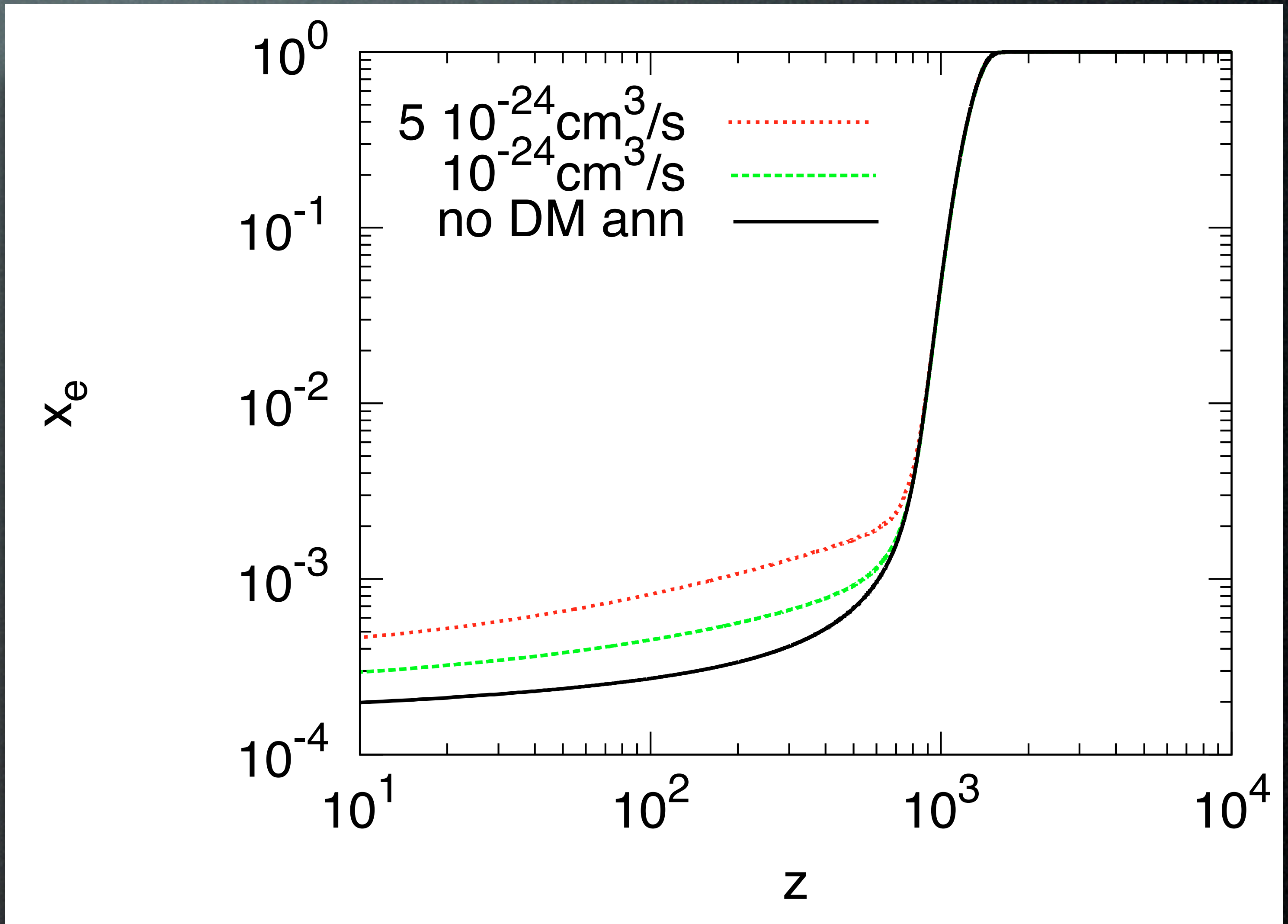
$$\mathcal{B}_i(z) = \frac{\Delta_{vir}(z)}{3\,\rho_c\Omega_M}\int_{M_{min}}^\infty dM\,M\frac{dn}{dM}(z,M)\,F_i(M,z),$$

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

Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

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

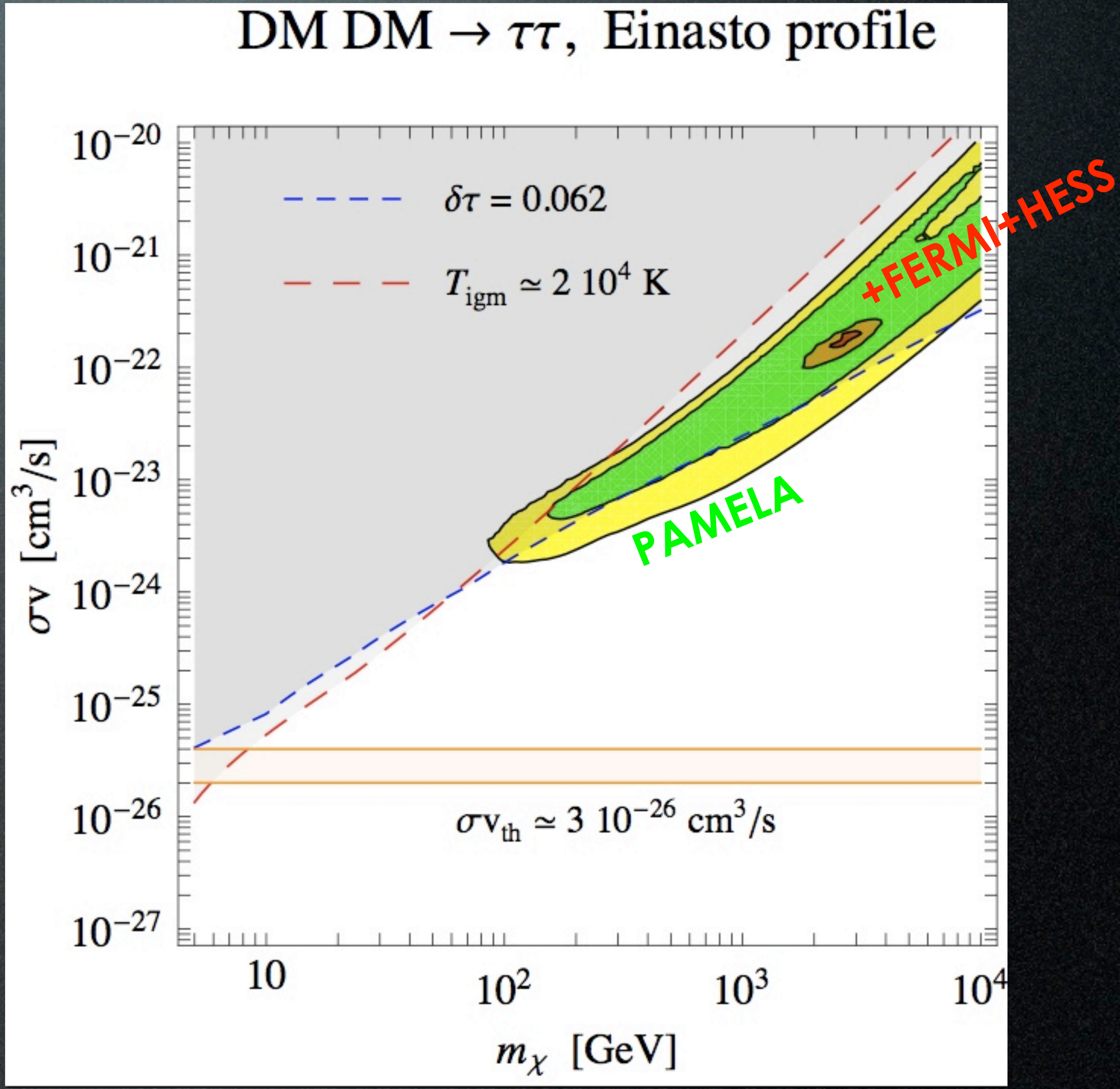


Kanzaki et al., 0907.3985

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

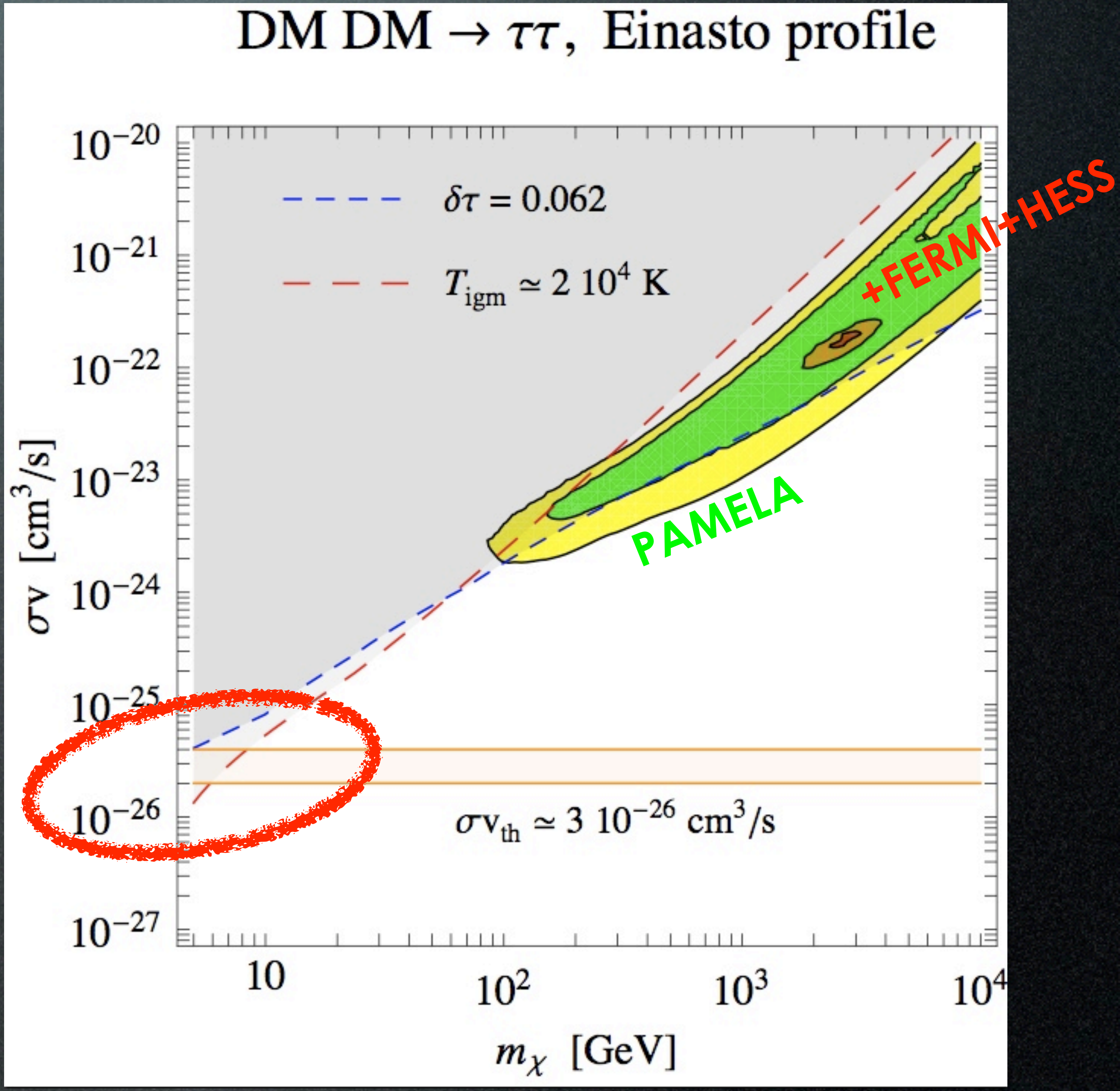
see also:
Huetsi, Hektor, Raidal 0906.4550
Kanzaki et al., 0907.3985

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)

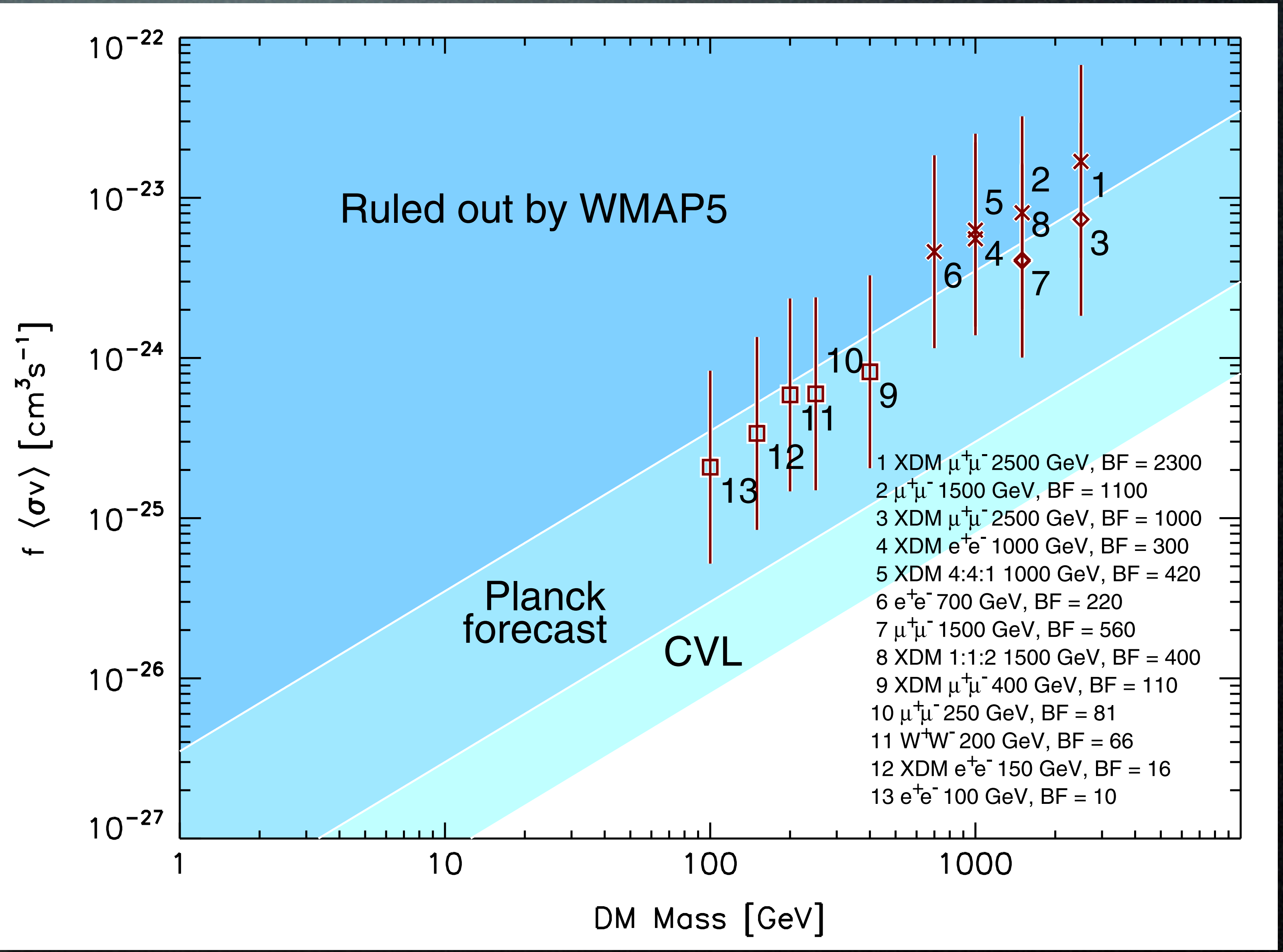
Starts constraining even thermal DM!



Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from CMB

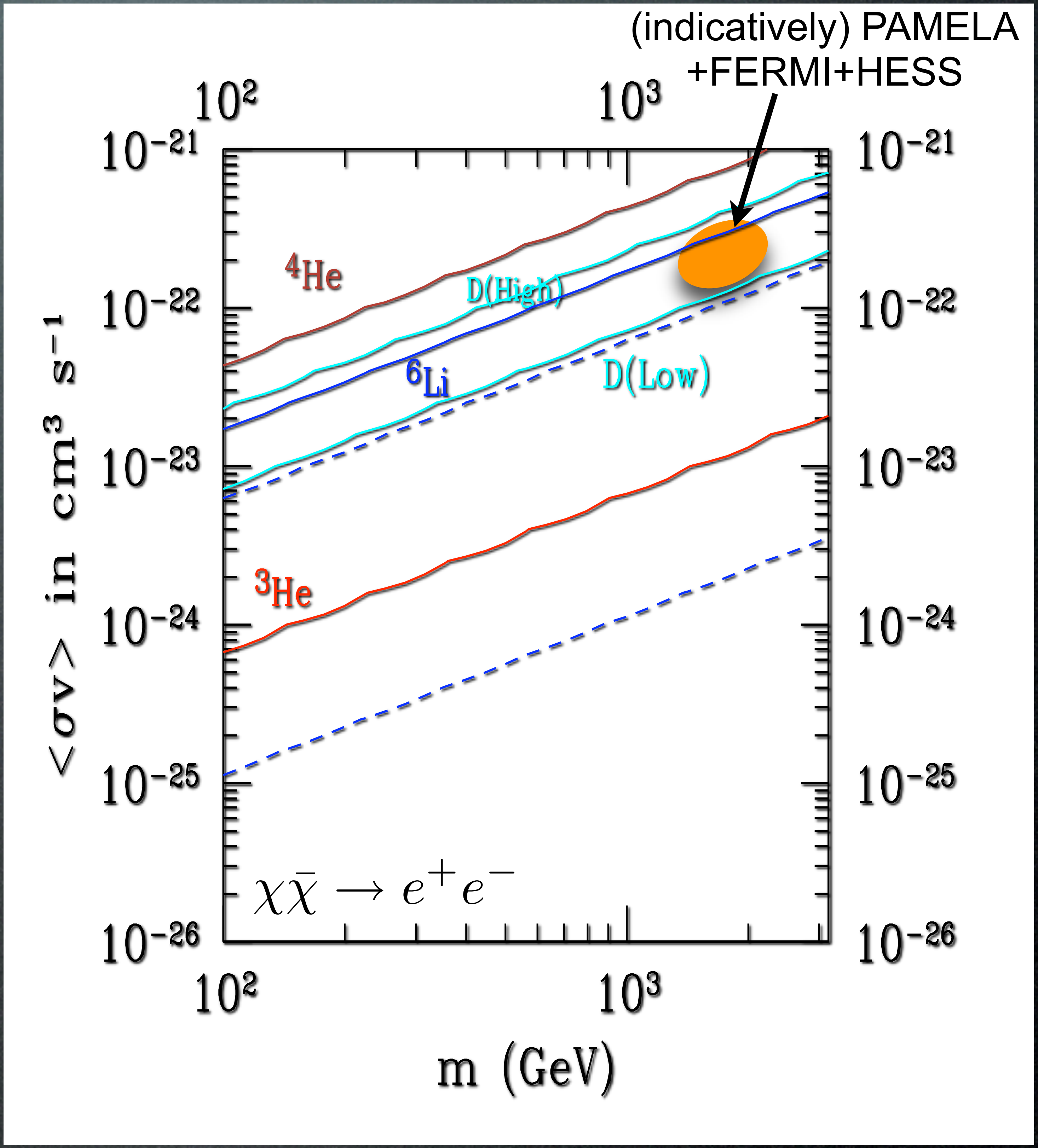
Similar conclusion from global CMB fits



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

Decaying DM

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

The current CR anomalies can be due to decay with:

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

Motivations from theory?

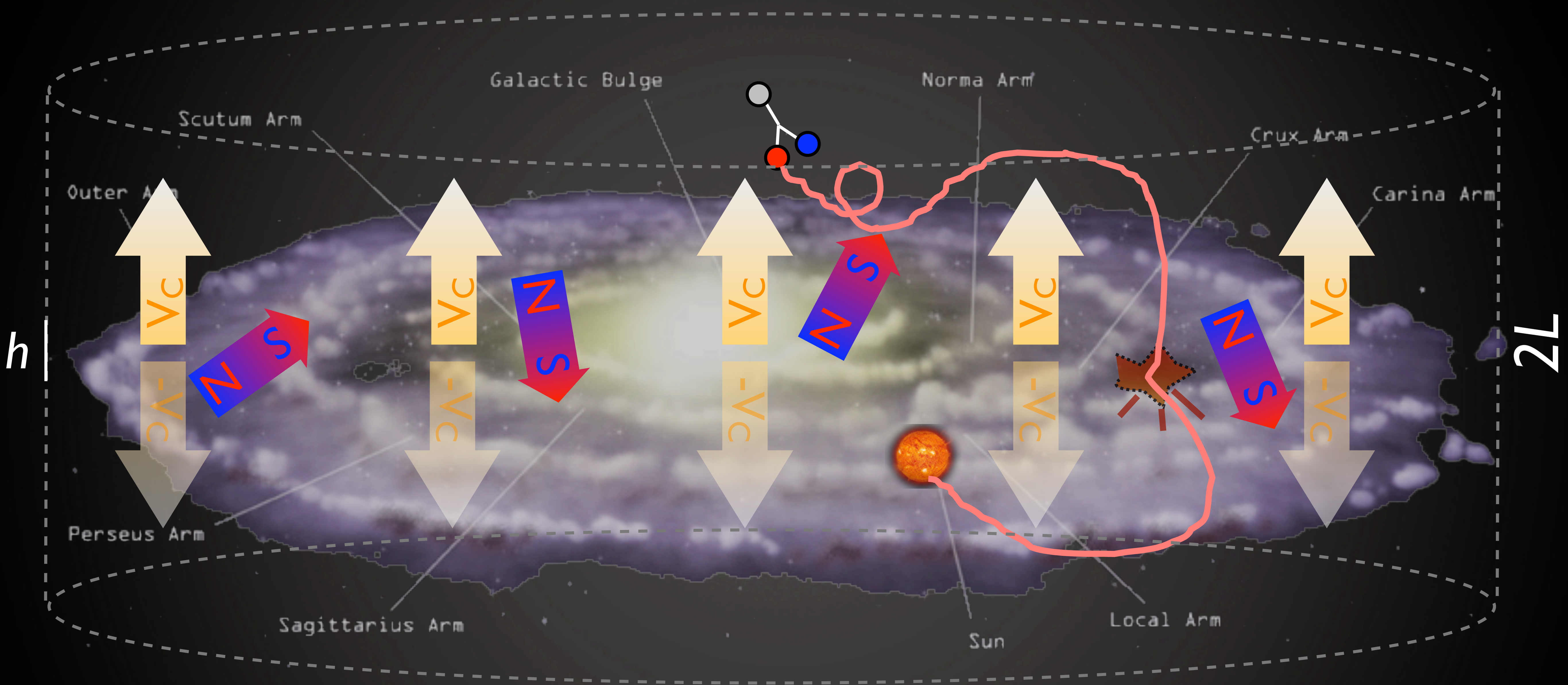
- dim 6 suppressed operator in GUT — Arvanitaki, Dimopoulos et al., 2008+09

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

- or in TechniColor — Nardi, Sannino, Strumia 2008
- gravitino in SuSy with broken R-parity...

Indirect Detection

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



What sets the overall expected flux?

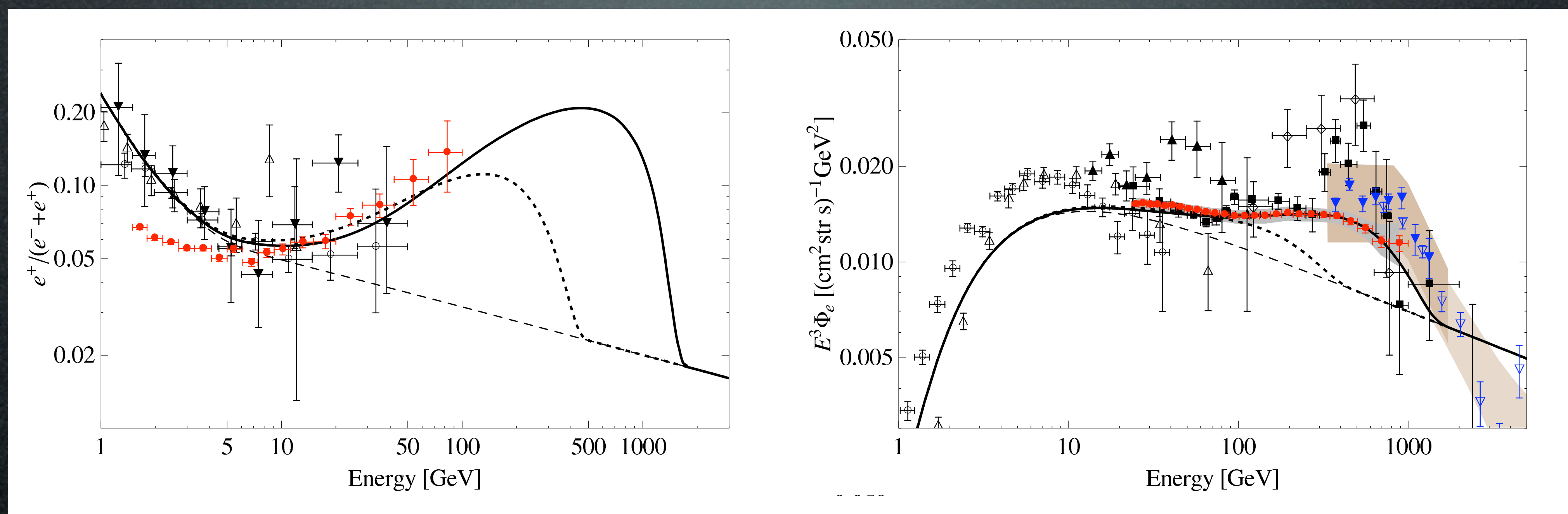
$$\text{flux} \propto n\,\Gamma_{\text{decay}}$$

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

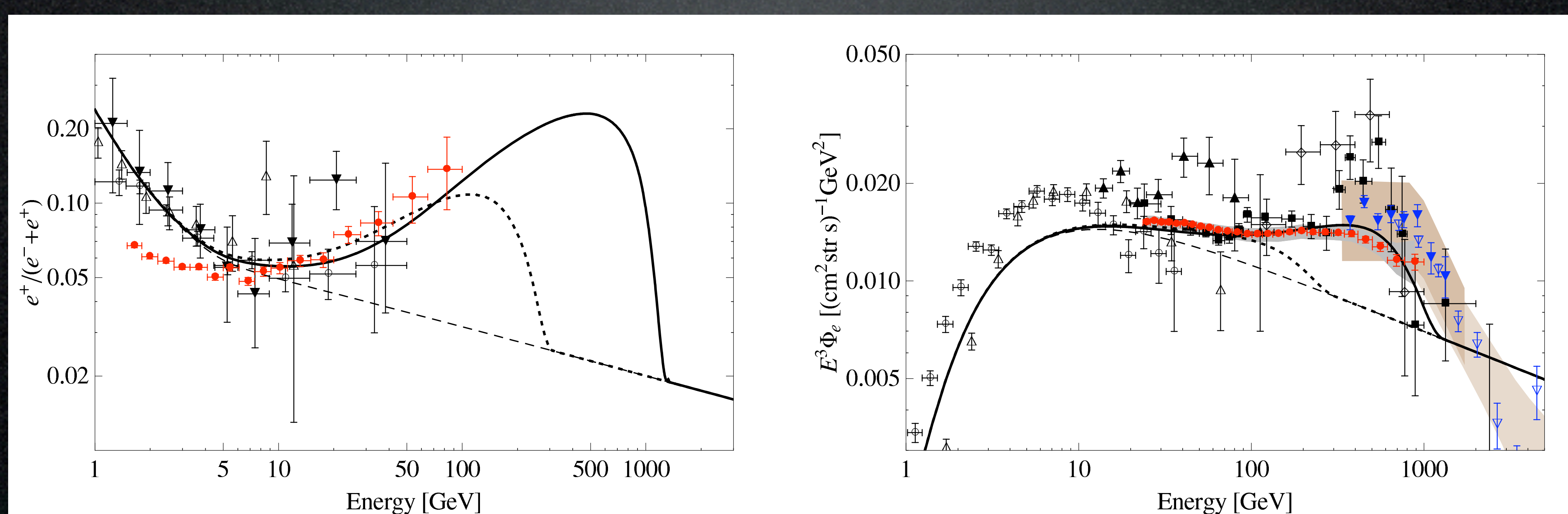
Decaying DM

Which DM spectra can fit the data?

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



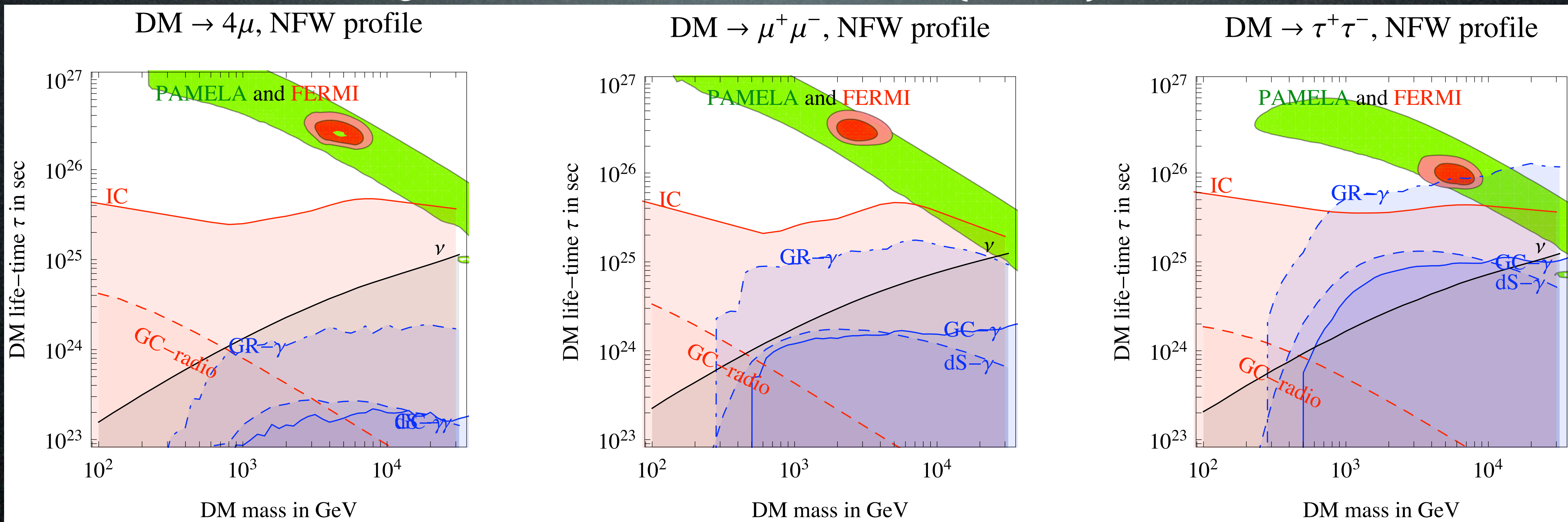
E.g. a scalar $\mathrm{DM} \to \mu^+\mu^-$ with $M_{\rm DM} = 2.5\,\mathrm{TeV}$:



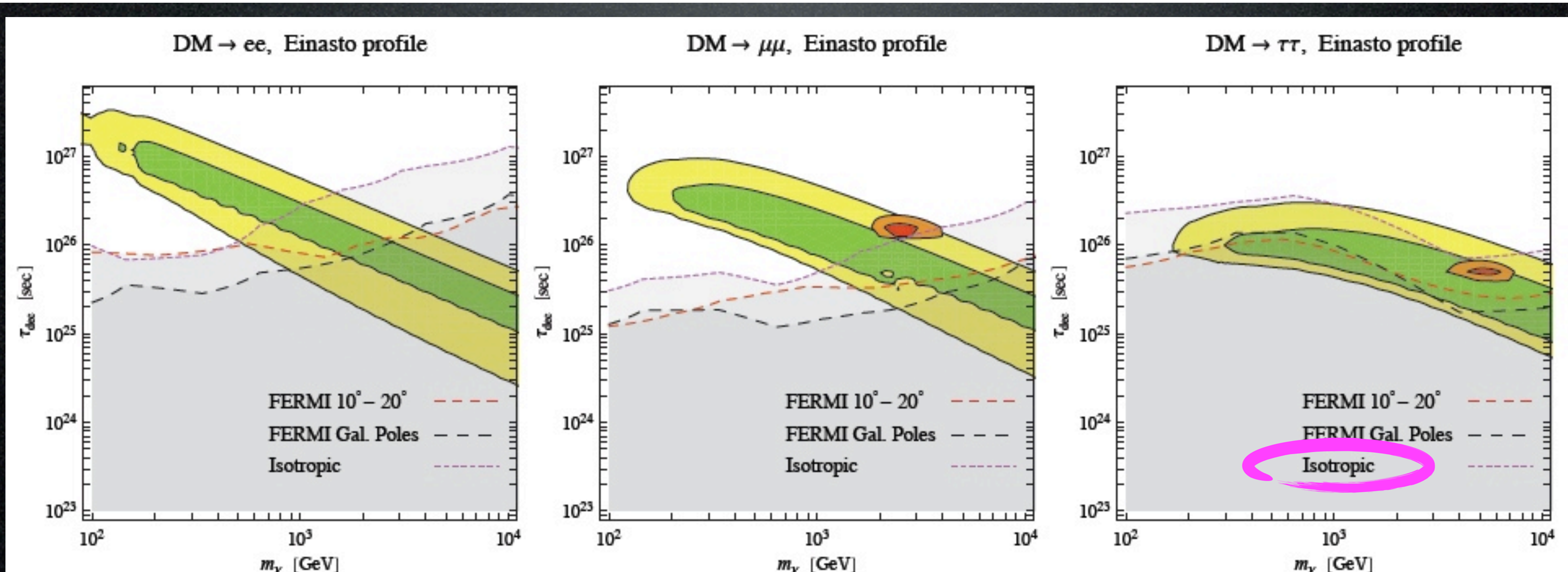
Ibarra, Tran, Weniger 2009

Decaying DM

Gamma ray, radio, neutrino (non)constraints:

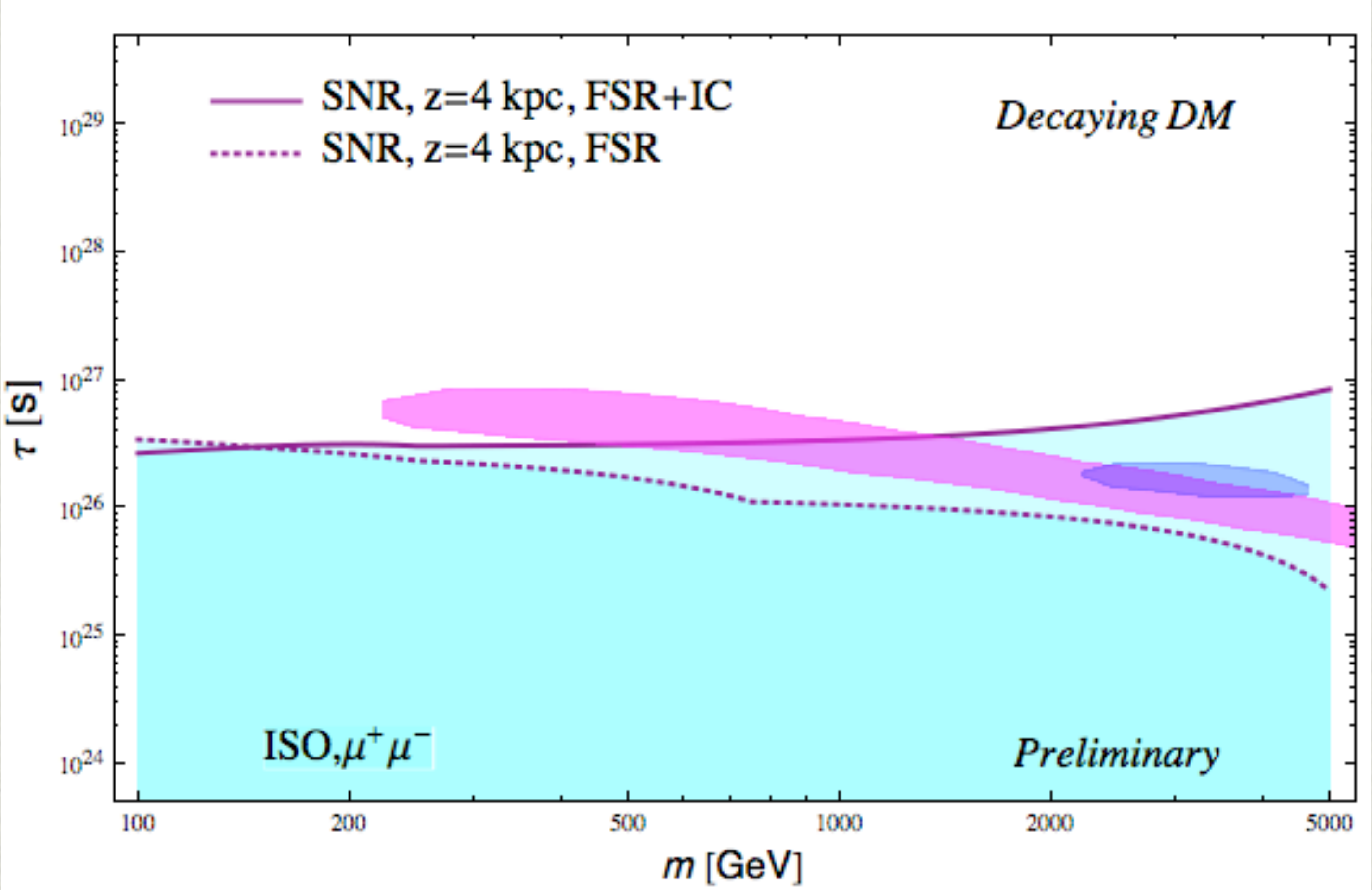


Strumia, Papucci et al. 0905.0480



Cirelli, Panci, Serpico 0912.0663

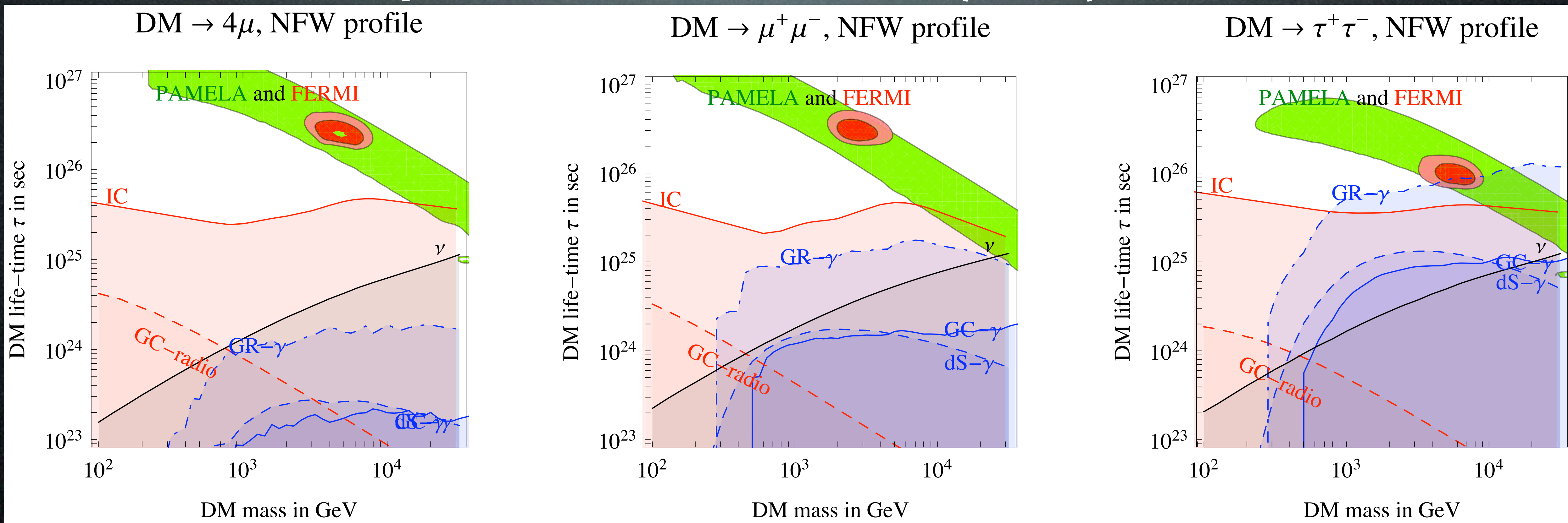
Exclusion plots, DM decay to $\mu\mu$ channel



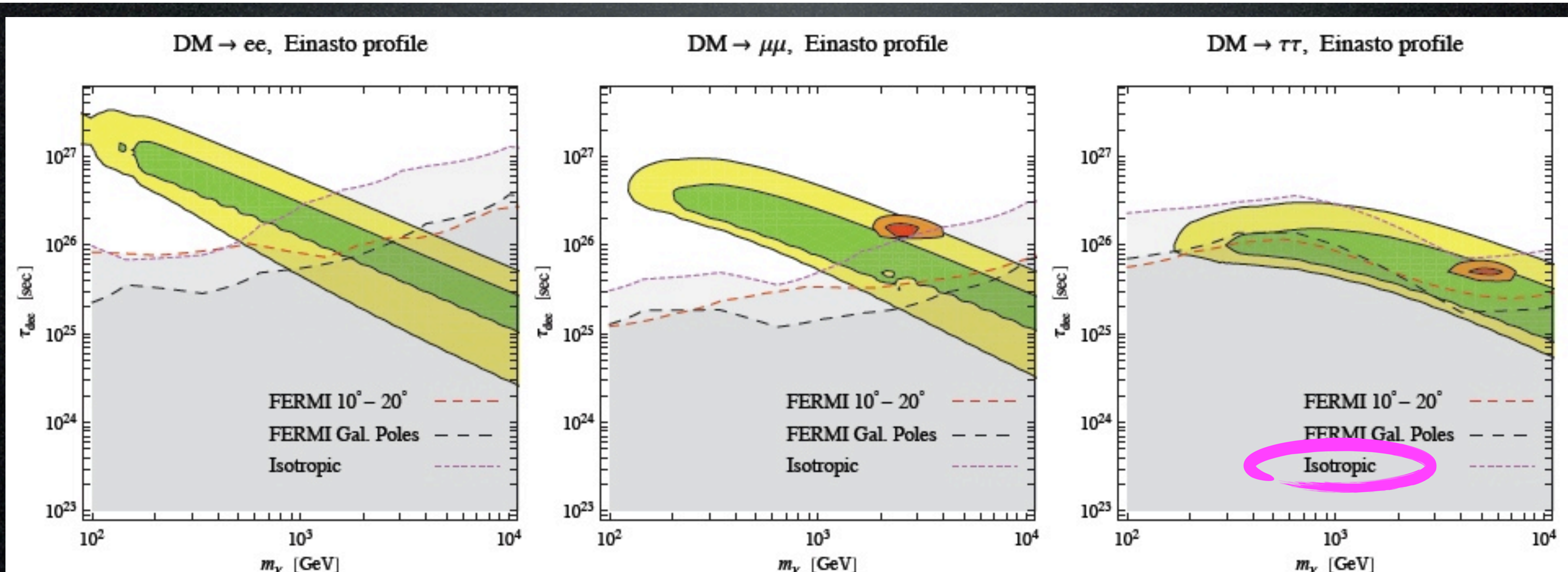
- *Also in the case of the decayibg DM, PAMELA (pink) and Fermi (Blue) regions are disfavored when full DM spectrum (FSR+IC) is considered.*

Decaying DM

Gamma ray, radio, neutrino (non)constraints:



Strumia, Papucci et al. 0905.0480



Cirelli, Panci, Serpico 0912.0663

Conclusions

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

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Status:

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

Conclusions

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

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

Conclusions

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

Status:

			Is it DM?
e^+/e^-	PAMELA, FERMI, HESS (ATIC, PPB-BETS)	something seen	heavy (few TeV)
$\bar{p}$	PAMELA	nothing strange	leptophilic
$\bar{d}$	GAPS?, AMS?	wait	
γ	FERMI, HESS	plenty of data	severe constraints
ν	SK, ICECUBE	data	not yet competitive, but stay tuned

What has the crazyness left?

Conclusions

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Hints.

And open-mindedness.

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Did we find DM in CR???

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What has the crazyness left?

Hints.

And open-mindedness.

Did we find DM in CR???

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

Back up slides

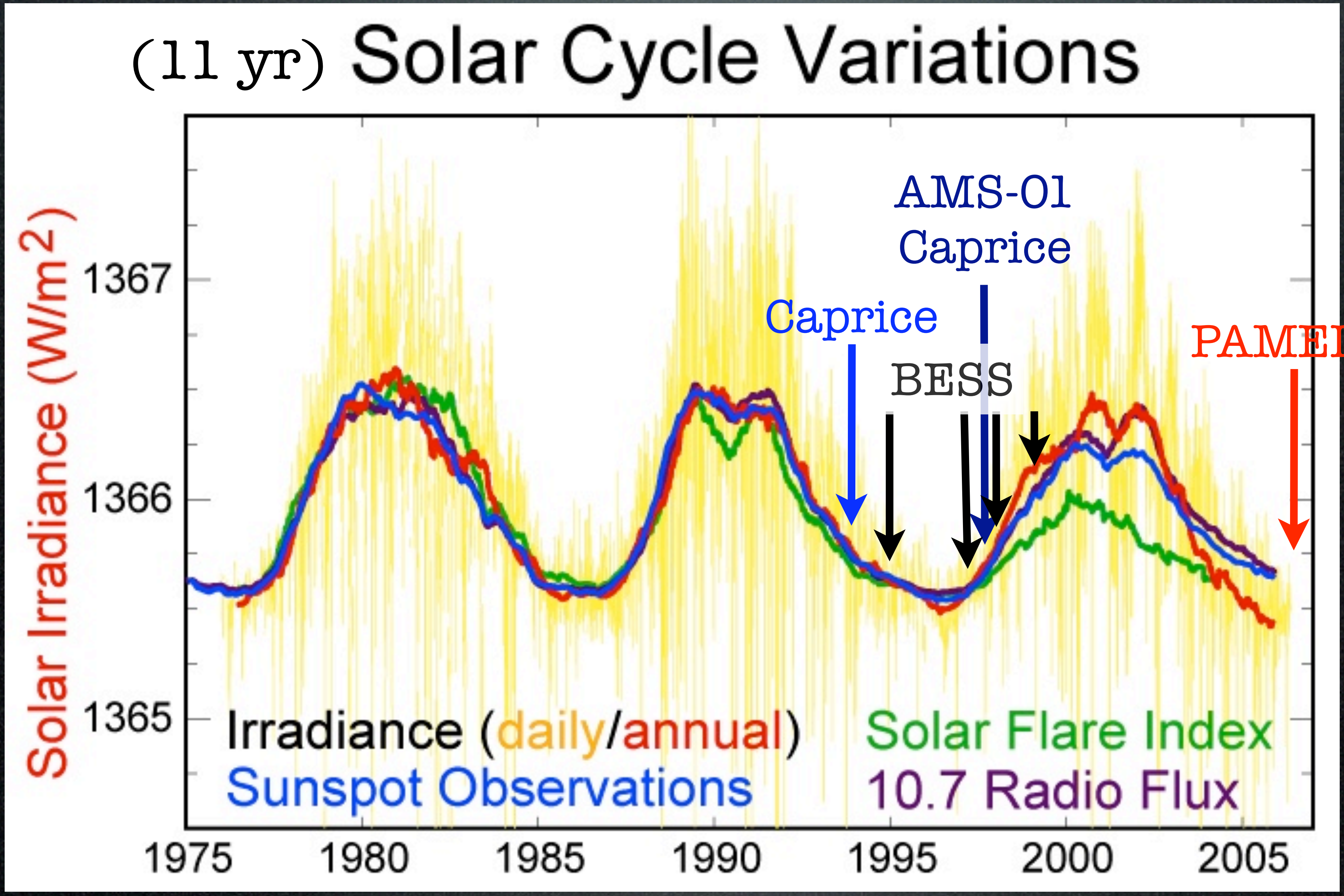
Indirect Detection

Solar wind Modulation of cosmic rays:

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

spectrum at Earth — spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV

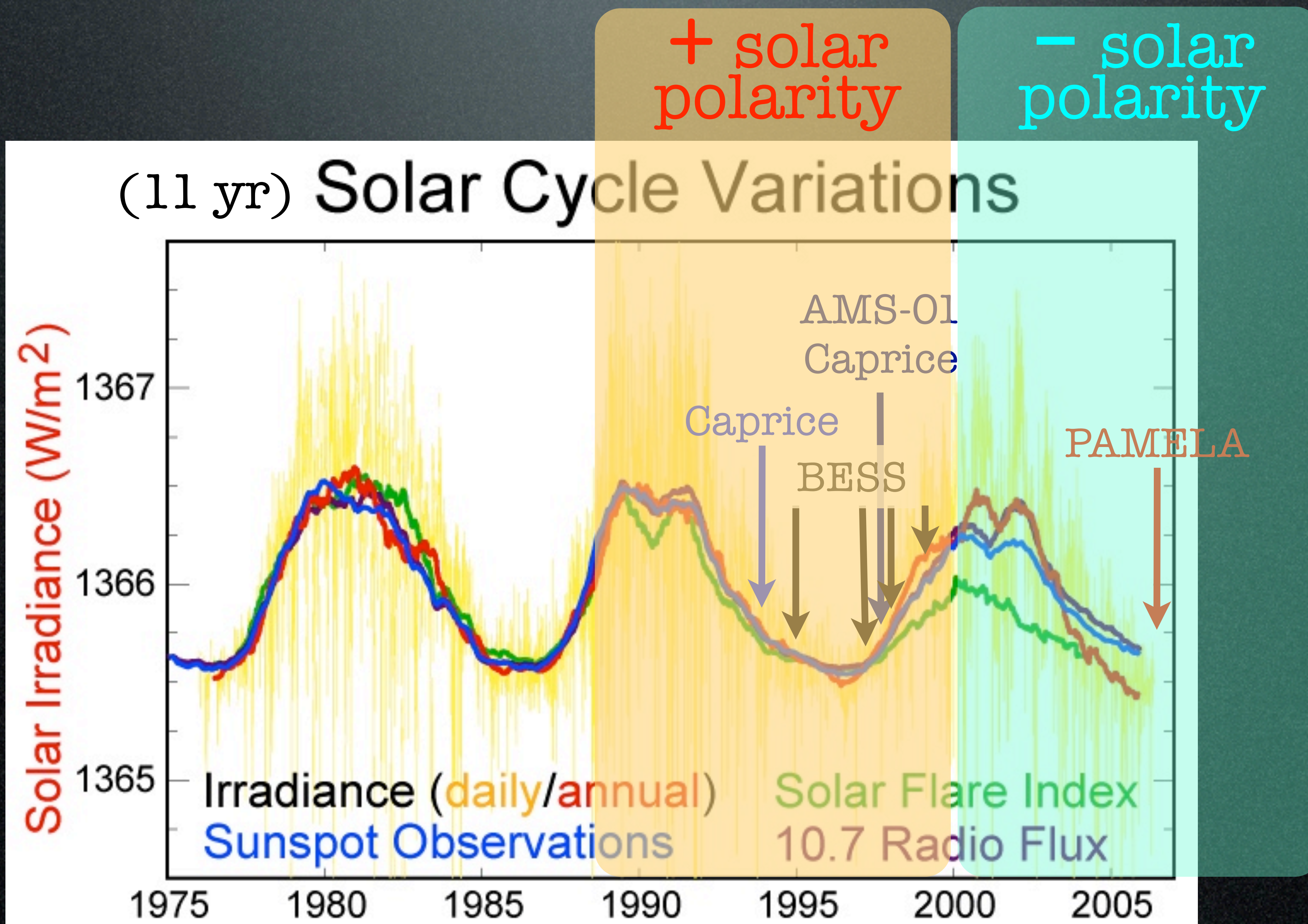


Indirect Detection

Solar polarity Modulation of cosmic rays:

solar magnetic polarity reverses at (the max of) each cycle;
during '– polarity' state, positive particles are more deflected away

+ = rotation parallel to magnetic field;
- = antiparallel



Enhancement

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

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

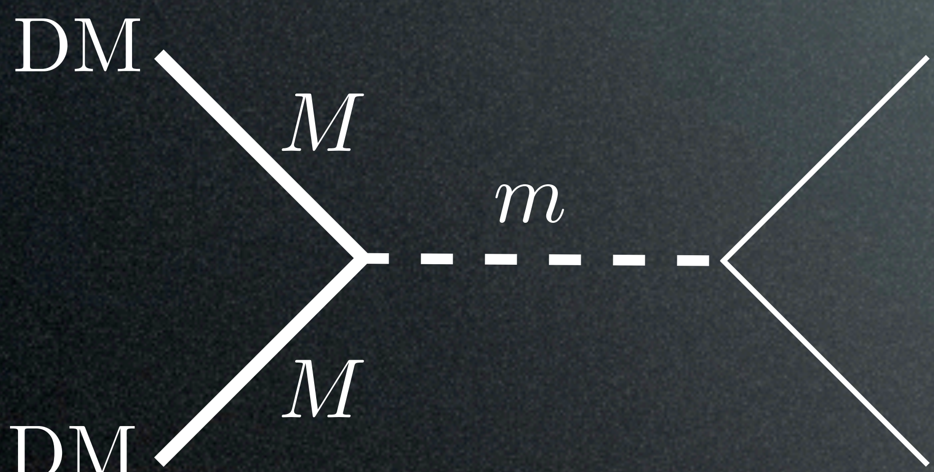
	at freeze-out	***today***
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$

+ (Wimponium)

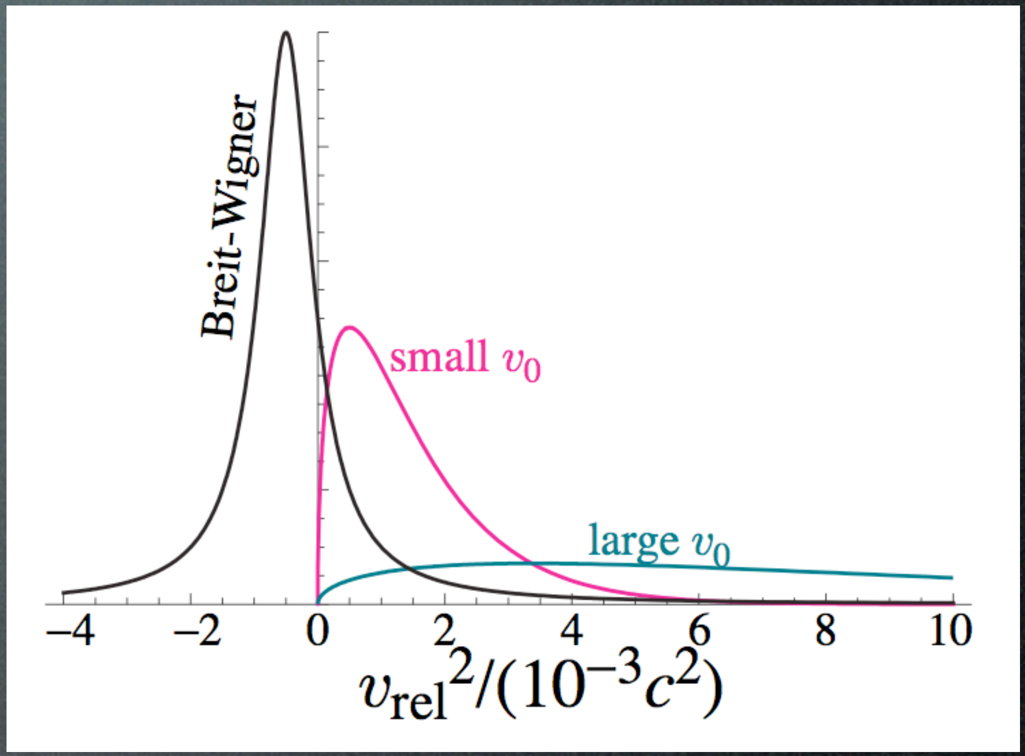
Resonance Enhancement

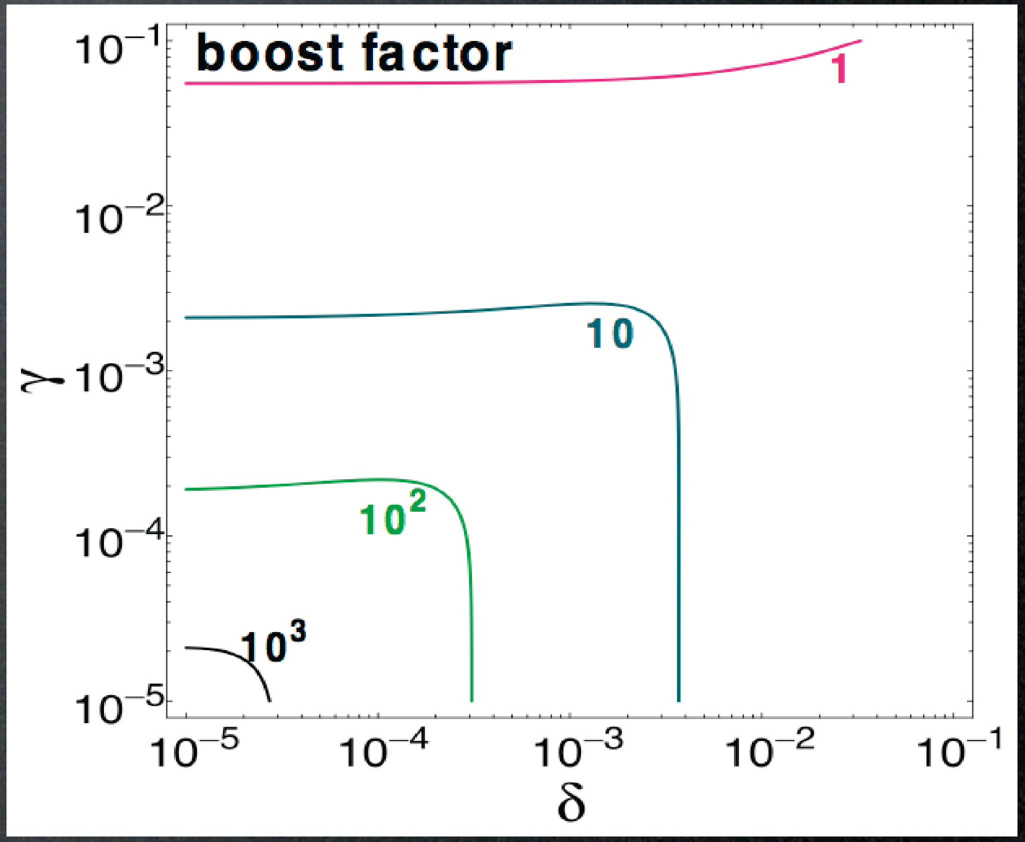
Cirelli, Kadastik, Raidal, Strumia, 2008, Sec.2
P.Nath et al. 0810.5762
Ibe, Murayama, Yanagida 0812.0072

DM annihilation via a narrow resonance just below the threshold:



$m \lesssim 2M$





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

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

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

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

Sommerfeld Enhancement

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

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

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

Cirelli, Tamburini, Strumia 0706.4071

Arkani-Hamed et al., 0810.0713

Sommerfeld Enhancement

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

A classical analogy:

Arkani-Hamed et al. 0810.0713

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

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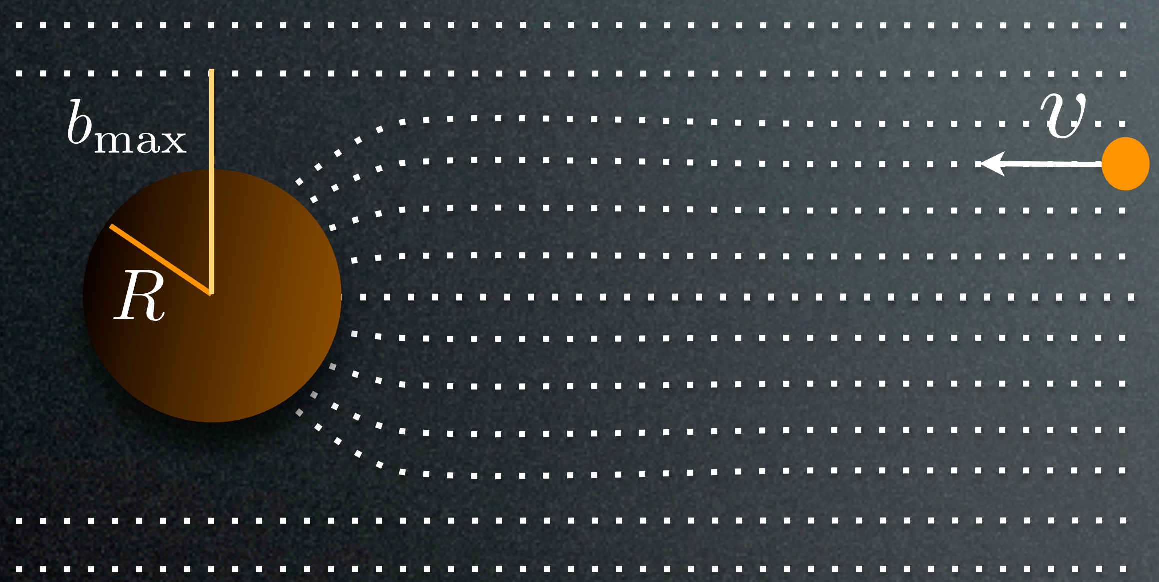

$$\sigma_0 = \pi R^2$$

$$\sigma = \pi R^2 \left(1 + \frac{2G_N M/R}{v^2}\right)$$

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

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

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

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

Sommerfeld Enhancement

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

Cirelli, Strumia, Tamburini 0706.4071

$\psi(\vec{r})$ wave function of two DM particles ($\vec{r} = \vec{r}_1 - \vec{r}_2$)
obeys (reduced) Schrödinger equation:

(V does not depend on time)

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

velocity

potential due to exchange of force carriers

At $r = 0$: annihilation

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

Sommerfeld enhancement:

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

unperturbed cross section

Sommerfeld Enhancement

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

Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071

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

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

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

Sommerfeld Enhancement

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

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Cirelli, Strumia, Tamburini 0706.4071

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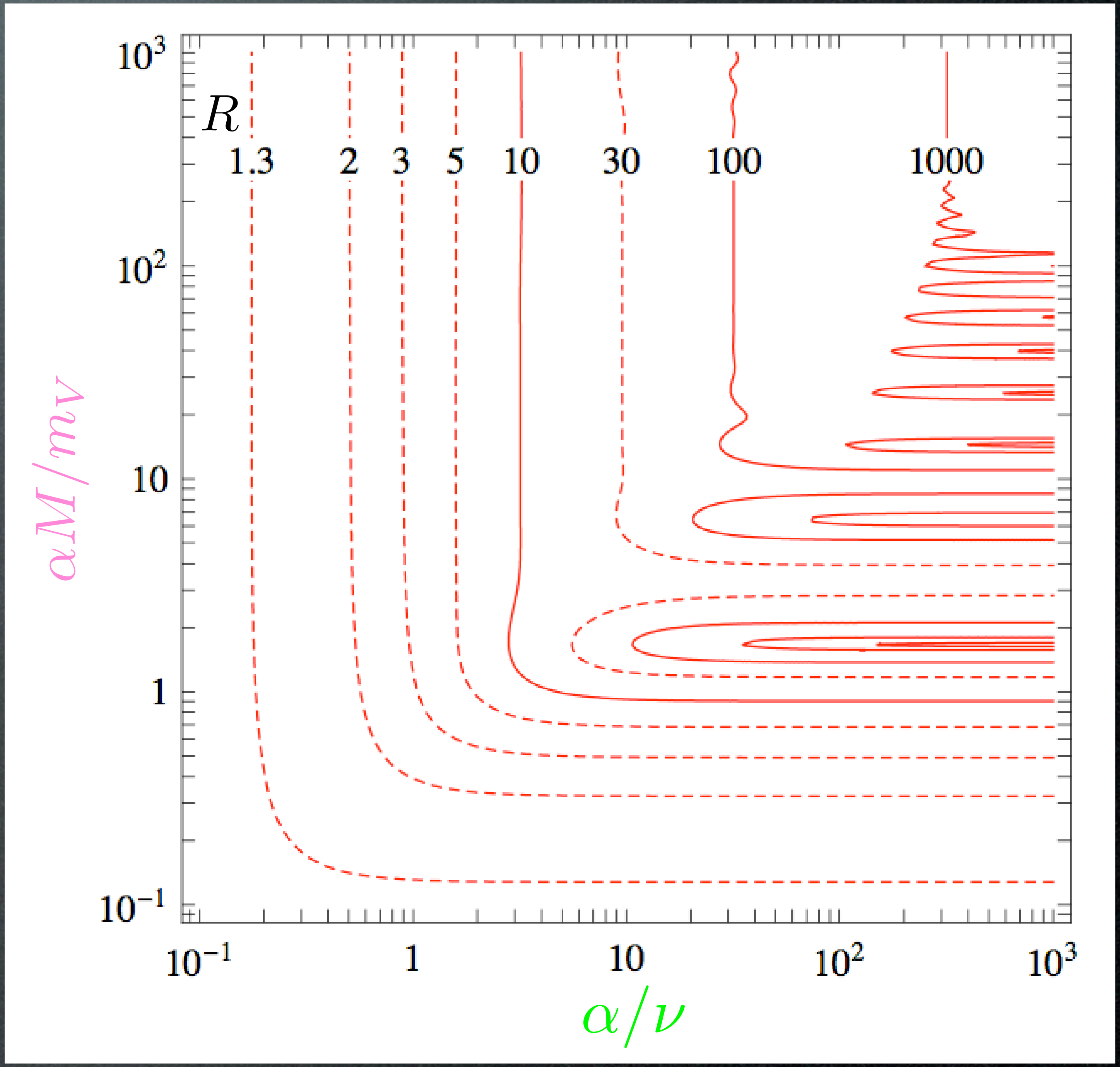
$$\text{with} \quad V = -\frac{\alpha}{r}e^{-m_V\, r}$$

parameters are: α, ν, m_V, M

R depends on: α/ν and $\alpha M/m_V$



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Cirelli, Strumia, Tamburini 0706.4071

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

parameters are: α, ν, m_V, M

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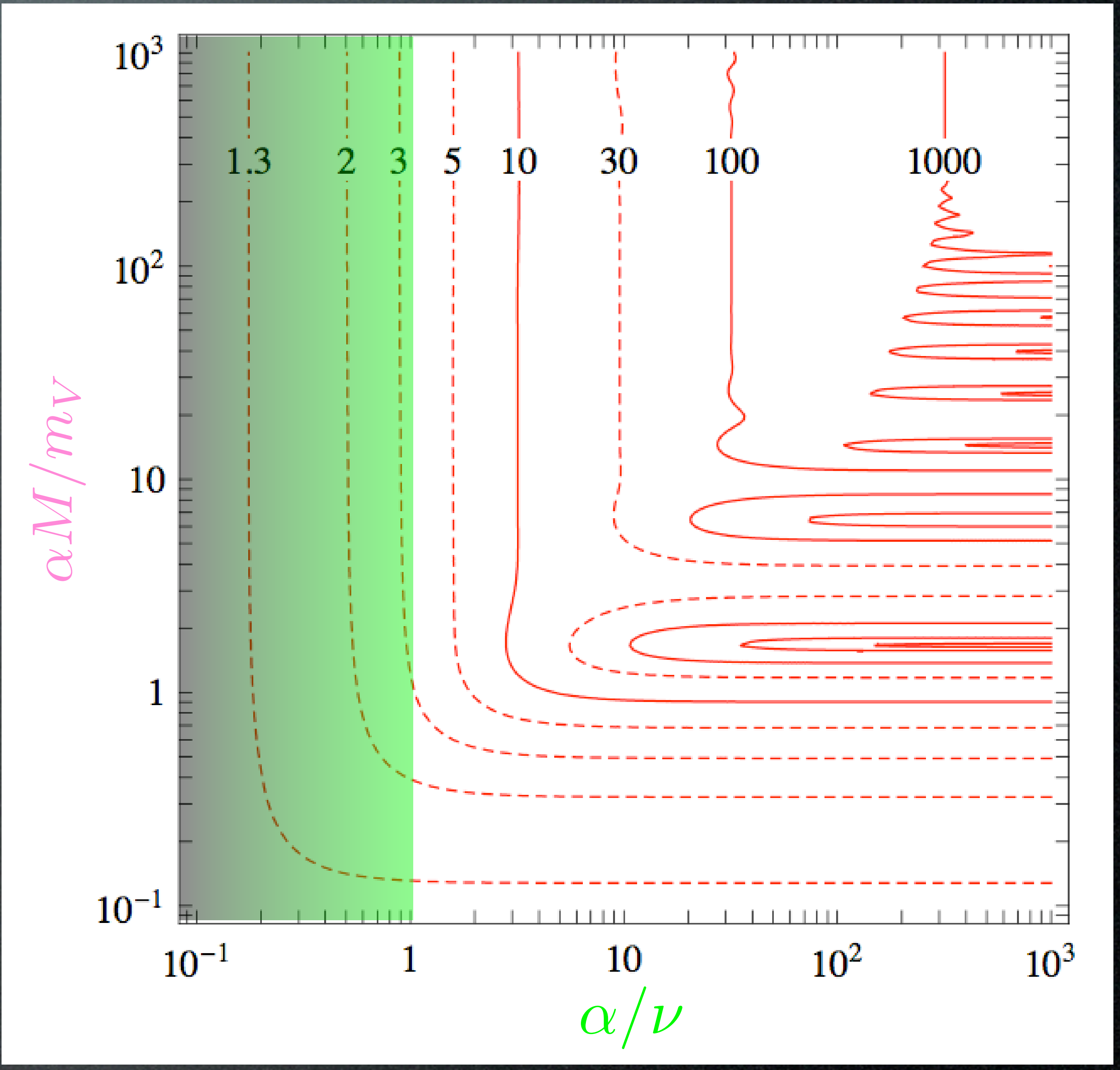


The effect is relevant for:

$\alpha/\nu \gtrsim 1$ i.e. small velocities

i.e today but not at f.o.

Sommerfeld Enhancement

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

Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071

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

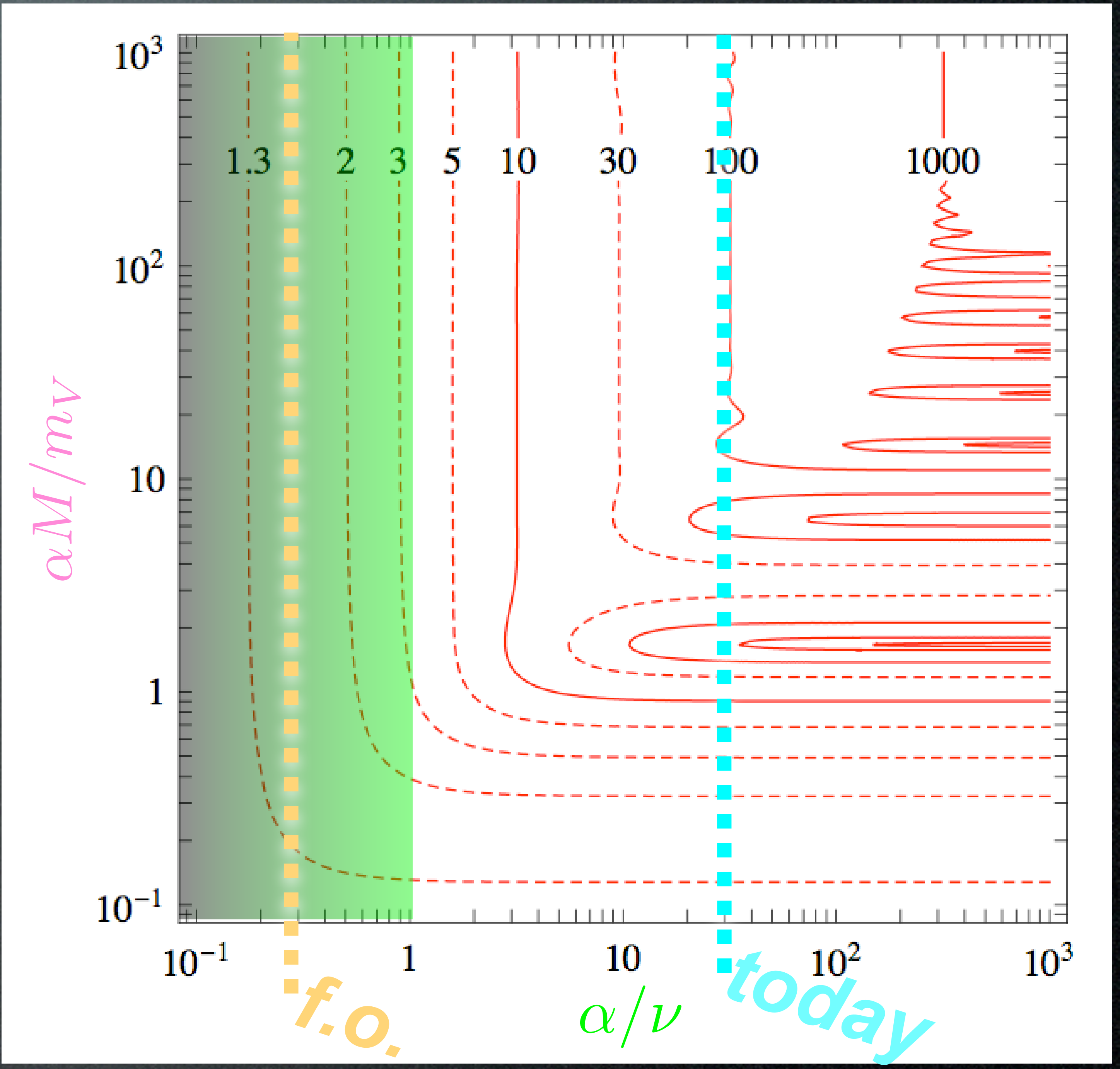
$$\text{with} \quad V = -\frac{\alpha}{r}e^{-m_V r}$$

parameters are: α, ν, m_V, M

R depends on: α/ν and $\alpha M/m_V$

The effect is relevant for:

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



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

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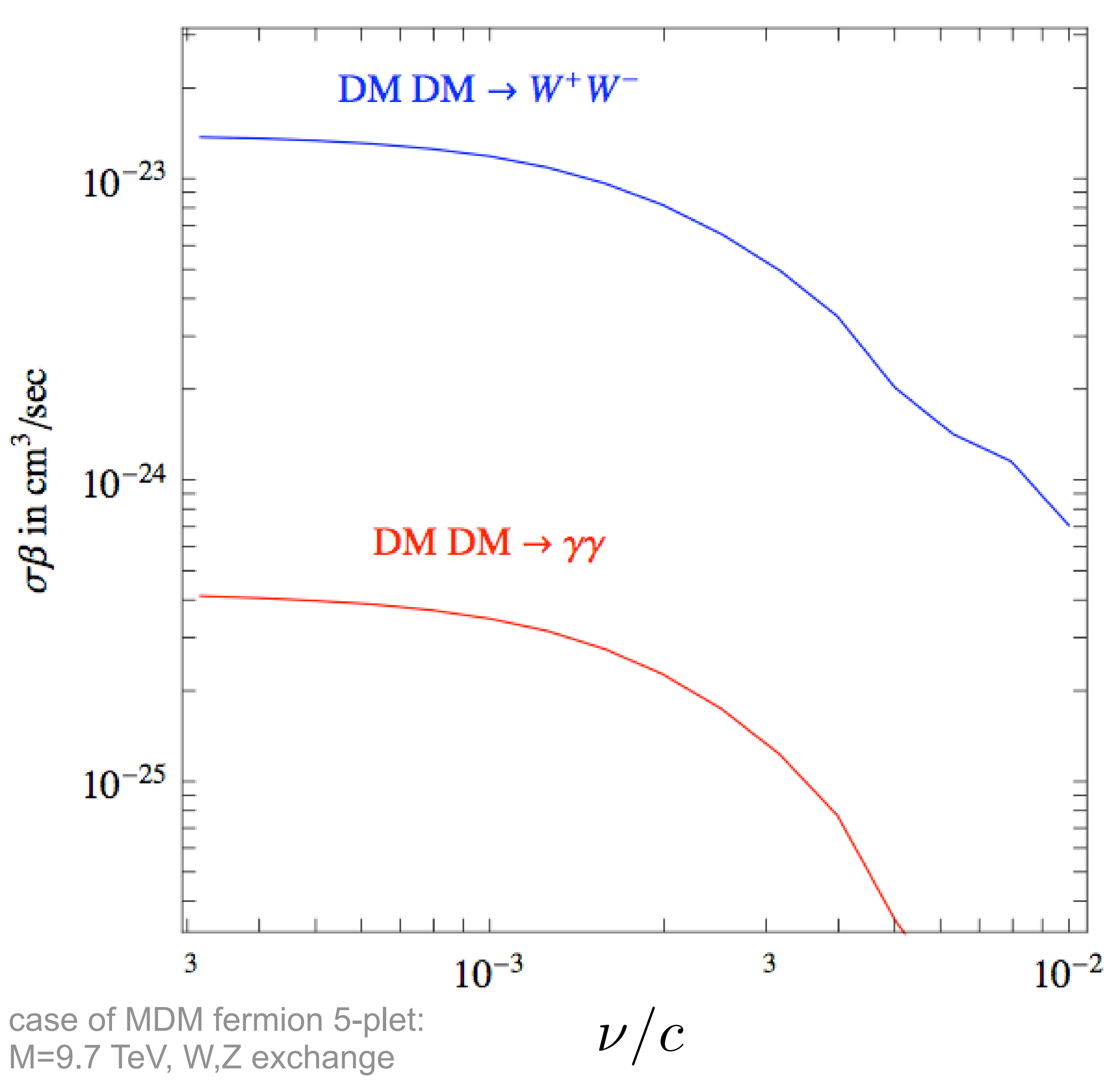

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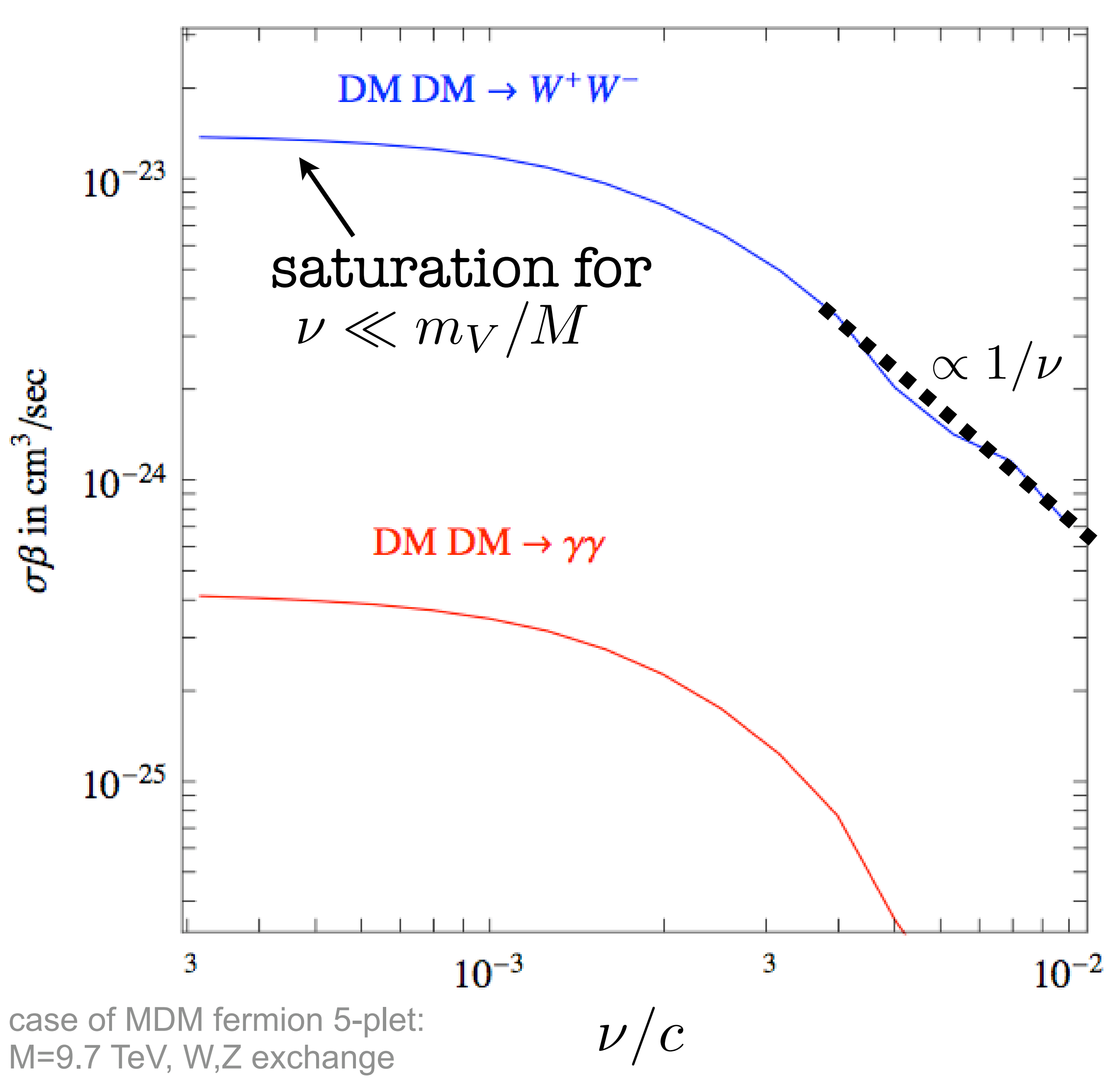

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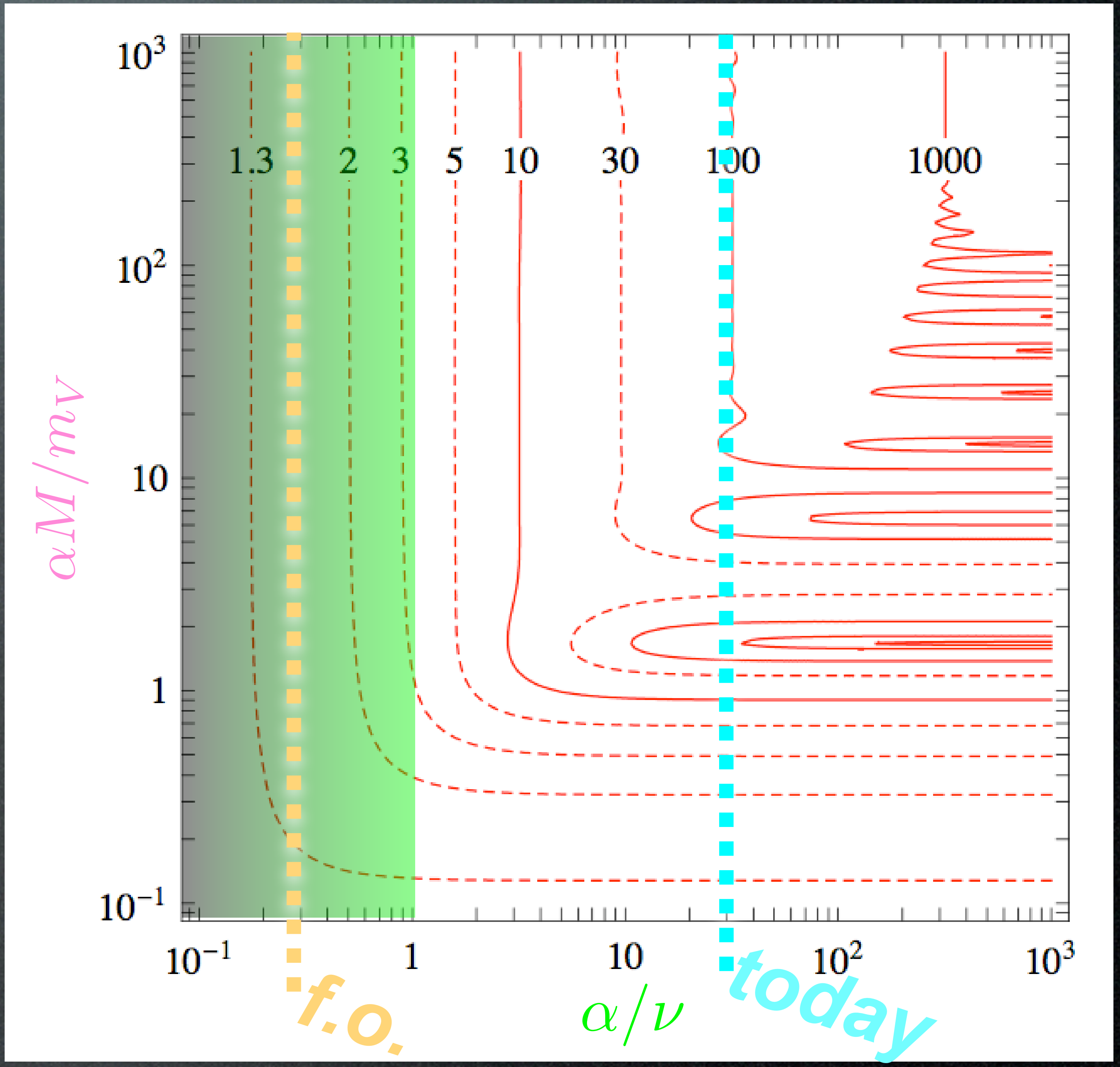

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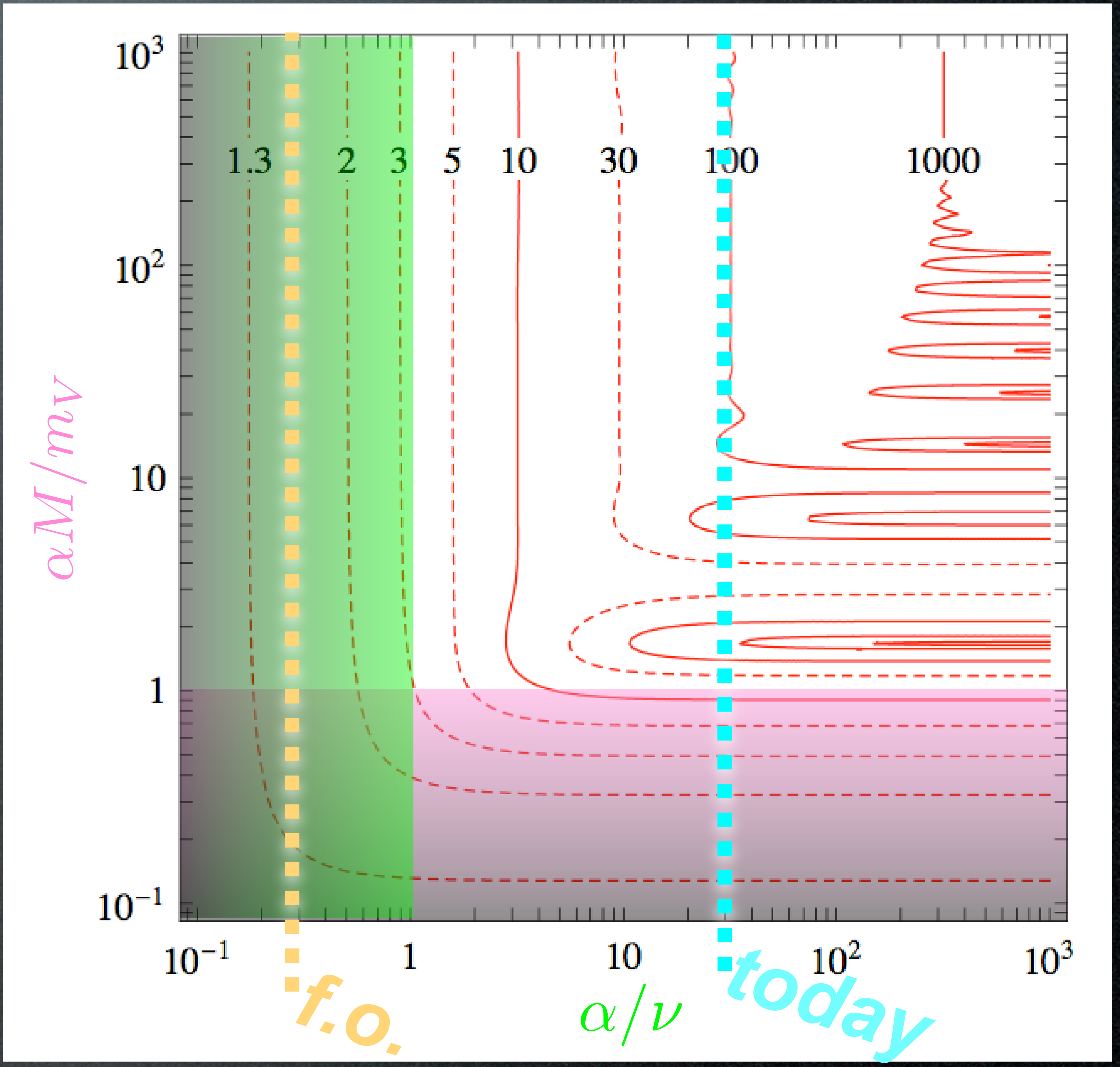

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$M \to \text{multi-TeV}$

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

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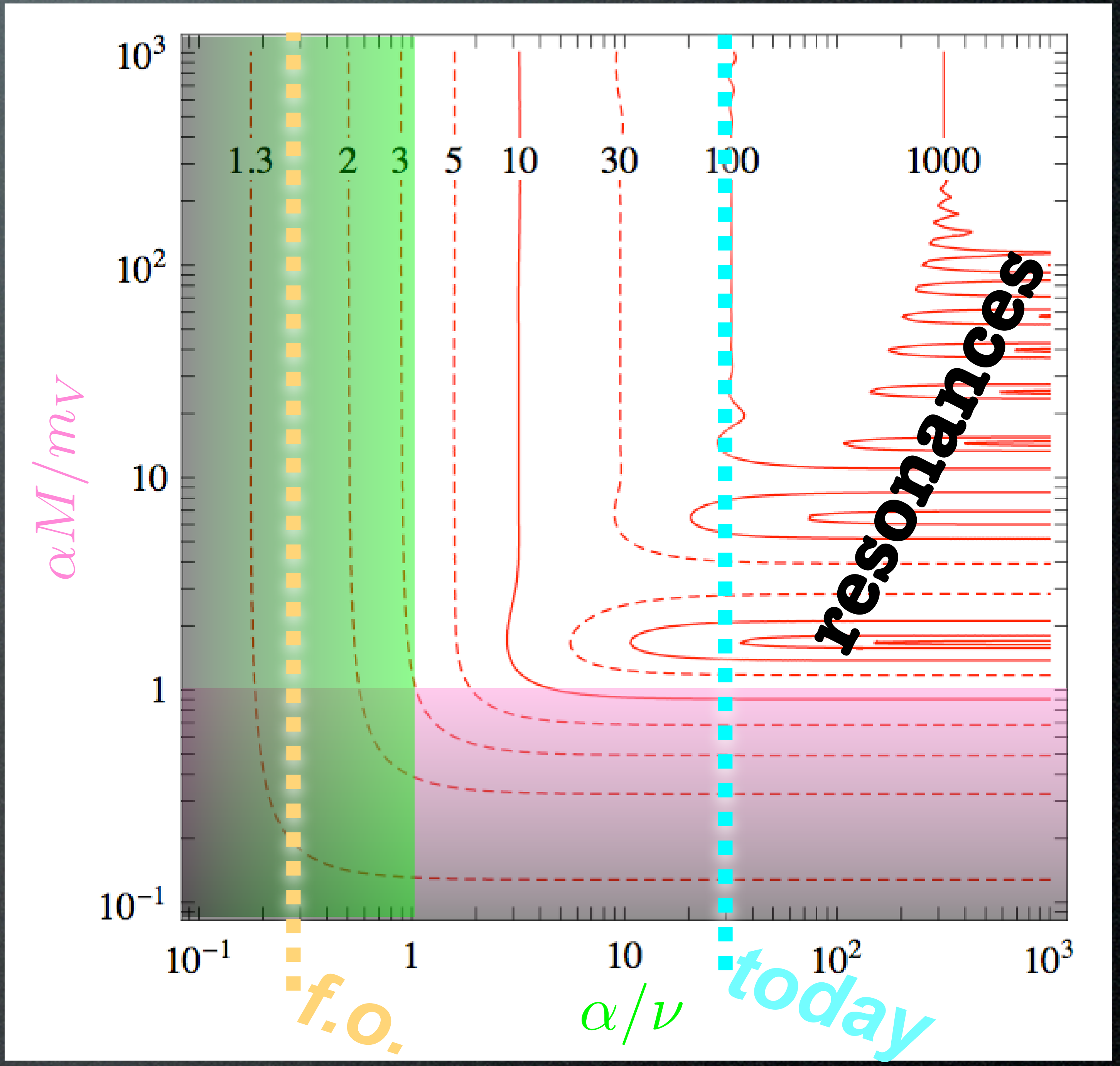

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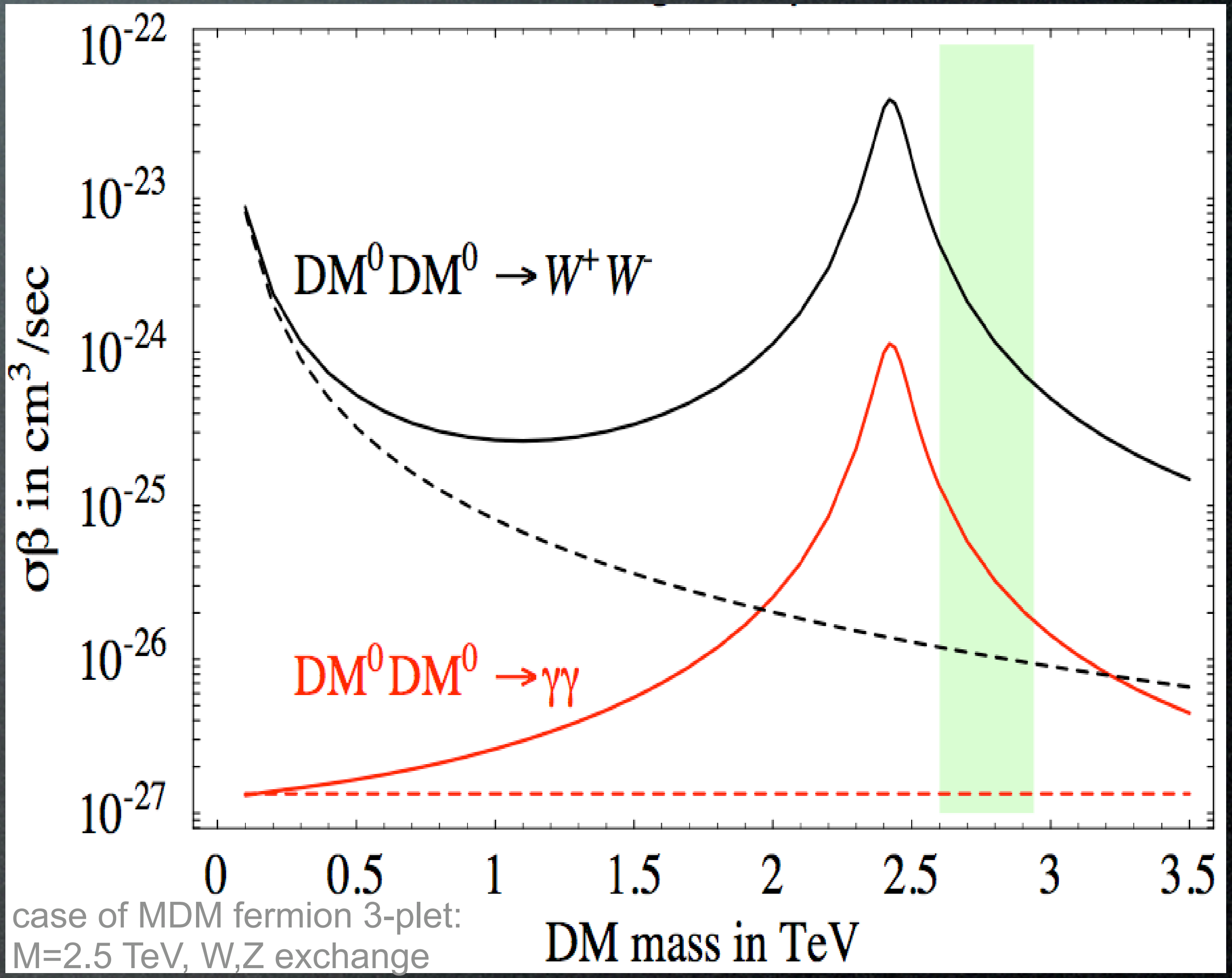


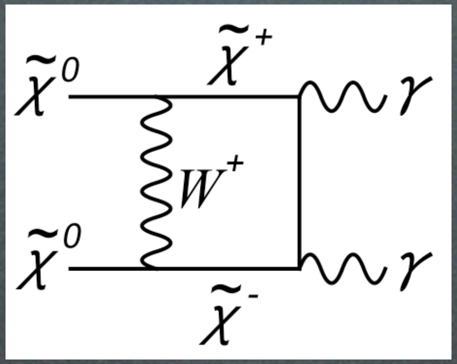
Sommerfeld Enhancement

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

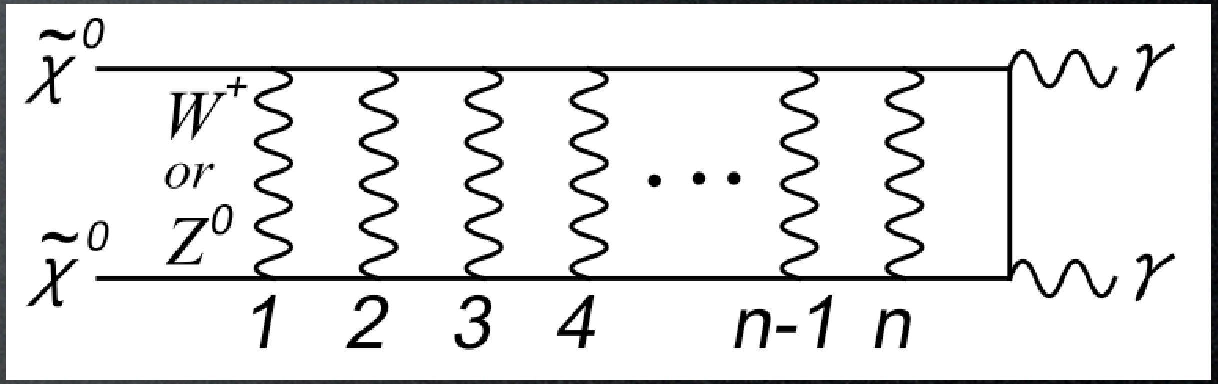
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



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



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

Sommerfeld Enhancement

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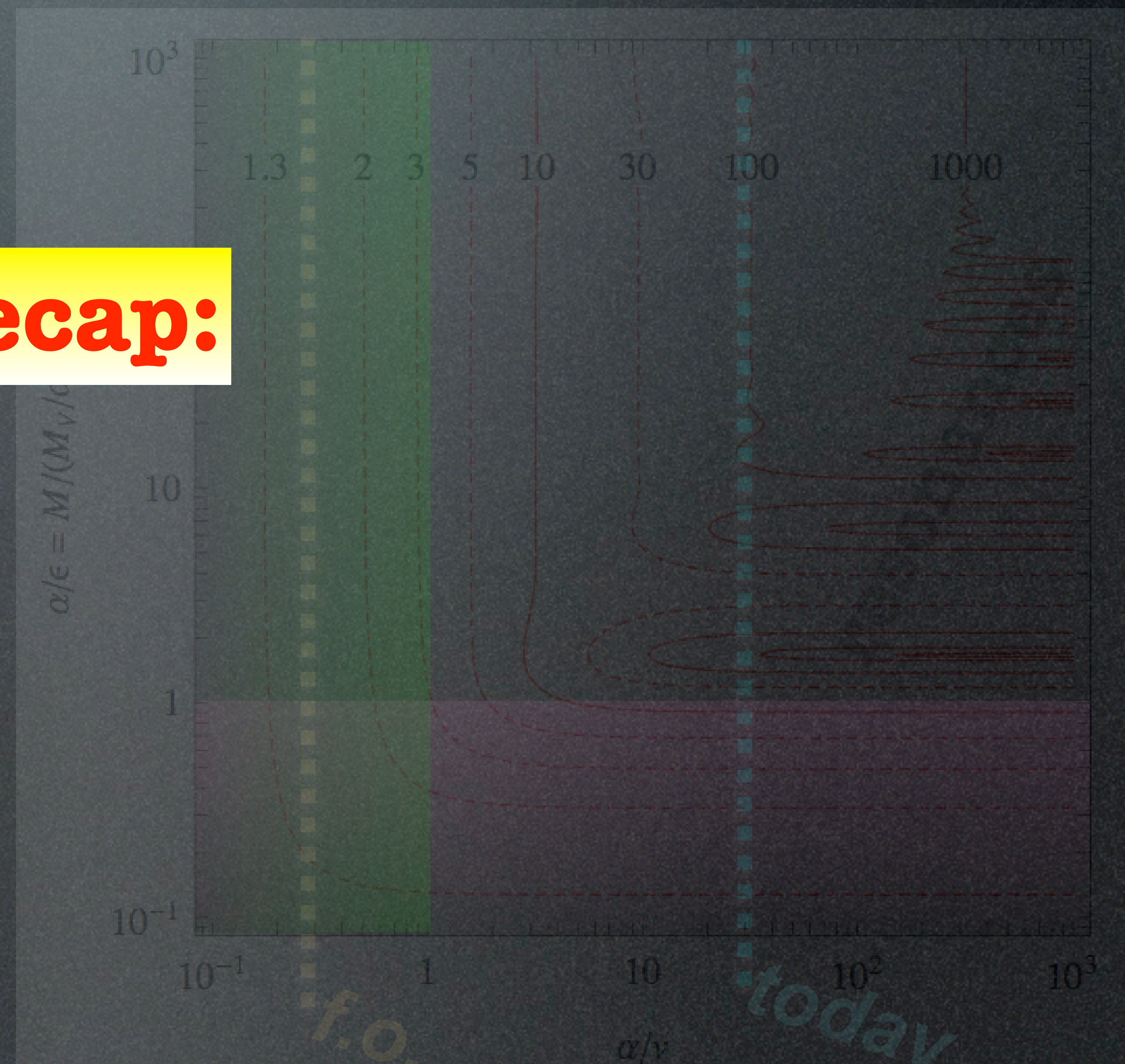

Recap:

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

- More drastic extensions:
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Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

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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 $M \sim 700+$ GeV

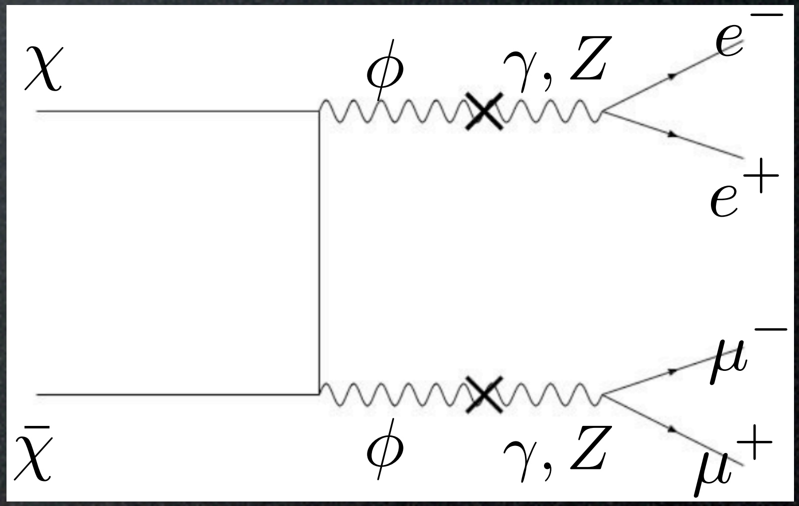
ϕ new gauge boson ("Dark photon"),

couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV

- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:

$\alpha M/m_V \gtrsim 1$ fulfilled

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



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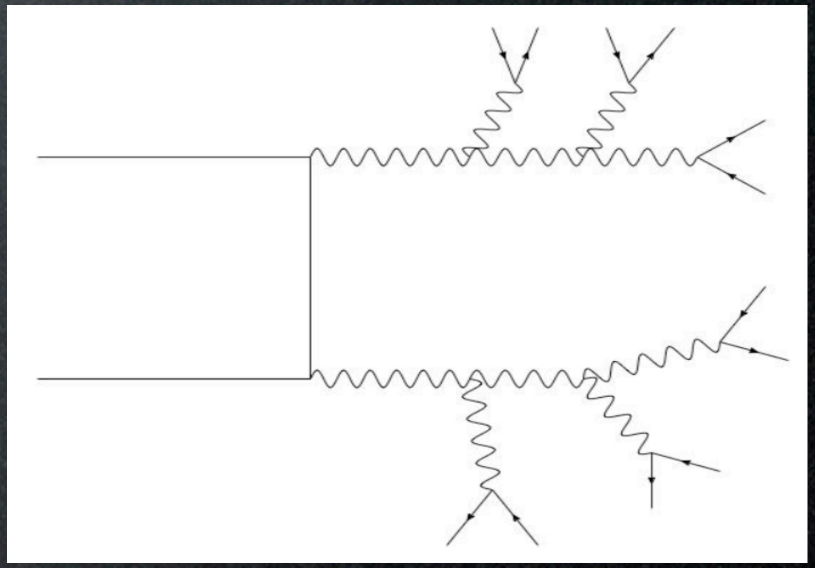
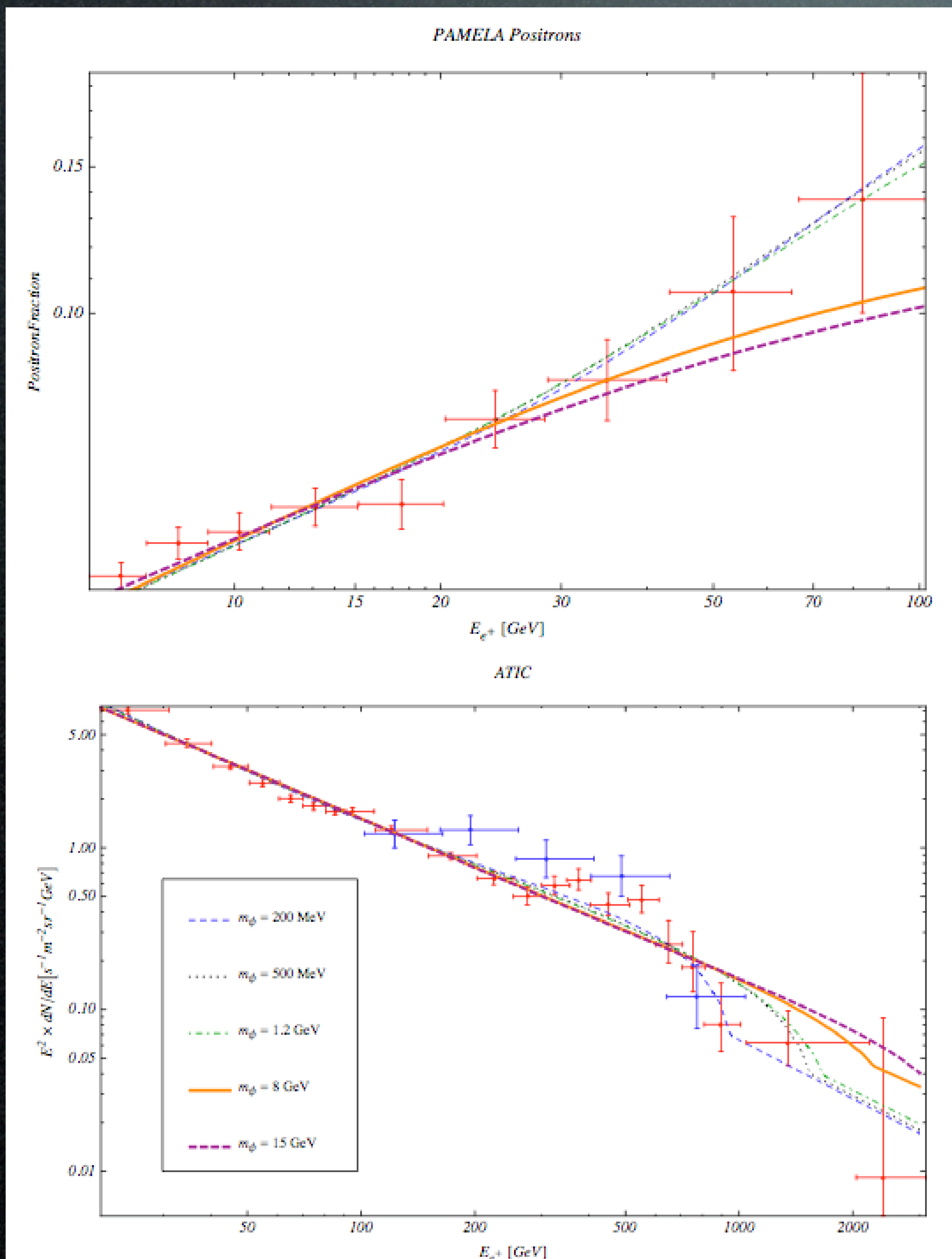


Extras:

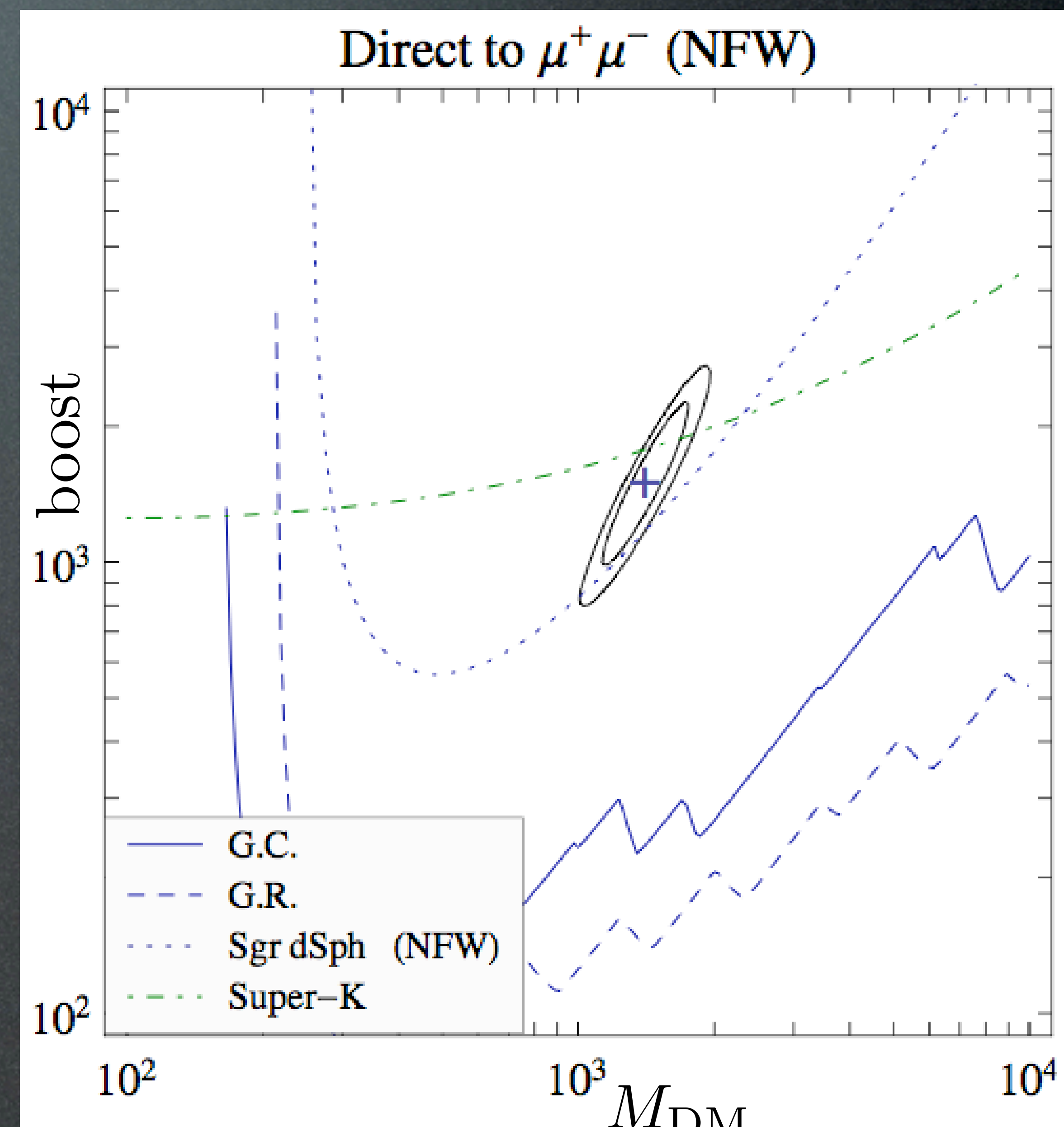
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200 \text{ KeV}$ (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The “Theory of DM”

Phenomenology:



Meade, Papucci, Volanski
0901.2925



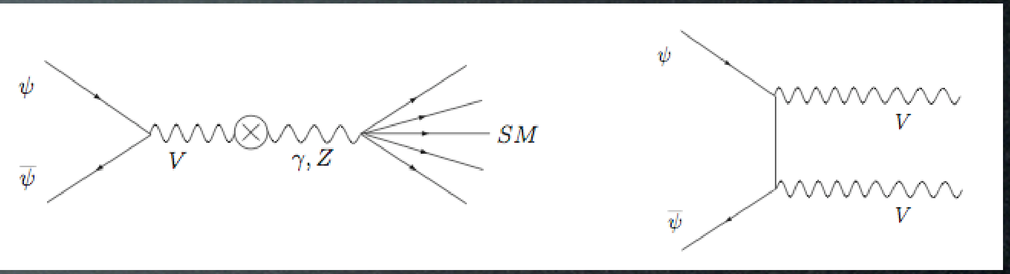
Mardon, Nomura, Stolarski,
Thaler 0901.2926

Variations

(selected)

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

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



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

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

  Bai, Han 0811.0387

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

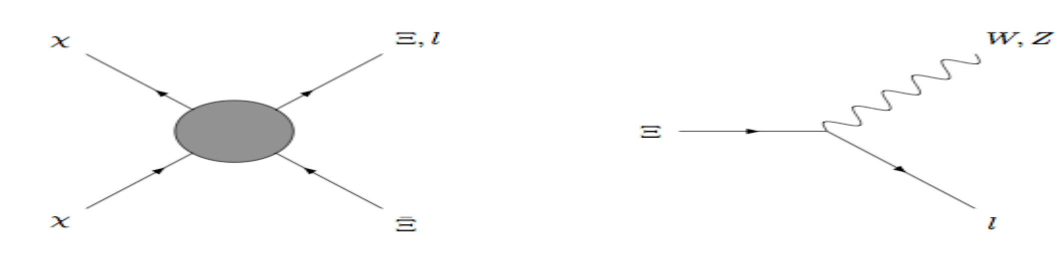
  Park, Shu 0901.0720

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

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

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

  Phalen, Pierce, Weiner 0901.3165



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