12 June 2014
APC-Perimeter-Solvay Workshop

DM Indirect Detection:
some anomalies and many constraints

Marco Cirelli
(CNRS IPhT Saclay)

IPhT SACLAY

erc NewDark

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Introduction

DM exists

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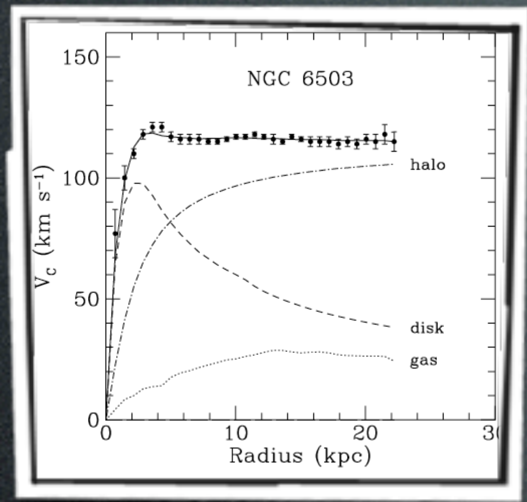
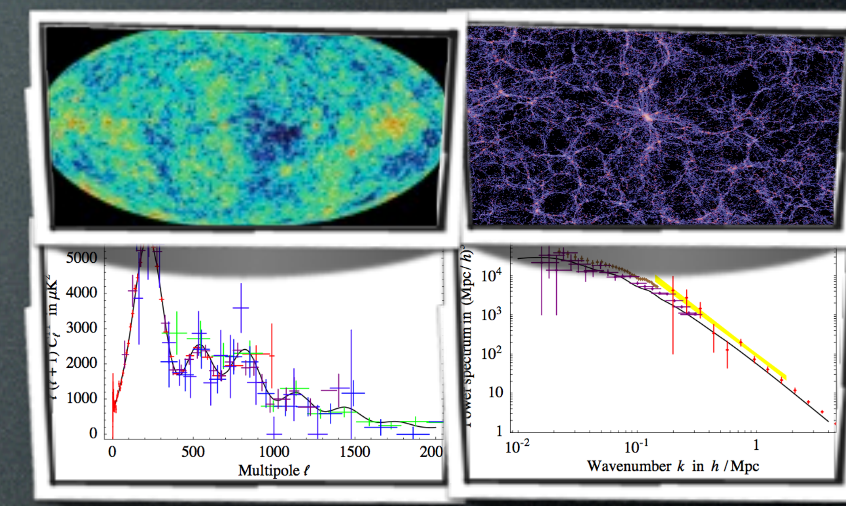


galactic rotation curves

weak lensing (e.g. in clusters)



‘precision cosmology’ (CMB, LSS)

Introduction

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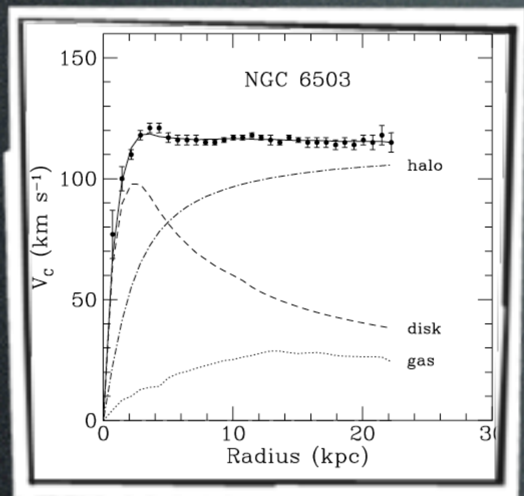

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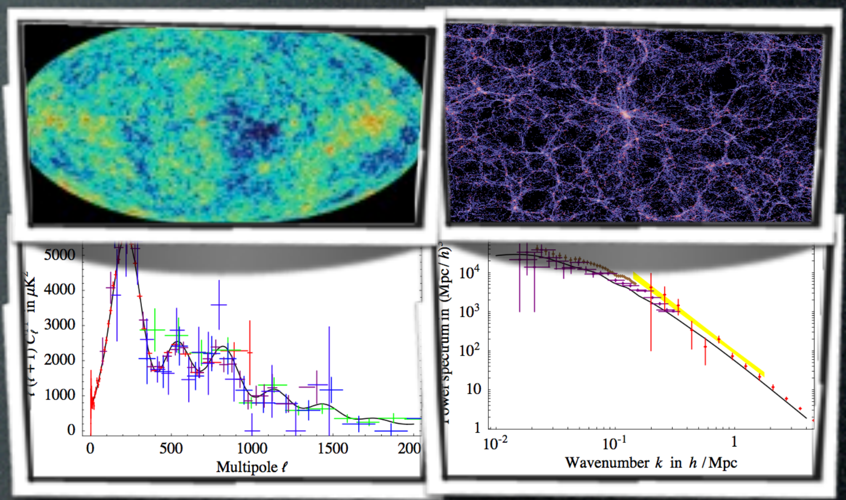

'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived, feebly- interacting corpuscle.

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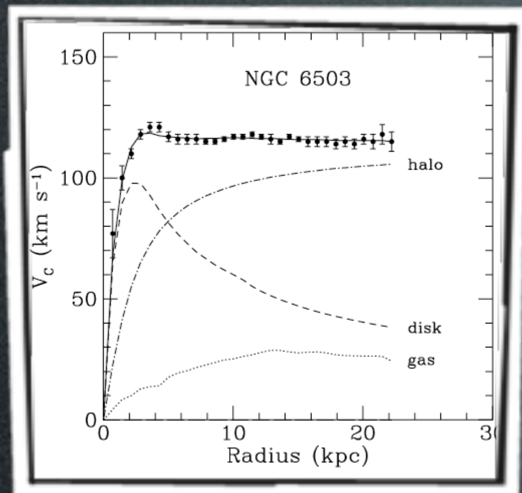

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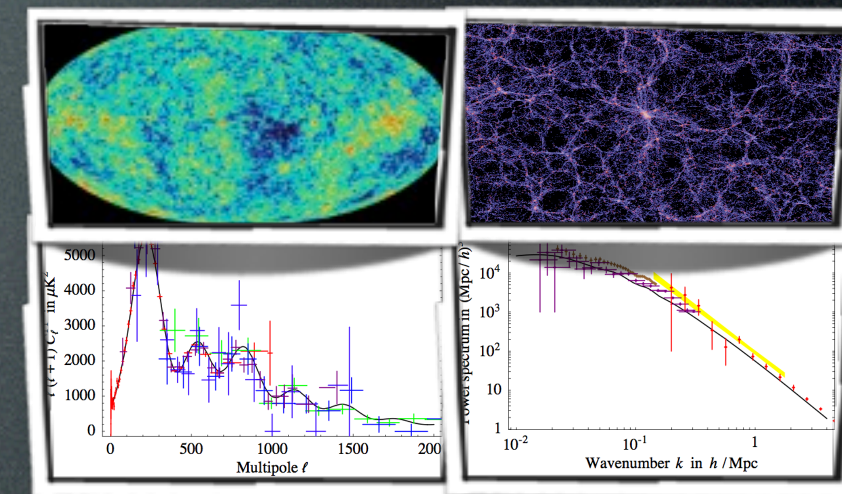
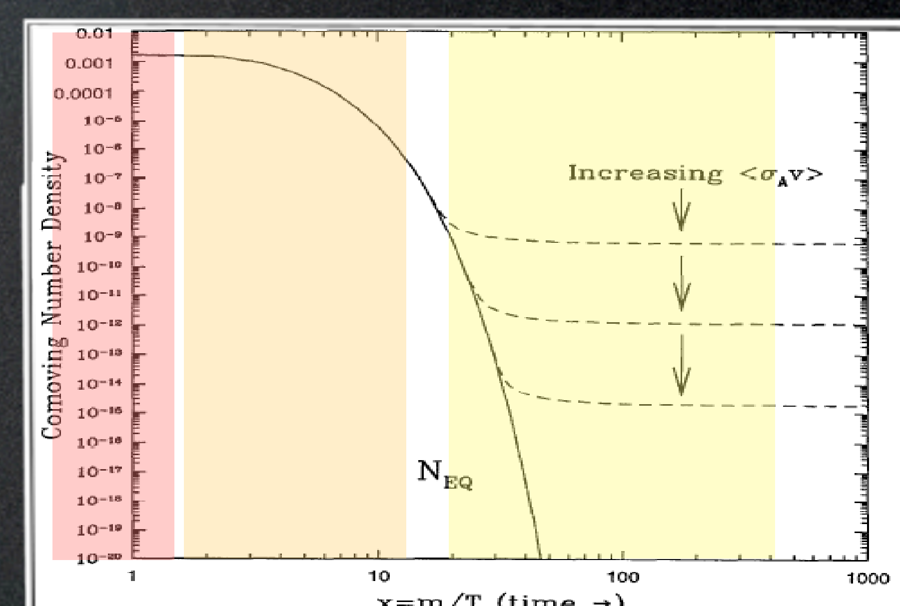


'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived, weakly interacting particle.

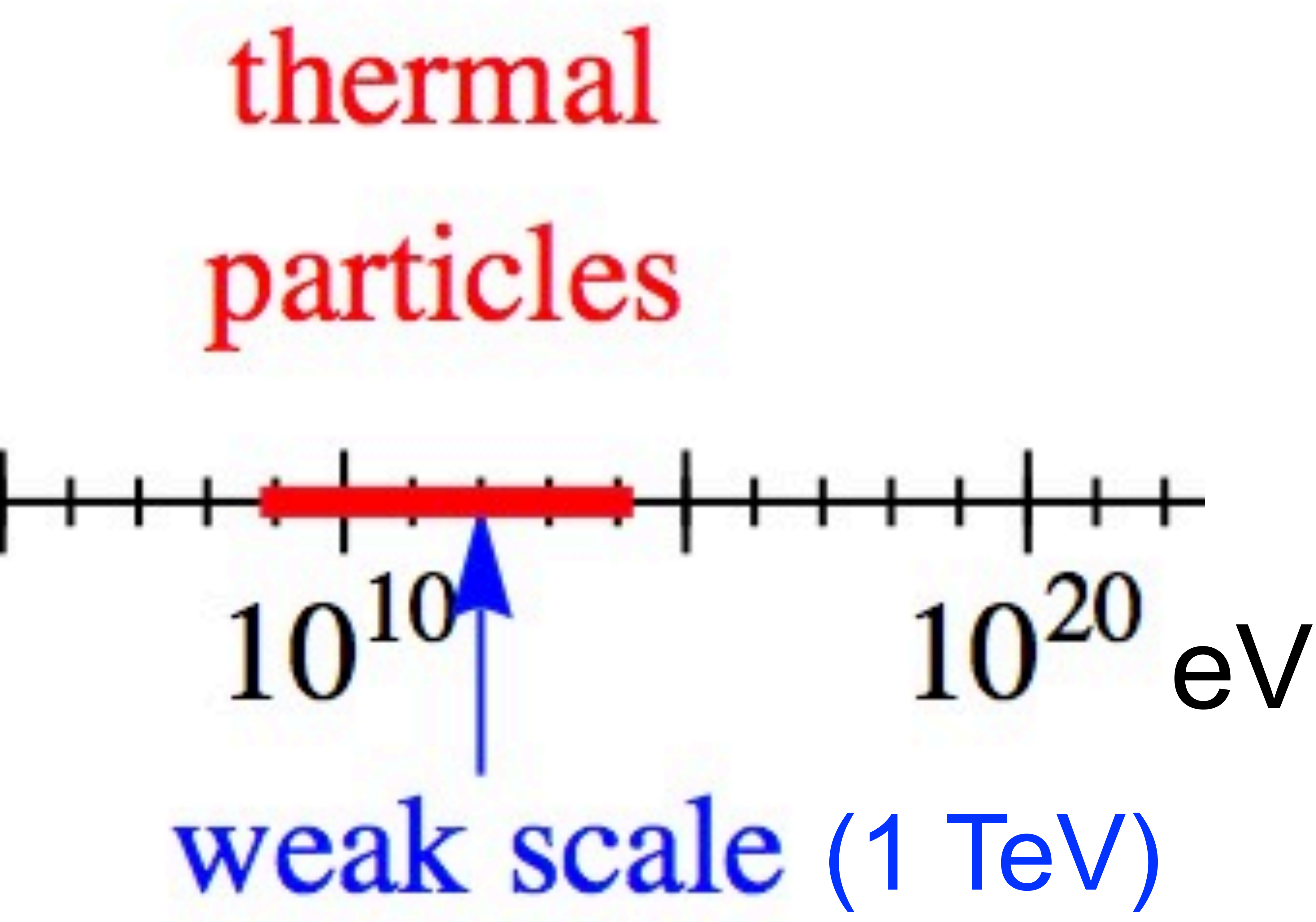
Some of us believe in the WIMP miracle.

- *weak*-scale mass (10 GeV - 1 TeV)
- *weak* interactions $\sigma v = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$
- give automatically correct abundance



Candidates

A matter of perspective: plausible mass ranges



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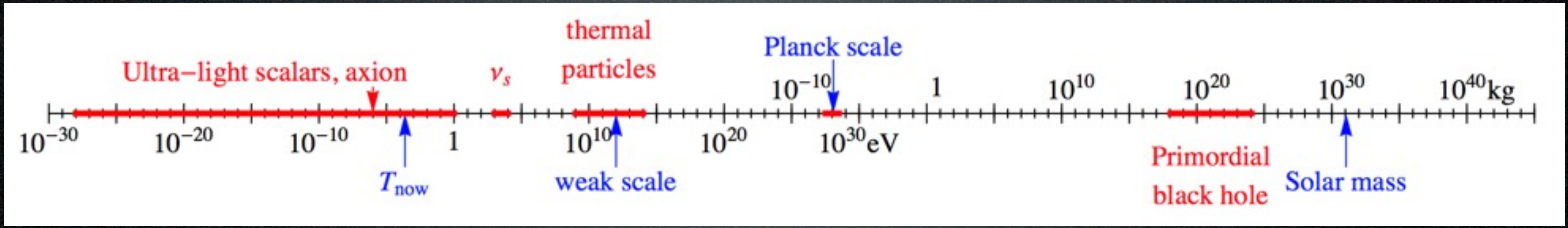

'only' 90 orders of magnitude!

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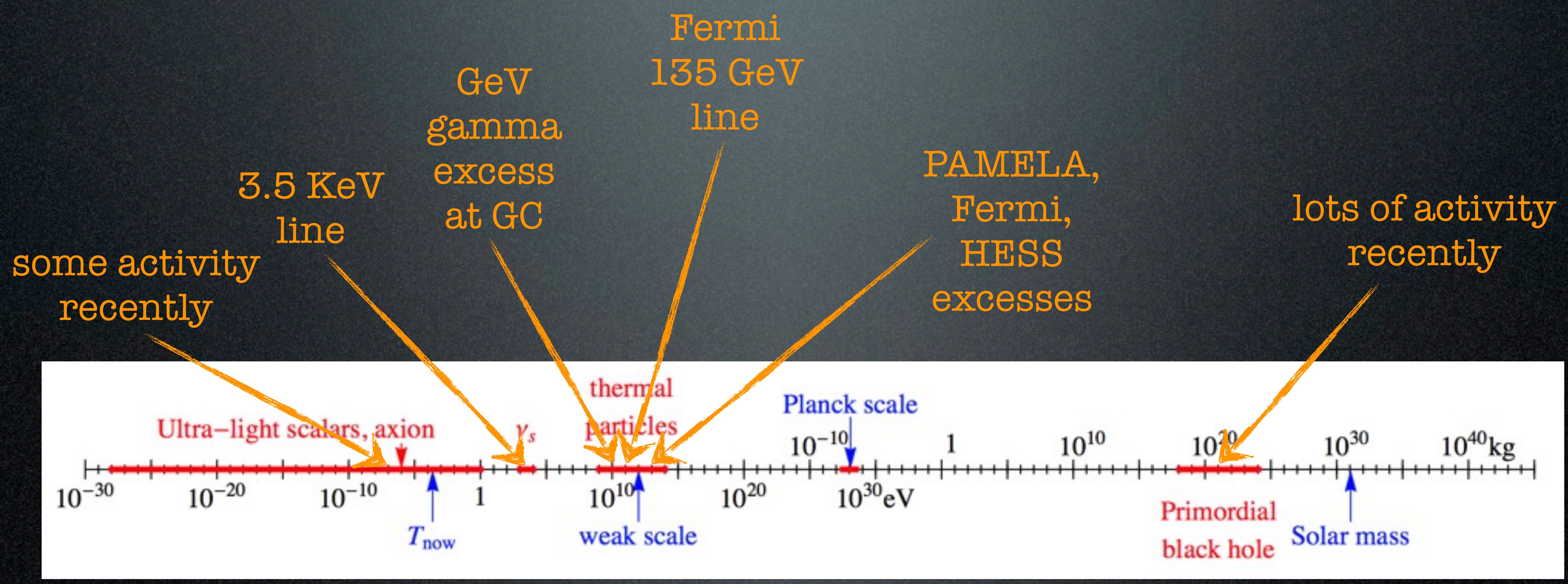

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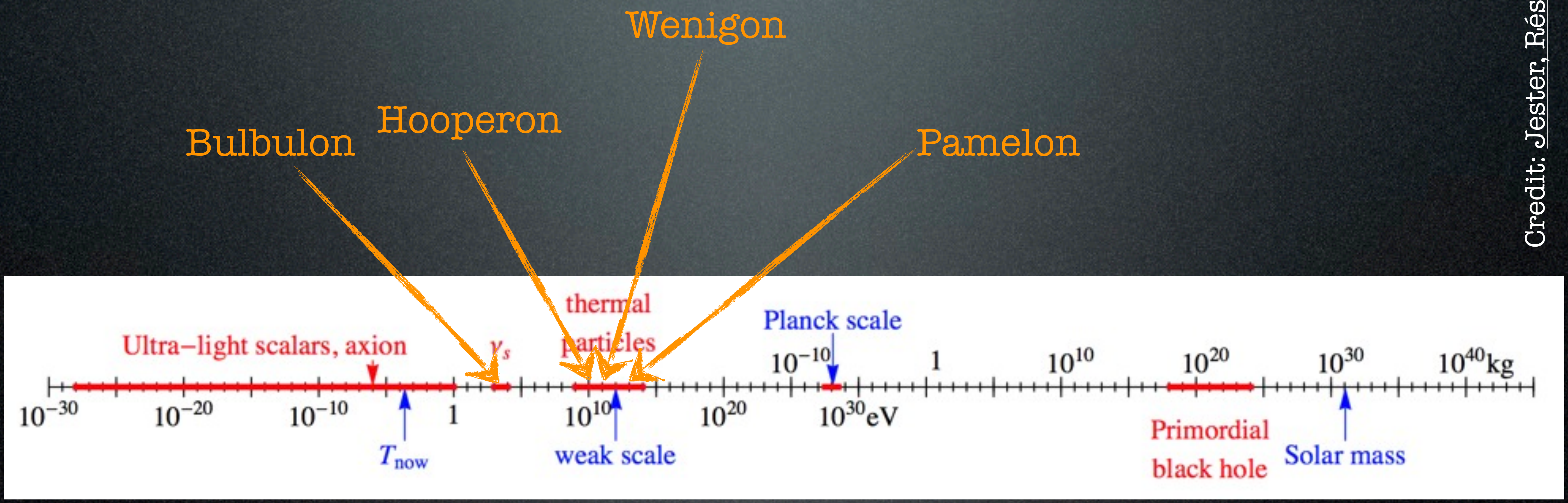

'only' 90 orders of magnitude!

Credit: Jester, Résonaances

DM detection

direct detection

Xenon, CDMS, Edelweiss... (CoGeNT, Dama/Libra...)

production at colliders

LHC

indirect

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

  Fermi, **ICT**, radio telescopes...

- e^+ from annihil in galactic halo or center

  PAMELA, **Fermi**, **HESS**, AMS, **balloons...**

- $\bar{p}$ 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

  SK, **Icecube**, Km3Net

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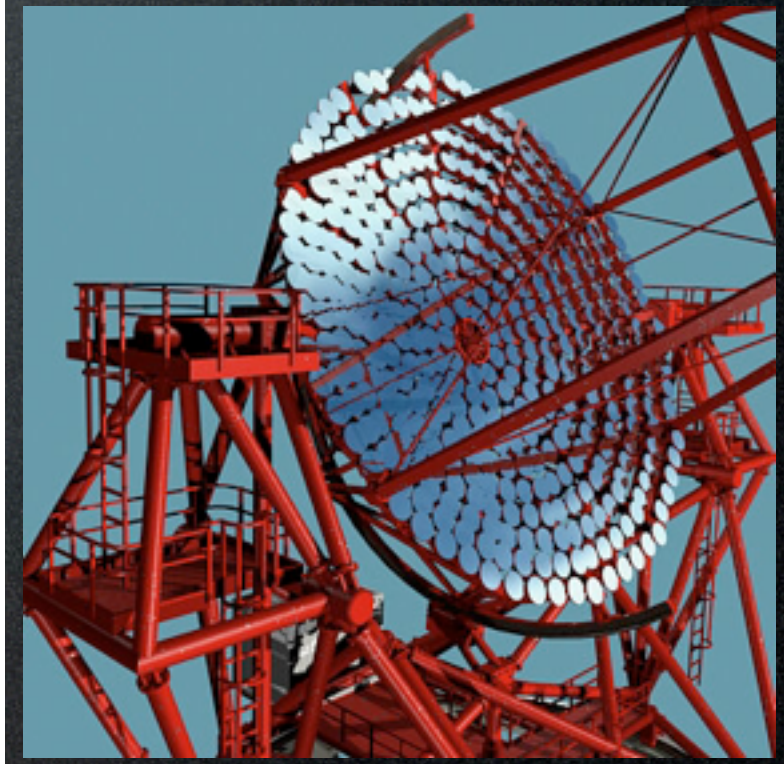
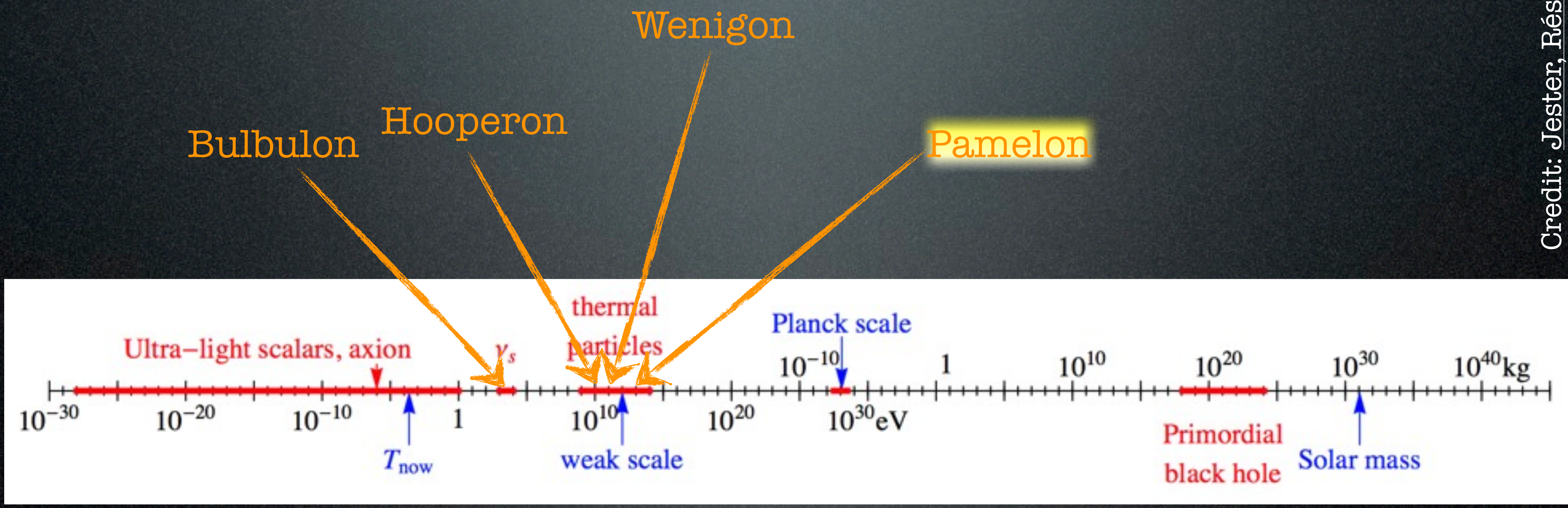
Charged CRs



1. the PAMELA/Fermi/HESS ‘excesses’

DM Candidates

A matter of perspective: plausible mass ranges



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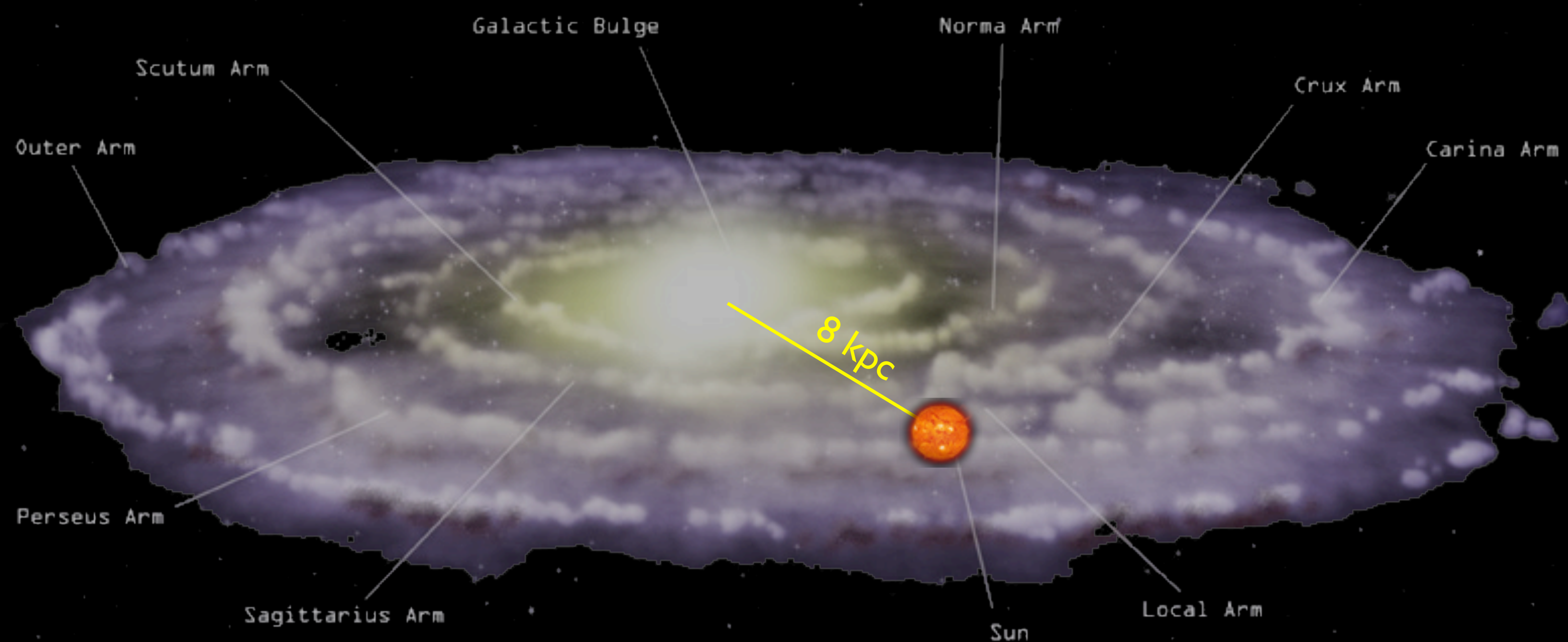
Indirect Detection: basics

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



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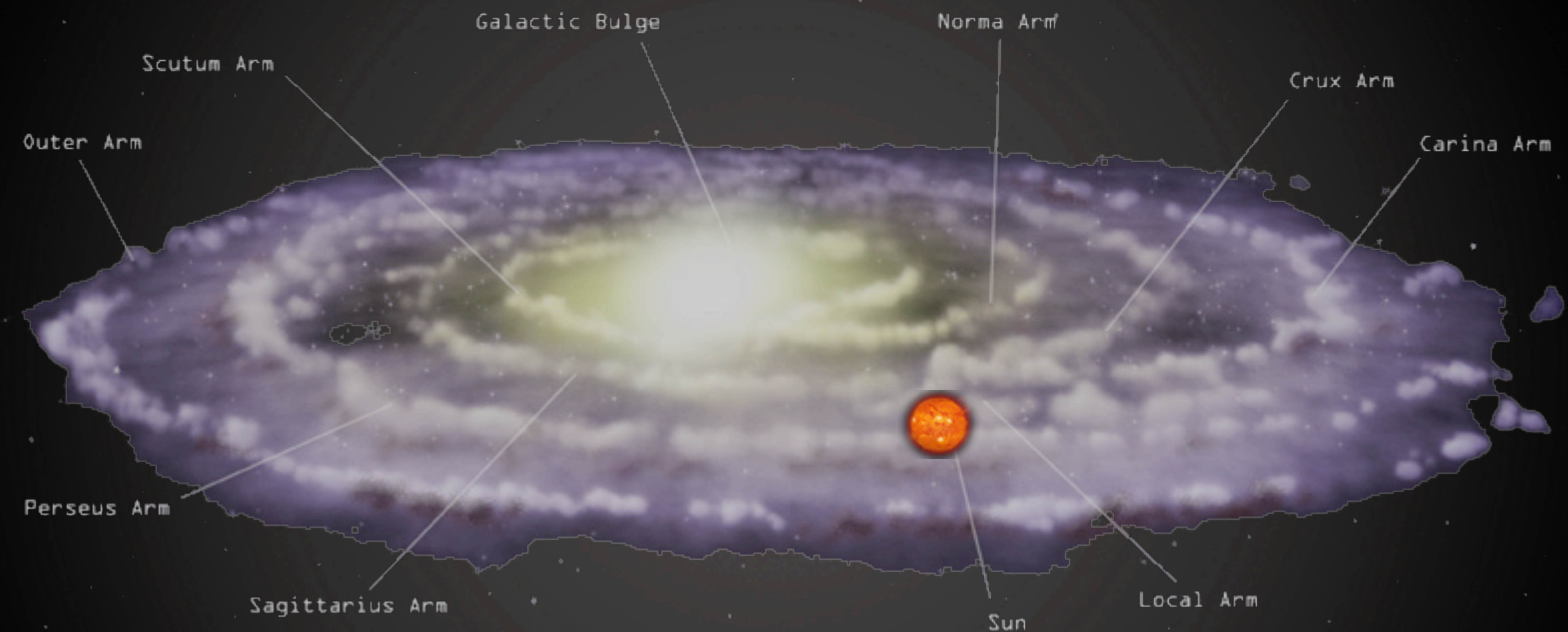

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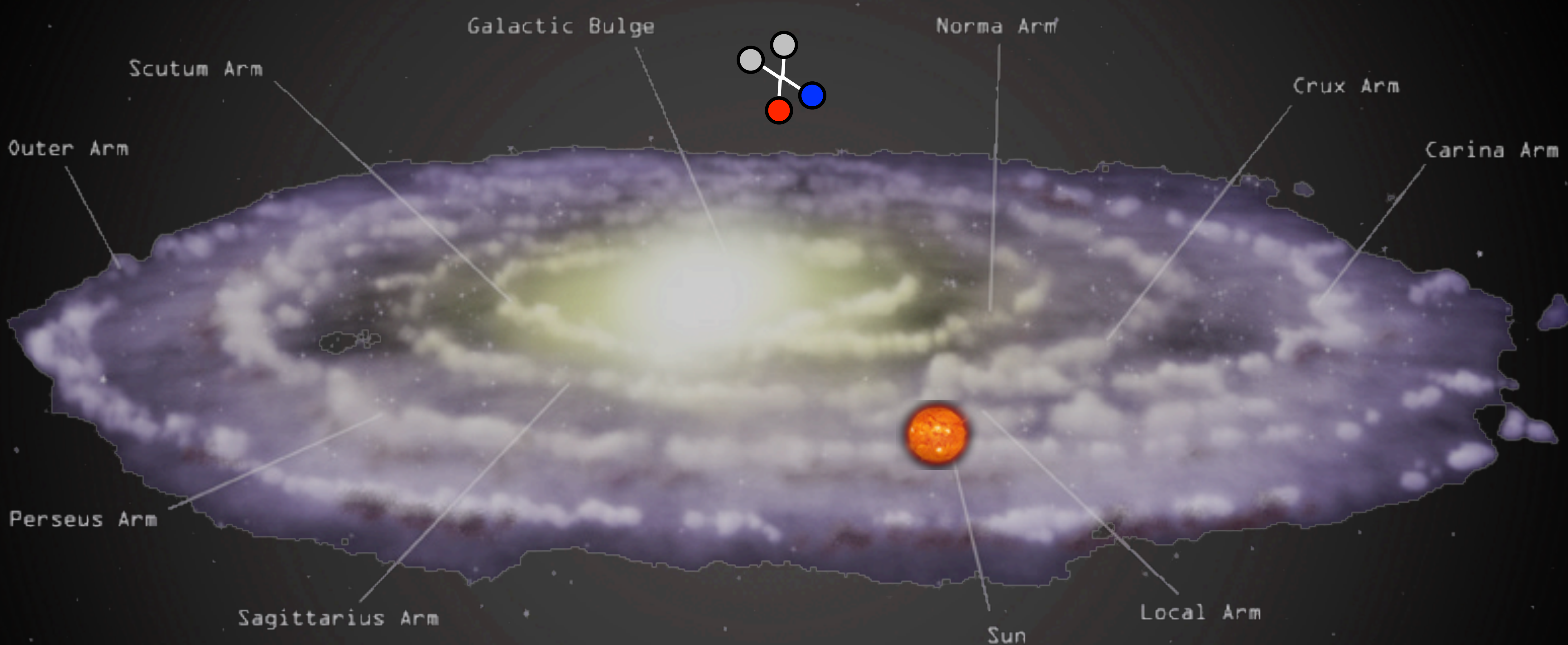

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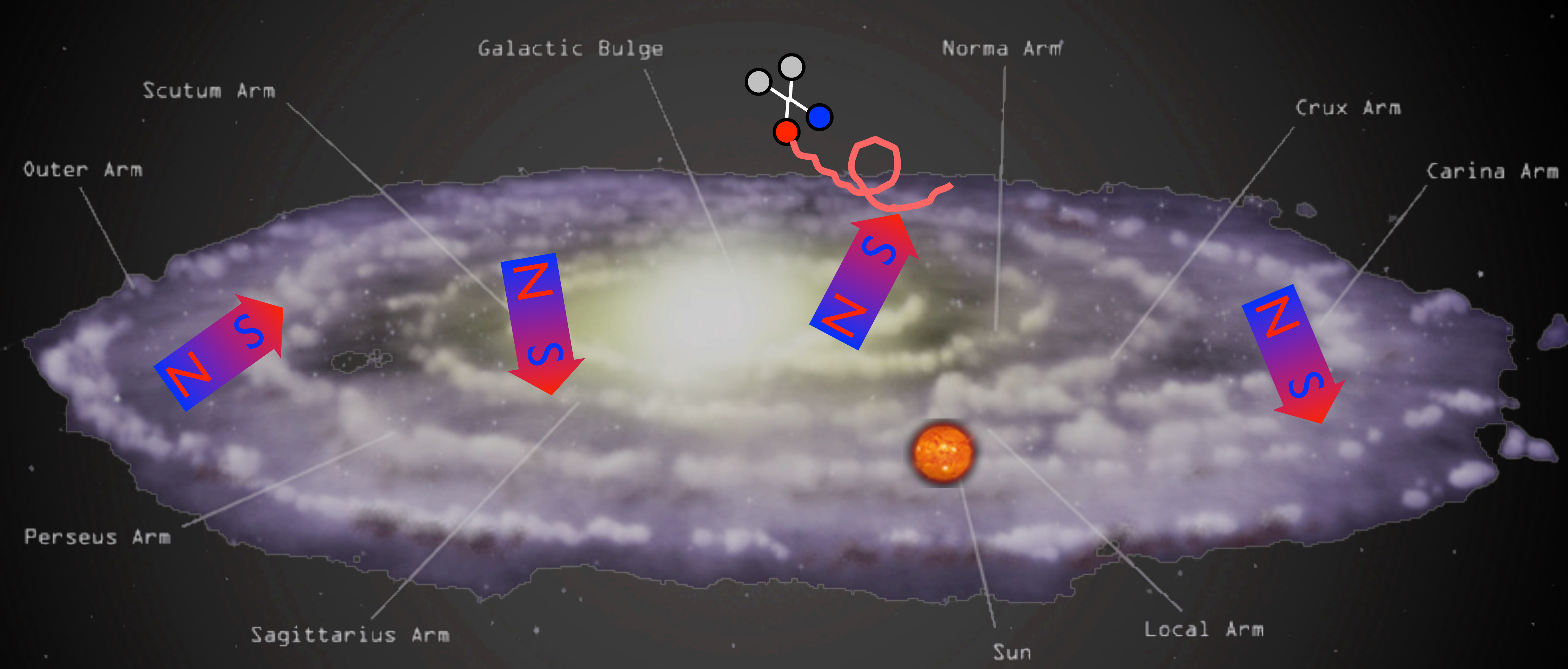

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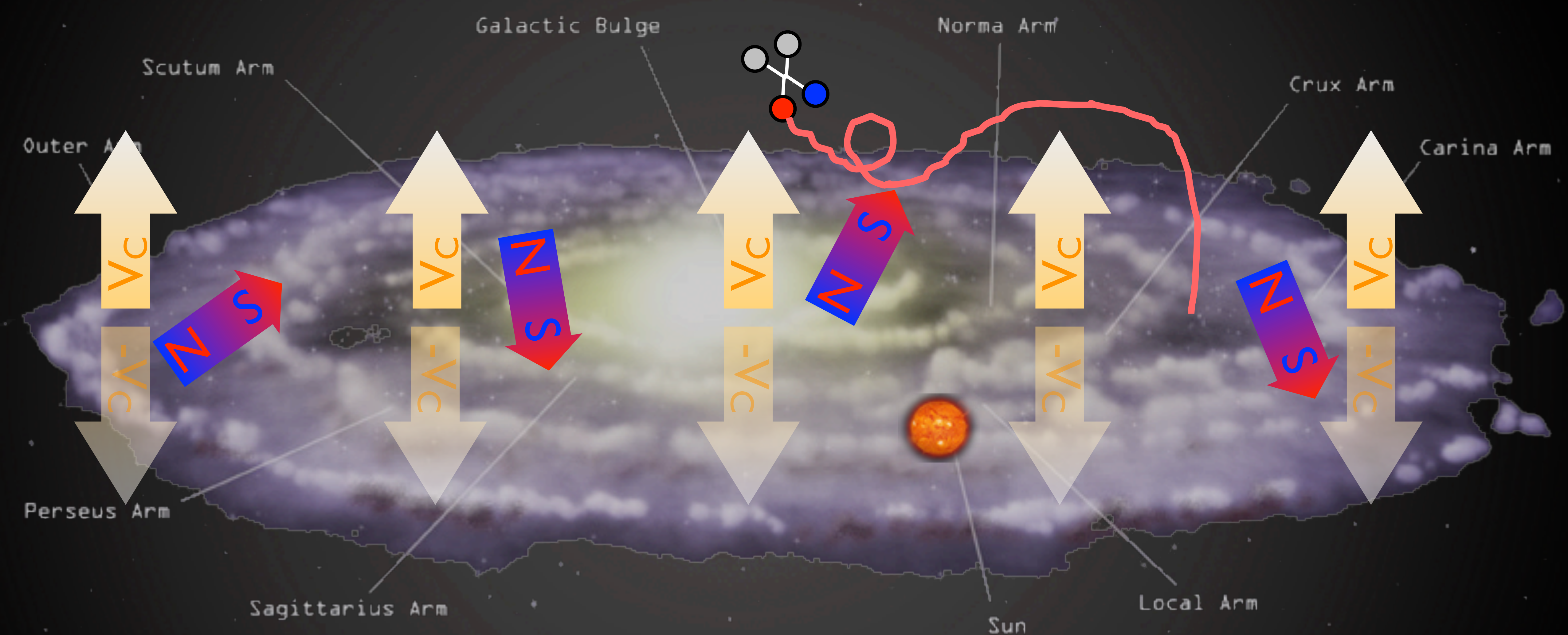

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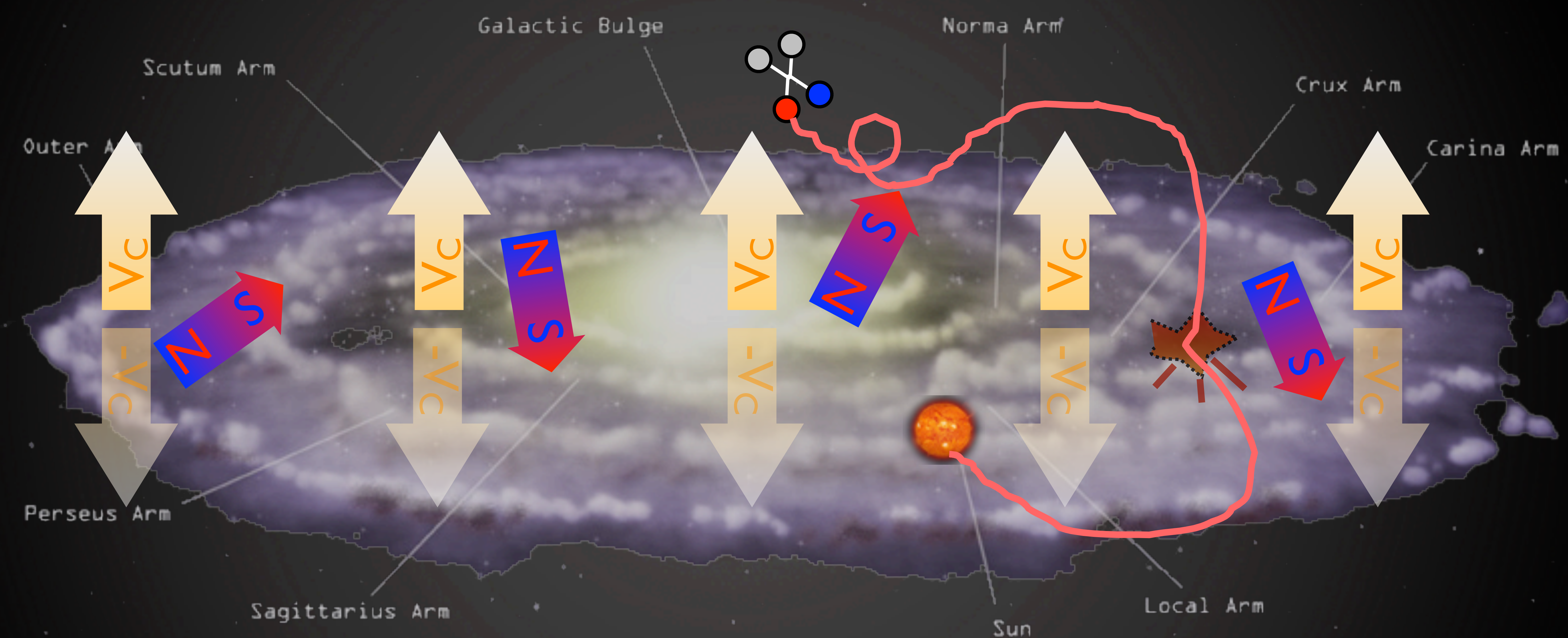

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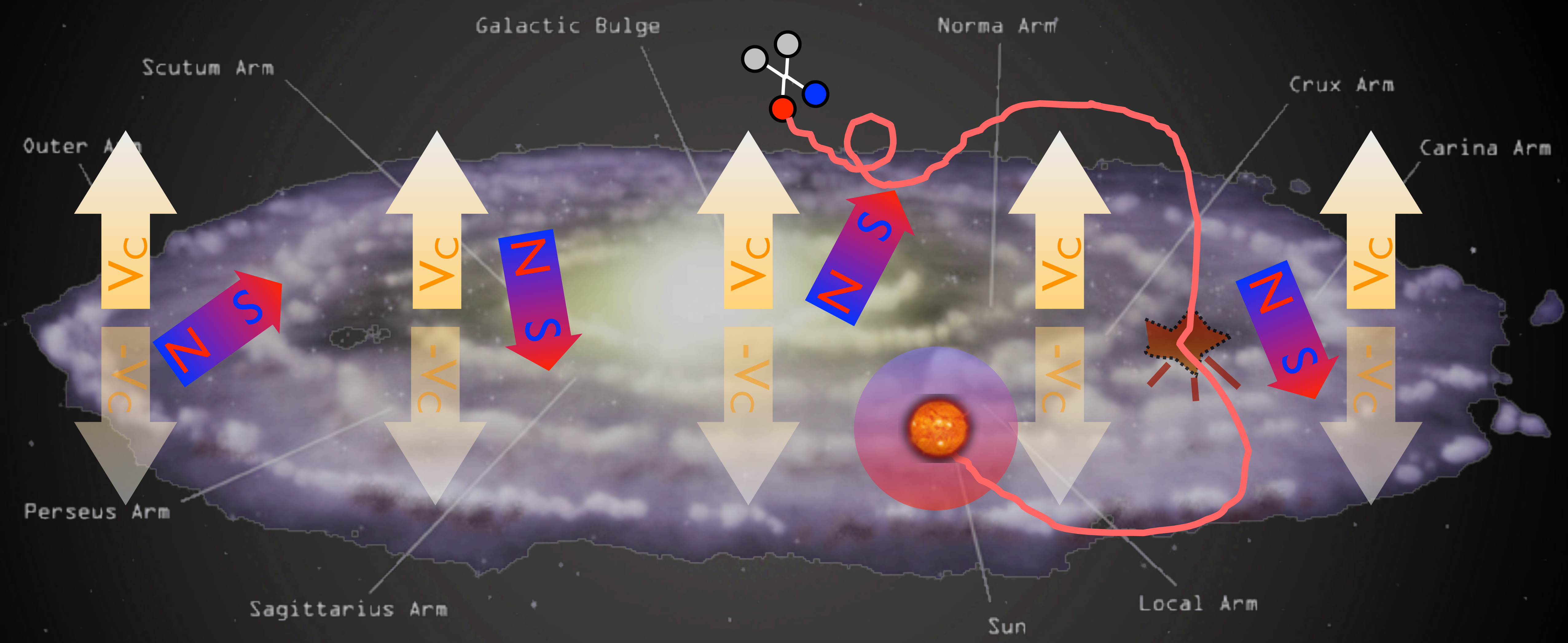

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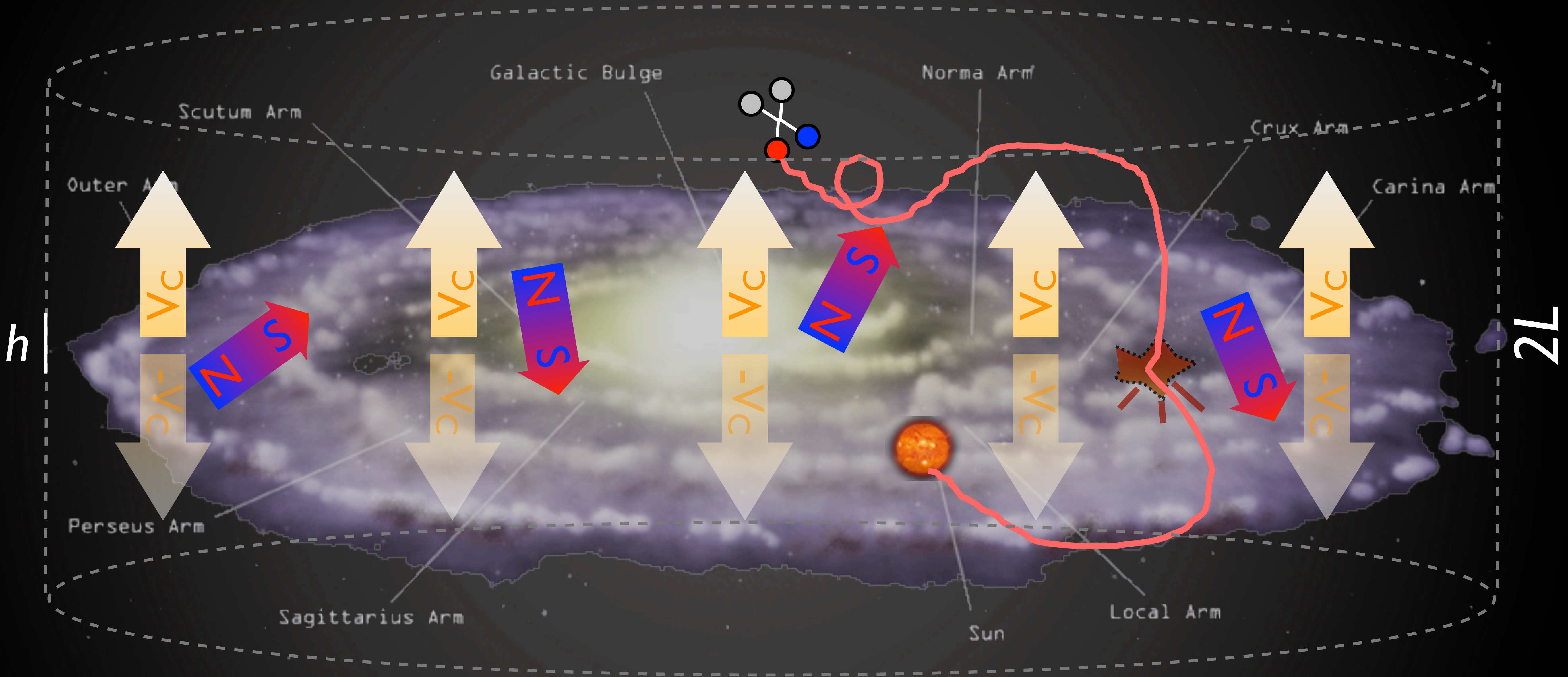


spectrum

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

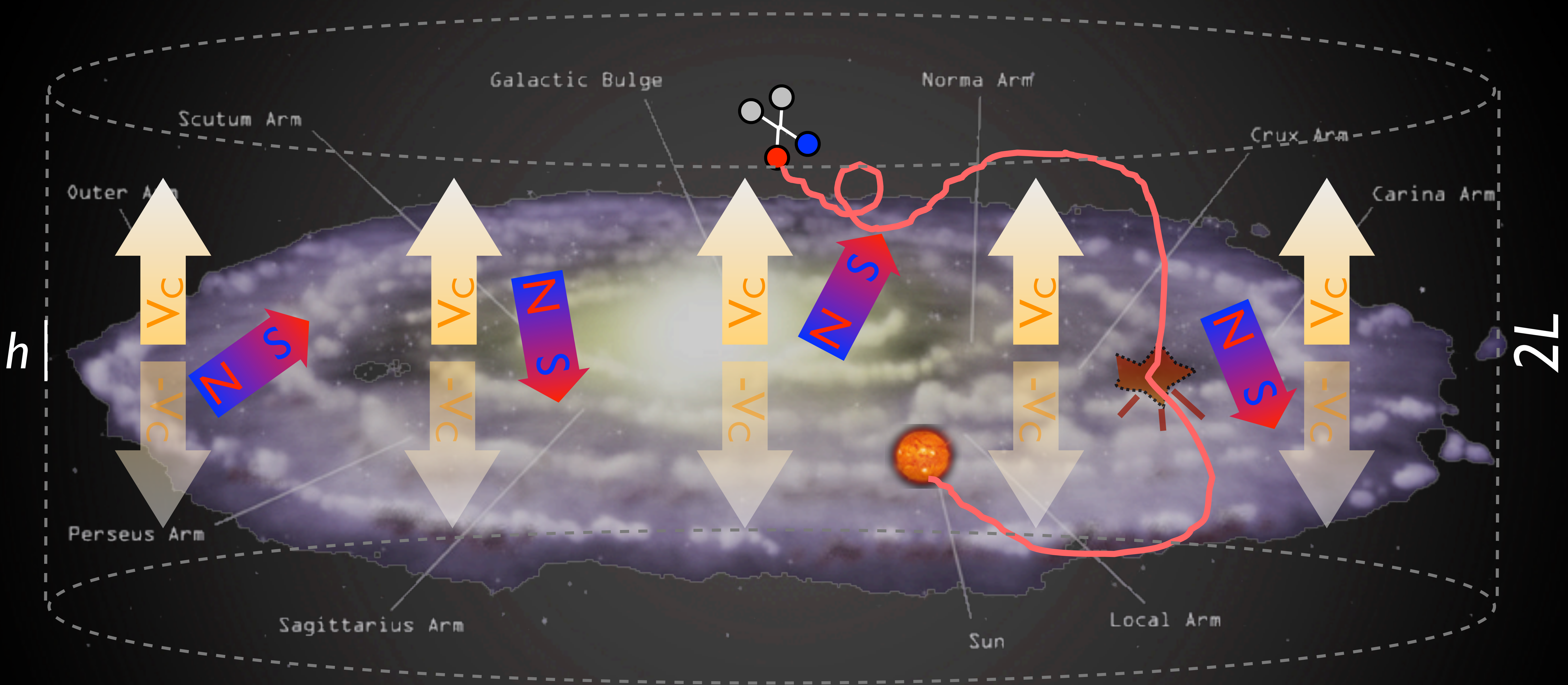
diffusion — energy loss — convective wind — source — spallations

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

[uncert]

Indirect Detection: basics

$\bar{p}$ 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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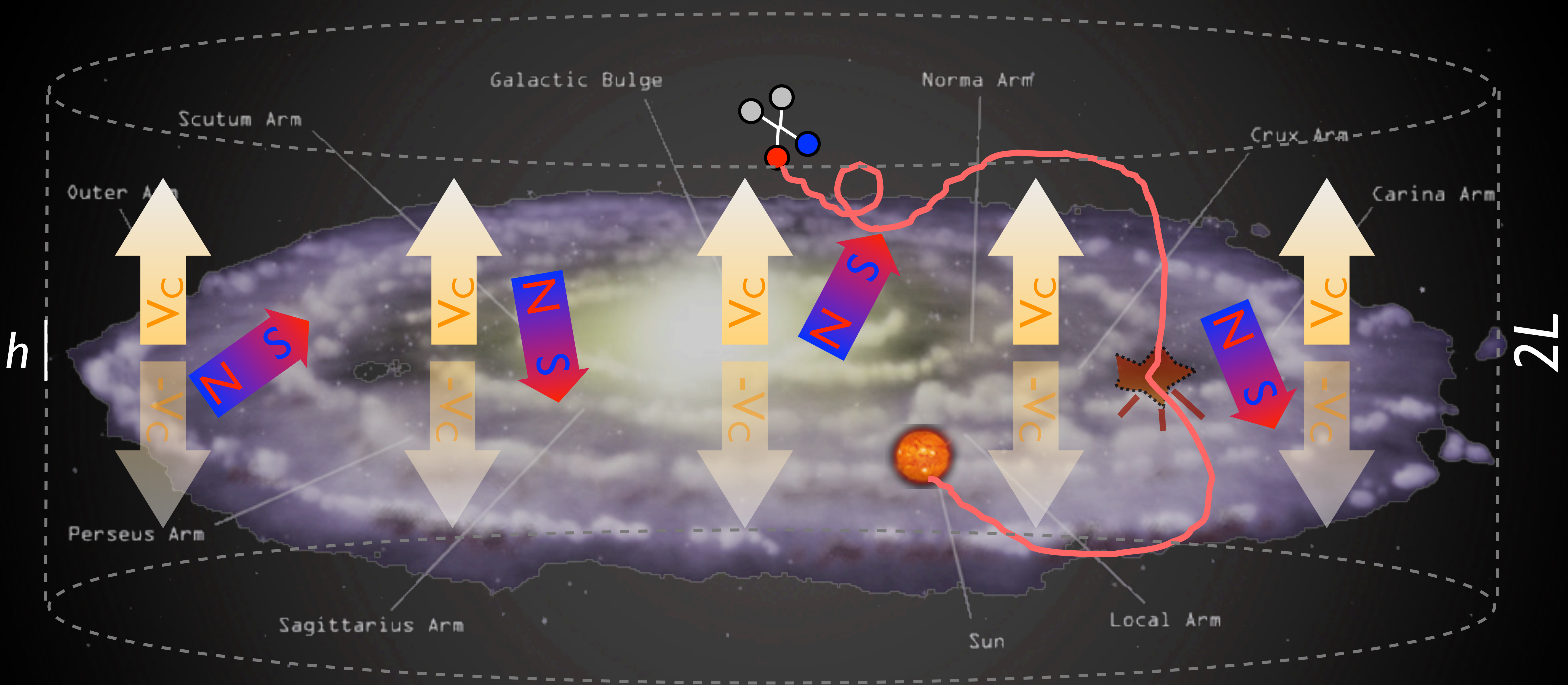

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astro& cosmo

particle

Indirect Detection: basics

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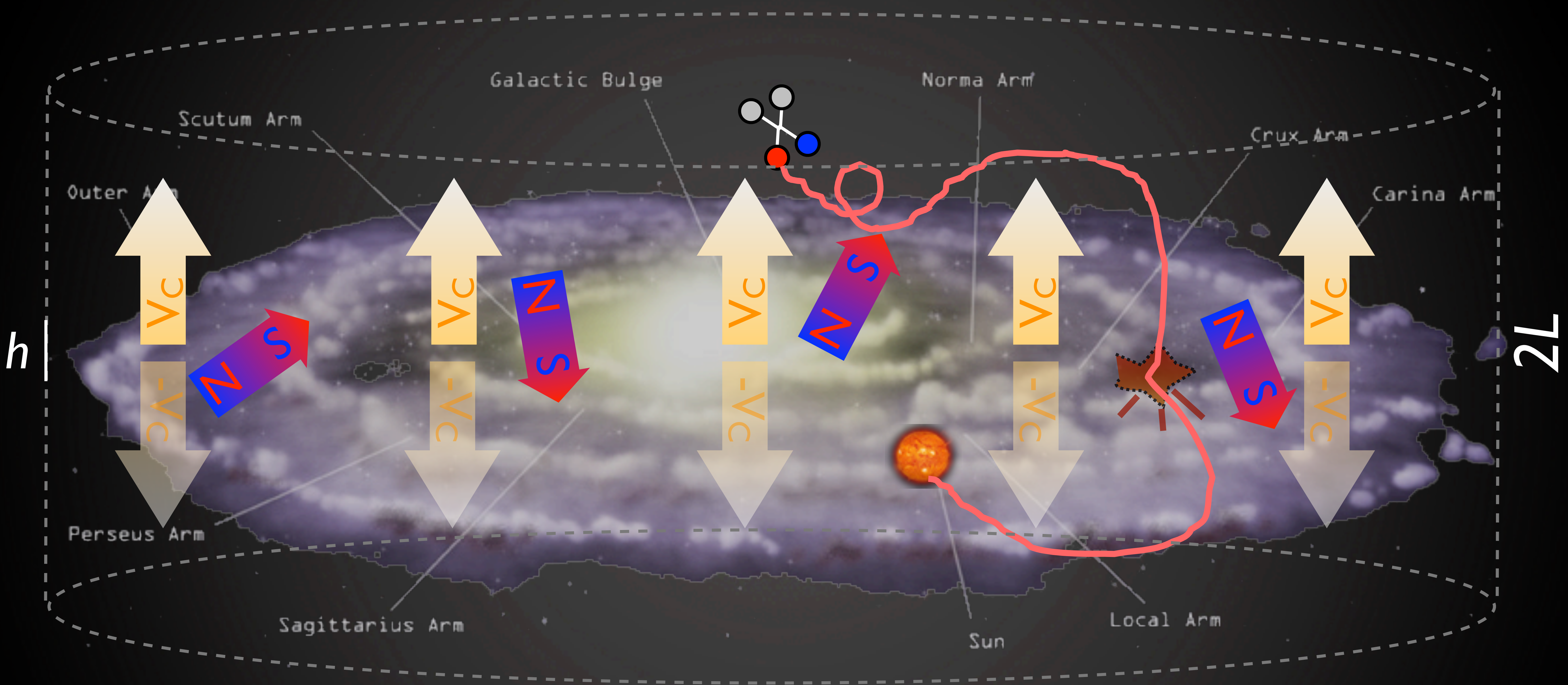


What sets the overall expected flux?

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:

$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s\left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	−	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	−	4.38	1.387
Burkert	−	12.67	0.712
Moore	−	30.28	0.105

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

6 profiles:

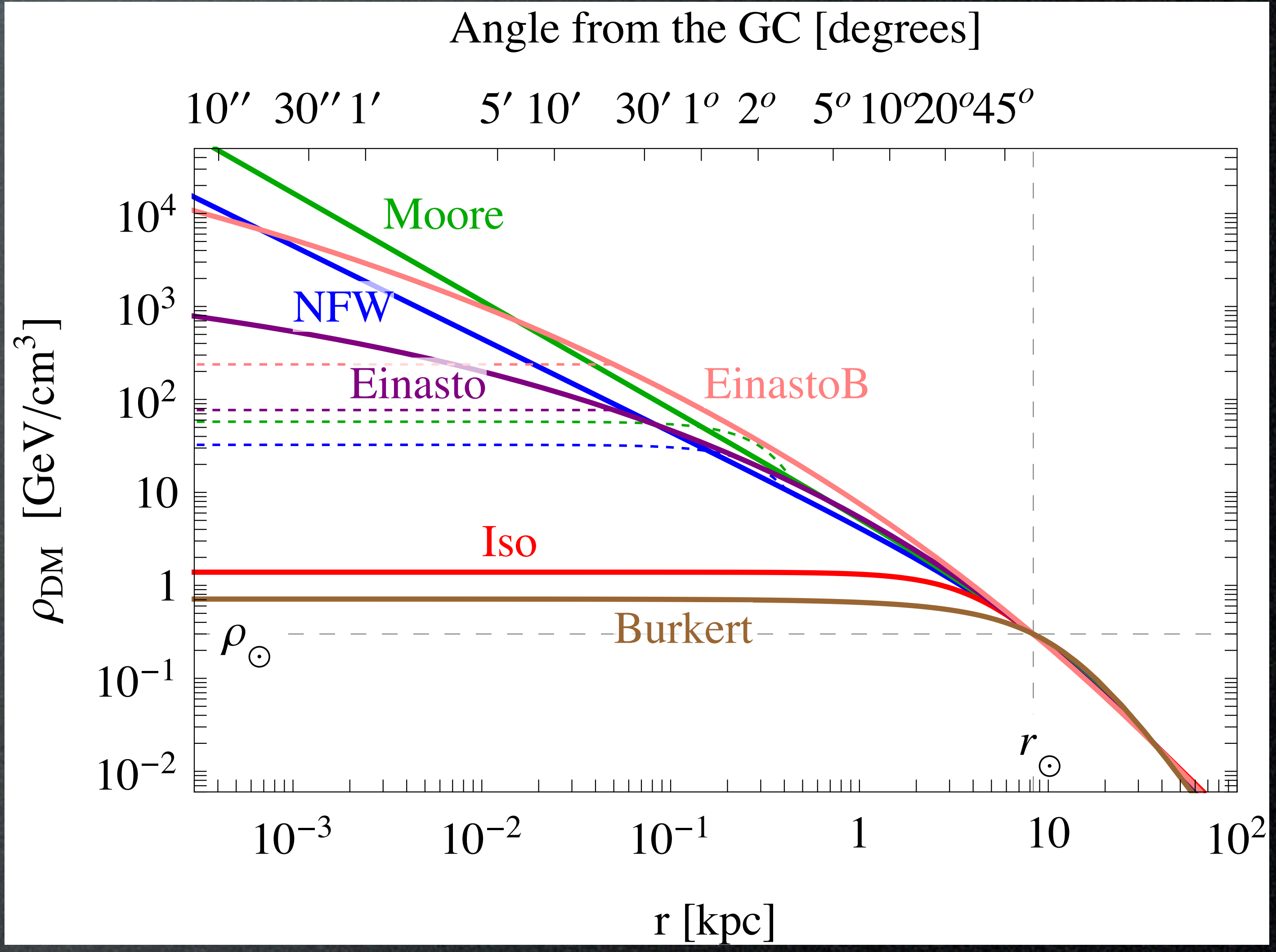
cuspy: NFW, Moore

mild: Einasto

smooth: isothermal, Burkert

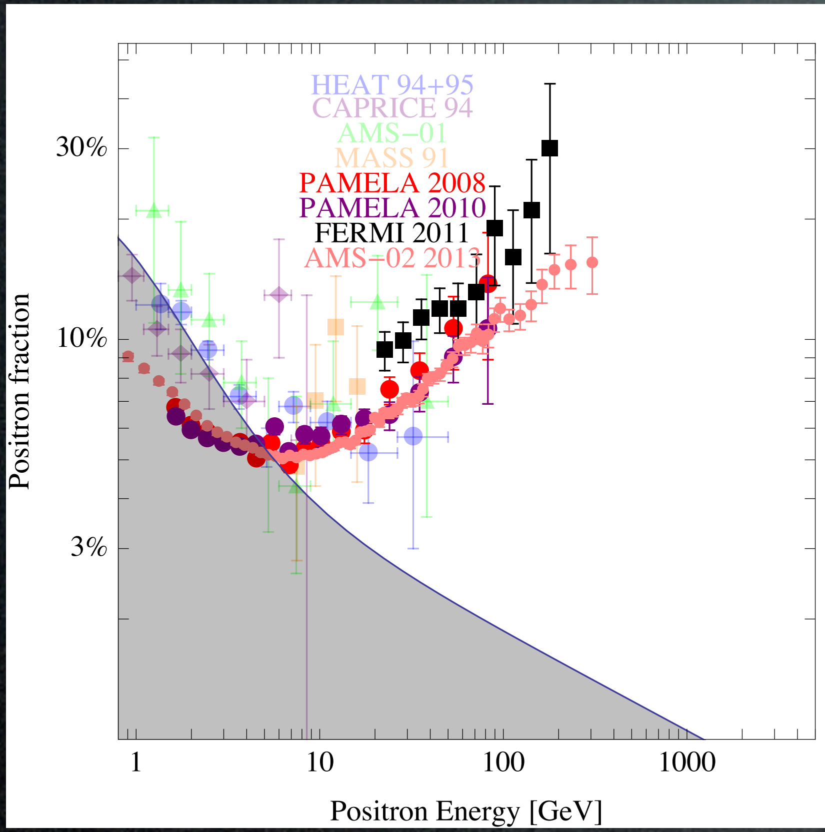
EinastoB = steepened Einasto

(effect of baryons?)

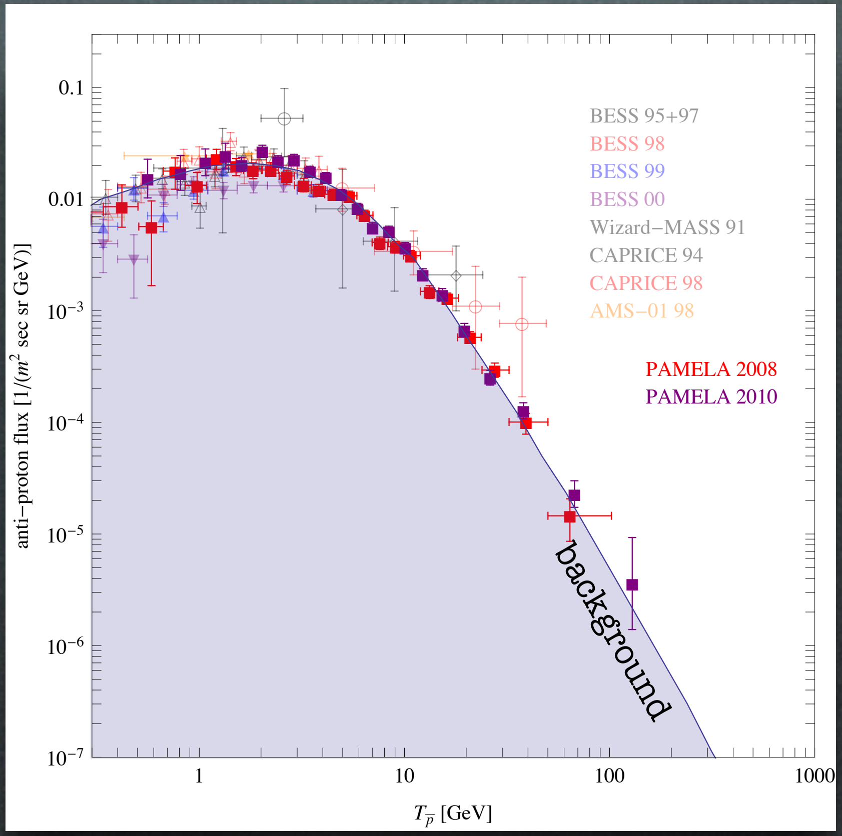


Indirect Detection: **hints**

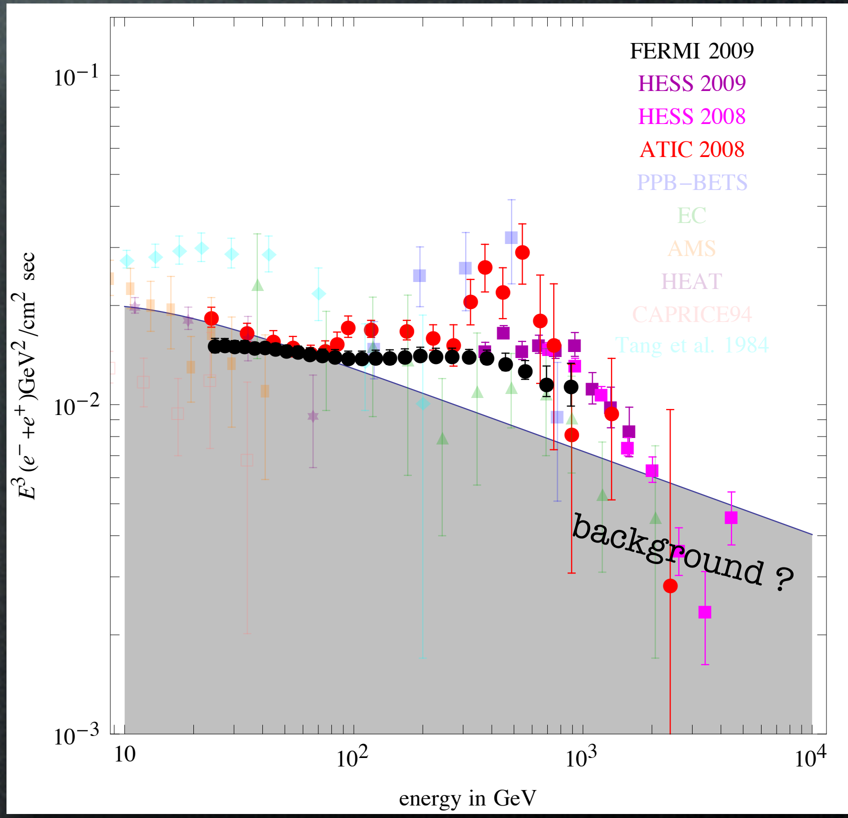
positron fraction



antiprotons

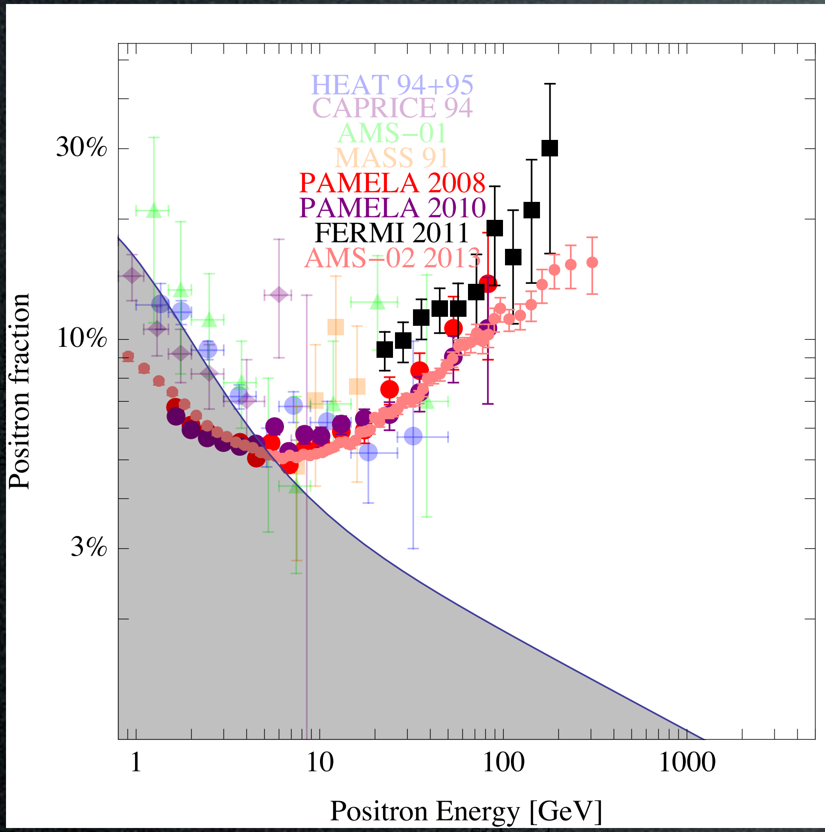


electrons + positrons



Positrons & Electrons

positron fraction



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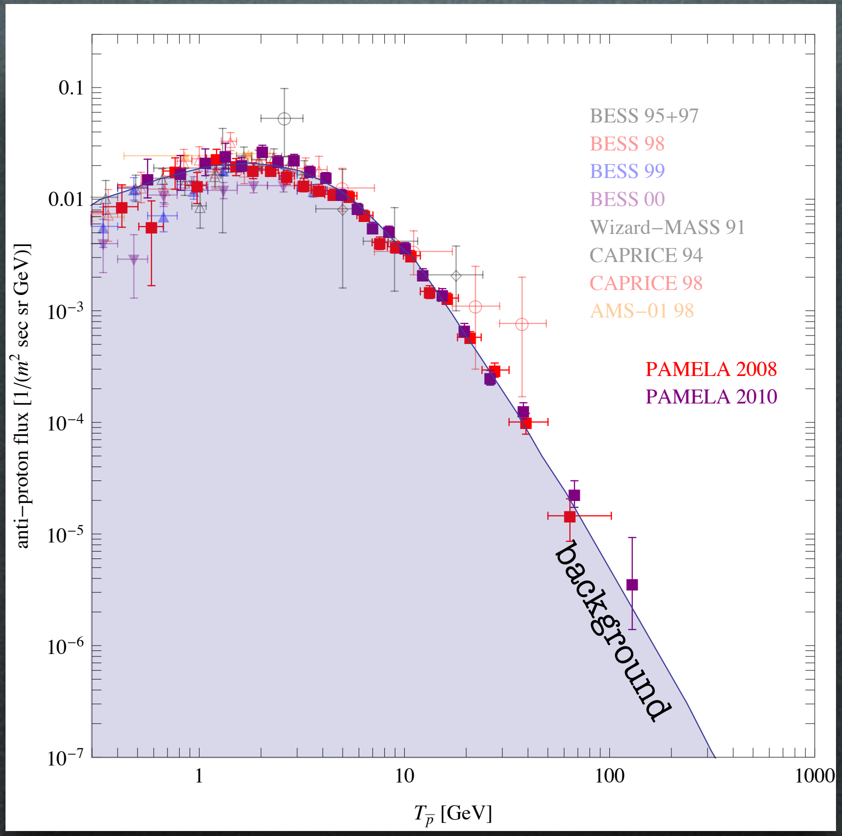

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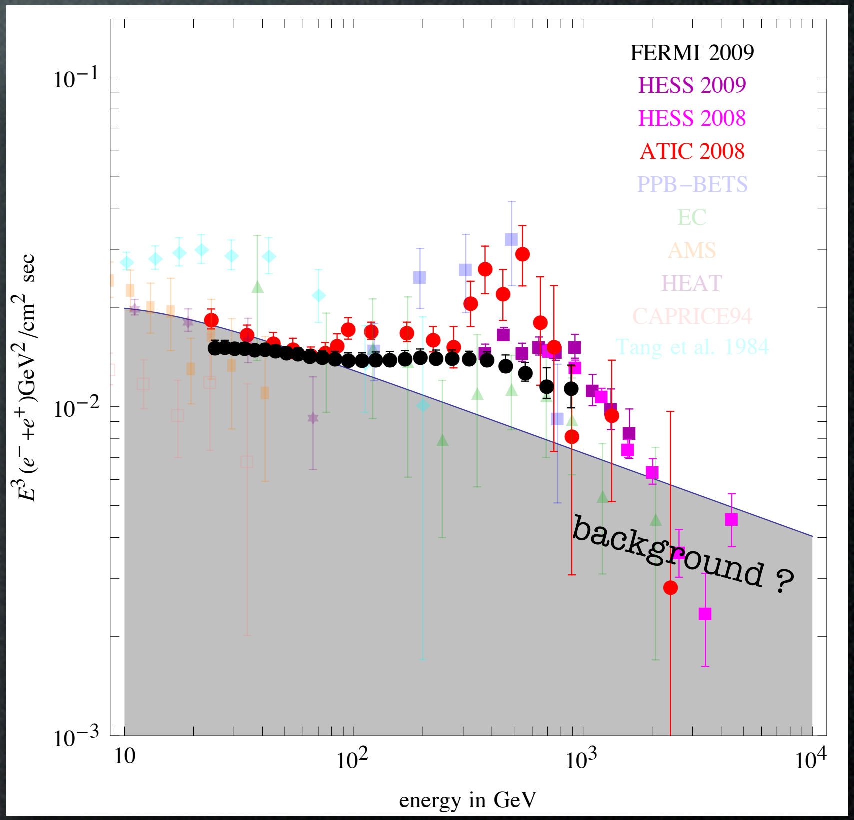
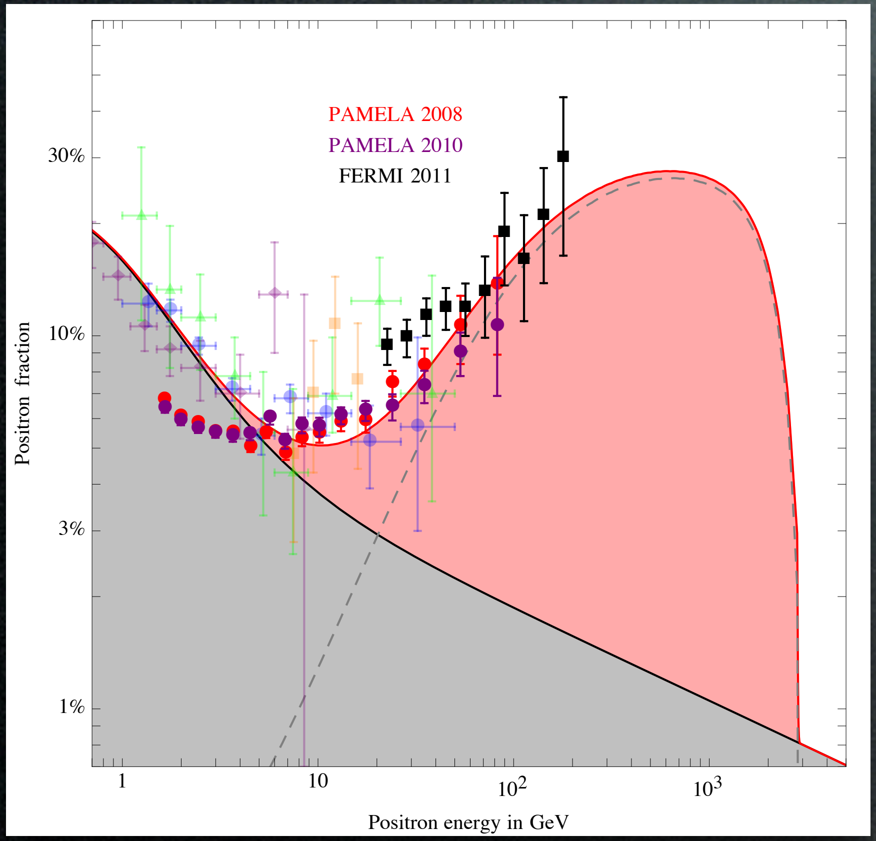


Are these signals of Dark Matter?

Positrons & Electrons

positron fraction



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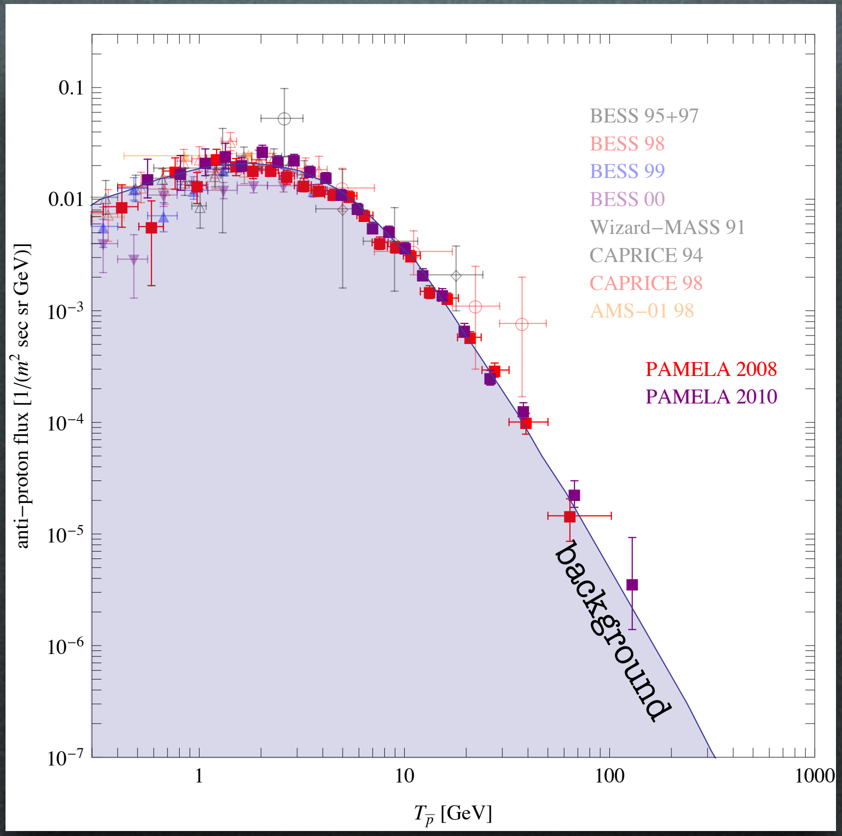

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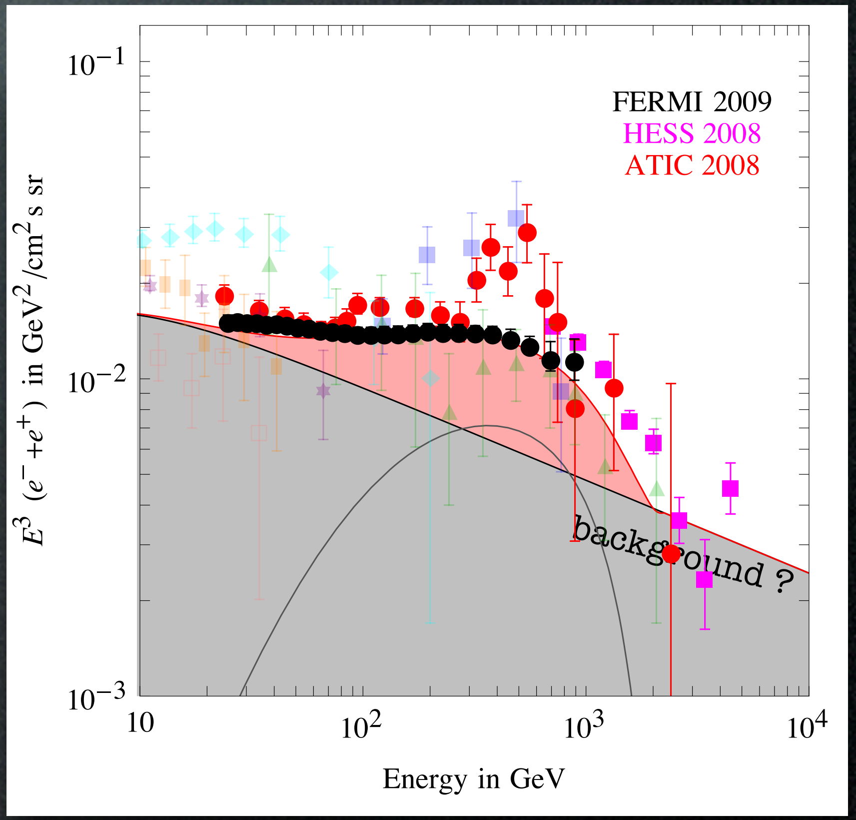
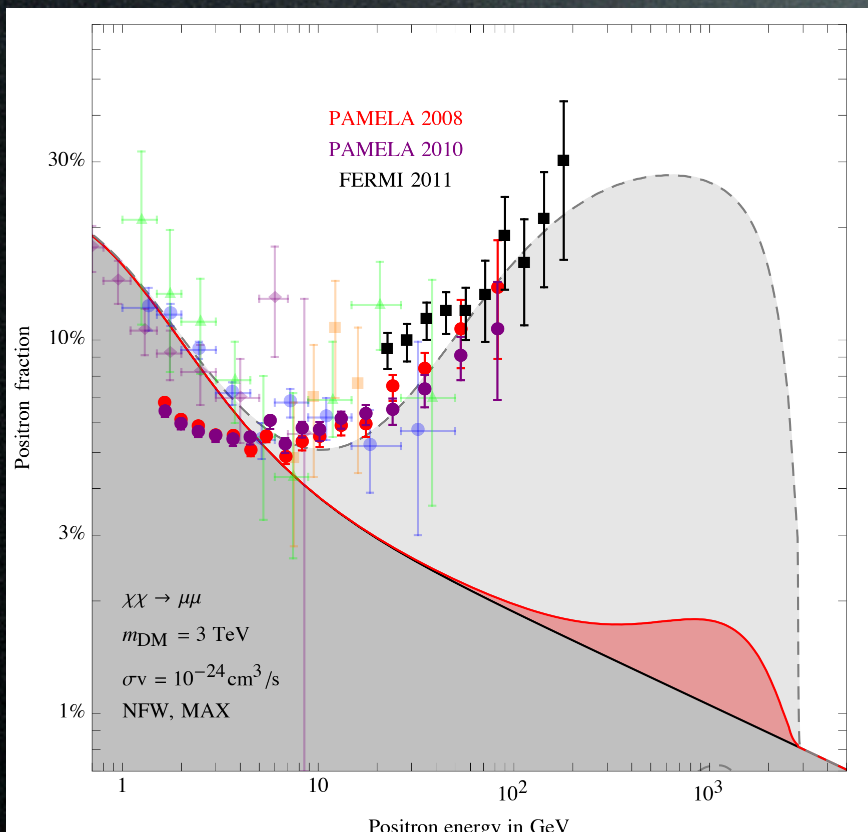


Are these signals of Dark Matter?

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

Positrons & Electrons

positron fraction



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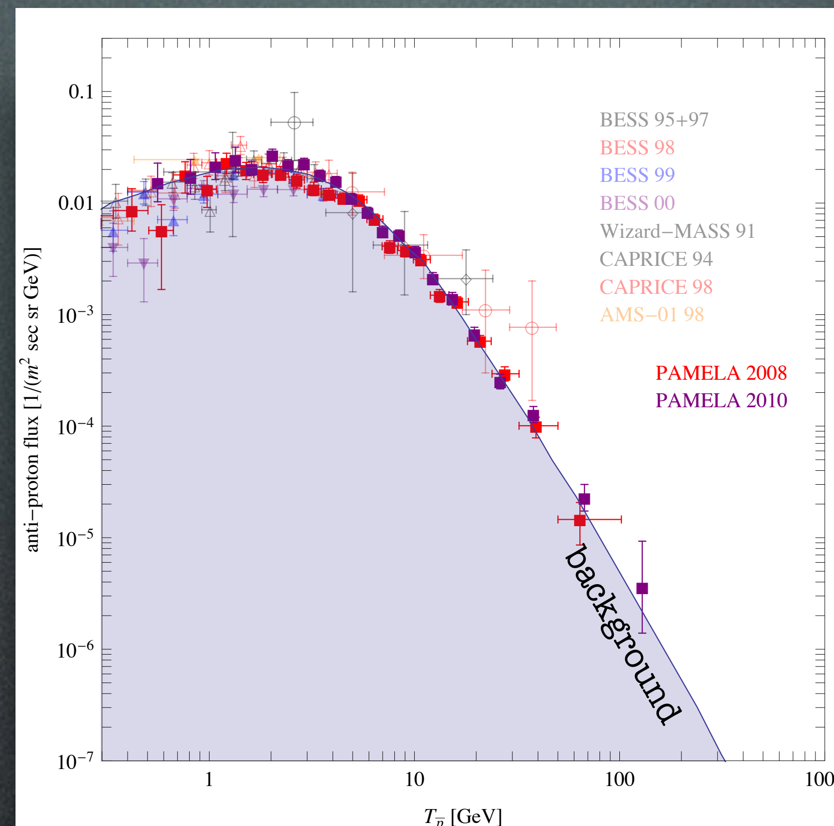

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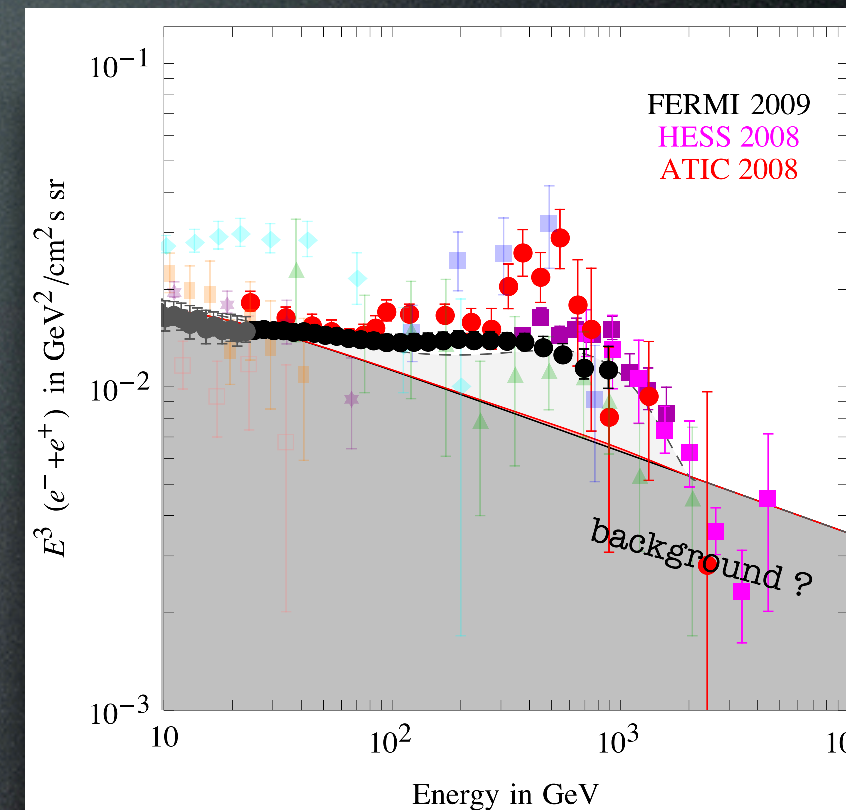

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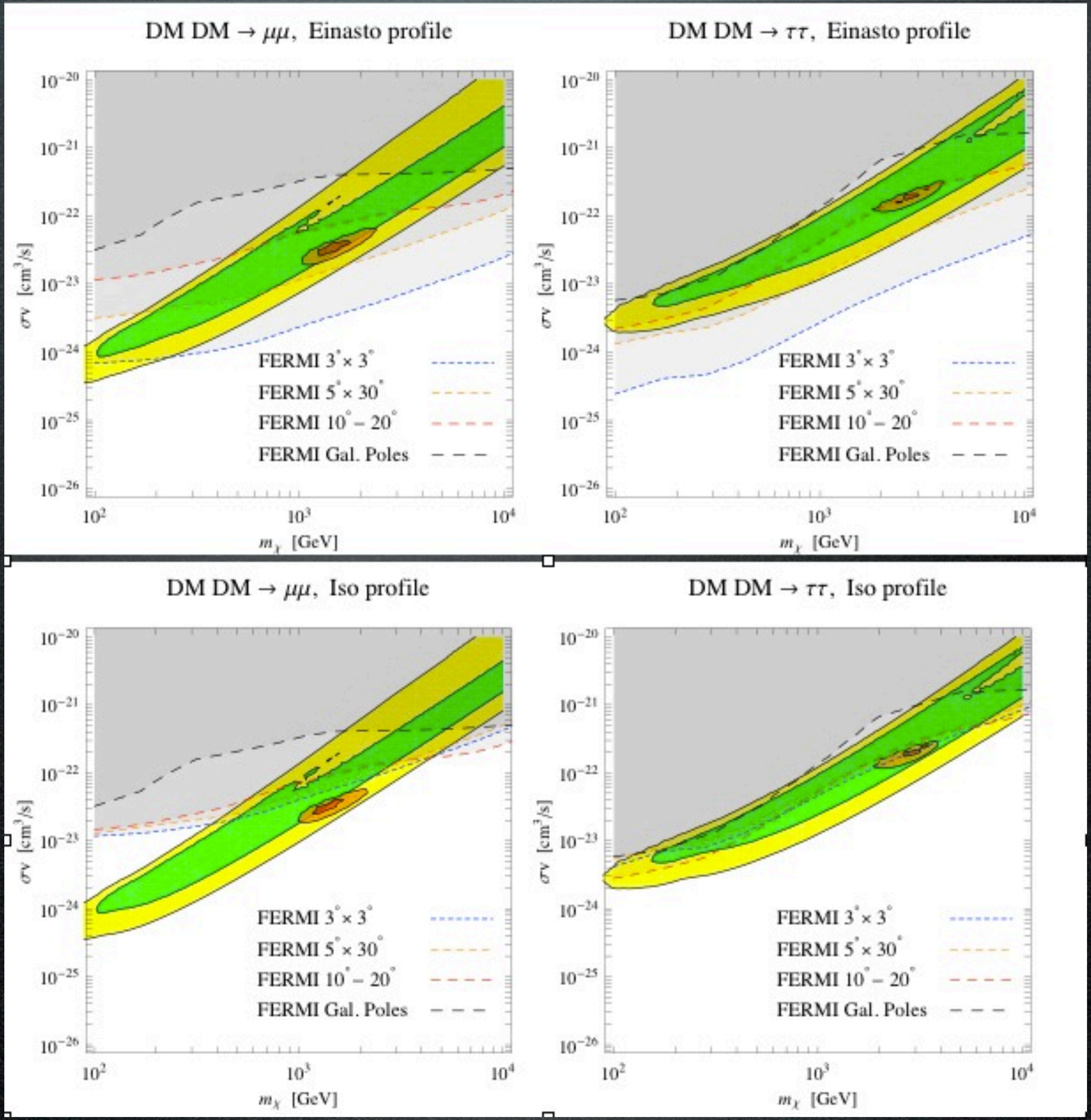
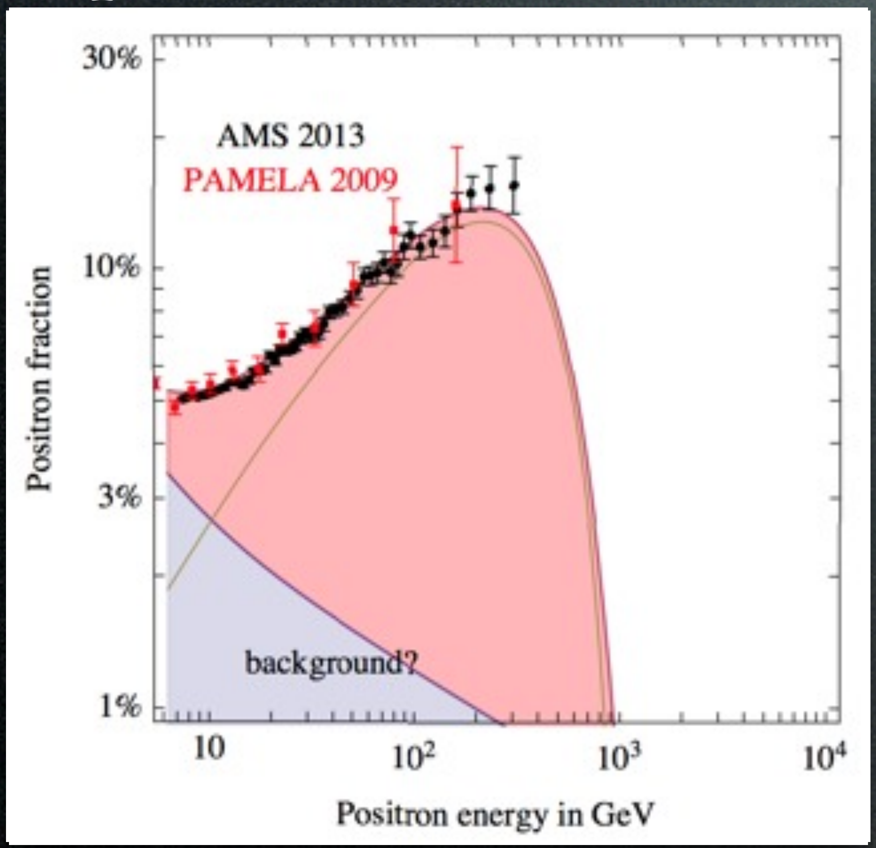
NO: a formidable ‘background’ for future searches

Positrons & Electrons



PS: post AMS 2013

positron fraction



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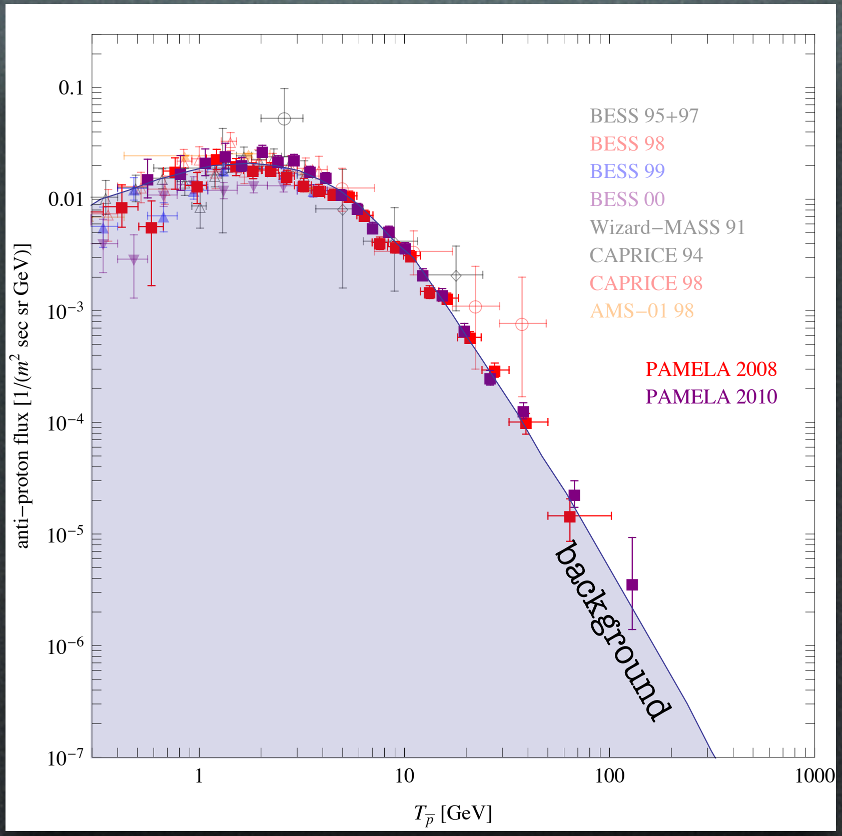

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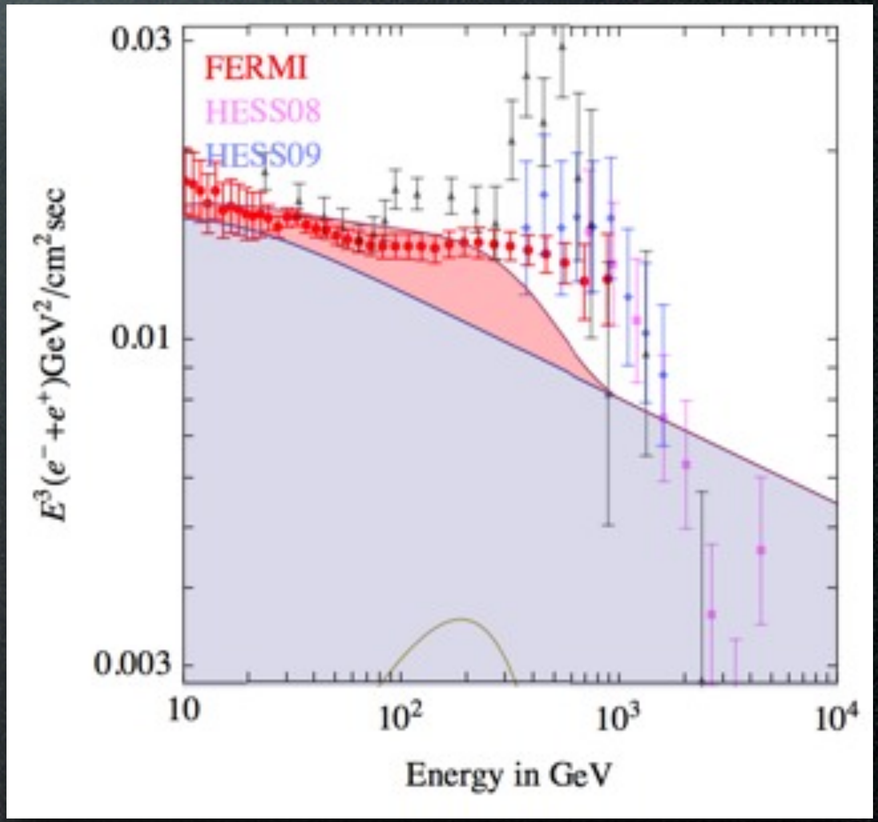

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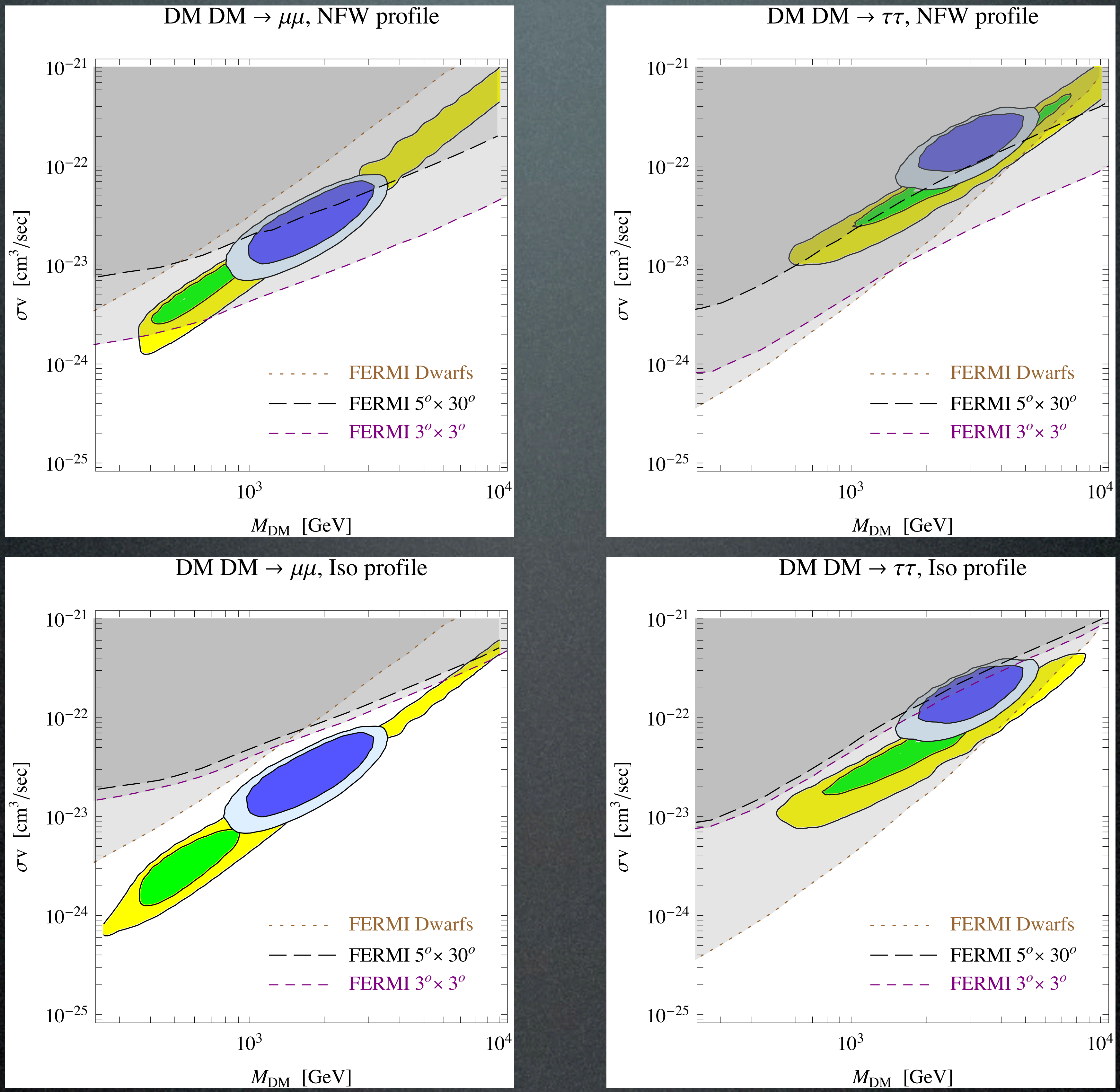
'tension' between positron frac and e^++e^-

Addendum (2013) to Cirelli, Kadastik, Raidal, Strumia 0809.2409 (2008)

PS: post AMS 2013



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Indirect Detection: **constraints**

direct detection

production at colliders

indirect

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

Fermi, ICT, radio telescopes...

e^+ from annihil in galactic halo or center

PAMELA, Fermi, HESS, AMS, **balloons...**

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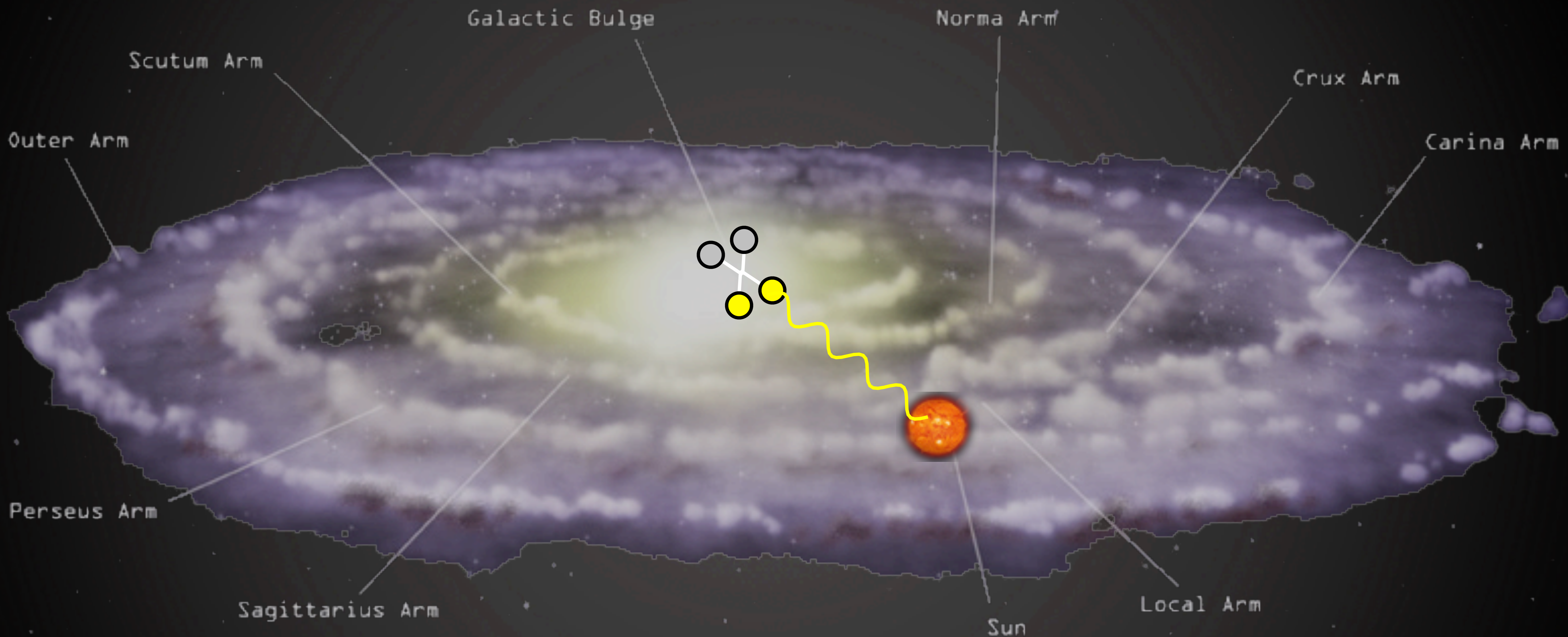
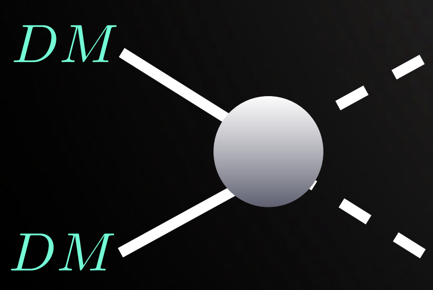
Indirect Detection: constraints

γ from DM annihilations in galactic center



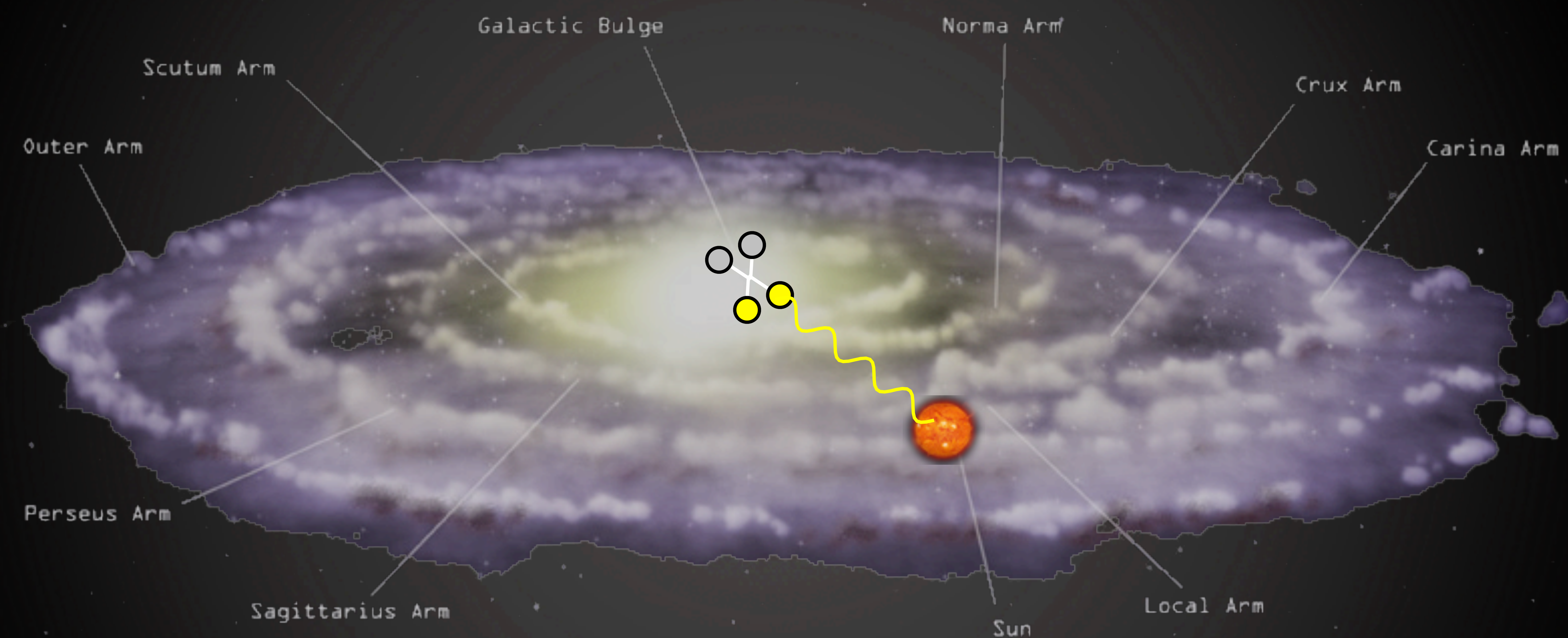


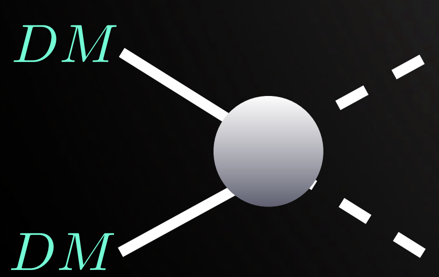
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \text{ and } \gamma$$

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

Indirect Detection: constraints

a. 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

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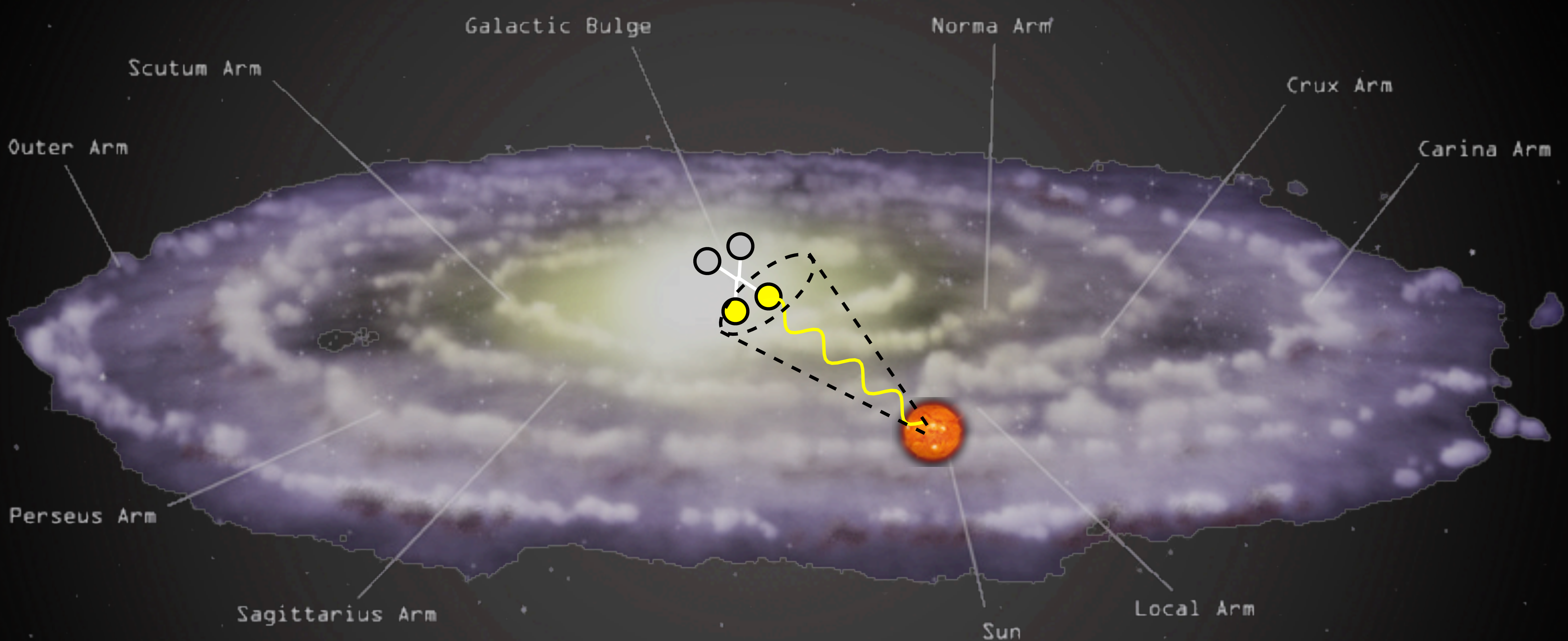
a. γ from DM annihilations in galactic center



DM, DM

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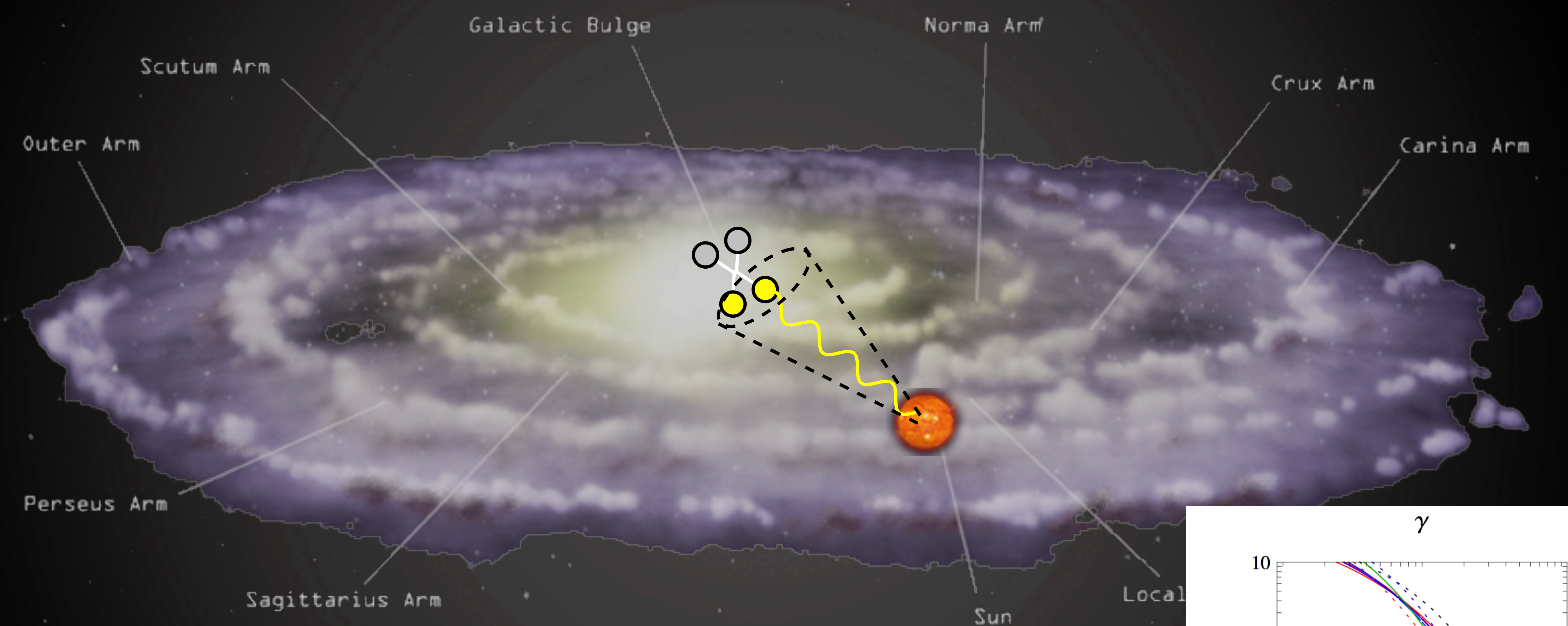
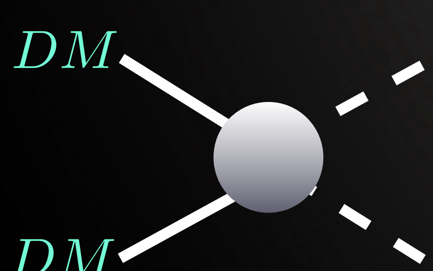
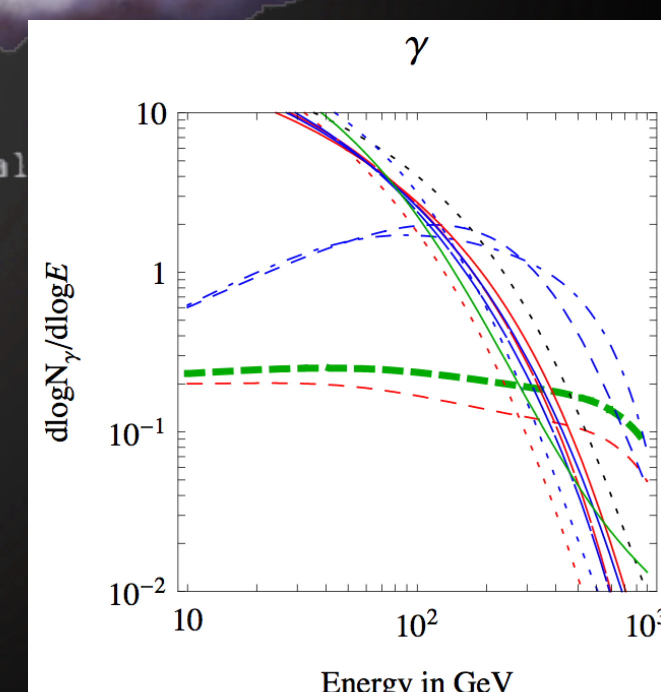




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

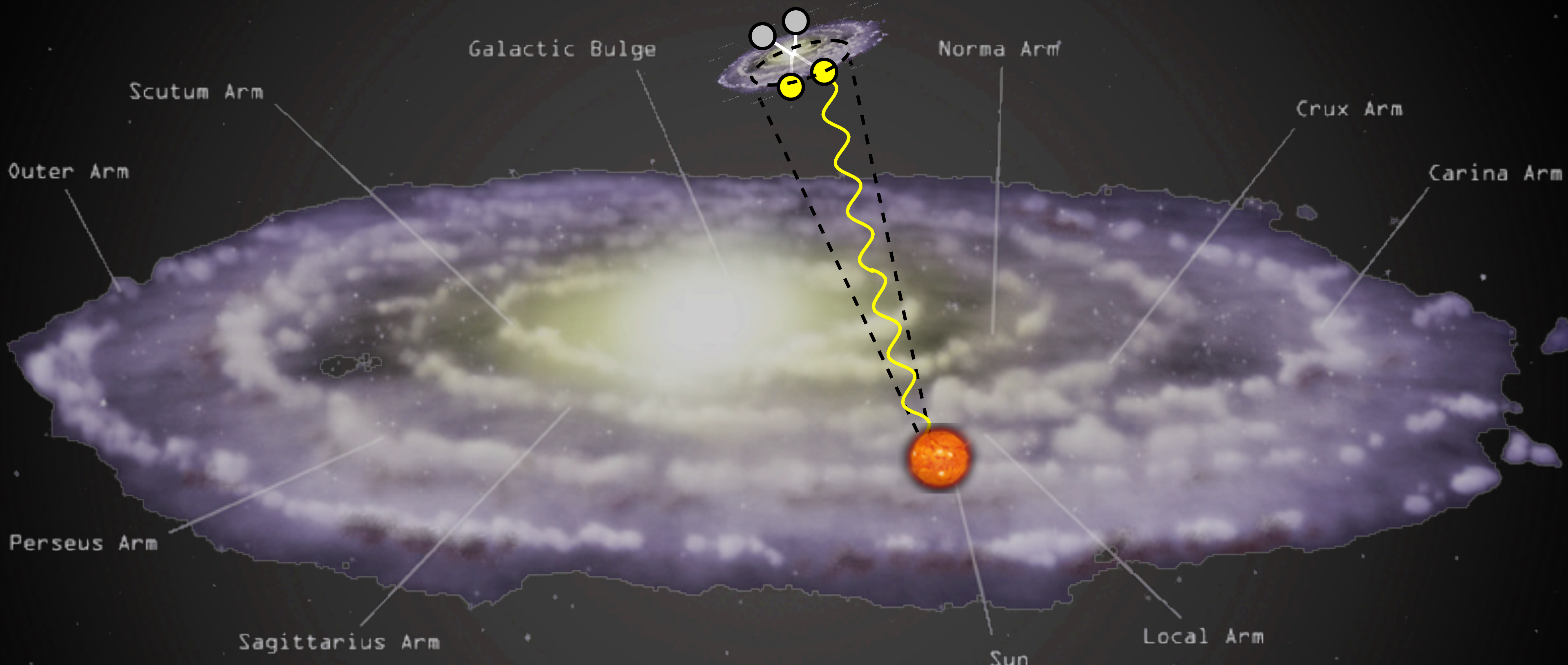
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

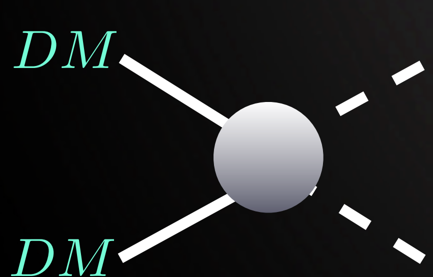


typically sub-TeV energies

Indirect Detection: constraints

b. γ from DM annihilations in Satellite Galaxies



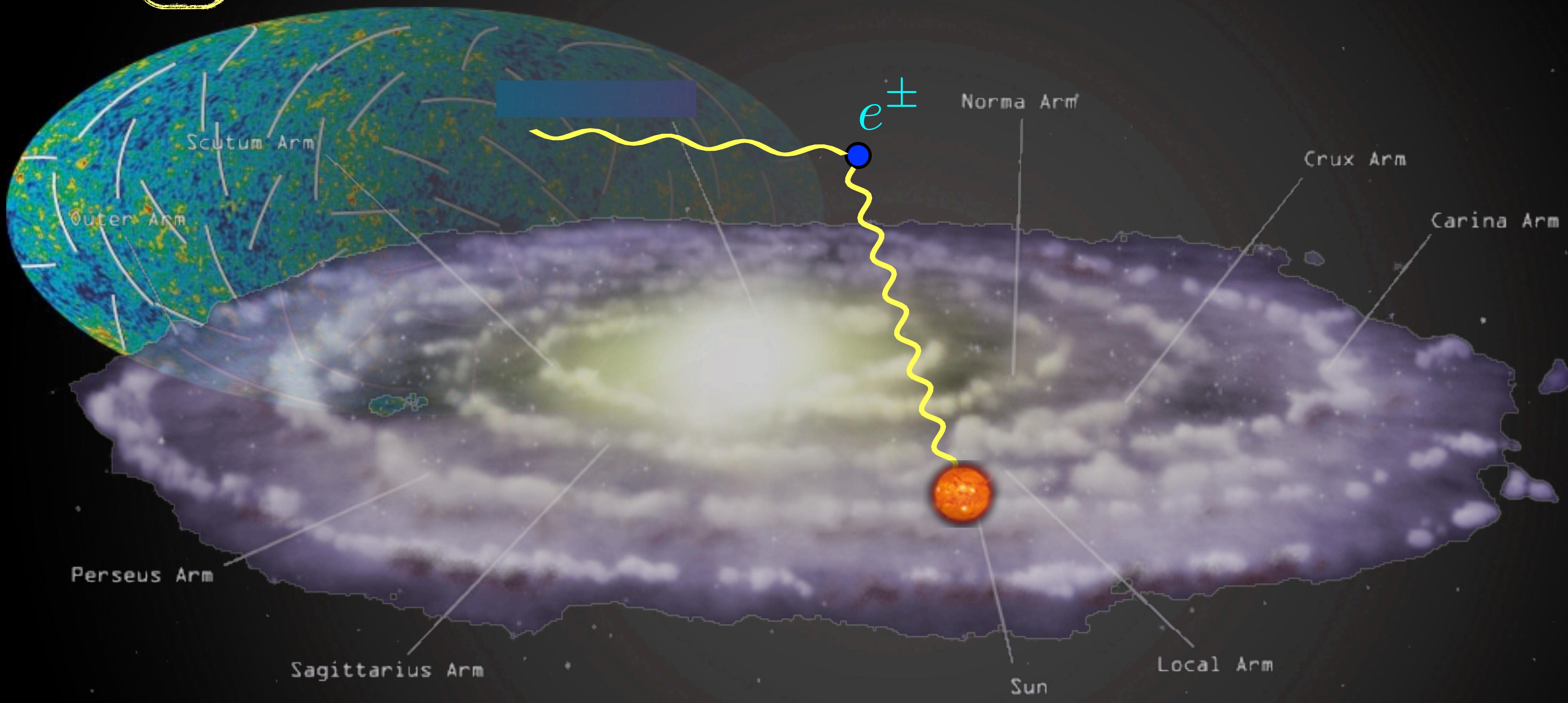


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \text{ and } \gamma$$

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

Indirect Detection: constraints

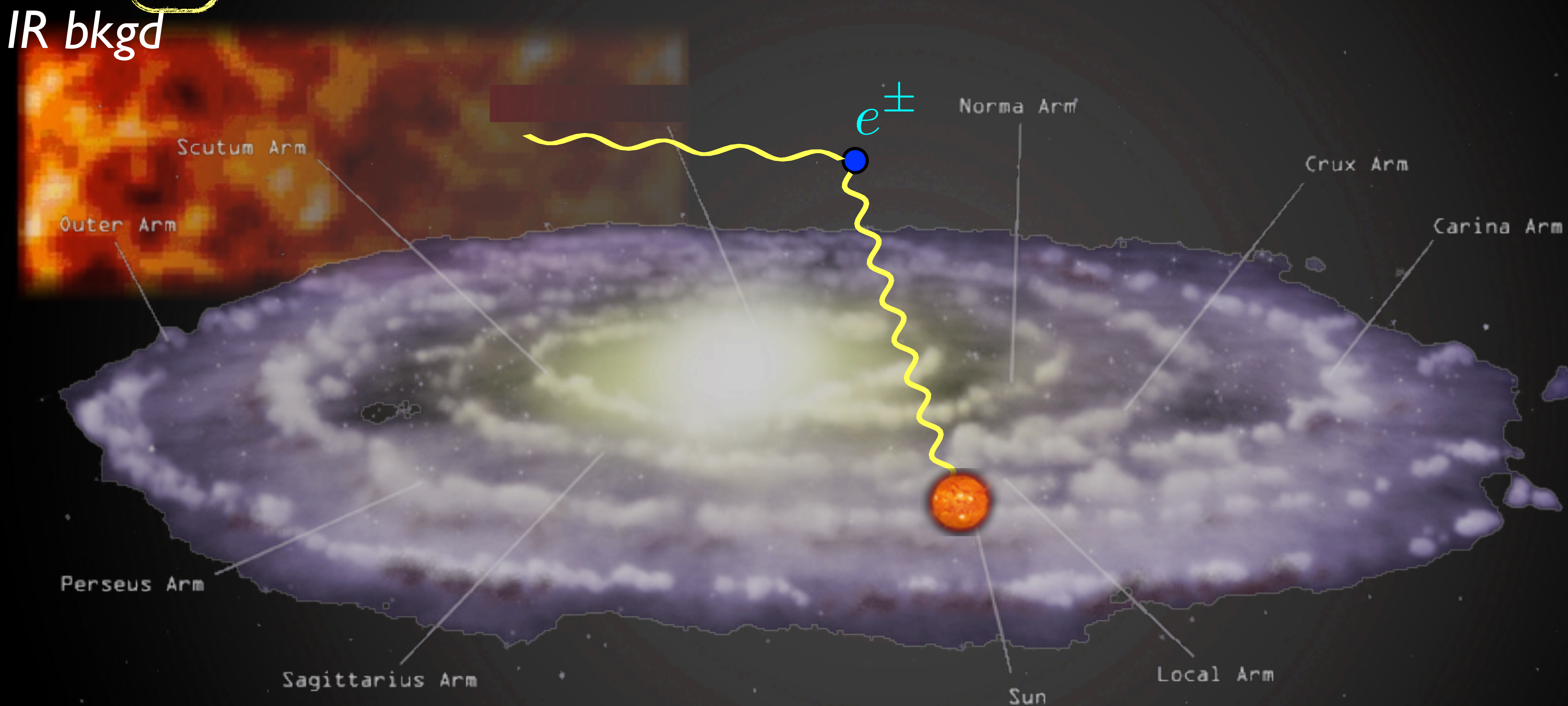
c. γ from Inverse Compton on $e^{\pm}$ in halo



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

Indirect Detection: constraints

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



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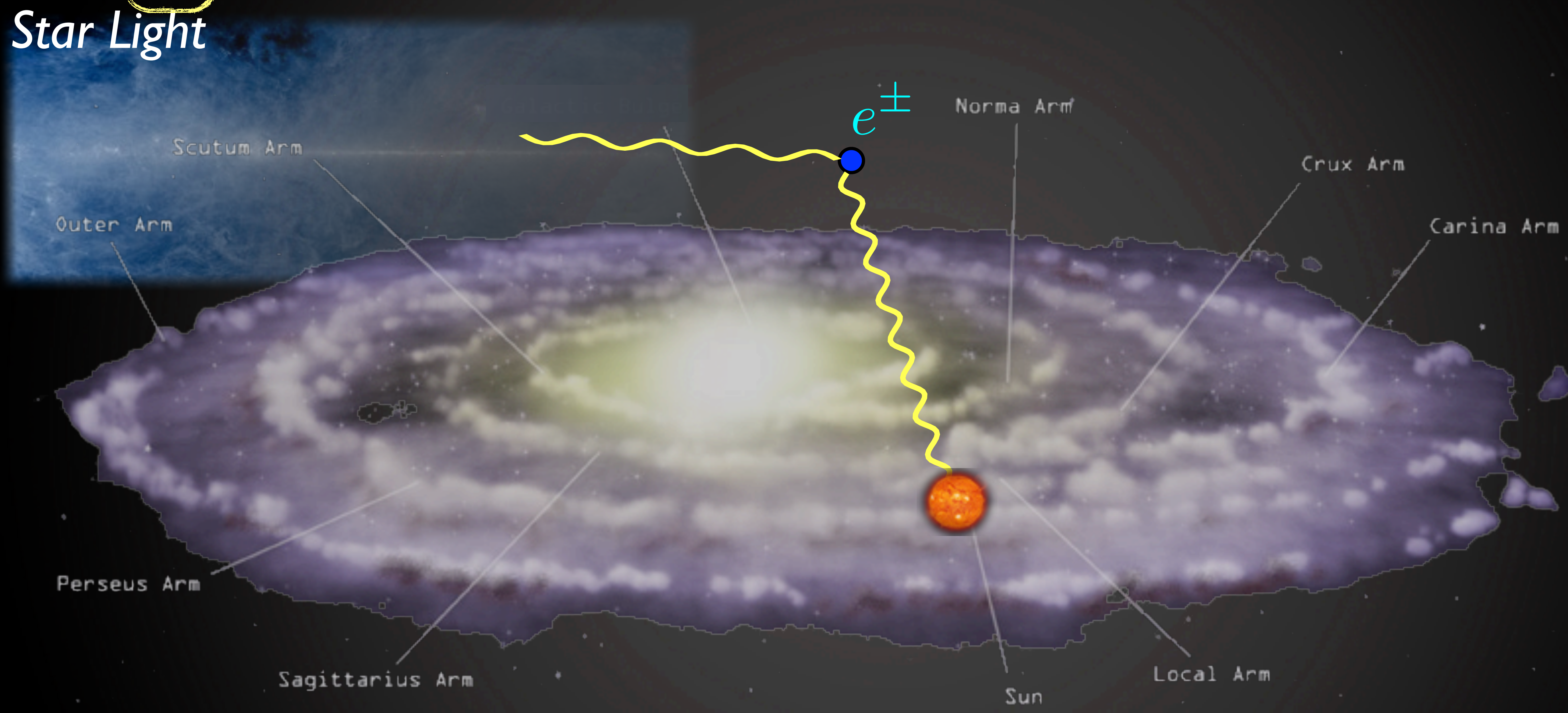

- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
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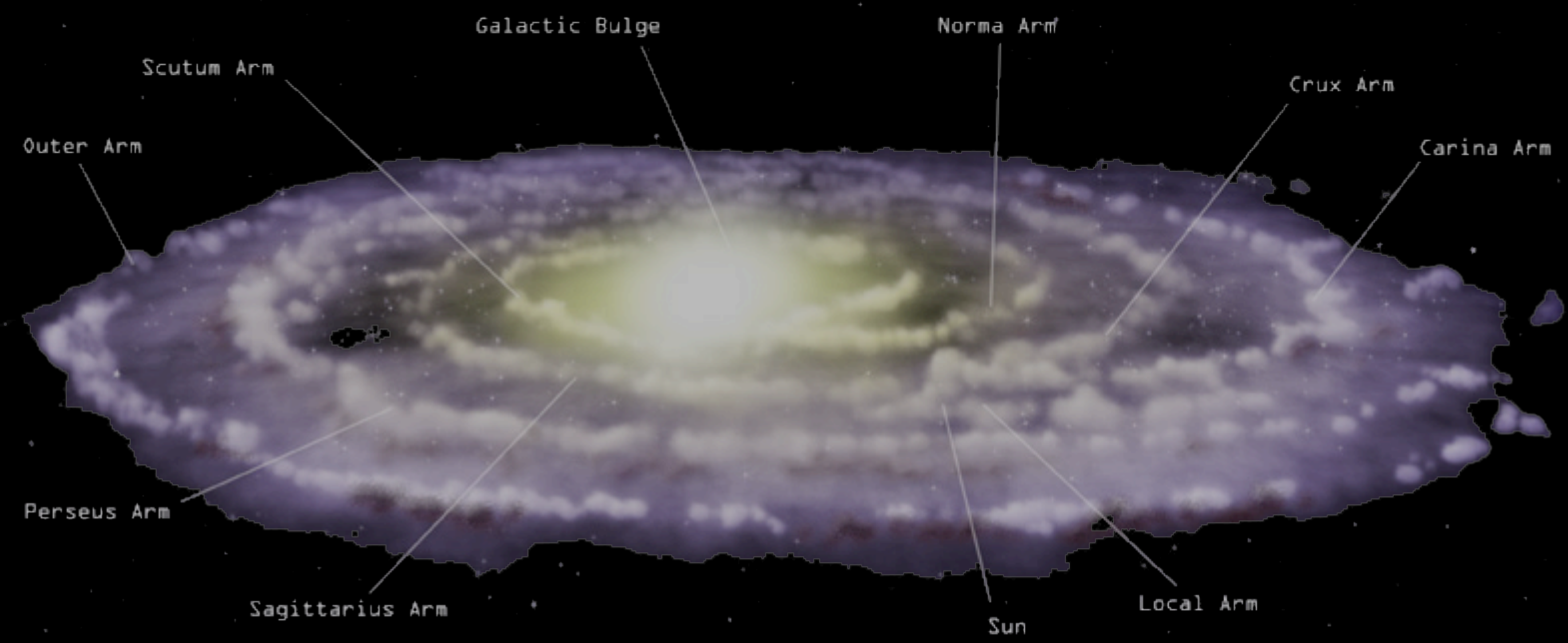
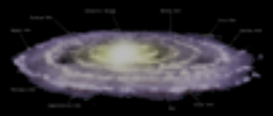
Indirect Detection: constraints

d. γ from outside the Galaxy



Indirect Detection: constraints

d. γ from outside the Galaxy

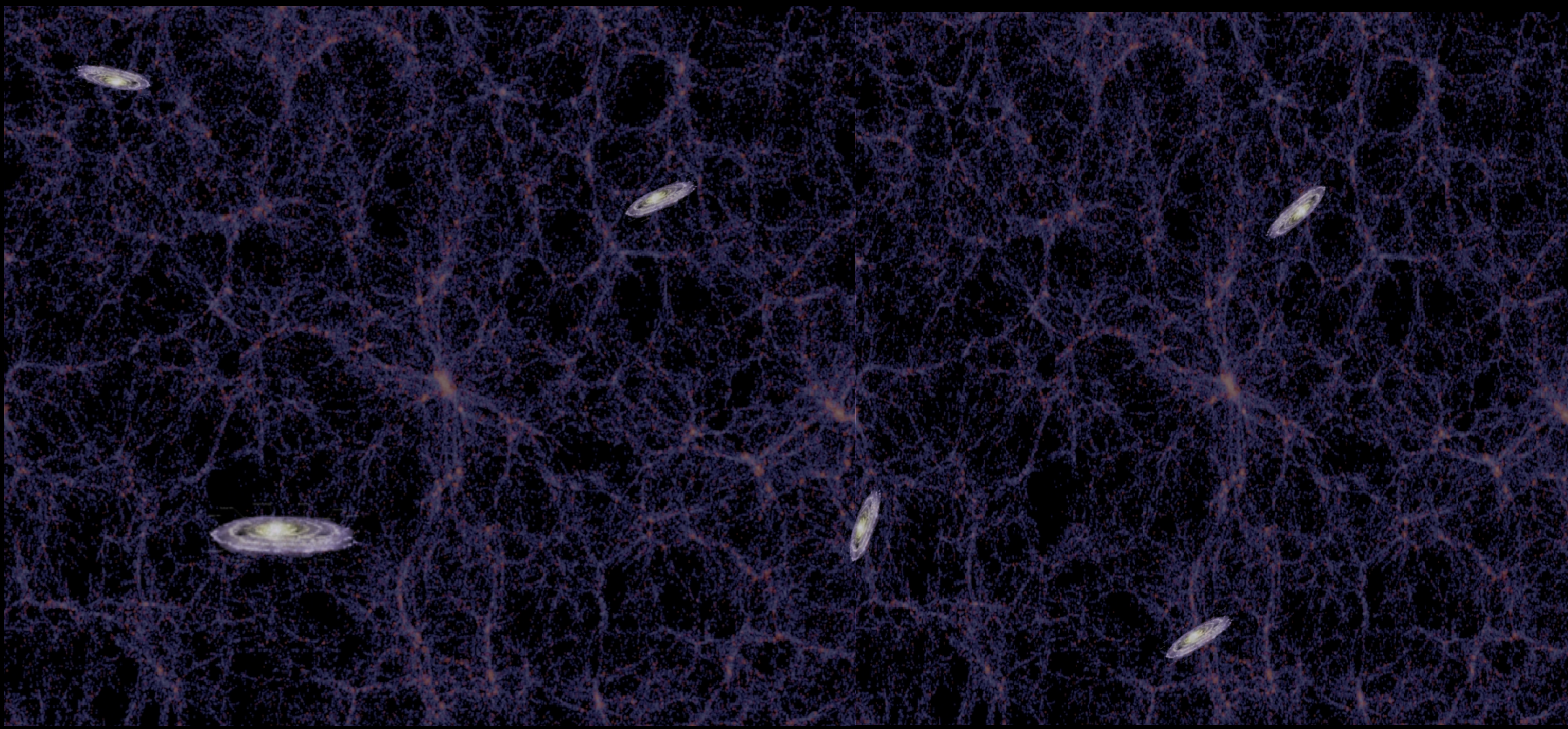


Indirect Detection: constraints

d. γ from outside the Galaxy

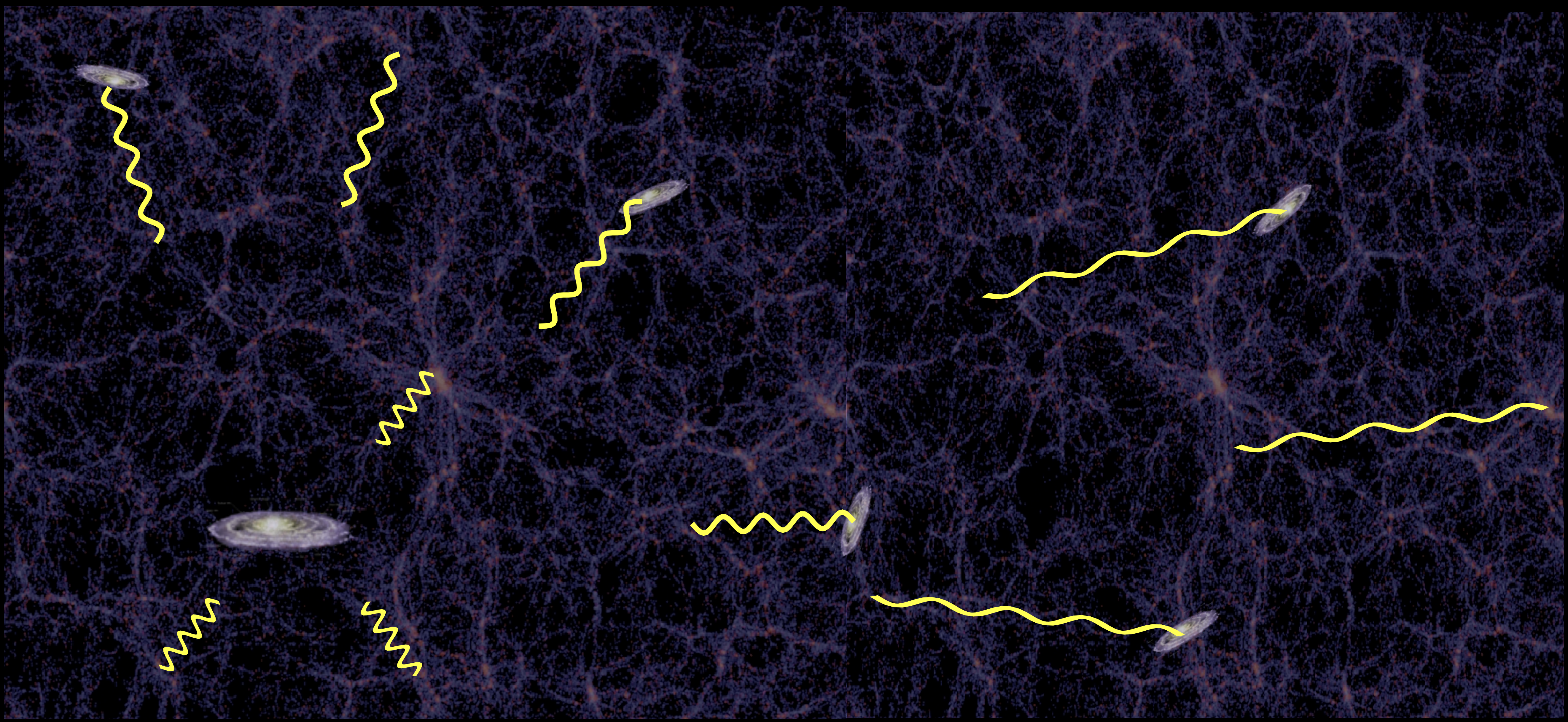
Indirect Detection: constraints

d. γ from outside the Galaxy



Indirect Detection: constraints

d. γ from outside the Galaxy



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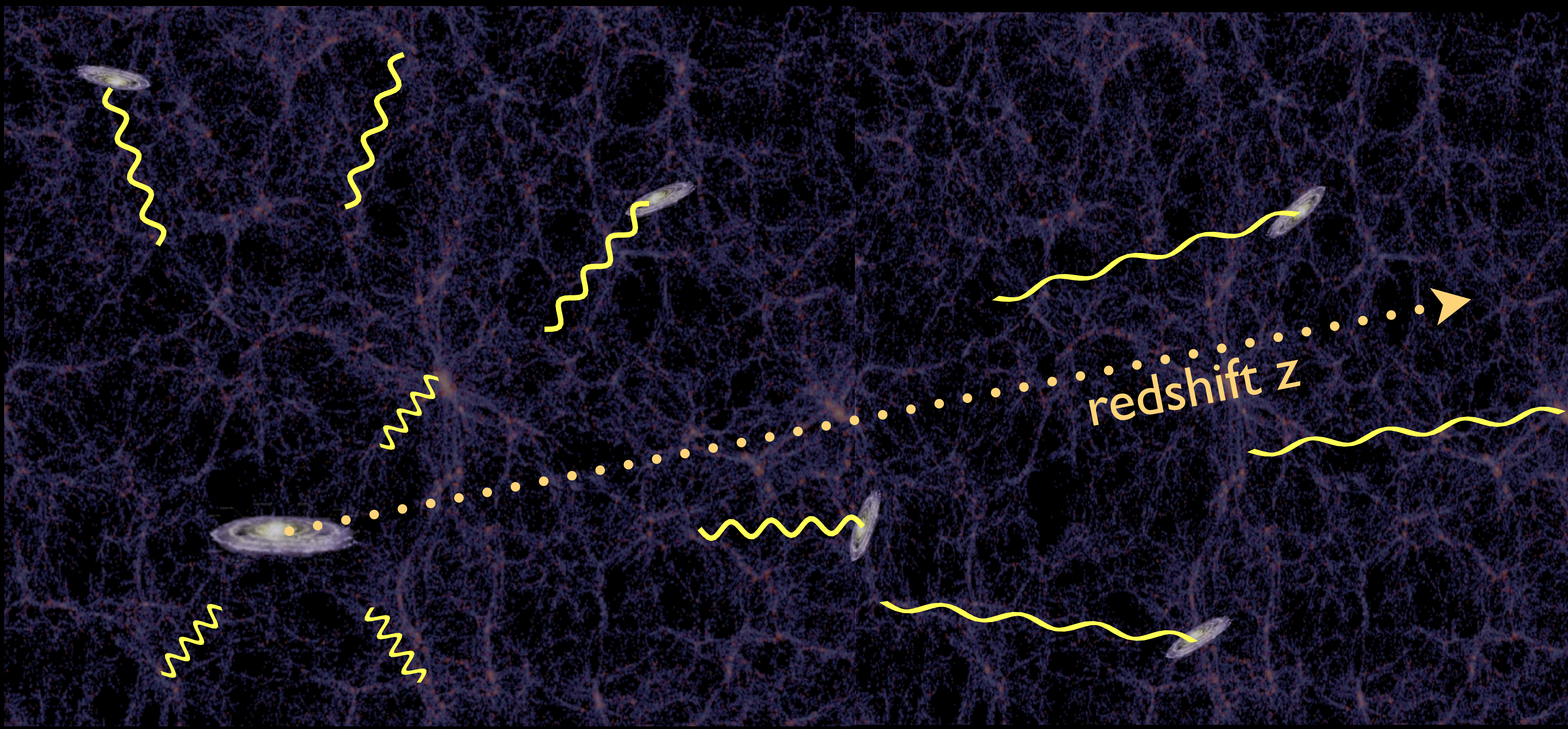
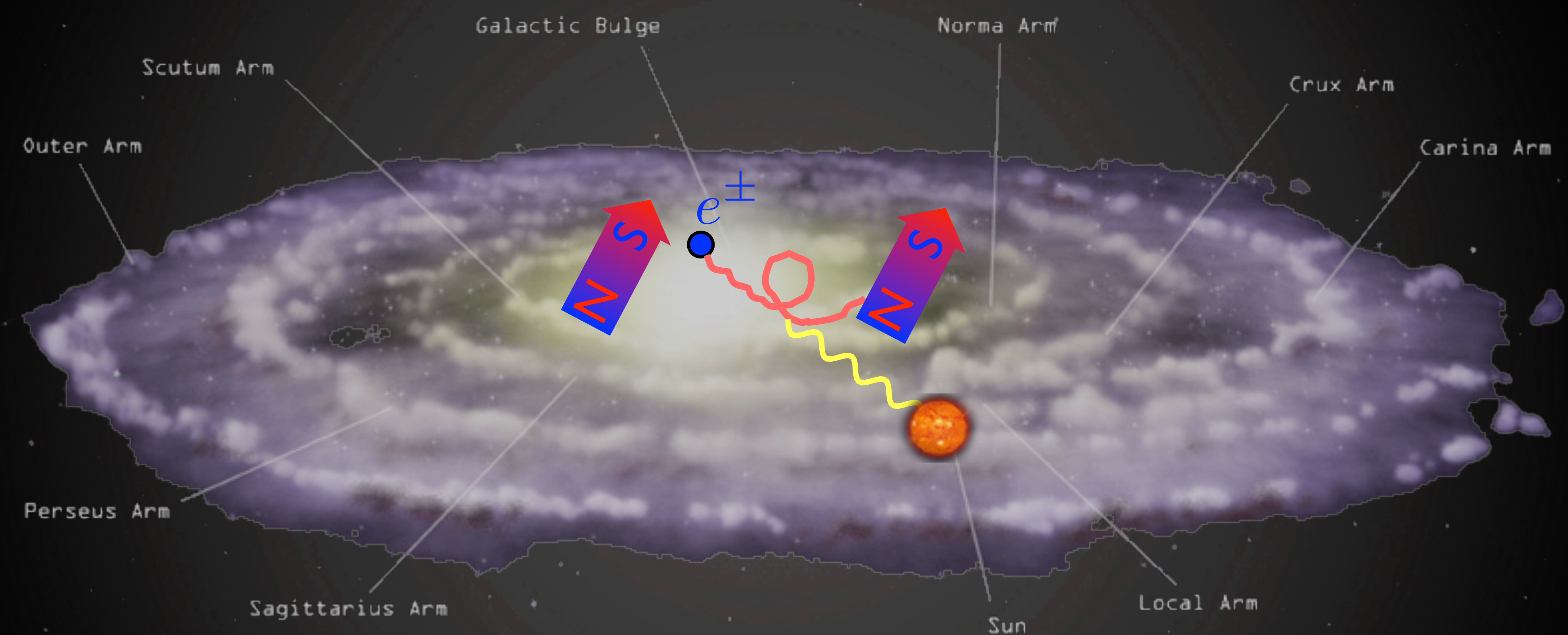


- isotropic flux of prompt and ICS gamma rays, integrated over z and r
- depends strongly on halo formation details and history

Indirect Detection: constraints

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



Indirect Detection: constraints

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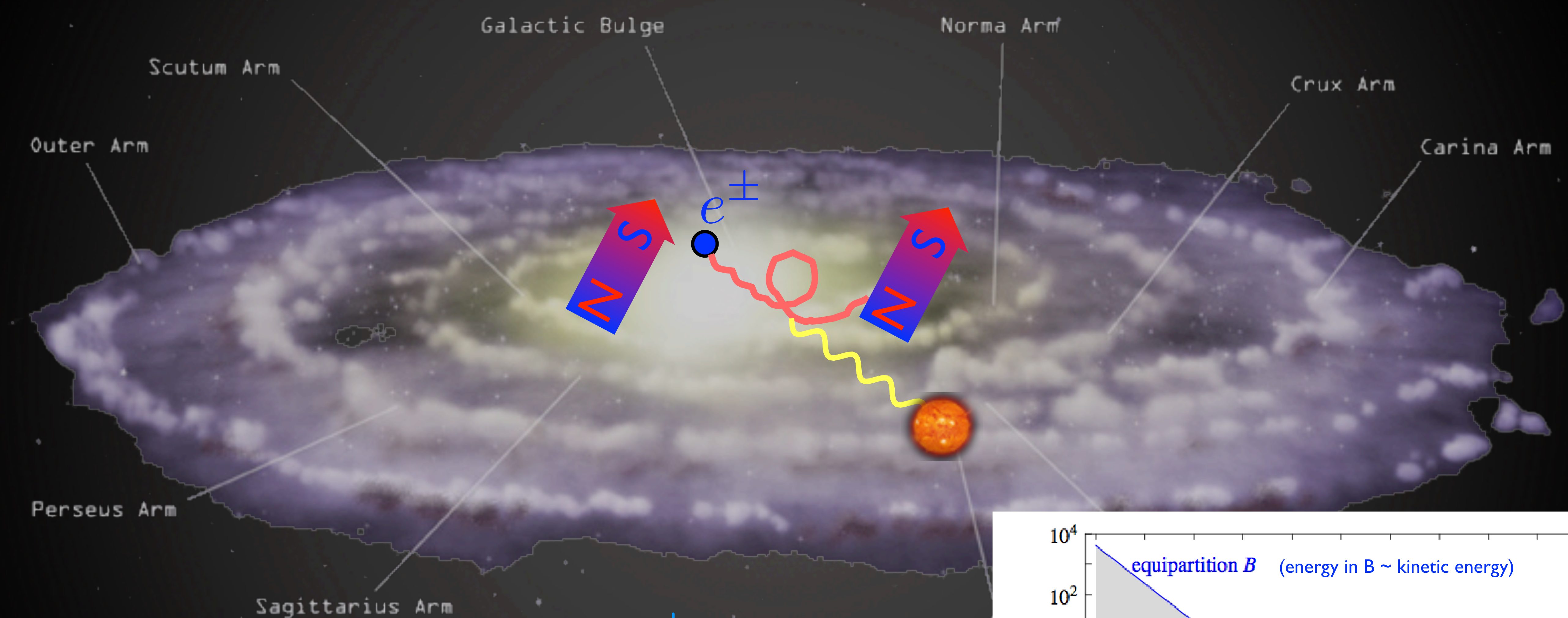
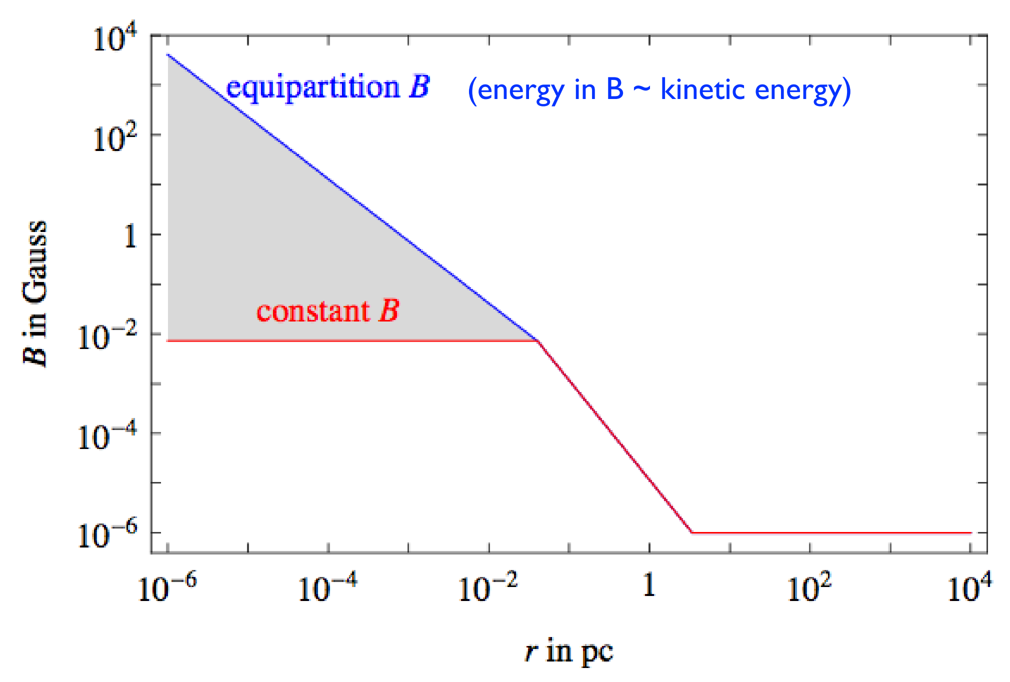


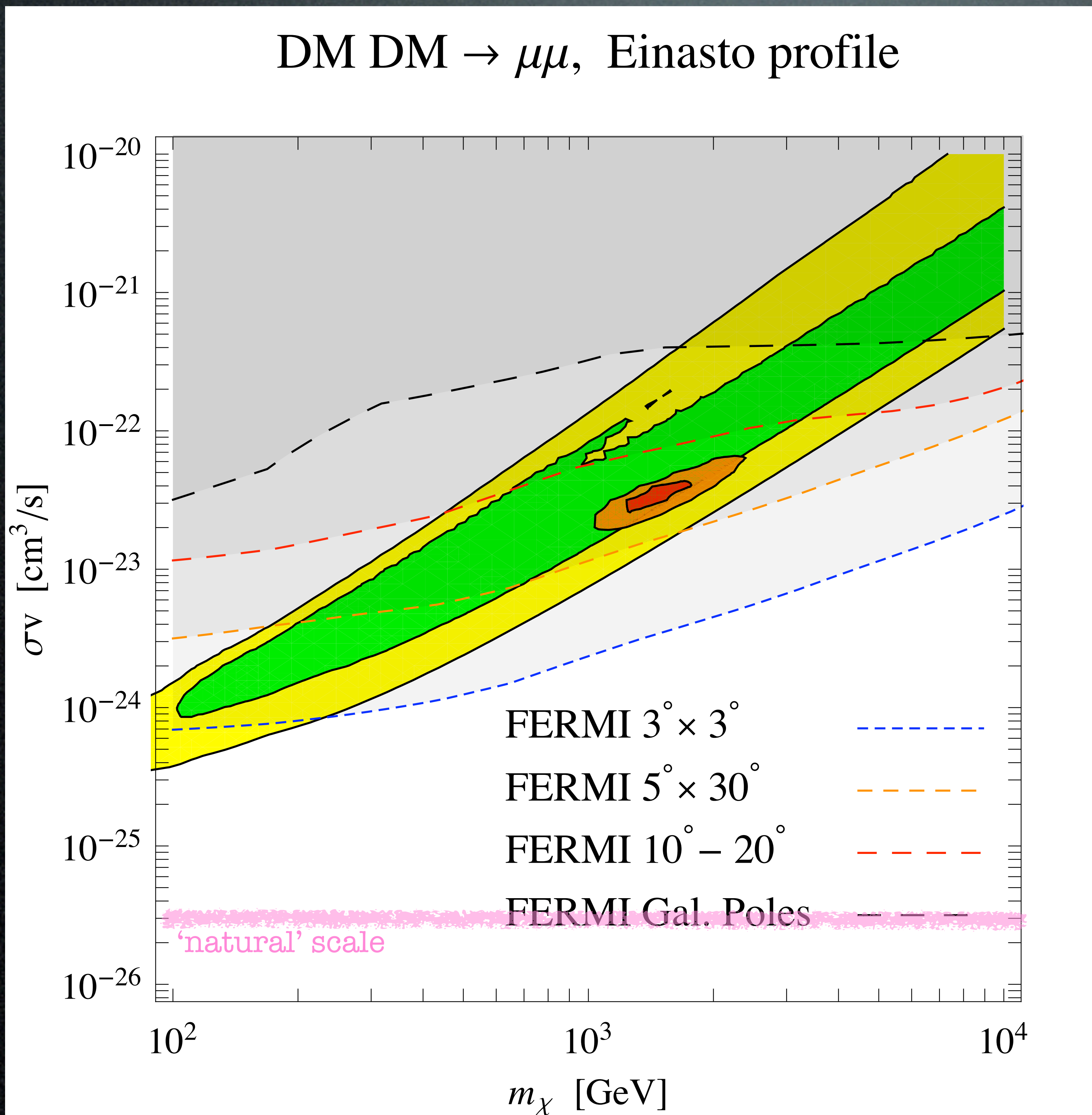


- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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

Gamma constraints

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

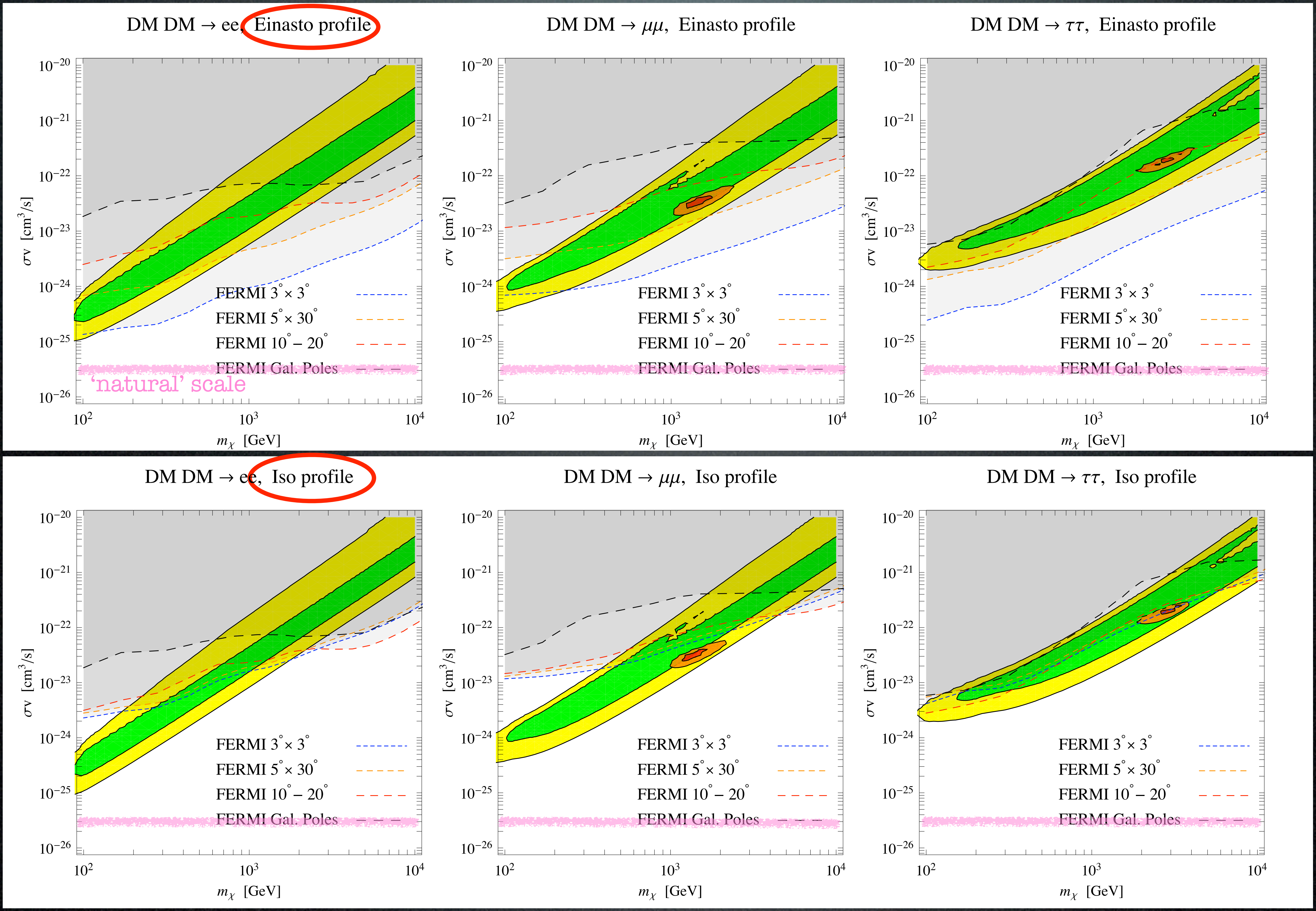


Cirelli, Panci, Serpico 0912.0663

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

Gamma constraints

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

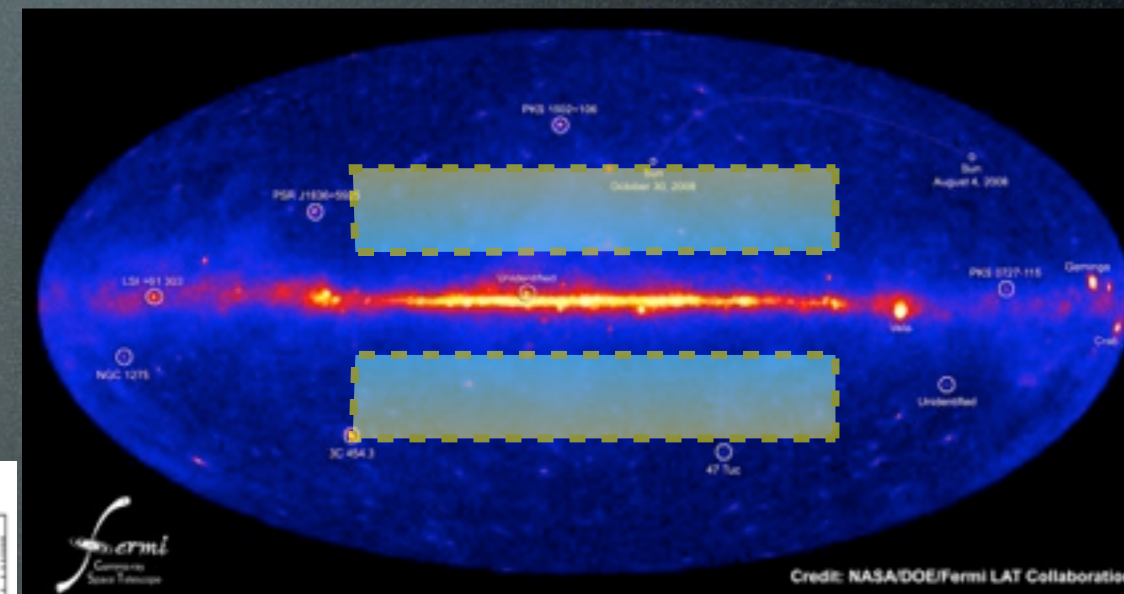


Cirelli, Panci, Serpico 0912.0663

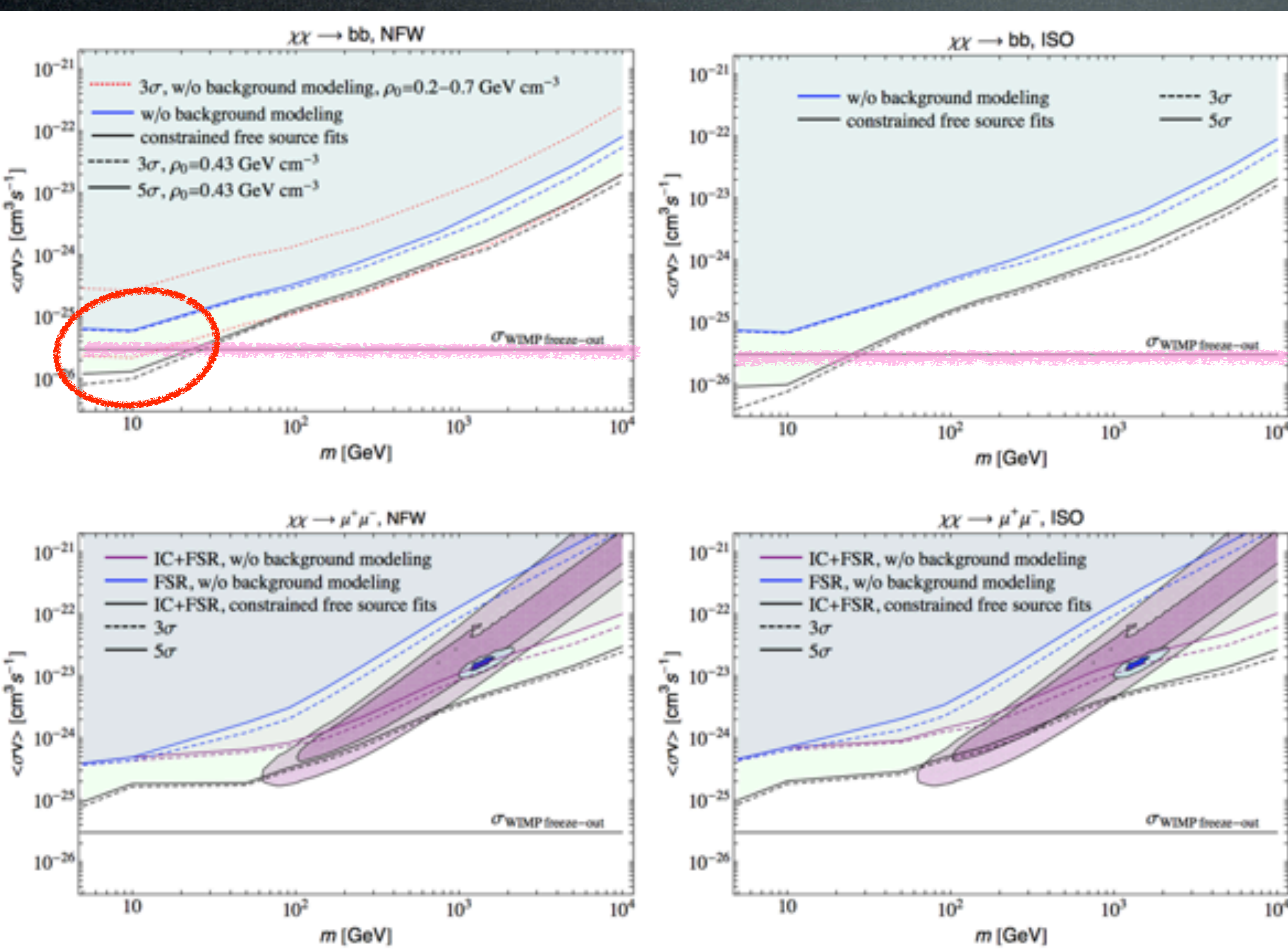
Gamma constraints

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

Updated results from the FERMI coll. itself



$5^\circ < b < 15^\circ$
$-80^\circ < \ell < +80^\circ$

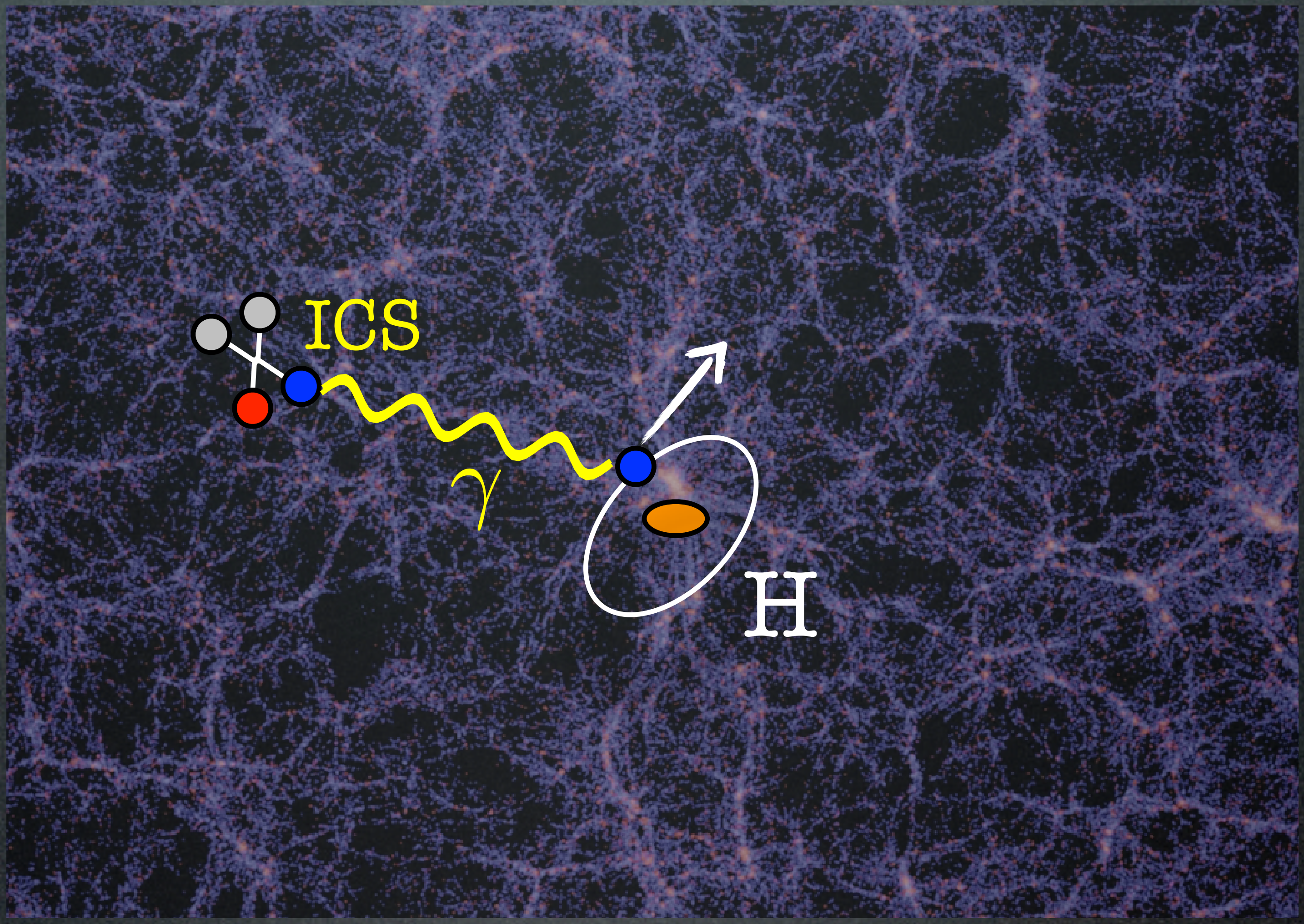


FERMI coll., Cuoco - Zaharijas, 1205.6474

See also:
Papucci, Strumia,
0912.0742

Cosmology: bounds from reionization

DM particle annihilations produce free electrons



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

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

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

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

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

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

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

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

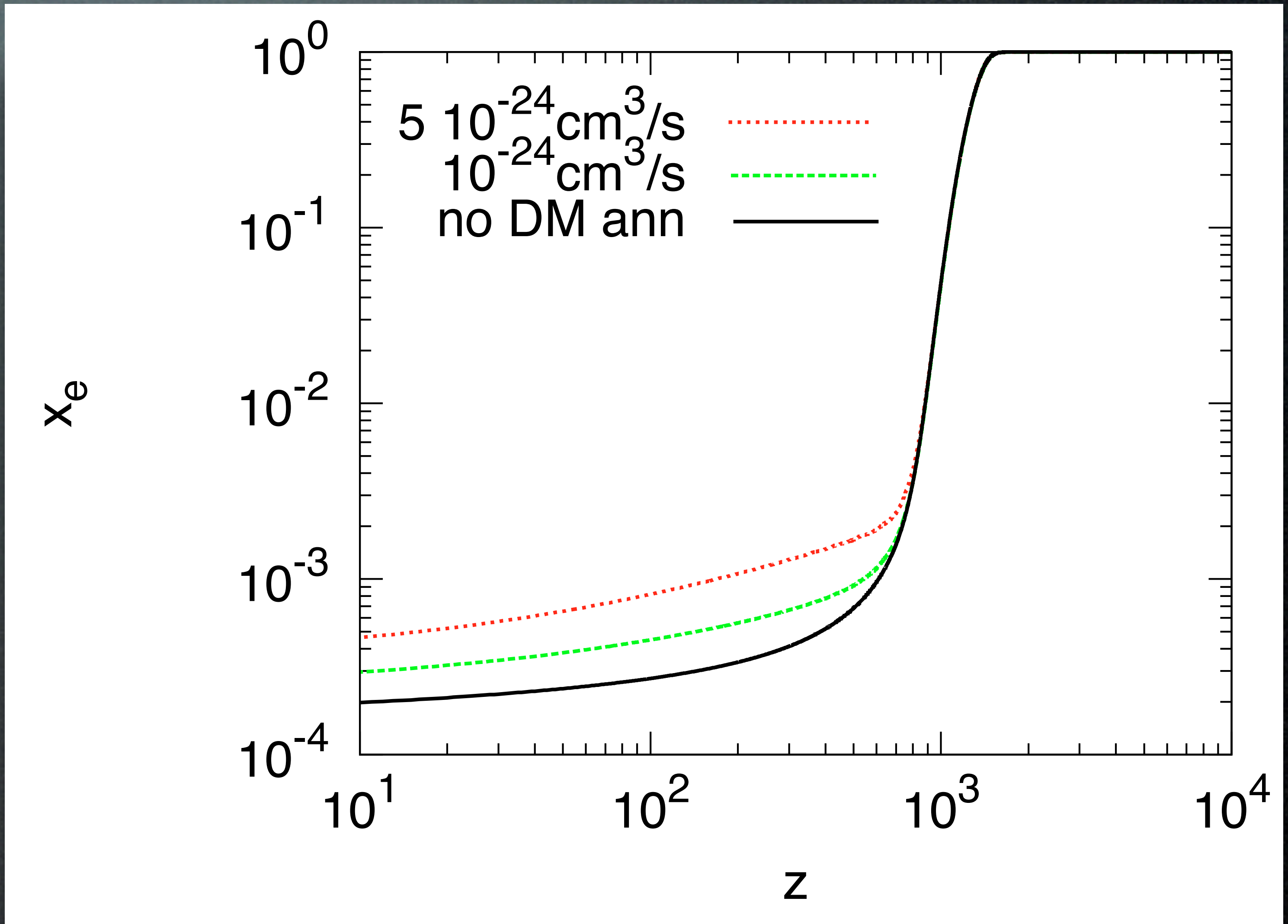
$$\mathcal{B}_i(z) = \frac{\Delta_{\rm vir}(z)}{3\, \rho_{\rm c} \Omega_{\rm M}} \int_{M_{\rm min}}^\infty dM\, M \frac{dn}{dM}(z, M)\, F_i(M, z),$$

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

Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

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

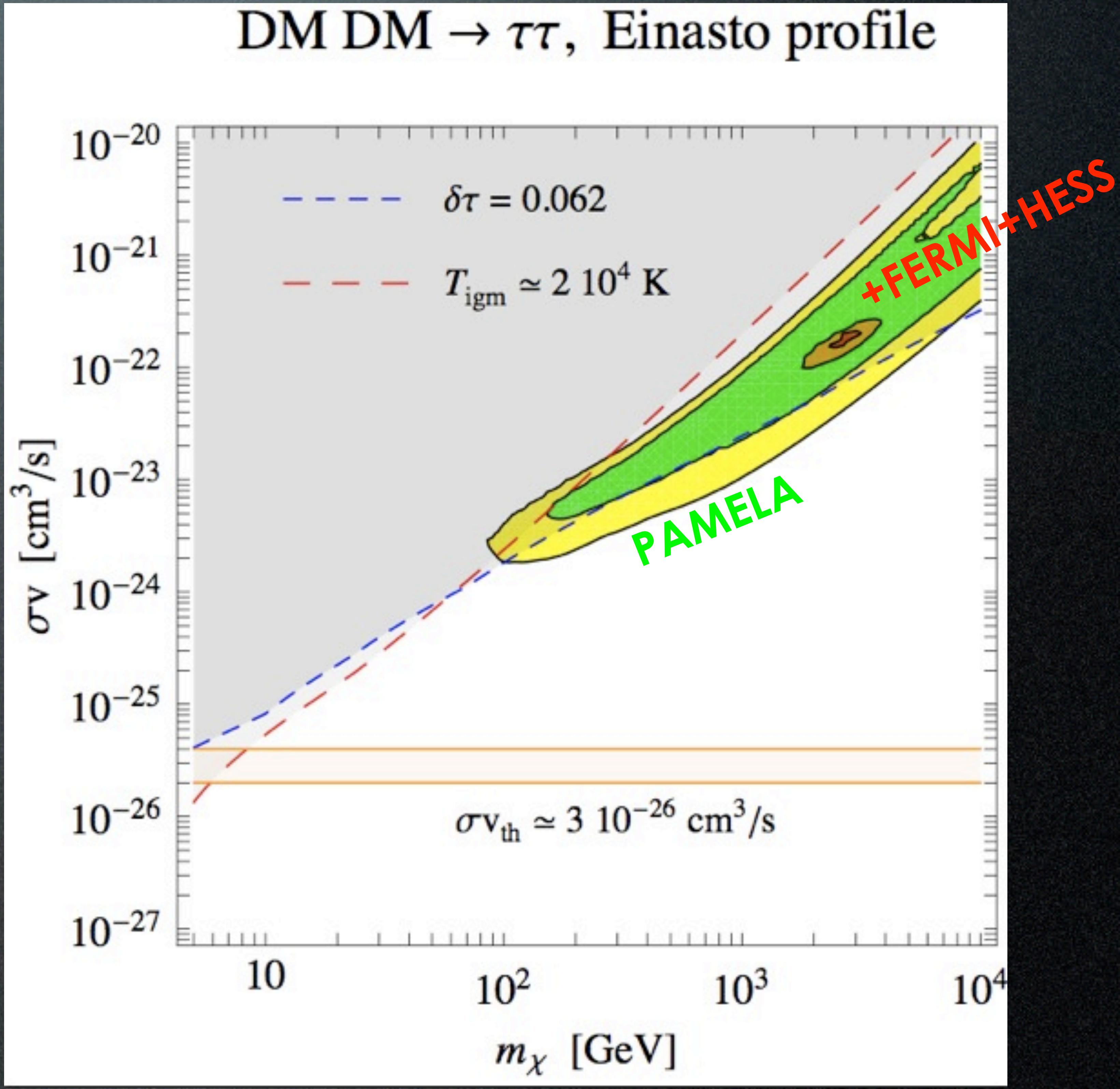


Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

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

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



Cirelli, Iocco, Panci, JCAP 0910

see also:
Huetsi, Hektor, Raidal 0906.4550
Kanzaki et al., 0907.3985
Huetsi et al., 1103.2766

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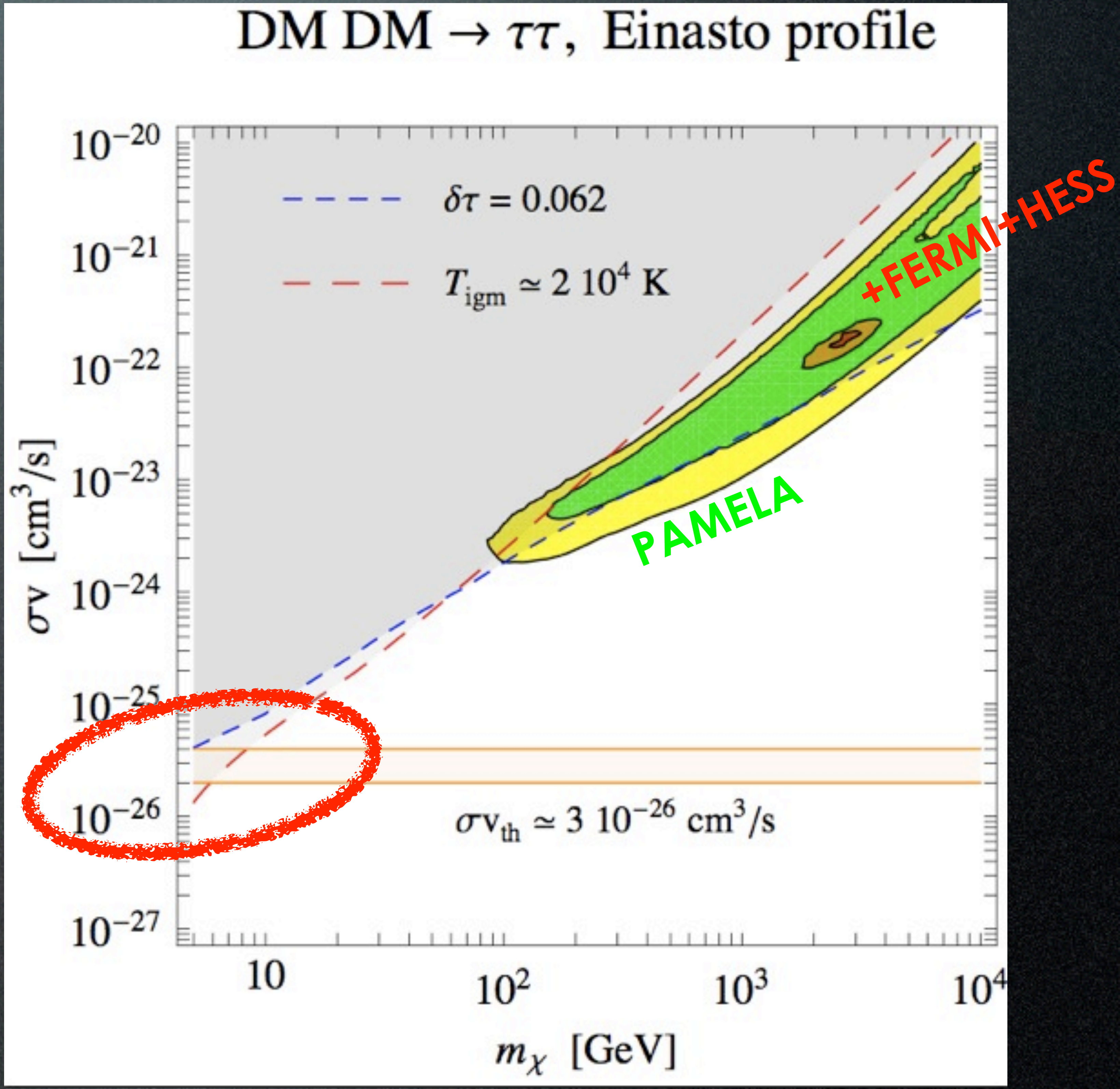
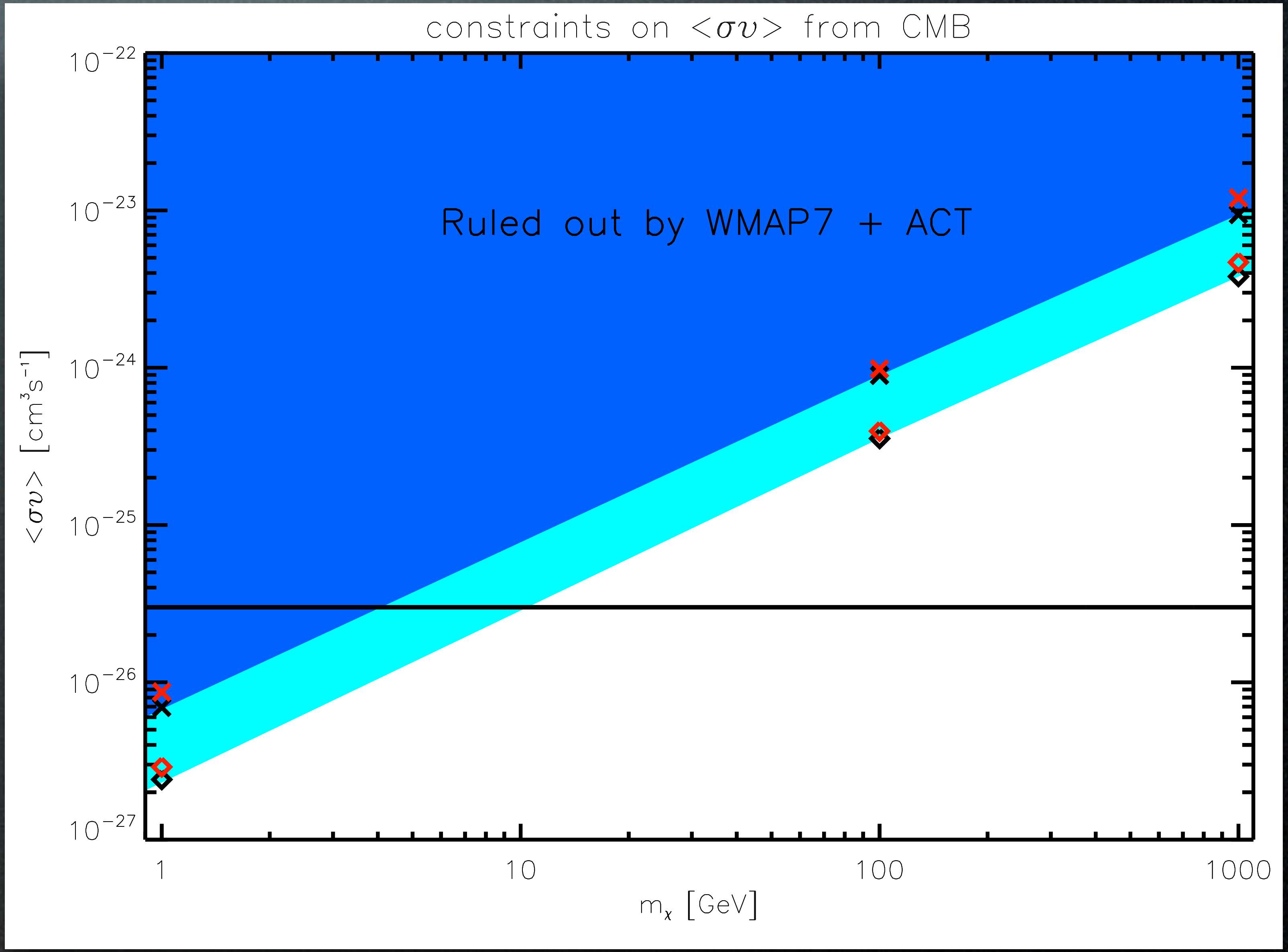


Starts constraining even thermal DM!

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)
Galli, Iocco, Bertone, Melchiorri, 1106.1528 (2011)

see also: Finkbeiner, Galli, Lin, Slatyer 1109.6322 (2011)
Galli, Slatyer, Valdes, Iocco, 1306.0563 (2013)

Cosmology: bounds from CMB

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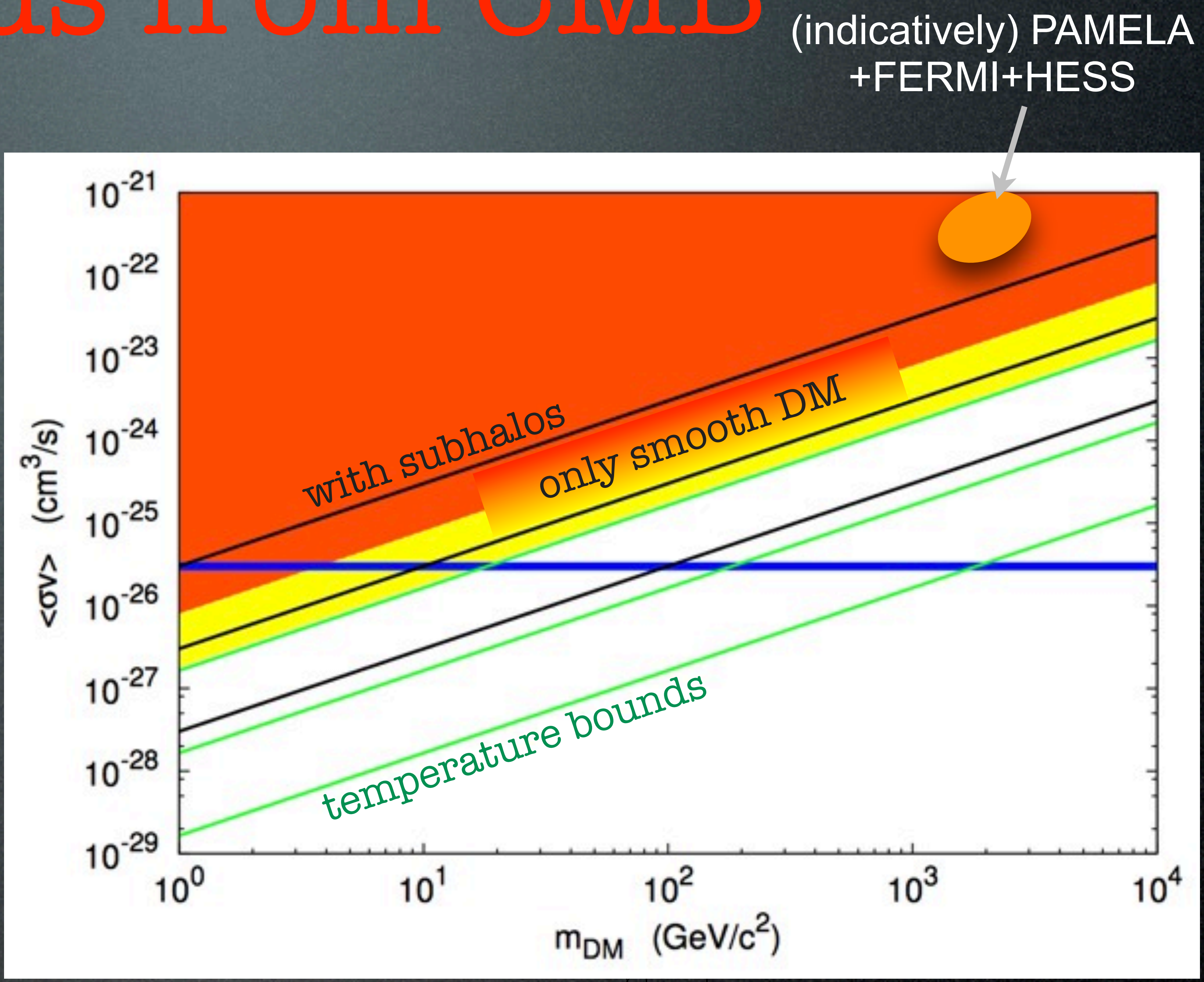


Giesen, Lesgourgues, Audren, Ali-Haïmoud (2012)

see also: Finkbeiner, Galli, Lin, Slatyer 1109.6322 (2011)
Galli, Slatyer, Valdes, Iocco, 1306.0563 (2013)

Theorist's reaction

Theorist's reaction

1. the 'PAMELA frenzy'

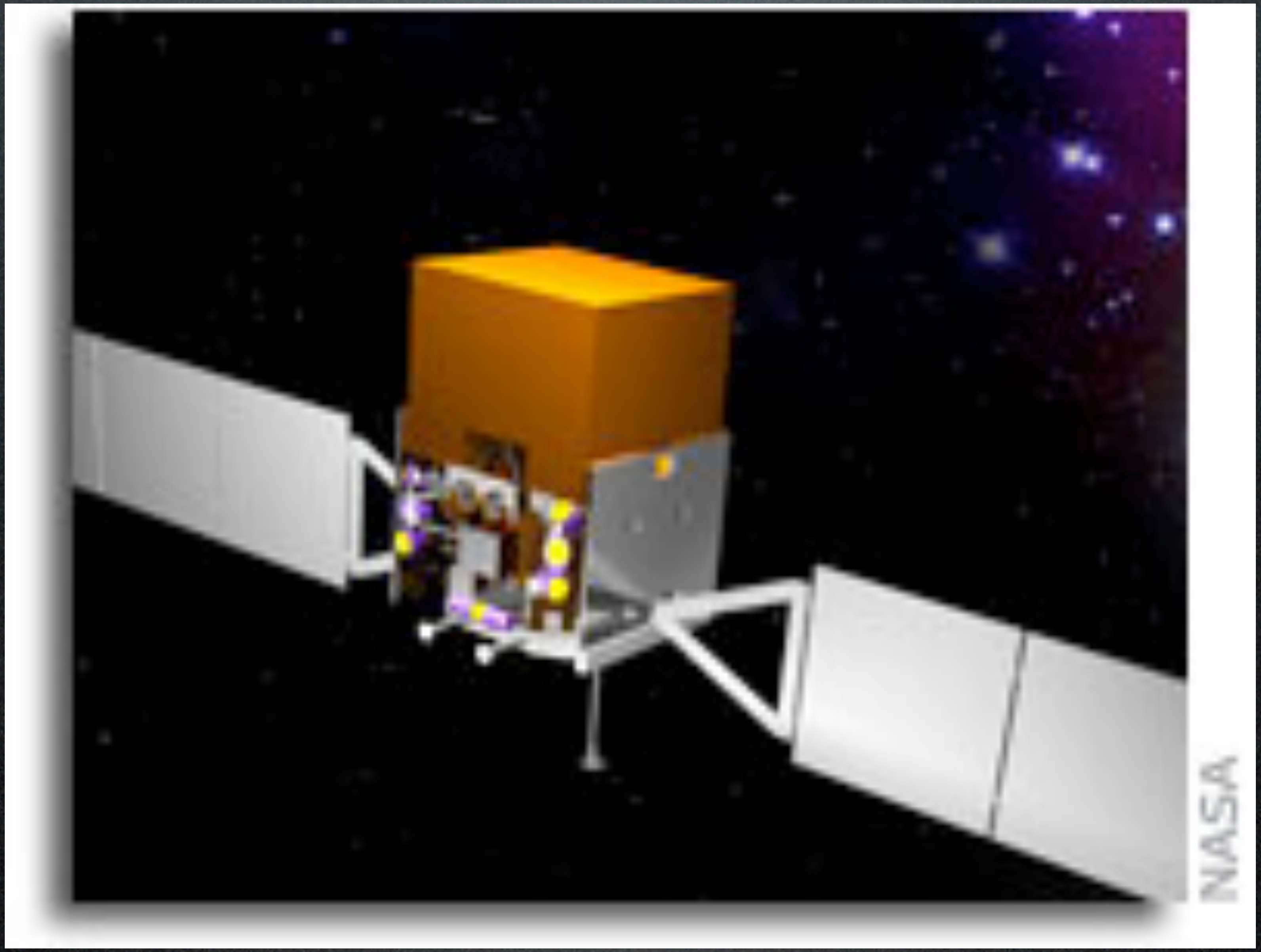
Challenges for the ‘conventional’ DM candidates

Needs:	SuSy DM	KK DM
- TeV or multi-TeV masses	difficult	ok
- no hadronic channels	difficult	difficult
- very large flux	no	ok

for any Majorana DM,
s-wave annihilation cross section

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

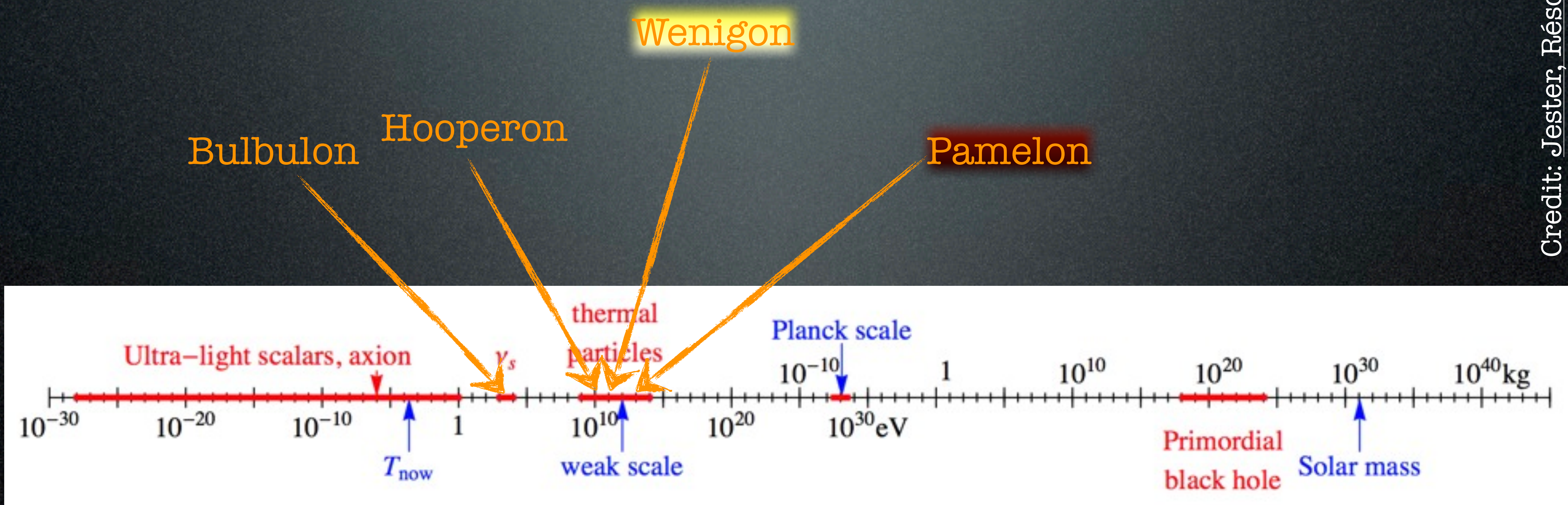
Gamma rays



2. the '130 GeV line'

DM Candidates

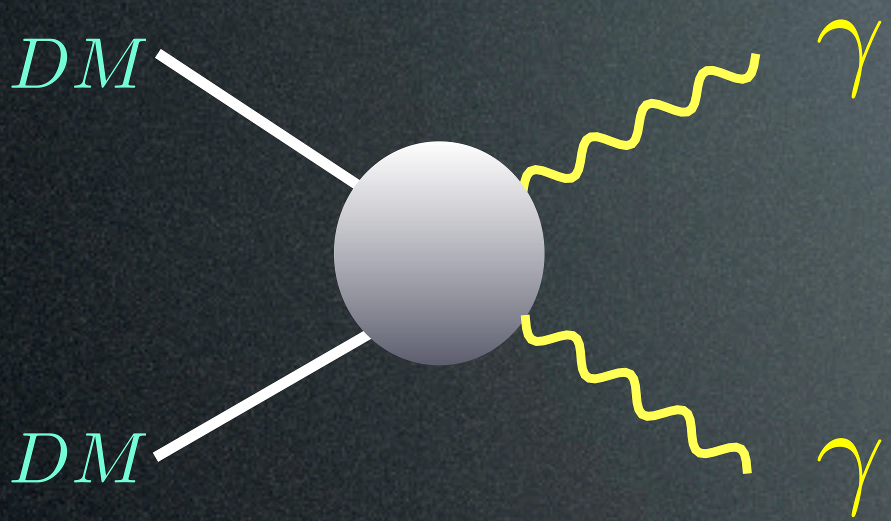
A matter of perspective: plausible mass ranges



Credit: Jester, Résonaances

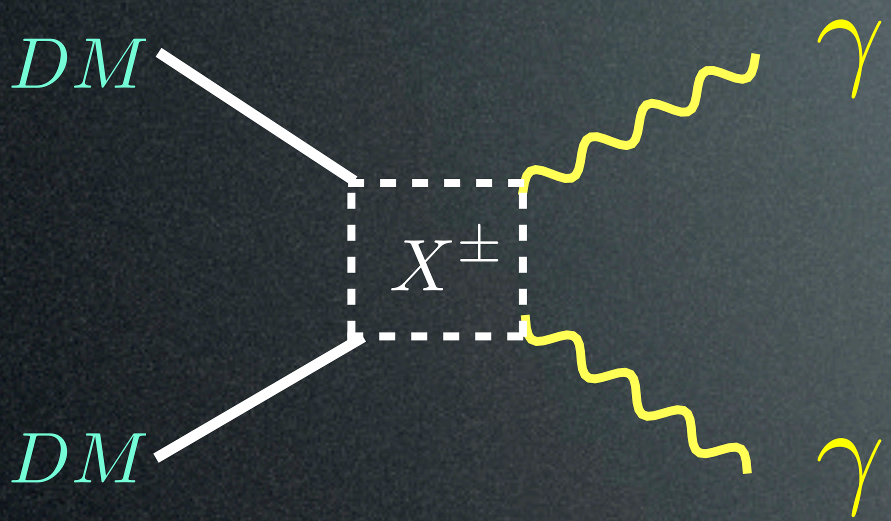
'only' 90 orders of magnitude!

Prompt emission: line(s)



primary
channels

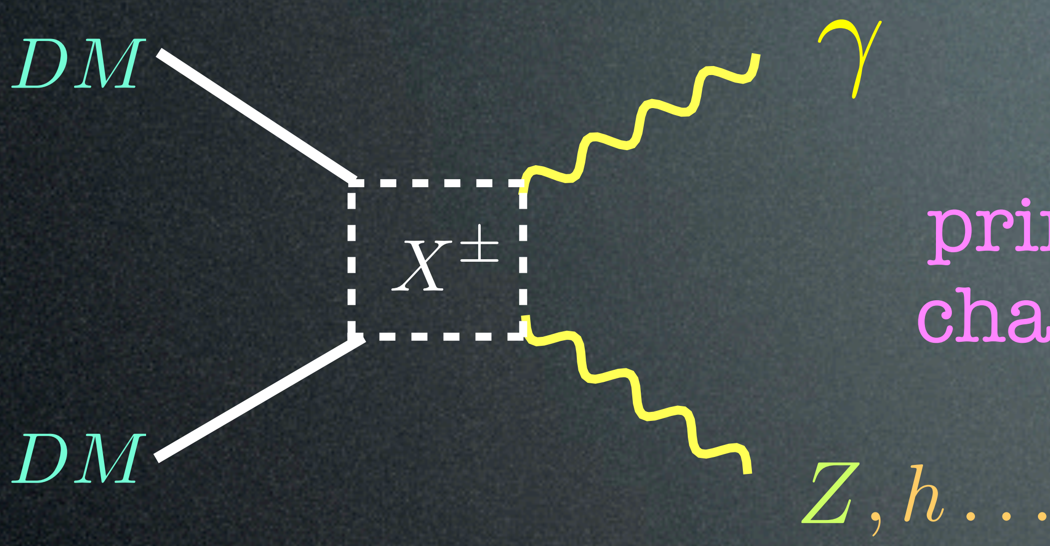
Prompt emission: line(s)



primary channels

$$E_\gamma = m_{\rm DM}$$

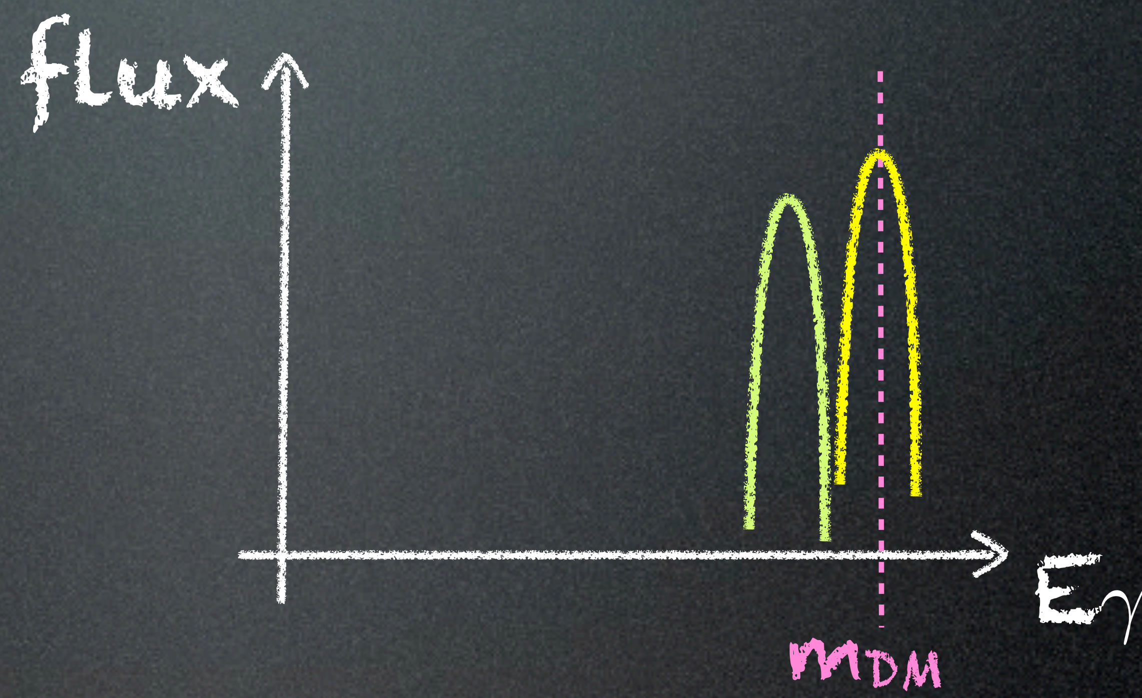
Prompt emission: line(s)



primary channels

$$E_\gamma = m_{\rm DM}$$

$$E_\gamma = m_{\rm DM}\left(1 - \frac{m_Z^2}{4\, m_{\rm DM}^2}\right)$$



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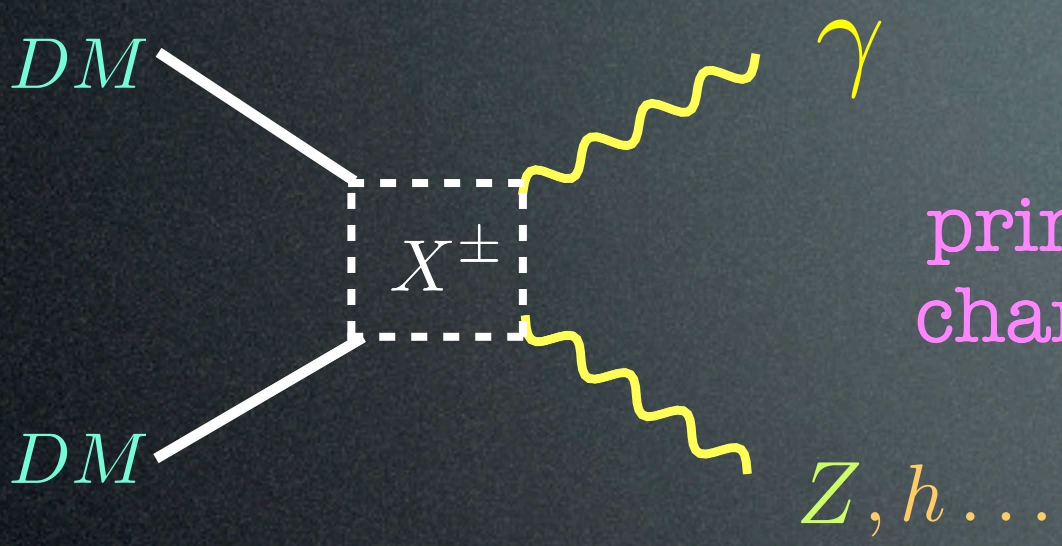

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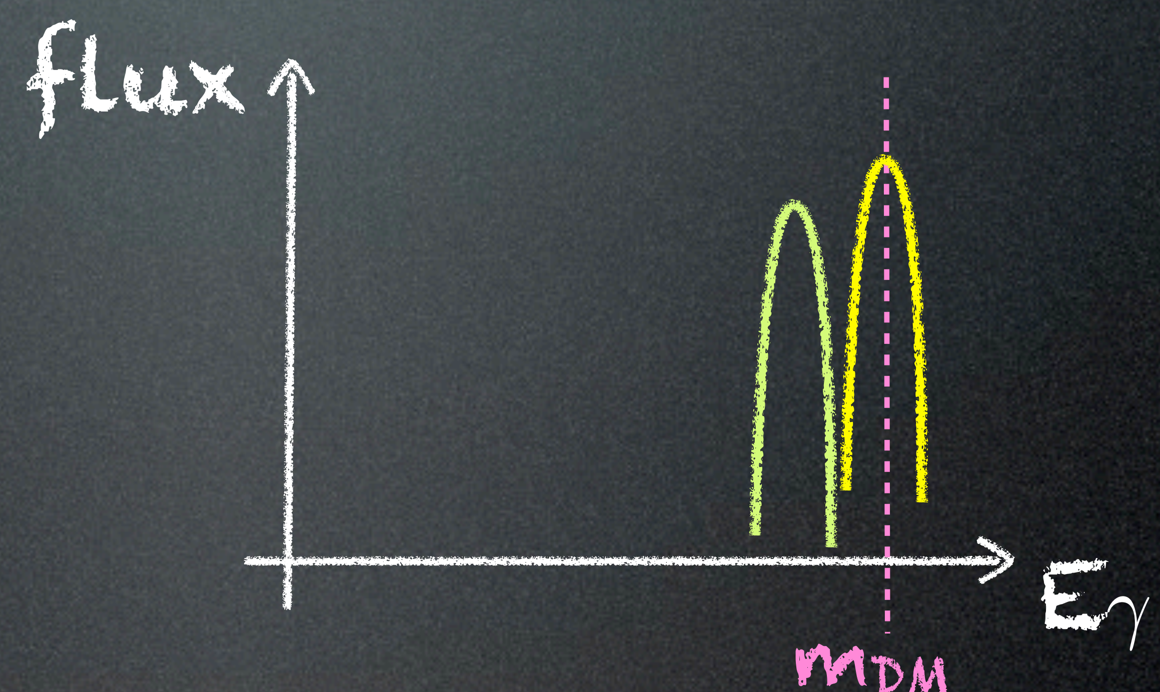


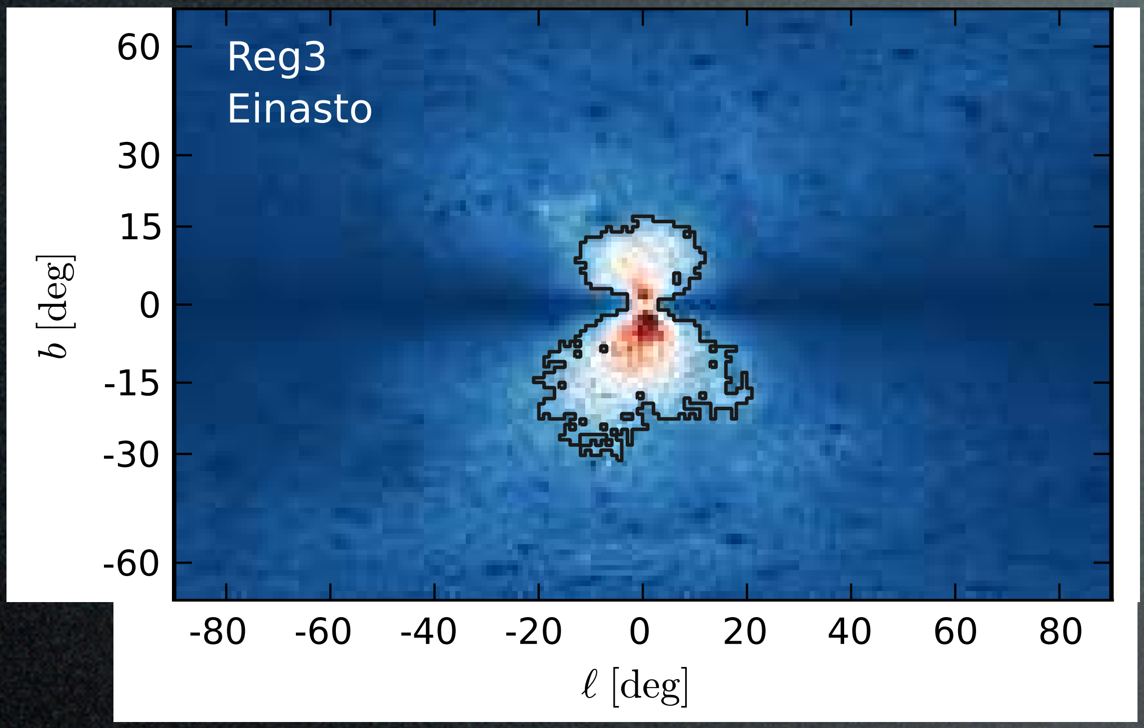
So what are the particle physics parameters?

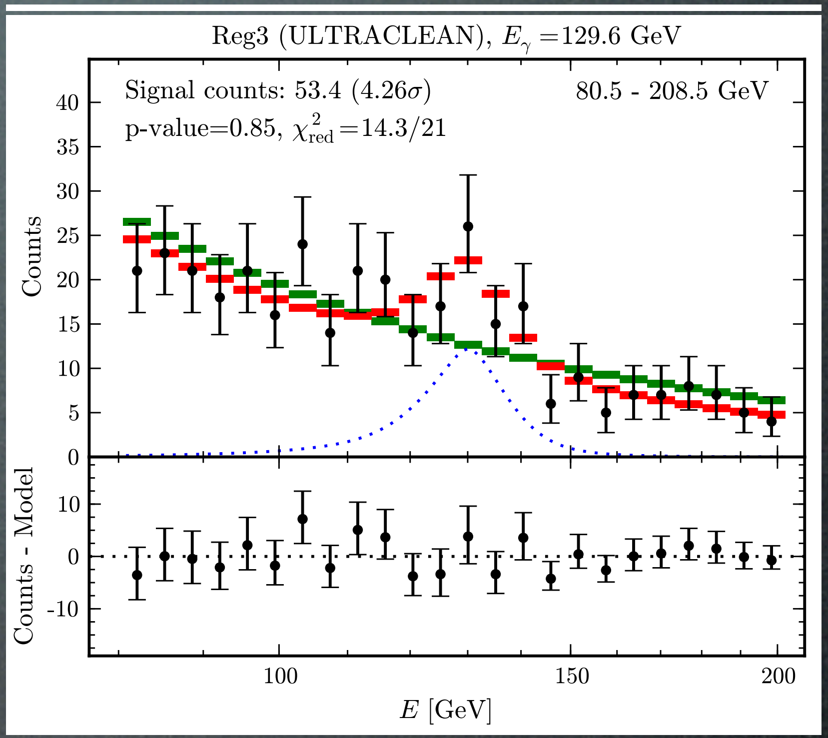
1. Dark Matter mass

2. annihilation cross section $\sigma_{\rm ann}$

Fermi 130 GeV line

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





Ch. Weniger, 1204.2797

4.6σ (3.3σ with LEE)

$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} \simeq$ $1.3 \cdot 10^{-27} \mathrm{cm}^3/\mathrm{s}$ (large!)

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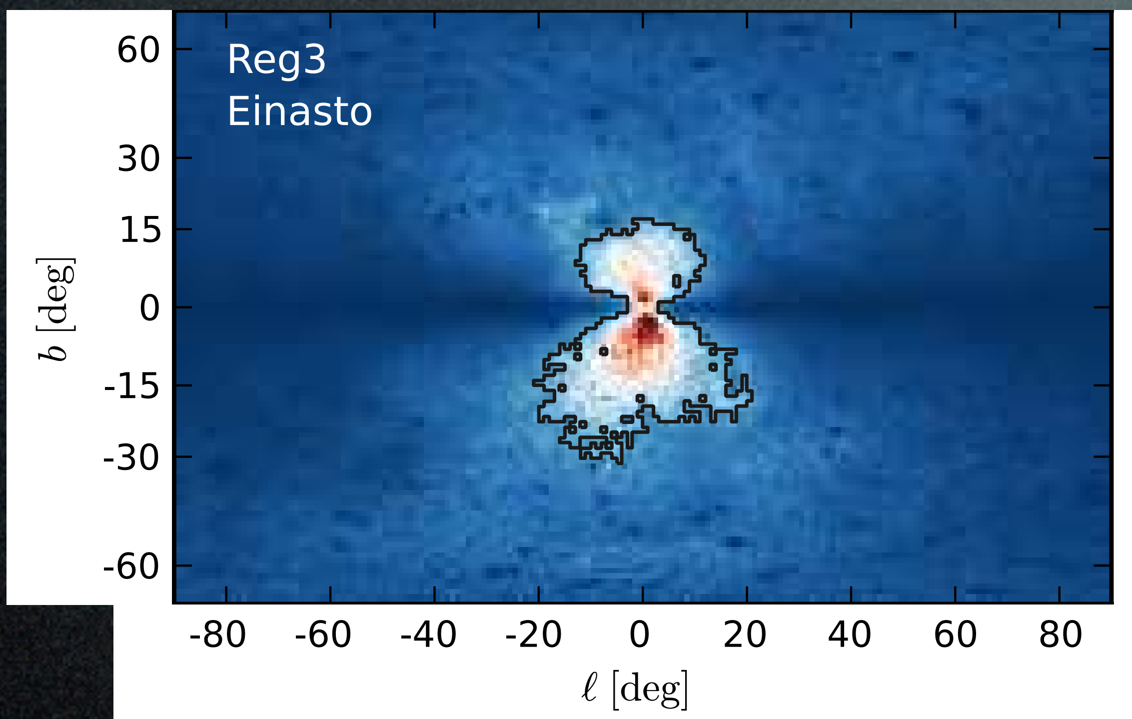

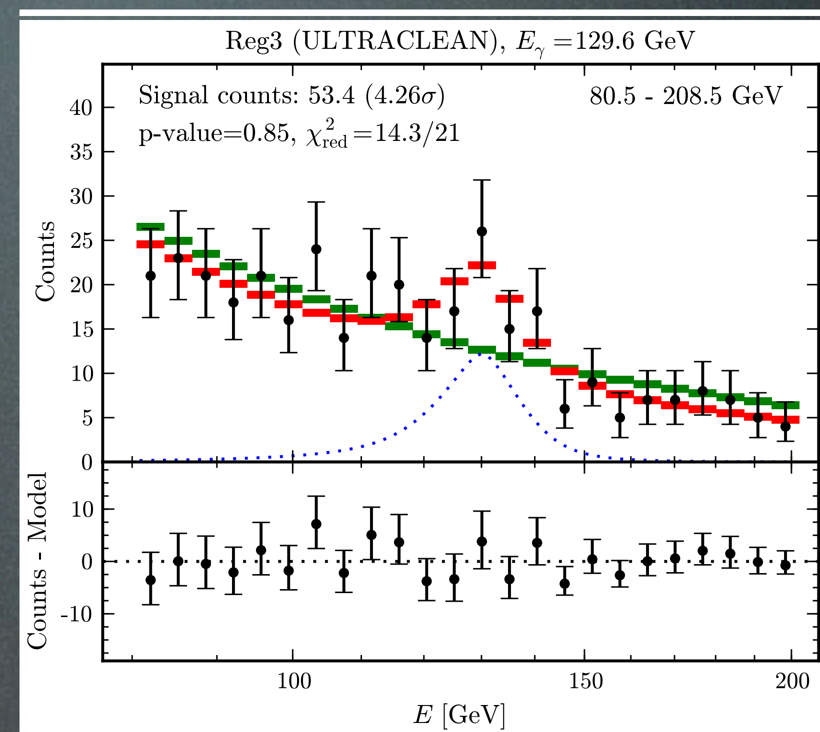

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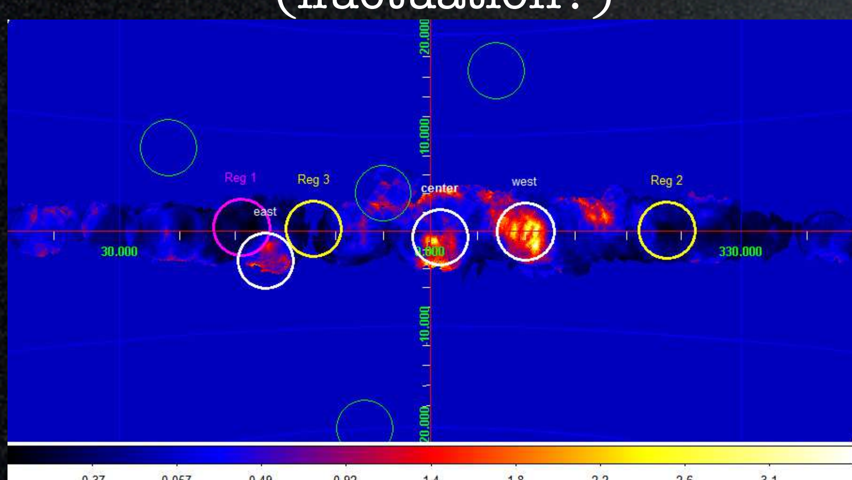
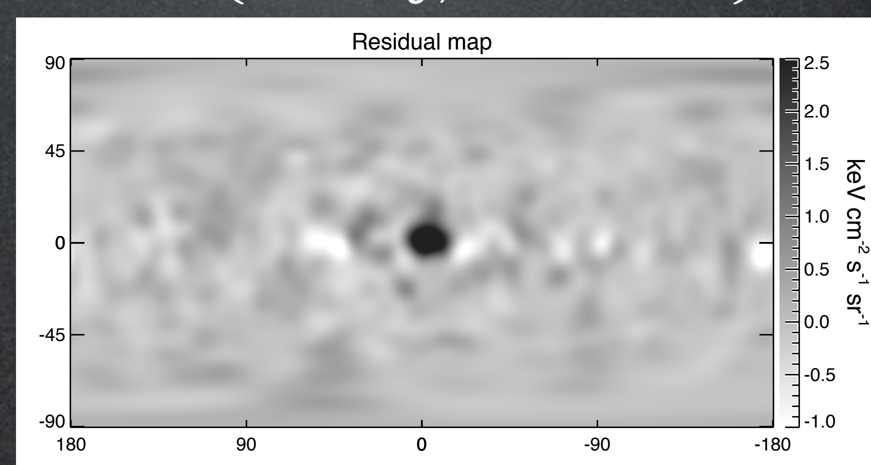
Similar excesses found elsewhere (fluctuation?)



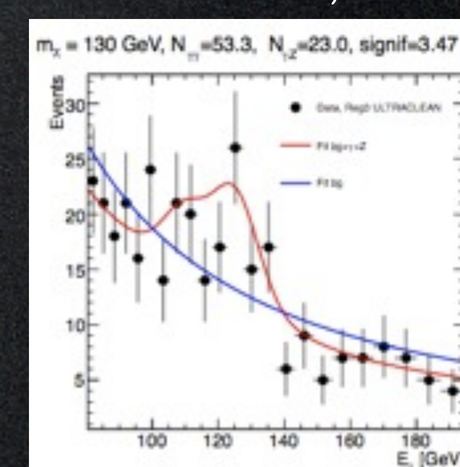
Boyarsky, Malyshev, Ruchayskyi, 1205.4700

The excess is only in the GC (actually, a bit off-set)



Su, Finkbeiner, 1206.1616

And there might be 2 lines: 111 GeV, 129 GeV



Rajaraman, Tait, Whiteson 1205.4723
Su, Finkbeiner 1206.1616
Su Finkbeiner 1207.7060

Fermi 130 GeV line

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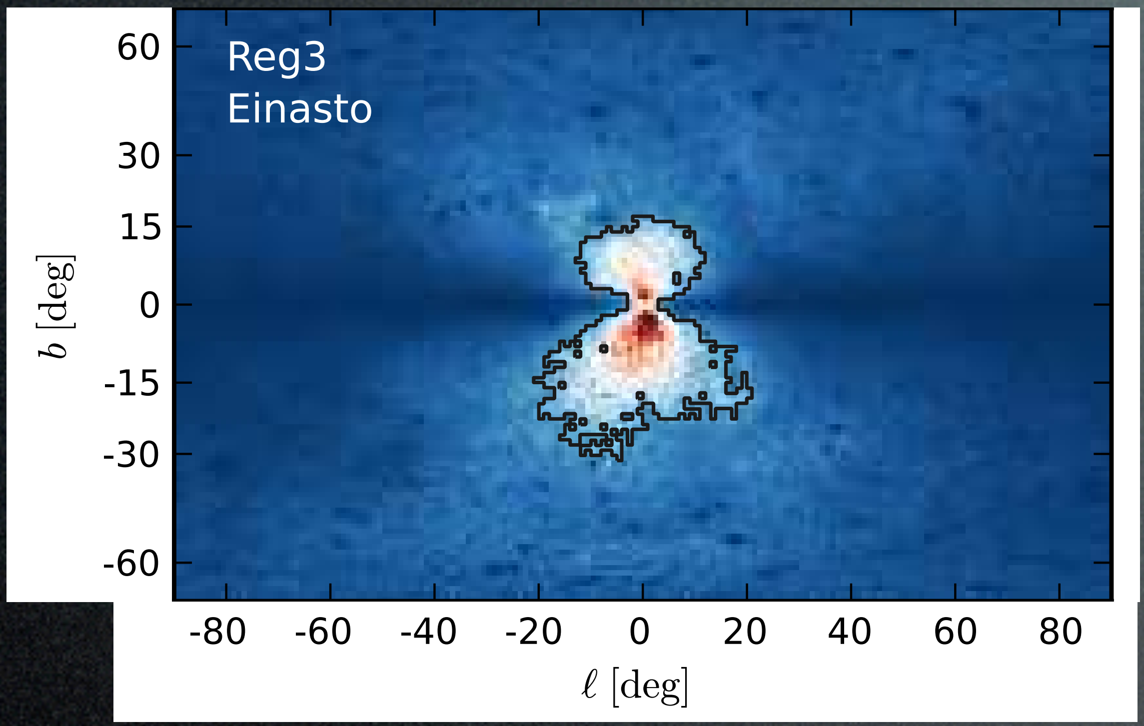

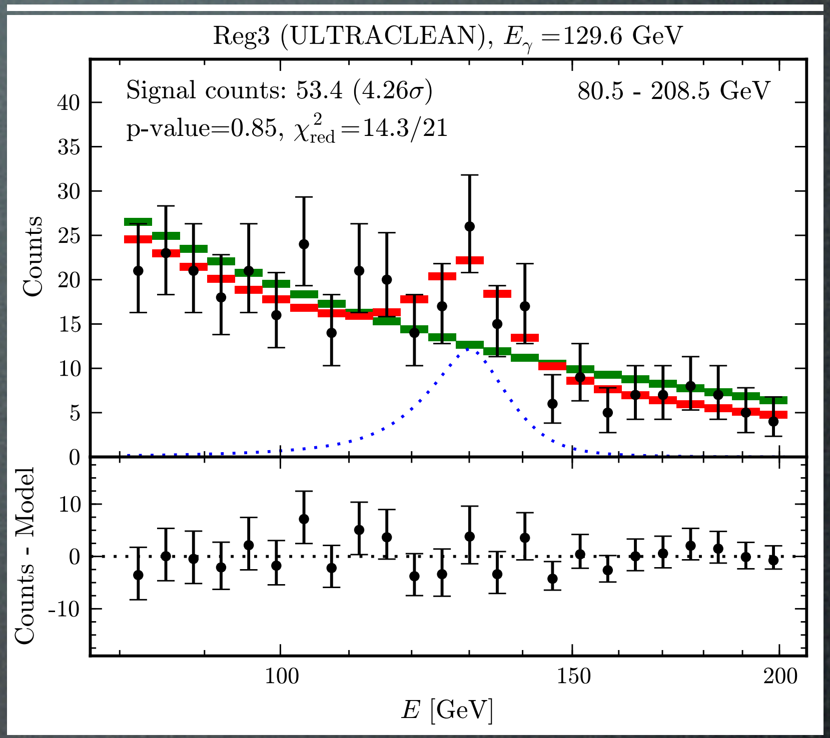

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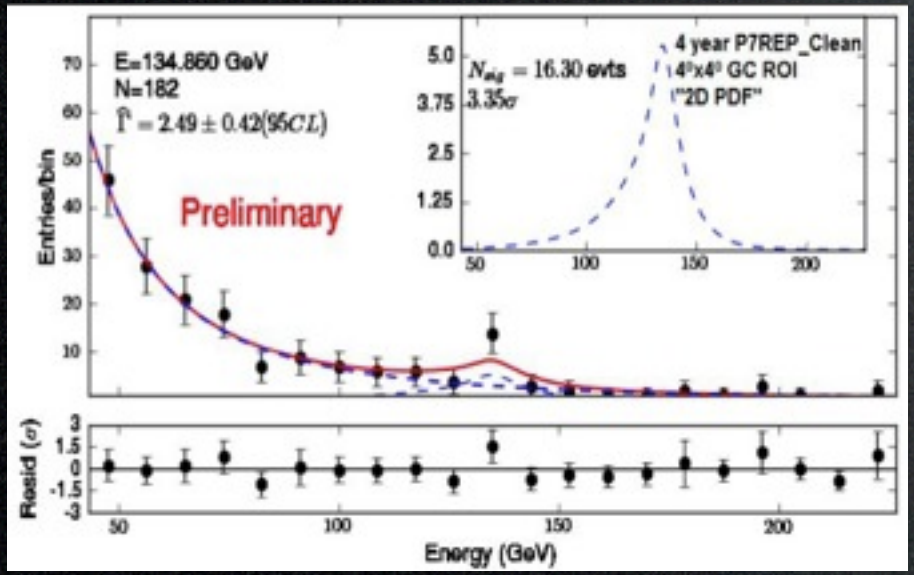
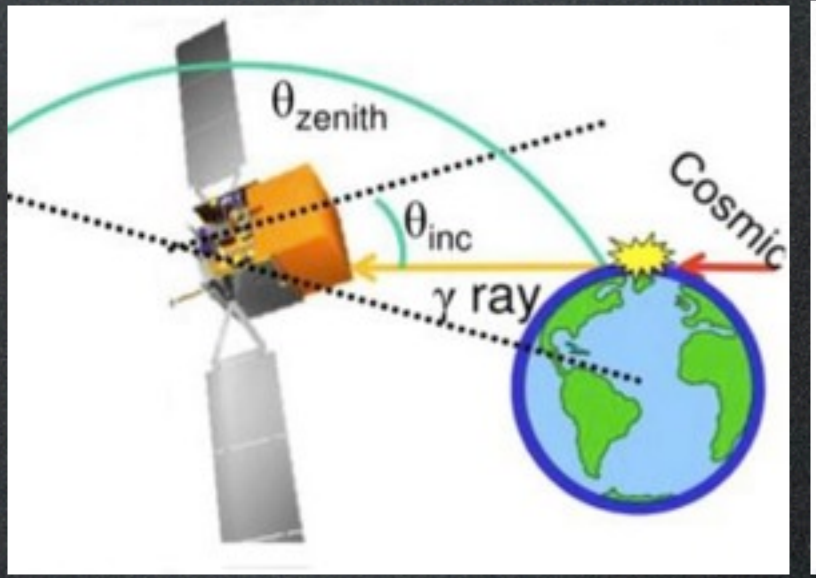
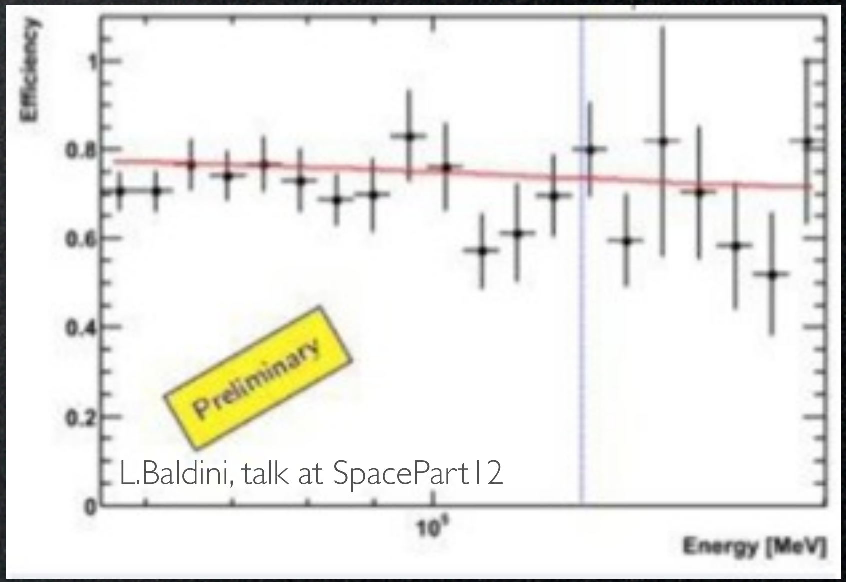
The Fermi coll's cold shower. An instrumental effect?







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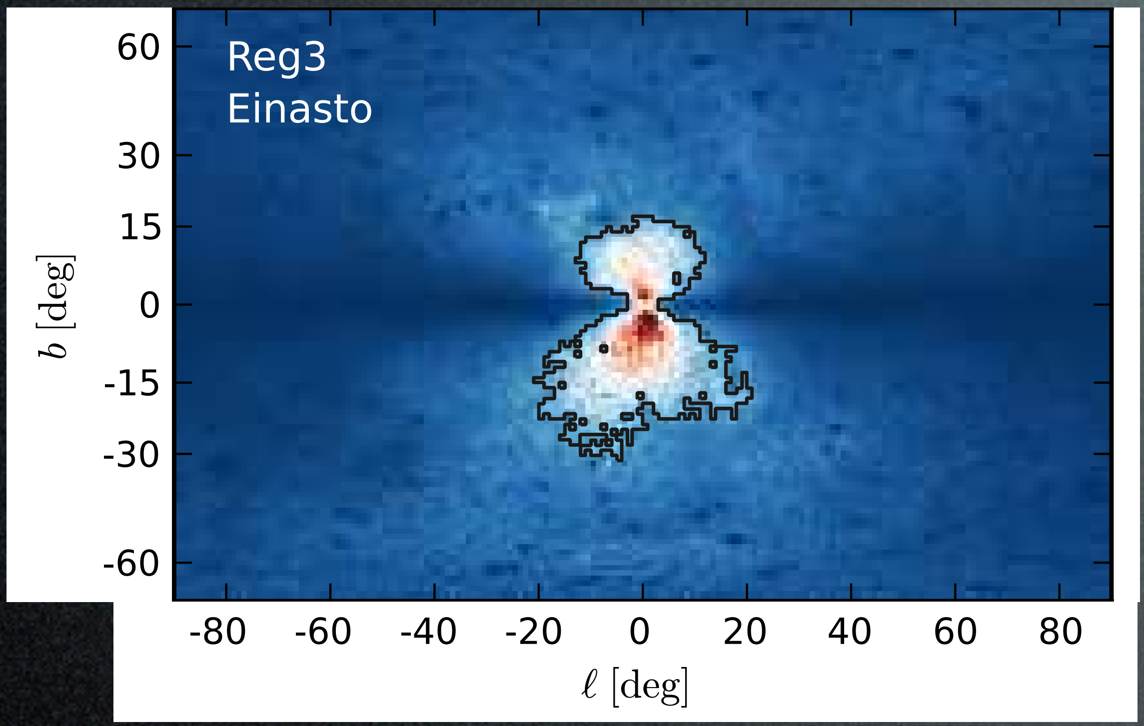

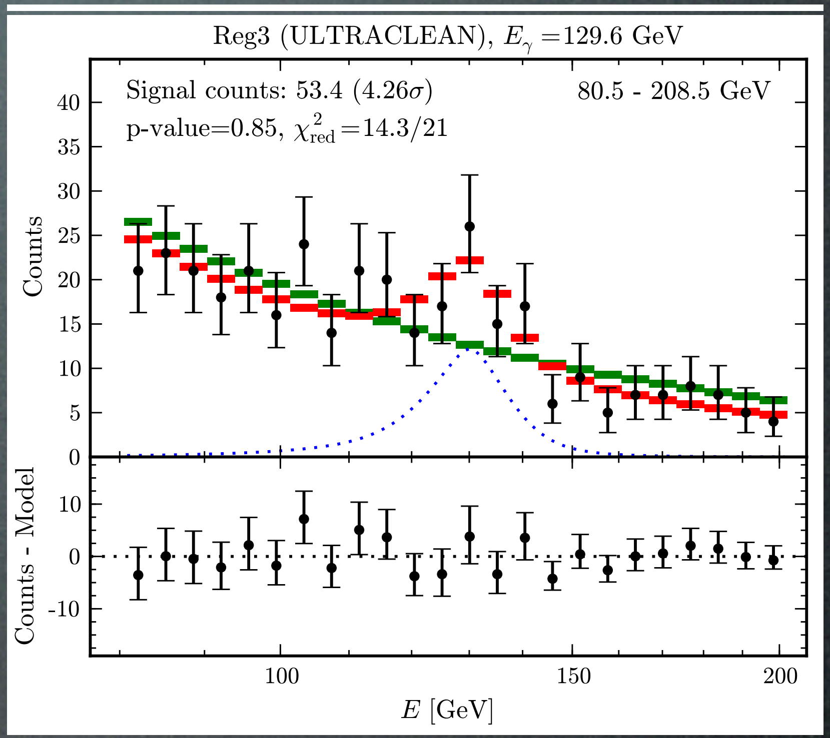

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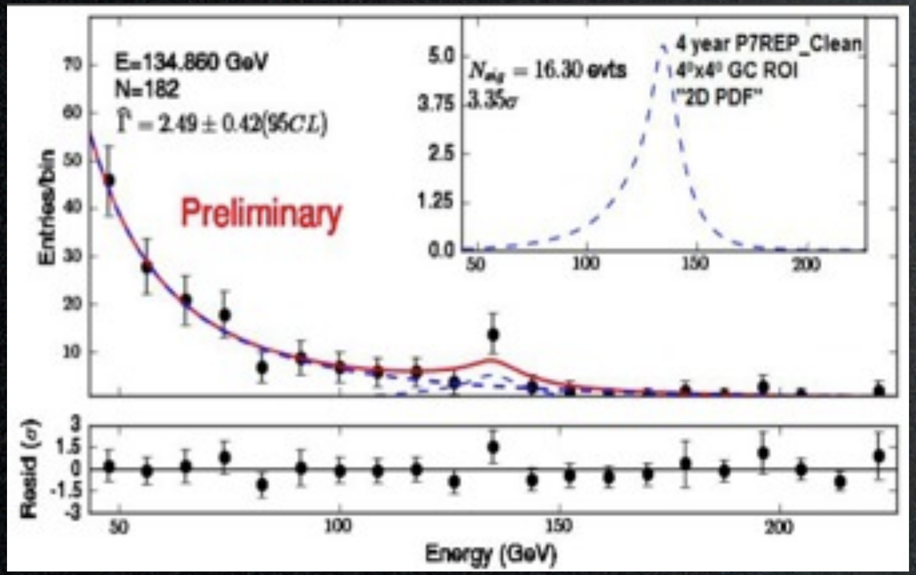
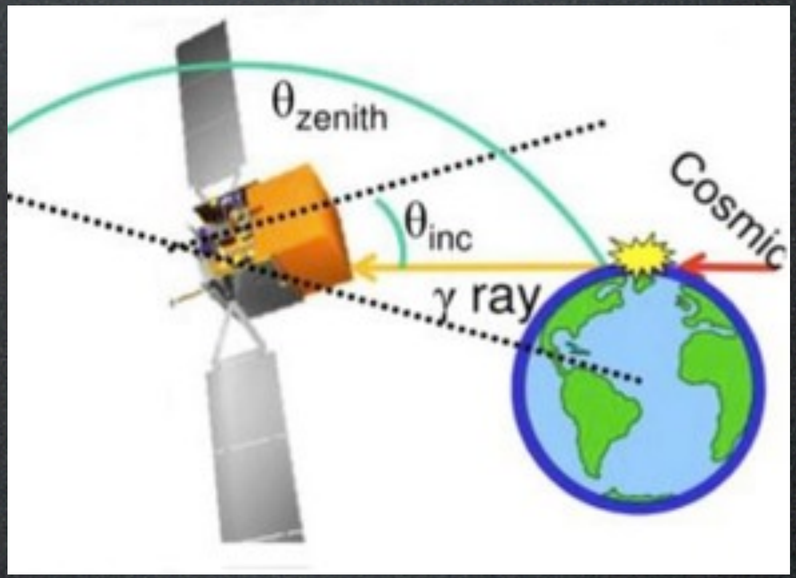




Theorist's reaction

2. the '130 GeV line' frenzy

It's 'easy' to make a line:
any 2-body final state
with at least one γ. But:

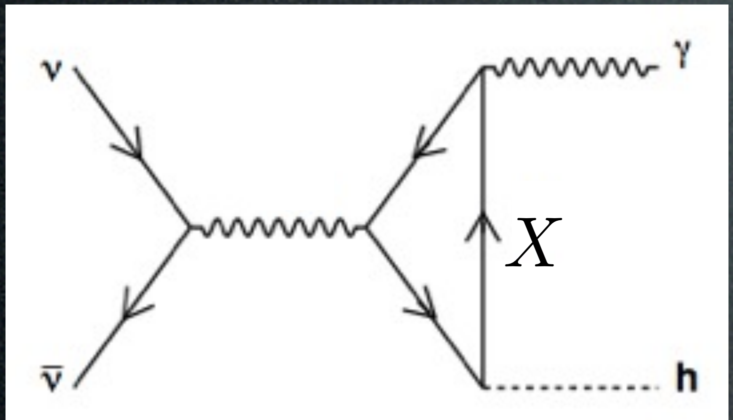
Challenges

DM is neutral: need '*something*' to couple to γ

Challenges

DM is neutral: need 'something' to couple to γ

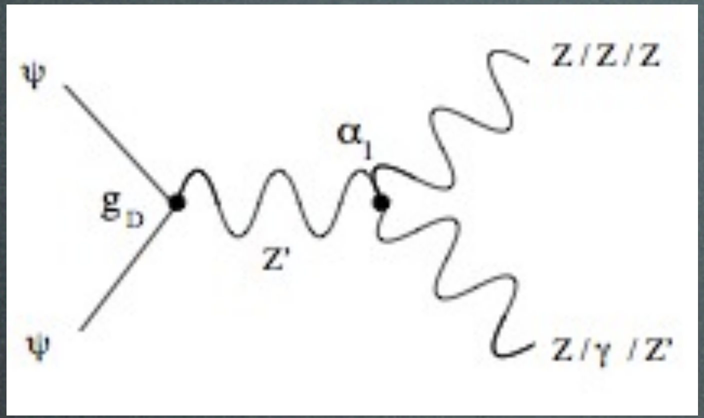
a loop



'Higgs in space!' 0912.0004
Kyae, Park 1205.4151
Cline 1205.2688

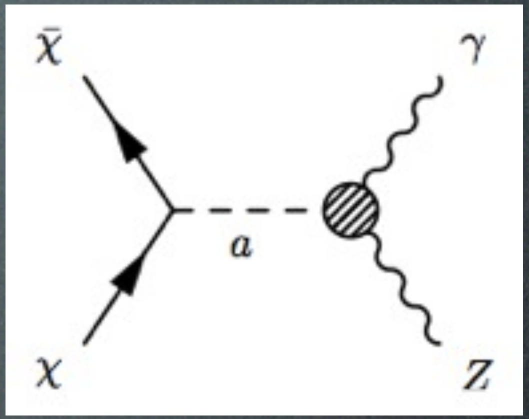
$X \in$ SM
MSSM
dark sector...

Chern-Simons



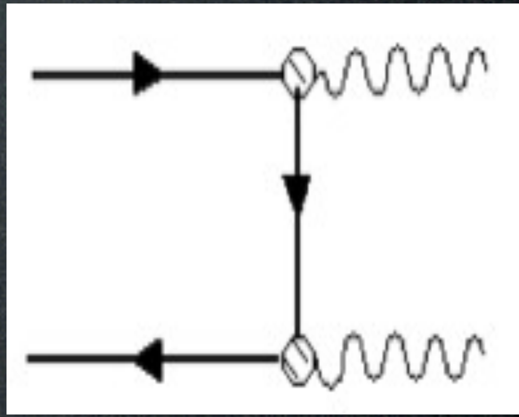
Dudas et al., 1205.1520

axions



Lee & Park[2] 1205.4675

magn dipole

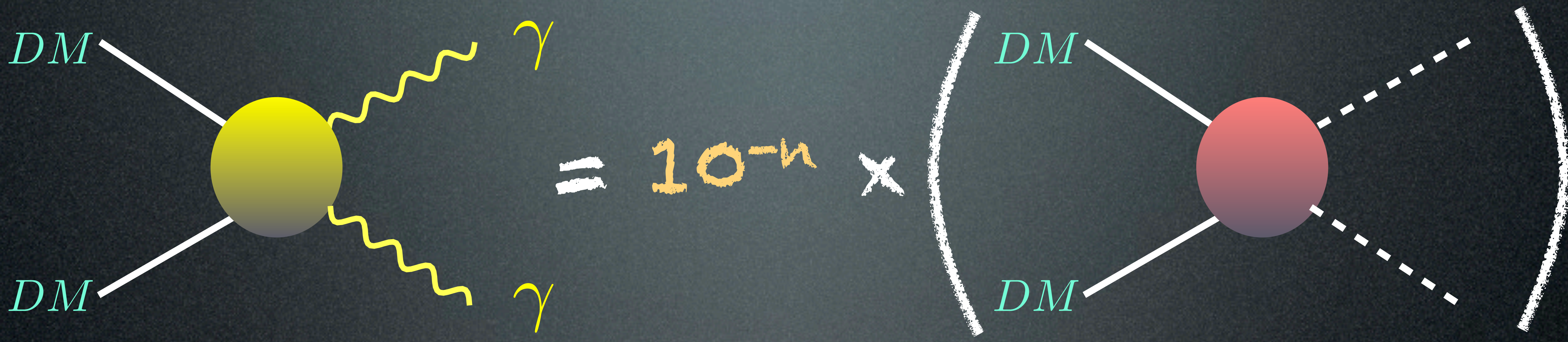


Heo, Kim 1207.1341

...

Challenges

DM is neutral: need 'something' to couple to γ



The 'something' implies usually a suppression,

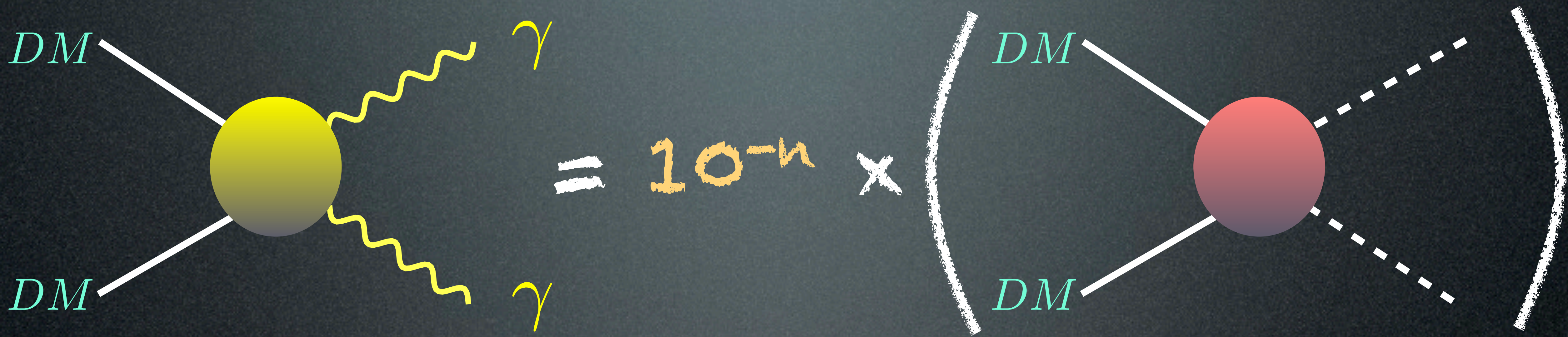
Challenges

DM is neutral: need 'something' to couple to γ

The 'something' implies usually a suppression, but one needs a large $\gamma\gamma$ cross section (o(10^{-27} cm^3/s))

Challenges

DM is <u>neutral</u>: need '**something**' to couple to γ



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but one needs a large $\gamma\gamma$ cross section (o(10^{-27} cm^3/s))

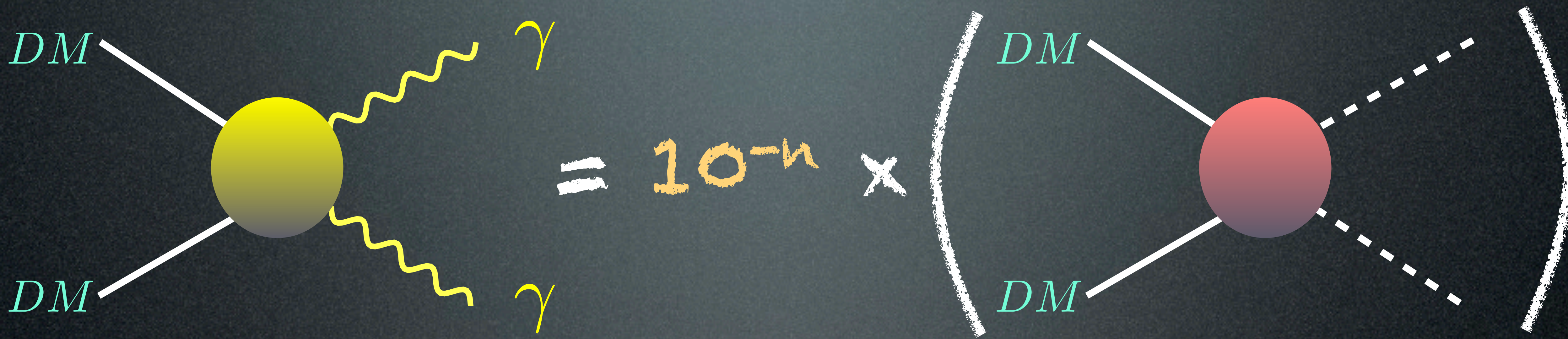
so the corresponding unsuppressed processes
are **too** large:

- may overshoot other observations
- too large annihilation in the EU

Buchmuller, Garny 1206.7056
Cohen et al. 1207.0800
Cholis, Tavakoli, Ullio 1207.1468
Huang et al. 1208.0267

Challenges

DM is neutral: need '*something*' to couple to γ



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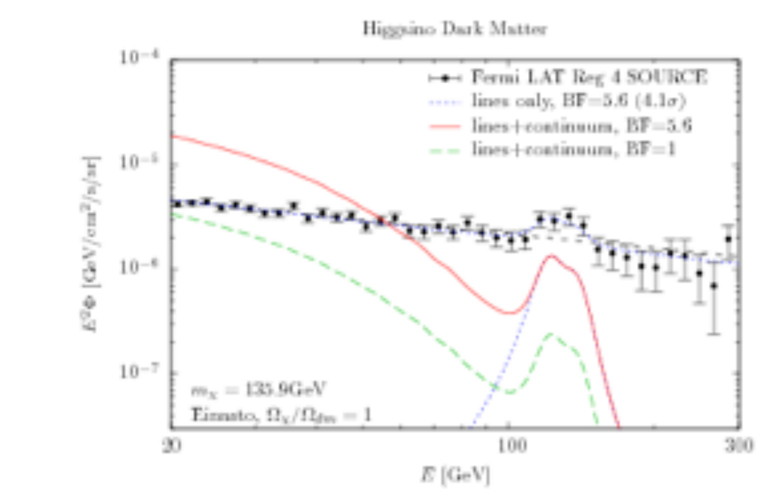

Challenges

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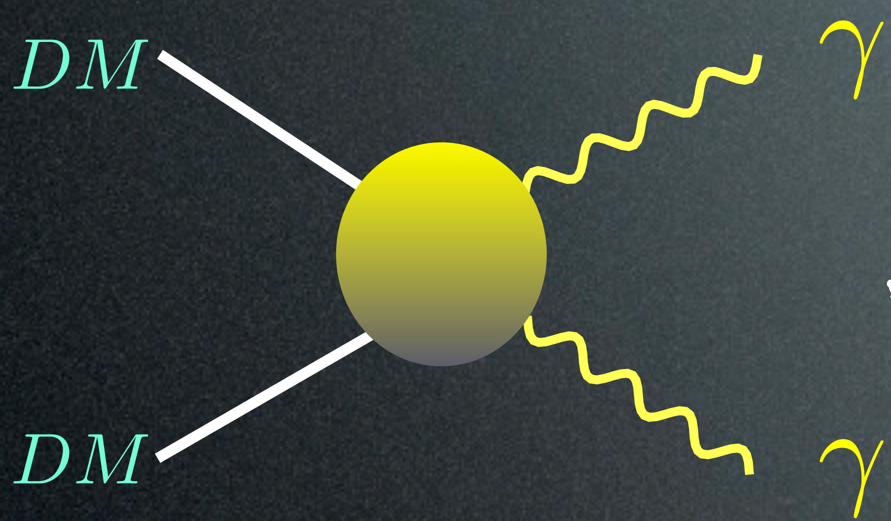
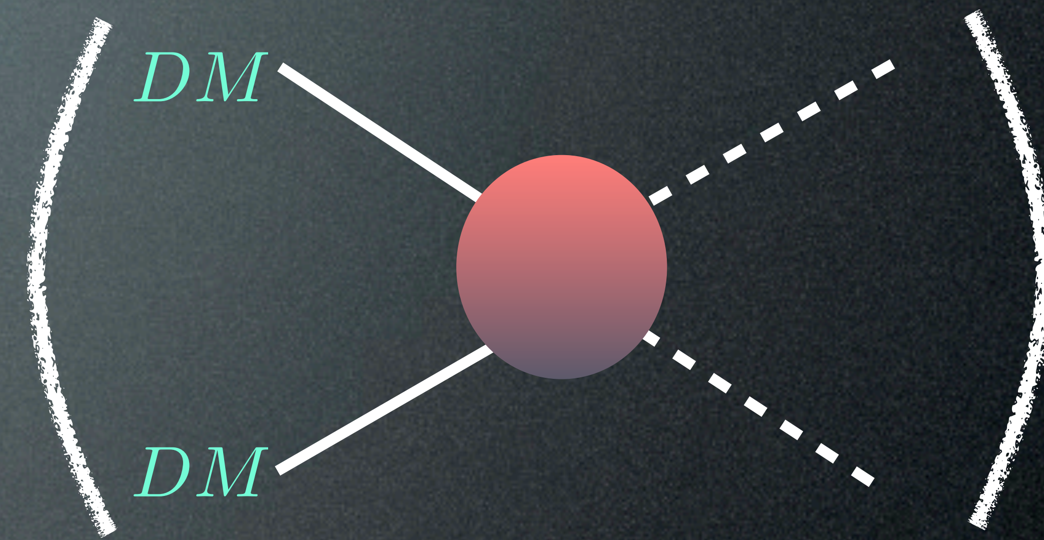


= 10^{-n} ×



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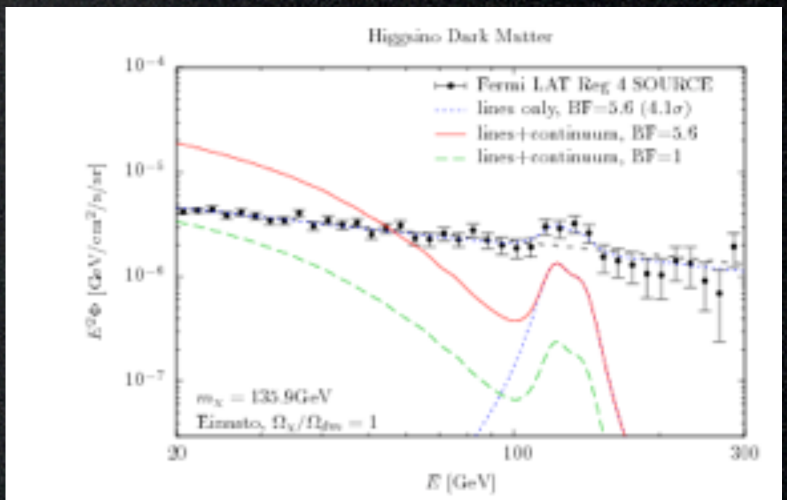


But solutions exist

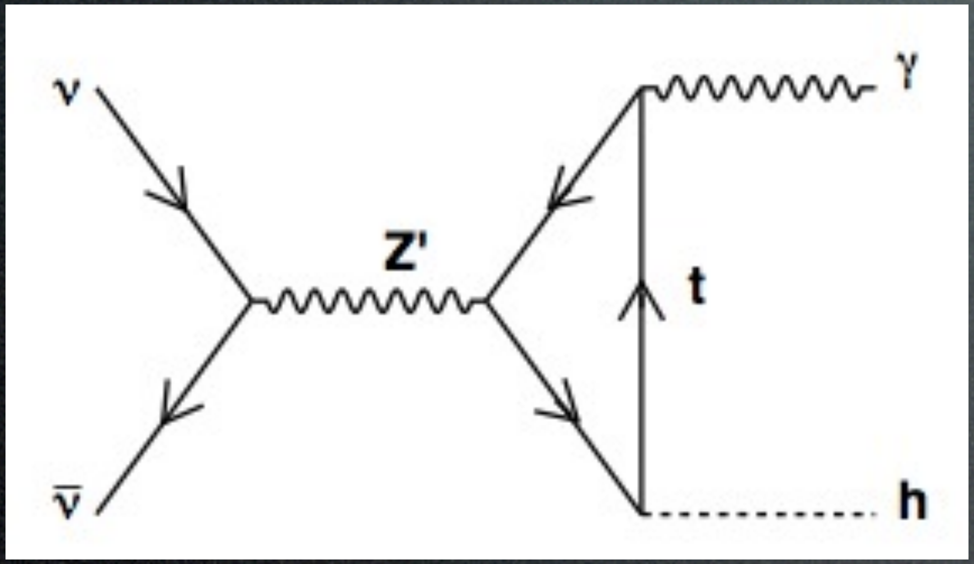
Model building

not exhaustive!

Ex. 1: ‘resonance, loop and forbidden channel’

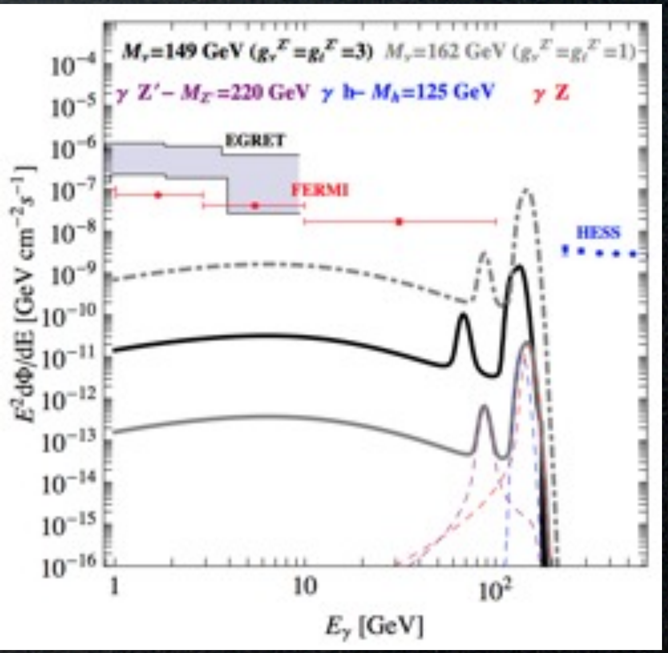
(a) DM charged under U’(1)
(b) Z’ is t_R-philic
(c) $m_{DM} \lesssim m_{top}$

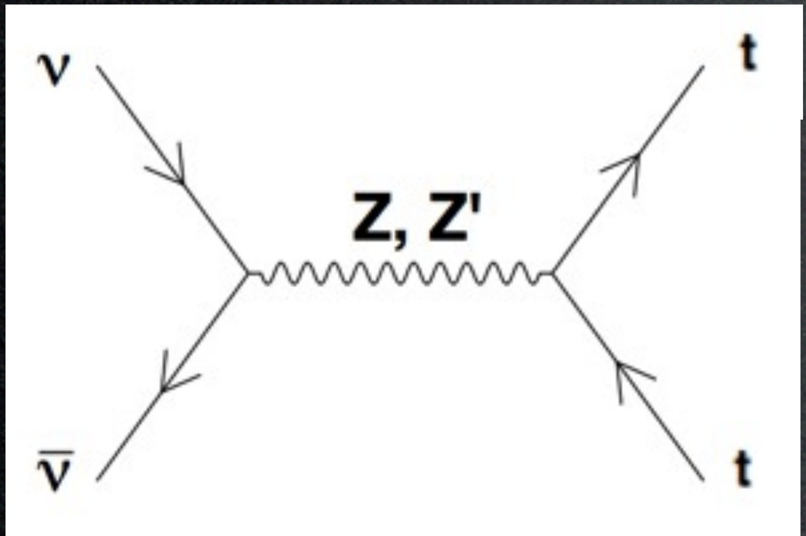
Jackson, Servant, Shaughnessy, Tait, Taoso, ‘Higgs in space’, 0912.0004



→ line(s)

with large rate
if on resonance (a)
(masses & couplings)





today:
kinematically forbidden (c)
little in other channels (b) (only via Z-Z’ mixing)
→ small continuum

Early Universe:
→ relic abundance

However:
- anomalies, need to UV complete (b)

Model building

not exhaustive!

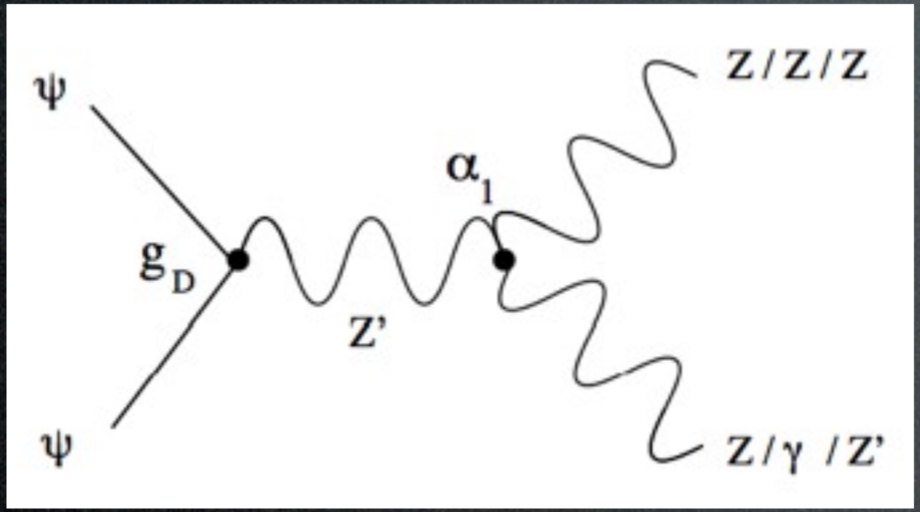
Ex. 2: ‘resonance, tri-boson vertices, Chern-Simons’

(a) DM charged under U′(1)
(b) anomaly cancellation → tri-boson CS terms

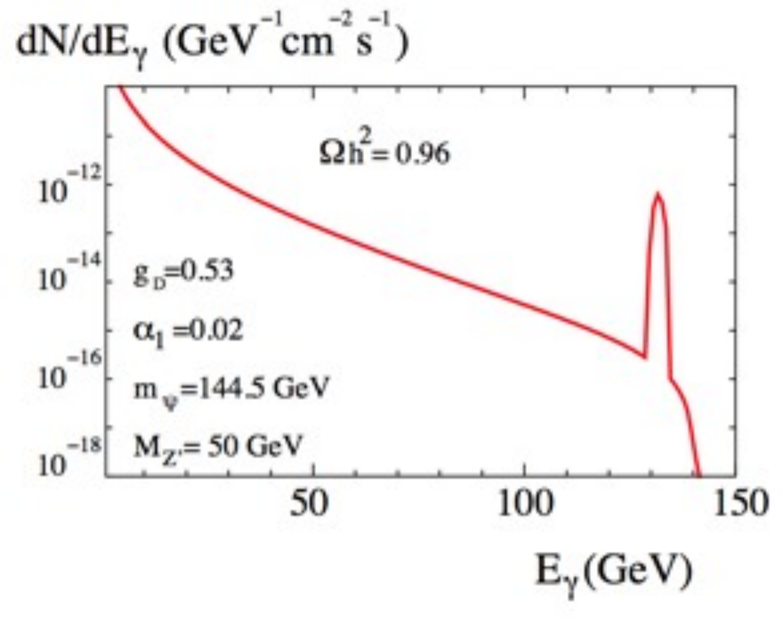
$$\mathcal{L}_{\rm CS} = \alpha\, \varepsilon^{\mu\nu\rho\sigma}\, Z'_\mu Z_\nu F^Y_{\rho\sigma}$$

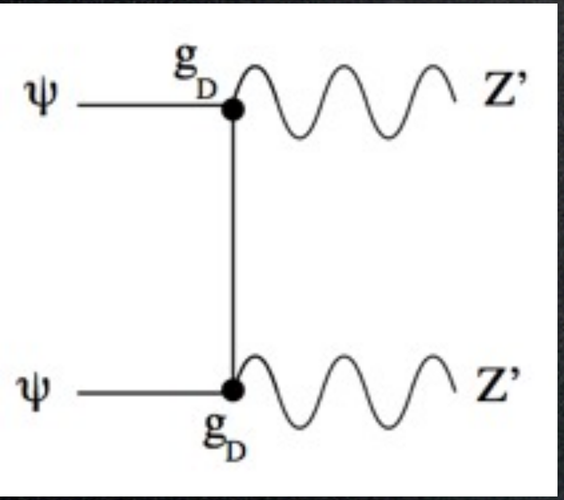
Dudas, Mambrini, Pokorski, Romagnoni 2009-2012, 1205.1520

(c) $m_{Z'} < m_{DM}$



→ line (b)

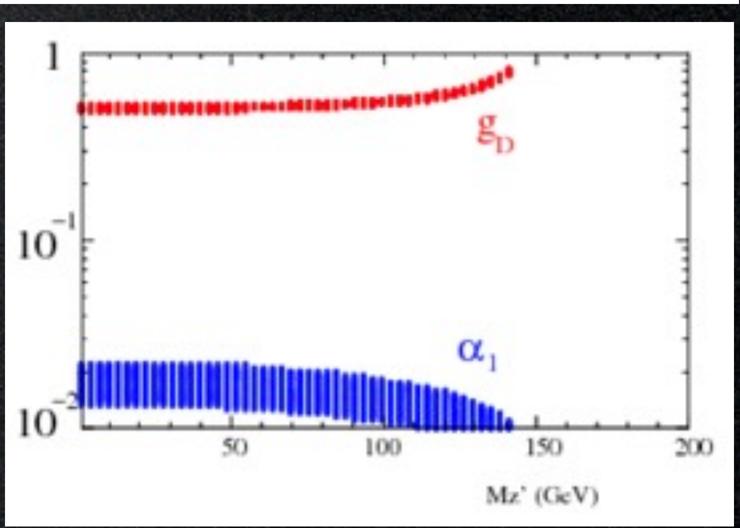




→ relic abundance

a different diagram wrt to line, open thanks to (c), works for large gauge coupling and small (loop?) CS coeff

→ Continuum? Under control



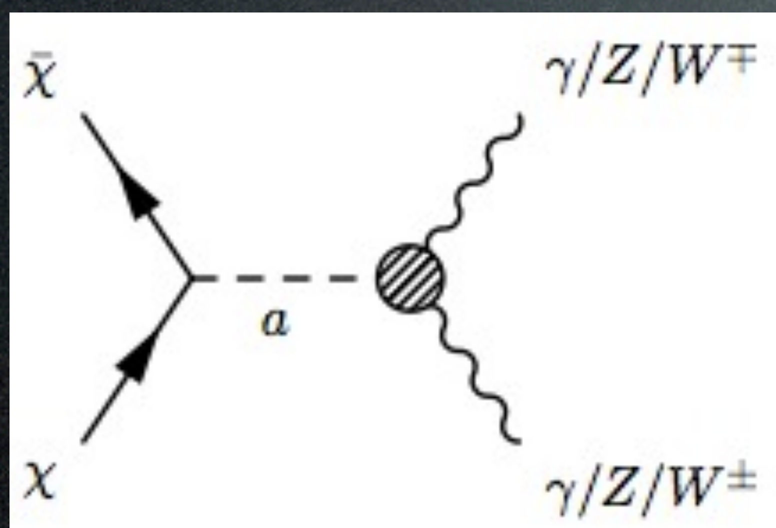
Model building

not exhaustive!

Ex. 3: ‘pseudo-scalar mediation, p- and s-waves’

(a) DM charged under $U(1)_{PQ}$
(b) anomalies → tri-boson terms

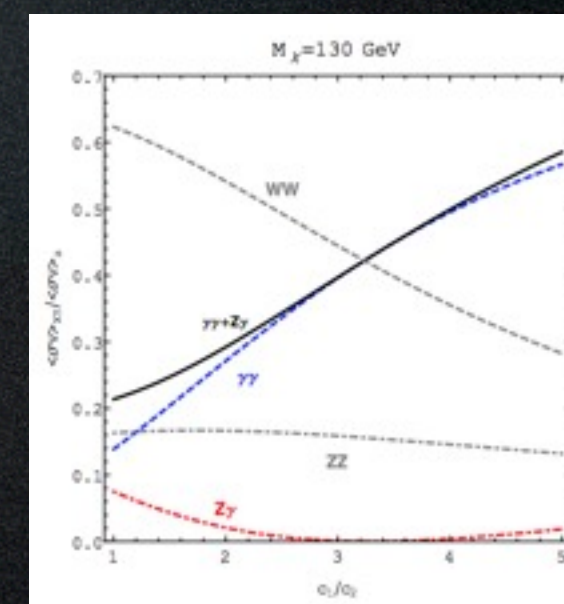
Lee, Park[2], 1205.4675

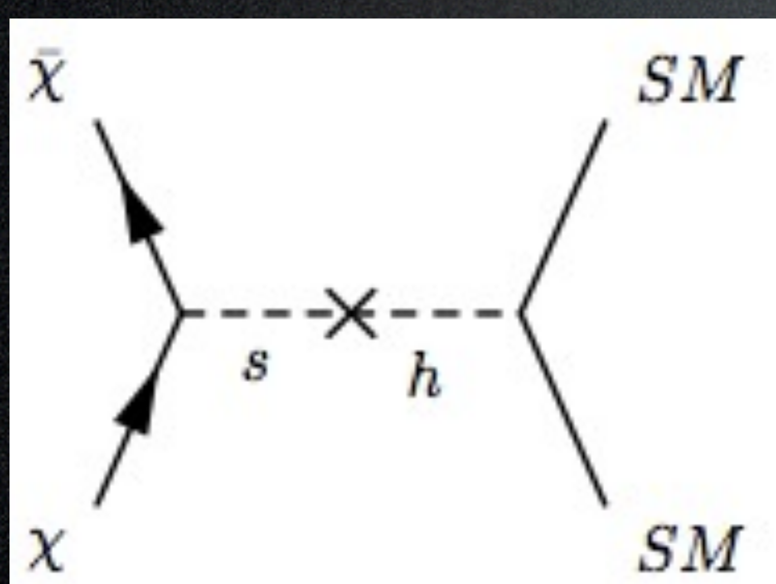


→ line (b)

with large rate
if on resonance (a)

→ Continuum? Assume couplings to W and Z are suppressed





Exchange of s/h is p-wave, i.e. v dependent.

Suppressed today, large in EU.

→ relic abundance

Model building

not exhaustive!

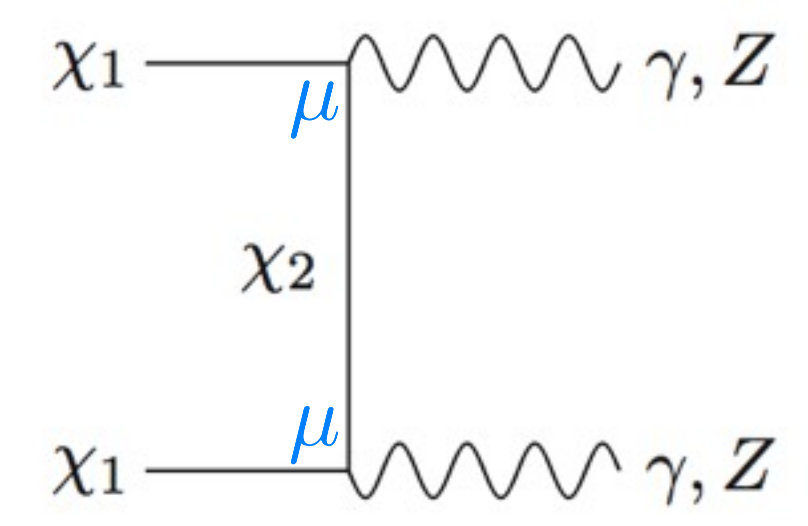
Ex. 4: ‘magnetic moments and coannihilations’

Tulin, Yu, Zurek 1208.0009
Cline, Moore, Frey 1208.2685

(a) DM has a magnetic moment

$$\mu\,\bar{\chi}_1\sigma_{\mu\nu}\chi_2\,F^{\mu\nu}$$

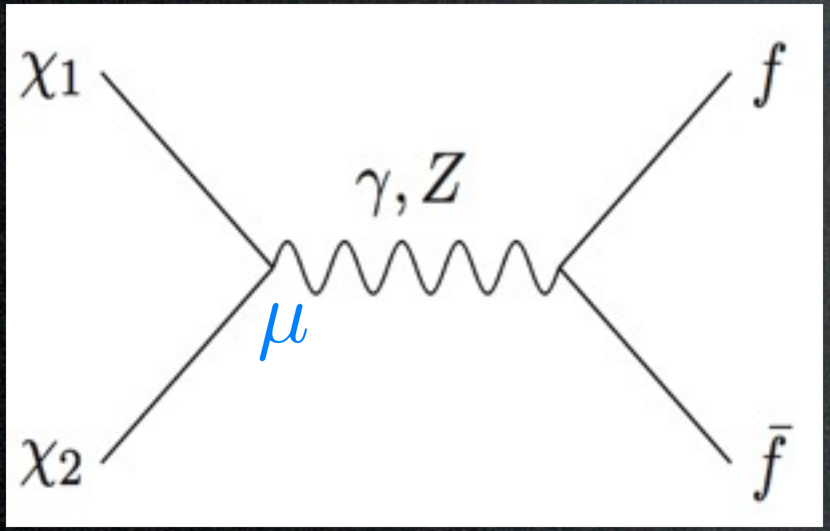
(b) DM sits in a multiplet with ~10 GeV splitting



→ line (a)

with large rate
if μ is large

→ Continuum? Under control (it’s same order as γγ)



→ relic abundance

is set by coannihilations,
they would be too effective for large μ,
but the splitting (b) suppresses.

→ Continuum? Ultra suppressed by the splitting (b)

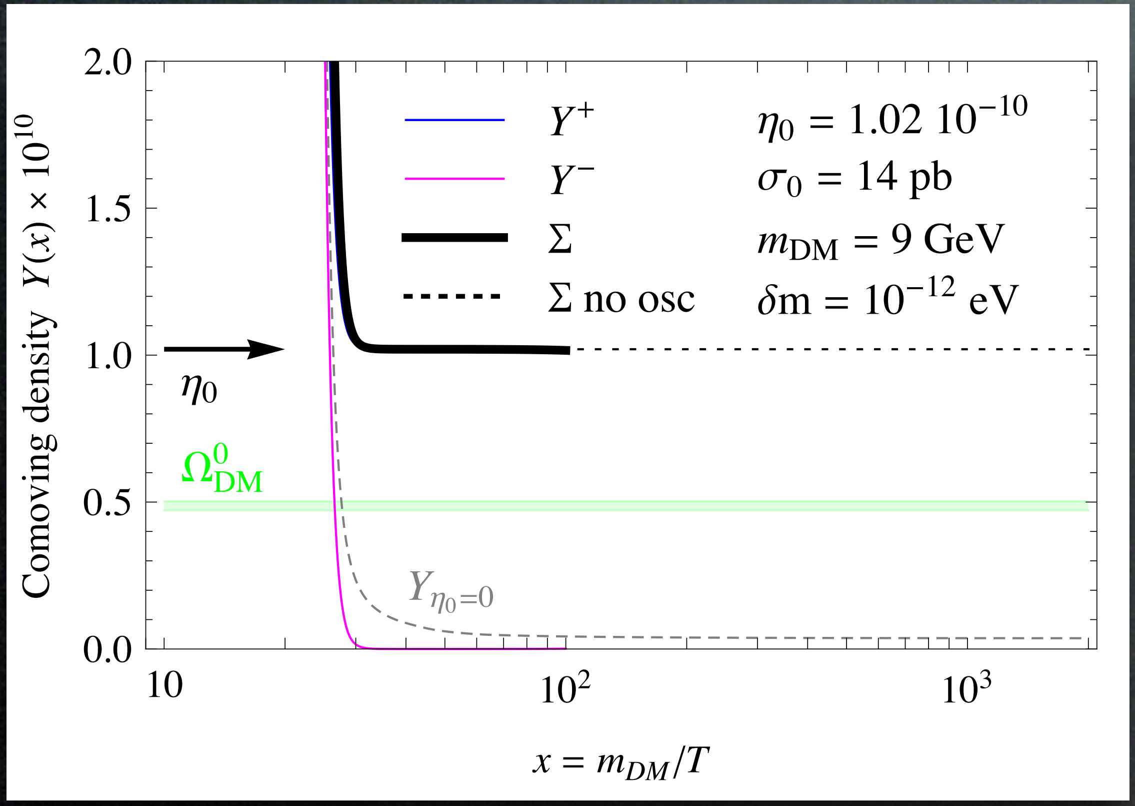
Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: ‘asymmetric DM’

(a) DM-$\overline{\text{DM}}$ initial asymmetry
(b) DM-$\overline{\text{DM}}$ mixing → late time oscillations, re-balance



➡ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Model building

not exhaustive!

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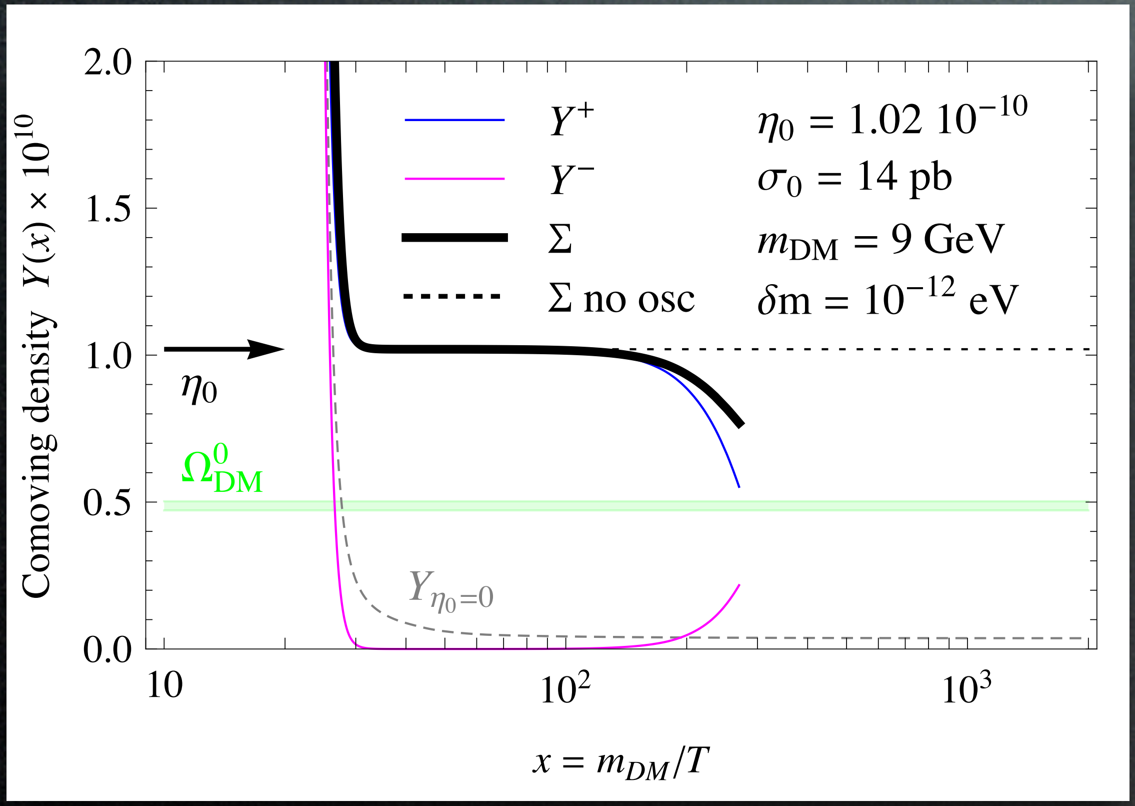

relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

Model building

not exhaustive!

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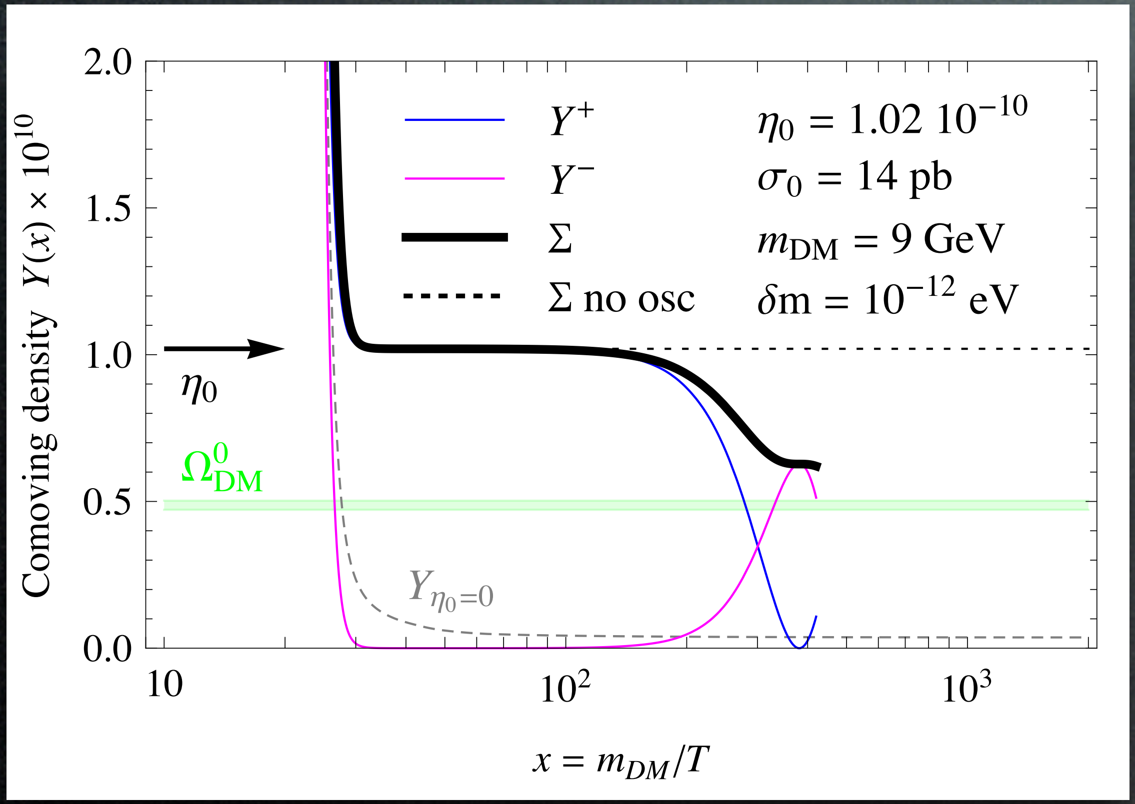

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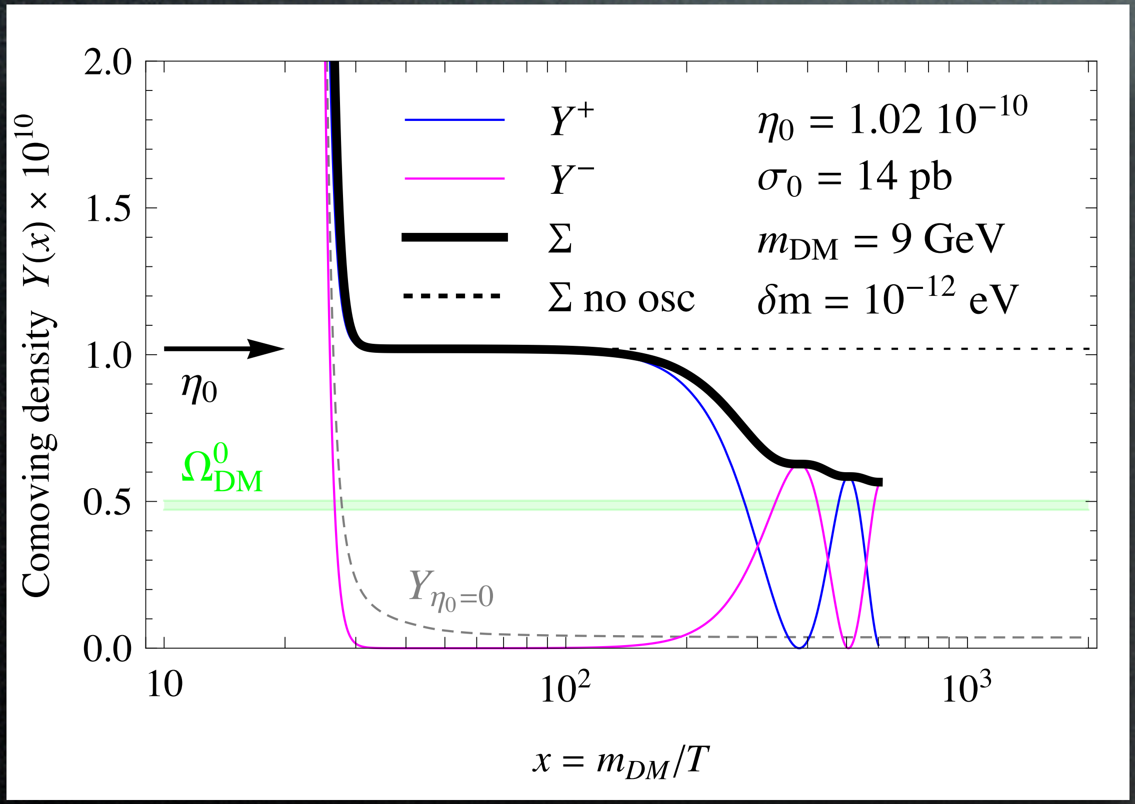

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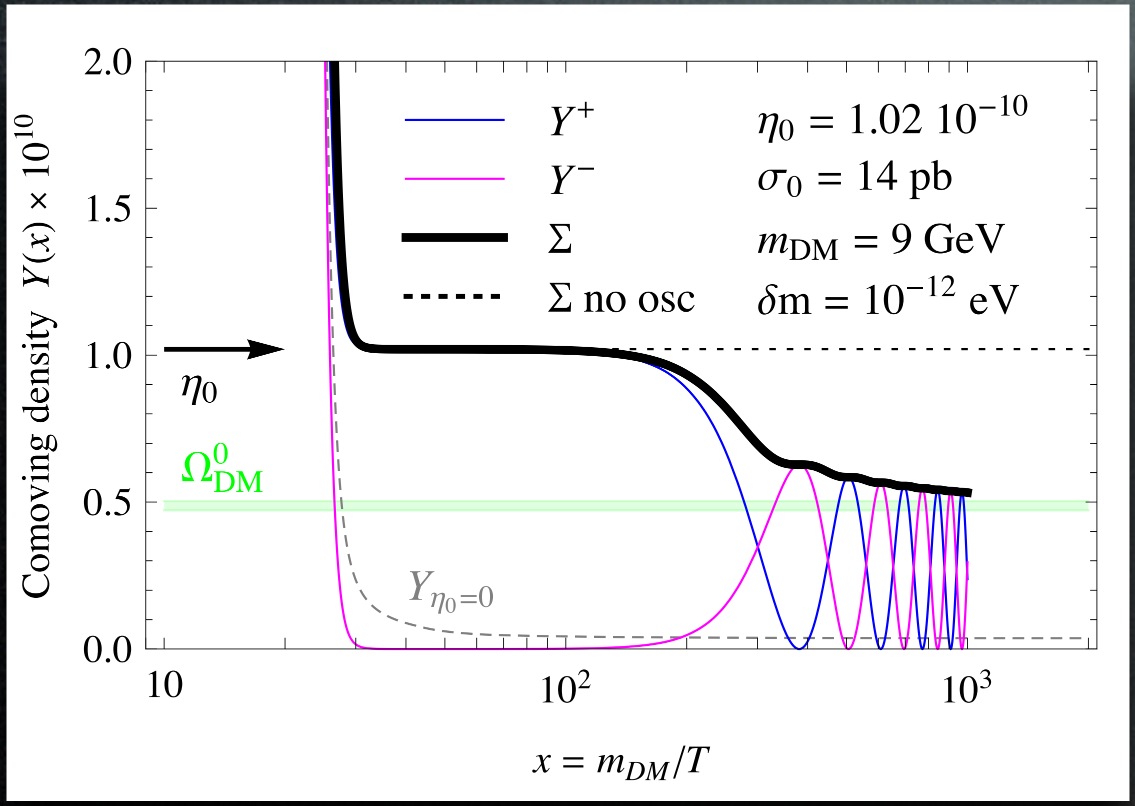

relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

(and the cross section needs to be large)

Model building

not exhaustive!

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Kaplan, Luty, Zurek 2009
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Tulin, Yu, Zurek 1208.0009

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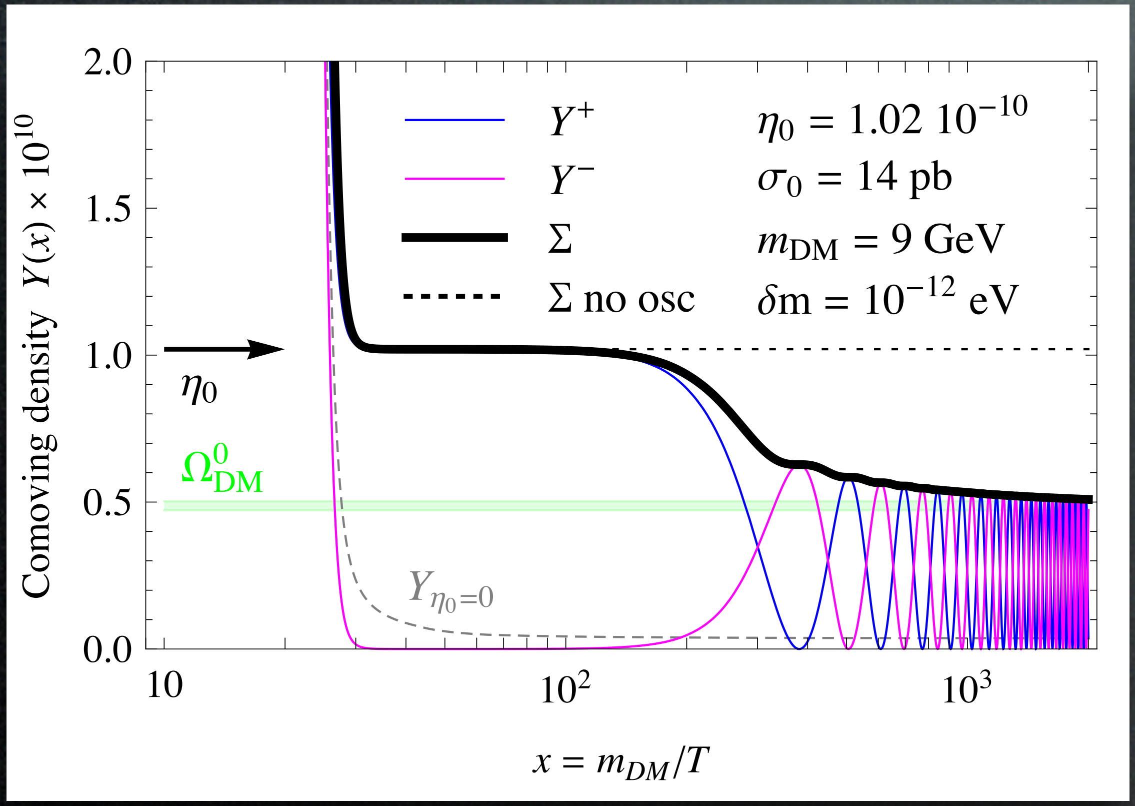

→ relic abundance (a)

is produced via the asymmetry
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Annihilations resume (b) → line

(and the cross section needs to be large)

Model building

not exhaustive!

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Kaplan, Luty, Zurek 2009
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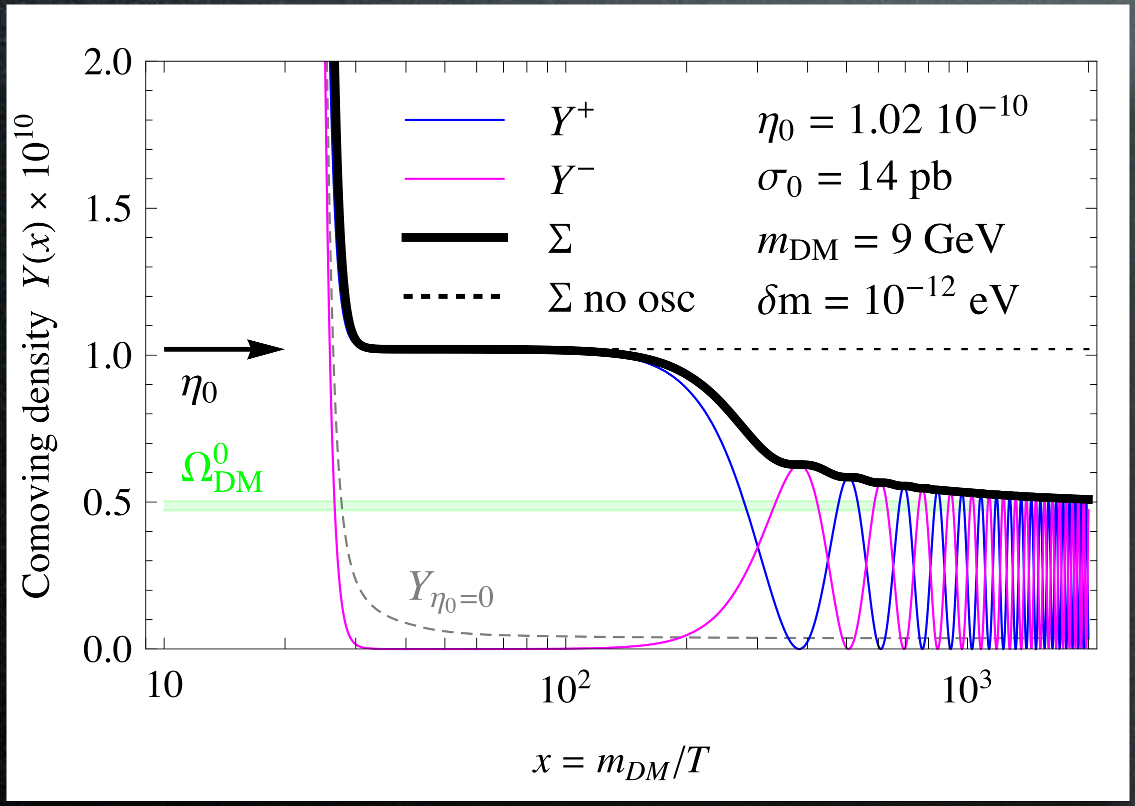

→ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b) → line
(and the cross section needs to be large)

→ Continuum? Needs to be suppressed in some way today.

Challenges

DM is neutral: need 'something' to couple to γ

The 'something' implies usually a suppression, but one needs a large $\gamma\gamma$ cross section (o(10^{-27} cm^3/s))

so the corresponding unsuppressed processes are **too** large:

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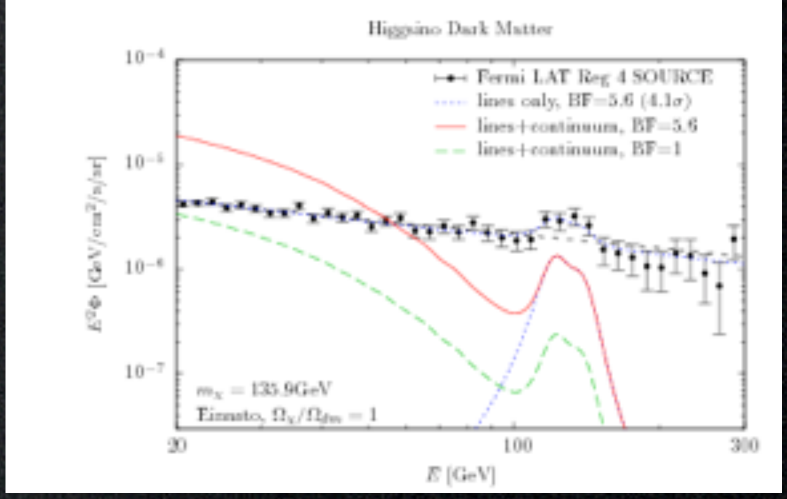


But solutions exist

Model building

- may overshoot other observations
- too large annihilation in the EU

But solutions exist

Model building

- may overshoot other observations
- too large annihilation in the EU

But solutions exist

In summary:

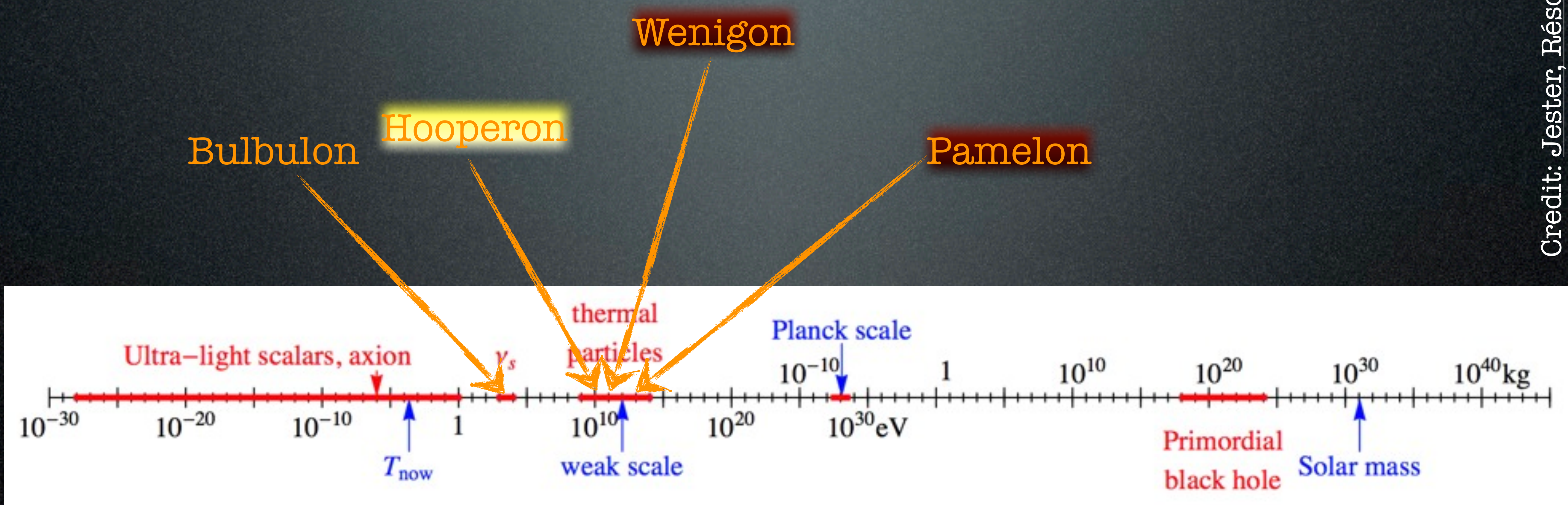
- kinematically forbidden channel
- different diagrams
- s-wave vs p-wave
- coannihilations and splitting
- DM production is decoupled from annihilations
- ...

Gamma rays

3. the 'Hooperon'

DM Candidates

A matter of perspective: plausible mass ranges



Credit: Jester, Résonaances

'only' 90 orders of magnitude!

GeV gamma excess?

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

A diffuse GeV excess from around the GC

Dan Hooper

GeV gamma excess?

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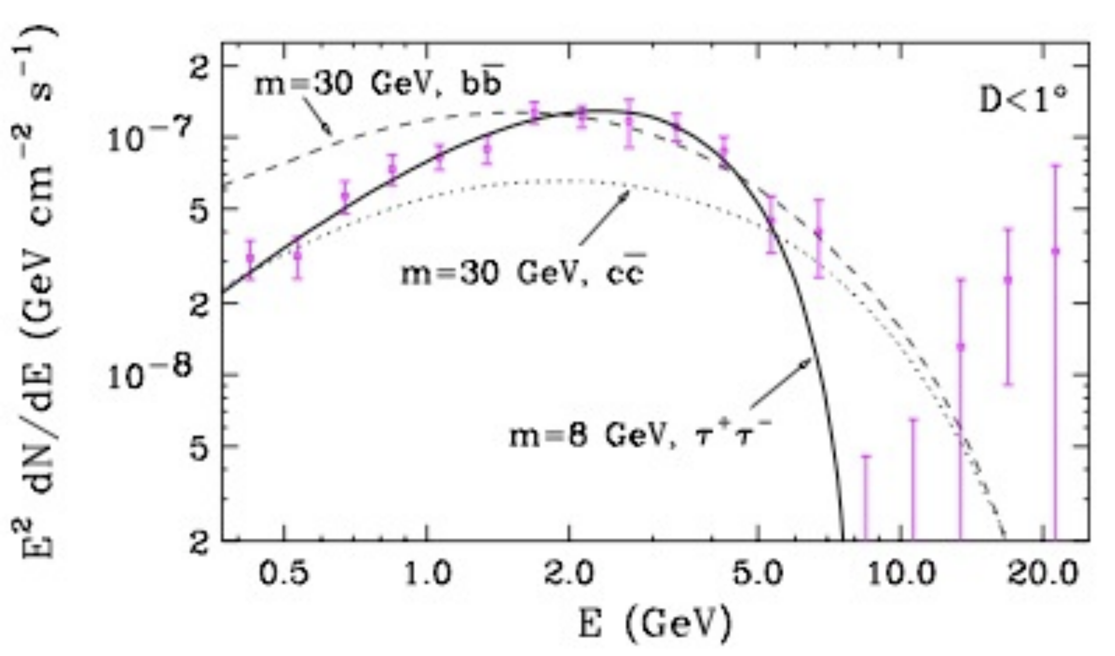

Hooper, Goodenough 1010.2752

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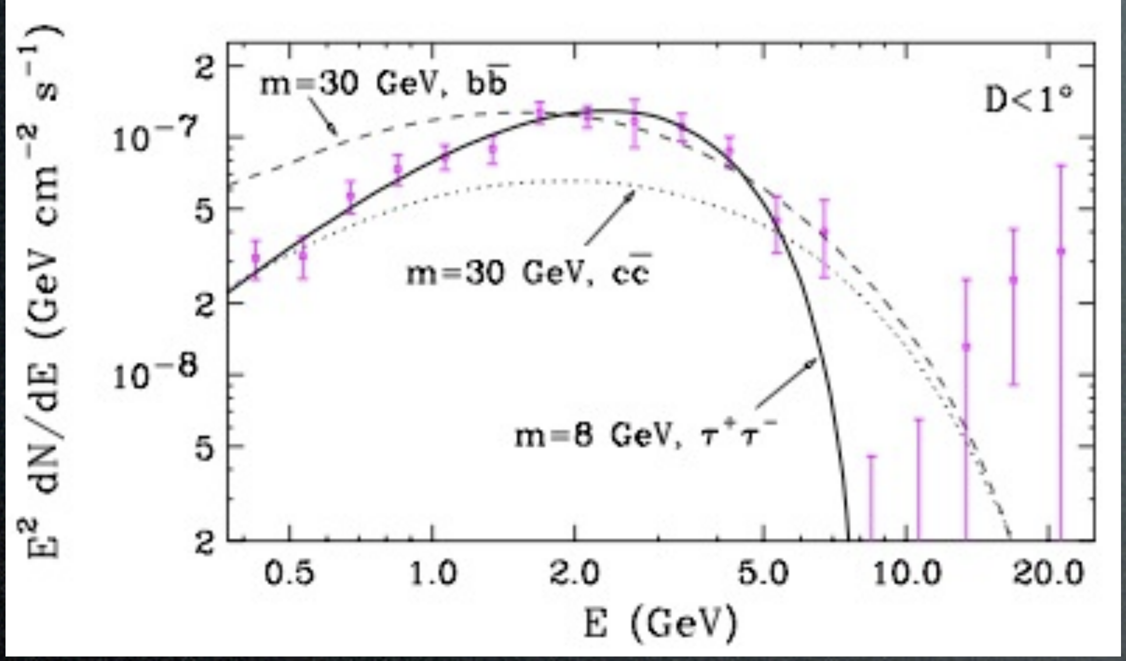
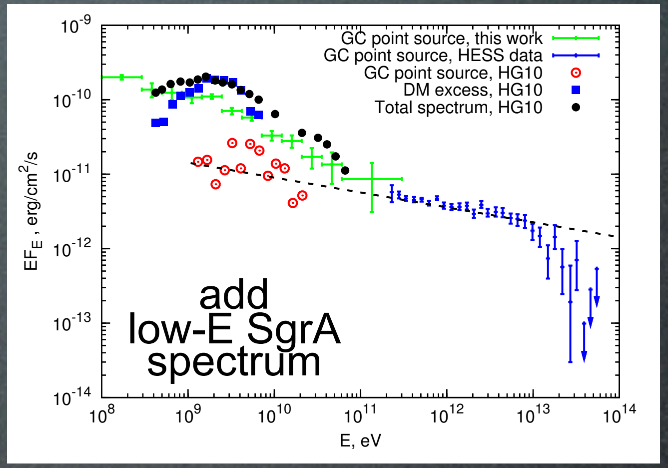
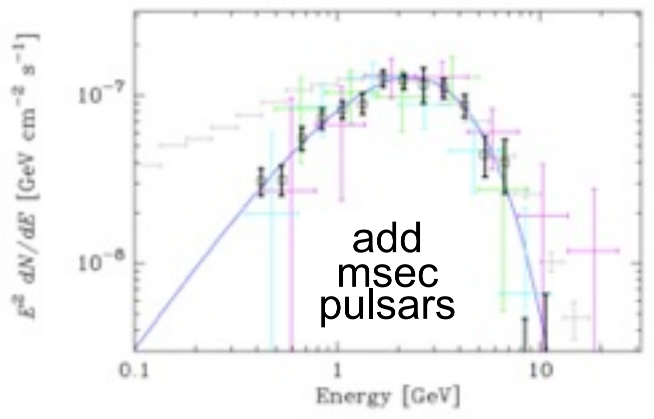


Hooper, Goodenough 1010.2752

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

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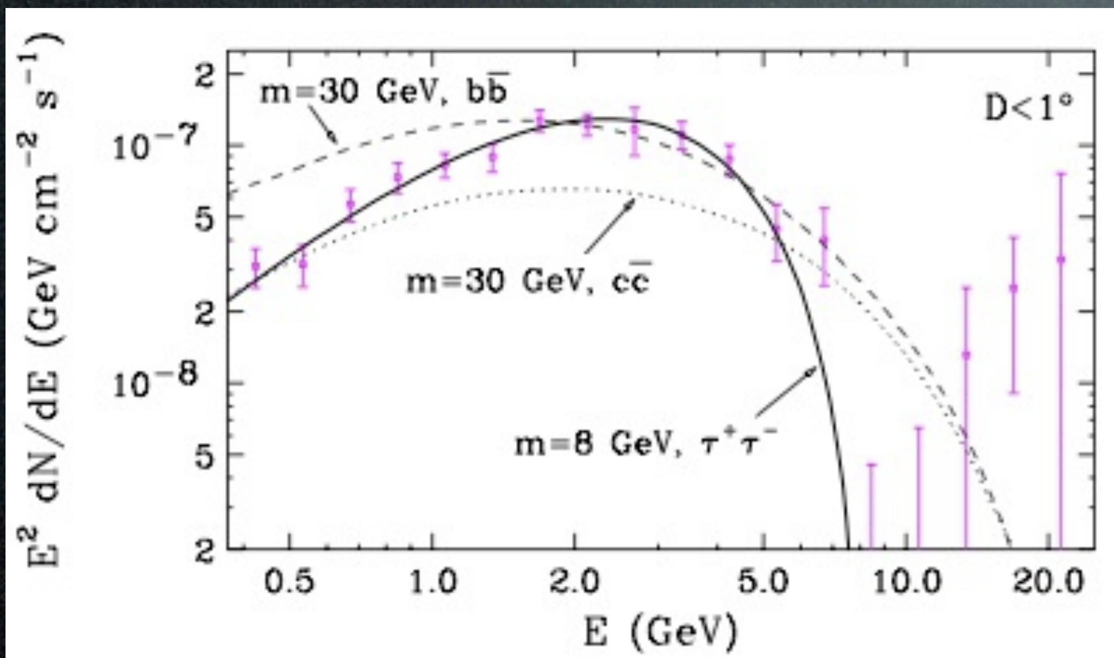

Hooper, Goodenough 1010.2752

Best fit: 8 GeV, $\tau^+ \tau^-$, ~thermal σv

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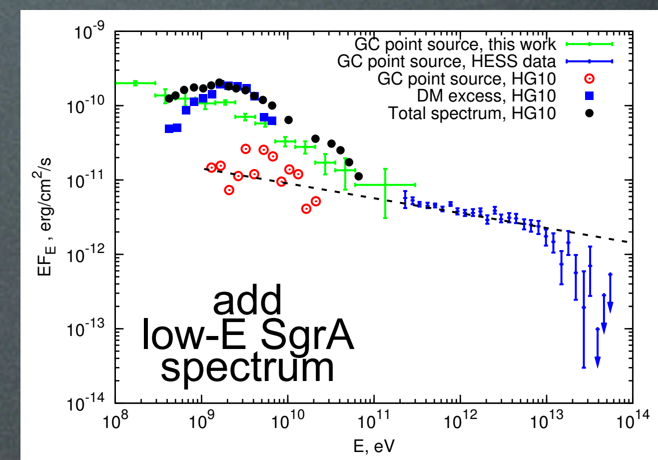
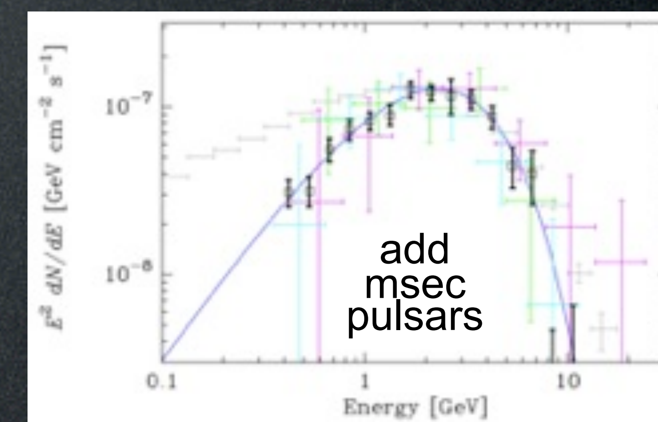


Boyarsky et al., 1012.5839



Abazajian 1011.4275

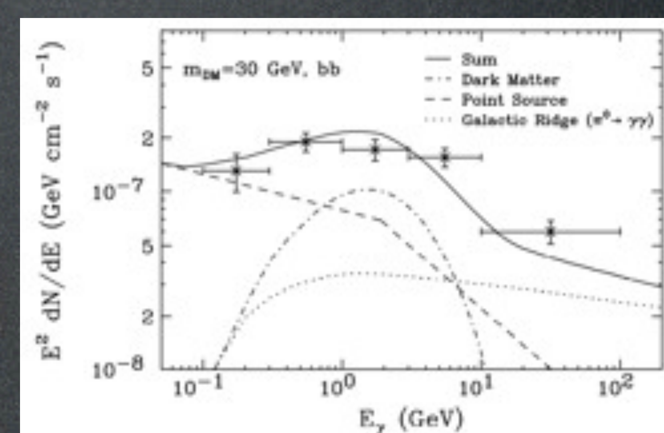
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

Still works...



Hooper, Linden 1110.0006

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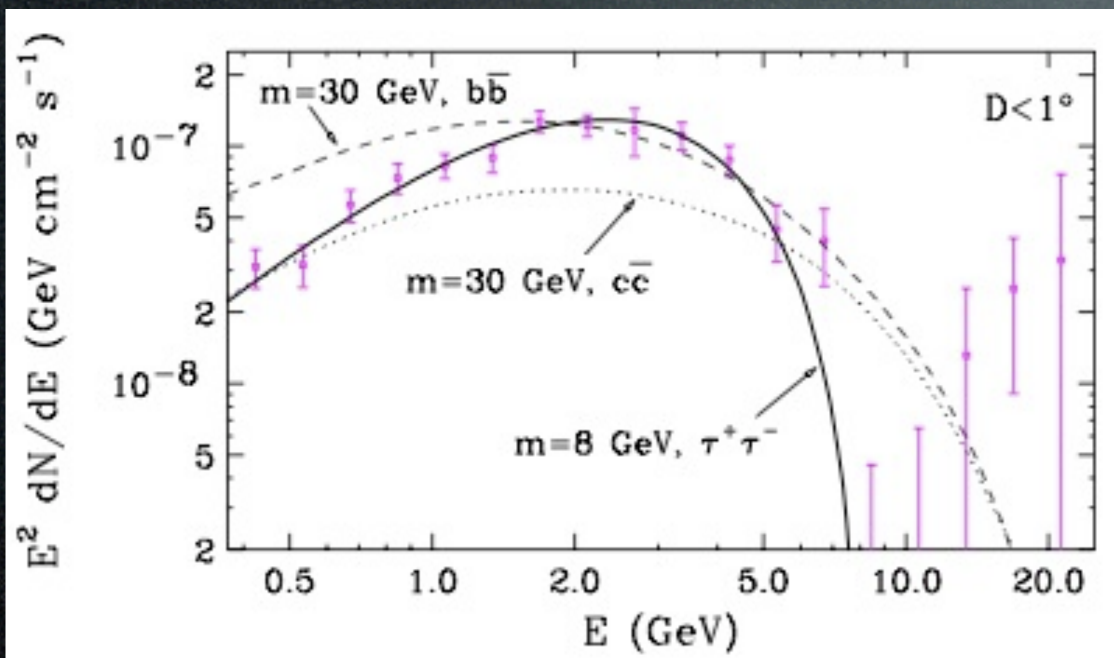

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A diffuse GeV excess from around the GC

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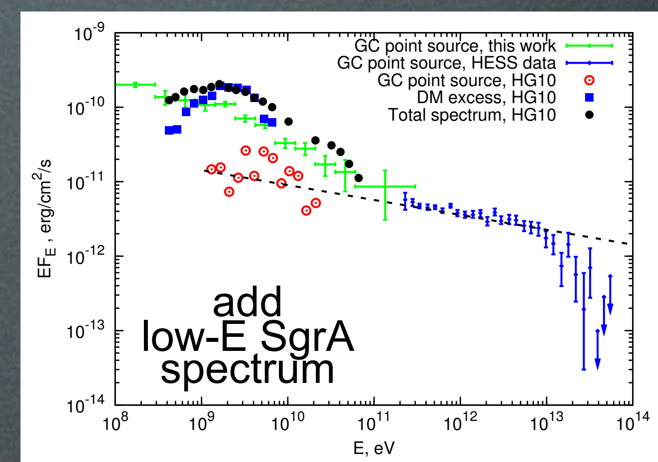
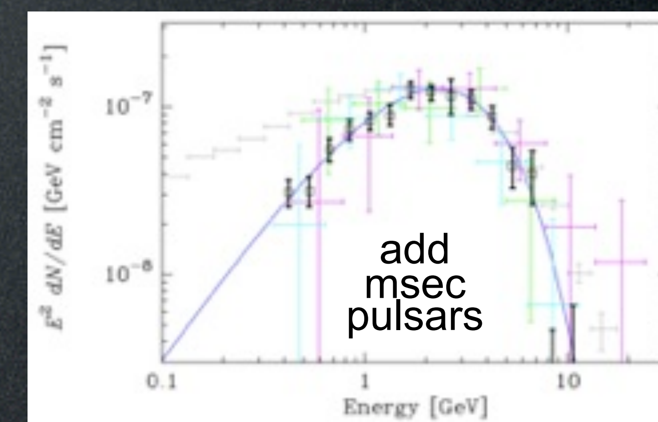


Boyarsky et al., 1012.5839



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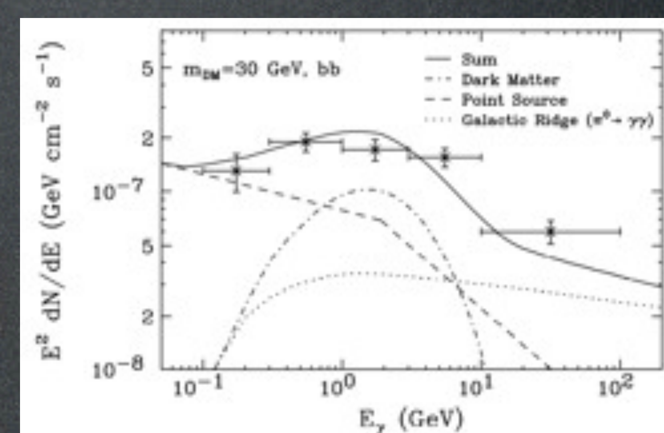

Hooper, Linden 1110.0006

No, too few

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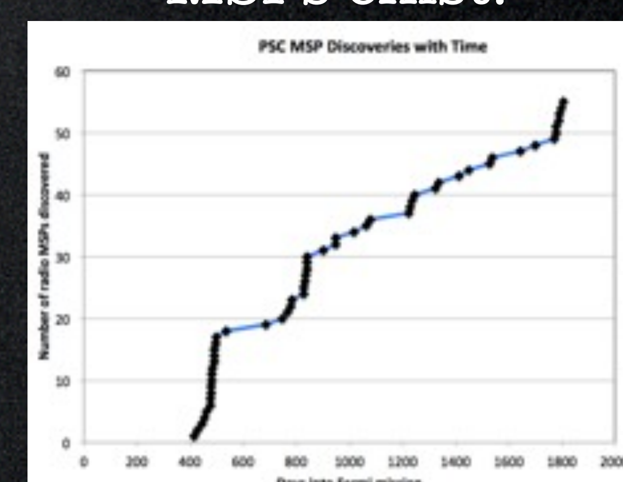
Hooper et al. 1305.0830

MSPs exist.



Caraveo 1312.2913

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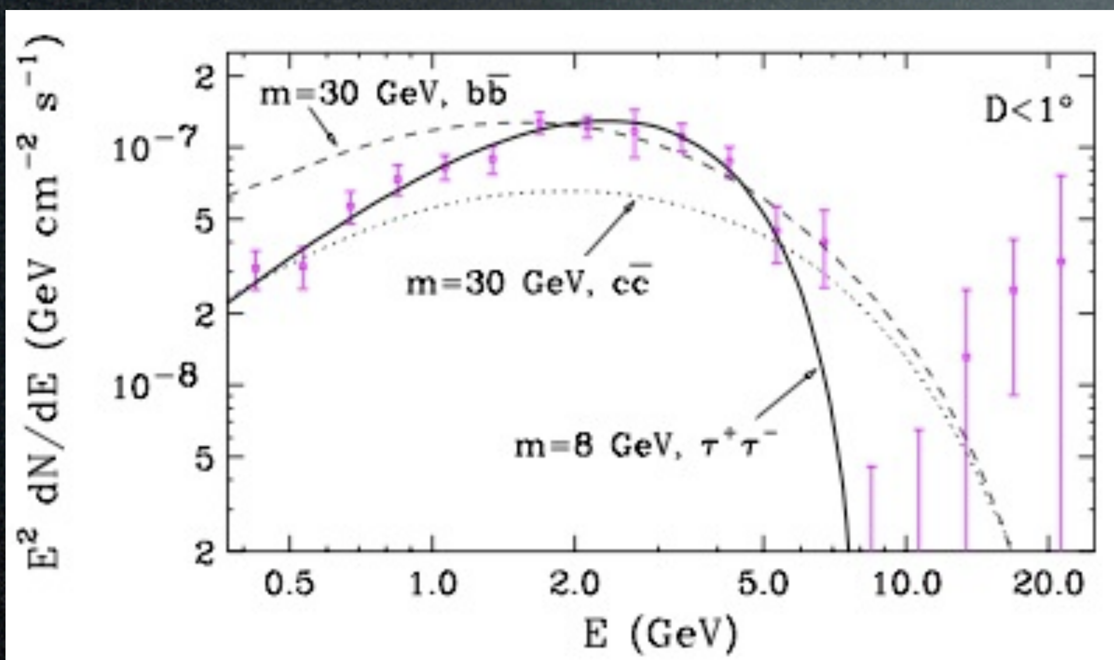

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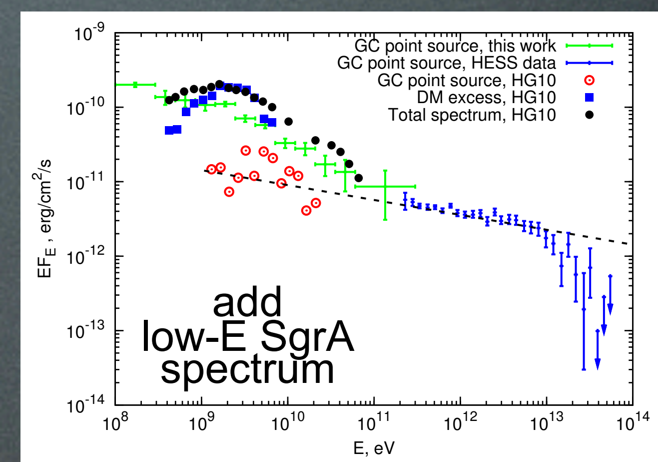

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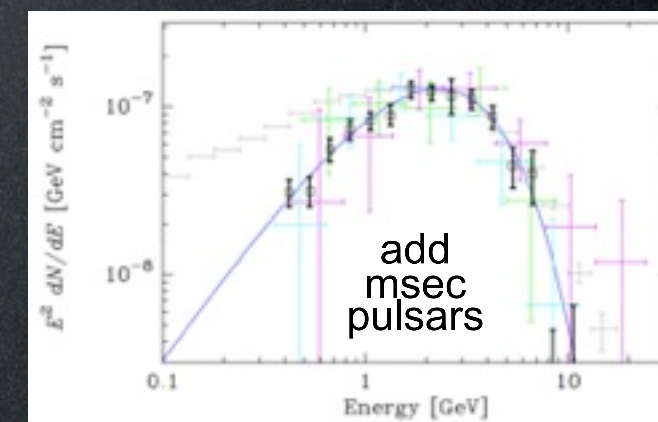
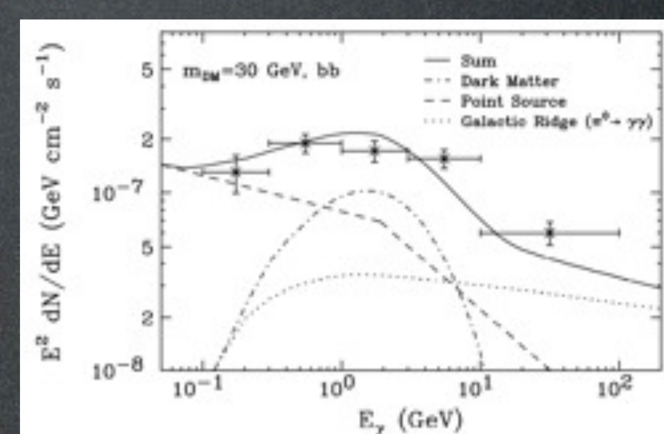


Abazajian 1011.4275

Still works...



Hooper, Linden 1110.0006

No, too few
(and we should have seen them elsewhere)
and wrong spectra

Hooper et al. 1305.0830

No no, MSPs can do.

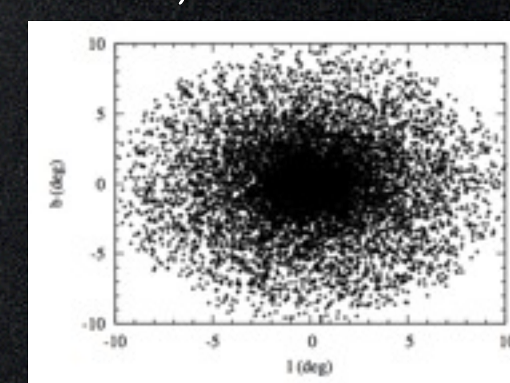


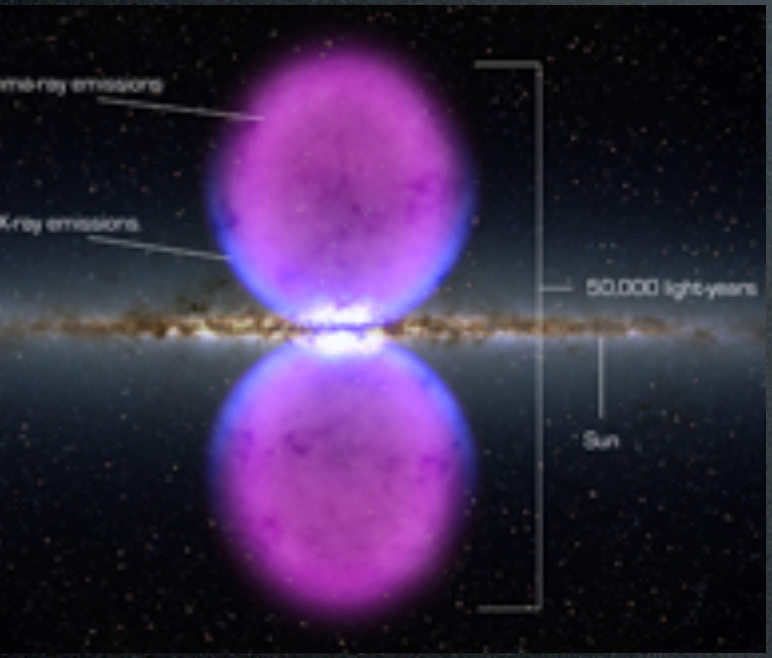
Figure 5: Simulated spatial distribution of the bulge MSPs.

Yuan, Zhang 1404.2318

(LMXB (tracers of MSP?) seen in M31 with this distribution)

GeV gamma excess?

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



Fermi bubbles

Dan Hooper

GeV gamma excess?

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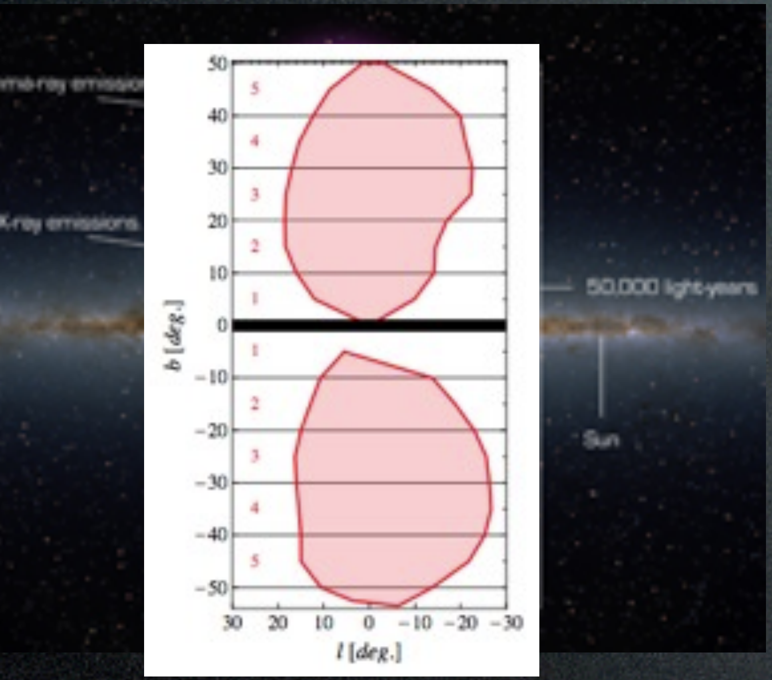

Fermi bubbles

Dan Hooper

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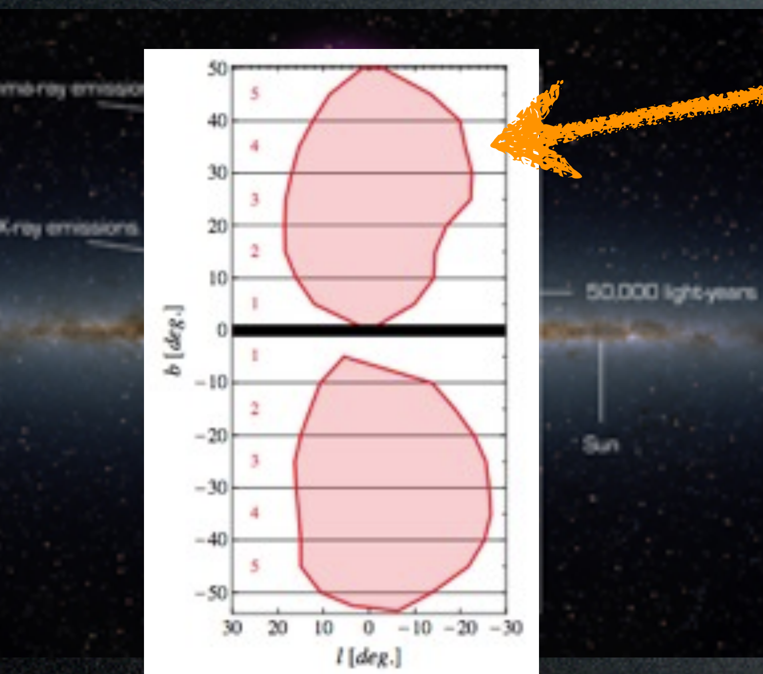
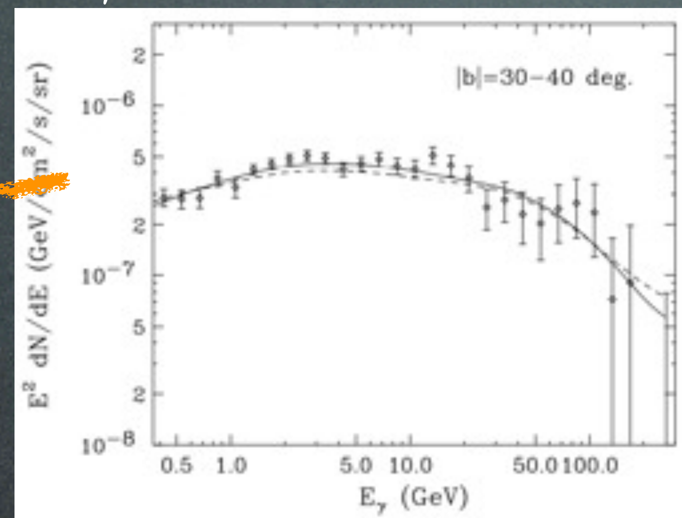




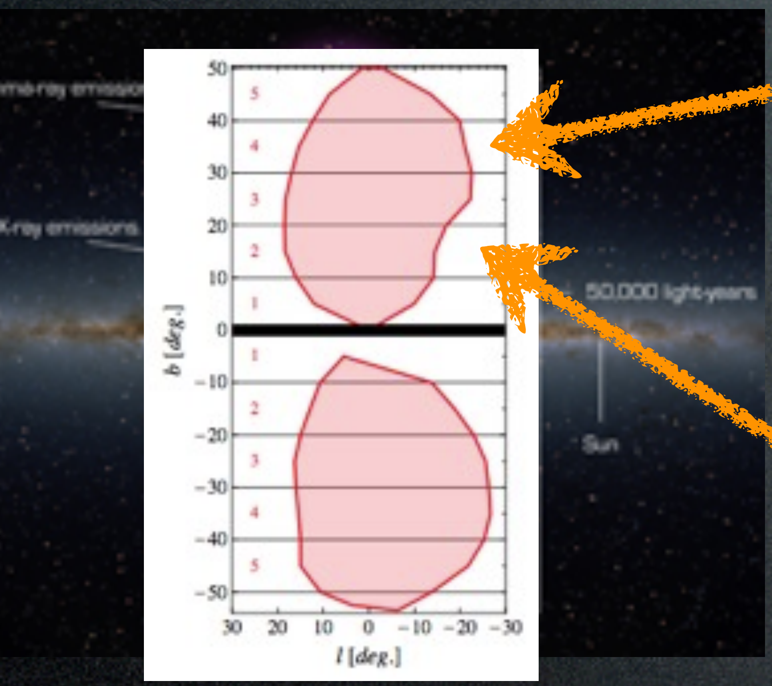
Here there's no excess which cannot be explained in terms of ordinary ICS.

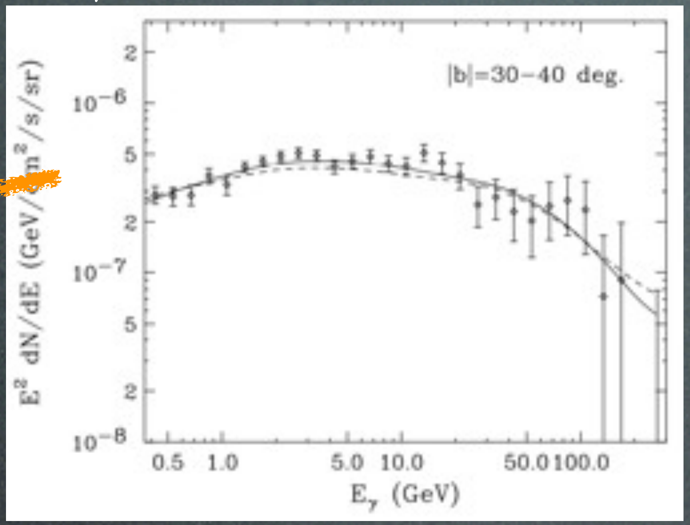
Fermi bubbles

Dan Hooper

GeV gamma excess?

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





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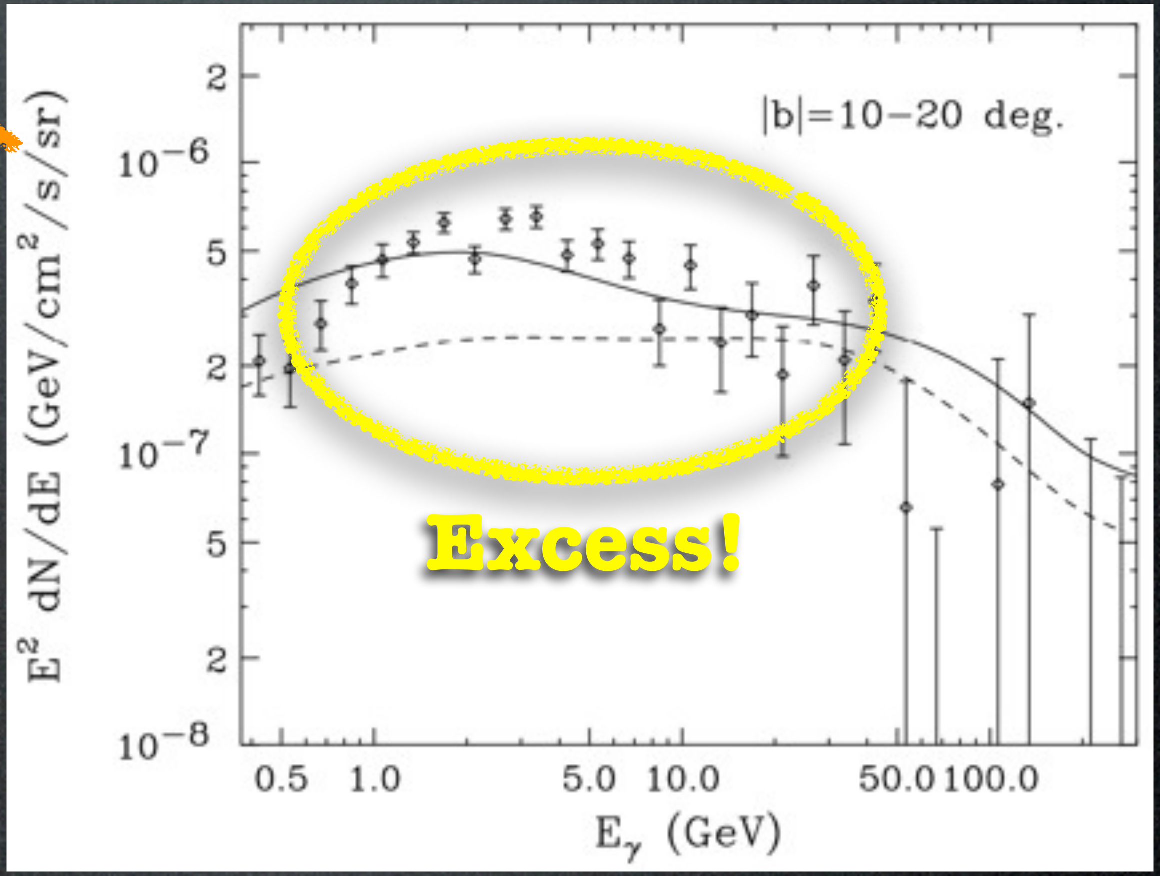


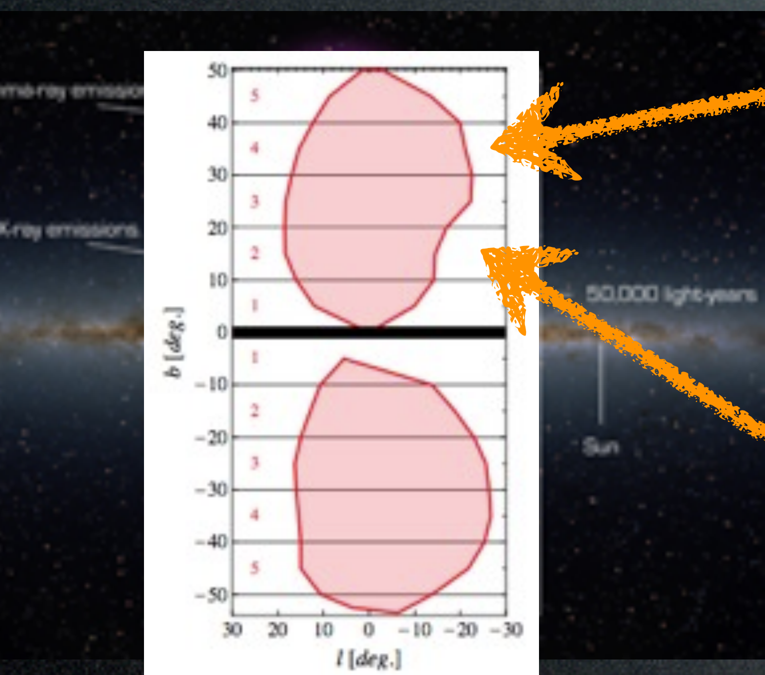
Best fit:
~10 GeV, leptons, ~thermal σv

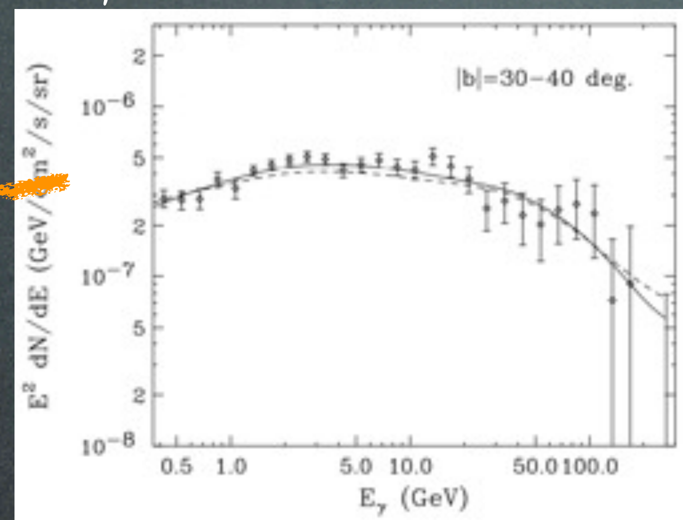
Fermi bubbles
Dan Hooper

Hooper, Slatyer 1302.6589
Essentially confirmed by: Huang, Urbano, Xue 1307.6862

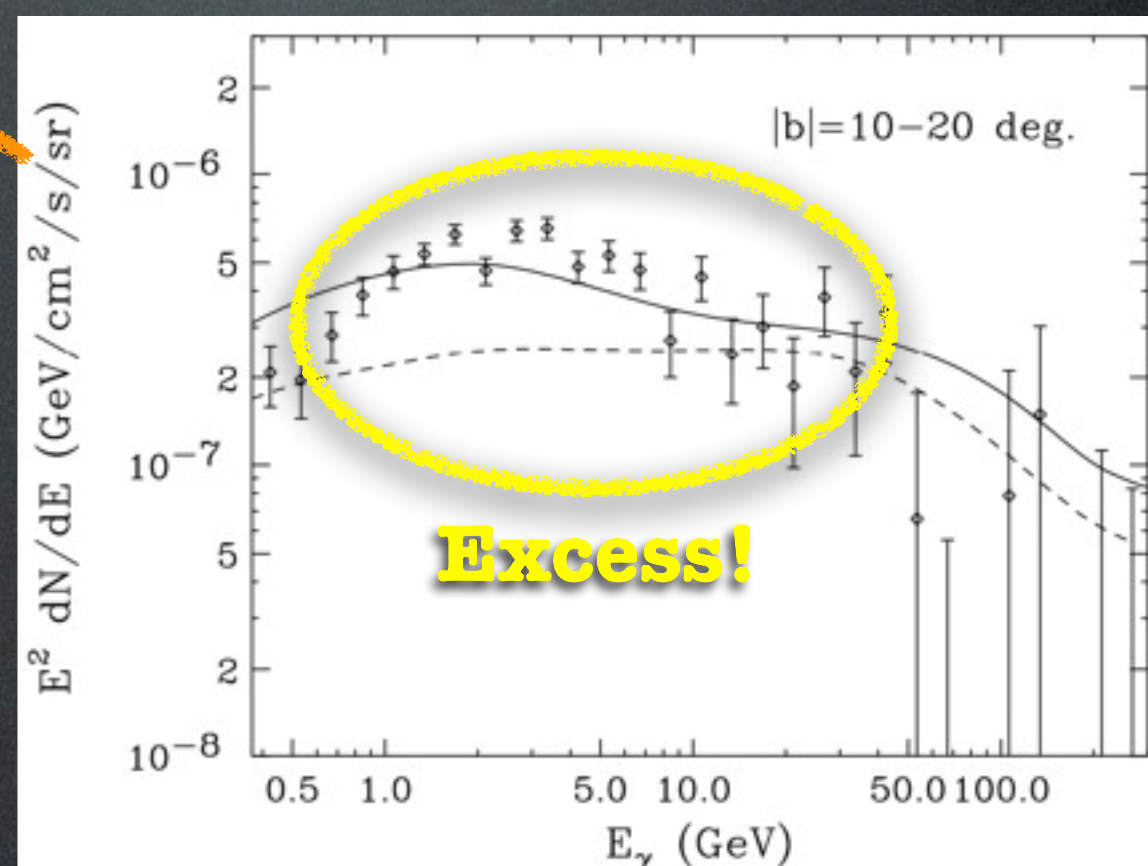
GeV gamma excess?

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





Here there's no excess which cannot be explained in terms of ordinary ICS.



Objection:
nothing tells you that the input $e^\pm$ spectrum stays the same at high and low latitudes
(the ISRF too, but one can better model that)

Best fit:
~10 GeV, leptons, ~thermal σv

Fermi bubbles

Dan Hooper

Hooper, Slatyer 1302.6589
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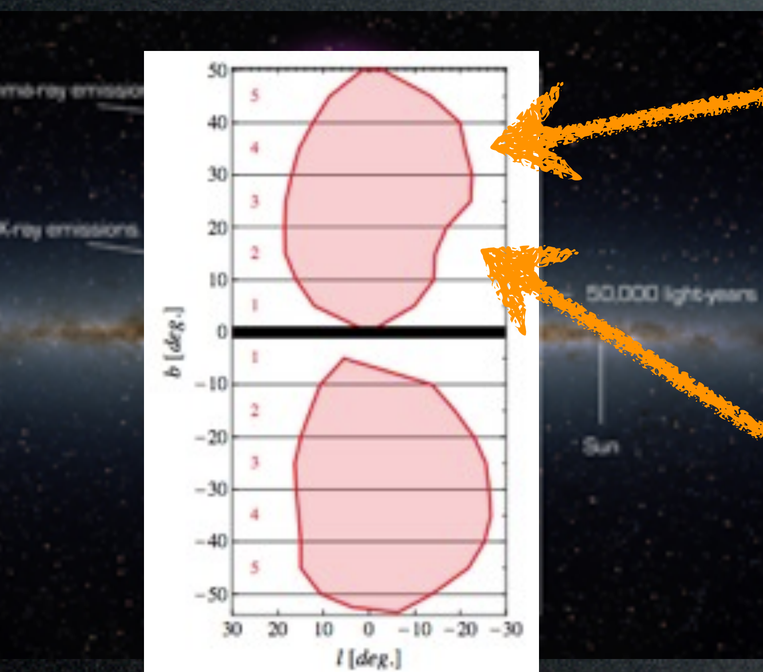
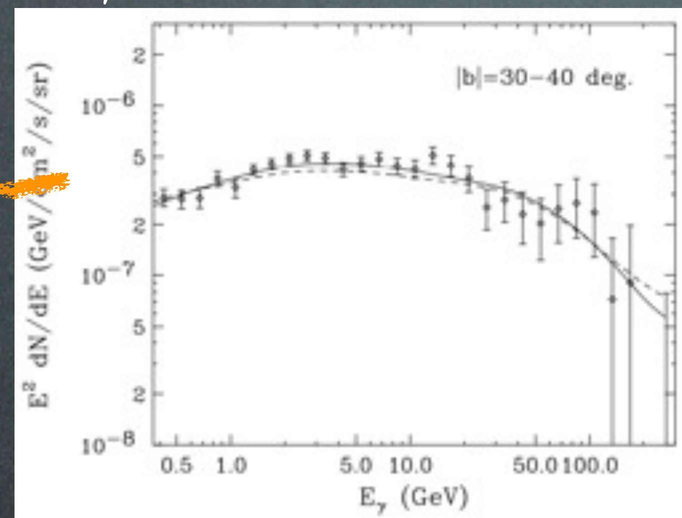
GeV gamma excess?

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





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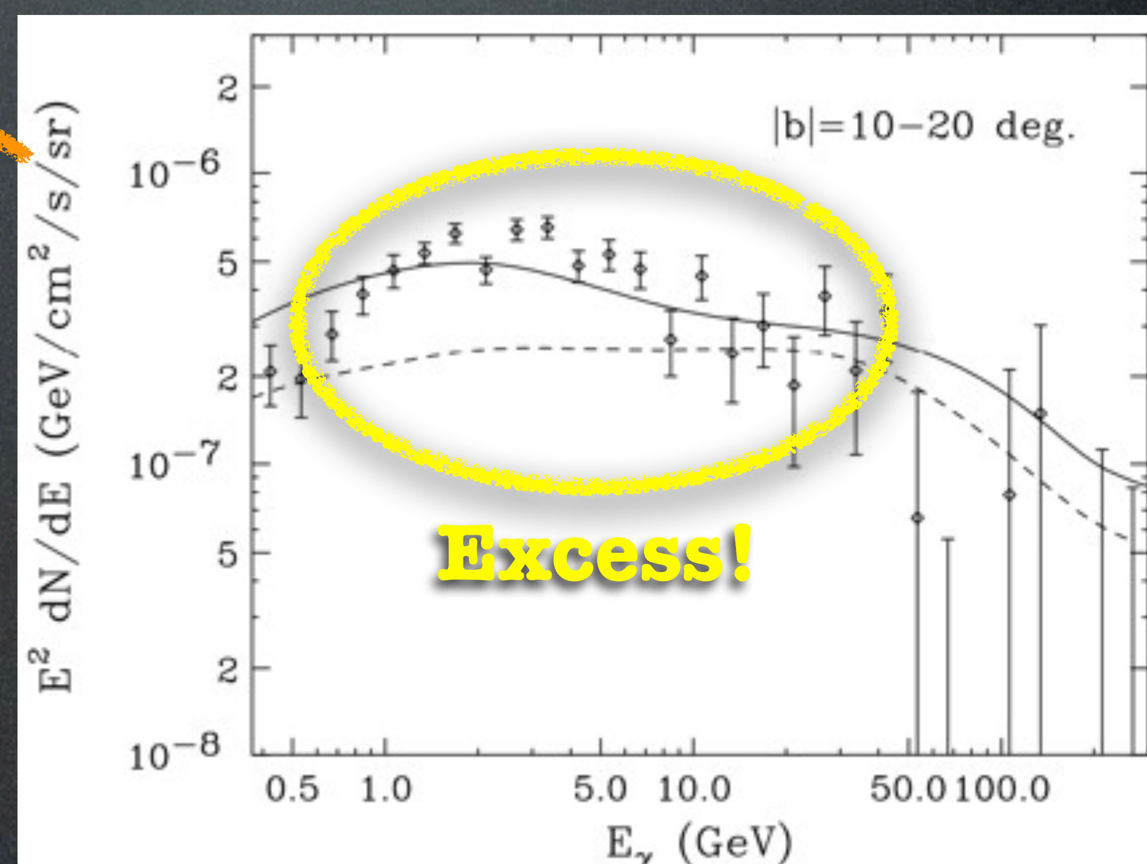


Best fit:
~10 GeV, leptons, ~thermal σv

Fermi bubbles
Dan Hooper

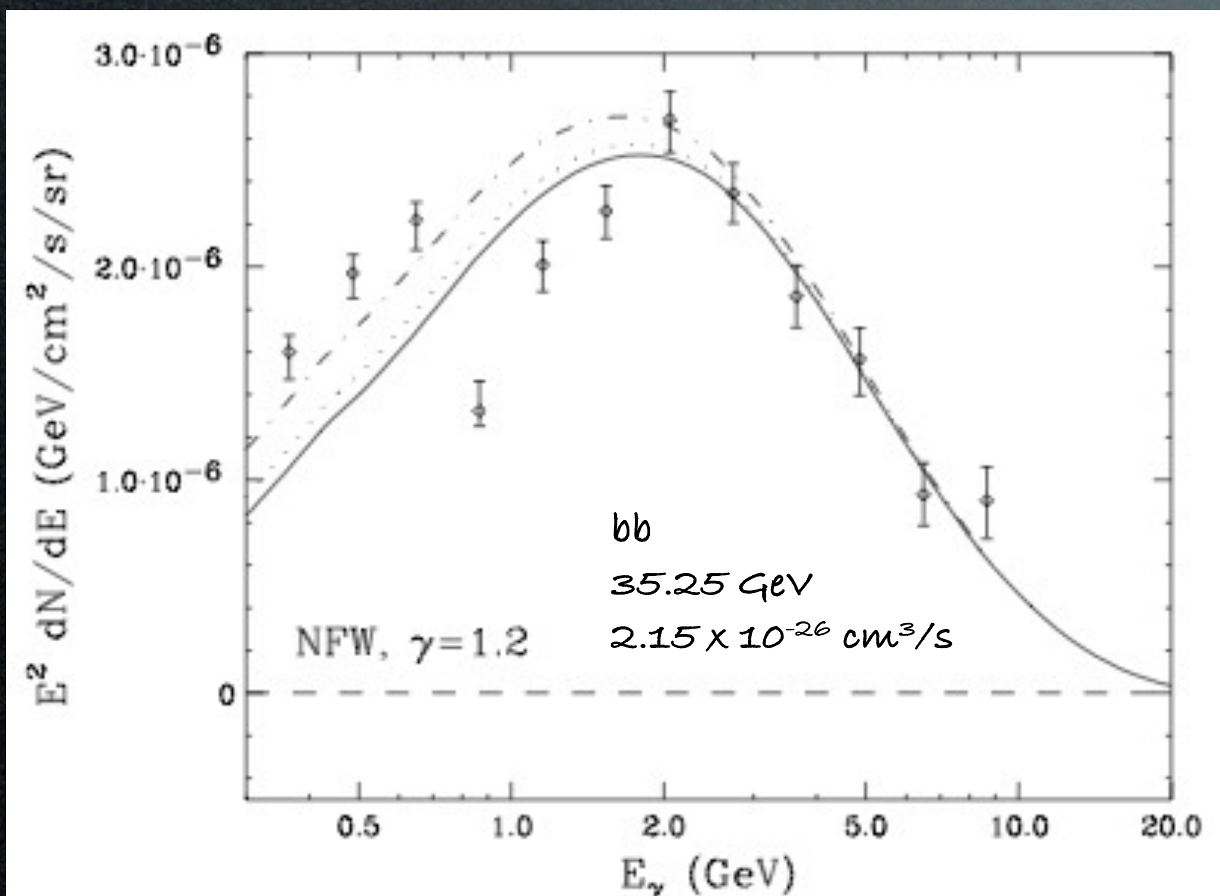
Objection:
nothing tells you that the input $e^{\pm}$ spectrum stays the same at high and low latitudes
(the ISRF too, but one can better model that)

Response:
even if you try, the input $e^{\pm}$ spectrum has to be weird
(a δ fnct at 16 GeV?!?)

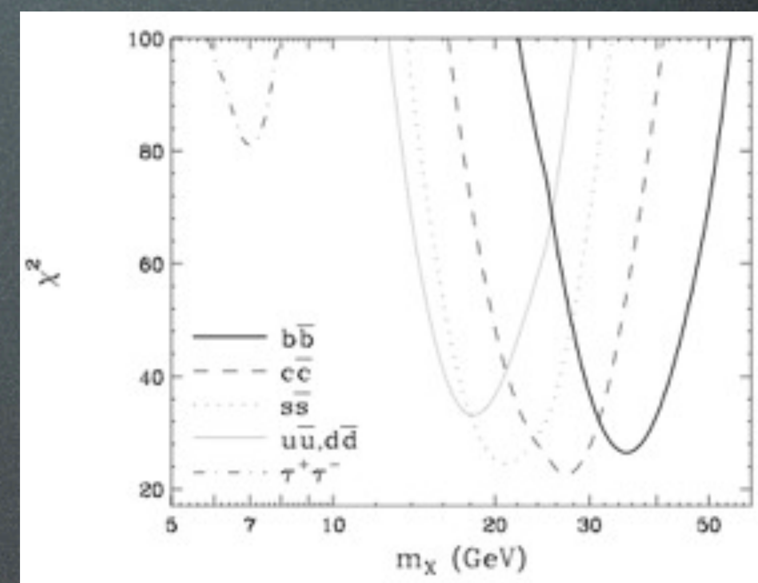
Hooper, Slatyer 1302.6589
Essentially confirmed by: Huang, Urbano, Xue 1307.6862

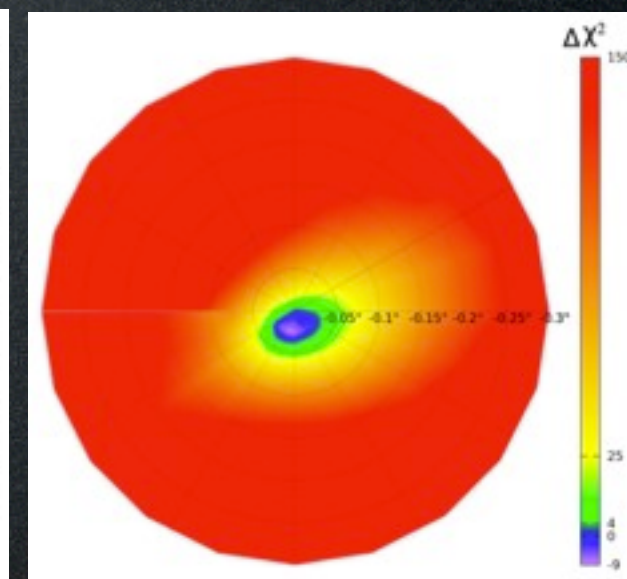
GeV gamma excess?

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



Using events with accurate directional reconstruction





Best fit:
~35 GeV, quarks, ~thermal σv

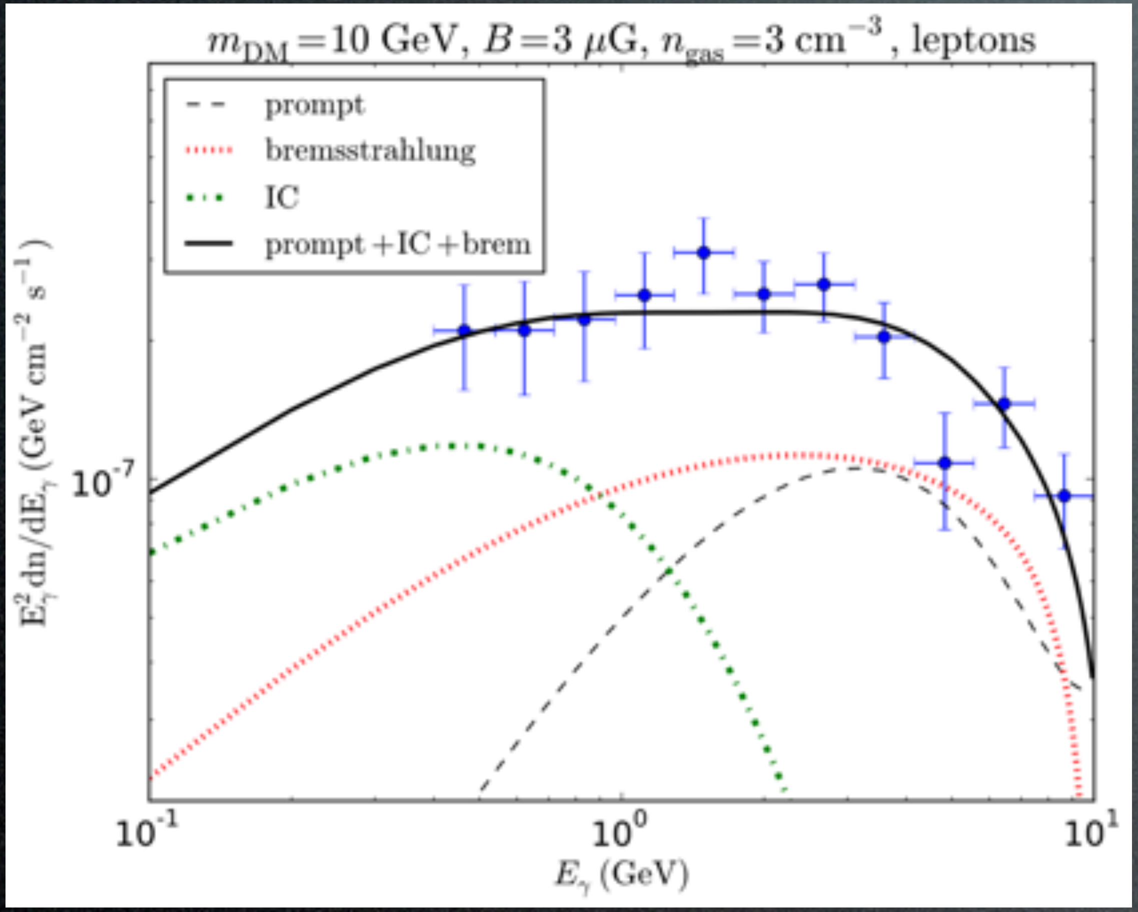
A compelling case for annihilating DM

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

As found in previous studies [8, 9], the inclusion of the dark matter template dramatically improves the quality of the fit to the *Fermi* data. For the best-fit spectrum and halo profile, we find that the inclusion of the dark matter template improves the formal fit by $\Delta\chi^2 \simeq 1672$, corresponding to a statistical preference greater than 40σ.

GeV gamma excess?

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



Lacroix, Bœhm, Silk 1403.1987

Including secondary emission changes the conclusions

But: propagation is approximate

Best fit:

~10 GeV, leptons, ~thermal σv

Fermi-LAT excess

Lacroix, Bœhm, Silk 1403.1987

GeV gamma excess?

An excess with respect to **what**?
Extracting 'data points' is not trivial:

i. choose a ROI (shape, extension, masking...) and harvest Fermi-LAT data
ii. impose sensible cuts (Pass N, angles, CTBCORE...)
iii. in each energy bin, fit to a sum of spatial templates:
1. Fermi Coll. diffuse
2. isotropic
3. unresolved point sources
4. features (bubbles...)
5. AOB (molecular gas...)

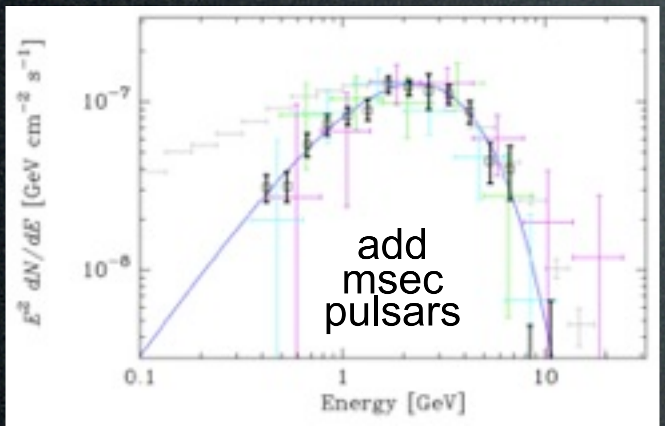
iv. repeat the same, adding a template for:
6. Dark Matter, having chosen a certain profile!

v. if iii. → iv. improves χ^2, there's evidence for DM
vi. the component fitted by 6 is the residual excess to be explained

Note:
Adding 6 will in general change the recipe of 1...5 (you'll need a bit more of x here, a bit less of y there...).
Changing the profile of 6 too.

Astrophysical interpretation

Millisec pulsars

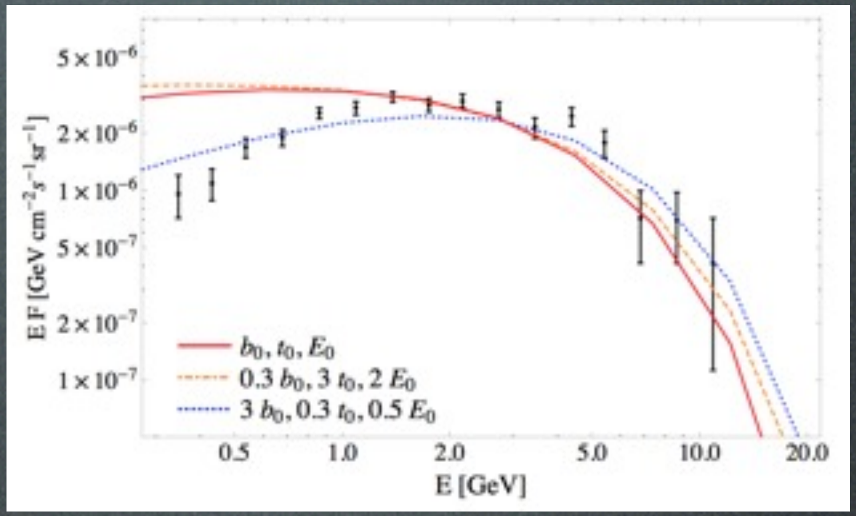


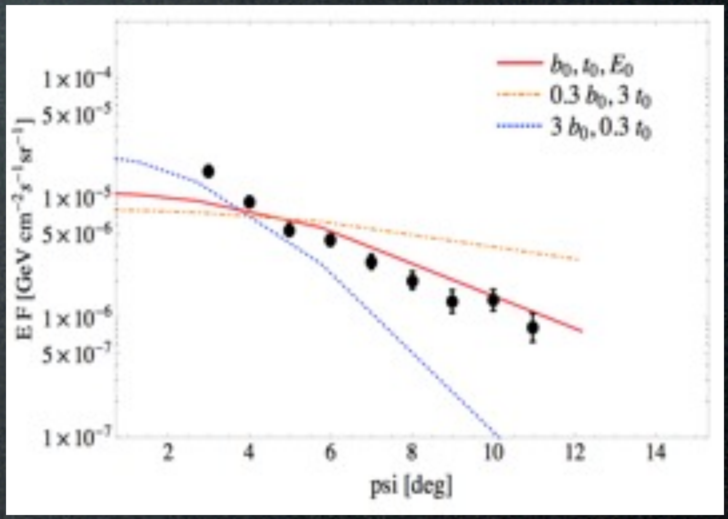
Abazajian 1011.4275
Hooper et al. 1305.0830
Yuan, Zhang 1404.2318

A transient phenomenon:

the GC spit 10^{52} ergs in $e^{\pm}$ 1 mln yrs ago and they do ICS on ambient light, ‘fits’ both spectrum and morphology

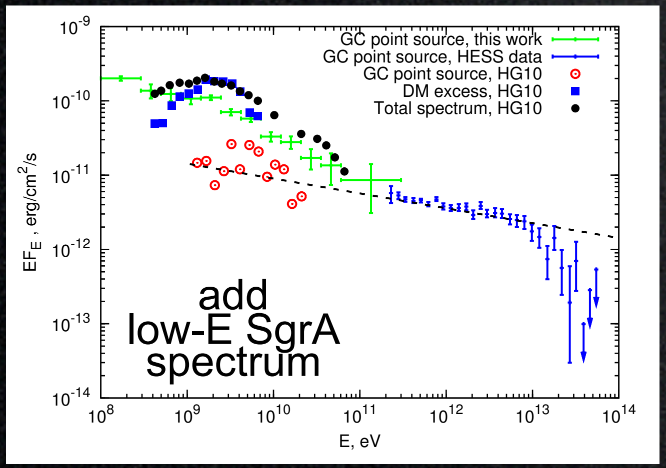
Petrović, Serpico, Zaharijas 1405.7928





but: can one really get everything right?

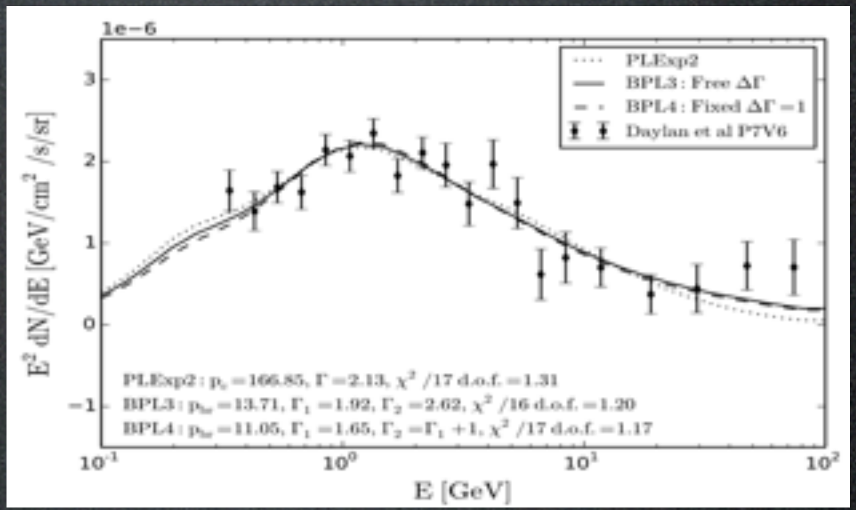
Non-trivial SgrA spectrum

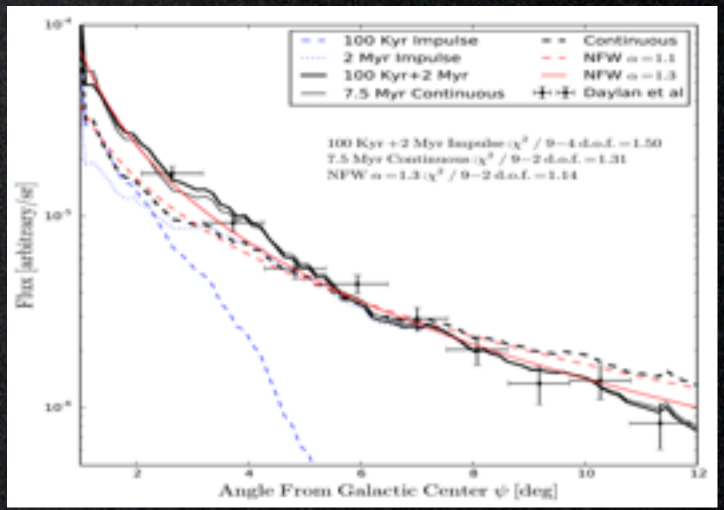


Boyarsky et al., 1012.5839

a SN explosion spits protons 5000 yrs ago and they do spallations + bremsstrahlung as well as $e^{\pm}$ which do ICS... fits spectrum & morphology

Carlson, Profumo 1405.7685



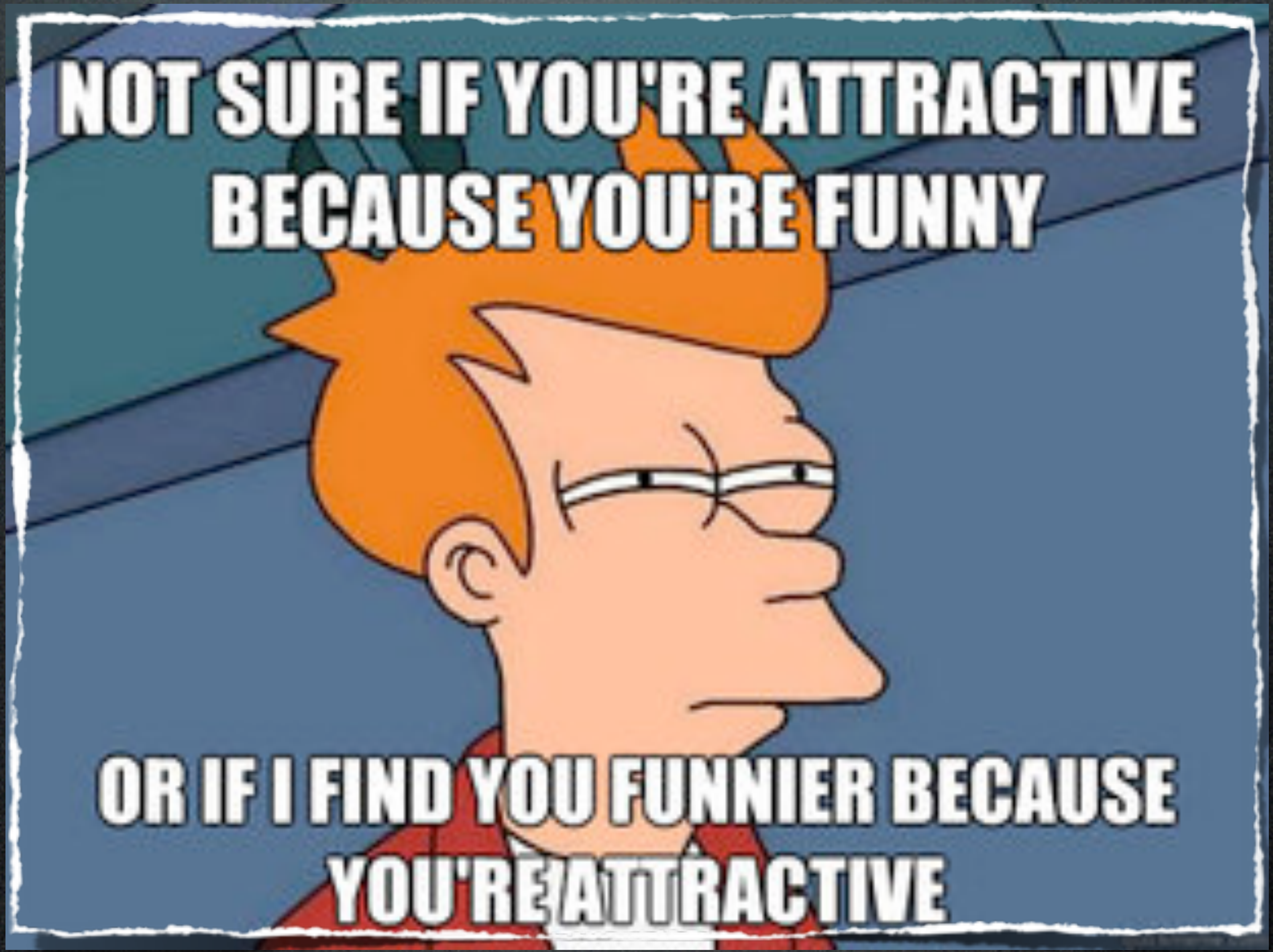


but: why correlation with gas density not seen?

Theorist’s reaction

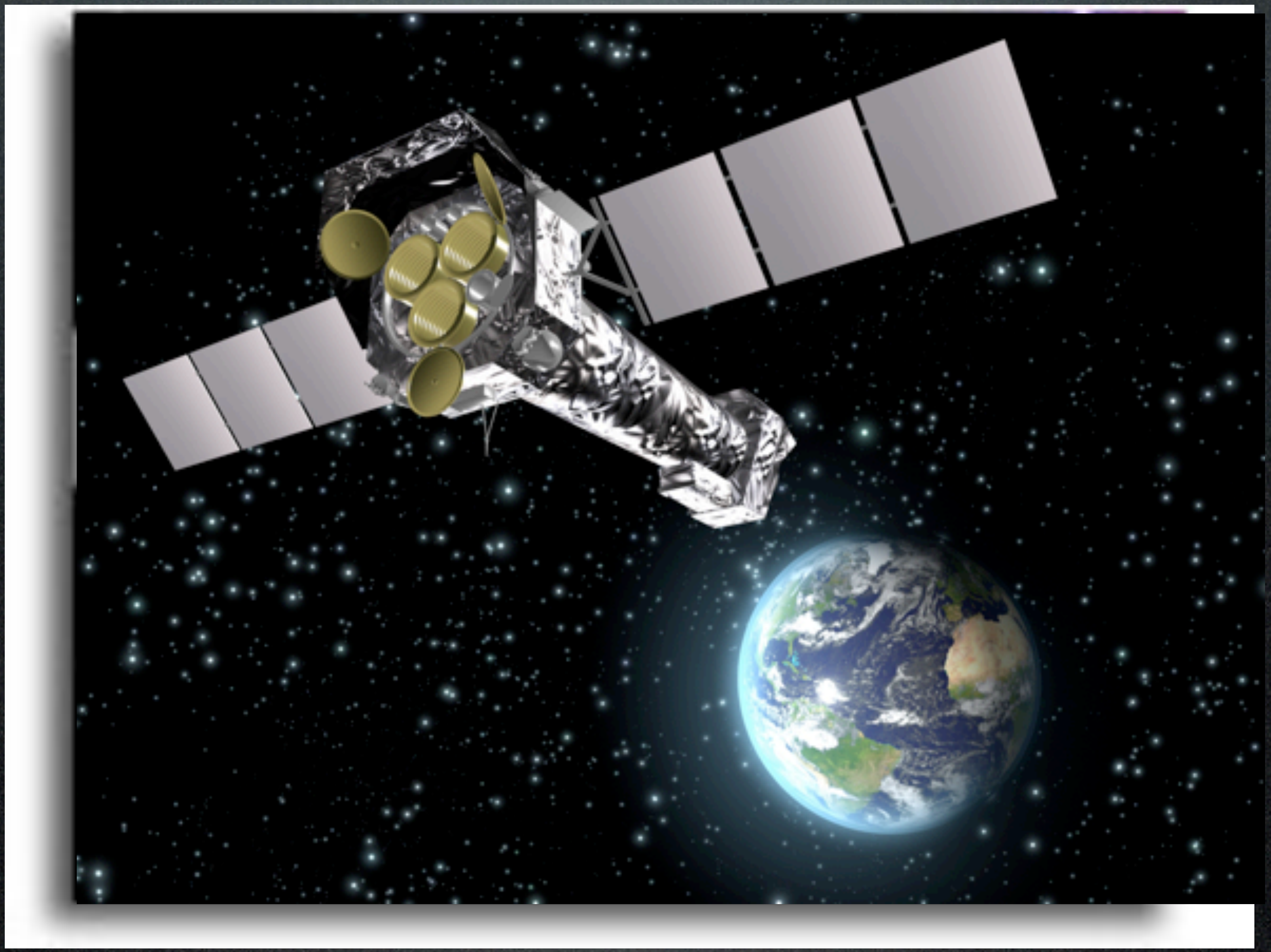
3. the ‘Hooperon’

Theorist's reaction



3. the 'Hooperon'

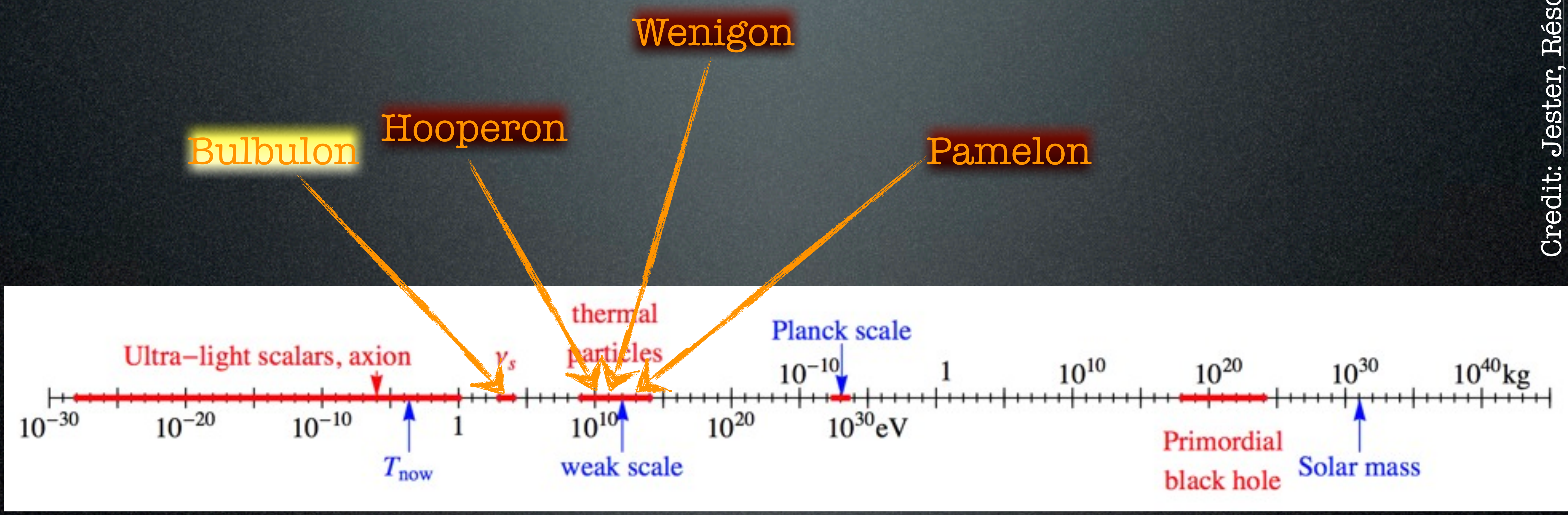
X-rays



4. the '3.5 KeV line'

DM Candidates

A matter of perspective: plausible mass ranges



Credit: Jester, Résonaances

'only' 90 orders of magnitude!

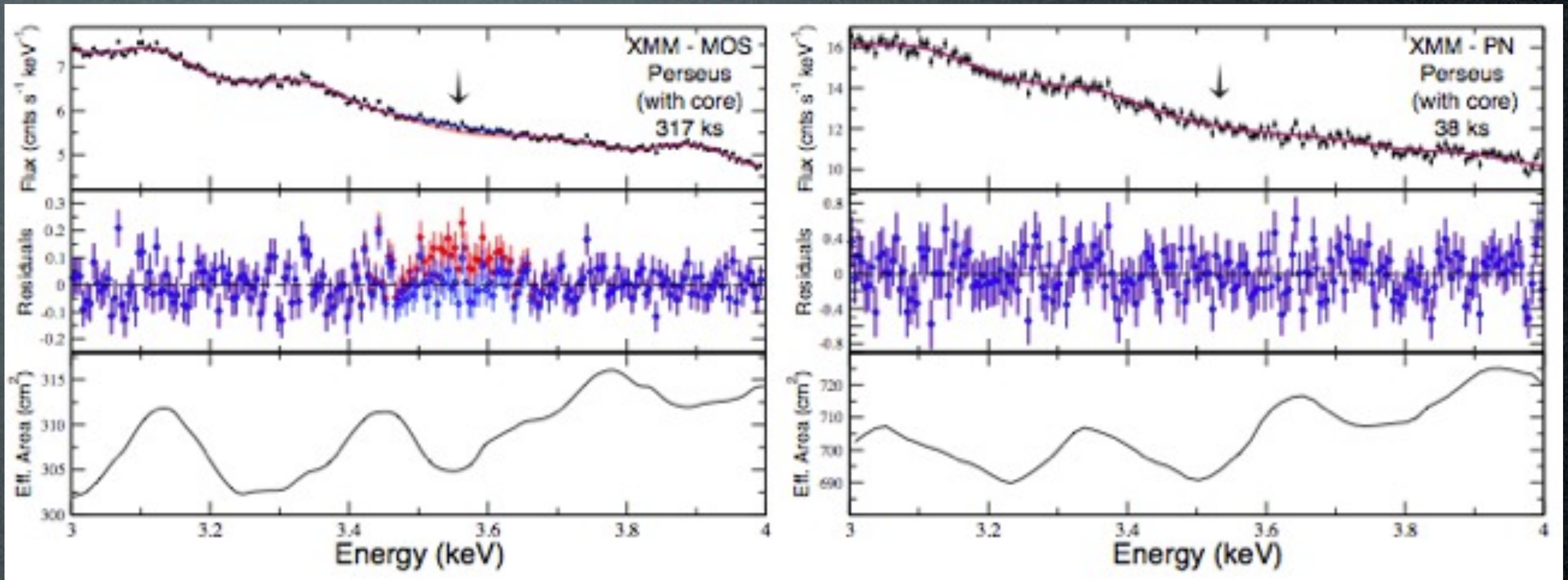
X-ray line

Bulbul et al., 1402.2301

3.55 - 3.57 ± 0.03 KeV

73 clusters

z = 0.01 - 0.35

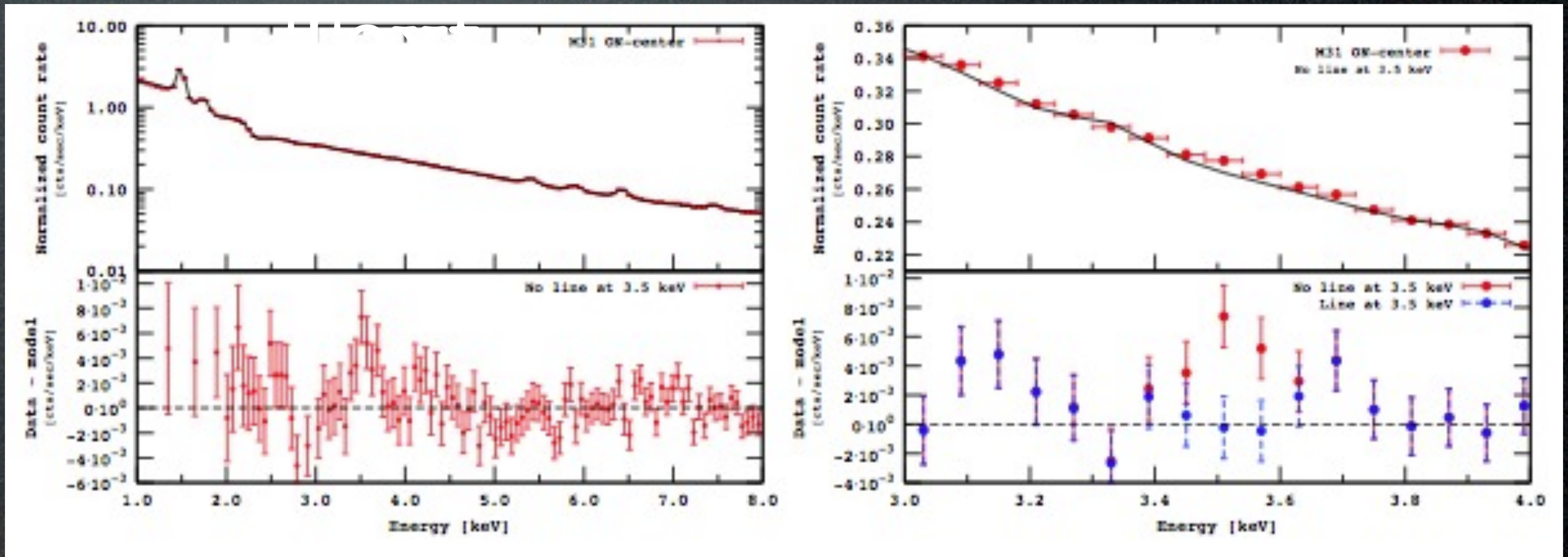


Boyarsky, Ruchayskiy, 1402.4119

3.5 KeV

Andromeda galaxy
+ Perseus cluster

z = 0 and 0.0179



Theorist's reaction

4. the '3.5 KeV' line

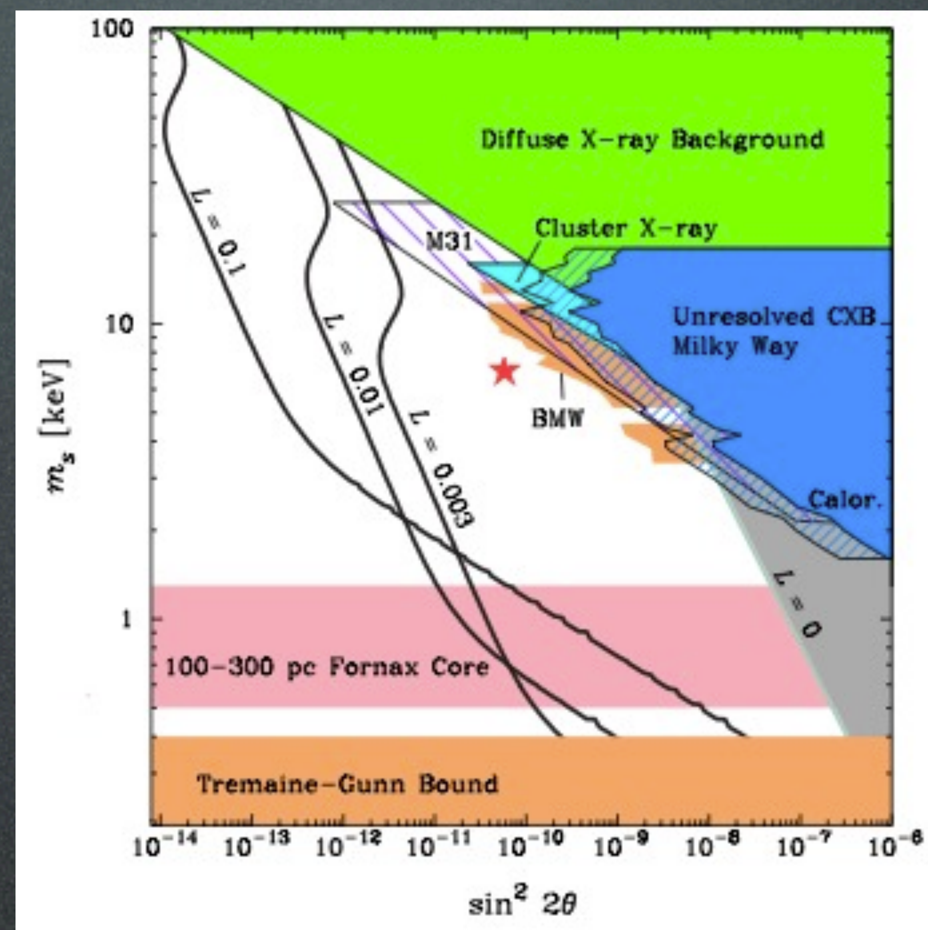
X-ray line

Sterile neutrino decay

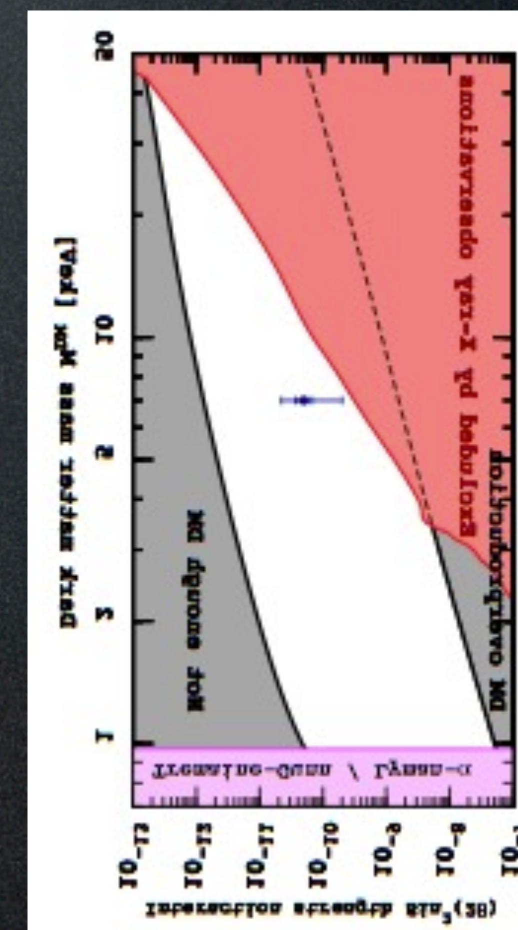
$m_\nu = 7.1\ \mathrm{KeV}$

$\tau \simeq 10^{29}\ \mathrm{sec}$

$\sin^2 2\theta \sim \mathrm{few}\ 10^{-11}$



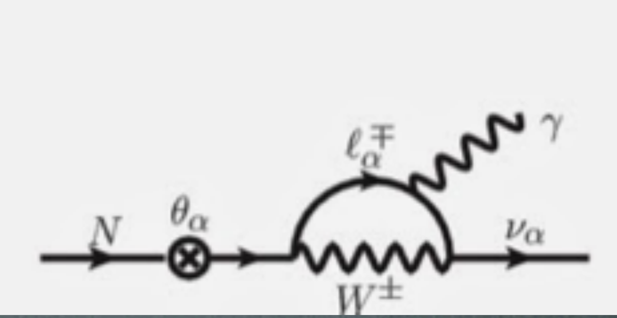
Bulbul et al., 1402.2301



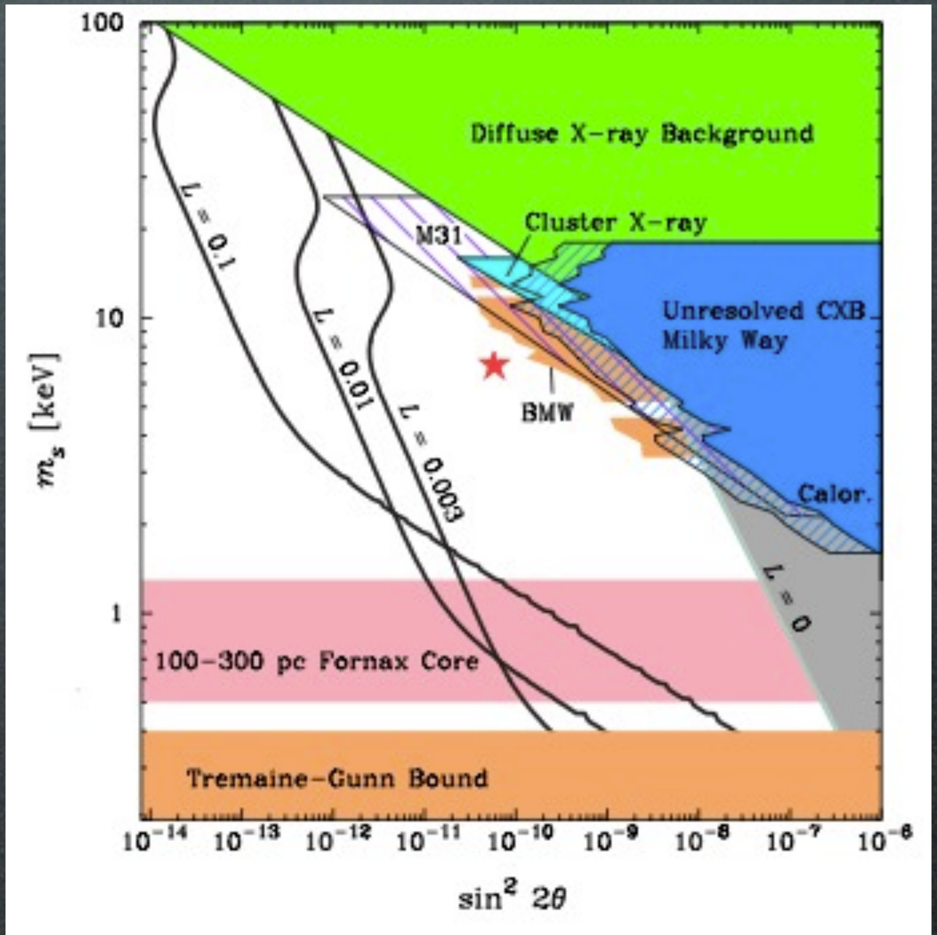
Boyarsky, Ruchayskiy et al., 1402.4119

X-ray line

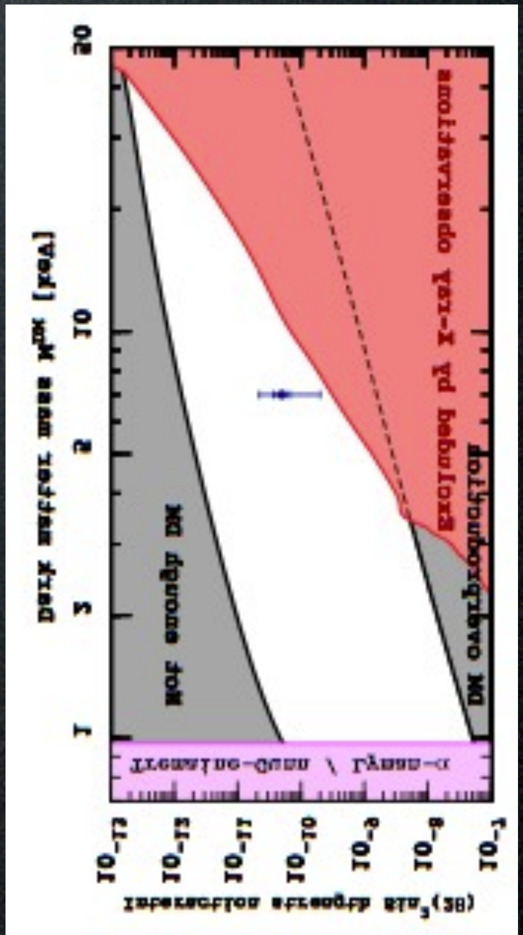
Sterile neutrino decay



$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$



Bulbul et al., 1402.2301



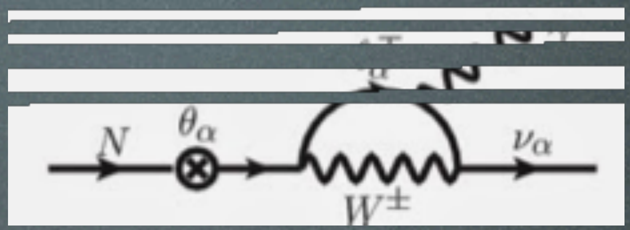
Boyarsky, Ruchayskiy et al., 1402.4119

Possible challenges:

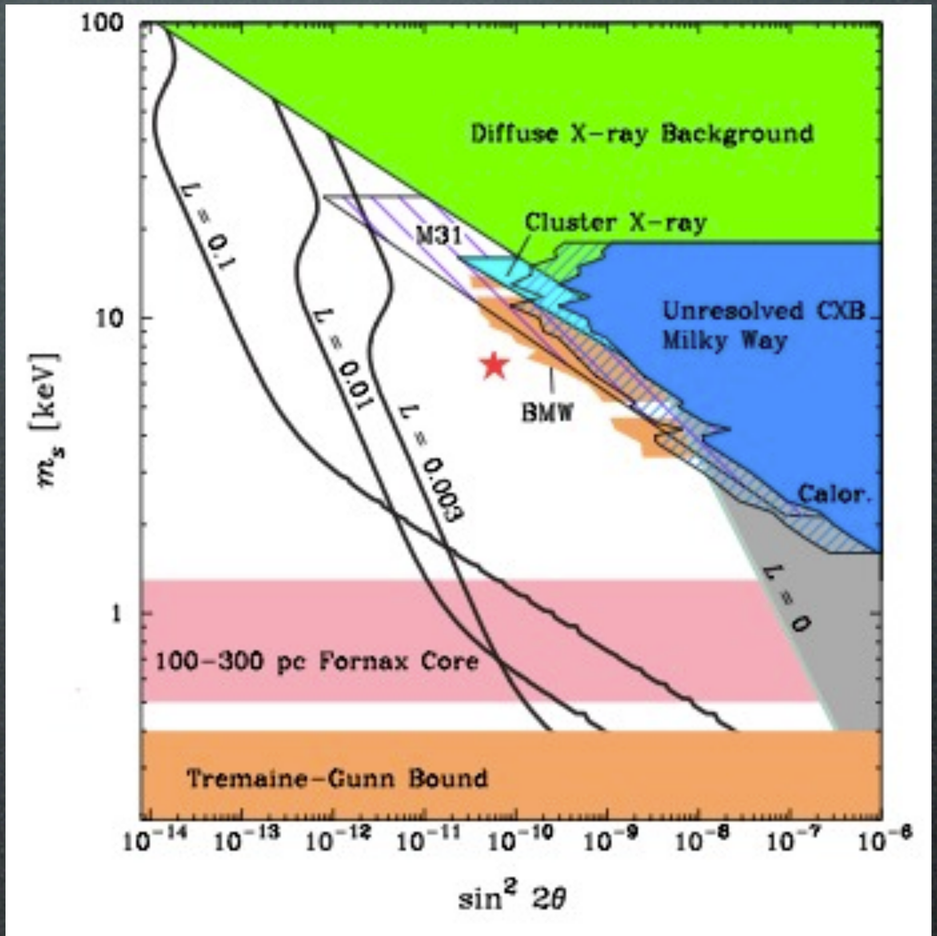
- EU production?
- Perseus flux too large?

X-ray line

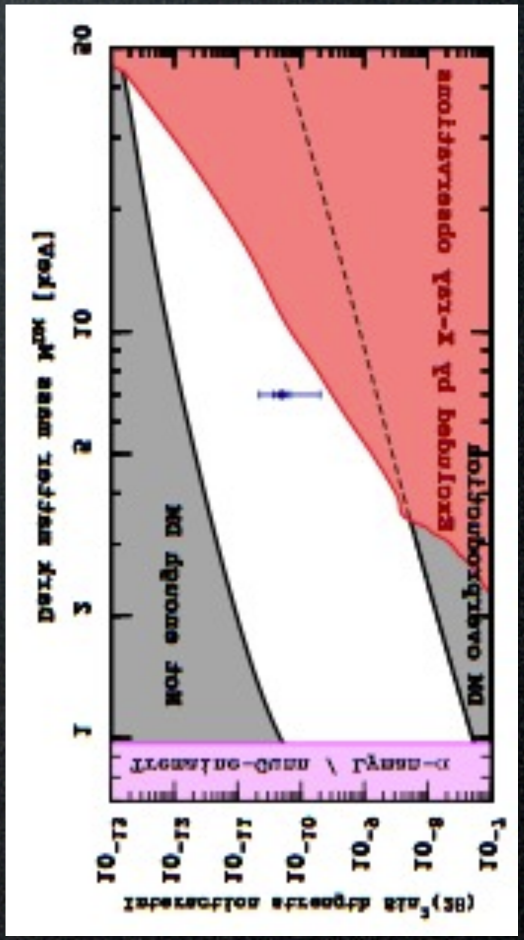
Sterile neutrino decay



$m_\nu = 7.1$ KeV
$\tau \simeq 10^{29}$ sec
$\sin^2 2\theta \sim$ few 10^{-11}



Bulbul et al., 1402.2301



Boyarsky, Ruchayskiy et al., 1402.4119

Possible challenges:

- EU production?
- Perseus flux too large?

Other possibilities:

axion (1402.7335), axino (1403.1536, 1403.1782, 1403.6621), modulus (1403.1733), ALP (1403.2370), gravitino (1403.6503), excited DM (1404.4795), the good the bad and the unlikely (1403.1570), sgoldstino (1404.1339), magnetic DM (1404.5446), majoron (1404.1400), annihilating effective DM (1404.1927), 7KeV scalar DM (1404.2220)...

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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 for Dark Matter Indirect Direction'

PPPC 4 DM ID

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays in the Galaxy and beyond.

Cirelli, Corcella, Hektor, Hütsi, Kadastik, Panci, Raidal, Sala, Strumia

1012.4515 [hep-ph]

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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?

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		Decay	
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.	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		Decay	
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).	Positrons:	The file ElectronHaloFunctEarthDec.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).	Antiprotons:	Table of fit coefficients for the propagation function R(T).
Antideuterons:	Table of fit coefficients for the propagation function R(T).	Antideuterons:	Table of fit coefficients for the propagation function R(T).

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

Annihilation		Decay	
Positrons:	*Mathematica* function: the file ElectronFluxAnn.m provides the	Positrons:	*Mathematica* function: the file ElectronFluxDec.m provides the

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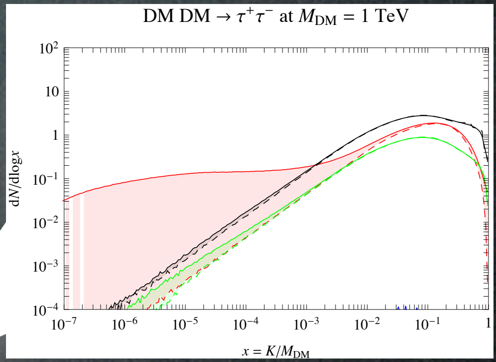
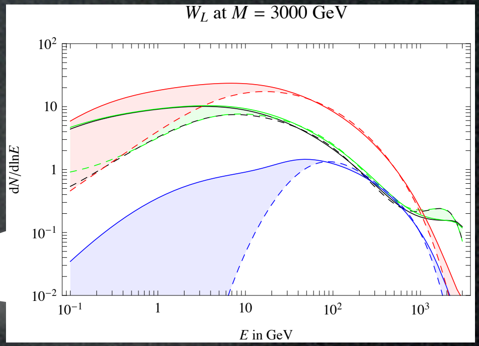
You want to compute all **signatures** of your DM model in positrons, electrons, neutrinos, gamma rays...
but you don't want to mess around with astrophysics?

Main added value features:

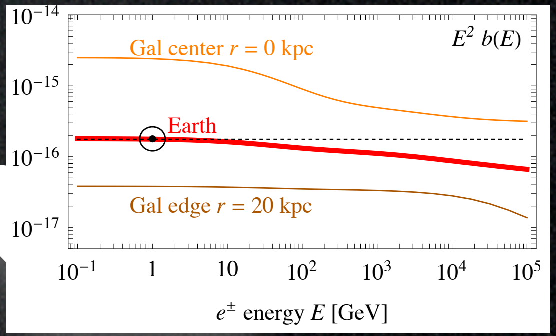


- ✔ compare different MCs



- ✔ include EW corrections

Ciafaloni, Riotto et al., 1009.0224



- ✔ improved $e^{\pm}$ propagation
- ✔ improved ICS γ-ray computation

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Conclusions & Outlook

Hints

Constraints

Hopes

Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
HESS

γ FERMI

X XMM-Newton

Constraints

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Constraints

γ FERMI, HESS, VERITAS etc

$\bar{p}$ PAMELA

ν SK, ICECUBE

Cosmology

Hopes

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$e^{\pm}$ PAMELA
FERMI
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γ FERMI

X XMM-Newton

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γ FERMI, HESS, VERITAS etc

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Cosmology

Hopes

$\bar{d}$ GAPS, AMS-02

γ ν

$\bar{p}$

AMS-02

- ‘enhancements’

- new theory directions

Conclusions & Outlook

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AMS-02

- ‘enhancements’

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Old wise remarks:

Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
HESS

γ FERMI

X XMM-Newton

Constraints

γ FERMI, HESS, VERITAS etc

$\bar{p}$ PAMELA

ν SK, ICECUBE

Cosmology

Hopes

$\bar{d}$ GAPS, AMS-02

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AMS-02

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Old wise remarks:

- any convincing result must be multimessenger

Conclusions & Outlook

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Cosmology

Hopes

$\bar{d}$ GAPS, AMS-02

γ ν

$\bar{p}$

AMS-02

- ‘enhancements’

- new theory directions

Old wise remarks:

- any convincing result must be multimessenger
- beware of uncertainties, beware of astrophysics