8 May 2014
INFN Pisa

DM Indirect Detection:
some anomalies and many constraints

Marco Cirelli
(CNRS IPhT Saclay)

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Introduction

DM exists

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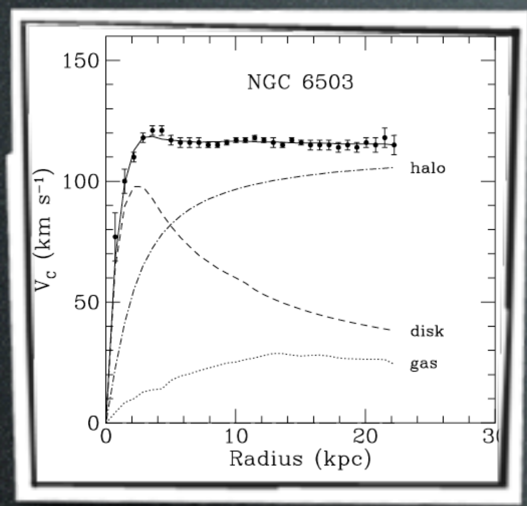
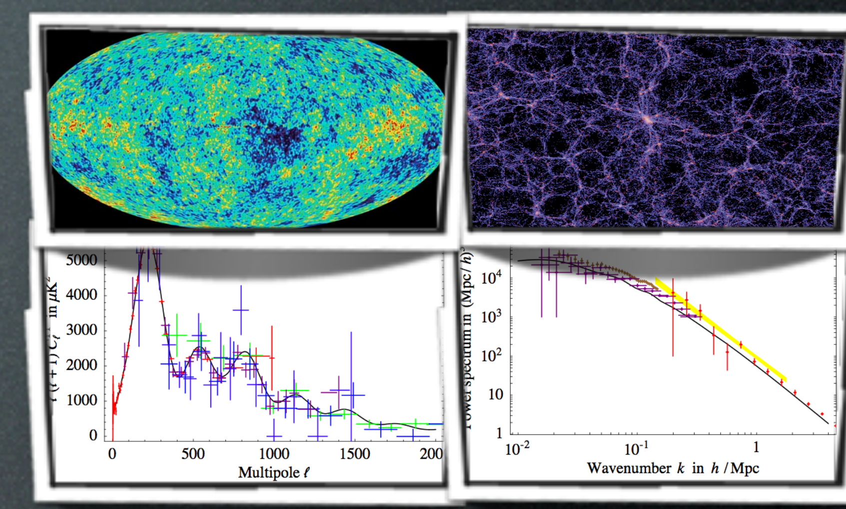


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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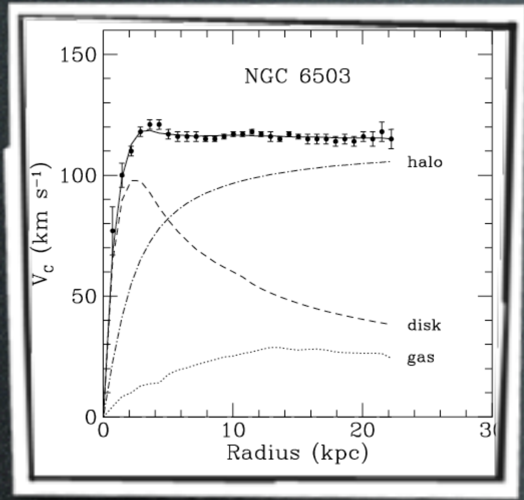

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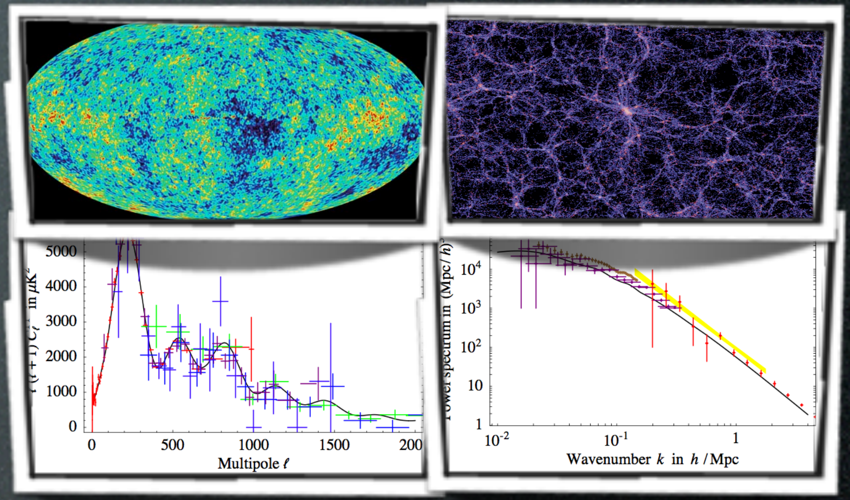

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DM is a neutral, very long lived, feebly interacting particle.

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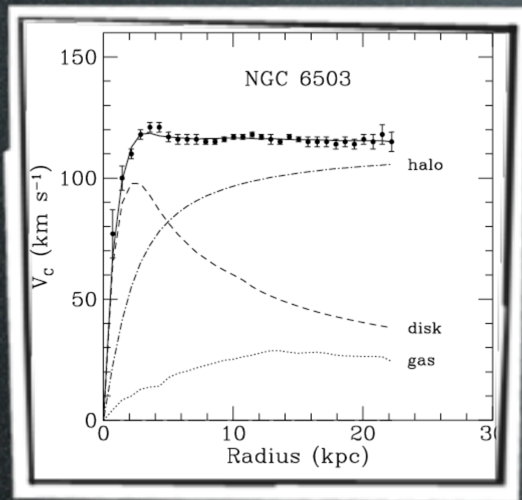

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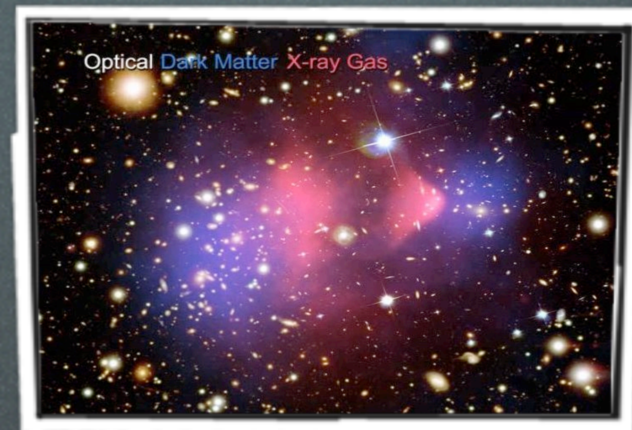

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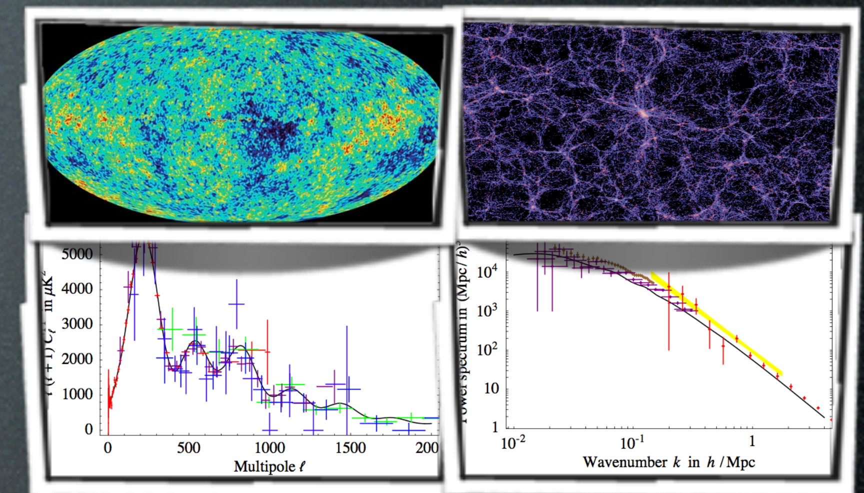
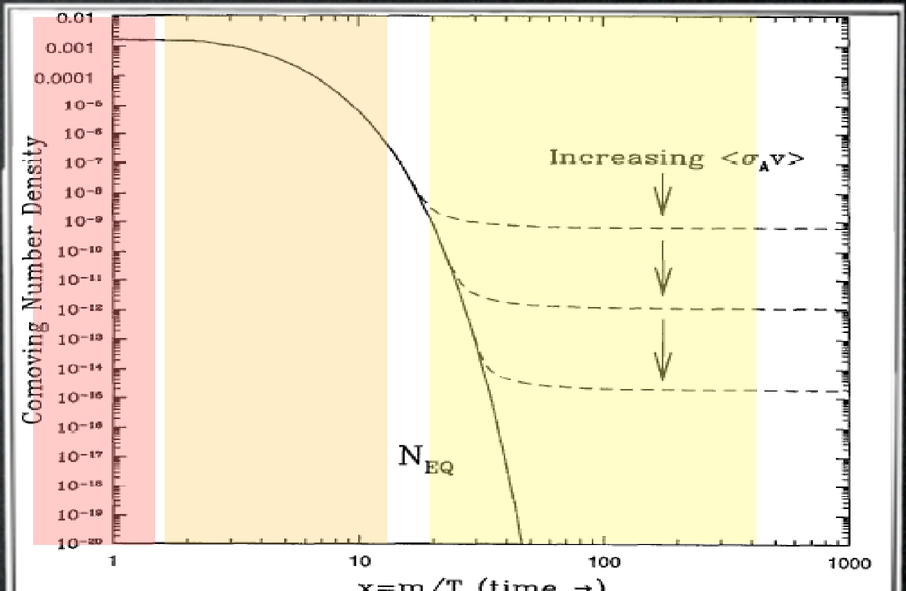


'precision cosmology' (CMB, LSS)

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

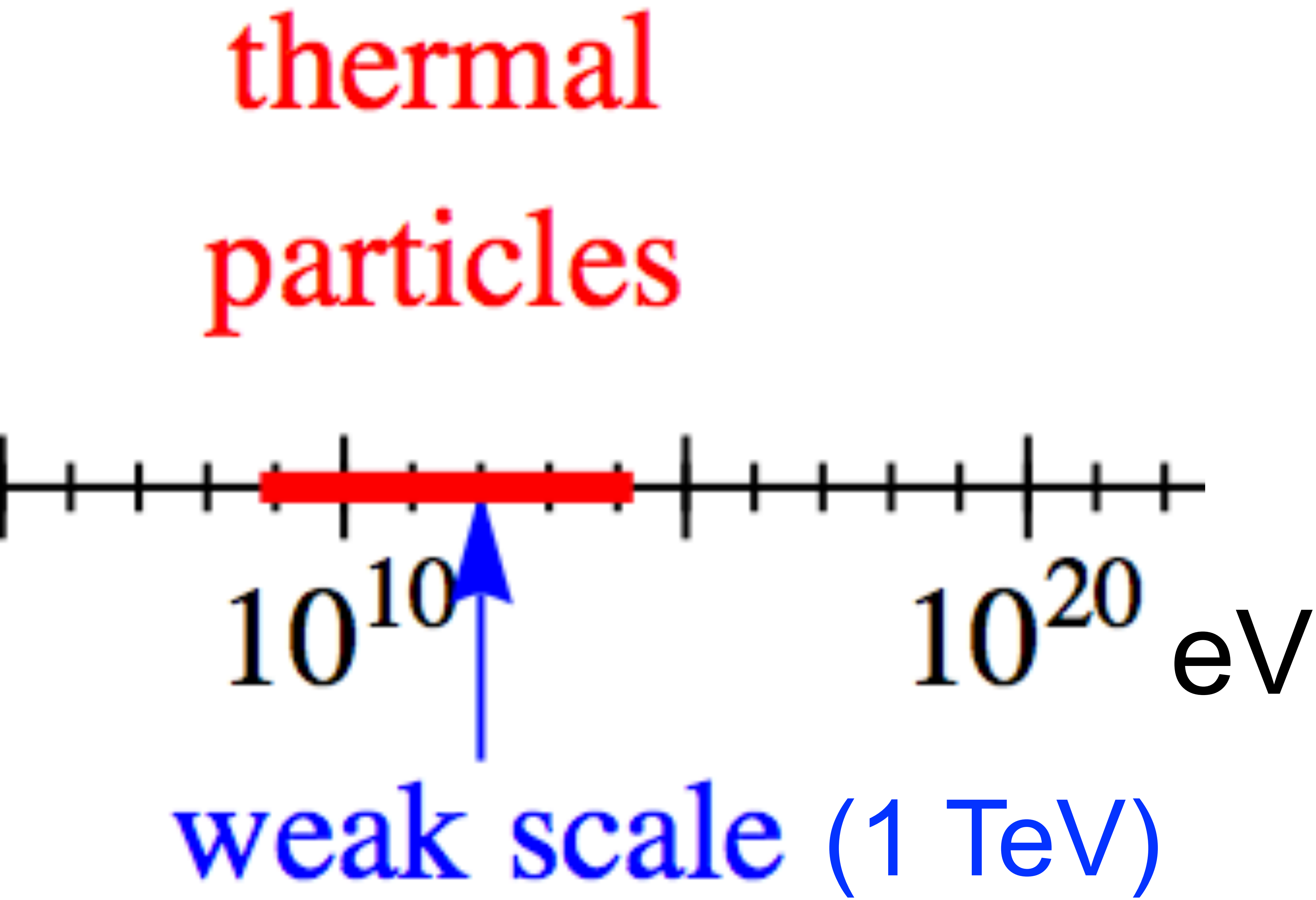
Some of us believe in the WIMP miracle.

- *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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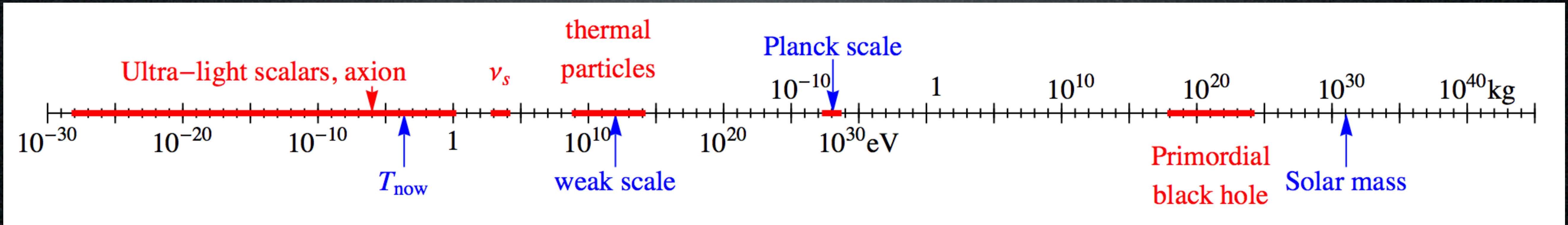

'only' 90 orders of magnitude!

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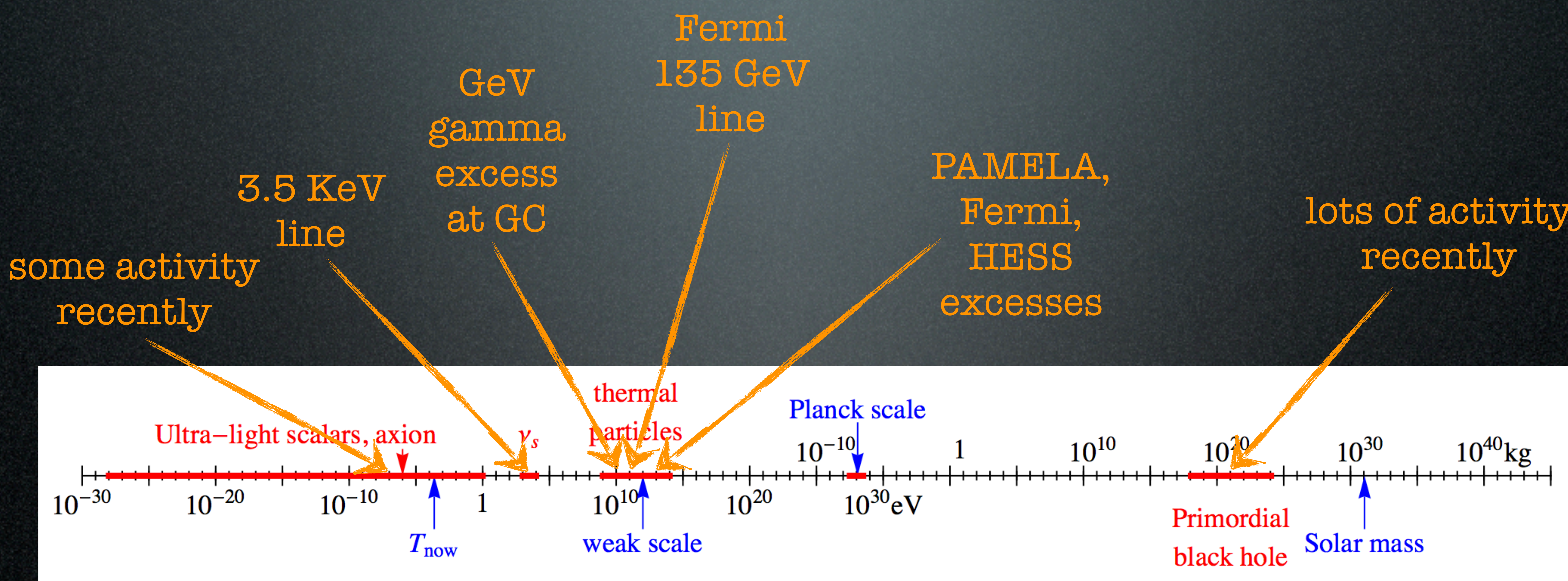

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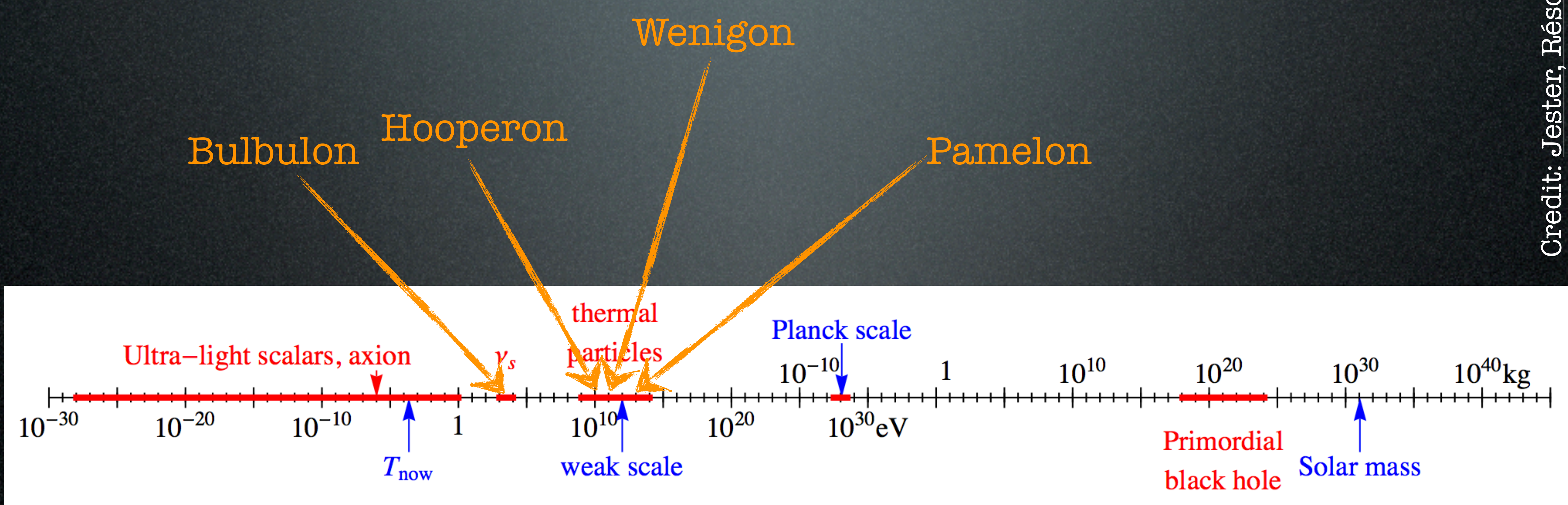

Credit: Jester, Résonaances

'only' 90 orders of magnitude!

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

DM detection

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indirect

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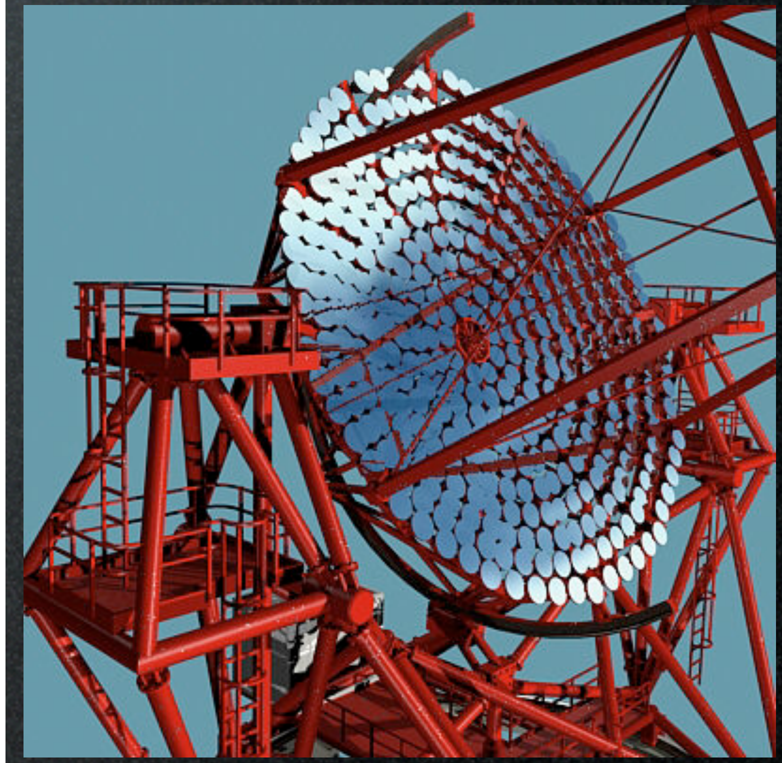
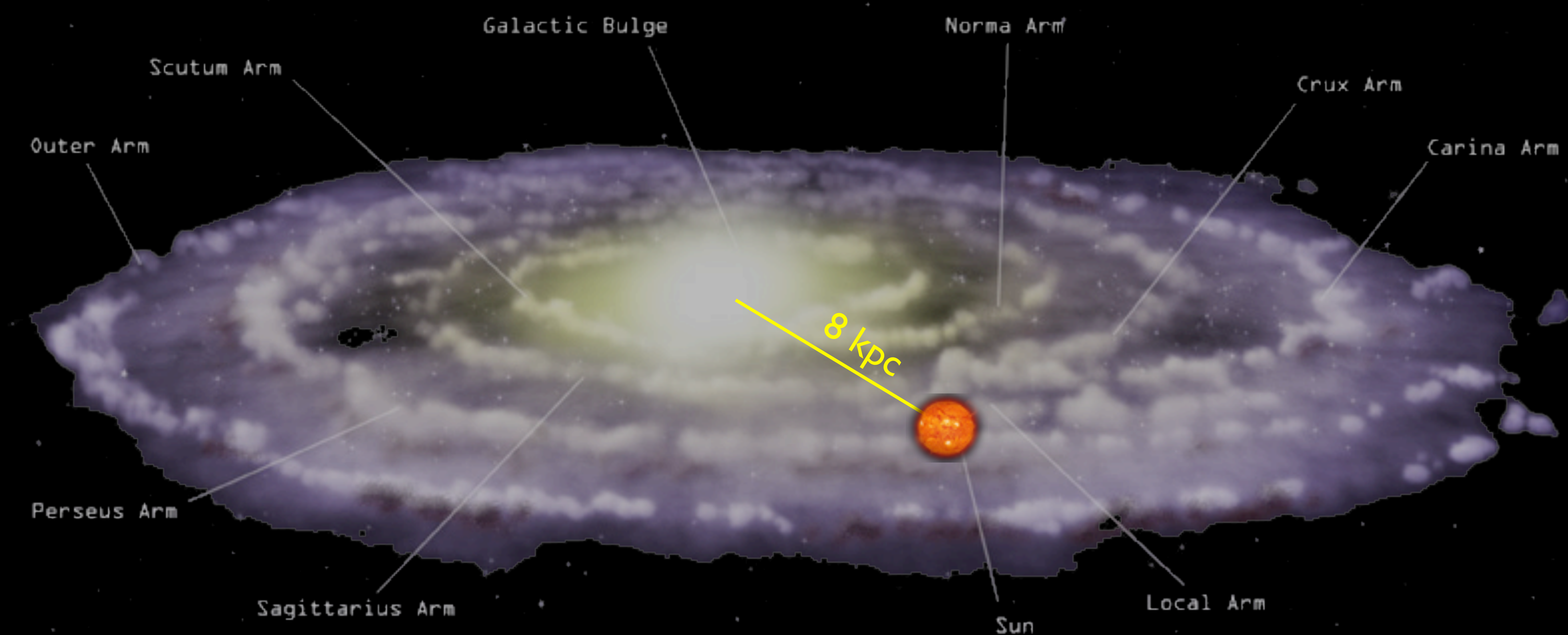
Charged CRs

1. the PAMELA/Fermi/HESS 'excesses'

Indirect Detection: basics

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



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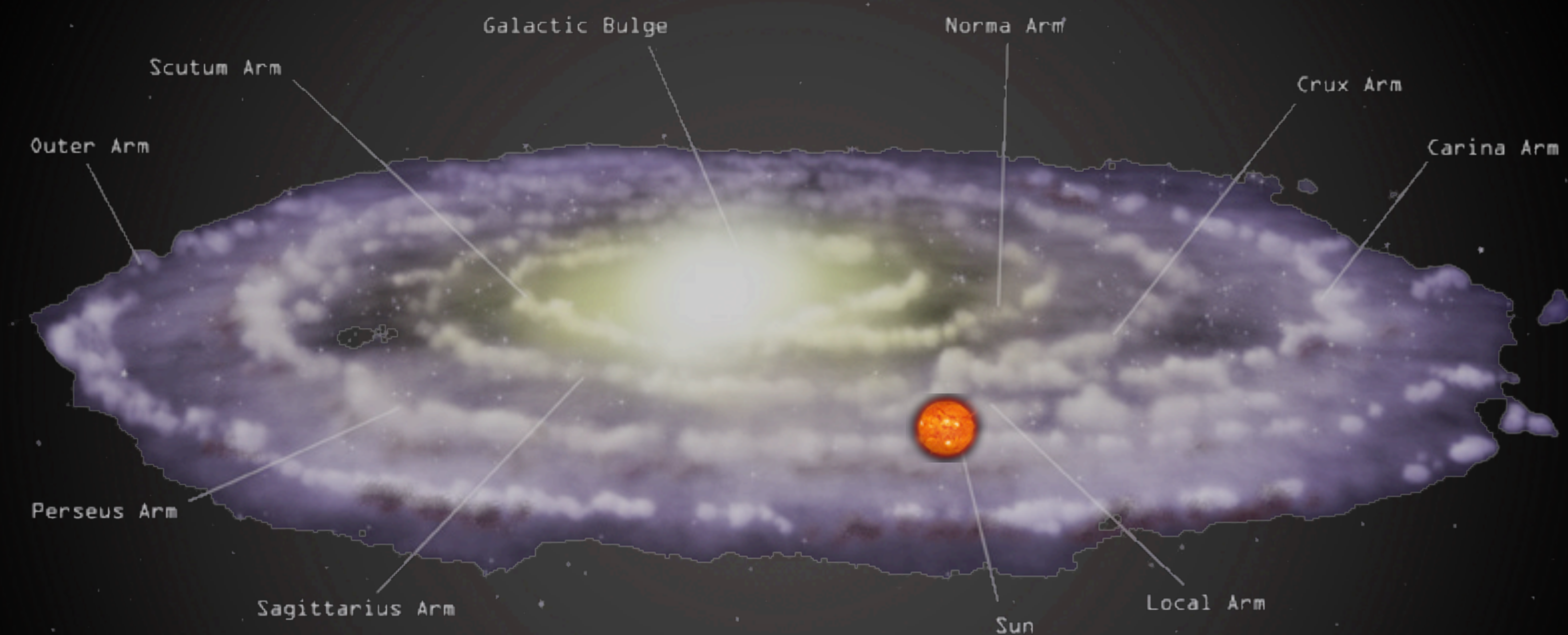

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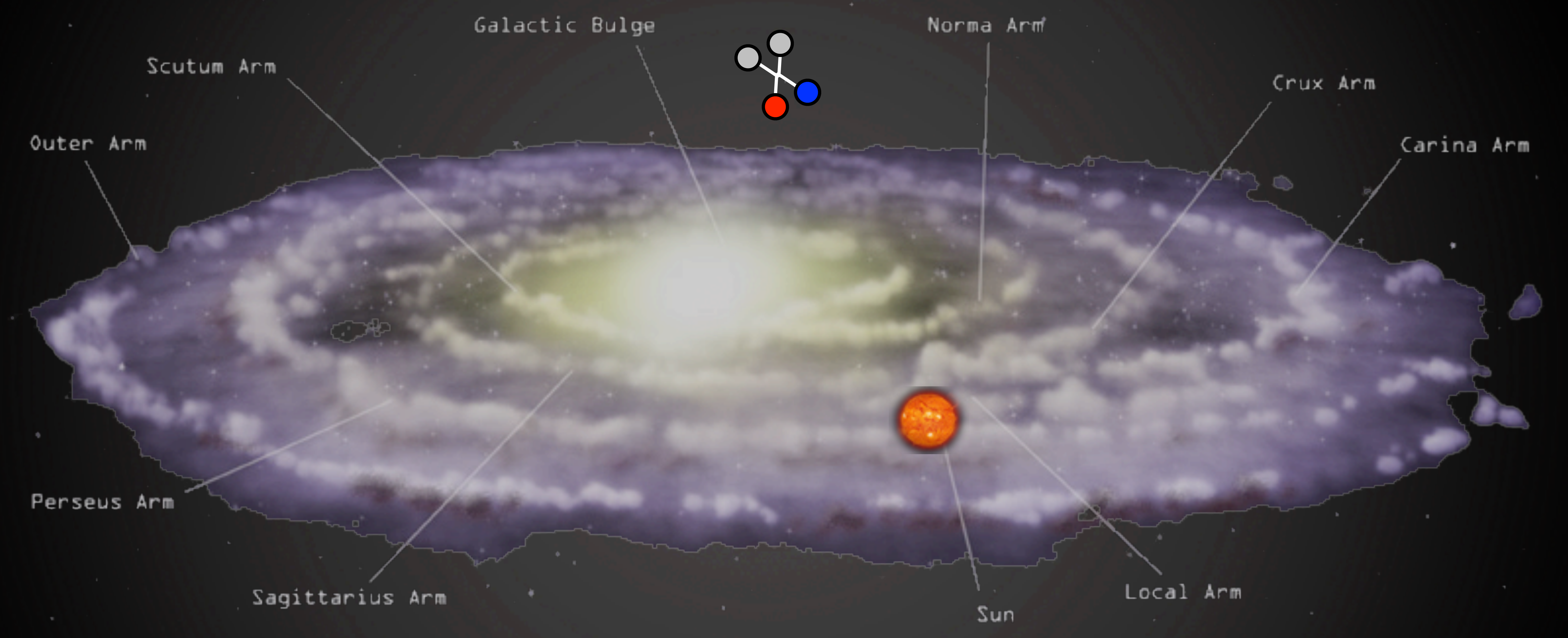

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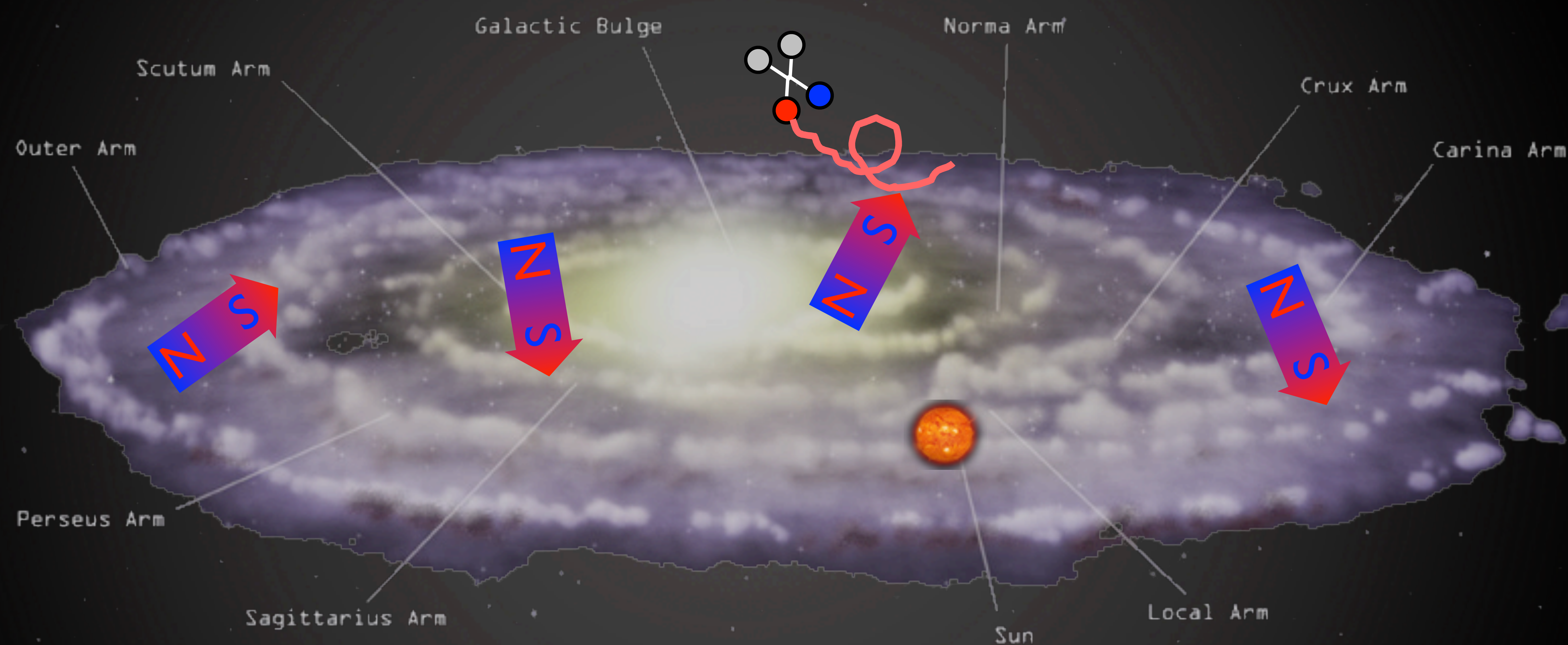

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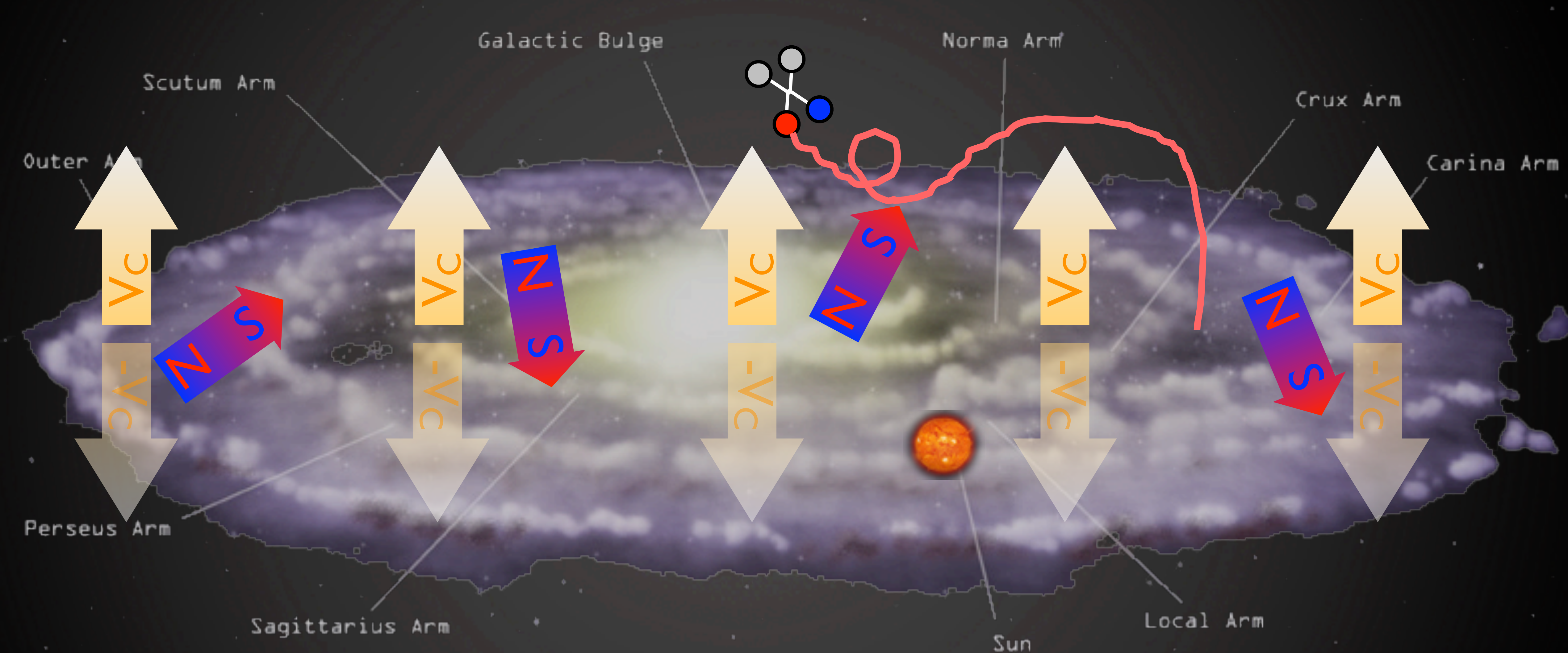

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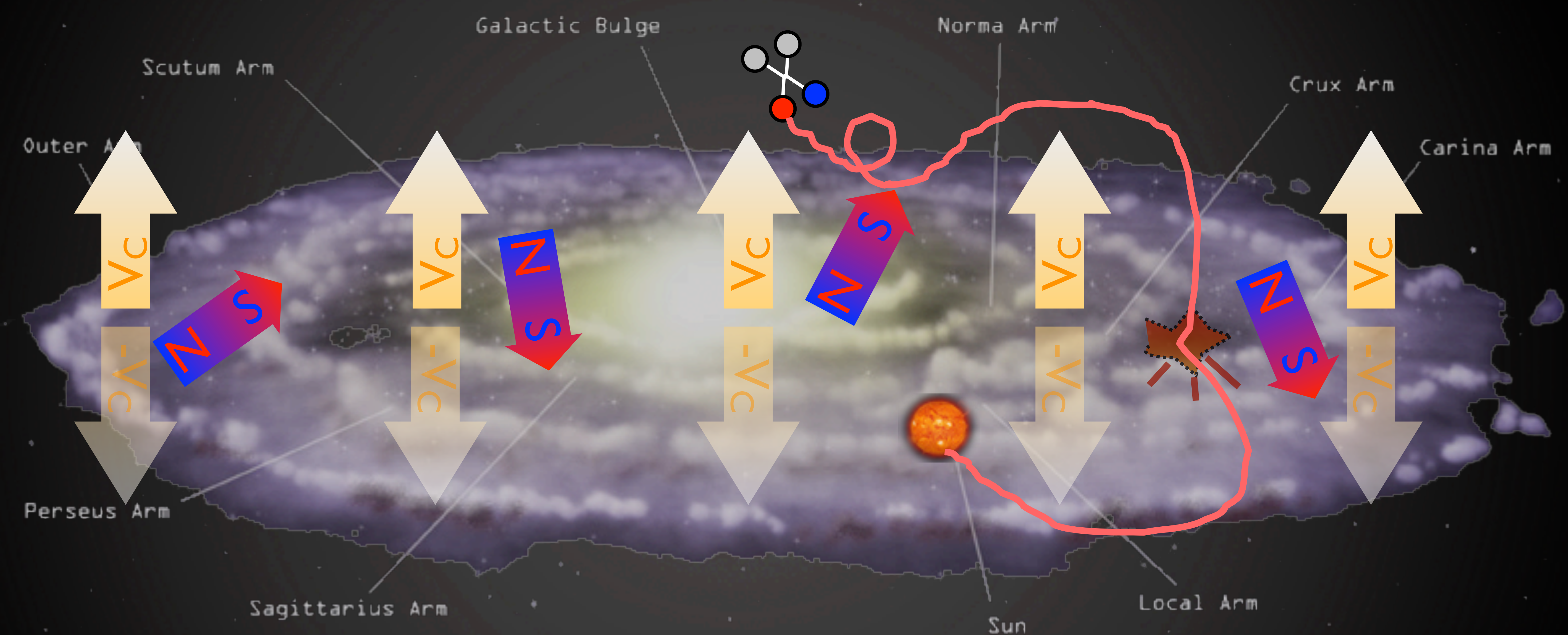

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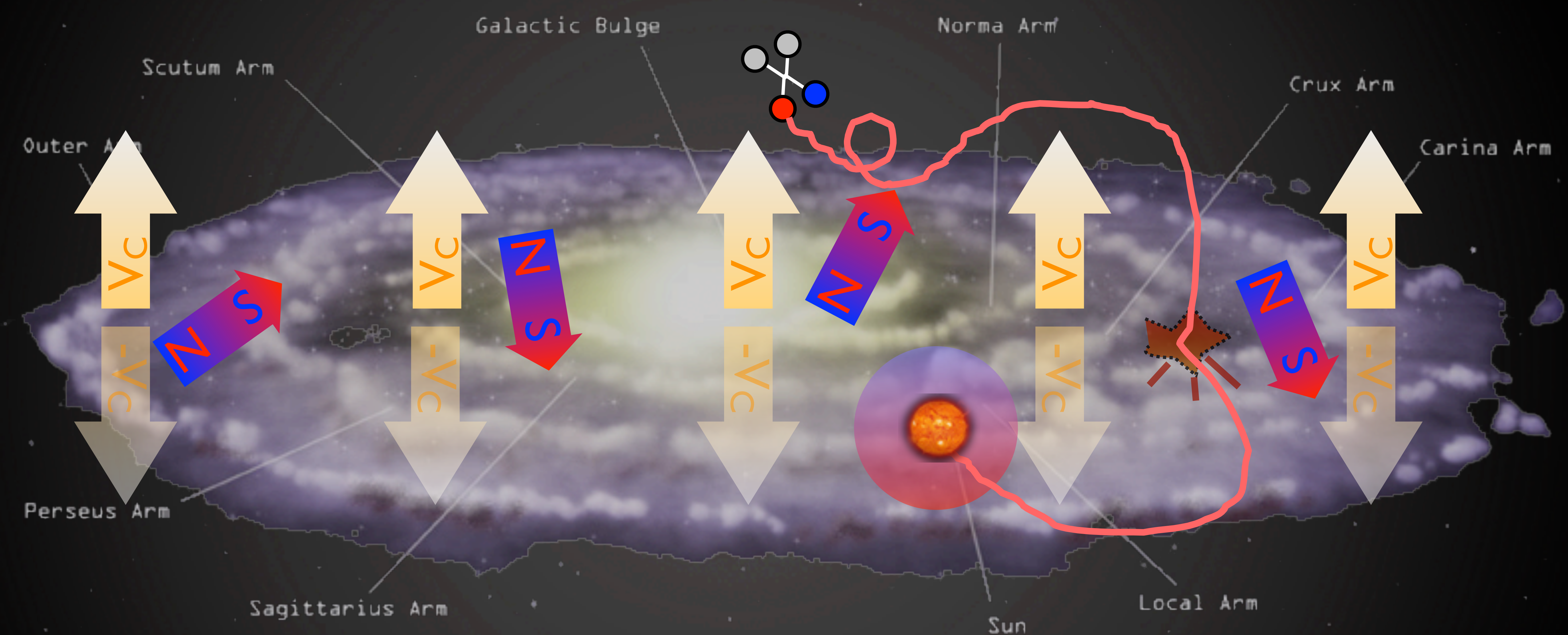

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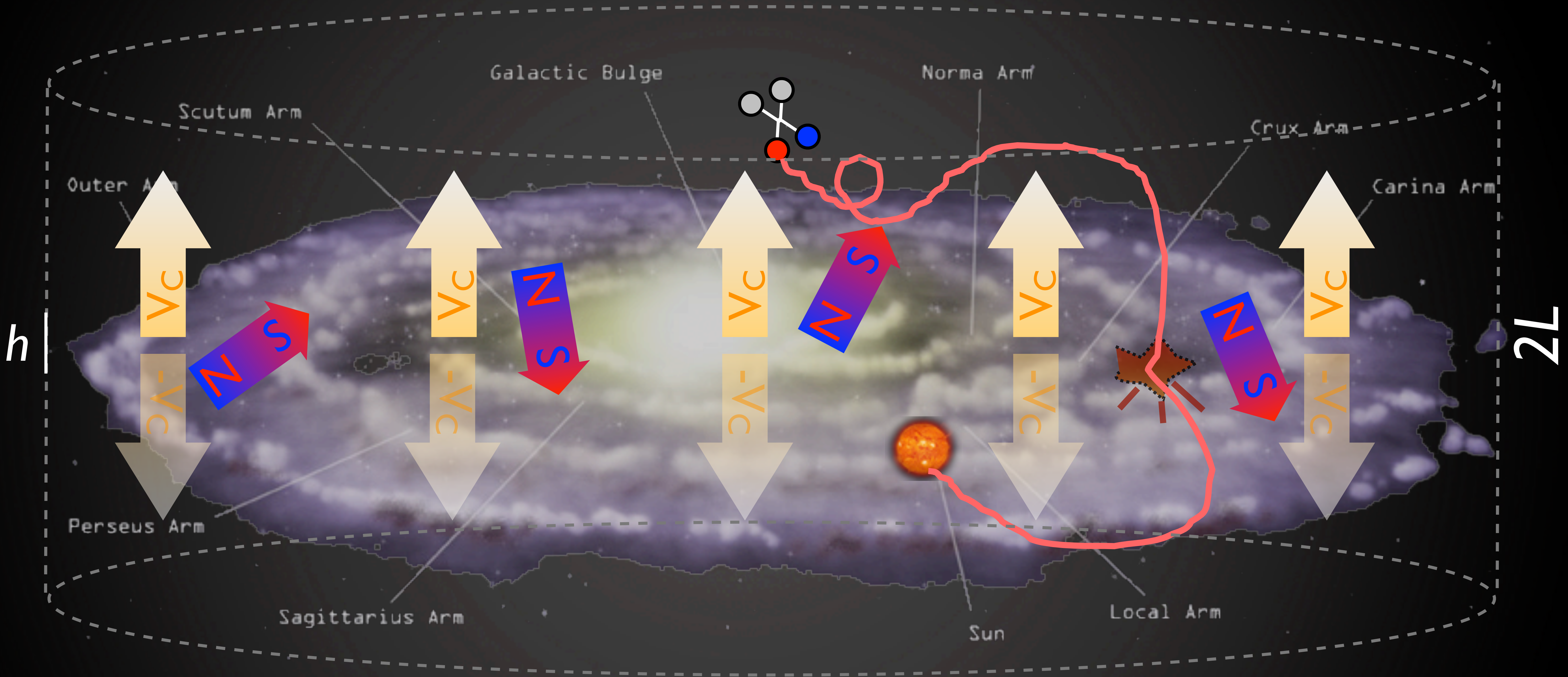


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum

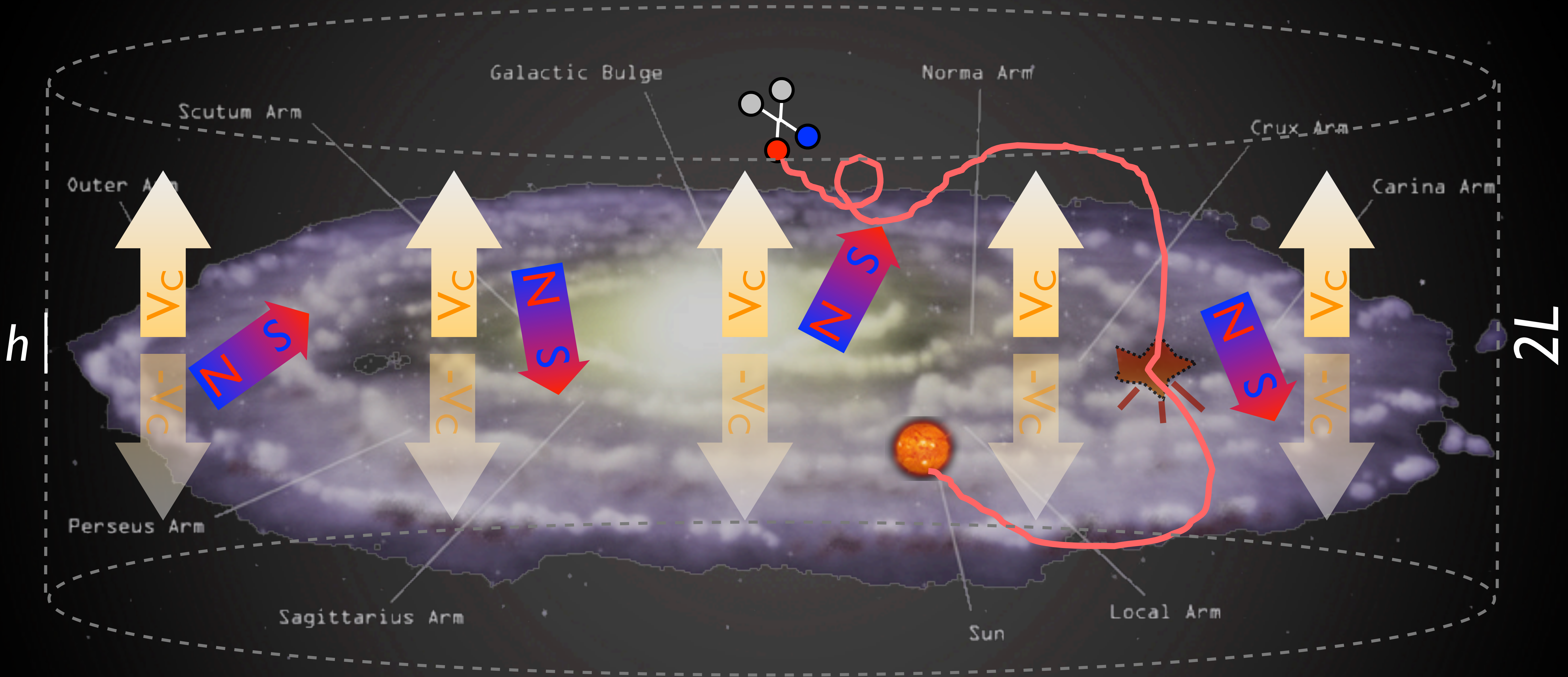
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

[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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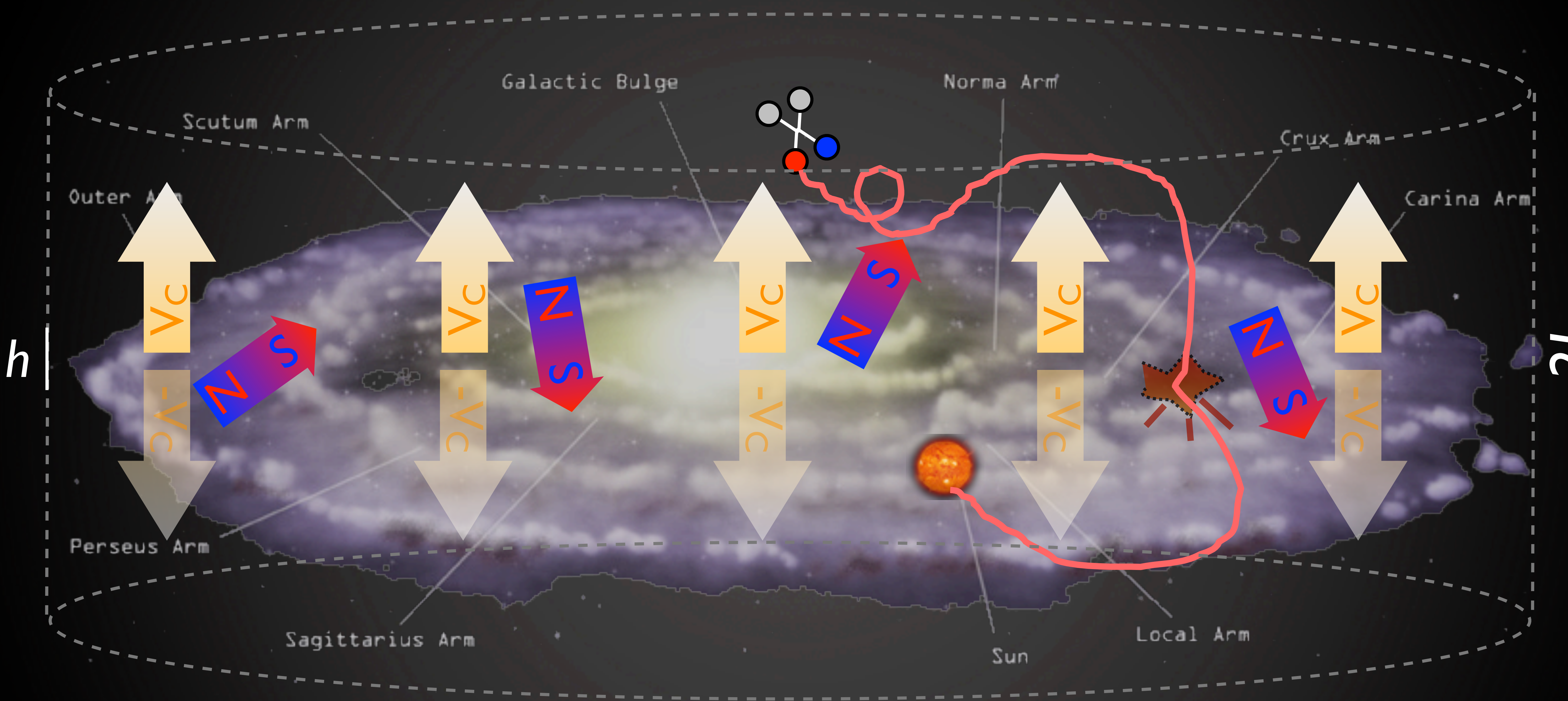

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astro& cosmo

particle

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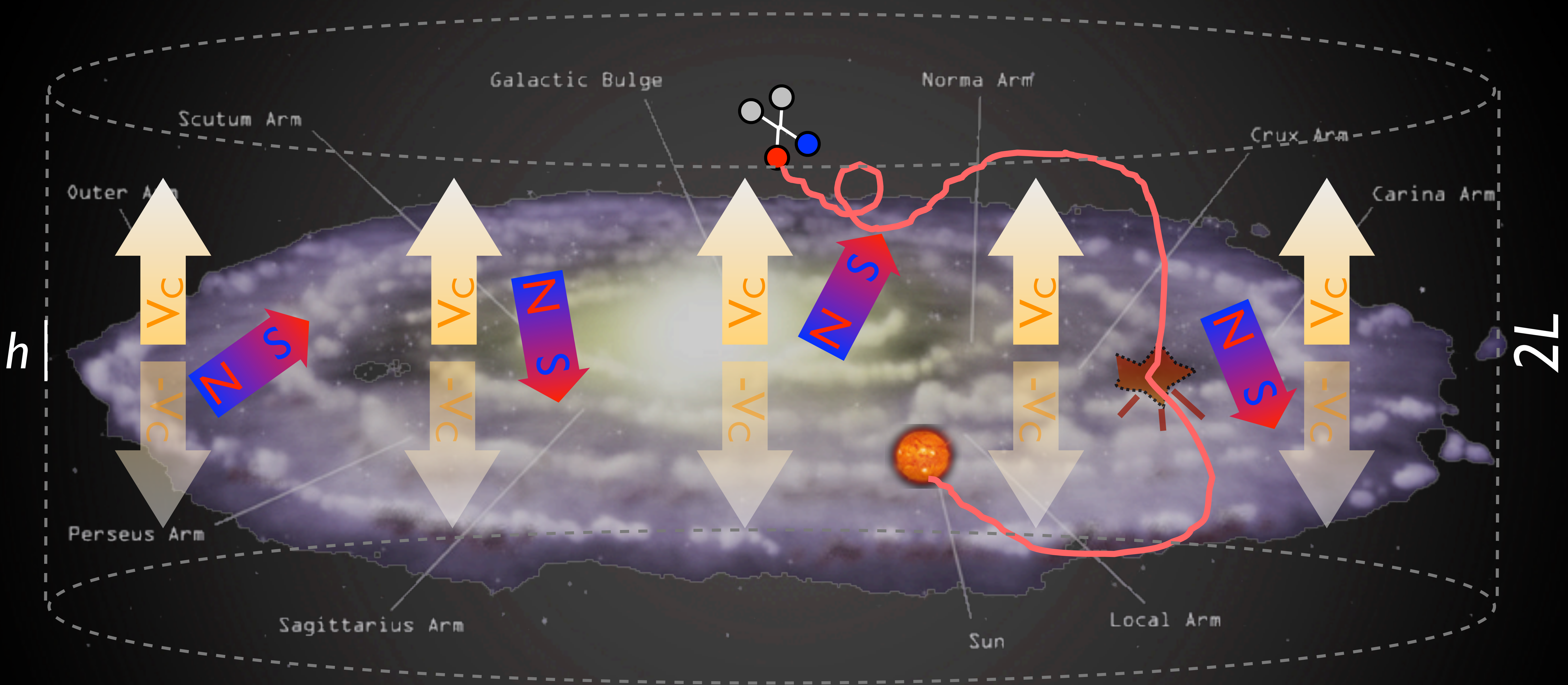


What sets the overall expected flux?

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

astro& cosmo

particle

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

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

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

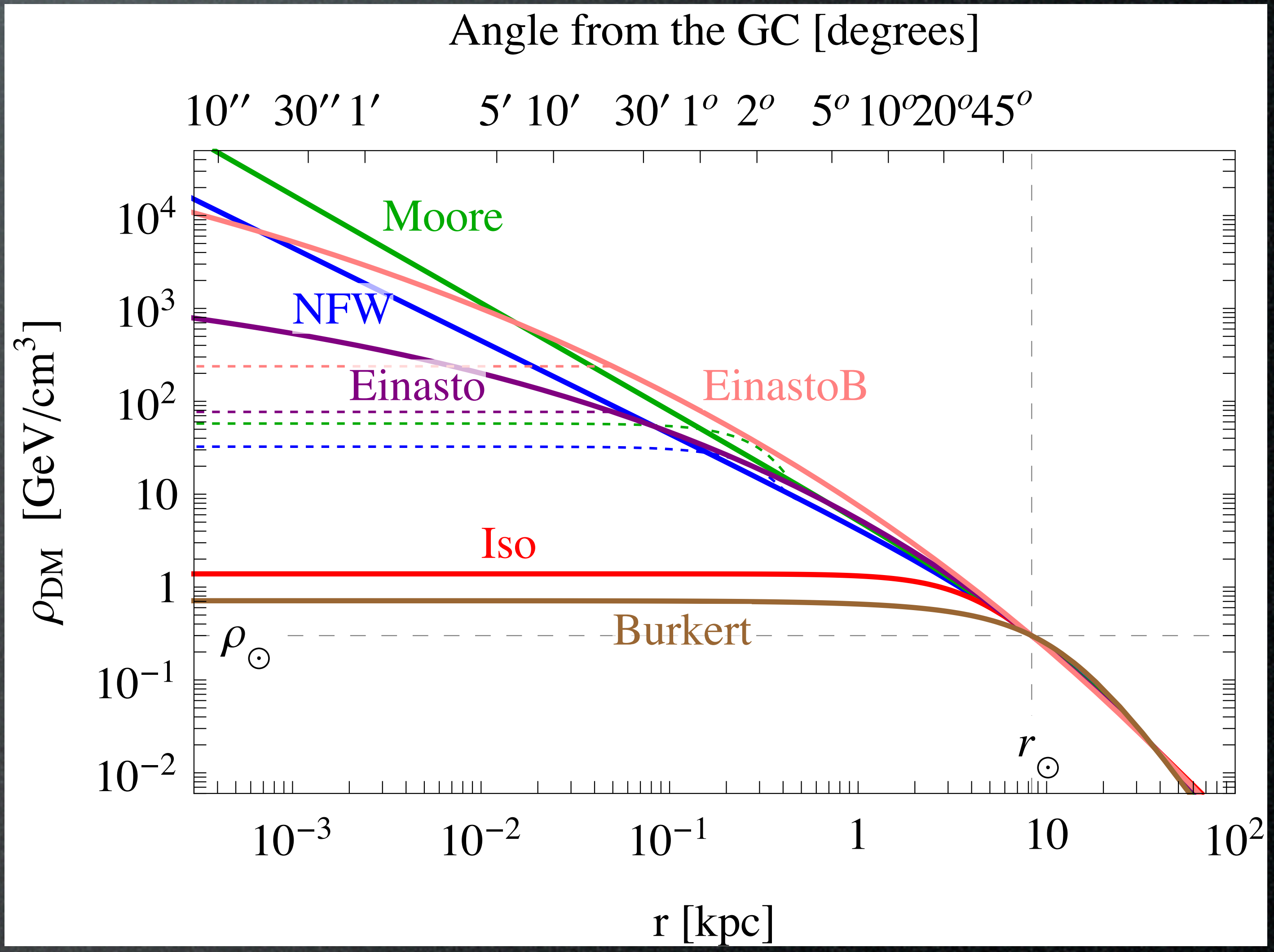
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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:

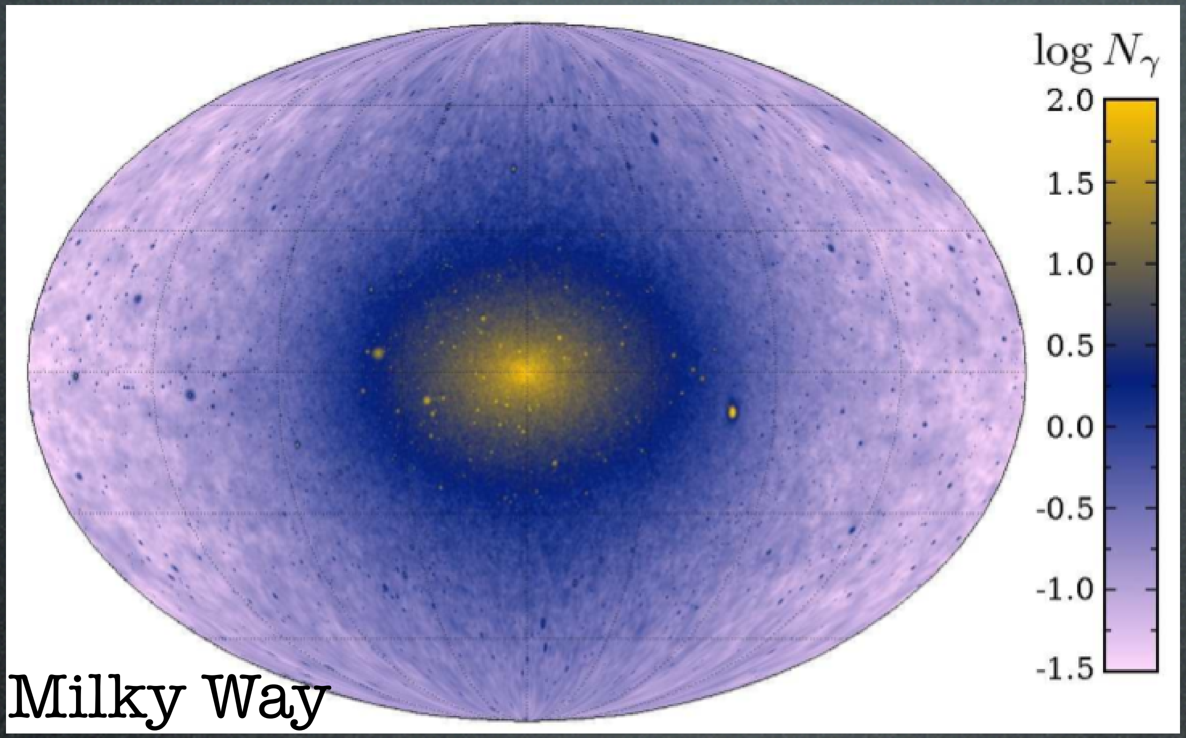
- cuspy: NFW, Moore
- mild: Einasto
- smooth: isothermal, Burkert

EinastoB = steepened Einasto (effect of baryons?)

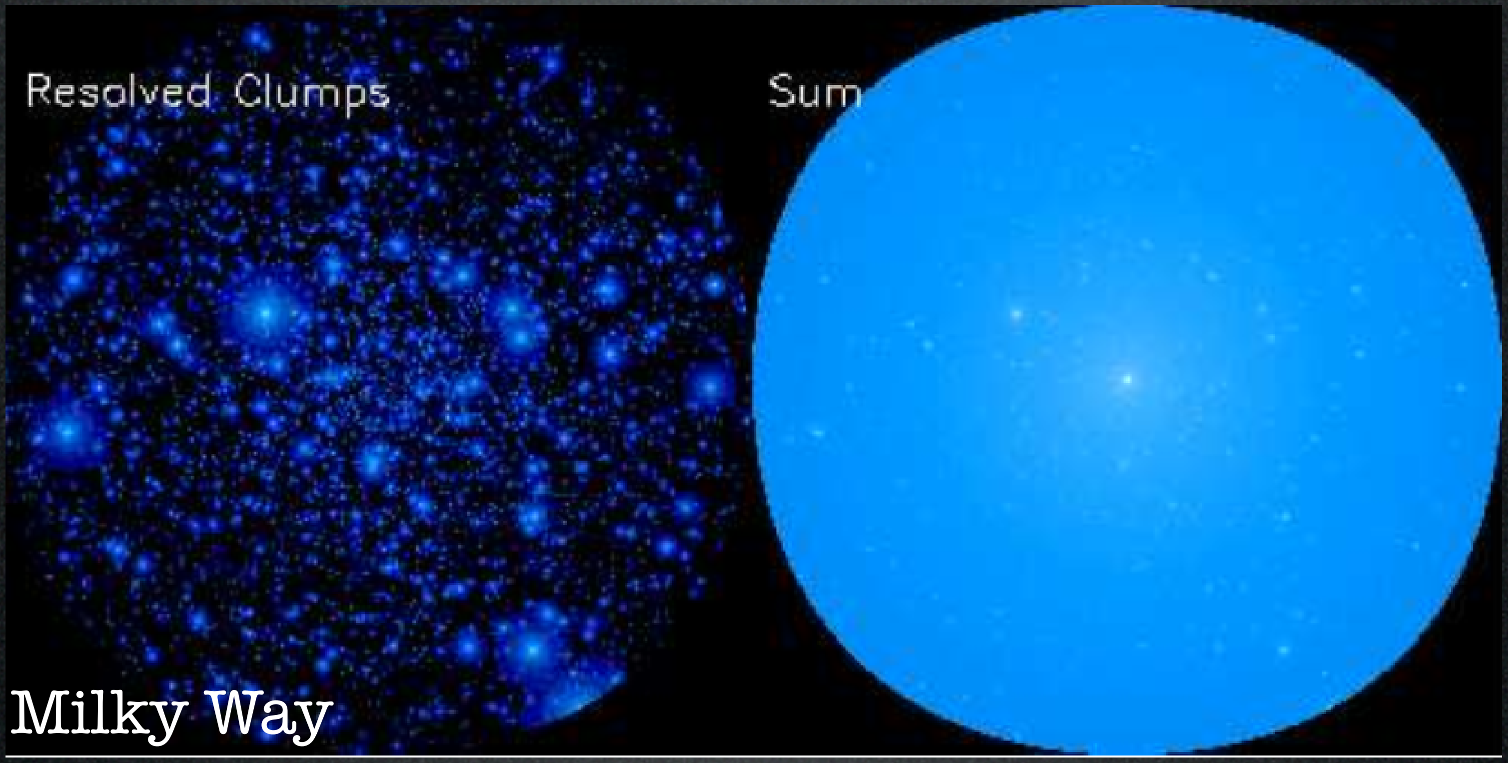
DM halo profiles

Local clumps in the DM halo enhance the density.

For illustration:

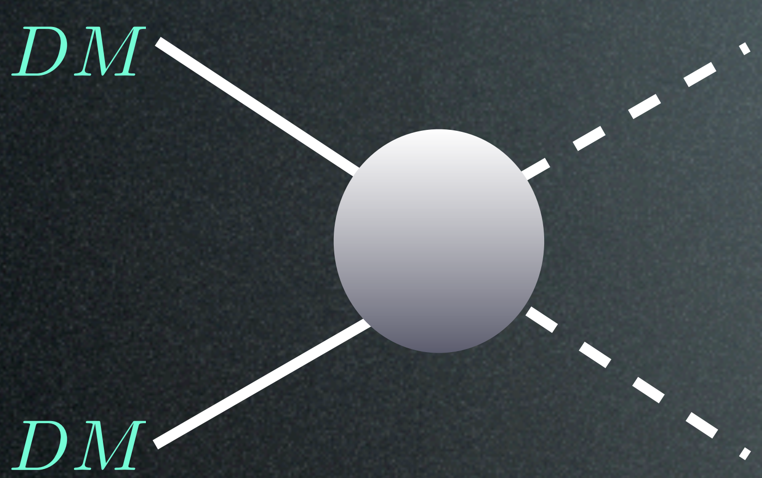


Kuhlen, Diemand, Madau 2007



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

Indirect Detection: basics



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

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

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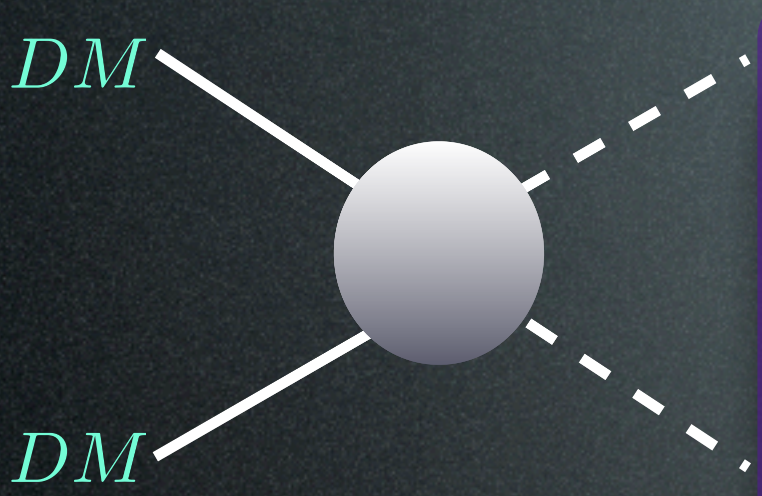
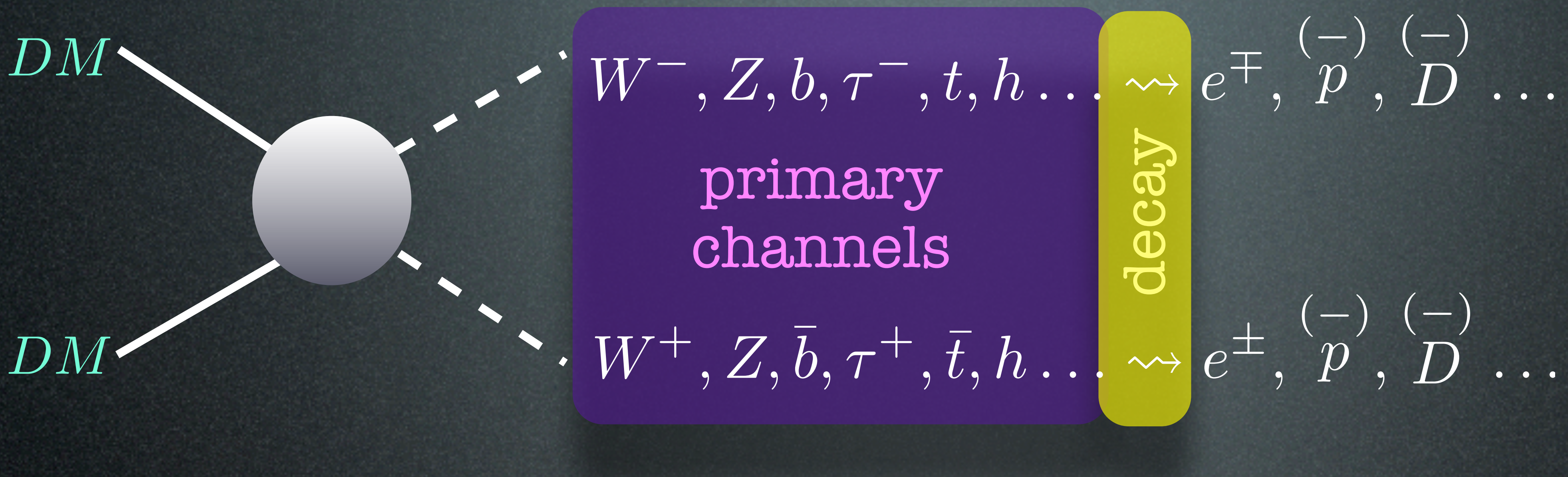


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

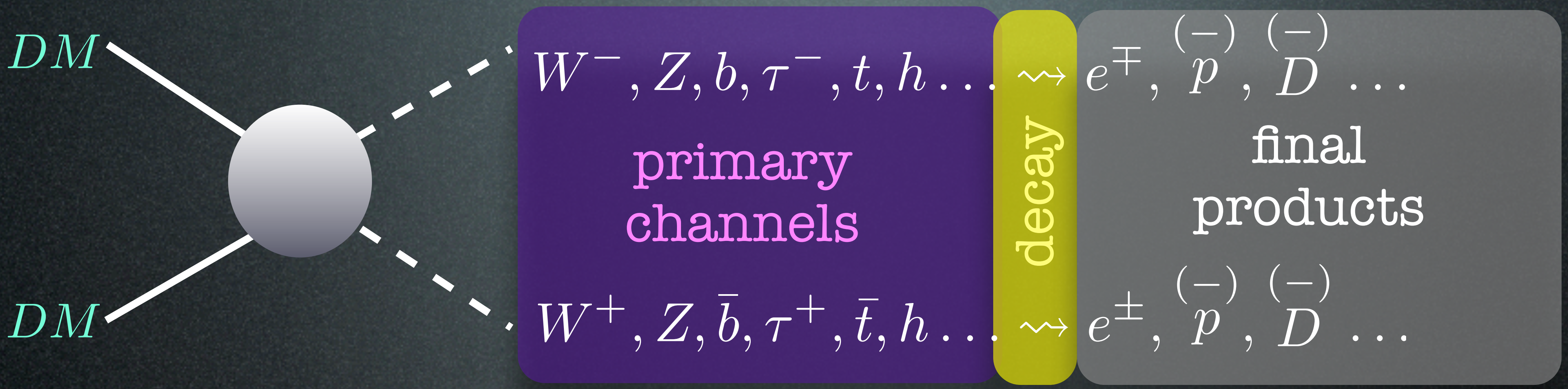
primary
channels

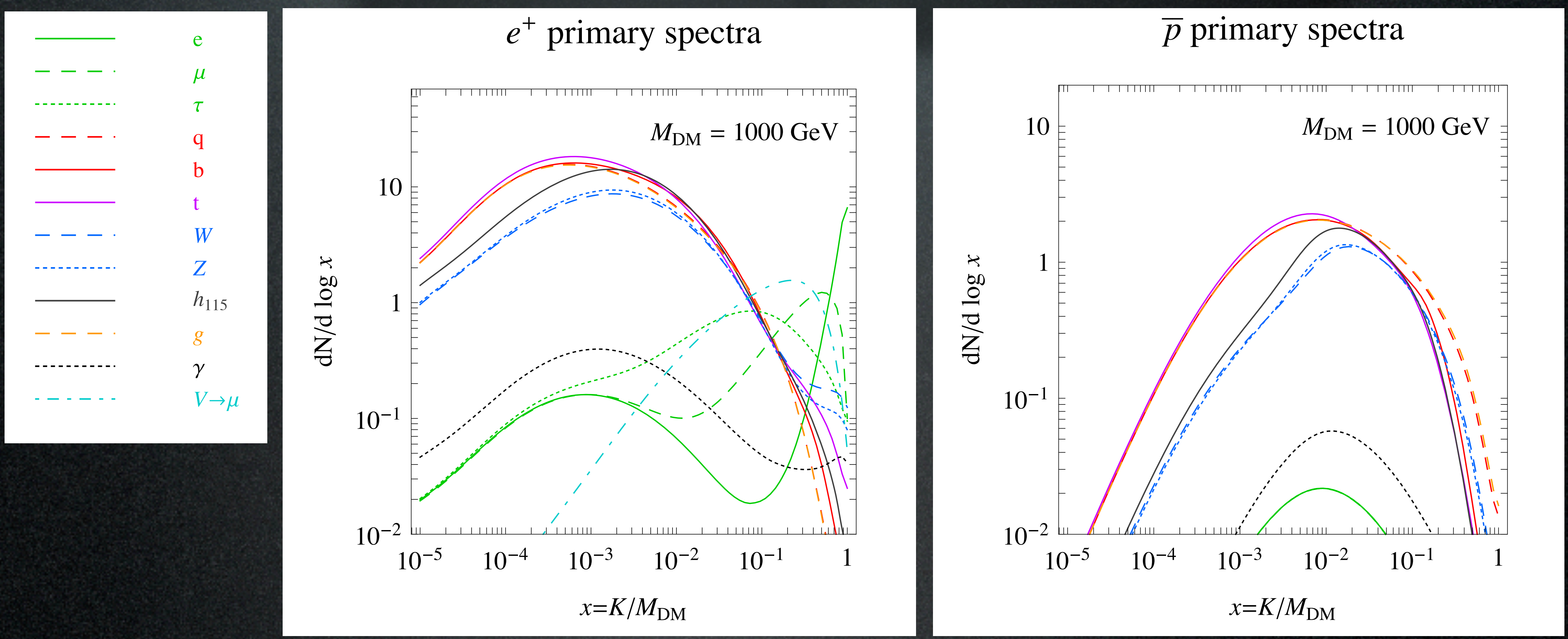
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

Indirect Detection: basics



Indirect Detection: basics





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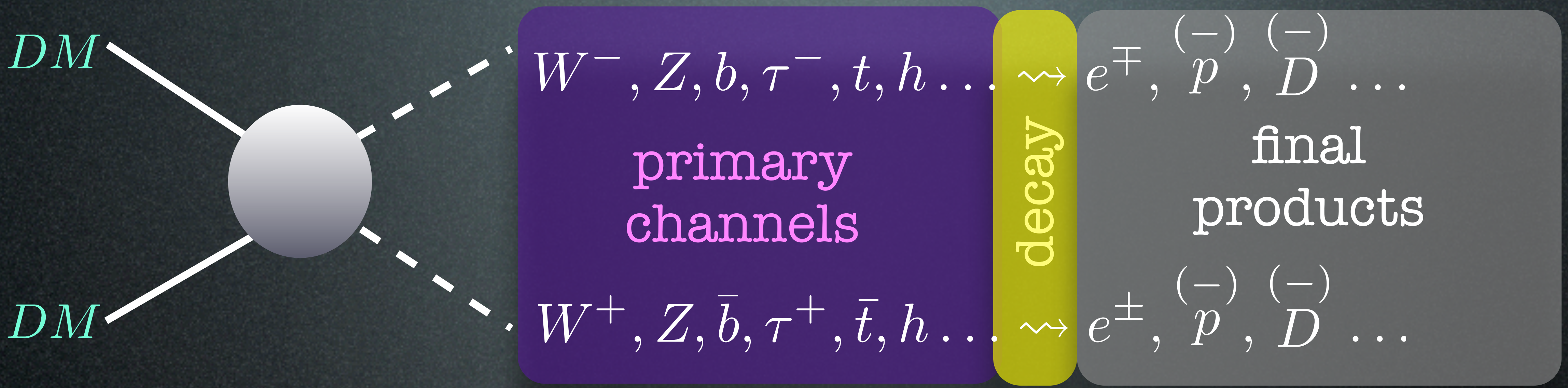
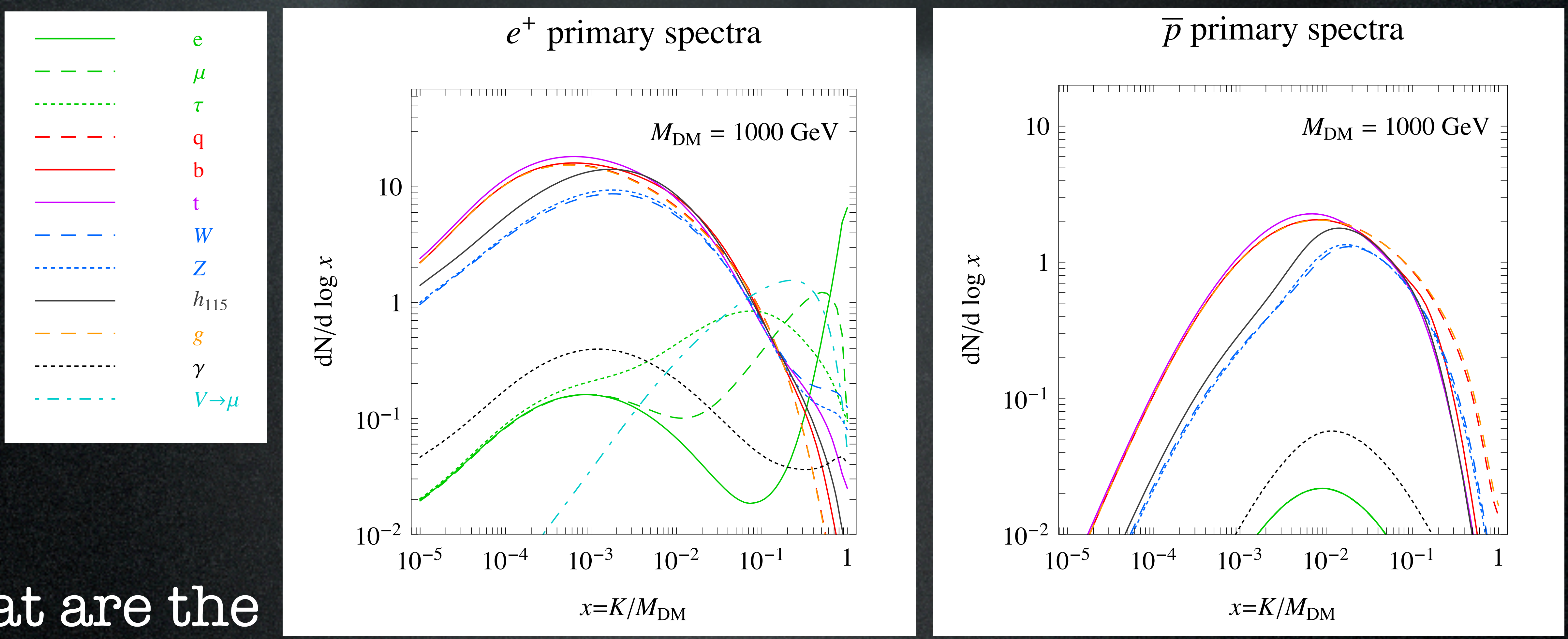


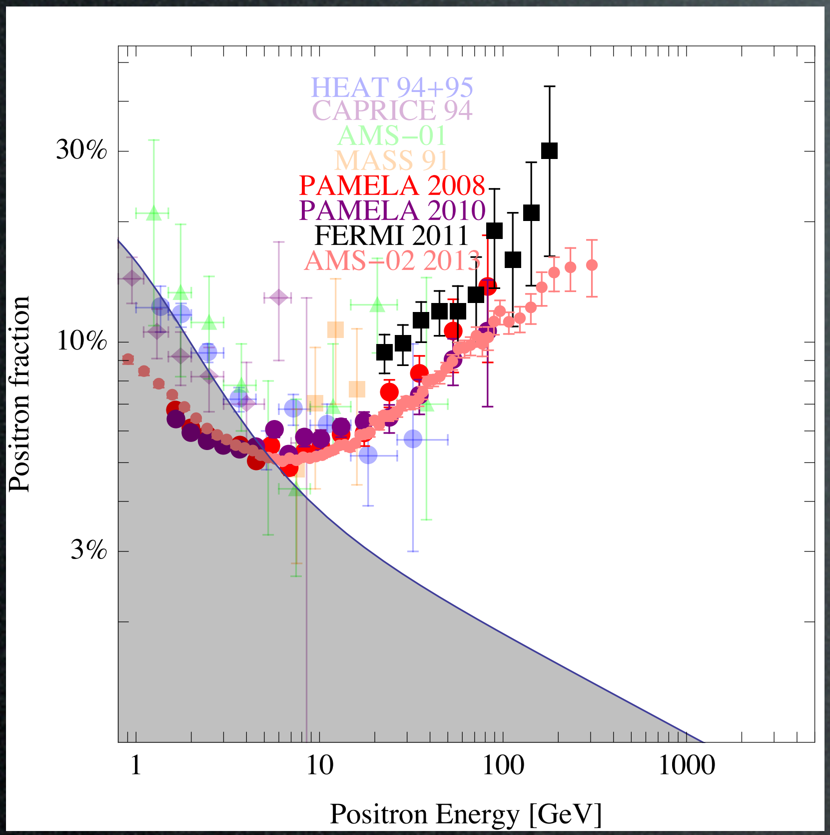


So what are the particle physics parameters?

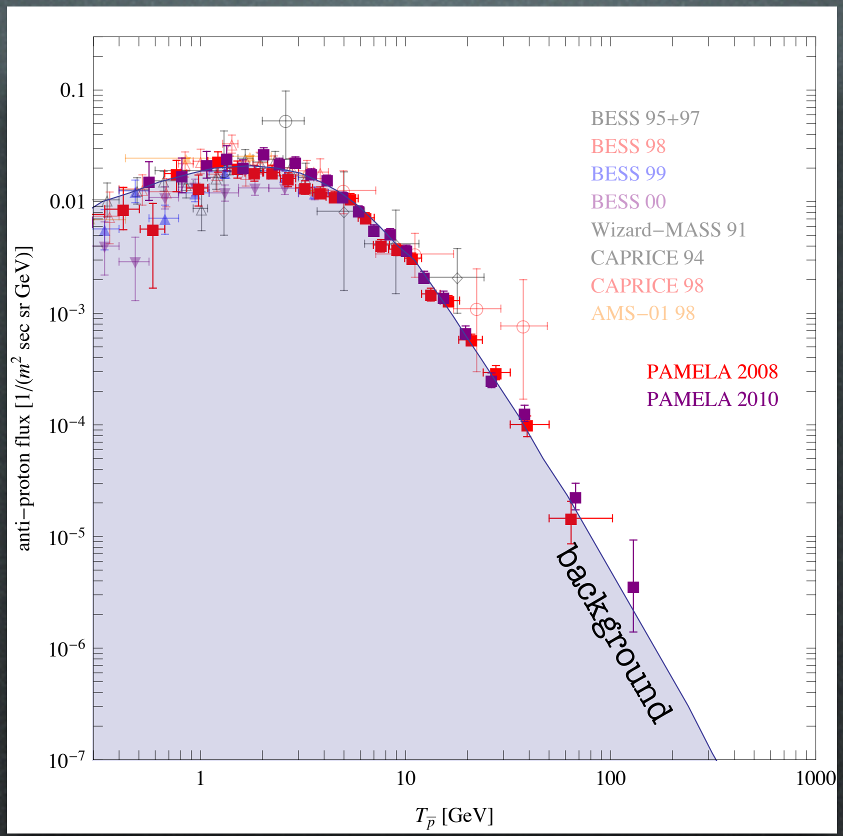
1. Dark Matter mass
2. primary channel(s)

Indirect Detection: **hints**

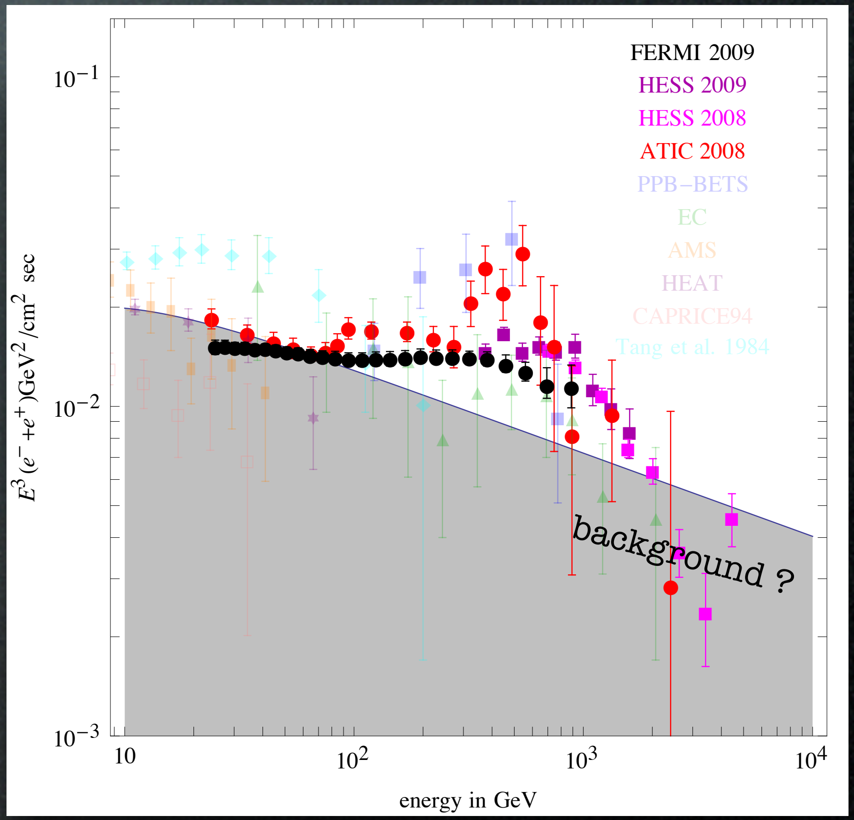
positron fraction



antiprotons



electrons + positrons



Positrons & Electrons

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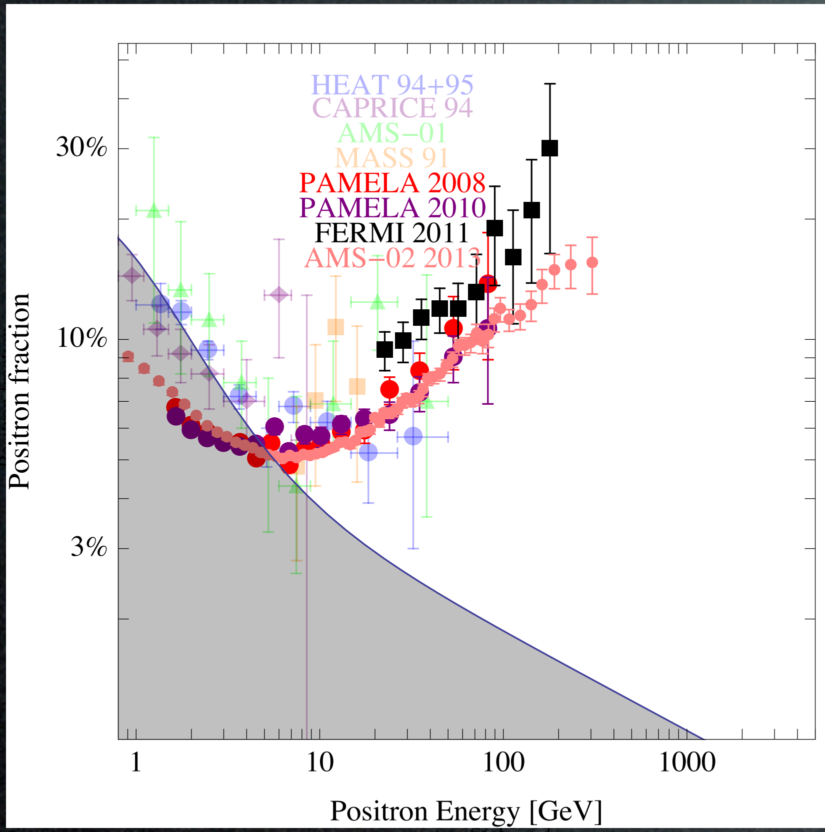

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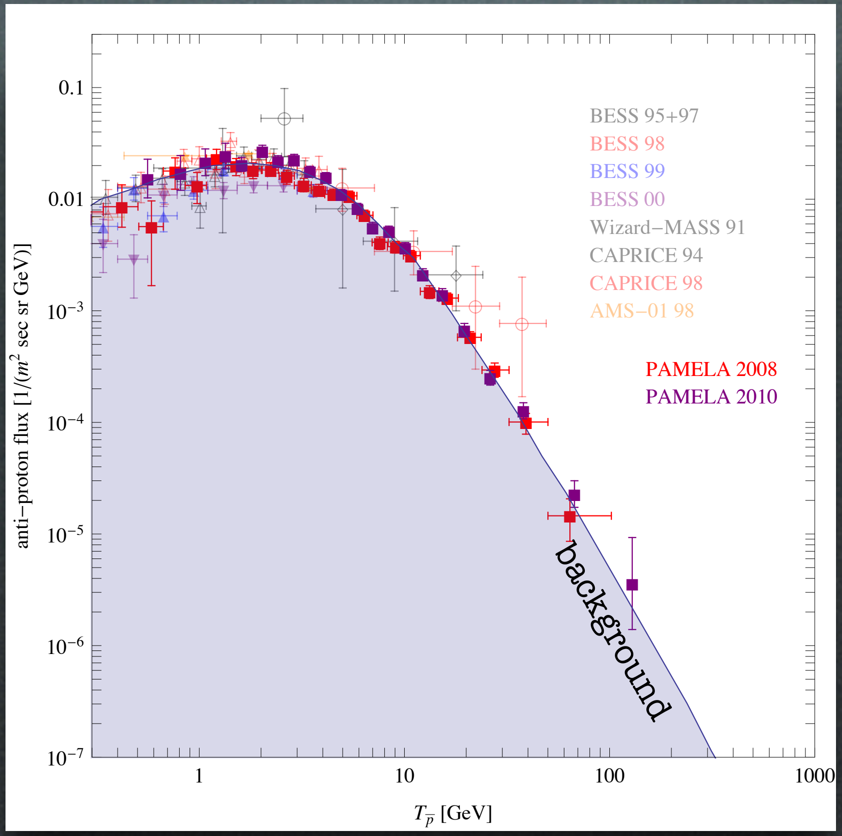

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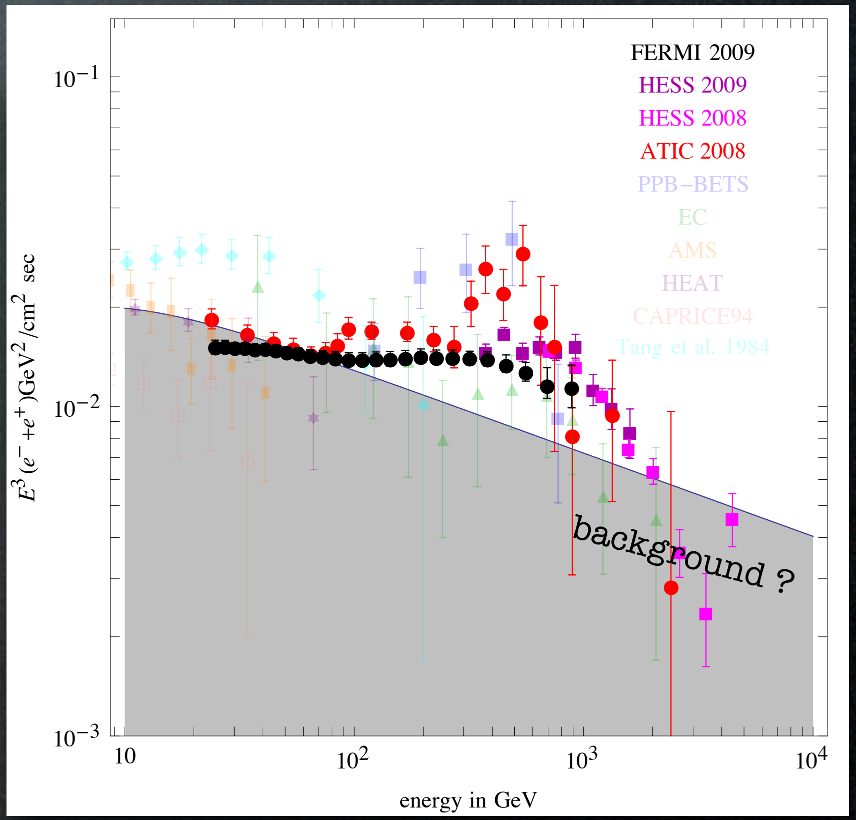

Are these signals of Dark Matter?

Positrons & Electrons

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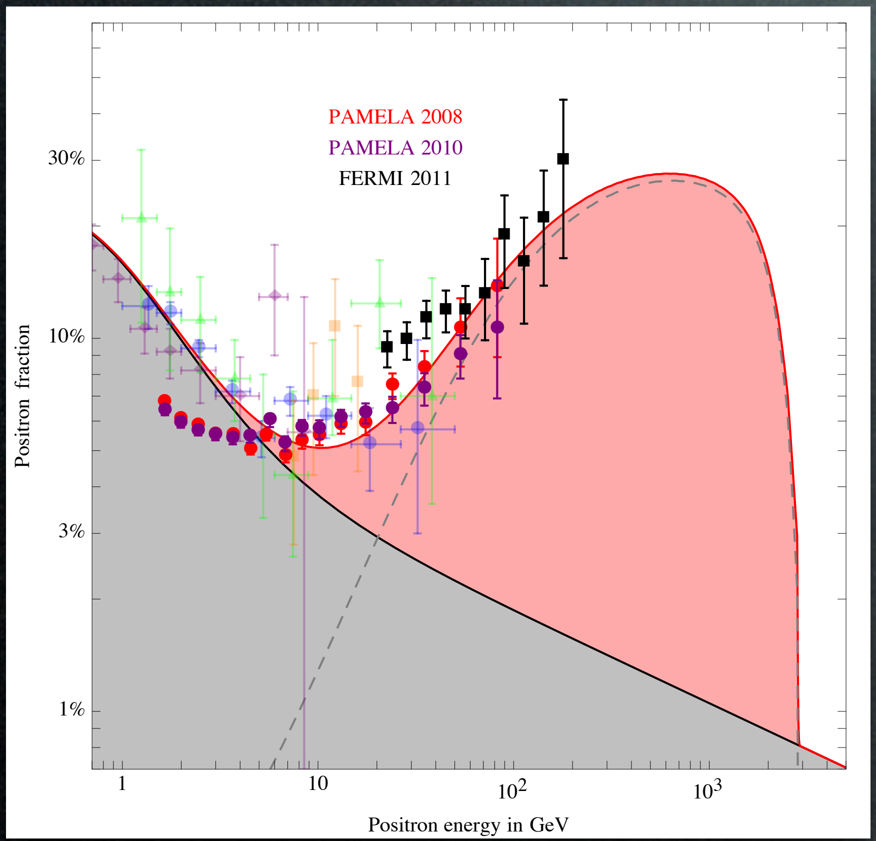

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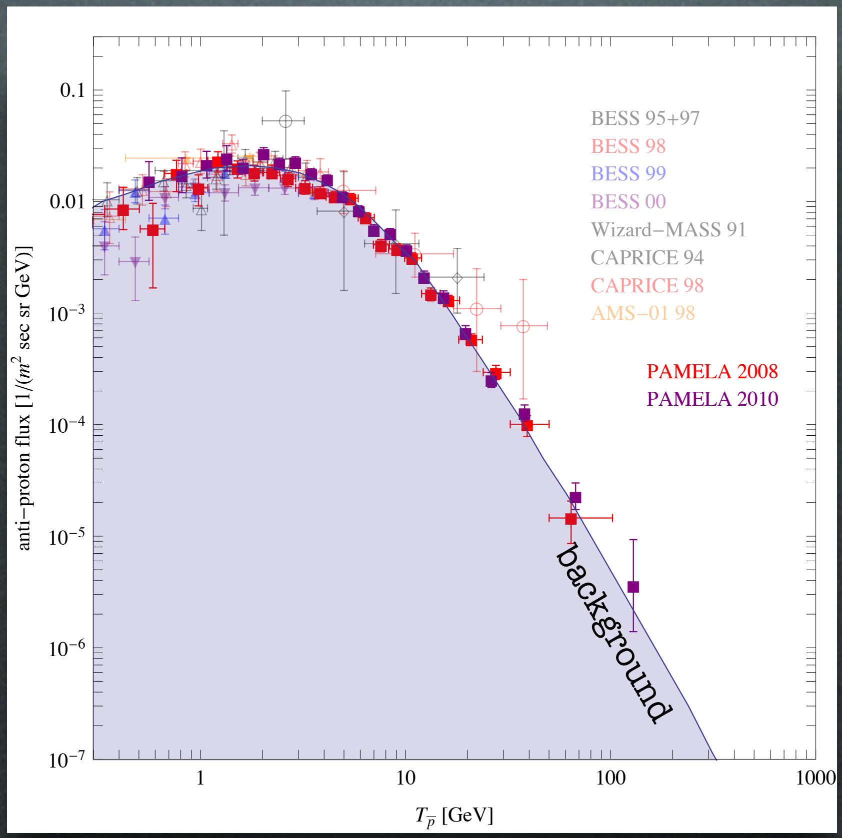

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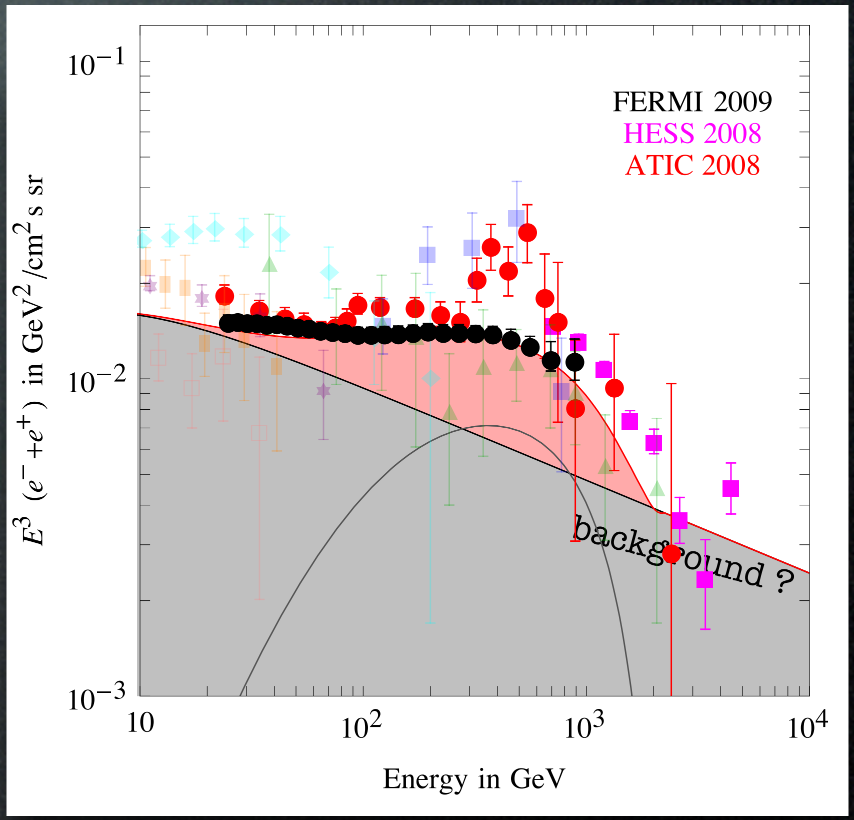
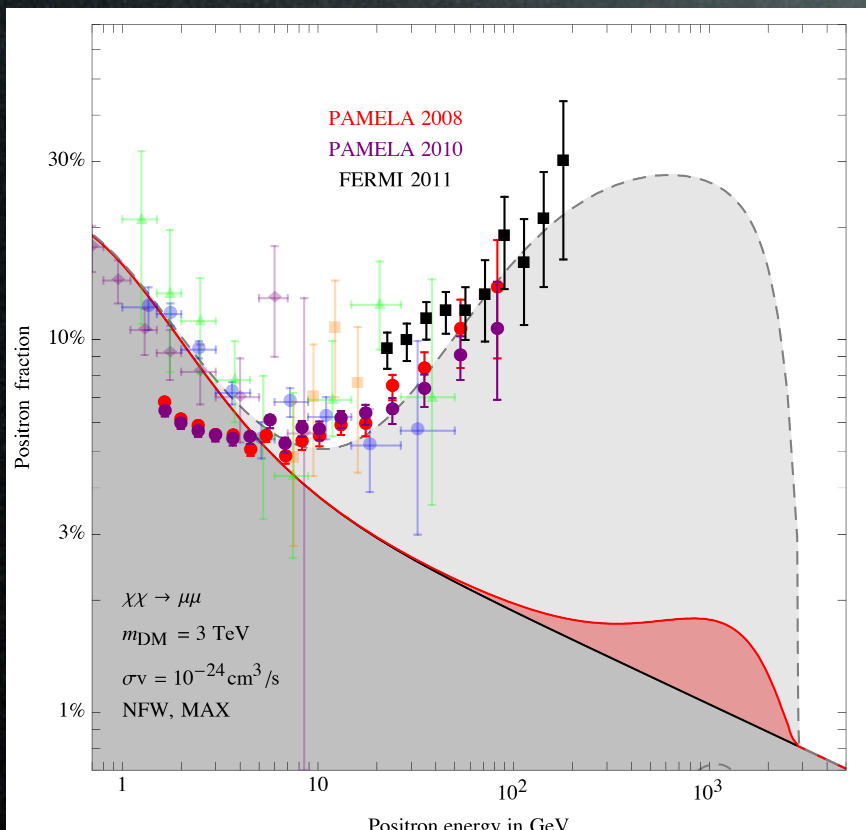


Are these signals of Dark Matter?

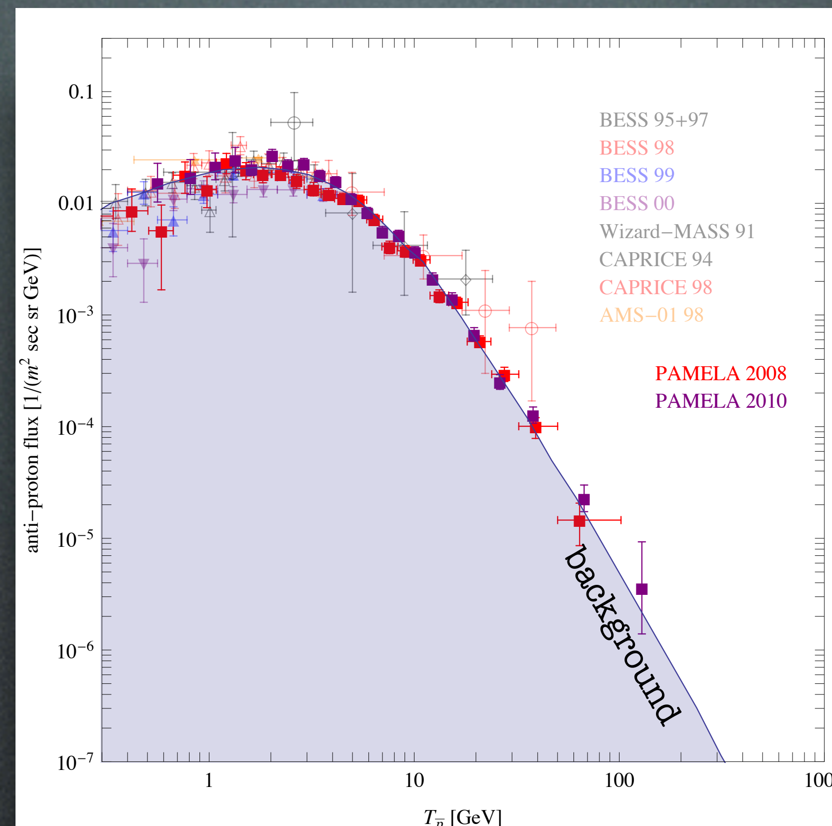
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\text{cm}^3/\text{sec}$

Positrons & Electrons

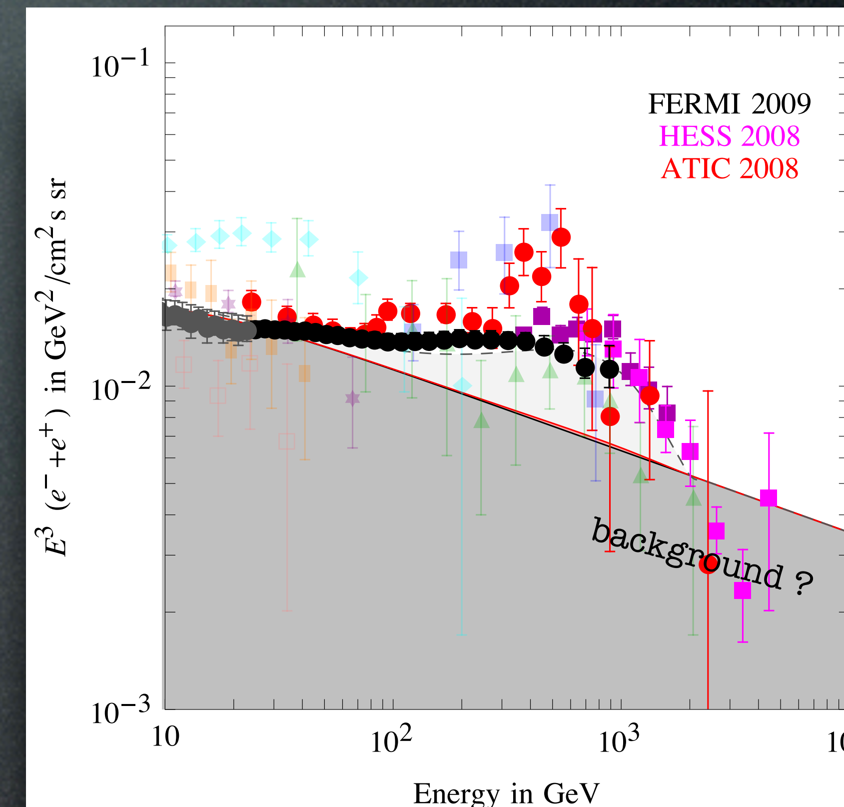
positron fraction



antiprotons



electrons + positrons

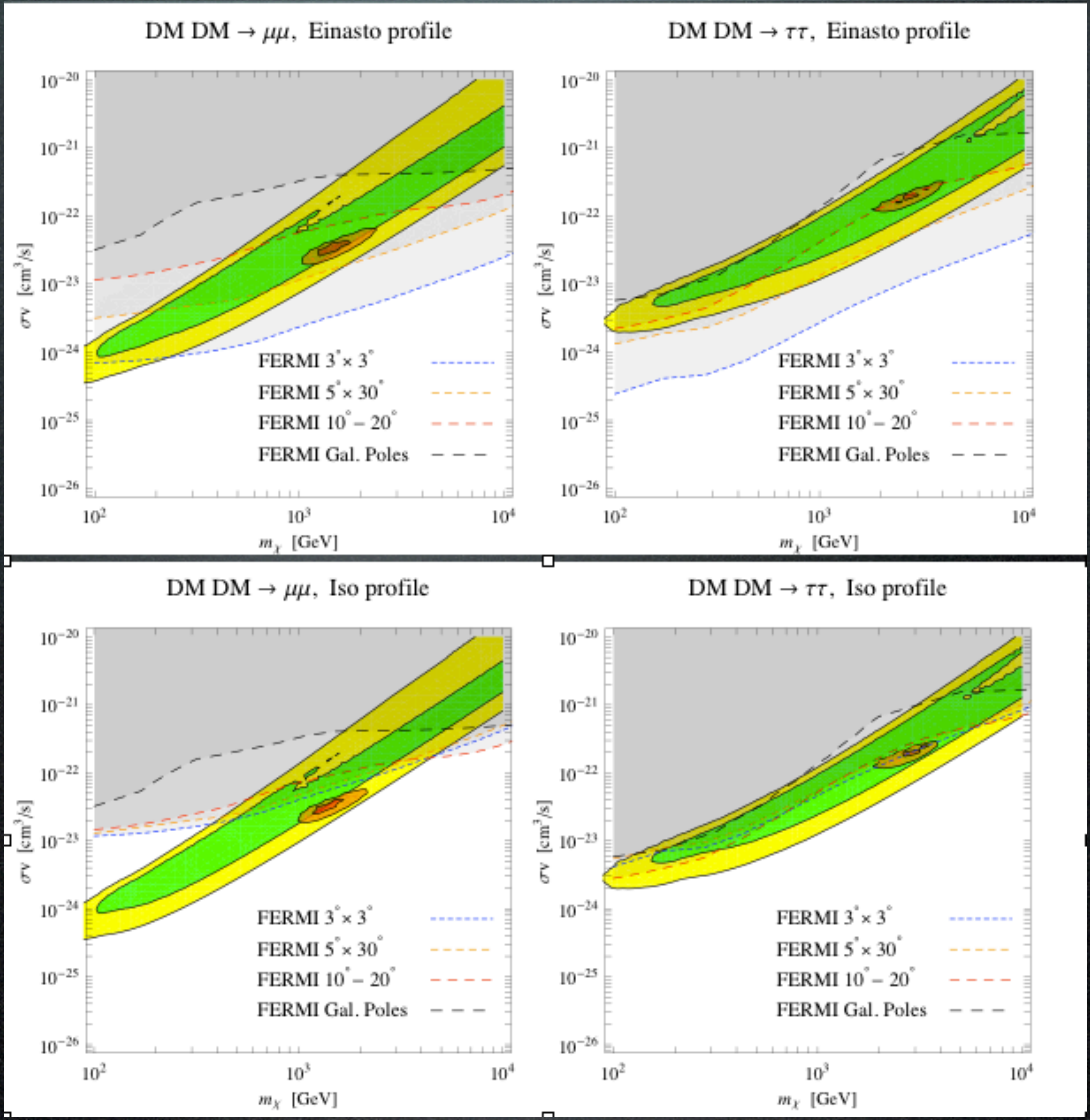


Are these signals of Dark Matter?

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

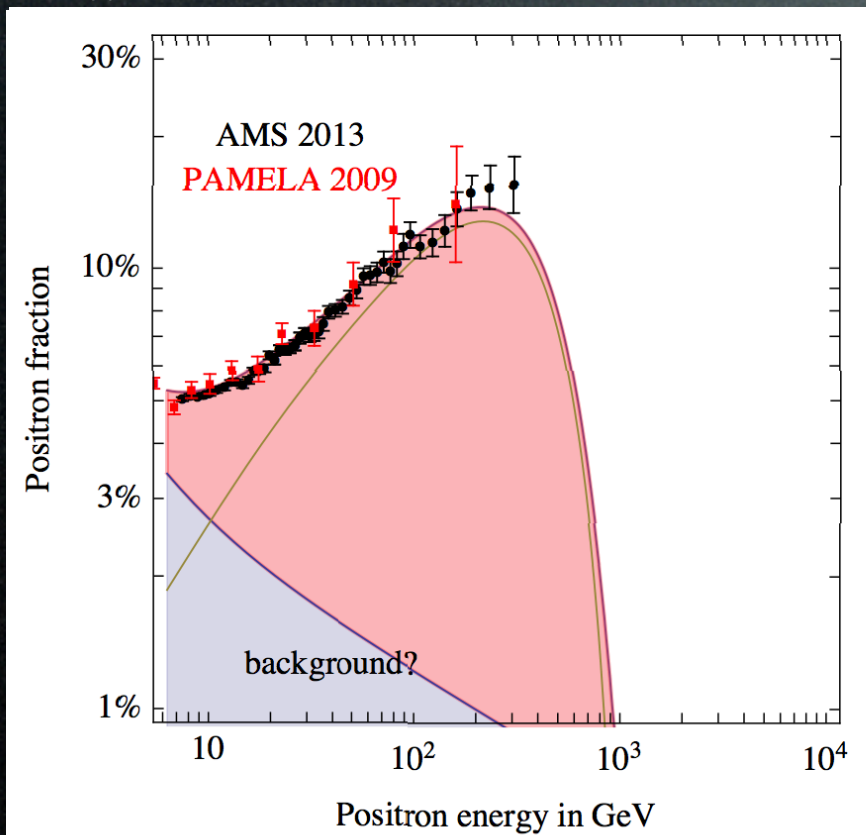
NO: a formidable ‘background’ for future searches

Positrons & Electrons

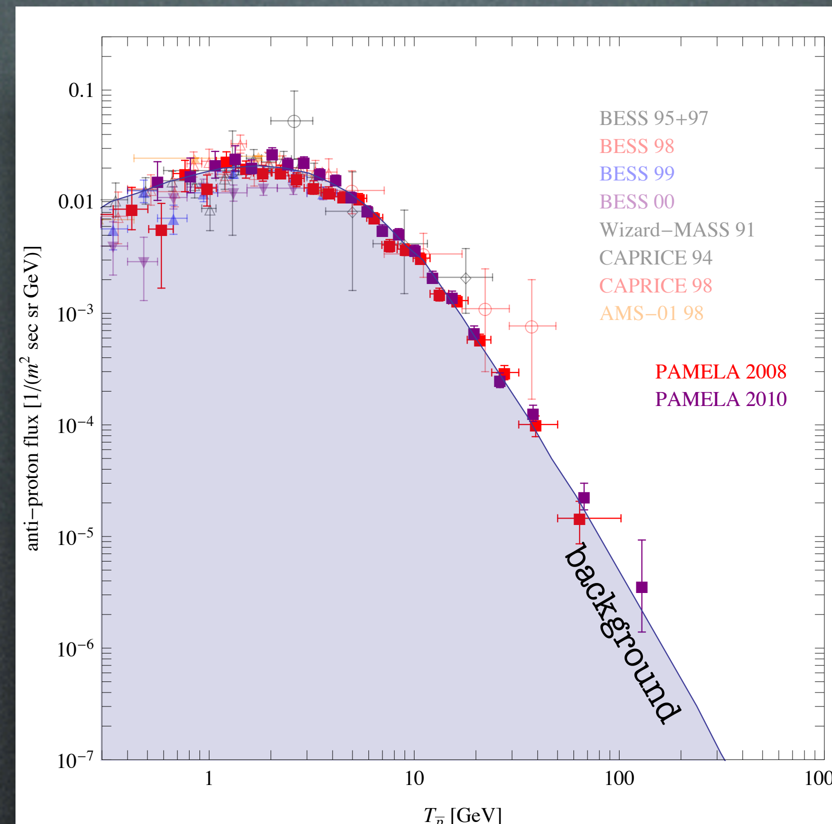


PS: post AMS 2013

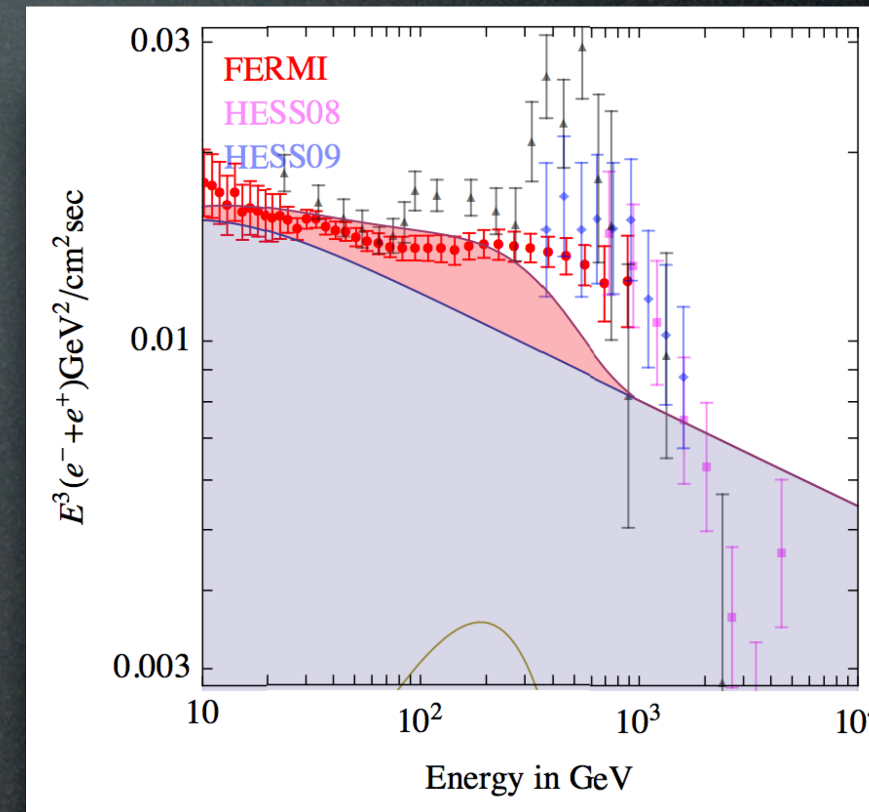
positron fraction



antiprotons



electrons + positrons



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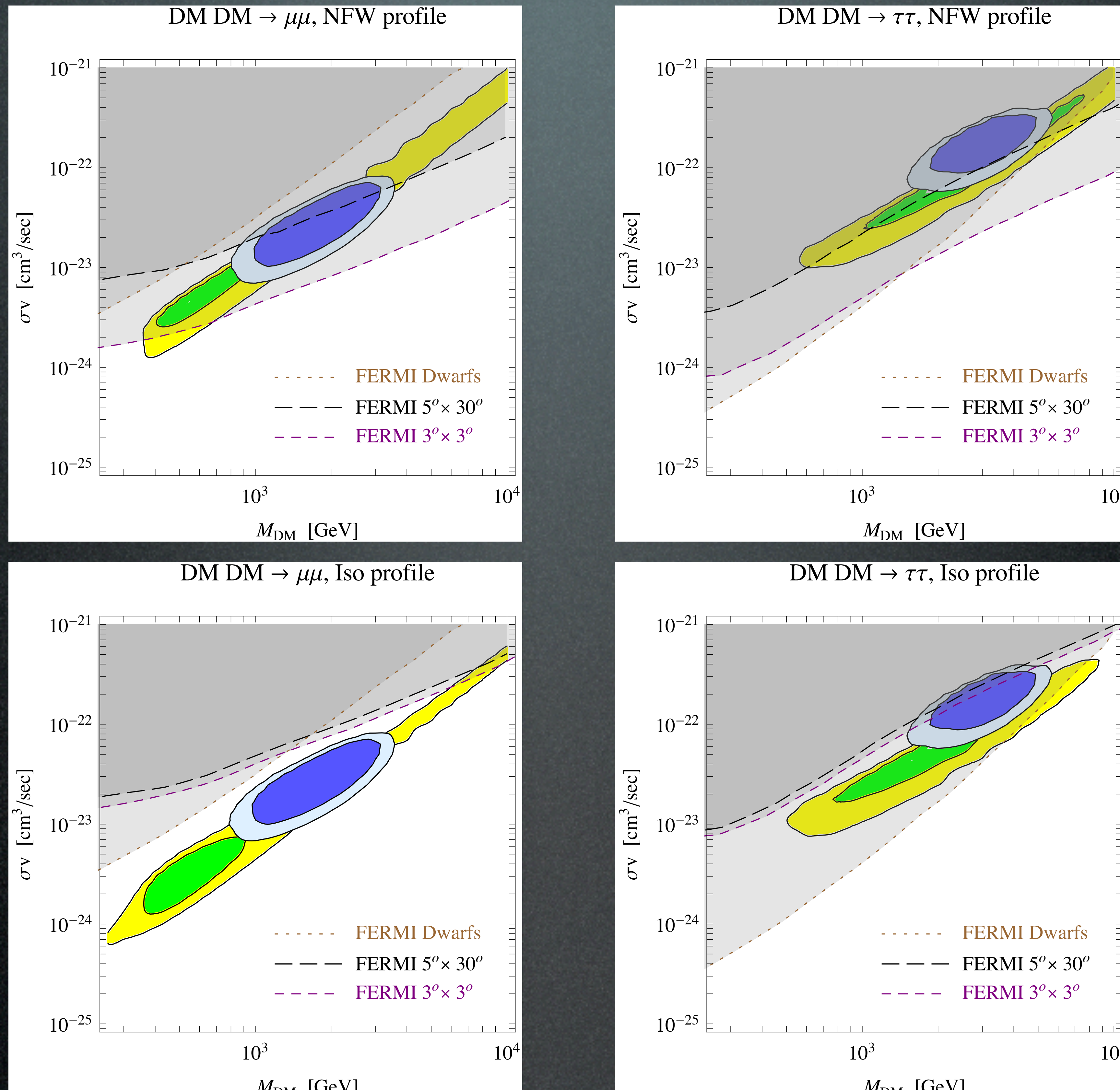
YES: one TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\, \text{cm}^3/\text{sec}$
'tension' between positron frac and $e^+ + e^-$

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

PS: post AMS 2013



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

Indirect Detection: **constraints**

direct detection

production at colliders

indirect

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- e^+ from annihil in galactic halo or center
  PAMELA, Fermi, HESS, AMS, **balloons...**
- $\bar{p}$ from annihil in galactic halo or center
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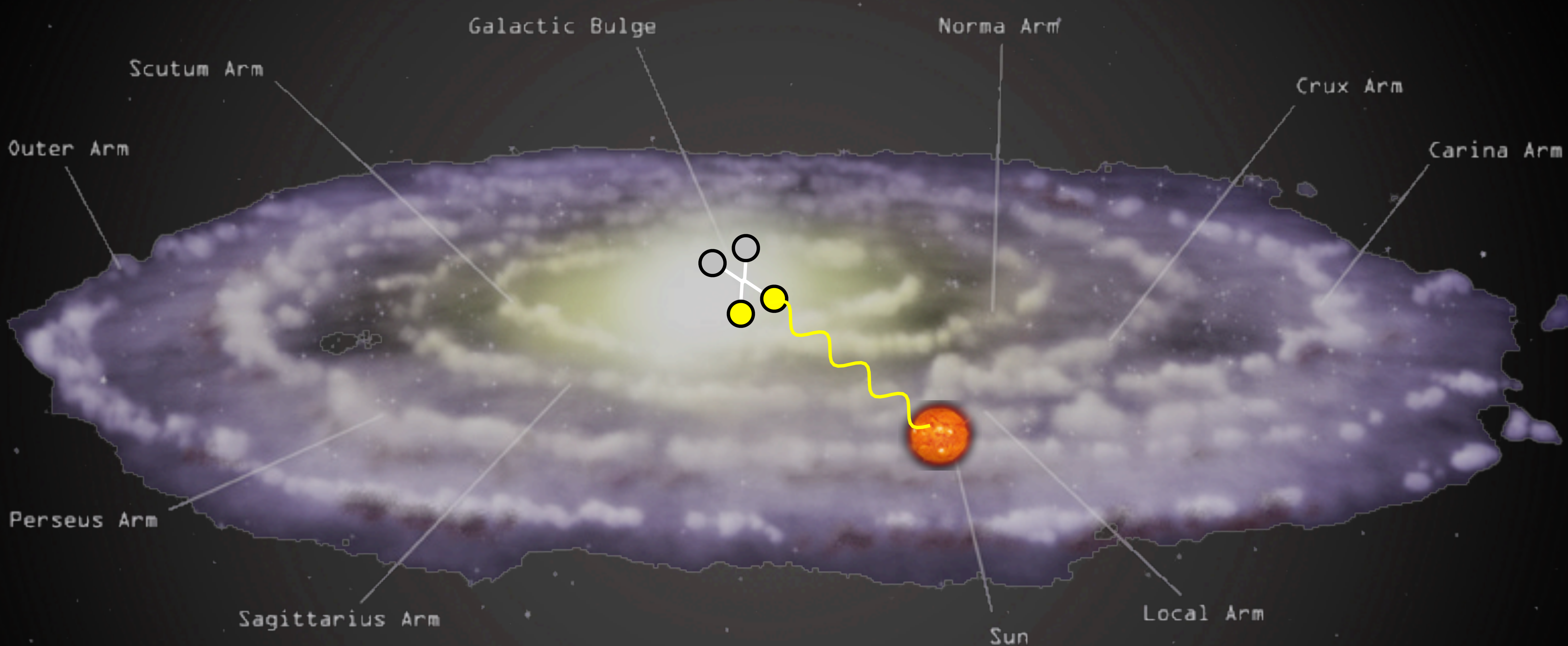
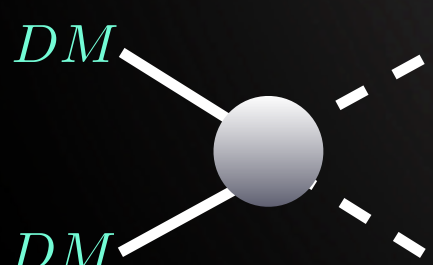
Indirect Detection: constraints

γ from DM annihilations in galactic center



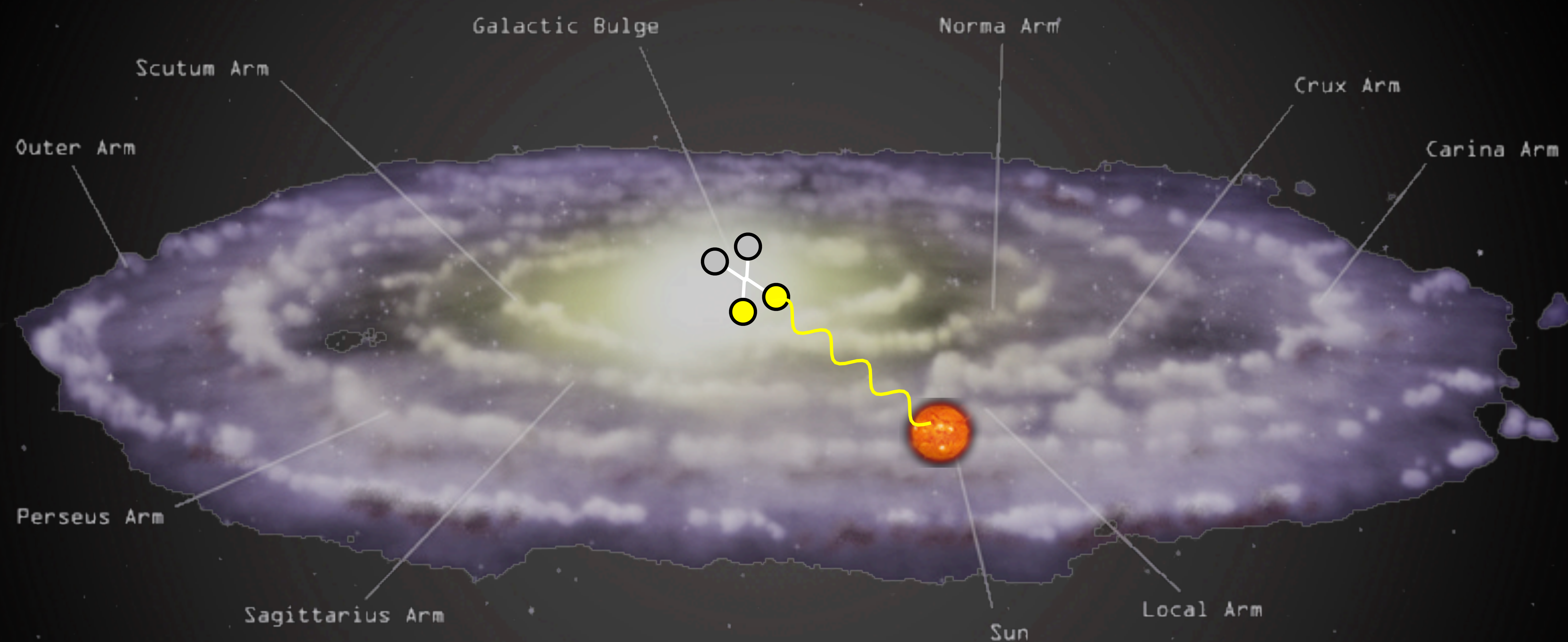


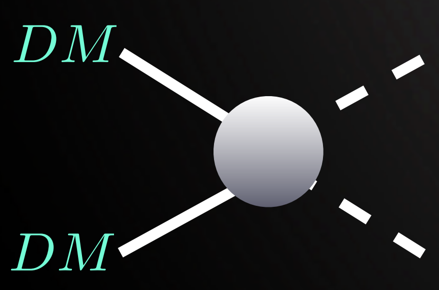
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

Indirect Detection: constraints

a. γ from DM annihilations in galactic center



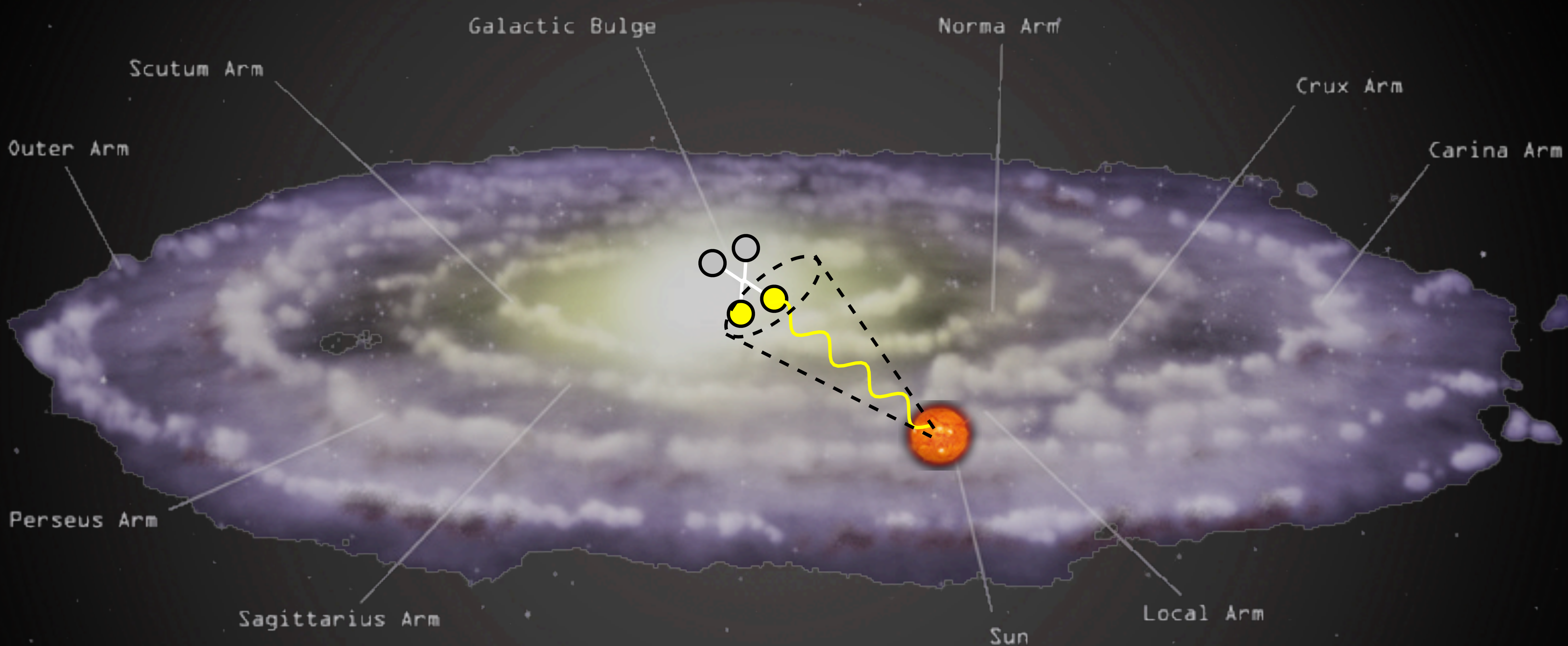


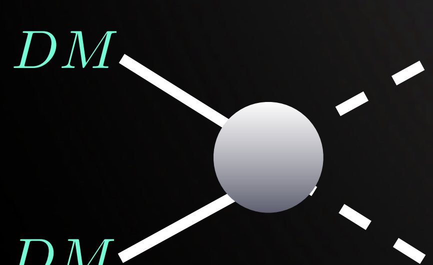
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

Indirect Detection: constraints

a. γ from DM annihilations in galactic center



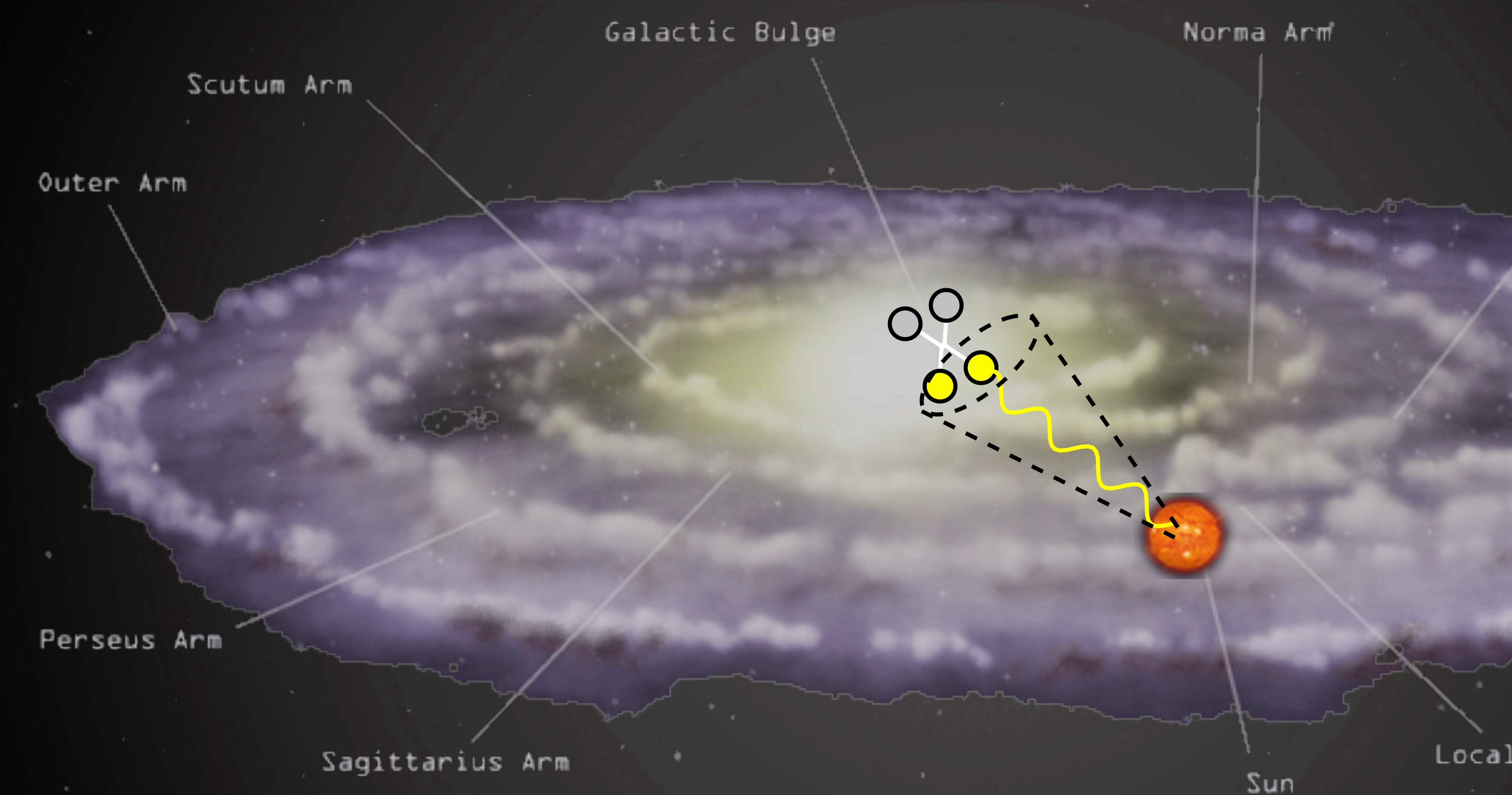


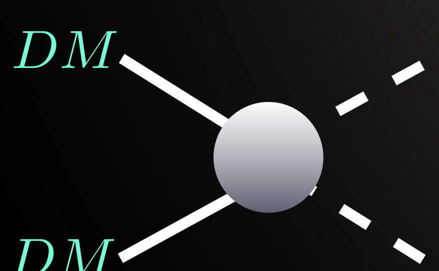
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

Indirect Detection: constraints

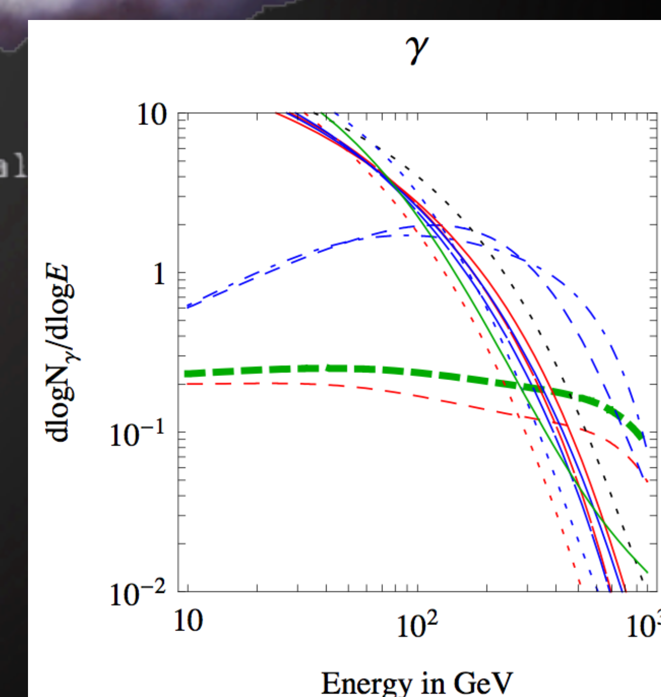
a. γ from DM annihilations in galactic center





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

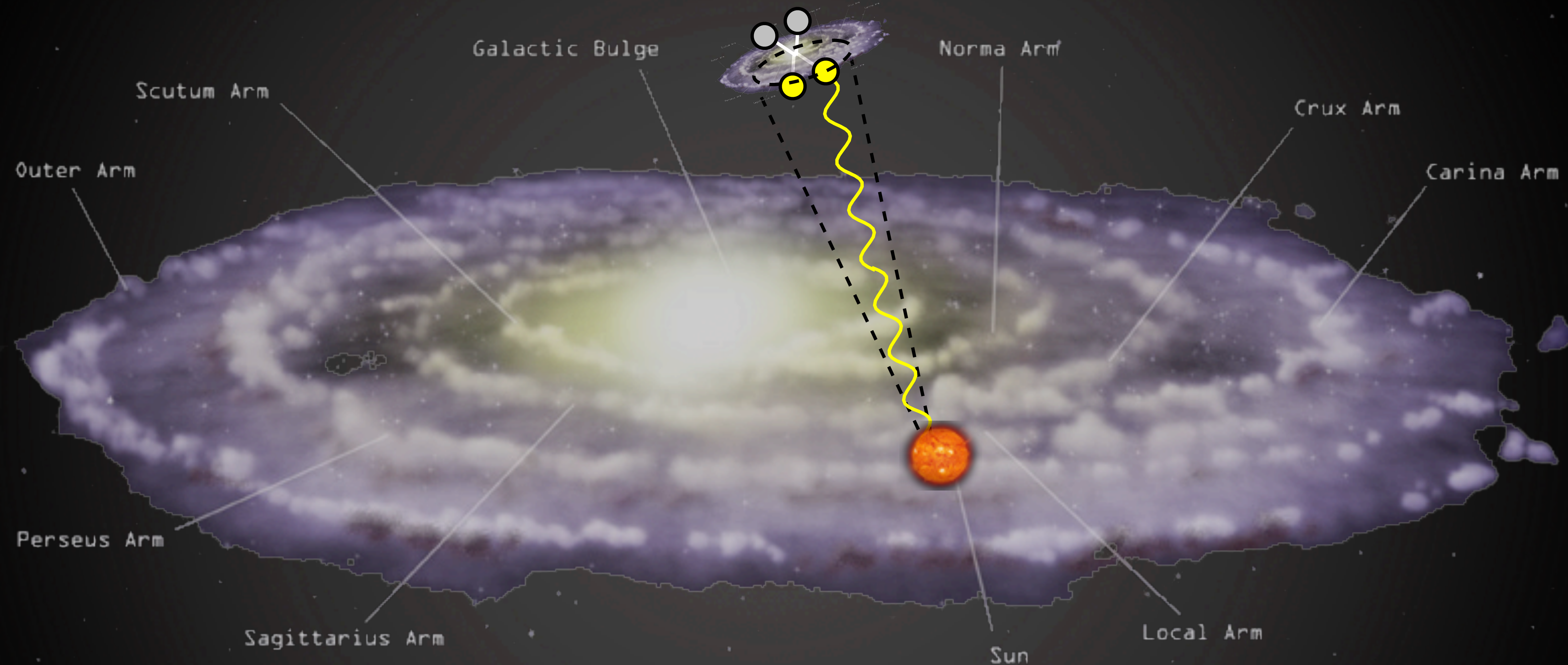
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

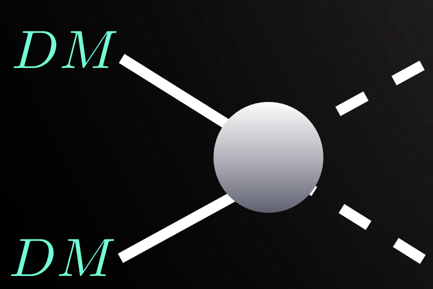


typically sub-TeV energies

Indirect Detection: constraints

b. γ from DM annihilations in Satellite Galaxies



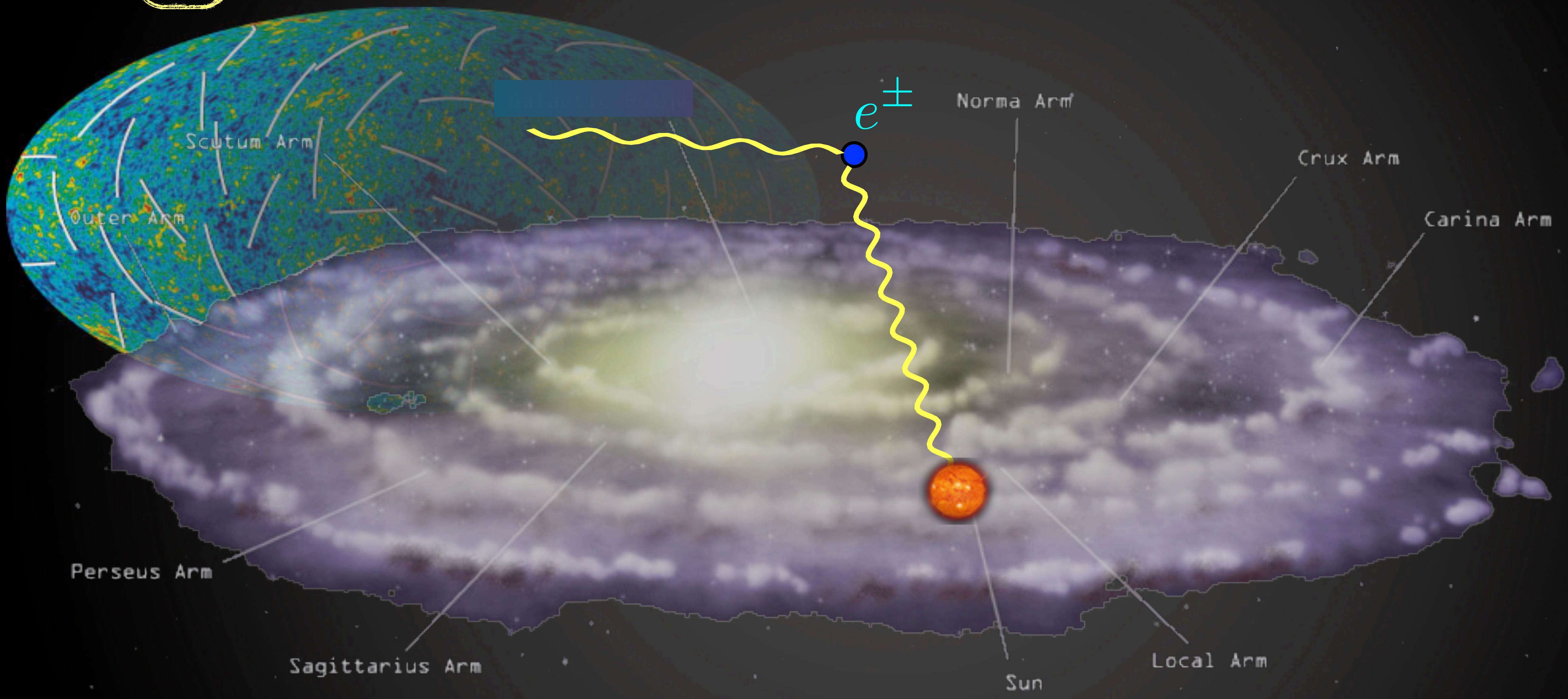


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

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

Indirect Detection: constraints

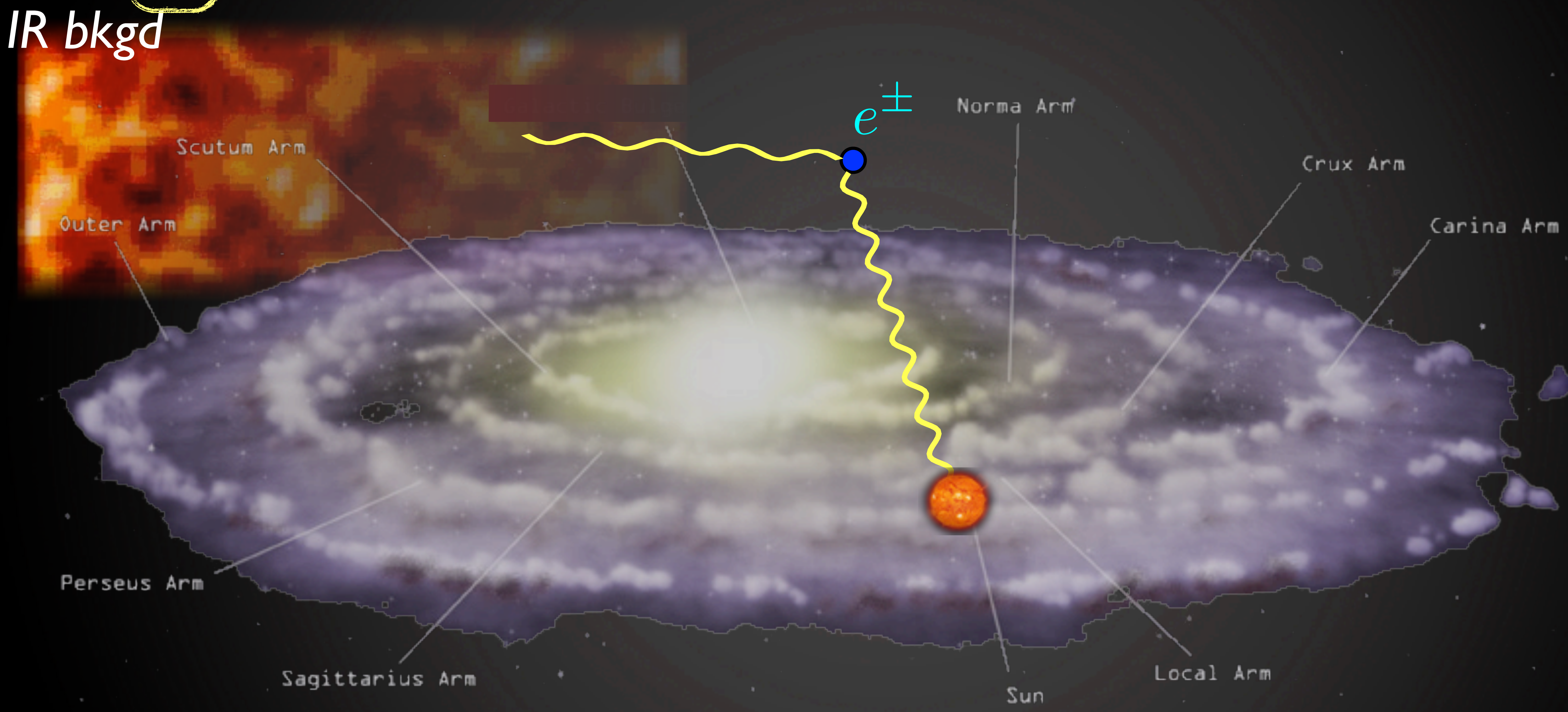
c. γ from Inverse Compton on $e^{\pm}$ in halo



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

Indirect Detection: constraints

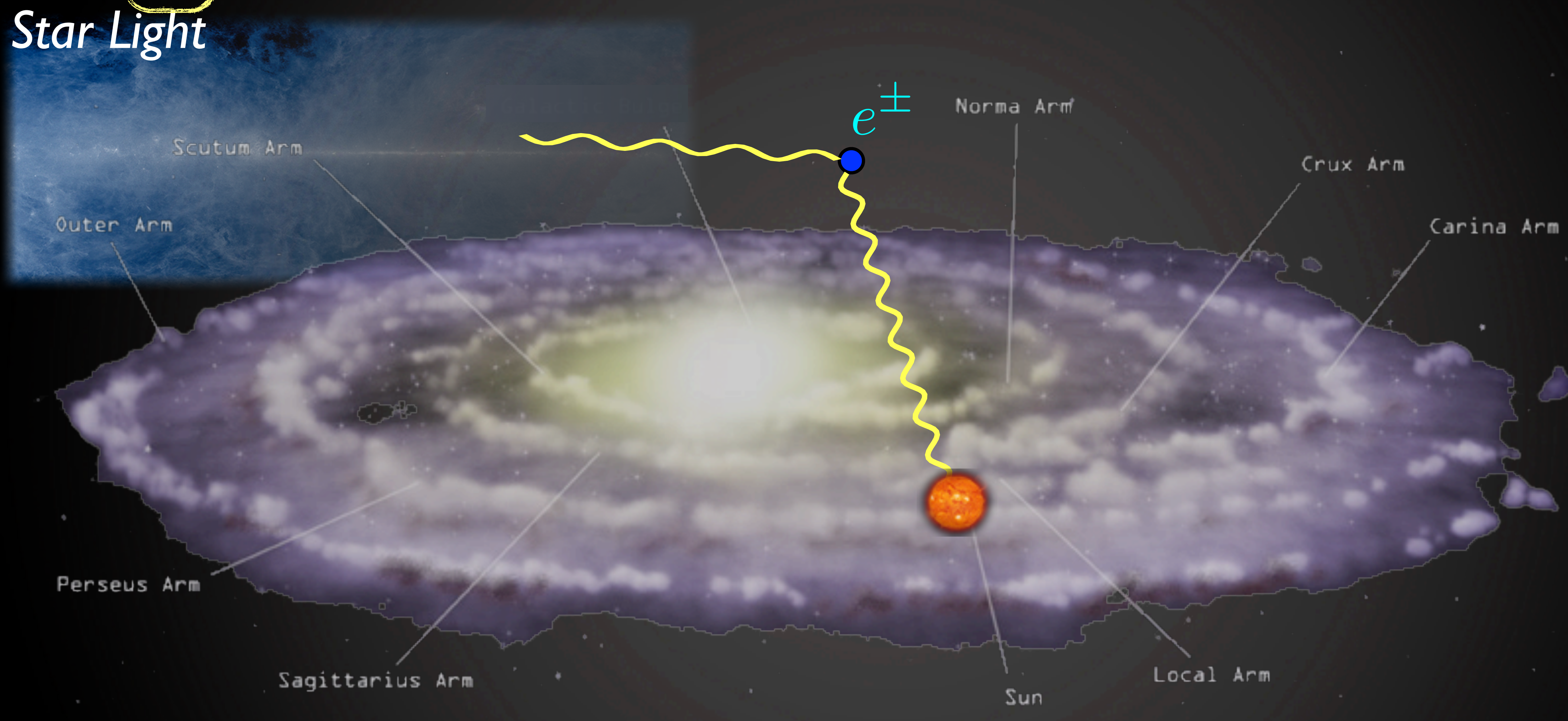
c. γ from Inverse Compton on $e^{\pm}$ in halo



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

Indirect Detection: constraints

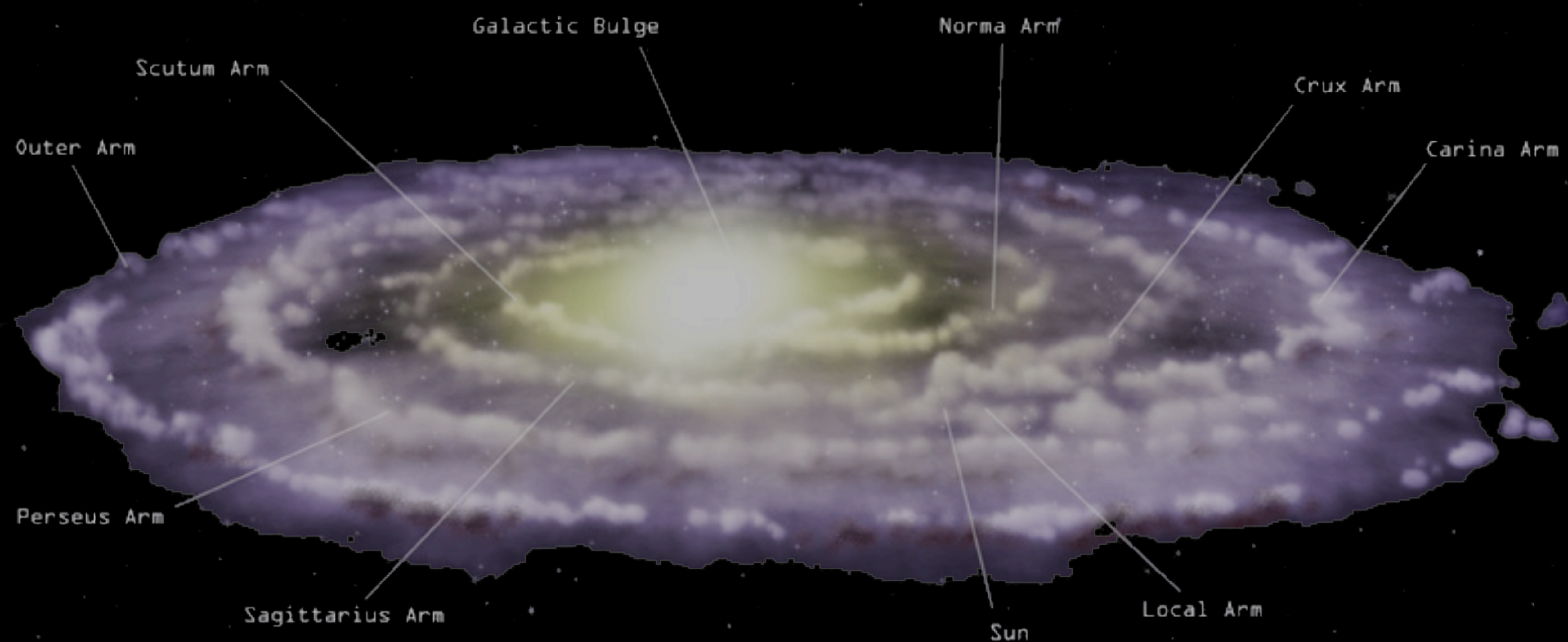
c. γ from Inverse Compton on $e^{\pm}$ in halo



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

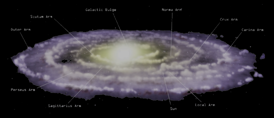
Indirect Detection: constraints

d. γ from outside the Galaxy



Indirect Detection: constraints

d. γ from outside the Galaxy

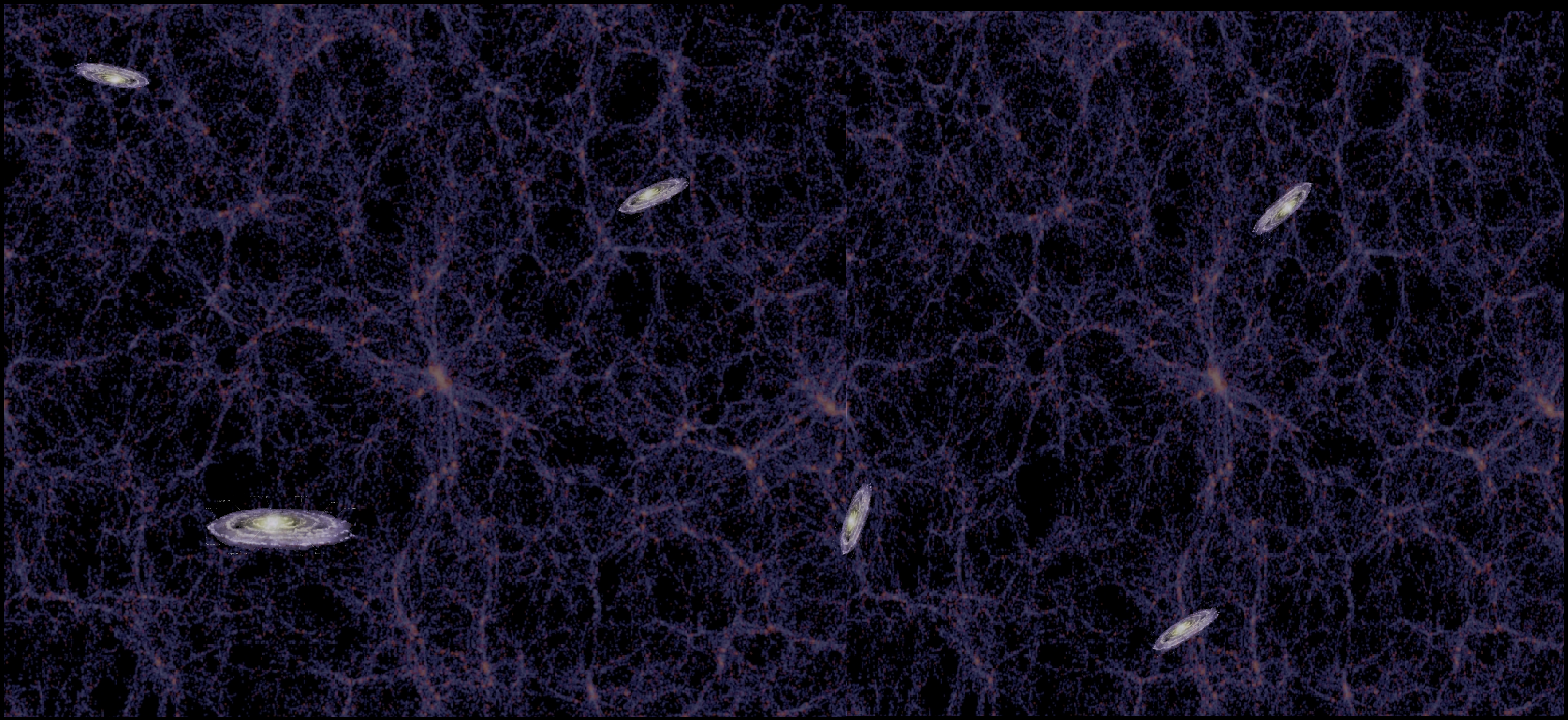


Indirect Detection: constraints

d. γ from outside the Galaxy

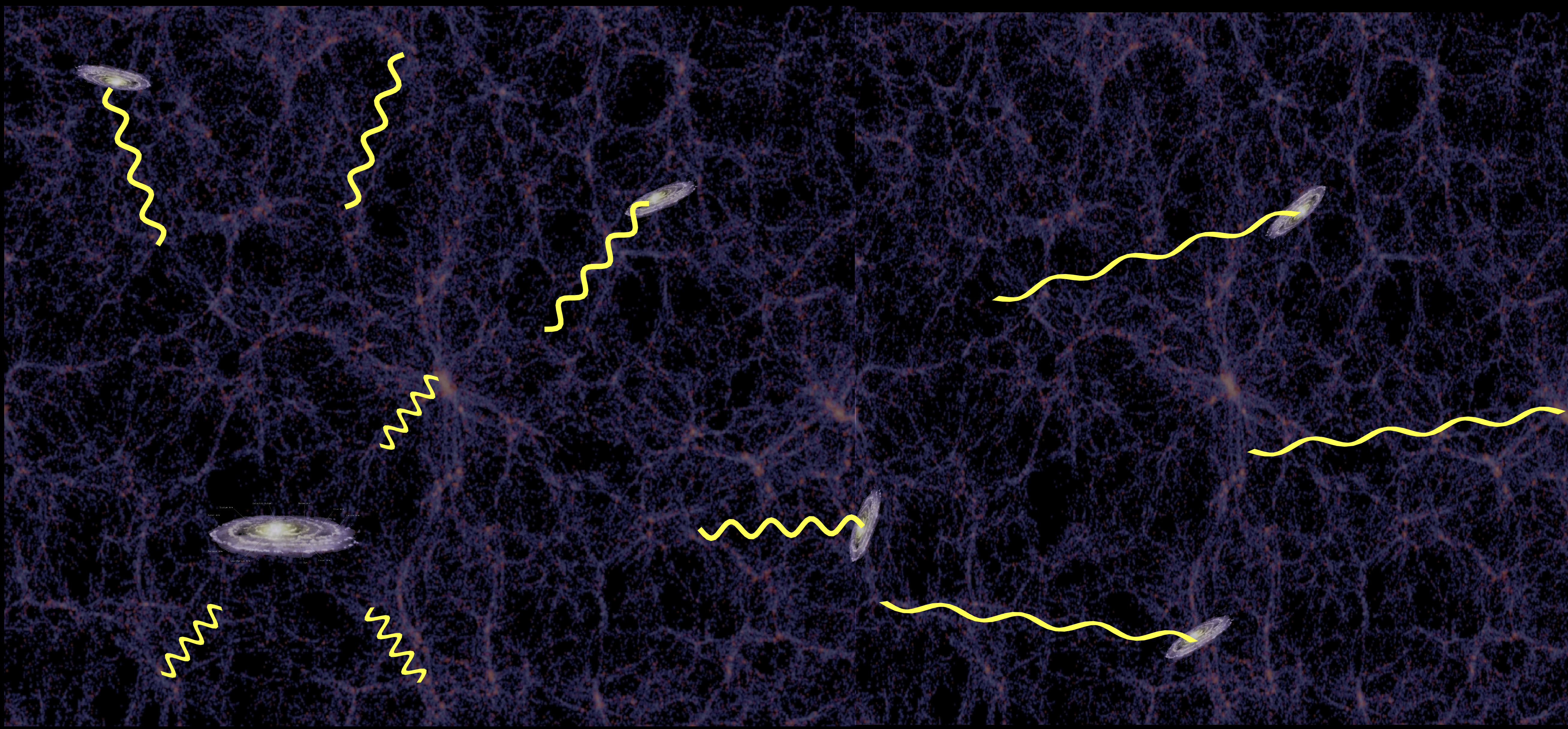
Indirect Detection: constraints

d. γ from outside the Galaxy



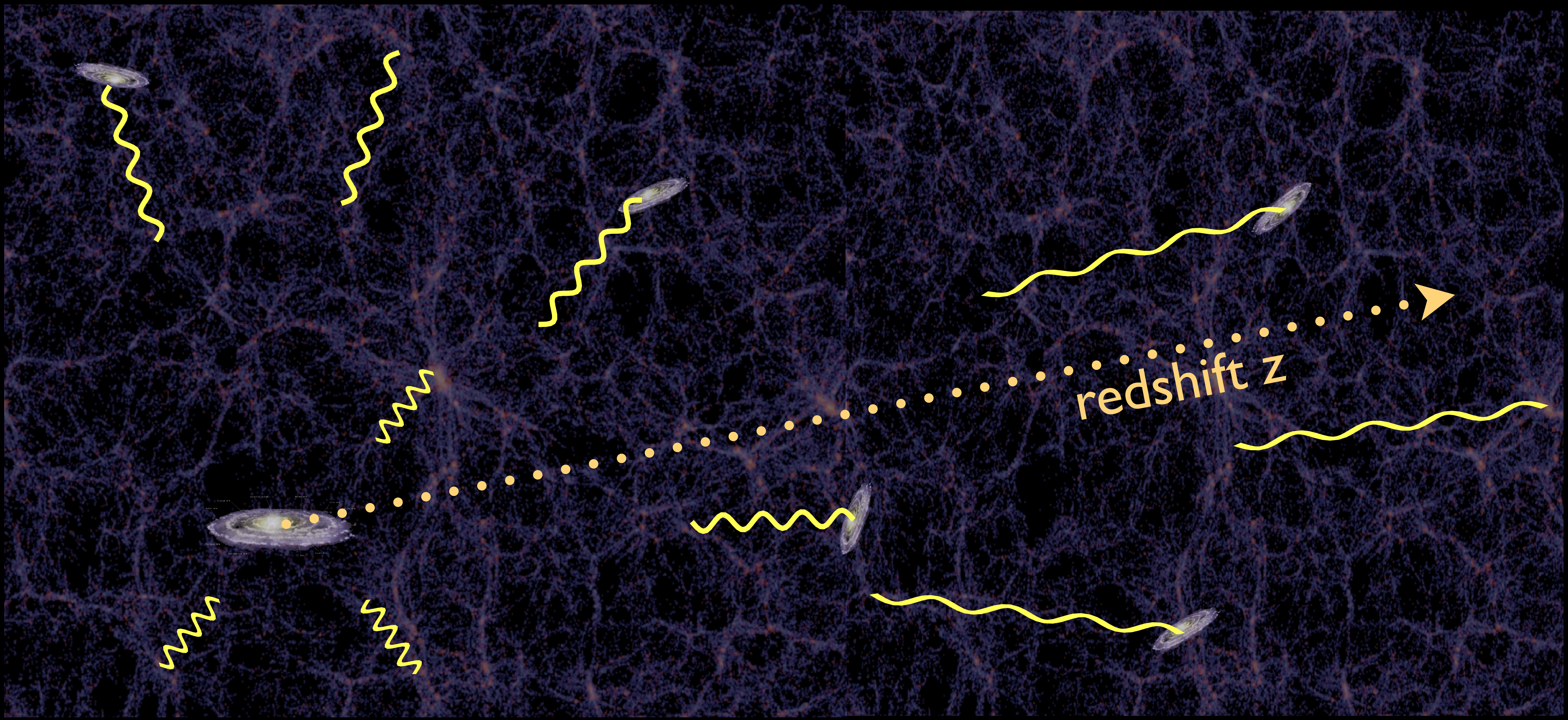
Indirect Detection: constraints

d. γ from outside the Galaxy



Indirect Detection: constraints

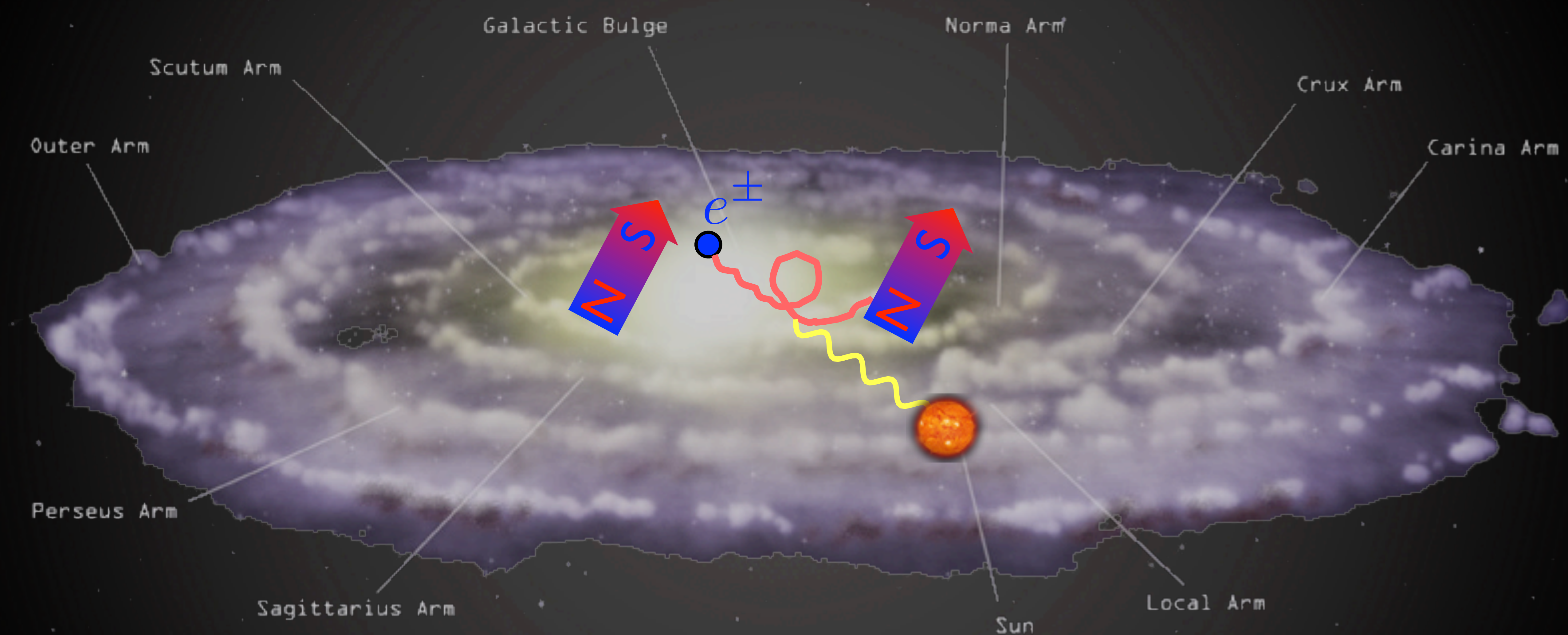
d. γ from outside the Galaxy



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

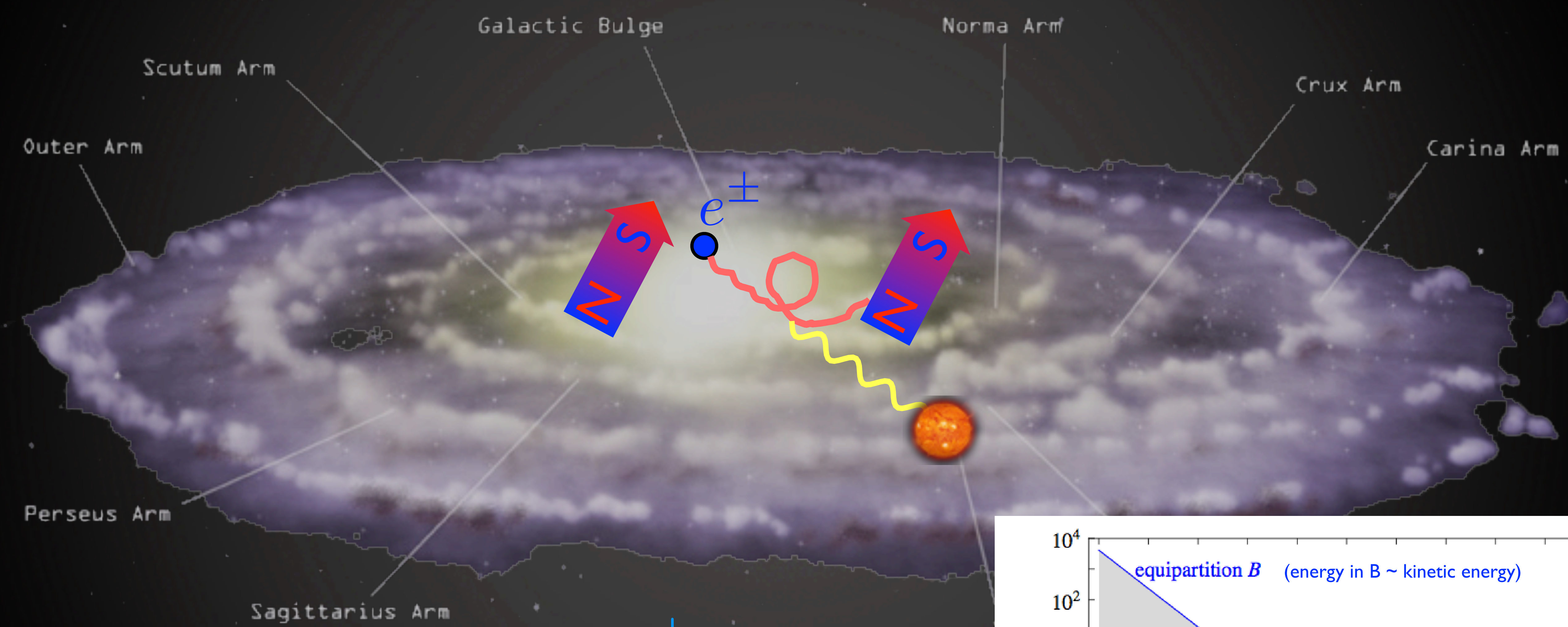
Indirect Detection: constraints

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



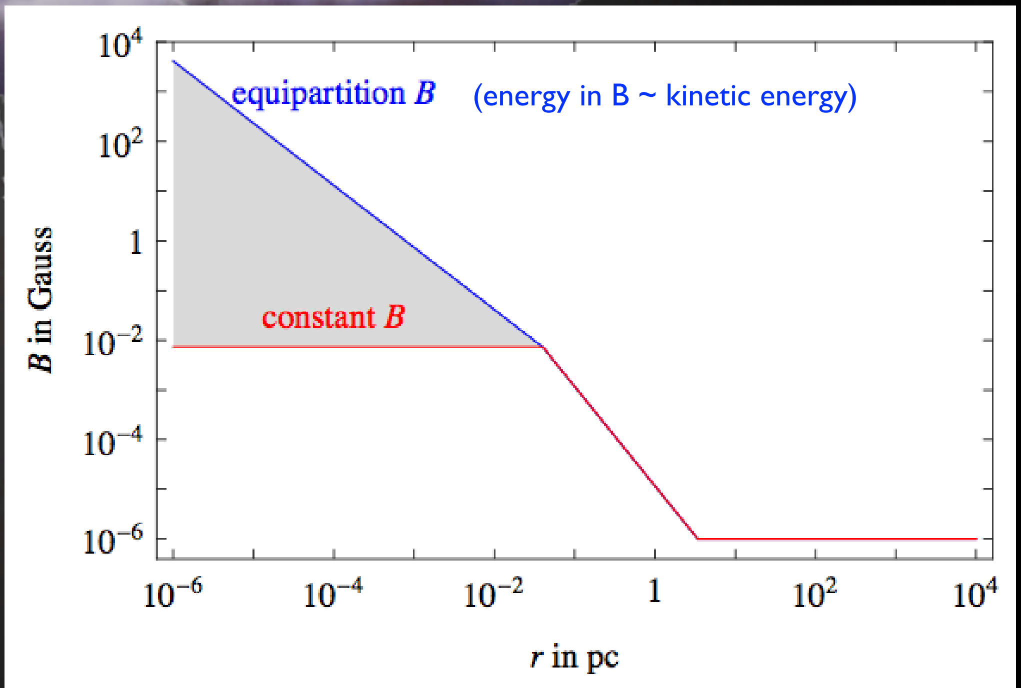
Indirect Detection: constraints

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



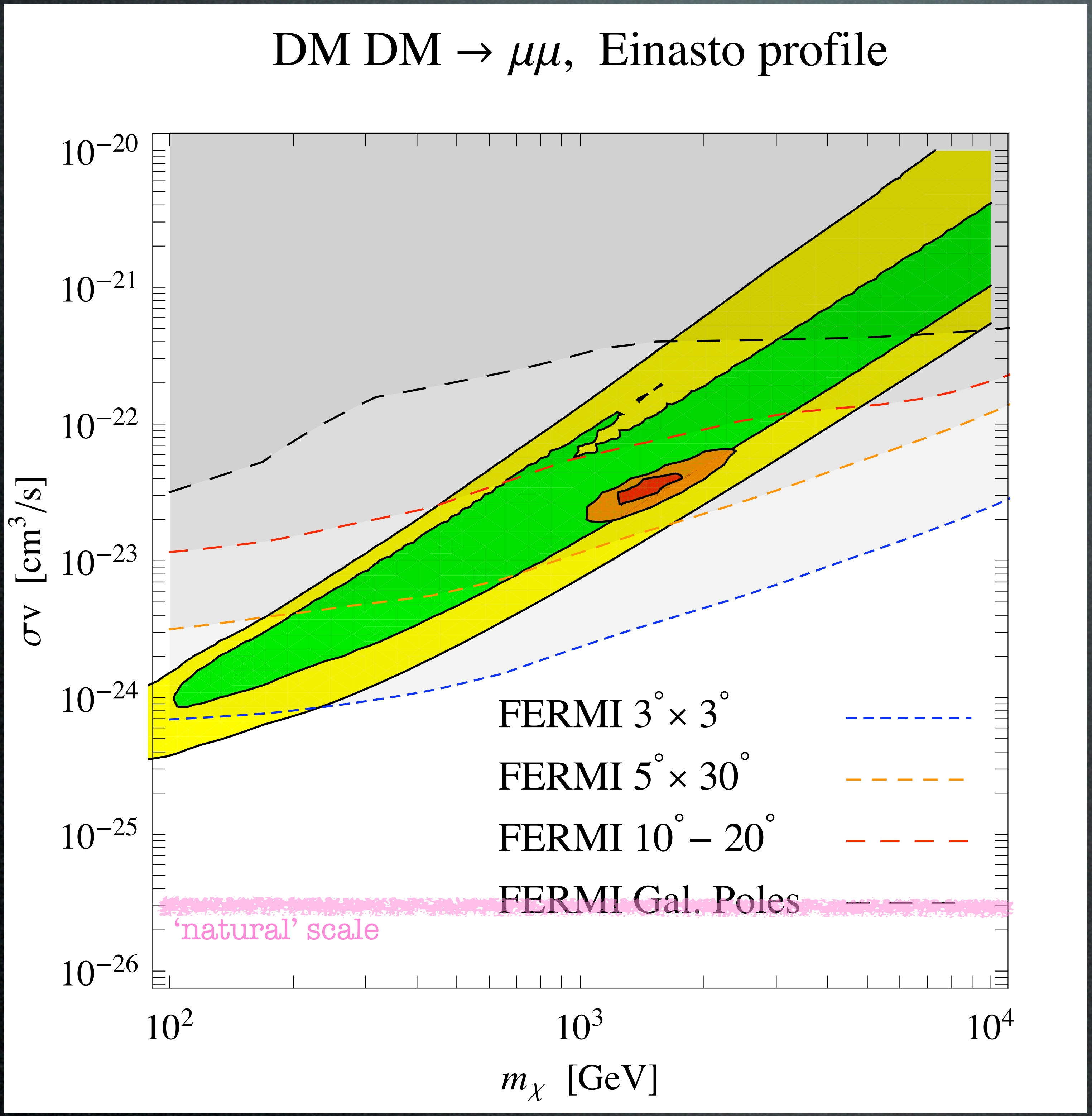
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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



Gamma constraints

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

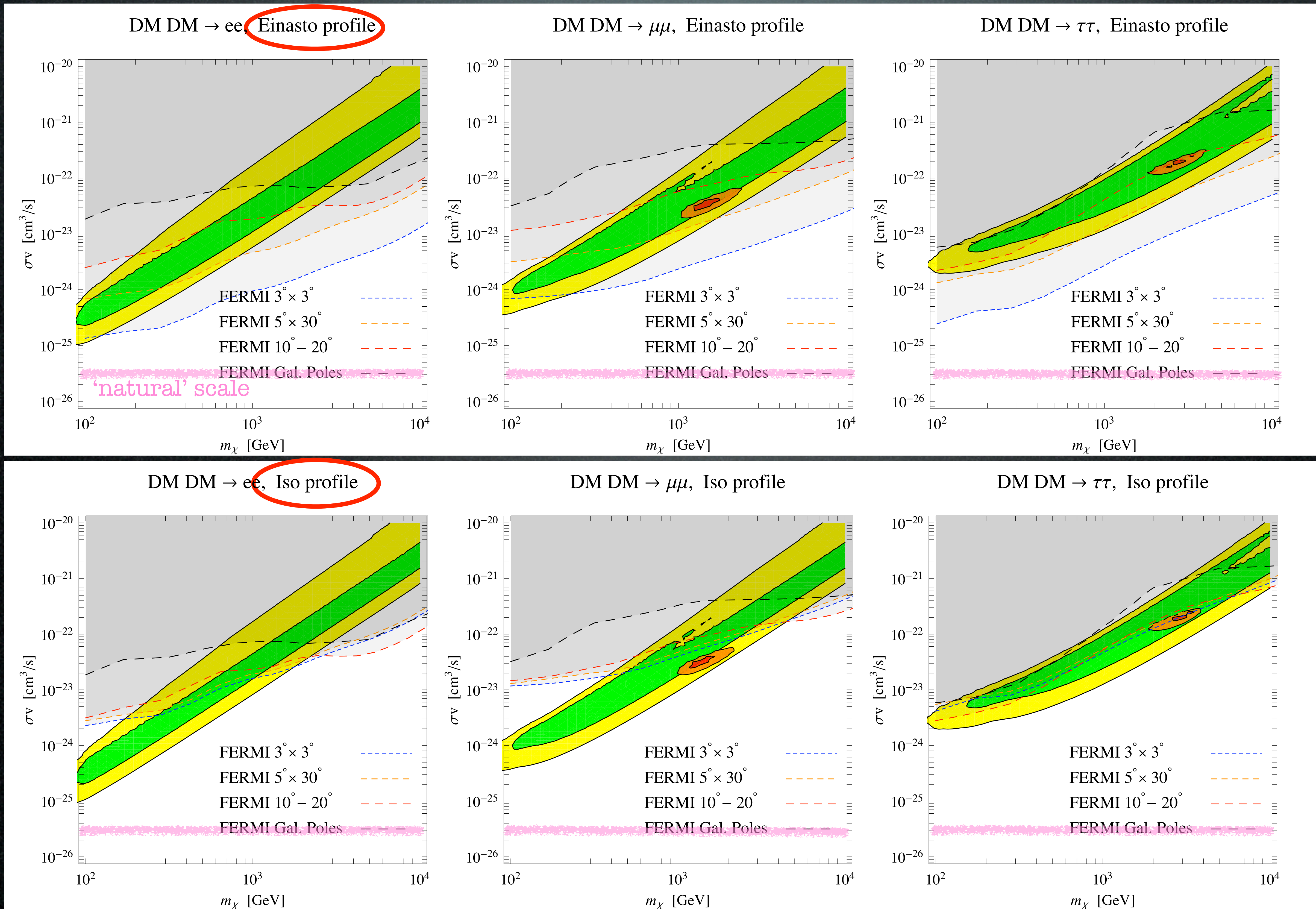


Cirelli, Panci, Serpico 0912.0663

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

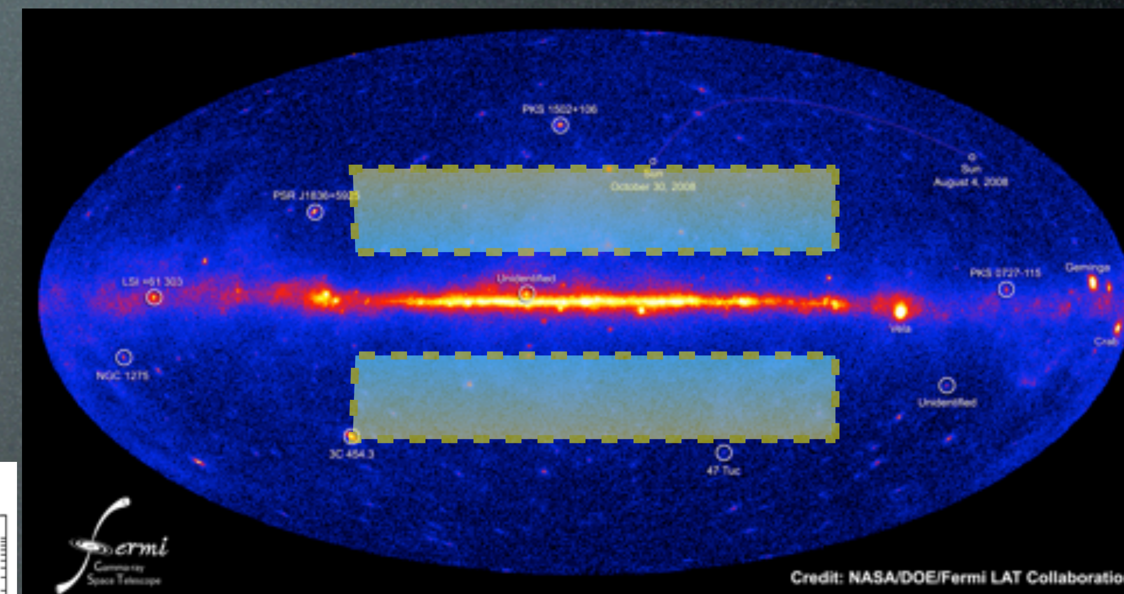


Cirelli, Panci, Serpico 0912.0663

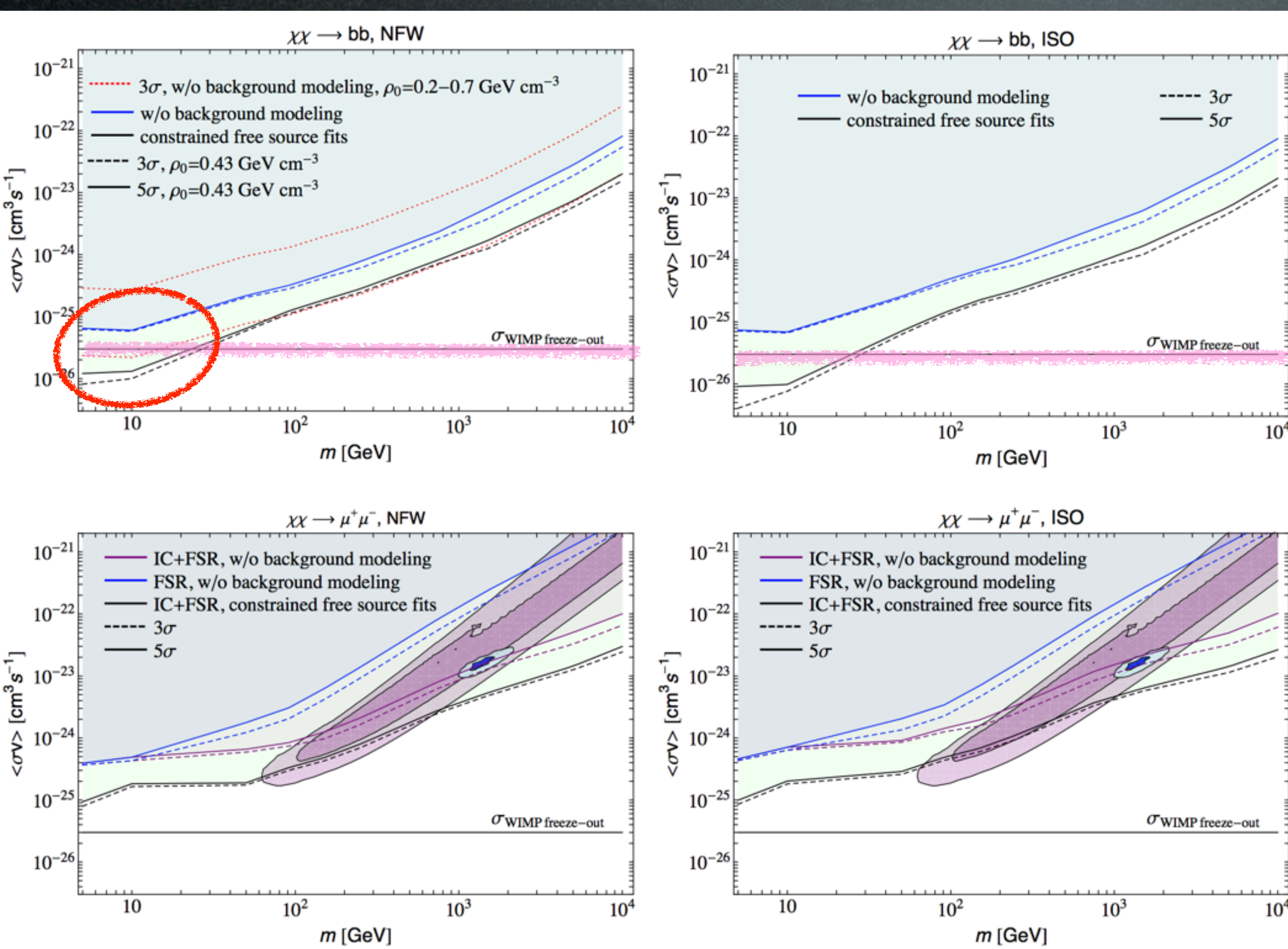
Gamma constraints

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

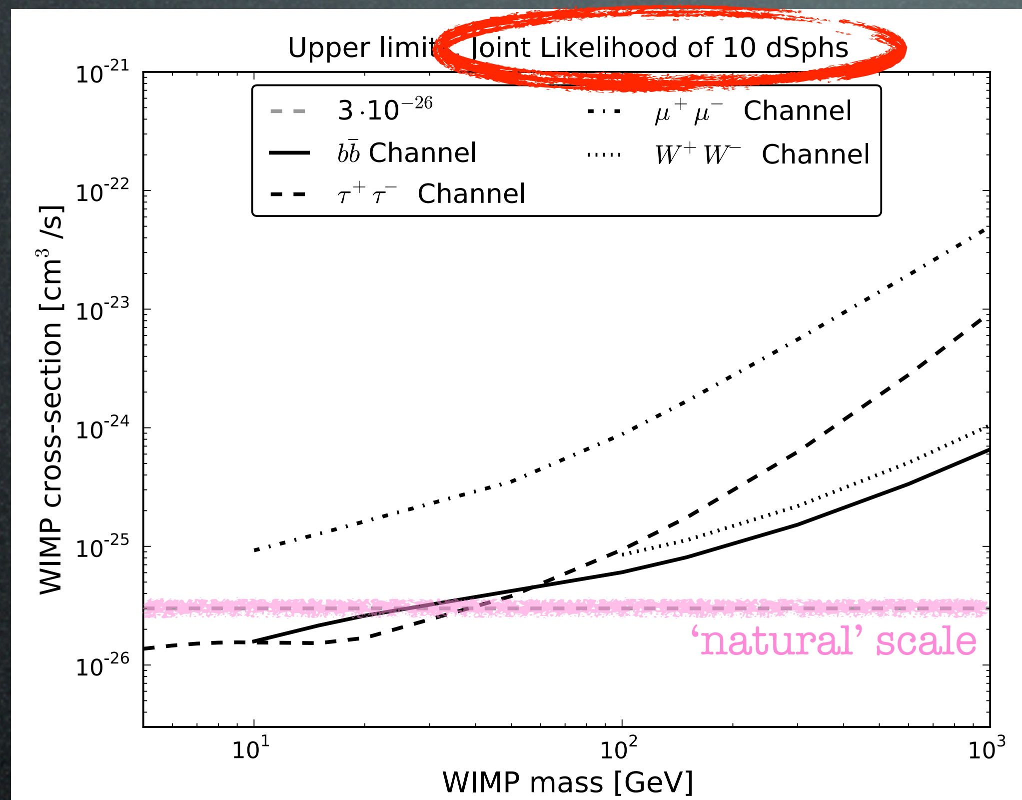
See also:
Papucci, Strumia,
0912.0742

Gamma constraints

γ from DM annihilations in Satellite Galaxies

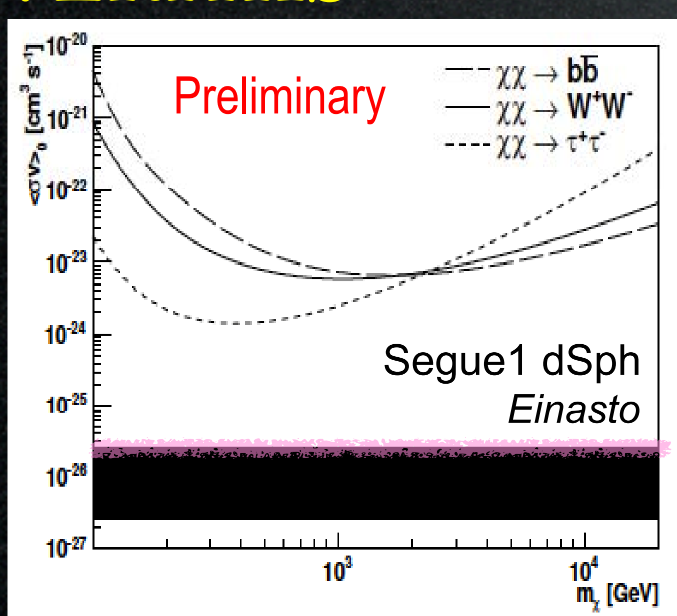
FERMI

FERMI coll., 1108.3546



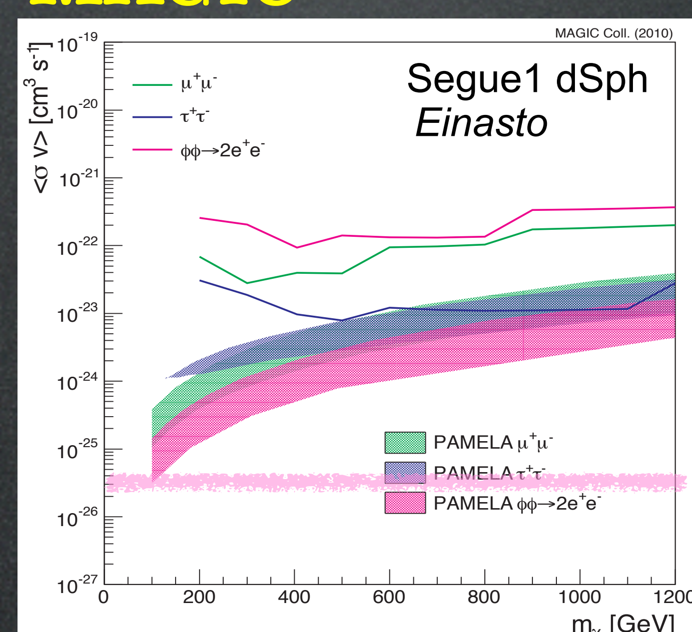
And the winner is...

VERITAS



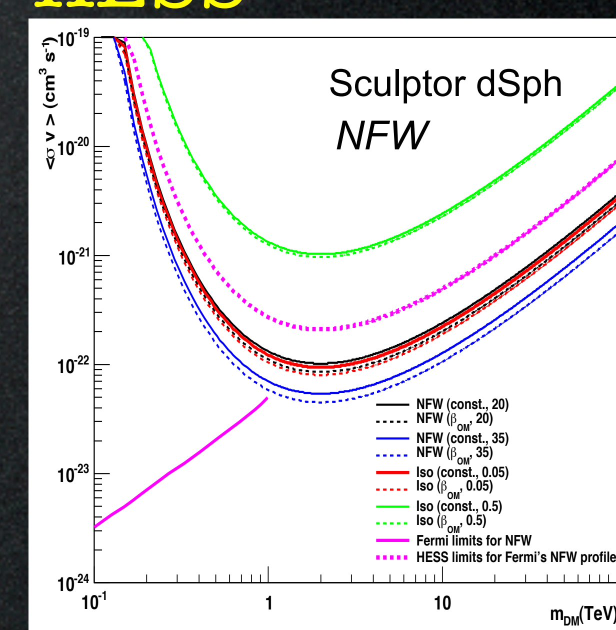
Veritas coll., courtesy of R.Ong

MAGIC



Magic coll., 1103.0477

HESS



HESS coll., 1012.5602

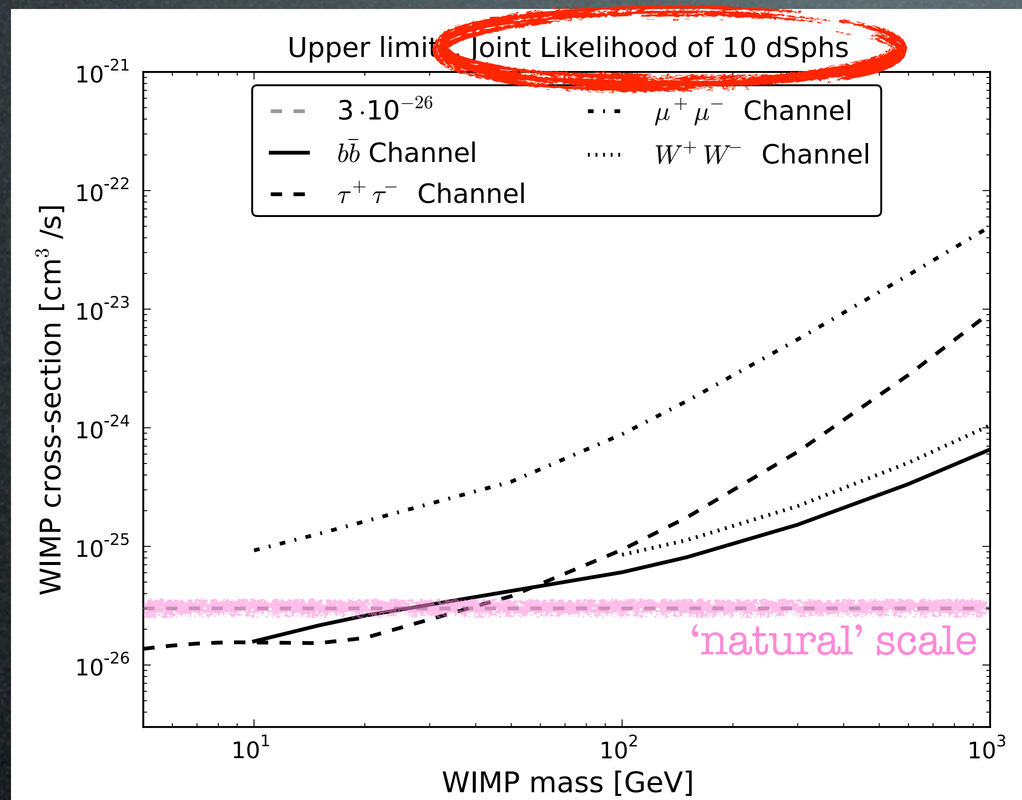
(HESS: Globular Clusters analysis too)

Gamma constraints

γ from DM annihilations in Satellite Galaxies

FERMI

FERMI coll., 1108.3546



And the winner is... FERMI.

But beware of different profiles, techniques...

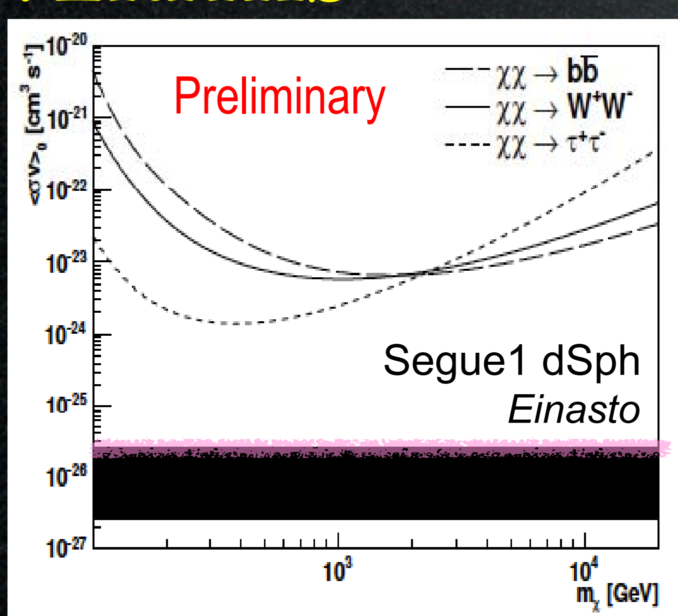
see also:

Geringer-Sameth, Koushiappas, 1108.2914

Strigari et al. (0902.4750, 1007.4199...)

Baxter, Dodelson et al.

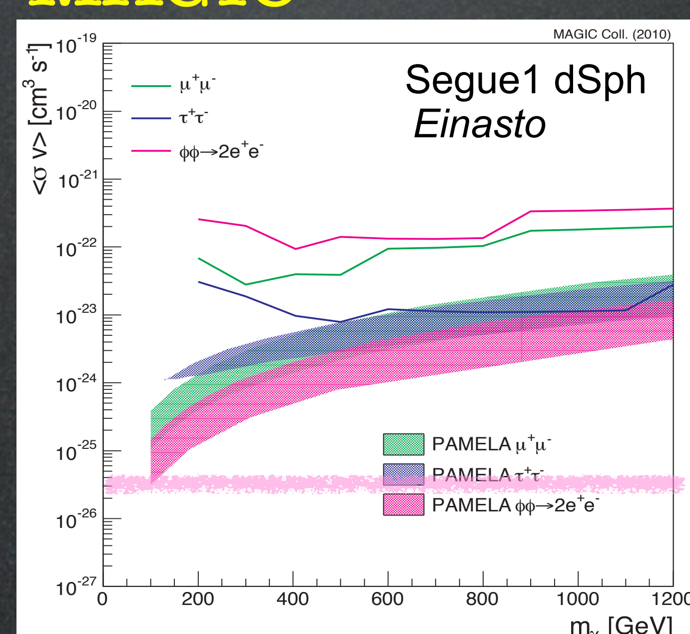
VERITAS



Veritas coll., courtesy of R.Ong

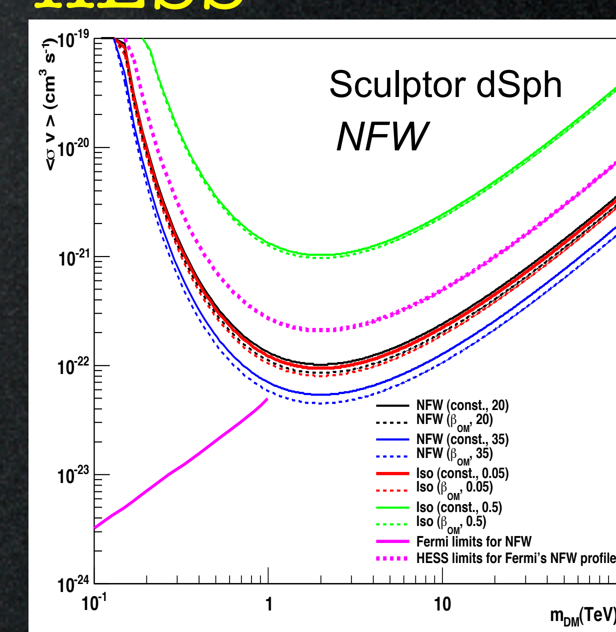
(currently the winner in the '1 dSph' category)

MAGIC



Magic coll., 1103.0477

HESS



HESS coll., 1012.5602

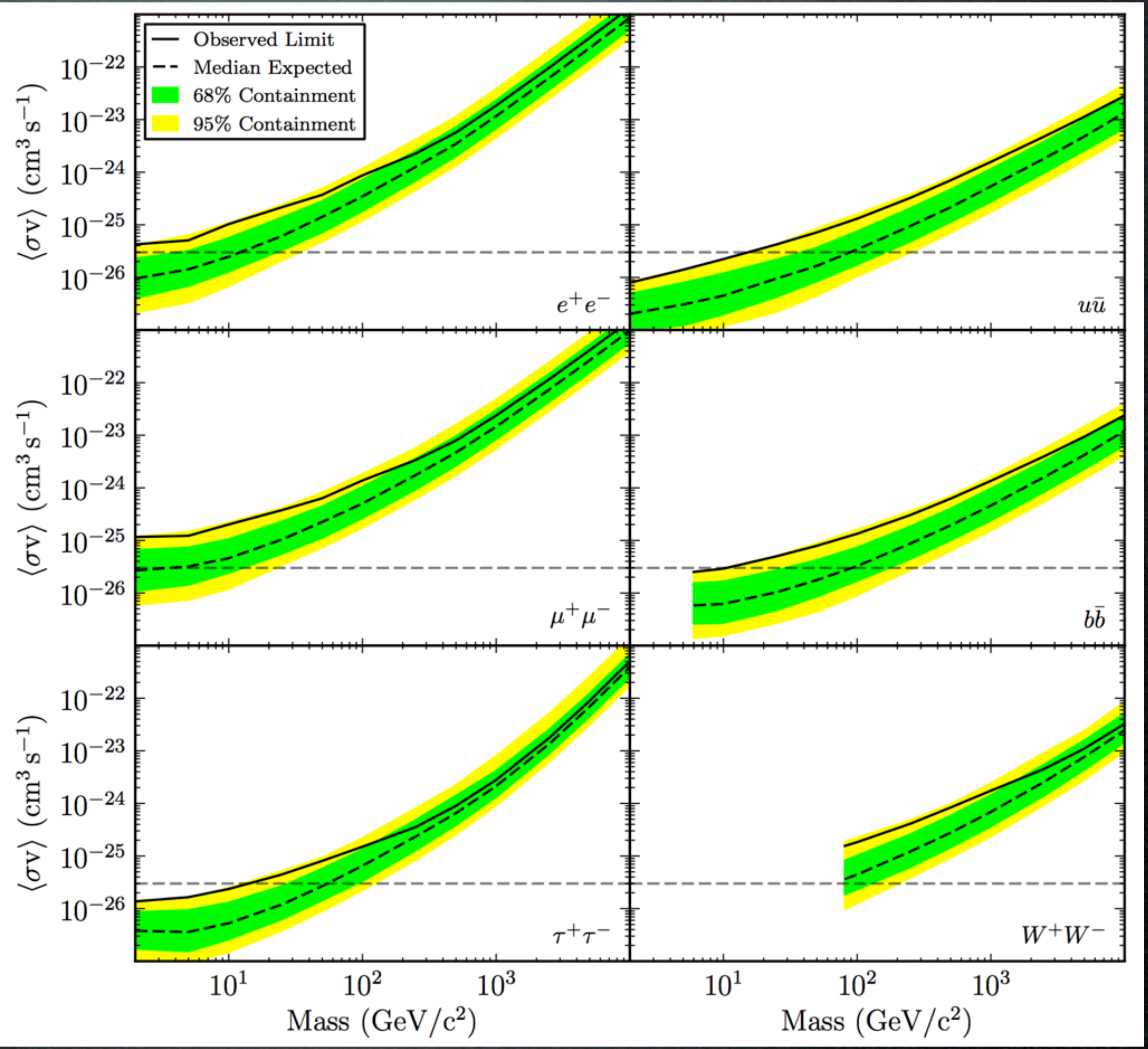
(HESS: Globular Clusters analysis too)

Gamma constraints

γ from DM annihilations in Satellite Galaxies

FERMI

1310.0828 Fermi coll.,
Alex Drlica-Wagner



4 years data:
weaker bound

(or 10 GeV DM
peeping out?)

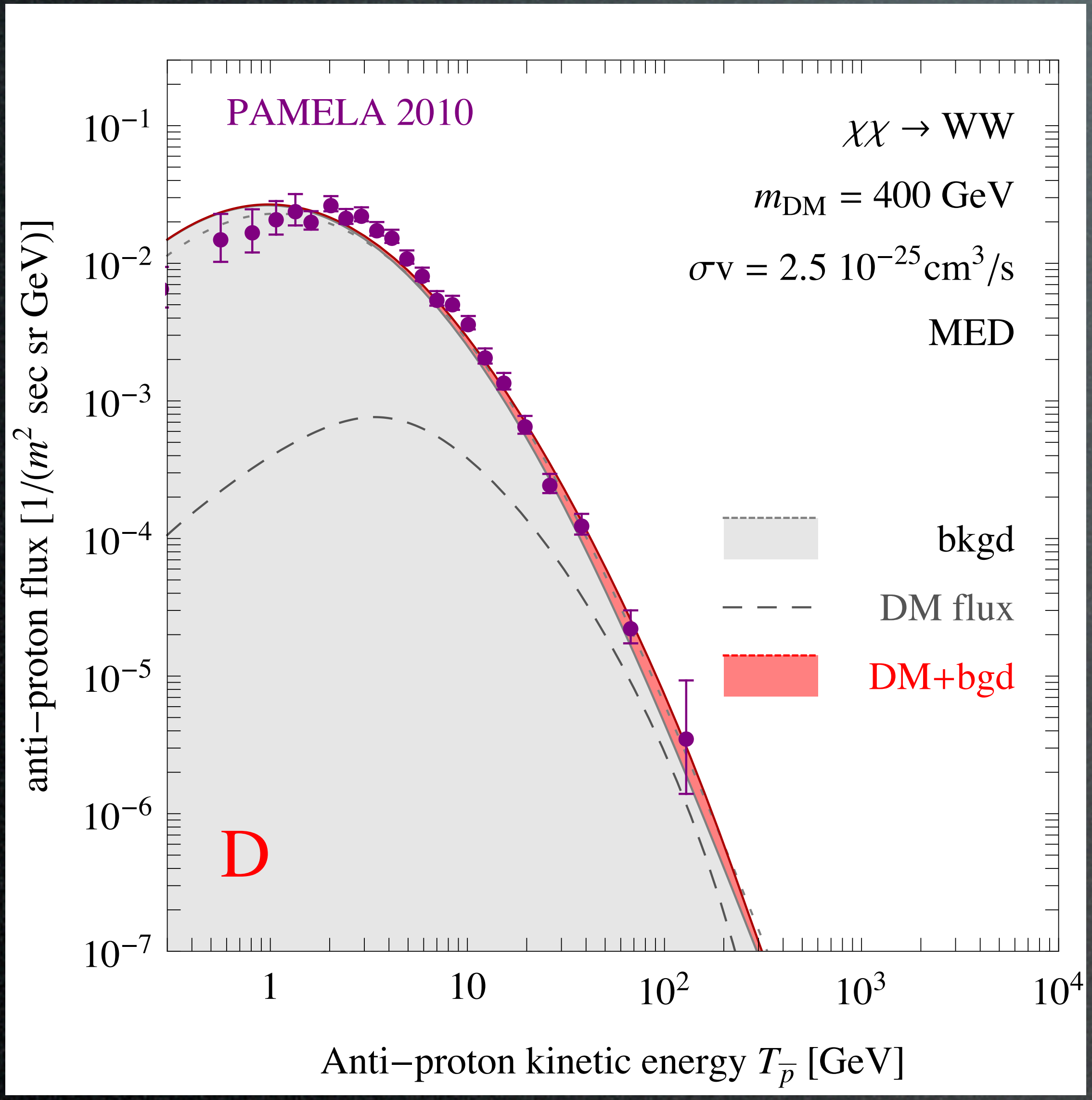
Antiproton **constraints**

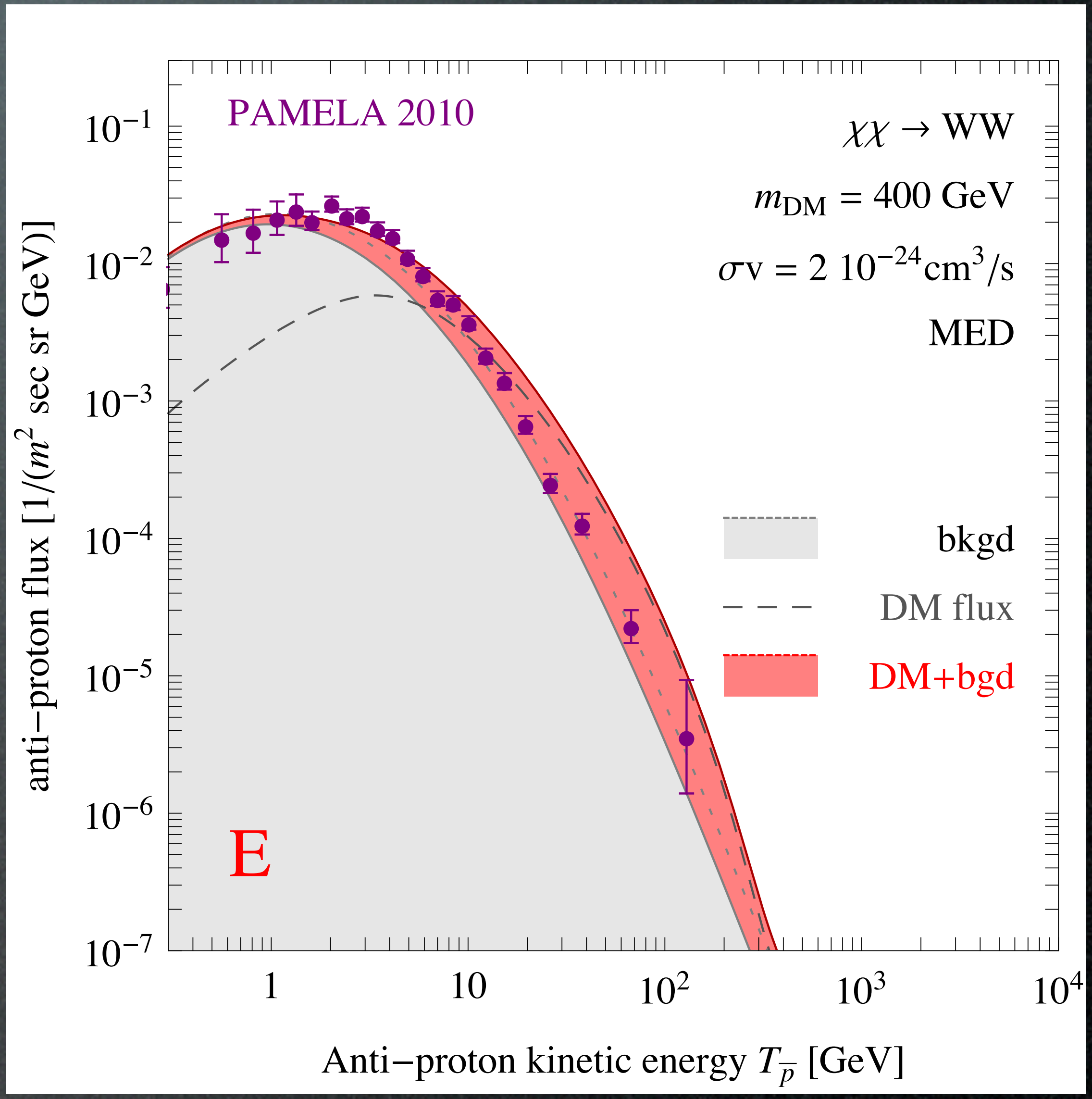
Cirelli, Giesen 1301.7079

Antiproton constraints

Constrain the DM flux on top of background

⇨ 95% C.L. bound on annihilation cross section $\langle \sigma v \rangle$



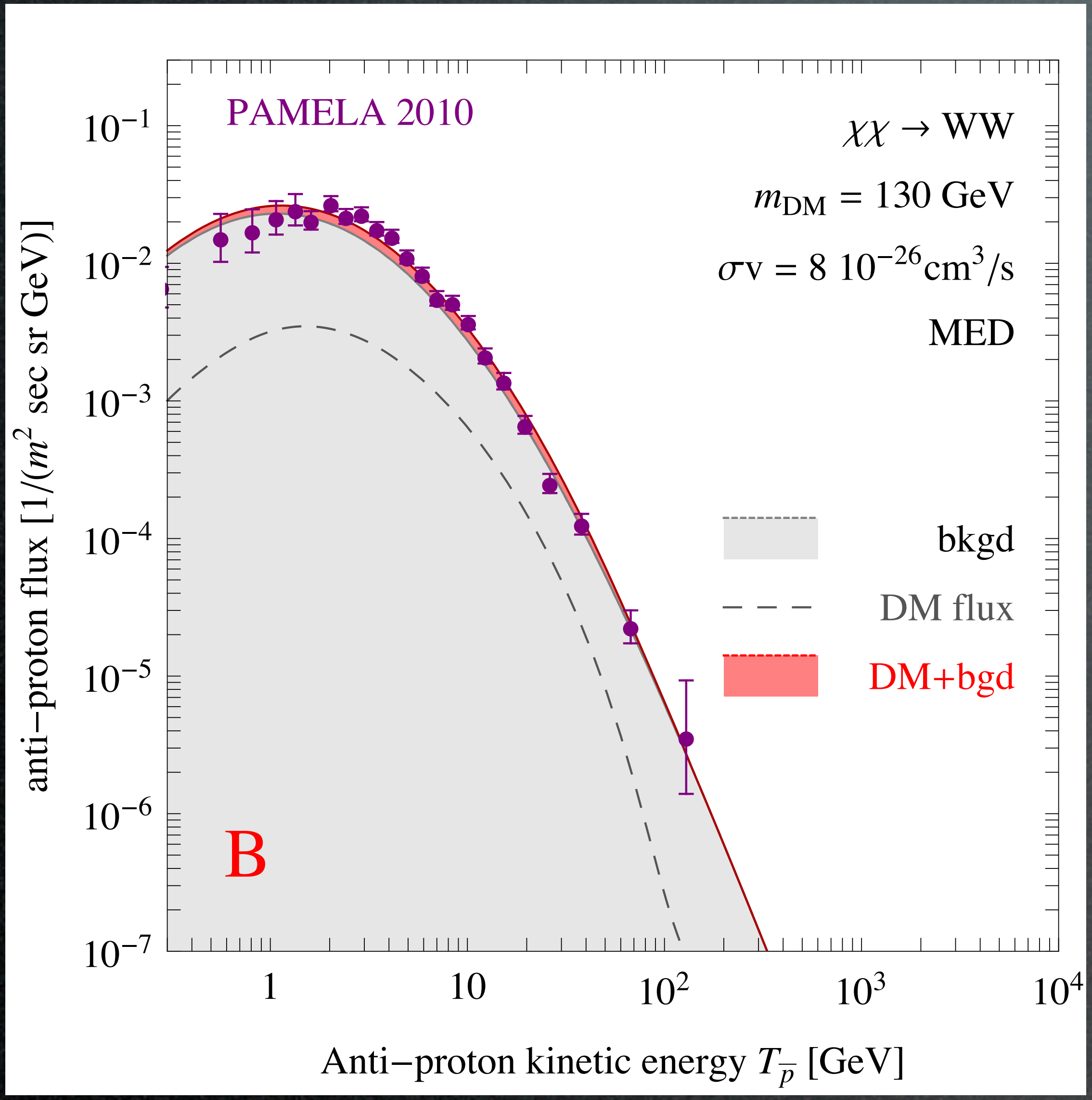


☑ allowed

☒ excluded

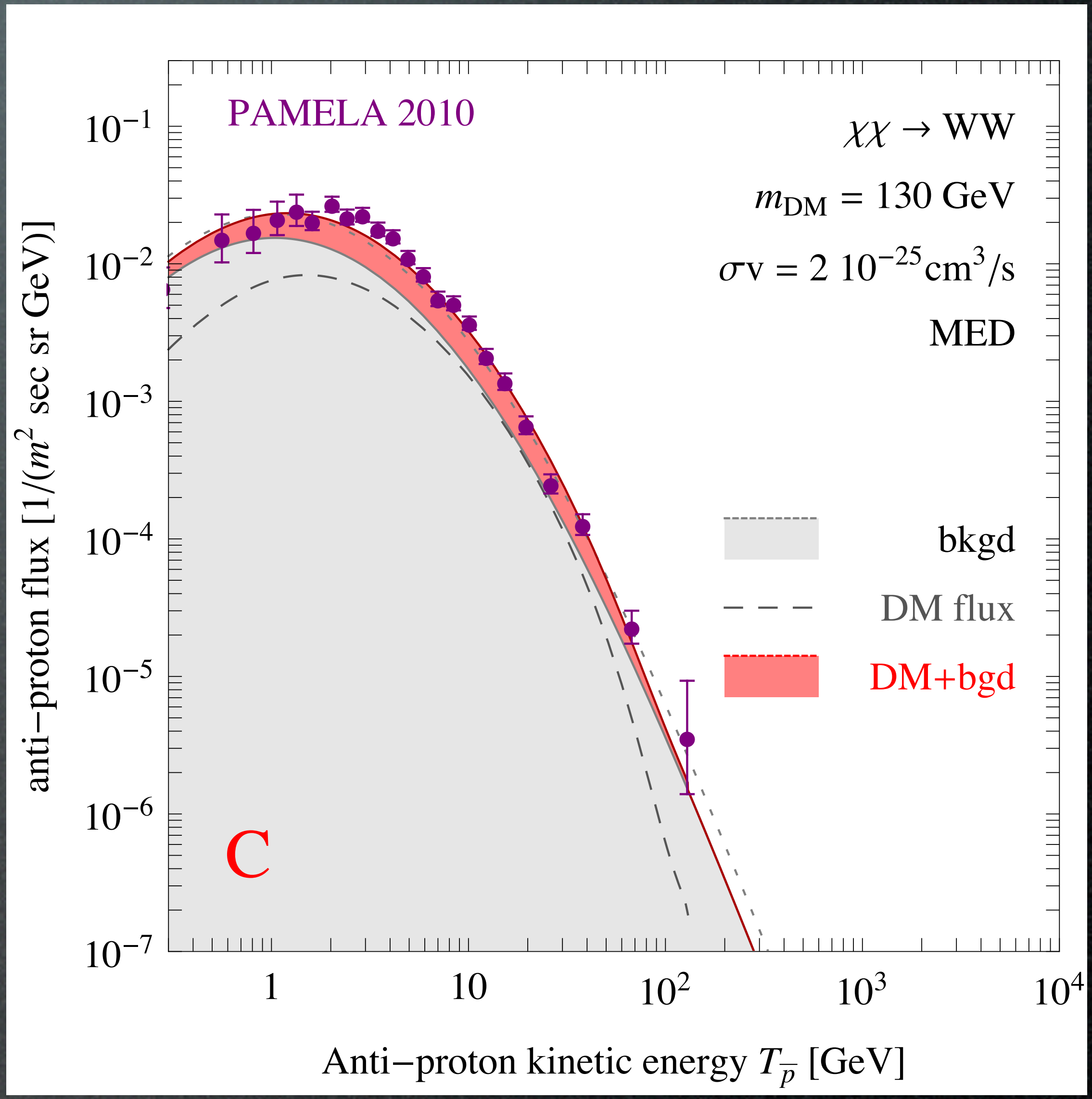
Antiproton constraints

We marginalize w.r.t. the slope
$E^p, \quad p = \pm 0.05$
and let normalization free by 10%.



fixed background

☑ allowed

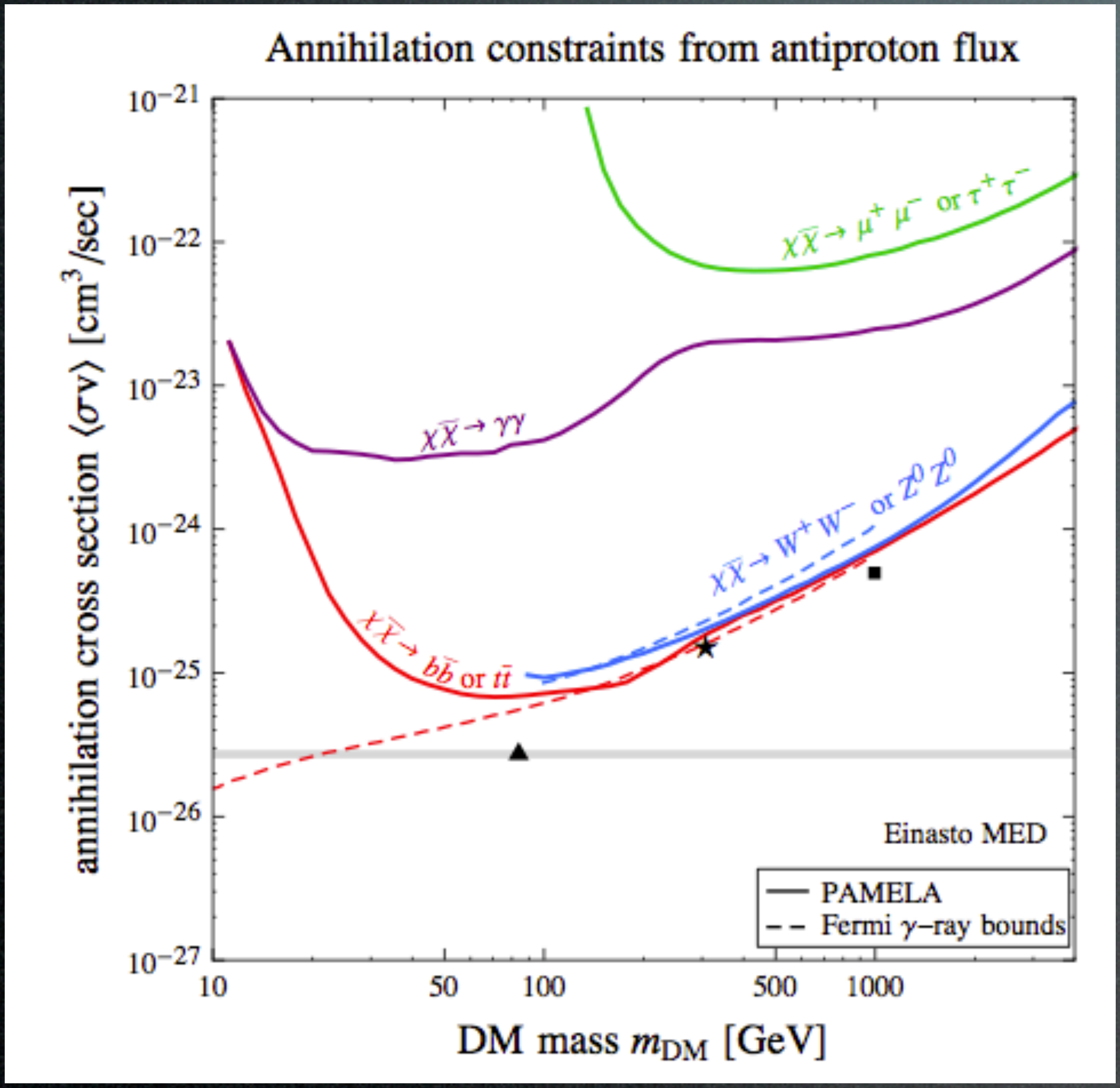


marginalized background

☑ allowed

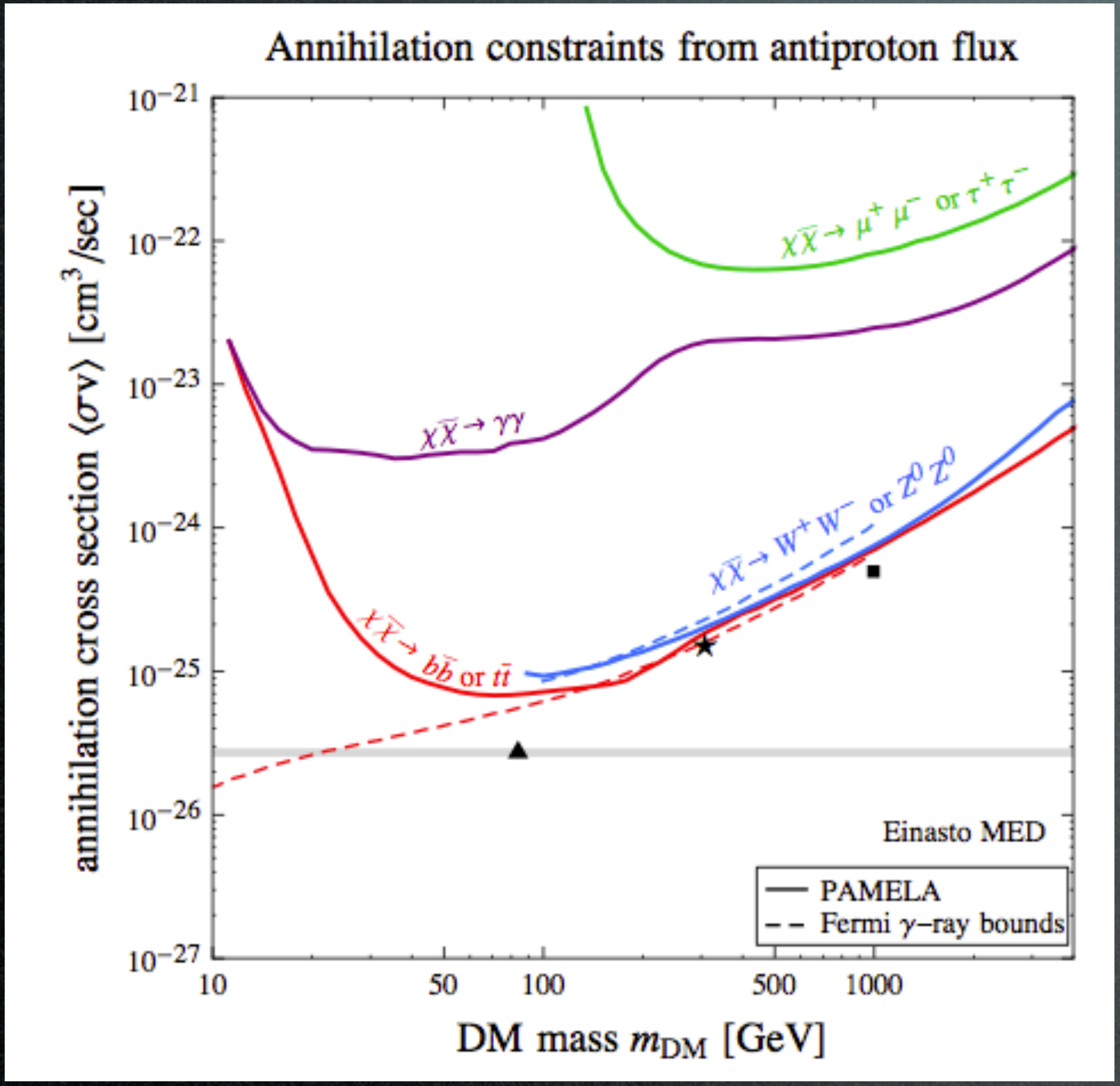
Antiproton constraints

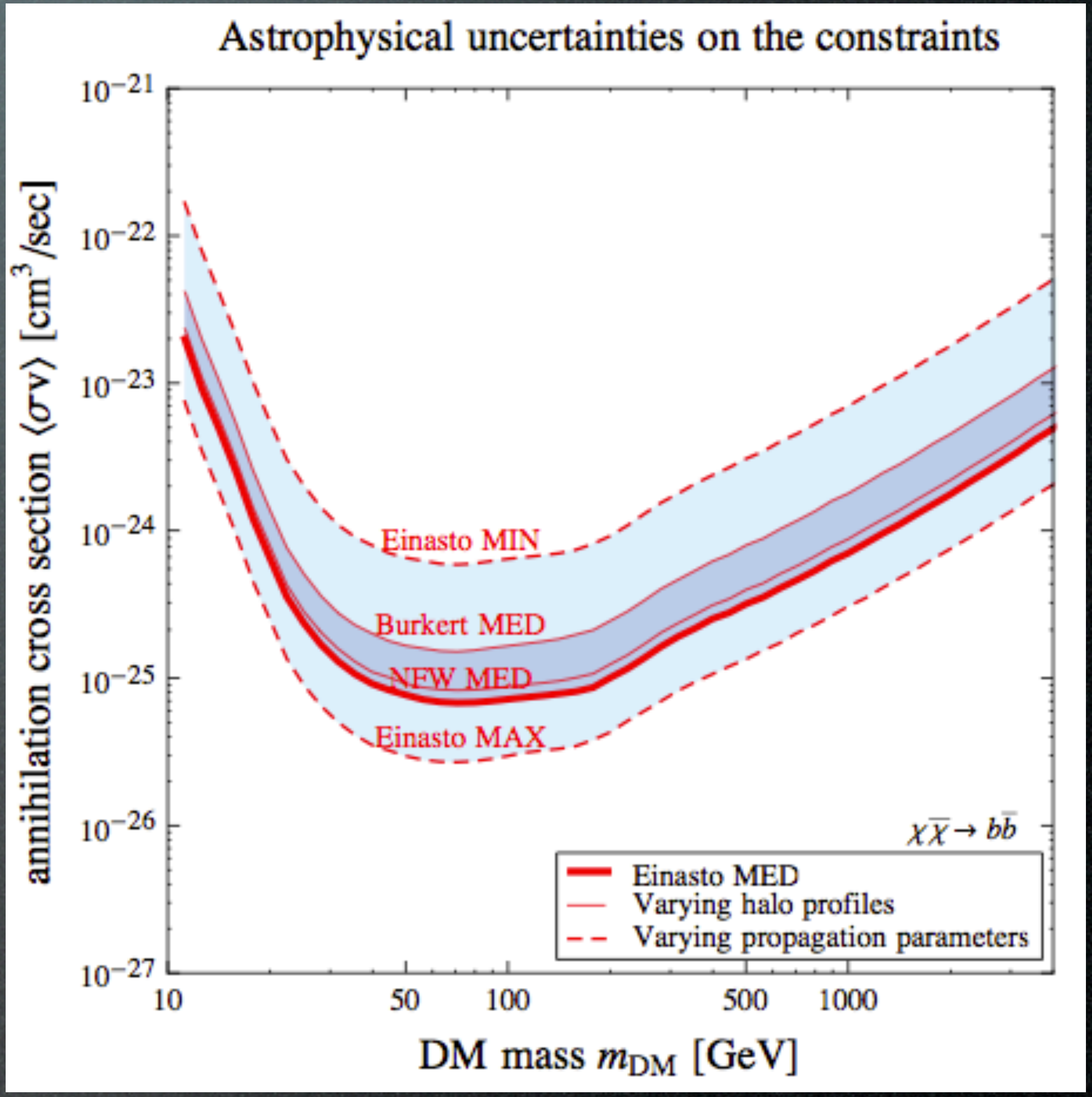
Constraints are powerful...



Antiproton constraints

Constraints are powerful...

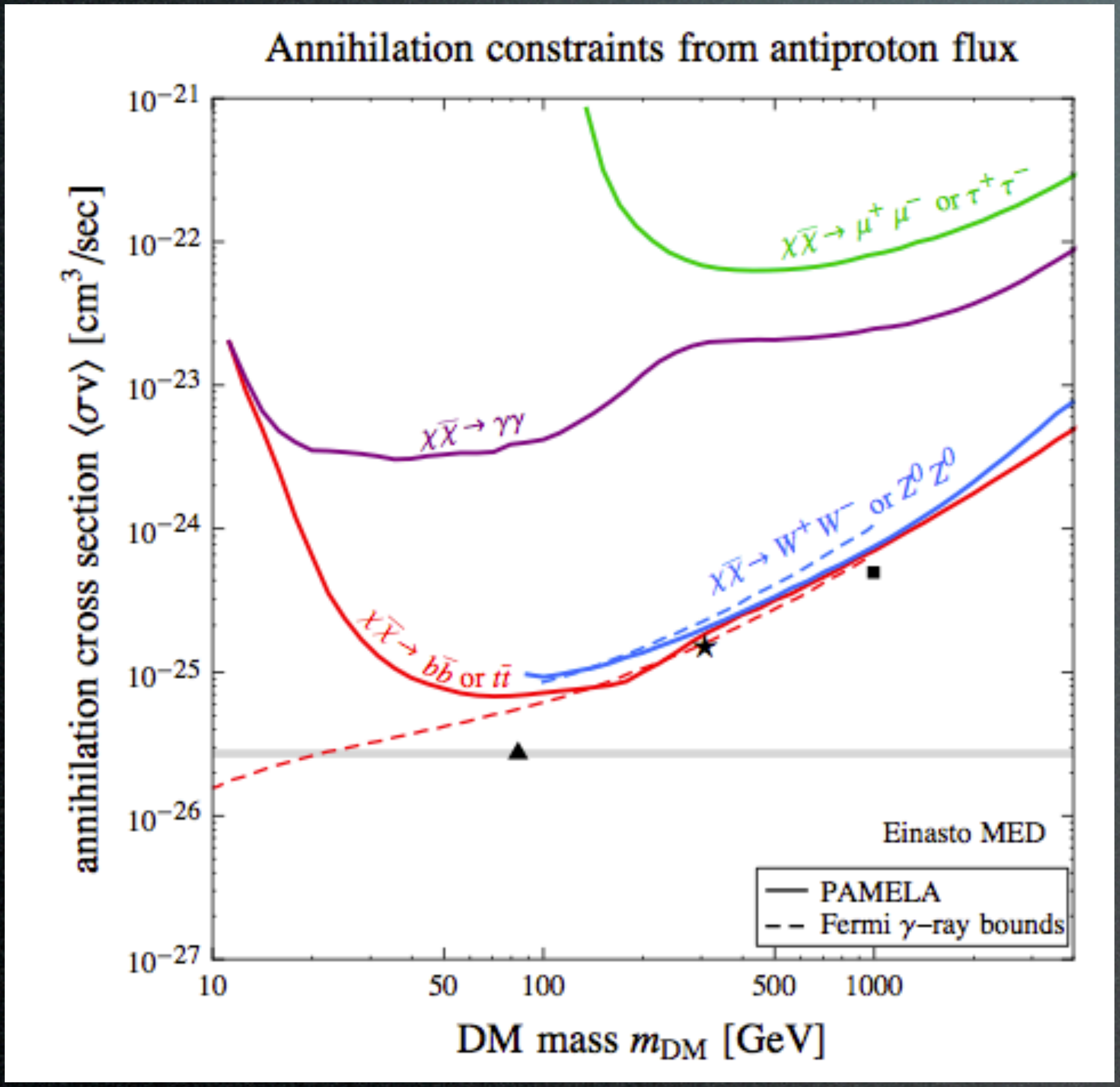




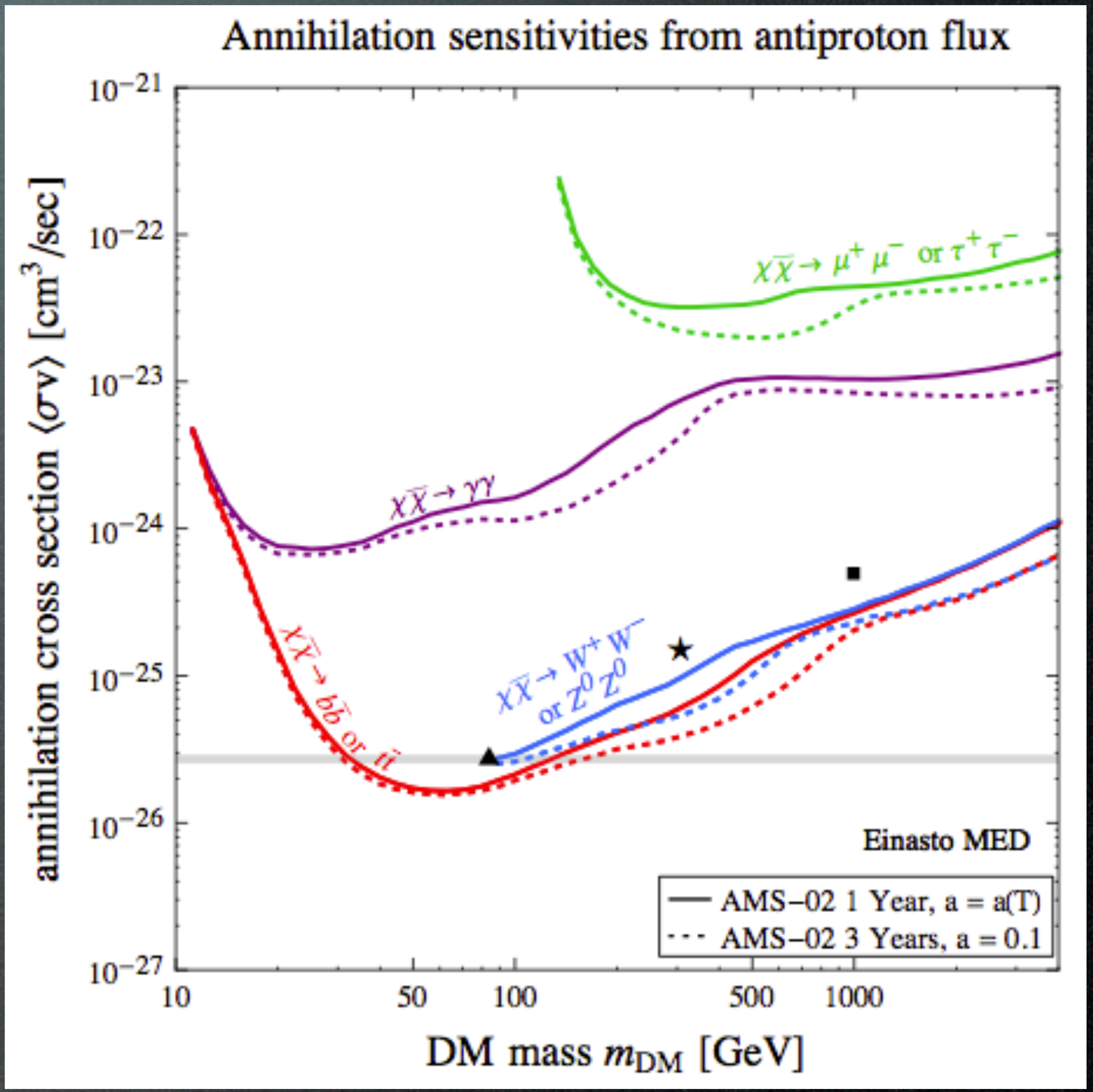
...but subject to uncertainties

Antiproton constraints

Constraints are powerful...

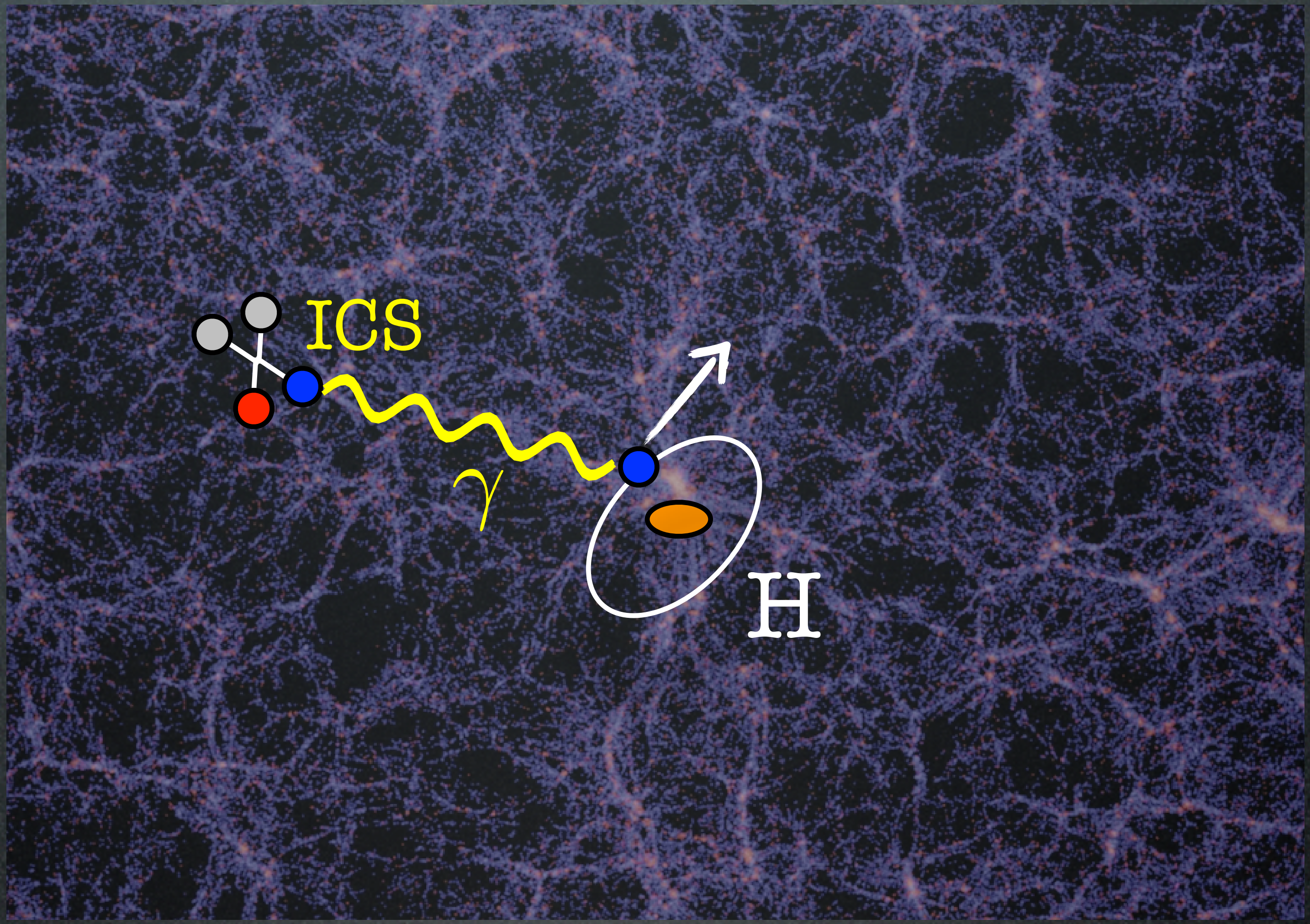


AMS-02 will improve



Cosmology: bounds from reionization

DM particle annihilations produce free electrons



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

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

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

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

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

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

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

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

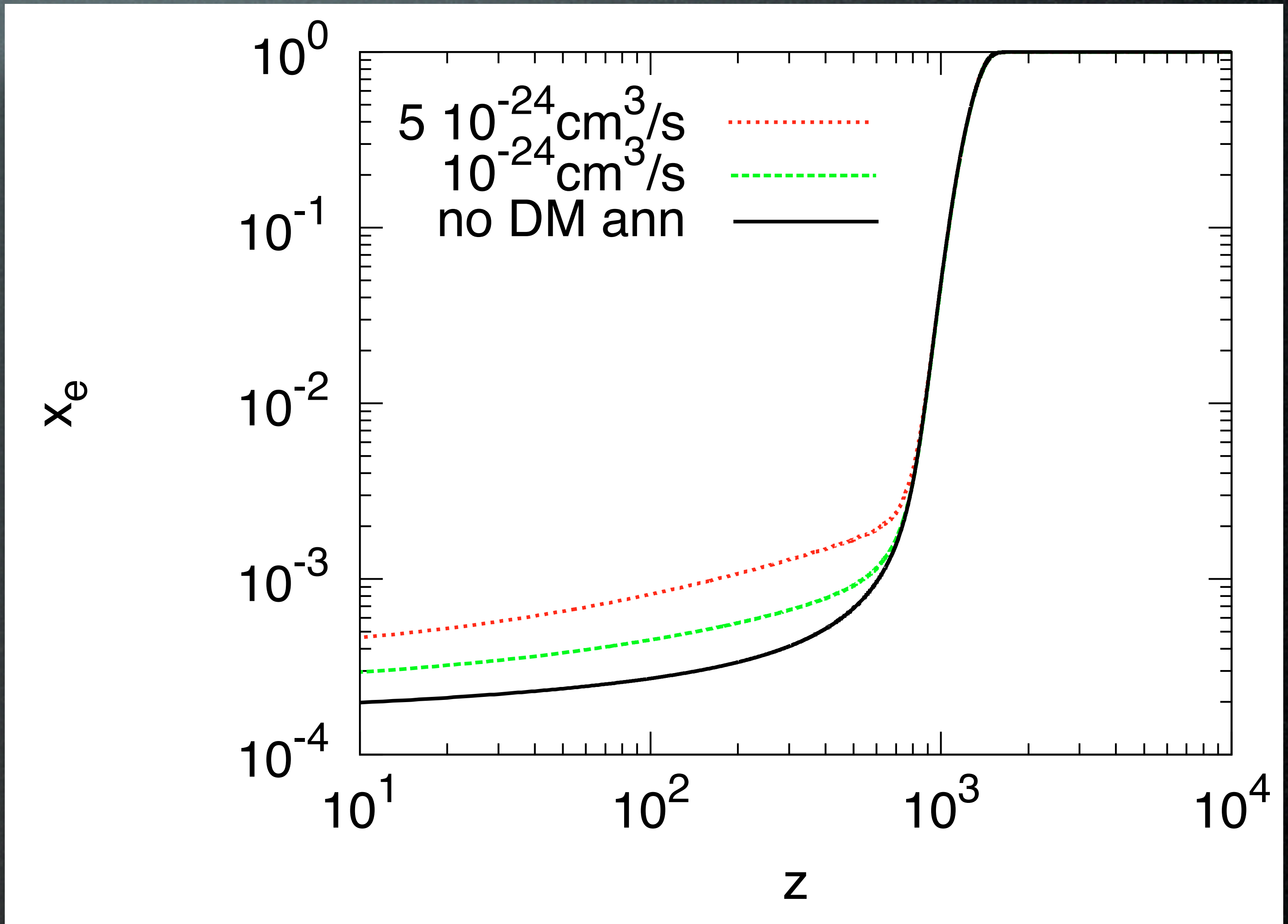
$$\mathcal{B}_i(z) = \frac{\Delta_{\rm vir}(z)}{3\,\rho_c\Omega_M}\int_{M_{\rm min}}^\infty dM\,M\frac{dn}{dM}(z,M)\,F_i(M,z),$$

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

Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

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

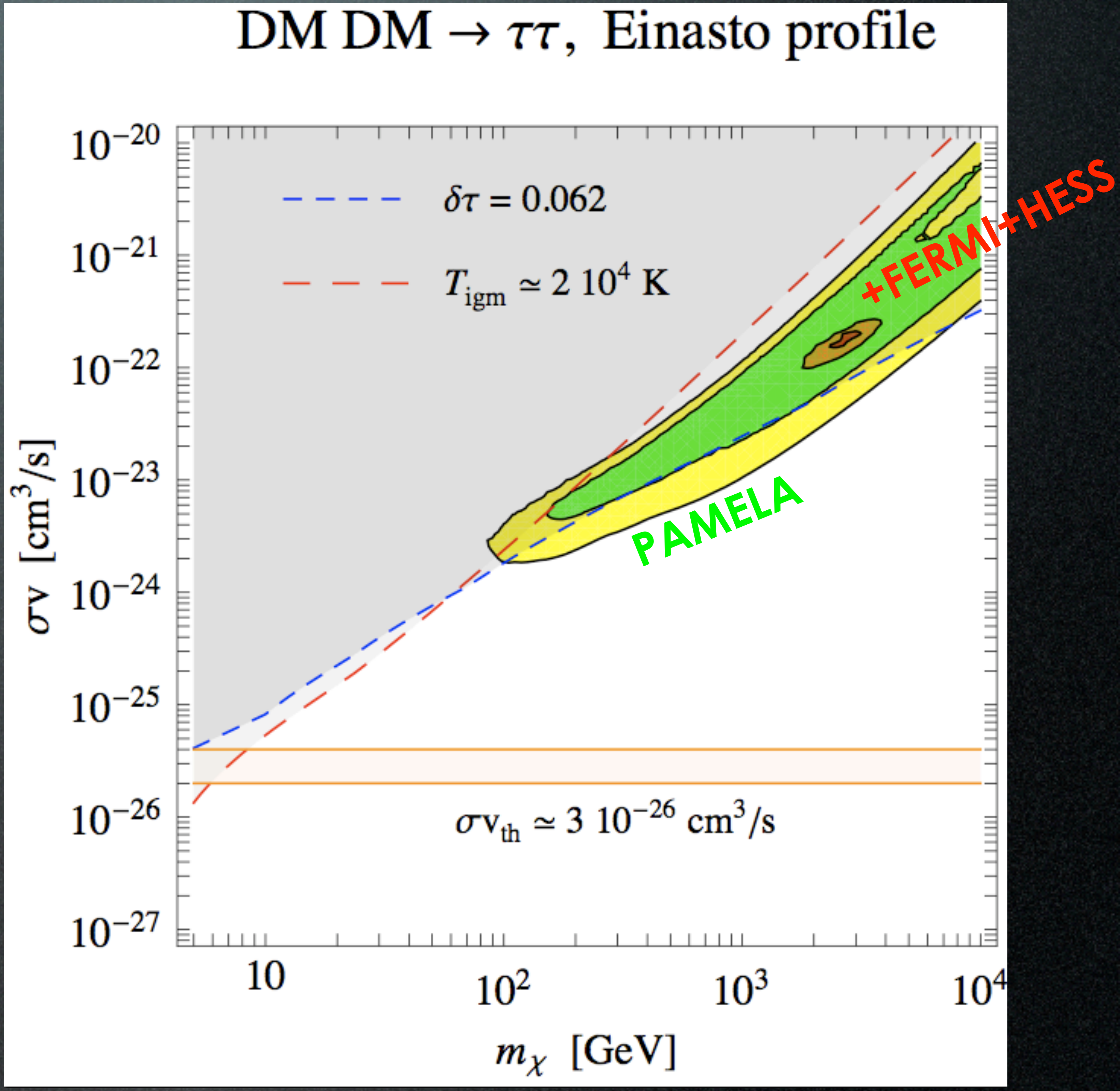


Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

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

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



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

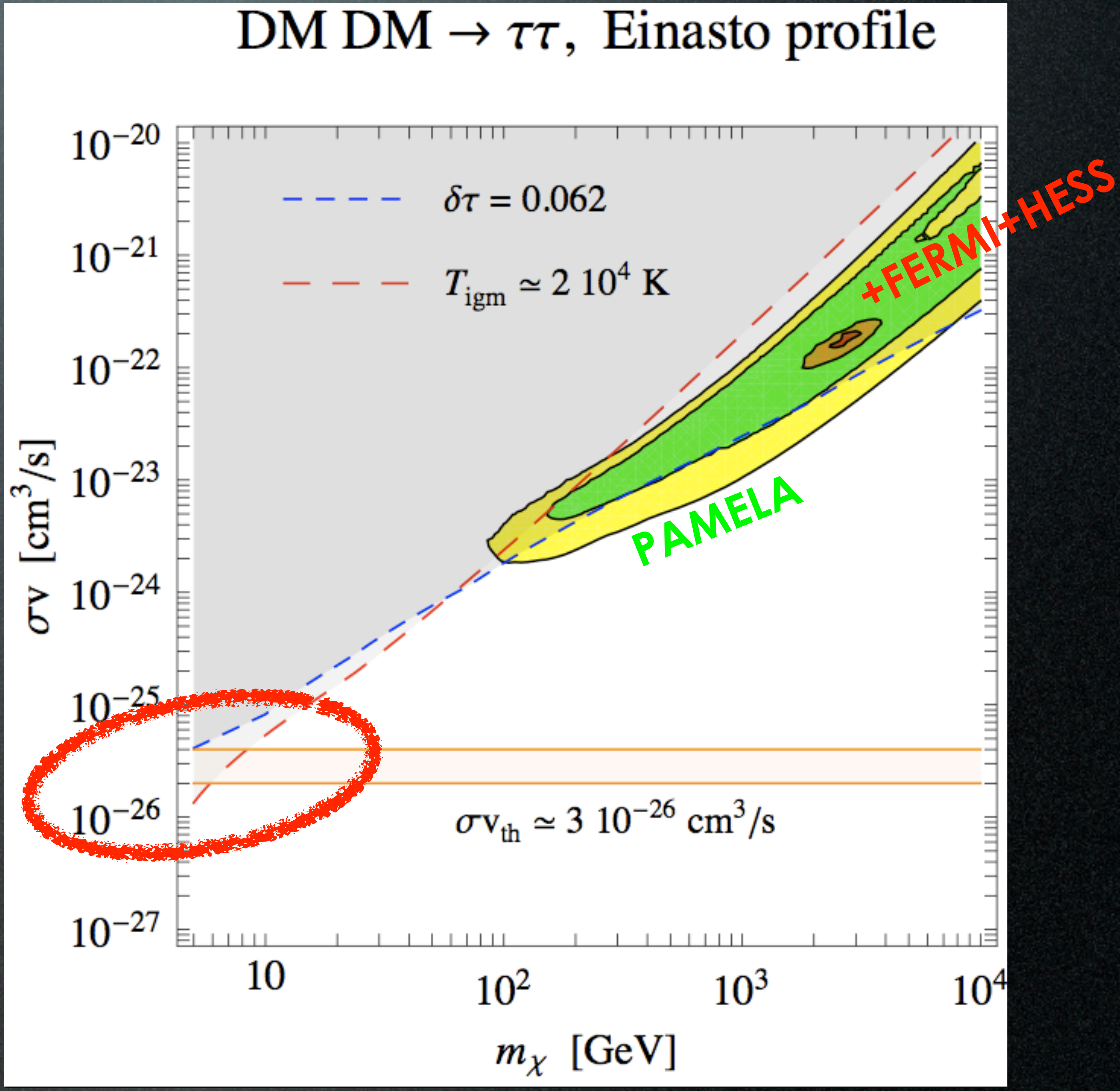
Cirelli, Iocco, Panci, JCAP 0910

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)

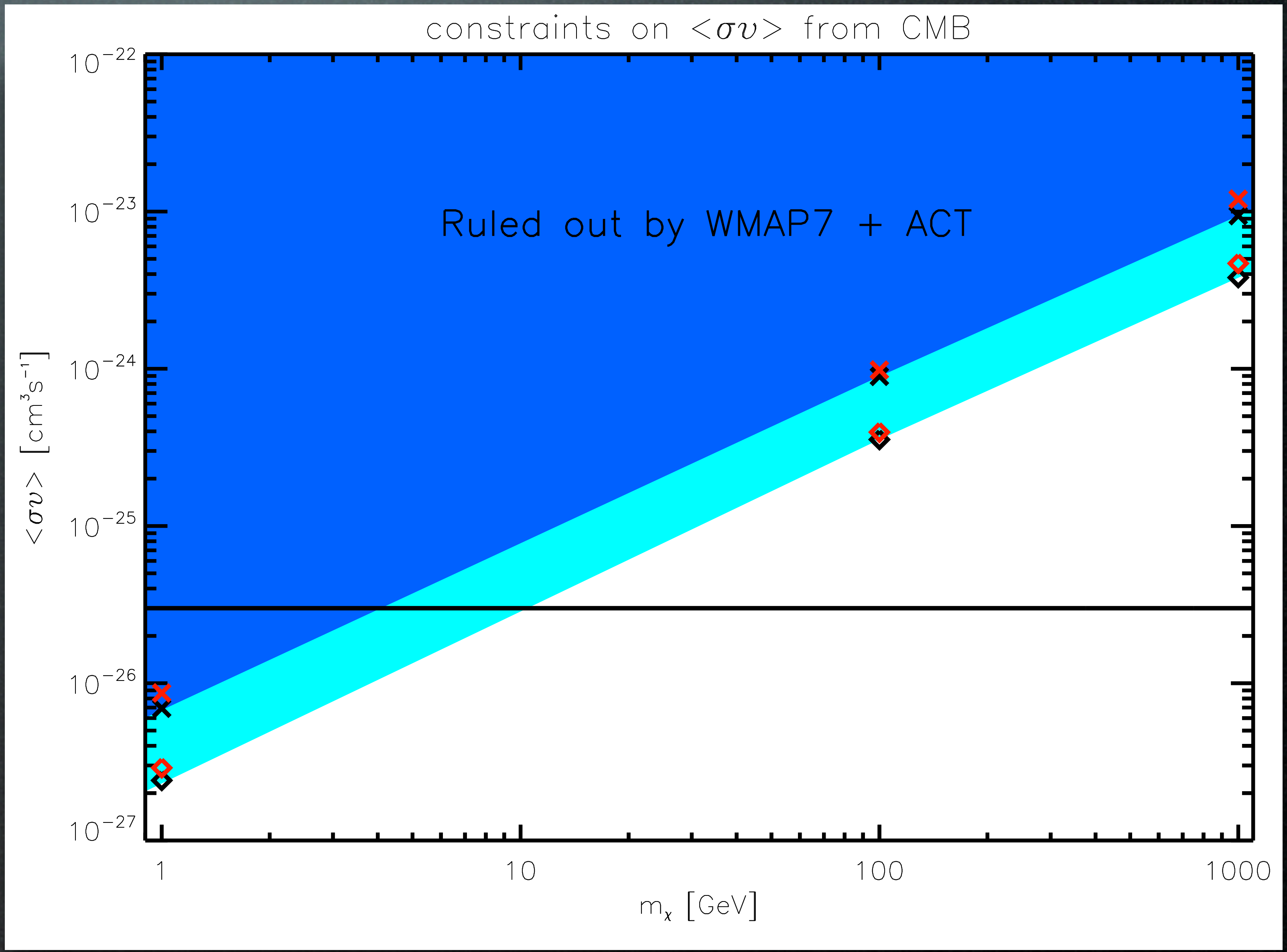
Starts constraining even thermal DM!



Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from CMB

Similar conclusion from global CMB fits

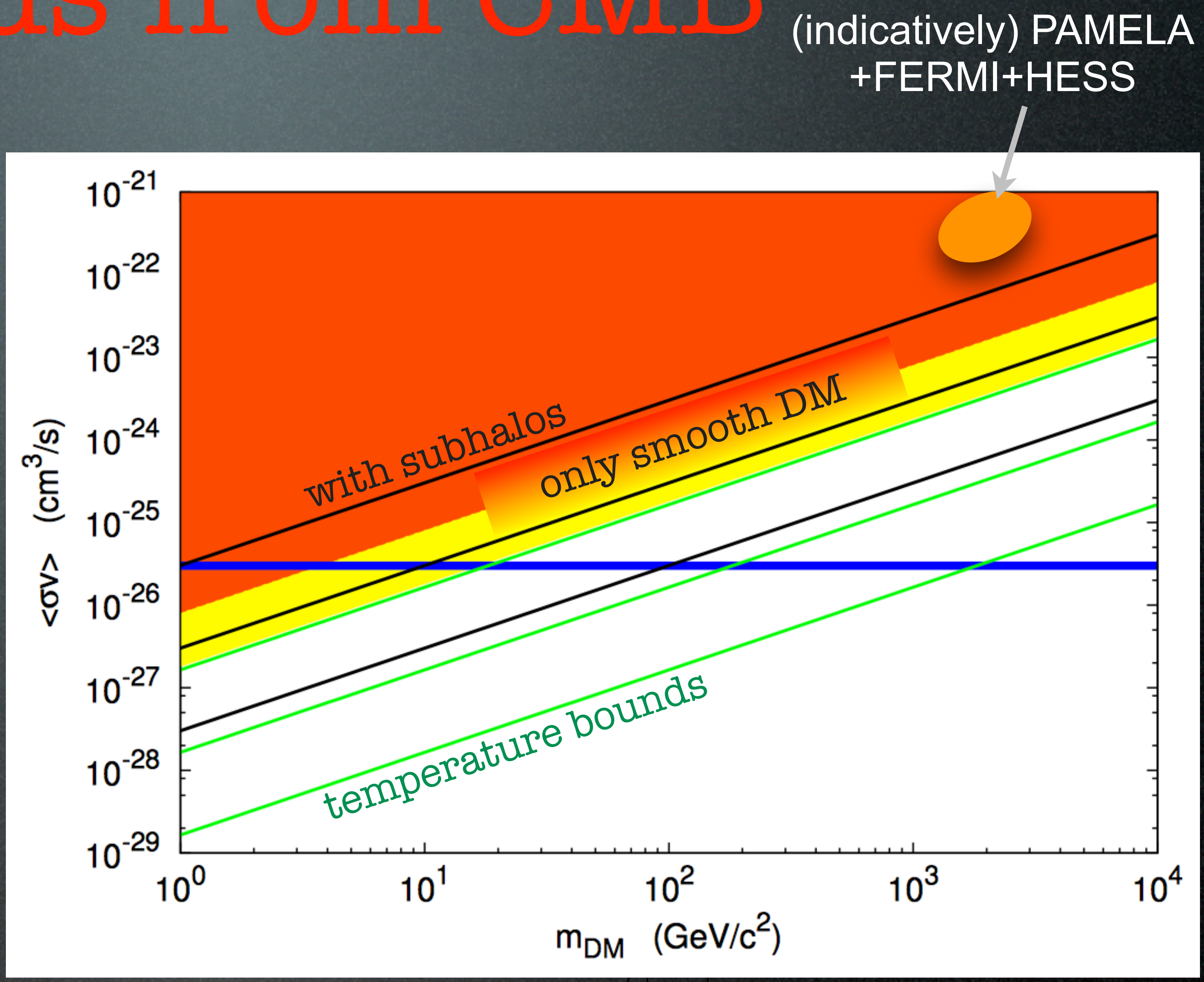


Galli, Iocco, Bertone, Melchiorri, PRD 80 (2009)
Slatyer, Padmanabahn, Finkbeiner, PRD 80 (2009)
Galli, Iocco, Bertone, Melchiorri, 1106.1528 (2011)

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

Cosmology: bounds from CMB

Similar conclusion from global CMB fits



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

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

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)

Model building

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

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

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

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- Decaying DM

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

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

Decaying DM

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

The current CR anomalies can be due to decay with:

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

Motivations from theory?

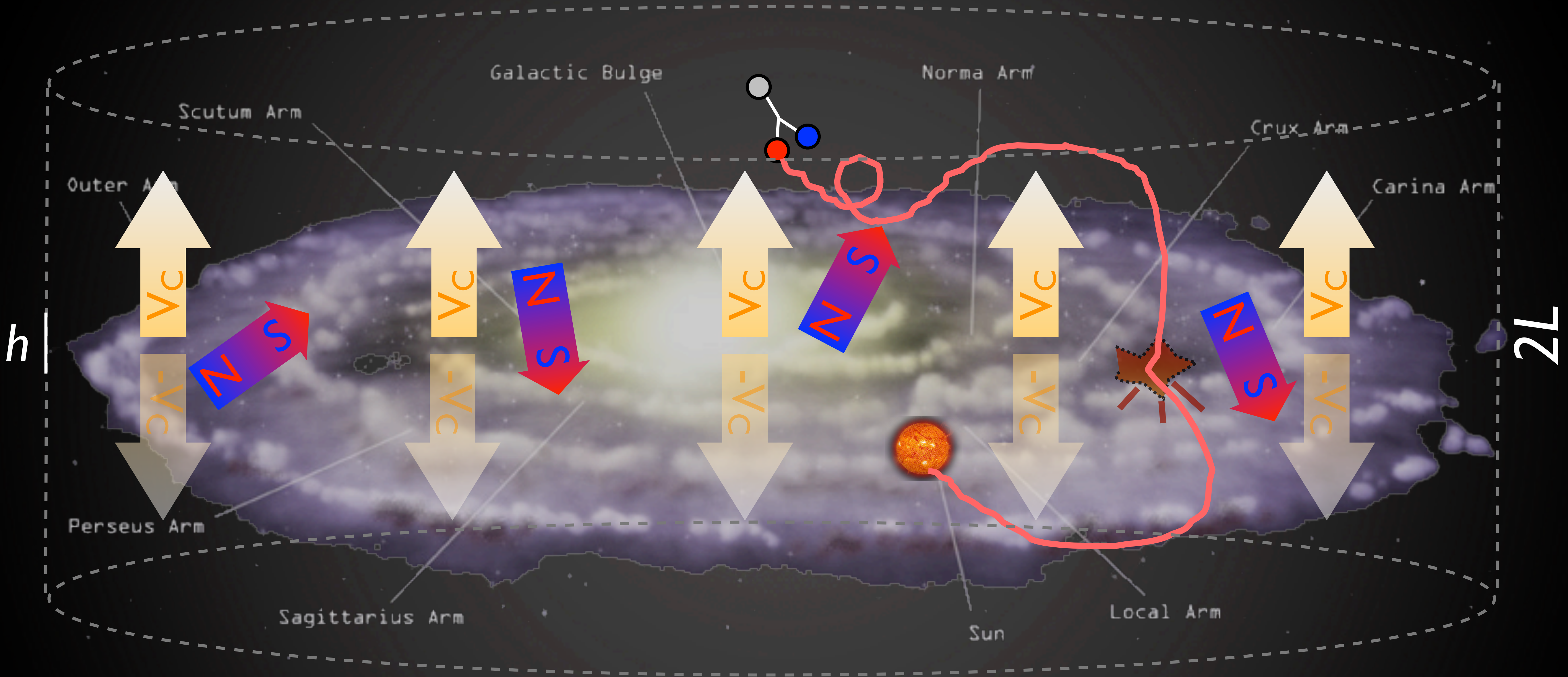
- dim 6 suppressed operator in GUT Arvanitaki, Dimopoulos et al., 2008+09

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

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

Indirect Detection

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



What sets the overall expected flux?

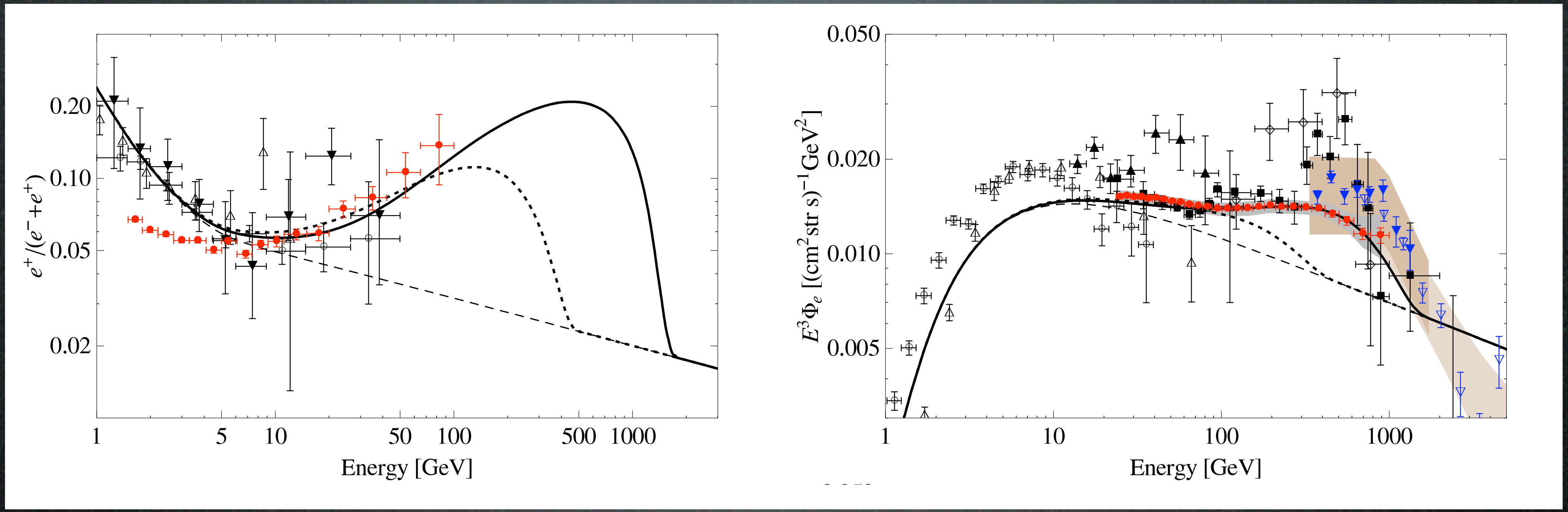
$$\text{flux} \propto n\,\Gamma_{\text{decay}}$$

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

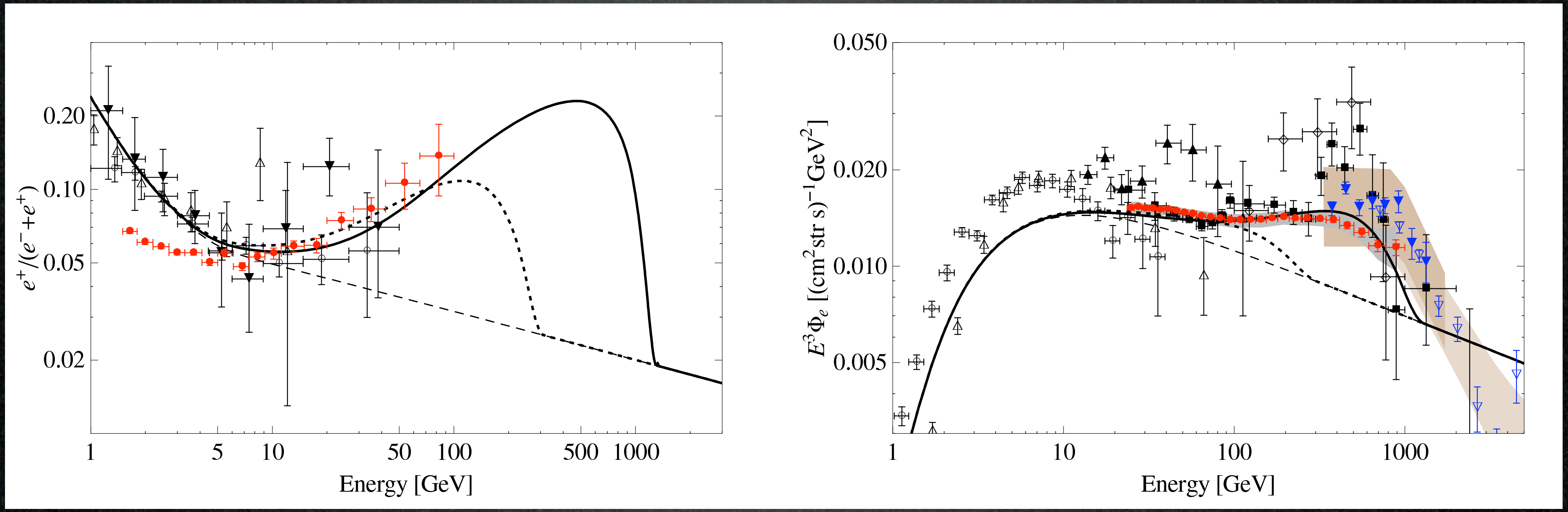
Decaying DM

Which DM spectra can fit the data?

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



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

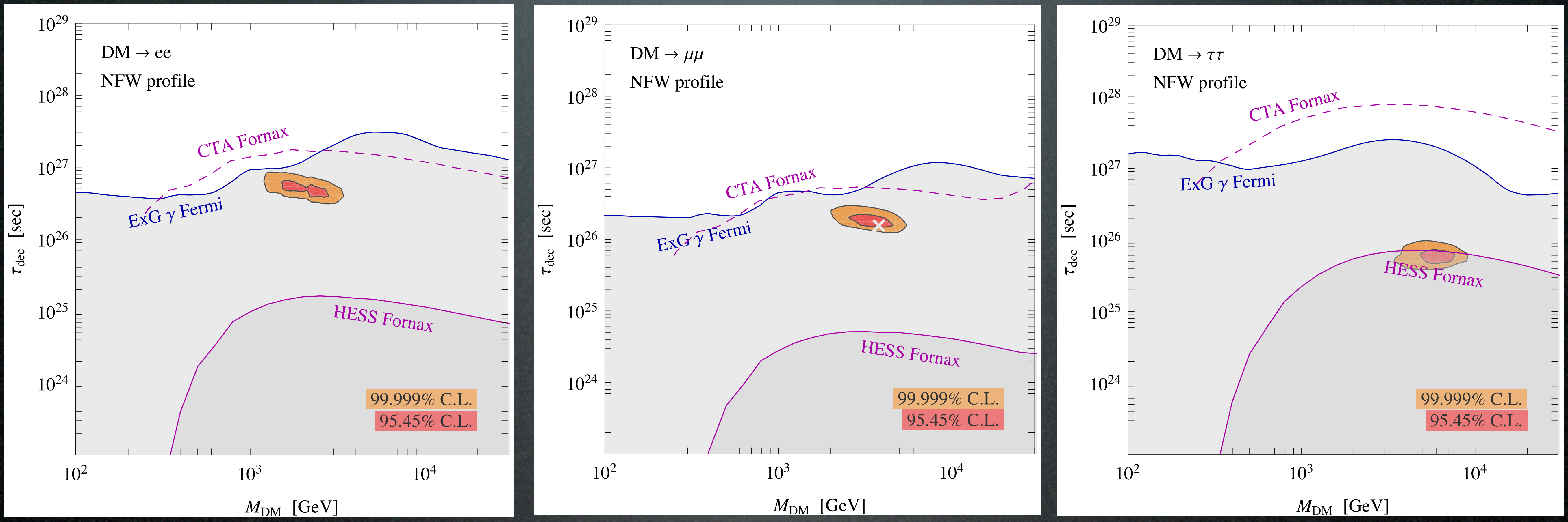


Ibarra, Tran, Weniger 2009

Decaying DM

But, again: gamma ray constraints

(although: no radio, neutrino constraints)



Cirelli, Moulin, Panci, Serpico, Viana 1205.5283

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

Model building

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

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

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

- More drastic extensions:
  New models with a rich Dark sector
    - TeV mass DM
    - new forces (that Sommerfeld enhance)
    - leptophilic because: - kinematics (light mediator)
      - DM carries lepton #

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The "Theory of DM"

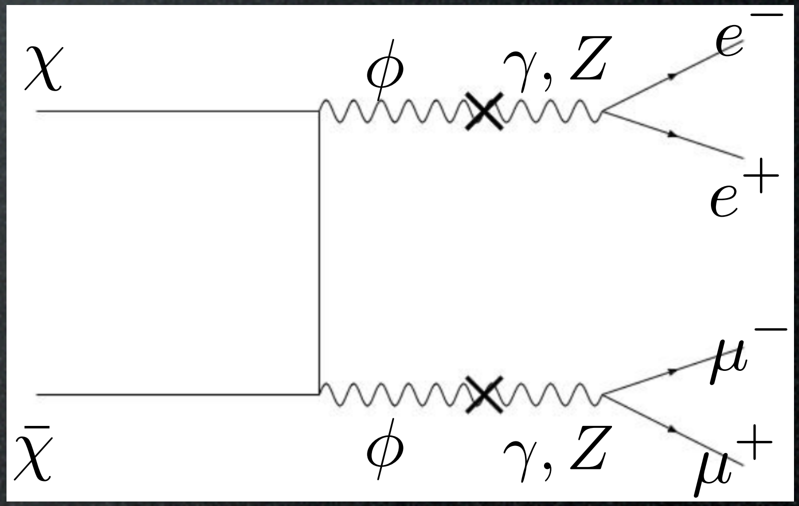
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

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

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim \text{few GeV}$
- 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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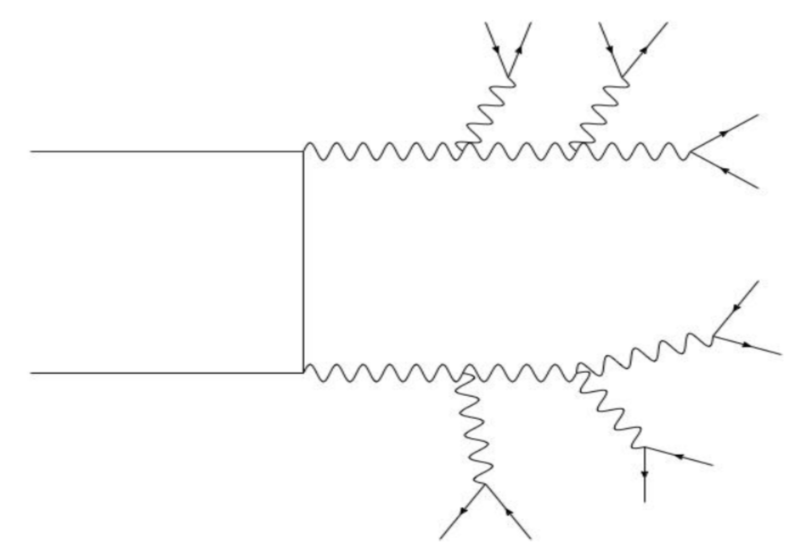
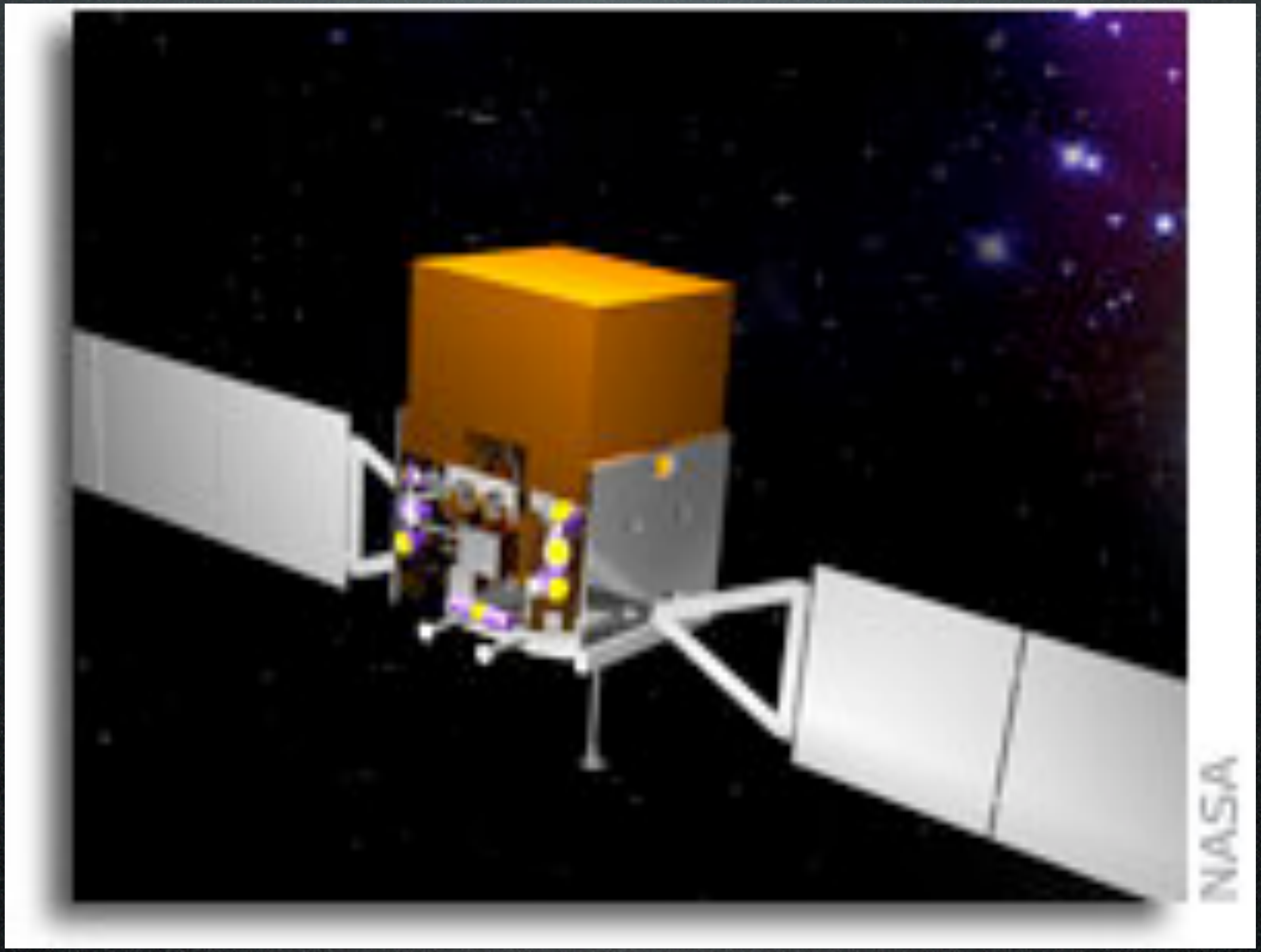


Extras:

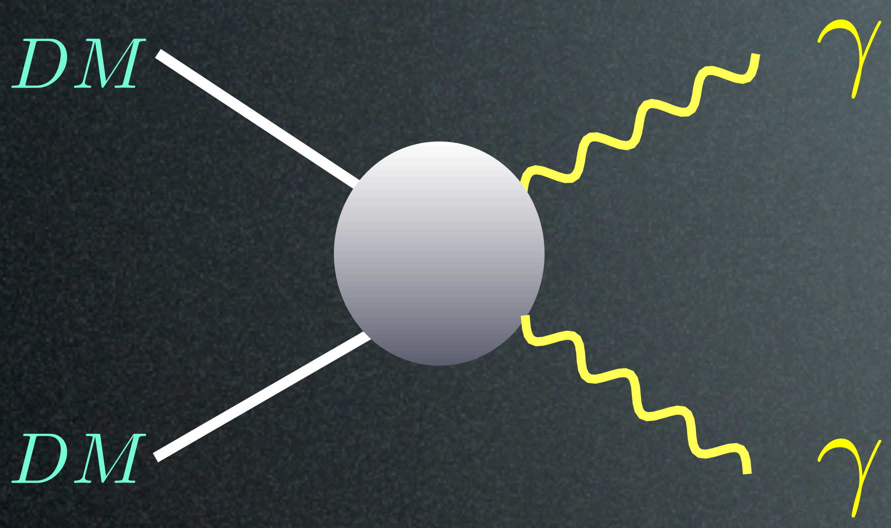
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

Gamma rays



2. the ‘130 GeV line’

Prompt emission: line(s)



primary
channels

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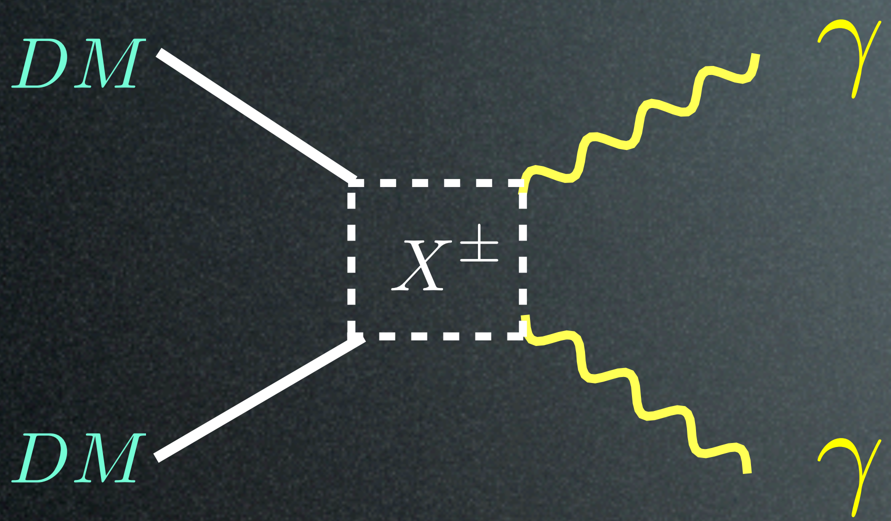
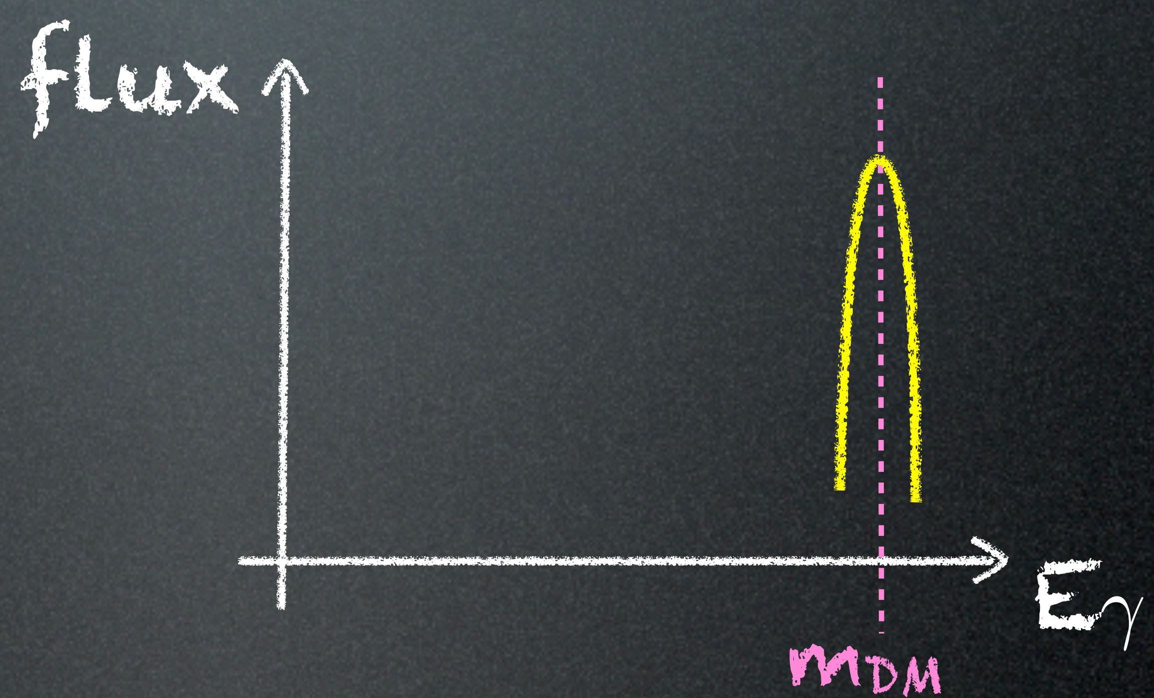


primary channels

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



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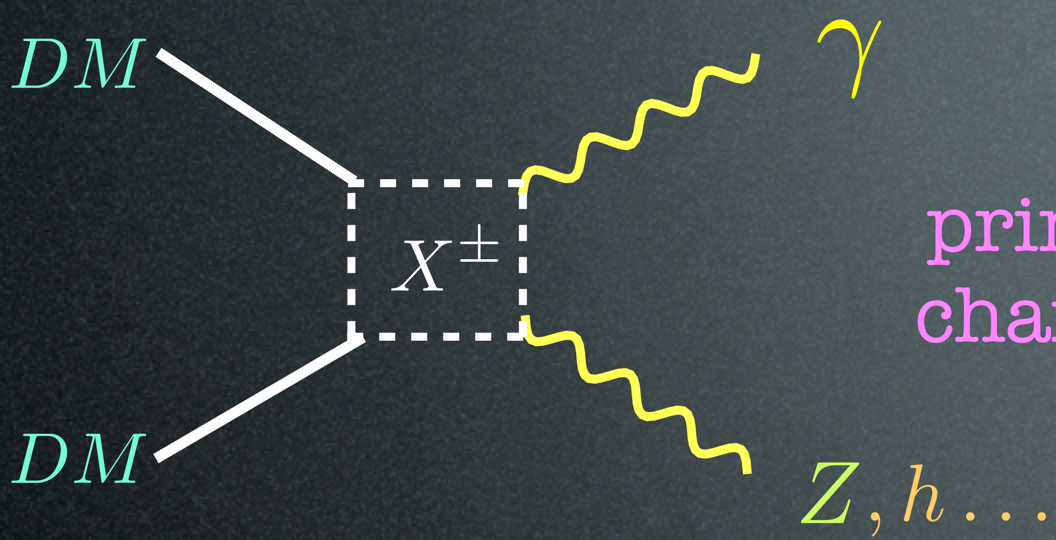

primary channels

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

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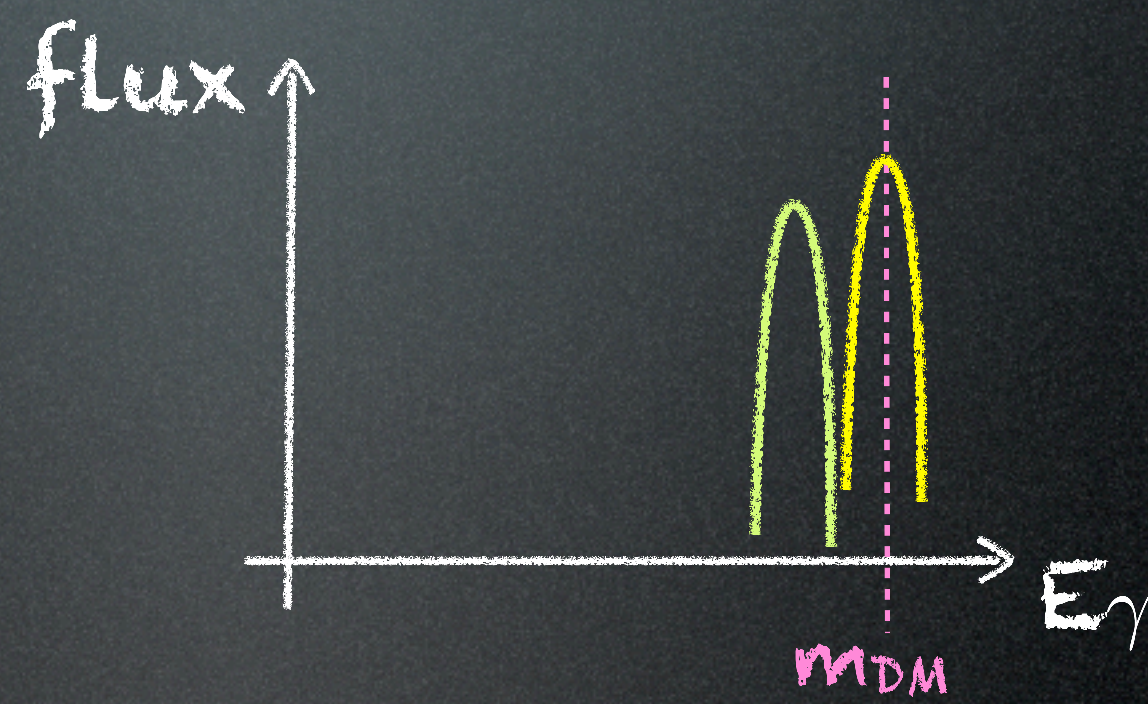

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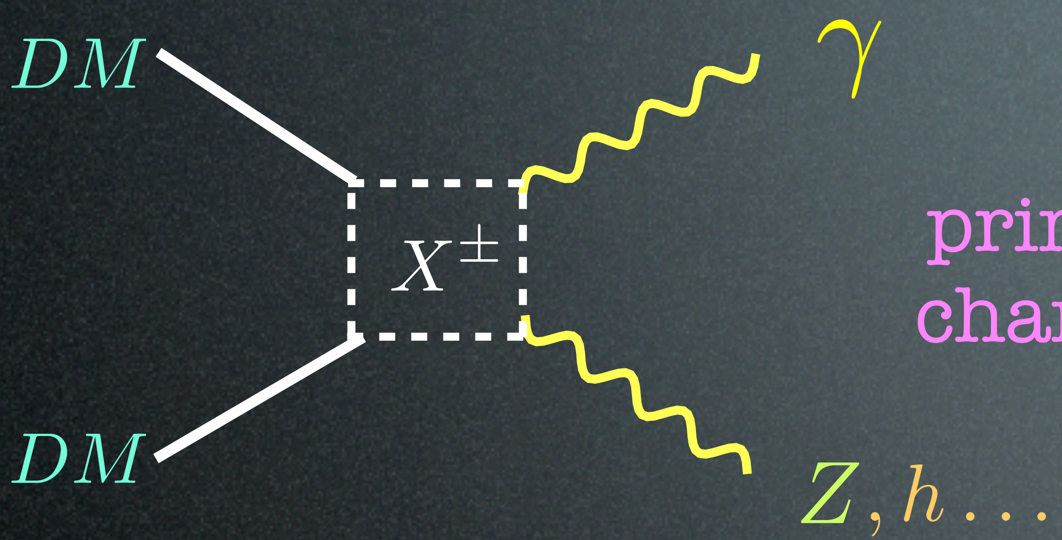

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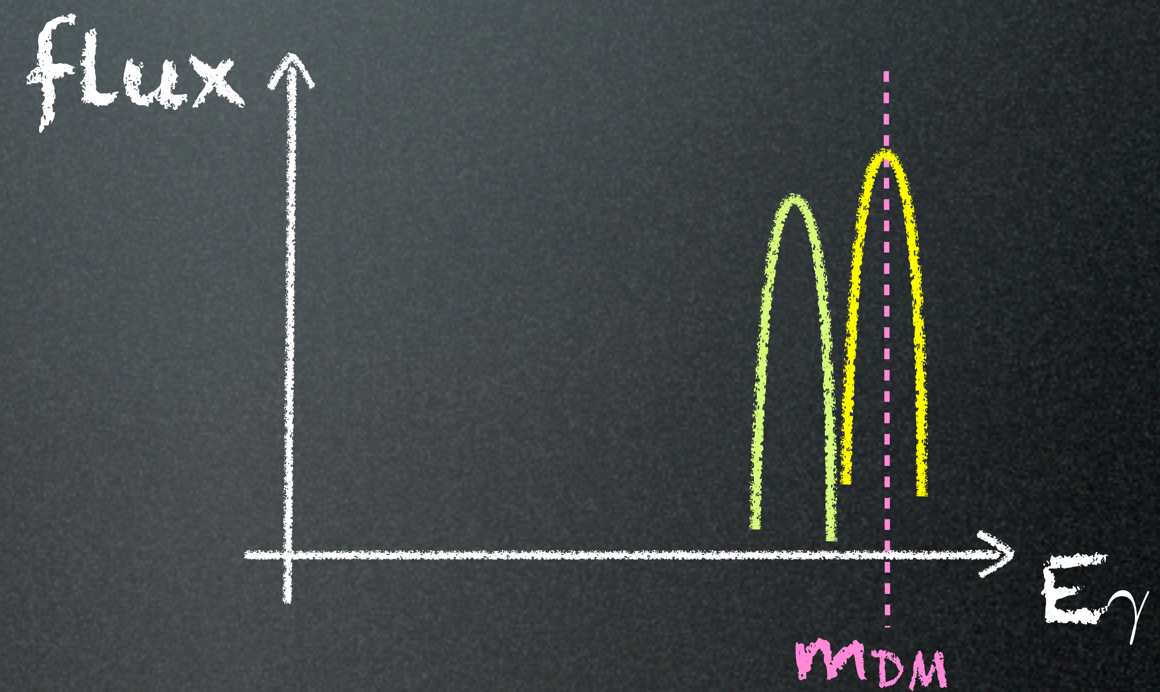


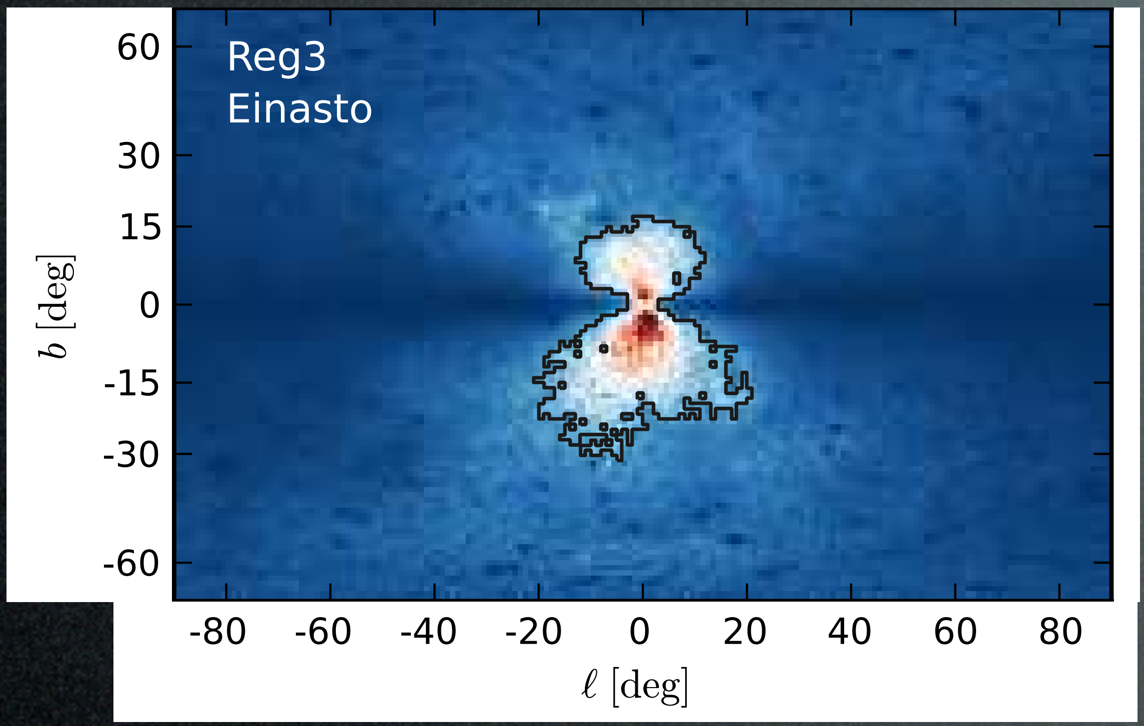
So what are the particle physics parameters?

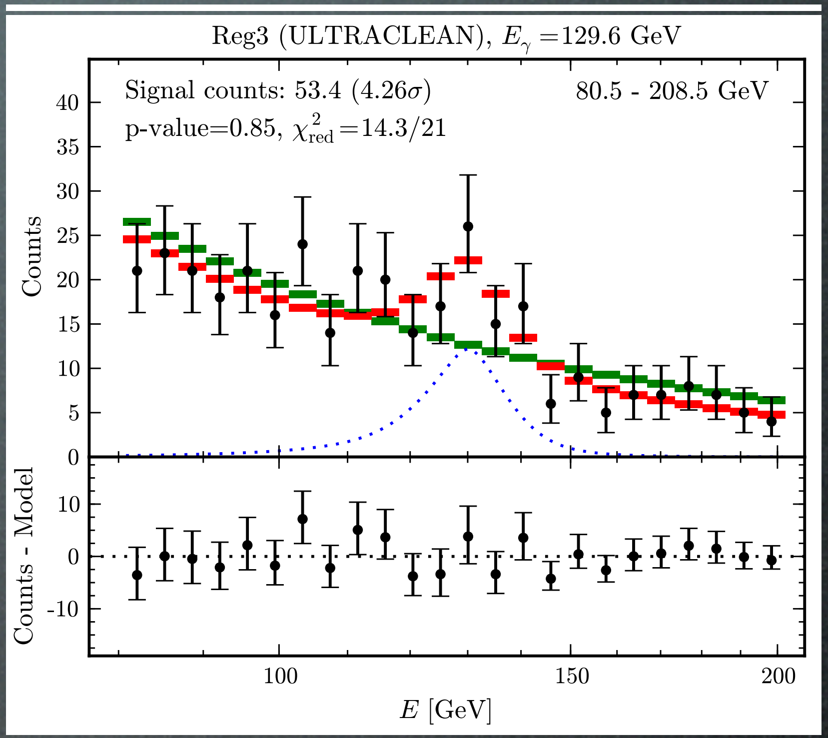
1. Dark Matter mass

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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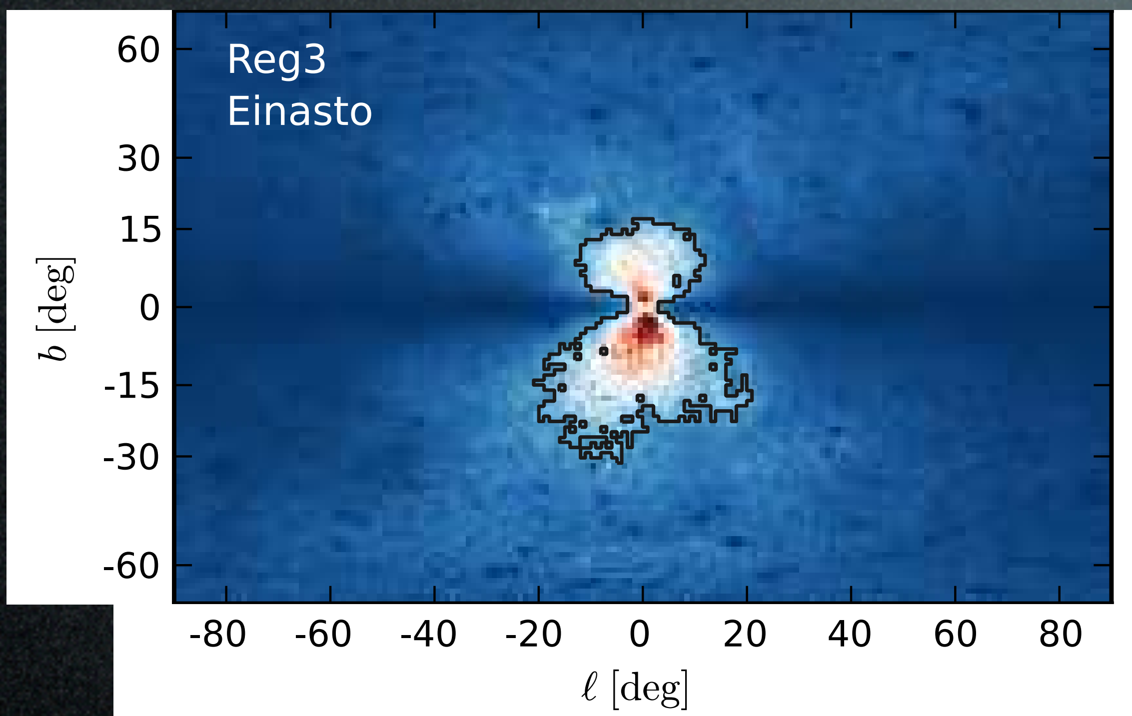

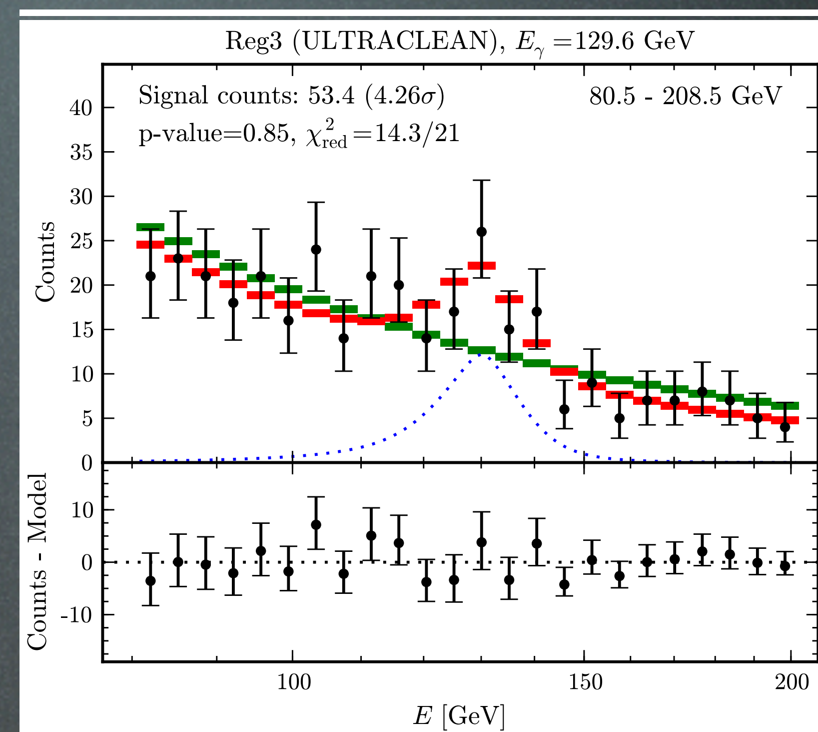

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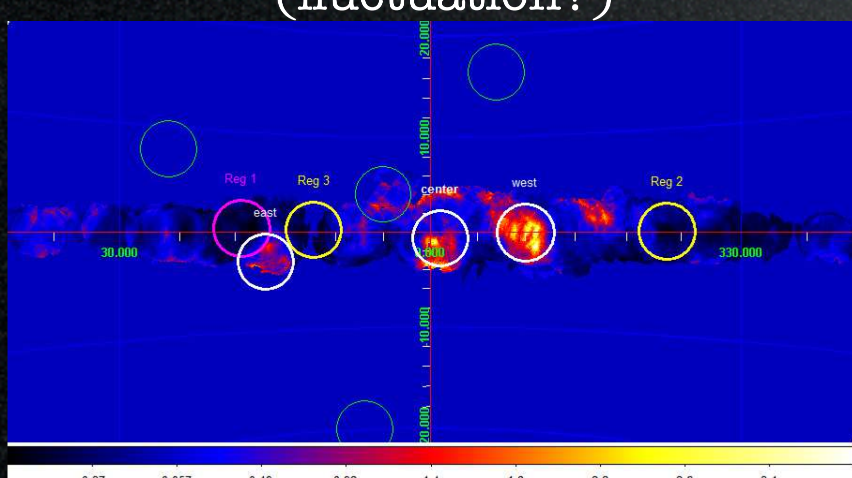
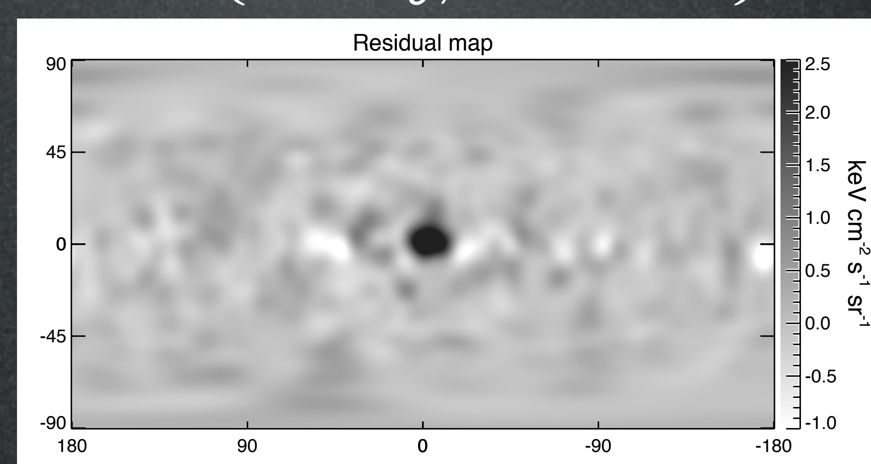
Similar excesses found elsewhere (fluctuation?)



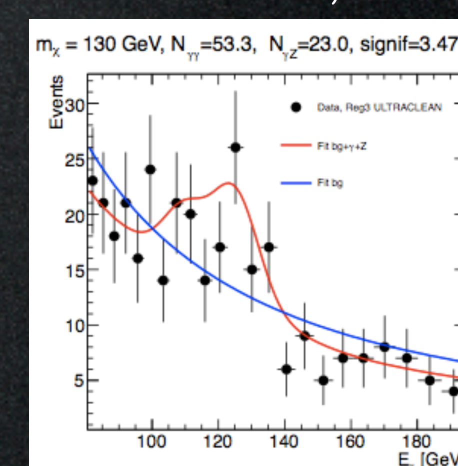
Boyarsky, Malyshev, Ruchayskyi, 1205.4700

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

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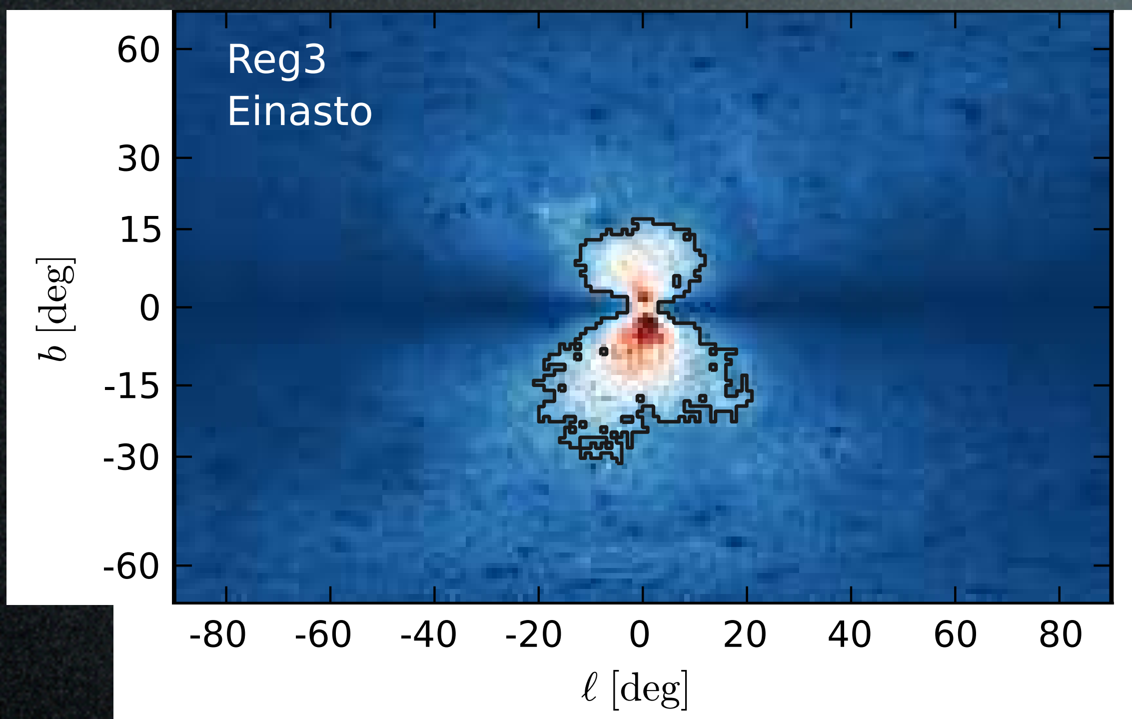

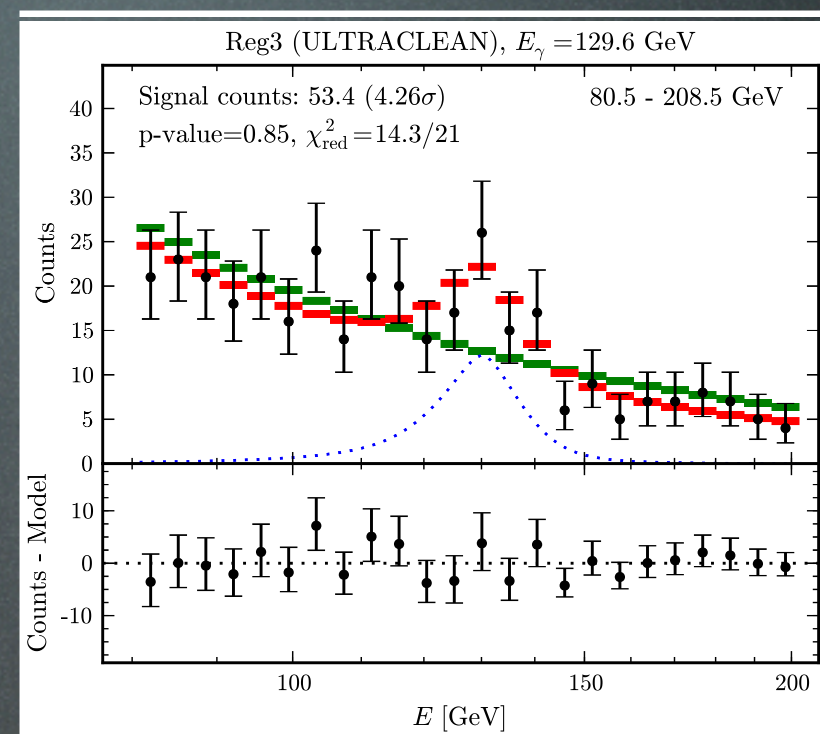

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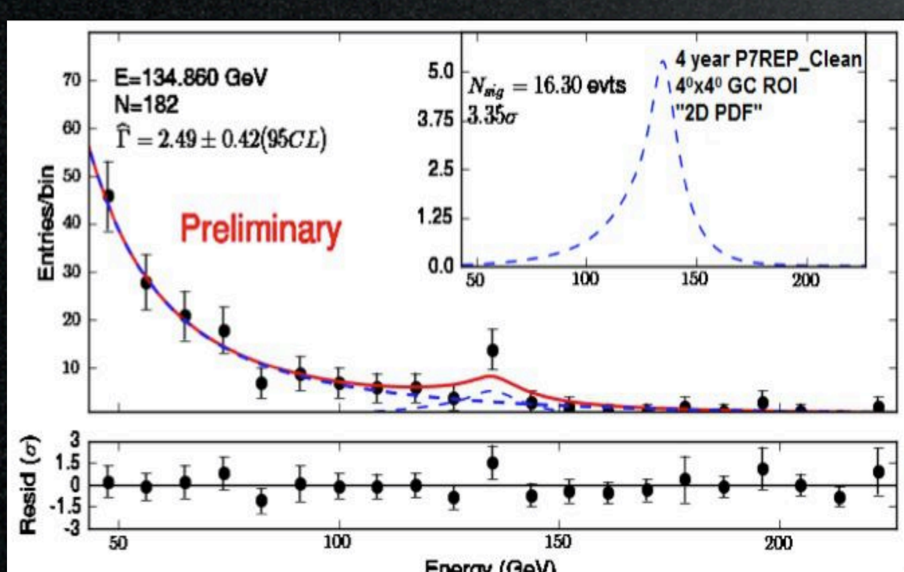
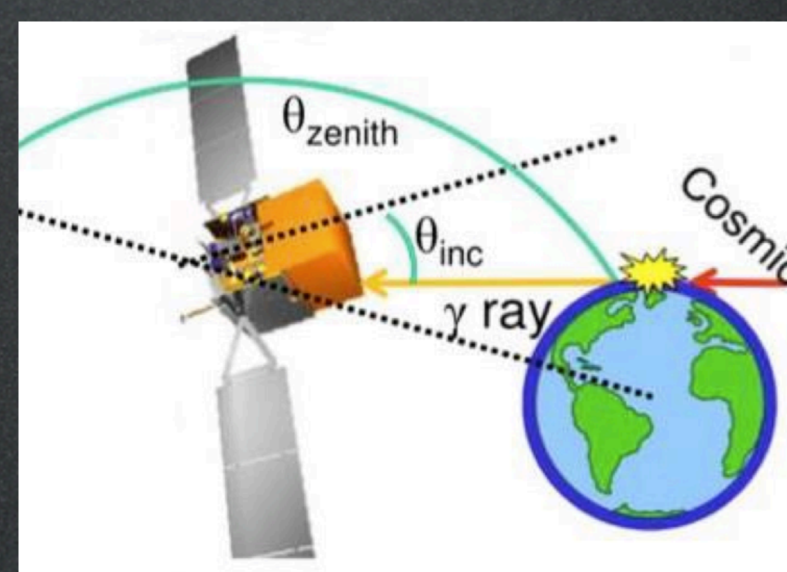
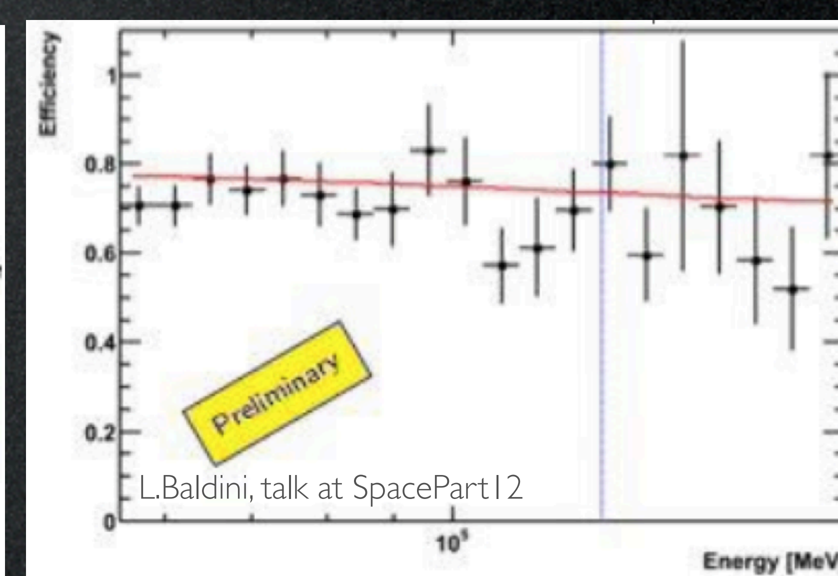
The Fermi coll's cold shower. An instrumental effect?







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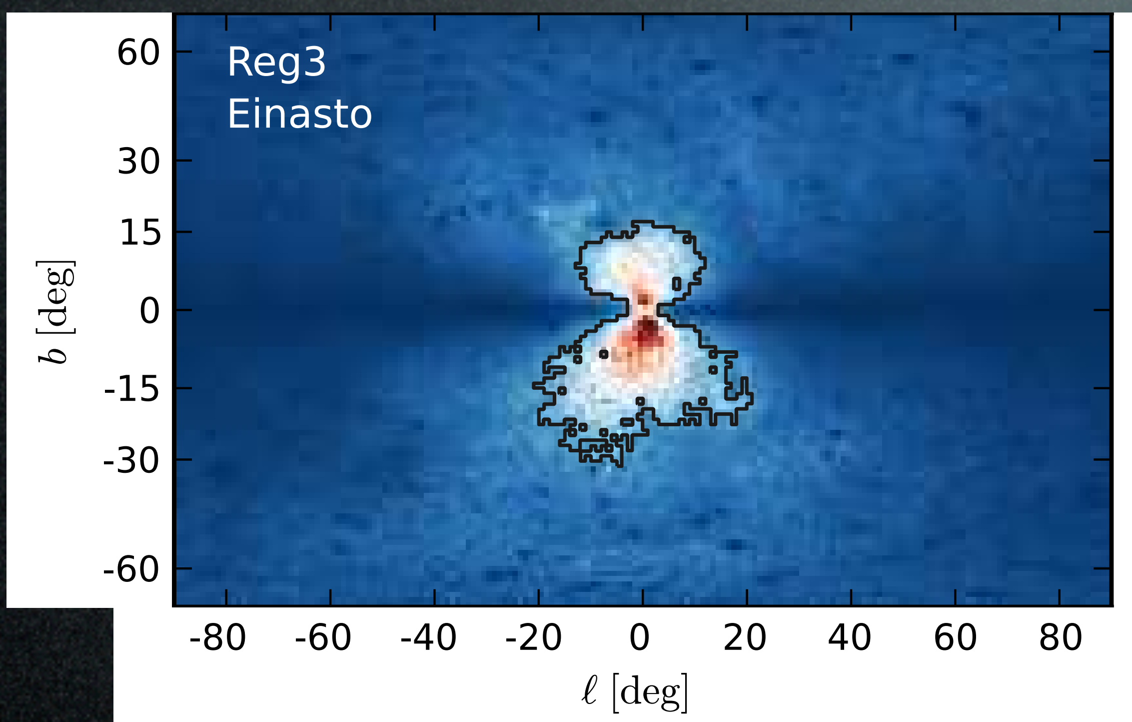

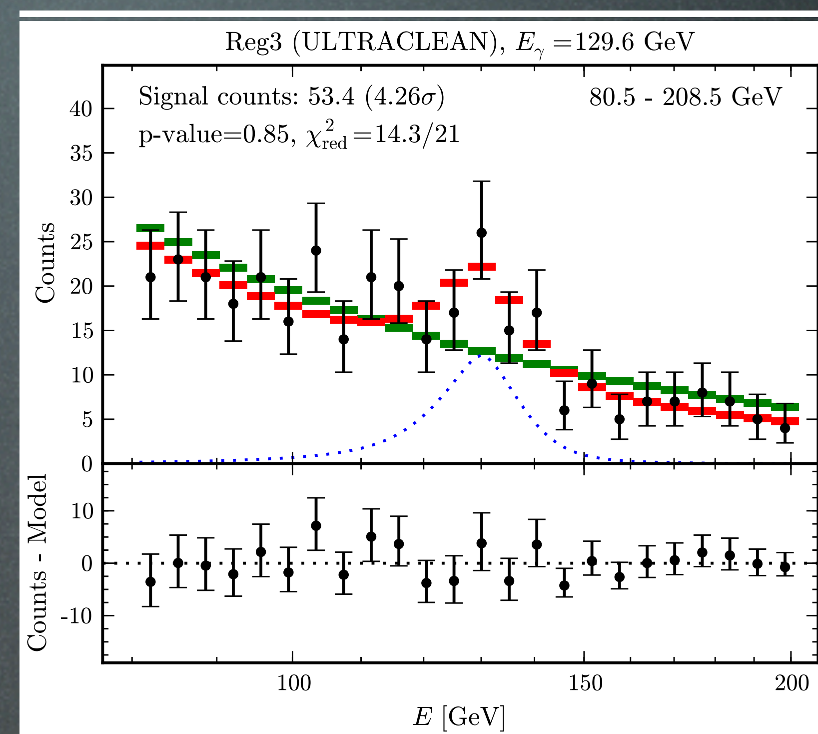

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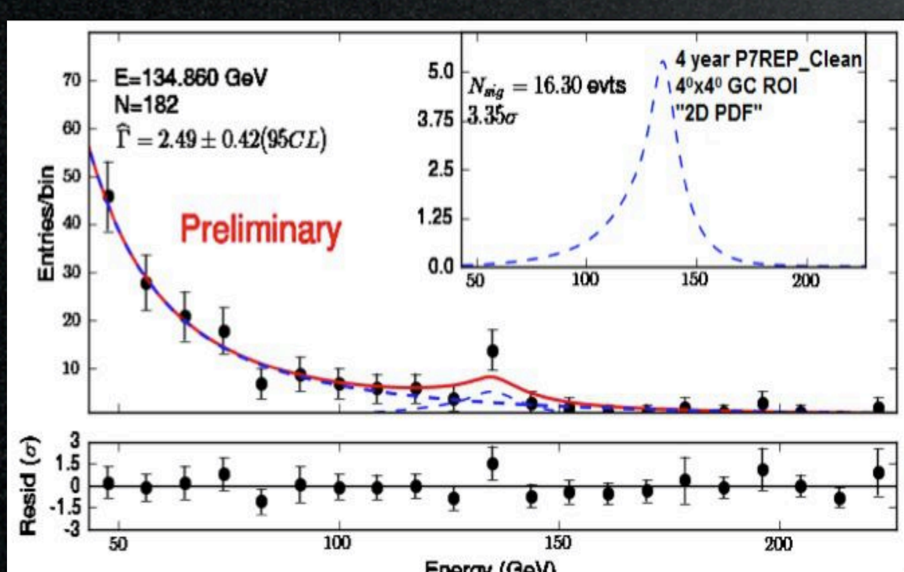
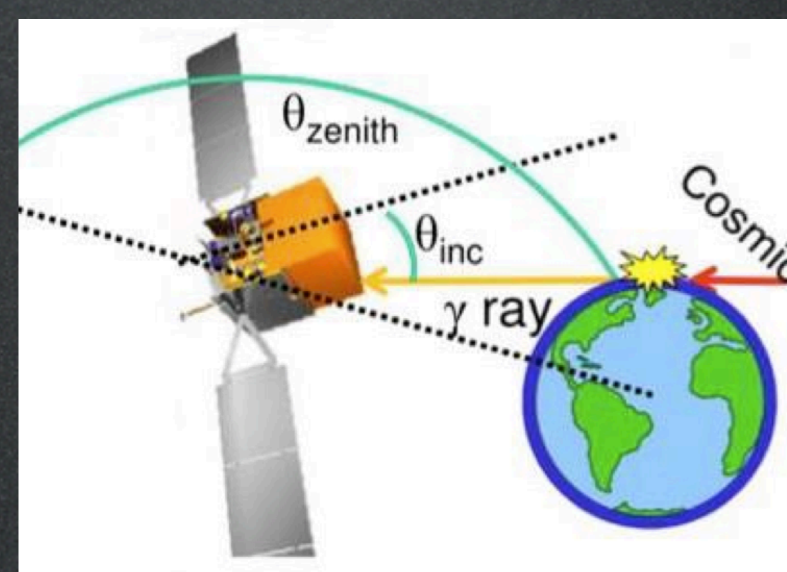
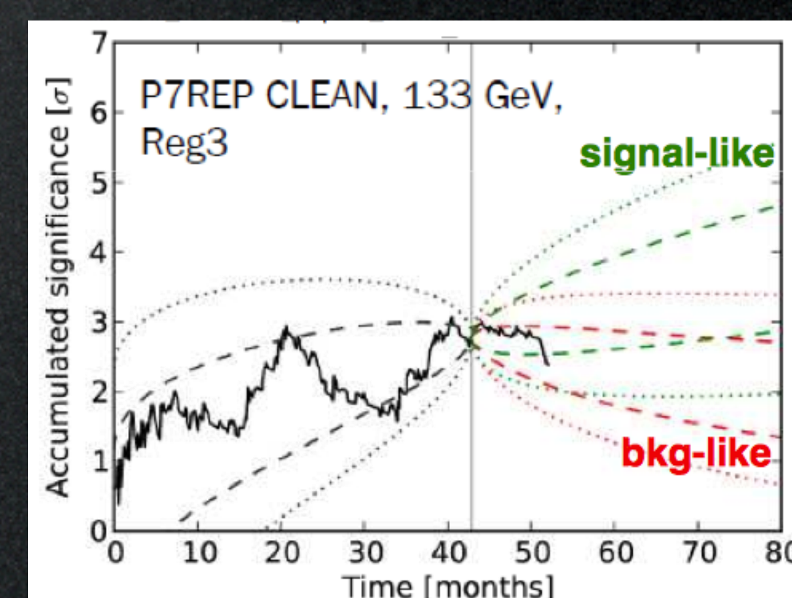
The Fermi coll's cold shower. An instrumental effect?







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:

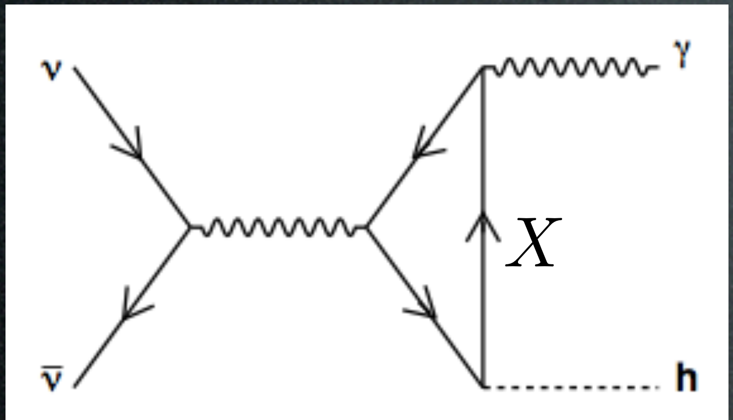
Challenges

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

Challenges

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

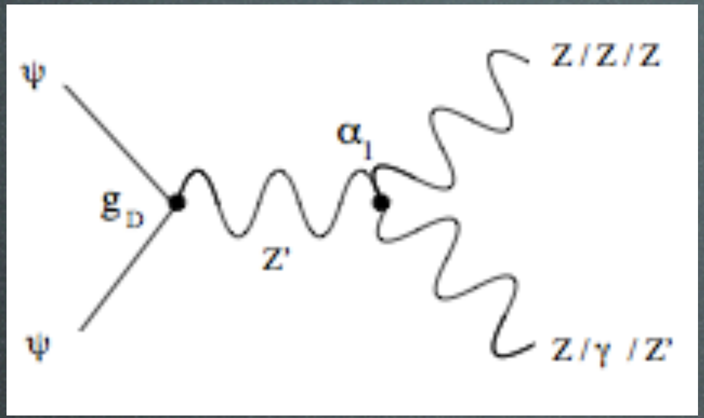
a loop



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

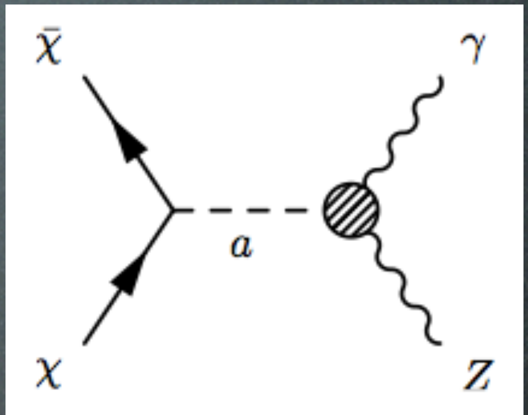
$X \in$ SM
MSSM
dark sector...

Chern-Simons



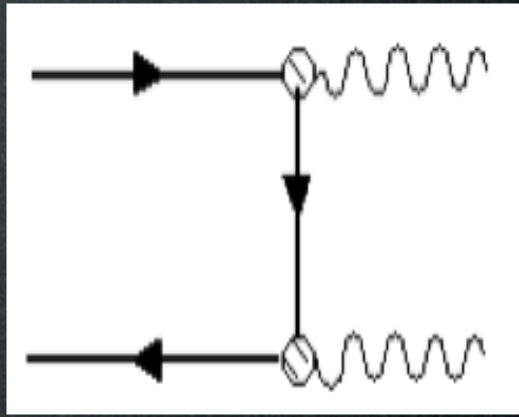
Dudas et al., 1205.1520

axions



Lee & Park[2] 1205.4675

magn dipole



Heo, Kim 1207.1341

...

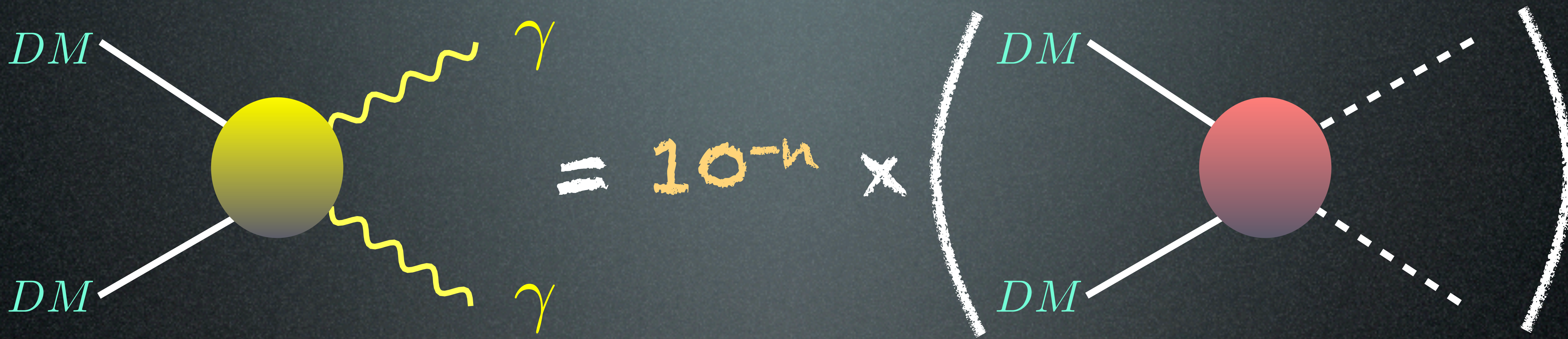
Challenges

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

The 'something' implies usually a suppression,

Challenges

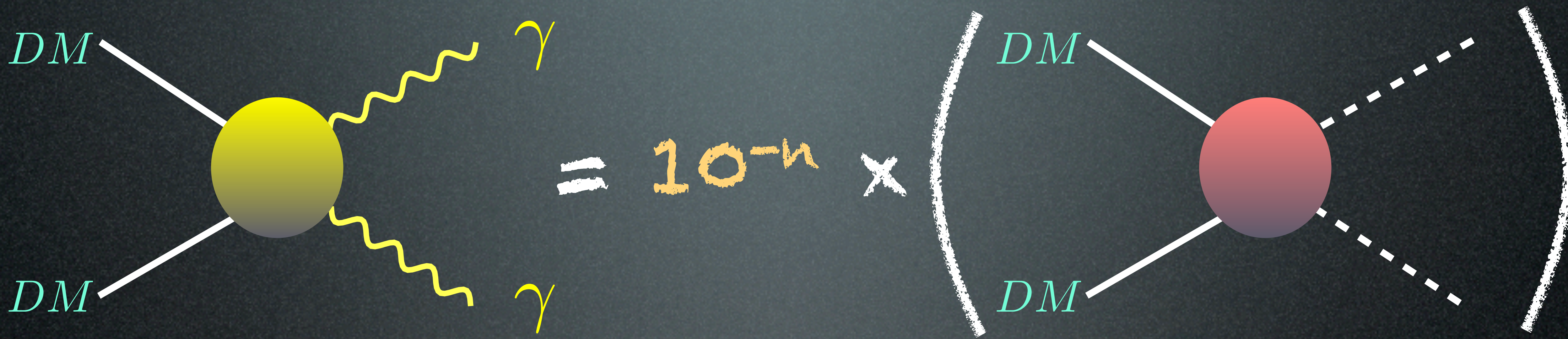
DM is neutral: need '*something*' to couple to γ



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

Challenges

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



The '*something*' implies usually a suppression,
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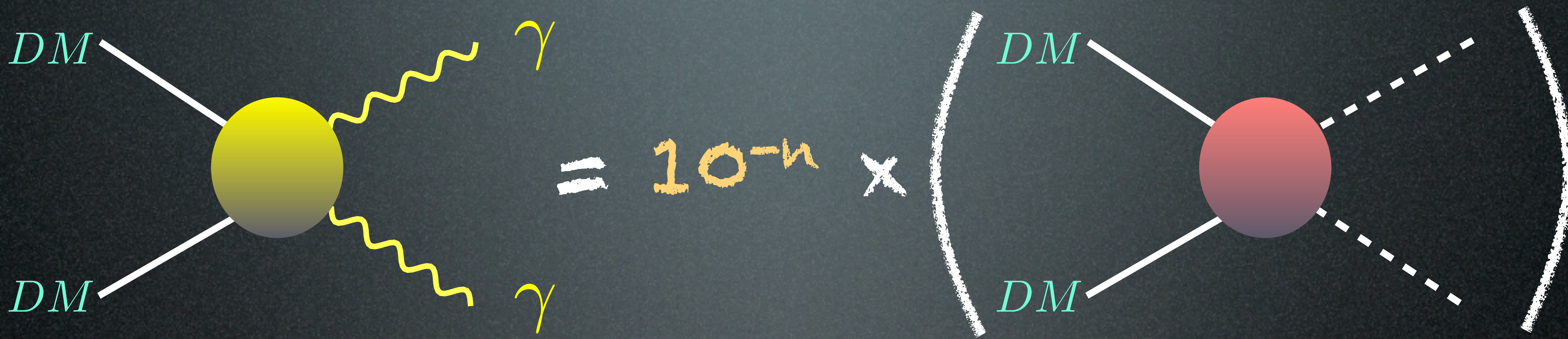
so the corresponding unsuppressed processes
are **too** large:

- 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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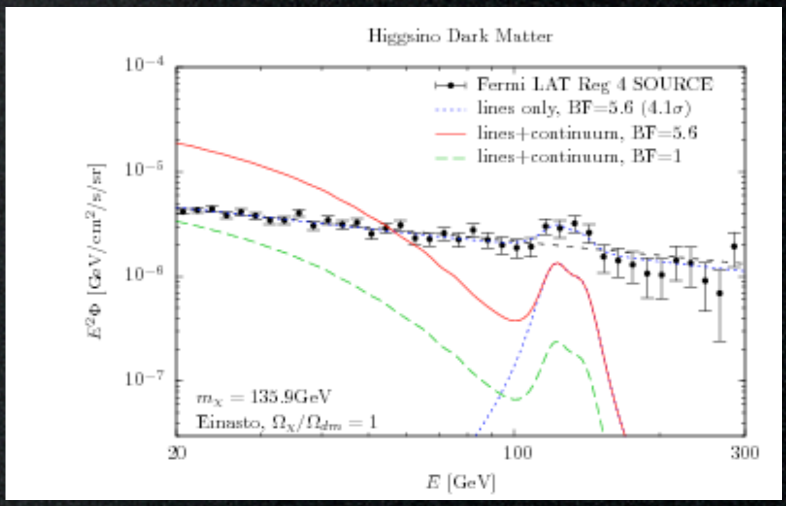

Challenges

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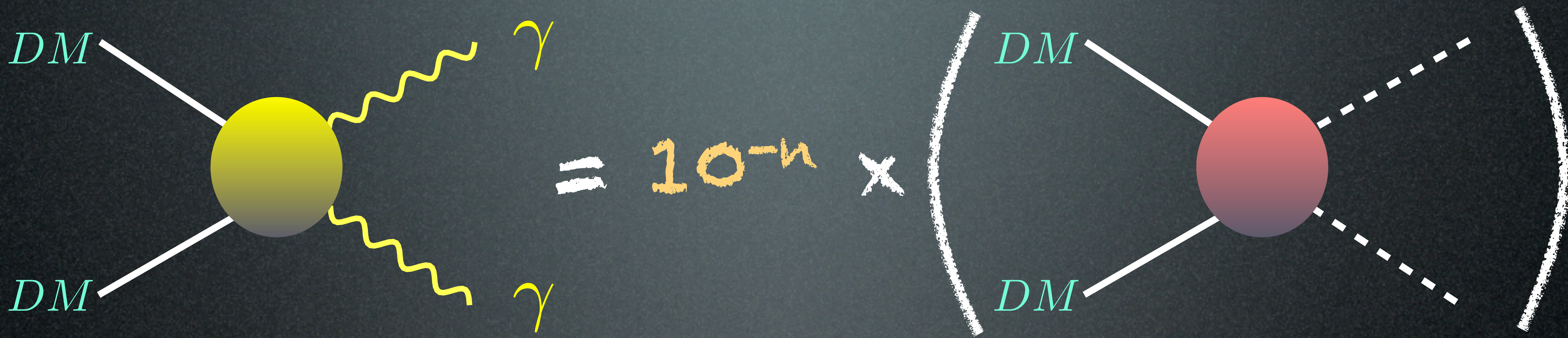

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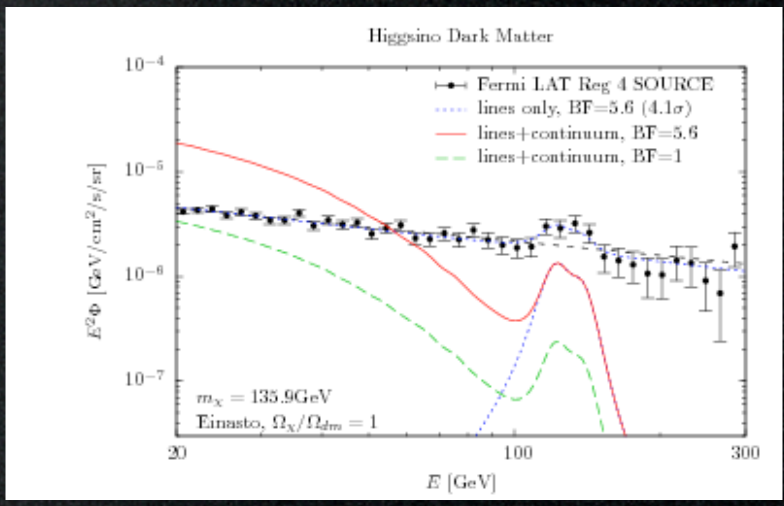


But solutions exist

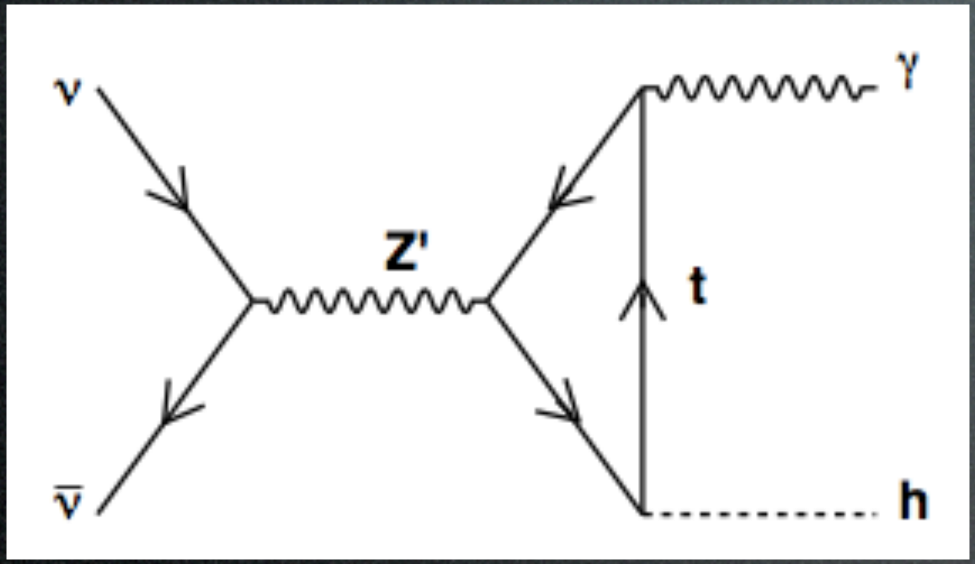
Model building

not exhaustive!

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

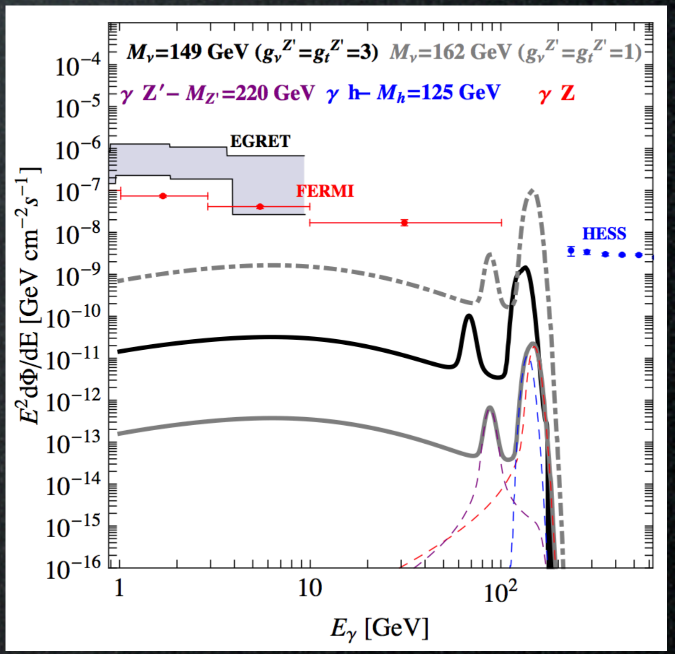
(a) DM charged under U′(1)
(b) Z′ is t_R-philic
(c) $m_{DM} \lesssim m_{top}$

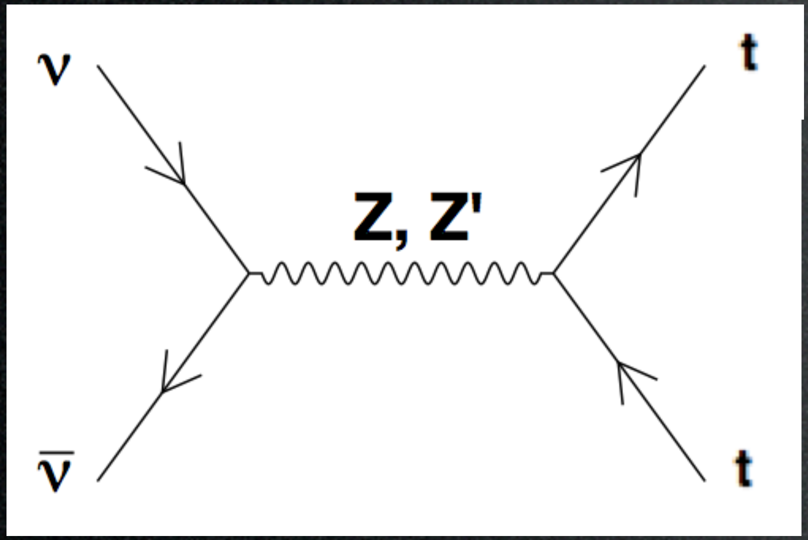
Jackson, Servant, Shaughnessy, Tait, Taoso, ‘Higgs in space’, 0912.0004



➡ 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!

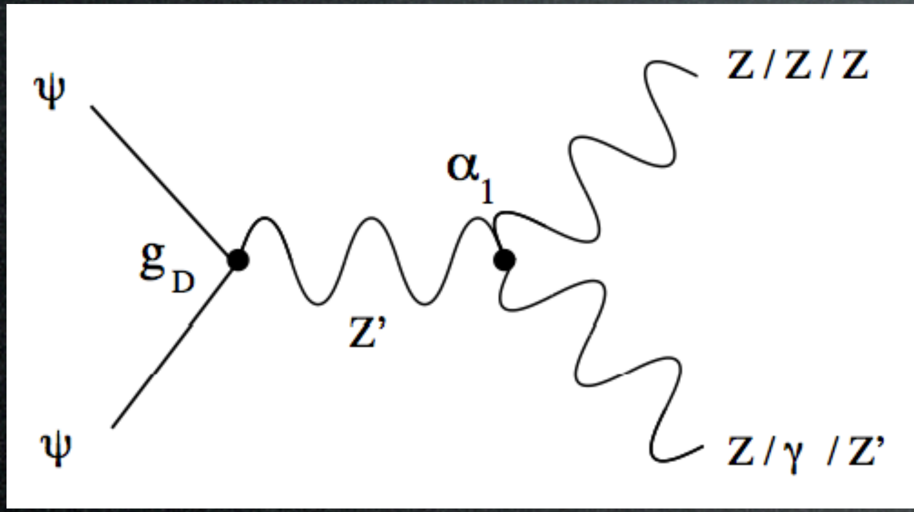
Ex. 2: ‘resonance, tri-boson vertices, Chern-Simons’

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

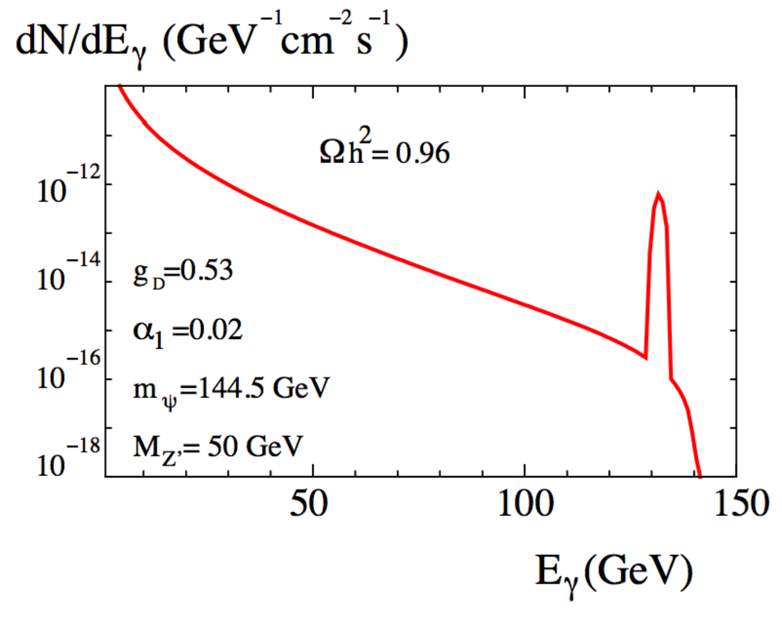
$$\mathcal{L}_{\rm CS} = \alpha\, \varepsilon^{\mu\nu\rho\sigma}\, Z'_\mu Z_\nu F^Y_{\rho\sigma}$$

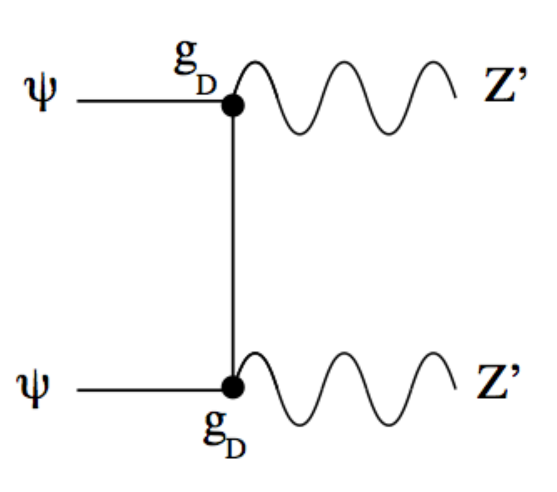
Dudas, Mambrini, Pokorski, Romagnoni 2009-2012, 1205.1520

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



→ line (b)

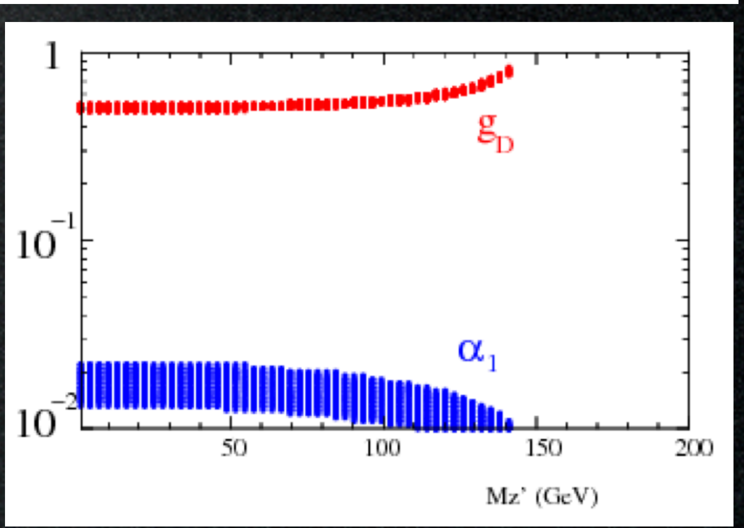




→ relic abundance

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

→ Continuum? Under control



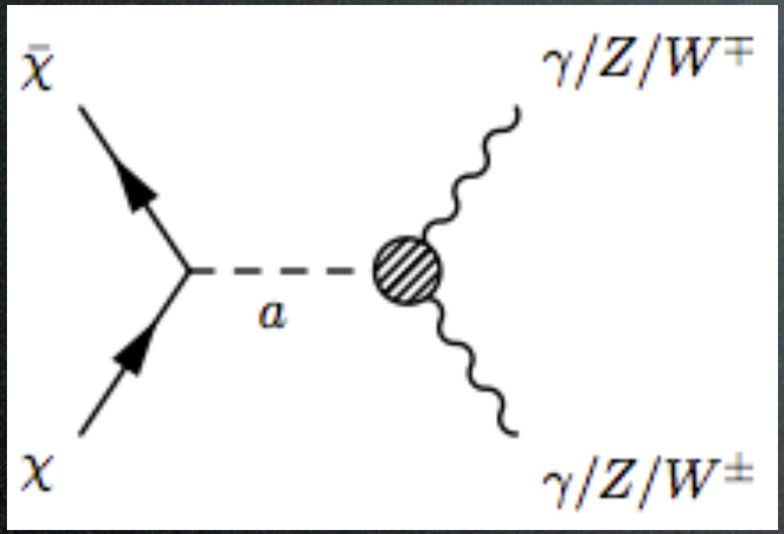
Model building

not exhaustive!

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

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

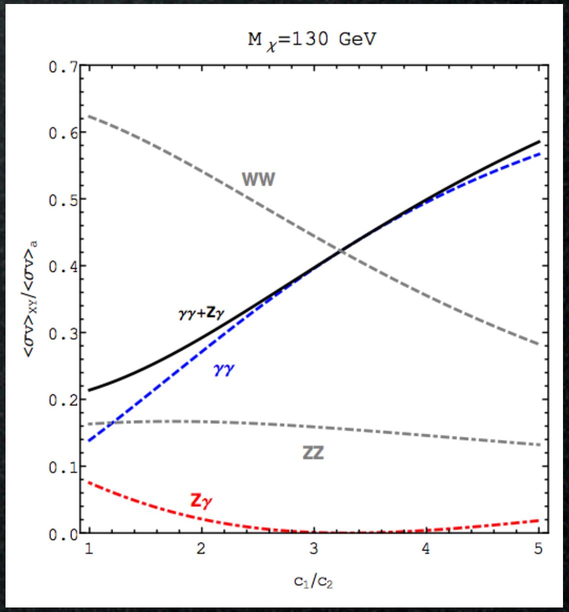
Lee, Park[2], 1205.4675

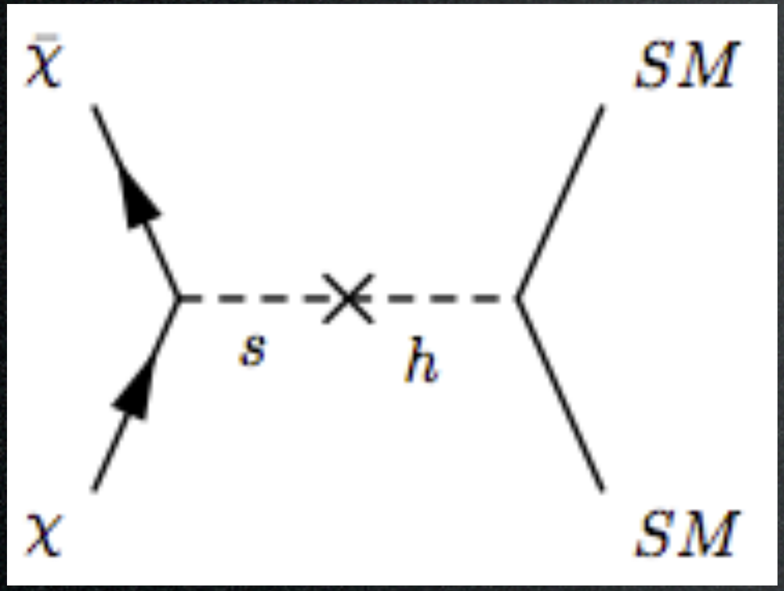


➡ line (b)

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!

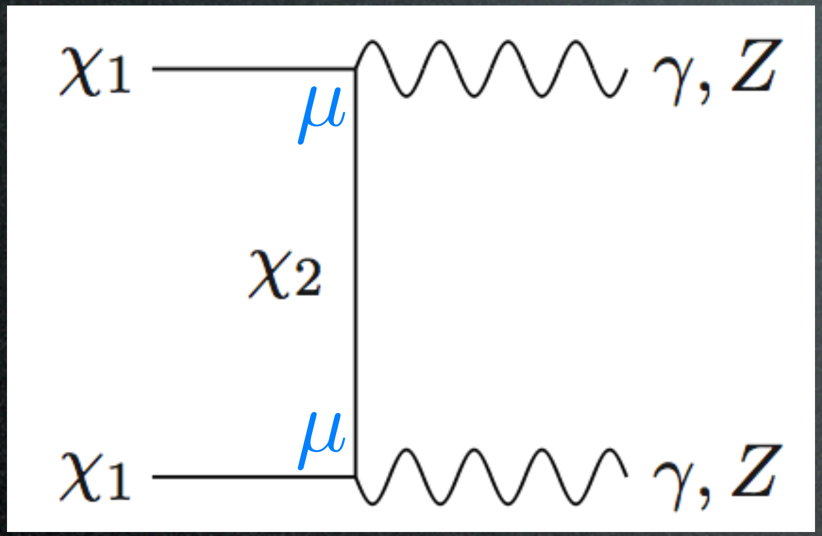
Ex. 4: 'magnetic moments and coannihilations'

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

(a) DM has a magnetic moment

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

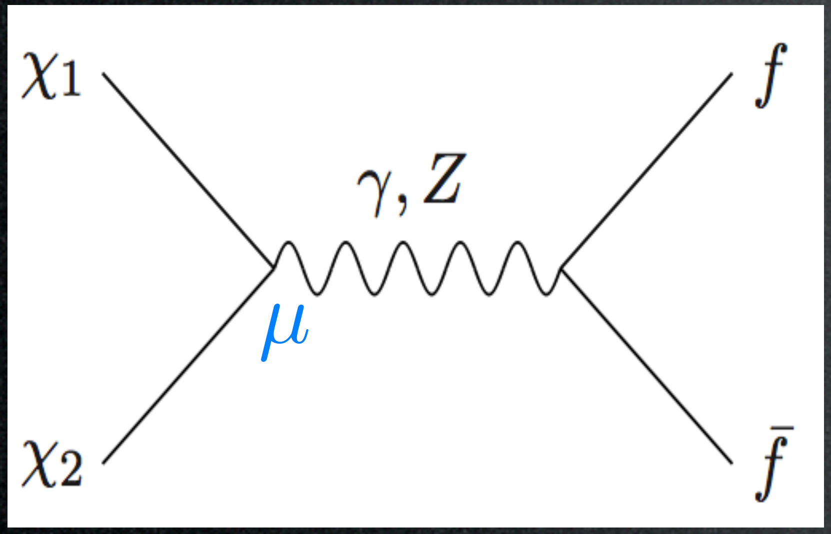
(b) DM sits in a multiplet with ~10 GeV splitting



→ line (a)

with large rate
if μ is large

→ Continuum? Under control (it's same order as $\gamma\gamma$)



→ 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)

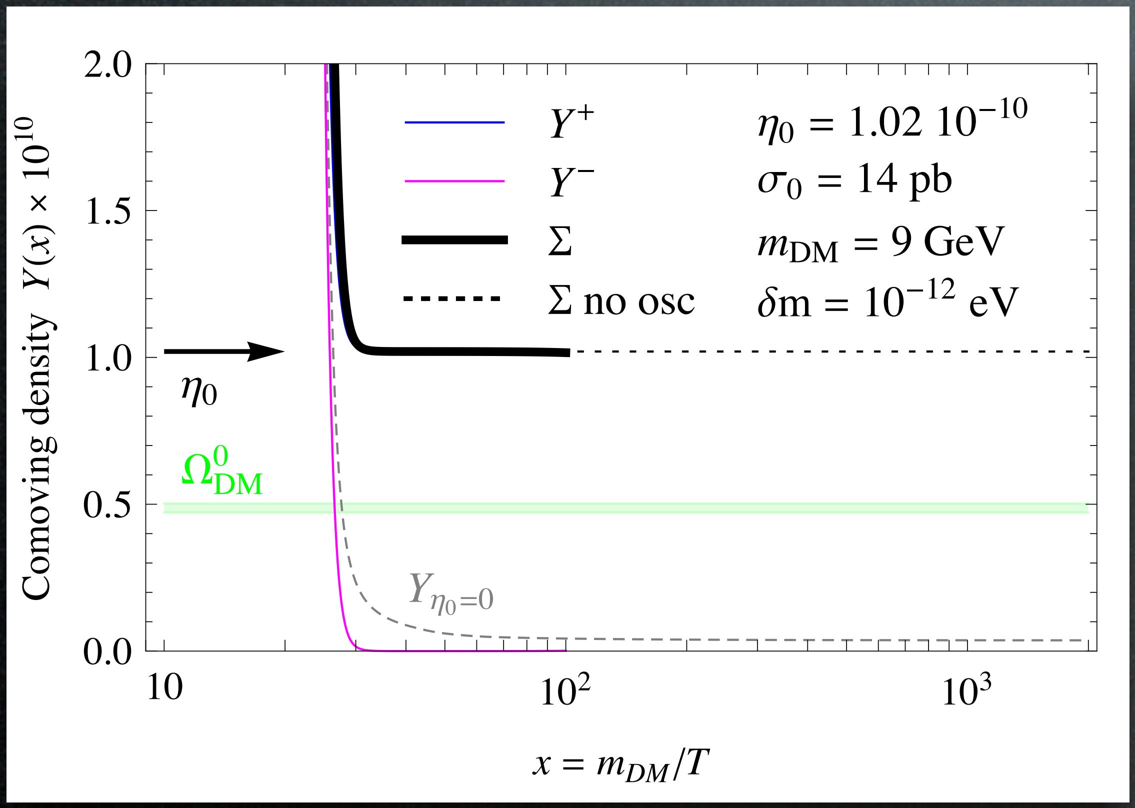
Model building

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!

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

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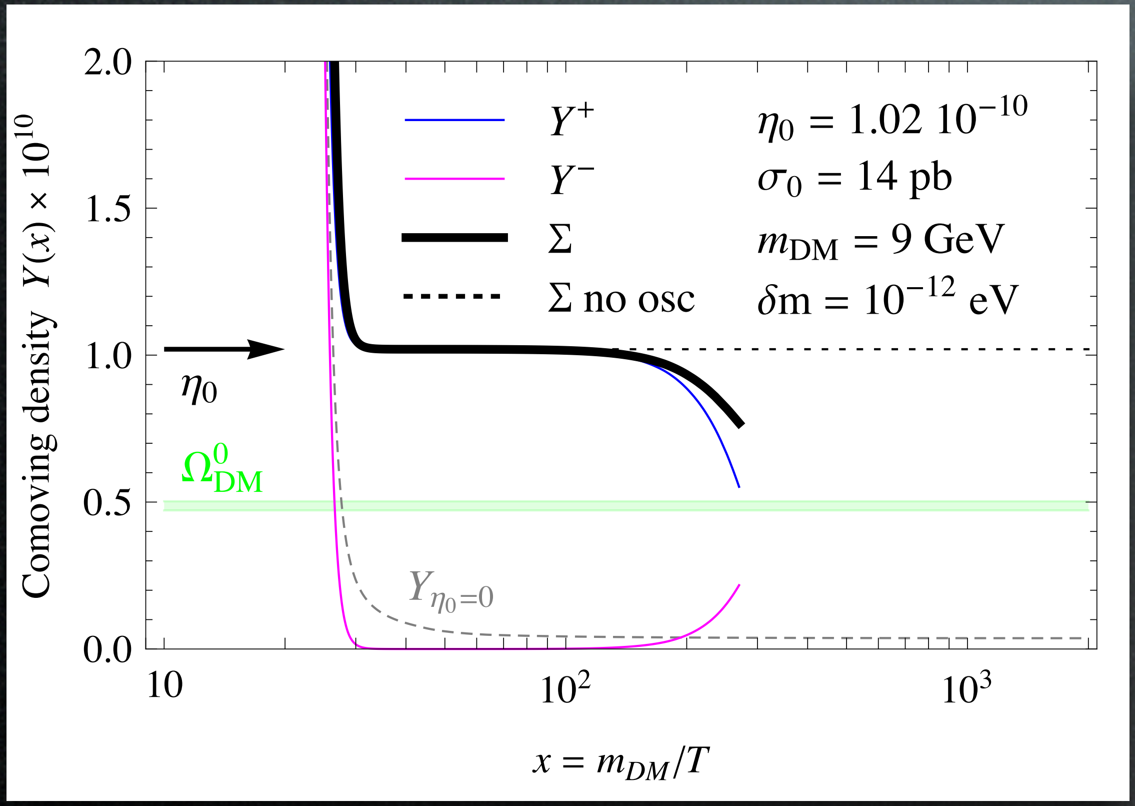

relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

Model building

not exhaustive!

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

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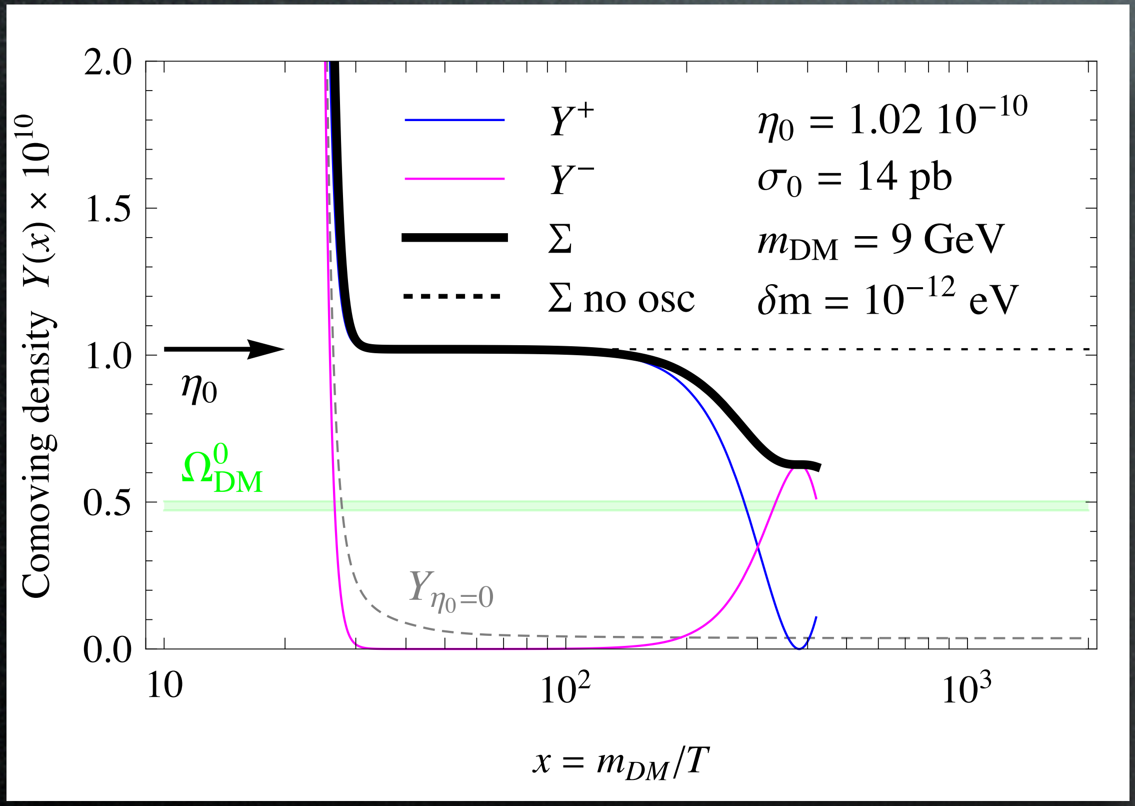

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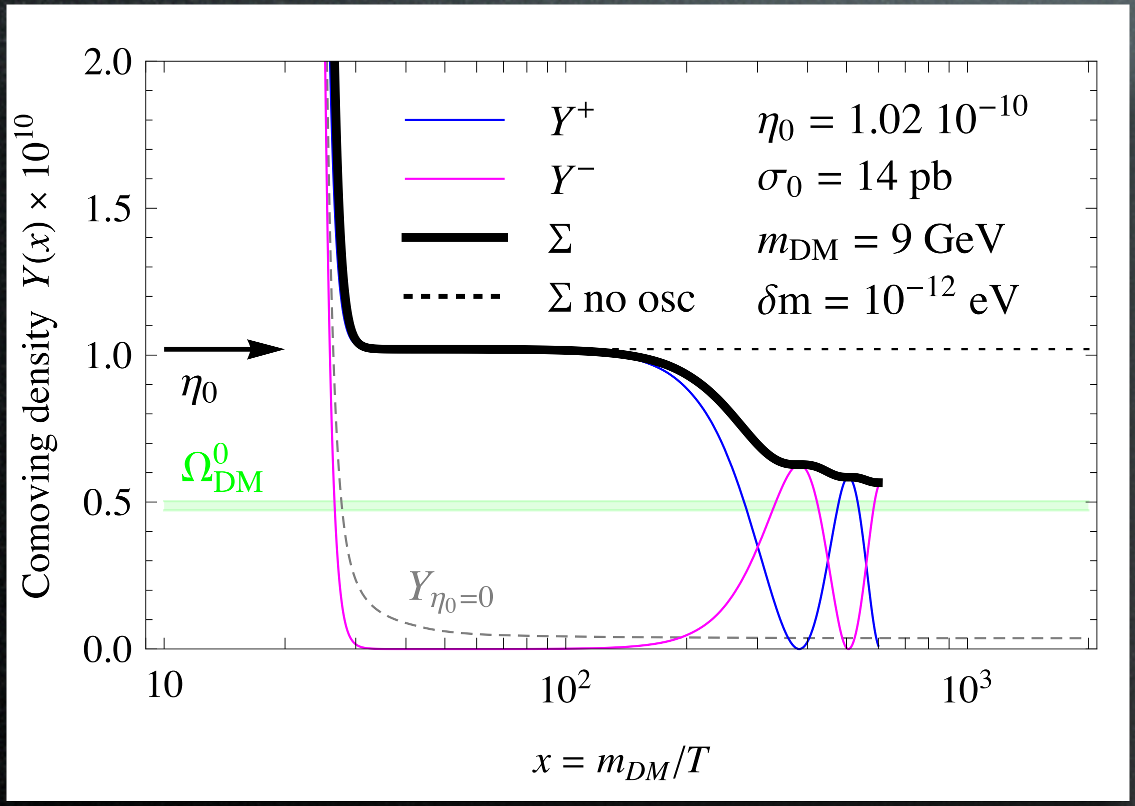

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Model building

not exhaustive!

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Kaplan, Luty, Zurek 2009
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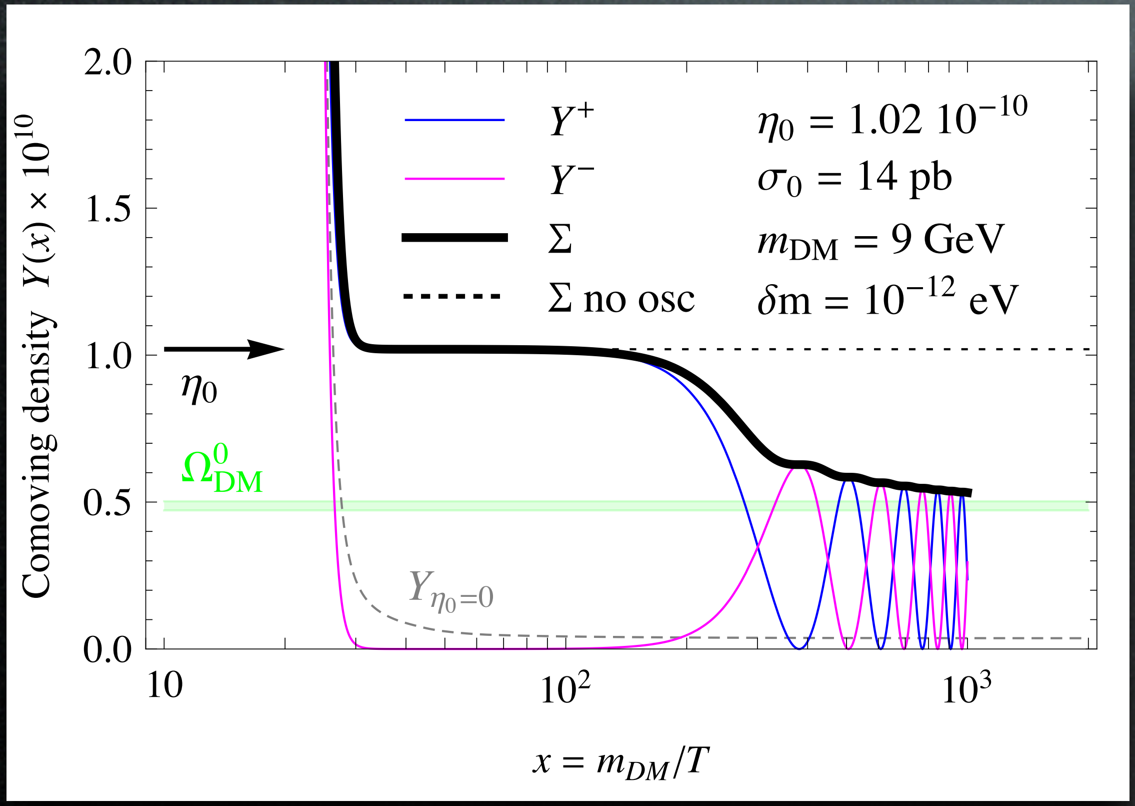

⇒ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

(and the cross section needs to be large)

Model building

not exhaustive!

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

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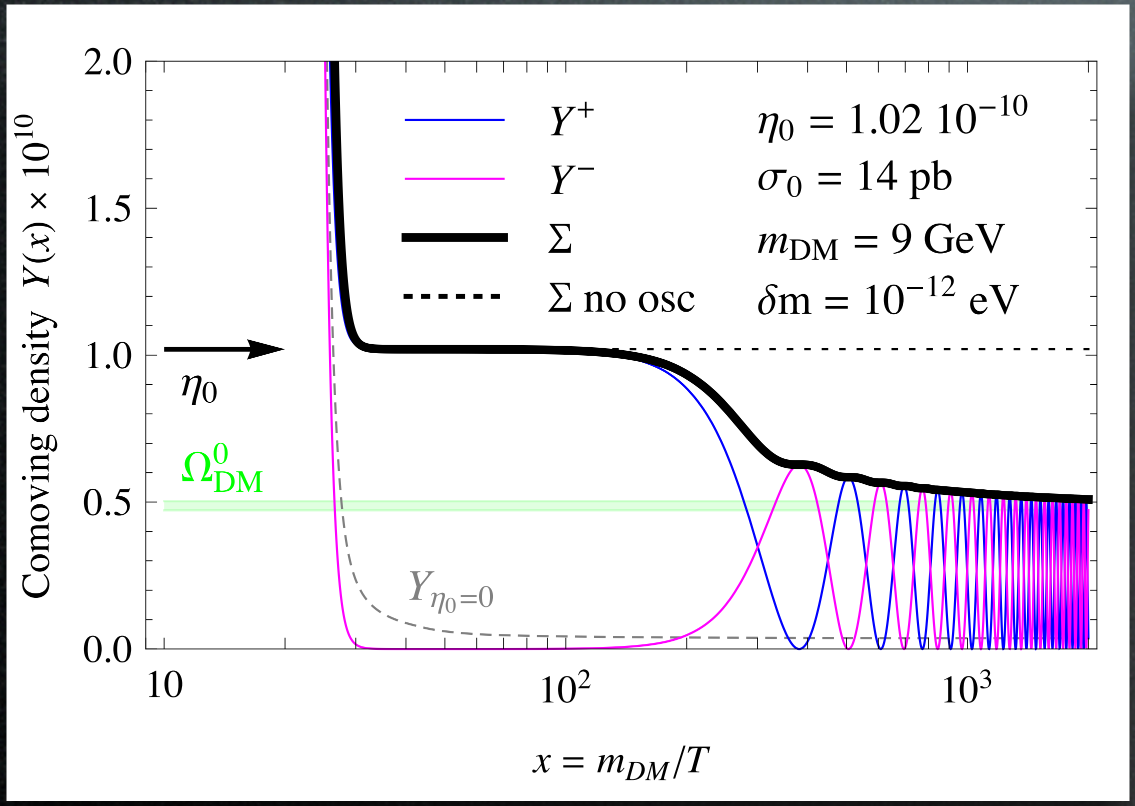

→ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b) → line

(and the cross section needs to be large)

Model building

not exhaustive!

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

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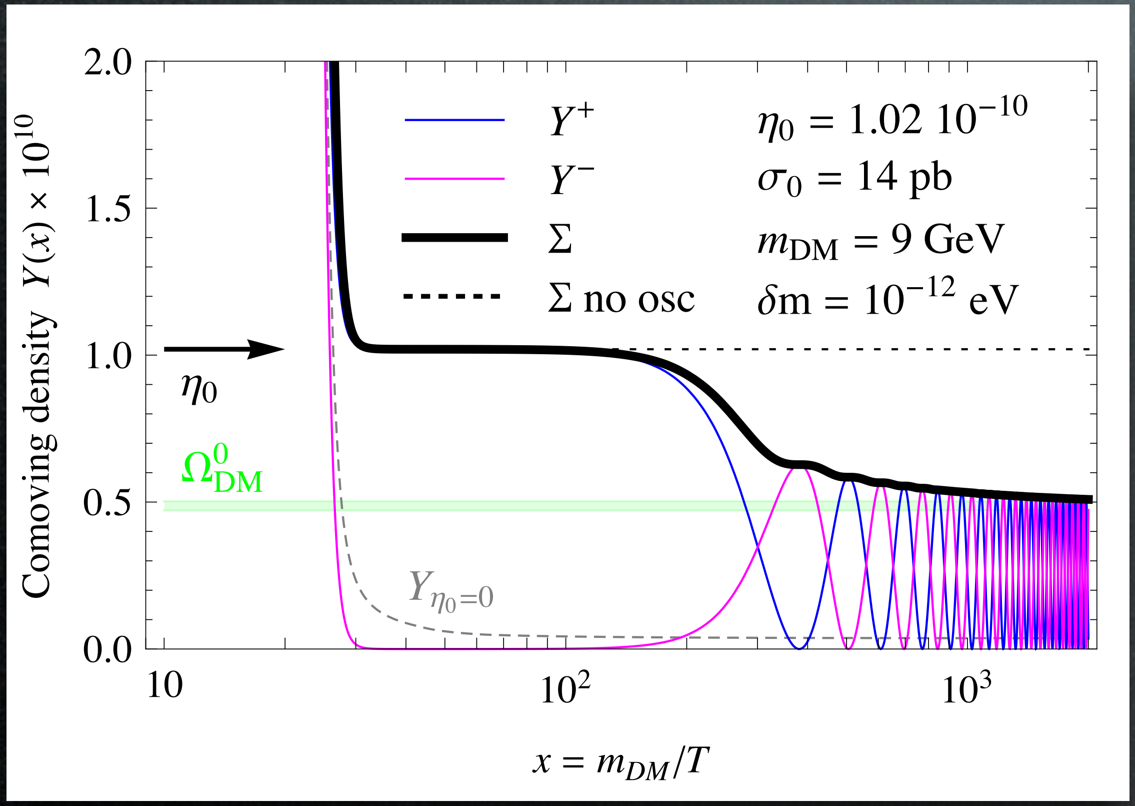


relic abundance (a)

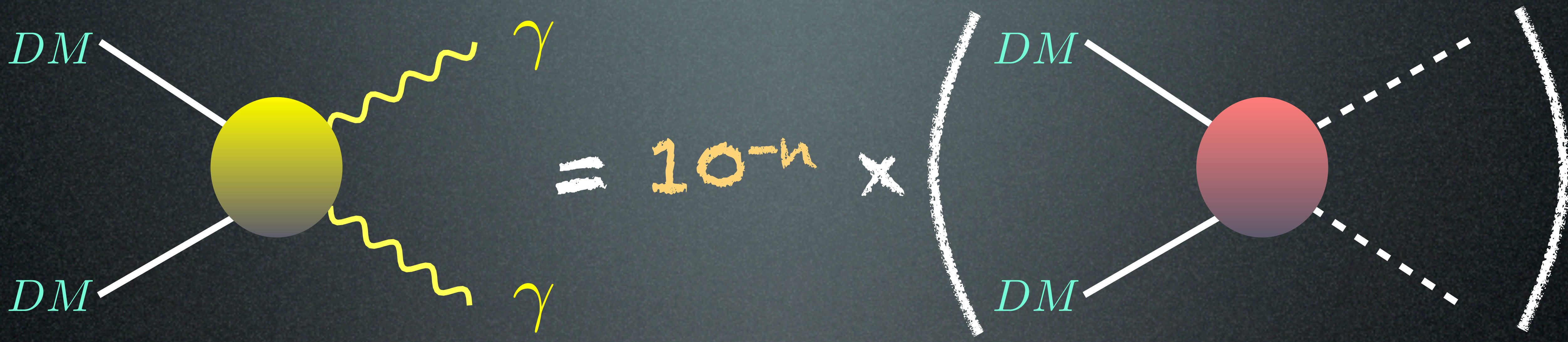
is produced via the asymmetry
is decoupled from the annihilation

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



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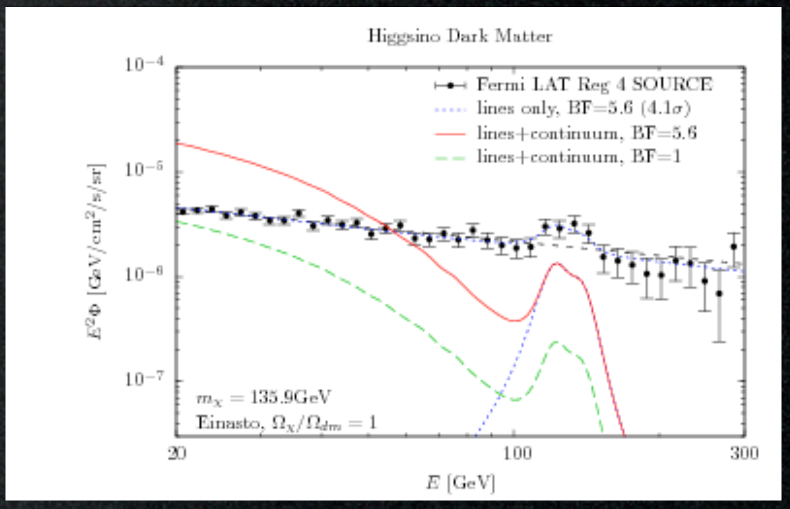


But solutions exist

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'

Gamma hints?

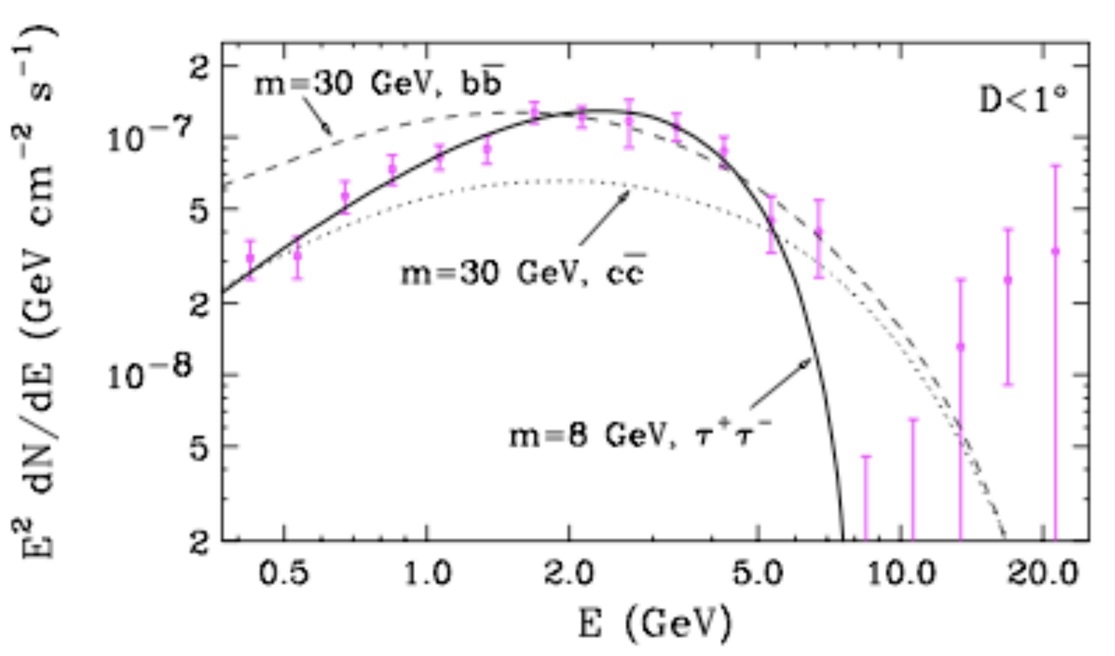
What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?

A diffuse GeV excess from around the GC

Dan Hooper

Gamma hints?

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



Hooper, Goodenough 1010.2752

A diffuse GeV excess from around the GC

Dan Hooper

Gamma hints?

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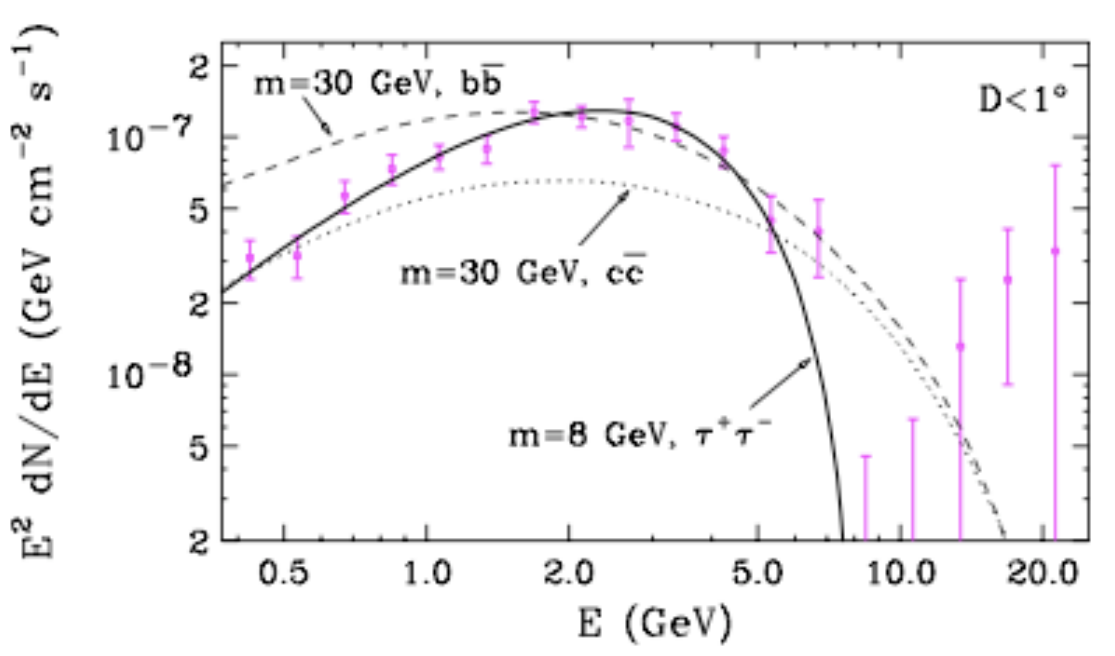
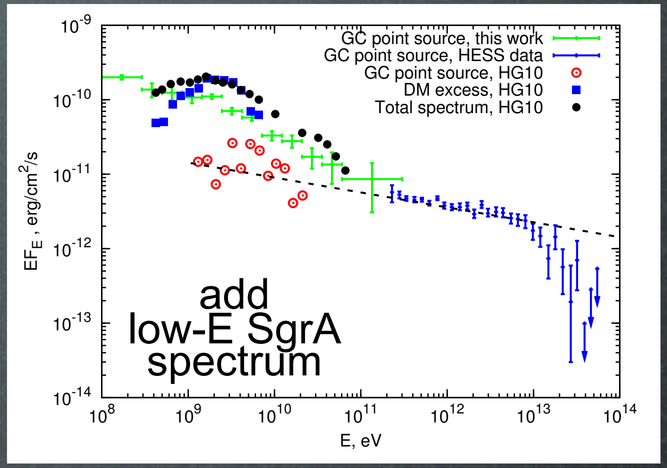
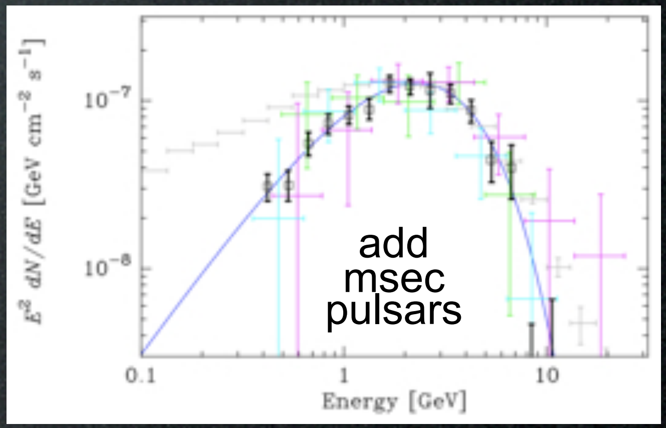


Hooper, Goodenough 1010.2752

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

A diffuse GeV excess from around the GC

Dan Hooper

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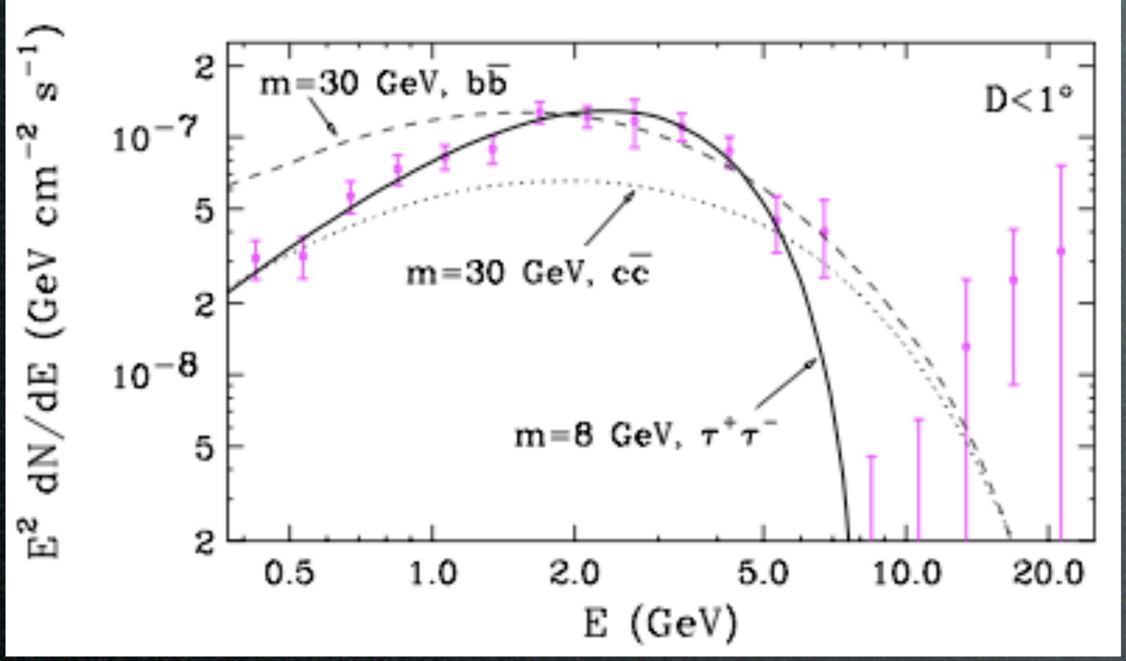


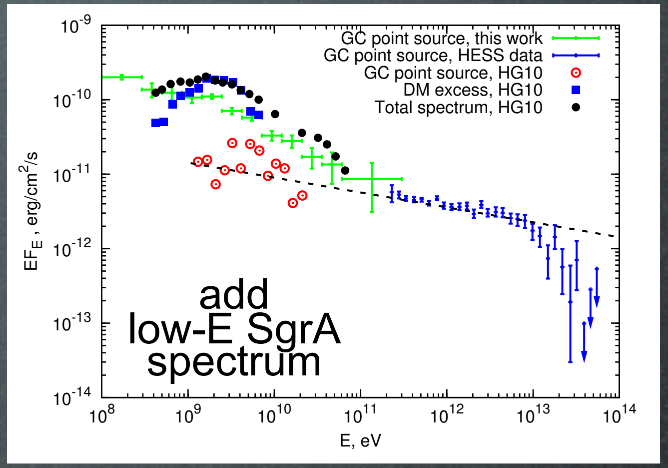
Hooper, Goodenough 1010.2752

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

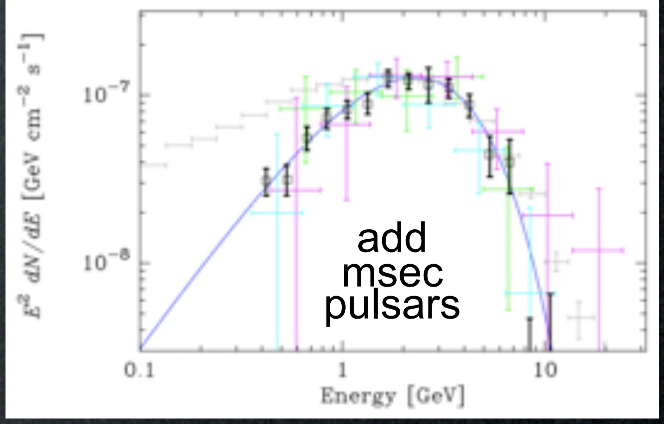
A diffuse GeV excess from around the GC

Dan Hooper

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

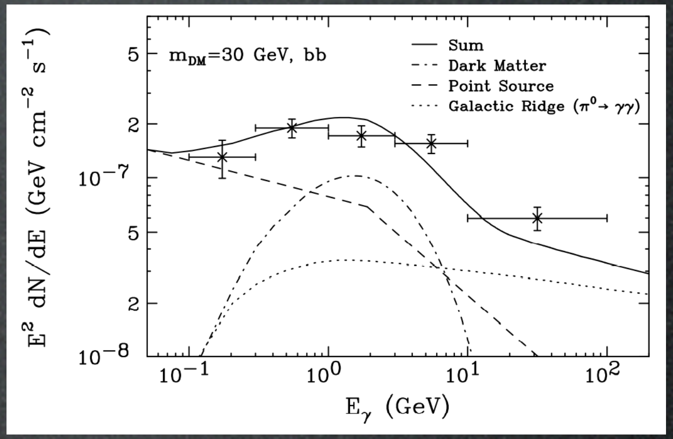
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

Still works...



Hooper, Linden 1110.0006

Gamma hints?

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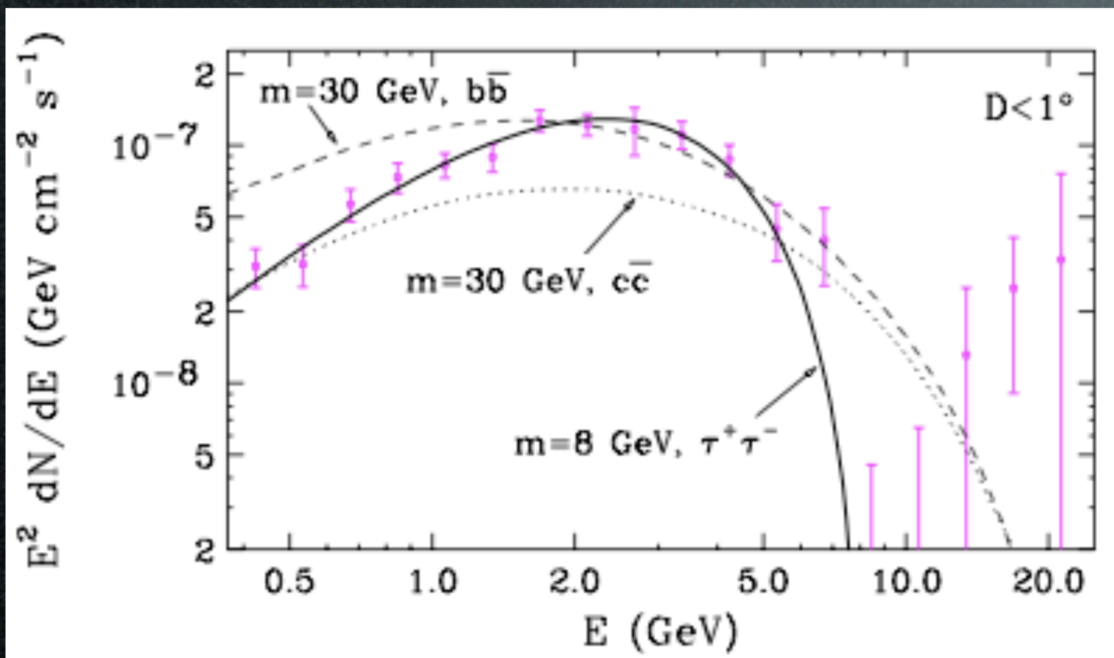
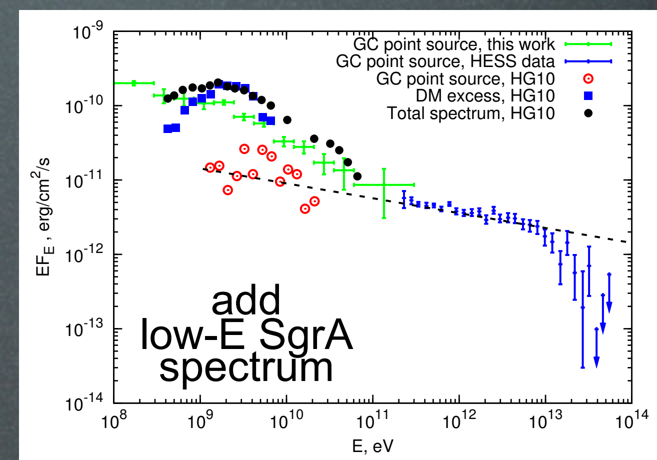


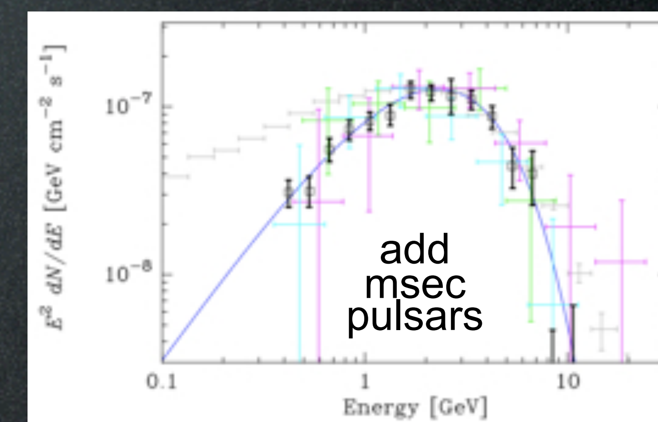
Hooper, Goodenough 1010.2752

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

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



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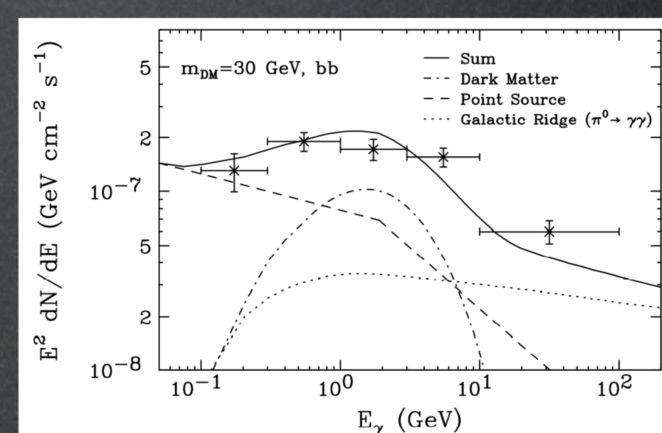


Hooper, Linden 1110.0006

No no, MSPs can do.

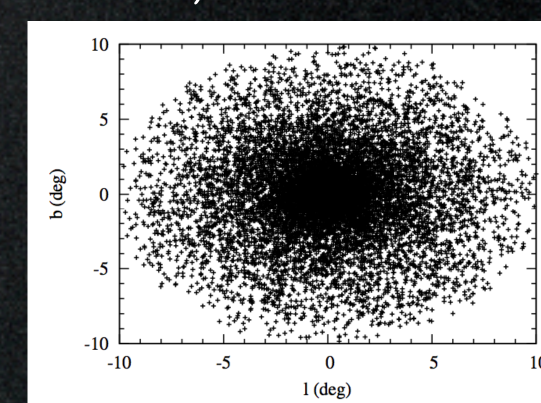


Figure 5: Simulated spatial distribution of the bulge MSPs.

Yuan, Zhang 1404.2318

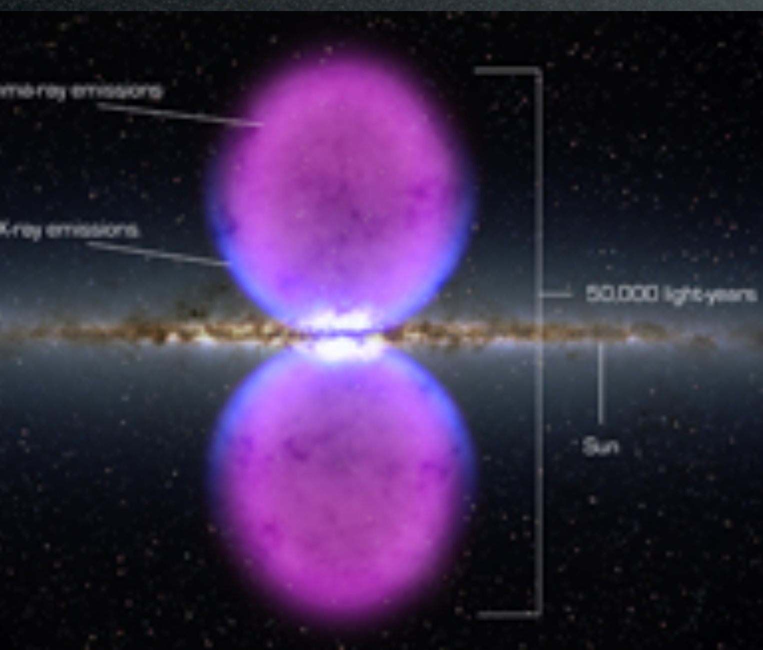
A diffuse GeV excess from around the GC

Dan Hooper

+ synchr from radio filaments
+ WMAP/Planck haze
+ Direct Detection... Hooper, 1201.1303

Gamma hints?

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



Fermi bubbles

Dan Hooper

Gamma hints?

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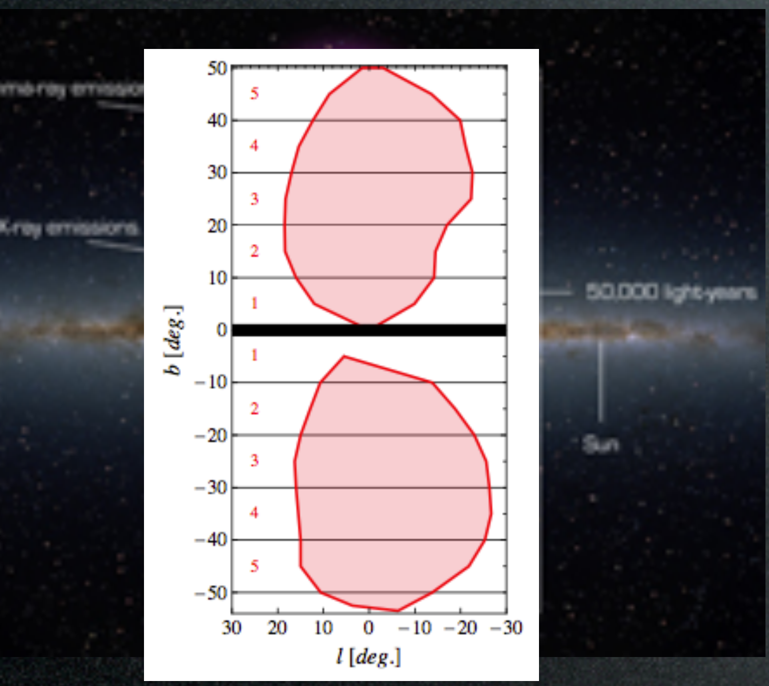

Fermi bubbles

Dan Hooper

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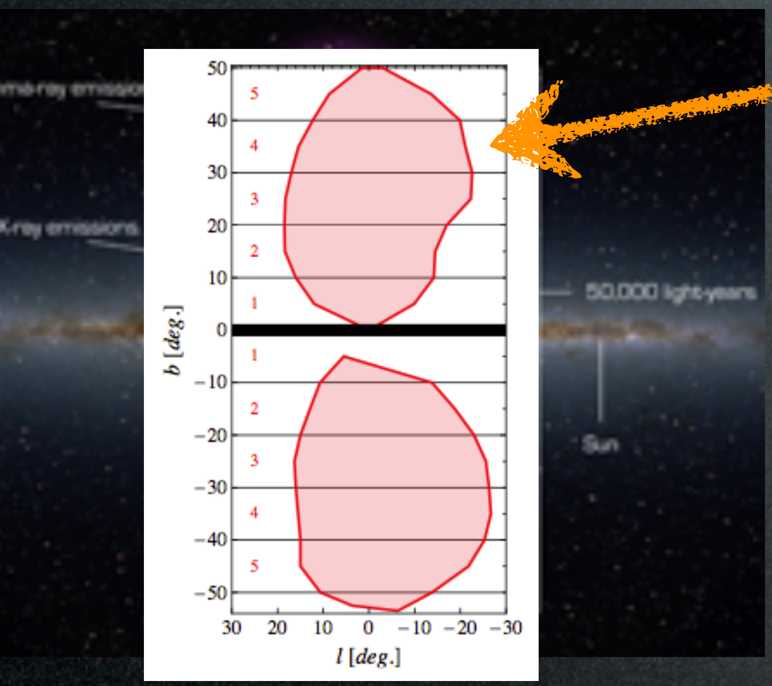

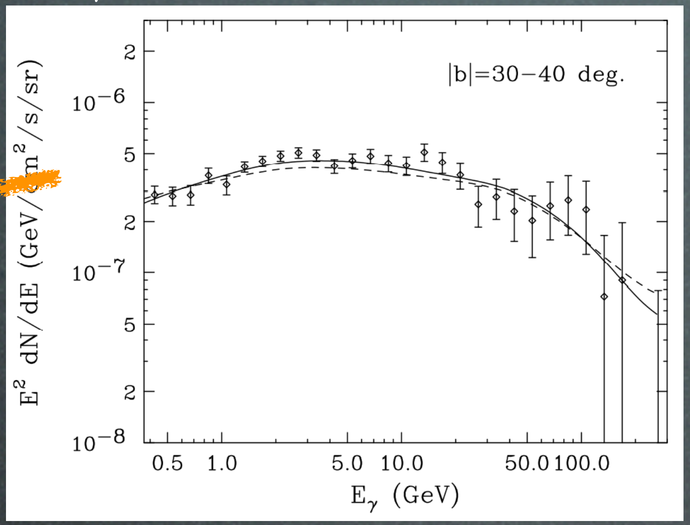

Here there's no excess which cannot be explained in terms of ordinary ICS.

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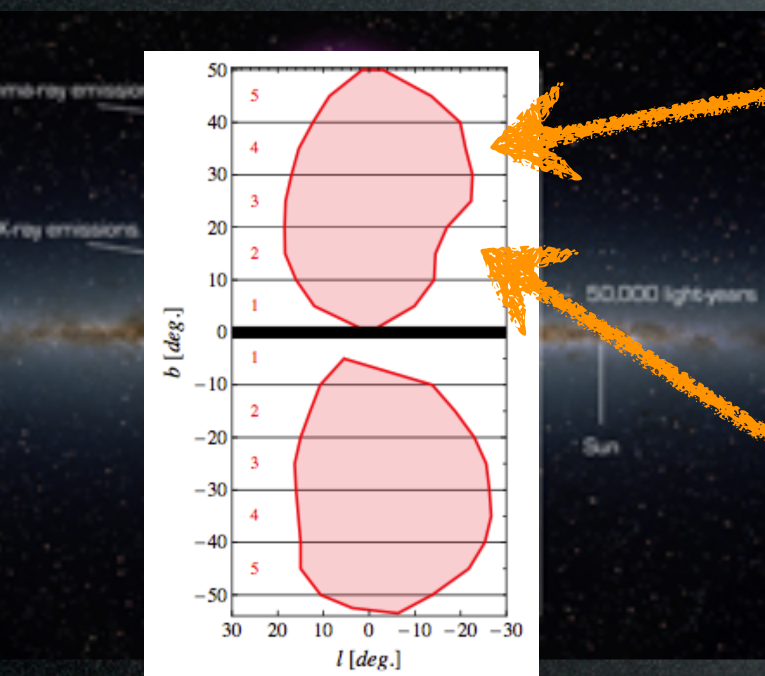

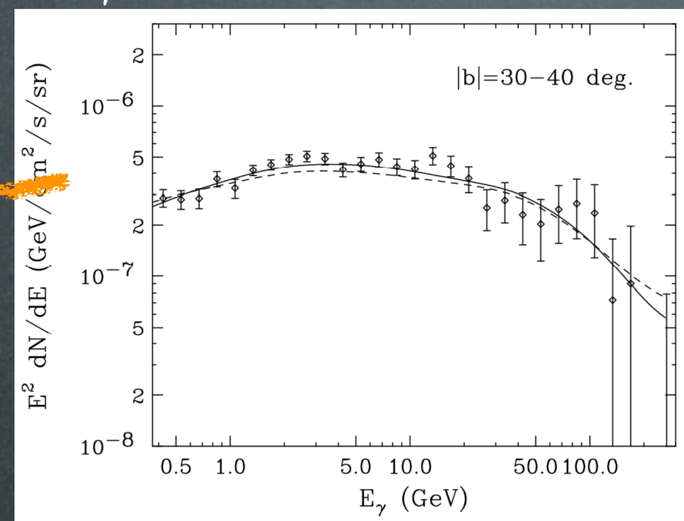

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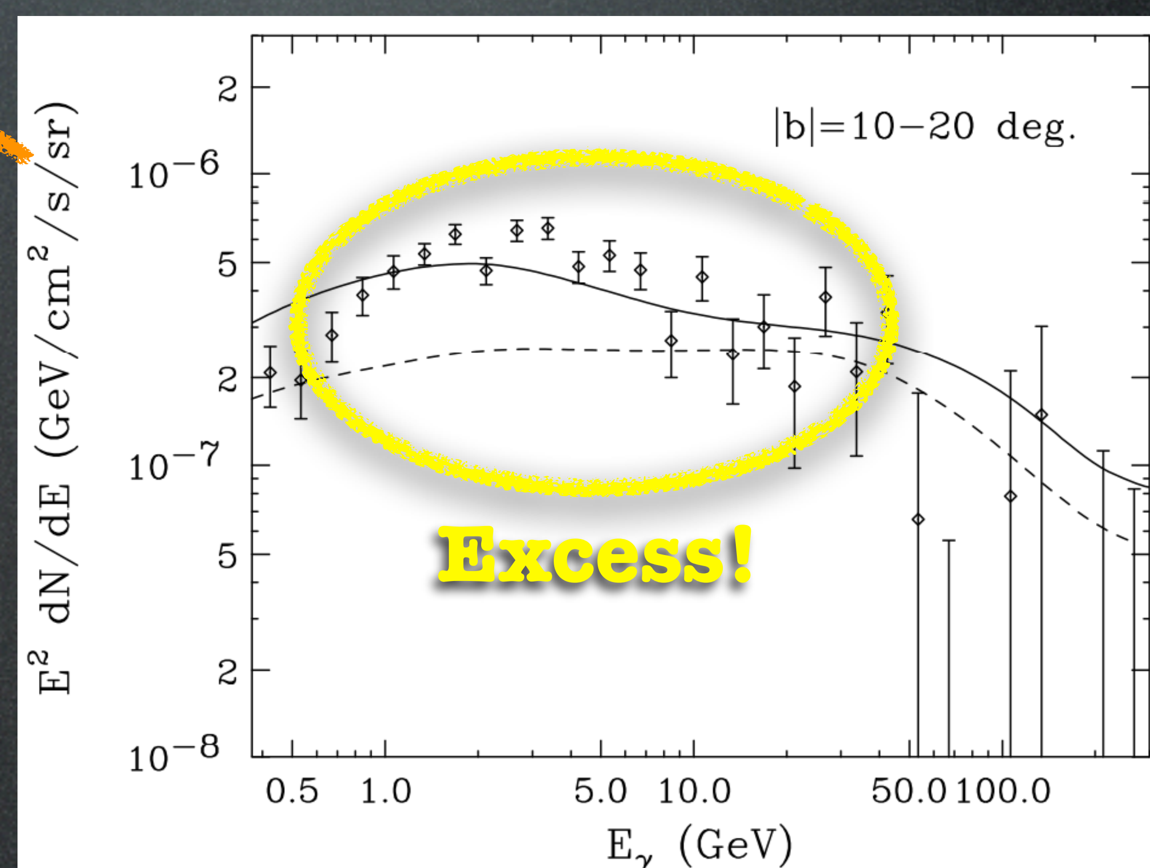
Best fit:
~10 GeV, leptons, ~thermal σv

Fermi bubbles

Dan Hooper



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

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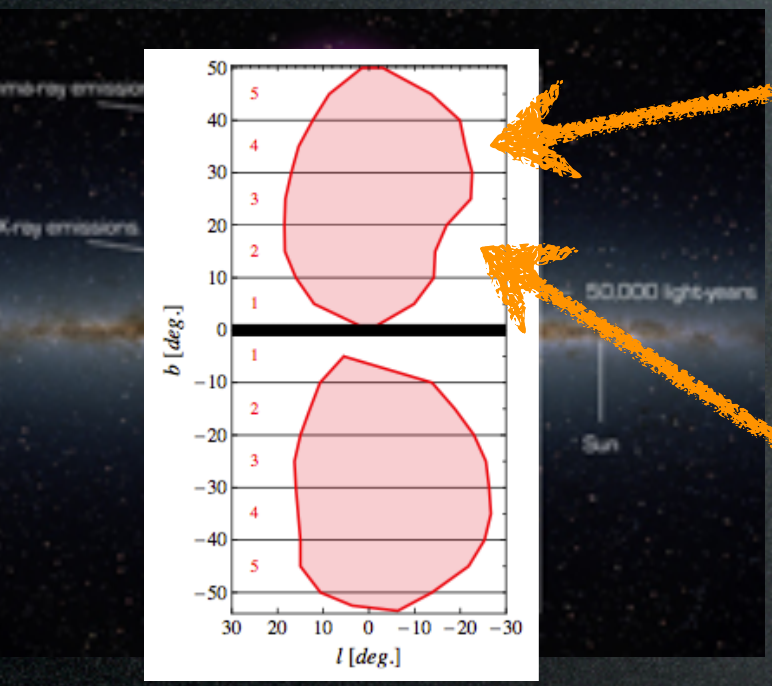

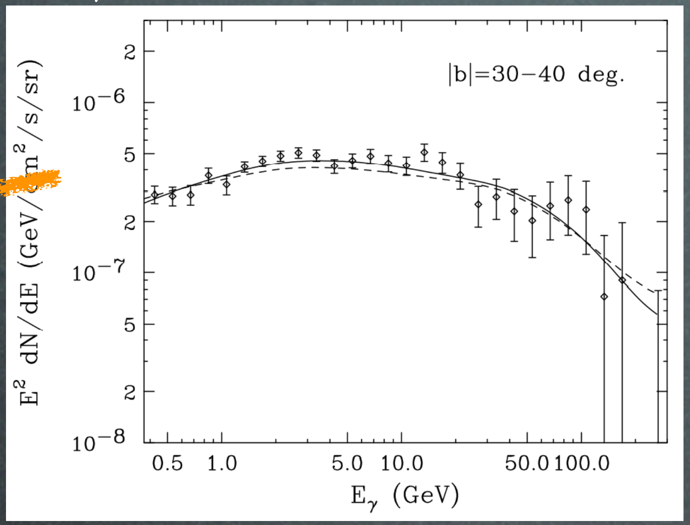

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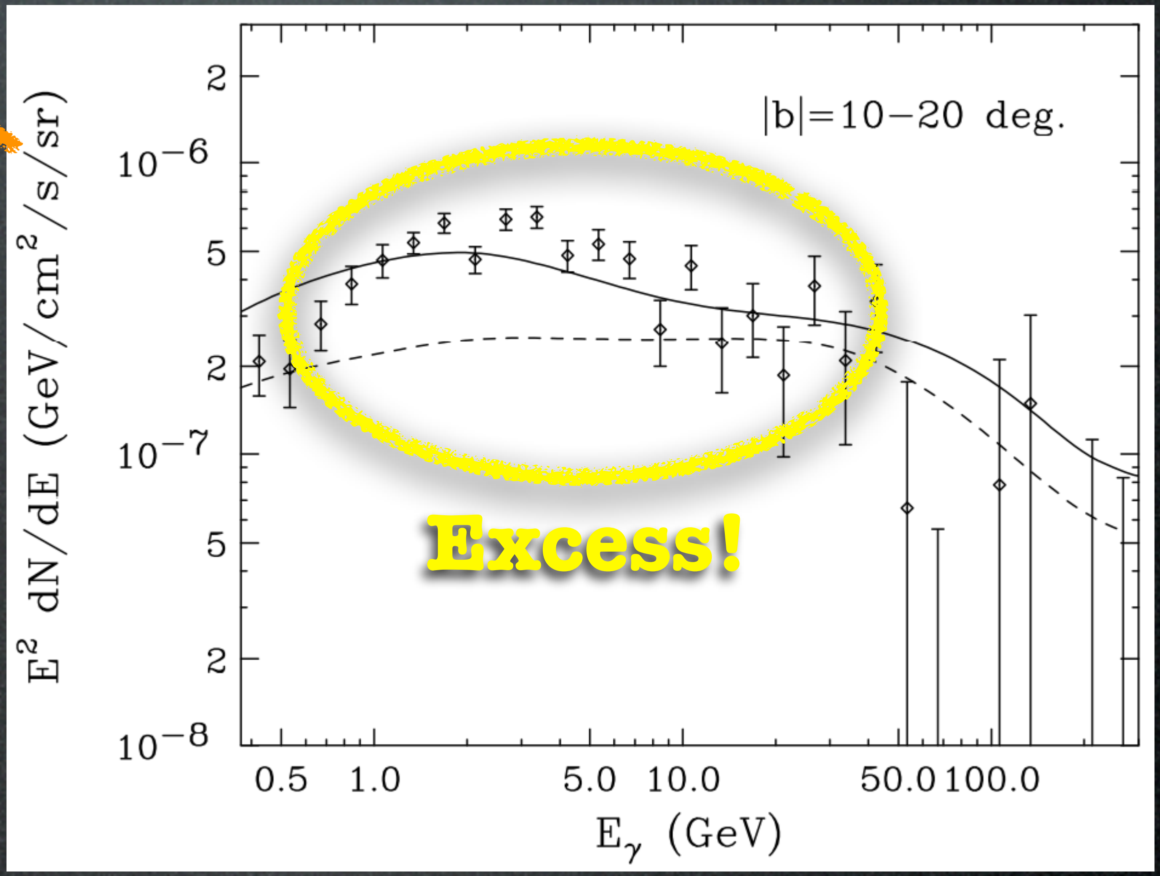

Objection:
nothing tells you that the input $e^\pm$ spectrum stays the same at high and low latitudes
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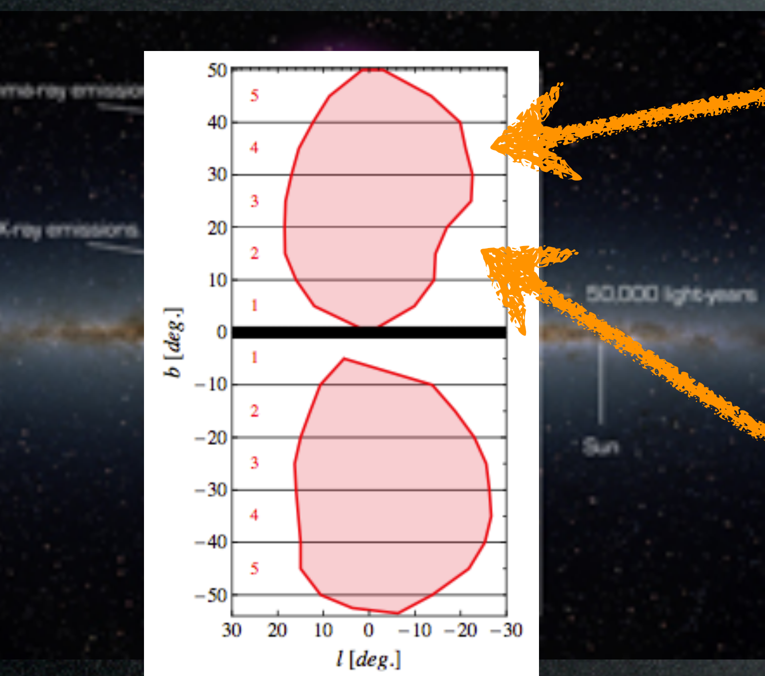

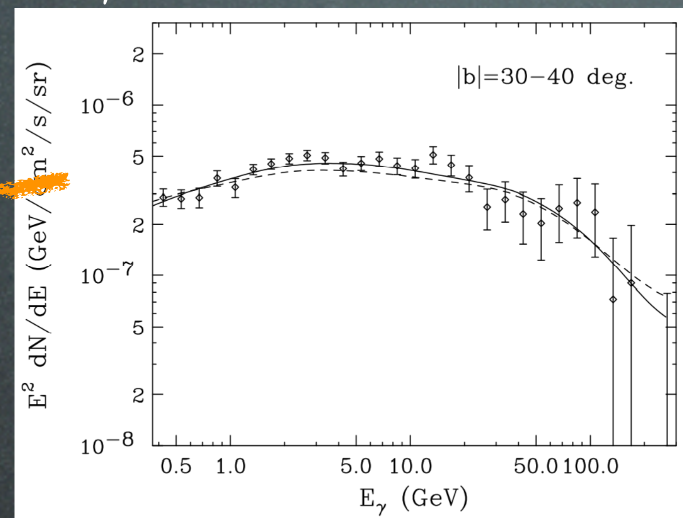

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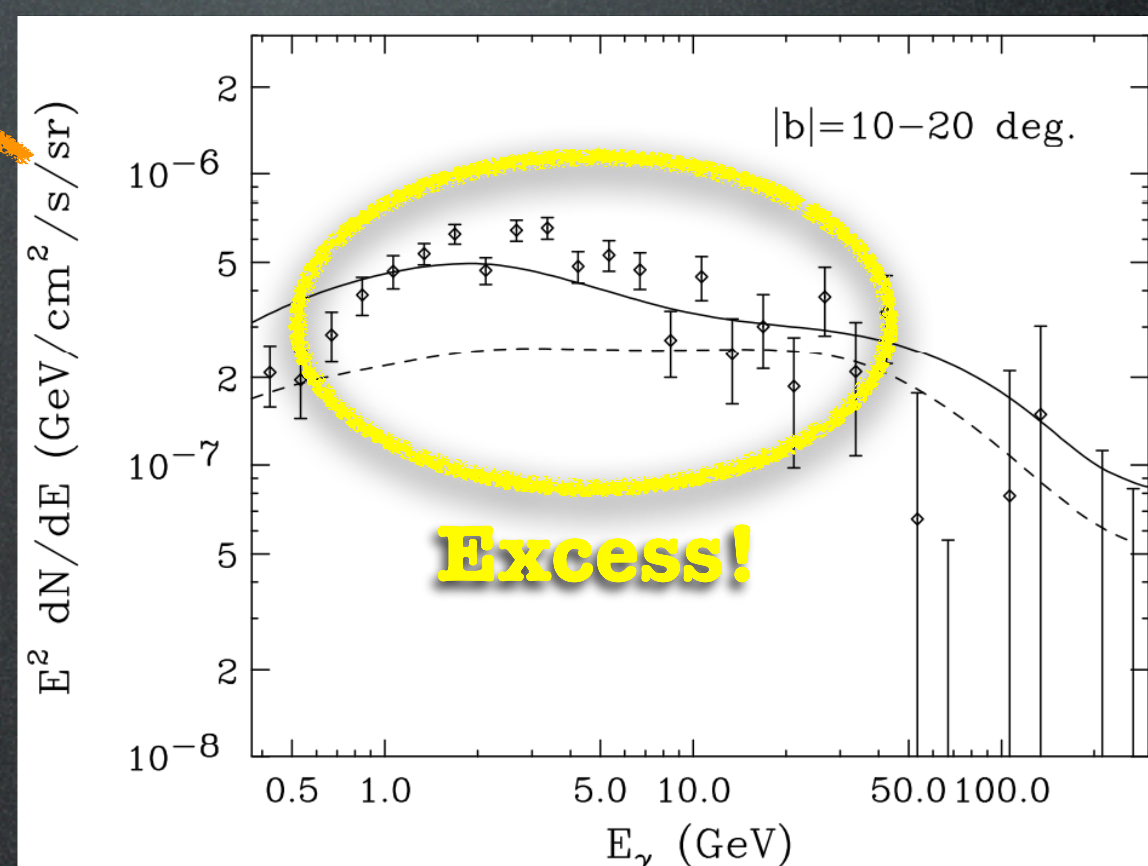

Objection:
nothing tells you that the input $e^\pm$ spectrum stays the same at high and low latitudes (the ISRF too, but one can better model that)

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

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

Fermi bubbles

Dan Hooper

Hooper, Slatyer 1302.6589
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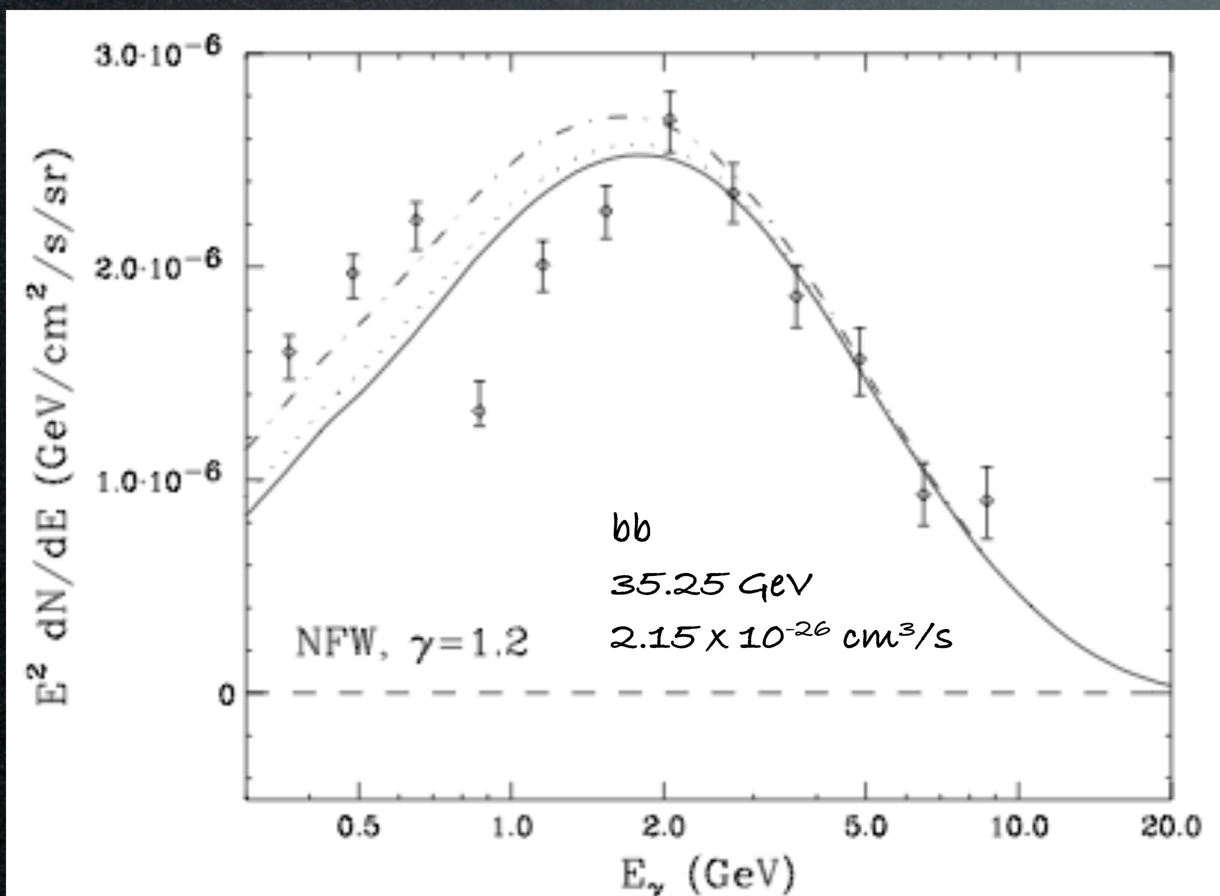
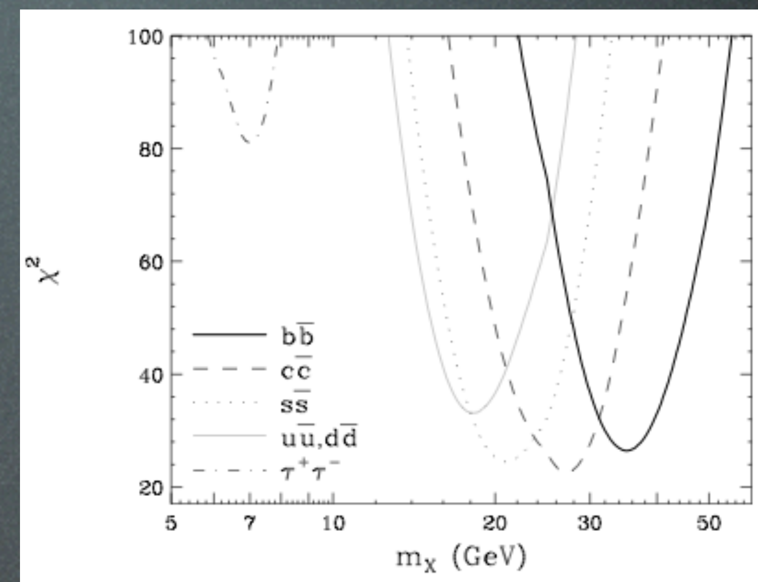
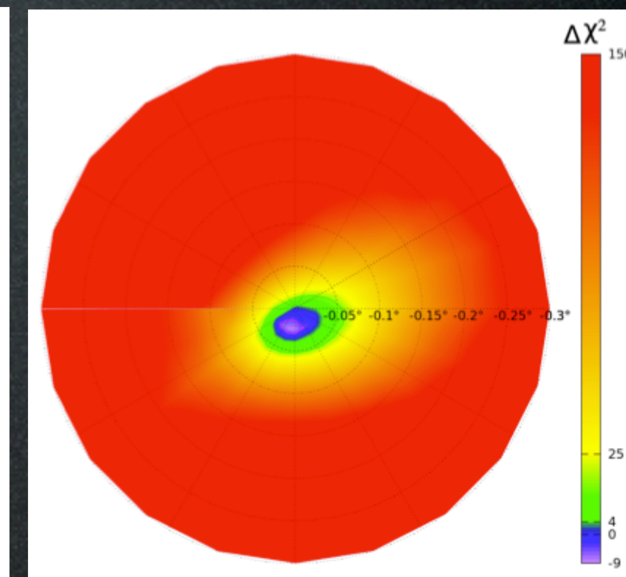






Best fit:
~35 GeV, quarks, ~thermal σv

A diffuse GeV excess from around the GC

Dan Hooper

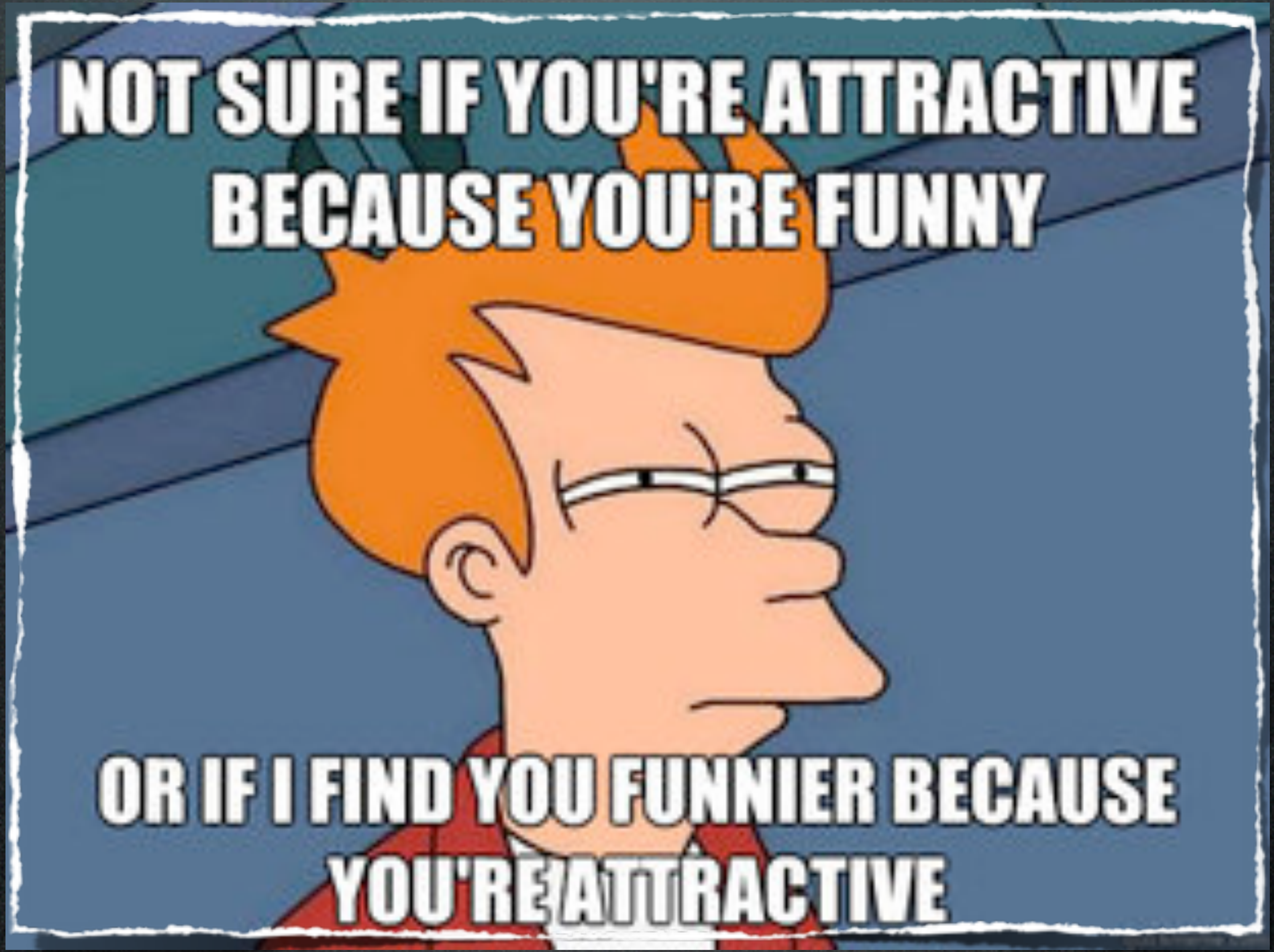
Dyalan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703:
'A compelling case for annihilating DM'

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.

Theorist's reaction

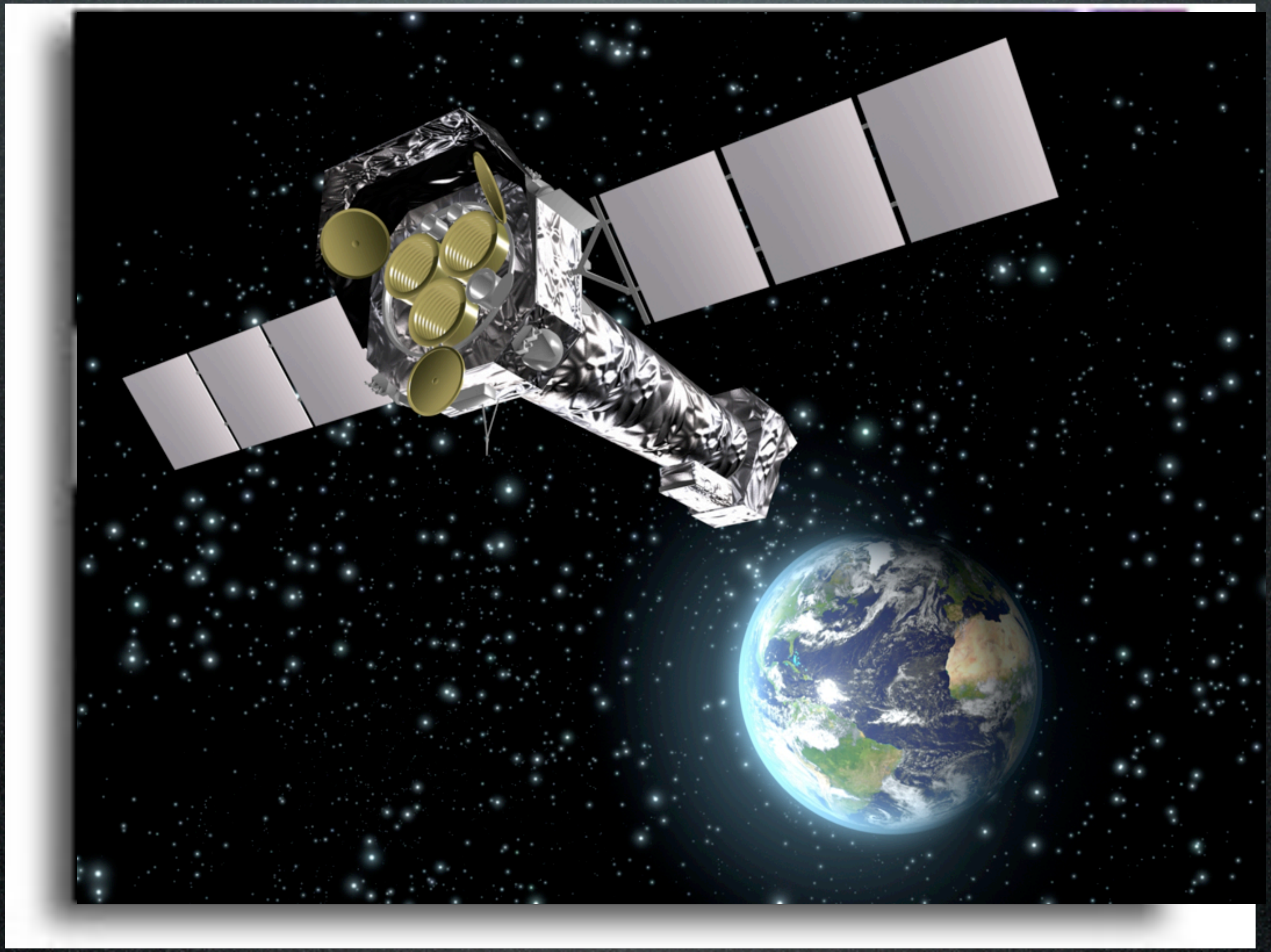
3. the 'Hooperon'

Theorist's reaction



3. the 'Hooperon'

X-rays



4. the ‘3.5 KeV line’

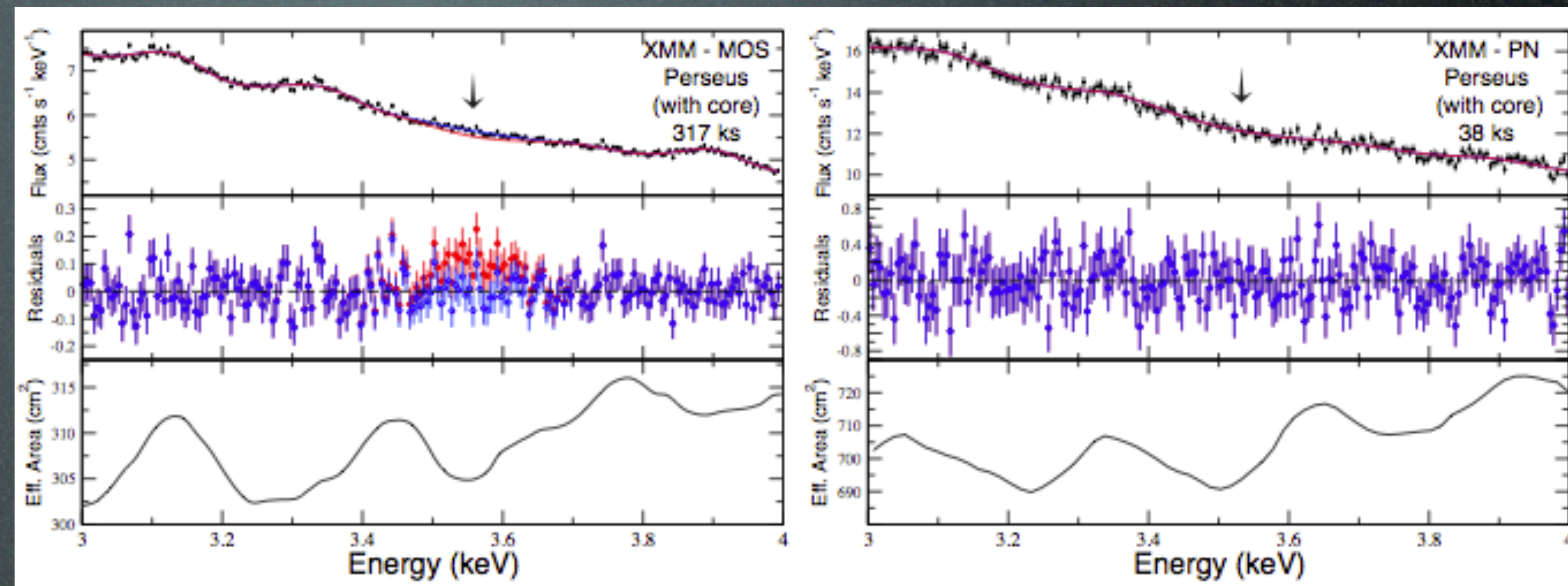
X-ray line

Bulbul et al., 1402.2301

3.55 - 3.57 ± 0.03 KeV

73 clusters

z = 0.01 - 0.35

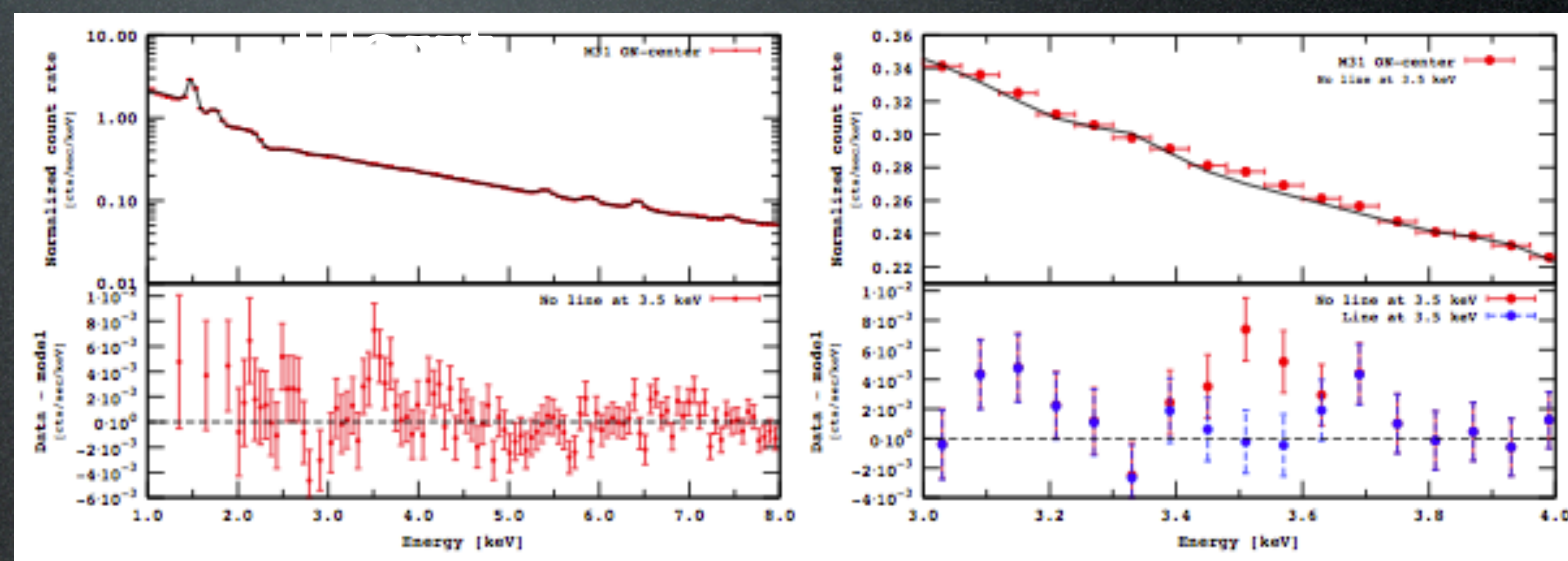


Boyarsky, Ruchayskiy, 1402.4119

3.5 KeV

Andromeda galaxy
+ Perseus cluster

z = 0 and 0.0179

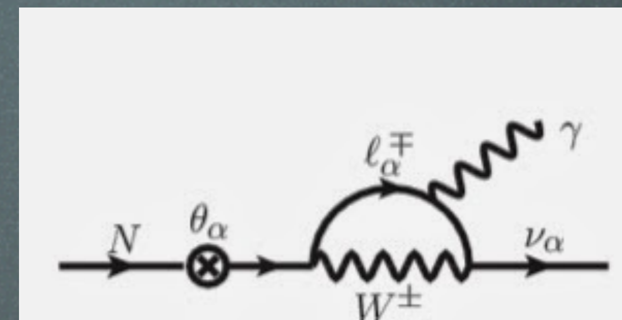


Theorist's reaction

4. the '3.5 KeV' line

X-ray line

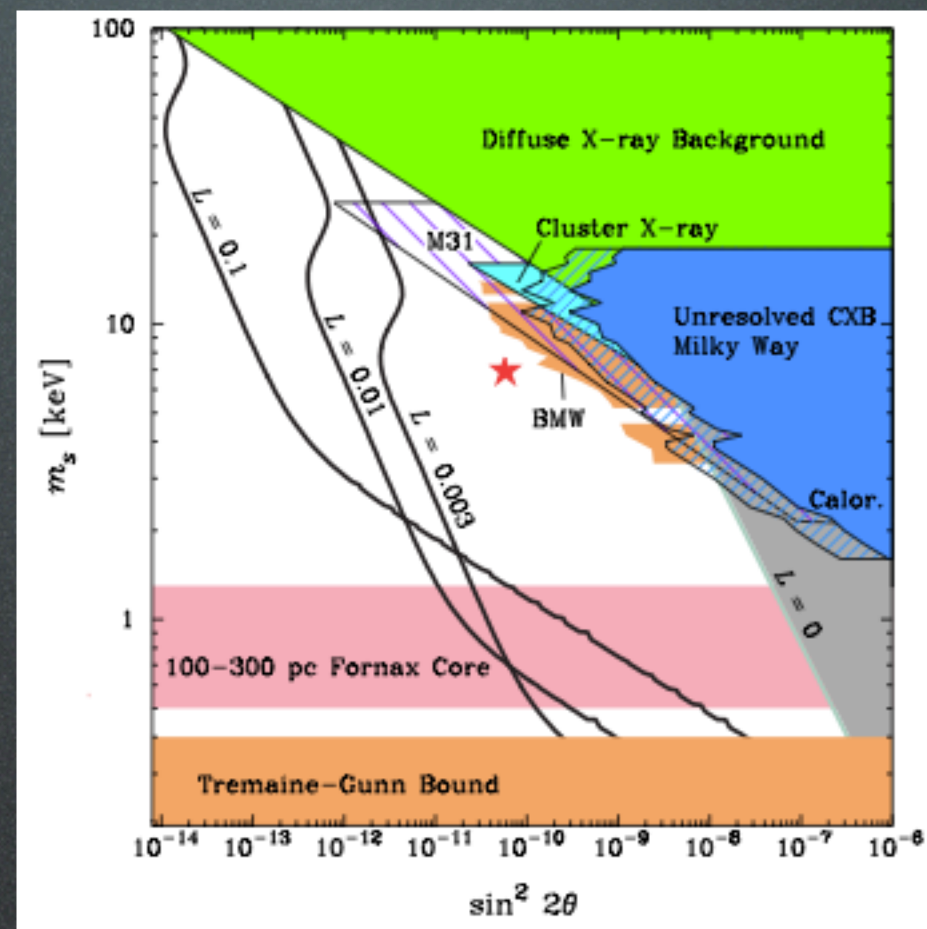
Sterile neutrino decay



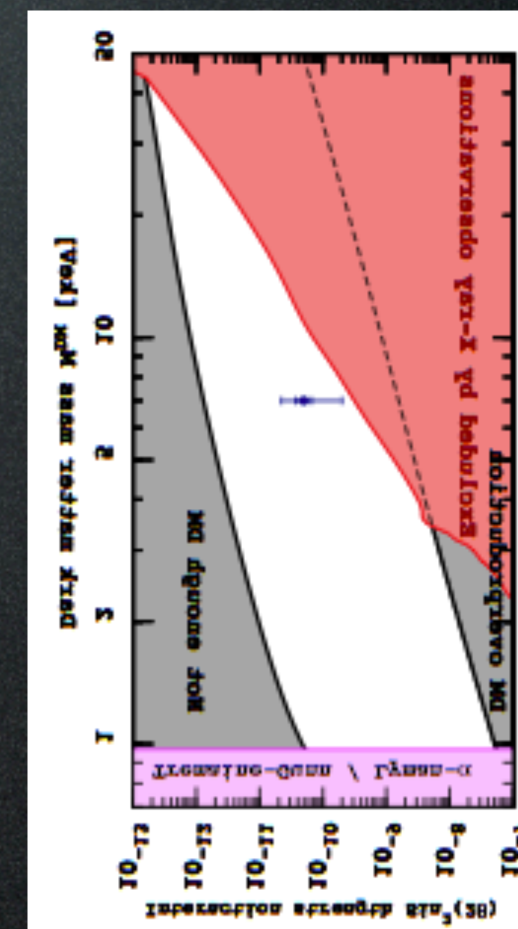
$m_\nu = 7.1 \text{ KeV}$

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

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



Bulbul et al., 1402.2301



Boyarsky, Ruchayskiy et al., 1402.4119

X-ray line

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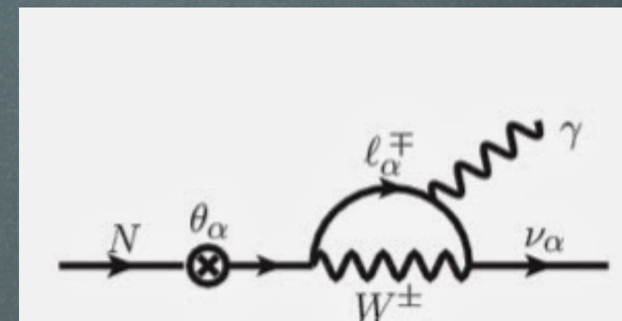

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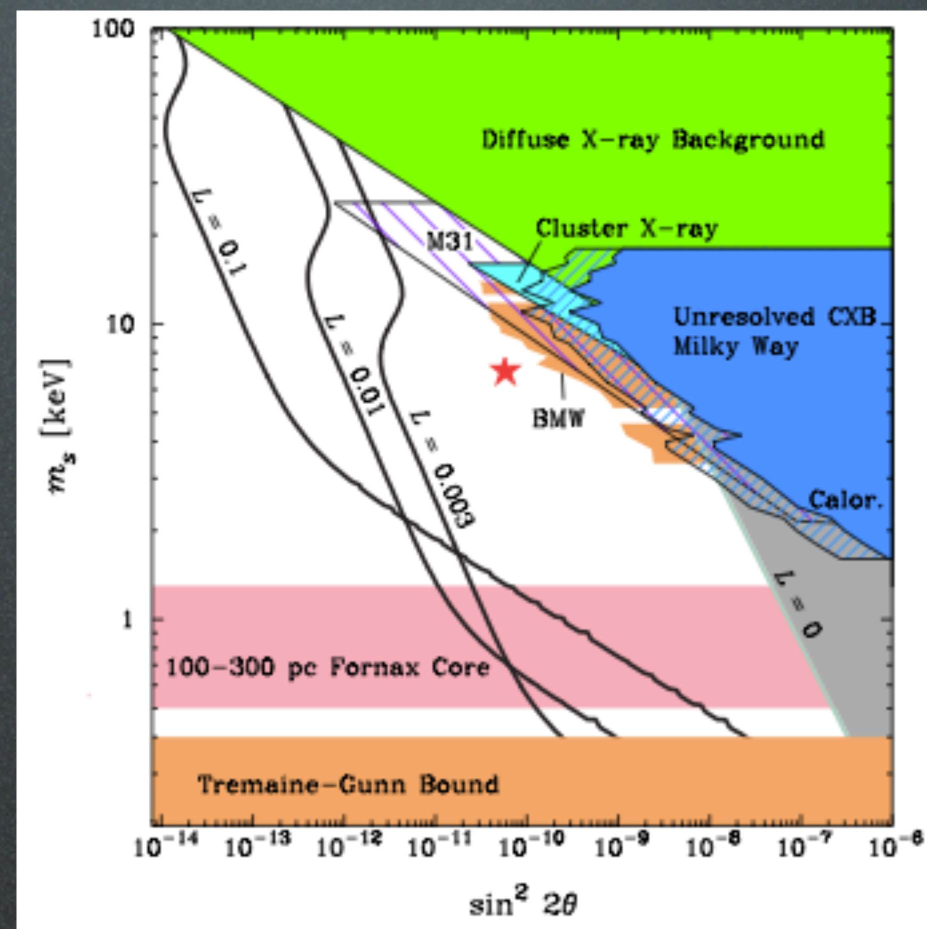
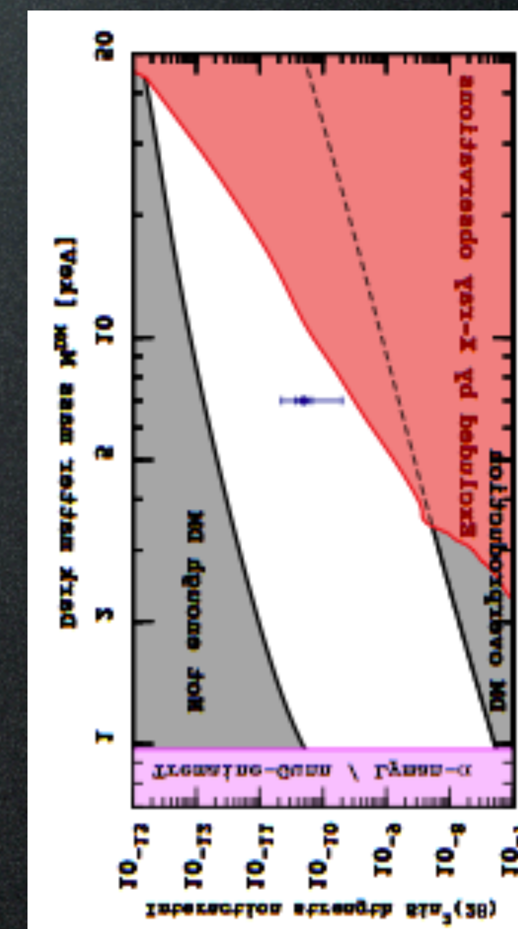


Bulbul et al., 1402.2301



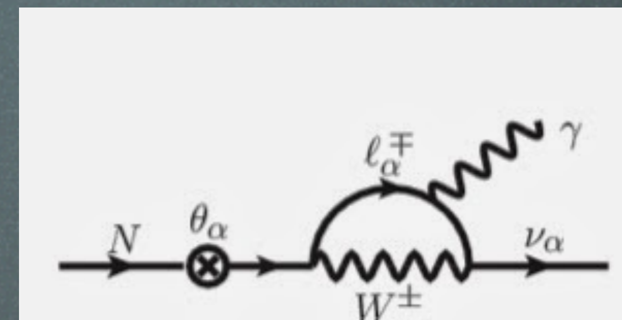
Boyarsky, Ruchayskiy et al., 1402.4119

Possible challenges:

- EU production?
- Perseus flux too large?

X-ray line

Sterile neutrino decay



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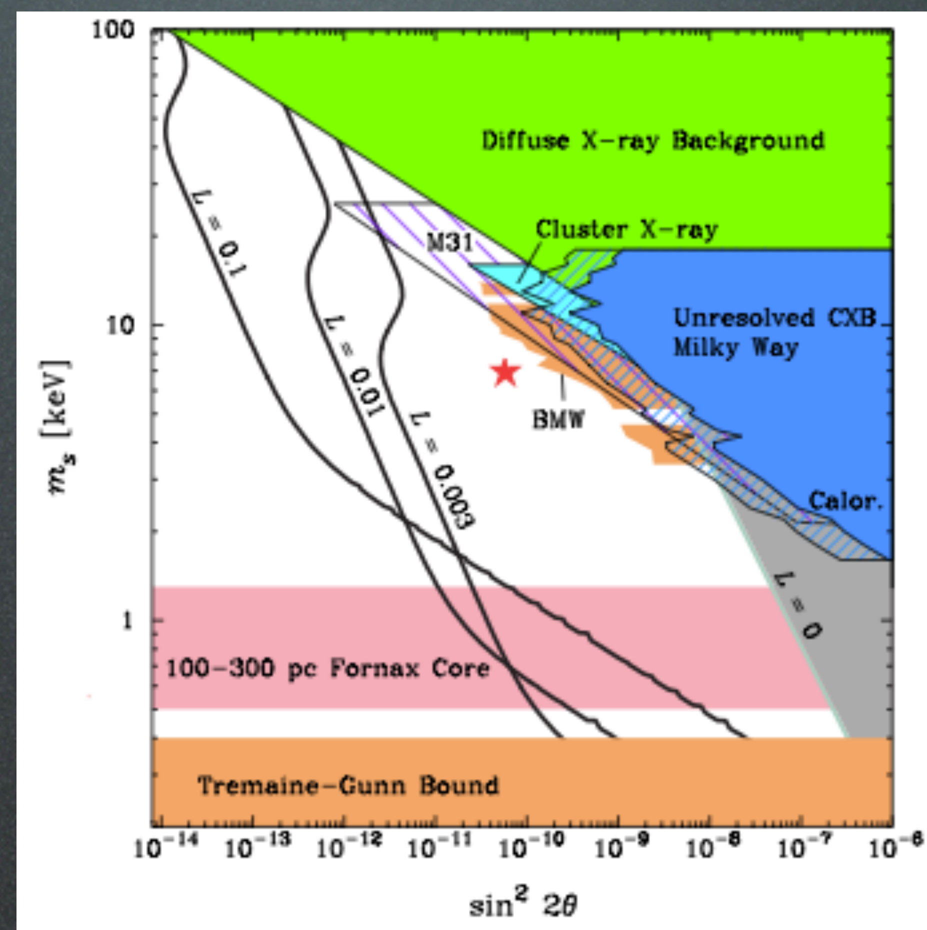
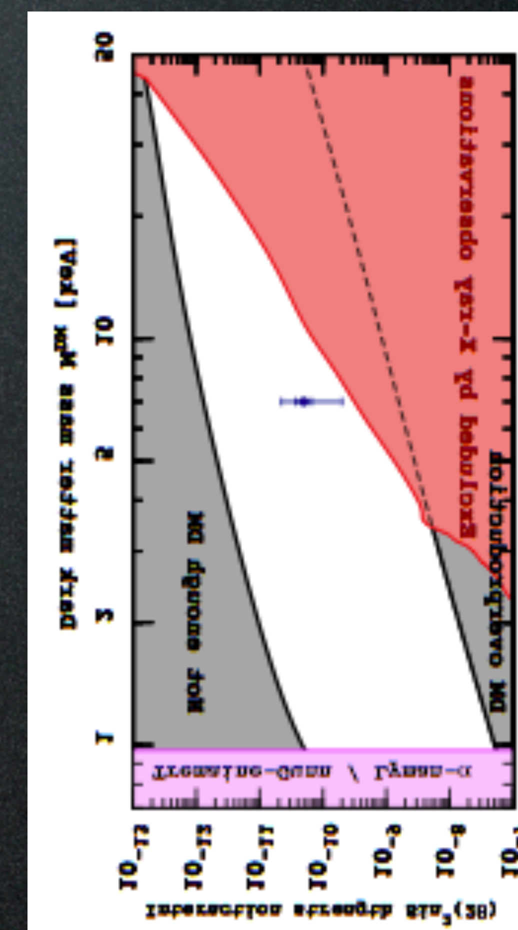


Bulbul et al., 1402.2301



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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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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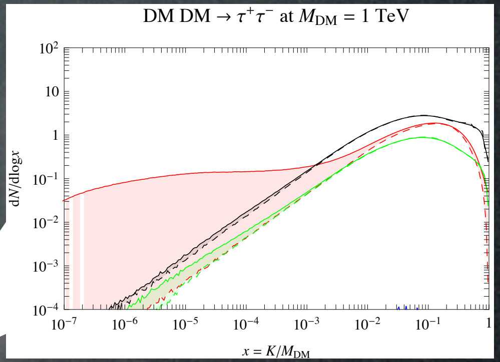
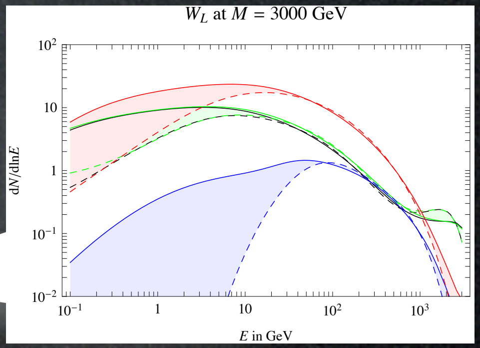
Main added value features:

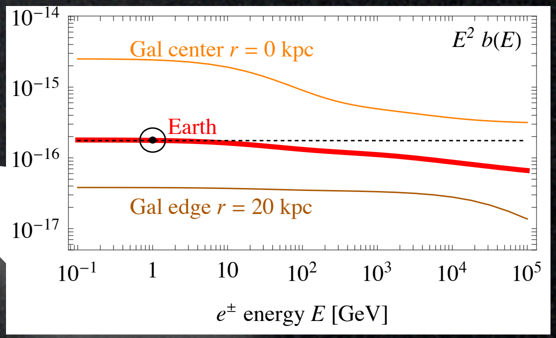


- ✔ compare different MCs



- ✔ 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

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$e^{\pm}$ PAMELA
FERMI
HESS

γ FERMI

X XMM-Newton

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γ FERMI, HESS,
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γ ν

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AMS-02

- 'enhancements'

- new theory directions

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Old wise remarks:

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Old wise remarks:

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