14 October 2015
CP3 Louvain-La-Neuve

Dark Matter Indirect Detection

amid hints & constraints

Marco Cirelli
(CNRS IPhT Saclay)

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IPhT SACLAY

erc NewDark

Introduction

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DM exists

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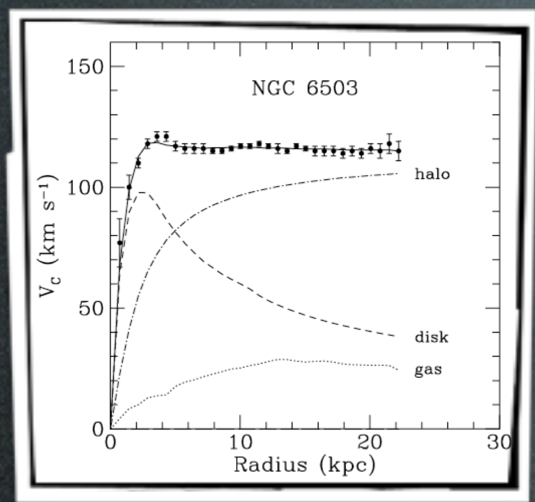
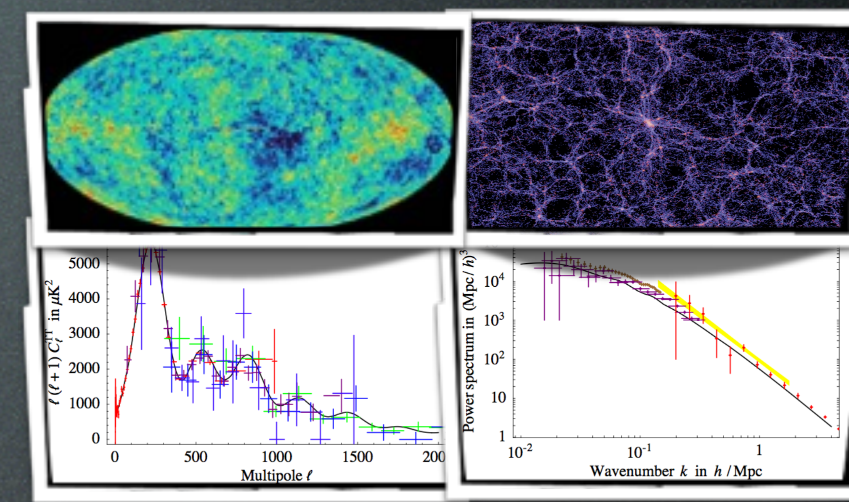


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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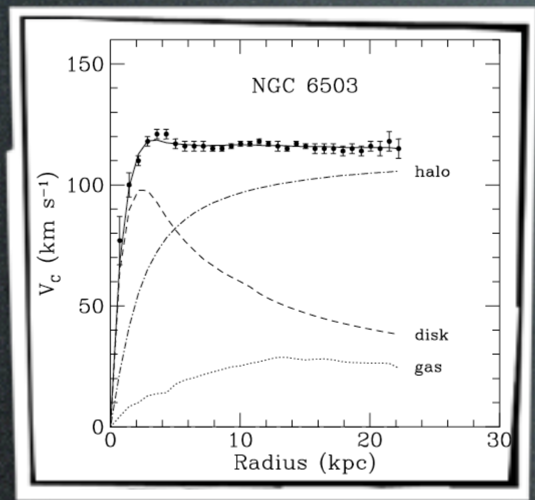

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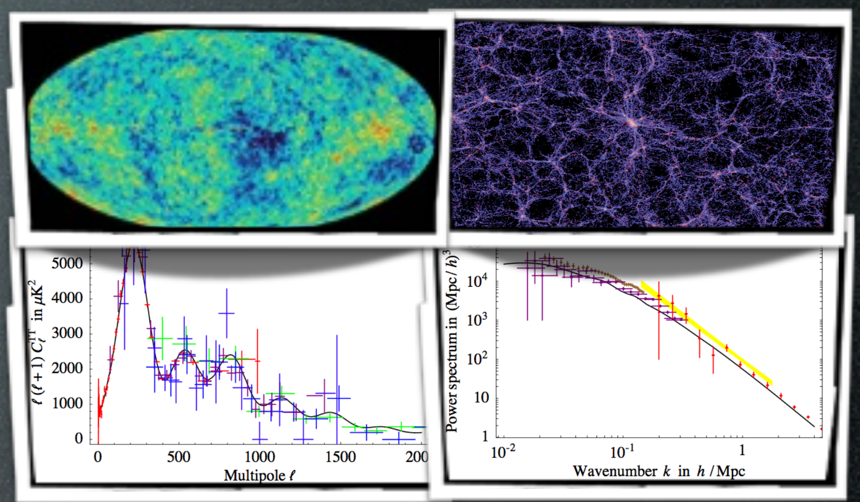

'precision cosmology' (CMB, LSS)

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

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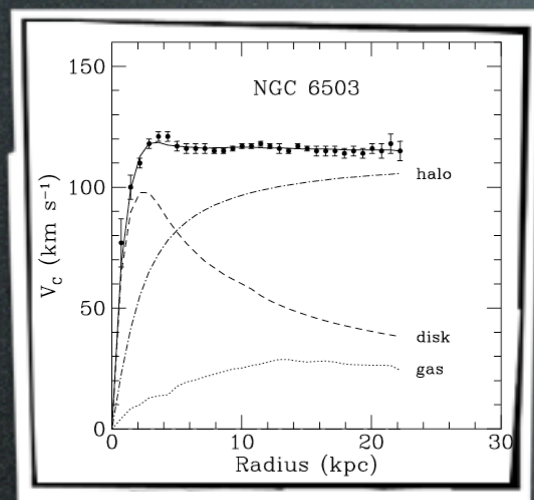

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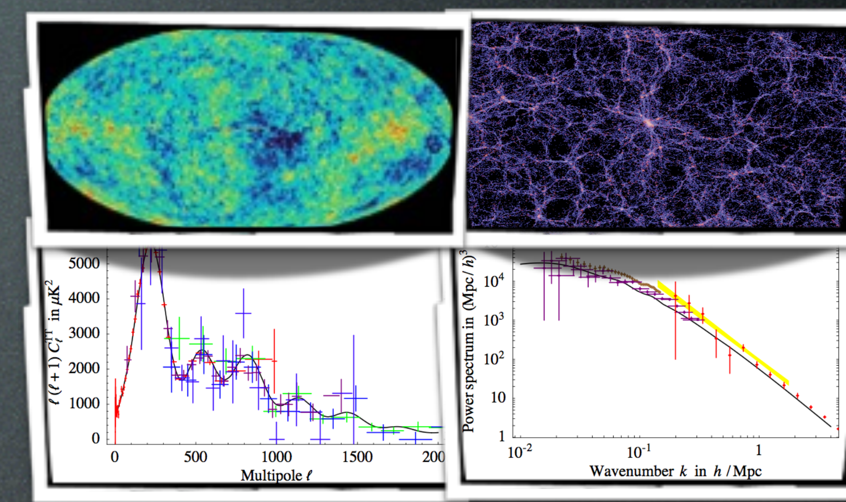
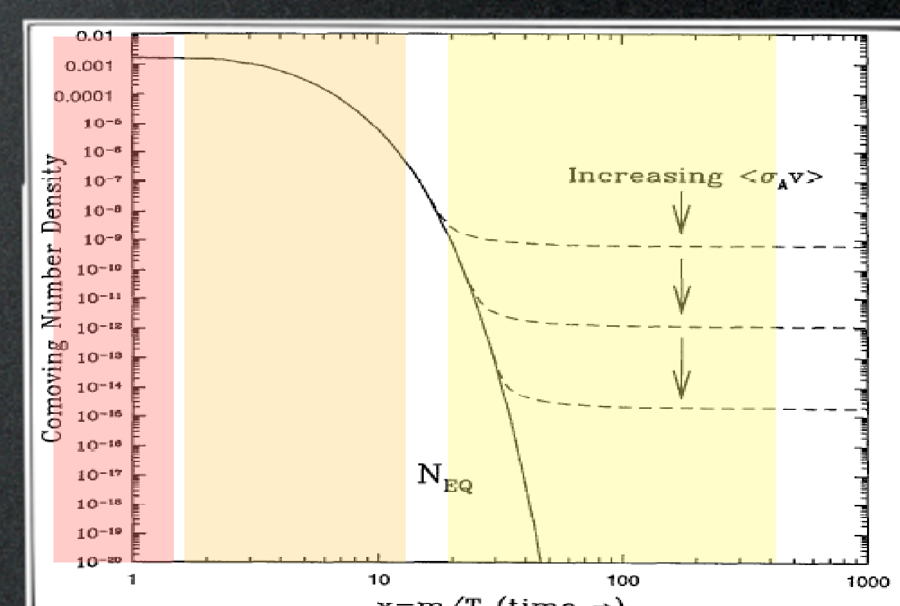


'precision cosmology' (CMB, LSS)

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

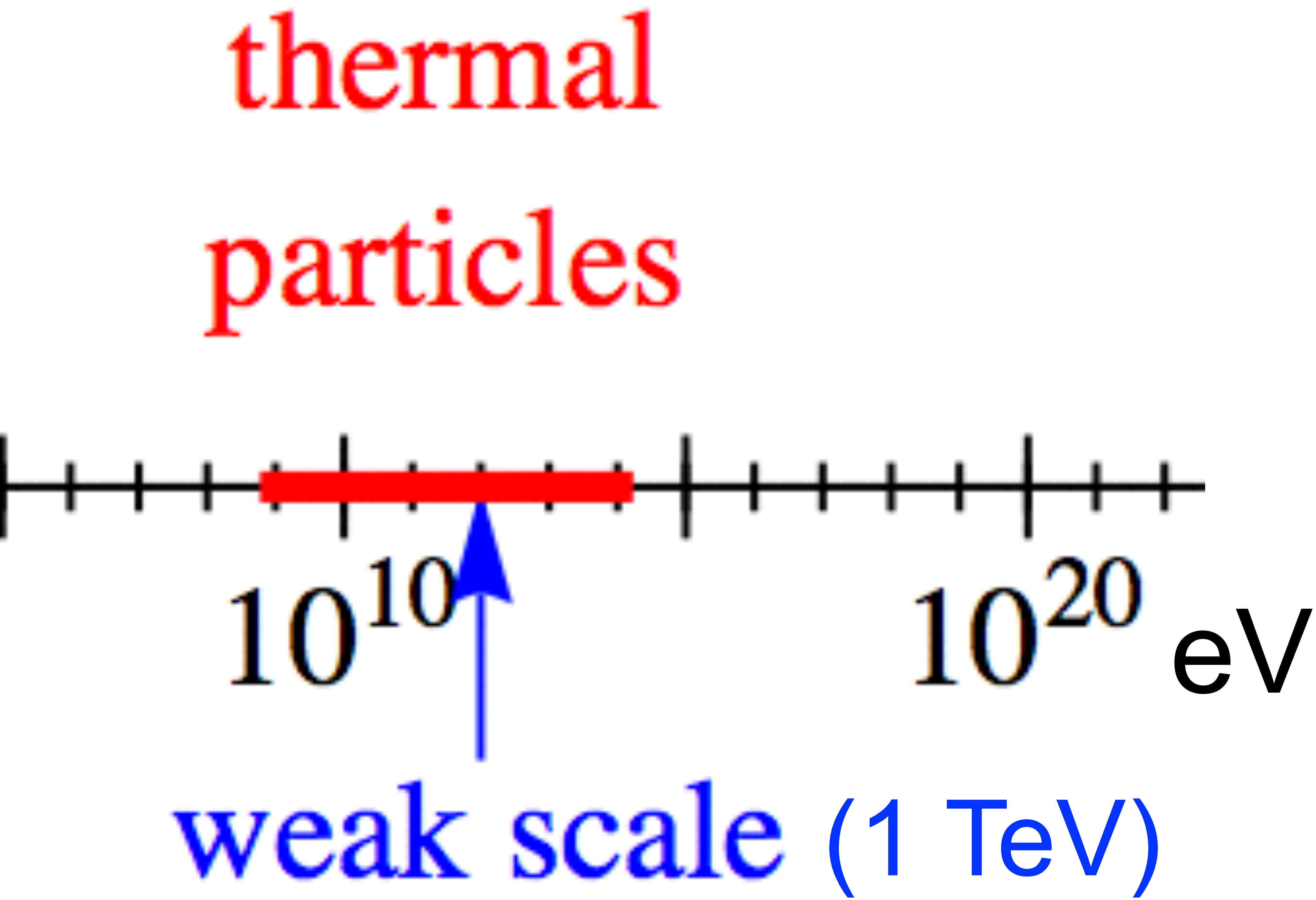
Some of us believe in the WIMP miracle.

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



DM Candidates

A matter of perspective: plausible mass ranges



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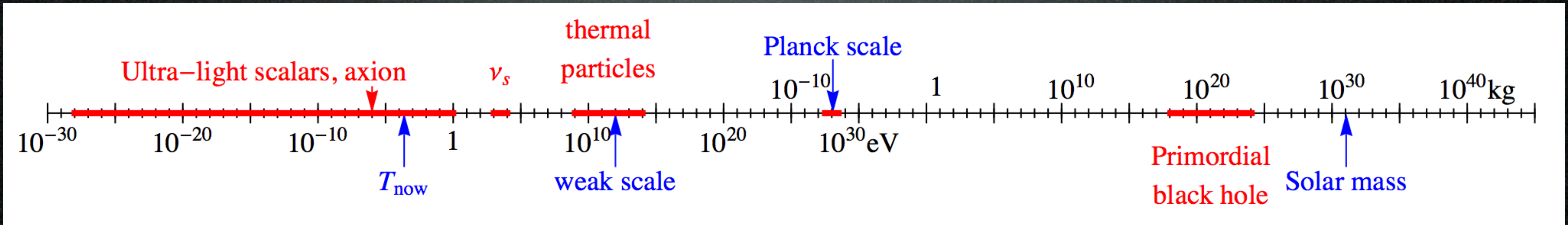
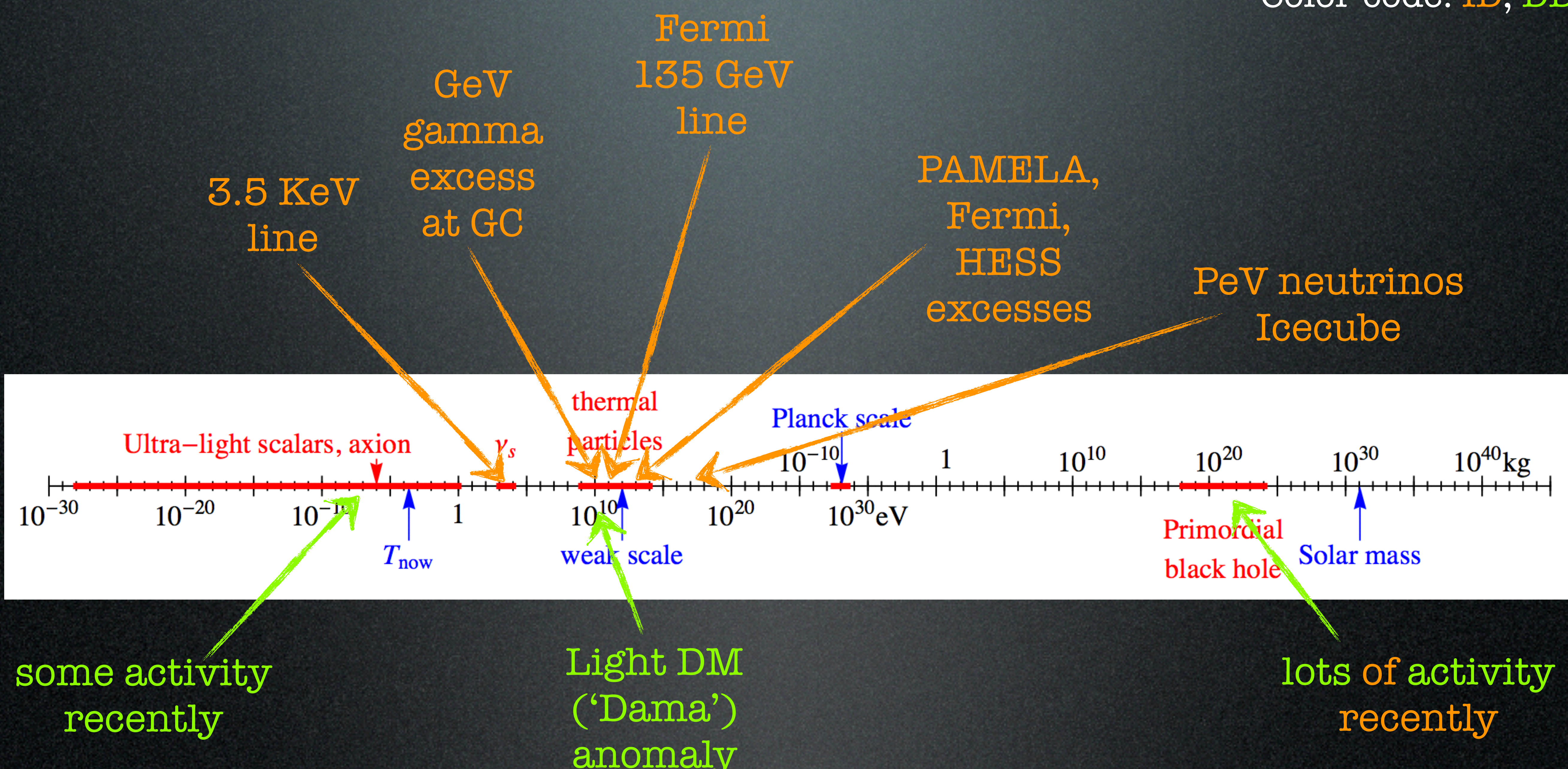


'only' 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges

Color code: ID, DD



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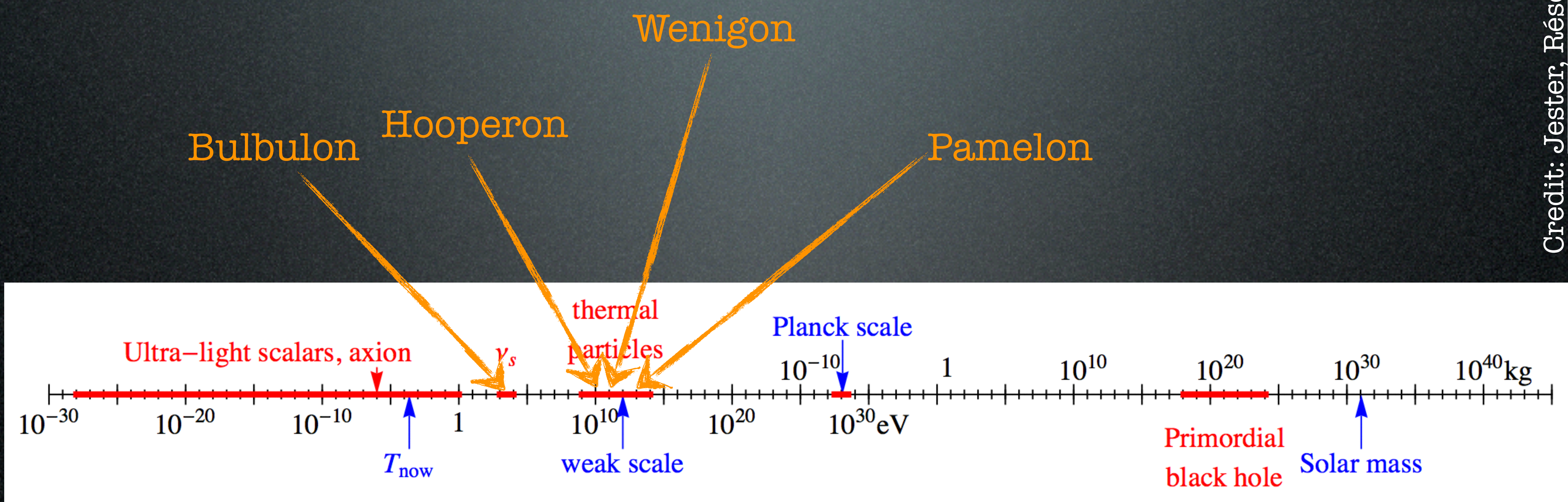

Credit: Jester, Résonaances

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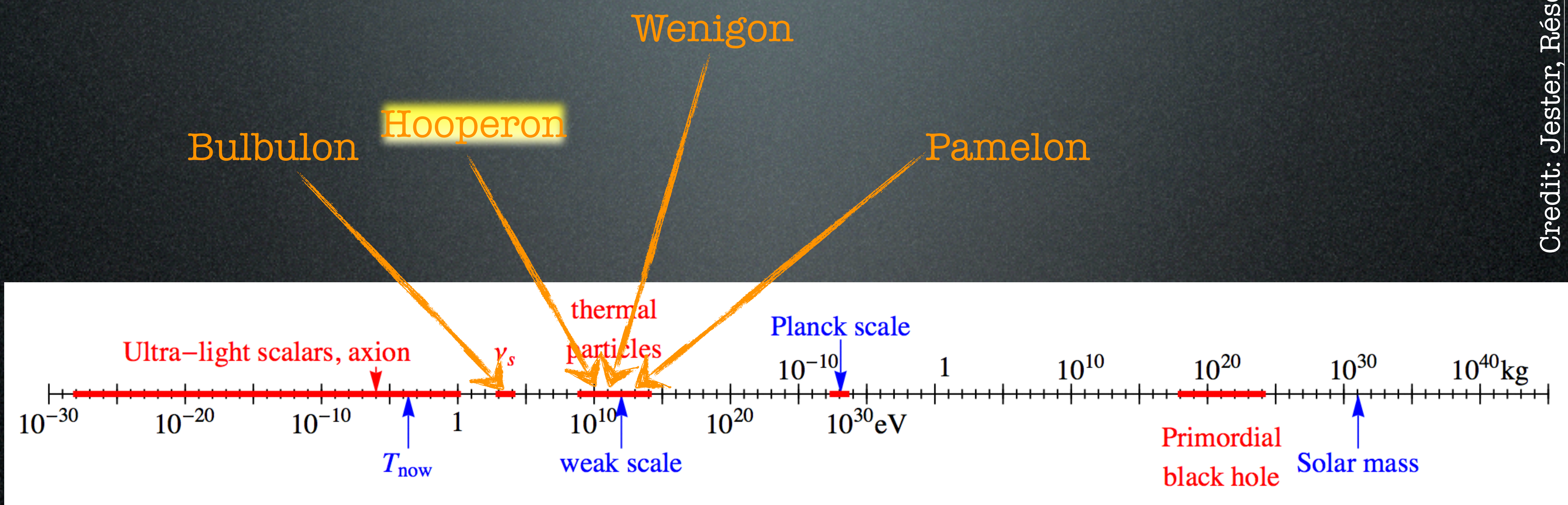

Credit: Jester, Résonaances

'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

direct detection

production at colliders

indirect

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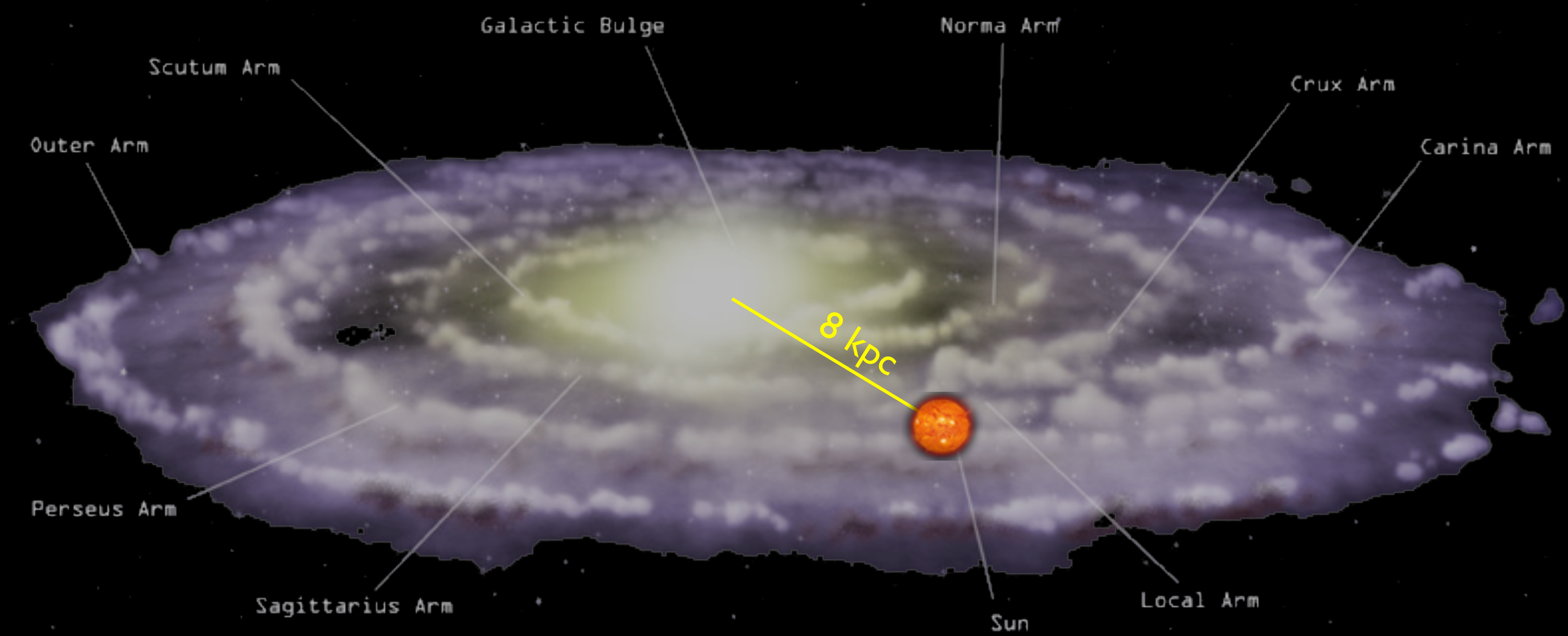
Indirect Detection: charged CRs

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



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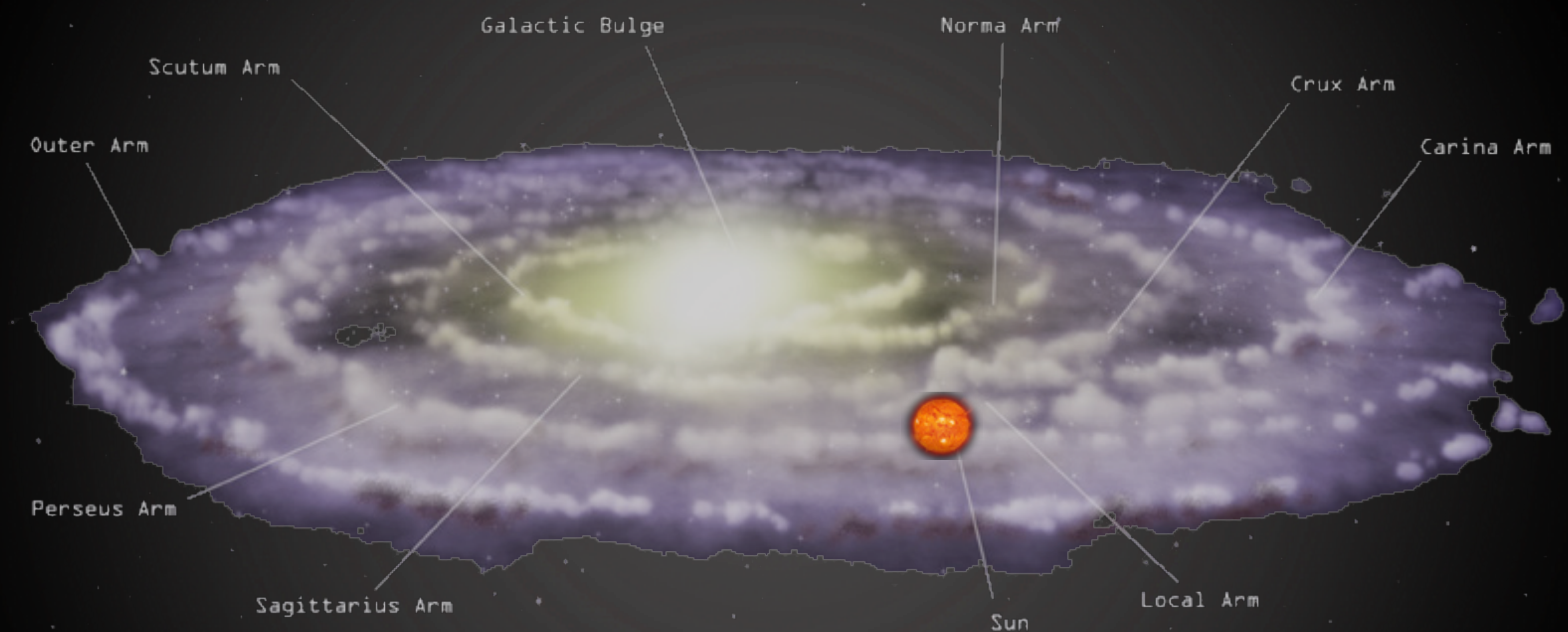

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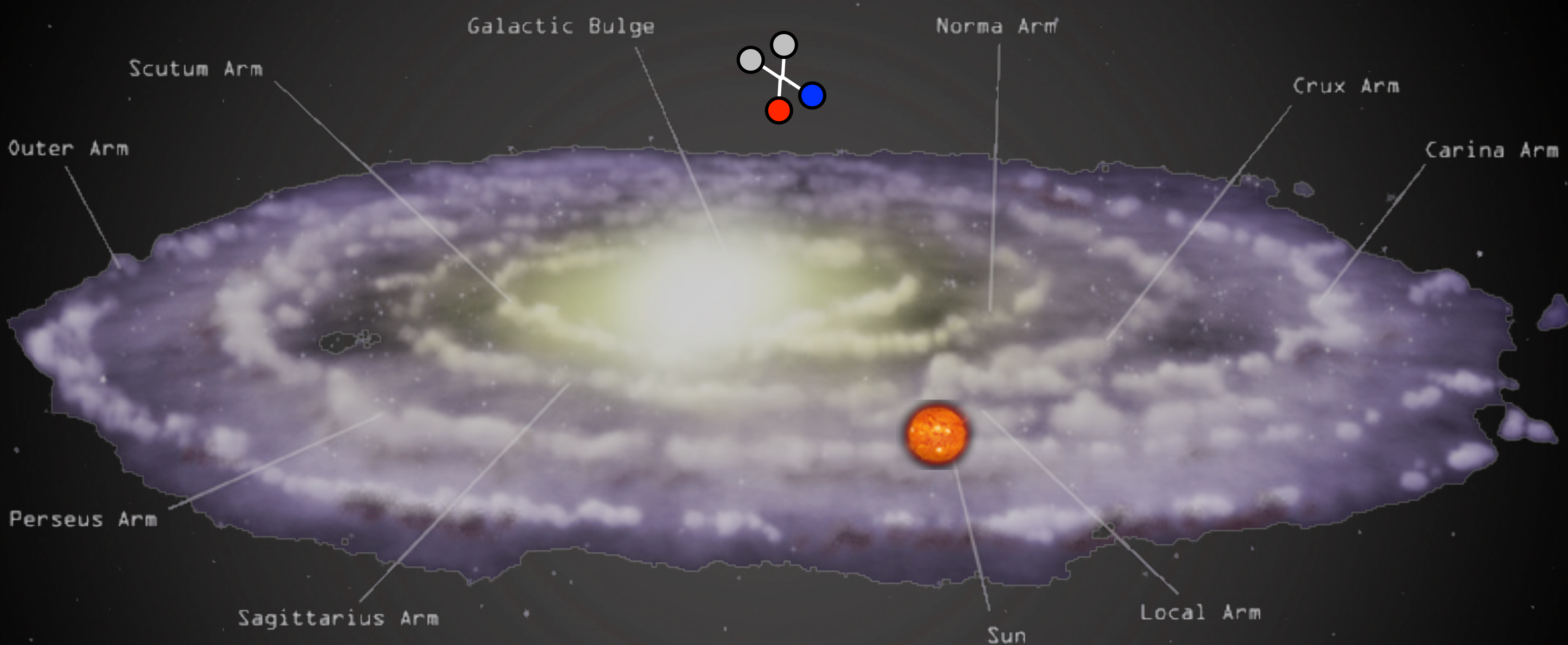

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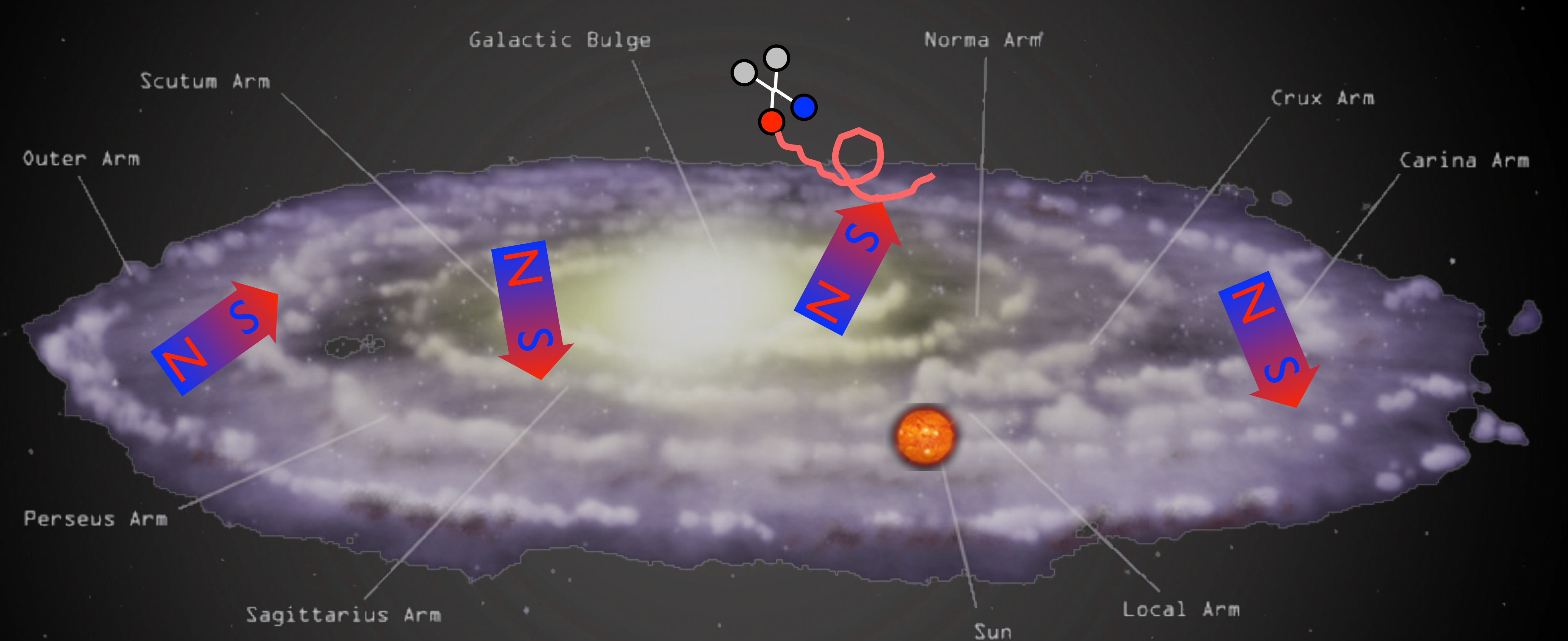

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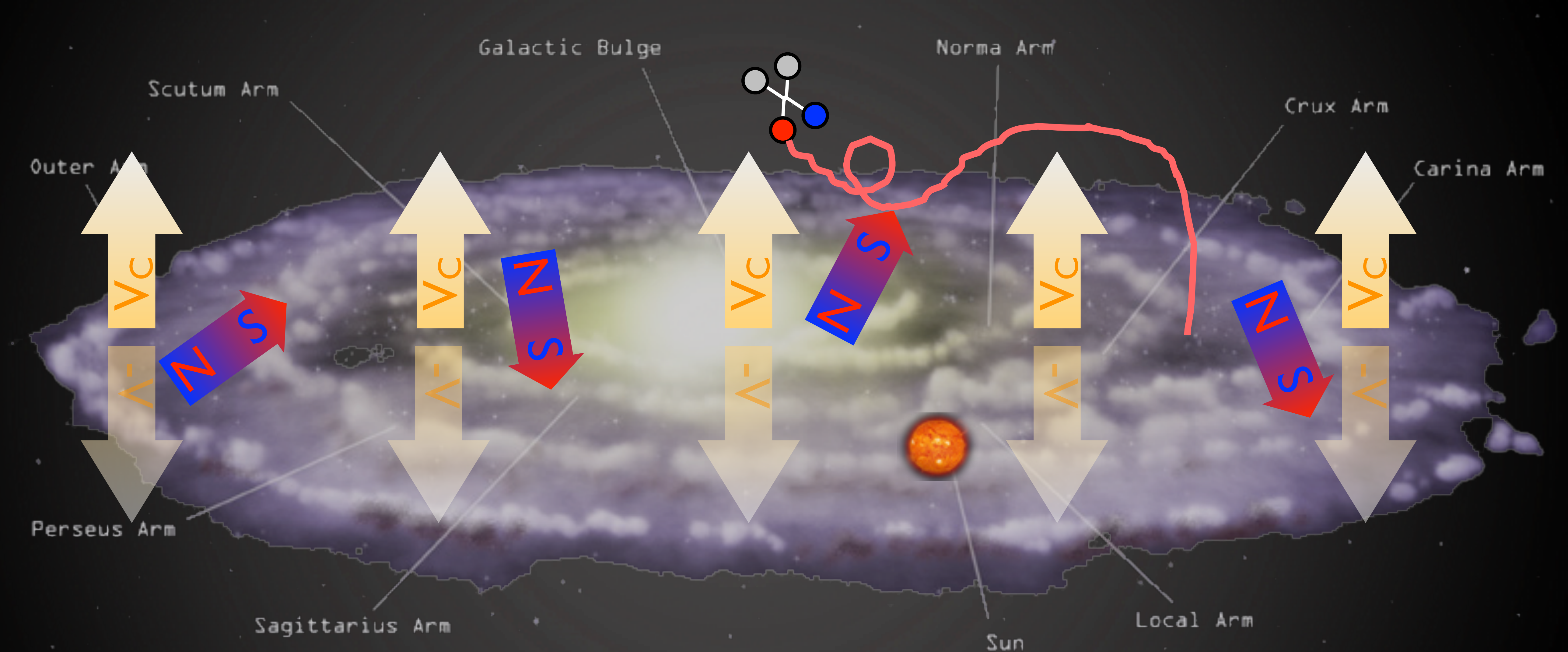

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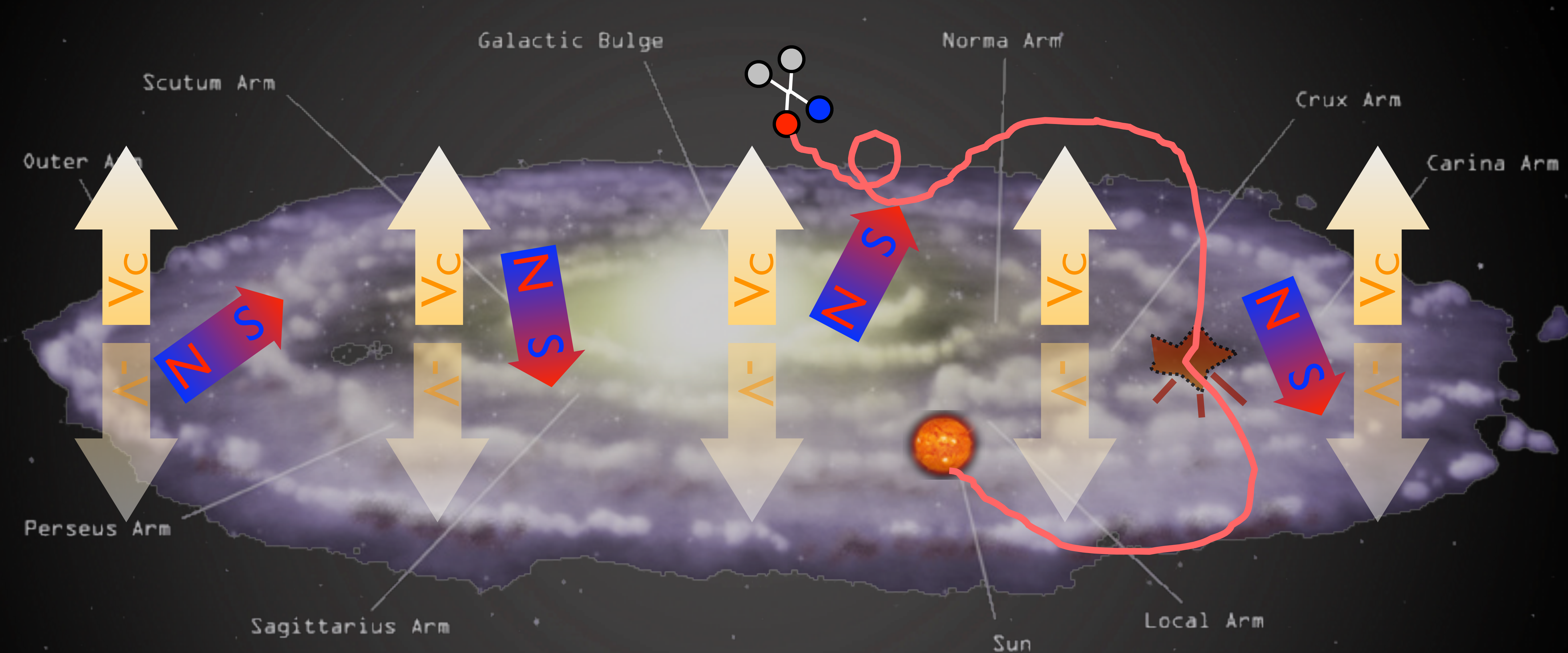

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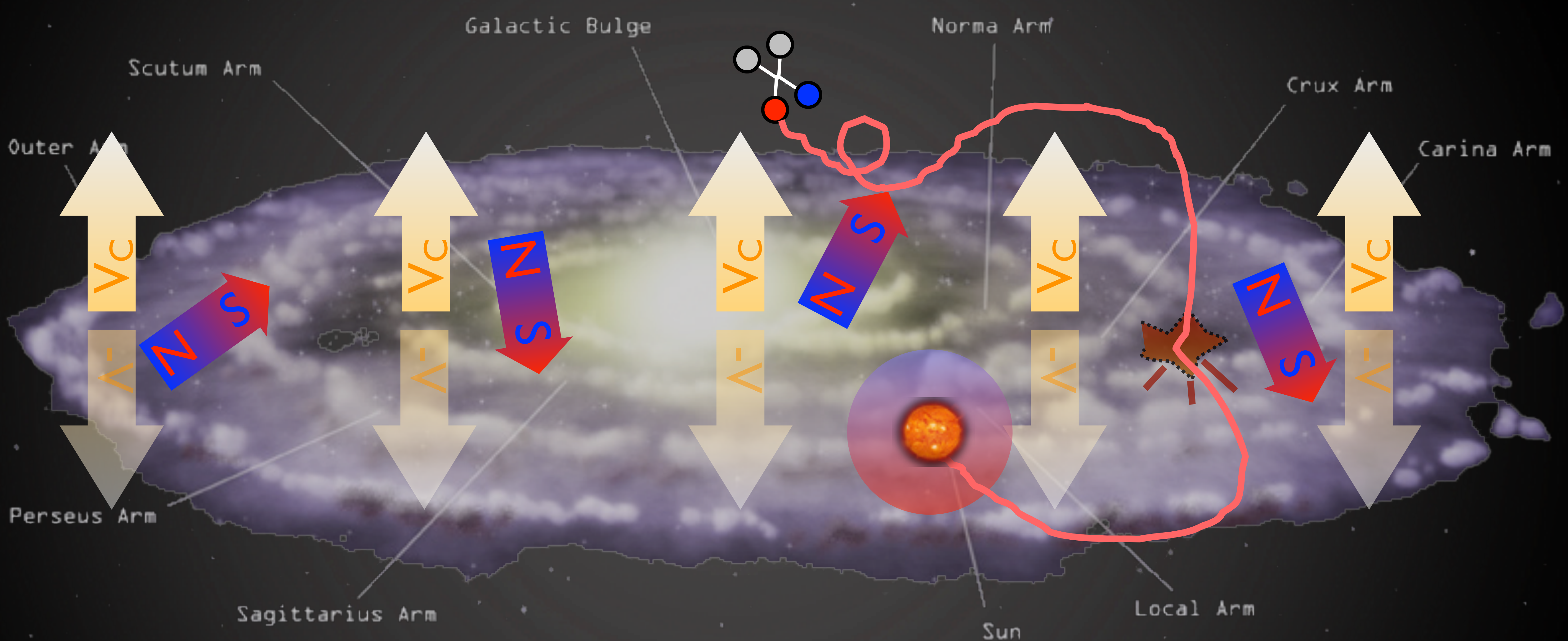

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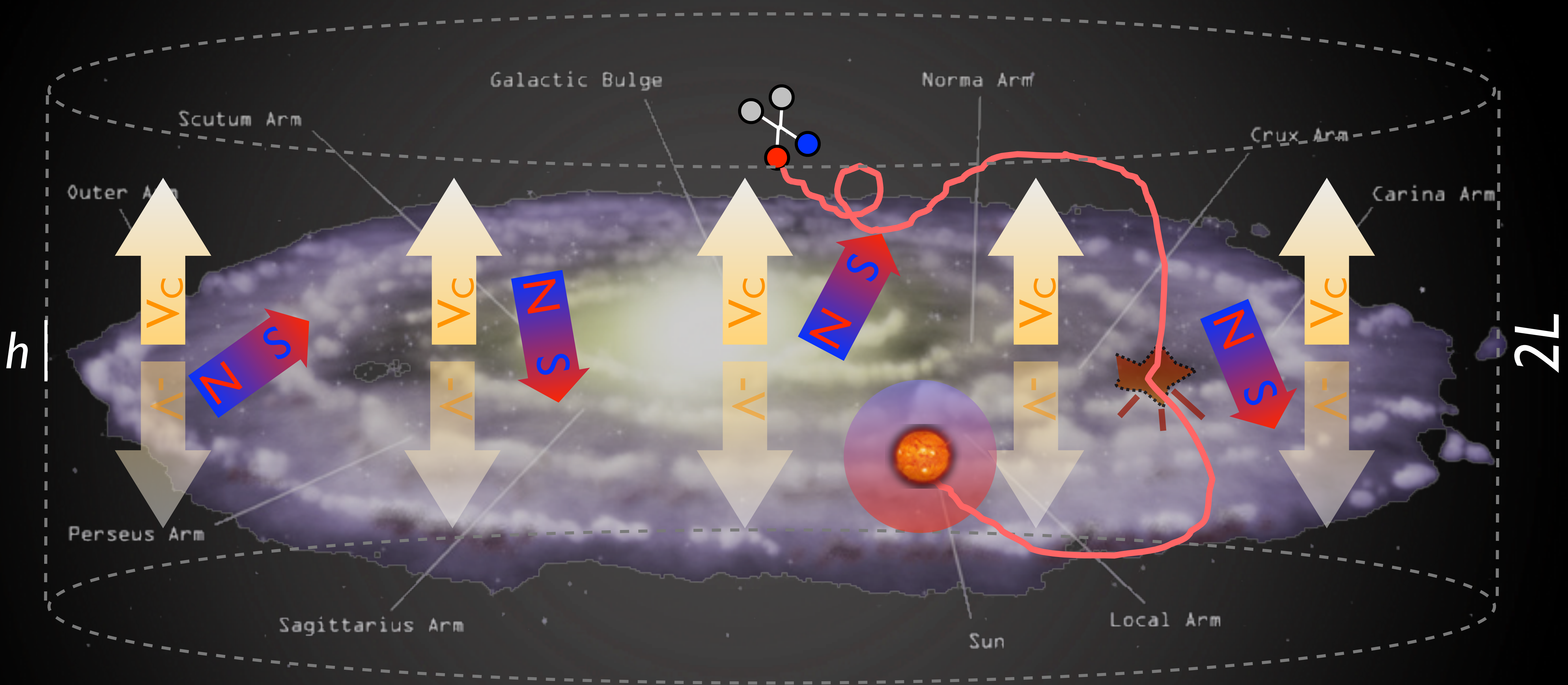


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maur Brun... '90s, '00s

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: charged CRs

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

		KRA	KOL	CON	THK	THN	THN2	THN3
thickness	L [kpc]	4	4	4	10	0.5	2	3
diffusion	D_0 [10^{28} cm^2 s^{-1}]	2.64	4.46	0.97	4.75	0.31	1.35	1.98
diffusion	δ	0.50	0.33	0.6	0.50	0.50	0.50	0.50
diffusion	η	-0.39	1	1	-0.15	-0.27	-0.27	-0.27
diff. reacc.	v_A [km s^{-1}]	14.2	36	38.1	14.1	11.6	11.6	11.6
p index	γ	2.35	1.78/2.45	1.62/2.35	2.35	2.35	2.35	2.35
convection	dv_c/dz [km s^{-1} kpc^{-1}]	0	0	50	0	0	0	0
solar mod.	ϕ_F^p [GV]	0.650	0.335	0.282	0.687	0.704	0.626	0.623
	χ^2_{min}/dof (p in [25])	0.462	0.761	1.602	0.516	0.639	0.343	0.339

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173
cfr. Evoli, Cholis, Grasso, Maccione, Ullio, 1108.0664

Model	Electrons or positrons δ	Electrons or positrons $\mathcal{K}_0$ [kpc^2/Myr]	Antiprotons (and antideuterons) δ	Antiprotons (and antideuterons) $\mathcal{K}_0$ [kpc^2/Myr]	Antiprotons (and antideuterons) V_{conv} [km/s]	L [kpc]
MIN	0.55	0.00595	0.85	0.0016	13.5	1
MED	0.70	0.0112	0.70	0.0112	12	4
MAX	0.46	0.0765	0.46	0.0765	5	15

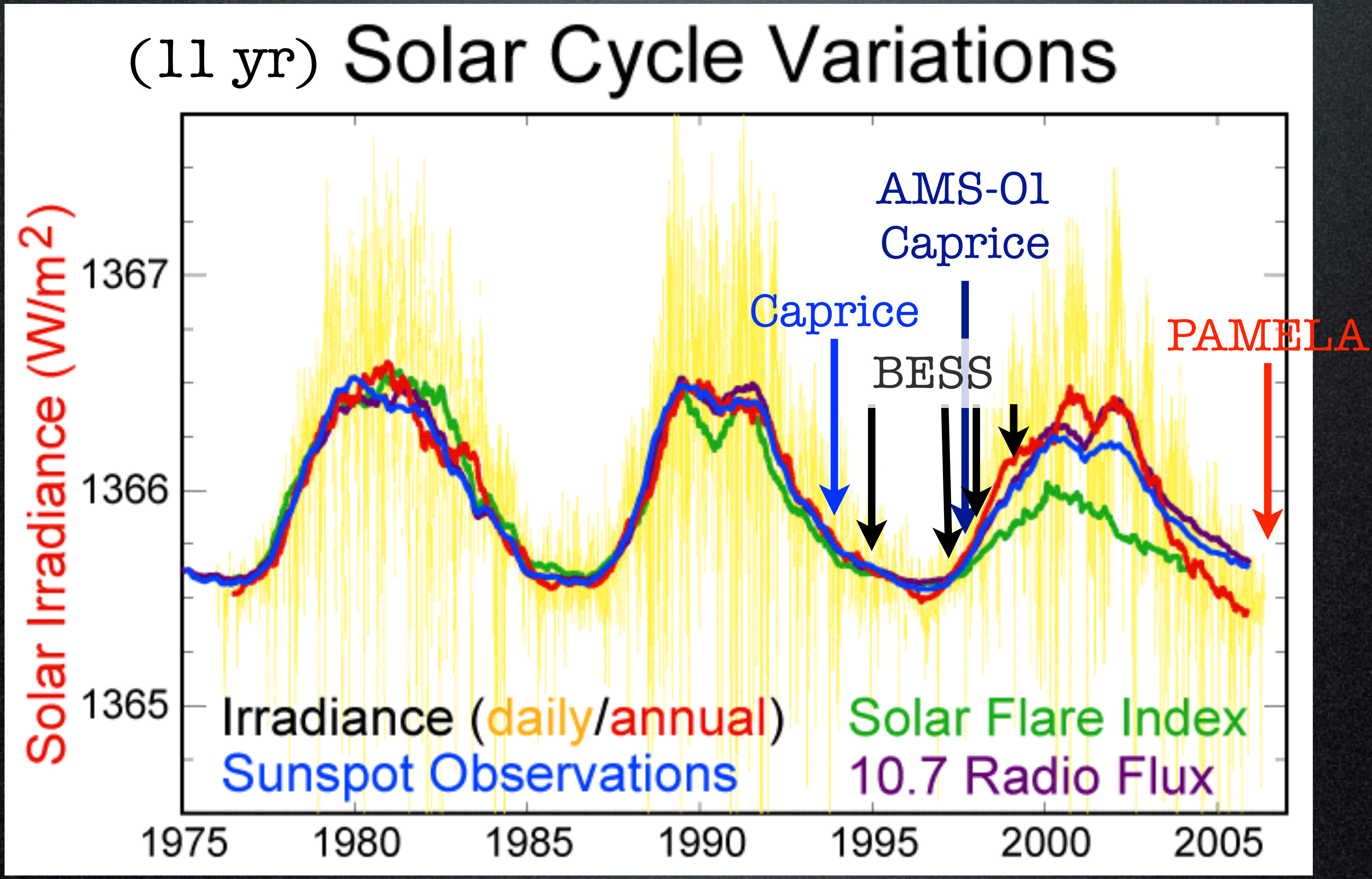
Donato et al., 2003+

Indirect Detection: charged CRs

Solar polarity Modulation of cosmic rays:

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

+ = rotation parallel to magnetic field;
- = antiparallel



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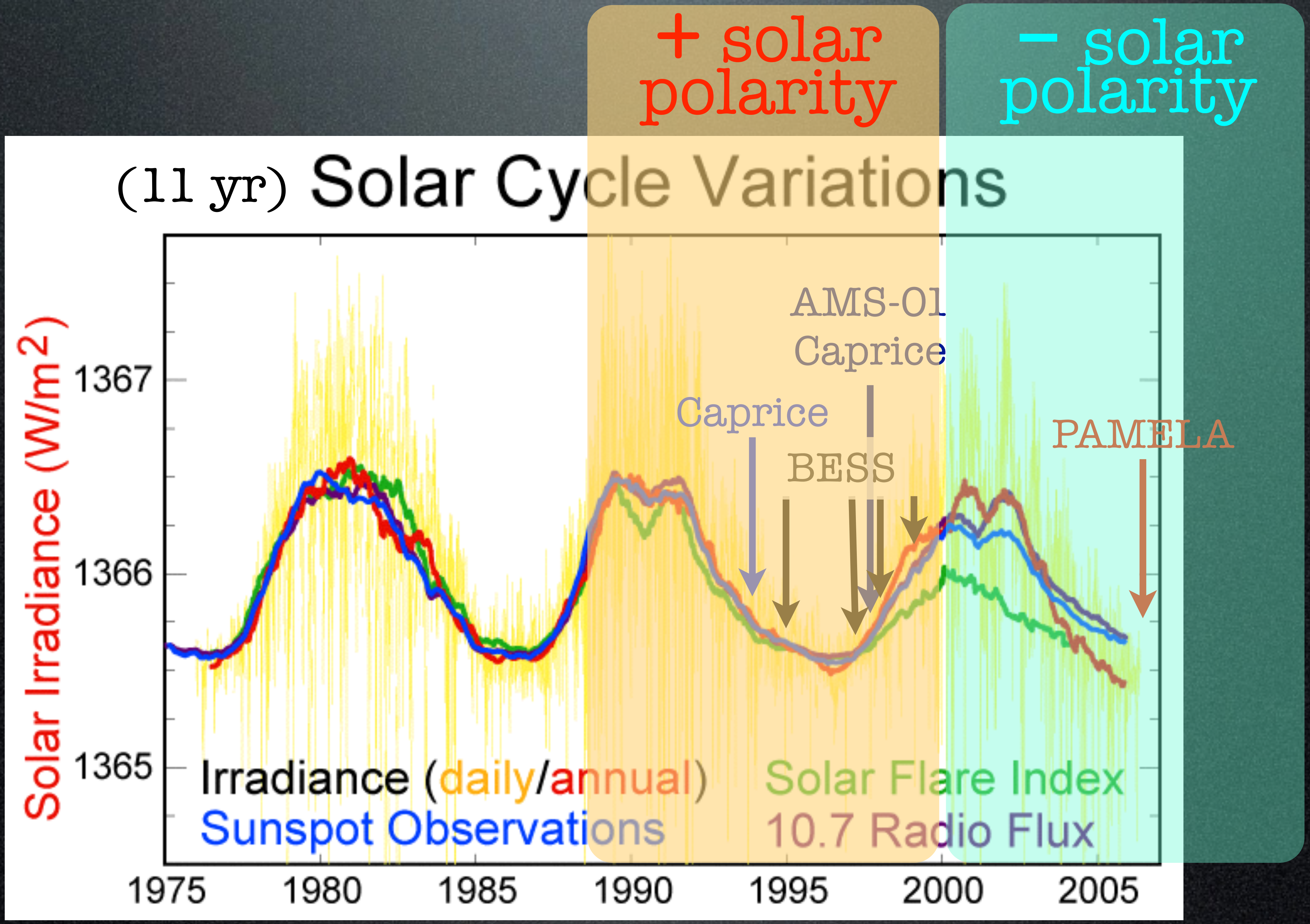


Indirect Detection: charged CRs

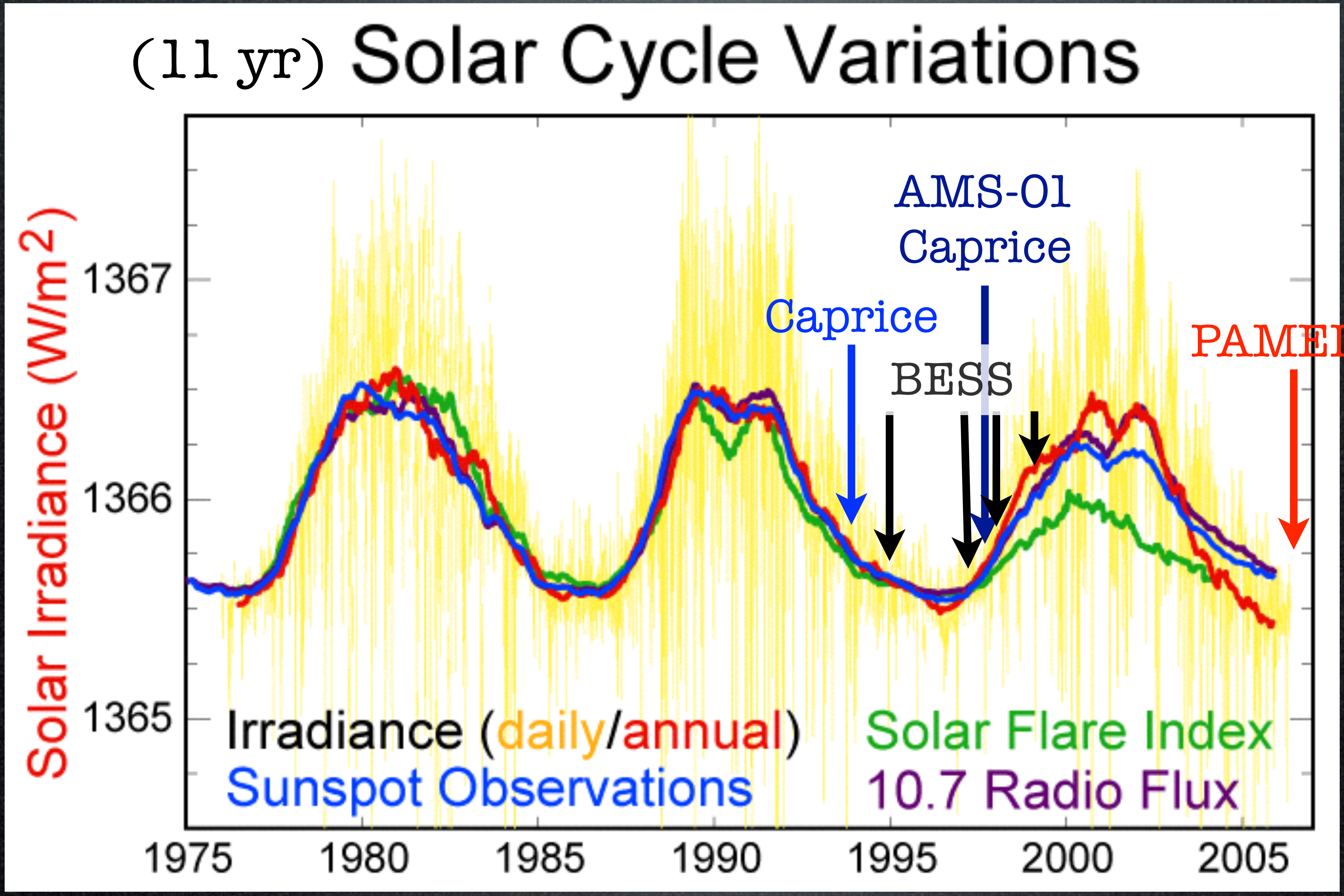
Solar wind Modulation of cosmic rays:

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

spectrum at Earth

spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV



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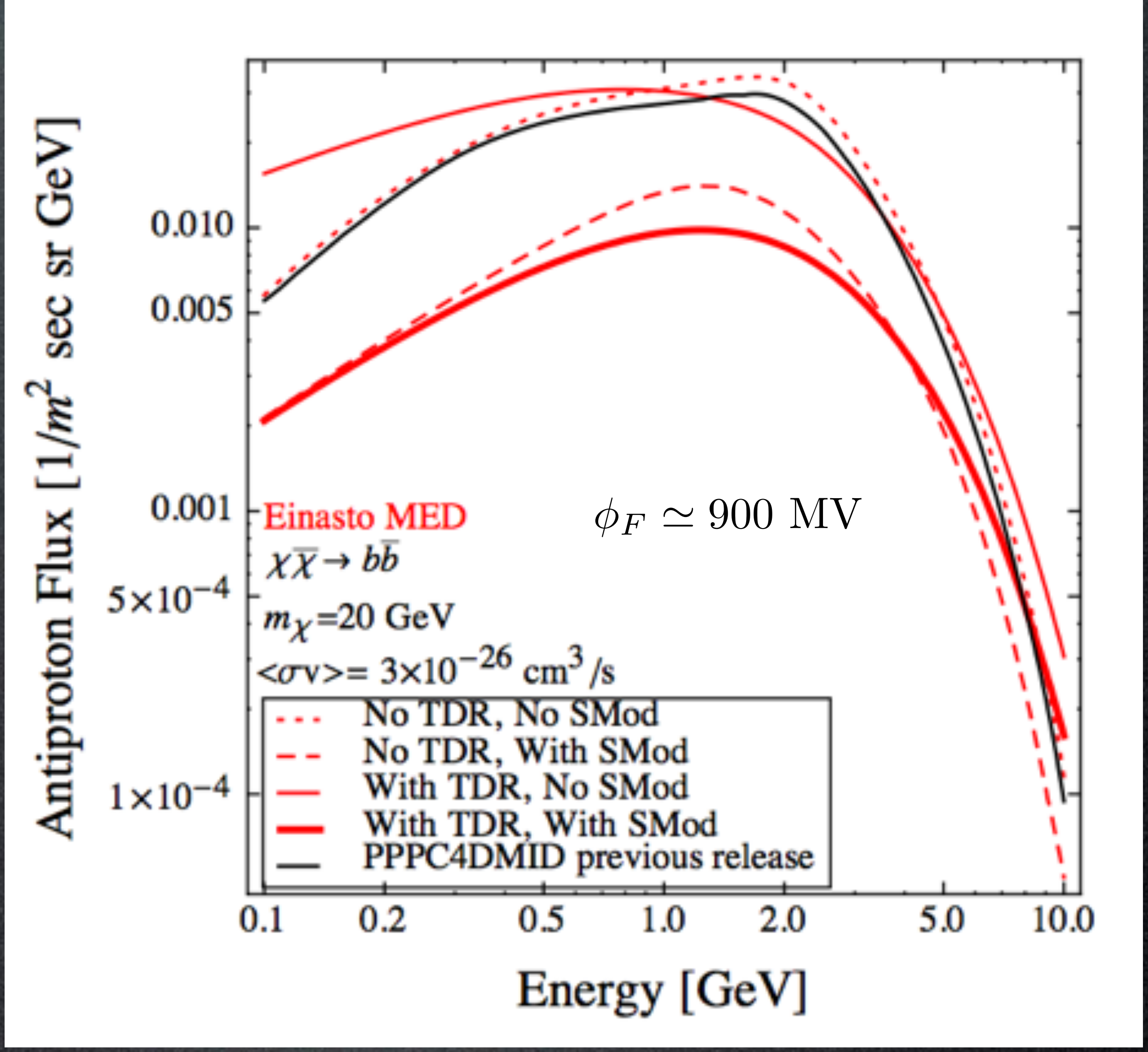
spectrum at Earth — spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV

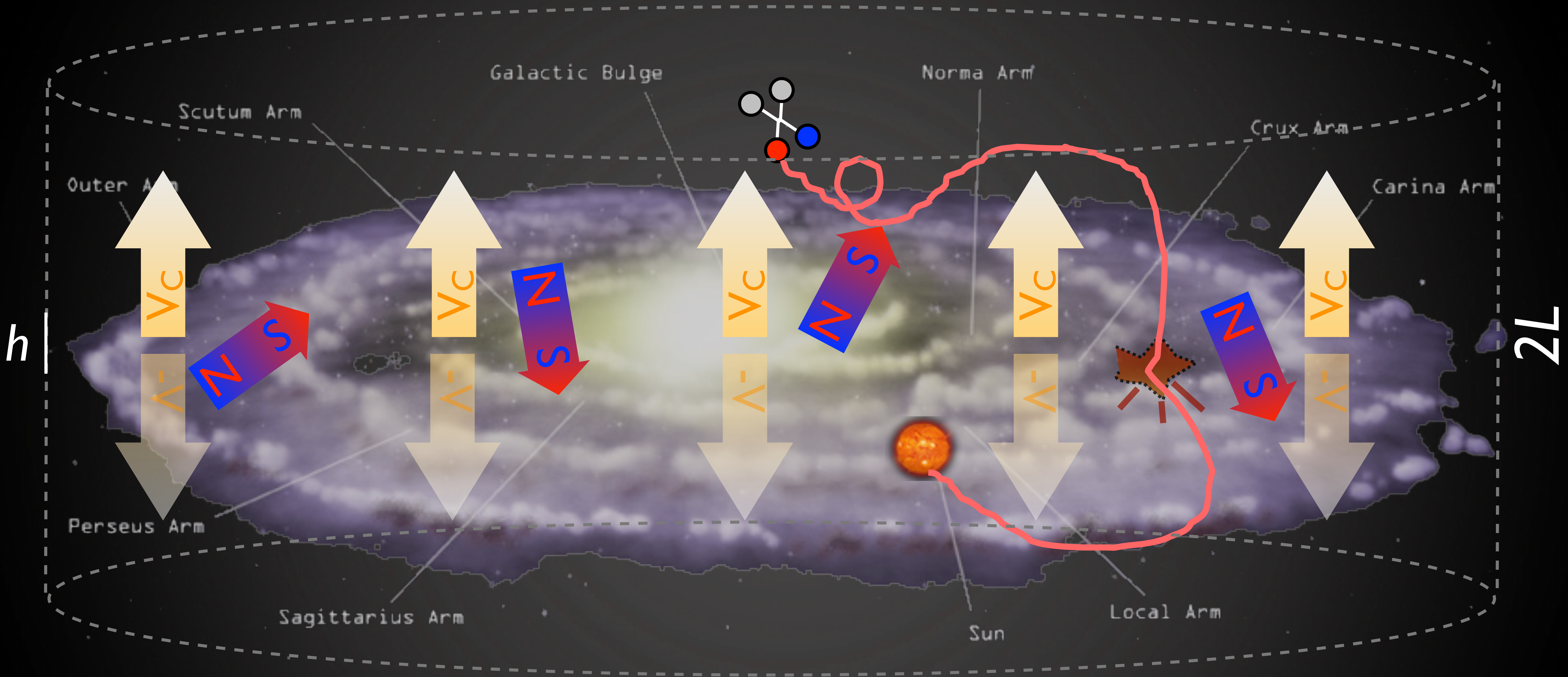
E.g.



Boudard, Cirelli, Giesen, Salati, 1412.5696

Indirect Detection: charged CRs

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



What sets the overall expected flux?

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

Indirect Detection: charged CRs

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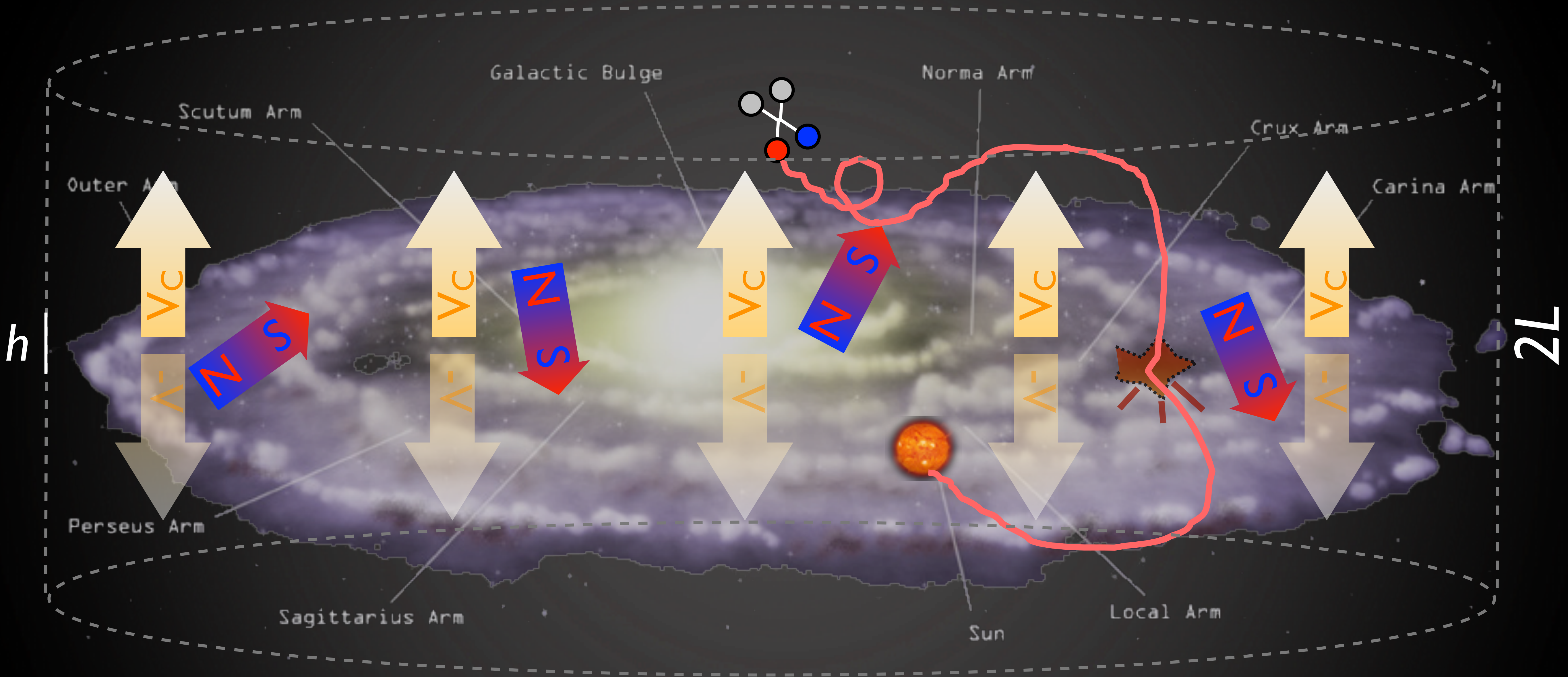

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astro& cosmo

particle

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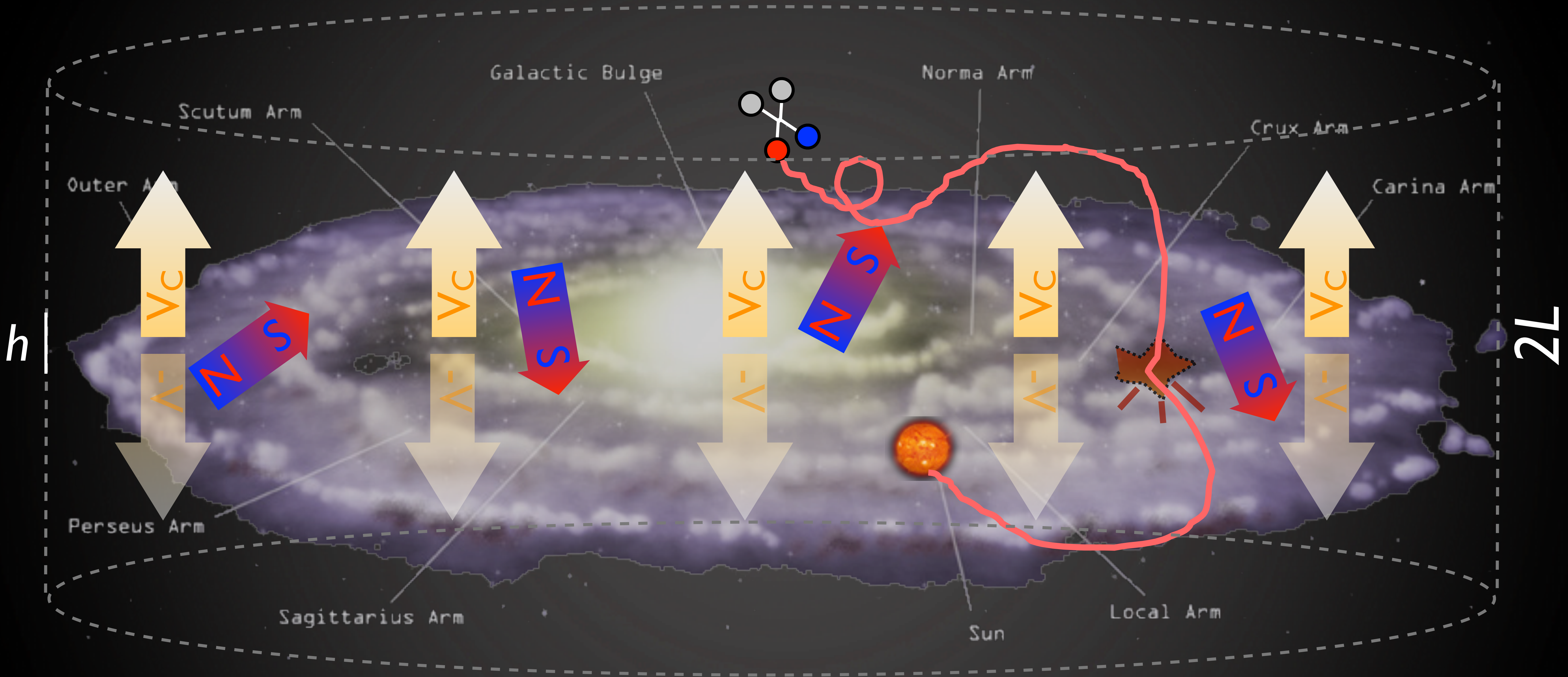


What sets the overall expected flux?

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

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:

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

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

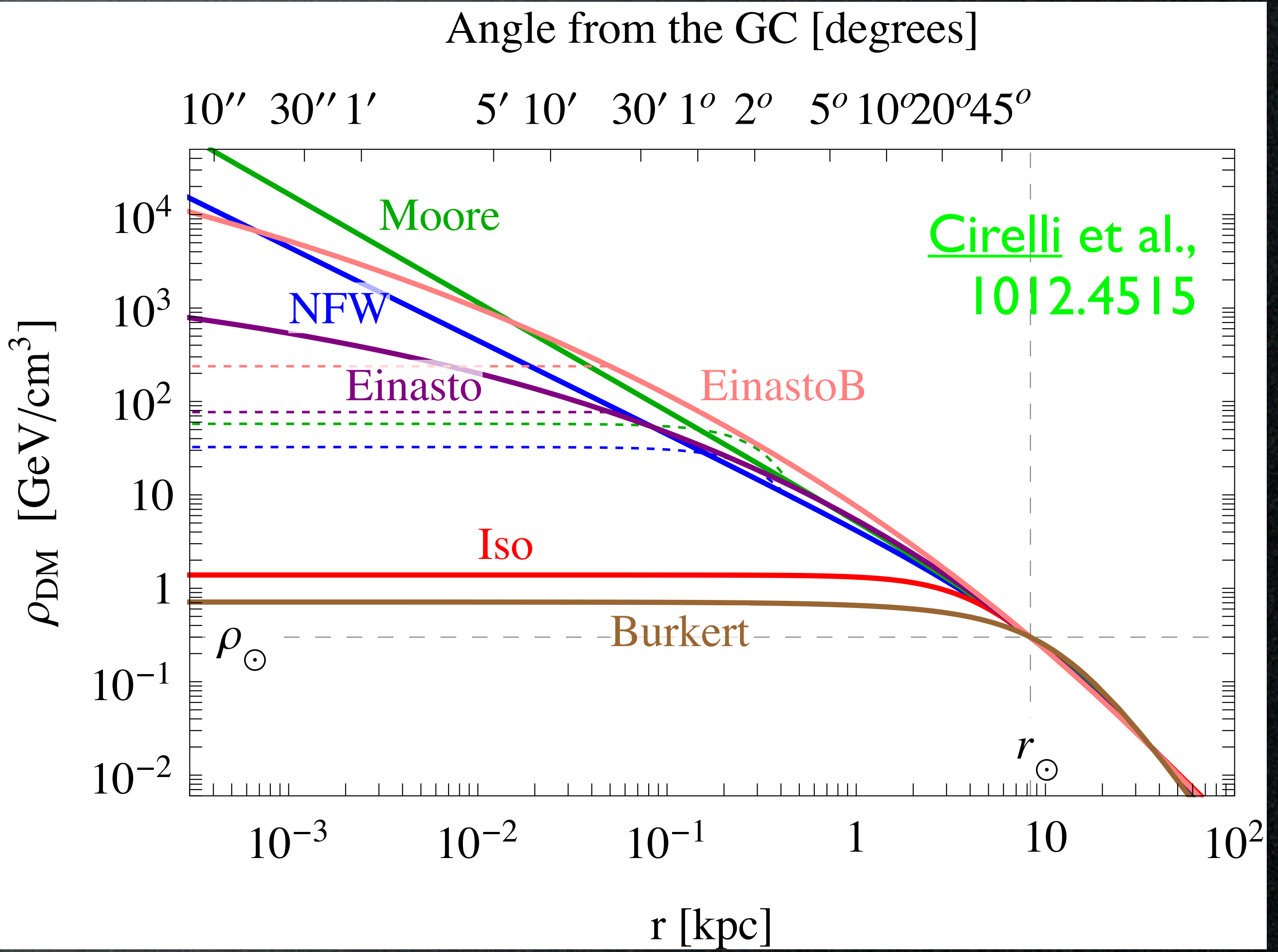
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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

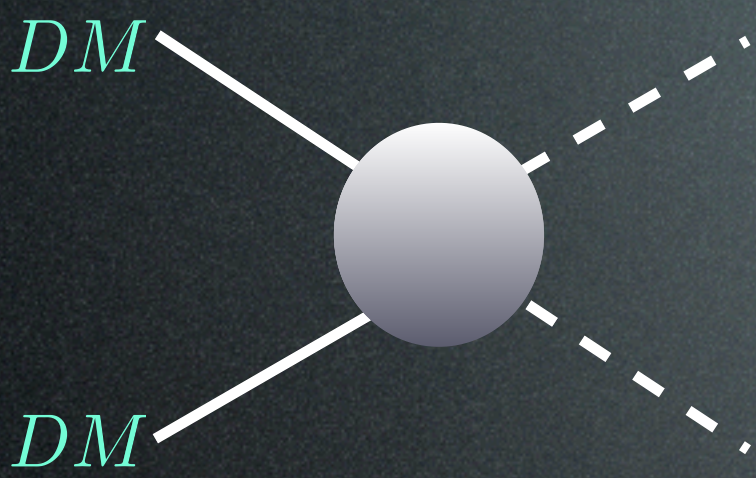


6 profiles:

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

EinastoB = steepened Einasto
(effect of baryons?)

Indirect Detection: basics



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

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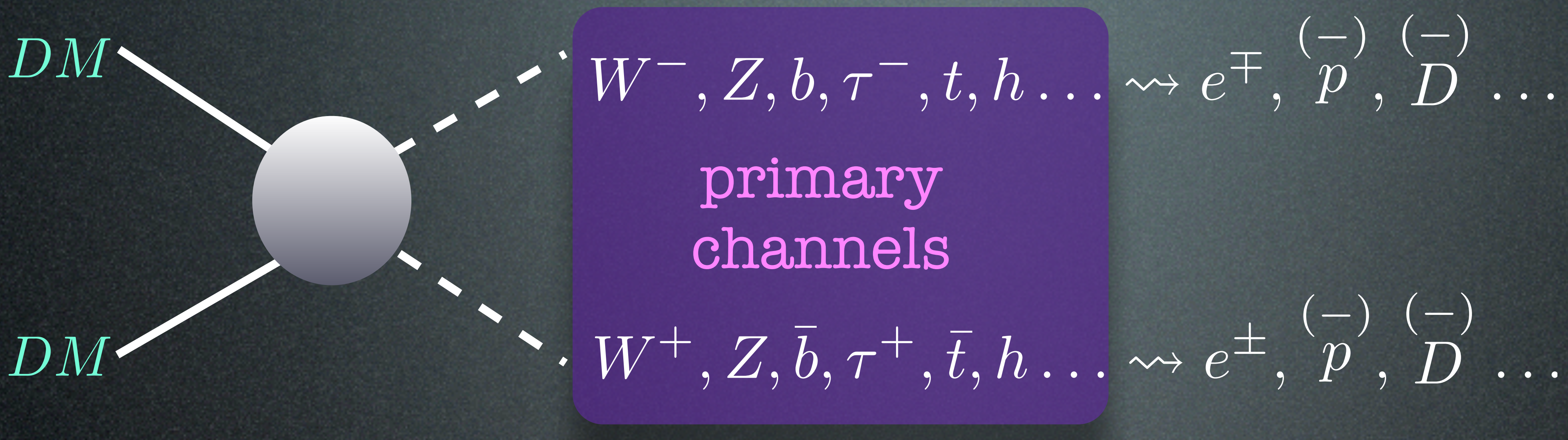

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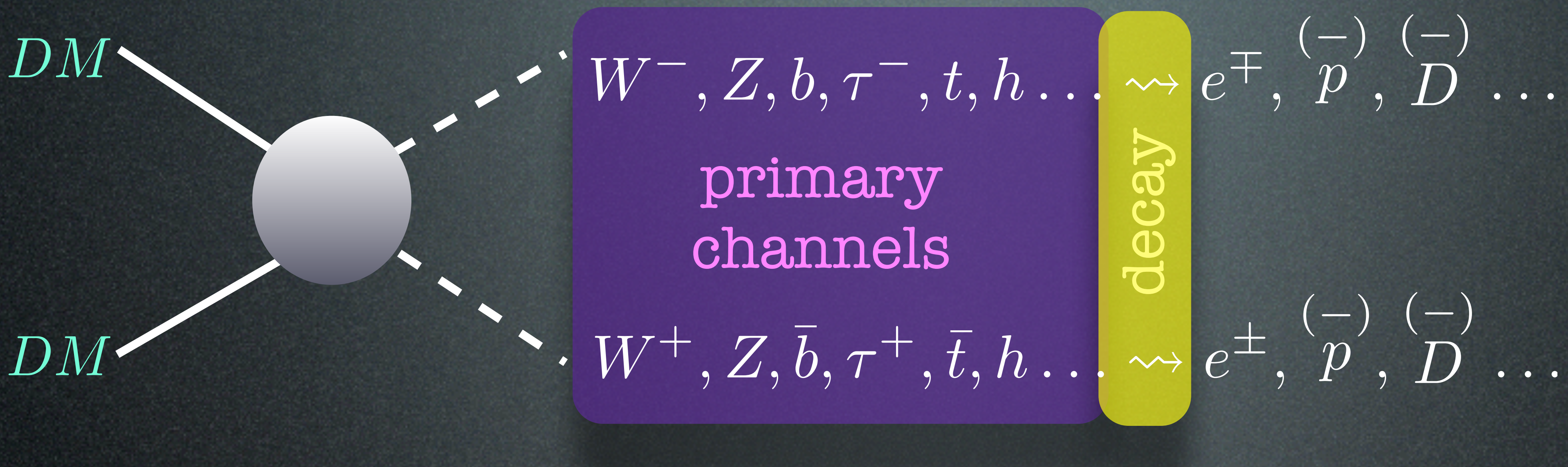

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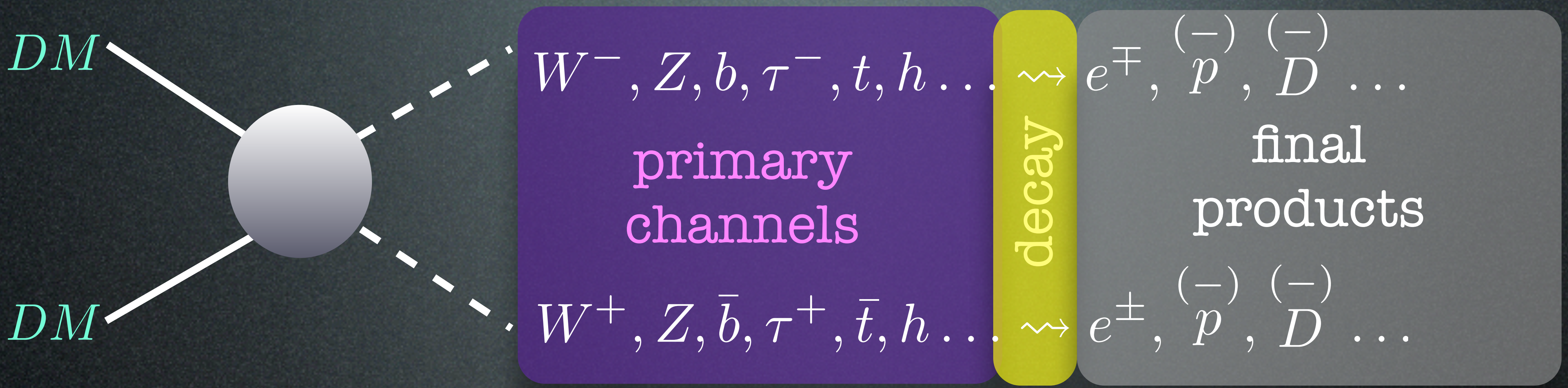

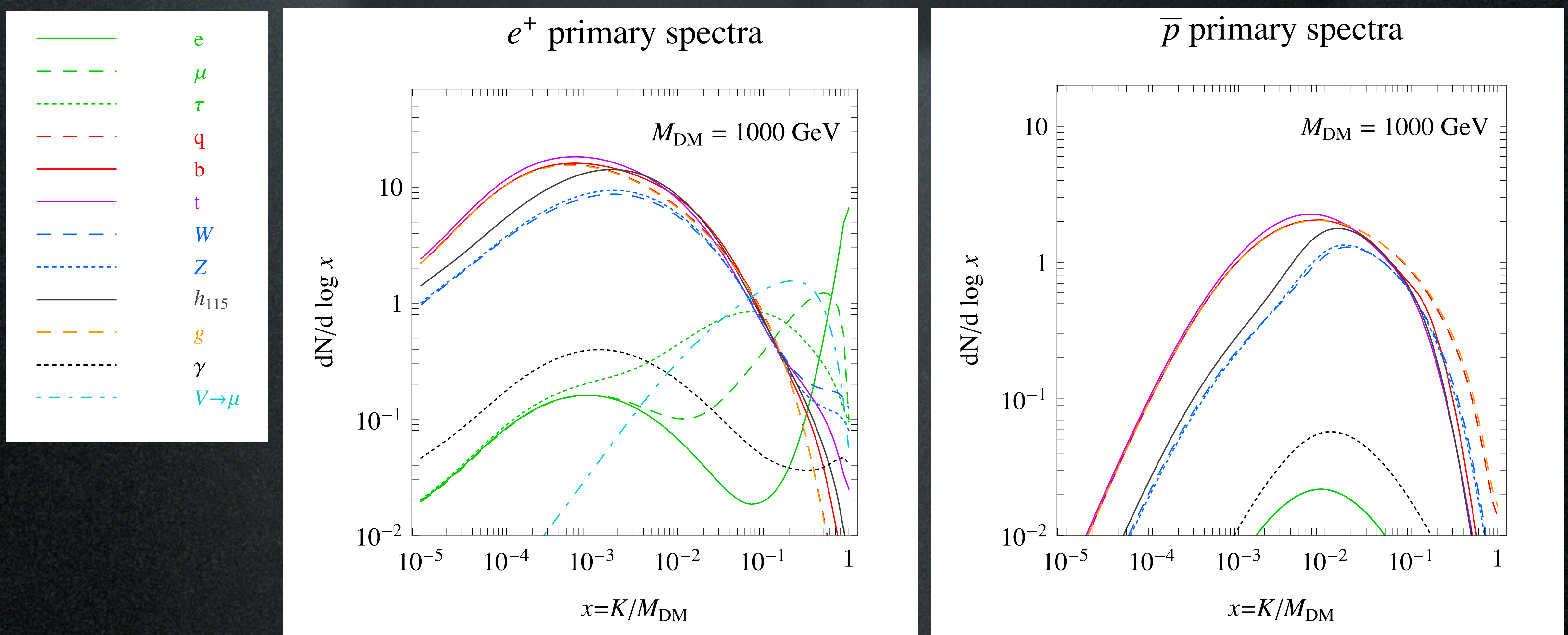

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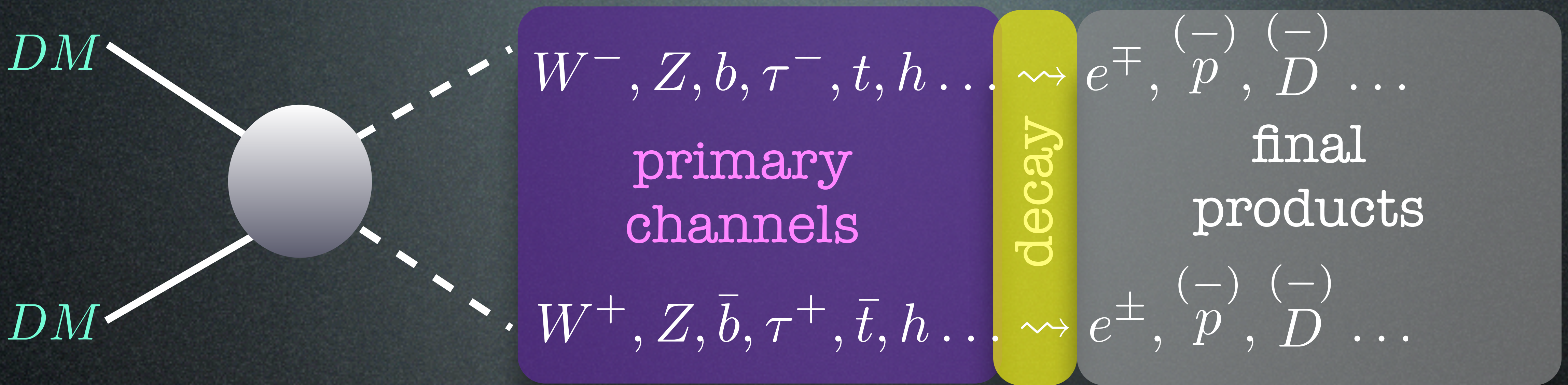
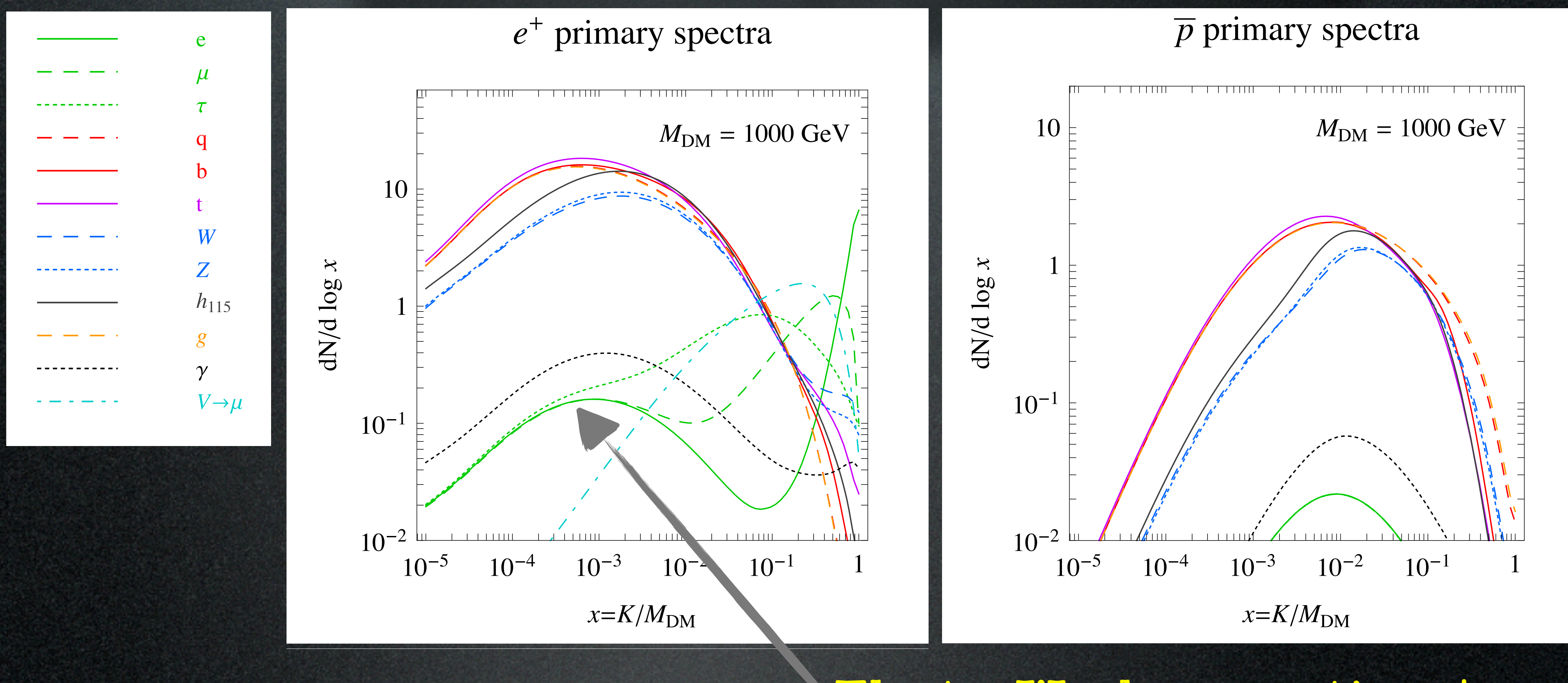


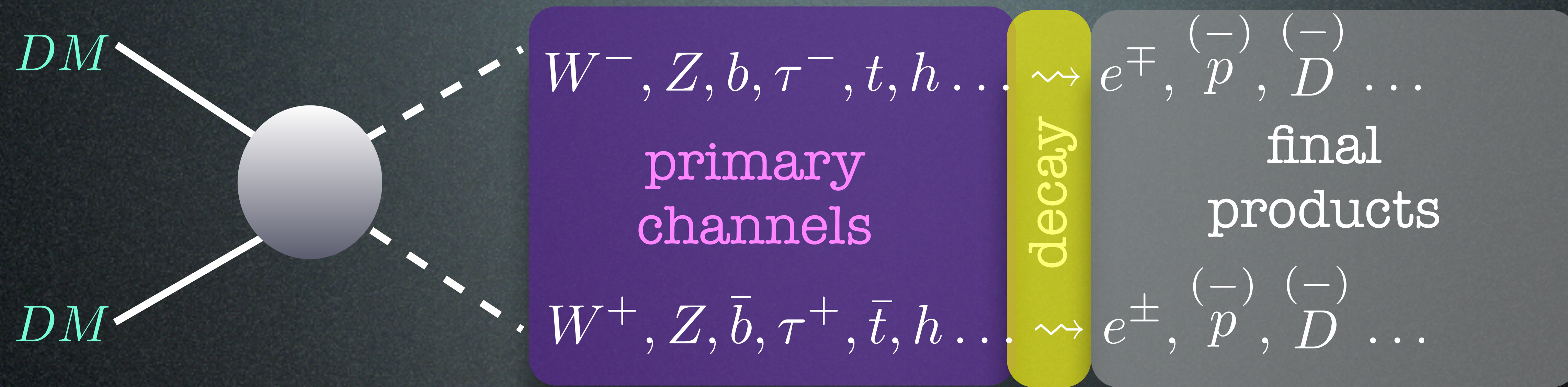


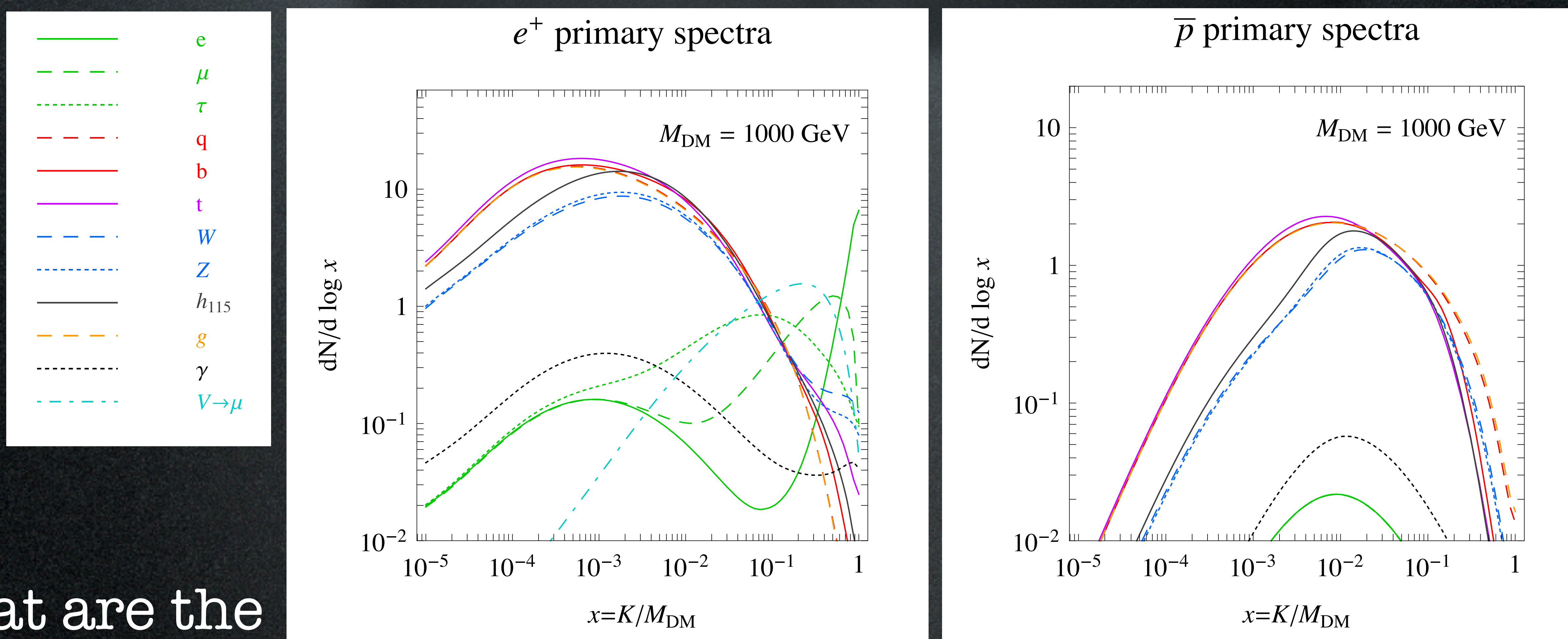
ElectroWeak corrections!

Sala et al., 1009.0224

Cirelli, Panci, Sala et al., 1012.4515

Indirect Detection: basics





So what are the particle physics parameters?

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

Indirect Detection: gammas

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,

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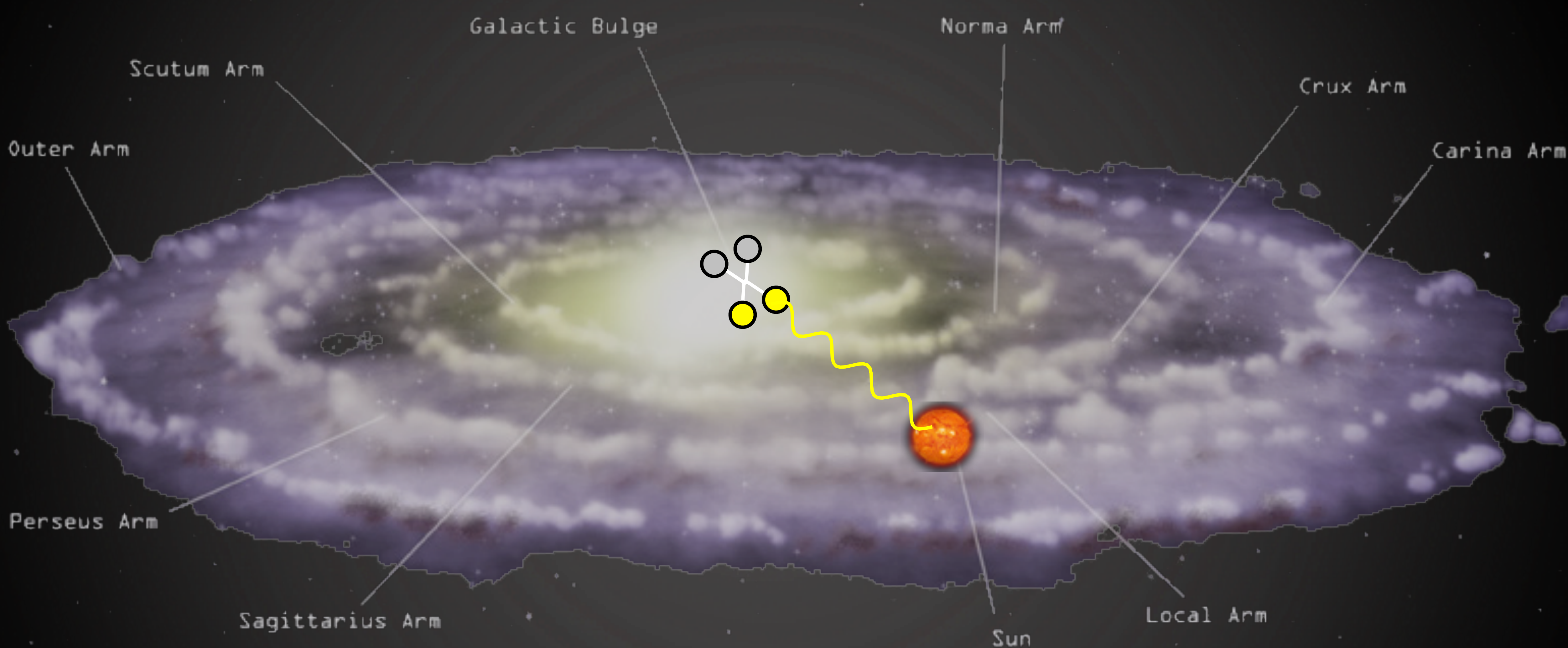
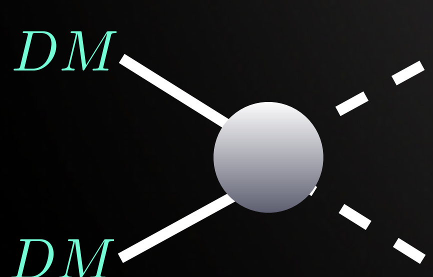
Indirect Detection: gammas

γ from DM annihilations in galactic center



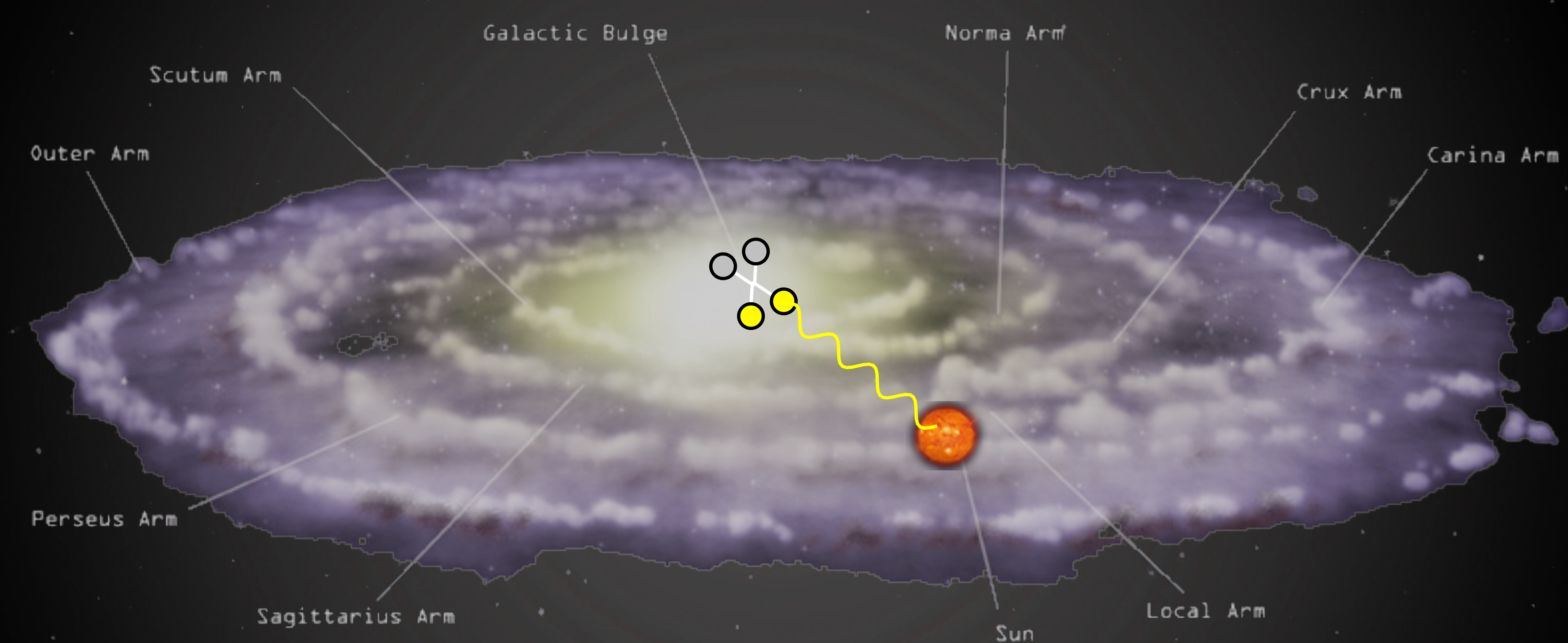


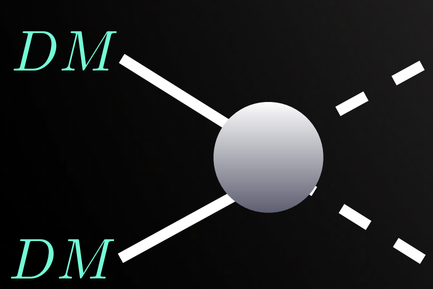
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

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

Indirect Detection: gammas

a. γ from DM annihilations in galactic center





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

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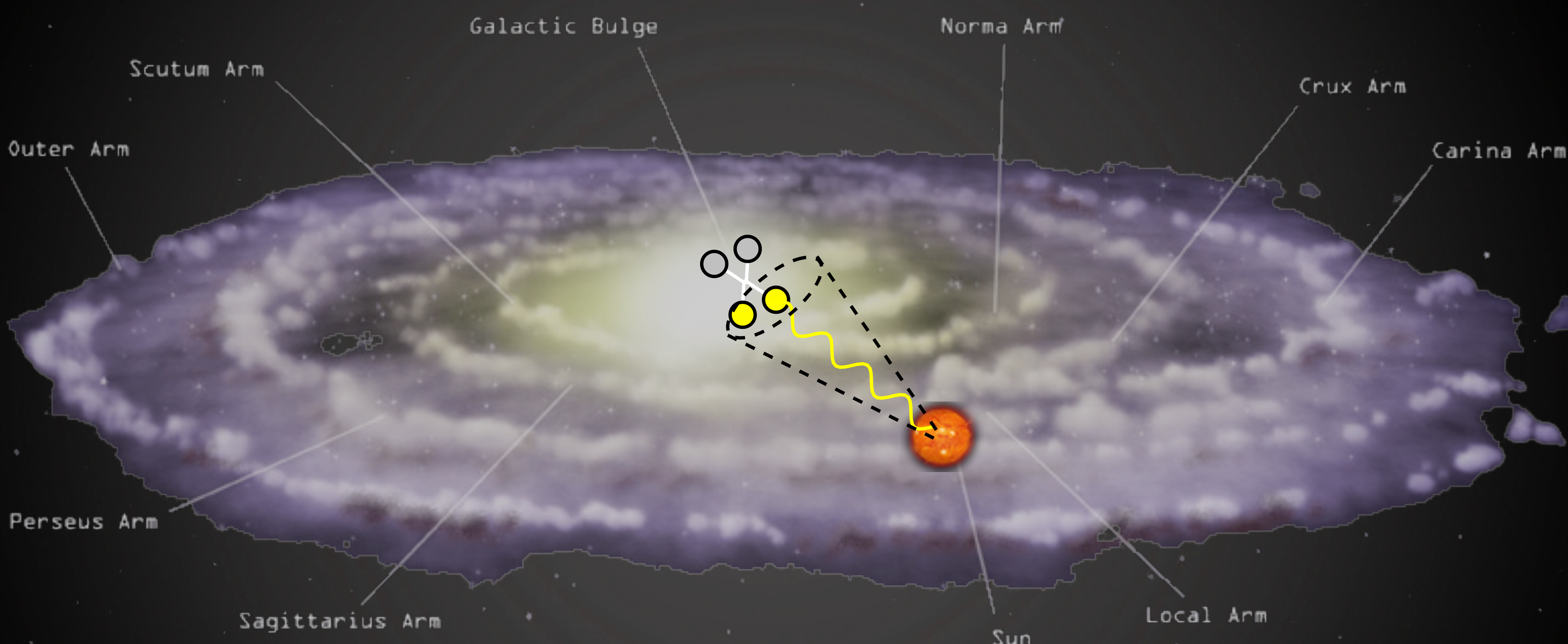
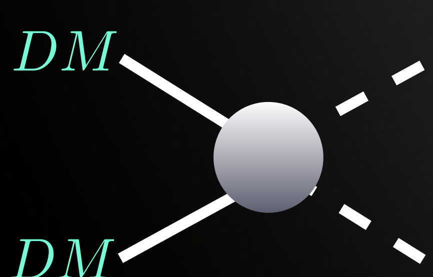
a. γ from DM annihilations in galactic center





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

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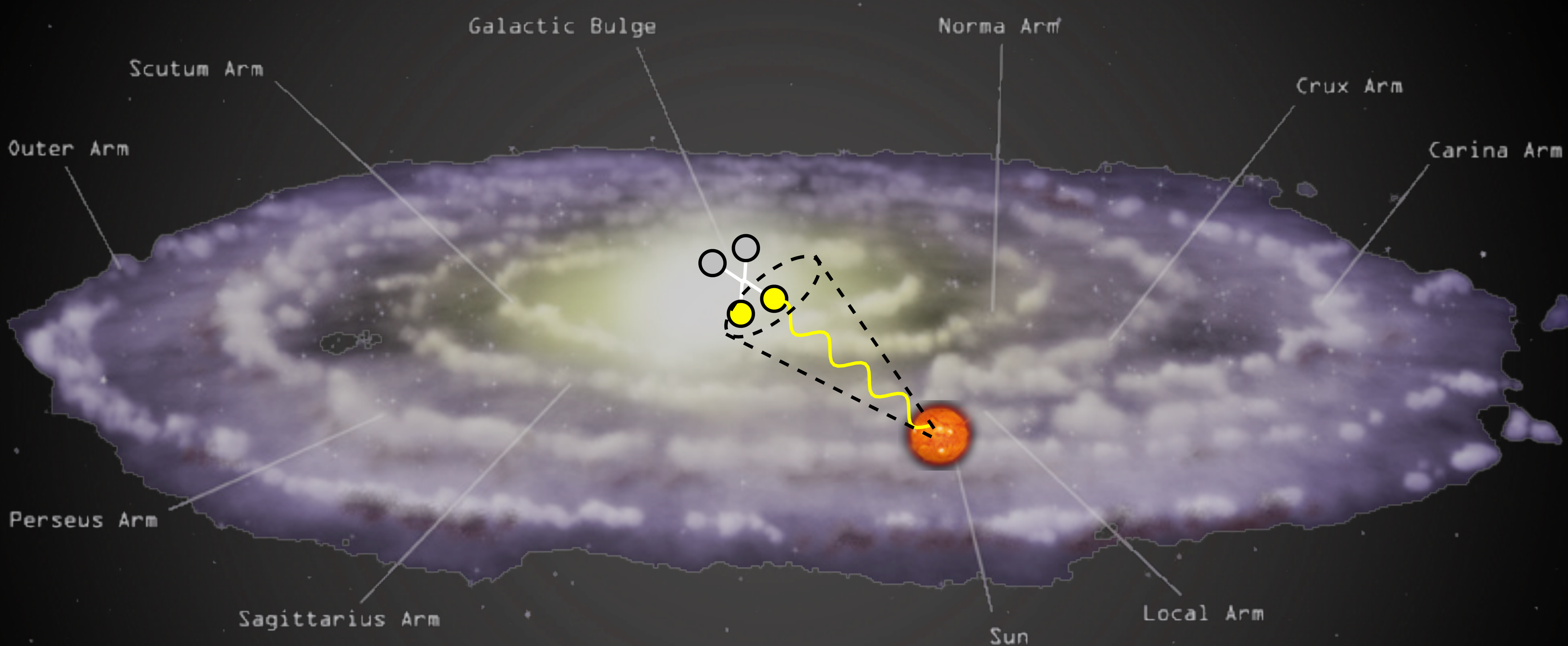
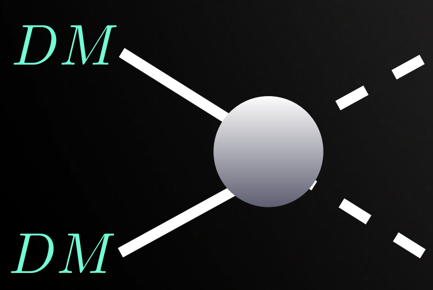
Indirect Detection: gammas

a. γ from DM annihilations in galactic center





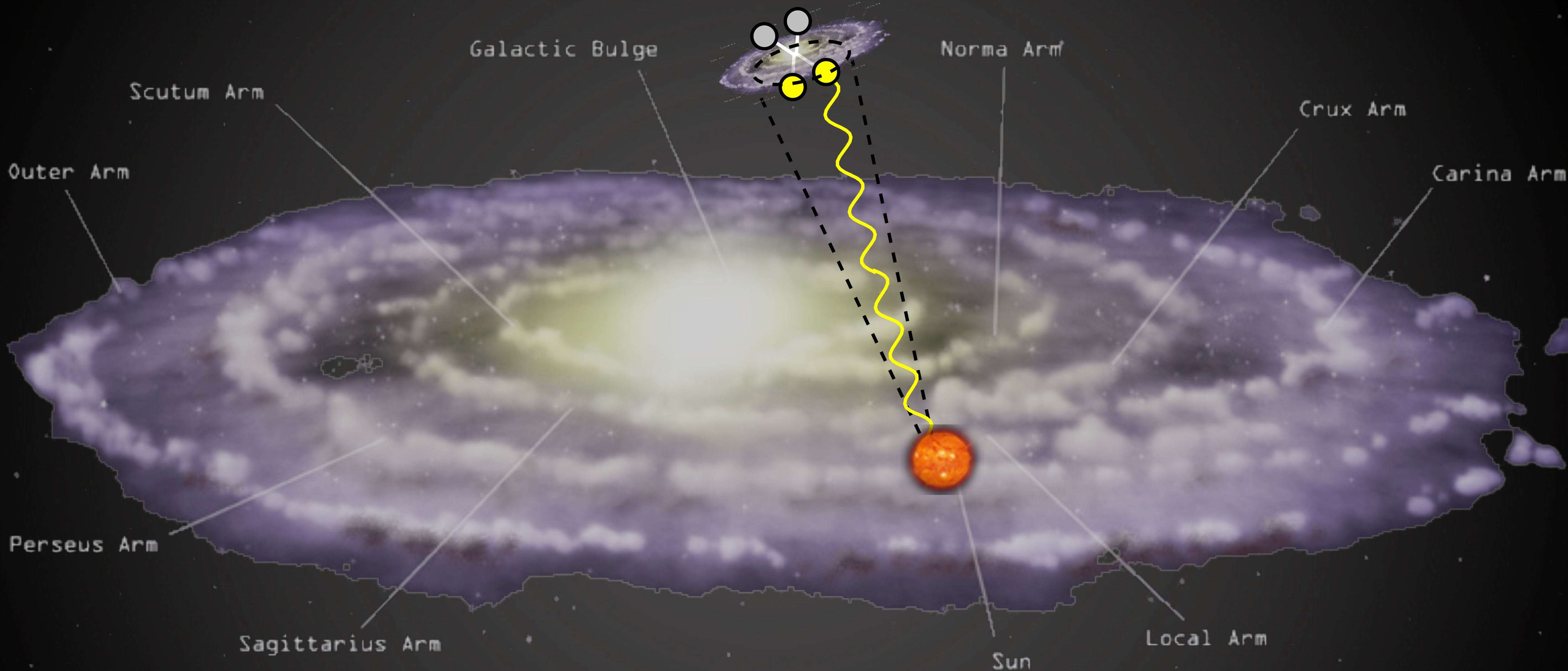
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

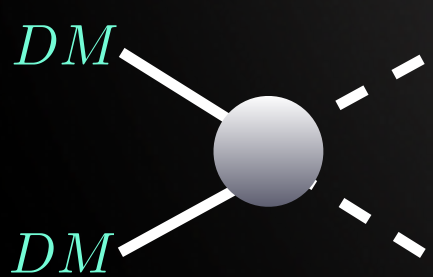
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

'prompt' gamma rays

Indirect Detection: gammas

b. γ from DM annihilations in Satellite Galaxies



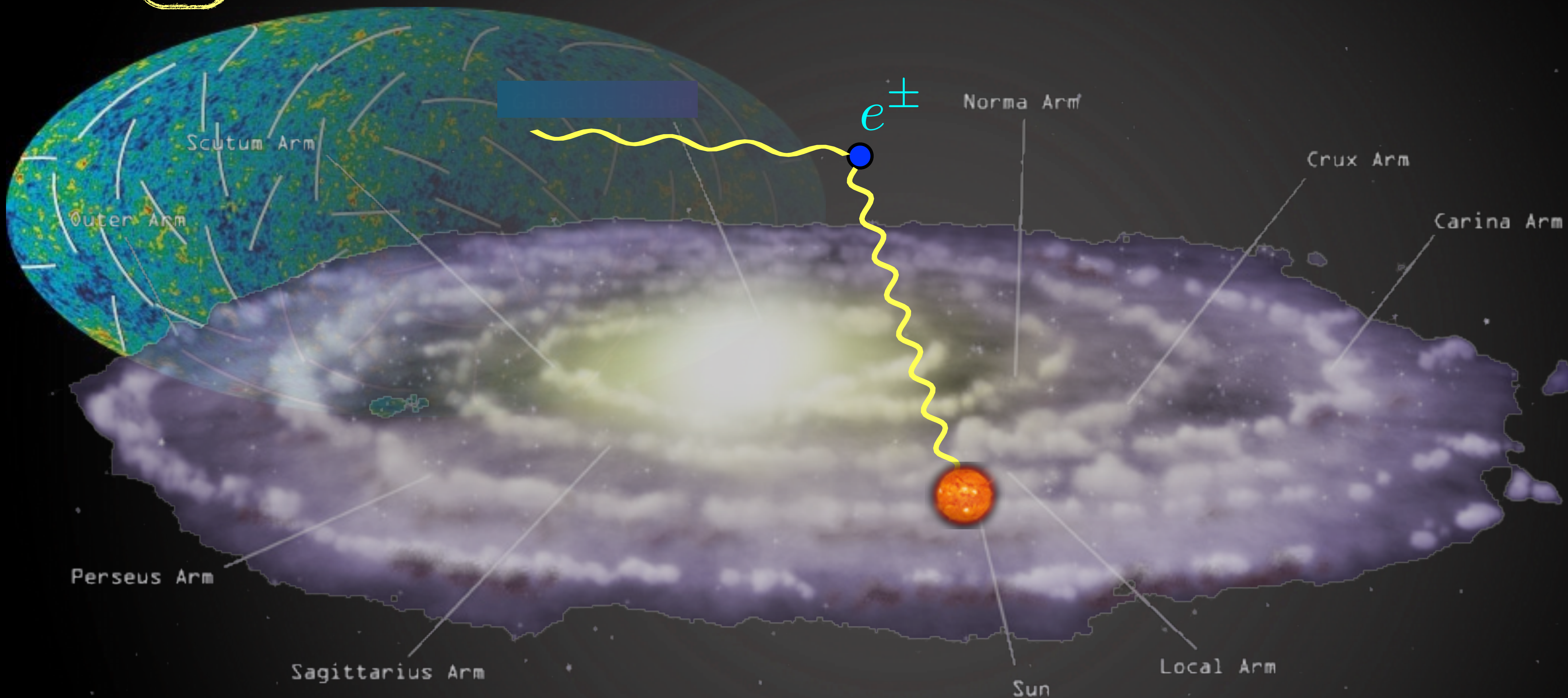


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

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

Indirect Detection: gammas

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

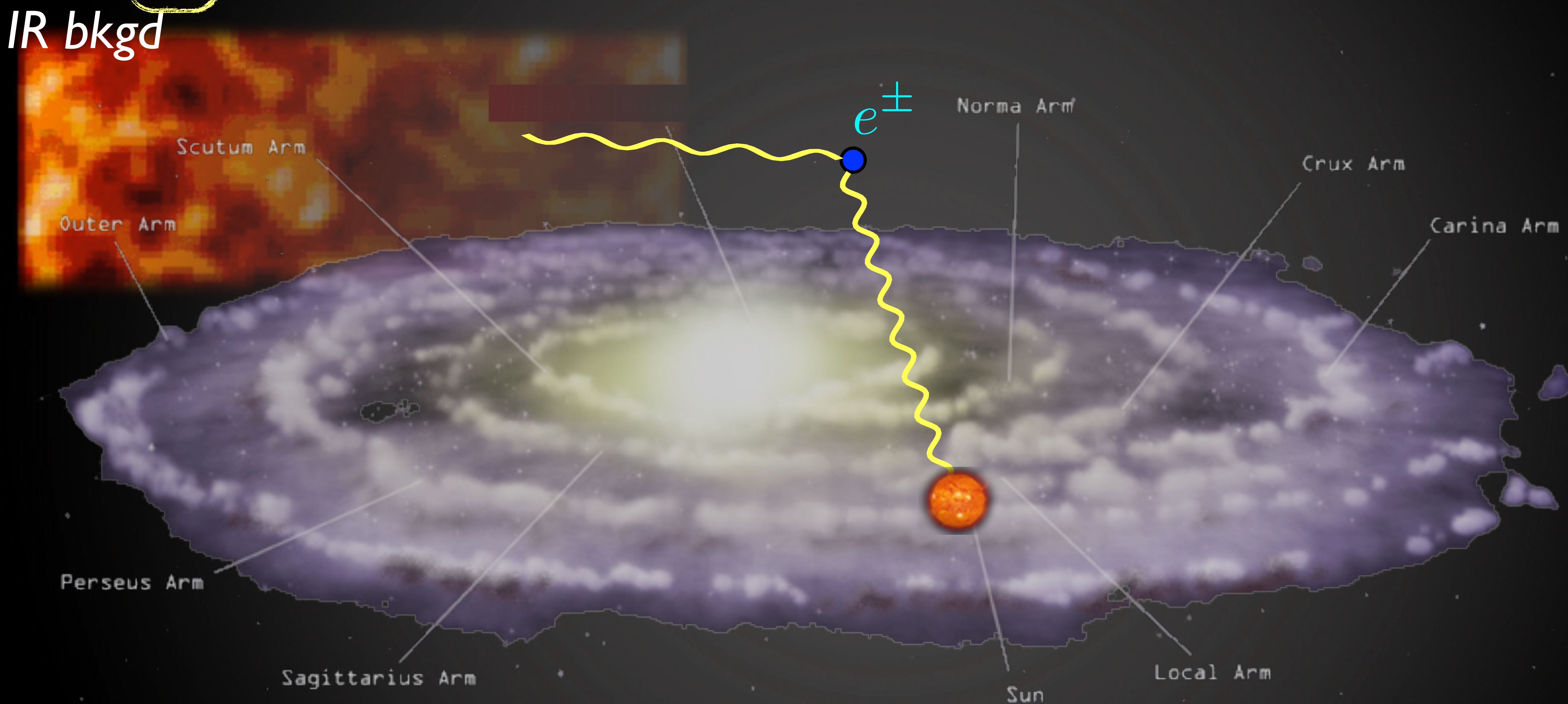


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Cirelli, Panci, 2009+

Indirect Detection: gammas

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



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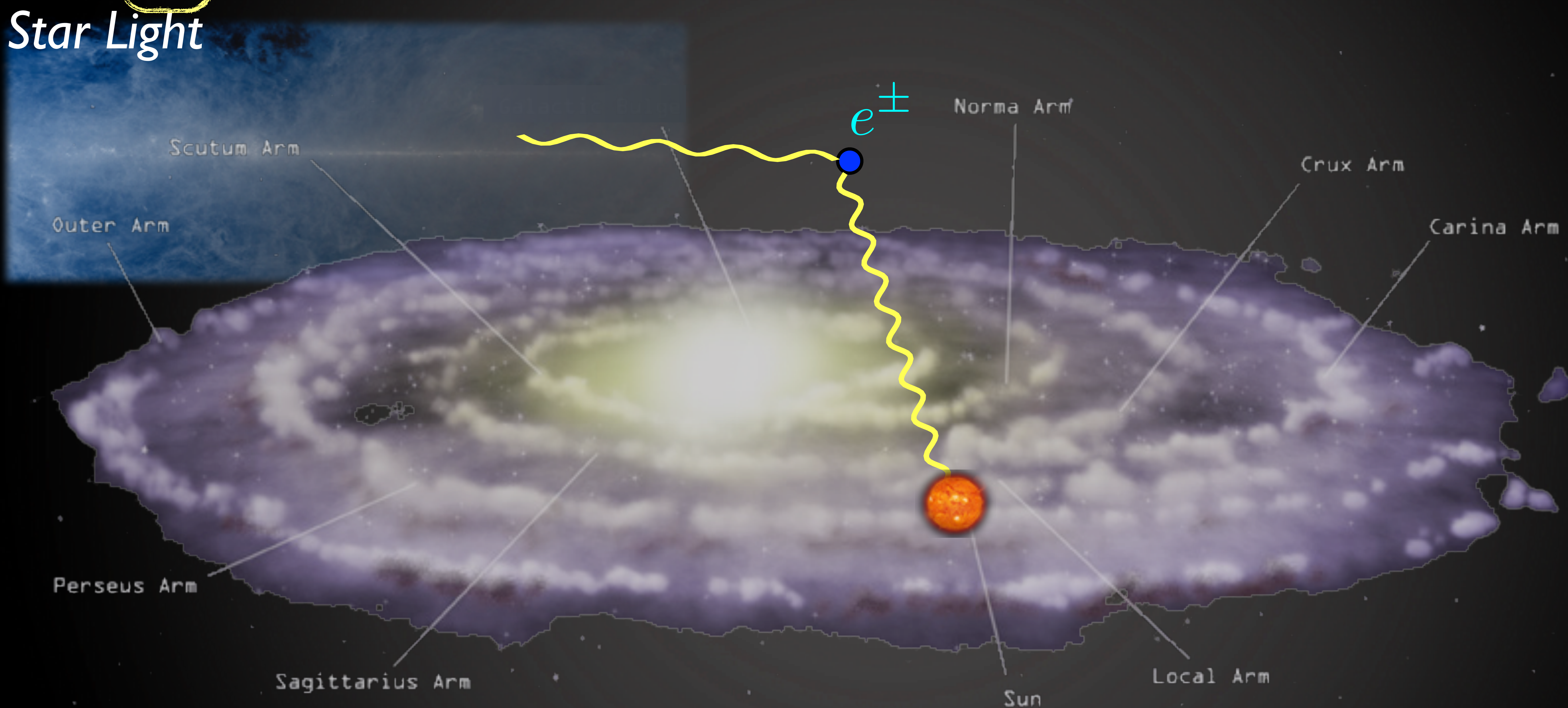
Cirelli, Panci, 2009+

Indirect Detection: gammas

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

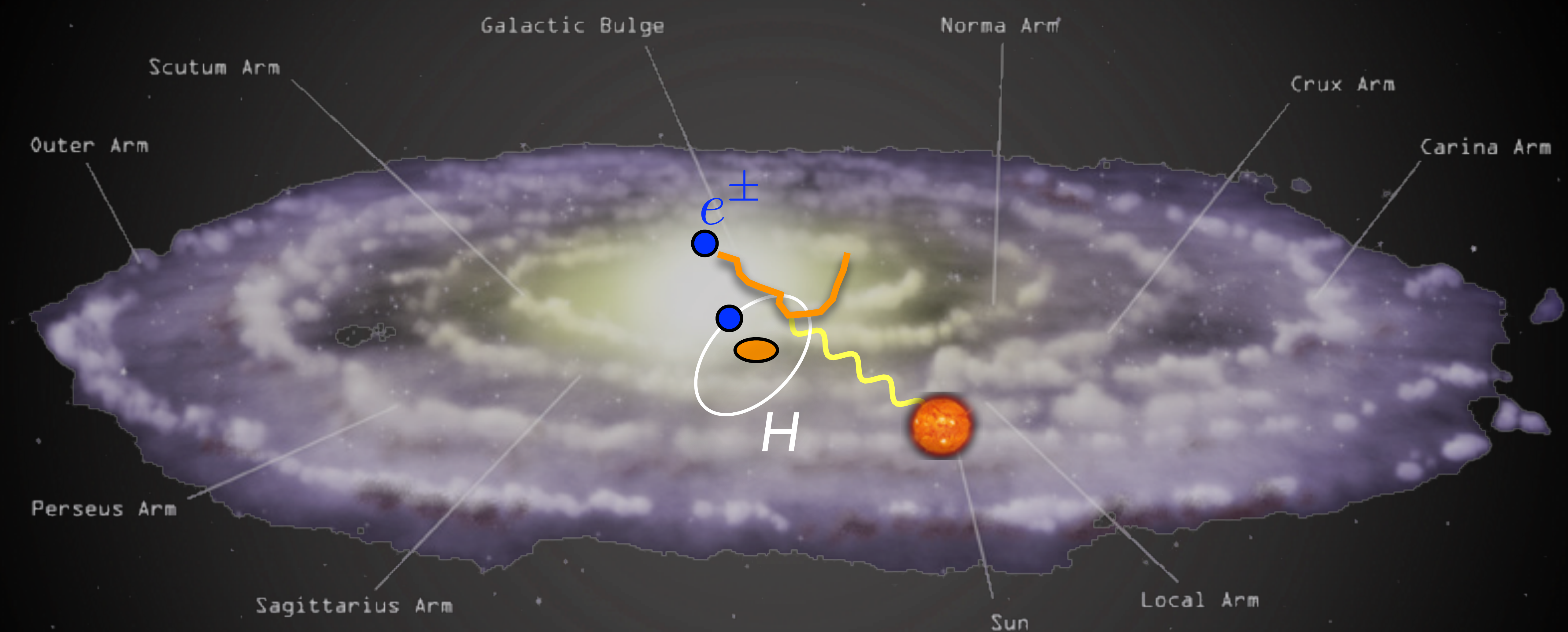


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Cirelli, Panci, 2009+

Indirect Detection: gammas

d. soft gammas from bremsstrahlung of $e^\pm$ on ISM

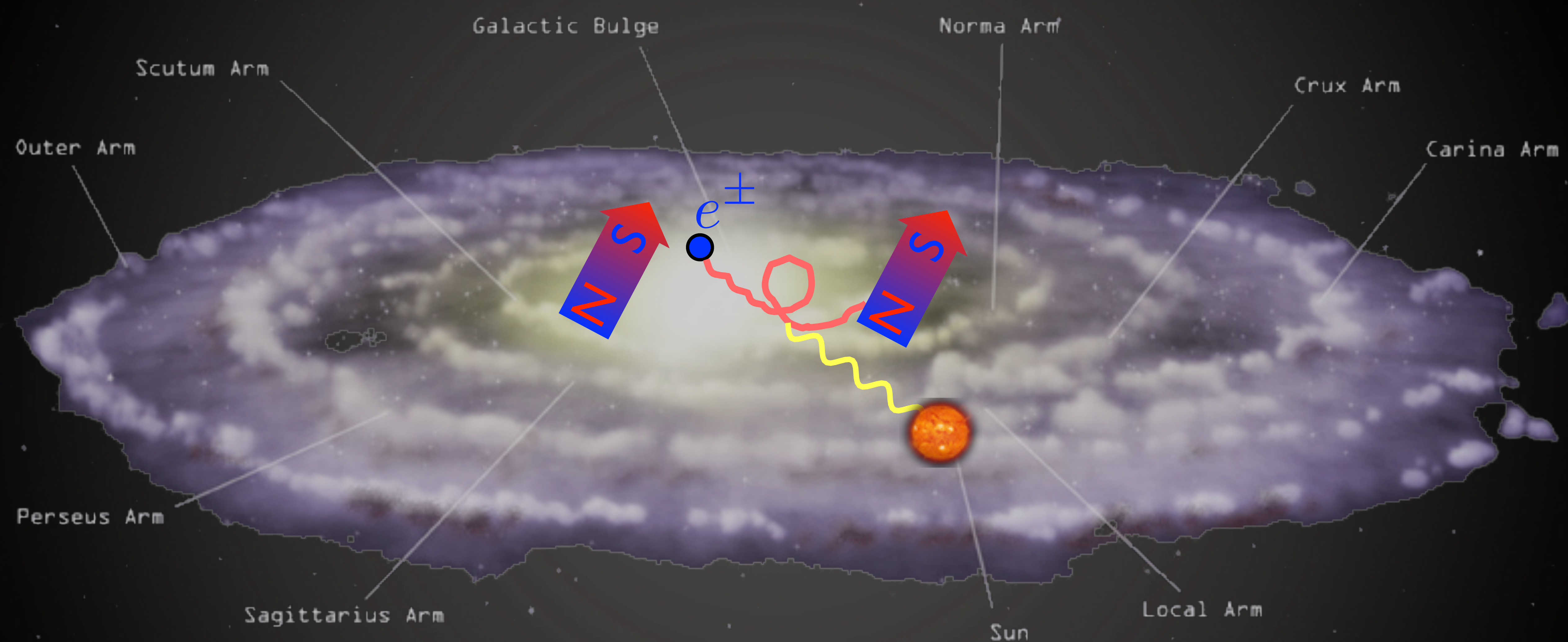


- (very) relevant at low energy, in the disk and at the GC

Cirelli, Serpico, Zaharijas,1307.7152

Indirect Detection: gammas

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



many many people, including:
Cirelli, Taoso et al., 0811.3744

How does DM produce γ-rays?

1. prompt emission

1a. continuum **1b.** line(s) **1c.** sharp features

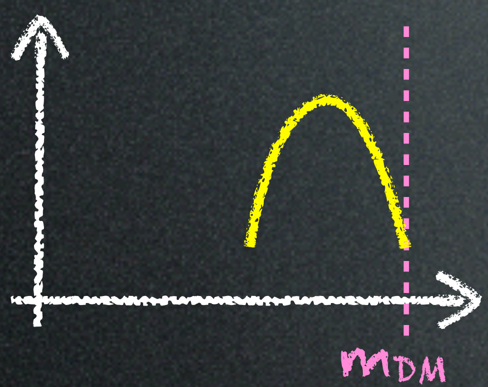
2. secondary emission

2a. ICS **2b.** bremsstrahlung **2c.** synchrotron

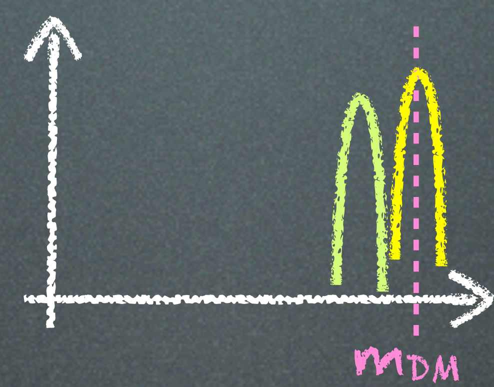
How does DM produce γ-rays?

1. prompt emission

1a. continuum



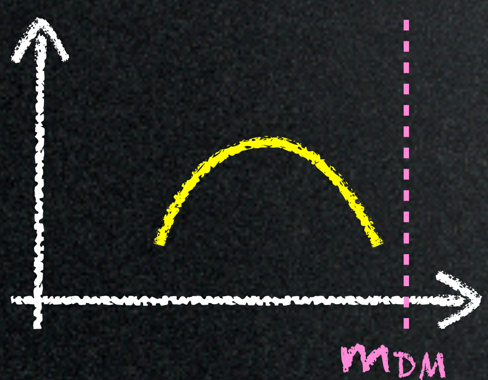
1b. line(s)



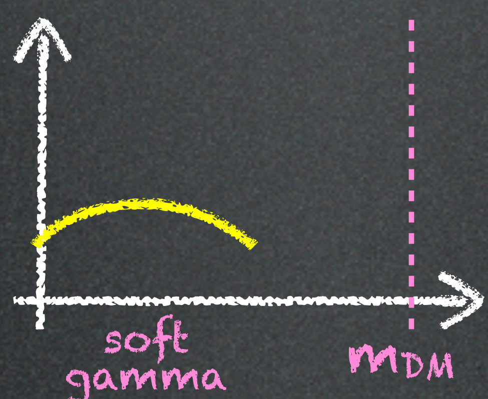
1c. sharp features

2. secondary emission

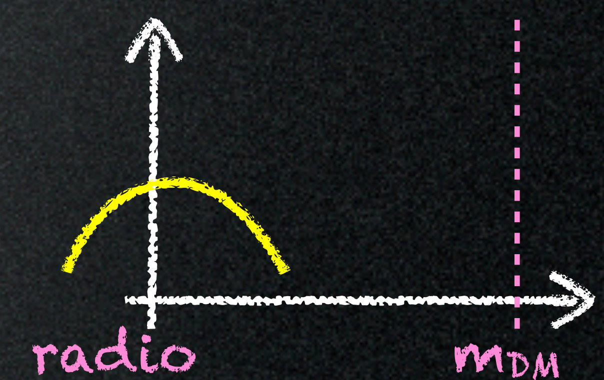
2a. ICS



2b. bremsstrahlung



2c. synchrotron

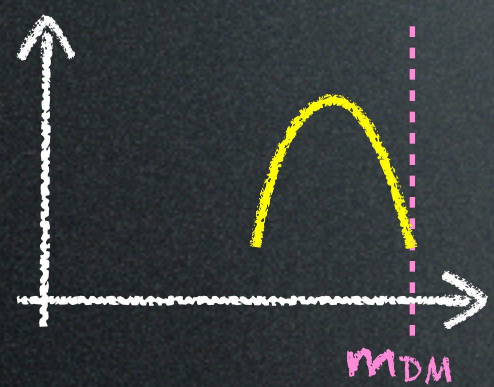


How does DM produce γ-rays?

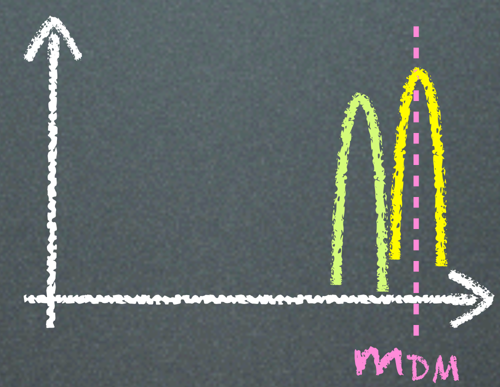
environment-independent

1. prompt emission

1a. continuum



1b. line(s)

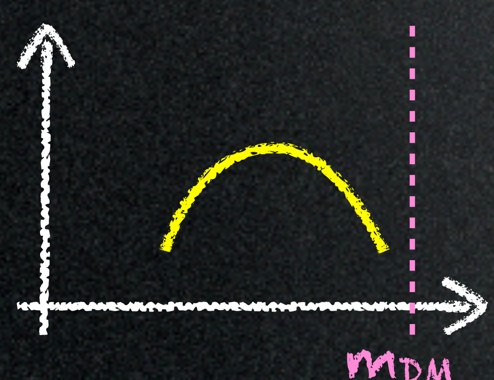


1c. sharp features

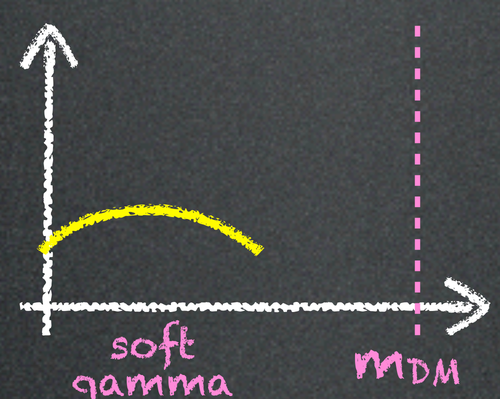
environment-dependent

2. secondary emission

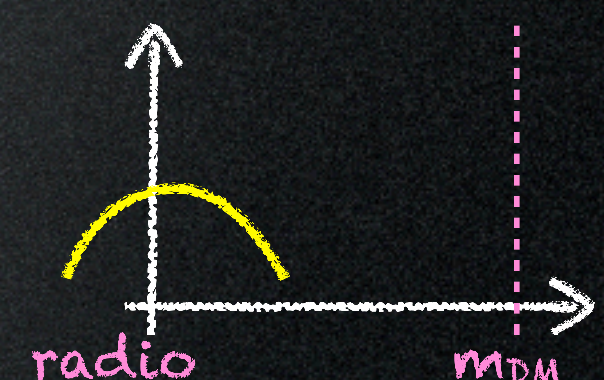
2a. ICS



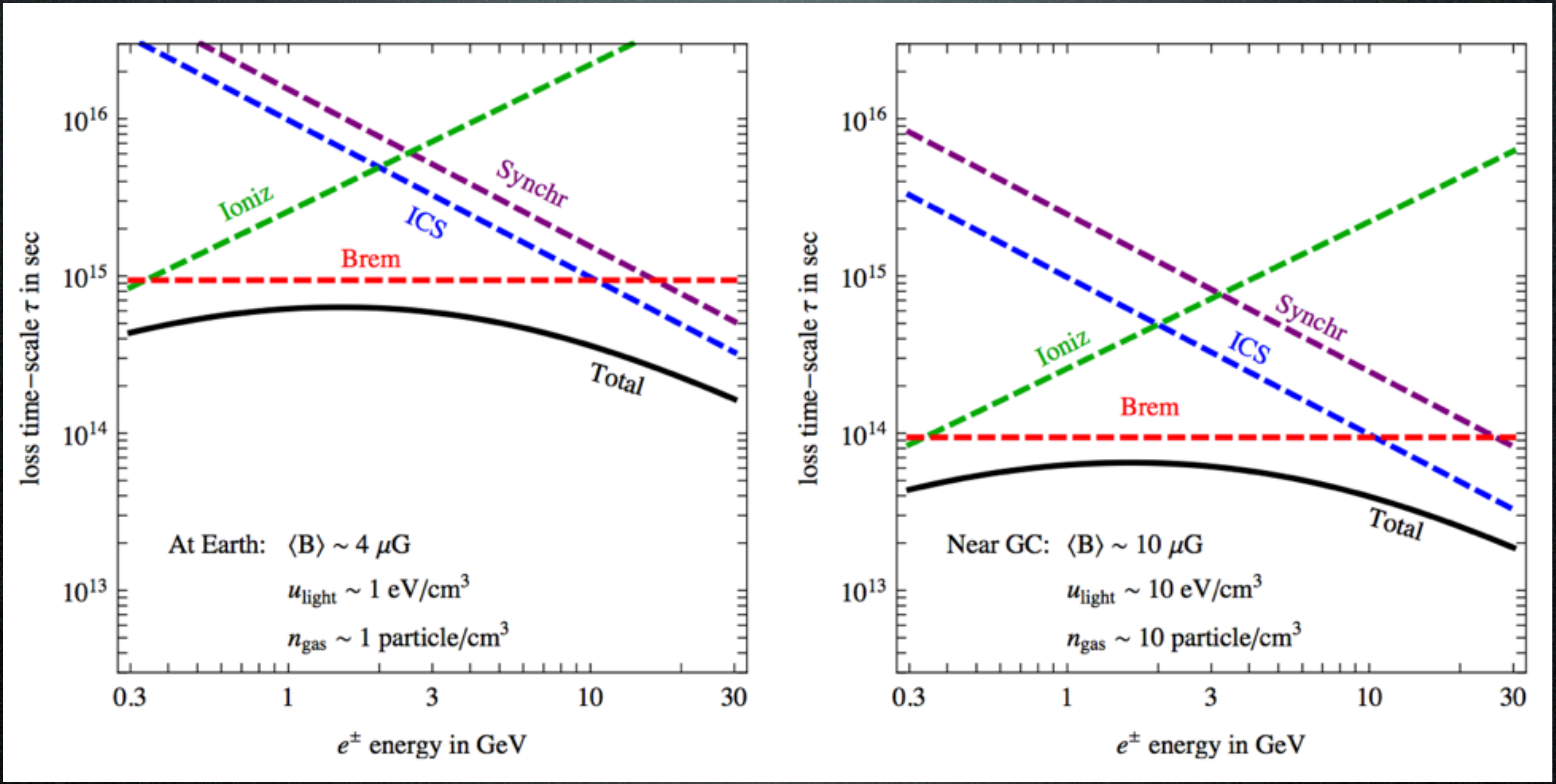
2b. bremsstrahlung



2c. synchrotron



Relative importance of secondary emissions



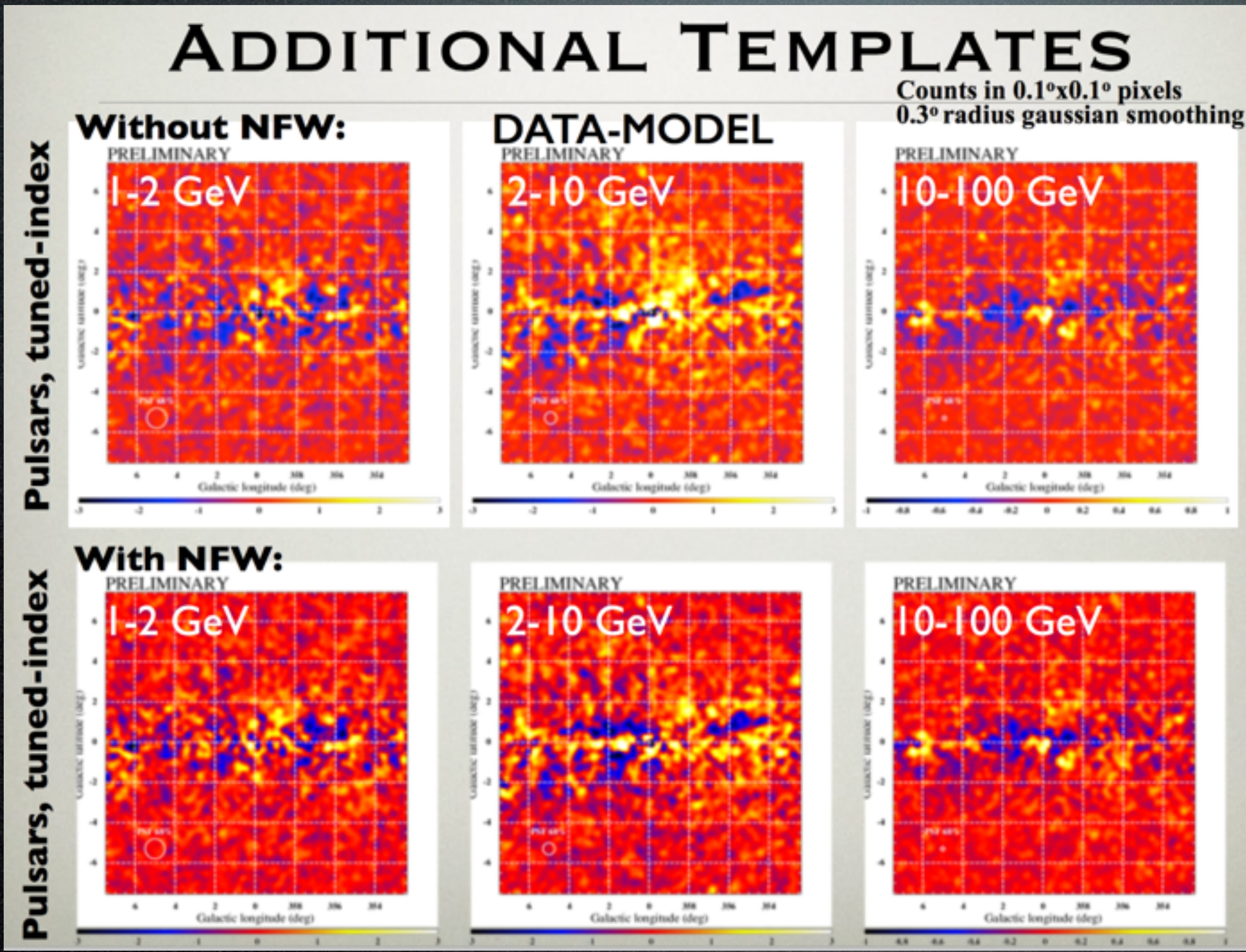
Cirelli, Serpico, Zaharijas, 1307.7152

=> brem is the dominant energy loss for low energy $e^{\pm}$!

GC GeV excess

GC GeV excess

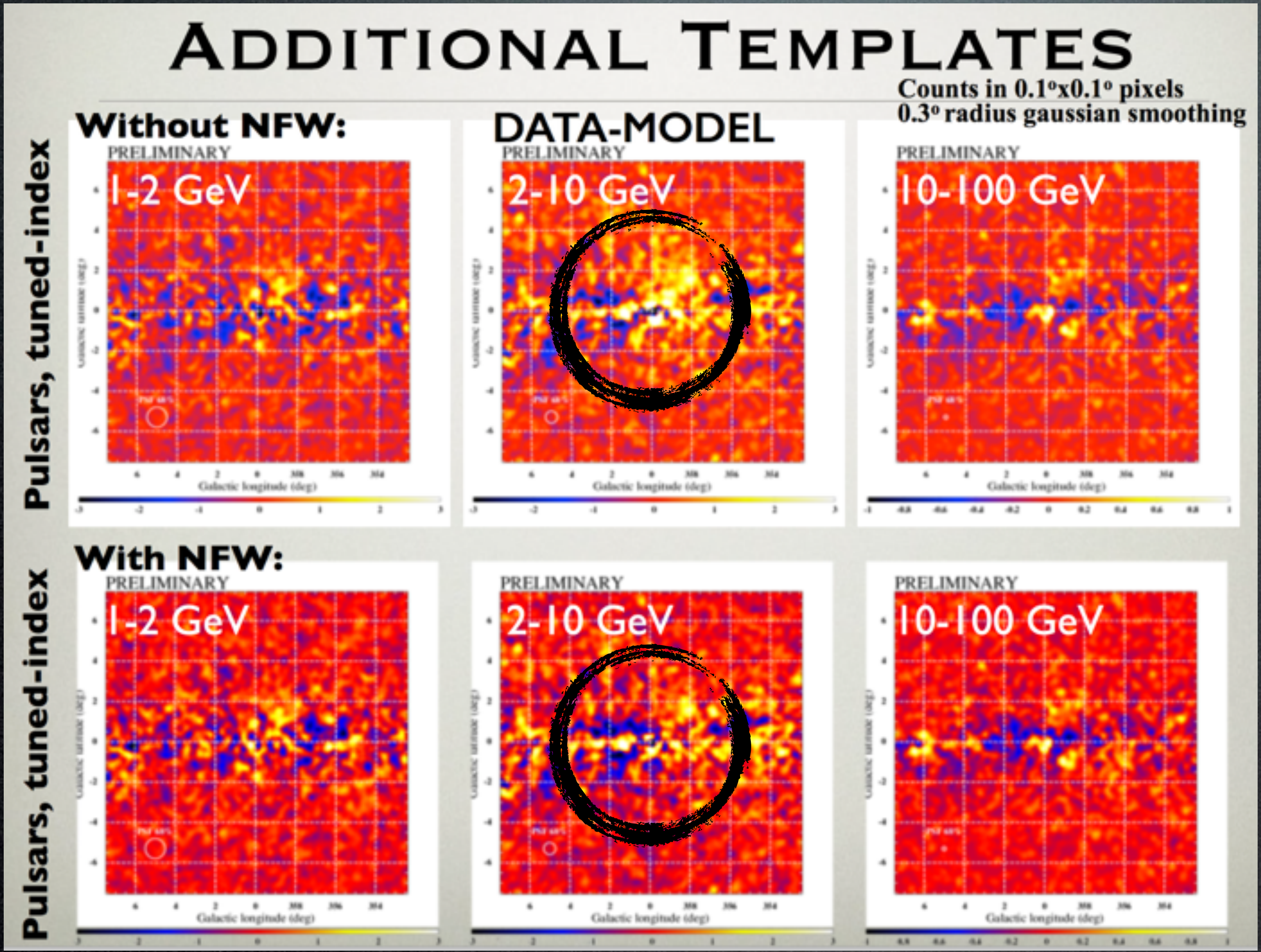
Dark Matter interpretation:



S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815

GC GeV excess

Dark Matter interpretation:

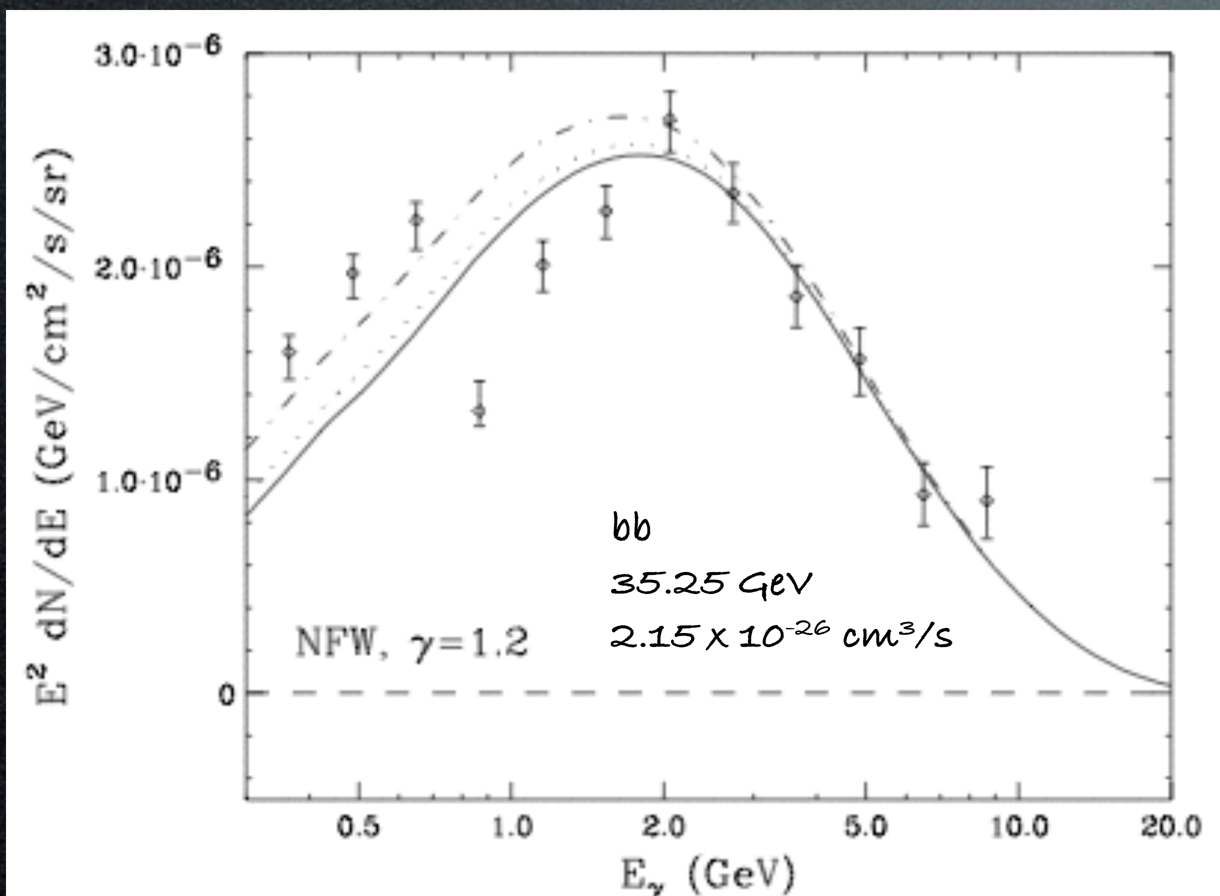


S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815

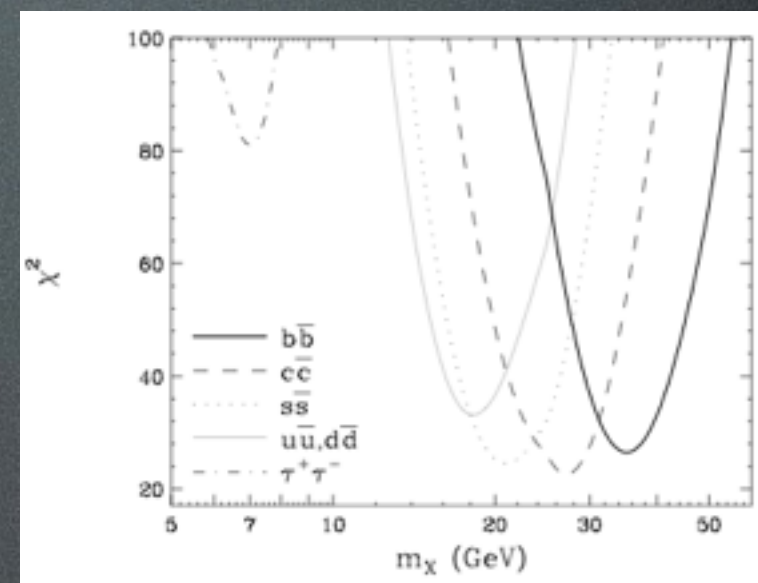
GC GeV excess

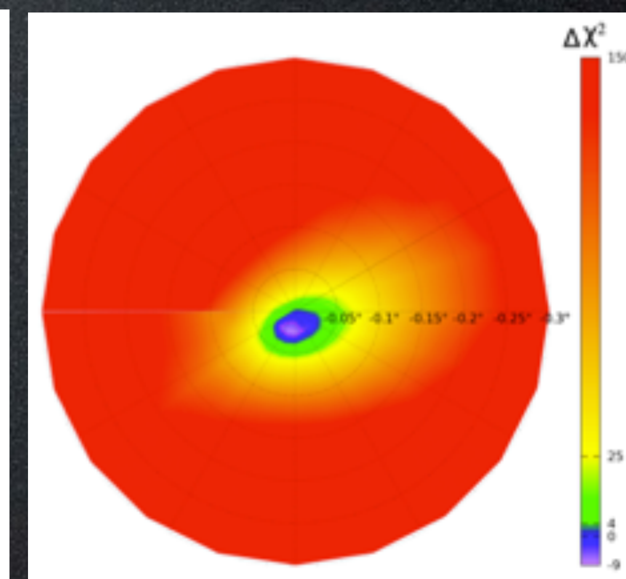
Dark Matter interpretation:

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



Using events with accurate directional reconstruction





A compelling case for annihilating DM

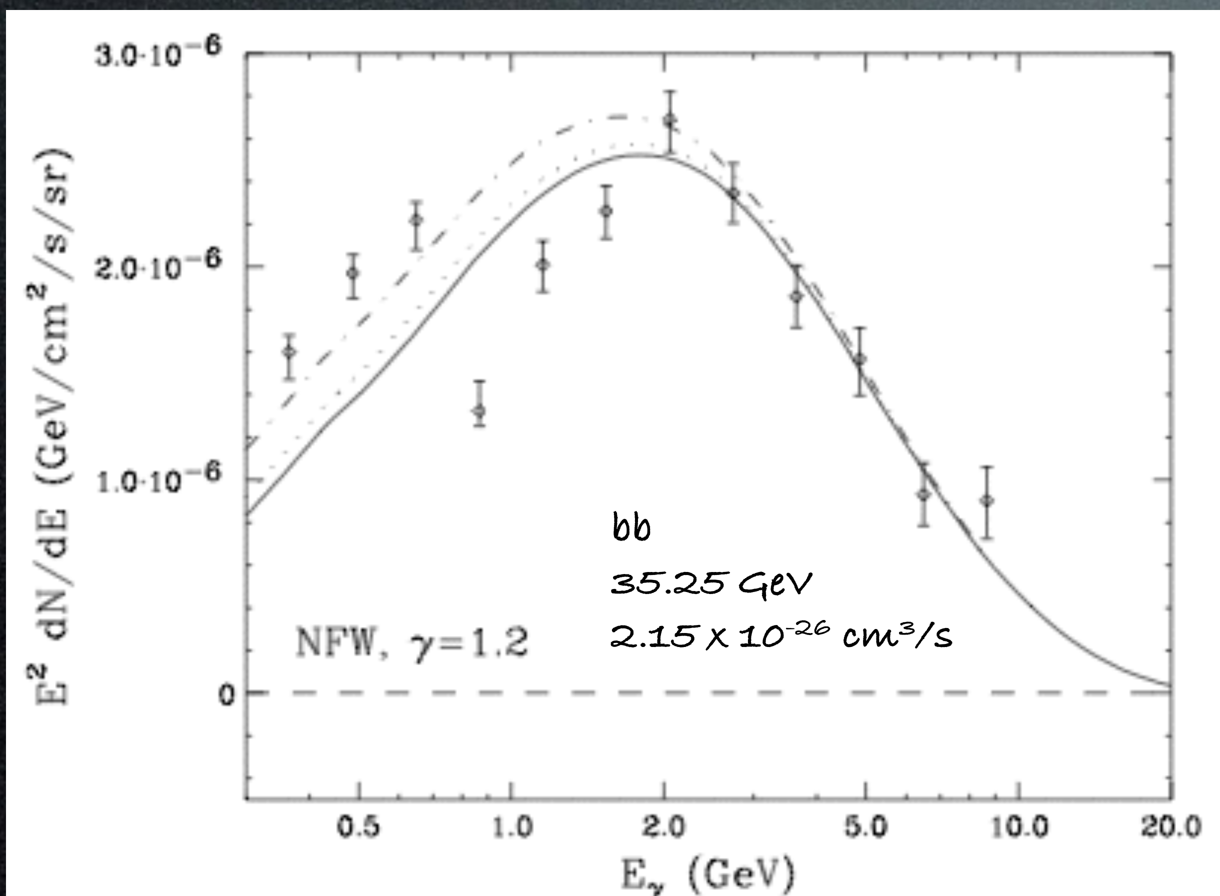
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

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.

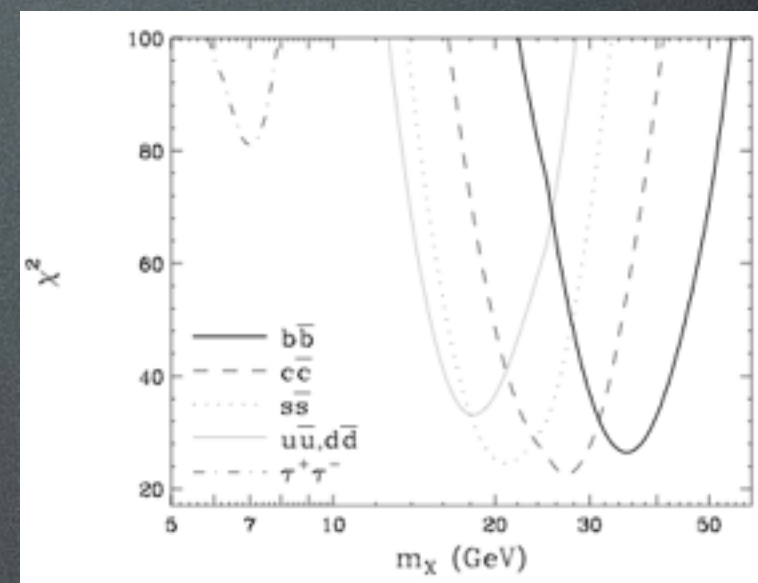
GC GeV excess

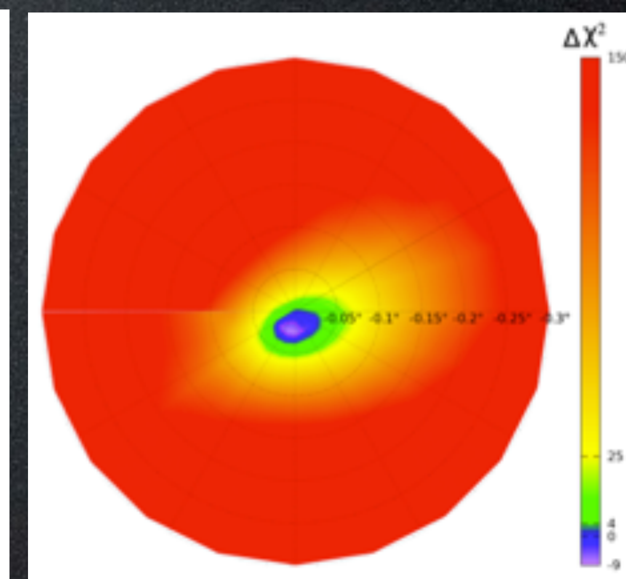
Dark Matter interpretation:

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



Using events with accurate directional reconstruction





A compelling case for annihilating DM

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

...as good as it can get.

GC GeV 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...)

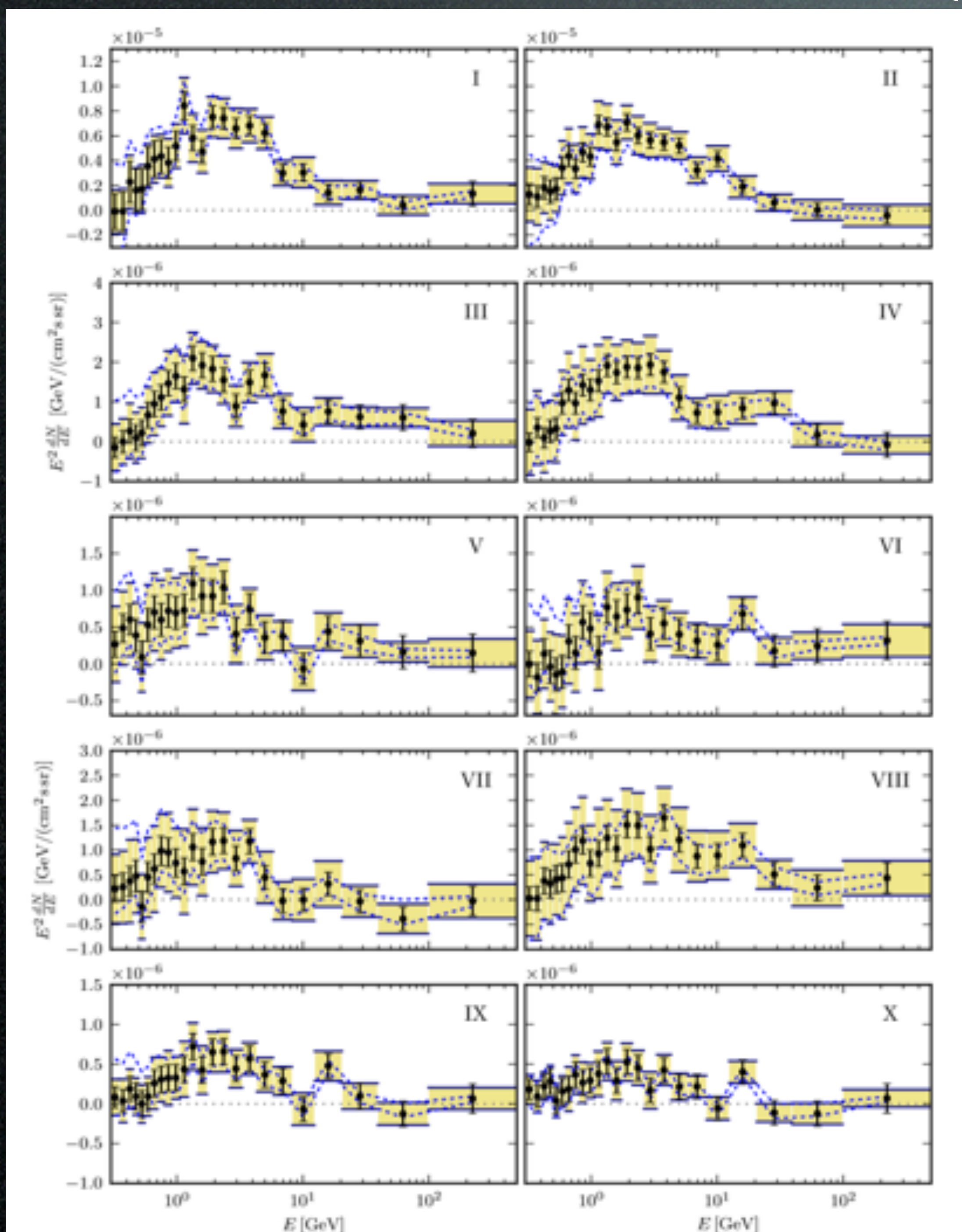
iv. repeat the same, adding a template for:
6. Dark Matter, having chosen a certain profile!

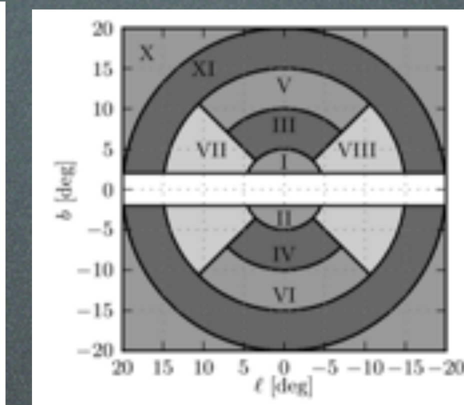
v. if iii. → iv. improves χ^2, there's evidence for DM
vi. the component fitted by 6 is the residual excess to be explained

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.

GC GeV excess

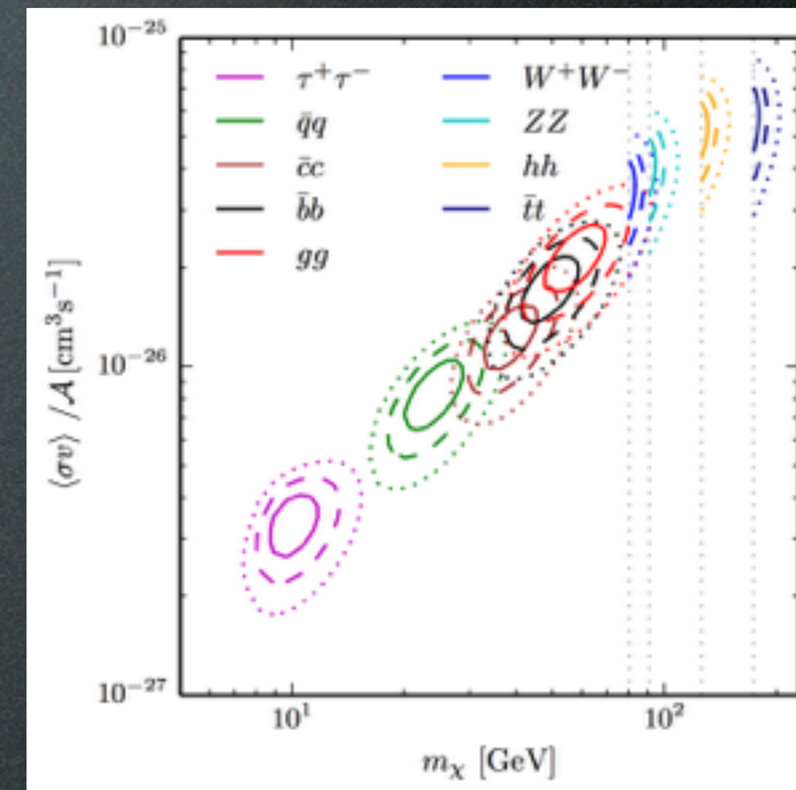
The excess is robust against uncertainties in foreground modelling, and it extends to o(10°):



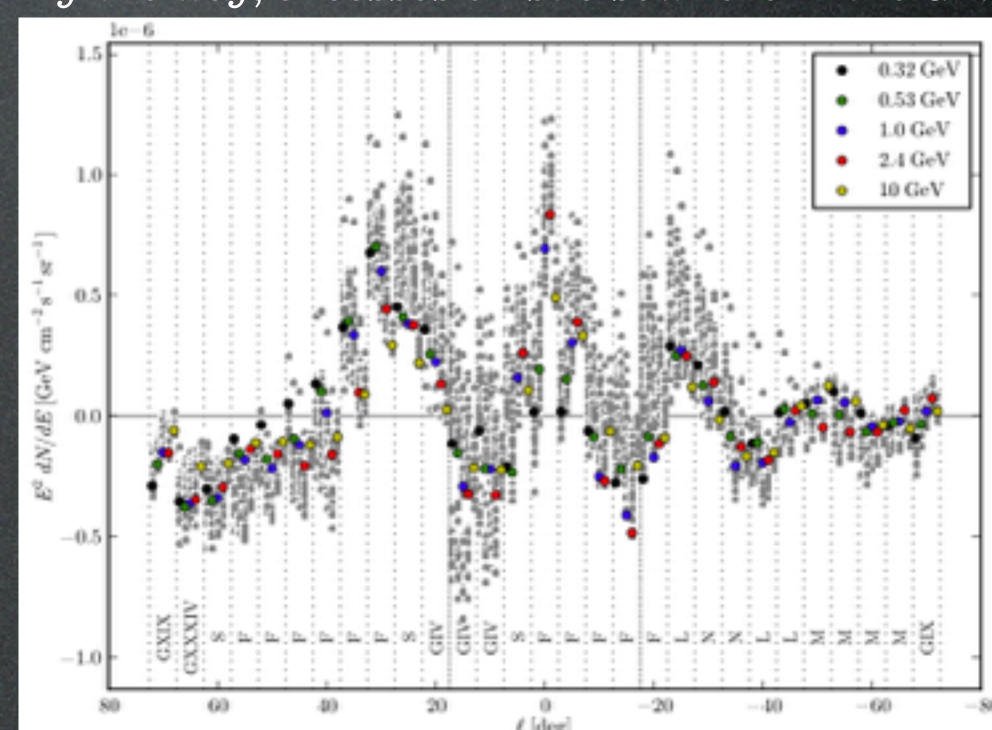


Calore, Cholis, Weniger 1409.0042
Calore, Cholis, McCabe, Weniger 1411.4647

More general DM good fits:



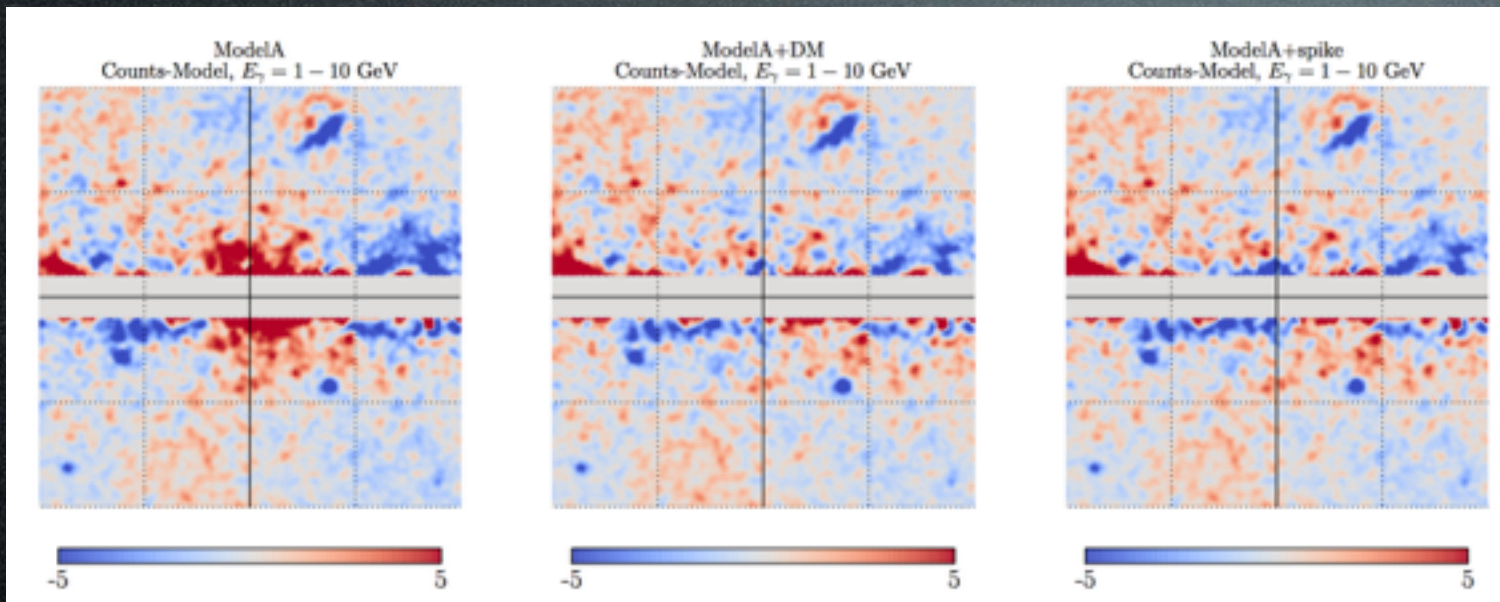
By the way, excesses exist elsewhere in the GP:

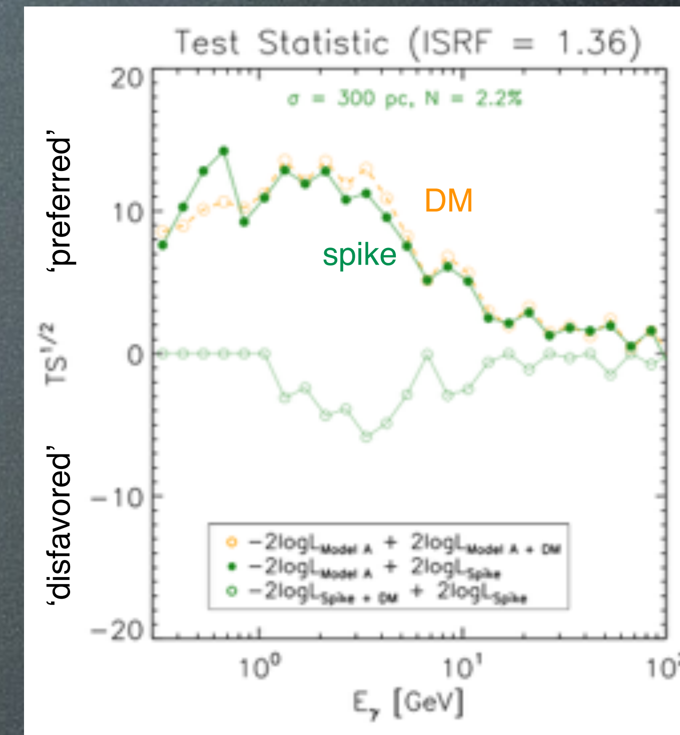


Gal plane

GC GeV excess

‘Astro’ interpretation(s):

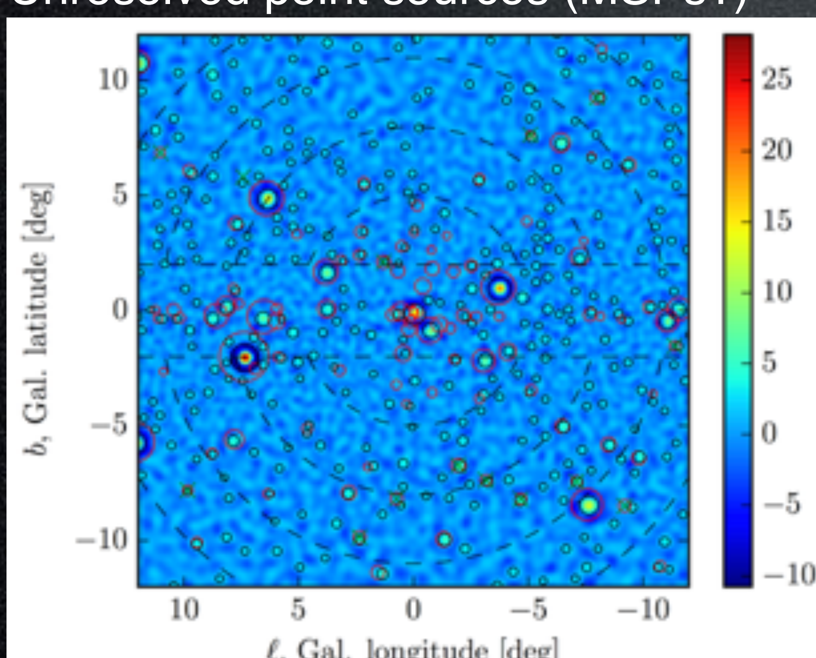




An additional steady-source spike of CRs (from SNRs?) that emit via ICS

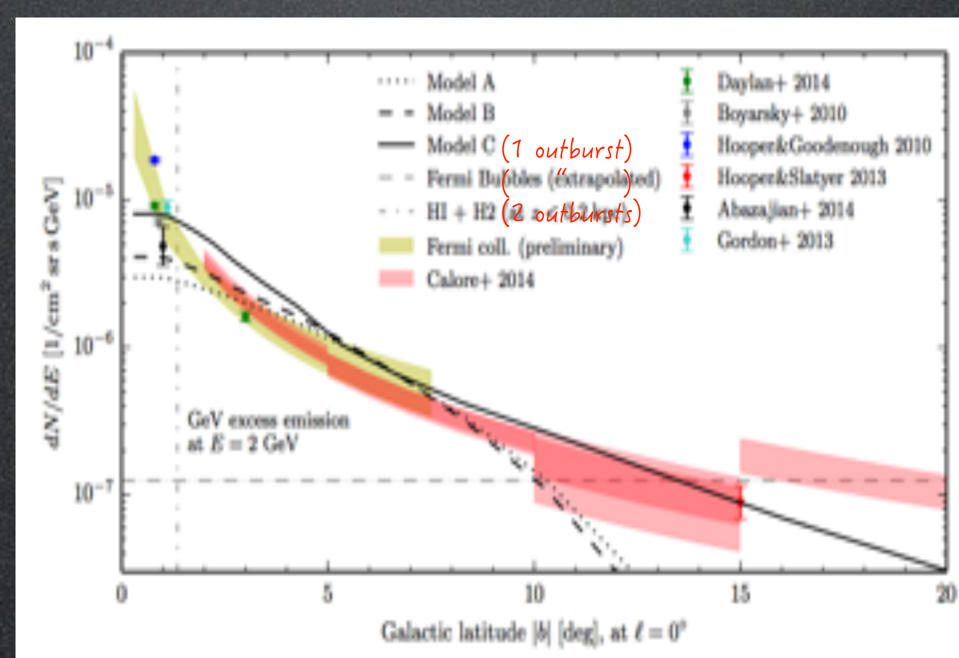
Gaggero, Taoso, Urbano, Valli, Ullio 1507.06129

Unresolved point sources (MSPs?)



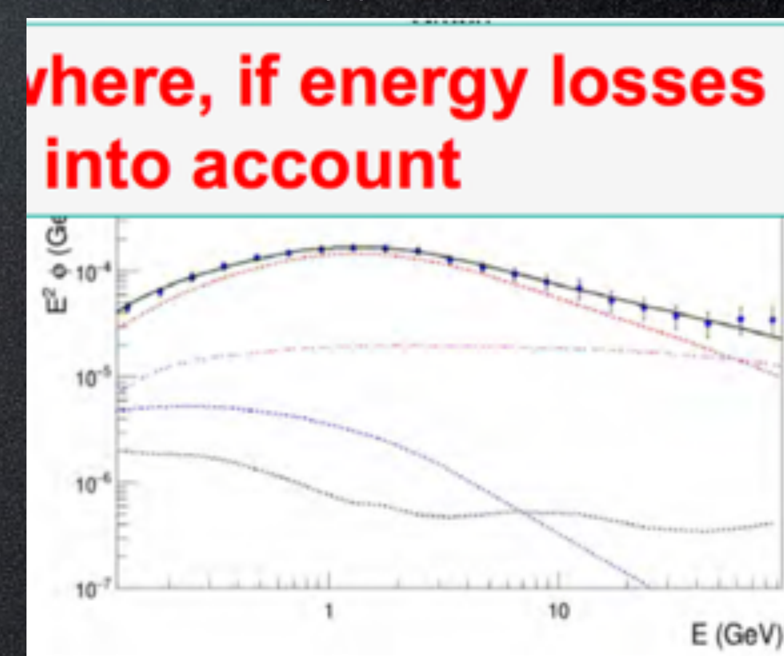
Lee, Lisanti, Safdi, Slatyer, Xue 1506.05124
Bartels, Krishnamurthy, Weniger 1506.05104
Abazajian 1011.4275
Hooper et al. 1305.0830
Yuan, Zhang 1404.2318
Petrović, Serpico, Zaharijas 1411.2980

Leptonic outbursts: old + young (1 + 0.1 Myr)
(but even this is not ideal)



Cholis, Evoli, Calore, Linden, Weniger 1506.05119
Petrović, Serpico, Zaharijas 1405.7928
Carlson, Profumo 1405.7685

Enhanced proton energy losses near the GC (?)

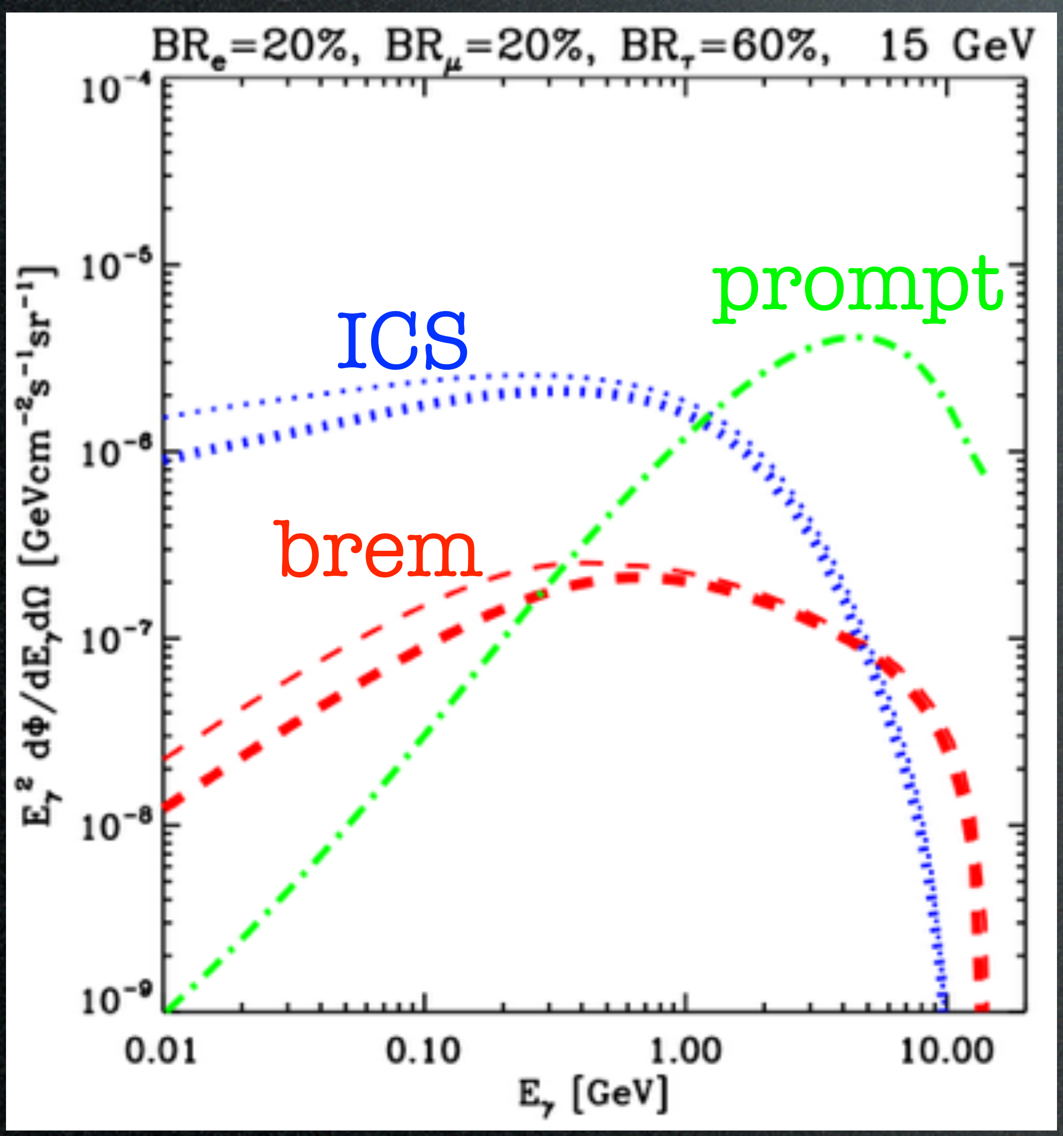


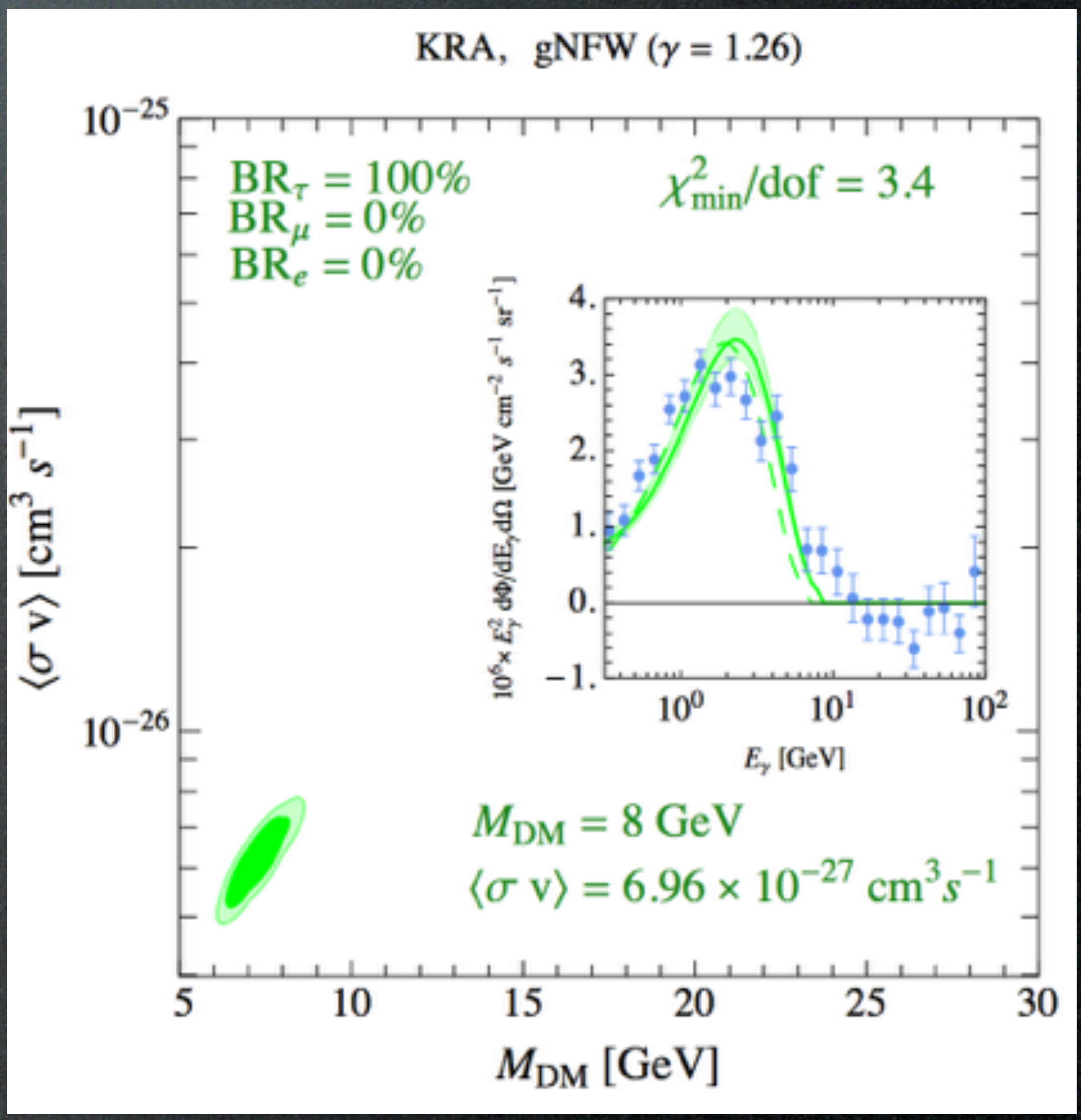
W. De Boer - ICRC 2015

GC GeV excess

Dark Matter interpretation:

Including secondary emission changes the conclusions





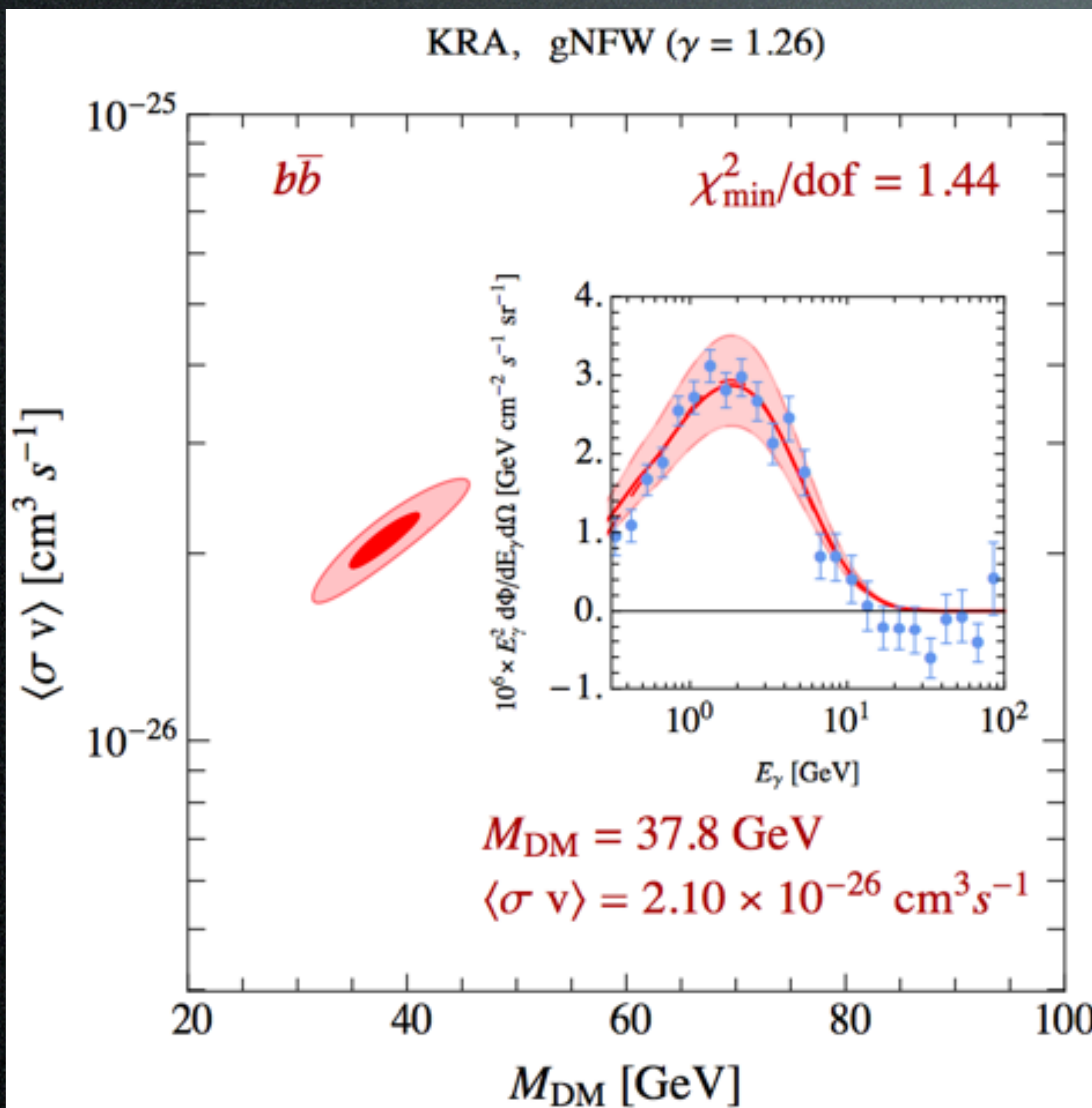
Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

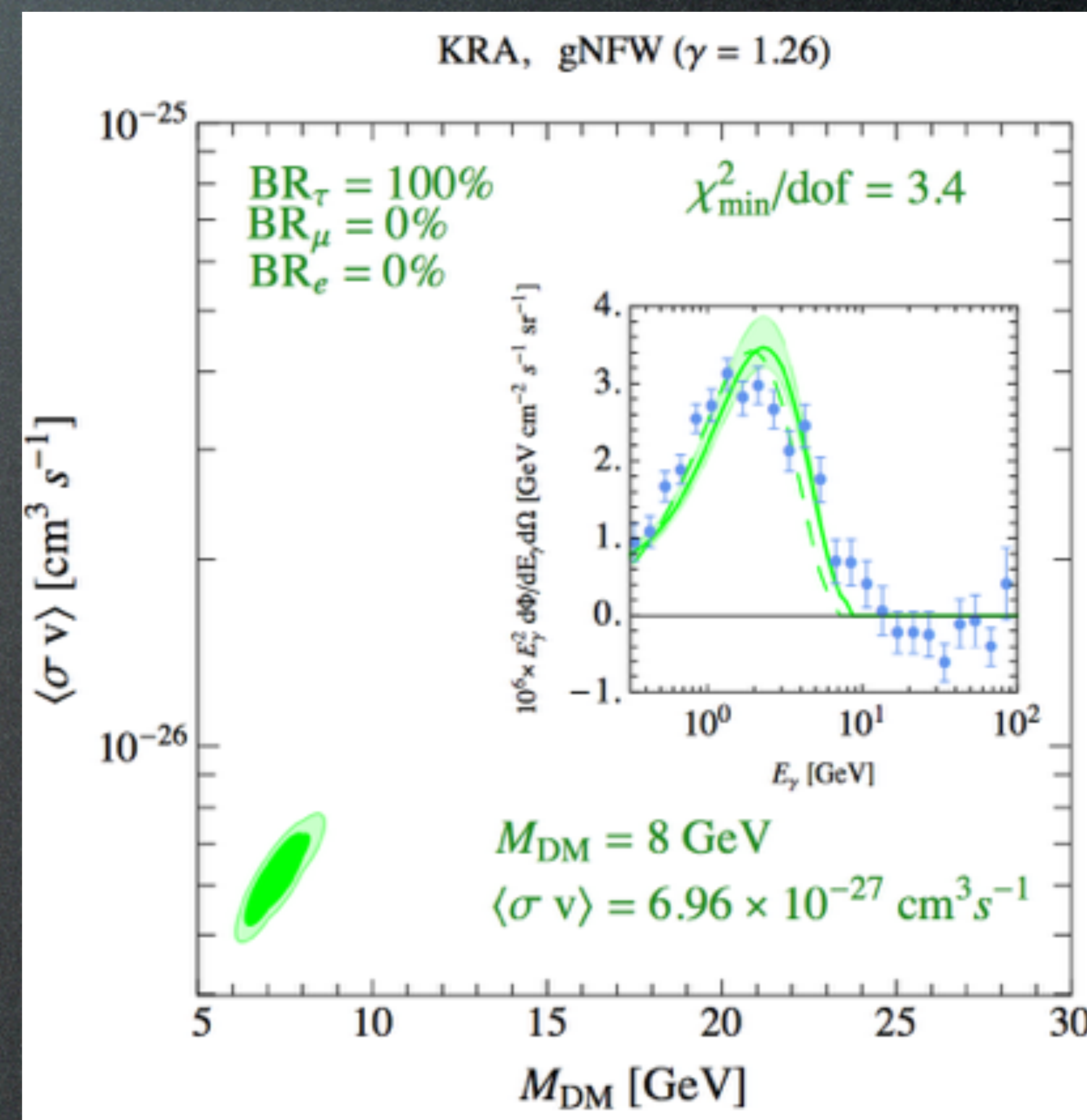
GC GeV excess

Dark Matter interpretation:

Analysis	Final State	Setup	M_{DM} [GeV]	$\langle \sigma v \rangle$ [cm^3 s^{-1}]	χ^2_{min}/dof
'Gal Center', $\gamma = 1.2$	$b\bar{b}$	KOL	35.53	2.14×10^{-26}	12.1
	leptonic mix $^{(*)}$	KOL	9.4	1.06×10^{-26}	6.3
'Inner Gal', $\gamma = 1.26$	$b\bar{b}$	KRA	37.8	2.10×10^{-26}	1.44
	$\tau^+\tau^-$	KRA	8	6.96×10^{-27}	3.4

'Best' fit:

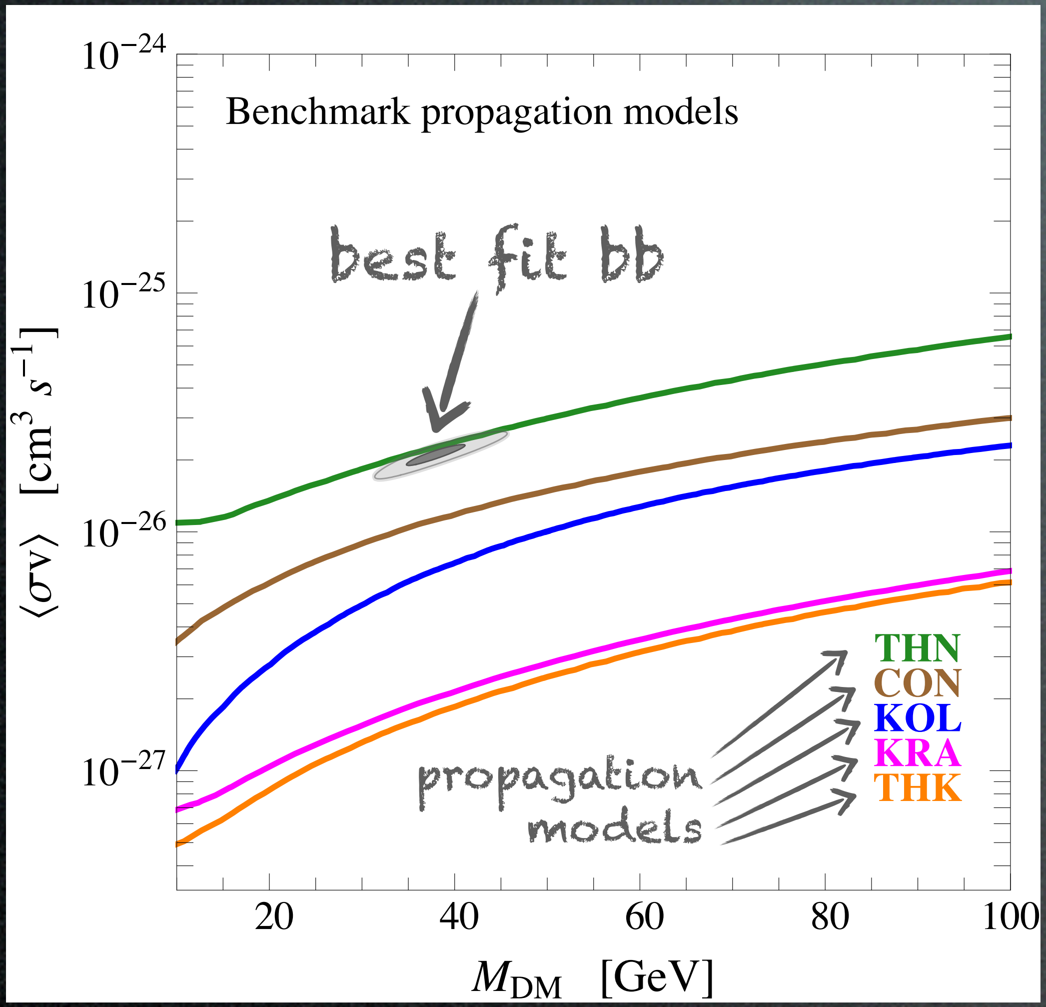




Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

GC GeV excess

Dark Matter interpretation:



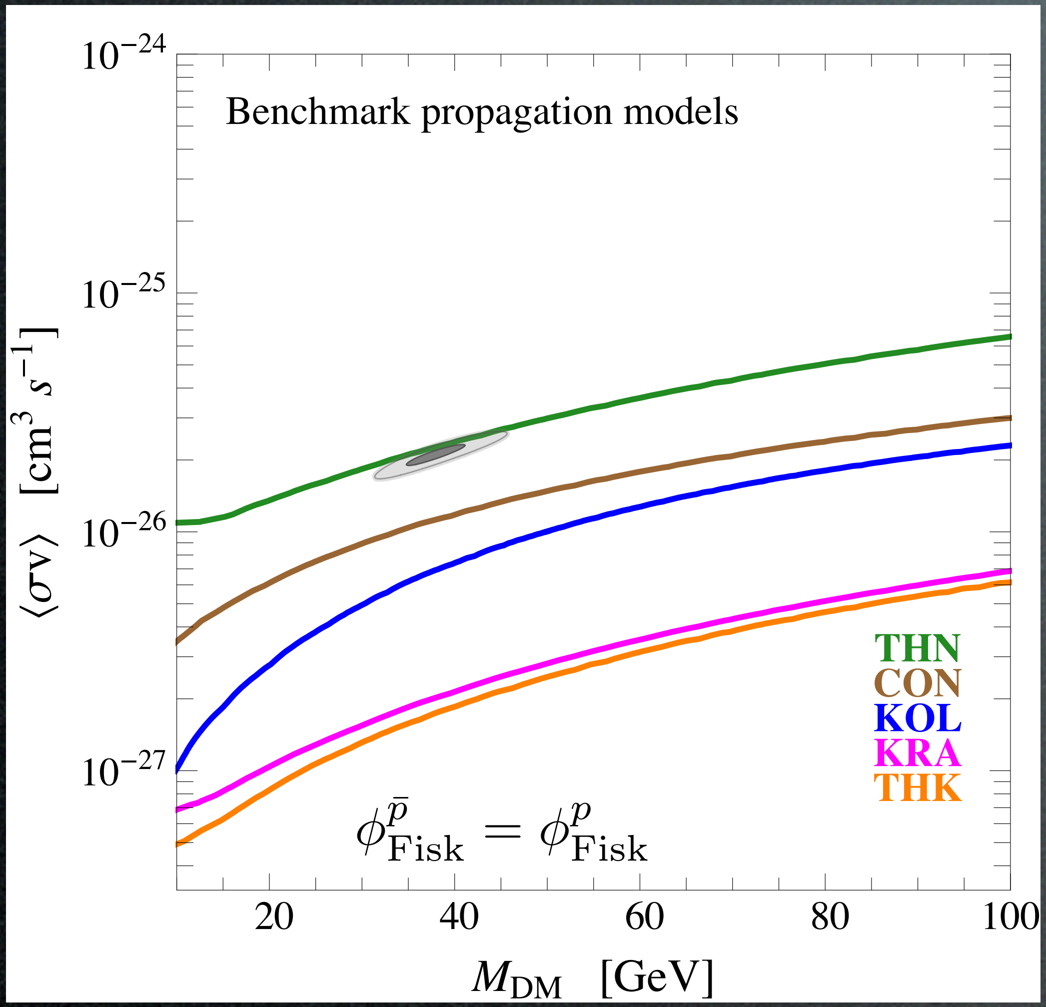
Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But not robust.

GC GeV excess

Antiproton constraints:



Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

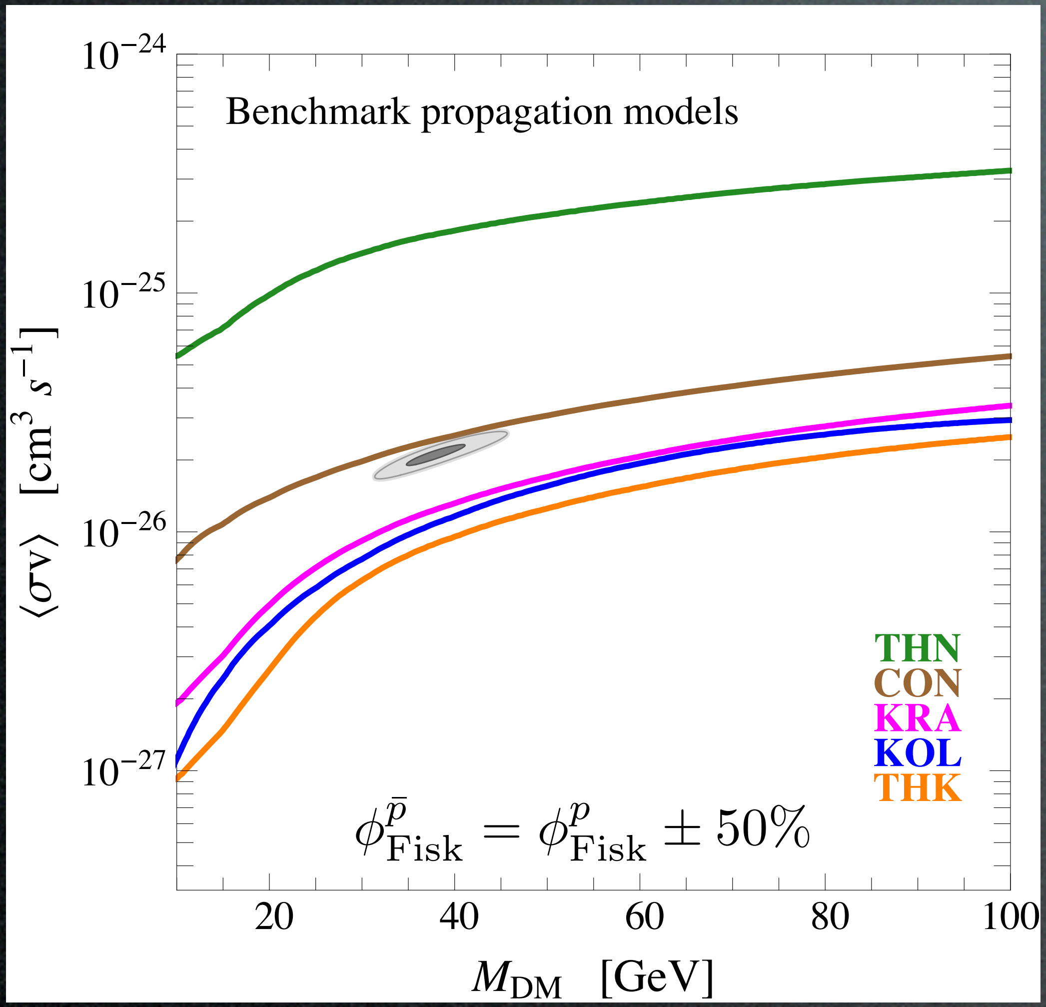
Antiproton constraints may be very relevant! But not robust.

Assumption: fixed solar modulation

Result: hooperon excluded
(except unrealistic THN)

GC GeV excess

Antiproton constraints:



Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But not robust.

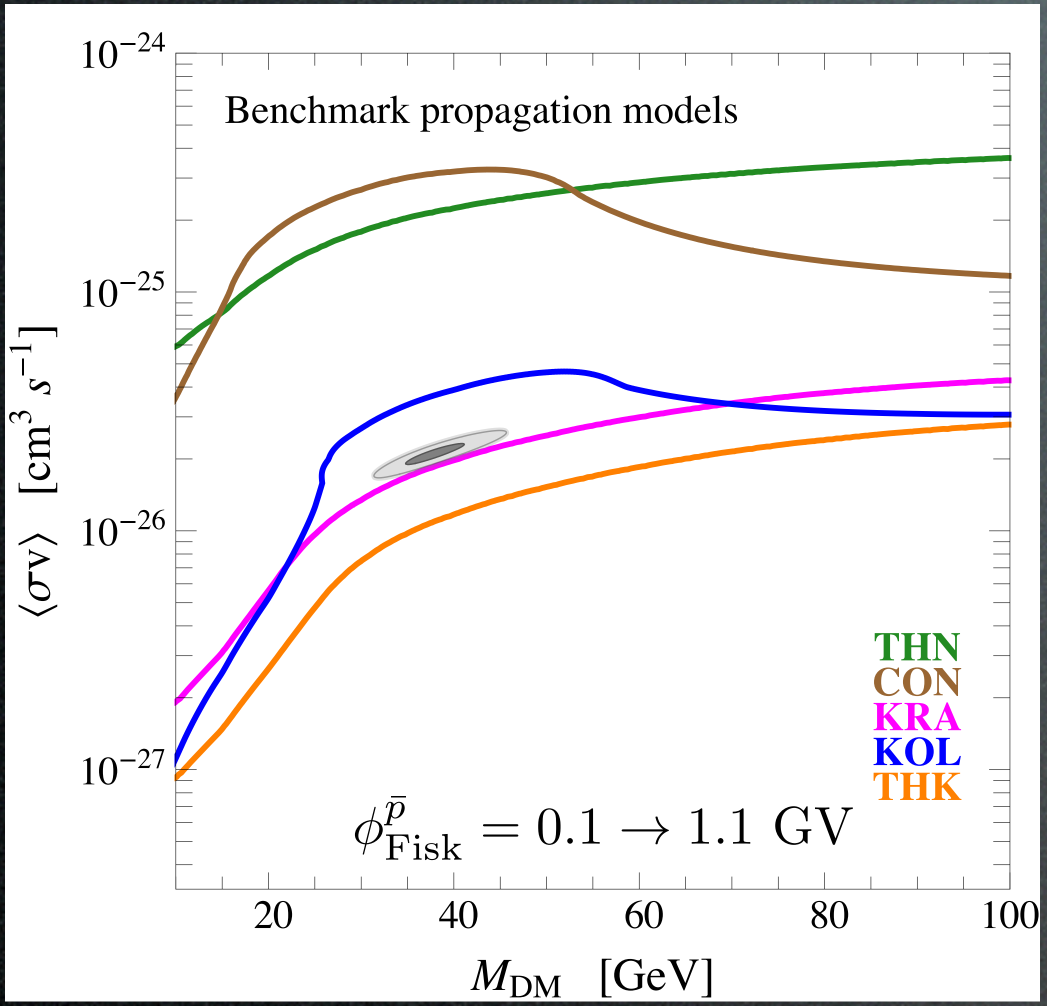
Assumption: flexible solar modulation

Result: hooperon may be excluded or not

GC GeV excess

Antiproton constraints:

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Fermi-LAT excess

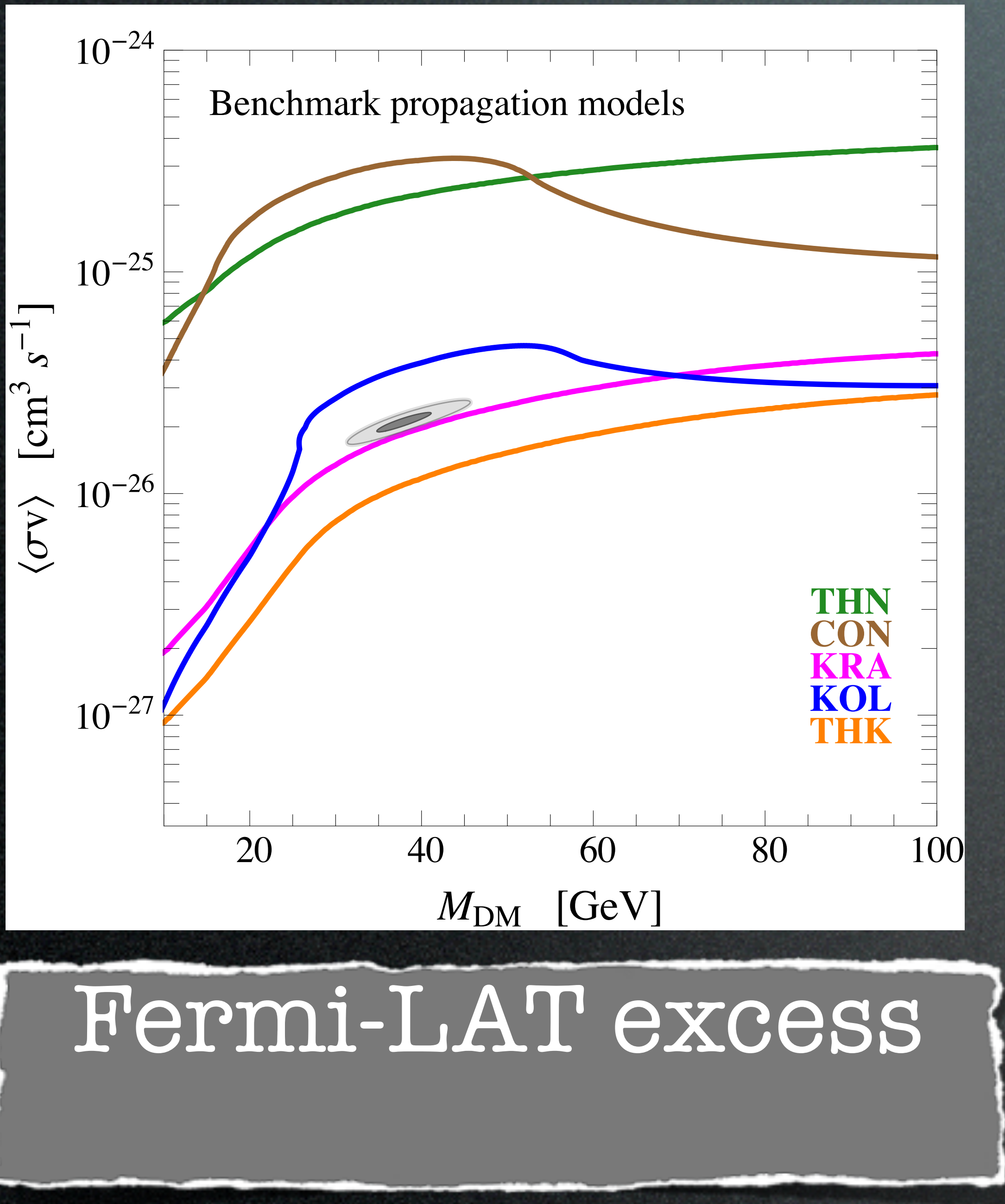
Antiproton constraints may be very relevant! But not robust.

Assumption: conservative solar modulation

Result: hooperon probably reallowed
(except THK models)

GC GeV excess

Antiproton constraints:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But not robust.

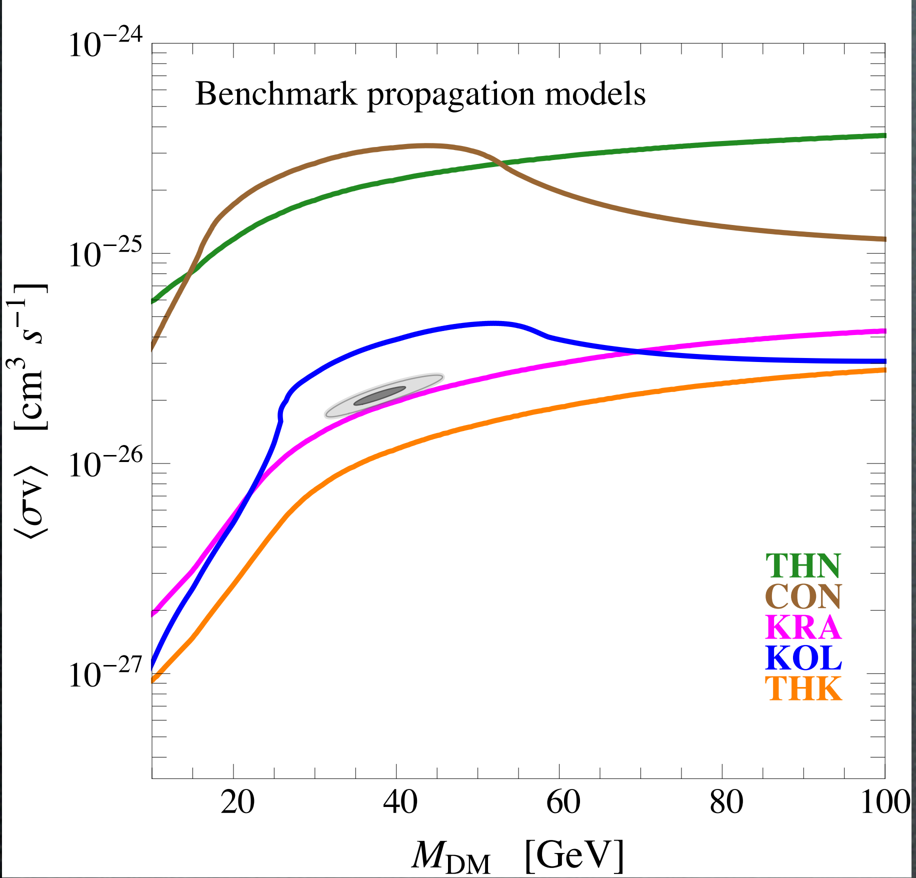
Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

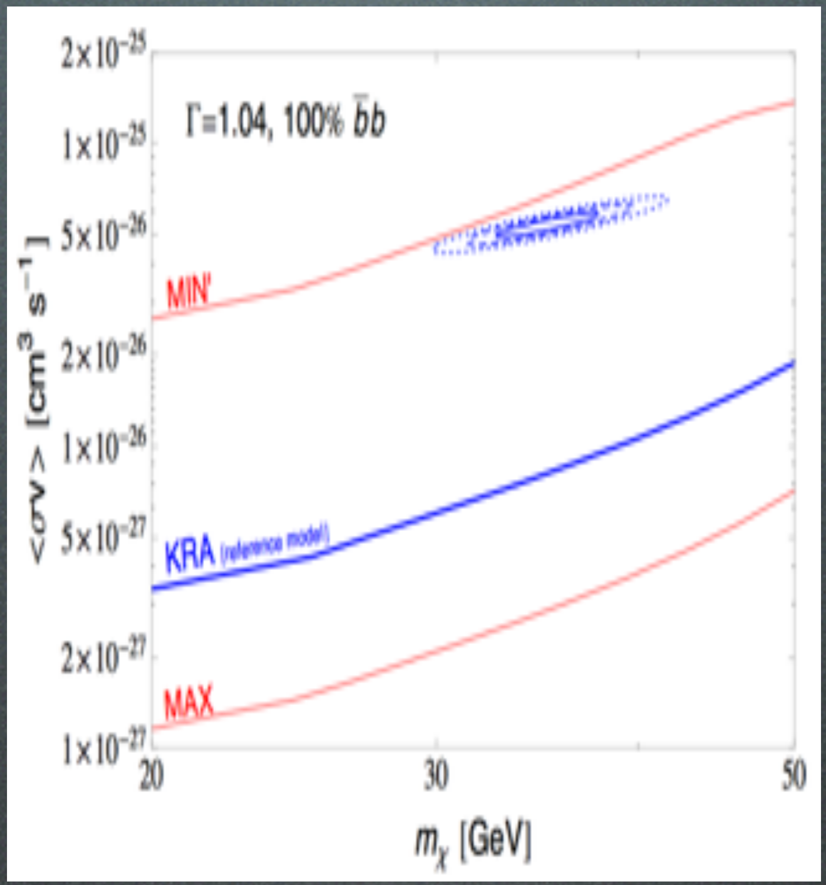
NB Conclusion differs from Bringmann, Vollmann, Weniger 1406.6027 which finds exclusion / strong tension

GC GeV excess

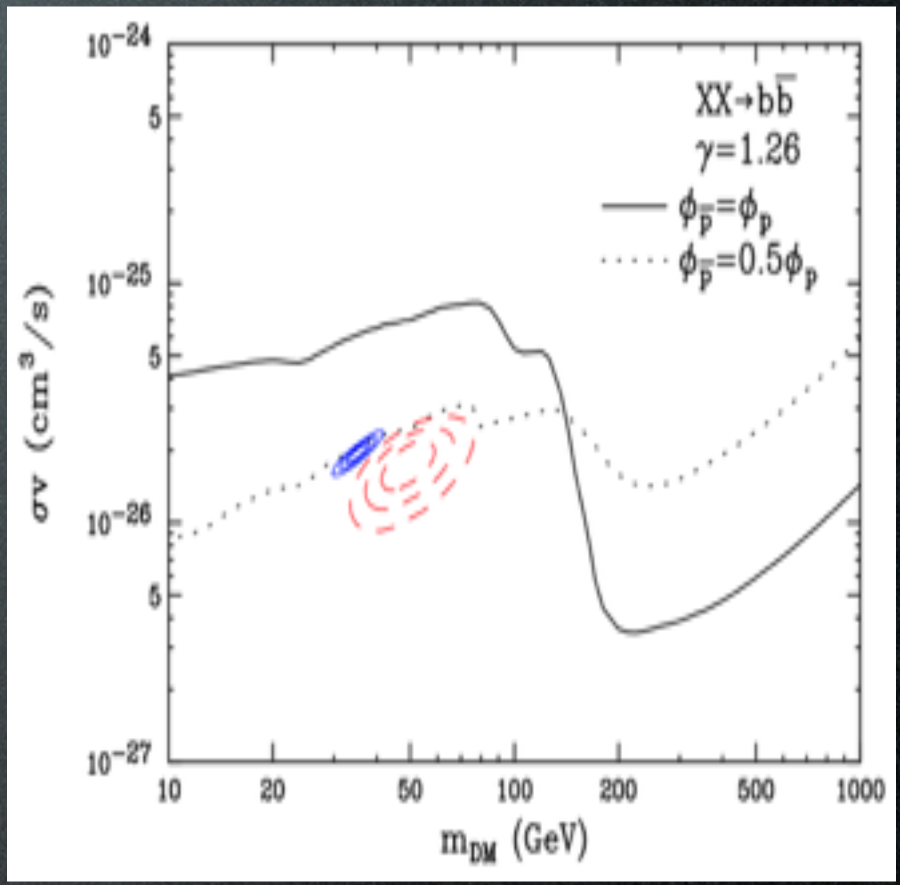
Antiproton constraints compared:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Bringmann, Vollmann, Weniger 1406.6027



Hooper, Linden, Mertsch 1410.1527

May be very relevant!
But not robust.

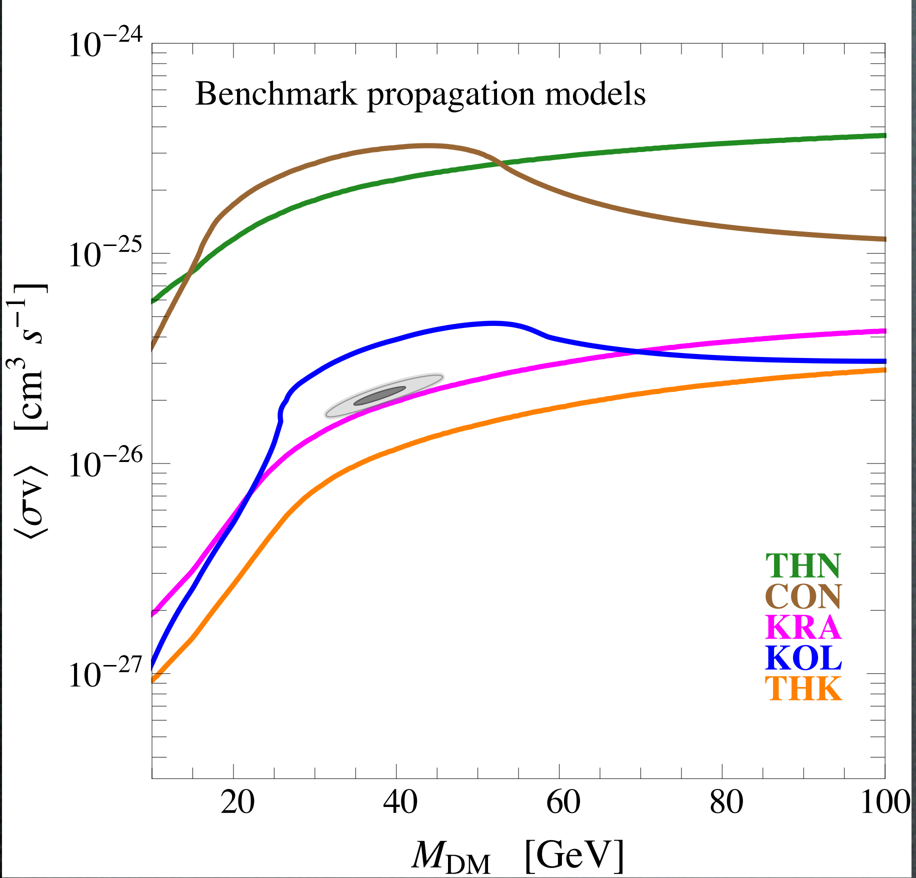
‘Rule out’ or
‘considerable tension’.

‘Significantly less stringent’.

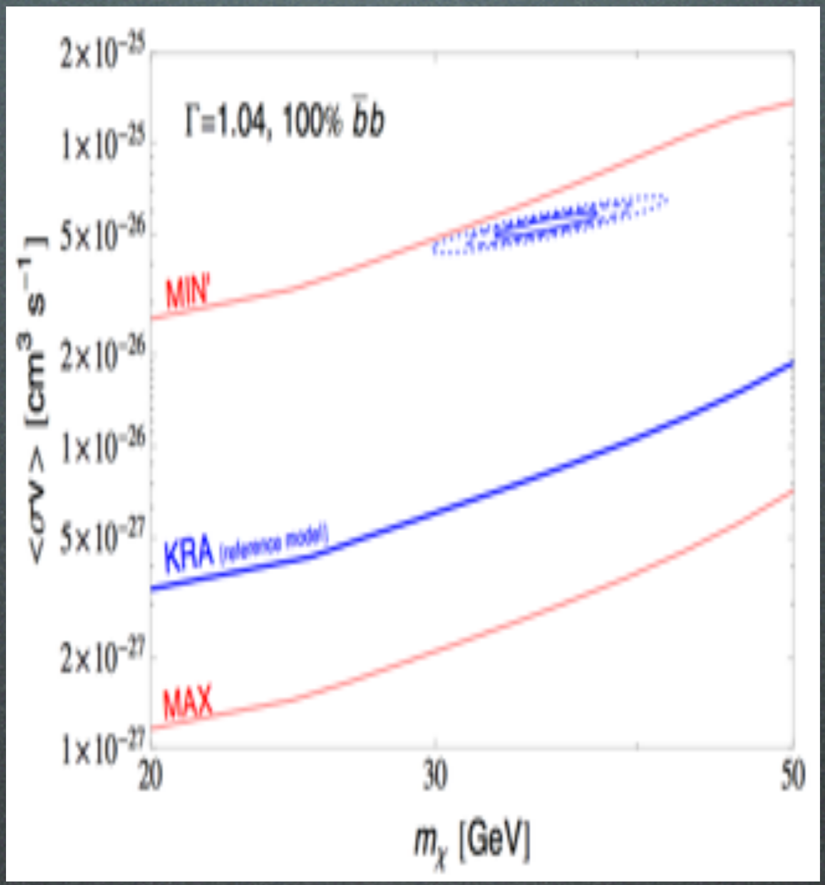
How come?!?

GC GeV excess

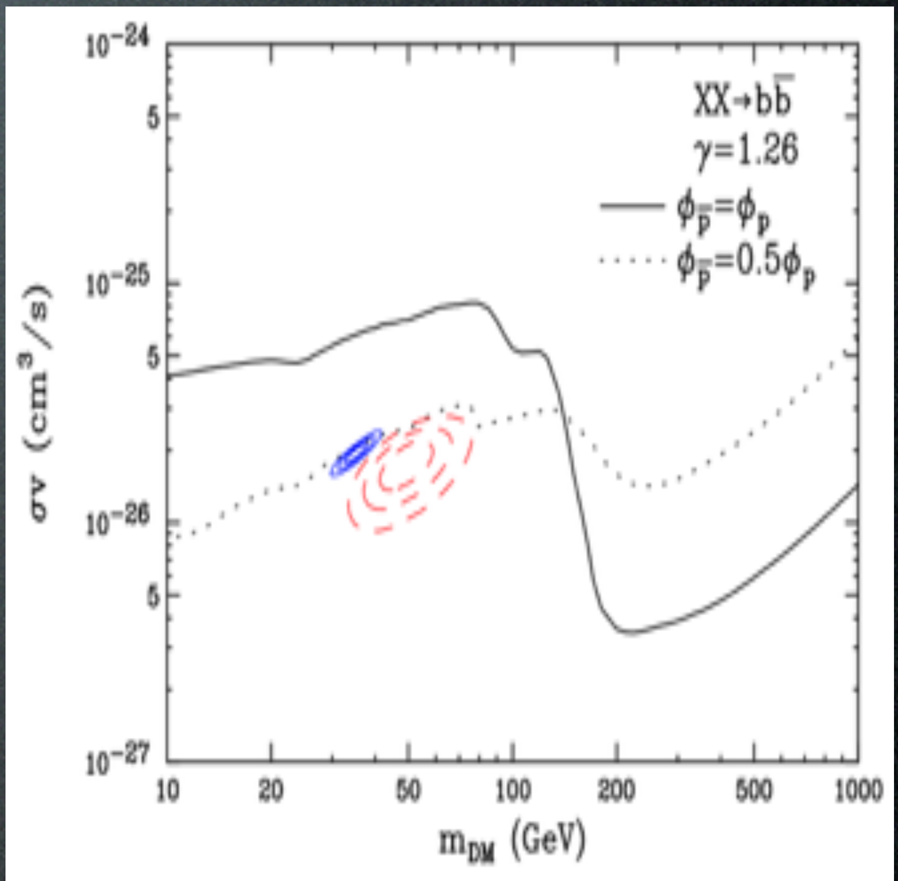
Antiproton constraints compared:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Bringmann, Vollmann, Weniger 1406.6027



Hooper, Linden, Mertsch 1410.1527

May be very relevant!
But not robust.

‘Rule out’ or
‘considerable tension’.

‘Significantly less stringent’.

How come?!? The devil is in the (CR propagation) details:
solar modulation, convection, primary injection spectrum, tertiaries...

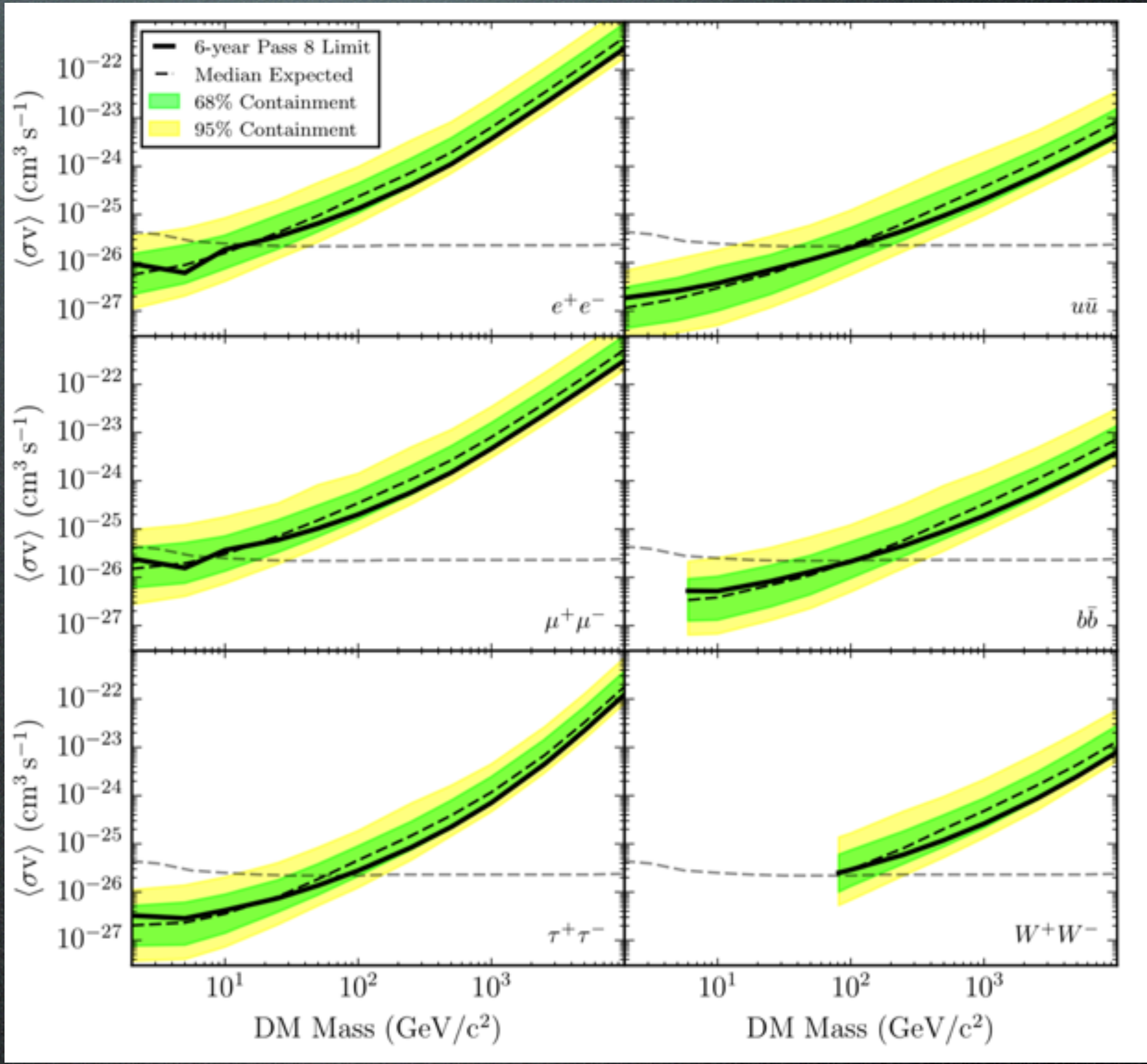
Gamma constraints

γ from DM annihilations in Satellite Galaxies

FERMI

1503.02641 Fermi coll., Ackermann et al.

6 years data, PASS 8



Gamma constraints

γ from DM annihilations in Satellite Galaxies

FERMI

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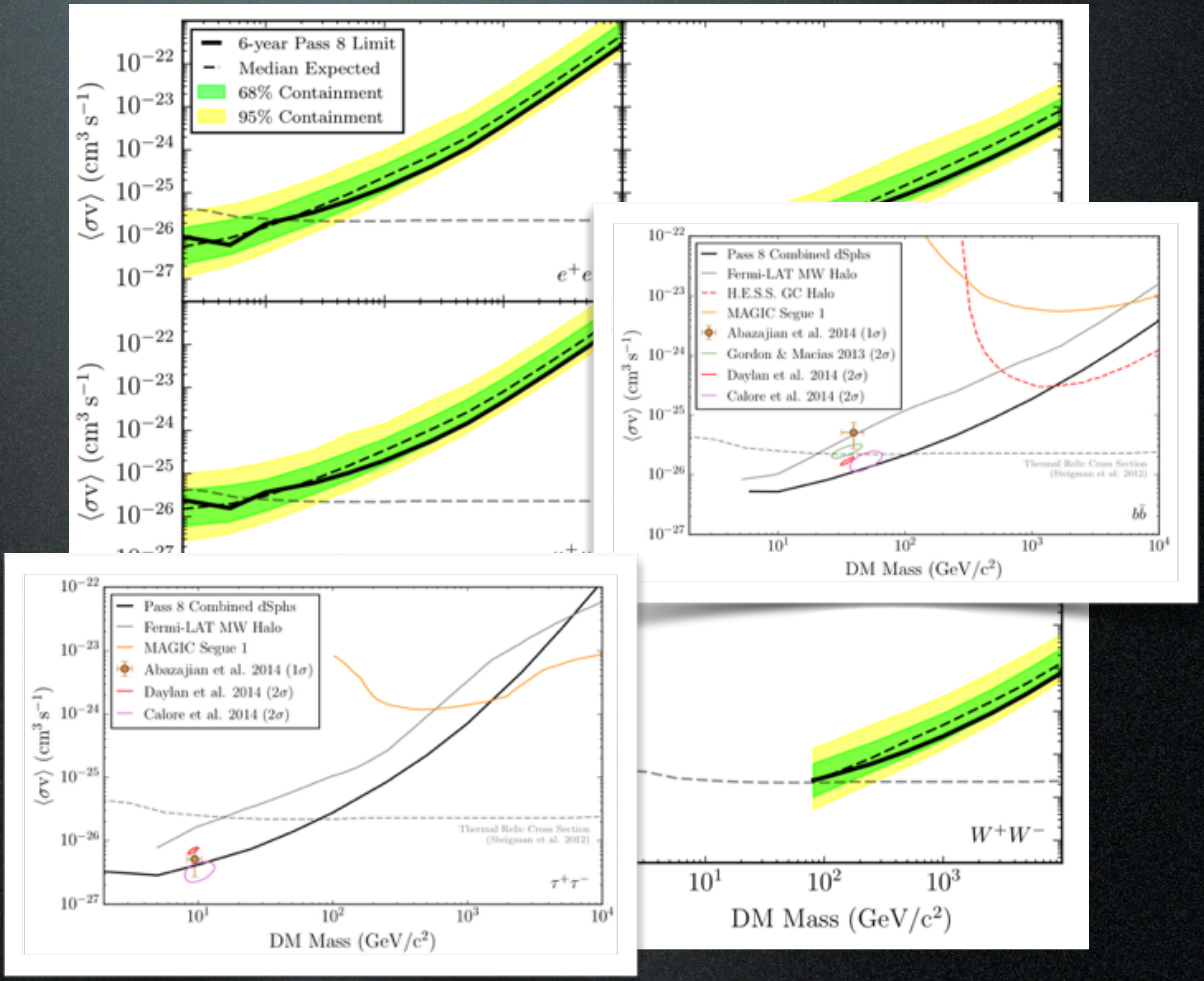

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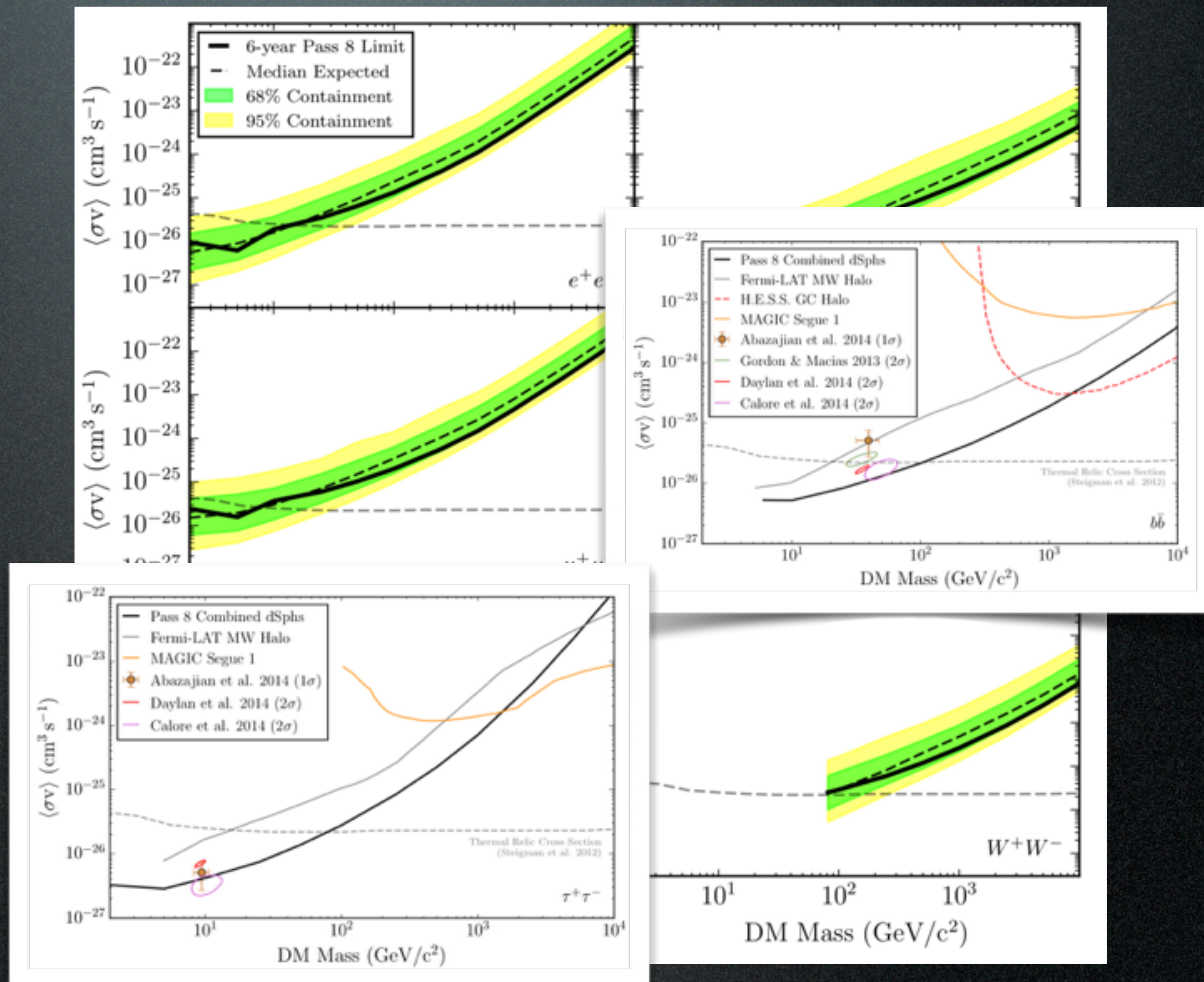

Note: Geringer-Sameth 1503.02320 claims an excess in Reticulum 2 (newly discovered dwarf), but FERMI coll. 1503.02632, using PASS 8, say it's only 1.5 σ

Conclusions & Outlook

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HESS

γ FERMI

X XMM-Newton

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- new theory directions

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is a typical example

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Old wise remarks:

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The GC GeV excess (a.k.a. hooperon) is a typical example

Old wise remarks:

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