3 March 2015
Neutrino Telescopes 2015 - Venezia

Dark Matter Indirect Detection

amid hints & constraints

Marco Cirelli
(CNRS IPhT Saclay)

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Introduction

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DM exists

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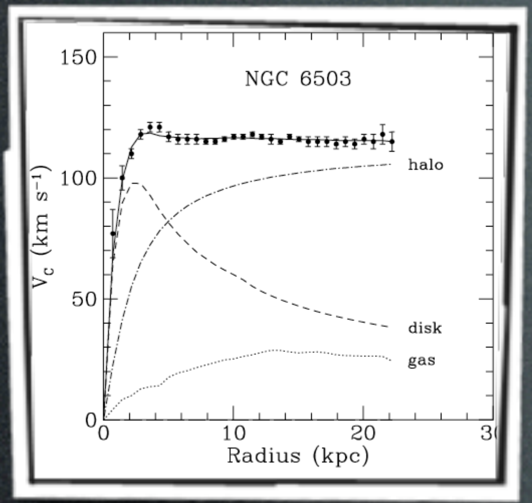
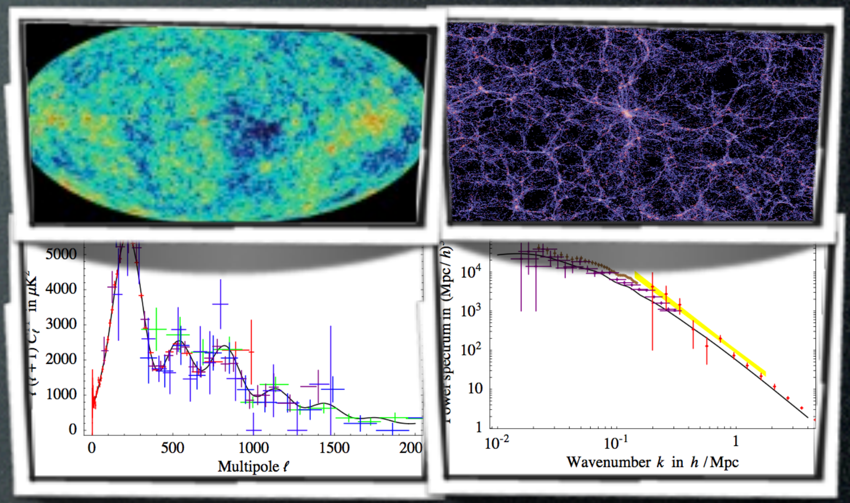


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Introduction

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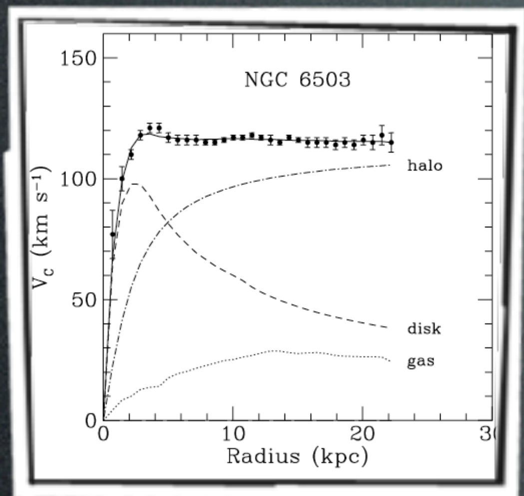

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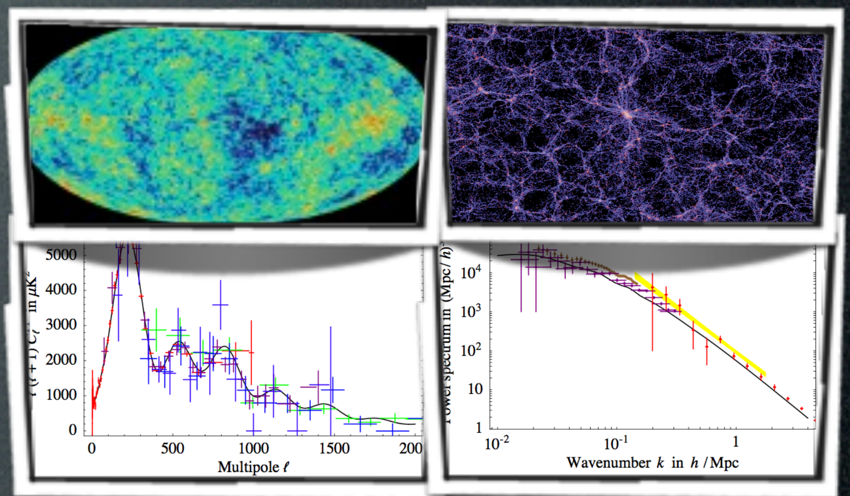

'precision cosmology' (CMB, LSS)

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

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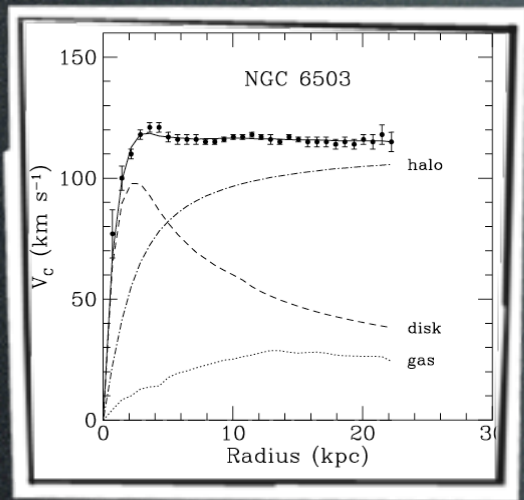

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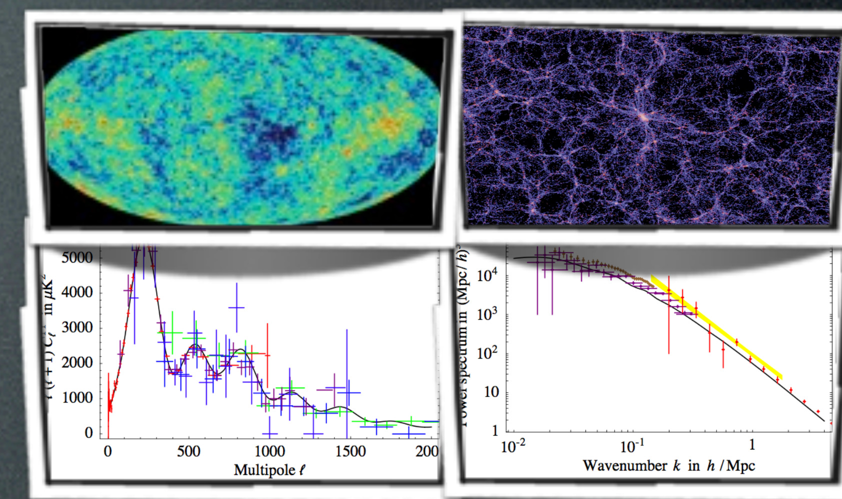
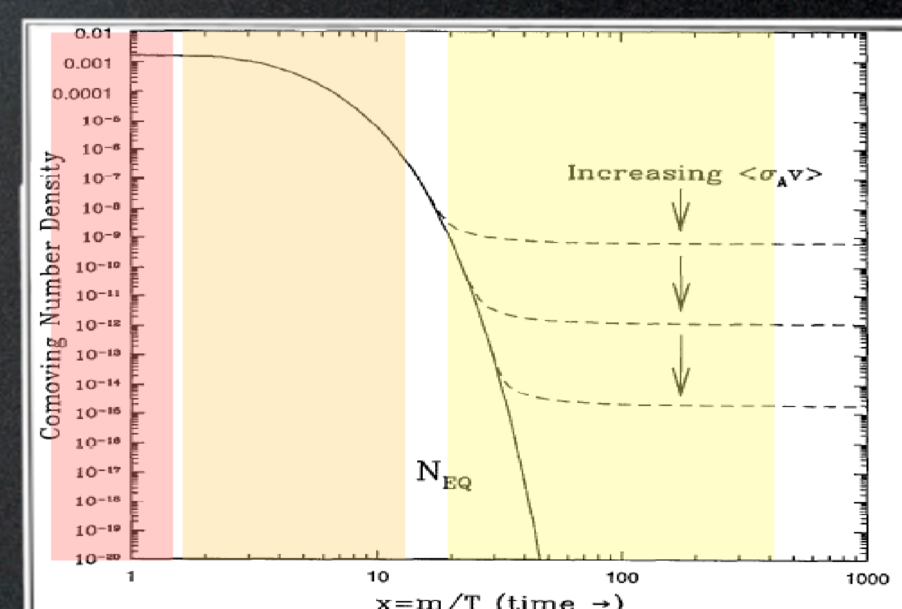


'precision cosmology' (CMB, LSS)

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

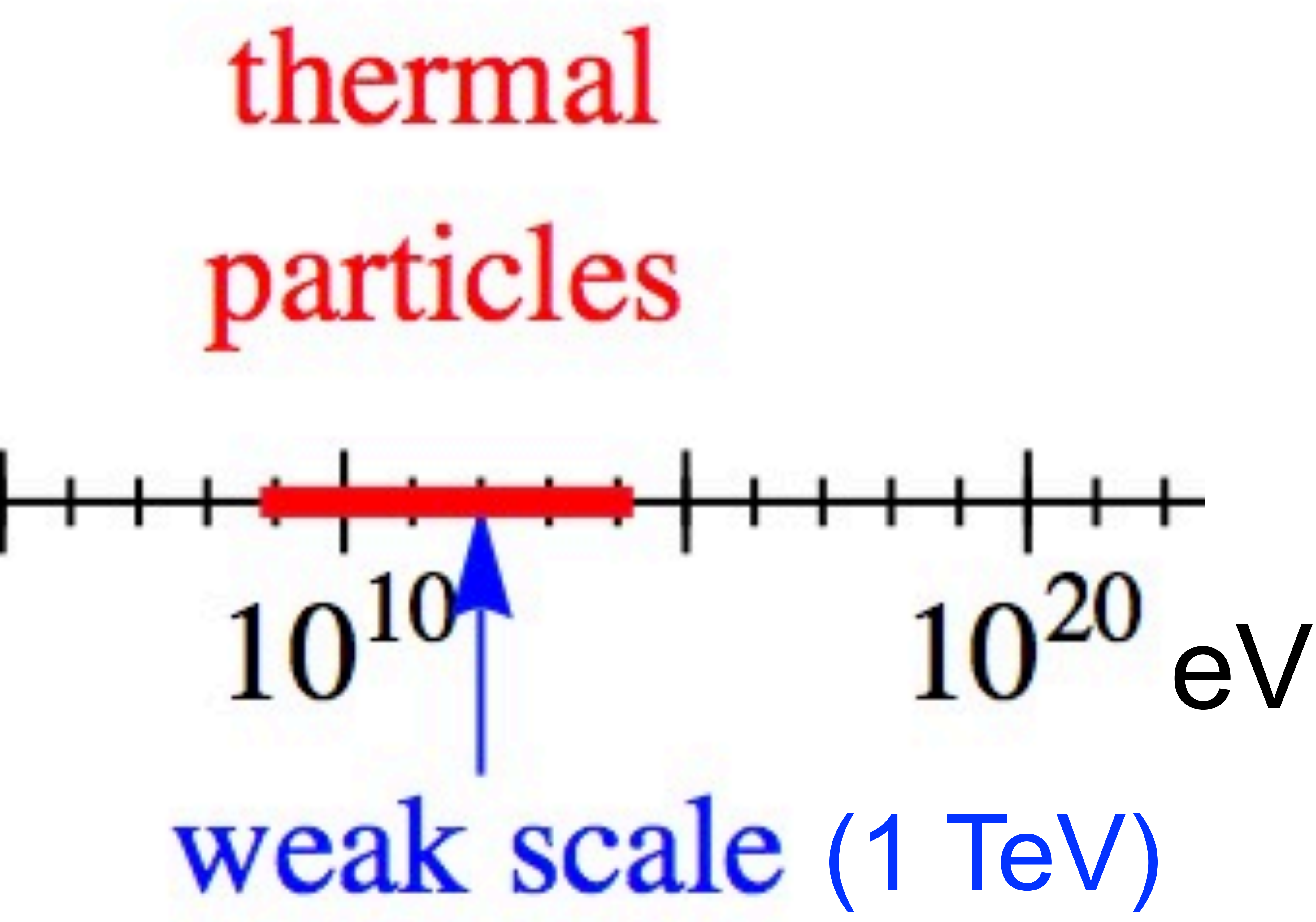
Some of us believe in the WIMP miracle.

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



DM Candidates

A matter of perspective: plausible mass ranges



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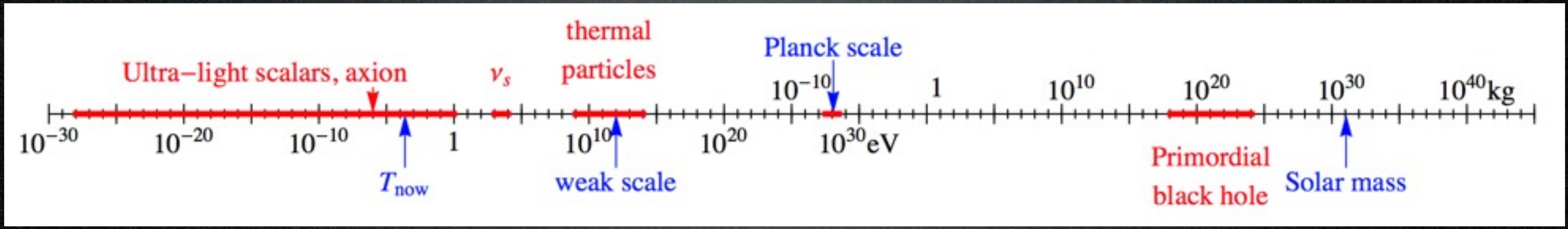


'only' 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges

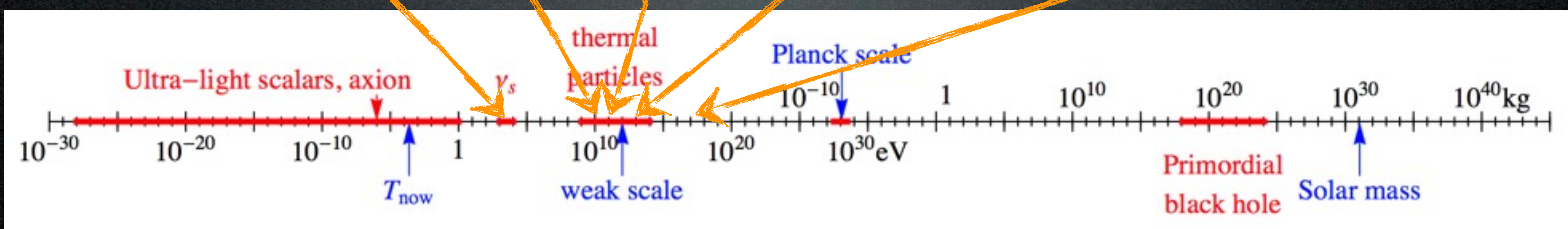
3.5 KeV line

GeV gamma excess at GC

Fermi 135 GeV line

PAMELA, Fermi, HESS excesses

PeV neutrinos Icecube



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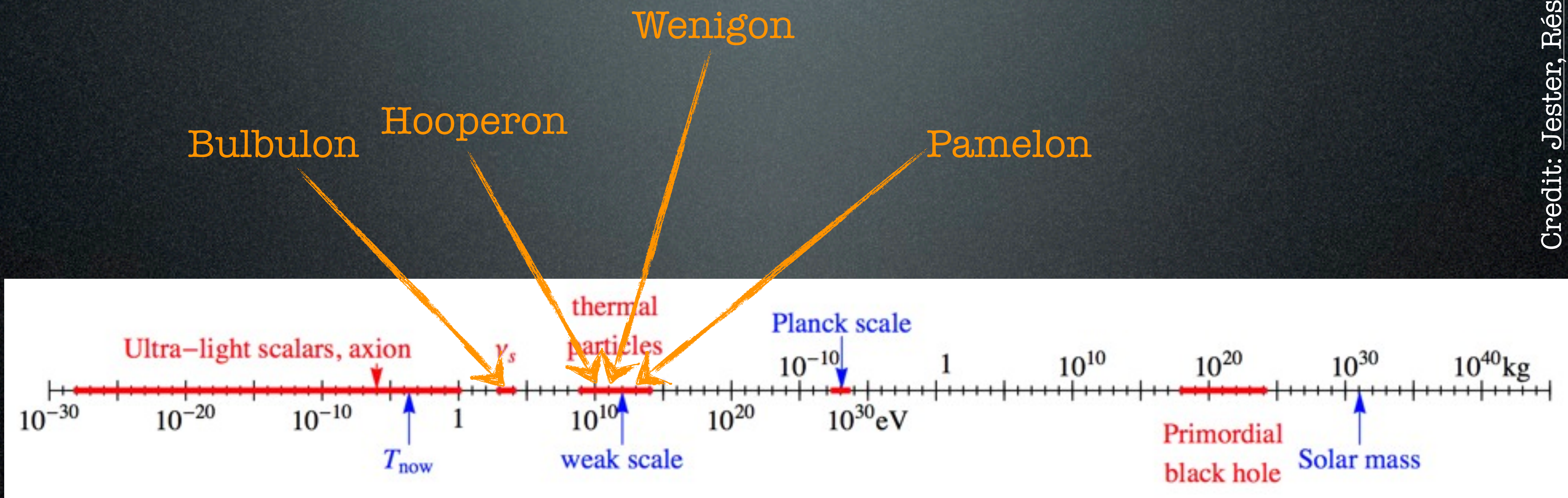

Credit: Jester, Résonaances

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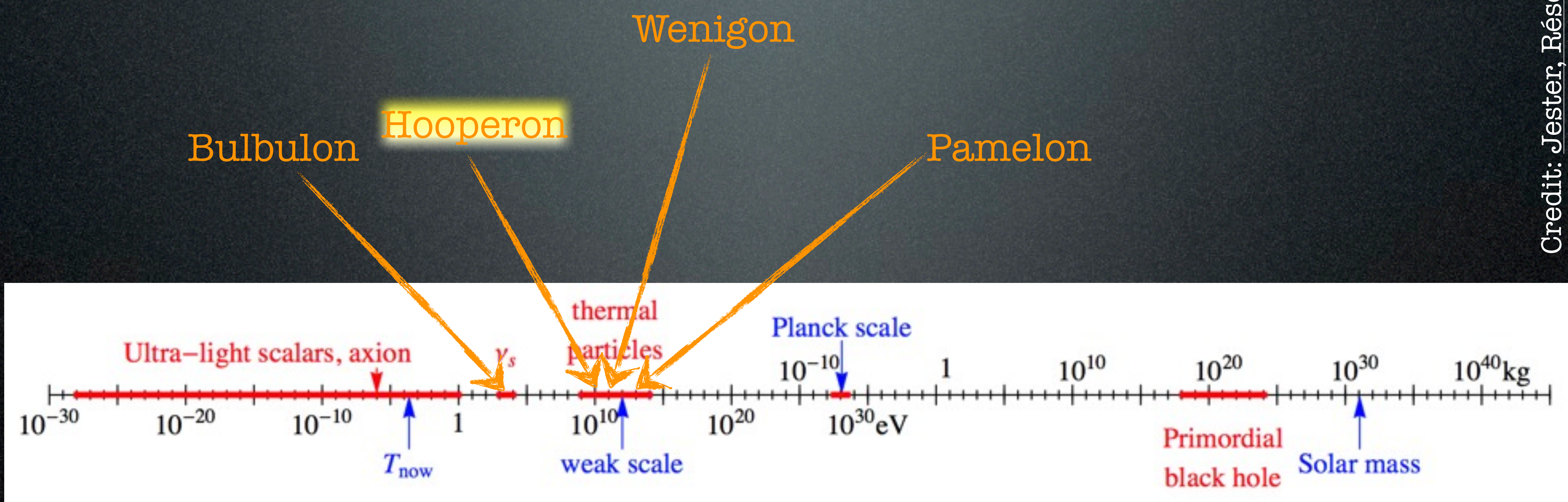

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‘only’ 90 orders of magnitude!

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

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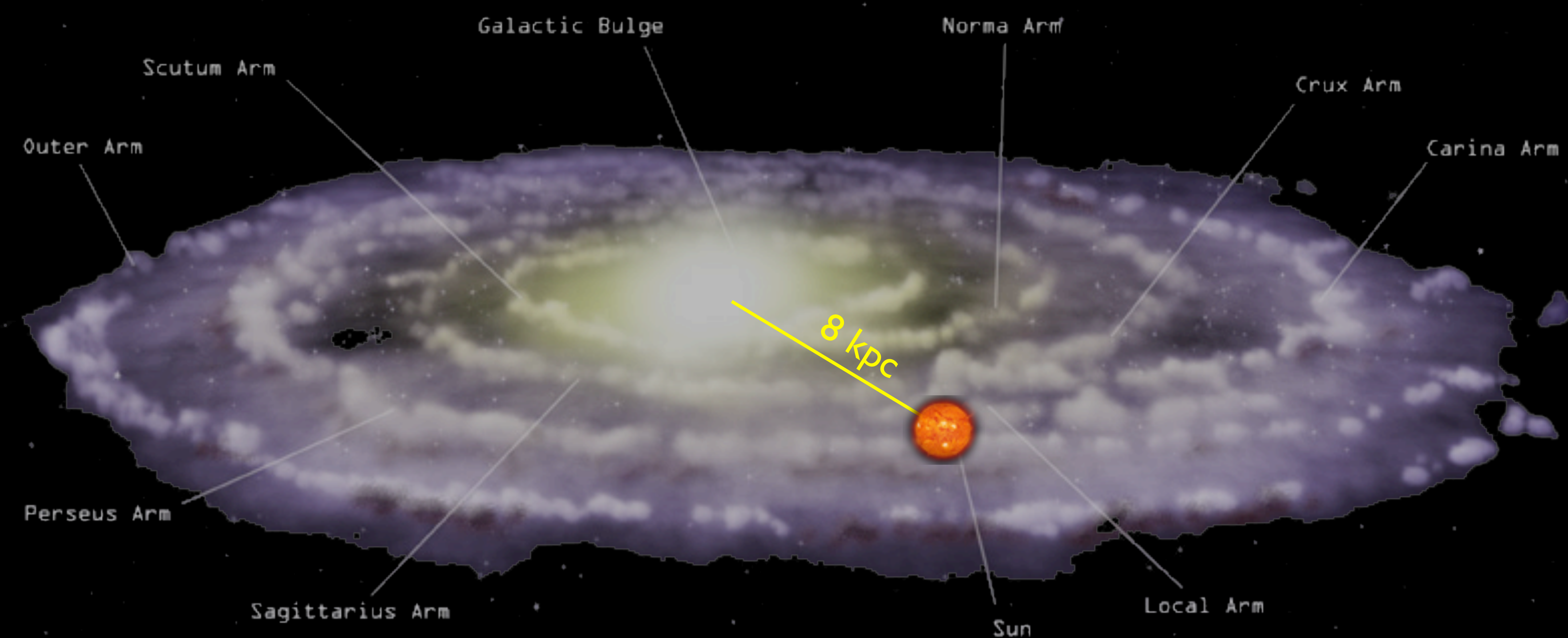
Indirect Detection: charged CRs

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



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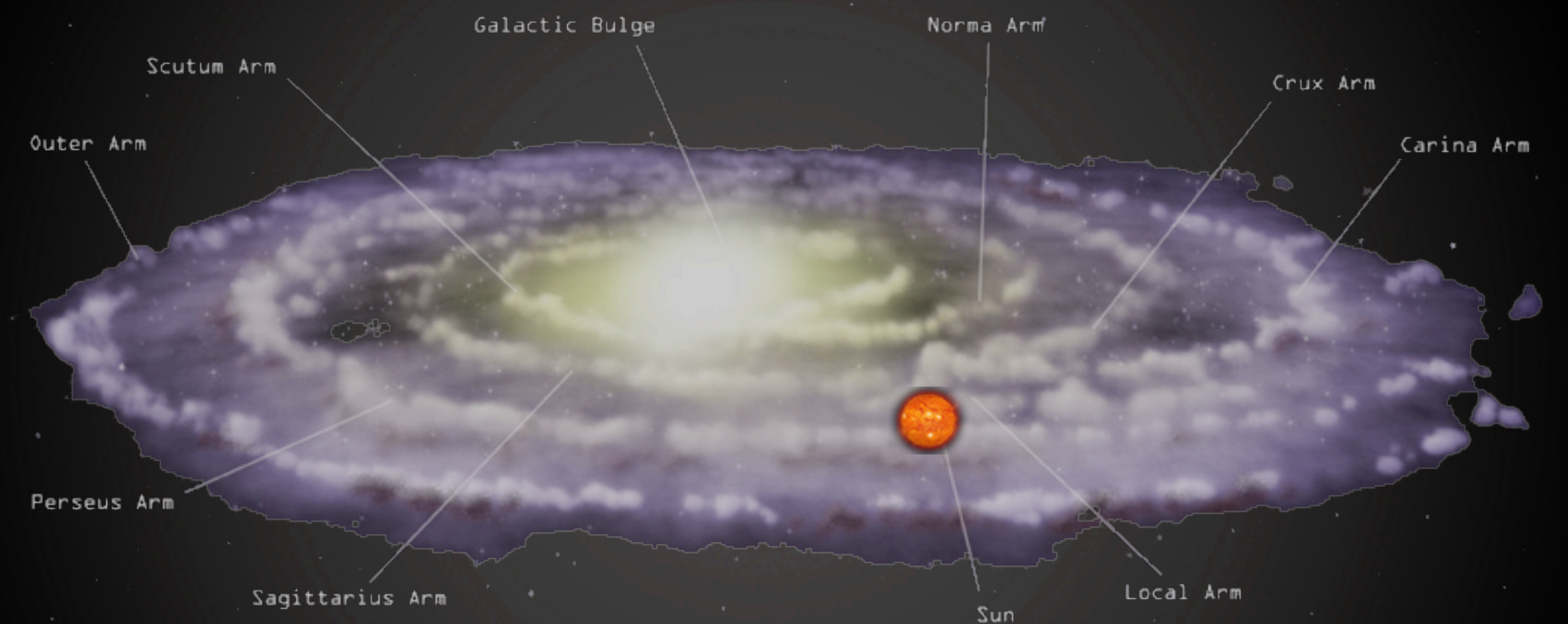

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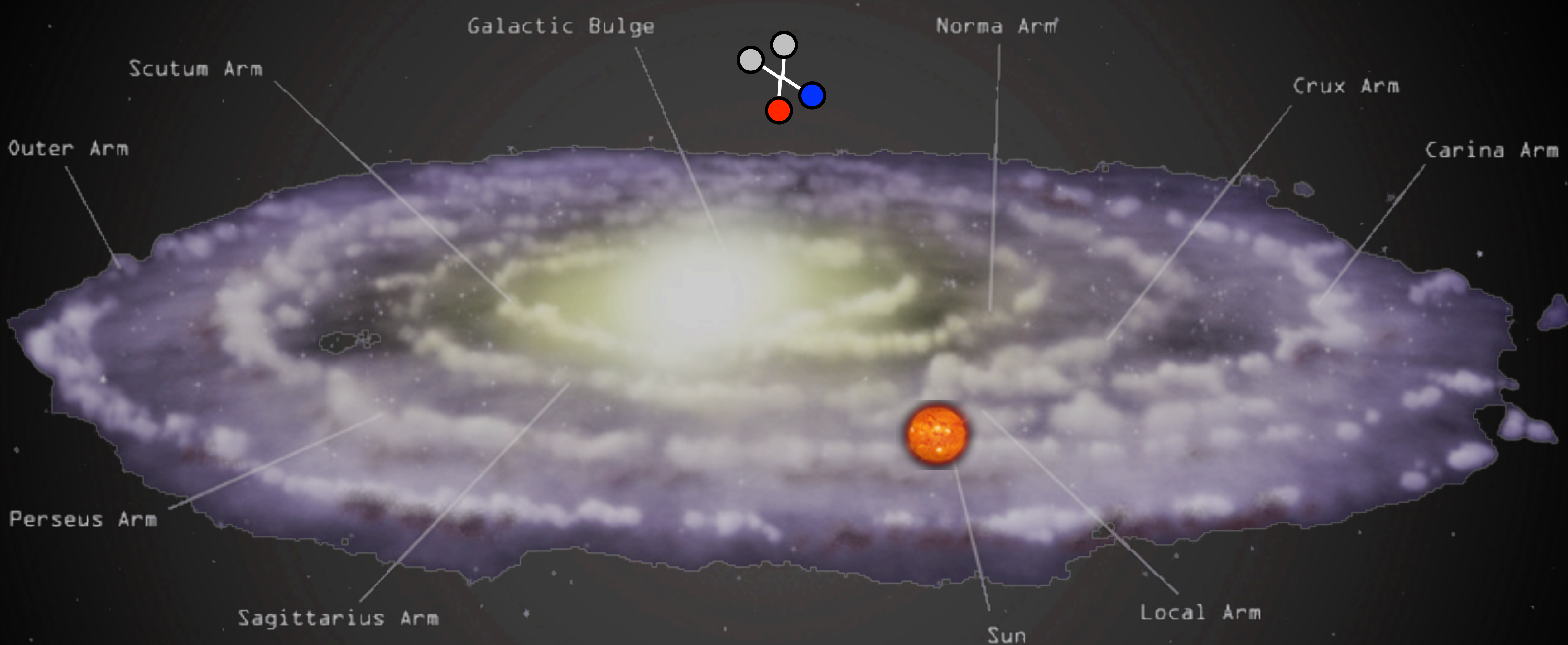

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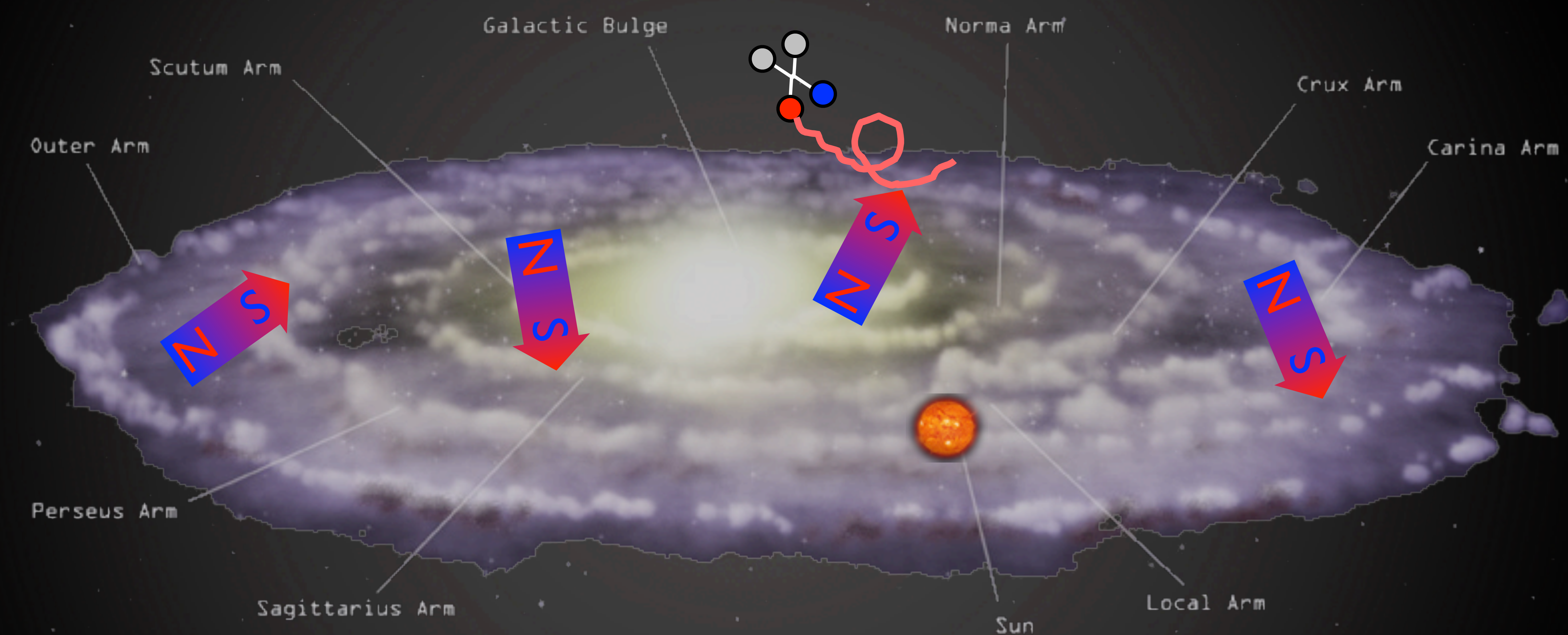

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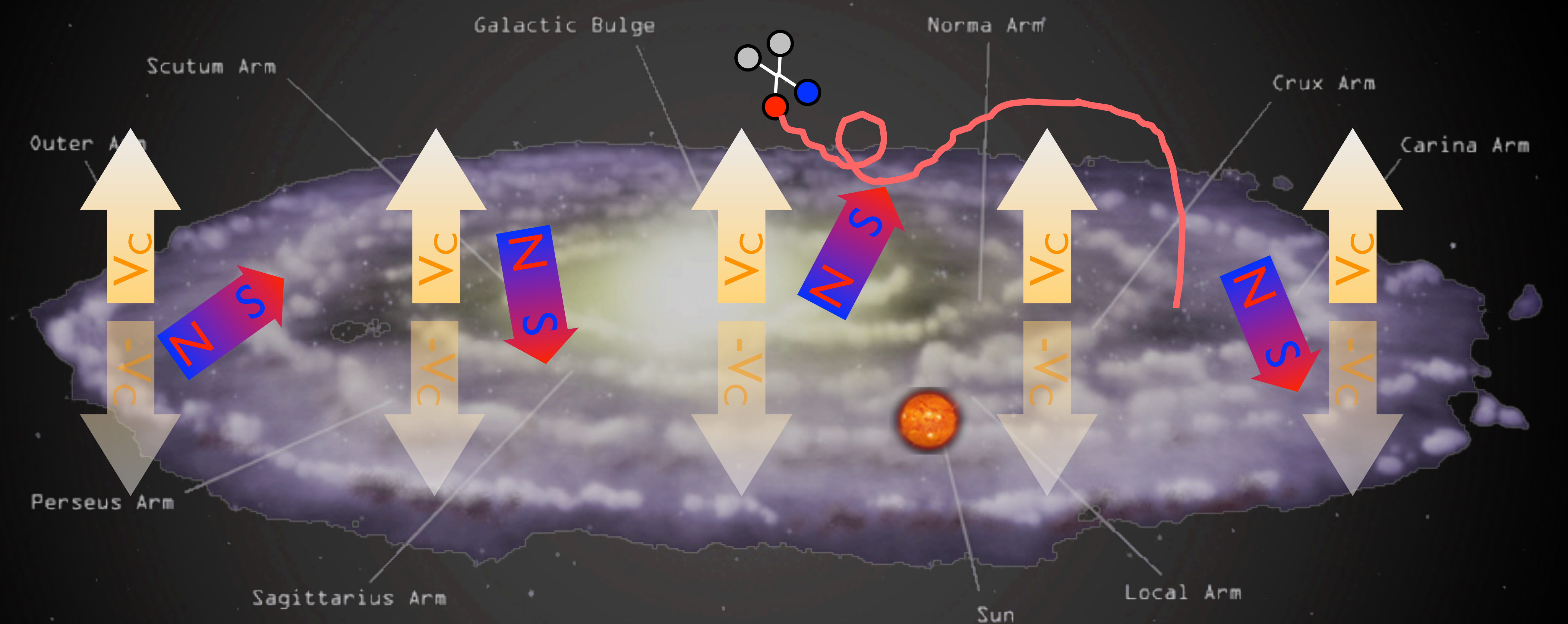

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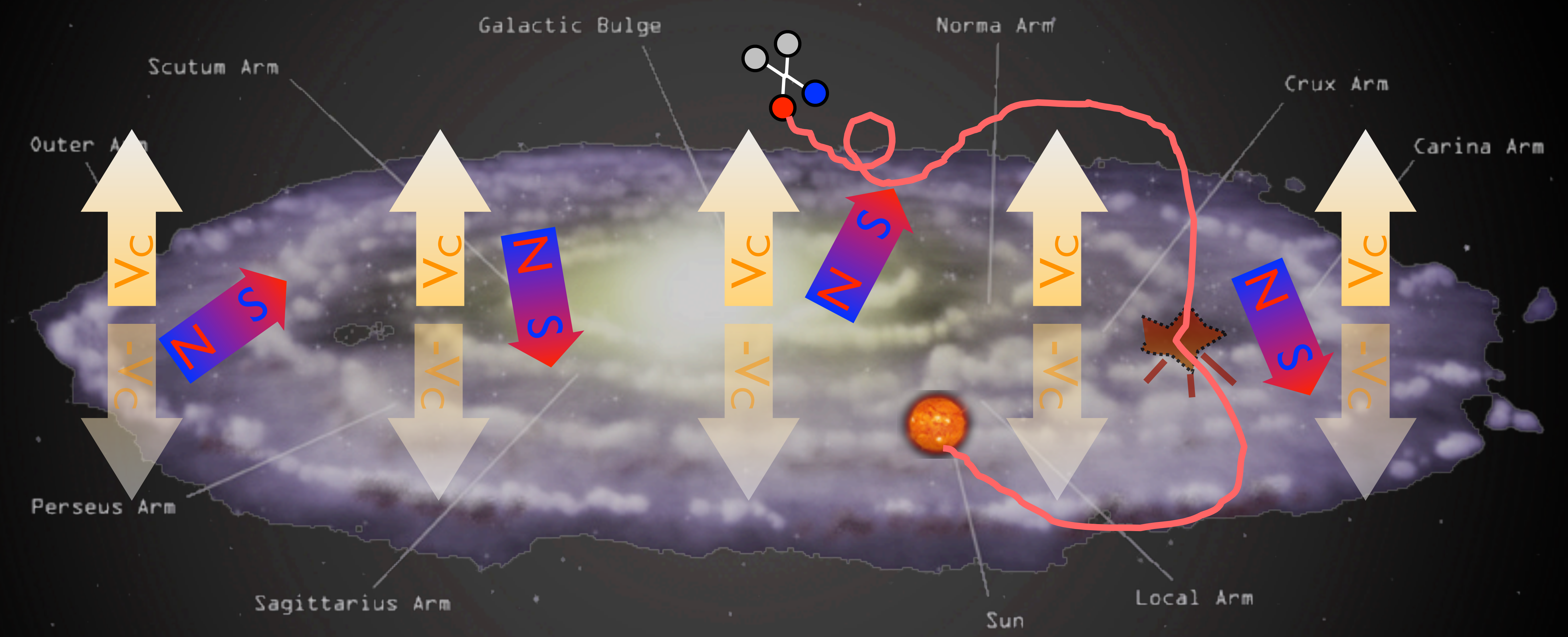

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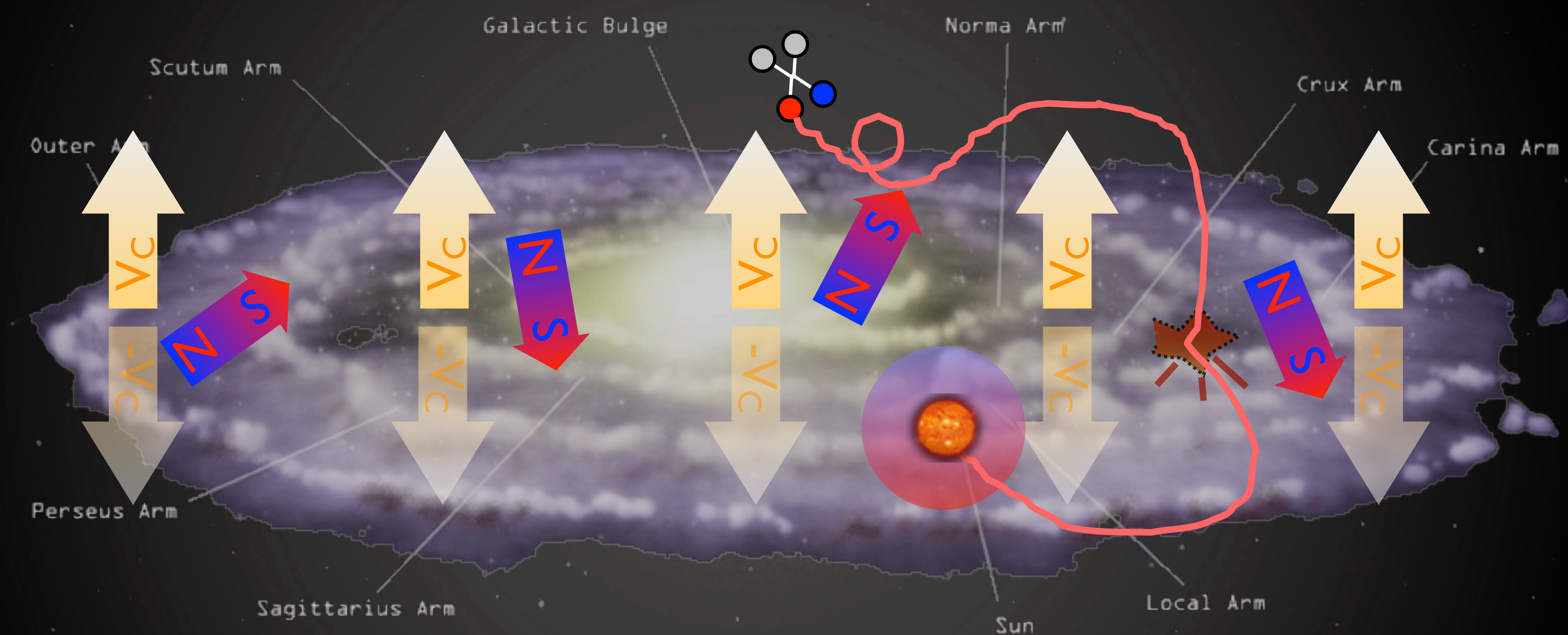

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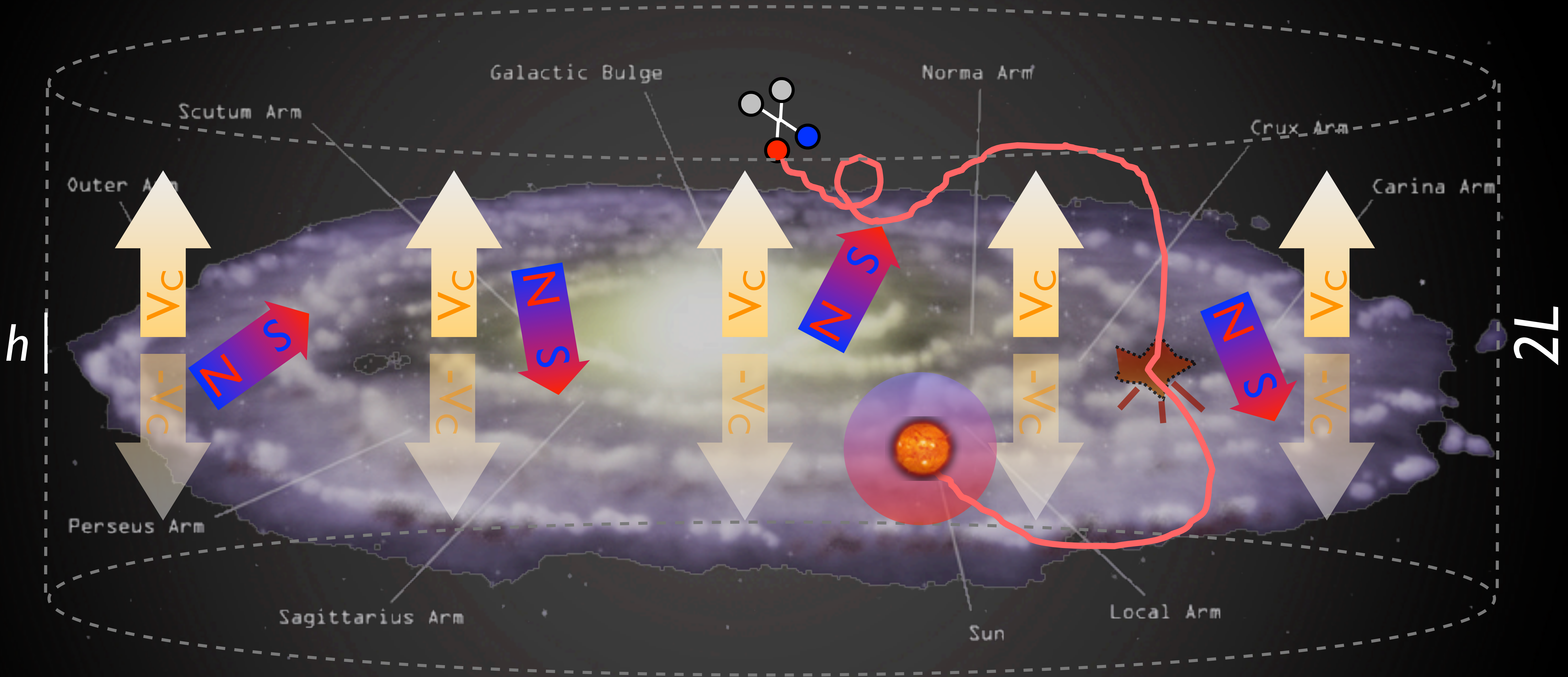


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

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: 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 $[10^{28}\ \mathrm{cm}^2\,\mathrm{s}^{-1}]$	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 $[\mathrm{km\,s^{-1}}]$	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 $[\mathrm{km\,s^{-1}\,kpc^{-1}}]$	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

	Electrons or positrons		Antiprotons (and antideuterons)			
Model	δ	$\mathcal{K}_0$ [kpc^2/Myr]	δ	$\mathcal{K}_0$ [kpc^2/Myr]	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+

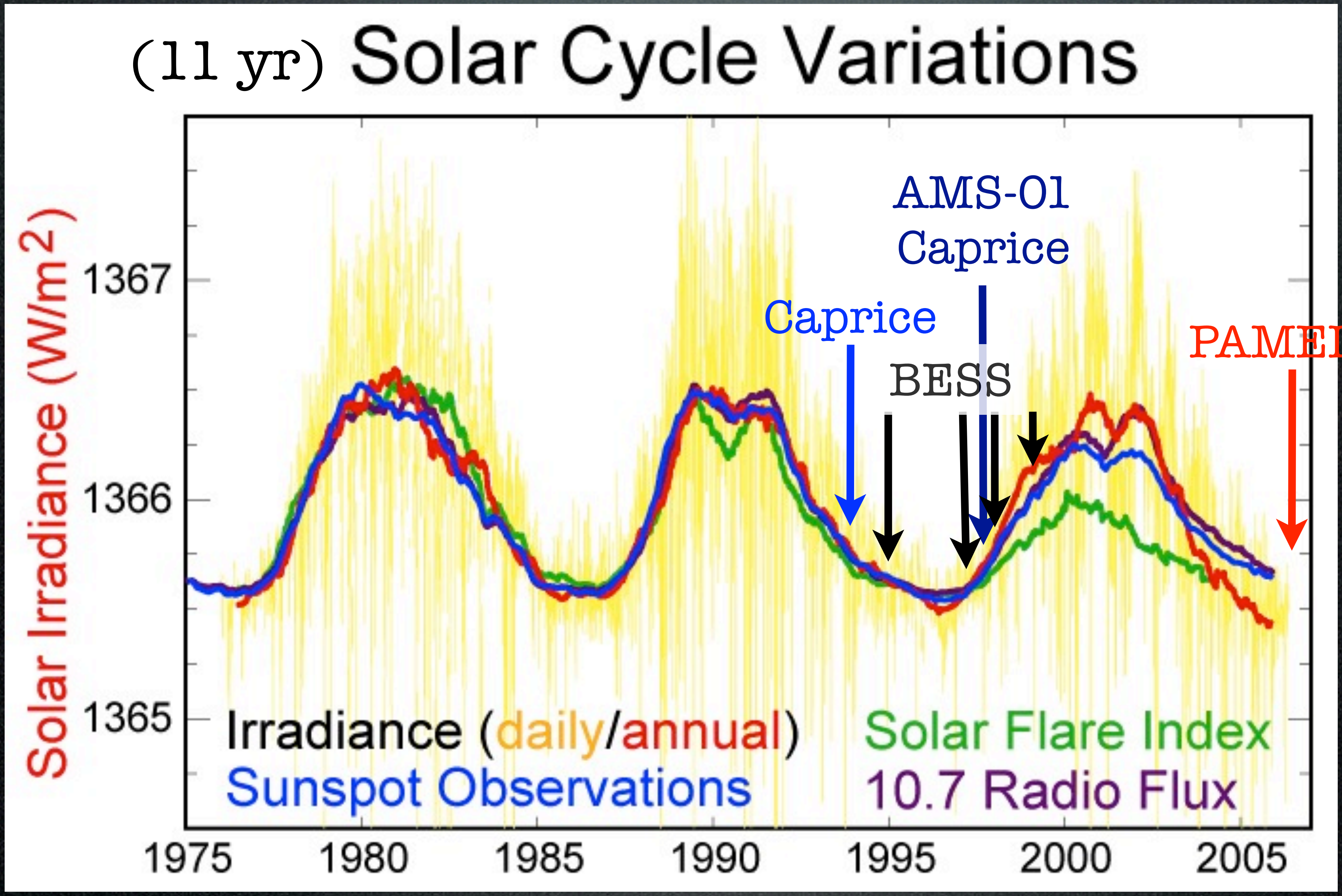
Indirect Detection: charged CRs

Solar 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

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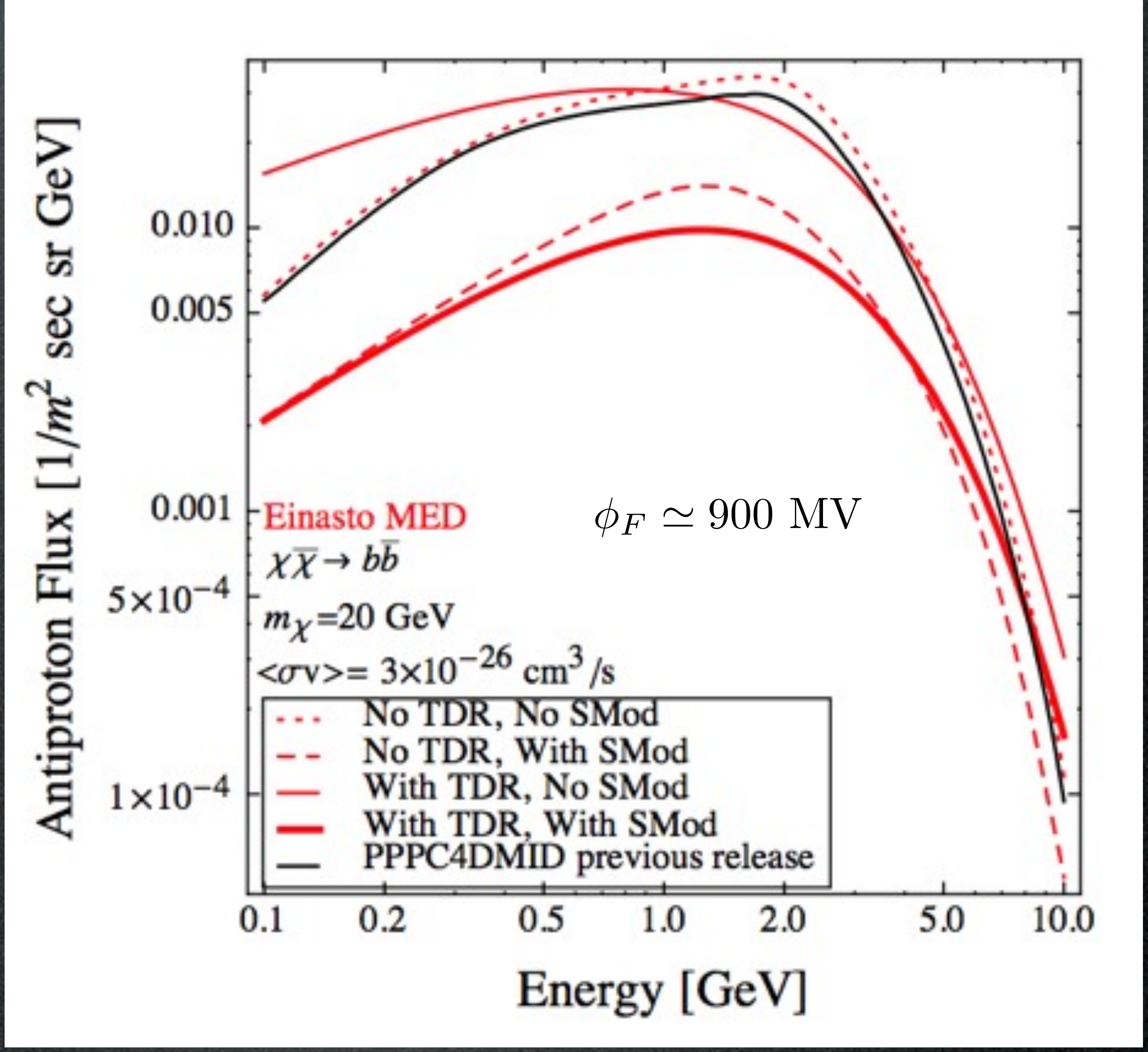
E.g.



Boudard, Cirelli, Giesen, Salati, 1412.5696

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

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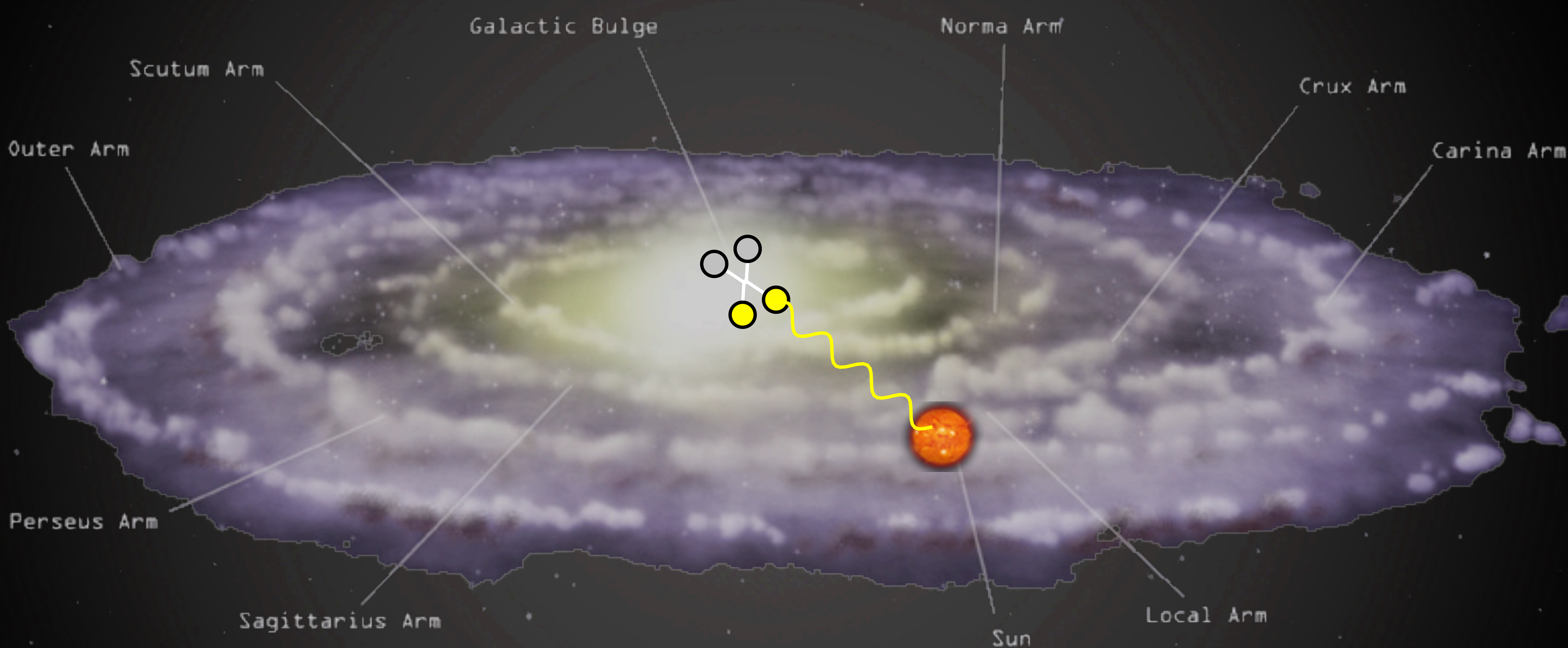
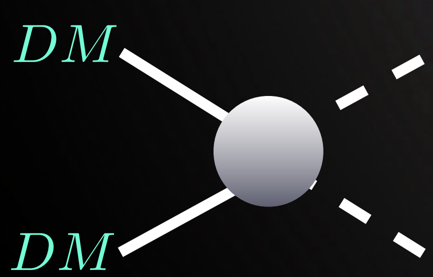
Indirect Detection: gammas

γ from DM annihilations in galactic center



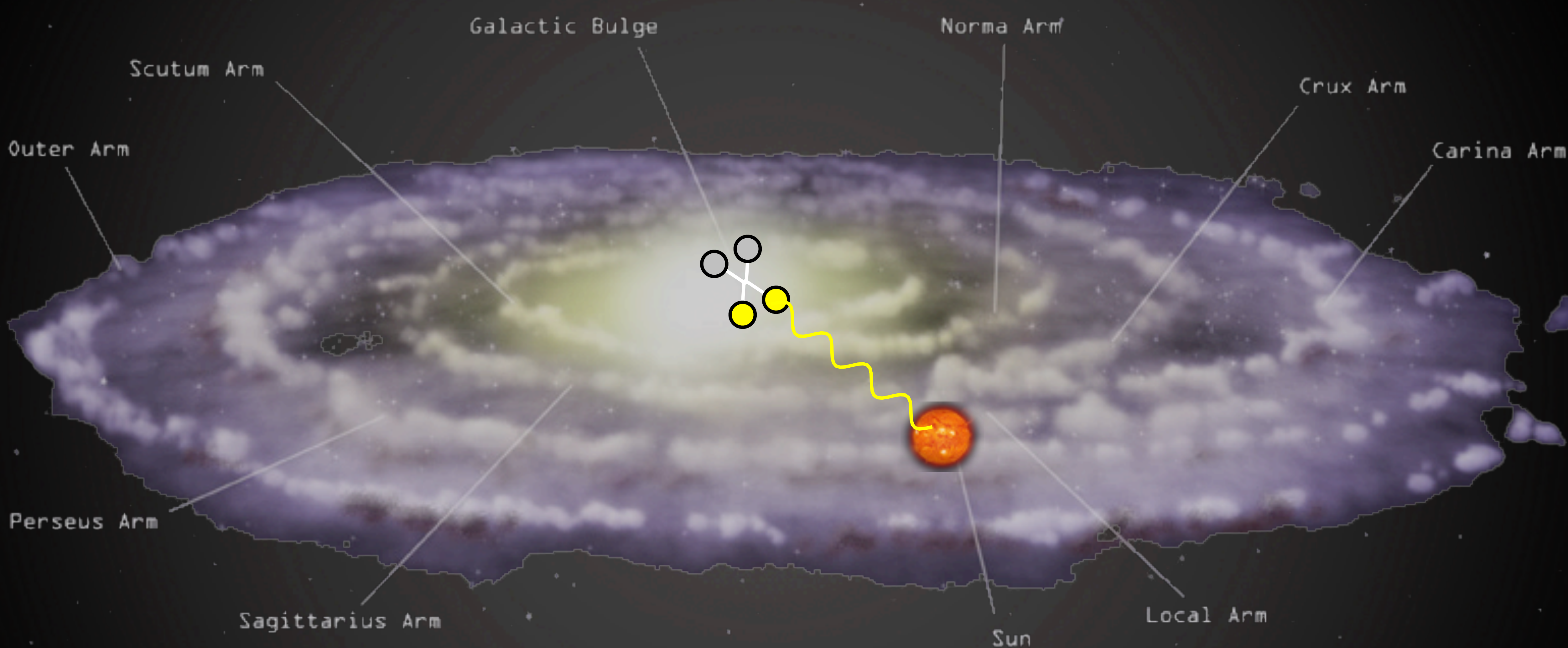


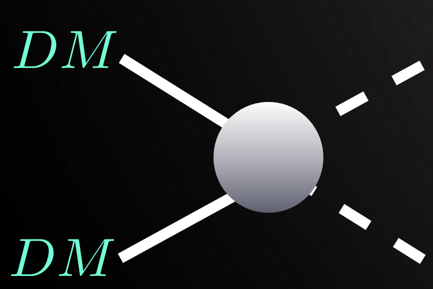
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

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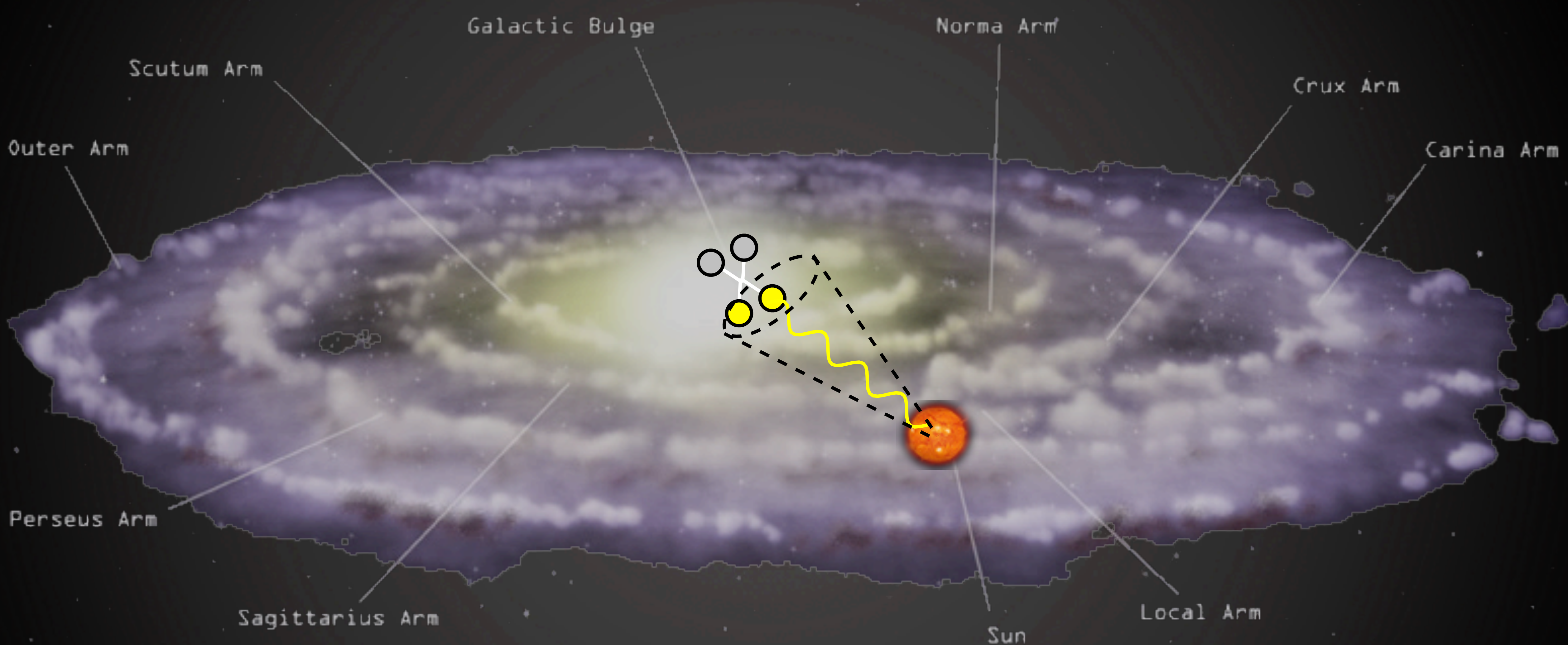

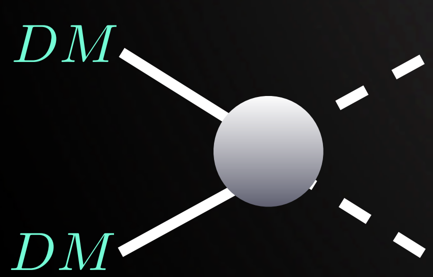

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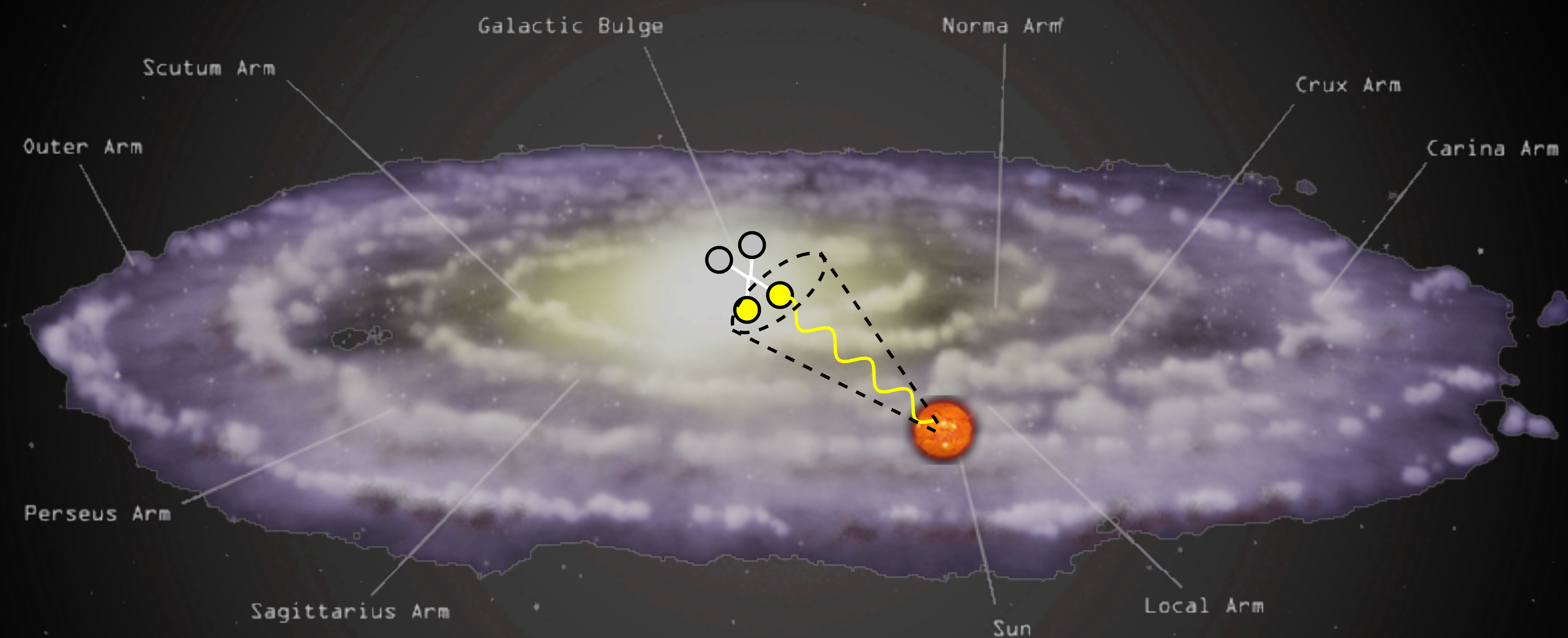

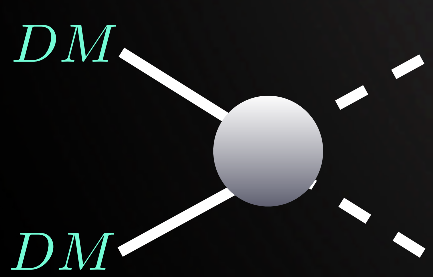

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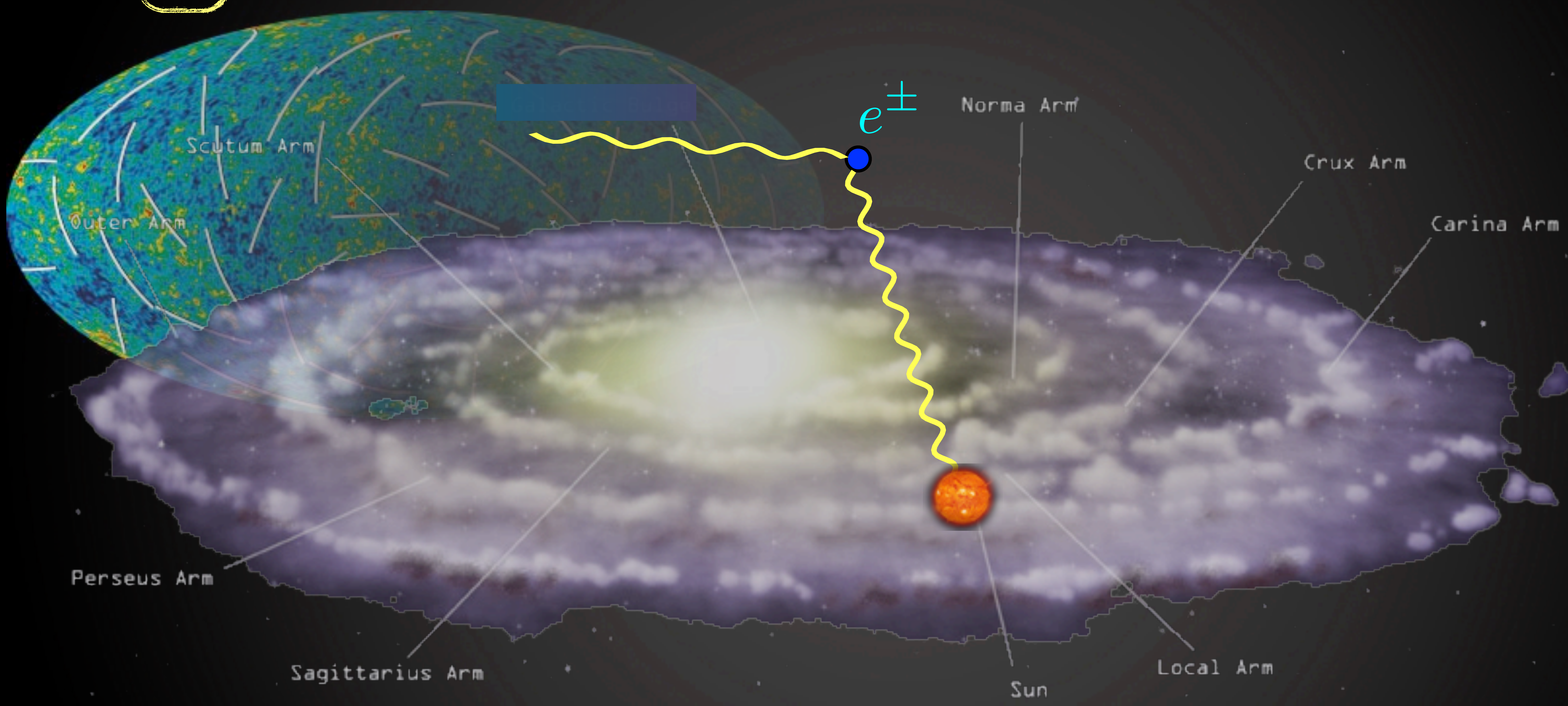
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

‘prompt’ gamma rays

Indirect Detection: gammas

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

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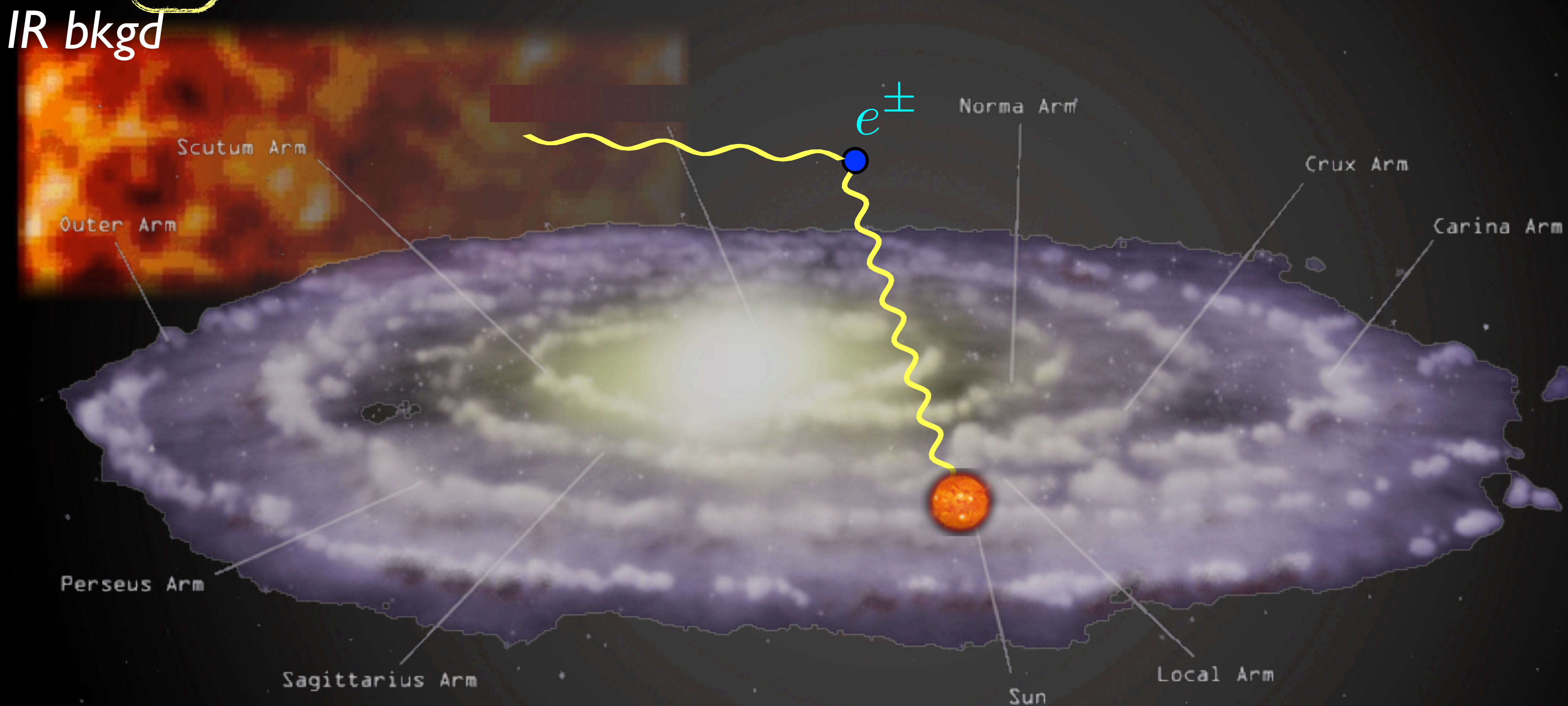

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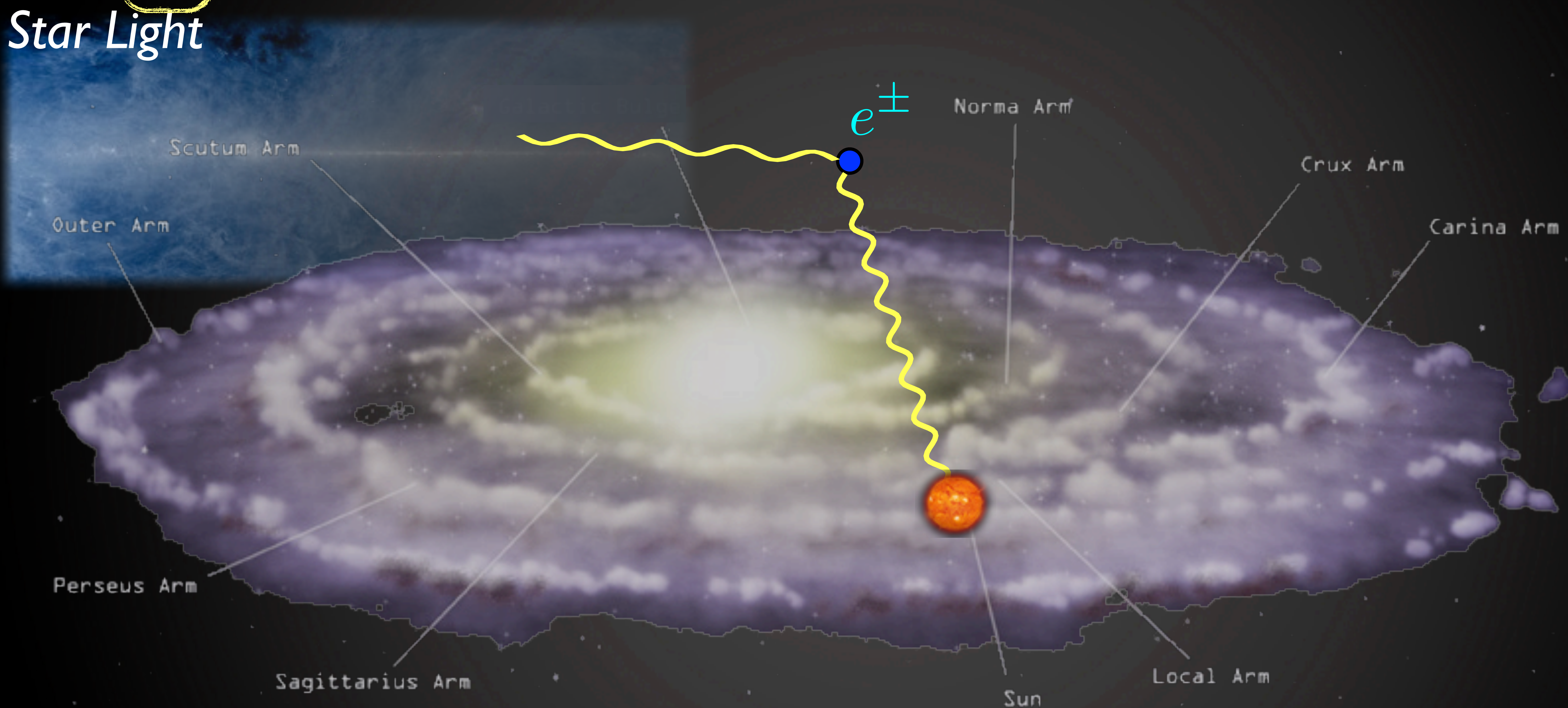

- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
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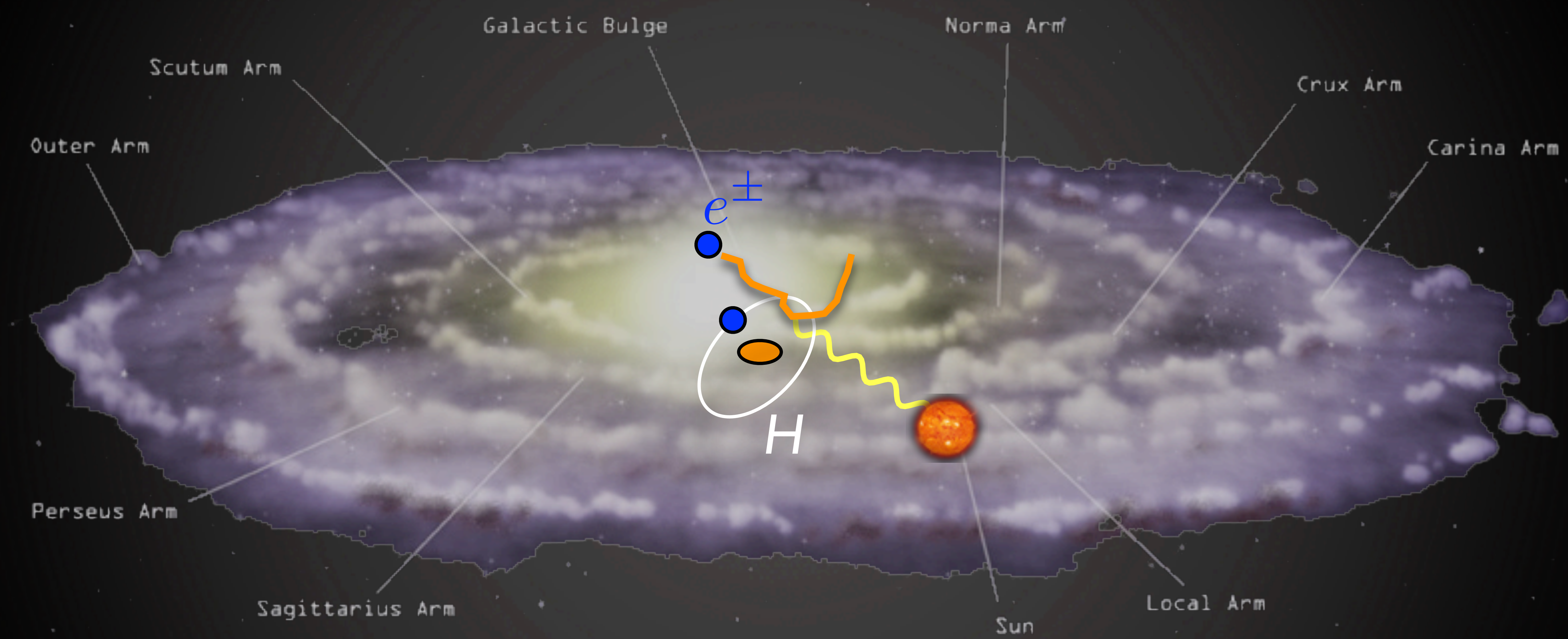
Cirelli, Panci, 2009+

Indirect Detection: gammas

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

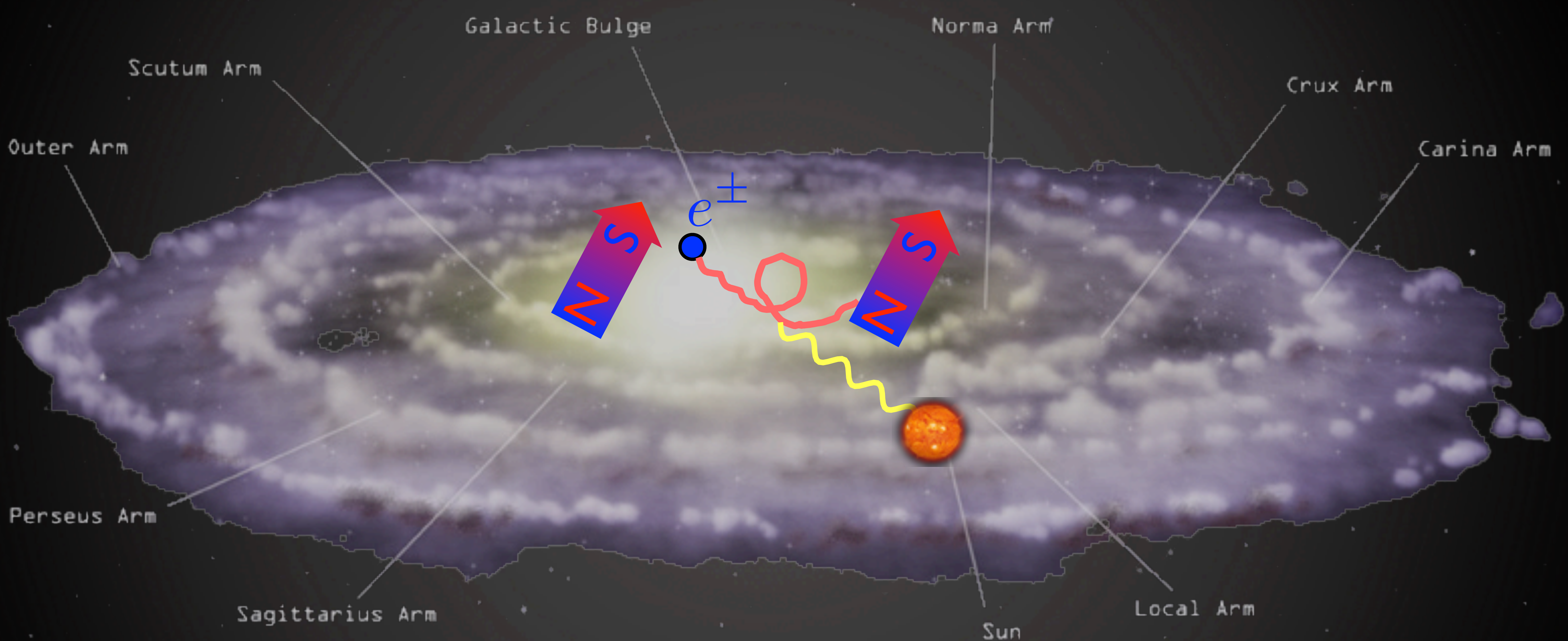


- (very) relevant at low energy, in the disk and at the GC

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

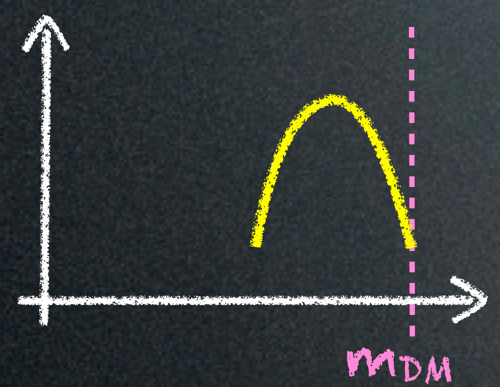
2. secondary emission

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

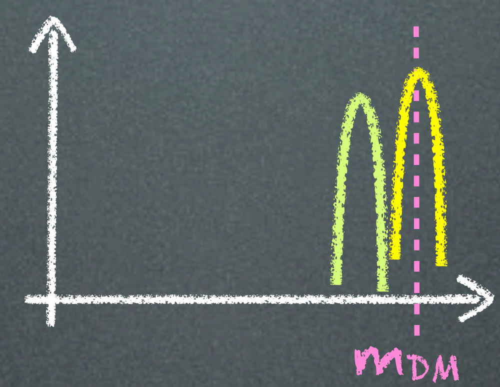
How does DM produce γ-rays?

1. prompt emission

1a. continuum



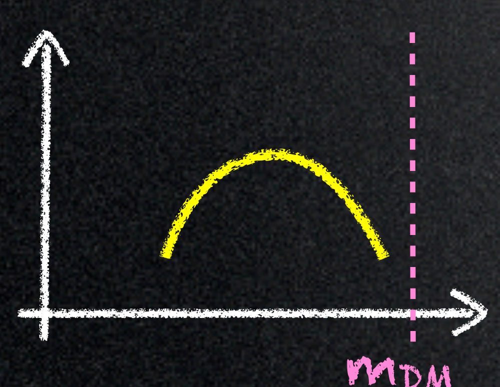
1b. line(s)



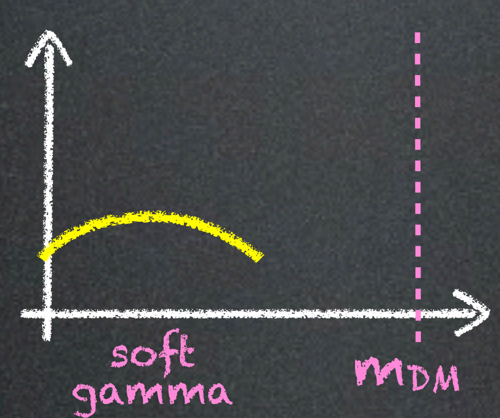
1c. sharp features

2. secondary emission

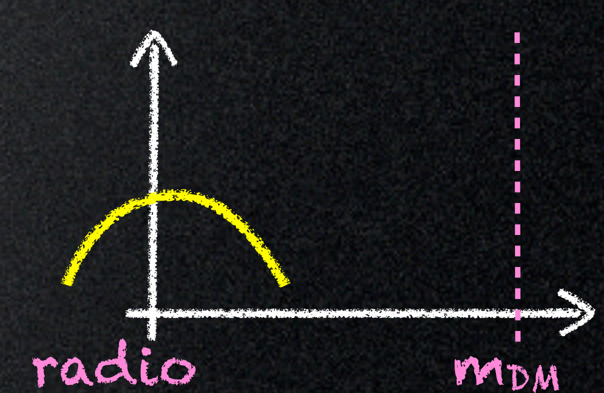
2a. ICS



2b. bremsstrahlung



2c. synchrotron



How does DM produce γ-rays?

environment-independent

1. prompt emission

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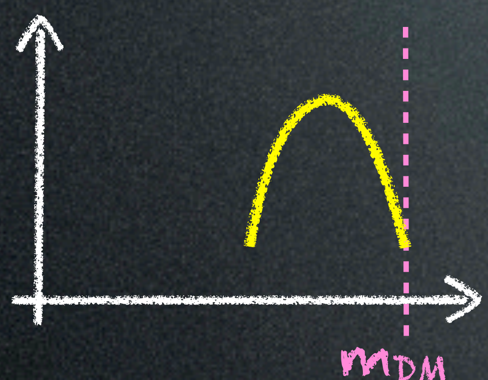
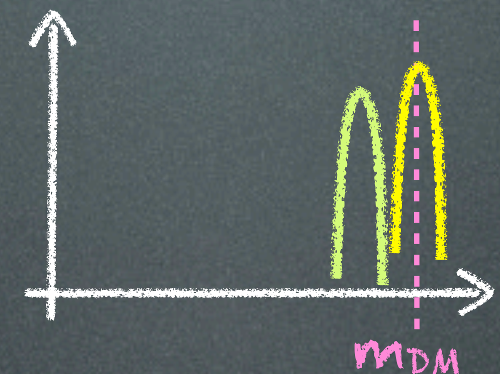
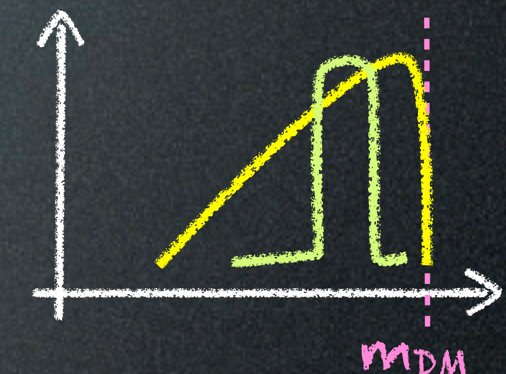


1b. line(s)



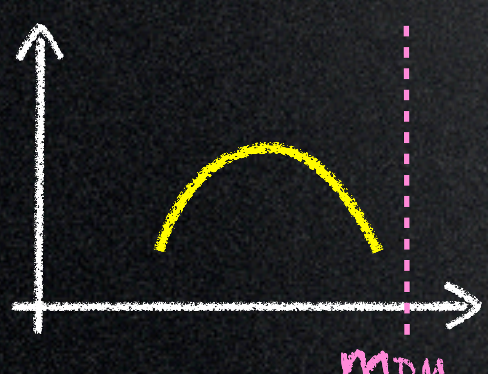
1c. sharp features



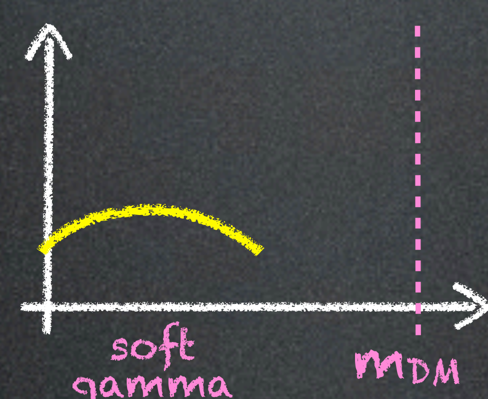
environment-dependent

2. secondary emission

2a. ICS

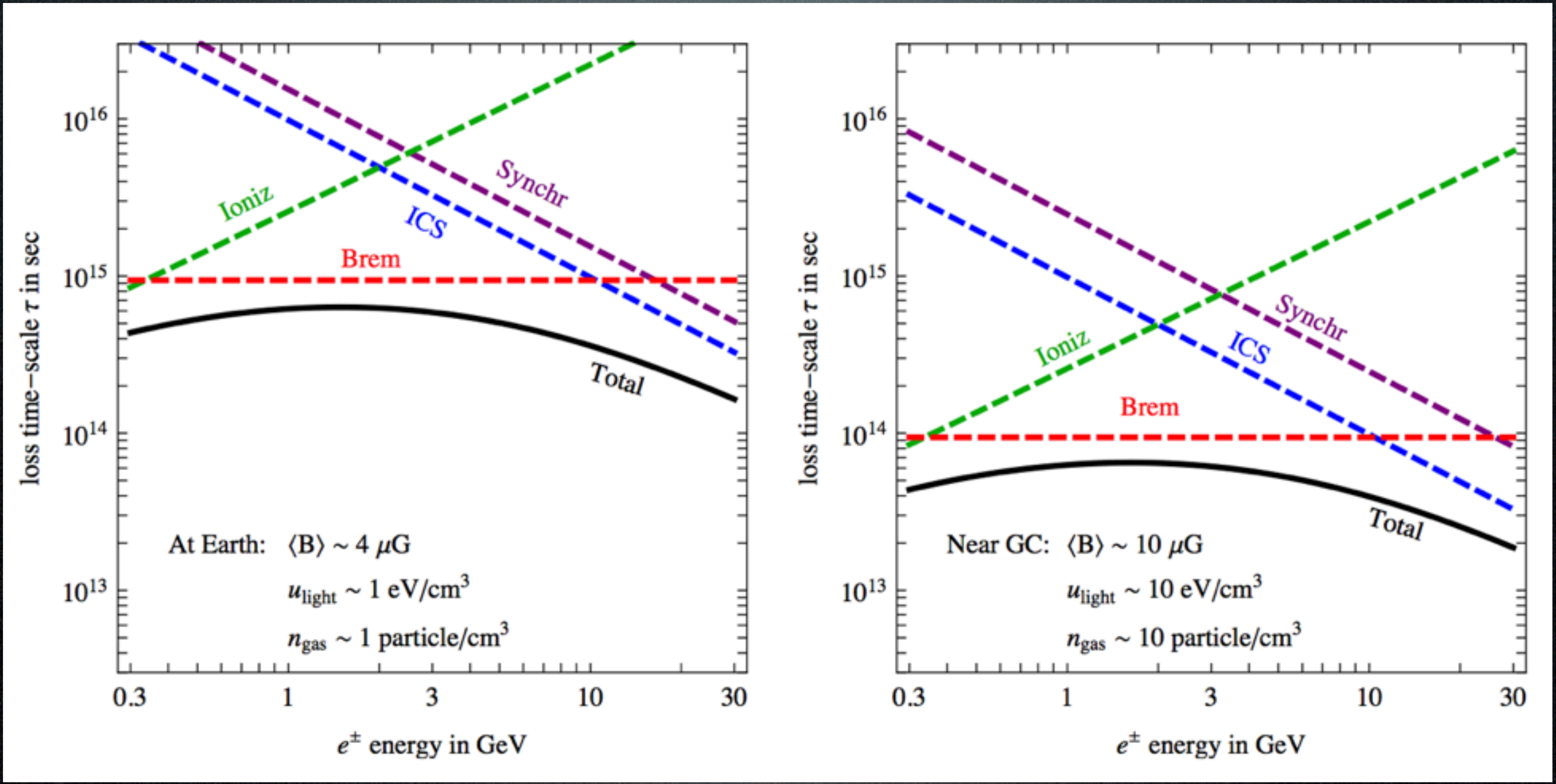


2b. bremsstrahlung



2c. synchrotron

Relative importance of secondary emissions



Cirelli, Serpico, Zaharijas, 1307.7152

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

GeV gamma excess?

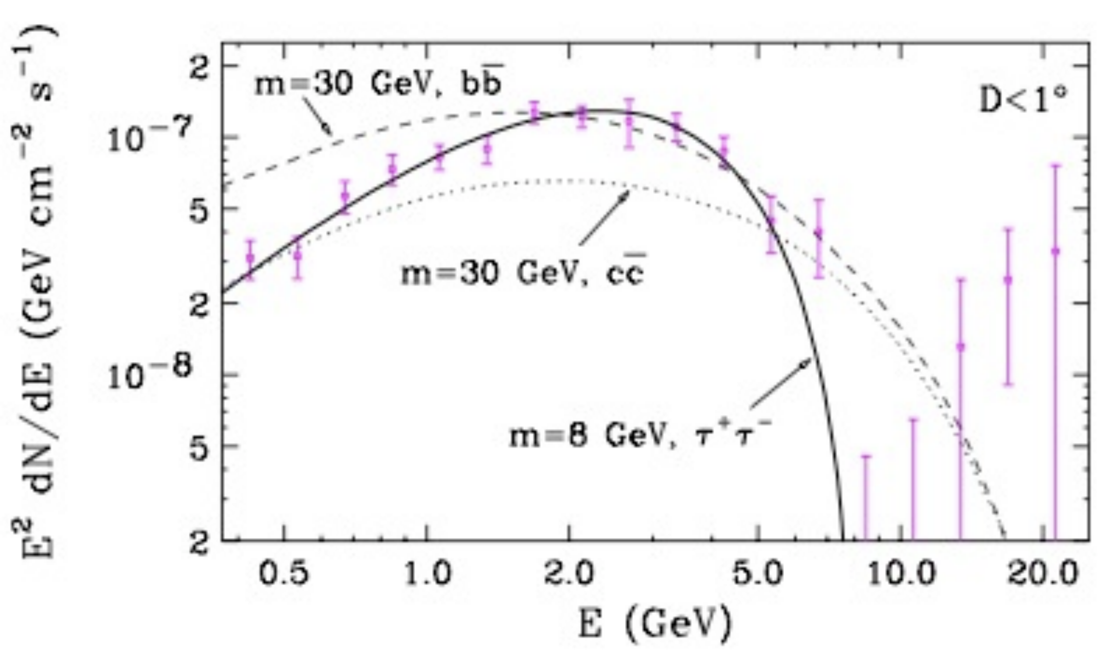
What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?

A diffuse GeV excess from around the GC

Dan Hooper

GeV gamma excess?

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

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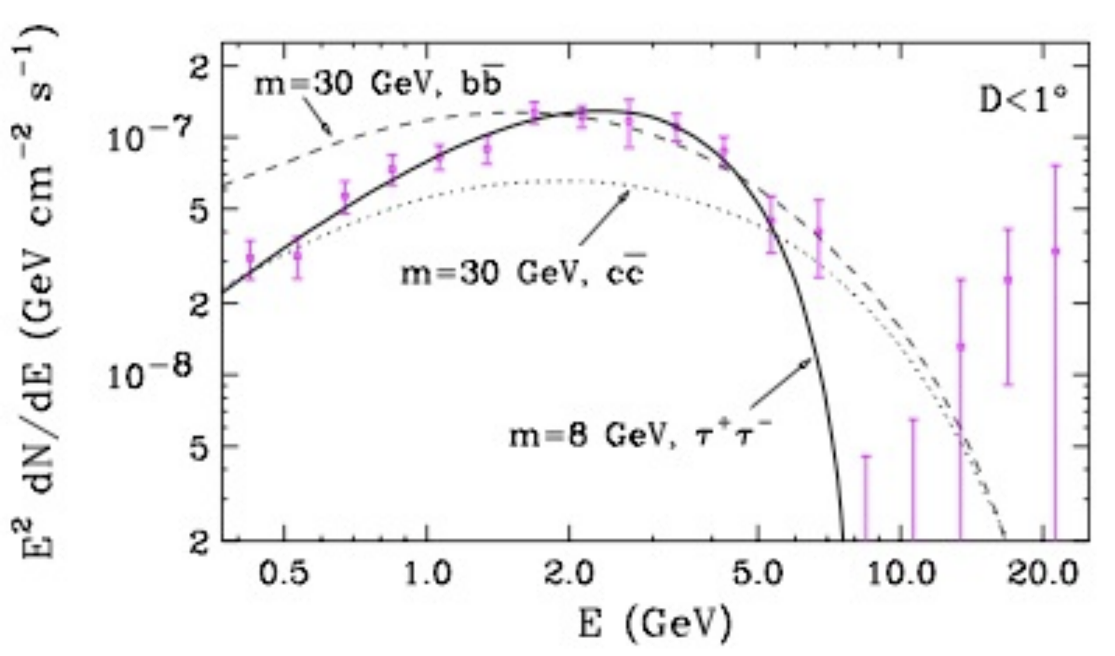
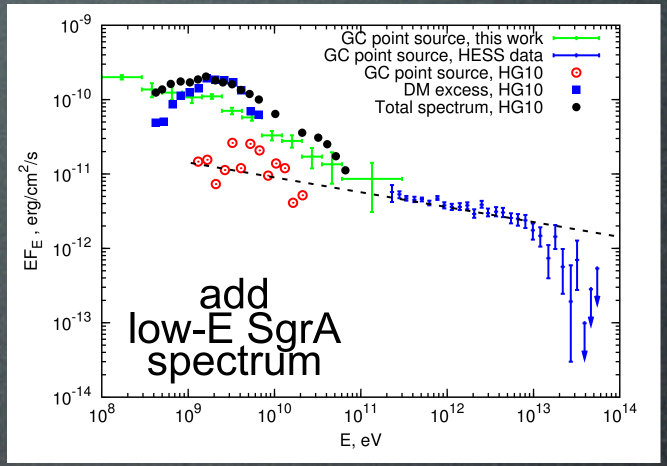
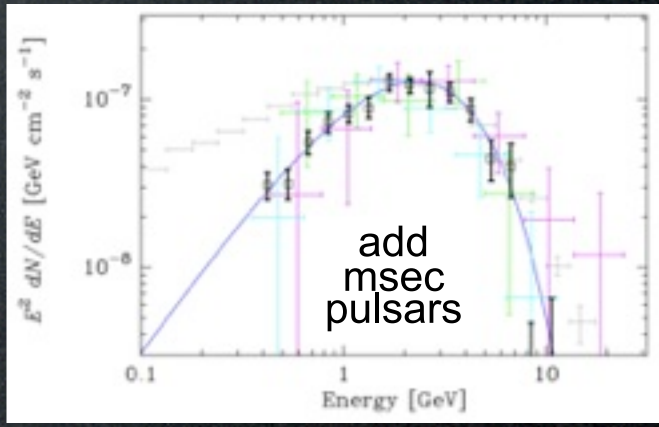


Hooper, Goodenough 1010.2752

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

A diffuse GeV excess from around the GC

Dan Hooper

GeV gamma excess?

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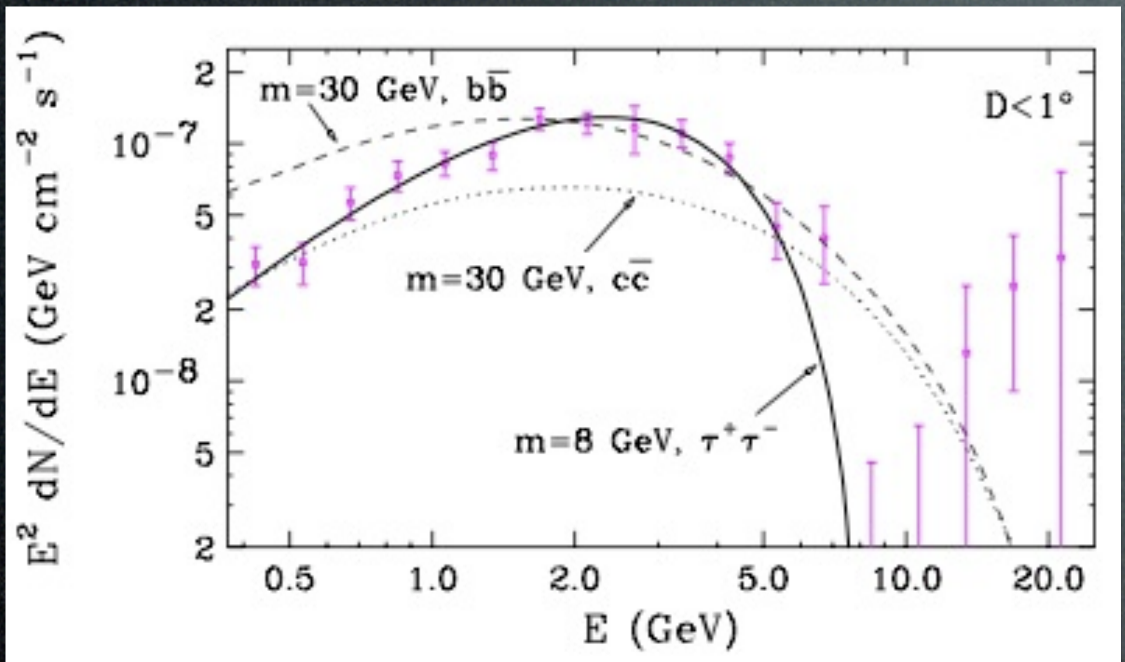

Hooper, Goodenough 1010.2752

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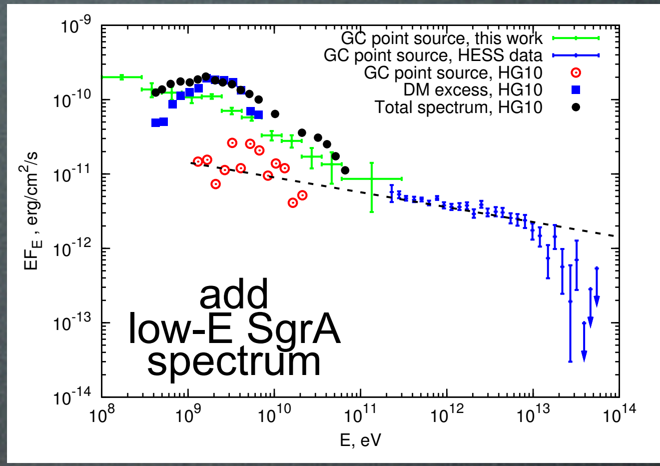
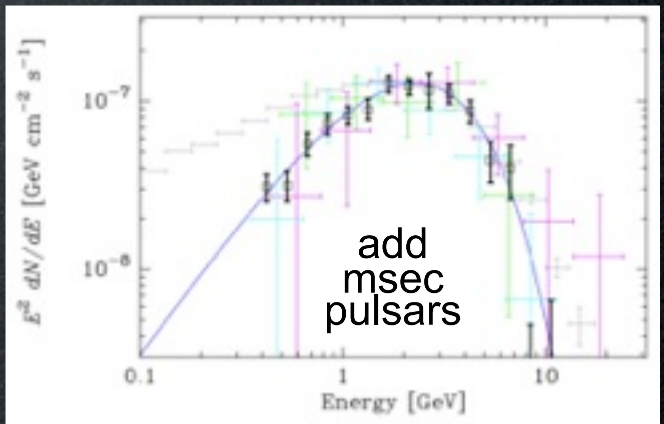


Boyarsky et al., 1012.5839



Abazajian 1011.4275

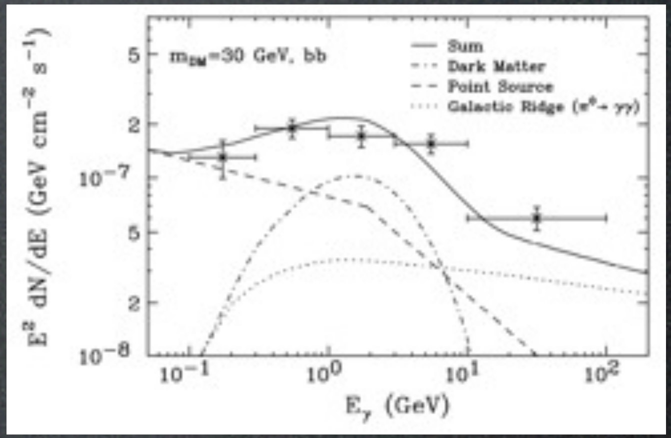
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

Still works...



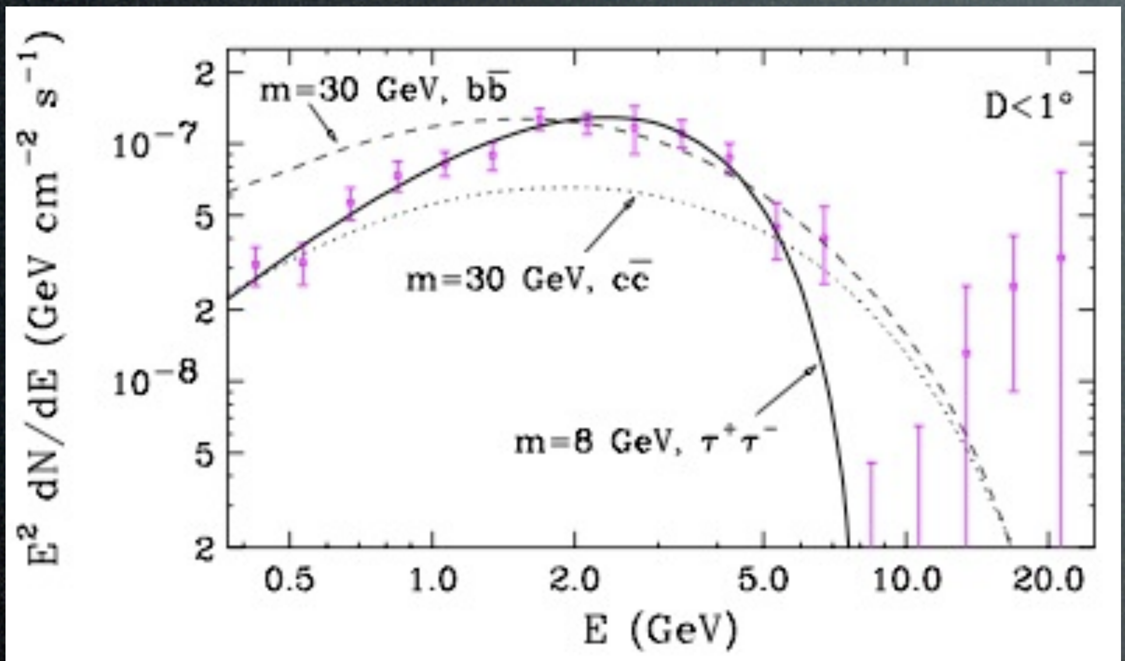
Hooper, Linden 1110.0006

A diffuse GeV excess from around the GC

Dan Hooper

GeV gamma excess?

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



Hooper, Goodenough 1010.2752

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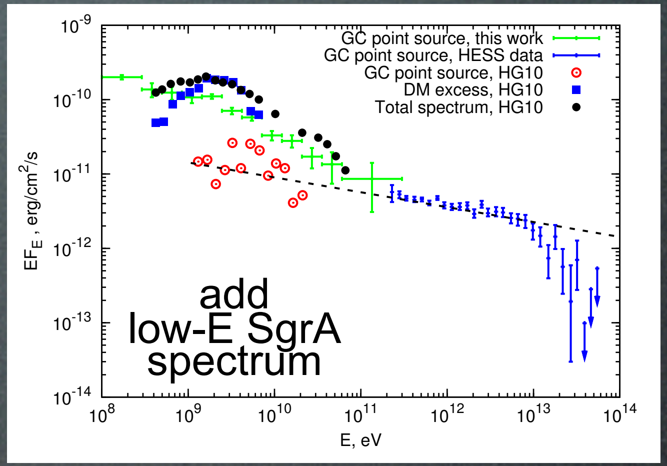
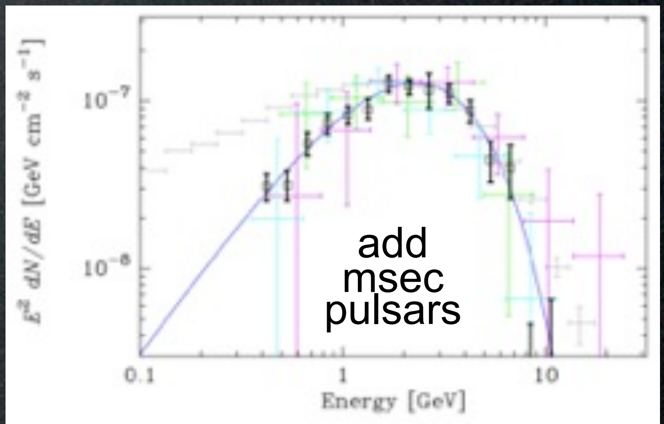


Boyarsky et al., 1012.5839



Abazajian 1011.4275

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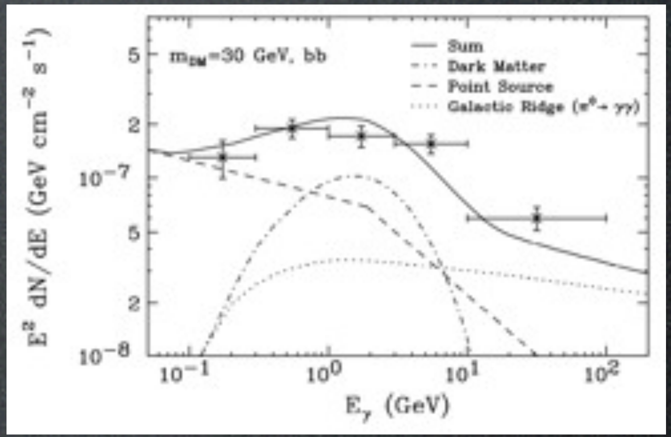


Hooper, Linden 1110.0006

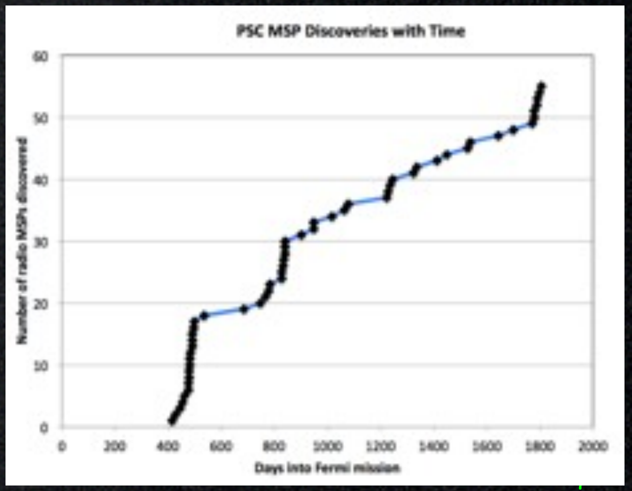
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

MSPs exist.



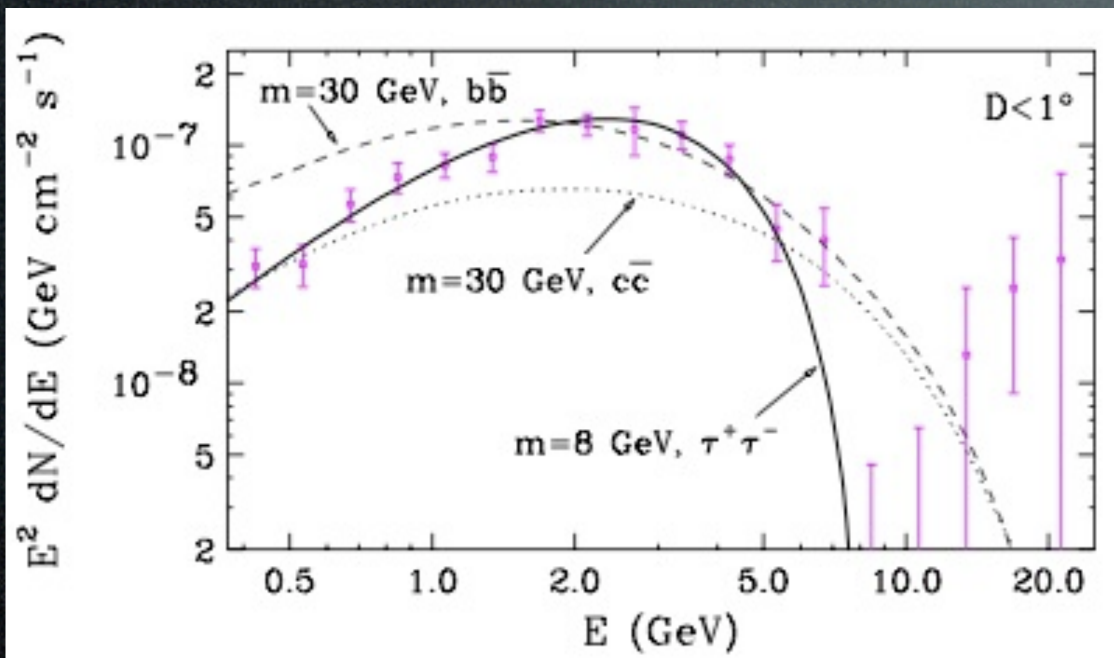
Caraveo 1312.2913

A diffuse GeV excess from around the GC

Dan Hooper

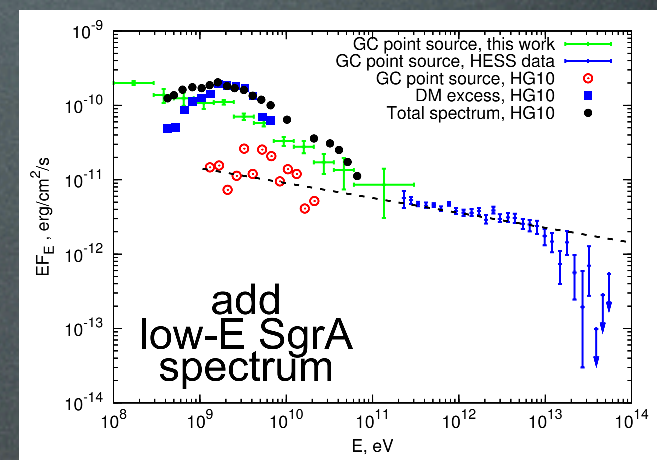
GeV gamma excess?

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

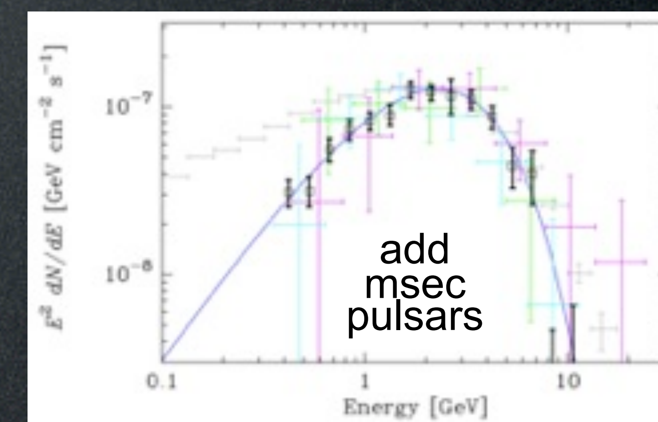


Hooper, Goodenough 1010.2752

Objection: know your backgrounds!

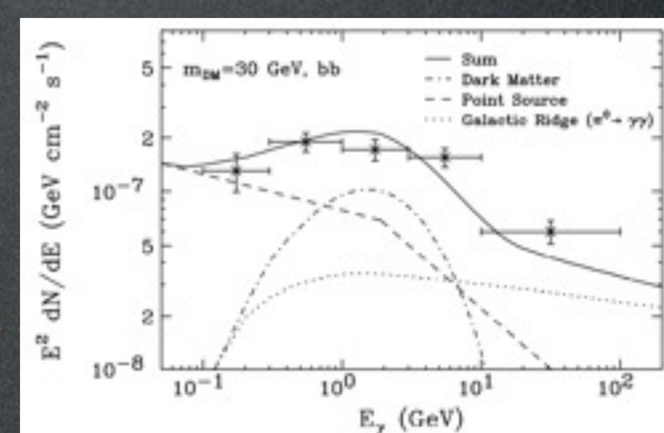


Boyarsky et al., 1012.5839



Abazajian 1011.4275

Still works...



Hooper, Linden 1110.0006

No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

MSPs can do the job.

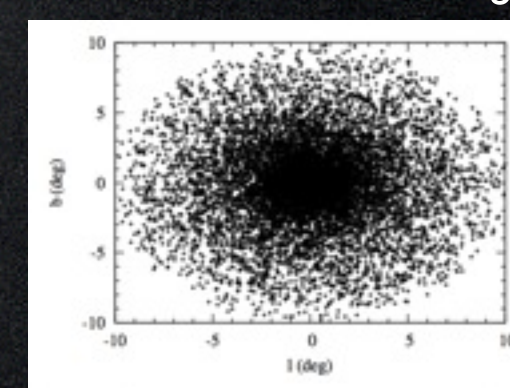


Figure 5: Simulated spatial distribution of the bulge MSPs.

Yuan, Zhang 1404.2318

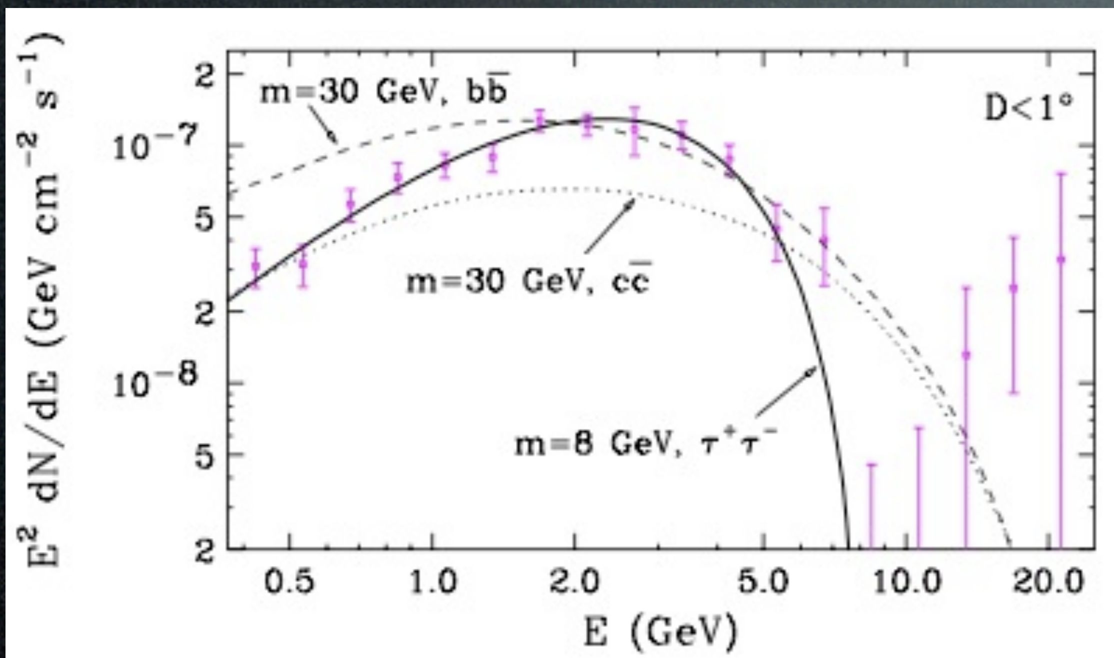
(LMXB (tracers of MSP?) seen in M31 with this distribution)

A diffuse GeV excess from around the GC

Dan Hooper

GeV gamma excess?

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



Hooper, Goodenough 1010.2752

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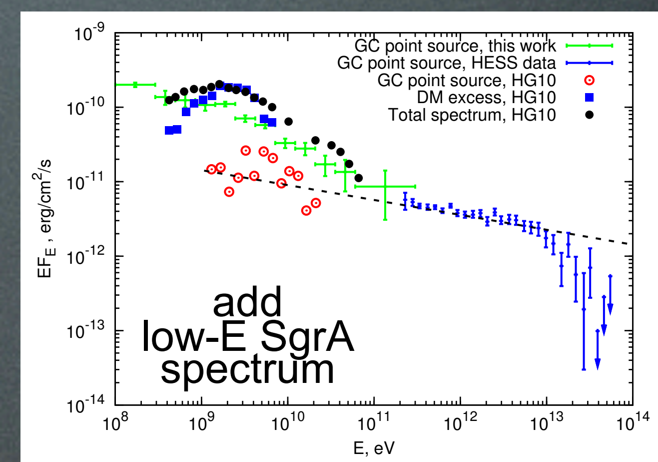
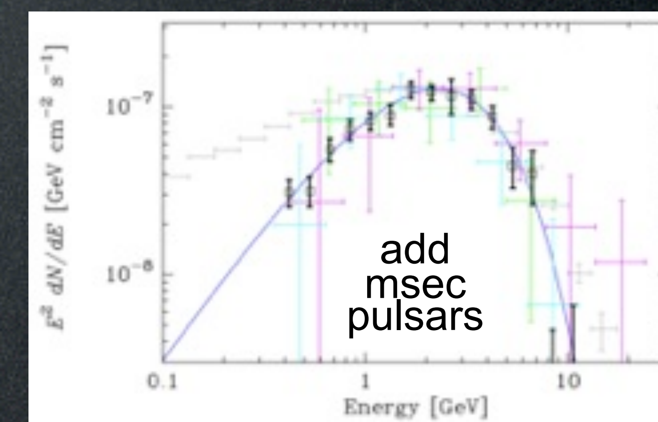


Boyarsky et al., 1012.5839



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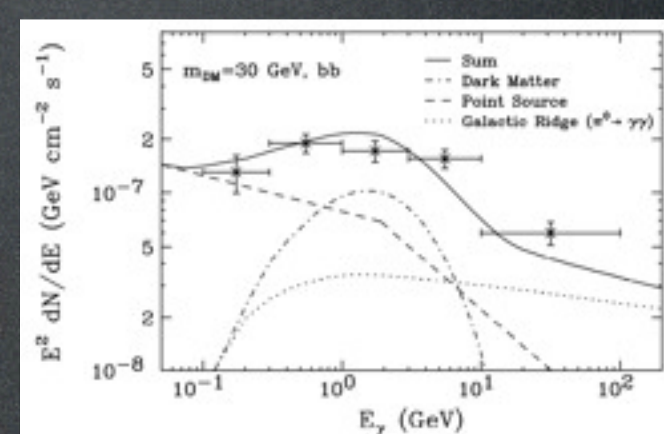


Hooper, Linden 1110.0006

A diffuse GeV excess from around the GC

Dan Hooper

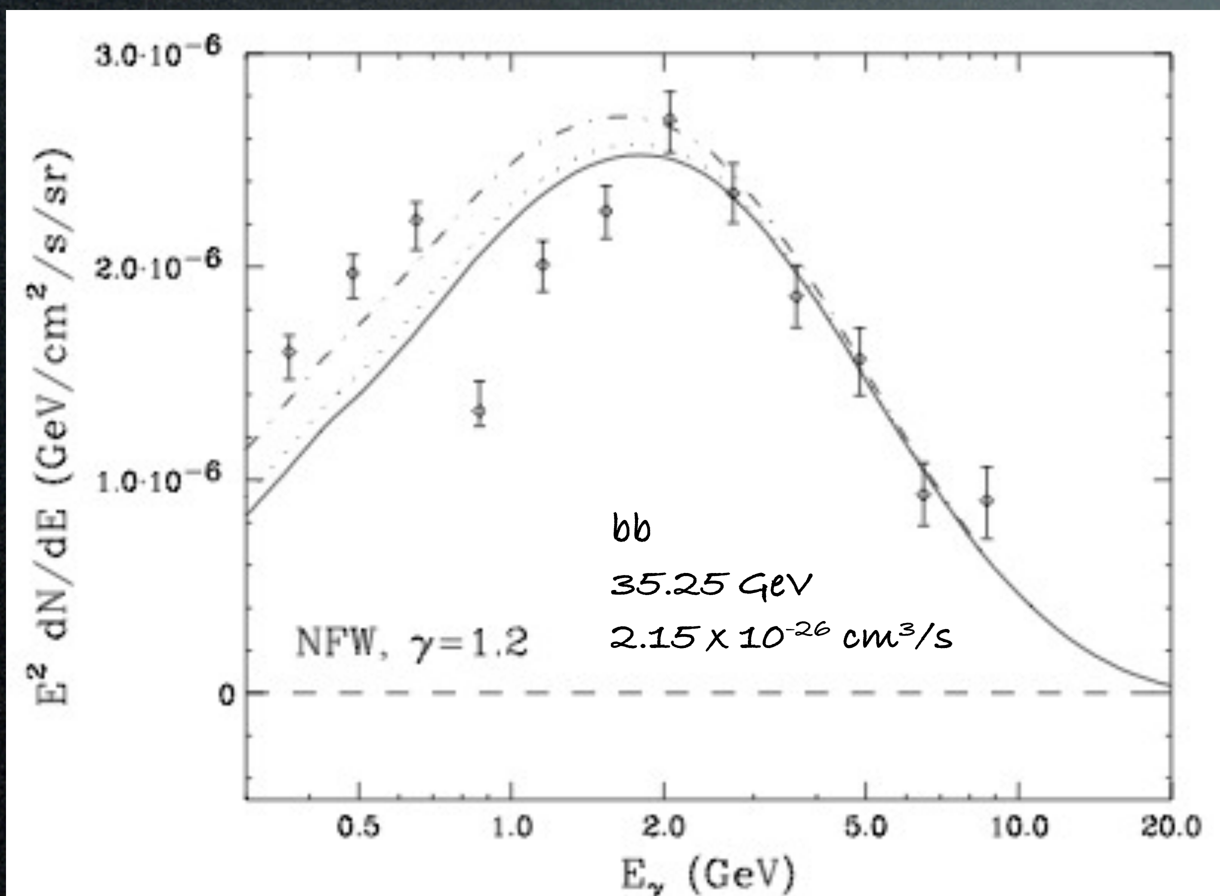
MSPs can do the job:

they can give a large if not dominant contribution to the excess.

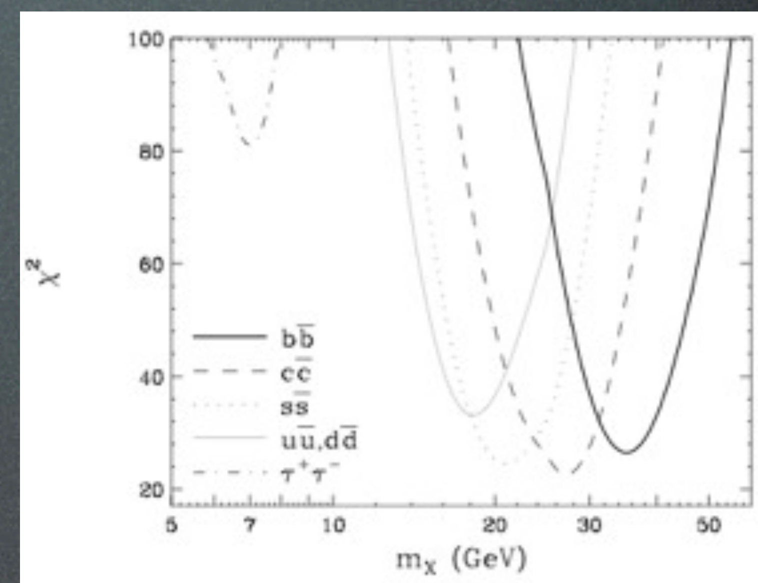
Petrović, Serpico, Zaharijas 1411.2980

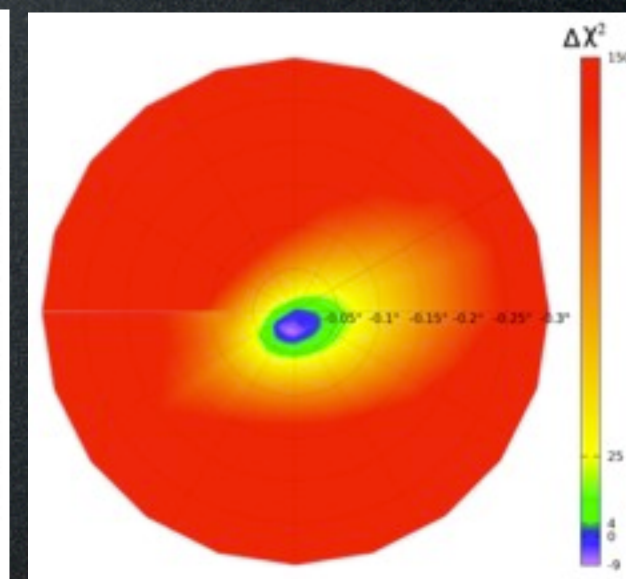
GeV gamma excess?

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



Using events with accurate directional reconstruction





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

A compelling case for annihilating DM
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

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

GeV gamma excess?

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

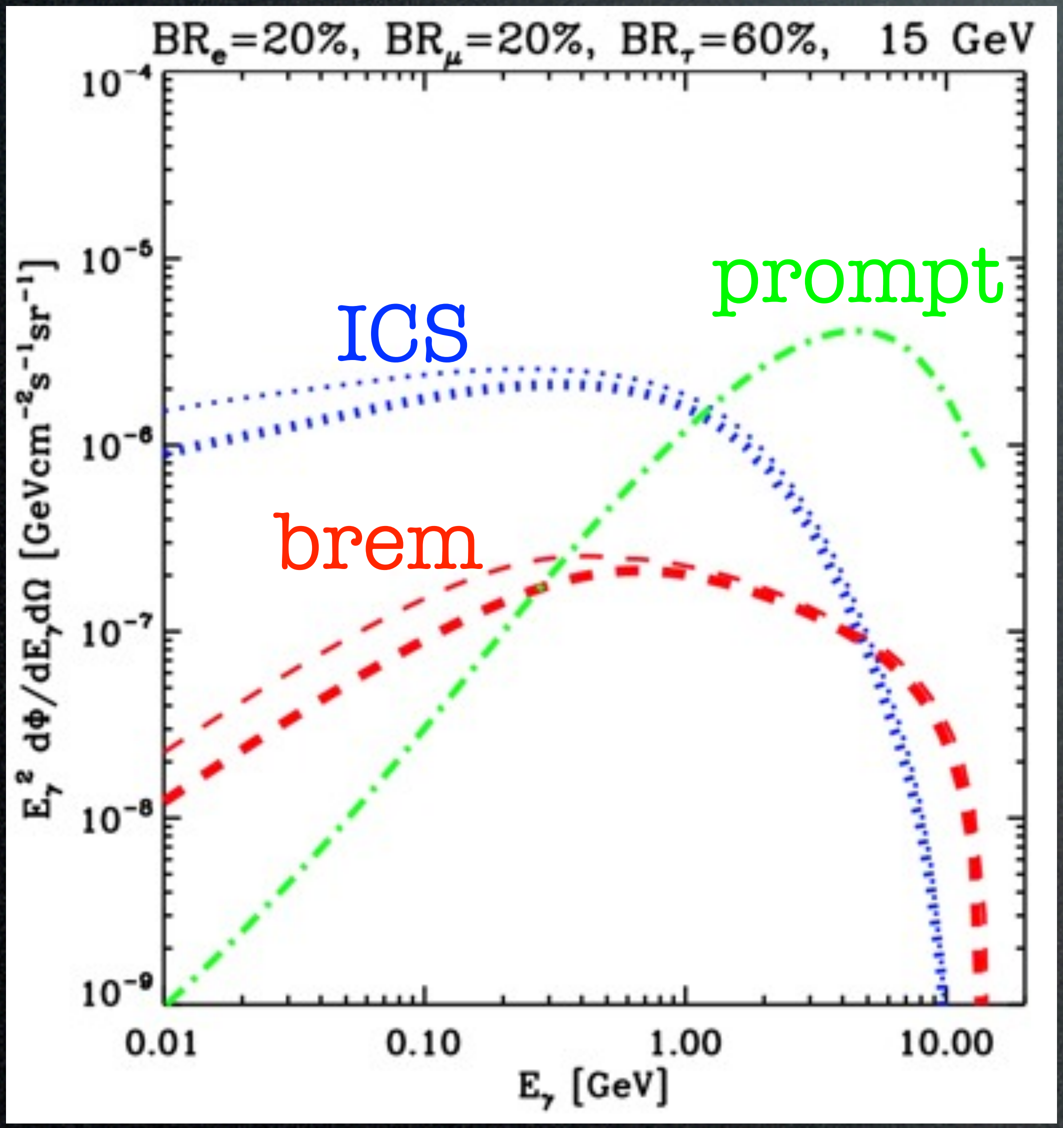
i. choose a ROI (shape, extension, masking...) and harvest Fermi-LAT data
ii. impose sensible cuts (Pass N, angles, CTBCORE...)
iii. in each energy bin, fit to a sum of spatial templates:
    1. Fermi Coll. diffuse
    2. isotropic
    3. unresolved point sources
    4. features (bubbles...)
    5. AOB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

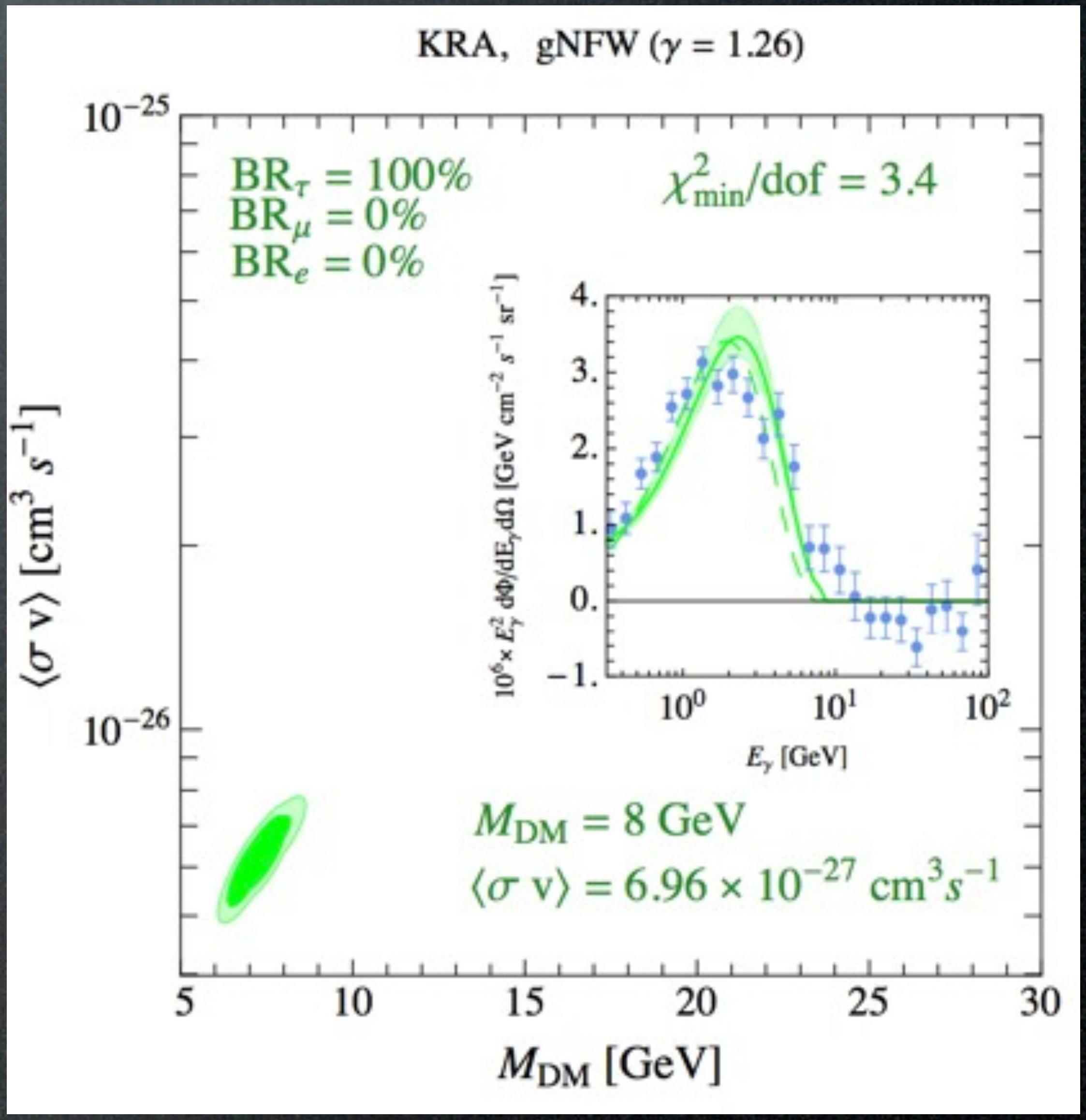
Note:
Adding 6 will in general change the recipe of 1...5 (you'll need a bit more of x here, a bit less of y there...).
Changing the profile of 6 too.

GeV gamma excess?

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

Including secondary emission changes the conclusions





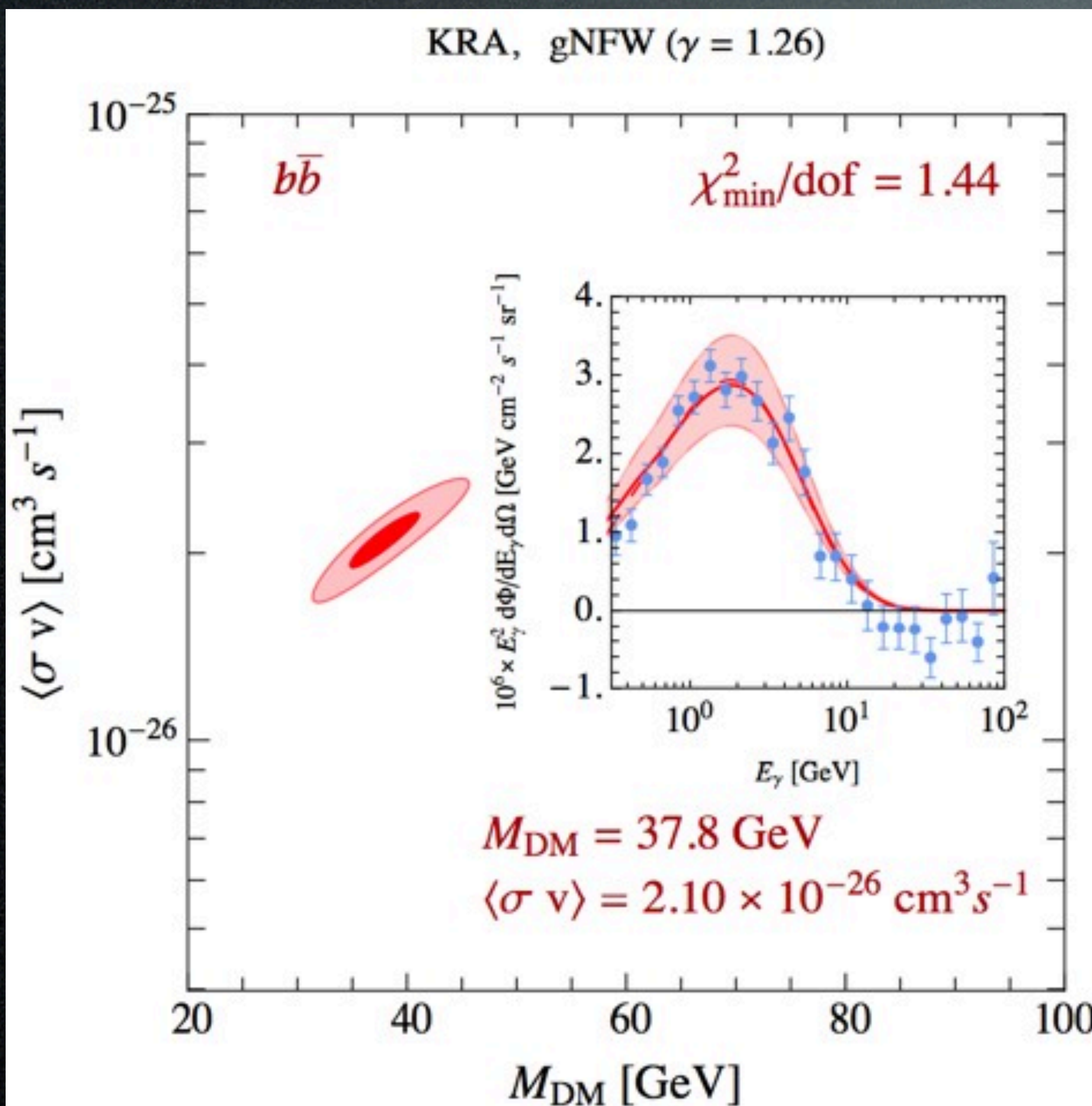
Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

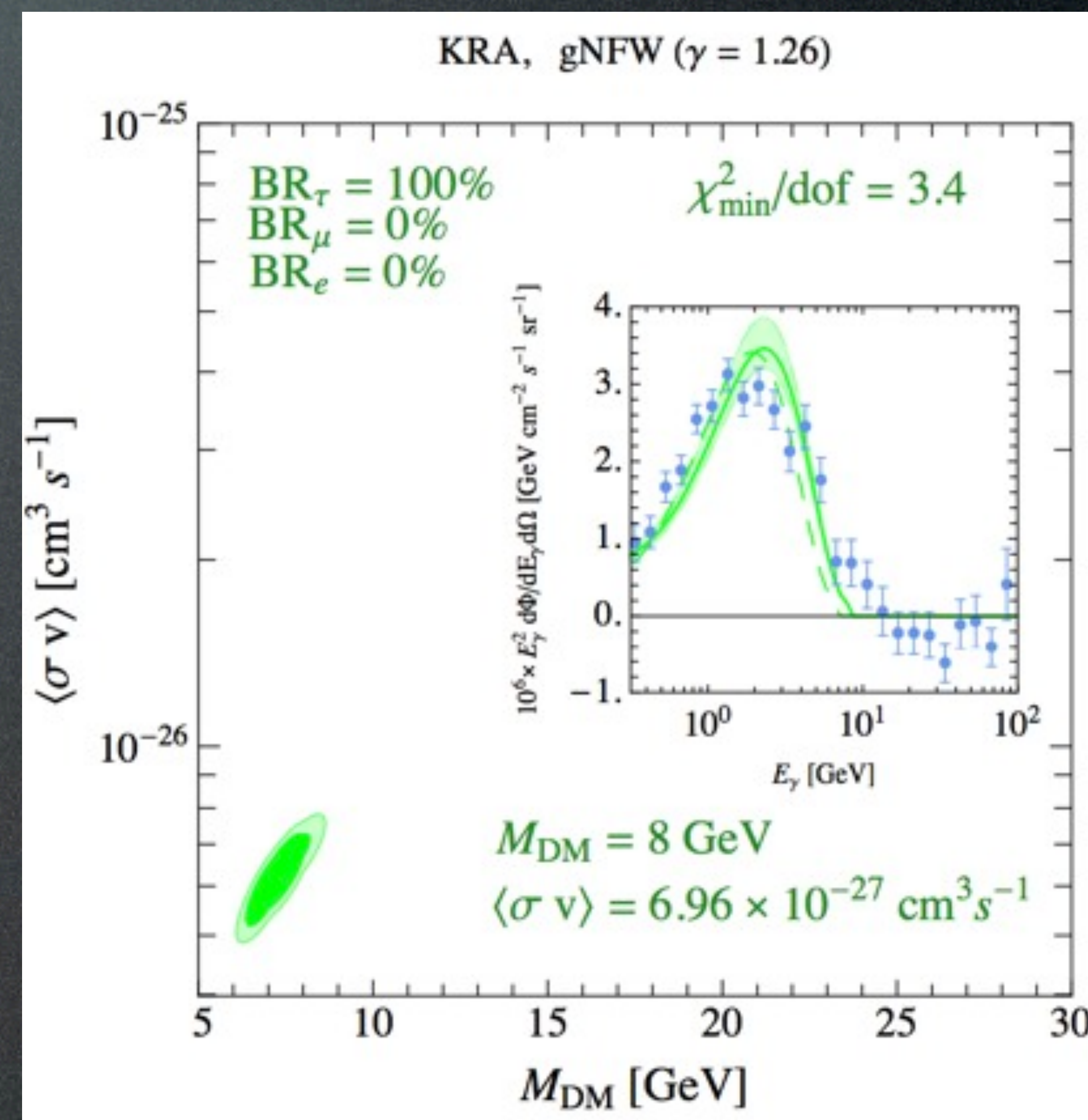
GeV gamma excess?

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

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

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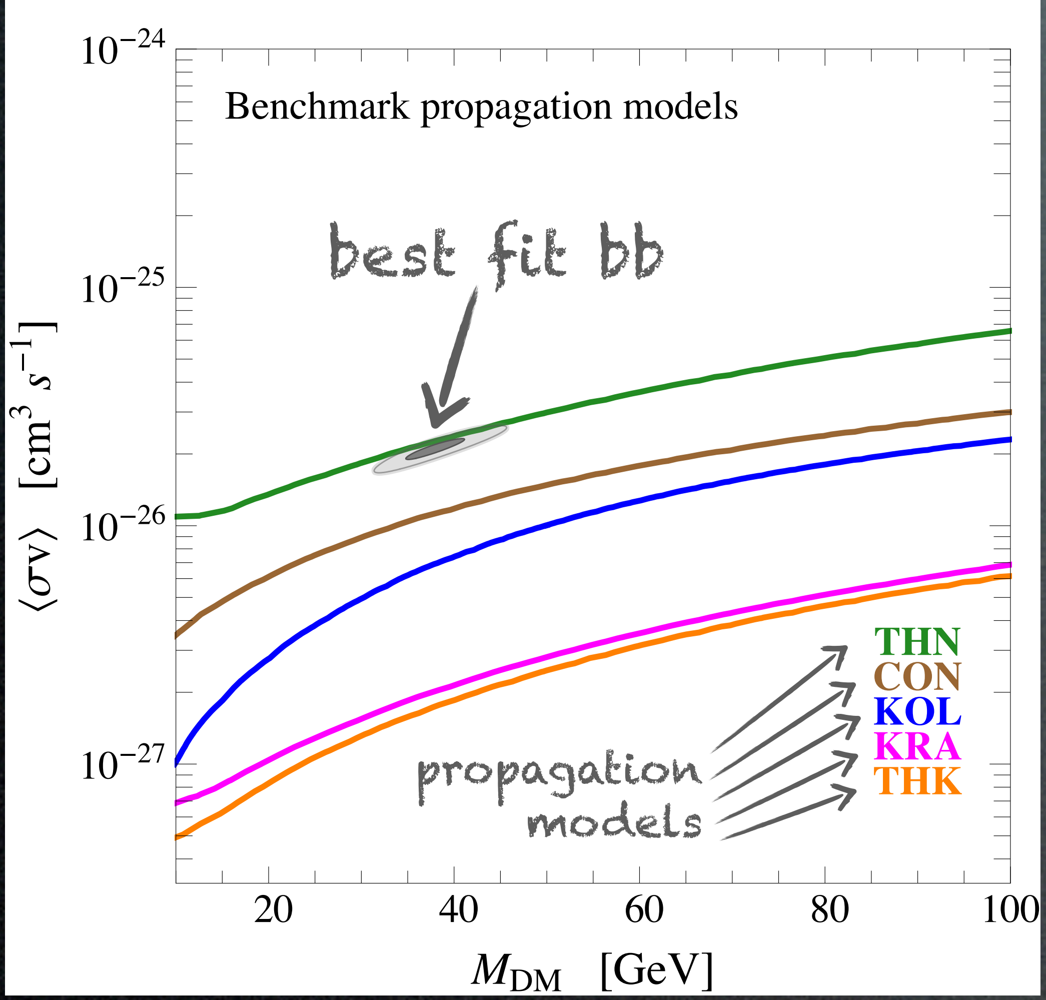


Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But <u>not</u> robust.

Fermi-LAT excess

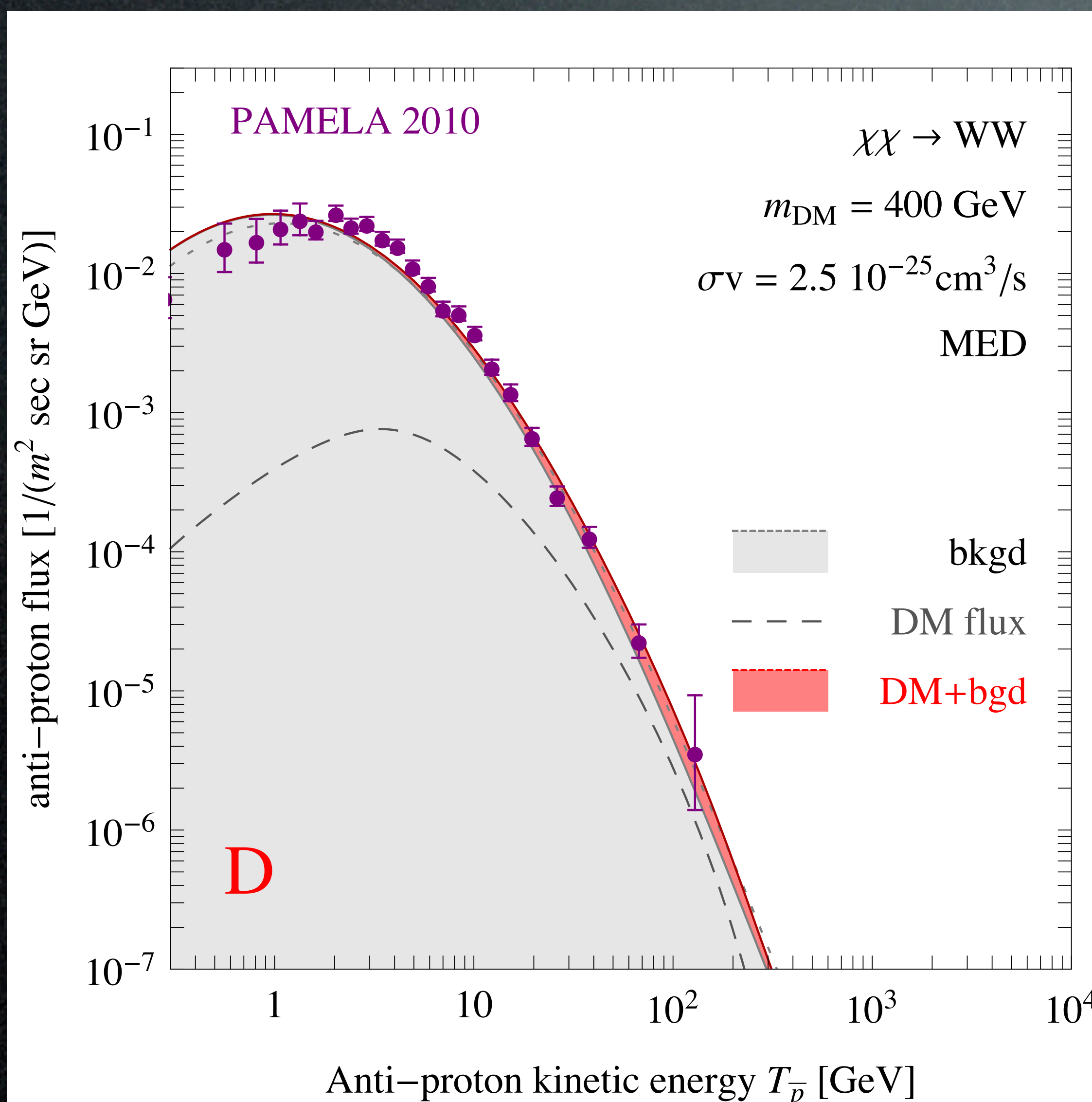
Antiproton **constraints**

Cirelli, Giesen 1301.7079

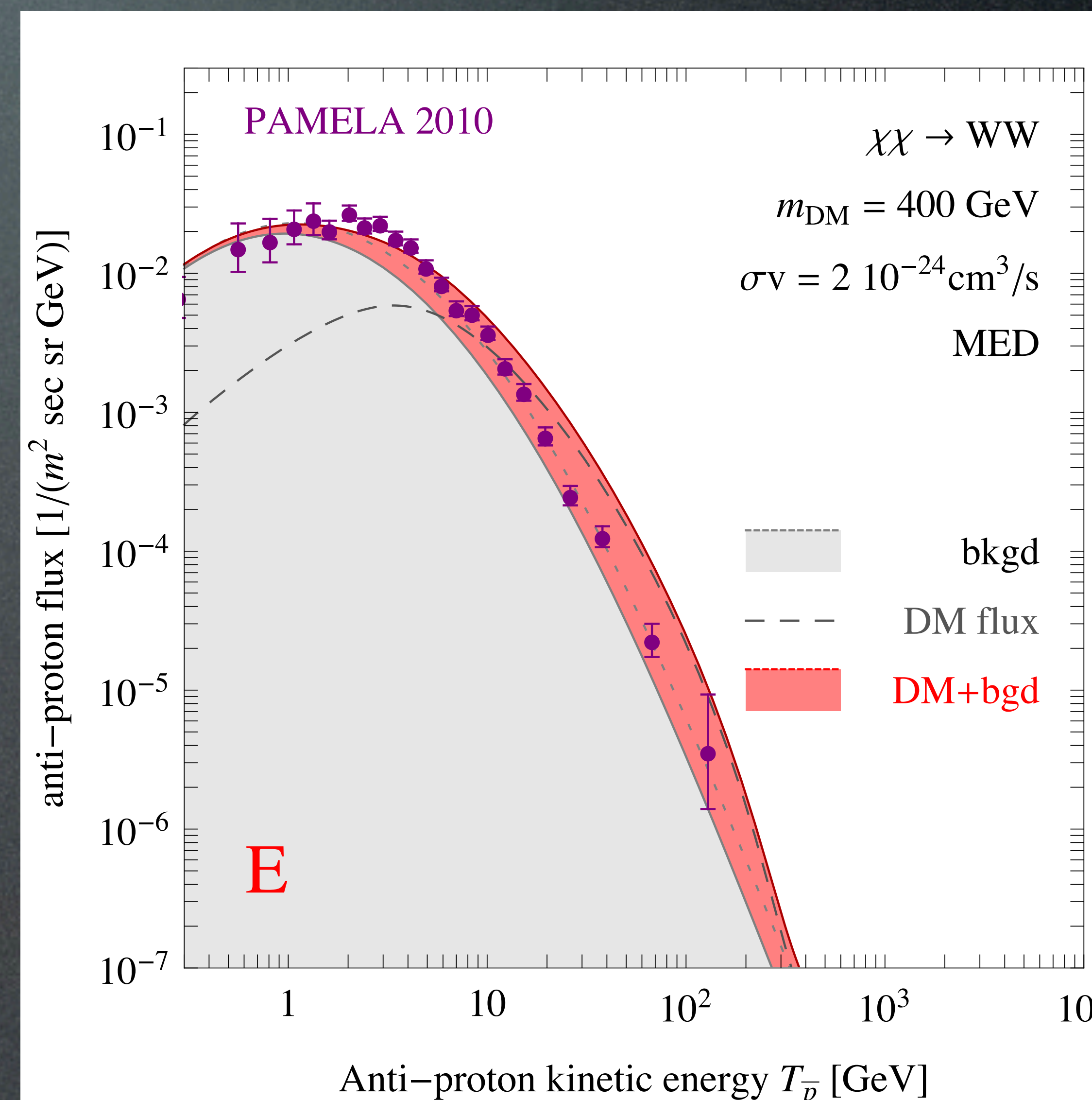
Antiproton constraints

Constrain the DM flux on top of background

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



☑ allowed



☒ excluded

GeV gamma excess?

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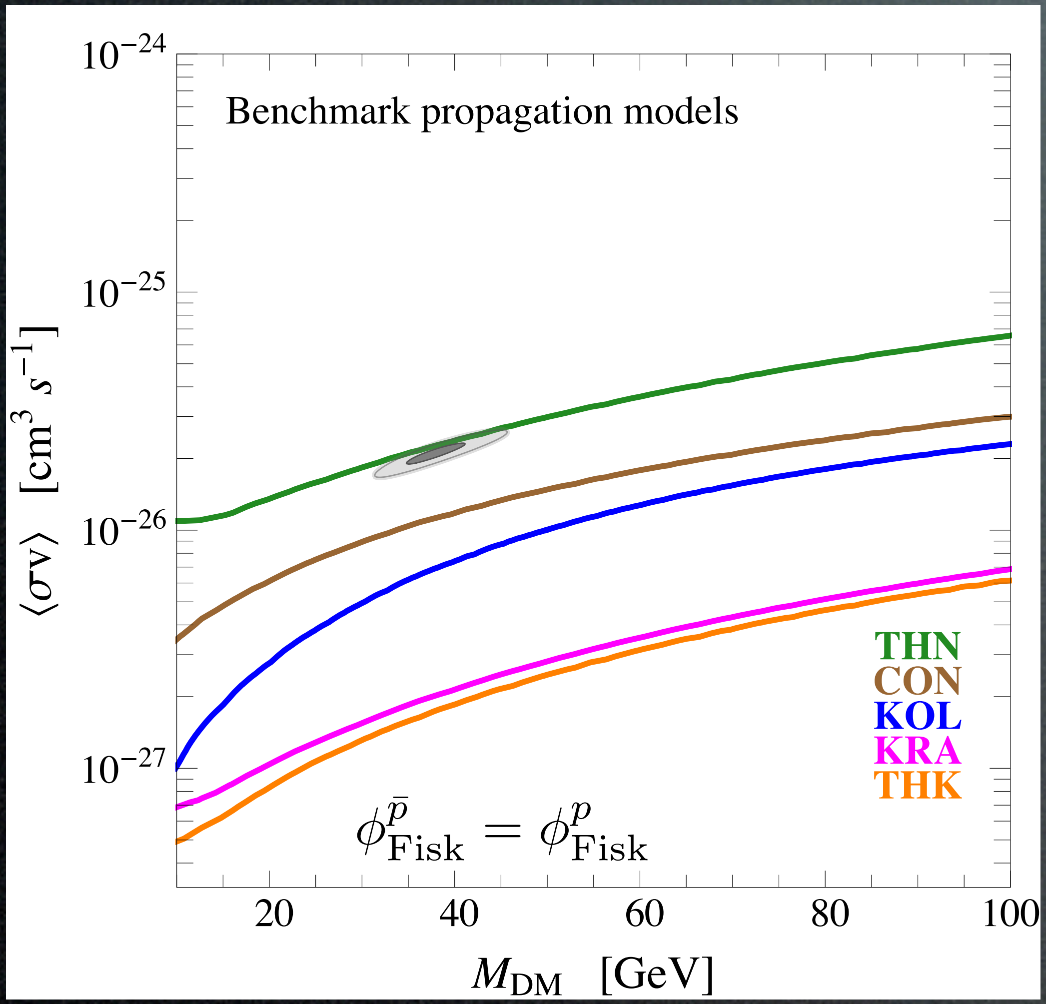
Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Fermi-LAT excess

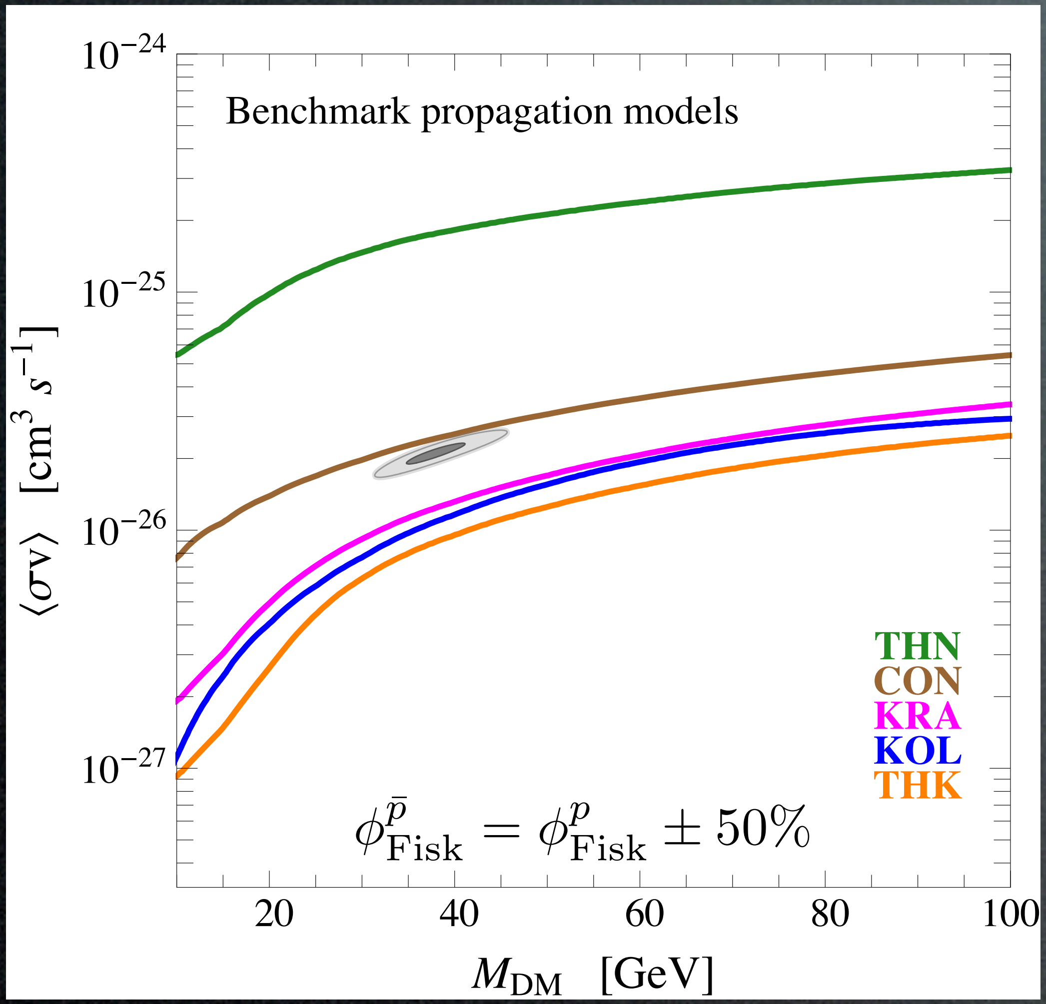
Antiproton constraints may be very relevant! But not robust.

Assumption: fixed solar modulation

Result: hooperon excluded (except unrealistic THN)

GeV gamma excess?

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



Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

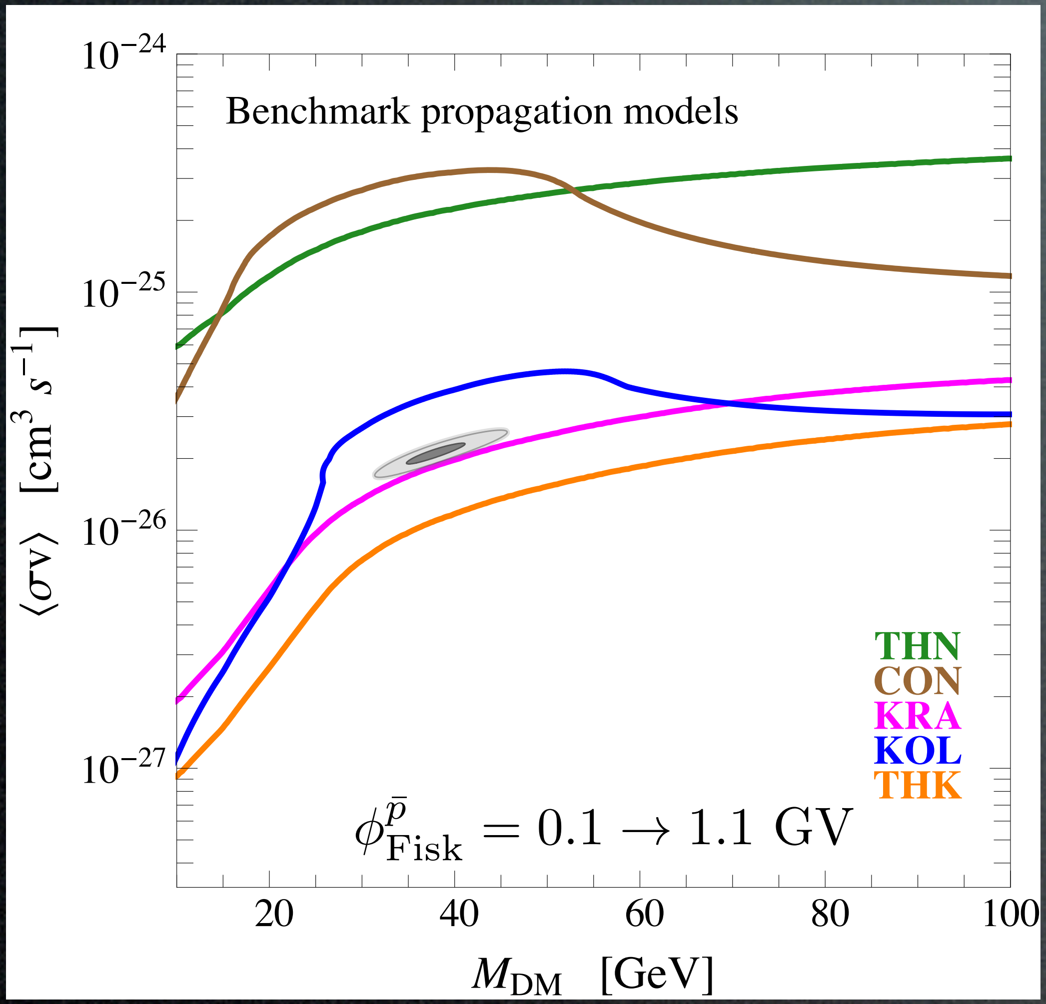
Antiproton constraints may be very relevant! But not robust.

Assumption: flexible solar modulation

Result: hooperon may be excluded or not

GeV gamma excess?

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



Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

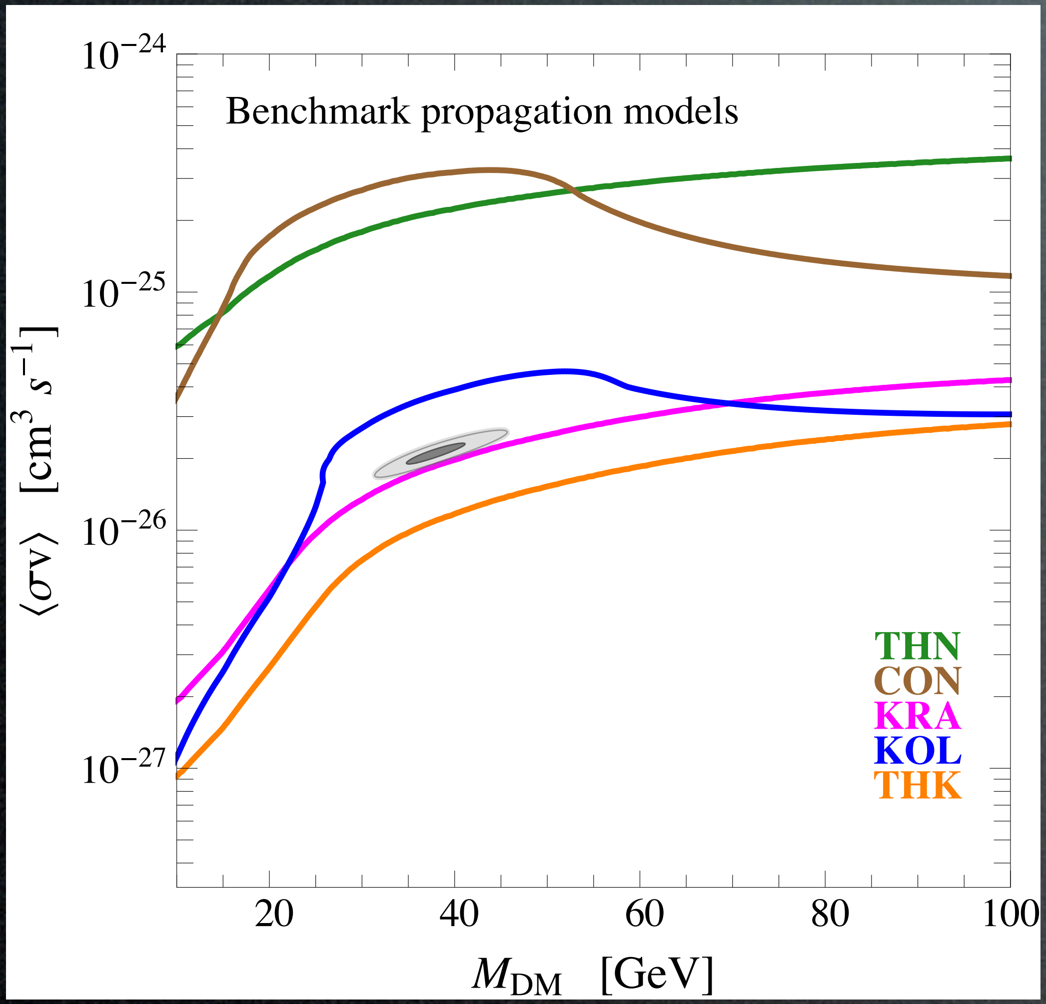
Antiproton constraints may be very relevant! But not robust.

Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

GeV gamma excess?

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



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Fermi-LAT excess

Antiproton constraints may be very relevant! But not robust.

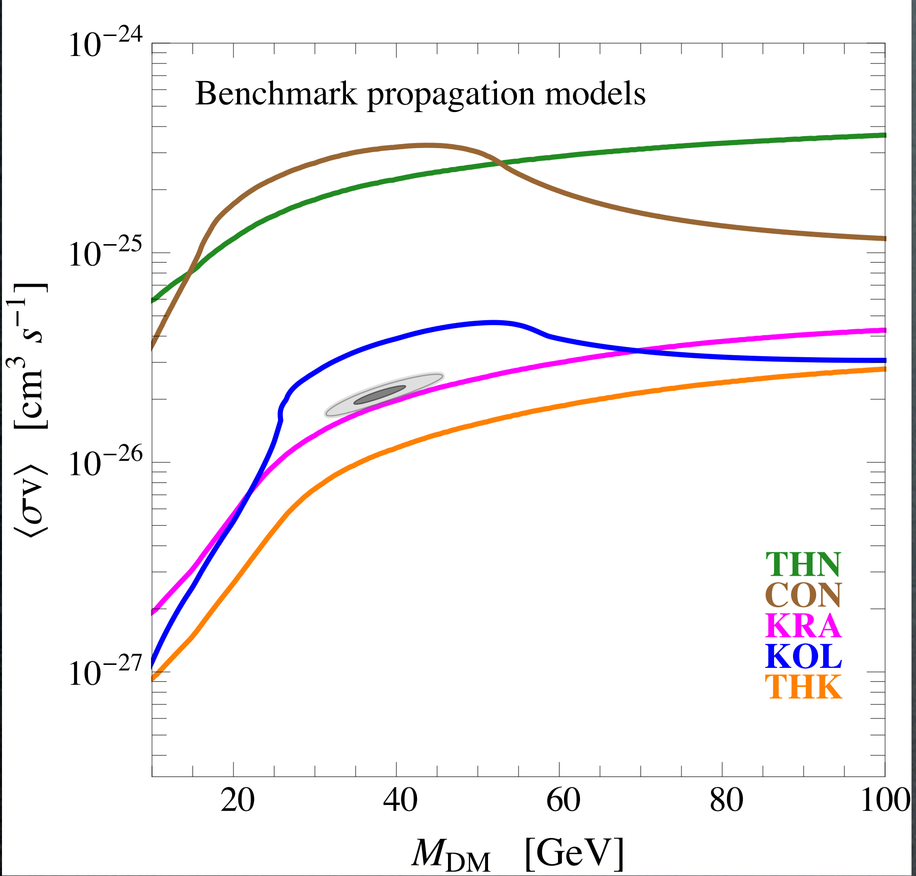
Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

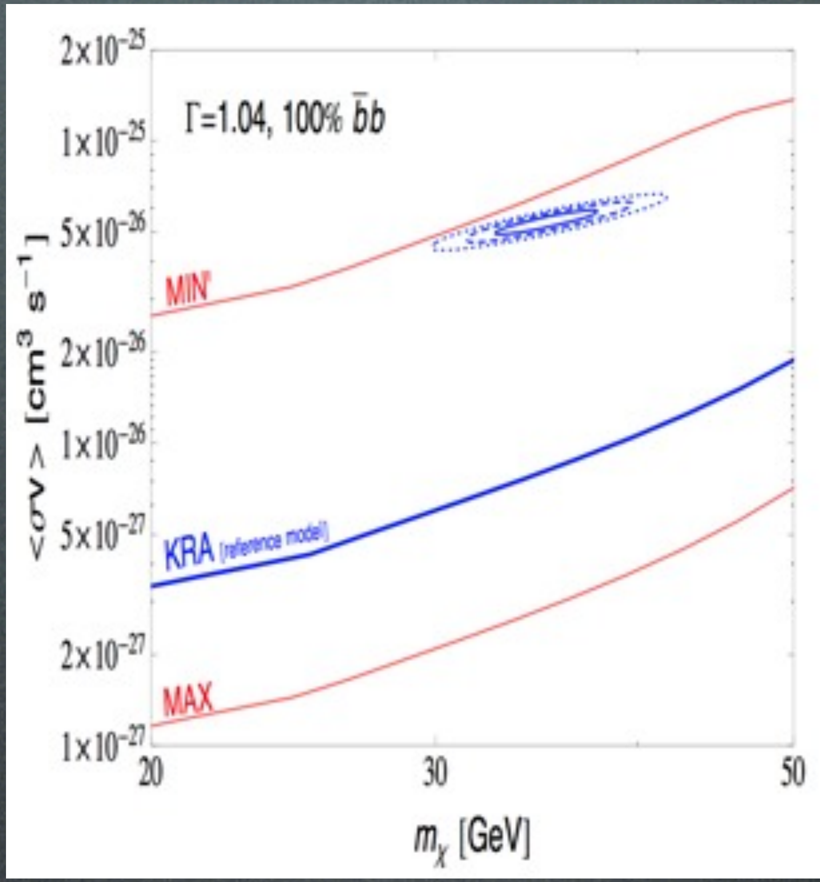
NB Conclusion differs from Bringmann, Vollmann, Weniger 1406.6027 which finds exclusion / strong tension

GeV gamma excess?

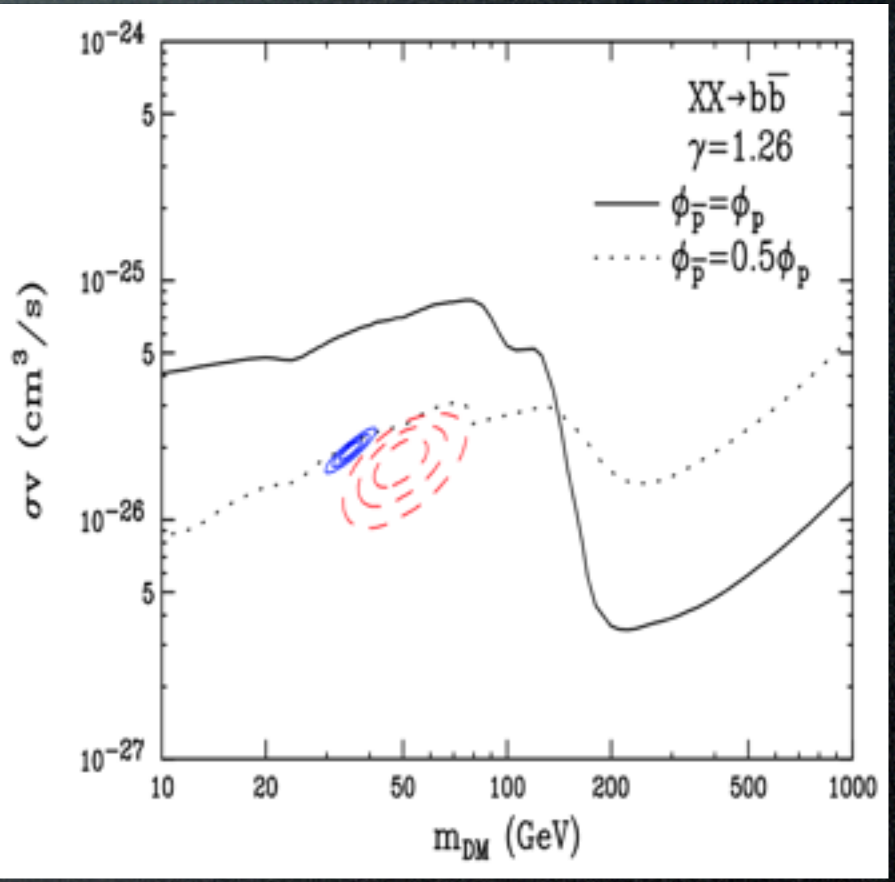
Antiproton constraints compared:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Bringmann, Vollmann, Weniger 1406.6027



Hooper, Linden, Mertsch 1410.1527

May be very relevant!
But <u>not</u> robust.

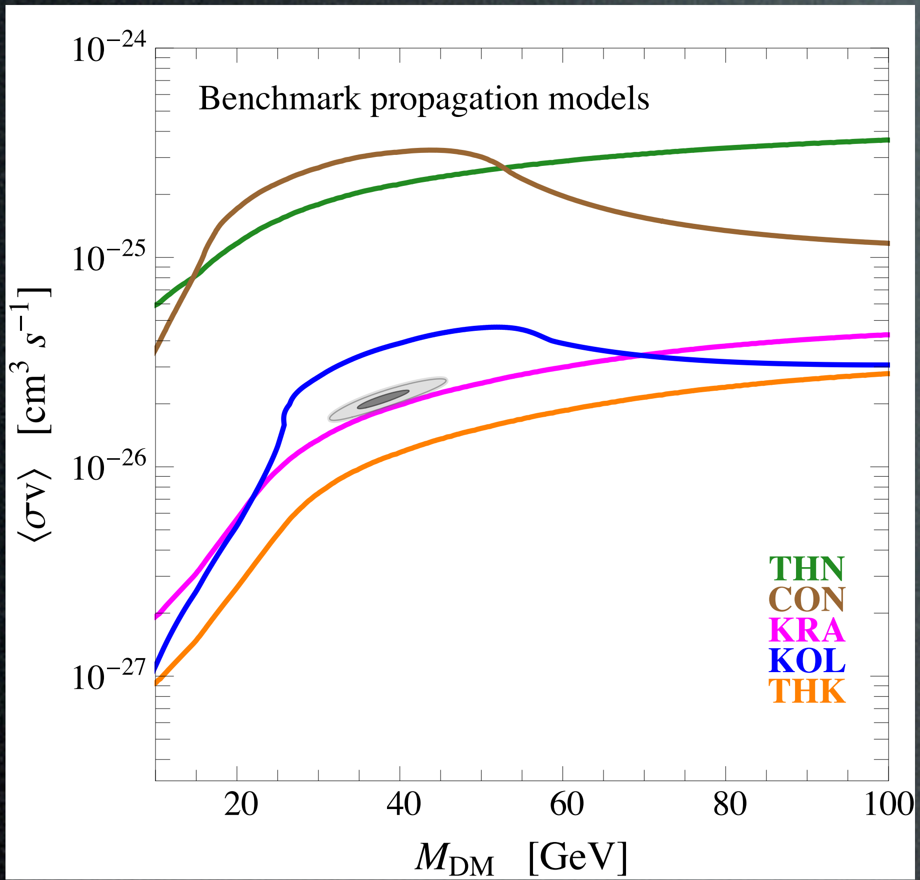
'Rule out' or
'considerable tension'.

'Significantly less stringent'.

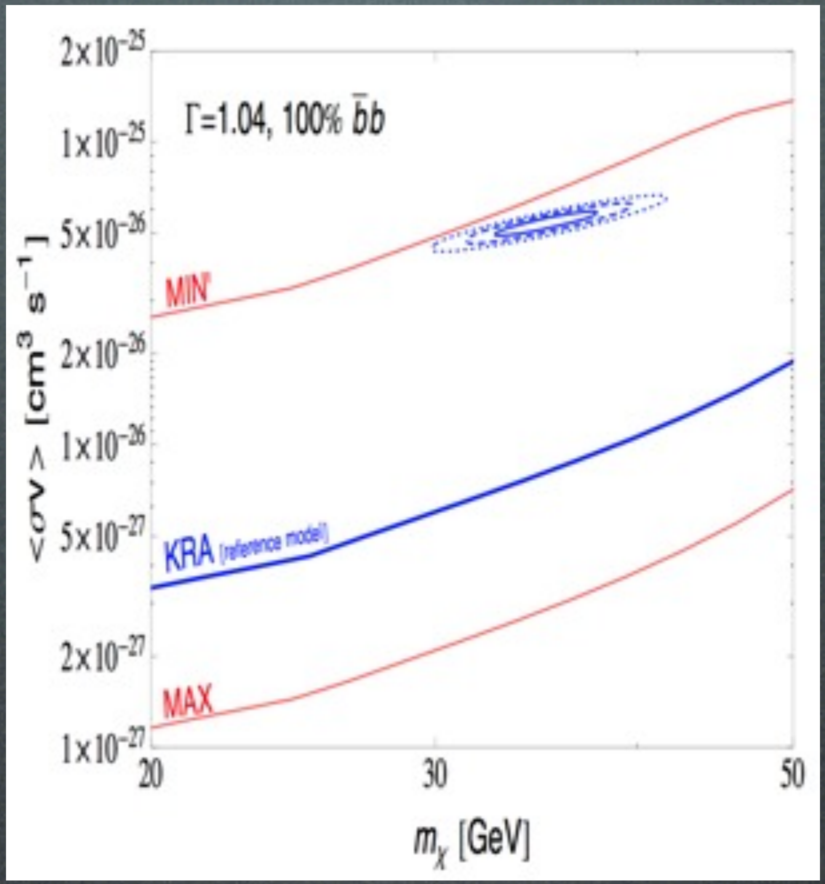
How come?!?

GeV gamma excess?

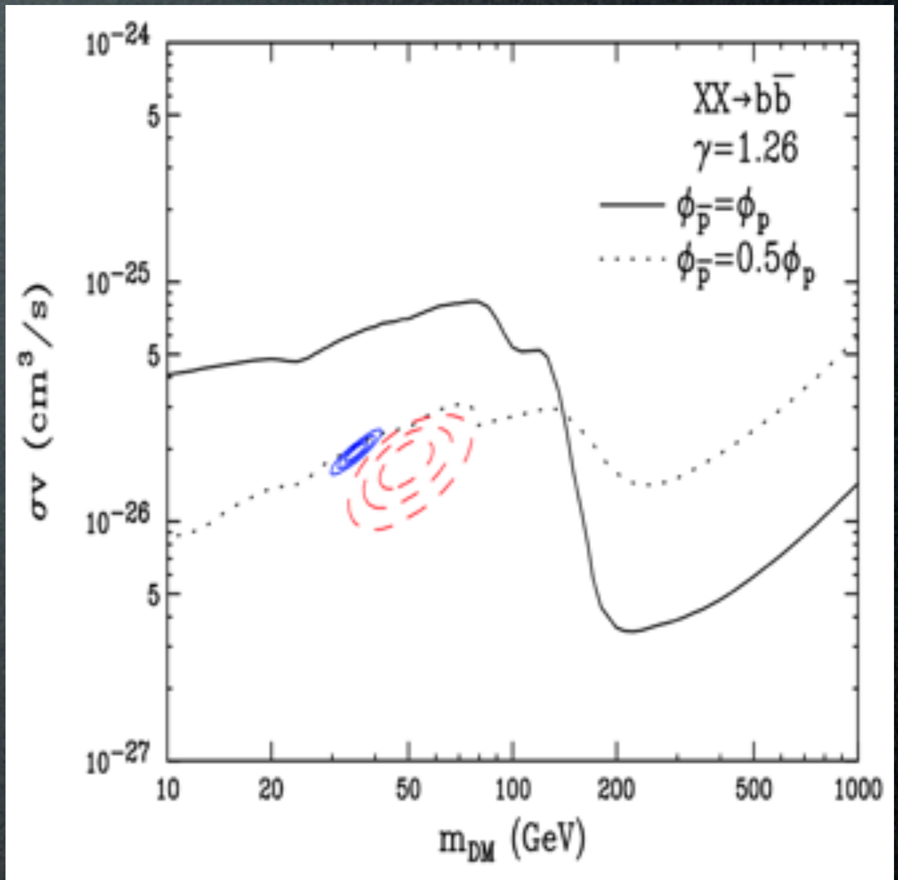
Antiproton constraints compared:



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'.

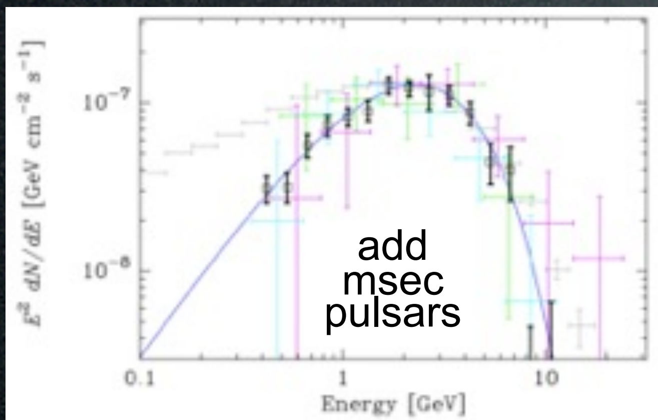
'Significantly less stringent'.

How come?!? The devil is in the (CR propagation) details:

solar modulation, convection, primary injection spectrum, tertiaries...

Astrophysical interpretation

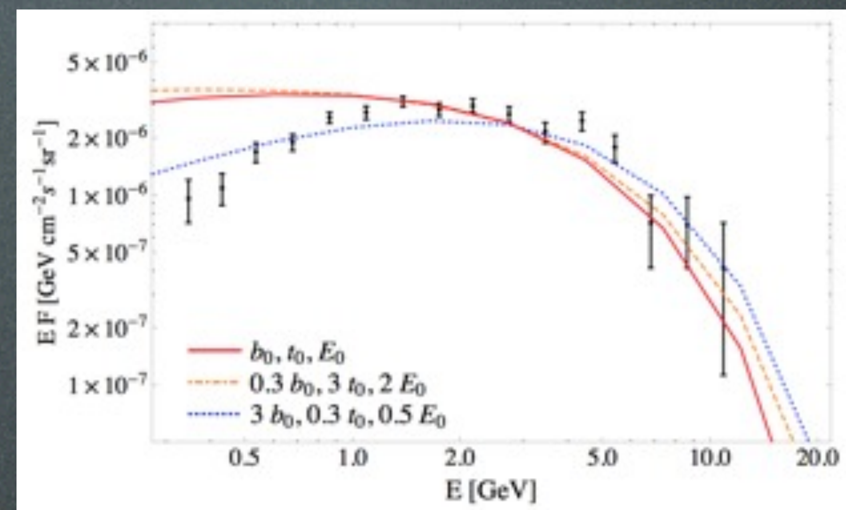
Millisec pulsars

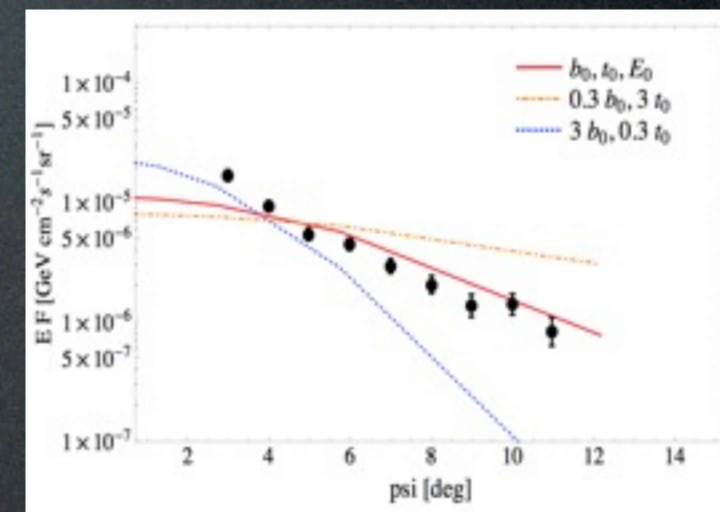


Abazajian 1011.4275
Hooper et al. 1305.0830
Yuan, Zhang 1404.2318
Petrović, Serpico, Zaharijas 1411.2980

A transient phenomenon:

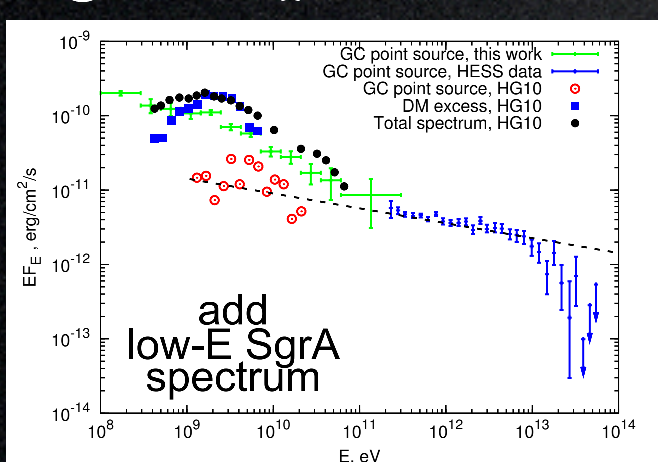
the GC spit 10^{52} ergs in $e^{\pm}$ 1 mln yrs ago and they do ICS on ambient light, ‘fits’ both spectrum and morphology Petrović, Serpico, Zaharijas 1405.7928





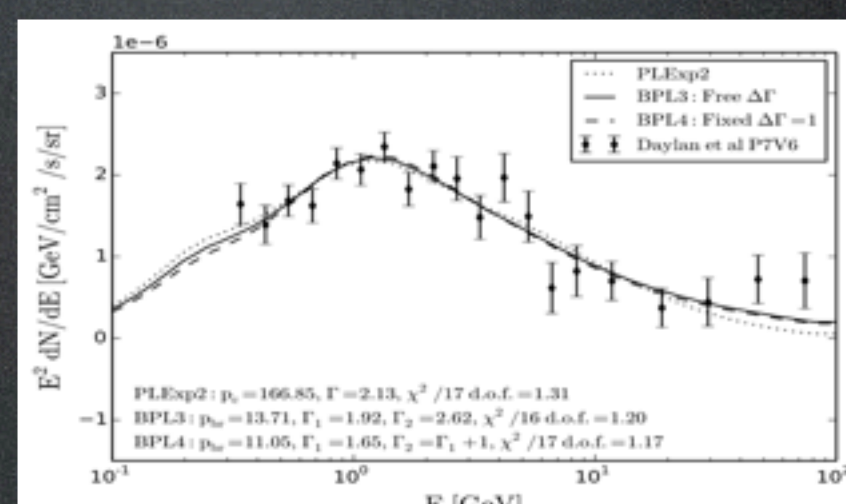
but: can one really get everything right?

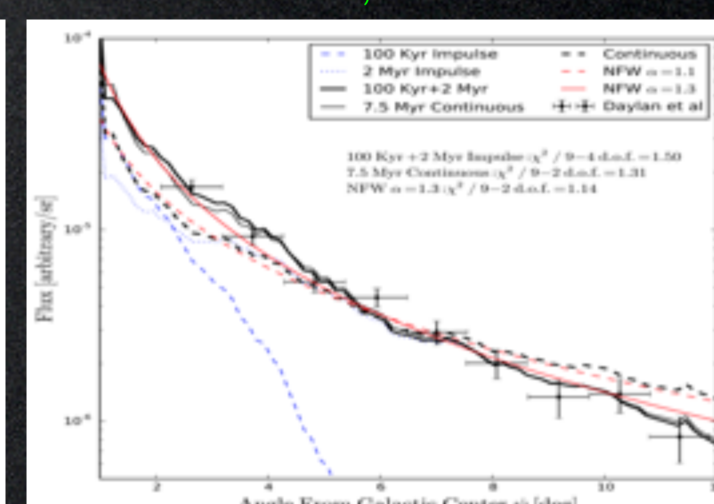
Non-trivial SgrA spectrum



Boyarsky et al., 1012.5839

a SN explosion spits protons 5000 yrs ago and they do spallations + bremsstrahlung as well as $e^{\pm}$ which do ICS... fits spectrum & morphology Carlson, Profumo 1405.7685





but: why correlation with gas density not seen?

Conclusions & Outlook

Hints

Constraints

Hopes

Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
HESS

γ FERMI

X XMM-Newton

Constraints

Hopes

Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
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γ FERMI

X XMM-Newton

Constraints

γ FERMI, HESS,
VERITAS etc

$\bar{p}$ PAMELA

ν SK, ICECUBE

Cosmology

Hopes

Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
HESS

γ FERMI

X XMM-Newton

Constraints

γ FERMI, HESS, VERITAS etc

$\bar{p}$ PAMELA

ν SK, ICECUBE

Cosmology

Hopes

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

γ ν

$\bar{p}$

AMS-02

- new theory directions

- ...

Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
HESS

γ FERMI

X XMM-Newton

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γ FERMI, HESS,
VERITAS etc

$\bar{p}$ PAMELA

ν SK, ICECUBE

Cosmology

Hopes

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

γ ν

$\bar{p}$

AMS-02

- new theory directions

- ...

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

Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
HESS

γ FERMI

X XMM-Newton

Constraints

γ FERMI, HESS,
VERITAS etc

$\bar{p}$ PAMELA

ν SK, ICECUBE

Cosmology

Hopes

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

γ ν

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AMS-02

- new theory directions

- ...

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

Old wise remarks:

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