1 December 2015
Prospects in Low Mass Dark Matter
MPI Munich

Challenges of Indirect Detection of low mass DM

Marco Cirelli
(CNRS LPTHE Jussieu)

1 December 2015
Prospects in Low Mass Dark Matter
MPI Munich

Challenges of Indirect Detection of low mass DM

Marco Cirelli
(CNRS LPTHE Jussieu)

1 December 2015
Prospects in Low Mass Dark Matter
MPI Munich

Challenges of Indirect Detection of low mass DM

$\lesssim$ 50 GeV

Marco Cirelli
(CNRS LPTHE Jussieu)

LPTHE PARIS

erc NewDark

OUTLINE

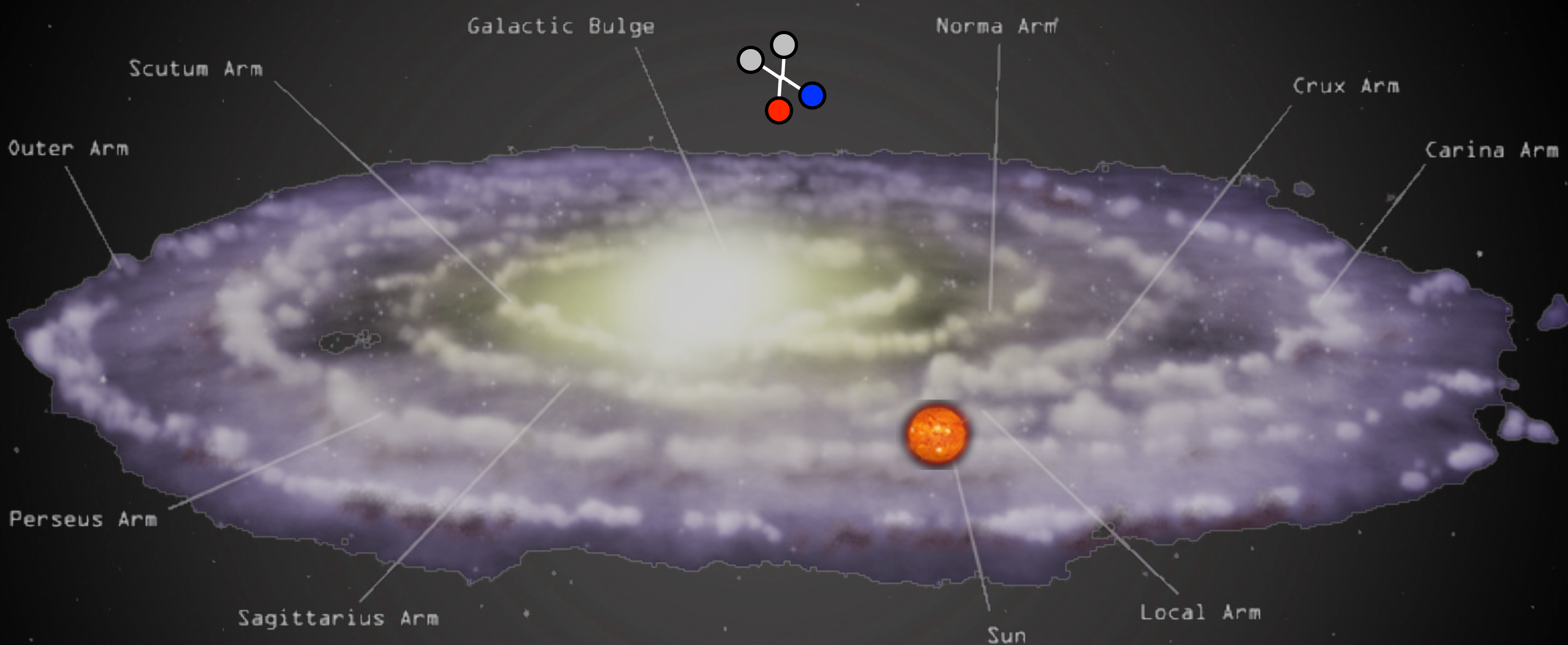
Antiprotons from low mass DM

Gamma-rays from low mass DM

The **GC GeV excess** as a case study

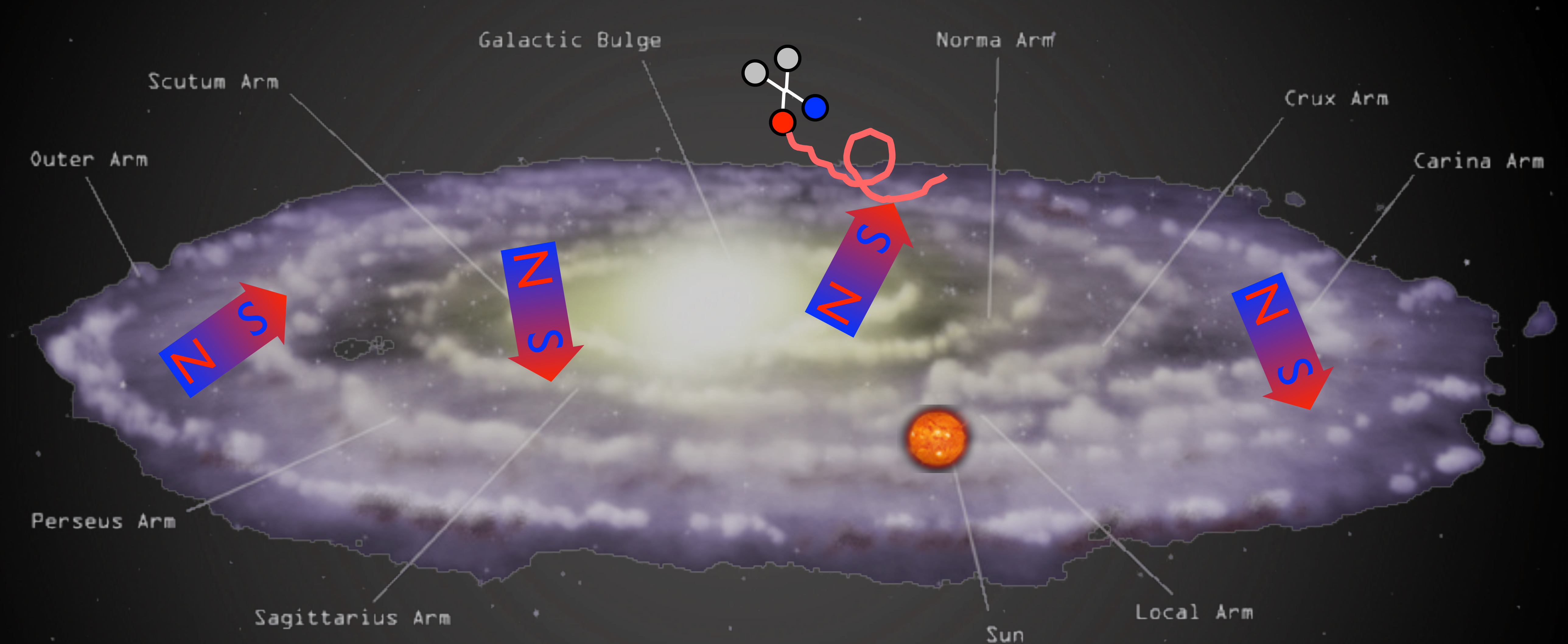
Indirect Detection: charged CRs

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



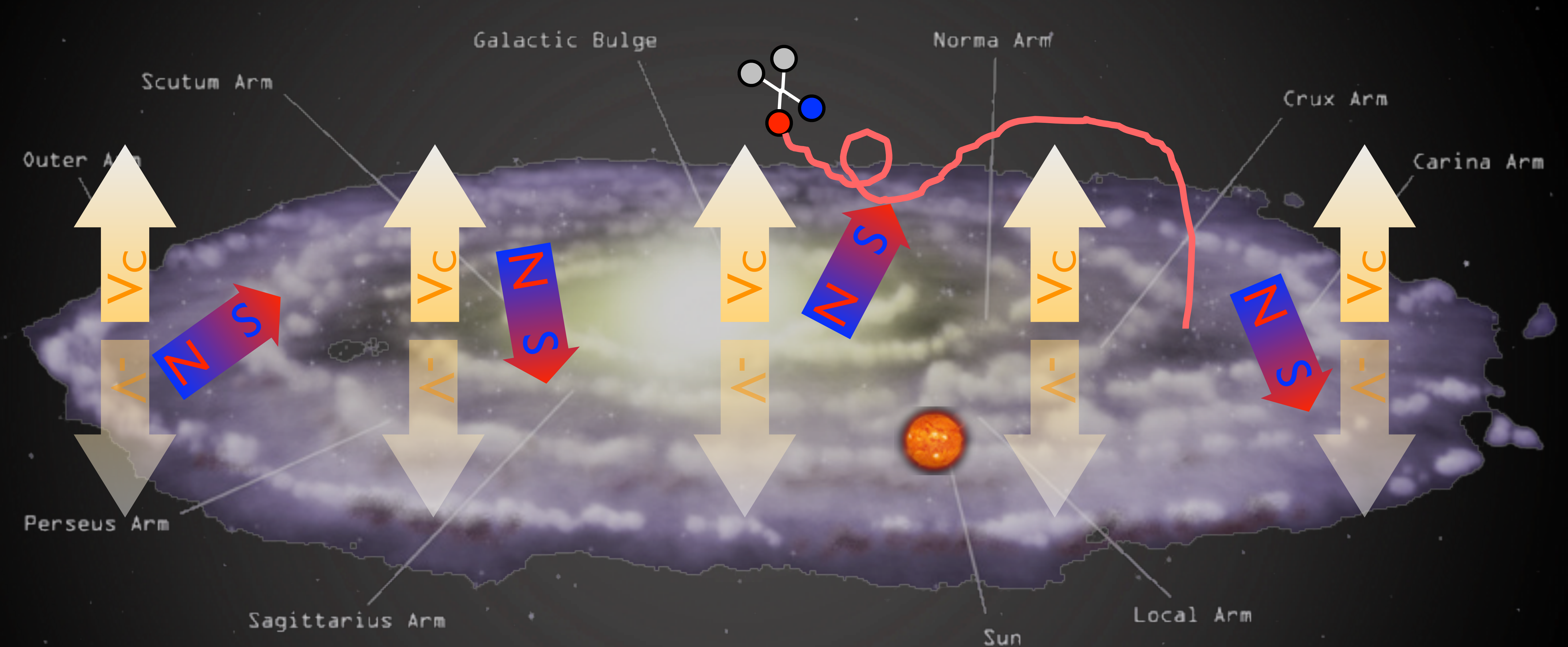
Indirect Detection: charged CRs

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



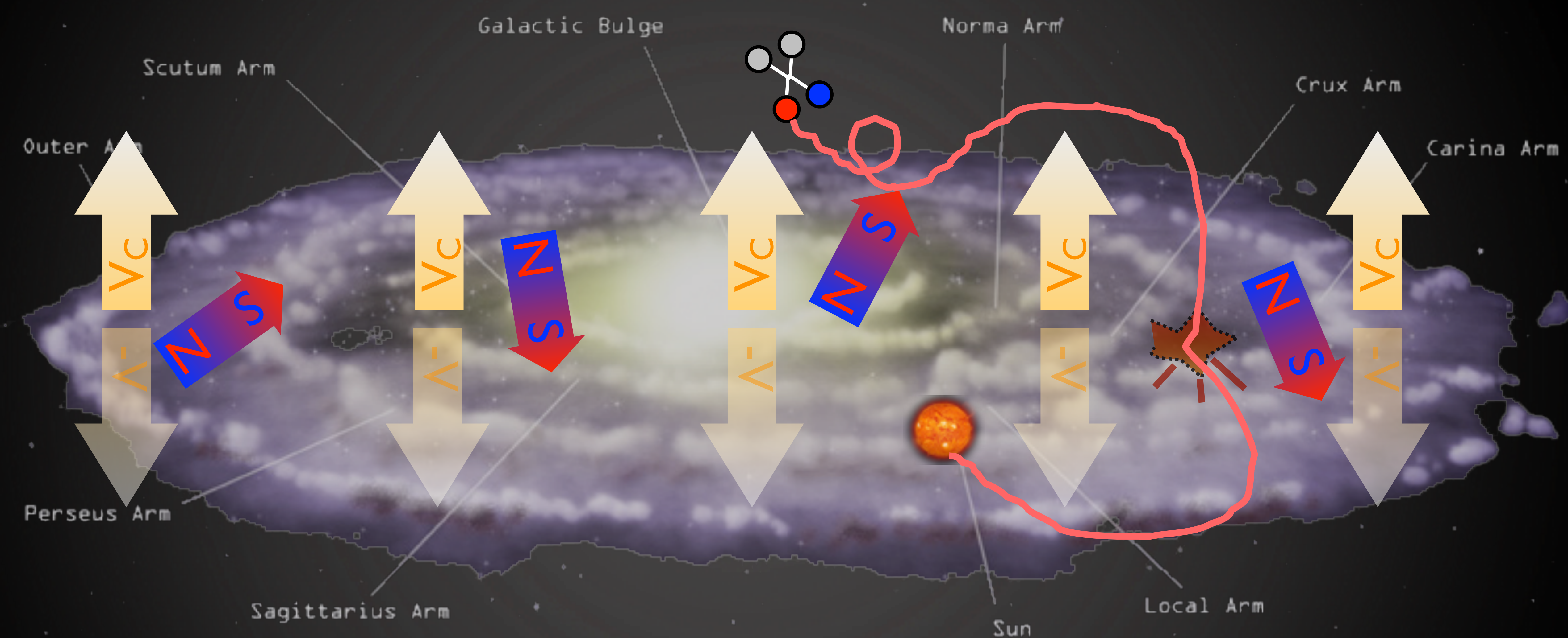
Indirect Detection: charged CRs

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



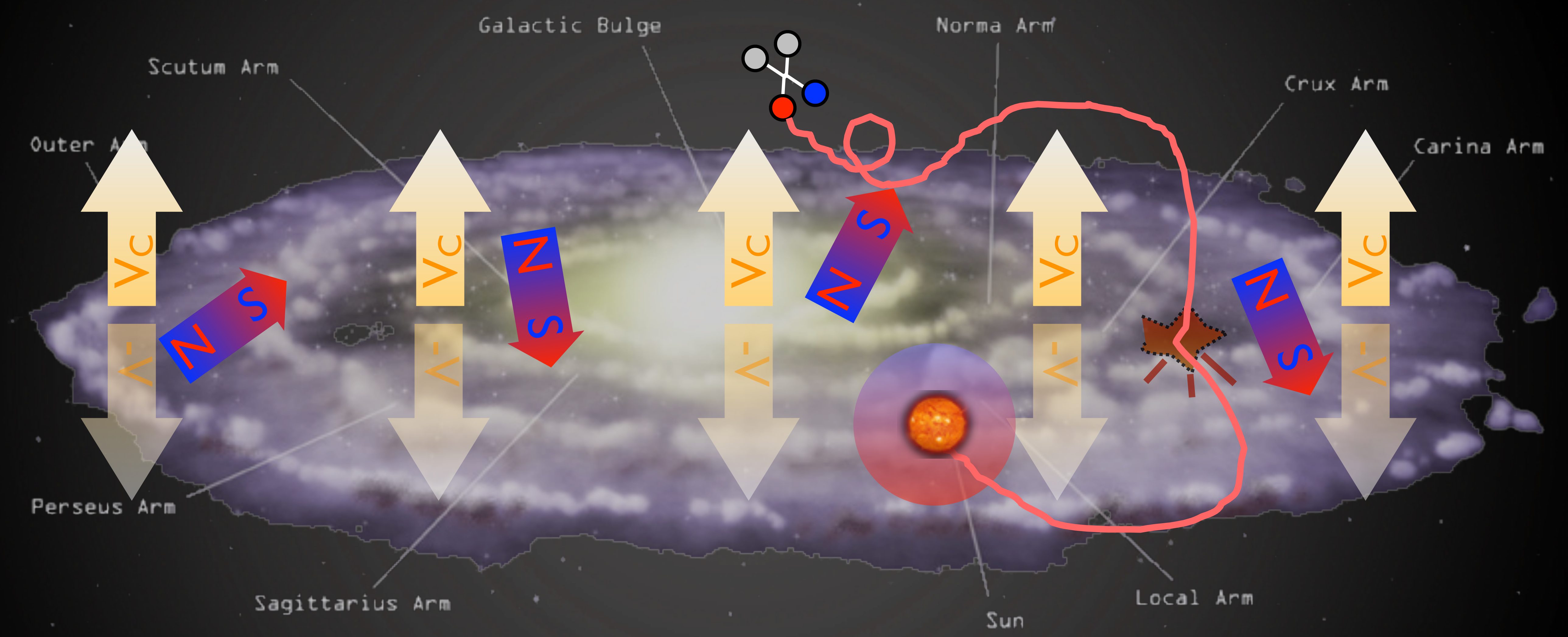
Indirect Detection: charged CRs

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



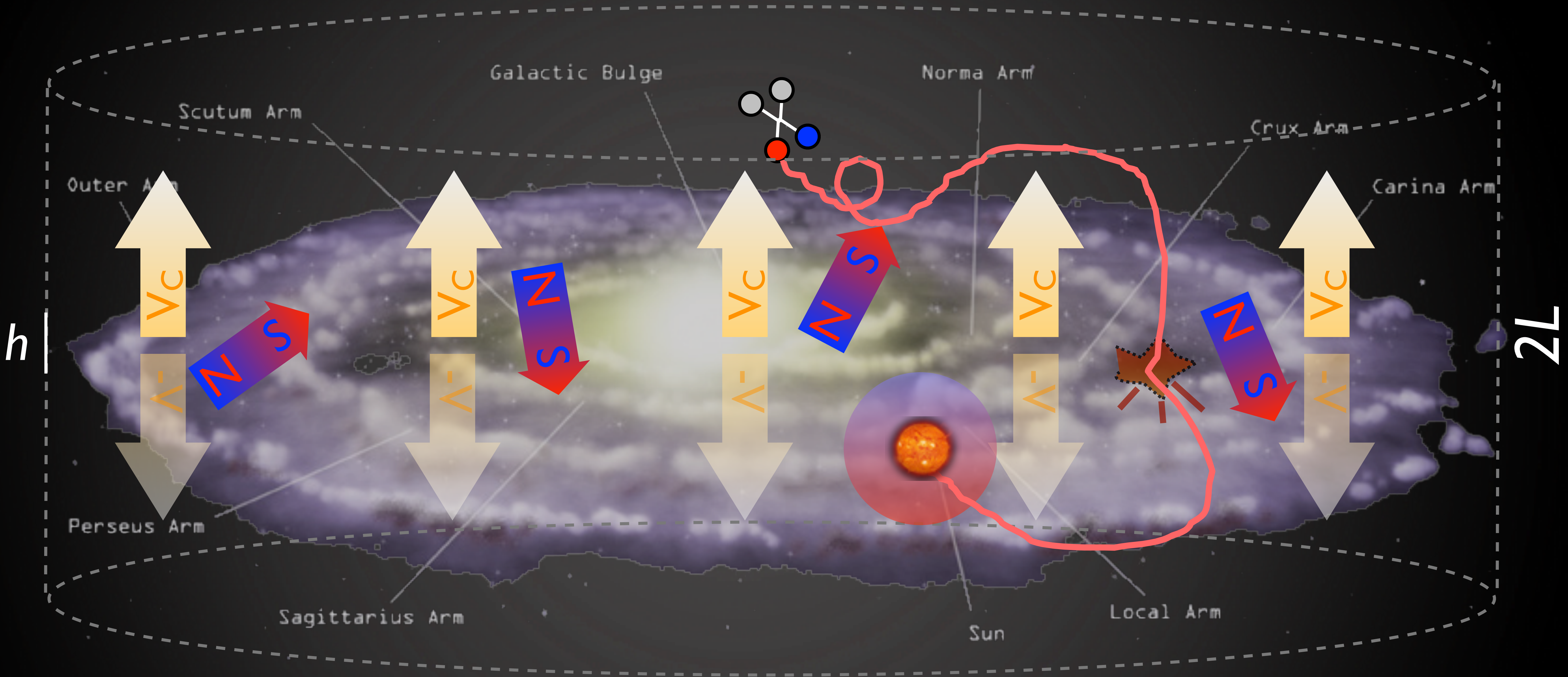
Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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



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
	$\chi^2_{\rm min}$/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]	$V_{\rm conv}$ [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

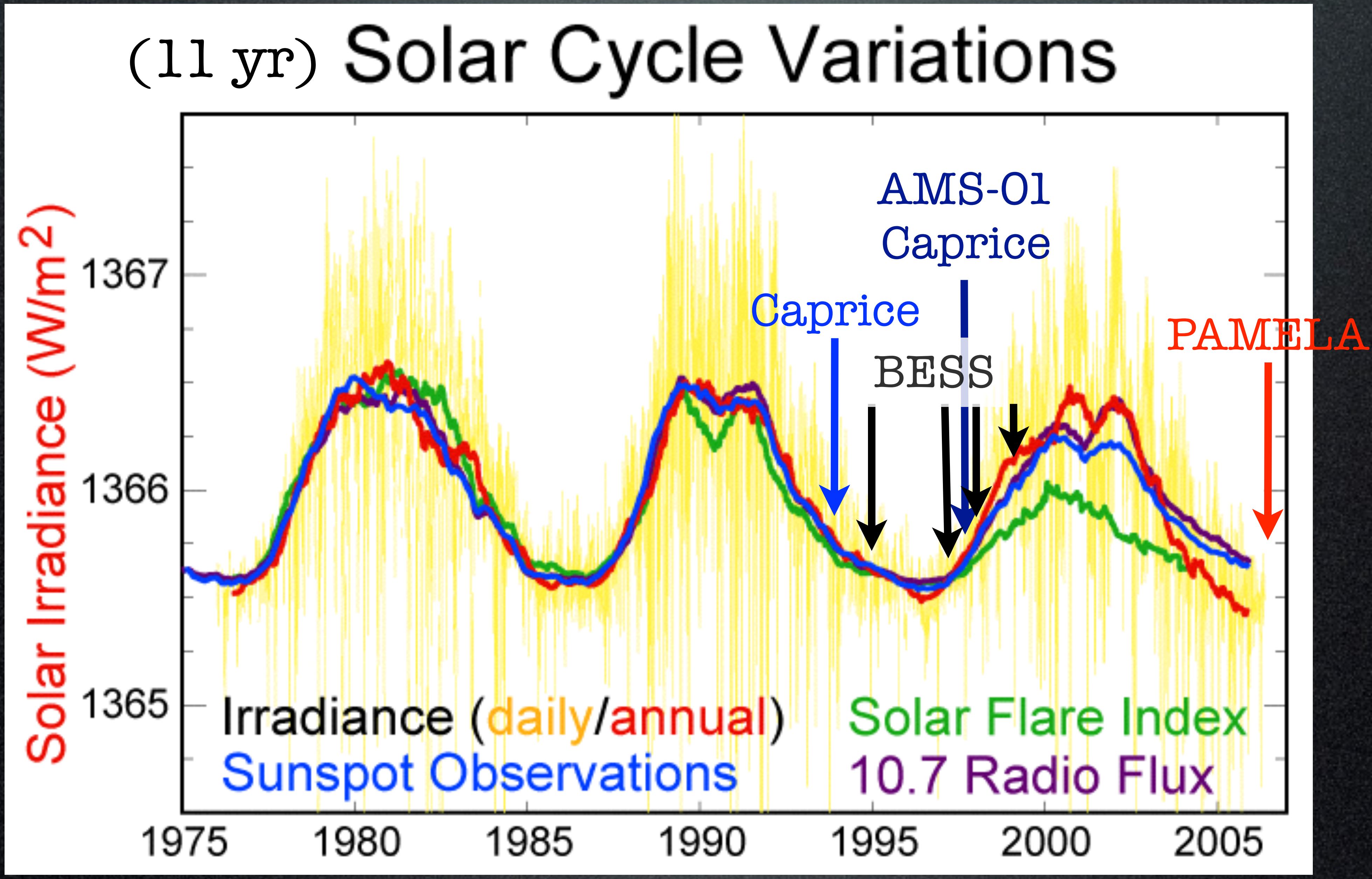
Donato et al., 2003+

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



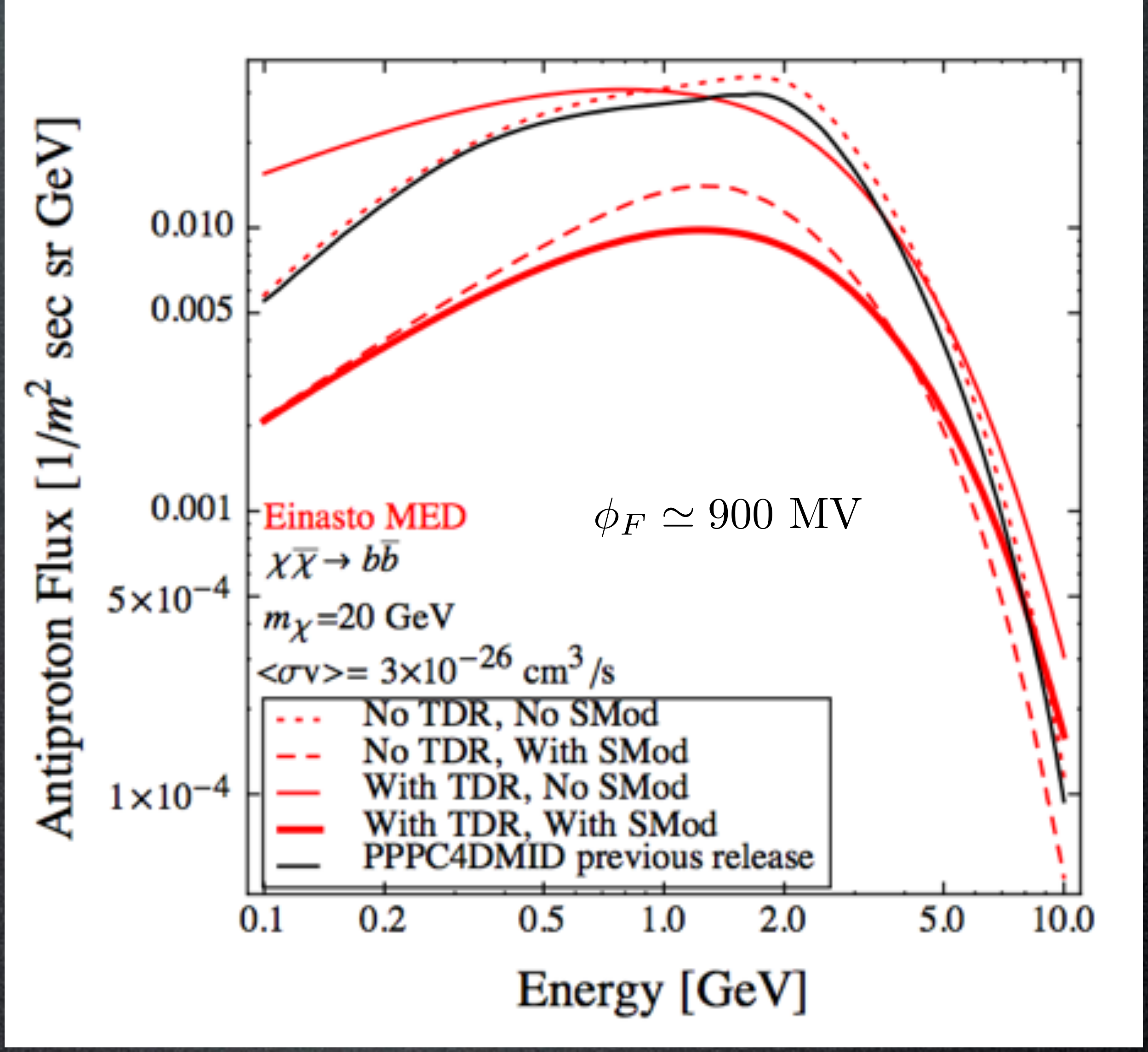
Indirect Detection: charged CRs

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

E.g.



Boudard, Cirelli, Giesen, Salati, 1412.5696

Indirect Detection: charged CRs

Solar wind Modulation of cosmic rays:
which value for ϕ_F?

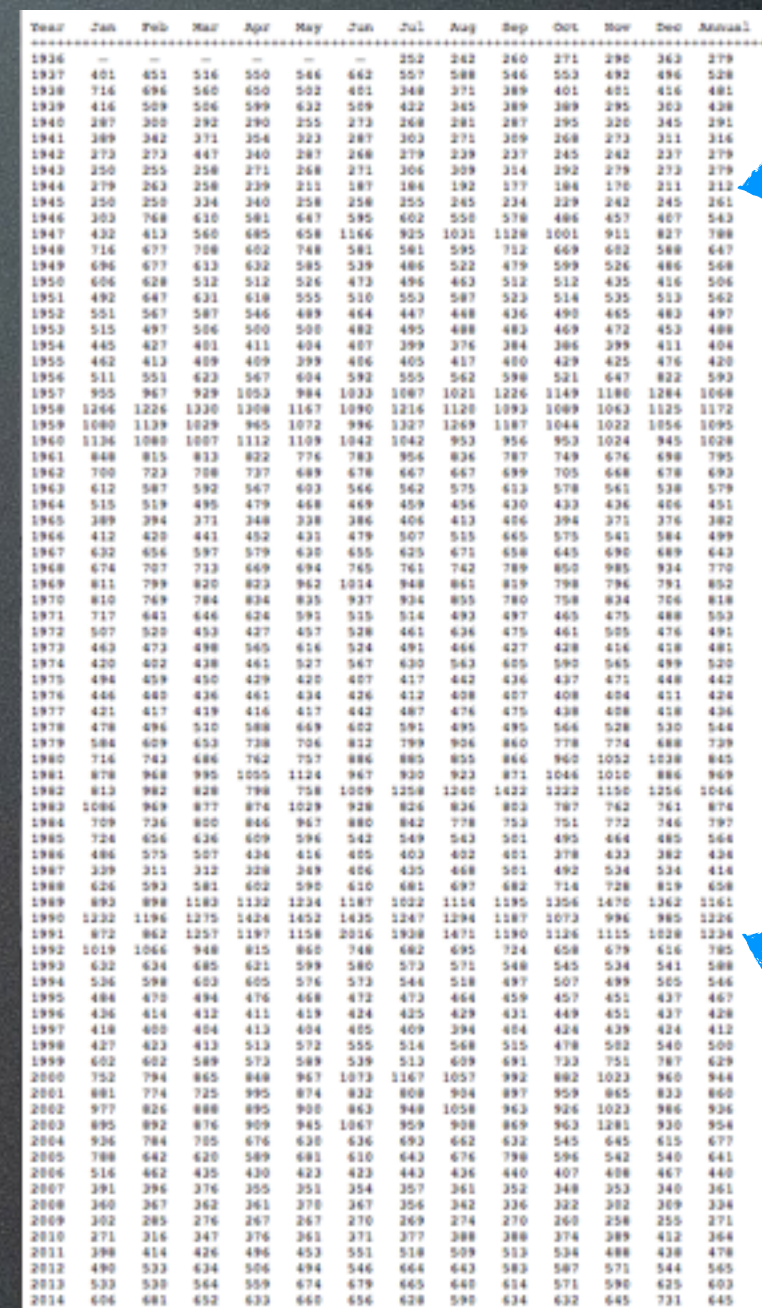
Dedicated code: HelioProp

L.Maccione, 2013

polarity	tilt angle α [deg]	m.f.p. λ_0 [AU]	δ [-]	ϕ_p [GV]	$\phi_{\bar{p}}$[GV]	rel. diff. [%]
-1.00	10.00	0.05	0.30	1.18	1.18	0.00%
-1.00	10.00	0.05	0.50	1.18	1.18	0.00%
-1.00	10.00	0.05	1.00	1.12	1.12	0.00%
-1.00	10.00	0.10	0.30	1.06	1.10	3.77%
-1.00	10.00	0.10	0.50	1.02	1.10	7.84%
-1.00	10.00	0.10	1.00	1.02	1.10	7.84%
-1.00	10.00	0.20	0.30	0.78	0.96	23.08%
-1.00	10.00	0.20	0.50	0.74	0.90	21.62%
-1.00	10.00	0.20	1.00	0.60	0.74	23.33%
-1.00	10.00	0.30	0.30	0.60	0.82	36.67%
-1.00	10.00	0.30	0.50	0.54	0.76	40.74%
-1.00	10.00	0.30	1.00	0.46	0.58	26.09%
-1.00	10.00	0.40	0.30	0.36	0.46	27.78%
-1.00	10.00	0.40	1.00	0.48	0.72	50.00%
-1.00	20.00	0.05	0.30	1.46	1.18	-19.18%
-1.00	20.00	0.05	1.00	1.28	1.12	-12.50%
-1.00	20.00	0.40	0.30	0.48	0.72	50.00%
-1.00	20.00	0.40	1.00	0.36	0.46	27.78%
-1.00	40.00	0.05	0.30	1.56	1.18	-24.36 %
-1.00	40.00	0.40	0.30	0.50	0.70	40.00%
-1.00	40.00	0.40	1.00	0.38	0.44	15.79%
-1.00	60.00	0.05	0.30	1.50	1.86	24.00%
-1.00	60.00	0.05	1.00	1.18	1.34	13.56%
-1.00	60.00	0.40	0.30	0.50	0.66	32.00%
-1.00	60.00	0.40	1.00	0.40	0.42	5.00 %

$$\phi_F^{\bar{p}} = \phi_F^p \pm 50\%$$

Neutron monitors



http://cosmicrays.oulu.fi/phi/Phi_mon.txt

212 MV

1234 MV

How does DM produce γ-rays?

1. prompt emission

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

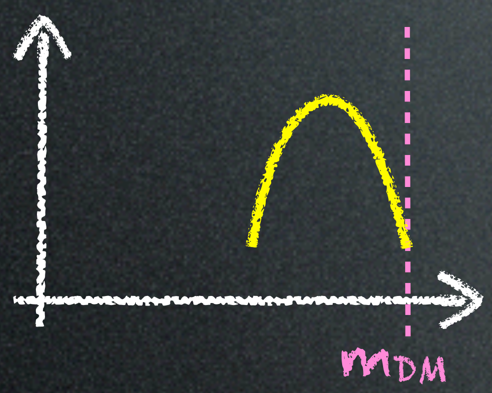
2. secondary emission

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

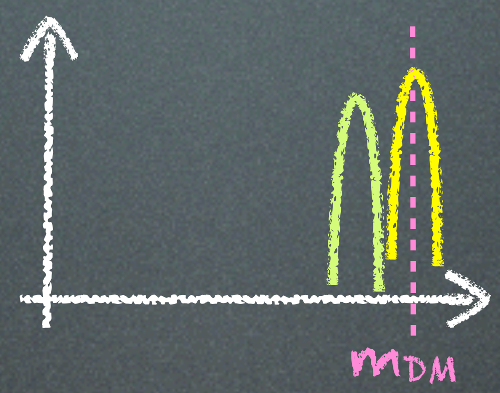
How does DM produce γ-rays?

1. prompt emission

1a. continuum



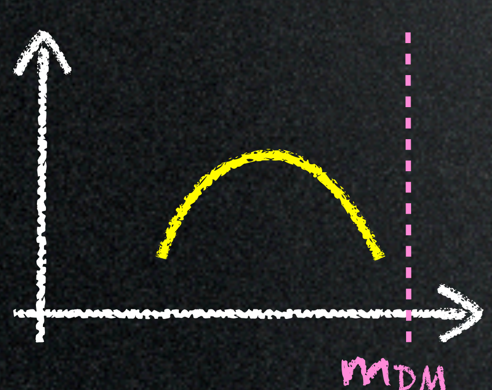
1b. line(s)



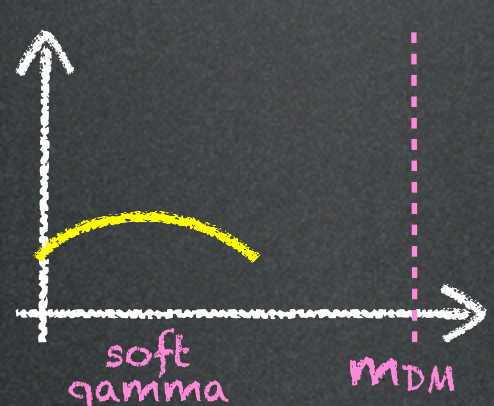
1c. sharp features

2. secondary emission

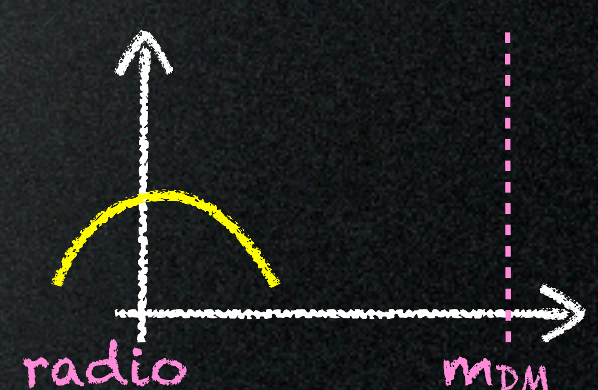
2a. ICS



2b. bremsstrahlung



2c. synchrotron

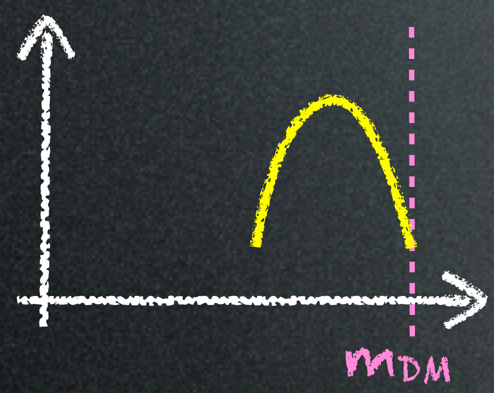


How does DM produce γ-rays?

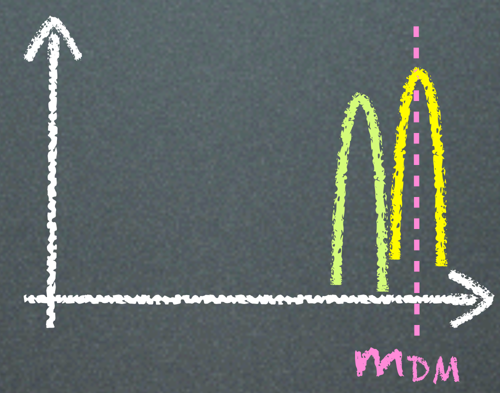
environment-independent

1. prompt emission

1a. continuum



1b. line(s)

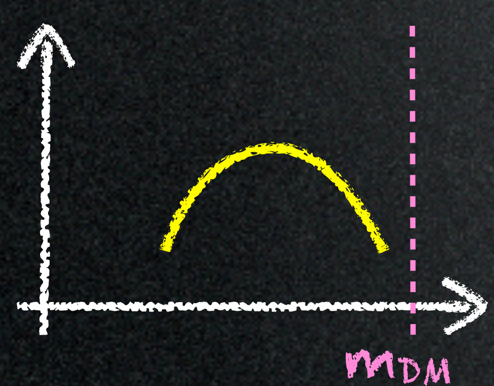


1c. sharp features

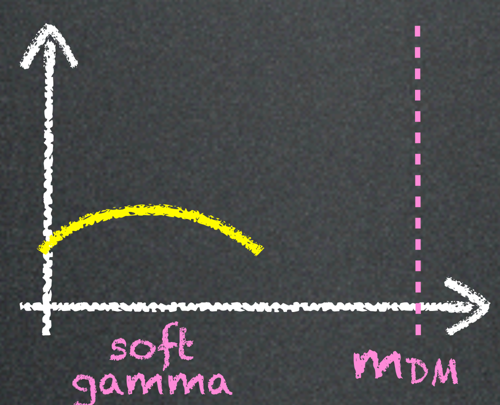
environment-dependent

2. secondary emission

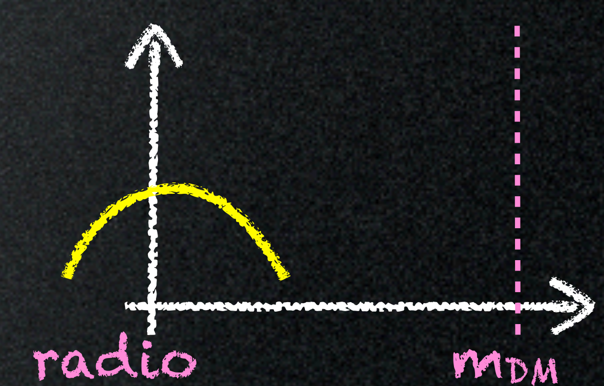
2a. ICS



2b. bremsstrahlung

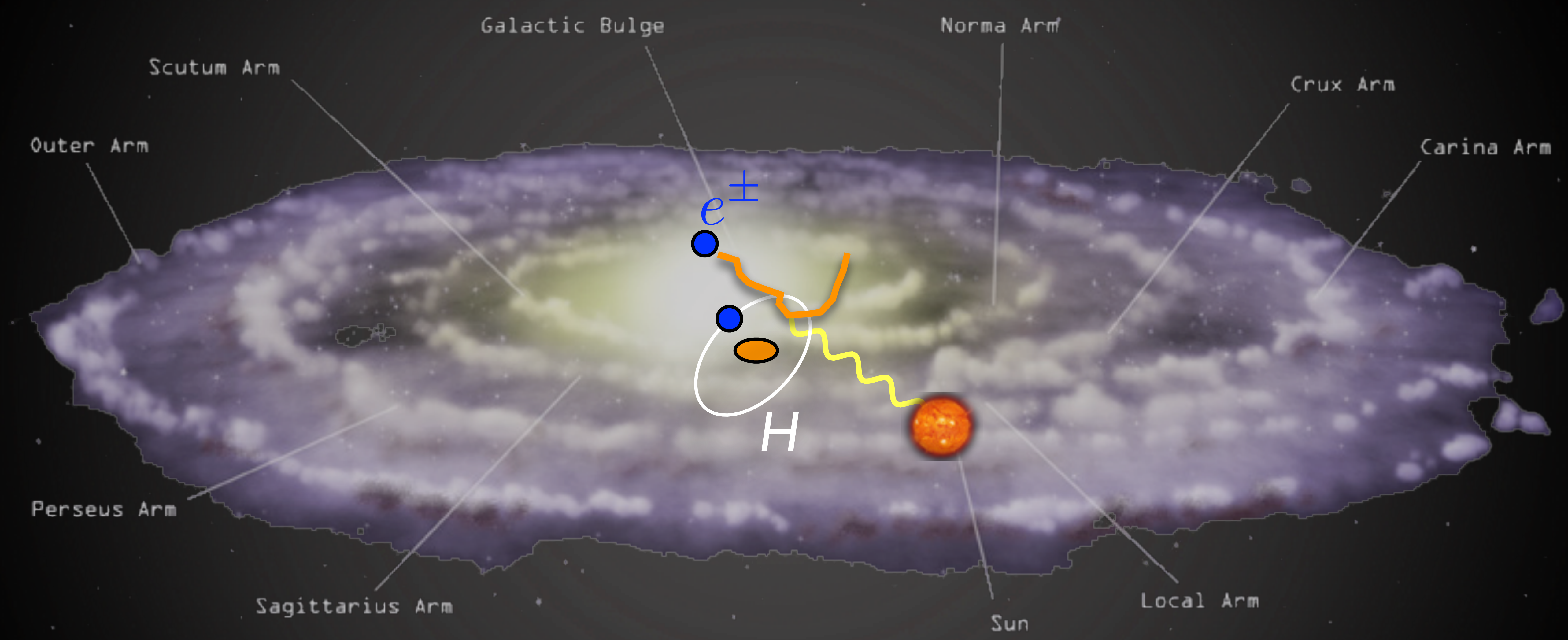


2c. synchrotron



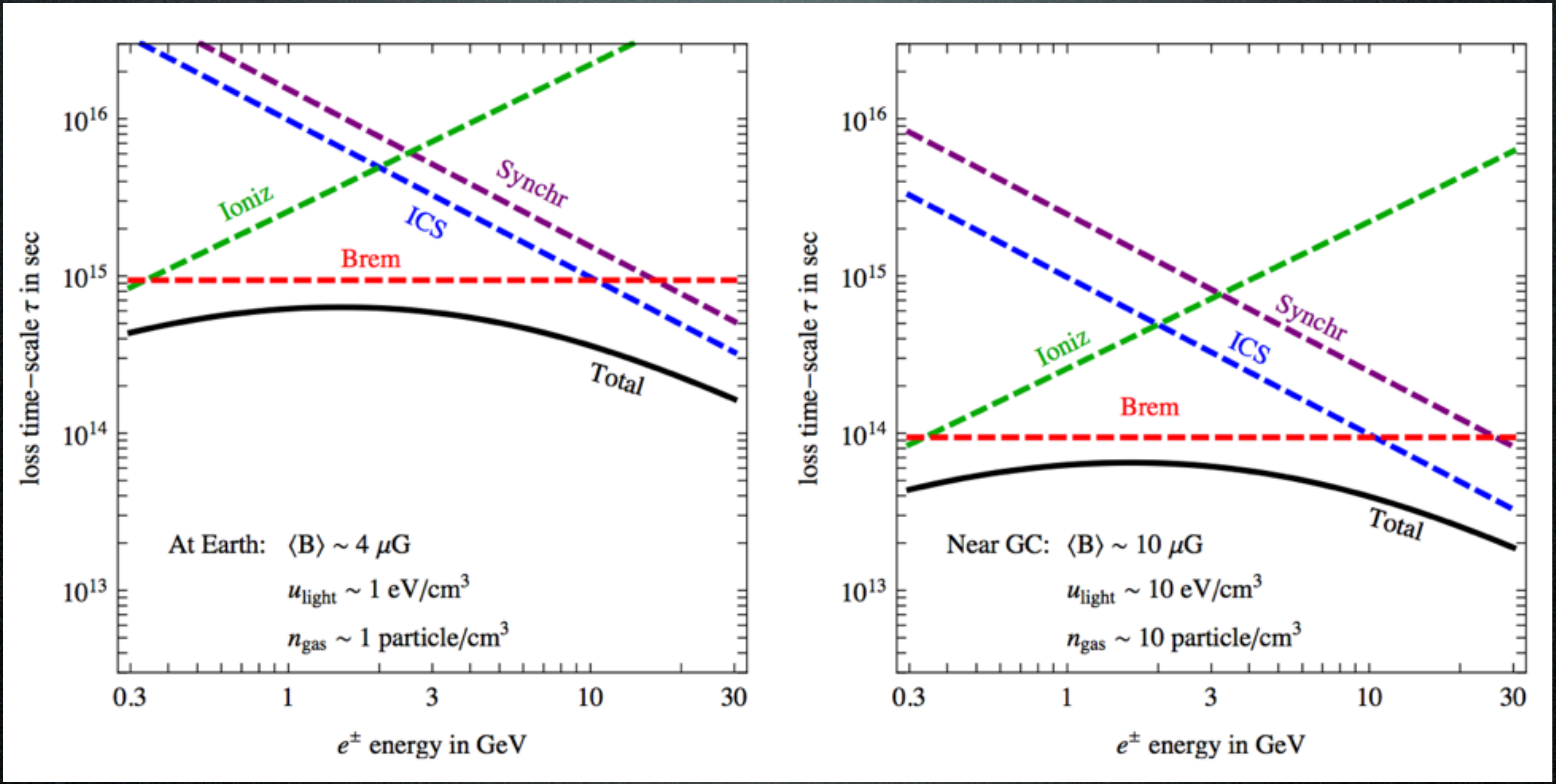
Secondary emission

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



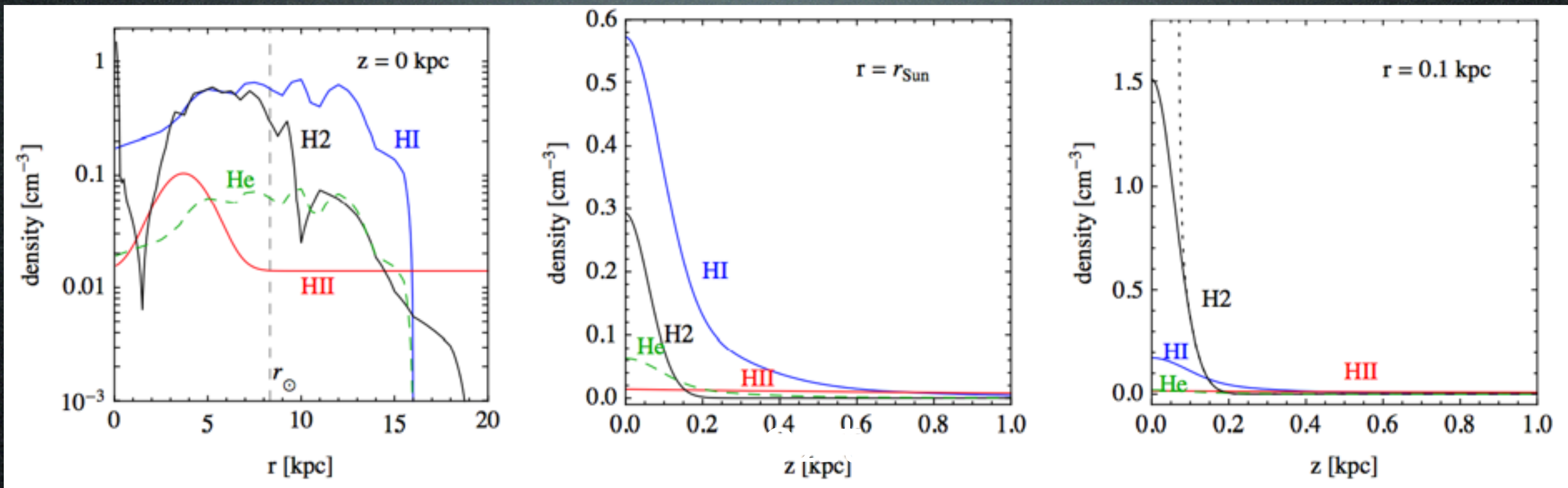
- (very) relevant at low energy, in the disk and at the GC

Relative importance of secondary emissions



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

Gas maps



But: inner kpc of the Galaxy is denser
(and more uncertain)

SNB	CMZ	CNR
Stellar Nuclear Bulge	Central Molecular Zone	Circum-Nuclear Ring
< 1 kpc	< 200 pc	< 3 pc
?	10^2-10^3 /cm^3	10^5/cm^3

Formalism

Formalism

Bremsstrahlung gamma emission:

$$\frac{\mathrm{d}\mathcal{E}_{\gamma,\mathrm{brem}}(\vec{x})}{\mathrm{d}E_\gamma} = \sum_i n_i(\vec{x}) \int_{E_L} \mathrm{d}E_{e^\pm}\ 2\frac{\mathrm{d}\Phi_{e^\pm}(\vec{x})}{\mathrm{d}E_{e^\pm}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_\gamma}$$

Formalism

Bremsstrahlung gamma emission:

$$\frac{\mathrm{d}\mathcal{E}_{\gamma,\mathrm{brem}}(\vec{x})}{\mathrm{d}E_\gamma} = \sum_i n_i(\vec{x}) \int_{E_L} \mathrm{d}E_{e^\pm}\ 2\frac{\mathrm{d}\Phi_{e^\pm}(\vec{x})}{\mathrm{d}E_{e^\pm}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_\gamma}$$

bremsstrahlung differential cross section

$$\frac{\mathrm{d}\sigma_i(E_{e^\pm}, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{3\,\alpha_{\mathrm{em}}\sigma_T}{8\pi\, E_\gamma}\left\{\left[1+\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)^2\right]\phi_1^i - \frac{2}{3}\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)\phi_2^i\right\}$$

Formalism

Bremsstrahlung gamma emission:

$$\frac{\mathrm{d}\mathcal{E}_{\gamma,\mathrm{brem}}(\vec{x})}{\mathrm{d}E_\gamma} = \sum_i n_i(\vec{x}) \int_{E_L} \mathrm{d}E_{e^\pm}\ 2\frac{\mathrm{d}\Phi_{e^\pm}(\vec{x})}{\mathrm{d}E_{e^\pm}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_\gamma}$$

$e^\pm$ population

bremsstrahlung differential cross section

$$\frac{\mathrm{d}\sigma_i(E_{e^\pm}, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{3\,\alpha_{\mathrm{em}}\sigma_T}{8\pi\, E_\gamma}\left\{\left[1+\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)^2\right]\phi_1^i - \frac{2}{3}\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)\phi_2^i\right\}$$

Formalism

Bremsstrahlung gamma emission:

$$\frac{\mathrm{d}\mathcal{E}_{\gamma,\mathrm{brem}}(\vec{x})}{\mathrm{d}E_\gamma} = \sum_i n_i(\vec{x}) \int_{E_L} \mathrm{d}E_{e^\pm}\; 2\frac{\mathrm{d}\Phi_{e^\pm}(\vec{x})}{\mathrm{d}E_{e^\pm}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_\gamma}$$

gas density

$e^{\pm}$ population

bremsstrahlung differential cross section

$$\frac{\mathrm{d}\sigma_i(E_{e^\pm}, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{3\,\alpha_{\mathrm{em}}\sigma_T}{8\pi\,E_\gamma}\left\{\left[1+\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)^2\right]\phi_1^i - \frac{2}{3}\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)\phi_2^i\right\}$$

Formalism

Bremsstrahlung gamma emission:

$$\frac{\mathrm{d}\mathcal{E}_{\gamma,\mathrm{brem}}(\vec{x})}{\mathrm{d}E_\gamma} = \sum_i n_i(\vec{x}) \int_{E_L} \mathrm{d}E_{e^\pm}\; 2\frac{\mathrm{d}\Phi_{e^\pm}(\vec{x})}{\mathrm{d}E_{e^\pm}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_\gamma}$$

gas density

$e^\pm$ population

bremsstrahlung differential cross section

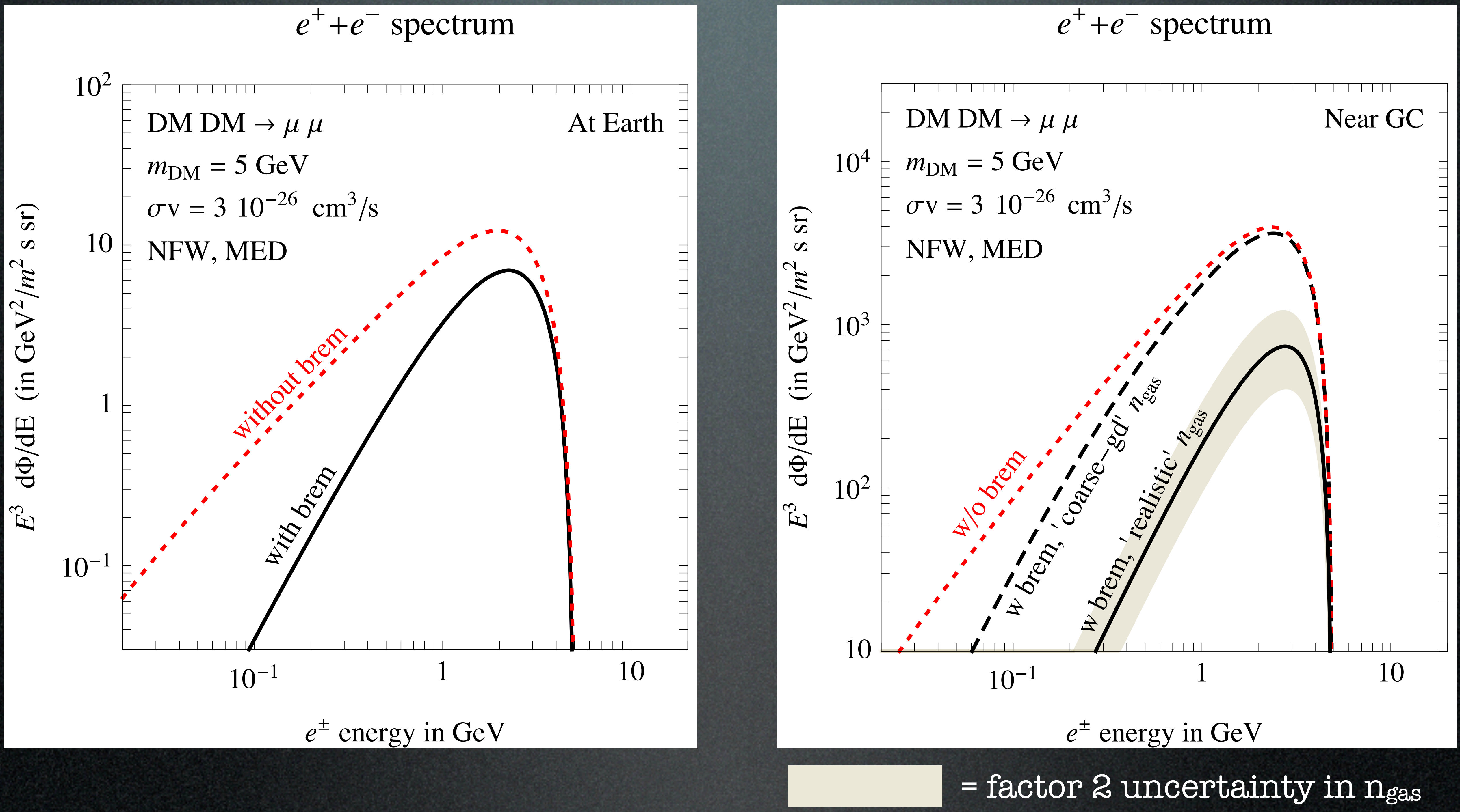
$$\frac{\mathrm{d}\sigma_i(E_{e^\pm}, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{3\,\alpha_{\mathrm{em}}\sigma_T}{8\pi\, E_\gamma}\left\{\left[1+\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)^2\right]\phi_1^i - \frac{2}{3}\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)\phi_2^i\right\}$$

$$\phi_1^{\mathrm{ion}}(E_{e^\pm}, E_\gamma) = \phi_2^{\mathrm{ion}}(E_{e^\pm}, E_\gamma) = 4(Z^2+Z)\left\{\log\left[\frac{2E_{e^\pm}}{m\,c^2}\left(\frac{E_{e^\pm}-E_\gamma}{E_\gamma}\right)\right] - \frac{1}{2}\right\}$$

$$\begin{aligned}
\phi_1^{\mathrm{H}}(\Delta=0) &\equiv \phi_{1,\mathrm{ss}}^{\mathrm{H}} = 45.79,\\
\phi_2^{\mathrm{H}}(\Delta=0) &\equiv \phi_{2,\mathrm{ss}}^{\mathrm{H}} = 44.46,\\
\phi_1^{\mathrm{He}}(\Delta=0) &\equiv \phi_{1,\mathrm{ss}}^{\mathrm{He}} = 134.60,\\
\phi_2^{\mathrm{He}}(\Delta=0) &\equiv \phi_{2,\mathrm{ss}}^{\mathrm{He}} = 131.40,\\
\phi_{(1,2)}^{\mathrm{H}_2}(\Delta=0) &\simeq 2\,\phi_{(1,2),\mathrm{ss}}^{\mathrm{H}},
\end{aligned}$$

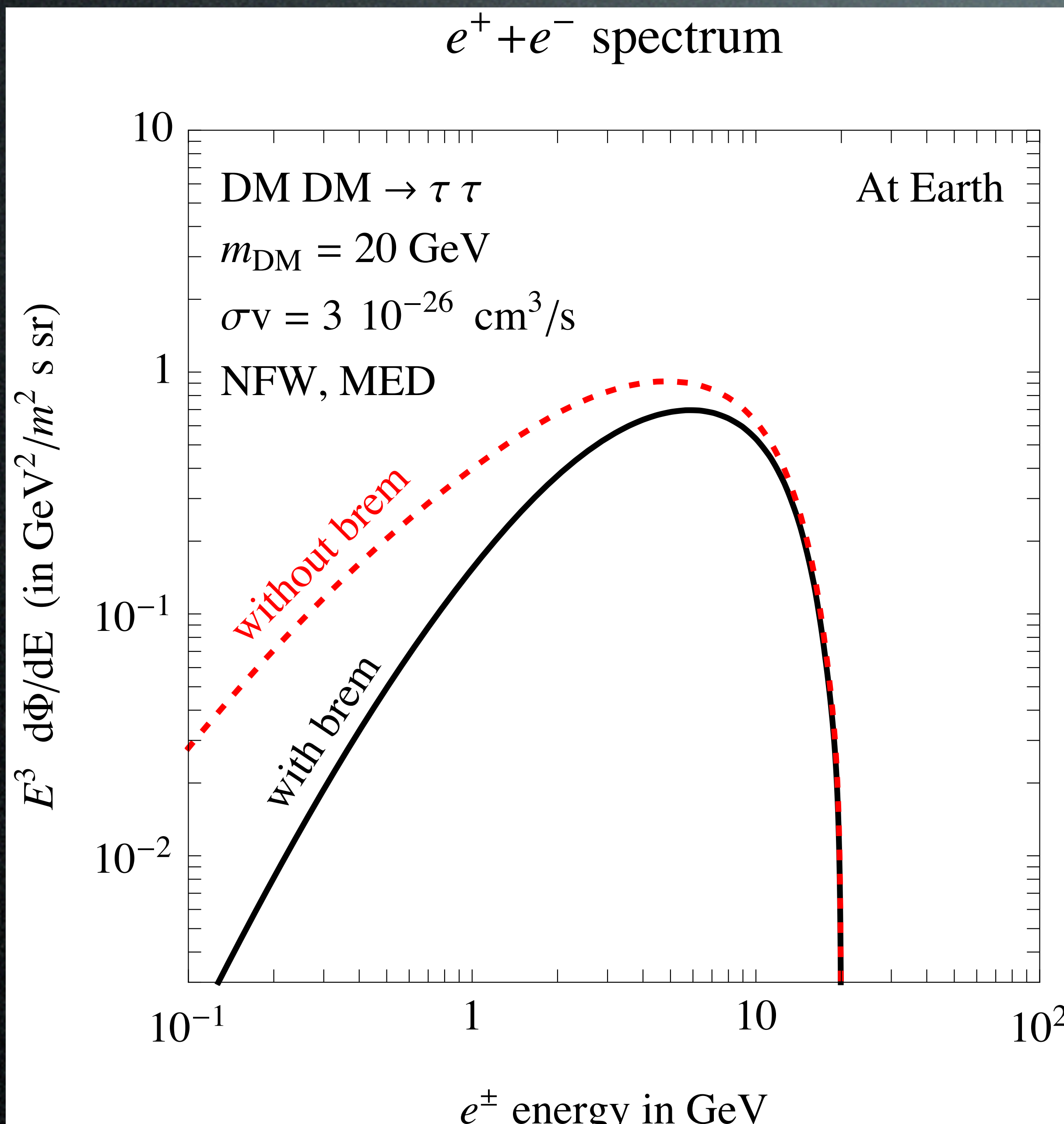
Results

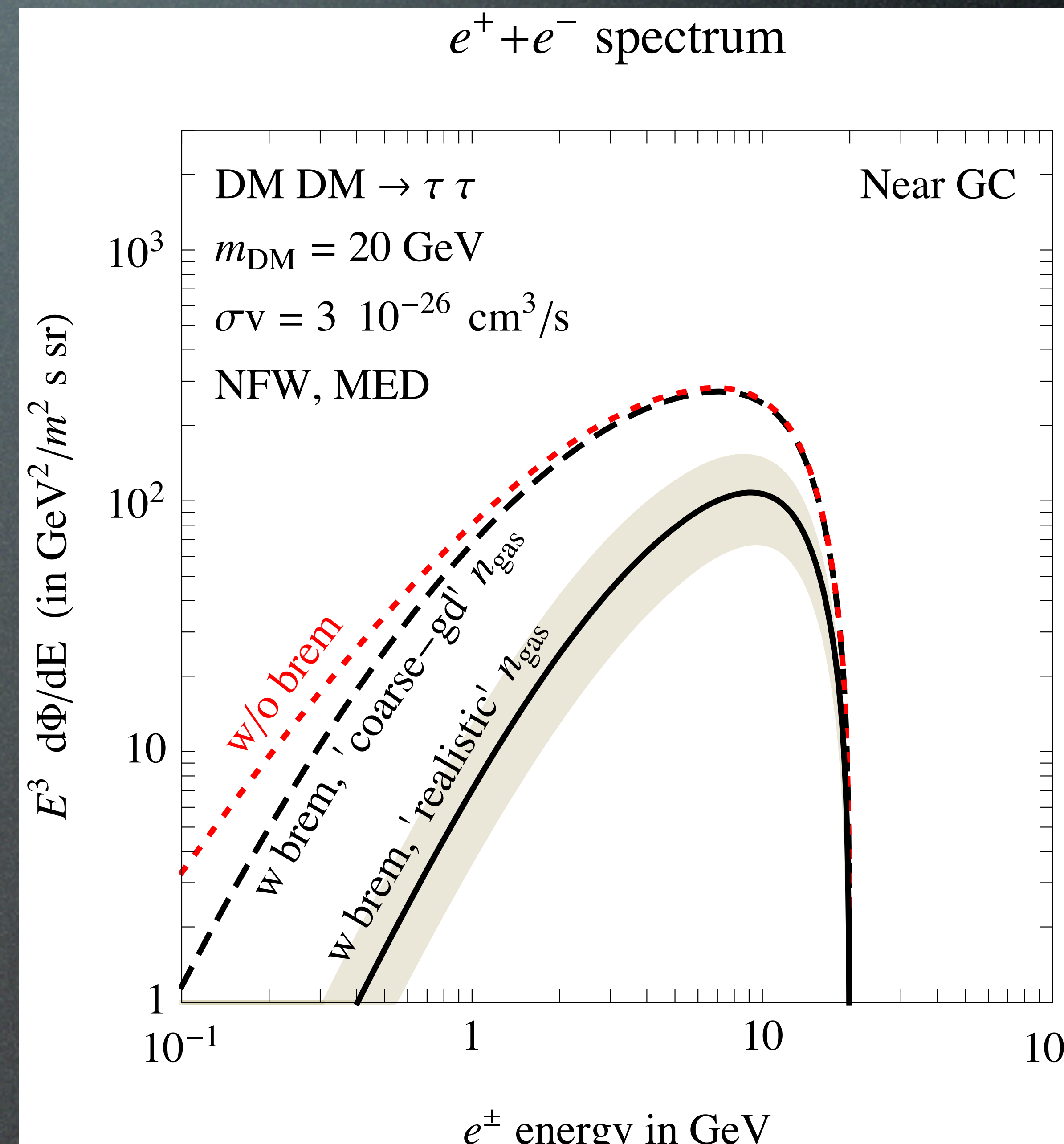
The e± population is affected by bremsstrahlung



Results

The e± population is affected by bremsstrahlung

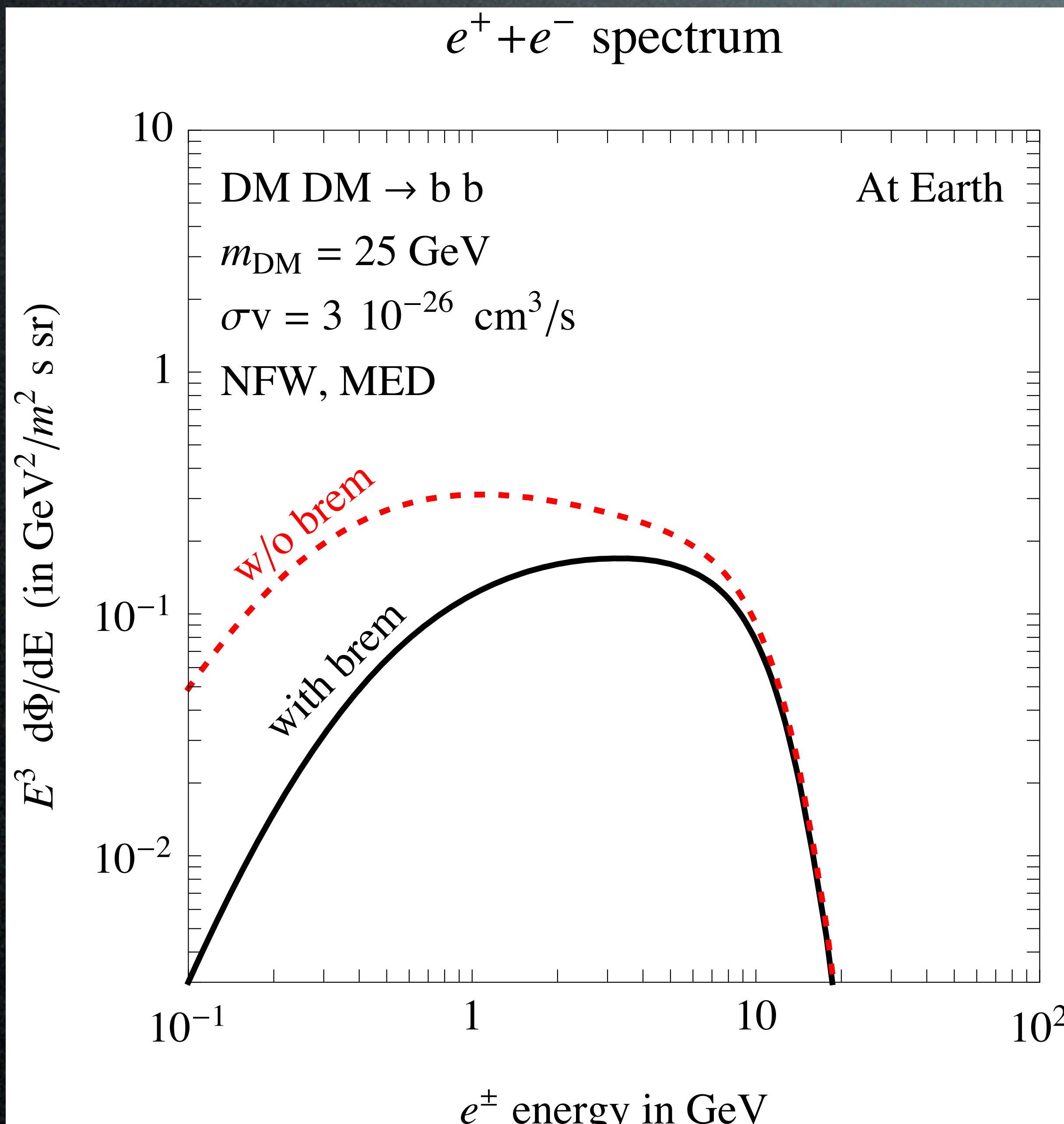


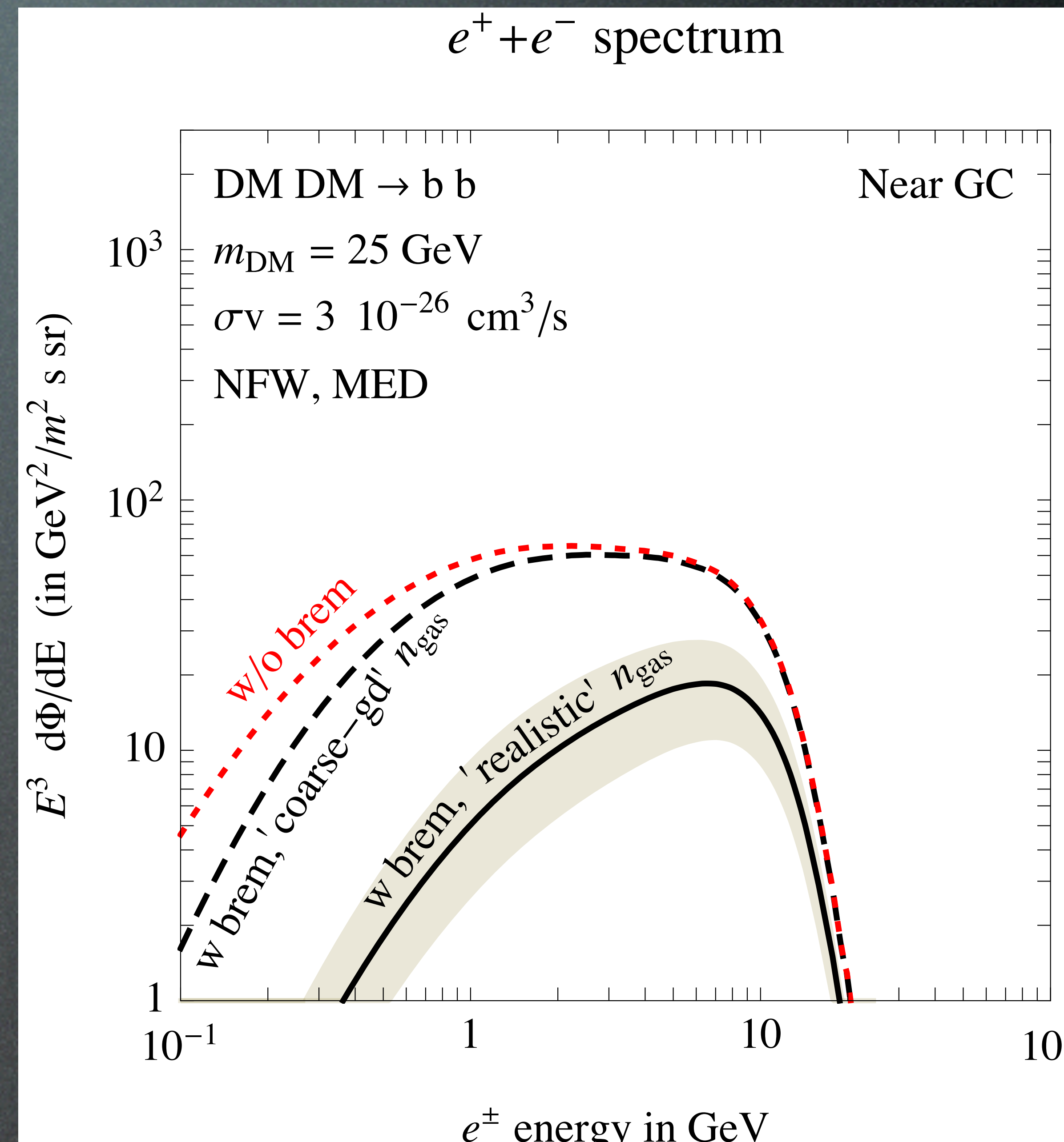


= factor 2 uncertainty in n_{gas}

Results

The e± population is affected by bremsstrahlung

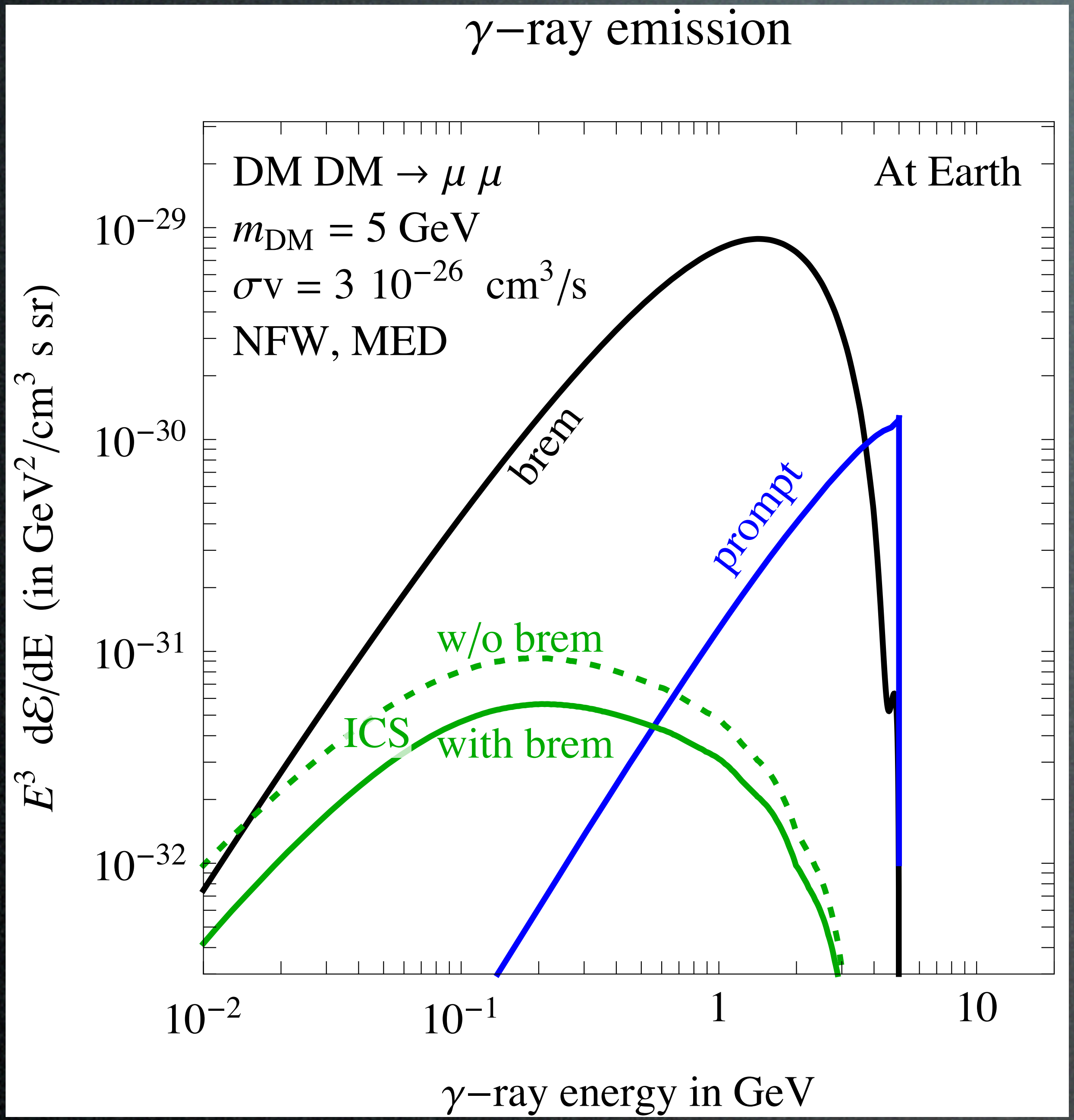


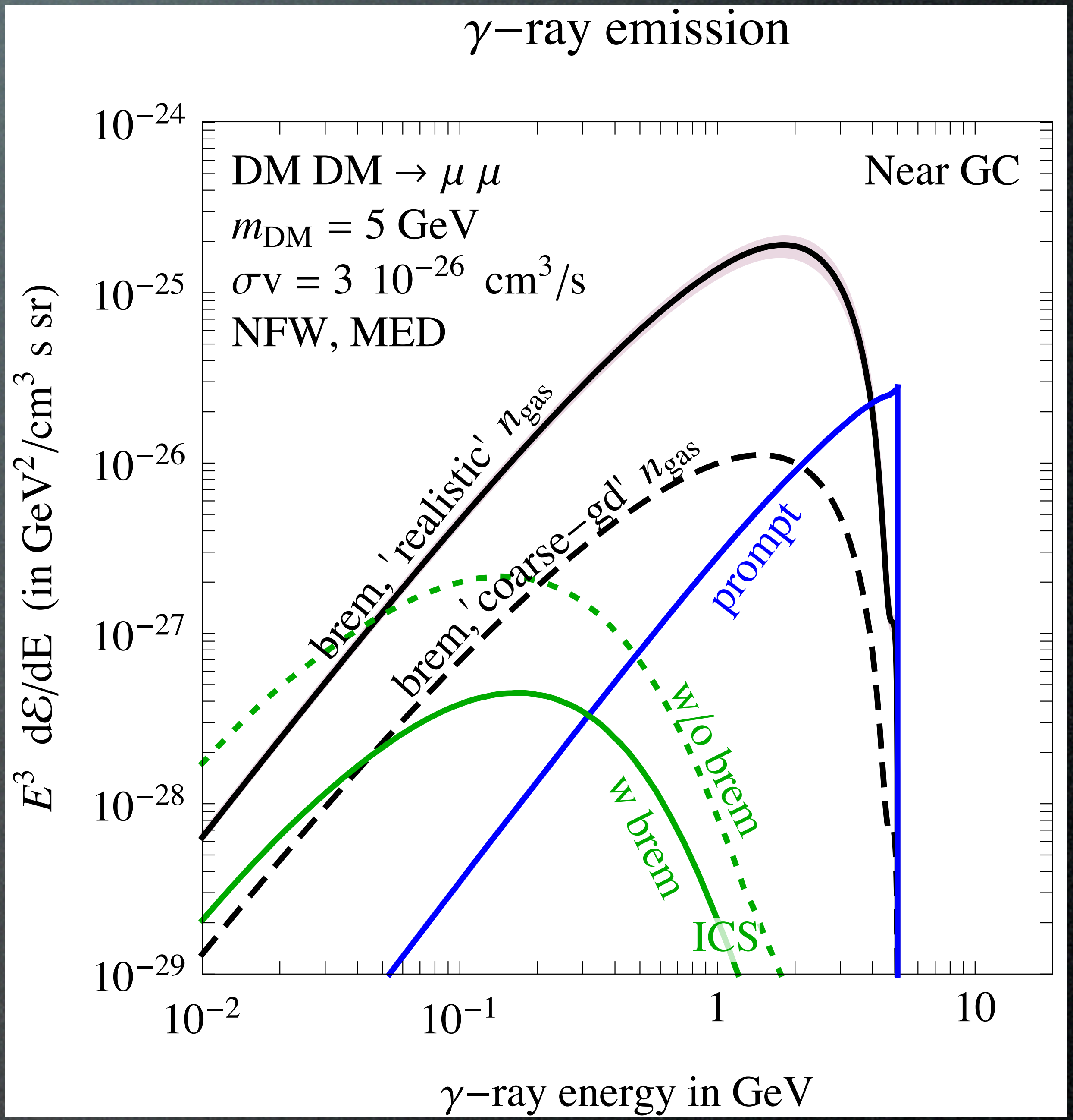


= factor 2 uncertainty in n_{gas}

Results

The total γ ray spectrum





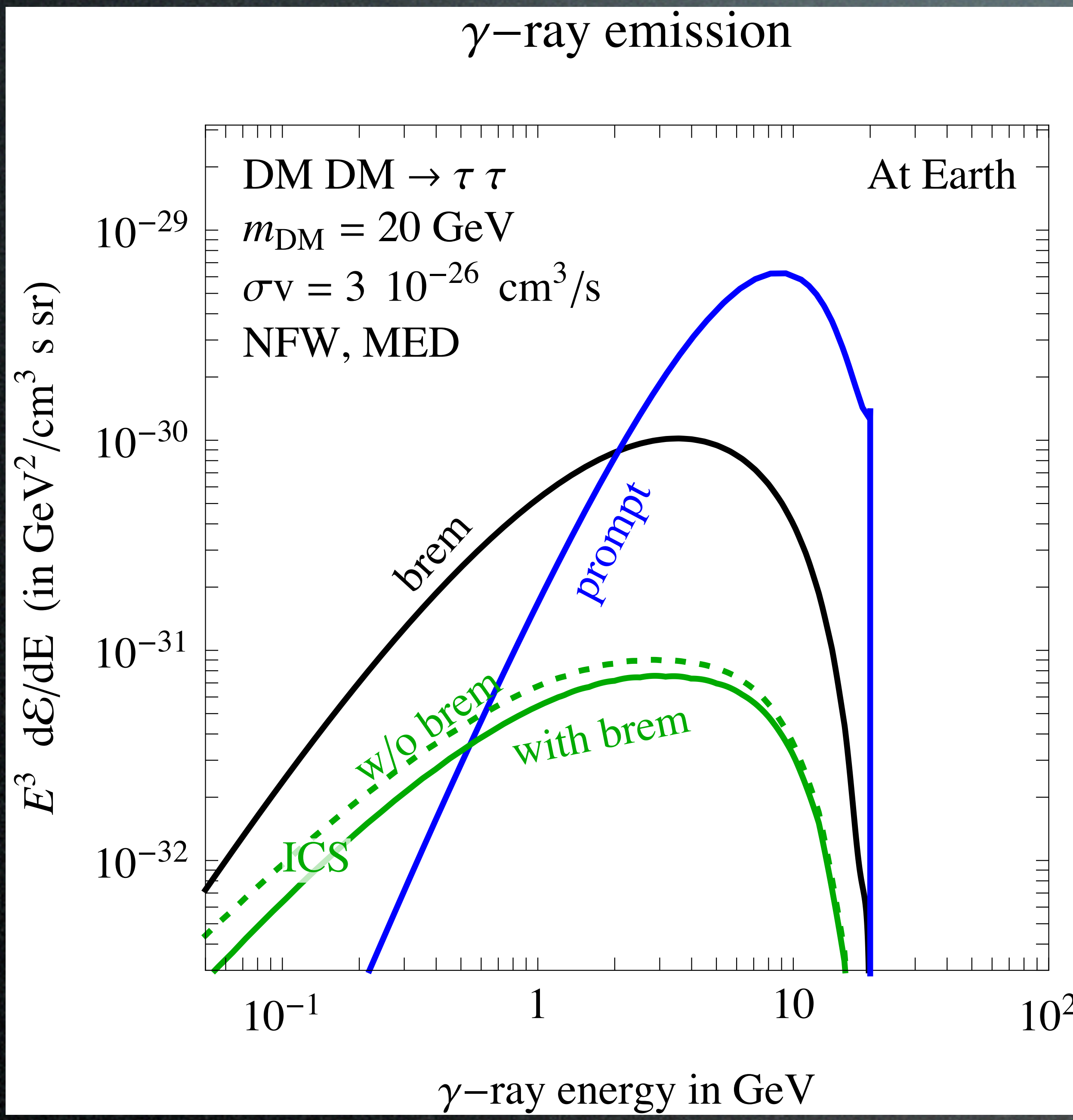
- brem is dominant
- ICS is affected

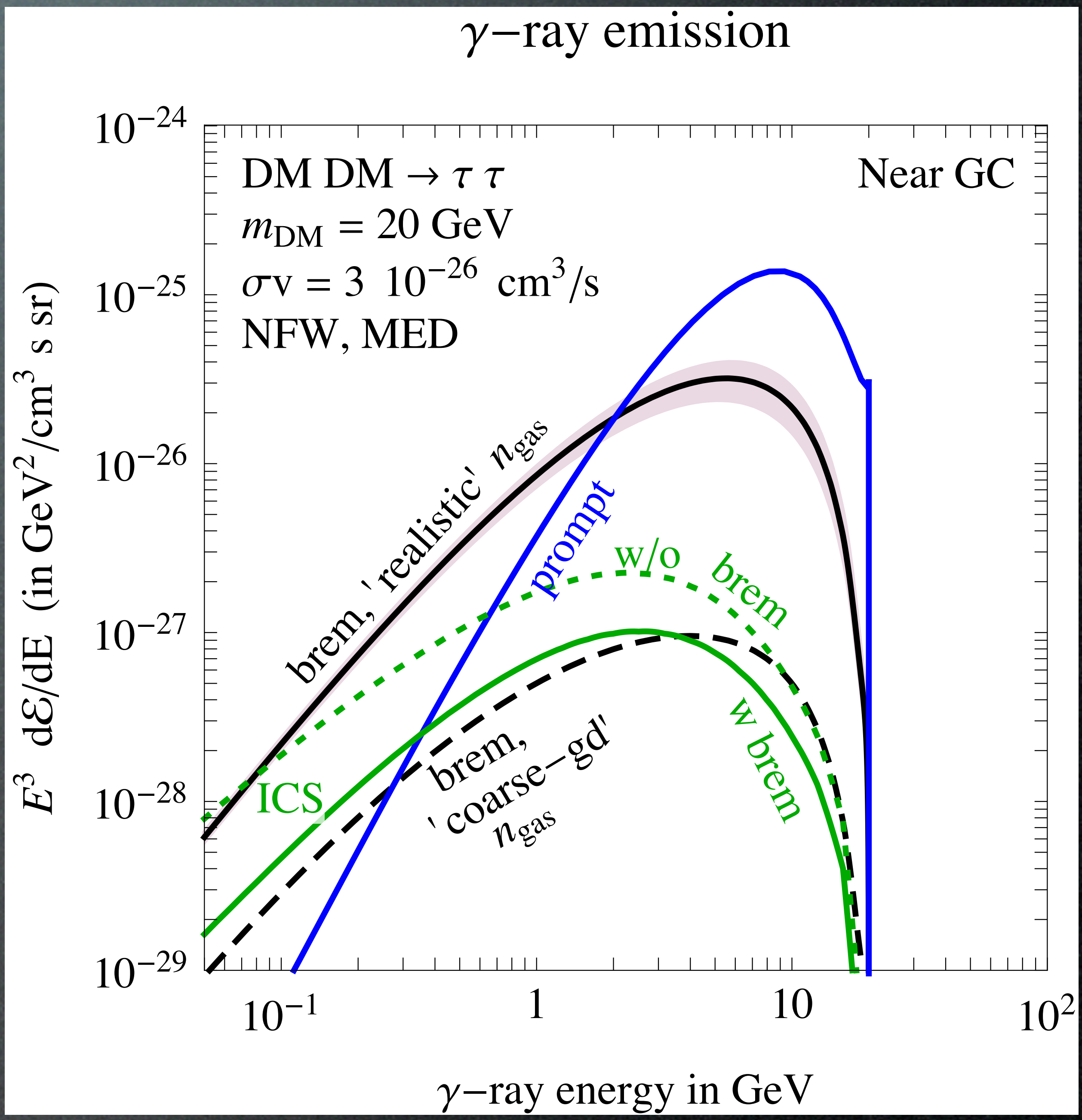
- uncertainty [shaded band] is somewhat reabsorbed:

large n_{gas} ⇨ more loss **and** more emission

Results

The total γ ray spectrum





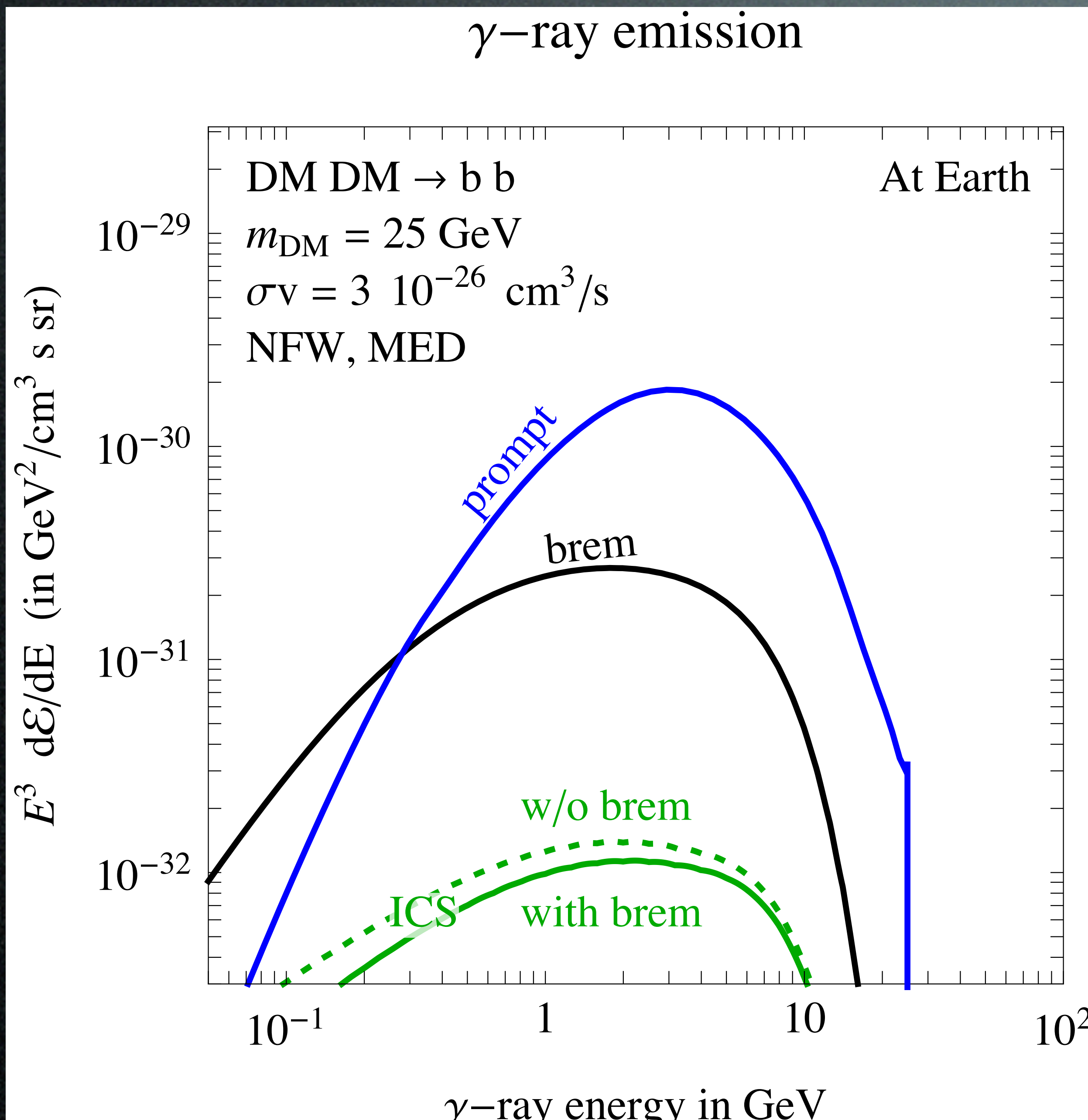
- brem is important
- ICS is affected

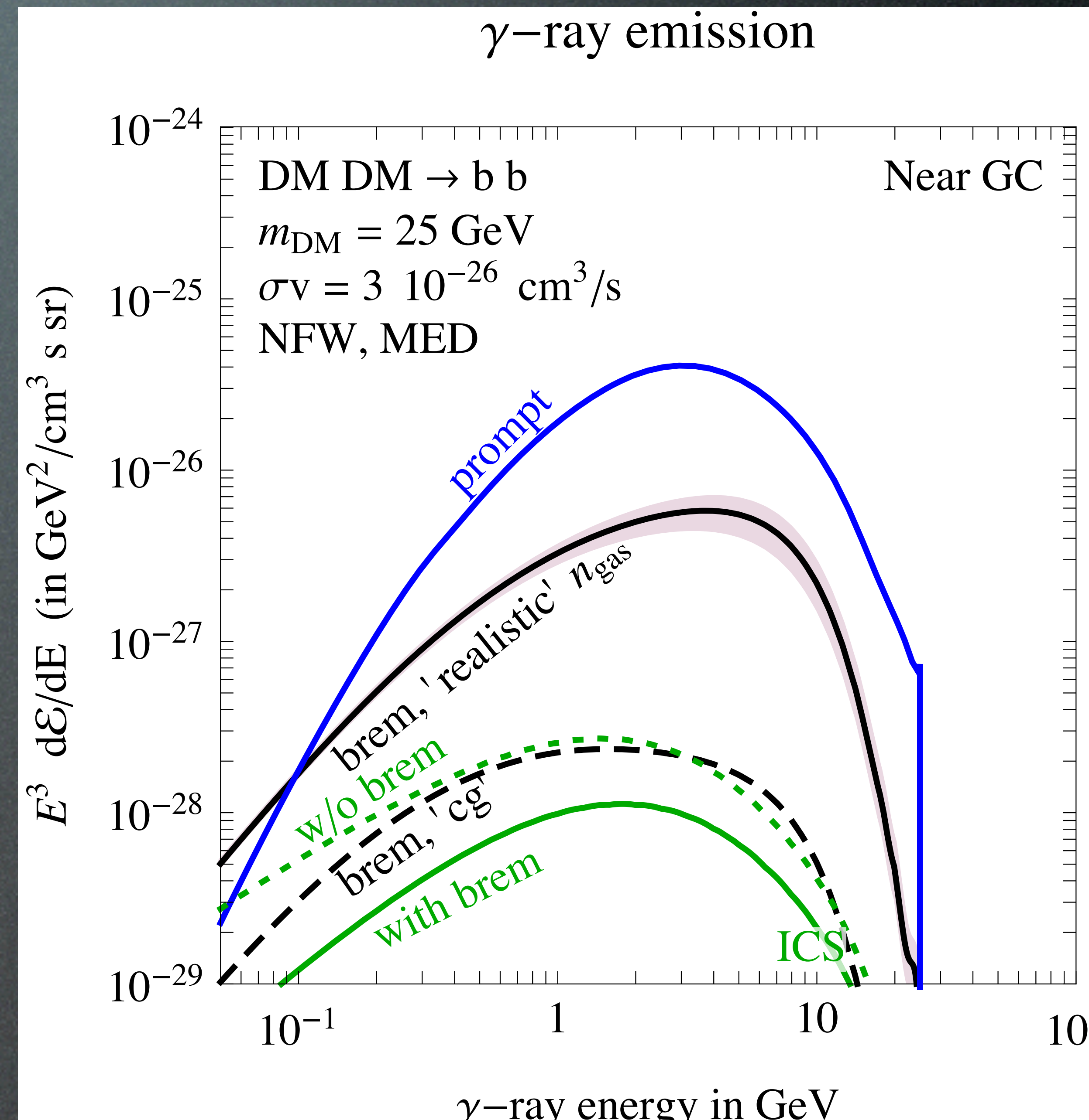
- uncertainty is somewhat reabsorbed:

large n_{gas} ⇨ more loss **and** more emission

Results

The total γ ray spectrum





- brem is important
- ICS is affected

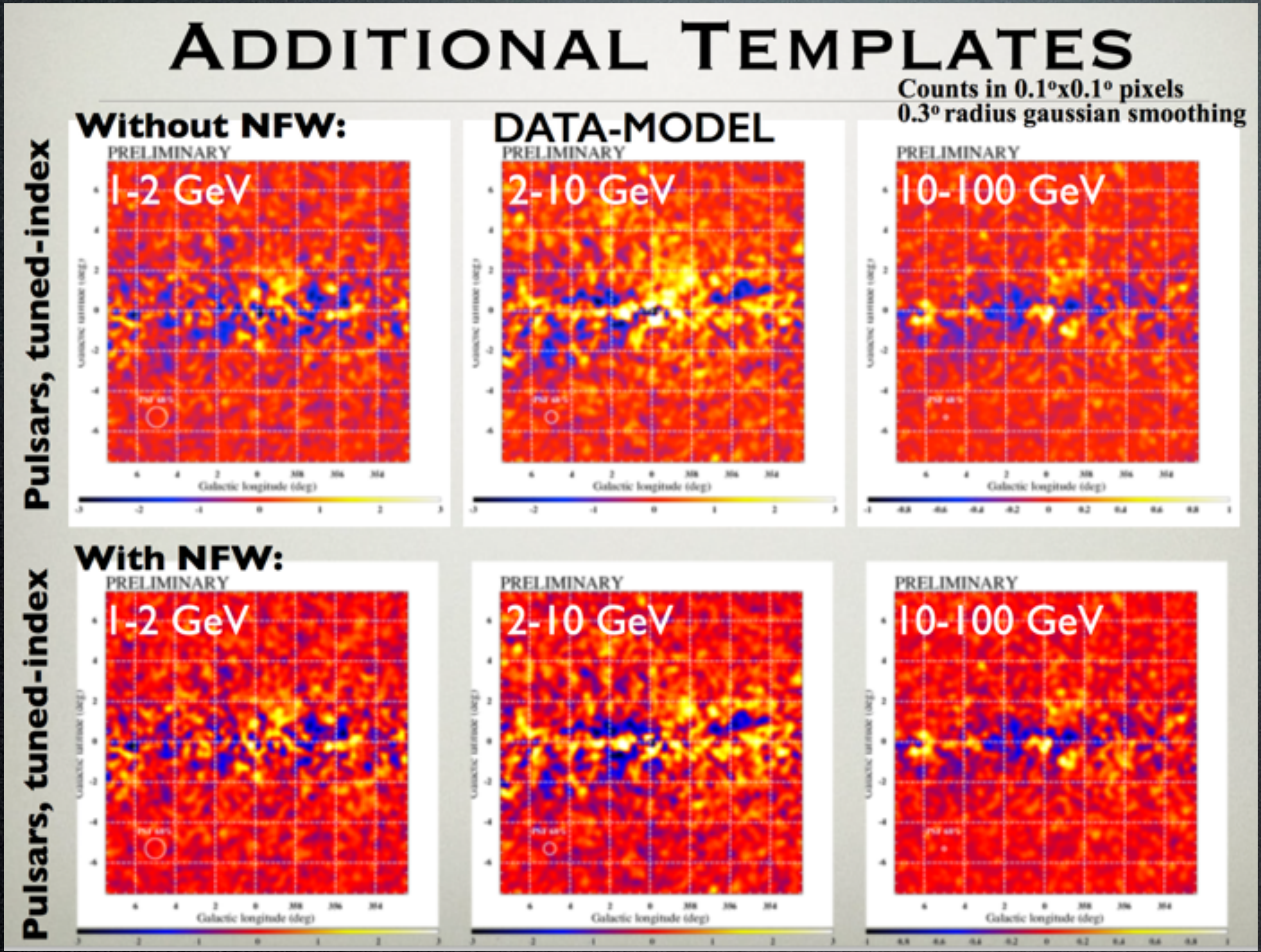
- uncertainty is somewhat reabsorbed:

large n_{gas} ⇨ more loss **and** more emission

GC GeV excess

GC GeV excess

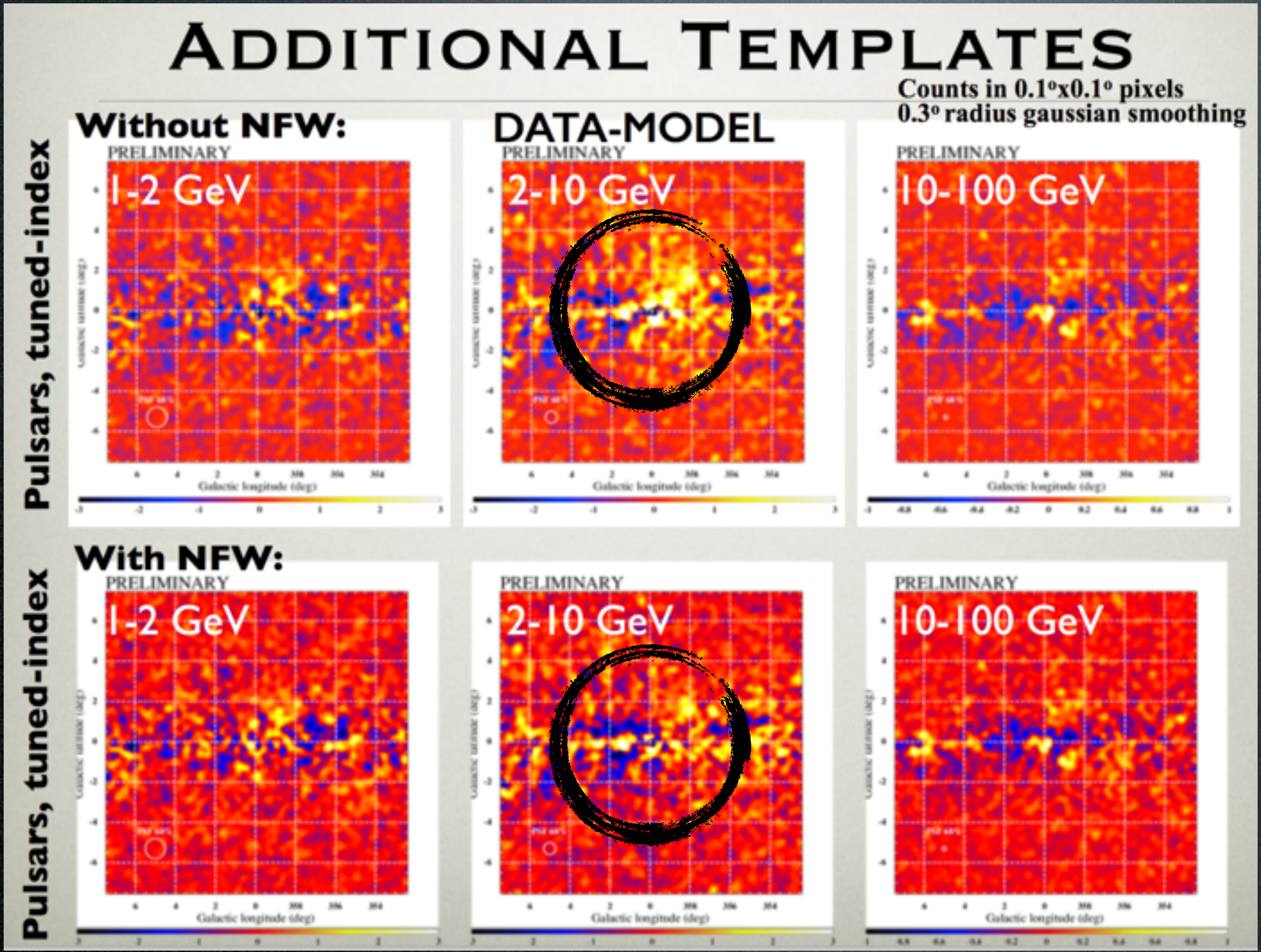
Dark Matter interpretation:



S. Murgia + T. Porter for FERMI-LAT - ICRC 2015
FERMI-LAT Coll., 1511.02938

GC GeV excess

Dark Matter interpretation:

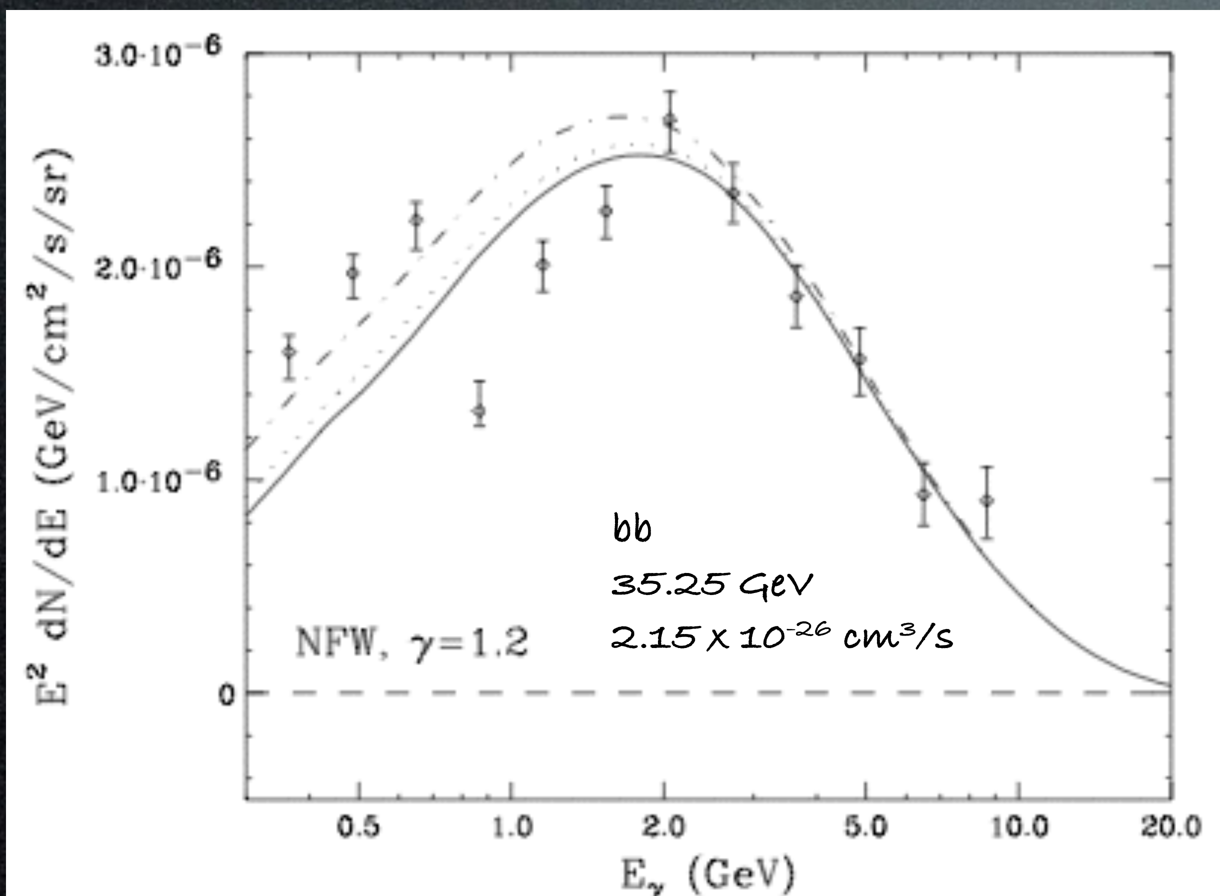


S. Murgia + T. Porter for FERMI-LAT - ICRC 2015
FERMI-LAT Coll., 1511.02938

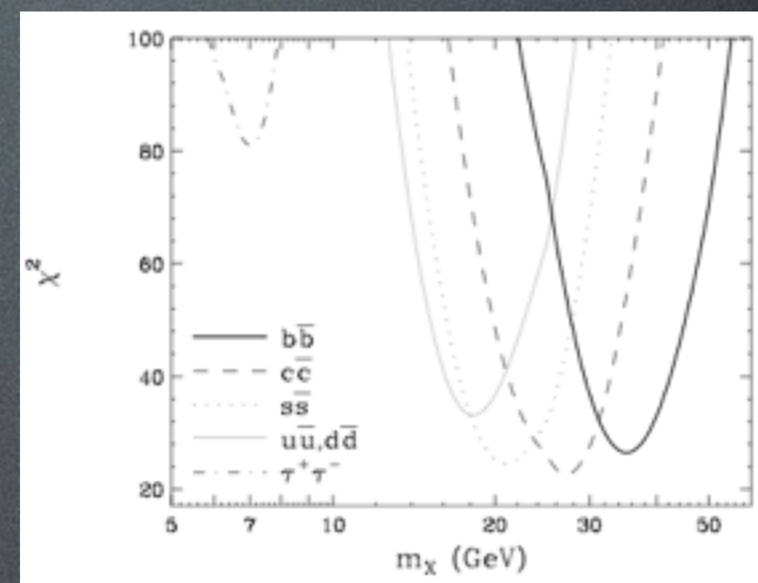
GC GeV excess

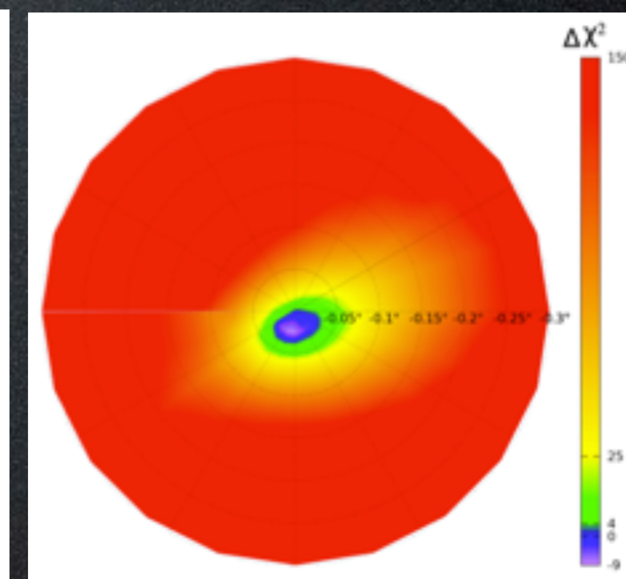
Dark Matter interpretation:

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



Using events with accurate directional reconstruction





A compelling case for annihilating DM

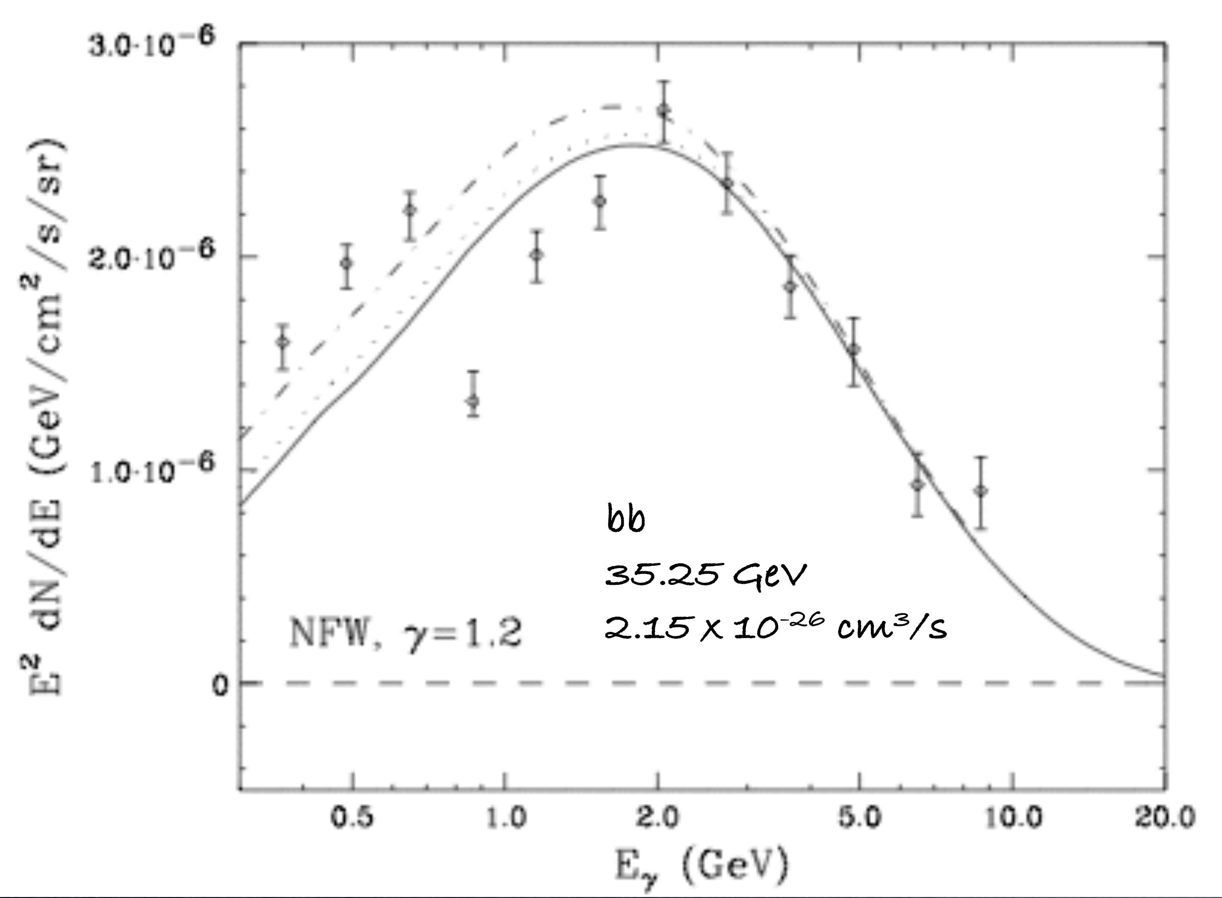
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

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.

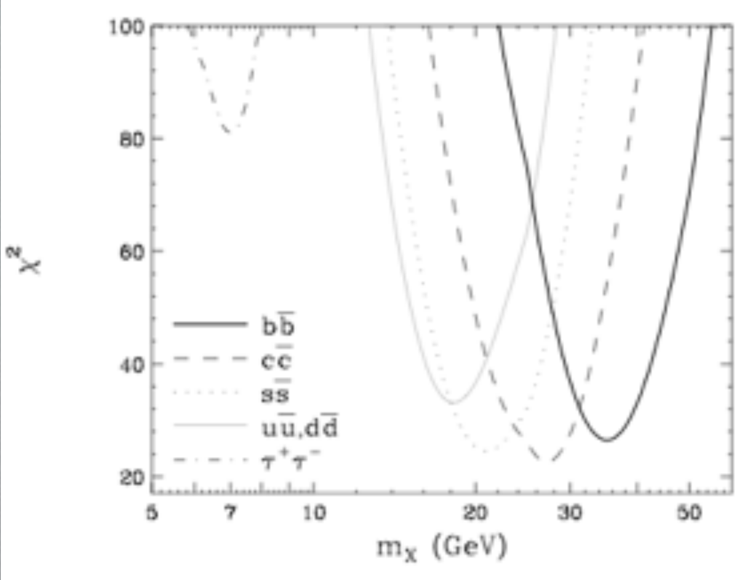
GC GeV excess

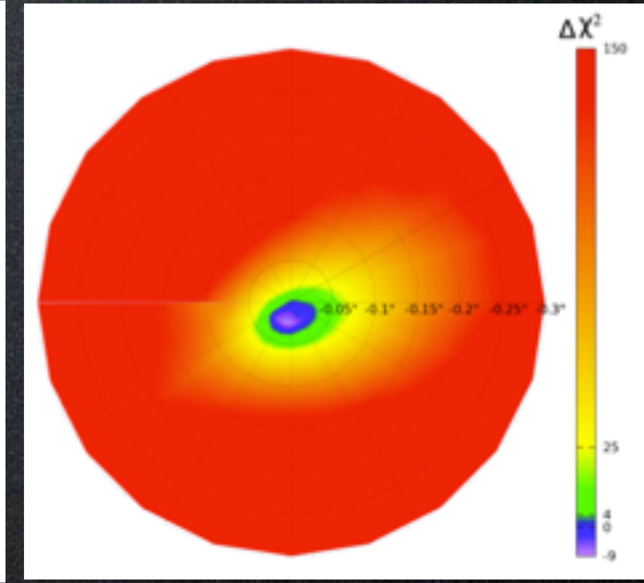
Dark Matter interpretation:

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:

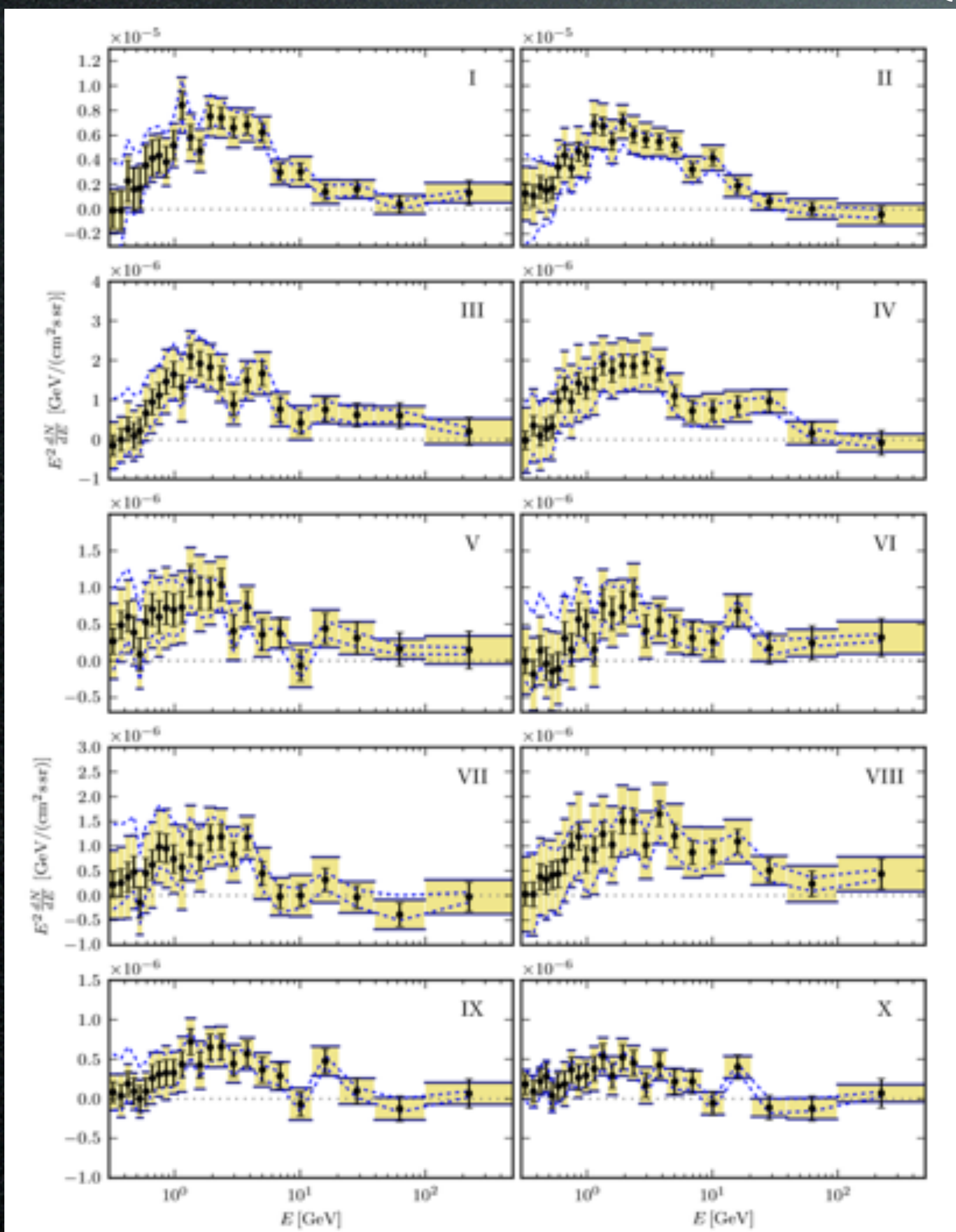
6. Dark Matter, having chosen a certain profile!

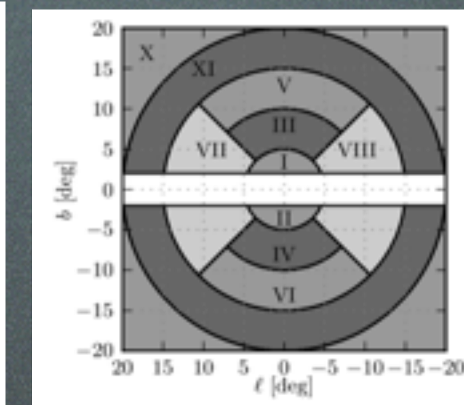
v. if iii. → iv. improves χ^2, there’s evidence for DM
vi. the component fitted by 6 is the residual excess to be explained

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

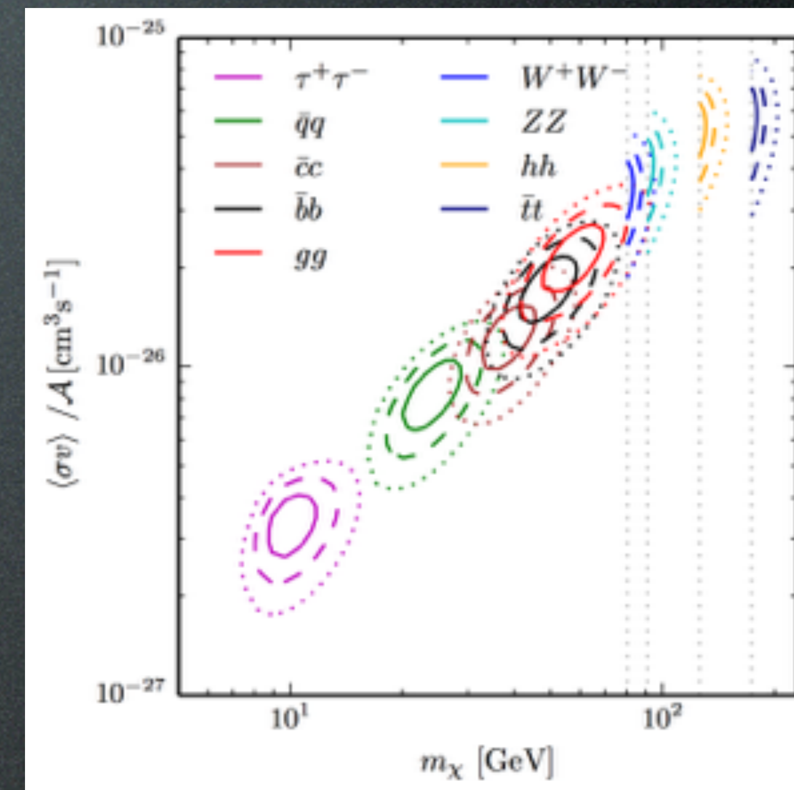
The excess is robust against uncertainties in foreground modelling, and it extends to o(10º):



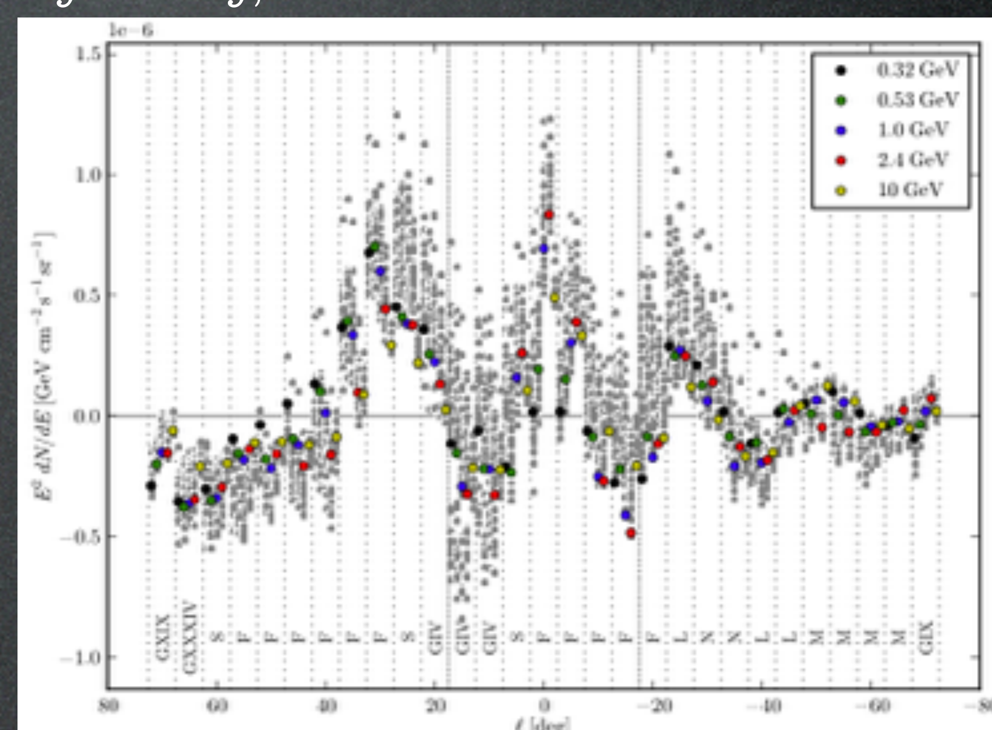


Calore, Cholis, Weniger 1409.0042
Calore, Cholis, McCabe, Weniger 1411.4647

More general DM good fits:



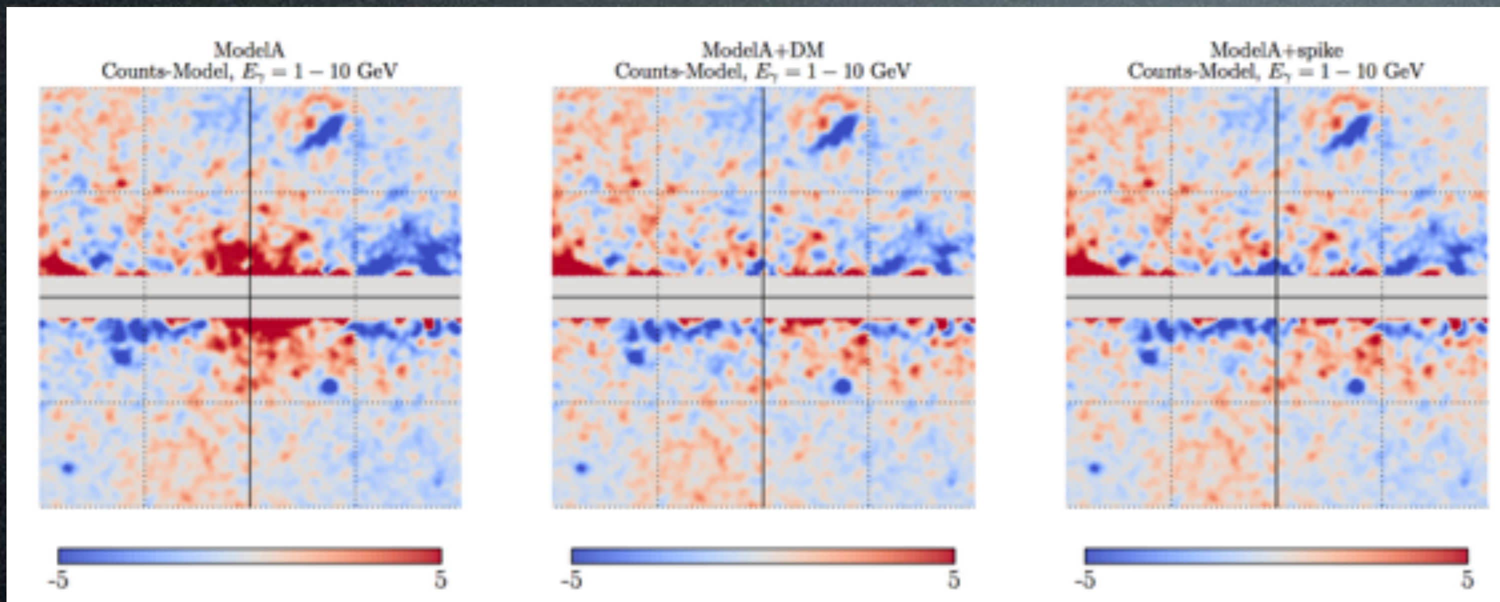
By the way, excesses exist elsewhere in the GP:

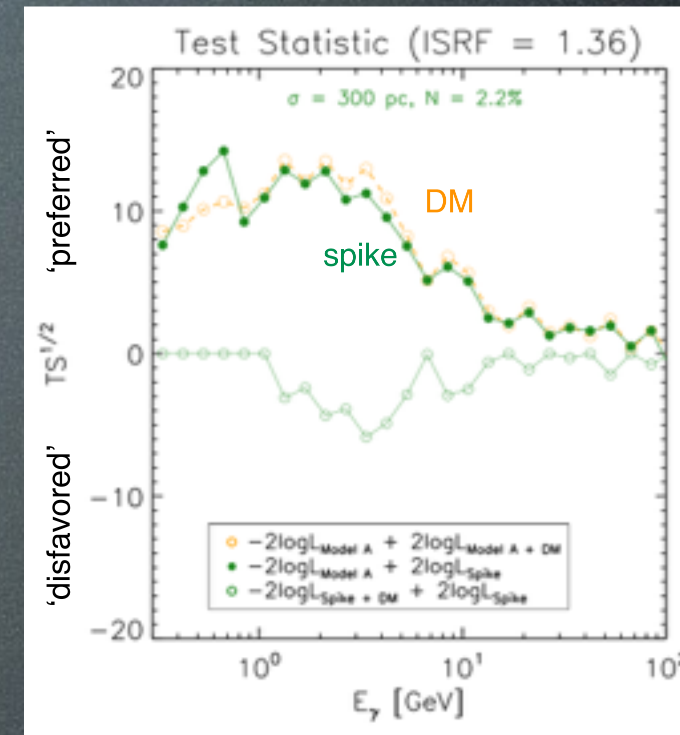


Gal plane

GC GeV excess

‘Astro’ interpretation(s):

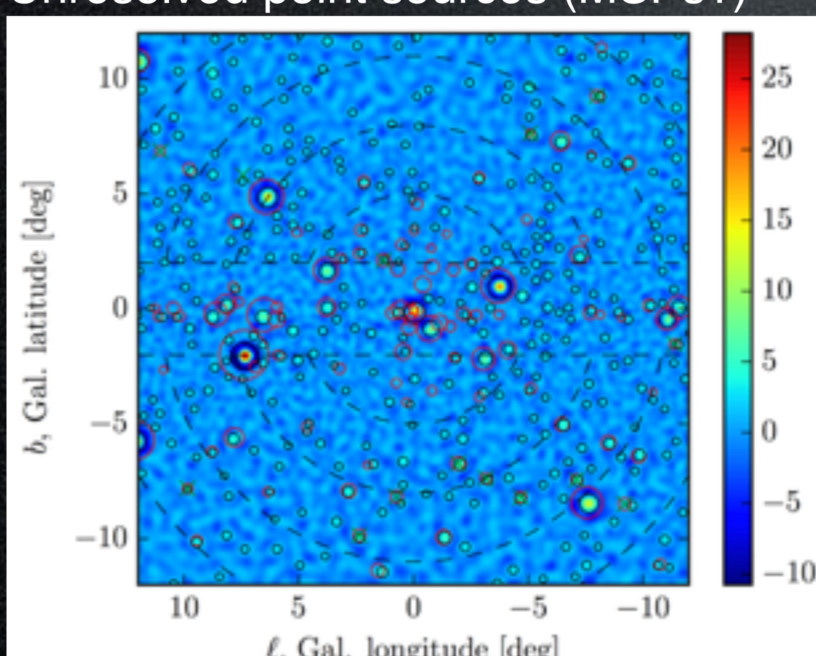




An additional steady-source spike of CRs (from SNRs?) that emit via ICS

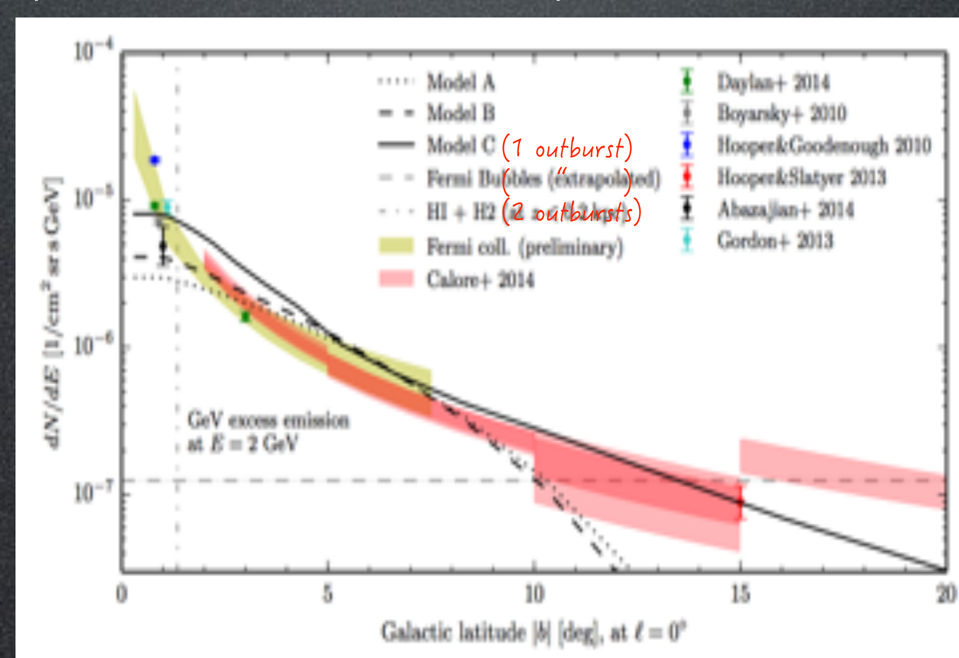
Gaggero, Taoso, Urbano, Valli, Ullio 1507.06129
see also: Carlson, Profumo, Linden 1510.04698
(which ‘motivates’ the spike with H2 distribution)

Unresolved point sources (MSPs?)



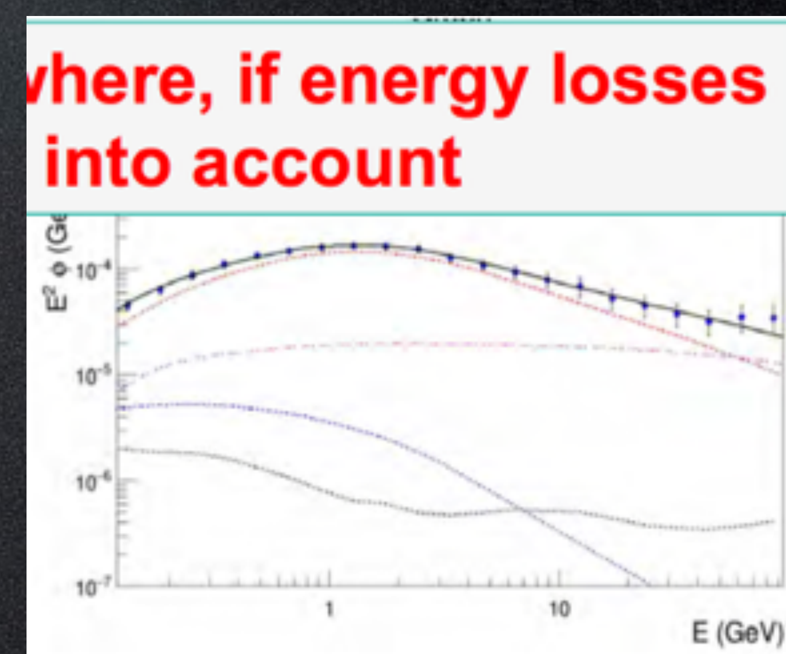
Lee, Lisanti, Safdi, Slatyer, Xue 1506.05124
Bartels, Krishnamurthy, Weniger 1506.05104
Abazajian 1011.4275
Hooper et al. 1305.0830
Yuan, Zhang 1404.2318
Petrović, Serpico, Zaharijas 1411.2980

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 (?)

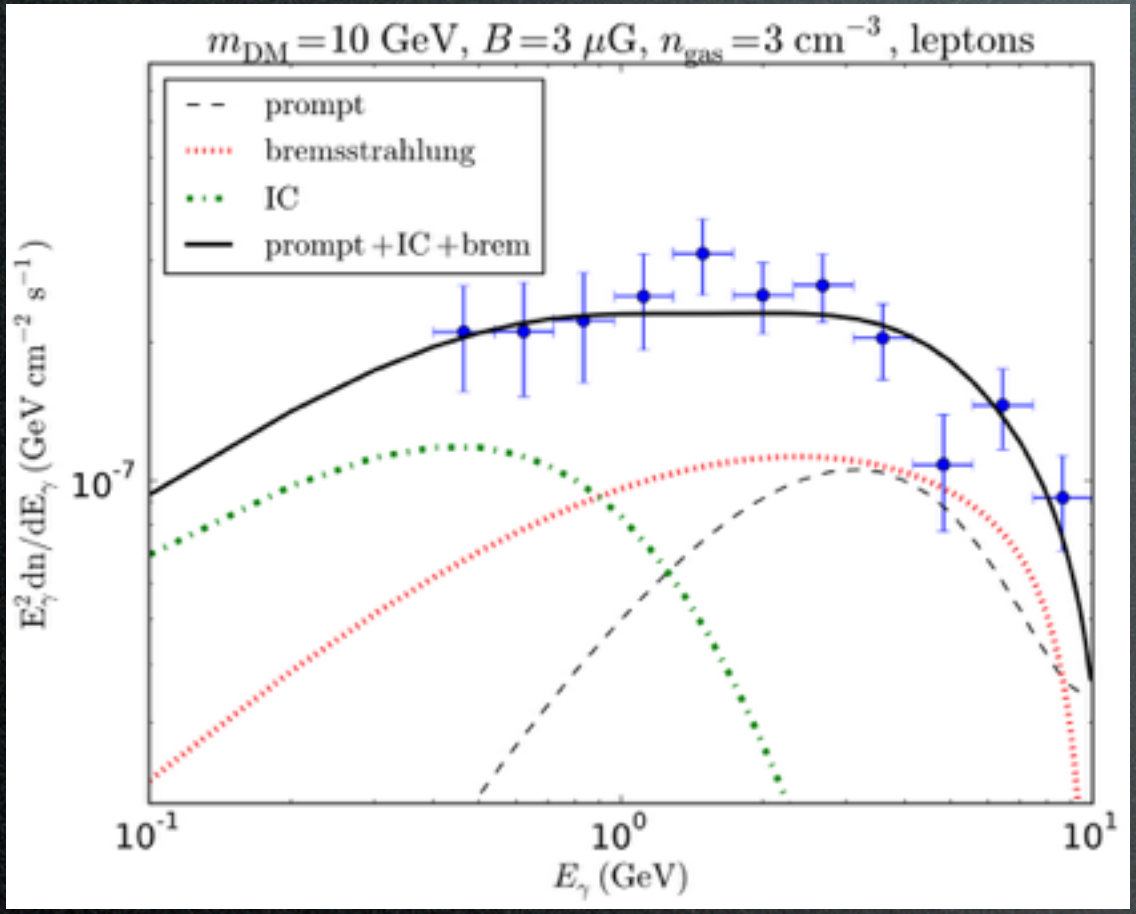


W. De Boer - ICRC 2015

GC GeV excess

Dark Matter interpretation:

Including secondary emission changes the conclusions



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

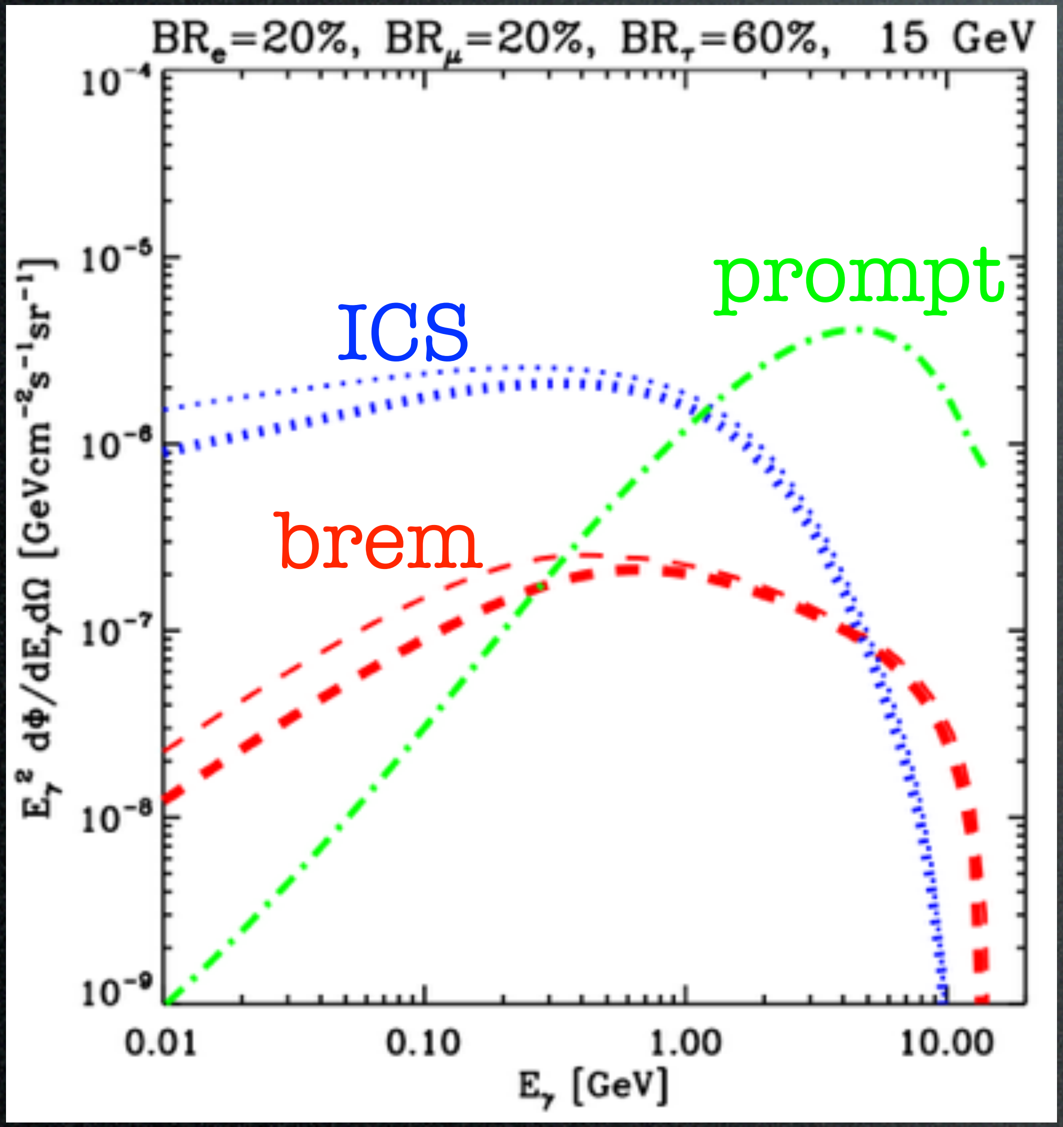
Lacroix, Bœhm, Silk 1403.1987

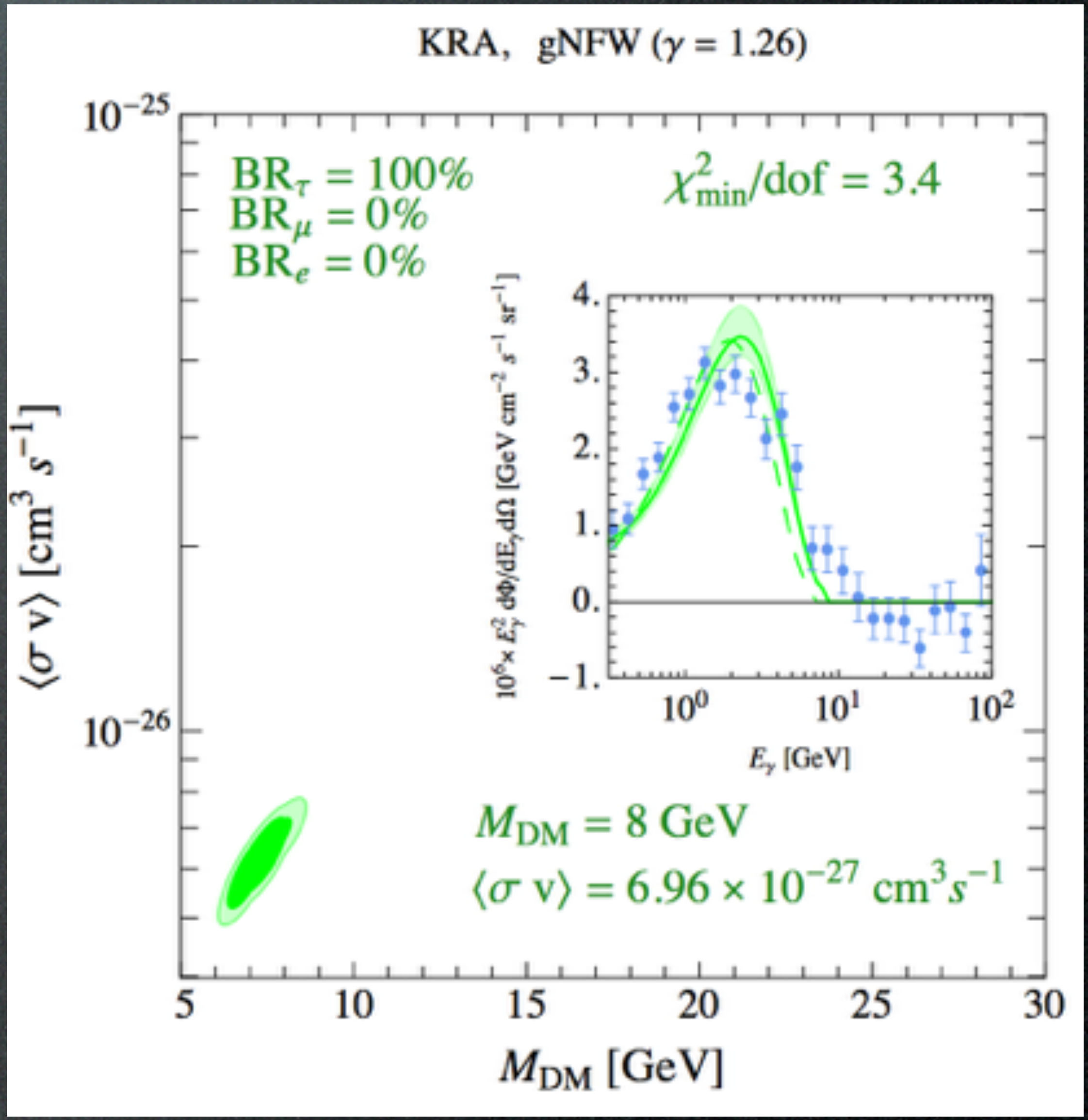
But: propagation is approximate

GC GeV excess

Dark Matter interpretation:

Including secondary emission changes the conclusions





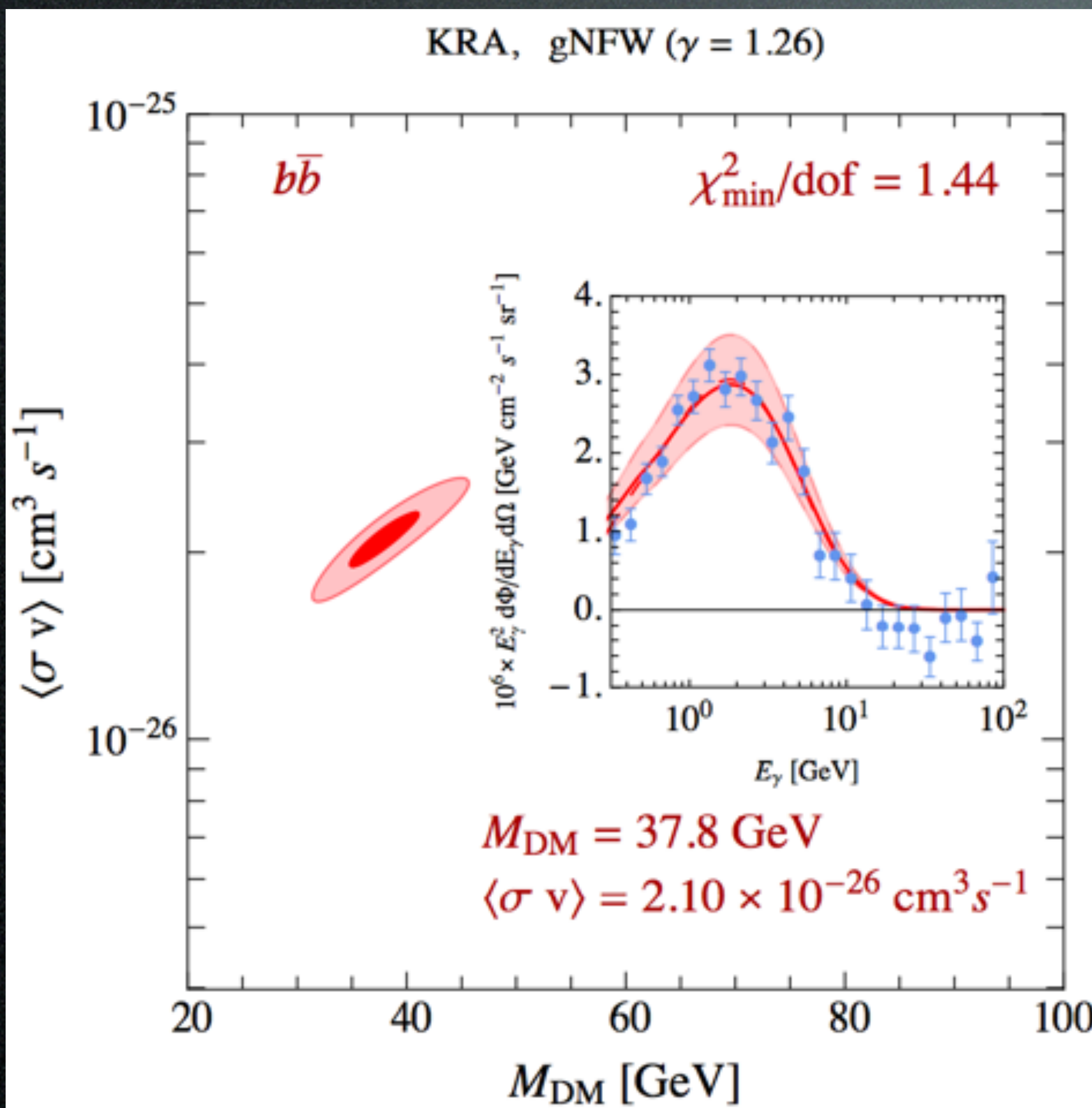
Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

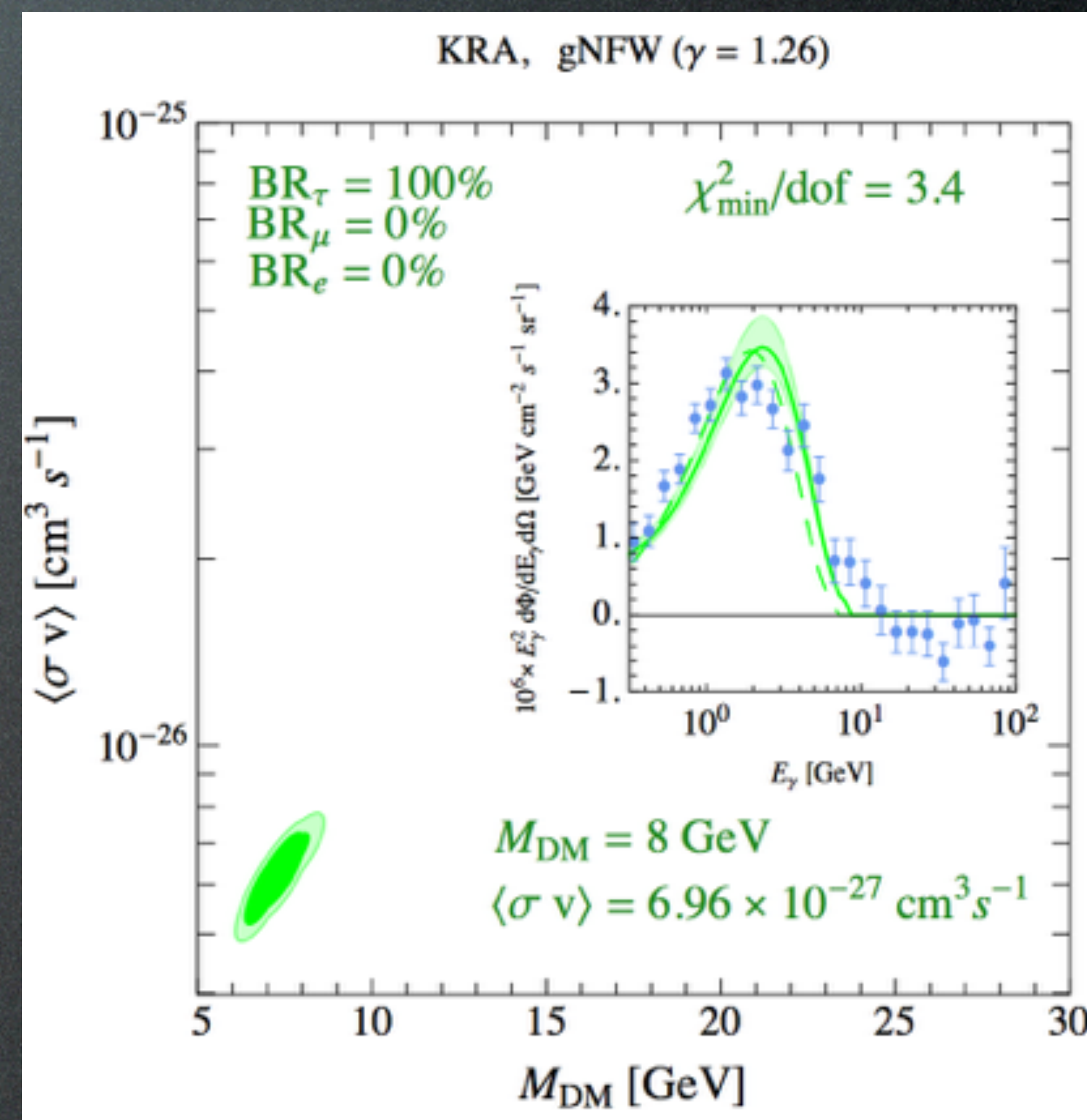
GC GeV excess

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 $^{(\star)}$	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:

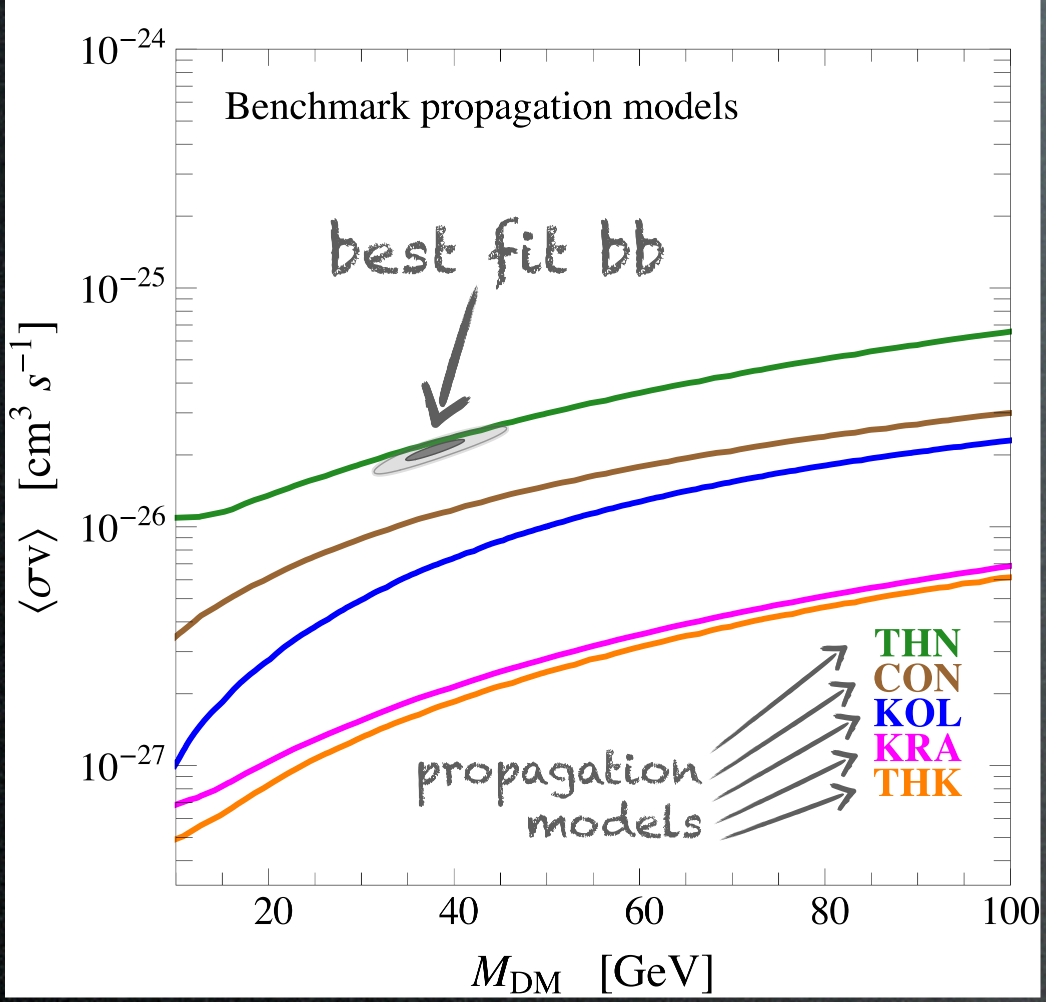




Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

GC GeV excess

Dark Matter interpretation:



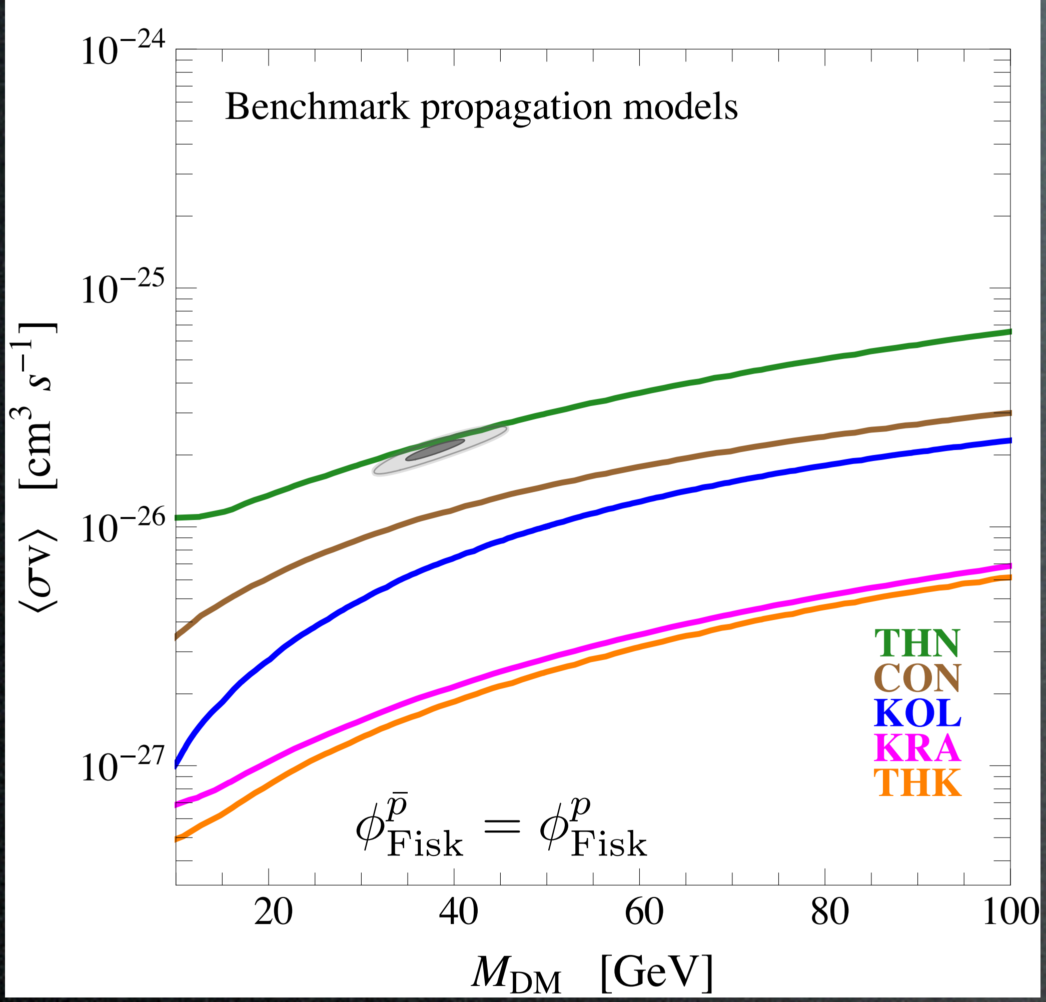
Fermi-LAT excess

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.

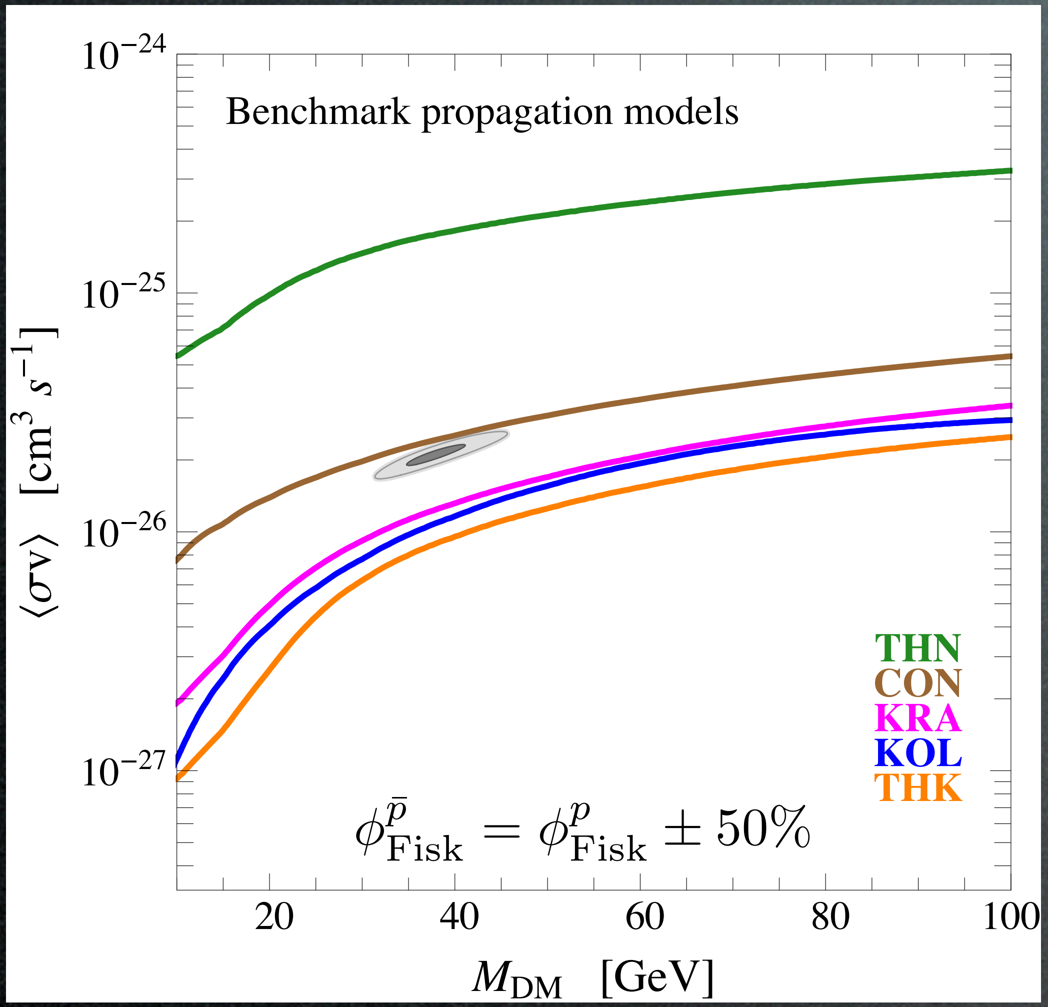
Assumption: fixed solar modulation

Result: hooperon excluded
(except unrealistic THN)

GC GeV excess

Antiproton constraints:

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Fermi-LAT excess

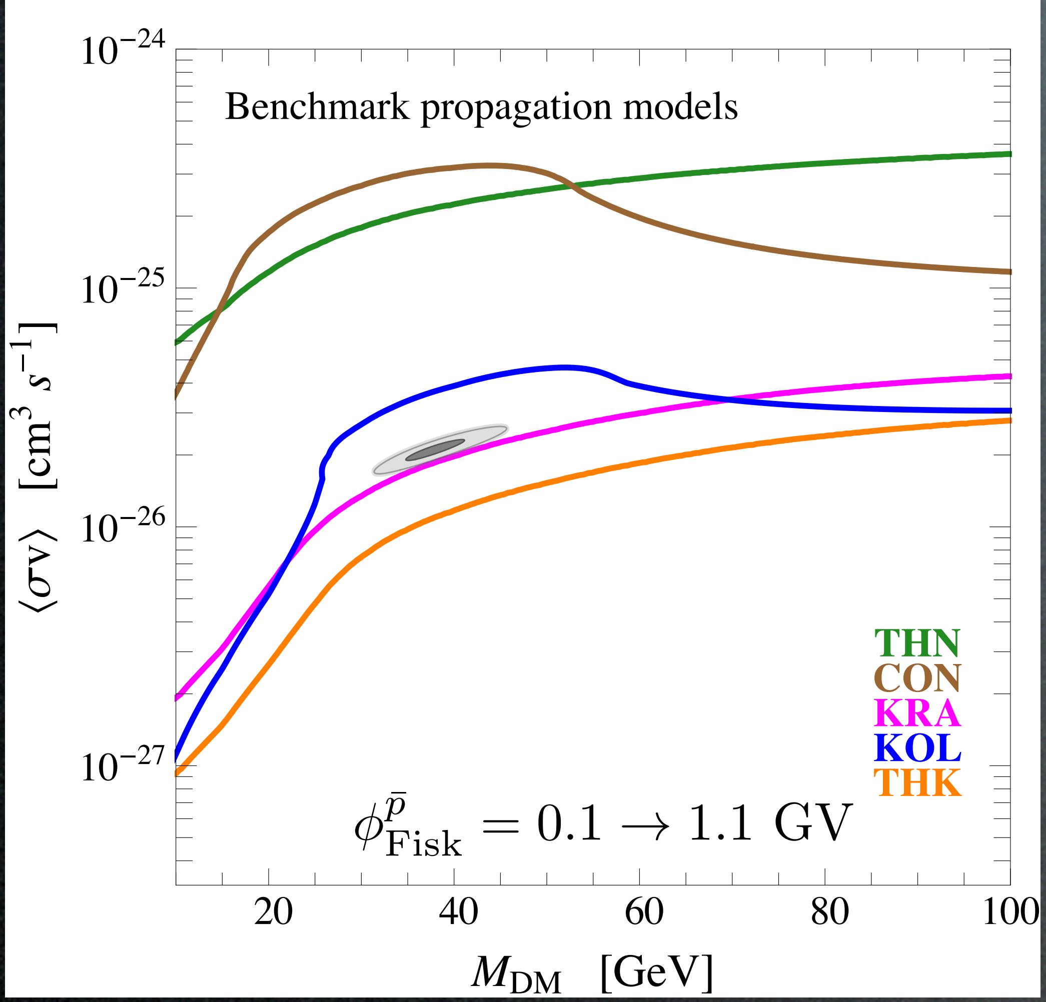
Antiproton constraints may be very relevant! But not robust.

Assumption: flexible solar modulation

Result: hooperon may be excluded or not

GC GeV excess

Antiproton constraints:



Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

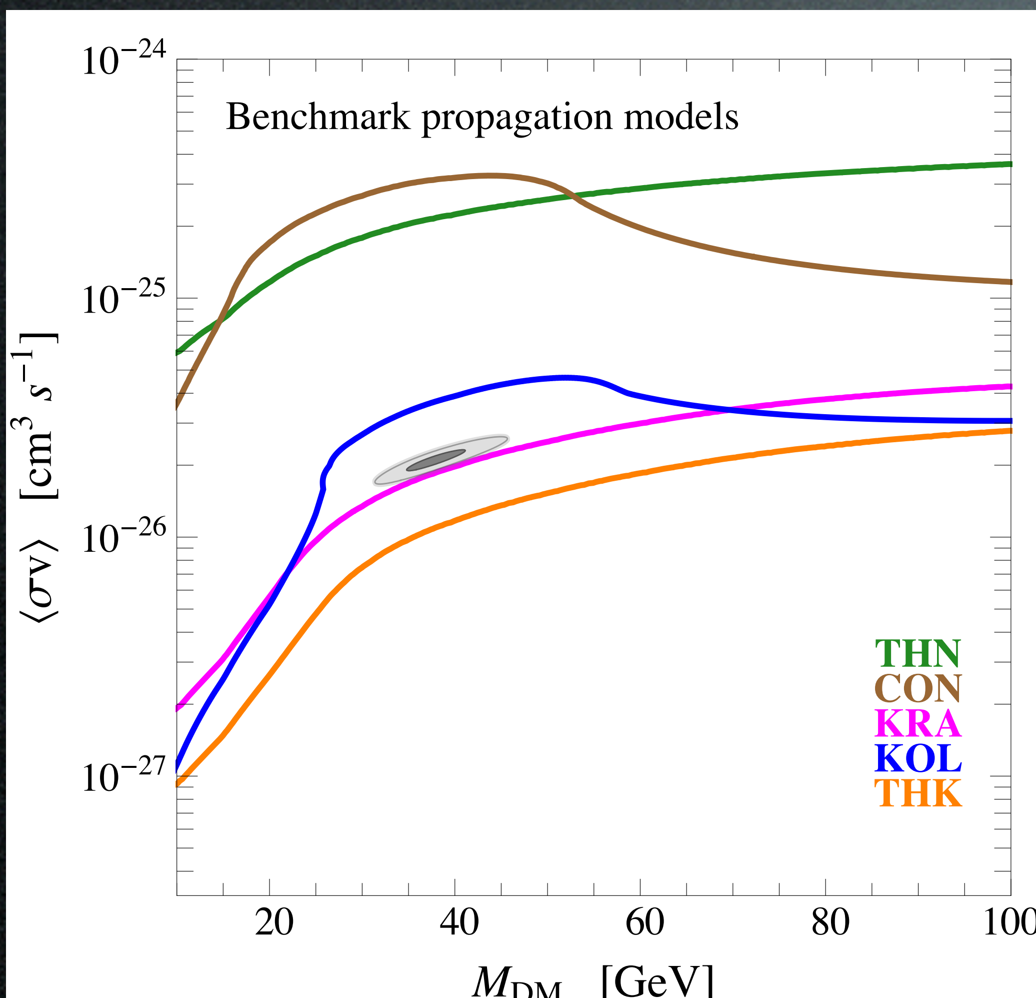
Antiproton constraints may be very relevant! But not robust.

Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

GC GeV excess

Antiproton constraints:



Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But not robust.

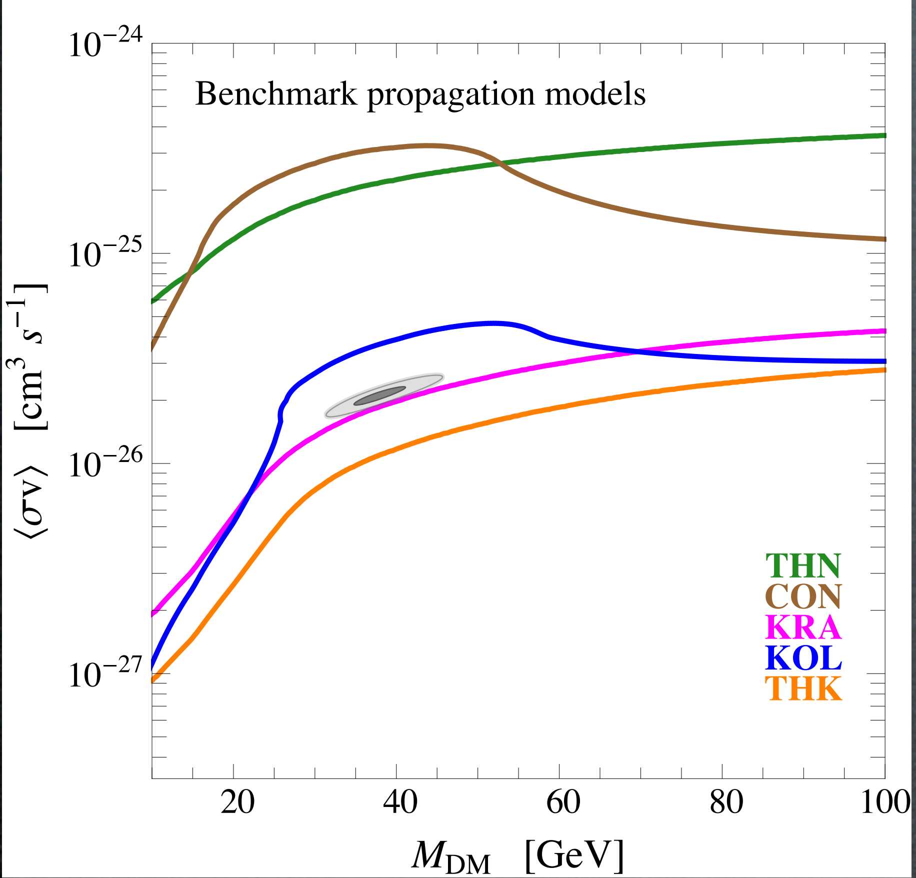
Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

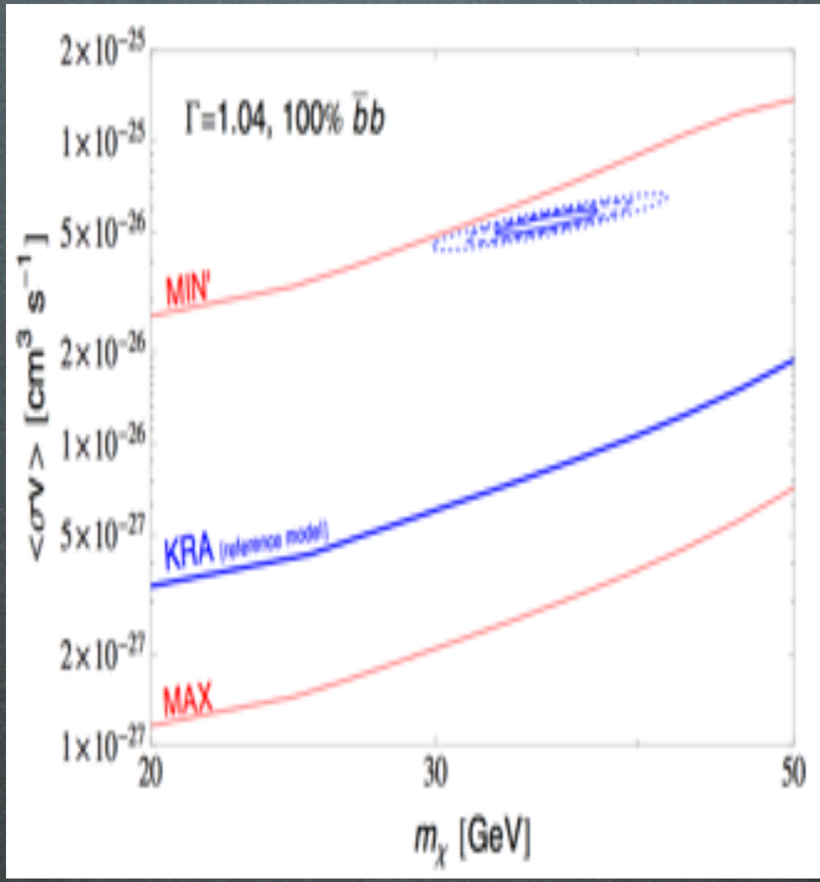
NB Conclusion differs from Bringmann, Vollmann, Weniger 1406.6027 which finds exclusion / strong tension

GC GeV excess

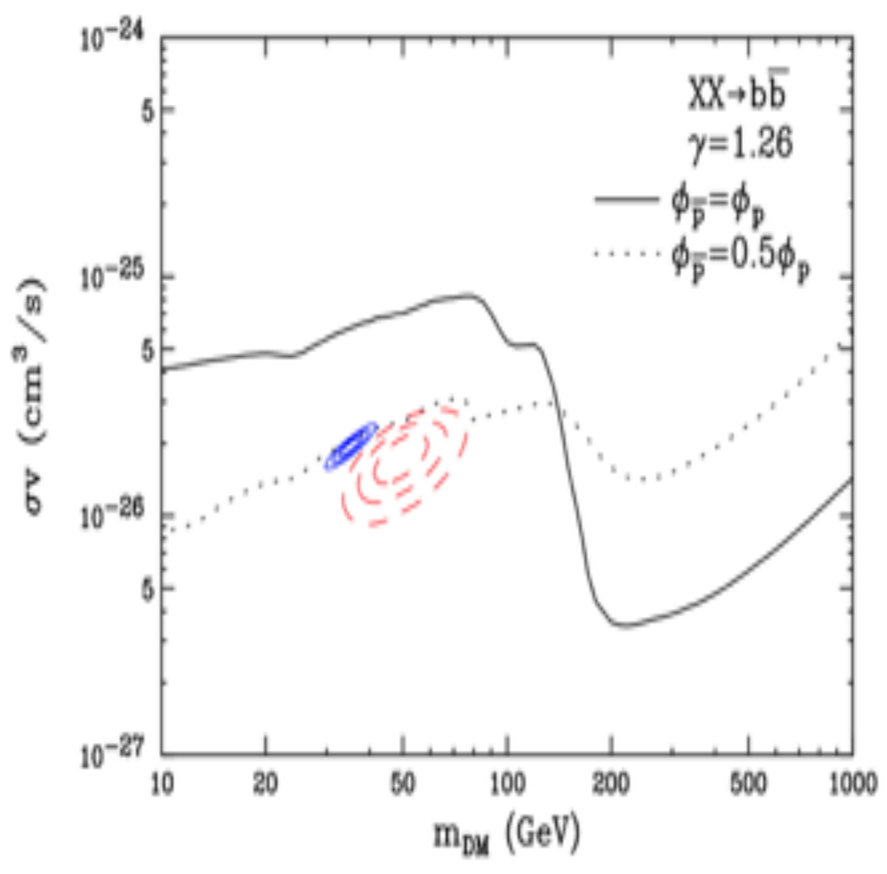
Antiproton constraints compared:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Bringmann, Vollmann, Weniger 1406.6027



Hooper, Linden, Mertsch 1410.1527

May be very relevant!
But not robust.

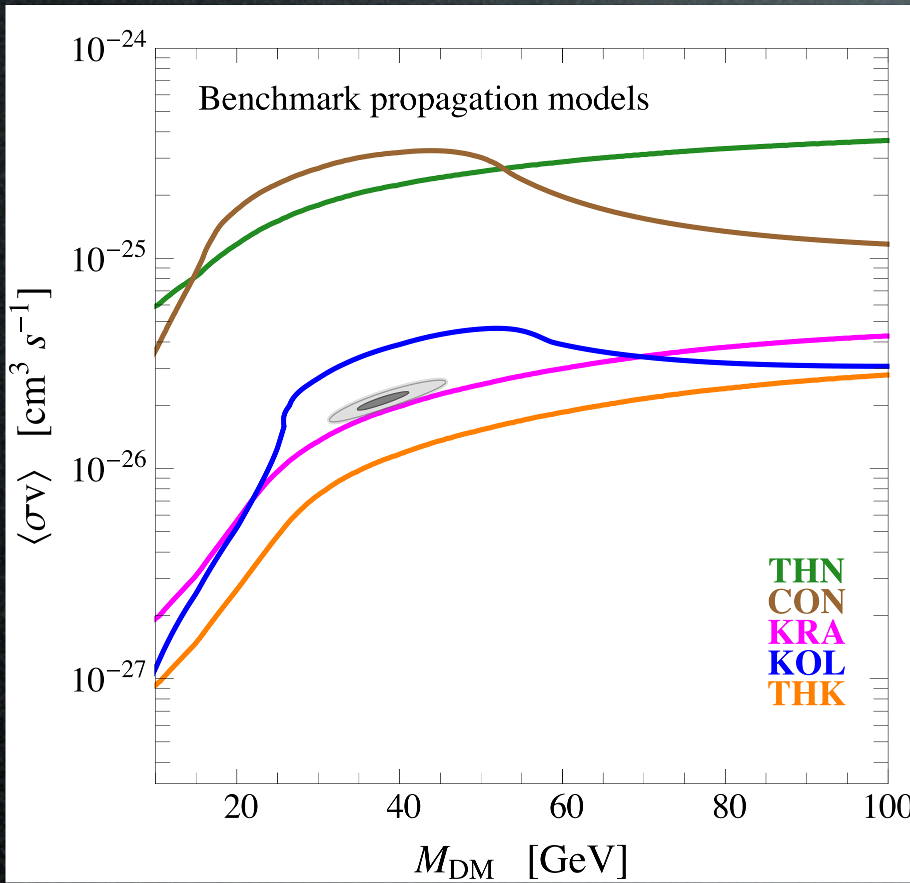
'Rule out' or
'considerable tension'.

'Significantly less stringent'.

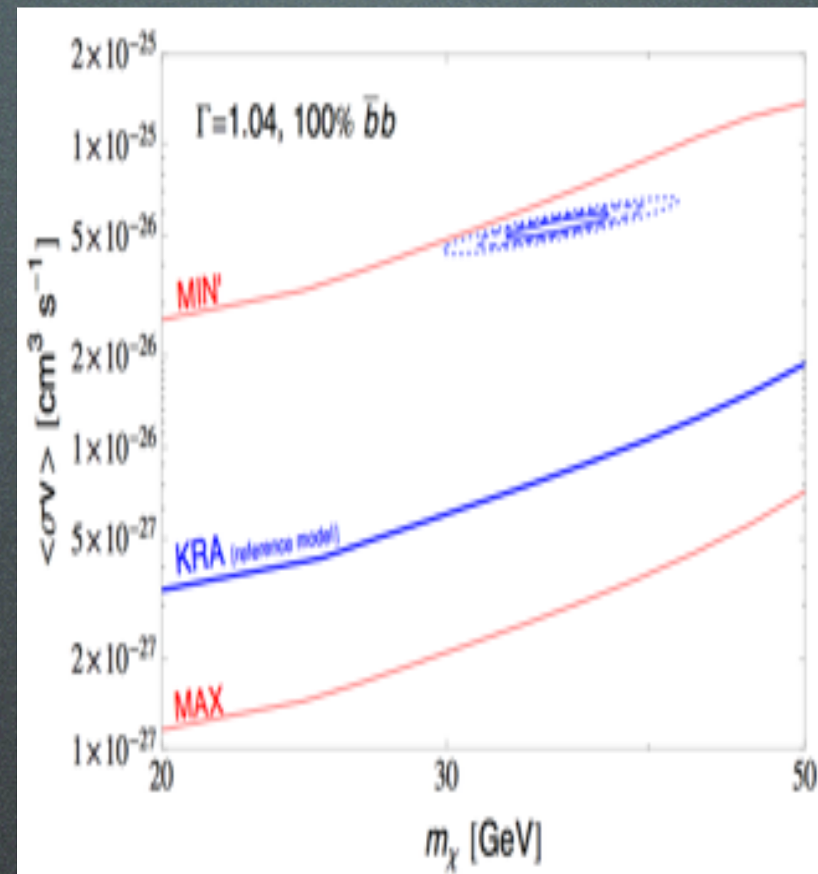
How come?!?

GC GeV excess

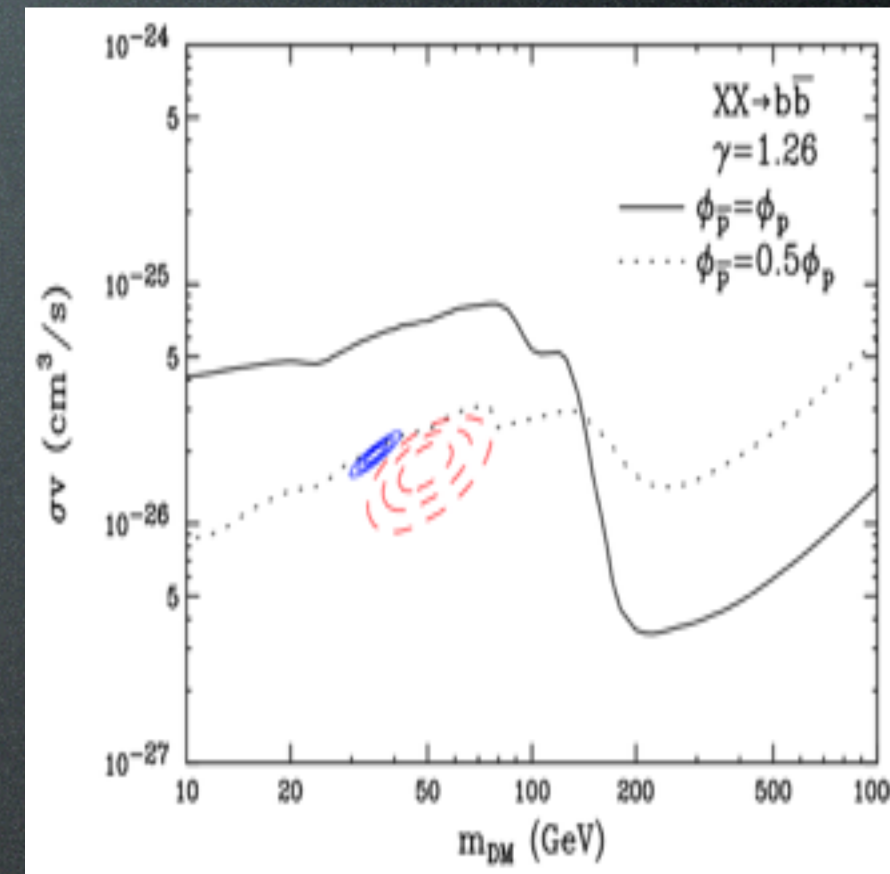
Antiproton constraints compared:



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…

CONCLUSIONS

Antiprotons from
low mass DM:

significantly affected
by solar modulation,
which is uncertain

Gamma-rays from
low mass DM:

environment-dependent
secondary radiation
is important, even dominant

The **GC GeV excess**
as a case study:

1. secondary radiation changes
the DM interpretation,
2. antiproton constraints
are inconclusive