9 June 2015
WIN 2015 Heidelberg

Dark Matter Indirect Detection:

antiprotons

Marco Cirelli
(CNRS IPhT Saclay)

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antiprotons

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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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DM detection

direct detection

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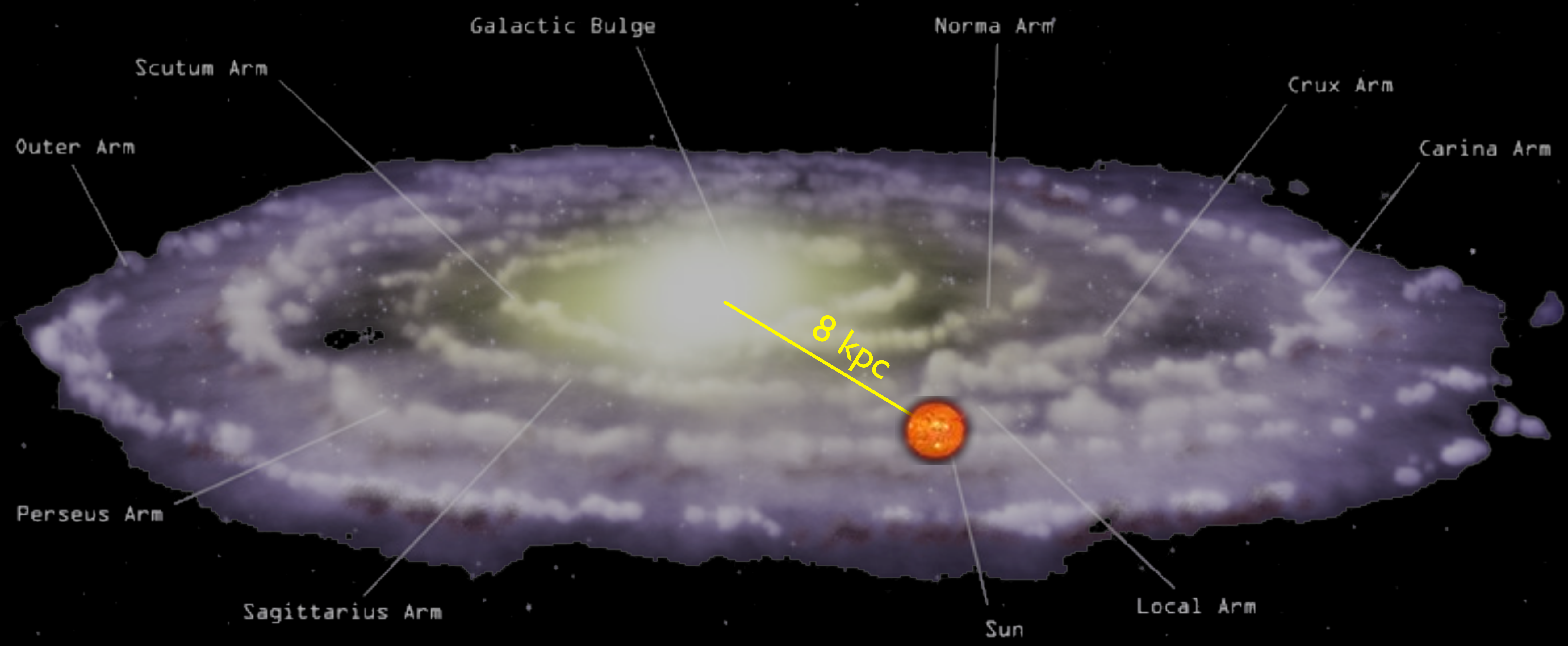
$\nu, \bar{\nu}$ from annihil in massive bodies

SK, Icecube

Predicting antiprotons from DM

Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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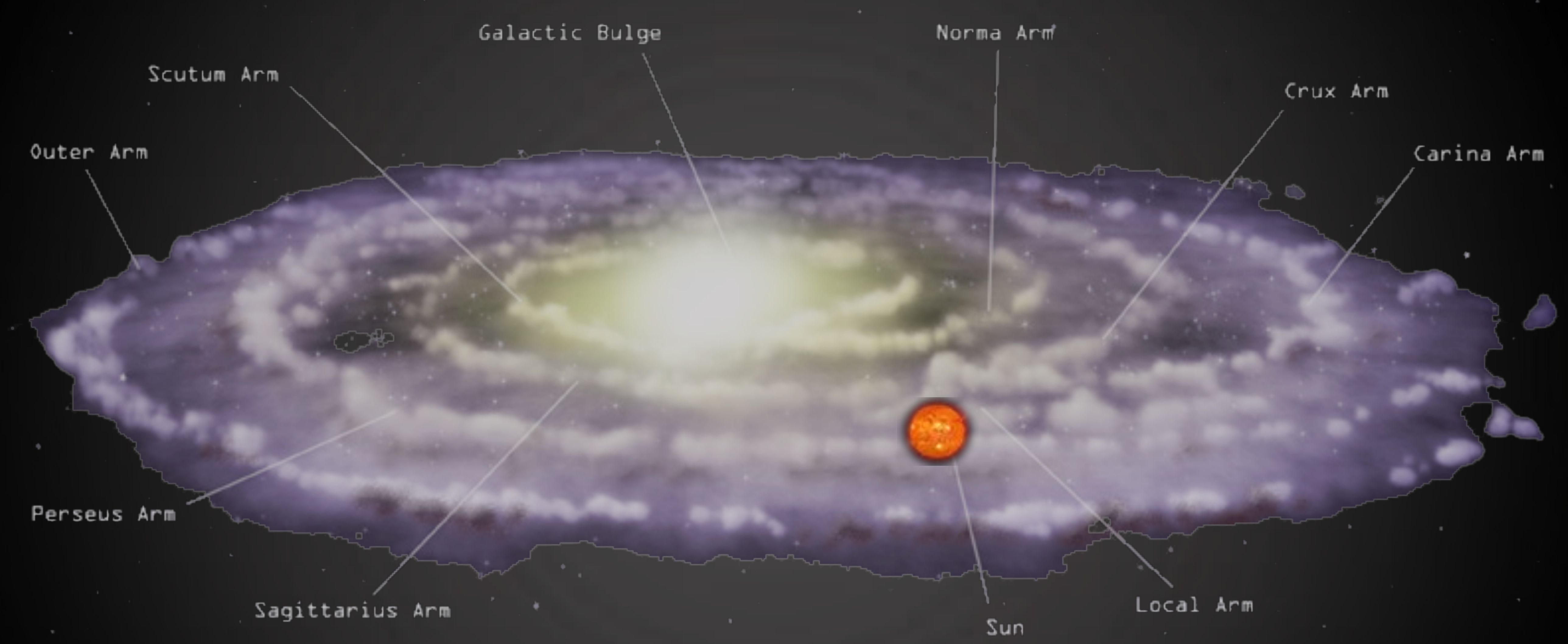

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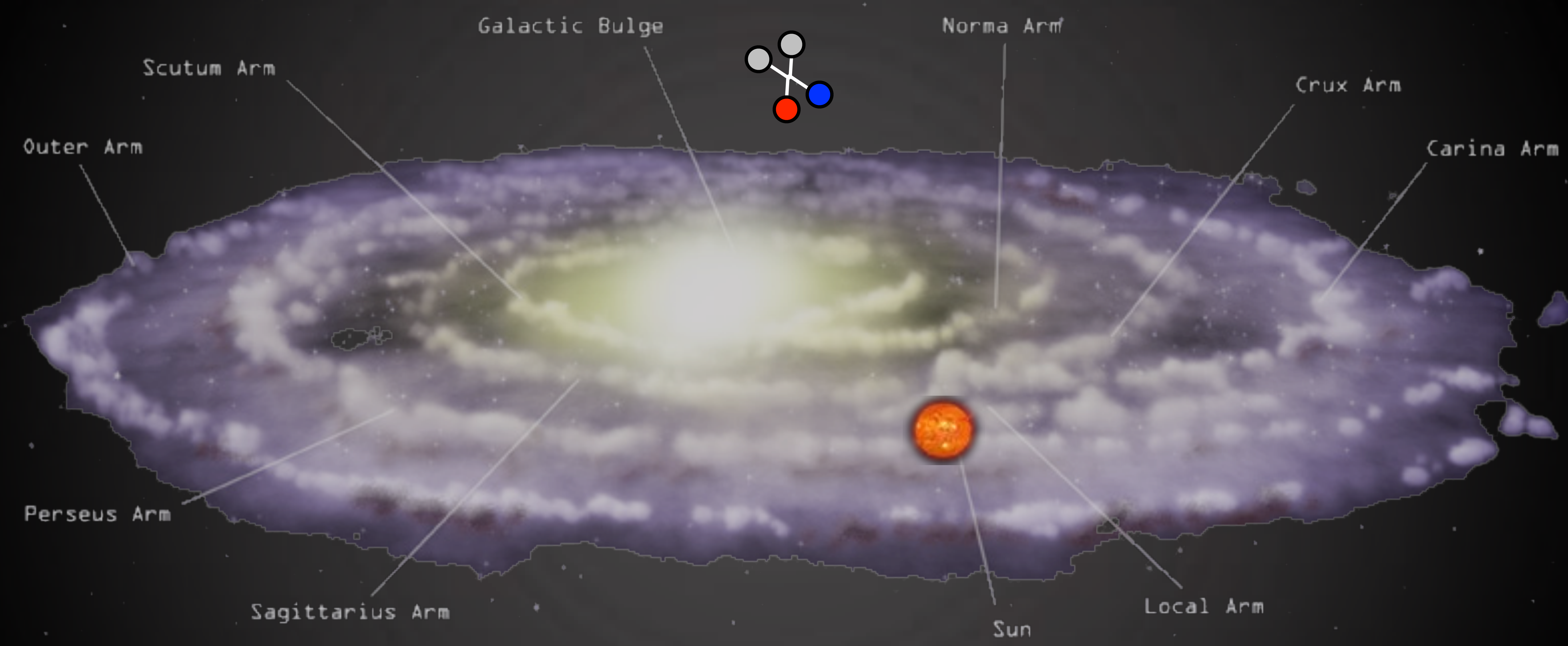
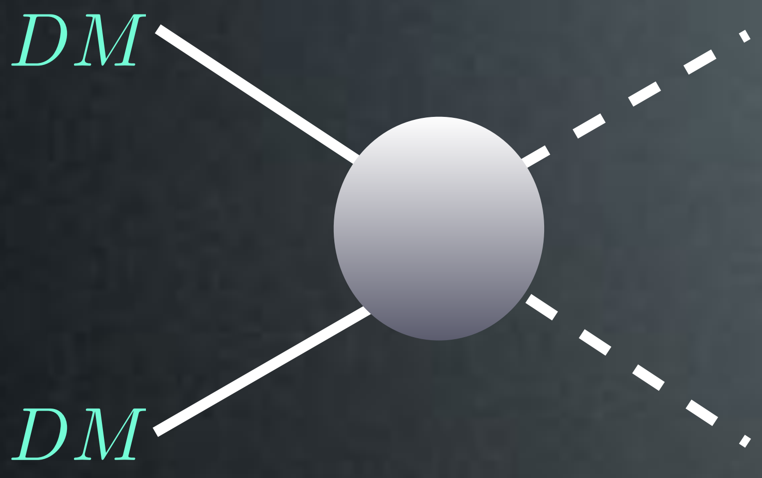


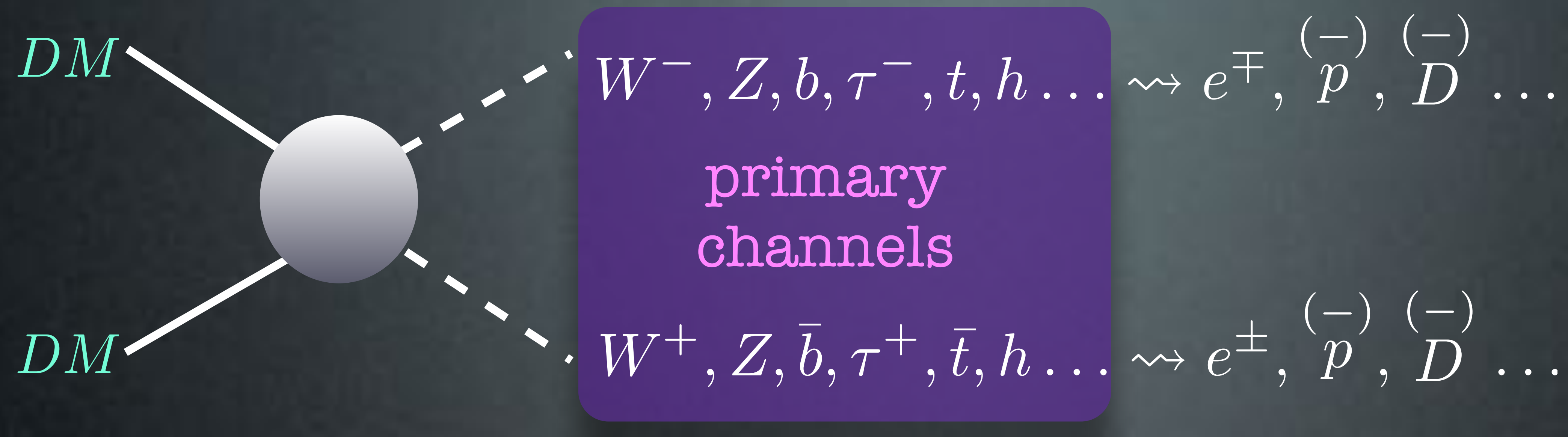
Indirect Detection: basics



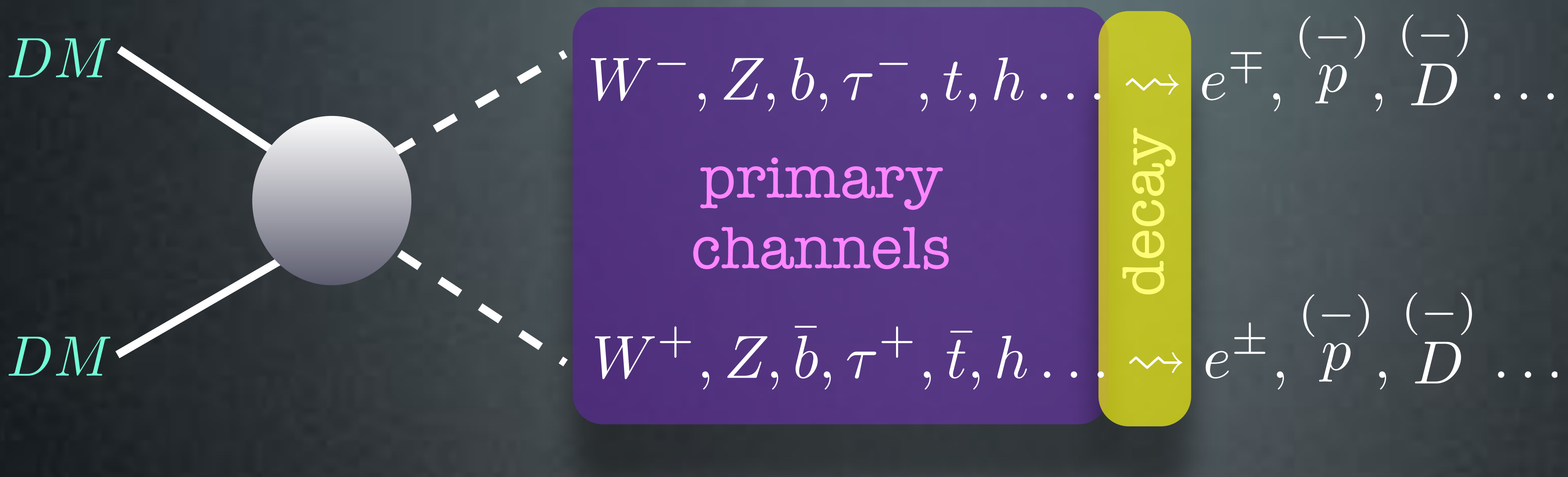
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \stackrel{(-)}{p}, \stackrel{(-)}{D} \ldots$$

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

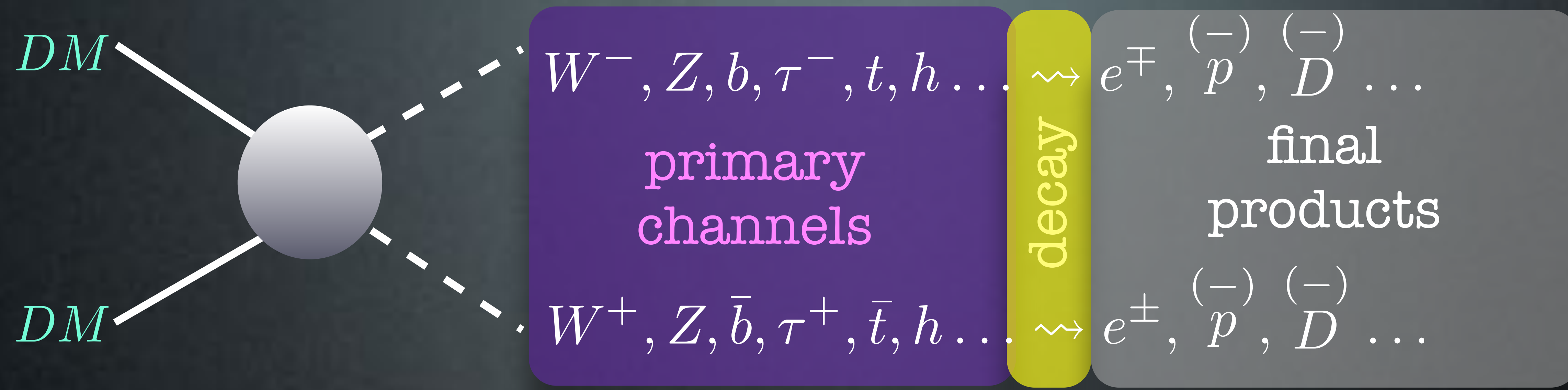
Indirect Detection: basics

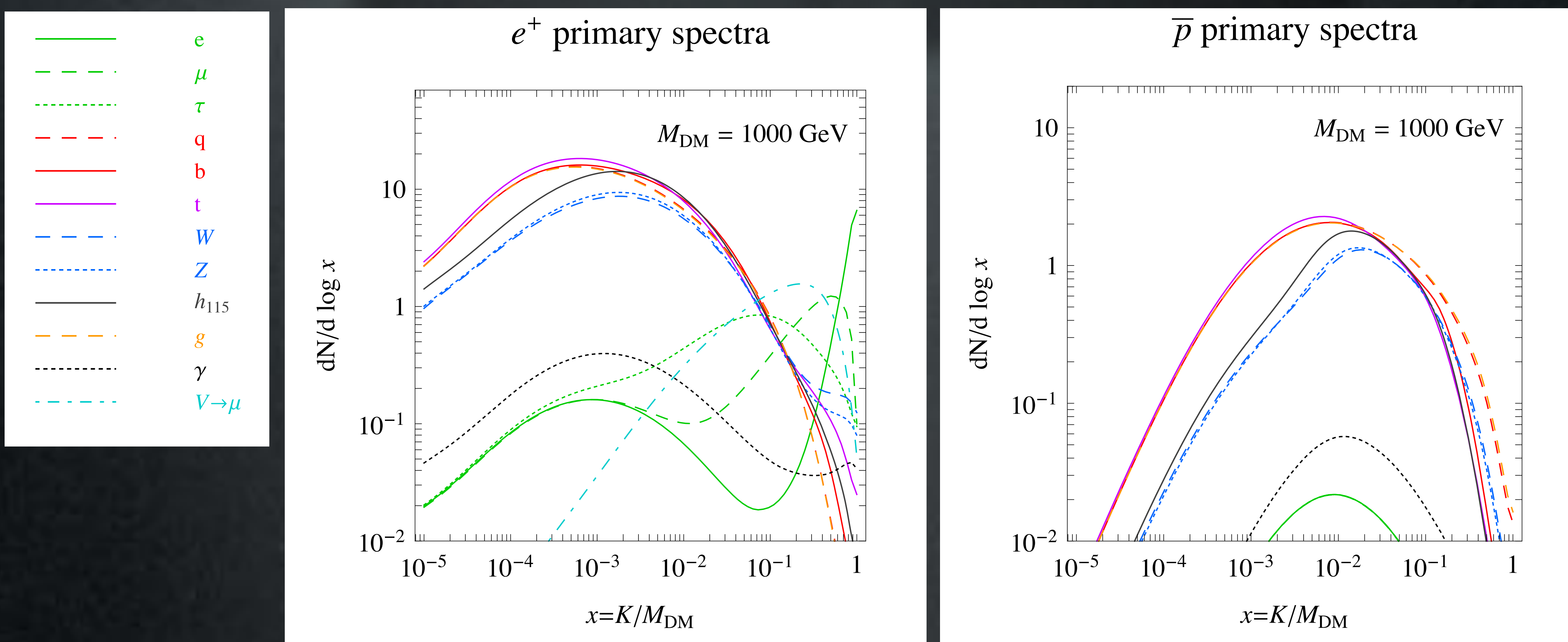


Indirect Detection: basics

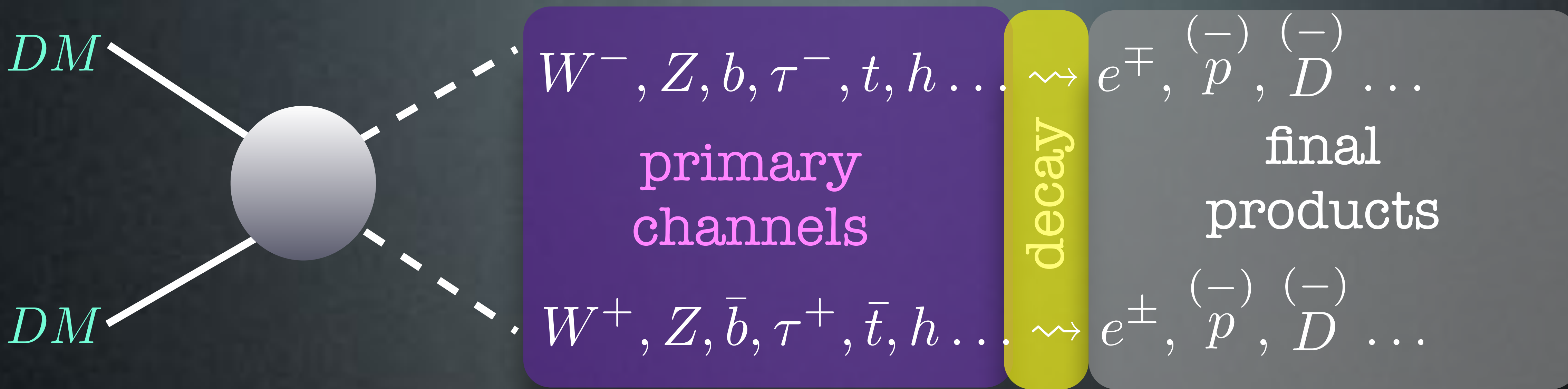


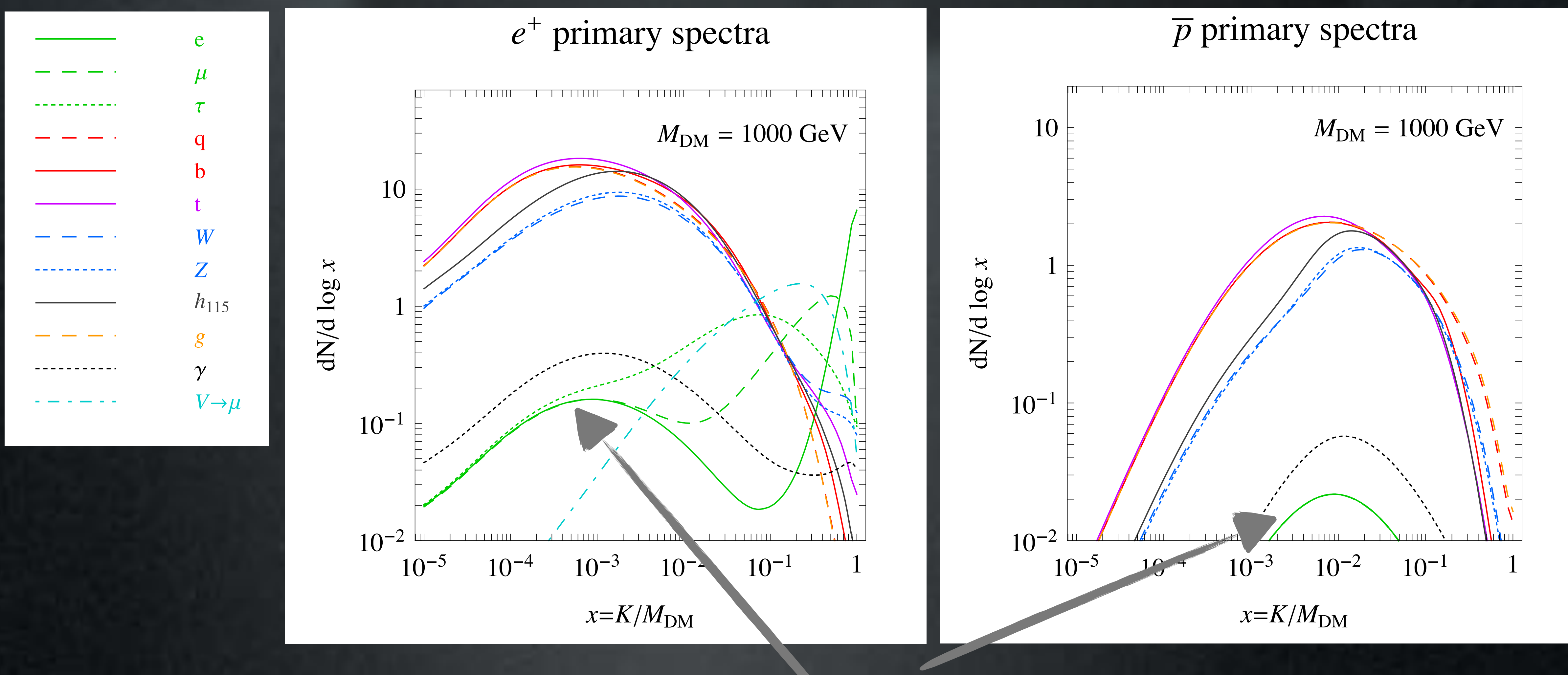
Indirect Detection: basics





Indirect Detection: basics



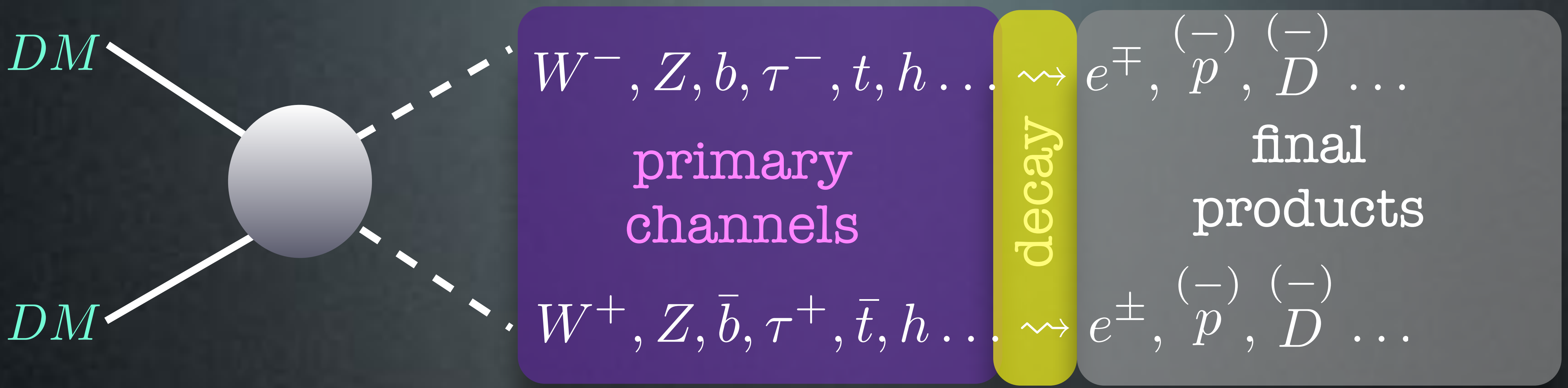


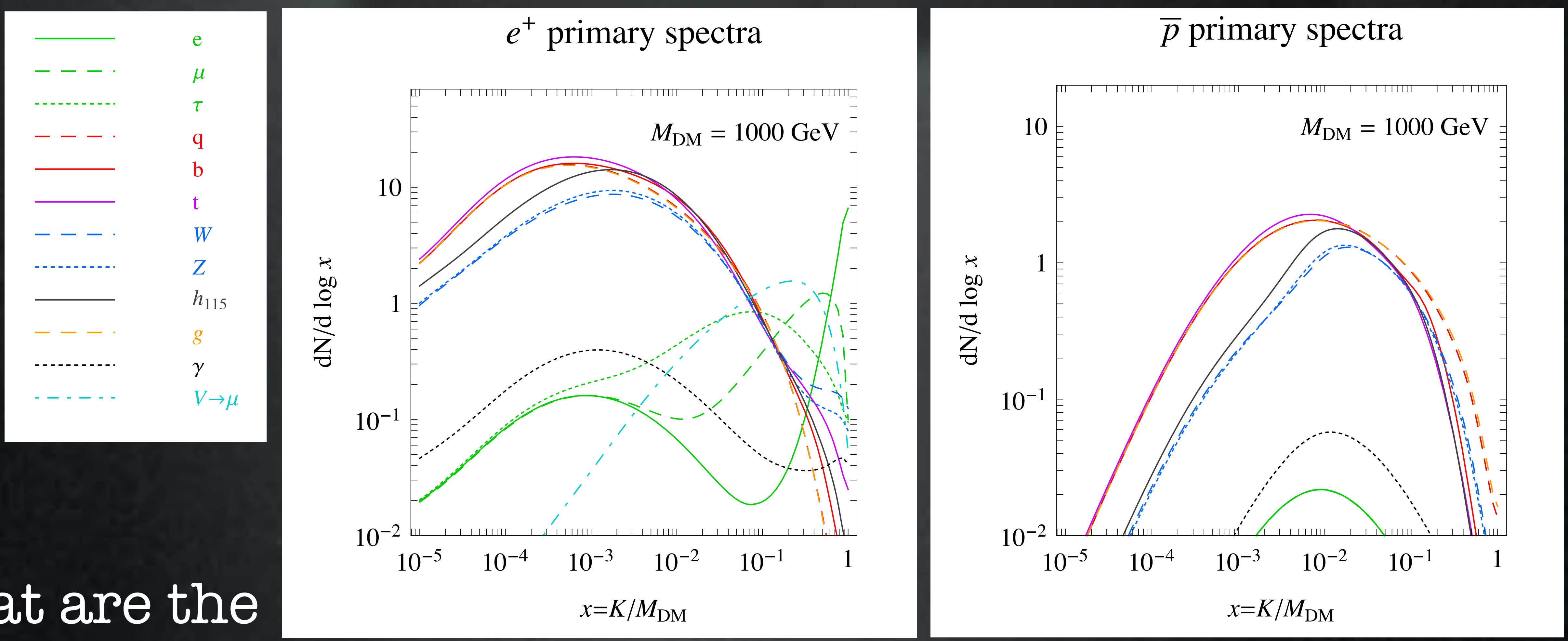
ElectroWeak corrections!

Sala et al., 1009.0224

Cirelli, Panci, Sala et al., 1012.4515

Indirect Detection: basics



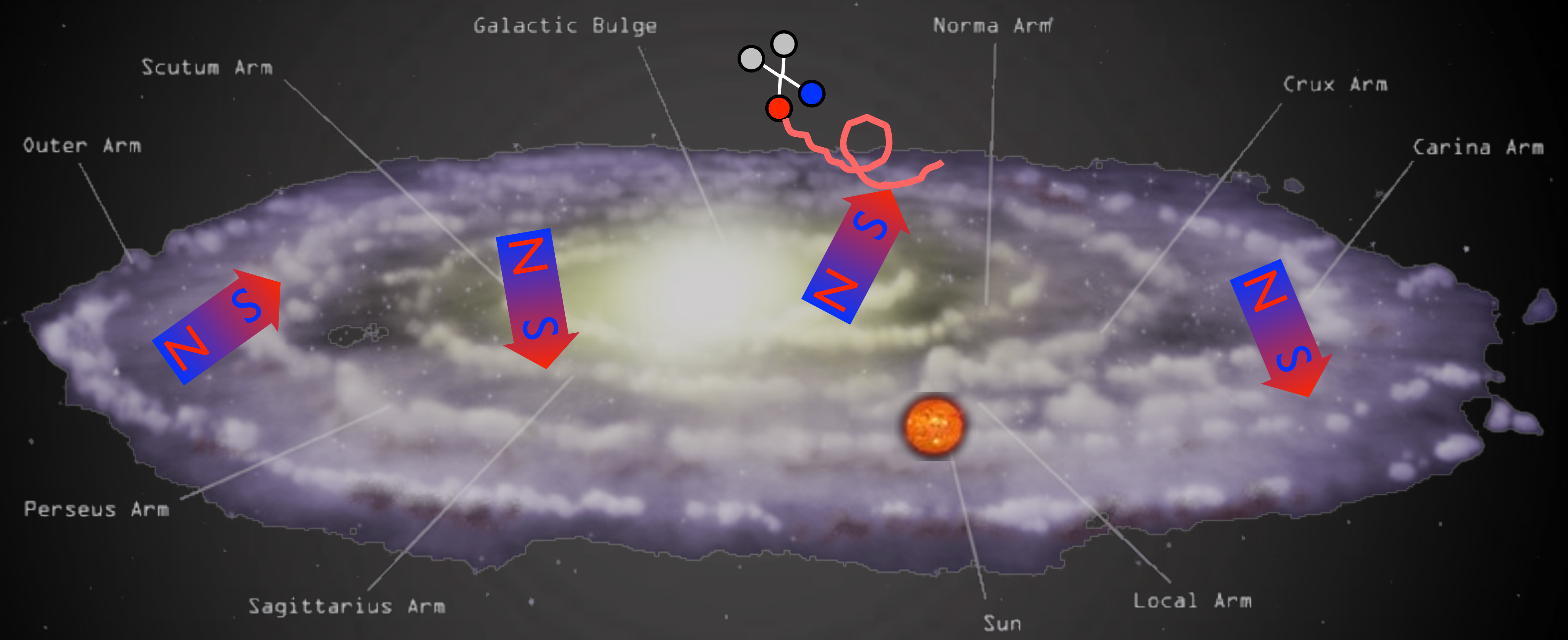


So what are the particle physics parameters?

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

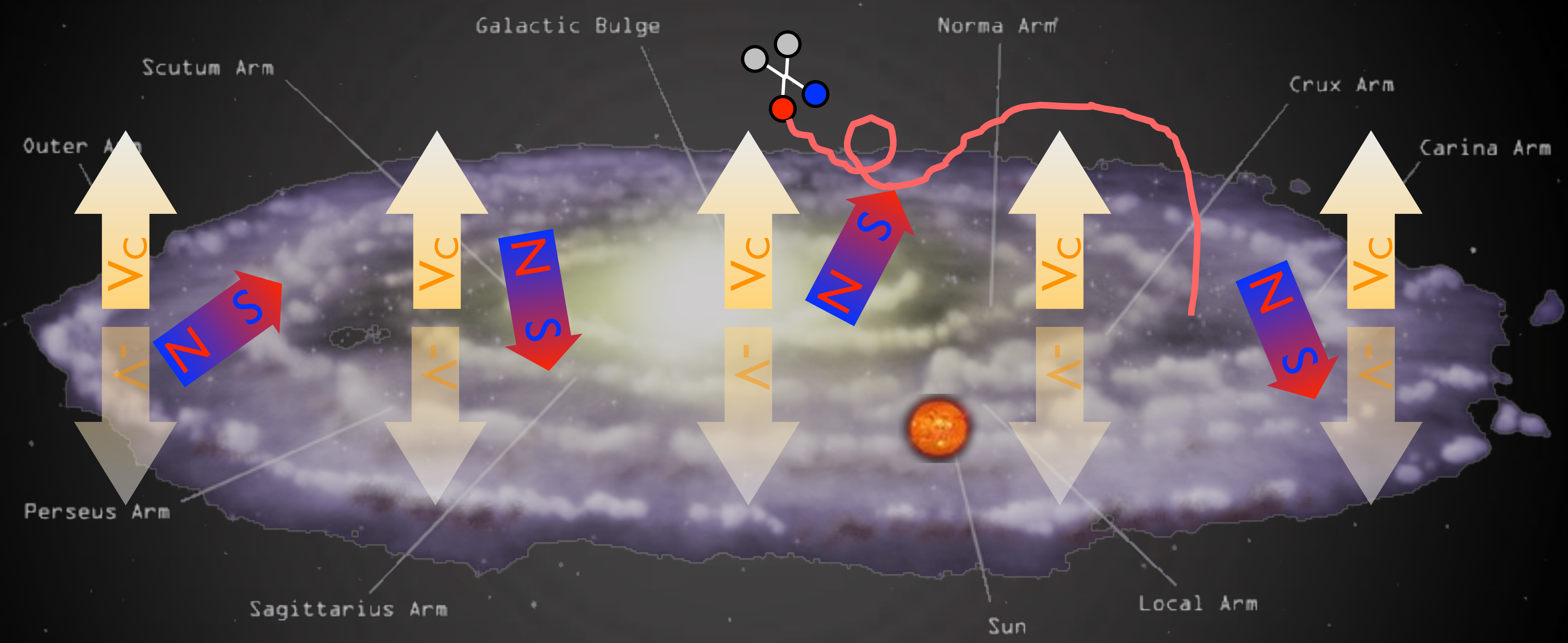
Indirect Detection: charged CRs

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



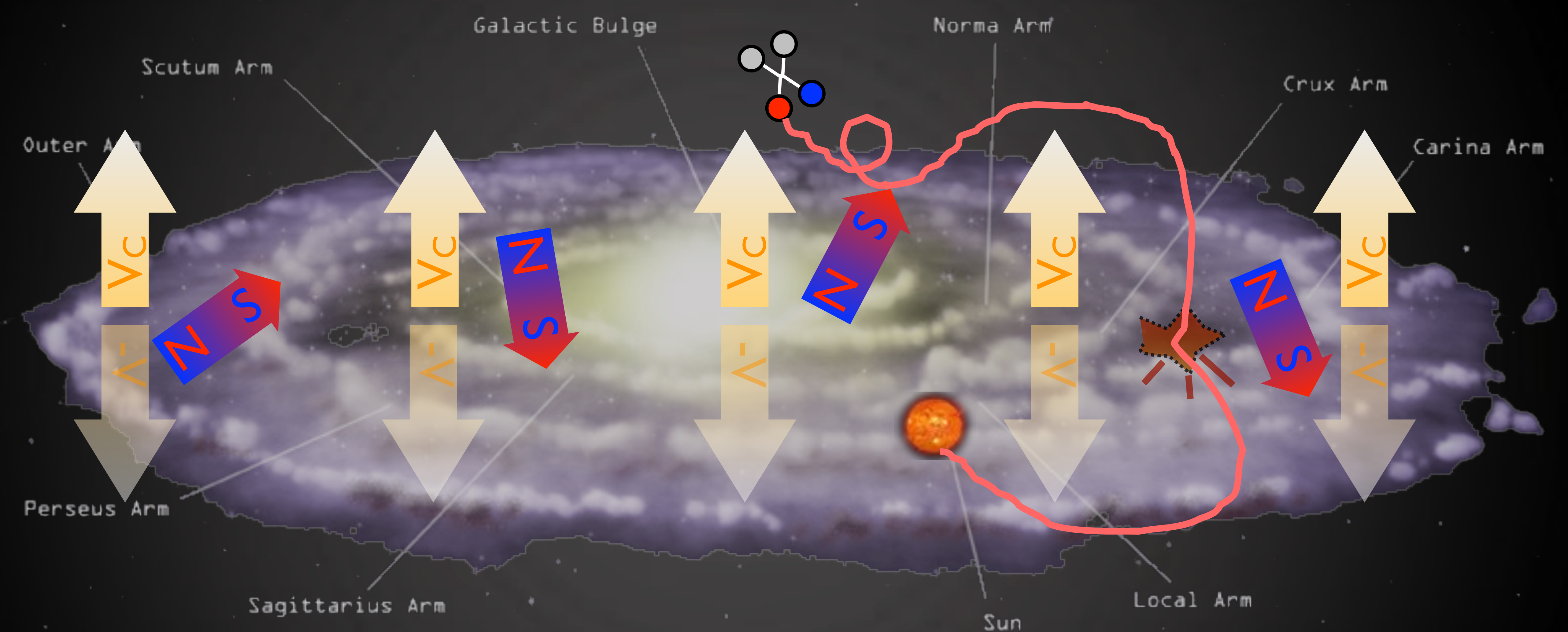
Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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



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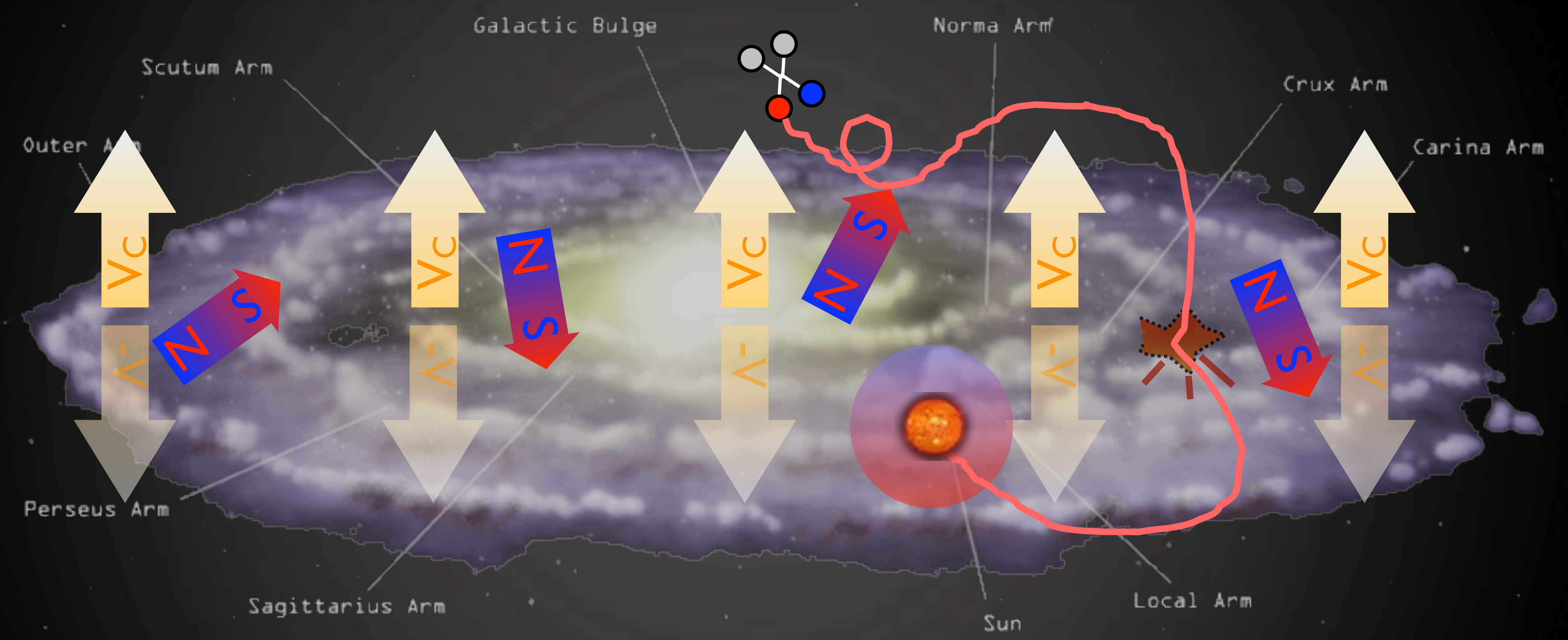
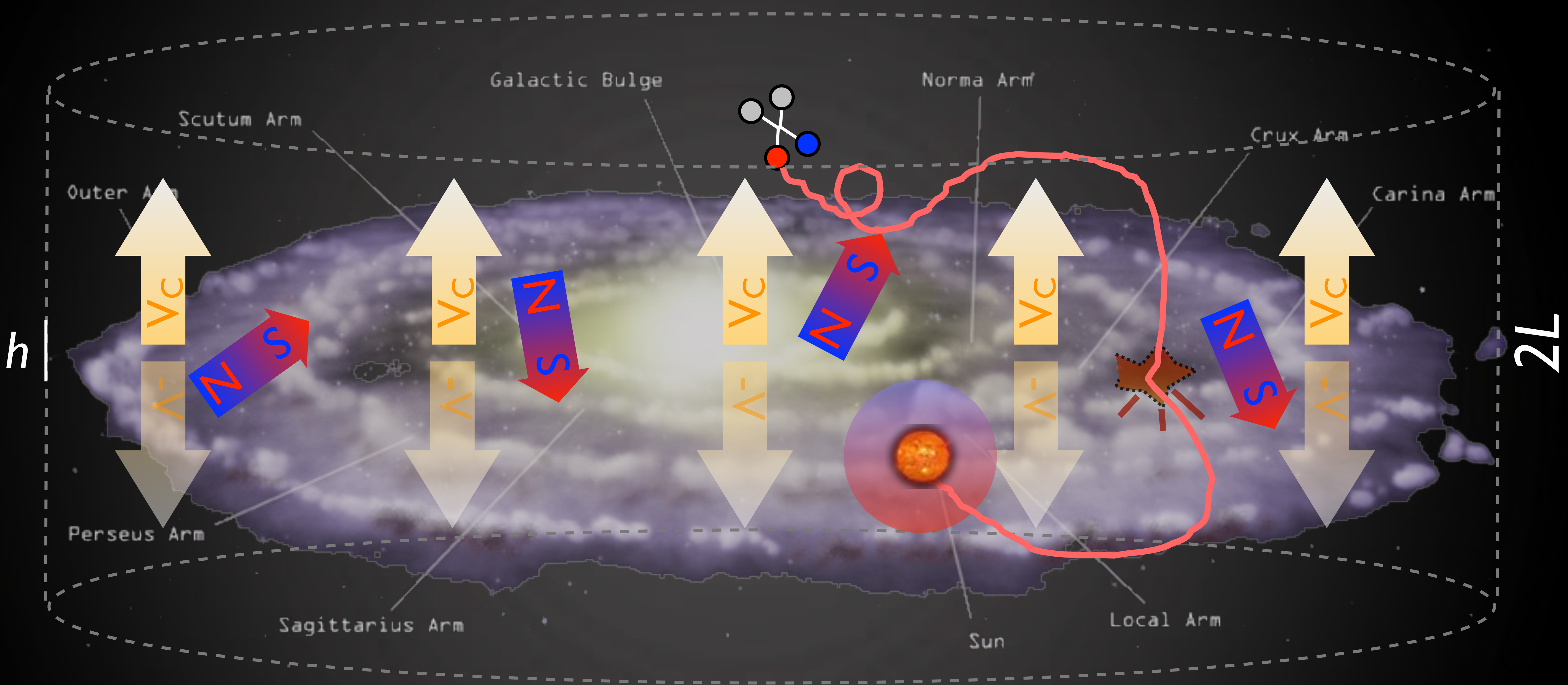


Indirect Detection: charged CRs

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



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

spectrum

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

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

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) $V_{\rm conv}$ [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+

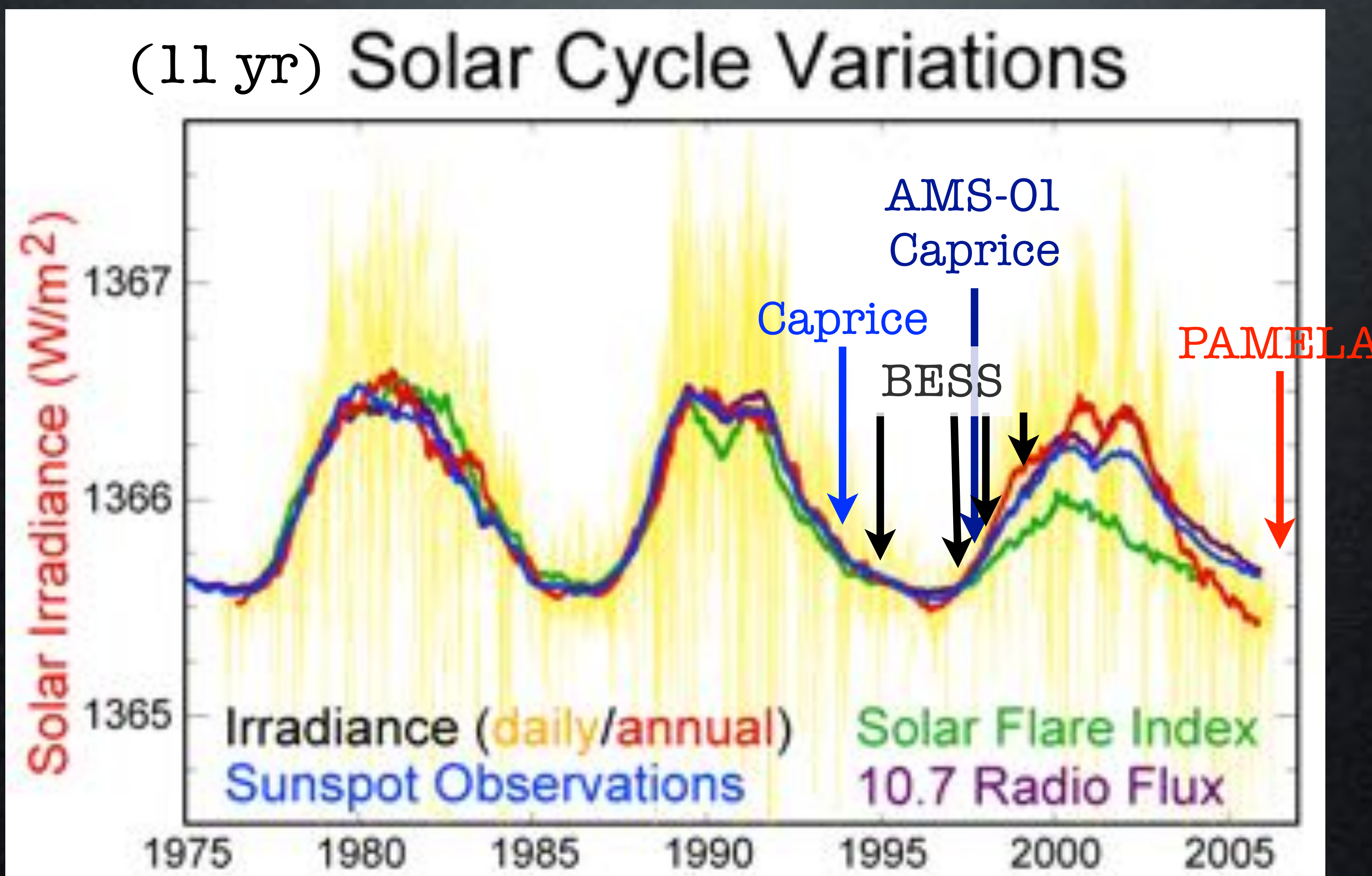
Indirect Detection: charged CRs

Solar 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



Indirect Detection: charged CRs

Solar wind Modulation of cosmic rays:

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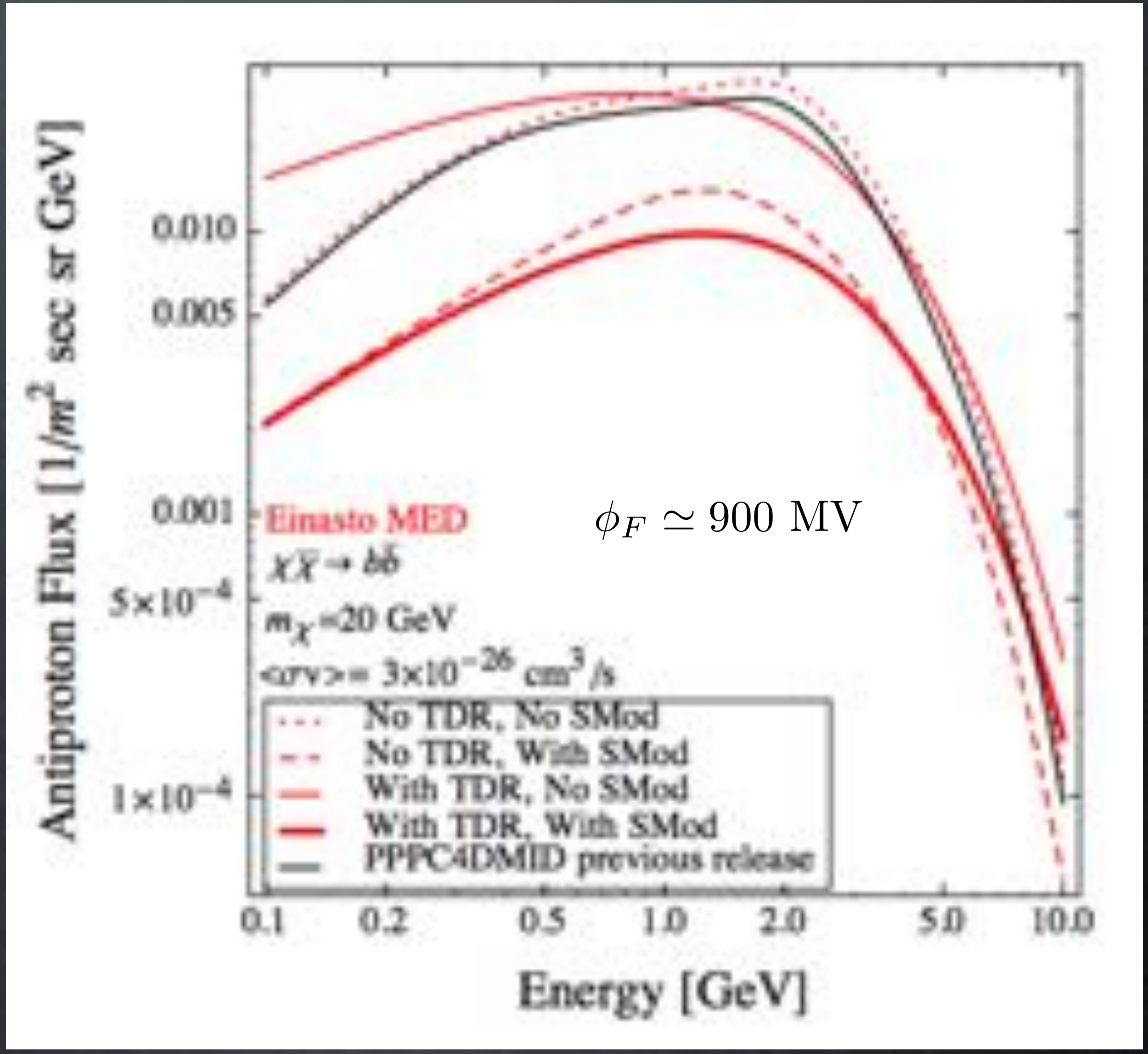
spectrum at Earth — spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV

E.g.



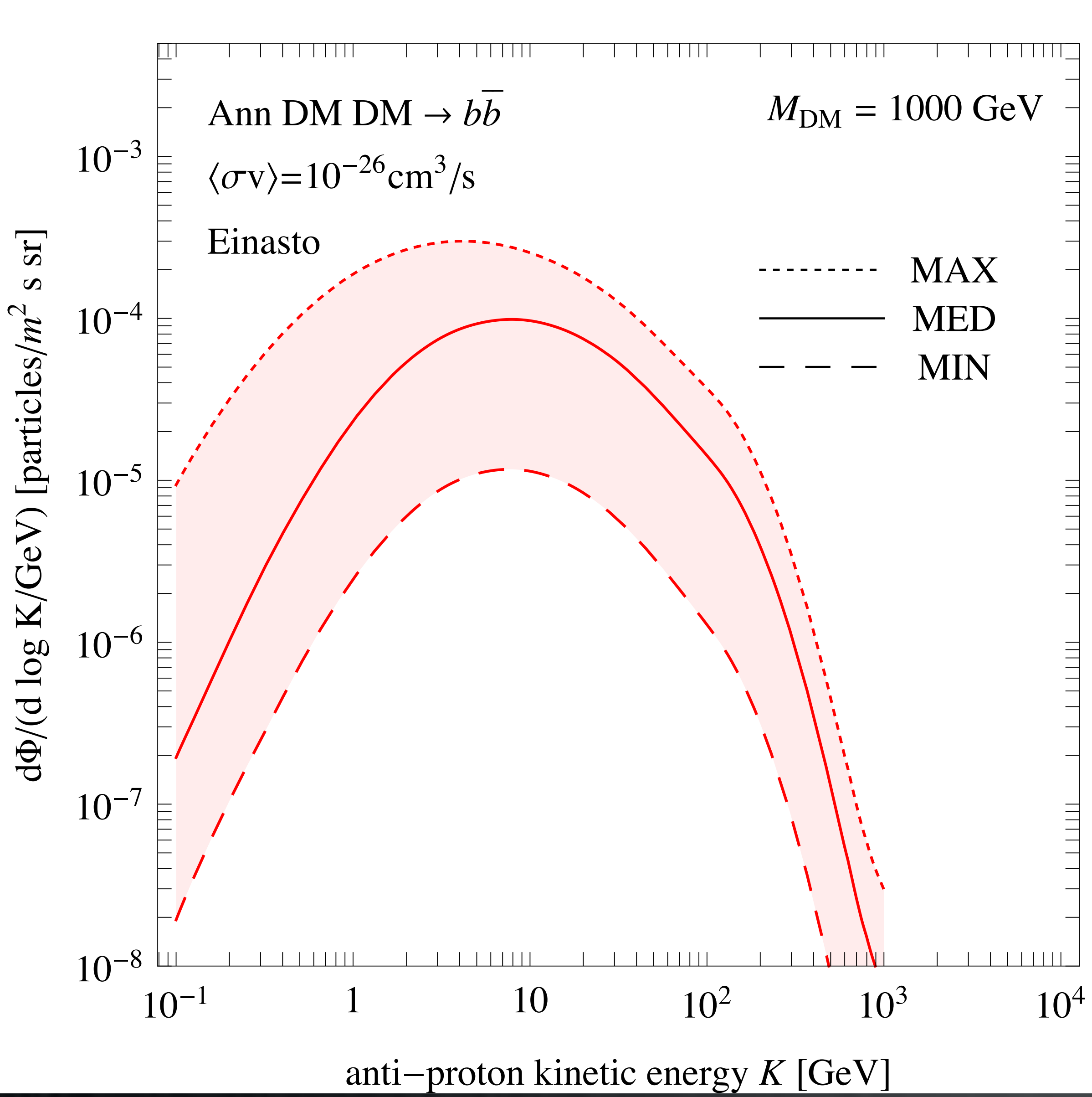
Boudaud, Cirelli, Giesen, Salati, 1412.5696

Propagated fluxes

Antiprotons

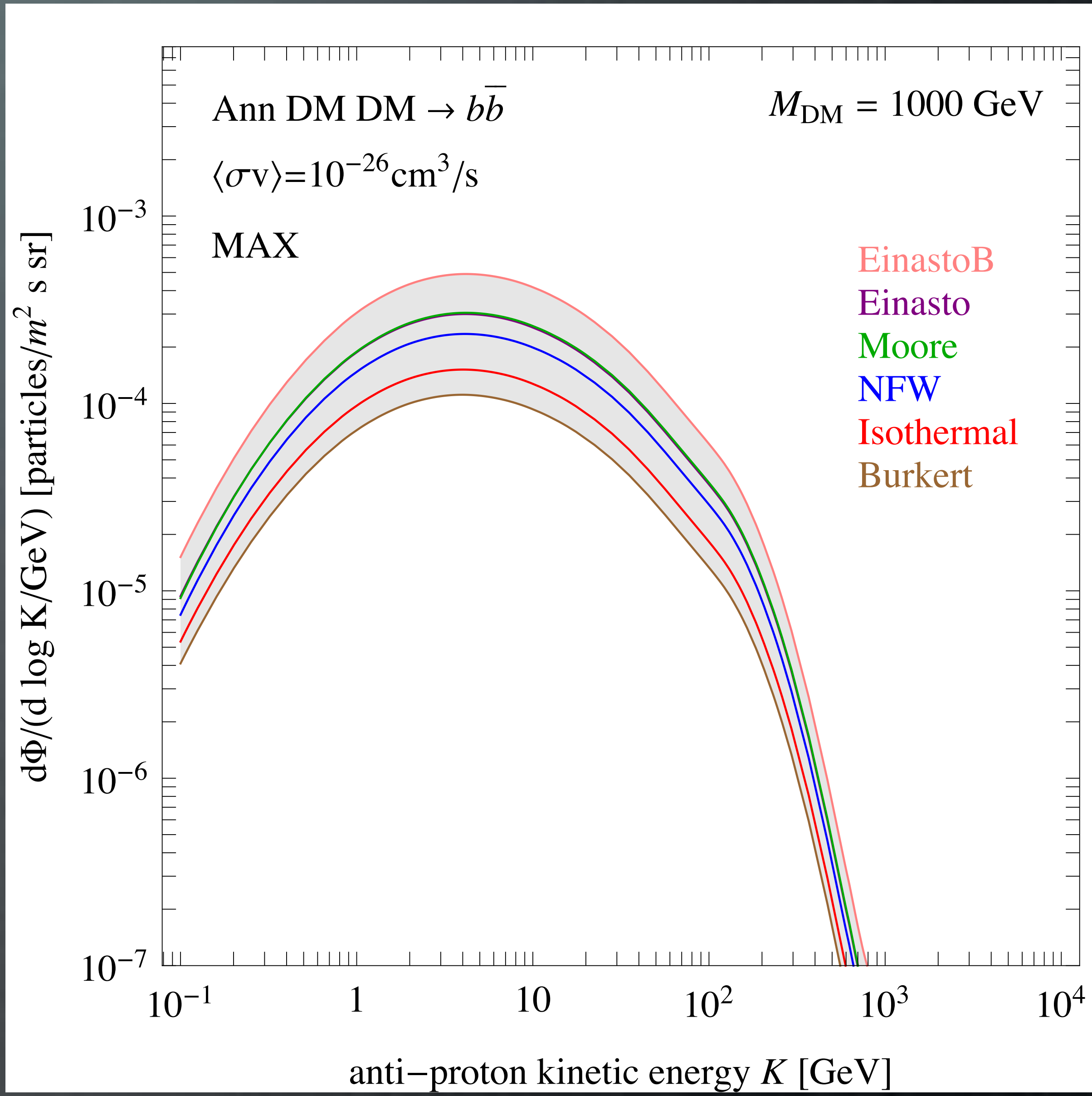
Cirelli, Panci, Sala et al., 1012.4515
Boudaud, Cirelli, Giesen, Salati 1412.5696

Varying prop parameters



Almost 2 orders of magnitude

Varying halo profile



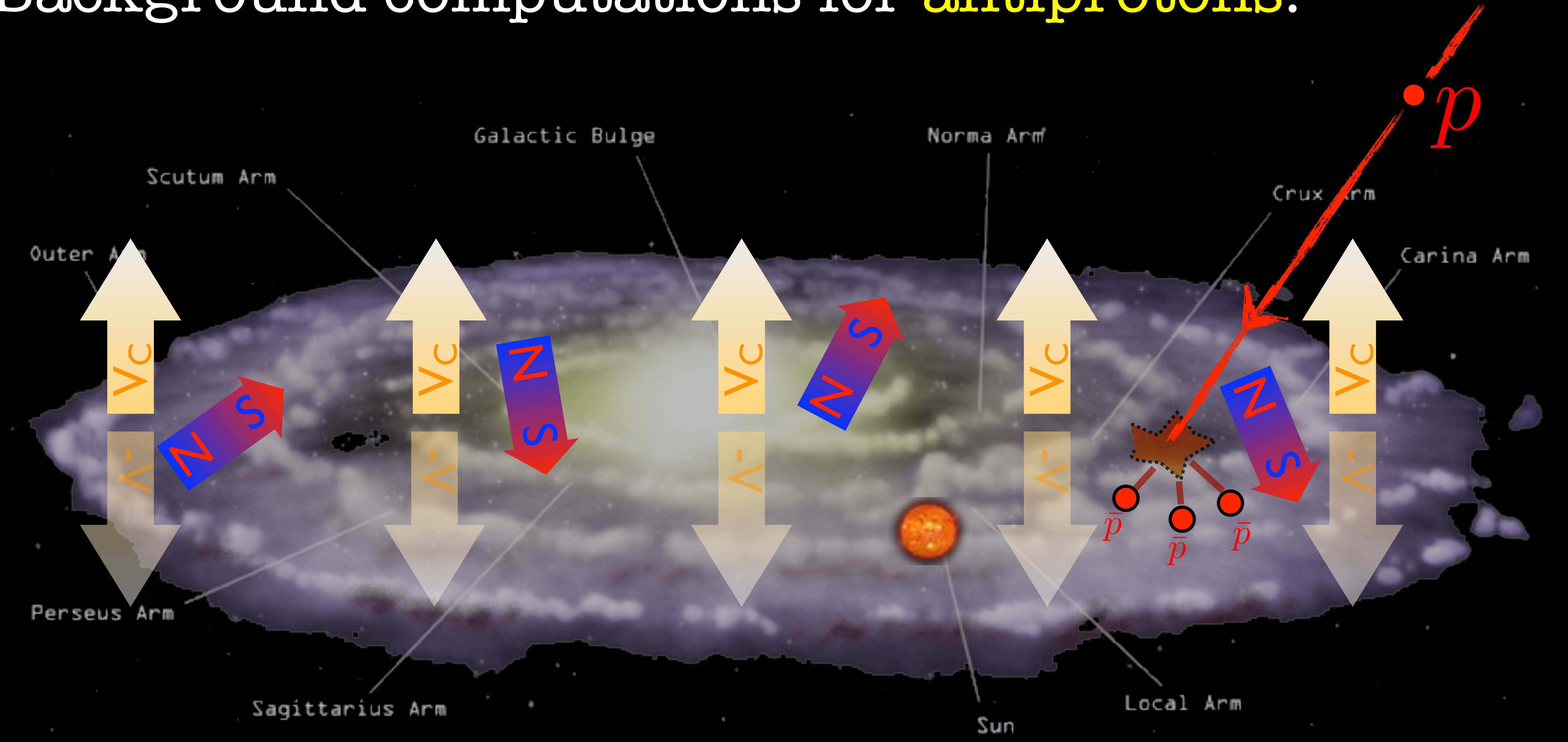
Almost 1 order of magnitude

Bottom line: Antiprotons are quite affected by propagation, but spectral shape somewhat preserved

Predicting antiprotons from astrophysics

Indirect Detection

Background computations for antiprotons:



Indirect Detection

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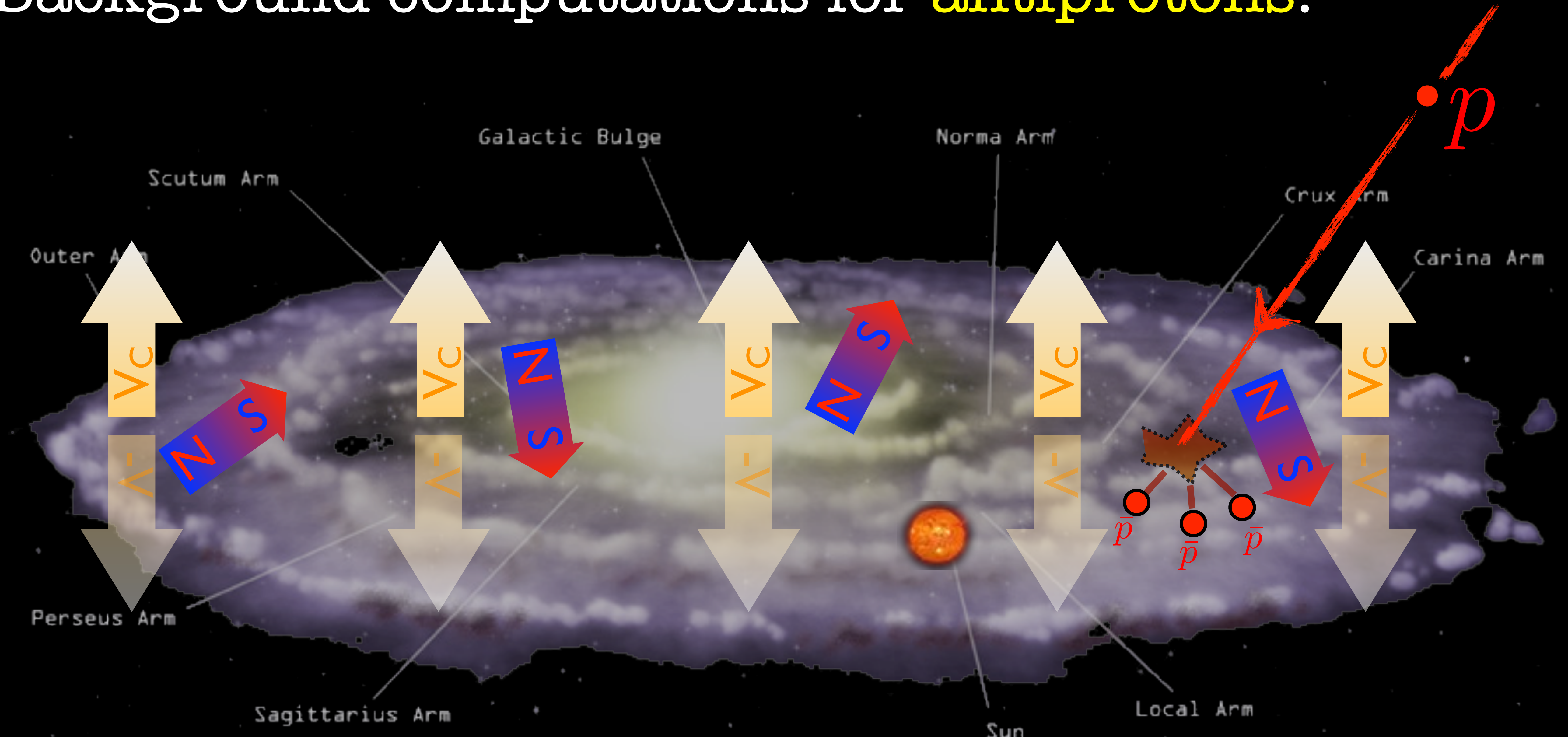
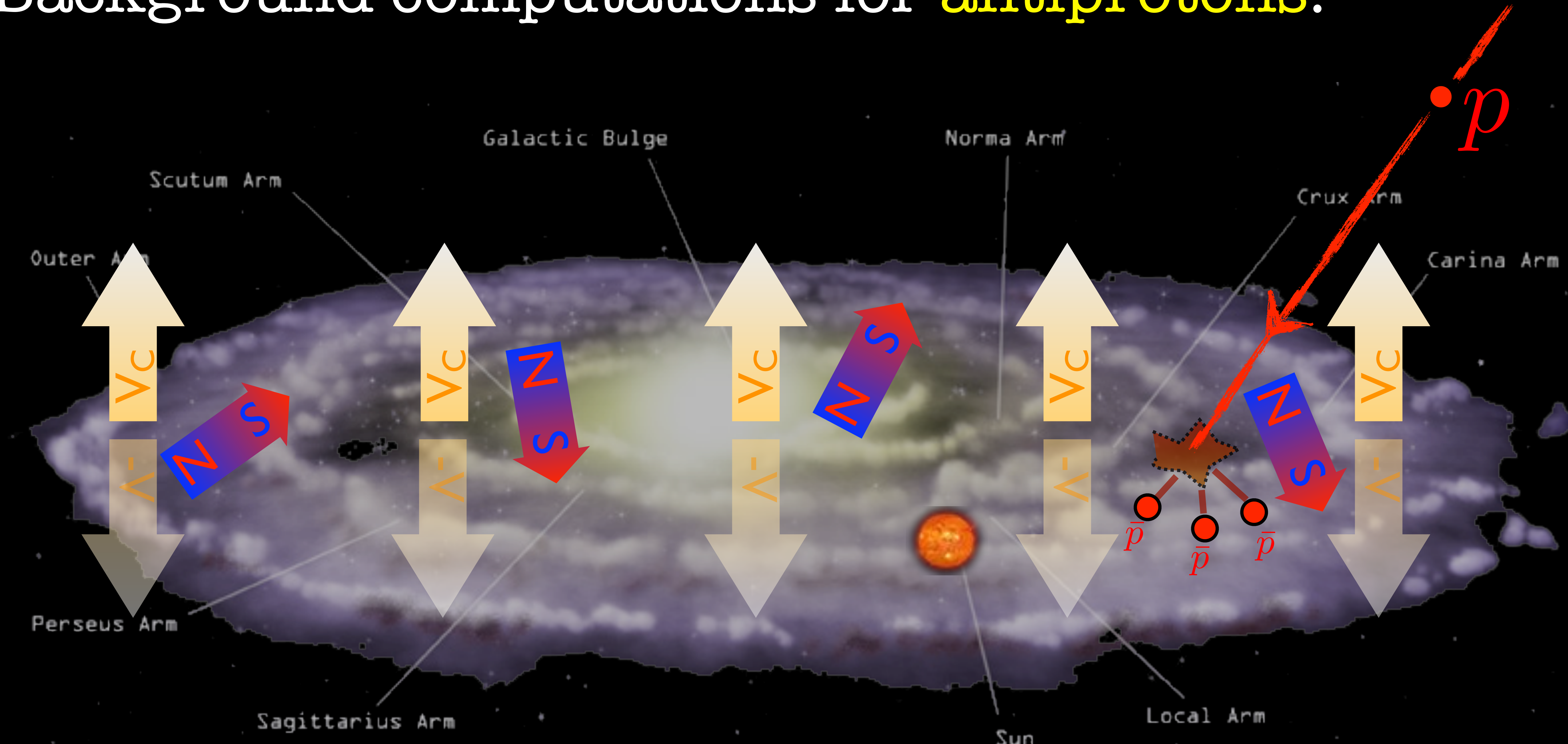


Main ingredients:

- primary p (and He)
- spallation cross-sections $\sigma_{pH\to\bar{p}X}$, $\sigma_{pHe\to\bar{p}X}$, $\sigma_{HeH\to\bar{p}X}$, $\sigma_{HeHe\to\bar{p}X}$
- propagation
- solar modulation

Indirect Detection

Background computations for antiprotons:



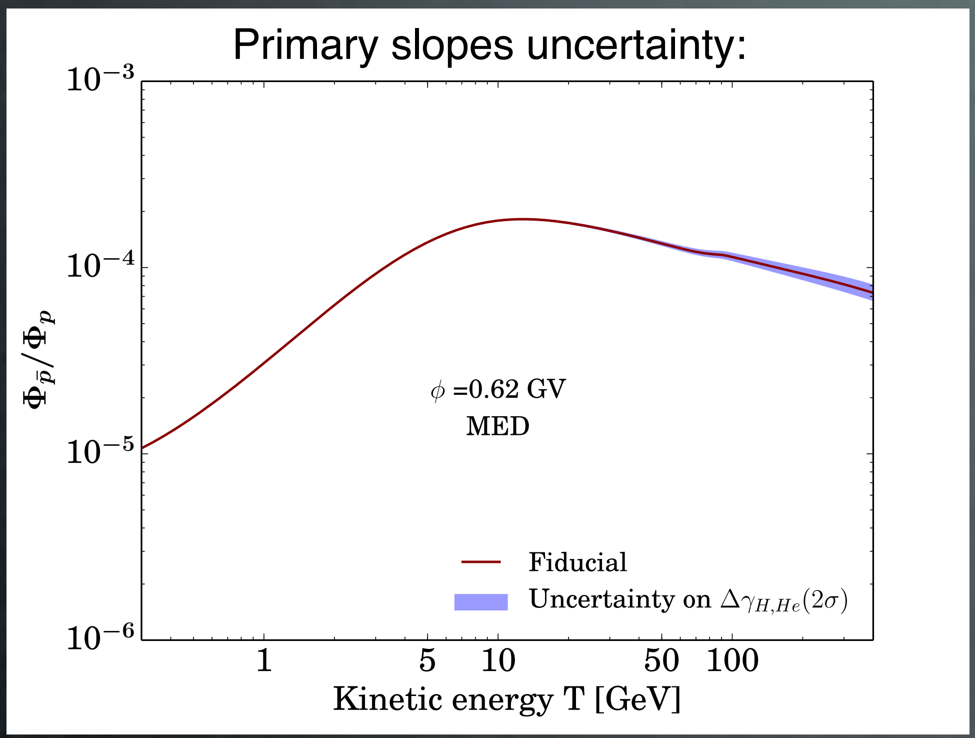
Main ingredients:

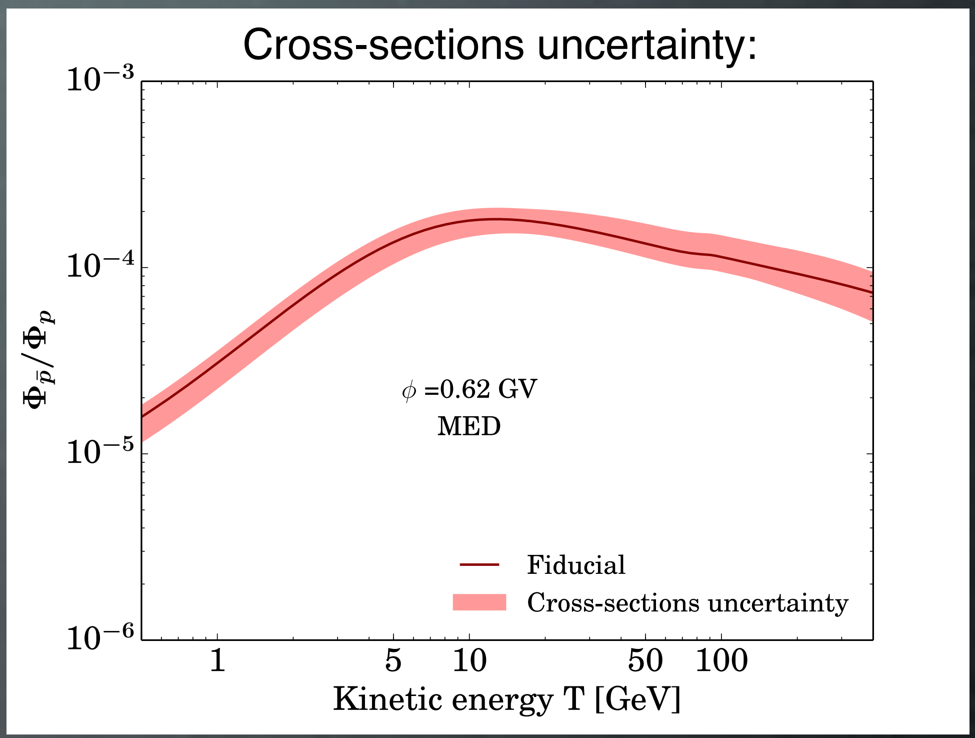
- primary p (and He) **New!**
- spallation cross-sections $\sigma_{pH\to\bar{p}X}$, $\sigma_{pHe\to\bar{p}X}$, $\sigma_{HeH\to\bar{p}X}$, $\sigma_{HeHe\to\bar{p}X}$ **New!**
- propagation
- solar modulation

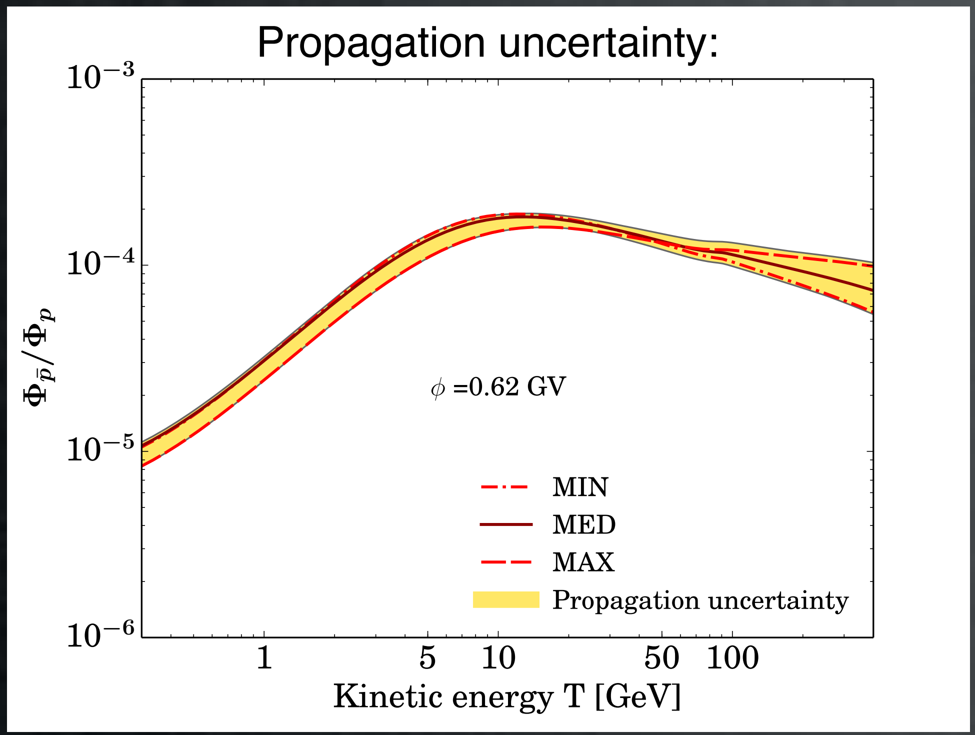
Indirect Detection

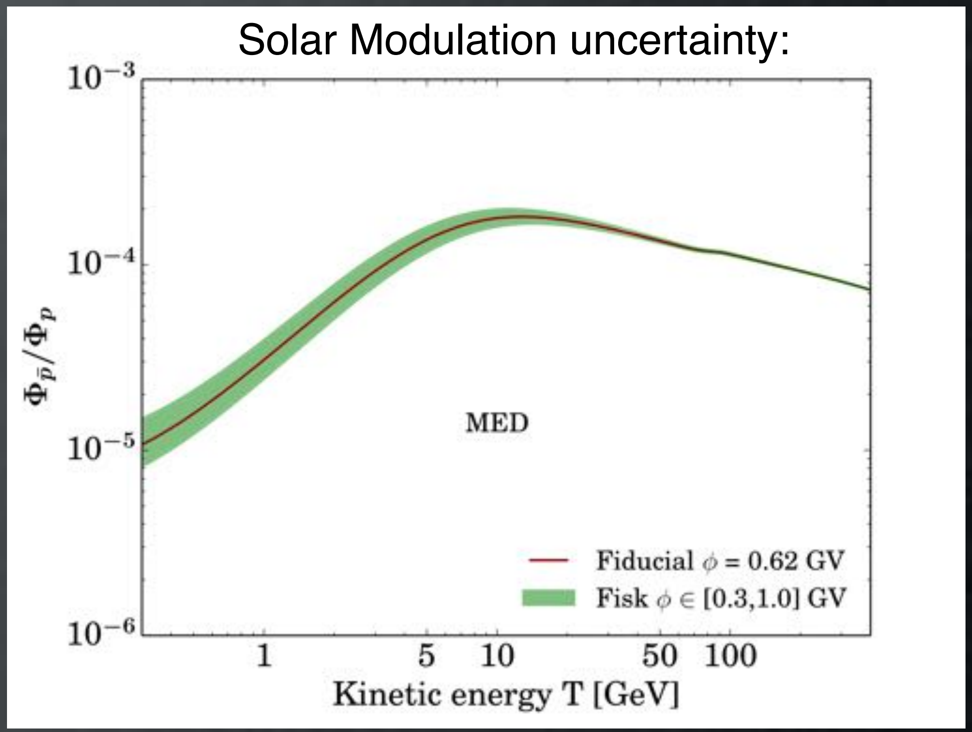
Background computations for antiprotons:

Uncertainties:





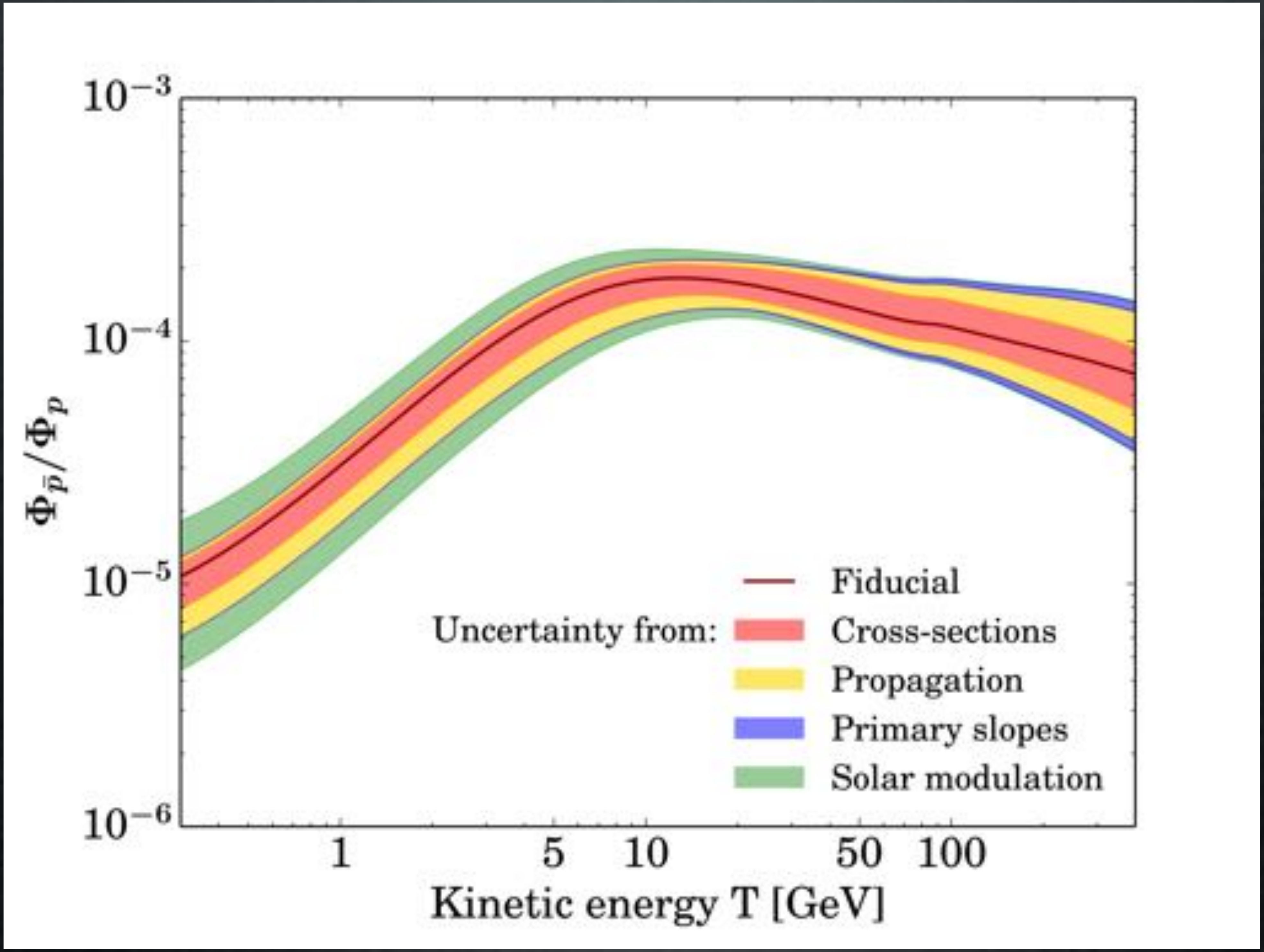




Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico
1504.04276

Indirect Detection

Background computations for antiprotons:

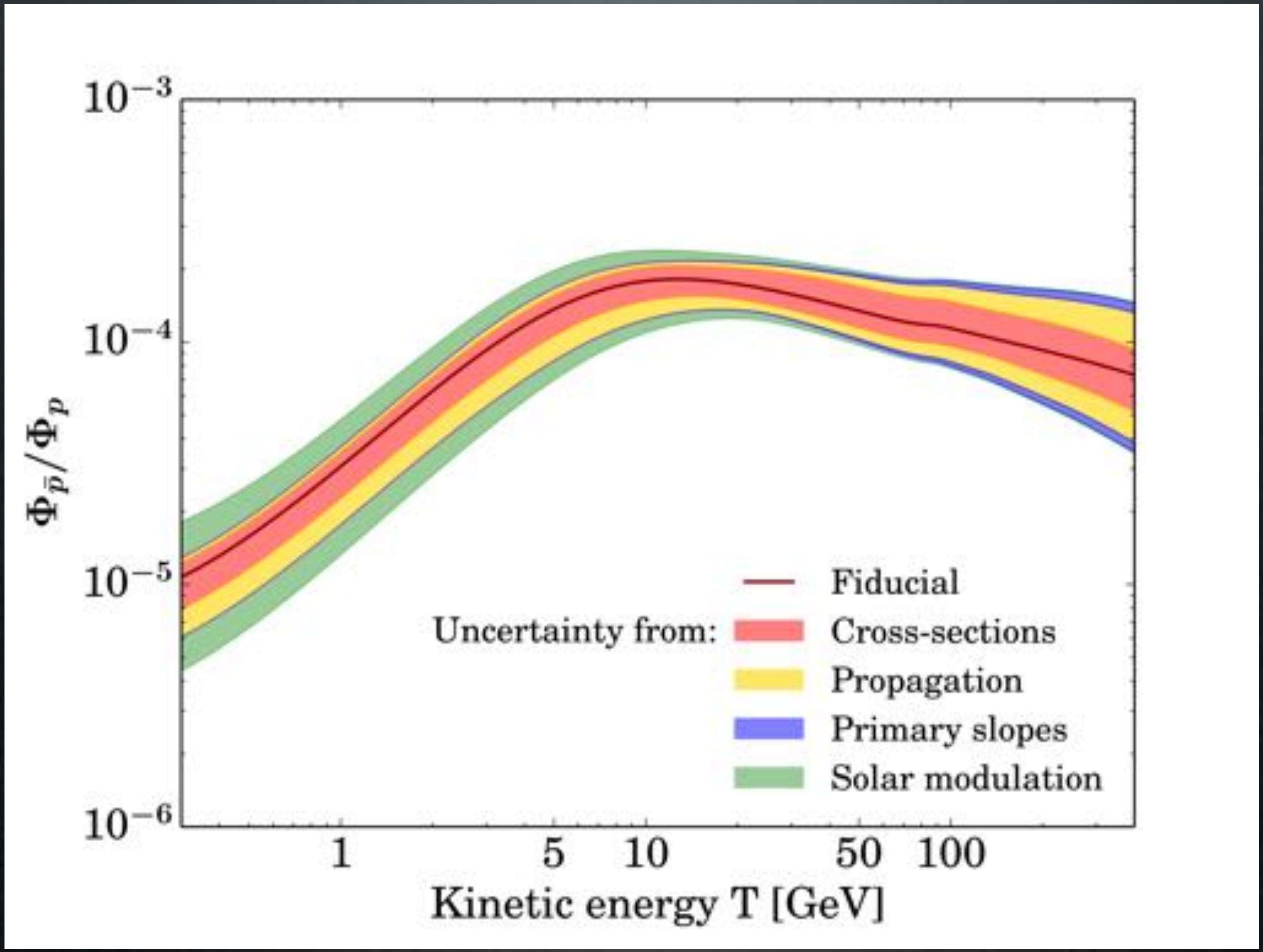


Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Data

Indirect Detection

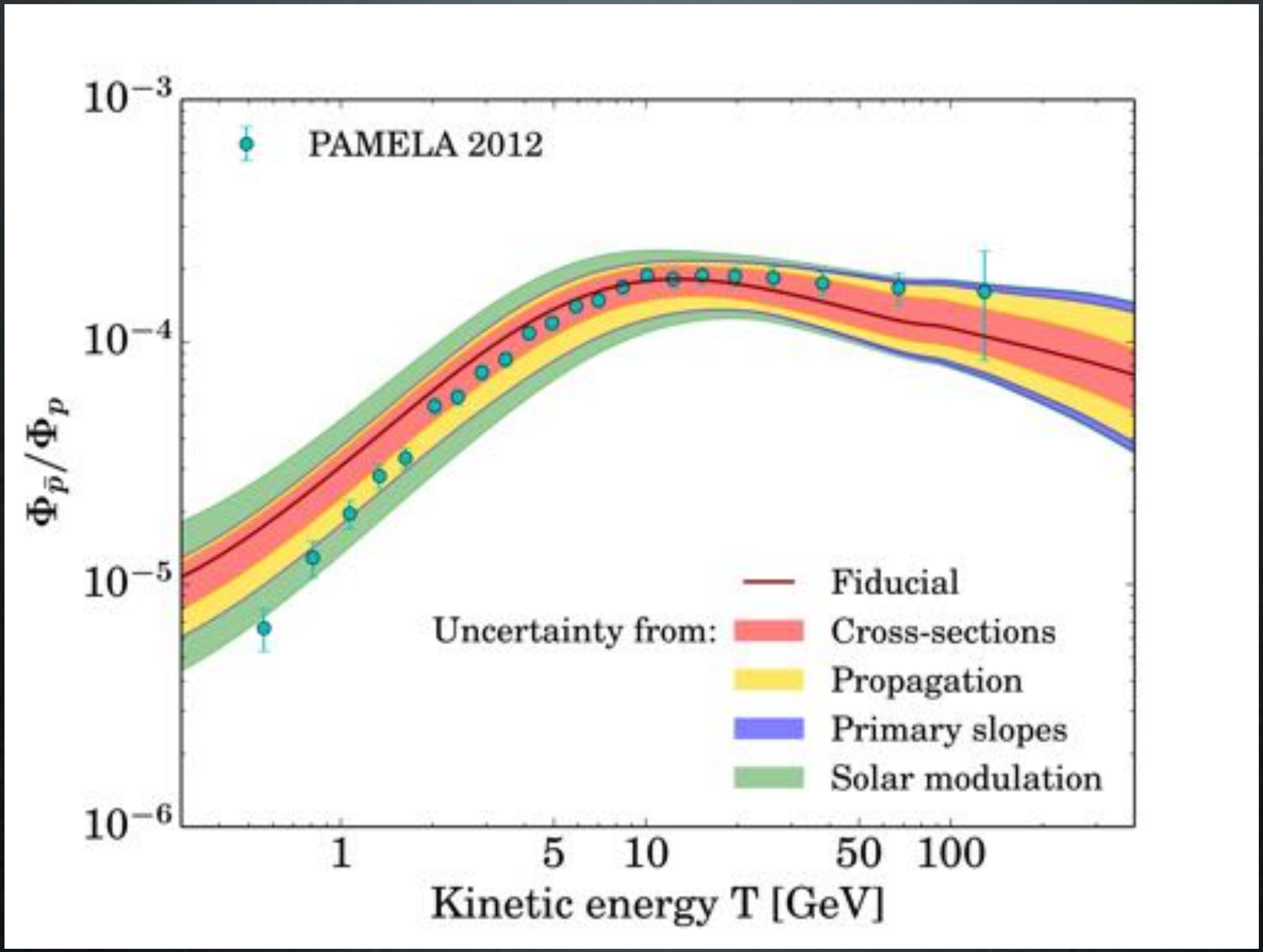
Antiproton data vis-à-vis the background:



Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Indirect Detection

Antiproton data vis-à-vis the background:



Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Indirect Detection

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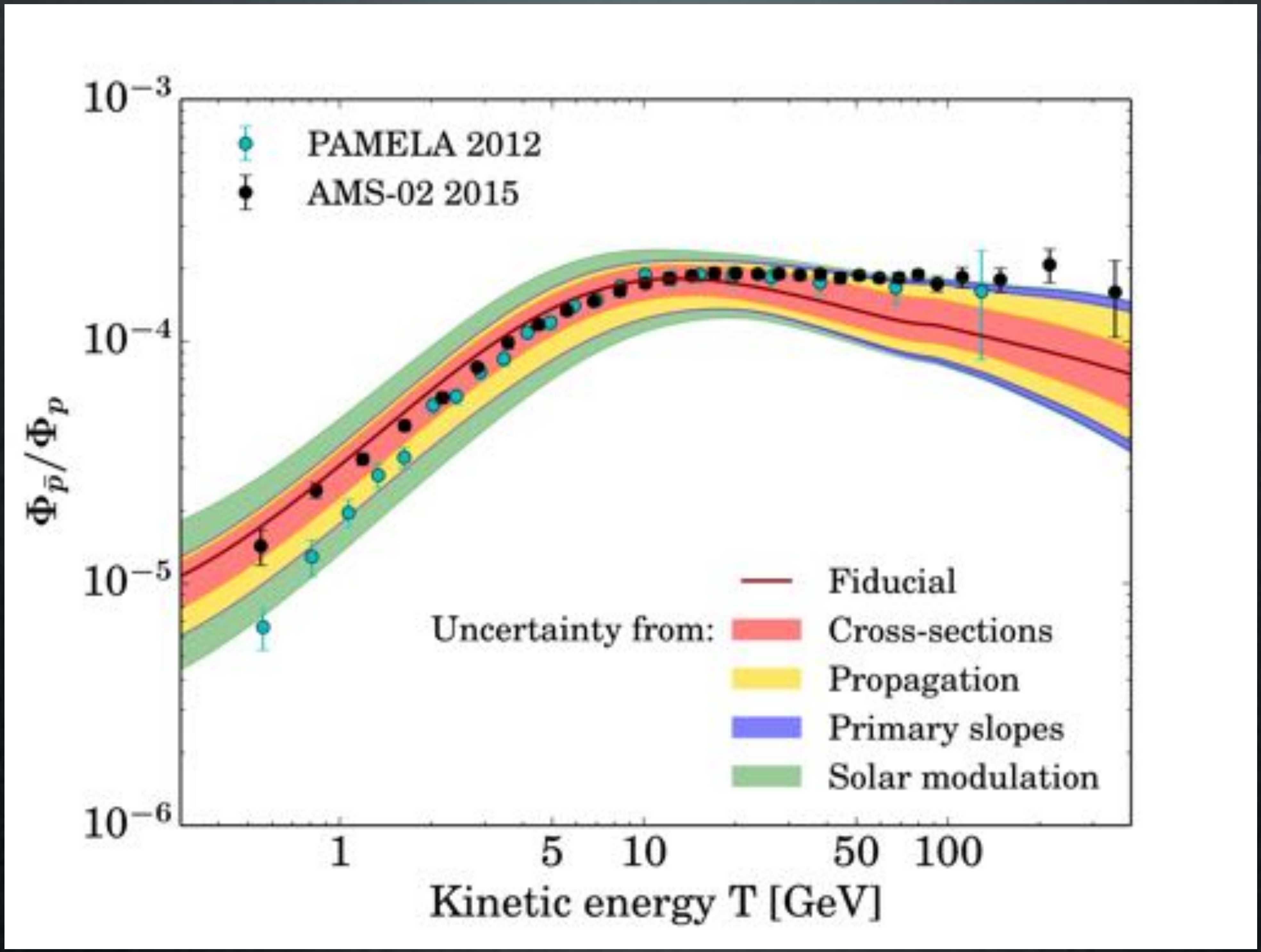

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Indirect Detection

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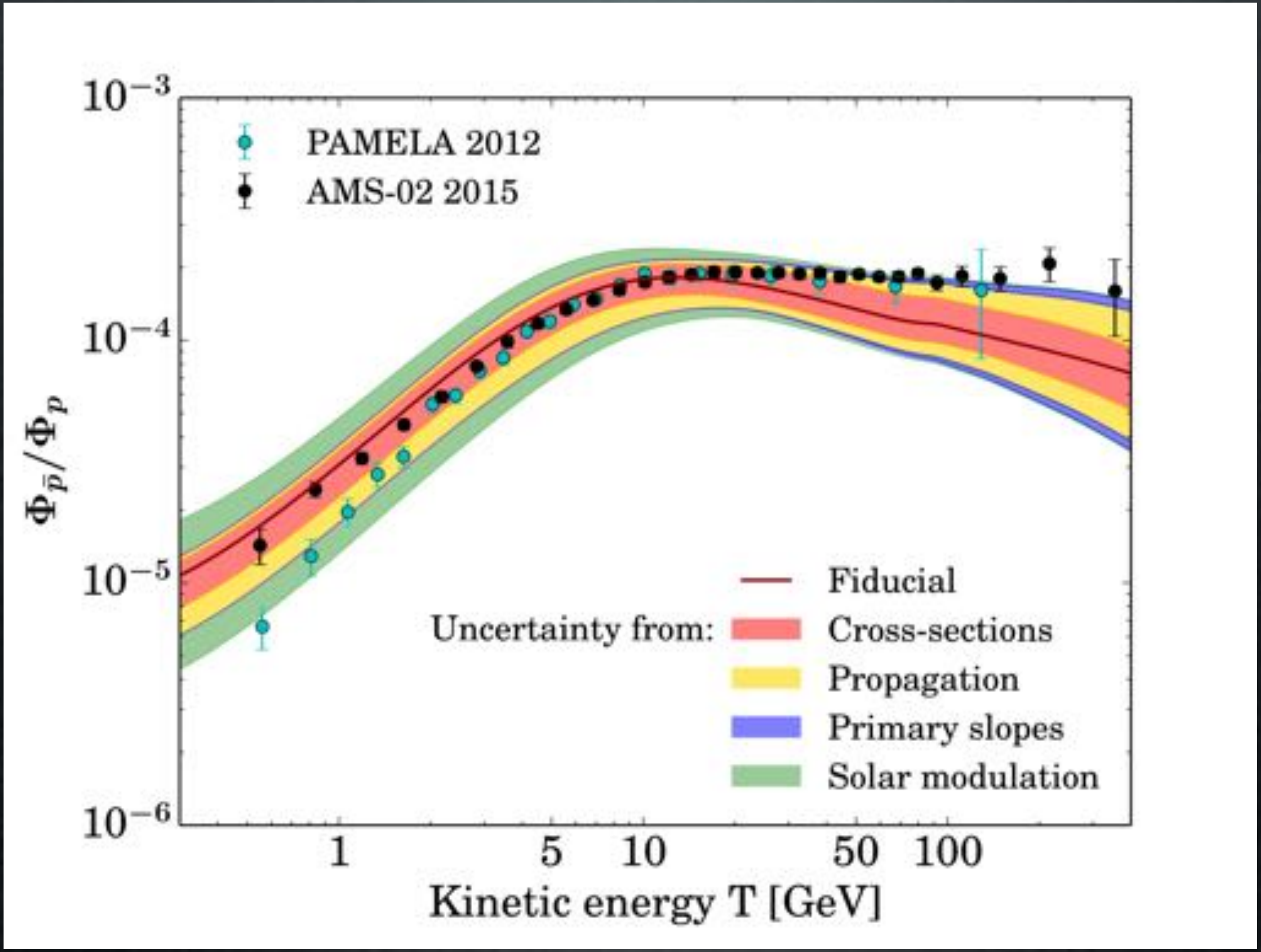
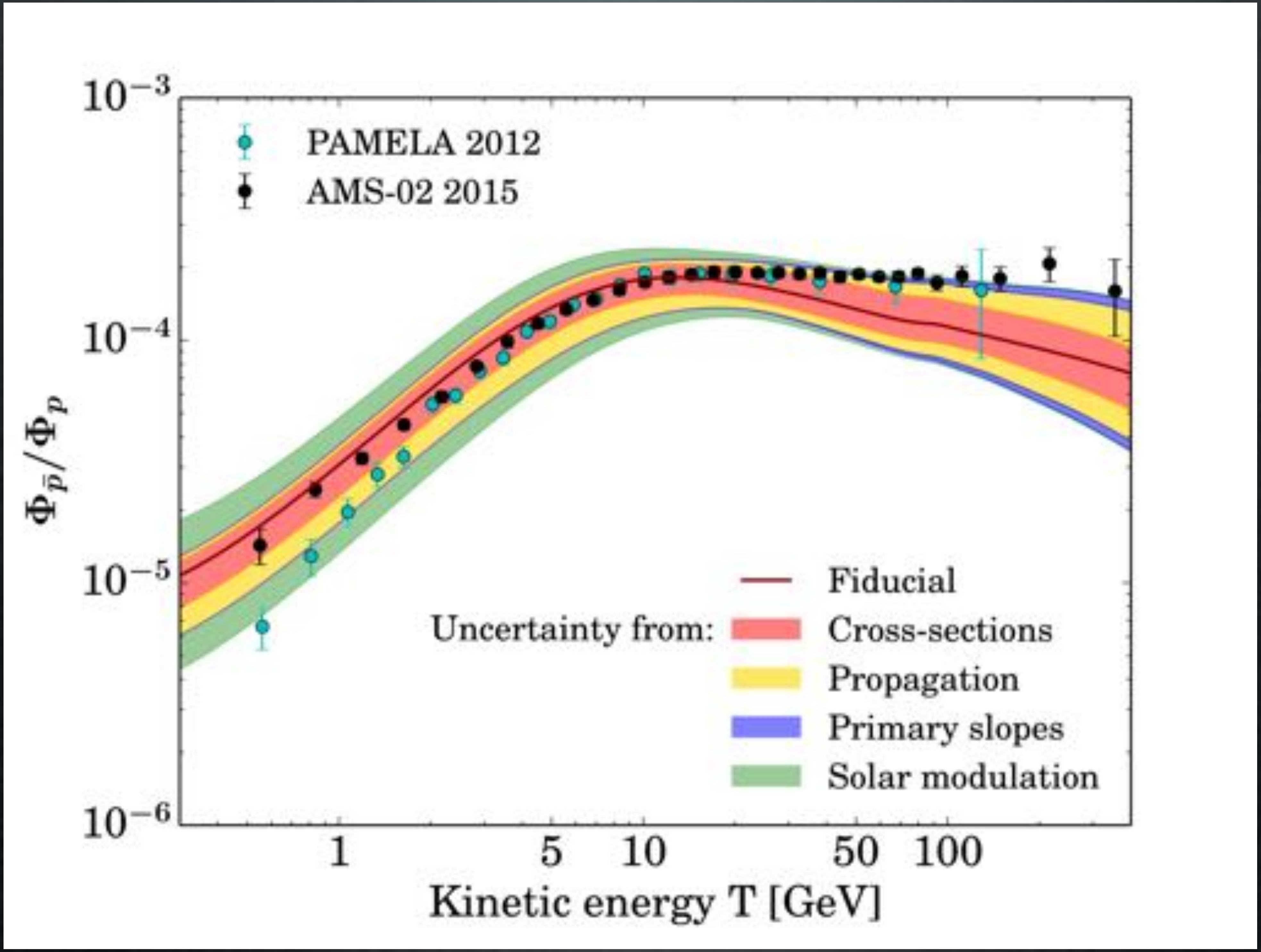


No evident **excess**

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Indirect Detection

Antiproton data vis-à-vis the background:



No evident **excess**

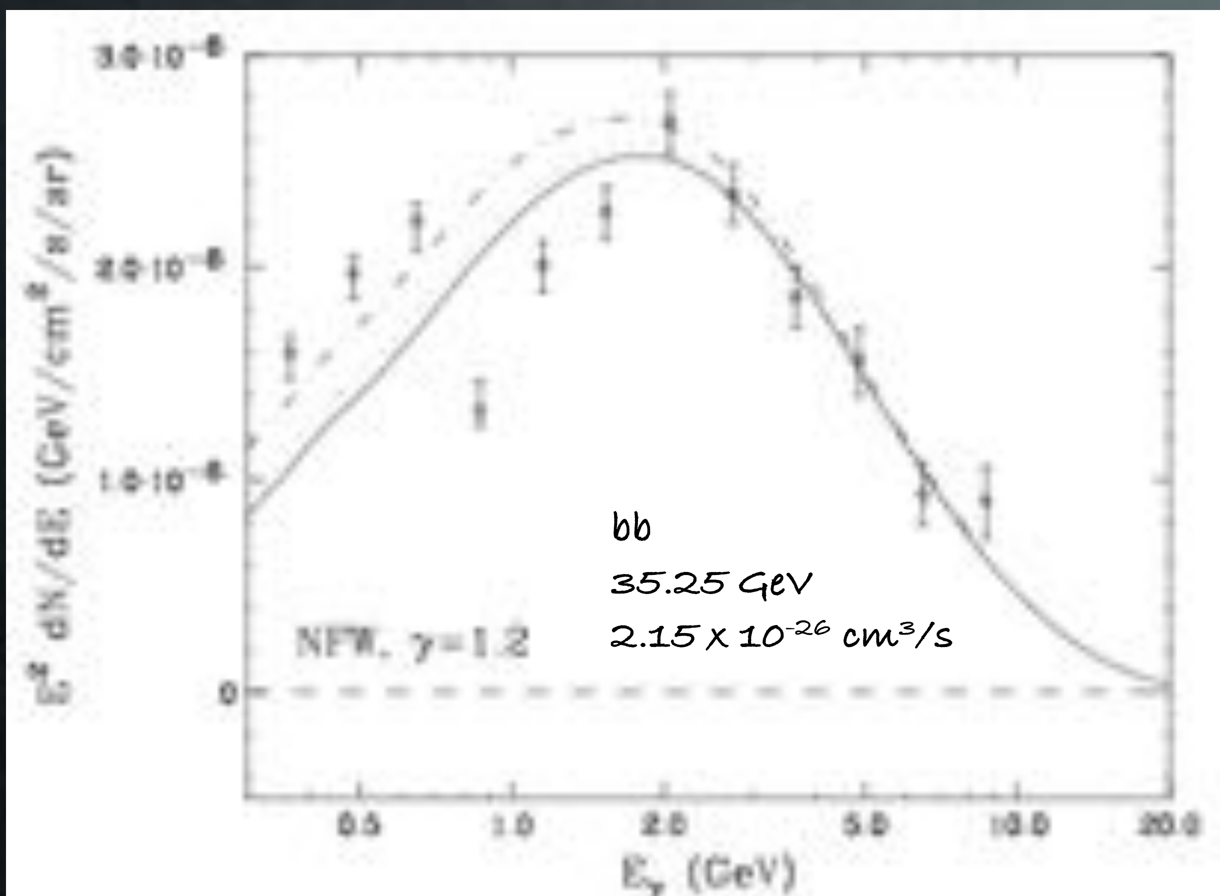
Some preference for flatness

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276

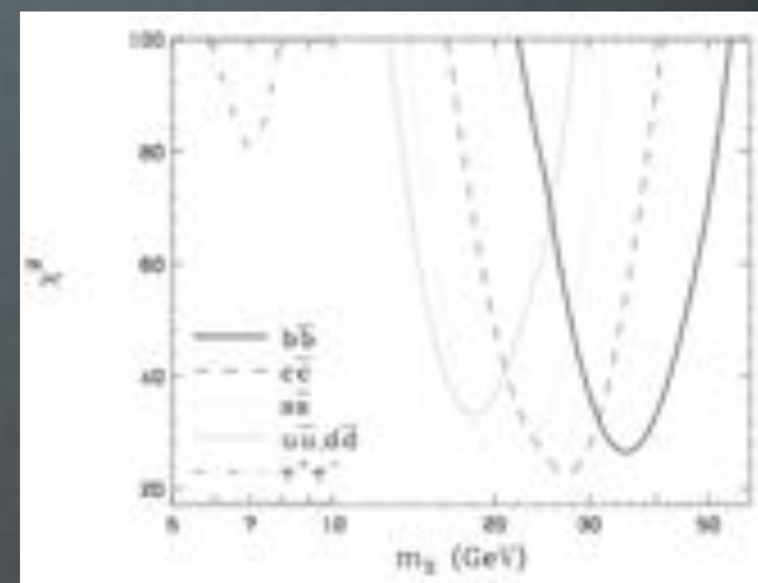
Constraints

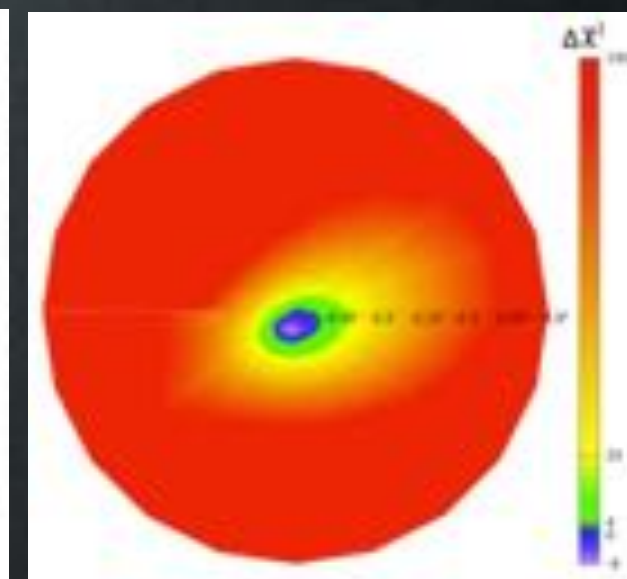
GC GeV gamma excess?

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



Using events with accurate directional reconstruction





A compelling case for annihilating DM

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

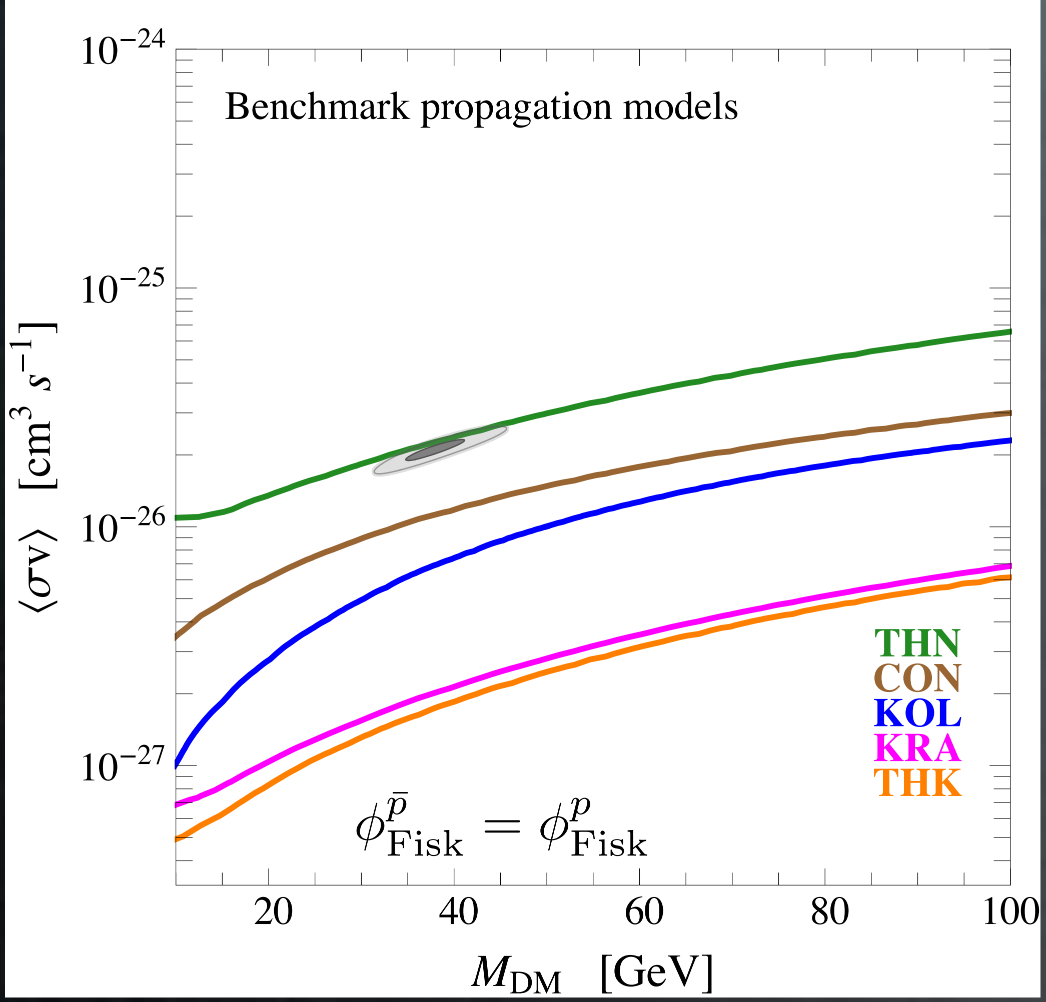
Best fit:

~35 GeV, quarks, ~thermal σv

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 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.

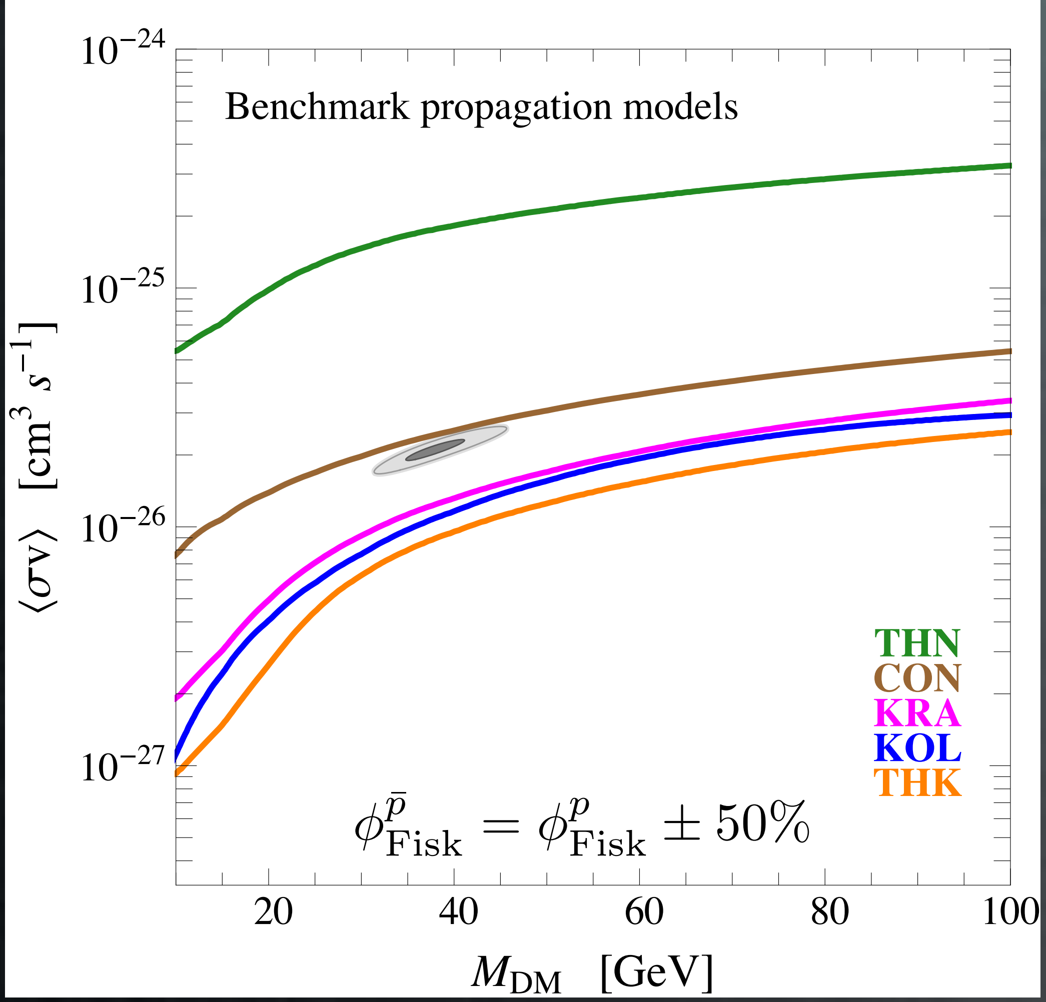
Assumption: fixed solar modulation

Result: hooperon excluded (except unrealistic THN)

GC 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

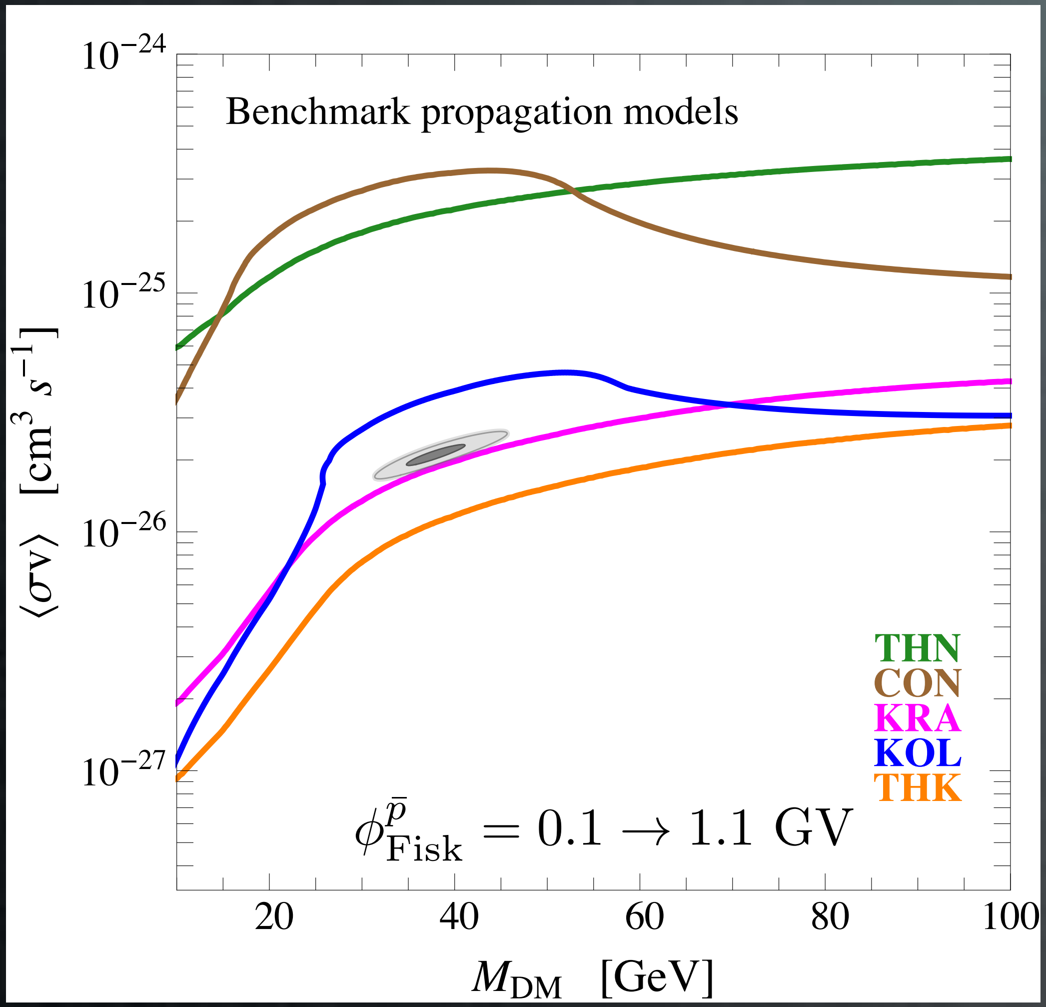
Antiproton constraints may be very relevant! But not robust.

Assumption: flexible solar modulation

Result: hooperon may be excluded or not

GC 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

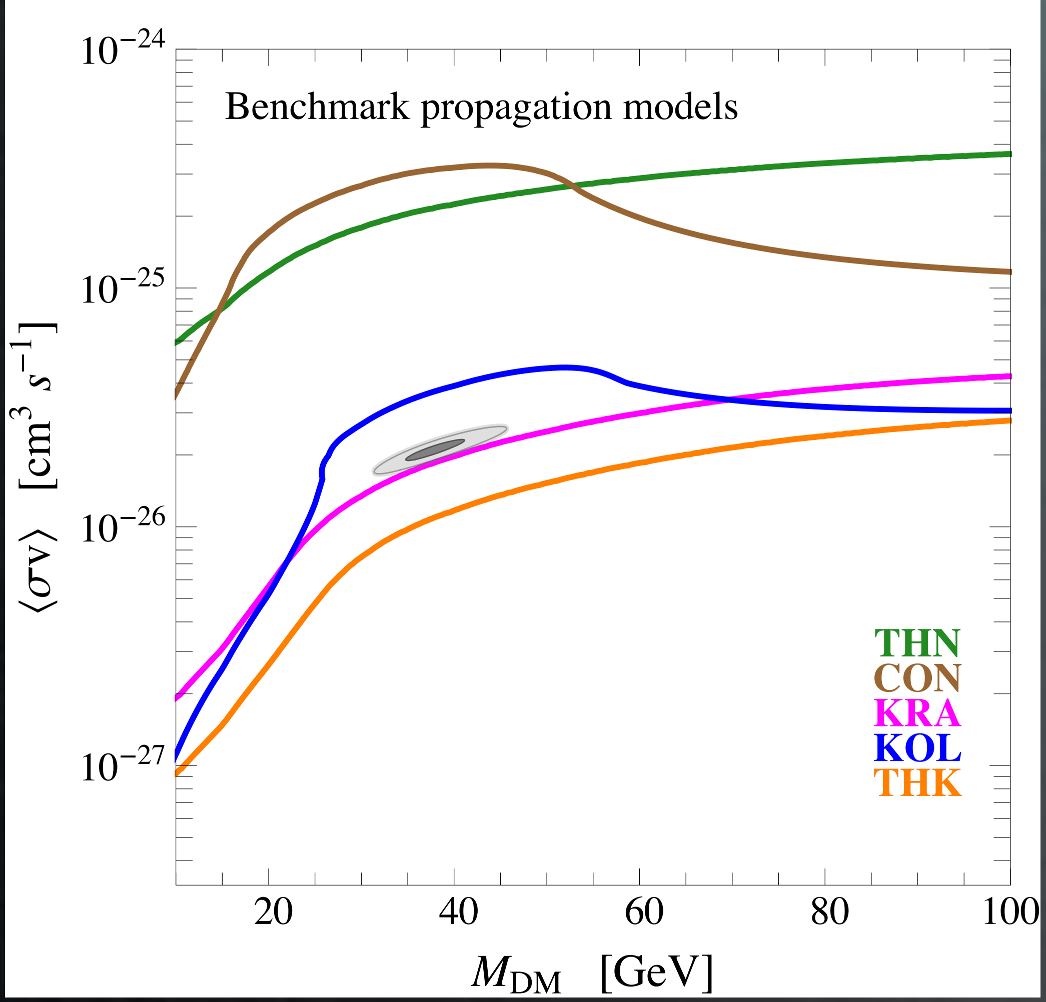
Antiproton constraints may be very relevant! But not robust.

Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

GC 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.

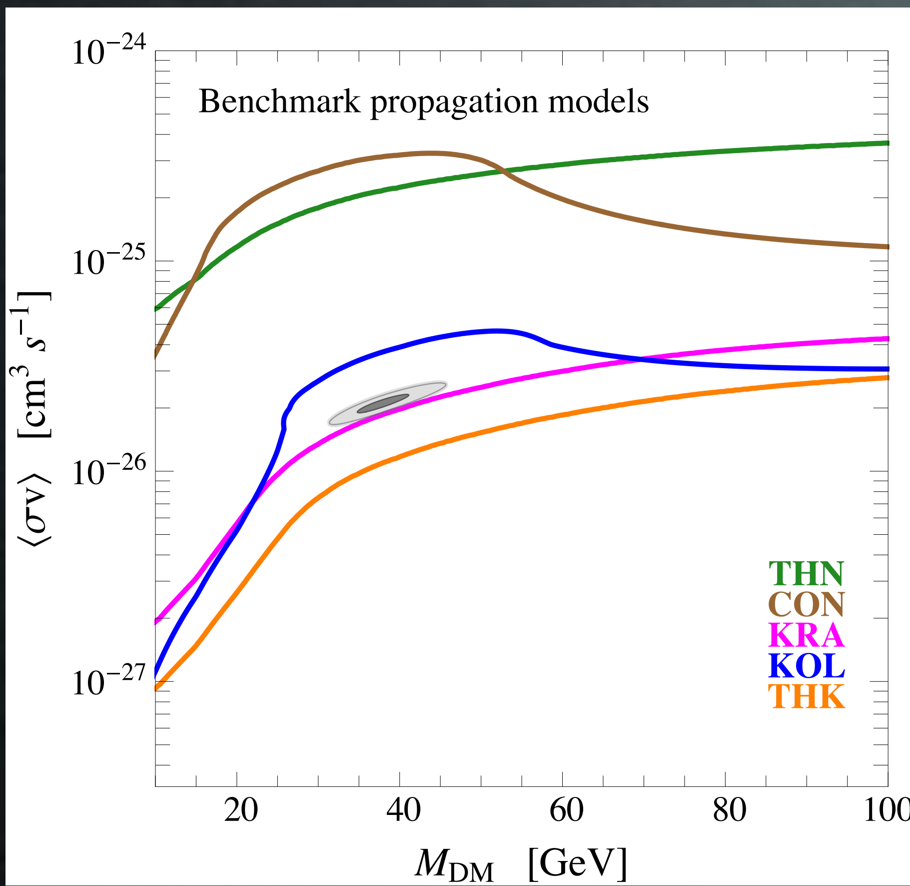
Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

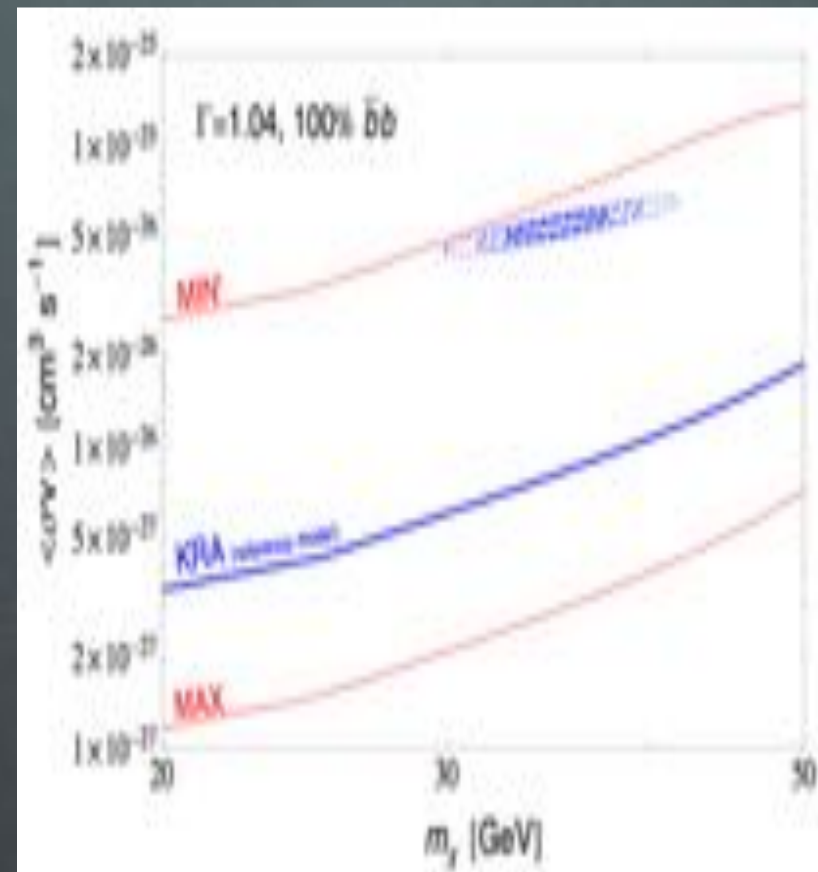
NB Conclusion differs from Bringmann, Vollmann, Weniger 1406.6027 which finds exclusion / strong tension

GC GeV gamma excess?

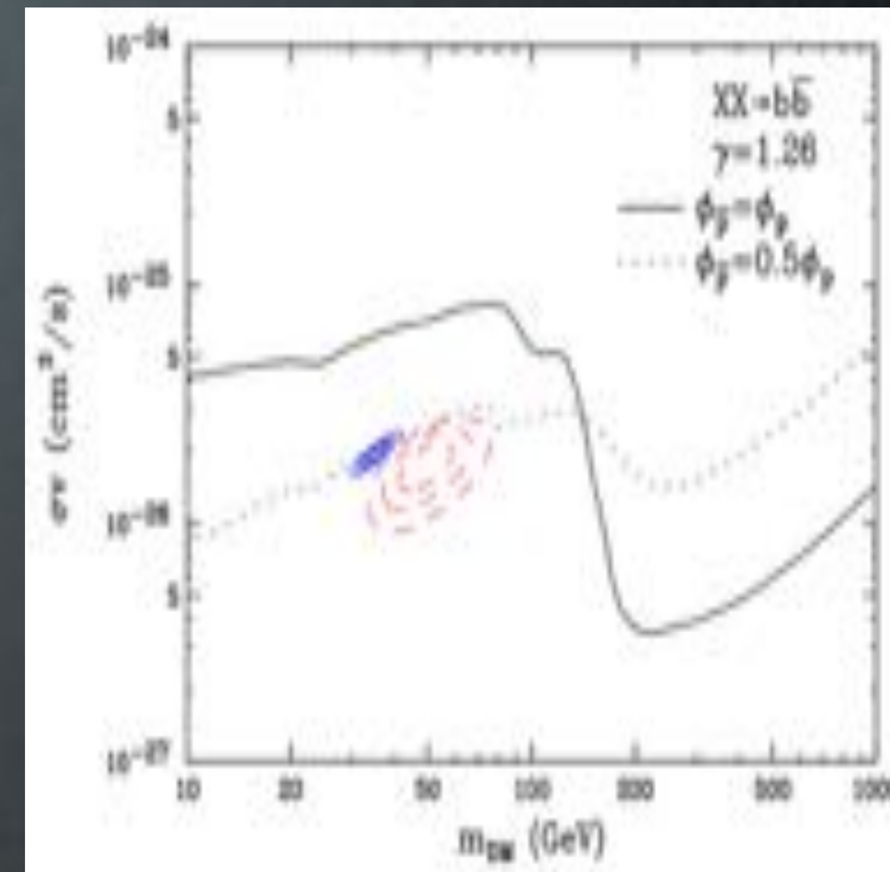
Antiproton constraints compared:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173



Bringmann, Vollmann, Weniger 1406.6027



Hooper, Linden, Mertsch 1410.1527

May be very relevant!
But not robust.

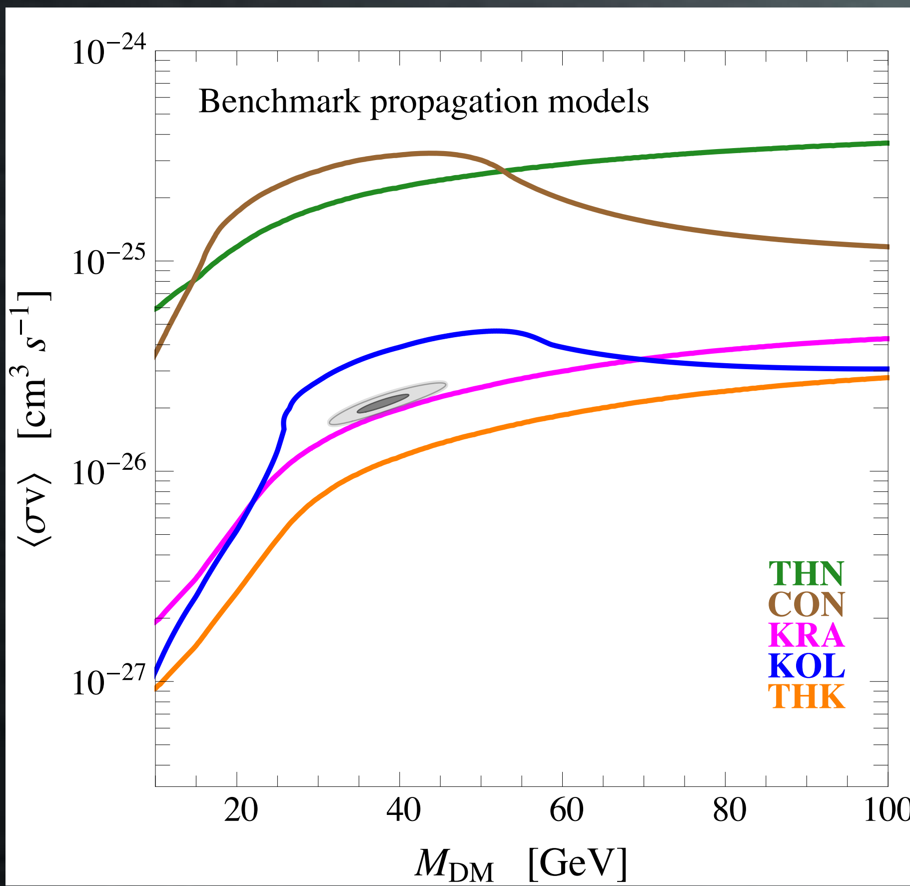
‘Rule out’ or
‘considerable tension’.

‘Significantly less stringent’.

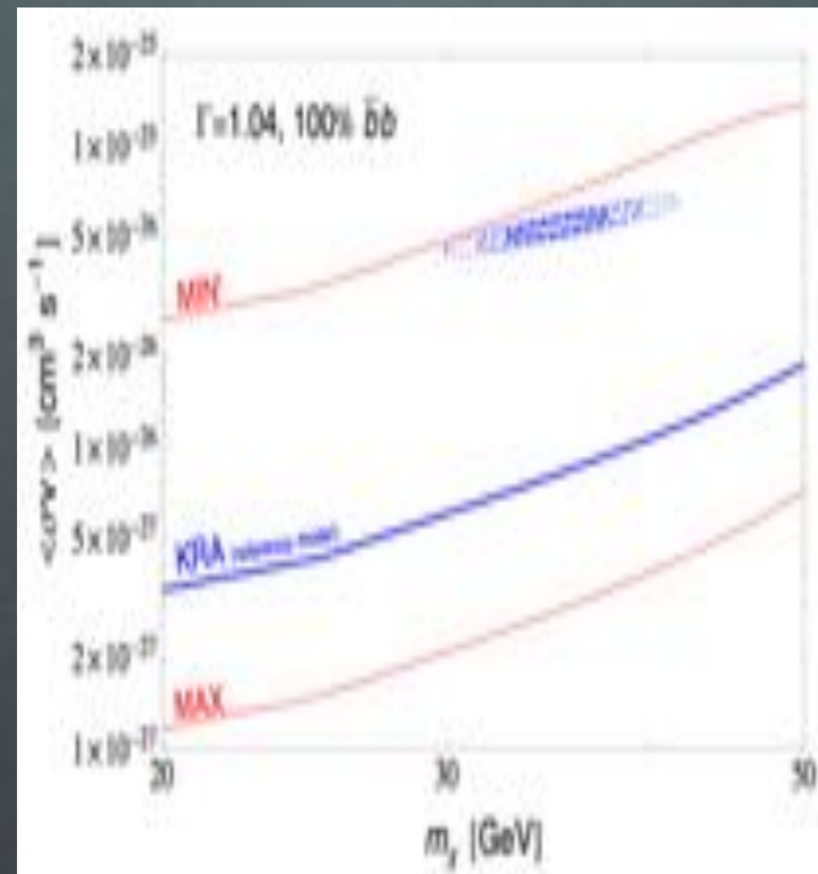
How come?!?

GC GeV gamma excess?

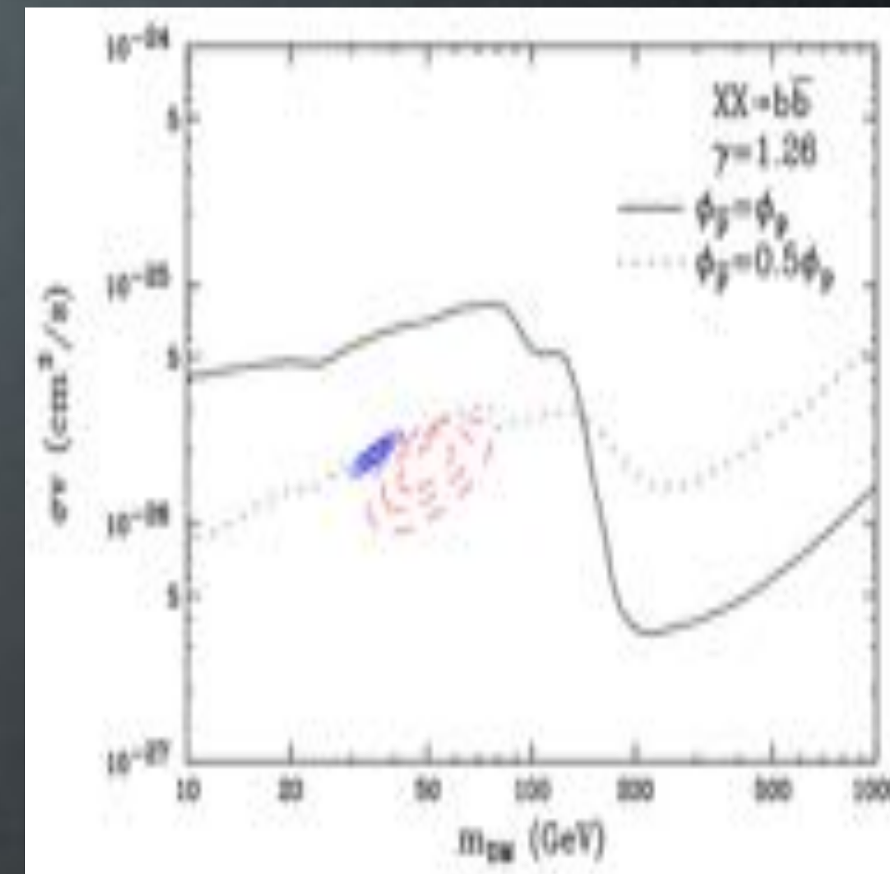
Antiproton constraints compared:



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…

Model independent bounds

Based on AMS-02 $\bar{p}/p$ data (april 2015)

'AMS-02 days' at CERN,
15-17 april 2015
talks by S. Ting, A. Kounine etc

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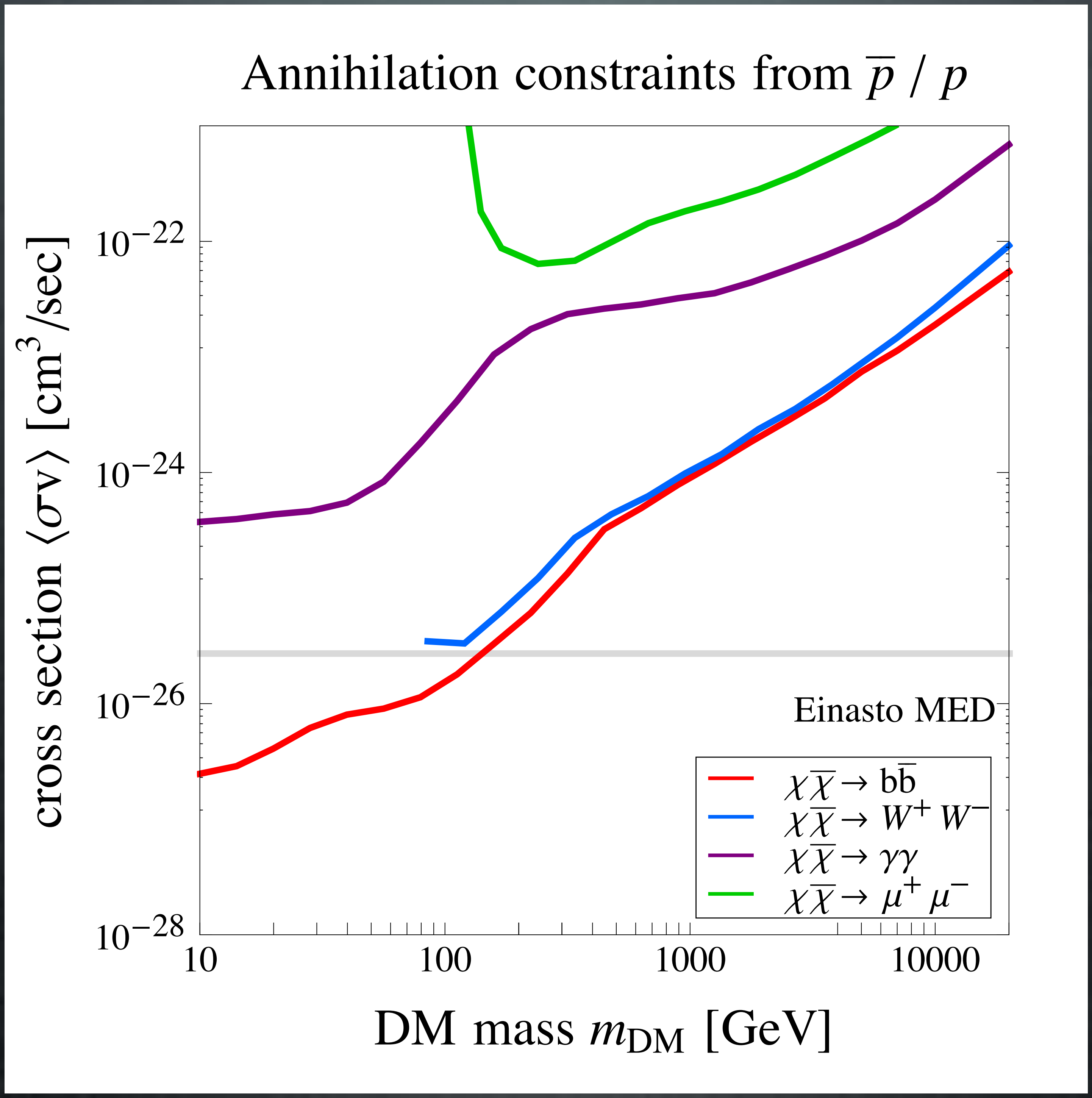

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico
1504.04276

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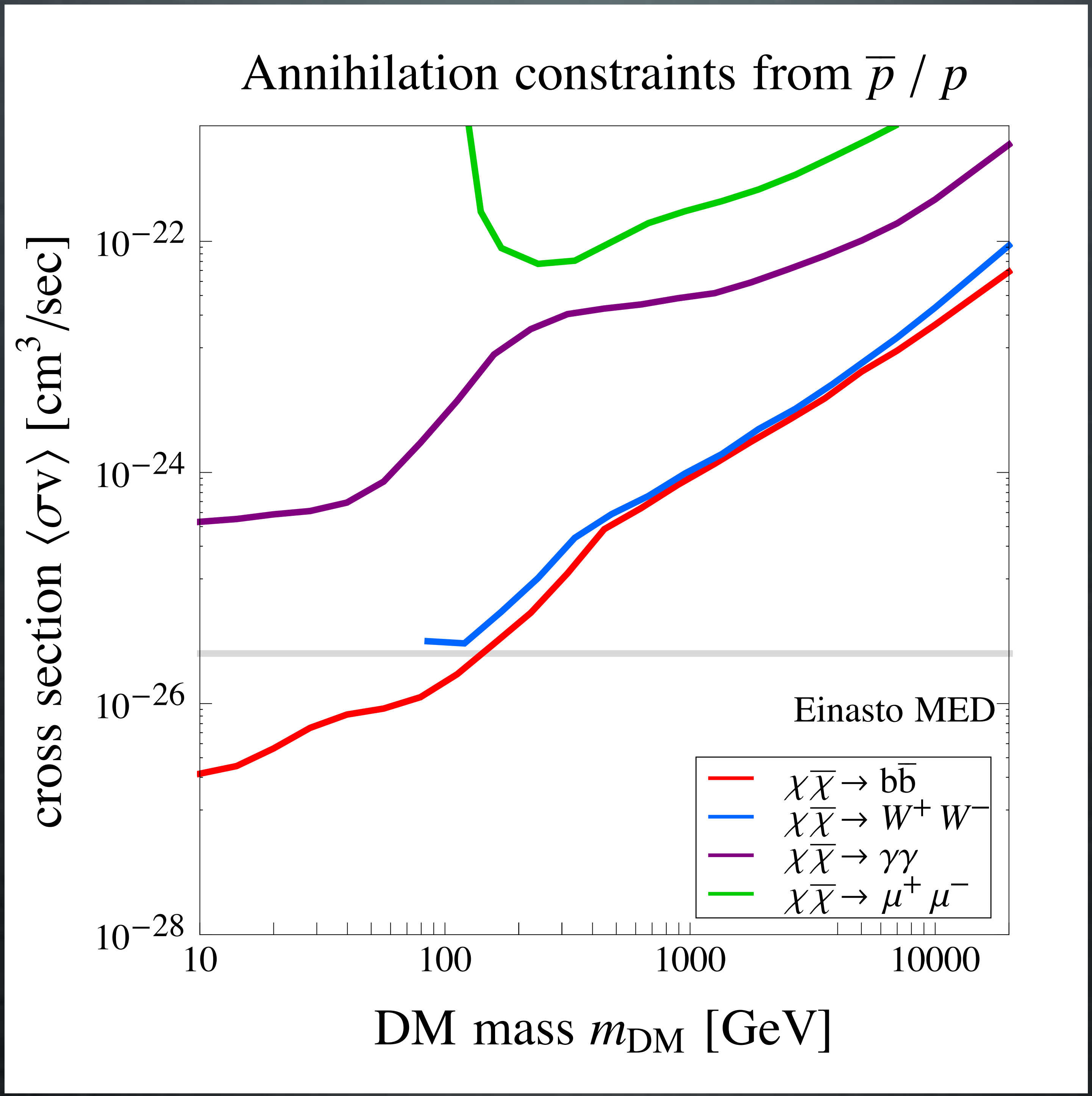

$m_{DM} > 150$ GeV
(bb Ein MED)

bounds on leptonic channels

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico
1504.04276

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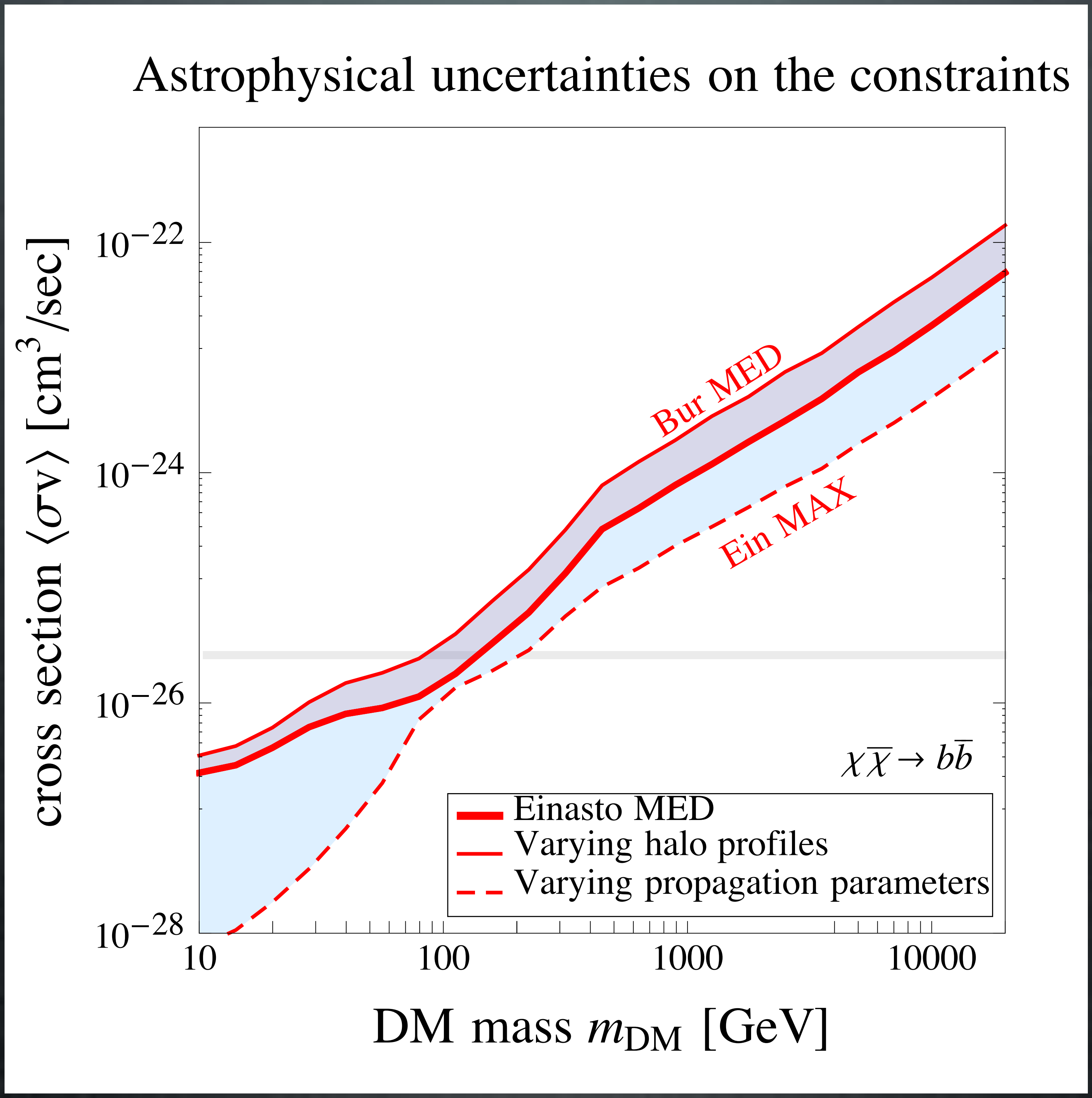

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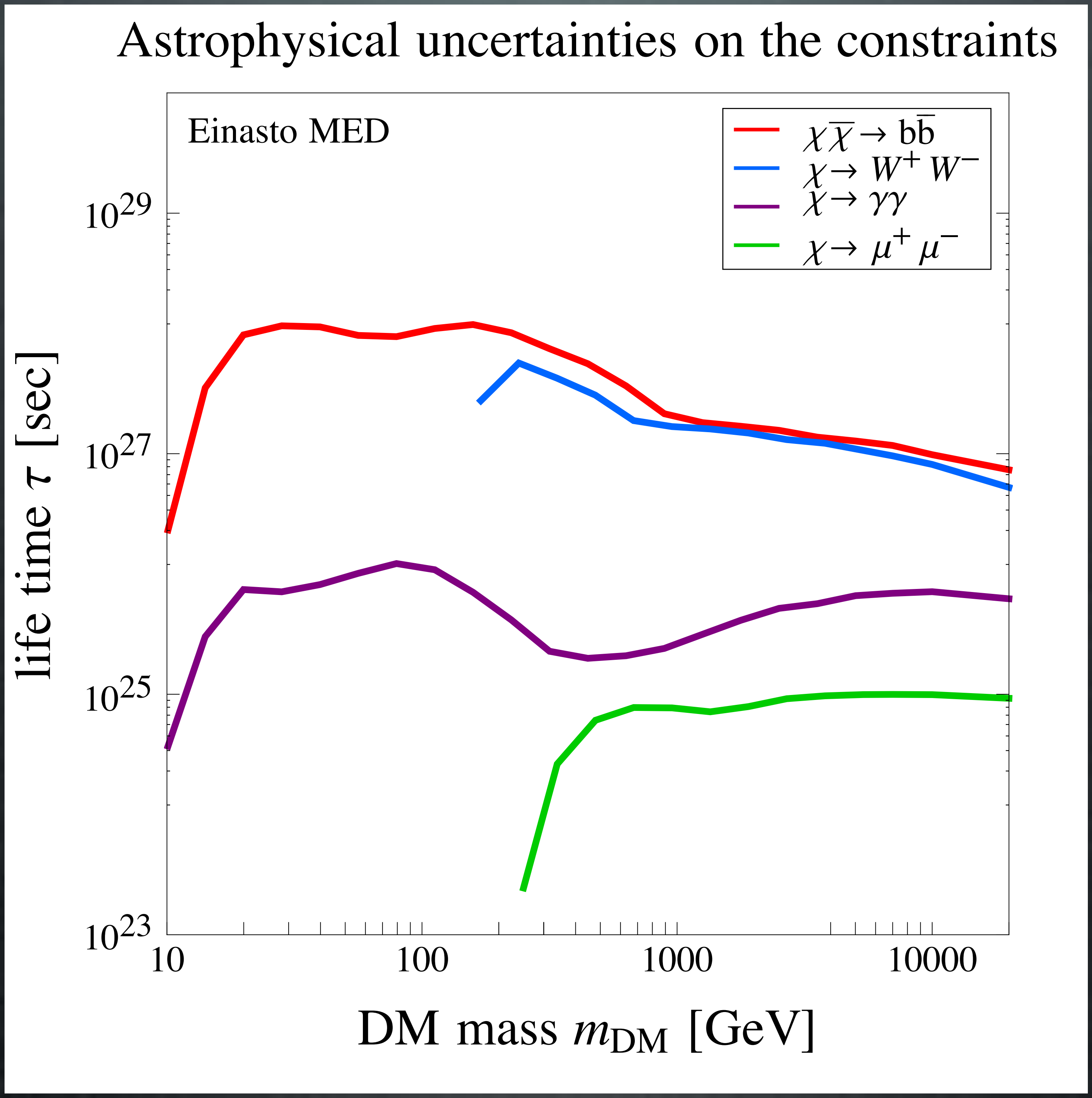

Giesen, Boudaud,
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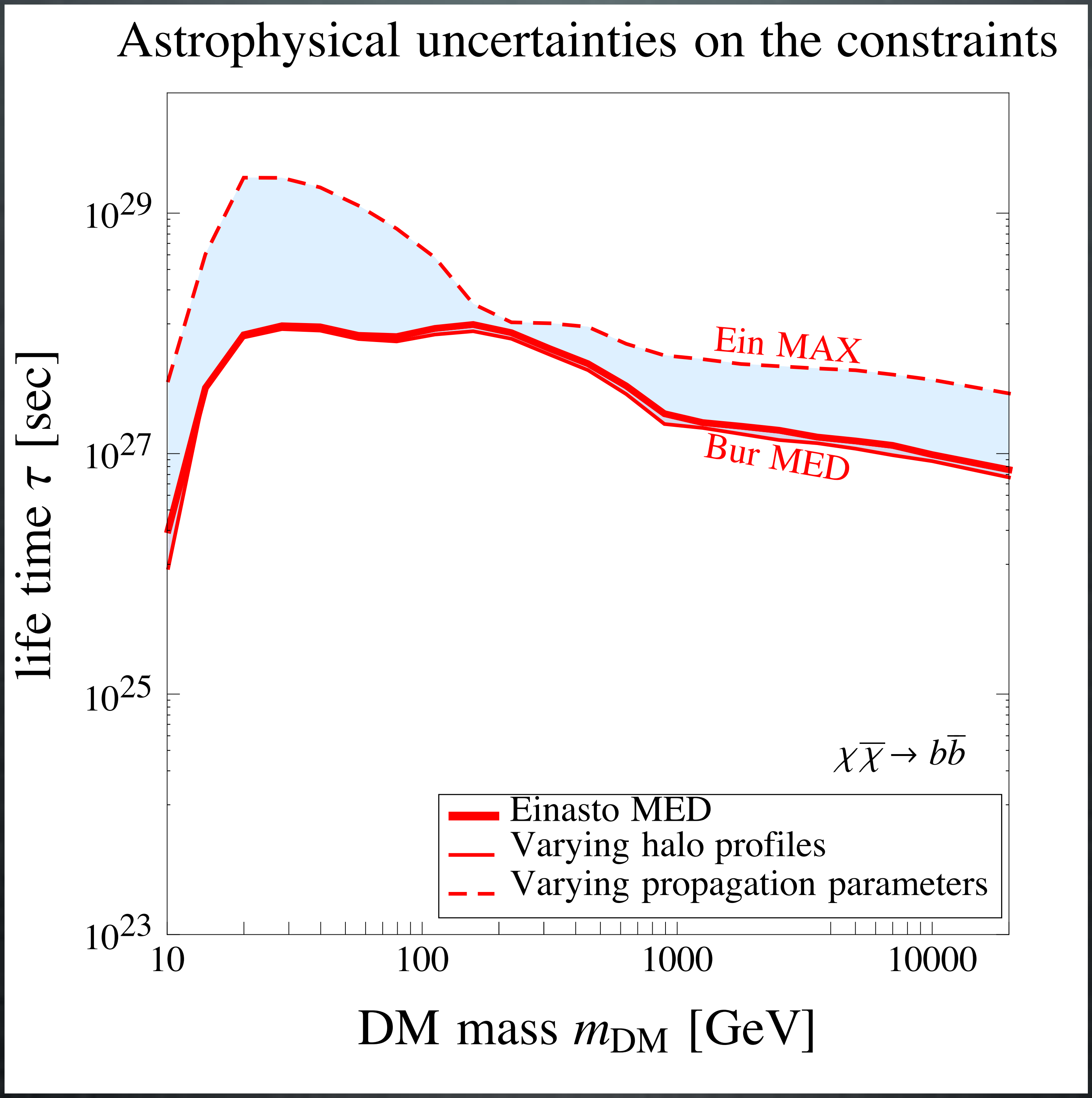


Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico
1504.04276

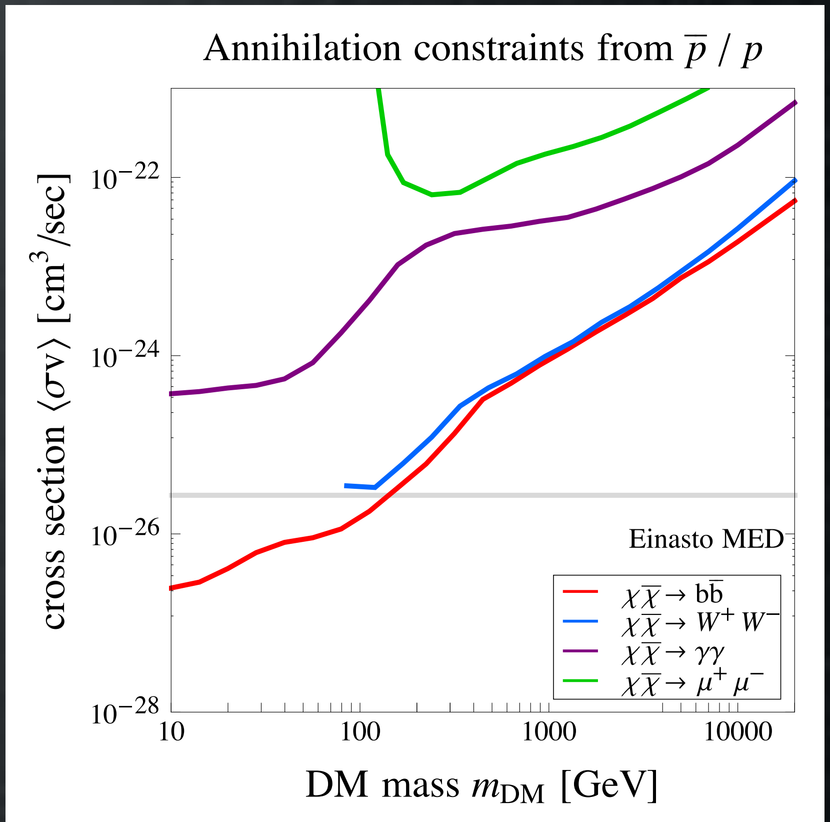
Conclusions

DM not seen yet (Damn!...)

Constraints are stronger and stronger

Antiproton constraints are interesting and competitive with (e.g.) gamma ray ones. But they have important uncertainties.

Giesen *et al.* 1504.04276



Back up slides

Introduction

Introduction

DM exists

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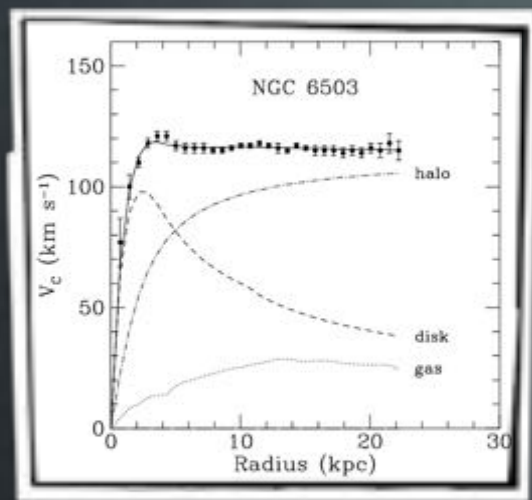
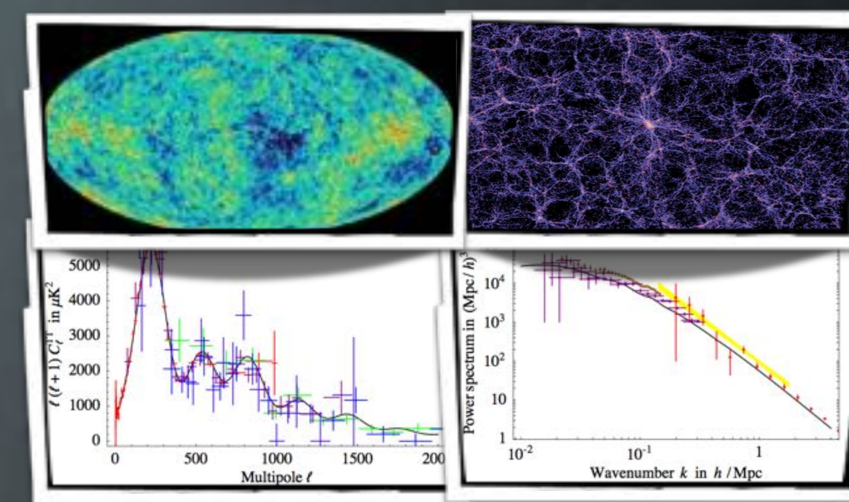
DM exists



galactic rotation curves

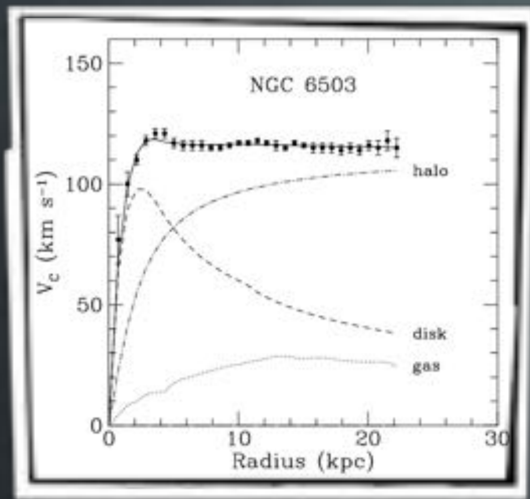
weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Introduction

DM exists



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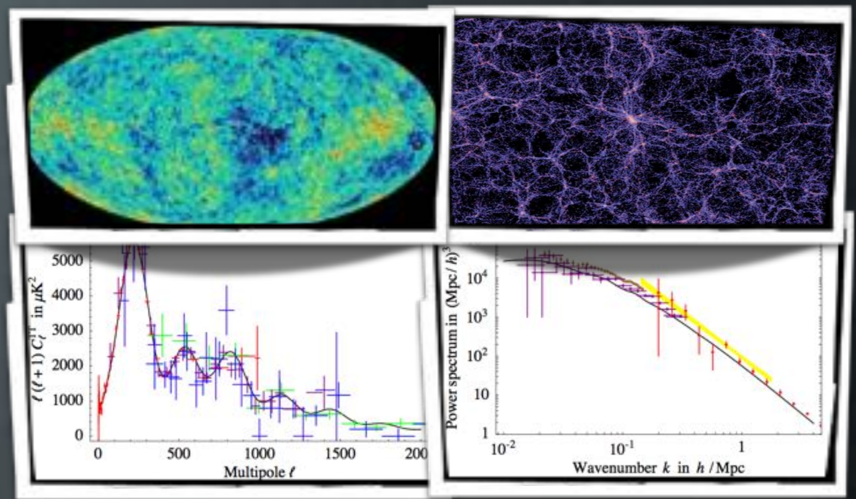

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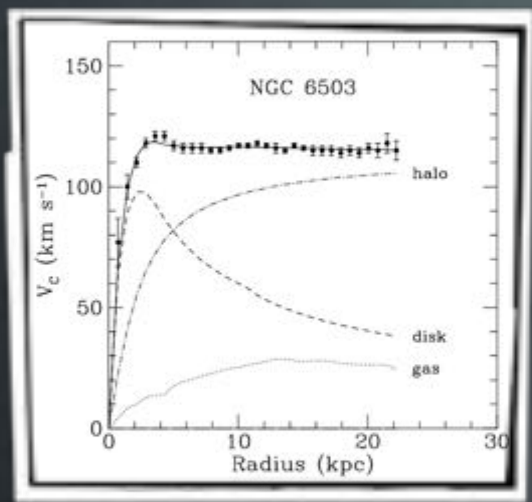
DM is a neutral, very long lived, feebly interacting particle.

Introduction

DM exists



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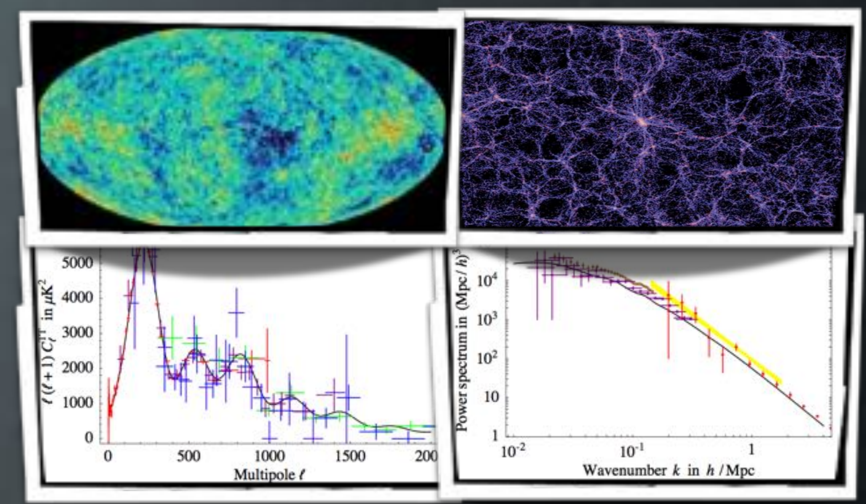
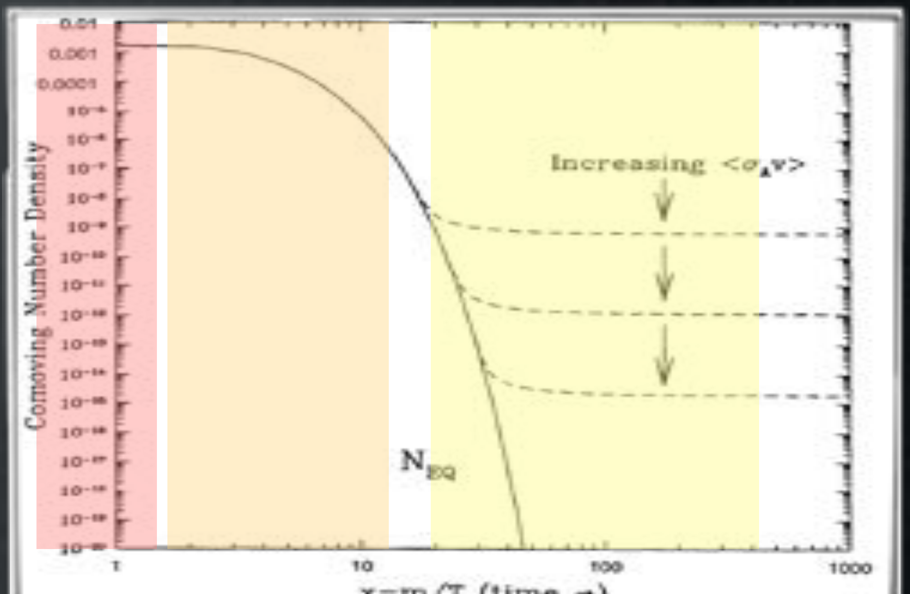


'precision cosmology' (CMB, LSS)

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

Some of us believe in the WIMP miracle.

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



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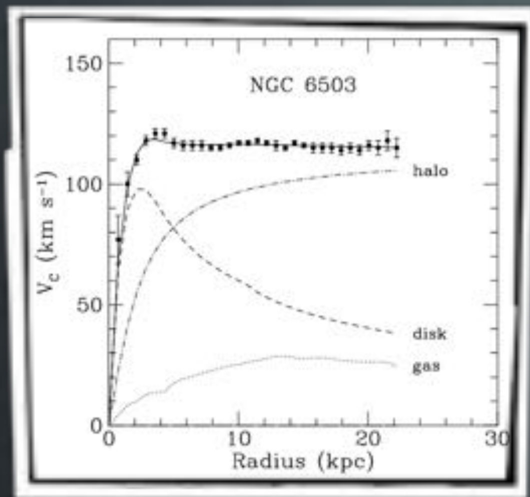

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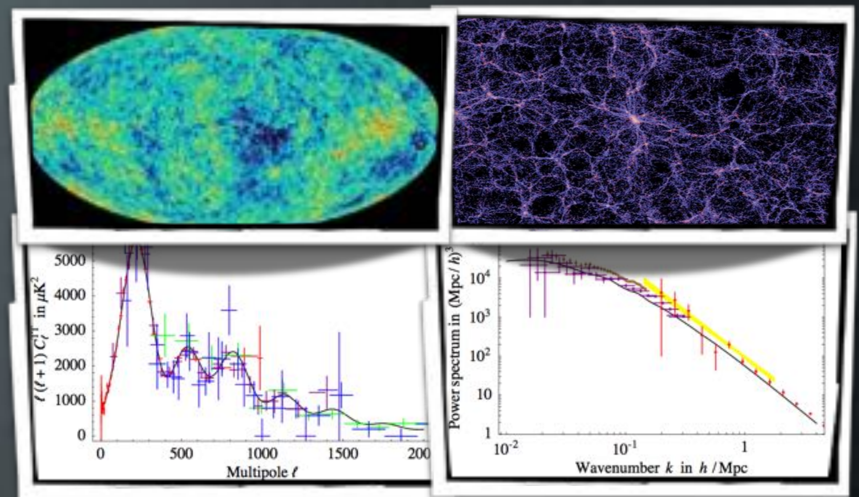


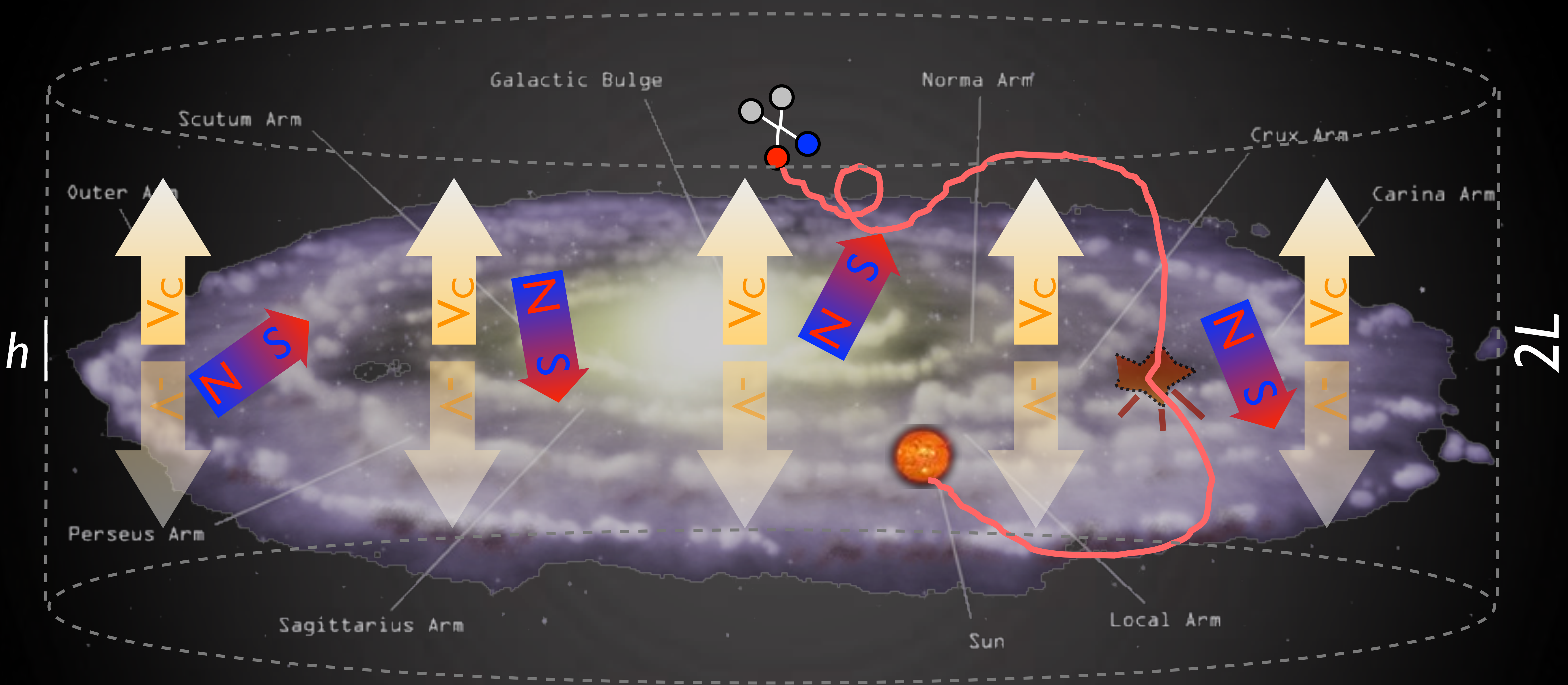
'precision cosmology' (CMB, LSS)

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

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

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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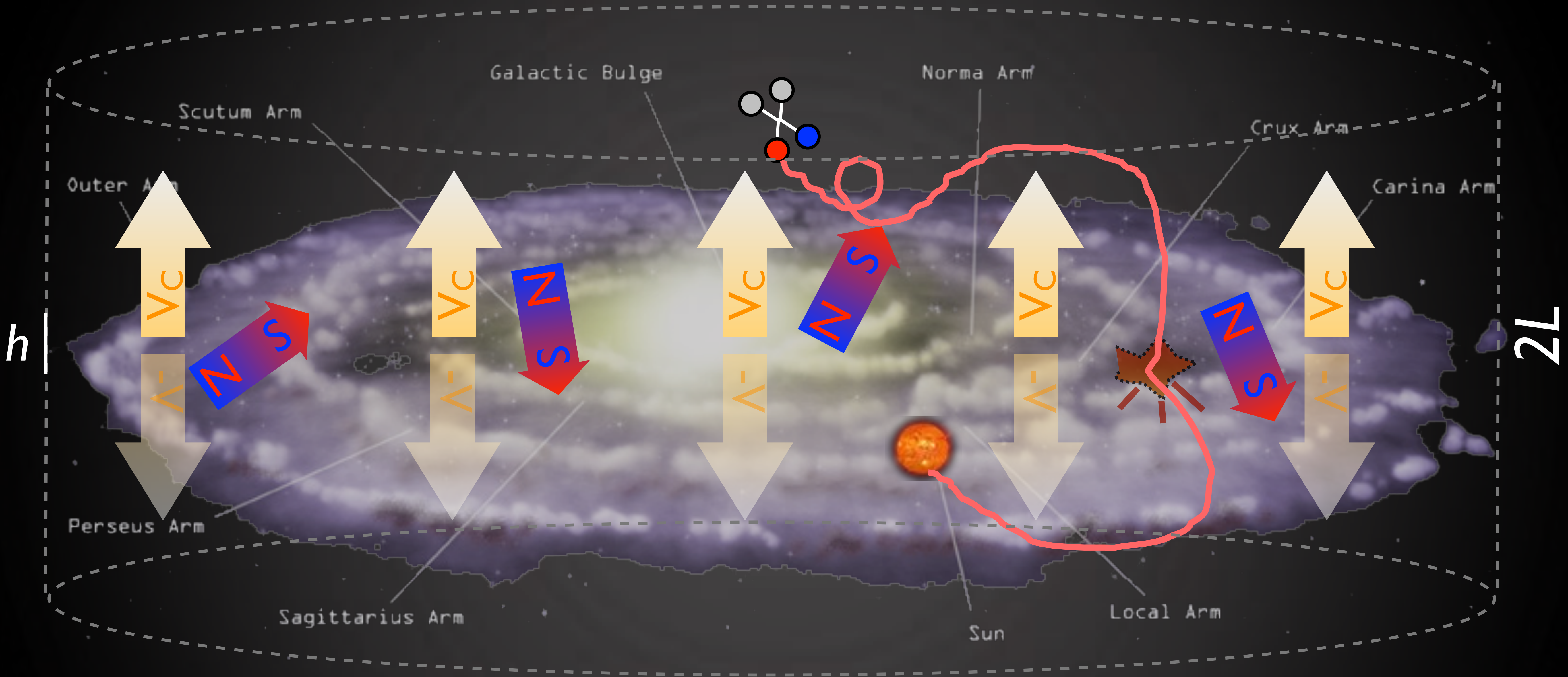

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astro& cosmo

particle

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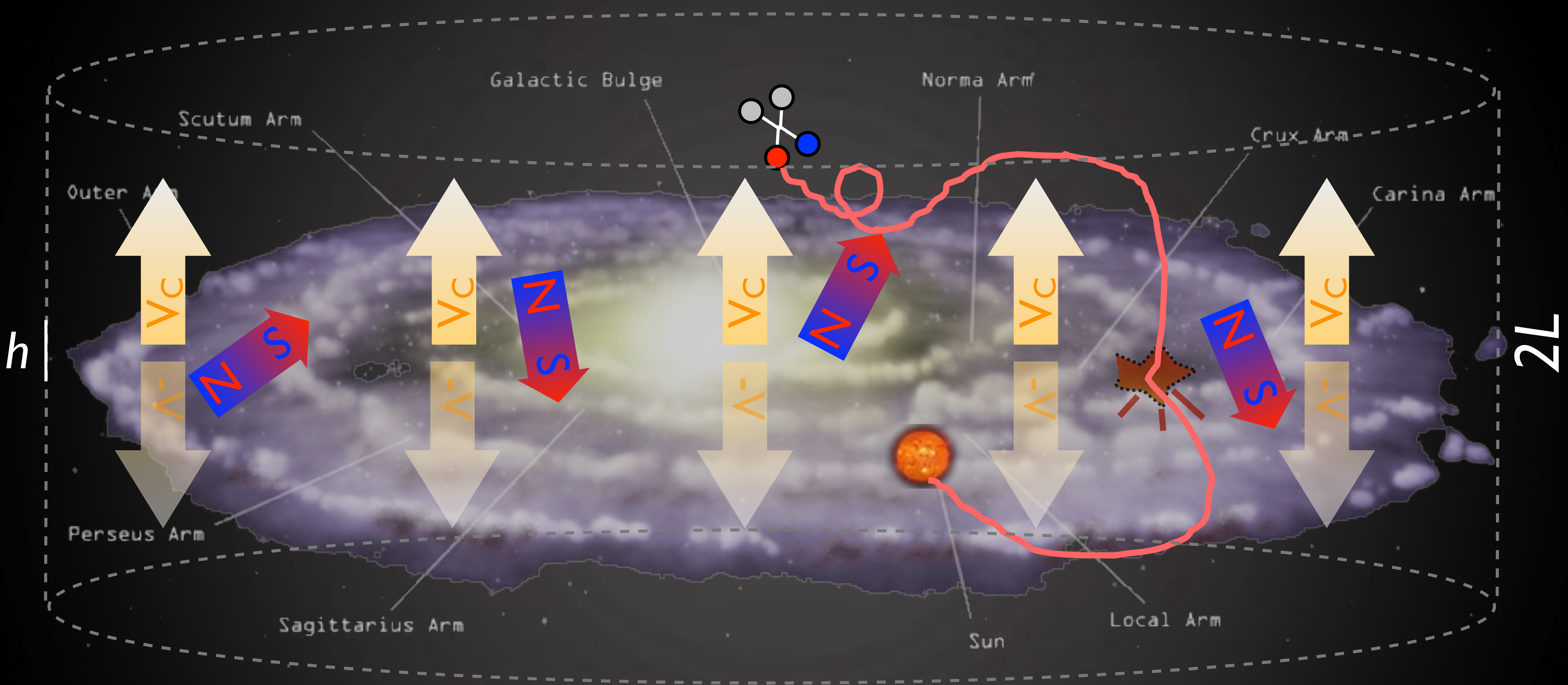


What sets the overall expected flux?

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

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:

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

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

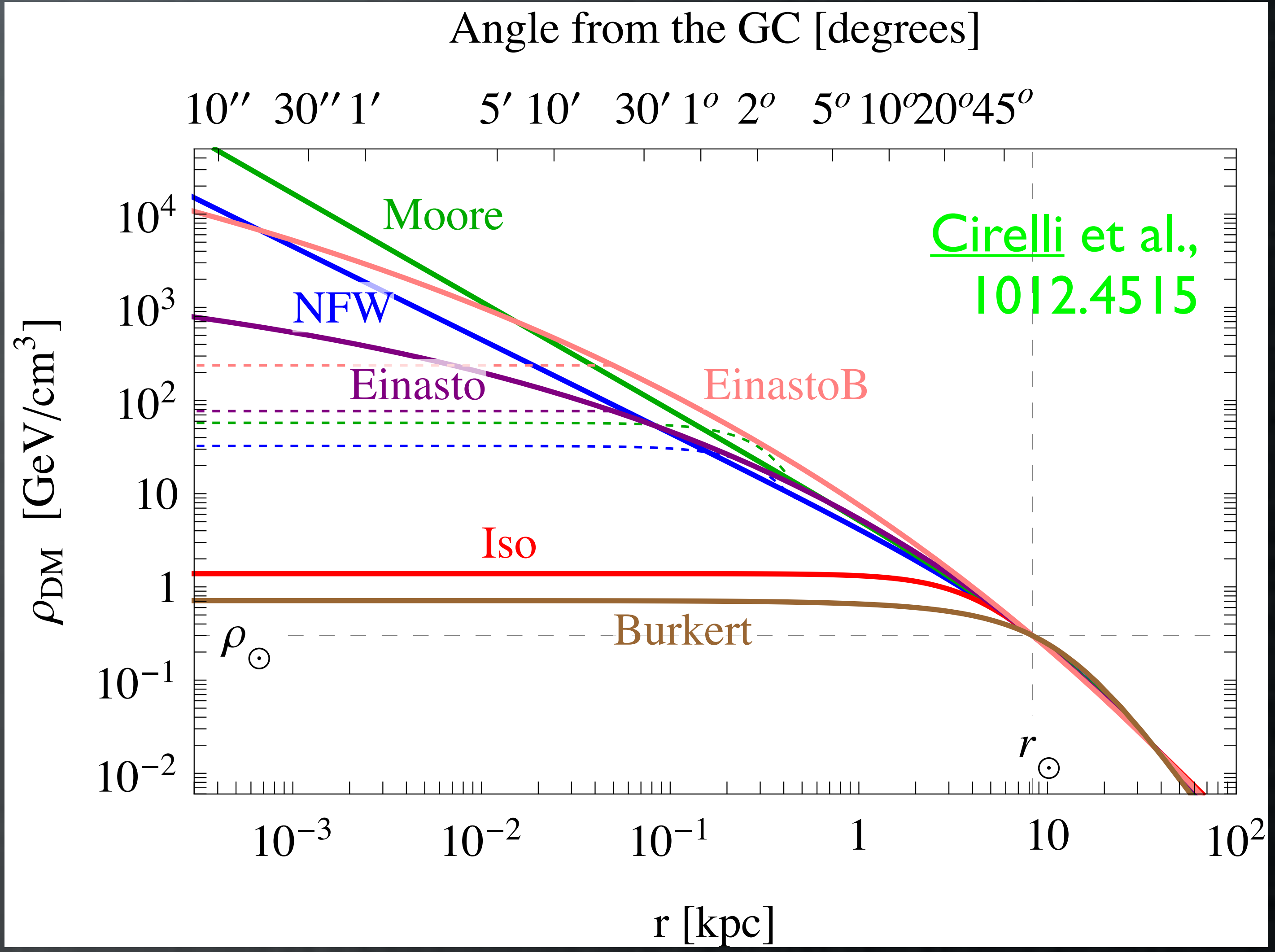
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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:

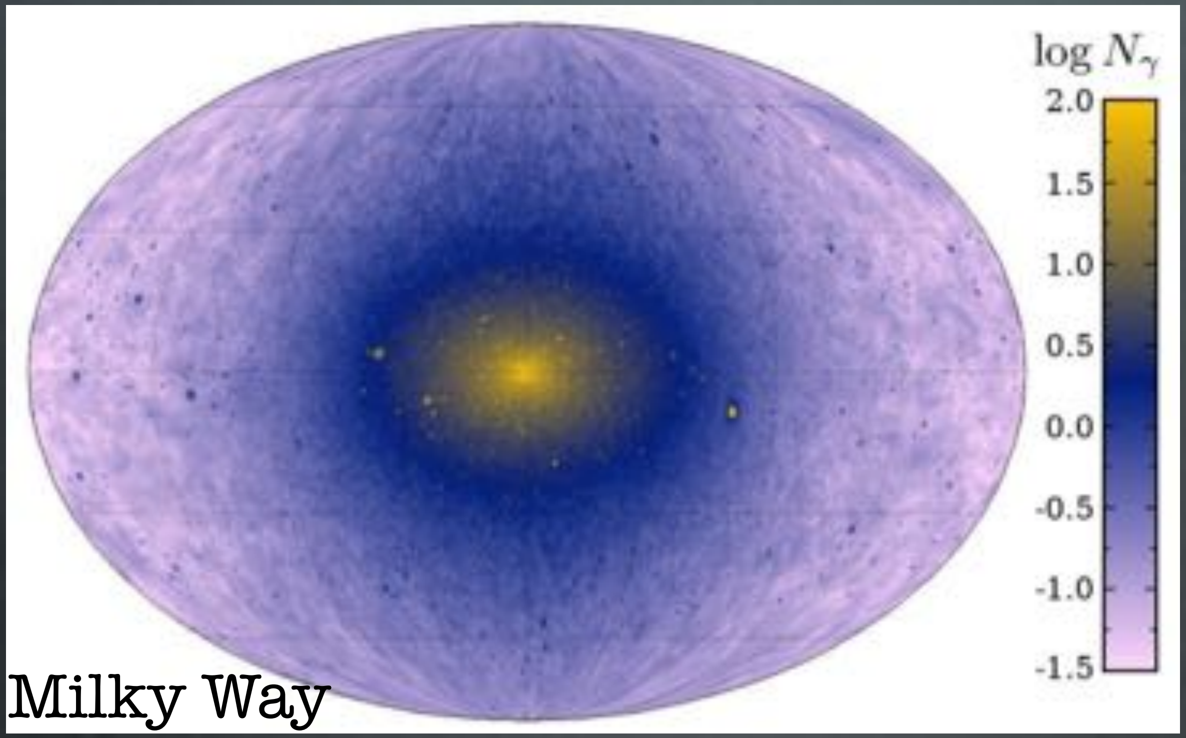
- cuspy: NFW, Moore
- mild: Einasto
- smooth: isothermal, Burkert

EinastoB = steepened Einasto (effect of baryons?)

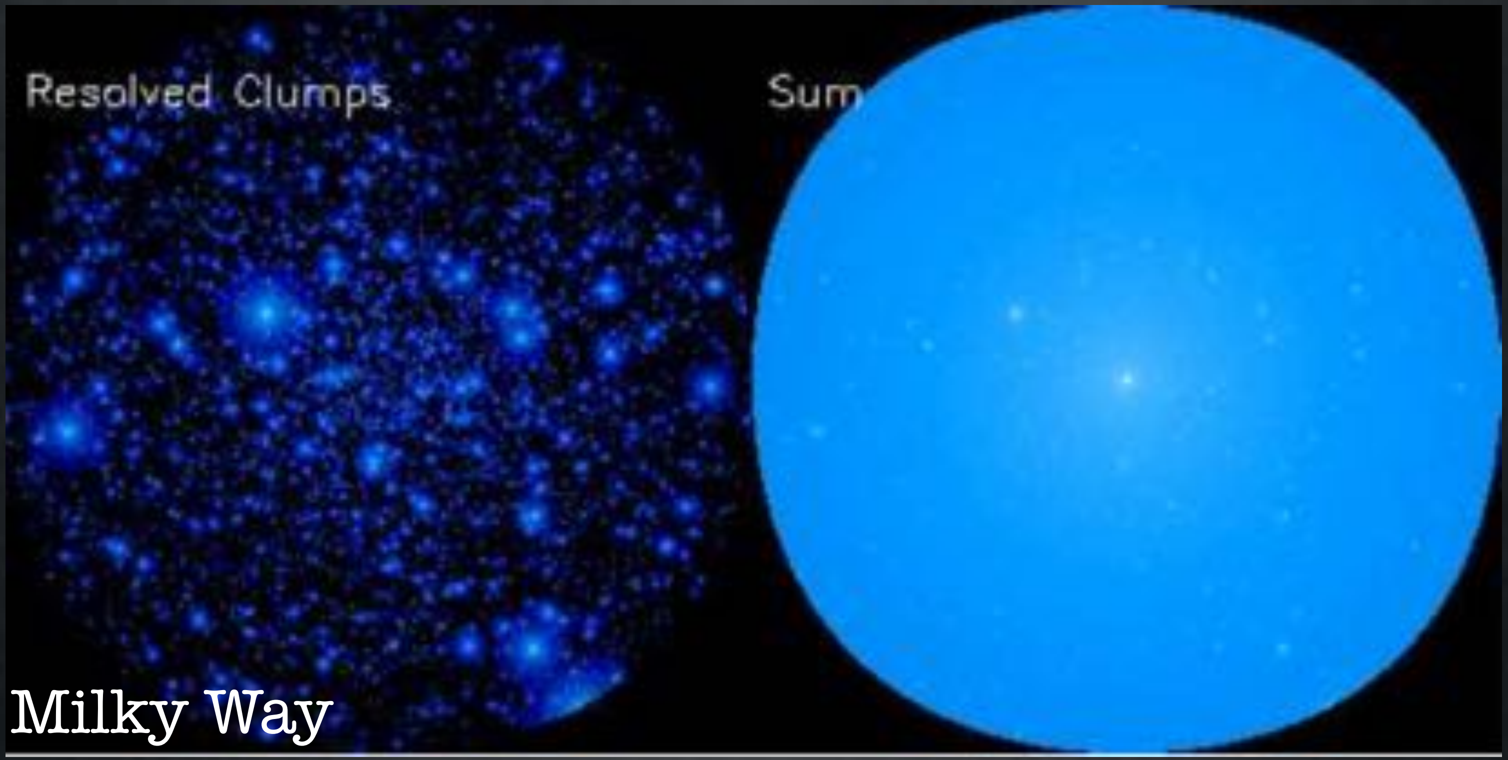
DM halo profiles

Local clumps in the DM halo enhance the density.

For illustration:



Kuhlen, Diemand, Madau 2007



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

Propagation

Propagation for antiprotons:

$$\frac{\partial f}{\partial t} - K(T) \cdot \nabla^2 f + \frac{\partial}{\partial z} \left(\mathrm{sign}(z)\, f\, V_{\mathrm{conv}} \right) = Q - 2h\, \delta(z)\, \Gamma_{\mathrm{ann}} f$$

diffusion

convective wind

spallations

$K(T) = K_0 \beta \, (p/\mathrm{GeV})^{\delta}$

T kinetic energy

Propagation

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diffusion — convective wind — spallations

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T kinetic energy

Model	δ	K_0 in kpc^2/Myr	L in kpc	$V_{\rm conv}$ in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5

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Solution:

$$\Phi_{\bar{p}}(T,\vec{r}_\odot) = B\,\frac{v_{\bar{p}}}{4\pi}\left(\frac{\rho_\odot}{M_{\mathrm{DM}}}\right)^2 R(T)\sum_k \frac{1}{2}\langle\sigma v\rangle_k \frac{dN^k_{\bar{p}}}{dT}$$

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