24 July 2017
Exploring the Dark Universe - Quy Nhon, Vietnam

Dark Matter Indirect Detection:

charged particles

Marco Cirelli
(CNRS LPTHE Jussieu)

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

erc
NewDark

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DM detection

direct detection

Xenon, CDMS, Edelweiss, LUX,... (CoGeNT, Dama/Libra...)

production at colliders

LHC

indirect

- γ from annihil in galactic center or halo and from secondary 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, AMS

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

  SK, Icecube, Km3Net

DM detection

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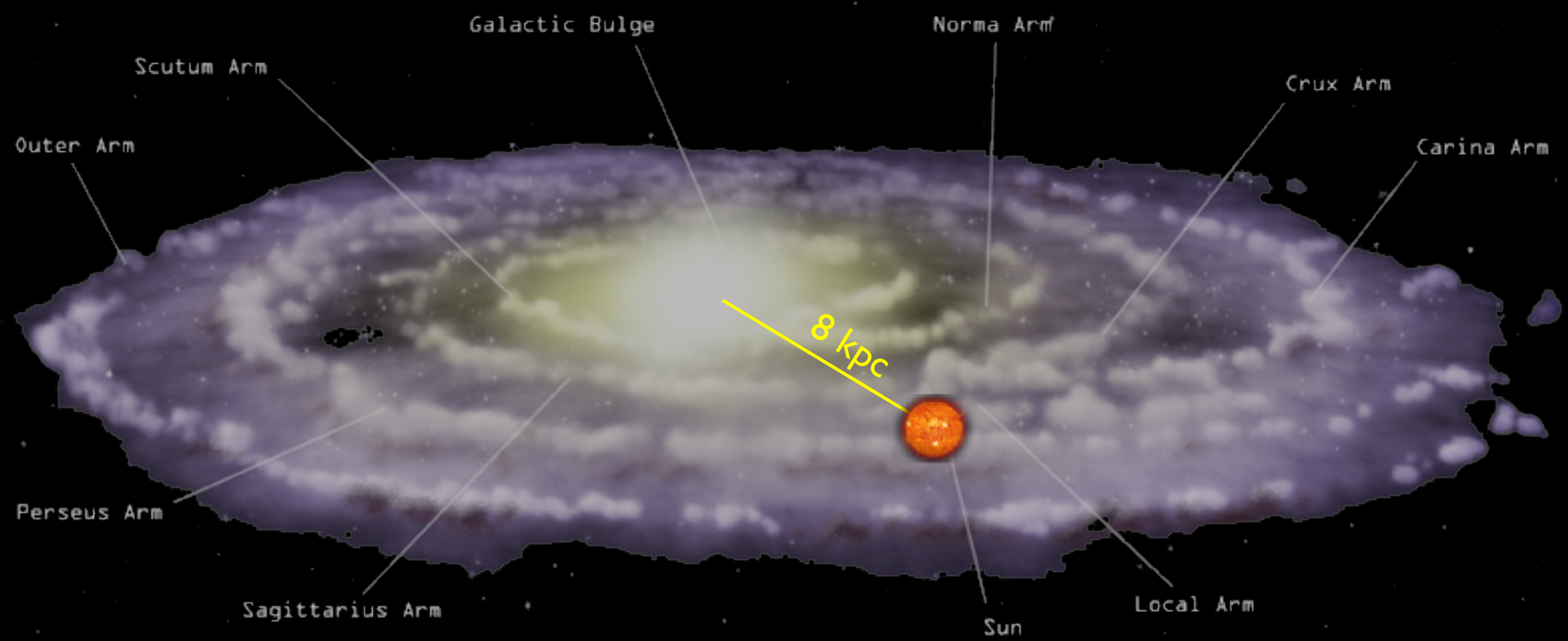
Indirect Detection: basics

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



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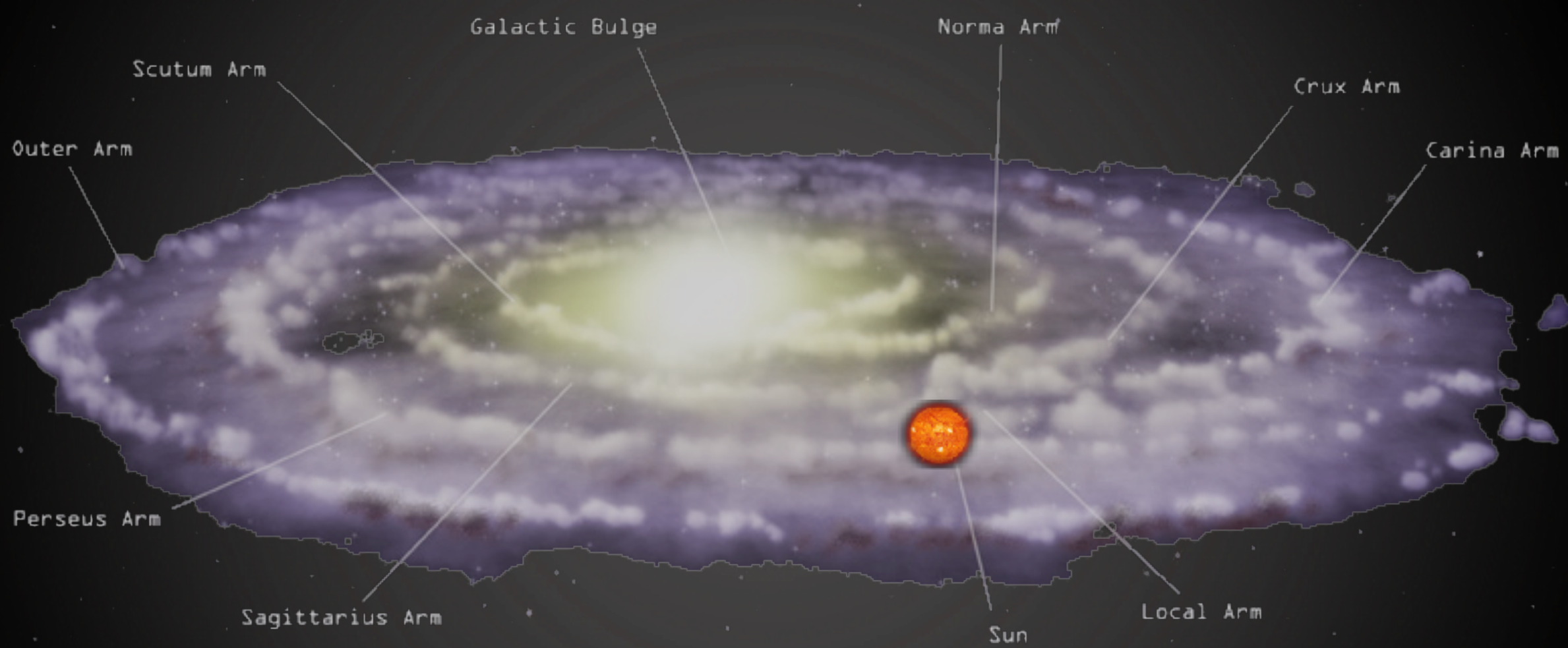

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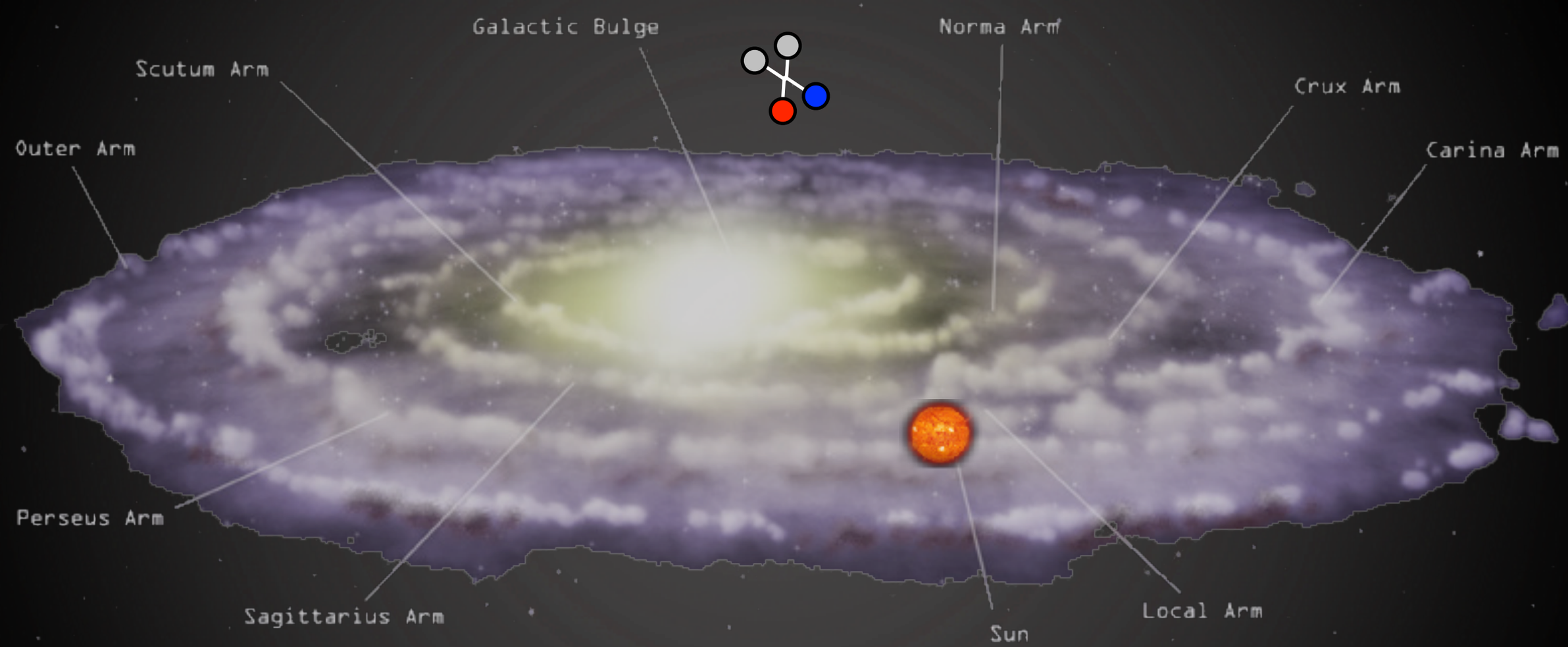

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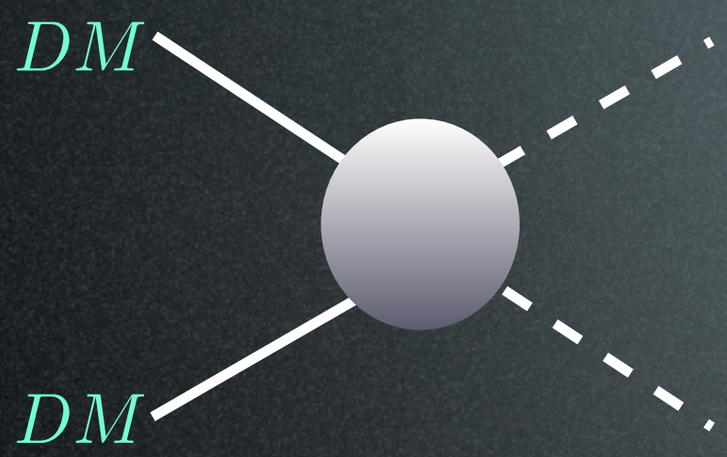
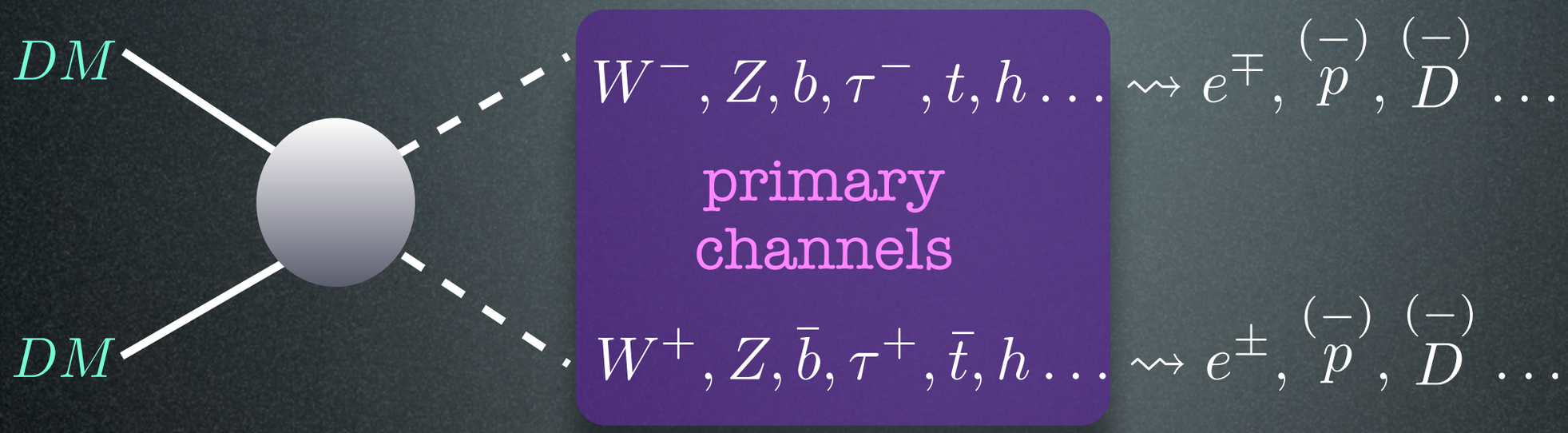


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

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

Indirect Detection: basics



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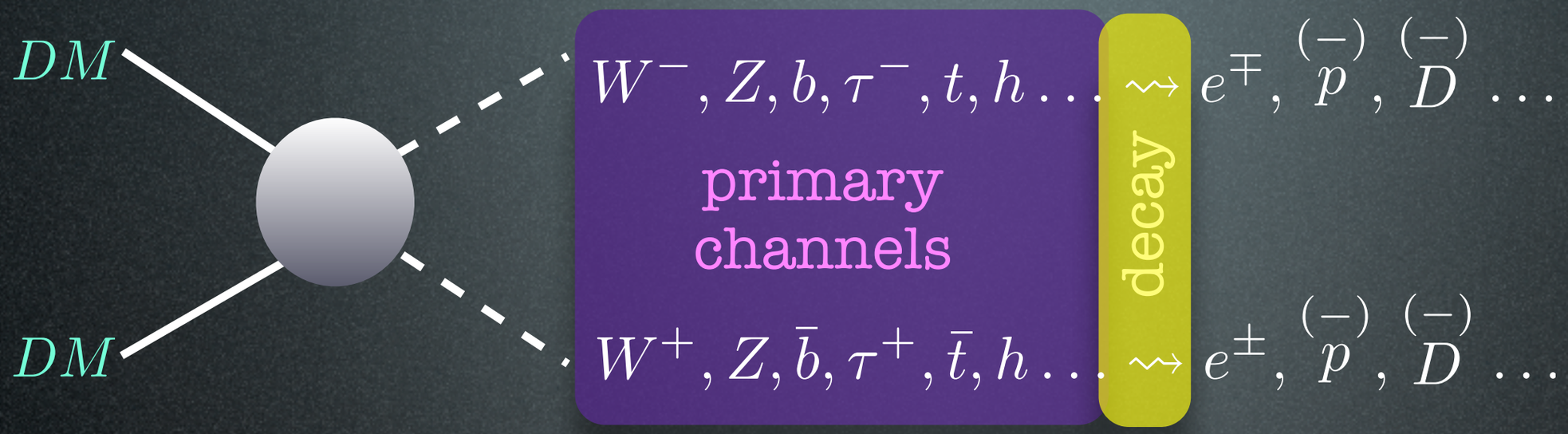
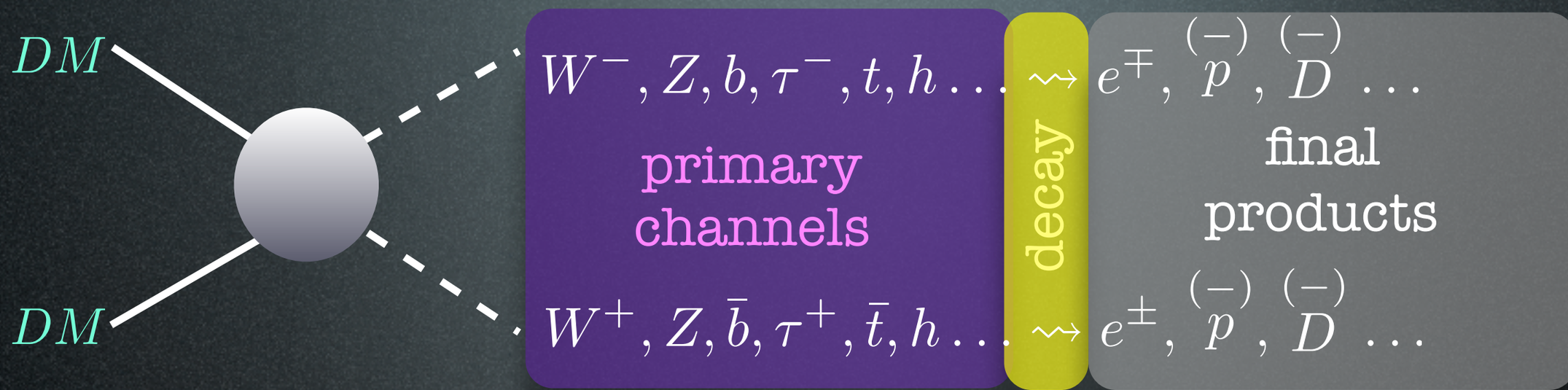
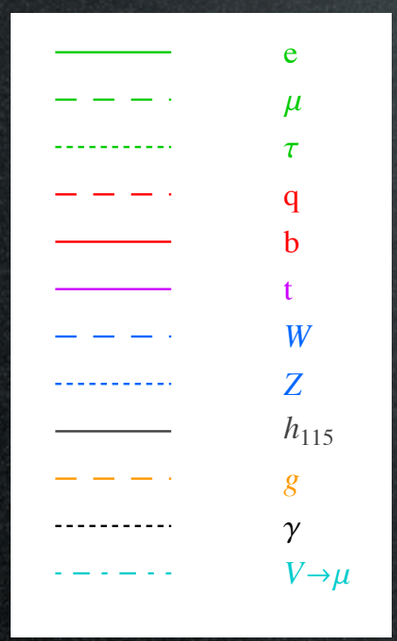
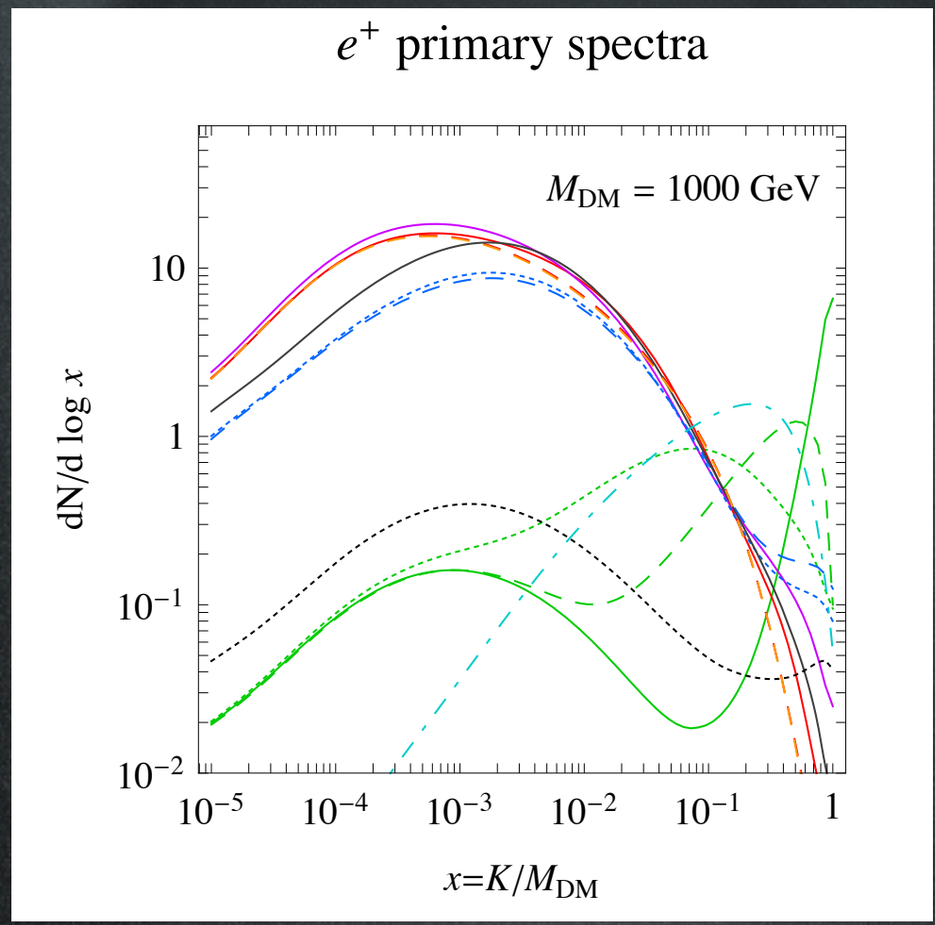
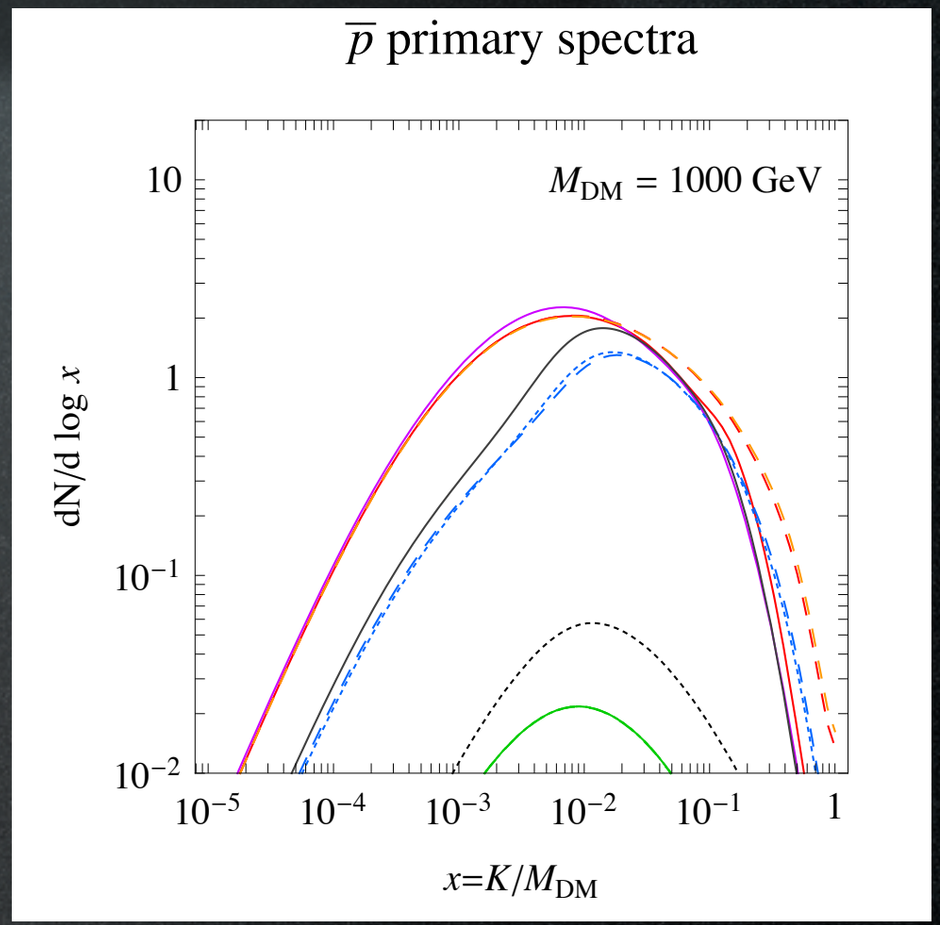


Indirect Detection: basics

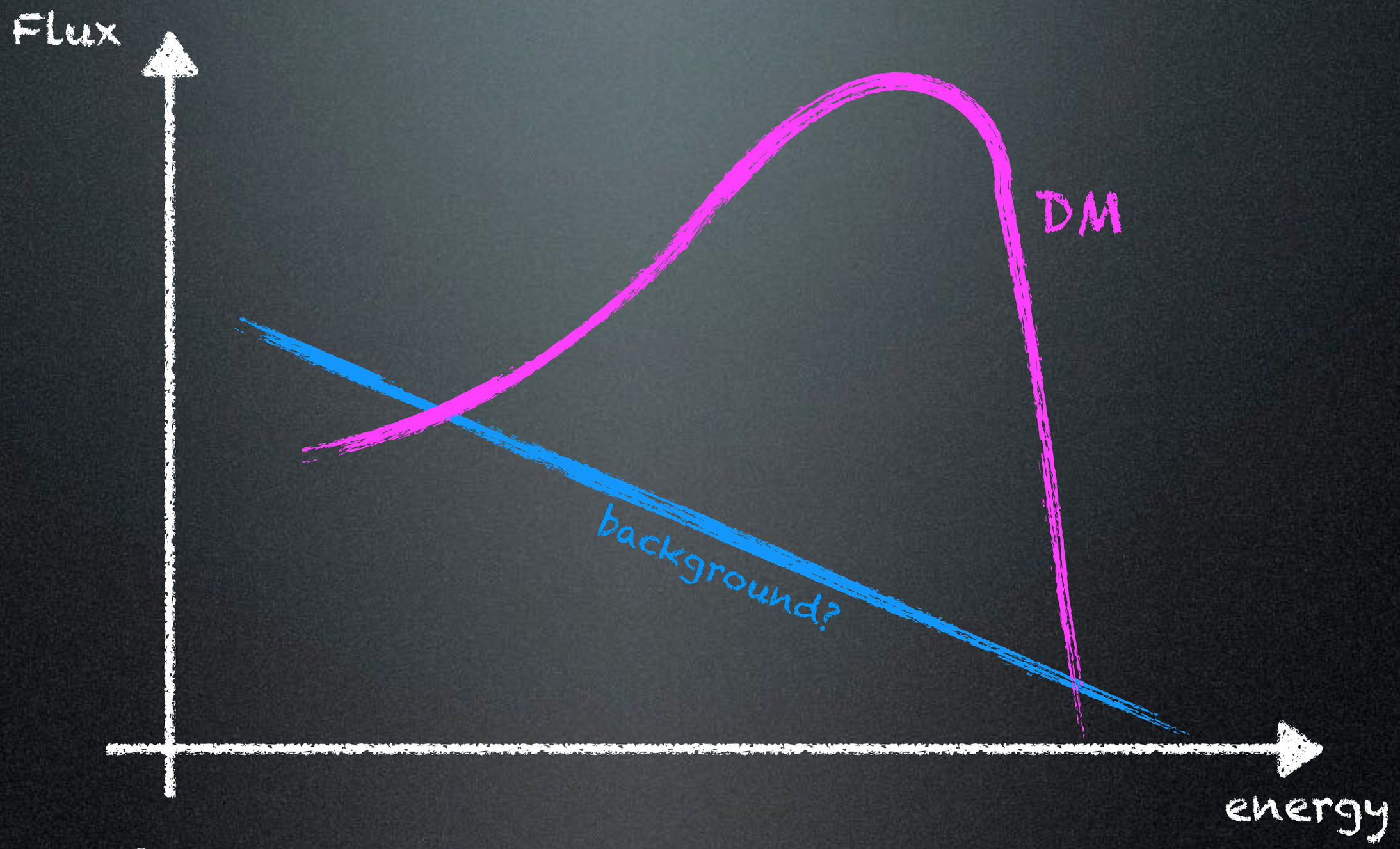






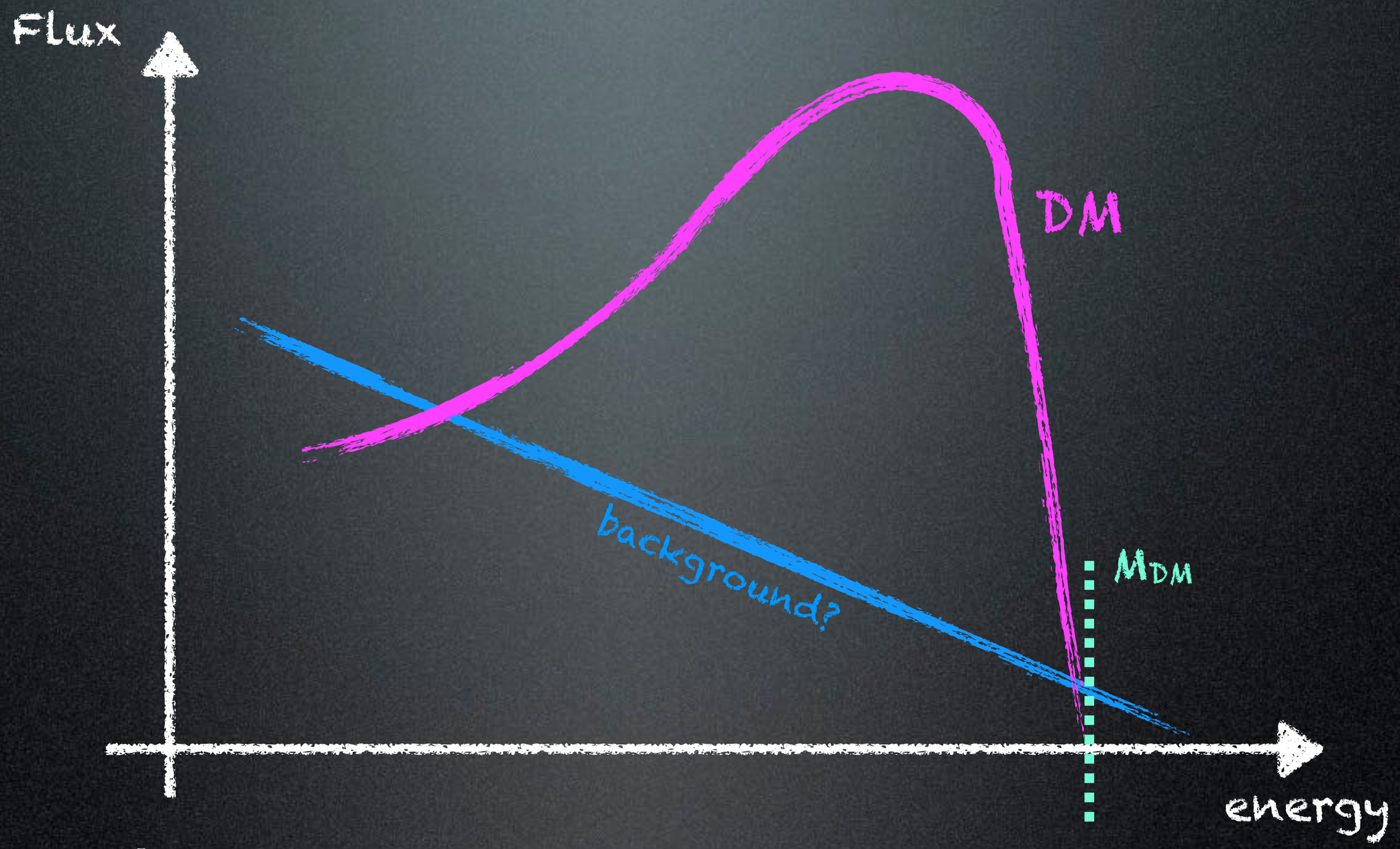


Fluxes at production



So what are the particle physics parameters?

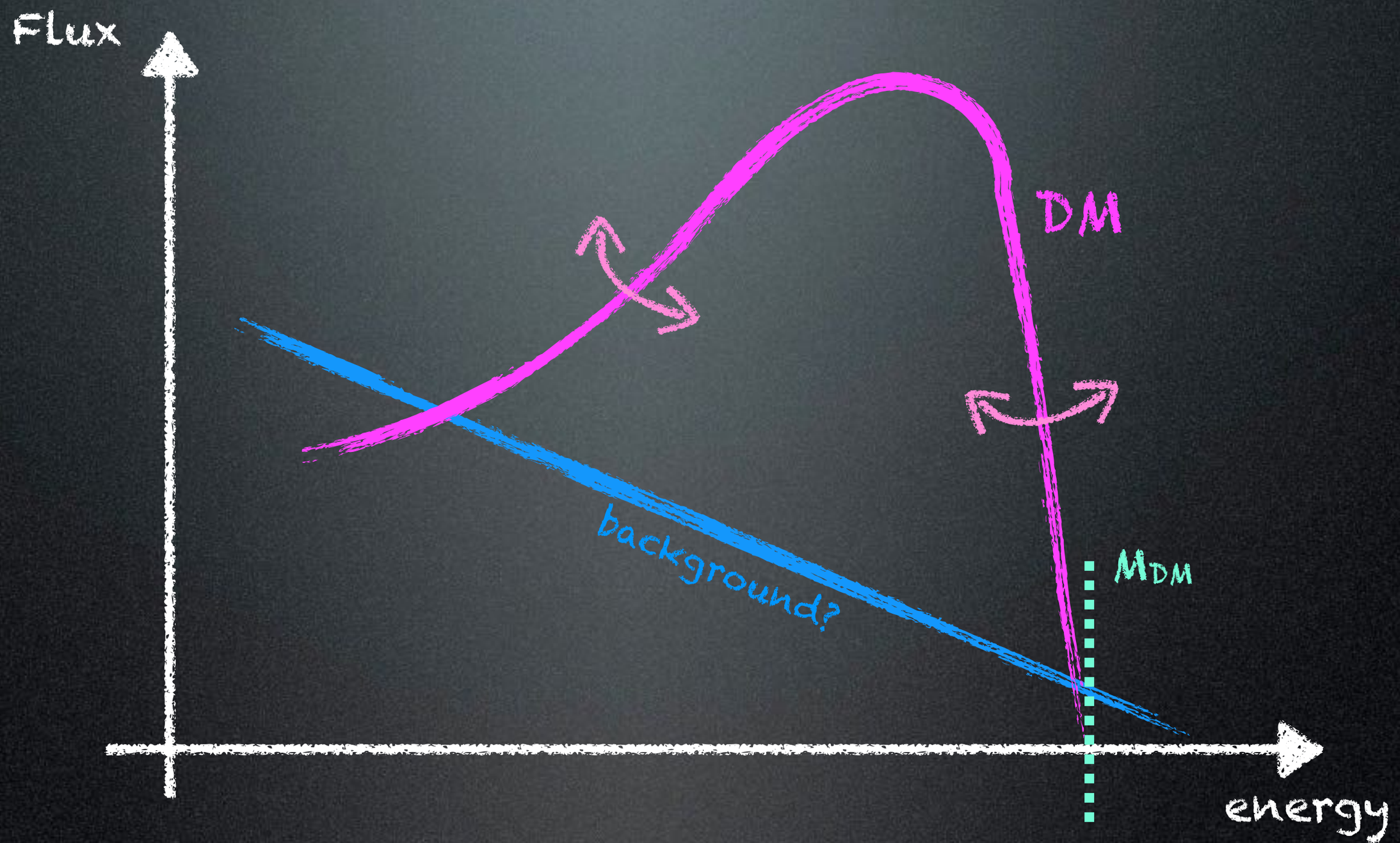
Fluxes at production



So what are the particle physics parameters?

1. Dark Matter mass

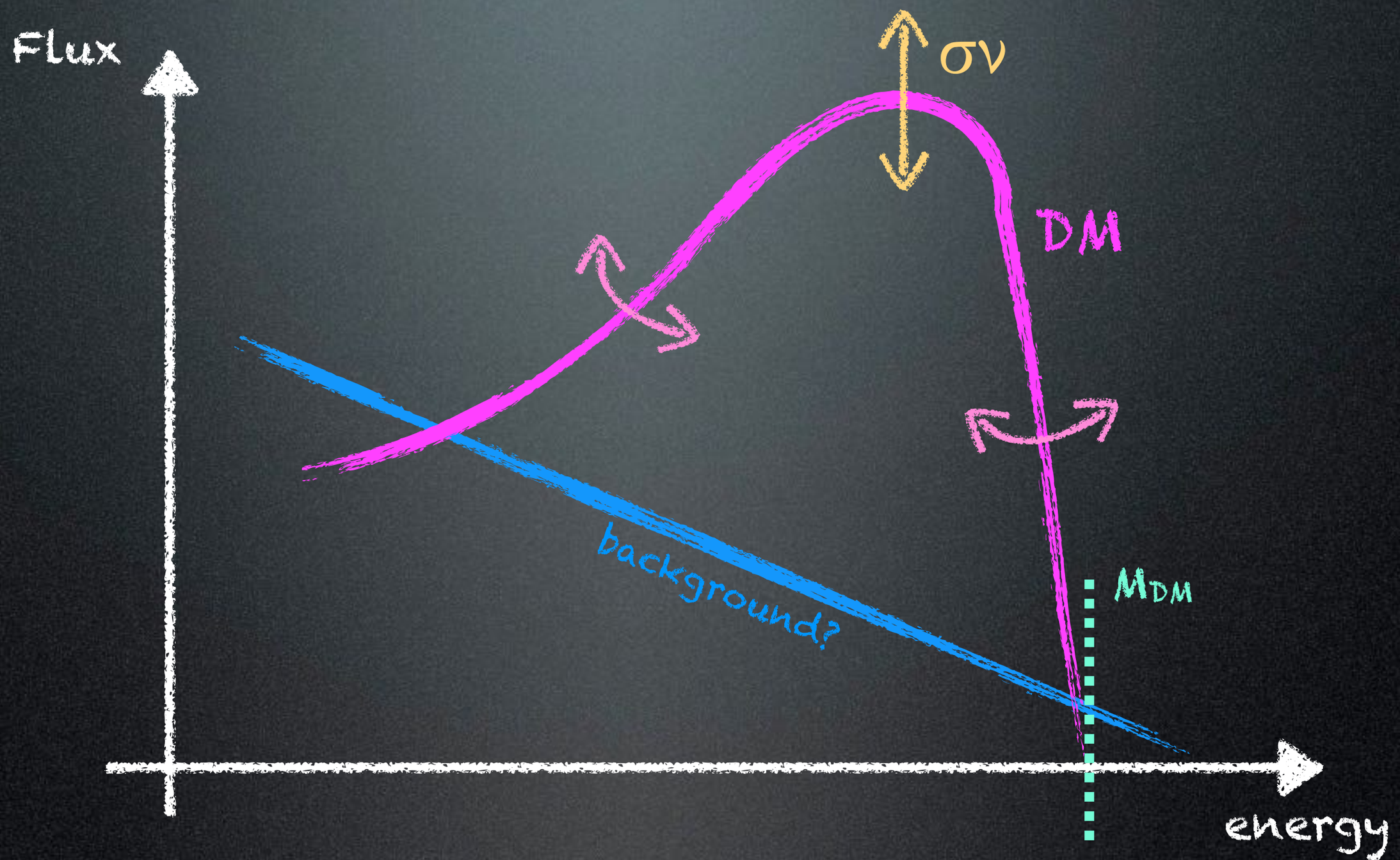
Fluxes at production



So what are the particle physics parameters?

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

Fluxes at production

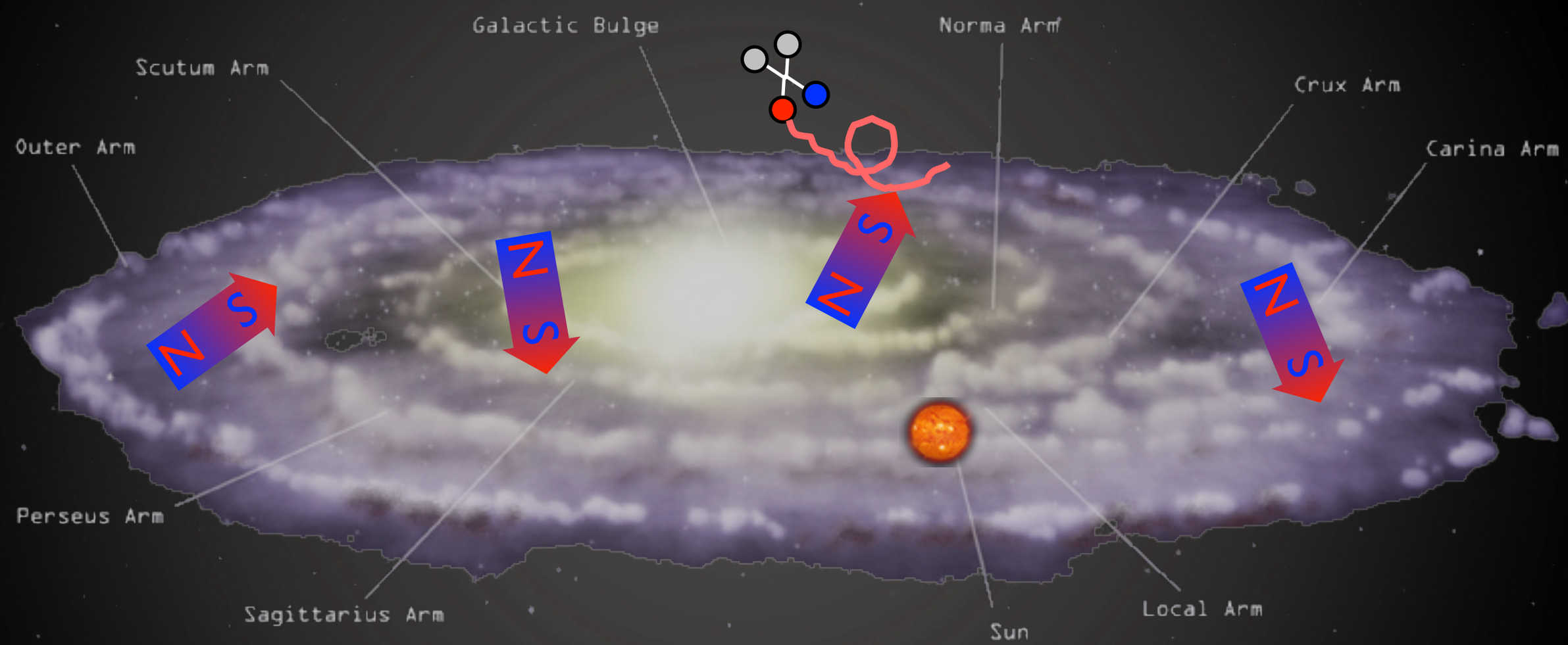


So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

Indirect Detection: charged CRs

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



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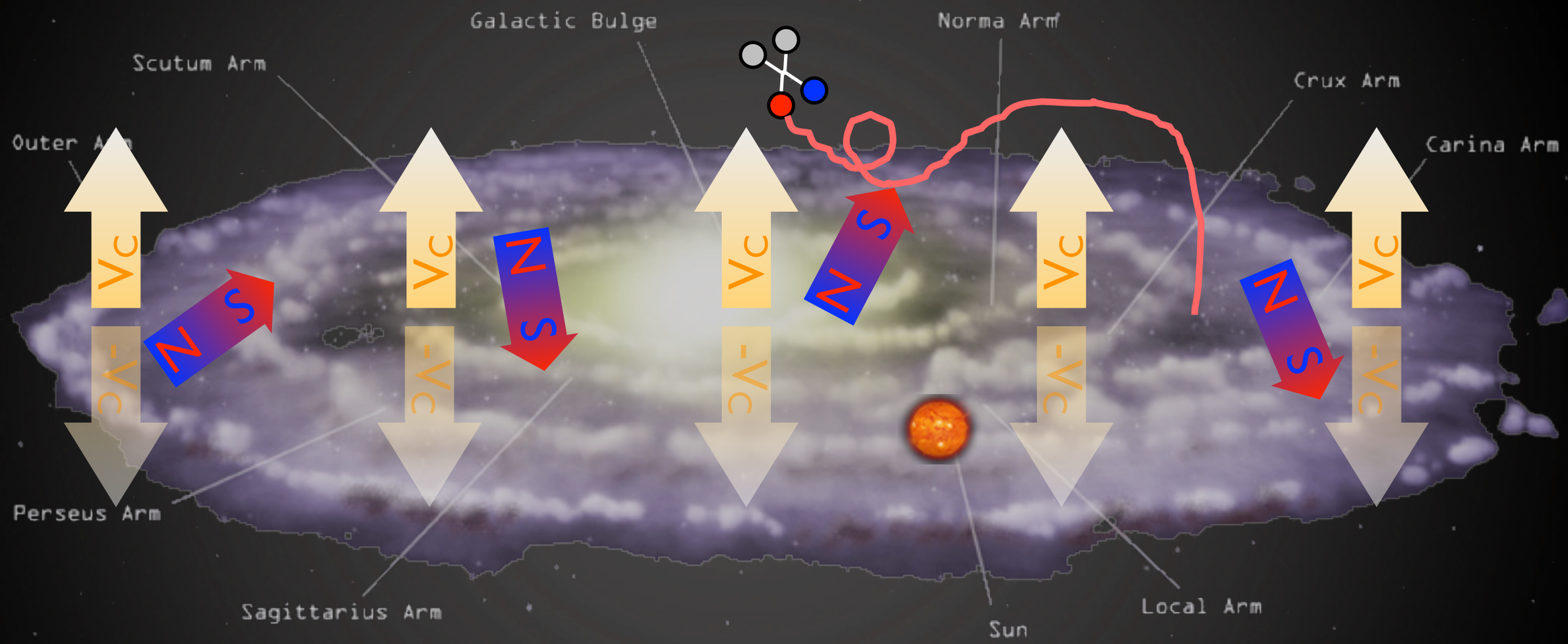

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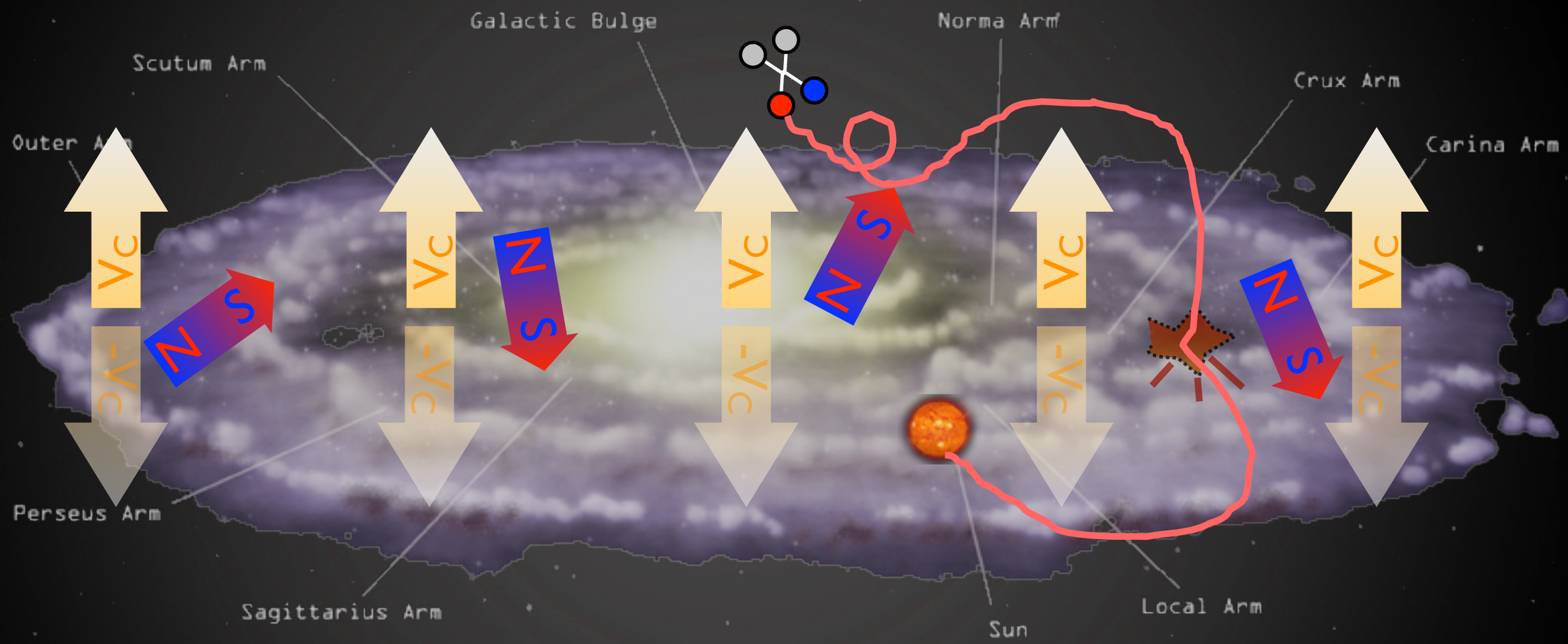

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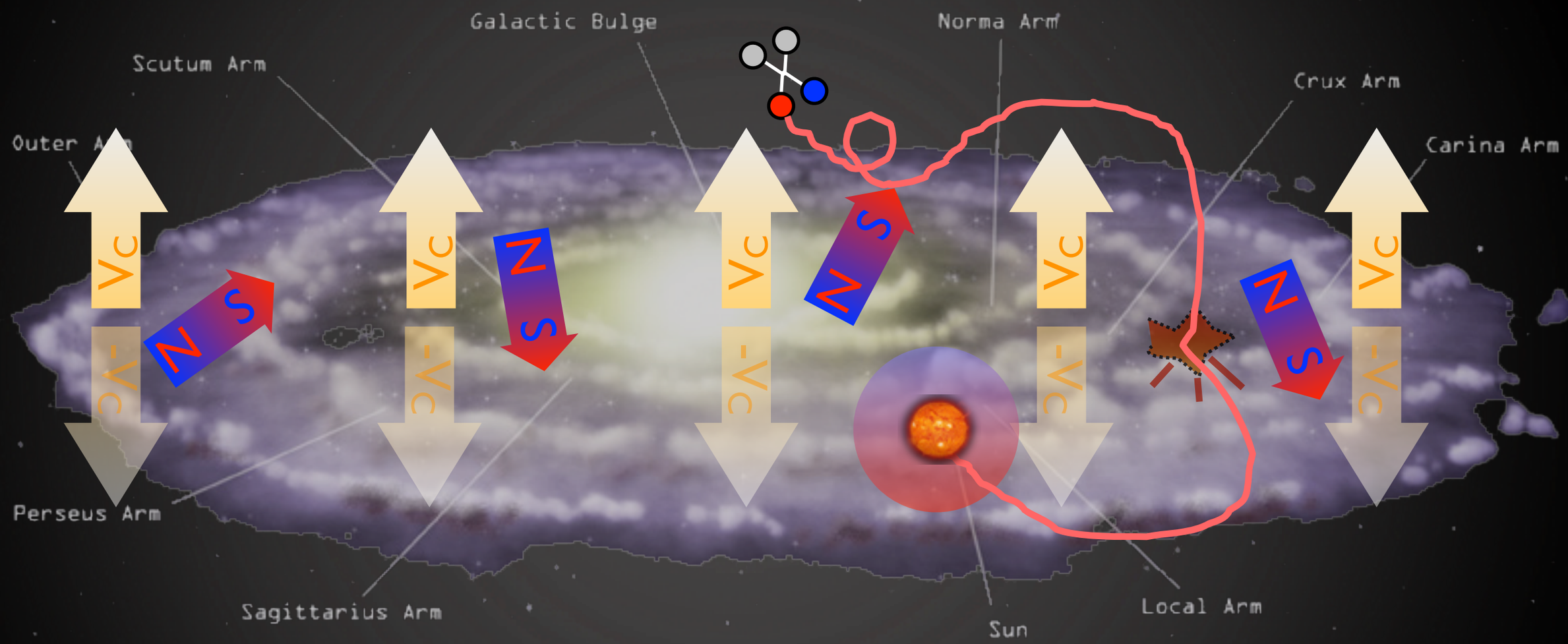

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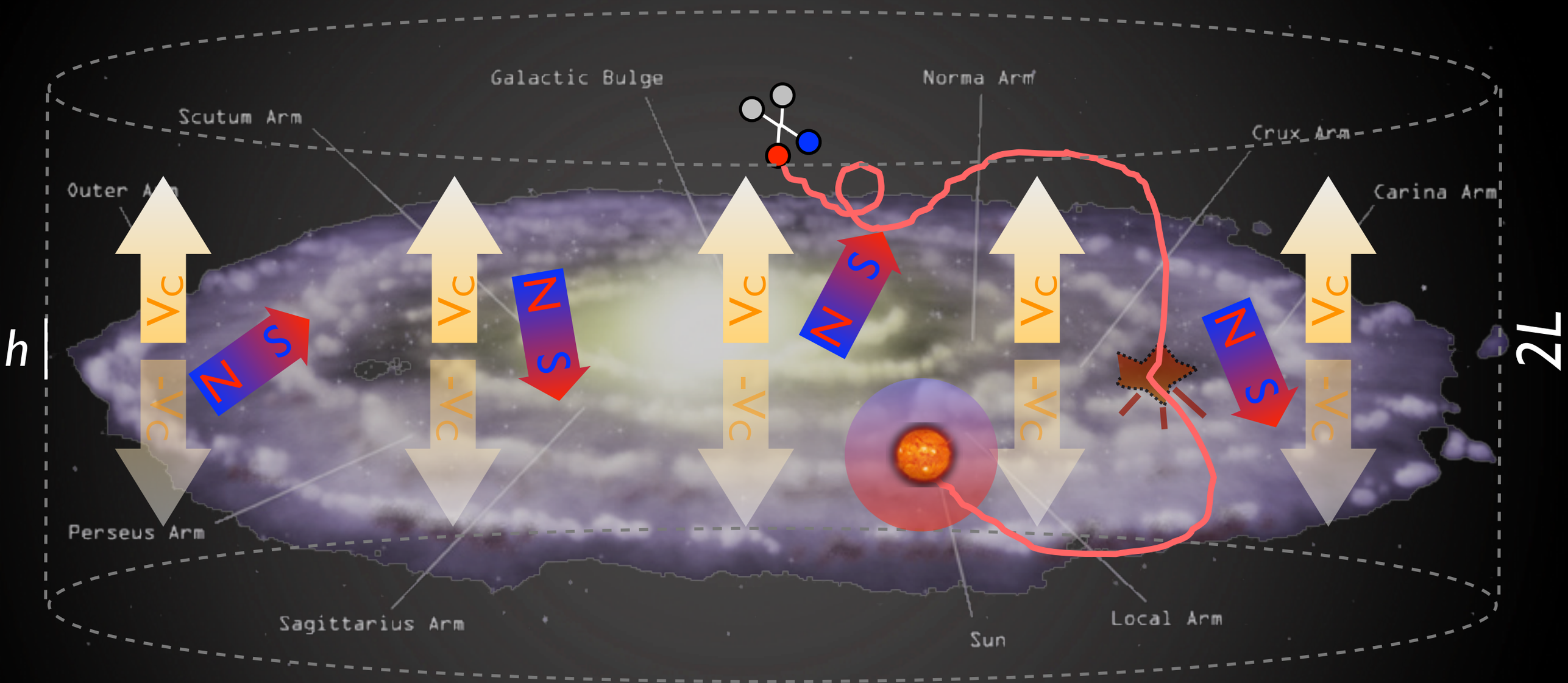

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maur Brun... '90s, '00s

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
diff. reacc.	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+

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convection dv_c/dz [km s^{-1} kpc^{-1}]	0	0	50	[illegible]	[illegible]	0	0
solar mod. ϕ_F^p [GV]	0.650	0.335	[illegible]	[illegible]	[illegible]	0.626	0.623
$\chi^2_{\rm min}$/dof (p in [25])	[illegible]	[illegible]	[illegible]	[illegible]	0.639	[illegible]	[illegible]

YOANN GÉNOLINI'S TALK

CARMELO EVOLI'S TALK

Cirelli, Gaggero [illegible] 173
cfr. [illegible] 1108.0664

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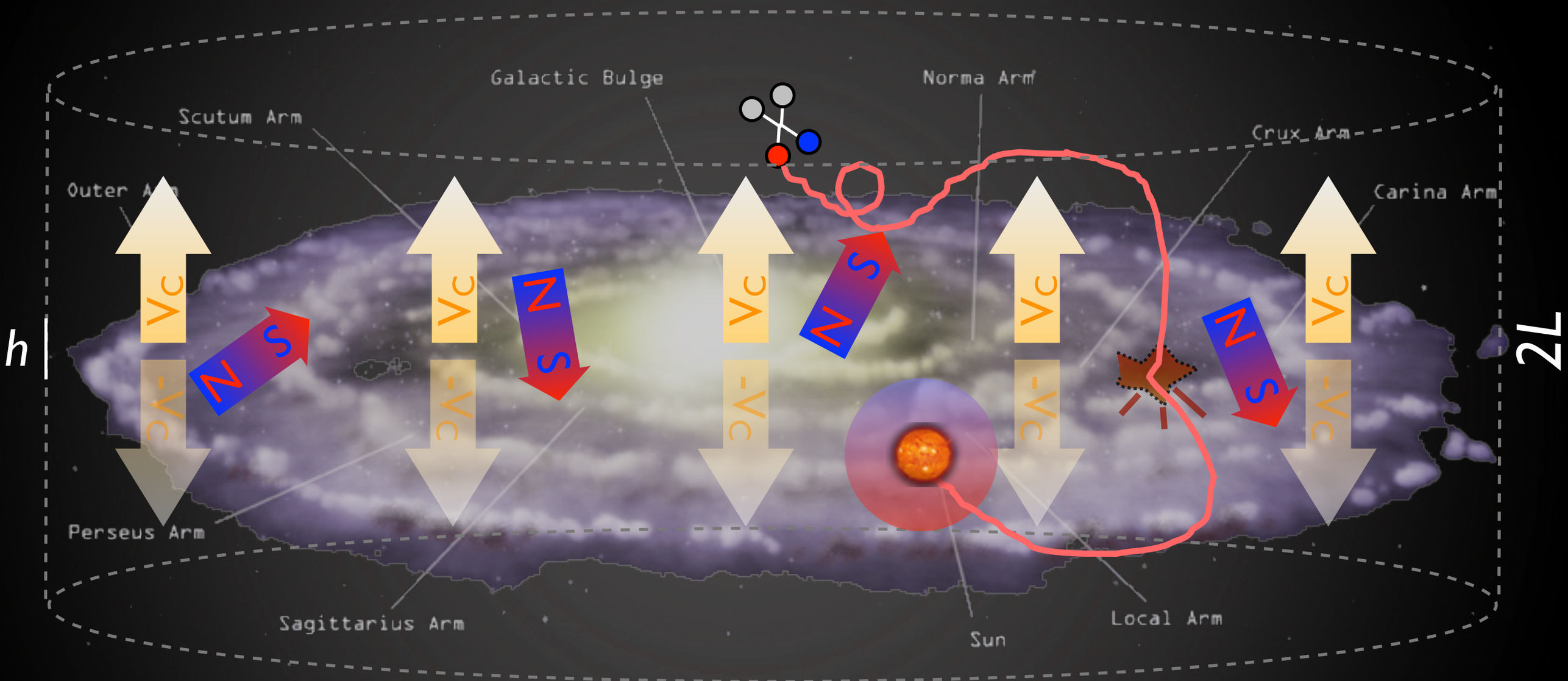

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diffusion | energy loss | convective wind | source | spallations

[uncert]

DM halo profiles

From N-body numerical simulations:

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

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

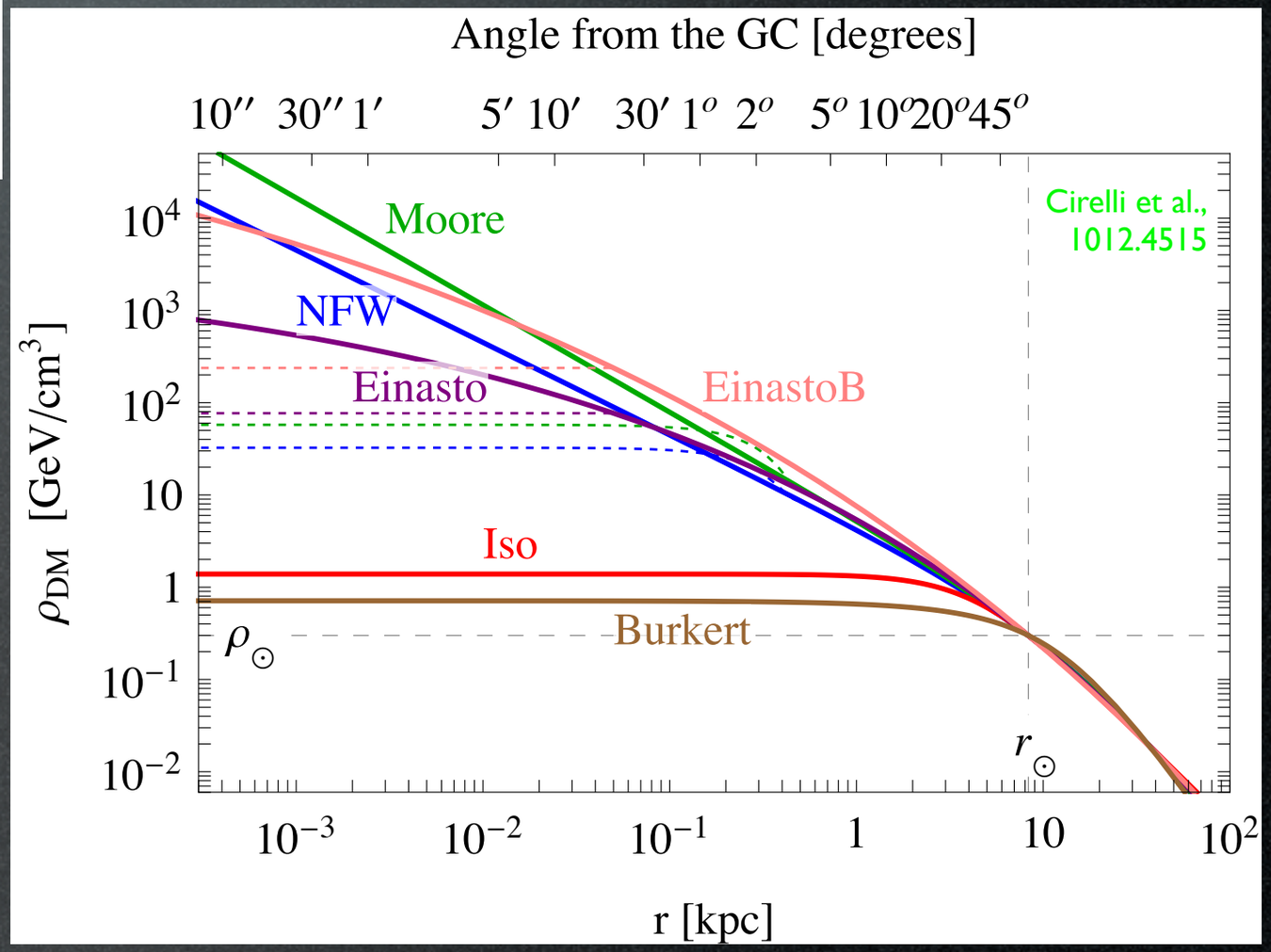
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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

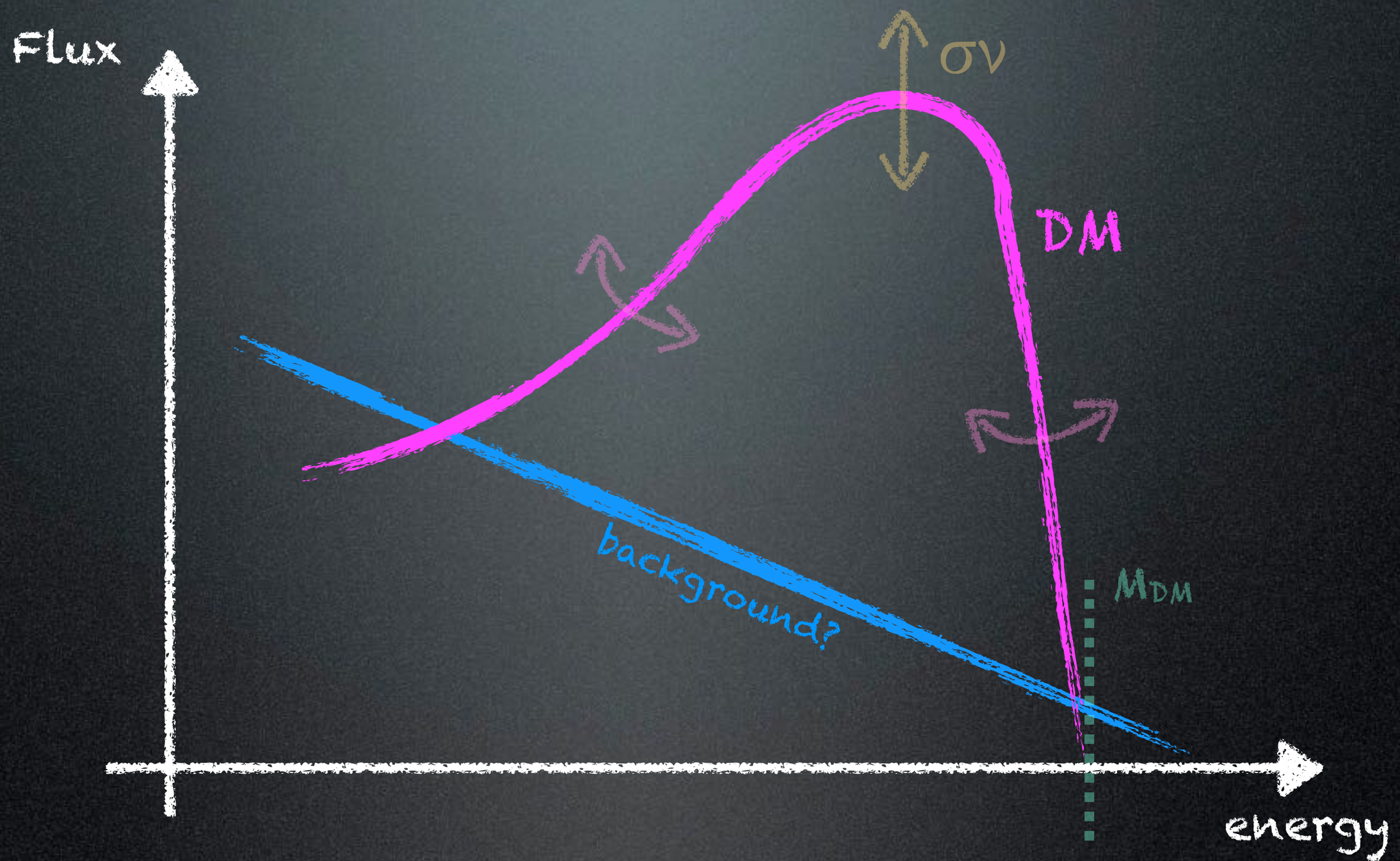
mild: Einasto

smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)

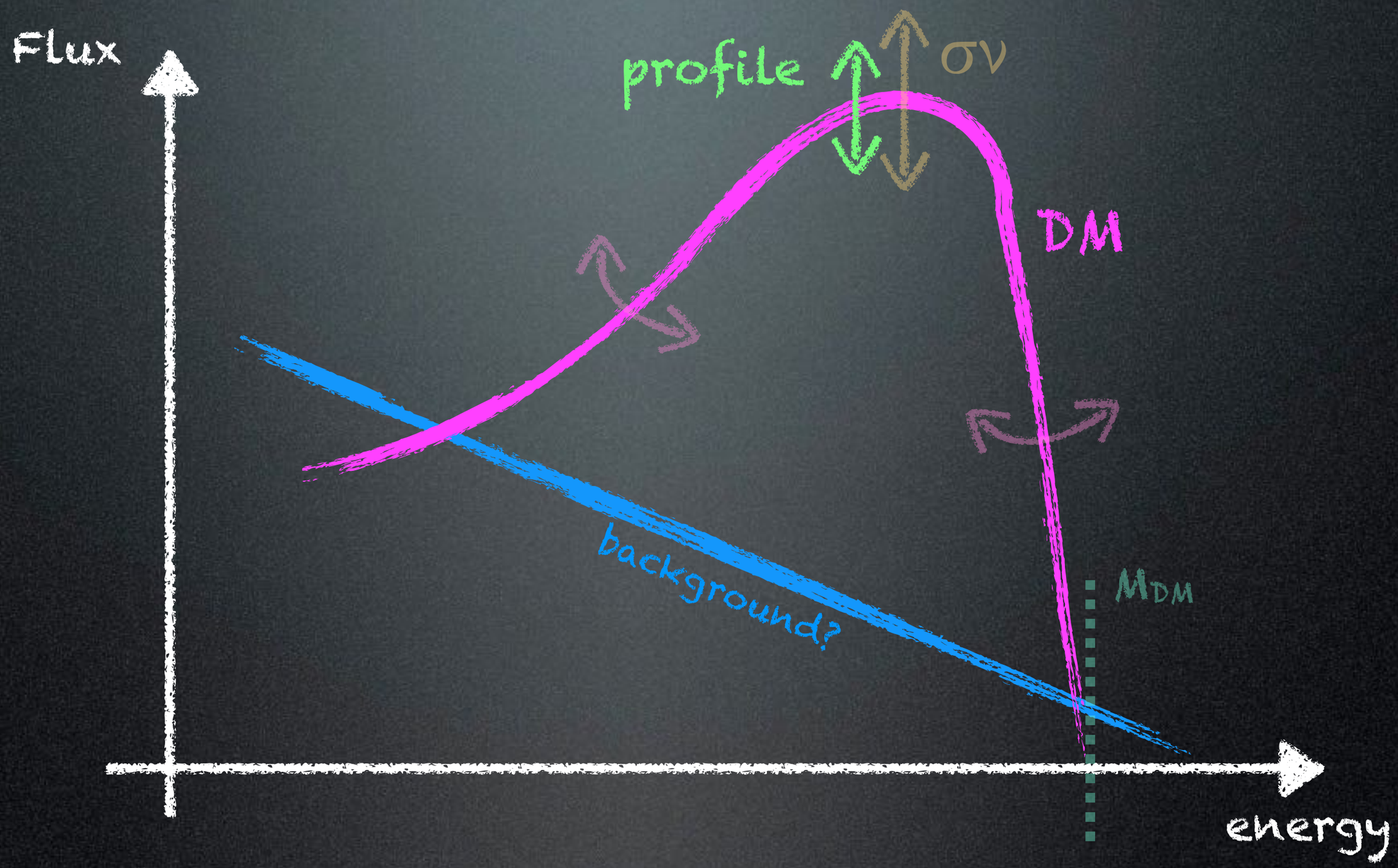
Fluxes at detection



So what are the astrophysics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

Fluxes at detection



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1. DM abundance/profile

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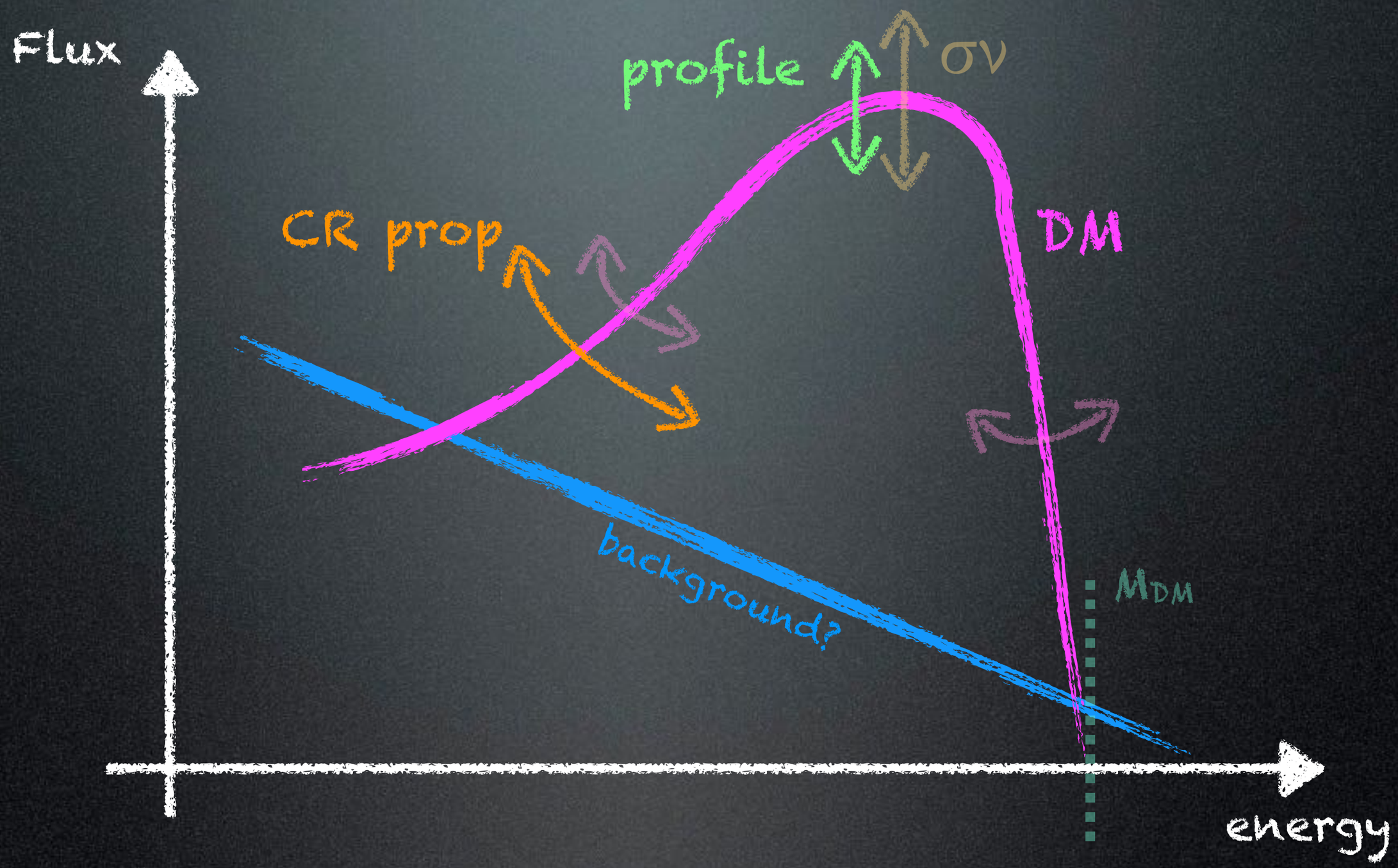

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1. DM abundance/profile
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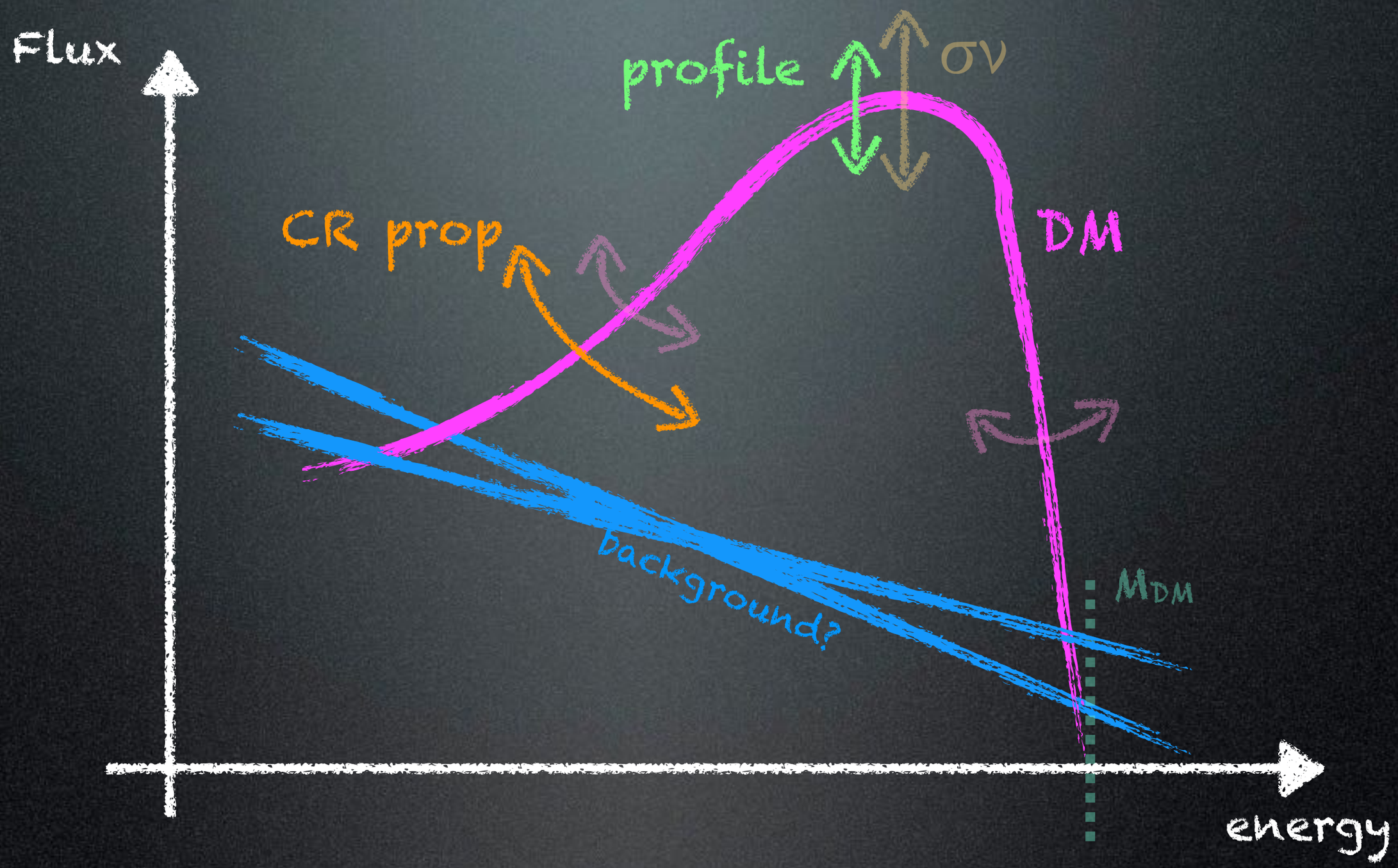
Fluxes at detection



So what are the astrophysics parameters?

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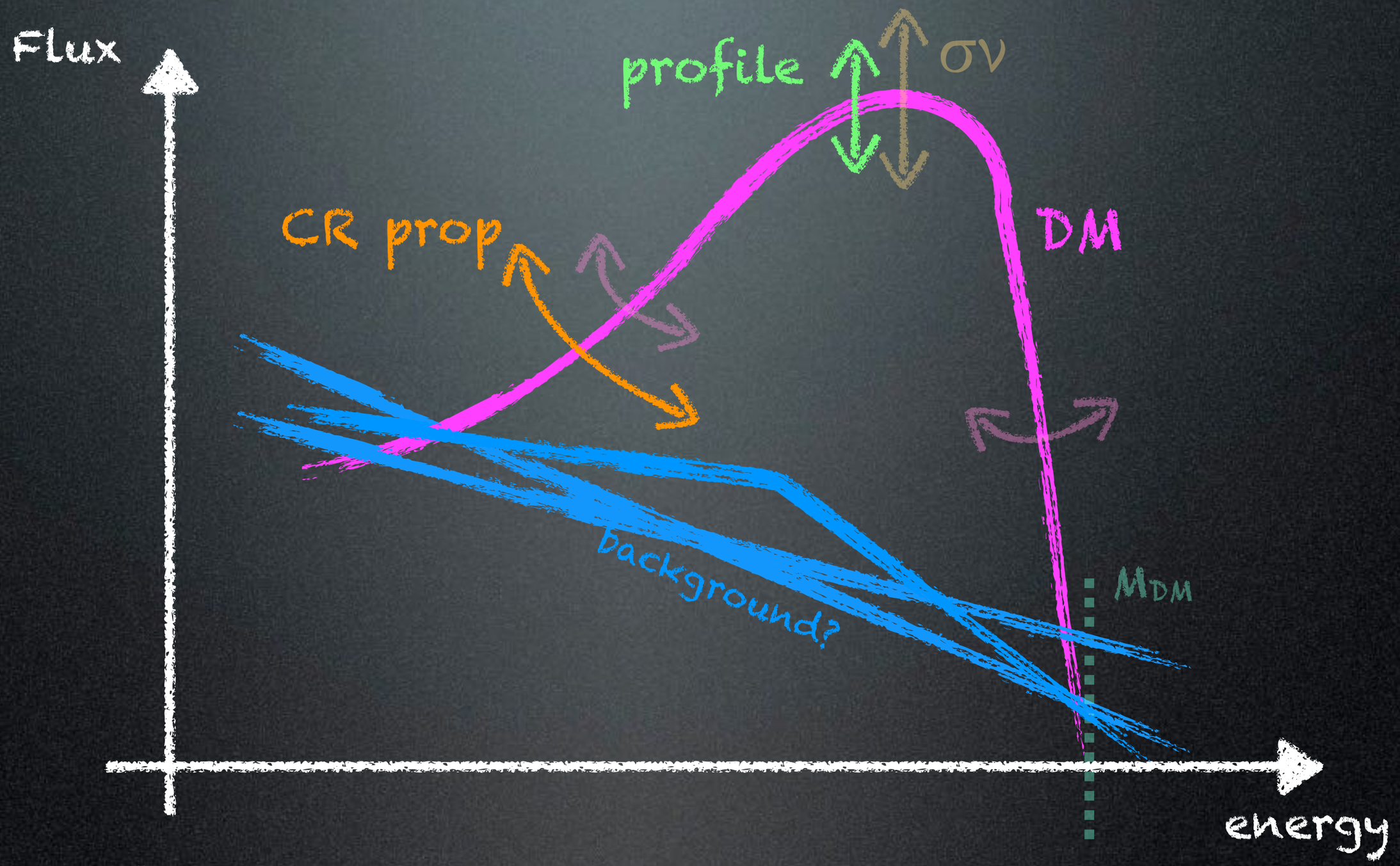
1. DM abundance/profile
2. propagation
3. background

Fluxes at detection



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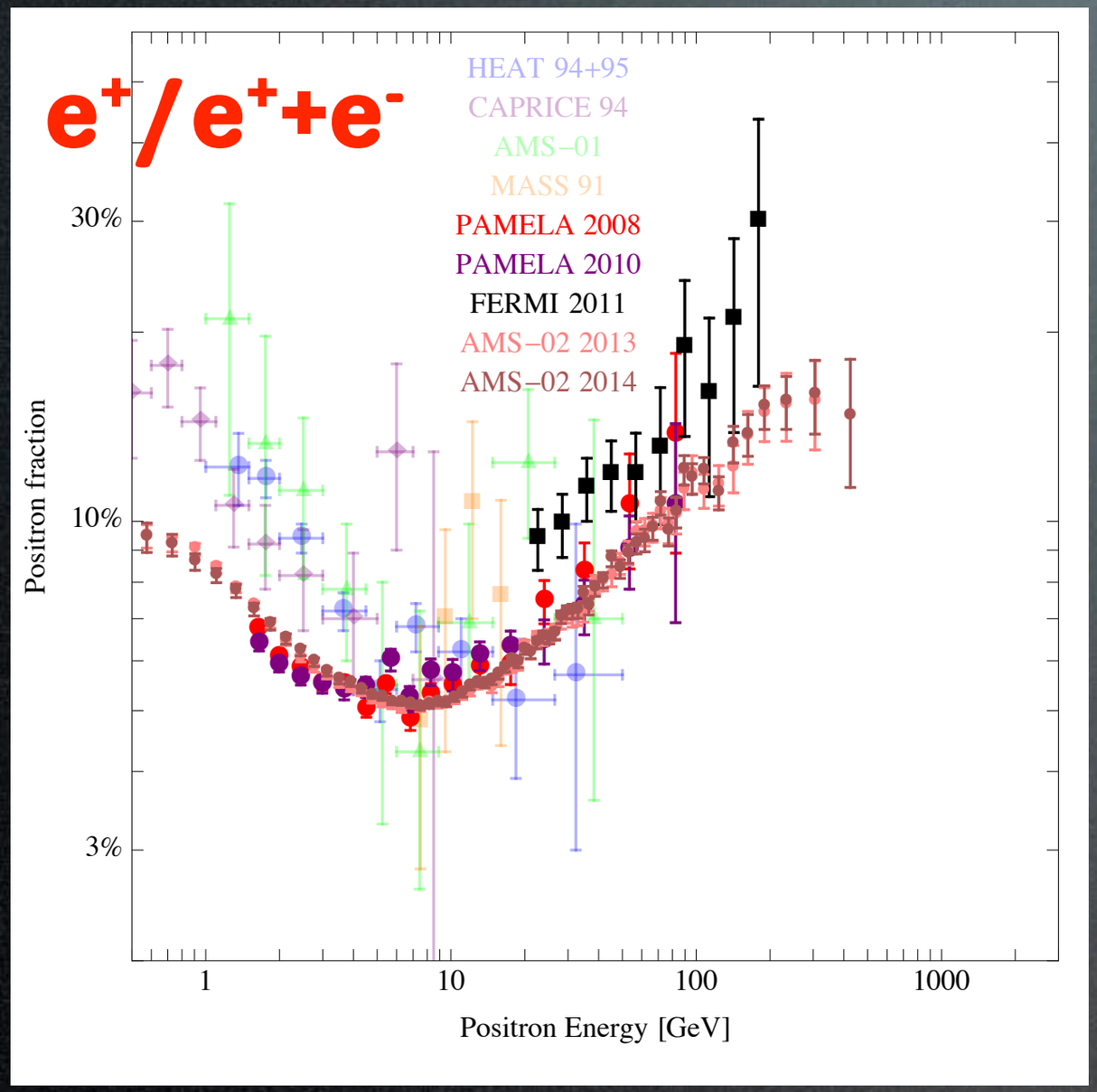
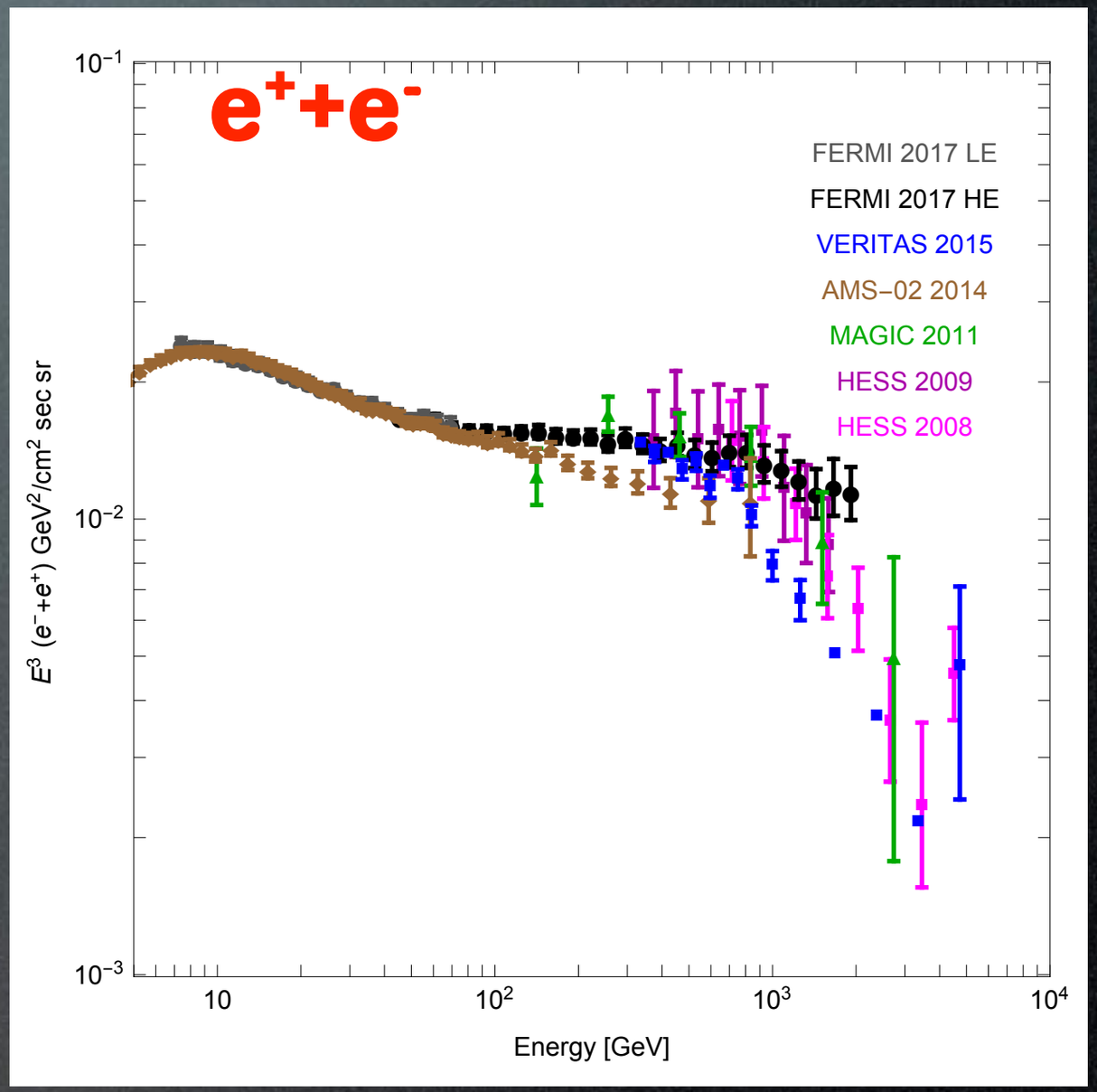
Data

Data: leptons



M. Cirelli - compilation ICRC 2015



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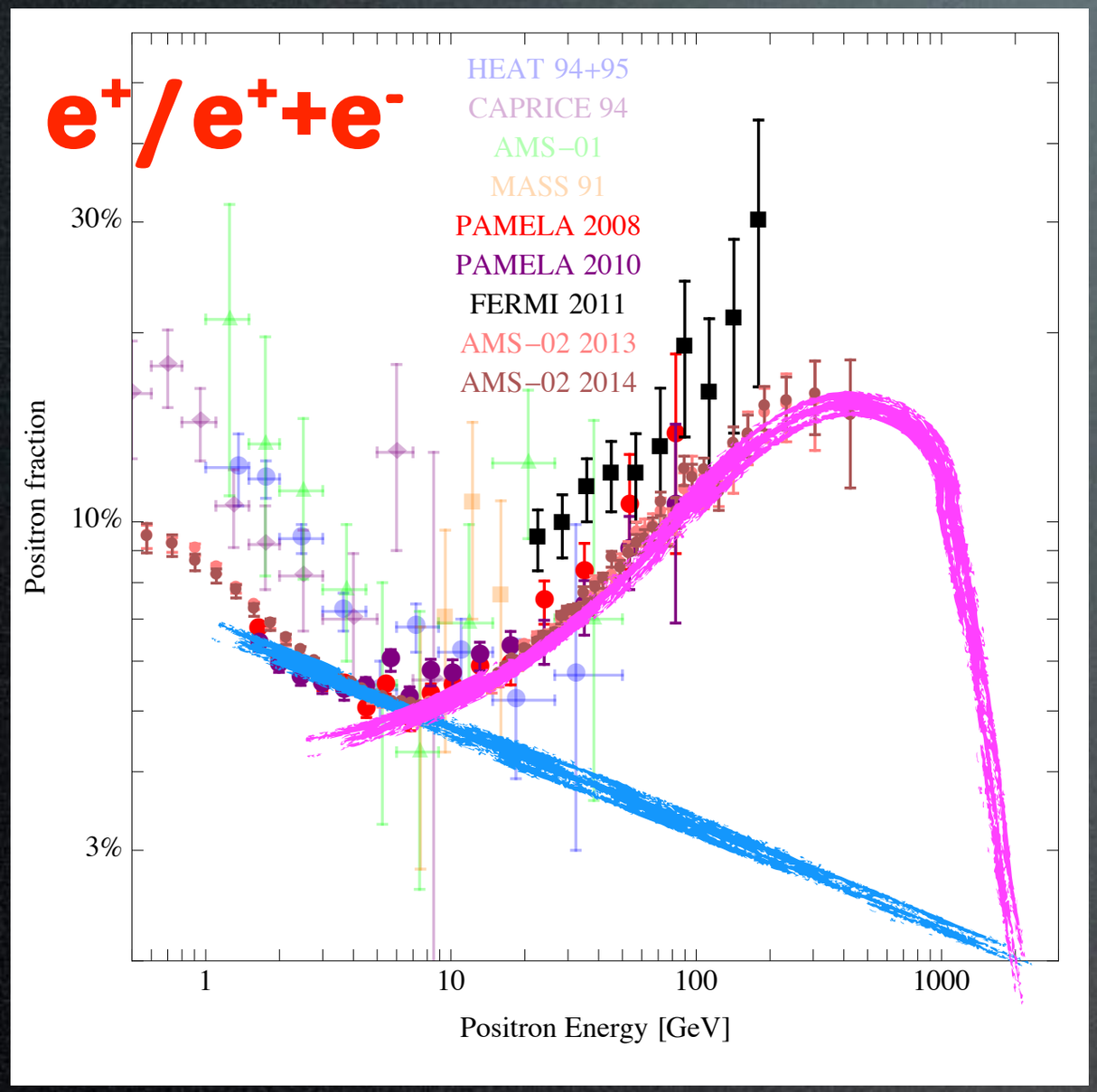

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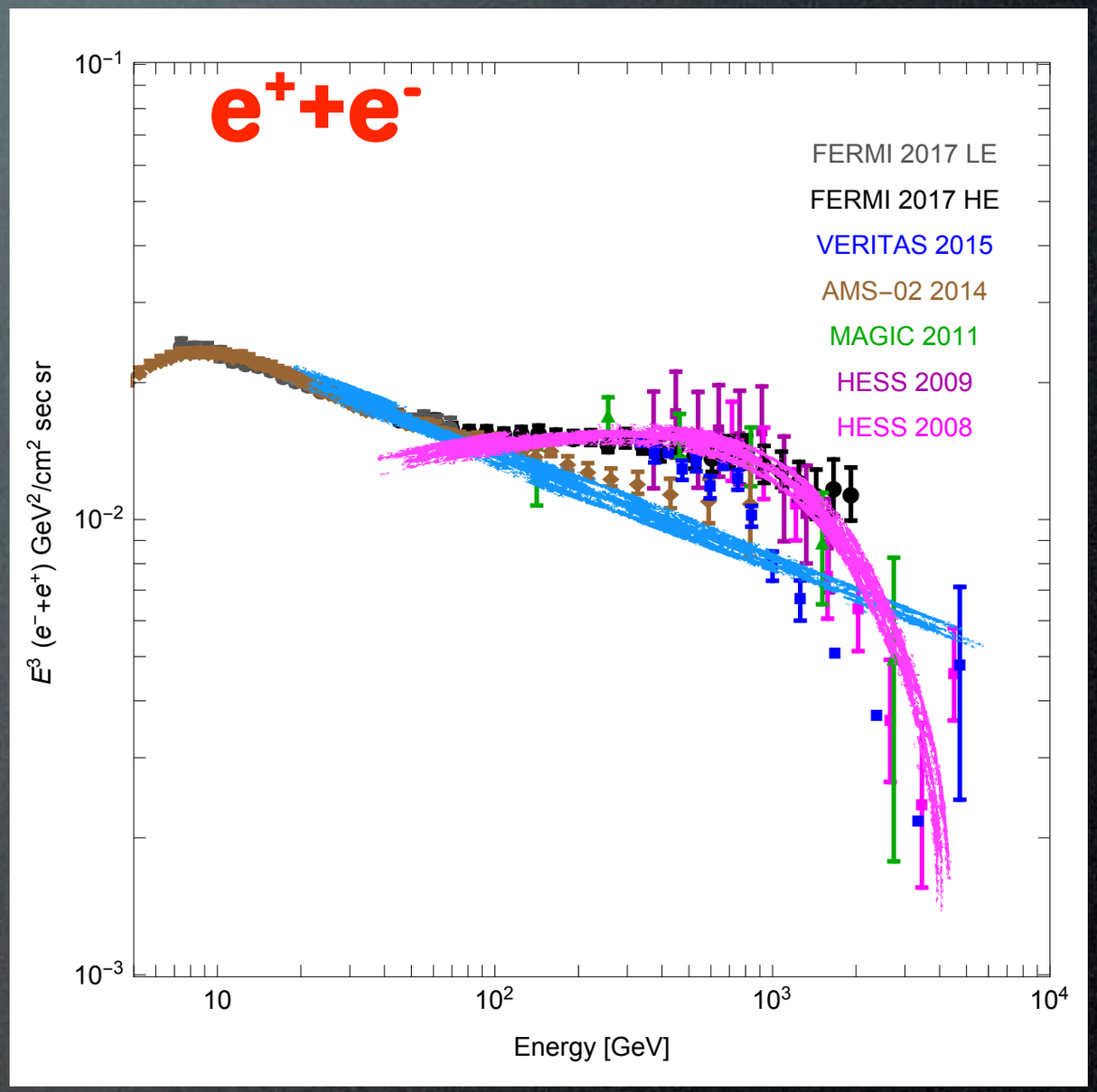

M. Cirelli - compilation ICRC 2015

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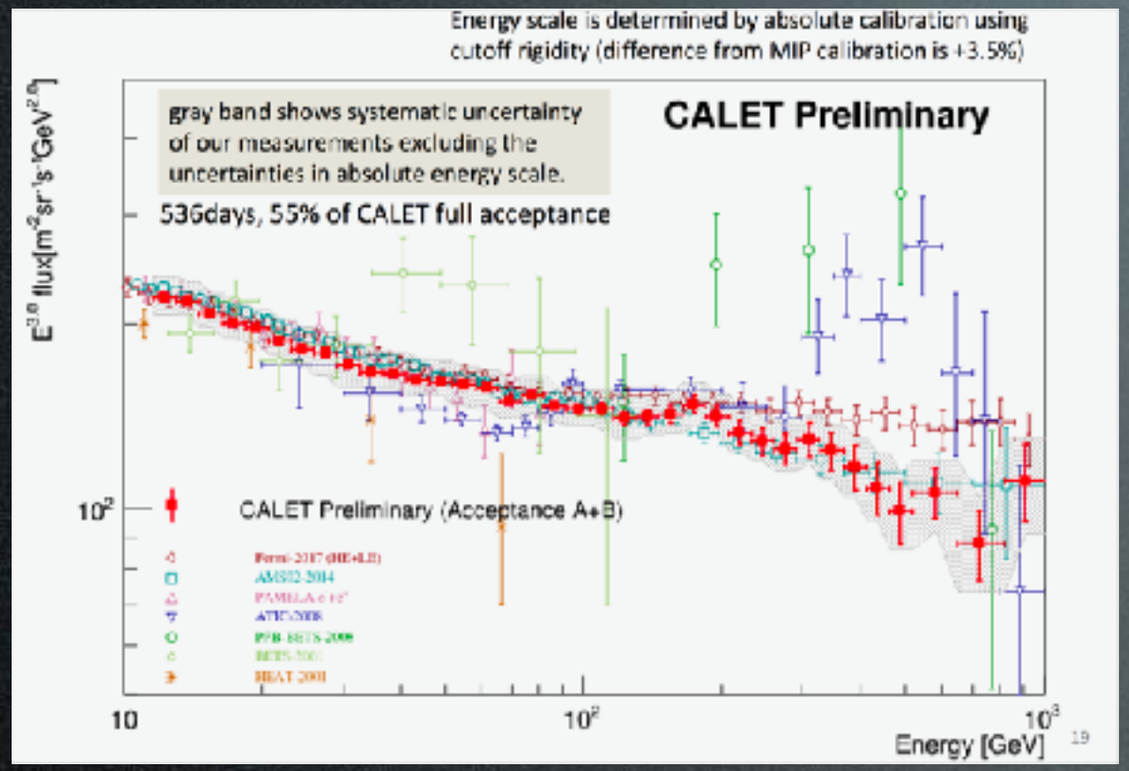
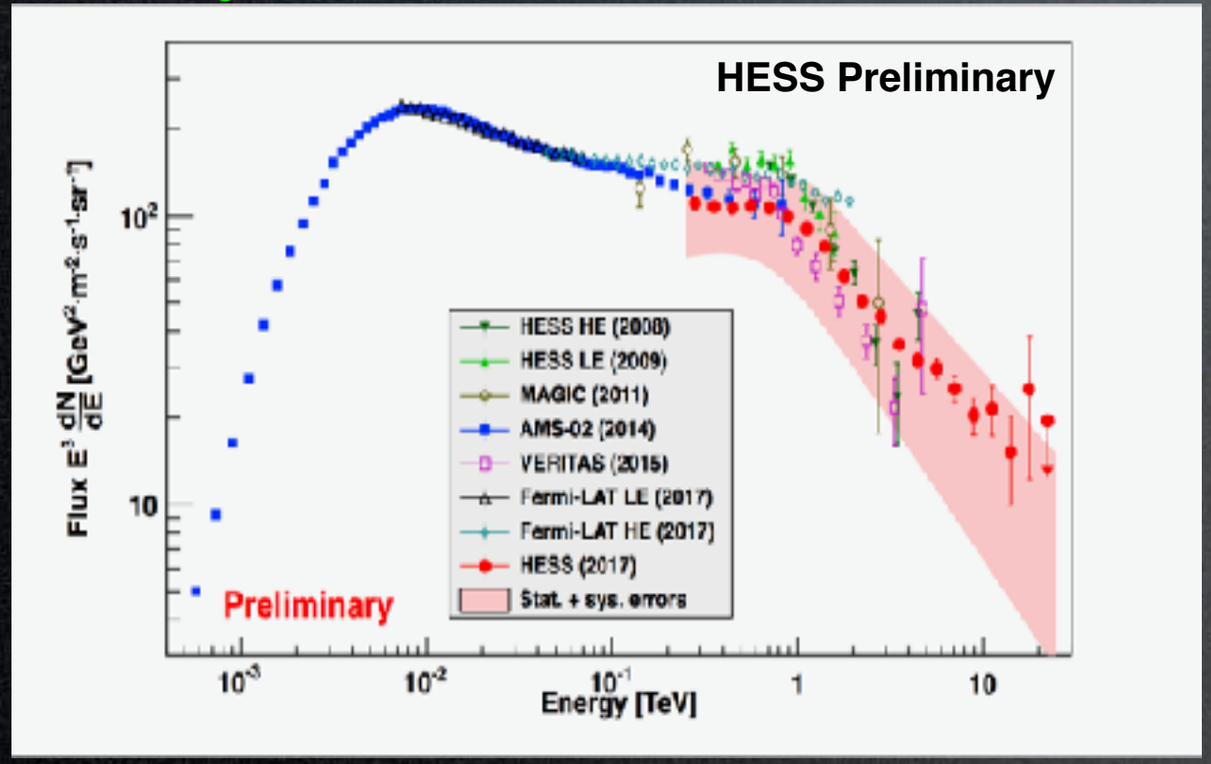
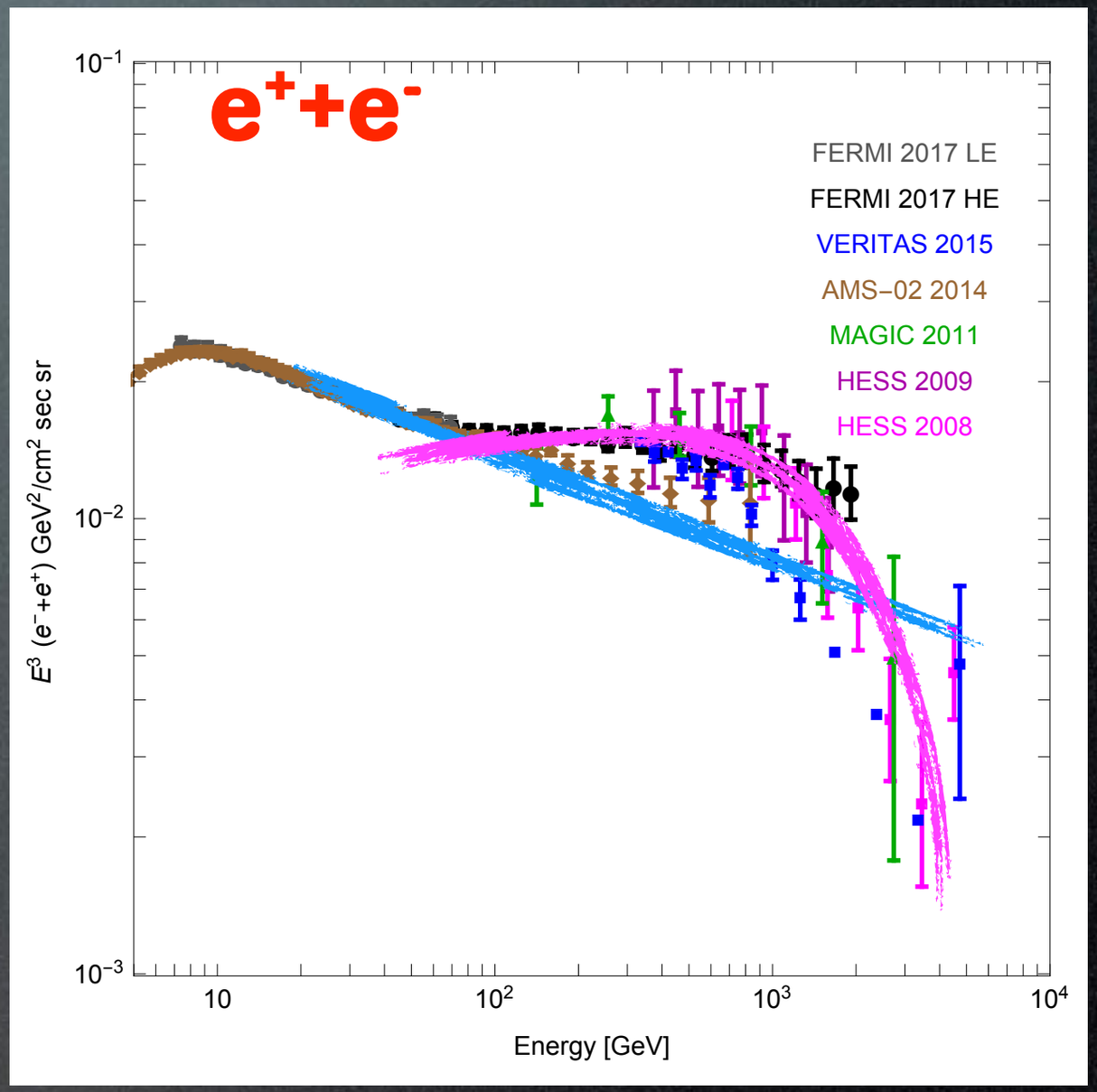
CALET coll., ICRC 2017



D. Kerszberg, HESS coll., ICRC 2017





M. Cirelli - compilation ICRC 2015

+ DAMPE coll. —> soon

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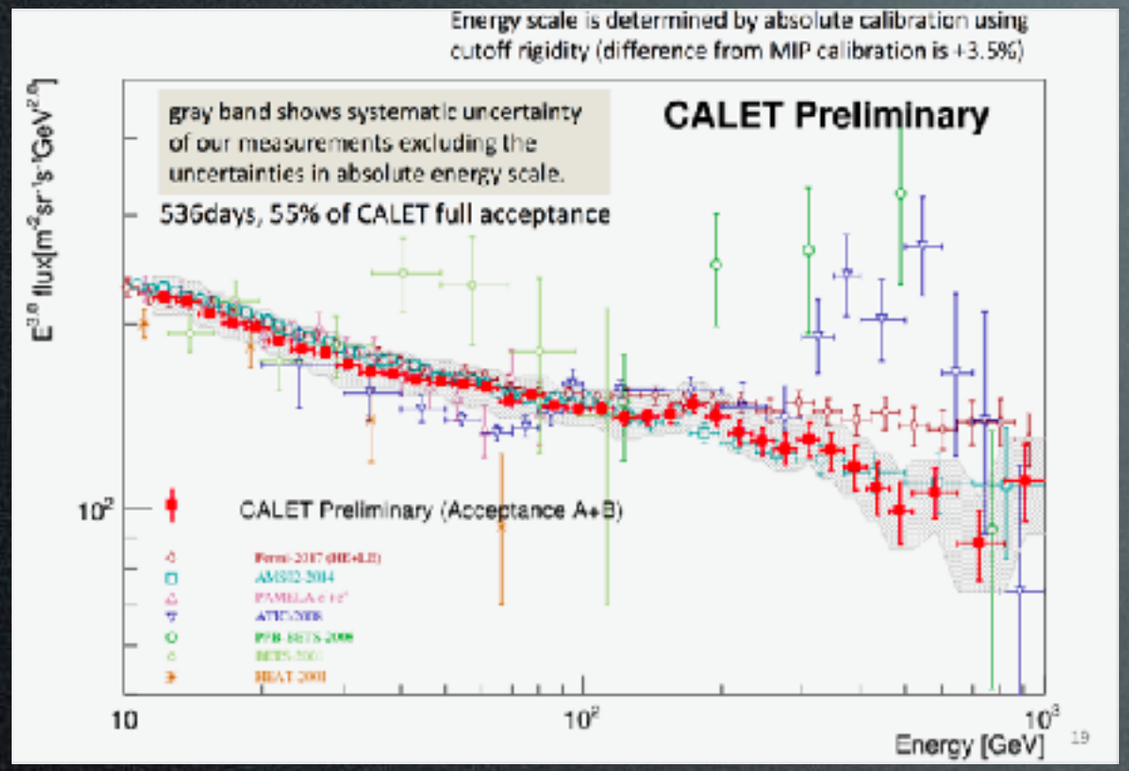

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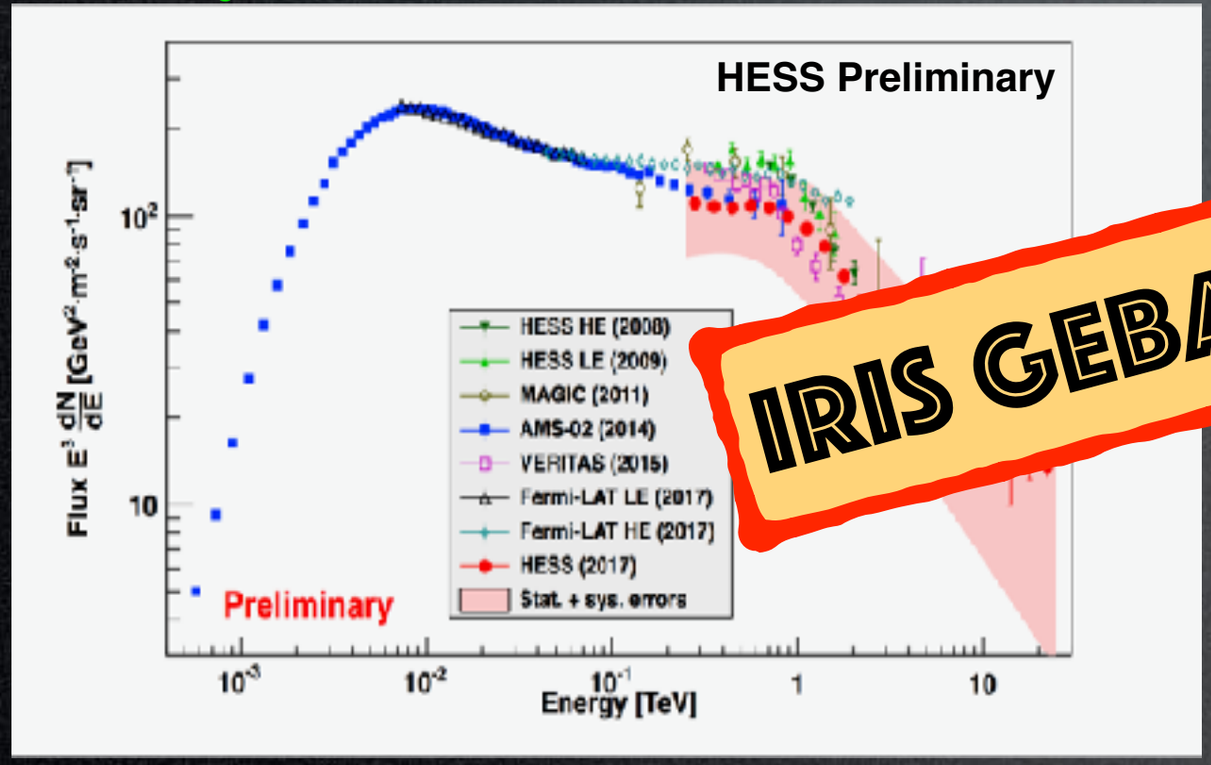
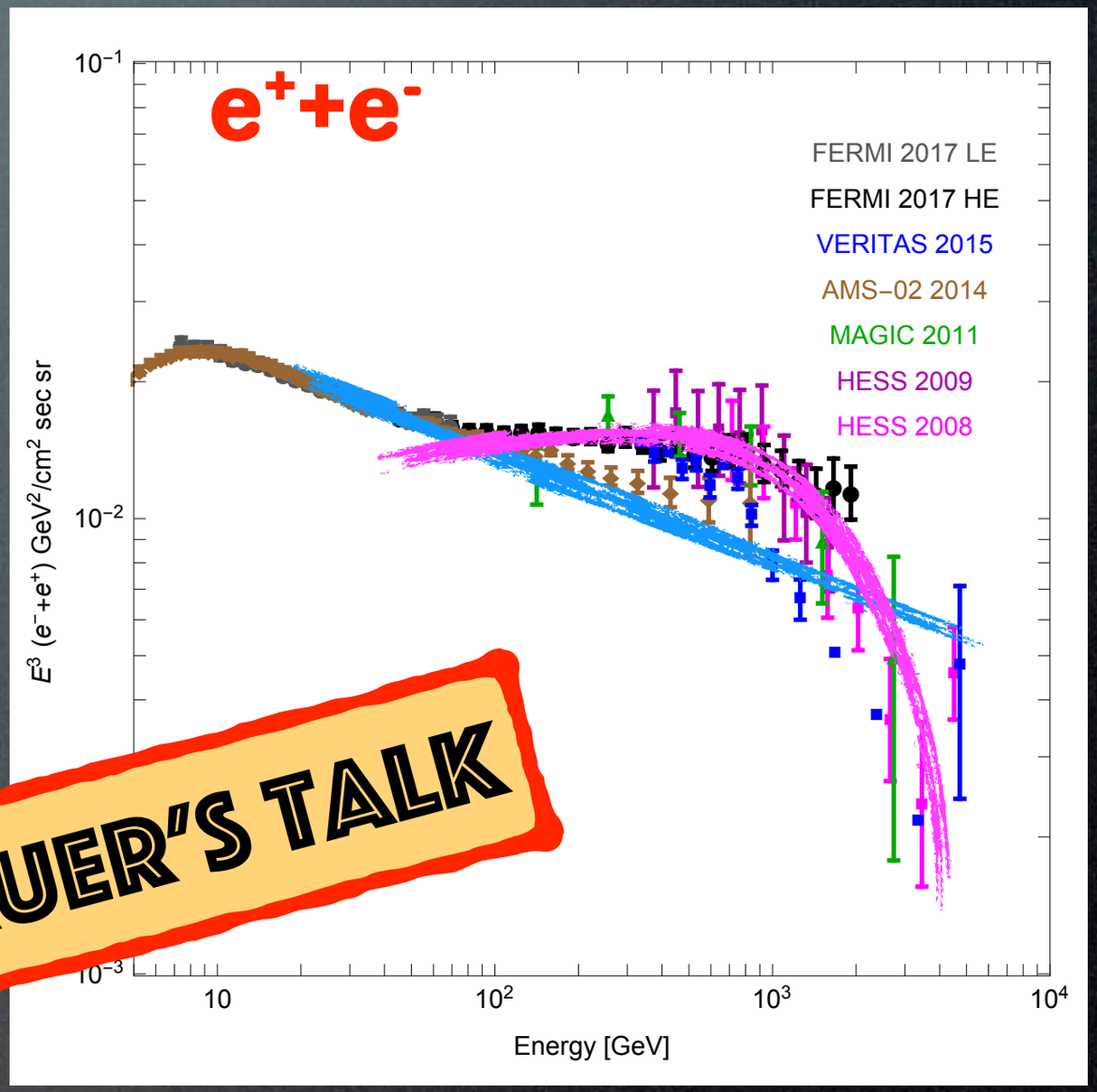




IRIS GEBAUER'S TALK

M. Cirelli - compilation ICRC 2015

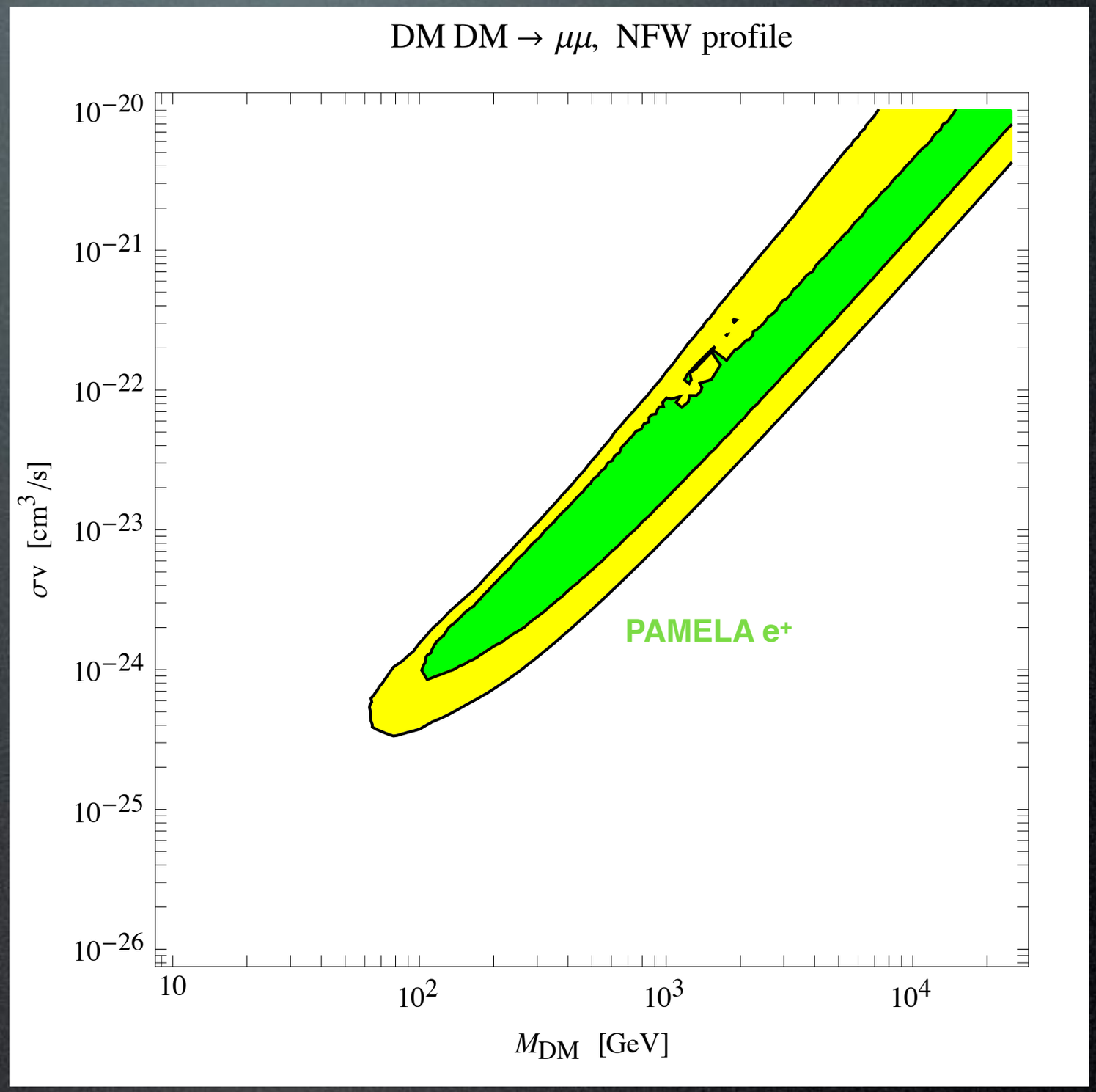
+ DAMPE coll. —> soon

Dark Matter interpretation

- leptophilic

- m_{DM} > few 100 GeV

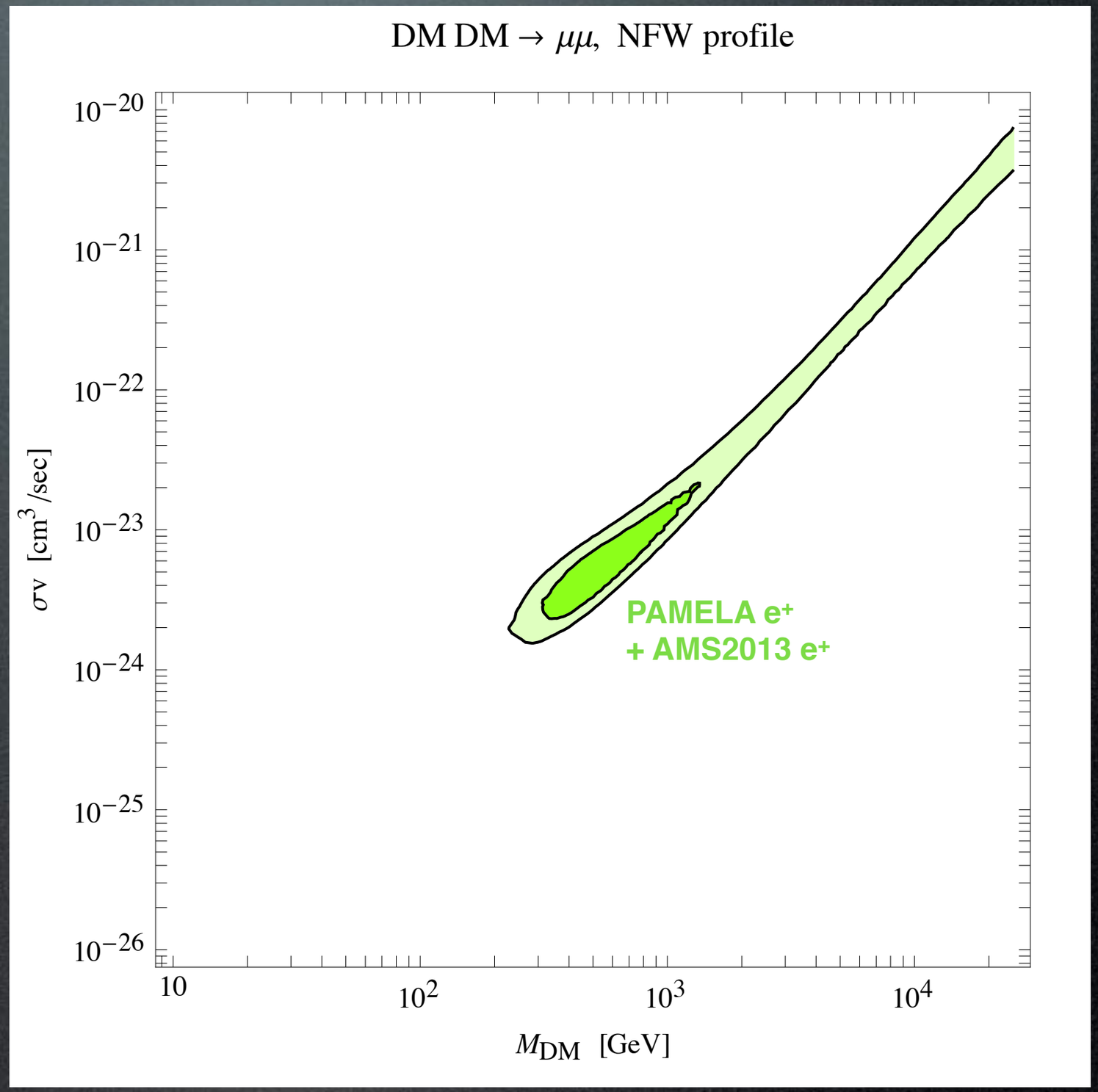
- huge annihilation cross section



M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

- leptophilic
- $m_{DM} \sim 1$ TeV
- huge annihilation cross section



M. Cirelli - compilation ICRC 2015

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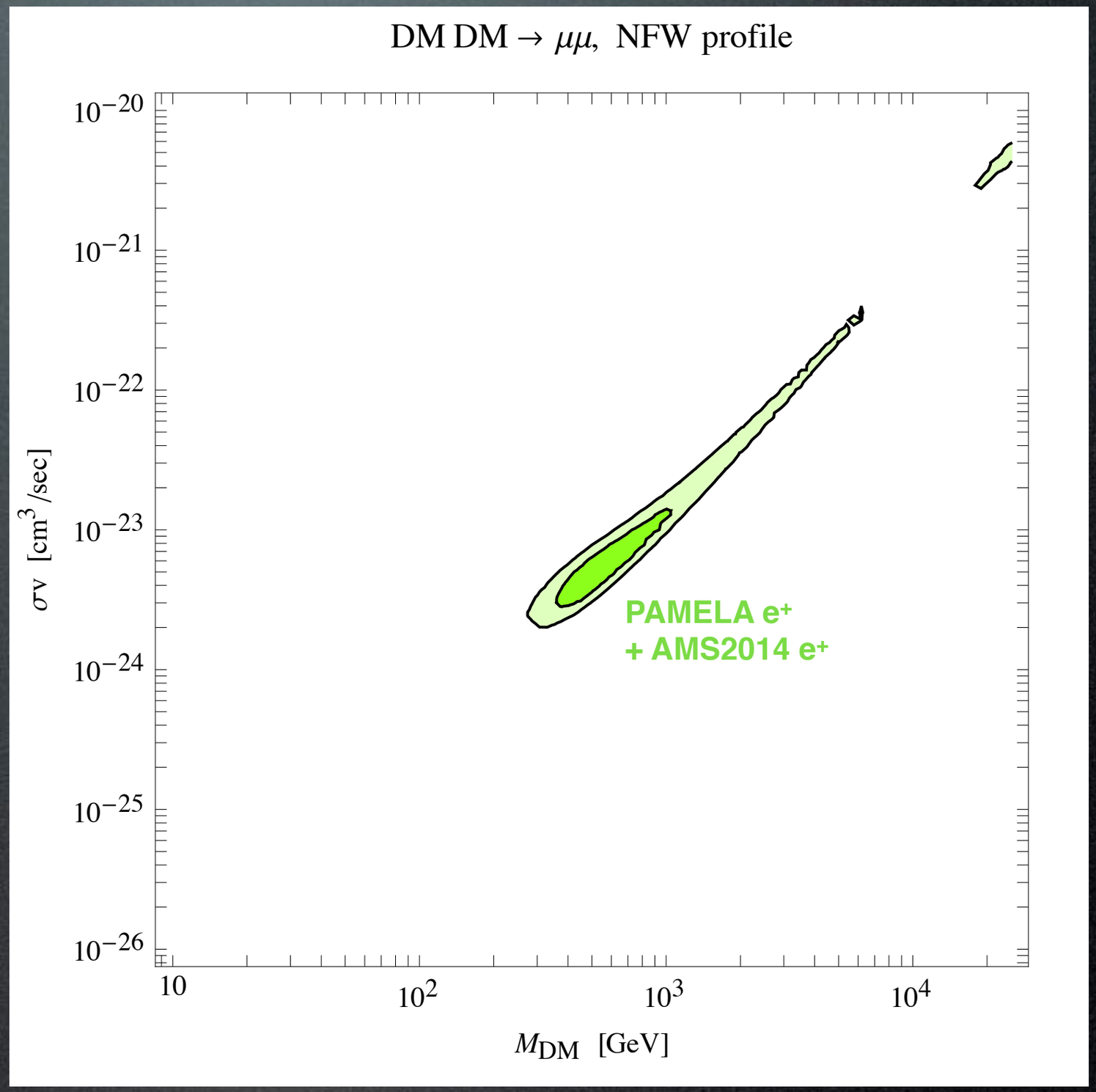

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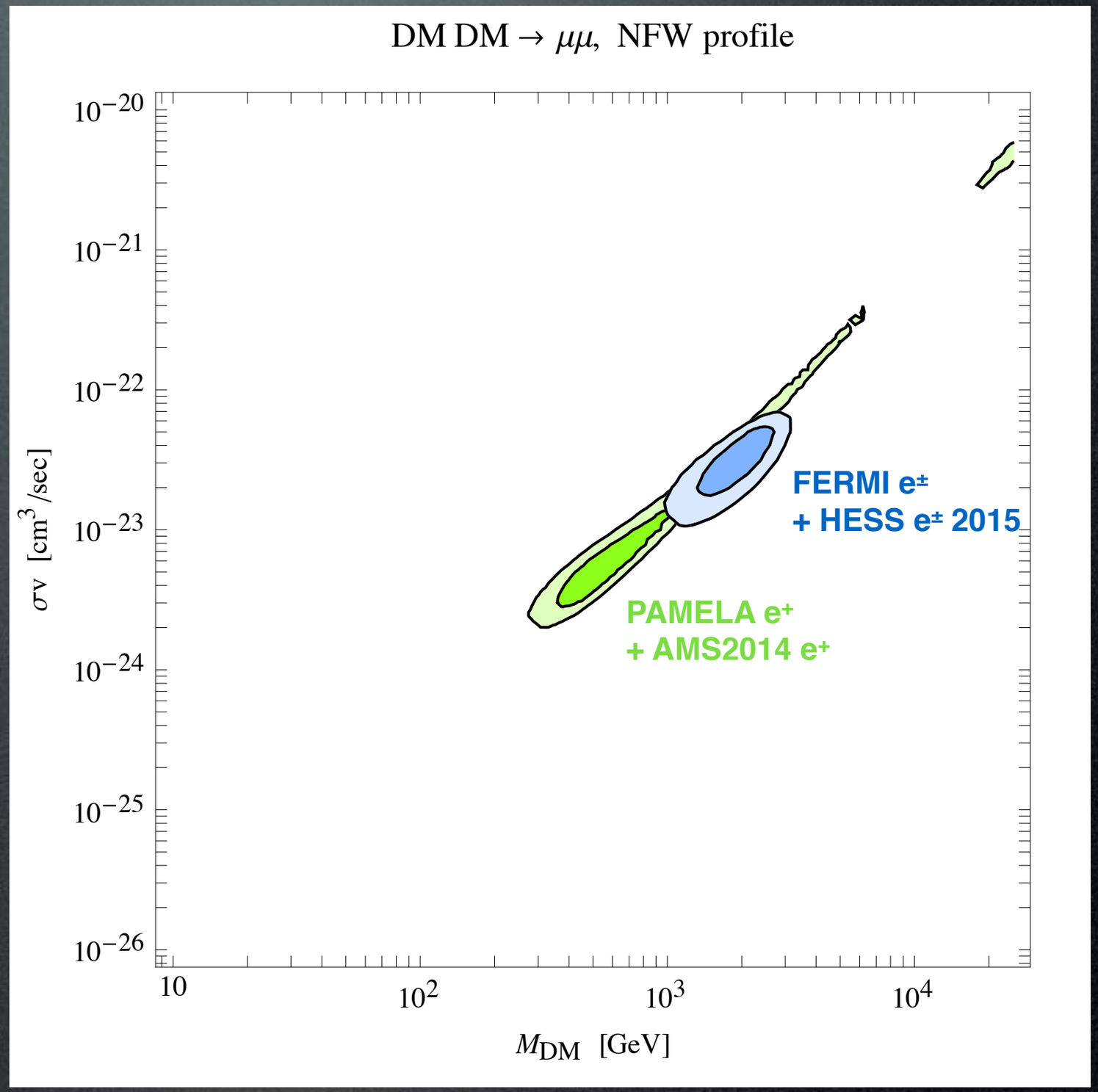

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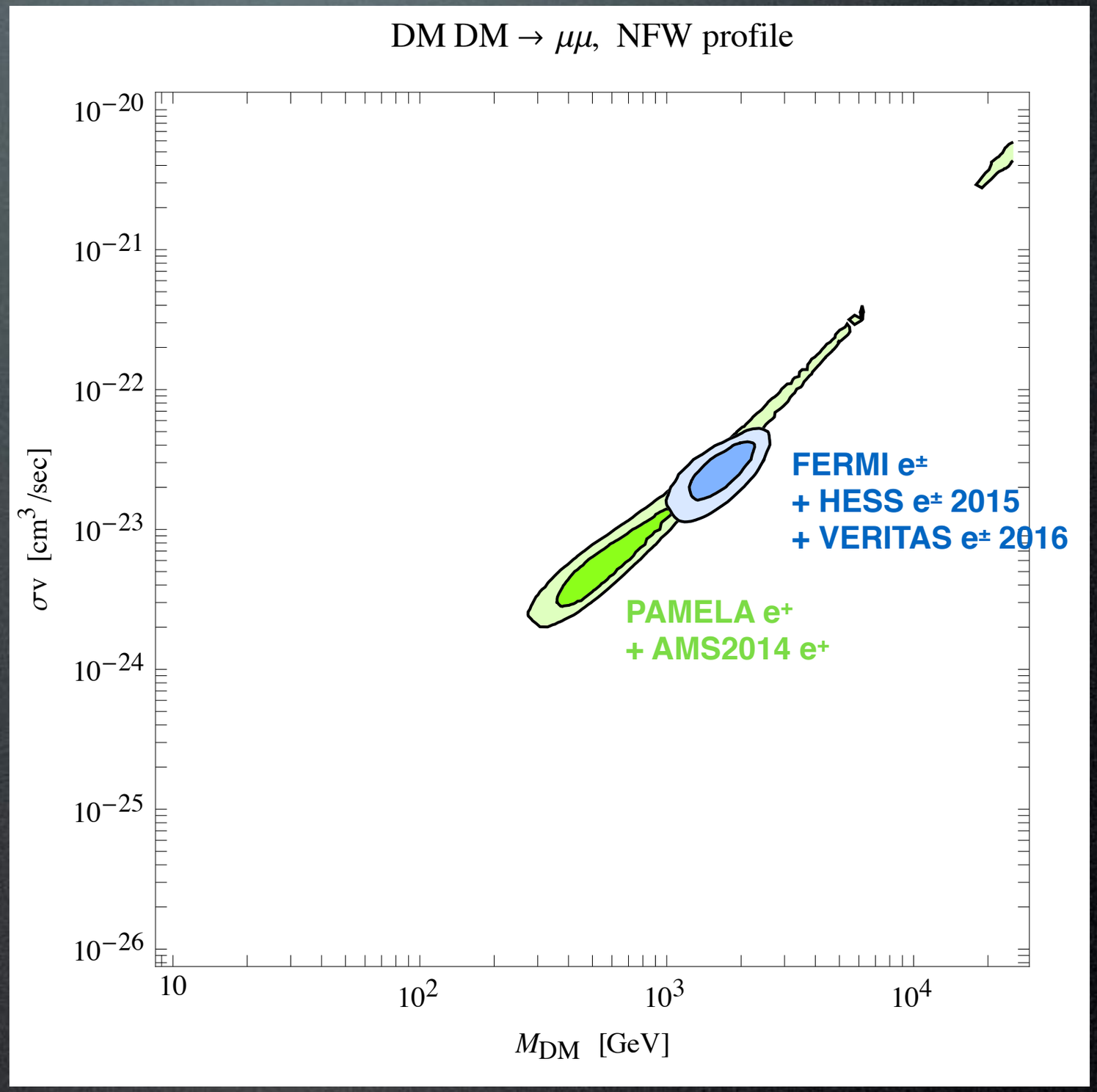

M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

However:

Dark Matter interpretation

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- increased precision brings increased tension

  "The improved accuracy of AMS-02 on the lepton flux now excludes channels previously allowed."

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Dark Matter interpretation

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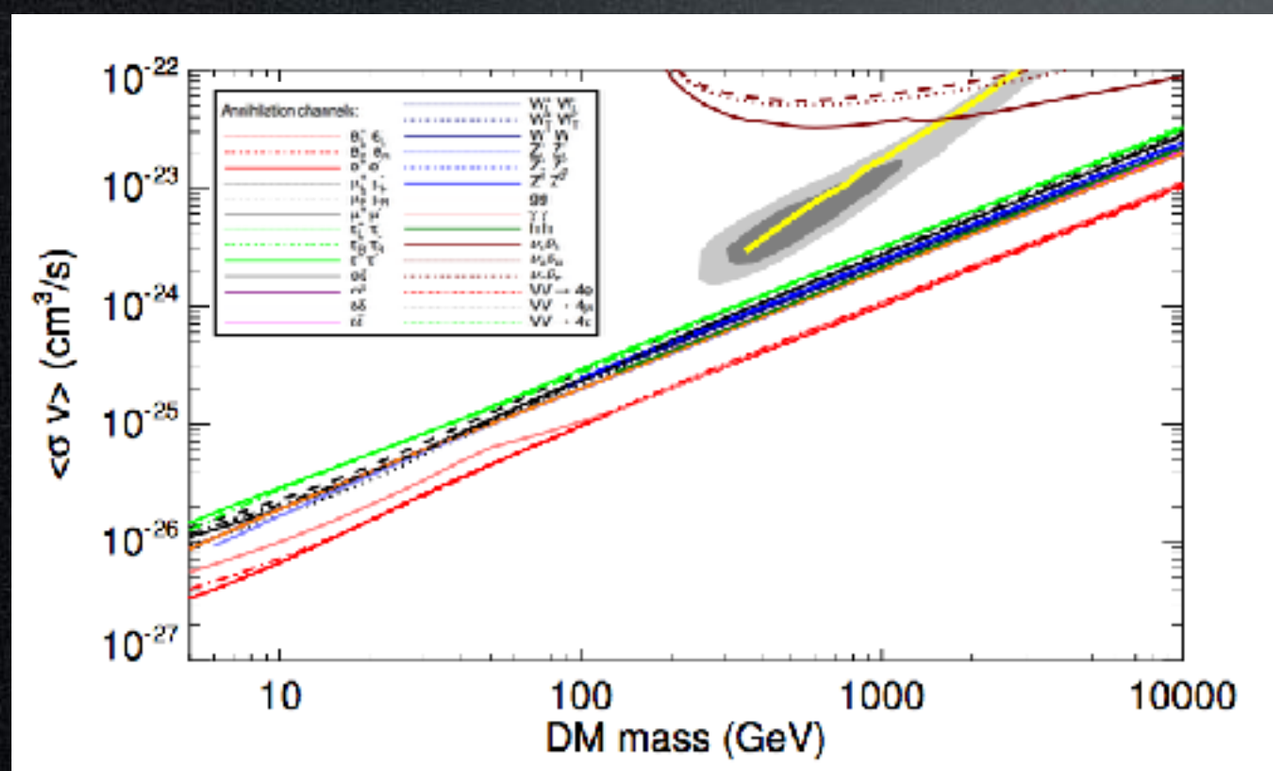
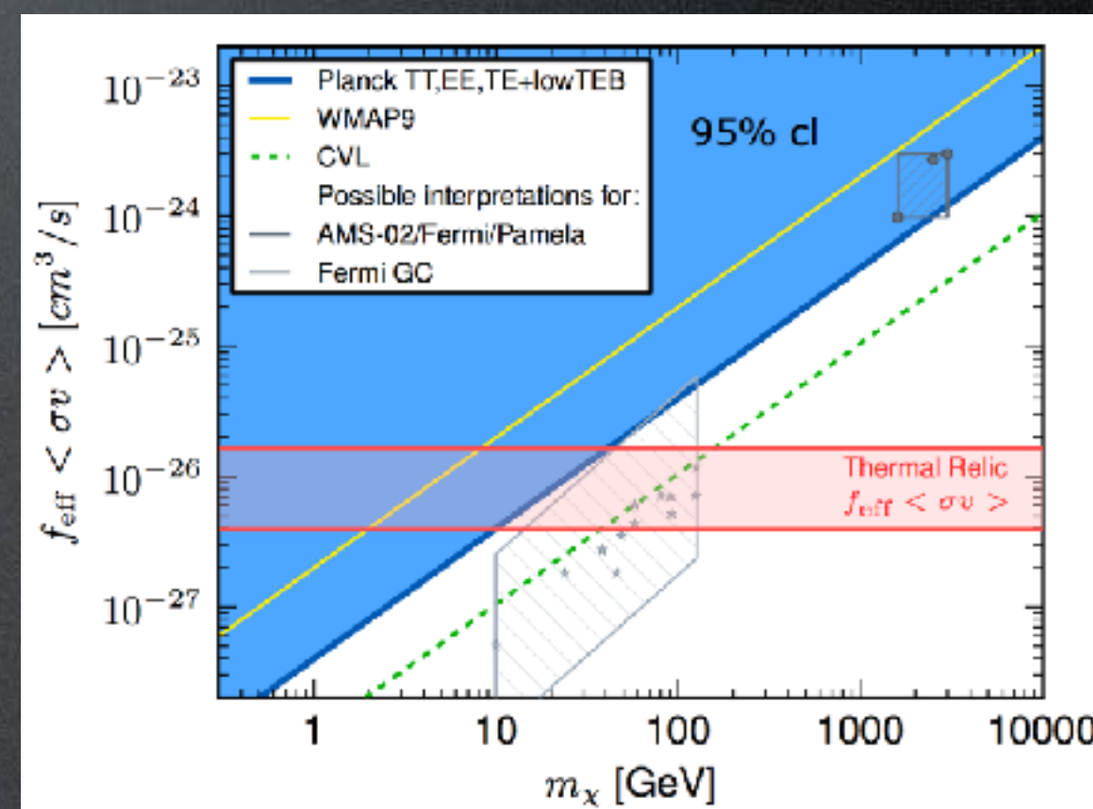
  "The improved accuracy of AMS-02 on the lepton flux now excludes channels previously allowed."

- combination of annihilation channels are possible

- constraints: gamma rays, neutrinos, CMB...

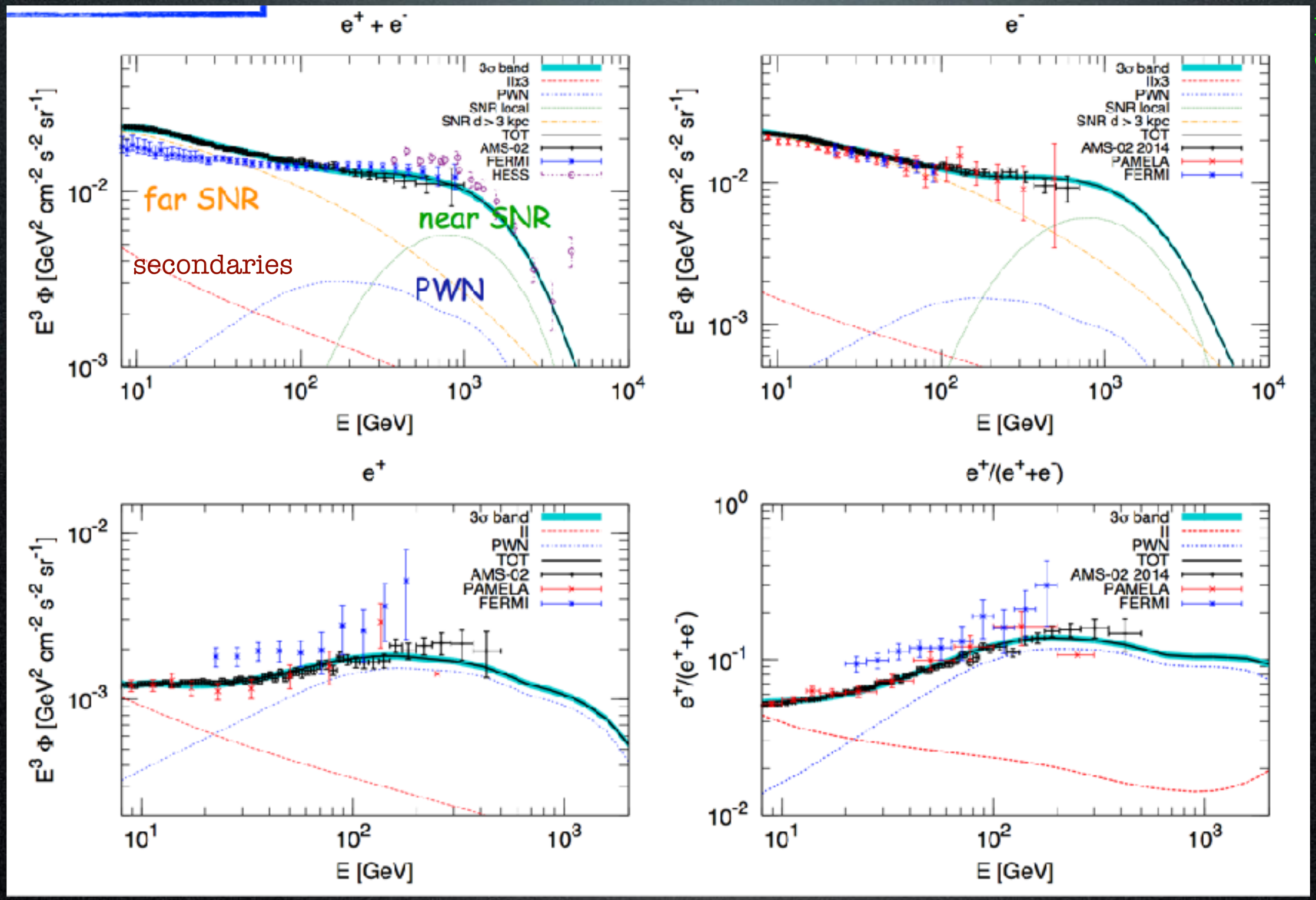


T.Slatyer 1506.03811



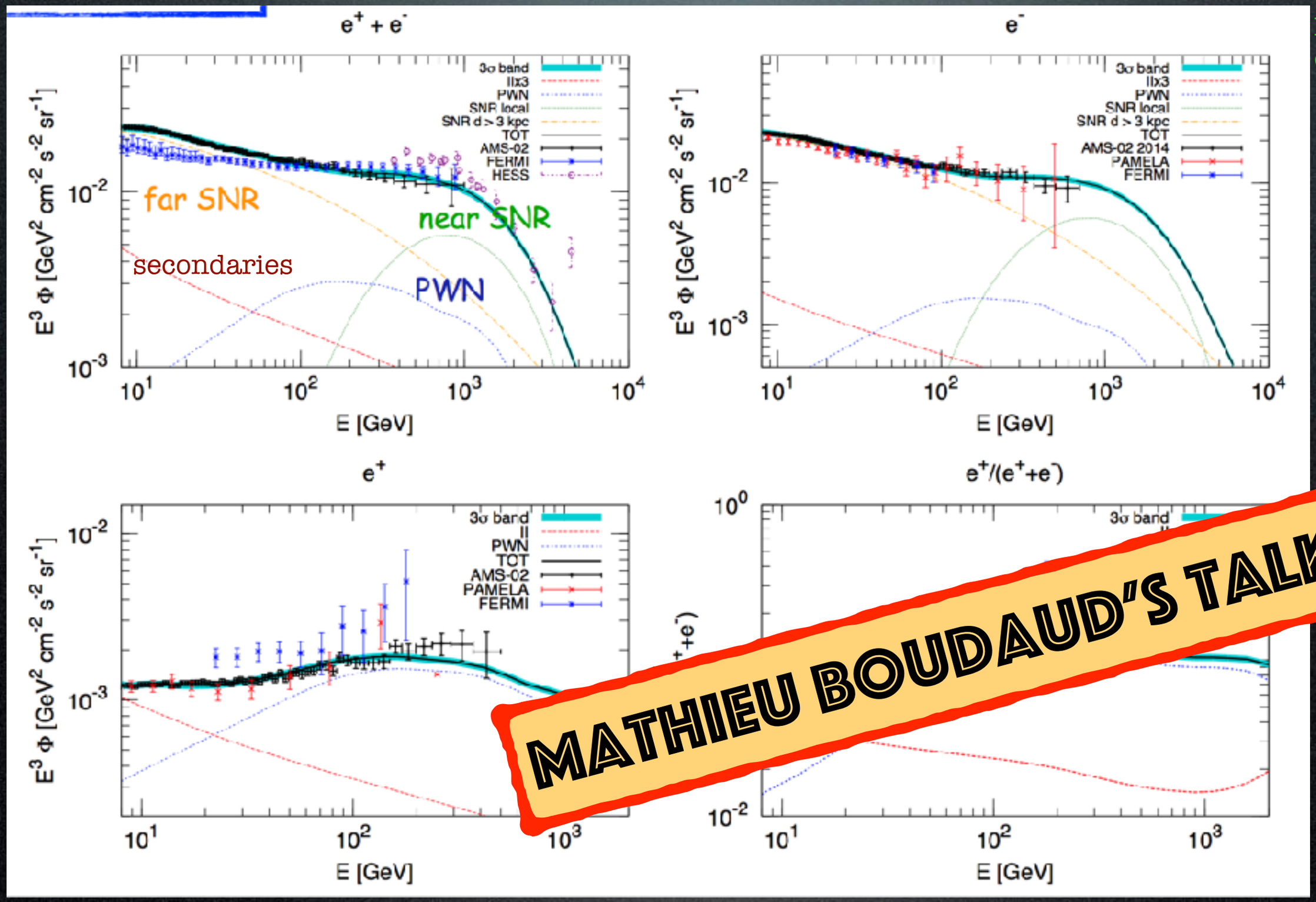
Planck 2015 (1502.01589)

Astro interpretation



M. Di Mauro et al. 1507.07001

Astro interpretation



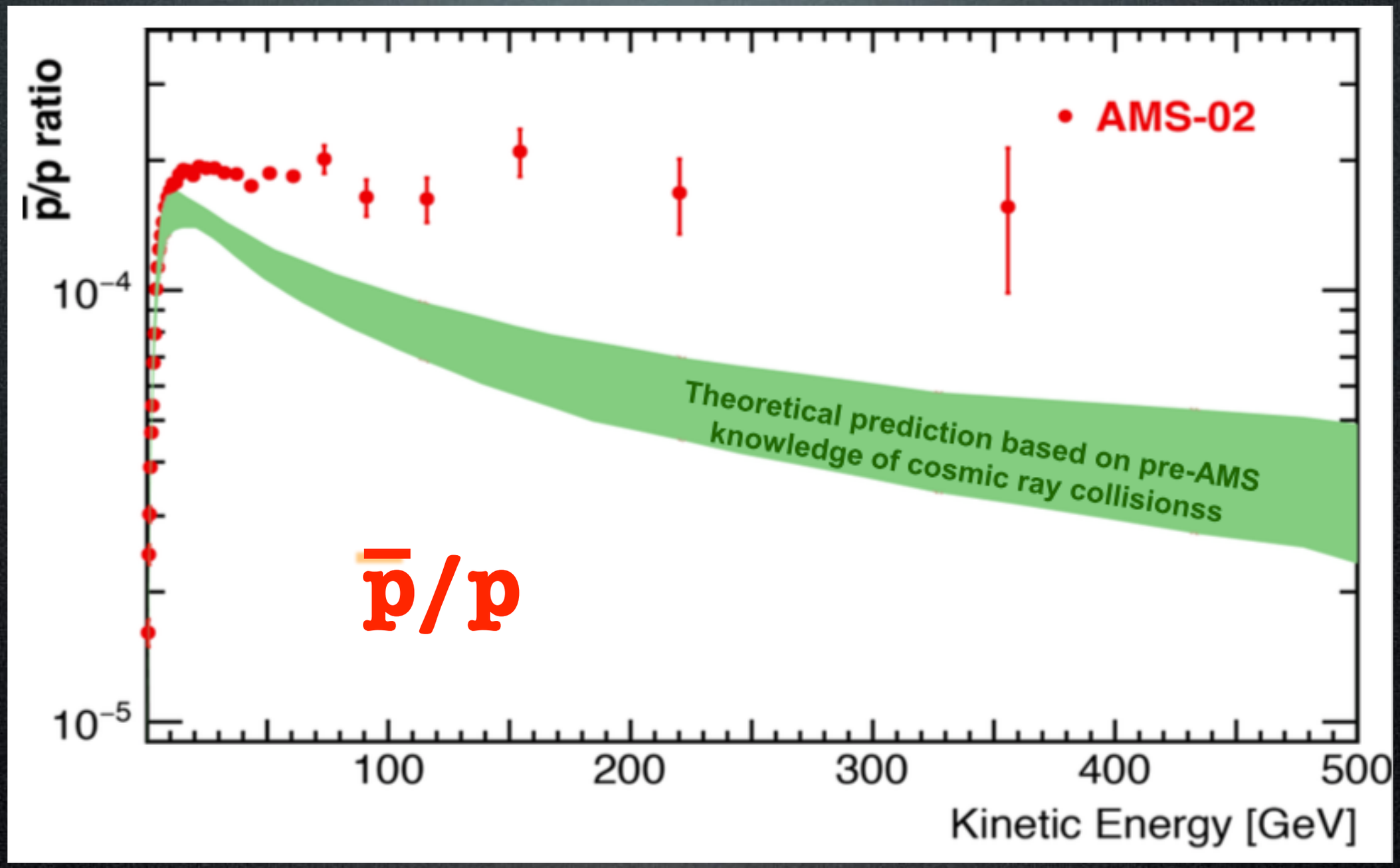
M. Di Mauro et al. 1507.07001

MATHIEU BOUDAUD'S TALK

Data

Data: antiprotons

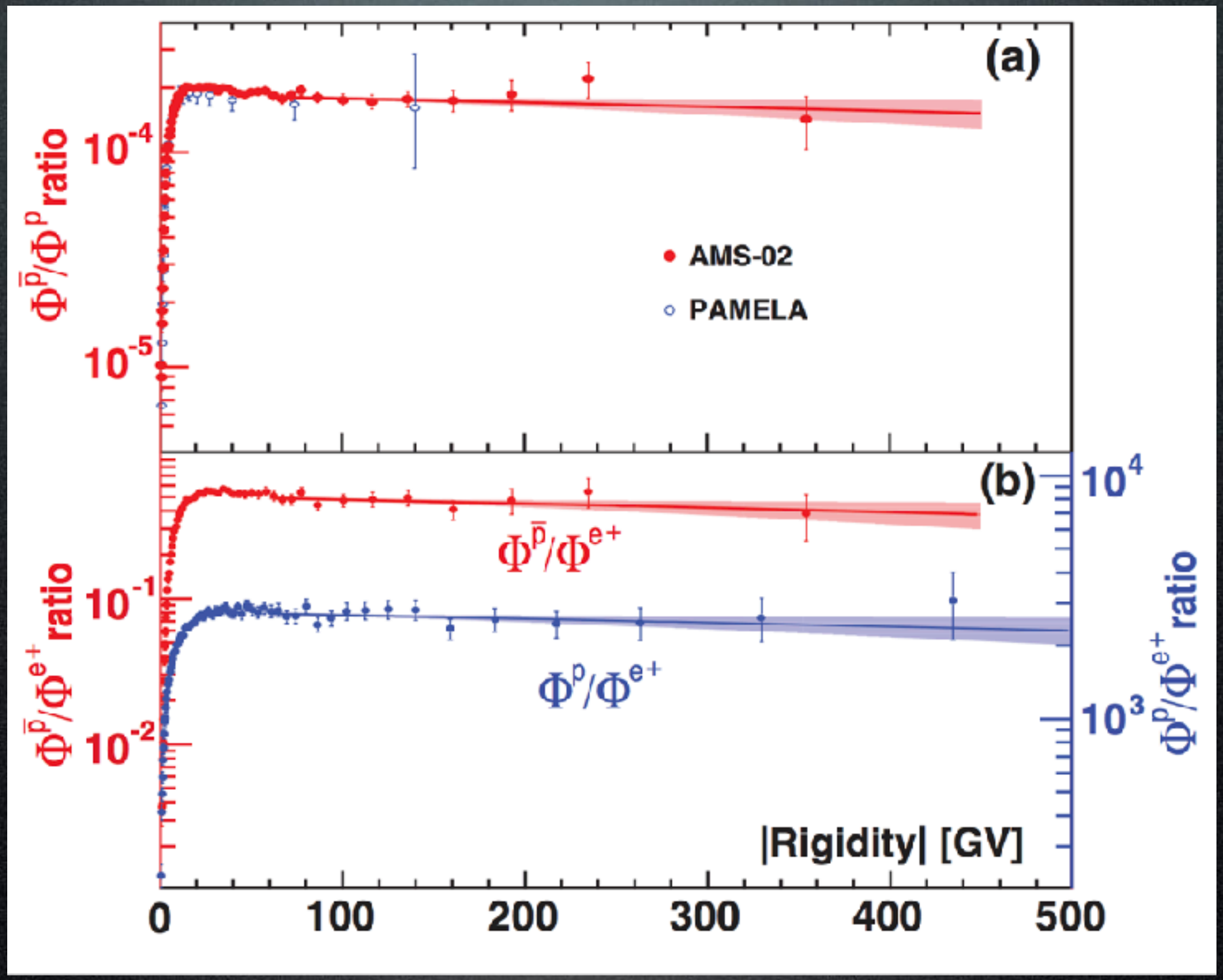
AMS-02



S. Ting - AMS days @ CERN apr 2015
A. Kounine - AMS days @ CERN apr 2015

Data: antiprotons

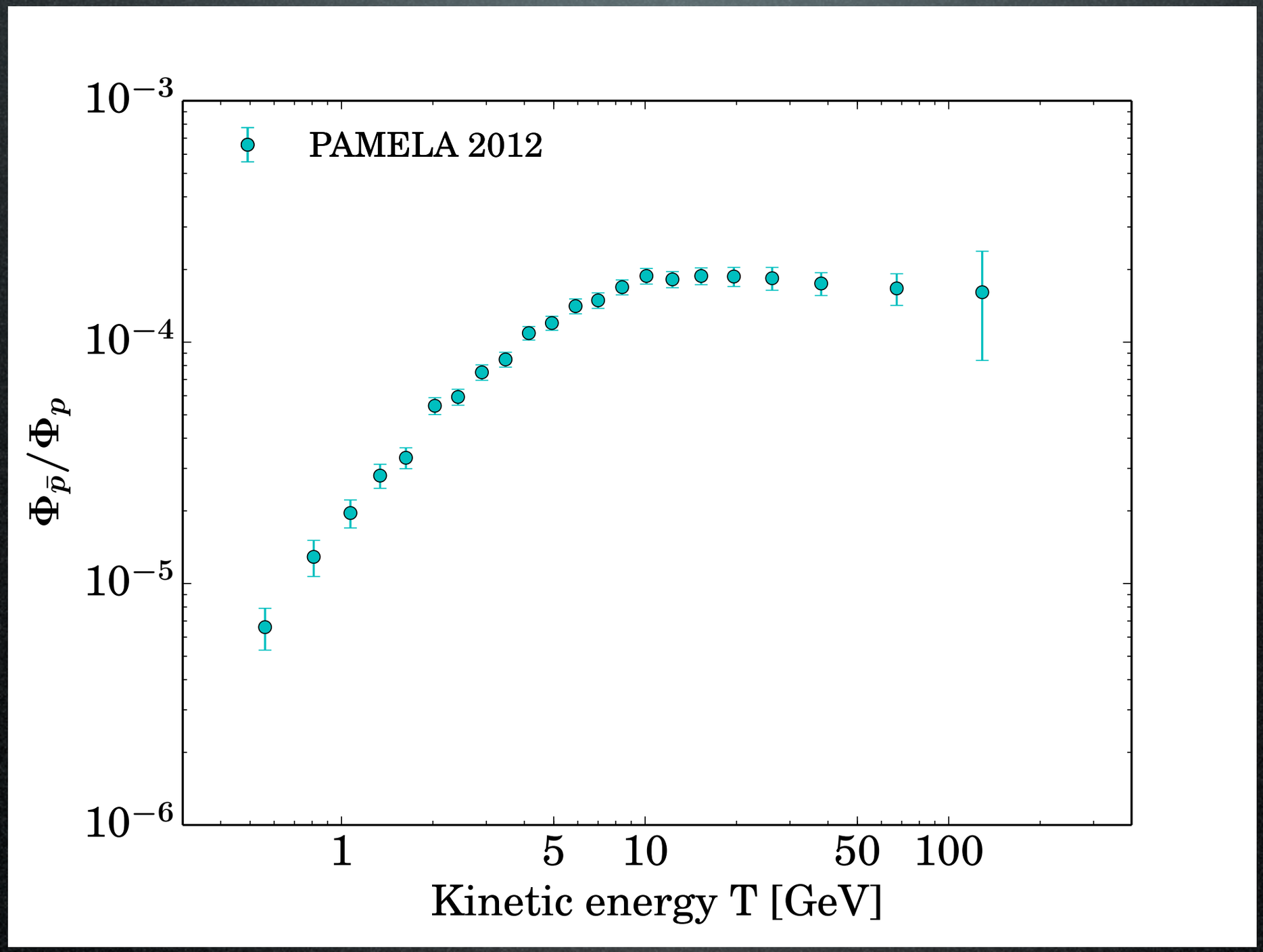
AMS-02



AMS coll.,PRL 117, 091103 (2016)

Antiprotons

Antiproton data vis-à-vis the secondaries:



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

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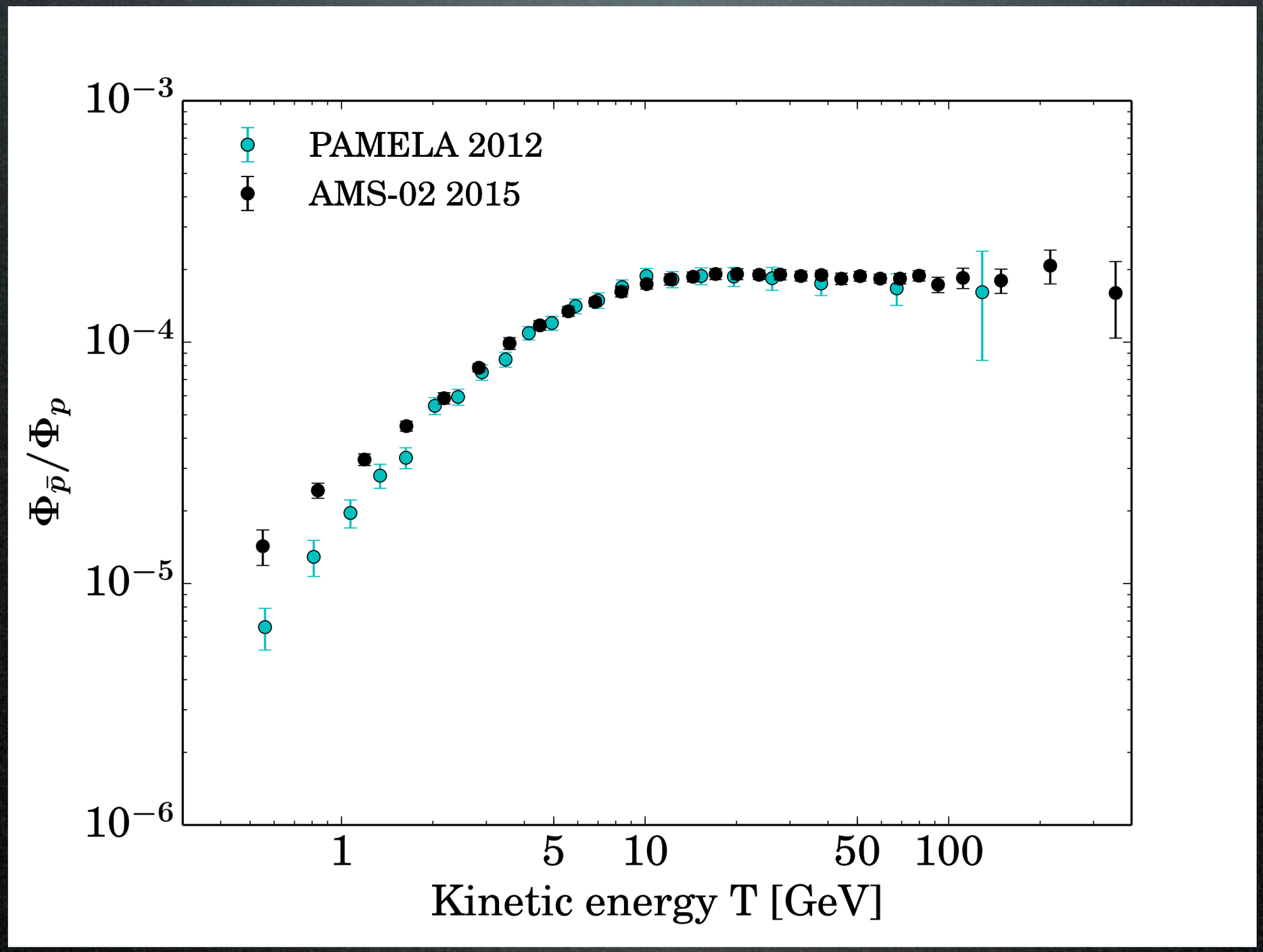

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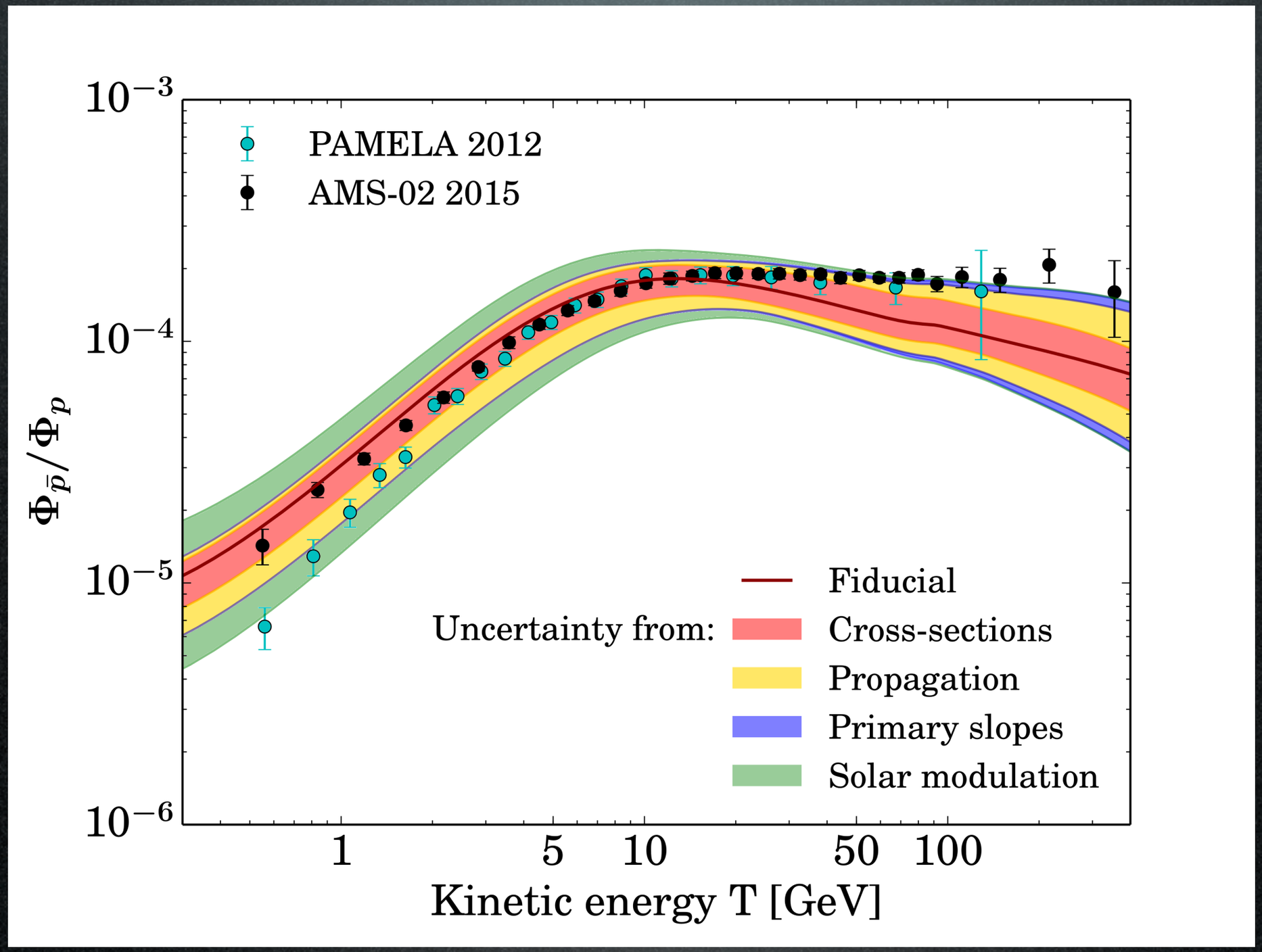

Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico
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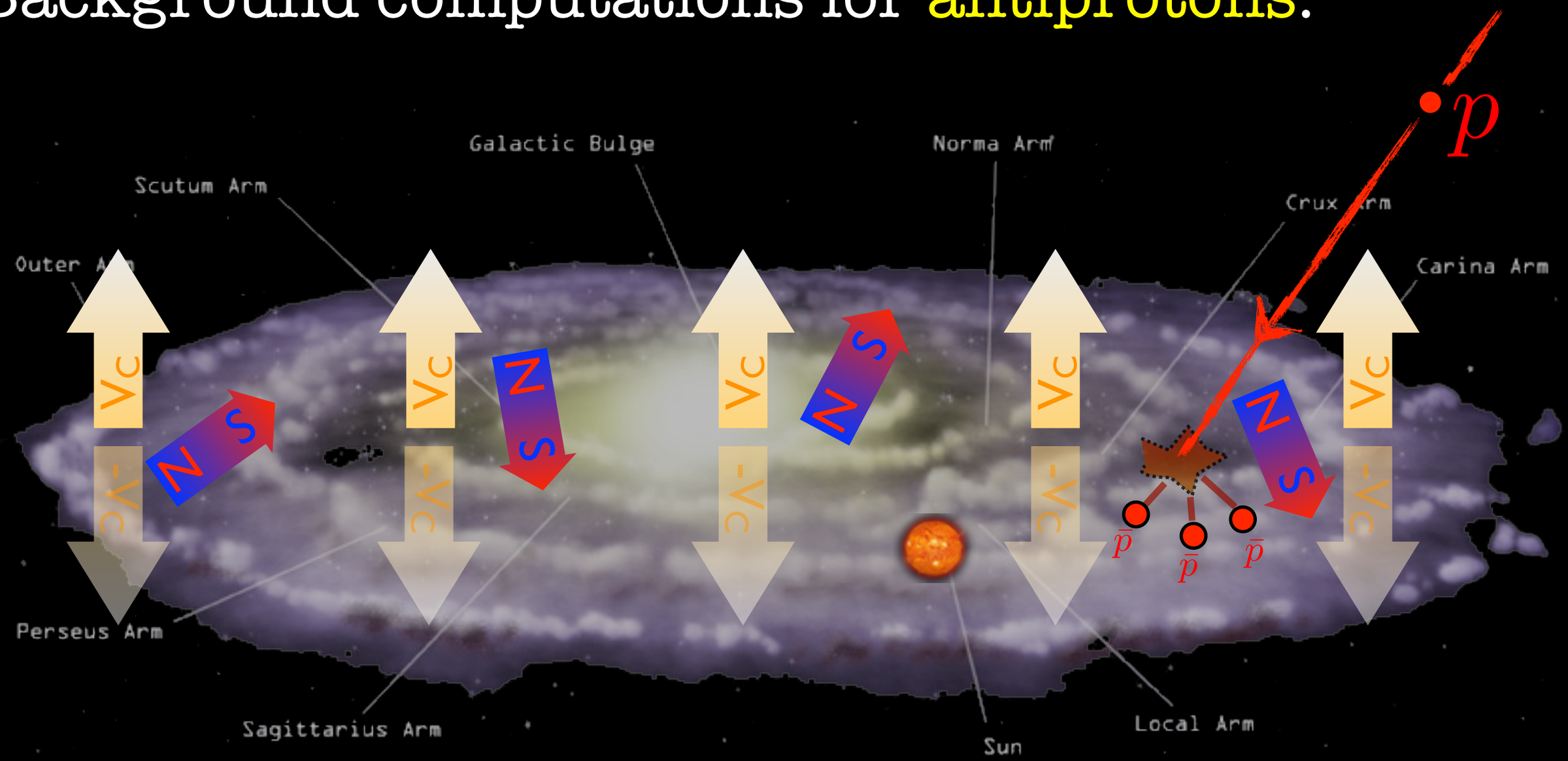
Indirect Detection

Background computations for antiprotons:



Indirect Detection

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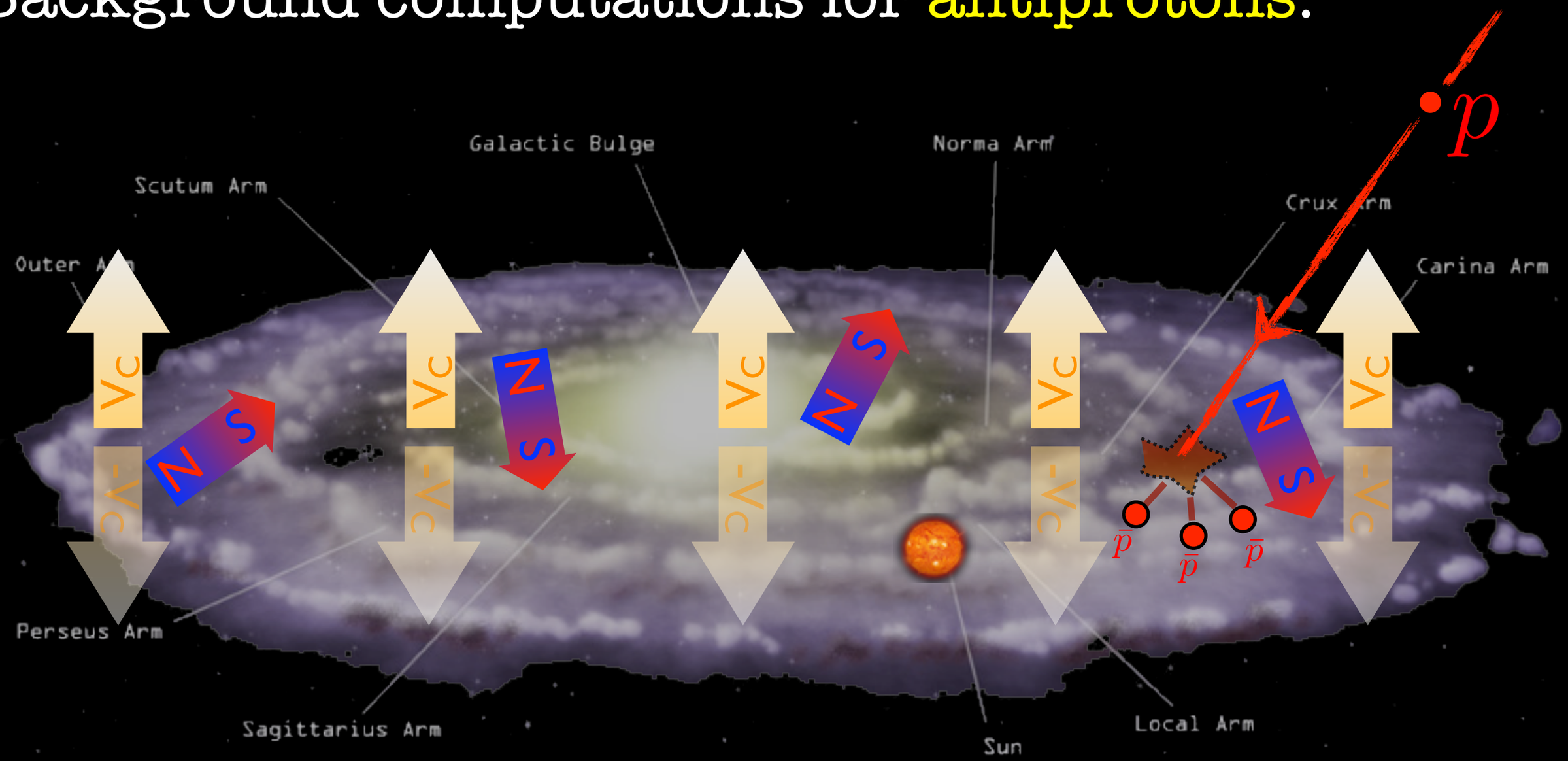

Main ingredients:

- primary p (and He)
- spallation cross-sections $\sigma_{p\mathrm{H}\to\bar{p}\mathrm{X}}$, $\sigma_{p\mathrm{He}\to\bar{p}\mathrm{X}}$, $\sigma_{\mathrm{He}\mathrm{H}\to\bar{p}\mathrm{X}}$, $\sigma_{\mathrm{He}\mathrm{He}\to\bar{p}\mathrm{X}}$
- propagation
- solar modulation

Indirect Detection

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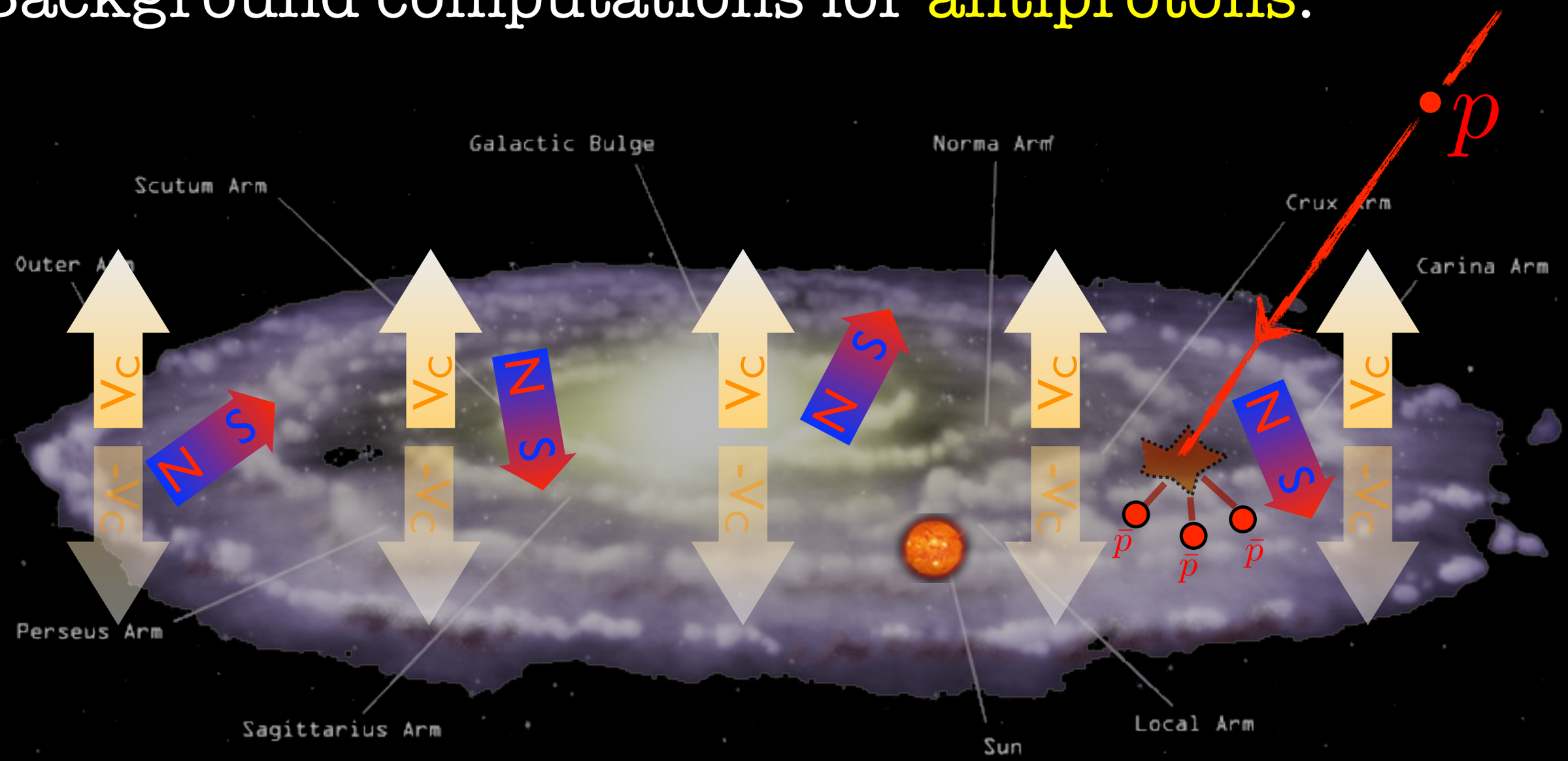

Main ingredients:

- primary p (and He) **New!**
- spallation cross-sections $\sigma_{p\mathrm{H}\to\bar{p}\mathrm{X}}$, $\sigma_{p\mathrm{He}\to\bar{p}\mathrm{X}}$, $\sigma_{\mathrm{He}\mathrm{H}\to\bar{p}\mathrm{X}}$, $\sigma_{\mathrm{He}\mathrm{He}\to\bar{p}\mathrm{X}}$ **New!**
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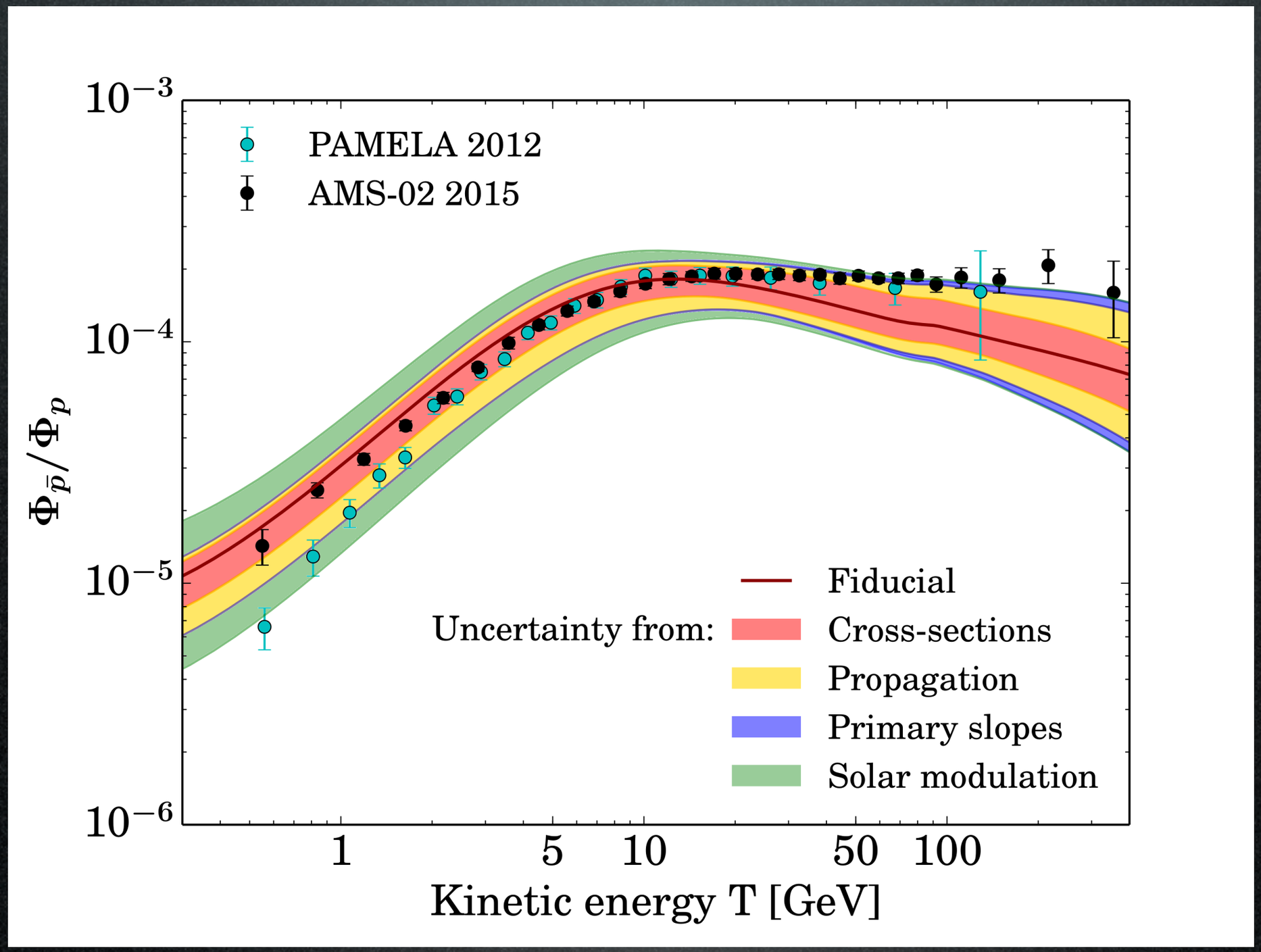
Antiprotons

Antiproton data vis-à-vis the secondaries:



No evident **excess**

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

Antiprotons

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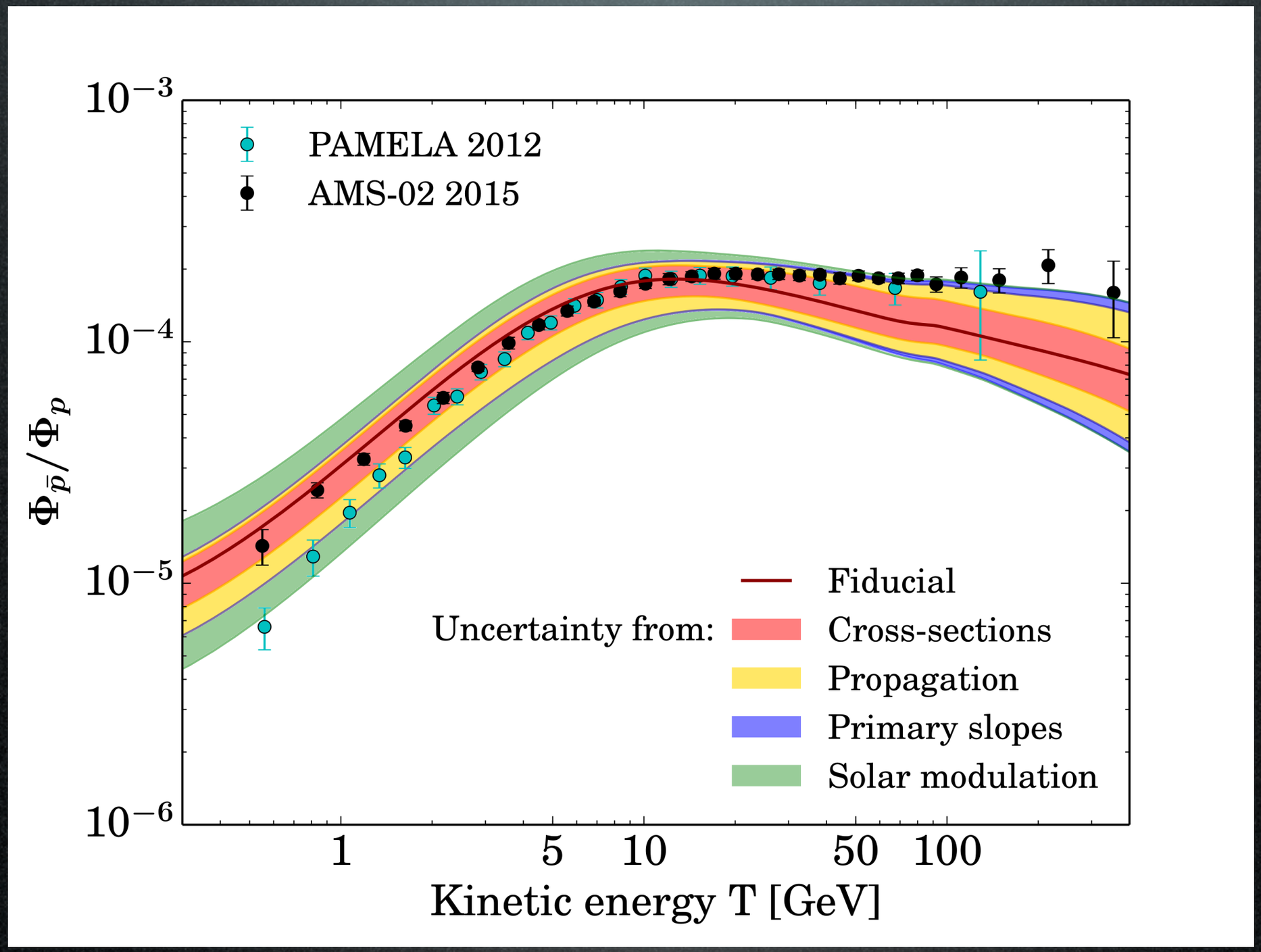

No evident **excess**

Some preference for flatness

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

Antiprotons

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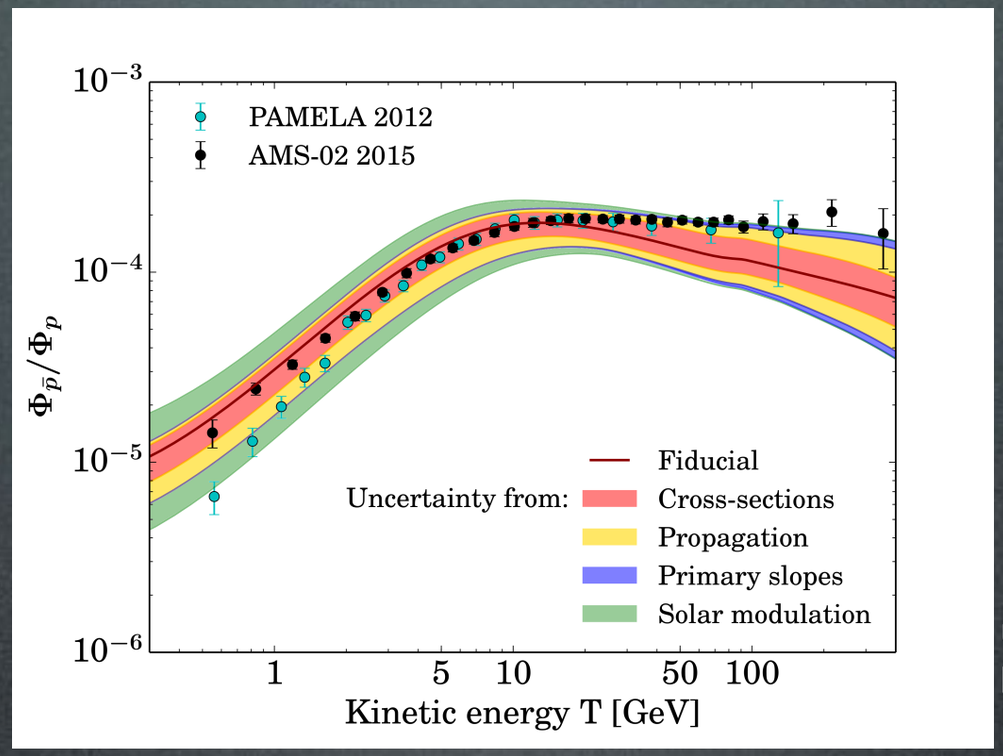
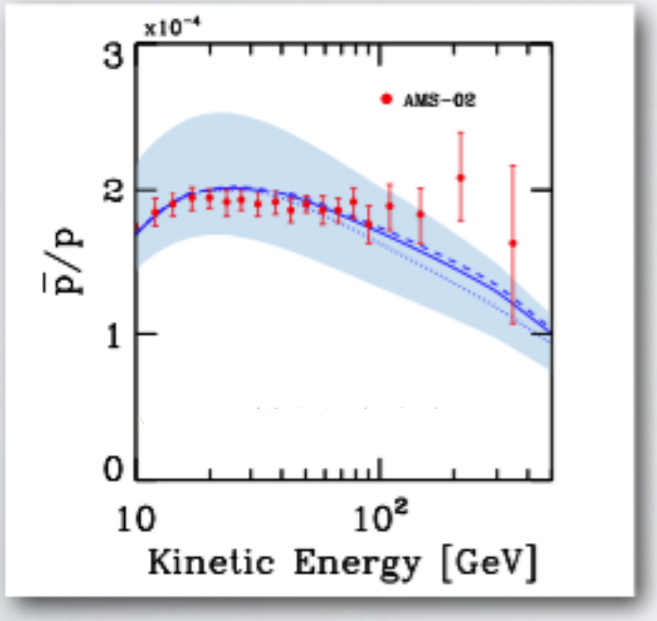


Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico 1504.04276

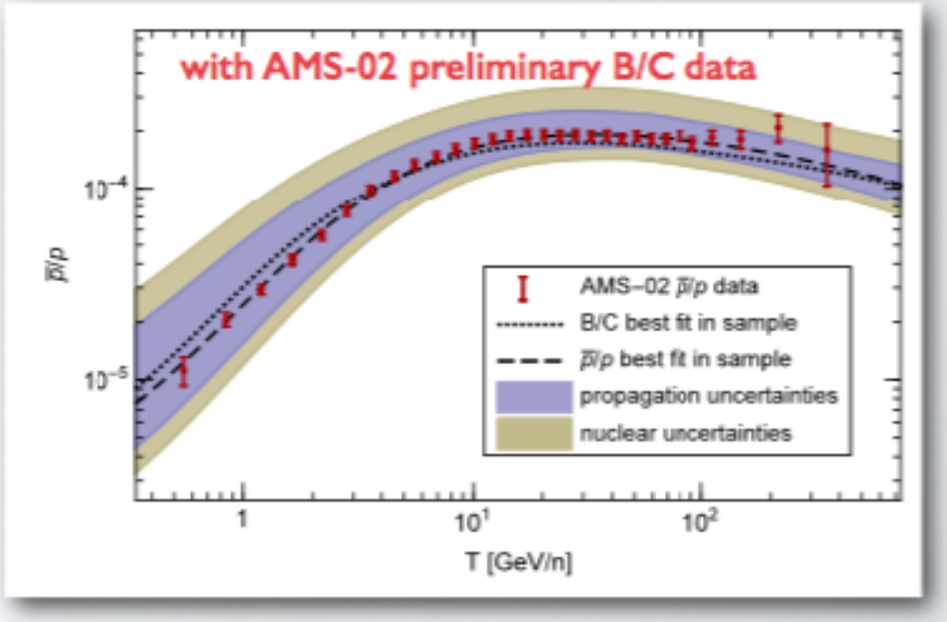
using
p, He by AMS-02,
B/C by PAMELA

C. Evoli, D. Gaggero and D. Grasso, arXiv:1504.05175



using
p, He, B/C
by AMS-02

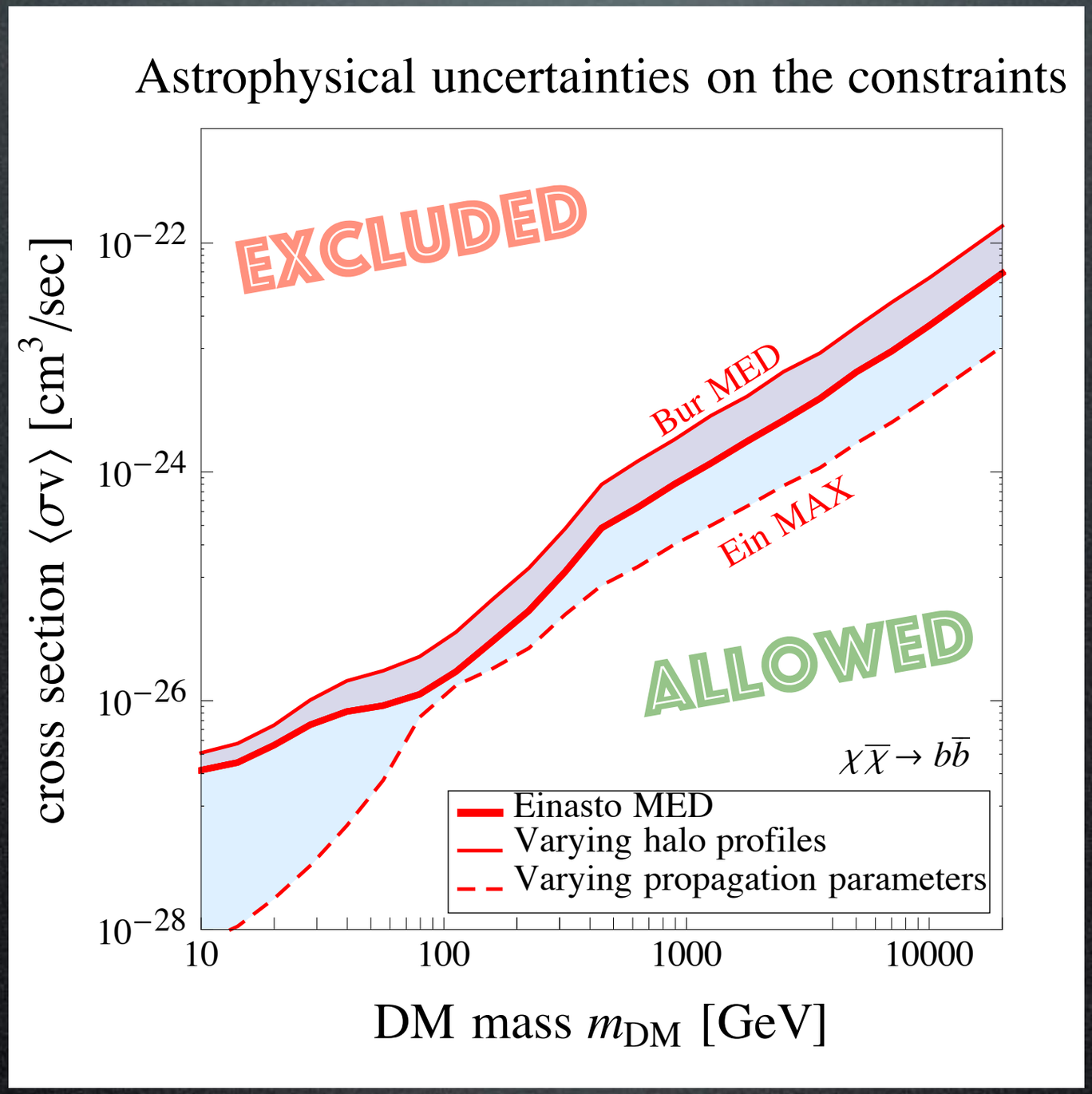
R. Kappl, A. Reinert and M.W. Winkler, arXiv:1506.04145



using
p, He by AMS-02 and CREAM,
B/C by AMS-02,
heavier nuclei by compilation

Dark Matter interpretation

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

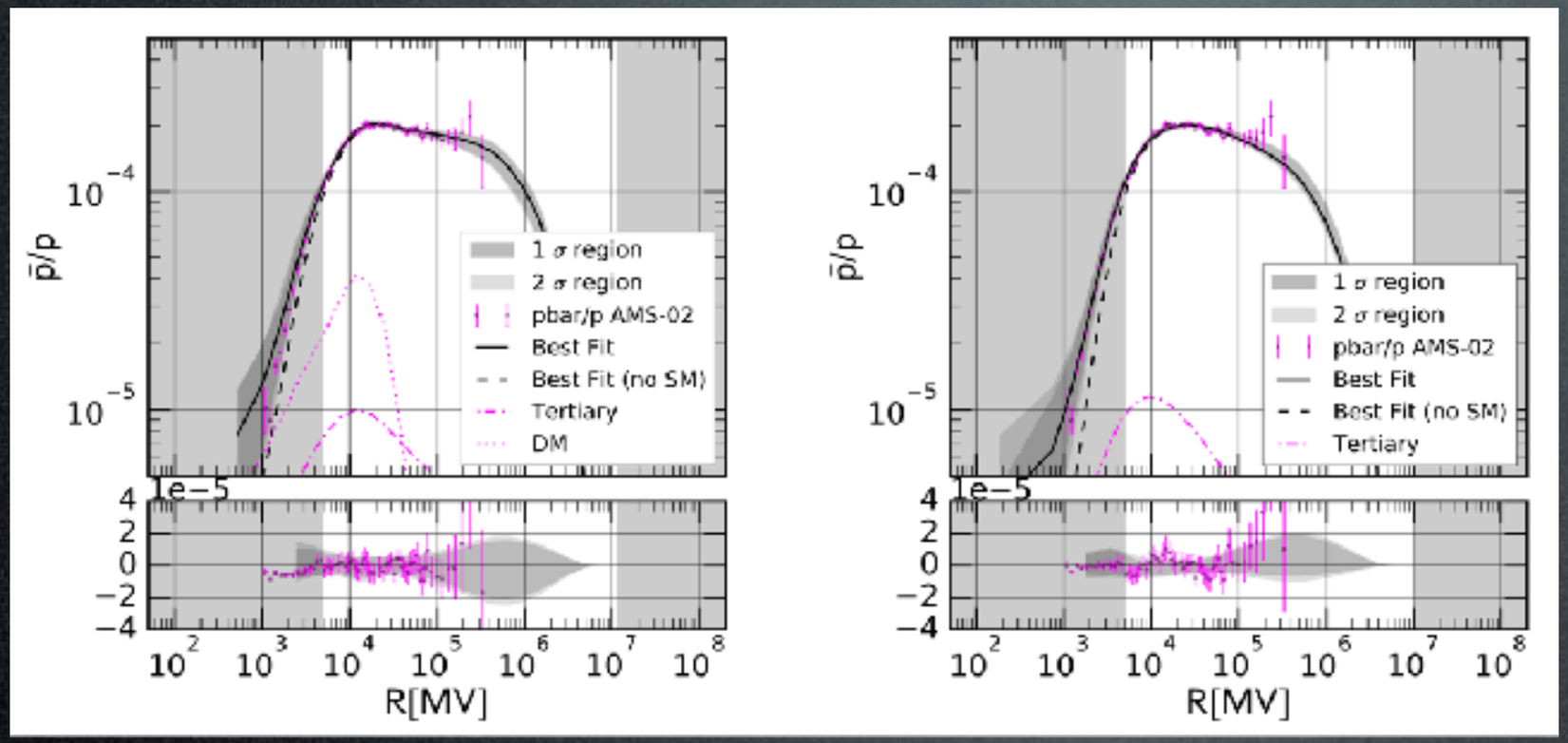


Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



finds a possible excess

(formally ~4.5σ)

m_{DM} = 80 GeV, bb, thermal cross-section

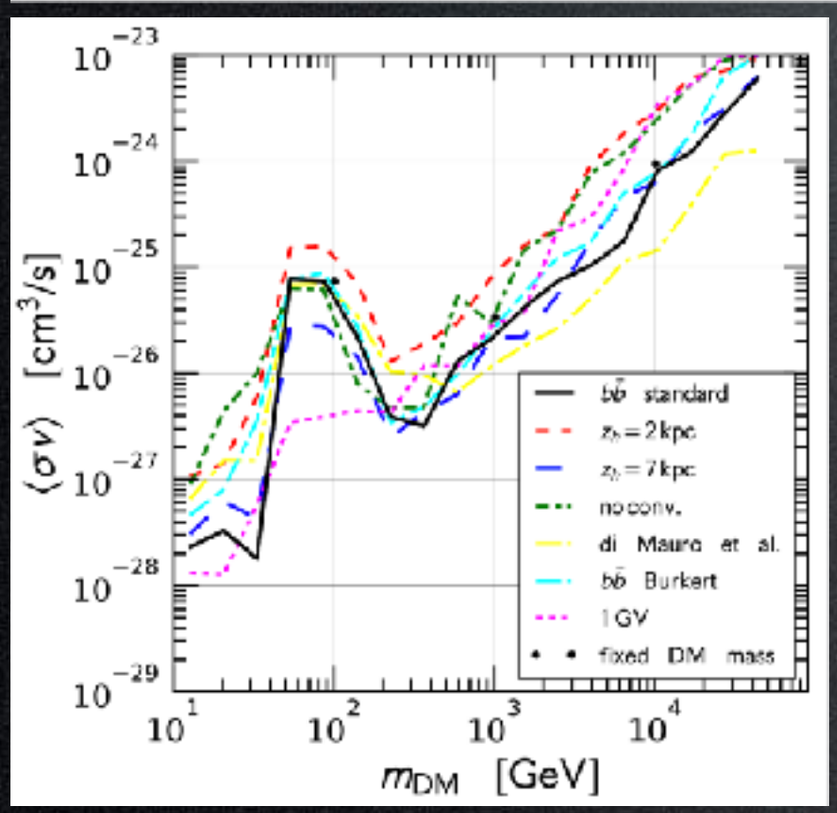
similarly:

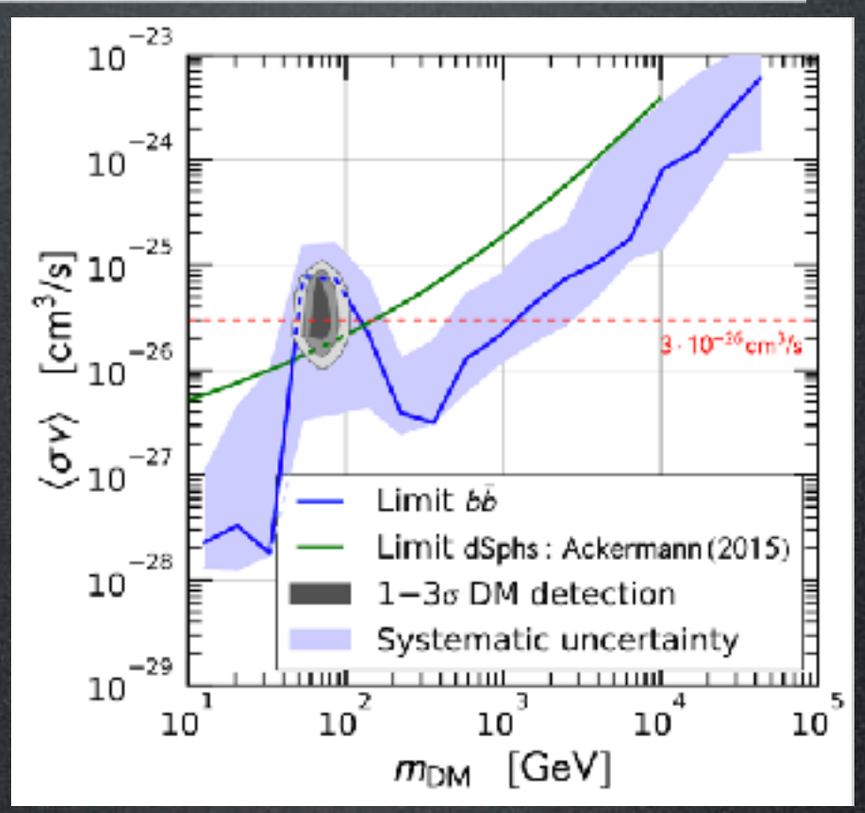
Cui, Yuan, Tsai, Fang 1610.03840

Huang, Wei, Wu, Zhang, Zhou 1611.01983

(light mediators)

Feng, Zhang 1701.02263





Antiprotons

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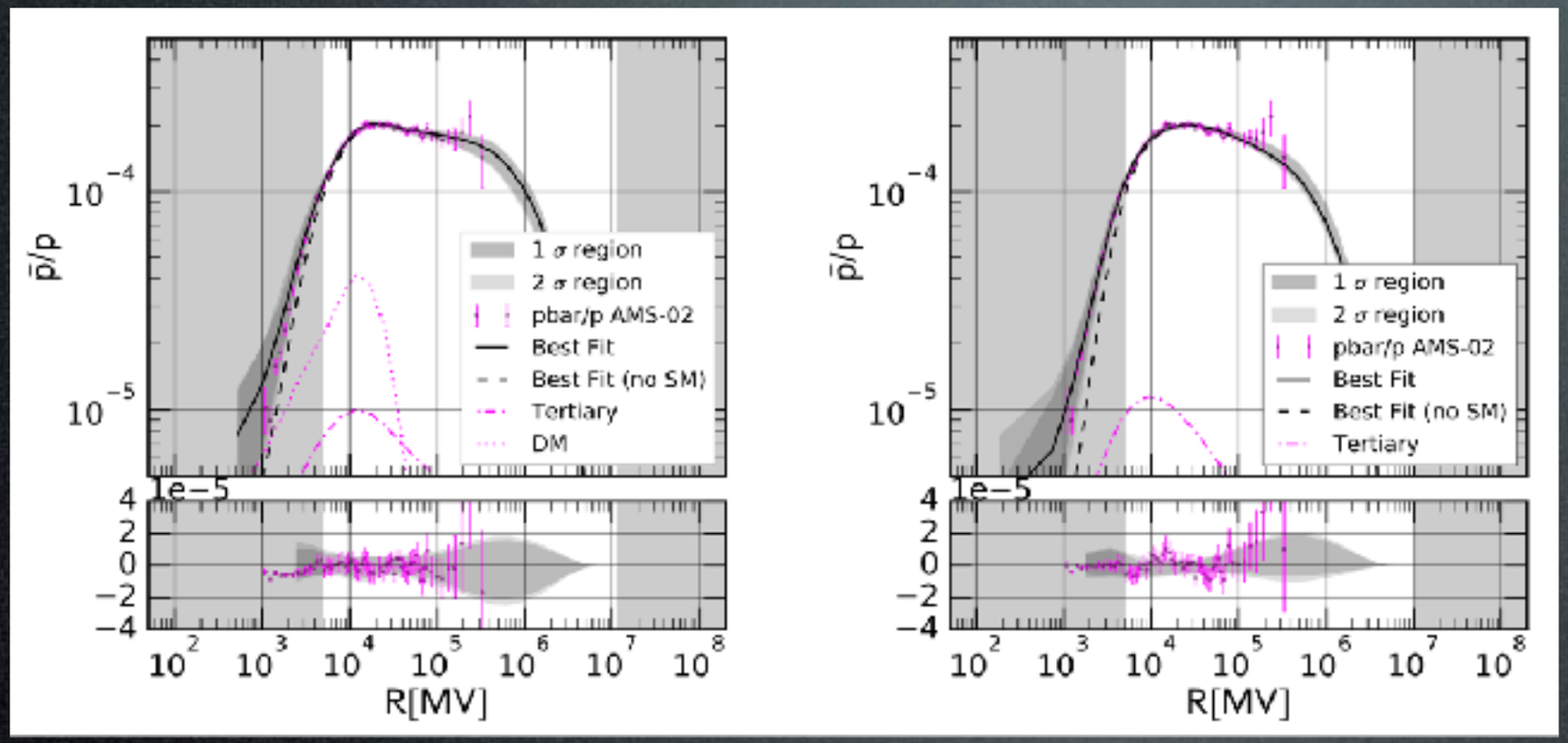

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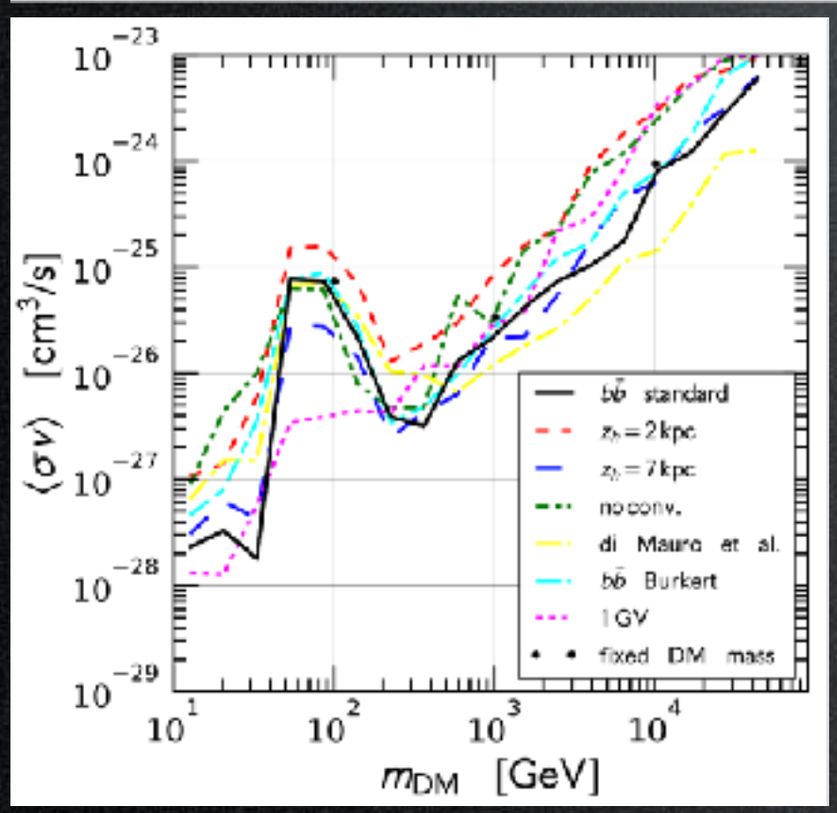
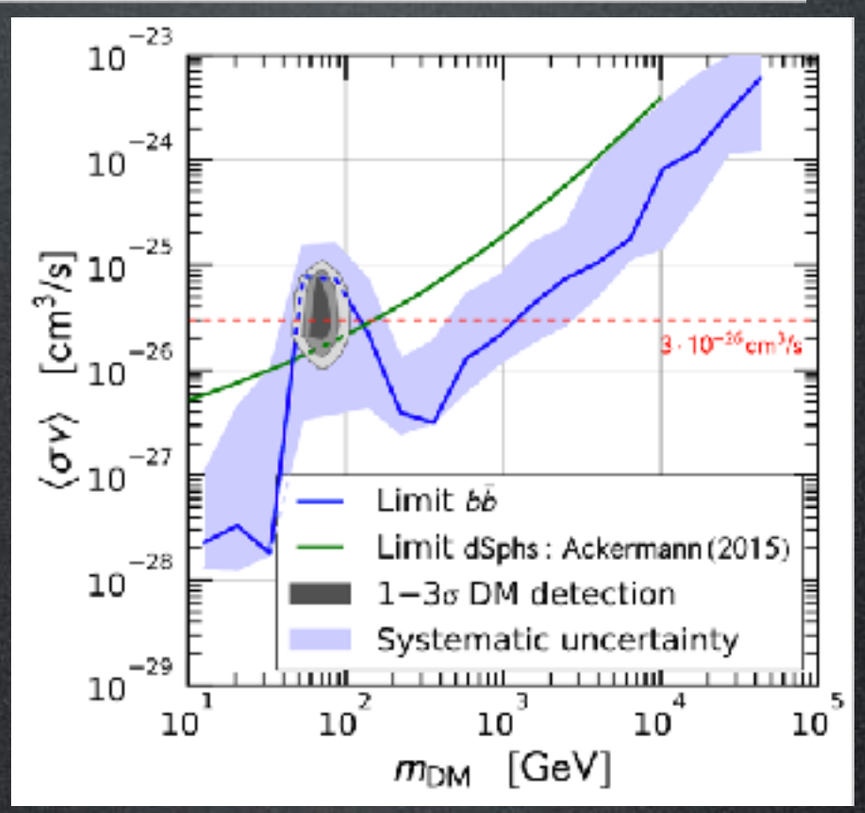




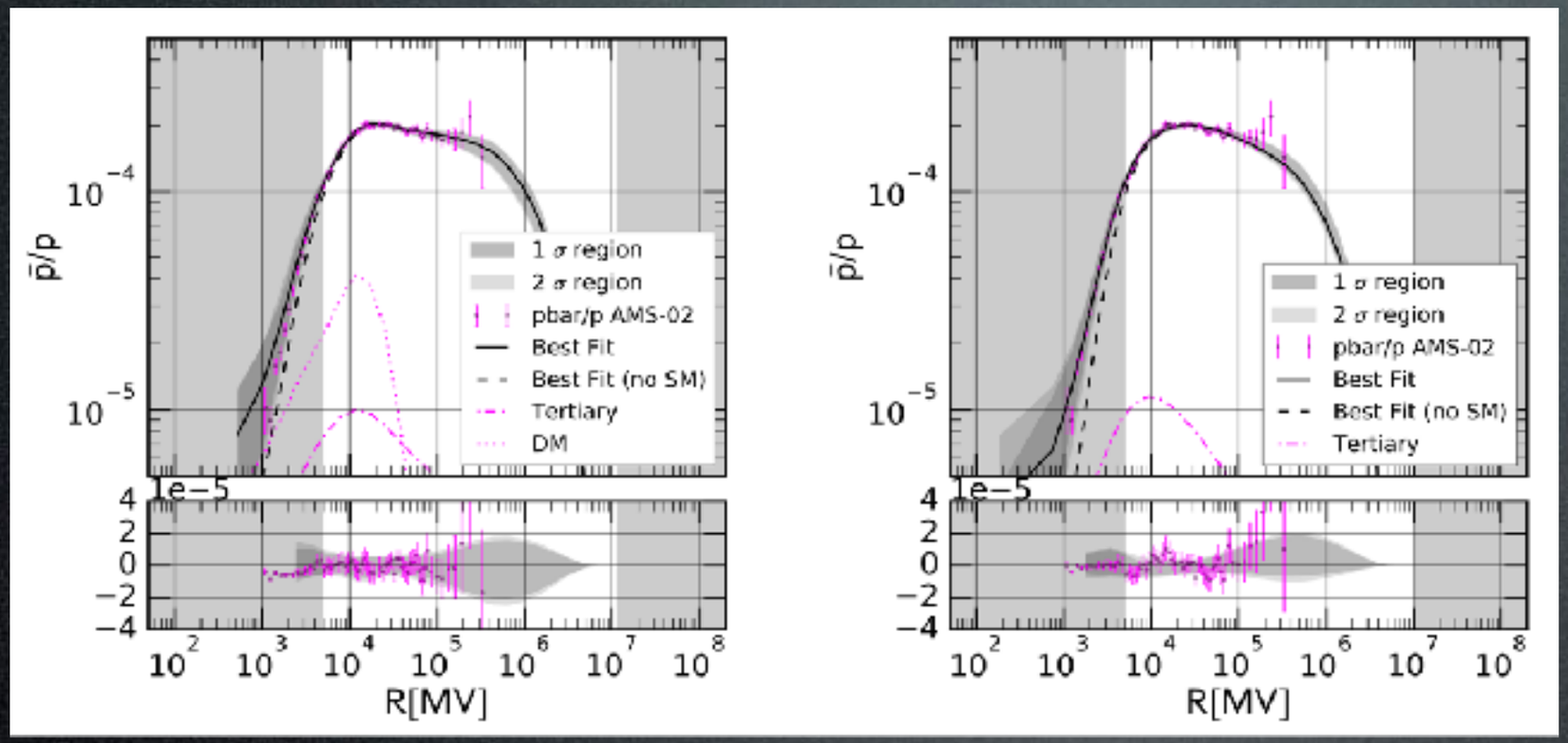
propagation parameters determined with p, He data only, w/o B/C

excess evaporates including low energies

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



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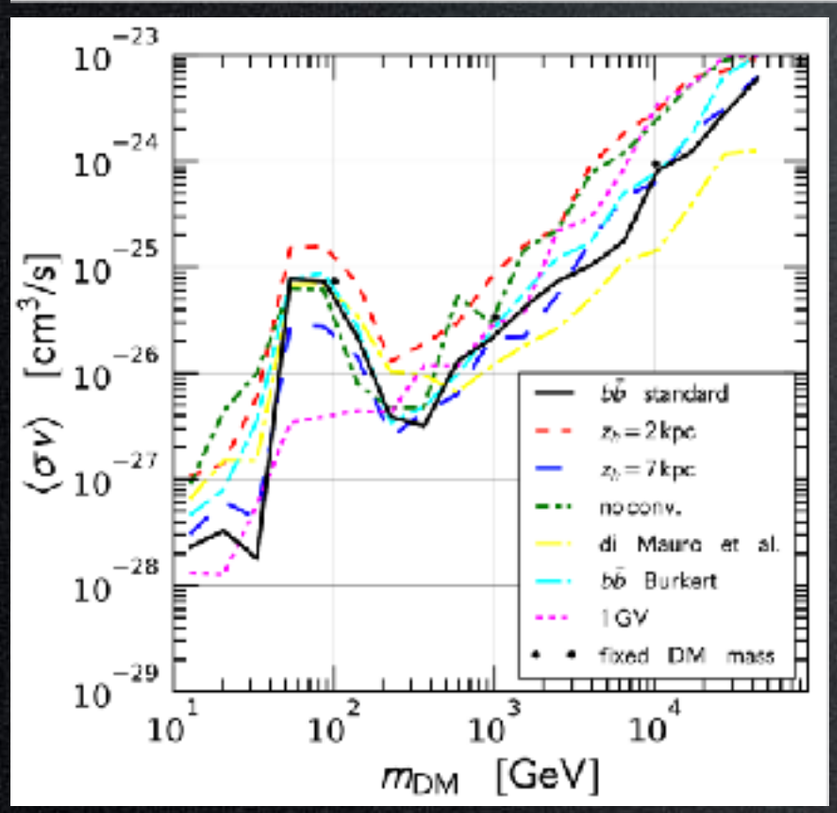
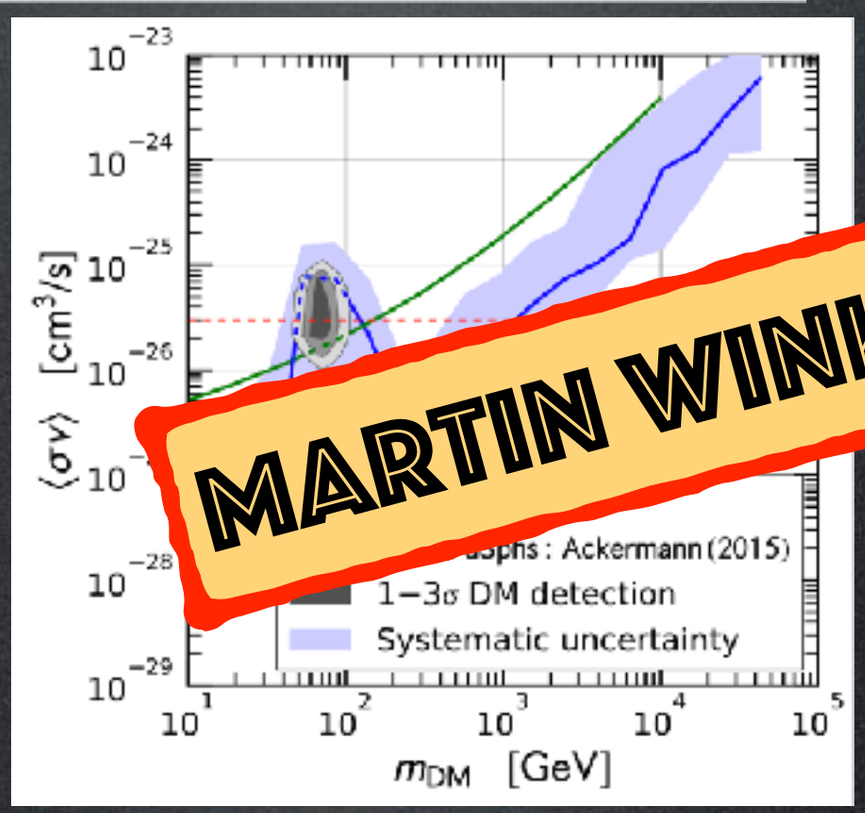


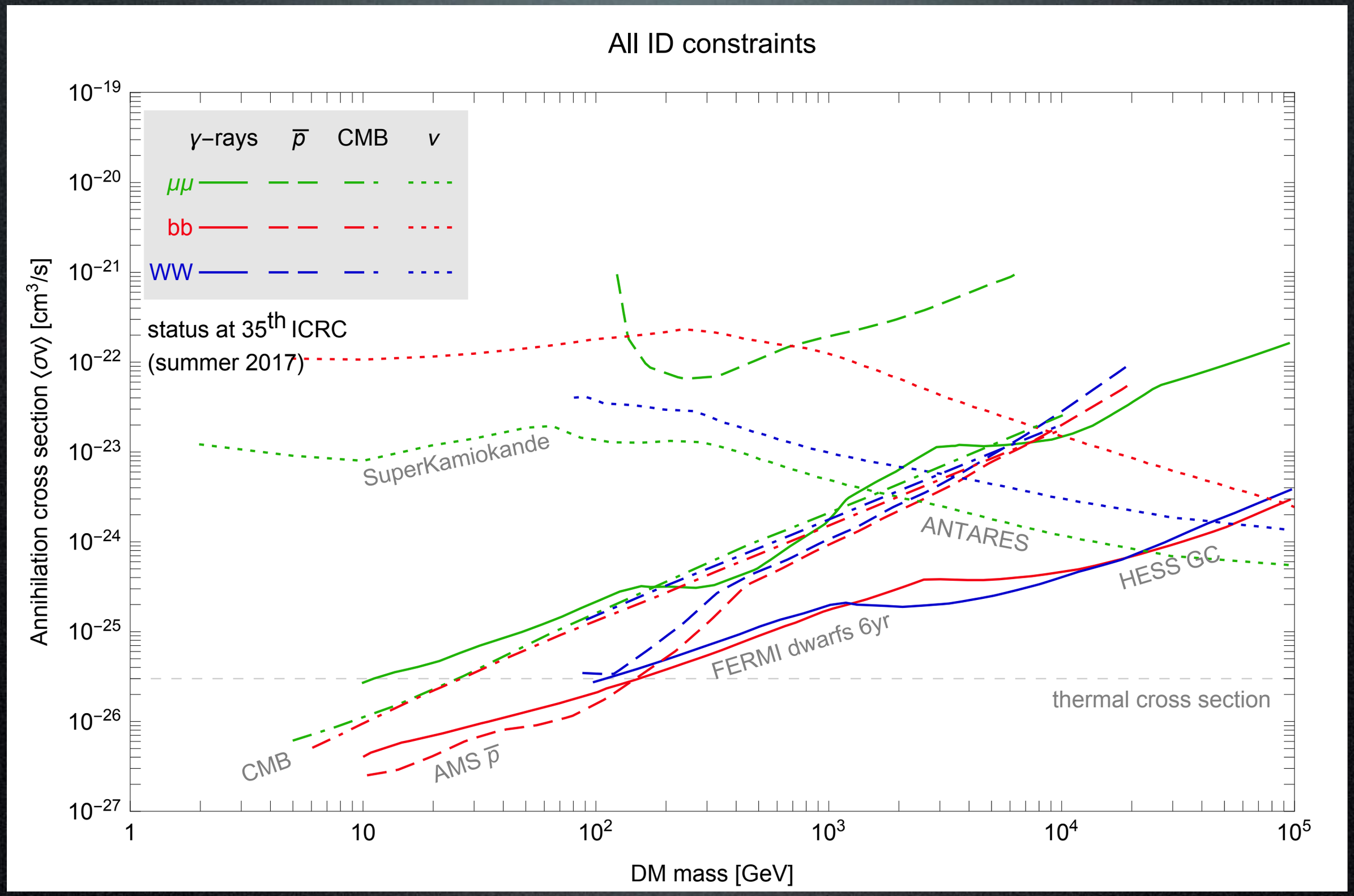


propagati… …rs

excess evaporates including low energies

MARTIN WINKLER'S TALK

Compared to other bounds



updated from M. Cirelli 1511.02031; M. Cirelli, A. Strumia, J. Zupan to appear

DM detection

direct detection

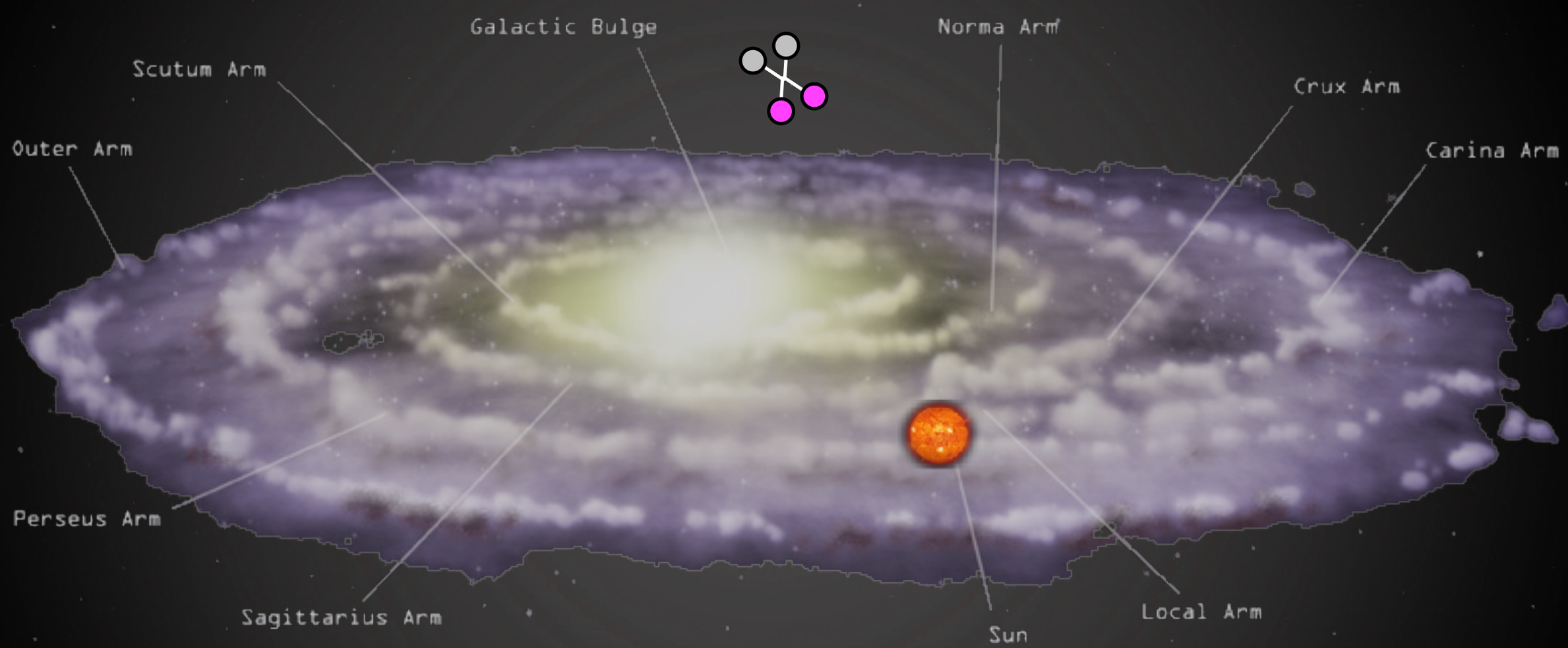
production at colliders

indirect

- γ from annihil in galactic center or halo and from secondary 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, AMS
- $\nu, \bar{\nu}$ from annihil in massive bodies
  SK, Icecube, Km3Net

Indirect Detection

$\bar{d}$ from DM annihilations in halo



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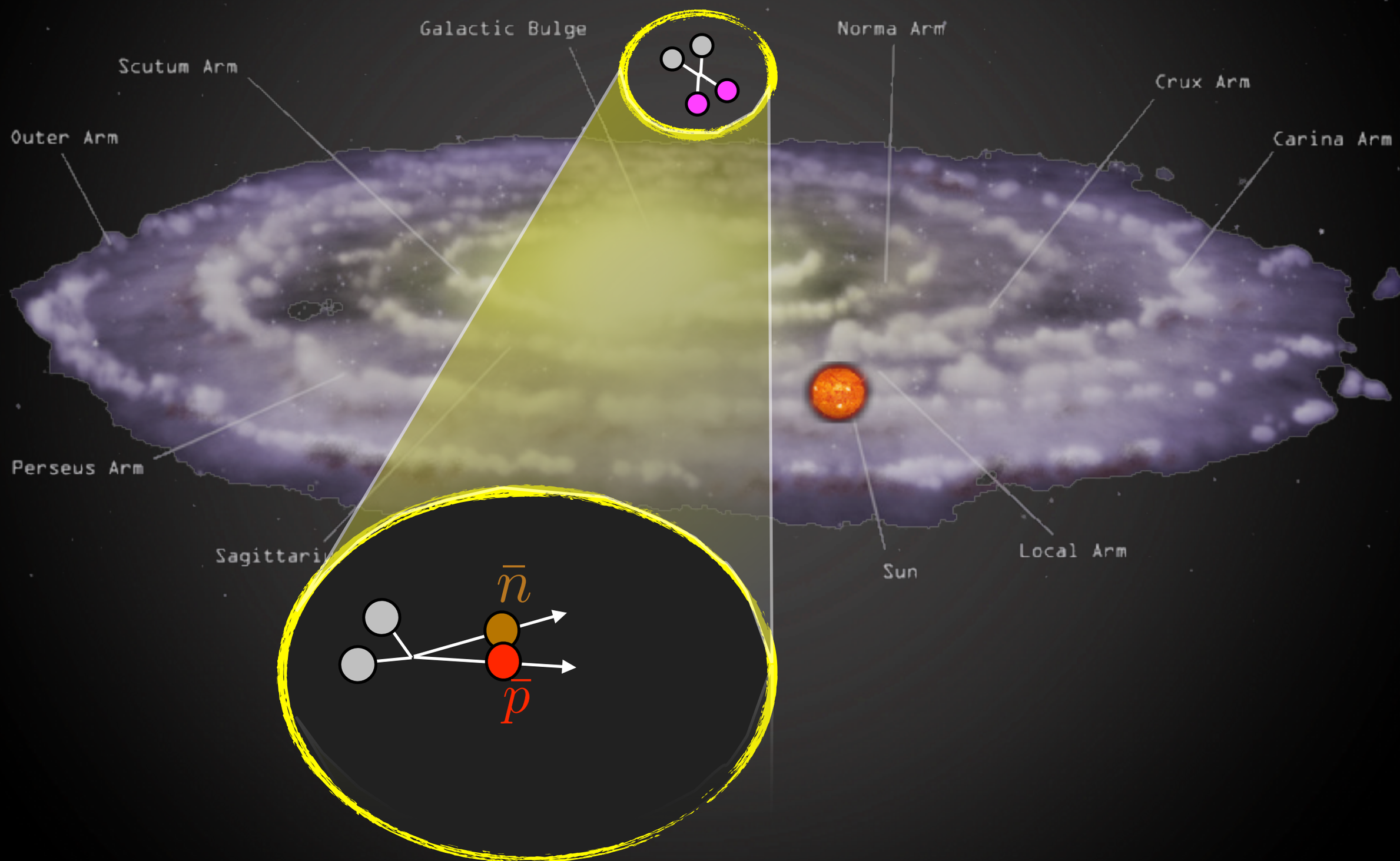

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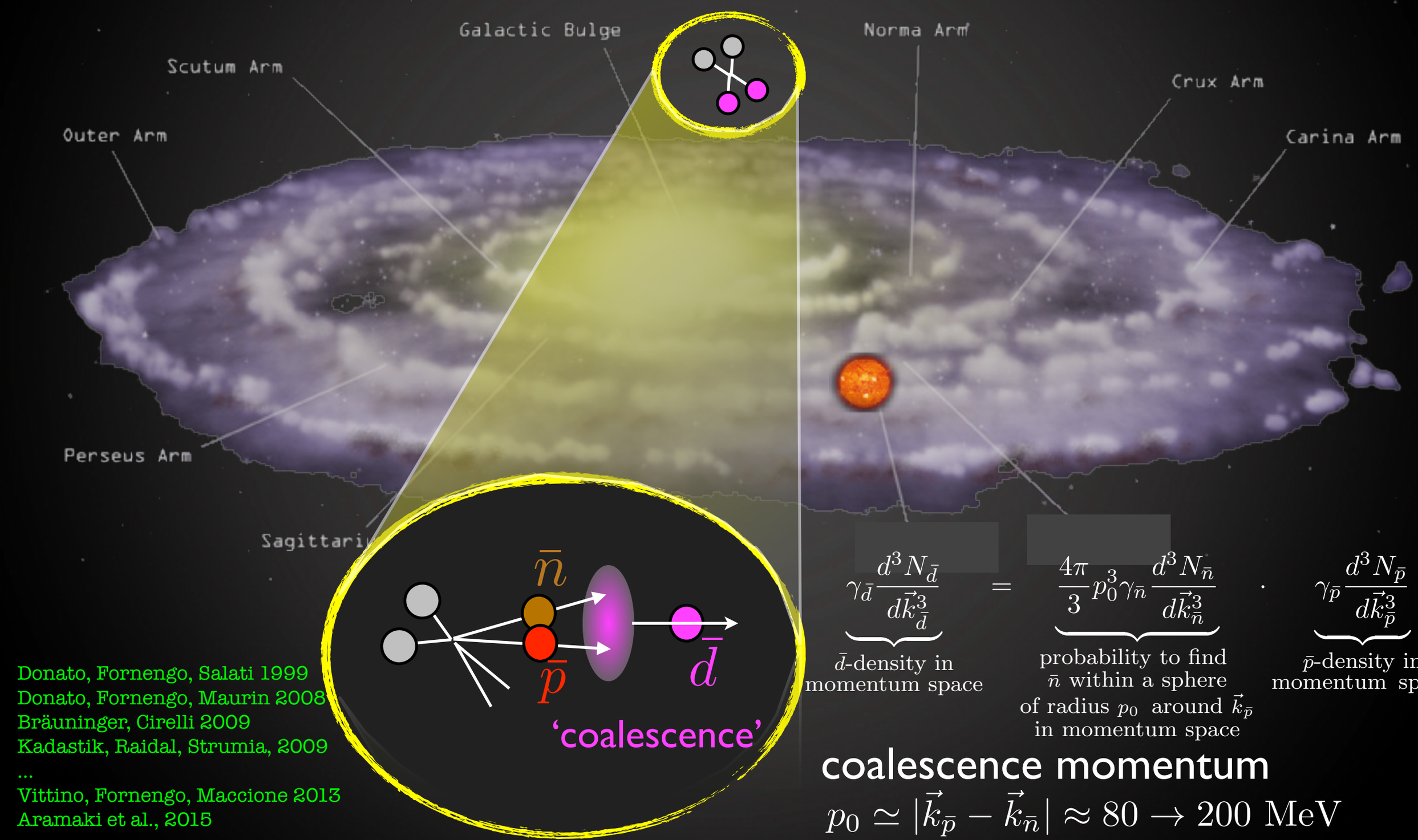

$$\underbrace{\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d\vec{k}^3_{\bar{d}}}}_{\bar{d}\text{-density in momentum space}} = \underbrace{\frac{4\pi}{3} p_0^3 \gamma_{\bar{n}} \frac{d^3 N_{\bar{n}}}{d\vec{k}^3_{\bar{n}}}}_{\substack{\text{probability to find } \bar{n} \text{ within a sphere} \\ \text{of radius } p_0 \text{ around } \vec{k}_{\bar{p}} \\ \text{in momentum space}}} \cdot \underbrace{\gamma_{\bar{p}} \frac{d^3 N_{\bar{p}}}{d\vec{k}^3_{\bar{p}}}}_{\bar{p}\text{-density in momentum space}}$$

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Bräuninger, Cirelli 2009
Kadastik, Raidal, Strumia, 2009
...
Vittino, Fornengo, Maccione 2013
Aramaki et al., 2015

coalescence momentum

$$p_0 \simeq |\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}| \approx 80 \rightarrow 200 \text{ MeV}$$

Indirect Detection

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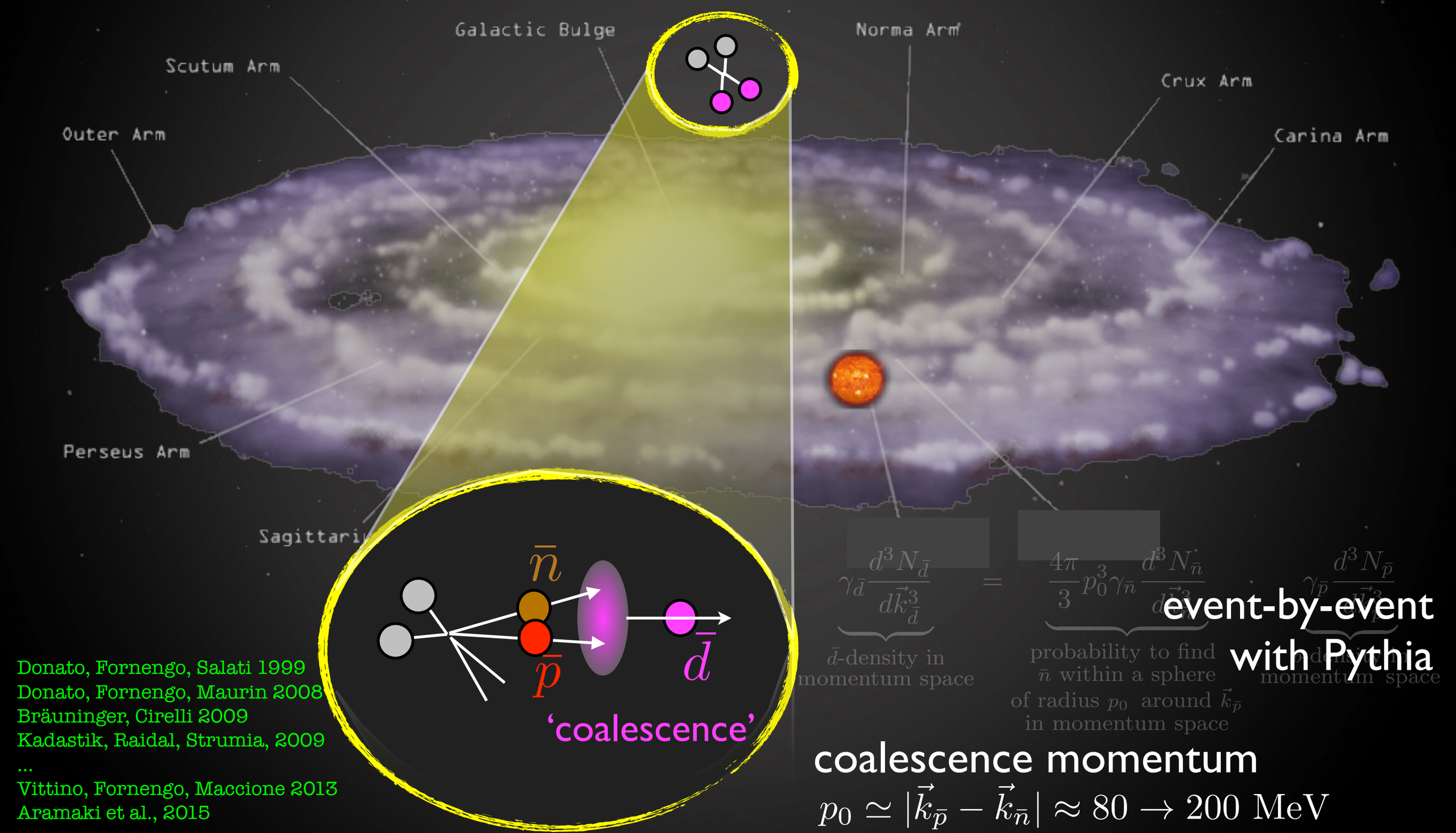

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event-by-event with Pythia

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
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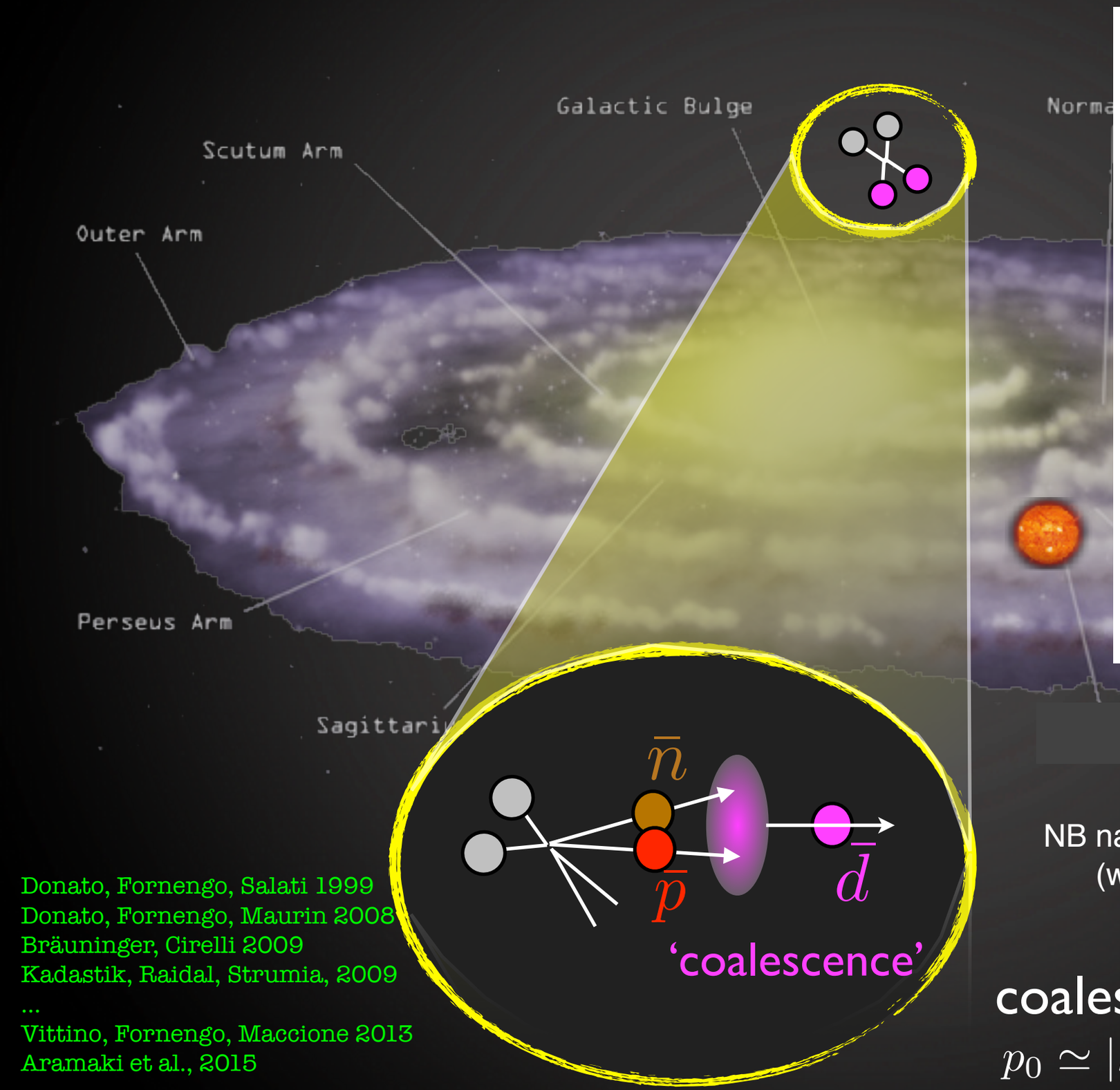

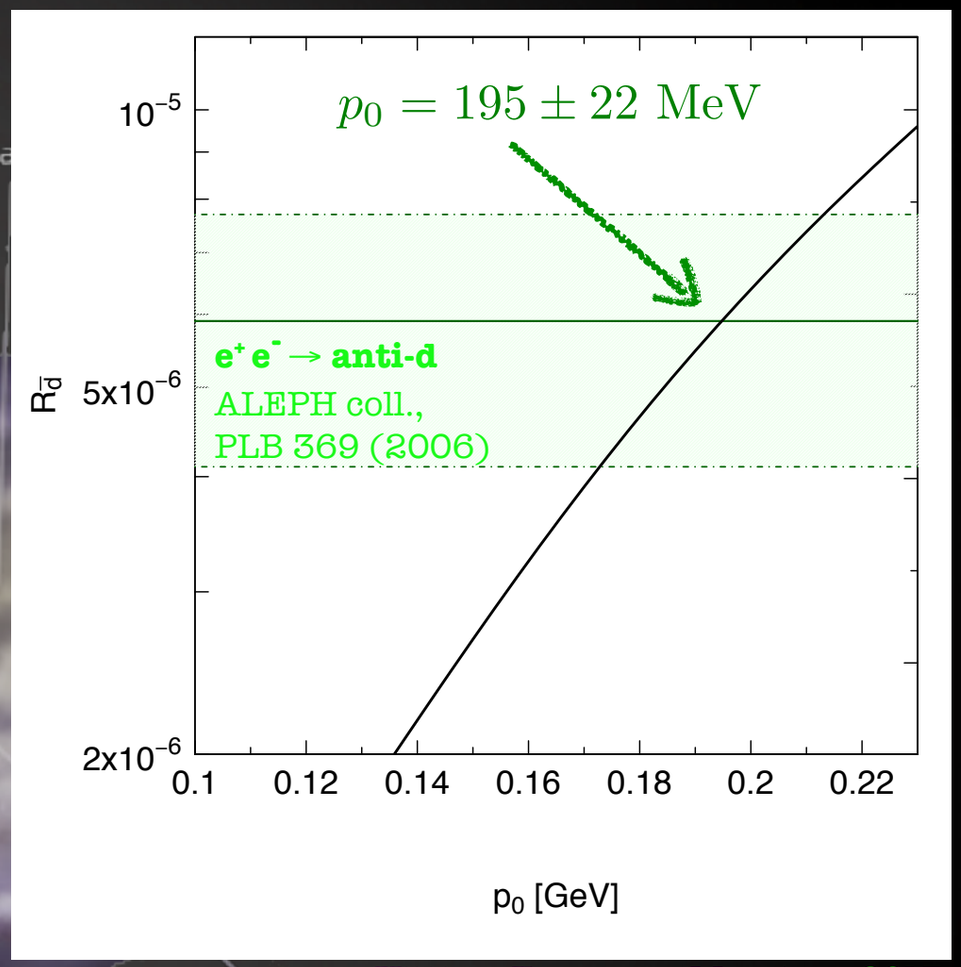

Vittino, Fornengo, Maccione 2013

NB naïve guess would be $p_0 = \sqrt{E_b\, m_p} = 47$ MeV (with E_b the d binding energy): not too far…

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Bräuninger, Cirelli 2009
Kadastik, Raidal, Strumia, 2009
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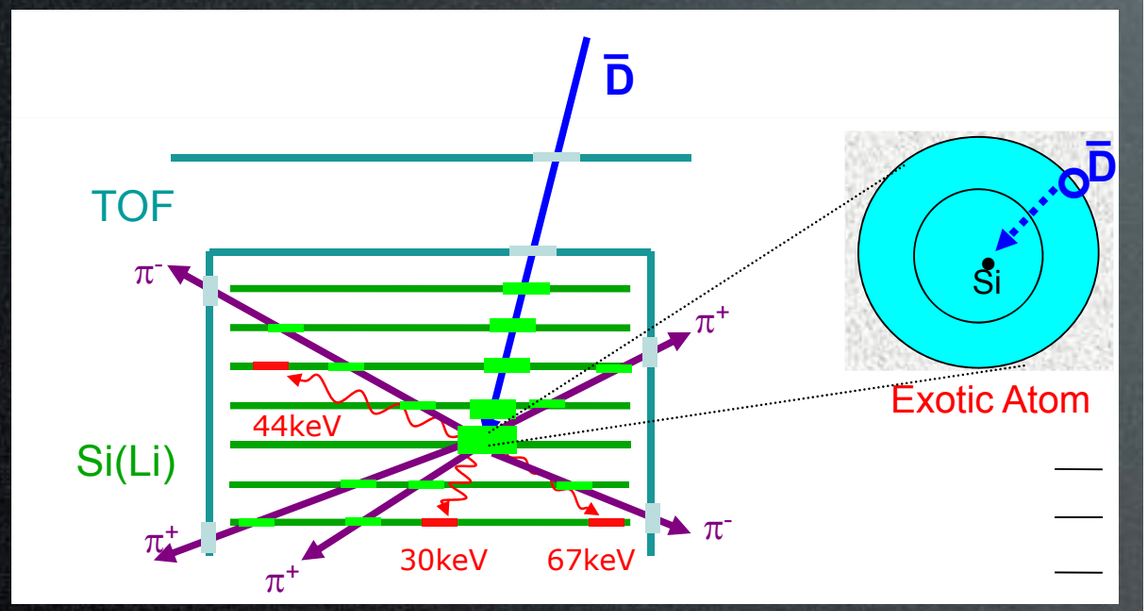
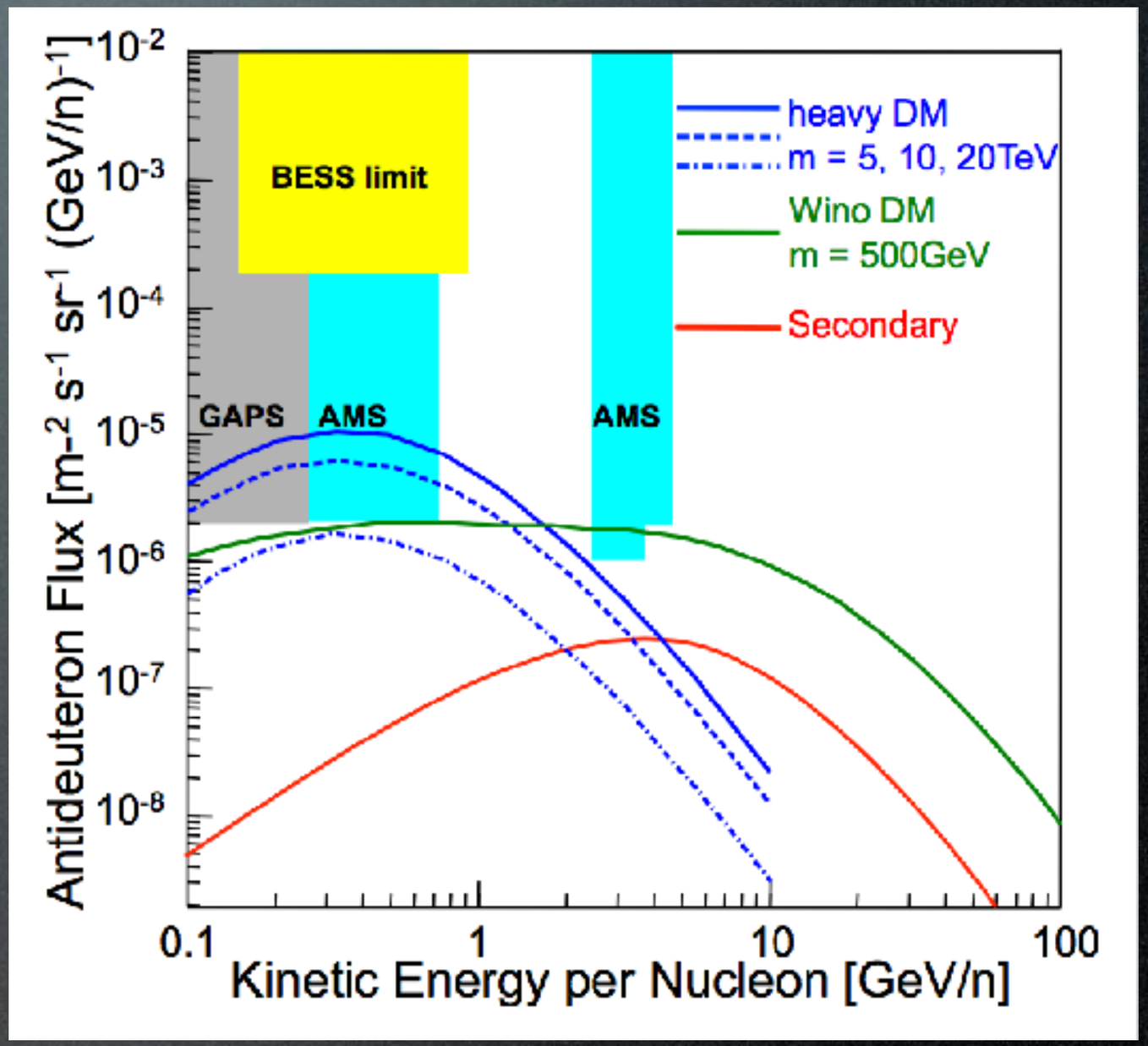
Indirect Detection

$\bar{d}$ from DM annihilations in halo

GAPS detection principle



$\bar{d}$ is slowed down,
captured (exotic atom),
annihilates w distinctive emissions



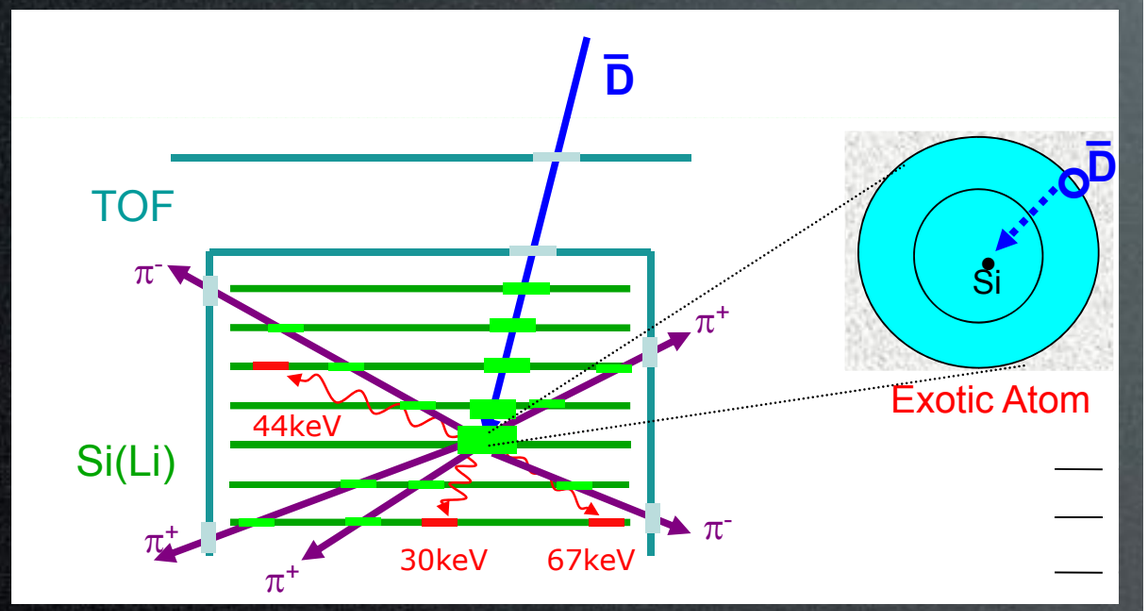
P. von Doetinchem et al., 2015

DM signal in the reach of GAPS and AMS-02

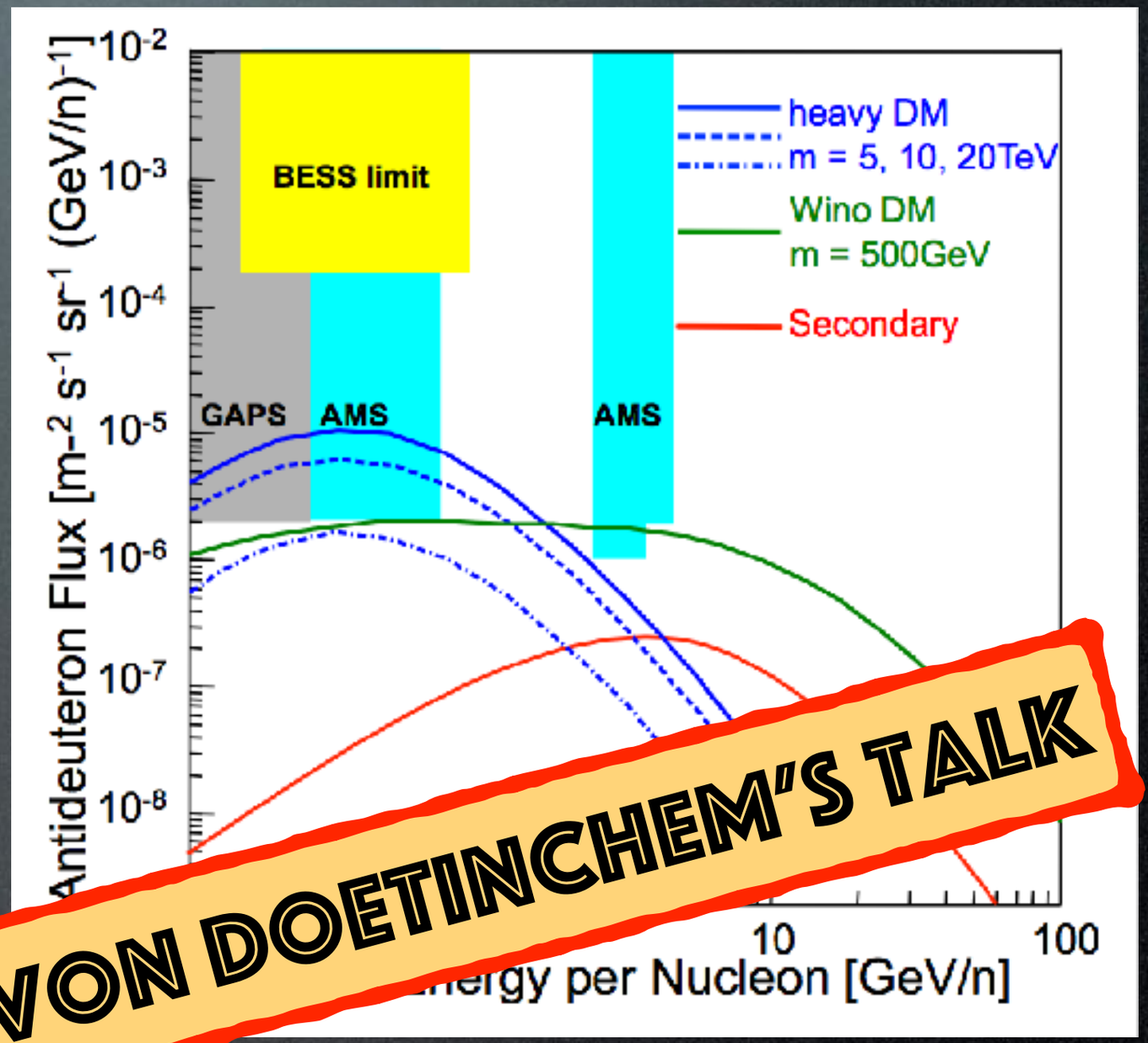
Indirect Detection

$\bar{d}$ from DM annihilations in halo

GAPS detection principle



$\bar{d}$ is slowed down,
captured (exotic atom),
annihilates w distinctive emissions



PHILIPP VON DOETINCHEM'S TALK

P. von Doetinchem et al., 2015

DM signal in the reach of GAPS and AMS-02

DM detection

direct detection

production at colliders

indirect

γ from annihil in galactic center or halo and from secondary 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, AMS

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

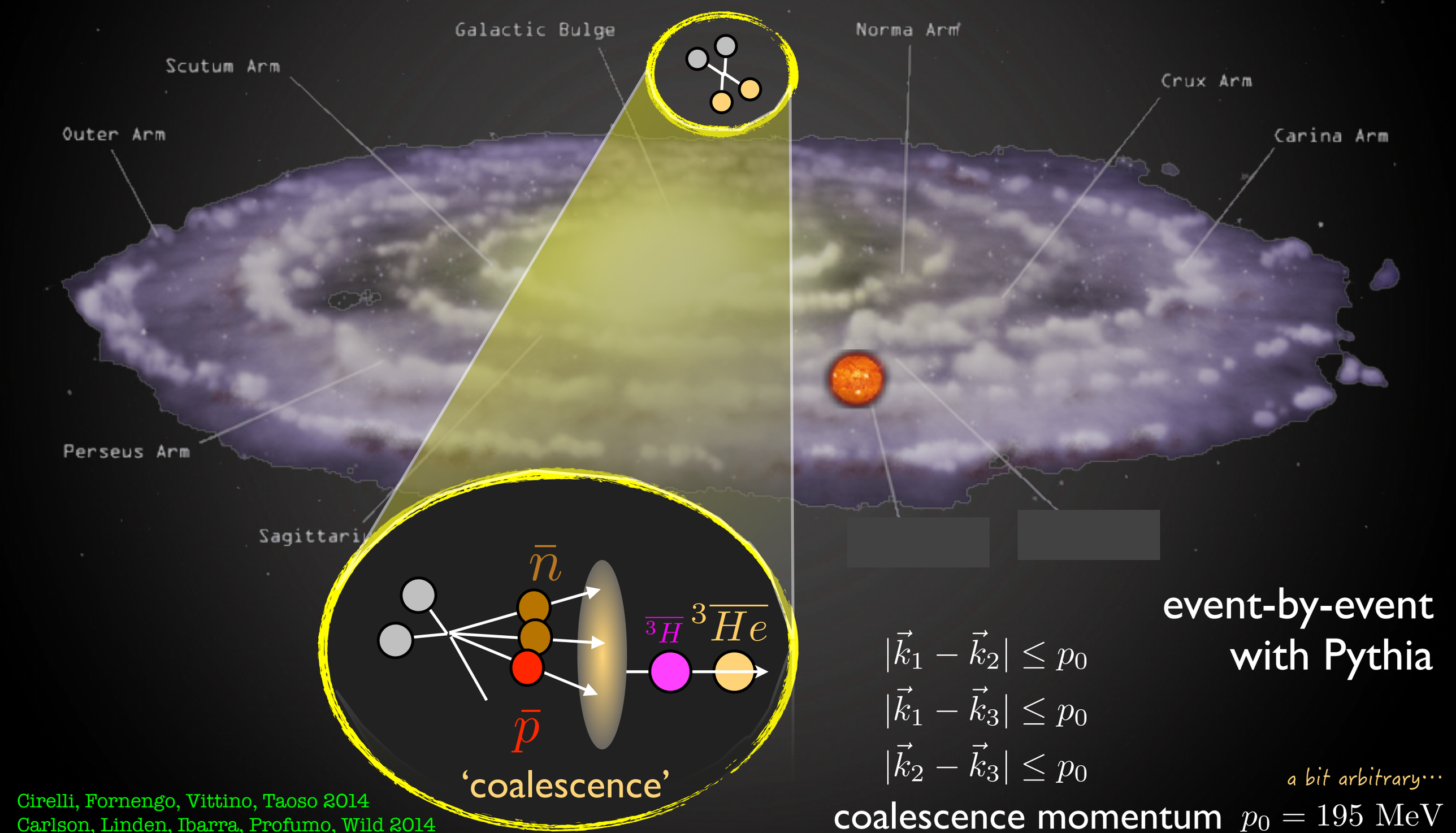
SK, Icecube, Km3Net

$\overline{He}$ from annihil in galactic halo or center

AMS?

Indirect Detection

$\overline{He}$ from DM annihilations in halo



event-by-event with Pythia

$$|\vec{k}_1 - \vec{k}_2| \leq p_0$$
$$|\vec{k}_1 - \vec{k}_3| \leq p_0$$
$$|\vec{k}_2 - \vec{k}_3| \leq p_0$$

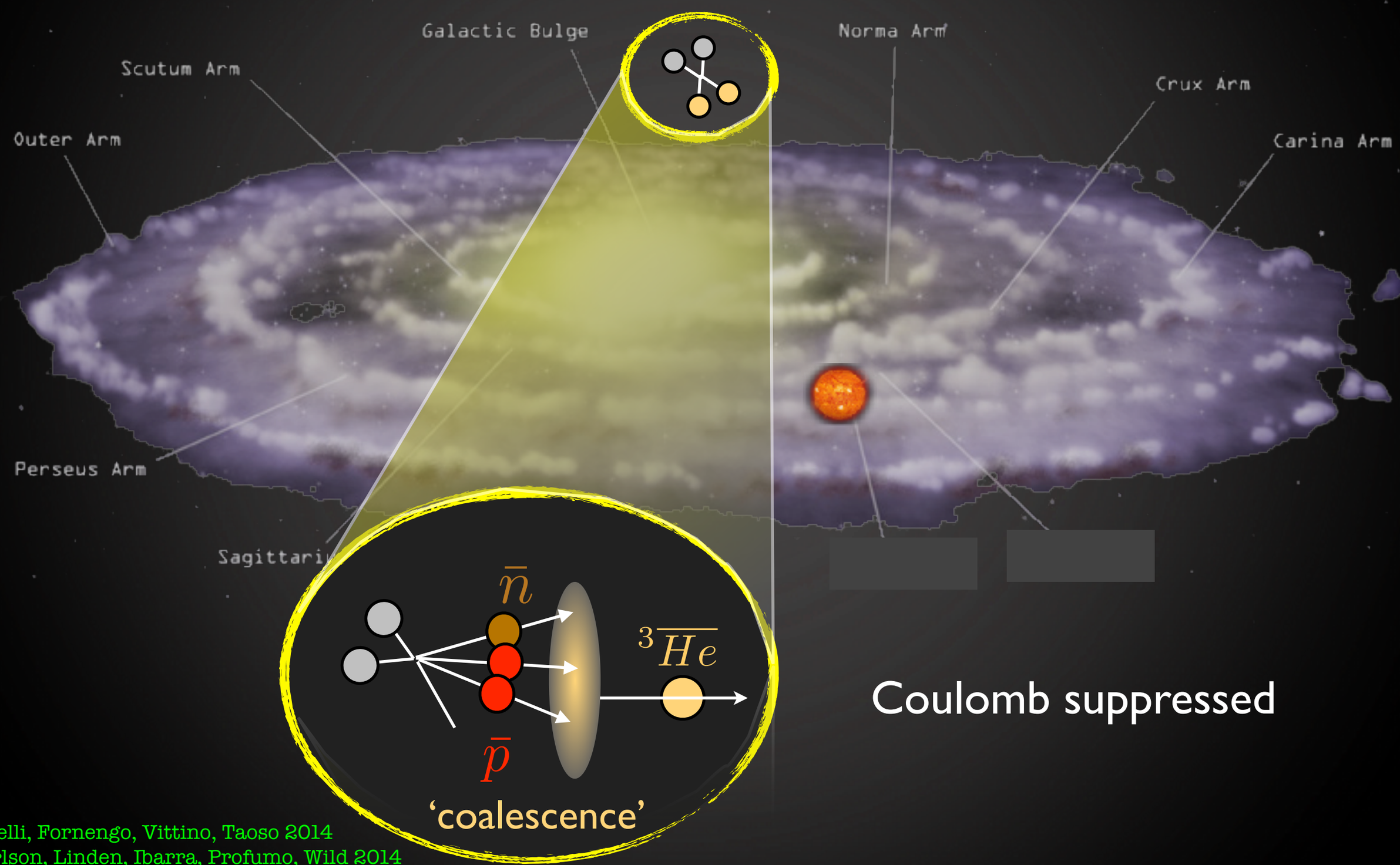
a bit arbitrary…

coalescence momentum $p_0 = 195$ MeV

Cirelli, Fornengo, Vittino, Taoso 2014
Carlson, Linden, Ibarra, Profumo, Wild 2014

Indirect Detection

$\overline{He}$ from DM annihilations in halo

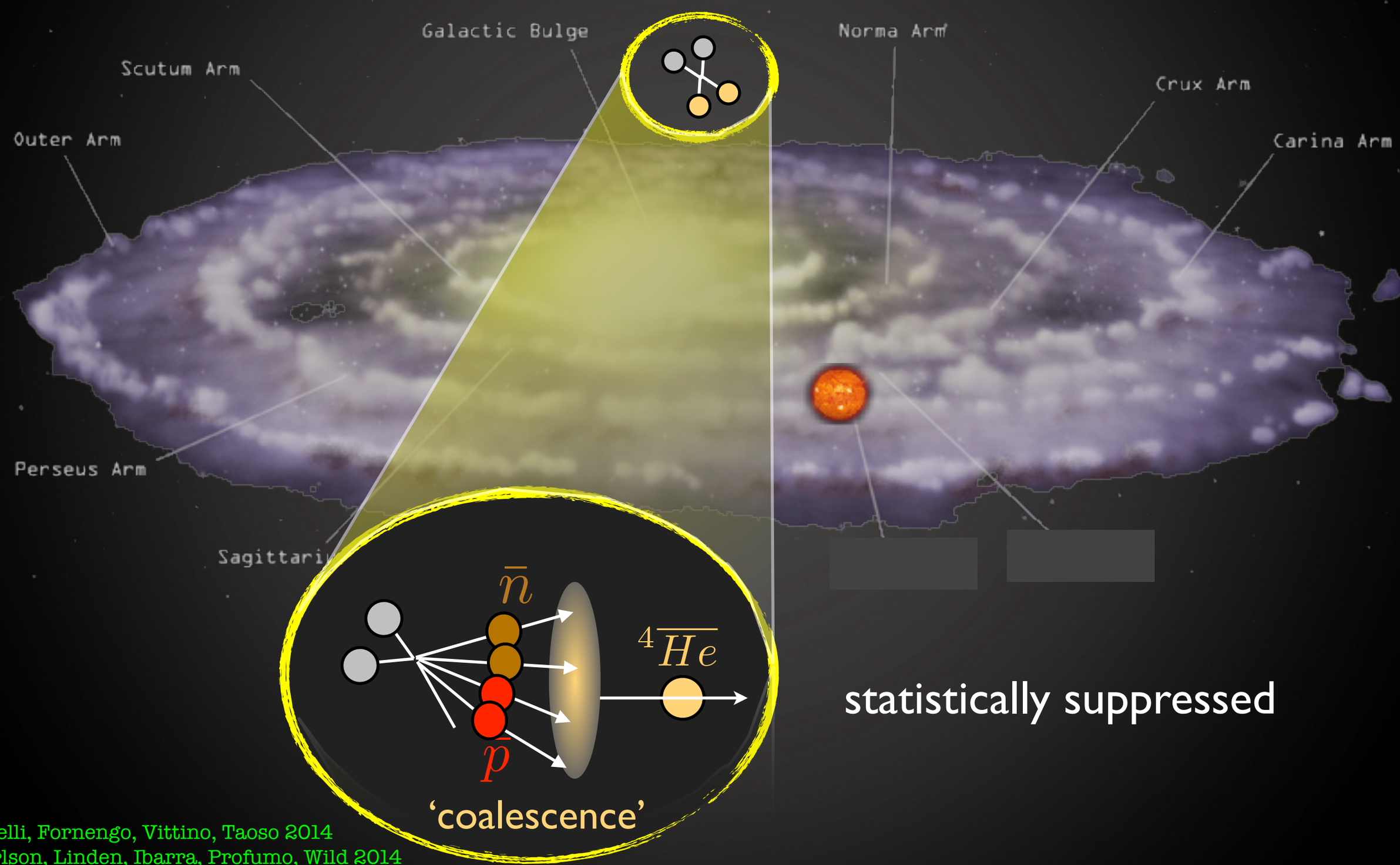


Coulomb suppressed

Cirelli, Fornengo, Vittino, Taoso 2014
Carlson, Linden, Ibarra, Profumo, Wild 2014

Indirect Detection

$\overline{He}$ from DM annihilations in halo



statistically suppressed

Cirelli, Fornengo, Vittino, Taoso 2014
Carlson, Linden, Ibarra, Profumo, Wild 2014

Indirect Detection

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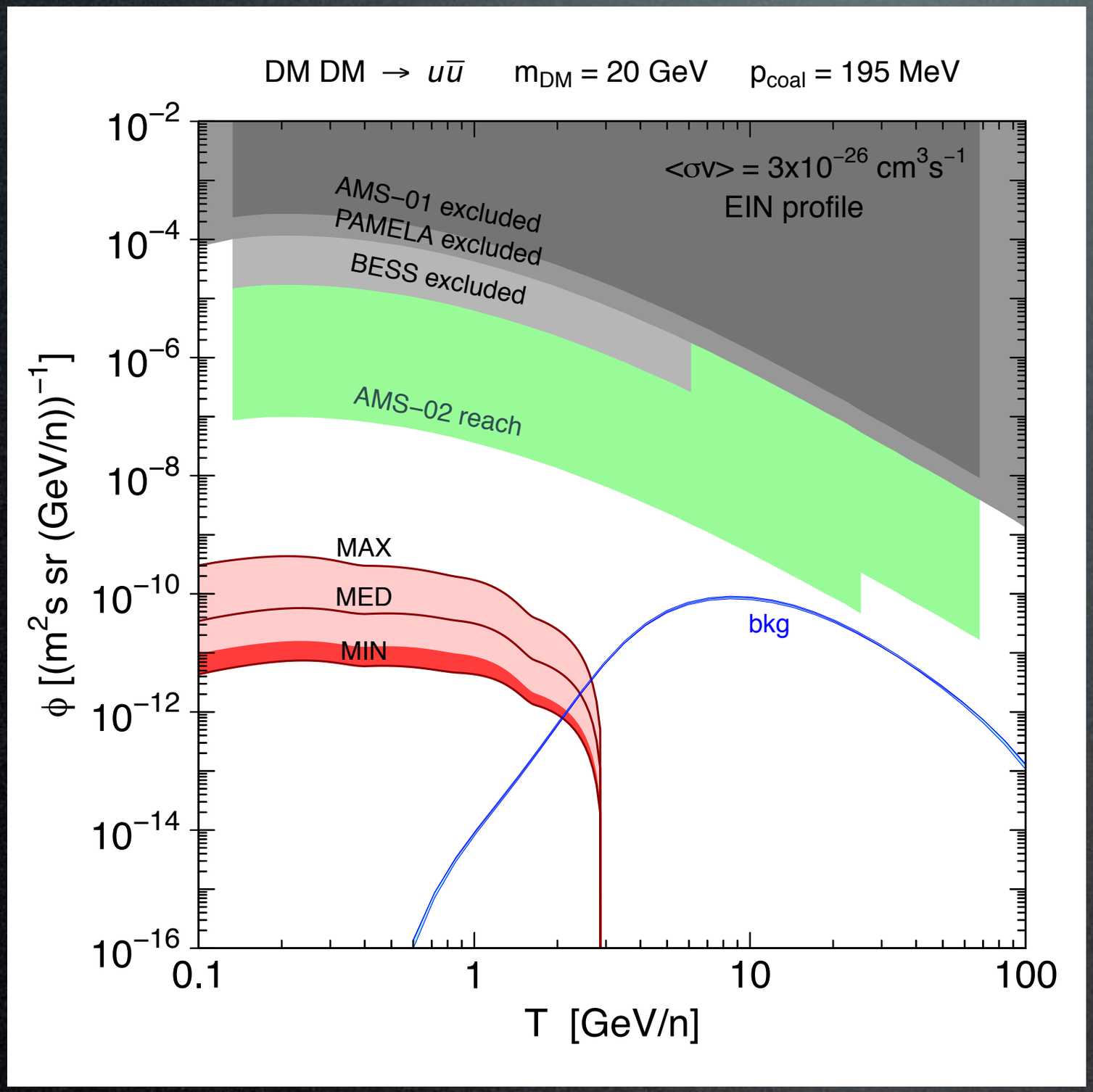
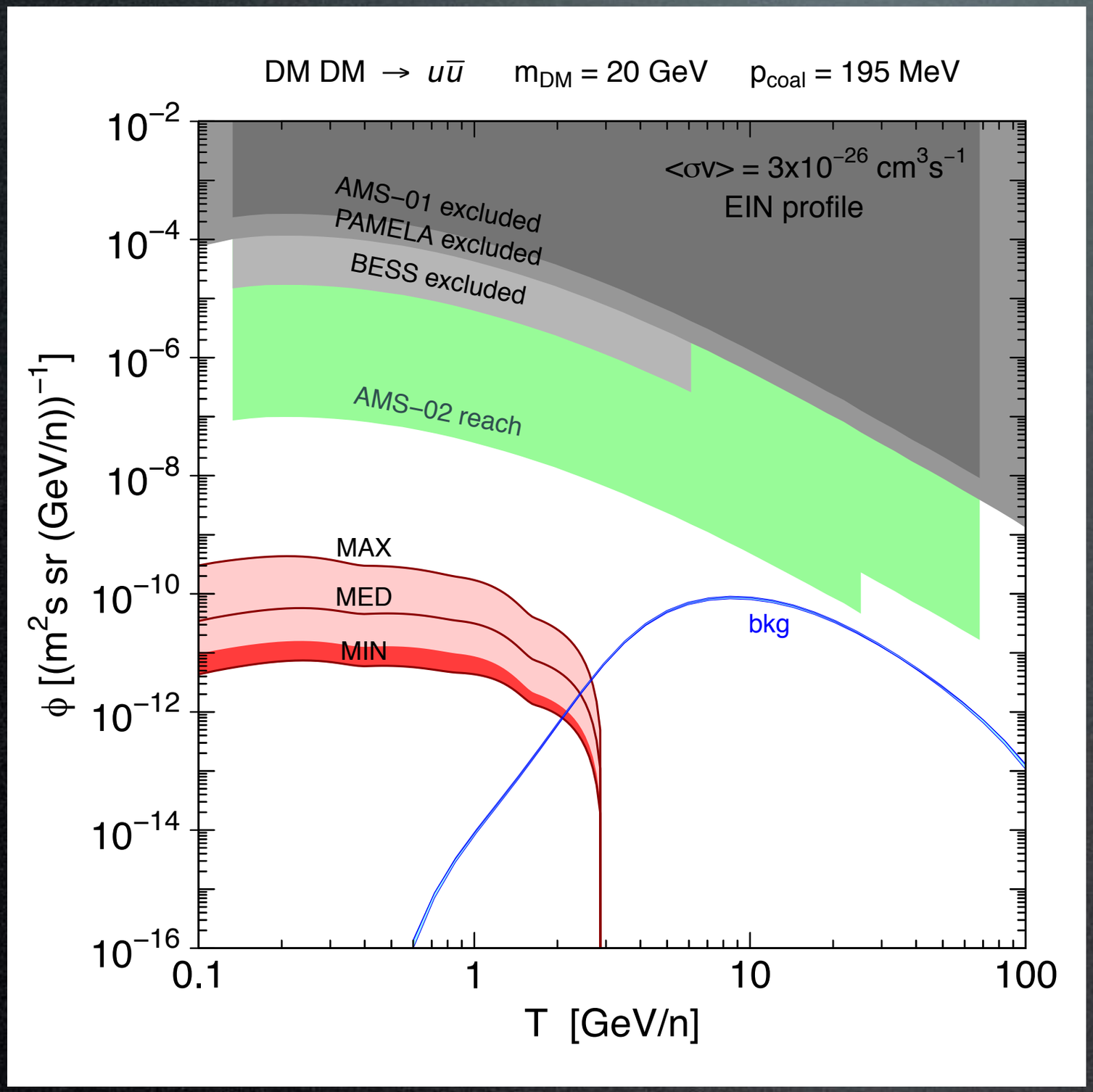


all

consistent with antiproton bounds

Indirect Detection

$\overline{He}$ from DM annihilations in halo



Indirect Detection

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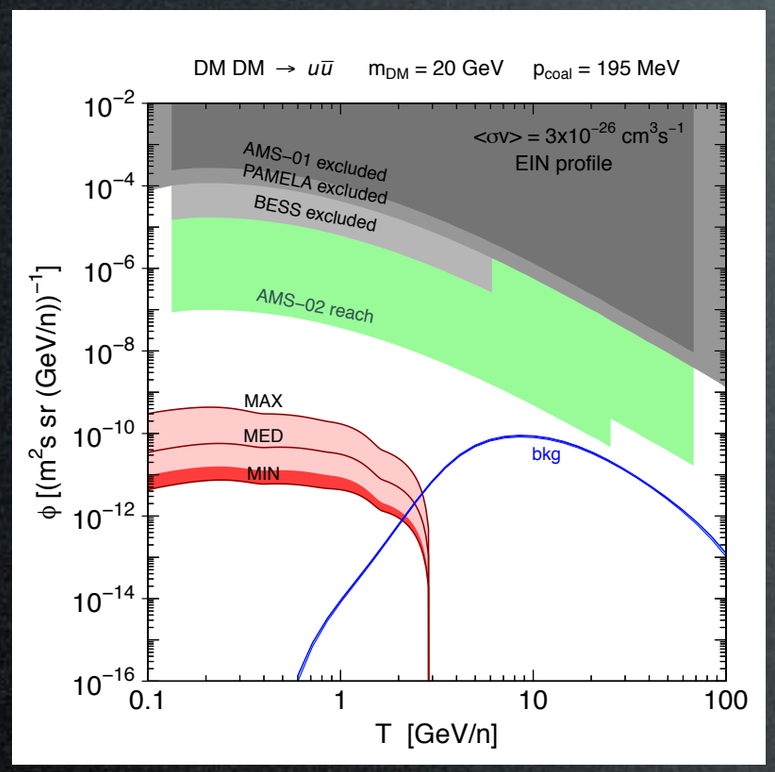

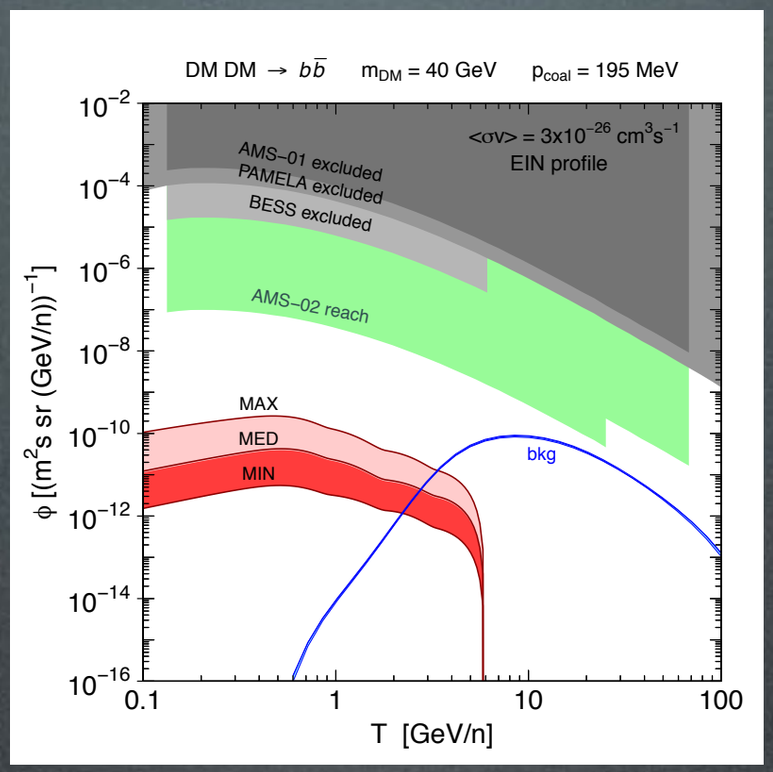

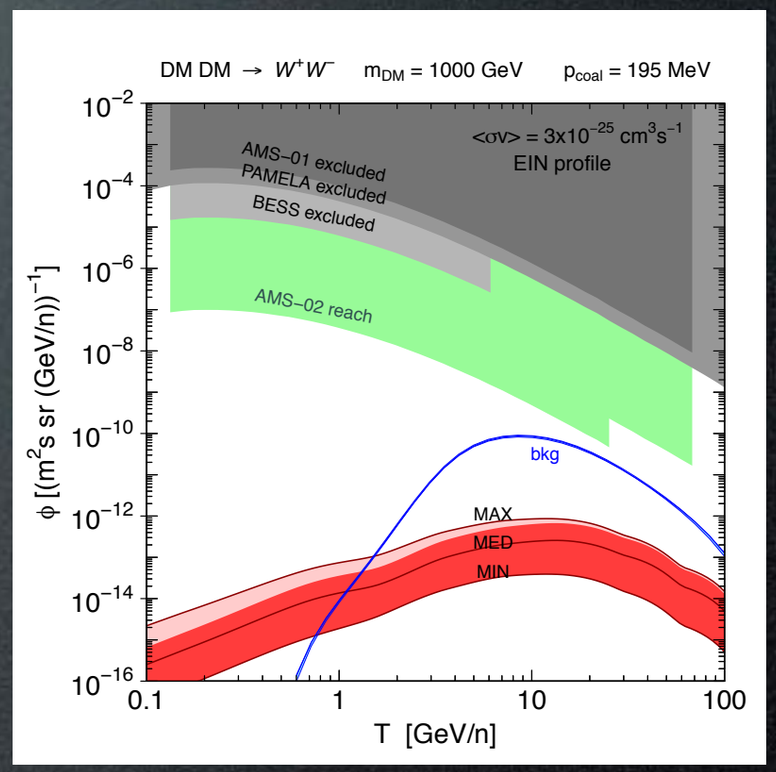

Indirect Detection

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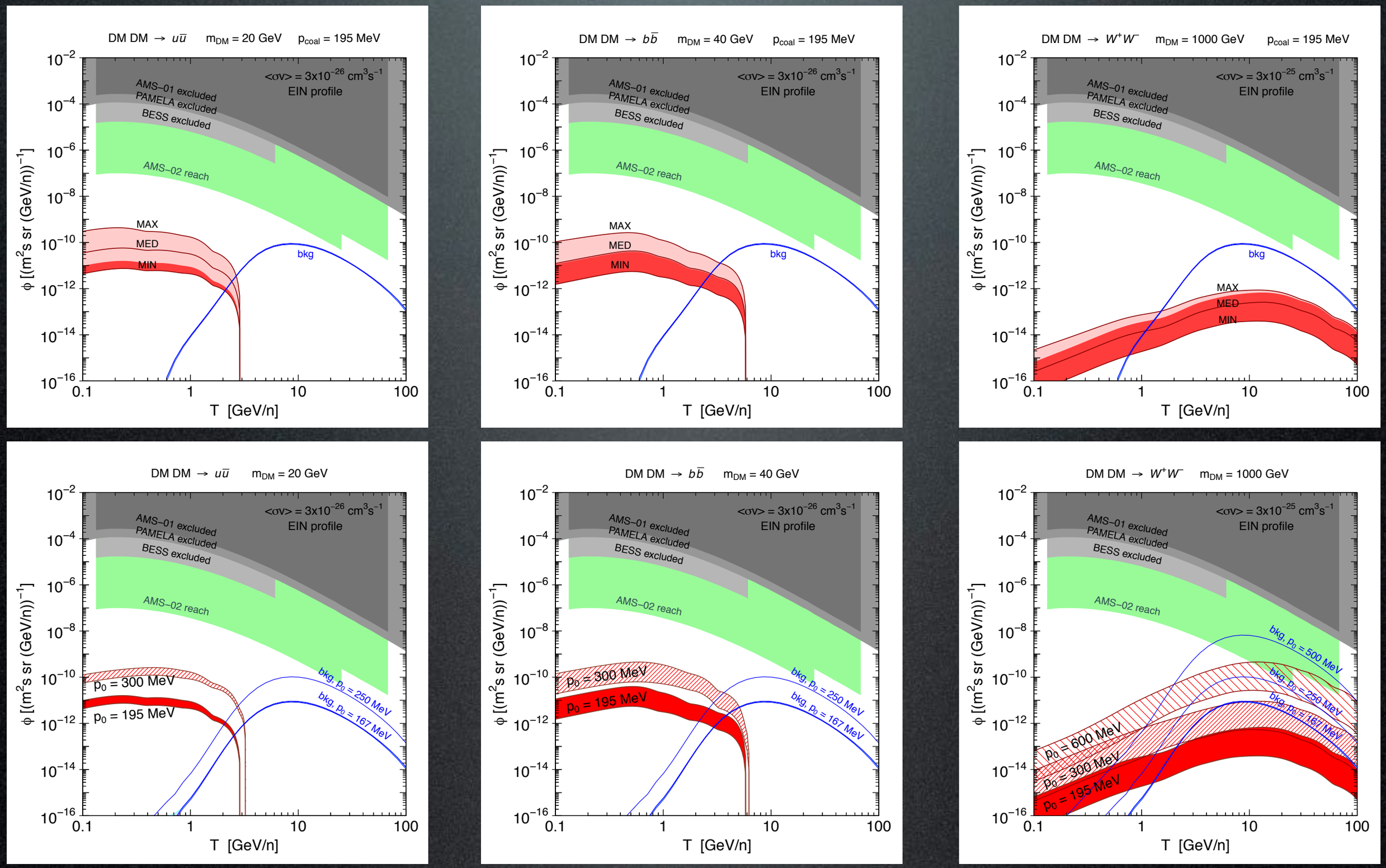

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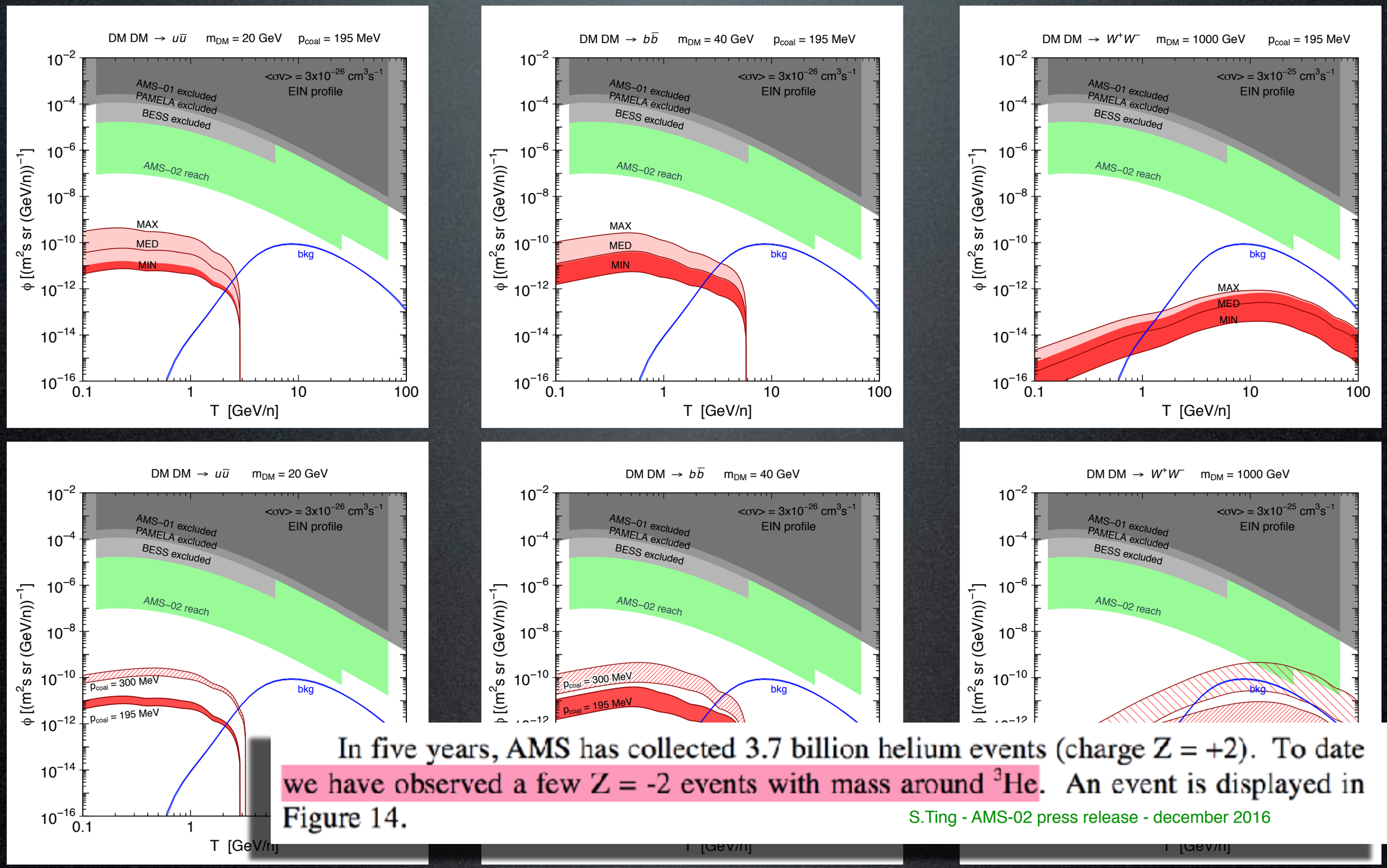
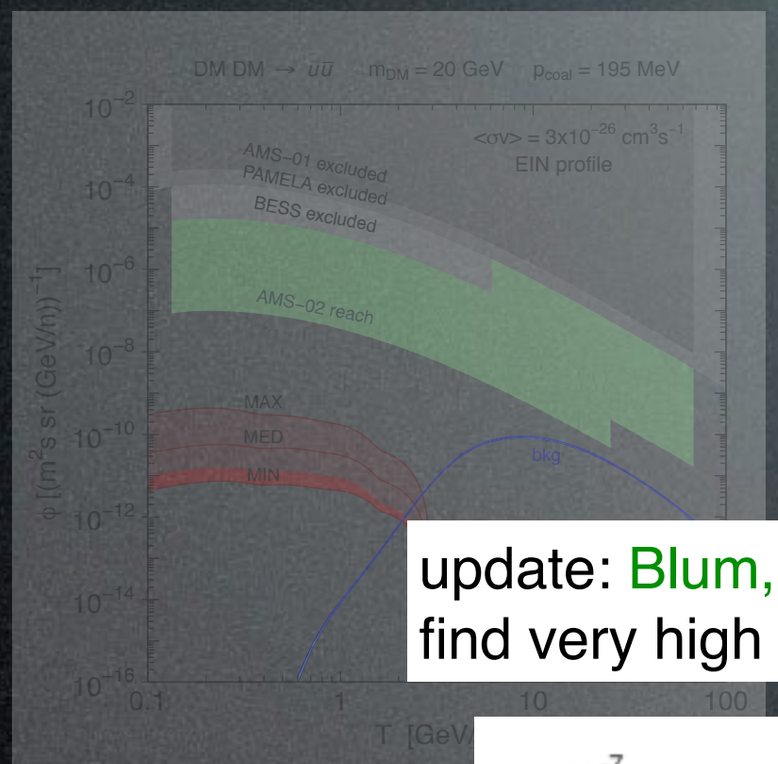


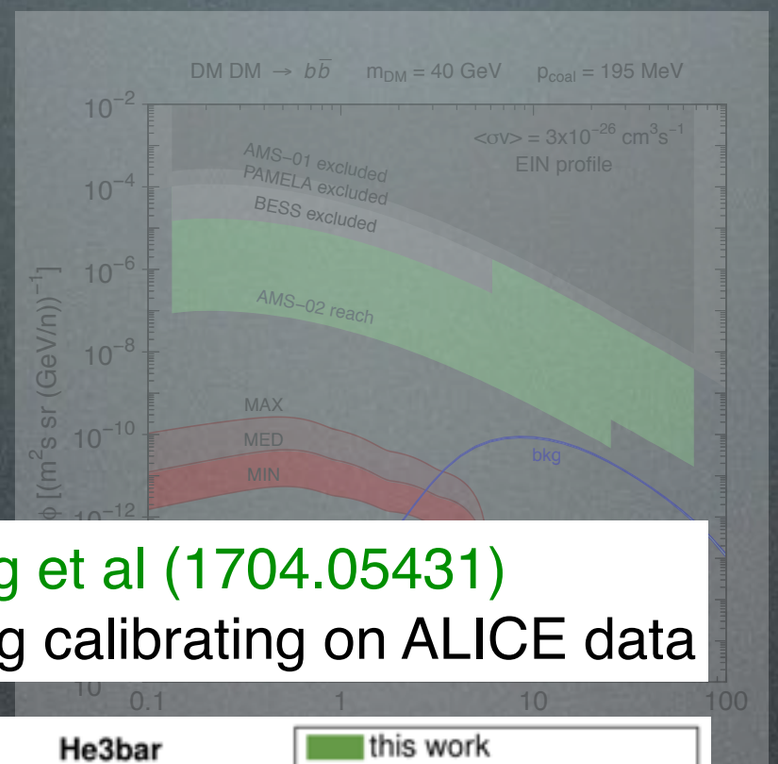
In five years, AMS has collected 3.7 billion helium events (charge Z = +2). To date we have observed a few Z = -2 events with mass around ^{3}He. An event is displayed in Figure 14.

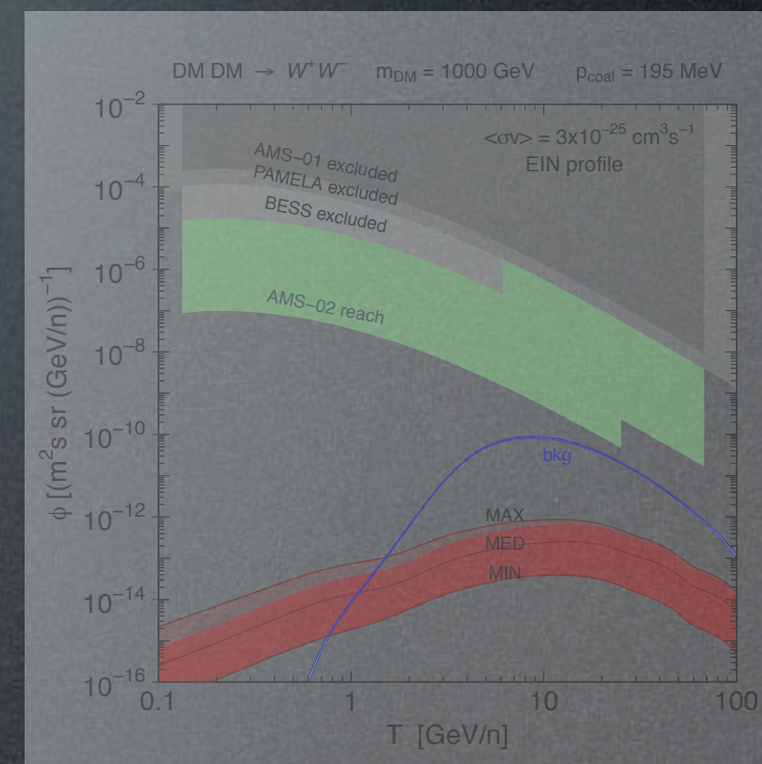
S.Ting - AMS-02 press release - december 2016

Indirect Detection

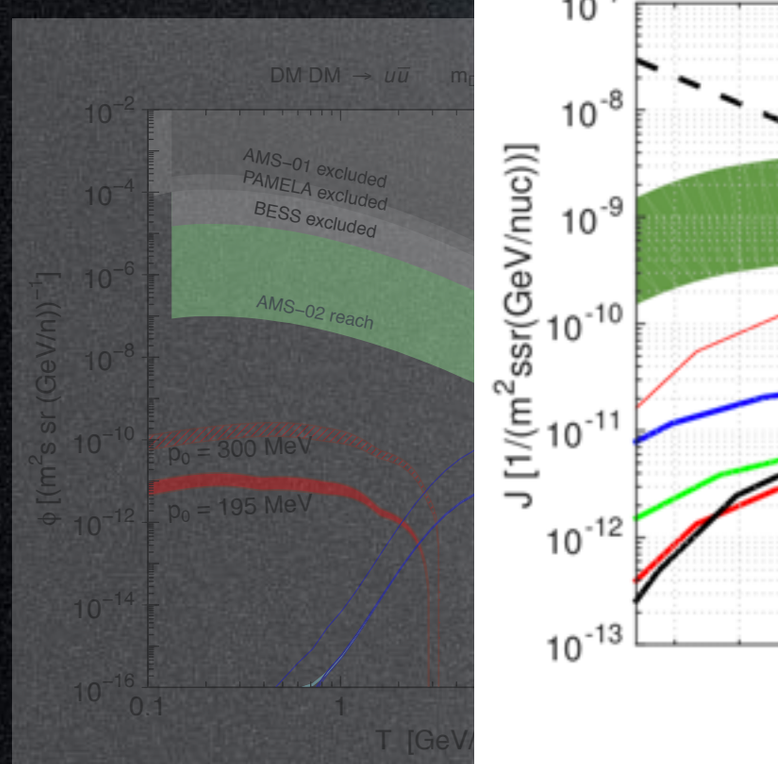
$\overline{He}$ from DM annihilations in halo

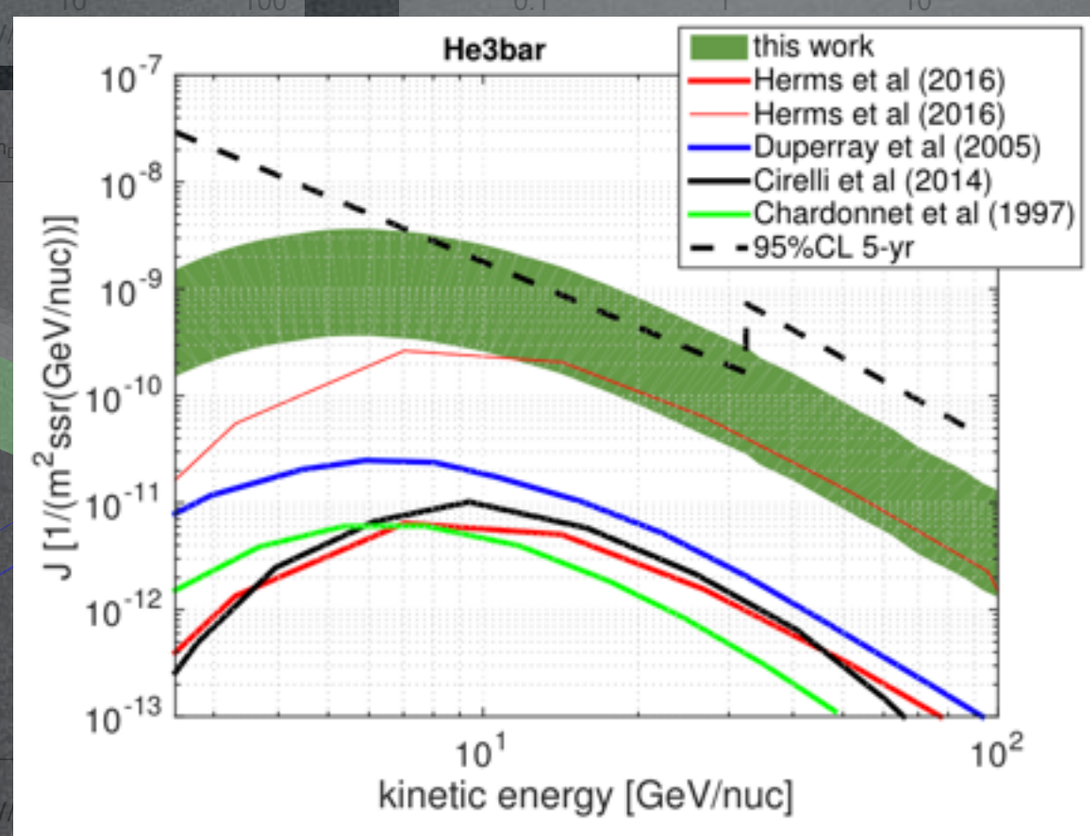


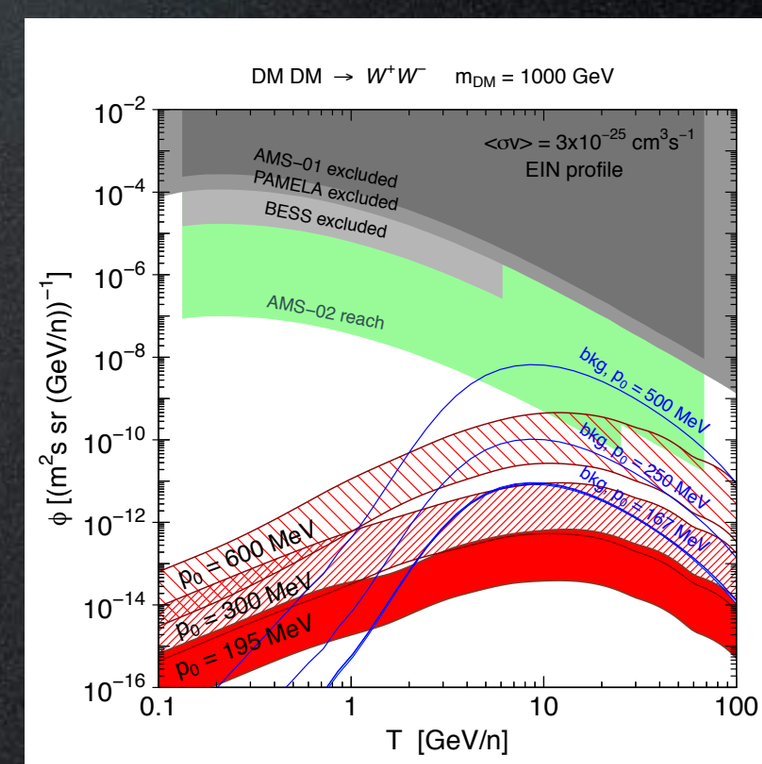




update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data







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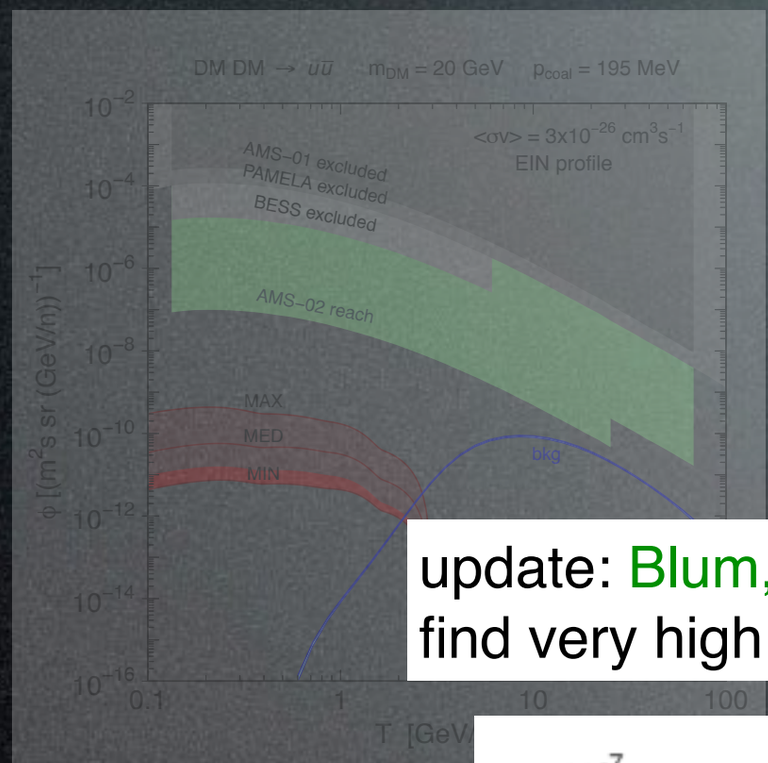
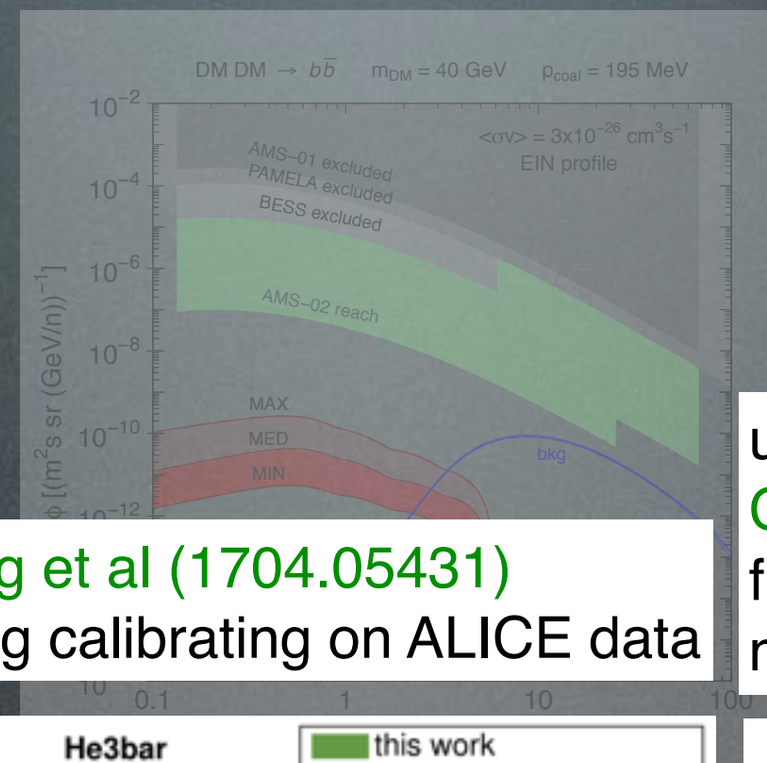
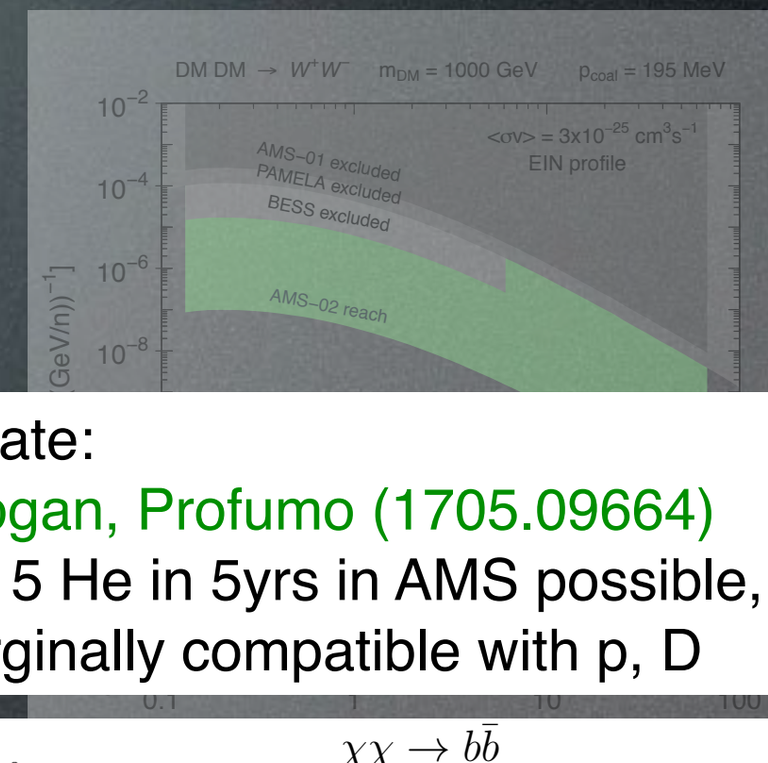
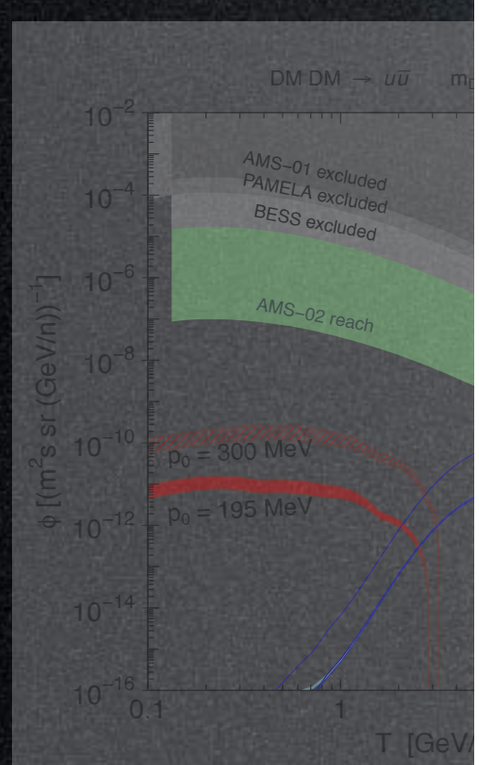


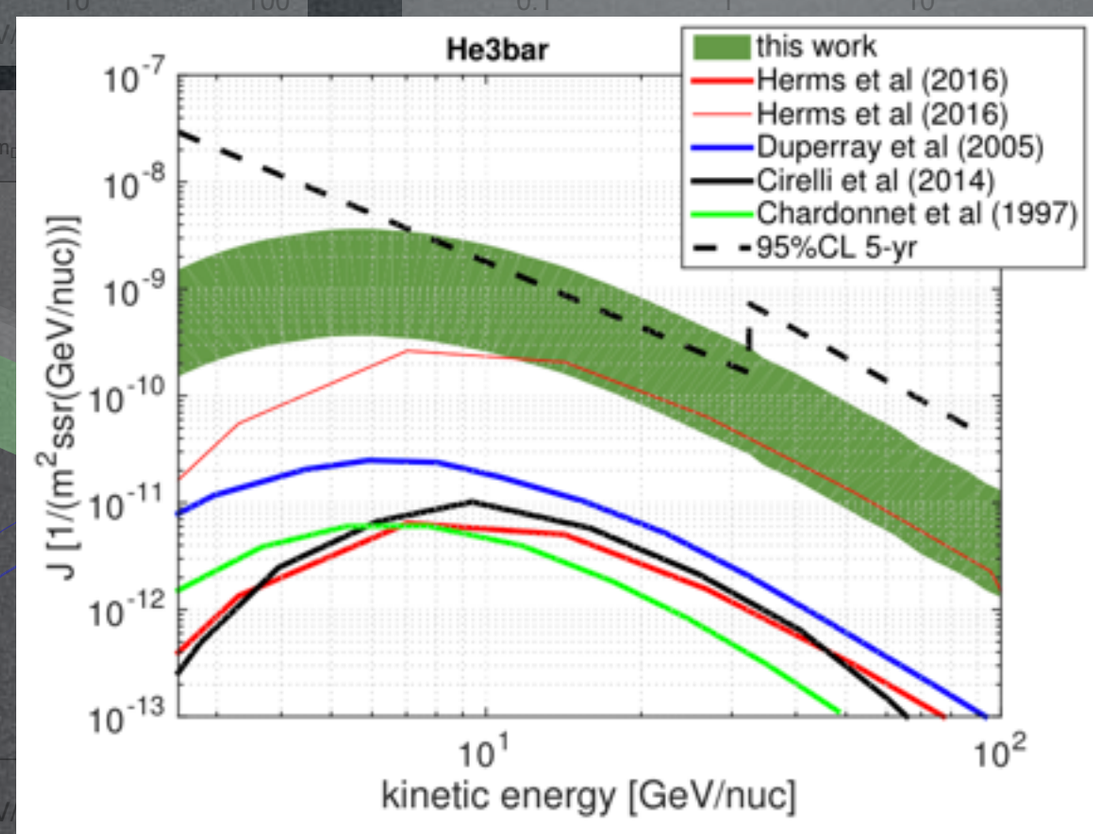


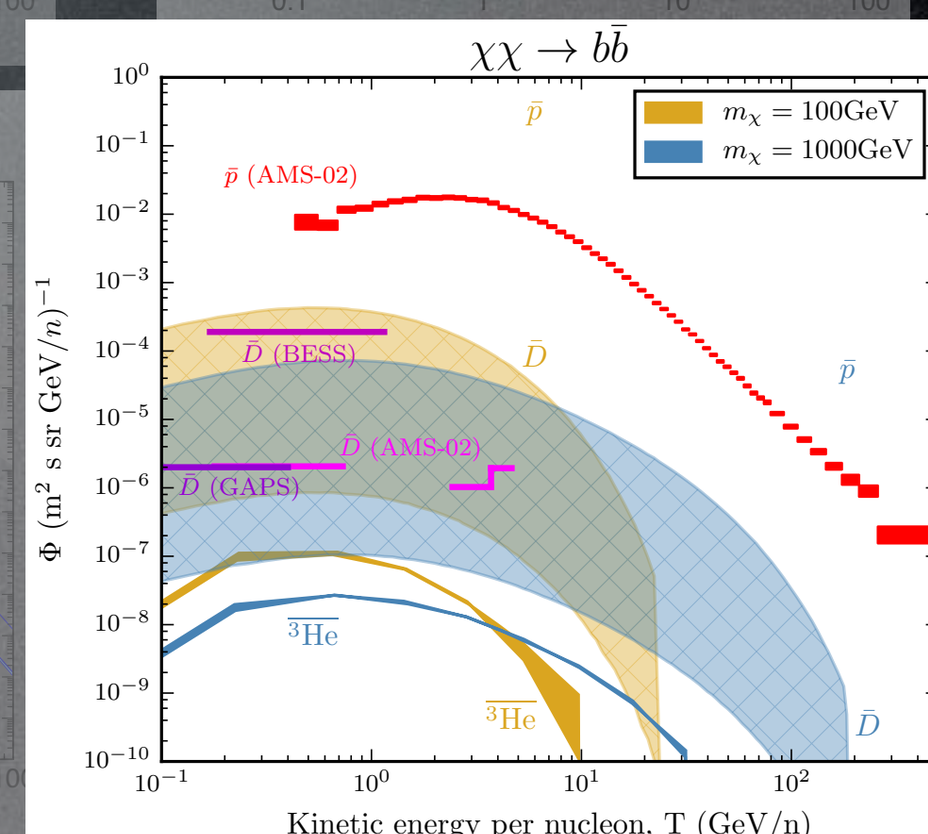


update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data

update:
Coogan, Profumo (1705.09664)
find 5 He in 5yrs in AMS possible,
marginally compatible with p, D







Conclusions

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DM not seen yet (Damn!...)

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Charged cosmic rays are in principle
a very powerful tool

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in *p*: still large uncertainties
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in *He*: hopeless? who knows

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Back up slides

Introduction

Introduction

DM exists

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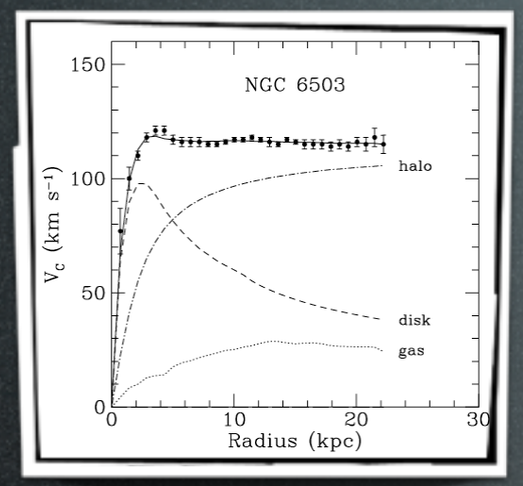
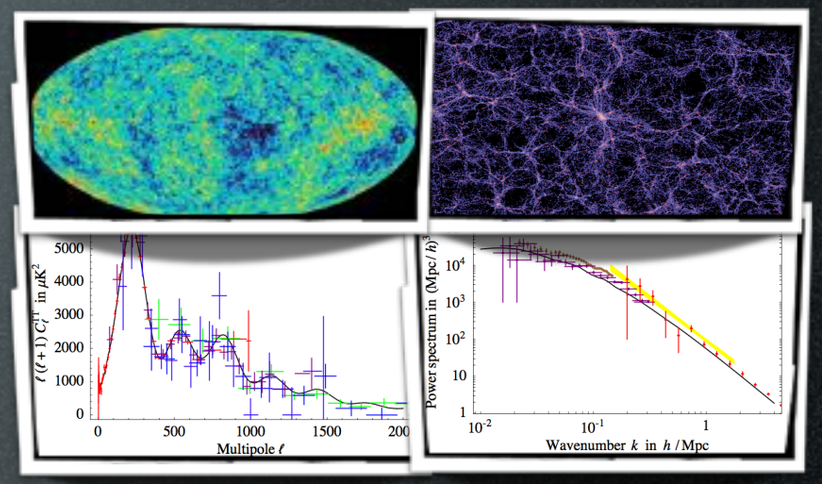
DM exists



galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Introduction

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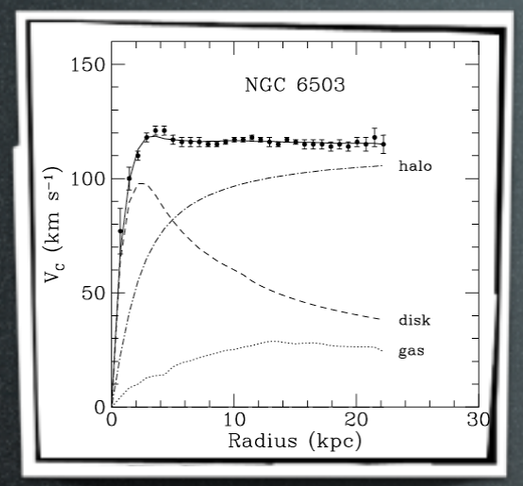

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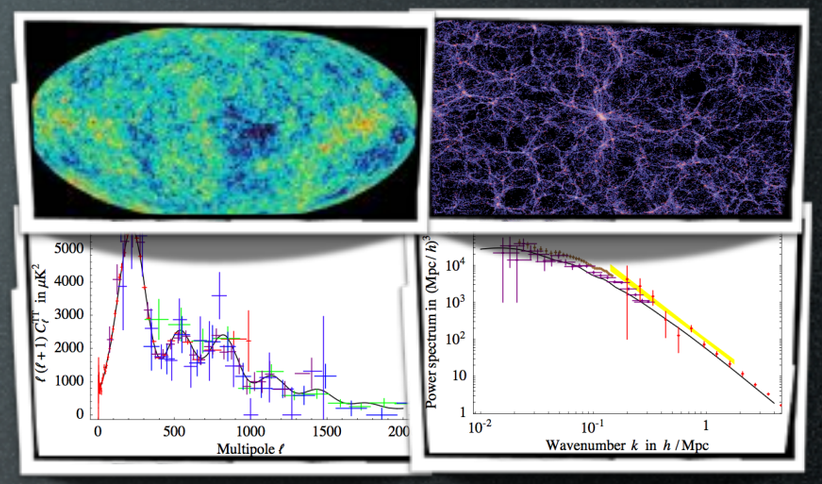

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DM is a neutral, very long lived, feebly interacting particle.

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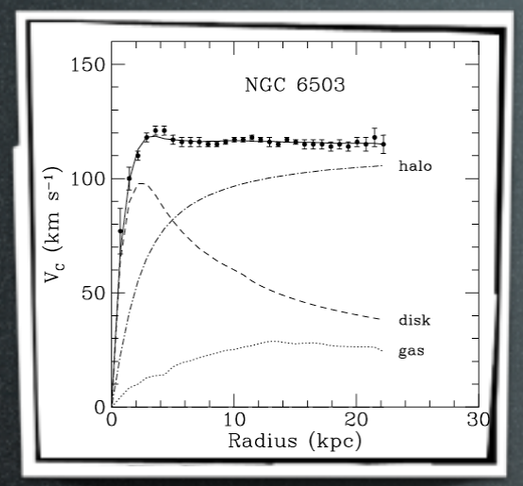

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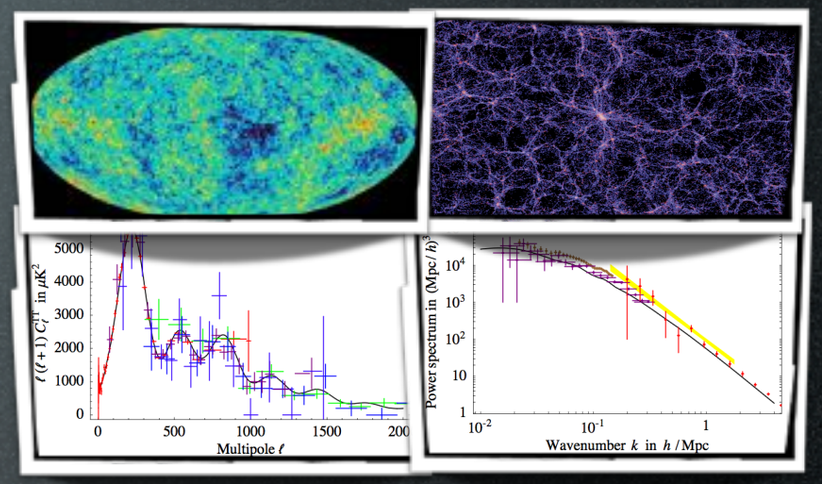
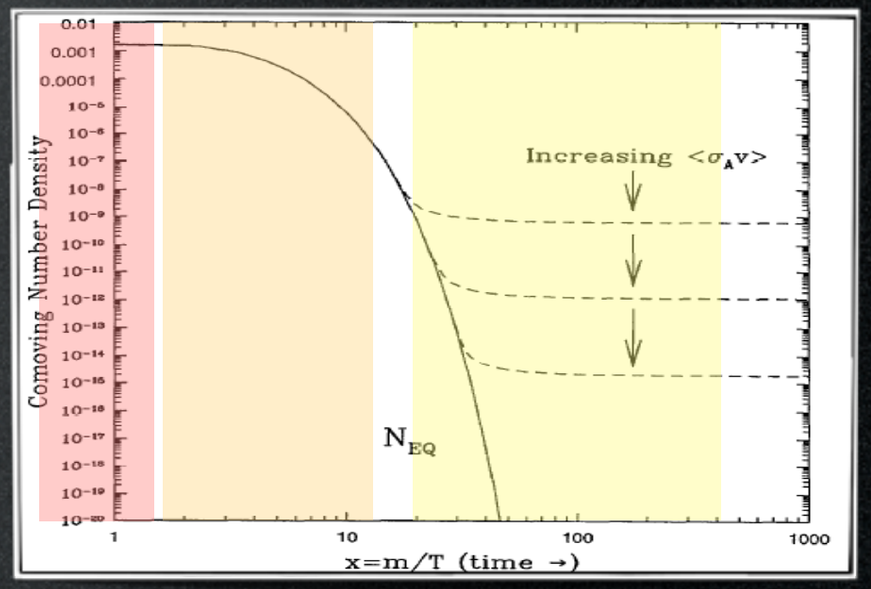


'precision cosmology' (CMB, LSS)

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

Some of us believe in the WIMP miracle.

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



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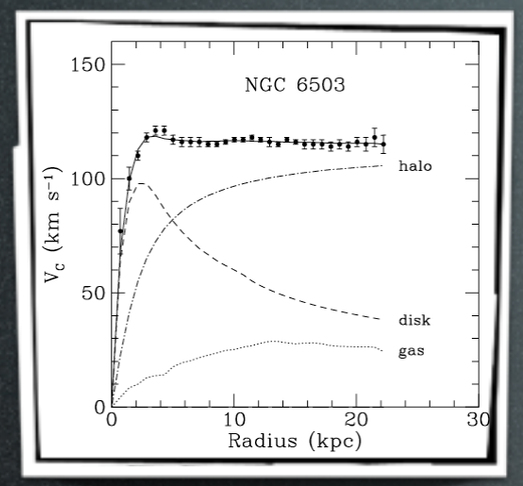

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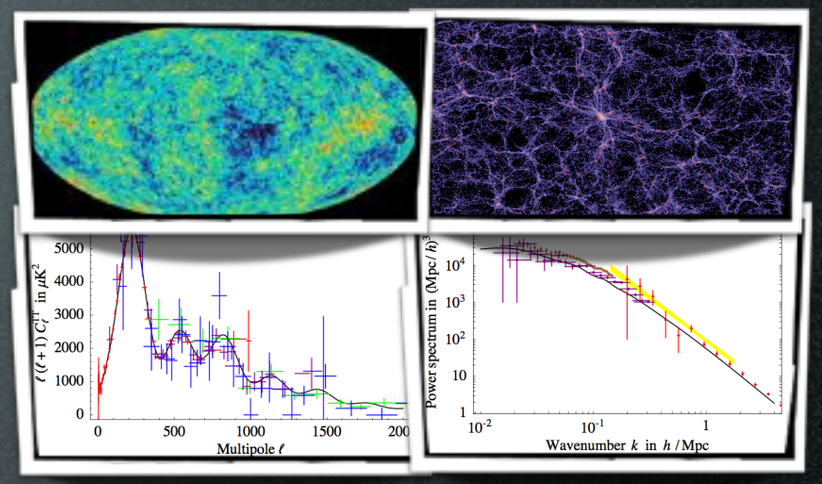


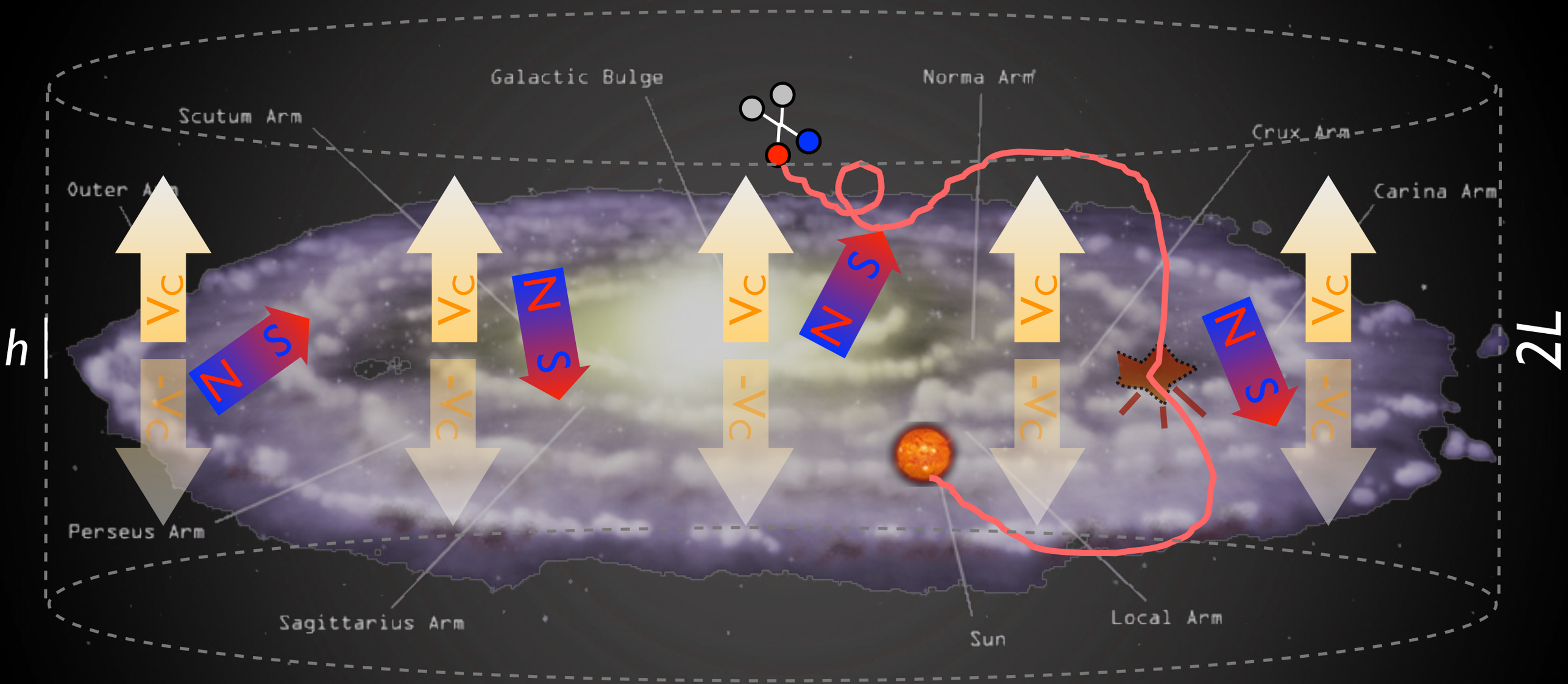
'precision cosmology' (CMB, LSS)

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?

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

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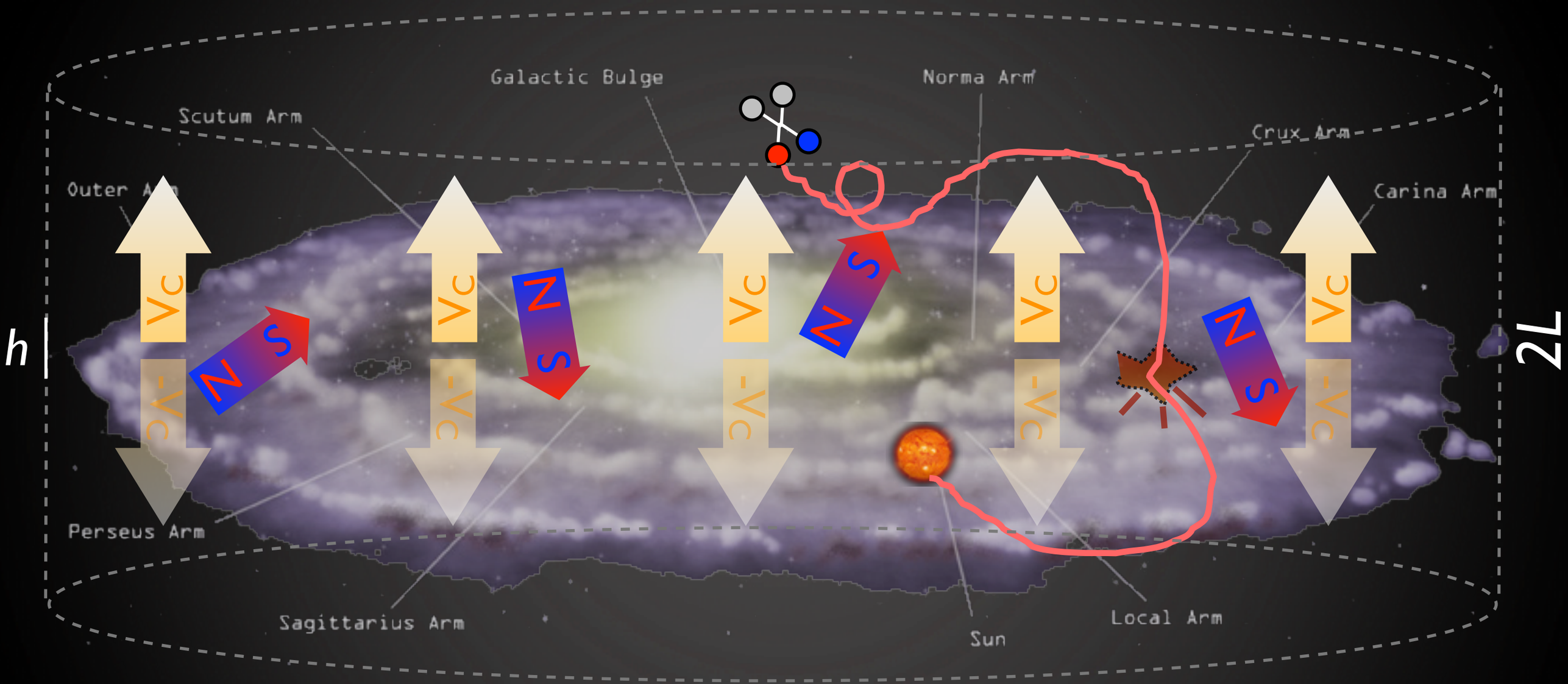

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astro& cosmo

particle

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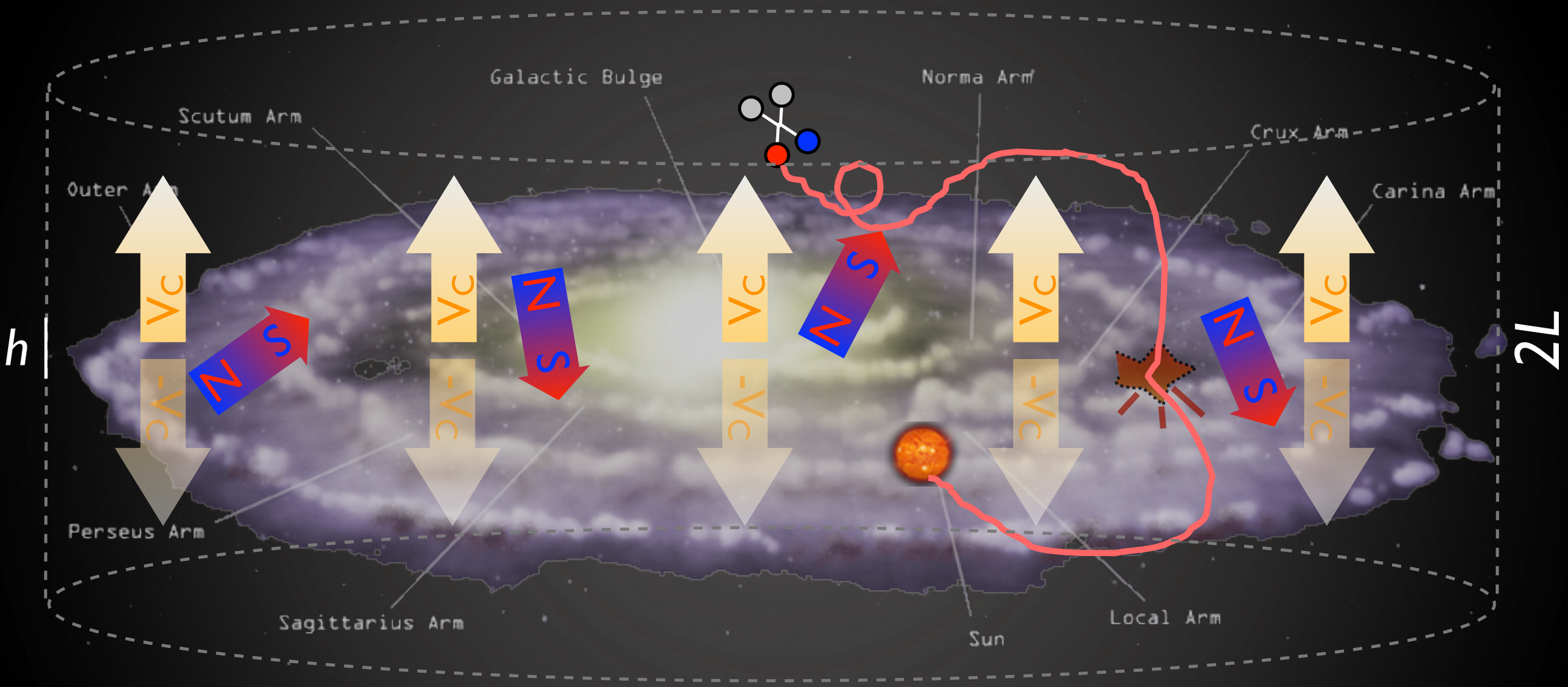

What sets the overall expected flux?

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astro& cosmo

particle

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

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

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

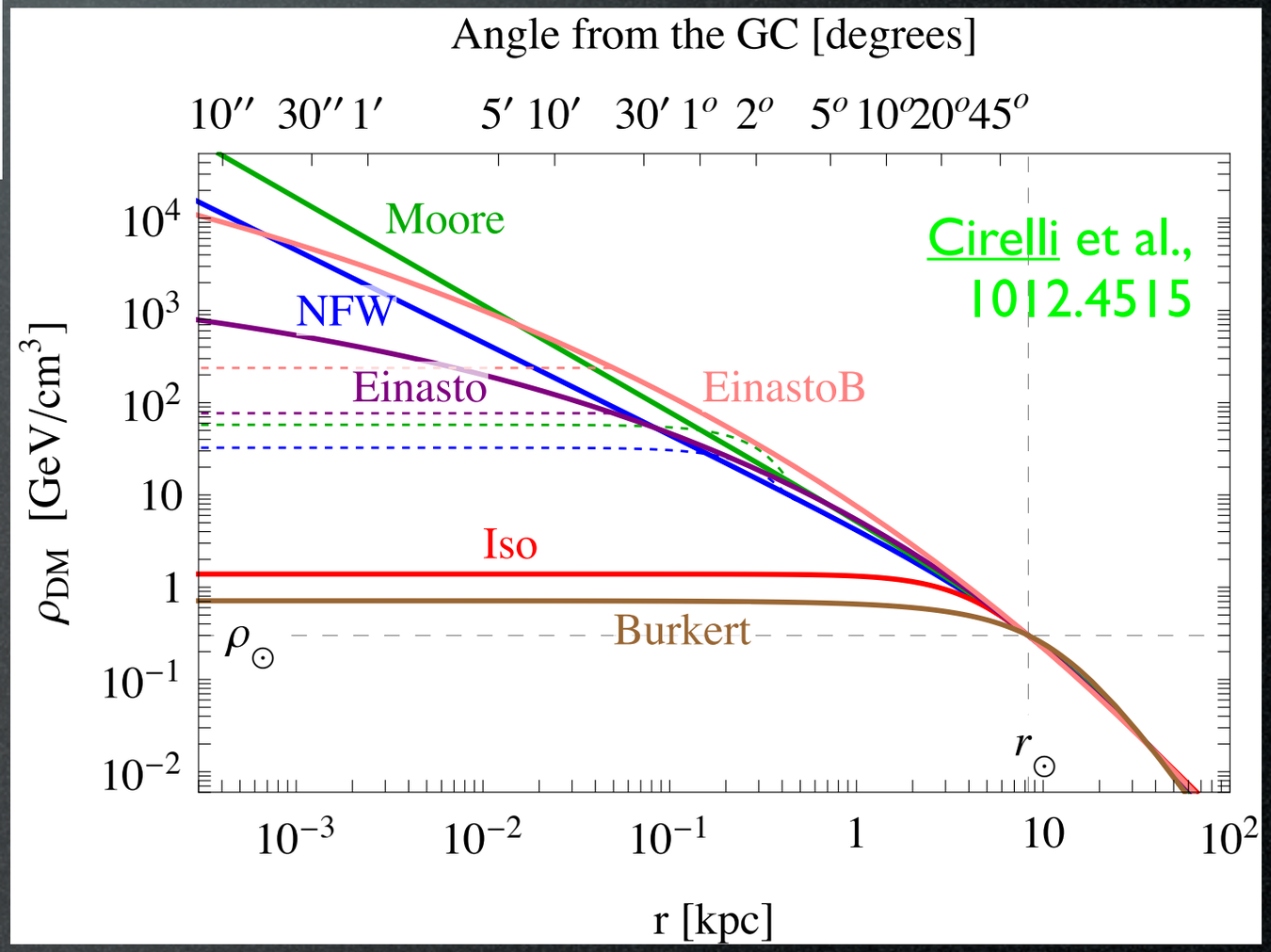
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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

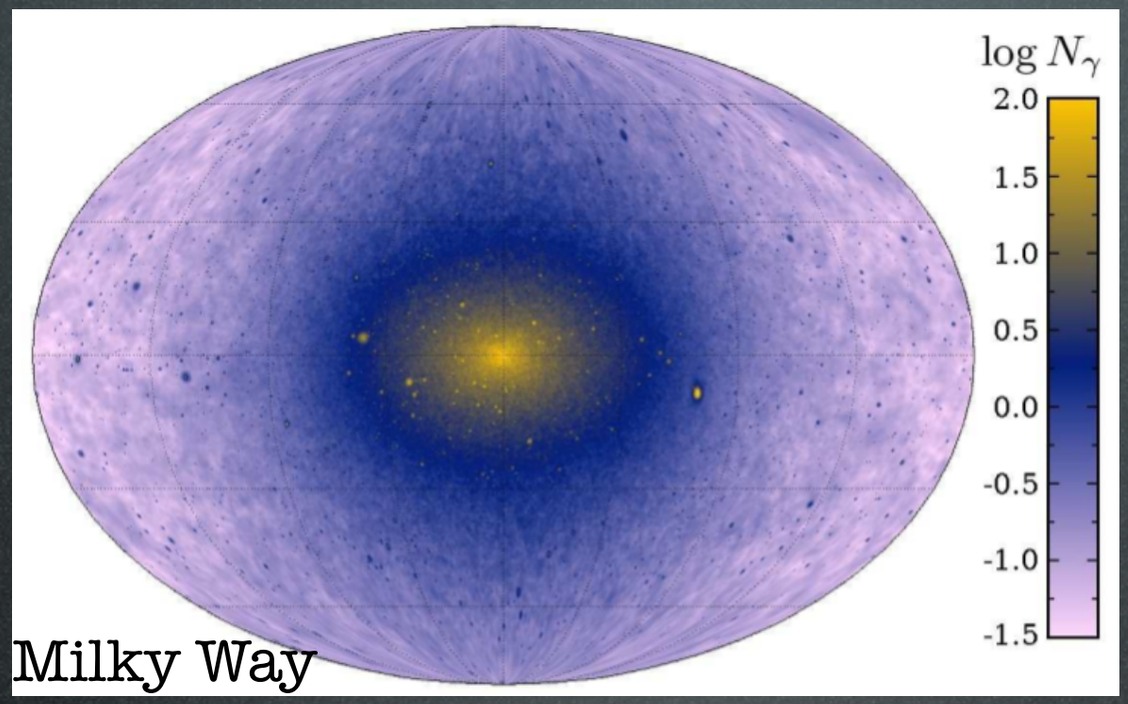
EinastoB = steepened Einasto

(effect of baryons?)

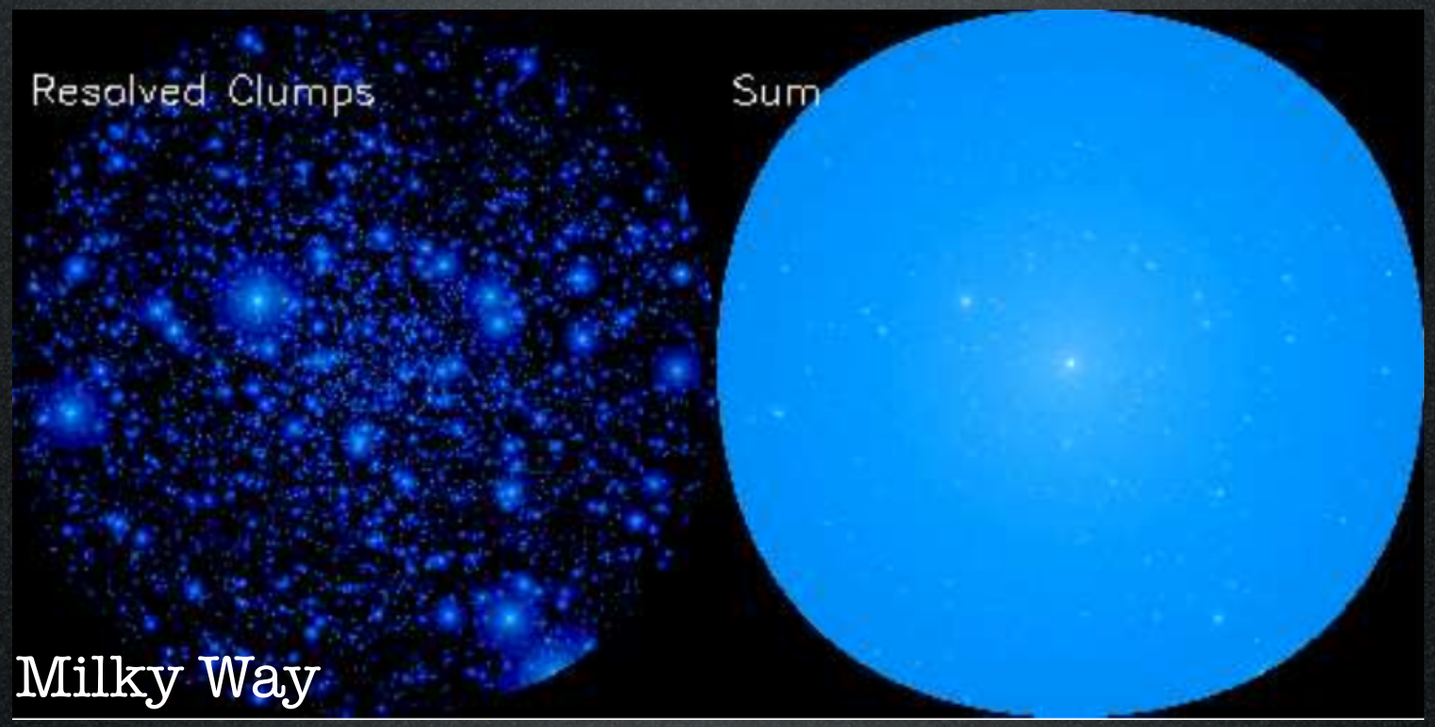
DM halo profiles

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

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

T kinetic energy

convective wind

spallations

Propagation

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Model	δ	K_0 in kpc^2/Myr	L in kpc	V_{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:

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

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

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max	0.46	0.0765	15	5

Solution:

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