19 December 2017
Annual UK Theory Meeting
Durham

Dark Matter Indirect Searches

Marco Cirelli
(CNRS LPTHE Jussieu)

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Introduction

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DM exists

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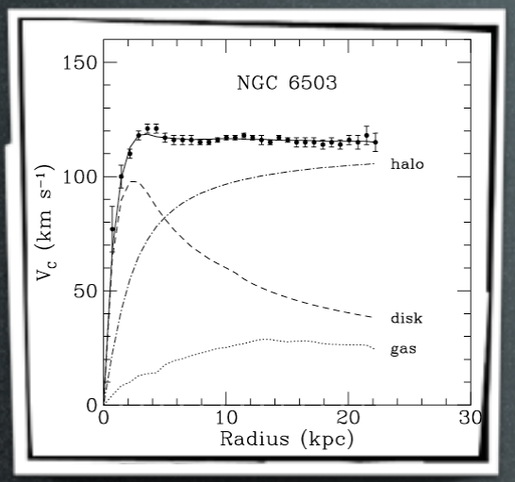
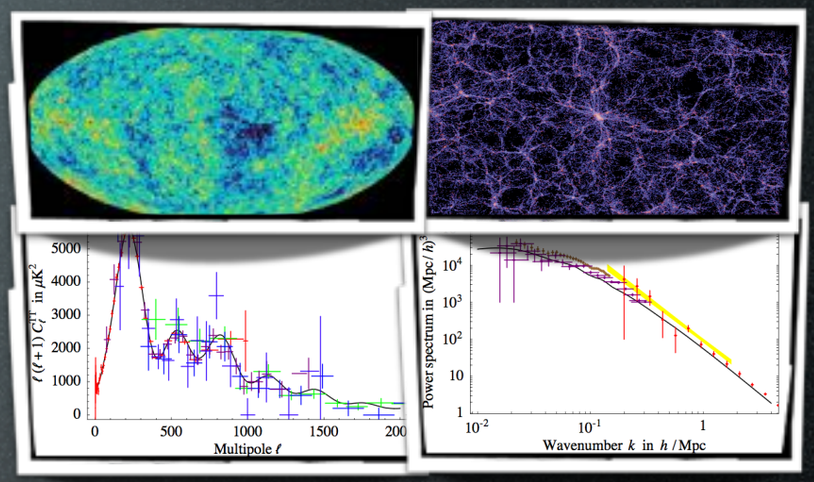


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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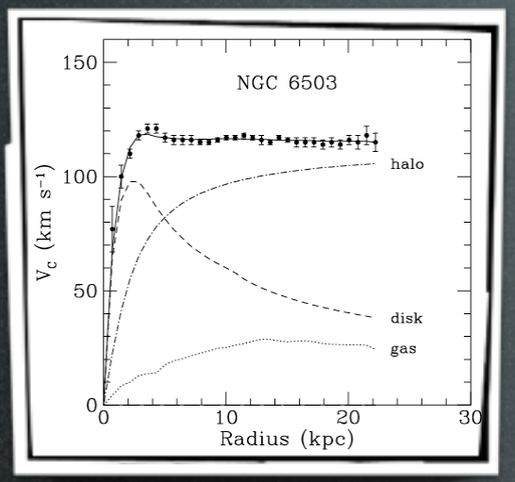

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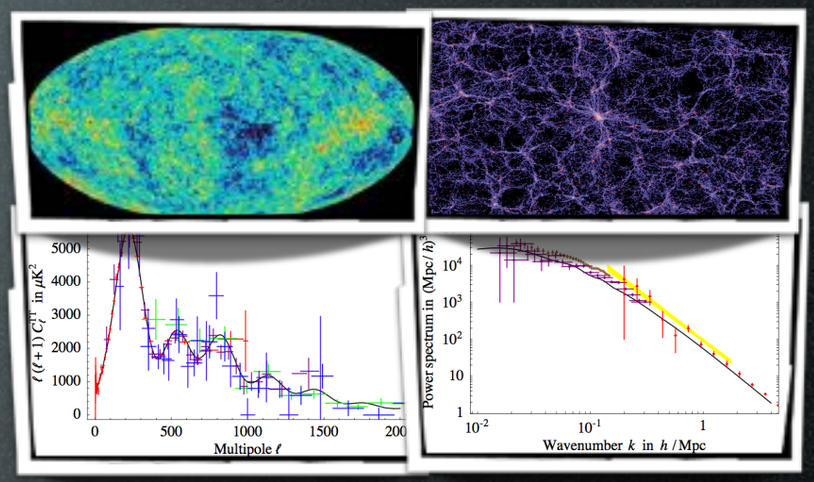

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DM is a neutral, very long lived, feebly- interacting corpuscle.

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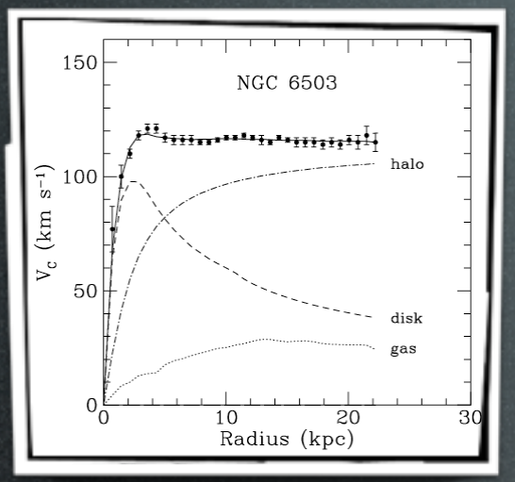

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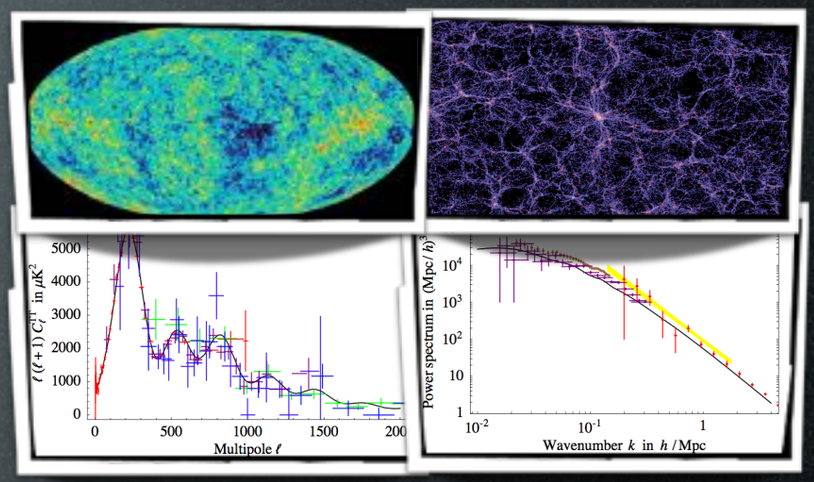
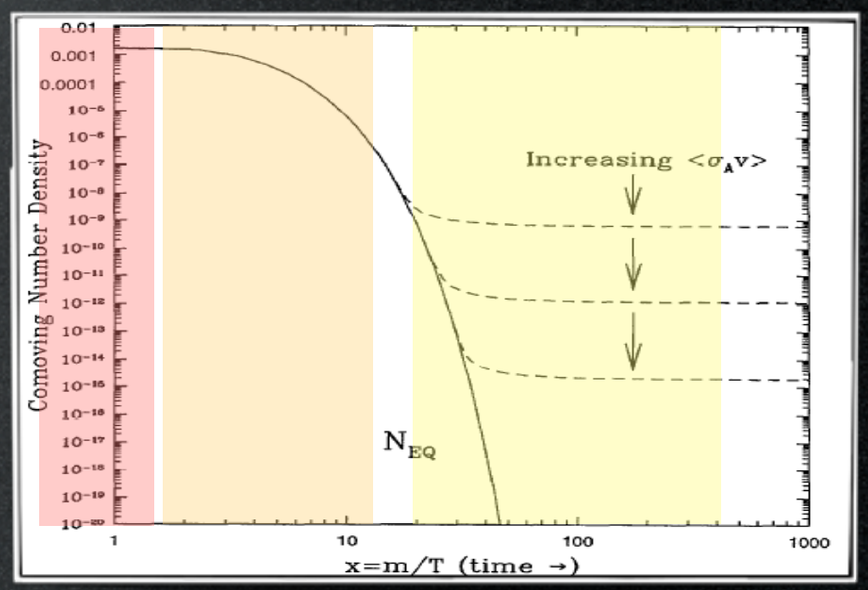


'precision cosmology' (CMB, LSS)

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

Some of us believe in the WIMP miracle.

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



DM 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, Antares

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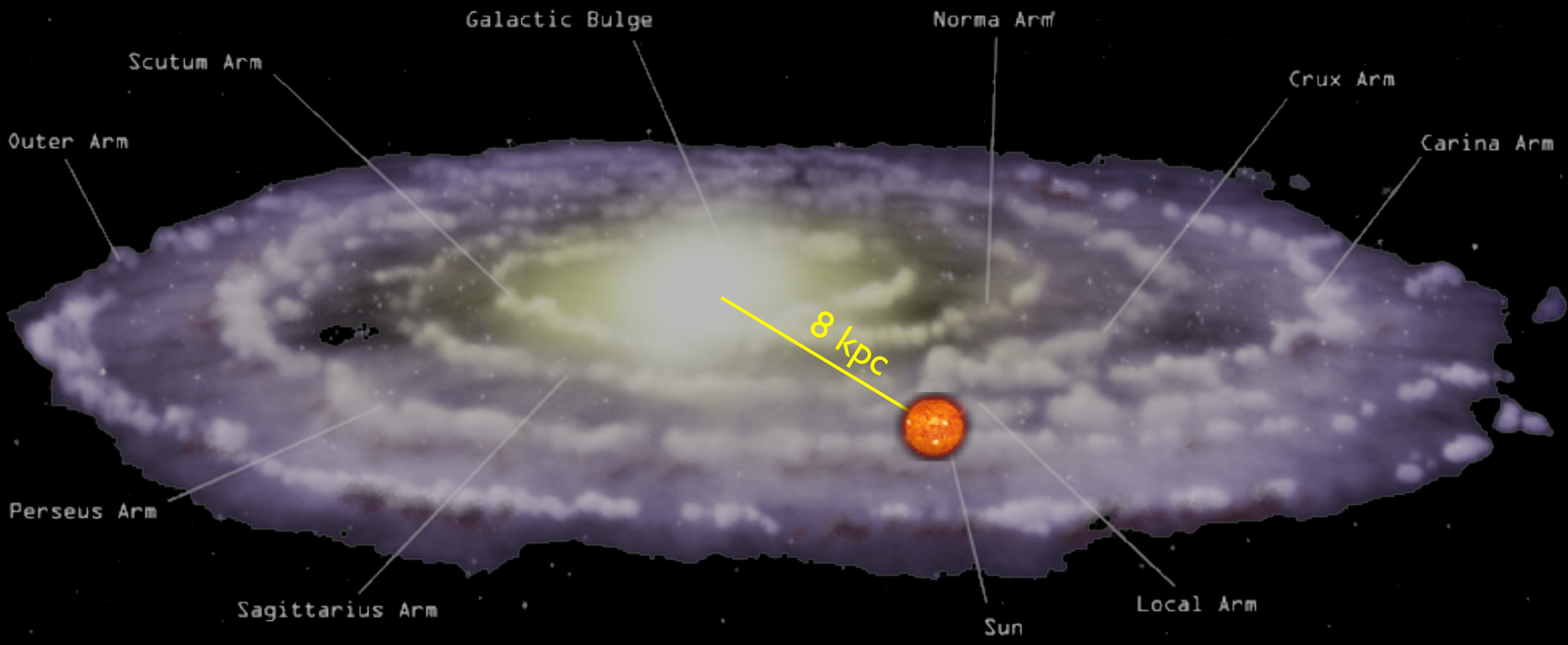
Indirect Detection: basics

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



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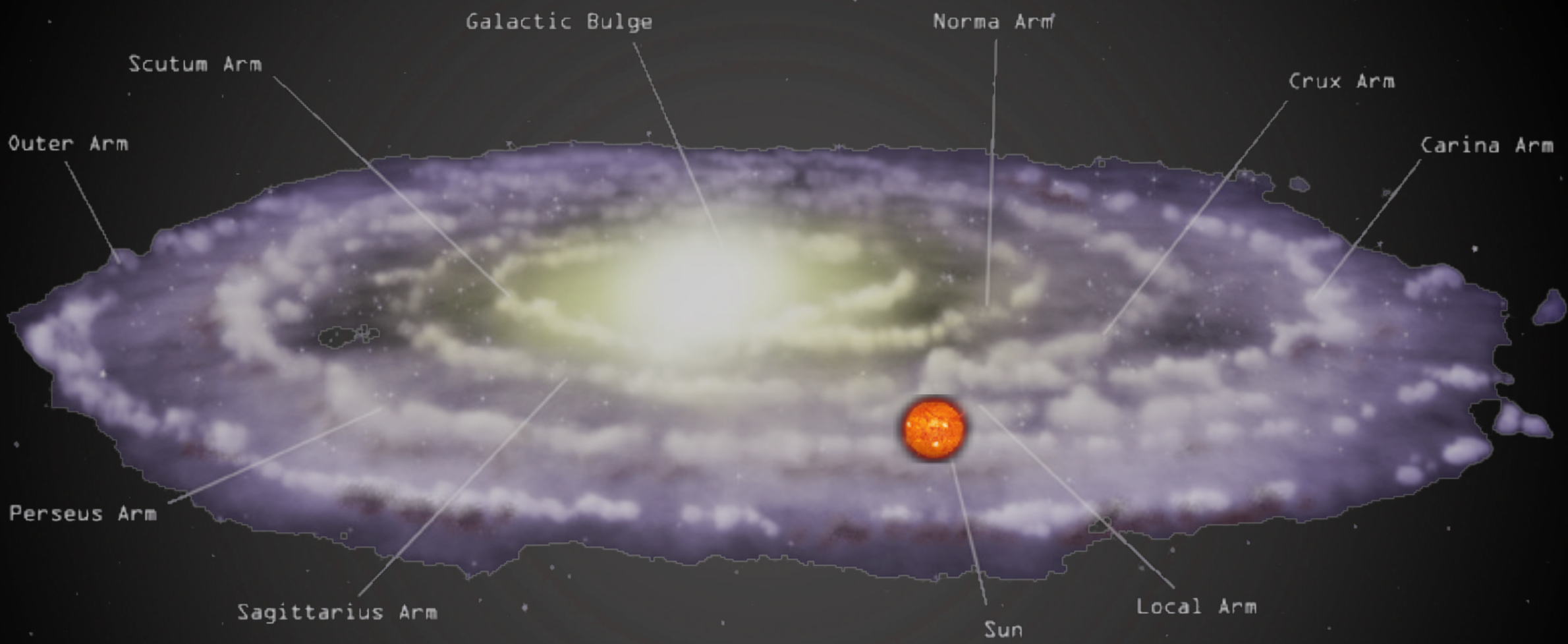

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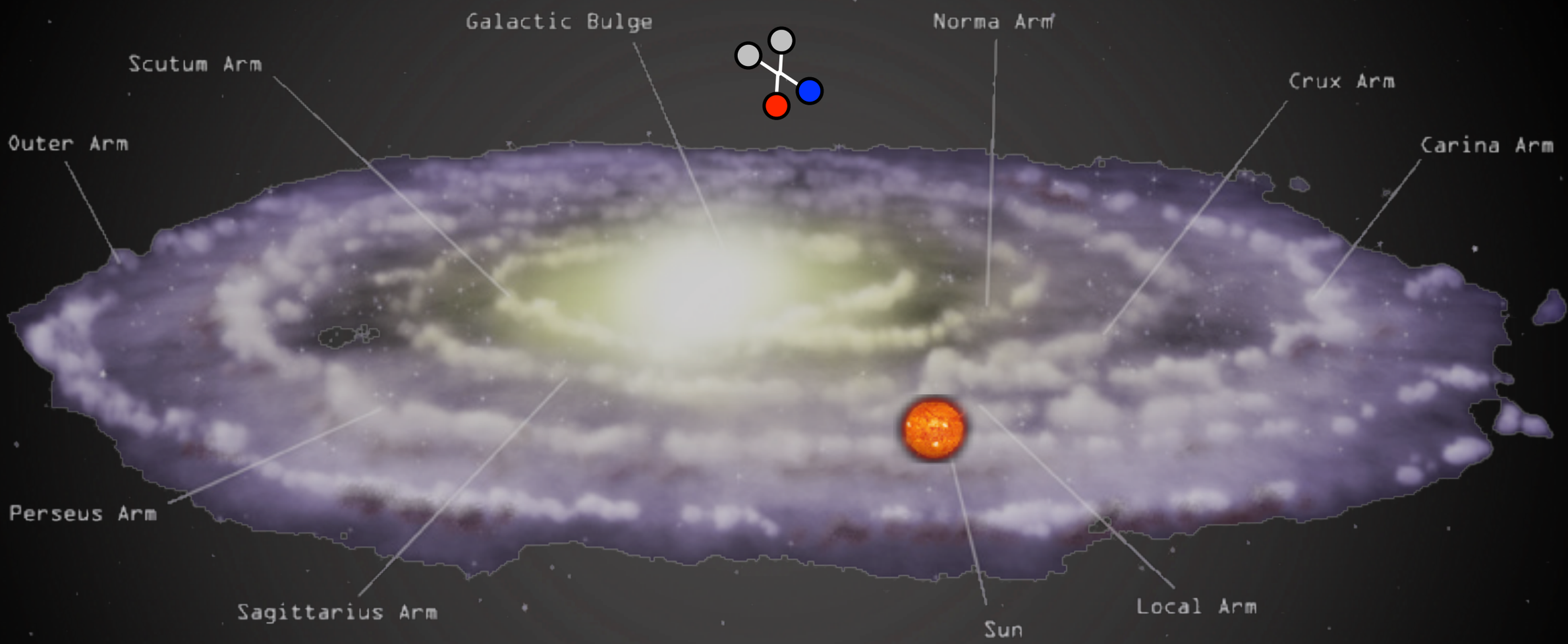

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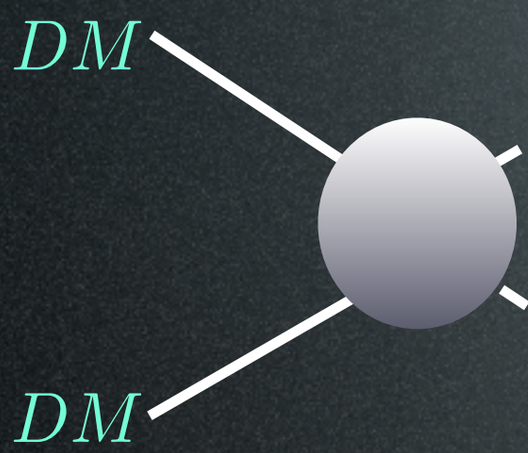

$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

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

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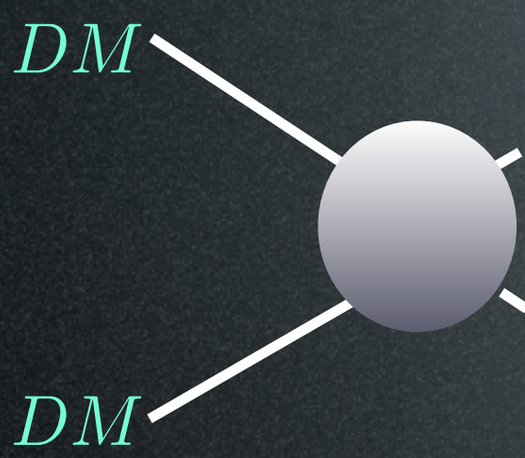

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

primary channels

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

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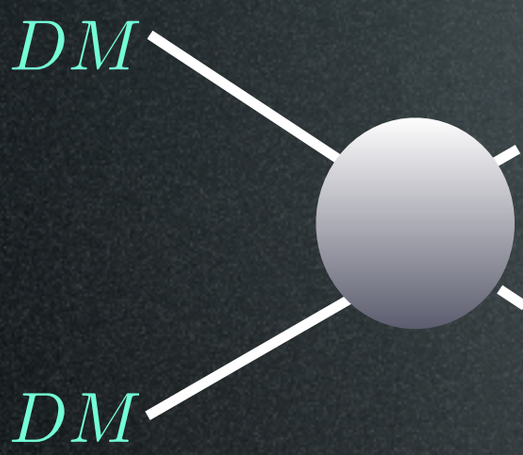

$W^-, Z, b, \tau^-, t, h \ldots$

primary channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

decay

$\rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

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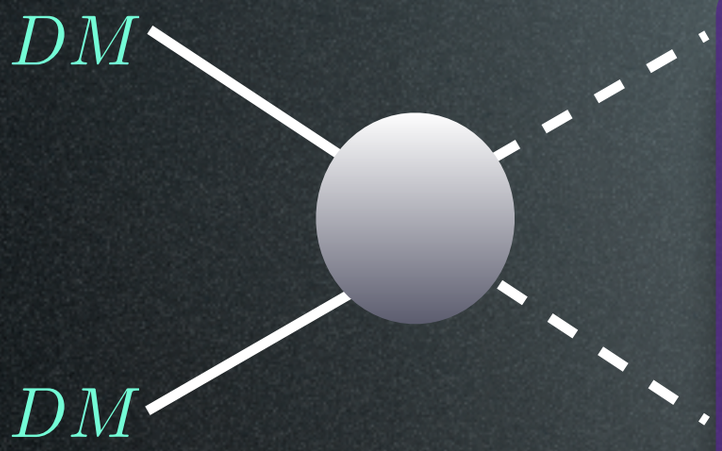
Indirect Detection: basics



$W^-, Z, b, \tau^-, t, h \ldots$

primary channels

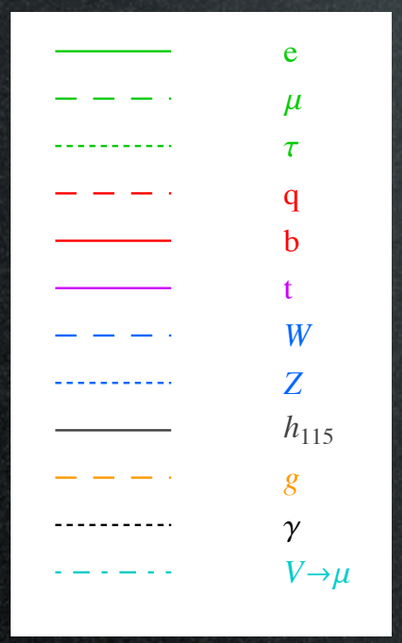
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

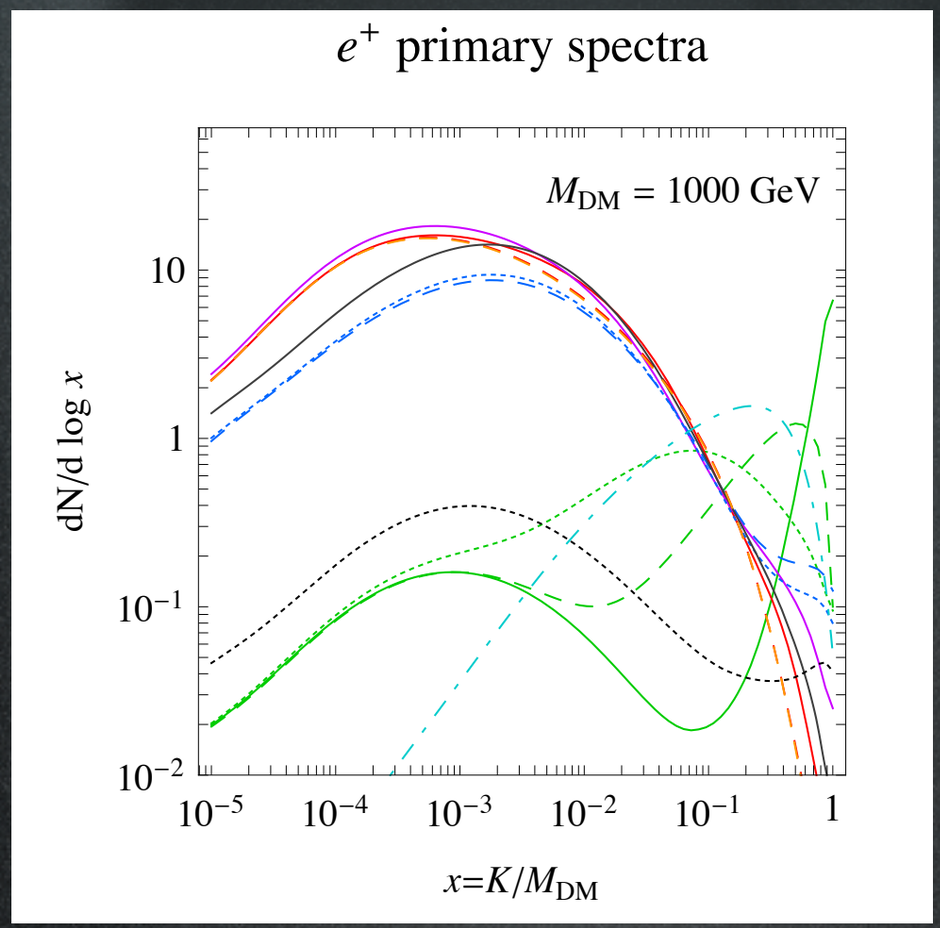
decay

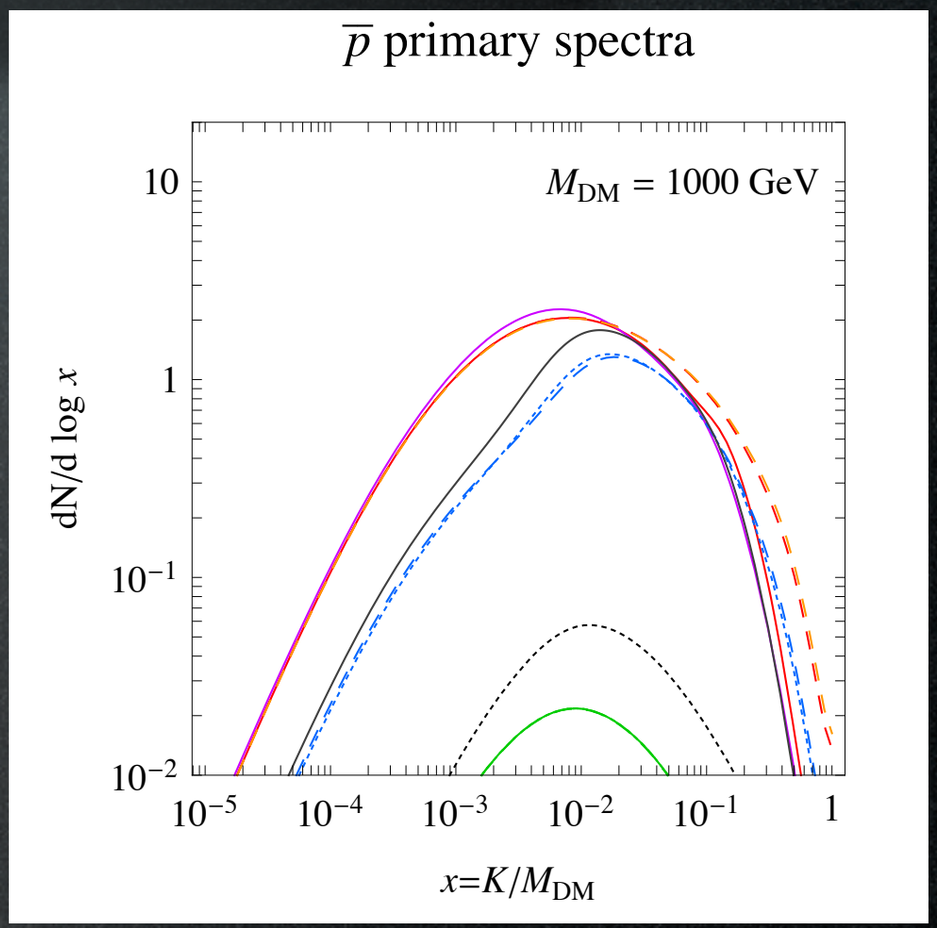
$e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

final products

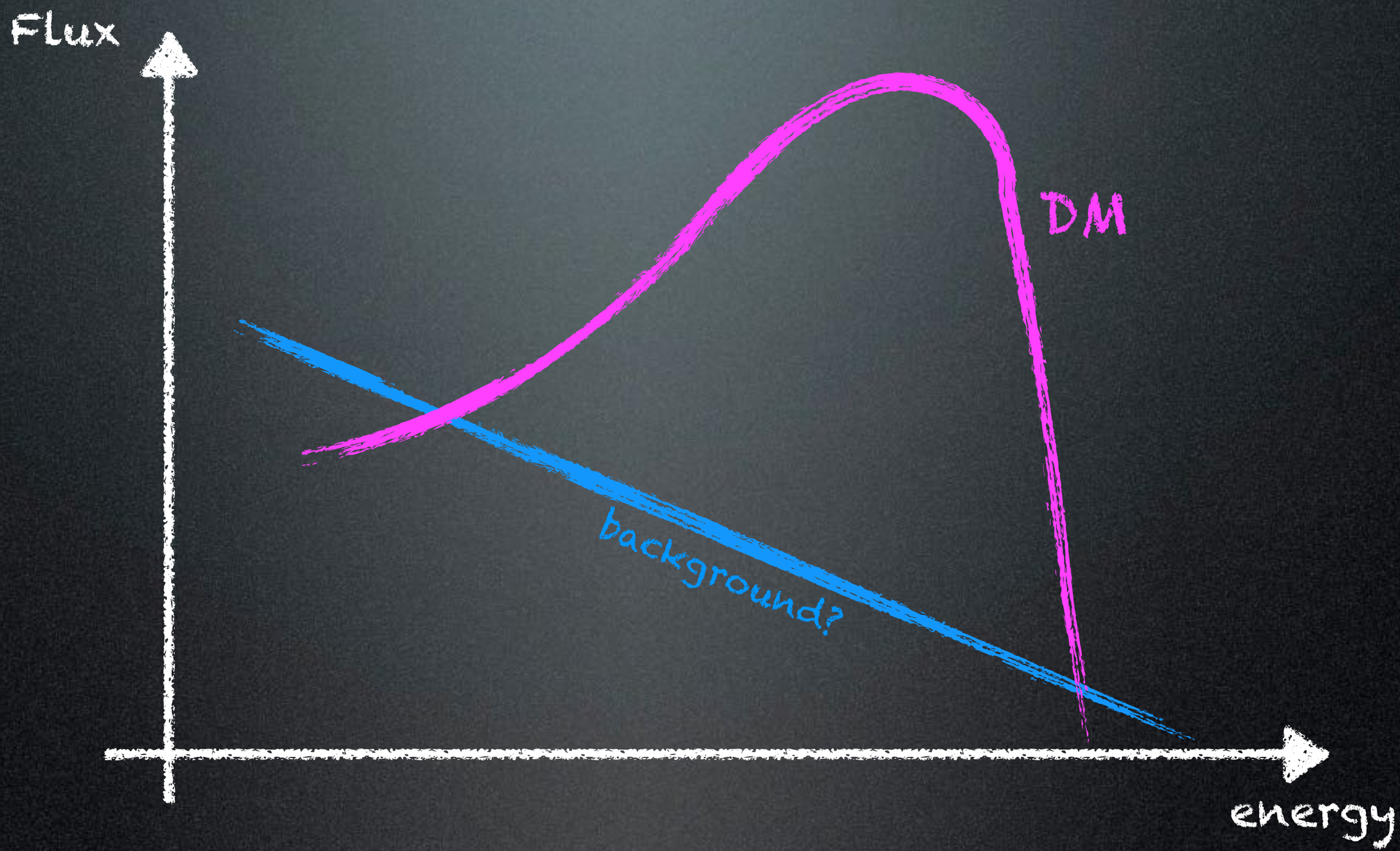
$e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$





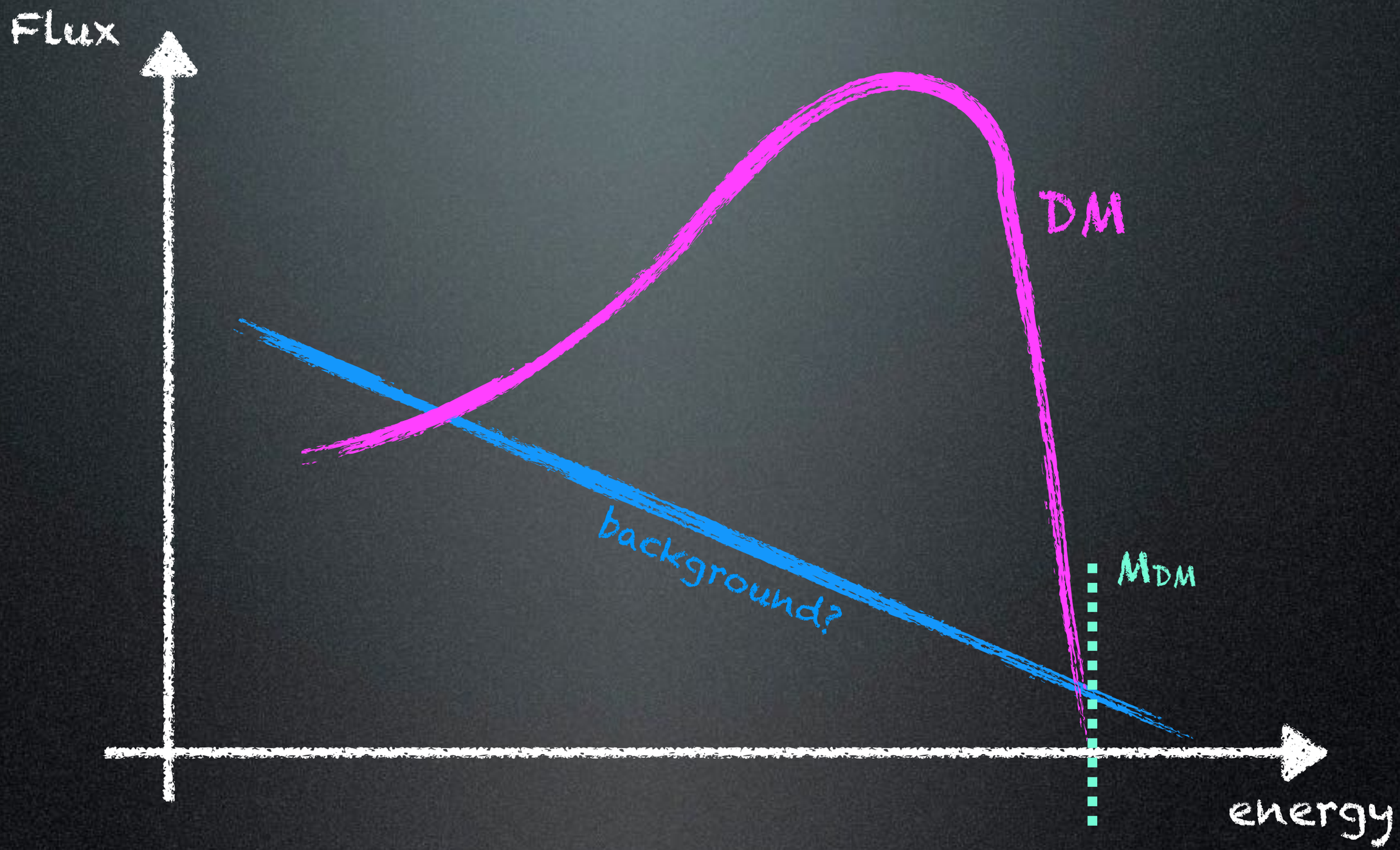


Fluxes at production



So what are the particle physics parameters?

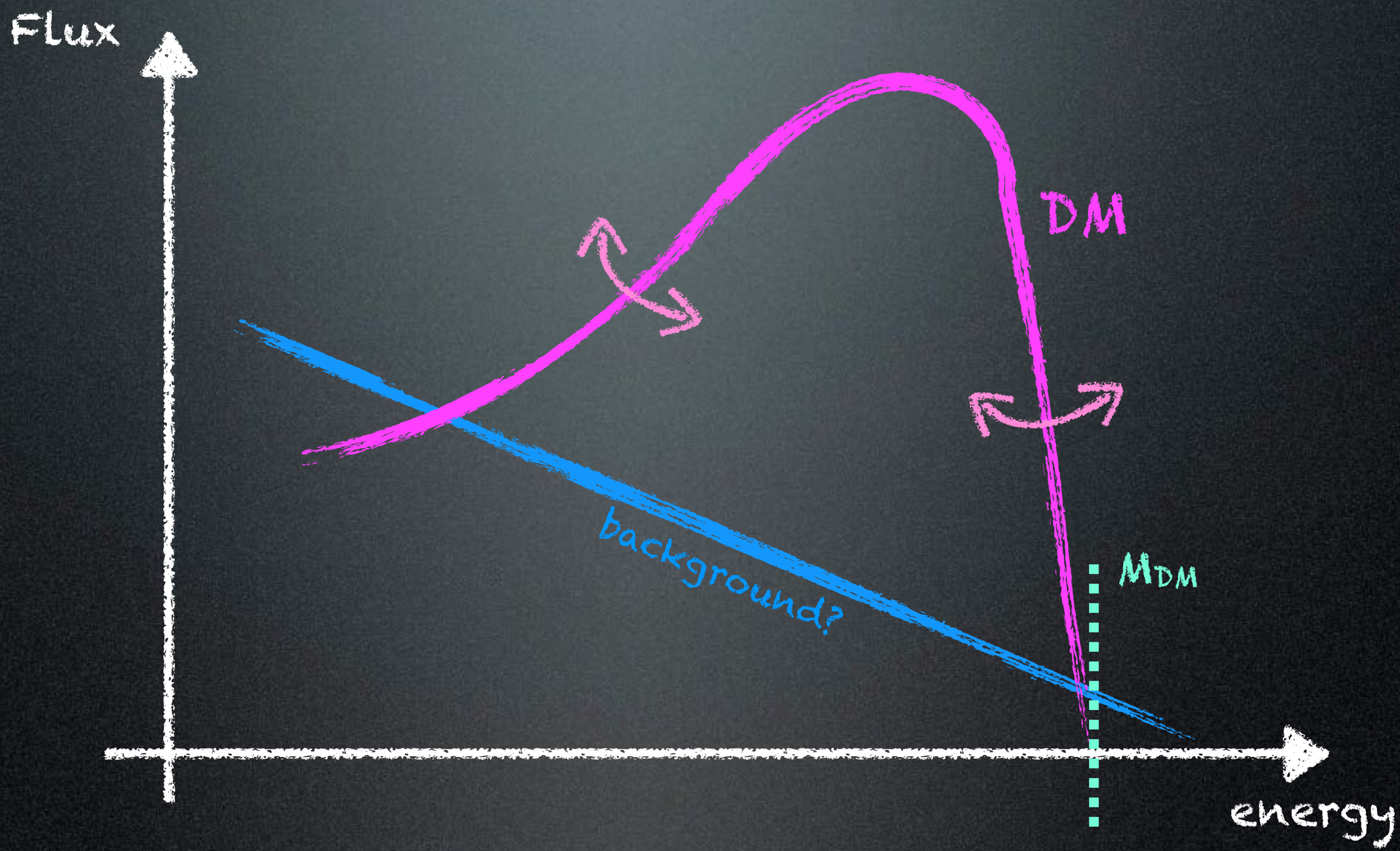
Fluxes at production



So what are the particle physics parameters?

1. Dark Matter mass

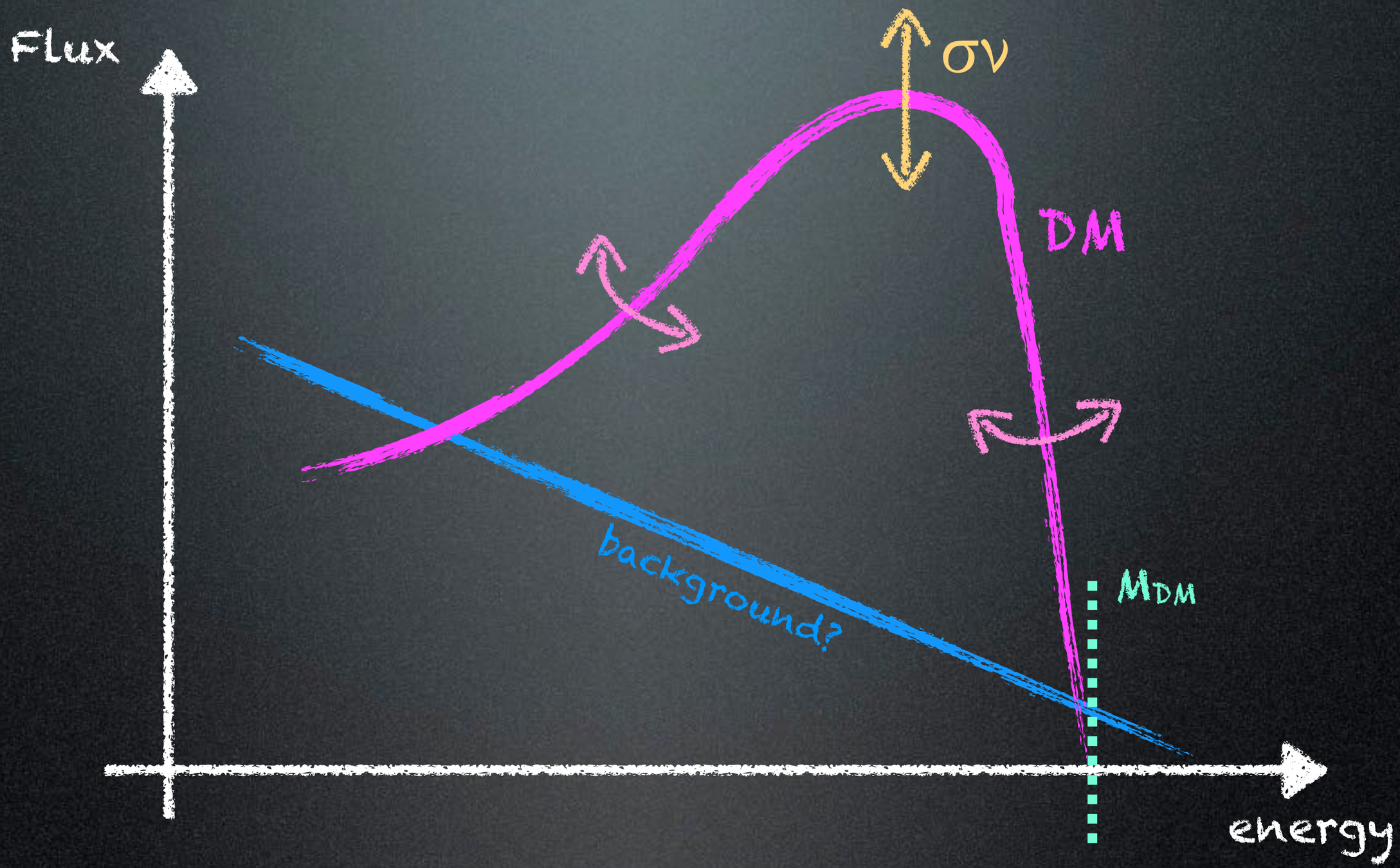
Fluxes at production



So what are the particle physics parameters?

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

Fluxes at production

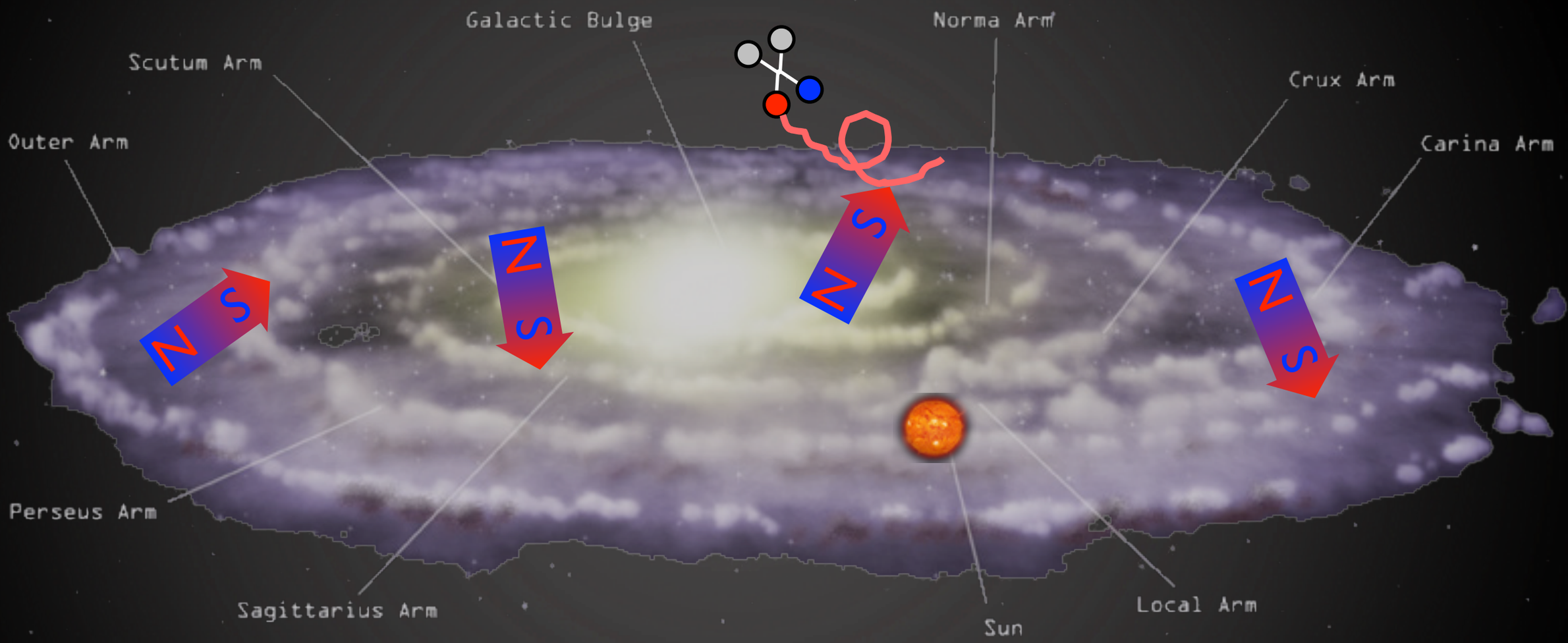


So what are the particle physics parameters?

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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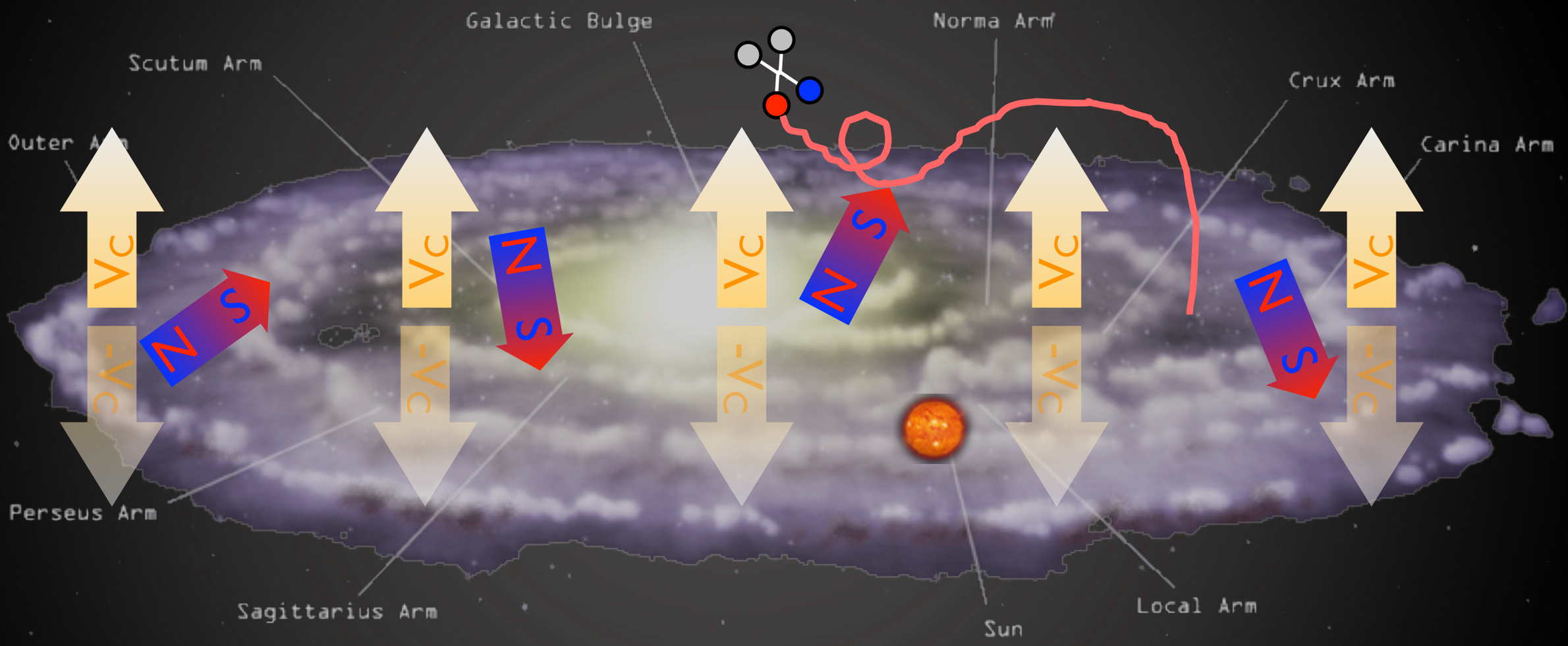

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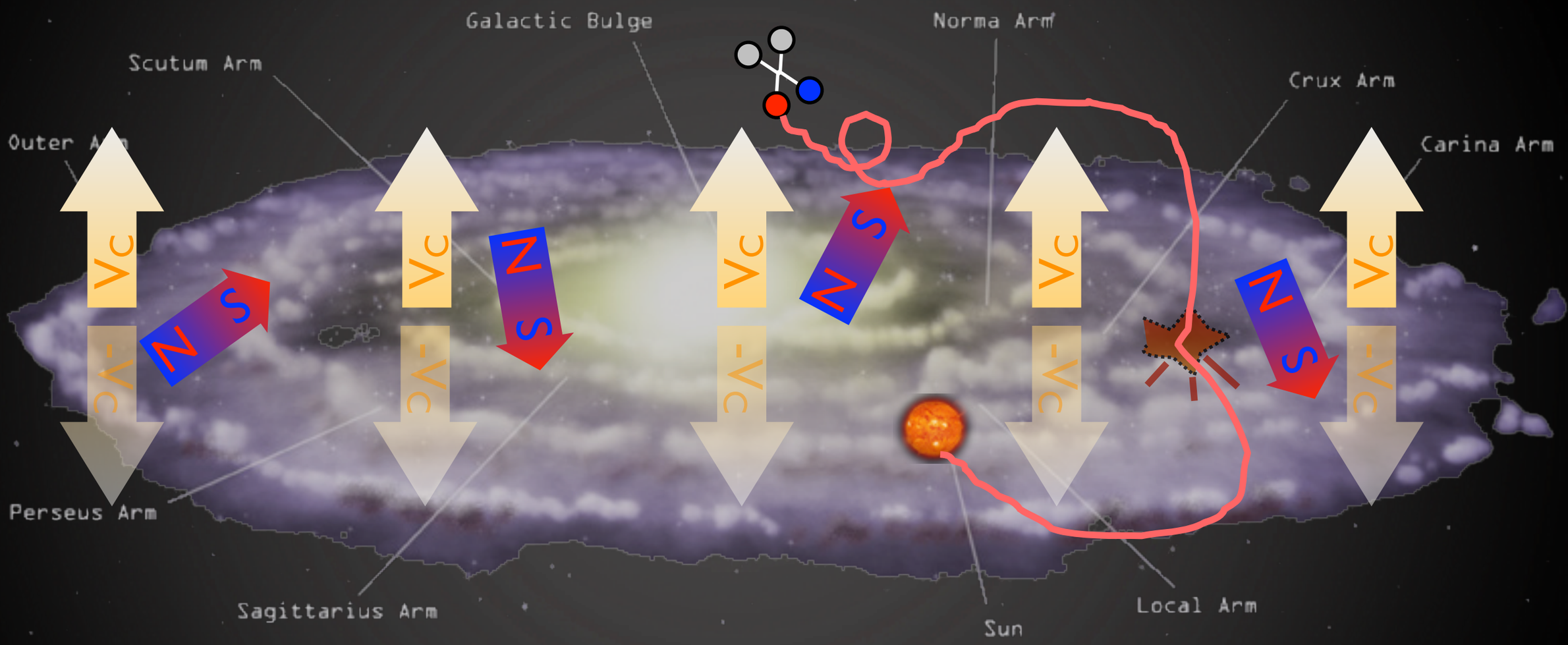

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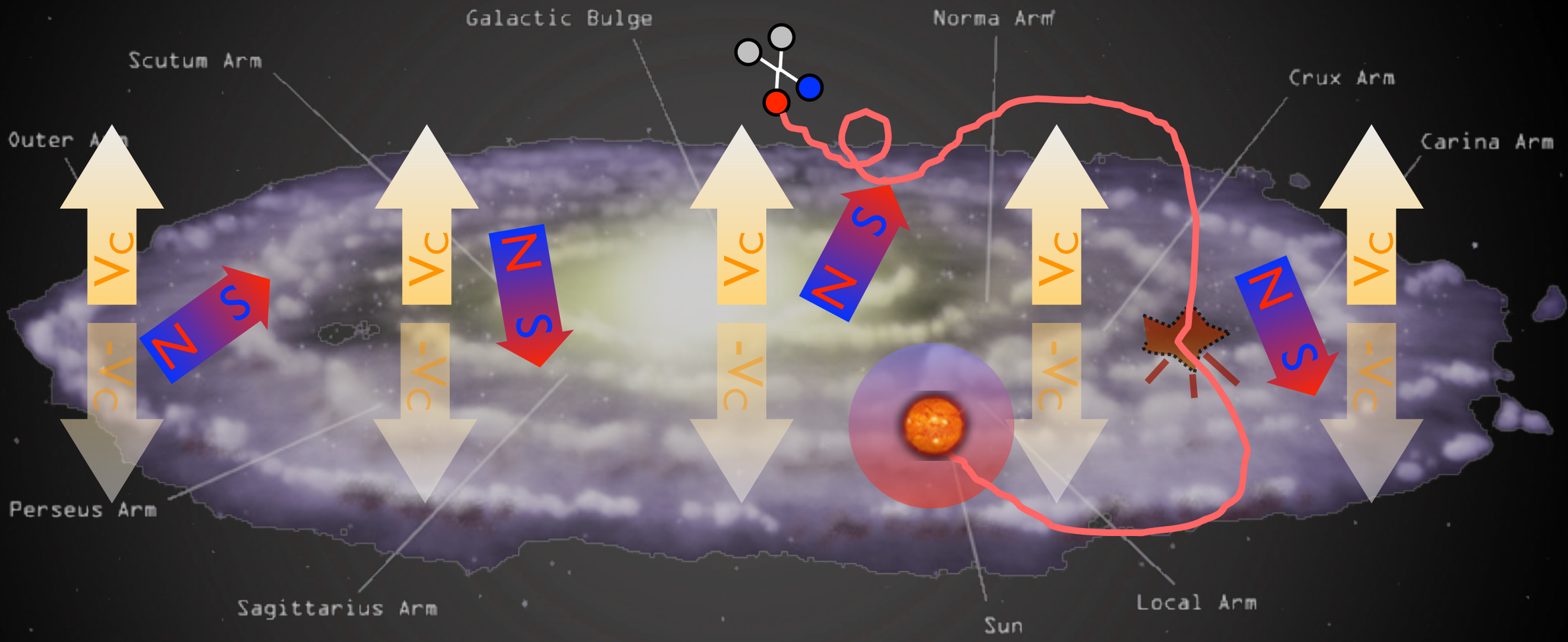

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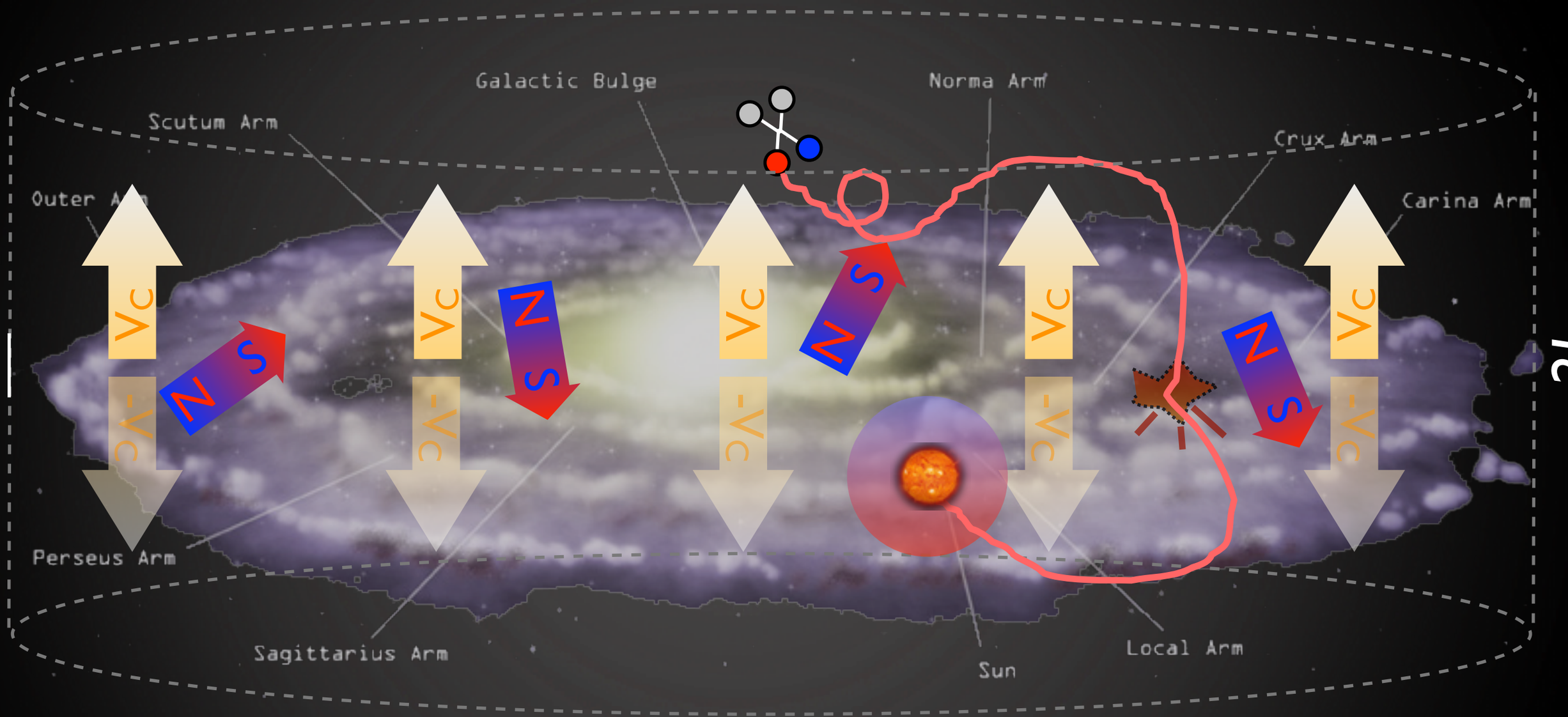

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum

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

diffusion | energy loss | convective wind | source | spallations [uncert]

Indirect Detection: charged CRs

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

thickness

diffusion {

diff. reacc.

p index

convection

solar mod.

	KRA	KOL	CON	THK	THN	THN2	THN3
L [kpc]	4	4	4	10	0.5	2	3
D_0 [10^{28} cm^2 s^{-1}]	2.64	4.46	0.97	4.75	0.31	1.35	1.98
δ	0.50	0.33	0.6	0.50	0.50	0.50	0.50
η	-0.39	1	1	-0.15	-0.27	-0.27	-0.27
v_A [km s^{-1}]	14.2	36	38.1	14.1	11.6	11.6	11.6
γ	2.35	1.78/2.45	1.62/2.35	2.35	2.35	2.35	2.35
dv_c/dz [km s^{-1} kpc^{-1}]	0	0	50	0	0	0	0
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+

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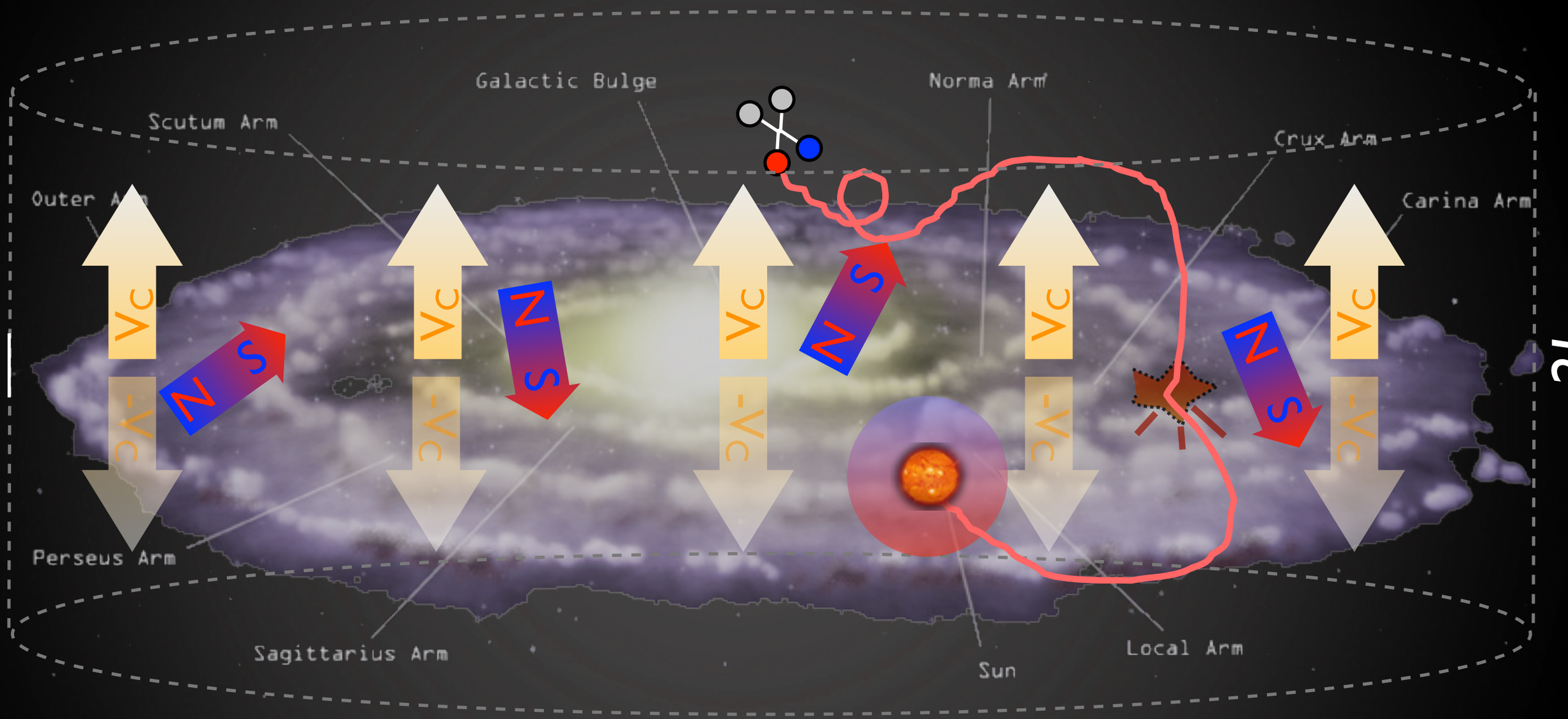

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diffusion | energy loss | convective wind | source | spallations

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

[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:

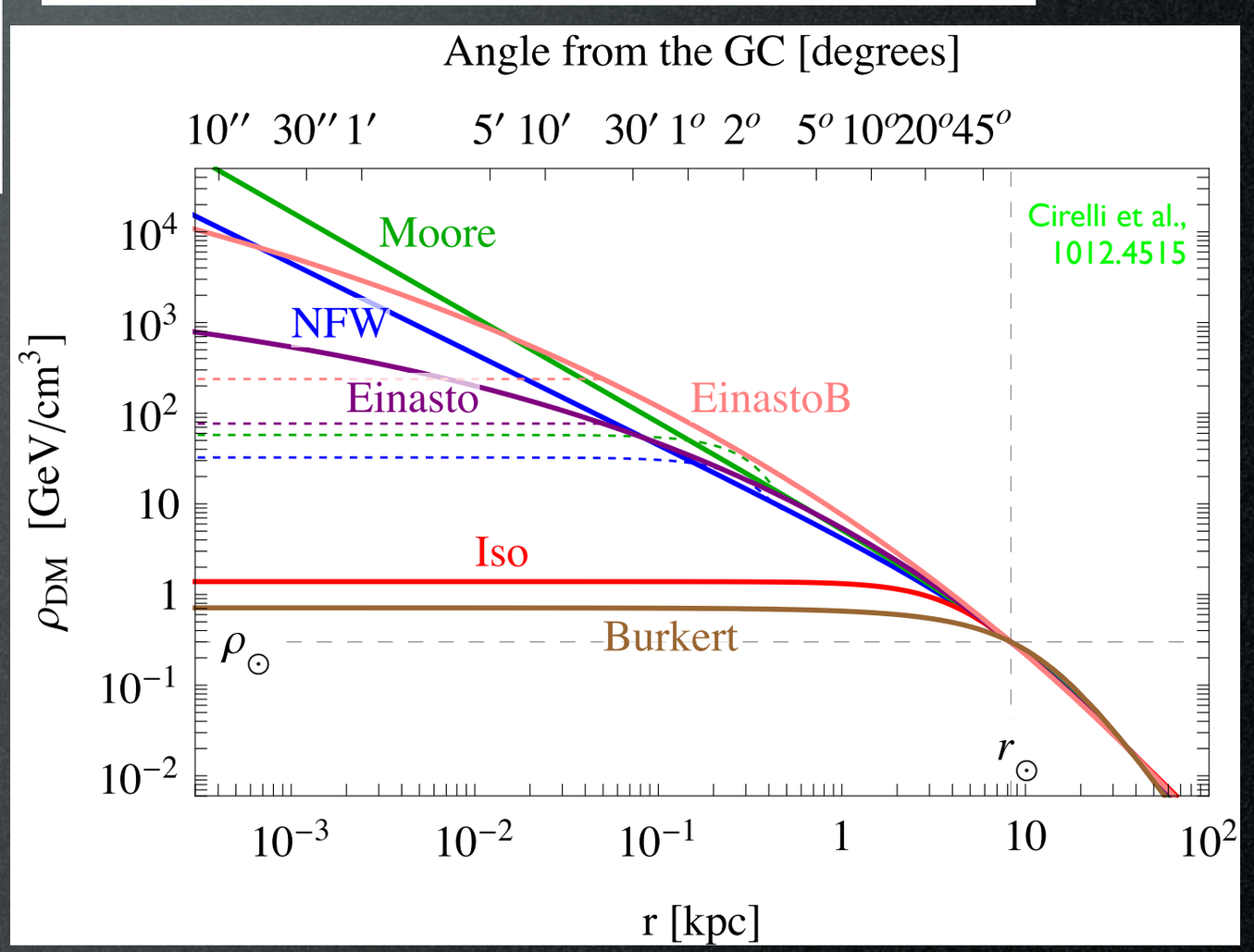
cuspy: NFW, Moore

mild: Einasto

smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)



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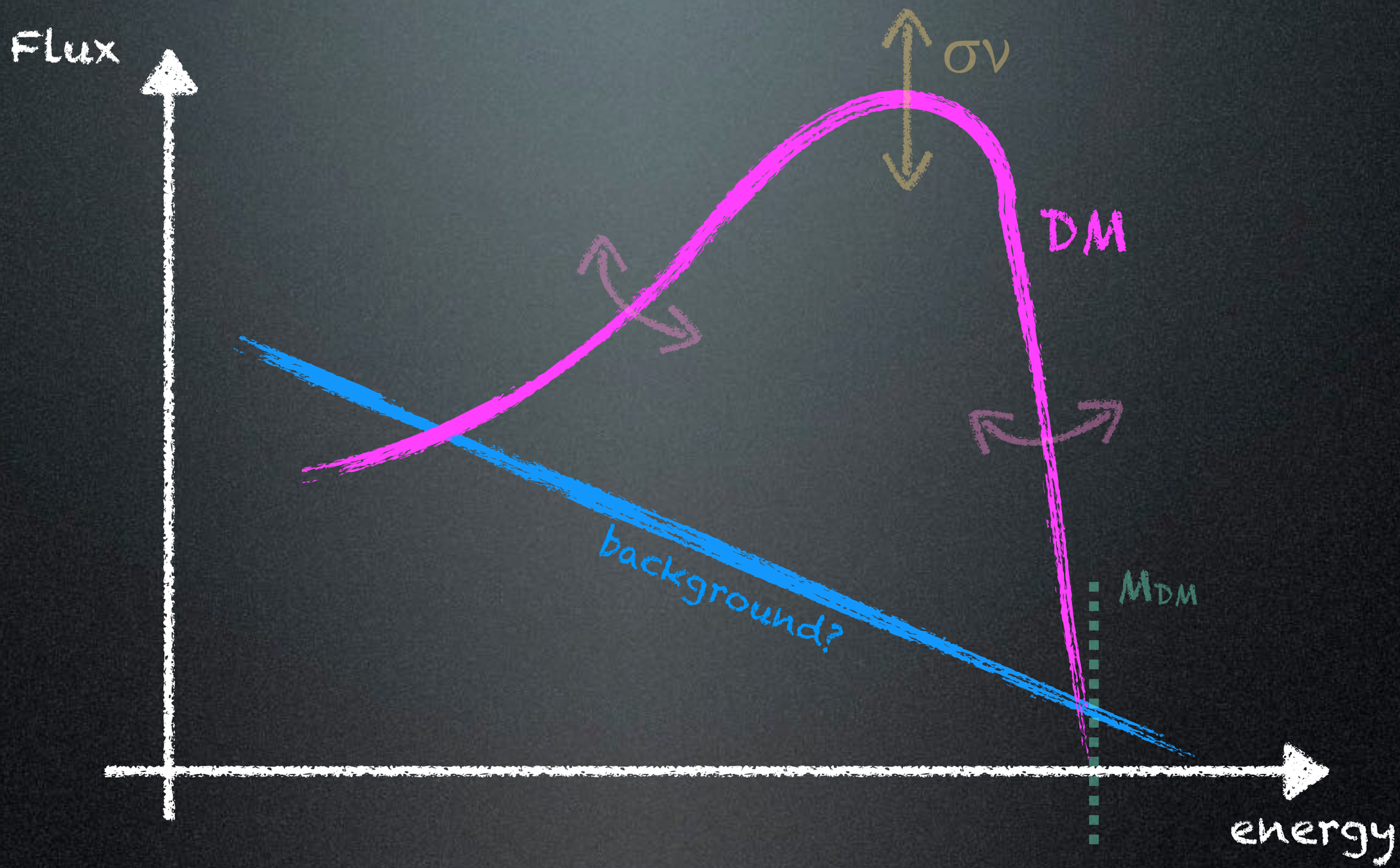

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1. Dark Matter mass
2. primary channel(s)
3. cross section

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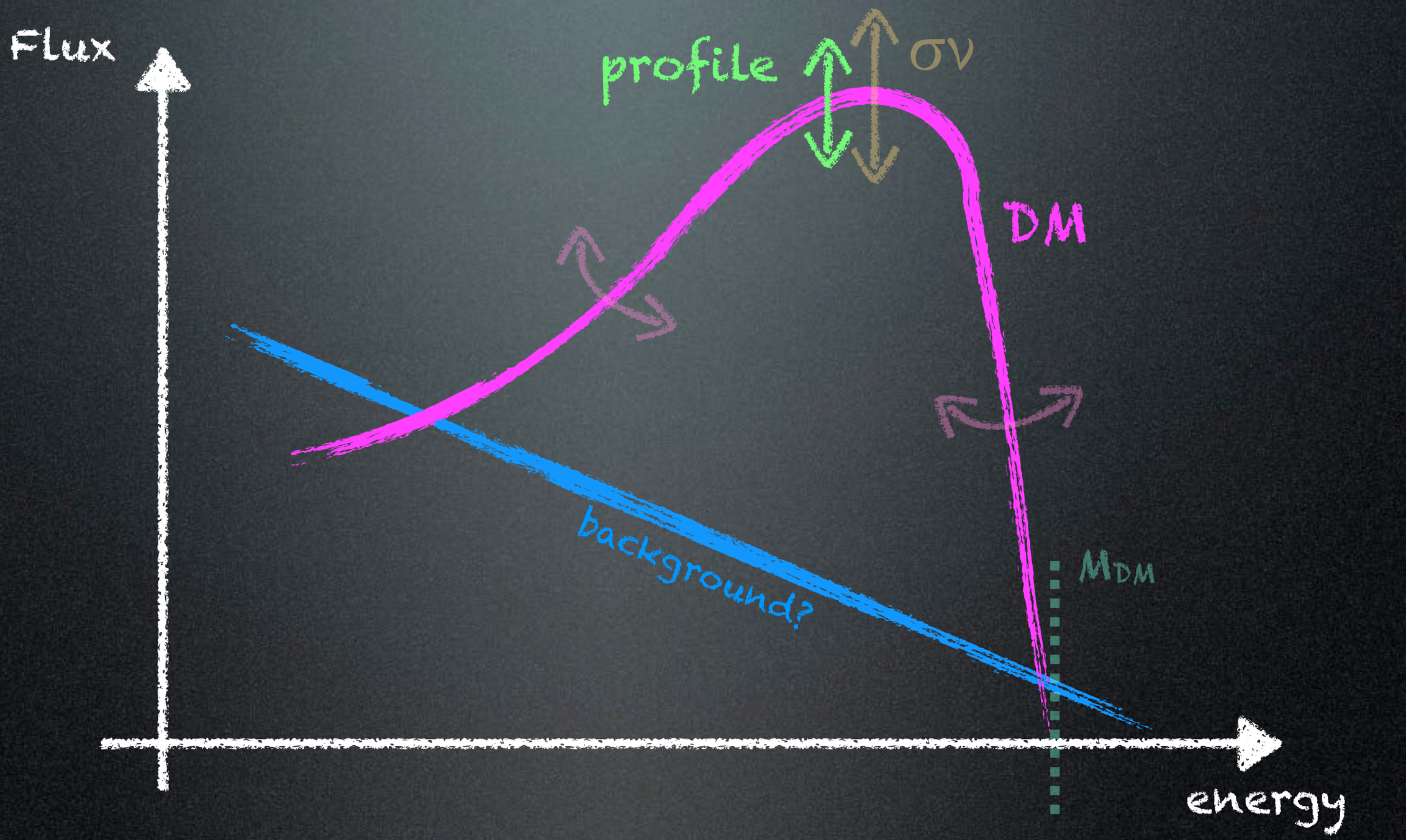

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1. DM abundance/profile

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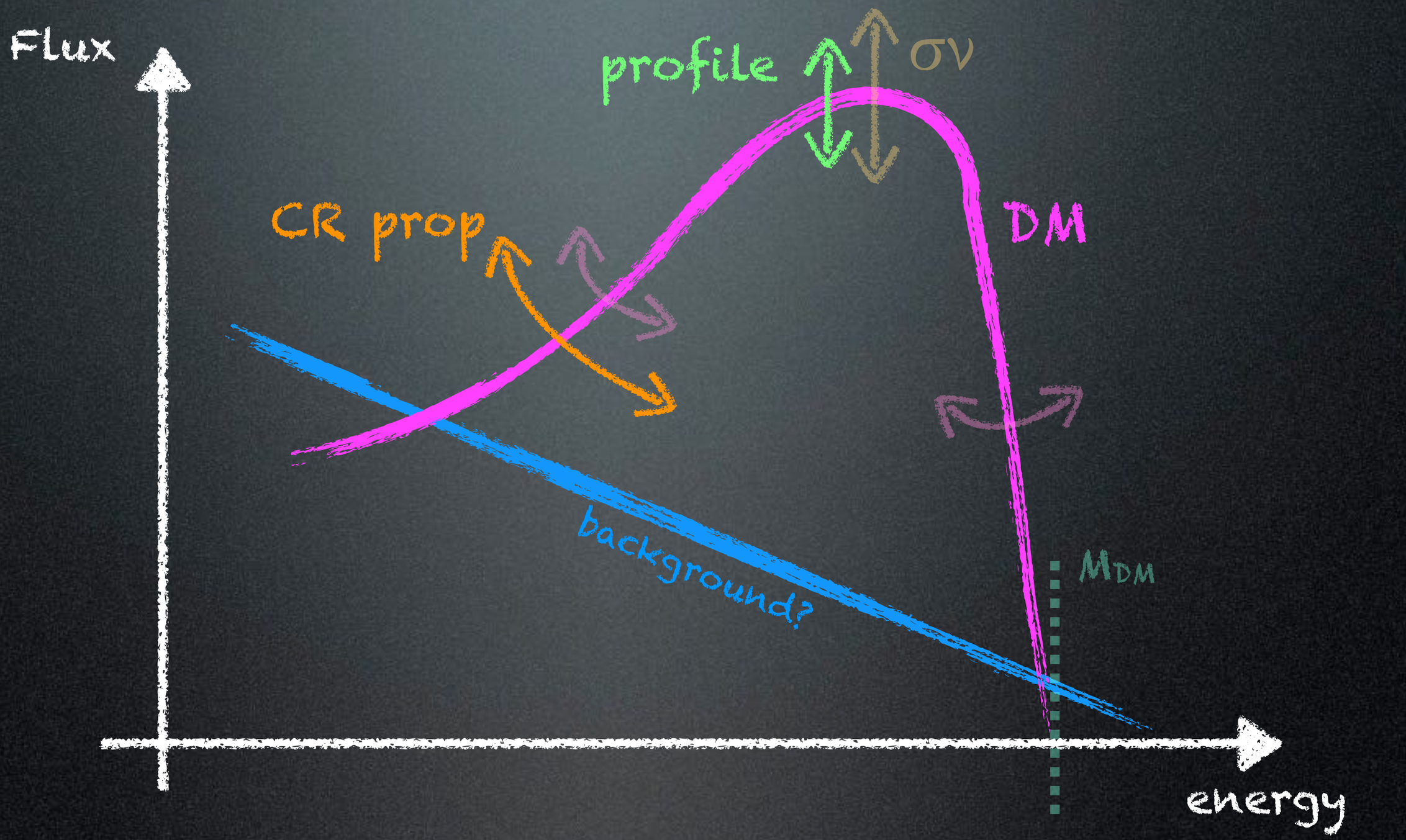

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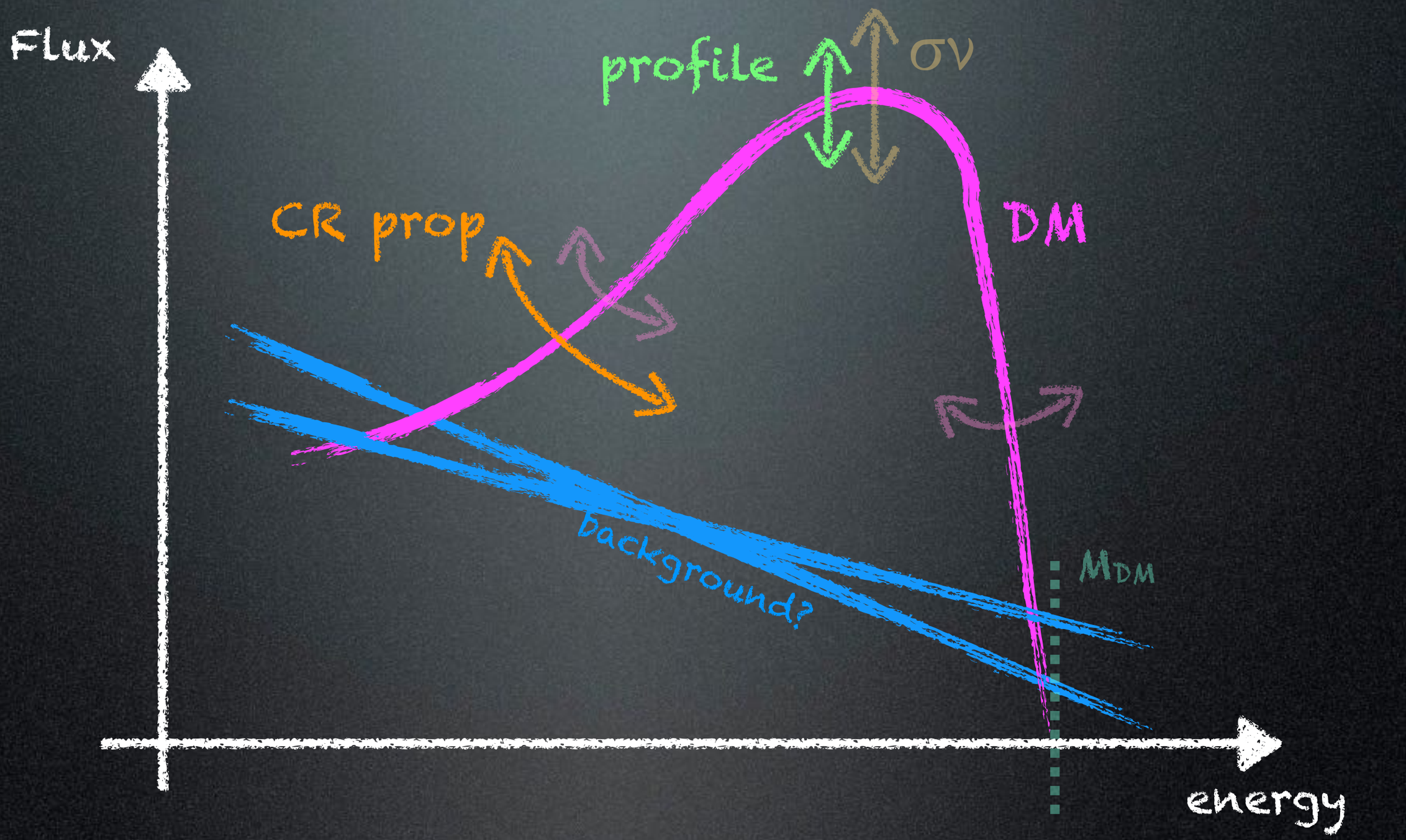
Fluxes at detection



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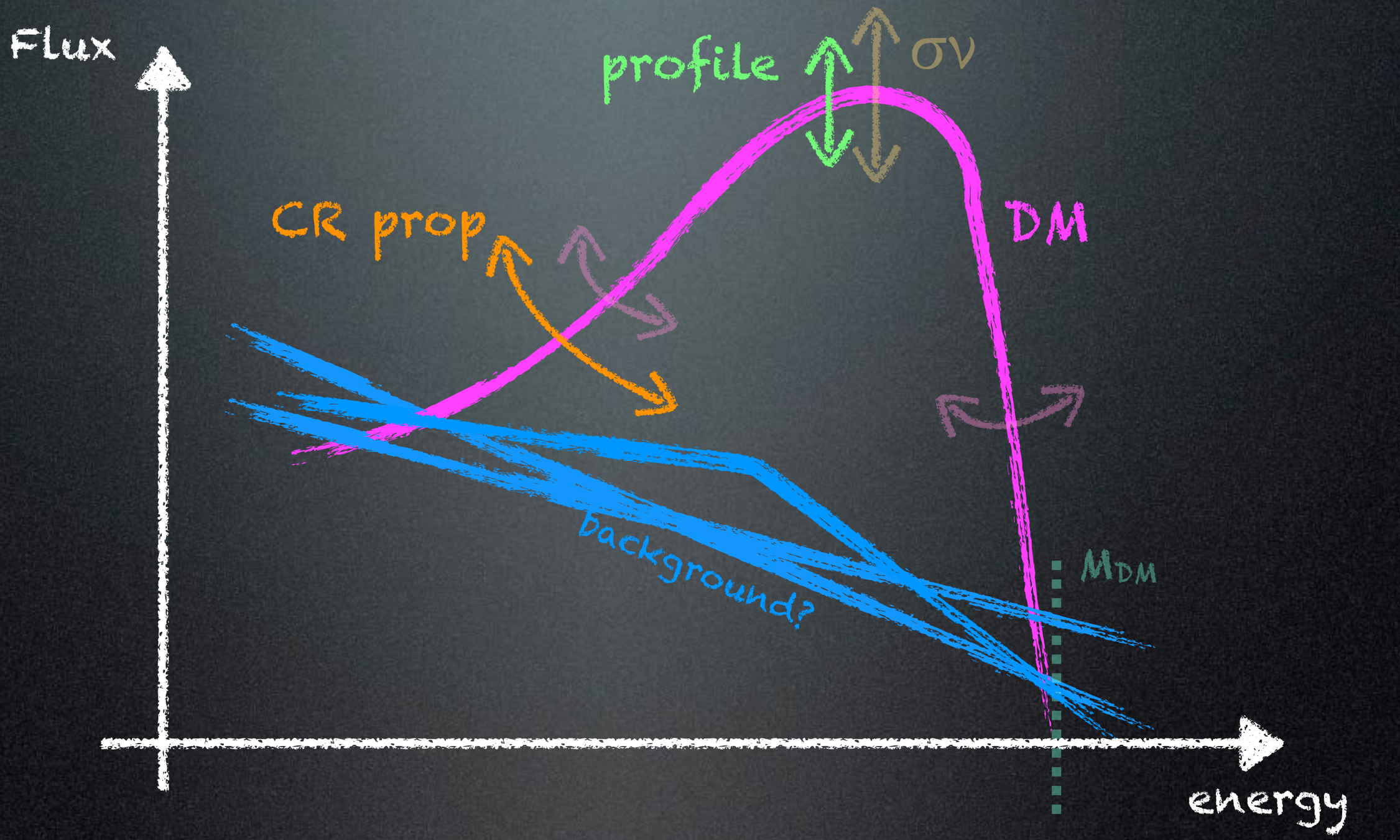
1. DM abundance/profile
2. propagation
3. background

Fluxes at detection



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Antiprotons

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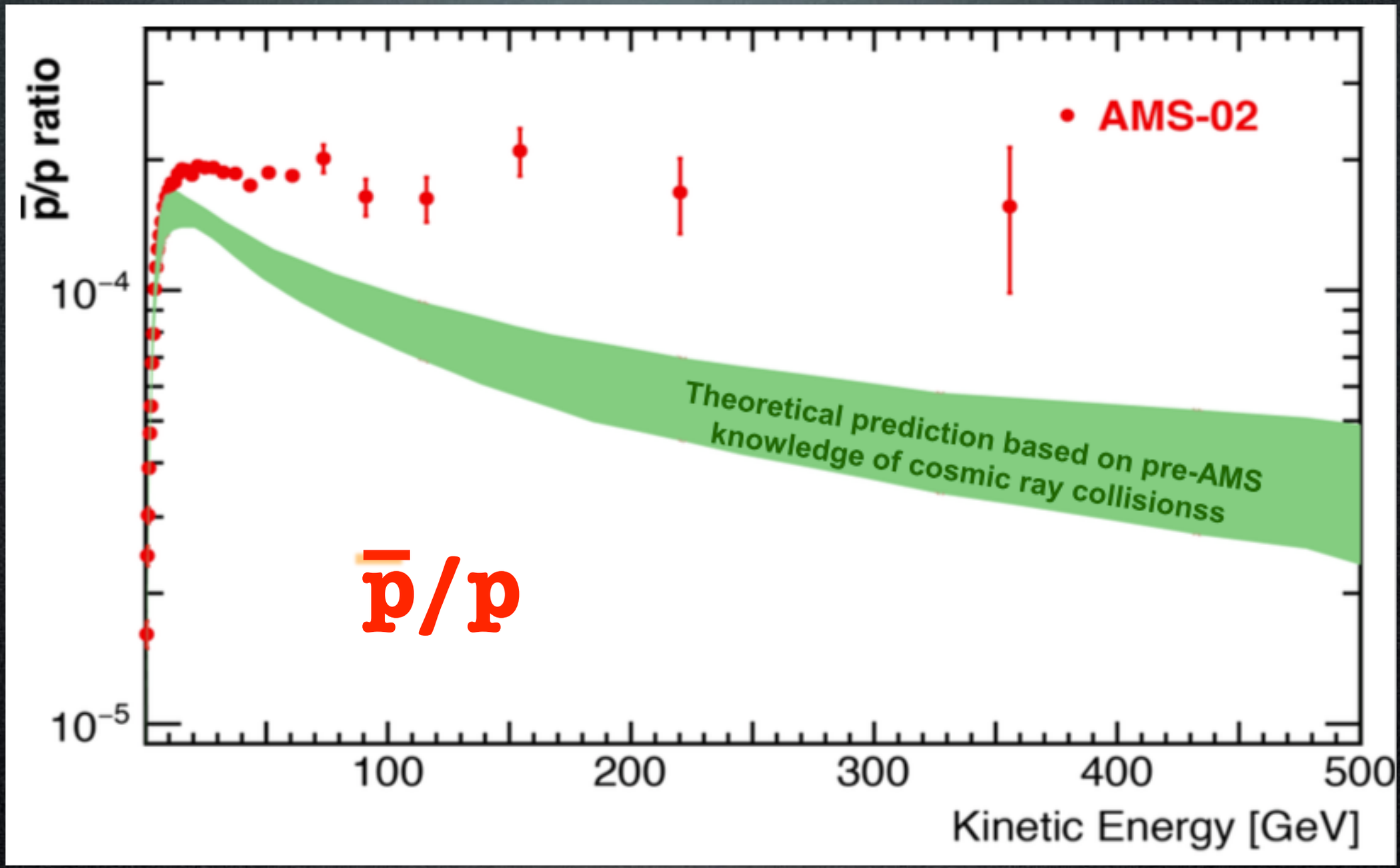
  SK, Icecube, Km3Net

Data: antiprotons

AMS-02

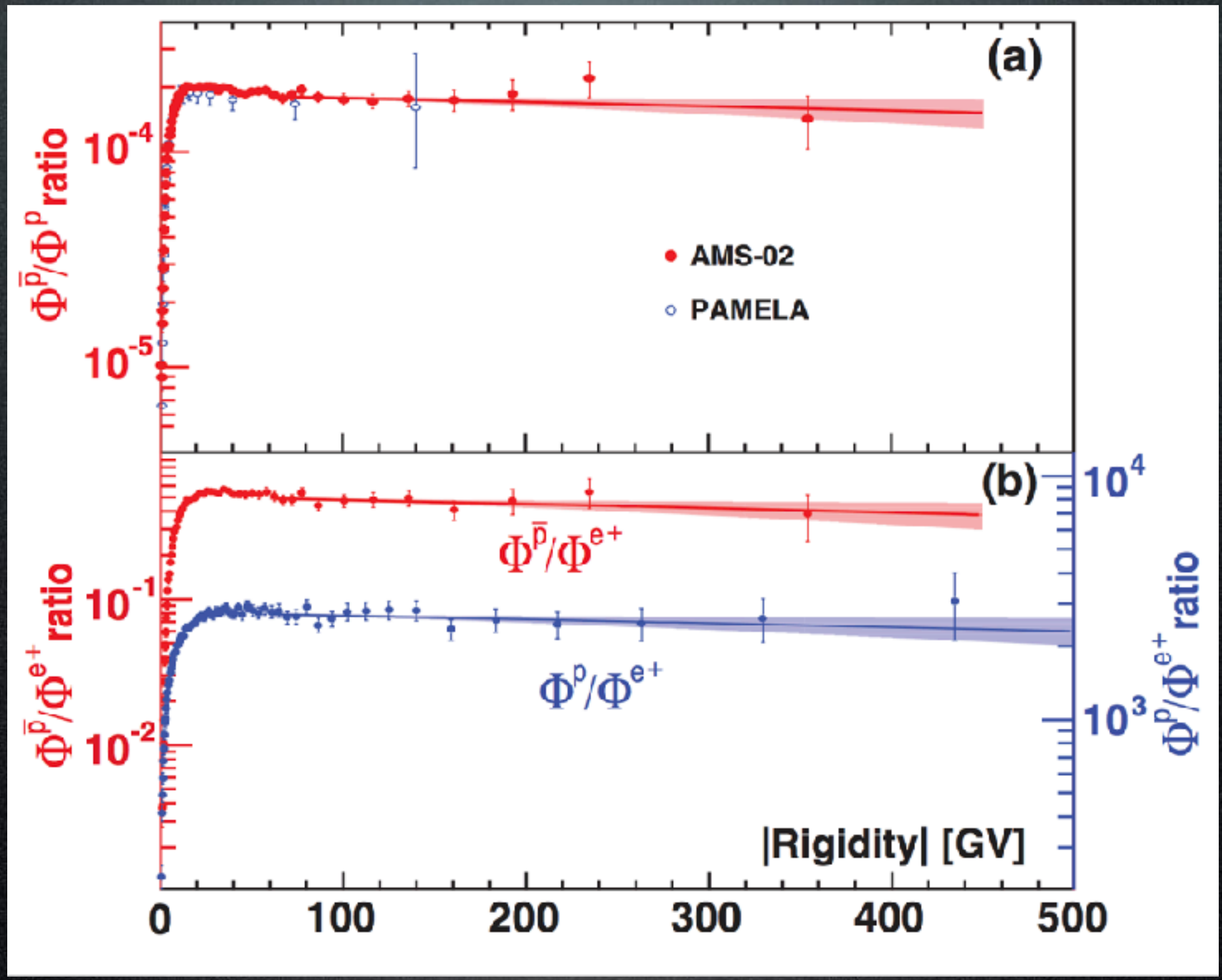


S. Ting - AMS days @ CERN apr 2015

A. Kounine - AMS days @ CERN apr 2015

Data: antiprotons

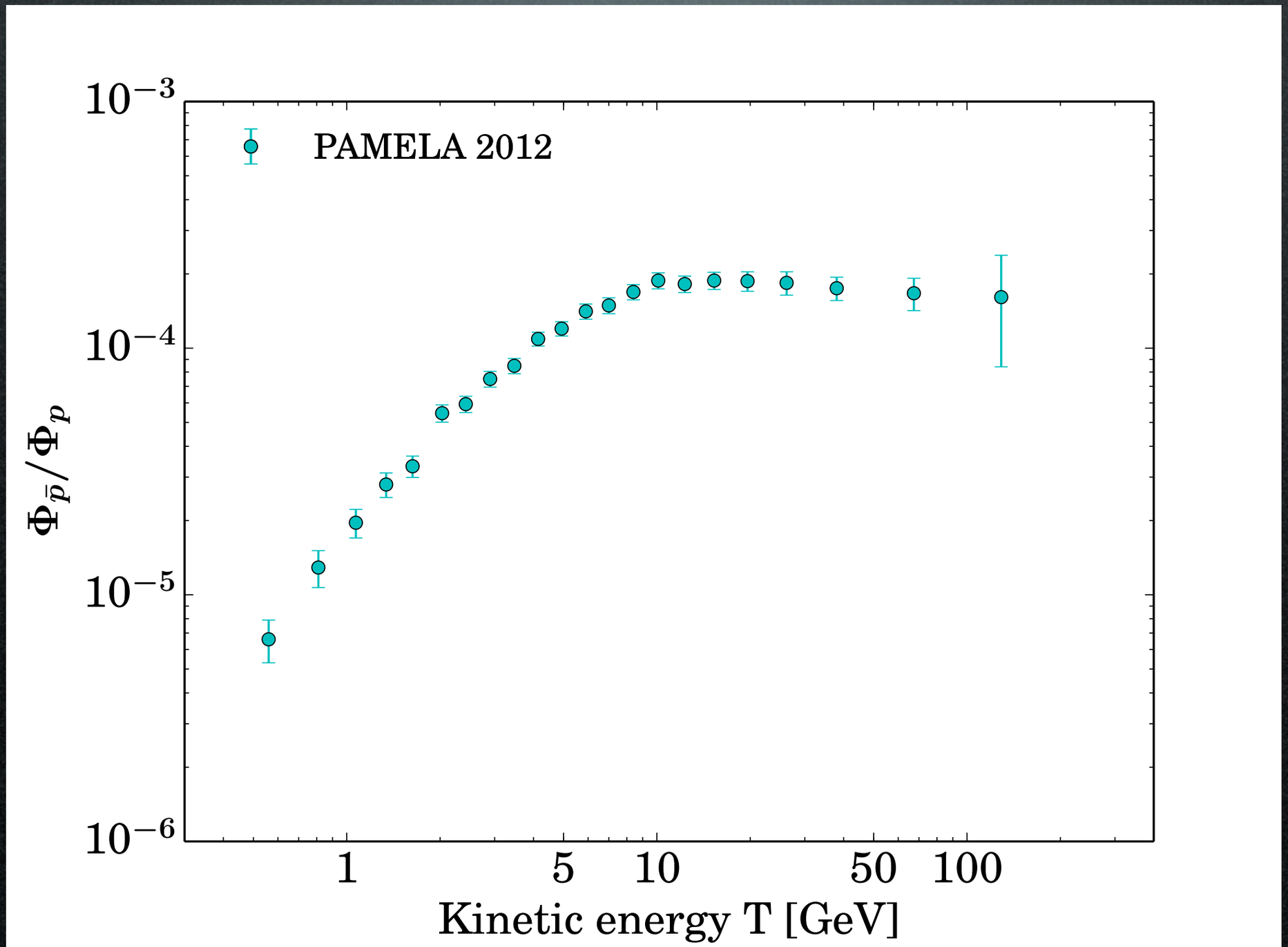
AMS-02



AMS coll.,PRL 117, 091103 (2016)

Antiprotons

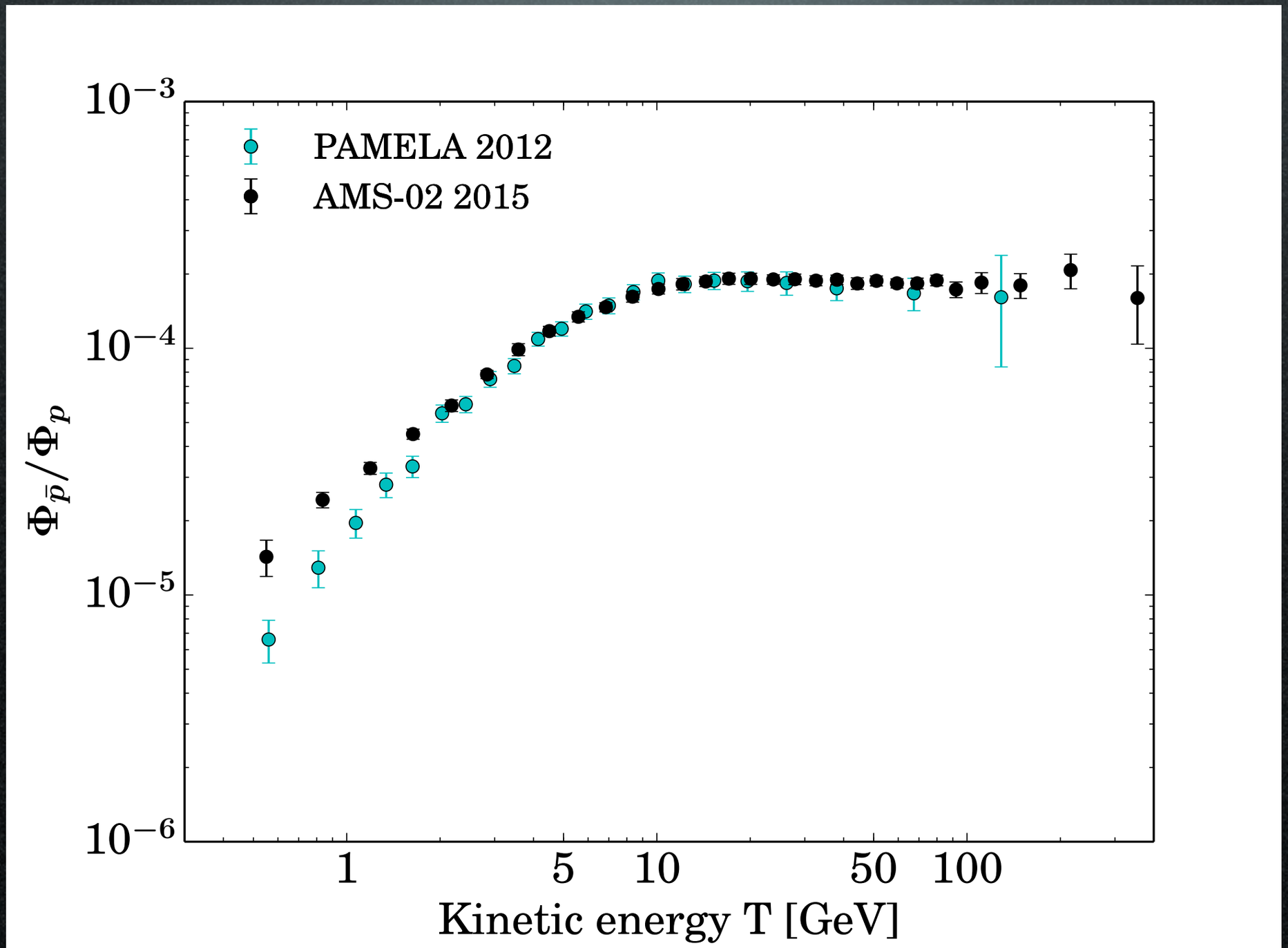
Antiproton data vis-à-vis the secondaries:



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

Antiprotons

Antiproton data vis-à-vis the secondaries:



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

Antiprotons

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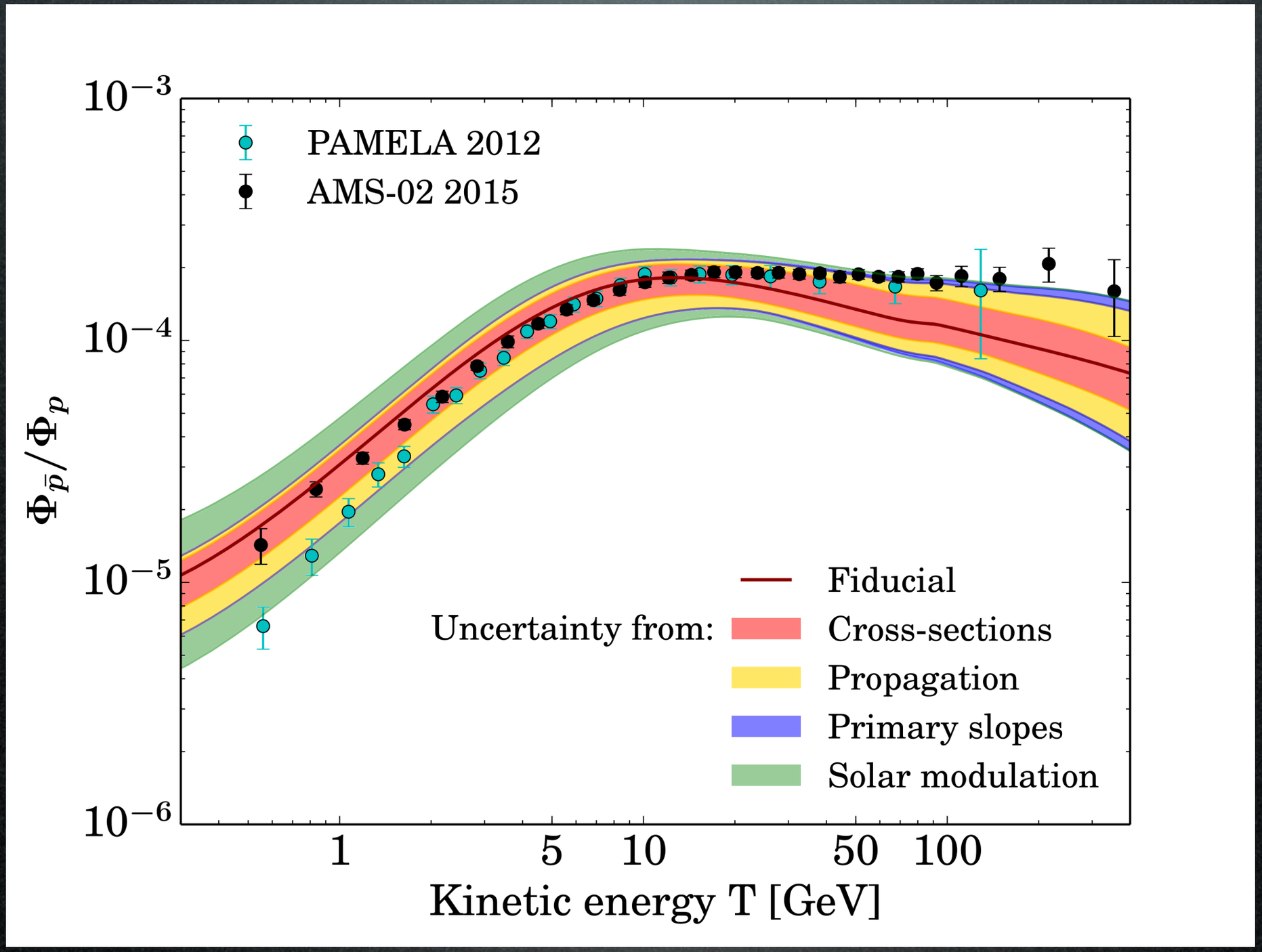
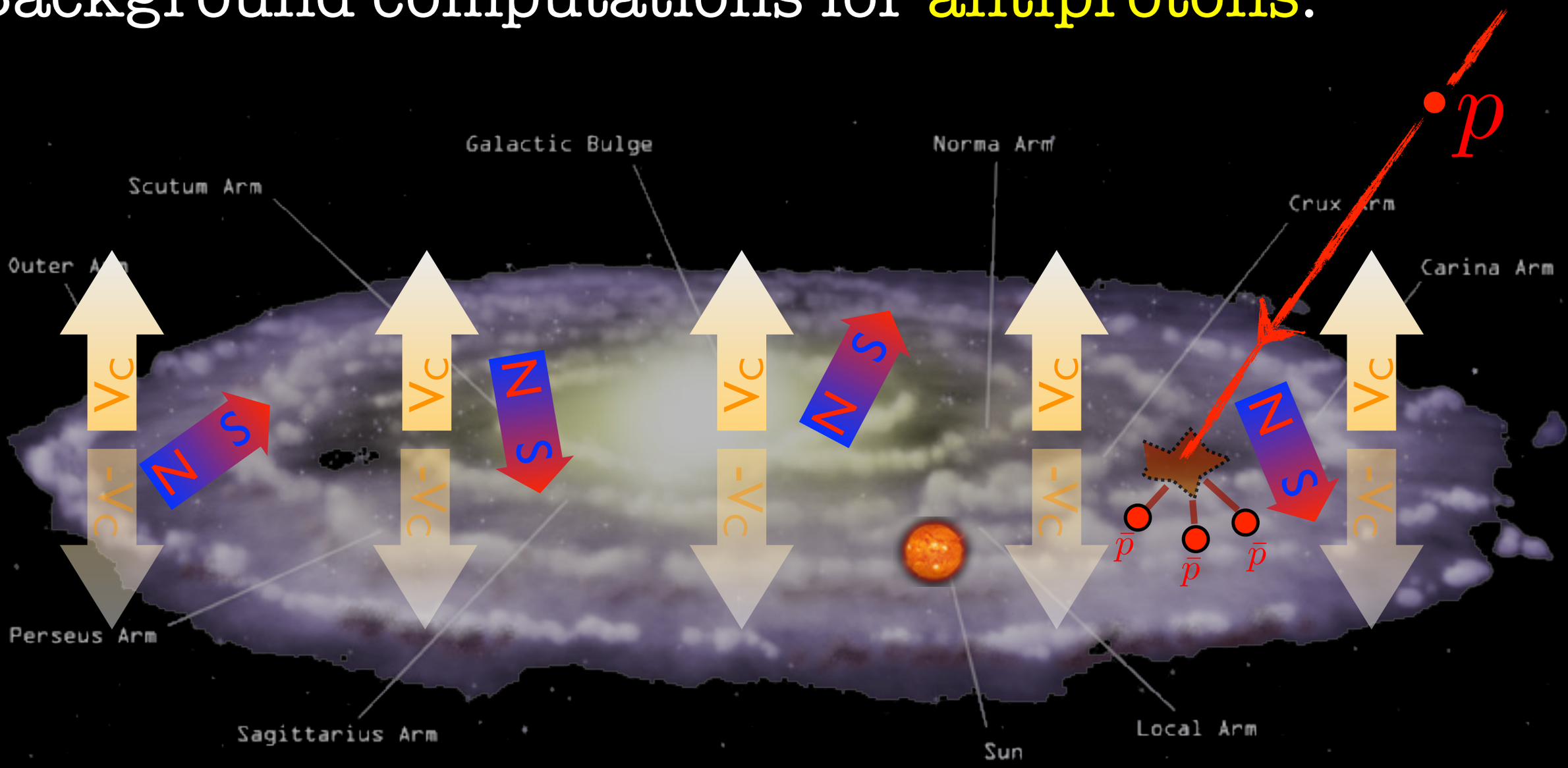


Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Indirect Detection

Background computations for antiprotons:



Indirect Detection

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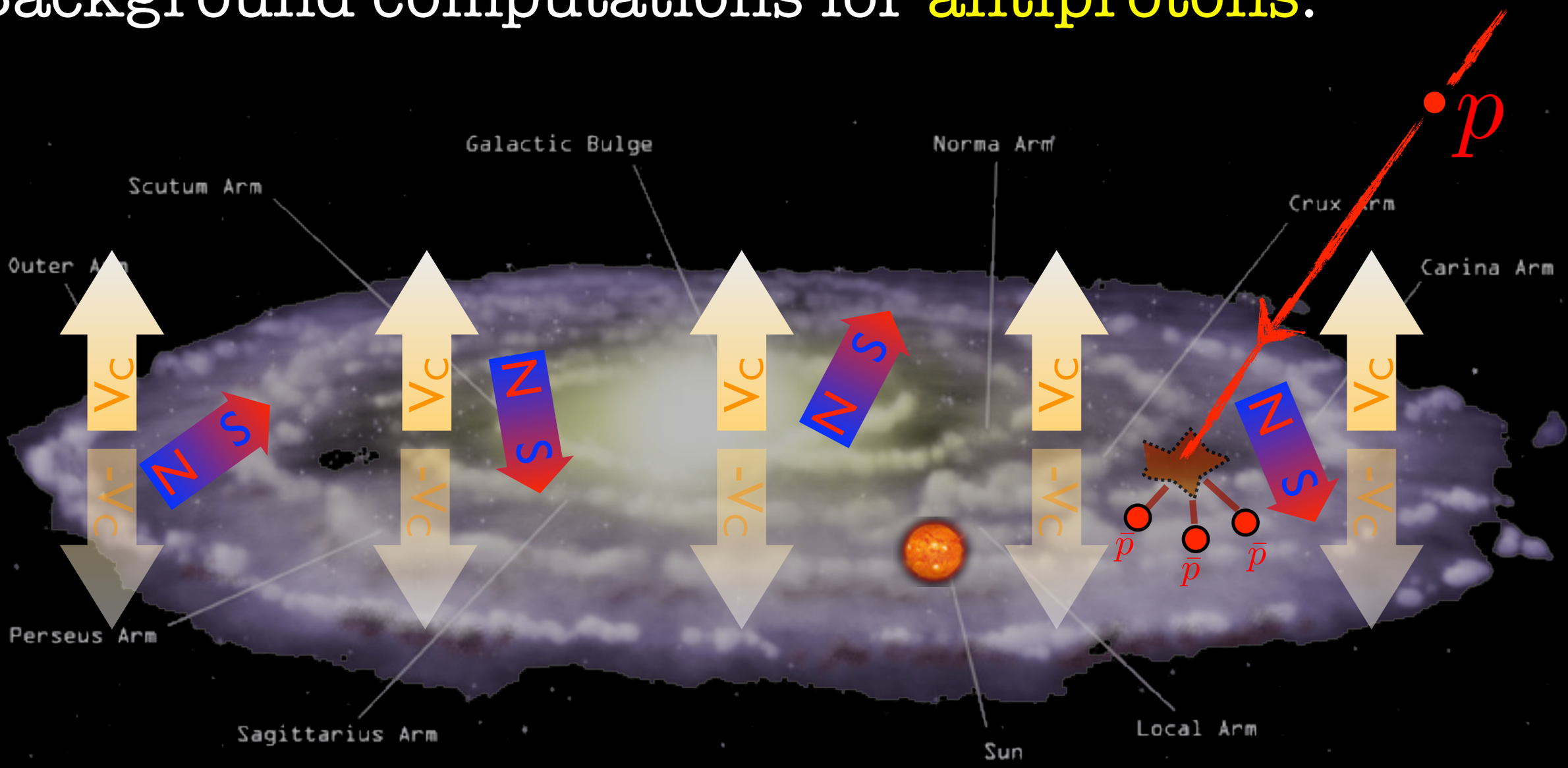
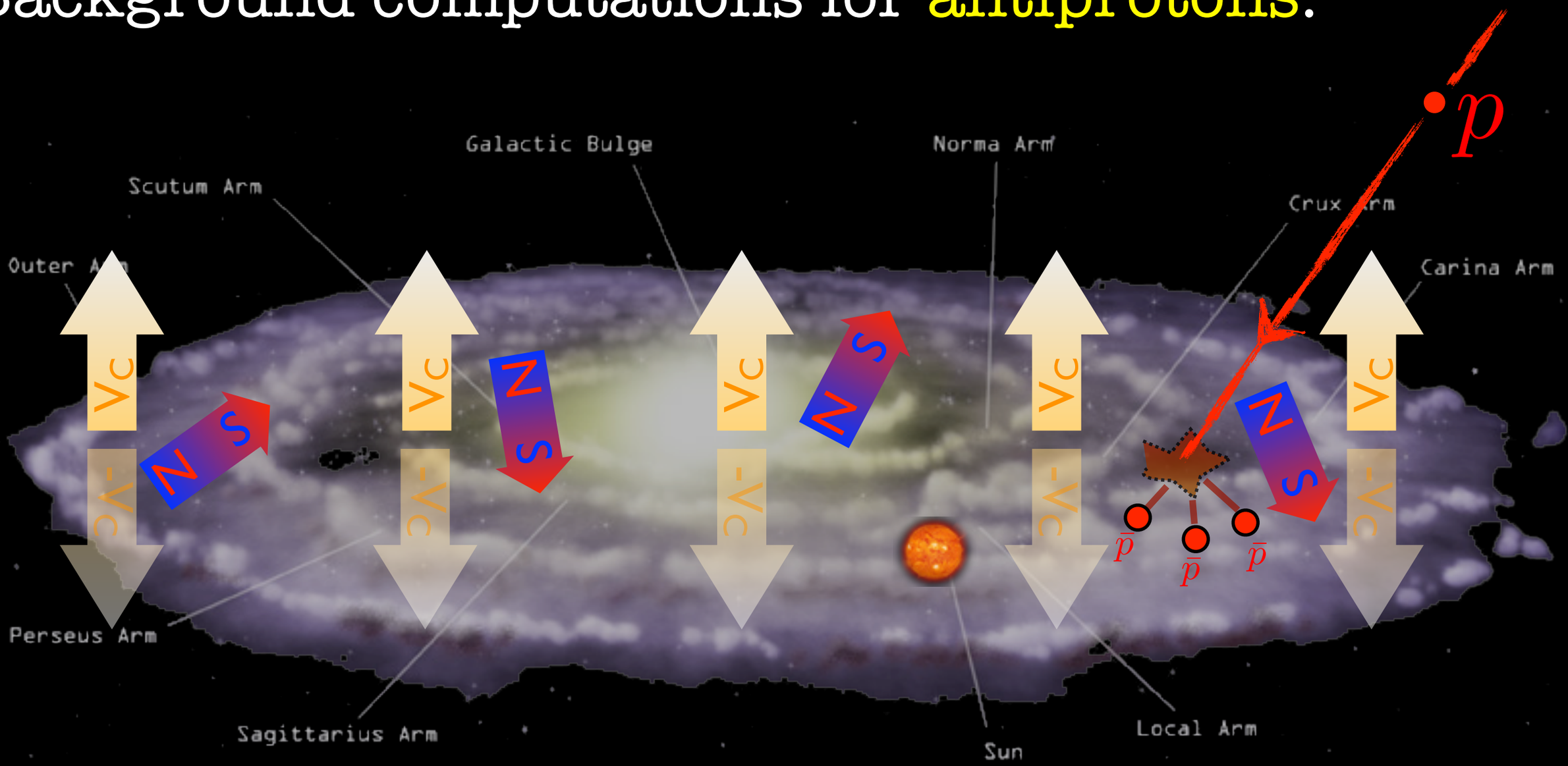


Main ingredients:

- 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

Background computations for antiprotons:

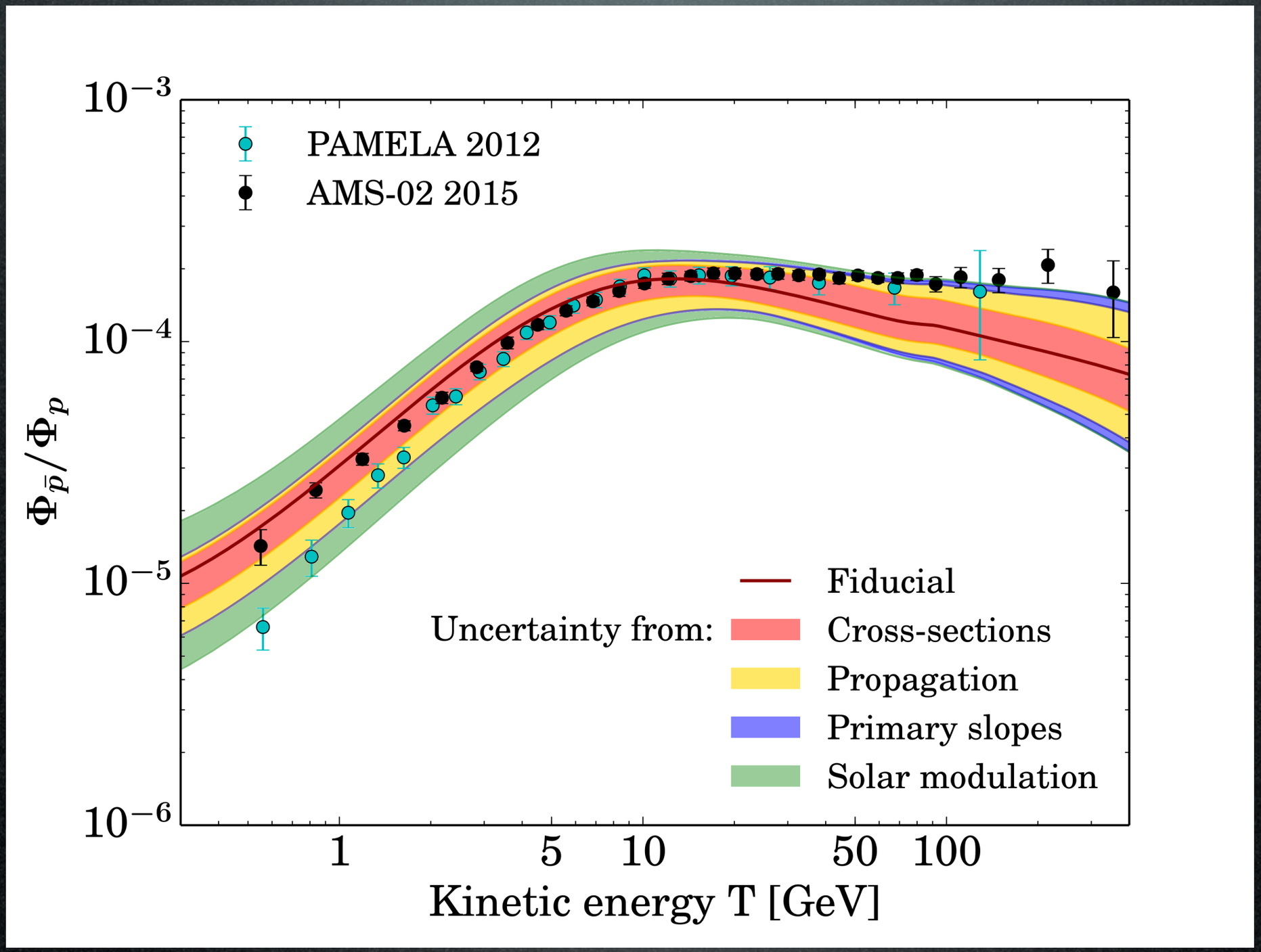


Main ingredients:

- 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!**
- propagation
- solar modulation

Antiprotons

Antiproton data vis-à-vis the secondaries:

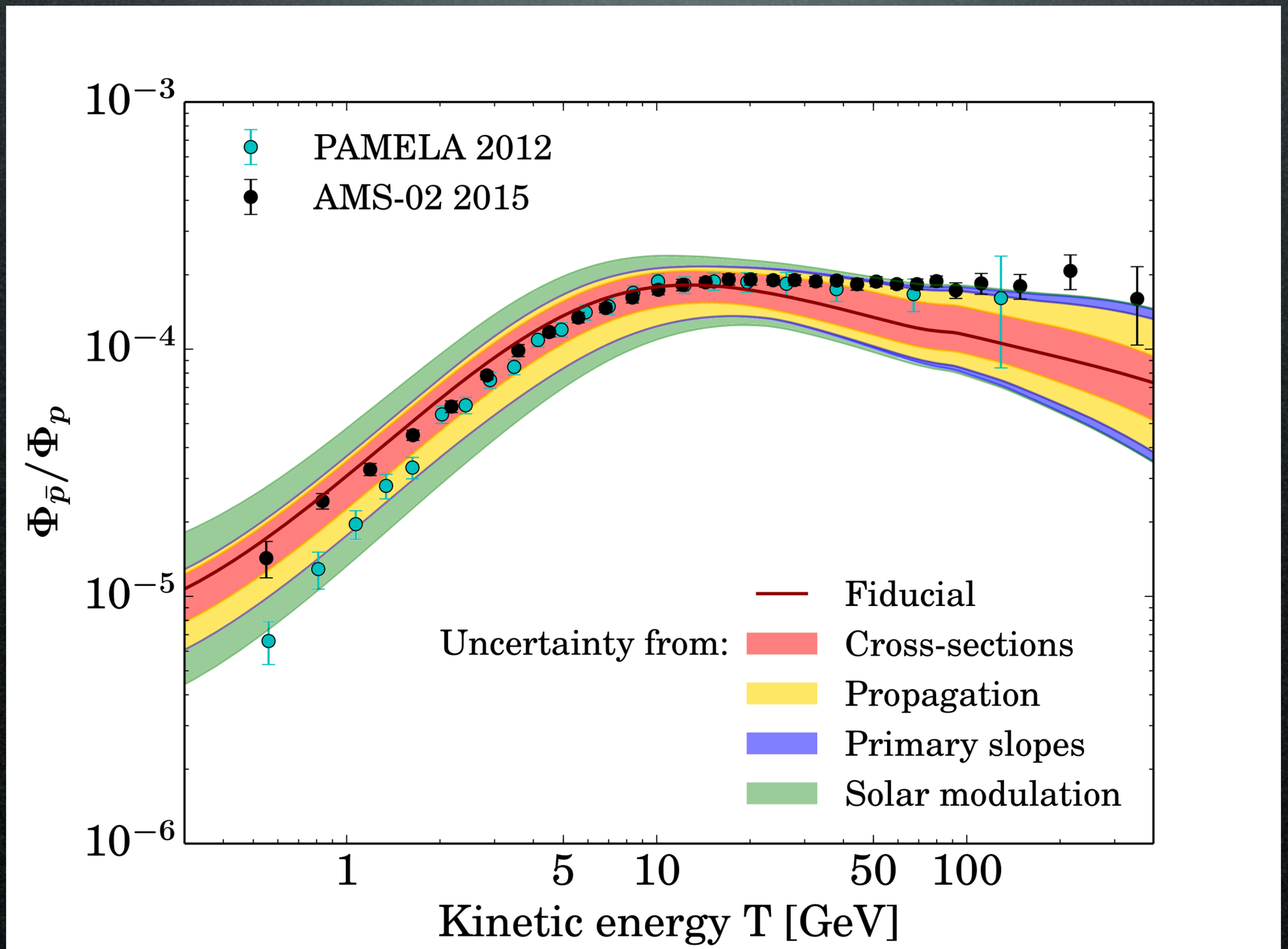


No evident **excess**

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

Antiprotons

Antiproton data vis-à-vis the secondaries:



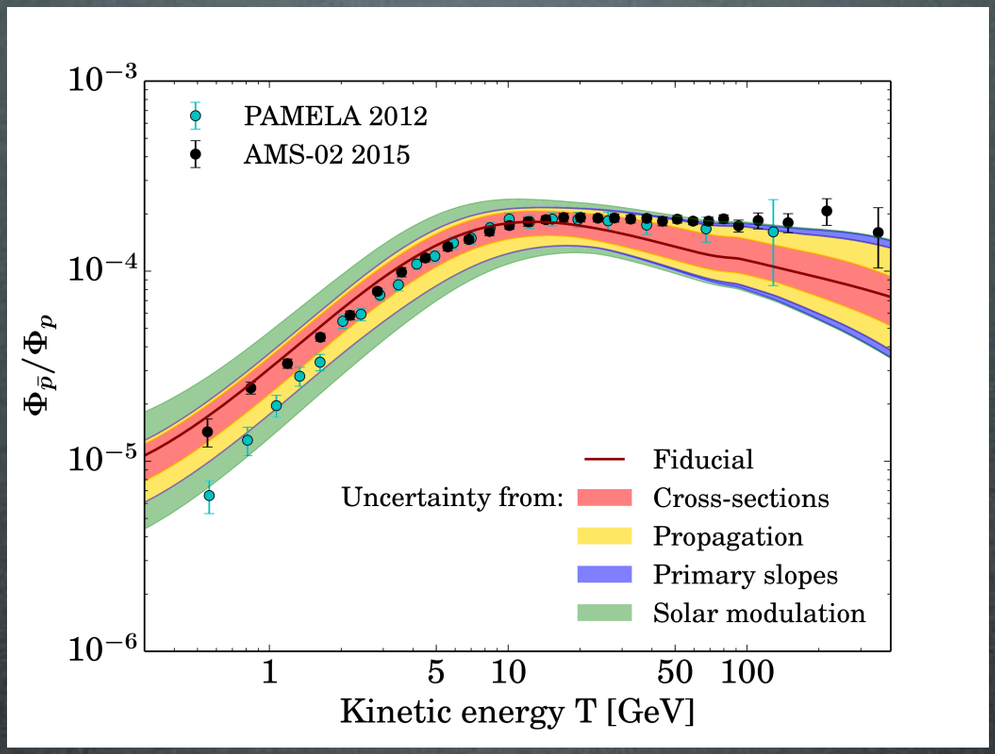
No evident **excess**

Some preference for flatness

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

Antiprotons

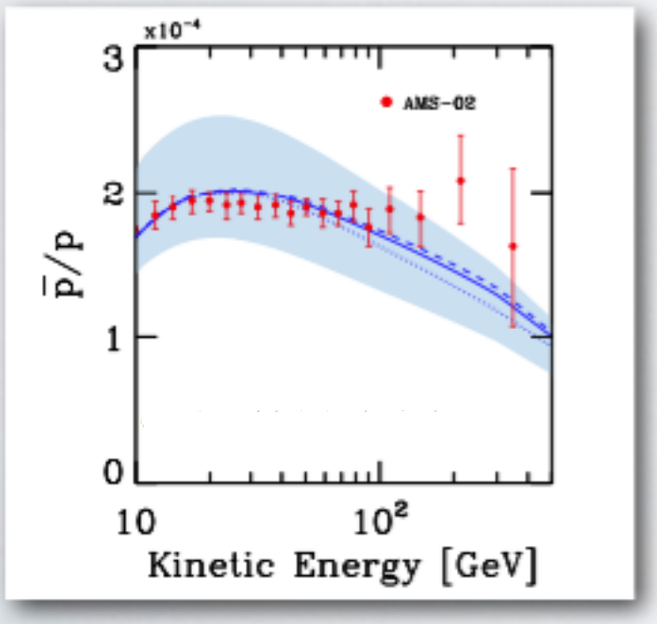
Antiproton data vis-à-vis the secondaries:



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

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

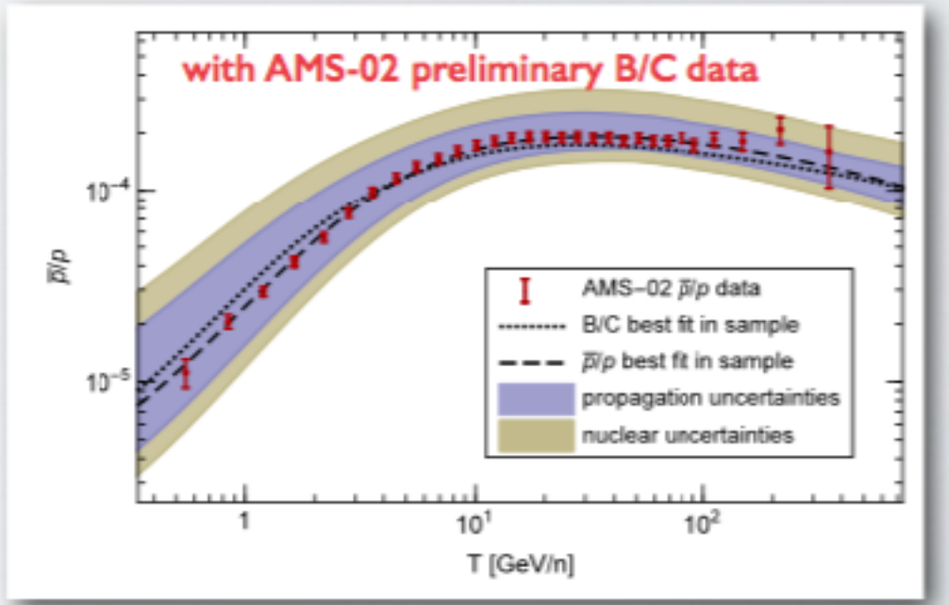
C. Evoli, D. Gaggero and D. Grasso, arXiv:1504.05175



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

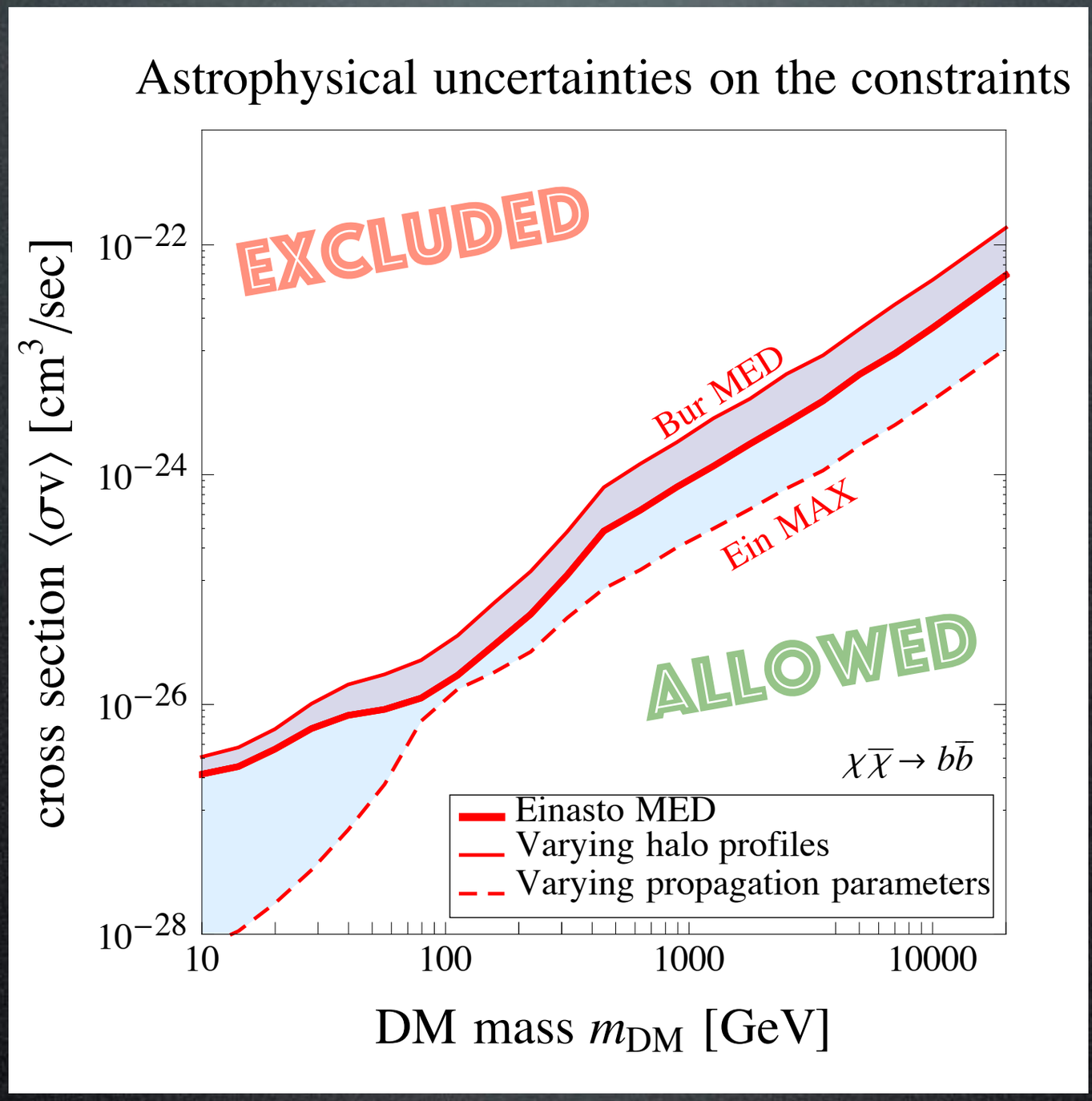
using
p, He by AMS-02 and CREAM,
B/C by AMS-02,
heavier nuclei by compilation

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



Dark Matter interpretation

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

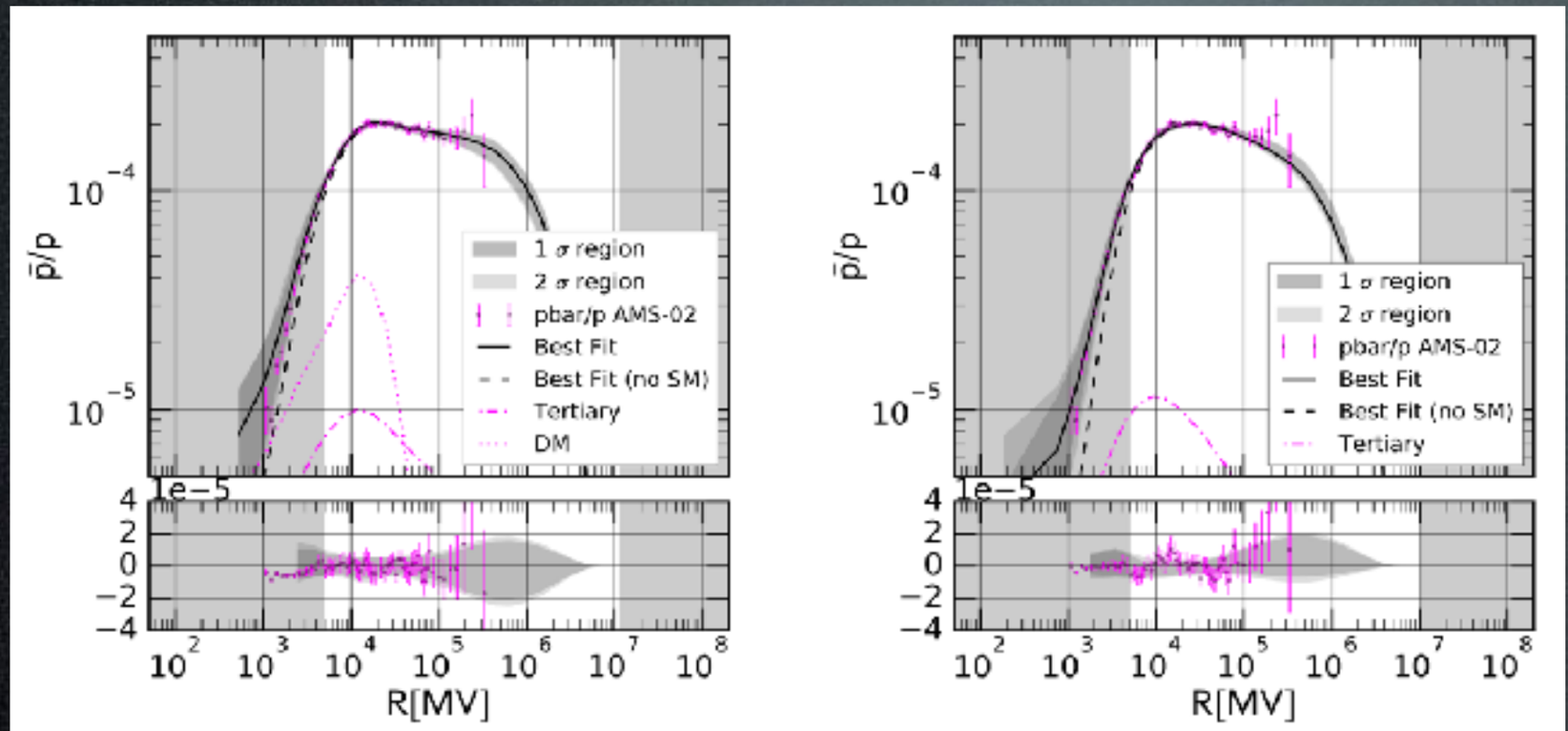


Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico
1504.04276

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



finds a possible excess

(formally ~4.5σ)

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

similarly:

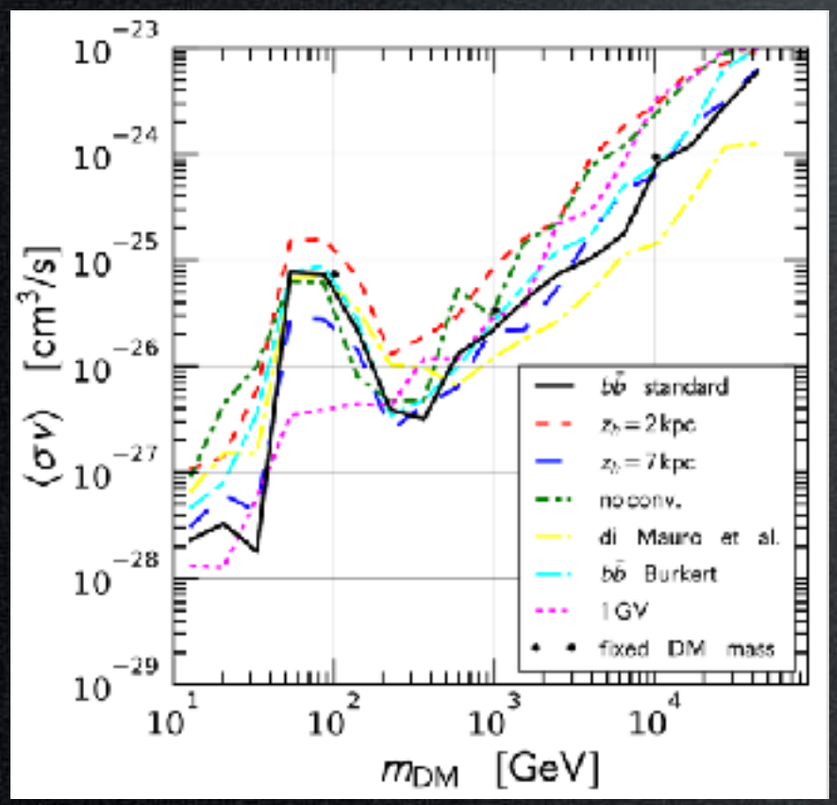
Cui, Yuan, Tsai, Fang 1610.03840

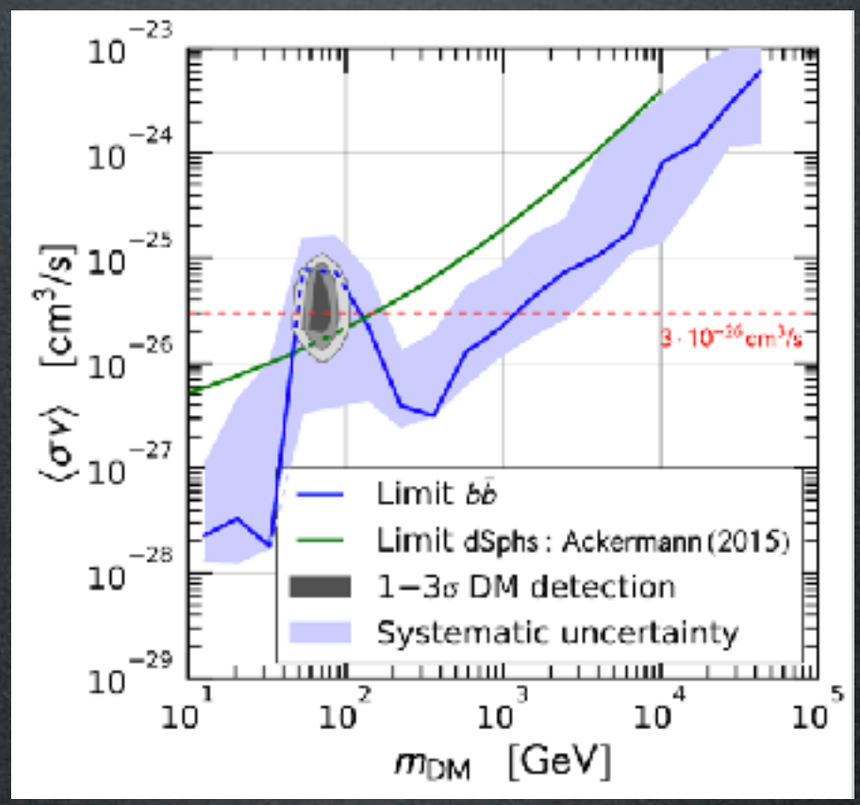
Huang + 1611.01983 (light mediators)

Feng, Zhang 1701.02263

Cuoco, Heisig, Krämer, Korsmeier 1704.08258

Boschini+ (Galprop) 1704.06337 (but only 1σ)

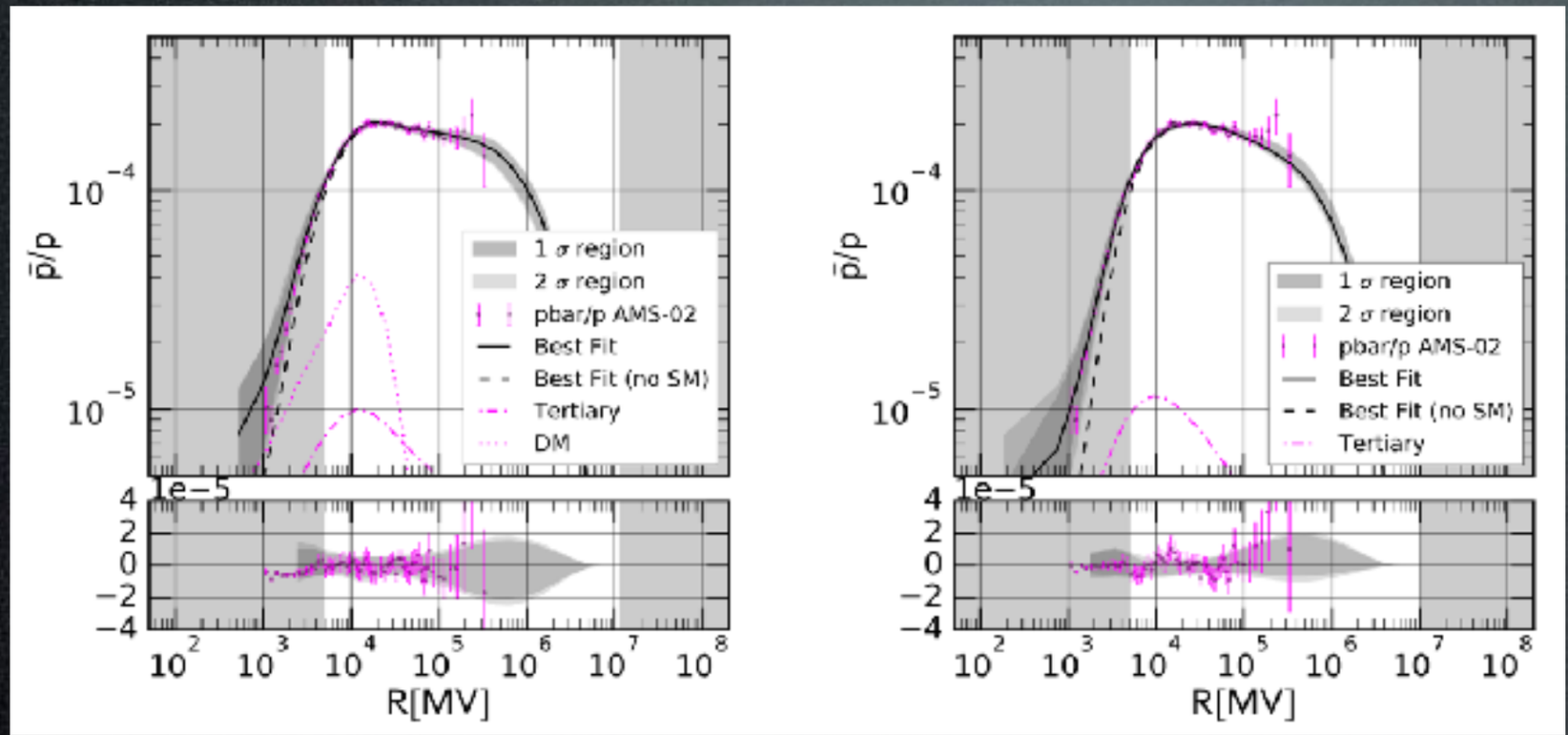




Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



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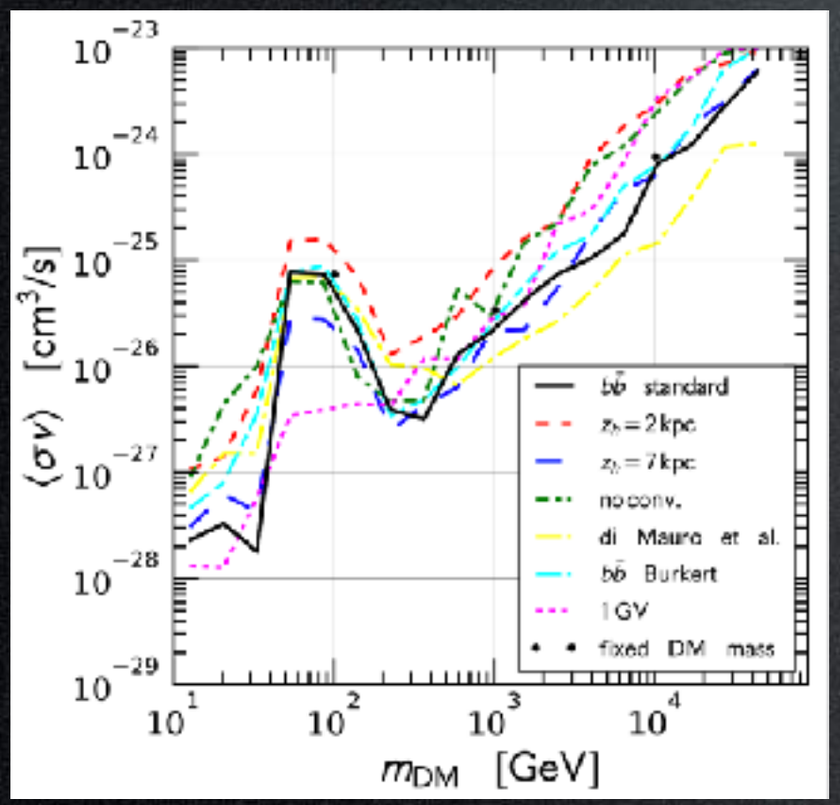
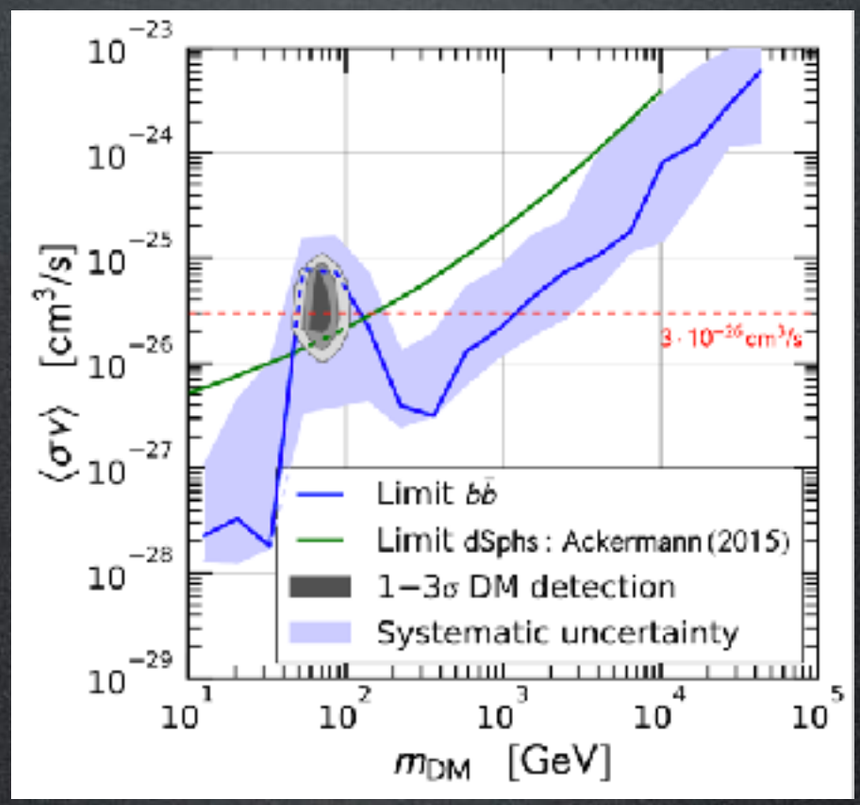




criticisms:

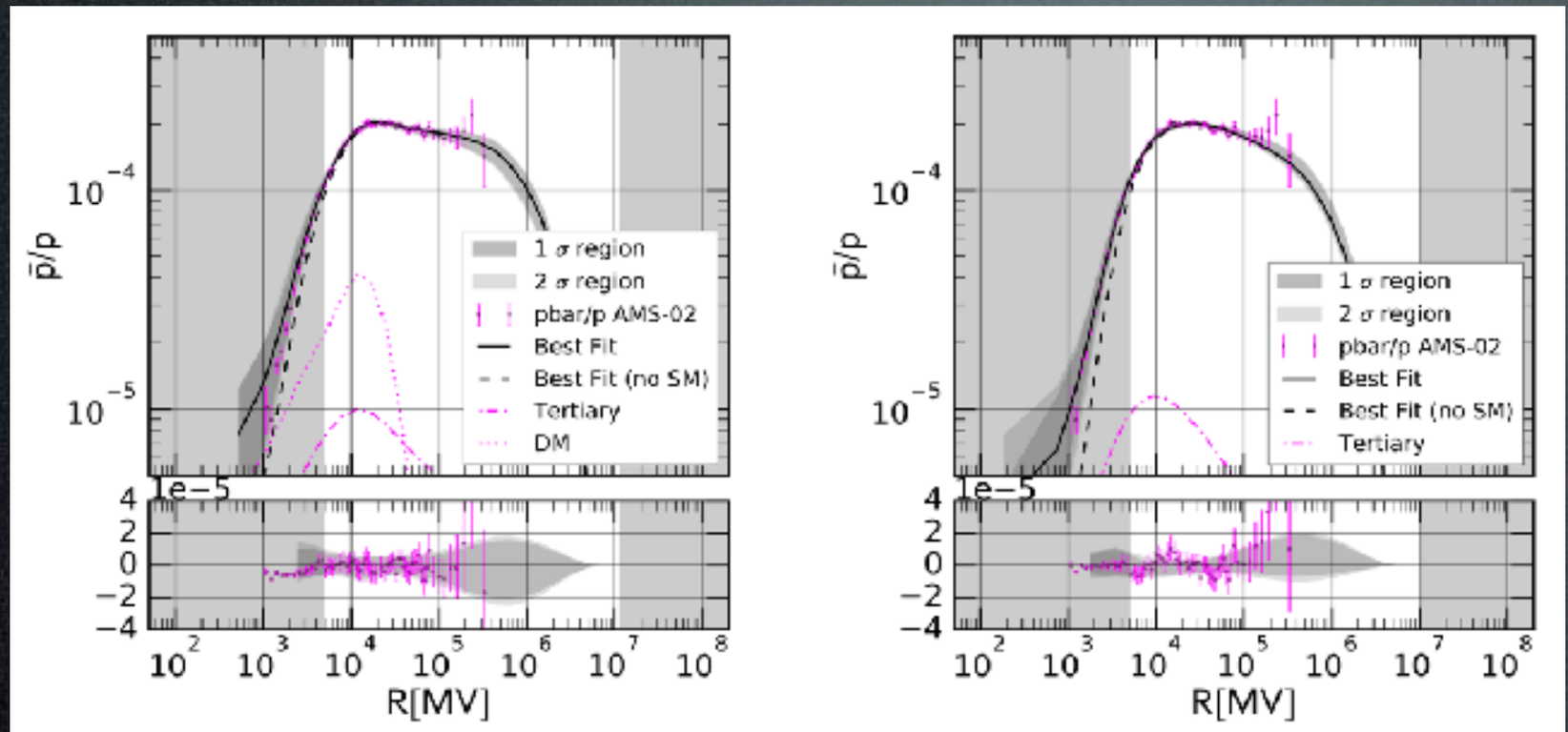
propagation parameters determined with p, He data only, w/o B/C

excess evaporates including low energies

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



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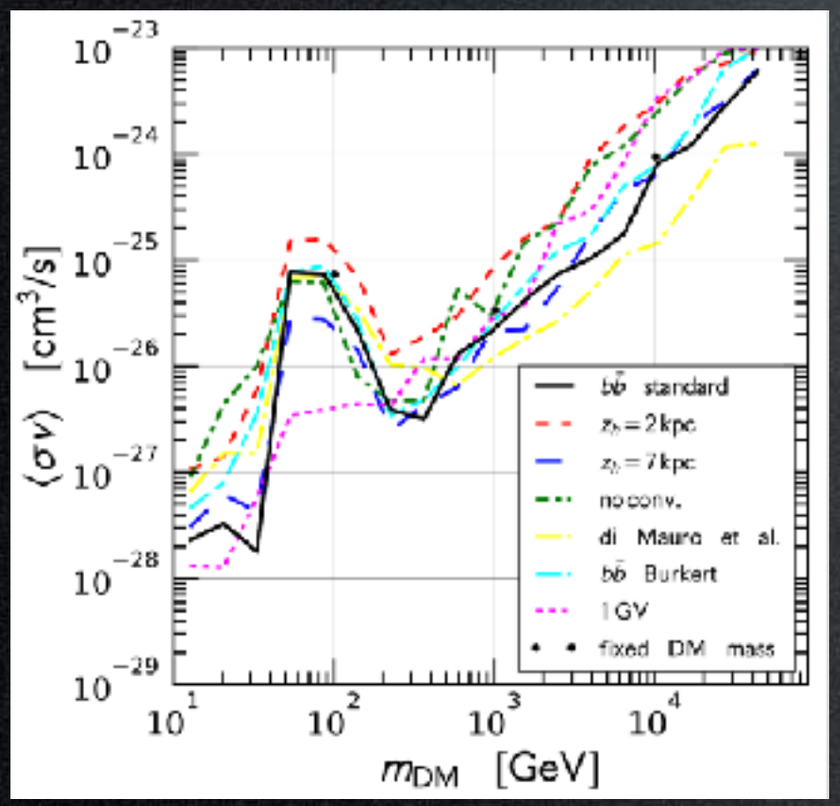
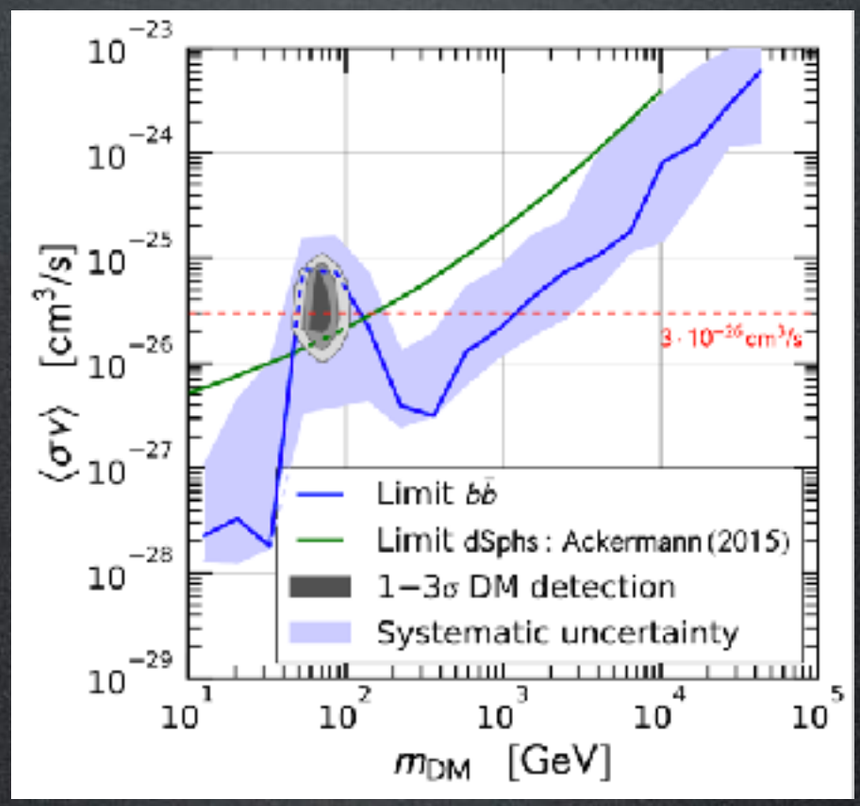




on the other hand:

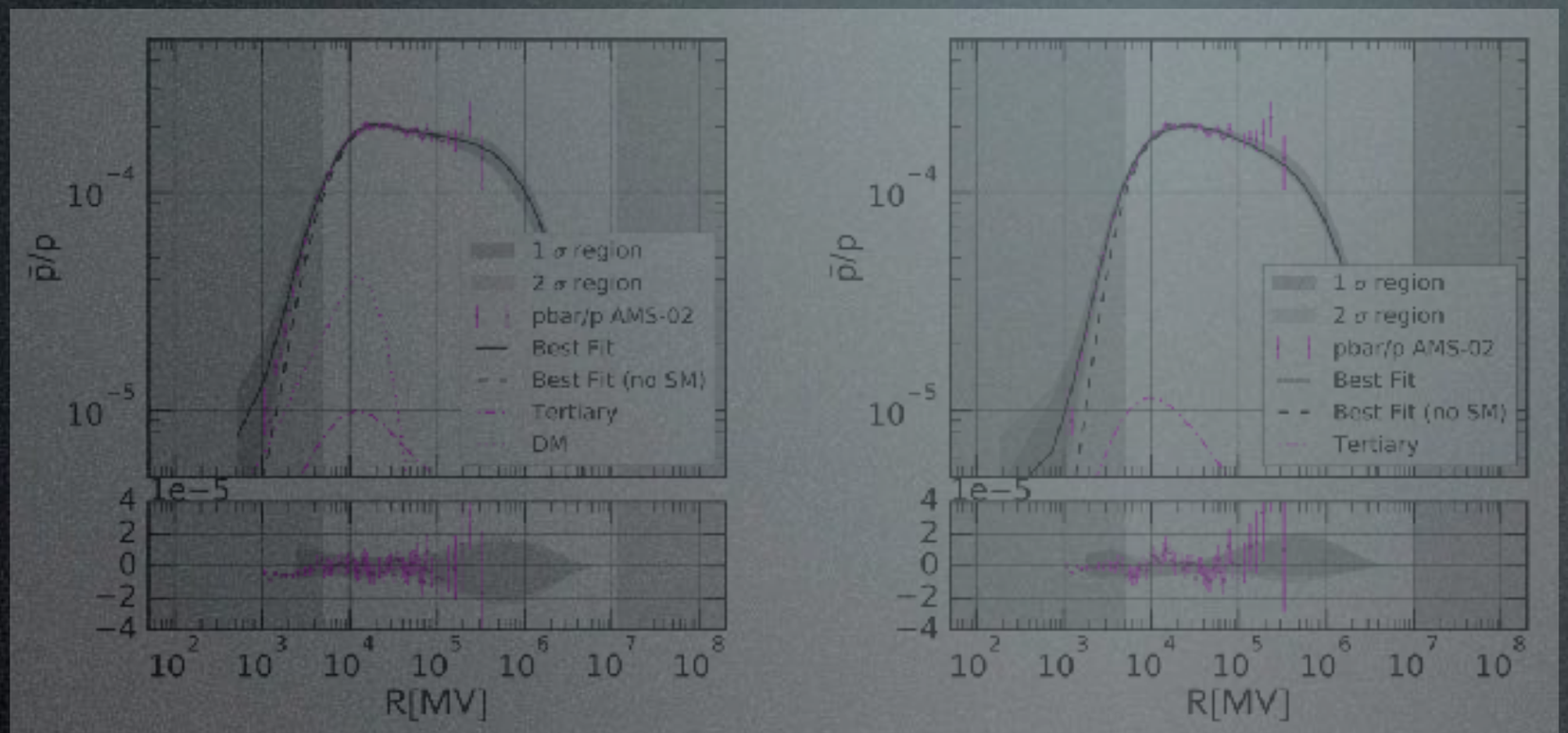
B/C and p probably probe different regions

it's a very tricky region, cool things can hide there

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



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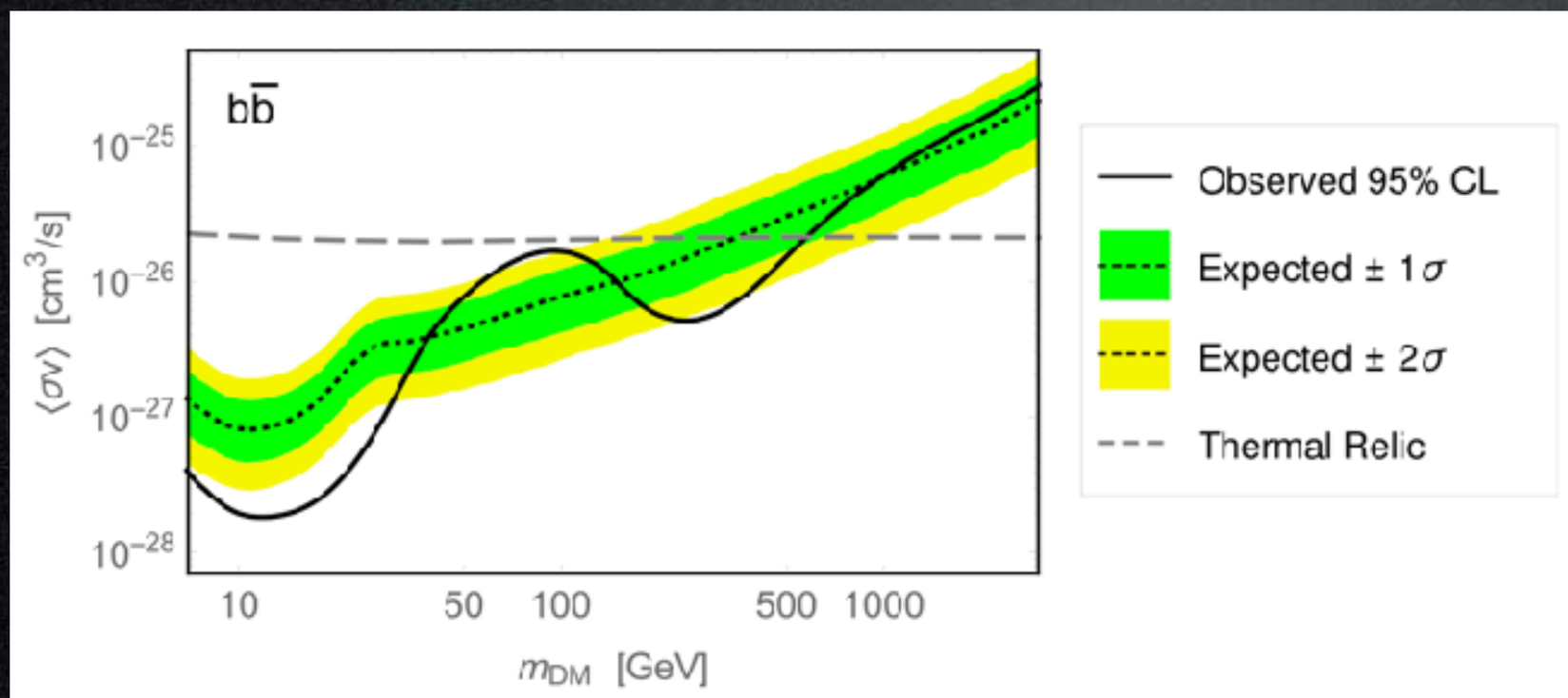


Reinert, Winkler 1712.00002

excess exists

but significance ~1σ, given all uncertainties

Positrons (and electrons)

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

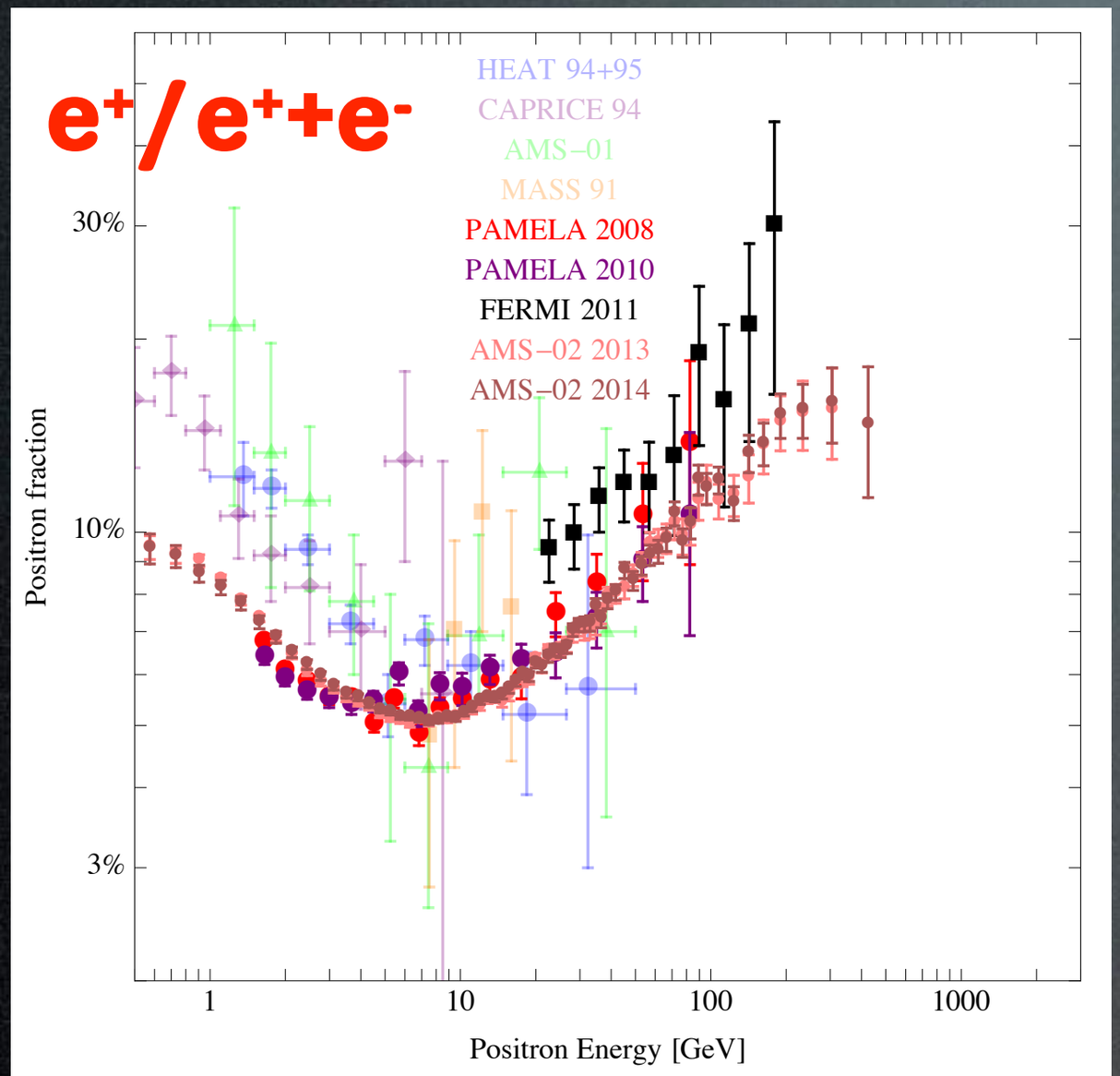
$\bar{d}$ from annihil in galactic halo or center

GAPS, AMS

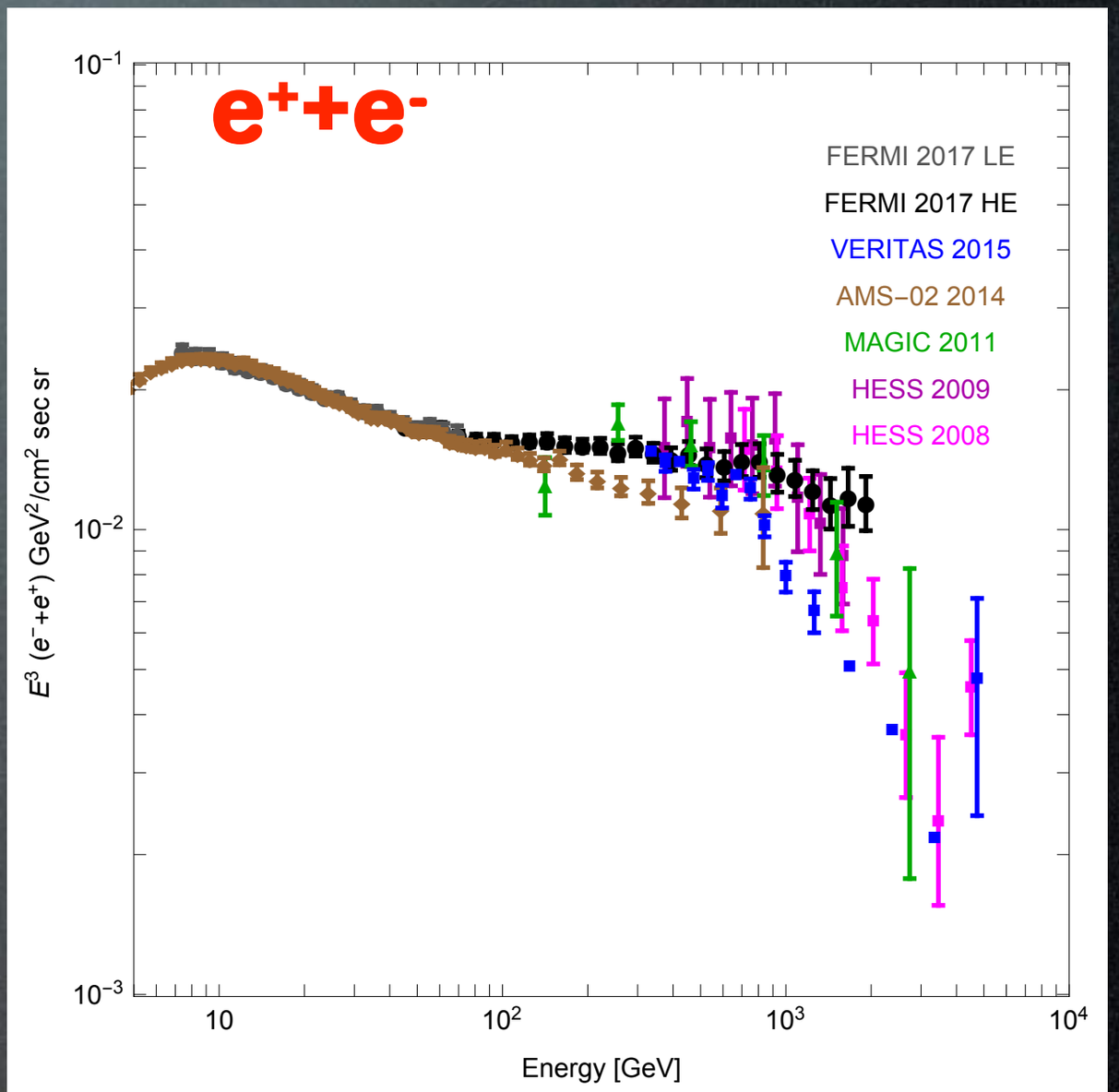
$\nu, \bar{\nu}$ from annihil in massive bodies

SK, Icecube, Km3Net

Data: leptons

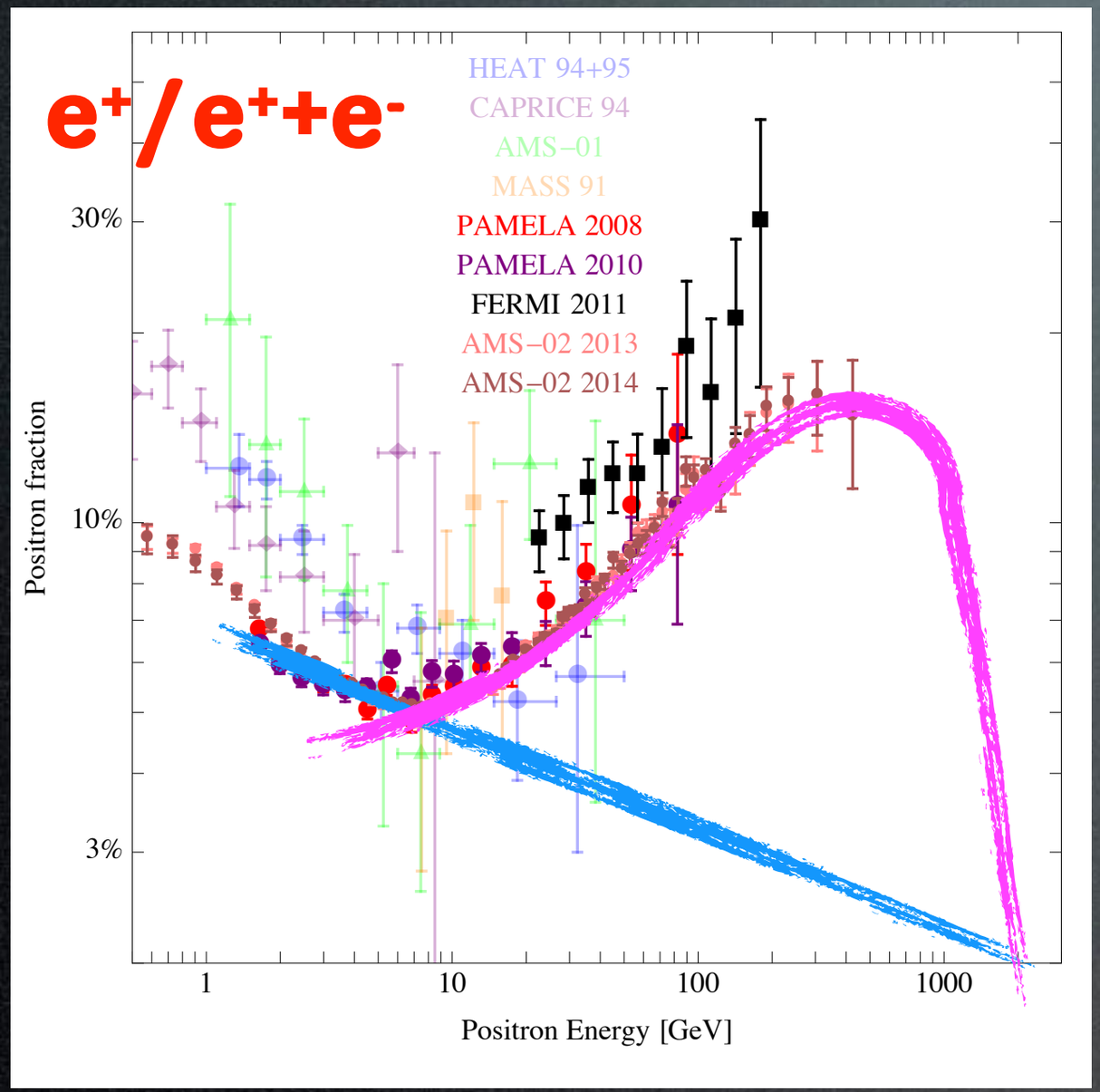


M. Cirelli - compilation ICRC 2015

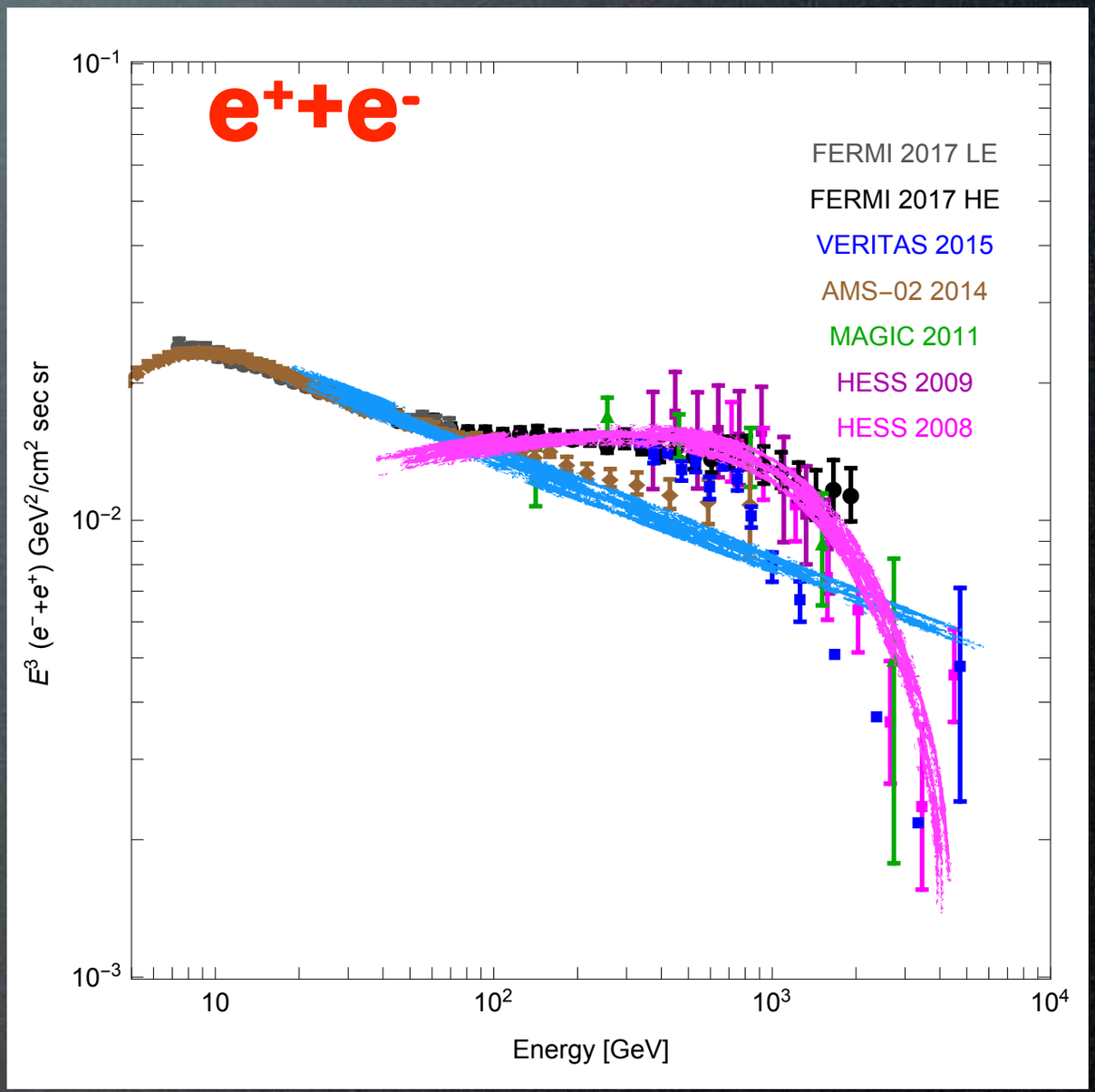


M. Cirelli - compilation ICRC 2015

Data: leptons



M. Cirelli - compilation ICRC 2015



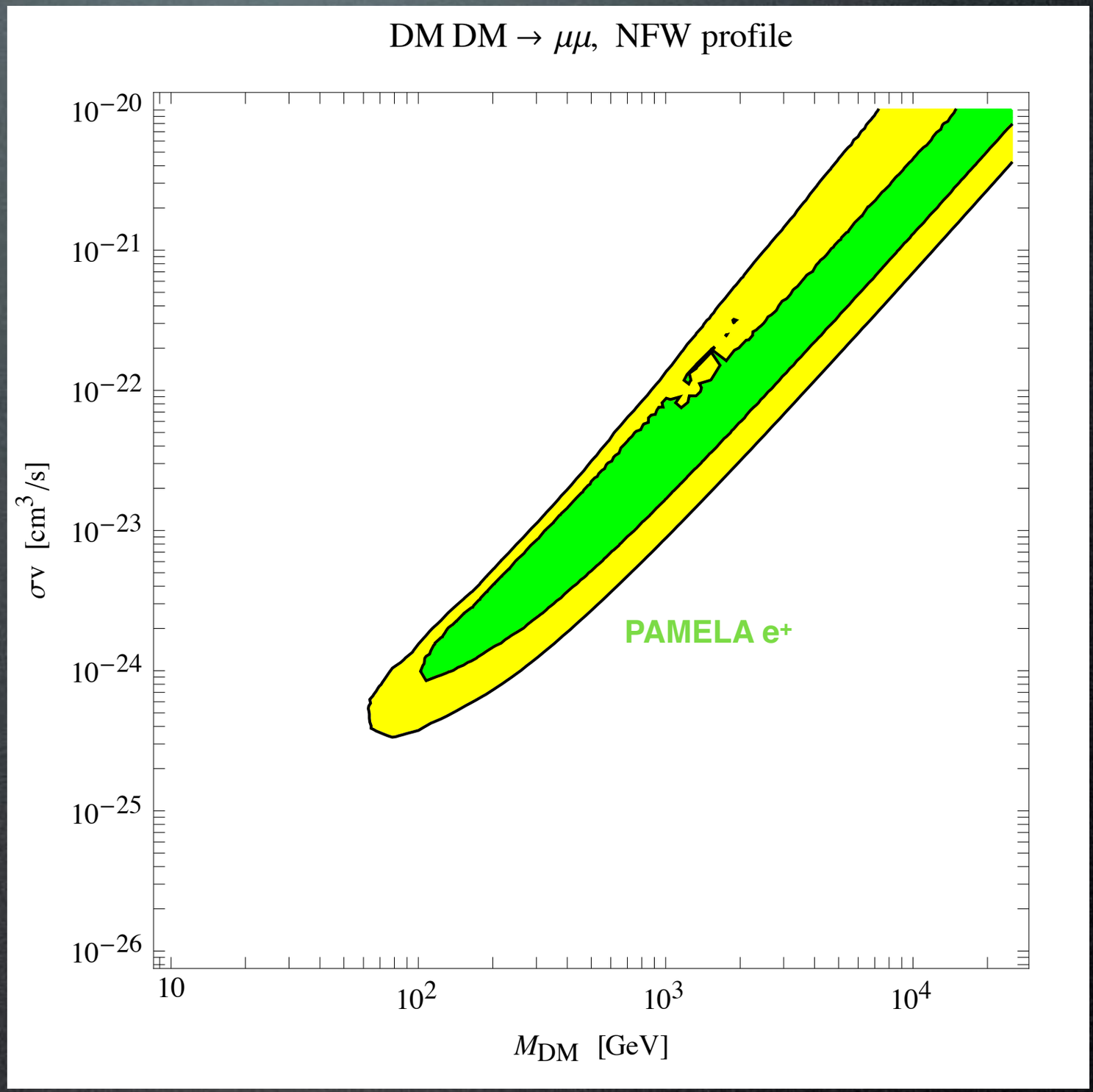
M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

- leptophilic

- m_{DM} > few 100 GeV

- huge annihilation cross section



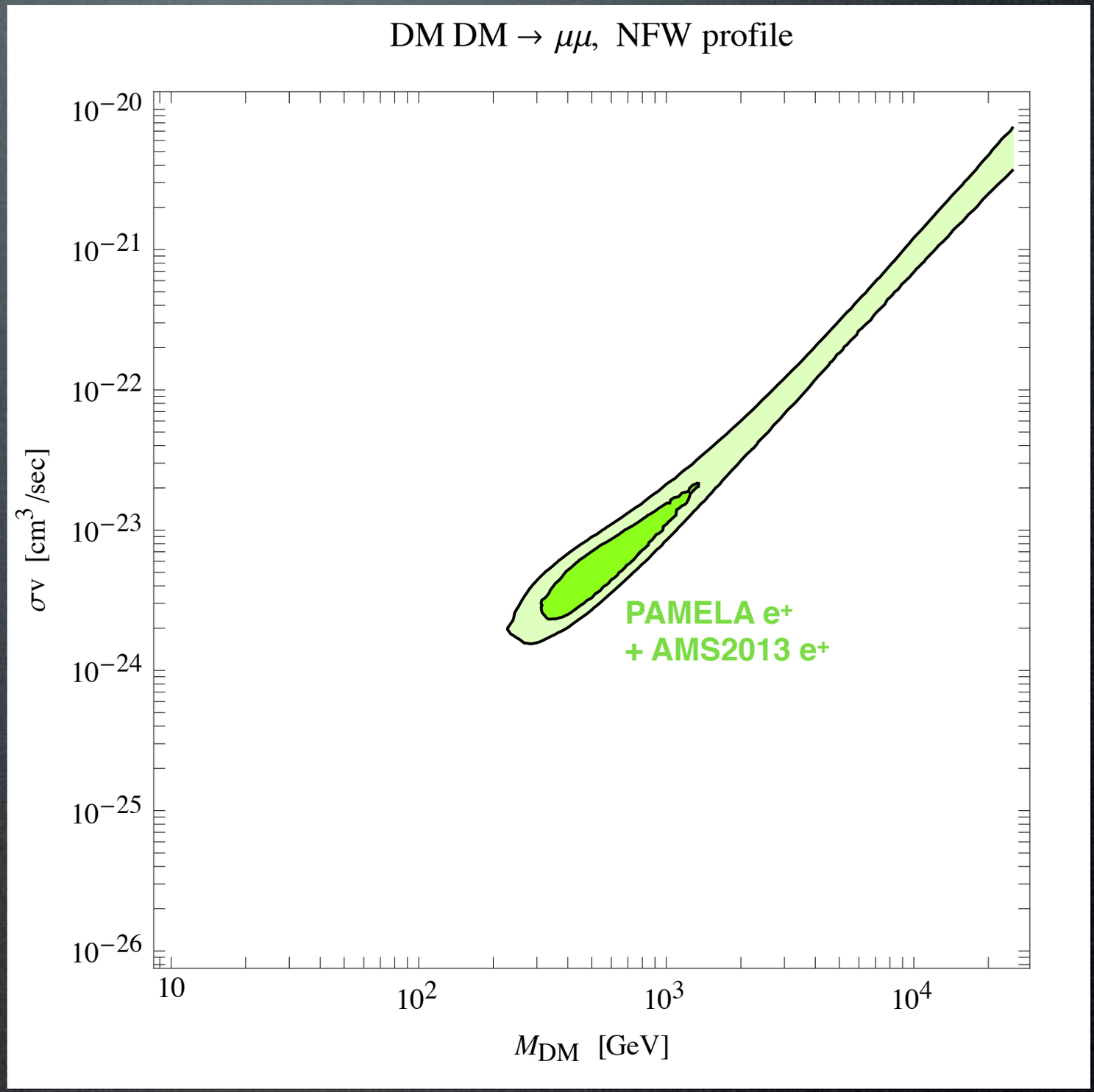
M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

- leptophilic

- $m_{DM} \sim 1$ TeV

- huge annihilation cross section



M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

- leptophilic

- $m_{DM} \lesssim 1$ TeV

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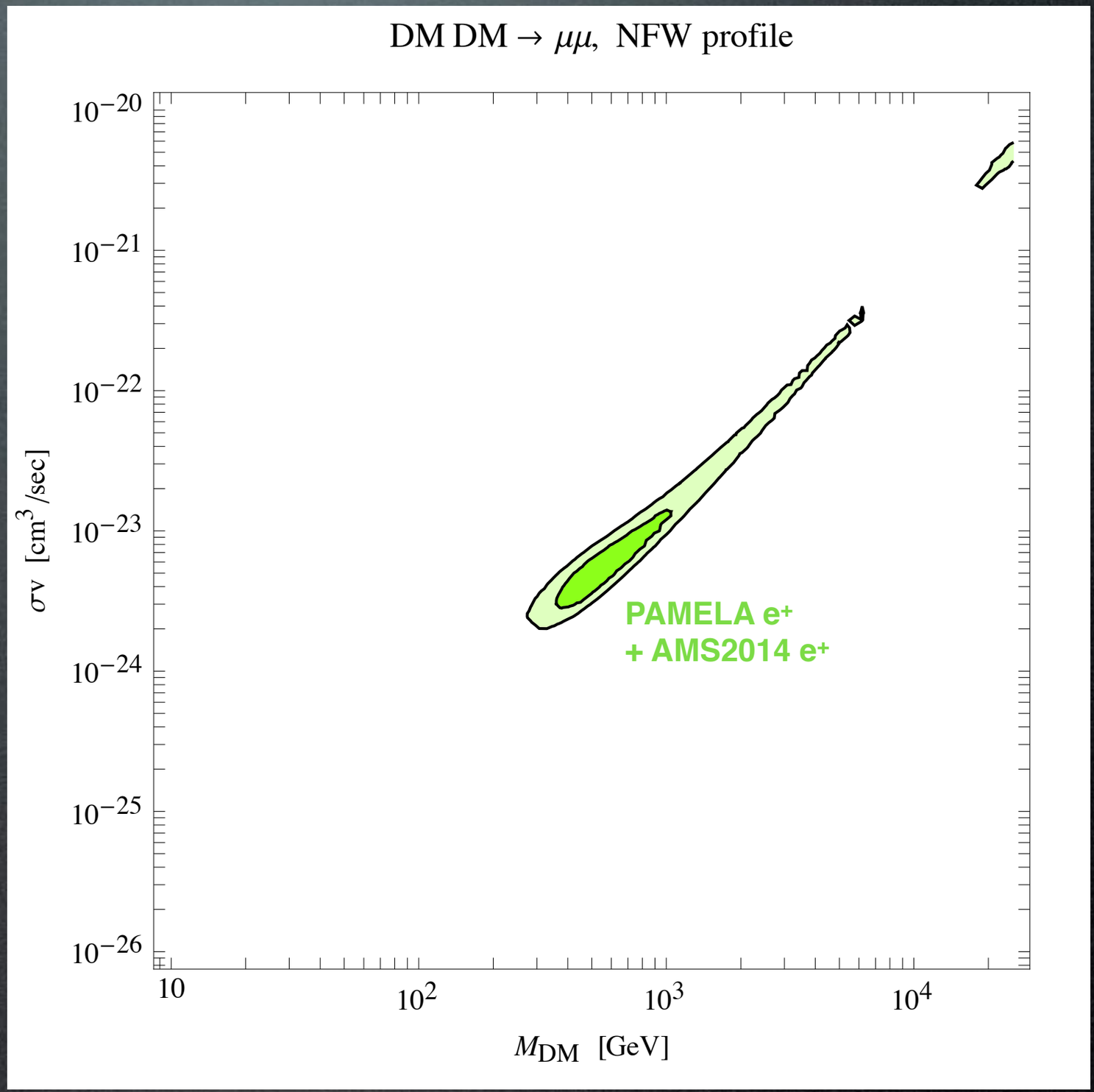

M. Cirelli - compilation ICRC 2015

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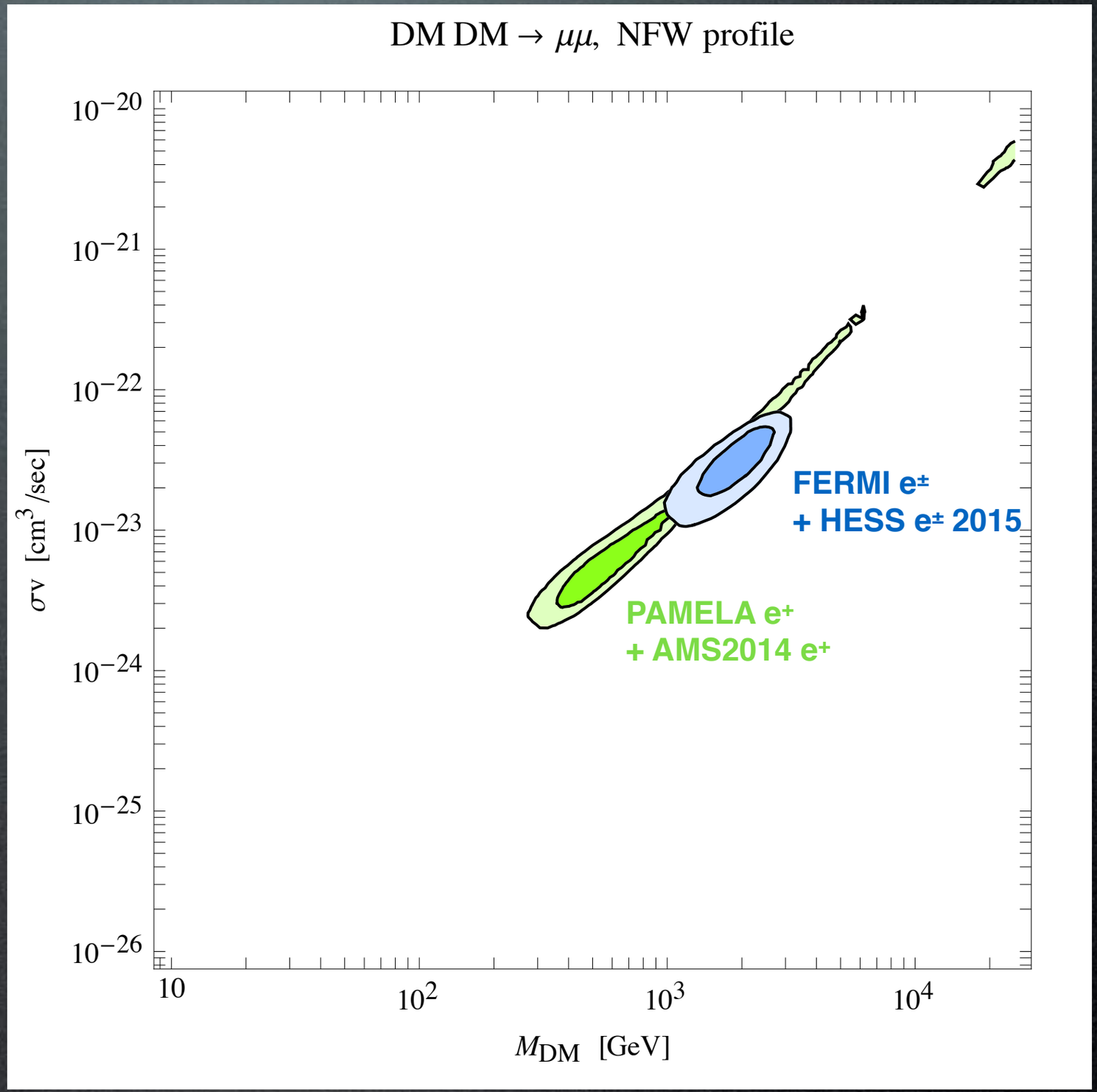

M. Cirelli - compilation ICRC 2015

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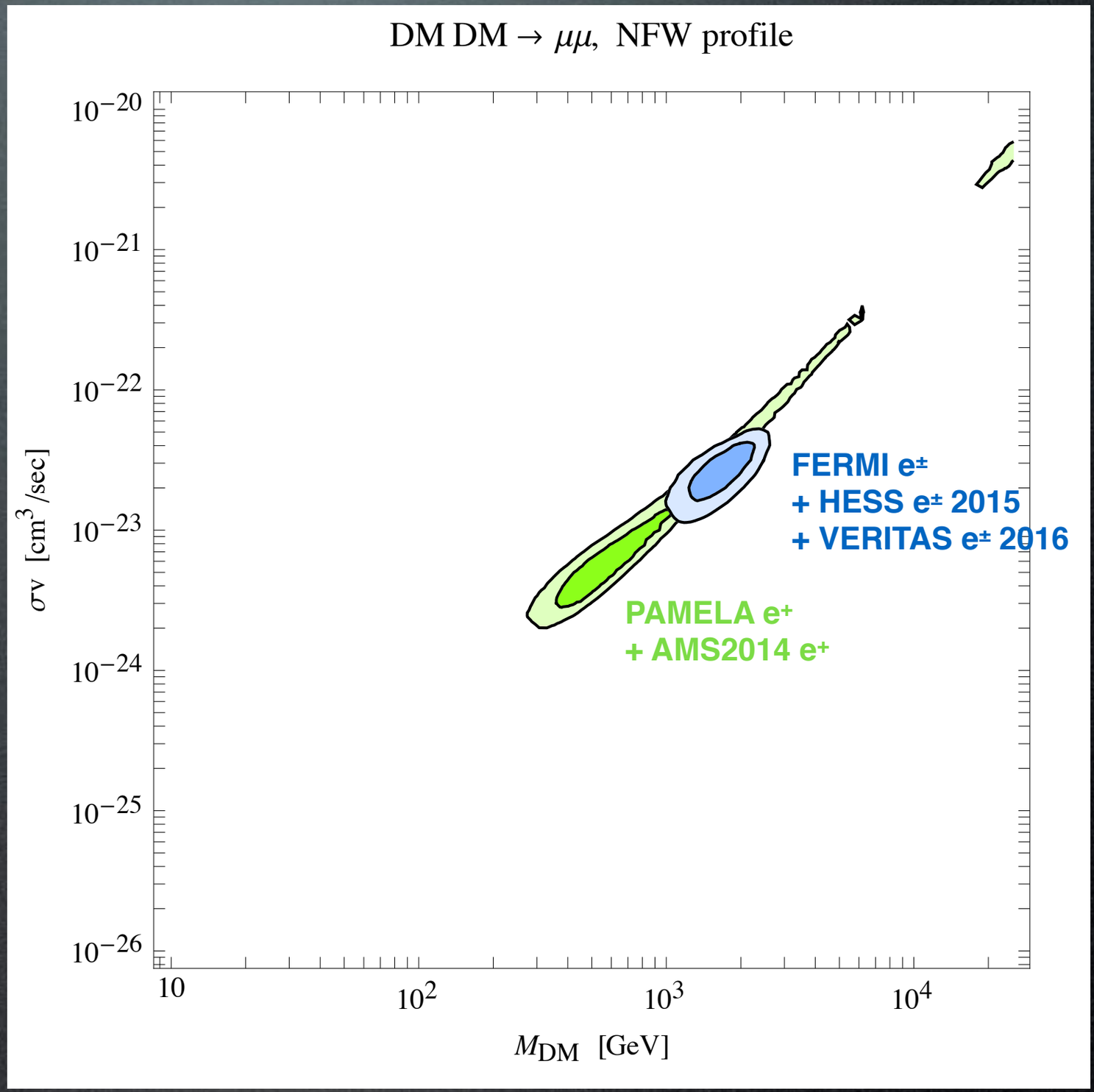

M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

However:

Dark Matter interpretation

However:

- increased precision brings increased tension

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

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- combination of annihilation channels are possible

Dark Matter interpretation

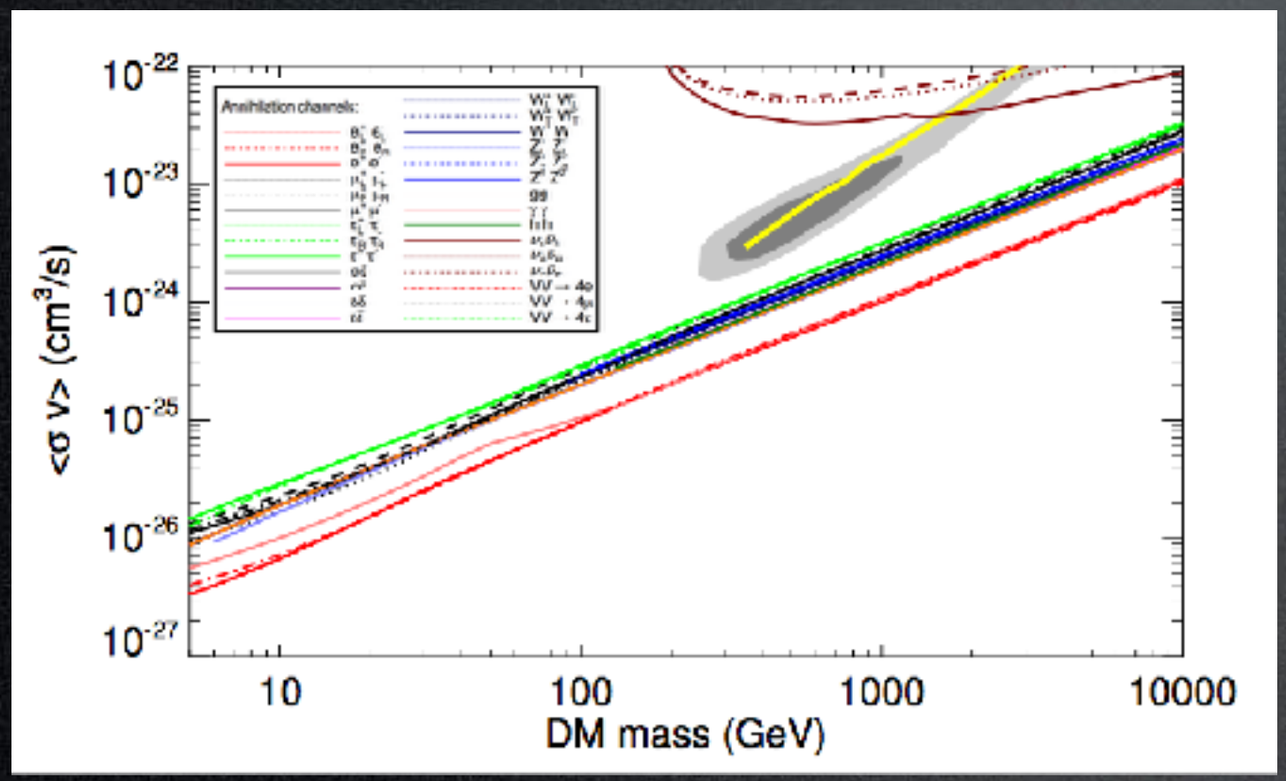
However:

- increased precision brings increased tension

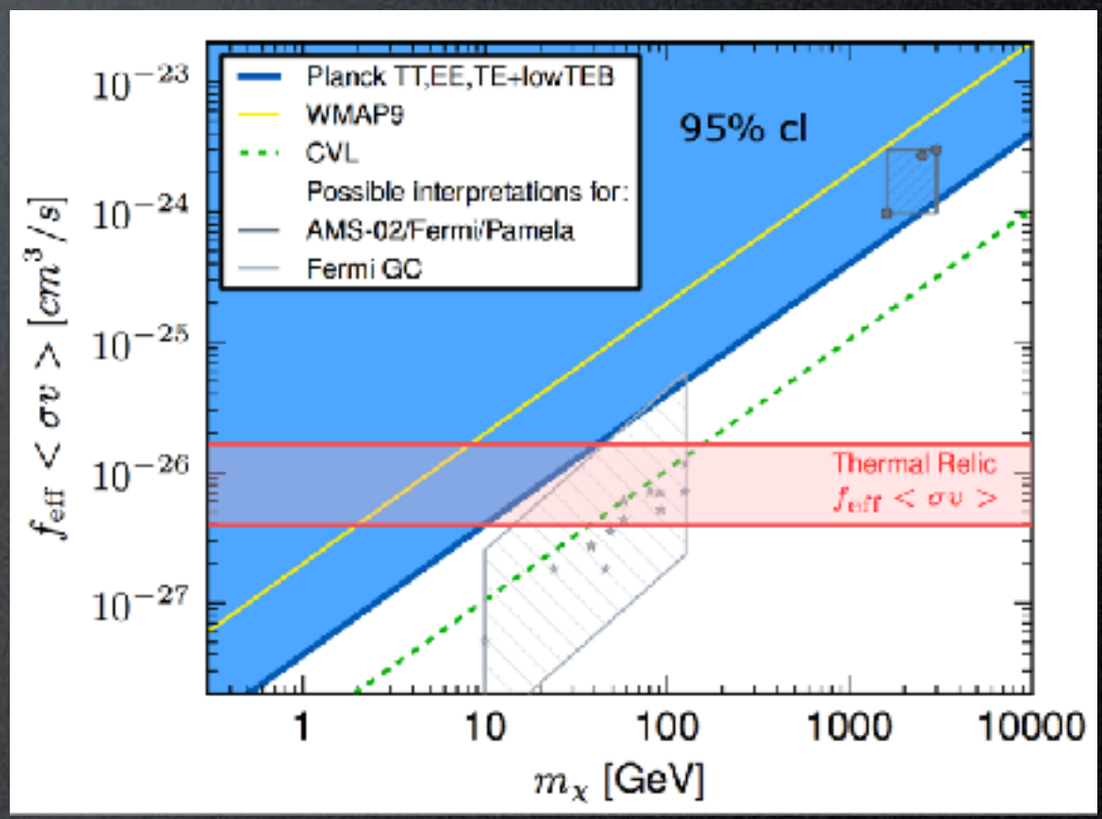
  "The improved accuracy of AMS-02 on the lepton flux now excludes channels previously allowed."

- combination of annihilation channels are possible

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

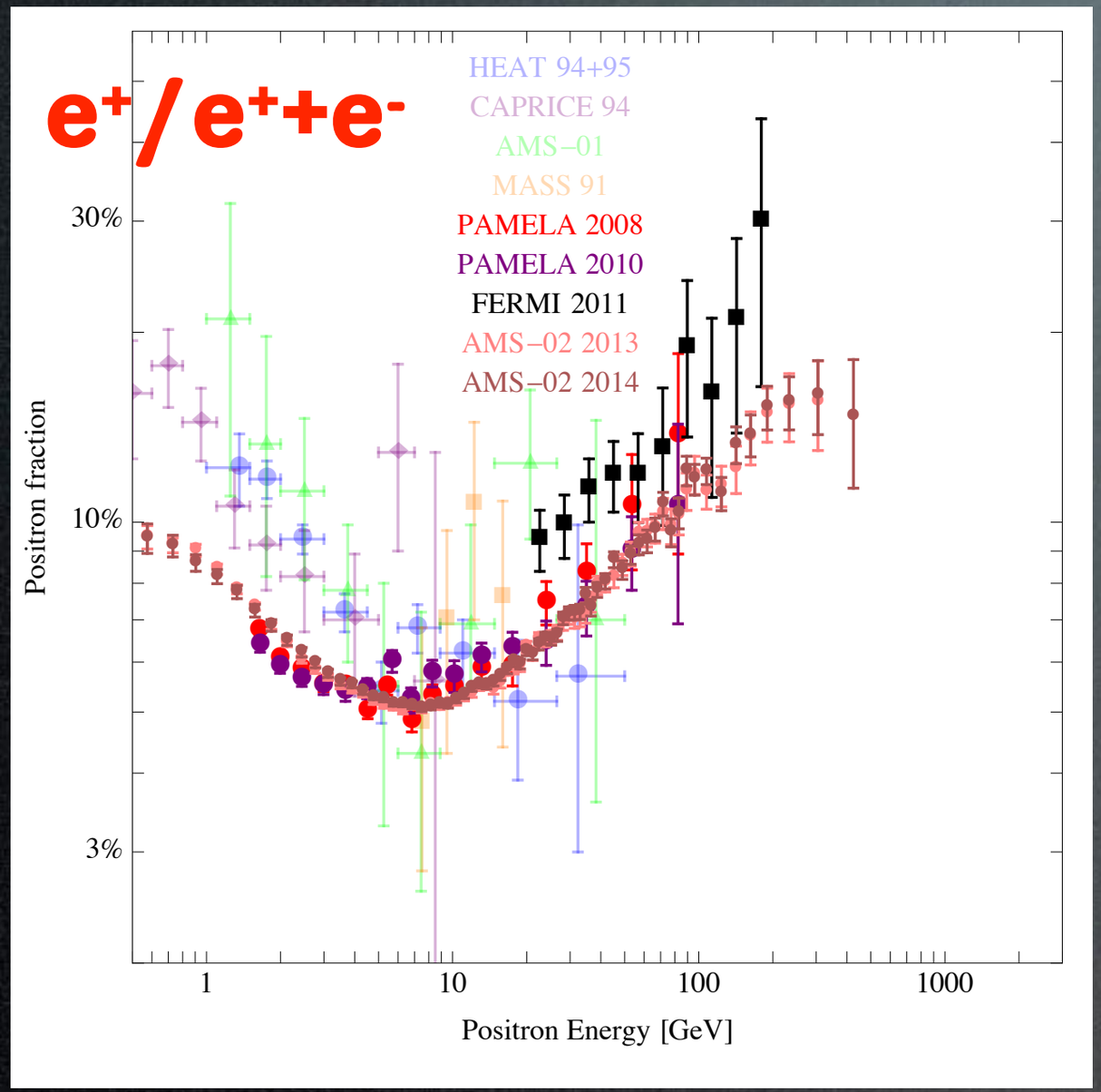


T.Slatyer 1506.03811

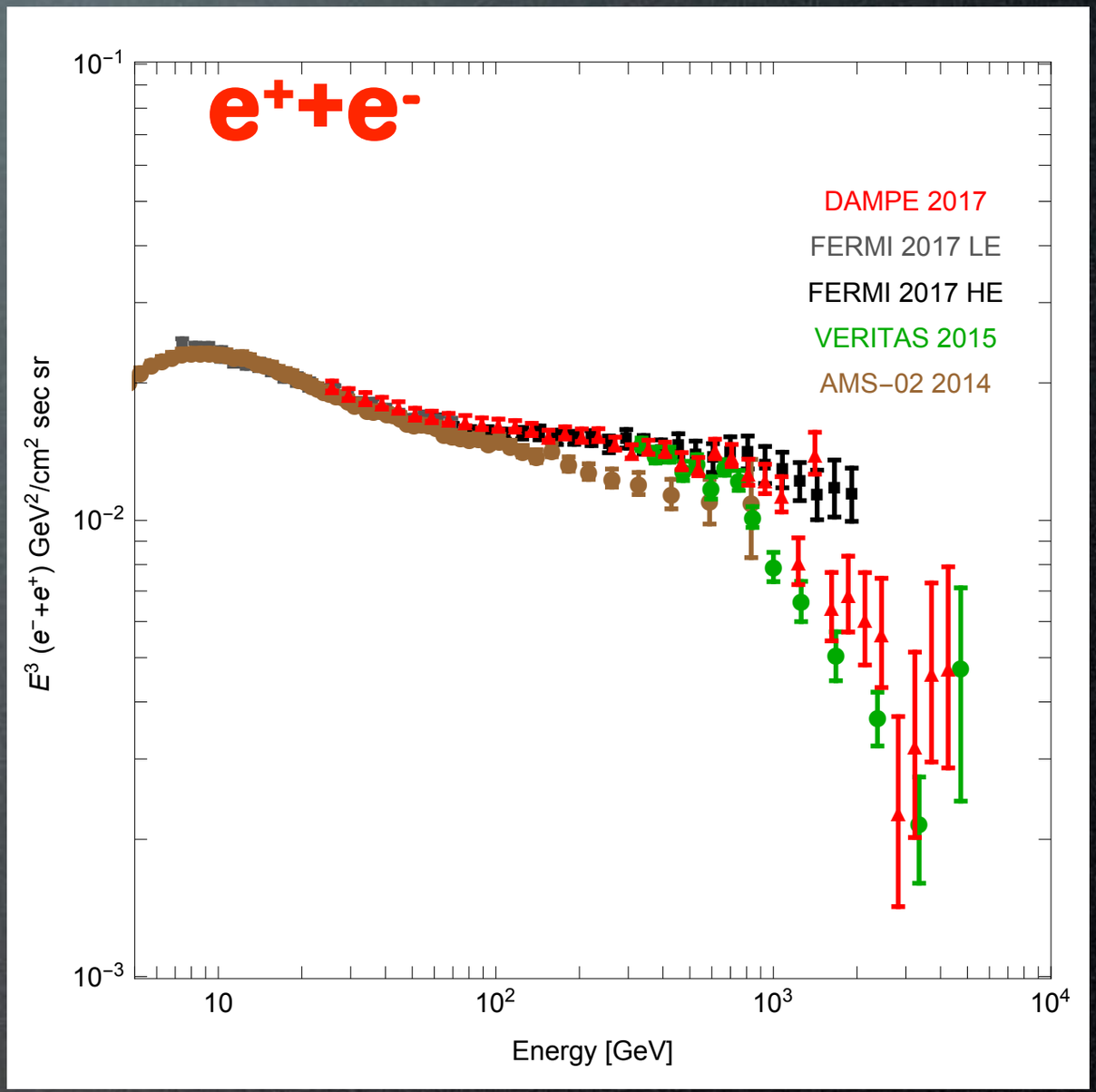


Planck 2015 (1502.01589)

Data: leptons

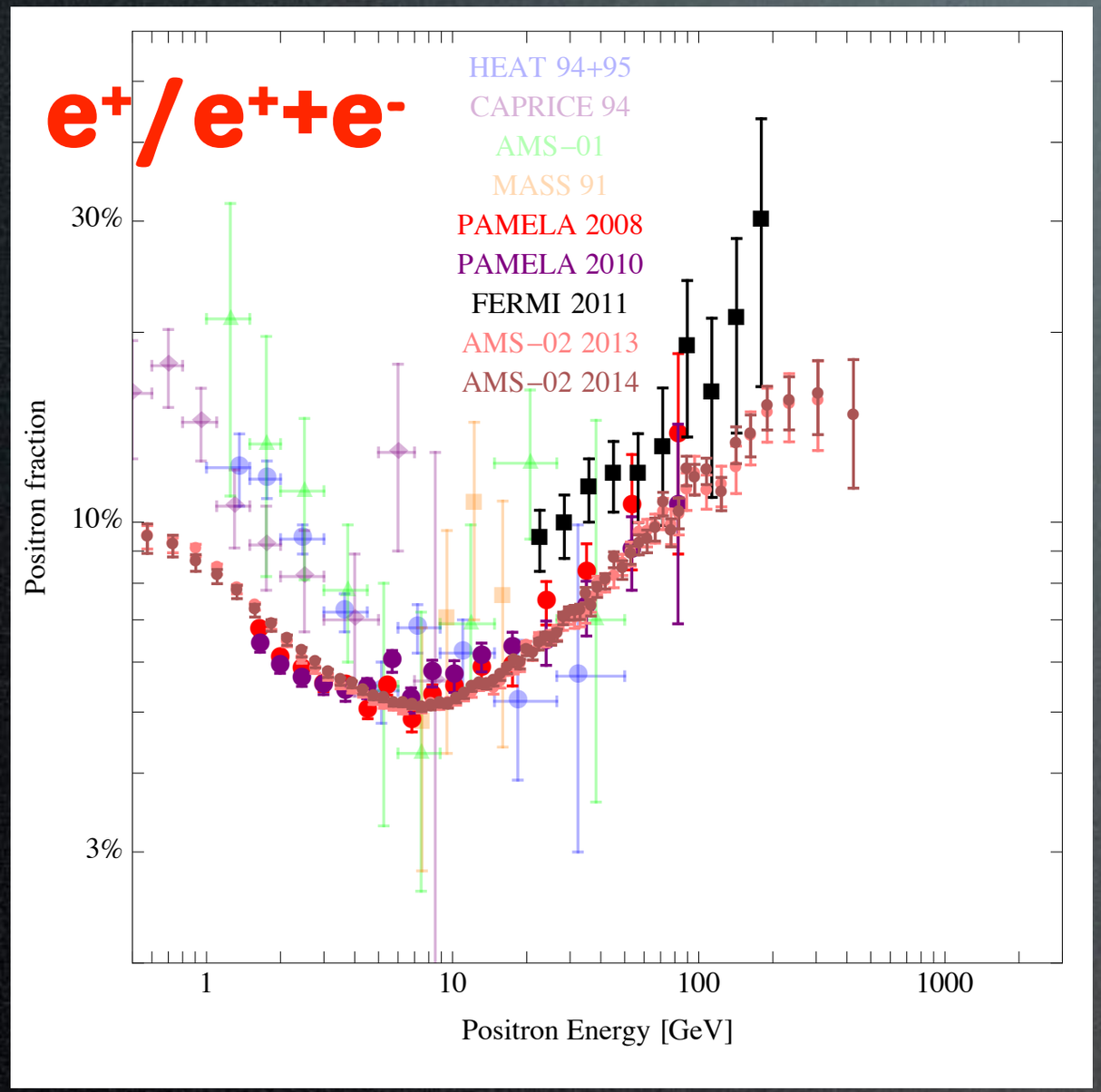


M. Cirelli - compilation ICRC 2015

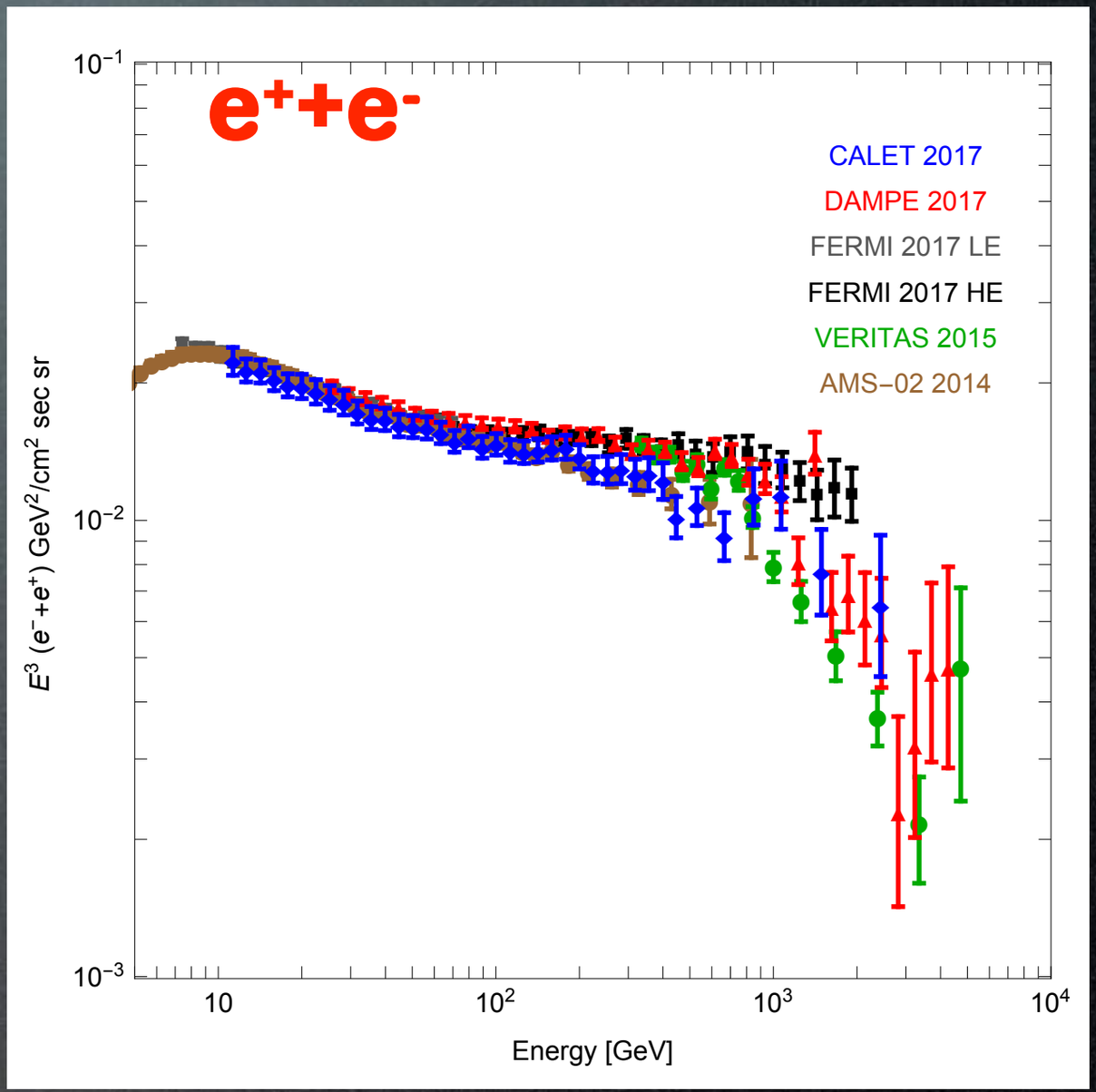


M. Cirelli - private collection

Data: leptons



M. Cirelli - compilation ICRC 2015



M. Cirelli - private collection

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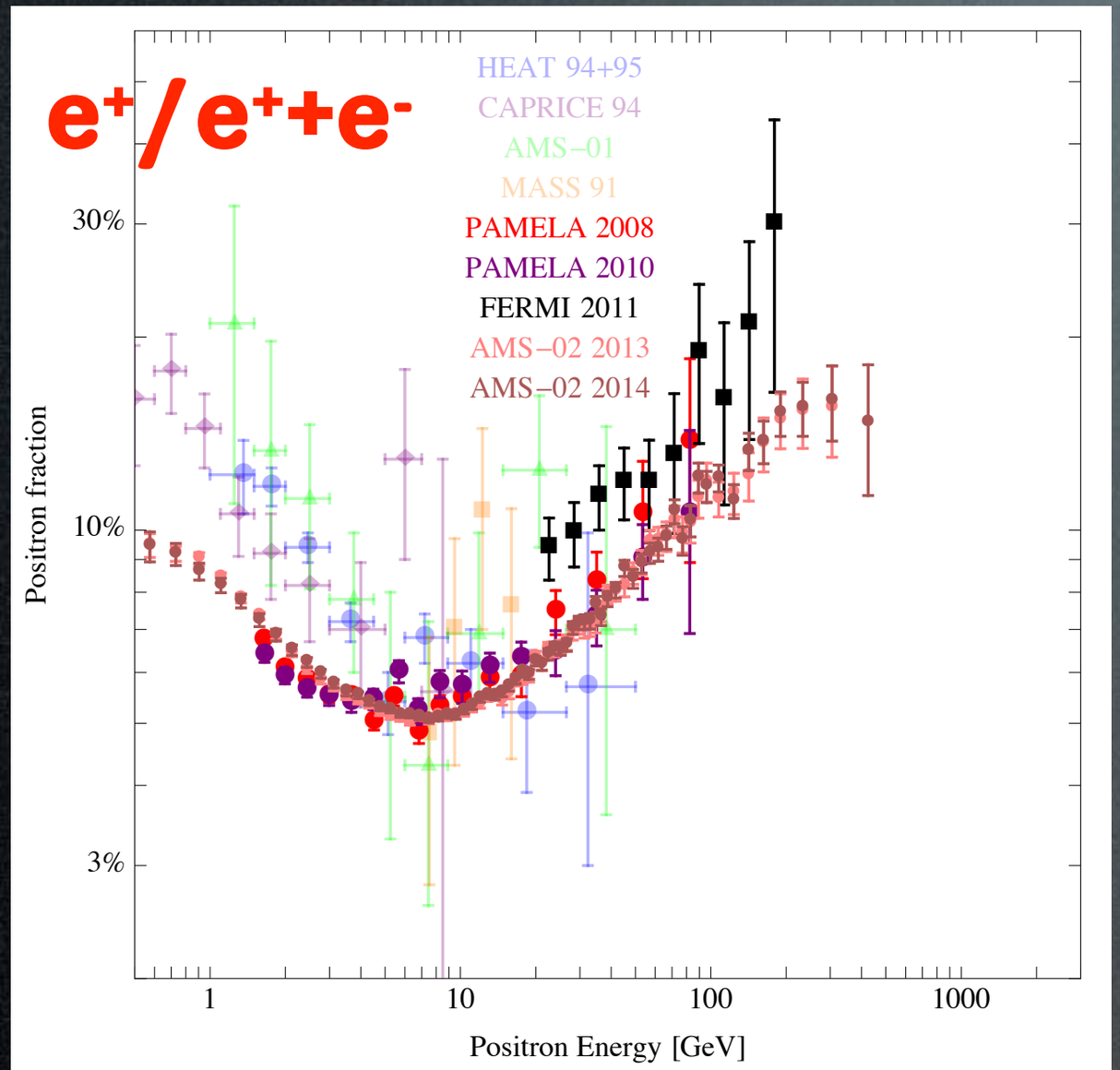
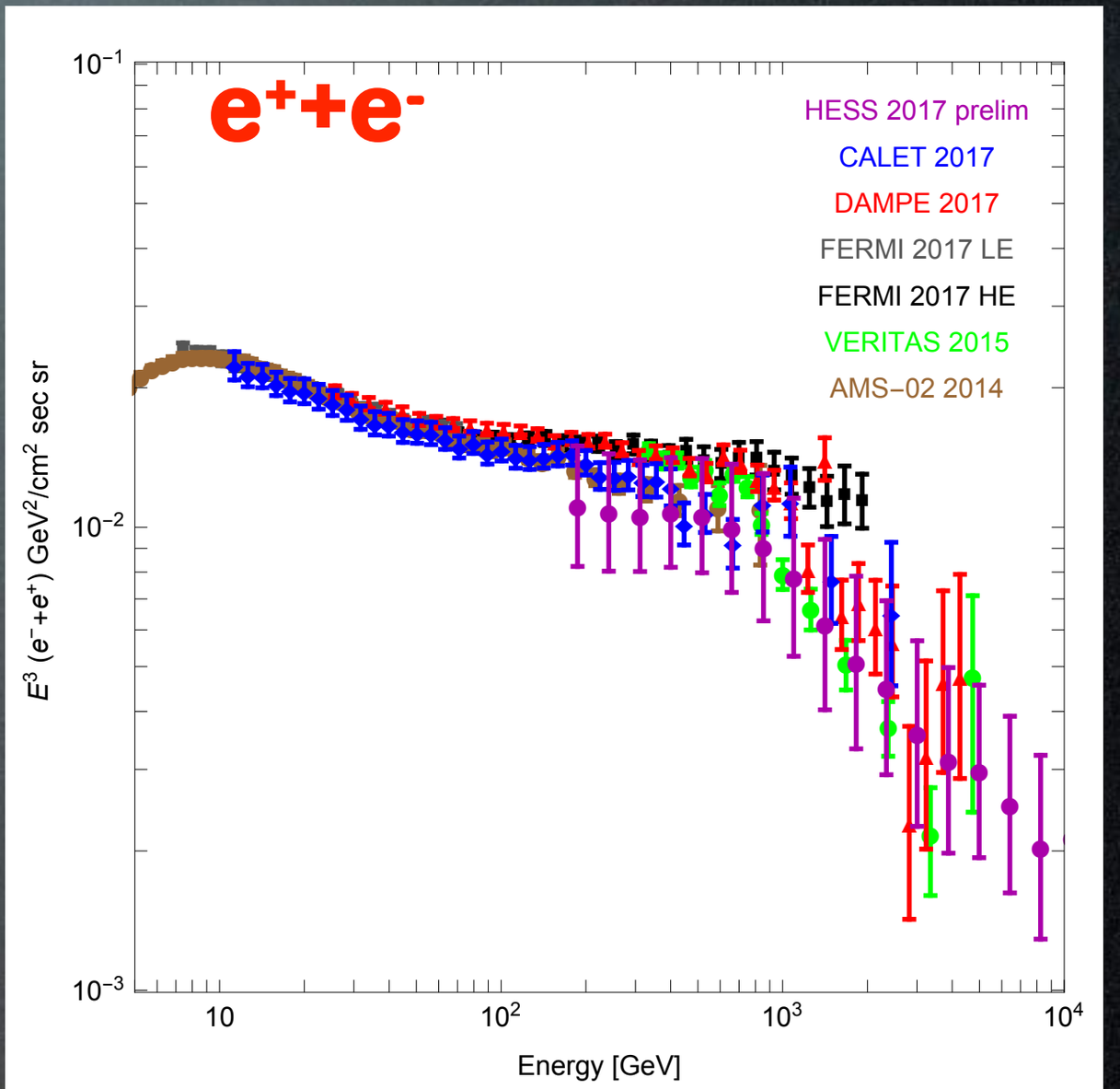


M. Cirelli - compilation ICRC 2015



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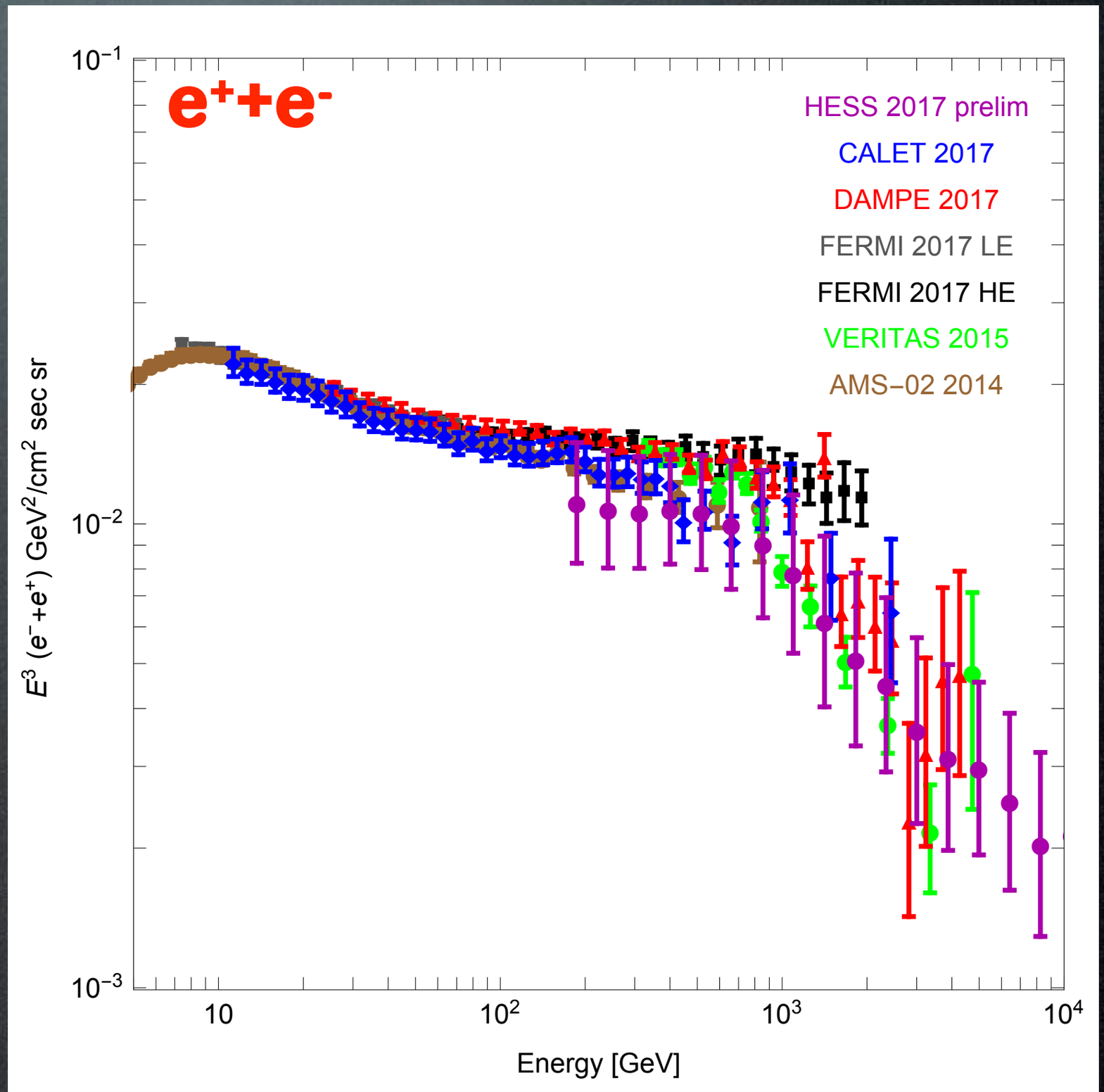

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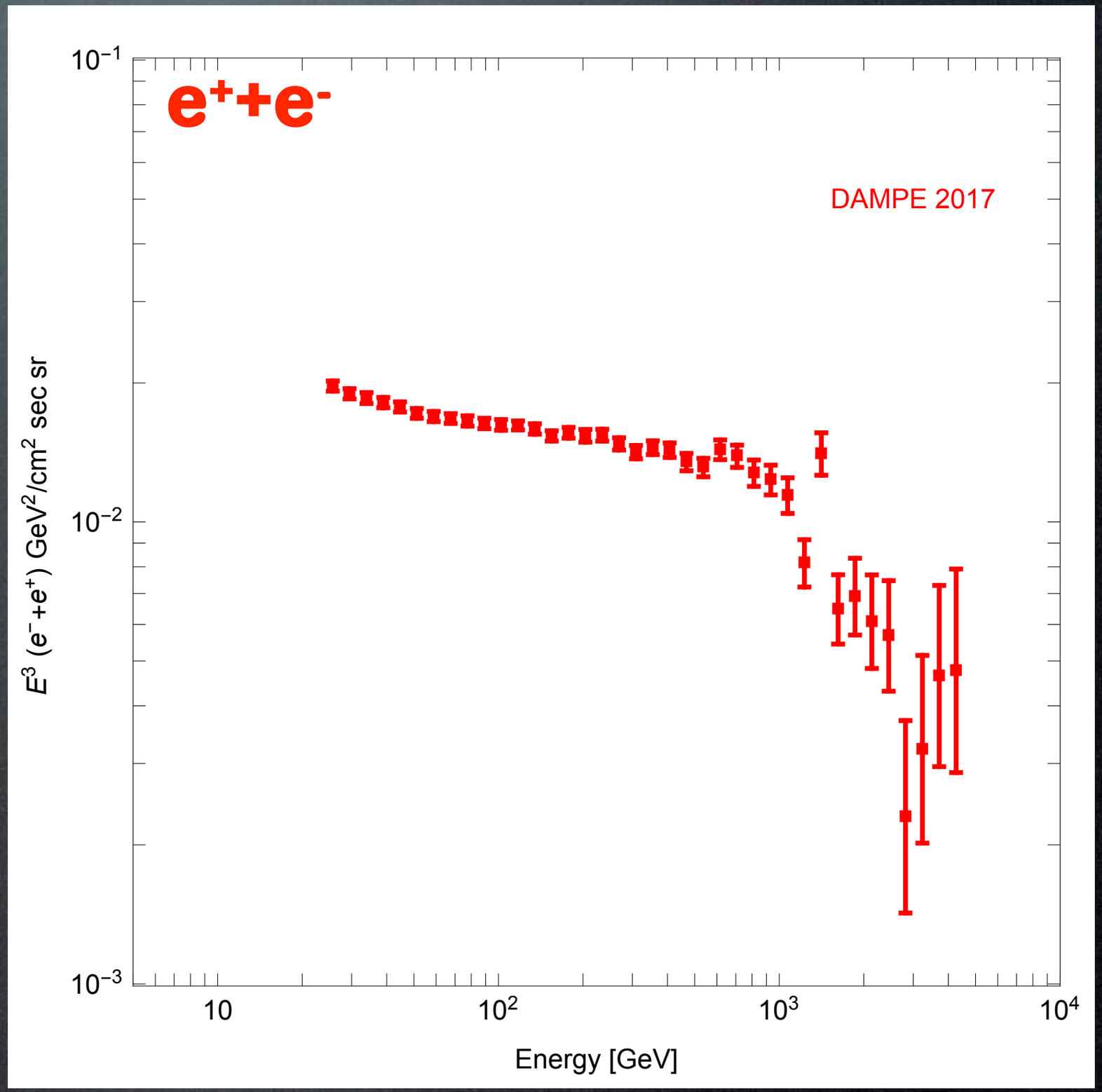
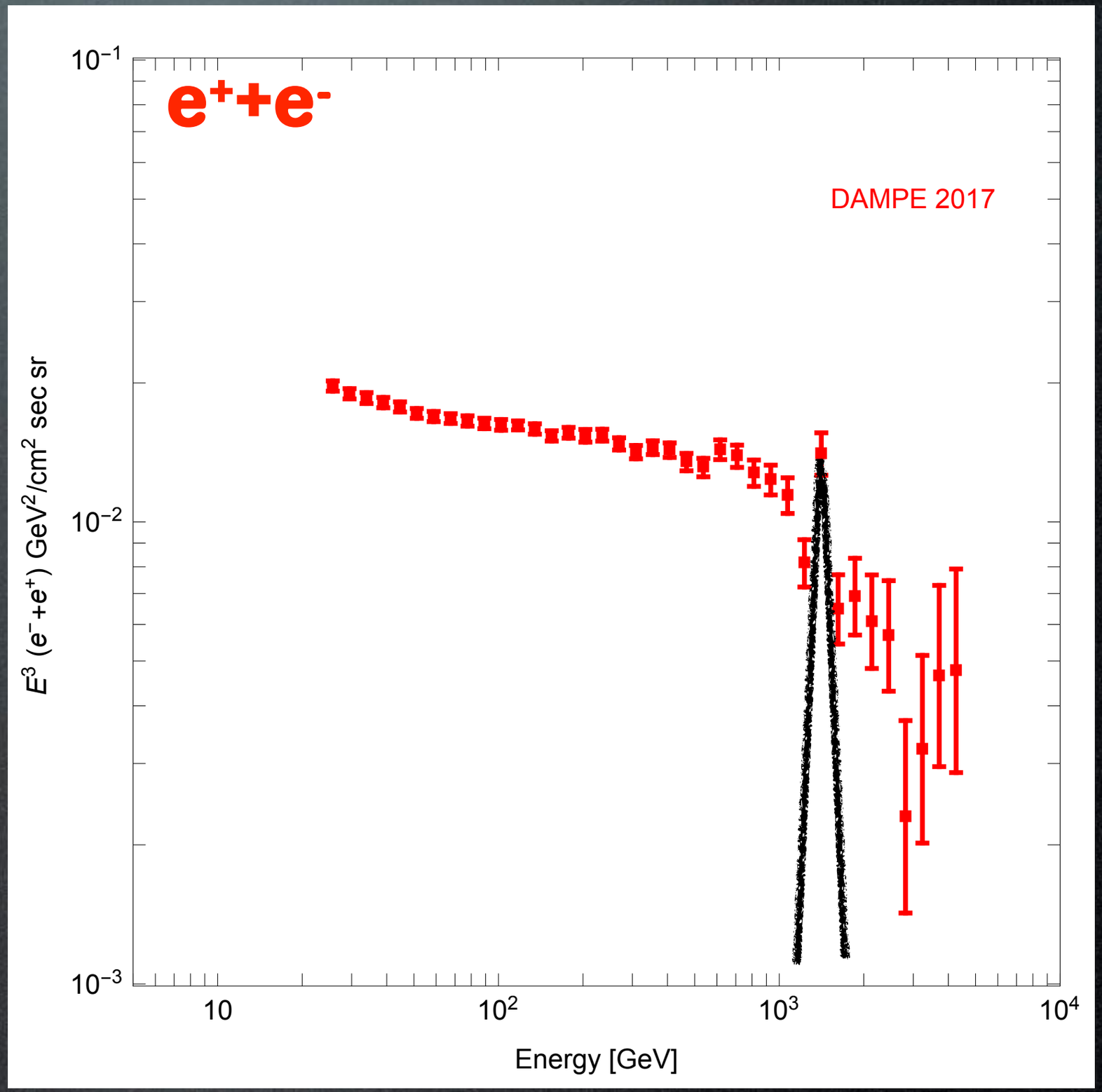


Data: leptons

frenetic activity in december 2017



Gamma rays

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

$\bar{p}$ 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

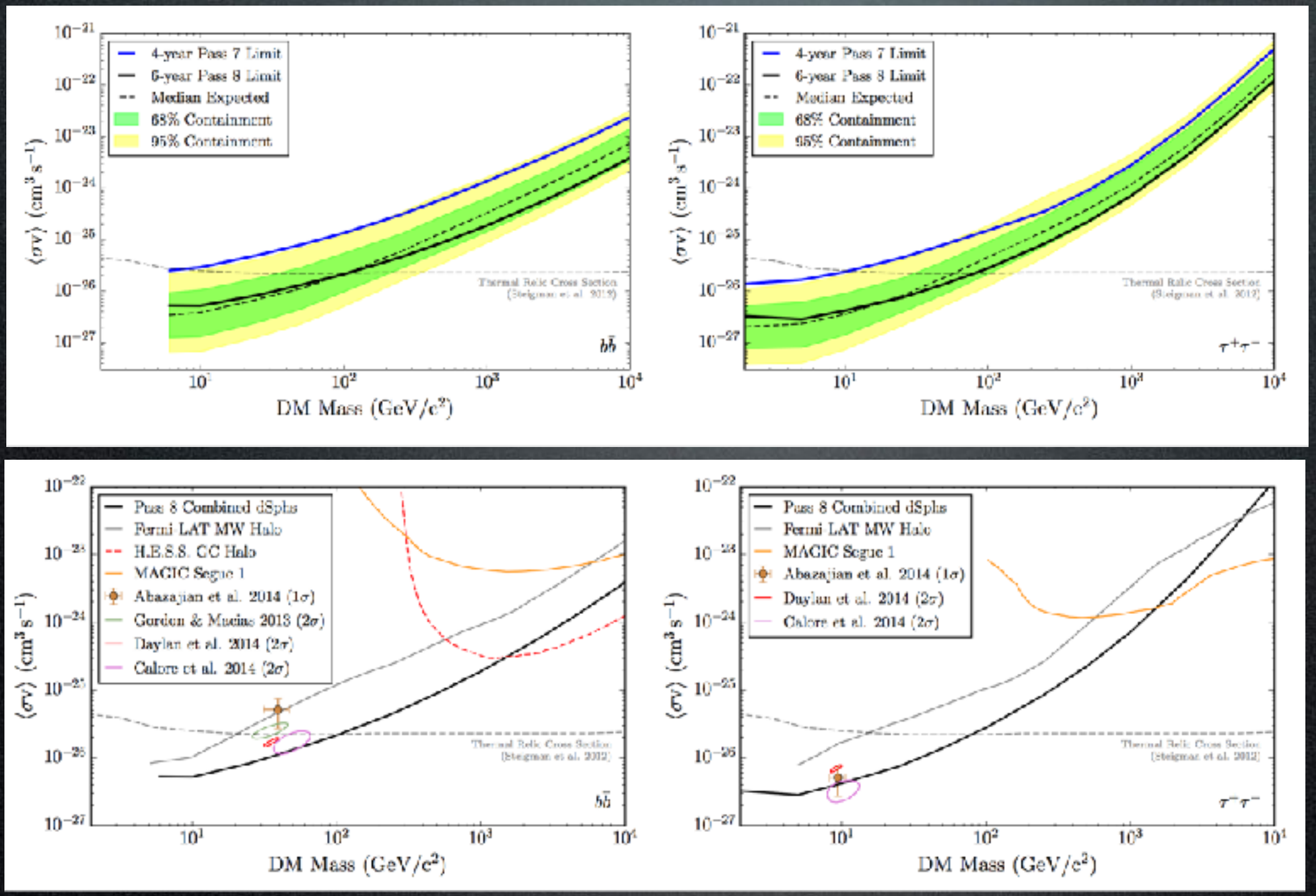
SK, Icecube, Antares

Constraints

Dwarf galaxies

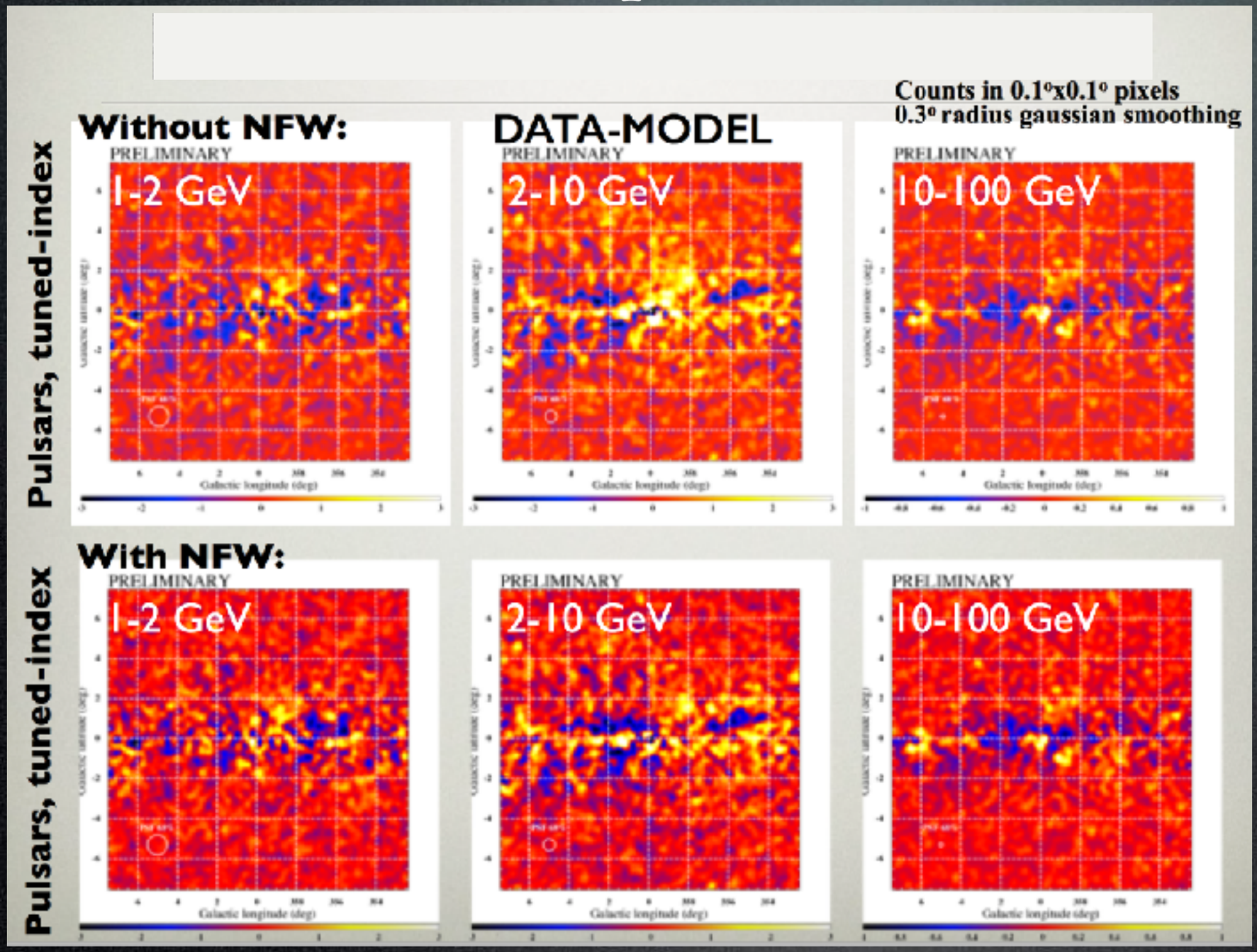
FERMI

FERMI 1503.02641



GC GeV excess

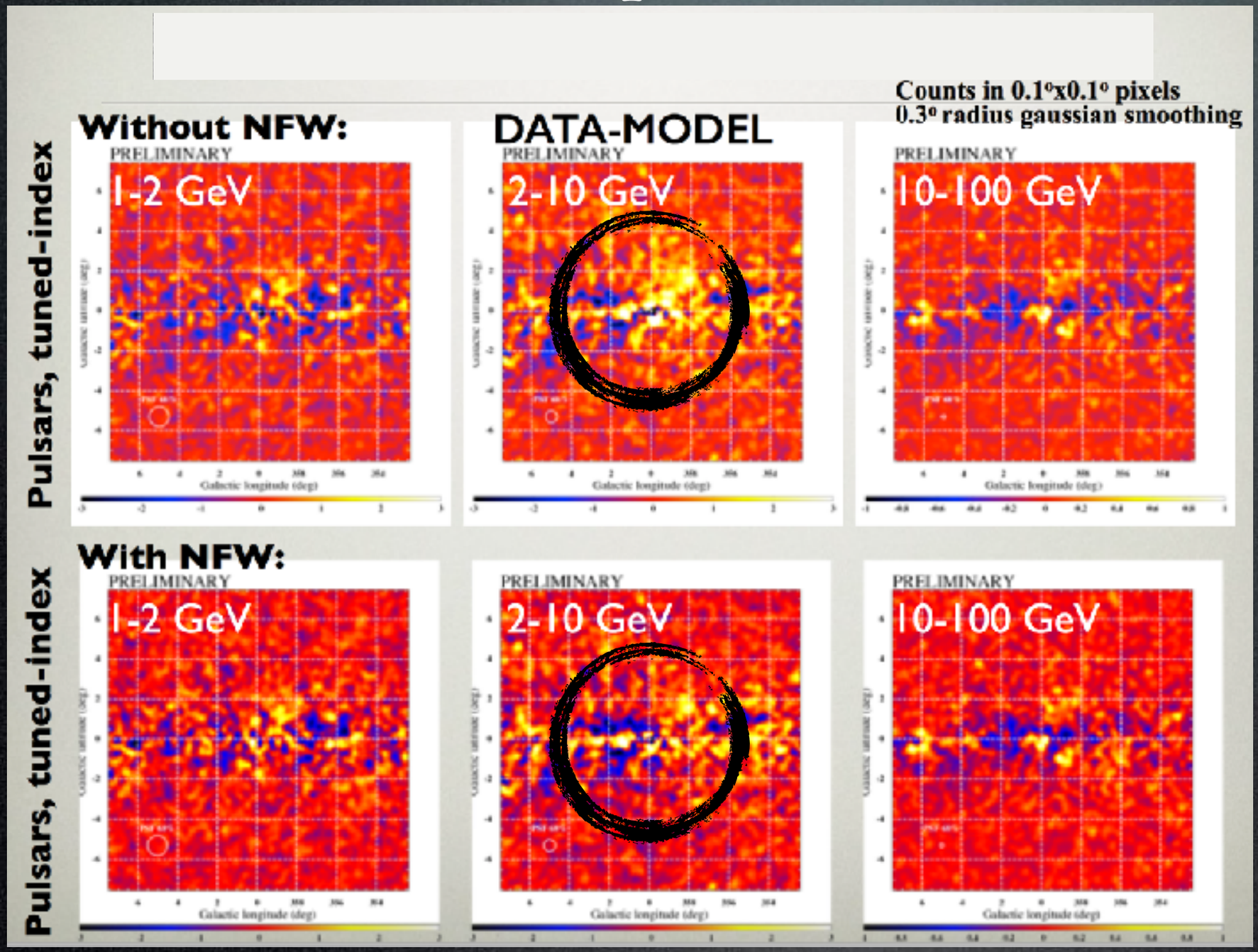
Dark Matter interpretation:



S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815
Fermi coll. 1511.02938

GC GeV excess

Dark Matter interpretation:



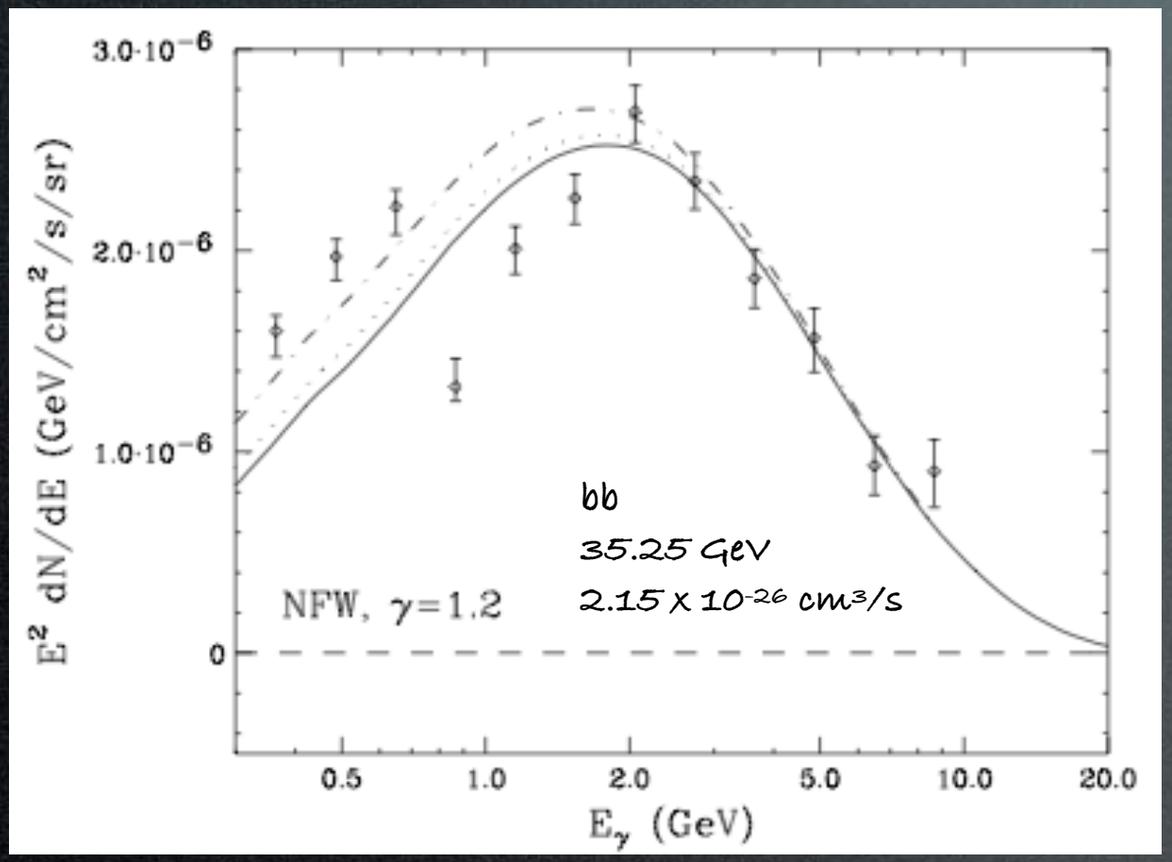
S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815
Fermi coll. 1511.02938

GC GeV excess

Dark Matter interpretation:

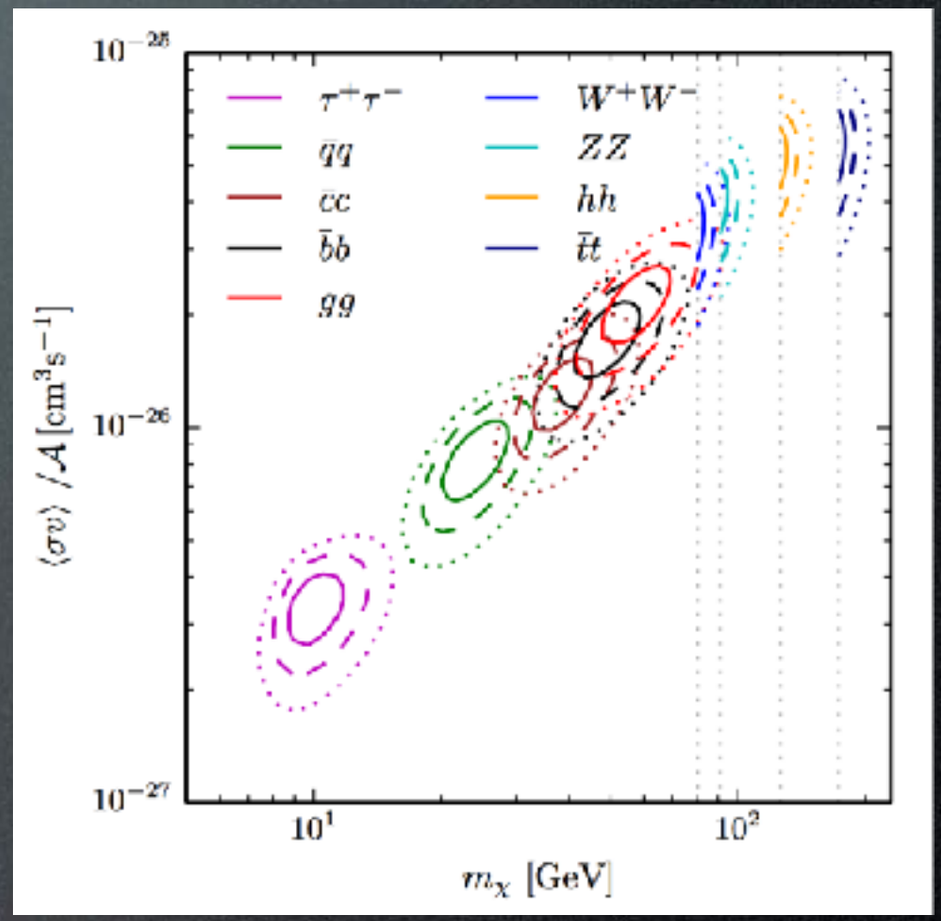
Best fit:

~35 GeV, quarks, ~thermal σv



A compelling case for annihilating DM

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



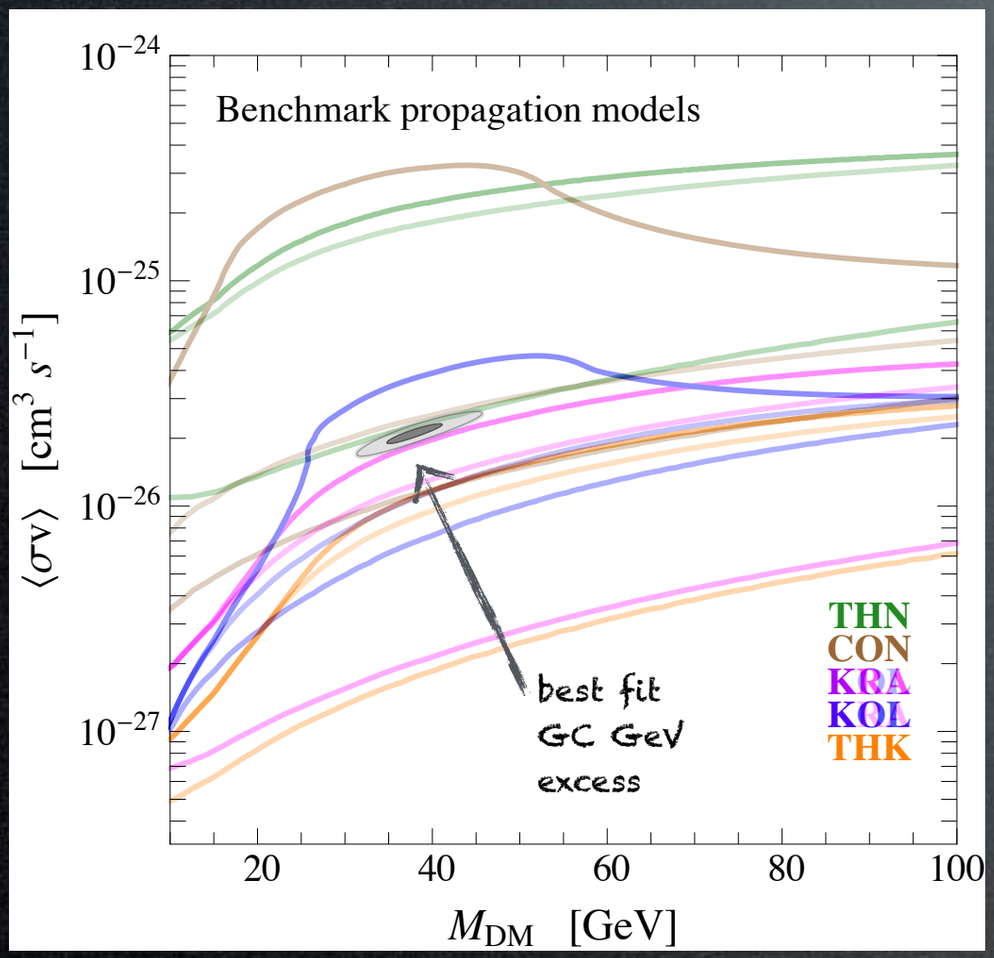
F. Calore et al. 1411.4647

...as good as it can get.

GC GeV excess

Dark Matter interpretation:

Antiproton constraints
are not conclusive



Cirelli, Gaggero,
Giesen, Taoso,
Urbano 1407.2173

Also:

Bringmann, Vollmann,
Weniger 1406.6027

Hooper, Linden, Mertsch
1410.1527

GC GeV excess

Dark Matter interpretation:

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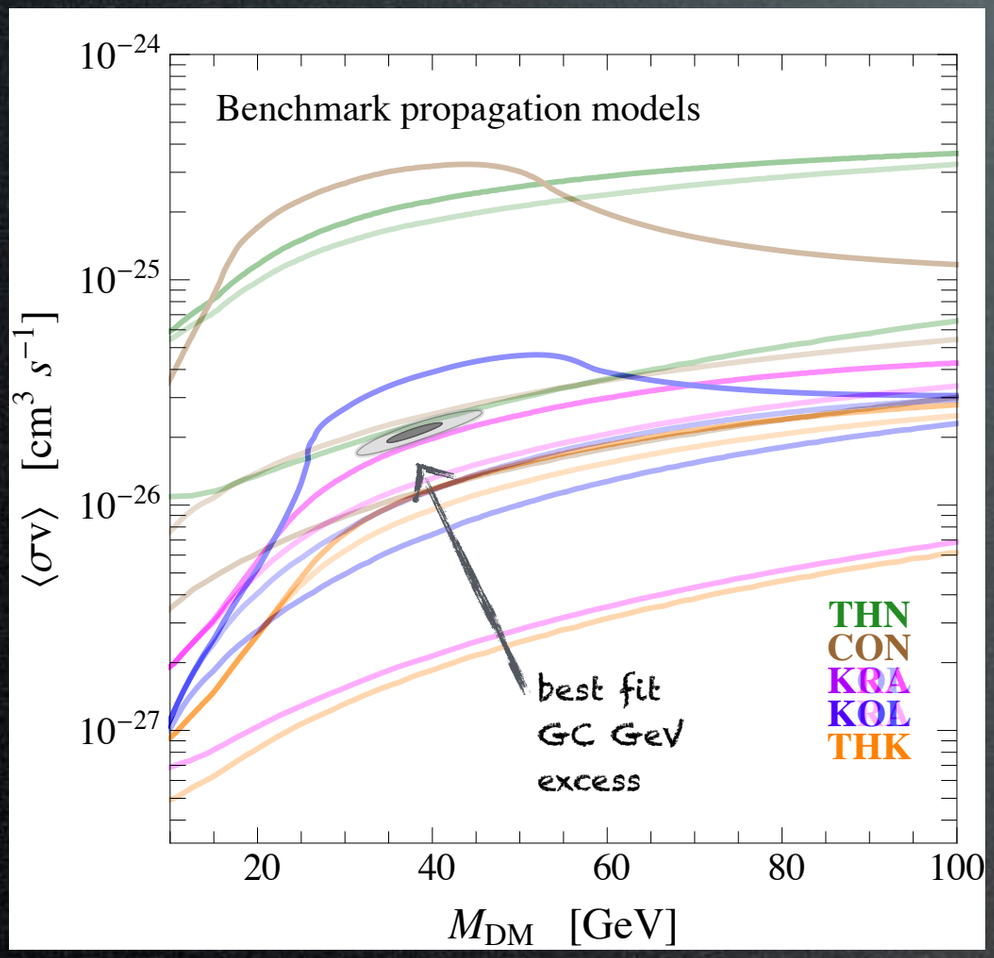
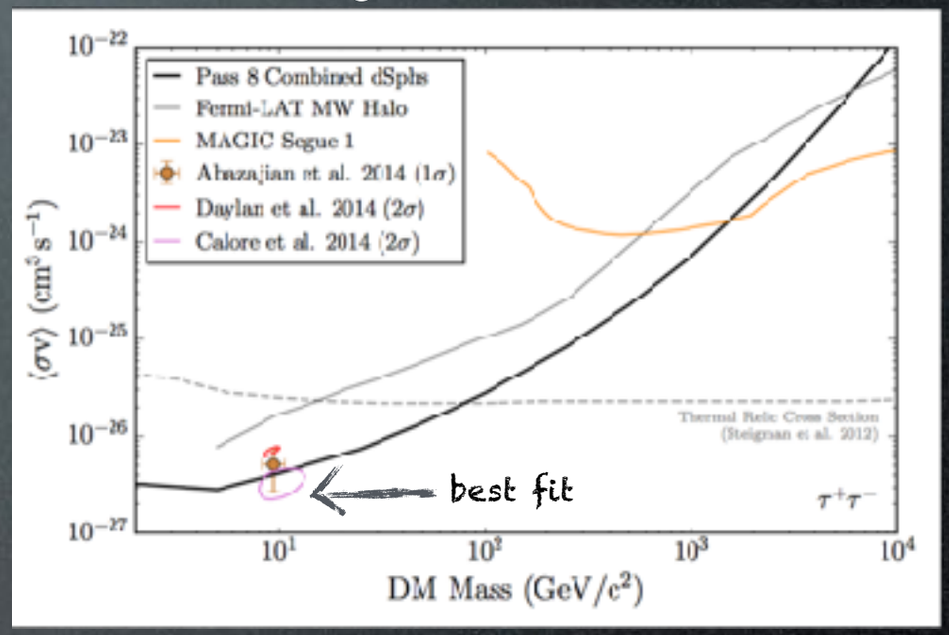


Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Gamma ray ones neither



FERMI 1503.02641

Also:

Bringmann, Vollmann, Weniger 1406.6027

Hooper, Linden, Mertsch 1410.1527

GC GeV excess

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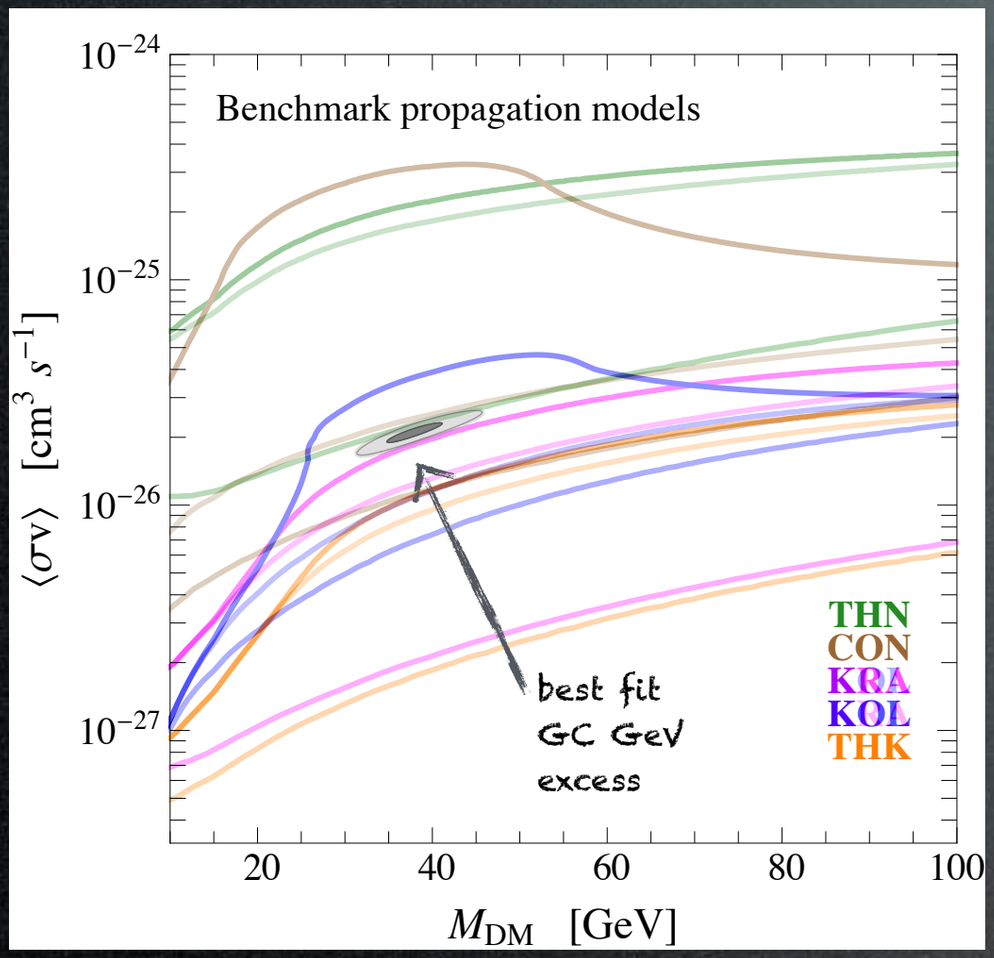

Cirelli, Gaggero,
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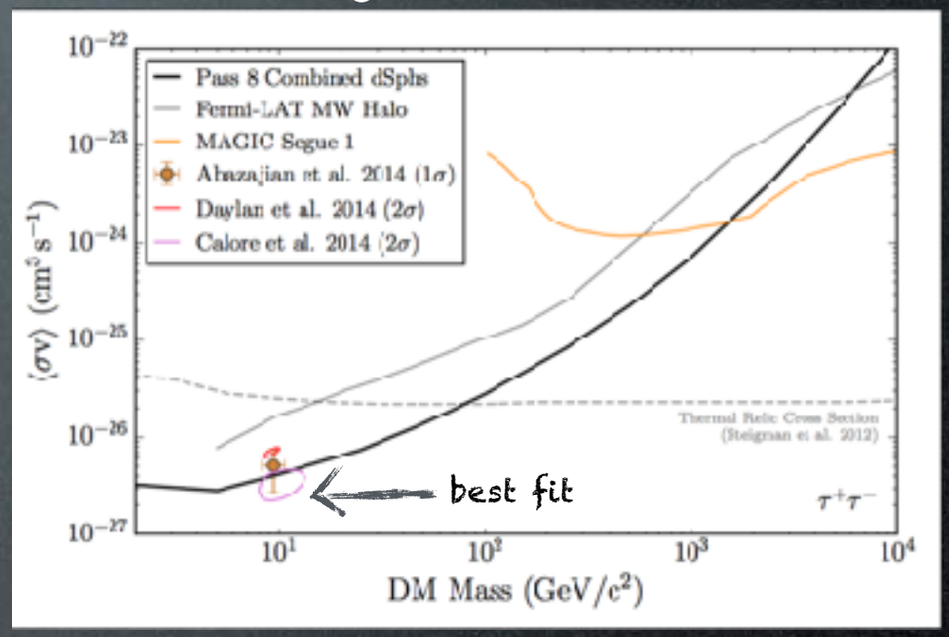
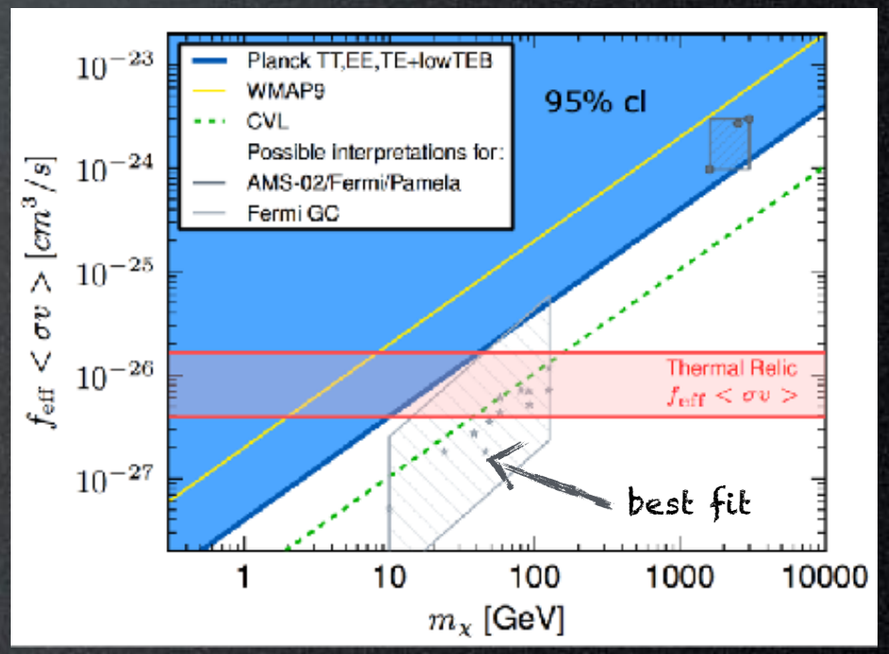
Gamma ray ones neither



FERMI 1503.02641

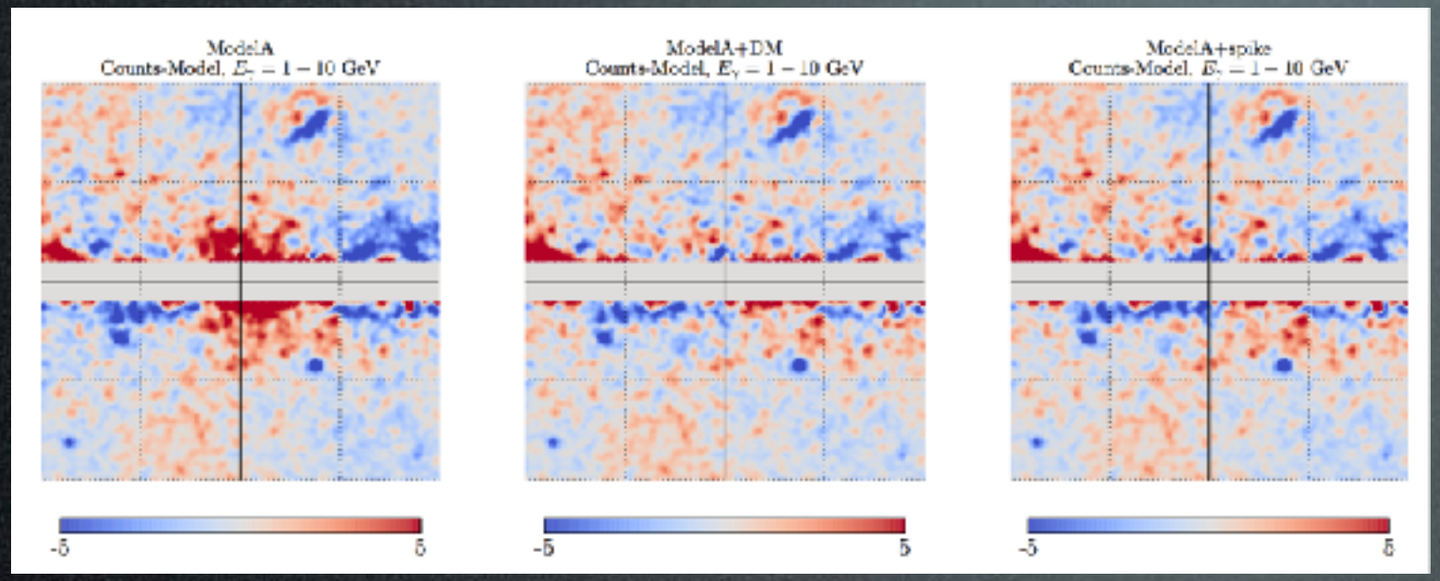
Nor CMB



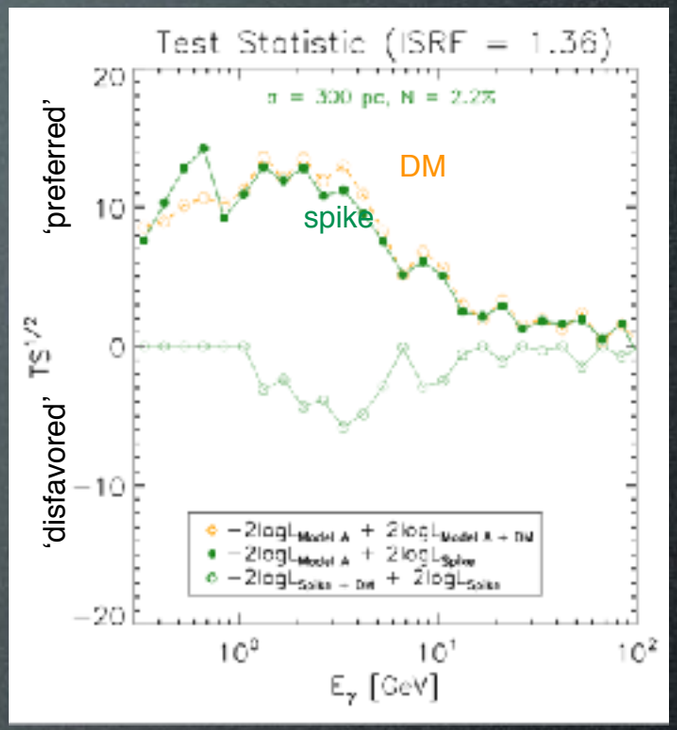
Planck
2015

GC GeV excess

‘Astro’ interpretation(s):

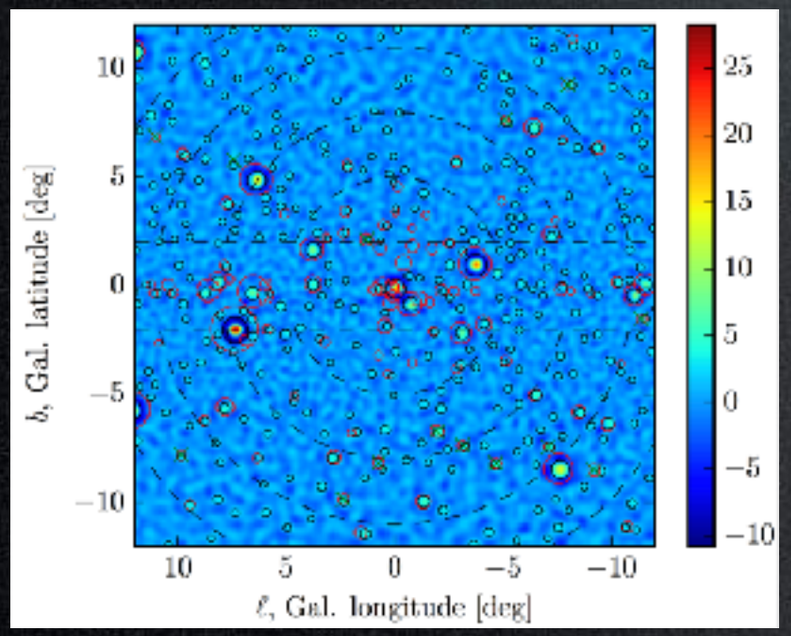


An additional steady-source spike of CRs (from SNRs?) that emit via ICS



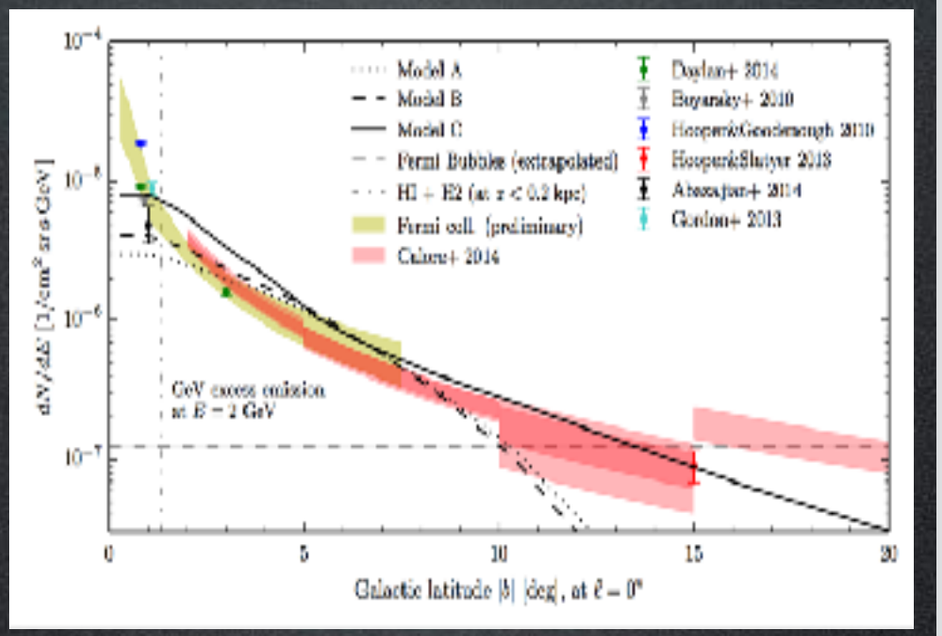
D. Gaggero et al 1507.06129

Unresolved point sources (MSPs?)



Bartels...Weniger 1506.05104
Lee, Lisanti...Slatyer 1506.05124

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



F. Calore 1506.05119

What does the FERMI coll. say?

Unclear…

- Excess exists (1511.02938), adding DM improves the fit.
- Excesses elsewhere in the GP, the GC one not significant (1704.03910).
- We found point sources! DM ‘strongly disfavored’ (1705.00009v1).
- *Sure? (Bartels et al., 1710.10266)*
- Ah, no, sorry, we had a mistake (1705.00009v2).

Neutrinos

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

$\bar{p}$ from annihil in galactic halo or center

$\bar{d}$ from annihil in galactic halo or center

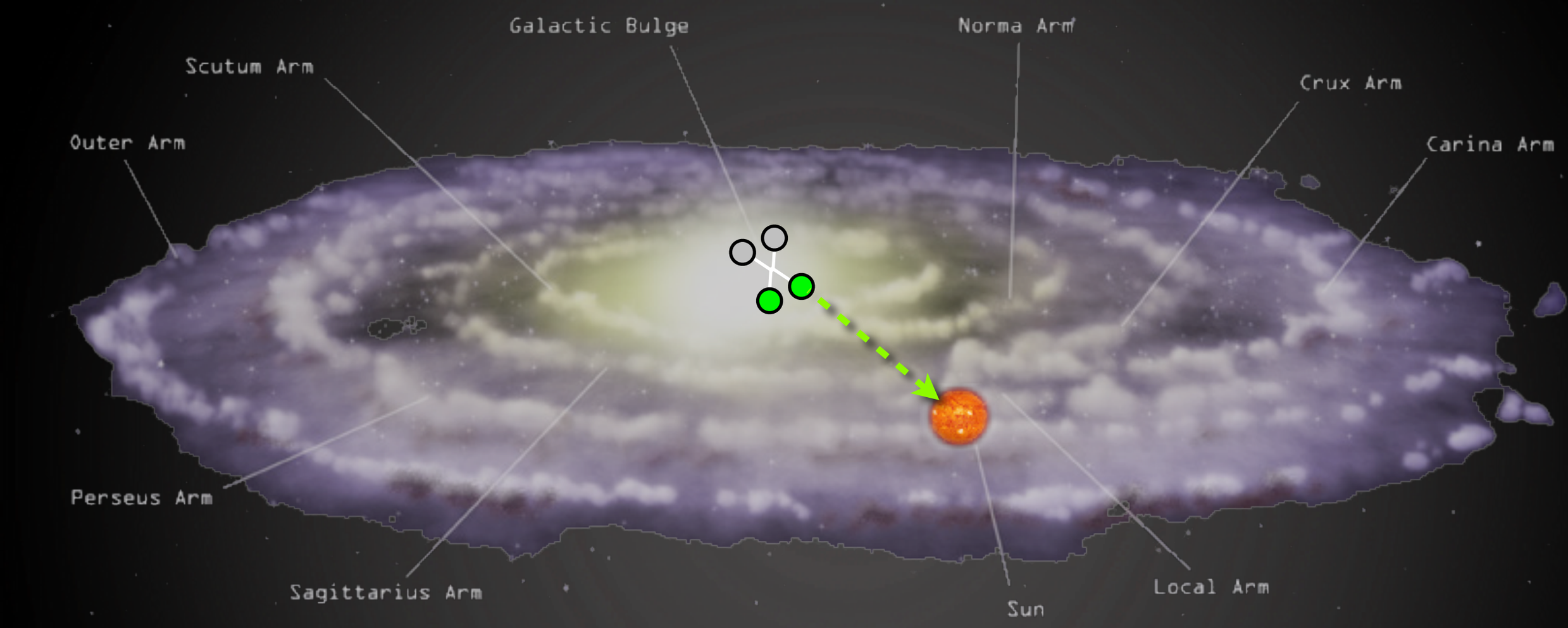
GAPS, AMS

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

SK, Icecube, Antares

ID with neutrinos

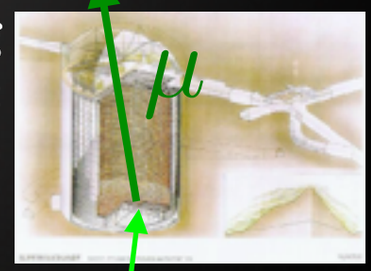
ν from DM annihilations in galactic center



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

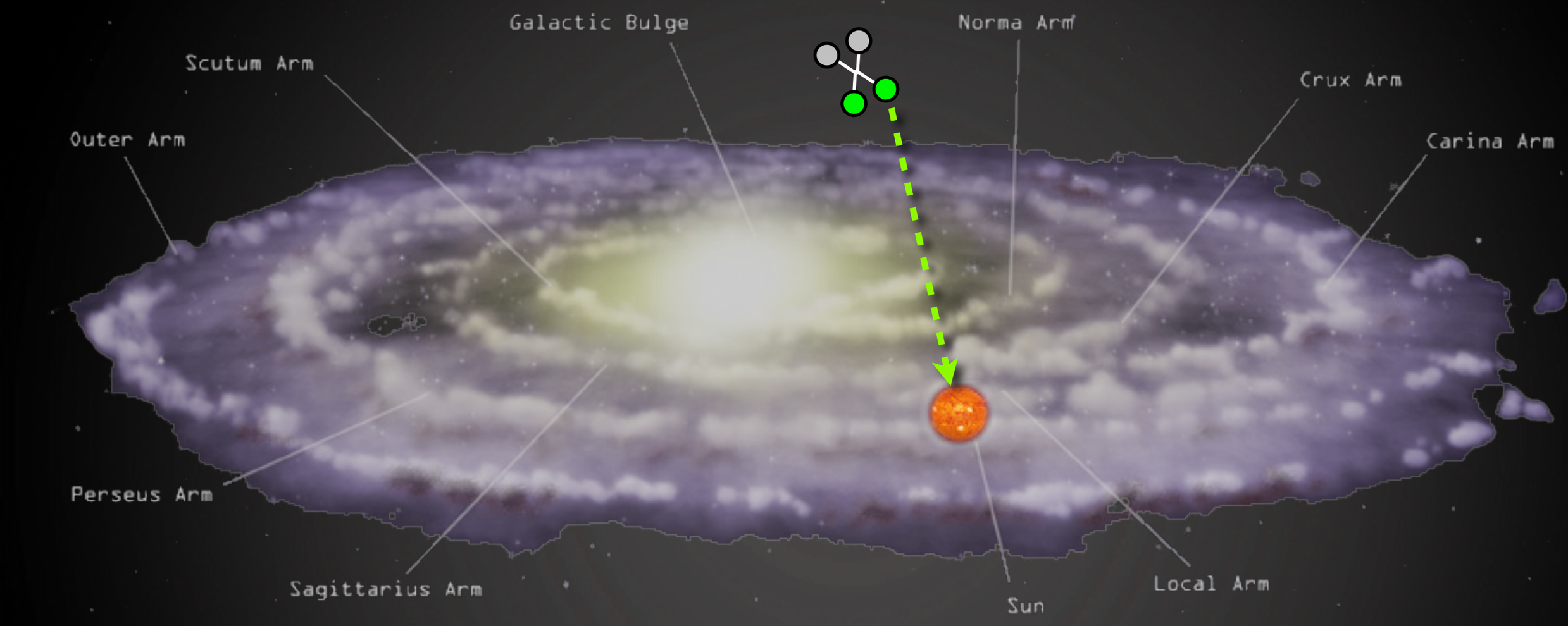
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \nu$$

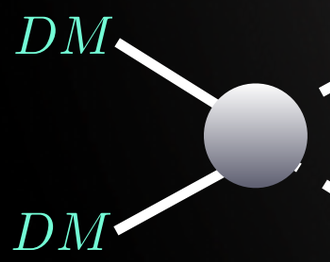
up-going muons:



ID with neutrinos

ν from DM annihilations in galactic halo

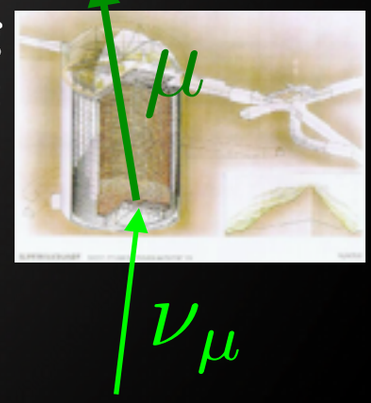




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \nu$$

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

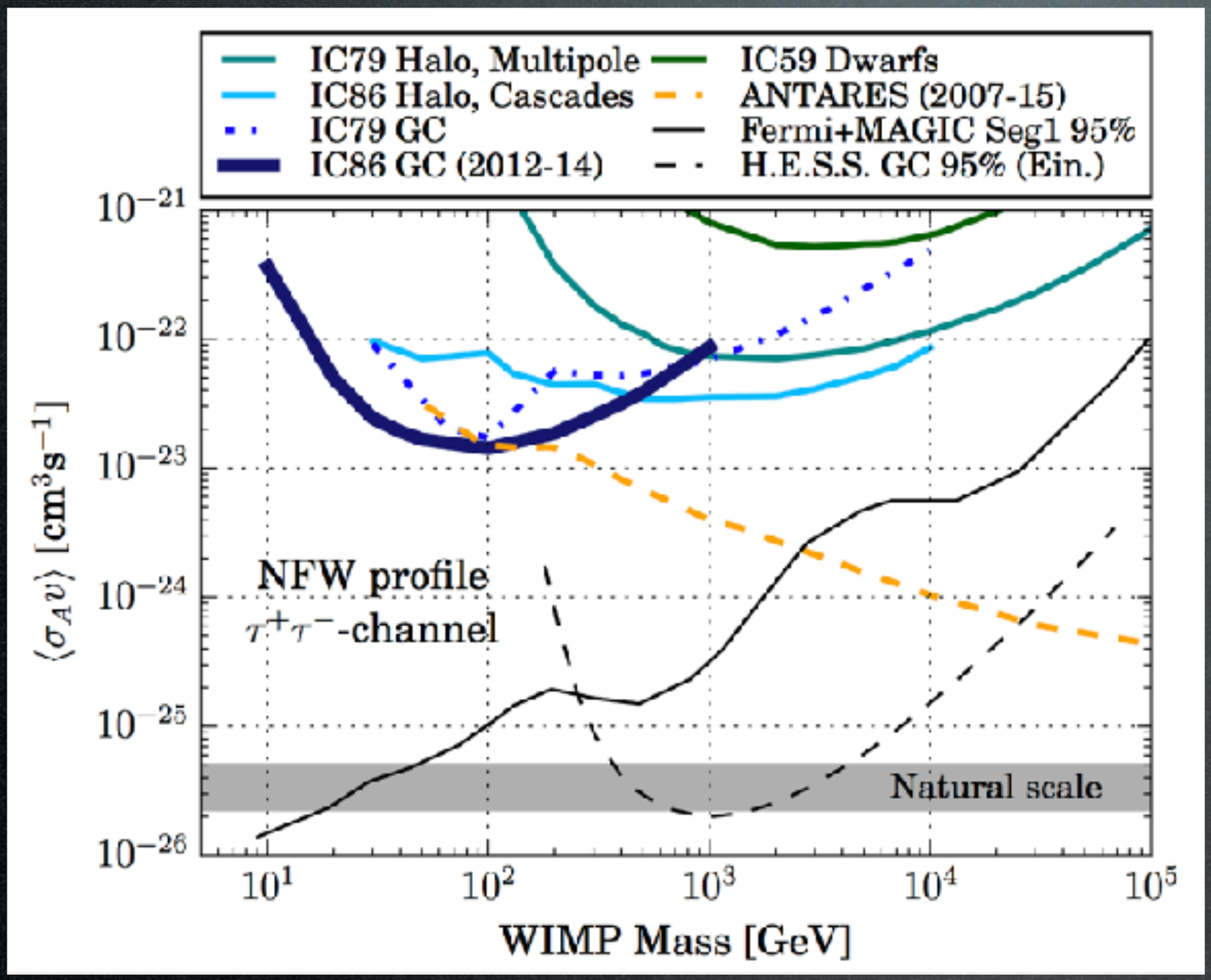
up-going muons:



ID with neutrinos

ν from DM annihilations in galactic center/halo

ICECUBE & Antares



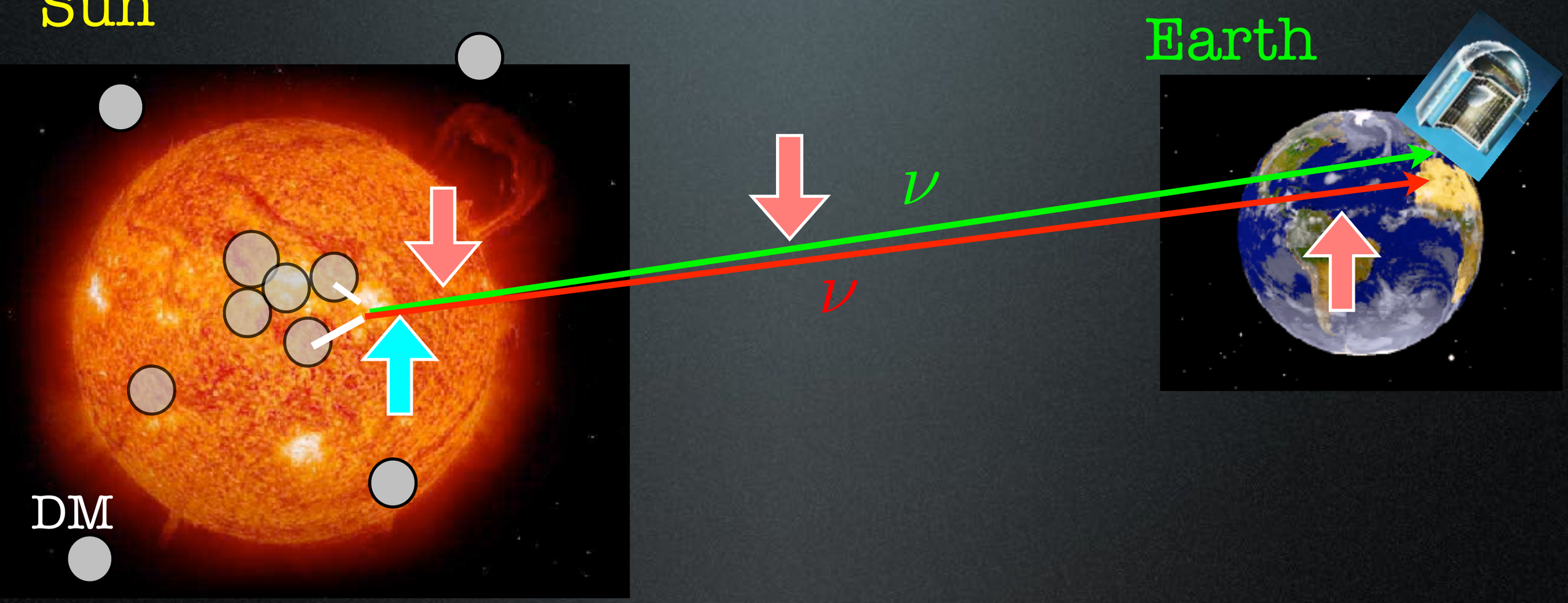
Icecube Coll., 1705.08103

Competitive constraints

(especially for large m_{DM})

ID with neutrinos

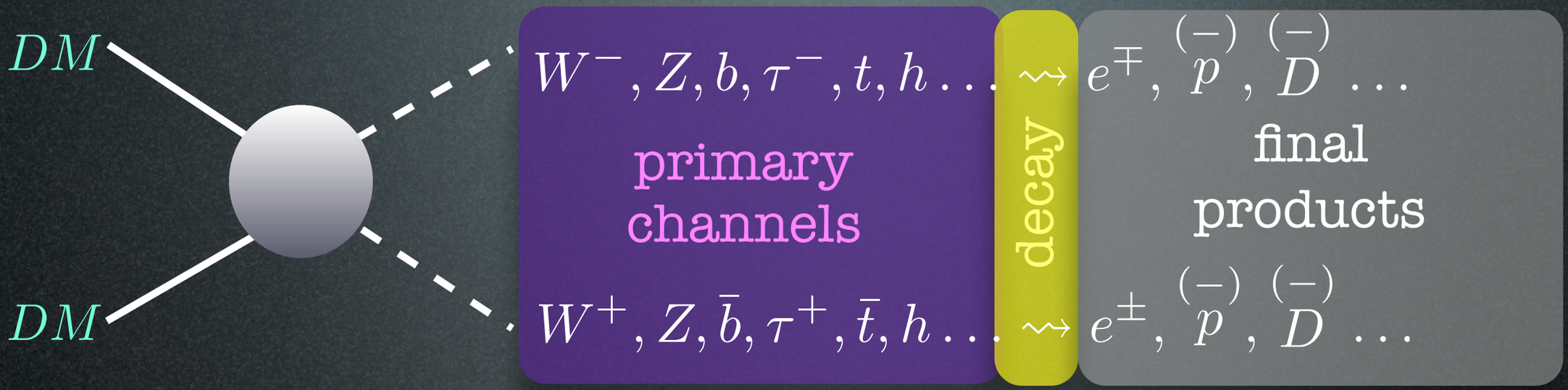
ν from DM annihilations in the Sun



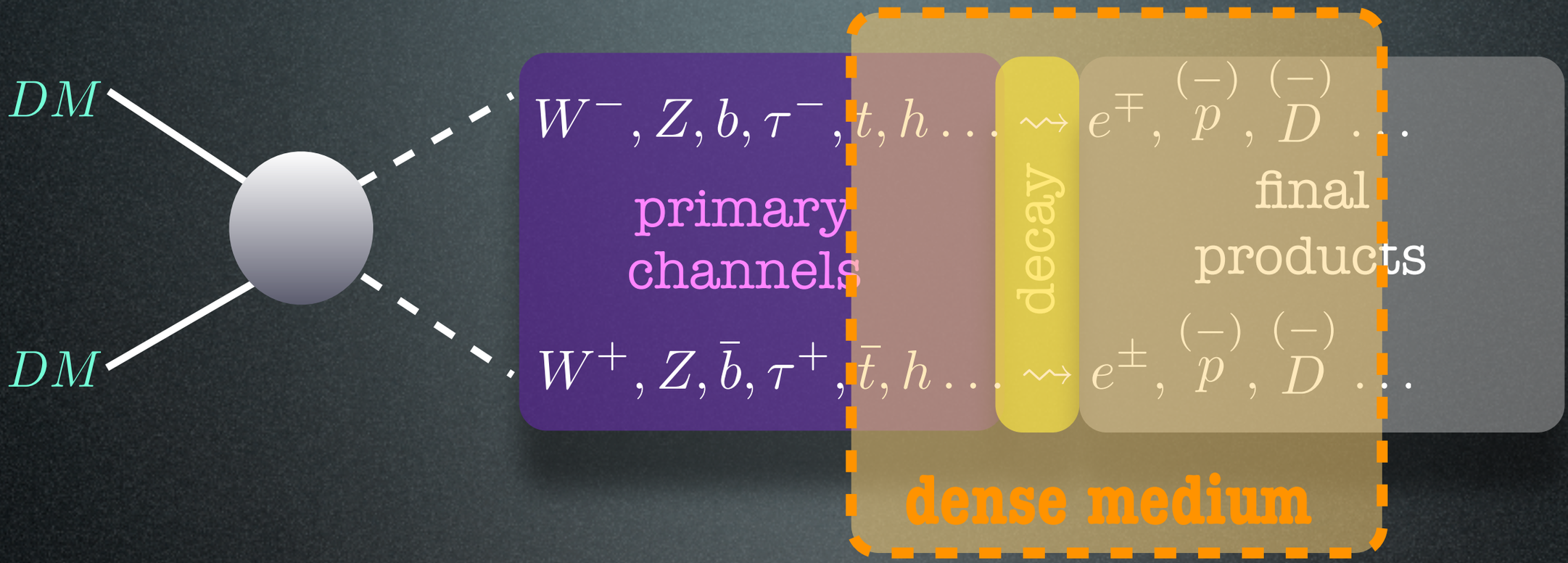
Include oscillations + interactions:

- reshuffling of the 3 flavors
- distortions the spectra
- attenuations of the fluxes

ID with neutrinos



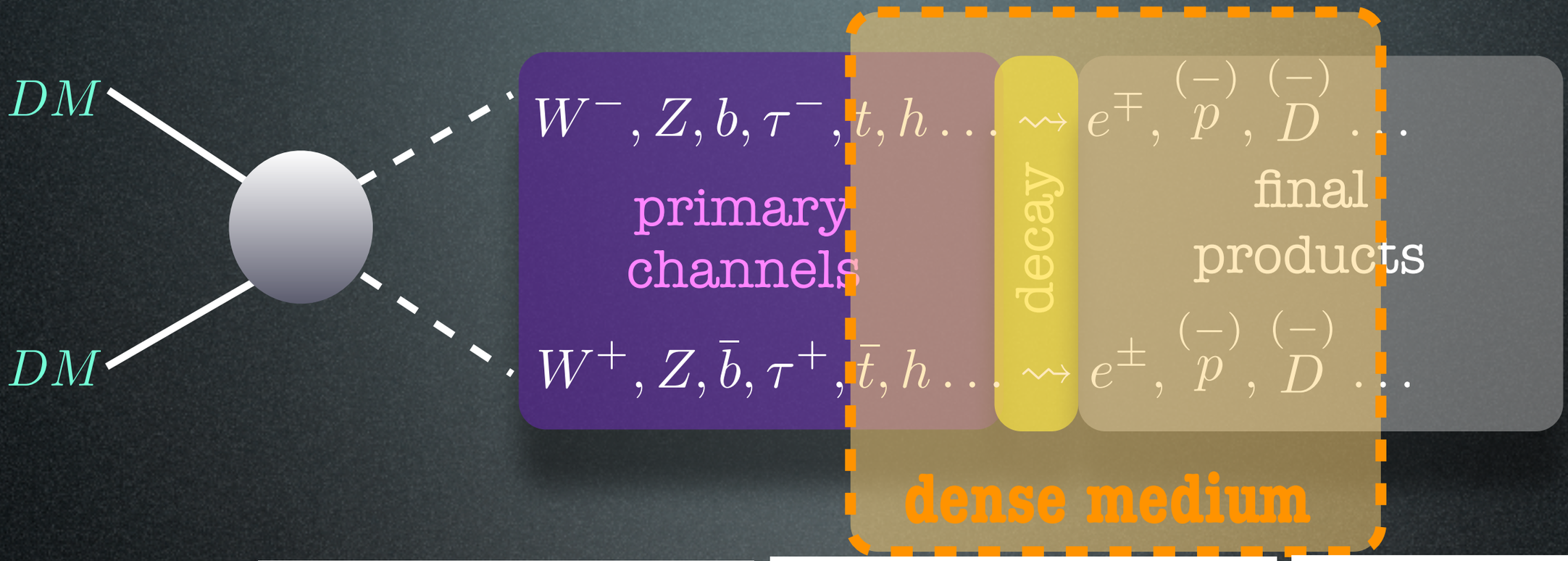
ID with neutrinos

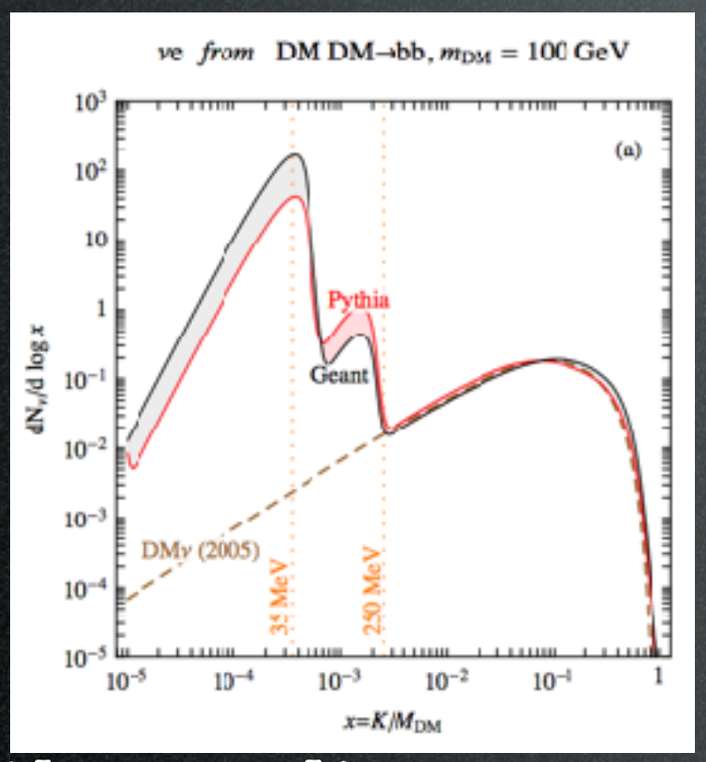


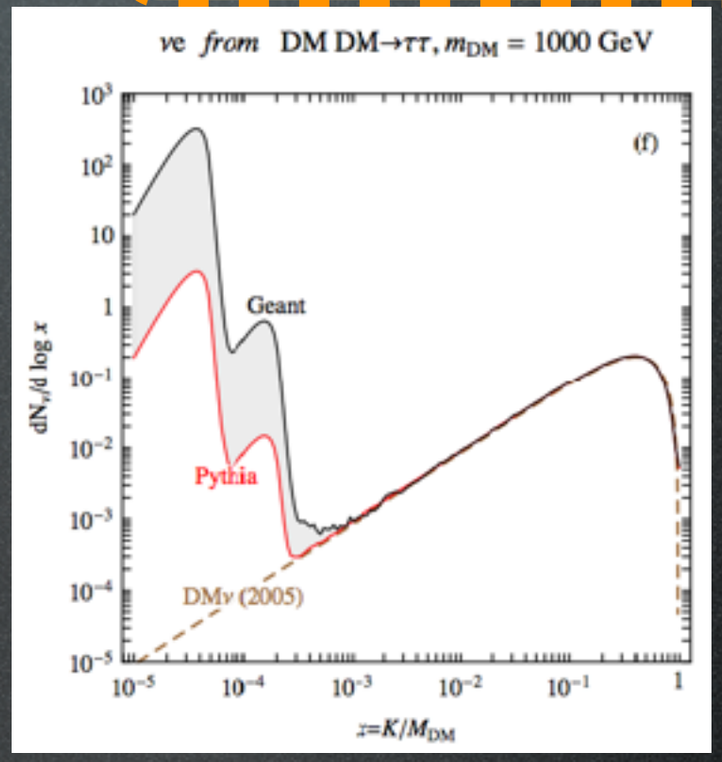
Effects of the medium:

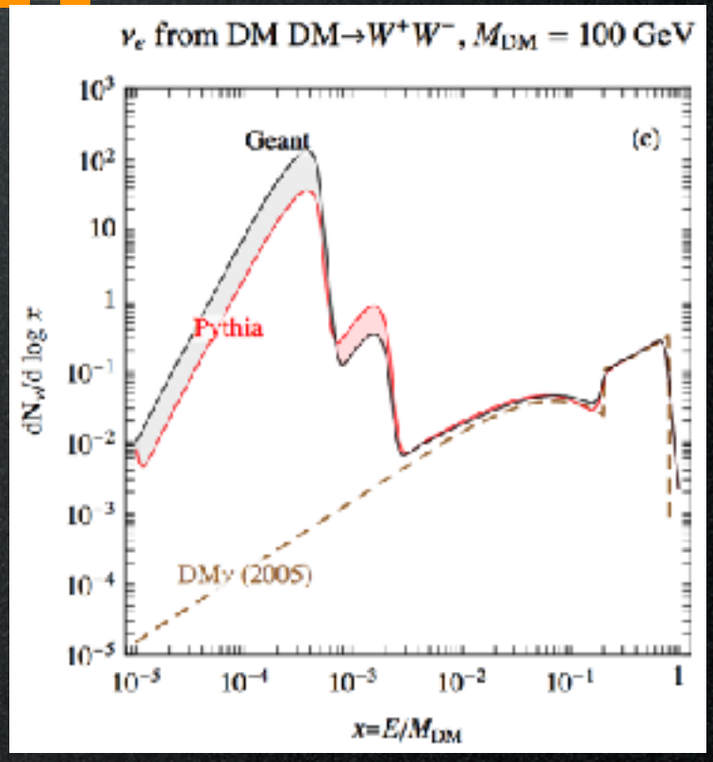
1) light hadrons (π, K...) and leptons (μ) are stopped and decay at rest
2) heavy hadrons/leptons lose some energy before decaying

ID with neutrinos









Effects of the medium:

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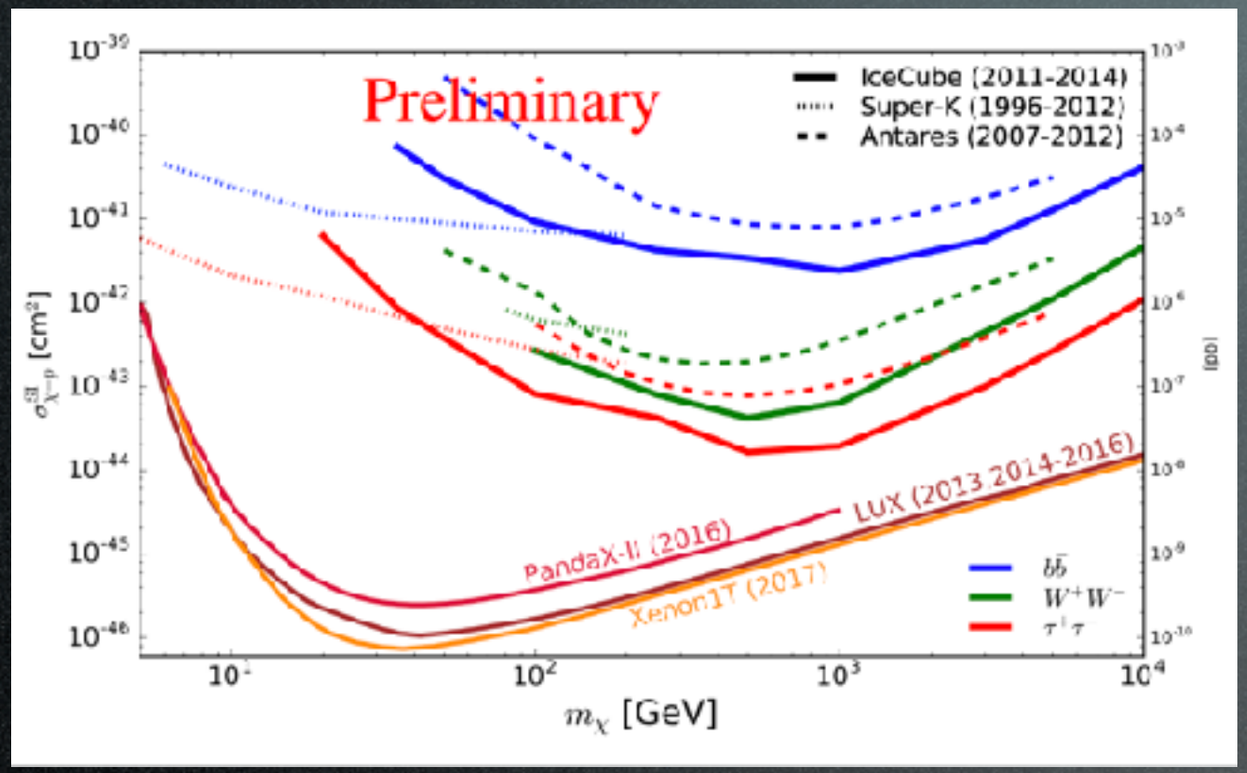
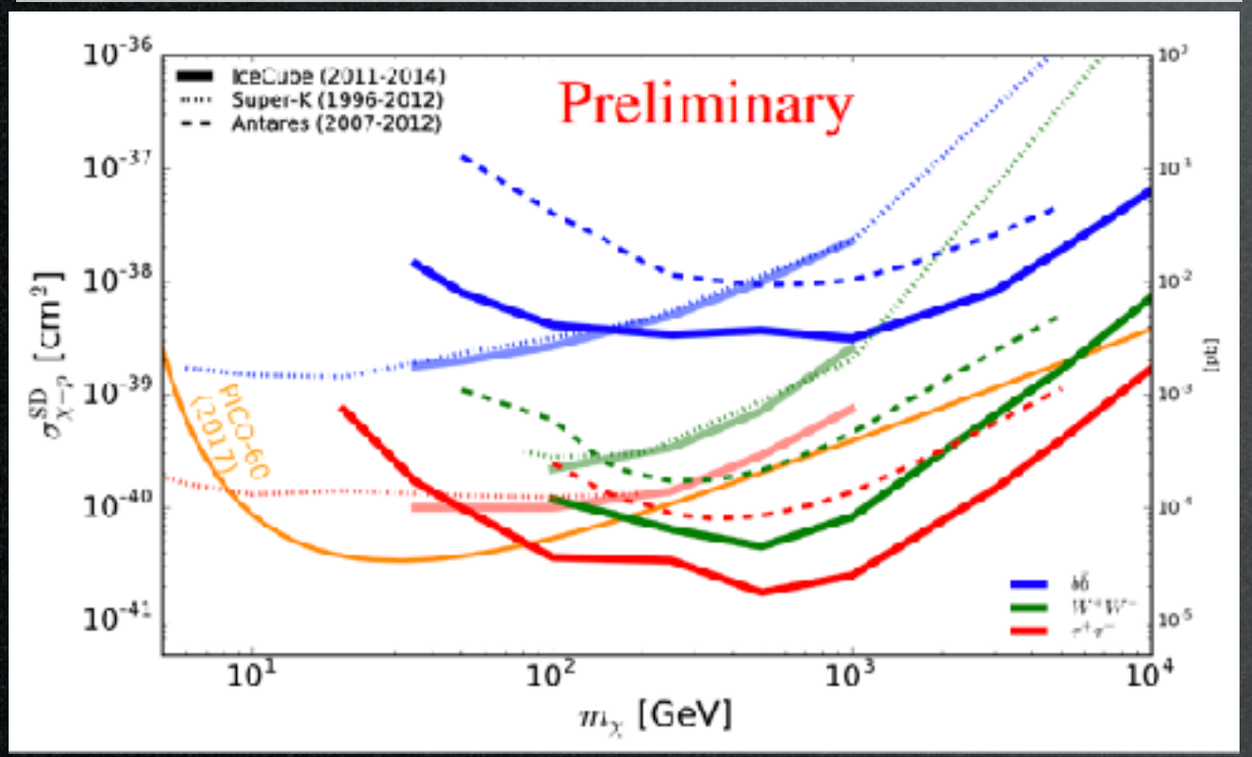
2) heavy hadrons/leptons lose some energy before decaying

ID with neutrinos

ICECUBE, Antares & SuperKamiokande





Subdominant constraints

Competitive constraints

status as of ICRC 2017,
C. Rott, rapporteur talk,
1712.00666

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

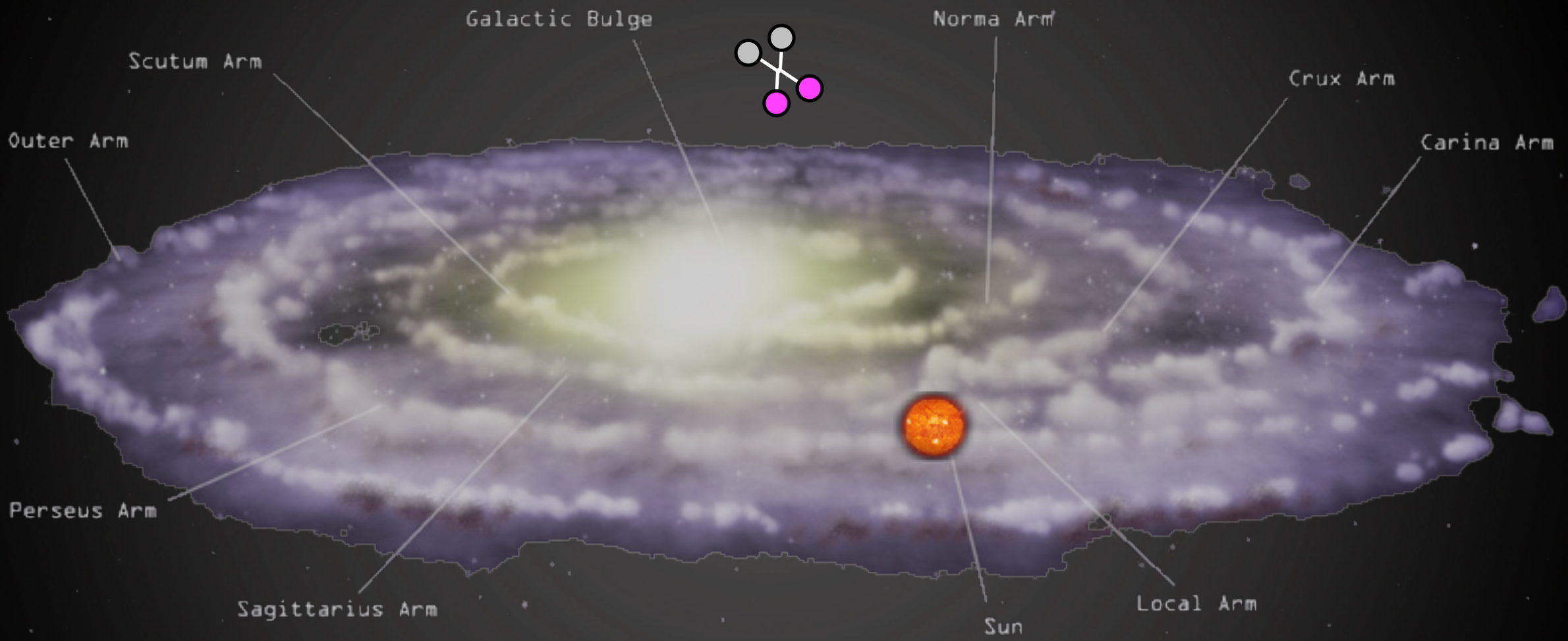
GAPS, AMS

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

SK, **Icecube**, Km3Net

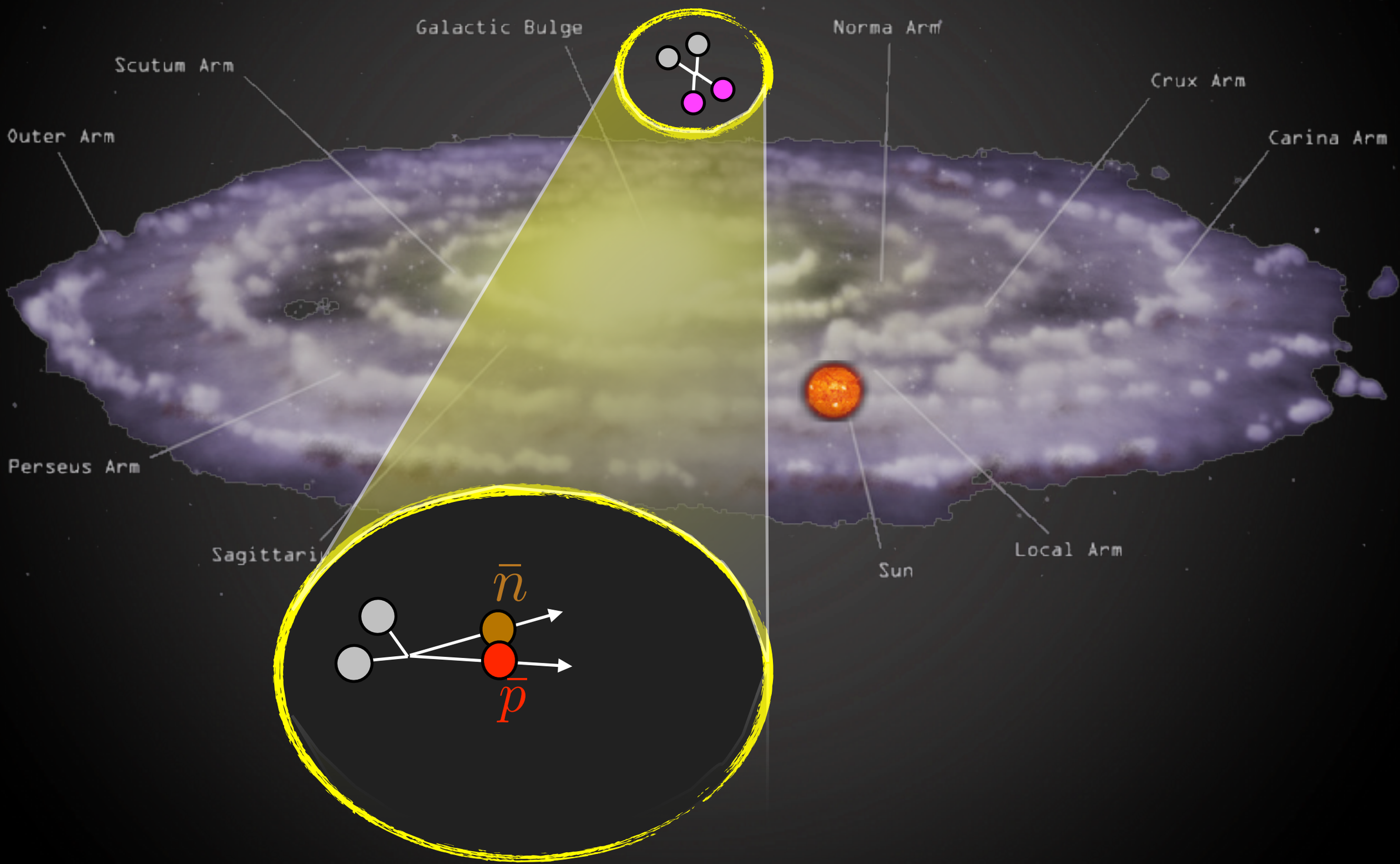
Indirect Detection

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



Indirect Detection

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



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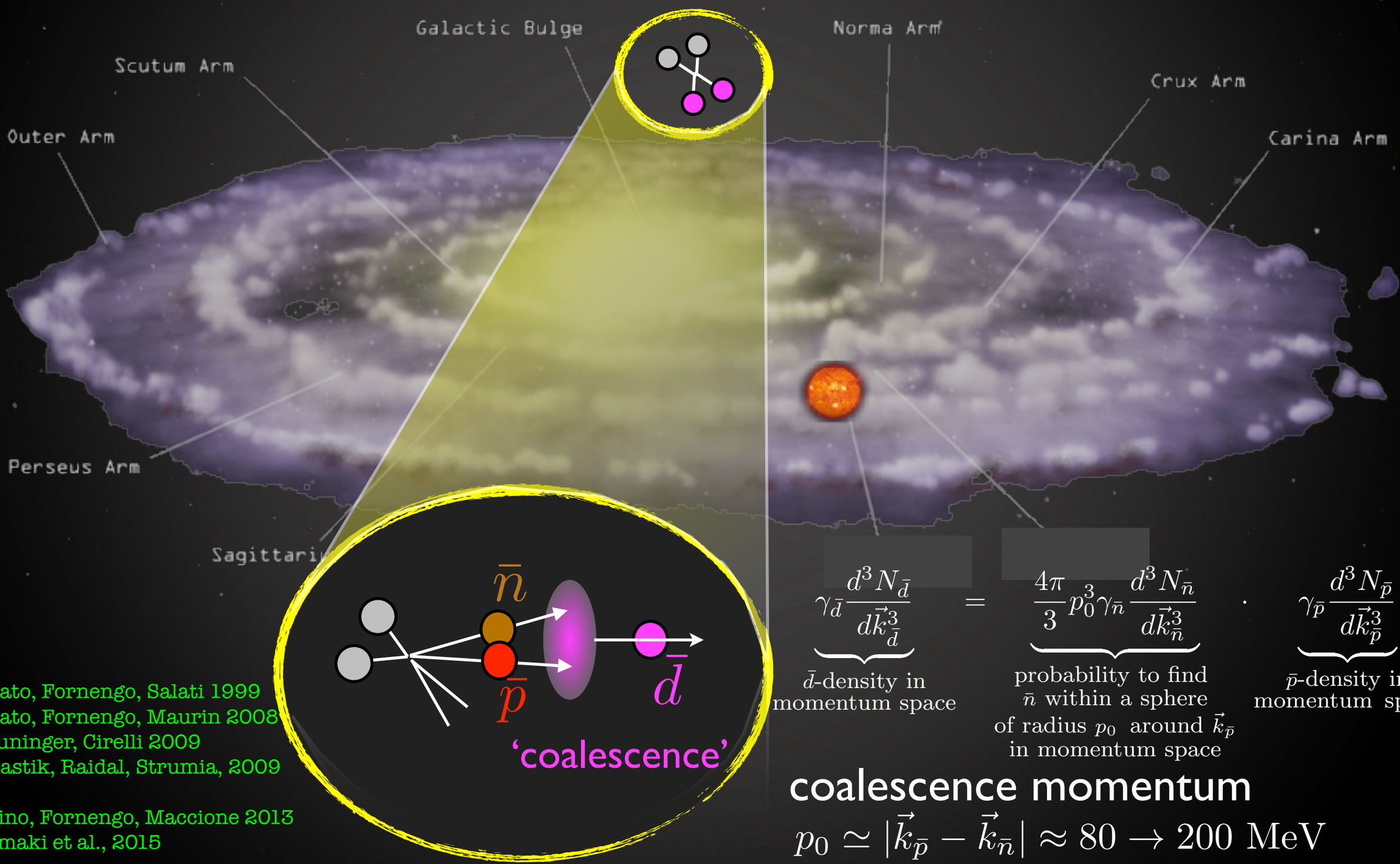


Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Bräuninger, Cirelli 2009
Kadastik, Raidal, Strumia, 2009
...
Vittino, Fornengo, Maccione 2013
Aramaki et al., 2015

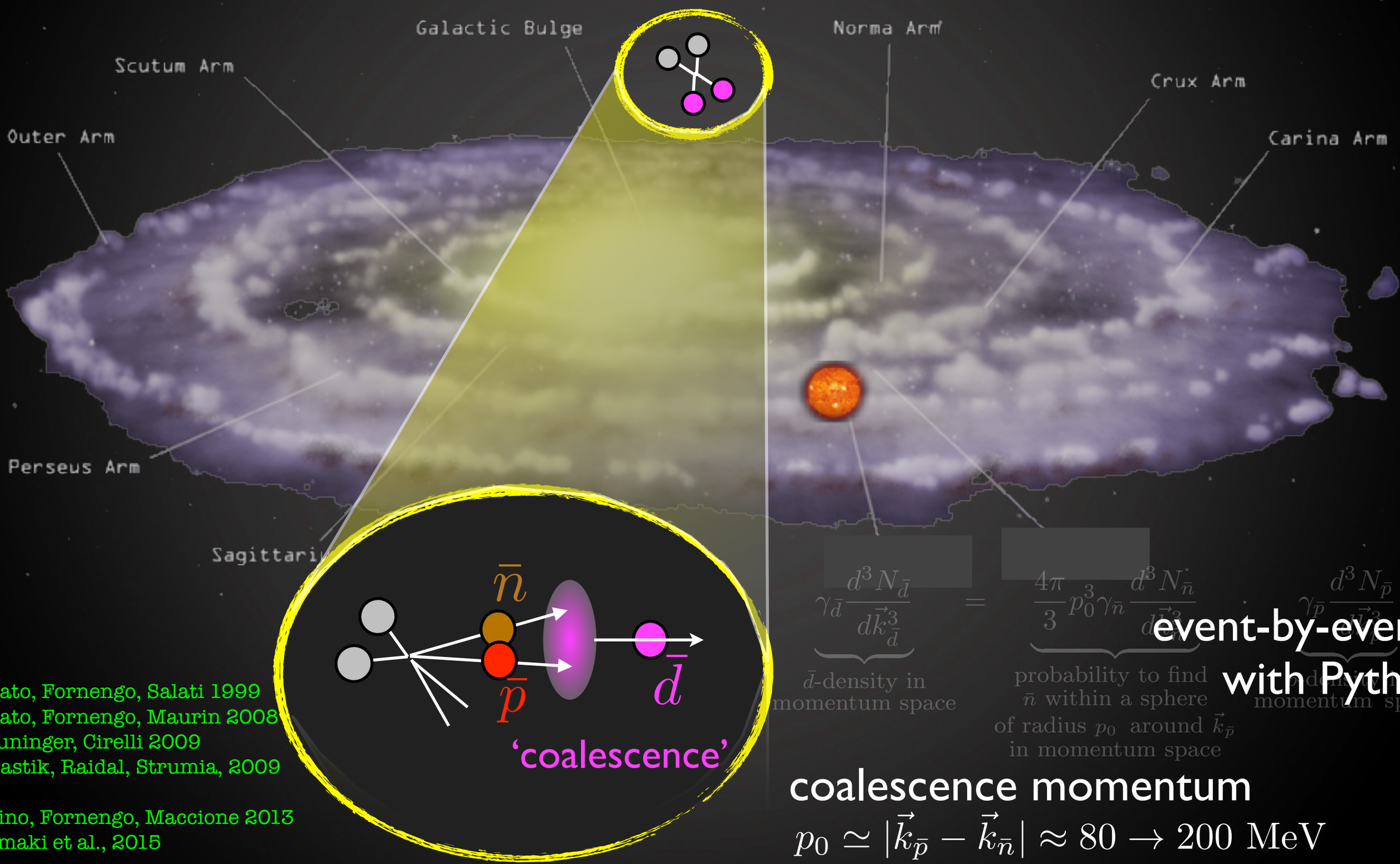
$$\underbrace{\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d\vec{k}^3_{\bar{d}}}}_{\bar{d}\text{-density in momentum space}} = \underbrace{\frac{4\pi}{3} p_0^3 \gamma_{\bar{n}} \frac{d^3 N_{\bar{n}}}{d\vec{k}^3_{\bar{n}}}}_{\substack{\text{probability to find } \bar{n} \text{ within a sphere} \\ \text{of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

coalescence momentum

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

Indirect Detection

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



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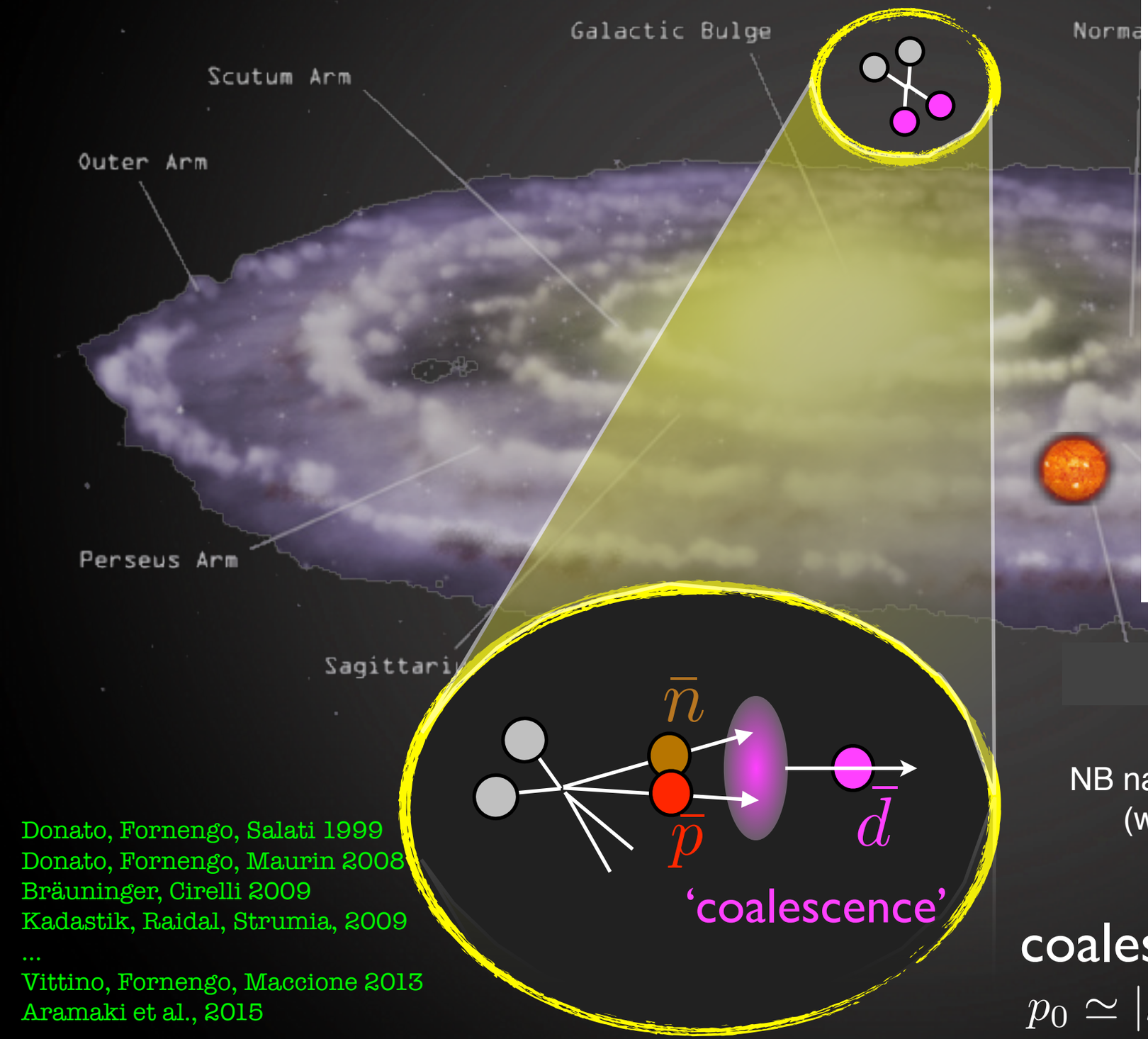
event-by-event with Pythia

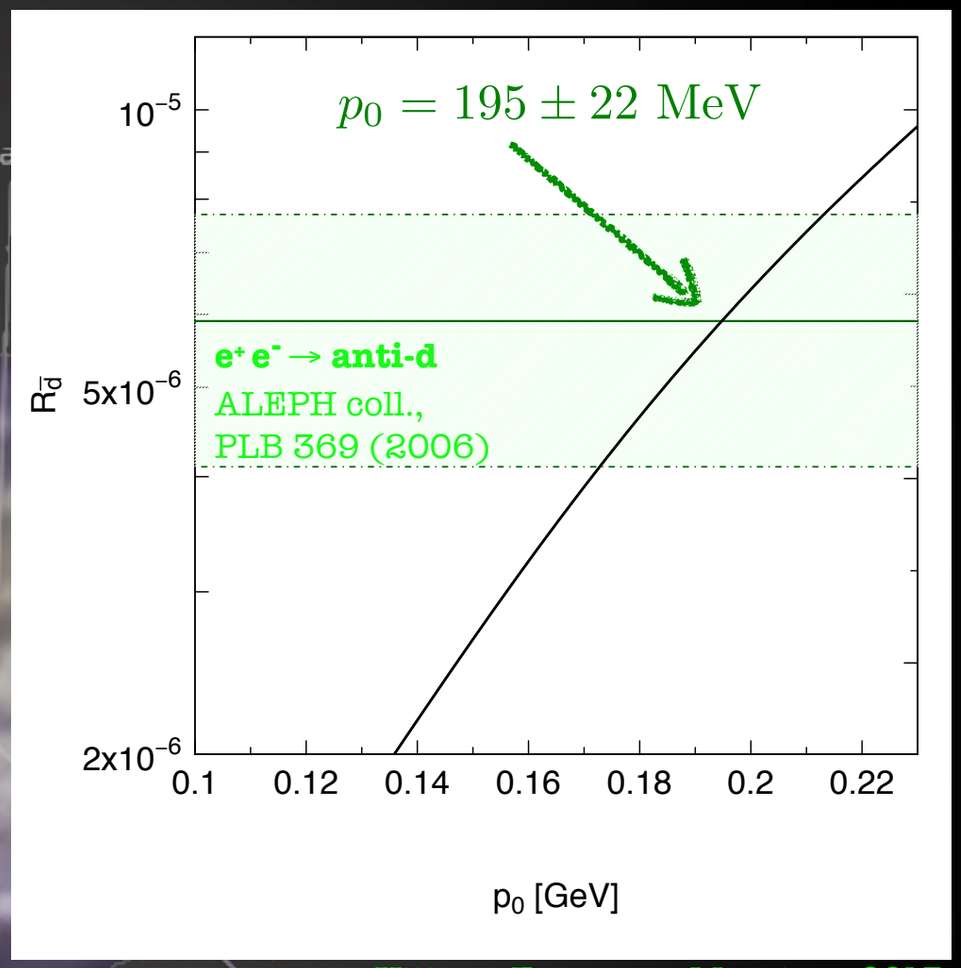
coalescence momentum

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

Indirect Detection

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





Vittino, Fornengo, Maccione 2013

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

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

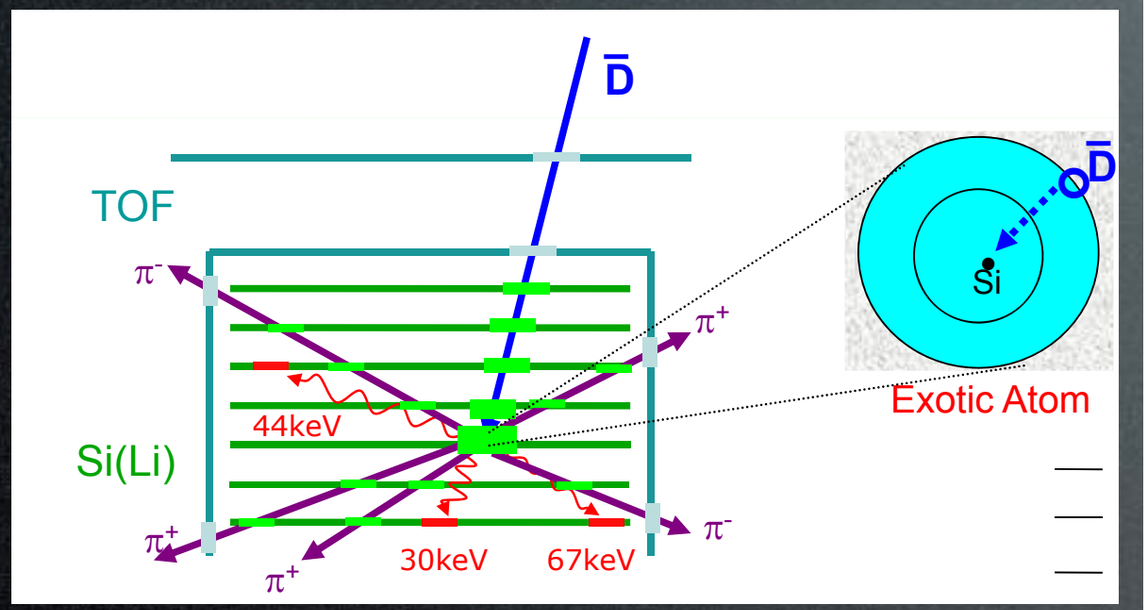
coalescence momentum

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

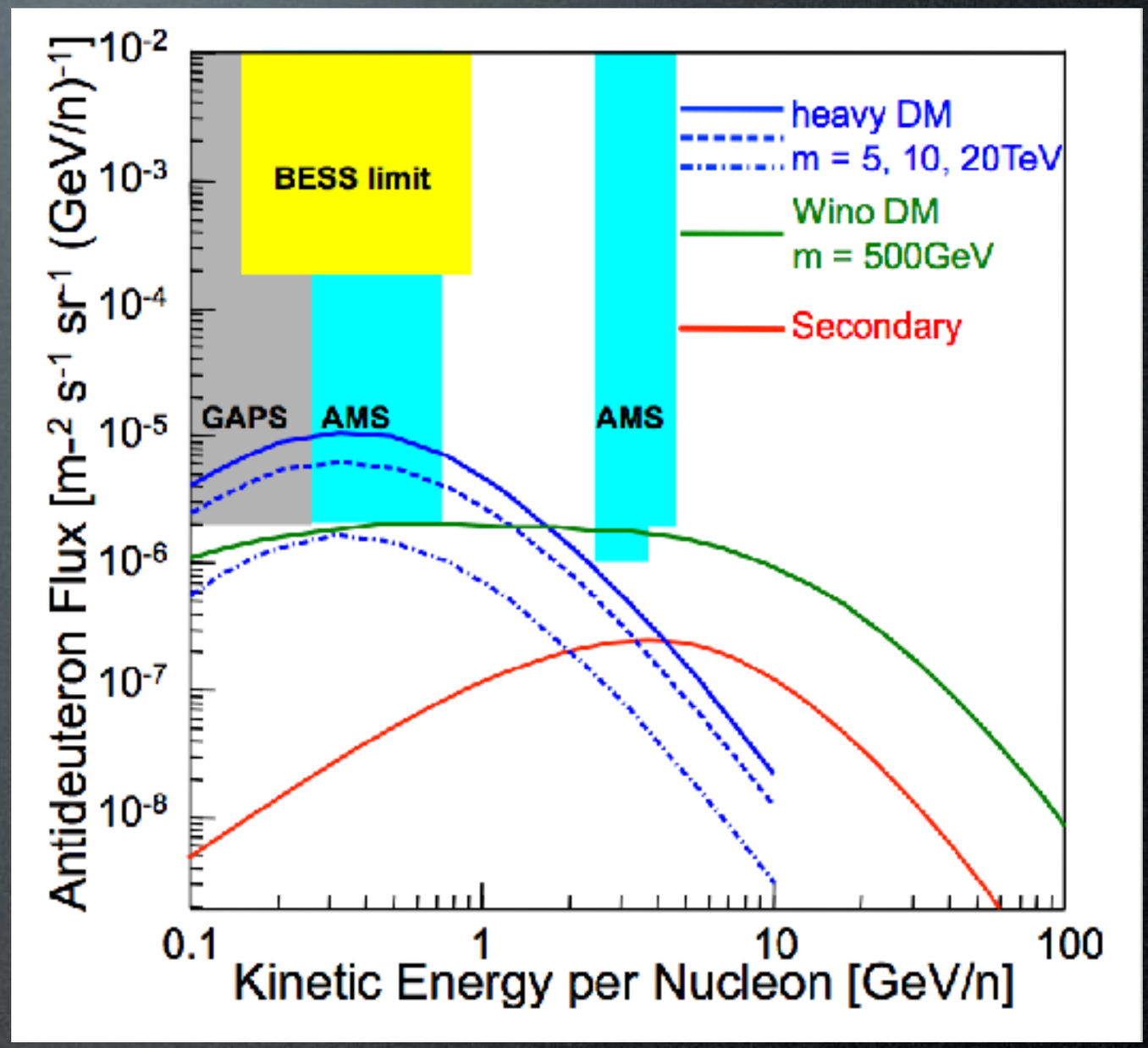
Indirect Detection

$\bar{d}$ 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

DM detection

direct detection

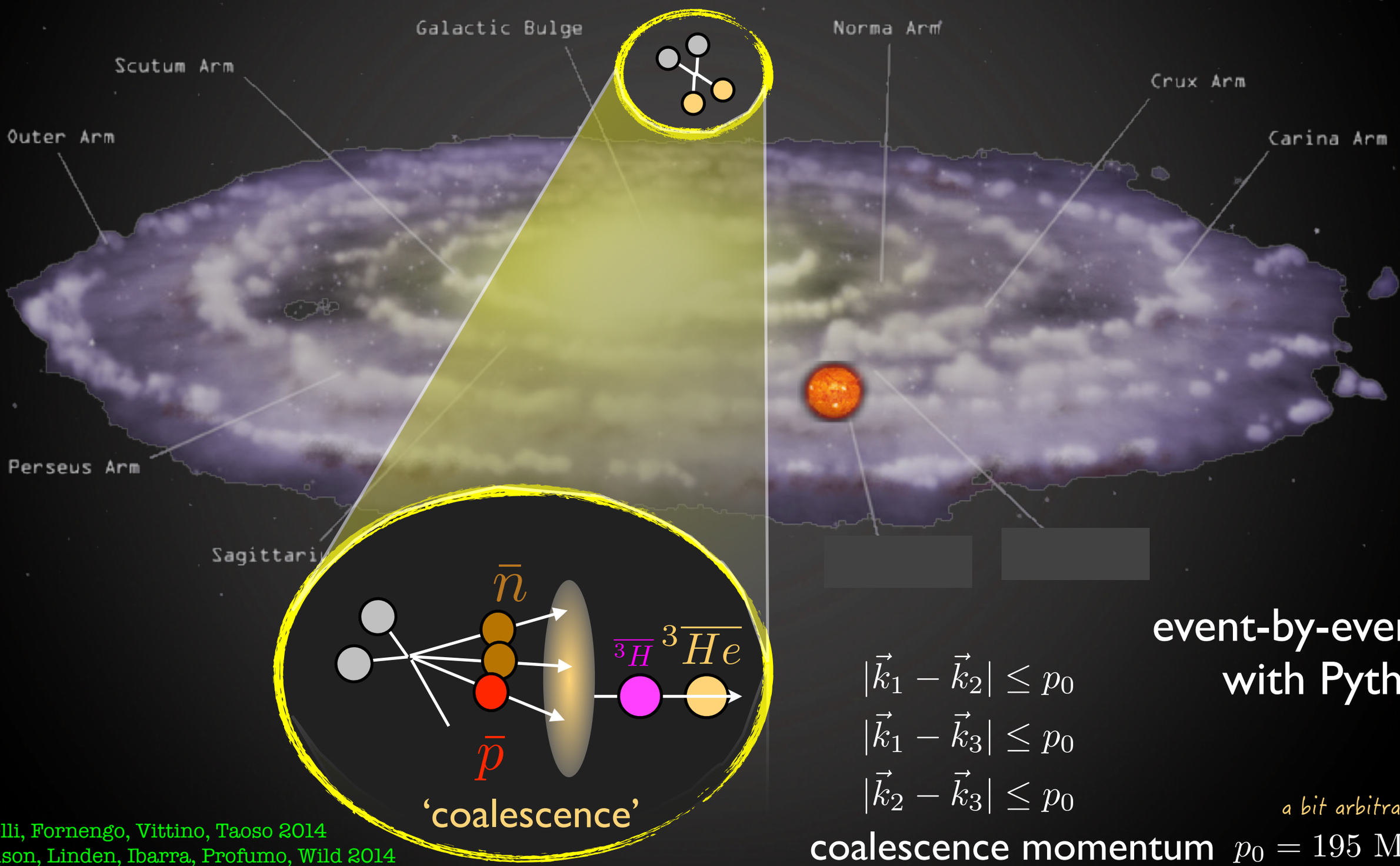
production at colliders

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



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

event-by-event
with Pythia

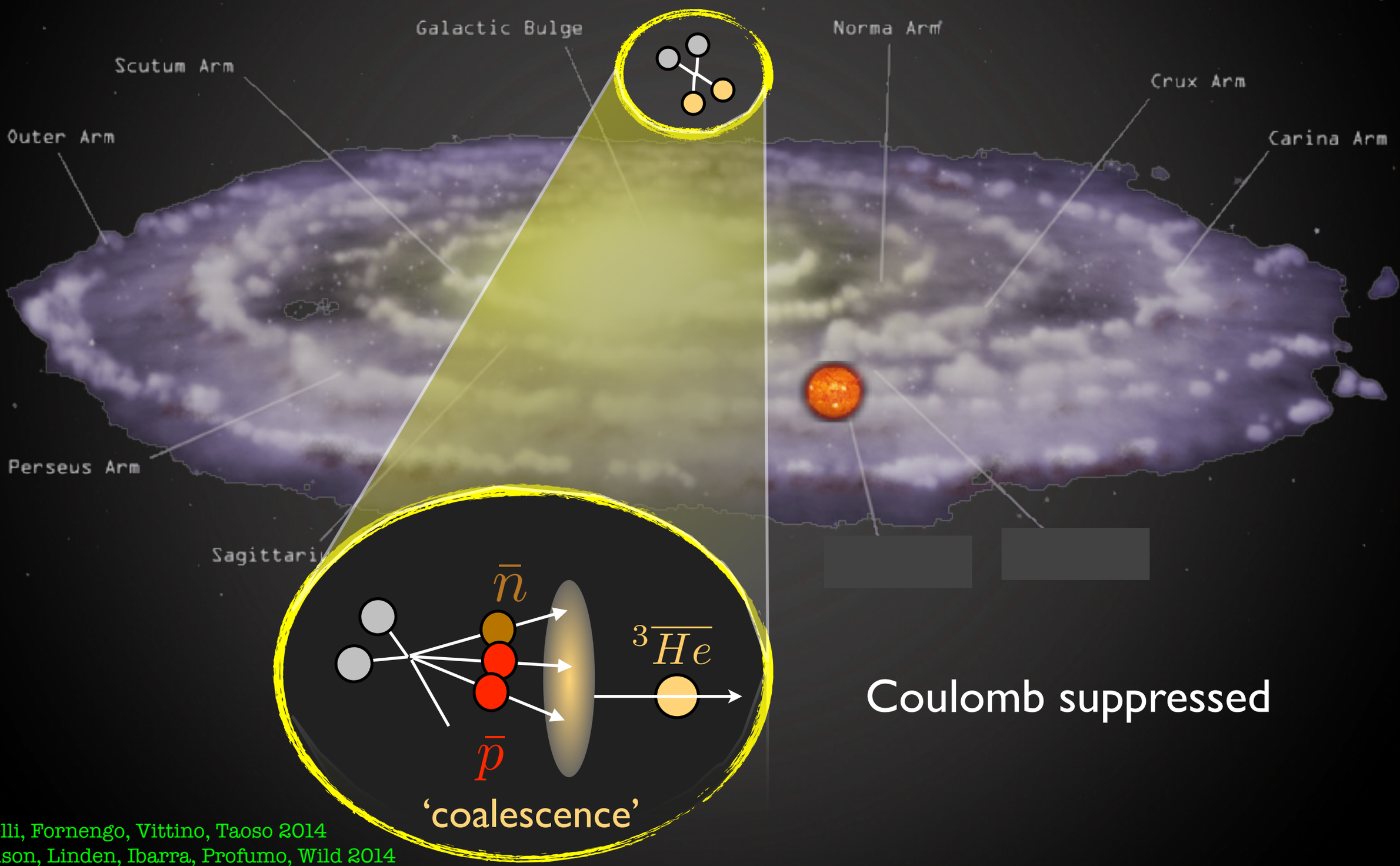
$$|\vec{k}_1 - \vec{k}_2| \leq p_0$$
$$|\vec{k}_1 - \vec{k}_3| \leq p_0$$
$$|\vec{k}_2 - \vec{k}_3| \leq p_0$$

a bit arbitrary…

coalescence momentum $p_0 = 195$ MeV

Indirect Detection

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

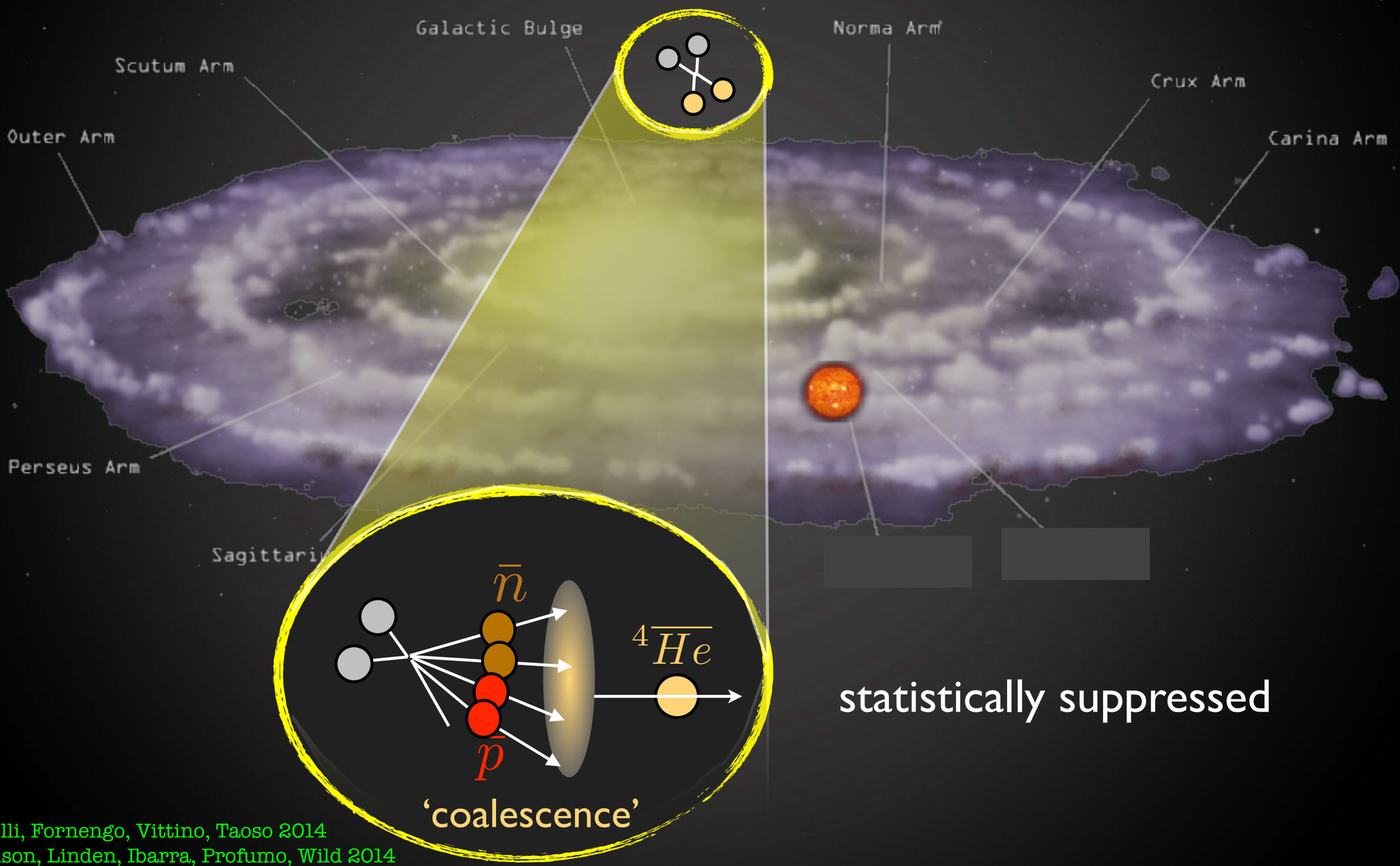


Coulomb suppressed

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

Indirect Detection

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

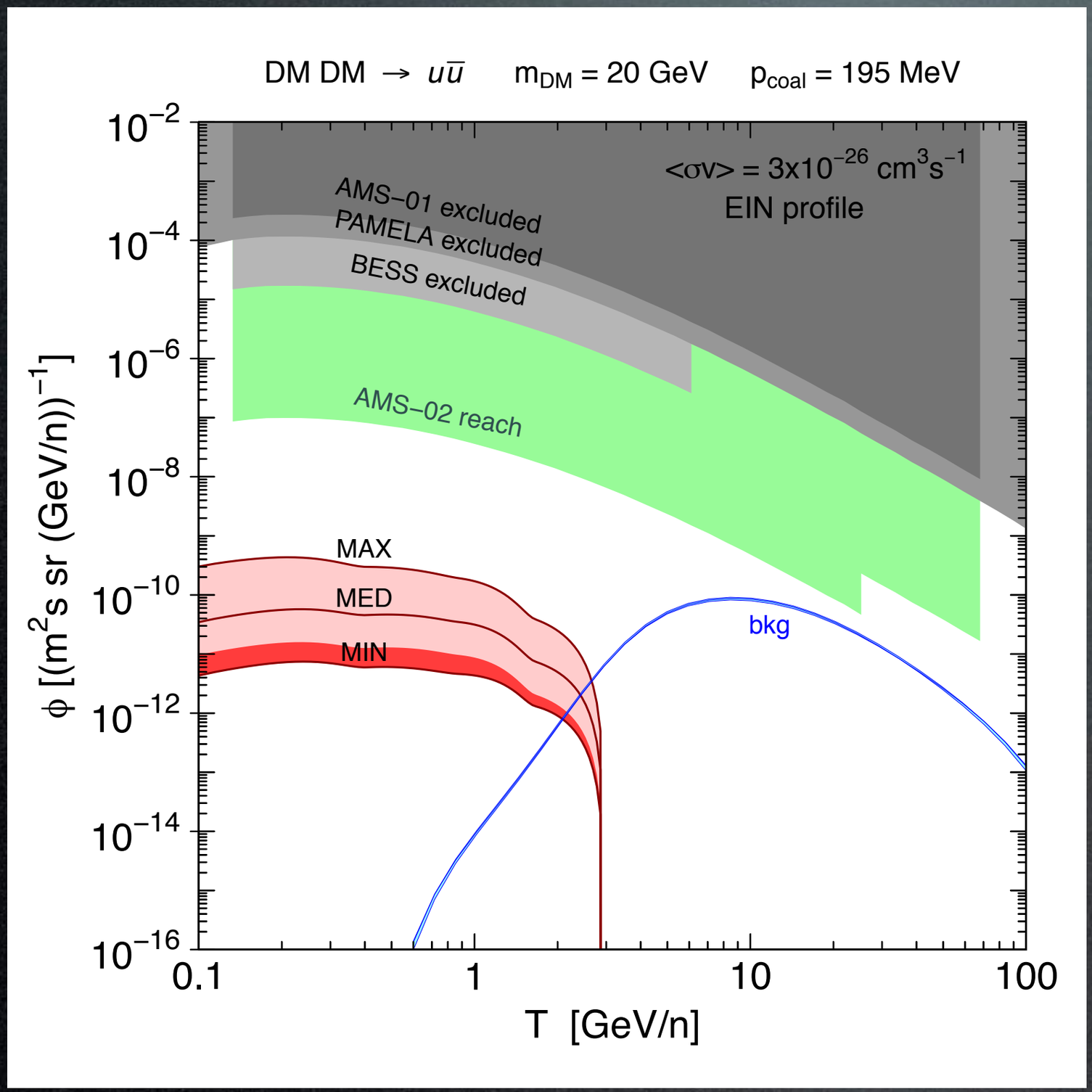


statistically suppressed

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

Indirect Detection

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



all

consistent with antiproton bounds

Indirect Detection

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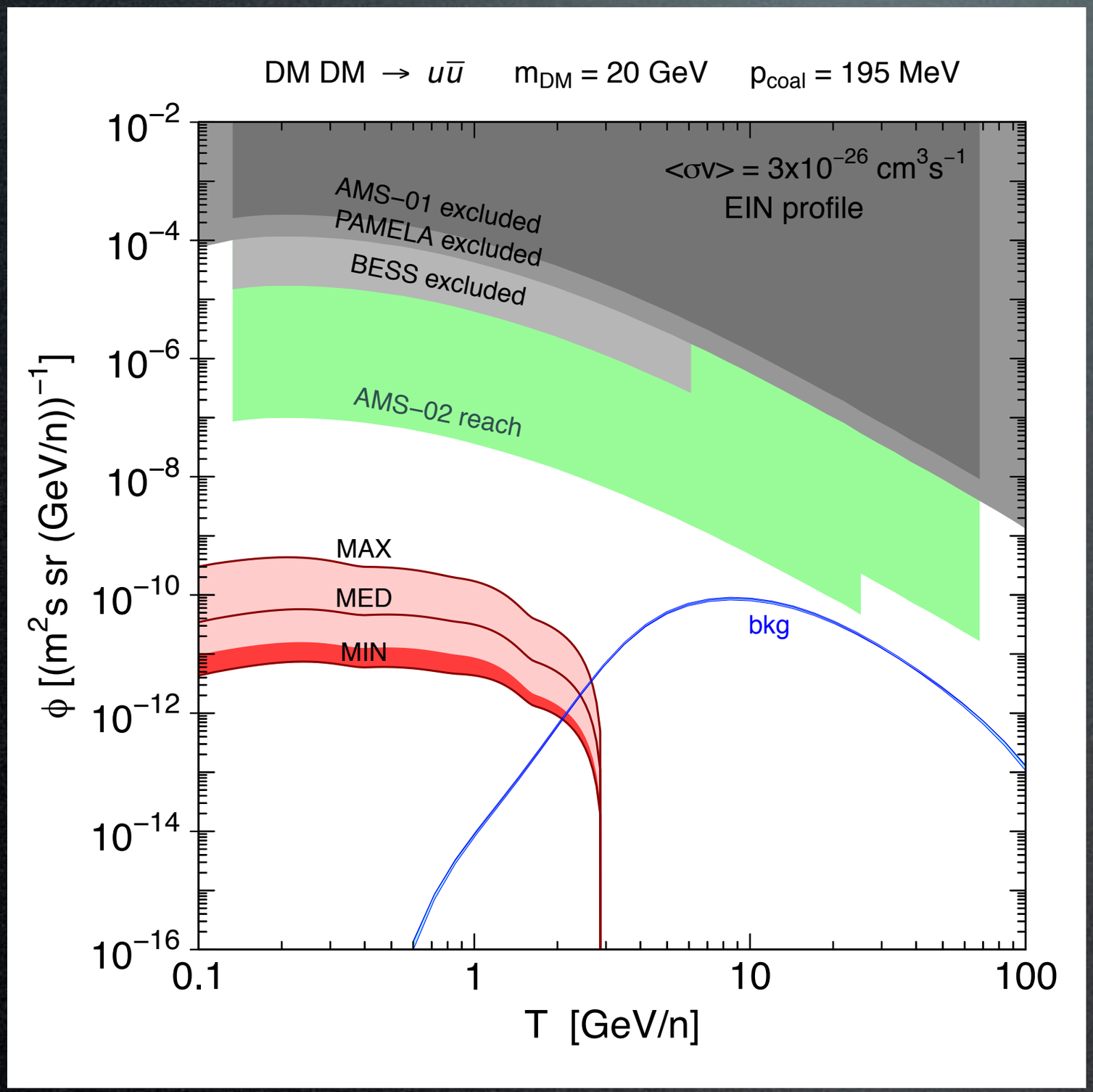

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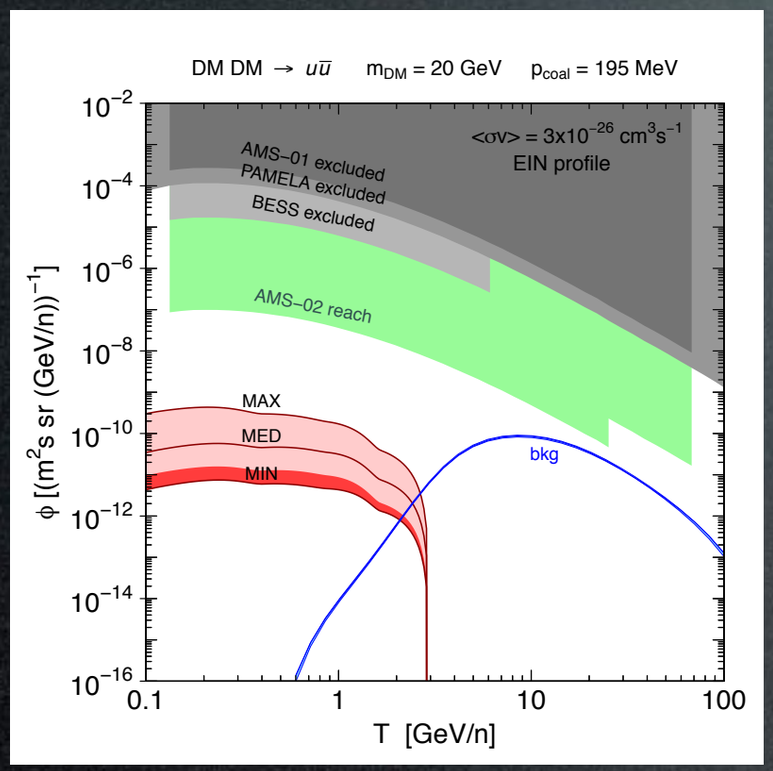

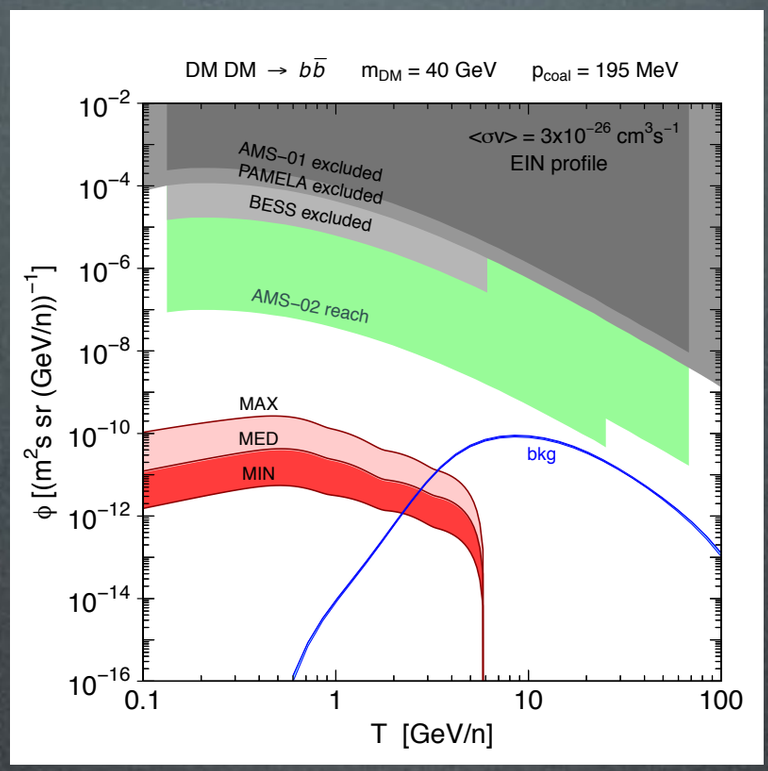

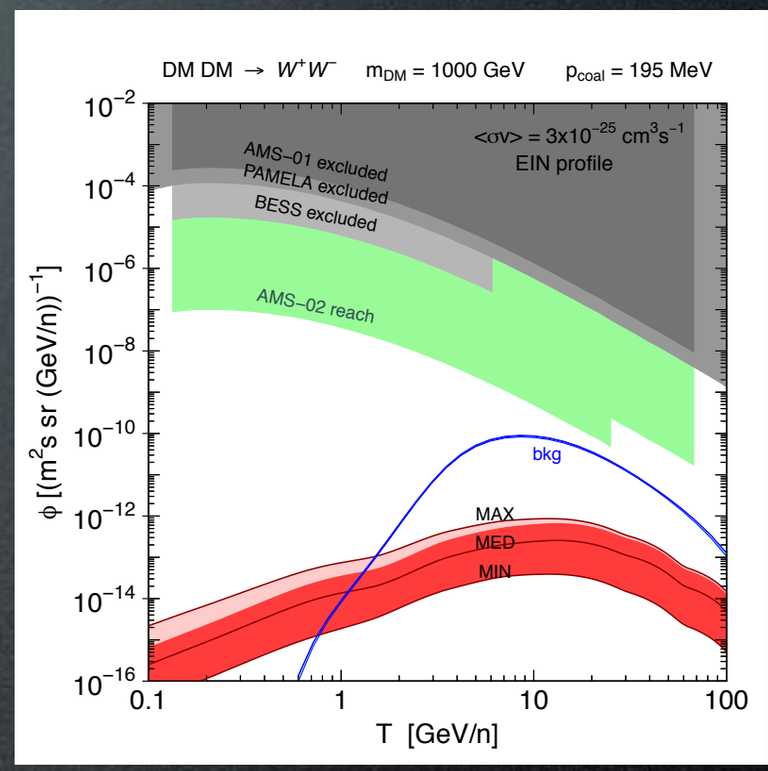

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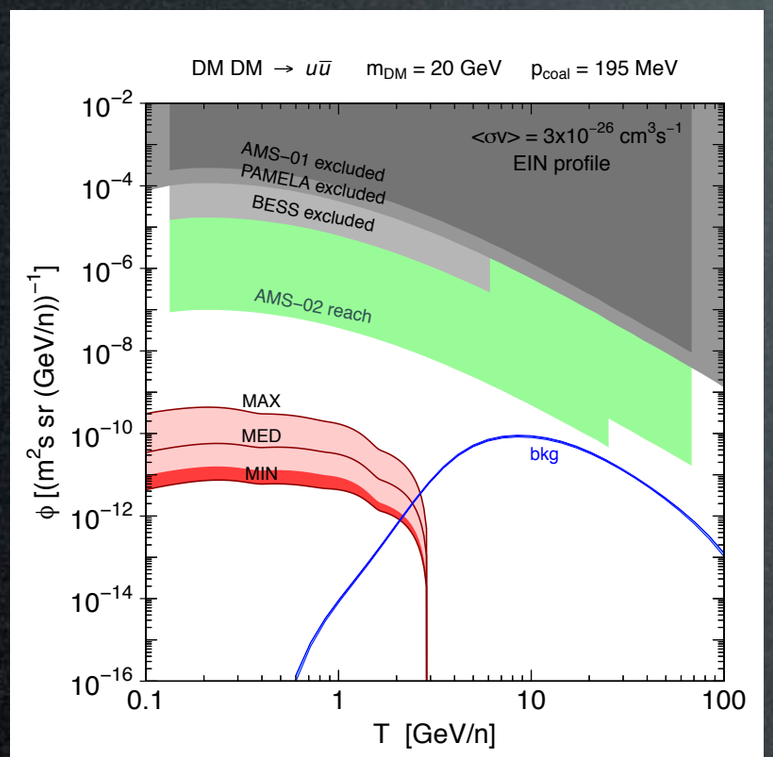

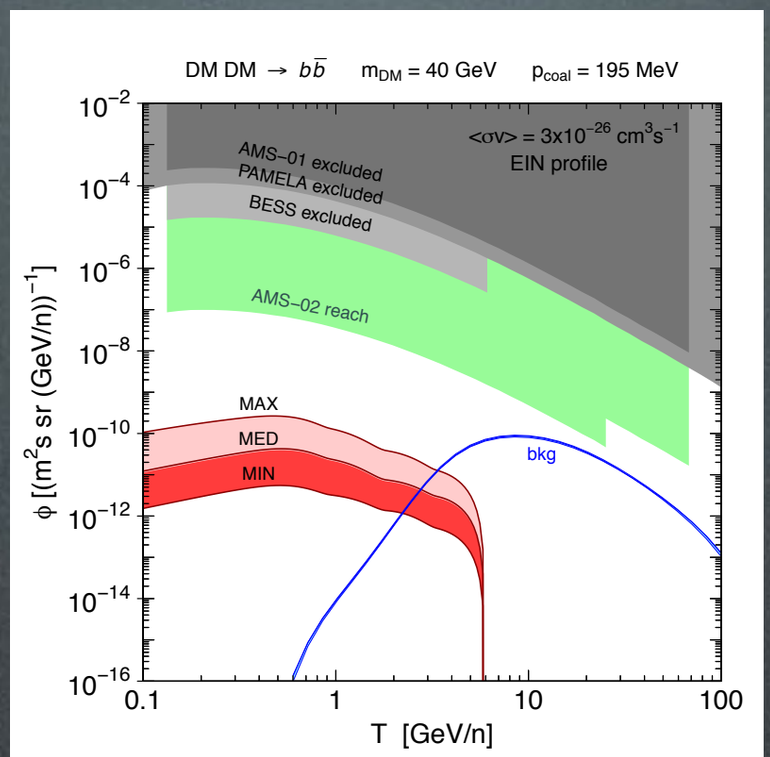

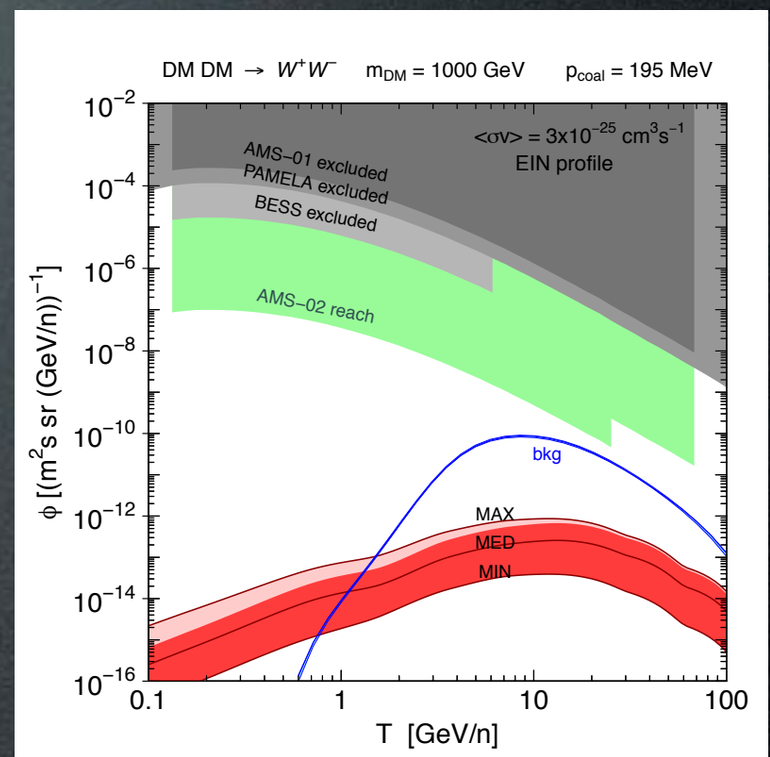

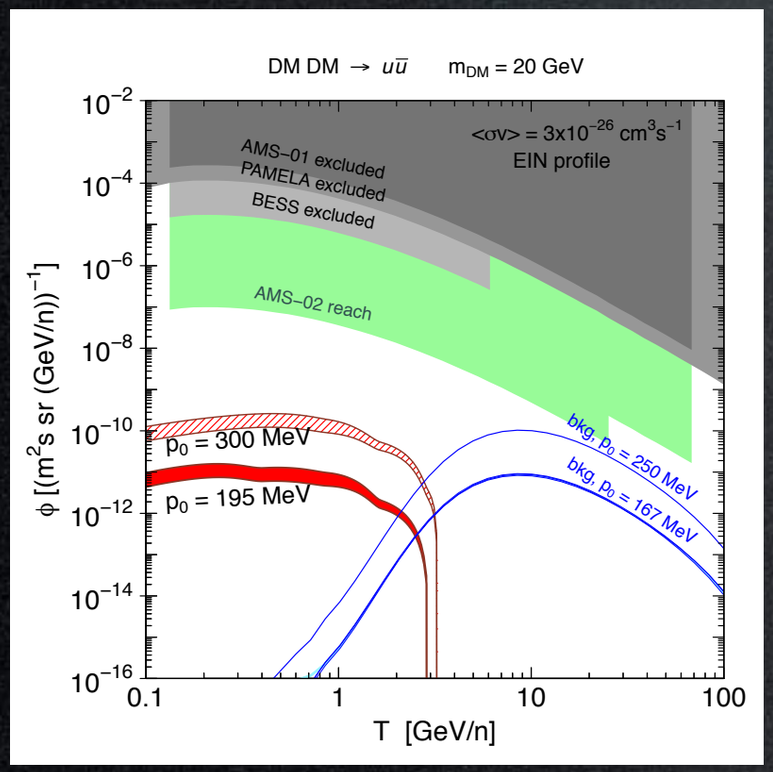

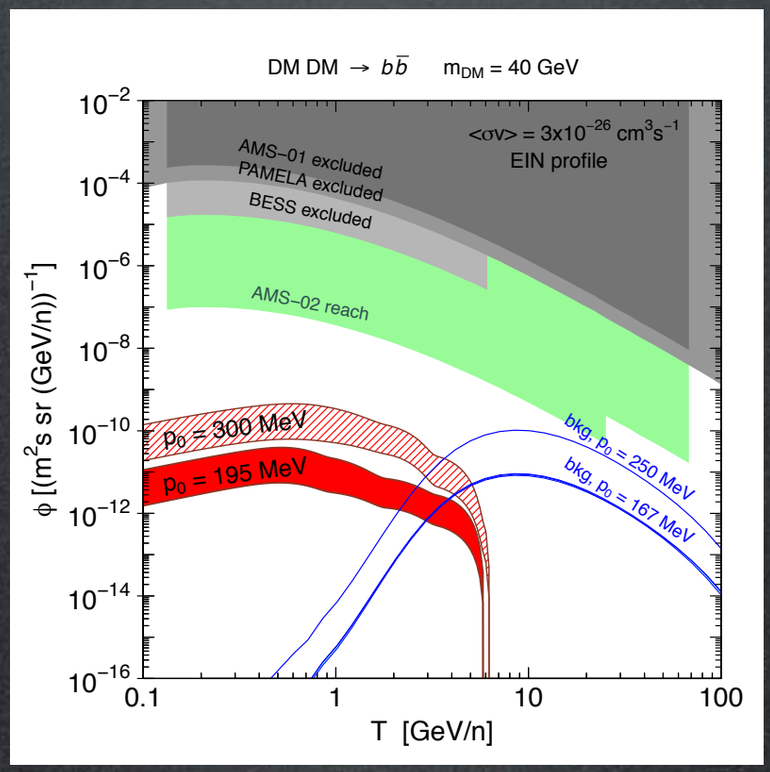

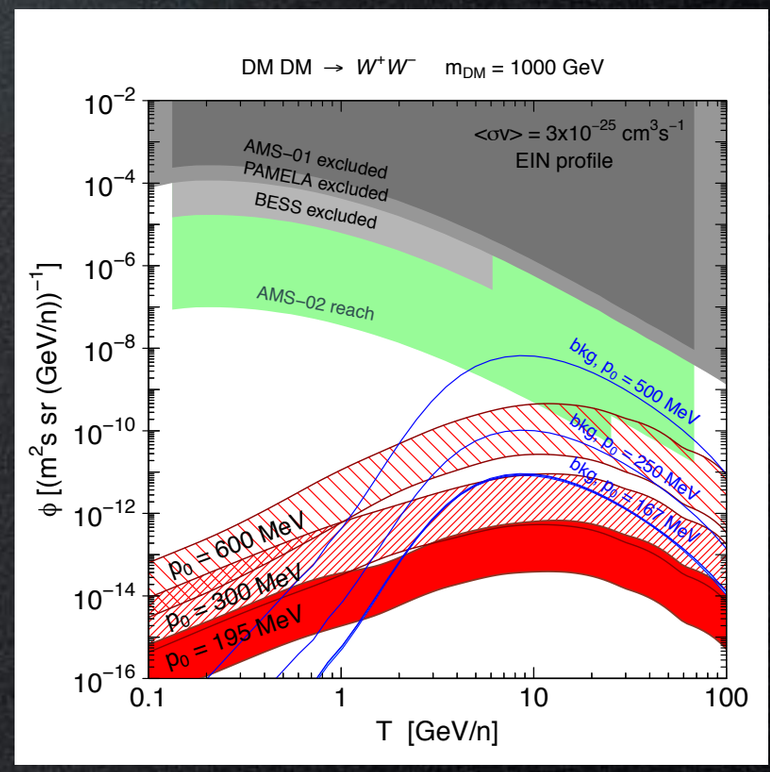

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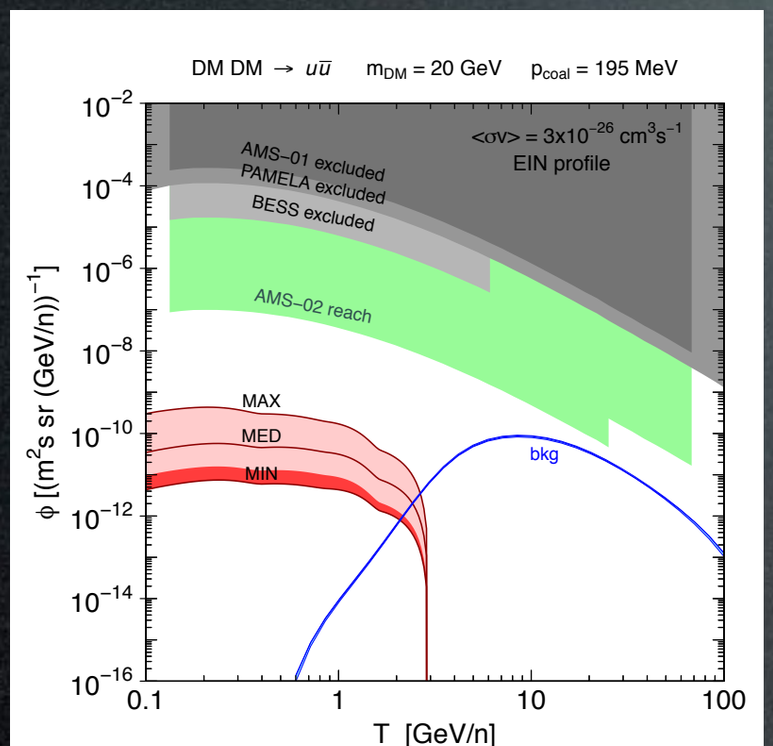

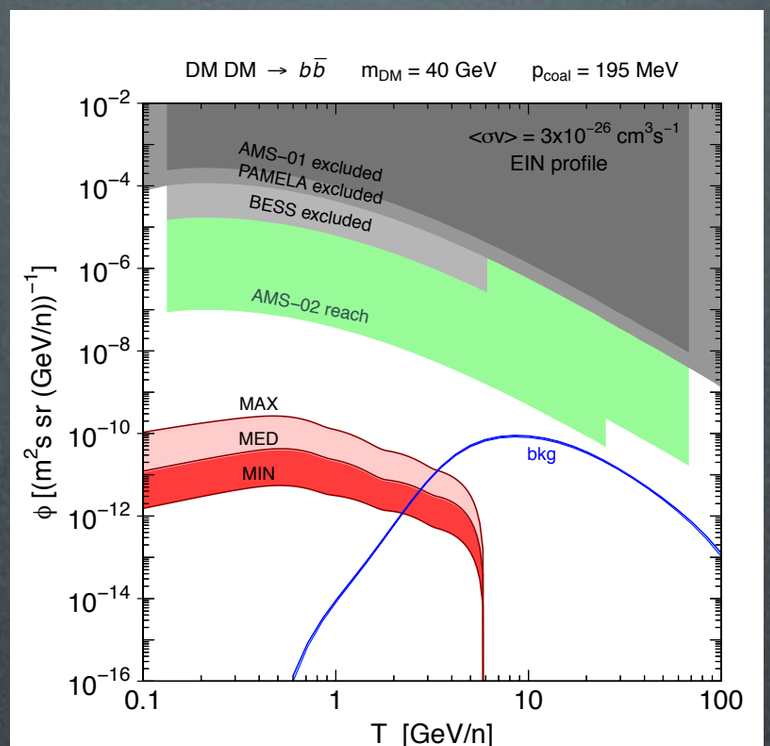

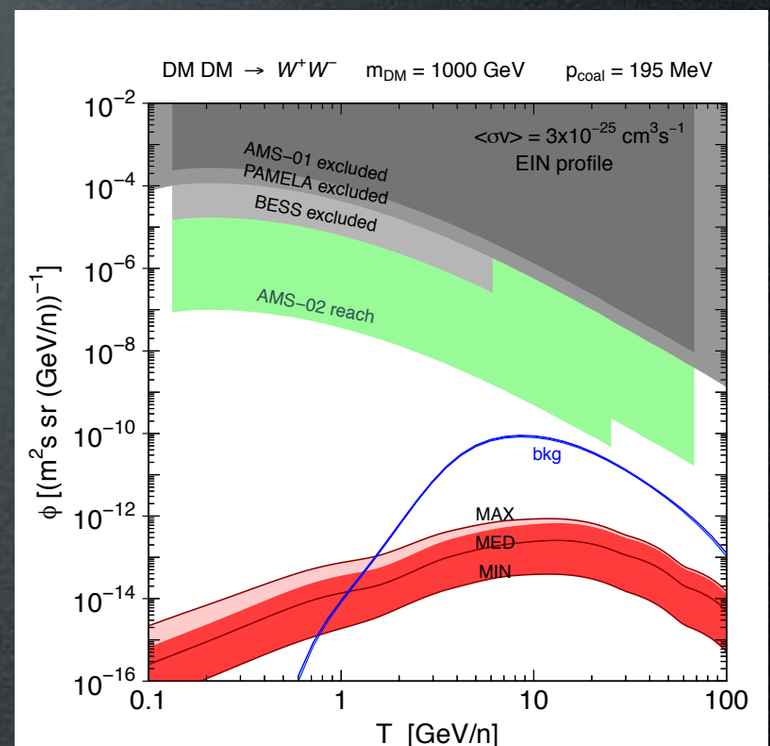

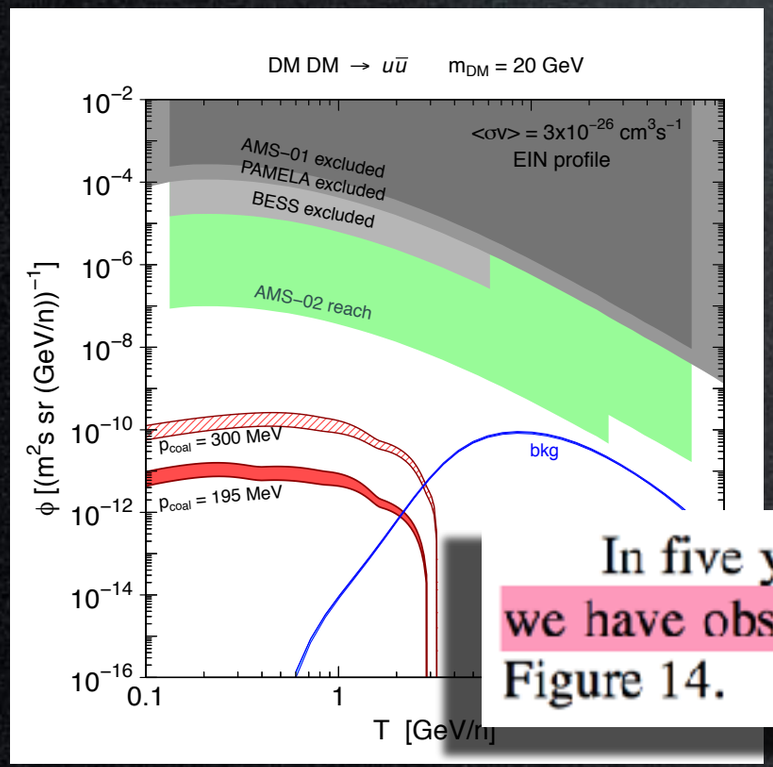

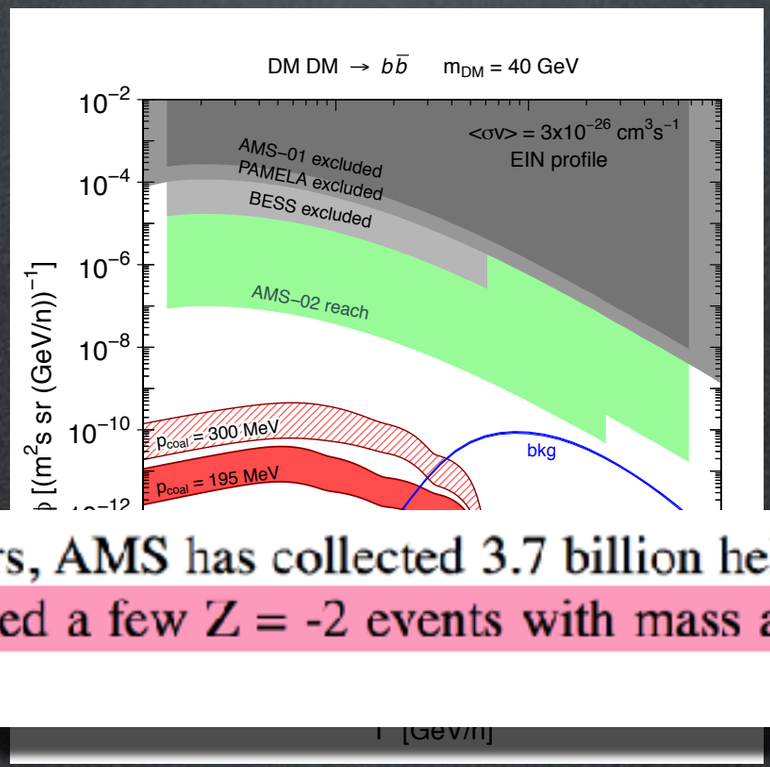

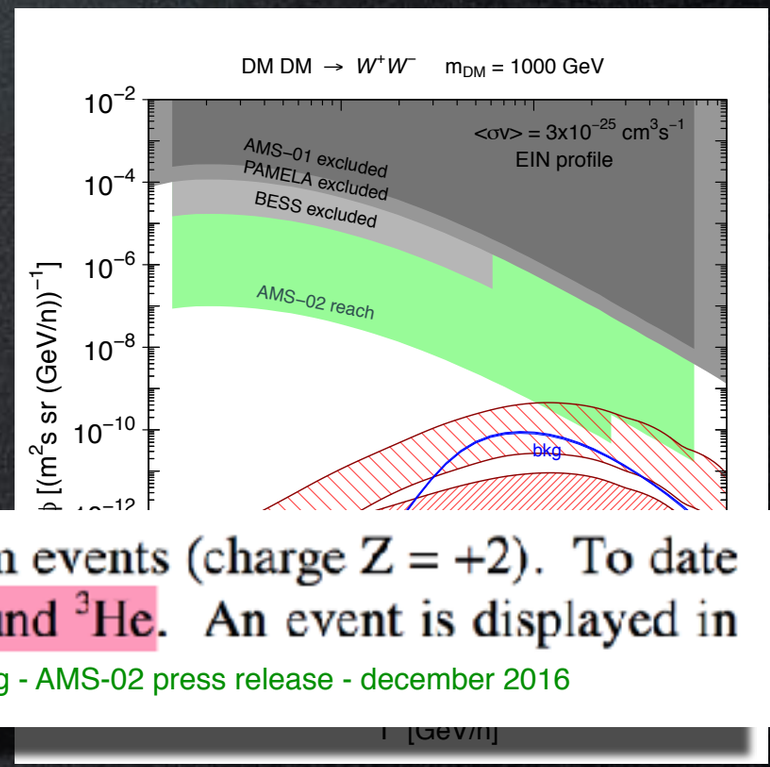

In five years, AMS has collected 3.7 billion helium events (charge Z = +2). To date we have observed a few Z = -2 events with mass around ^{3}He. An event is displayed in Figure 14.

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

Indirect Detection

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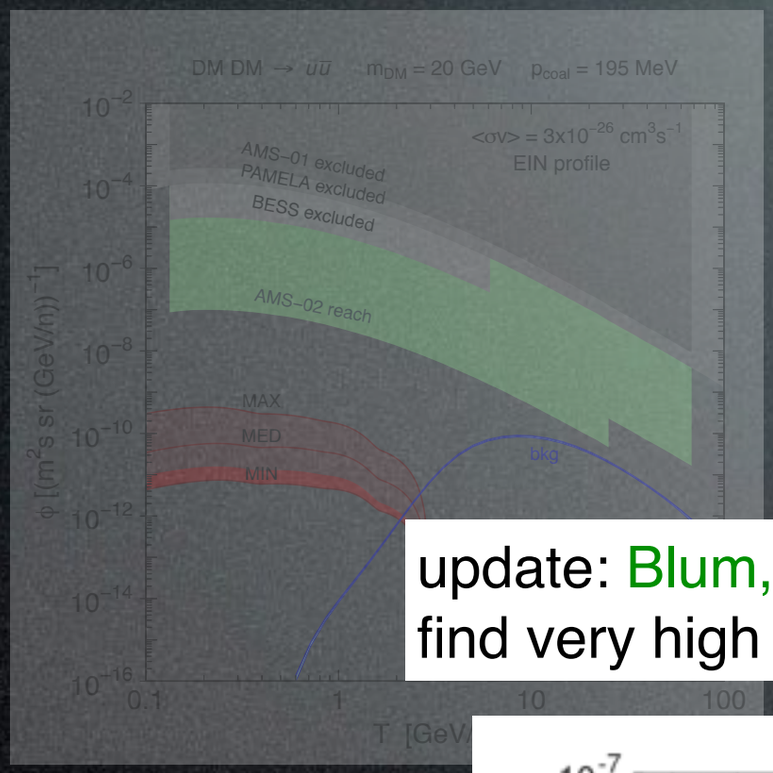
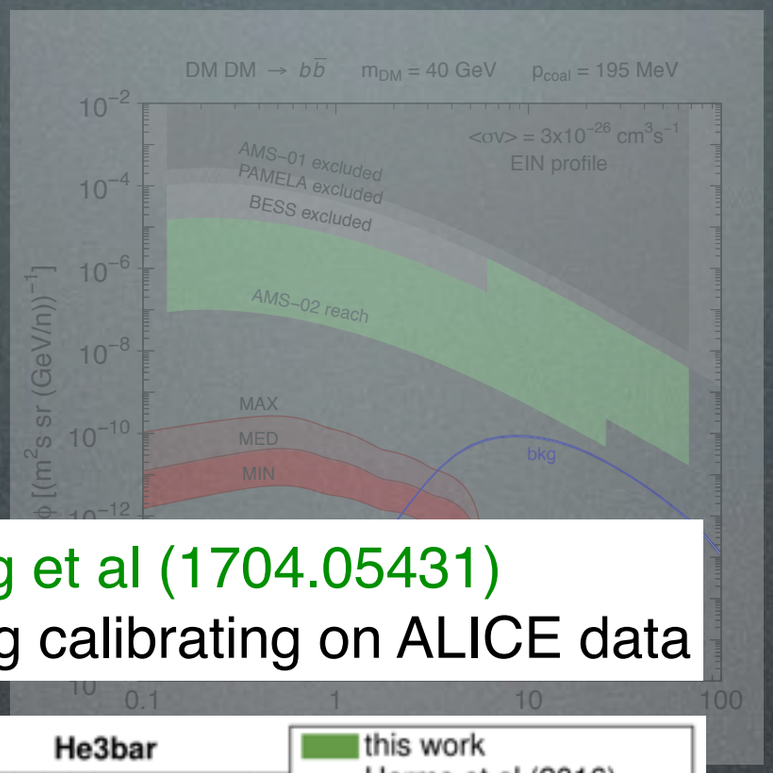
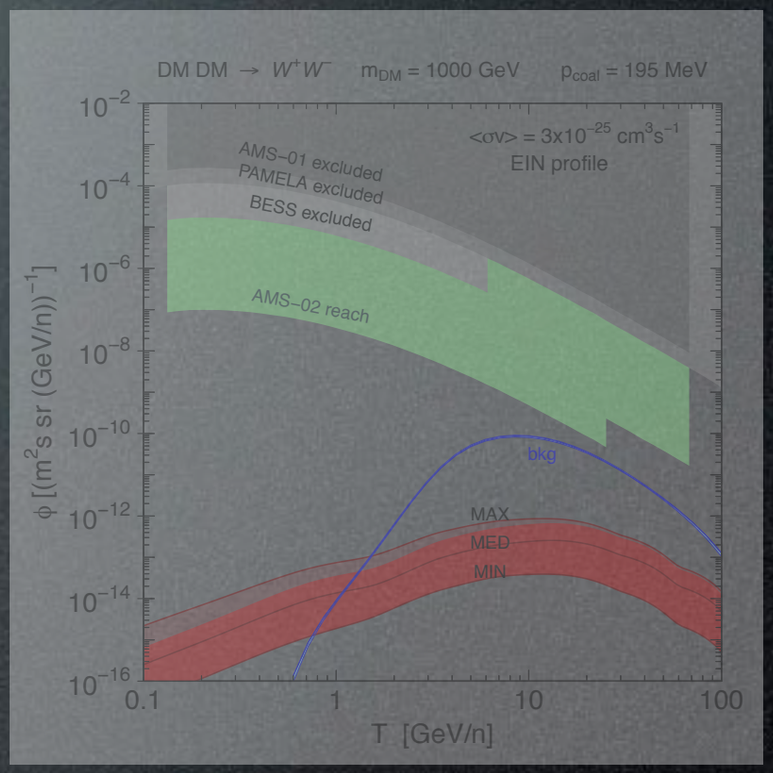
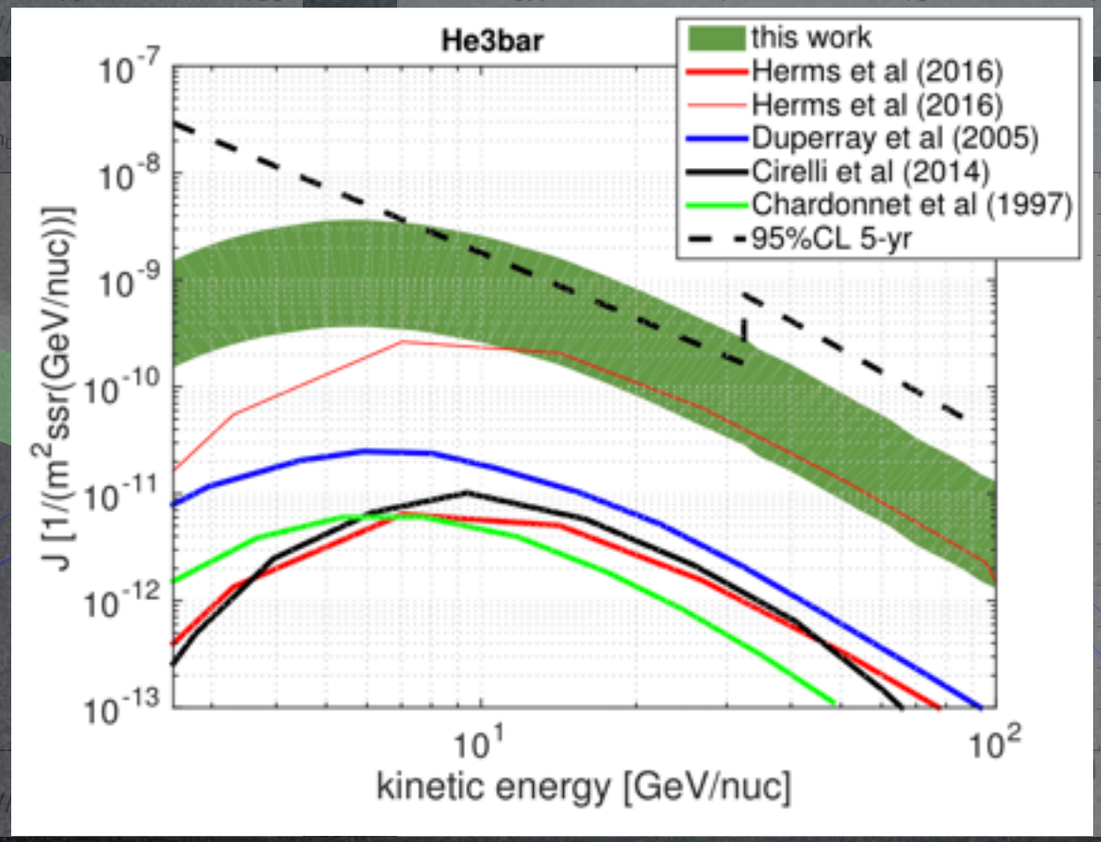
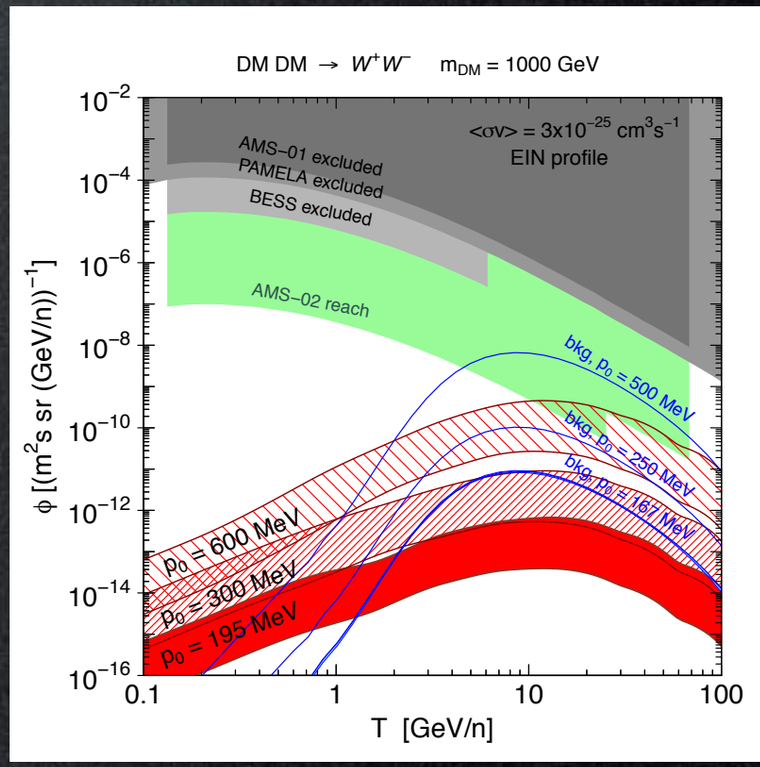






update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data





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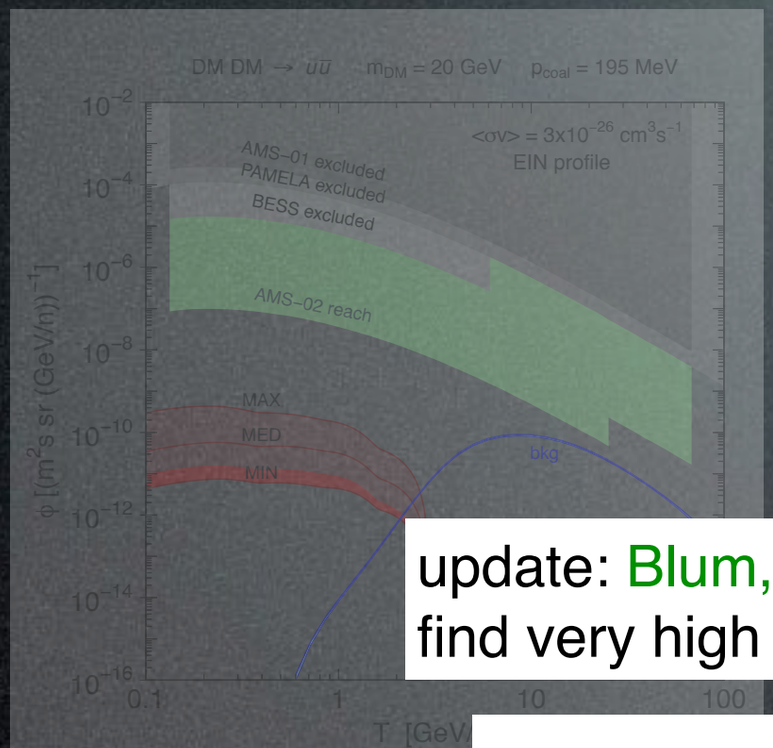

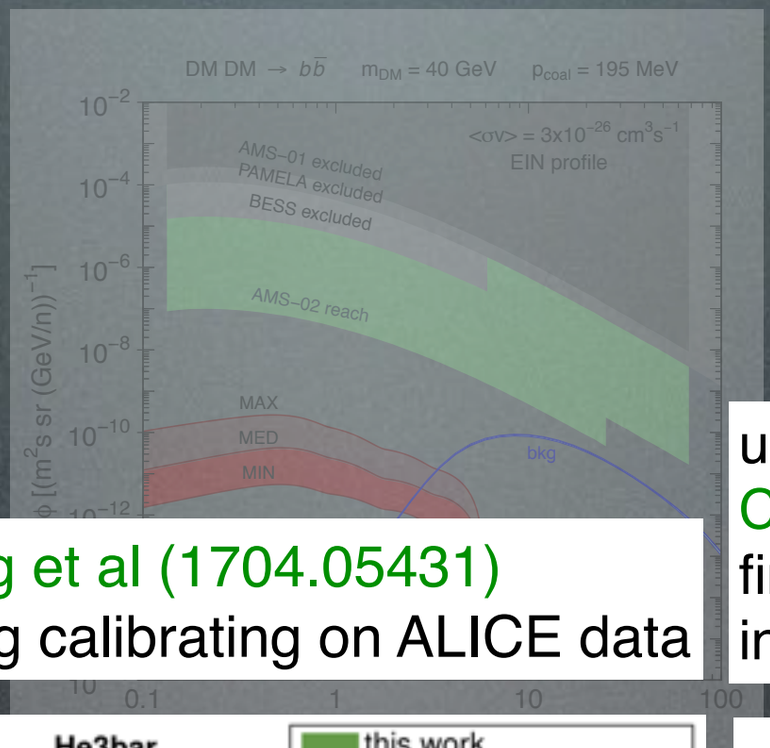

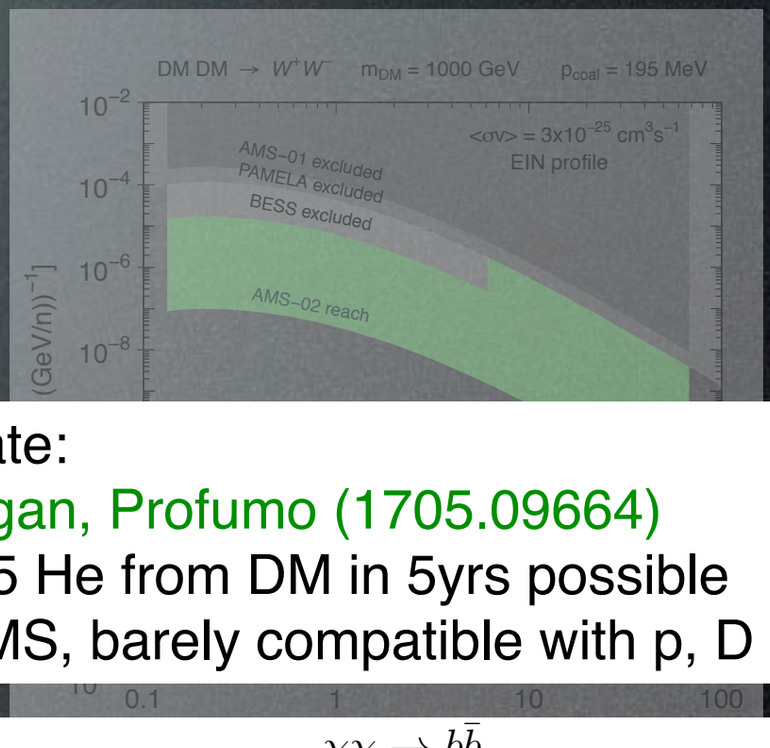

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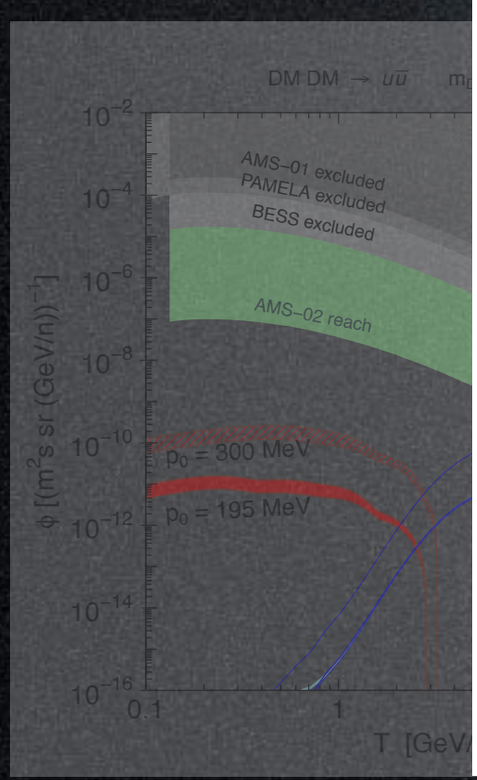
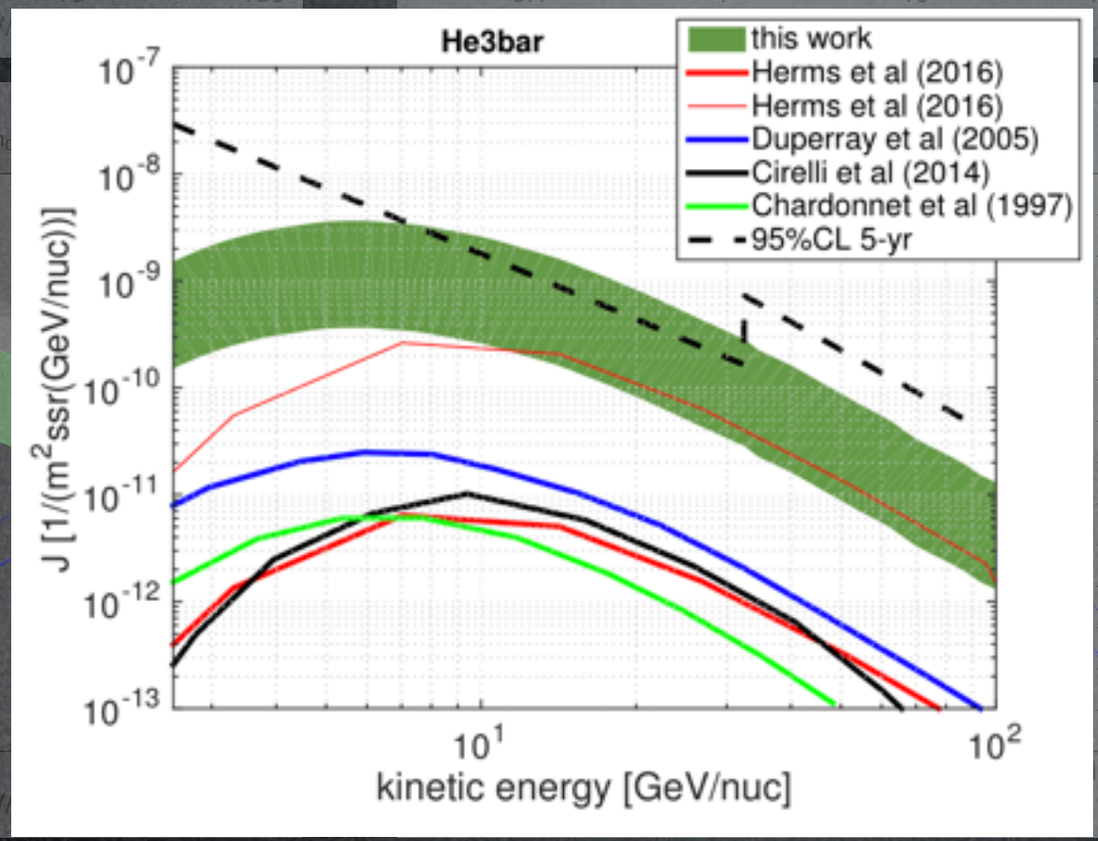
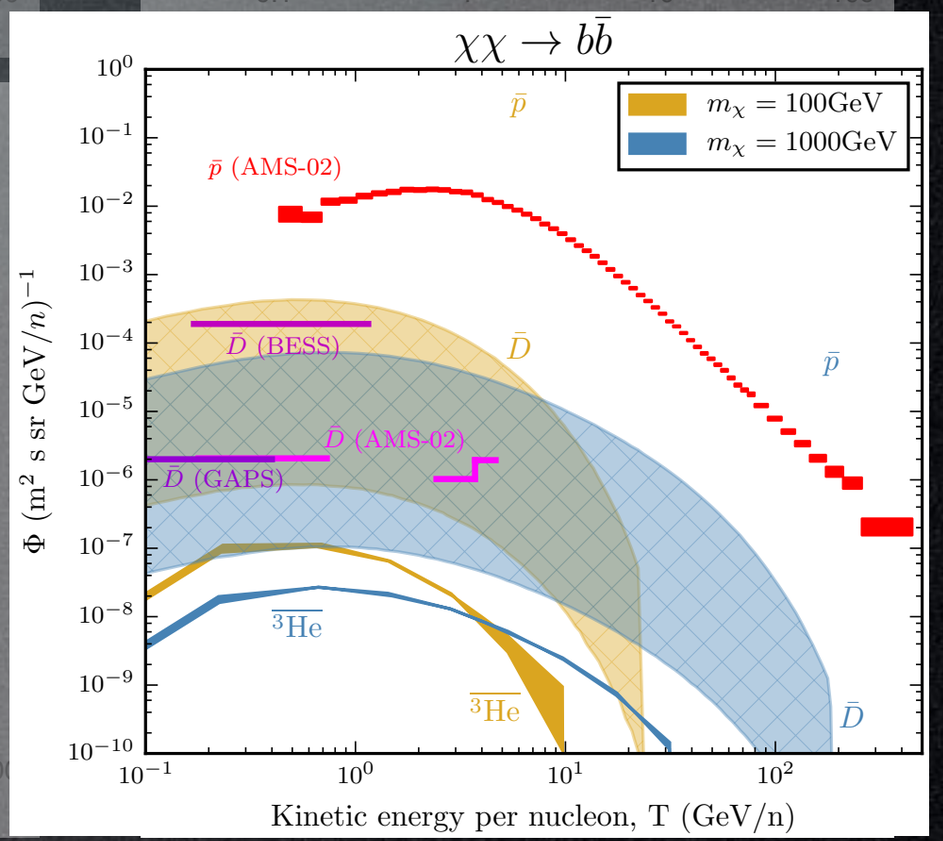
find very high bkg calibrating on ALICE data

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







Comparing all bounds

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

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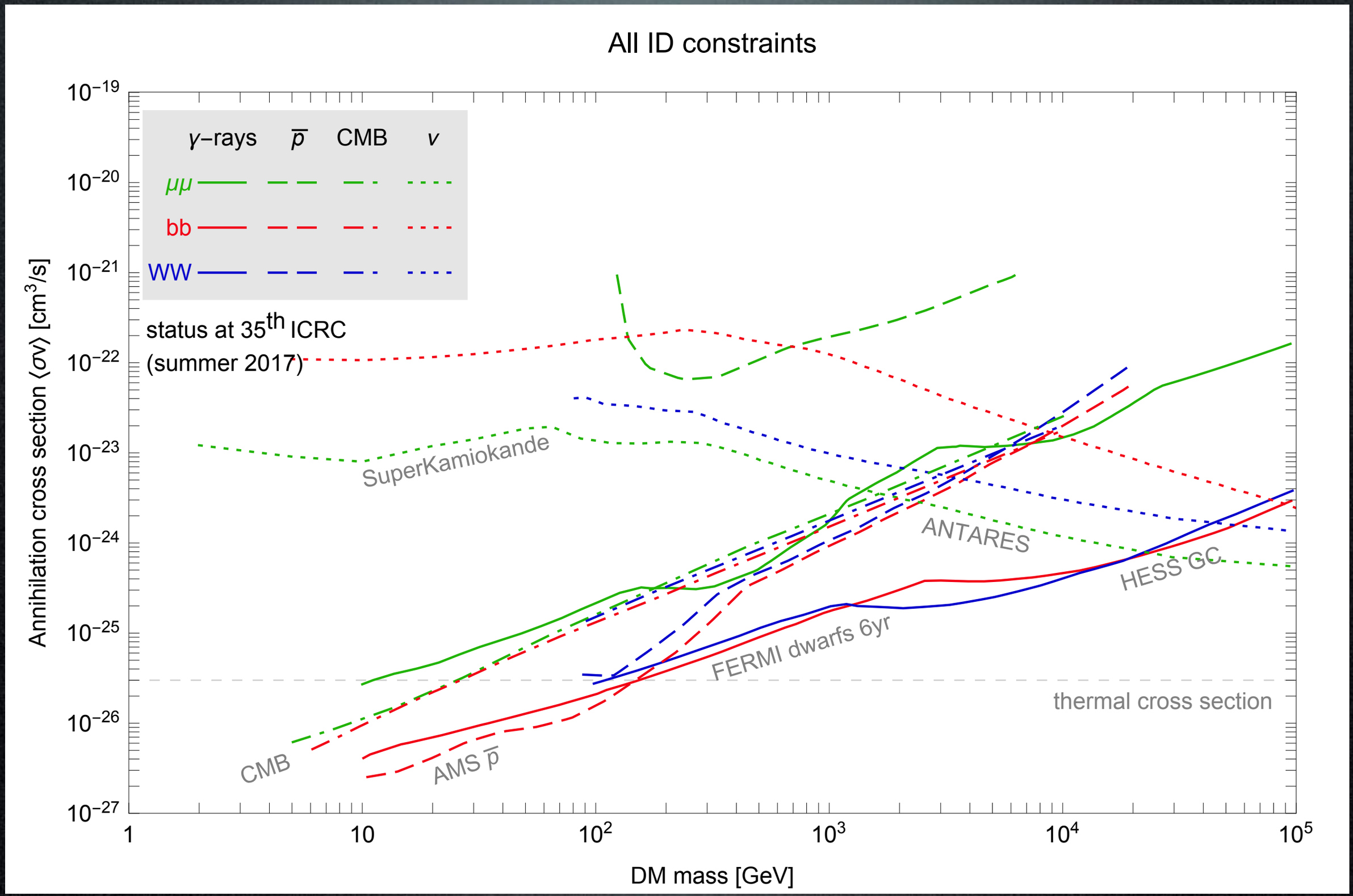

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Conclusions

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in $\bar{p}$: still large uncertainties
in $\bar{d}$: challenging flux
in $\overline{He}$: hopeless? who knows
in ν: challenging detection
in γ: astrophysical background

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Solution:

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Back up slides

Introduction

Introduction

DM exists

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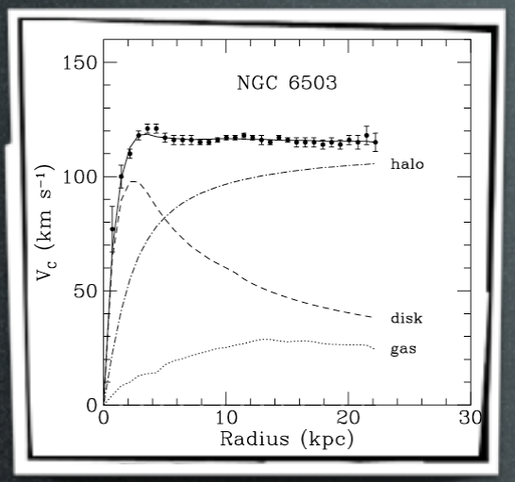
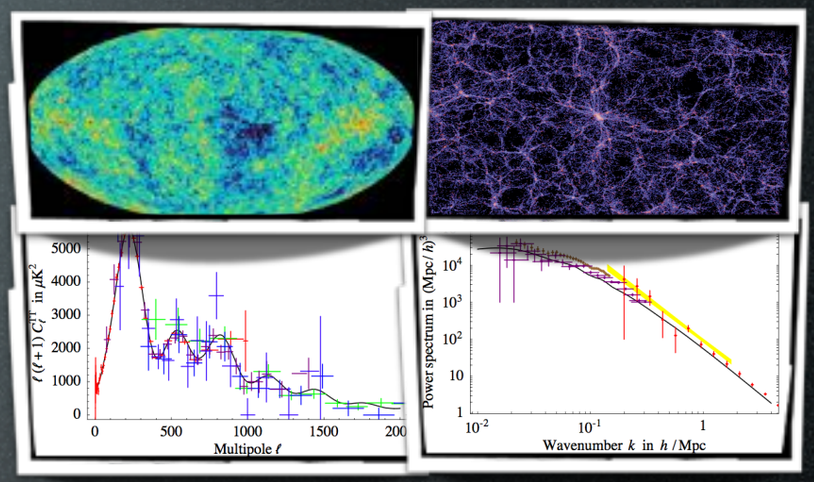


galactic rotation curves

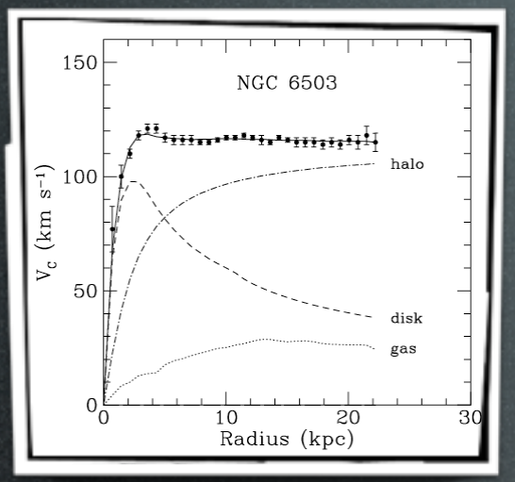
weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Introduction

DM exists



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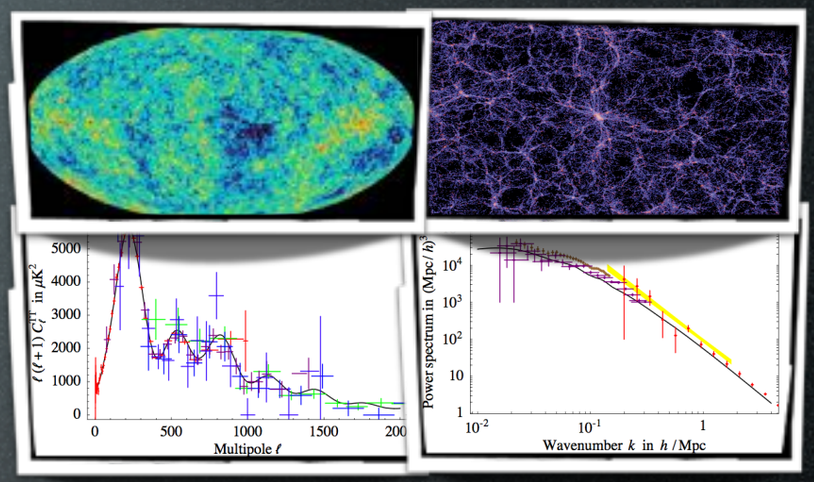

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DM is a neutral, very long lived, feebly interacting particle.

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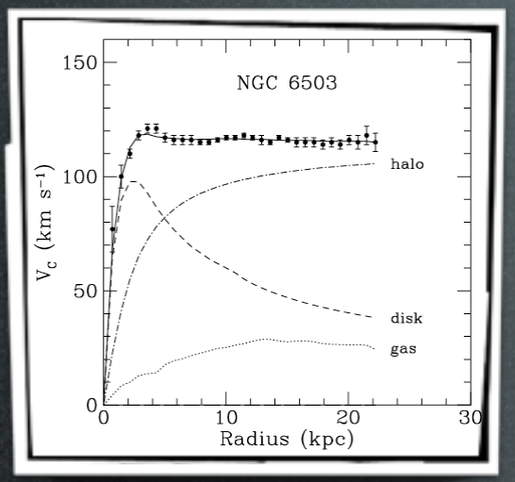

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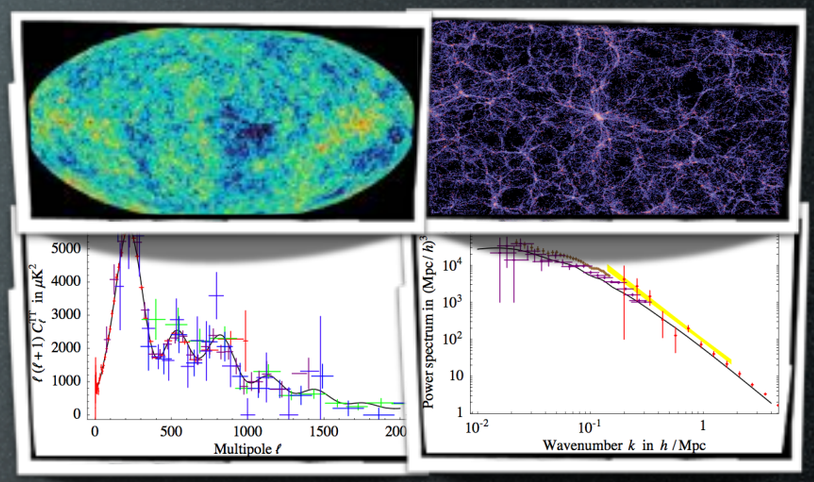
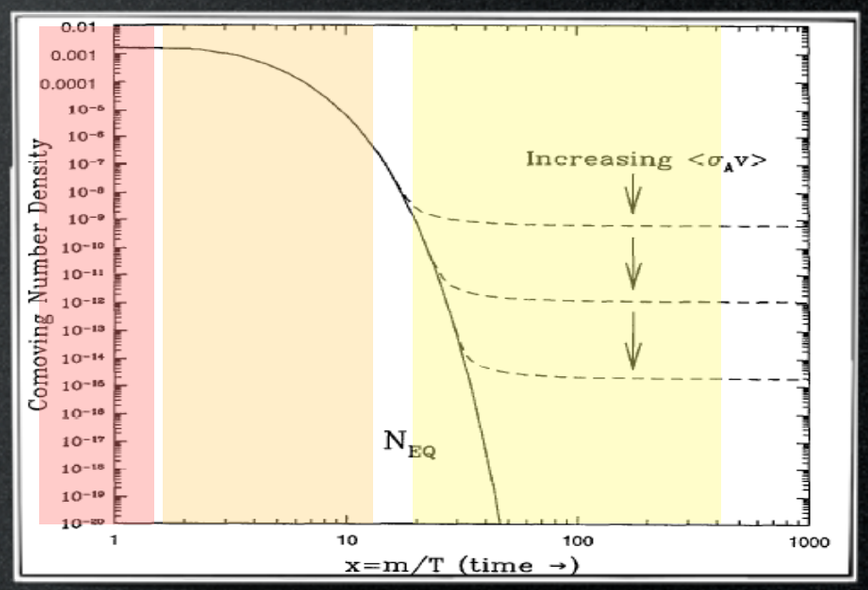


'precision cosmology' (CMB, LSS)

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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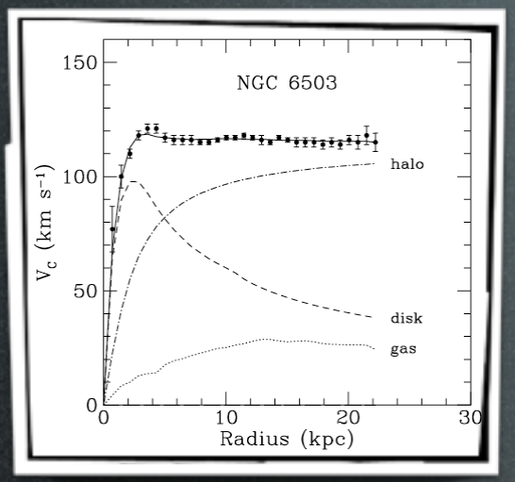

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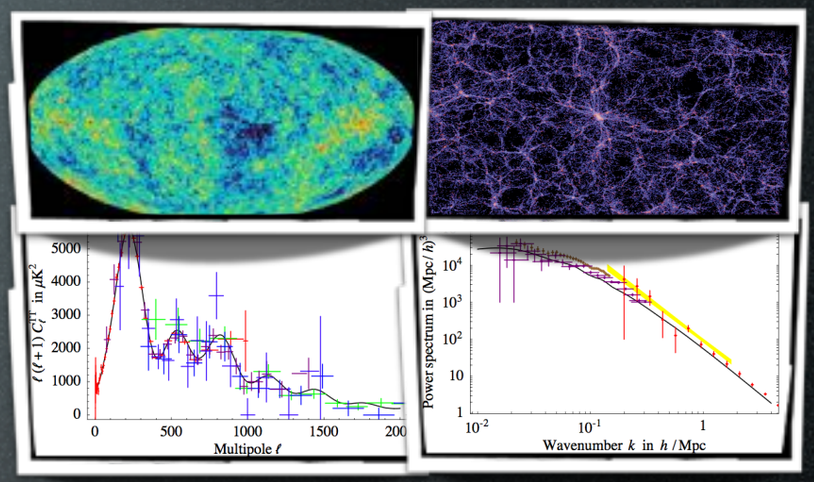


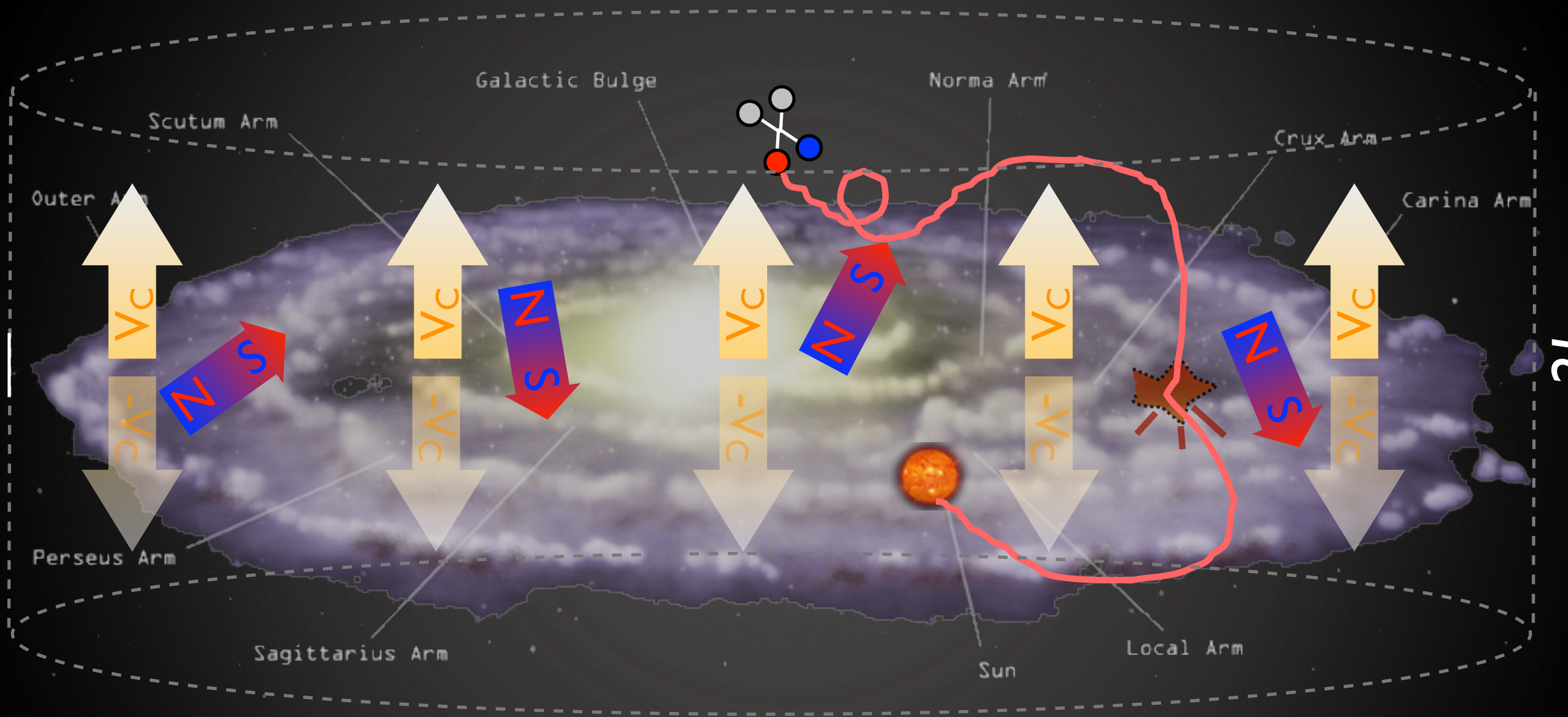
'precision cosmology' (CMB, LSS)

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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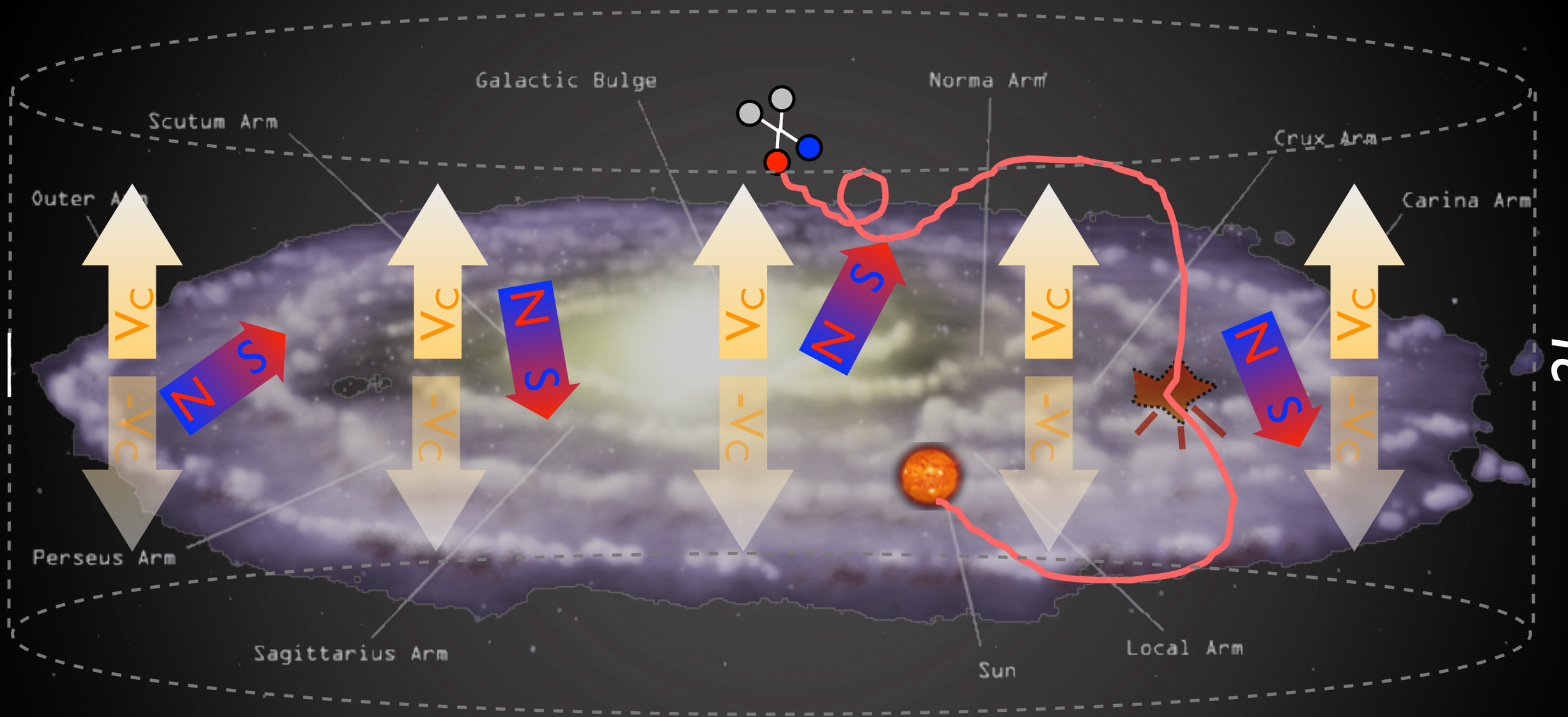

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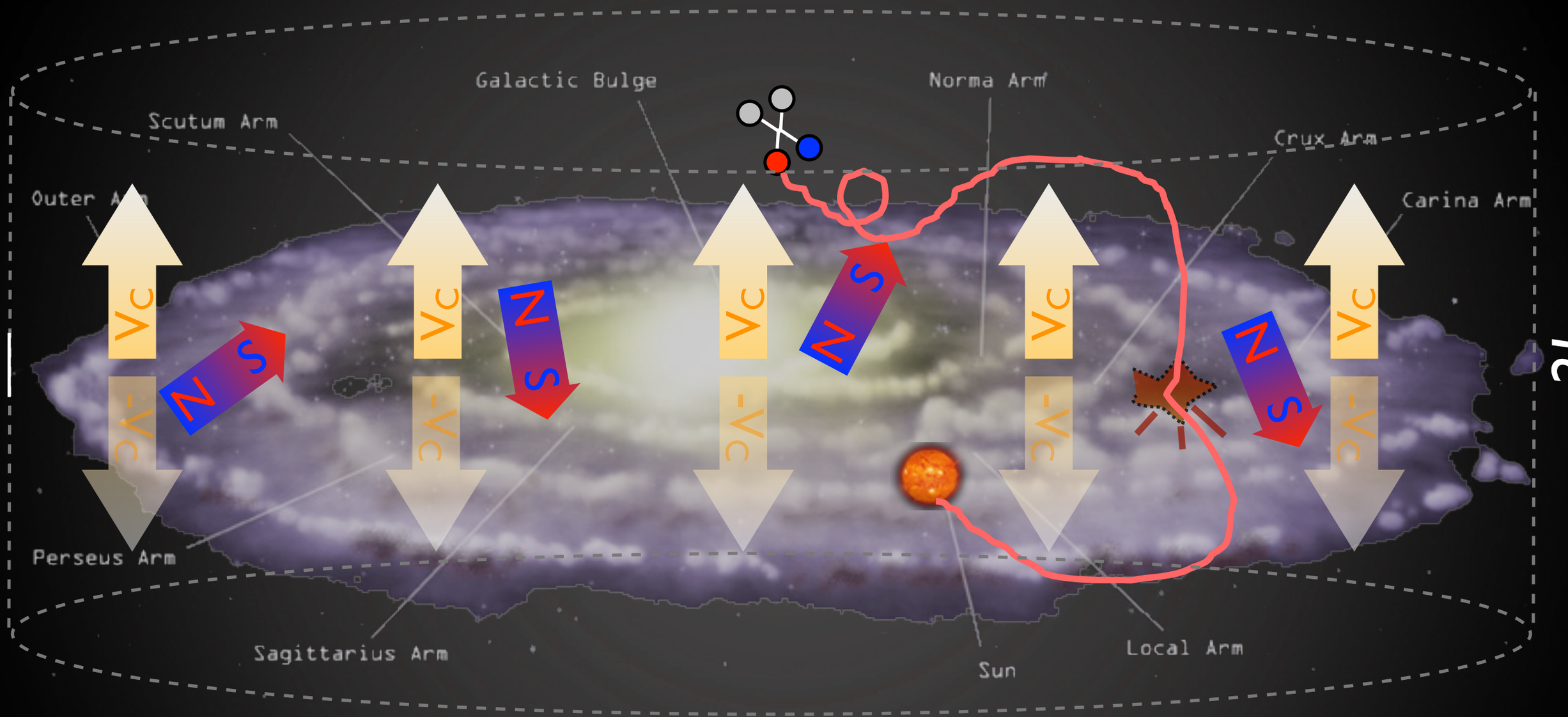


What sets the overall expected flux?

$$\text{flux} \propto \underbrace{n^2}_{\text{astro\& cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

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

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

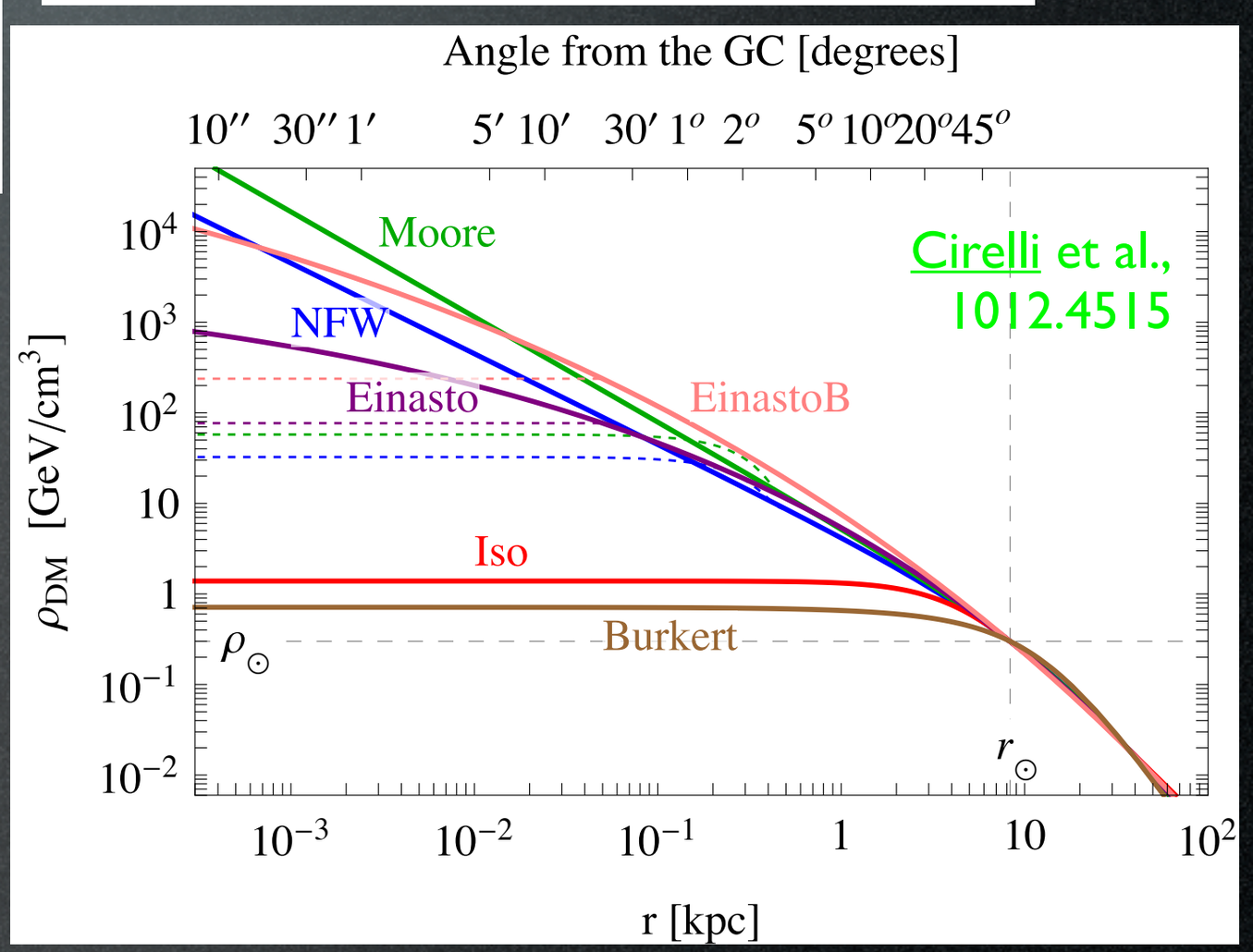
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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

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



6 profiles:

cuspy: NFW, Moore

mild: Einasto

smooth: isothermal, Burkert

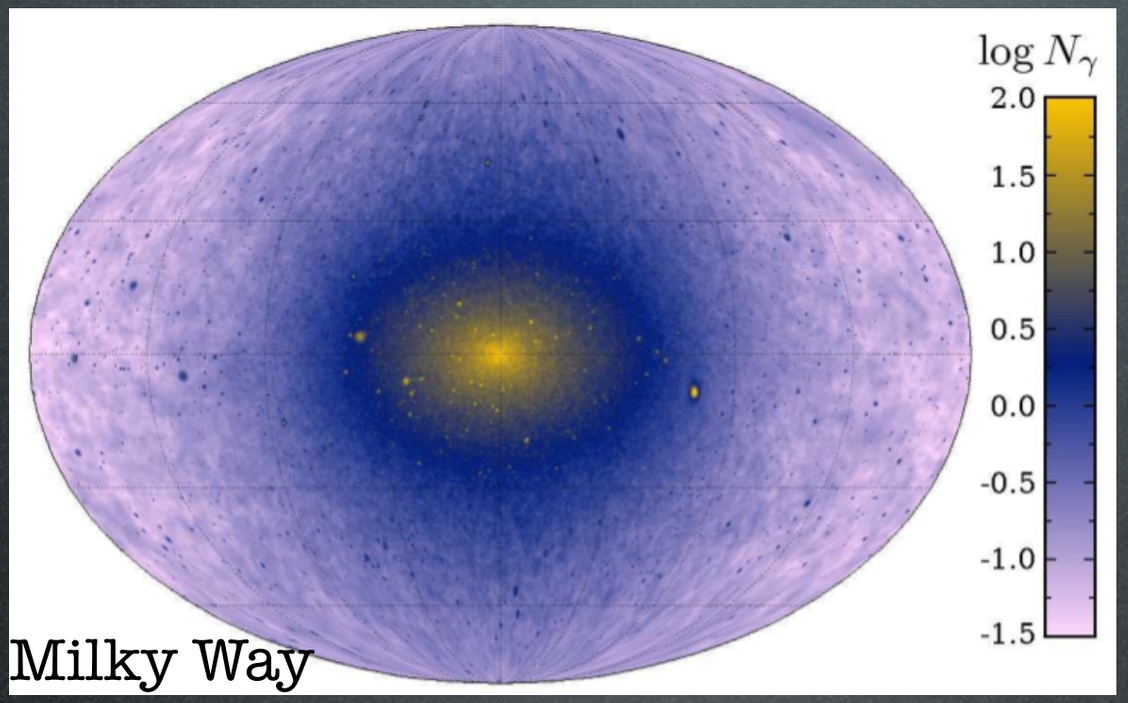
EinastoB = steepened Einasto

(effect of baryons?)

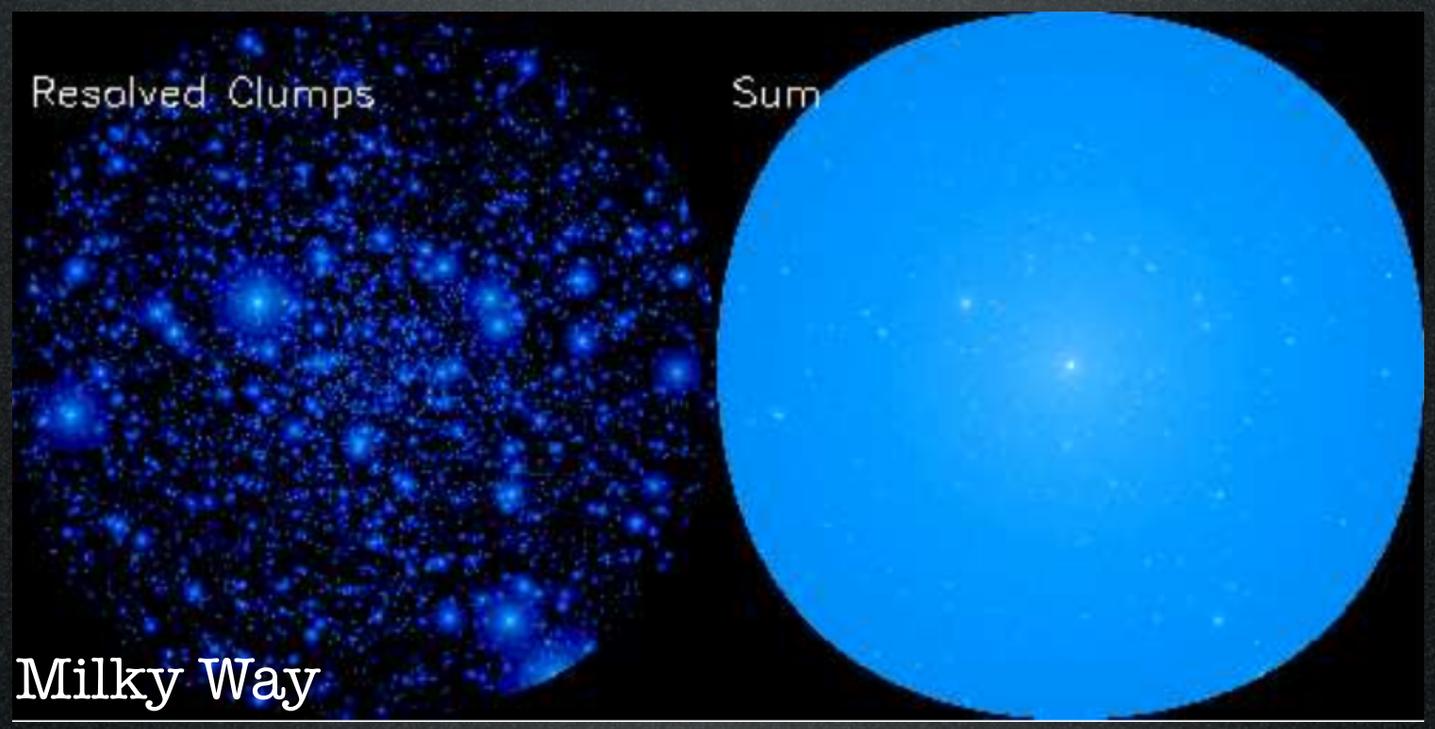
DM halo profiles

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

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

T kinetic energy

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

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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

Solution:

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

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

Model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
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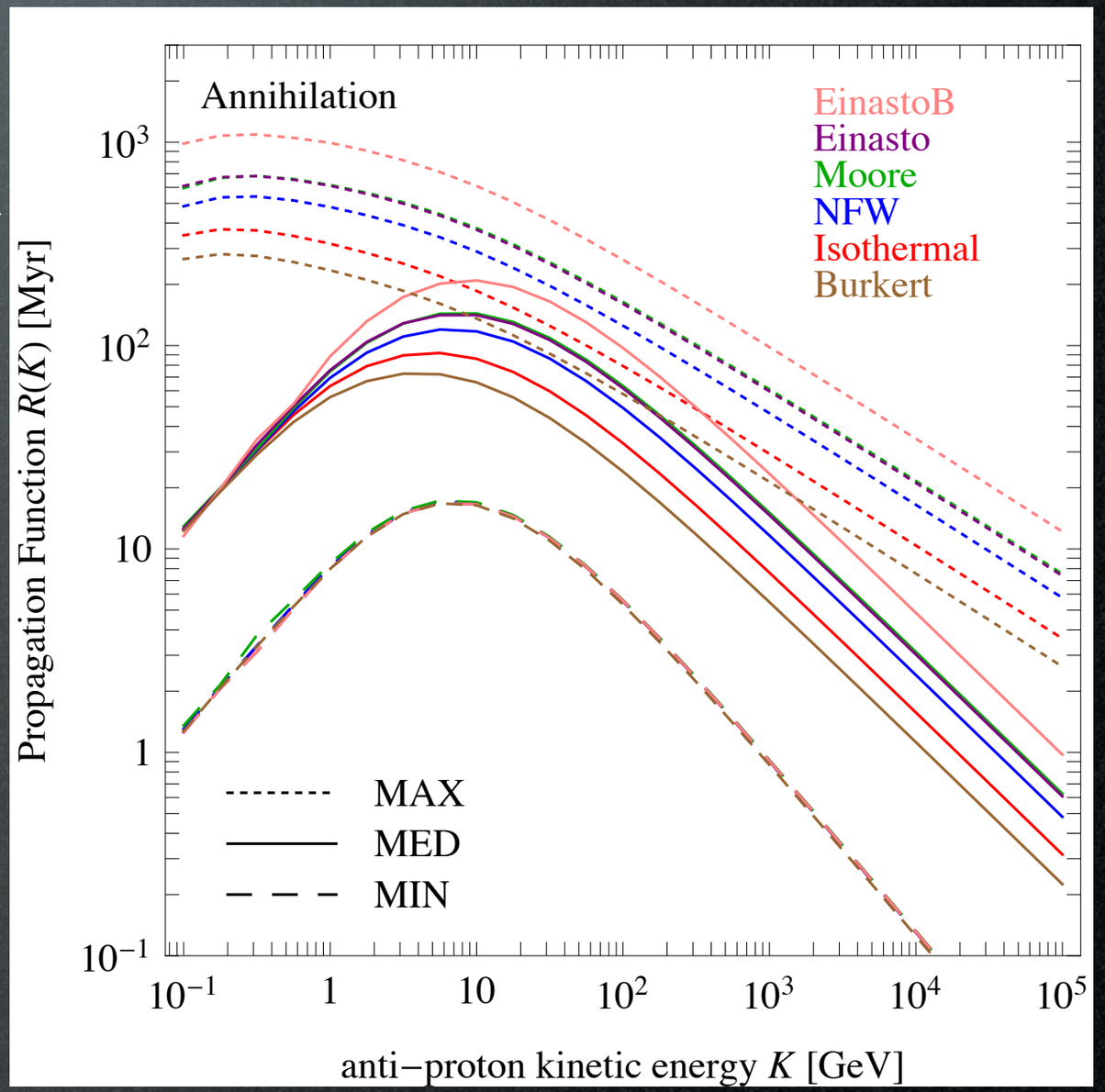


DM detection

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

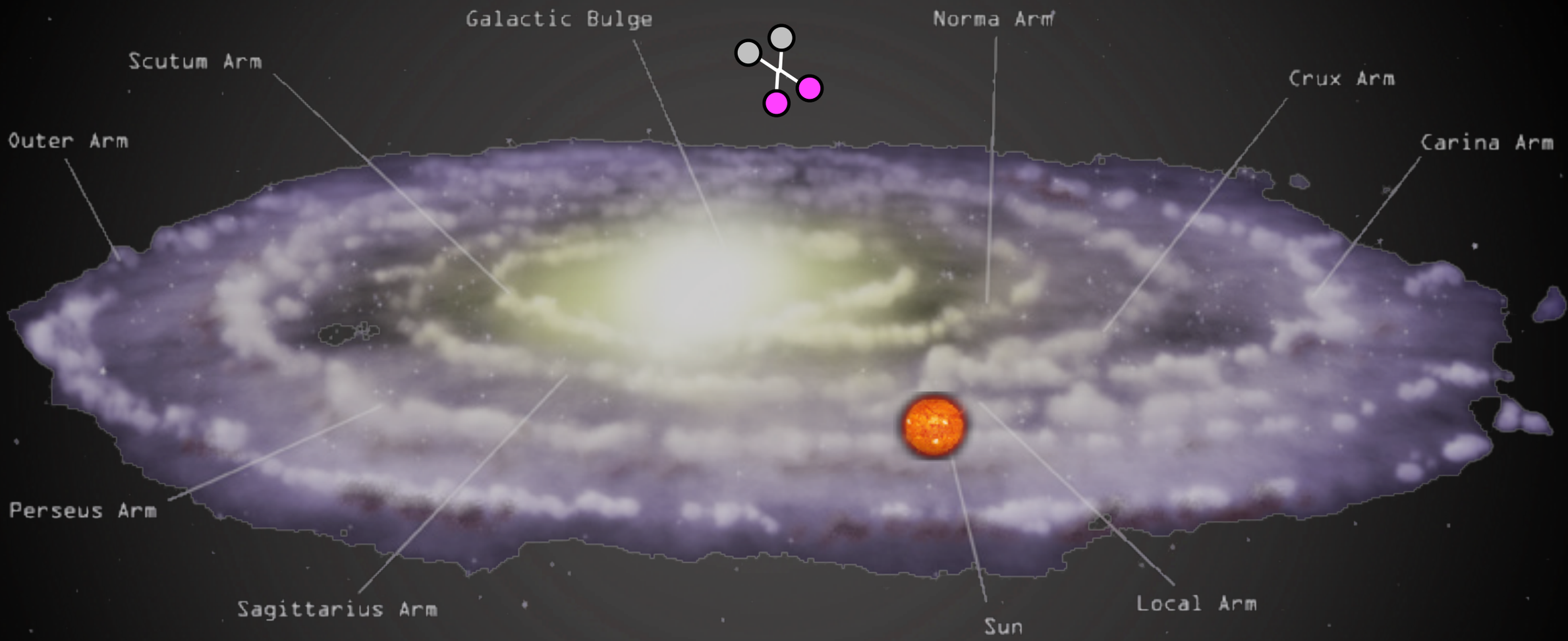
GAPS, AMS

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

SK, **Icecube**, Km3Net

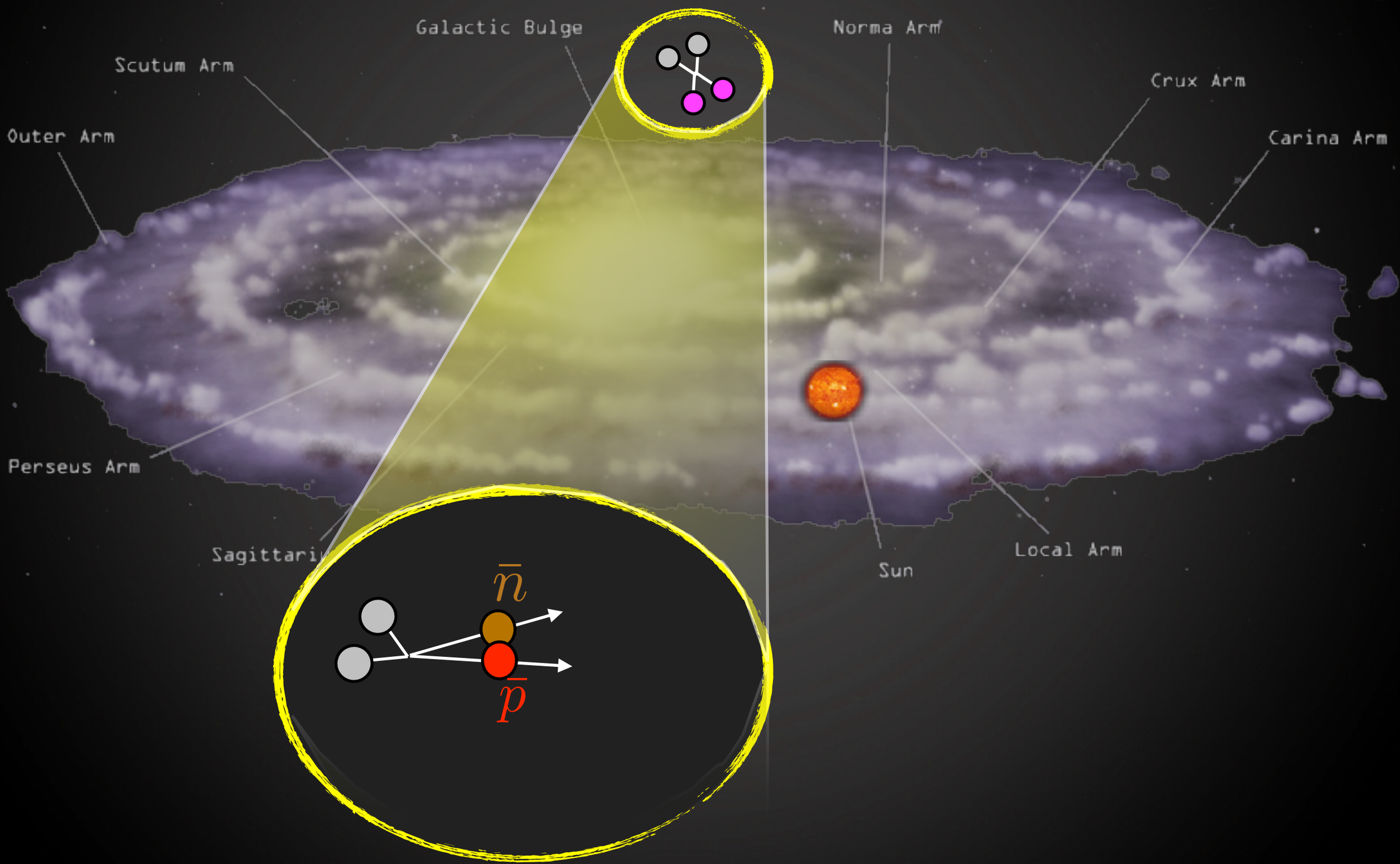
Indirect Detection

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



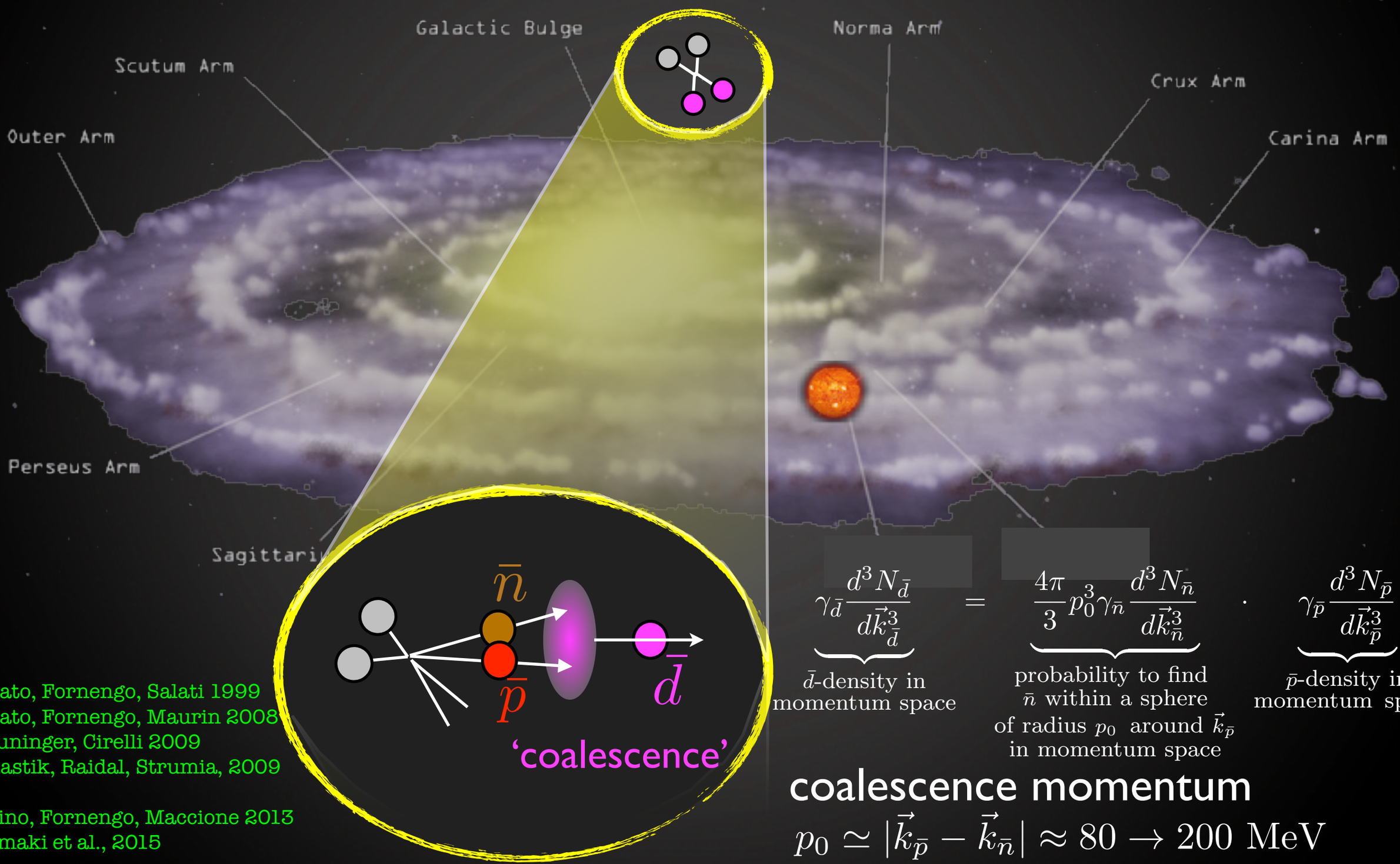
Indirect Detection

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



Indirect Detection

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



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

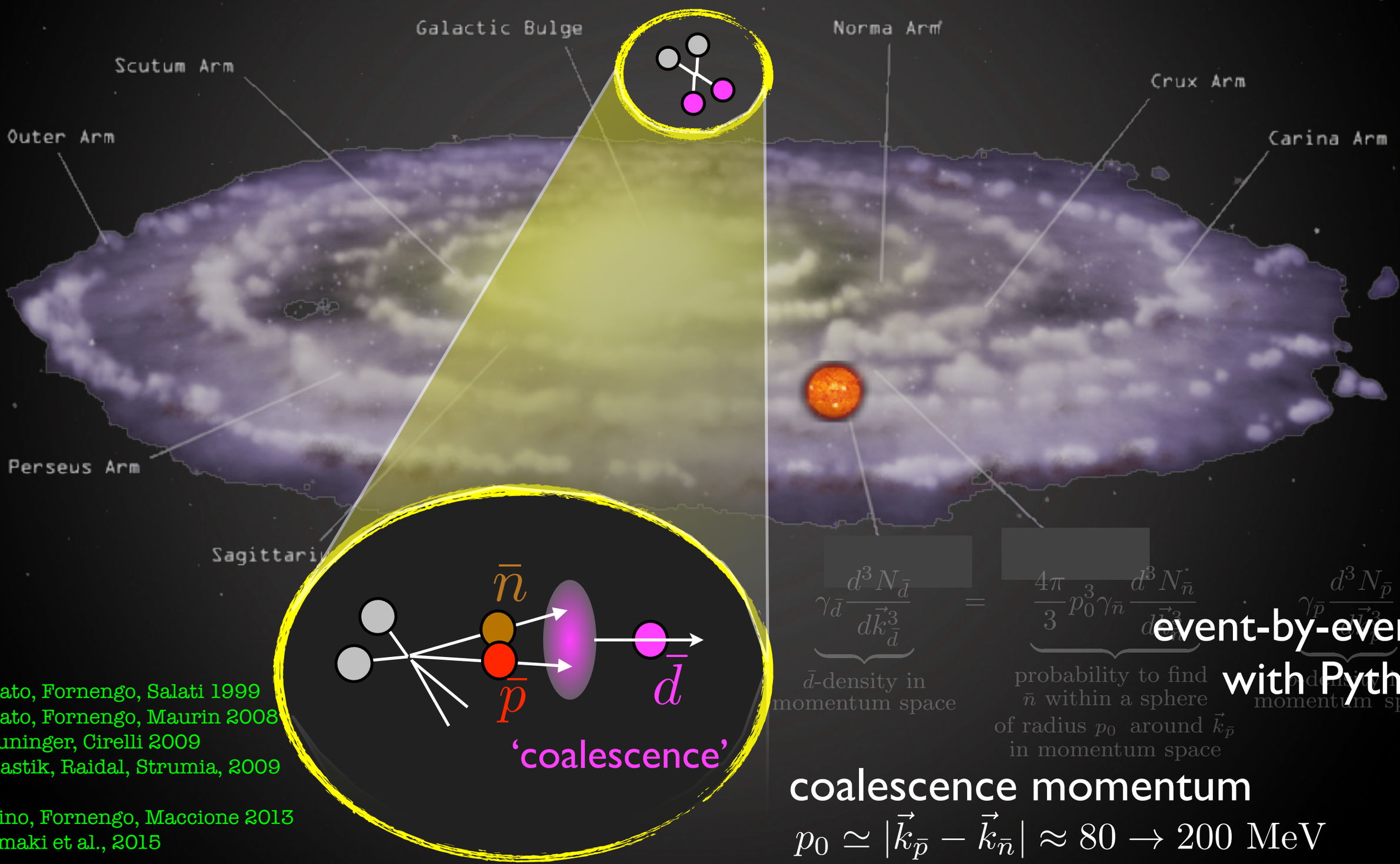
$$\underbrace{\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d\vec{k}^3_{\bar{d}}}}_{\bar{d}\text{-density in momentum space}} = \underbrace{\frac{4\pi}{3} p_0^3 \gamma_{\bar{n}} \frac{d^3 N_{\bar{n}}}{d\vec{k}^3_{\bar{n}}}}_{\substack{\text{probability to find } \bar{n} \text{ within a sphere} \\ \text{of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

coalescence momentum

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

Indirect Detection

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



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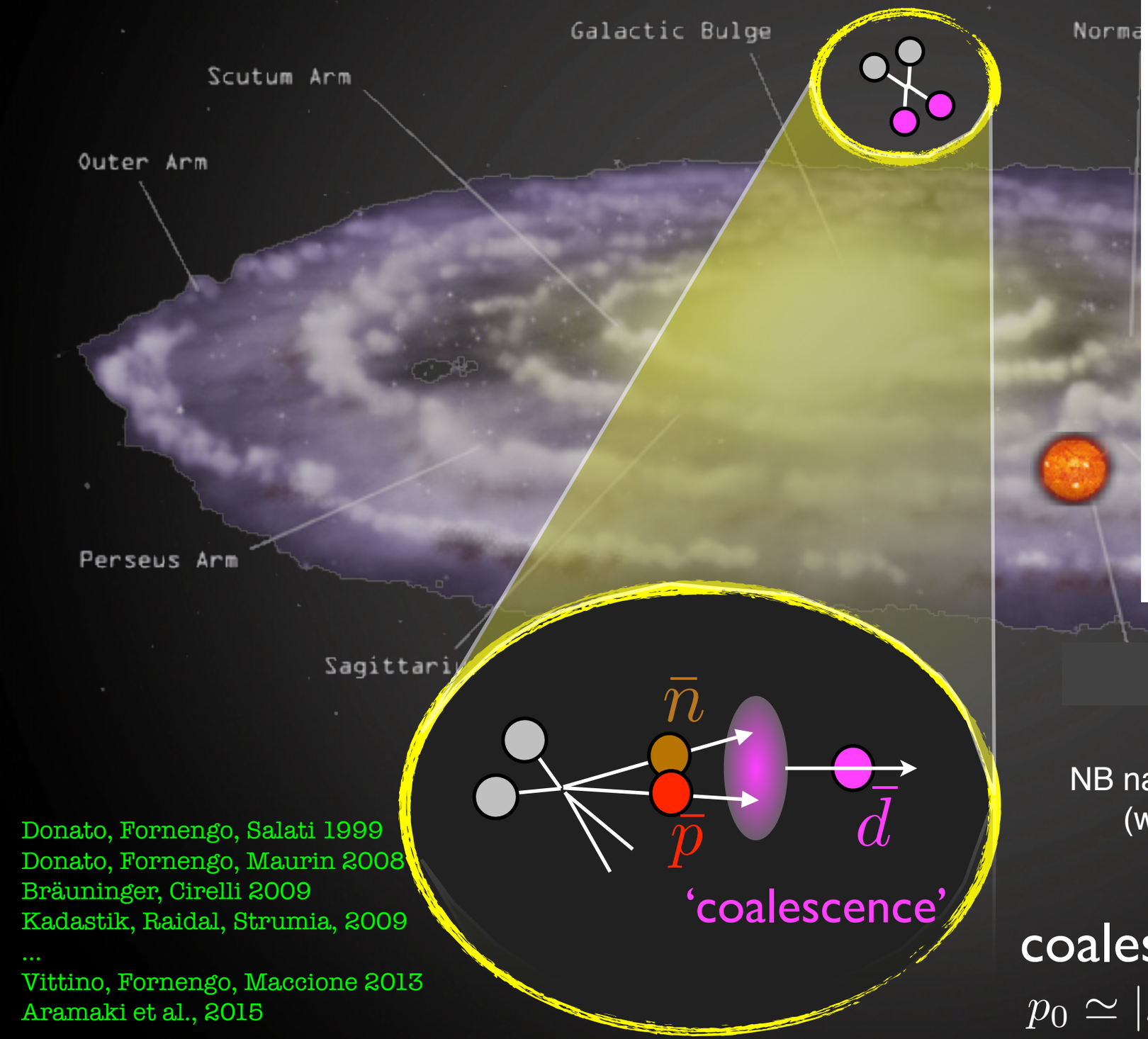
event-by-event with Pythia

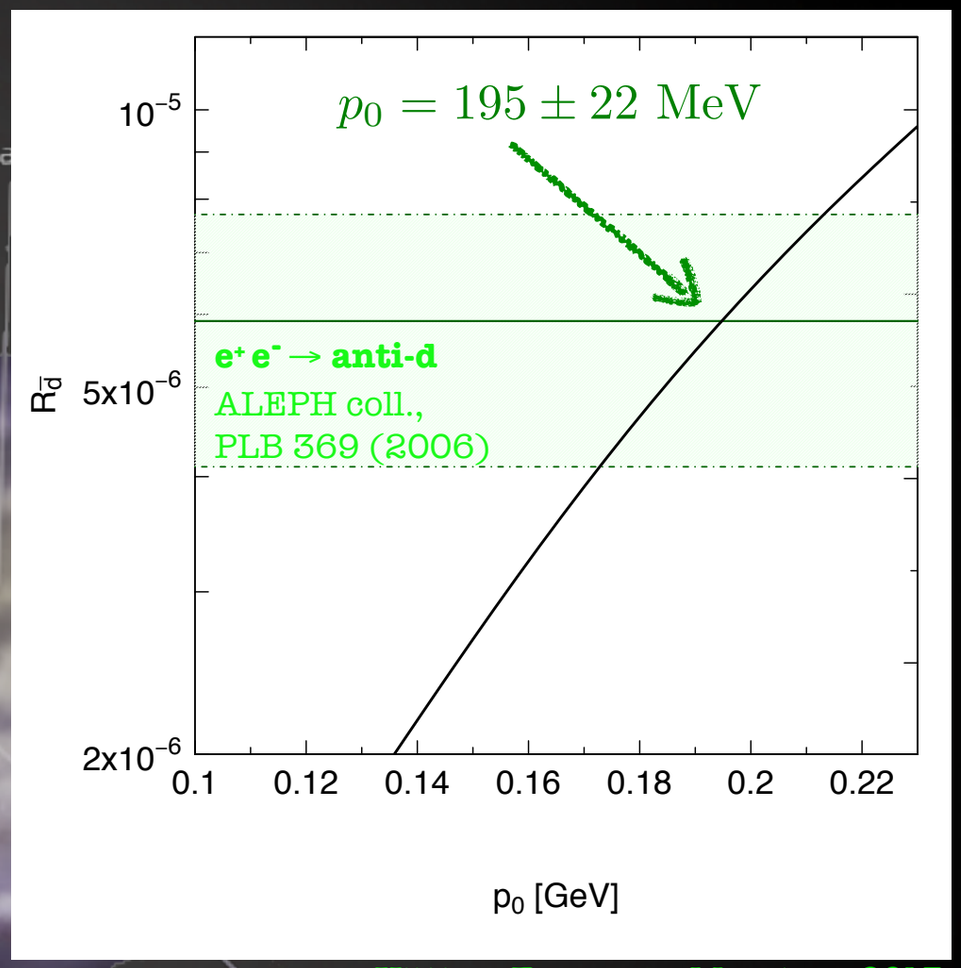
coalescence momentum

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

Indirect Detection

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





Vittino, Fornengo, Maccione 2013

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

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

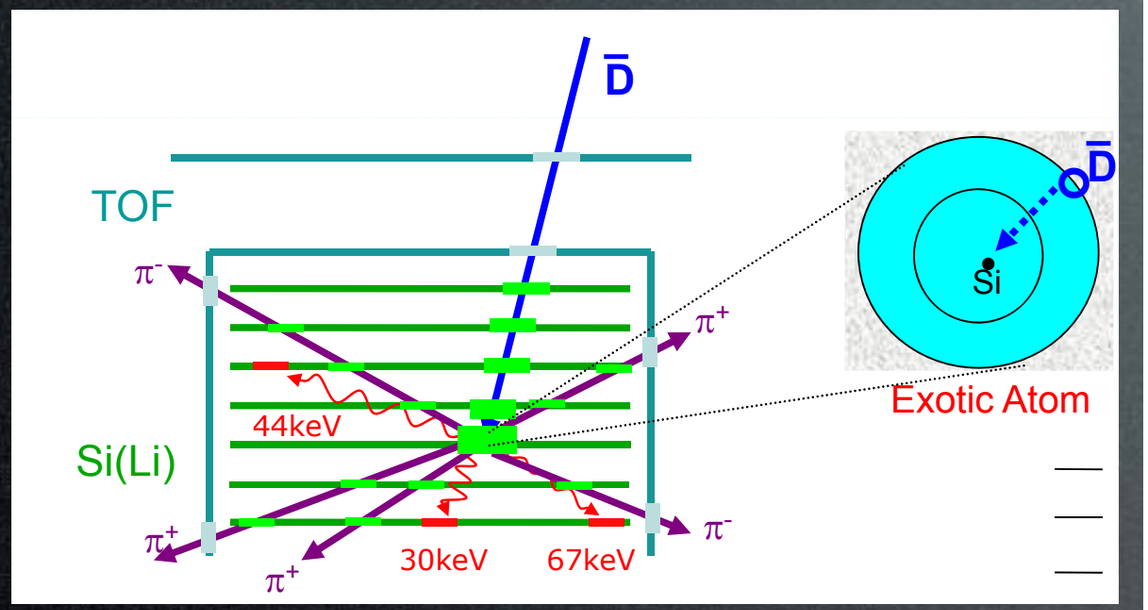
coalescence momentum

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

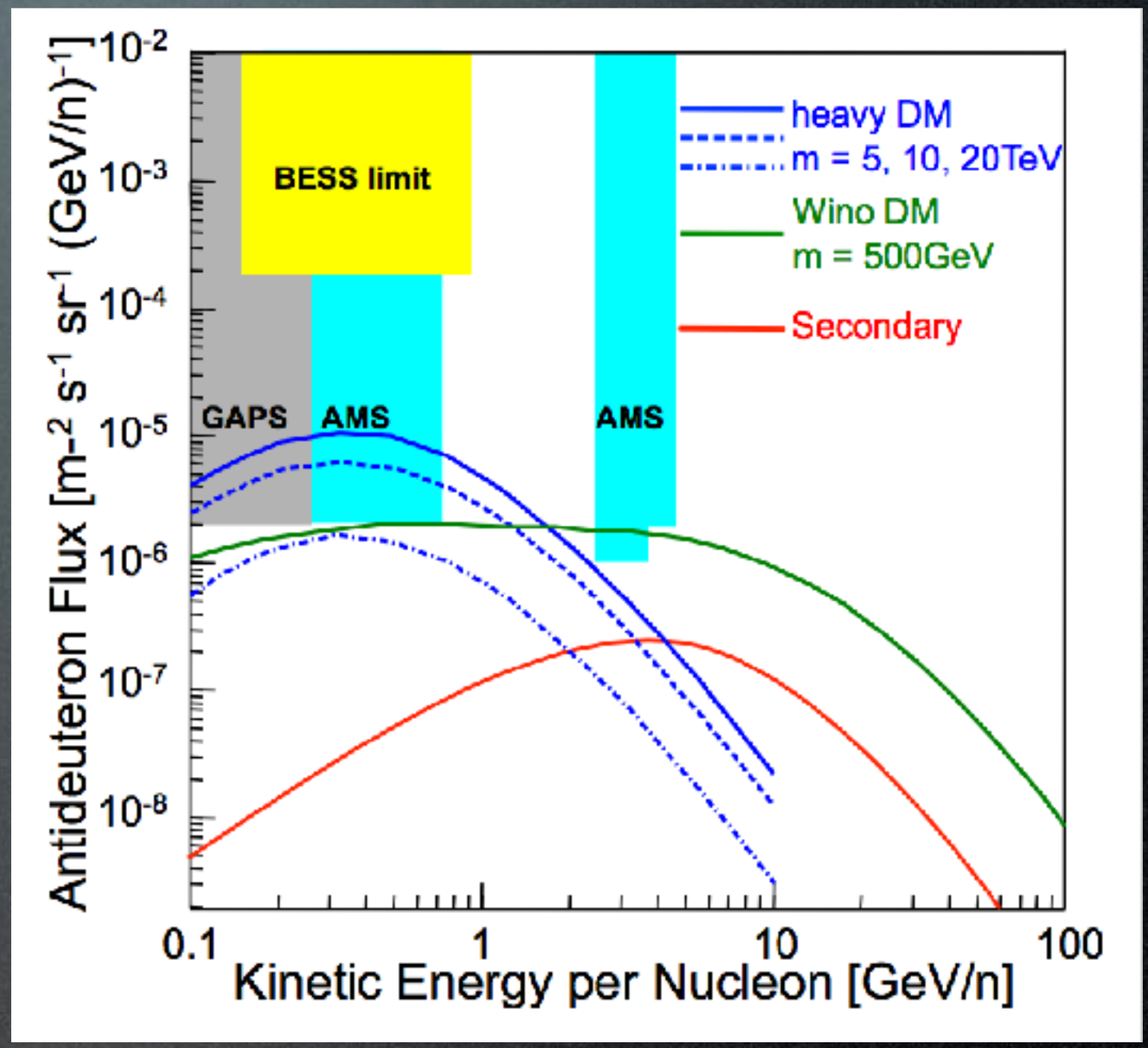
Indirect Detection

$\bar{d}$ 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

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**...
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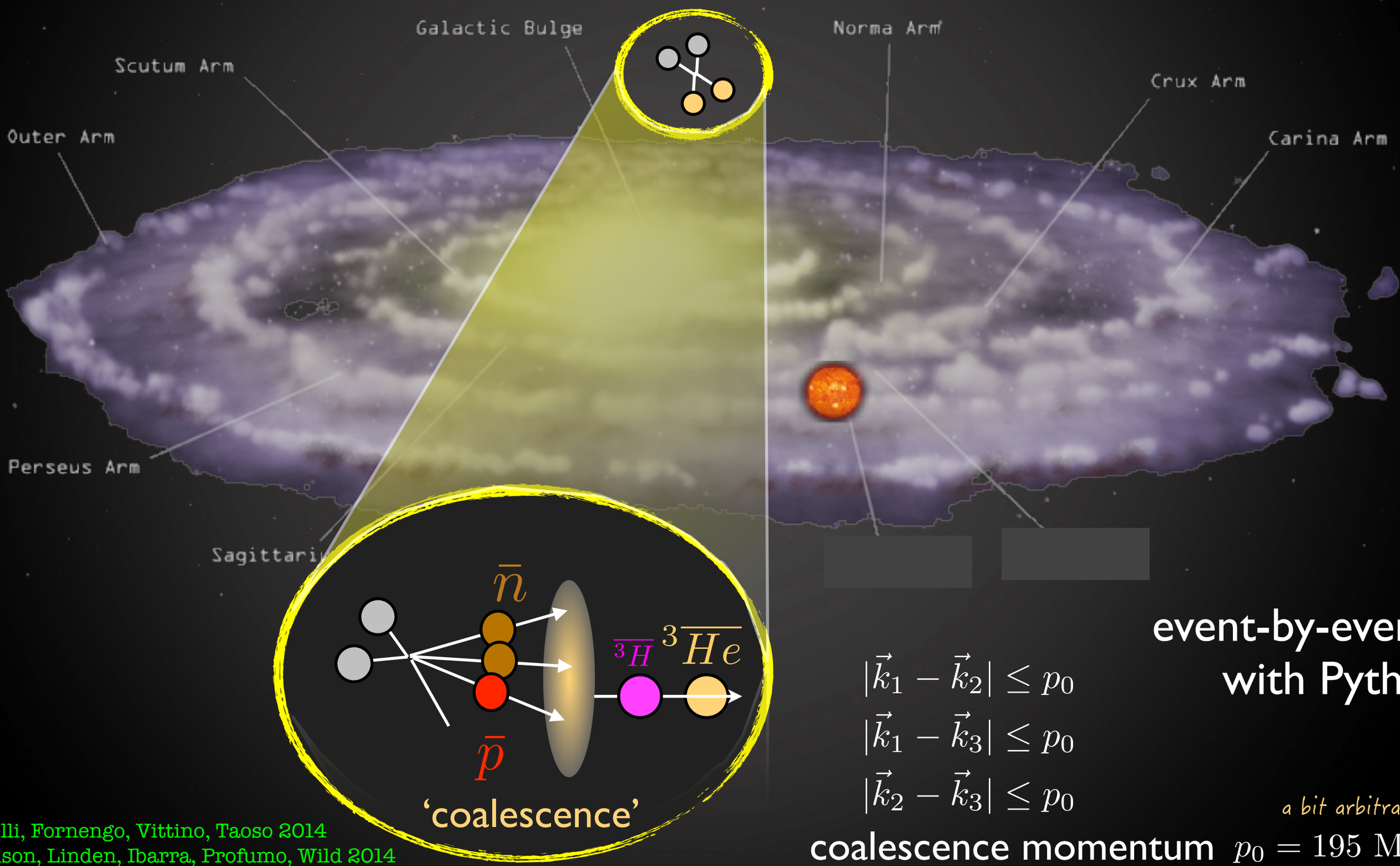
- $\bar{d}$ from annihil in galactic halo or center
  GAPS, AMS
- $\nu, \bar{\nu}$ from annihil in massive bodies
  SK, **Icecube**, Km3Net
- $\overline{He}$ from annihil in galactic halo or center
  AMS?

Indirect Detection

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



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

event-by-event
with Pythia

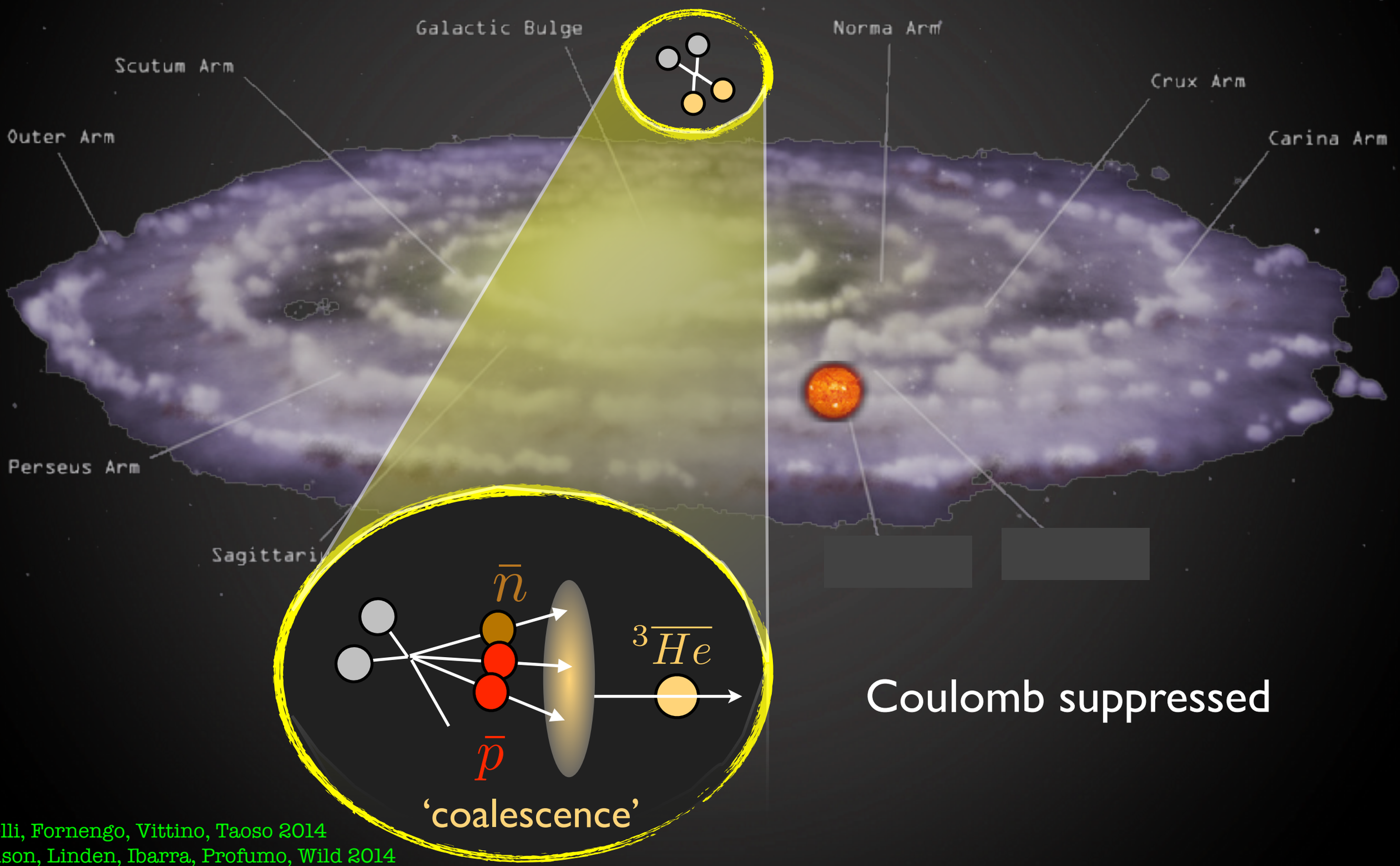
$$|\vec{k}_1 - \vec{k}_2| \leq p_0$$
$$|\vec{k}_1 - \vec{k}_3| \leq p_0$$
$$|\vec{k}_2 - \vec{k}_3| \leq p_0$$

a bit arbitrary…

coalescence momentum $p_0 = 195$ MeV

Indirect Detection

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

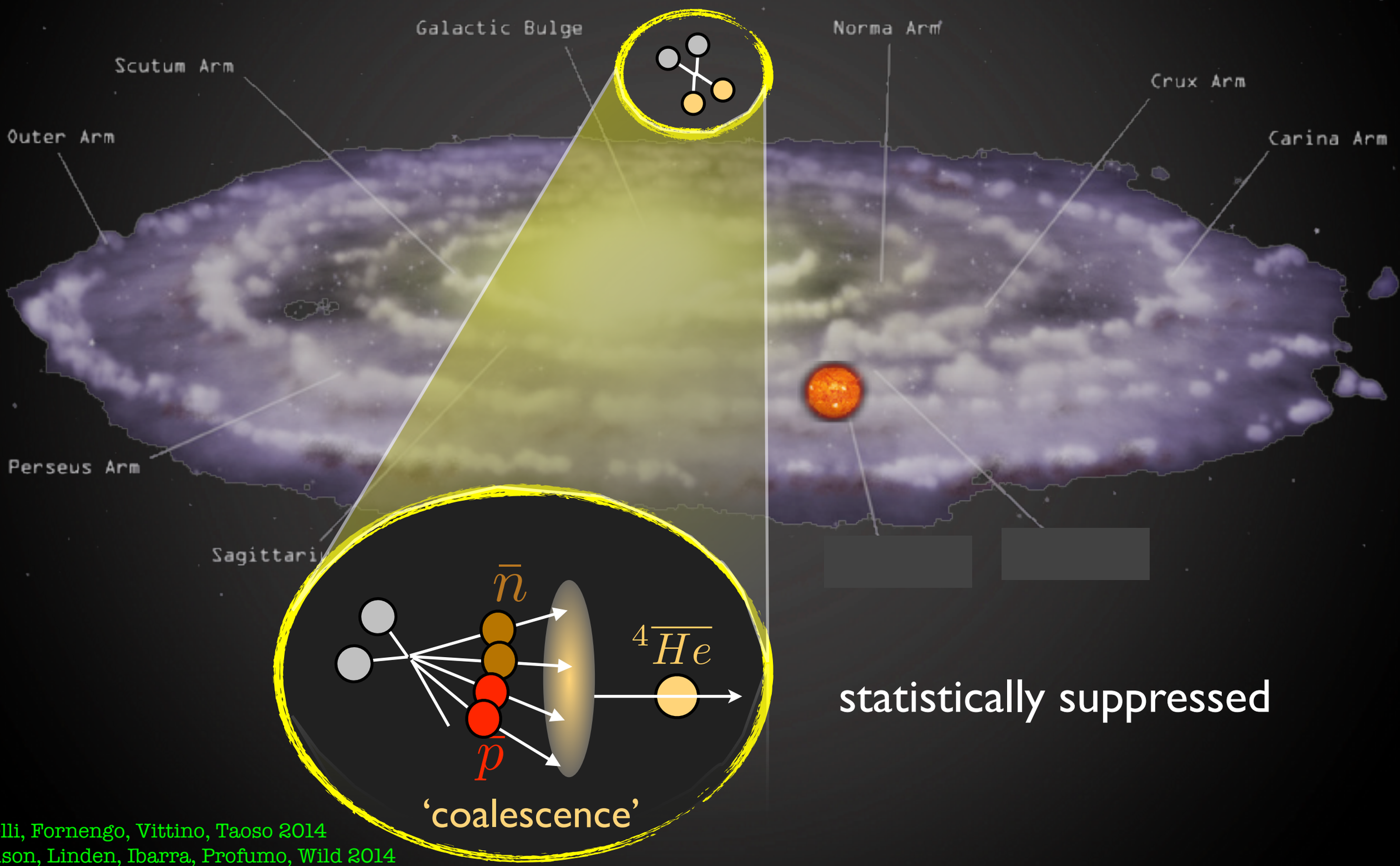


Coulomb suppressed

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

Indirect Detection

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

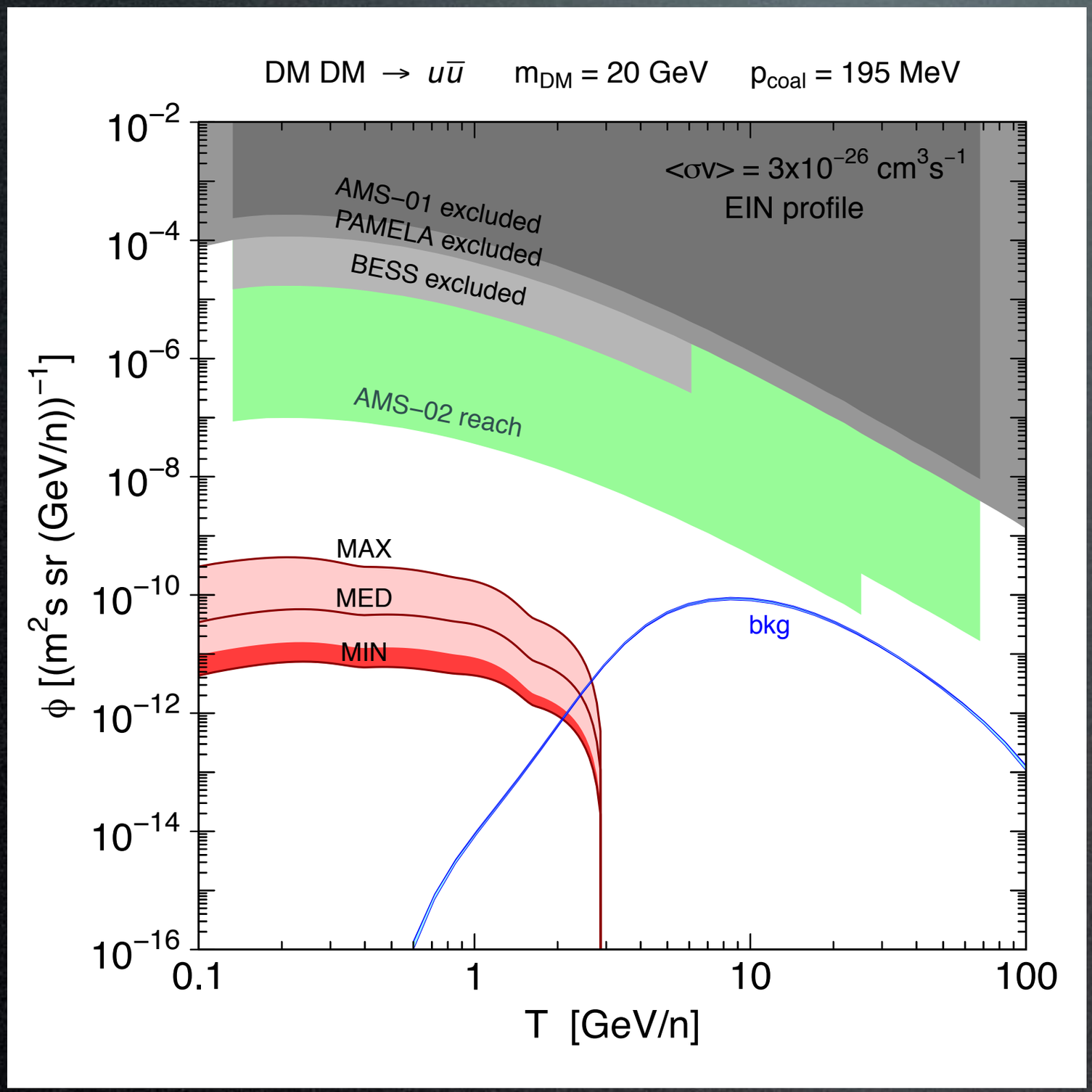


statistically suppressed

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

Indirect Detection

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

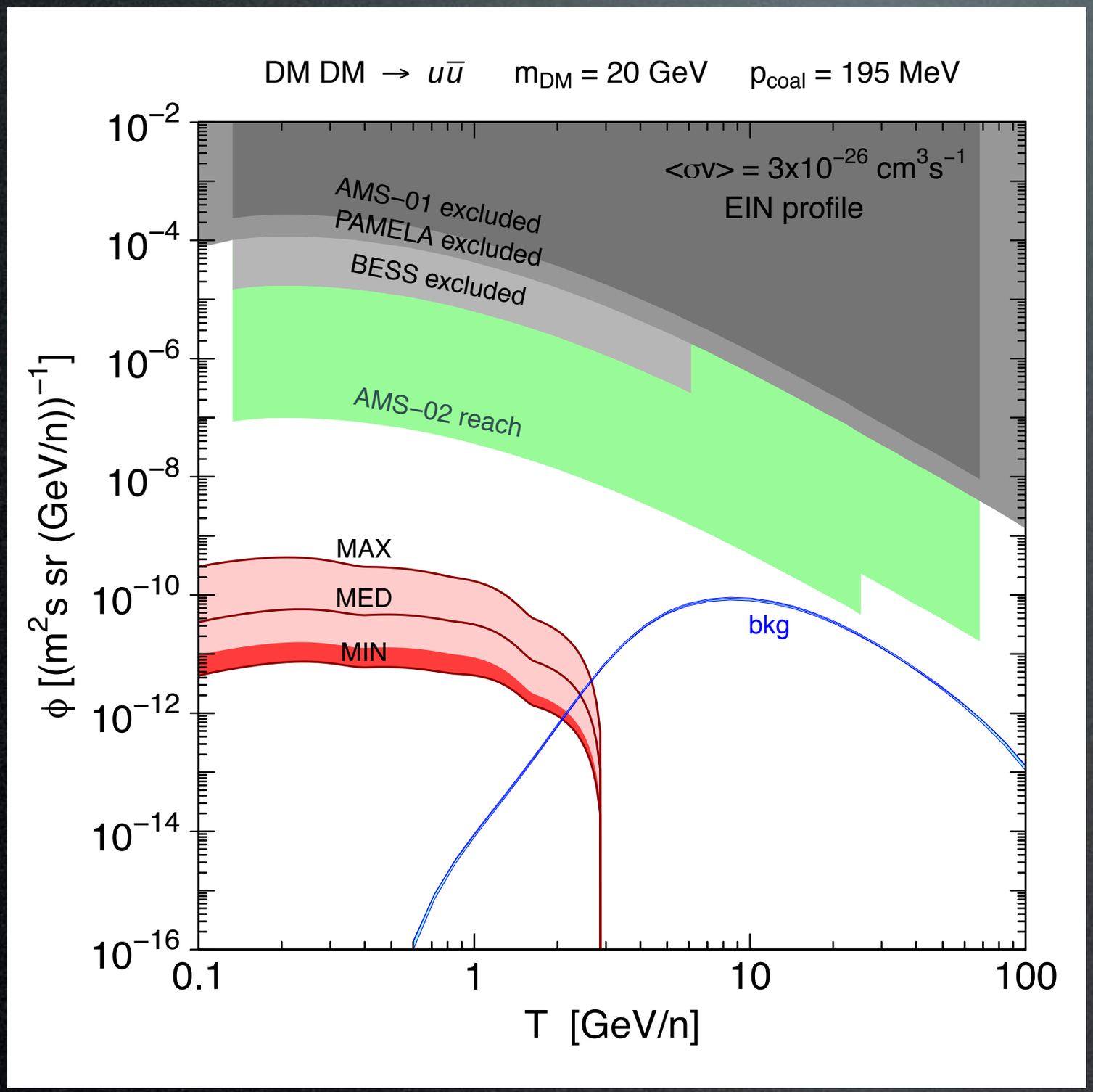


all

consistent with antiproton bounds

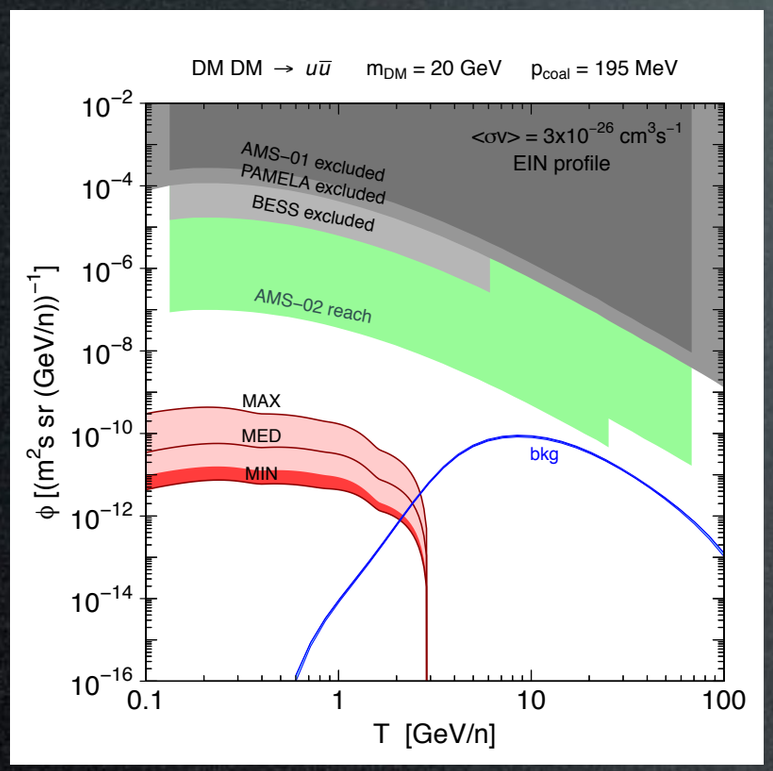
Indirect Detection

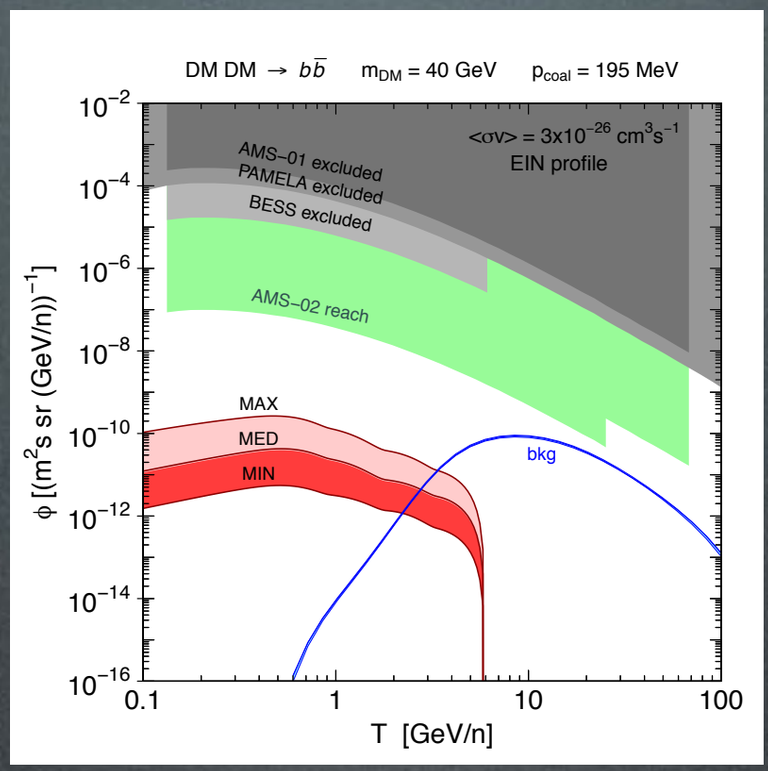
$\overline{He}$ from DM annihilations in halo

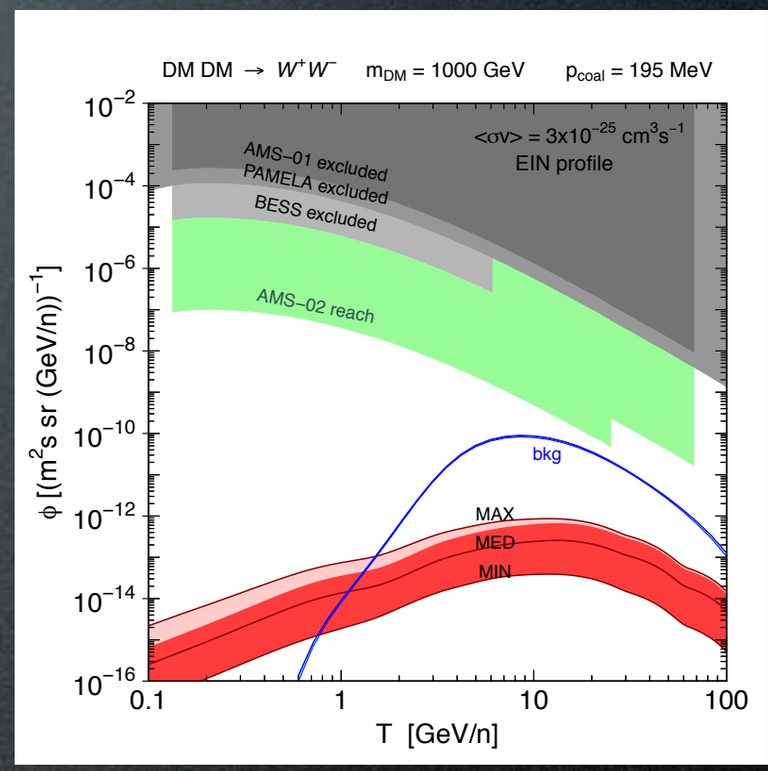


Indirect Detection

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

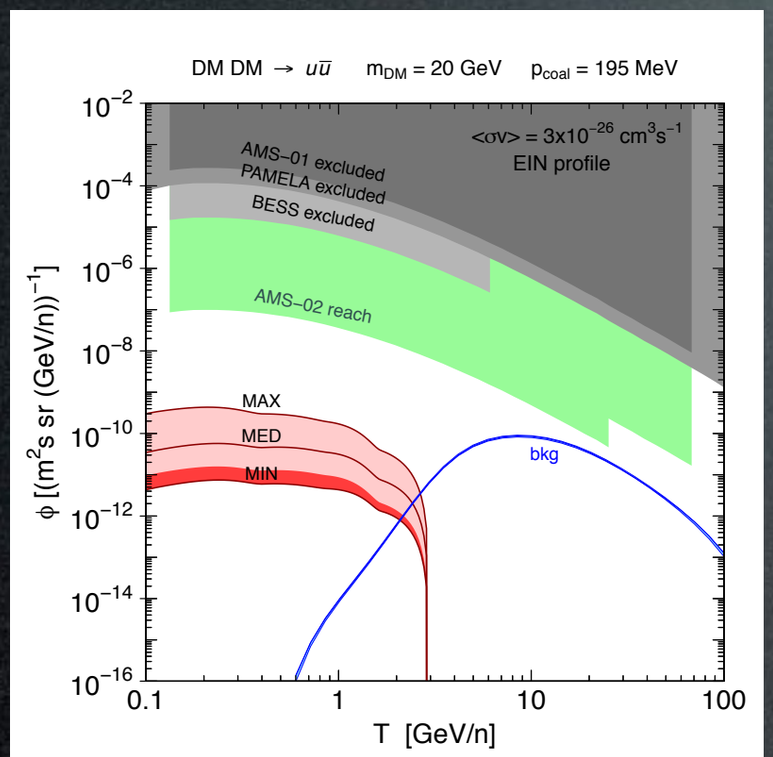


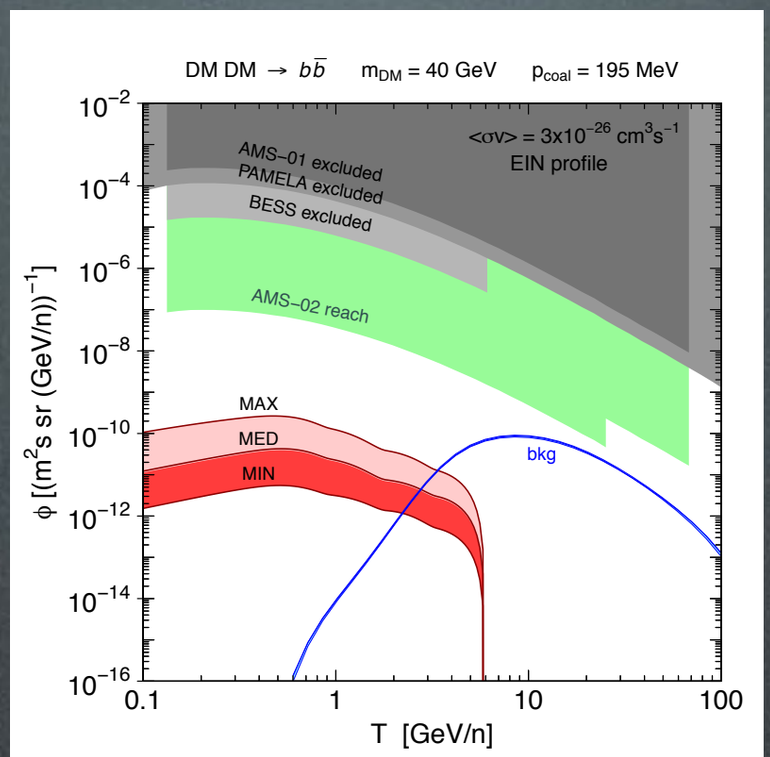


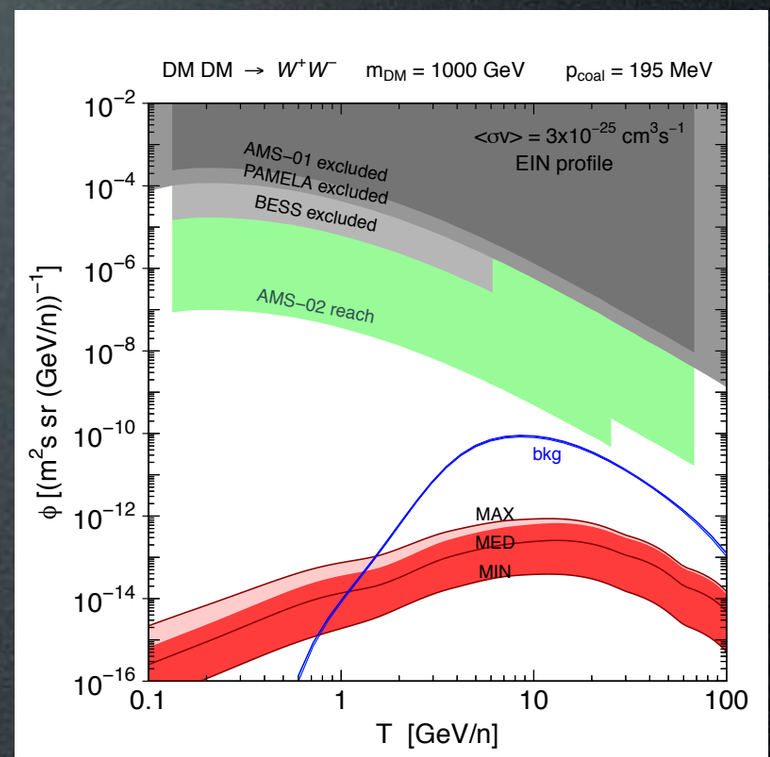


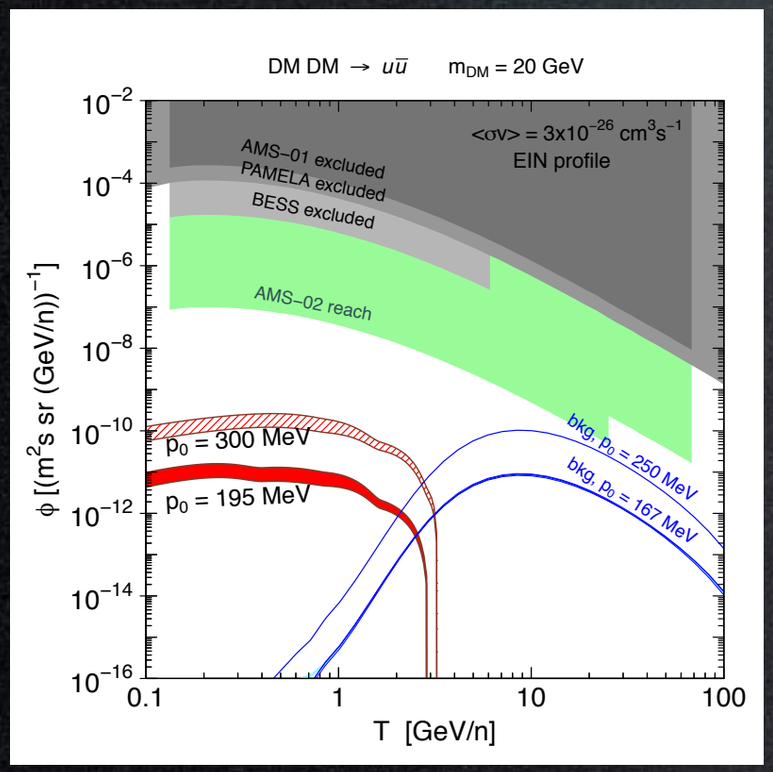
Indirect Detection

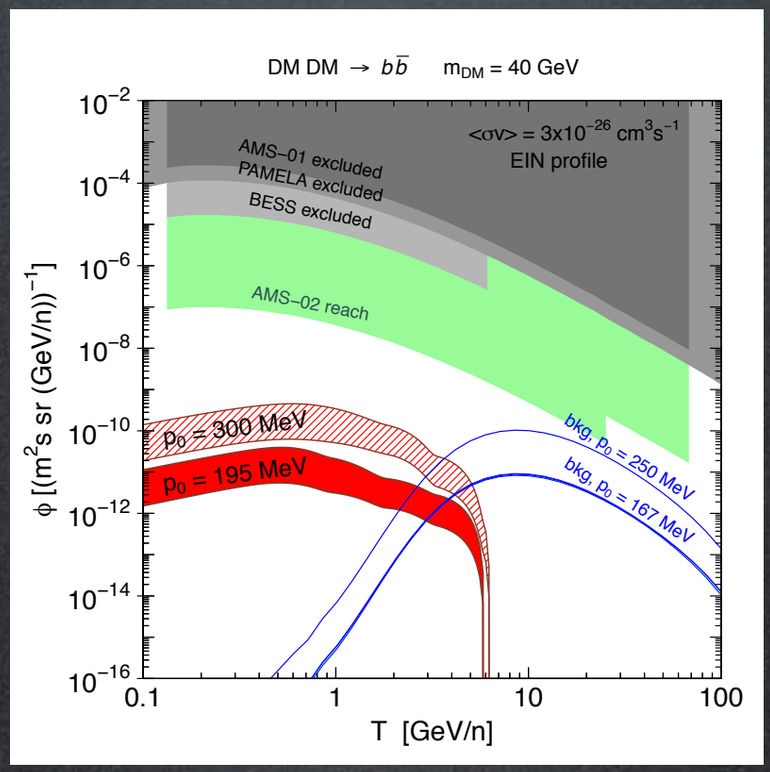
$\overline{He}$ from DM annihilations in halo

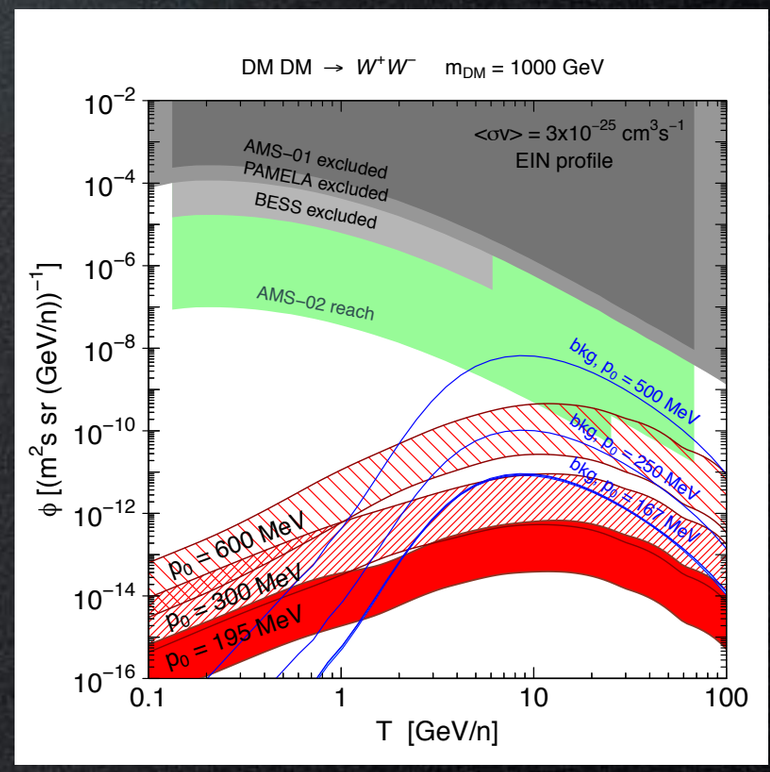






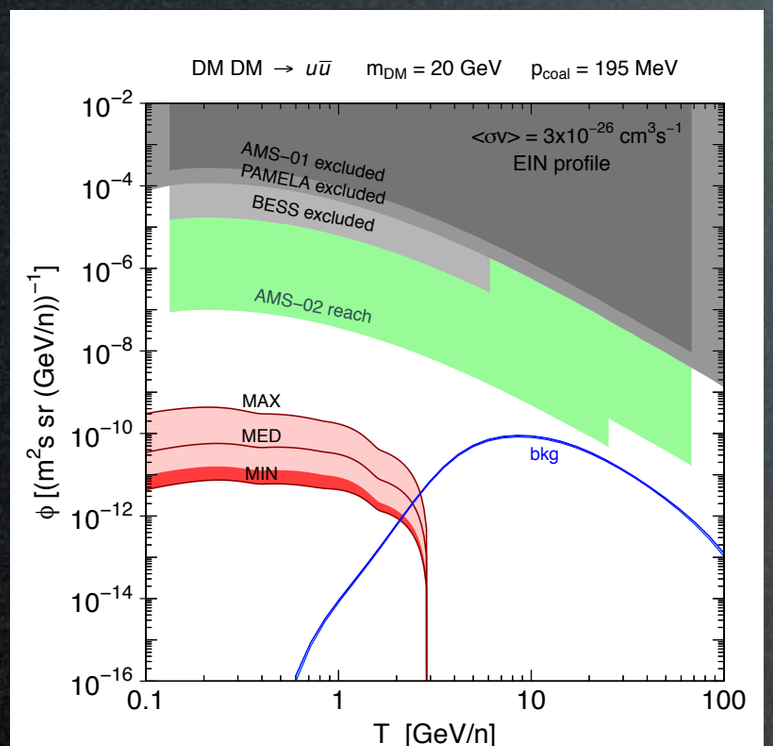


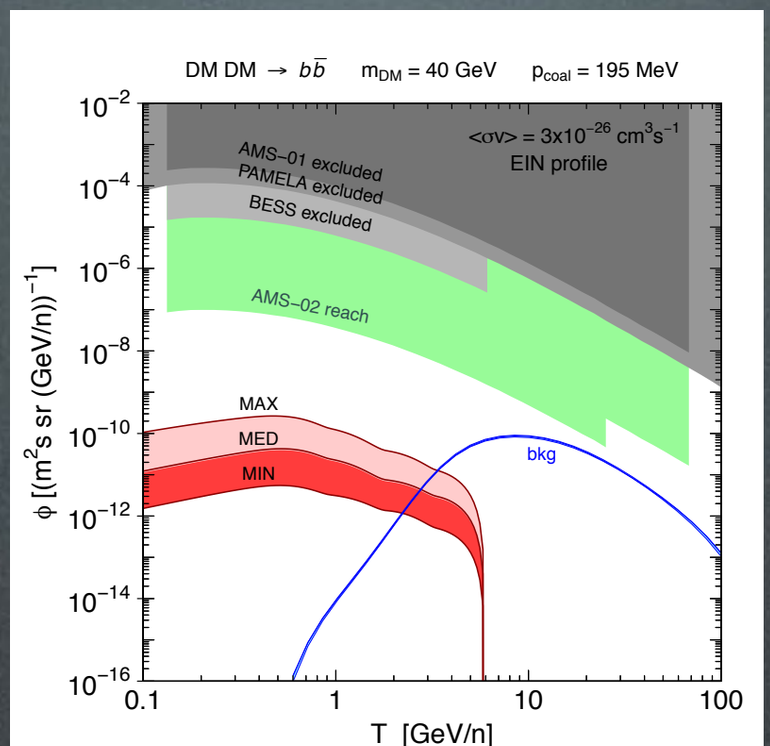


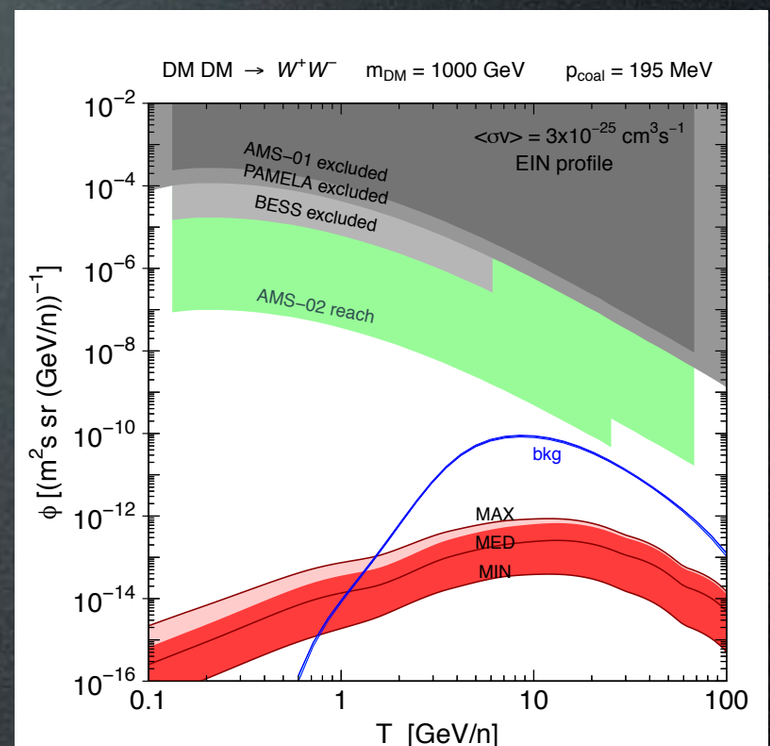


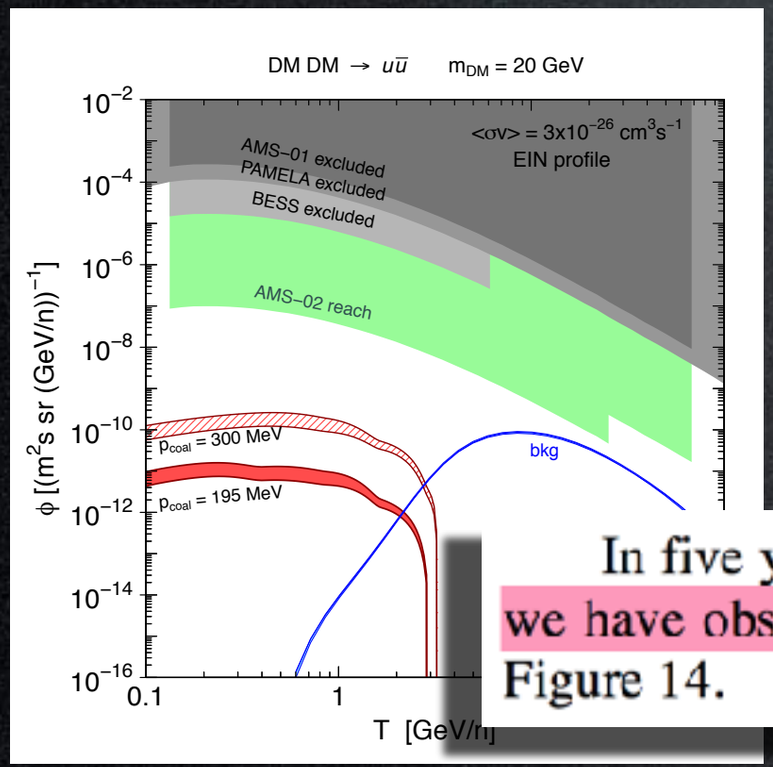
Indirect Detection

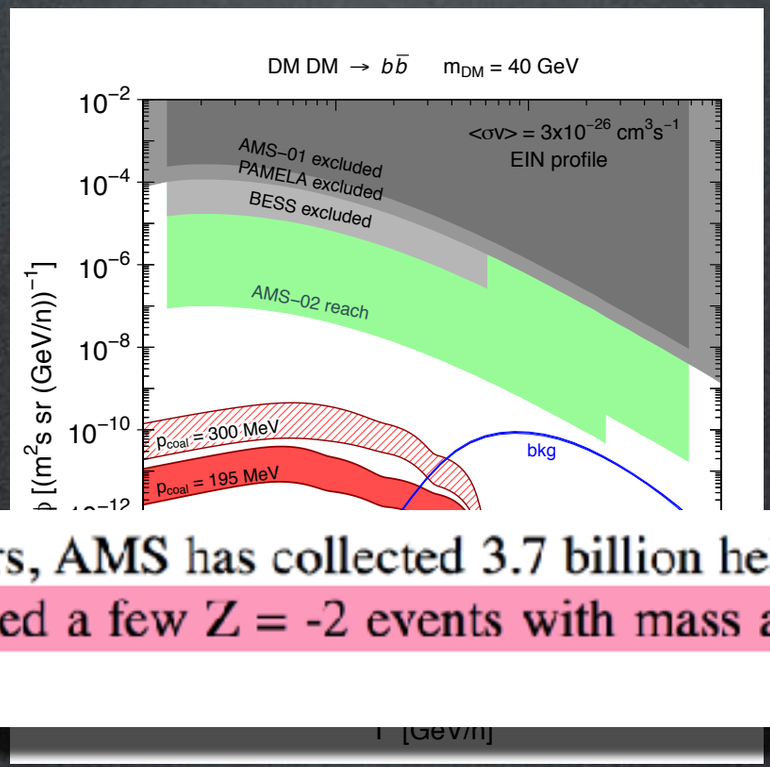
$\overline{He}$ from DM annihilations in halo

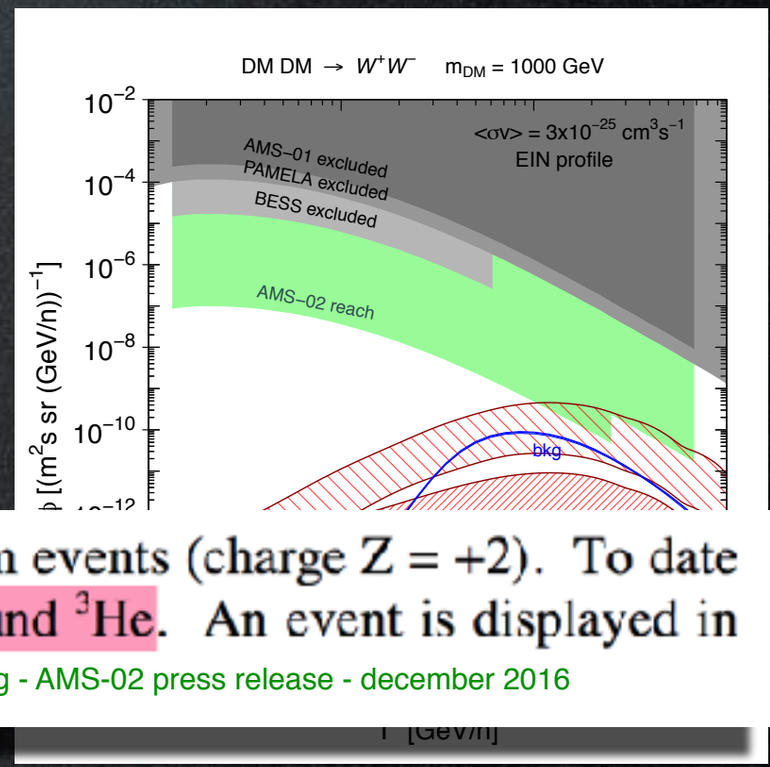










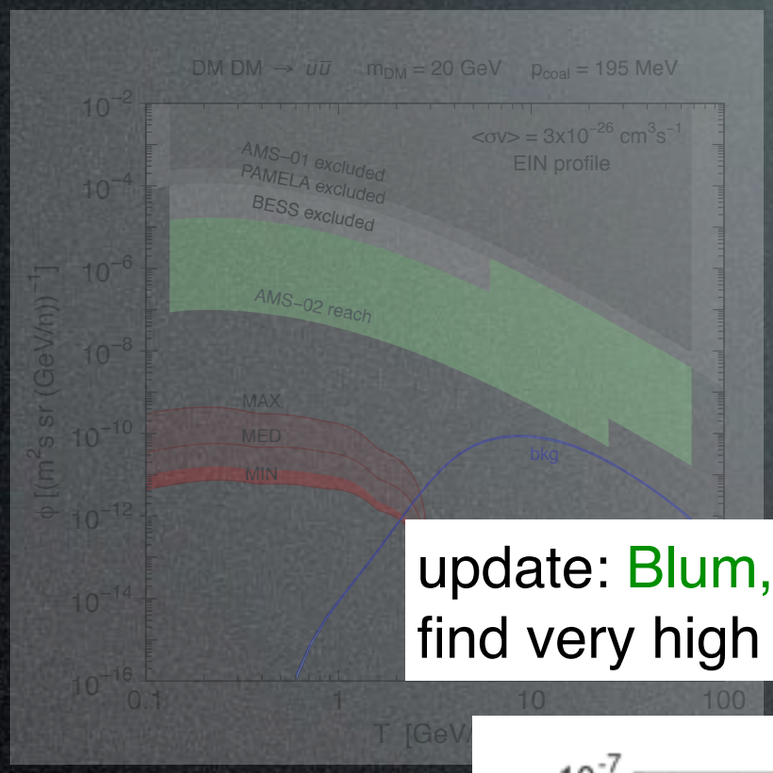


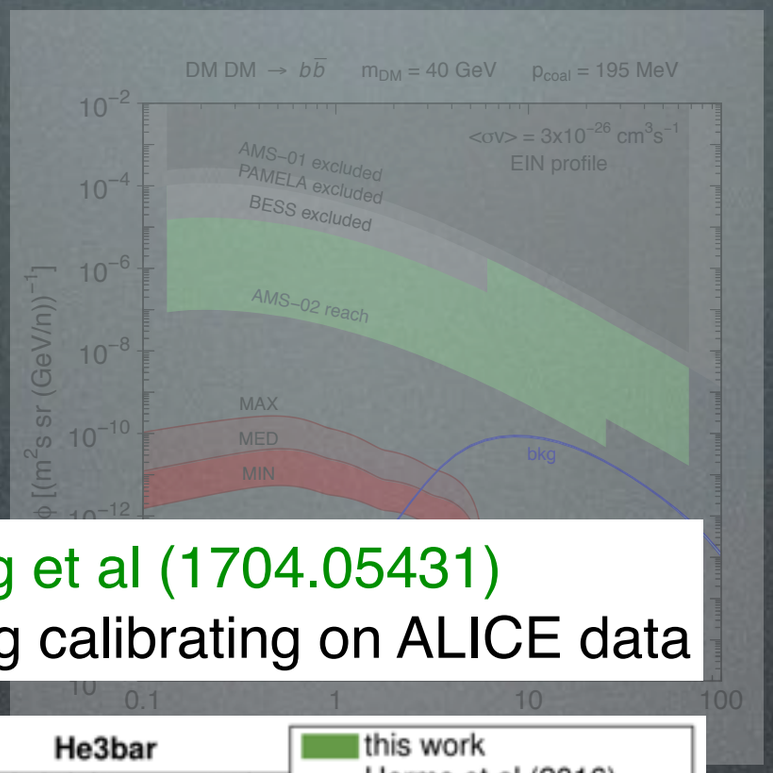
In five years, AMS has collected 3.7 billion helium events (charge Z = +2). To date we have observed a few Z = -2 events with mass around ^{3}He. An event is displayed in Figure 14.

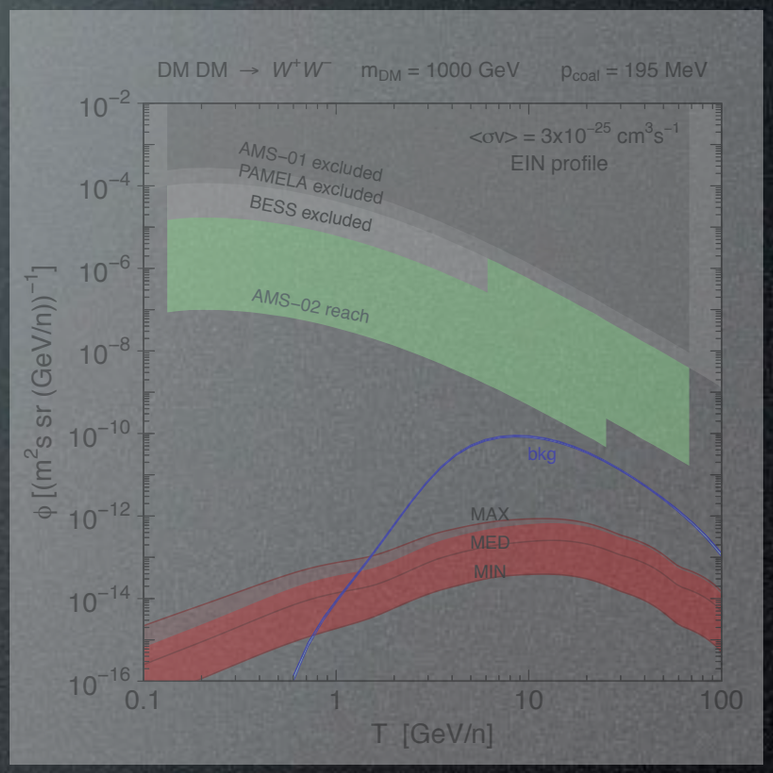
S.Ting - AMS-02 press release - december 2016

Indirect Detection

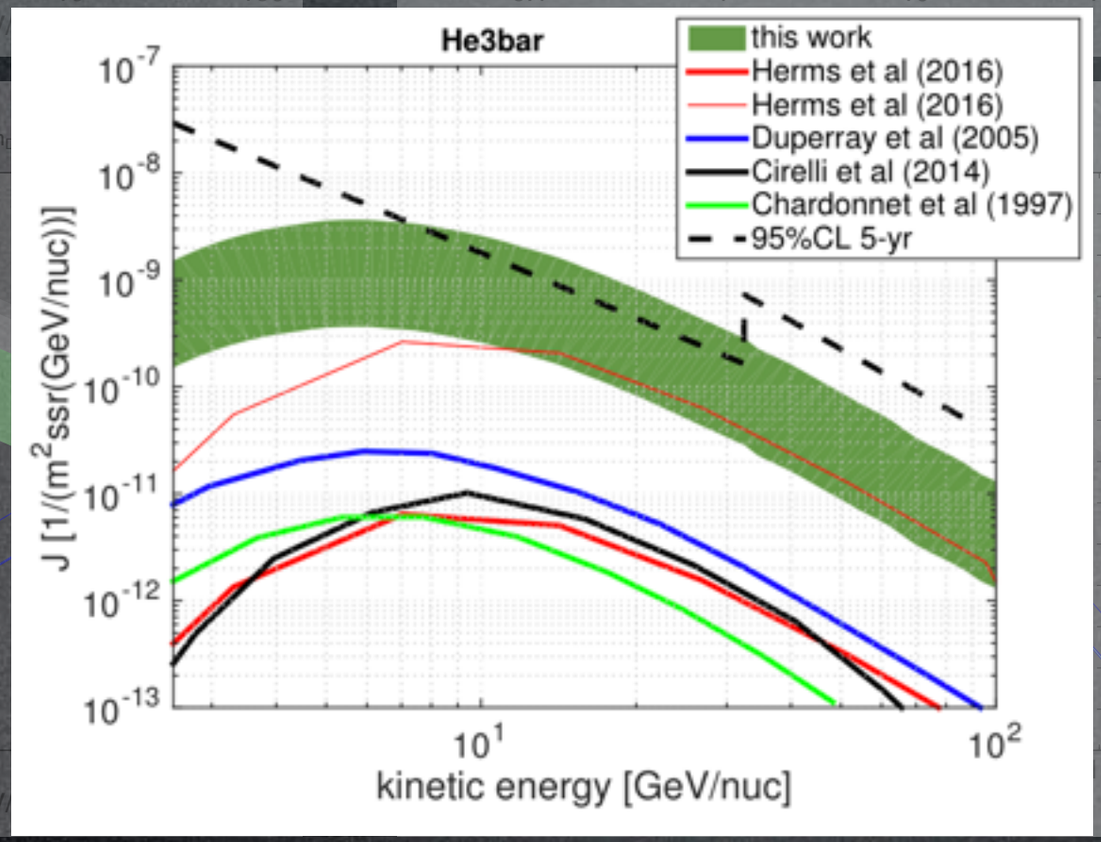
$\overline{He}$ from DM annihilations in halo

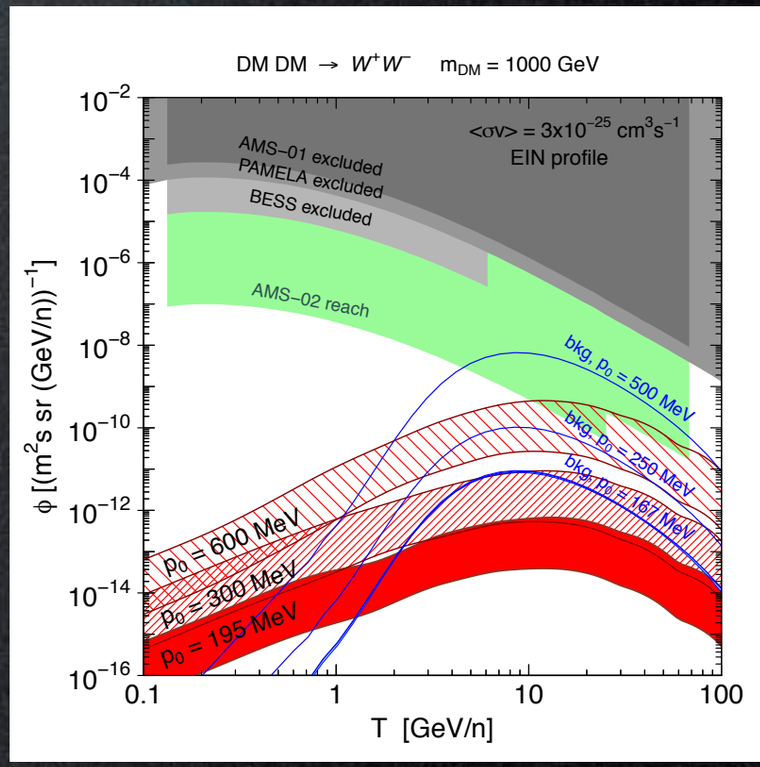






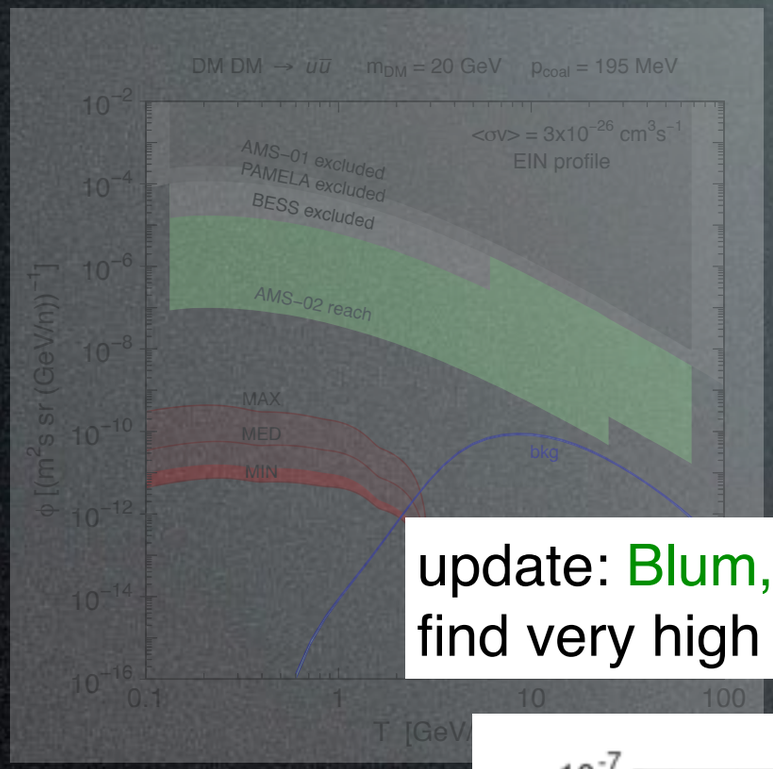
update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data

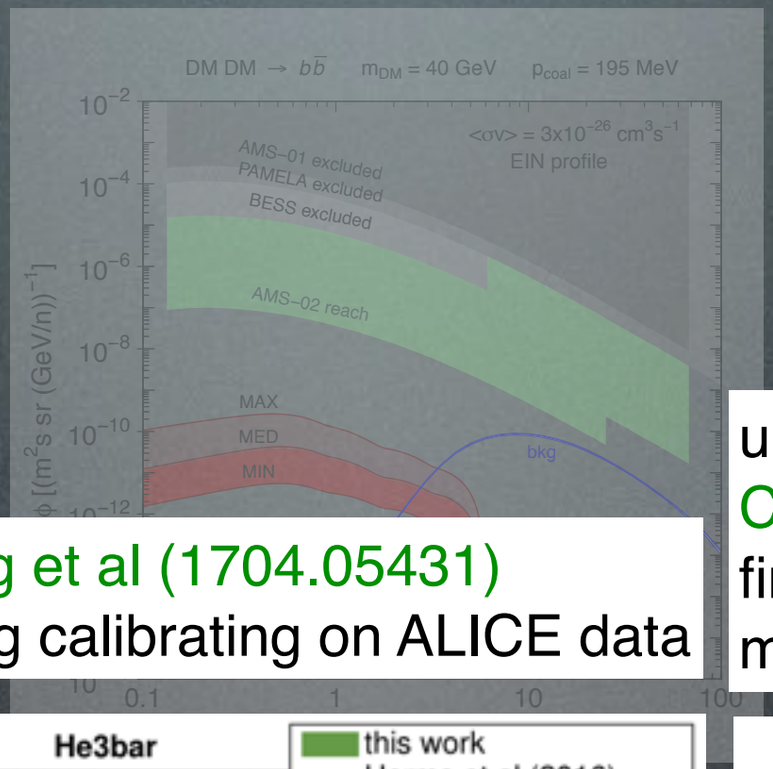


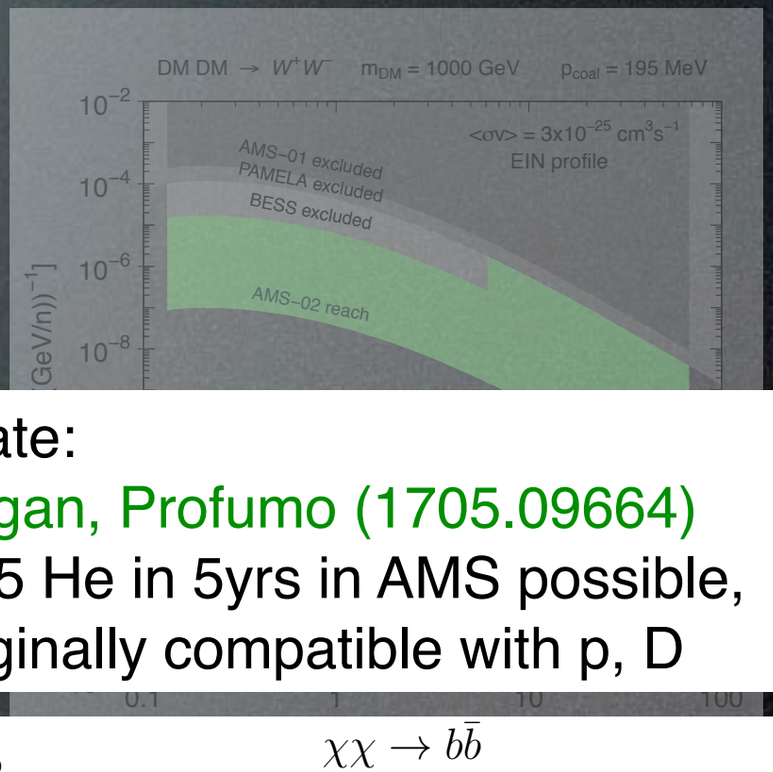


Indirect Detection

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







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