

19 June 2018
PACTS Tallinn

Dark Matter Indirect Searches

Marco Cirelli
(CNRS LPTHE Jussieu)



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DM detection

direct detection

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

production at colliders

LHC

γ from annihil in galactic center or halo
and from secondary emission

Fermi, ICT, radio telescopes...

indirect

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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Antiprotons

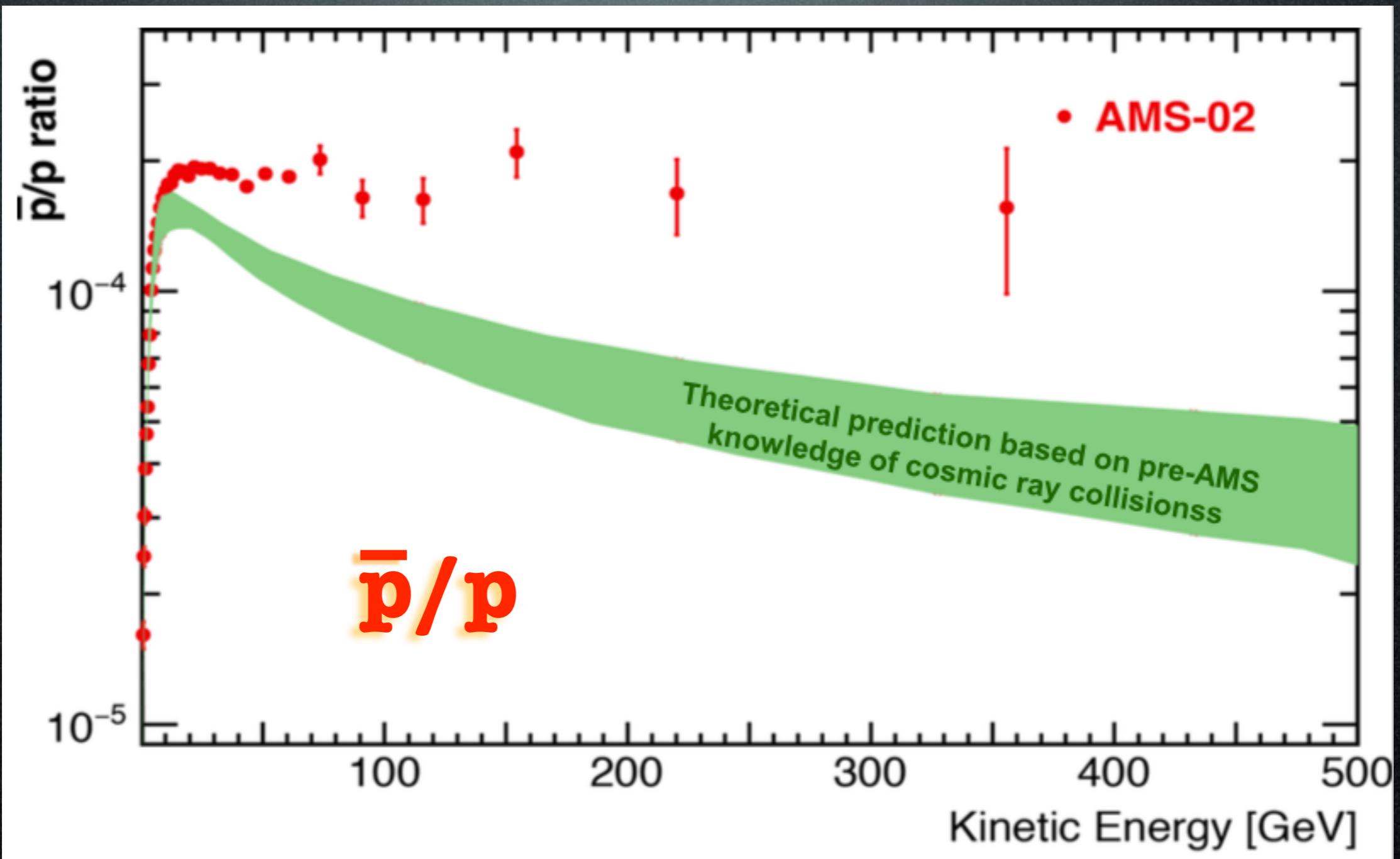
direct detection

production at colliders

- indirect
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Fermi, ICT, radio telescopes...
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SK, Icecube, Km3Net

Data: antiprotons

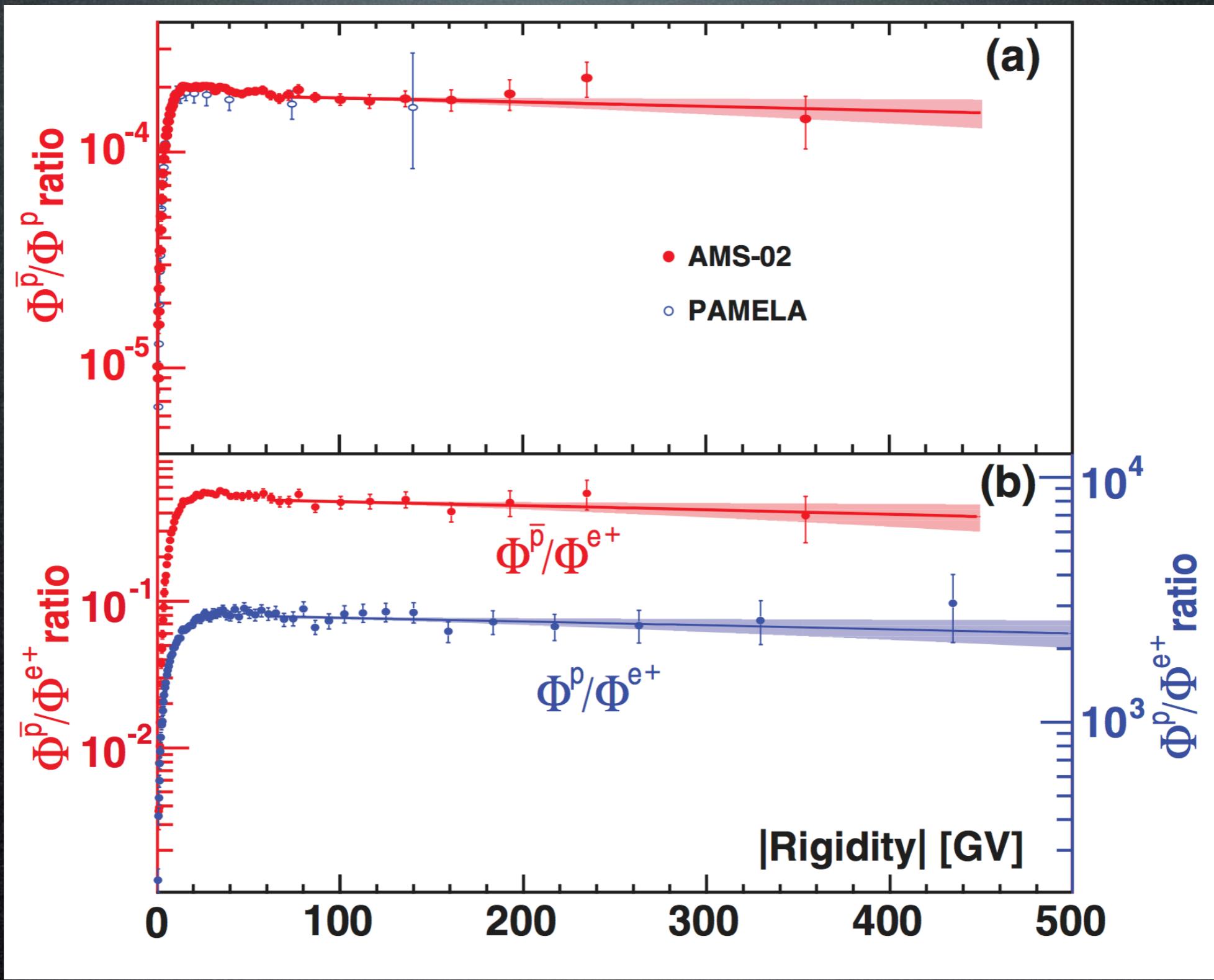
AMS-02



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

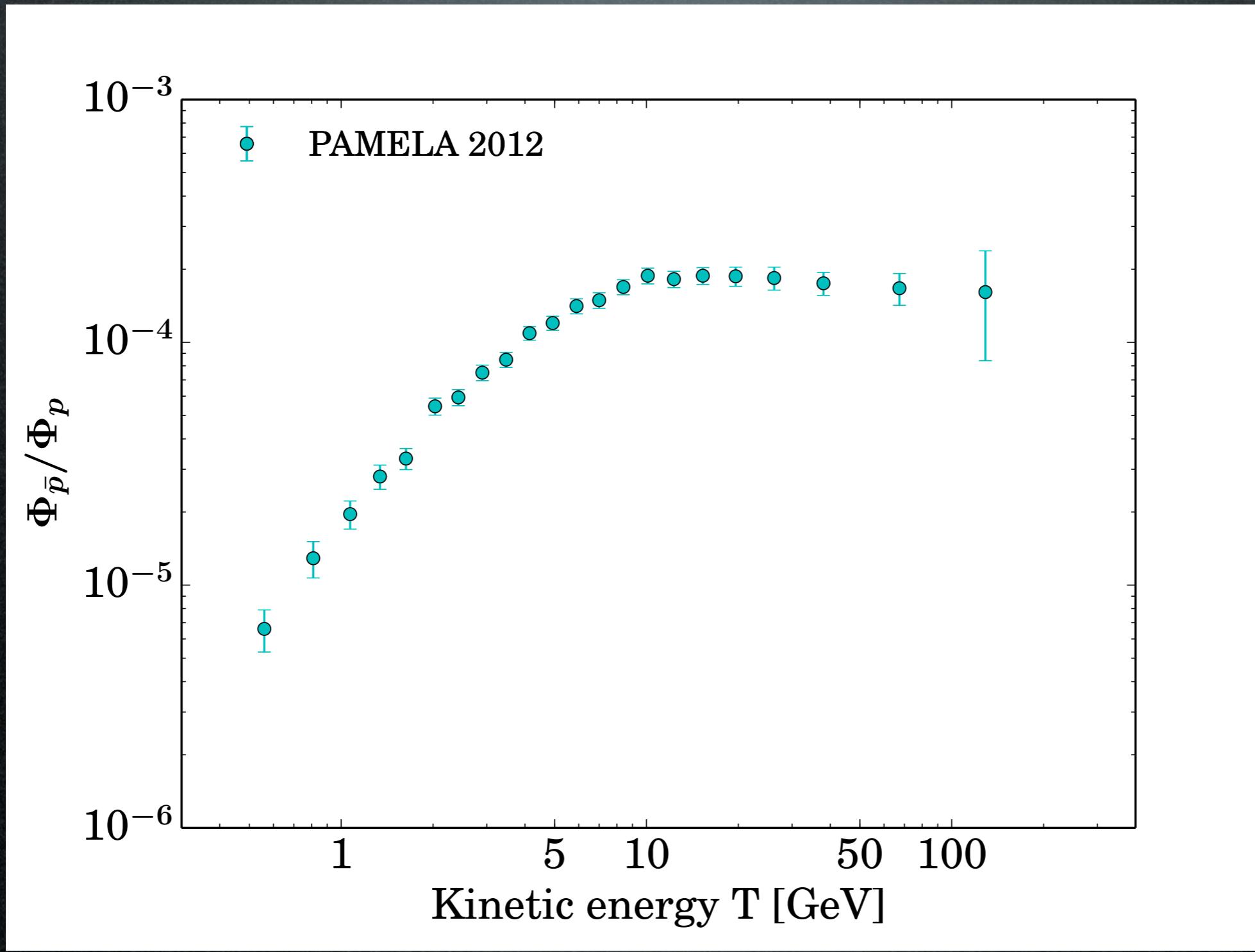
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AMS-02



Antiprotons

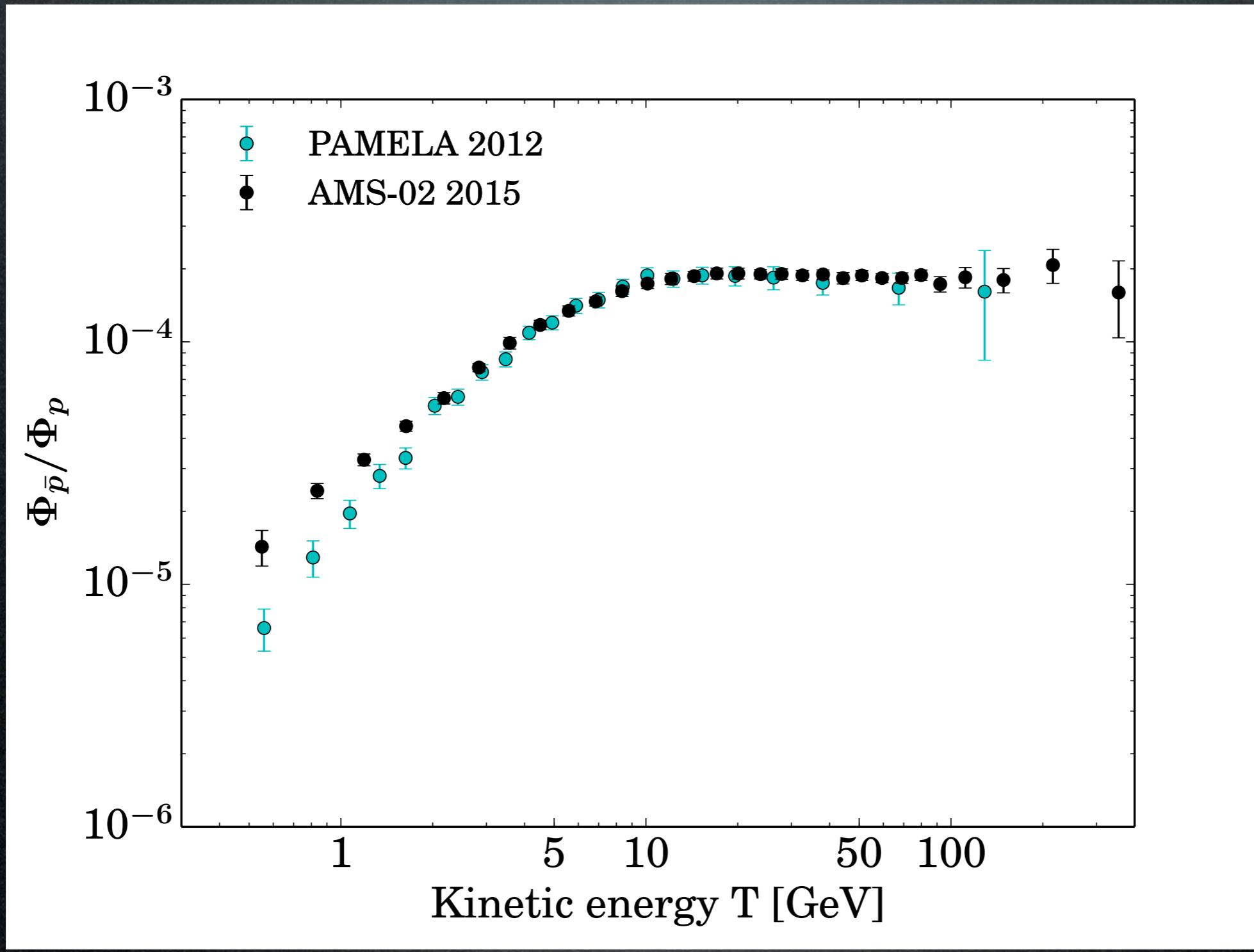
Antiproton data vis-à-vis the secondaries:



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

Antiprotons

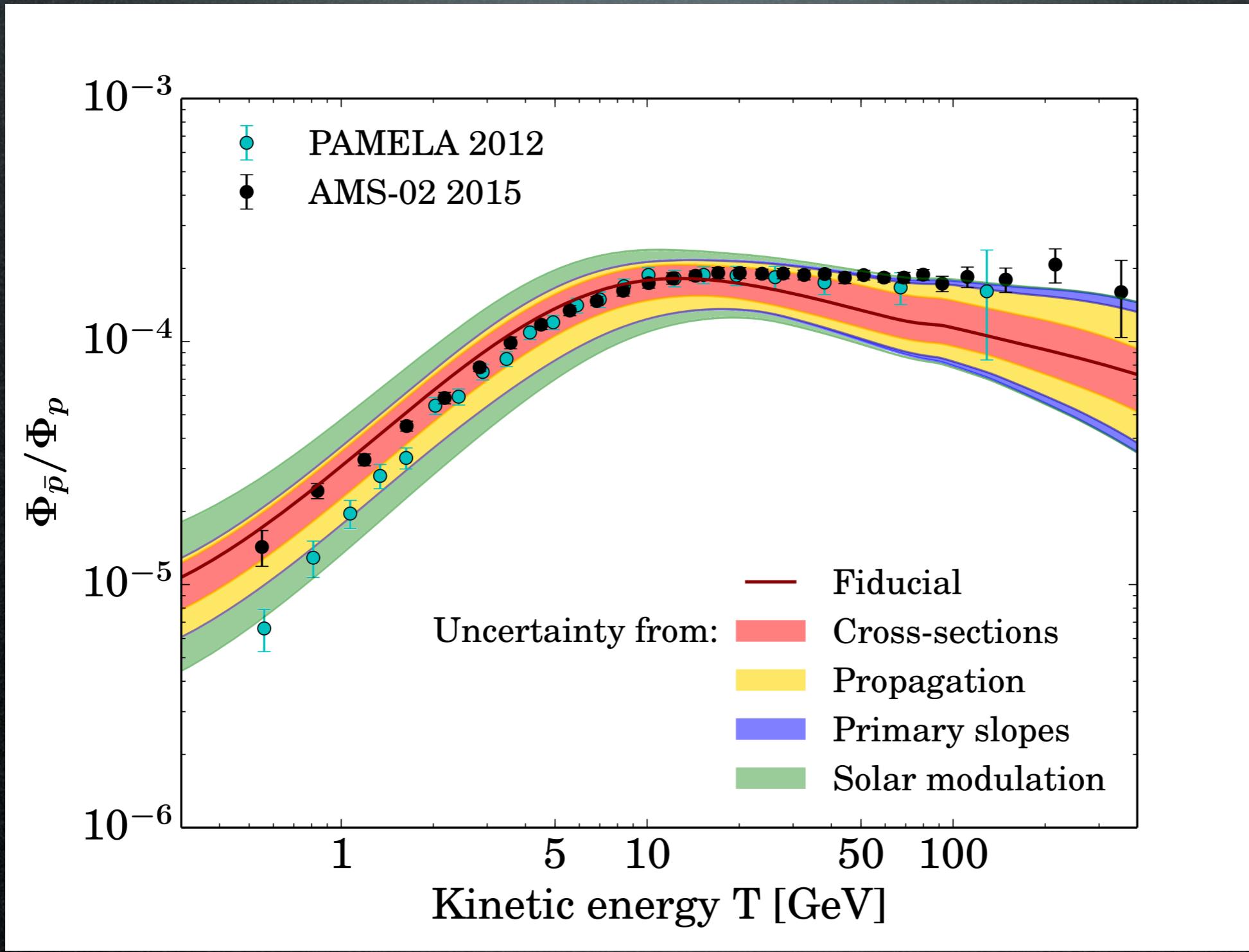
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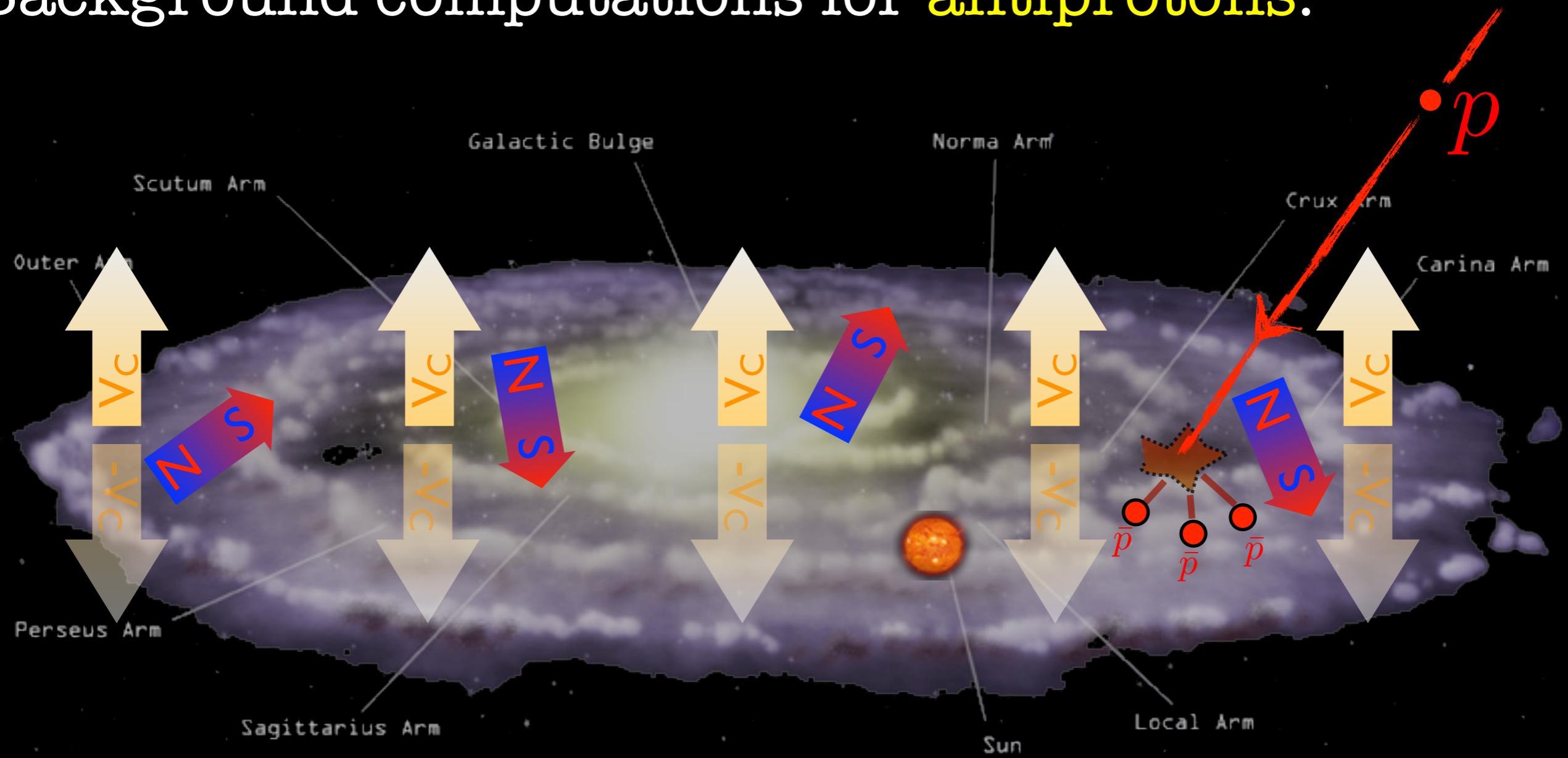
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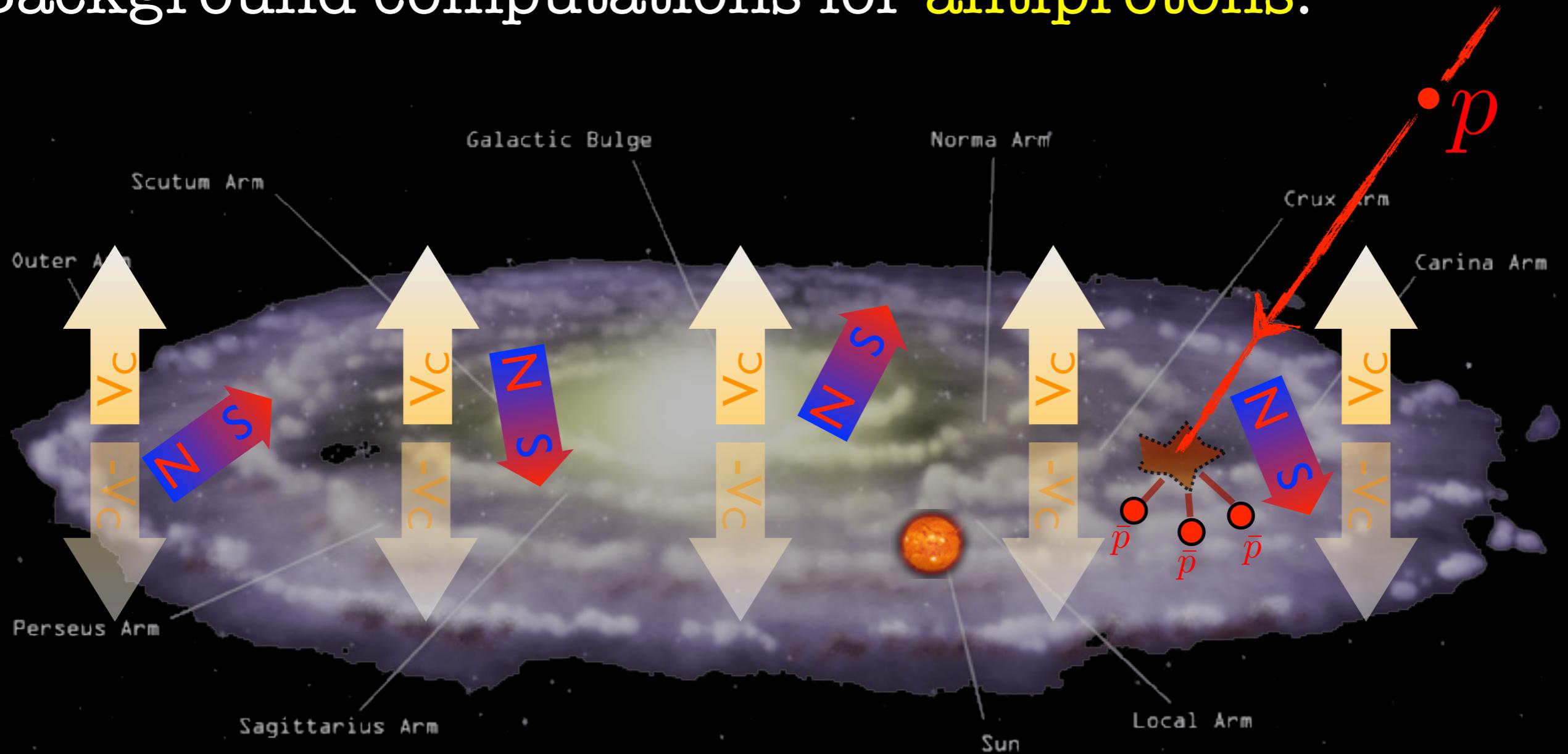
Indirect Detection

Background computations for antiprotons:



Indirect Detection

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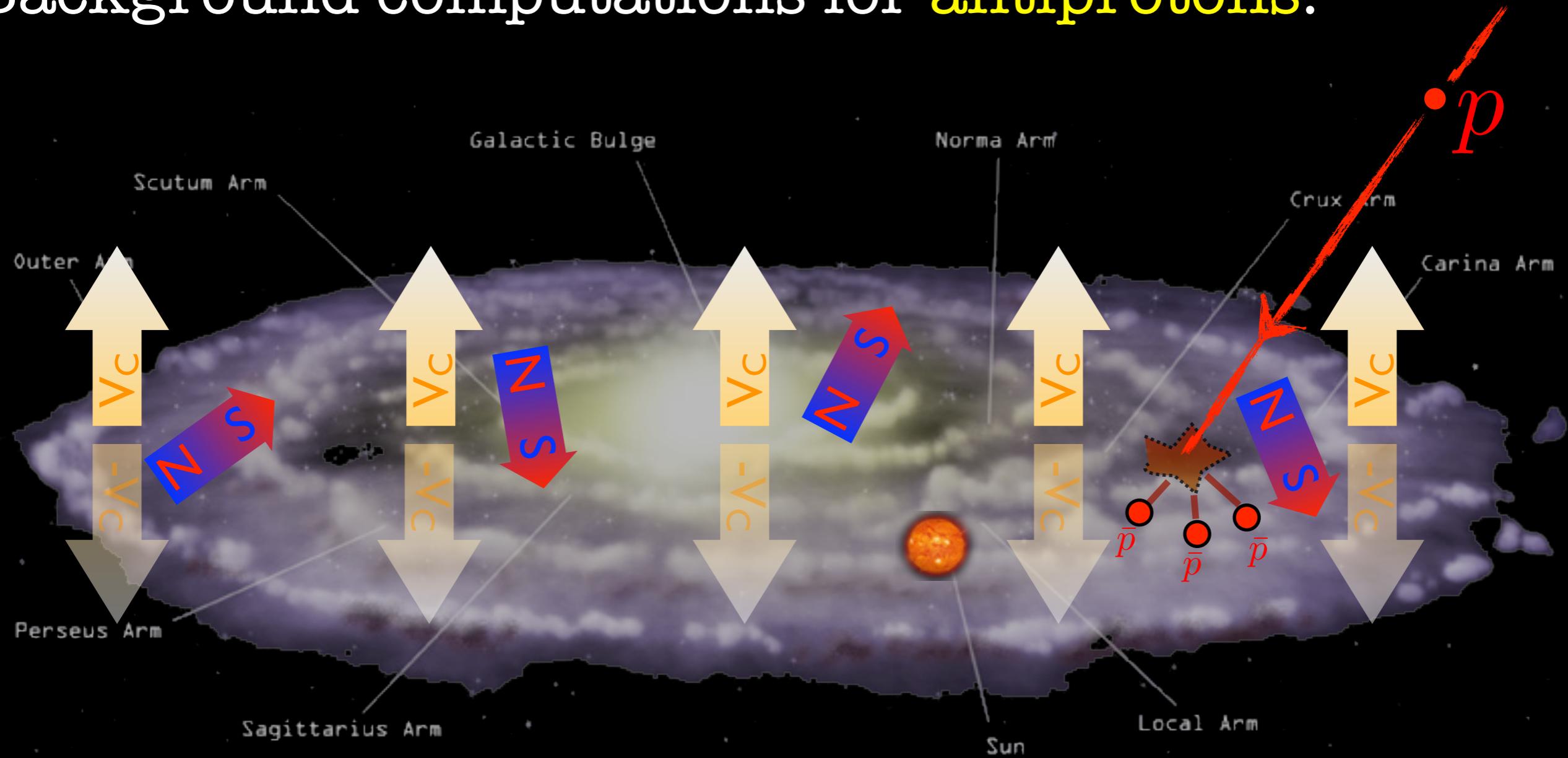


Main ingredients:

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

Indirect Detection

Background computations for antiprotons:

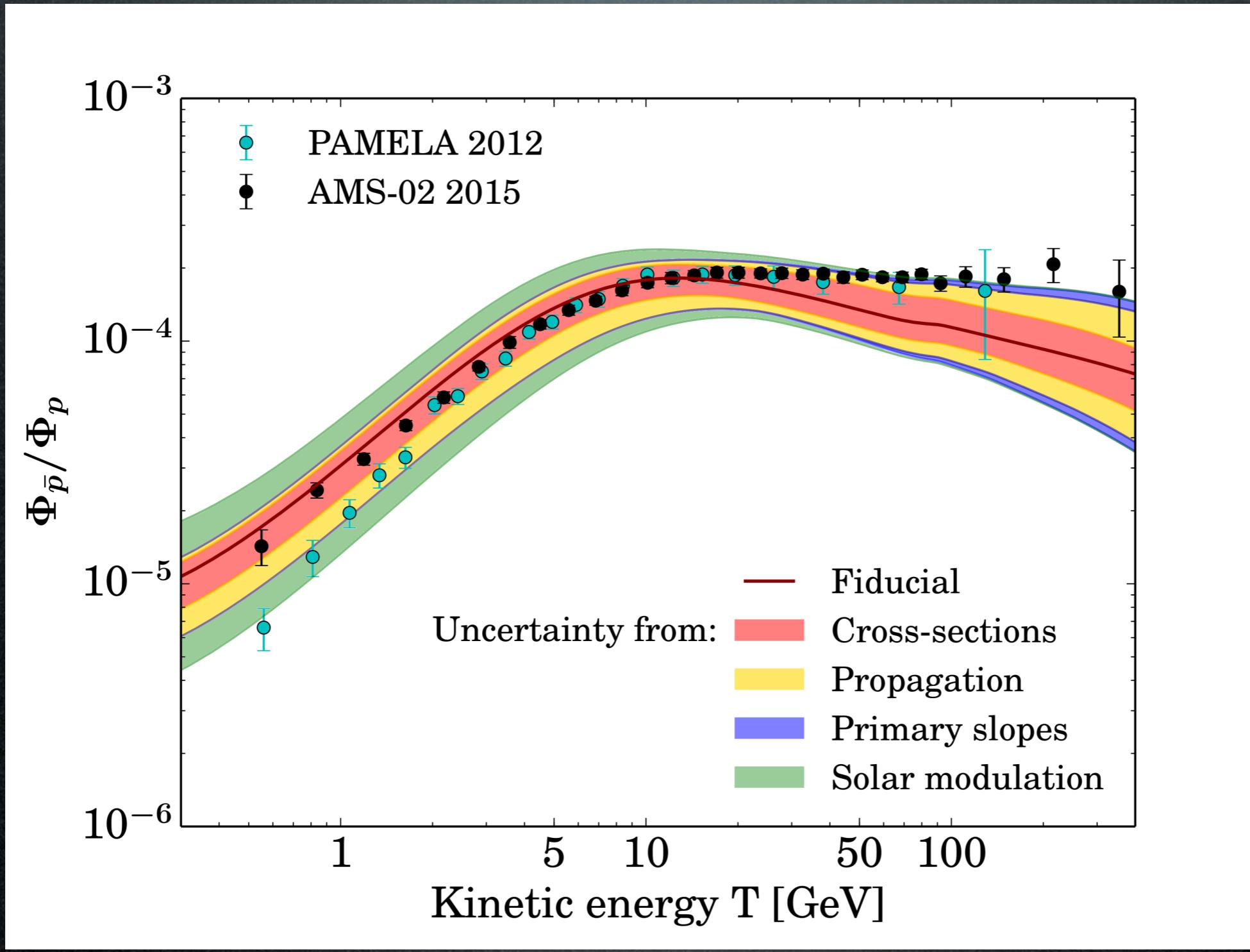


Main ingredients:

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

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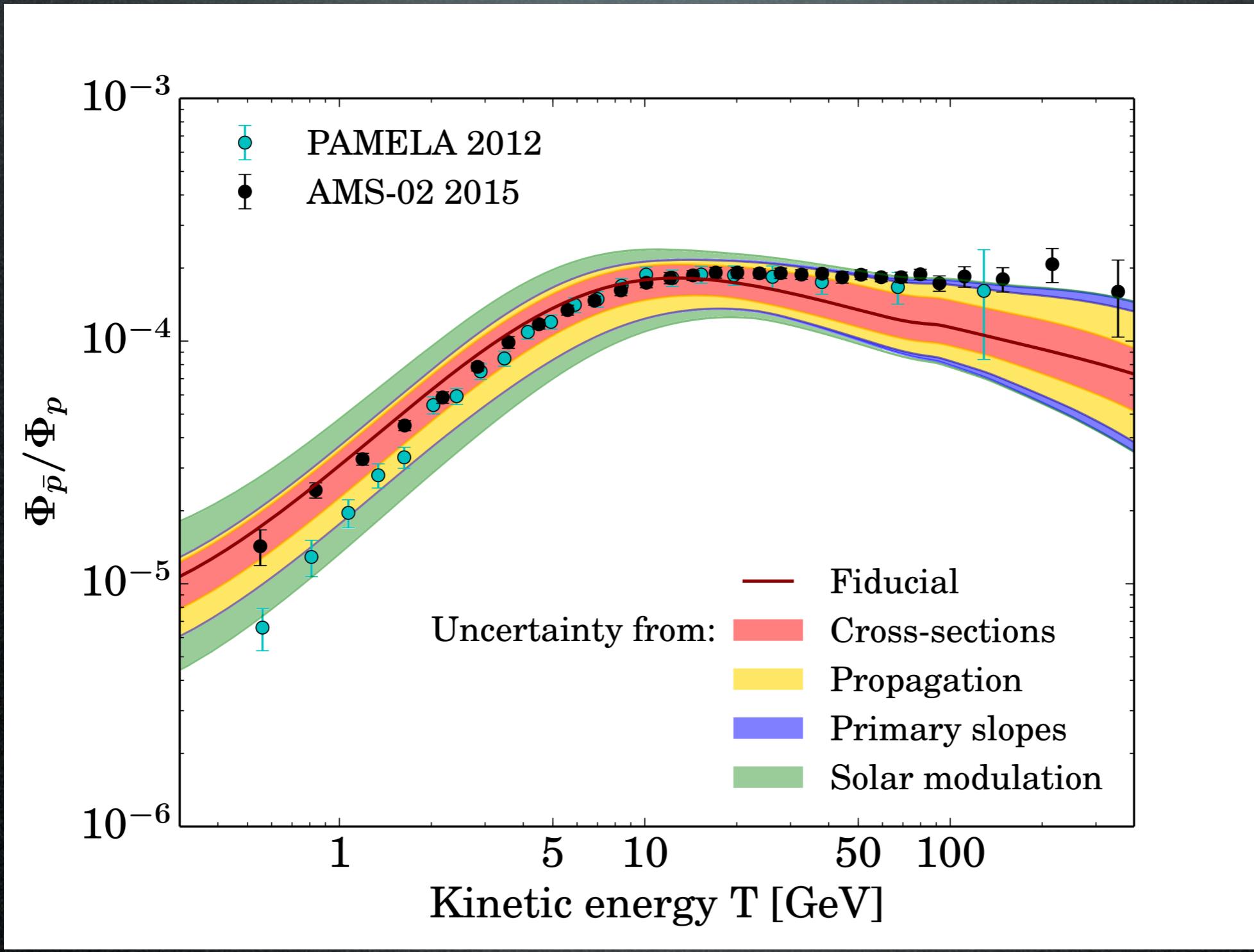


No
evident
excess

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

Antiprotons

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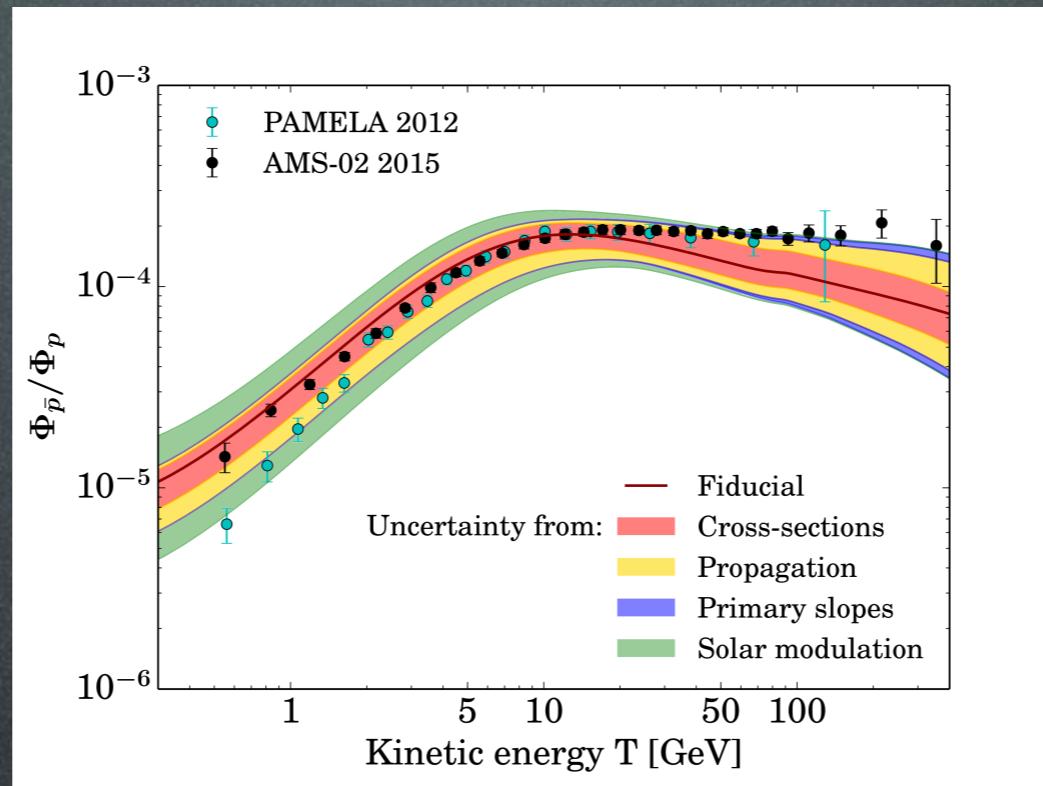
No
evident
excess

Some
preference
for flatness

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

Antiprotons

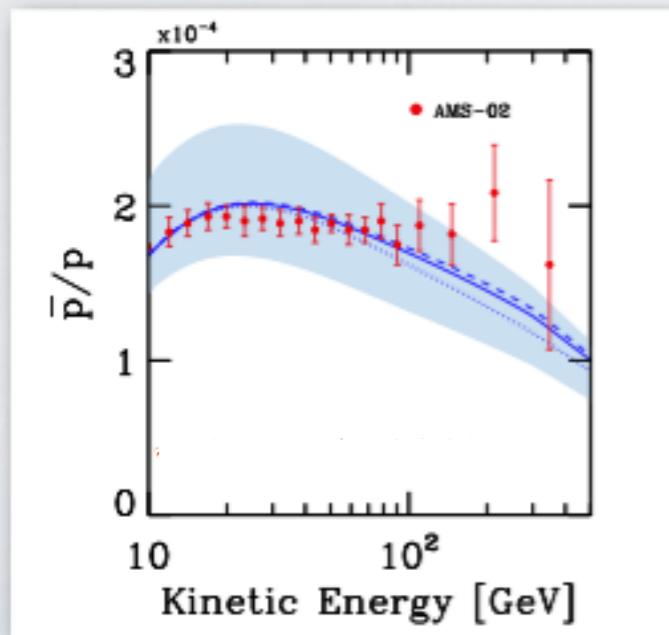
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Serpico
1504.04276

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

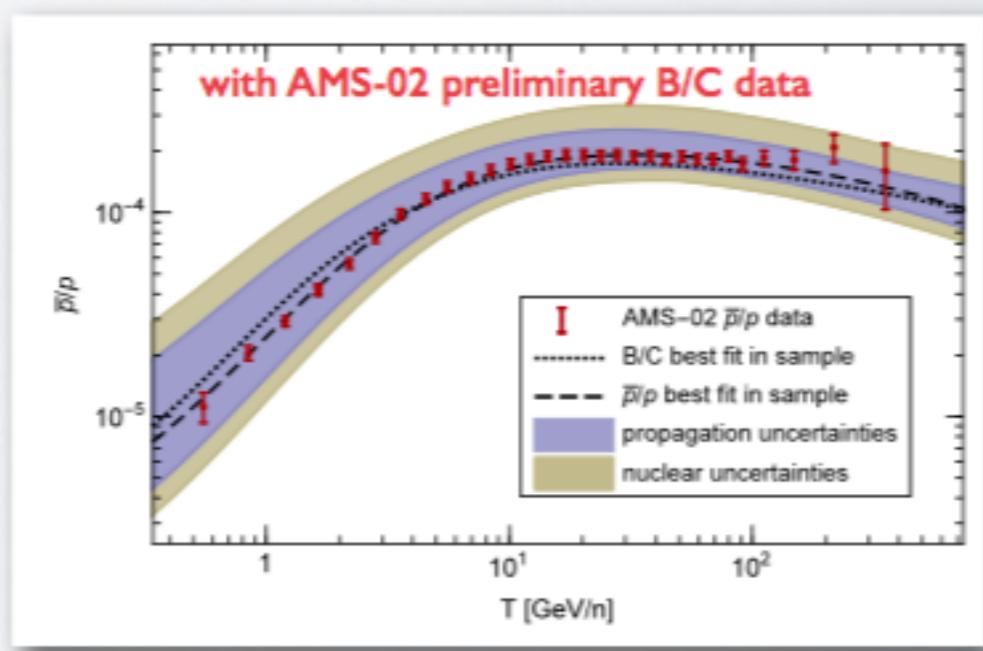
C. Evoli, D. Gaggero and D. Grasso, arXiv:1504.05175



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

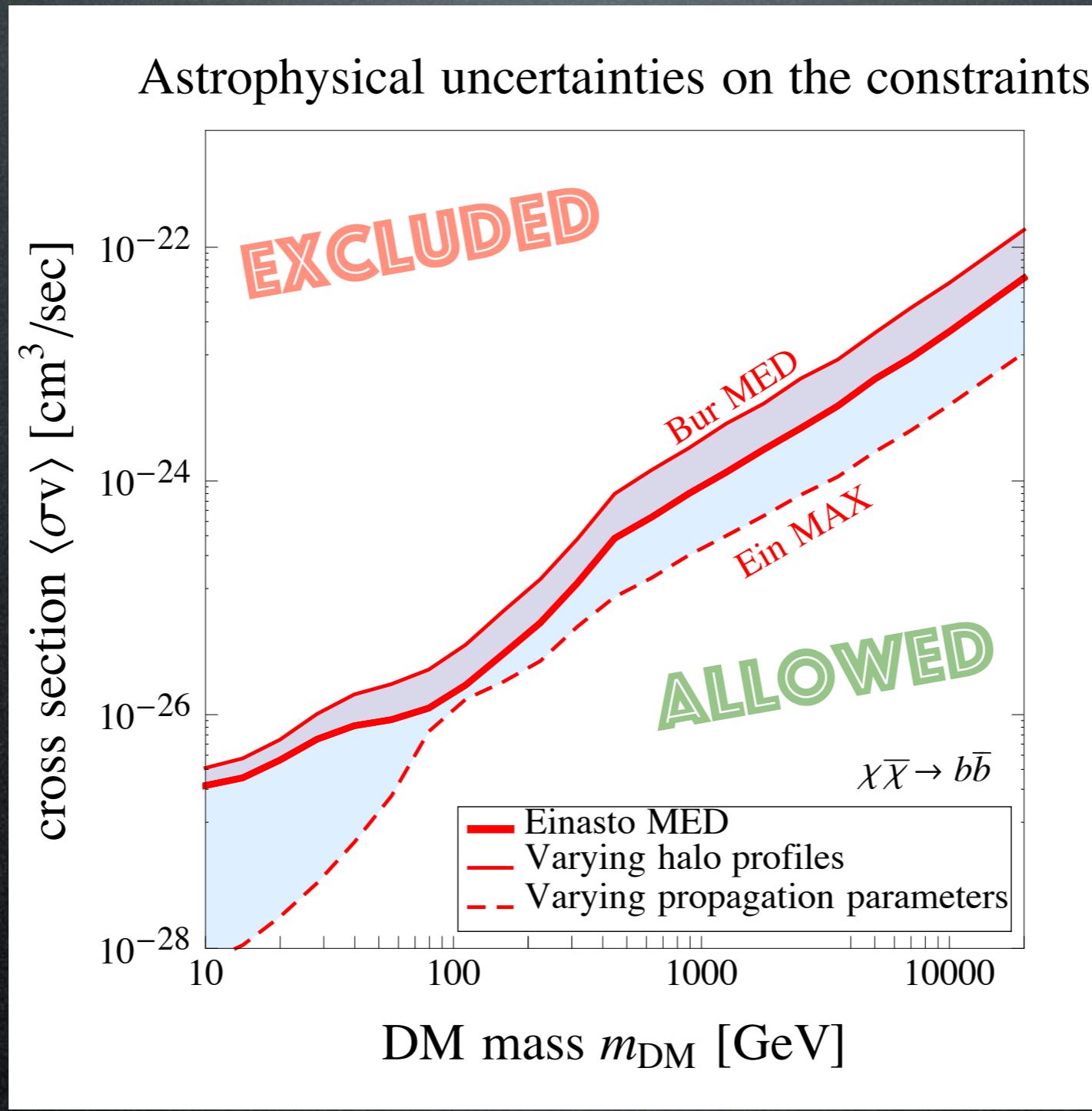
using
 p , He by AMS-02 and CREAM,
B/C by AMS-02,
heavier nuclei by compilation

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



Dark Matter interpretation

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

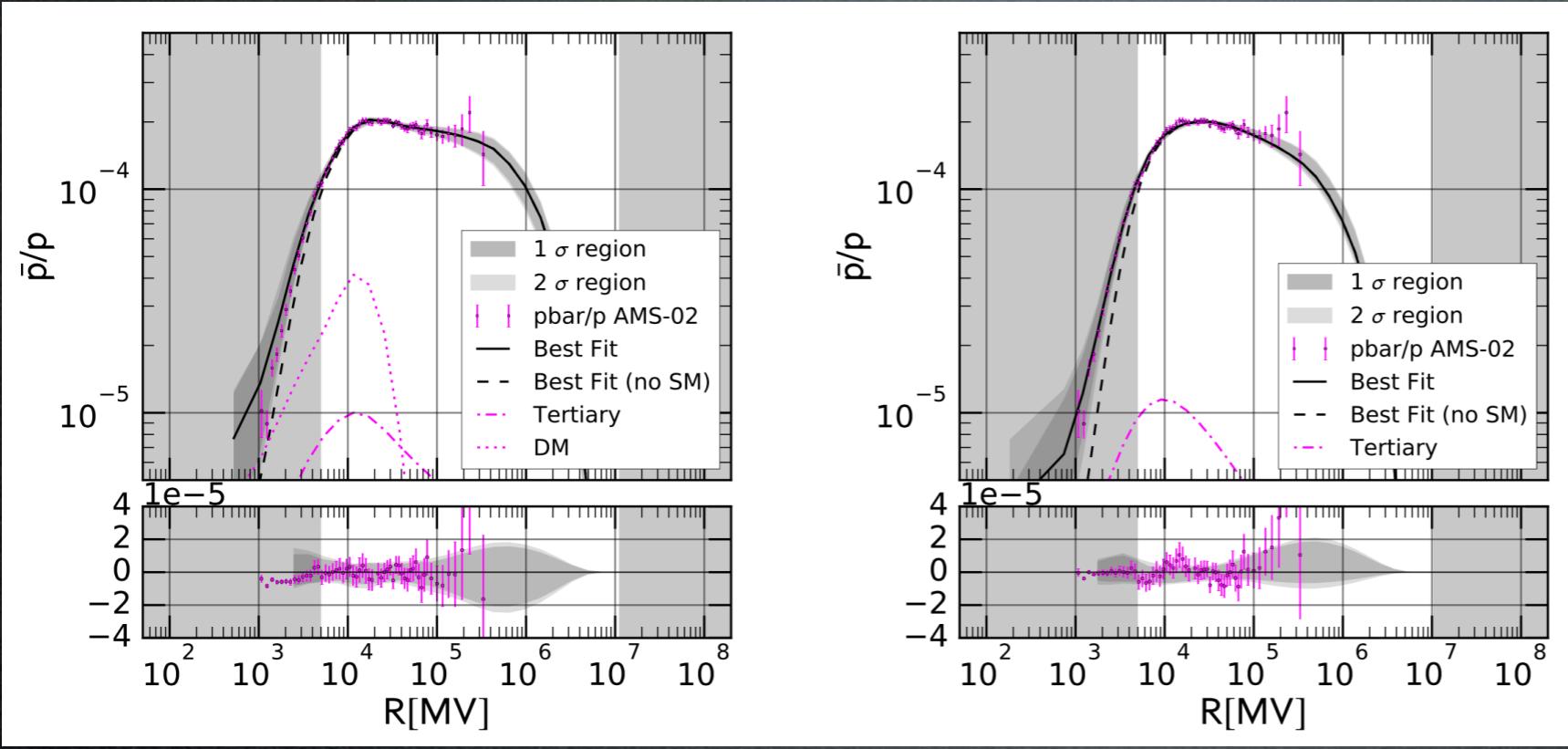


Giesen, Boudaud,
Génolini, Poulin,
Cirelli, Salati,
Serpico
1504.04276

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071

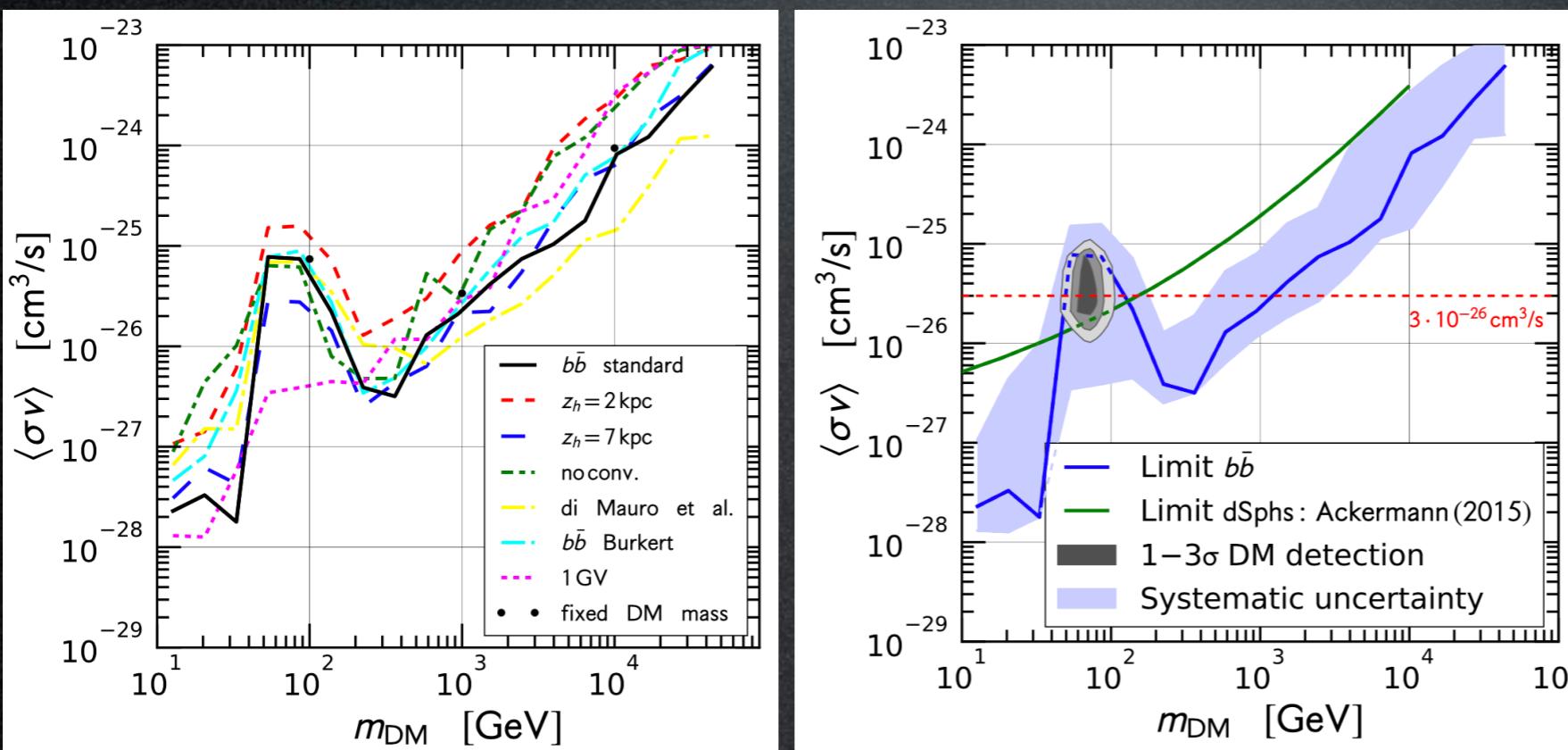


finds a **possible excess**
(formally $\sim 4.5\sigma$)

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

similarly:

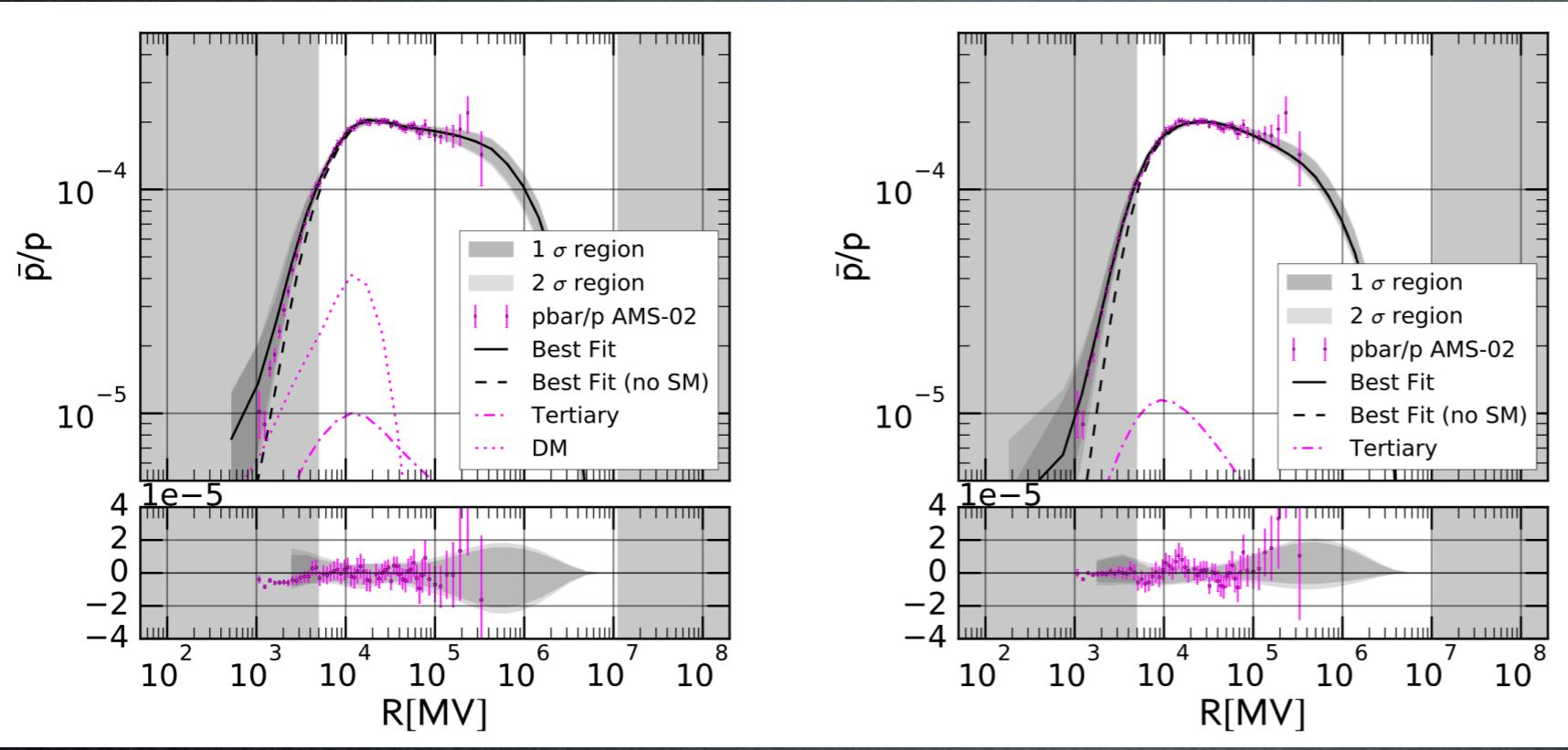
Cui, Yuan, Tsai, Fang 1610.03840
 Huang + 1611.01983 (light mediators)
 Feng, Zhang 1701.02263
 Cuoco, Heisig, Krämer, Korsmeier 1704.08258
 Boschini+ (Galprop) 1704.06337 (but only 1σ)



Antiprotons

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Cuoco, Krämer, Korsmeier 1610.03071

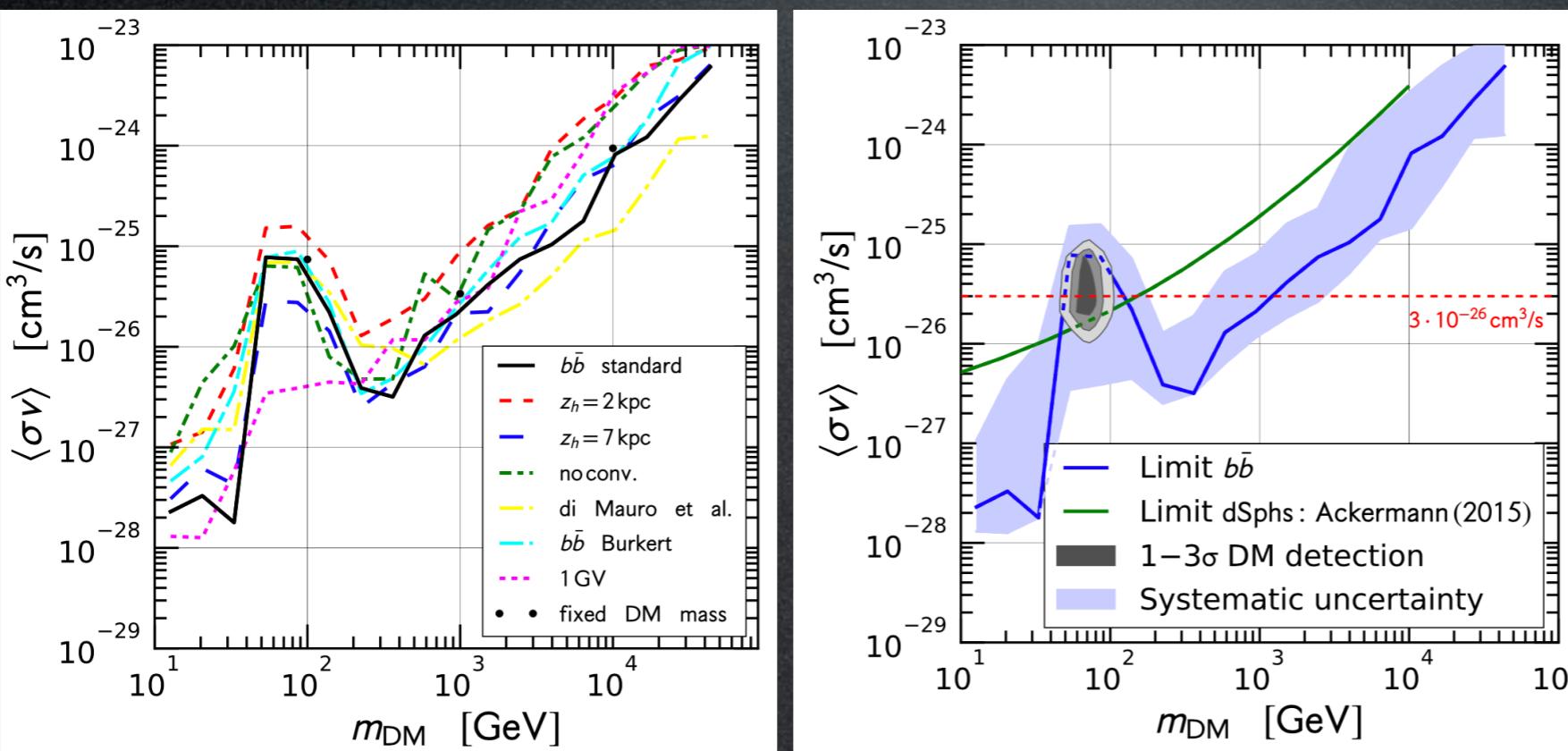


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criticisms:

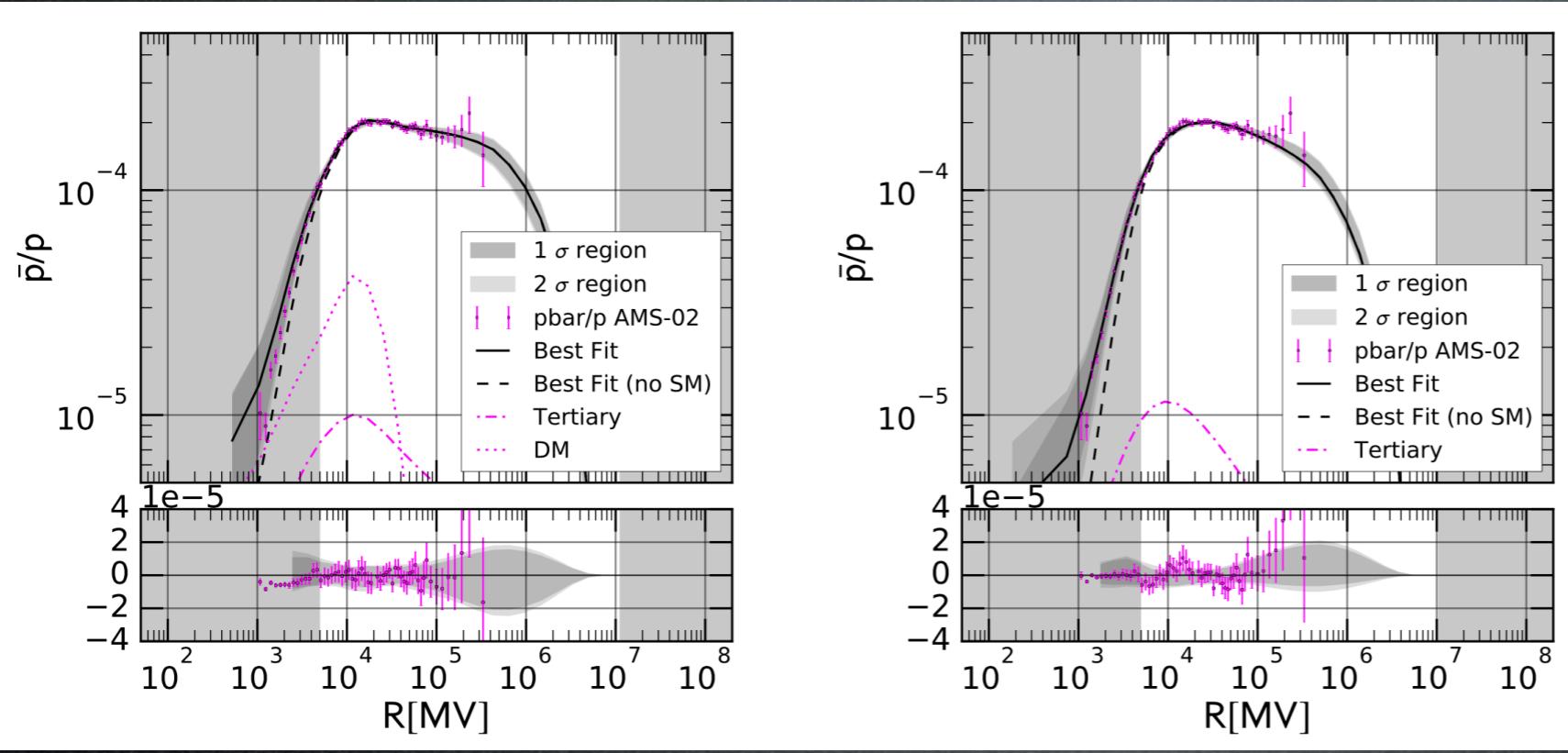
*propagation parameters determined with
 p , He data only,
 w/o B/C*

*excess evaporates
 including low energies*

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071

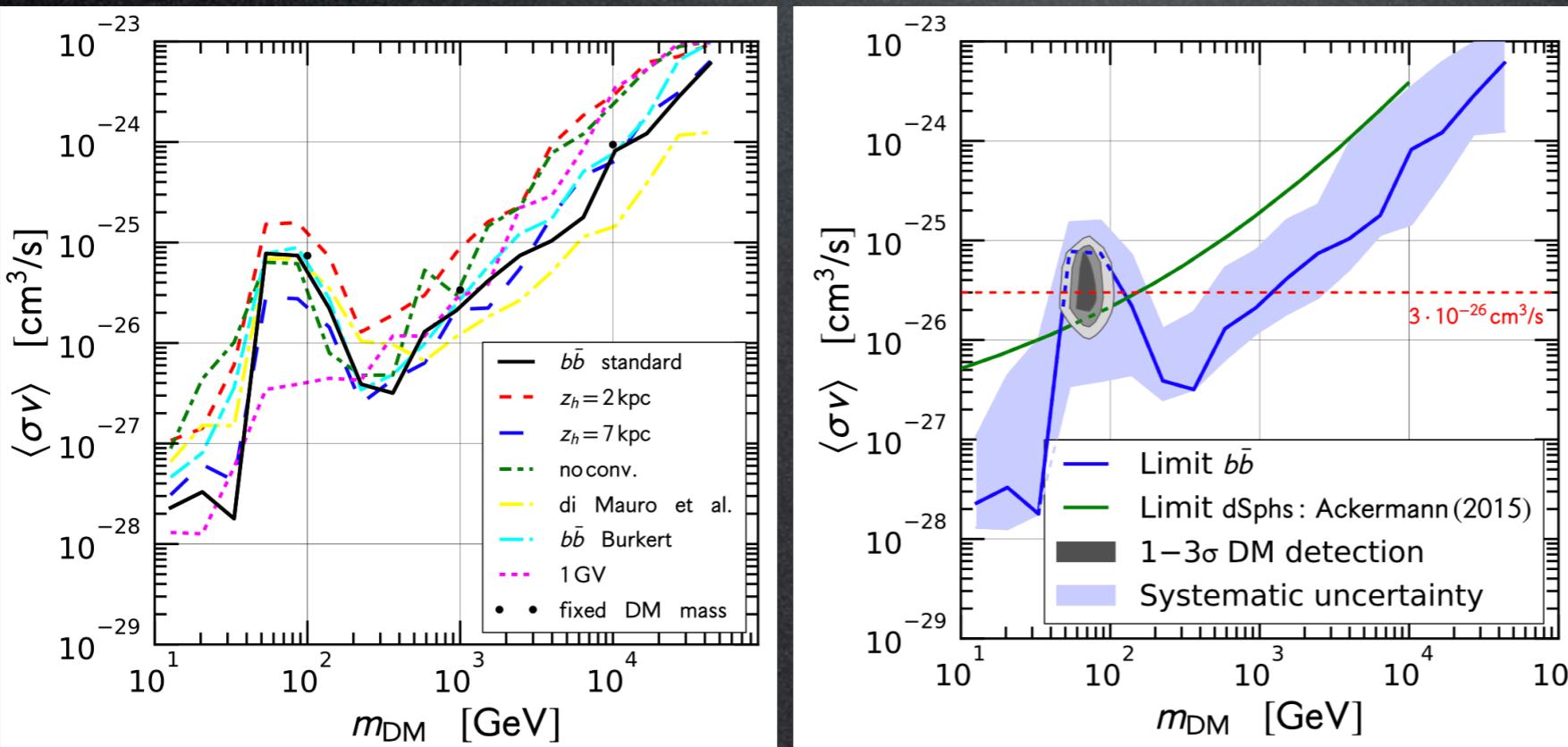


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on the other hand:

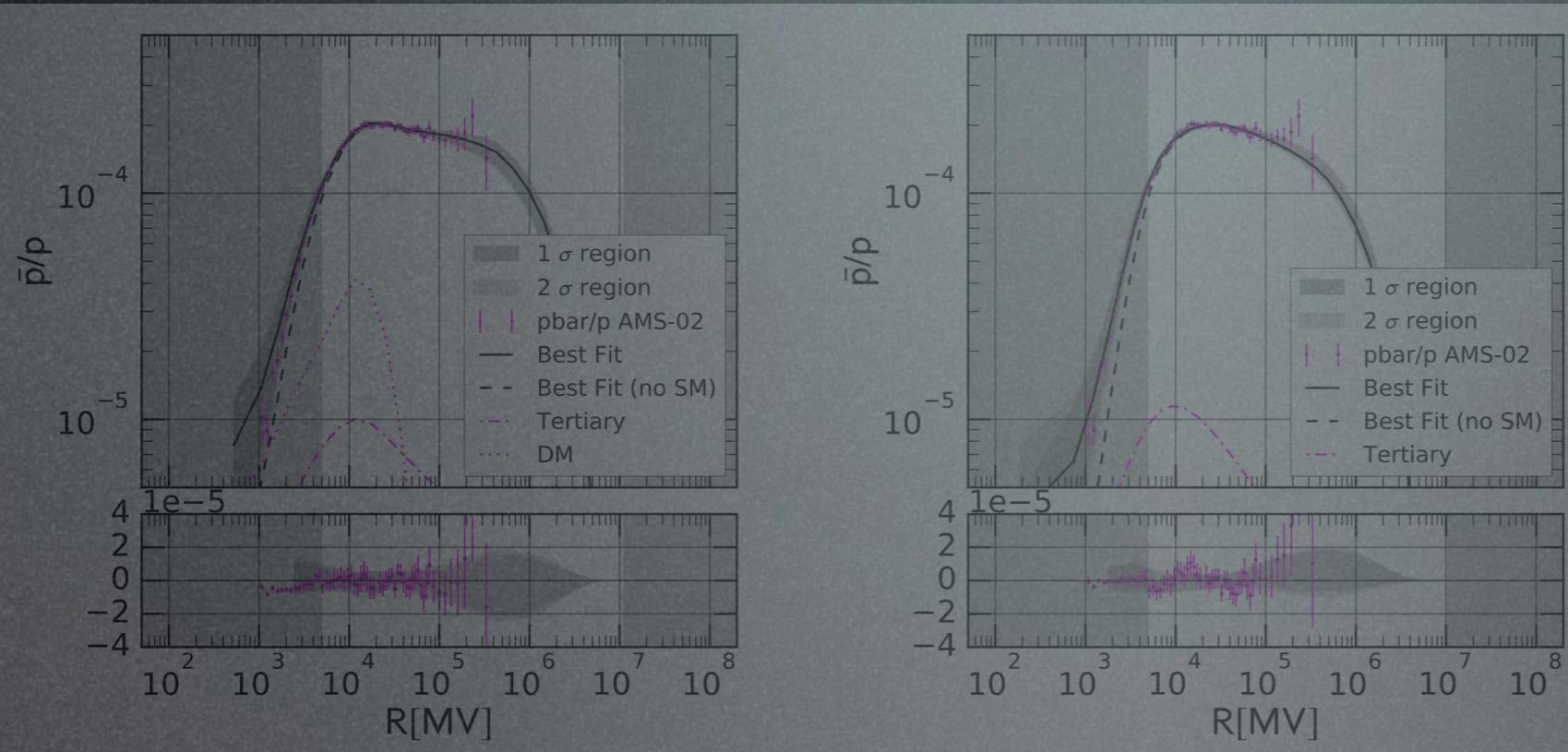
B/C and p probably probe different regions

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

Antiprotons

Recent developments

Cucco, Krämer, Korsmeier 1610.03071

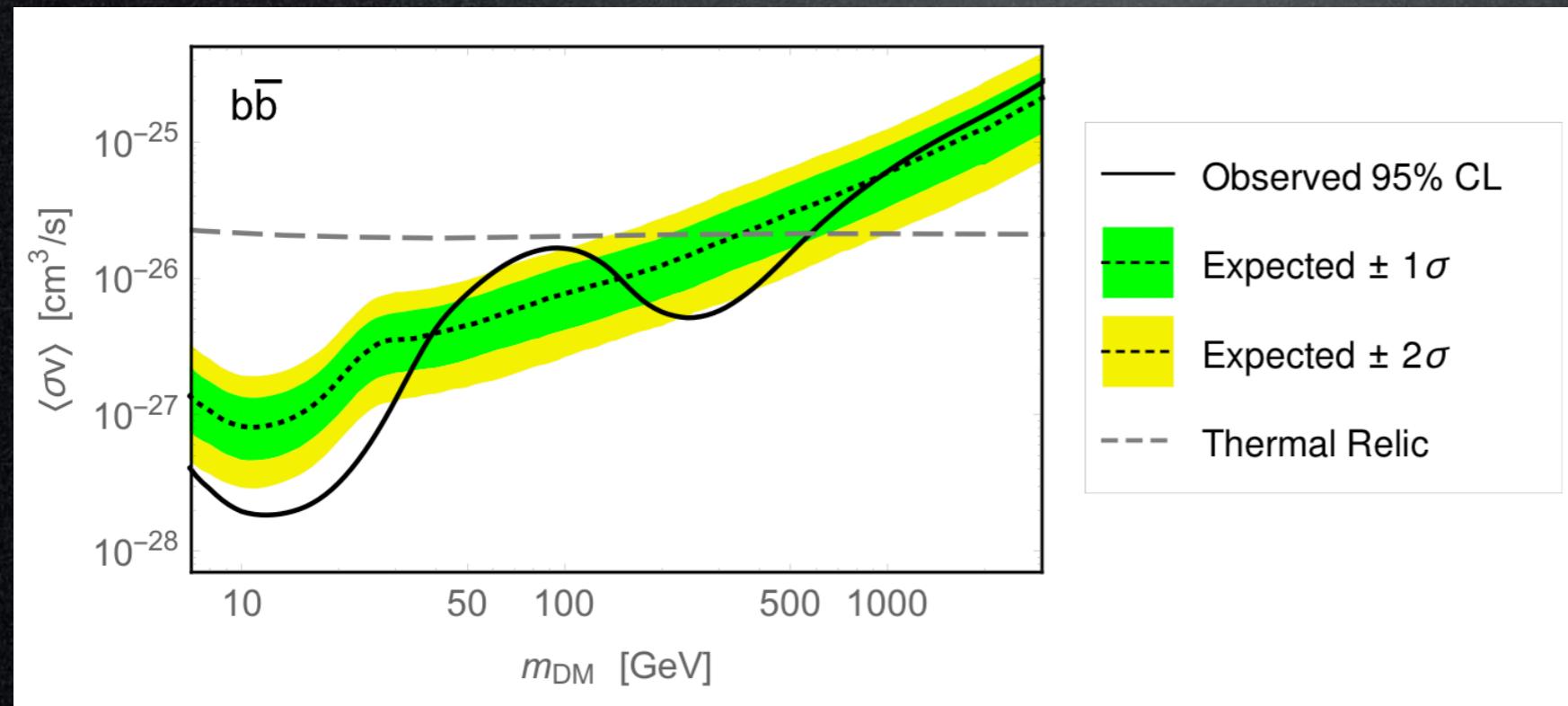


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Reinert, Winkler 1712.00002

excess exists

but significance $\sim 1\sigma$,
given all uncertainties

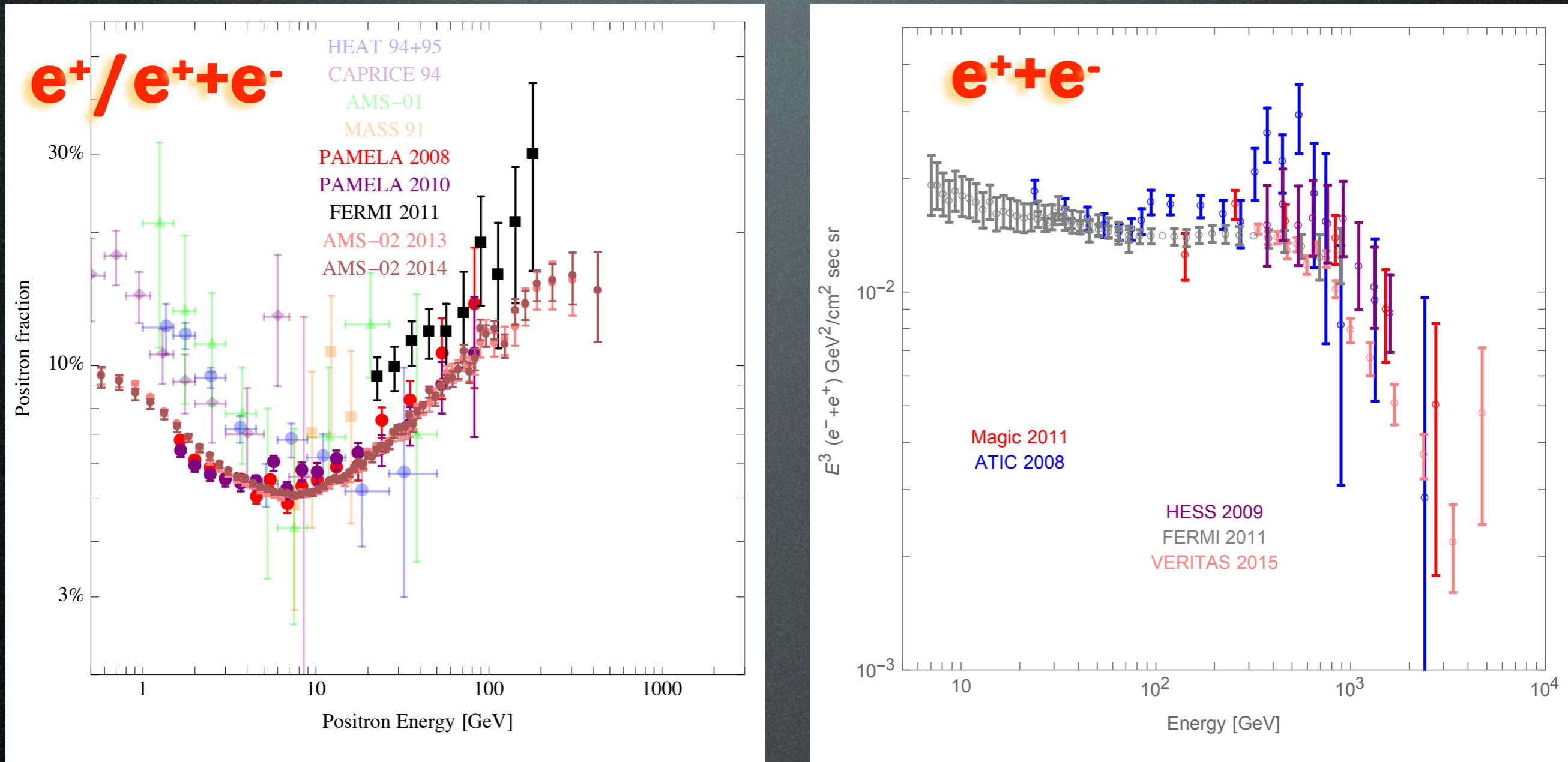
Positrons (and electrons)

direct detection

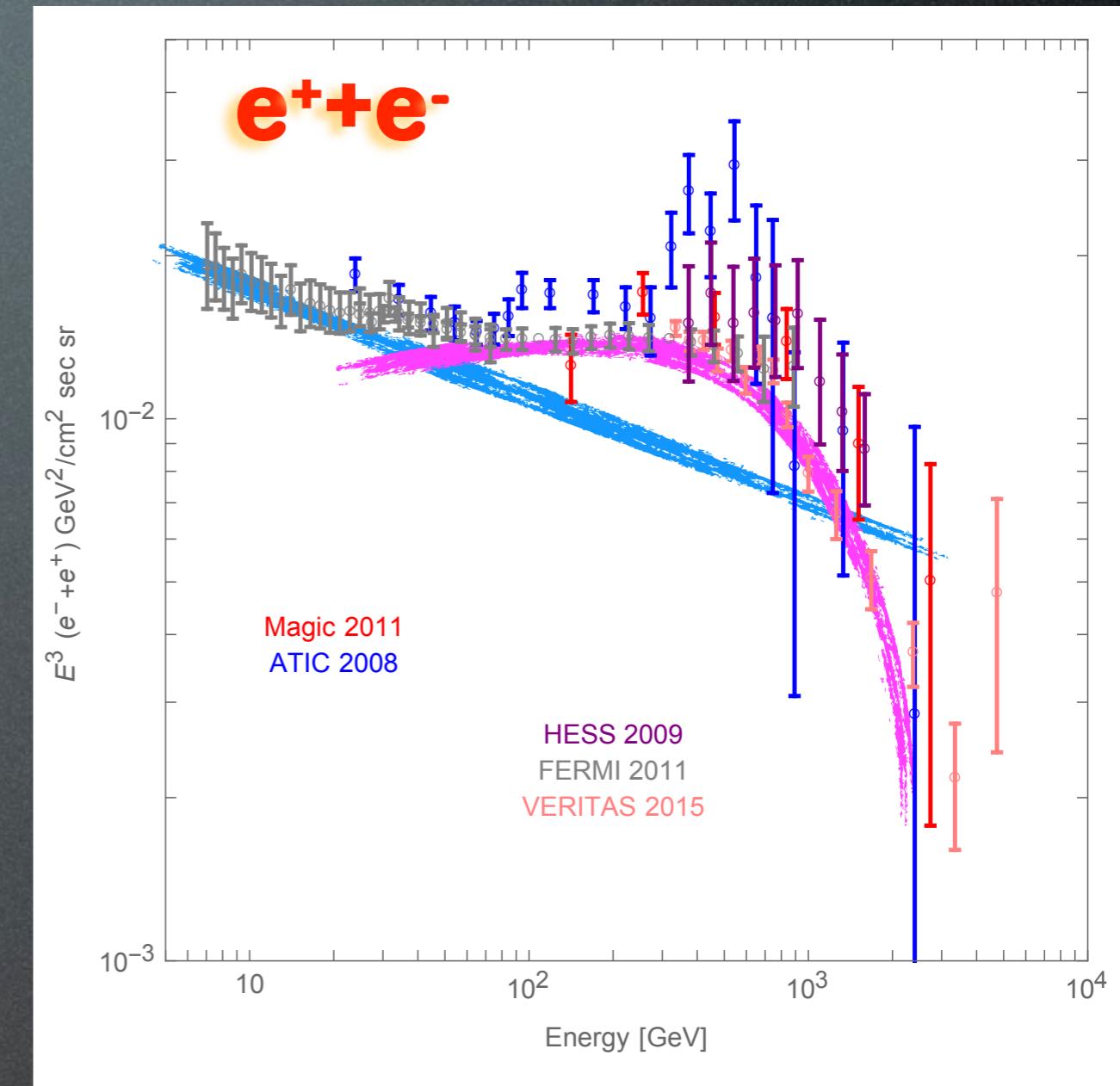
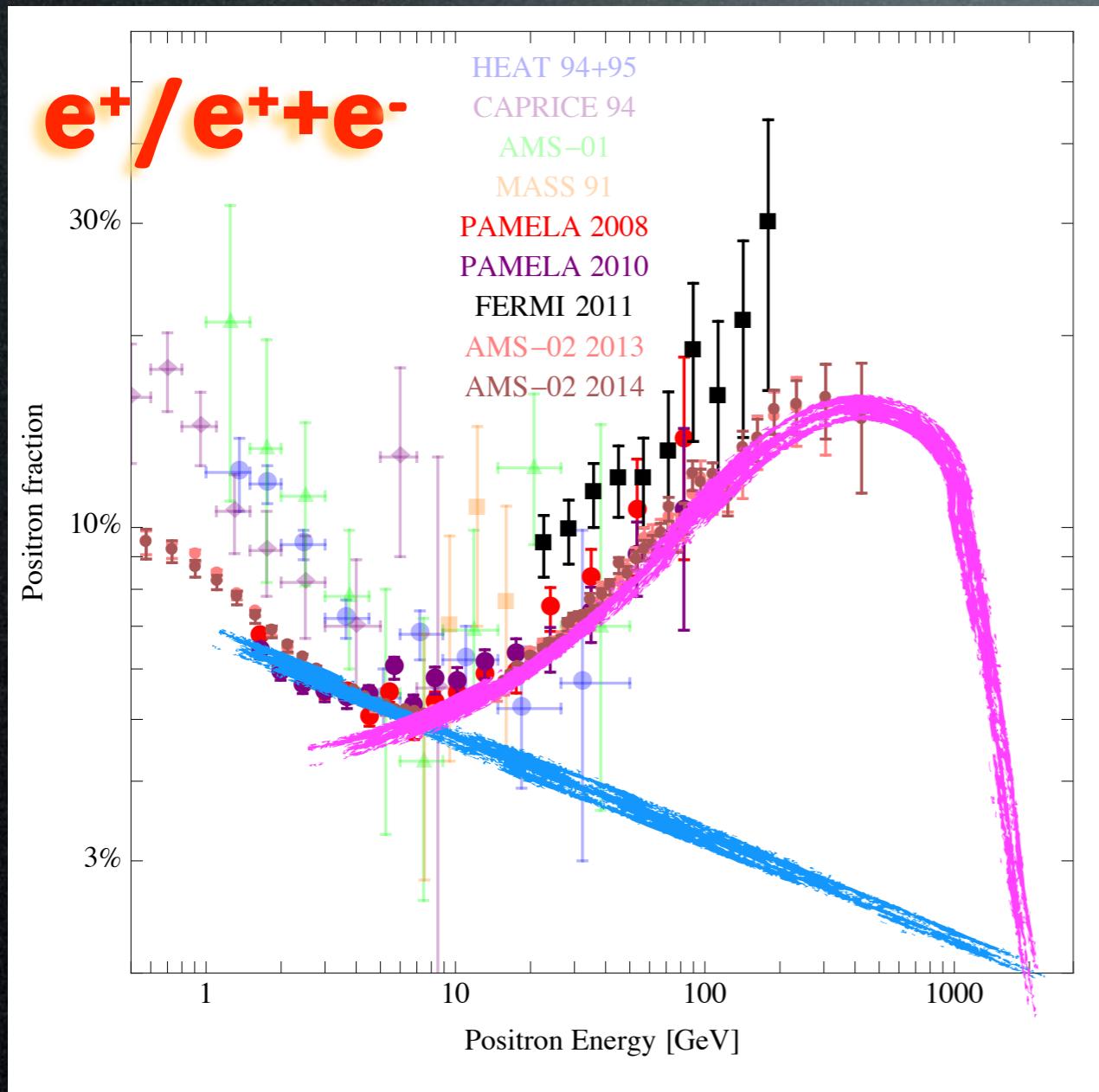
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Data: leptons

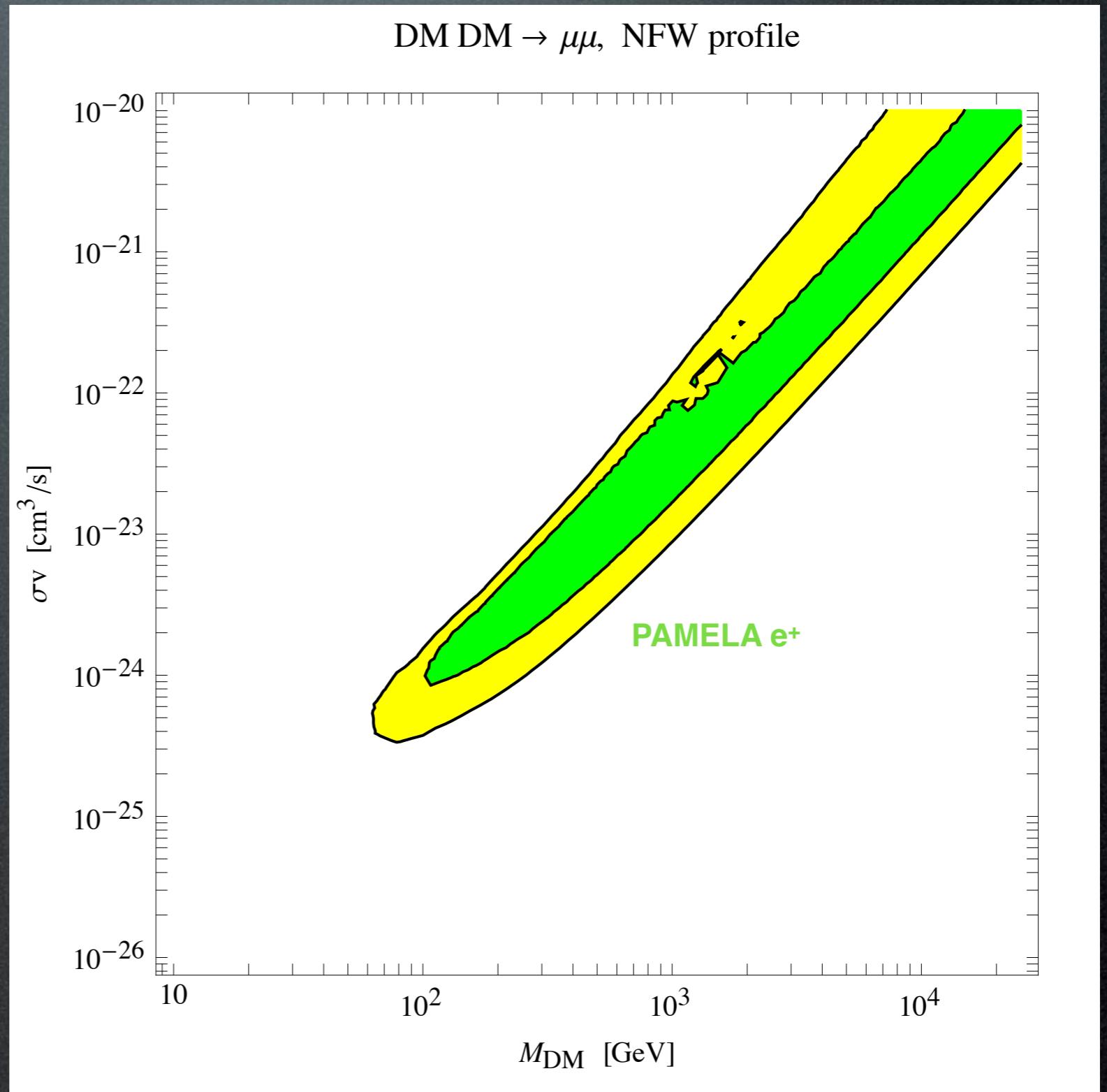


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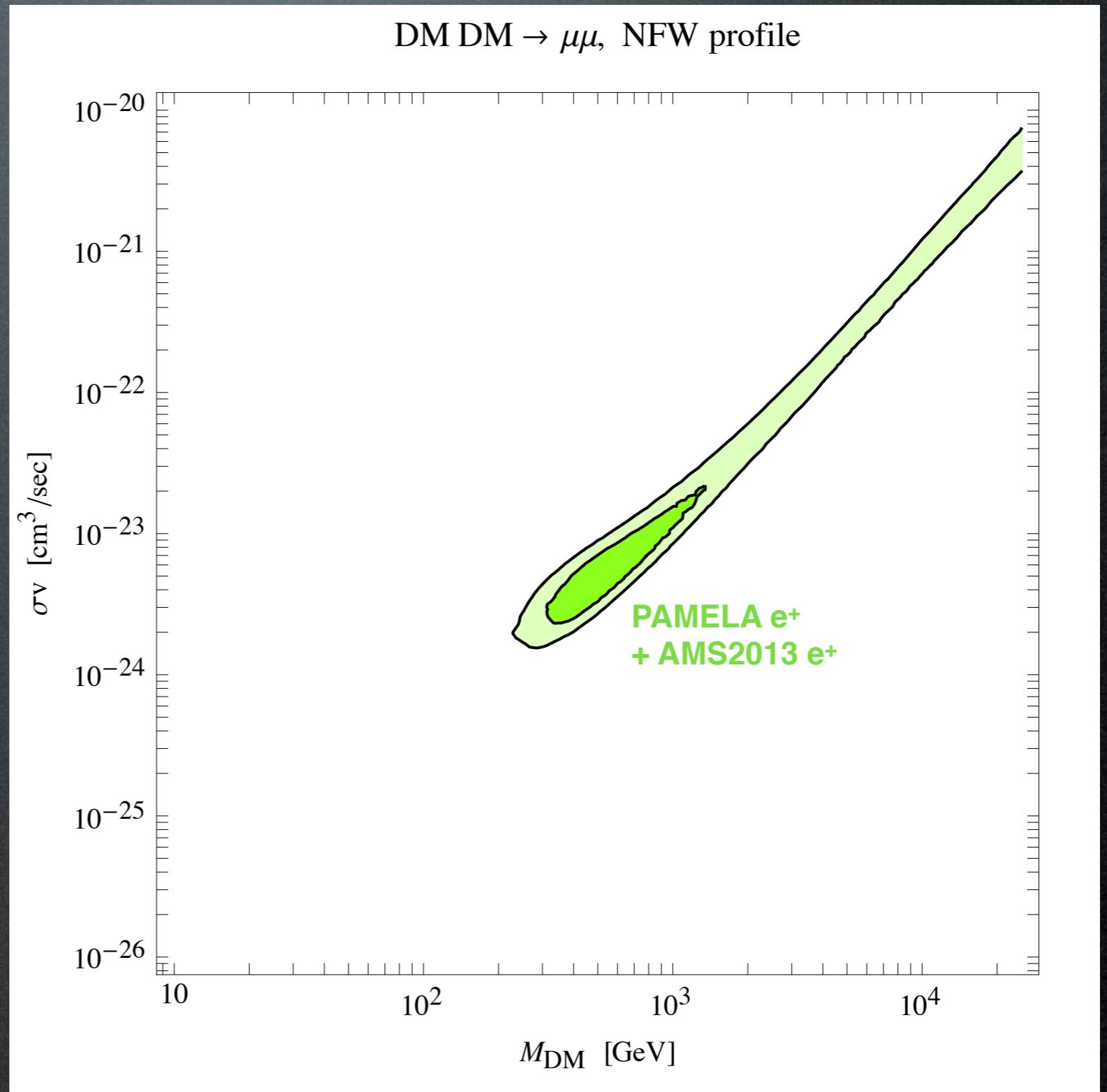
Dark Matter interpretation

- leptophilic
- $m_{DM} > \text{few } 100 \text{ GeV}$
- huge annihilation cross section



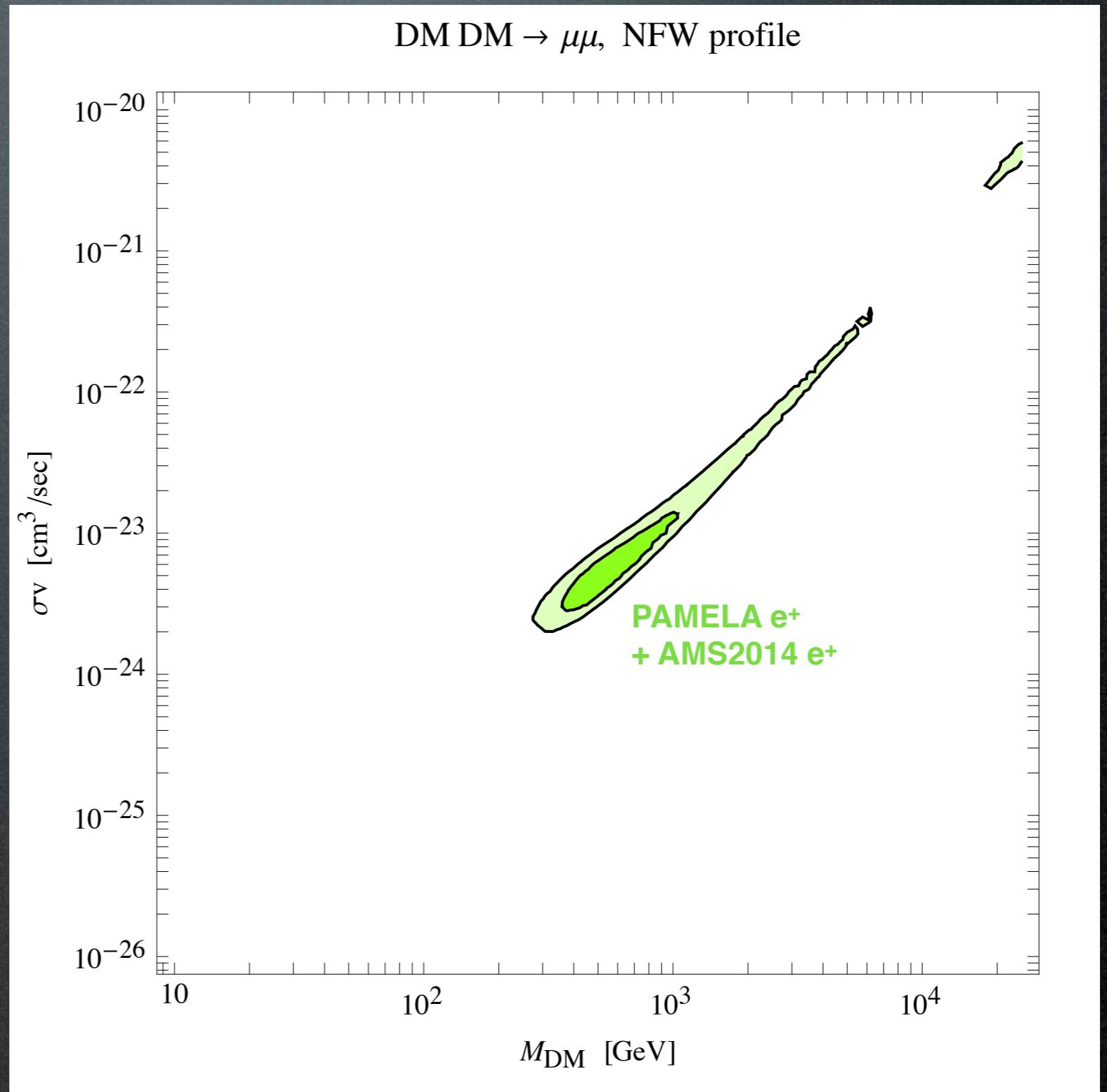
Dark Matter interpretation

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



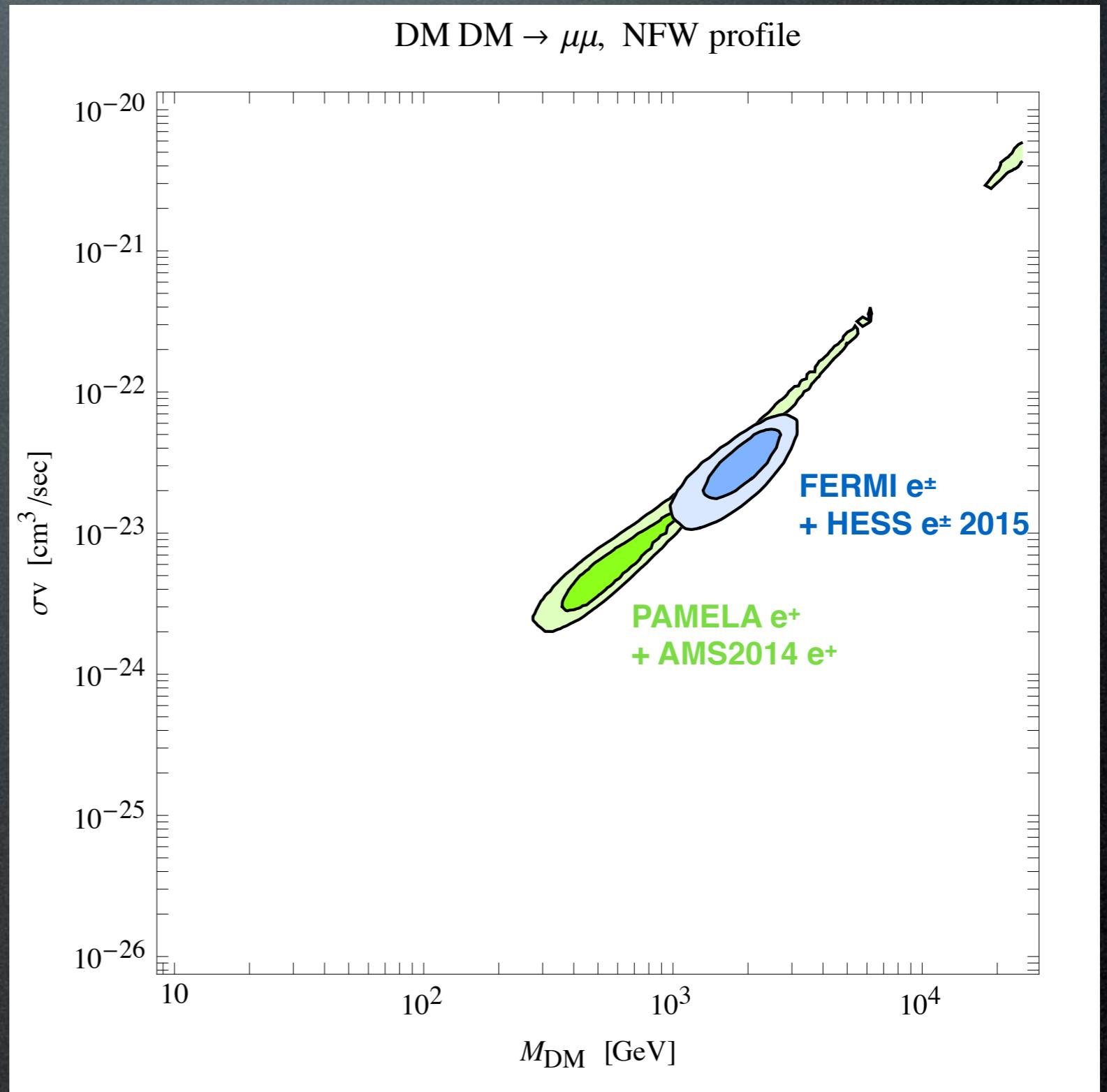
Dark Matter interpretation

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- $m_{DM} \lesssim 1 \text{ TeV}$
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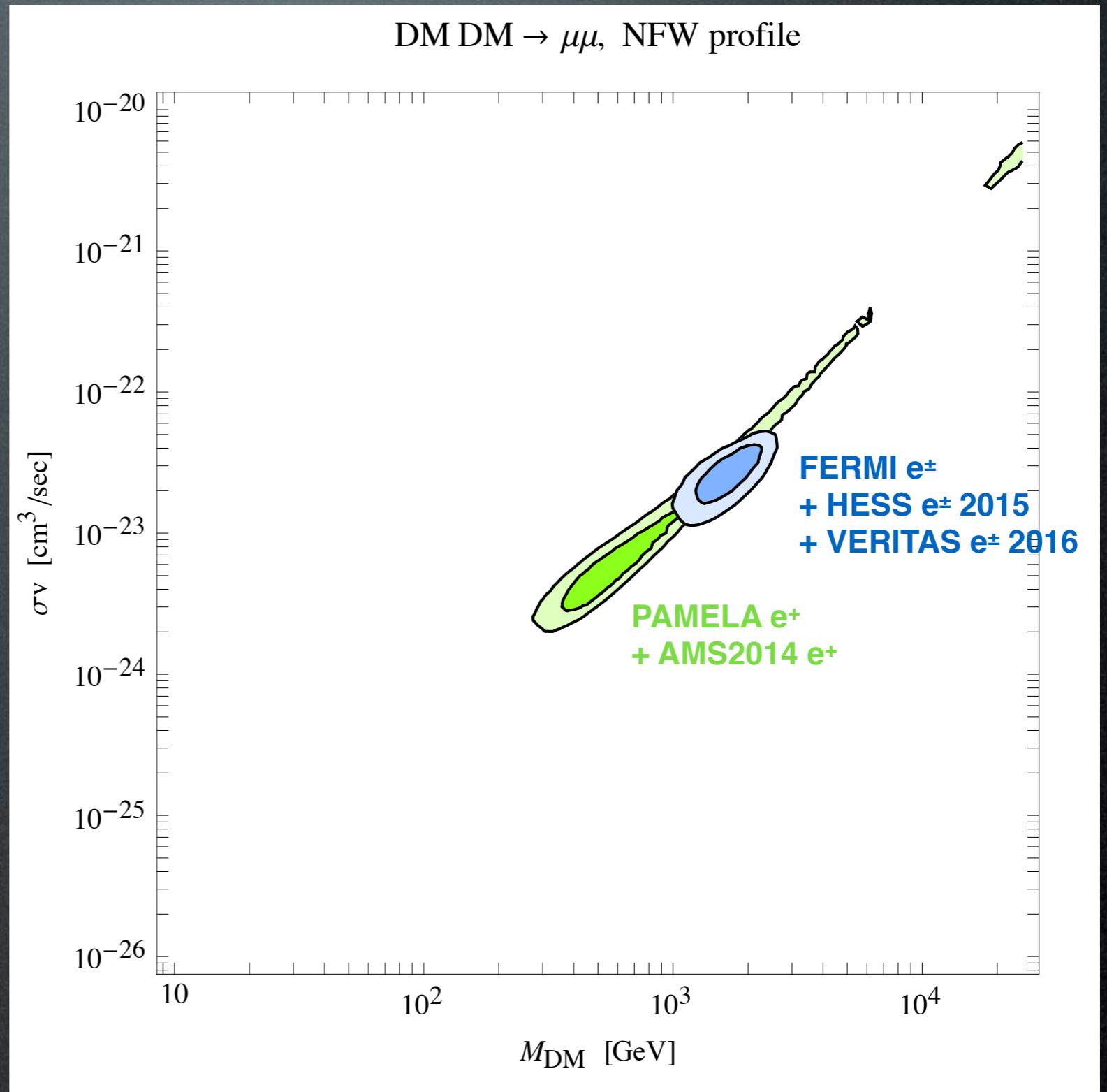
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Dark Matter interpretation

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- ▶ increased precision brings increased tension

“The improved accuracy of AMS-02 [...] now excludes channels previously allowed.”

M. Boudaud et al., 1410.3799

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M. Boudaud et al., 1410.3799

- ▶ combination of annihilation channels are possible

Dark Matter interpretation

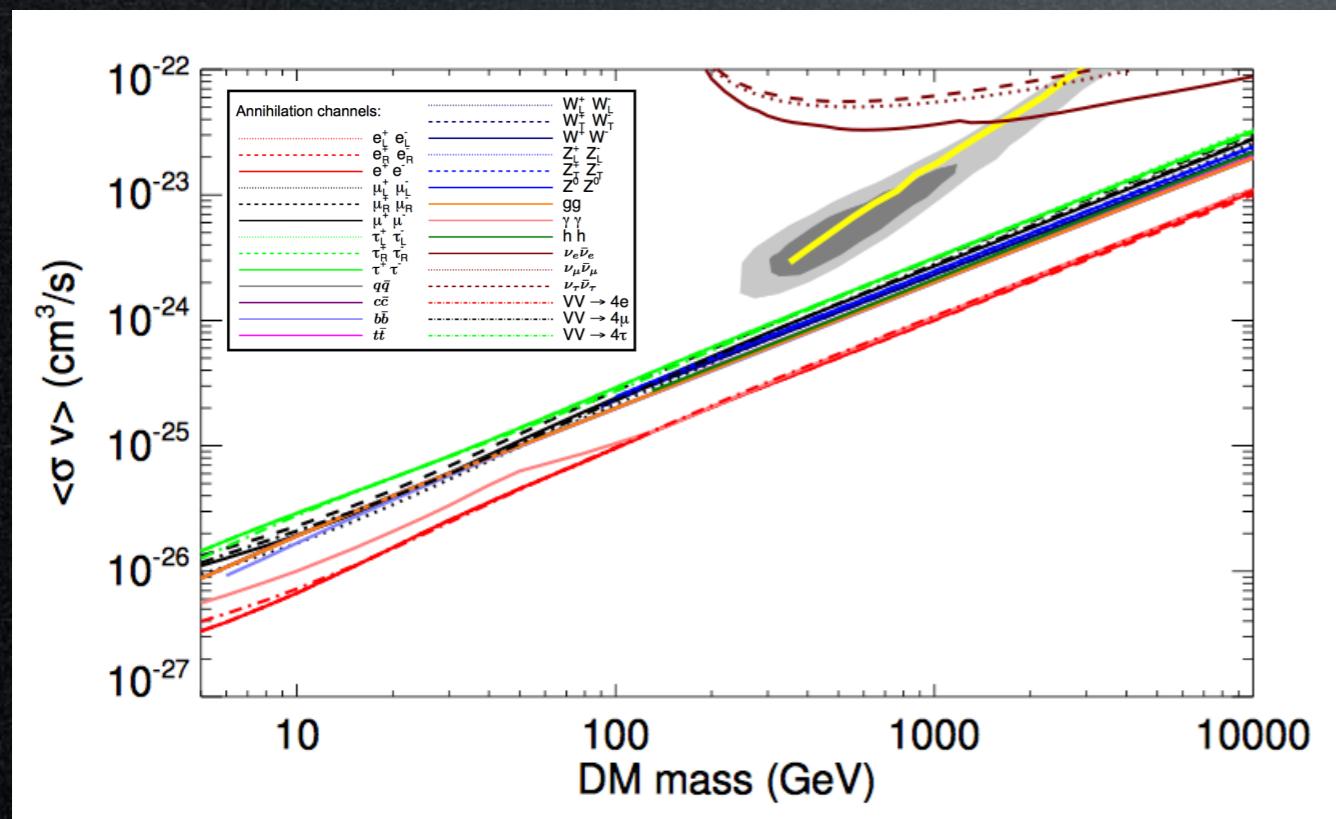
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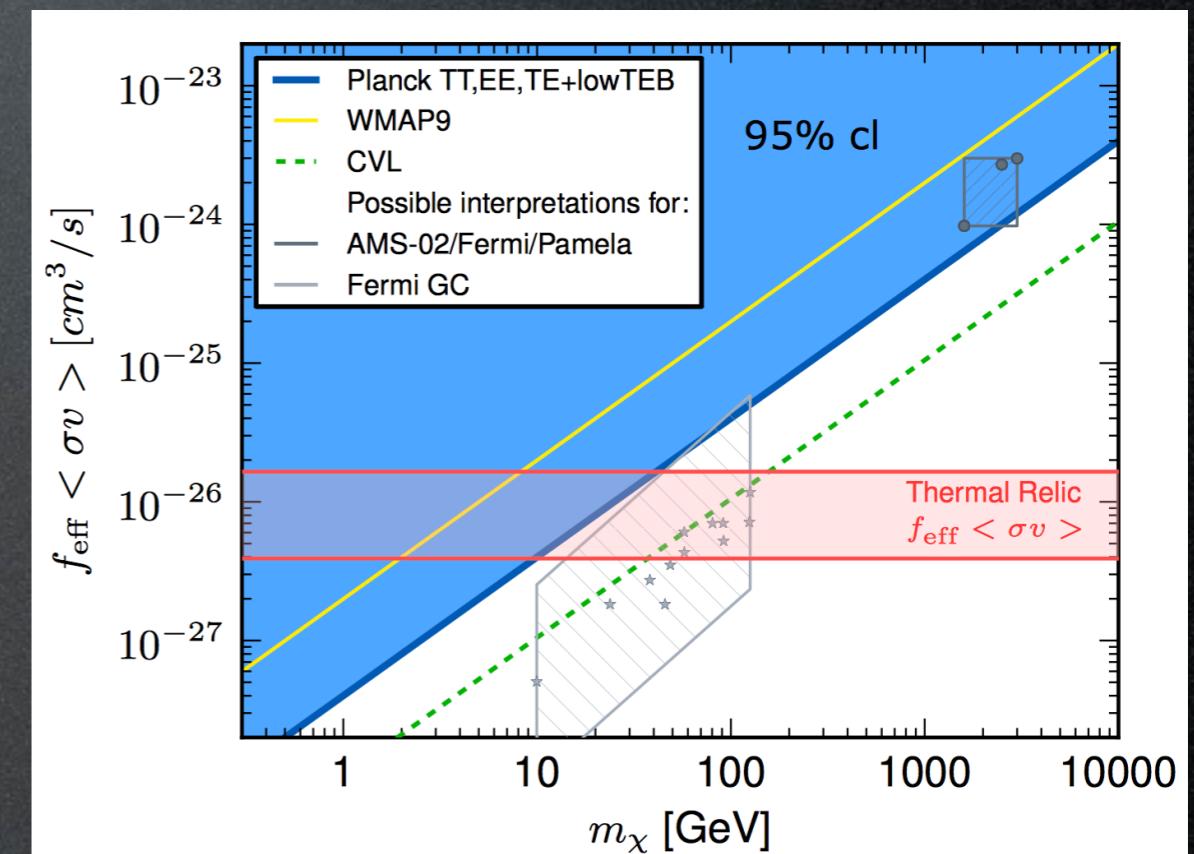
“The improved accuracy of AMS-02 [...] now excludes channels previously allowed.”

M. Boudaud et al., 1410.3799

- combination of annihilation channels are possible
- constraints: gamma rays, neutrinos, CMB...



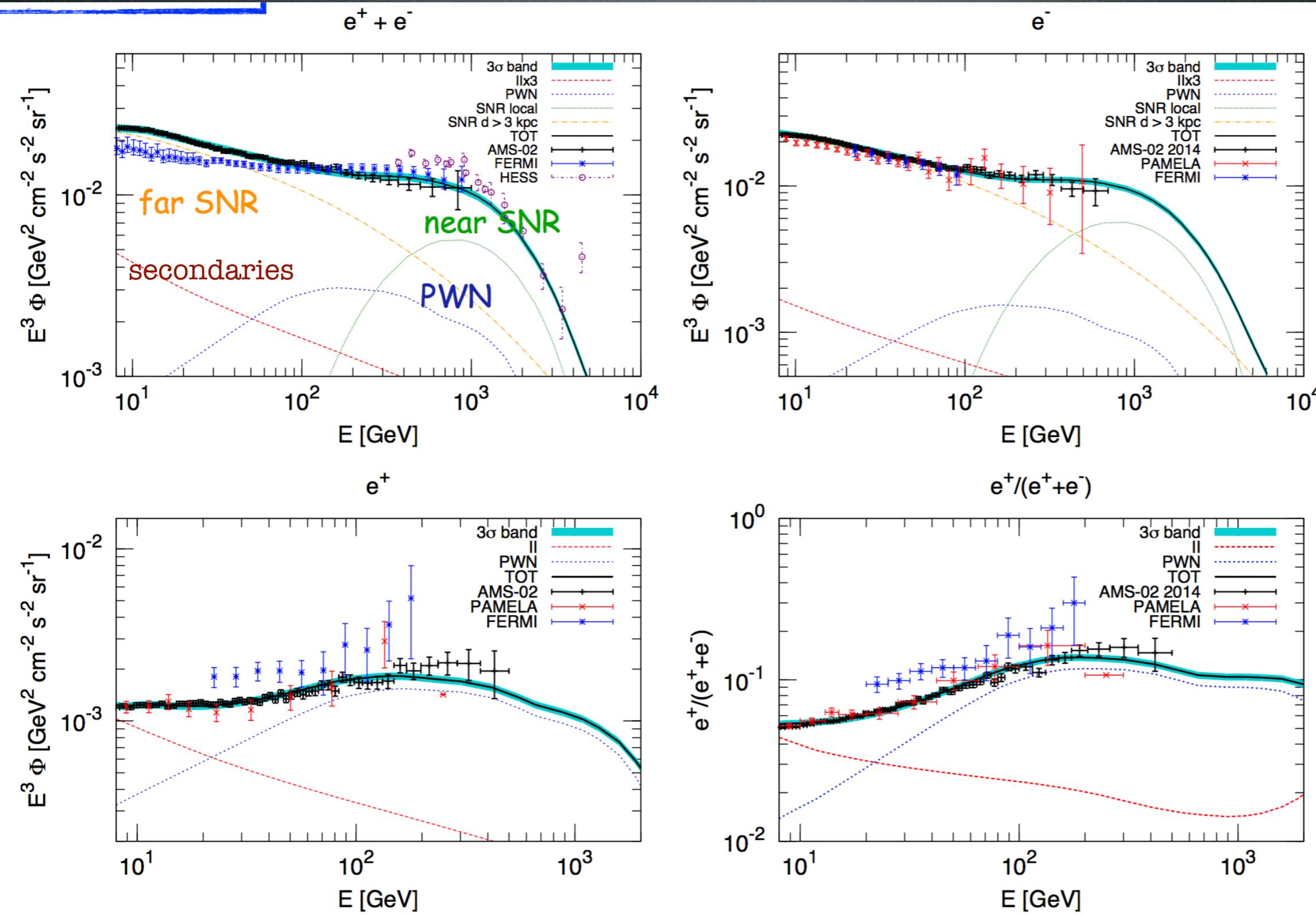
T.Slatyer 1506.03811



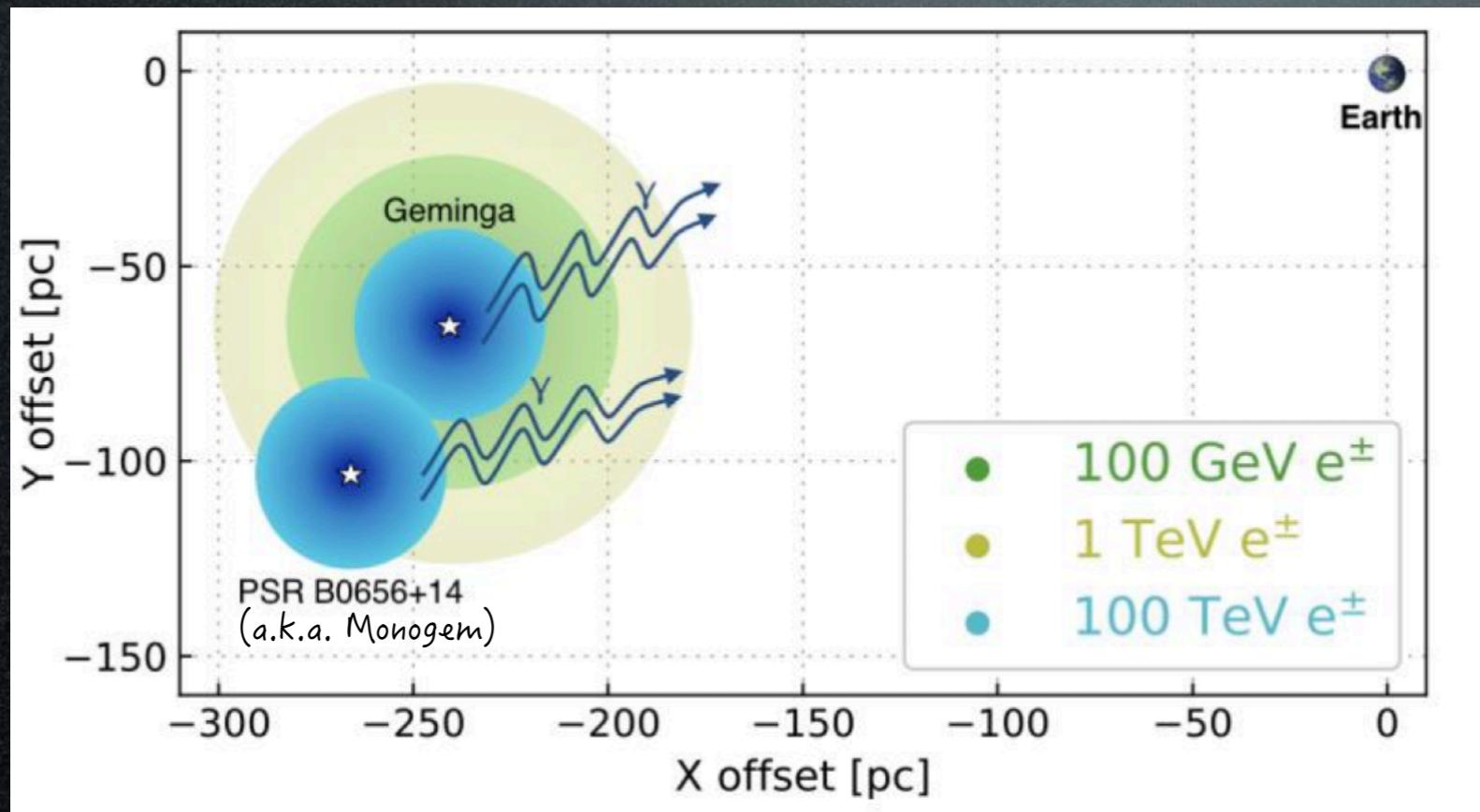
Planck 2015 (1502.01589)

Astro interpretation

M. Di Mauro
et al.
1507.07001



Dark Matter interpretation: the come back?



HAWC Coll., Science 359 (2017) 911 - 1711.06223

HAWC sees ICS TeV γ -rays
from ~ 100 TeV e^+e^-
from Geminga and Monogem



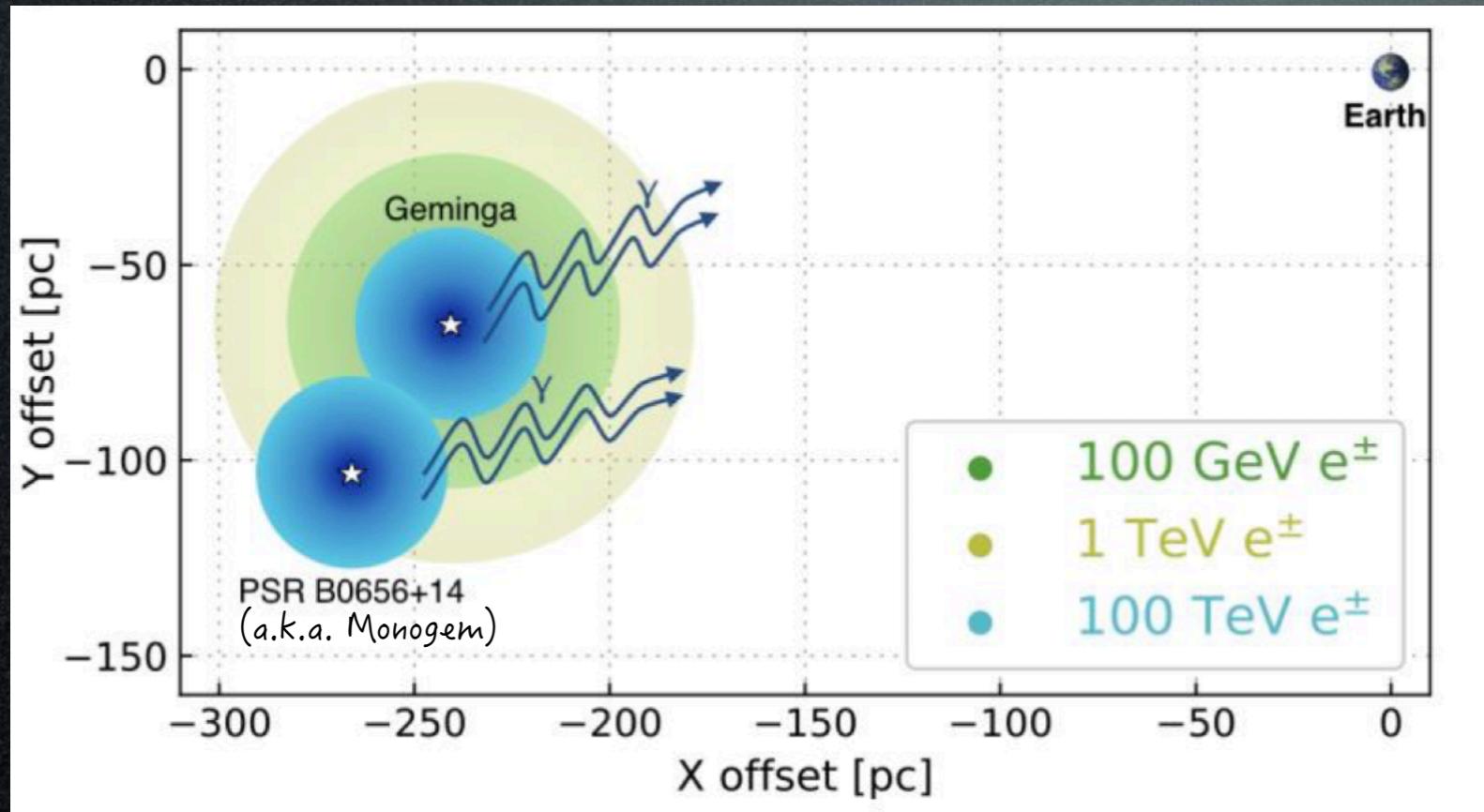
e^+ are ‘very trapped’ around these pulsars (diffusion is very slow)



e^+ cannot reach Earth to explain
100 GeV excesses, must be stg else
(DM?)

Geminga and PSR B0656+14 are the oldest pulsars for which a tera-electron volt nebula has so far been detected. Under our assumption of isotropic and homogeneous diffusion, the dominant source of the positron flux above 10 GeV cannot be either Geminga or PSR B0656+14. Under the unlikely situation that the field is nearly aligned along the direction between Earth and the nearby tera-electron volt nebulae, the local positron flux can be increased; however, the tera-electron volt morphology of the sources matches our isotropic diffusion model. We therefore favor the explanation that instead of these two pulsars, the origin of the local positron flux must be explained by other processes, such as different assumptions about secondary production [although that has been questioned (33; 34)], other pulsars, other types of cosmic accelerators such as micro-quasars (35) and supernova remnants (34), or the annihilation or decay of dark matter particles (9).

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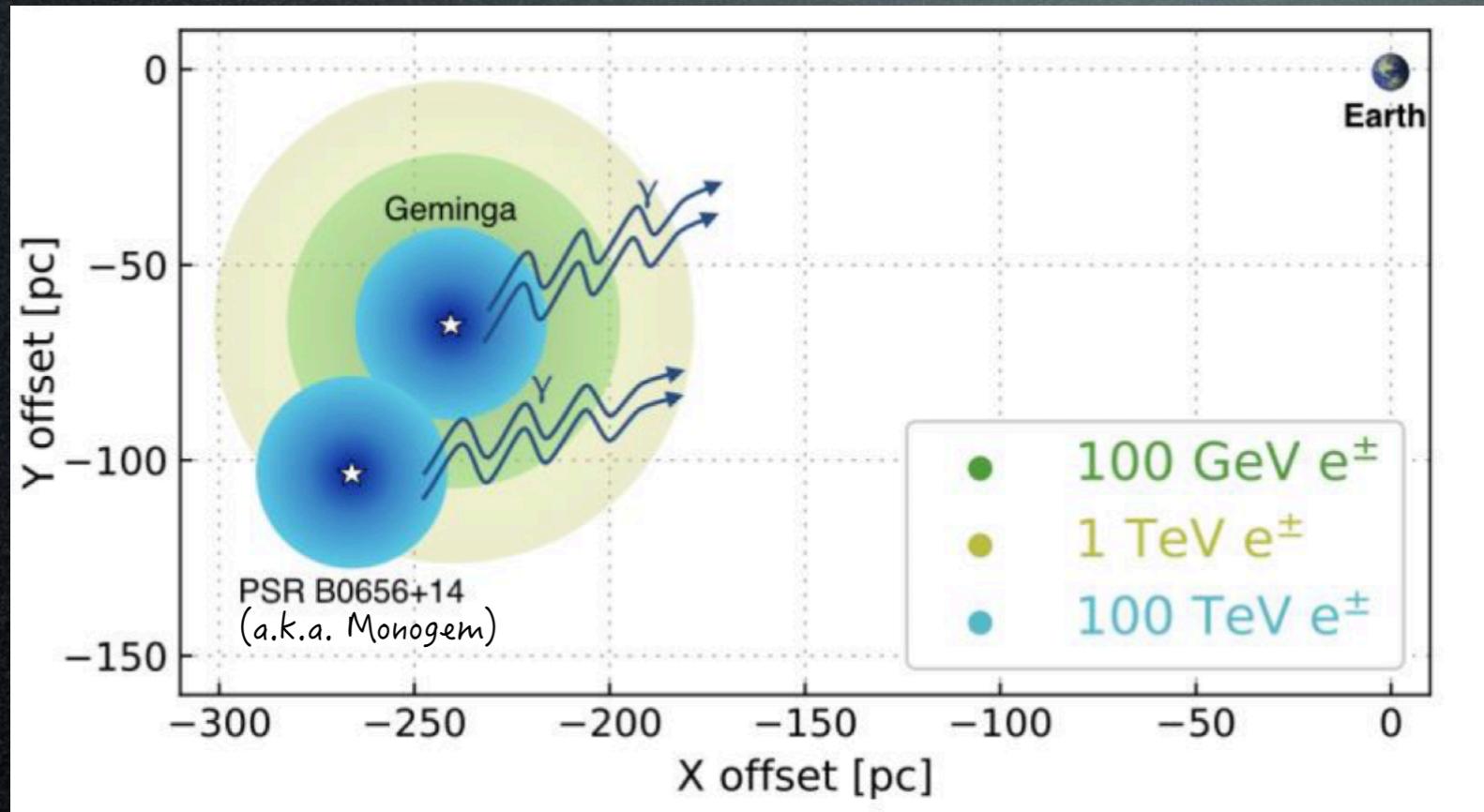
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Criticisms:

- space-dep diffusion: local \neq global

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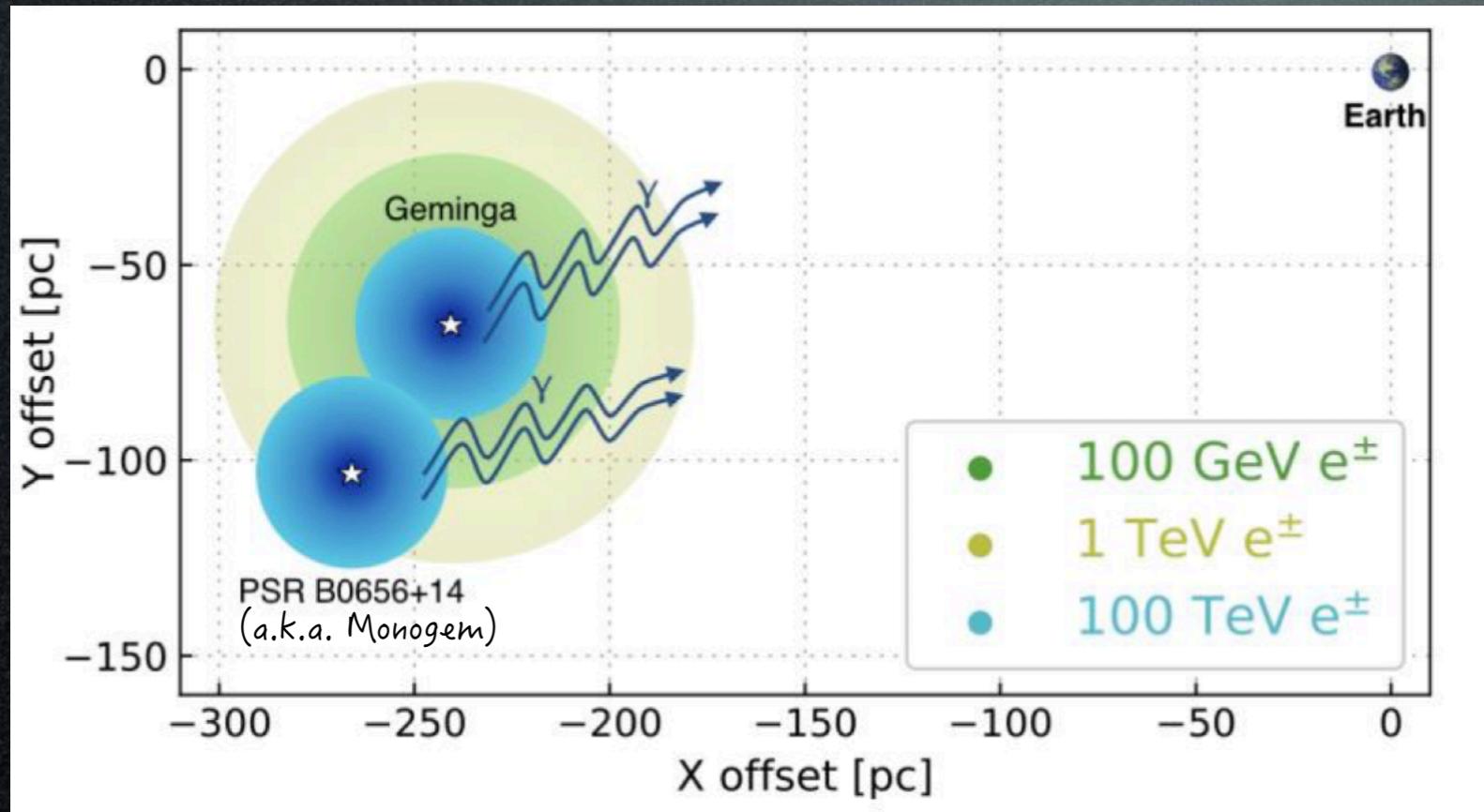
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Dark Matter interpretation: the come back?



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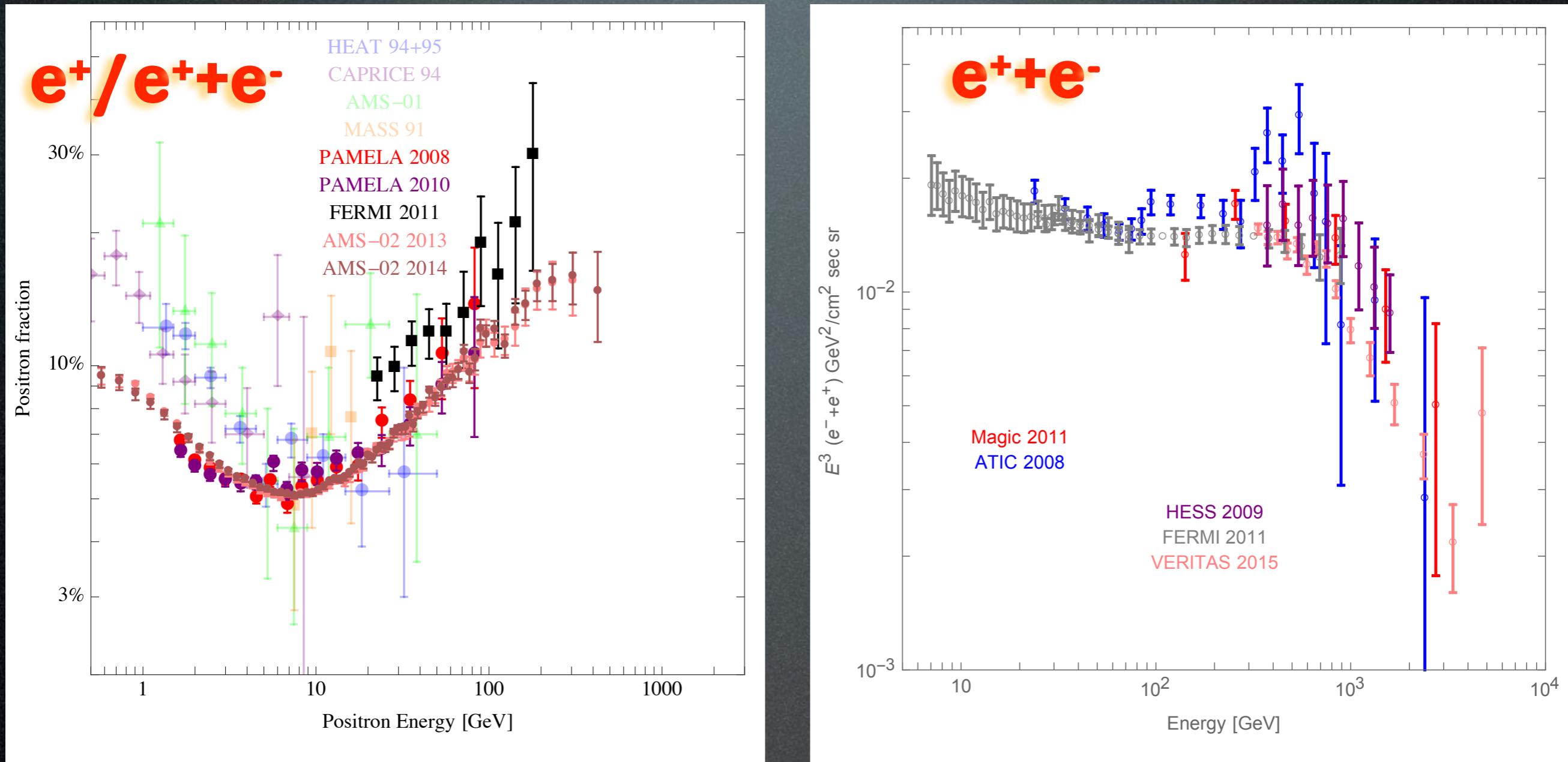
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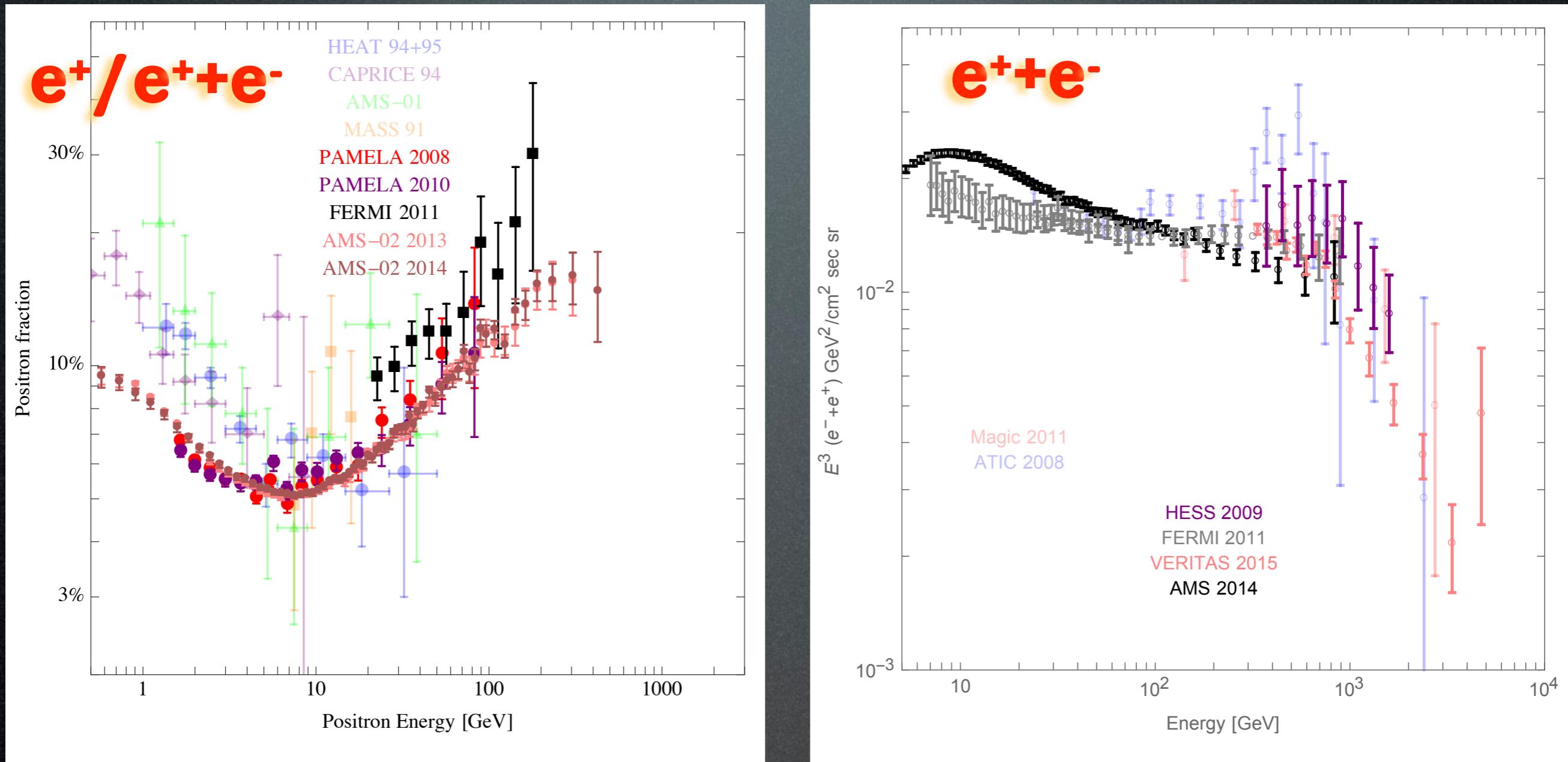
Criticisms:

- space-dep diffusion: local \neq global
- E-dep diffusion: 100 TeV vs 100 GeV
- t-dep: γ -rays today, but e^+ 10⁴ yrs ago

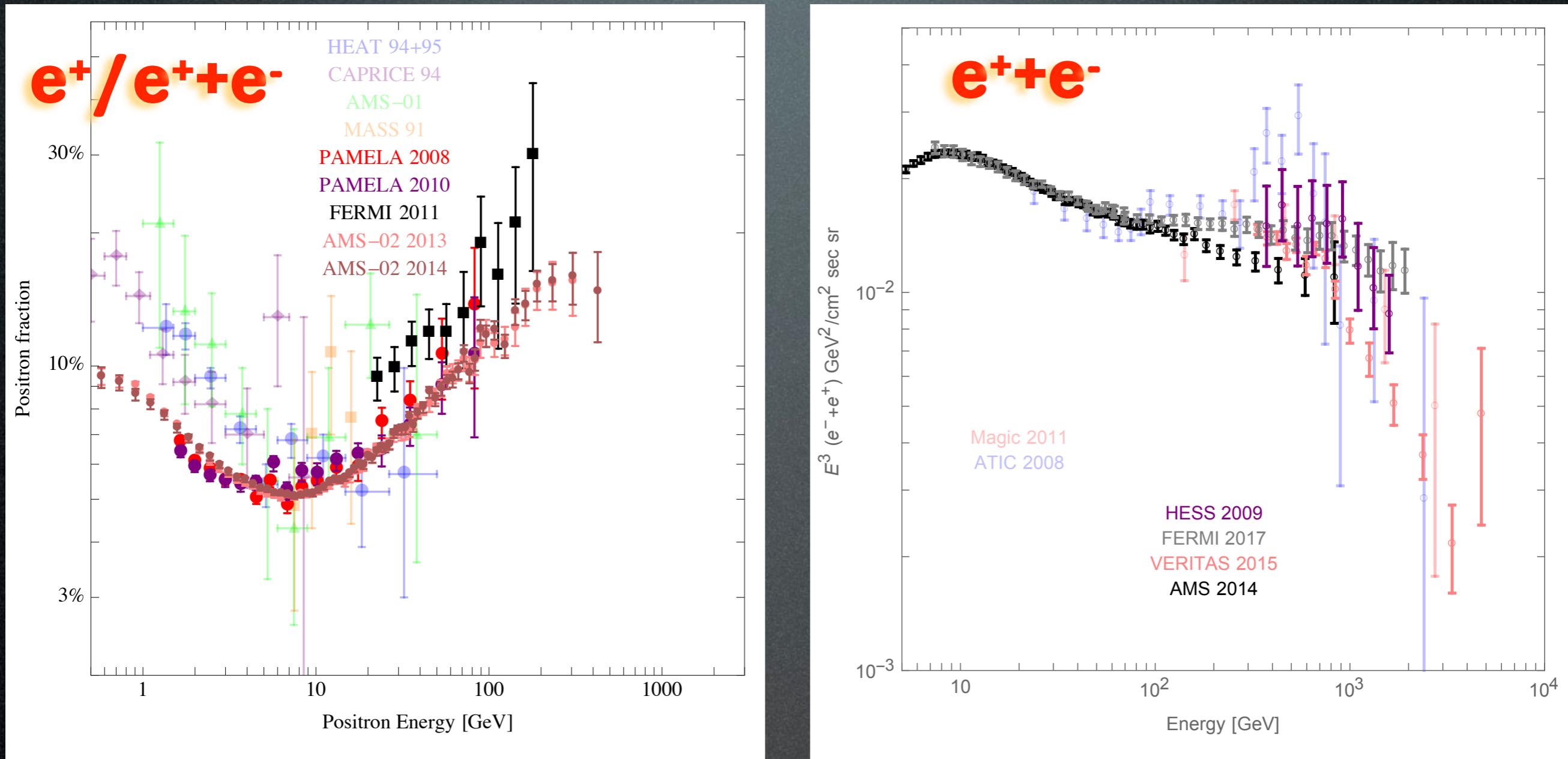
Data: leptons



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Data: leptons



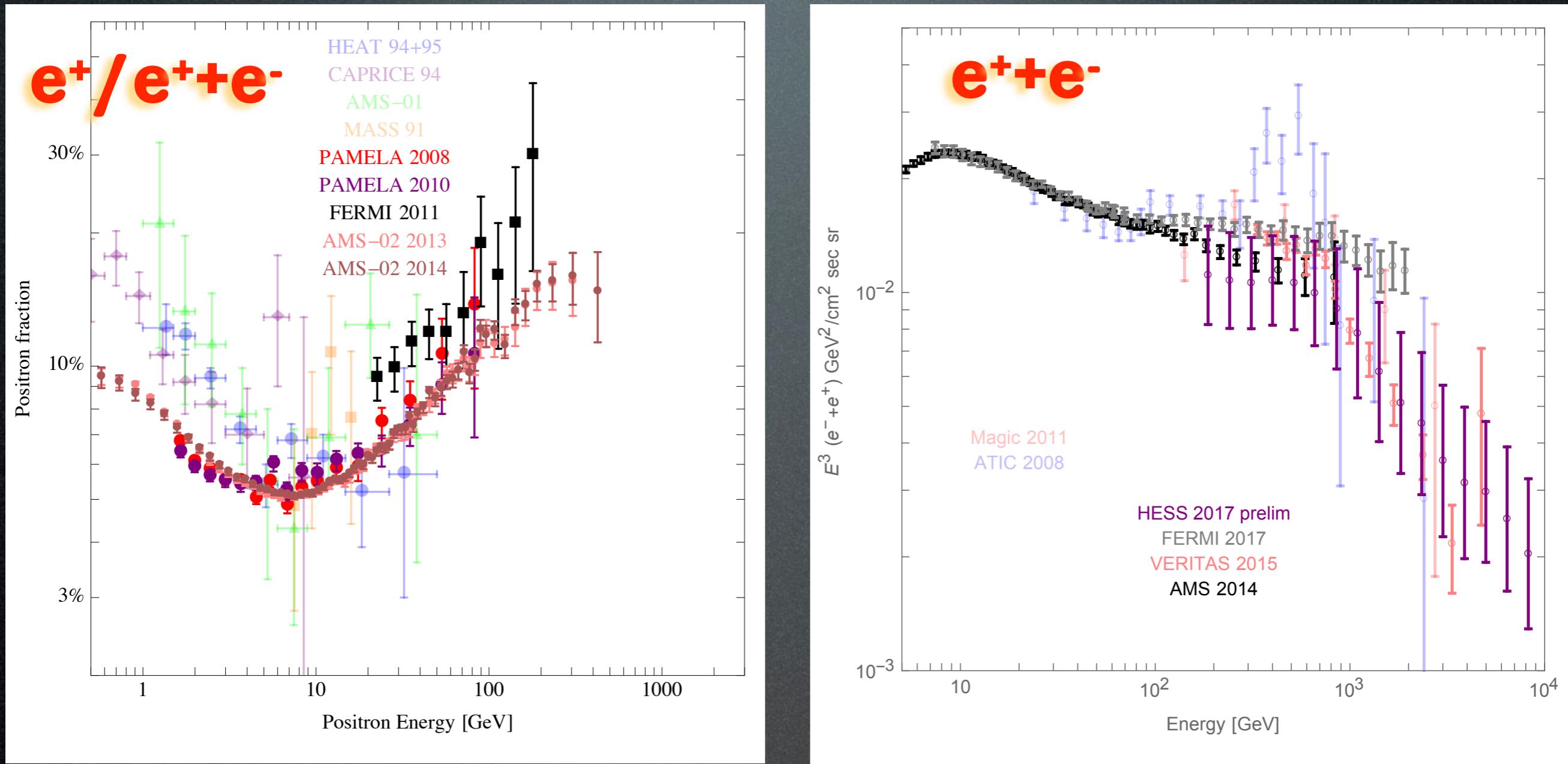
M. Cirelli - compilation ICRC 2015

Fermi Coll.
1704.07195
(PRD 96)

Below 100 GeV, the new LAT measurement differs from the previous one by 10–30%, as can be seen in Fig. 13. A large part of this difference below 30 GeV is due to the lack of correction in the previous analysis for the loss of CREs above the geomagnetic energy cutoff. After applying this correction, the remaining difference is 10–15% and is due to imperfections in the simulation that was used in the previous analysis (remnants of electronic signals from out-of-time particles were not simulated [34]).

M. Cirelli - compilation

Data: leptons

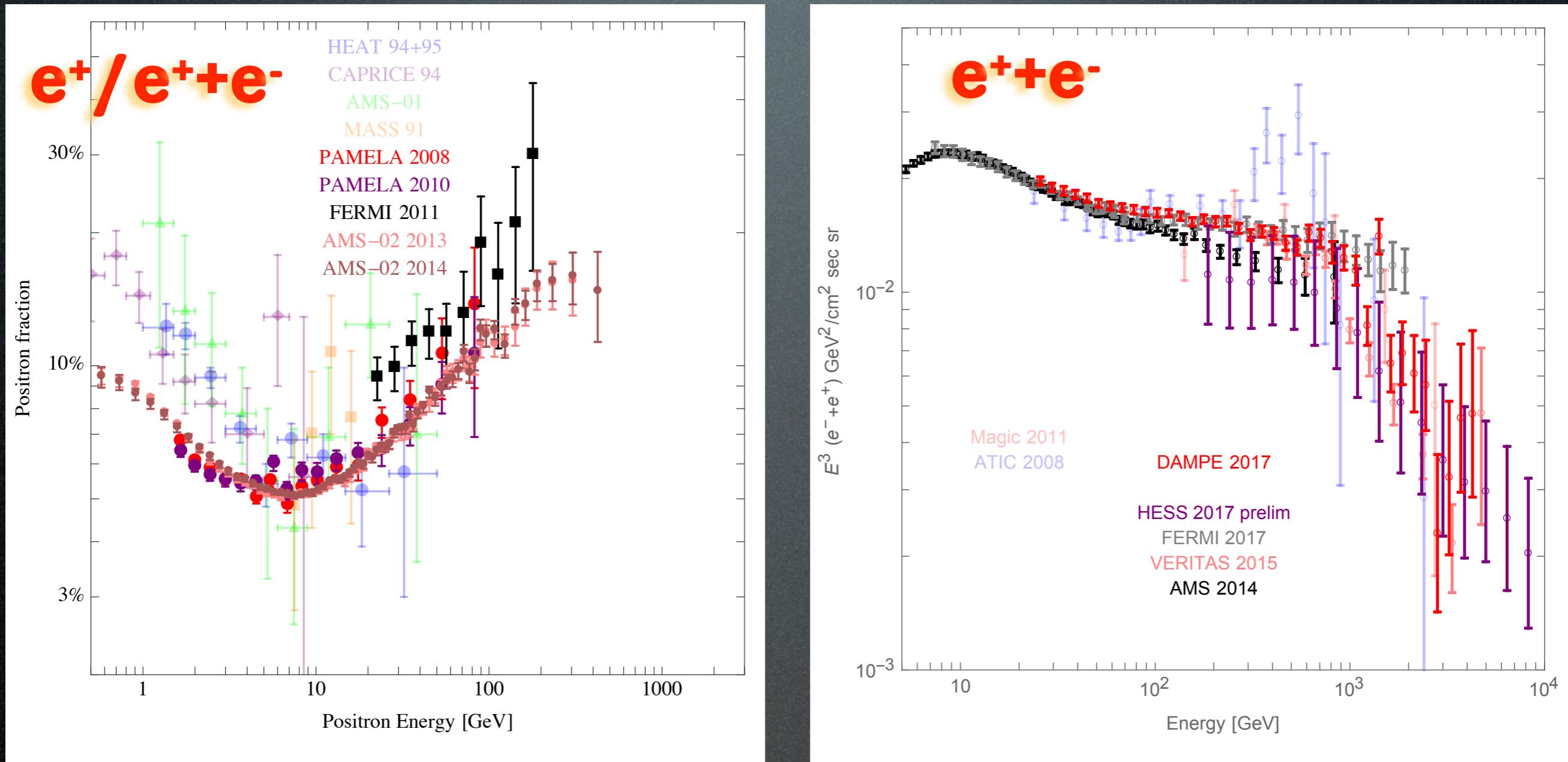


M. Cirelli - compilation ICRC 2015

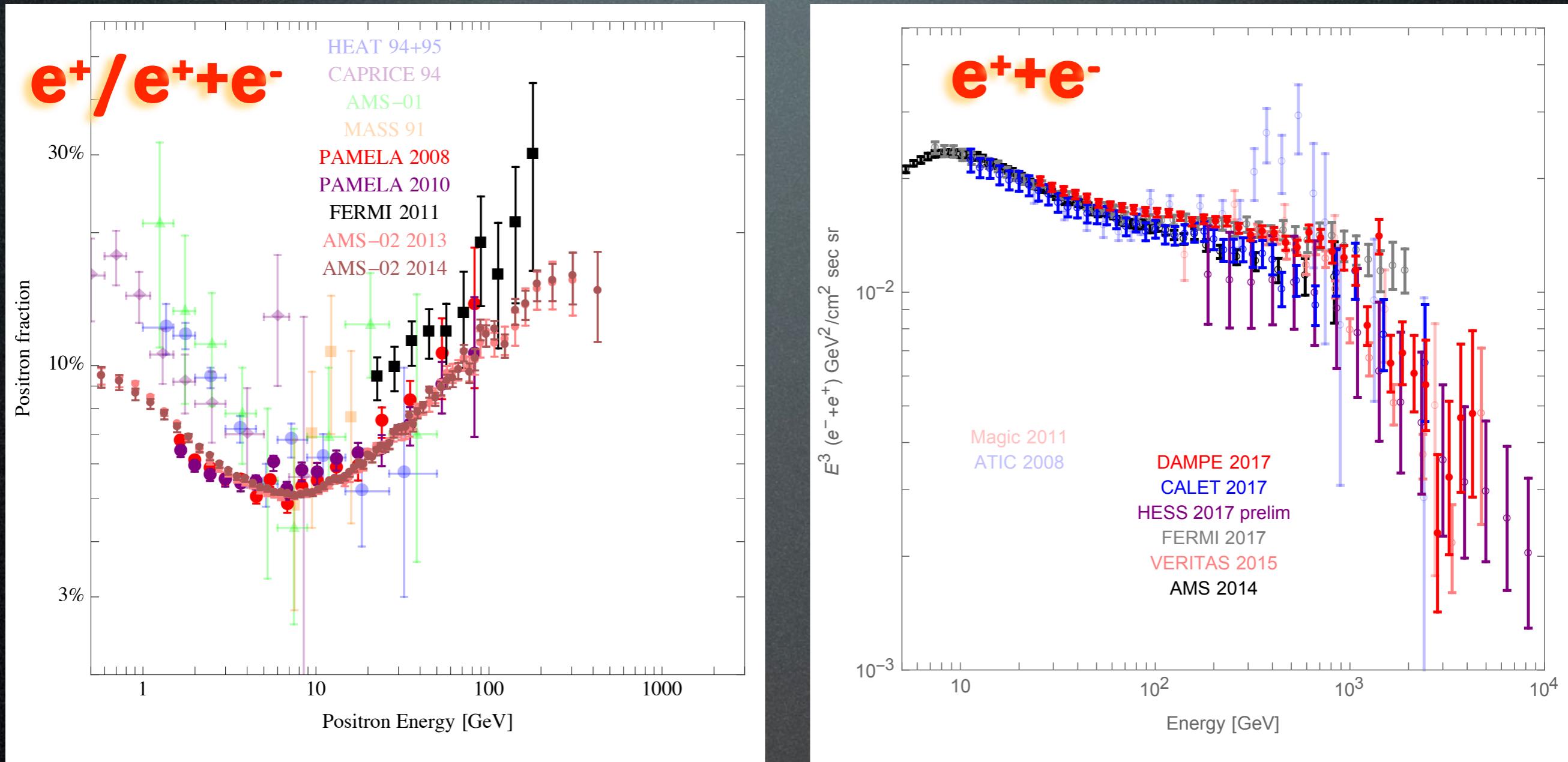
M. Cirelli - compilation

HESS Coll.
ICRC 2017
(D. Kerszberg)
no paper nor proceeding yet

Data: leptons



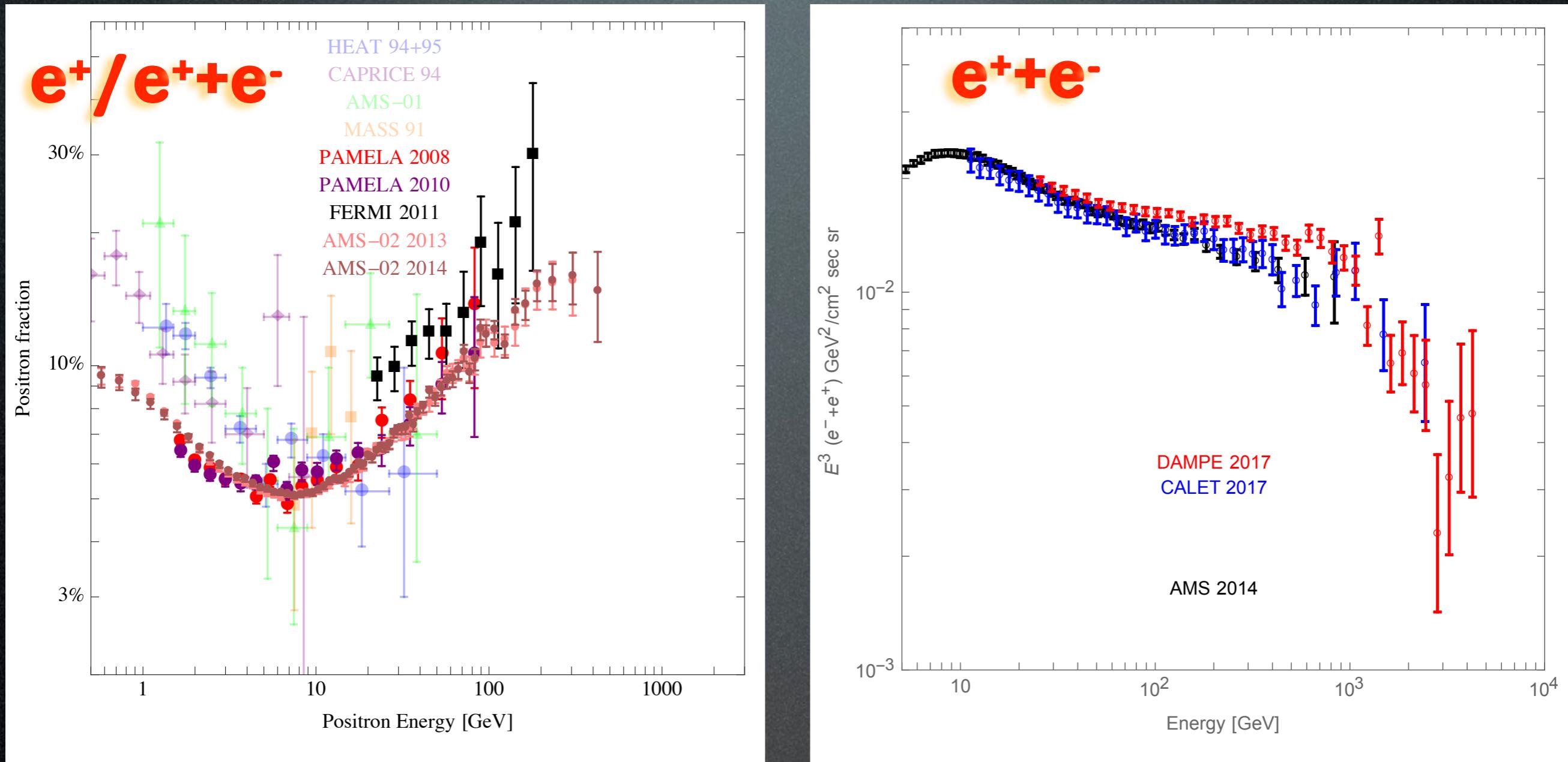
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M. Cirelli - compilation ICRC 2015

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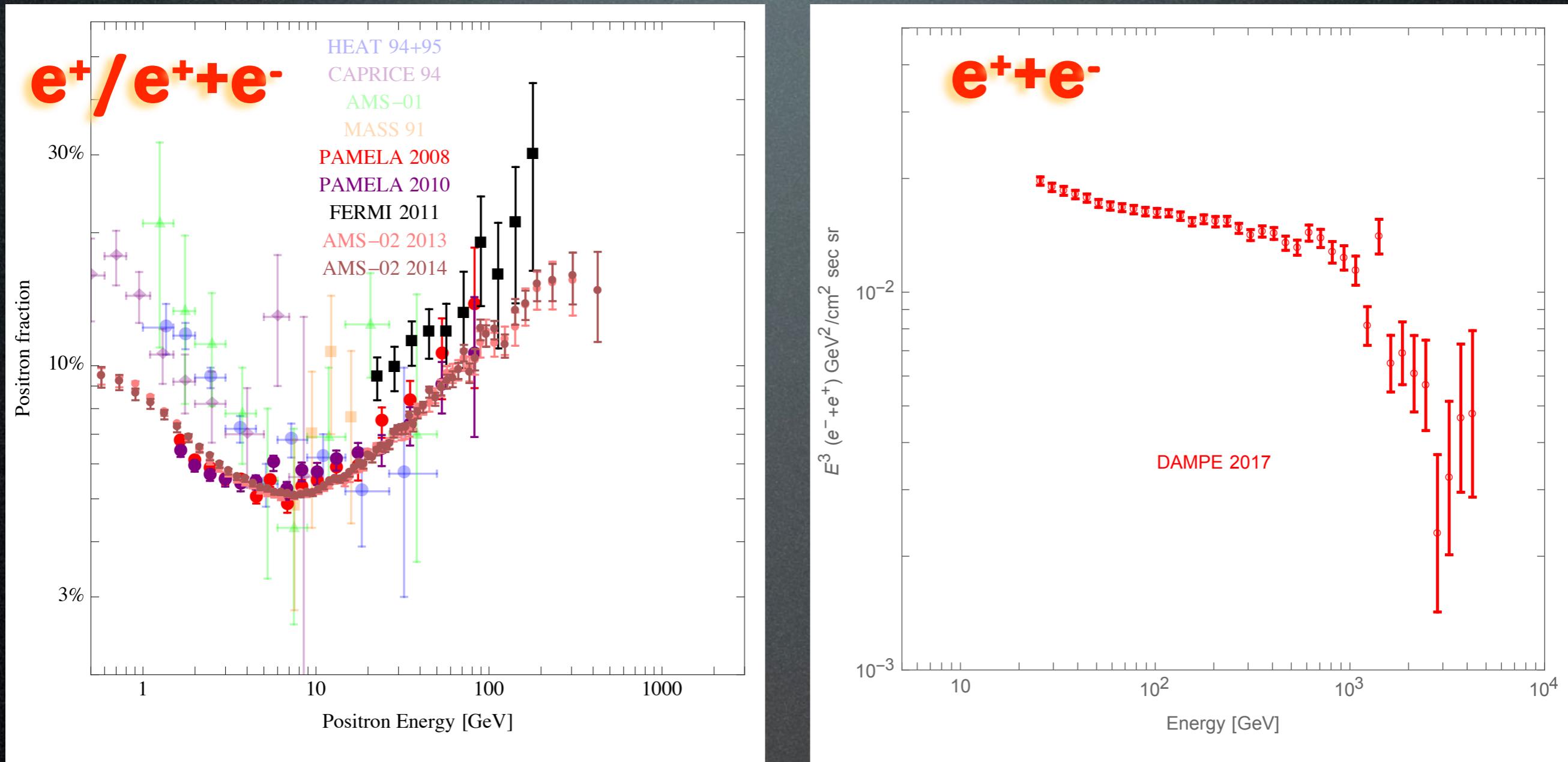
Data: leptons



M. Cirelli - compilation ICRC 2015

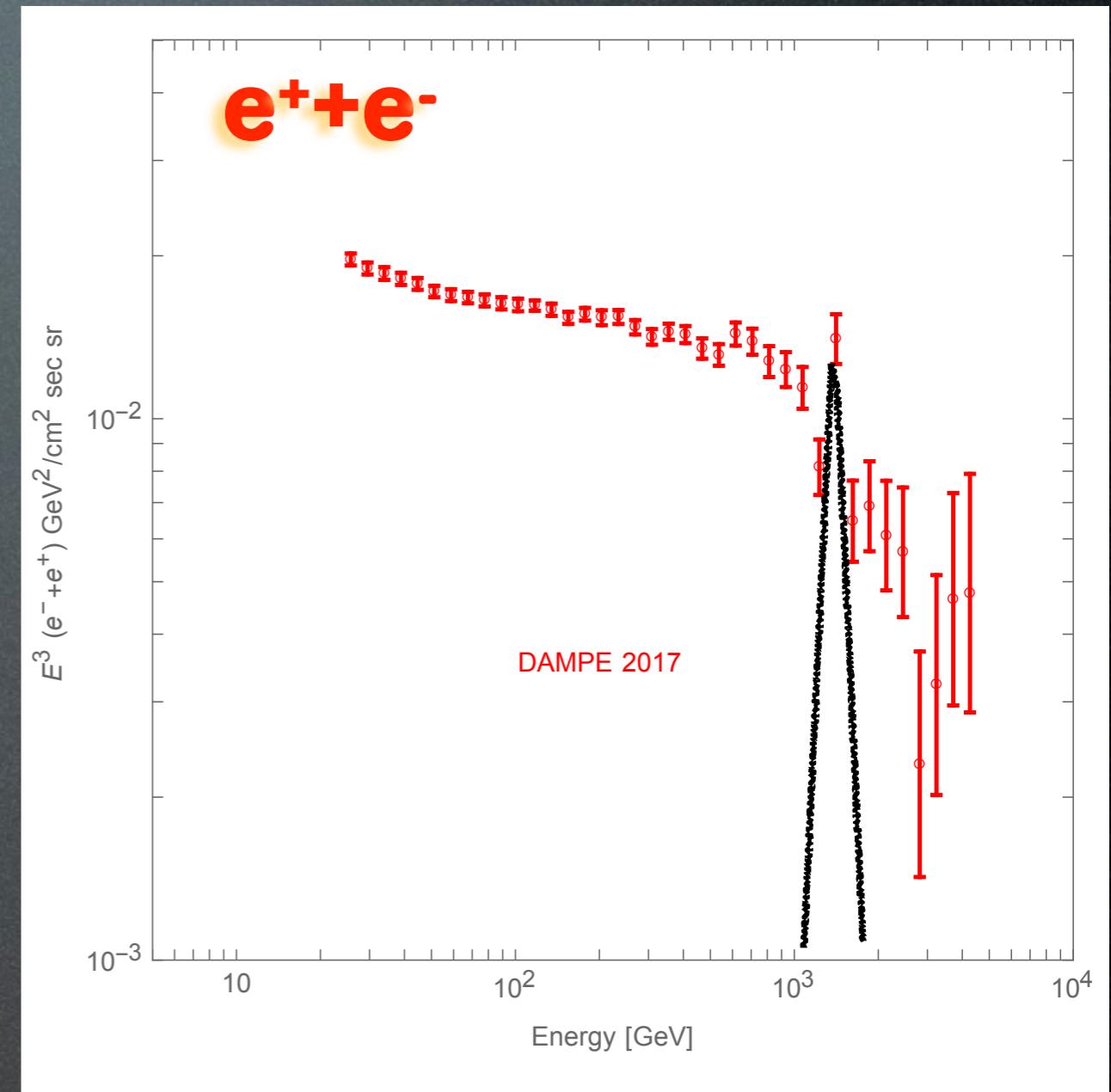
M. Cirelli - compilation

Data: leptons



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frenetic activity in December 2017
(38 papers / 29 days)

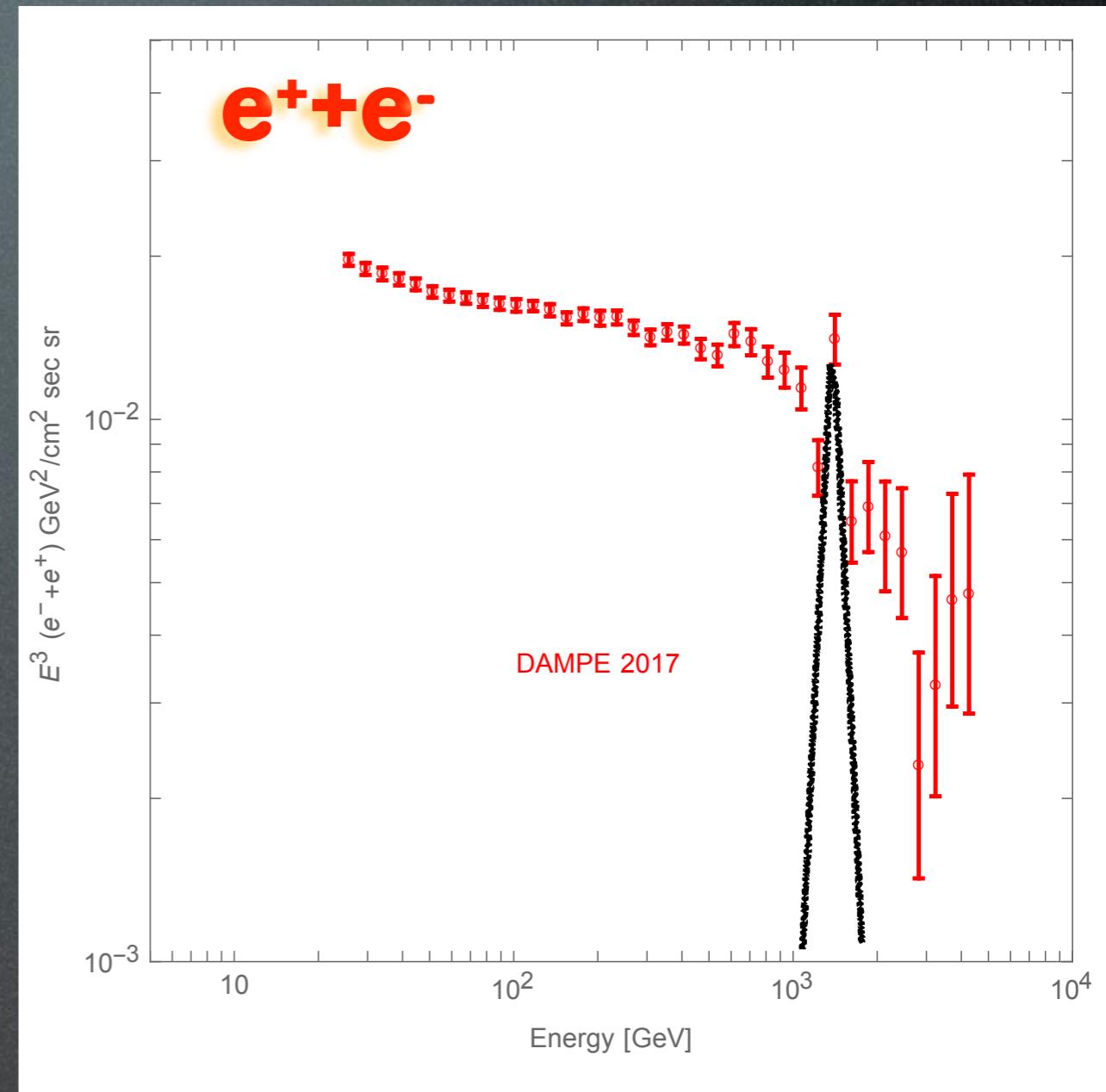


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Data: leptons

frenetic activity in December 2017
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- leptonic channel (e^+e^- or $\mu^+\mu^-$)
- nearby (0.2 kpc) huge ($10^8 M_{\text{sun}}$) DM clump
 - for large flux
 - for peaked spectrum



M. Cirelli - compilation

DM detection

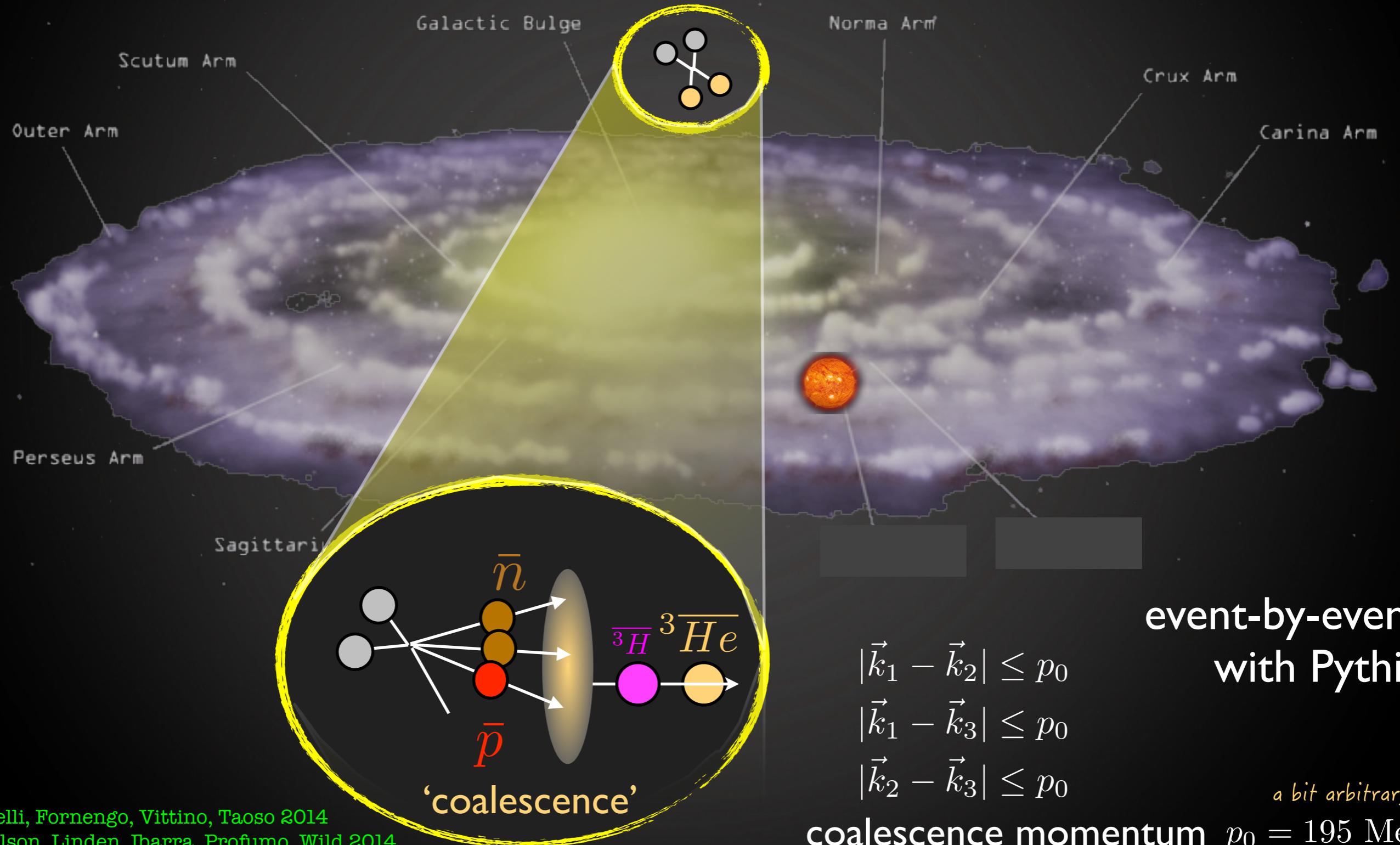
direct detection

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?

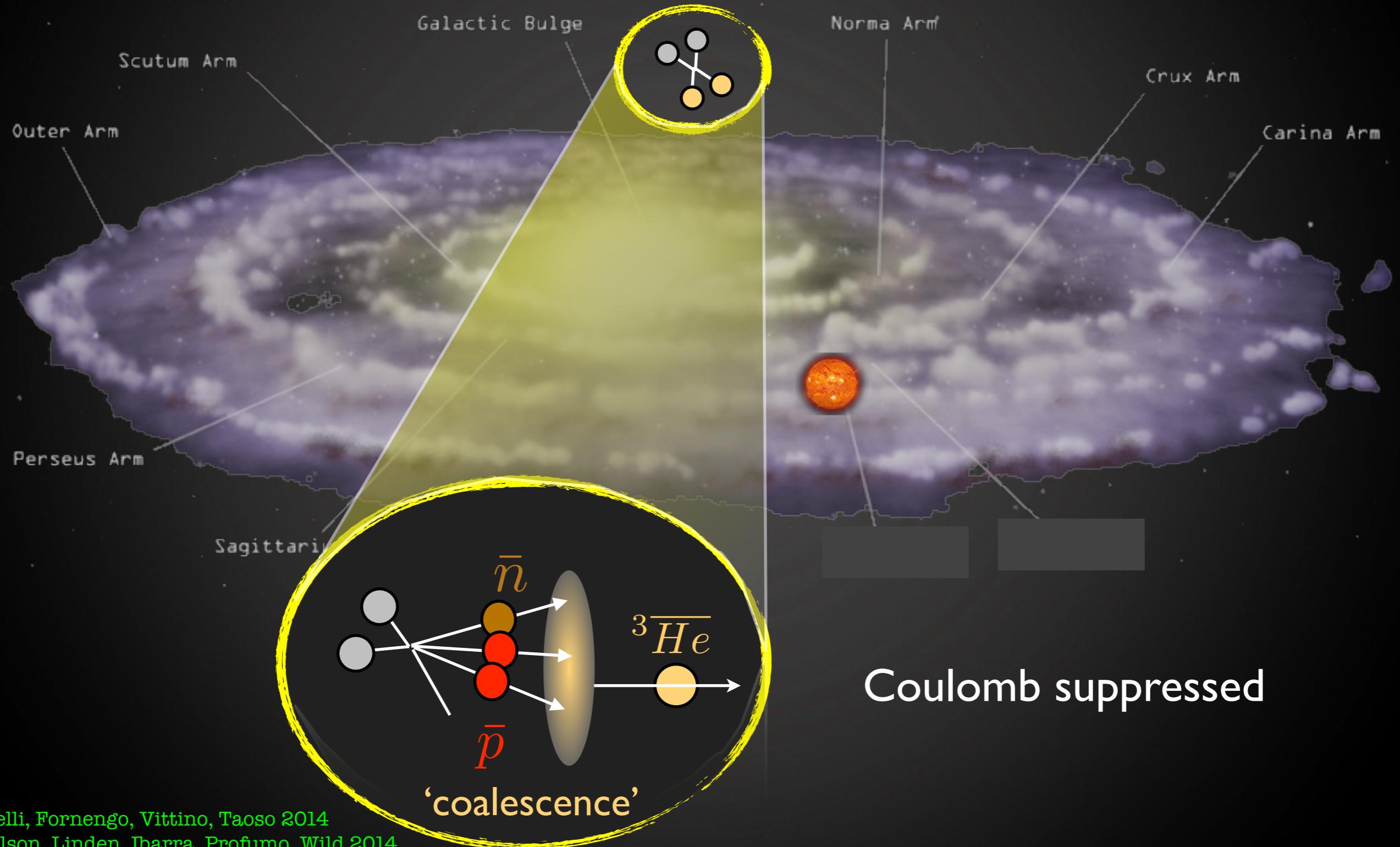
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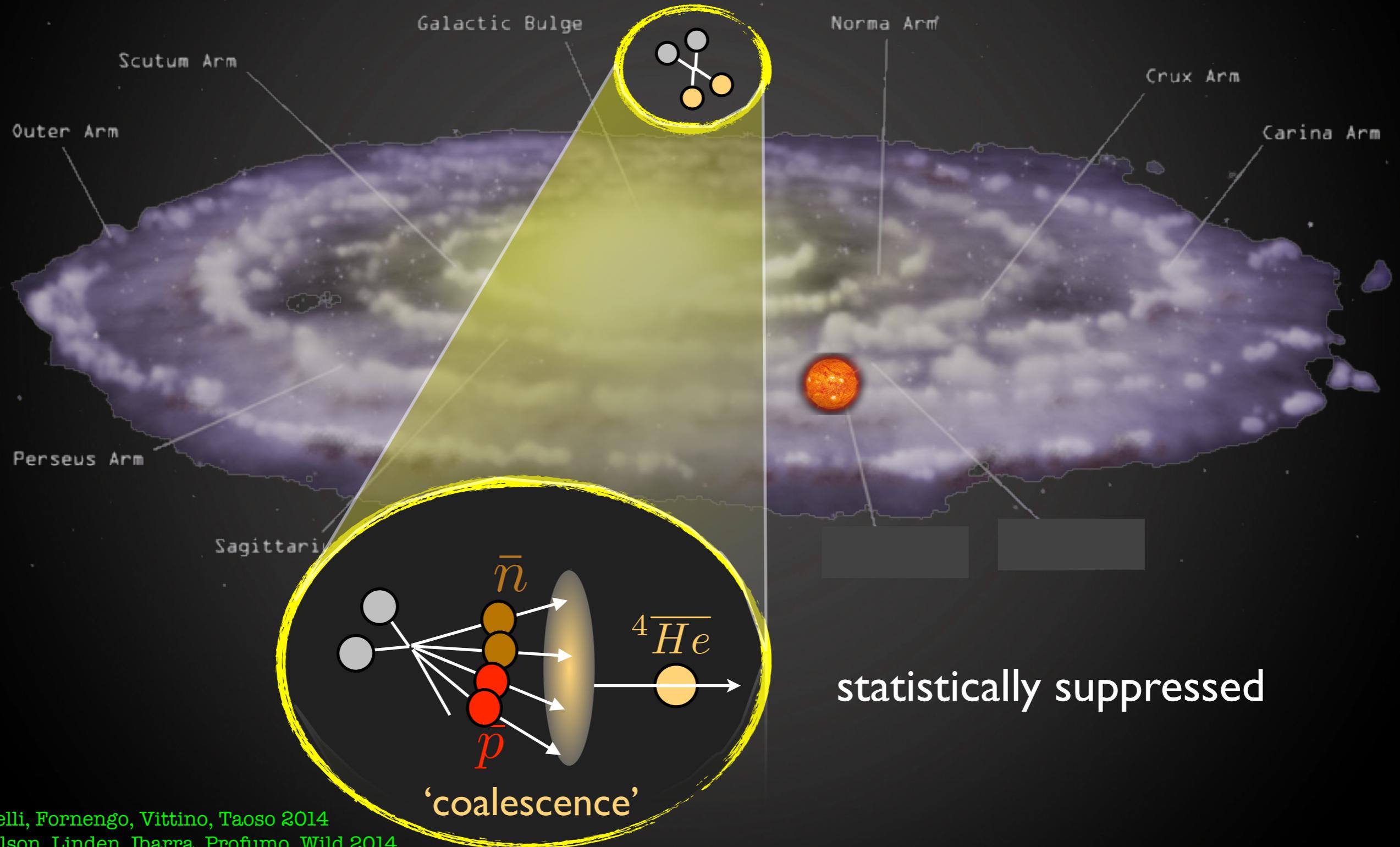
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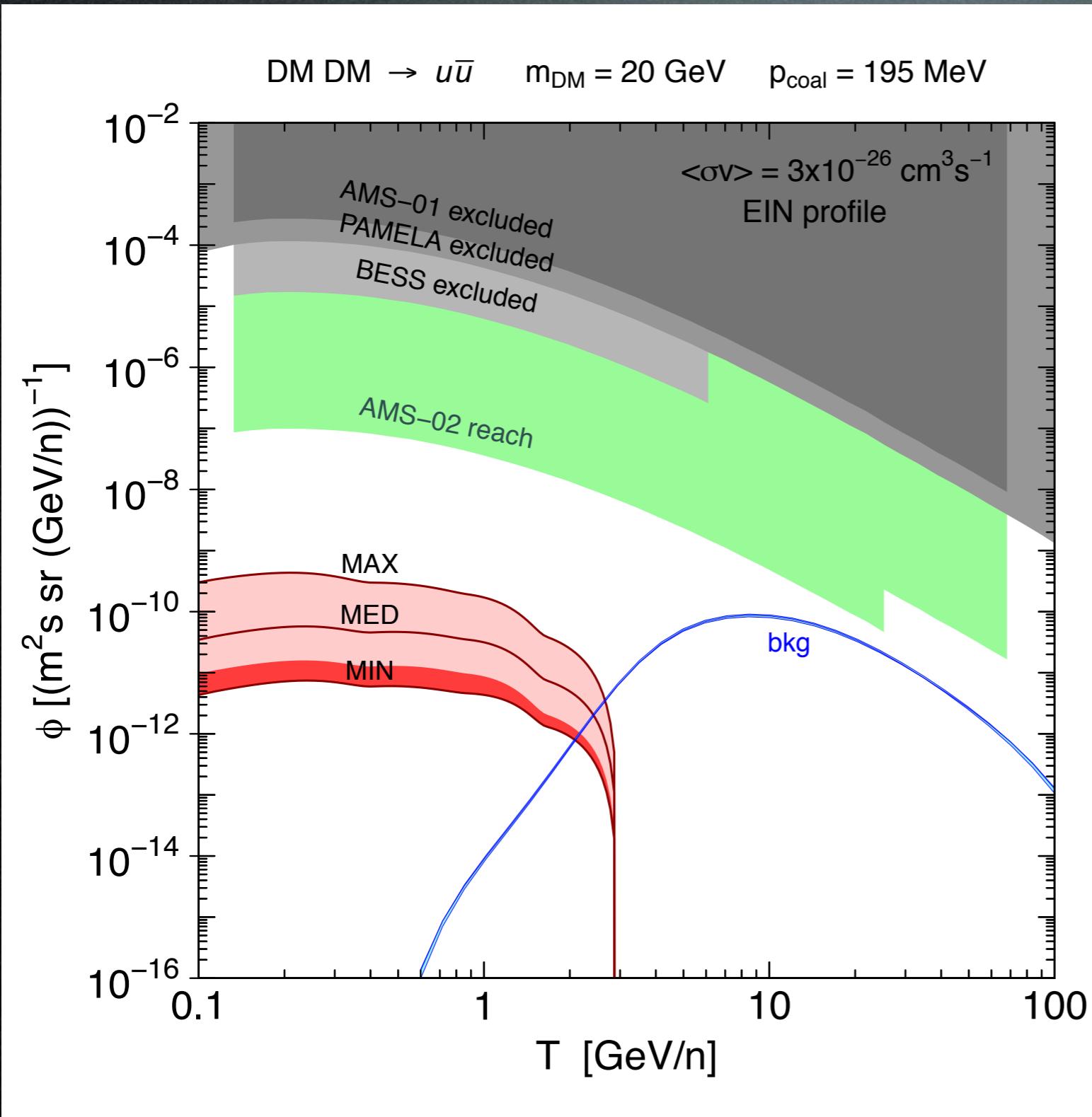
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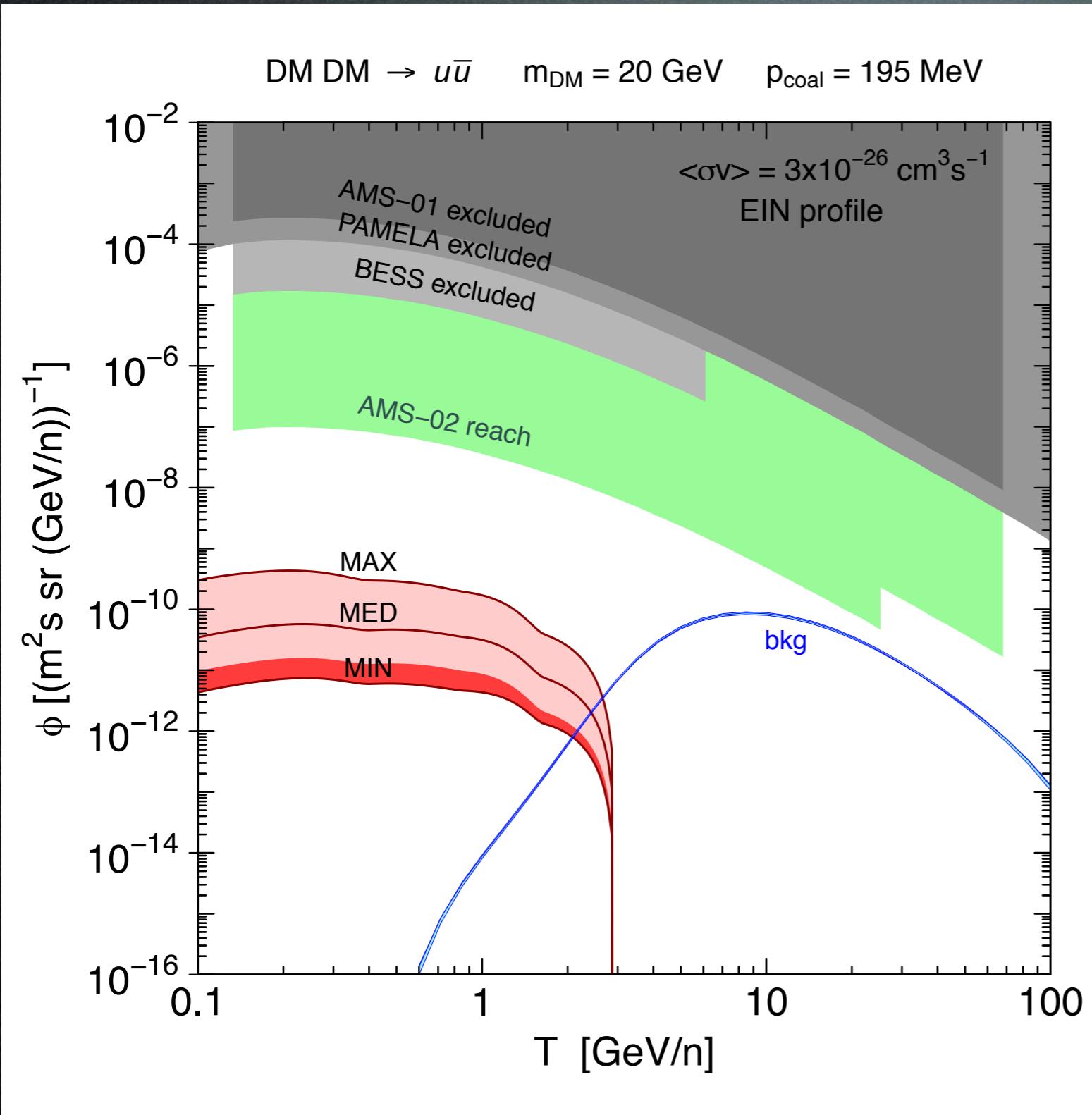
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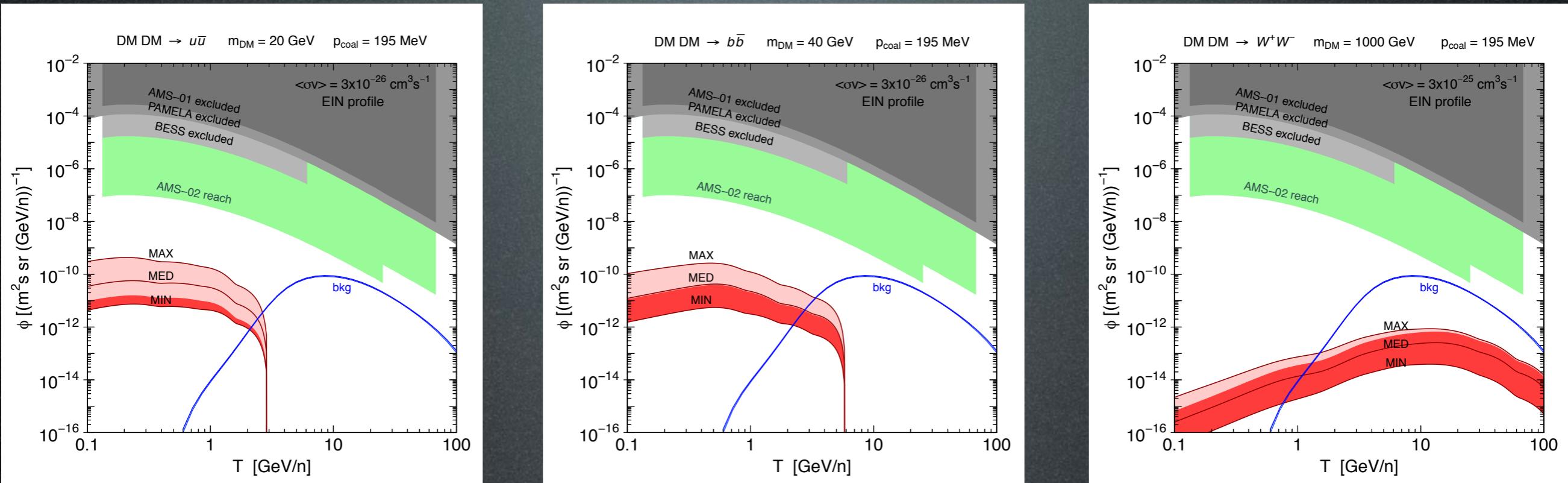
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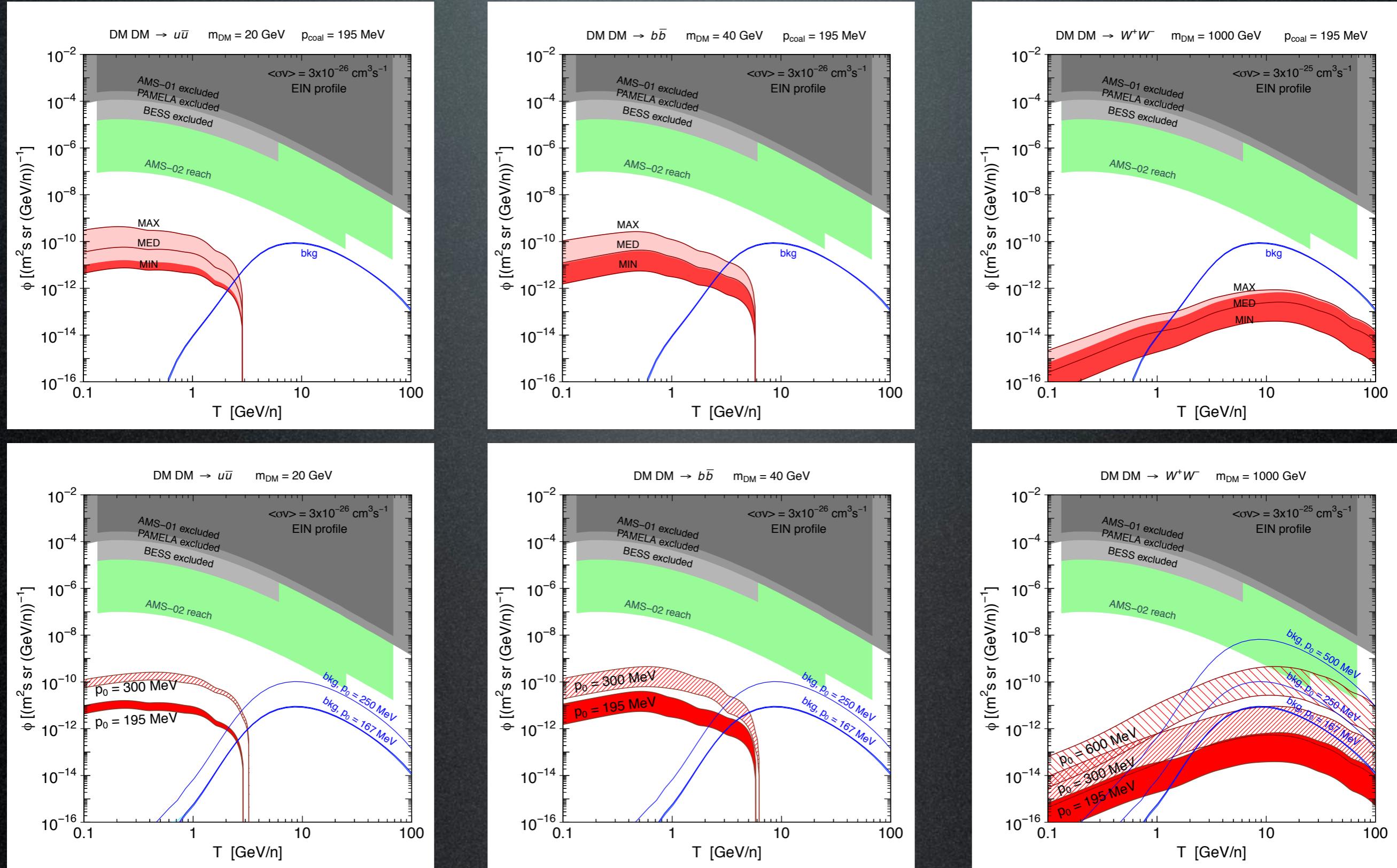
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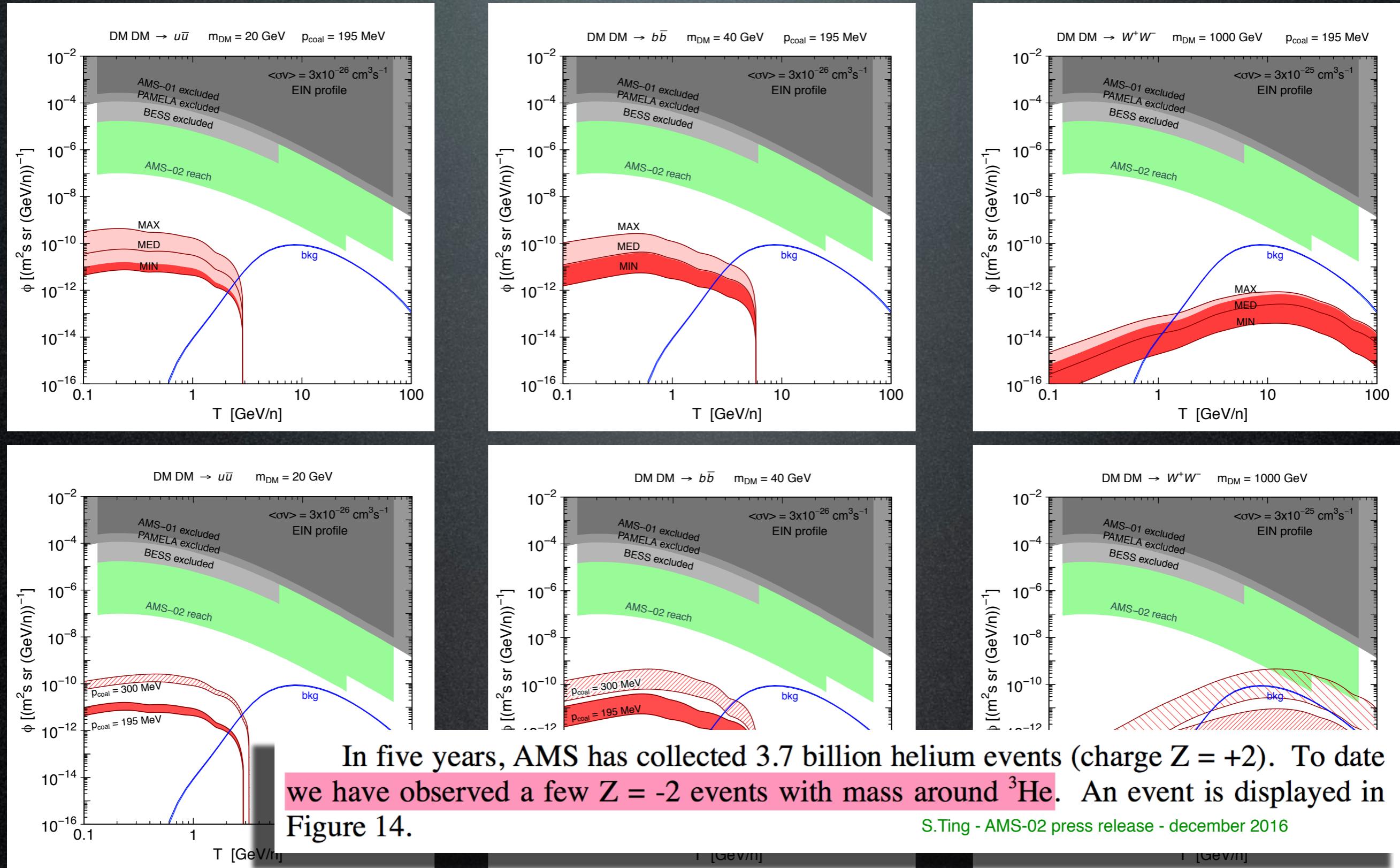
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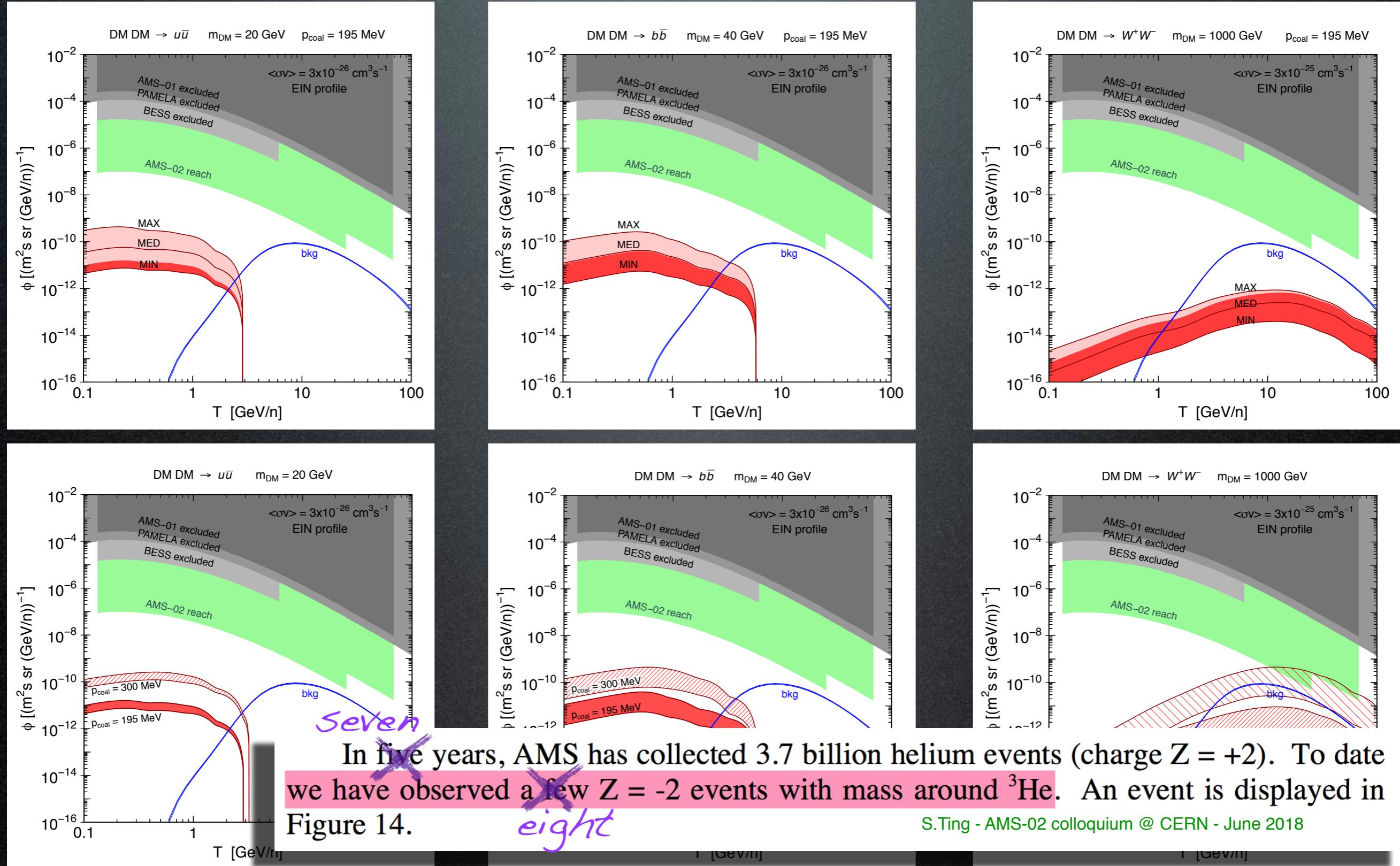
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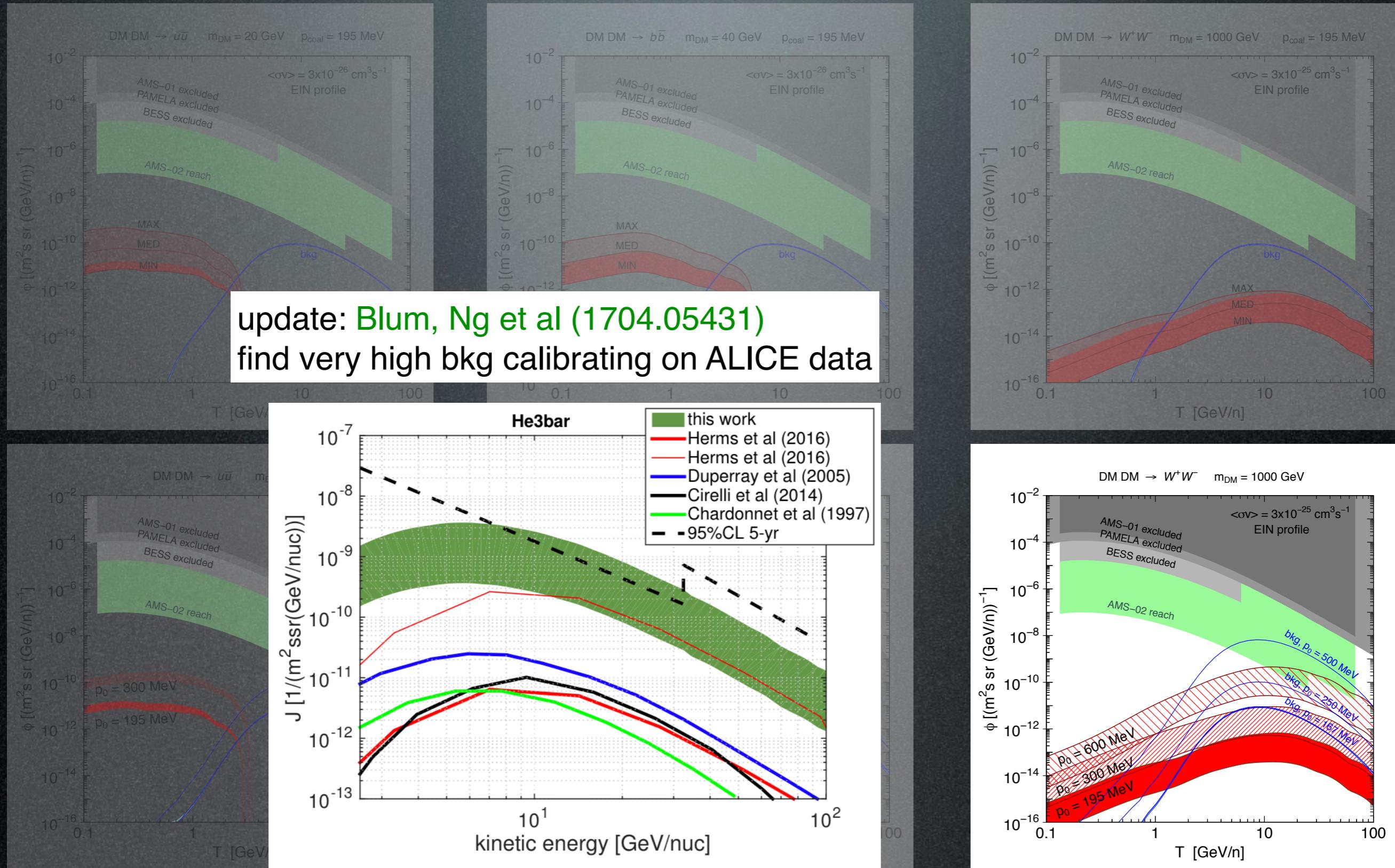
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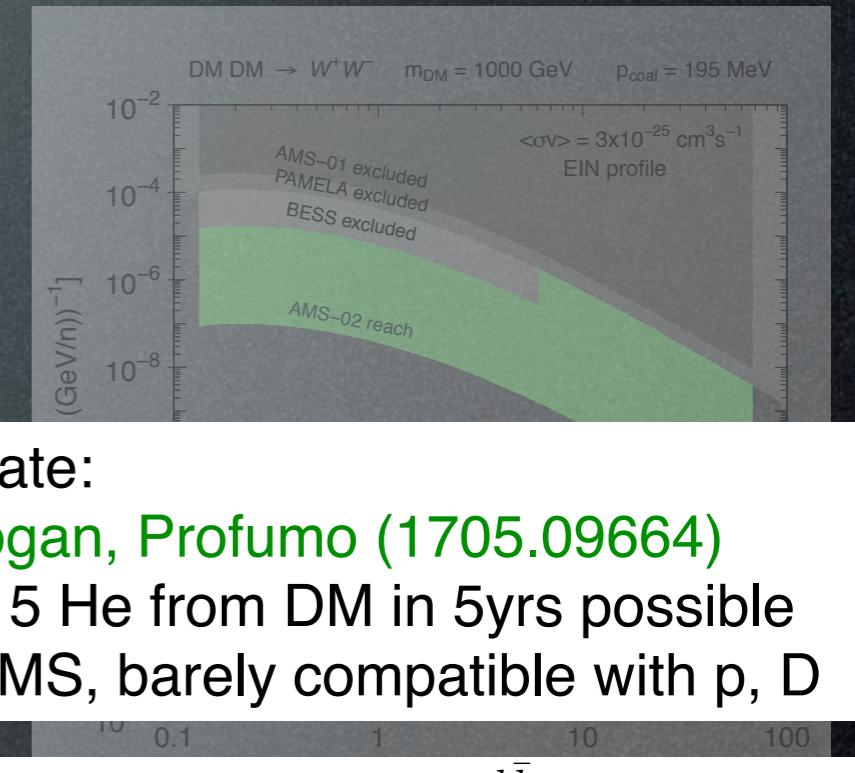
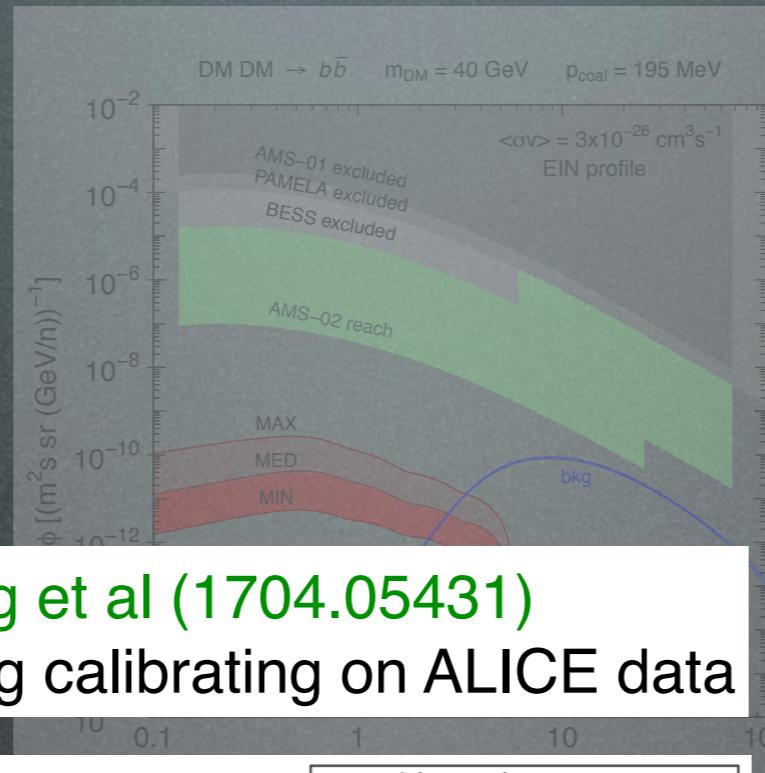
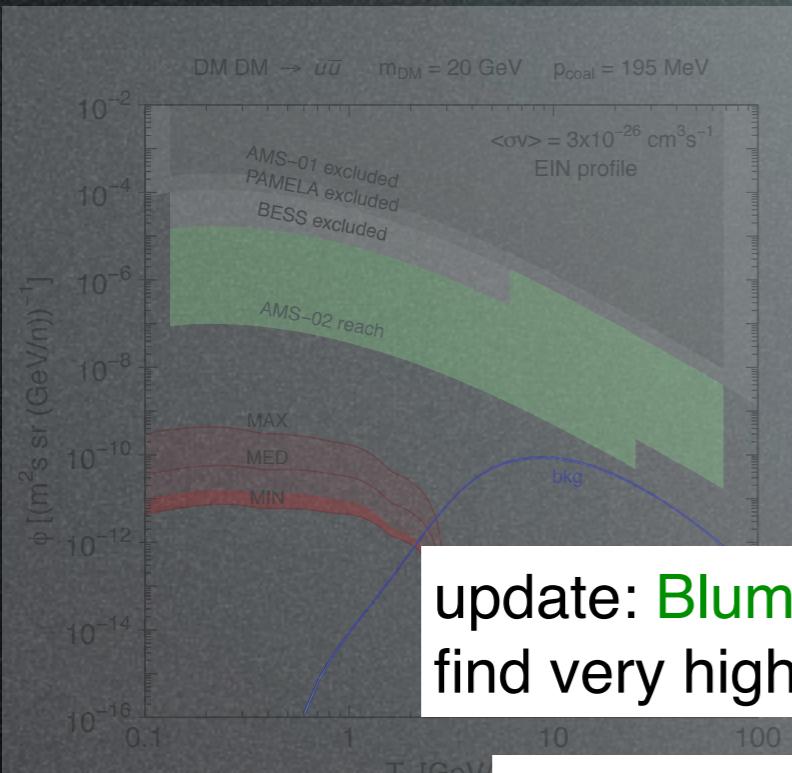
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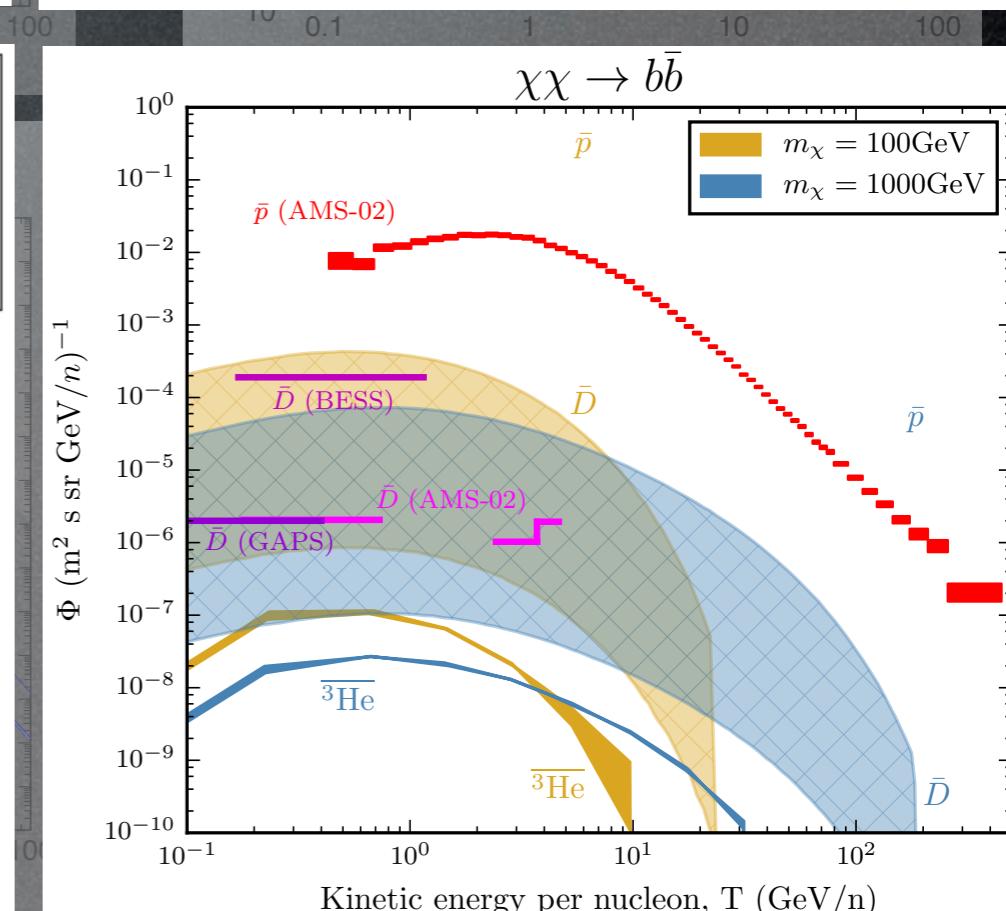
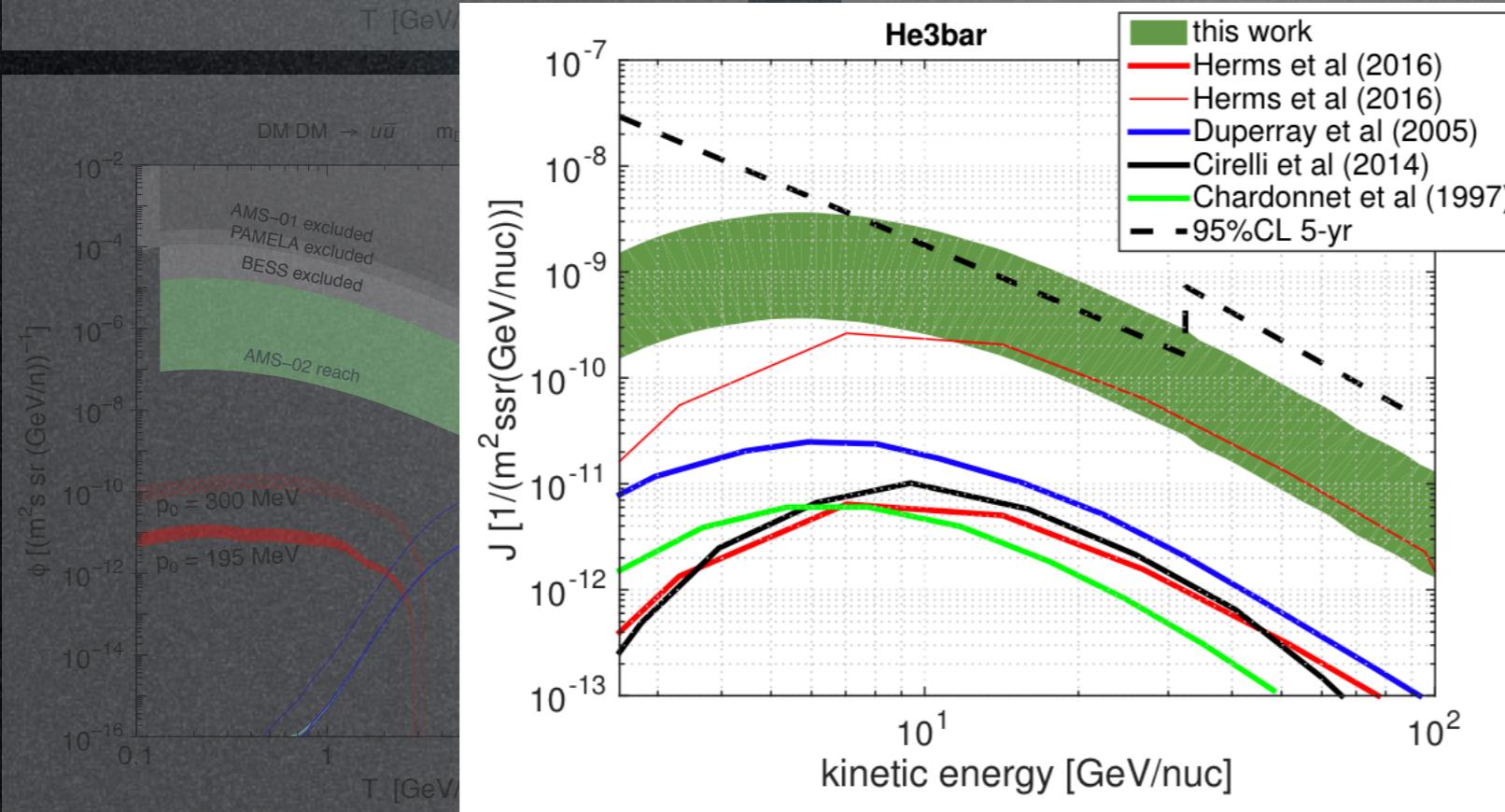
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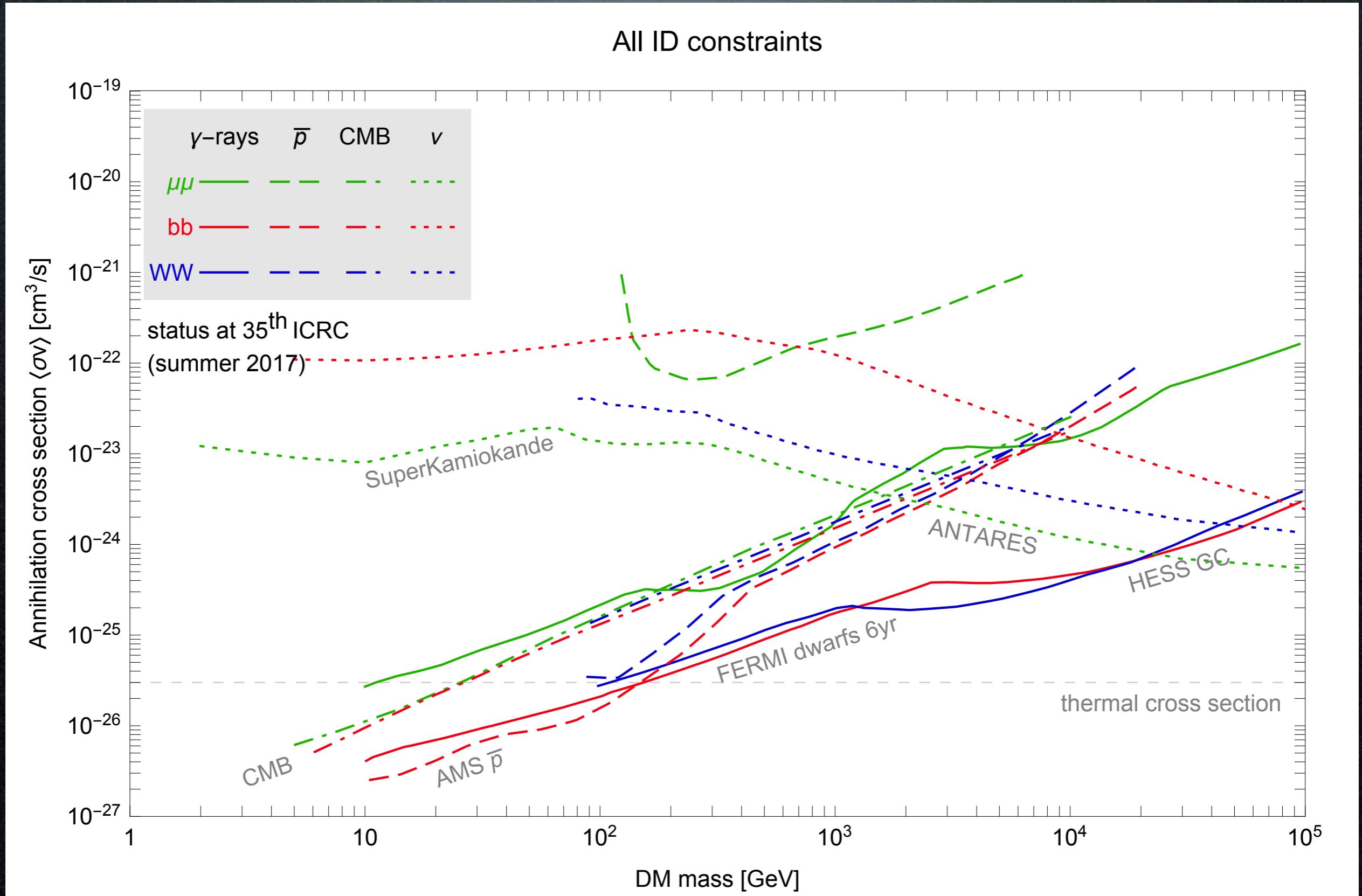


update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data

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



Comparing all bounds



Conclusions

DM not seen yet (^{Damn!...})

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ID with cosmic rays is in principle
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in e^\pm : long standing ‘excesses’

in \bar{p} : still large uncertainties

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Solution:

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Solution:

- multimessenger
- switch-off astrophysics

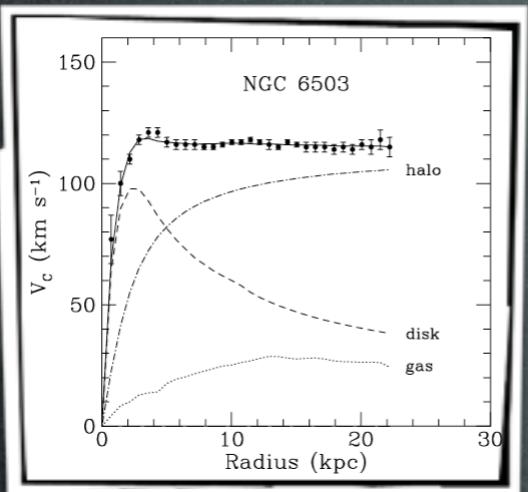
Back up slides

Introduction

DM exists

Introduction

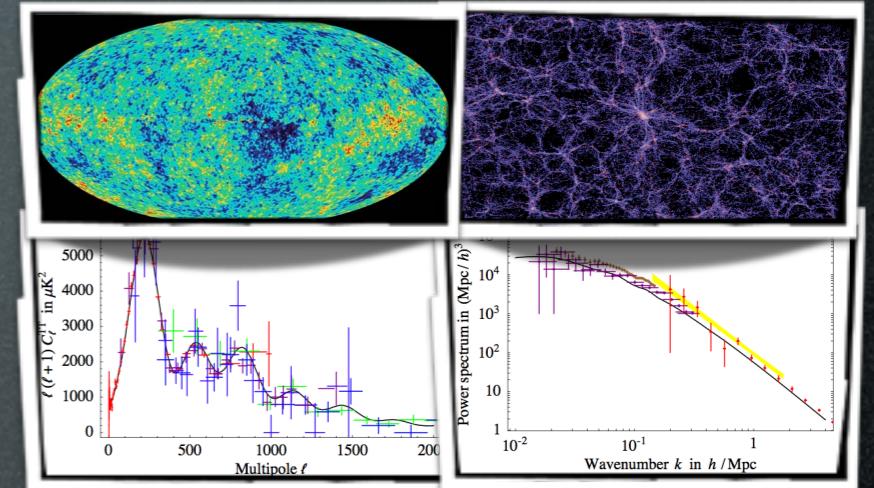
DM exists



galactic rotation curves



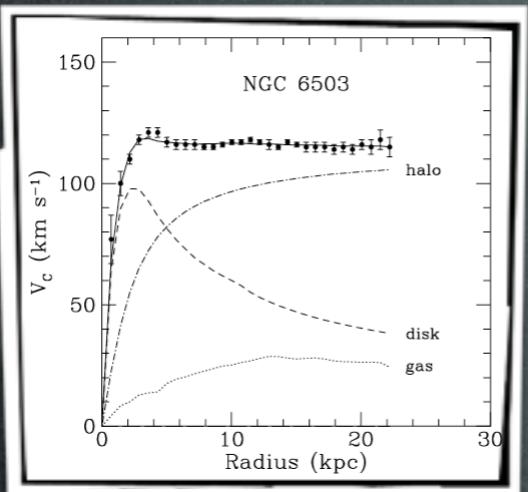
weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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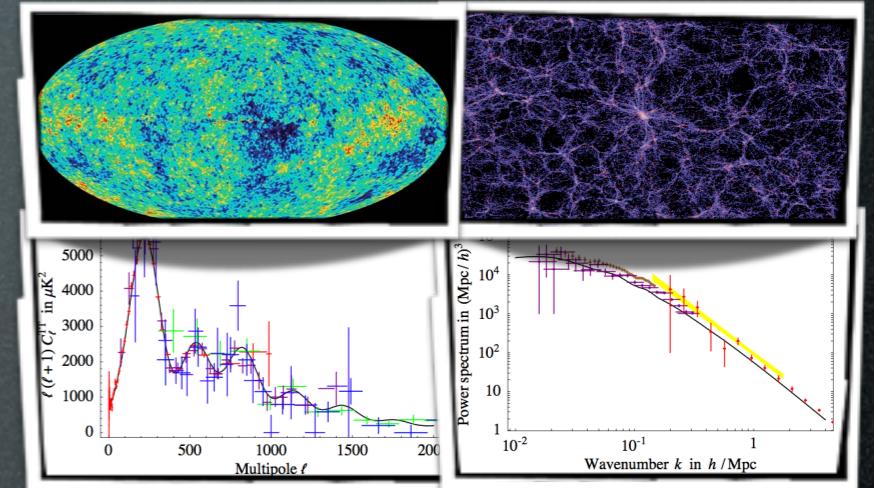
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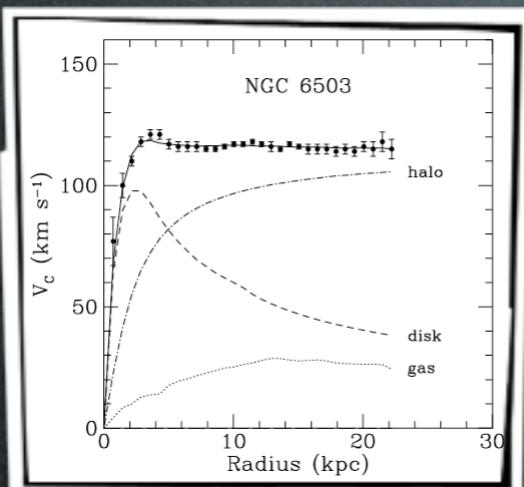


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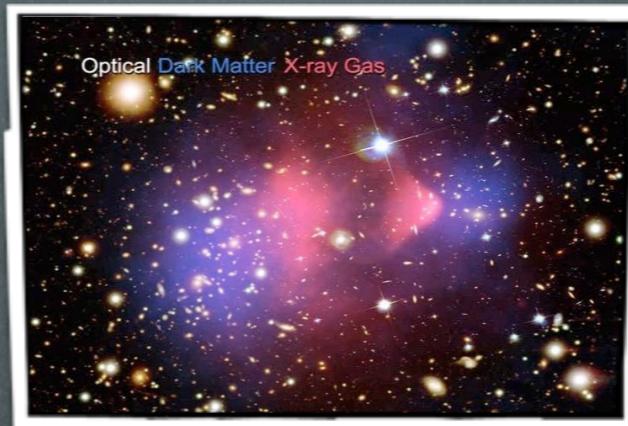
DM is a neutral, very long lived,
feebly interacting particle.

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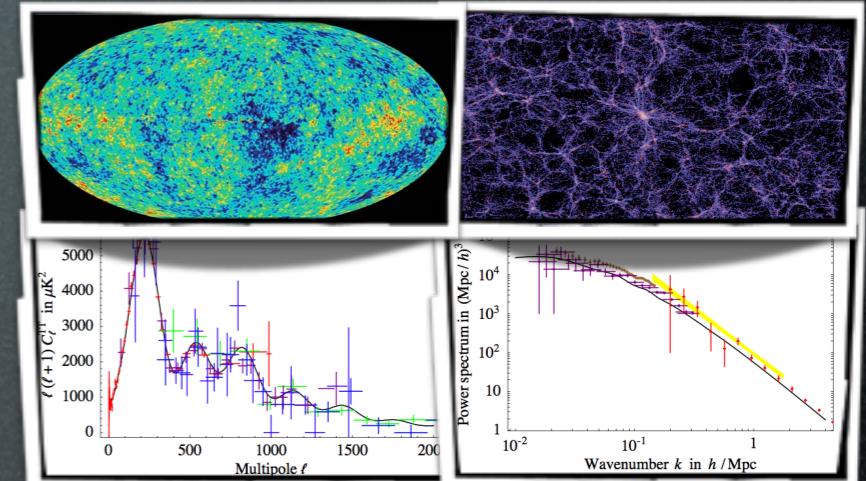
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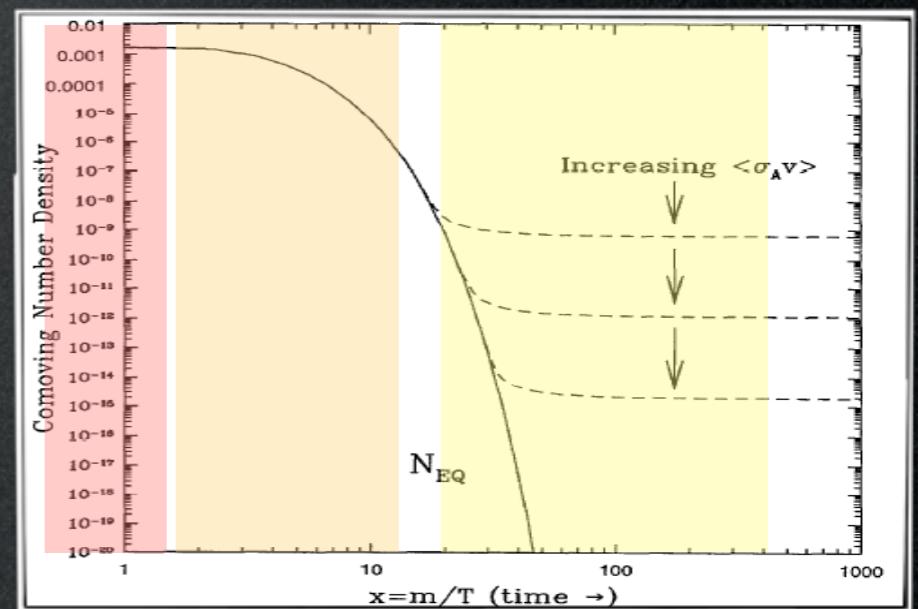


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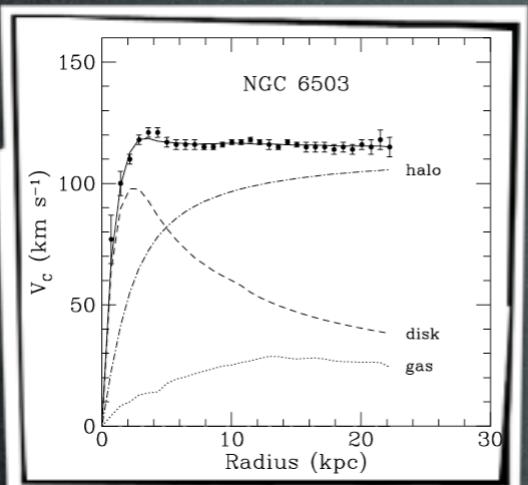
Some of us believe in the **WIMP** miracle.

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



Introduction

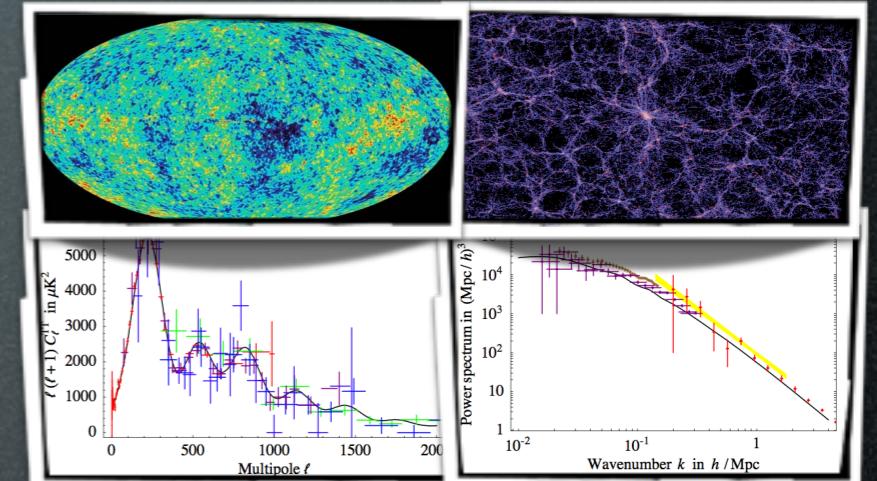
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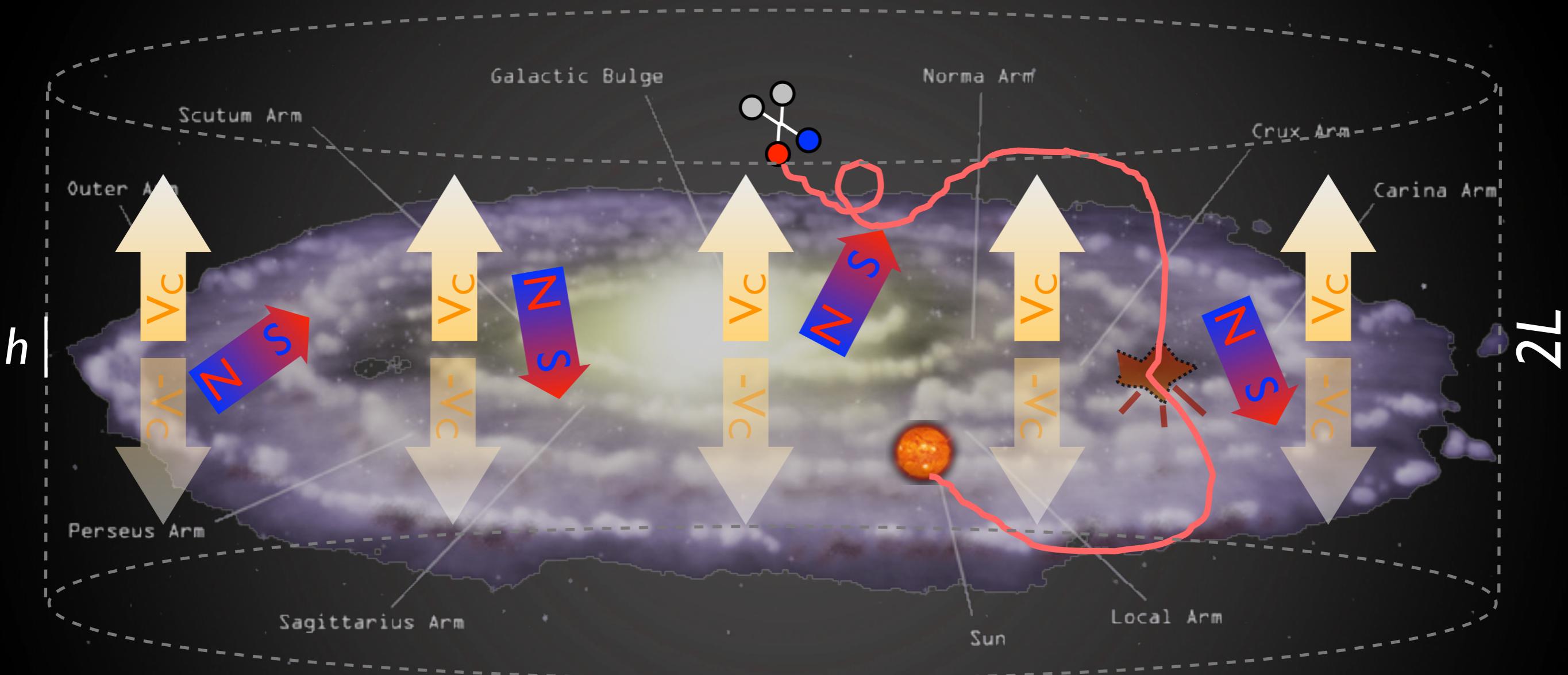
'precision cosmology' (CMB, LSS)

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

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

Indirect Detection: charged CRs

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

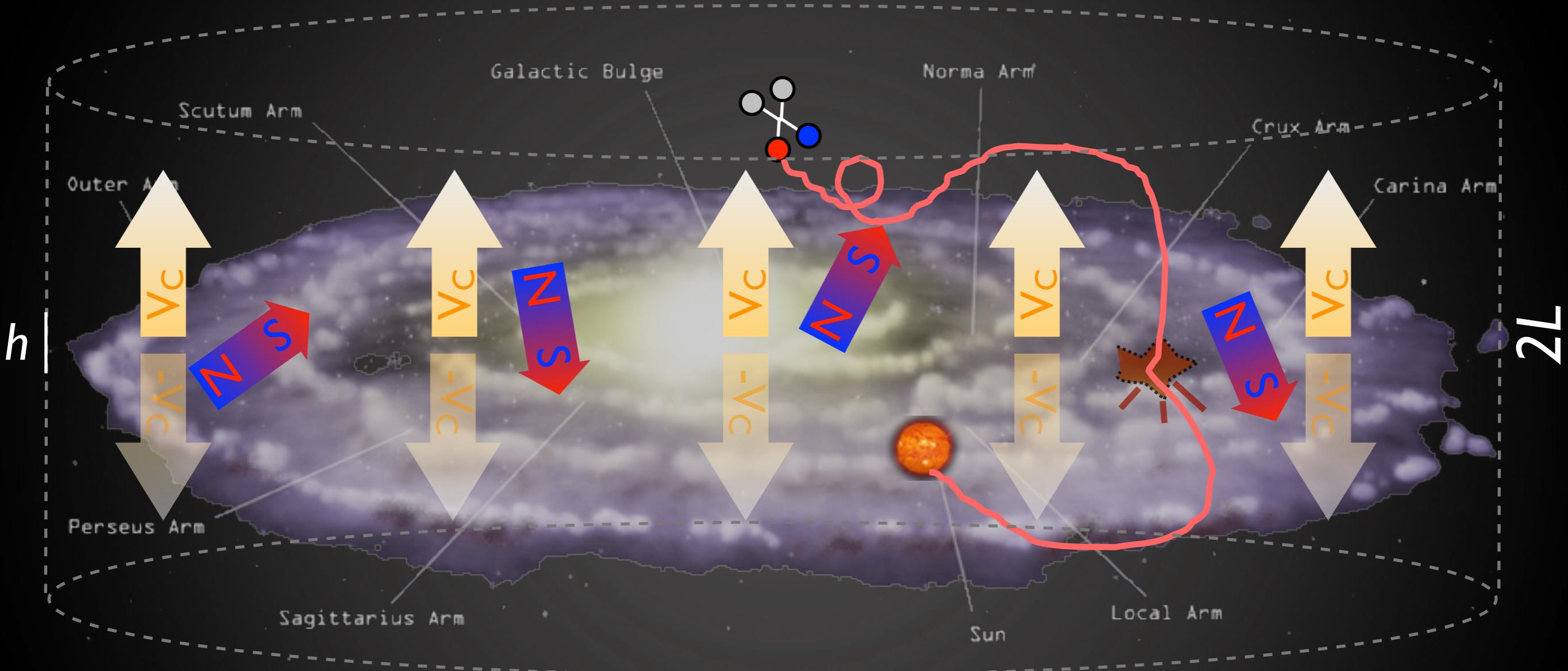


What sets the overall expected flux?

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

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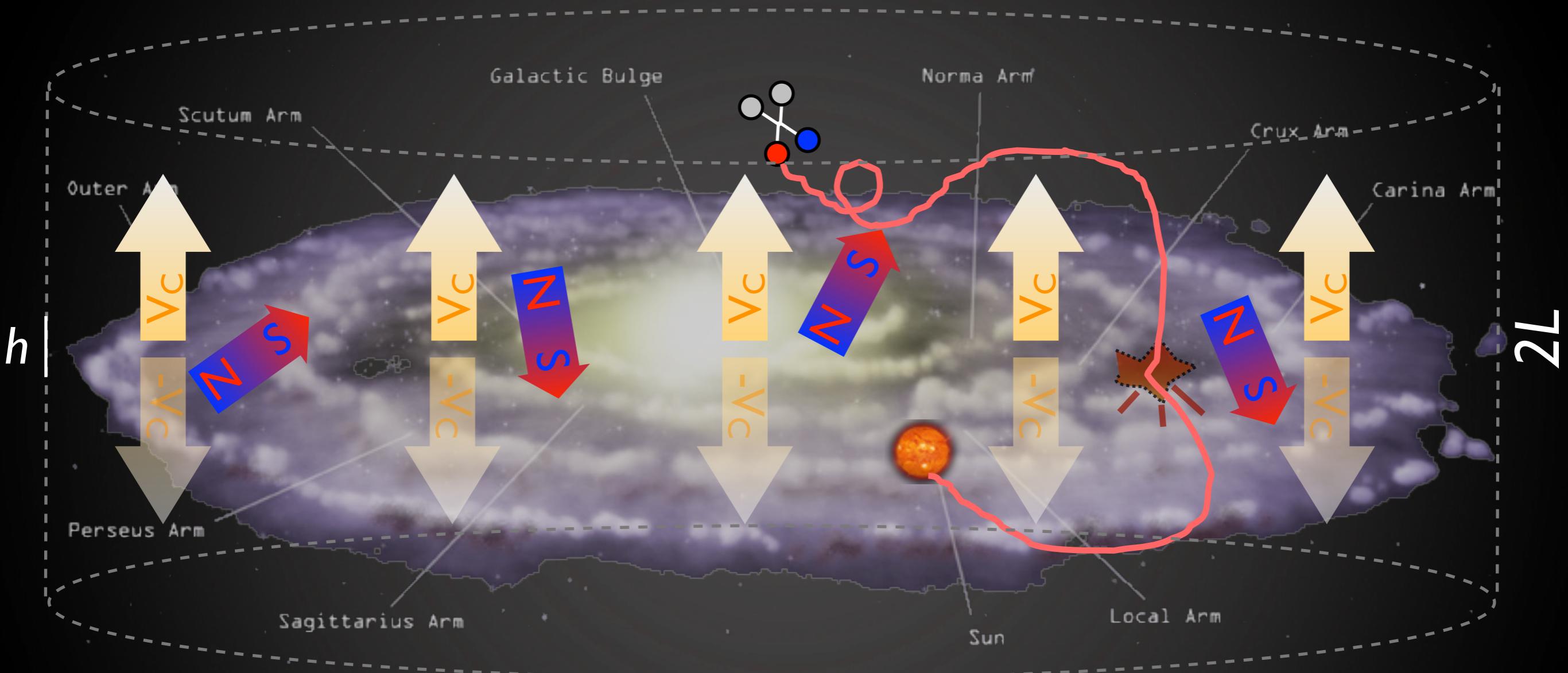
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astro&
cosmo

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What sets the overall expected flux?

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astro&cosmo

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

DM halo profiles

From N-body numerical simulations:

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

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

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

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

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

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

6 profiles:

cuspy: **NFW**, **Moore**

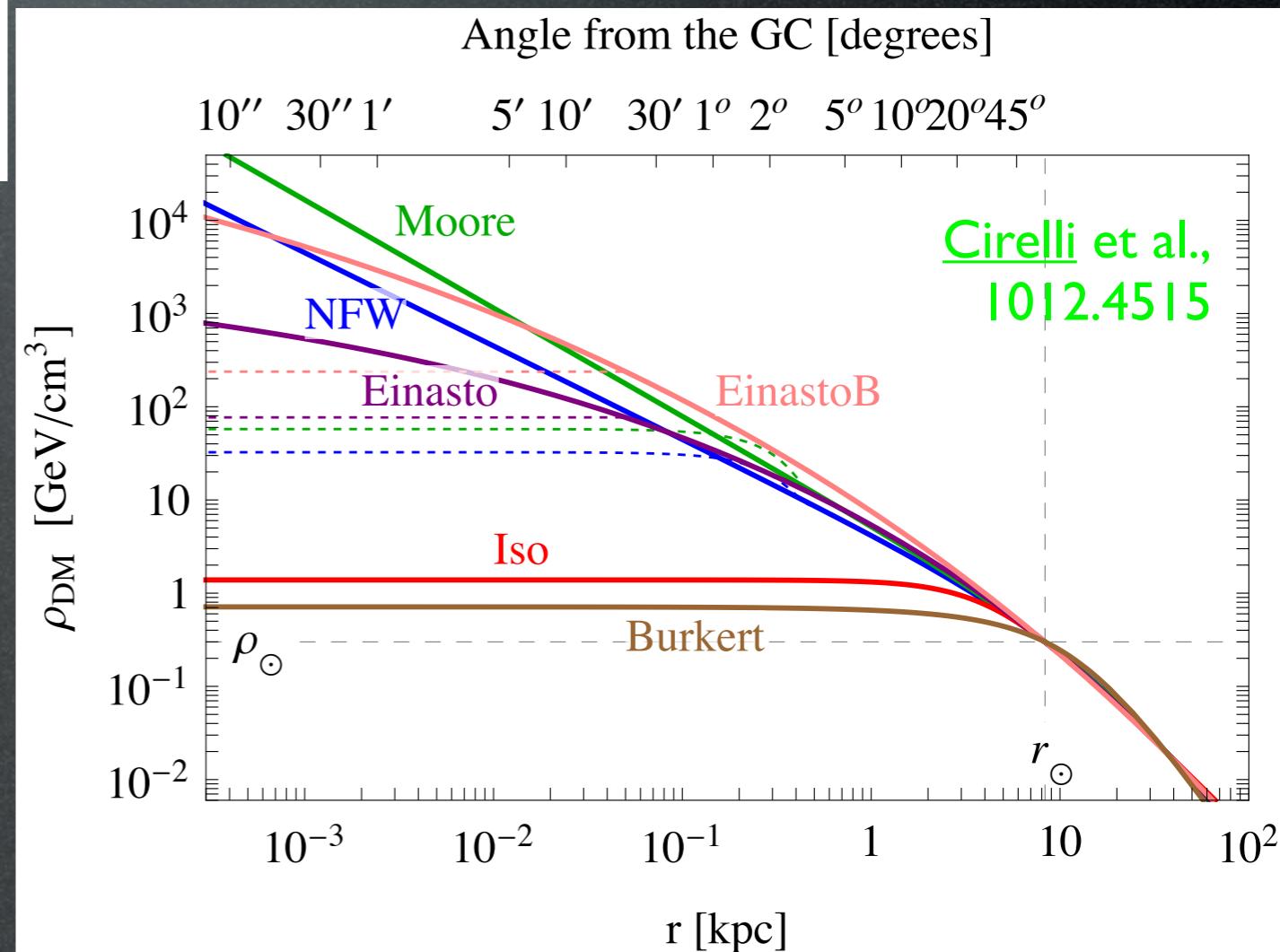
mild: **Einasto**

smooth: **isothermal**, **Burkert**

EinastoB = steepened Einasto

(effect of baryons?)

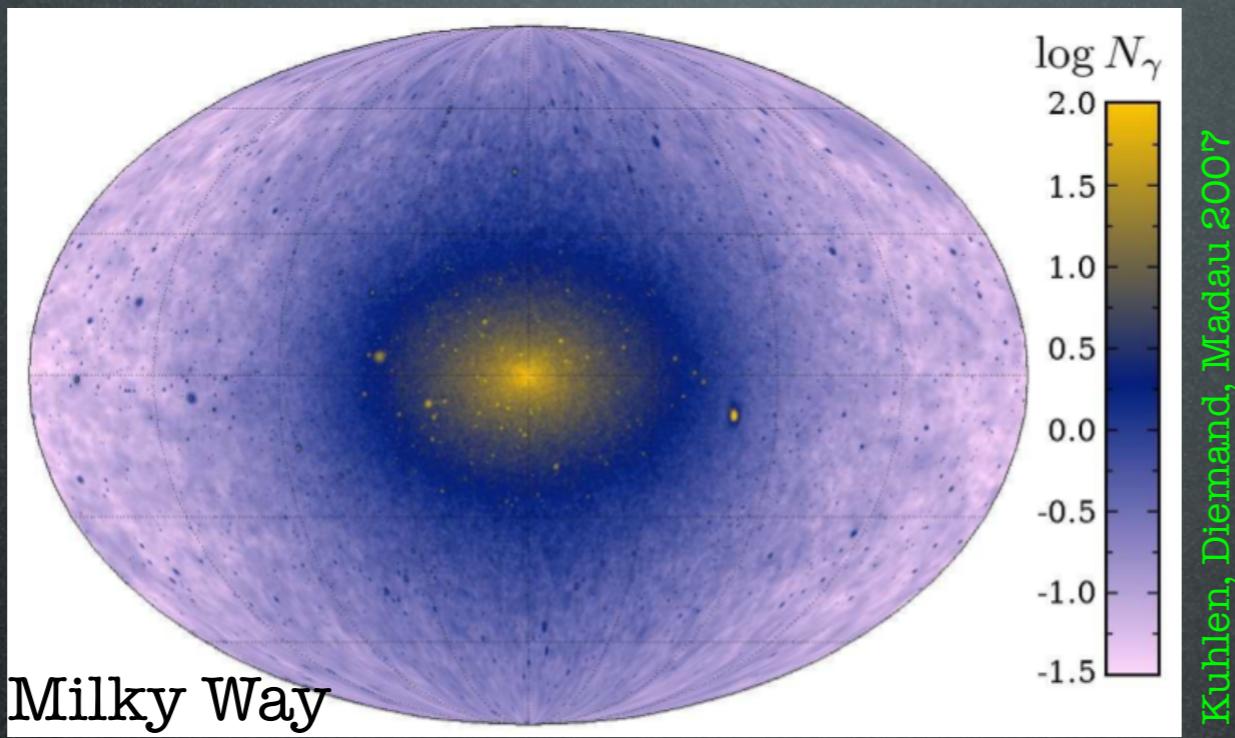
DM halo	α	r_s [kpc]	ρ_s [GeV/cm ³]
NFW	—	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	—	4.38	1.387
Burkert	—	12.67	0.712
Moore	—	30.28	0.105



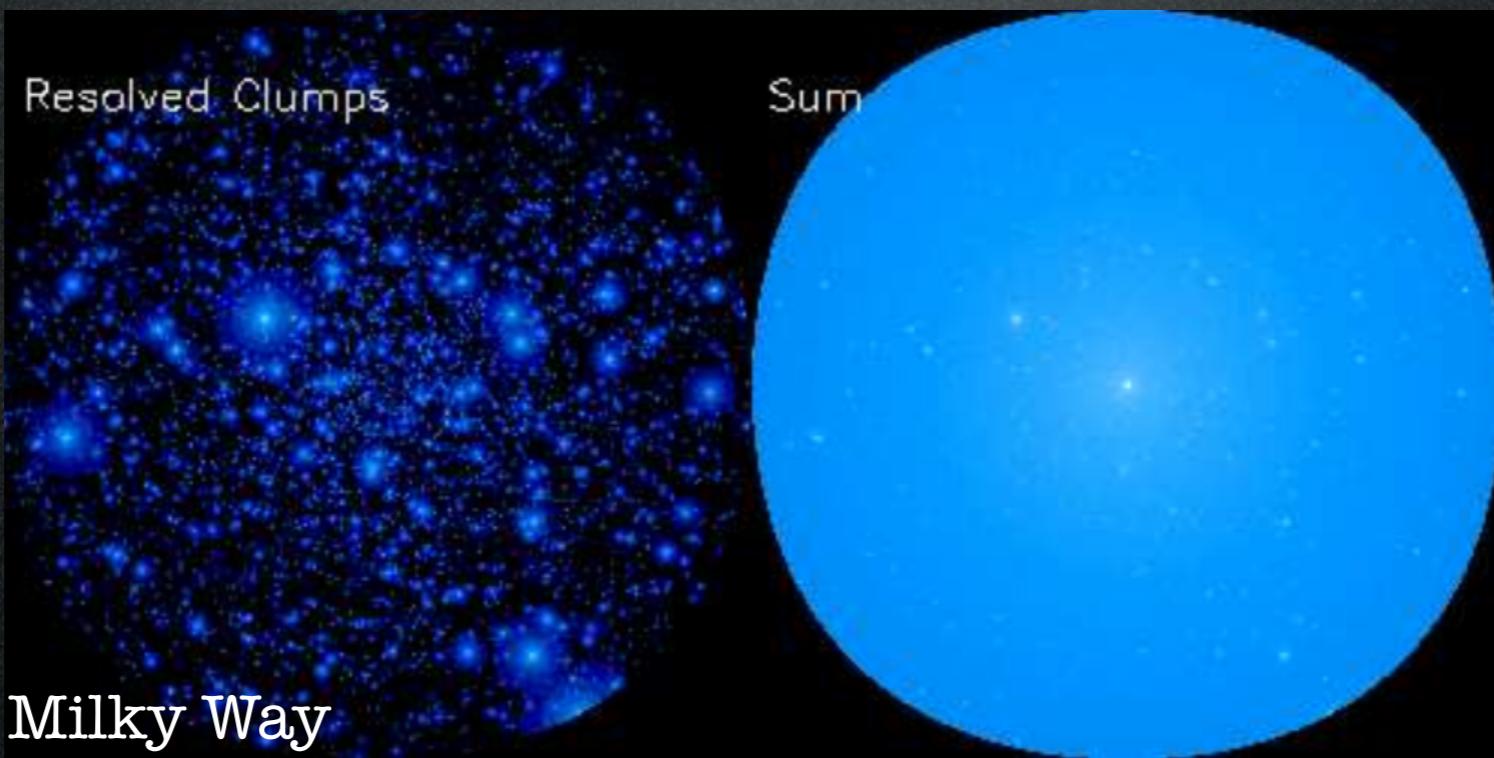
DM halo profiles

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:

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

diffusion

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

T kinetic energy

convective wind

spallations

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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:

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

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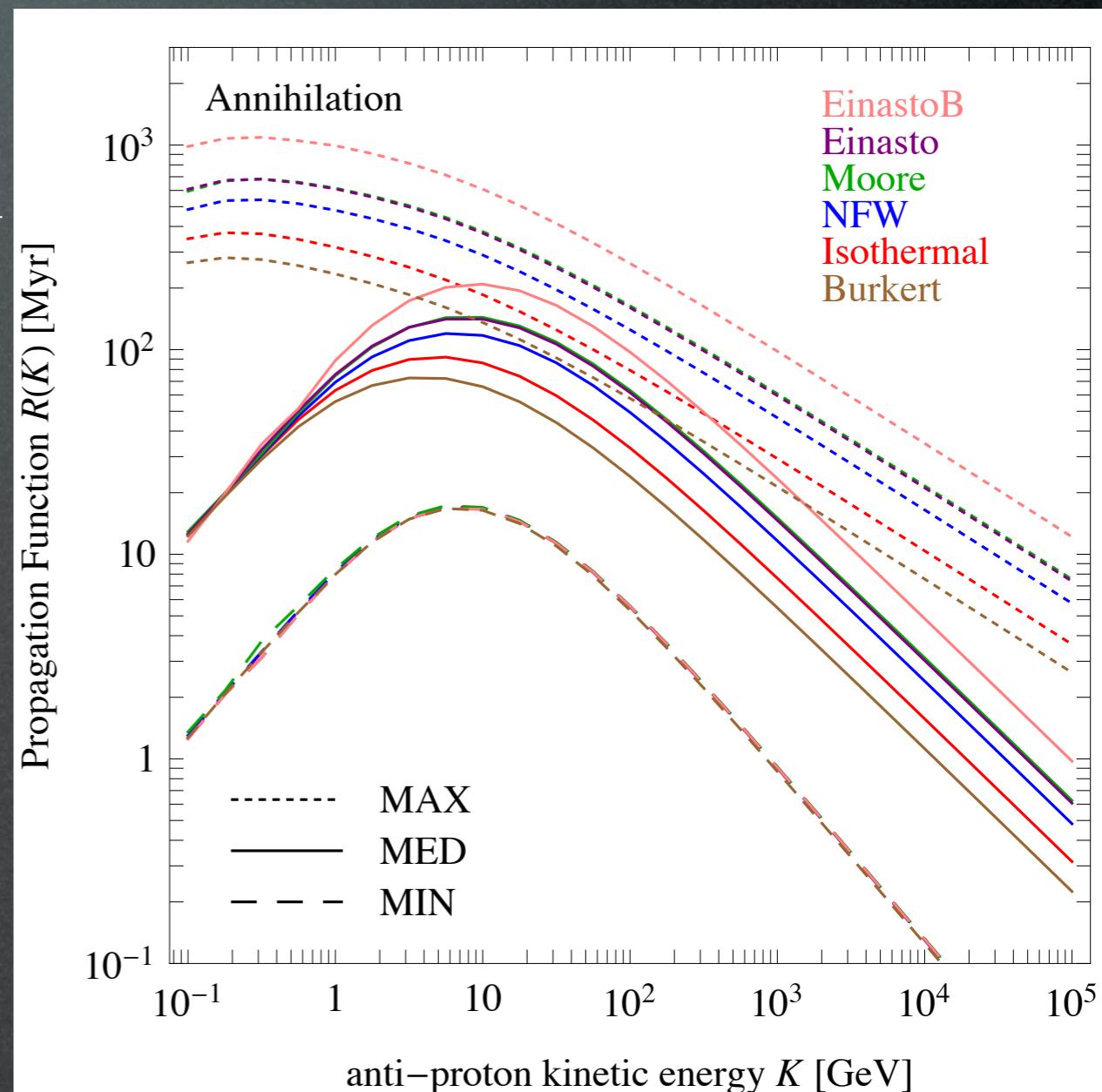
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DM detection

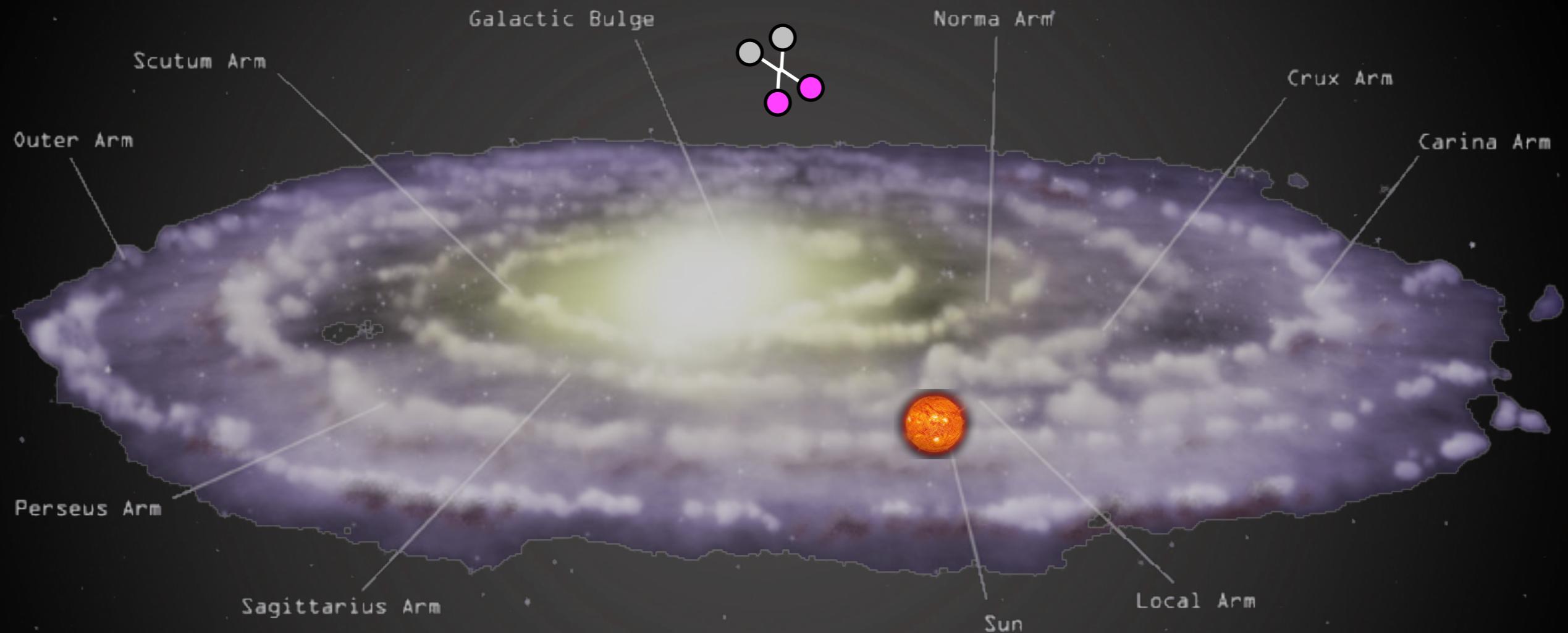
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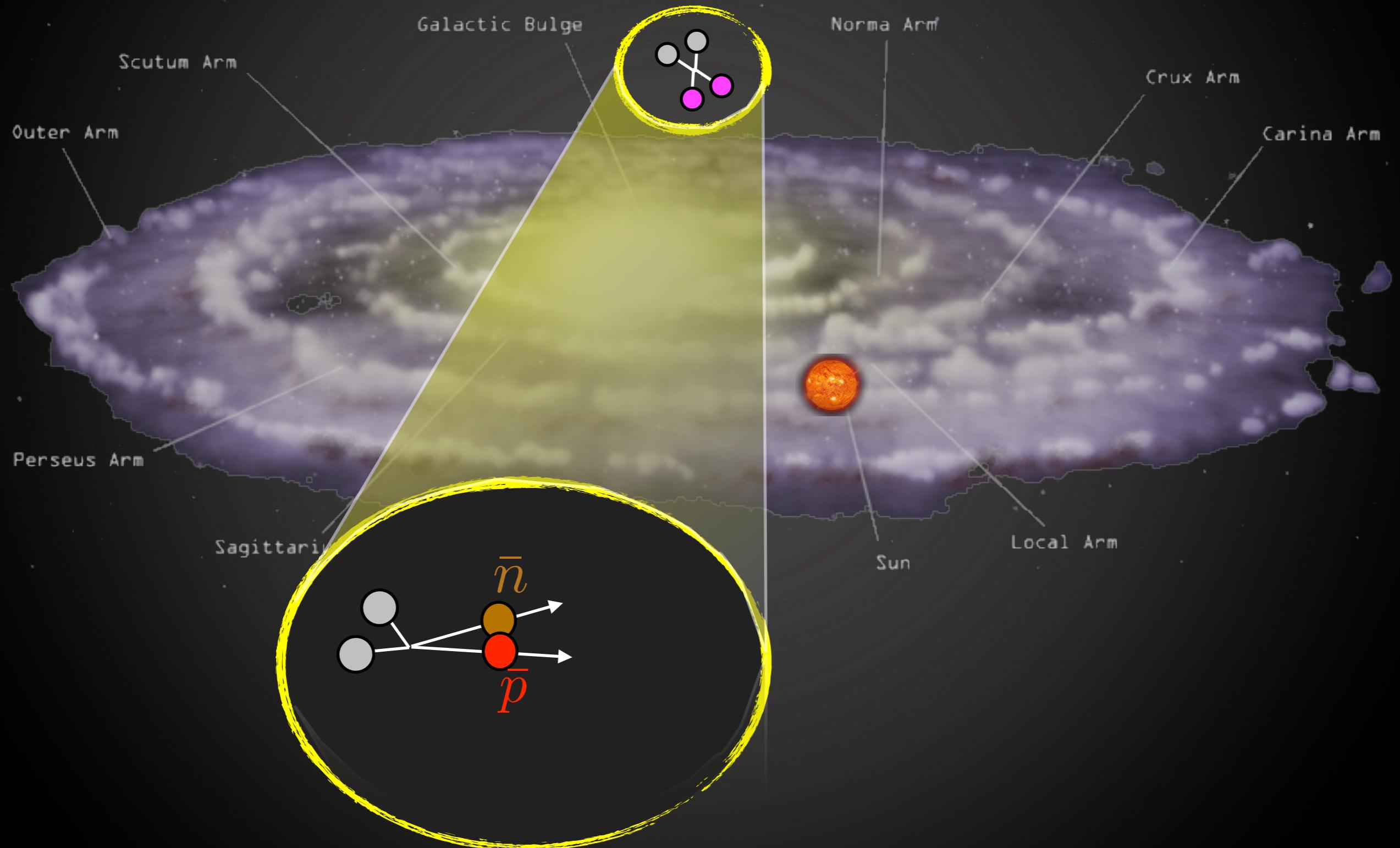
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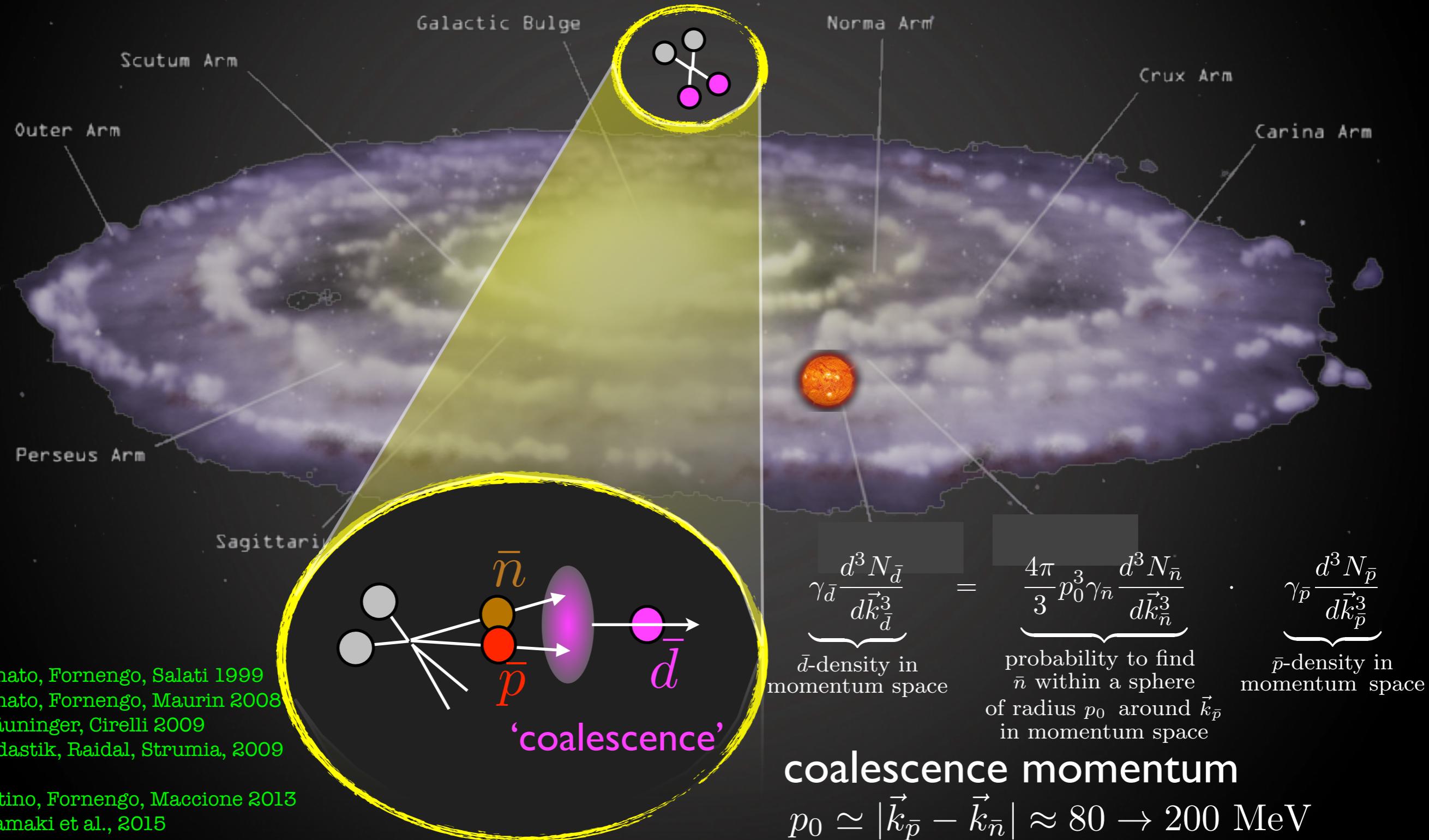
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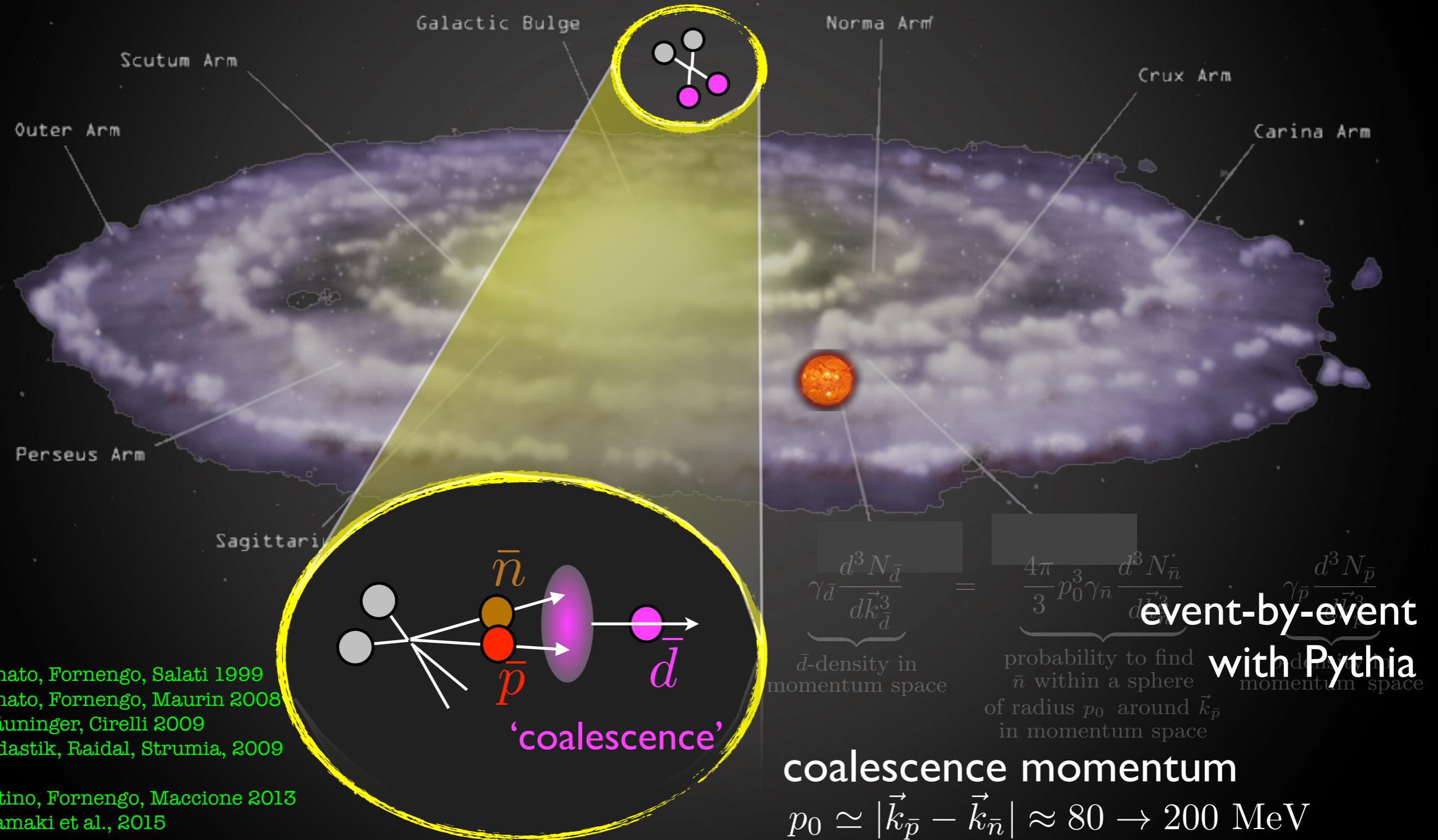
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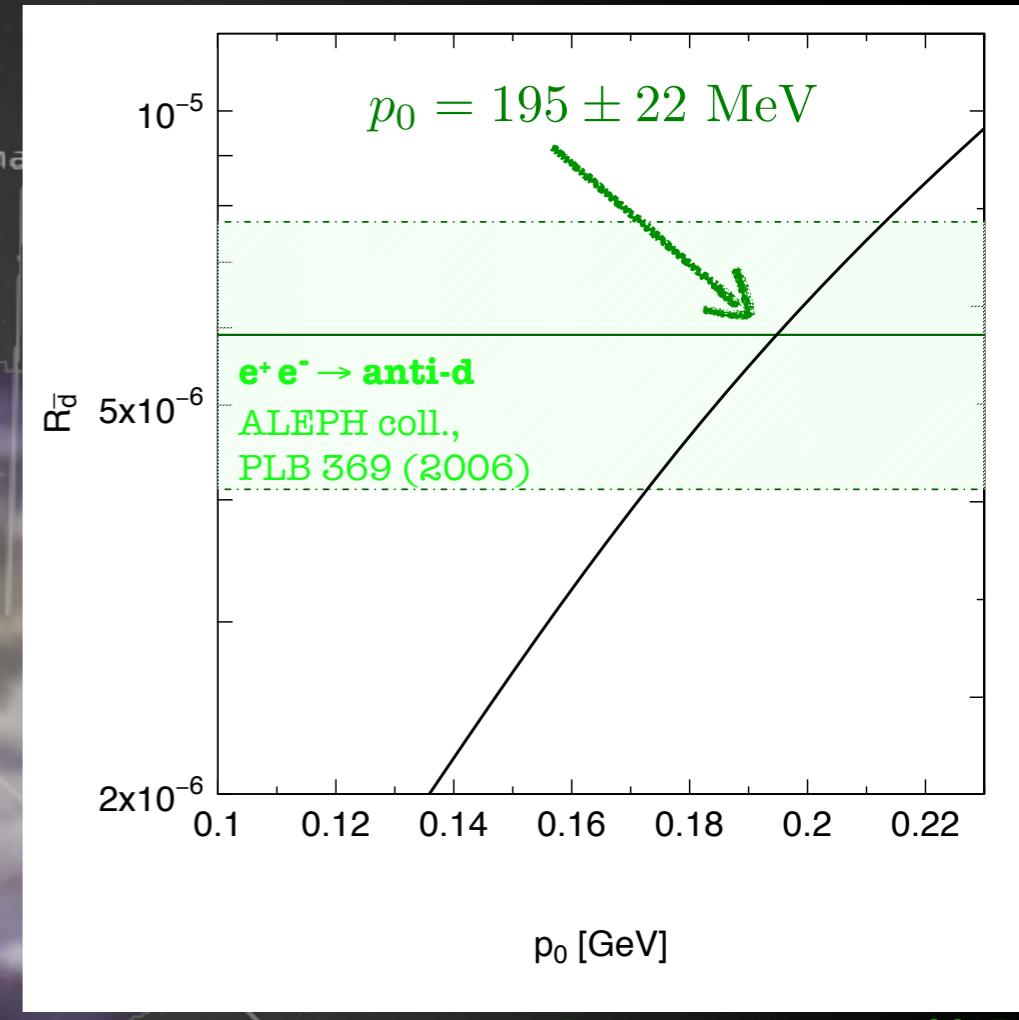
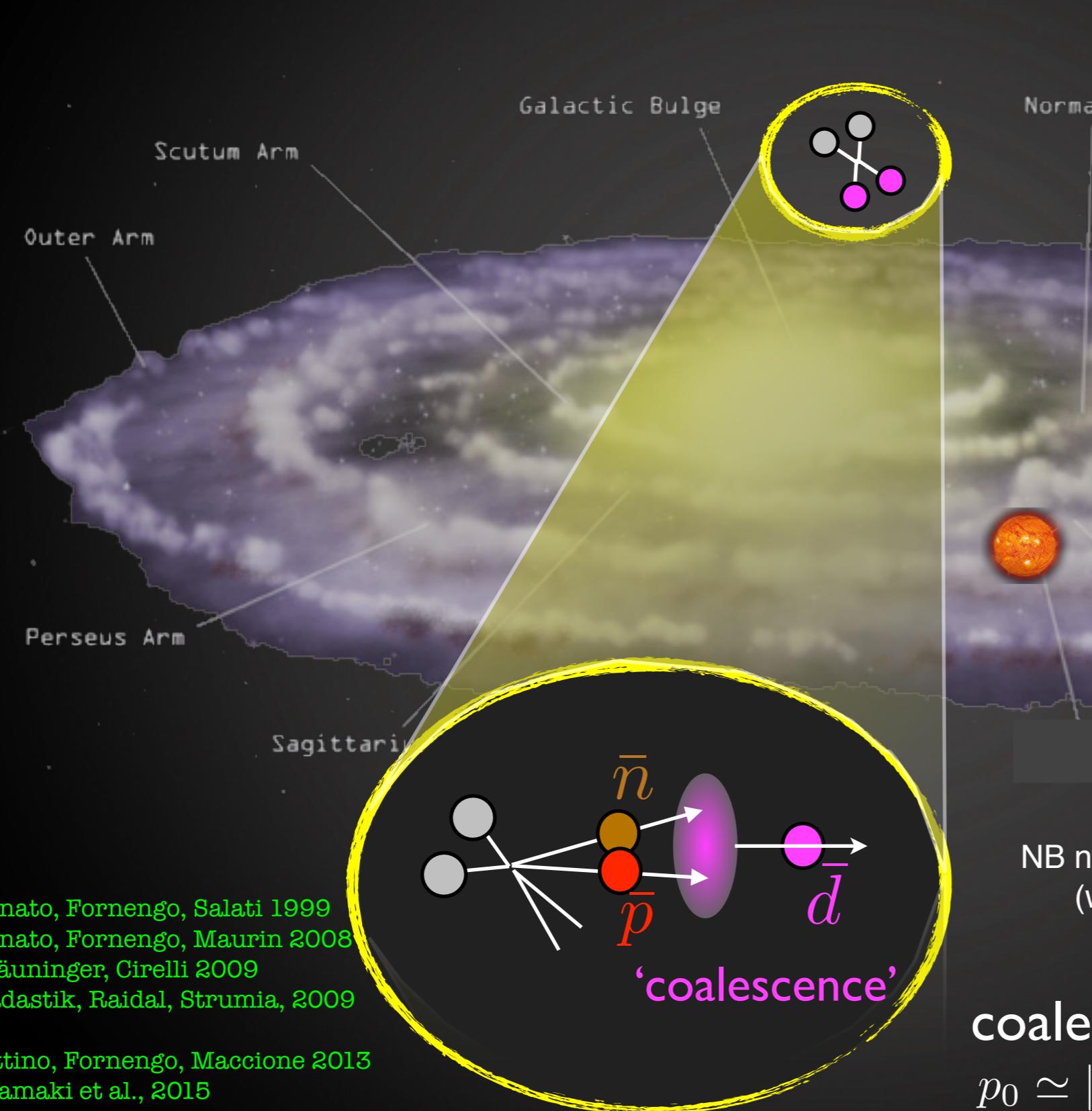
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NB naïve guess would be $p_0 = \sqrt{E_b m_p} = 47 \text{ MeV}$
(with E_b the d binding energy): not too far...

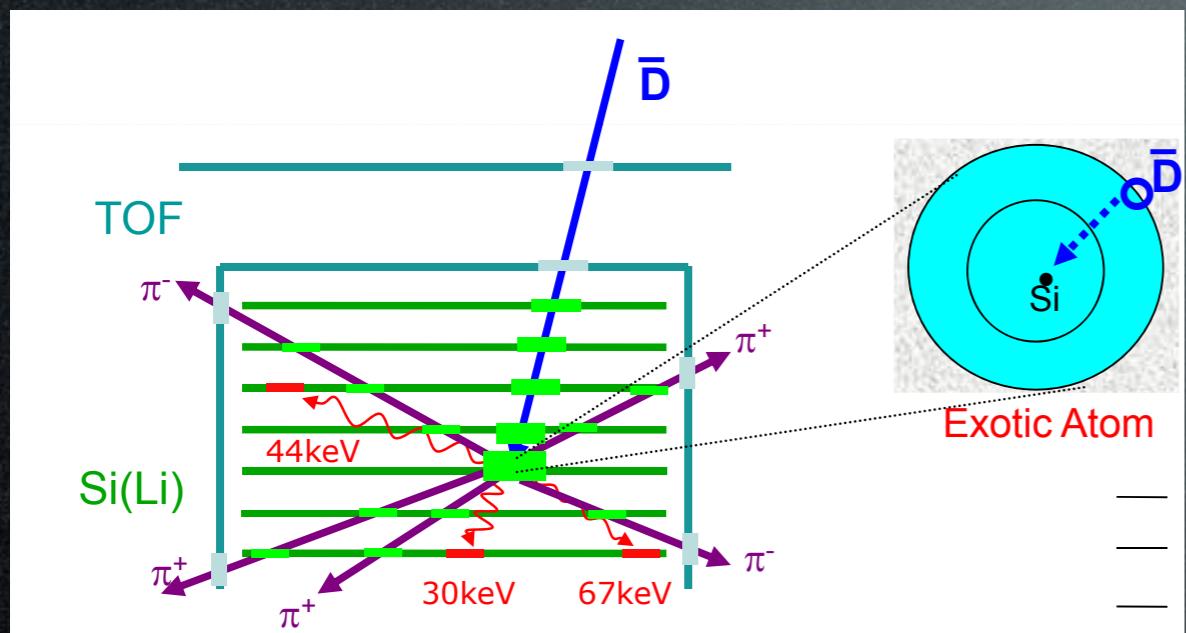
coalescence momentum

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

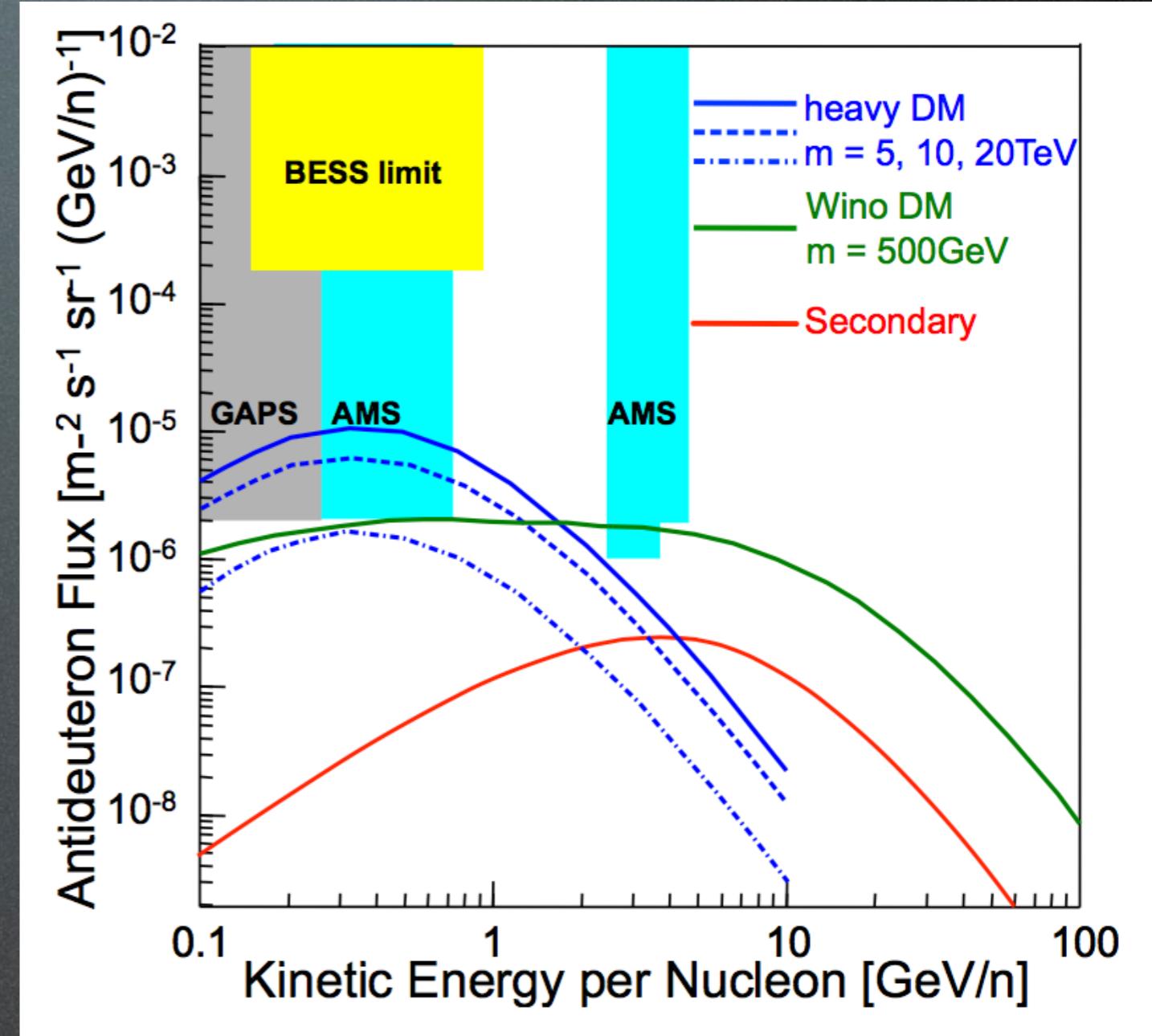
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\bar{d} from DM annihilations in halo

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

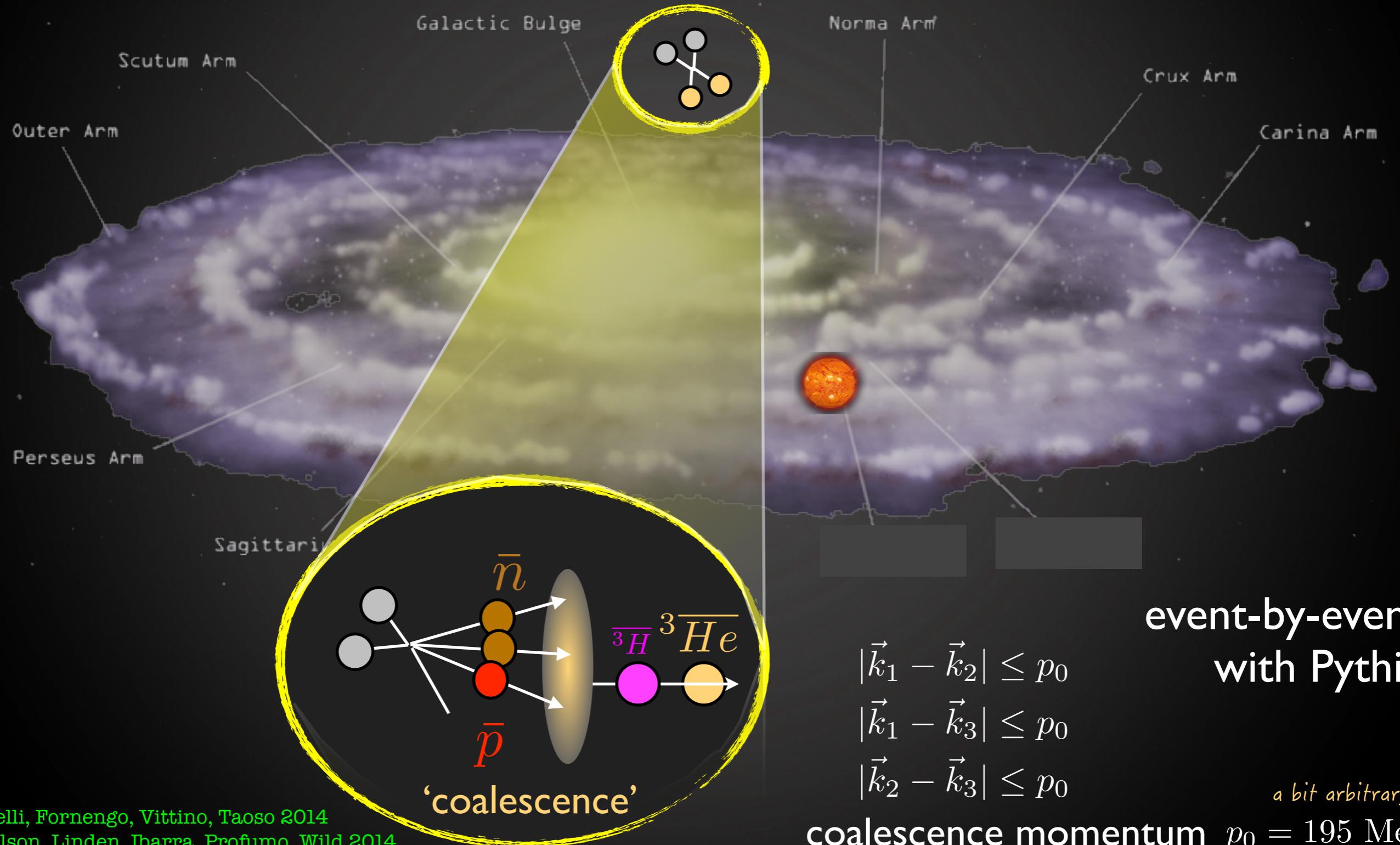
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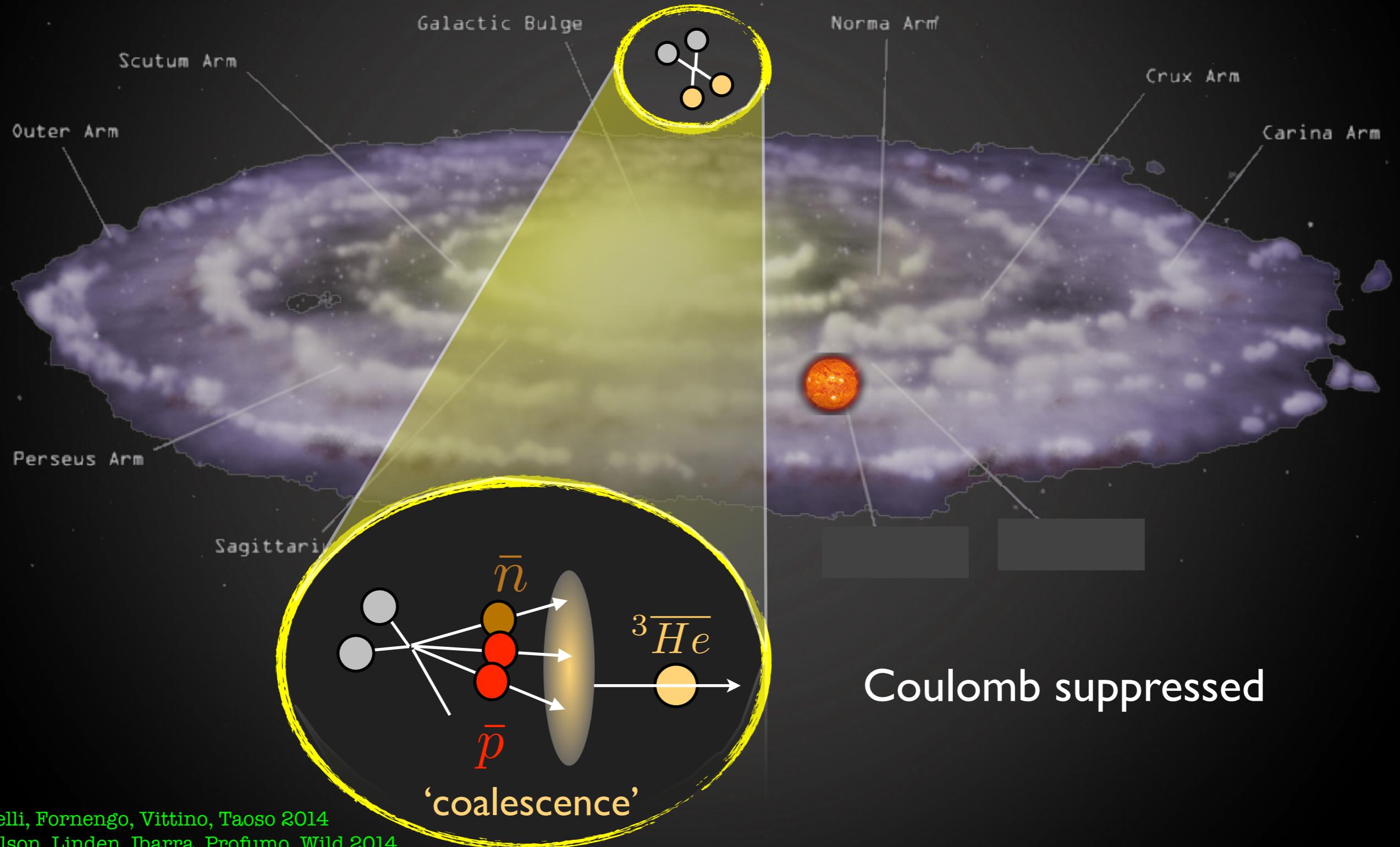
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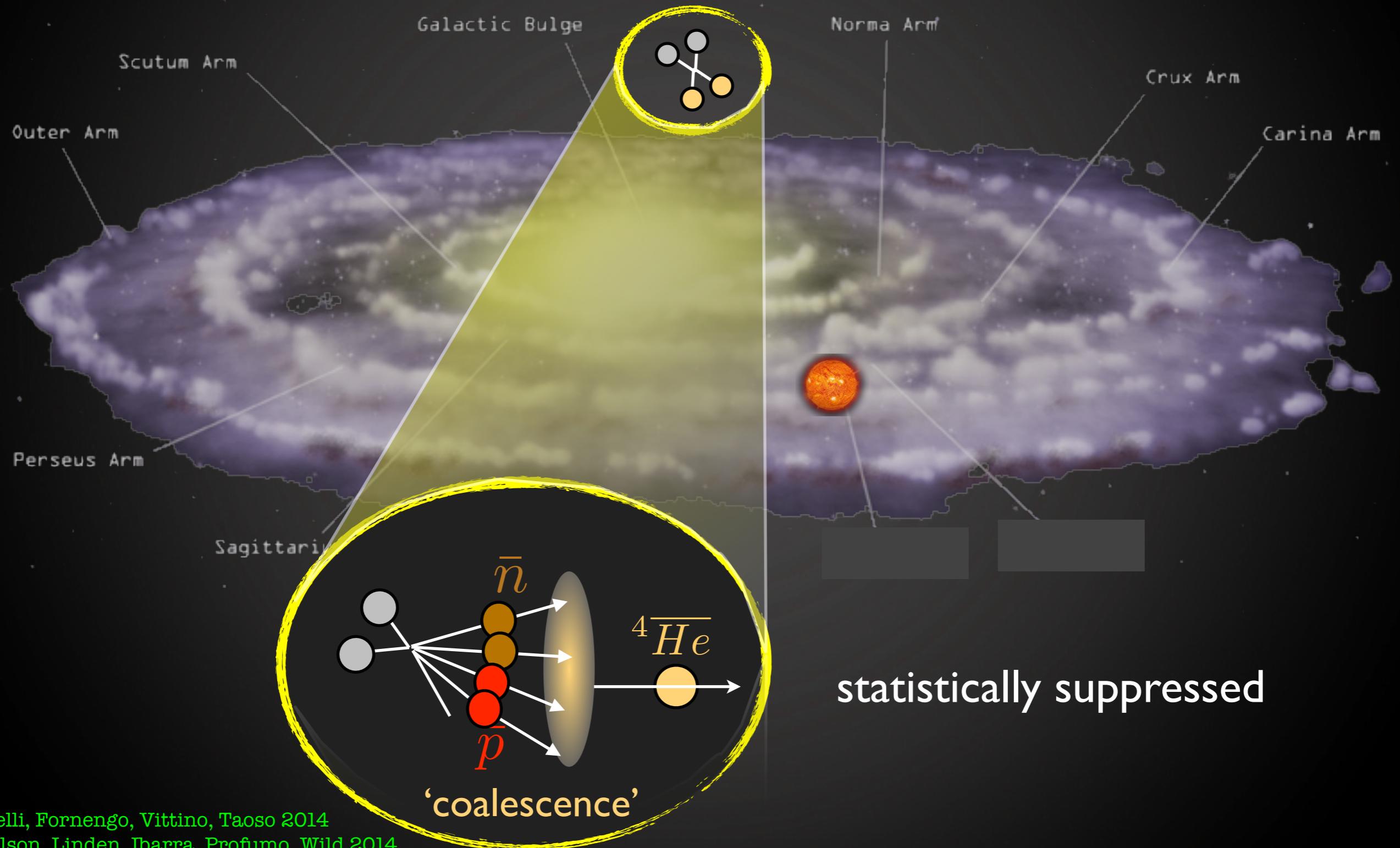
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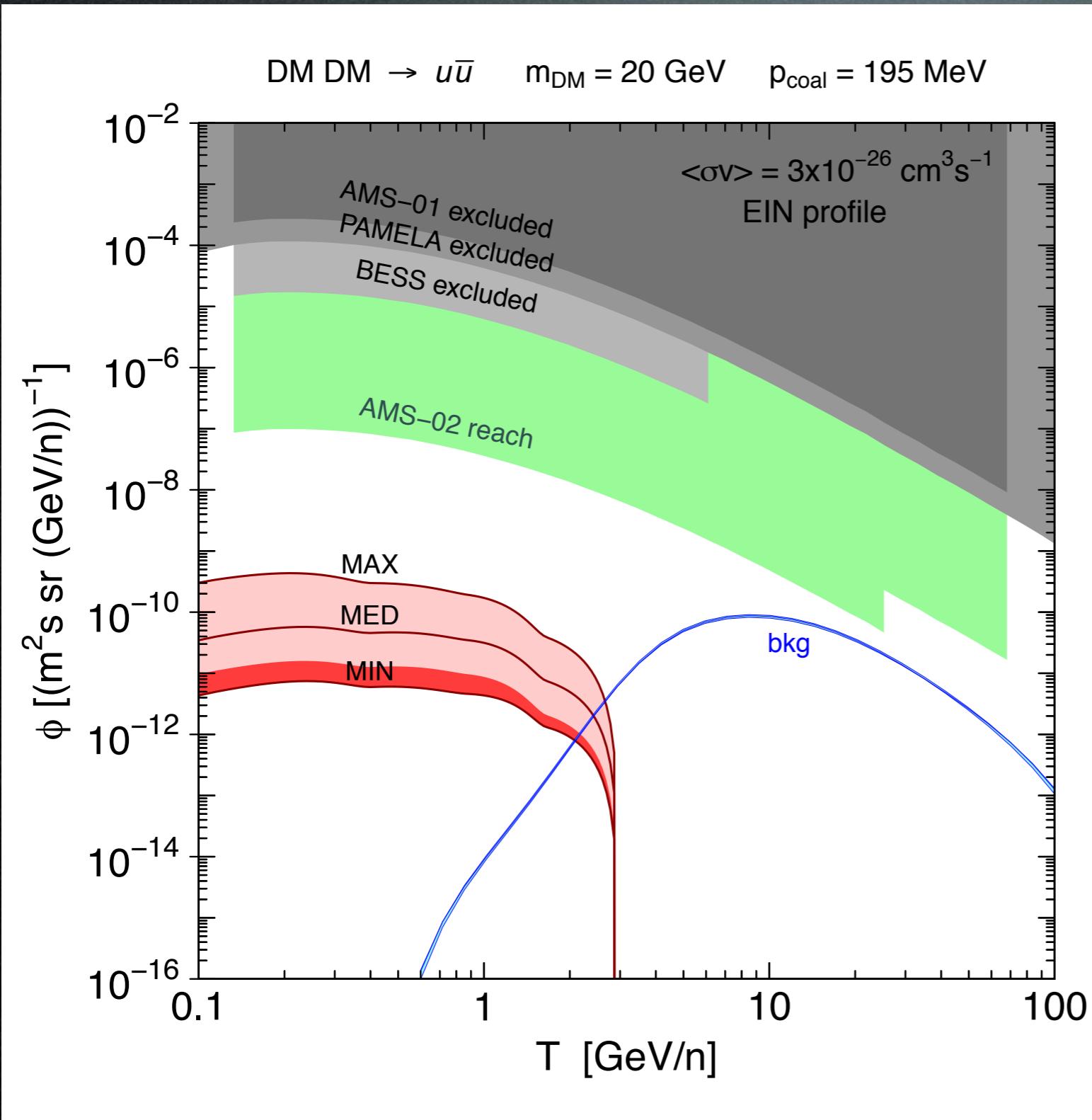
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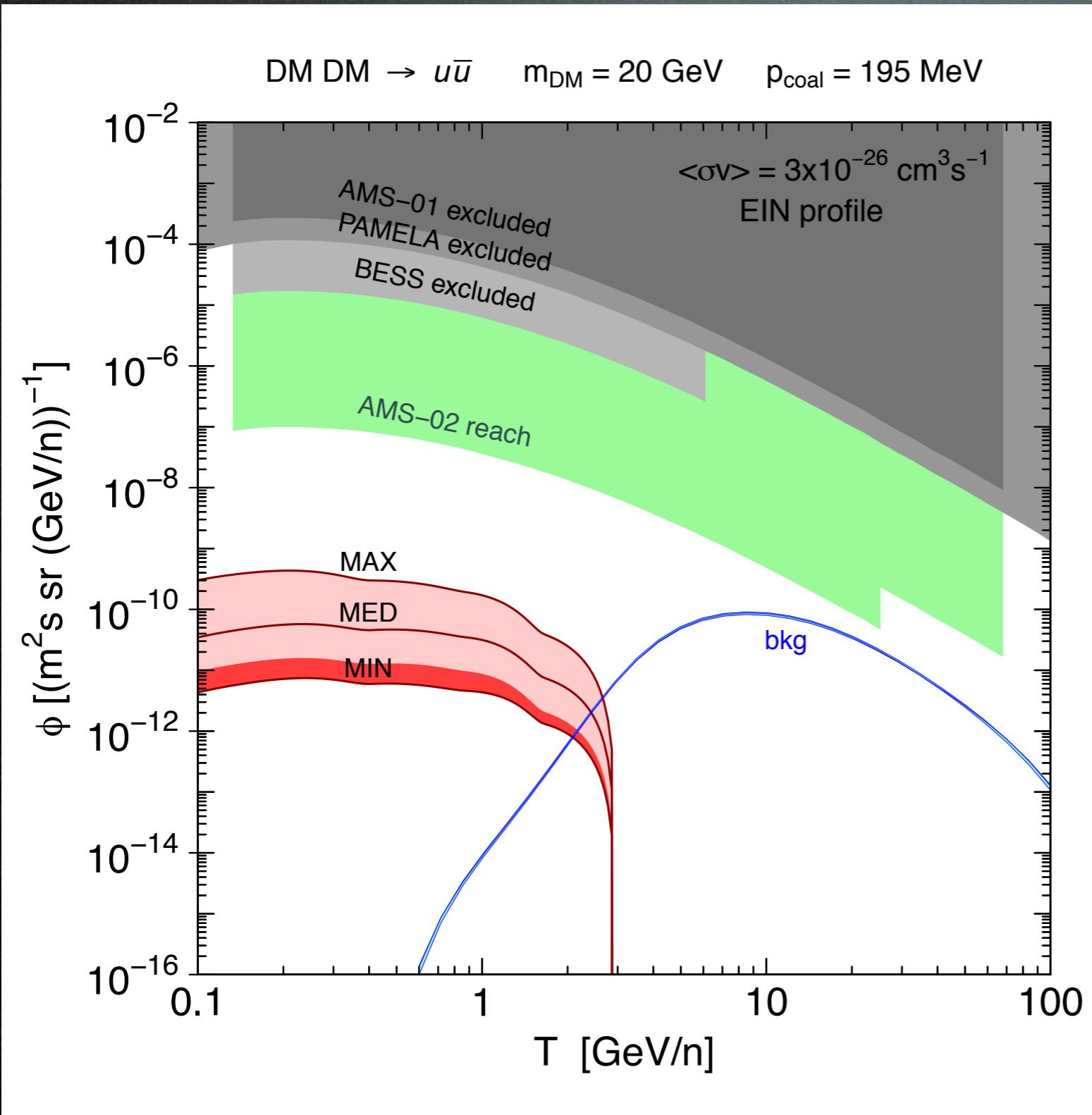
all



consistent with
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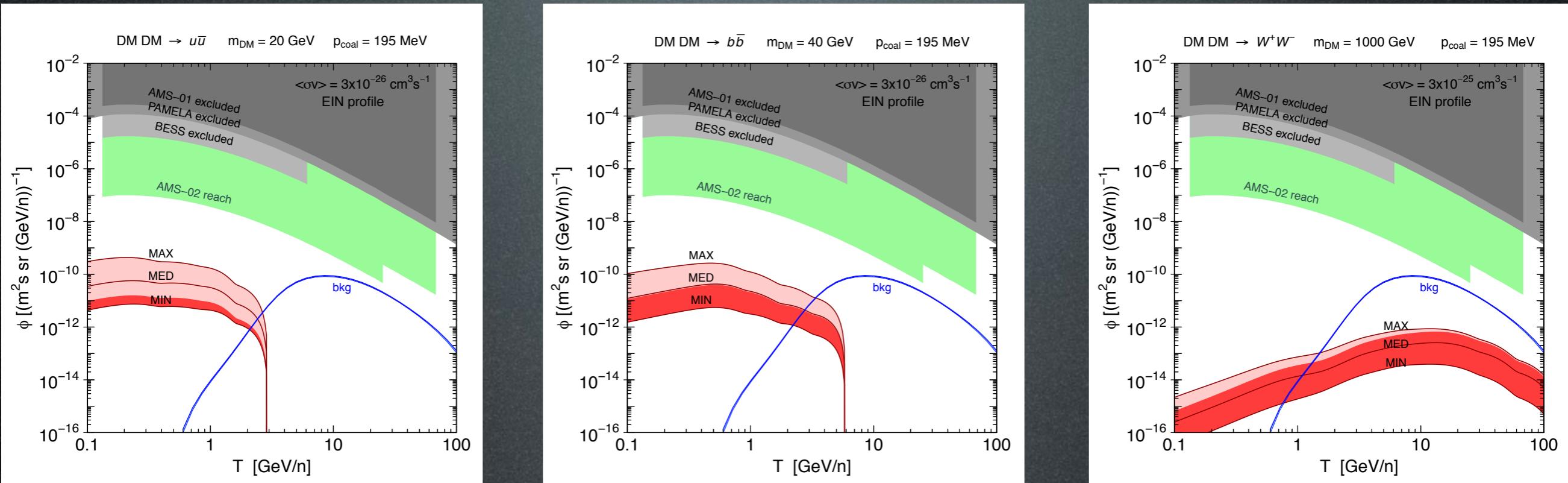
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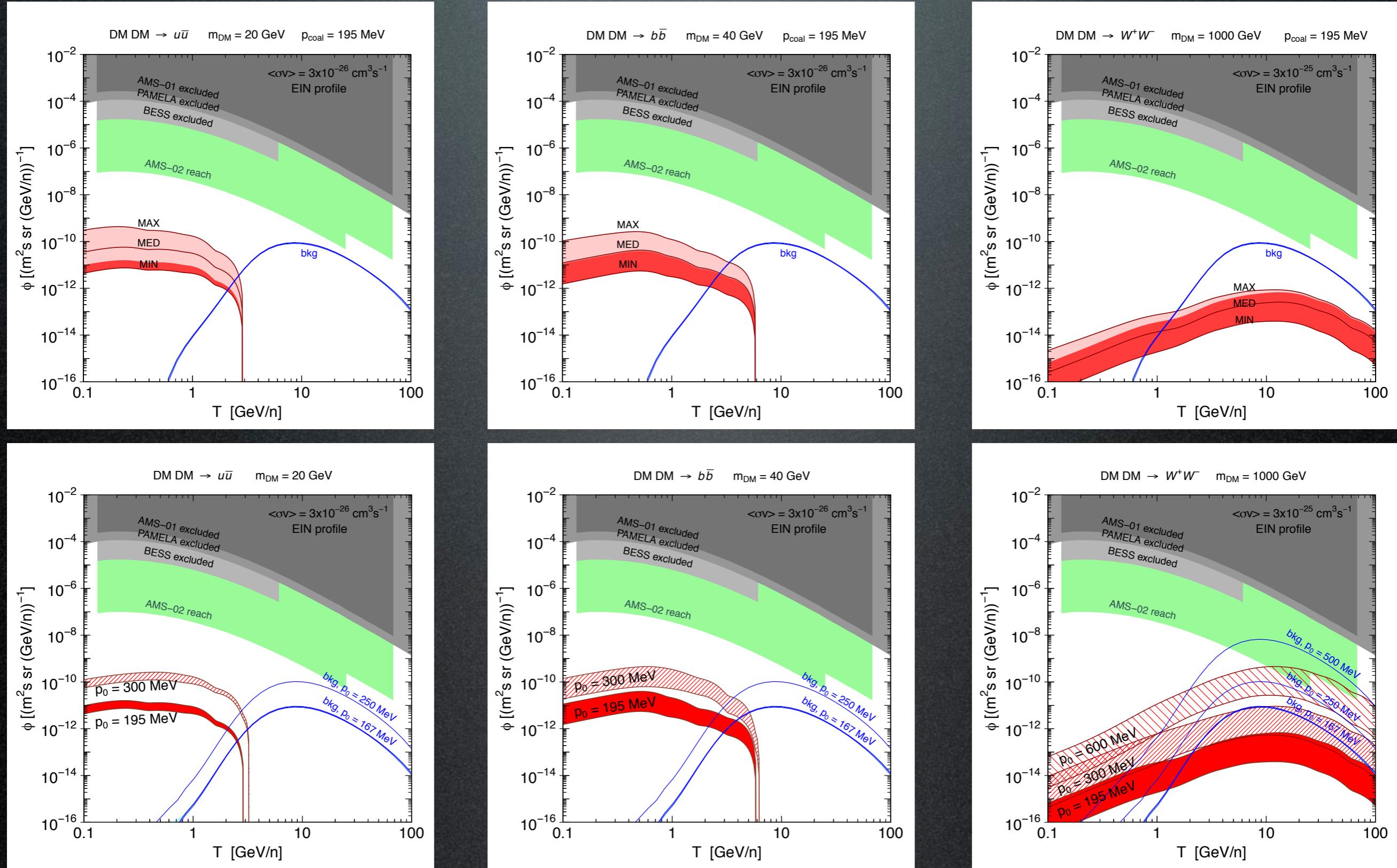
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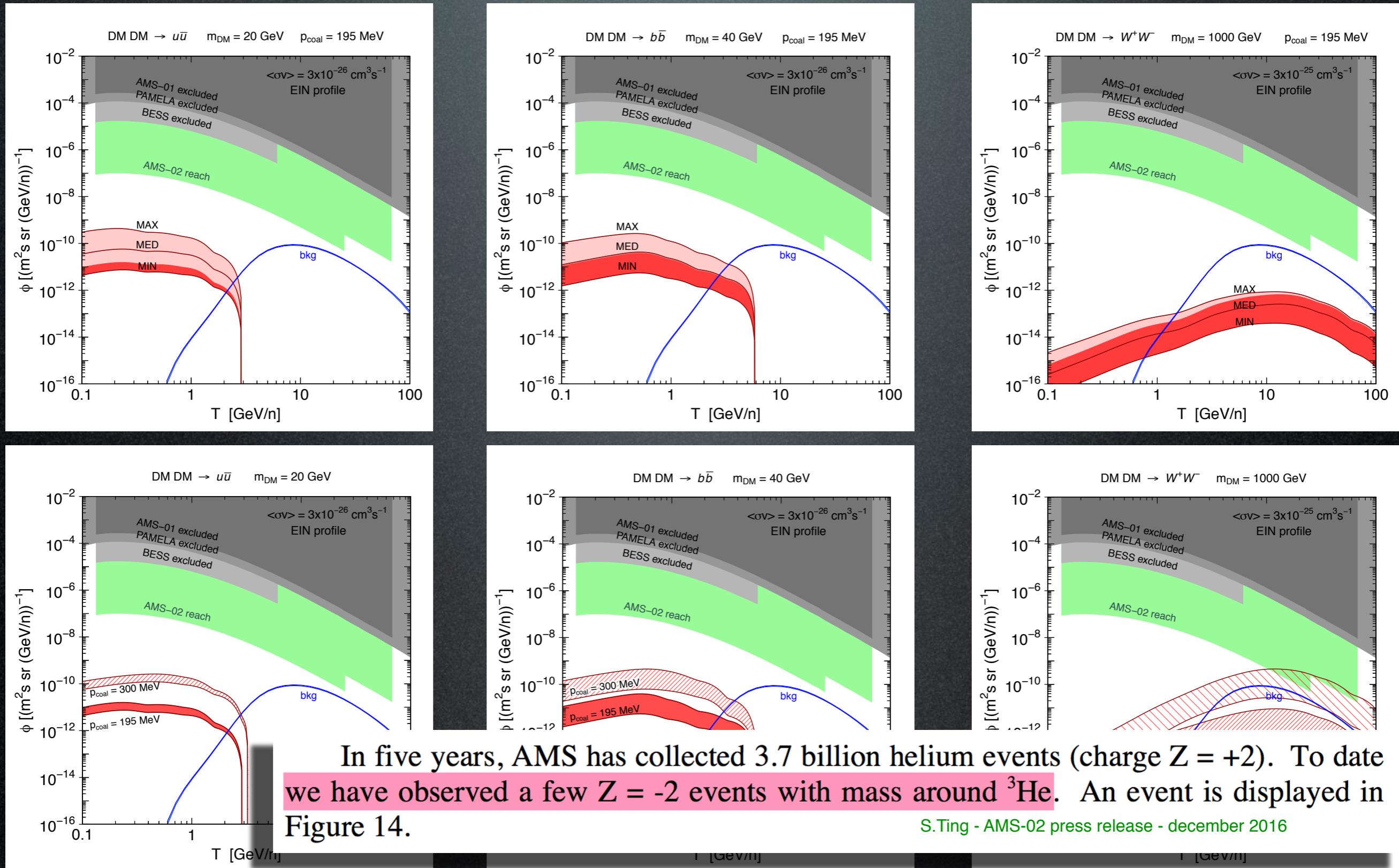
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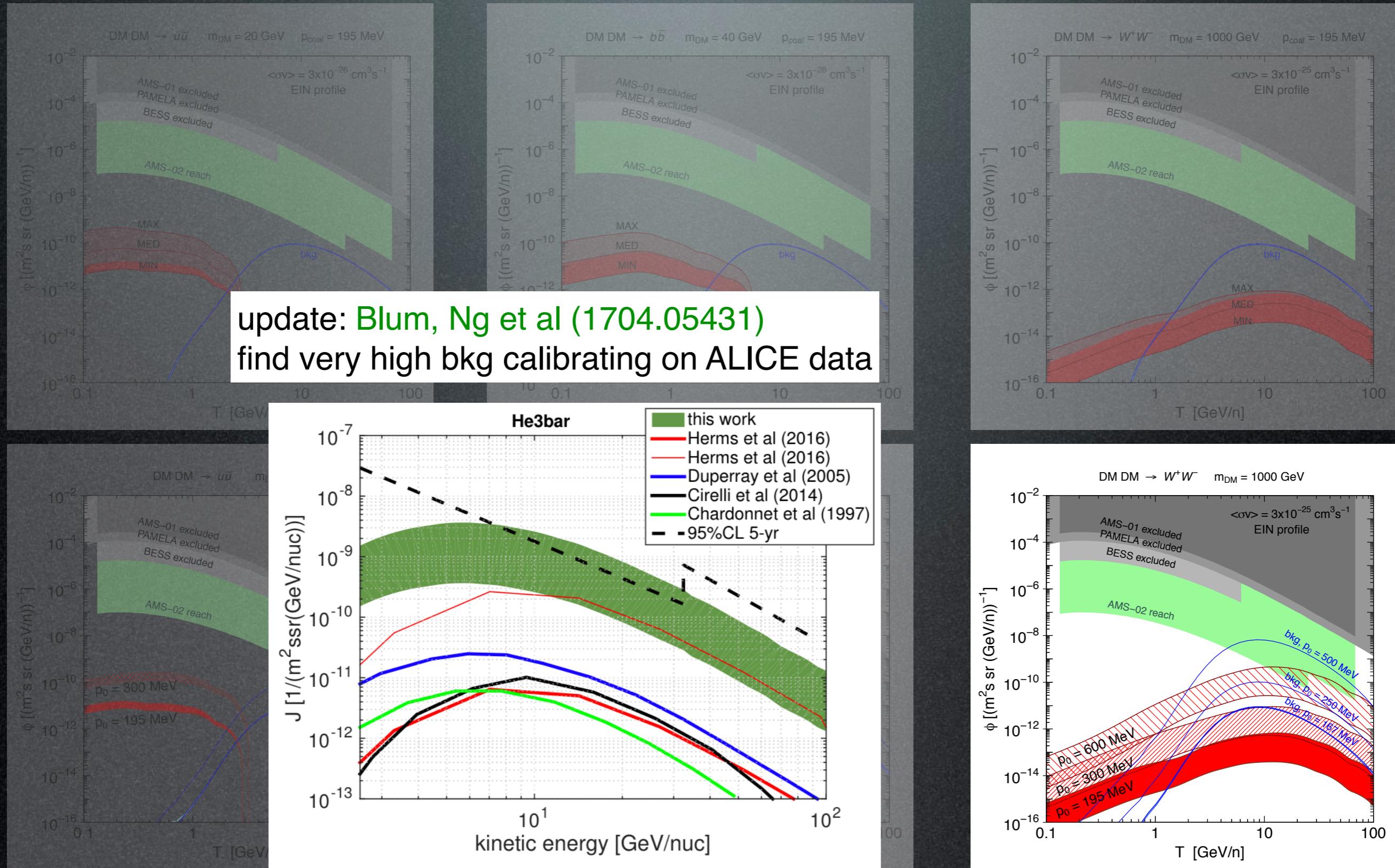
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\overline{He} from DM annihilations in halo



Indirect Detection

\overline{He} from DM annihilations in halo

