3 June 2019
Rencontres de Blois

Dark Matter Indirect Searches

as of 2019

Marco Cirelli
(CNRS LPTHE Jussieu)

LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

cnrs dépasser les frontières

SORBONNE UNIVERSITÉ CRÉATEURS DE FUTURS DEPUIS 1257

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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, Antares

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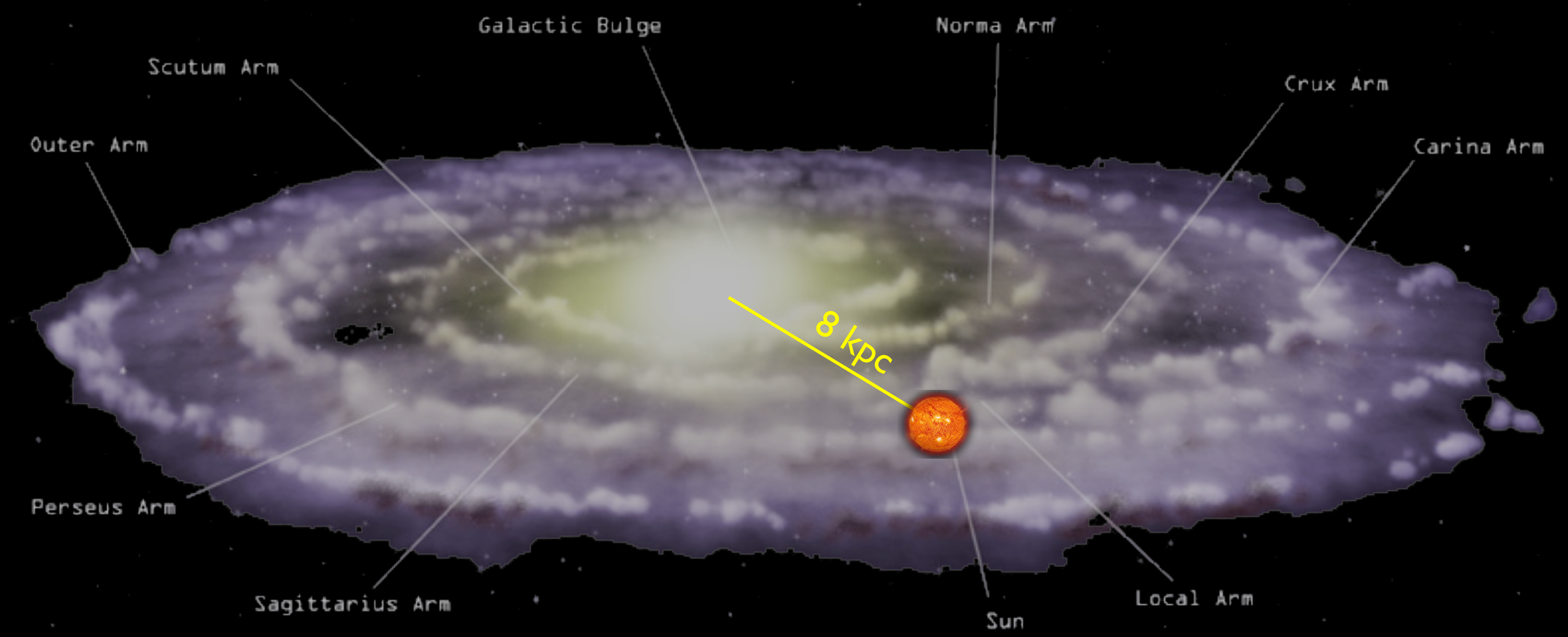
Indirect Detection: basics

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



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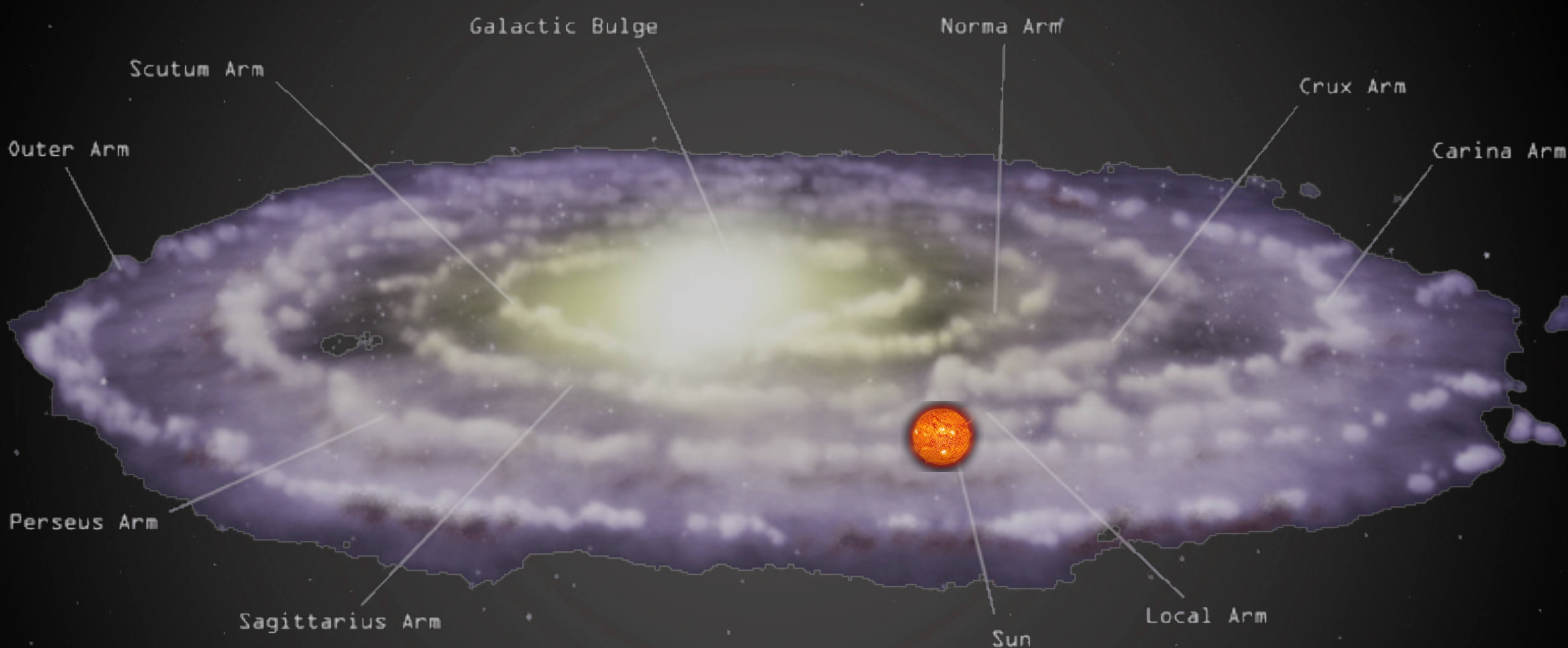

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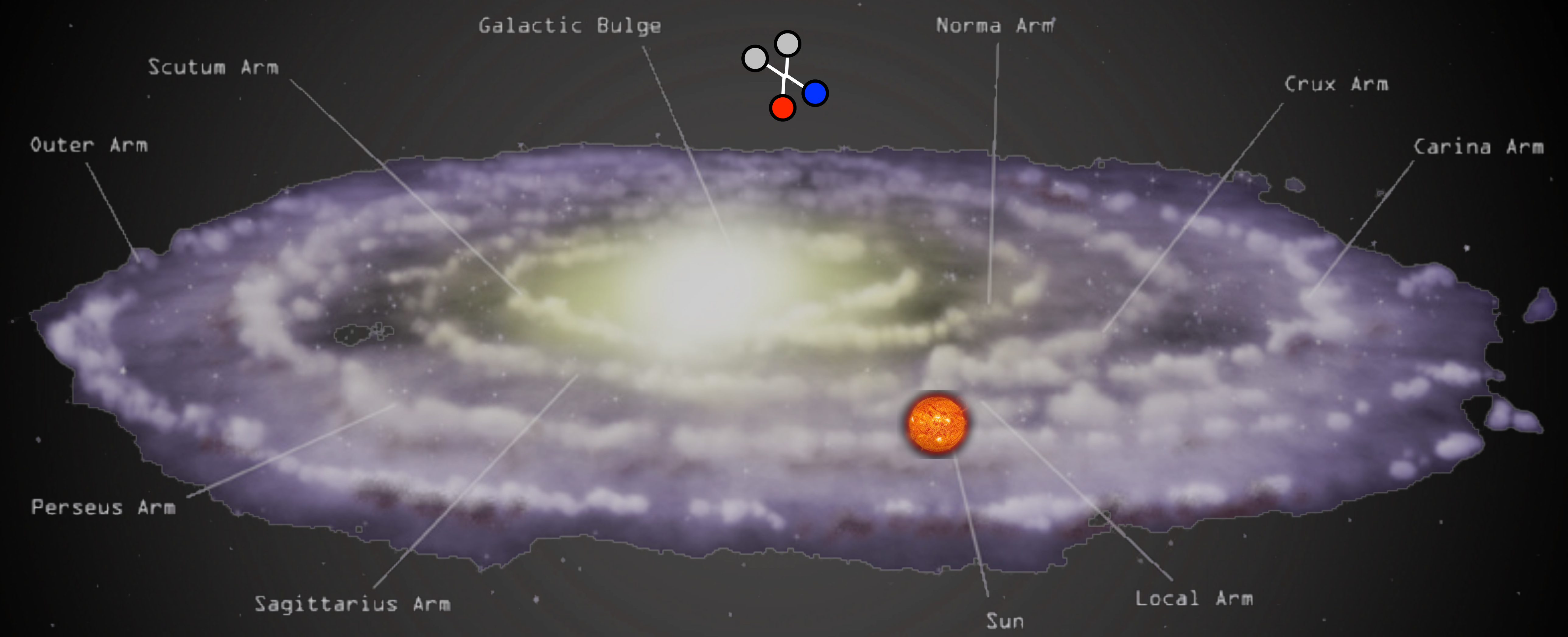

Indirect Detection: charged CRs

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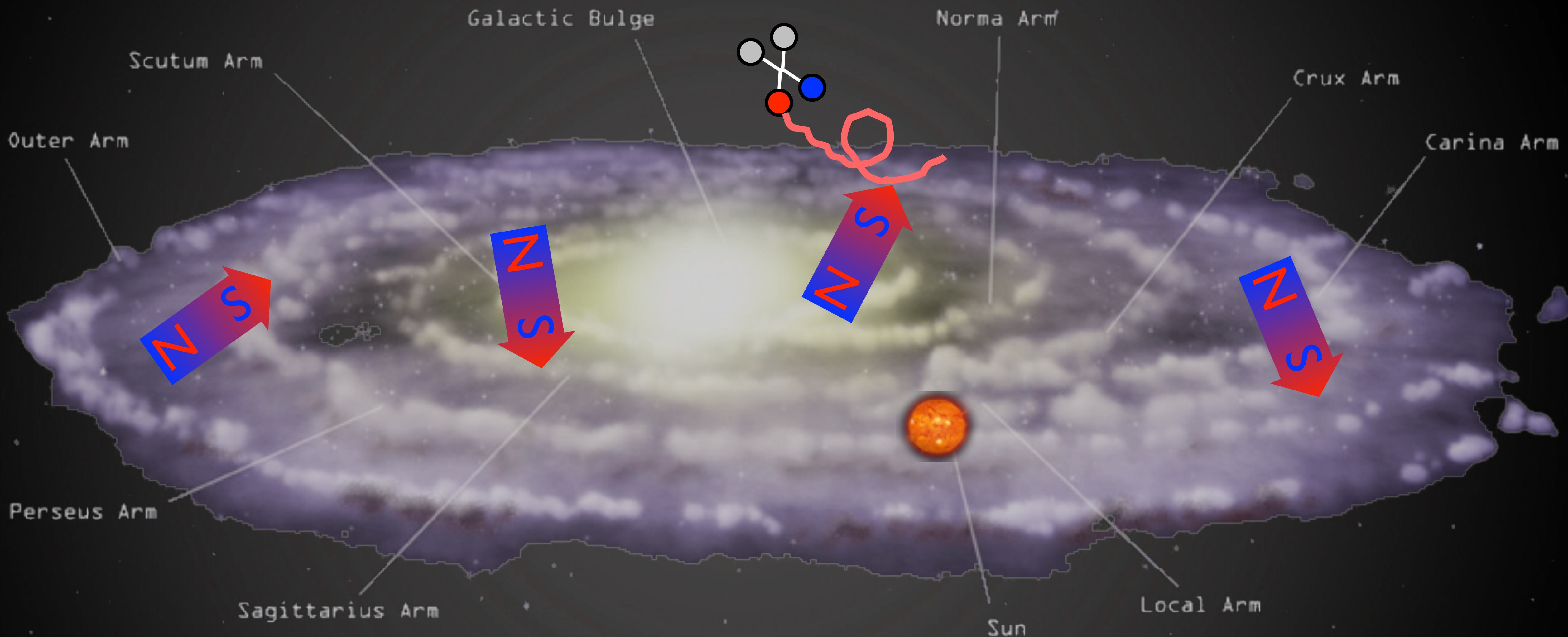

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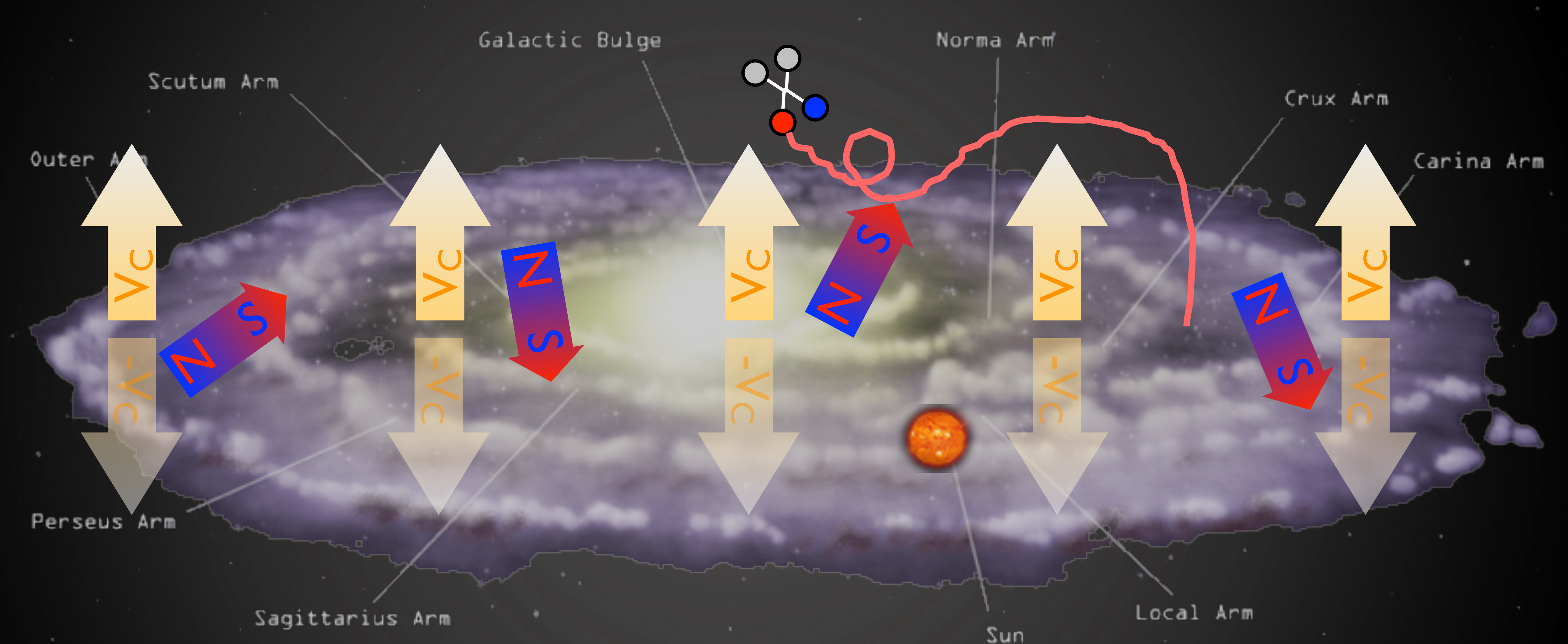

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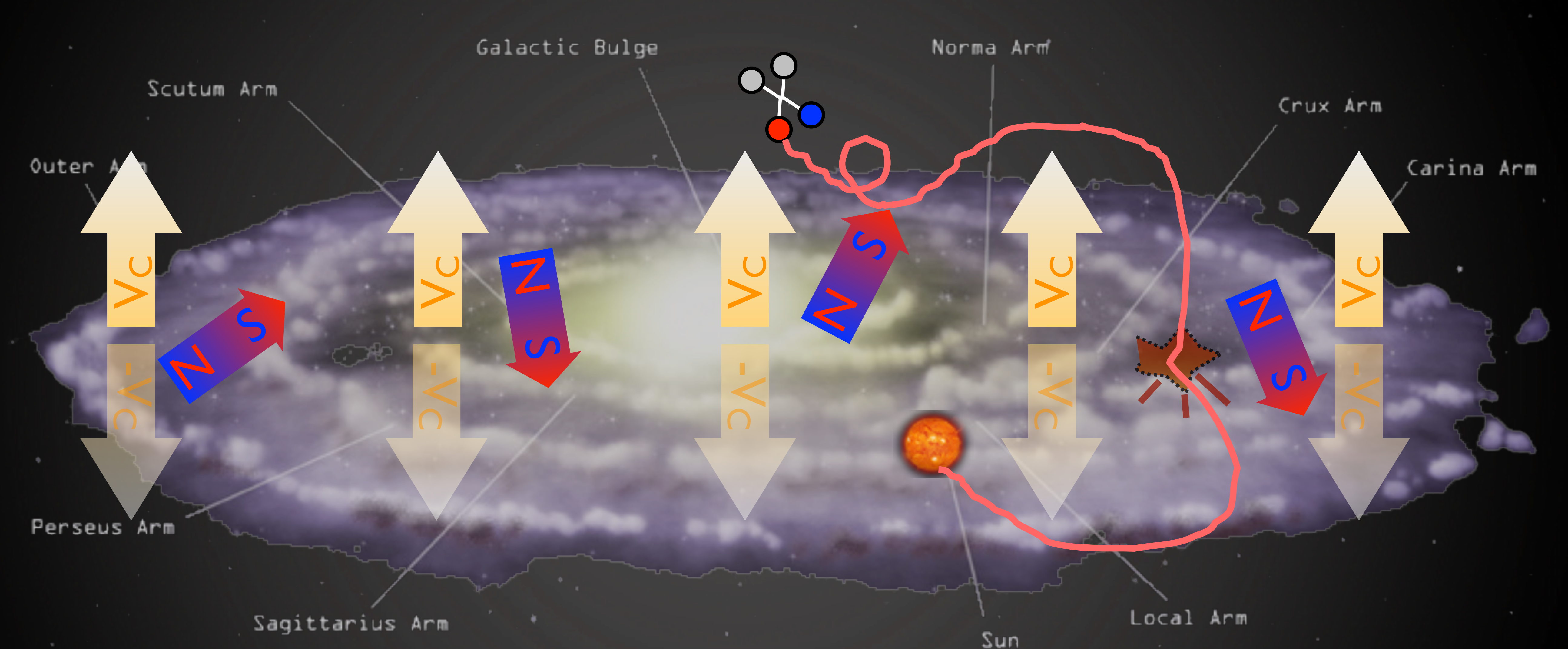

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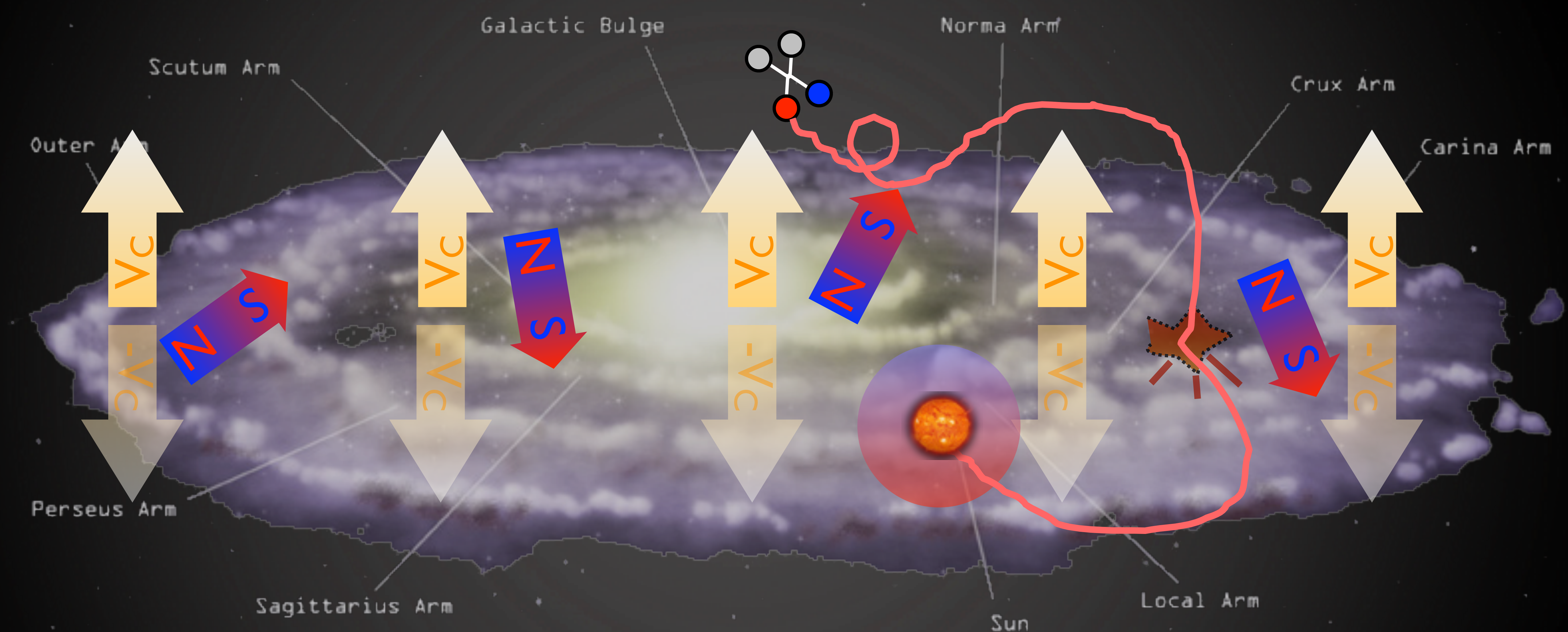

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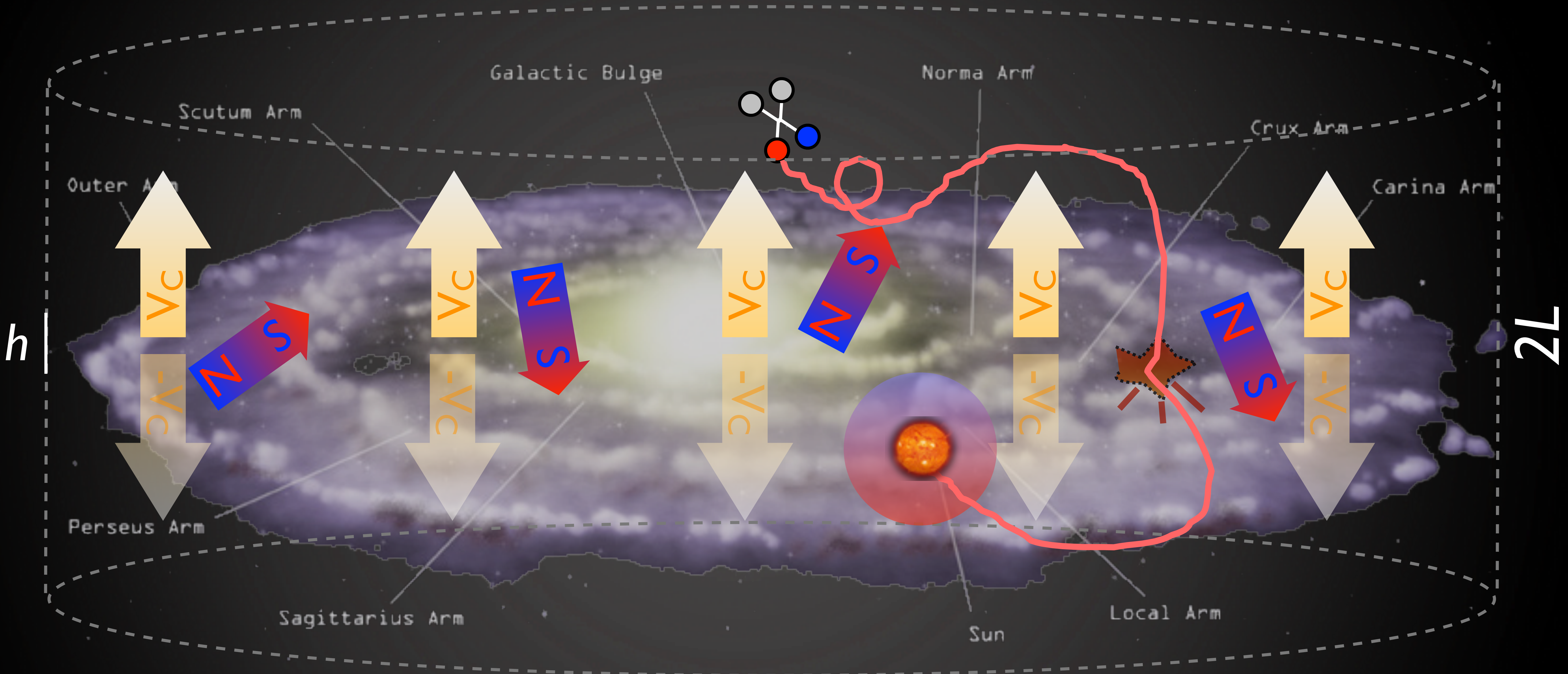

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

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

		KRA	KOL	CON	THK	THN	THN2	THN3
thickness	L [kpc]	4	4	4	10	0.5	2	3
diffusion	D_0 [10^{28} cm^2 s^{-1}]	2.64	4.46	0.97	4.75	0.31	1.35	1.98
diffusion	δ	0.50	0.33	0.6	0.50	0.50	0.50	0.50
diffusion	η	-0.39	1	1	-0.15	-0.27	-0.27	-0.27
diff. reacc.	v_A [km s^{-1}]	14.2	36	38.1	14.1	11.6	11.6	11.6
p index	γ	2.35	1.78/2.45	1.62/2.35	2.35	2.35	2.35	2.35
convection	dv_c/dz [km s^{-1} kpc^{-1}]	0	0	50	0	0	0	0
solar mod.	ϕ_F^p [GV]	0.650	0.335	0.282	0.687	0.704	0.626	0.623
	χ^2_{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_{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+

Antiprotons

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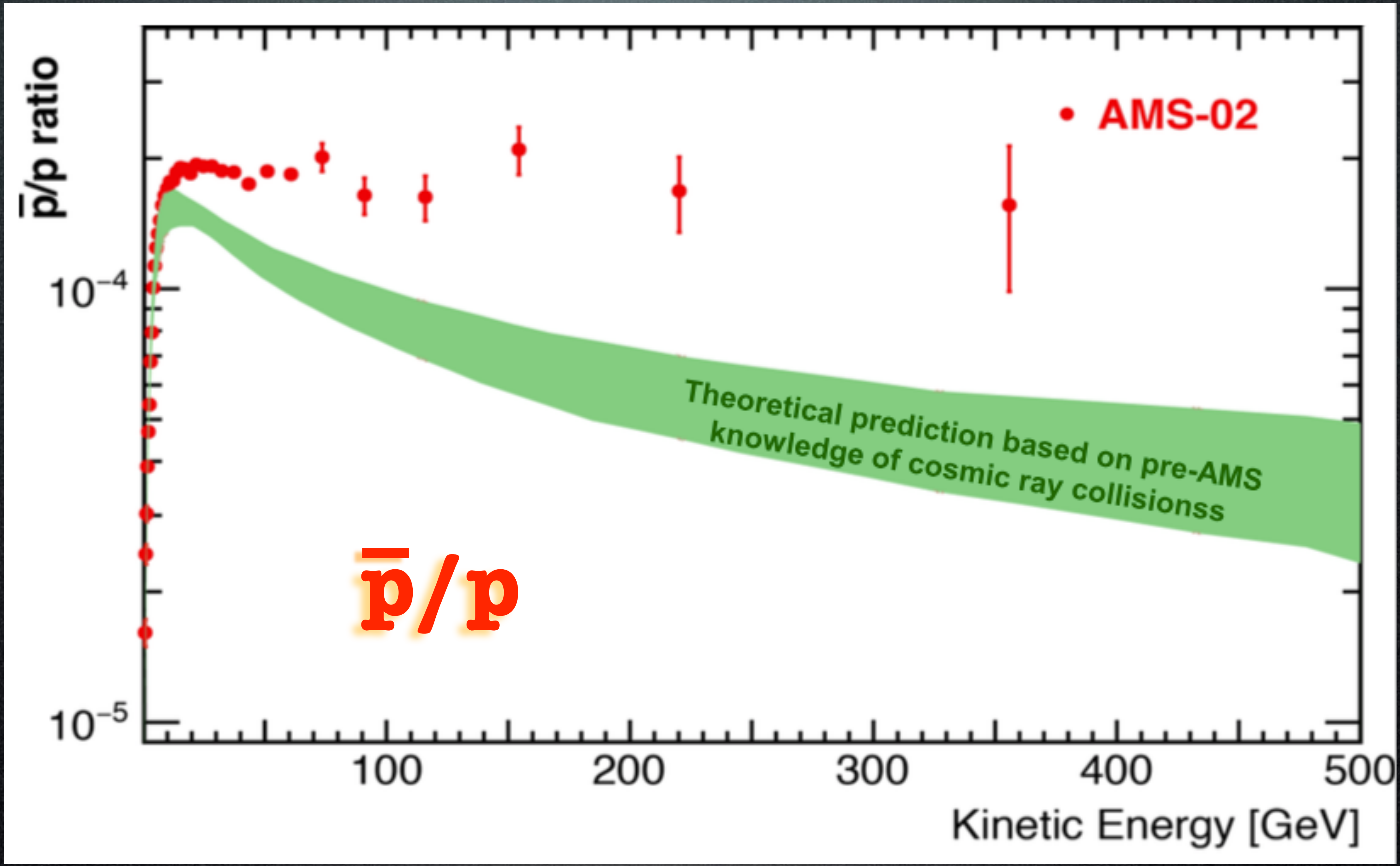
GAPS, AMS

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

SK, Icecube, Km3Net

Data: antiprotons

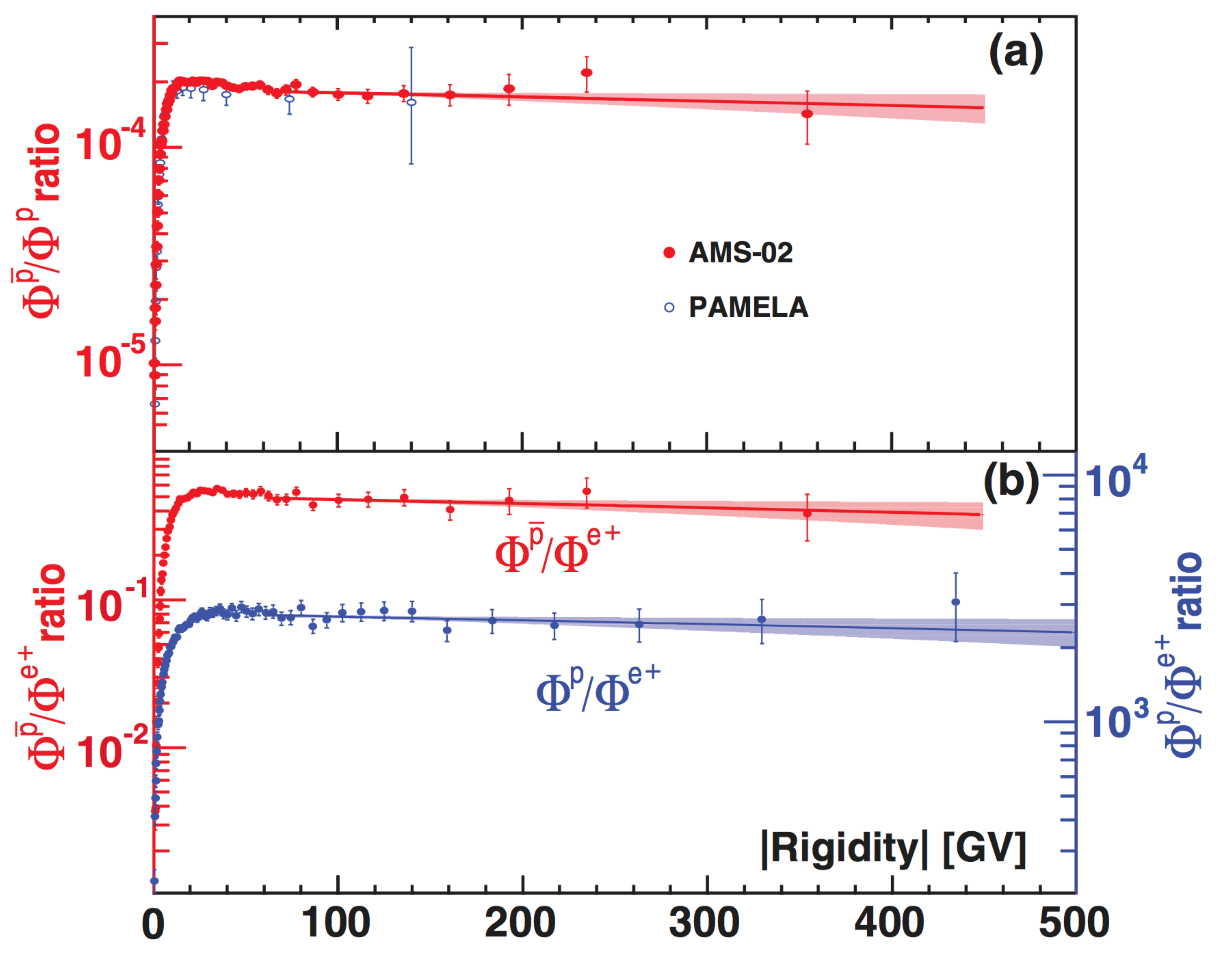
AMS-02



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

Data: antiprotons

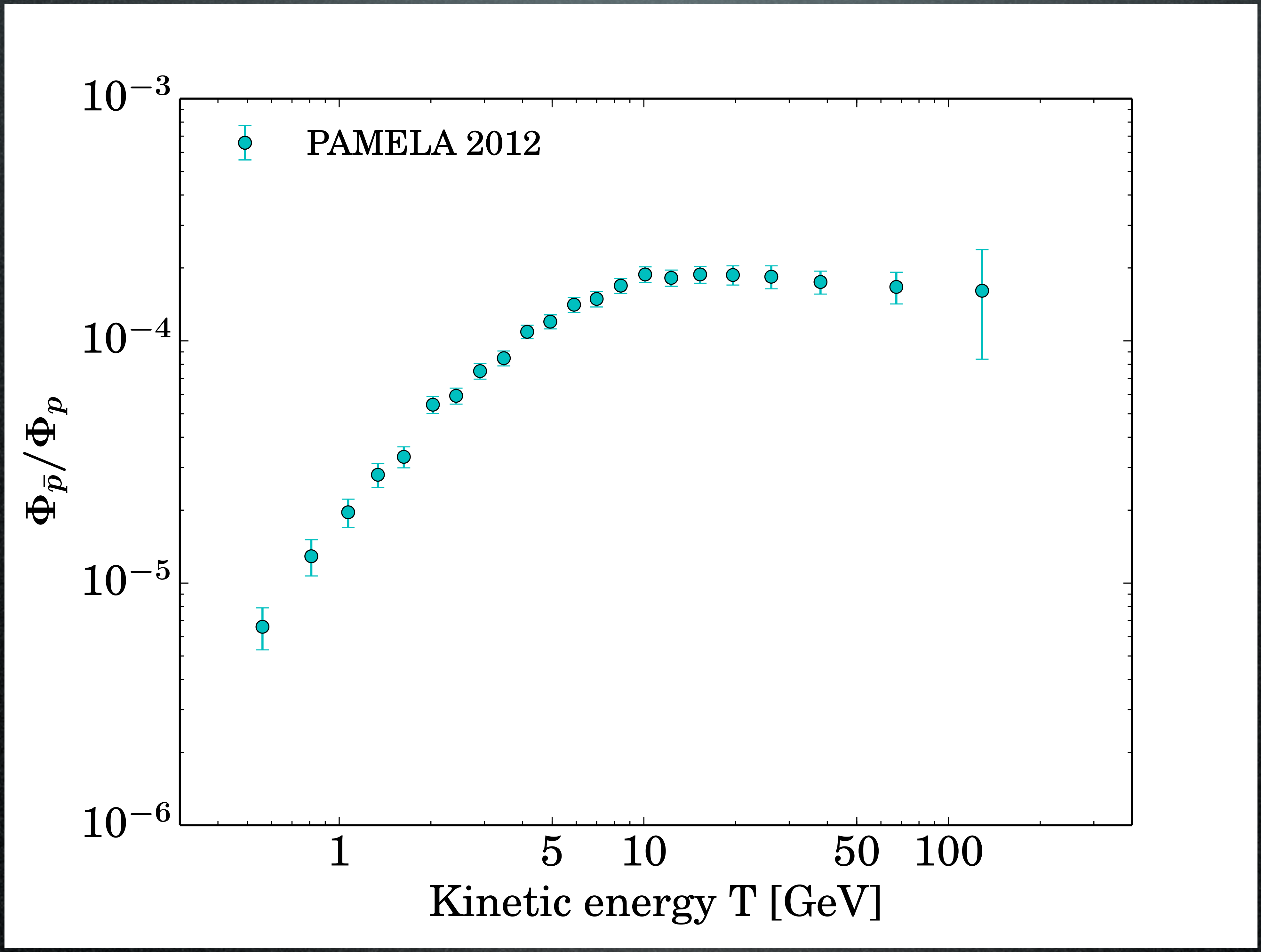
AMS-02



AMS coll.,PRL 117, 091103 (2016)

Antiprotons

Antiproton data vis-à-vis the secondaries:



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

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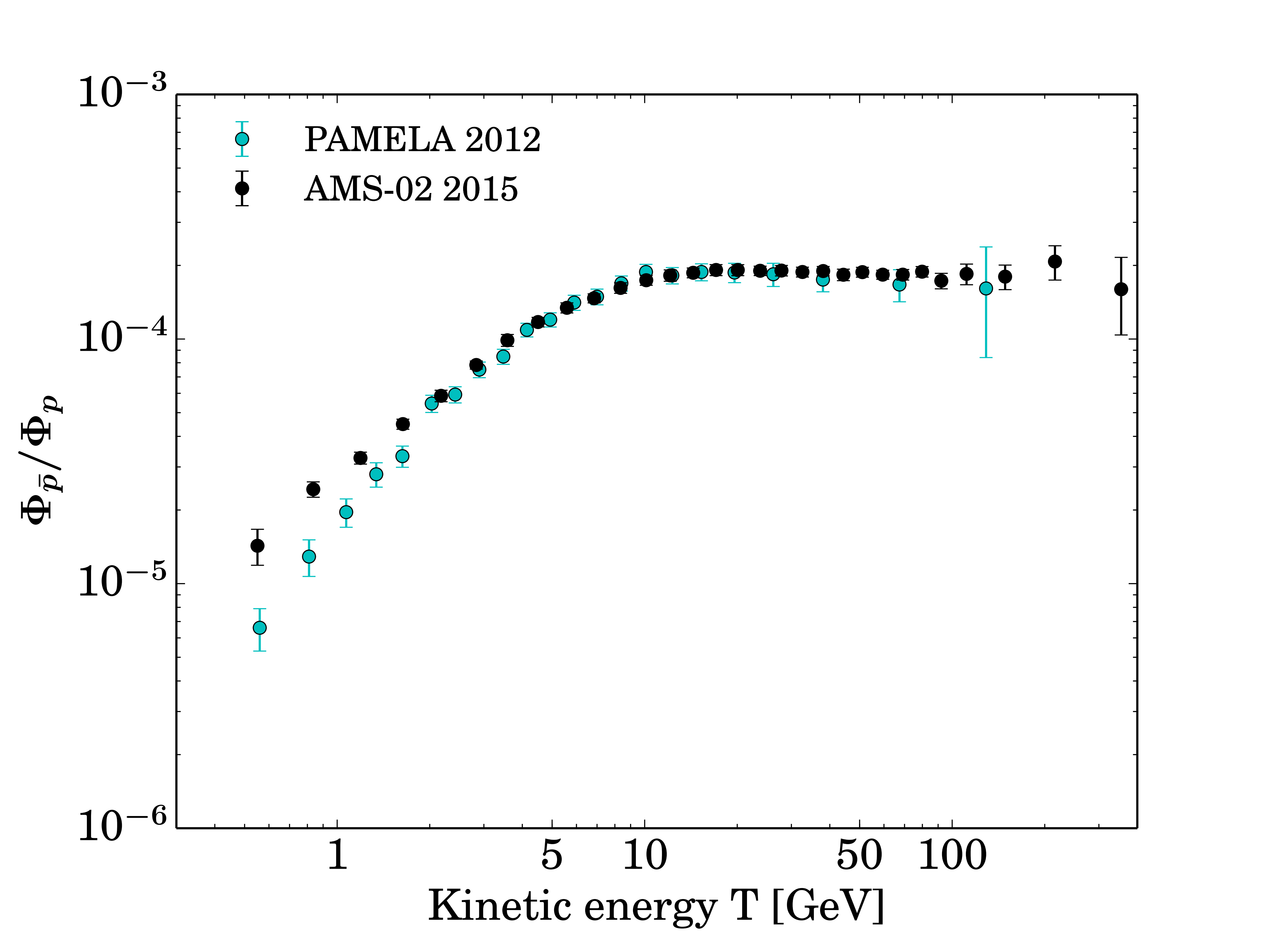

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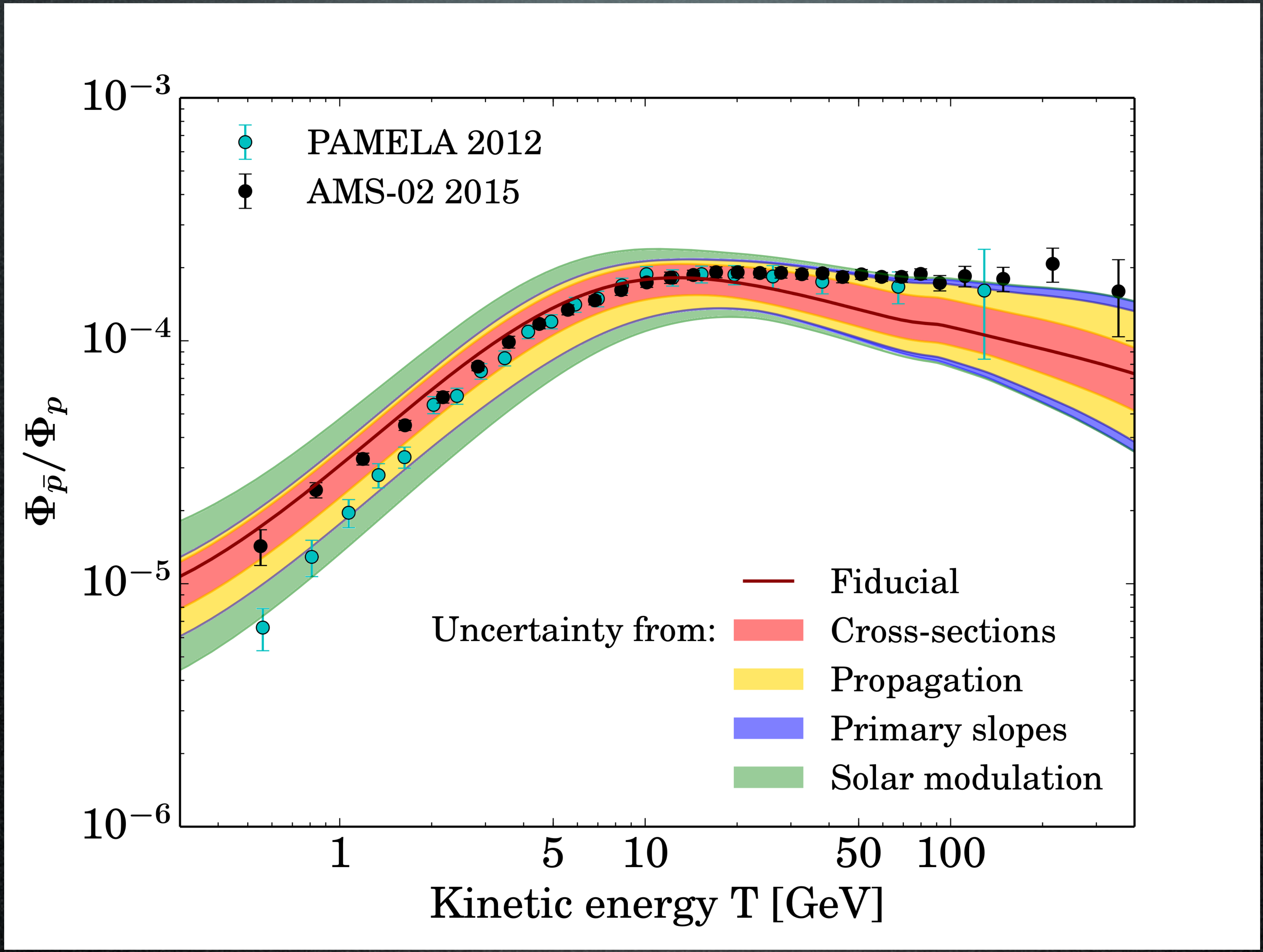

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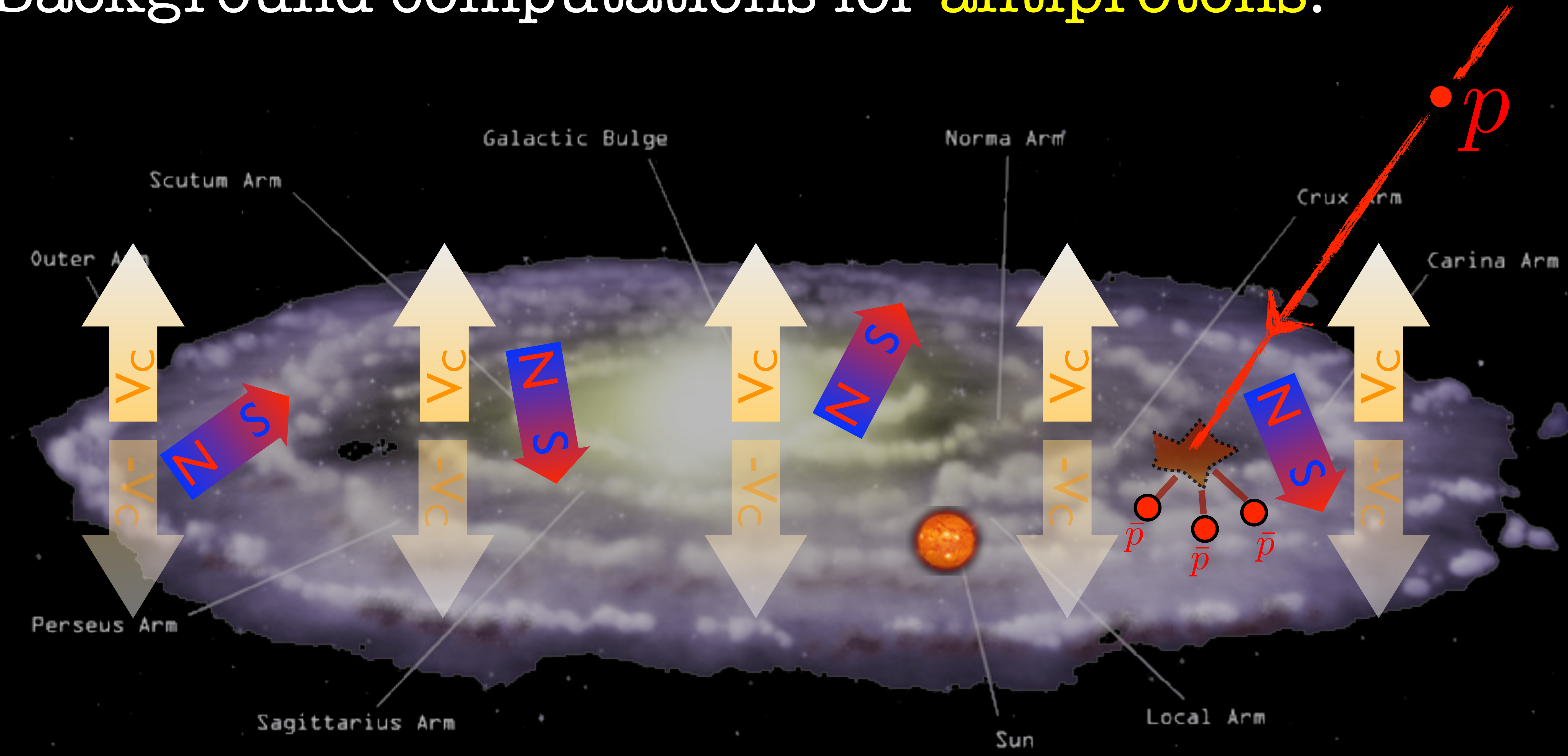
Indirect Detection

Background computations for antiprotons:



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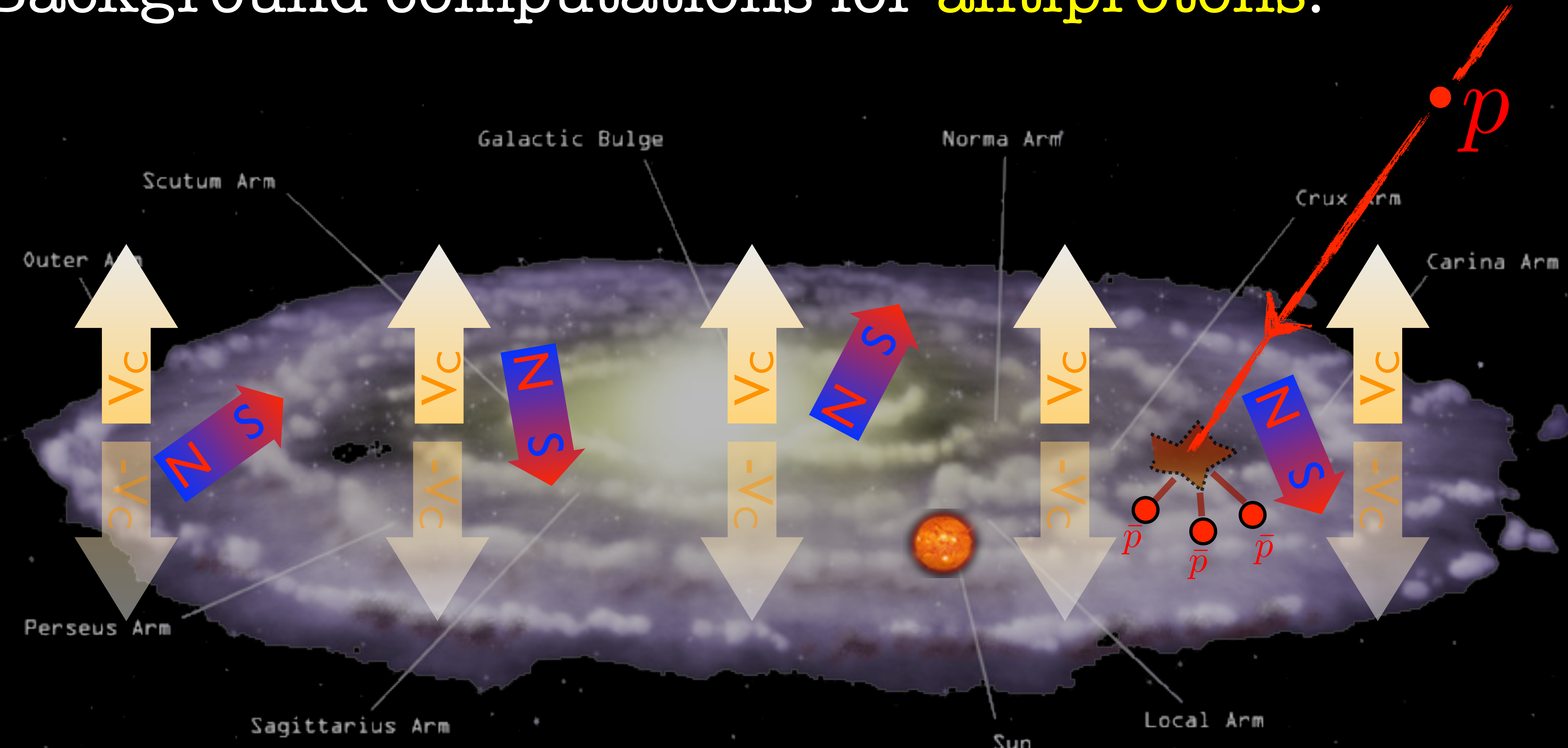
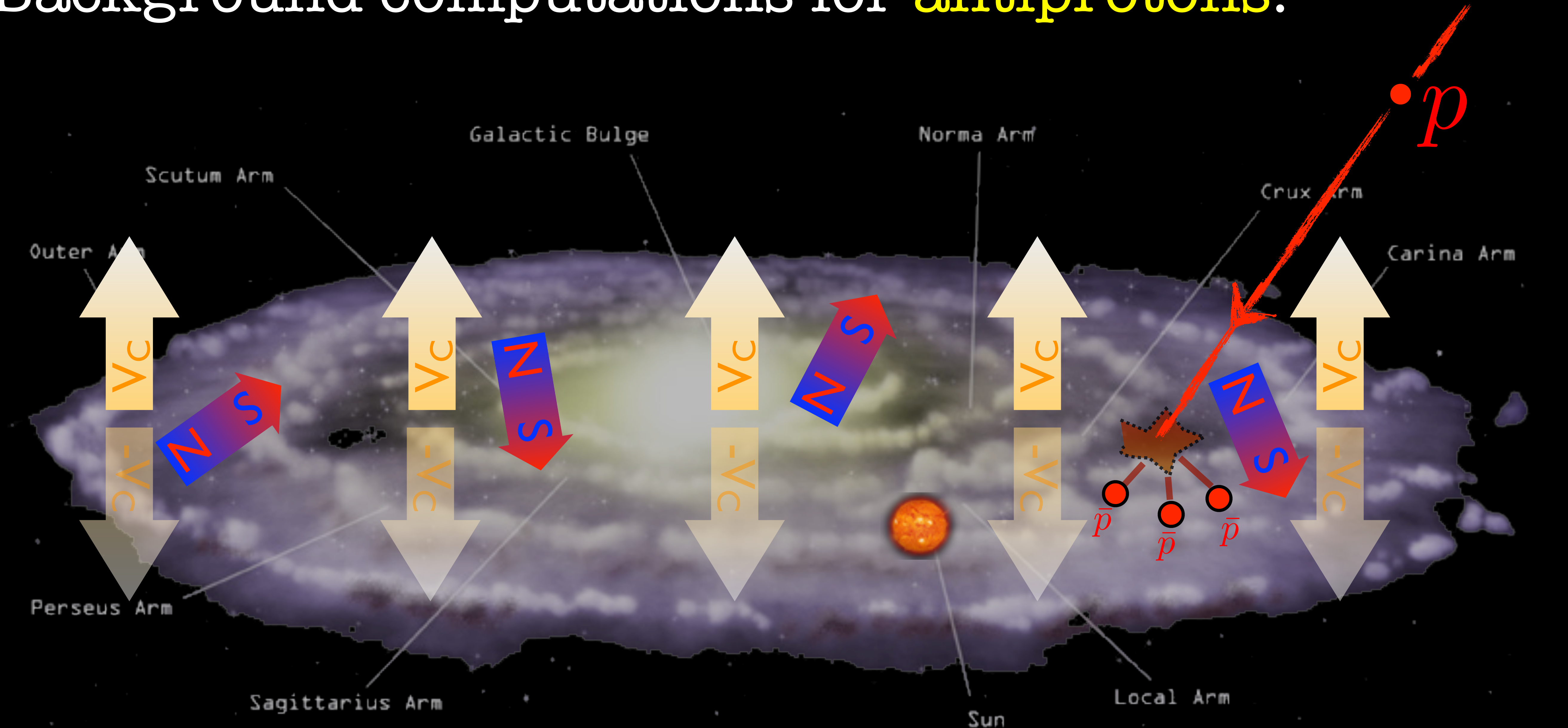


Main ingredients:

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

Indirect Detection

Background computations for antiprotons:

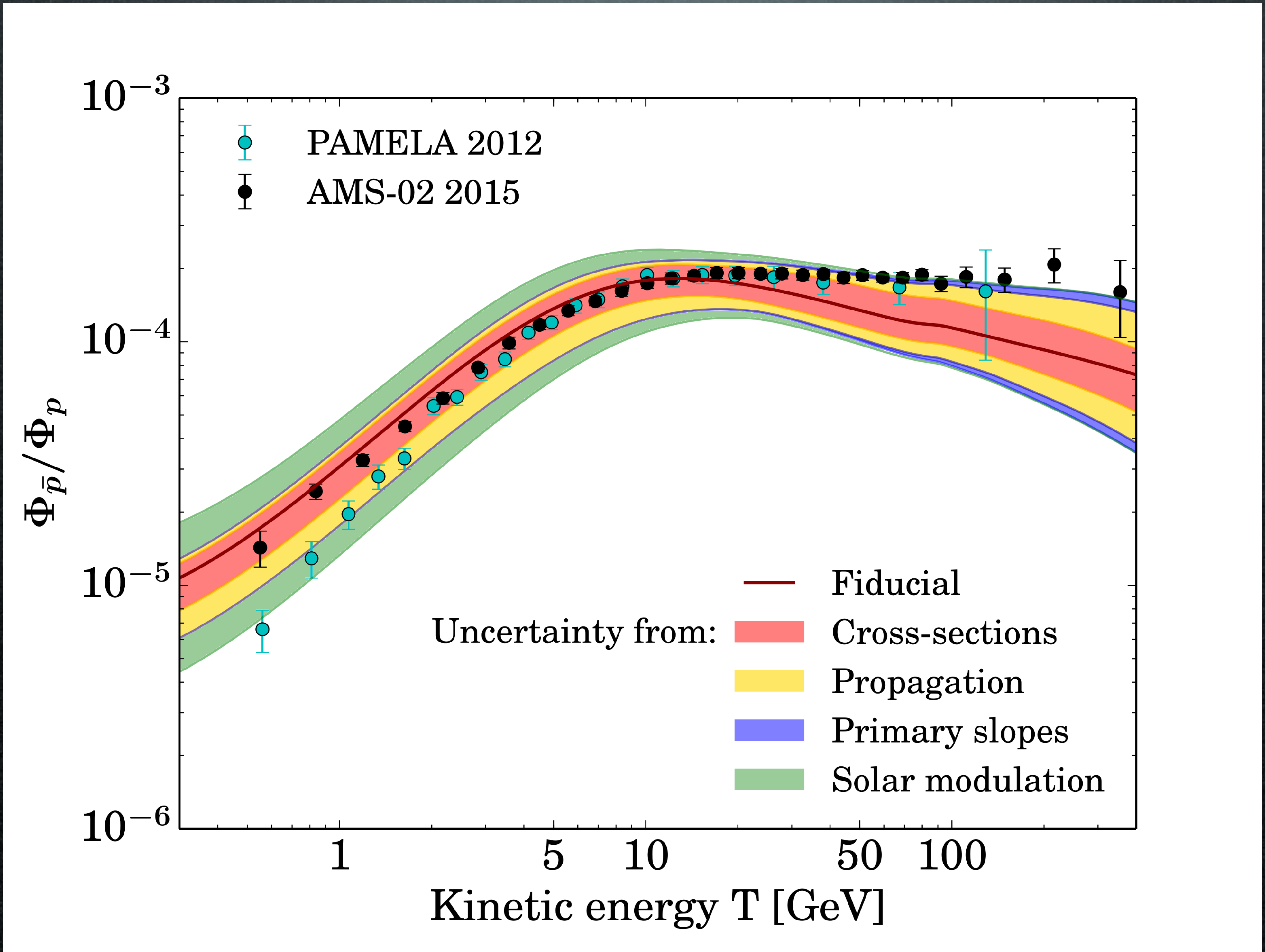


Main ingredients:

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

Antiprotons

Antiproton data vis-à-vis the secondaries:



No evident **excess**

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

Antiprotons

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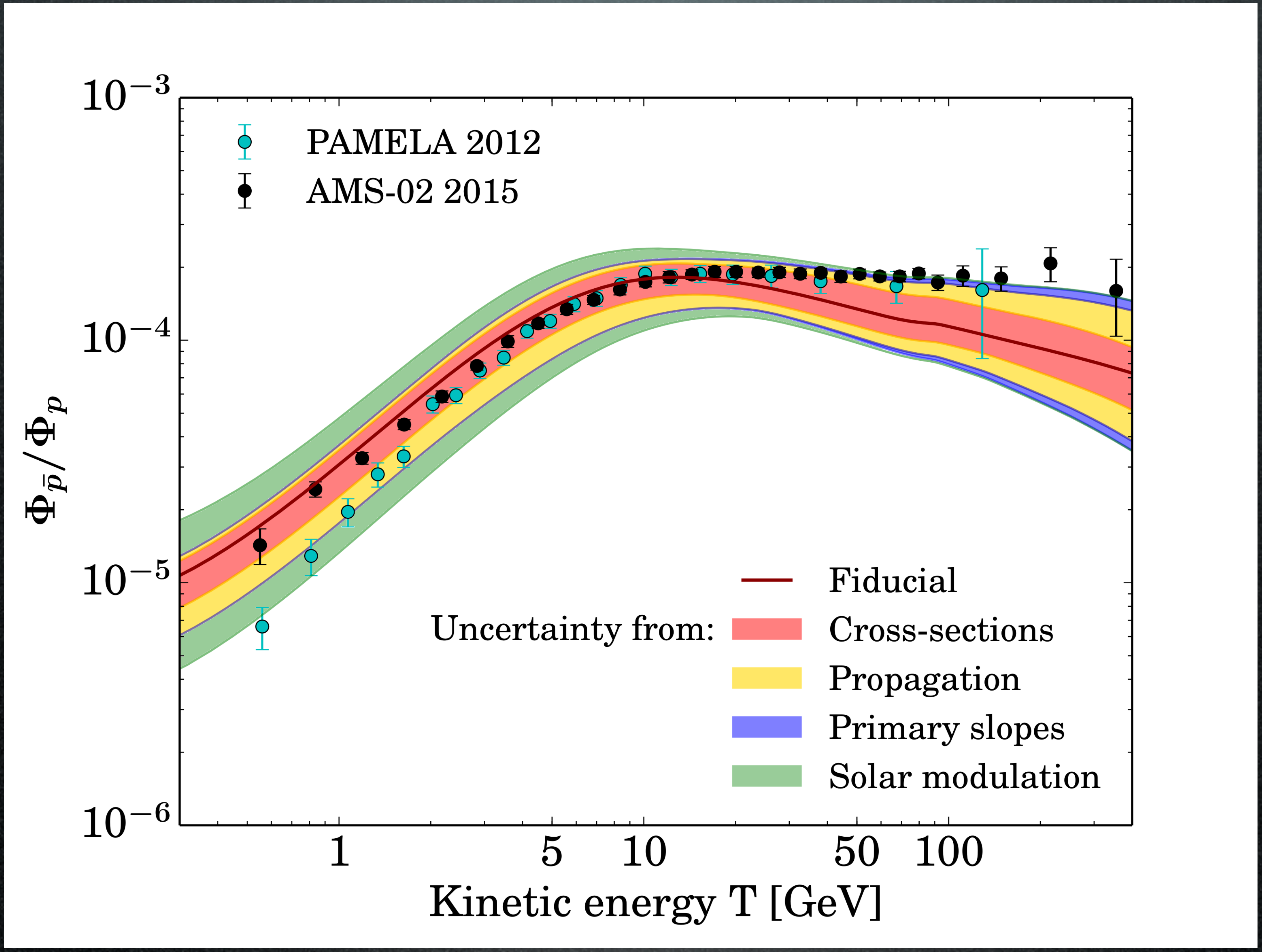

No evident **excess**

Some preference for flatness

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

Antiprotons

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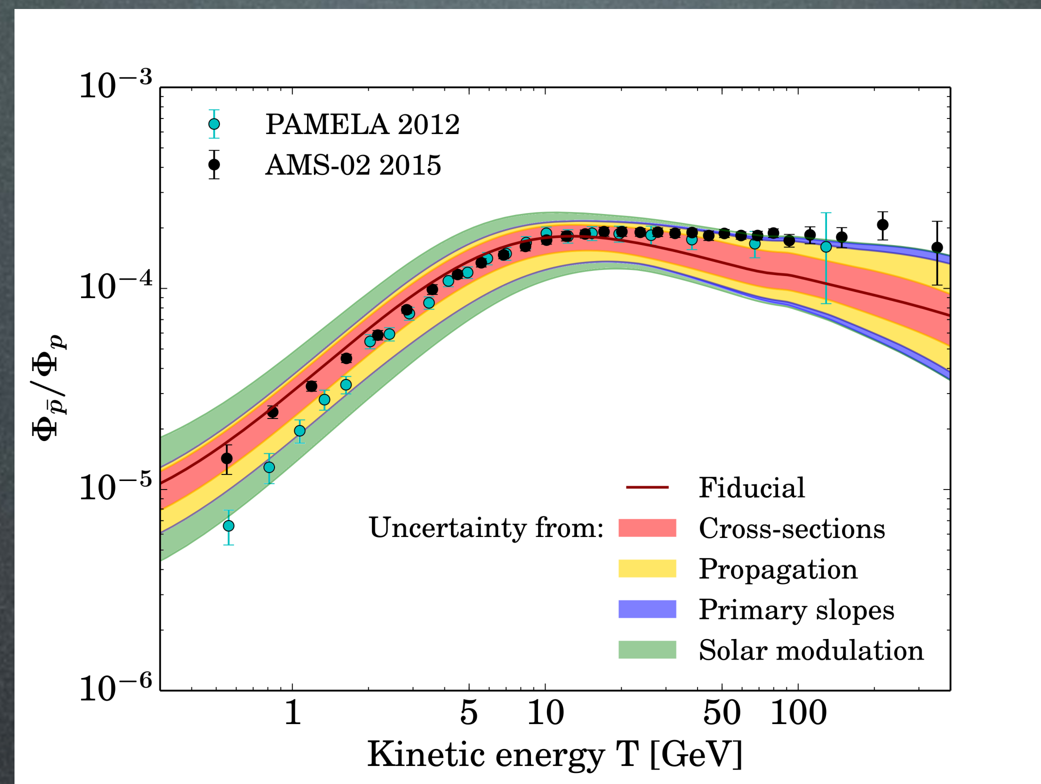
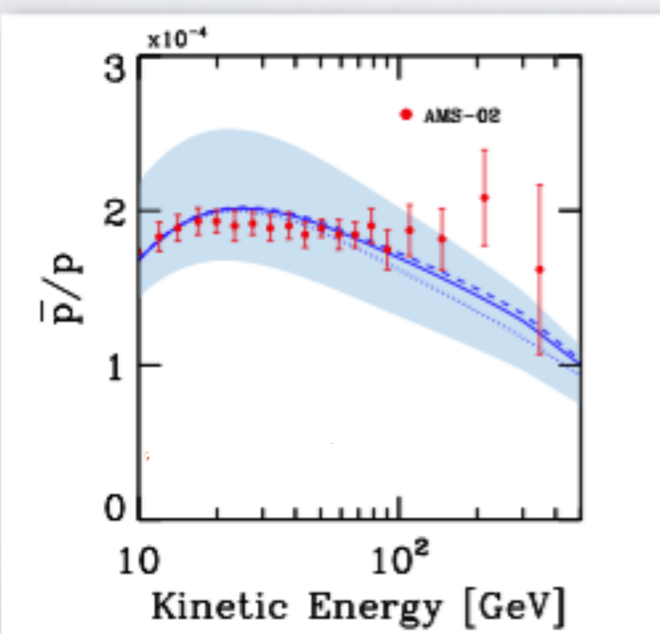


Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico 1504.04276

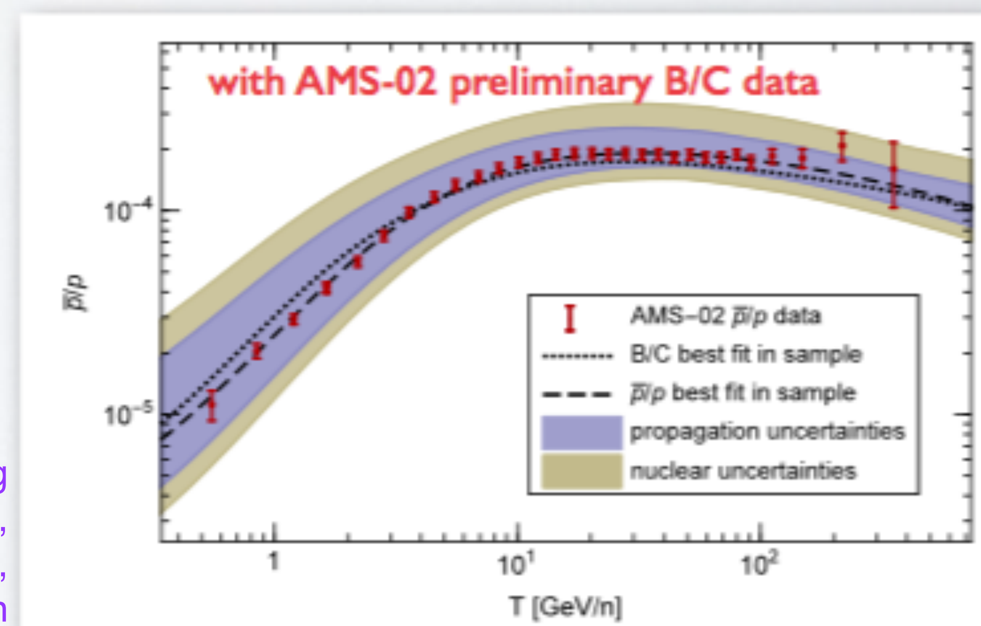
using
p, He by AMS-02,
B/C by PAMELA

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



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

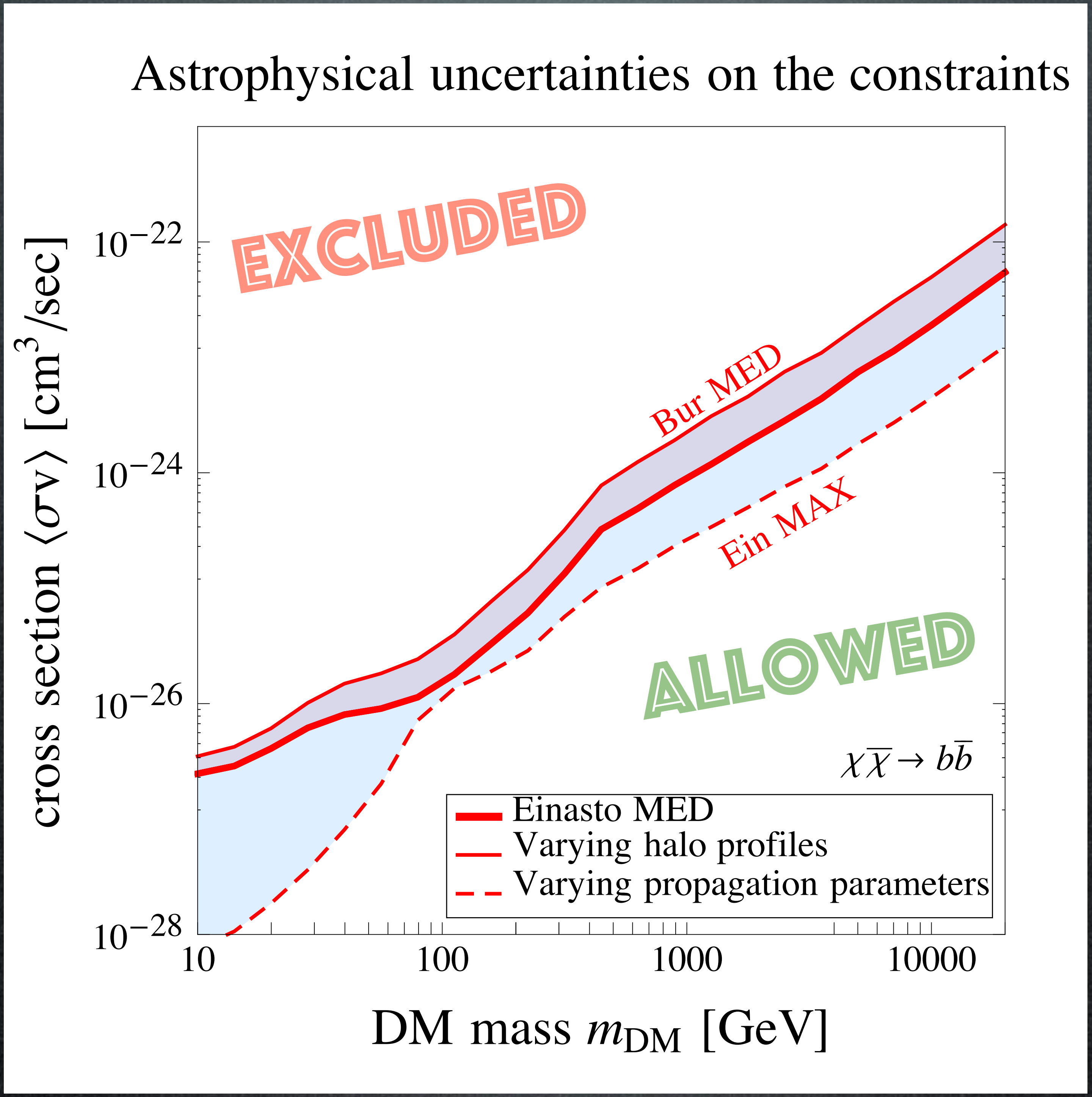
R. Kappl, A. Reinert and M.W. Winkler, arXiv:1506.04145



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

Dark Matter interpretation

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

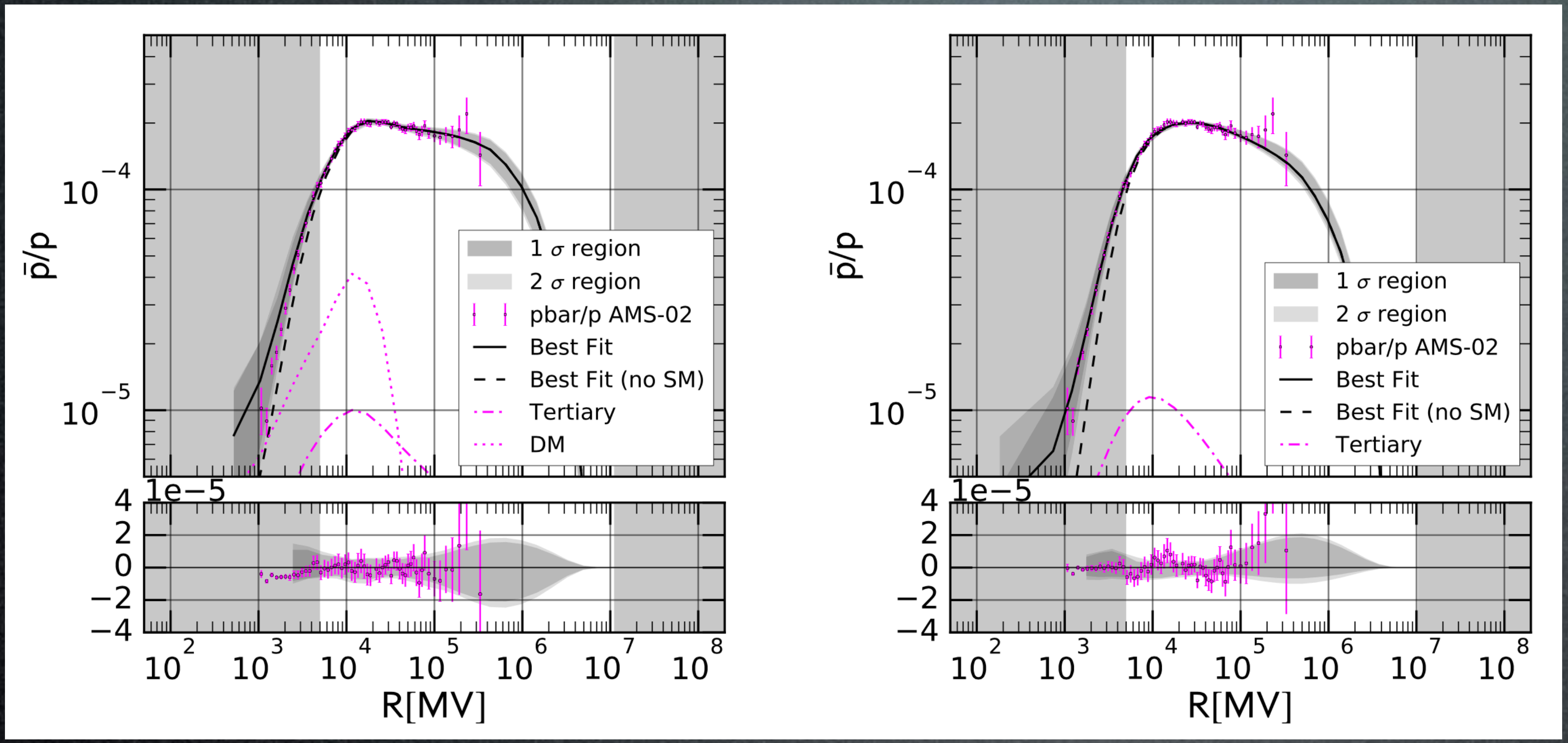


Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico 1504.04276

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



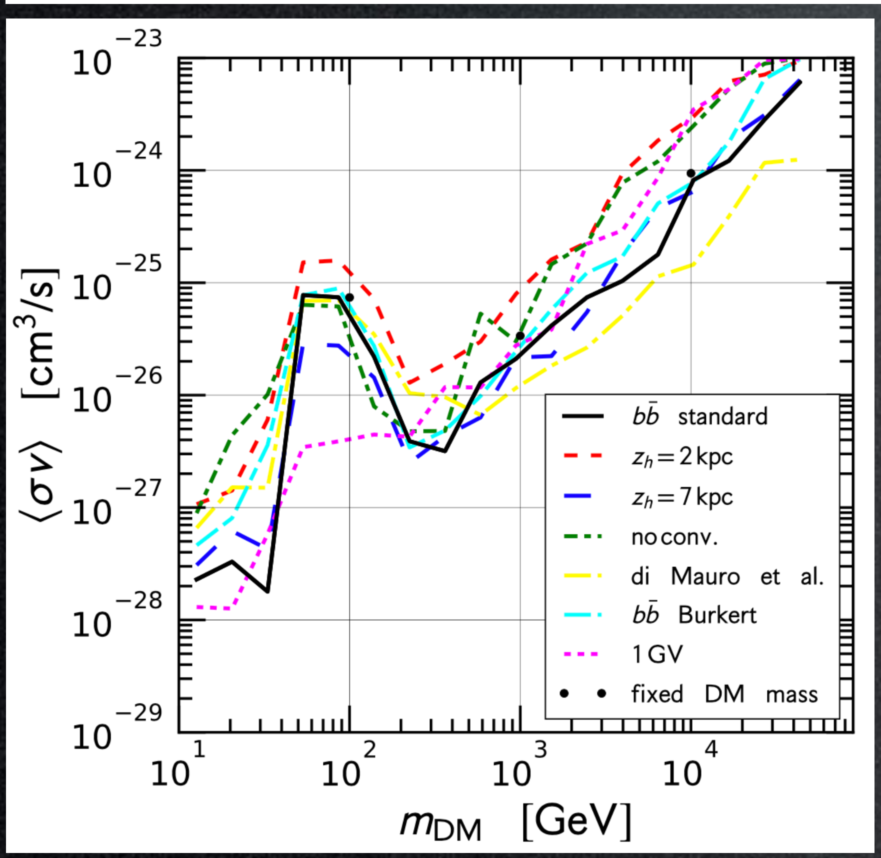
finds a possible excess

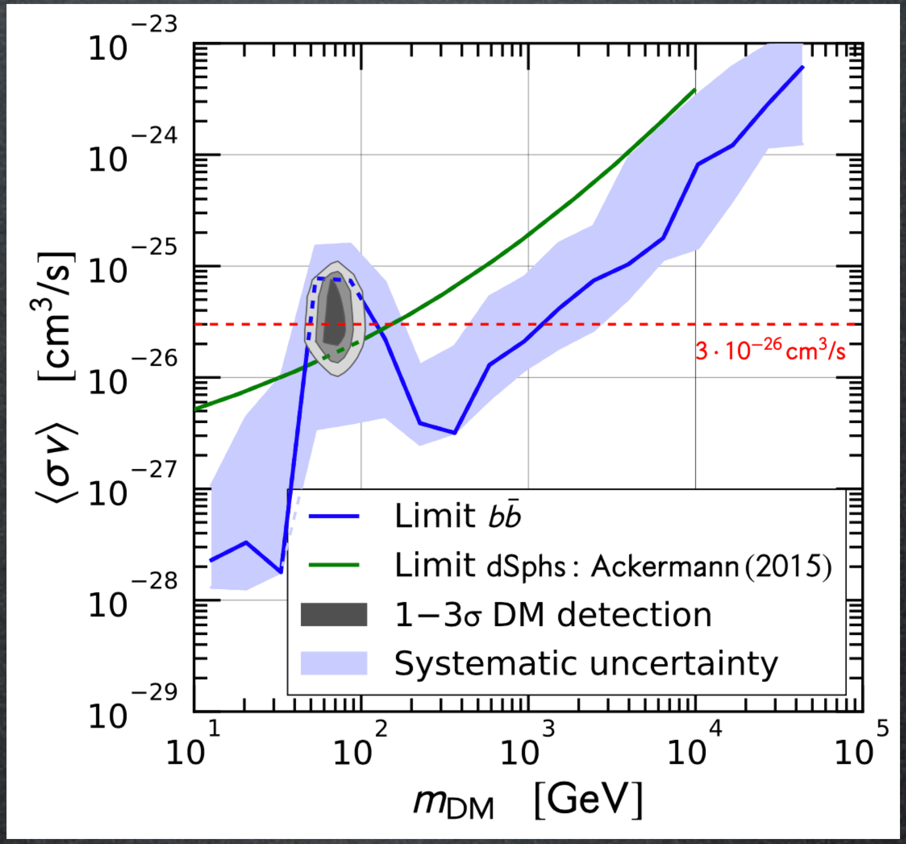
(formally ~4.5σ)

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

similarly:

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





reiterated:

Cuoco, Heisig, K³ 1903.01472
Cholis, Linden, Hooper 1903.02549

Antiprotons

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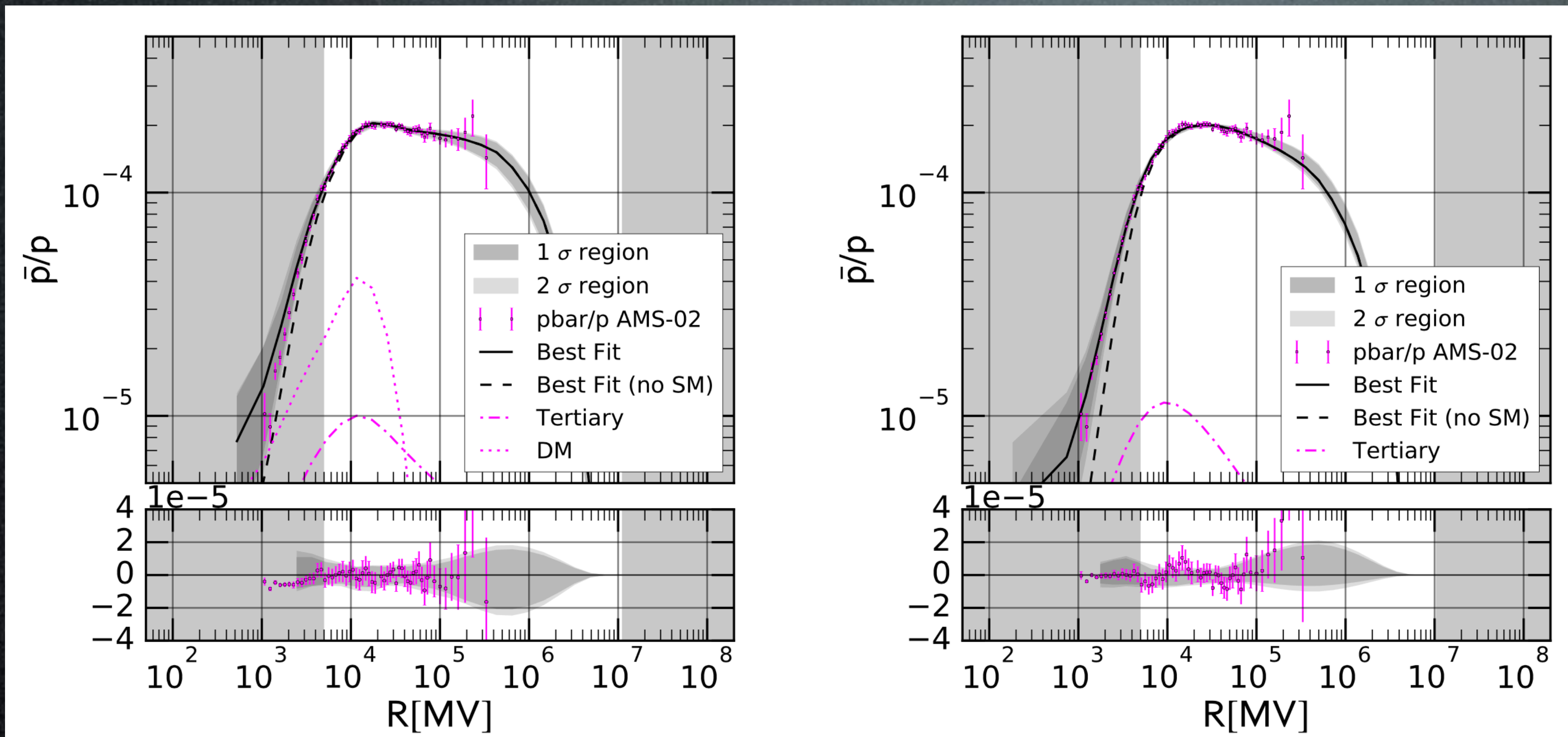

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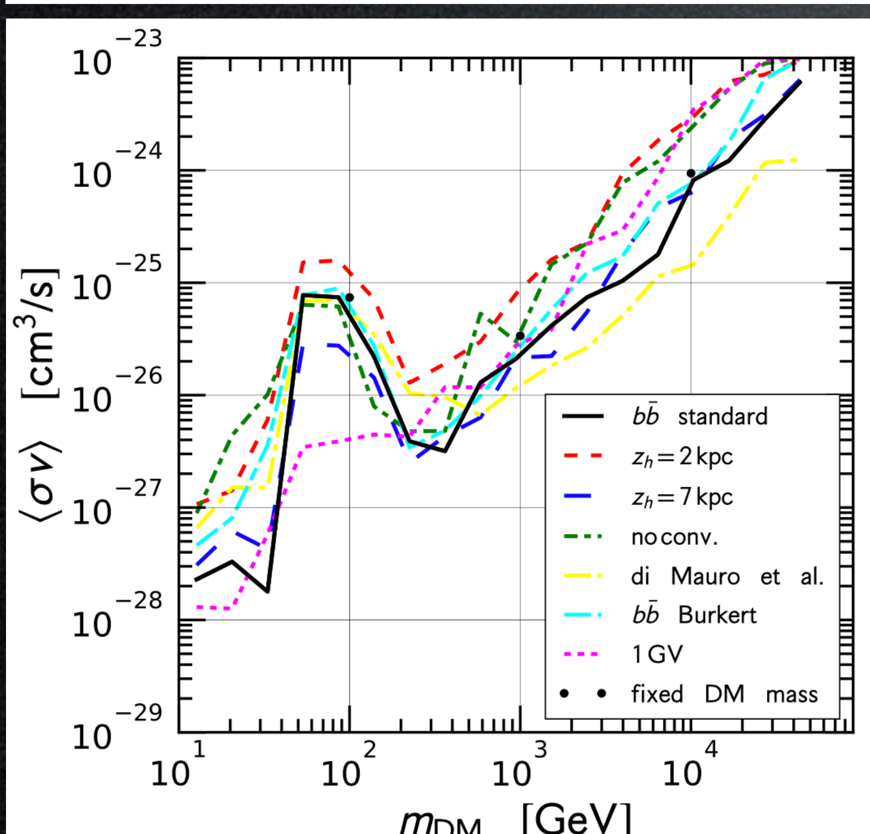
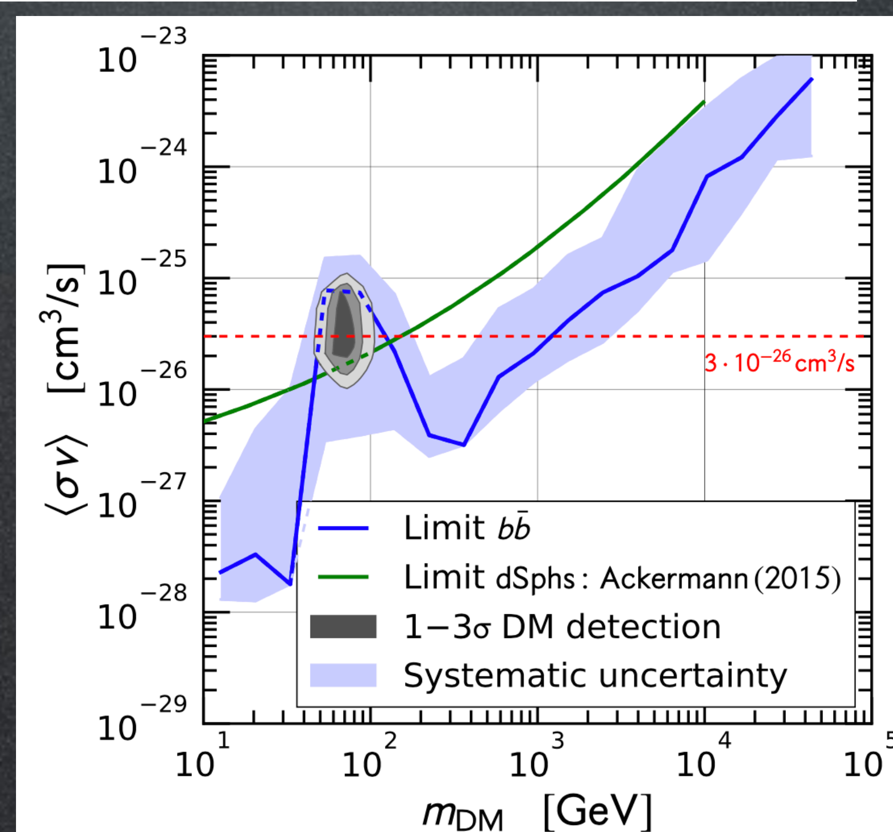




criticisms:

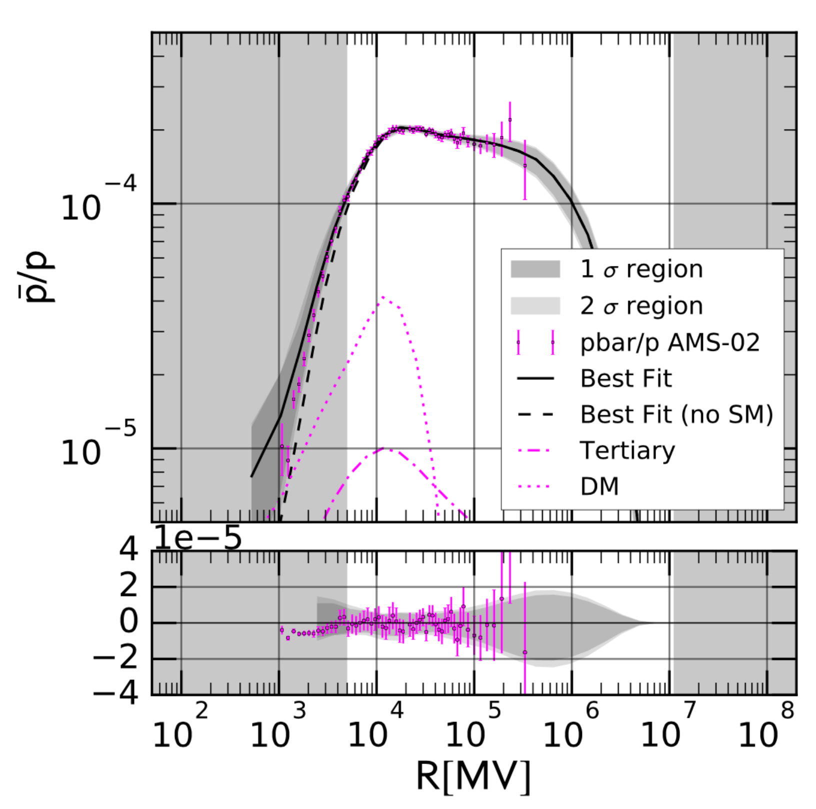
propagation parameters determined with p, He data only, w/o B/C

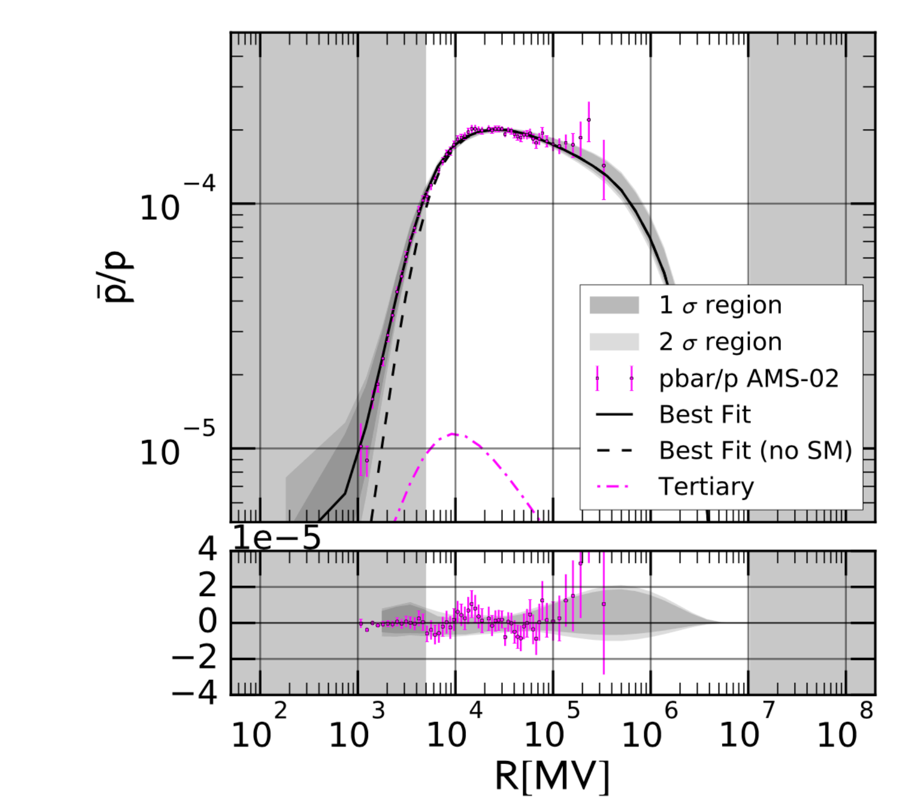
excess evaporates including low energies

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071





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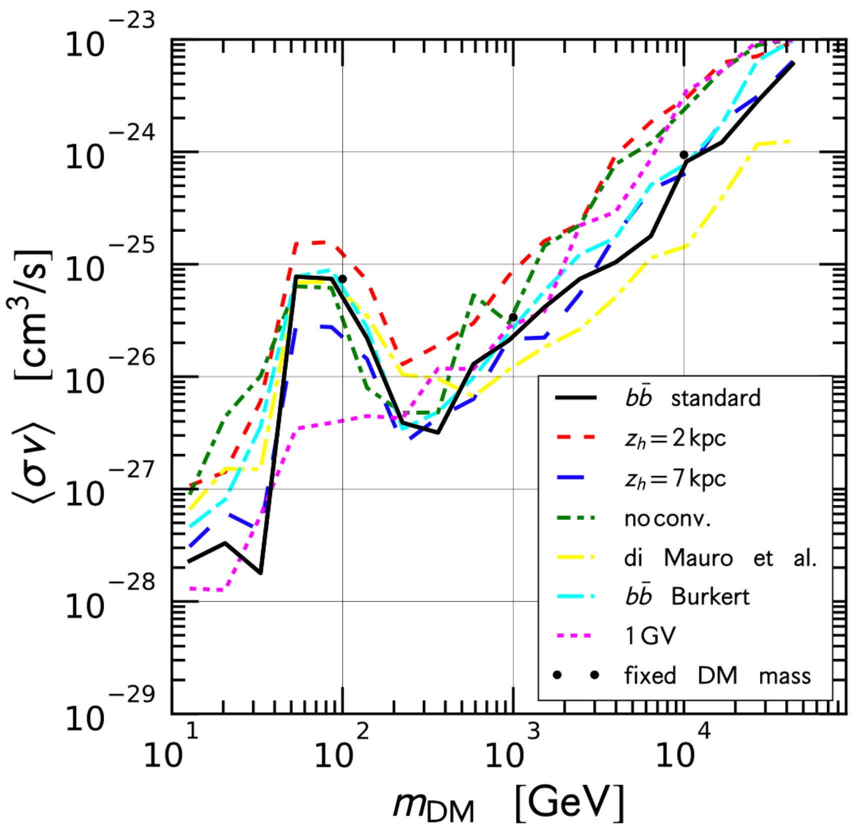

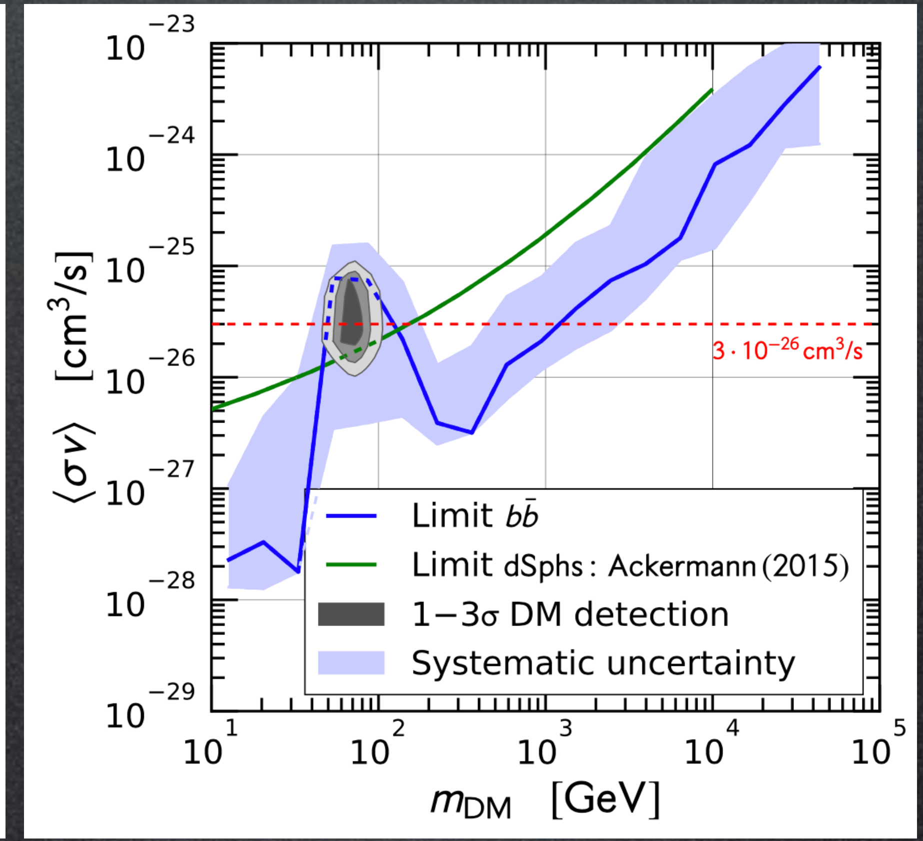

on the other hand:

B/C and p probably probe different regions

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

Antiprotons

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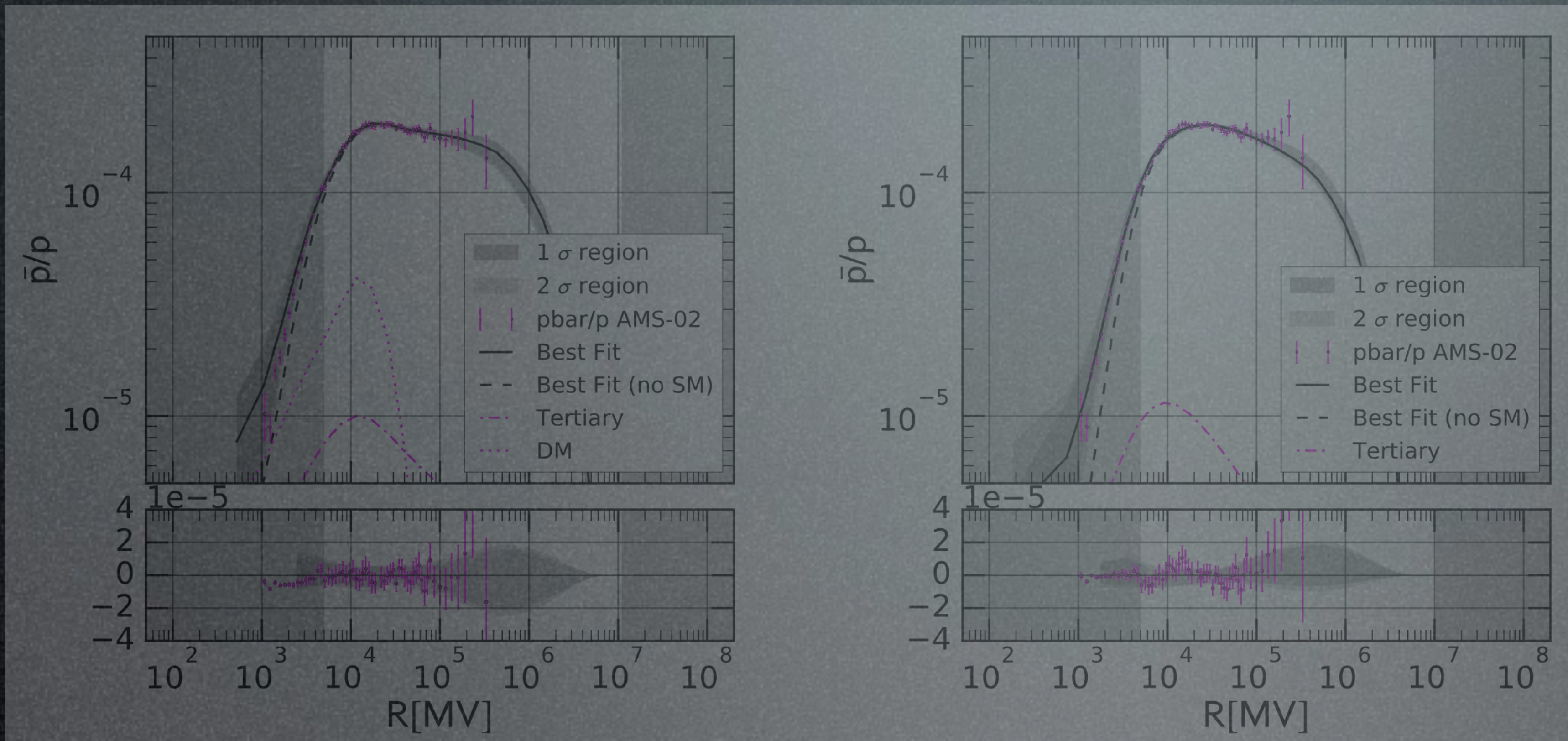

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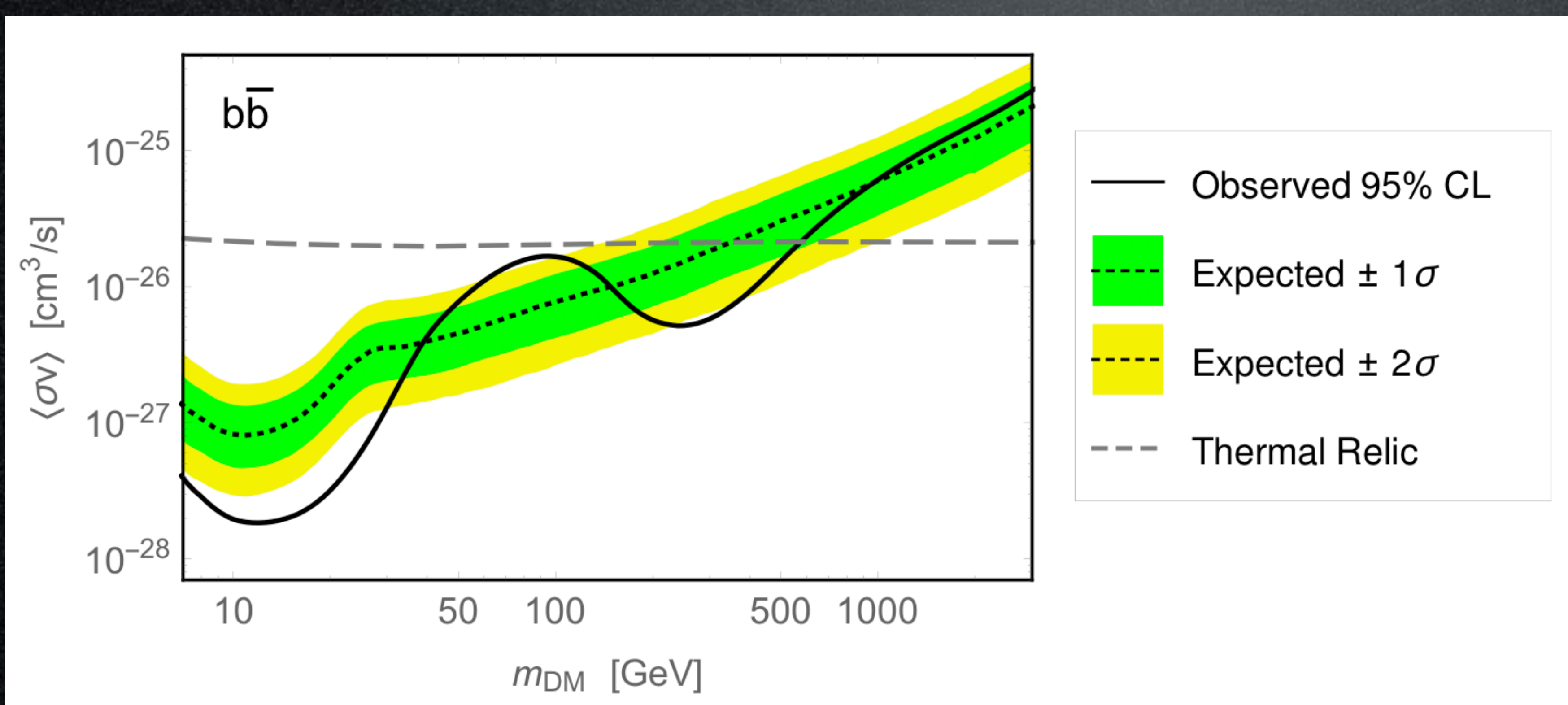

Reinert, Winkler 1712.00002

excess exists

but significance ~1σ,
given all uncertainties

Positrons (and electrons)

direct detection

production at colliders

indirect

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Fermi, ICT, radio telescopes...

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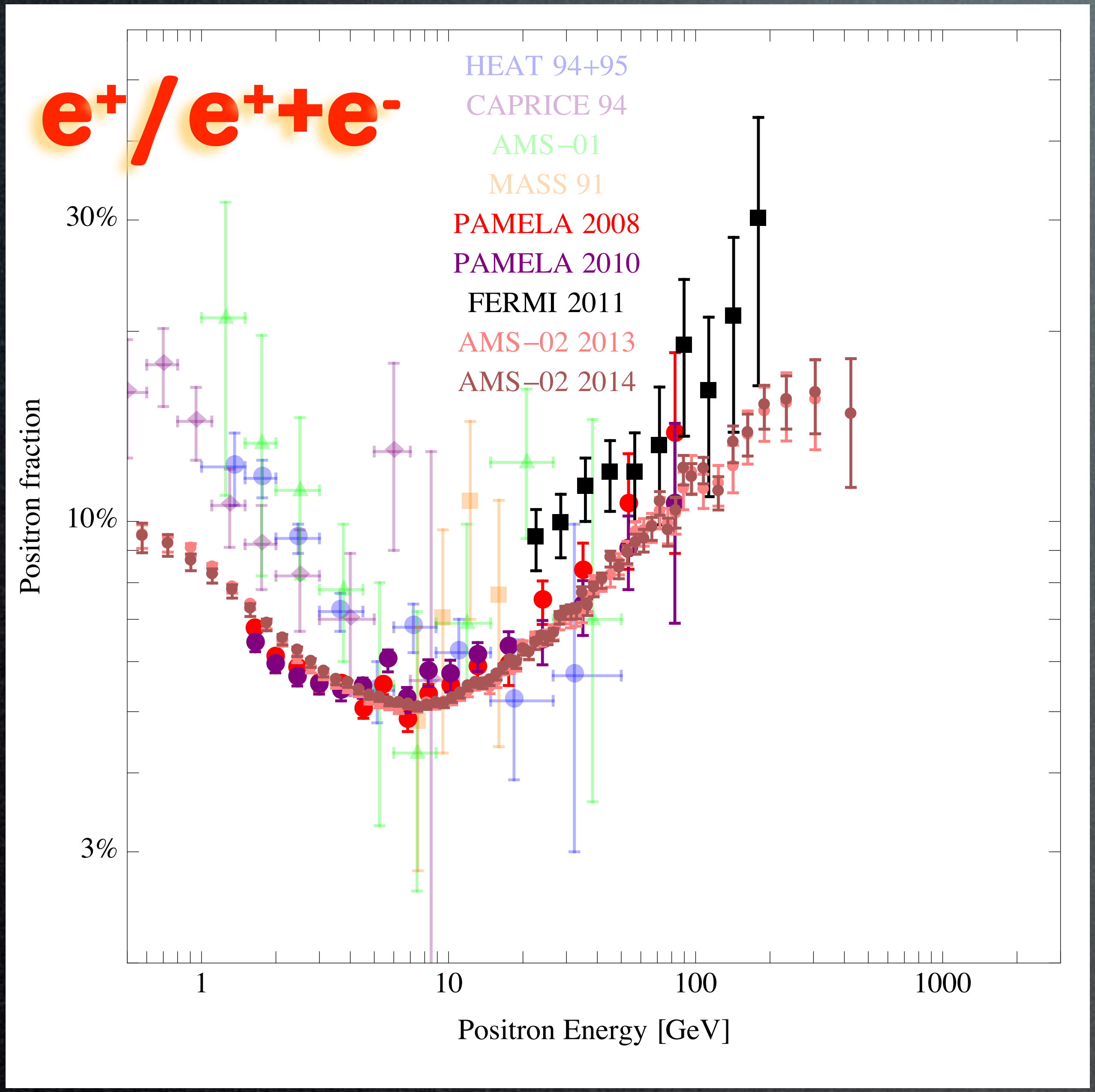
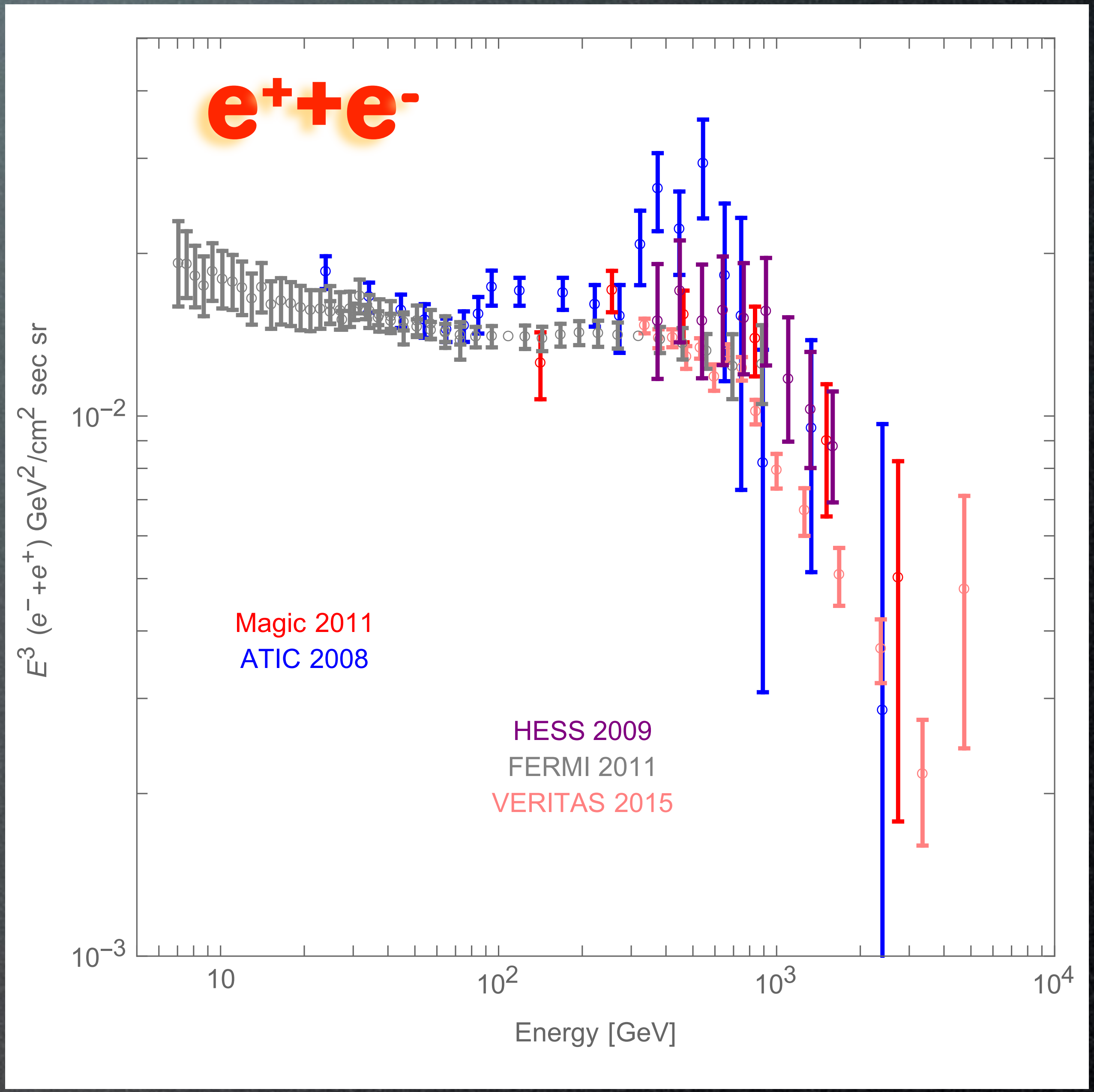
Data: leptons

high energy



M. Cirelli - compilation ICRC 2015



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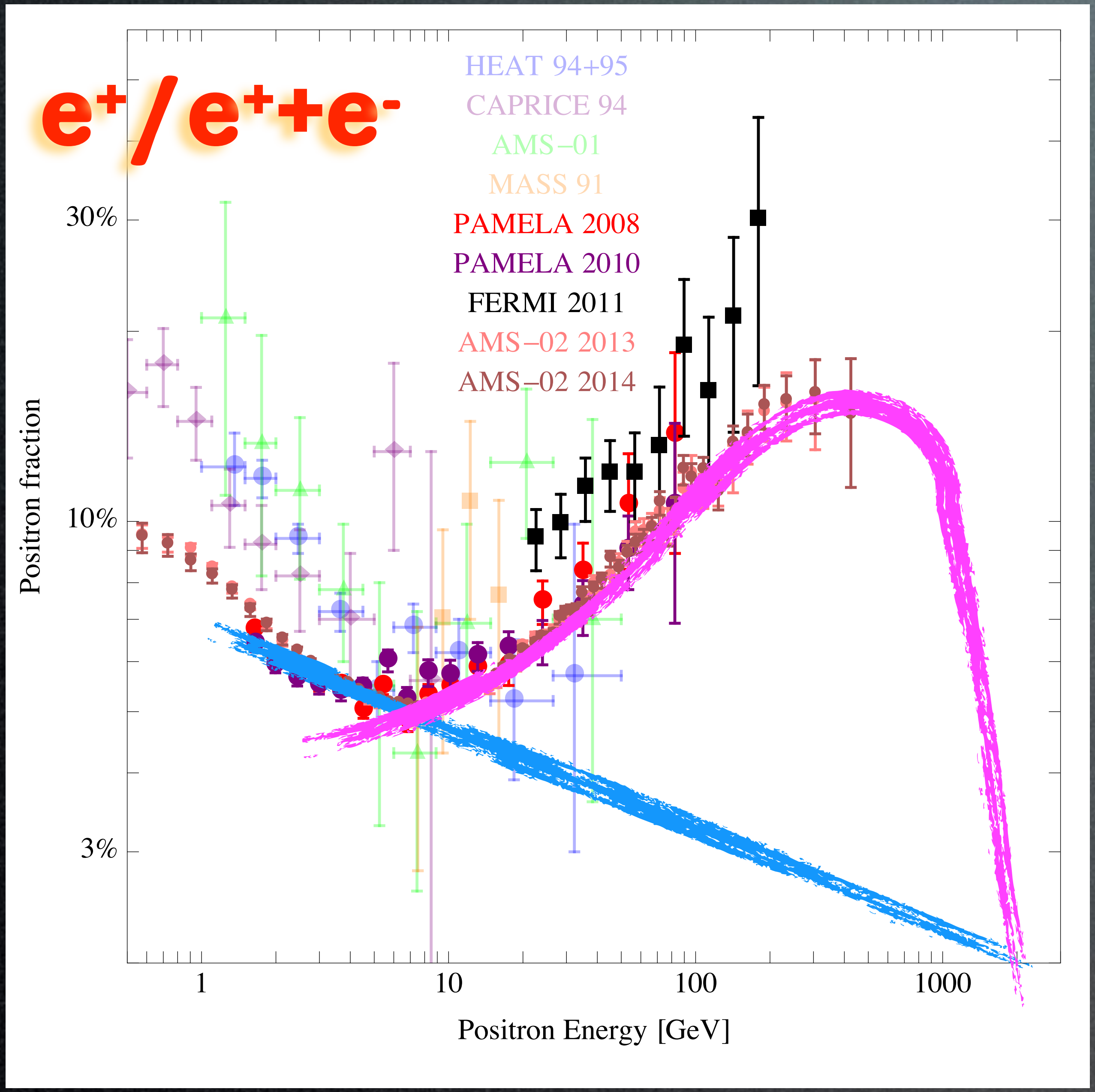

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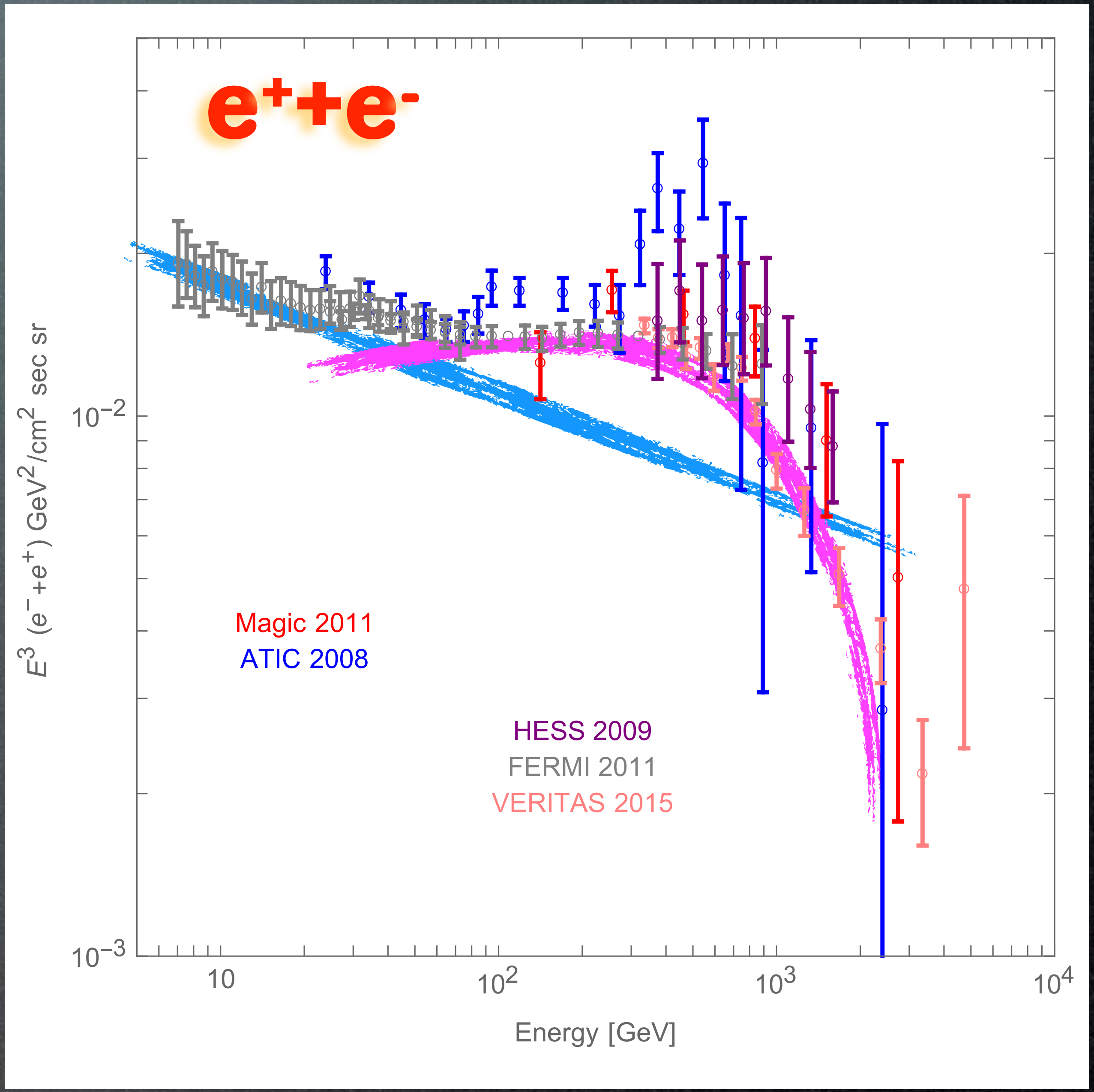
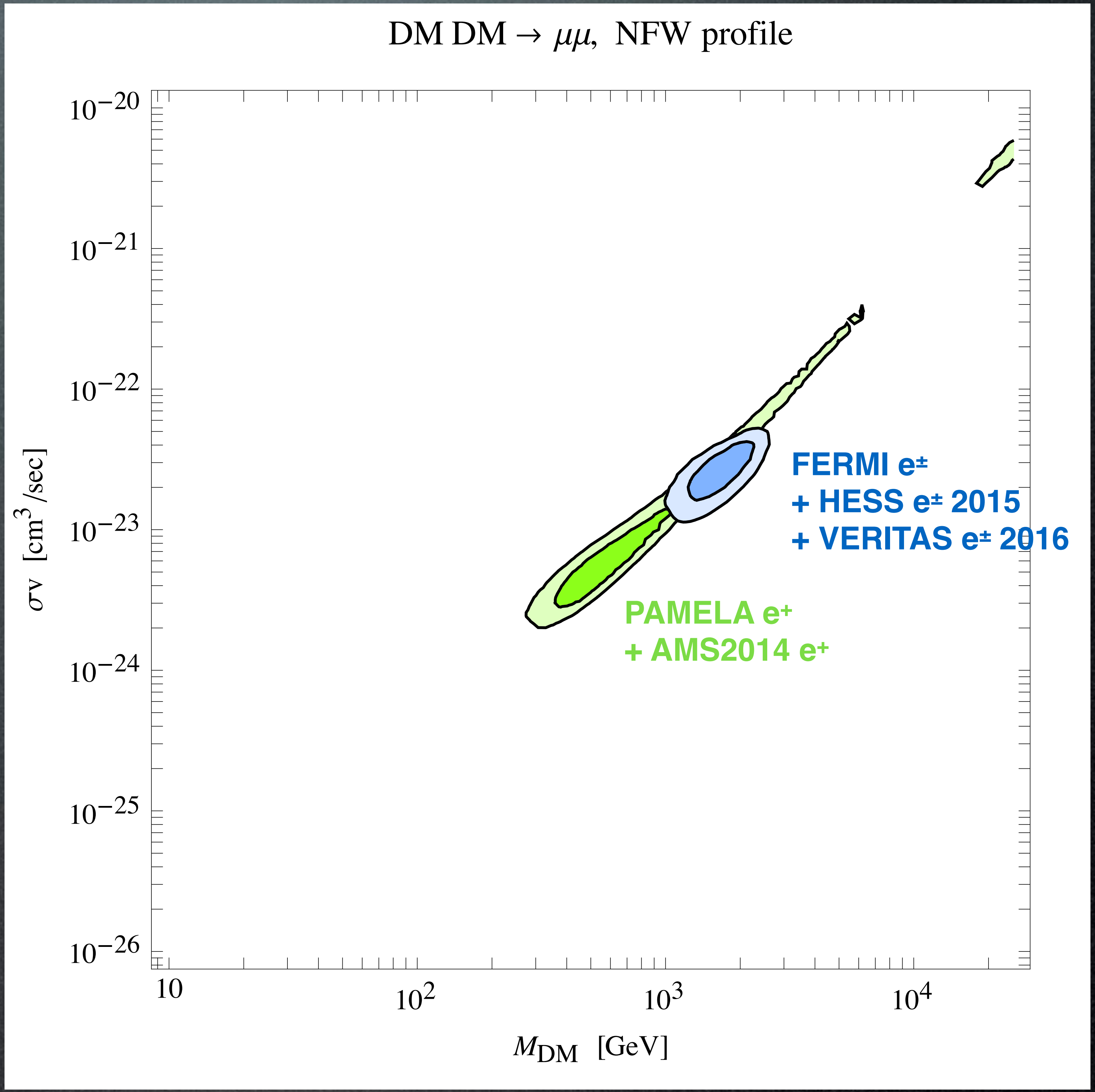


M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

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



M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

However:

Dark Matter interpretation

However:

- increased precision brings increased tension

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

  M. Boudaud et al., 1410.3799

Dark Matter interpretation

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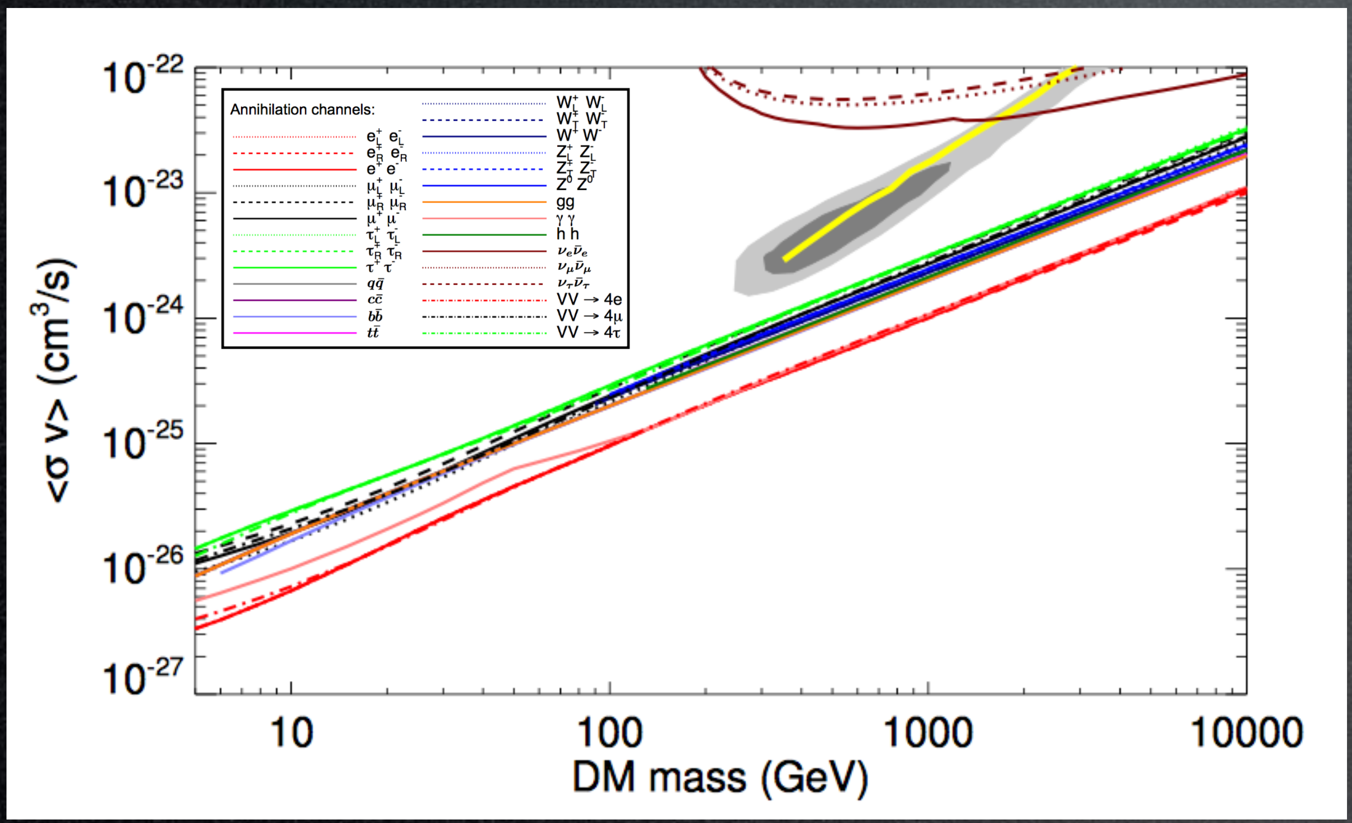
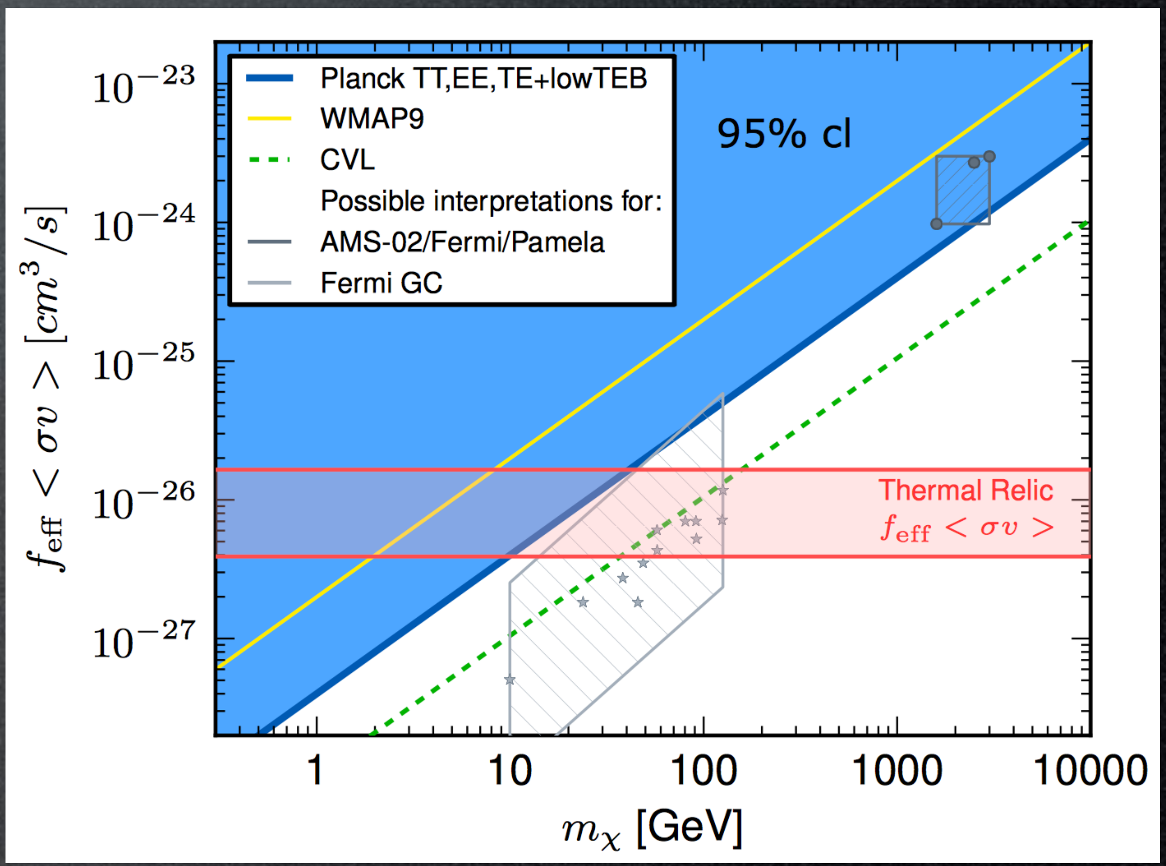
- constraints: gamma rays, neutrinos, CMB...

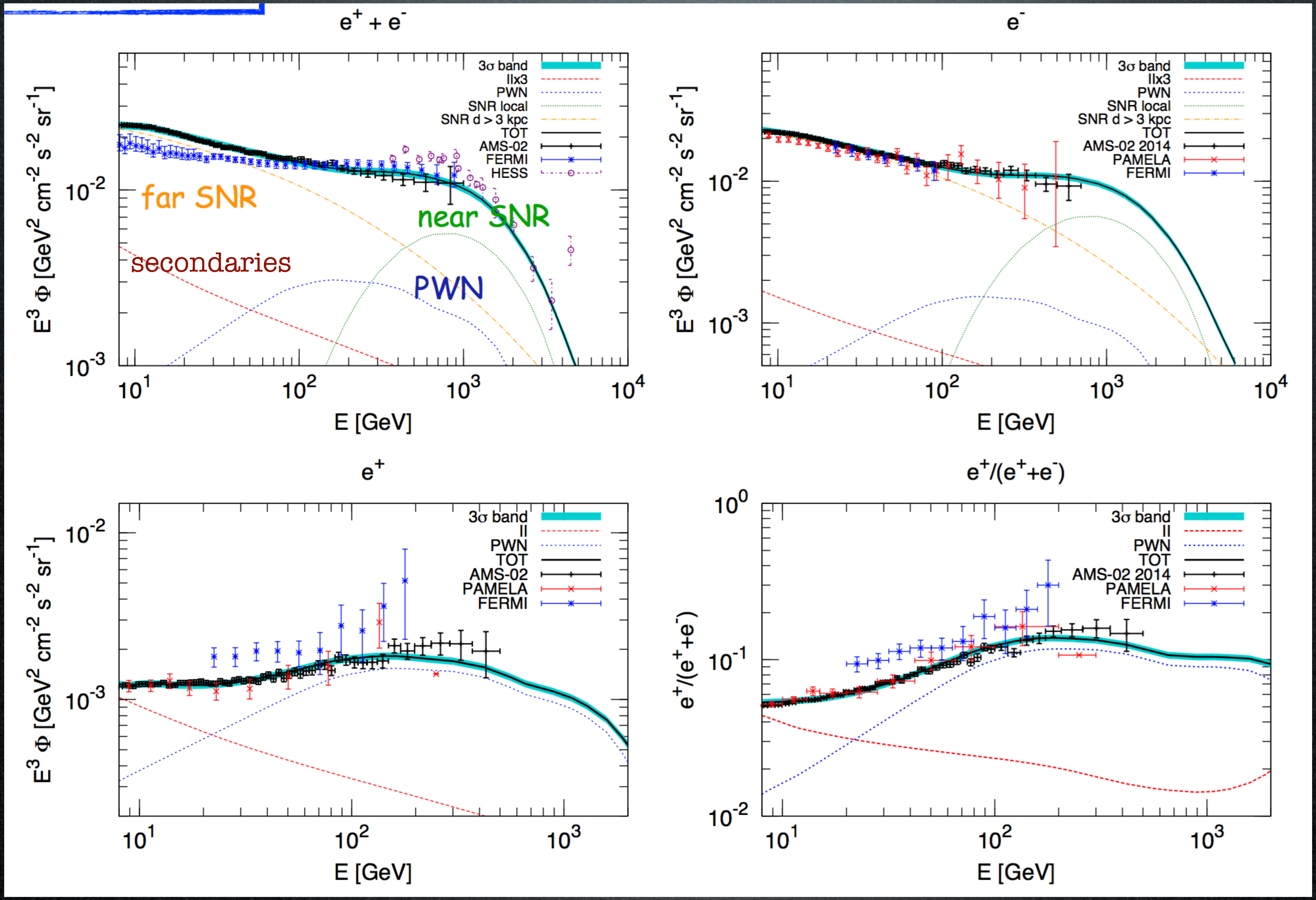


T.Slatyer 1506.03811



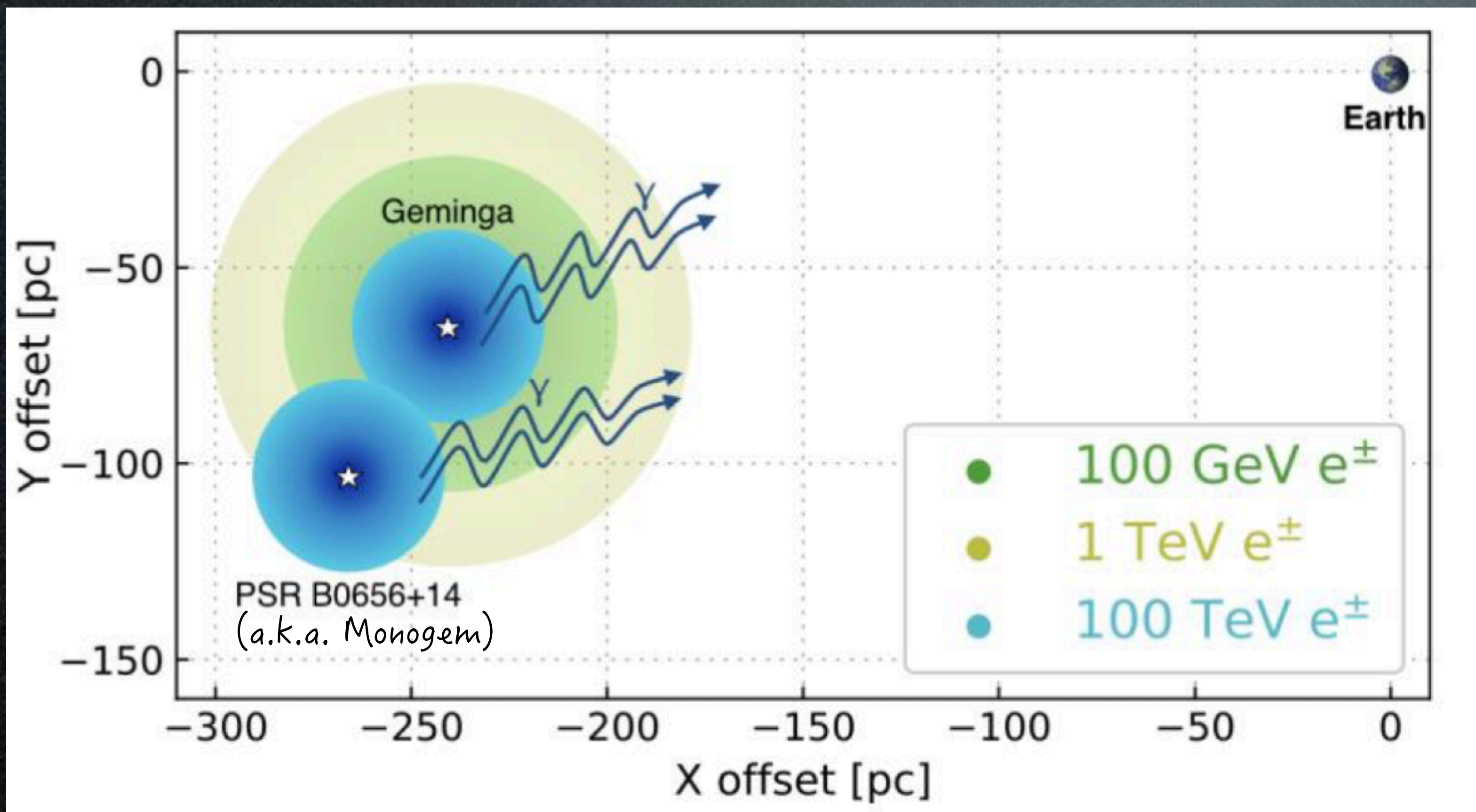
Planck 2015 (1502.01589)

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

⇓

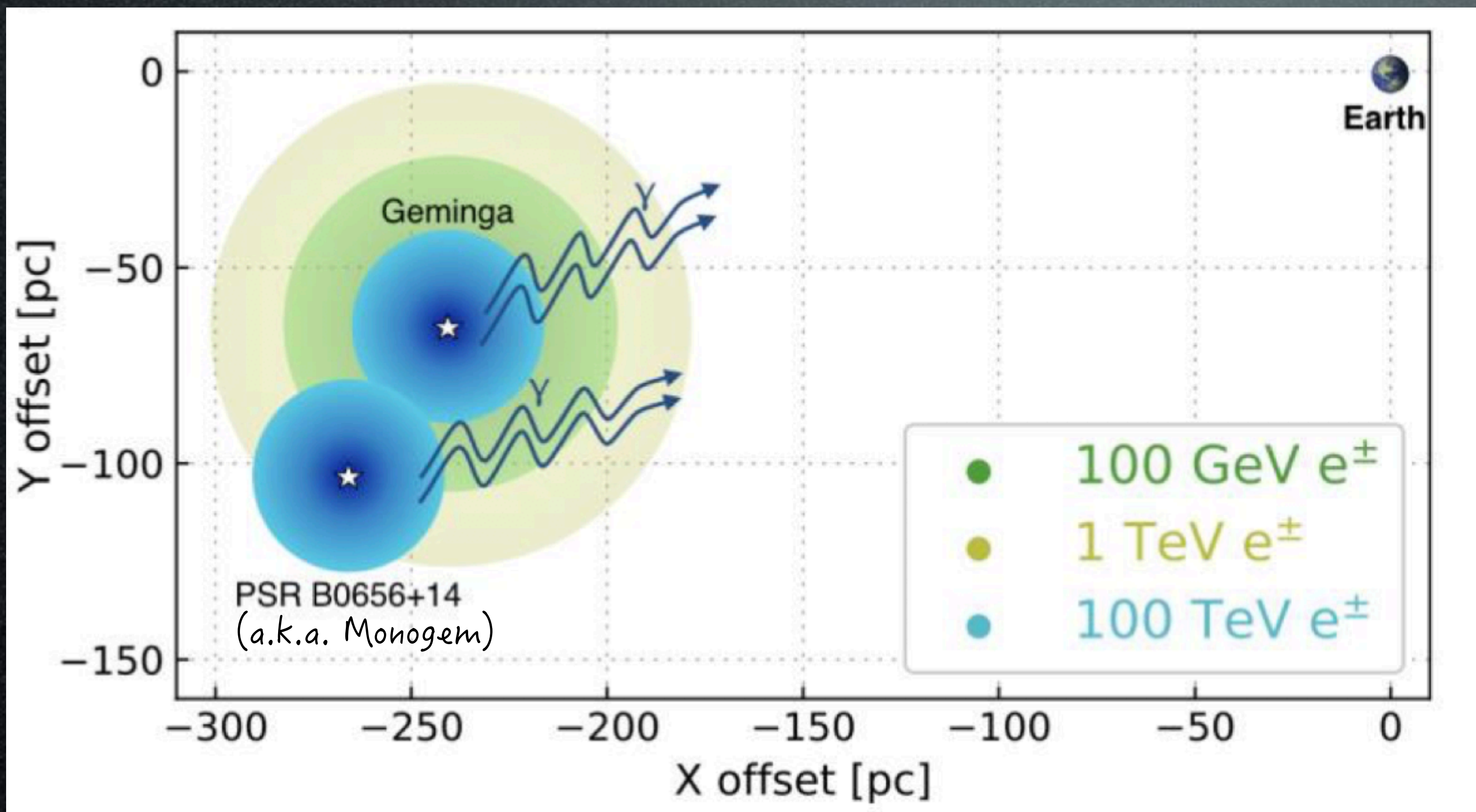
e^+ are 'very trapped' around these pulsars (diffusion is very slow)

⇓

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).

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)

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Criticisms:

- space-dep diffusion: local ≠ global

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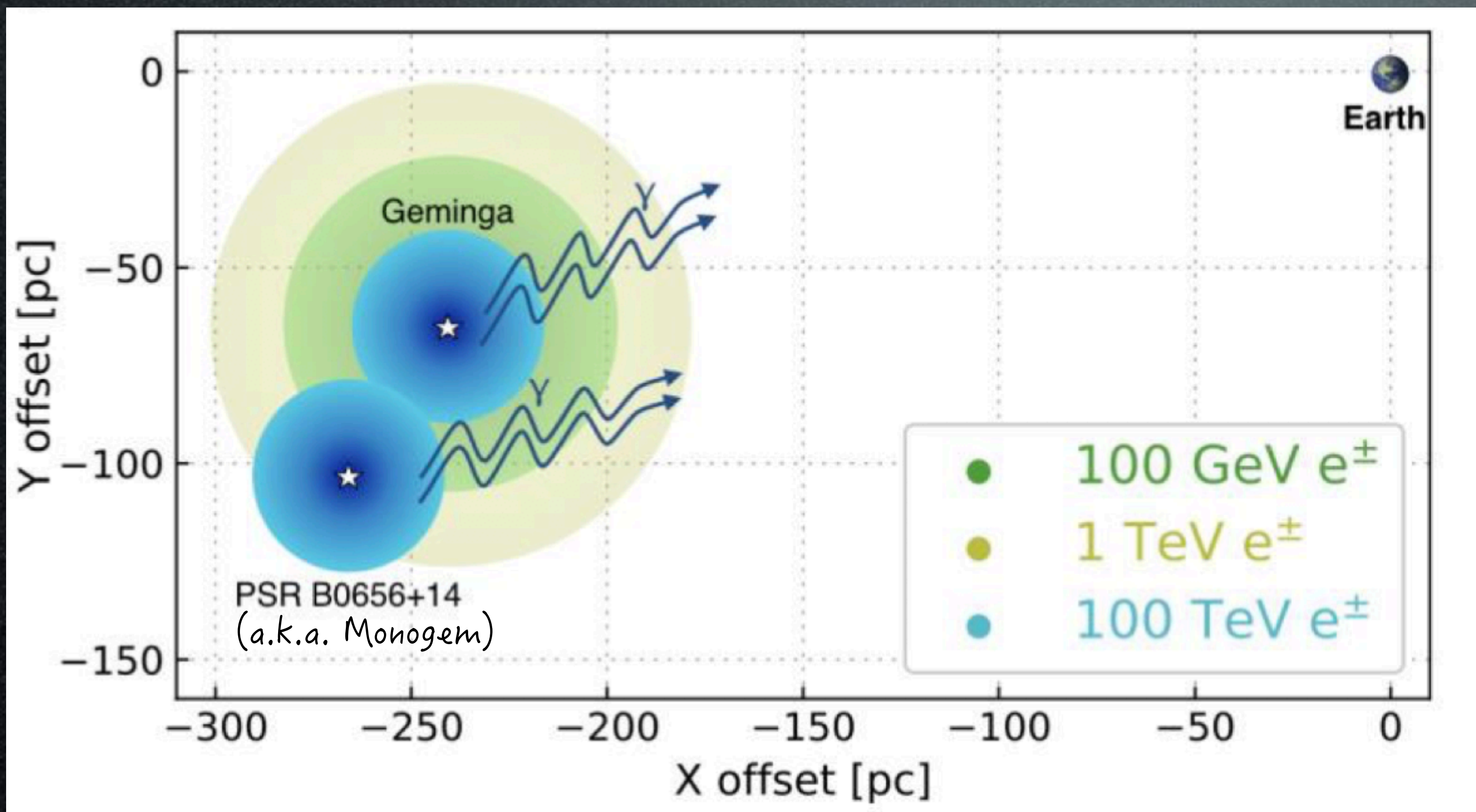

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Criticisms:

- space-dep diffusion: local ≠ global
- E-dep diffusion: 100 TeV vs 100 GeV

usually $\mathscr{K}(E) = \mathscr{K}_0\,(E/\mathrm{GeV})^\delta$ so E factored out, but cannot exclude residual dependance

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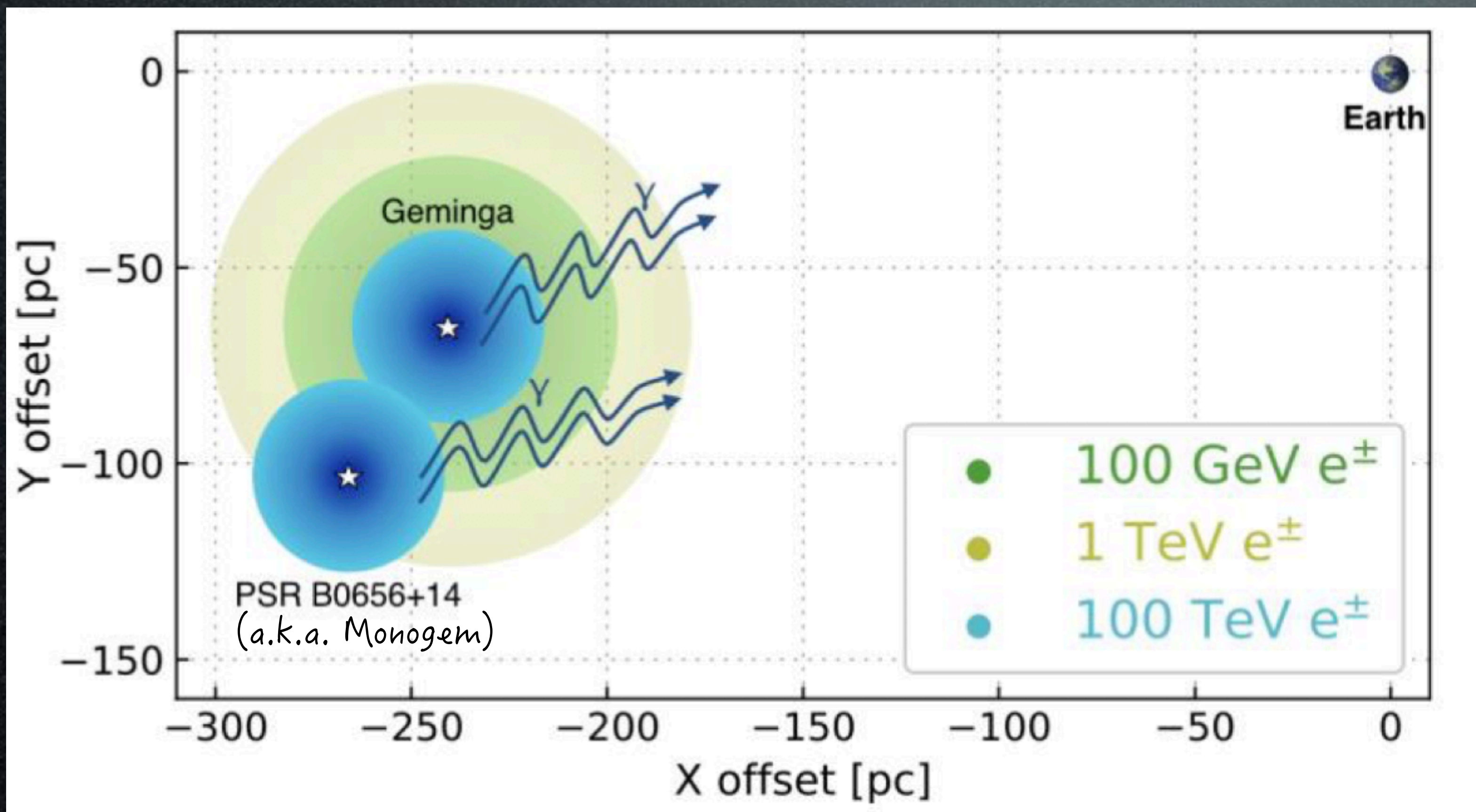

HAWC Coll., Science 359 (2017) 911 - 1711.06223

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)

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Criticisms:

- space-dep diffusion: local ≠ global
- E-dep diffusion: 100 TeV vs 100 GeV
- t-dep: γ-rays today, but e^+ 10^4 yrs ago

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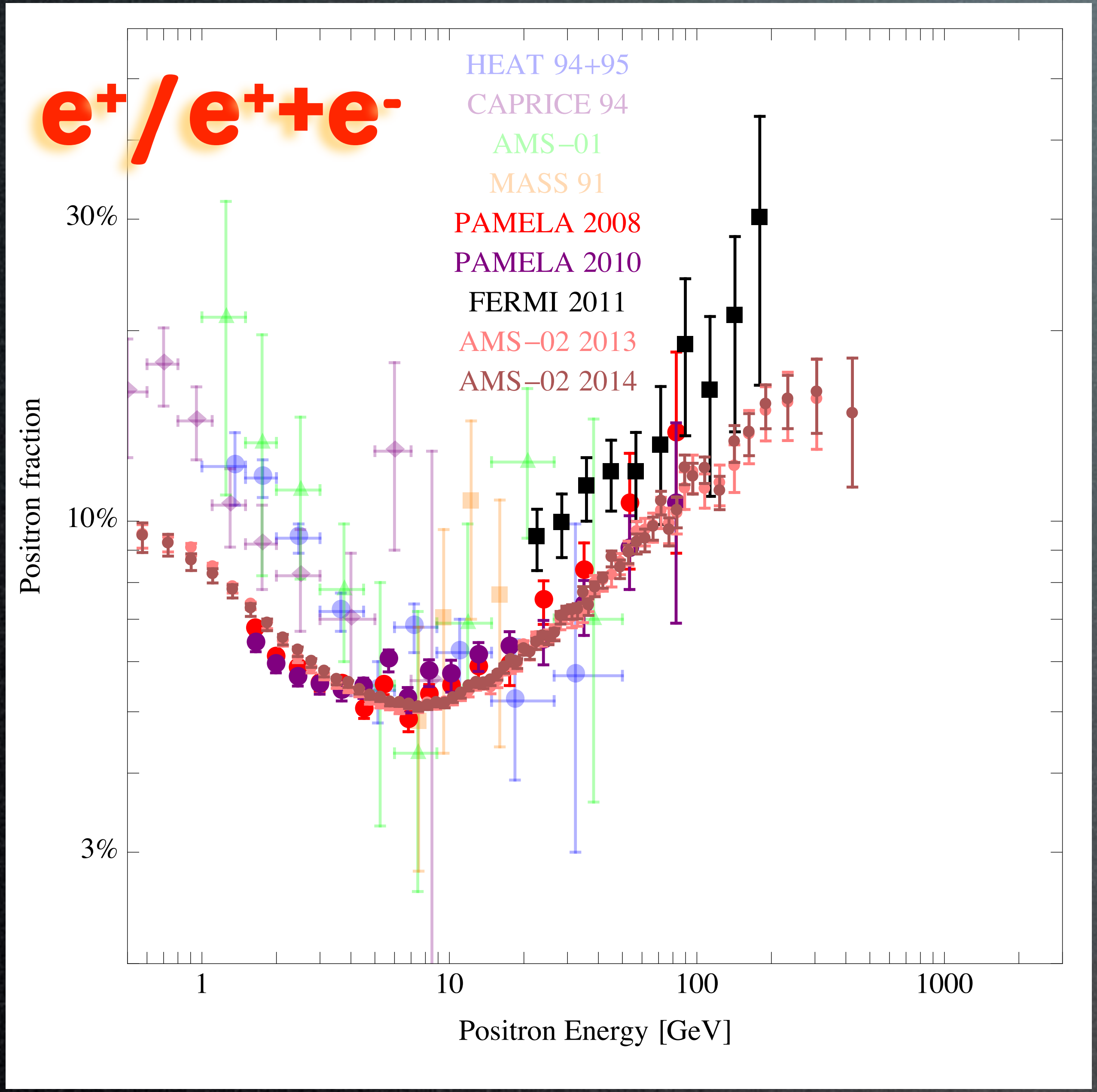
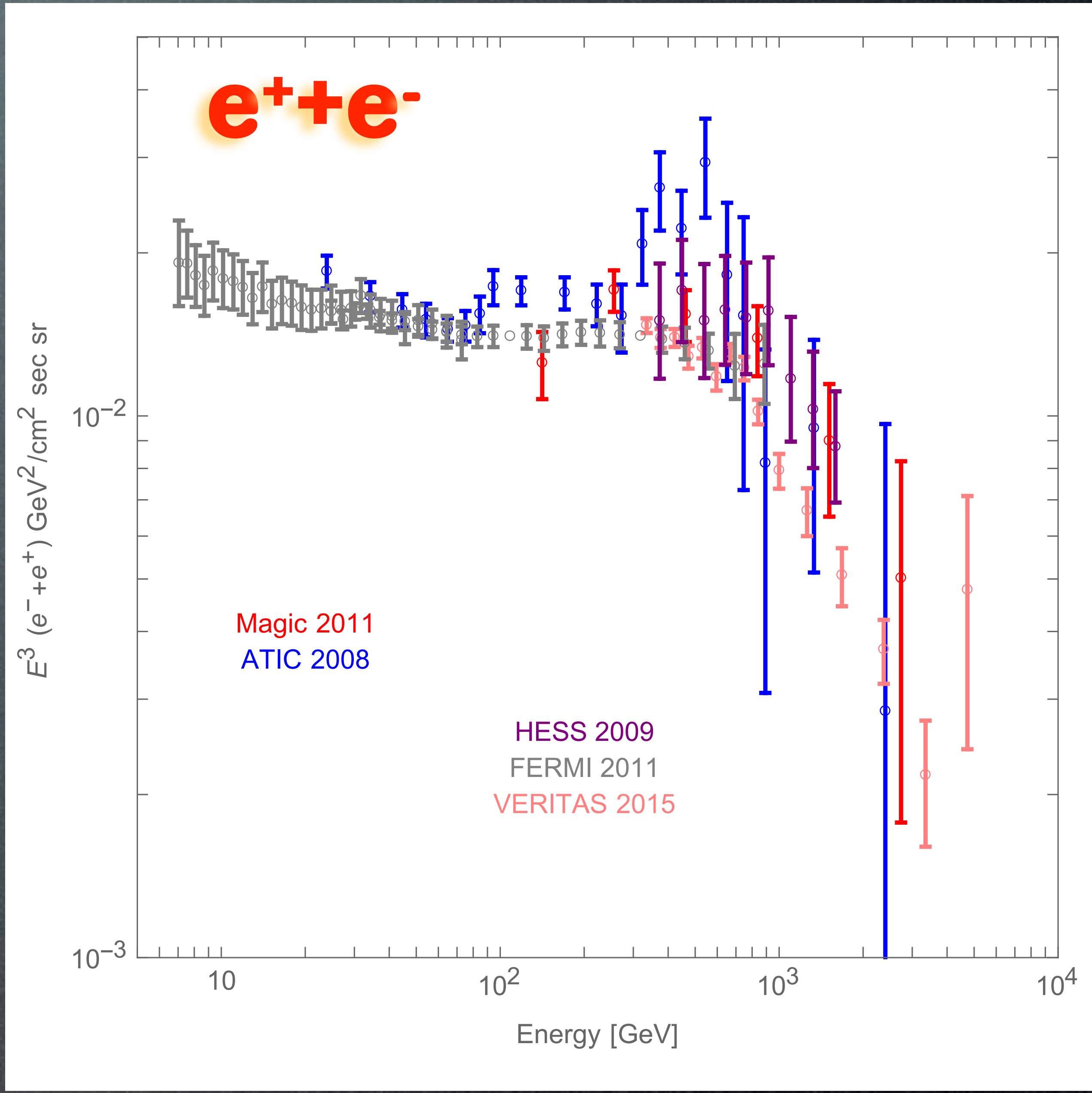
Credit: Mathieu Boudaud

Data: leptons

high energy



M. Cirelli - compilation ICRC 2015



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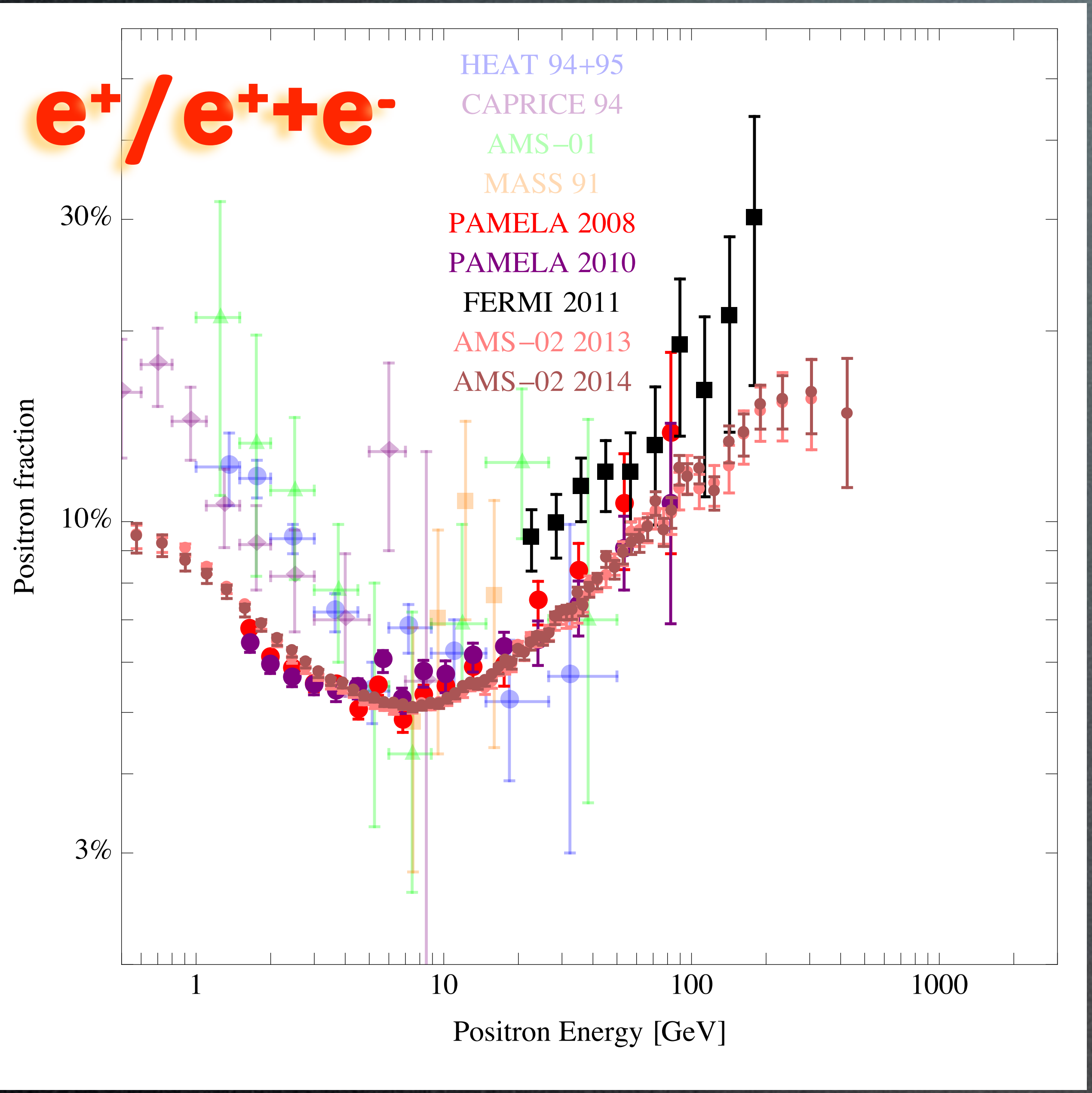
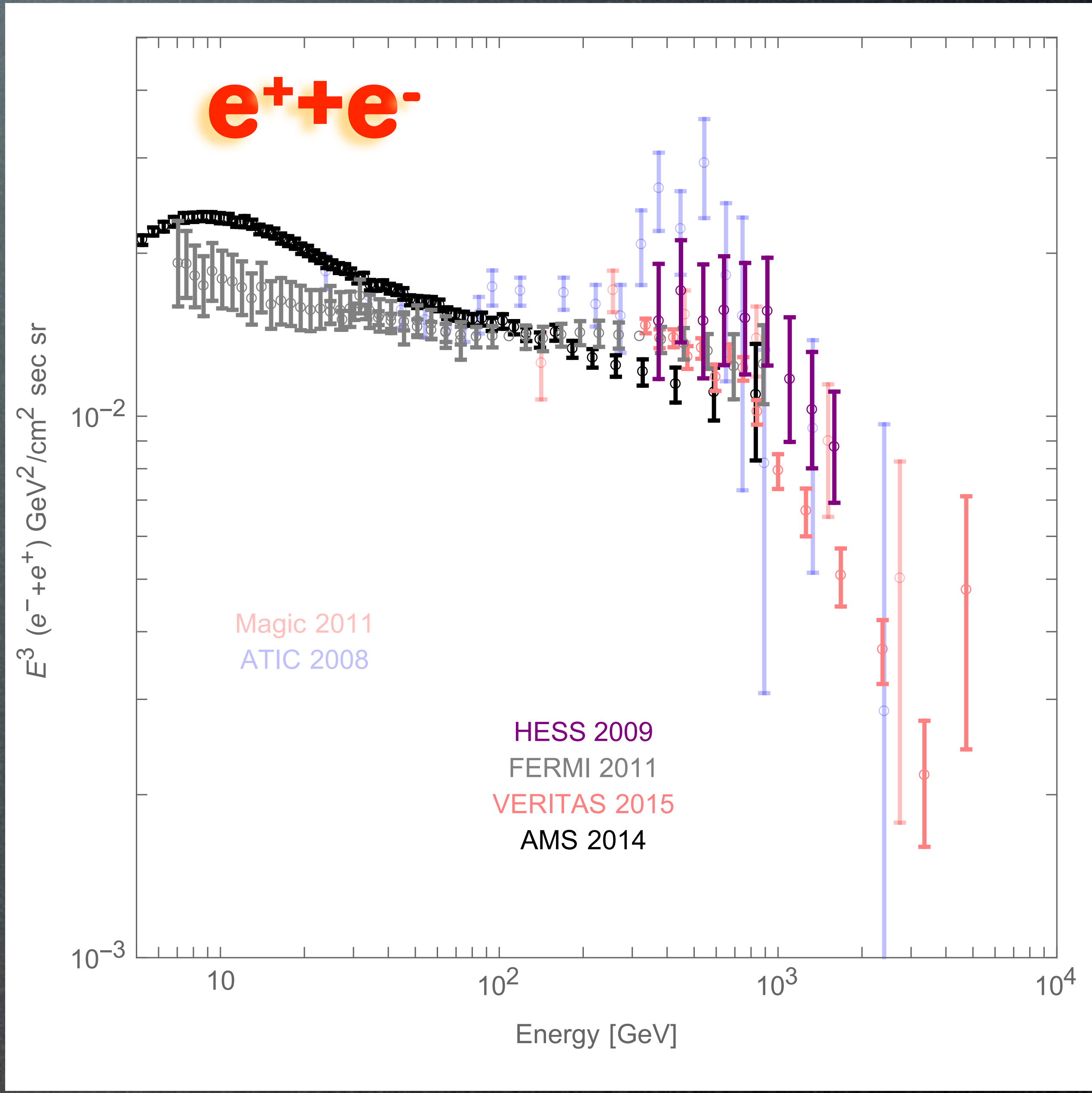


M. Cirelli - compilation ICRC 2015



M. Cirelli - compilation

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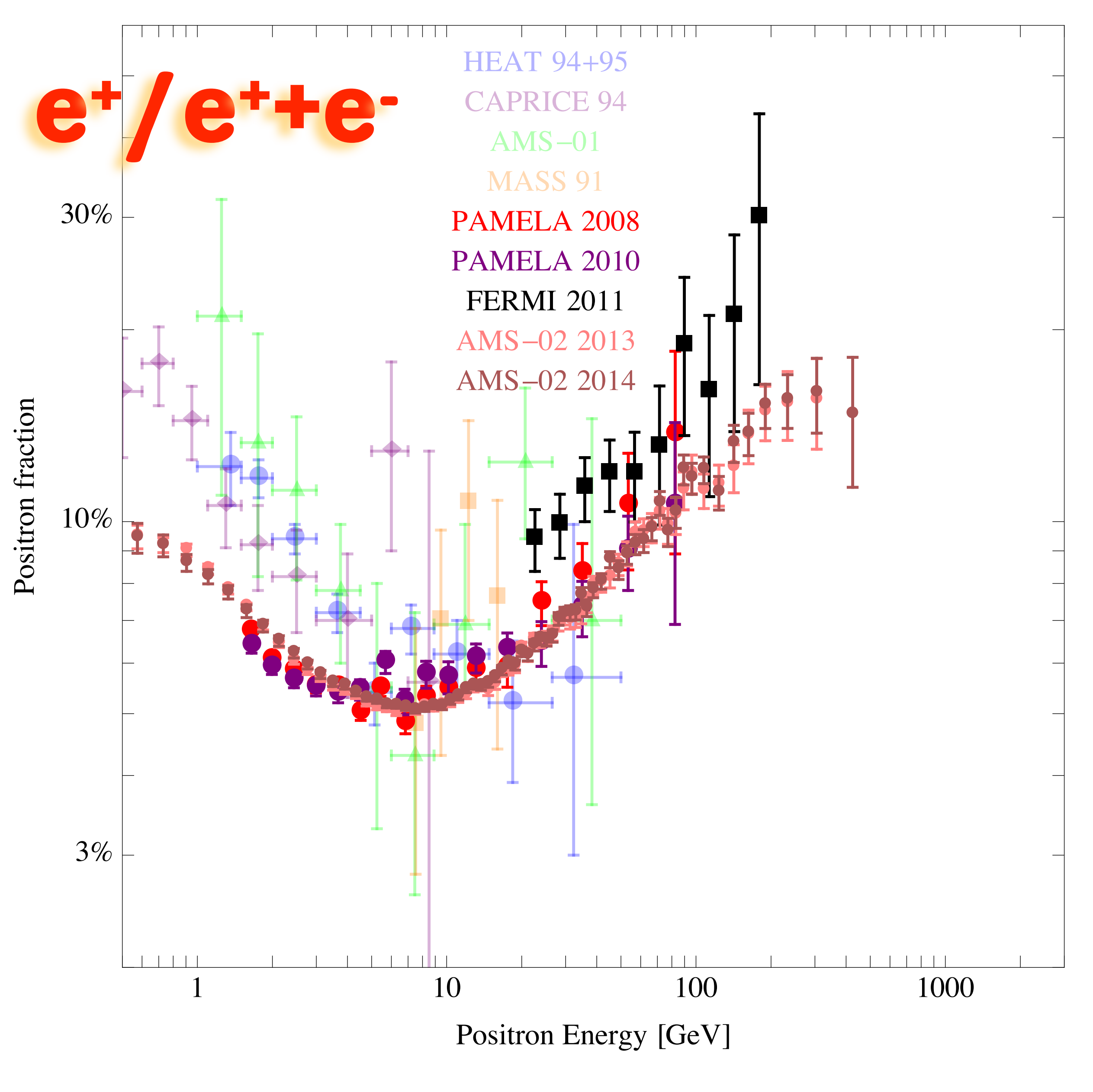

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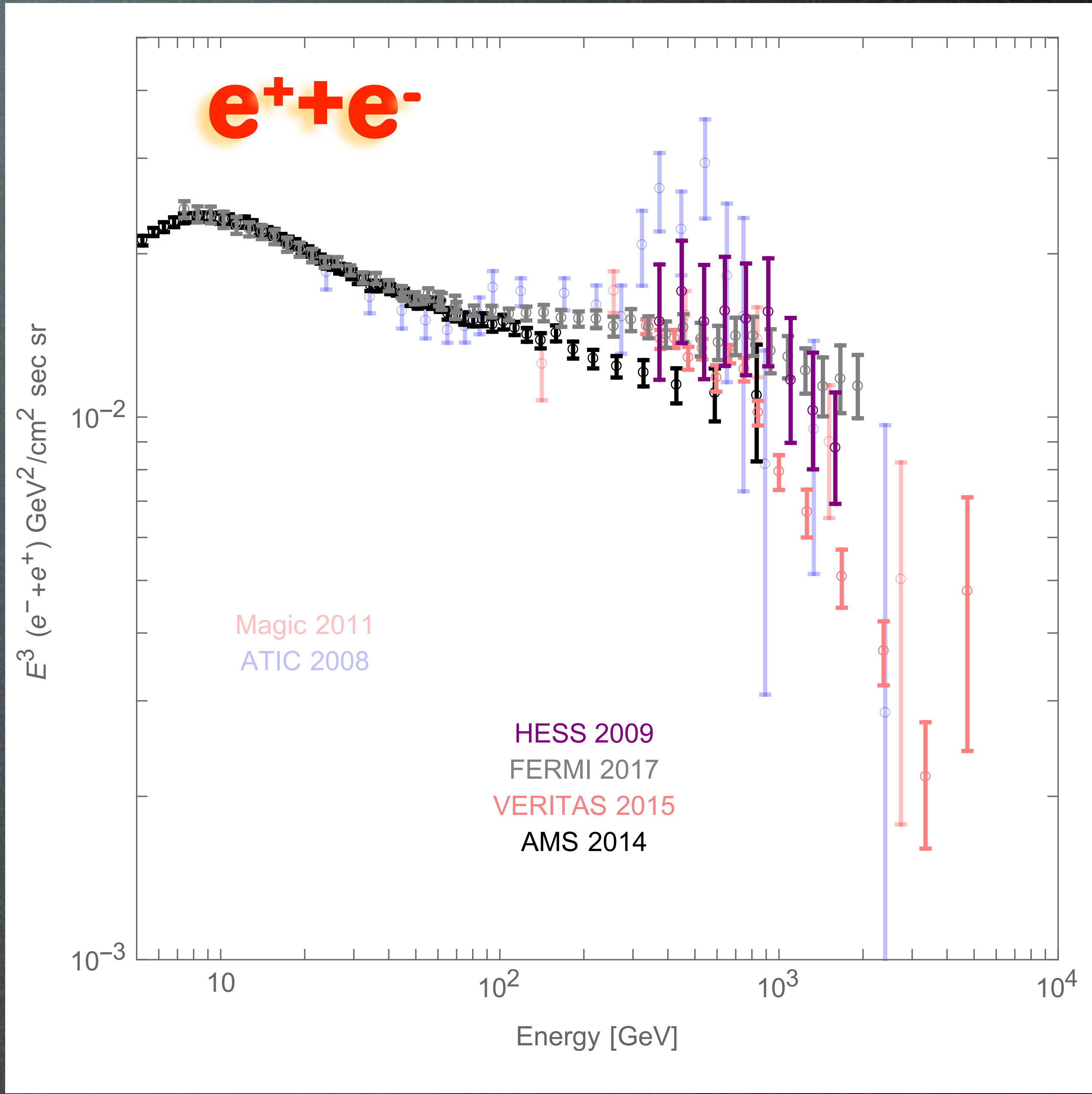


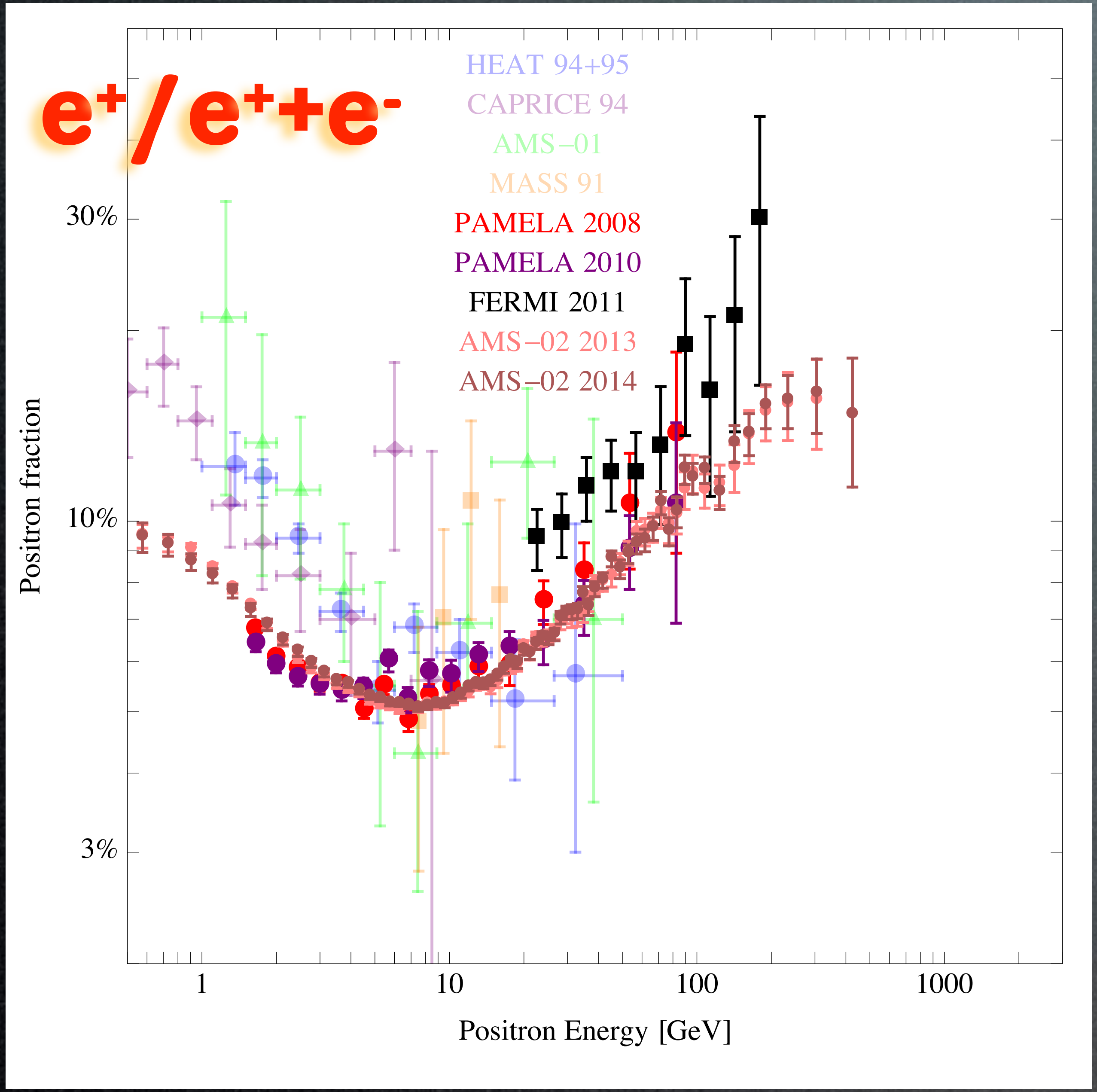
M. Cirelli - compilation

Fermi Coll.
1704.07195
(PRD 96)

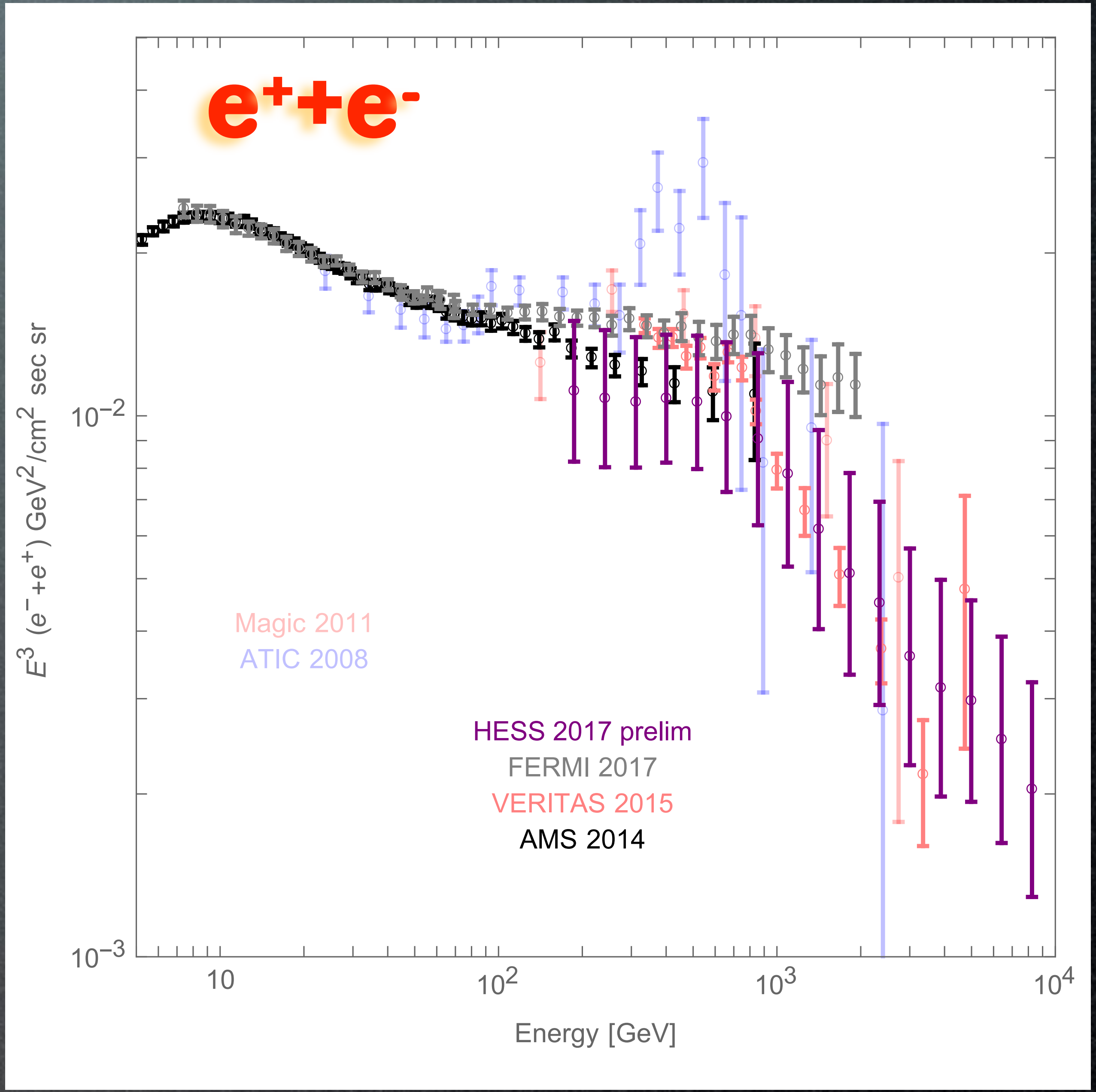
Below 100 GeV, the new LAT measurement differs from the previous one by 10–30%, as can be seen in Fig. 13. A large part of this difference below 30 GeV is due to the lack of correction in the previous analysis for the loss of CREs above the geomagnetic energy cutoff. After applying this correction, the 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]).

Data: leptons

high energy



M. Cirelli - compilation ICRC 2015

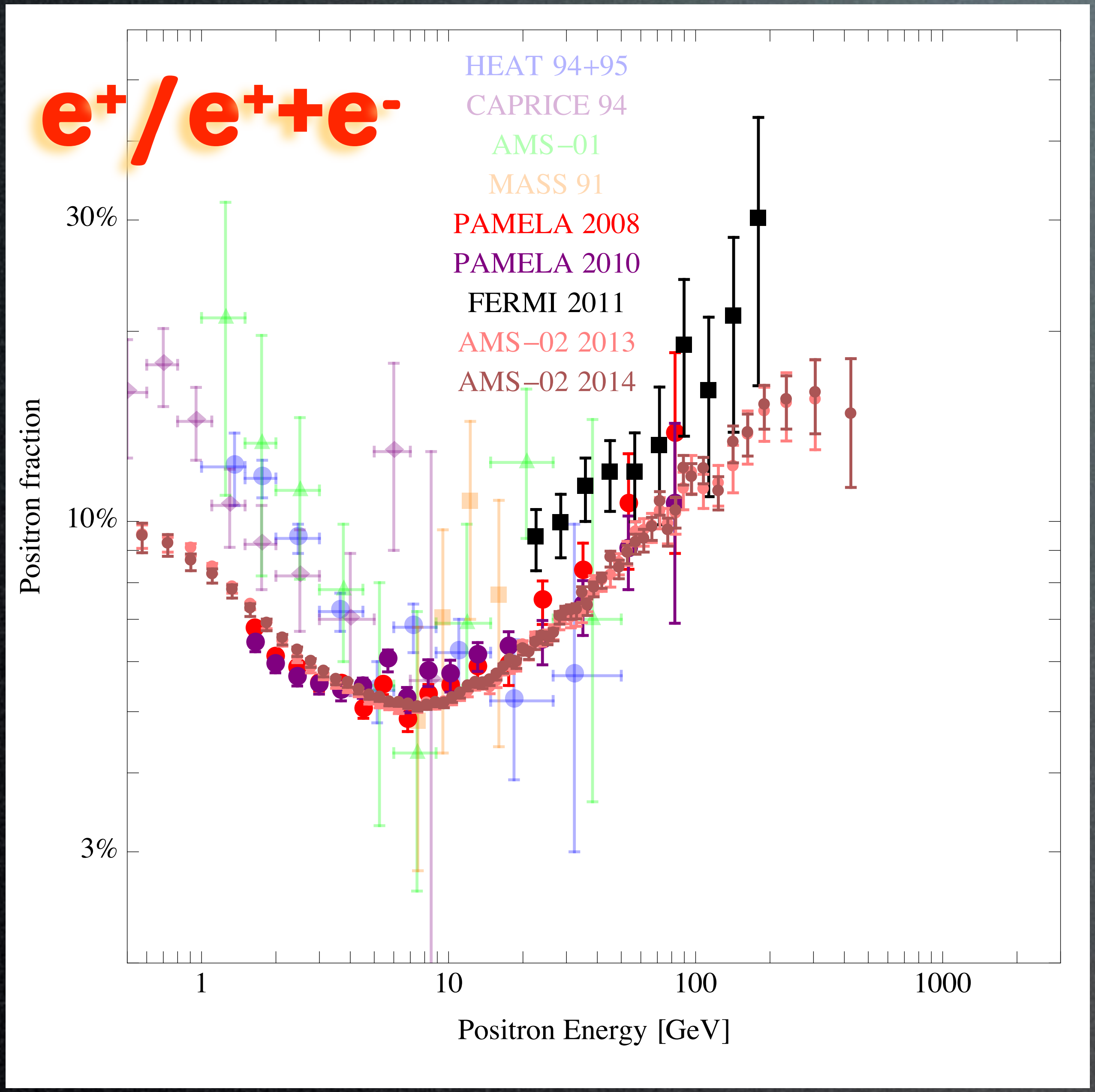


M. Cirelli - compilation

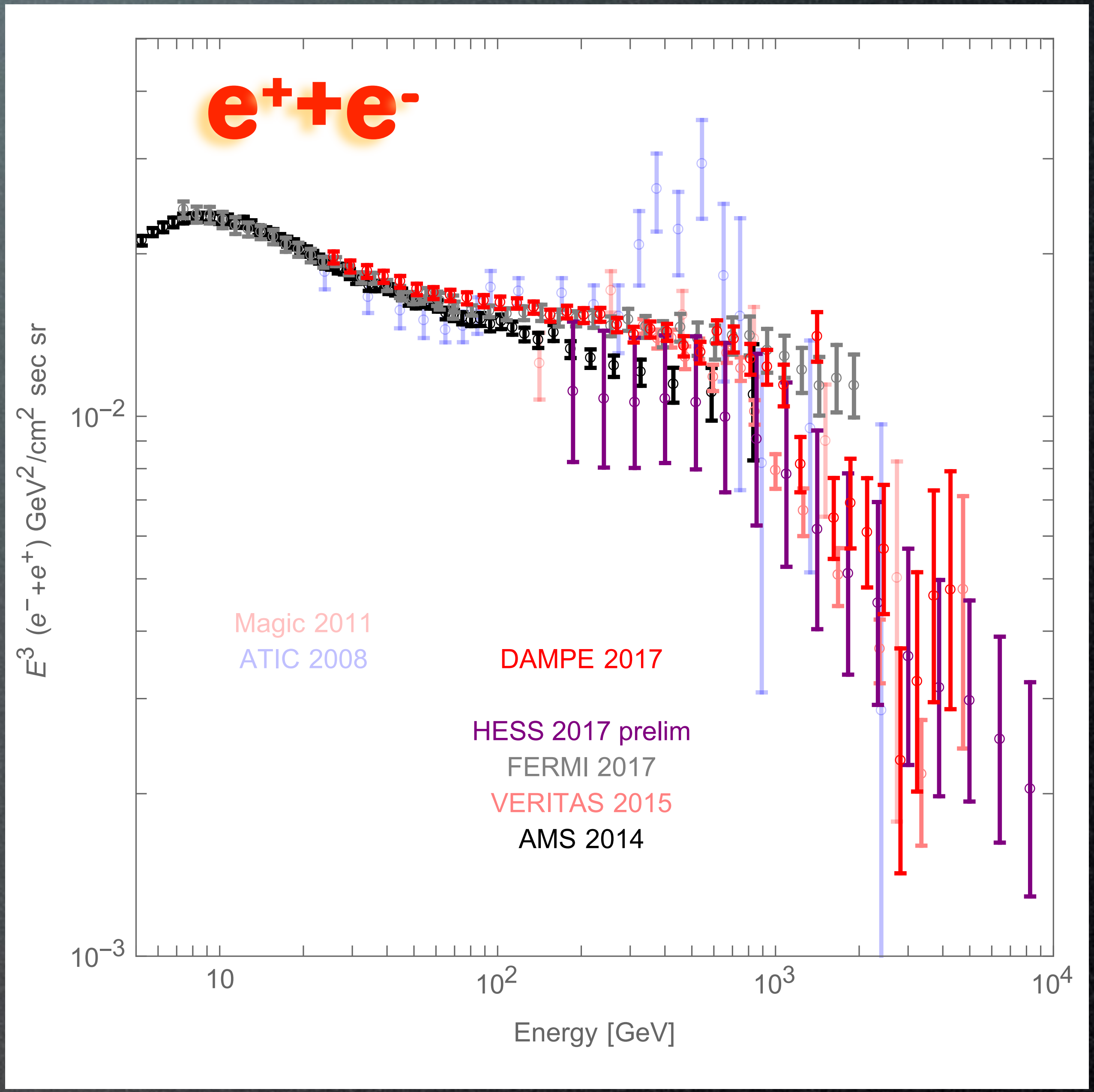
HESS Coll.
ICRC 2017
(D. Kerszberg)
no paper nor proceeding yet

Data: leptons

high energy



M. Cirelli - compilation ICRC 2015



M. Cirelli - compilation

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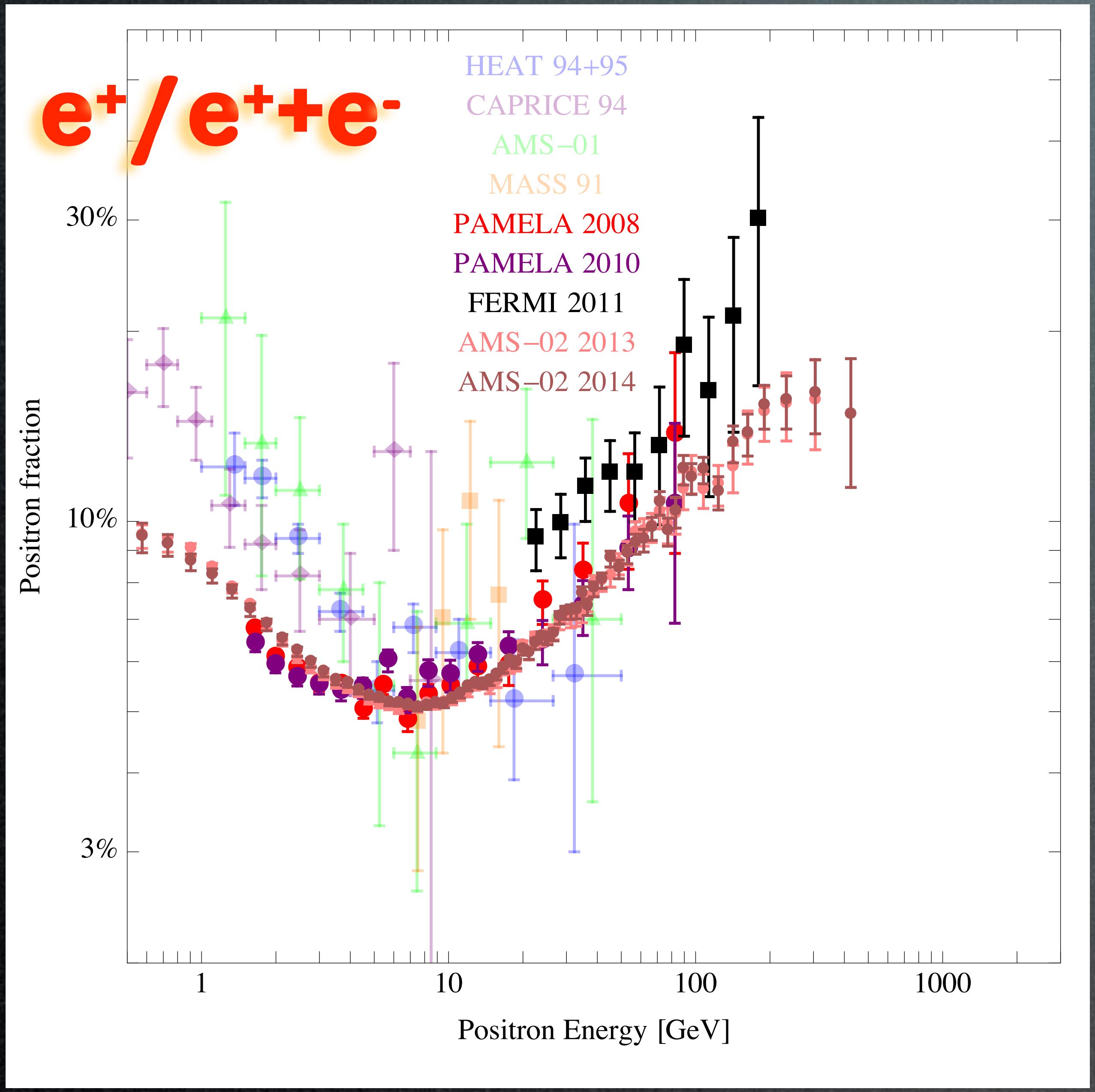
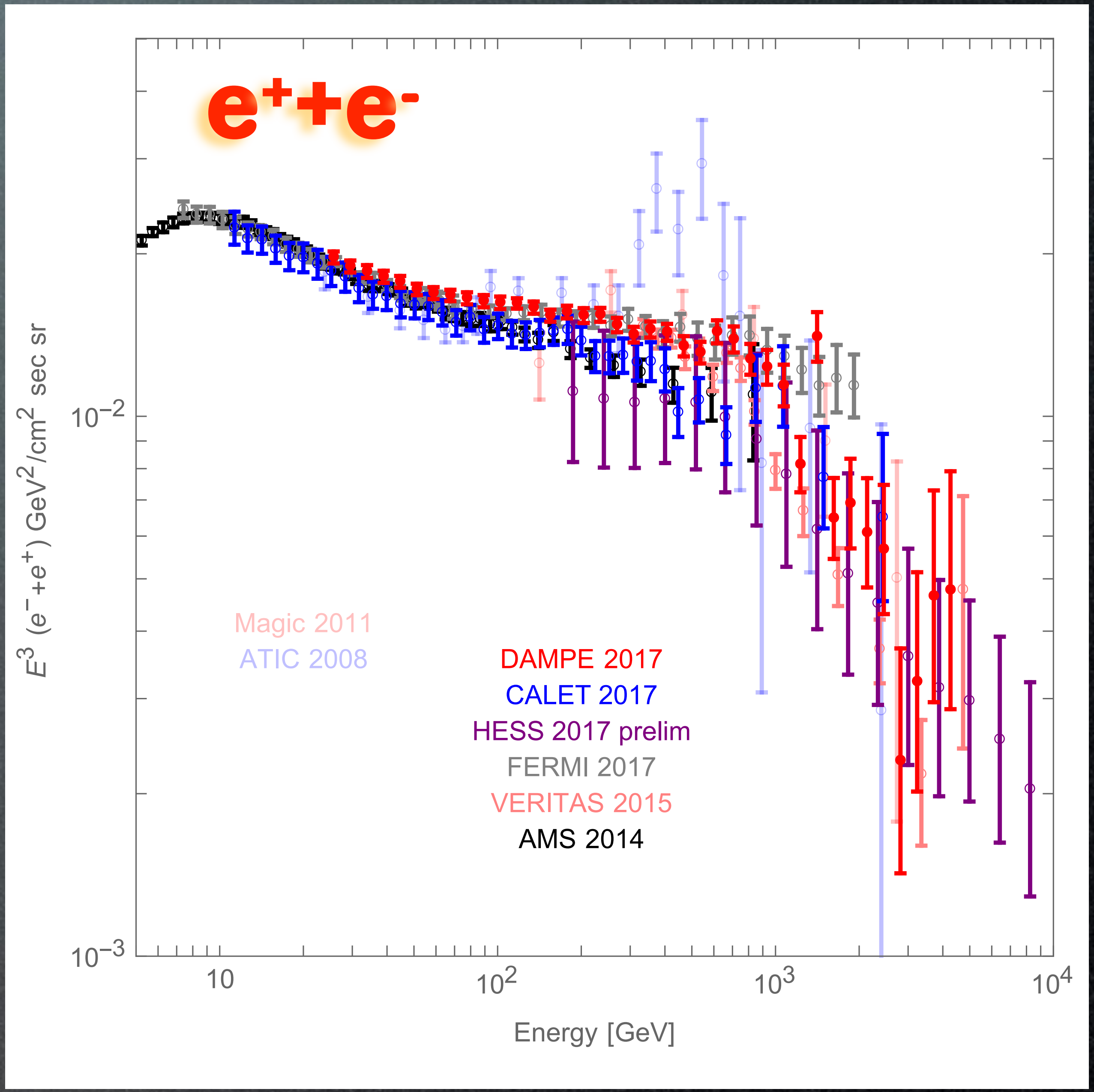


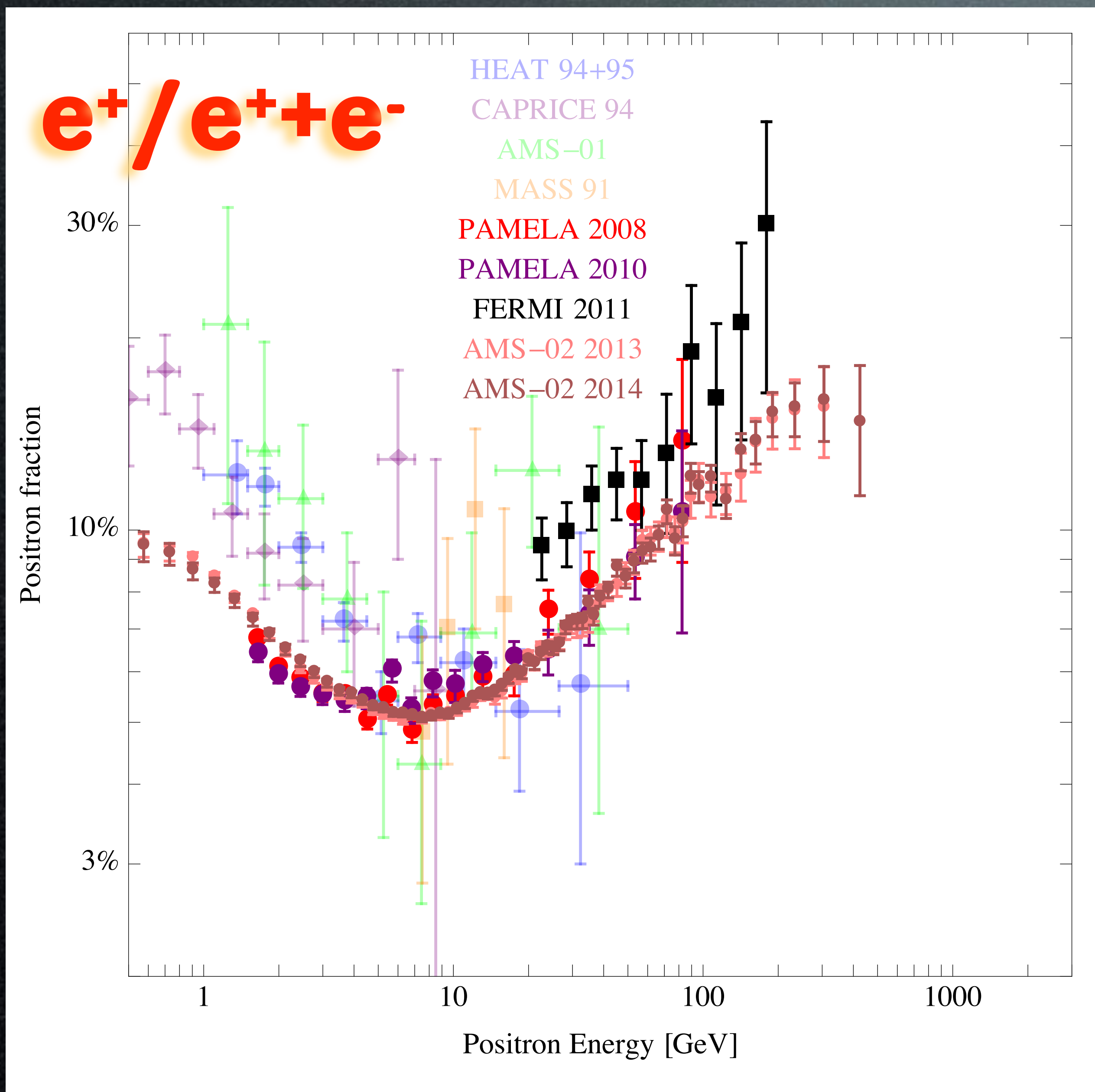
M. Cirelli - compilation ICRC 2015



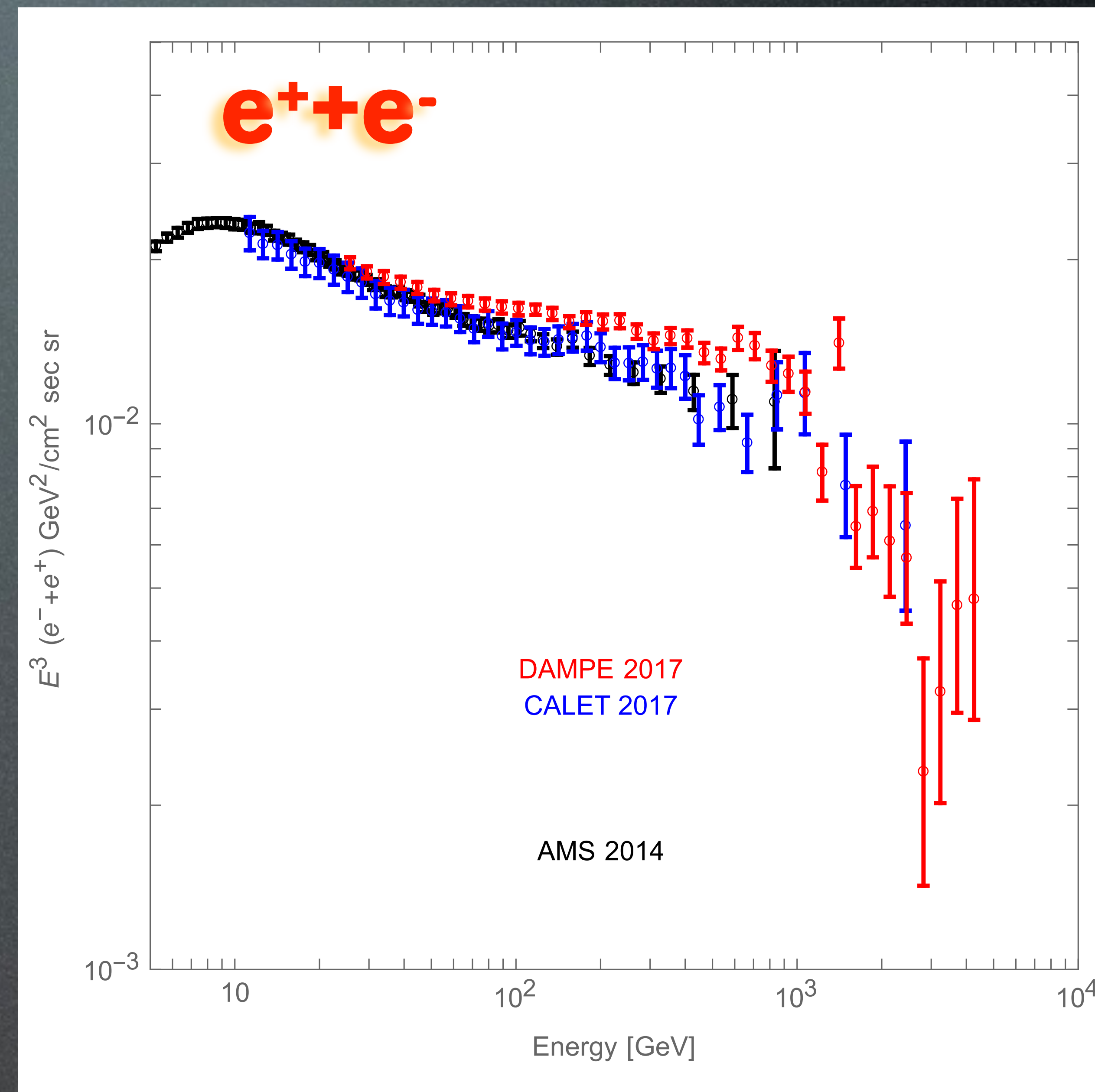
M. Cirelli - compilation

Data: leptons

high energy



M. Cirelli - compilation ICRC 2015



M. Cirelli - compilation

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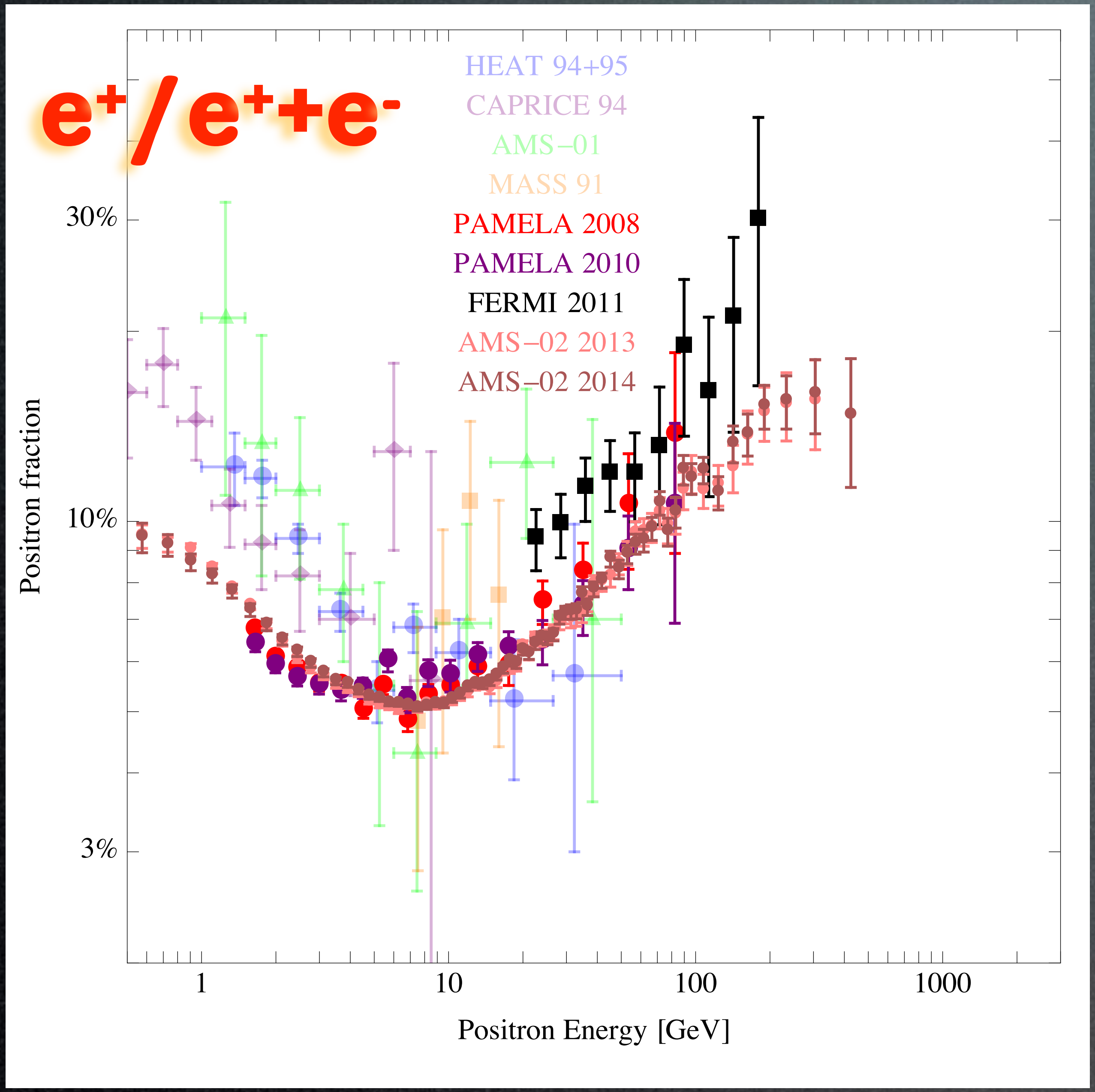

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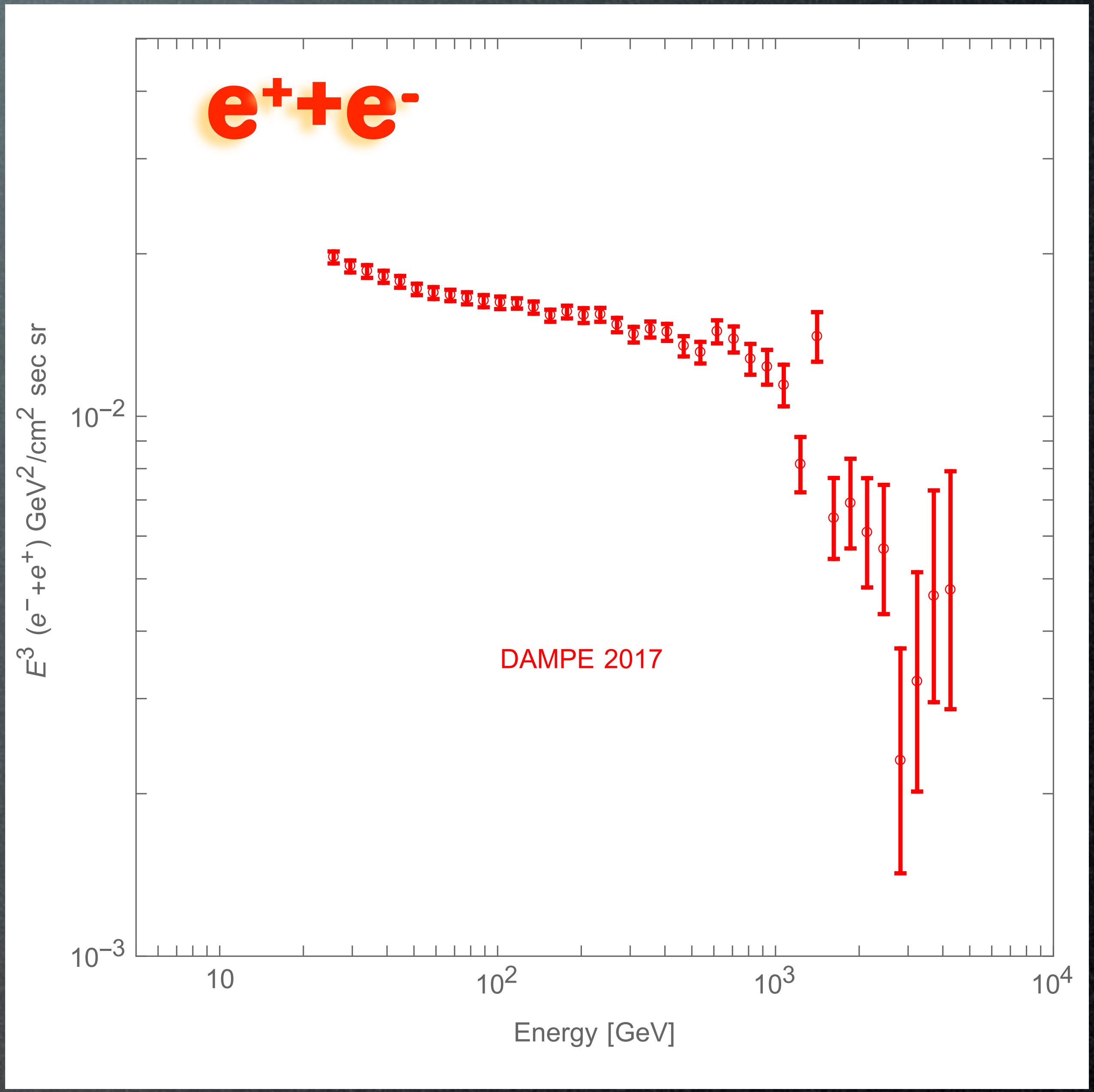


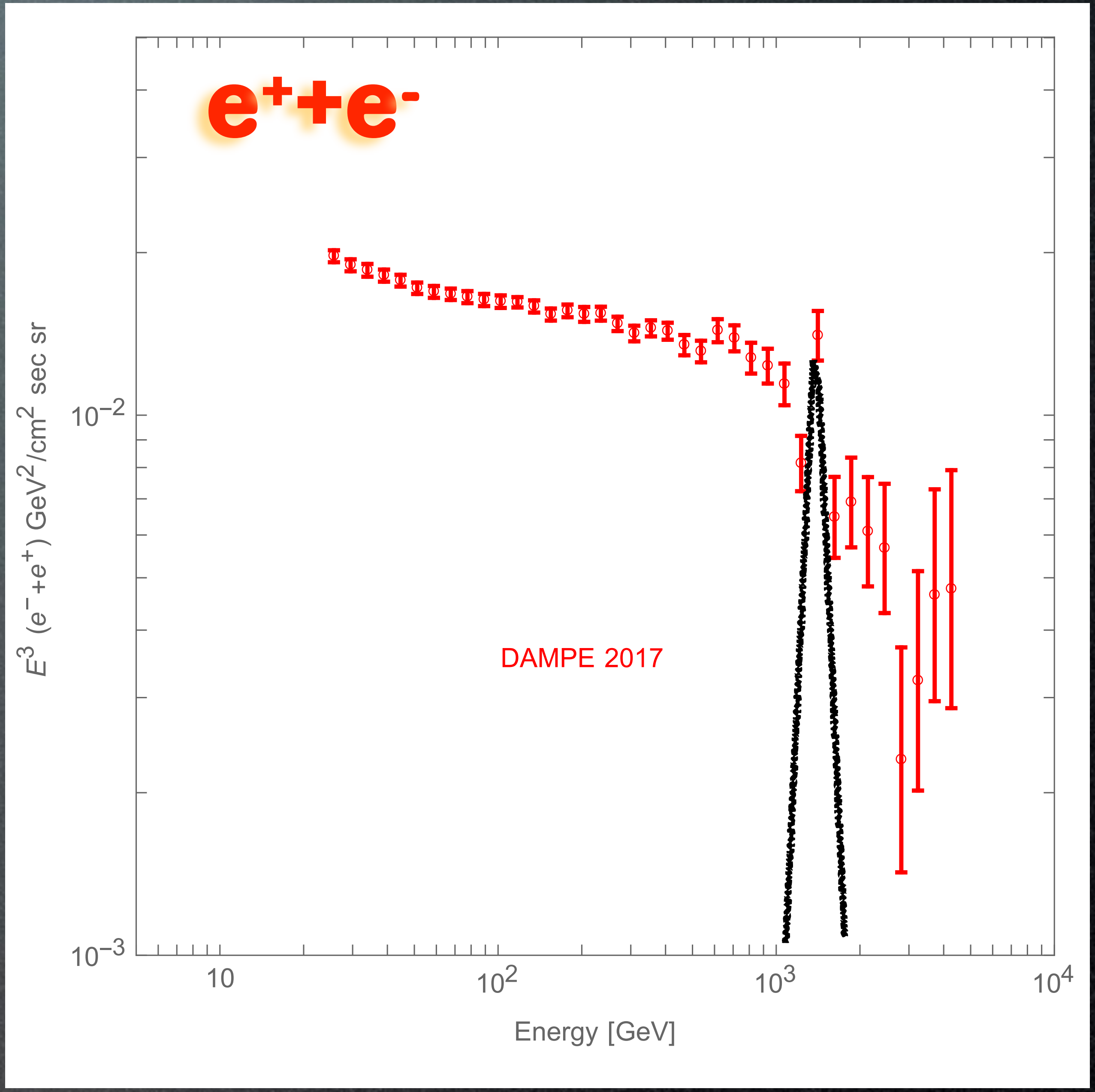
M. Cirelli - compilation

Data: leptons

high energy

frenetic activity in December 2017

(38 papers / 29 days)



M. Cirelli - compilation

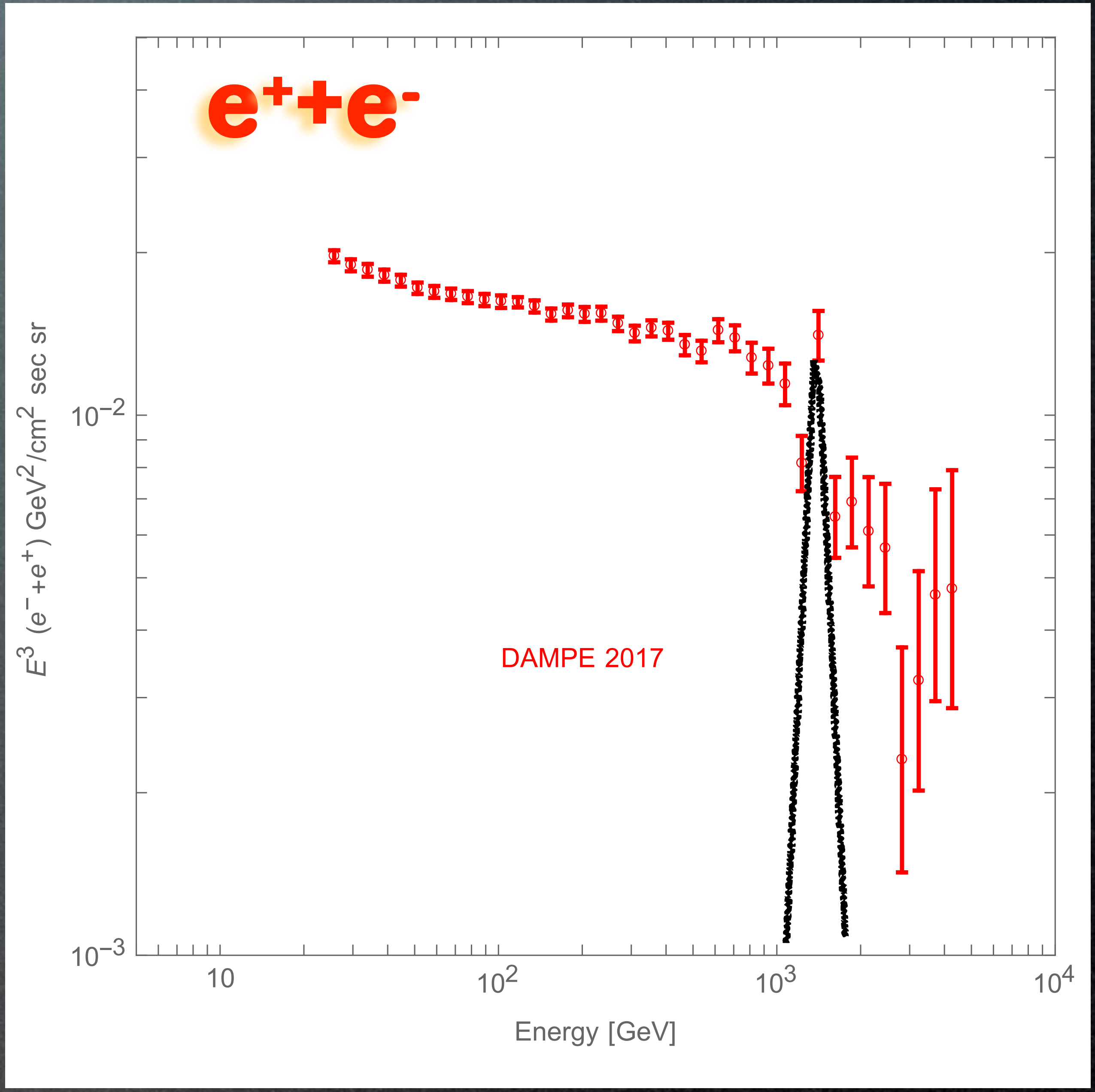
Data: leptons

high energy

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

- leptonic channel (e^+e^- or $\mu^+\mu^-$)

- nearby (0.2 kpc) huge (10^8 M_{sun}) DM clump
    - for large flux
    - for peaked spectrum

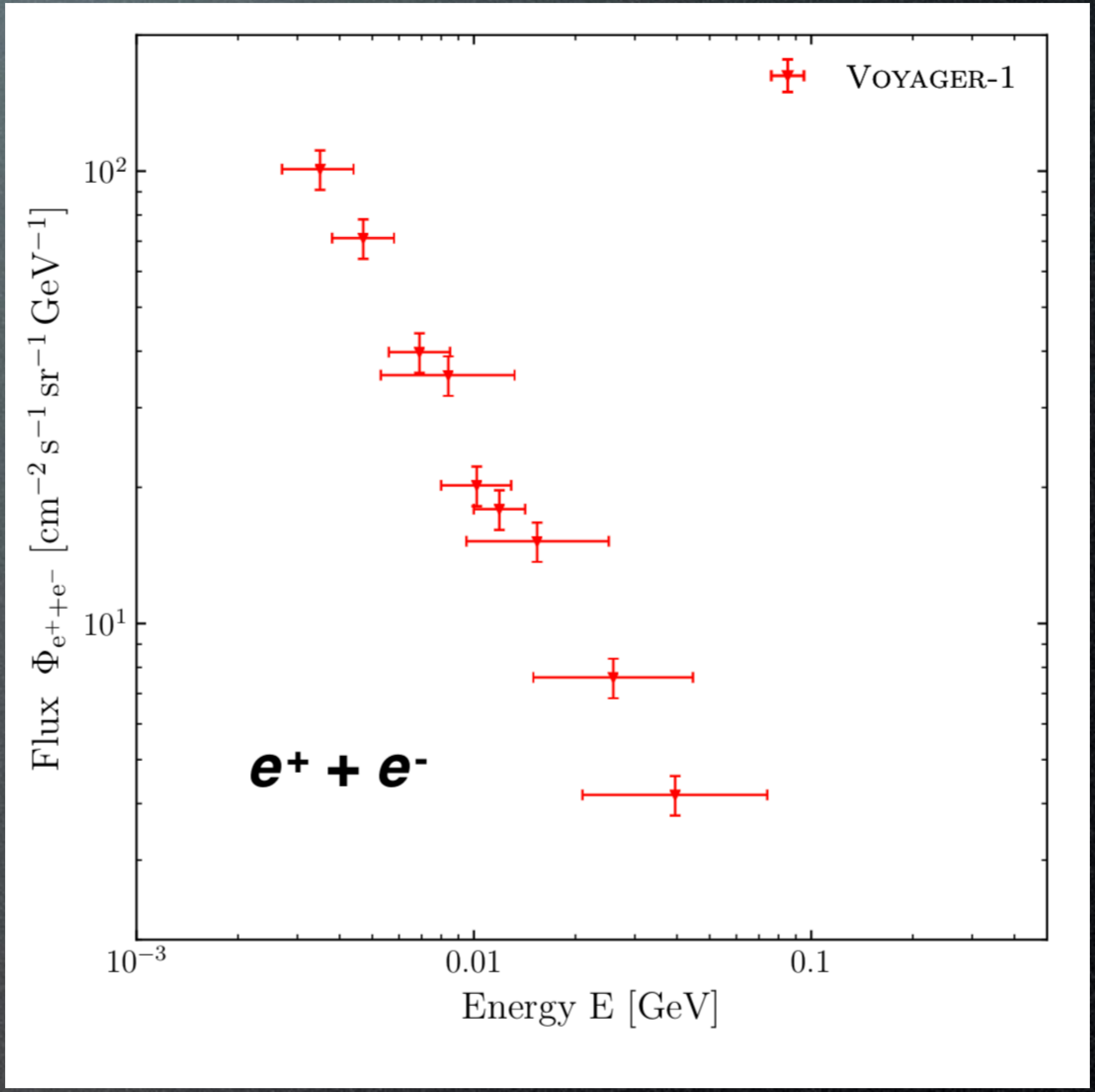


M. Cirelli - compilation

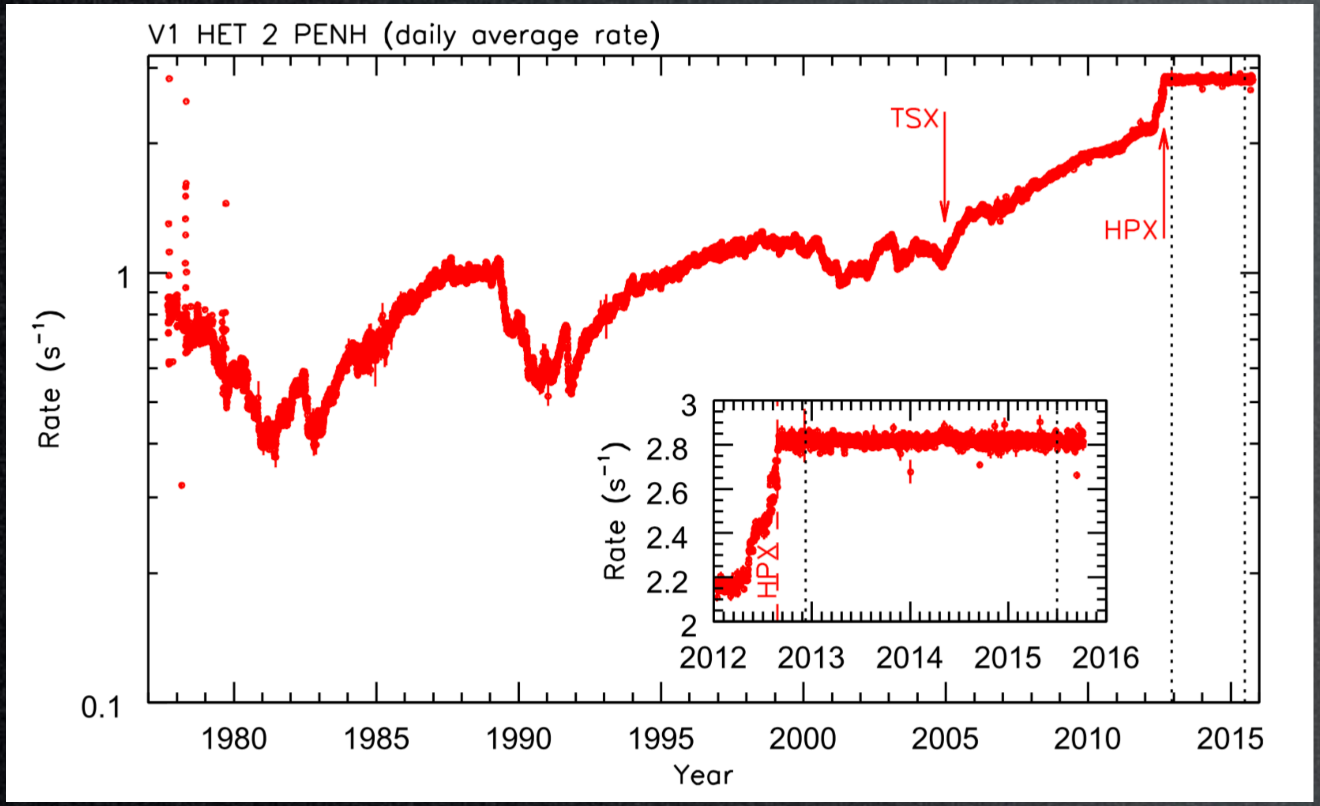
Data: leptons
low energy

Voyager-1 left the heliosphere in 08.2012

First ever measurement of sub-GeV $e^{+}+e^{-}$



courtesy of M. Boudaud, based on Cummings+ (Voyager-1 coll.), The Astrophysical Journal, 831:18, 2016

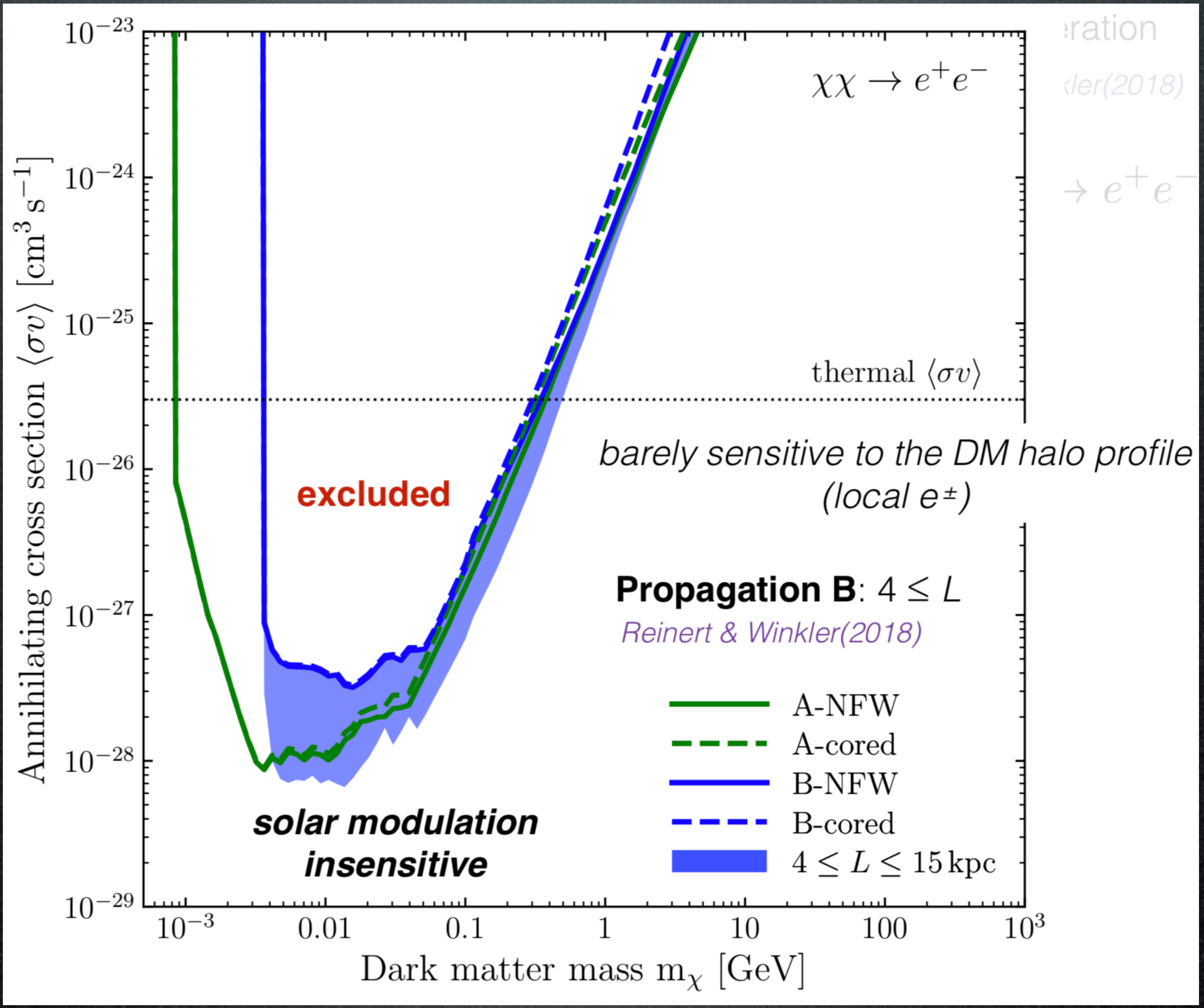


Cummings+ (Voyager-1 coll.), The Astrophysical Journal, 831:18, 2016

Dark Matter interpretation

low energy

Constraints on sub-GeV DM



Boudaud, Lavalle, Salati 1612.07698

Dark Matter interpretation

low energy

Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15}(t/10^{-23}\ \mathrm{sec})\ \mathrm{g}$$

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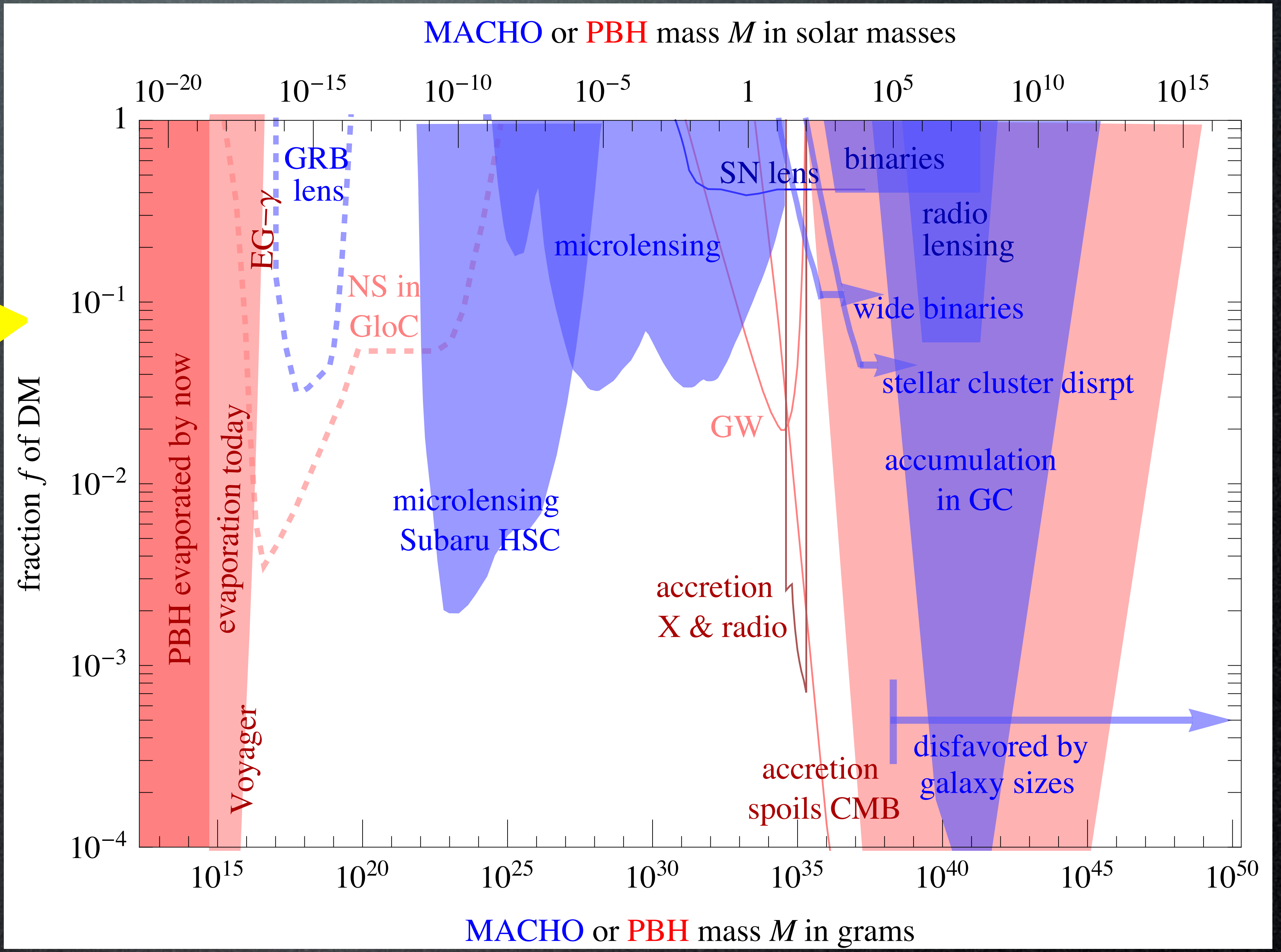

M. Cirelli, A. Strumia, J. Zupan to appear

Dark Matter interpretation

low energy

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constraints

'small' PBHs emit today by Hawking evaporation

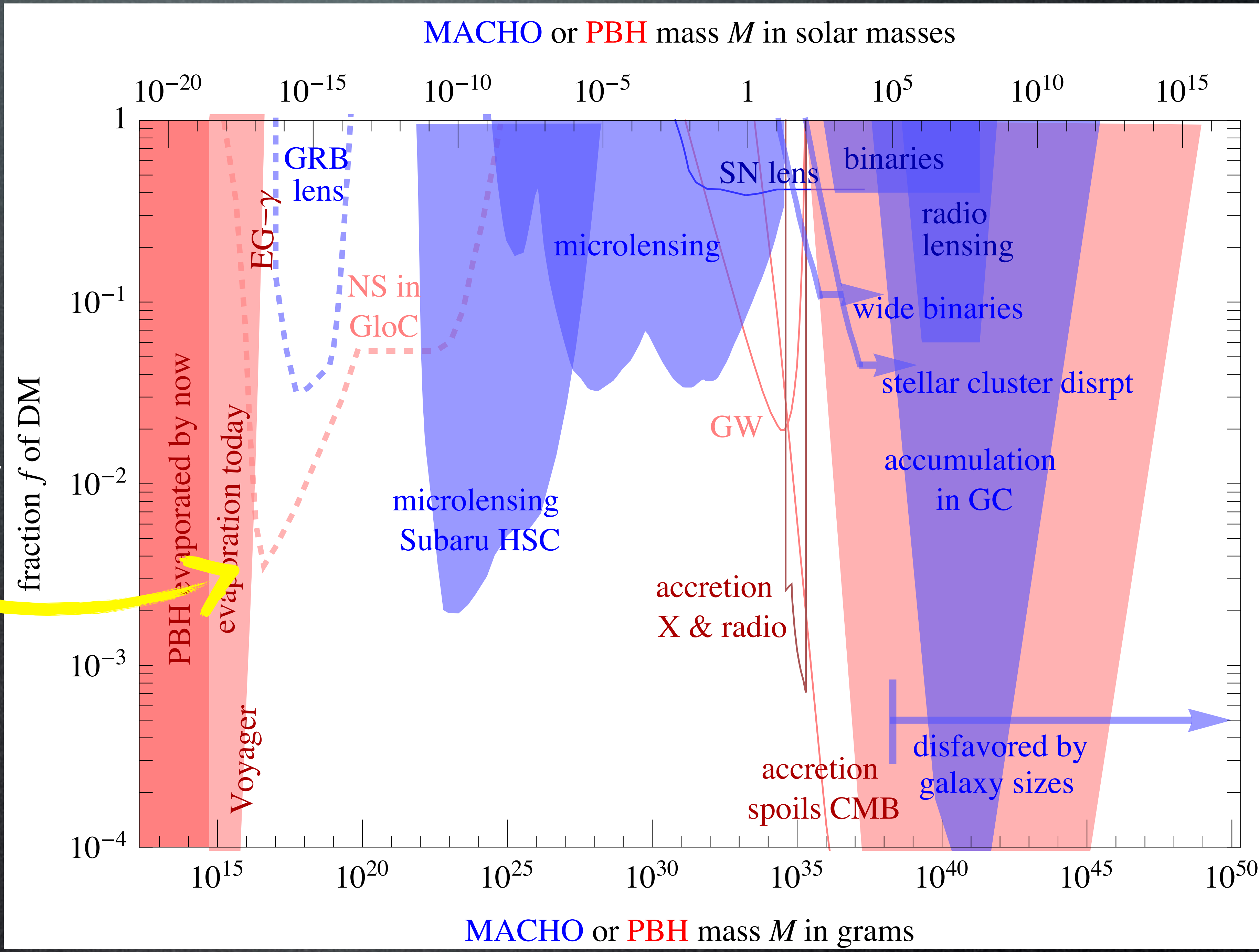
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25} f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\,dE} = \frac{27}{2\pi}\frac{G^2M^2E^2}{e^{E/T}+1}$$



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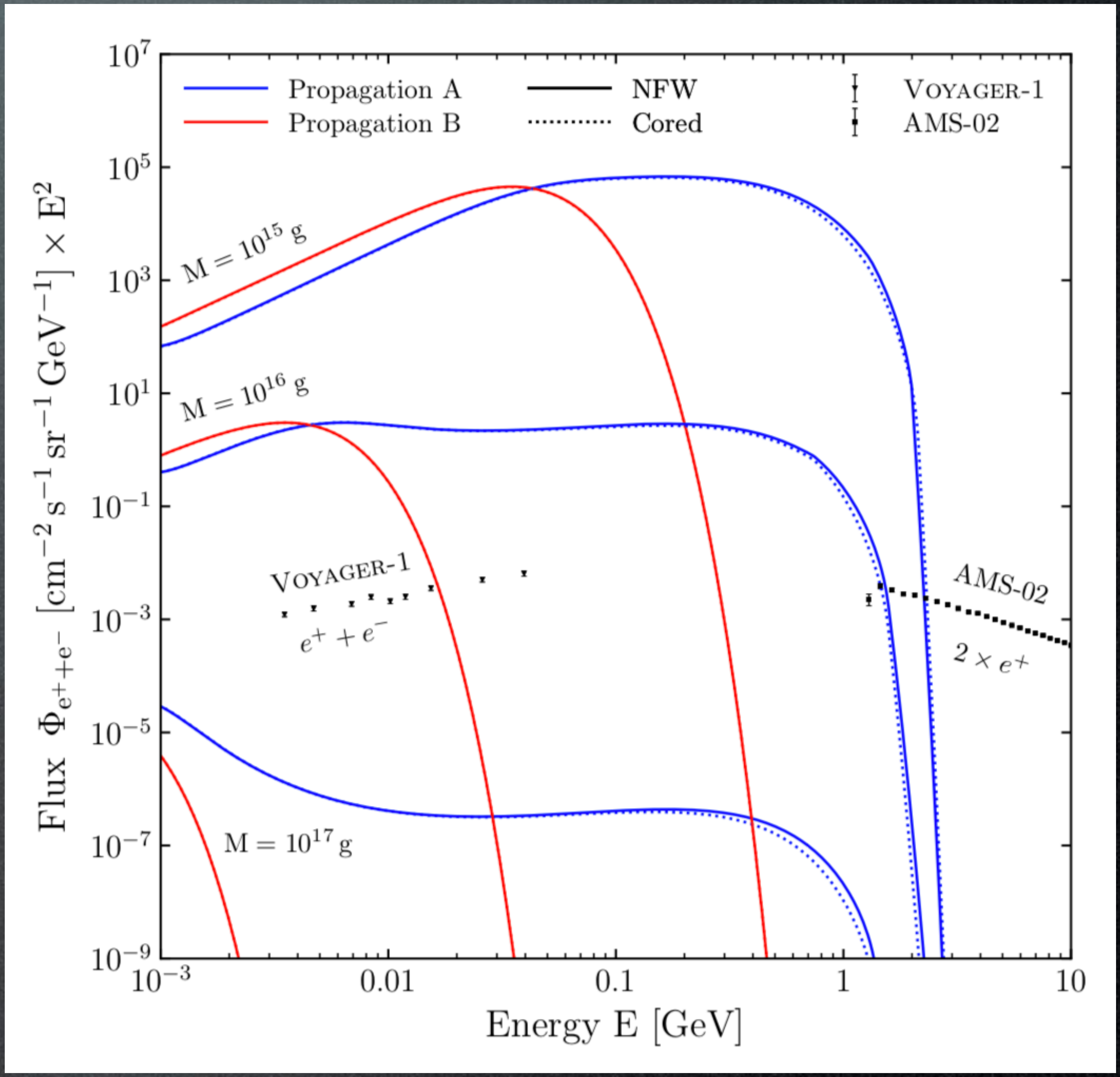

Boudaud, Cirelli 1807.03075, PRL in press

Dark Matter interpretation

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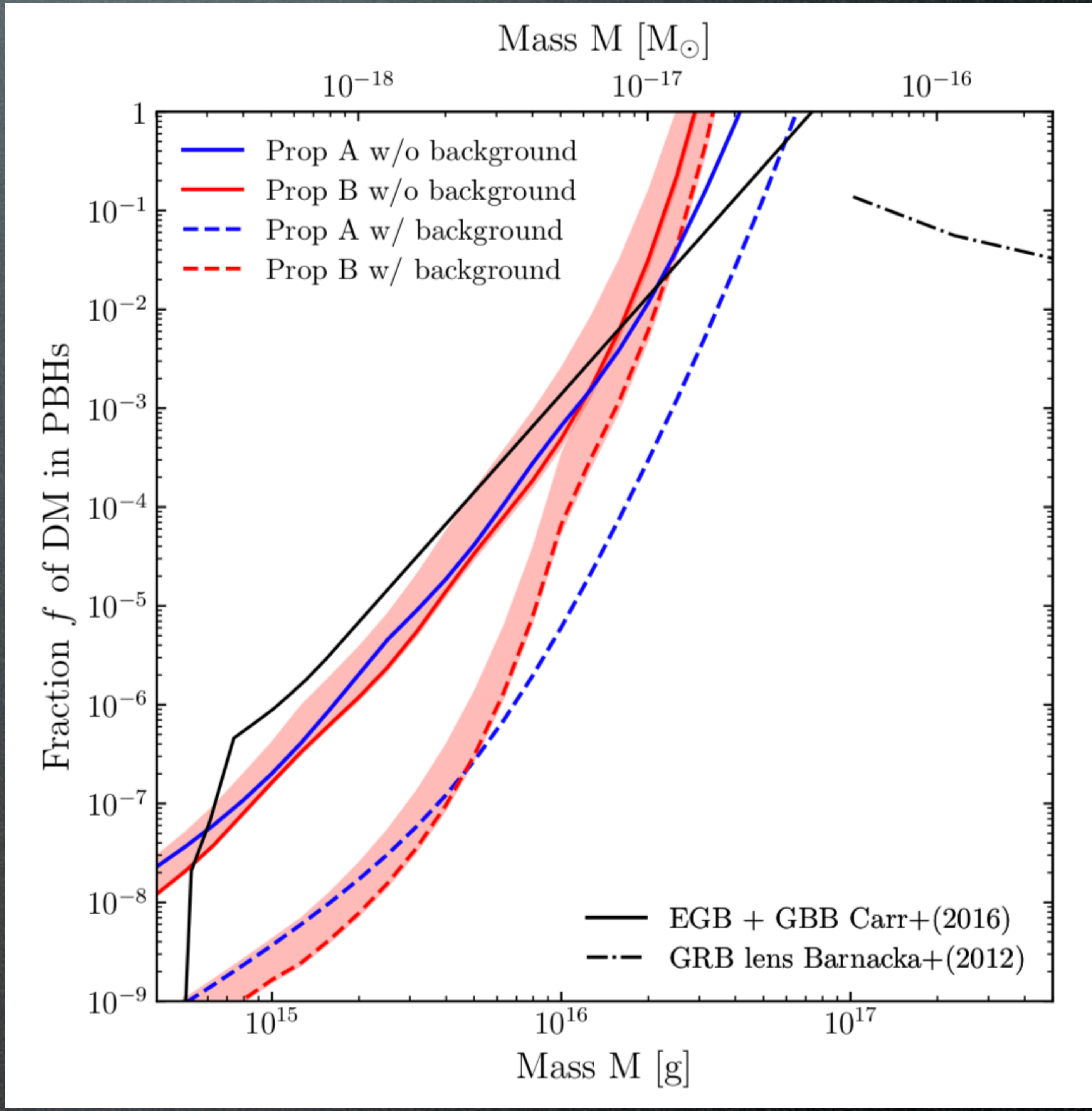


Boudaud, Cirelli 1807.03075, PRL in press

Dark Matter interpretation

low energy

Constraints on Primordial Black Holes

An illustration of Voyager 1, now 21.7 billion kilometers away JPL CALTECH/NASA

Aging Voyager 1 spacecraft undermines idea that dark matter is tiny black holes

By Adrian Cho | Jan. 9, 2019 , 2:25 PM

Forbes

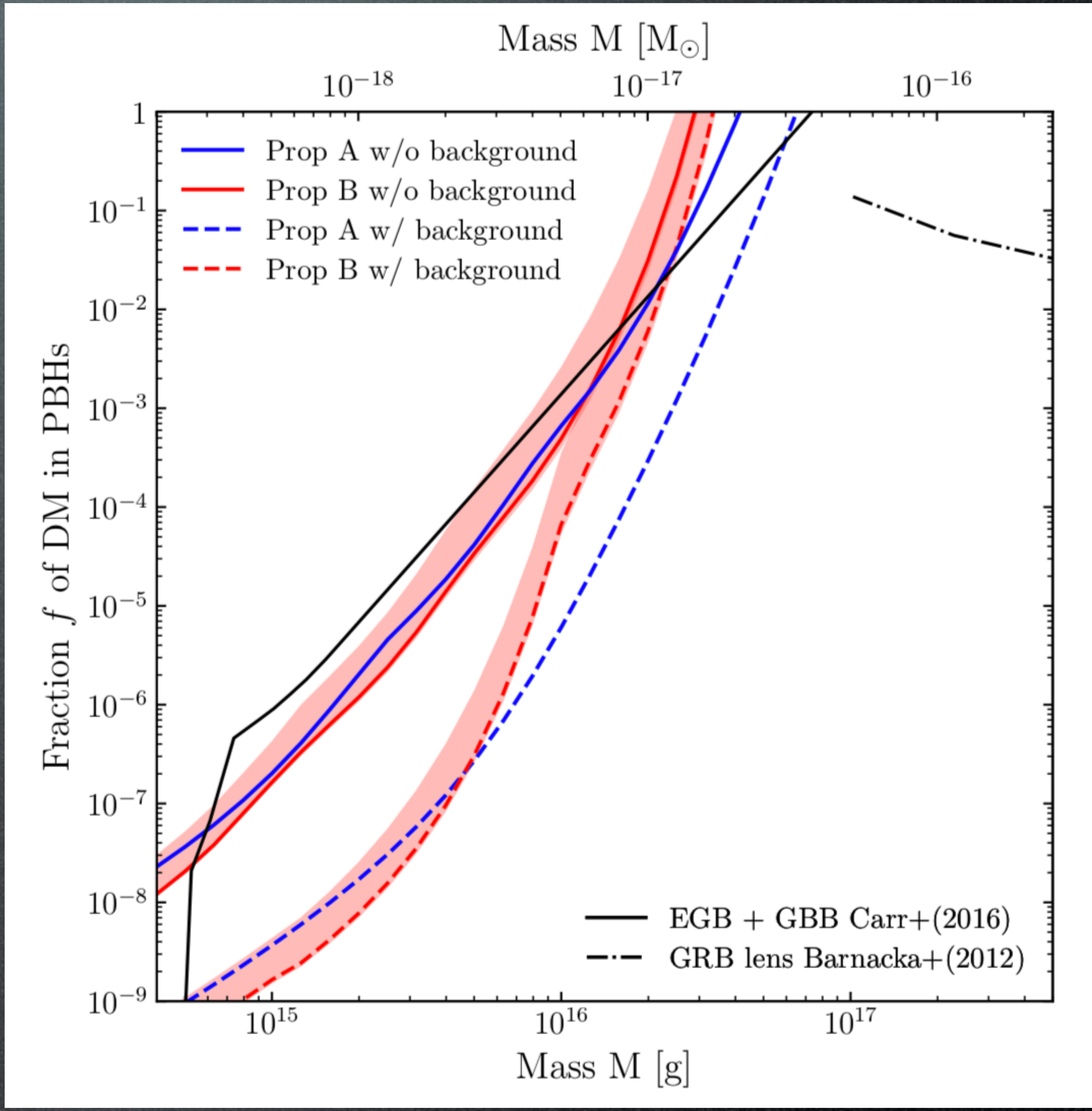
25,121 views | Jul 10, 2018, 05:59pm

NASA's Voyager-1 Spacecraft Opens Door On New Way To Look For Dark Matter

Bruce Dorminey Contributor ⓘ

Science

I cover over-the-horizon technology, aerospace and astronomy.



Boudaud, Cirelli 1807.03075, PRL in press

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

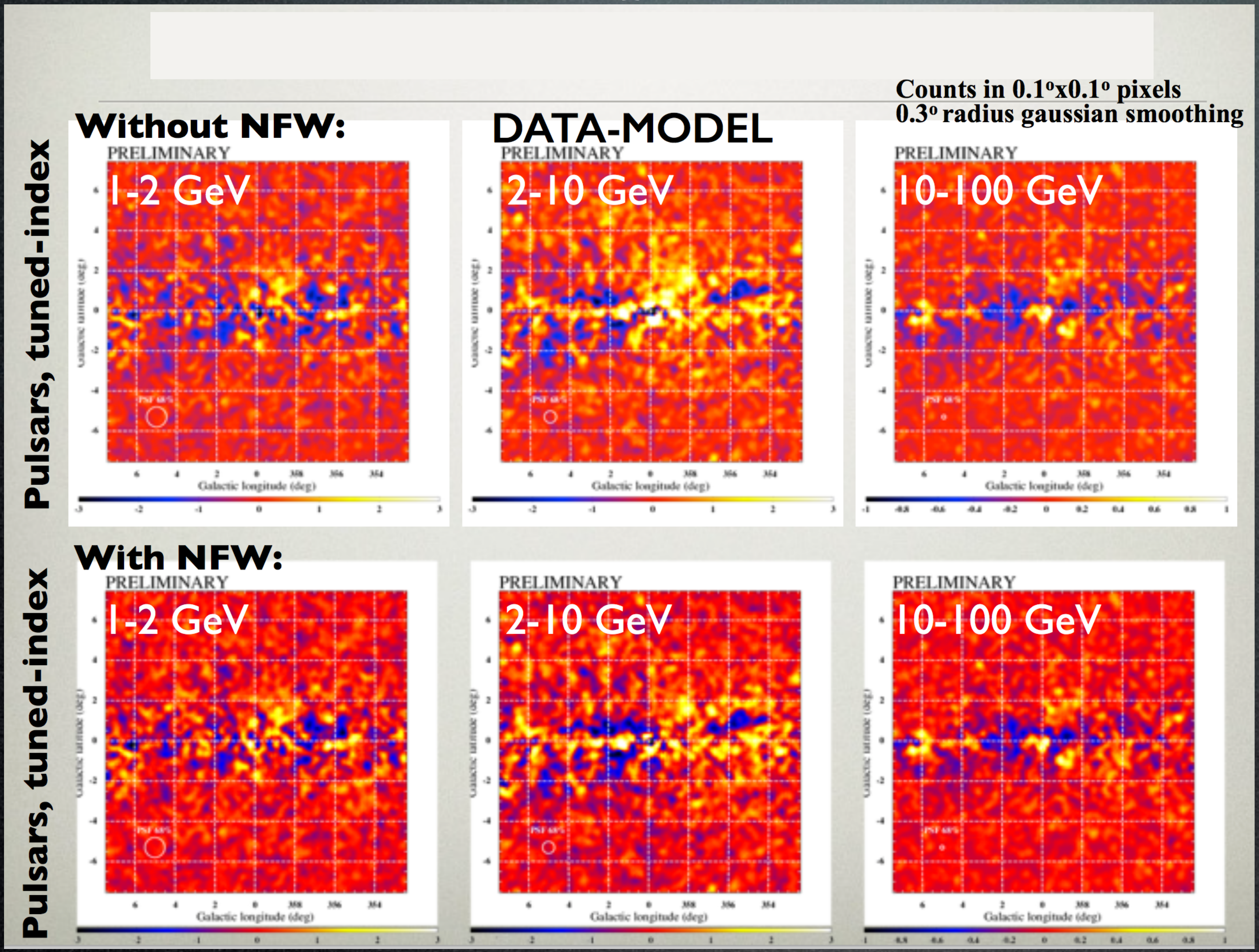
GAPS, AMS

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

SK, Icecube, Antares

GC GeV excess

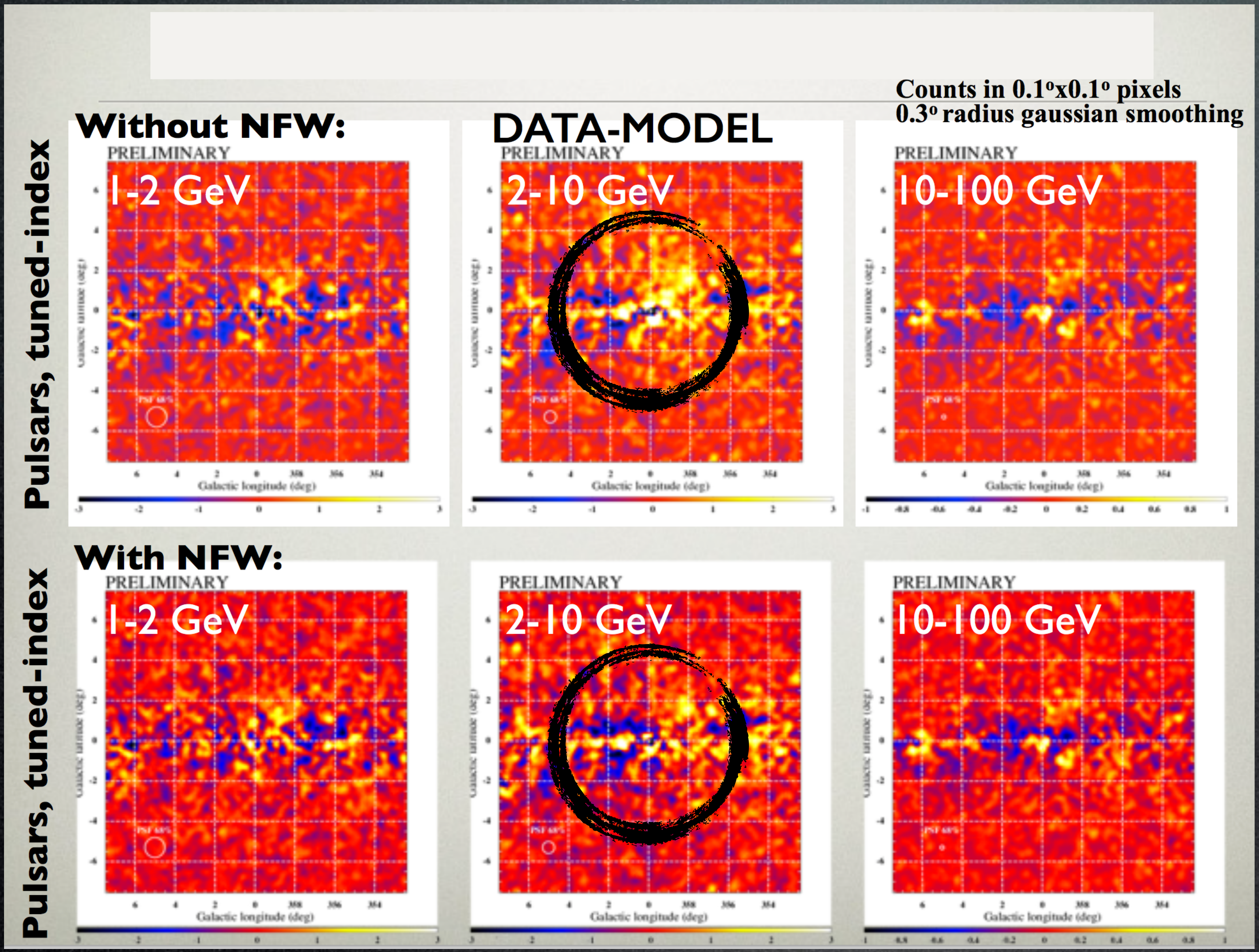
Dark Matter interpretation:



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:

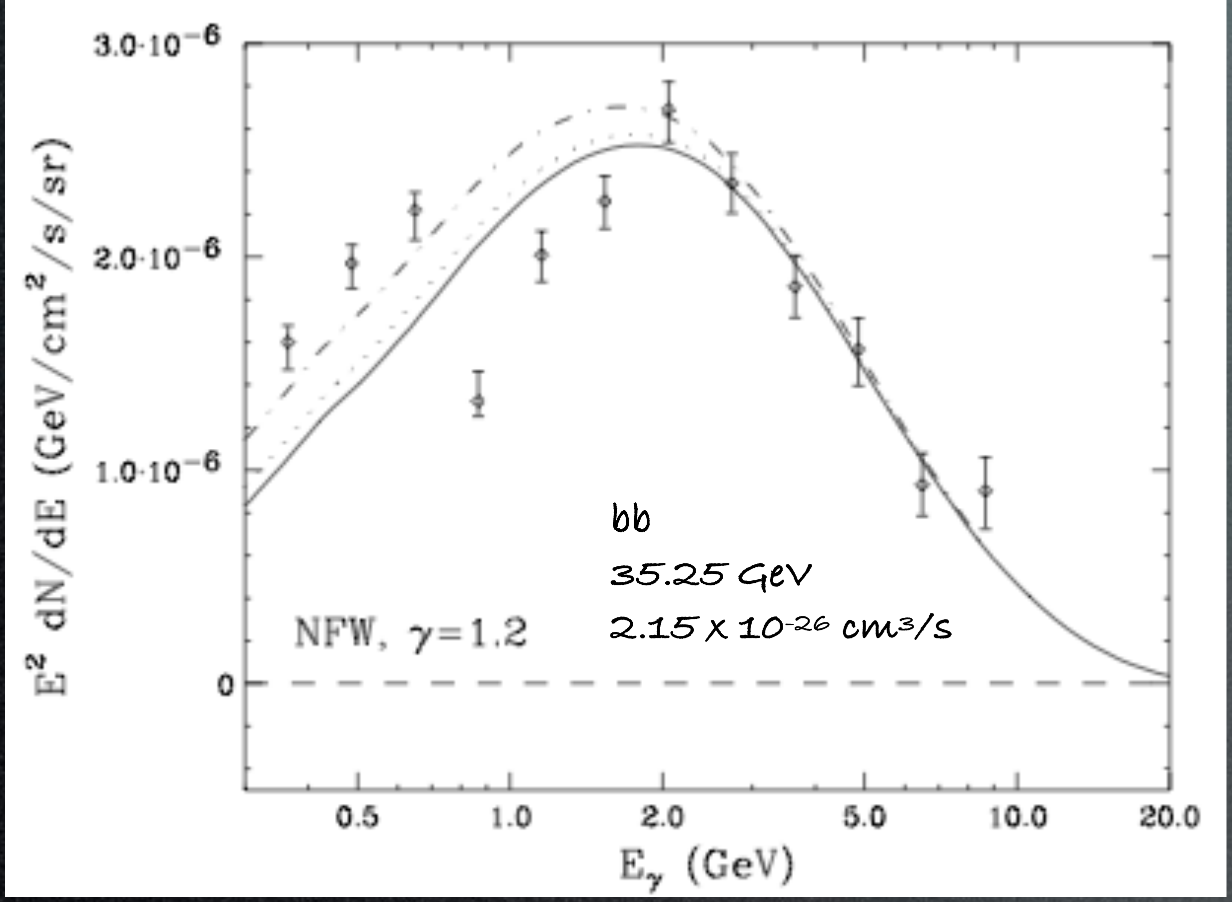


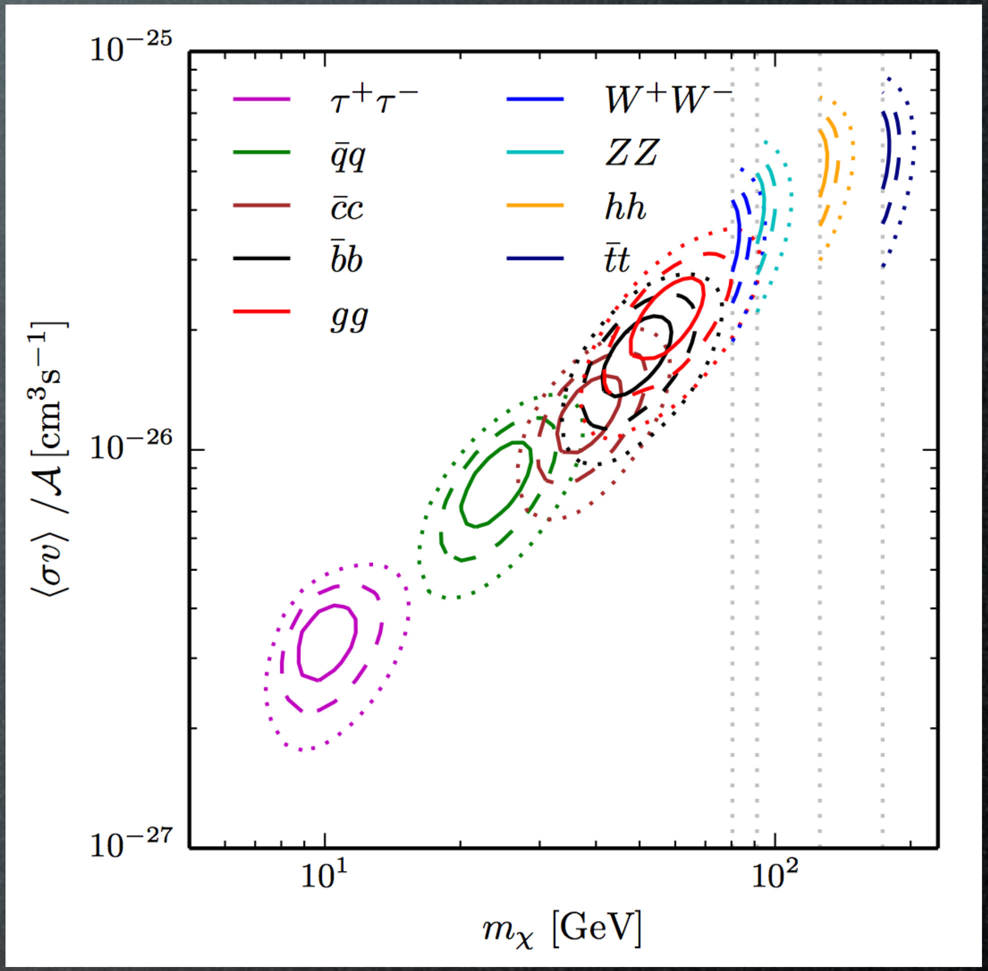
S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815
Fermi coll. 1511.02938

GC GeV excess

Dark Matter interpretation:

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





F. Calore et al. 1411.4647

A compelling case for annihilating DM

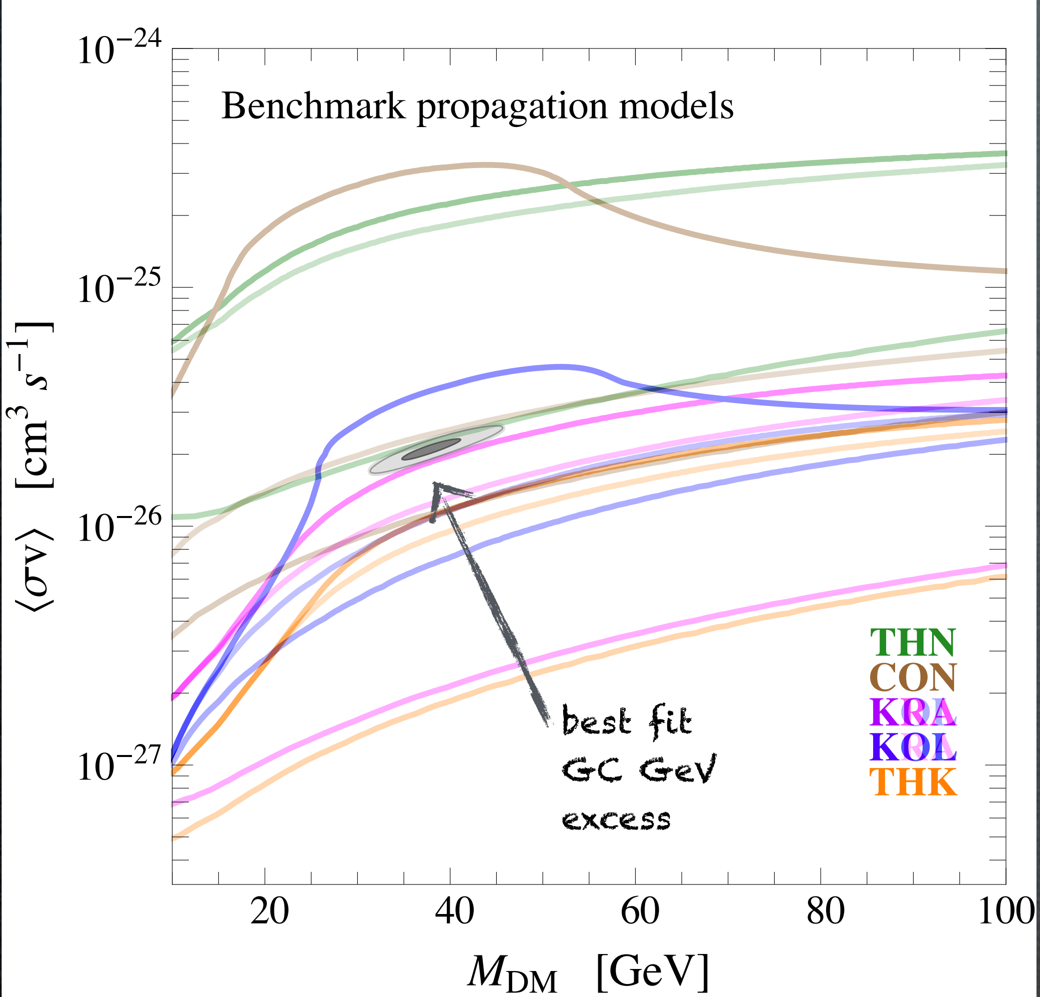
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

...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

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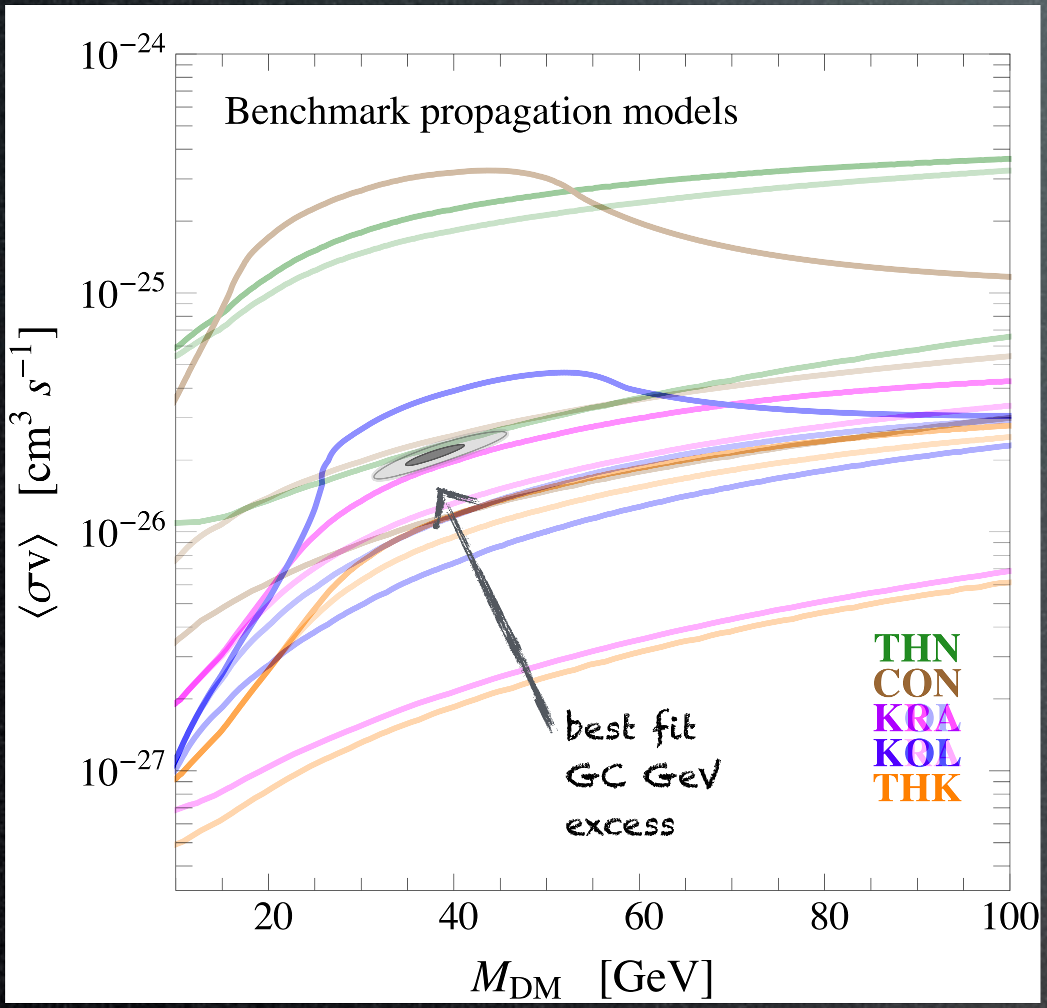
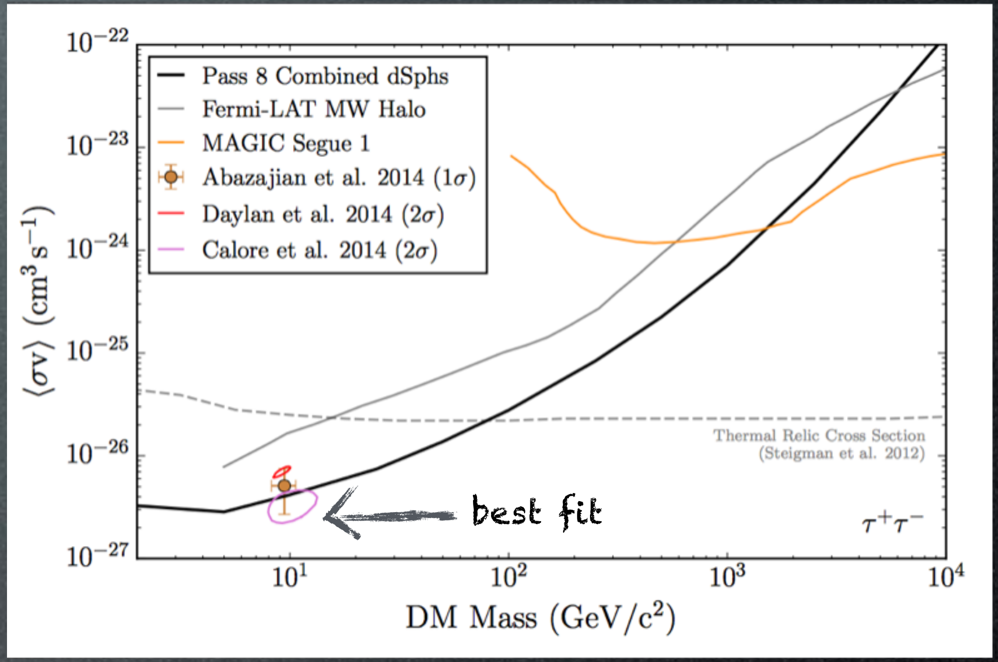


Cirelli, Gaggero,
Giesen, Taoso,
Urbano 1407.2173

Gamma ray ones neither



FERMI 1503.02641

Also:

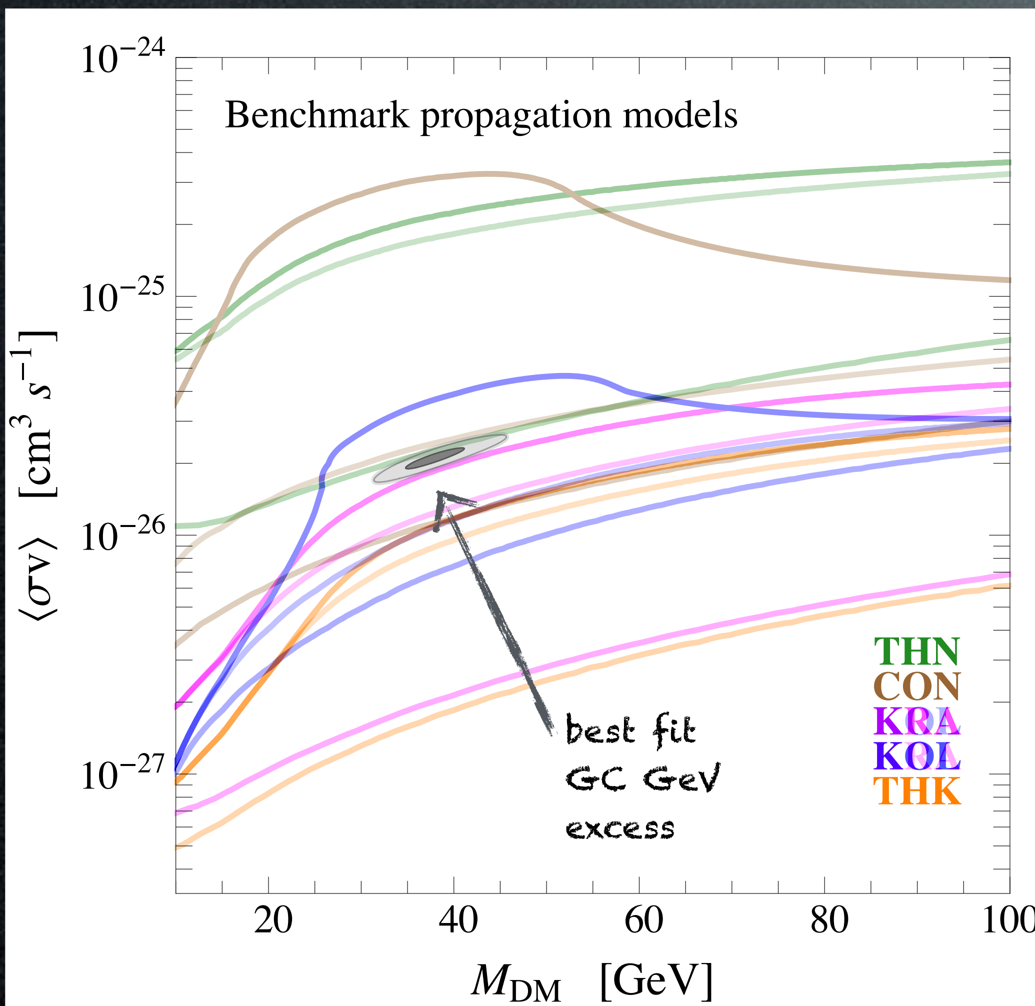
Bringmann, Vollmann,
Weniger 1406.6027

Hooper, Linden, Mertsch
1410.1527

GC GeV excess

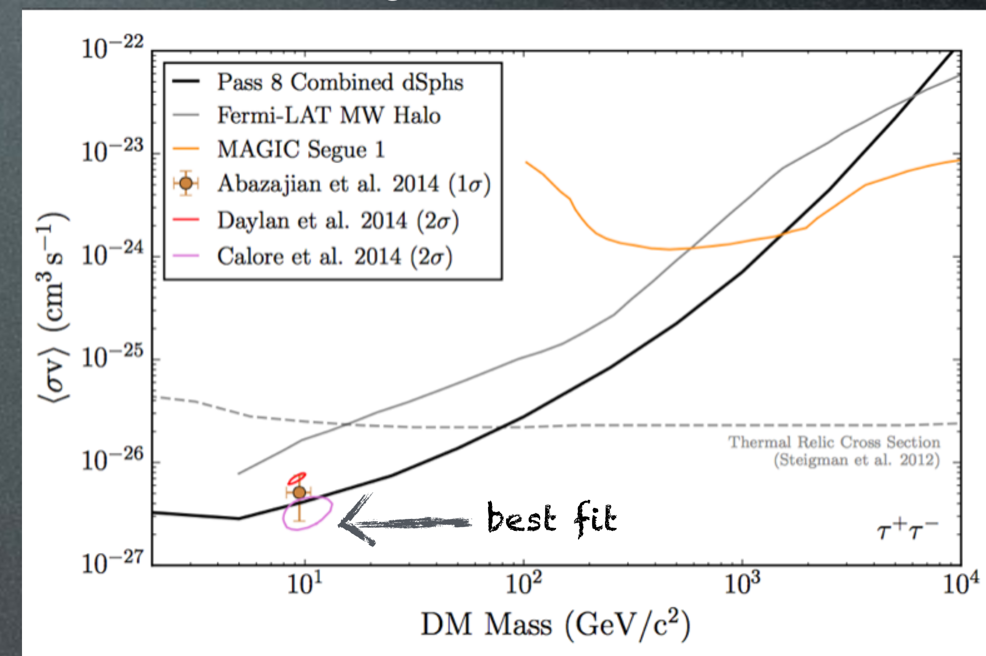
Dark Matter interpretation:

Antiproton constraints are not conclusive



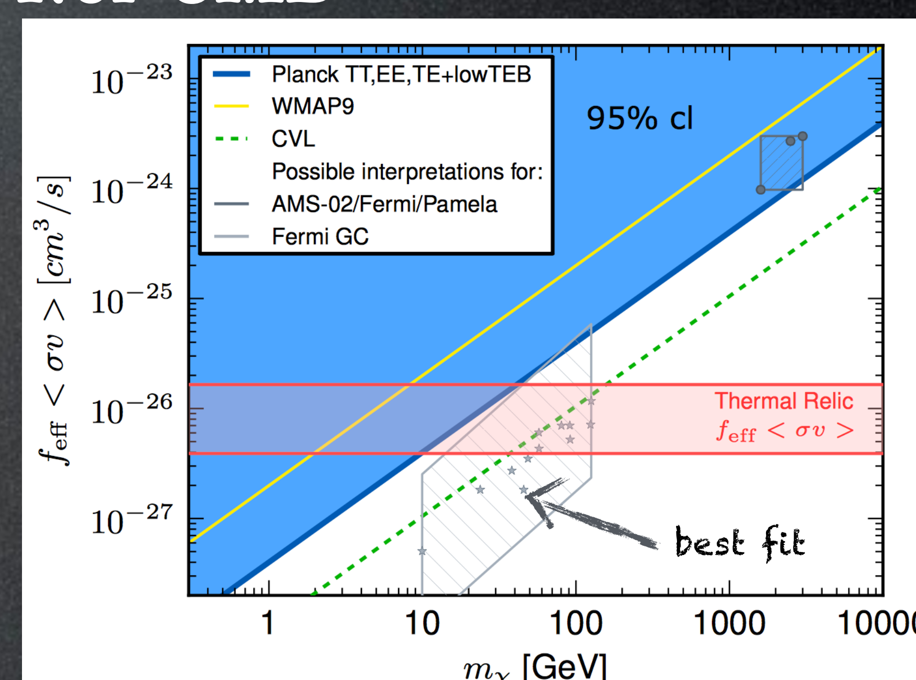
Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Gamma ray ones neither



FERMI 1503.02641

Nor CMB



Planck 2015

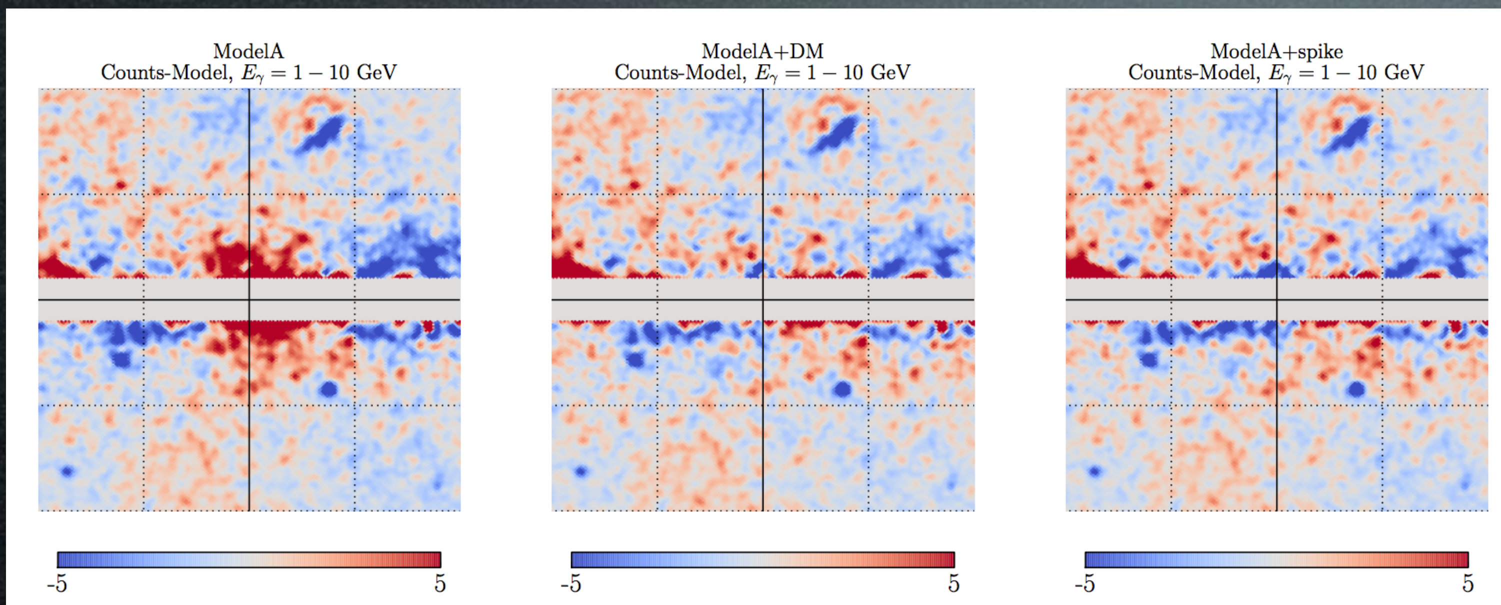
Also:

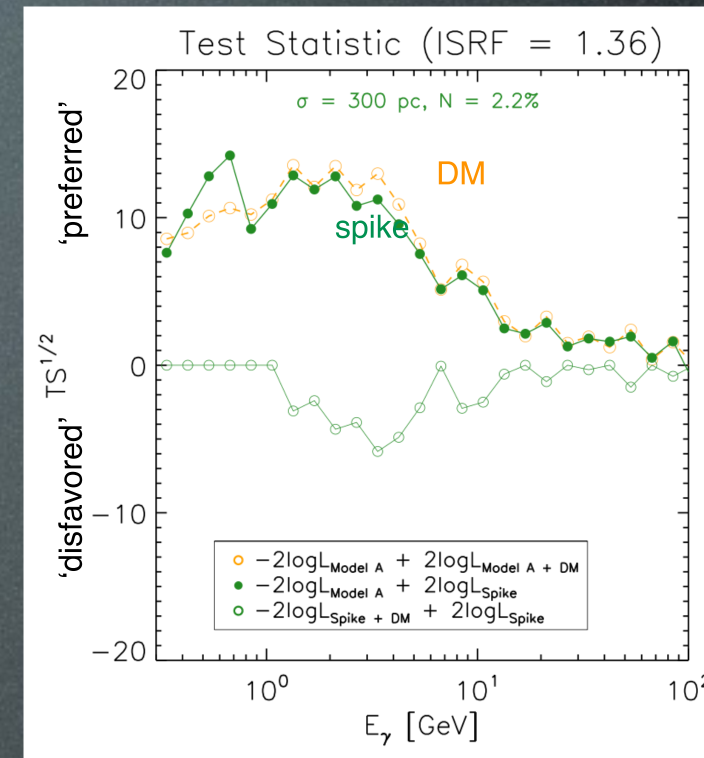
Bringmann, Vollmann, Weniger 1406.6027

Hooper, Linden, Mertsch 1410.1527

GC GeV excess

'Astro' interpretation(s):

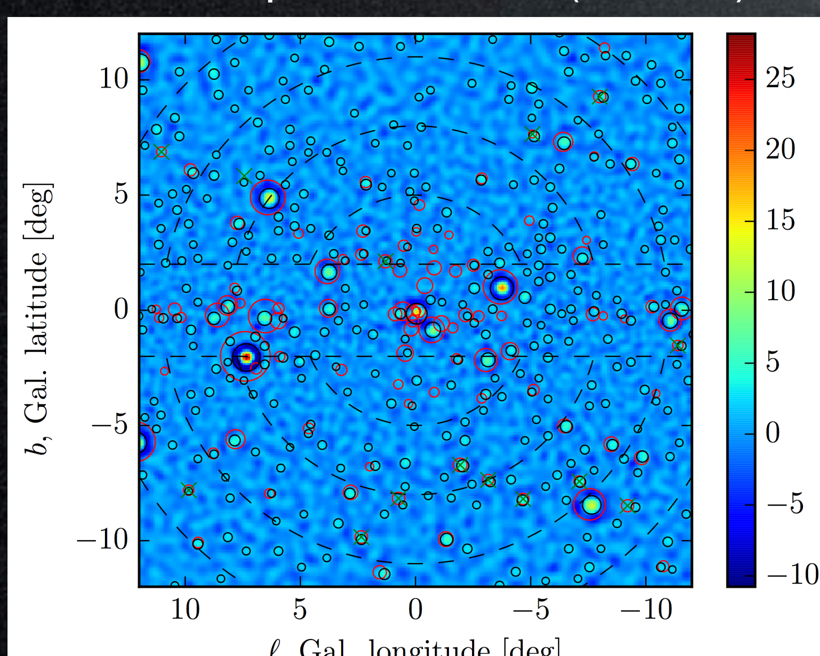




An additional steady-source spike of CRs (from SNRs?) that emit via ICS

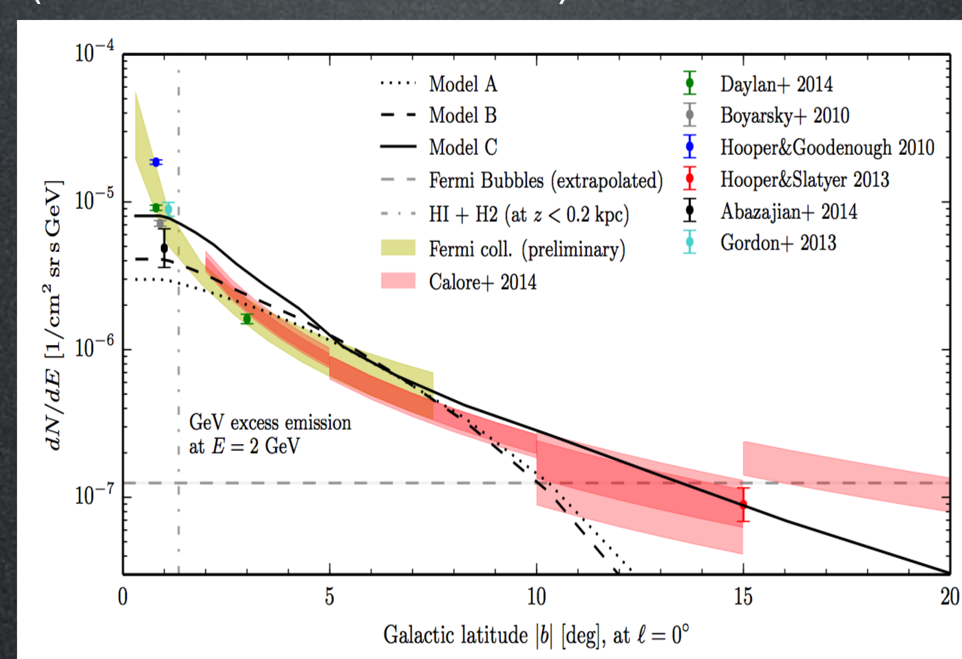
D. Gaggero et al 1507.06129

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.
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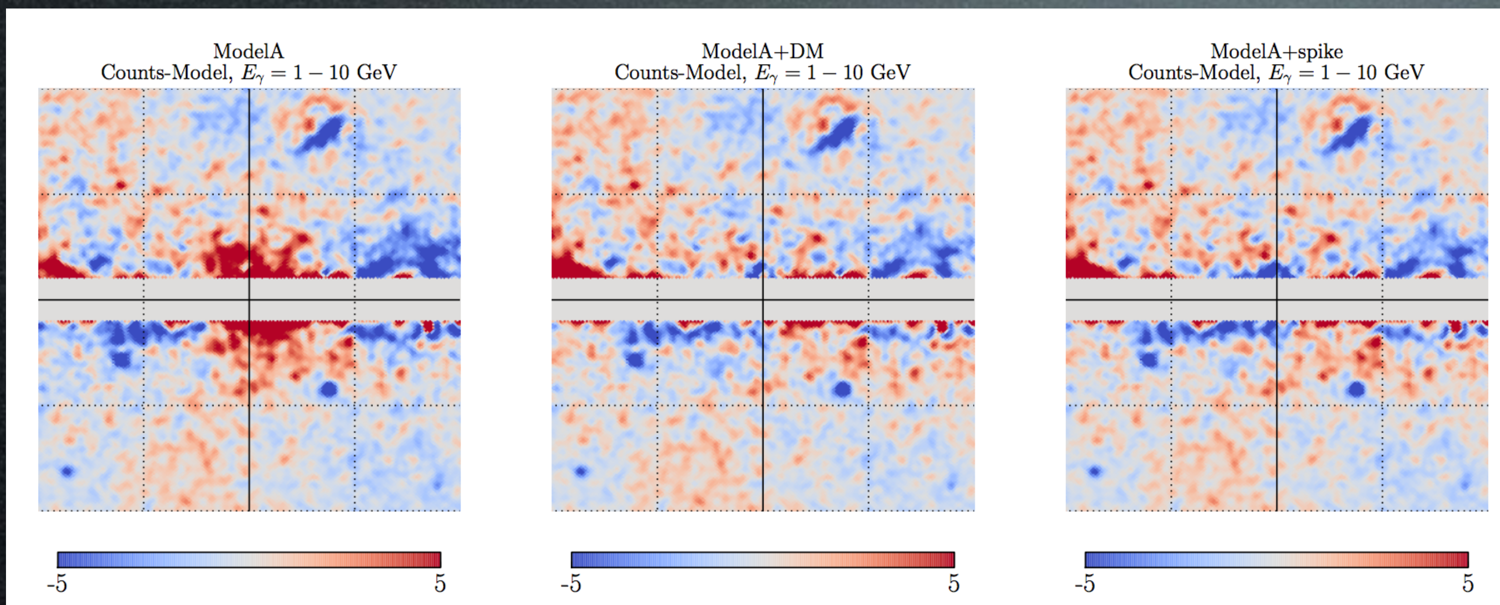
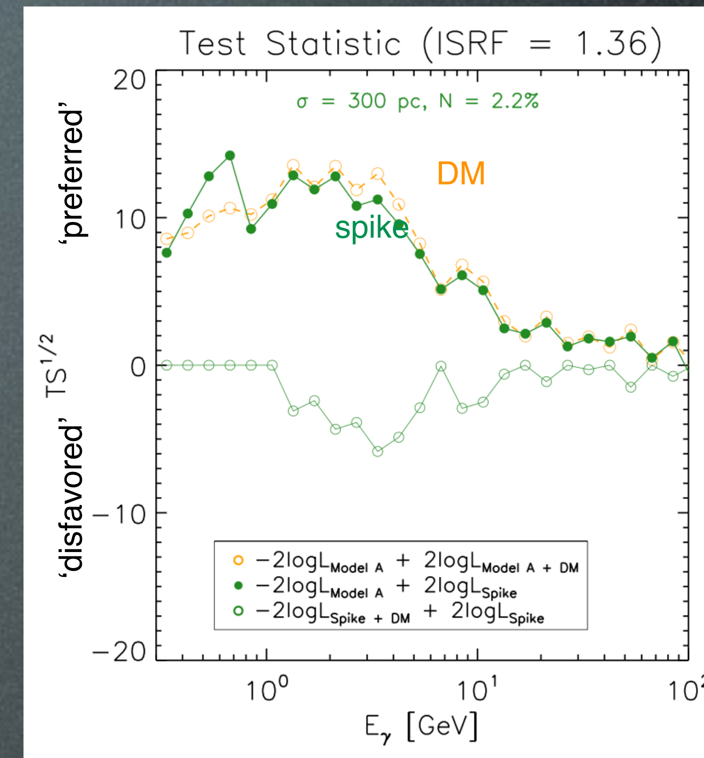
GC GeV excess

‘Astro’ interpretation(s):

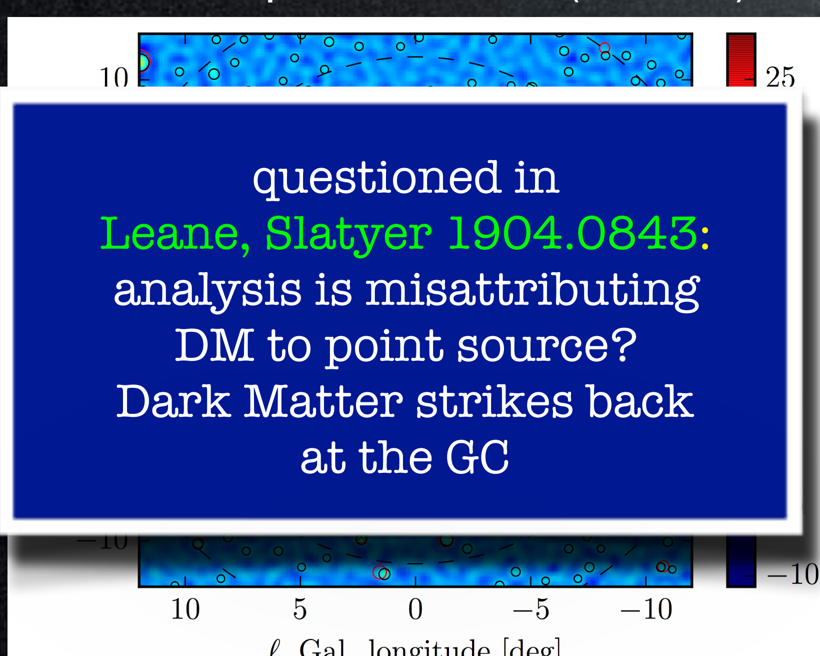


An additional steady-source spike of CRs (from SNRs?) that emit via ICS



D. Gaggero et al 1507.06129

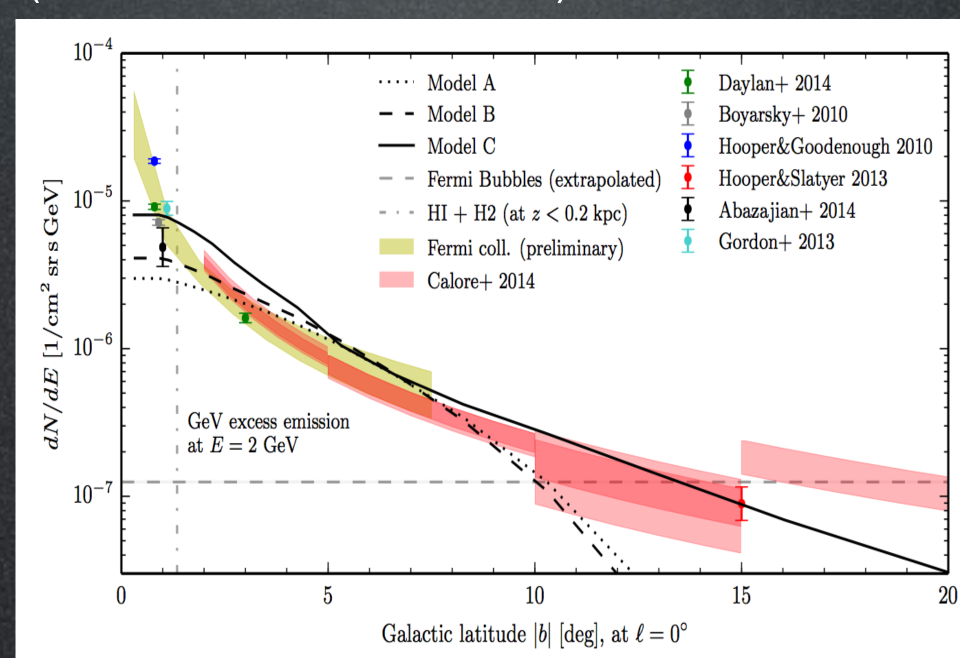
Unresolved point sources (MSPs?)



questioned in
Leane, Slatyer 1904.0843:
analysis is misattributing
DM to point source?
Dark Matter strikes back
at the GC

Bartels…Weniger 1506.05104
Lee, Lisanti…Slatyer 1506.05124

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



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PS: excesses in Andromeda?

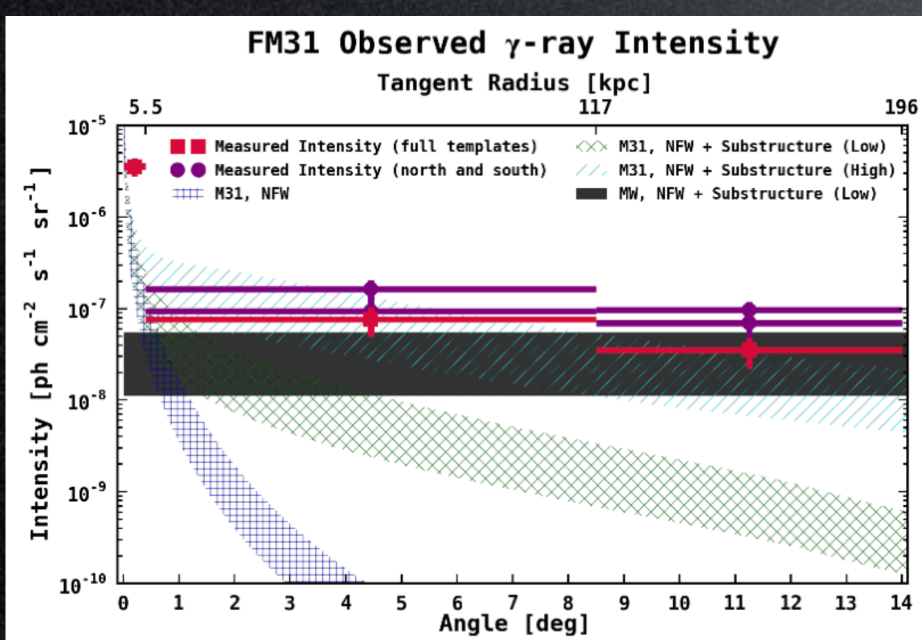
Fermi has also observed M31 (and M33):
any signal consistent with the GC GeV excess?

Ackermann et al, FERMI Coll. 1702.08602

an excess from the center of M31 **but:** intensity = 5 x GC GeV excess

Murgia, Moskalenko et al 1903.10533

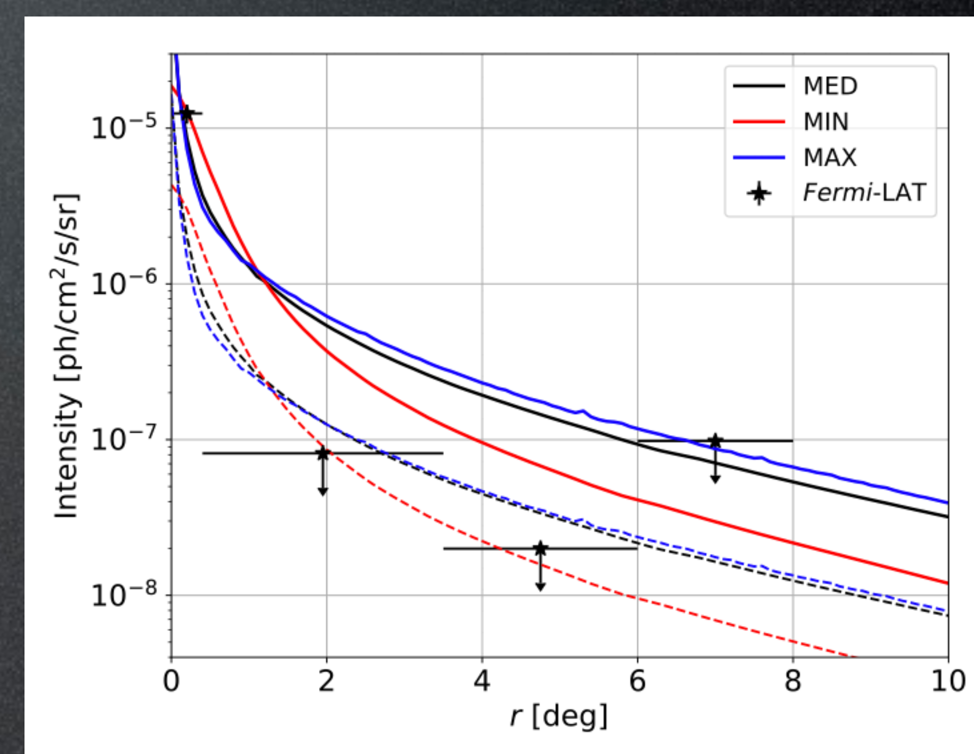
excess from the outer halo
spectrum agrees w GC GeV excess



but: fitting with DM requires huge subhalo boost, and in any case MW DM emission a.l.o.s. contributes at least as much, or more

Di Mauro, Zaharijas, Charles et al 1904.10977

no excess
upper limits only



DM detection

direct detection

production at colliders

indirect

γ from annihil in galactic center or halo and from secondary emission
Fermi, ICT, radio telescopes...

e^+ from annihil in galactic halo or center
PAMELA, Fermi, HESS, AMS,balloons...

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

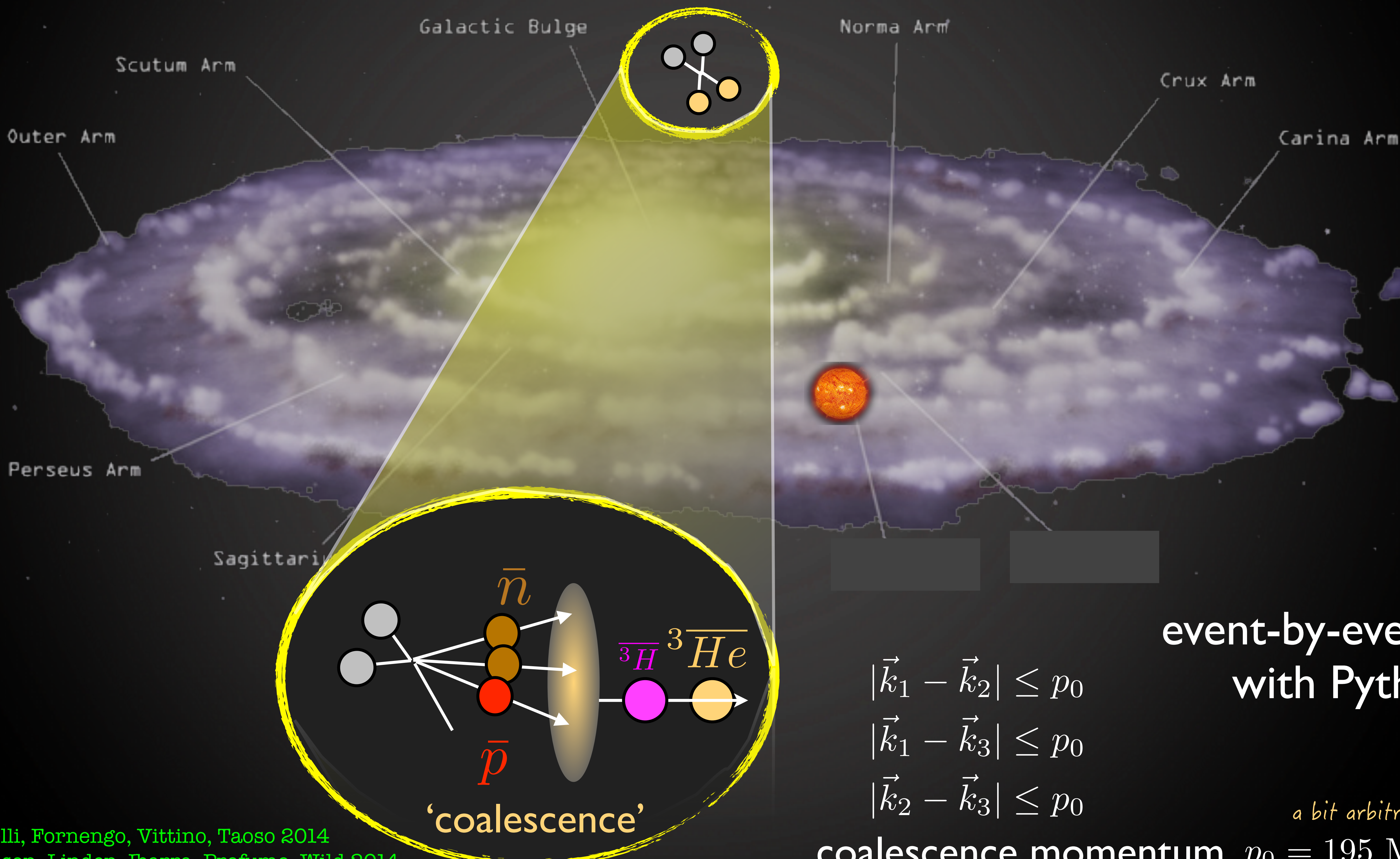
$\bar{d}$ from annihil in galactic halo or center
GAPS, AMS

$\nu, \bar{\nu}$ from annihil in massive bodies
SK, Icecube, Km3Net

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

Indirect Detection

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



event-by-event with Pythia

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

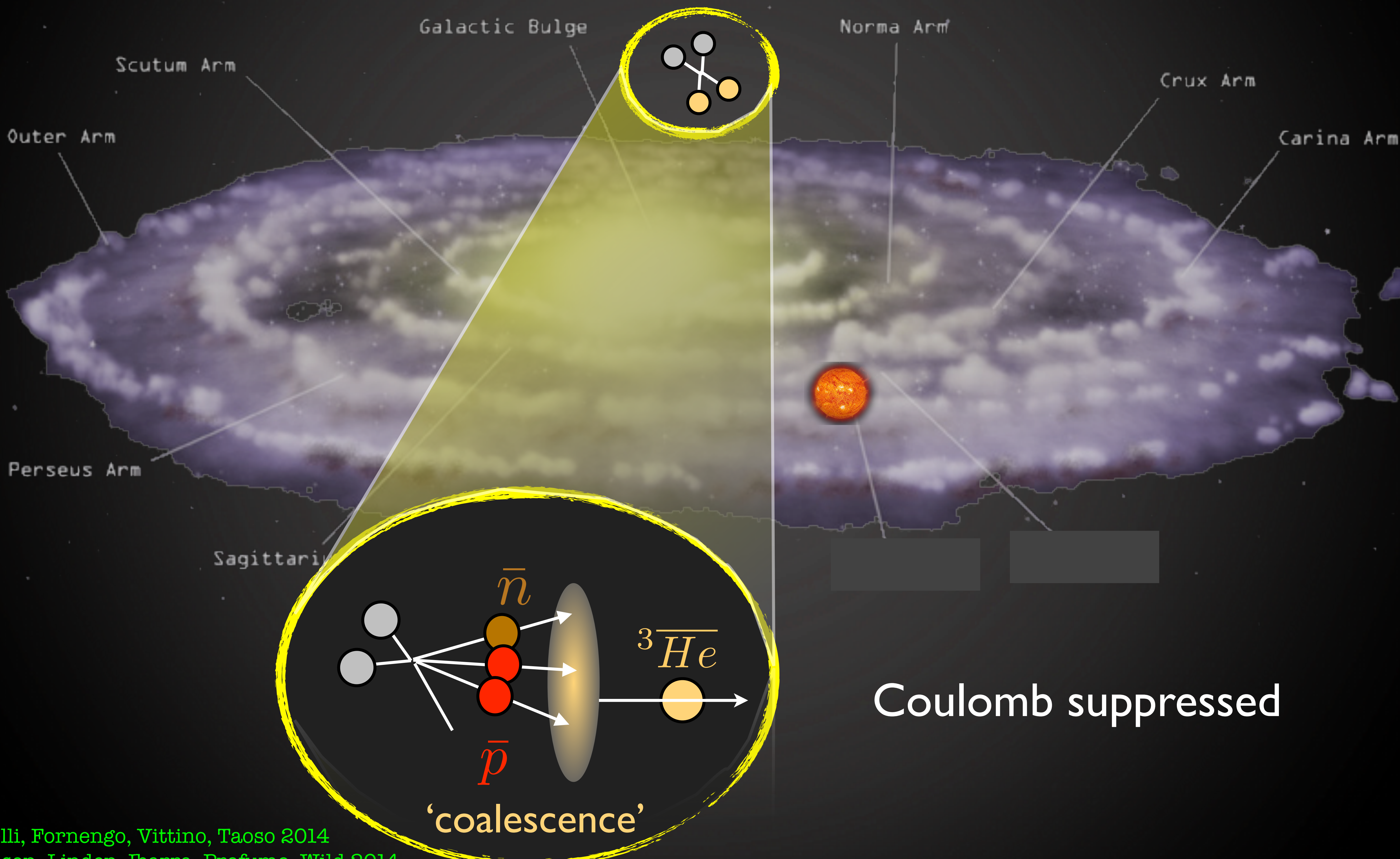
a bit arbitrary…

coalescence momentum $p_0 = 195$ MeV

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

Indirect Detection

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



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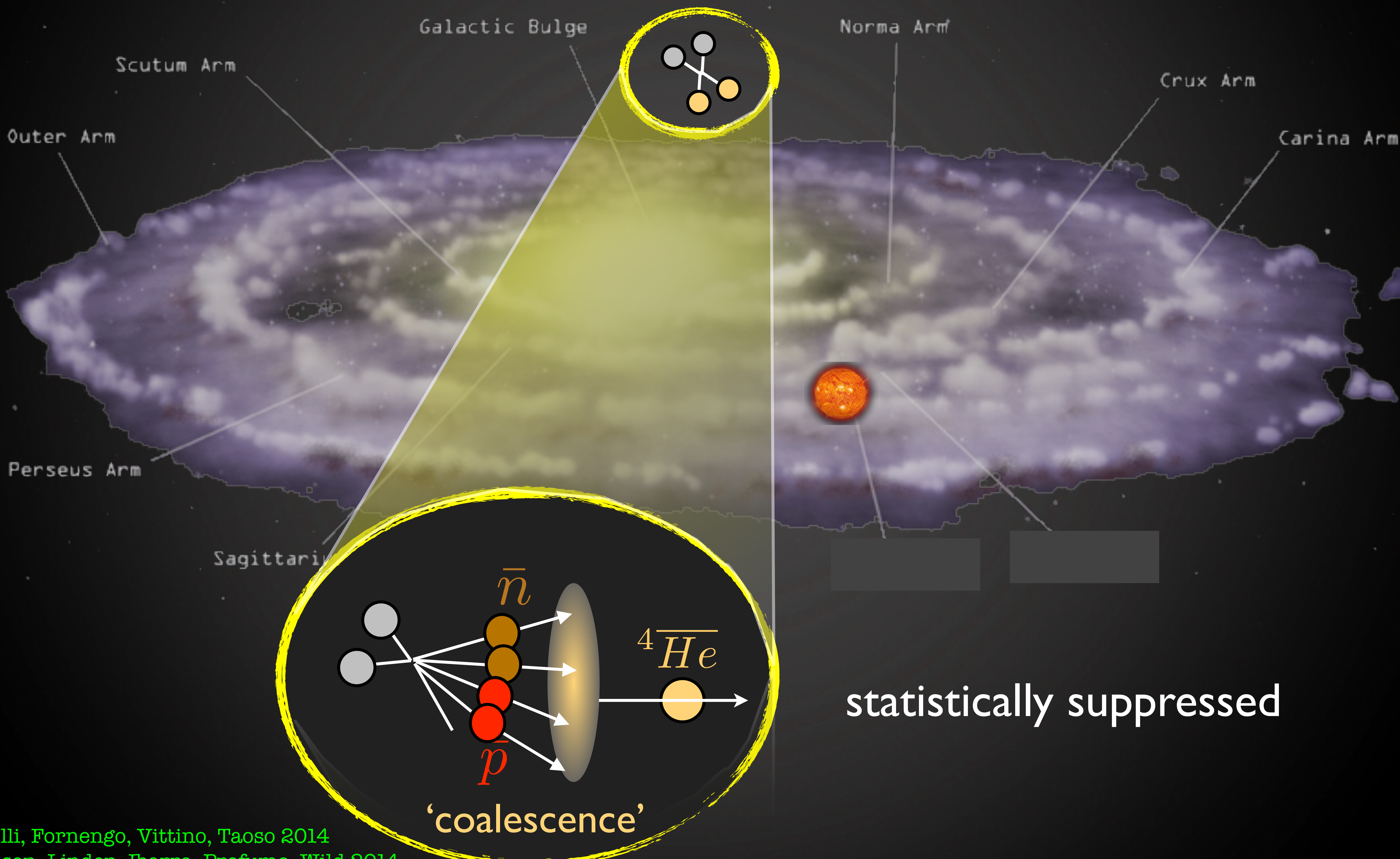

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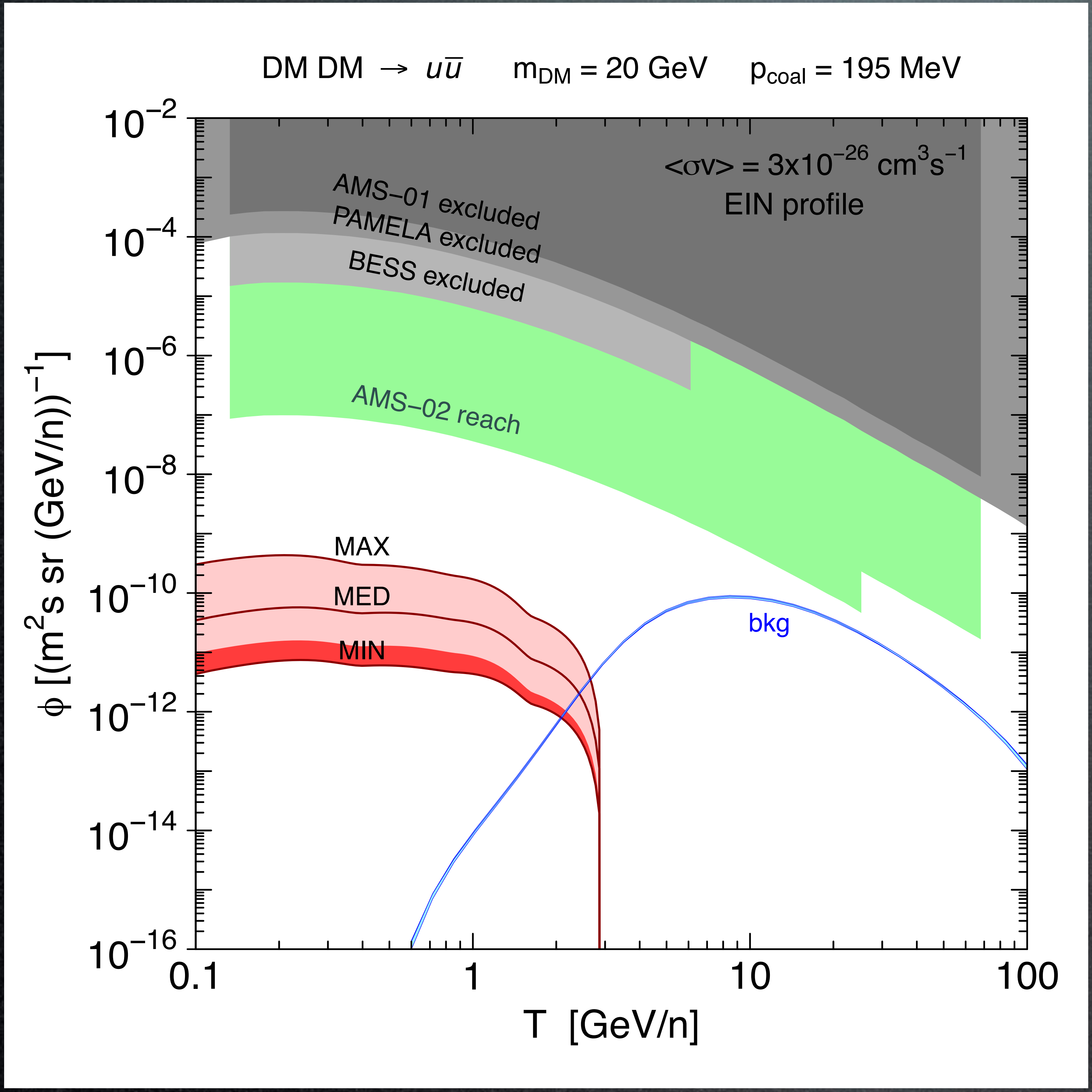
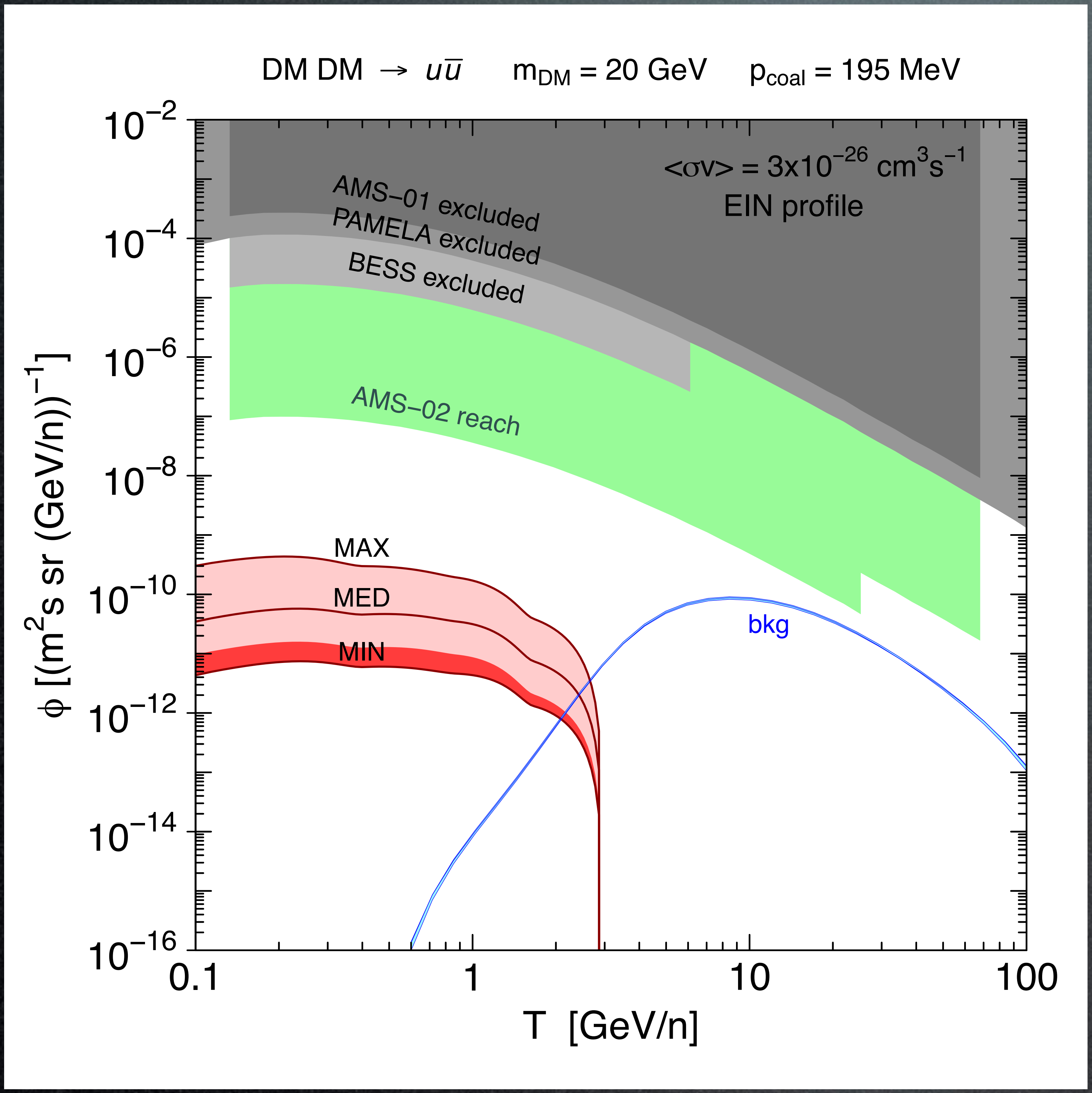


all

consistent with antiproton bounds

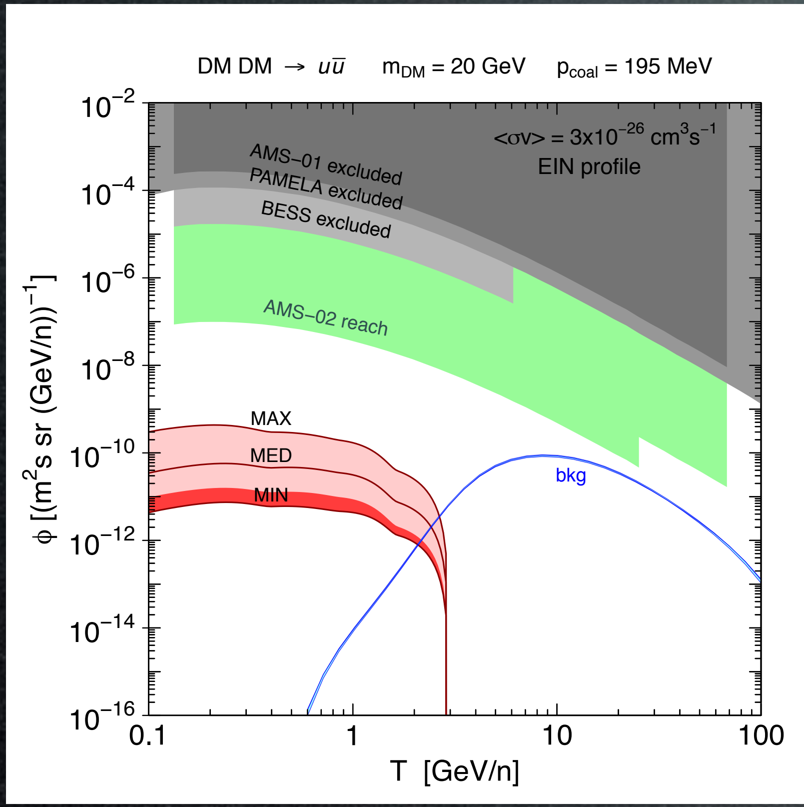
Indirect Detection

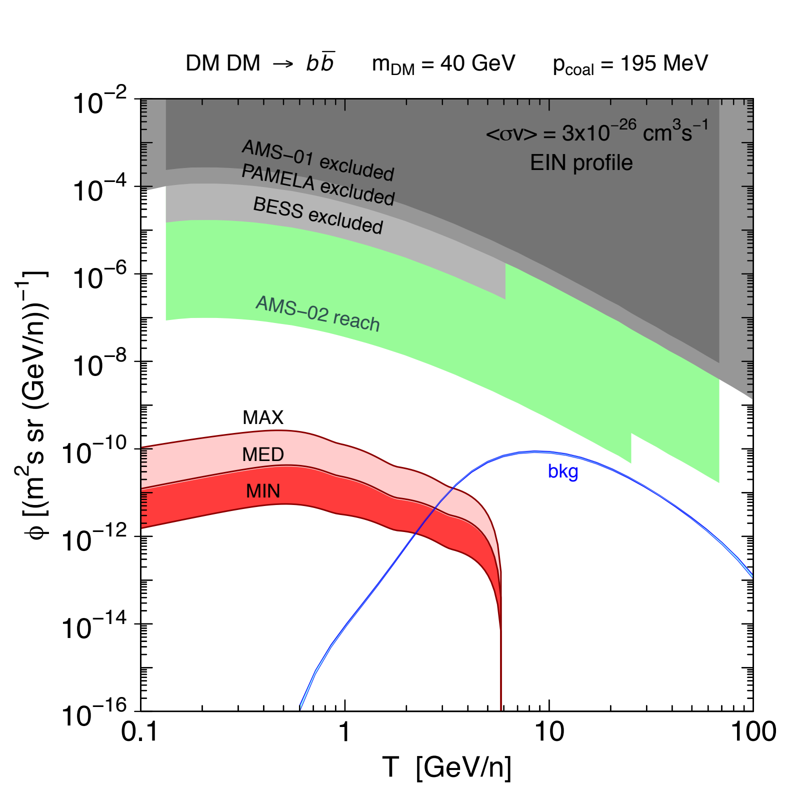
$\overline{He}$ from DM annihilations in halo

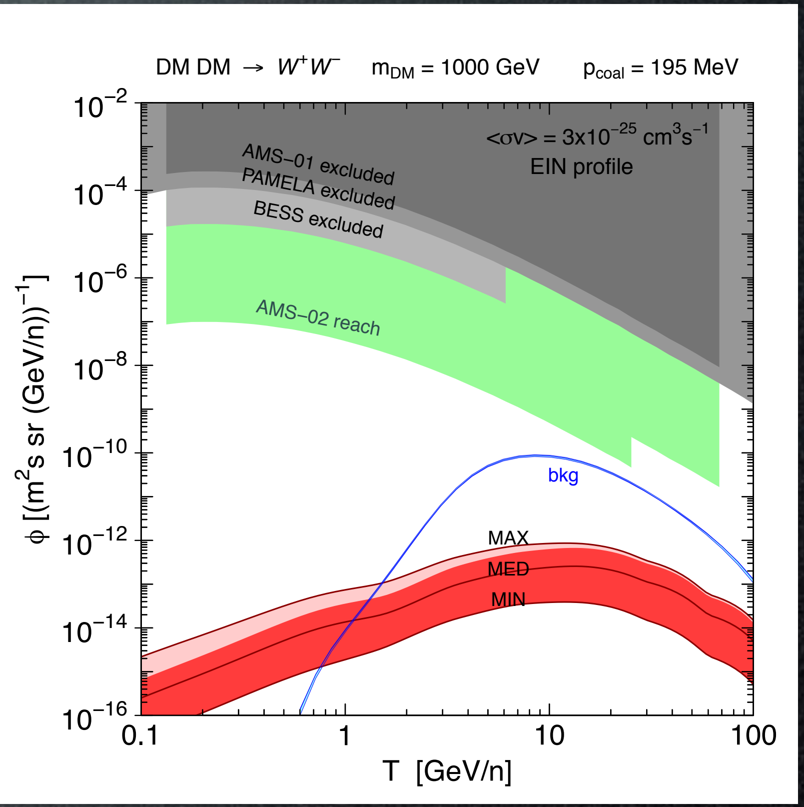


Indirect Detection

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







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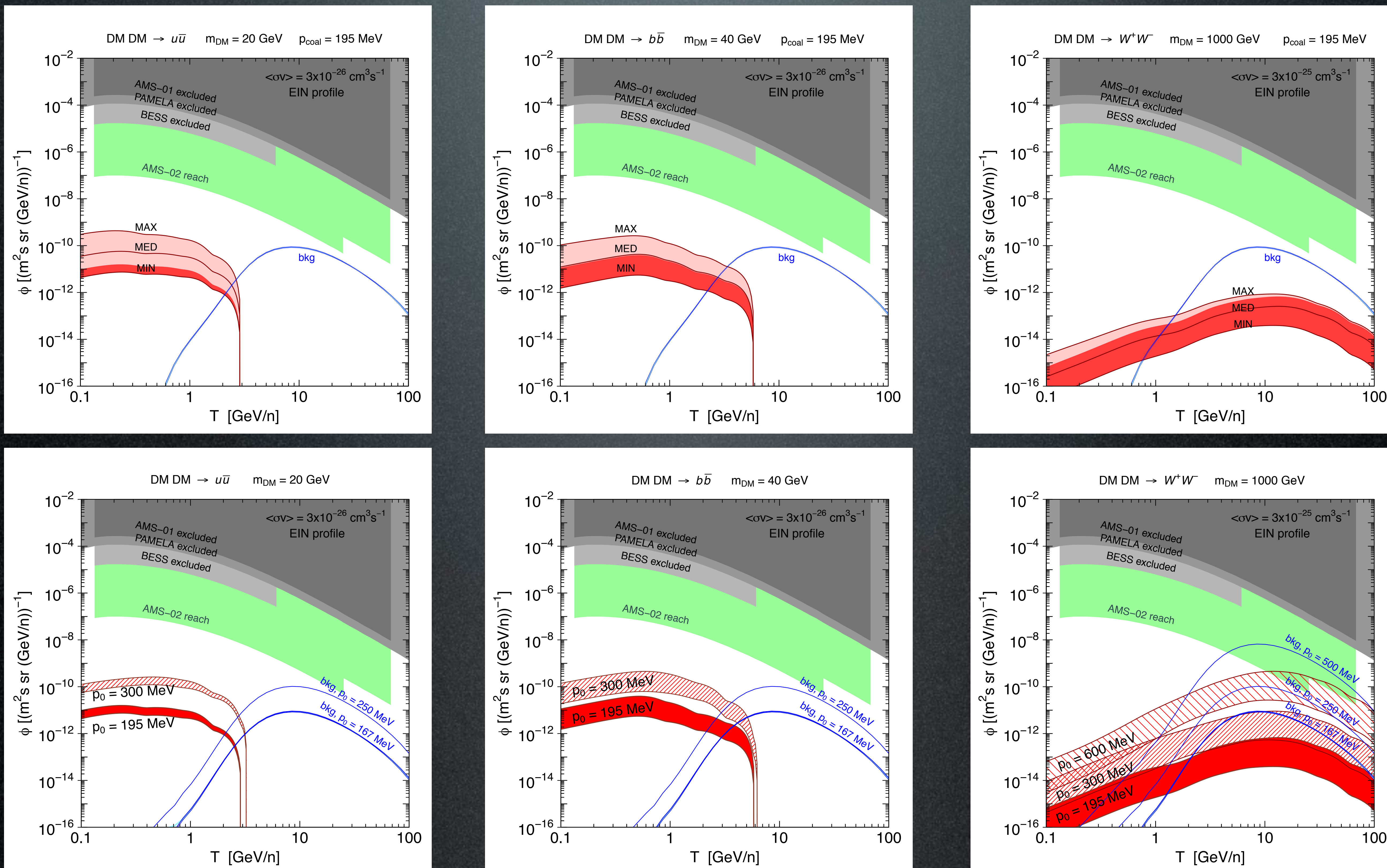

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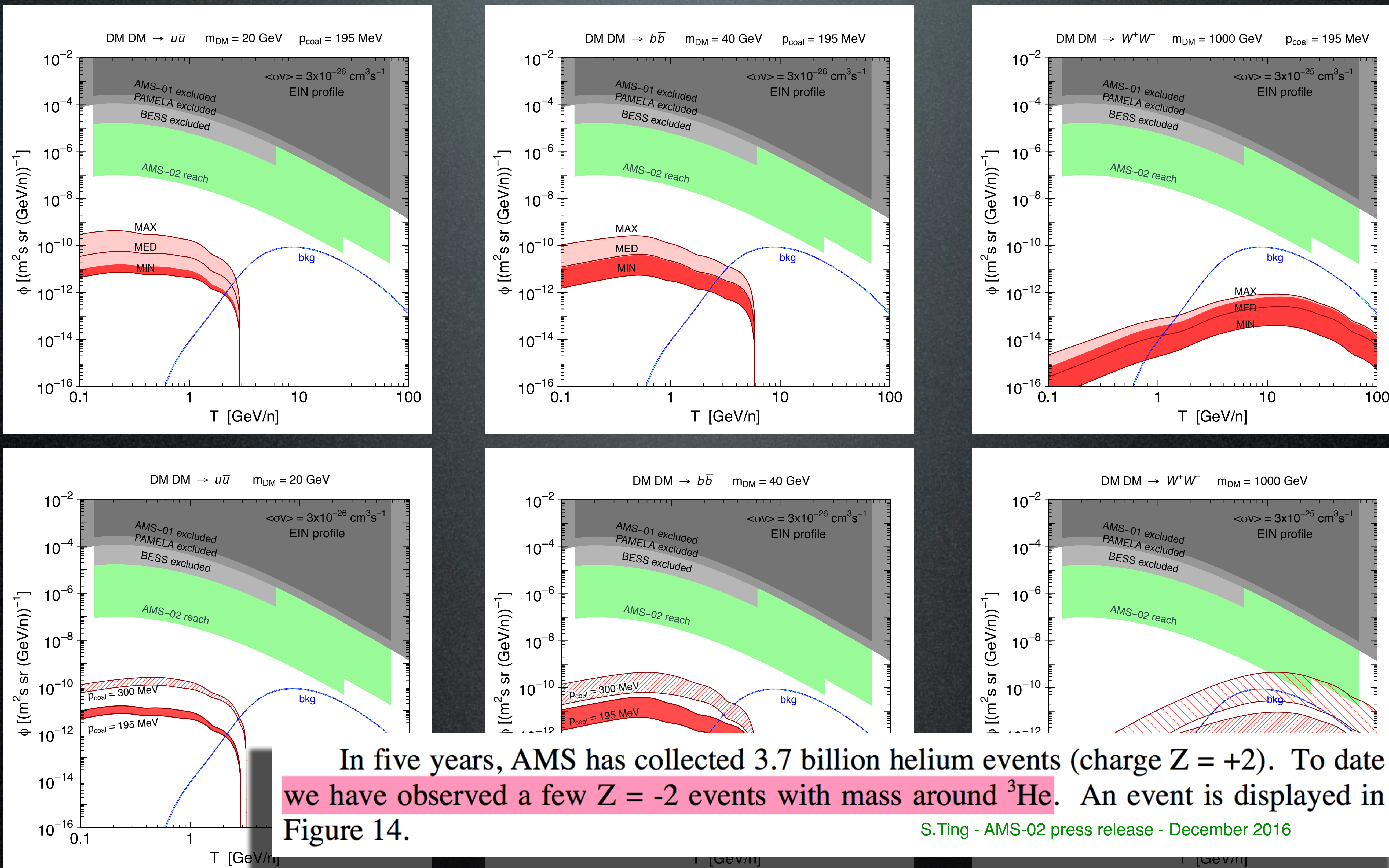
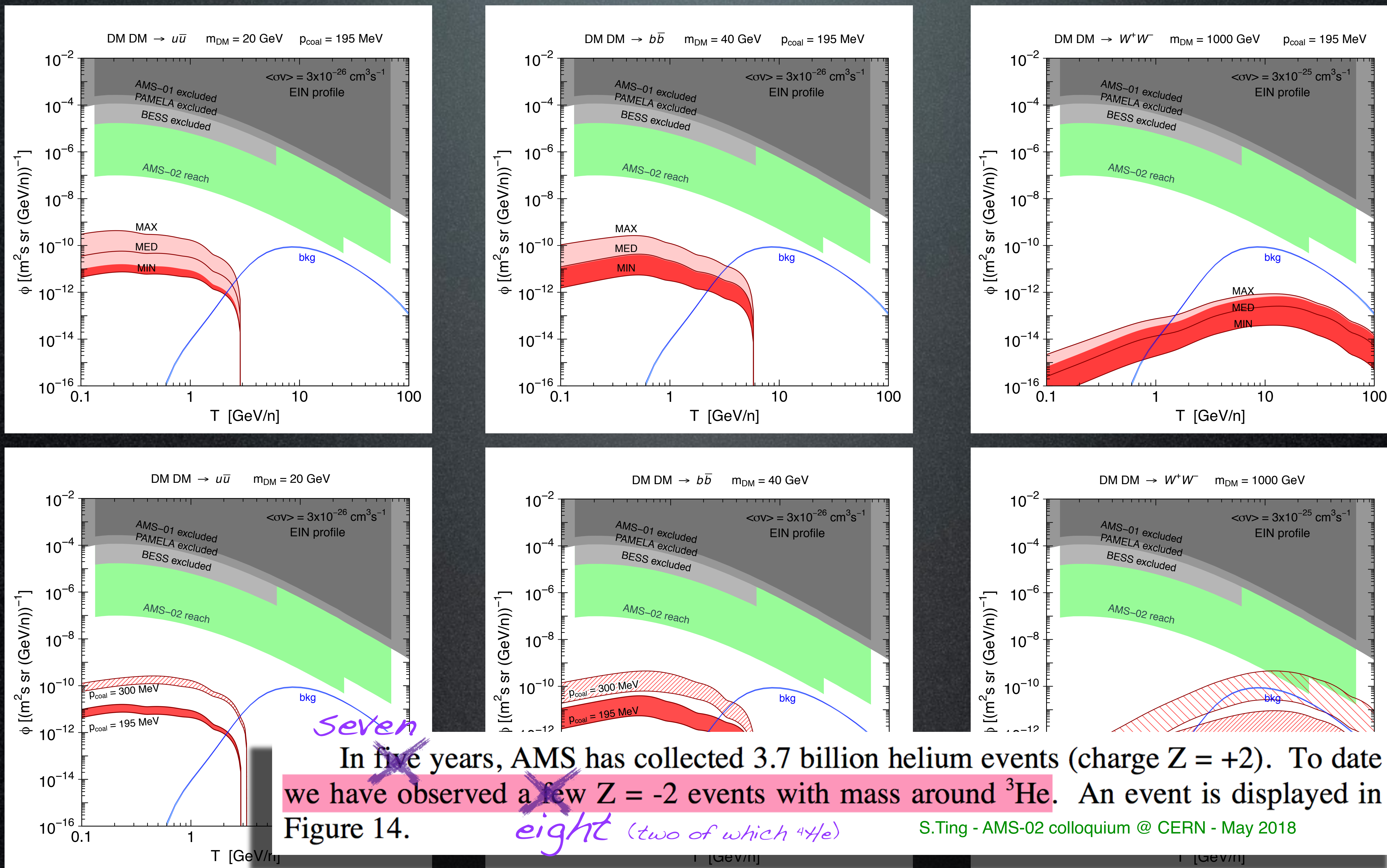


In five years, AMS has collected 3.7 billion helium events (charge Z = +2). To date we have observed a few Z = -2 events with mass around ^{3}He. An event is displayed in Figure 14.

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

Indirect Detection

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



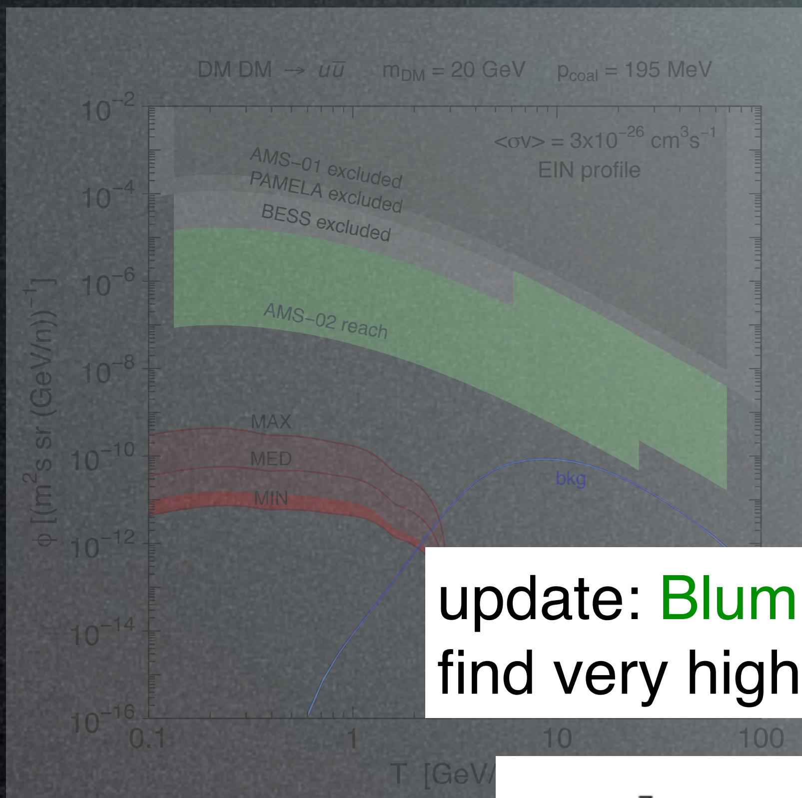
~~five~~ seven In ~~five~~ years, AMS has collected 3.7 billion helium events (charge Z = +2). To date we have observed a ~~few~~ Z = -2 events with mass around ^{3}He. An event is displayed in Figure 14.

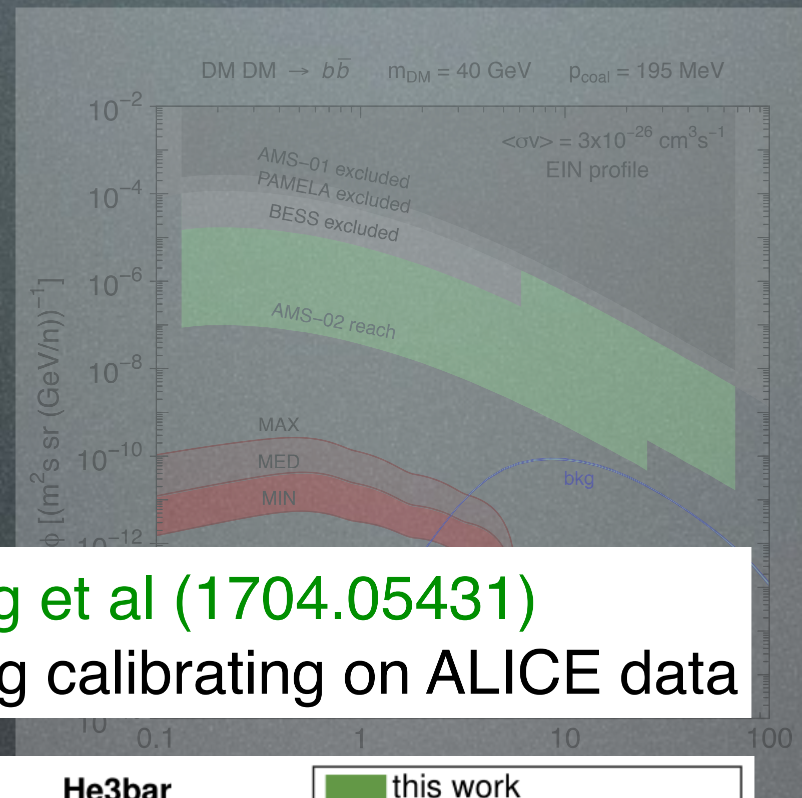
eight (two of which ^{4}He)

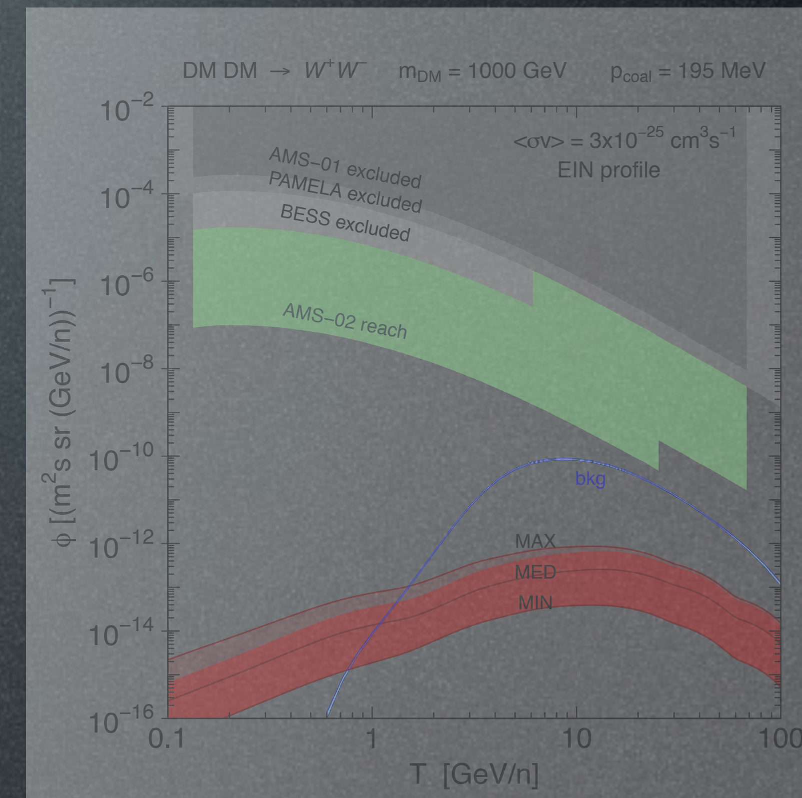
S.Ting - AMS-02 colloquium @ CERN - May 2018

Indirect Detection

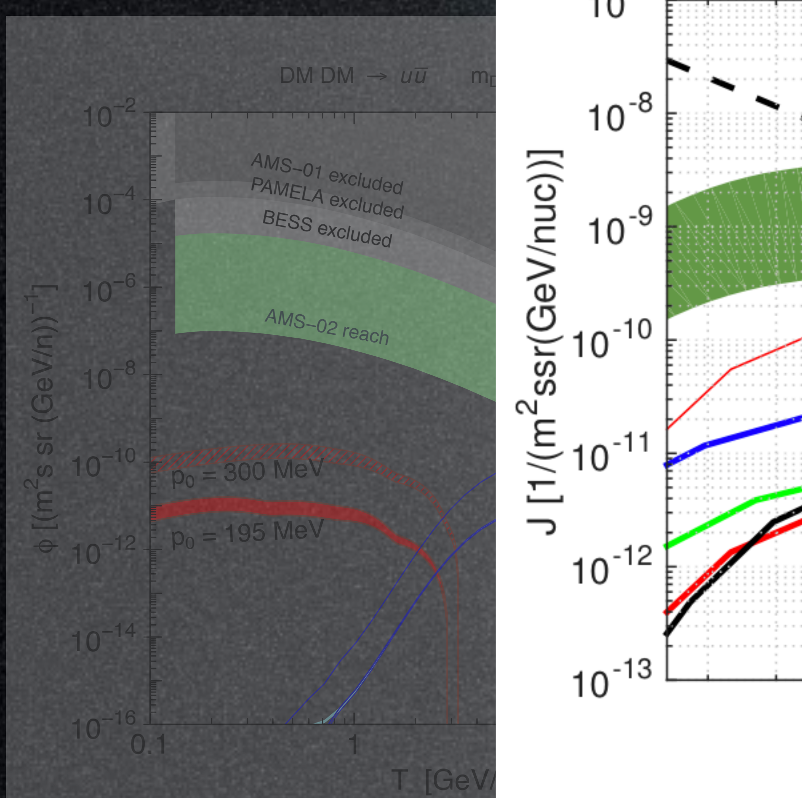
$\overline{He}$ from DM annihilations in halo

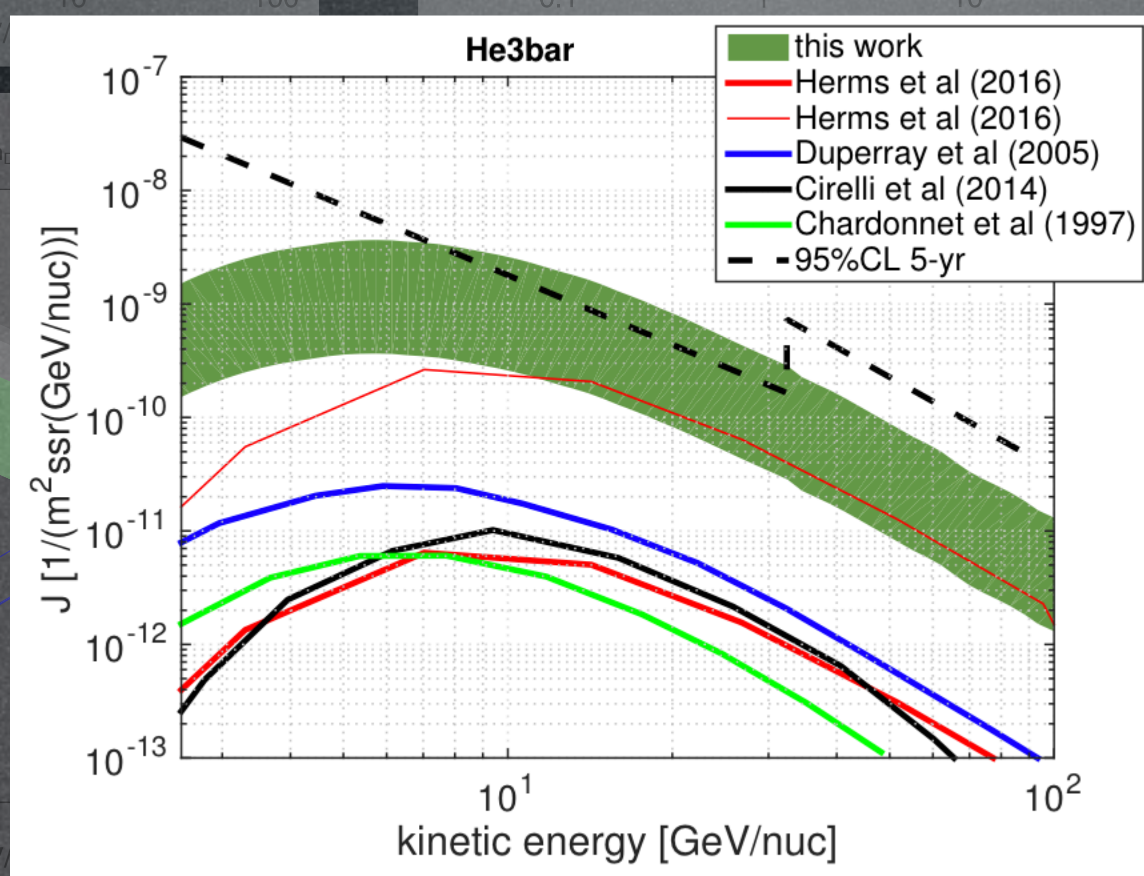


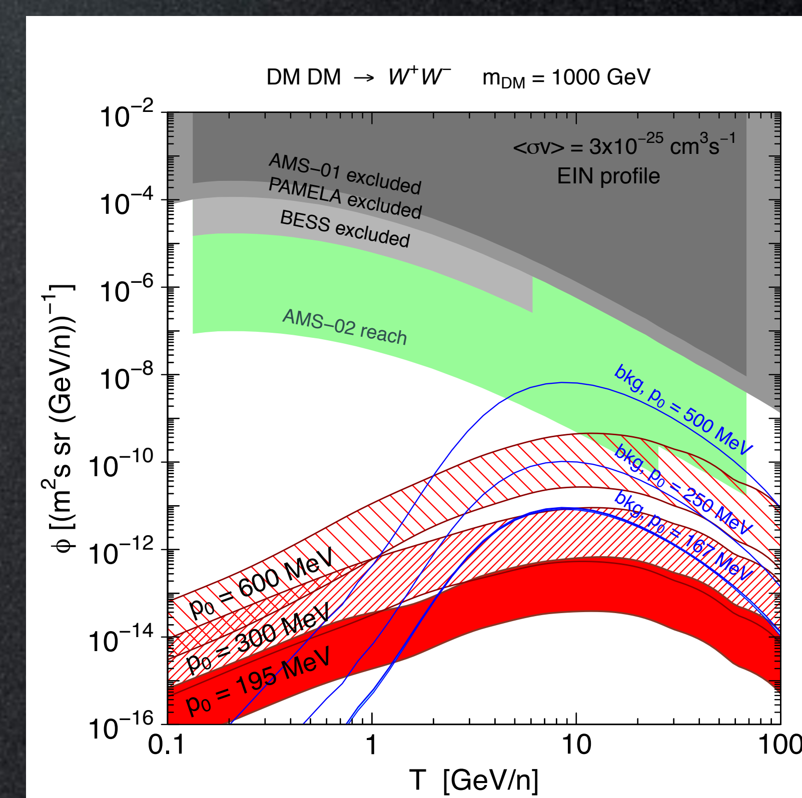




update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data

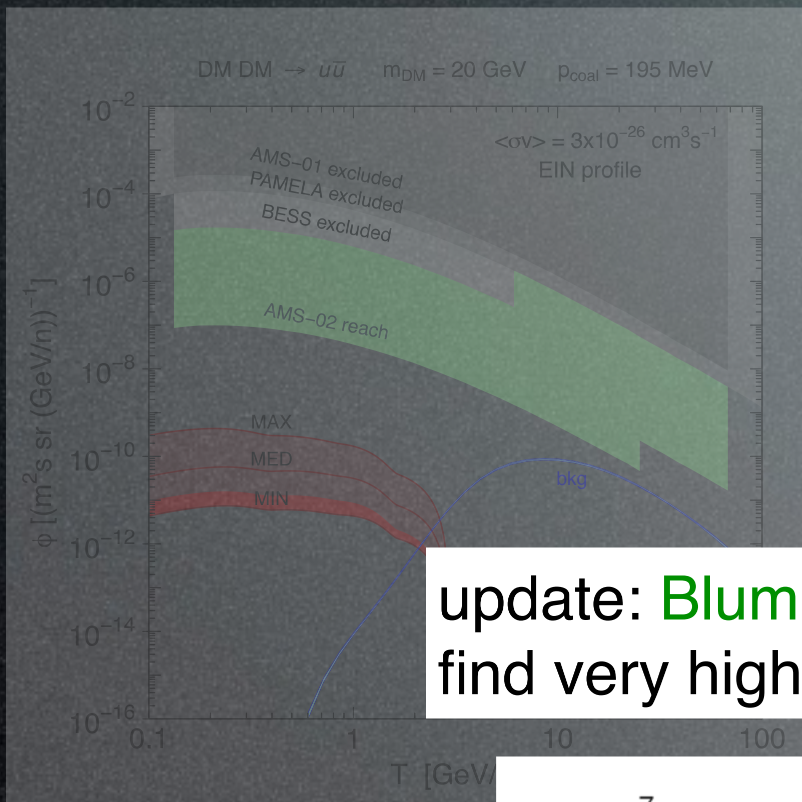
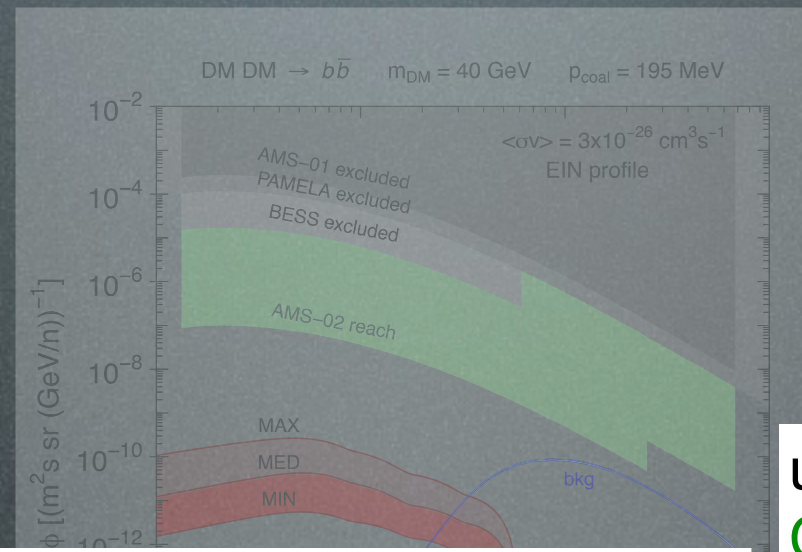
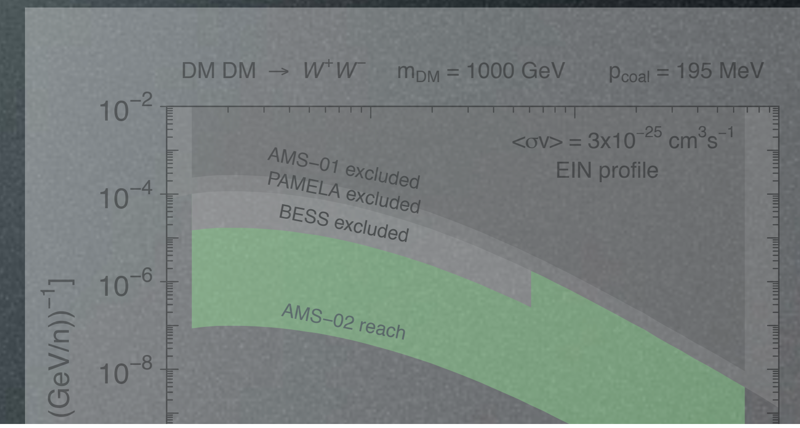
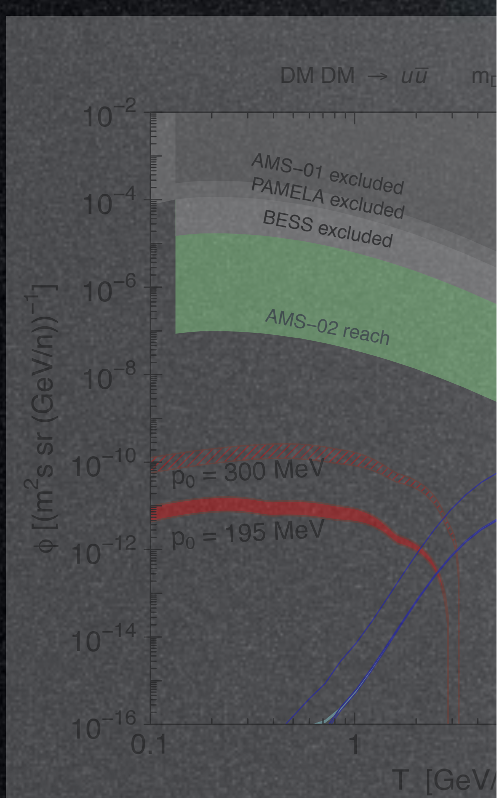






Indirect Detection

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

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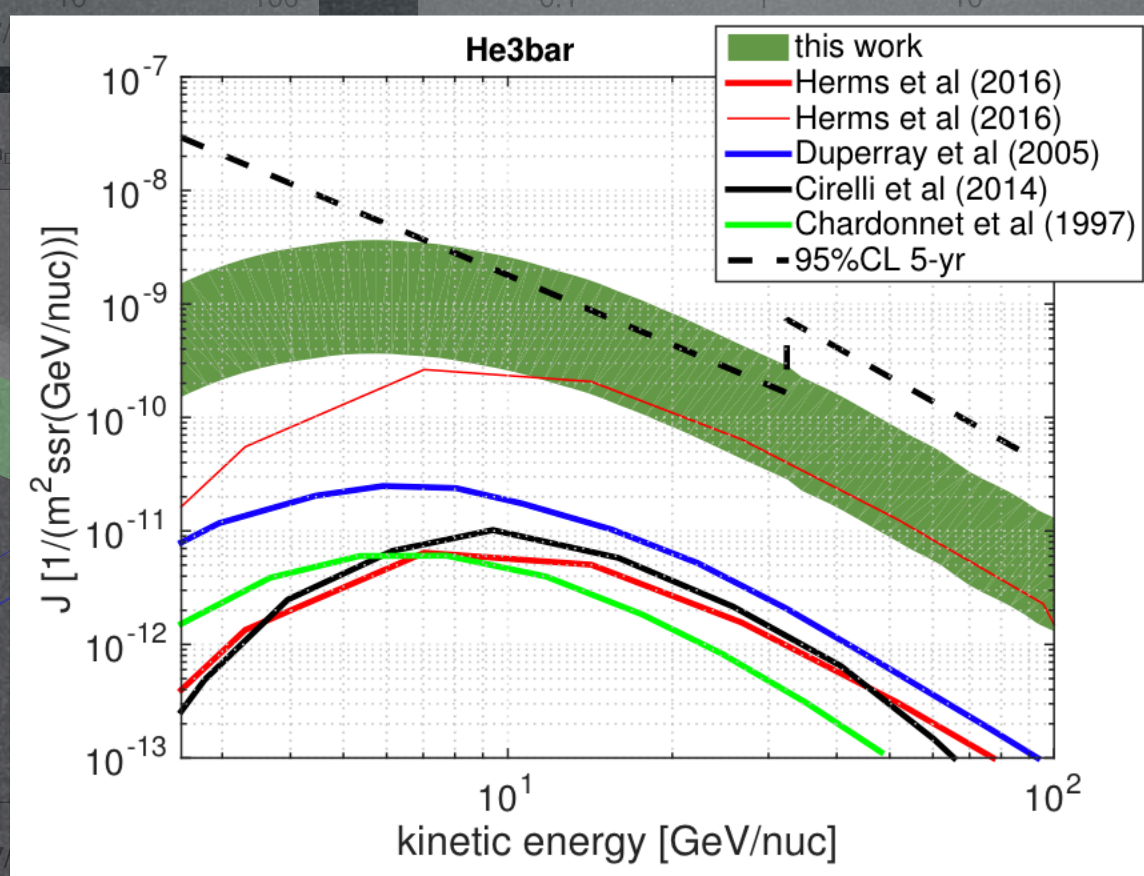

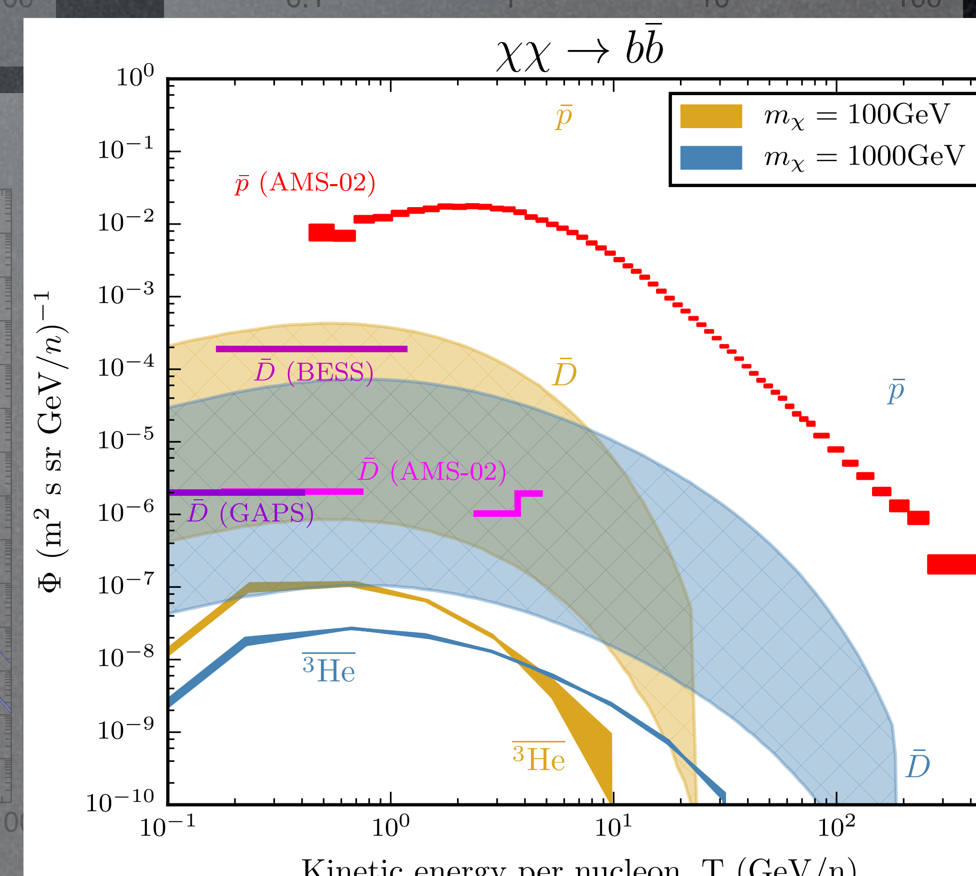

Indirect Detection

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

alternative: Poulin, Salati, Cholis, Kamionkowski, Silk (1808.08961)
anti-He from anti-clouds or anti-stars!
however: strong constraints from gamma-rays, CMB etc
need exotic (anti-)BBN to have right isotopic ratios…

update: Blum, Ng et al (1704.05431)
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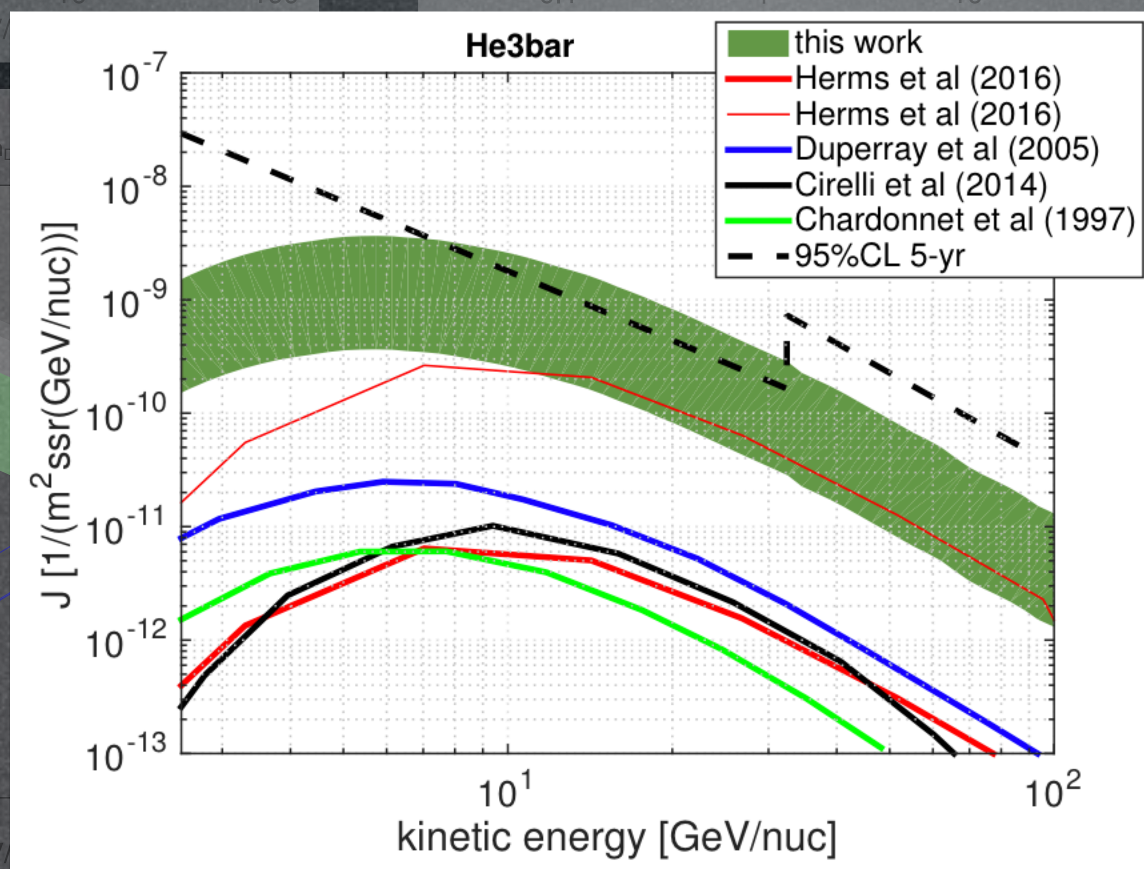

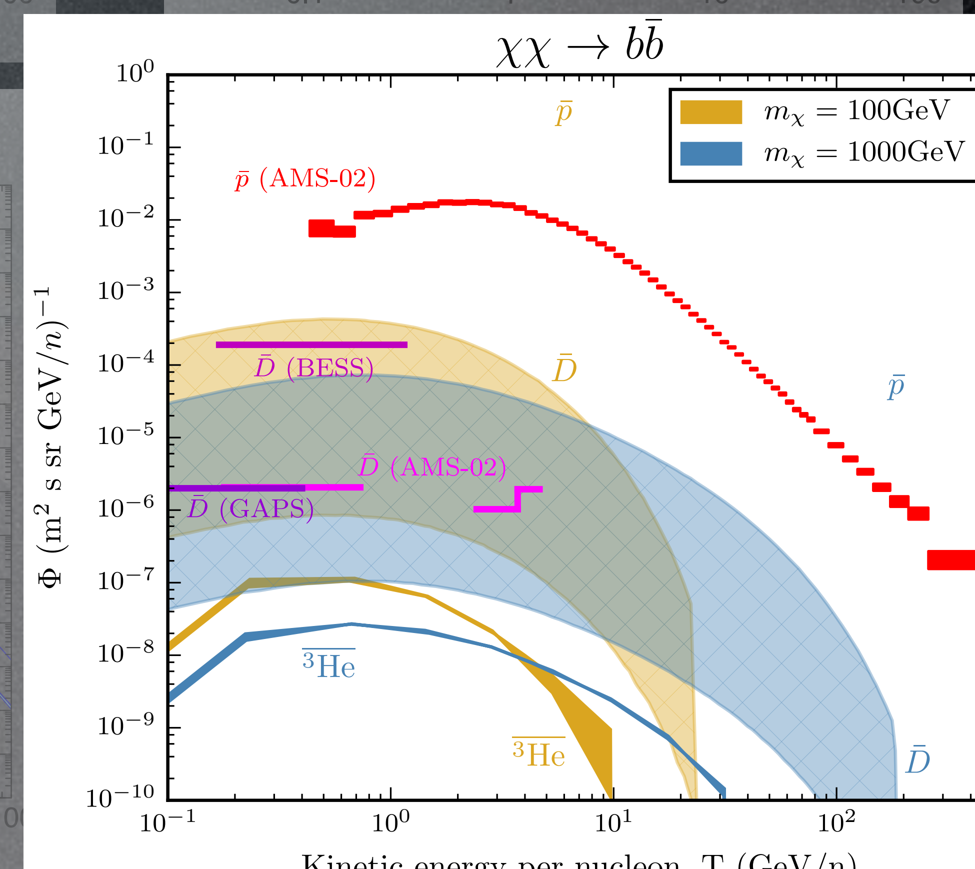

Conclusions

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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

Solution:

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Solution:

- multimessenger
- switch-off astrophysics