

24 September 2019
GGI conference - Next Frontiers in the Search for Dark Matter

Dark Matter Indirect Searches with charged cosmic rays

Marco Cirelli
(CNRS LPTHE Jussieu)



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Dark Matter Indirect Searches with charged cosmic rays

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DM detection

direct detection

production at colliders

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, Calet, Dampe, 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

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

AMS?

DM detection

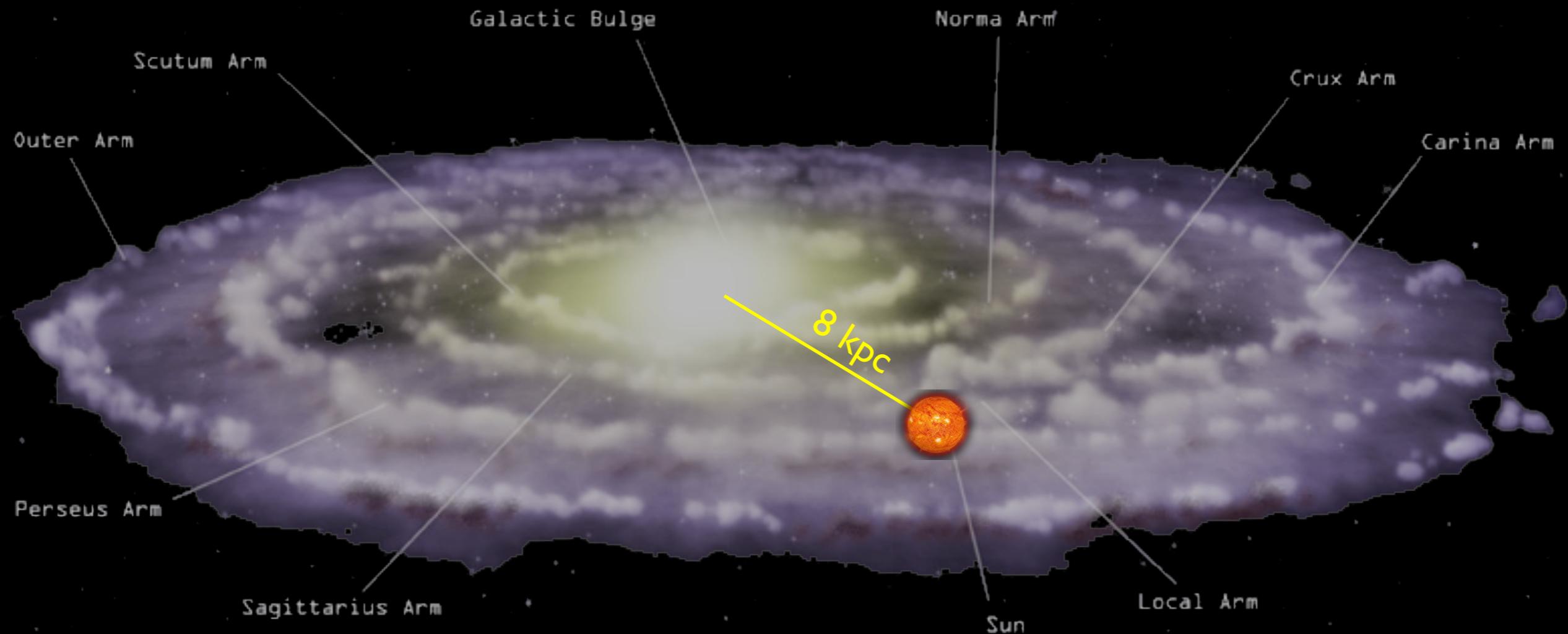
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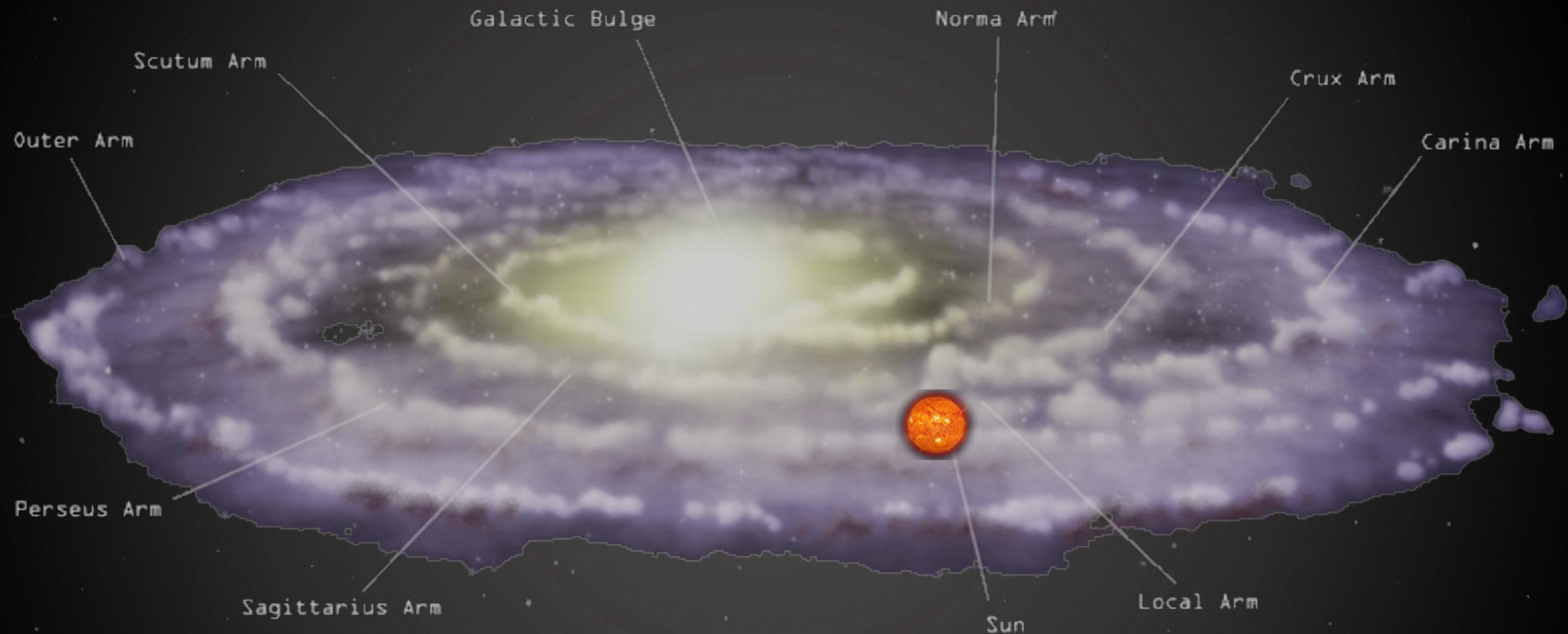
Indirect Detection: basics

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



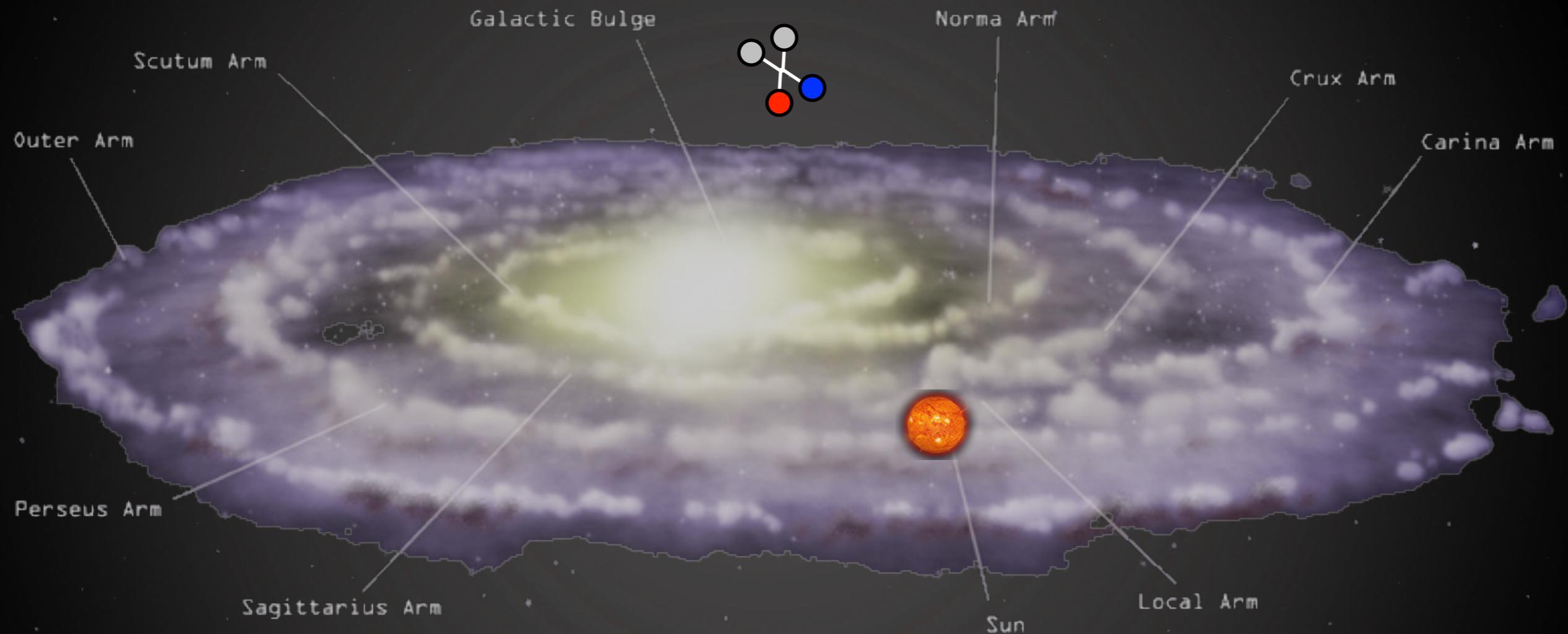
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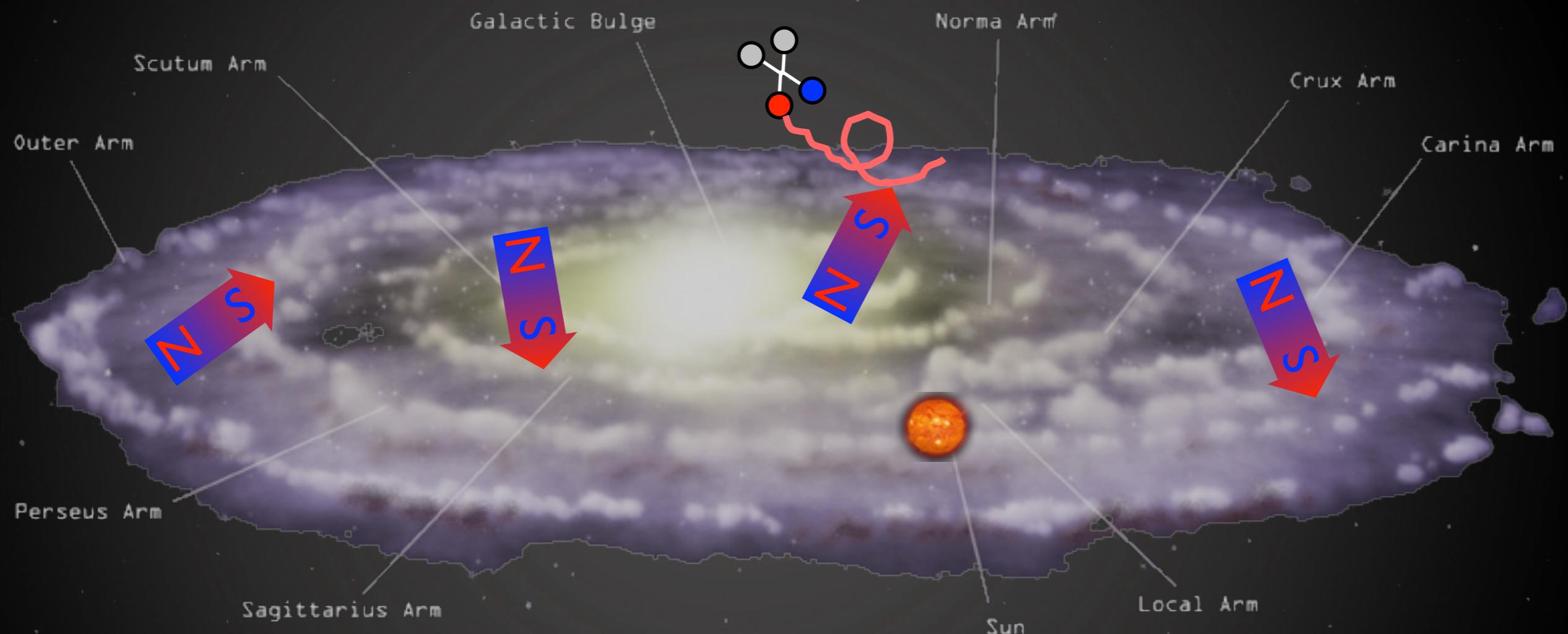
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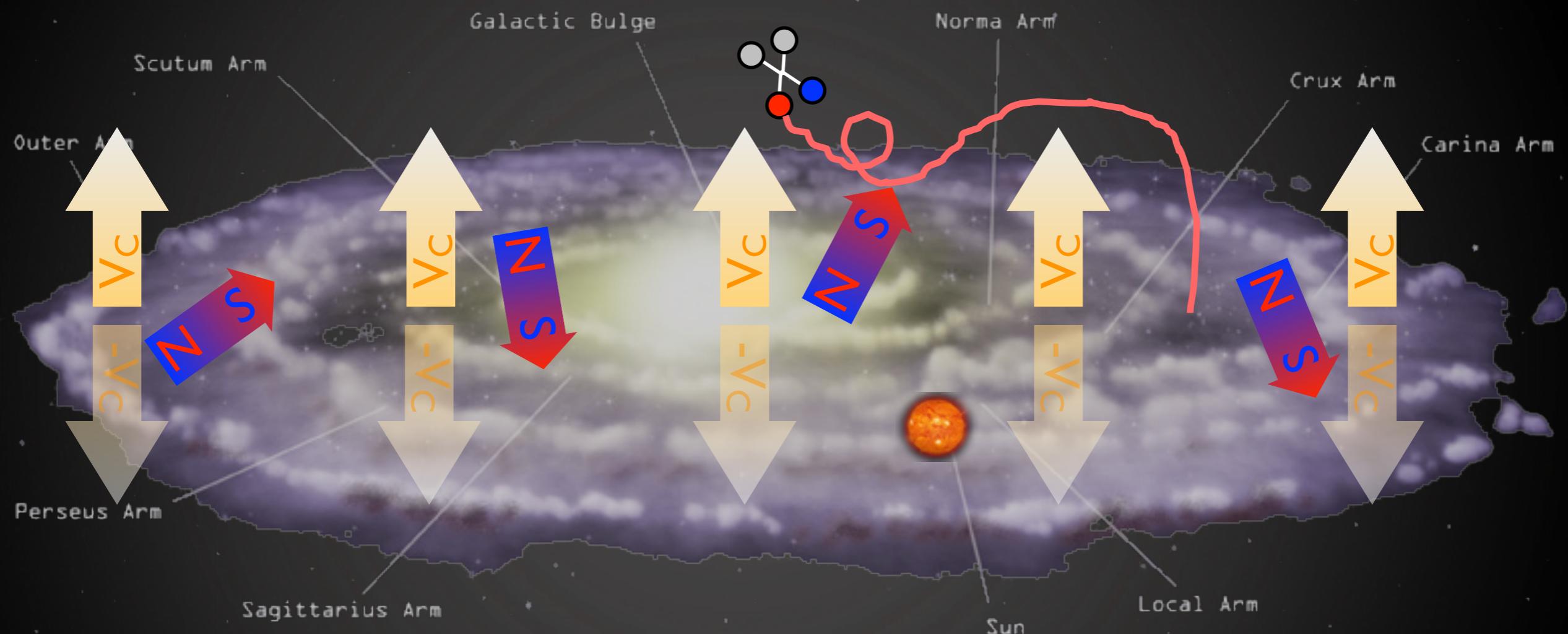
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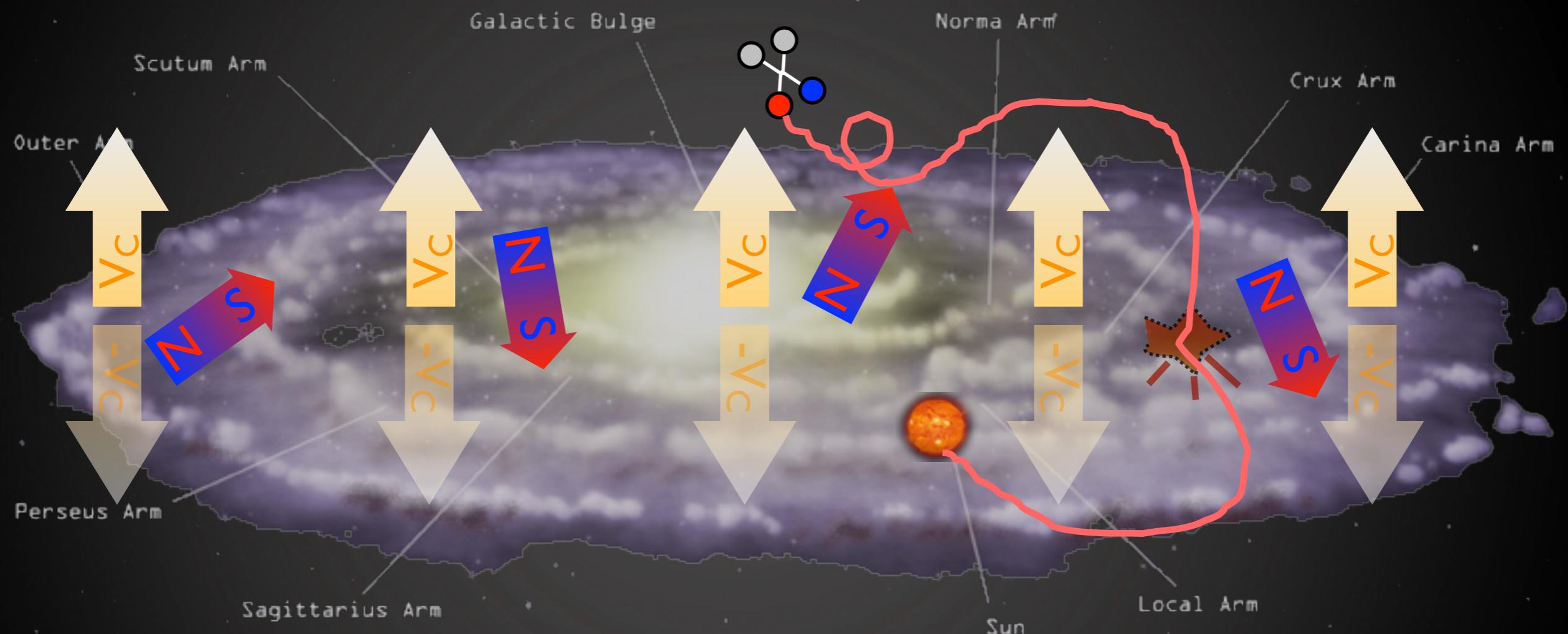
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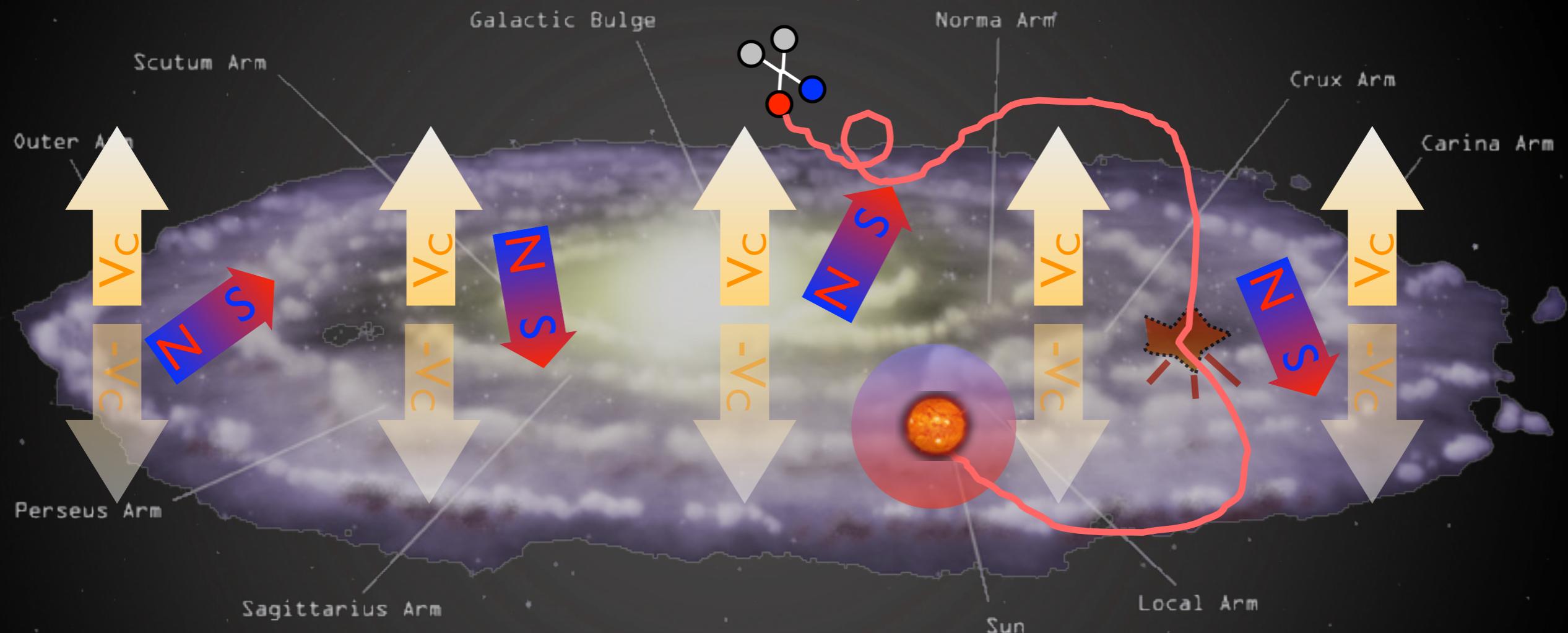
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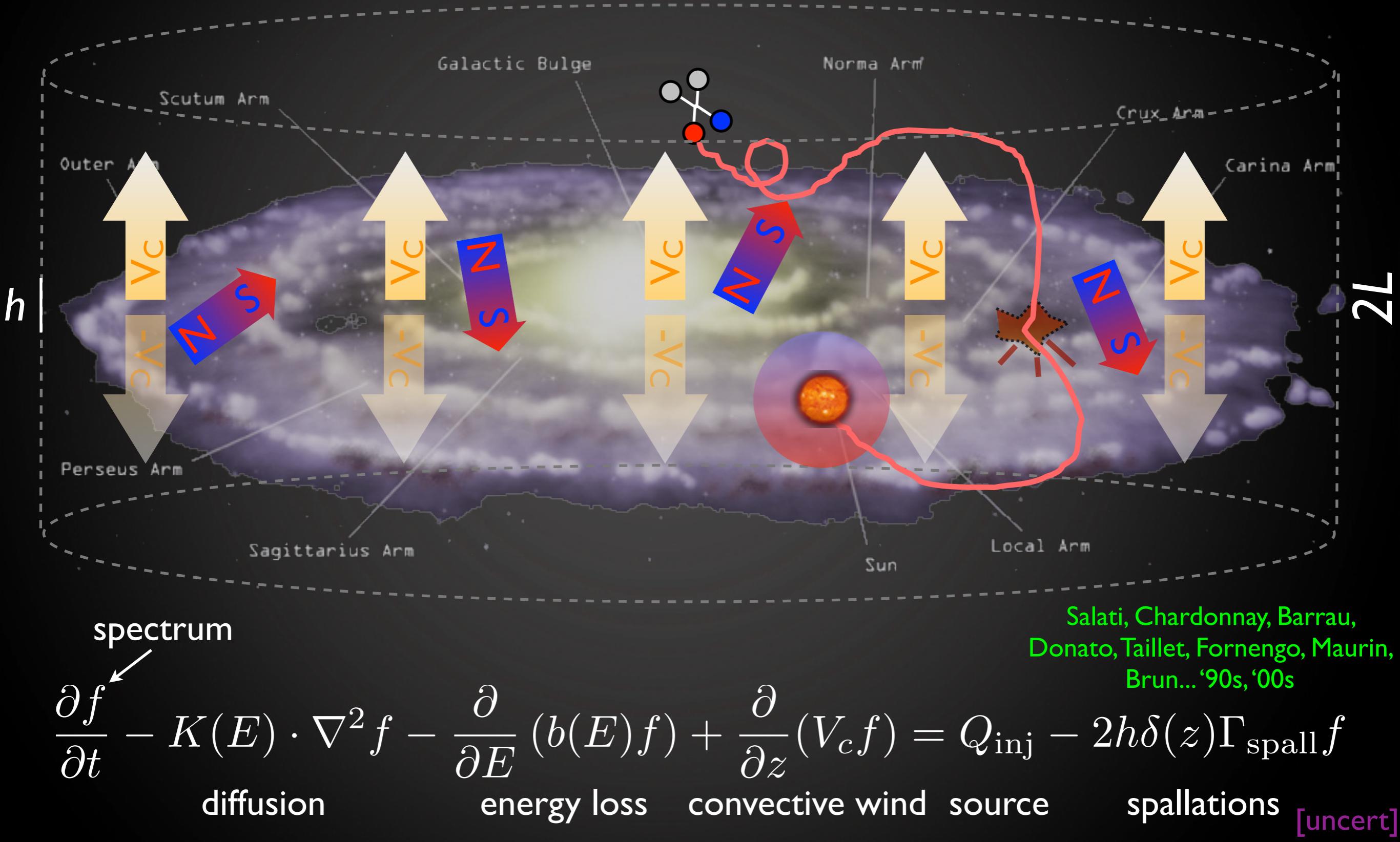
Indirect Detection: charged CRs

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Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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

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 [$10^{28} \text{ cm}^2 \text{ s}^{-1}$]	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
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 I407.2173
cfr. Evoli, Cholis, Grasso, Maccione, Ullio, I108.0664

Model	Electrons or positrons		Antiprotons (and antideuterons)			L [kpc]
	δ	\mathcal{K}_0 [kpc ² /Myr]	δ	\mathcal{K}_0 [kpc ² /Myr]	V_{conv} [km/s]	
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

Indirect Detection: charged CRs

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

thickness

diffusion

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dv_c/dz [$\text{km s}^{-1} \text{ kpc}^{-1}$]	0
ϕ_F^p [GV]	0.650
χ^2_{\min}/dof (p in [25])	0.462

Parameters	BIG	SLIM	QUAINT
χ^2/dof	61.7/61 = 1.01	61.8/63 = 0.98	62.1/62 = 1.00
Intermediate-rigidity parameters			
K_{10} [kpc 2 Myr $^{-1}$]	$0.30^{+0.03}_{-0.04}$	$0.28^{+0.02}_{-0.02}$	$0.33^{+0.03}_{-0.06}$
δ	$0.48^{+0.04}_{-0.03}$	$0.51^{+0.02}_{-0.02}$	$0.45^{+0.05}_{-0.02}$
Low-rigidity parameters			
V_c [km s^{-1}]	$0^{+7.4}$	N/A	0.0^{+8}
V_A [km s^{-1}]	67^{+24}_{-67}	N/A	101^{+14}_{-15}
η	1 (fixed)	1 (fixed)	$-0.09^{+0.35}_{-0.57}$
δ_l	$-0.69^{+0.61}_{-1.26}$	$-0.87^{+0.33}_{-0.31}$	N/A
R_l [GV]	$3.4^{+1.1}_{-0.9}$	$4.4^{+0.2}_{-0.2}$	N/A
High-rigidity break parameters (nuisance parameters)			
Δ_h	0.18	0.19	0.17
R_h [GV]	247	237	270
s_h	0.04	0.04	0.04
Model	Electrons or positrons	Antiprotons	
	δ	δ	
MIN	0.55	0.00595	0.85
MED	0.70	0.0112	0.70
MAX	0.46	0.0765	0.46
	\mathcal{K}_0 [kpc 2 /Myr]		
			more recent: Génolini et al. 1904.08917

Antiprotons

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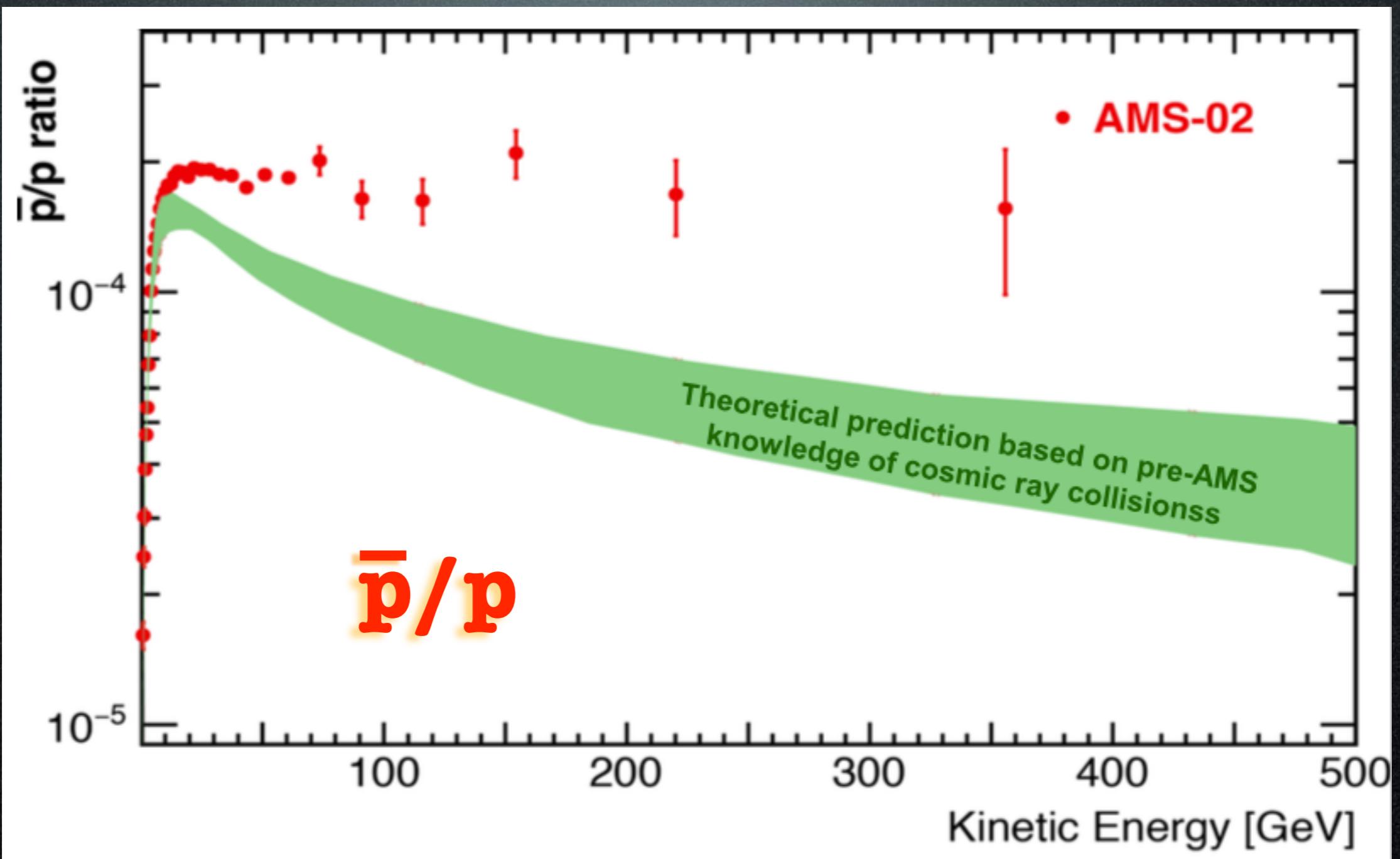
SK, Icecube, Km3Net

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

AMS?

Data: antiprotons

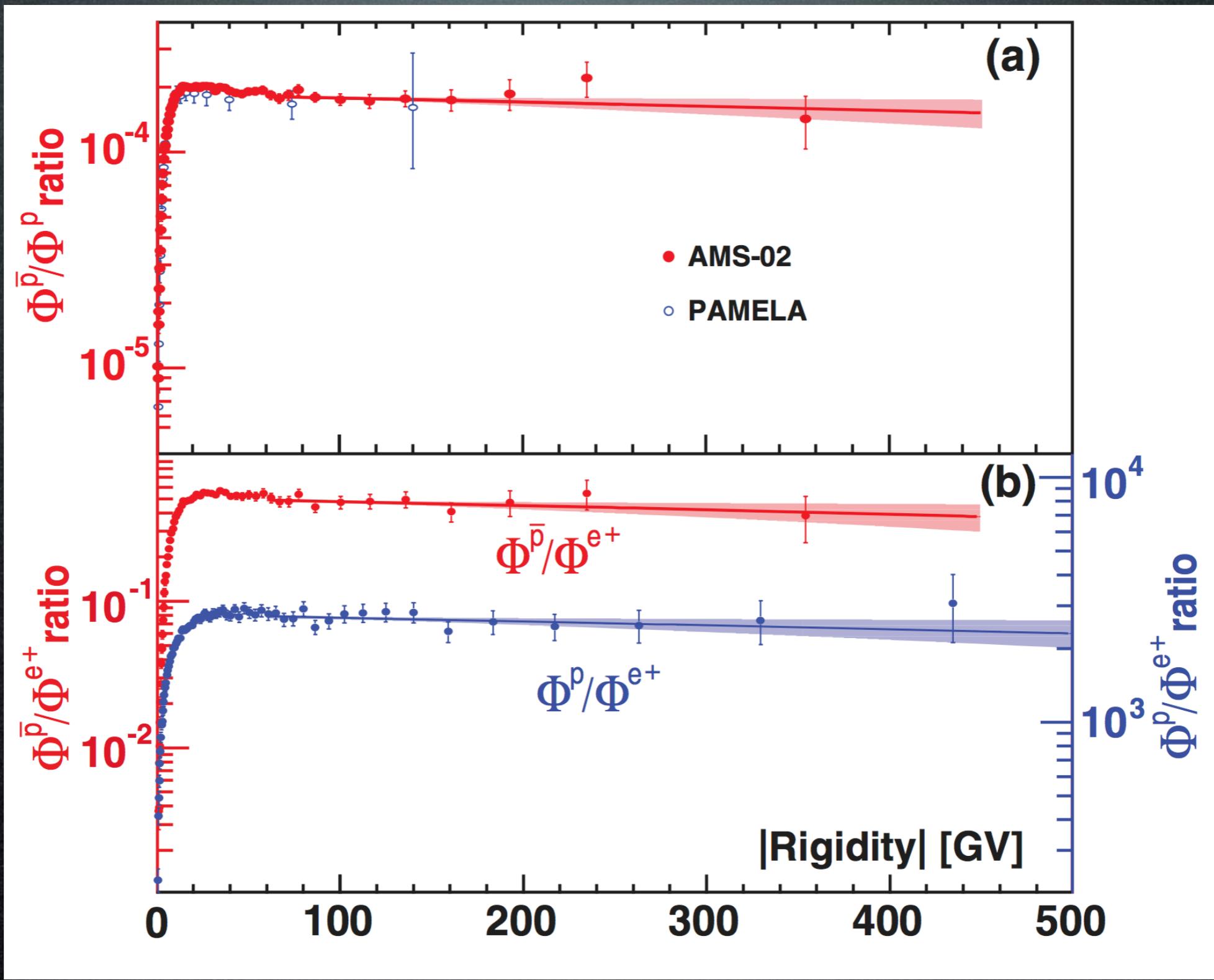
AMS-02



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

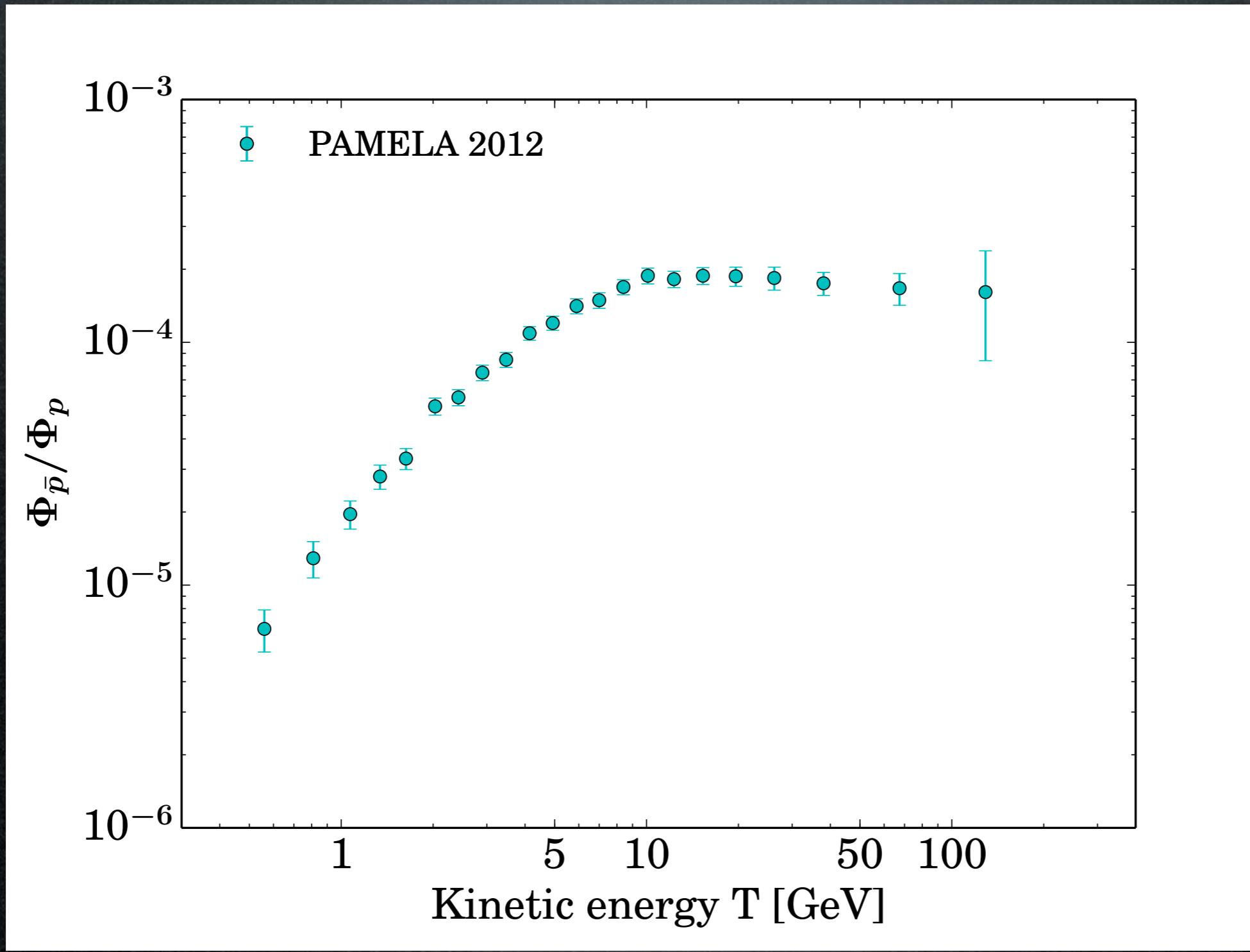
Data: antiprotons

AMS-02



Antiprotons

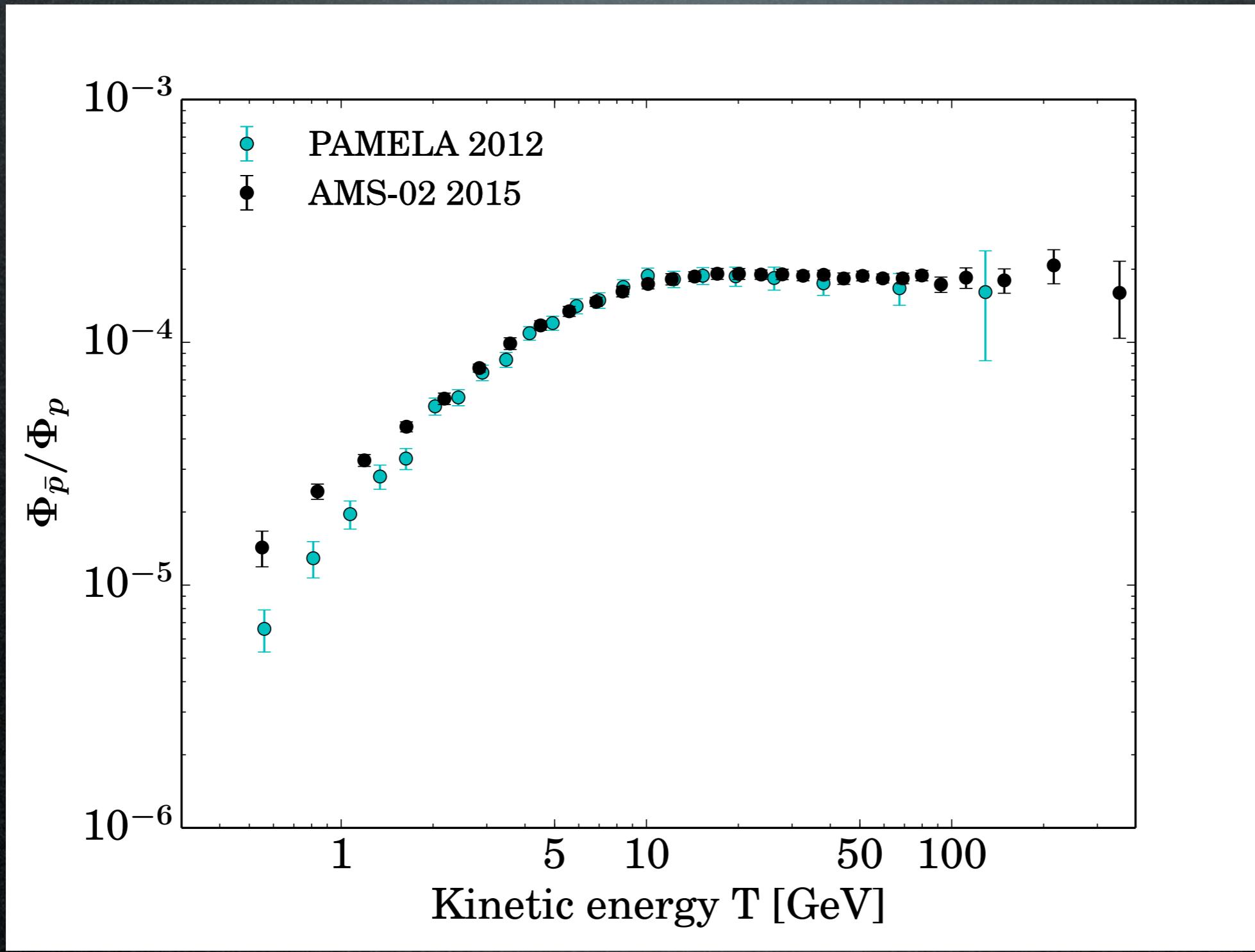
Antiproton data vis-à-vis the secondaries:



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

Antiprotons

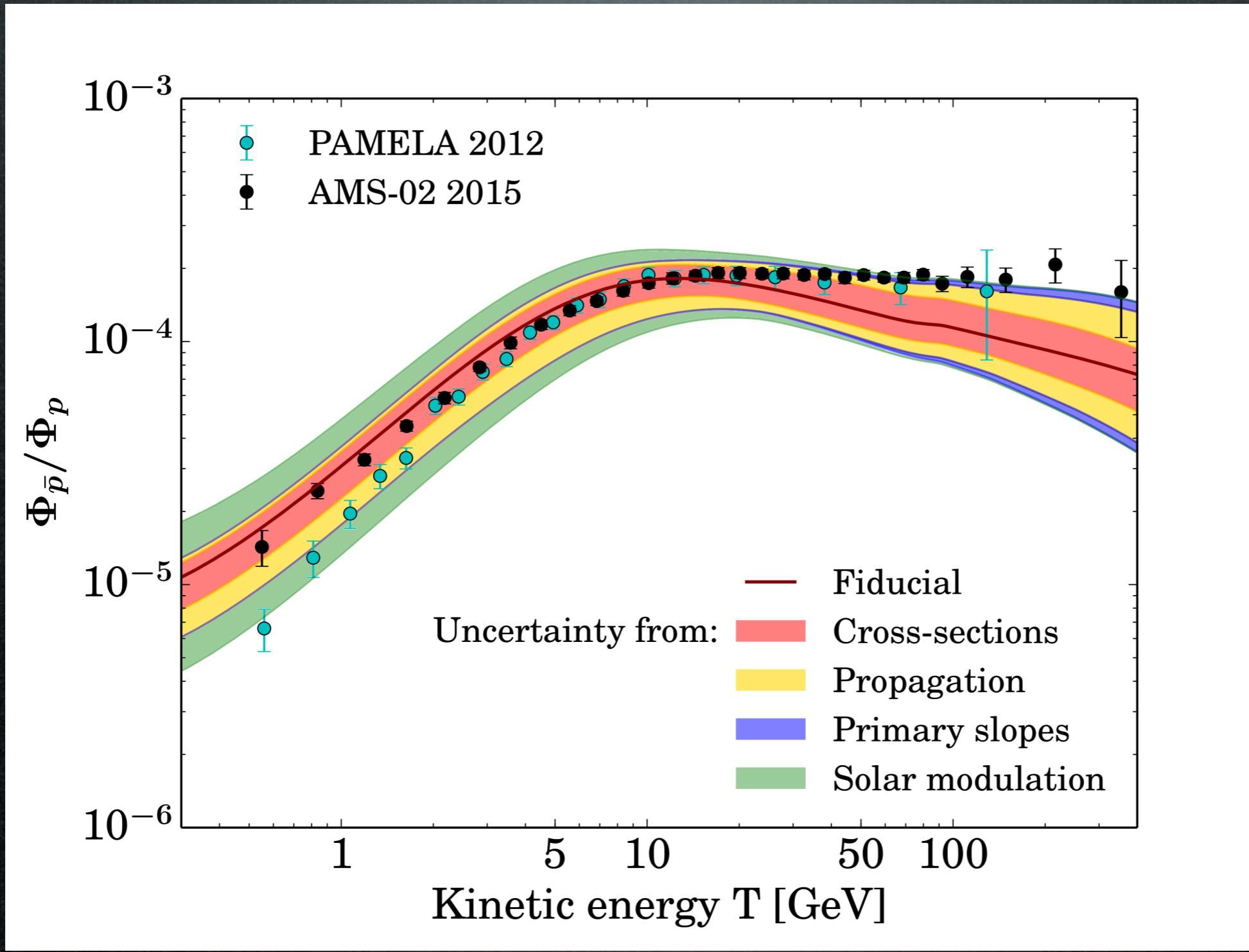
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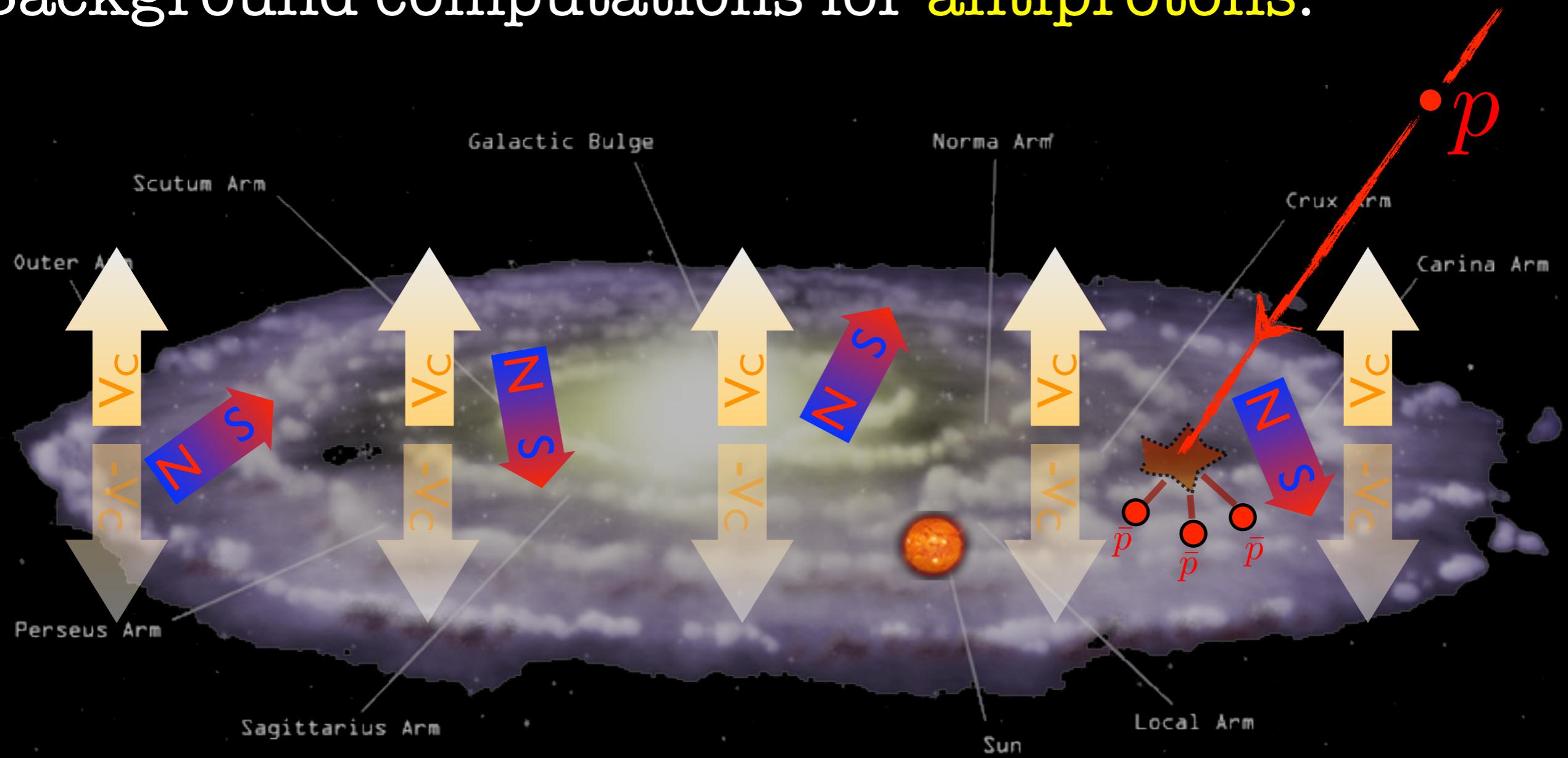
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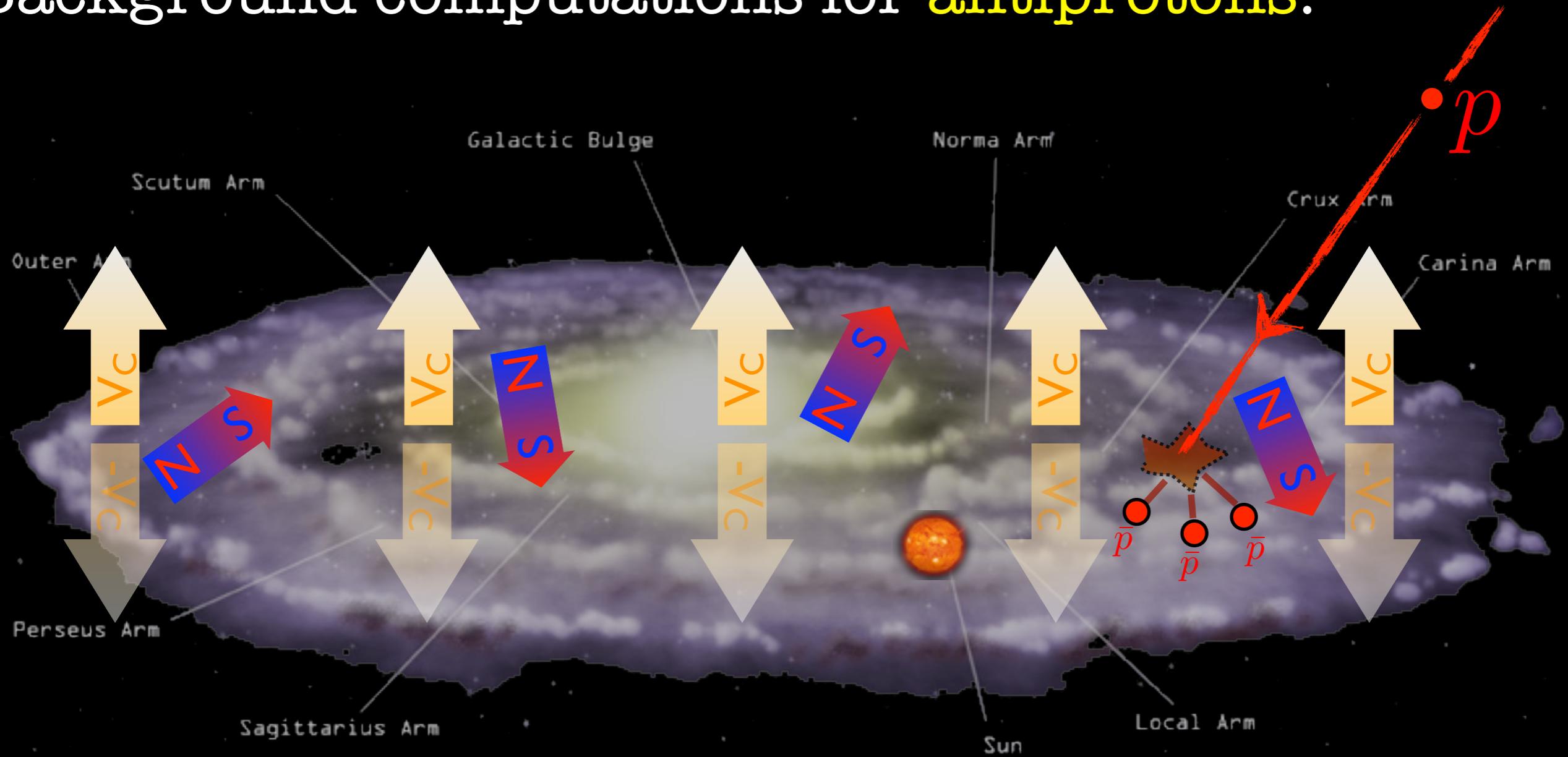
Indirect Detection

Background computations for antiprotons:



Indirect Detection

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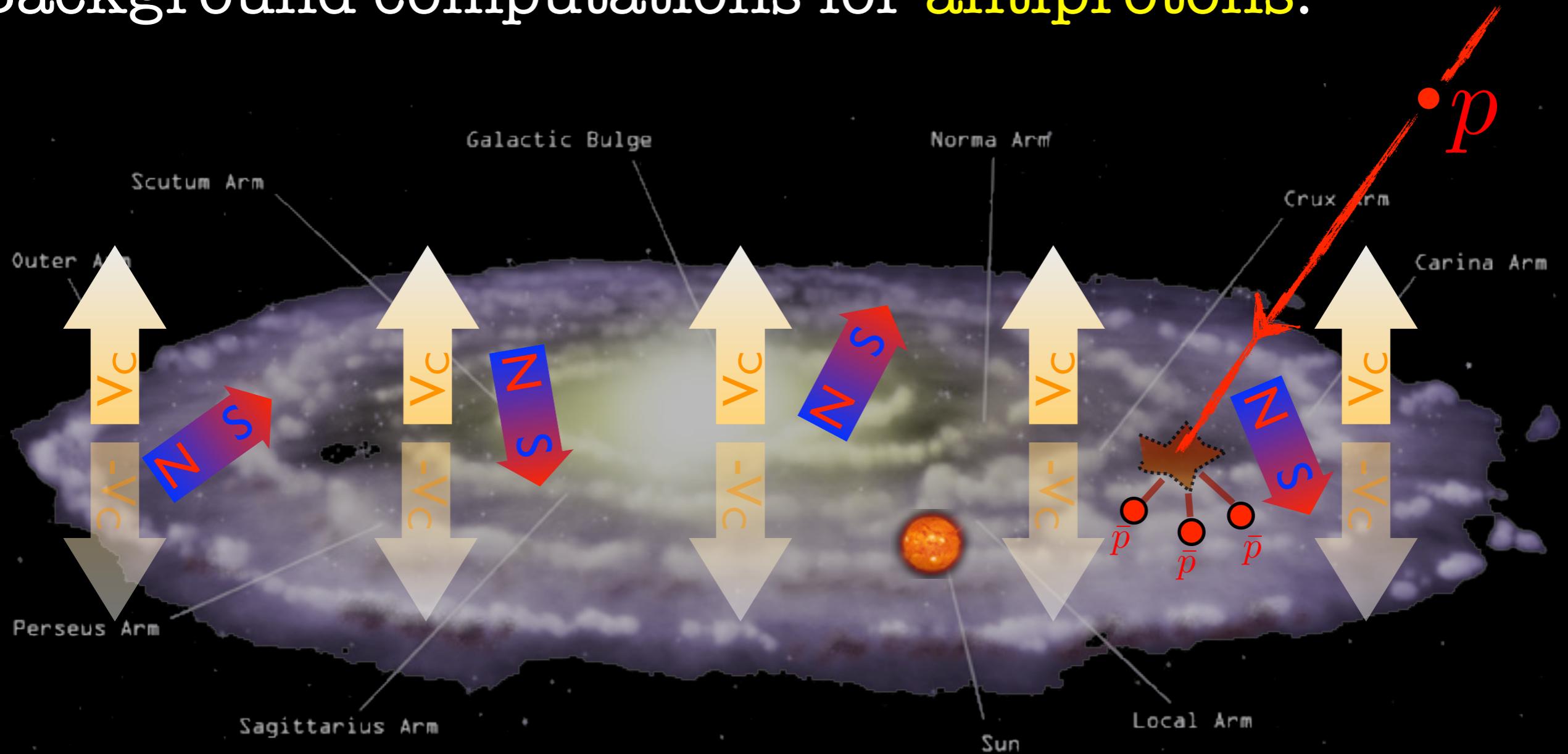


Main ingredients:

- 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

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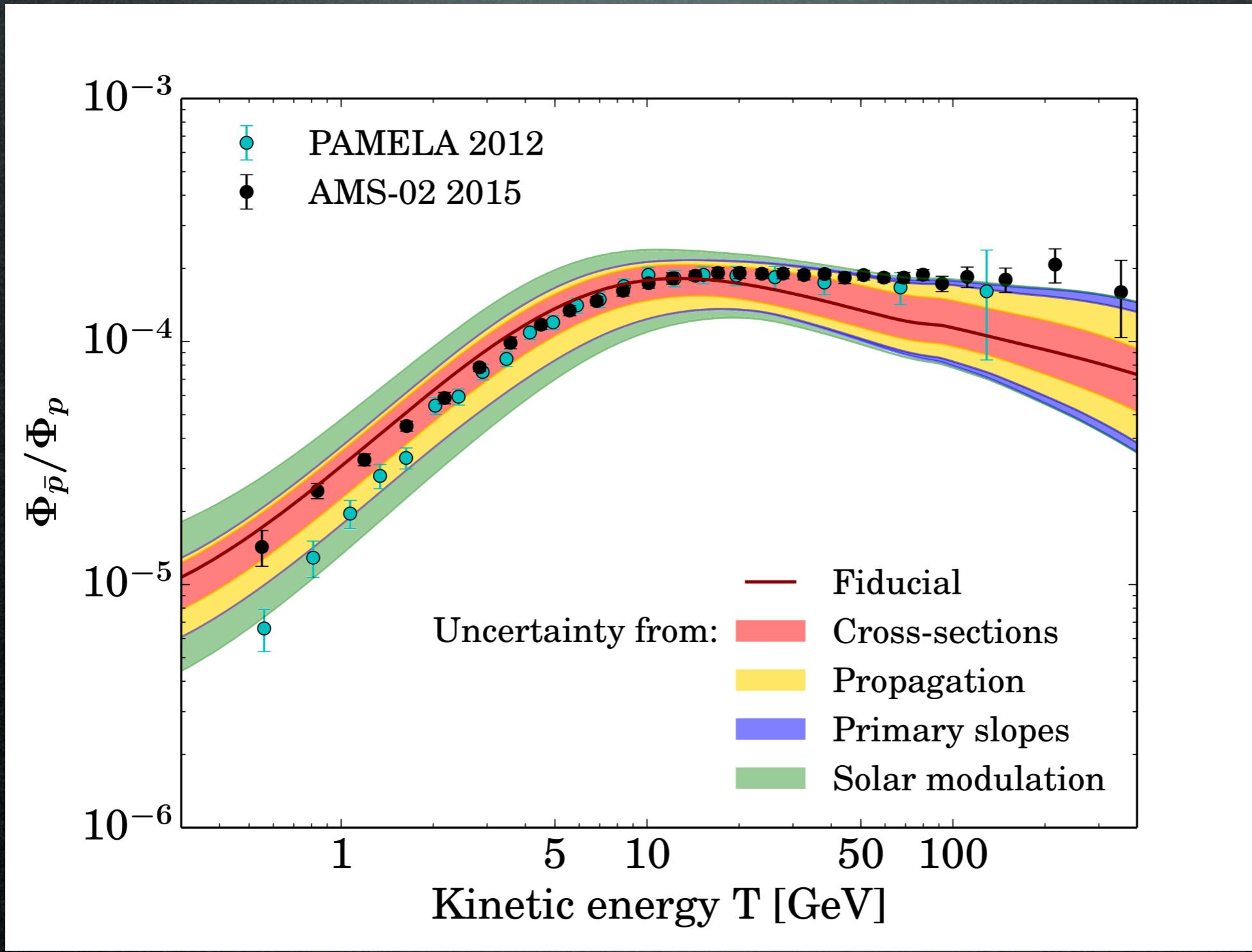


Main ingredients:

- primary p (and He) **New!**
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Antiprotons

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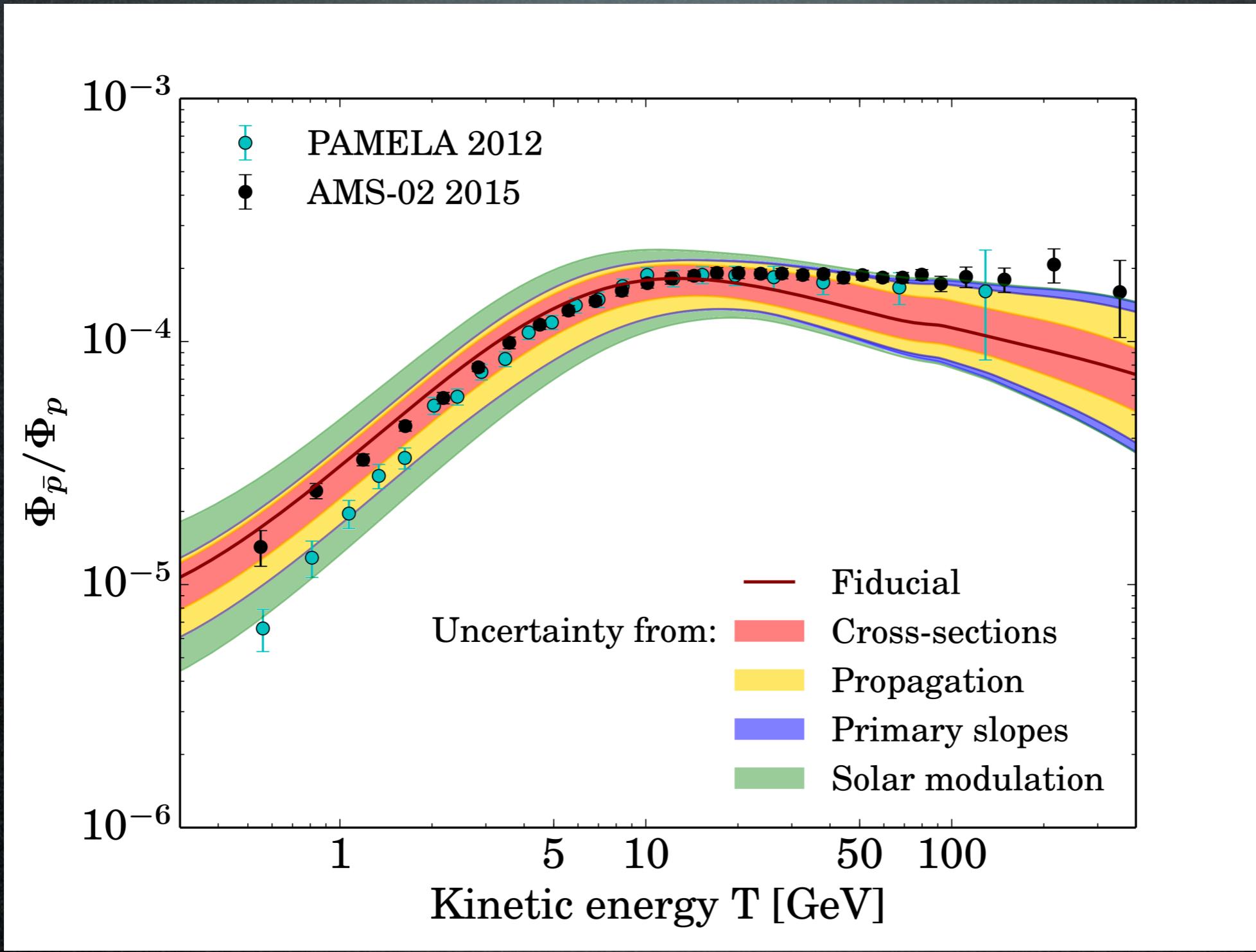


No
evident
excess

Giesen, Boudaud,
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Antiprotons

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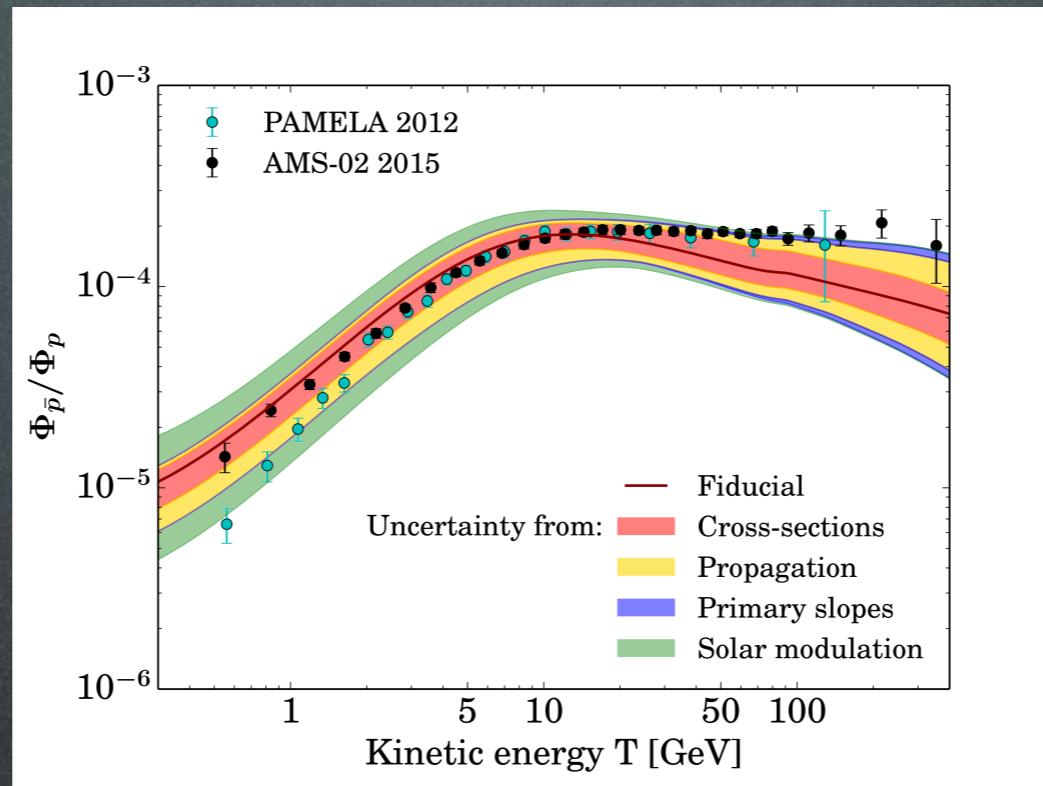
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Some
preference
for flatness

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Antiprotons

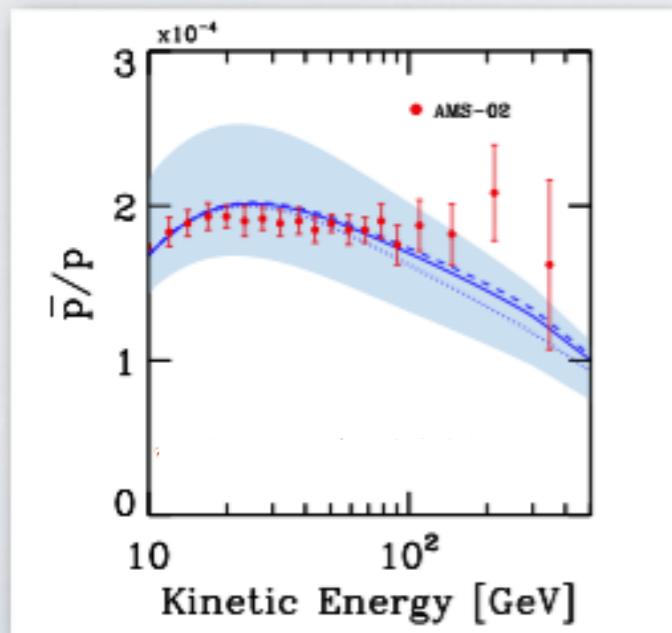
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using
 p , He by AMS-02,
B/C by PAMELA

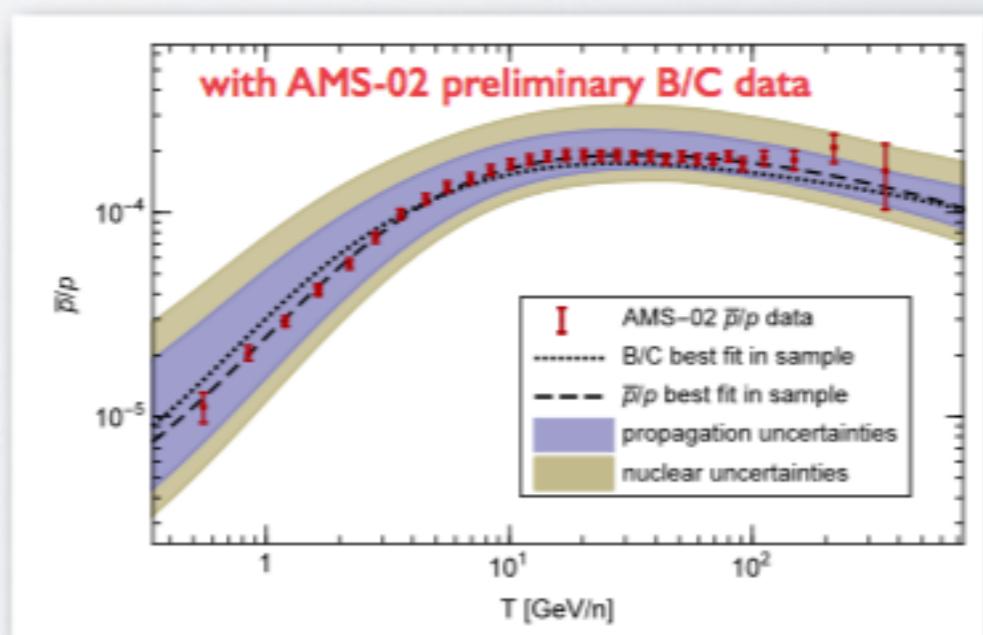
C. Evoli, D. Gaggero and D. Grasso, arXiv:1504.05175



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

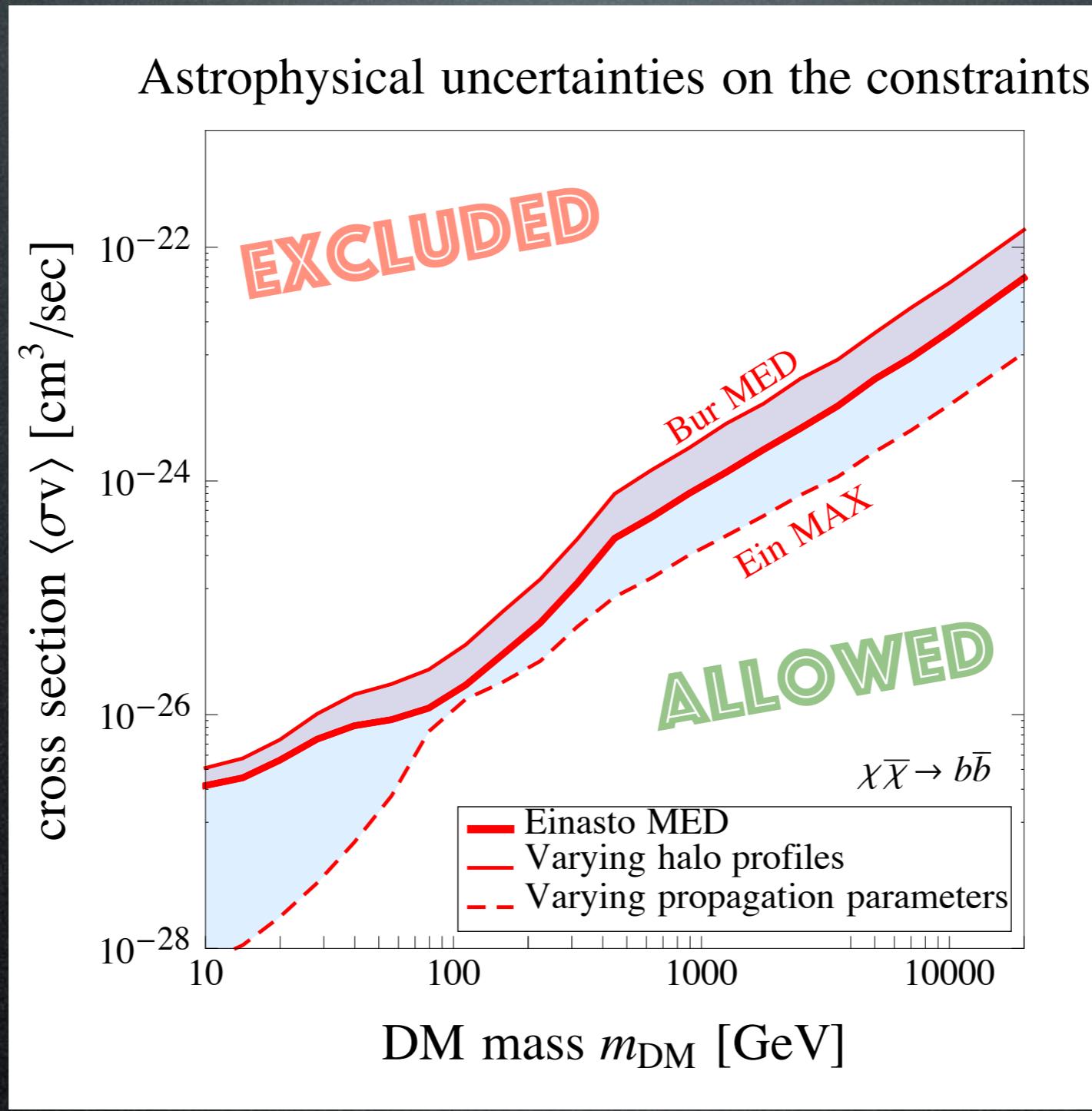
using
 p , He by AMS-02 and CREAM,
B/C by AMS-02,
heavier nuclei by compilation

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



Dark Matter interpretation

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

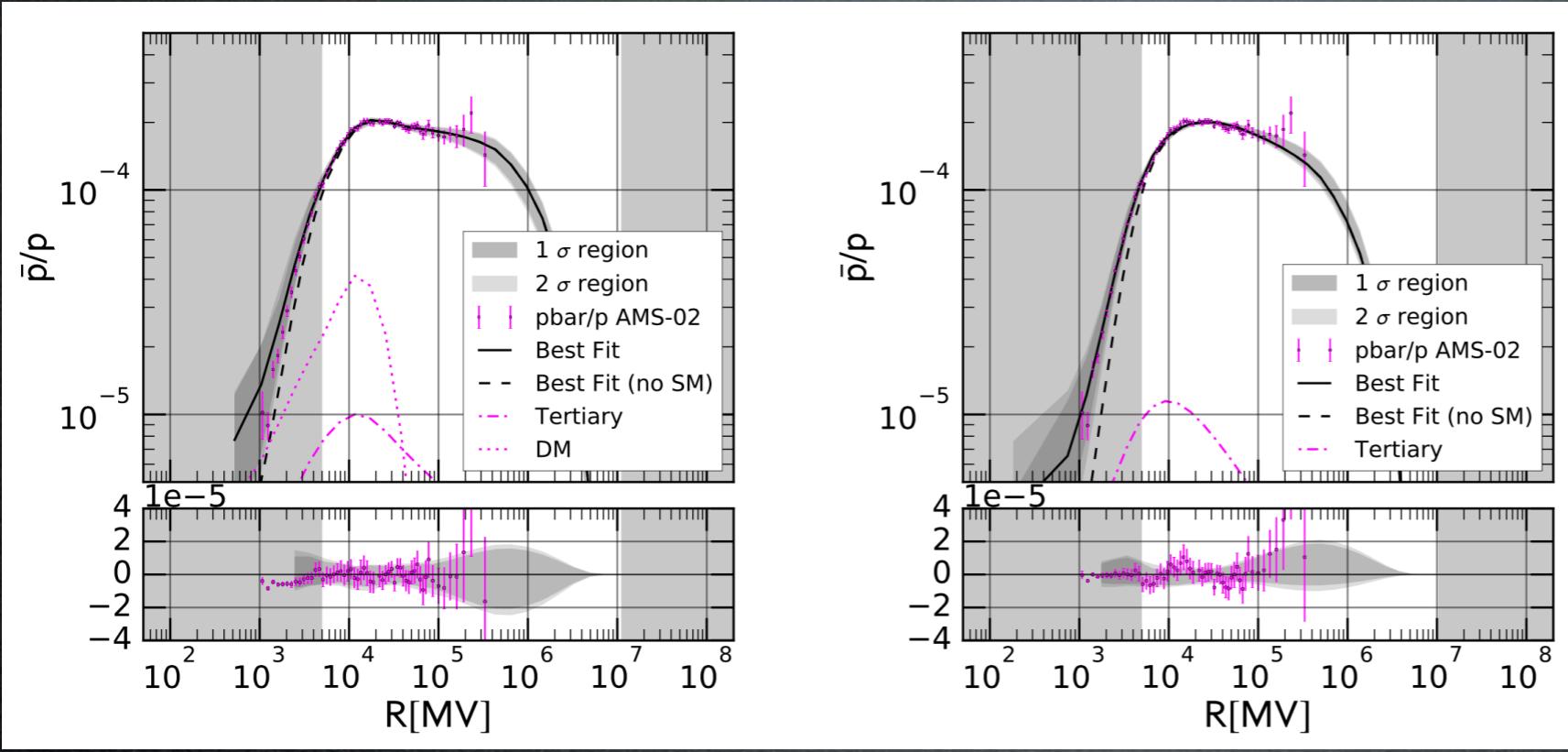


Giesen, Boudaud,
Génolini, Poulin,
Cirelli, Salati,
Serpico
1504.04276

Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071

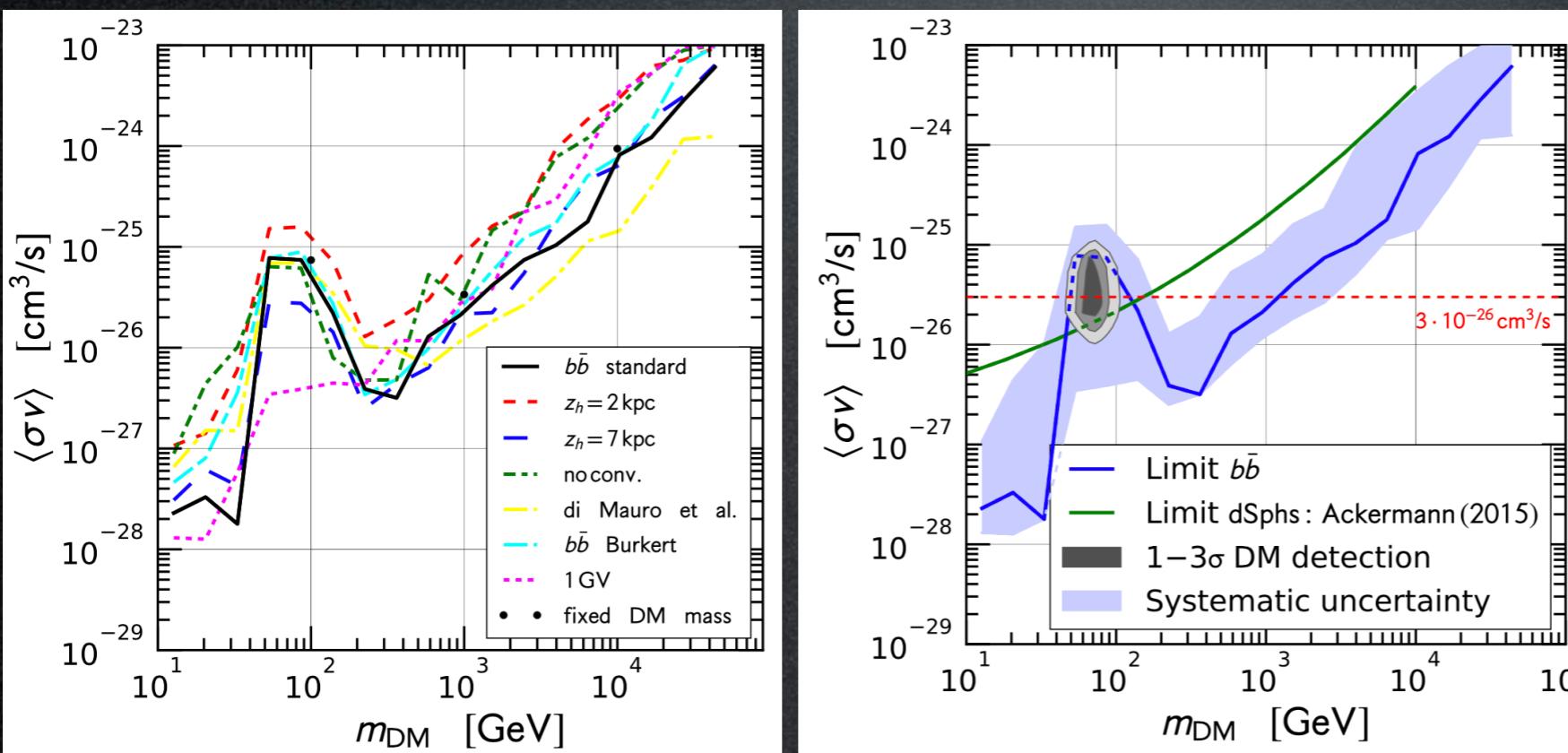


finds a **possible excess**
(formally $\sim 4.5\sigma$)

$m_{DM} = 80$ 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)



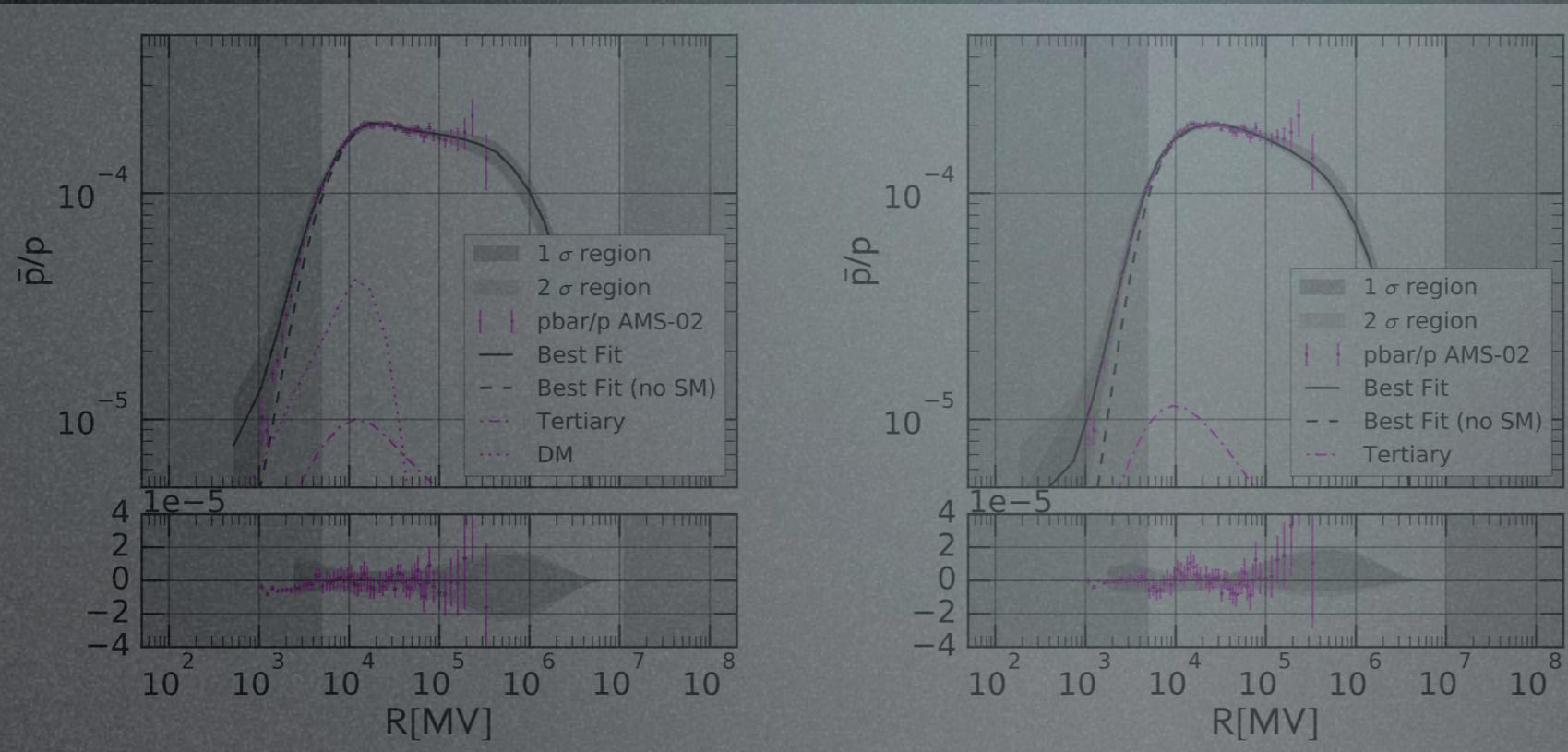
reiterated:

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

Antiprotons

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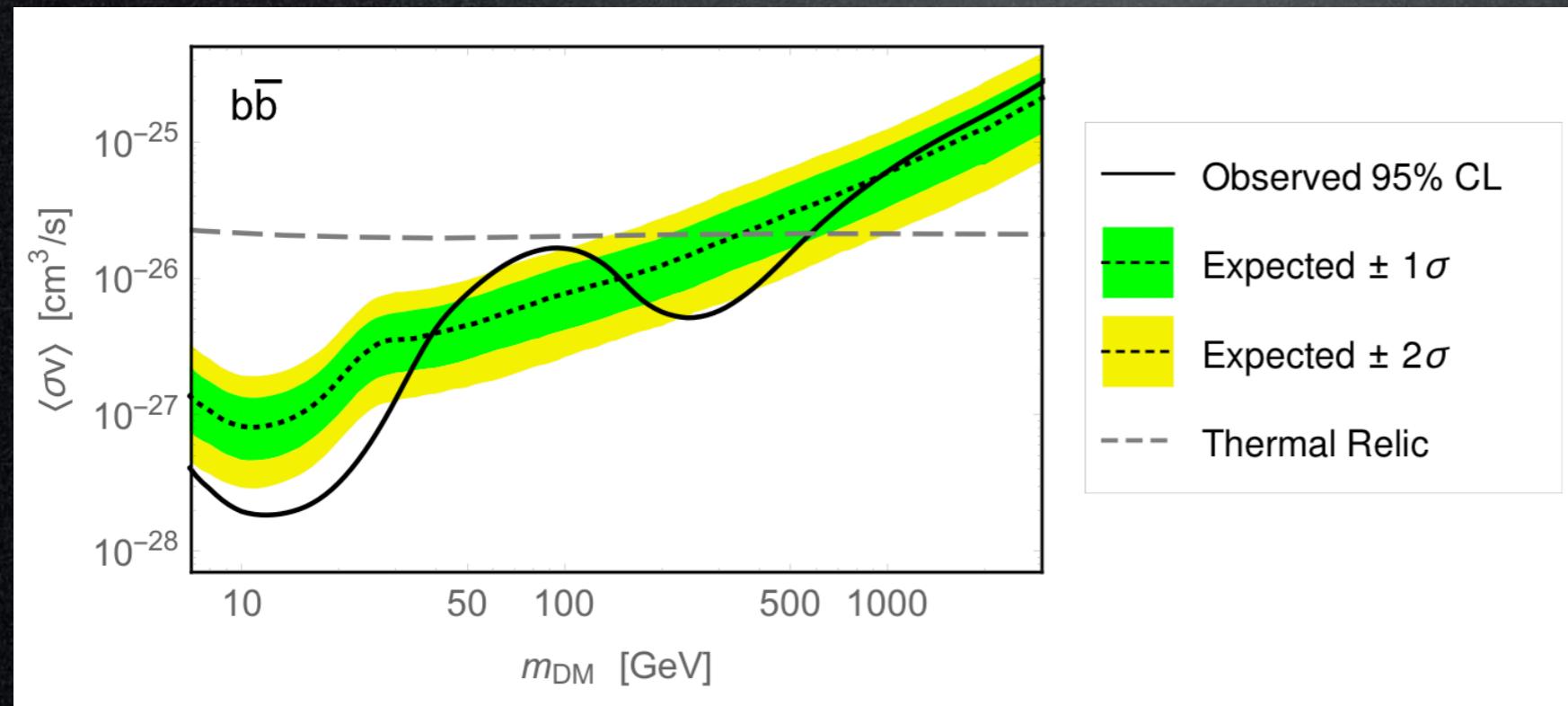


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Reinert, Winkler 1712.00002

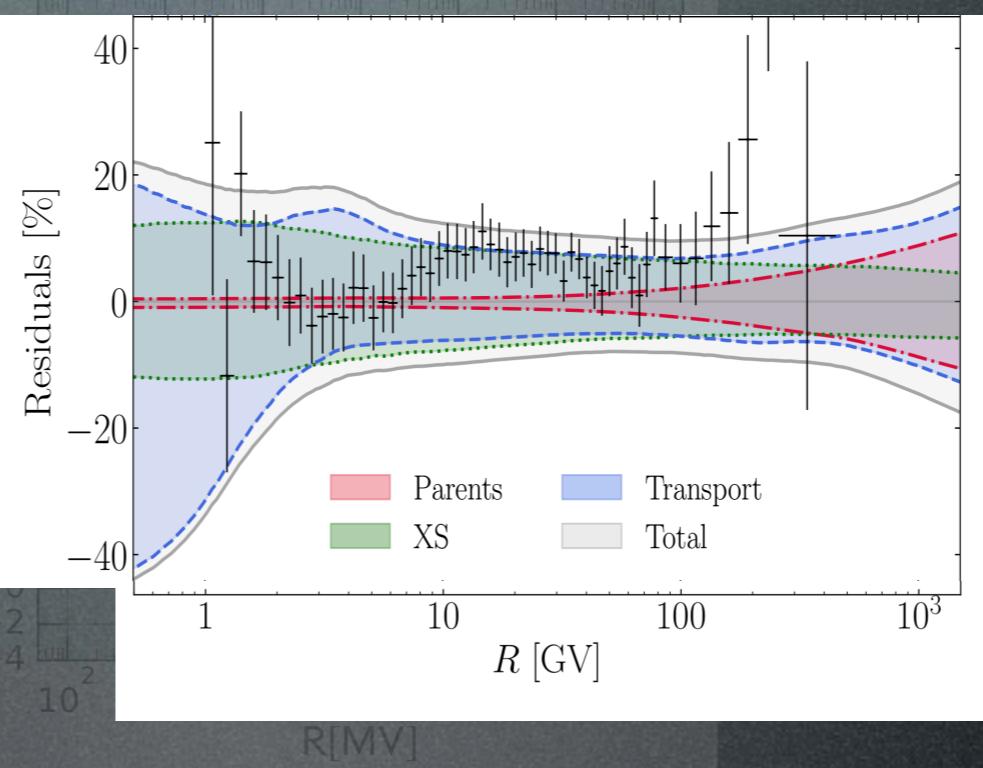
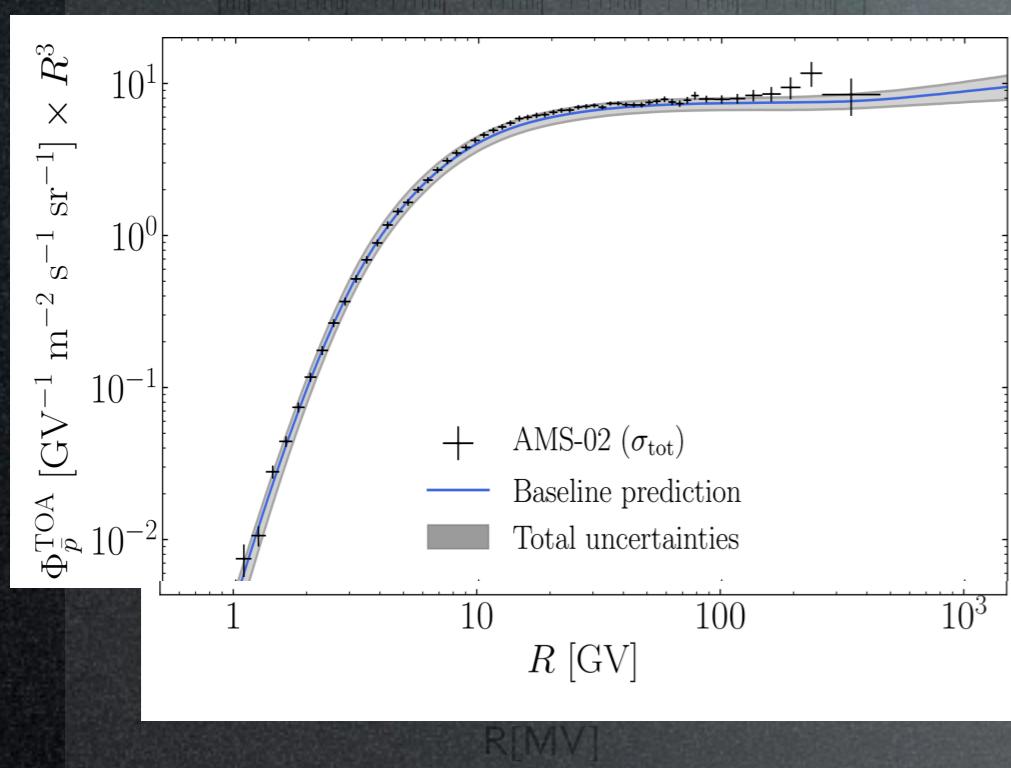
excess exists

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

Antiprotons

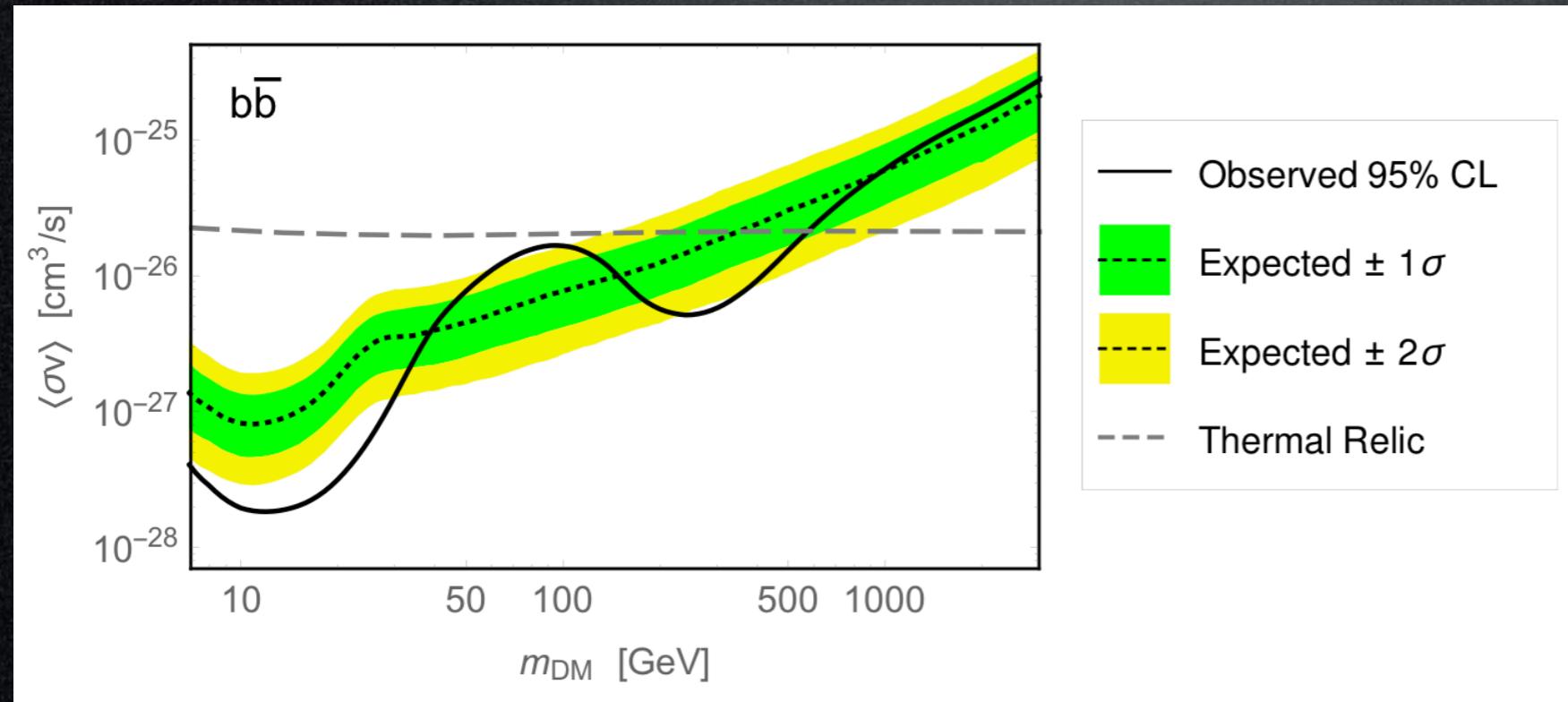
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Cheung, Krausen, Korsmeier 1610.03071



Boudaud et al.
1906.0719

“antiprotons
are consistent
with a secondary
astrophysical
origin”



Reinert, Winkler 1712.00002

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

Positrons (and electrons)

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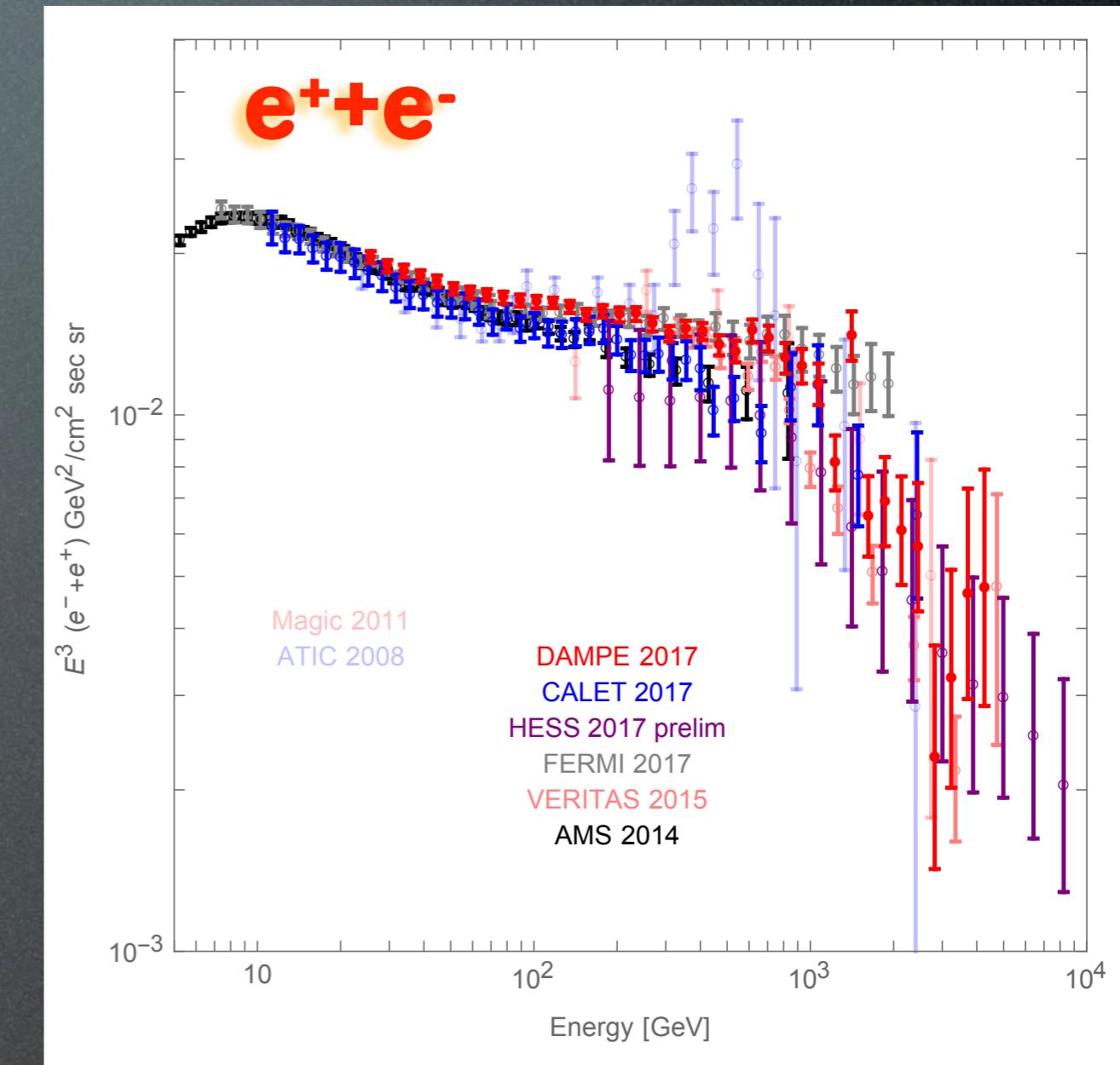
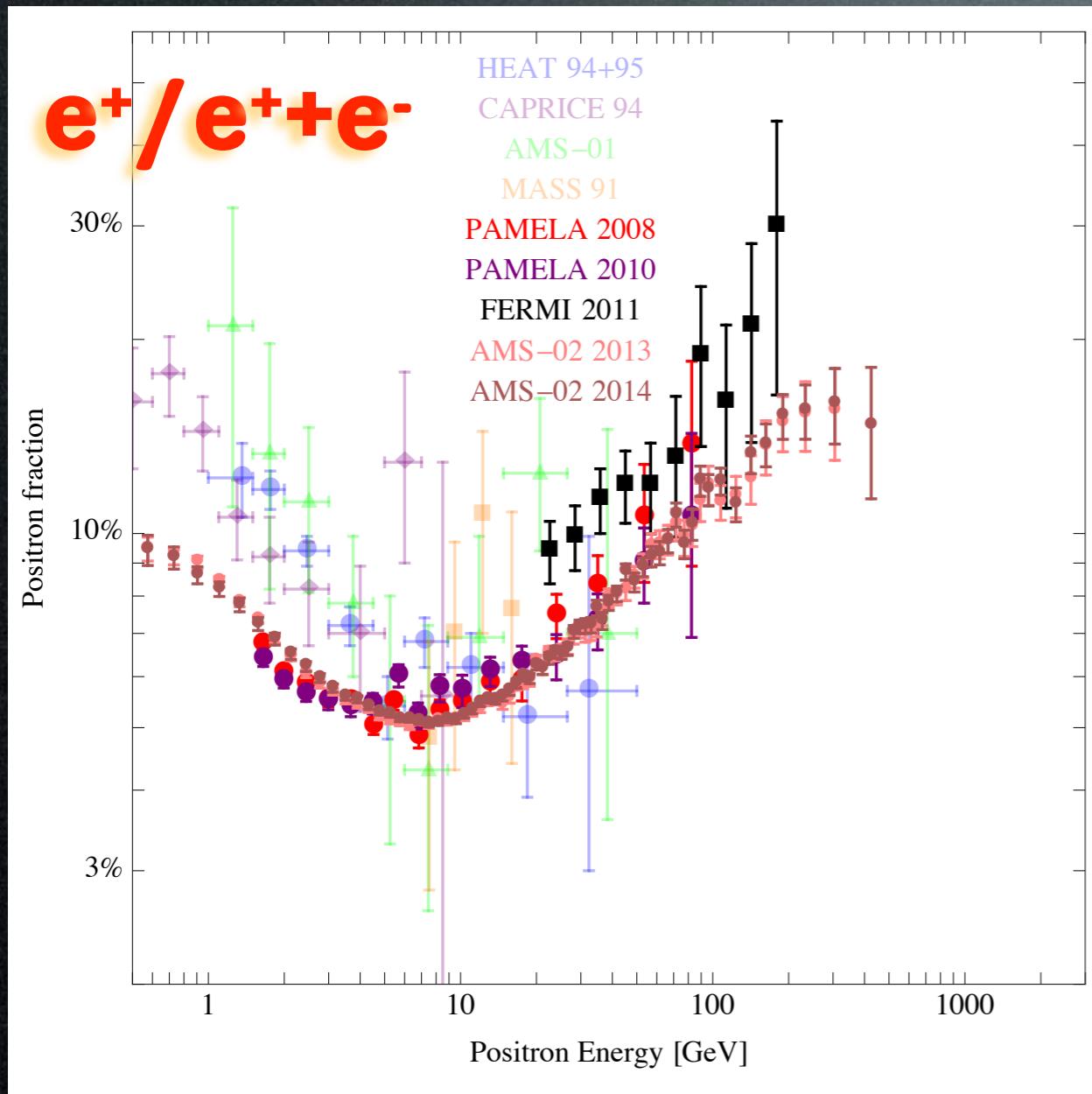
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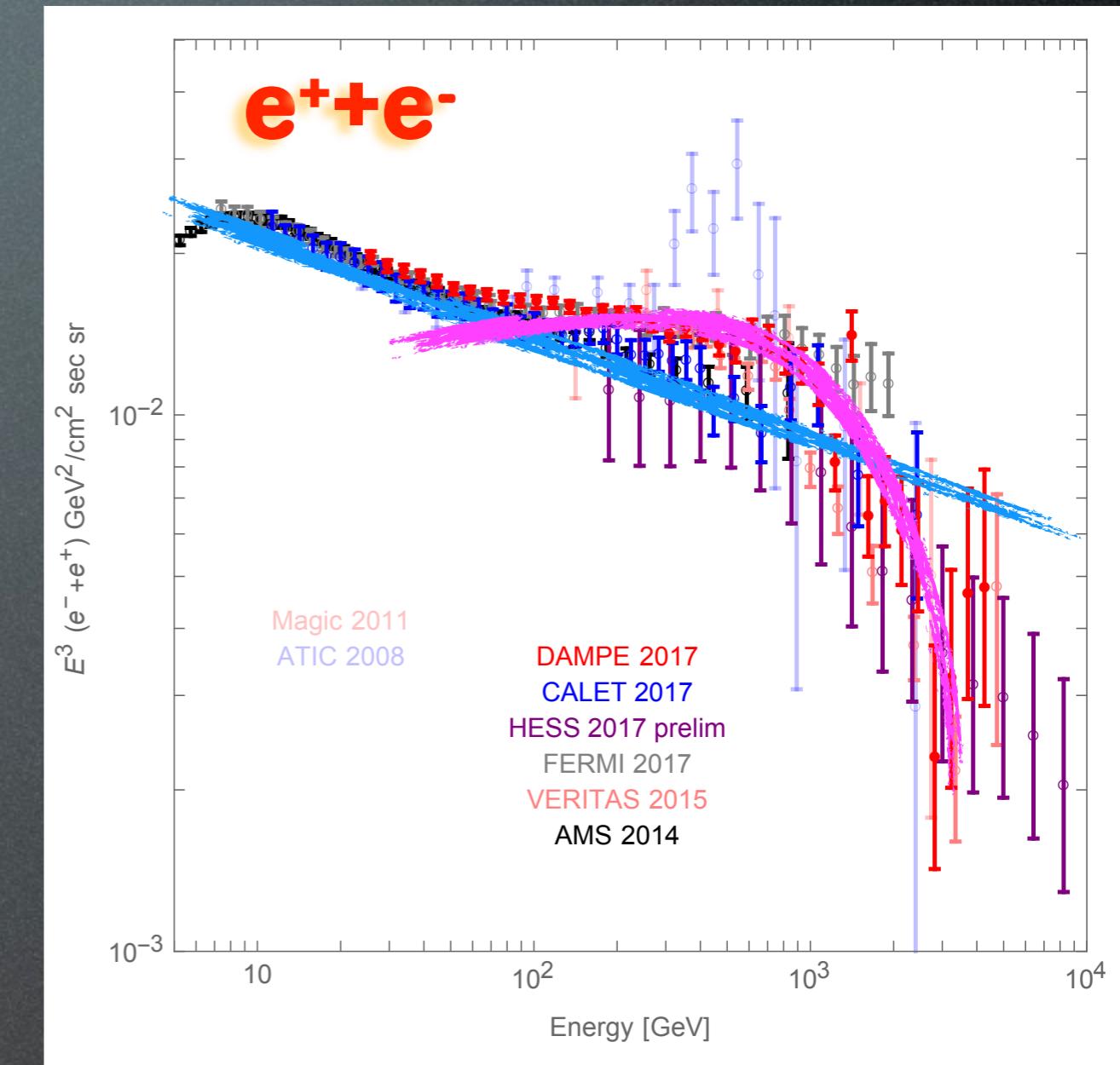
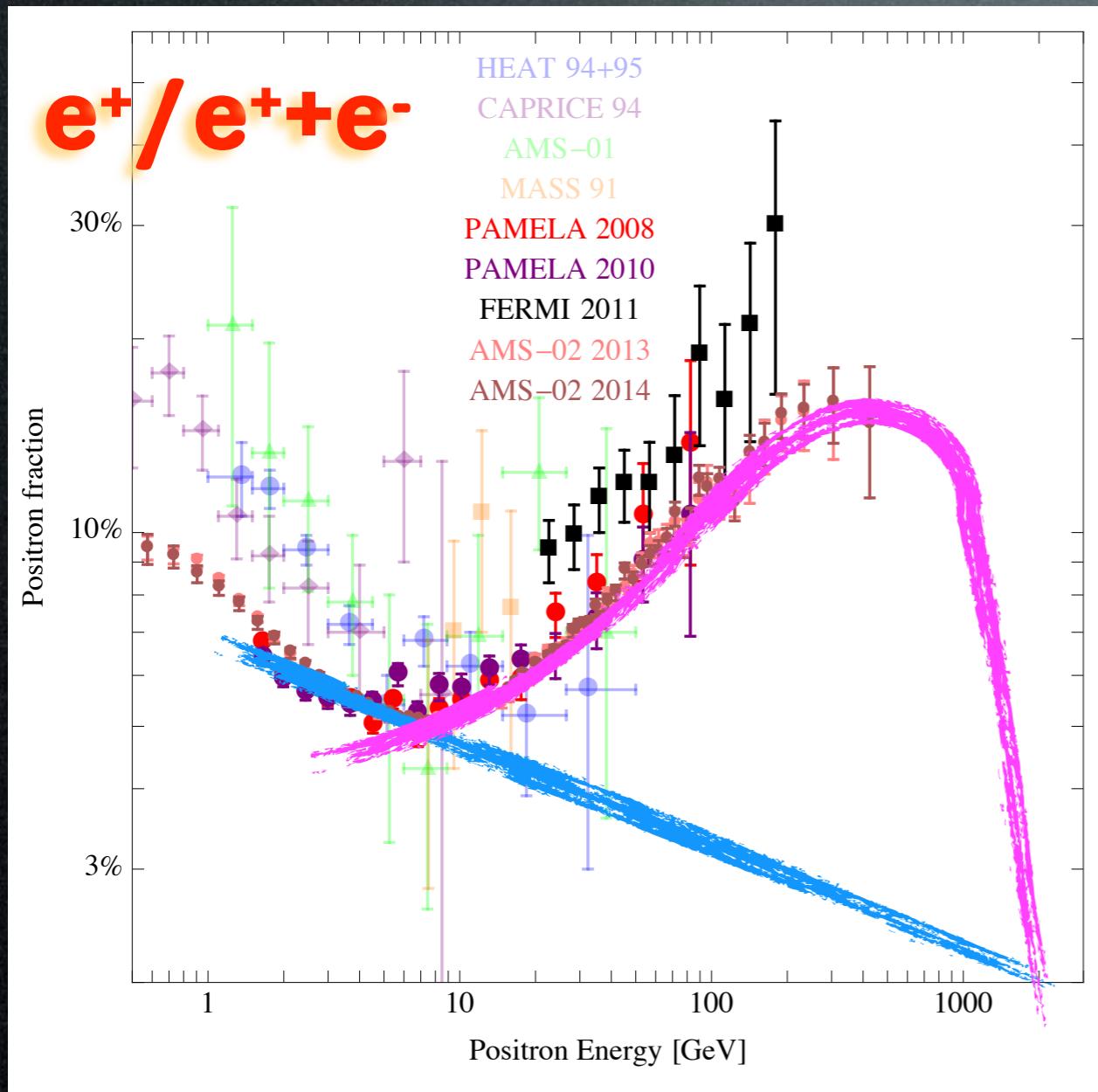
Data: leptons

high energy



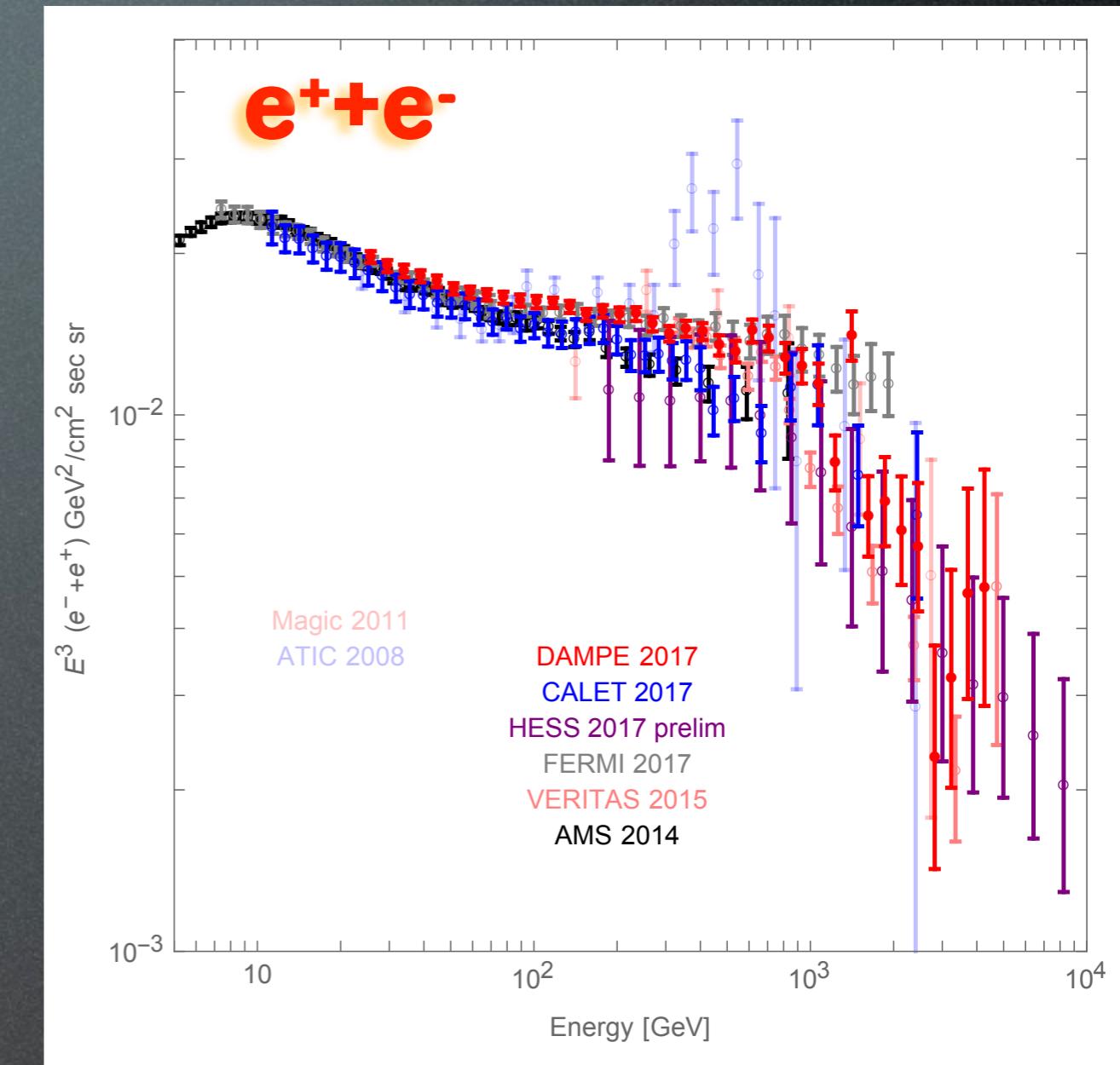
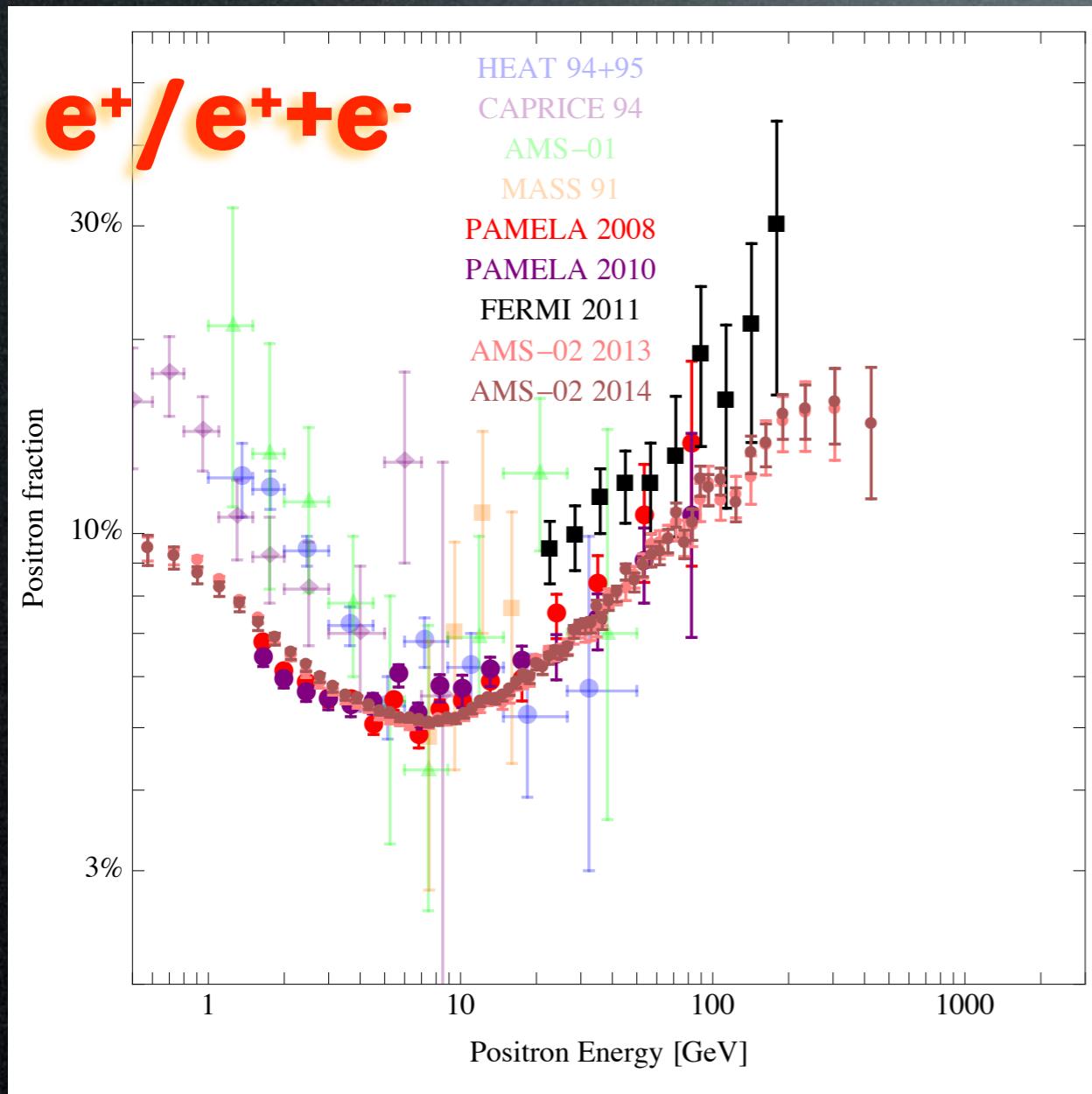
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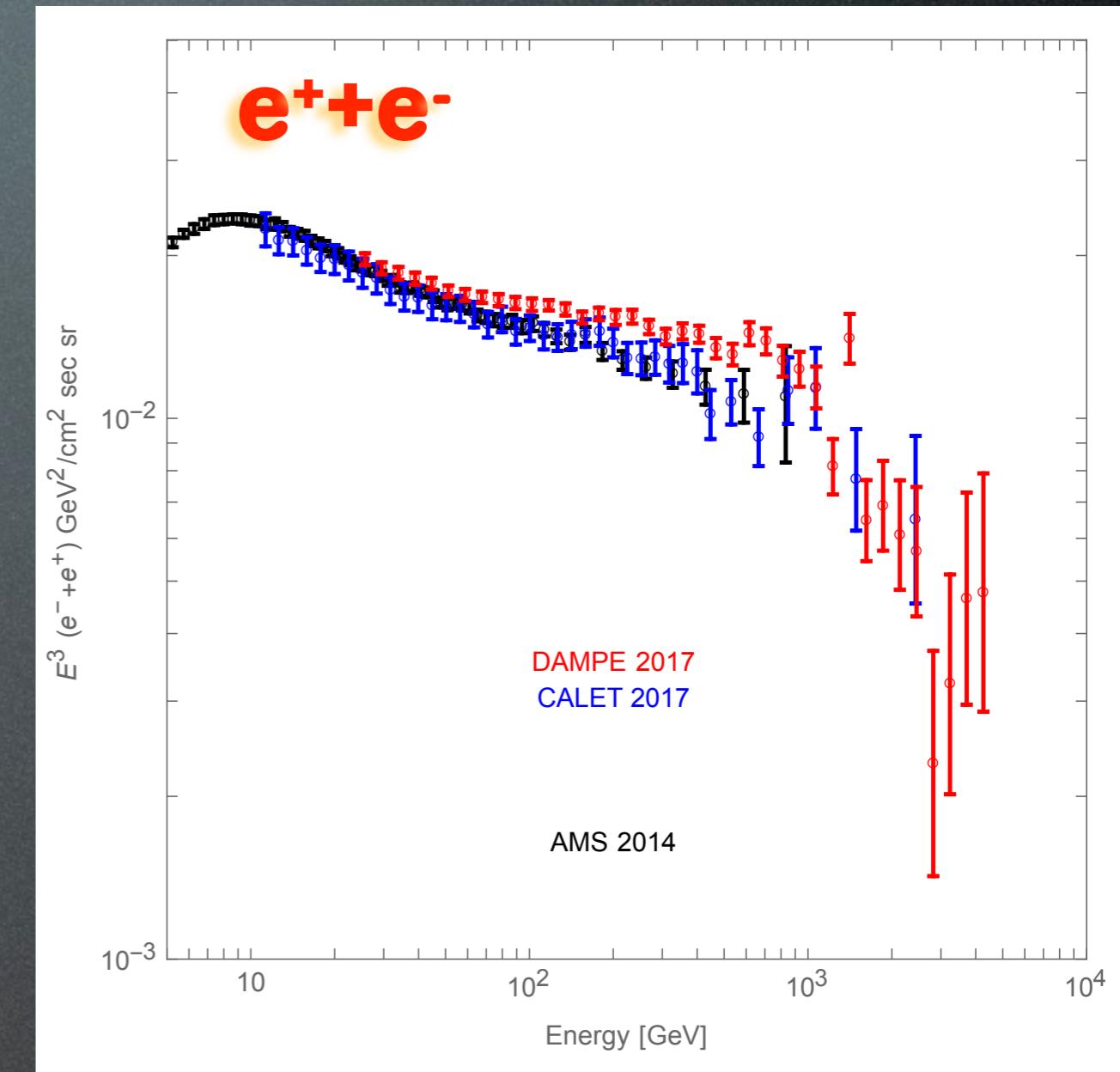
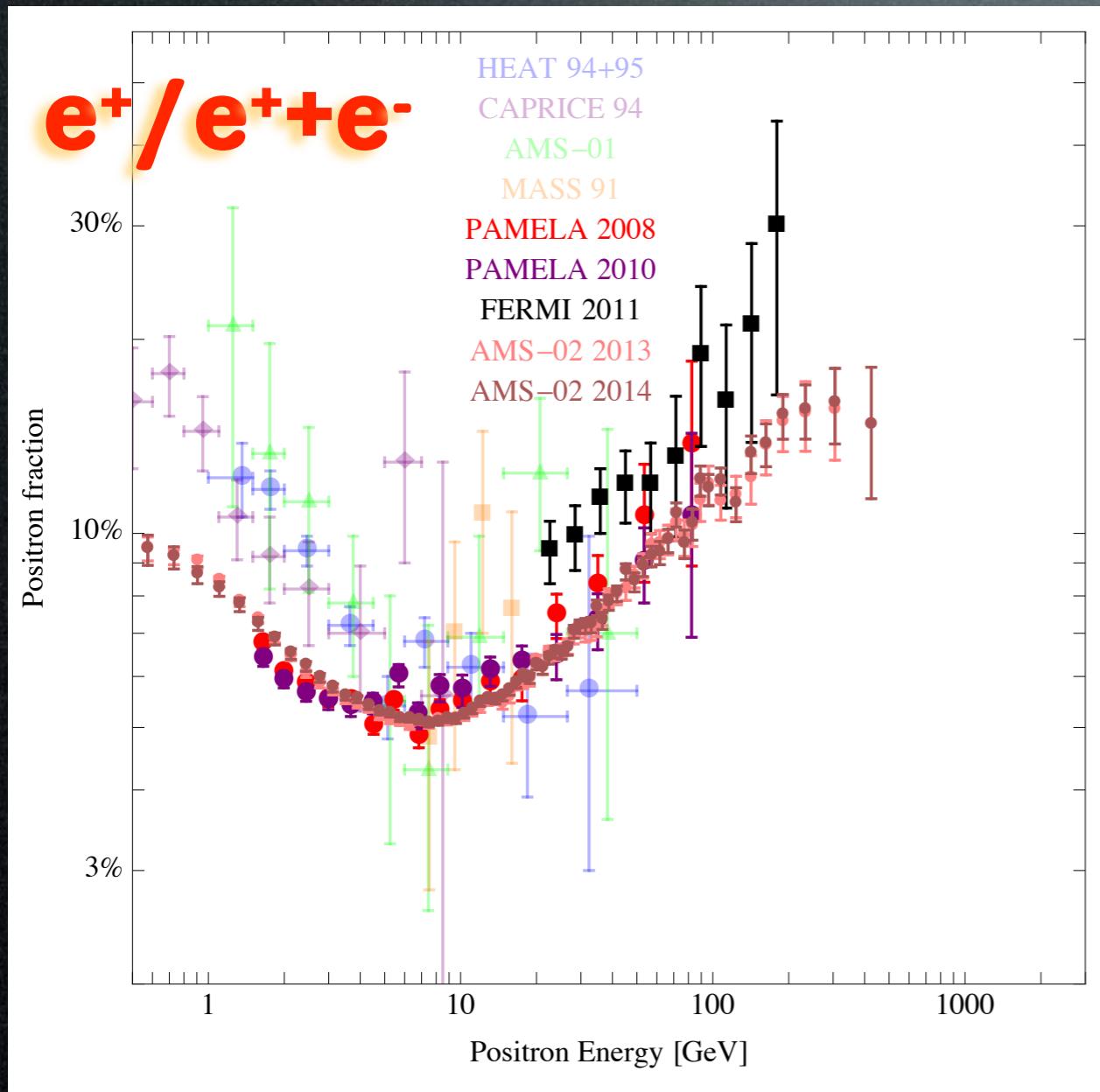
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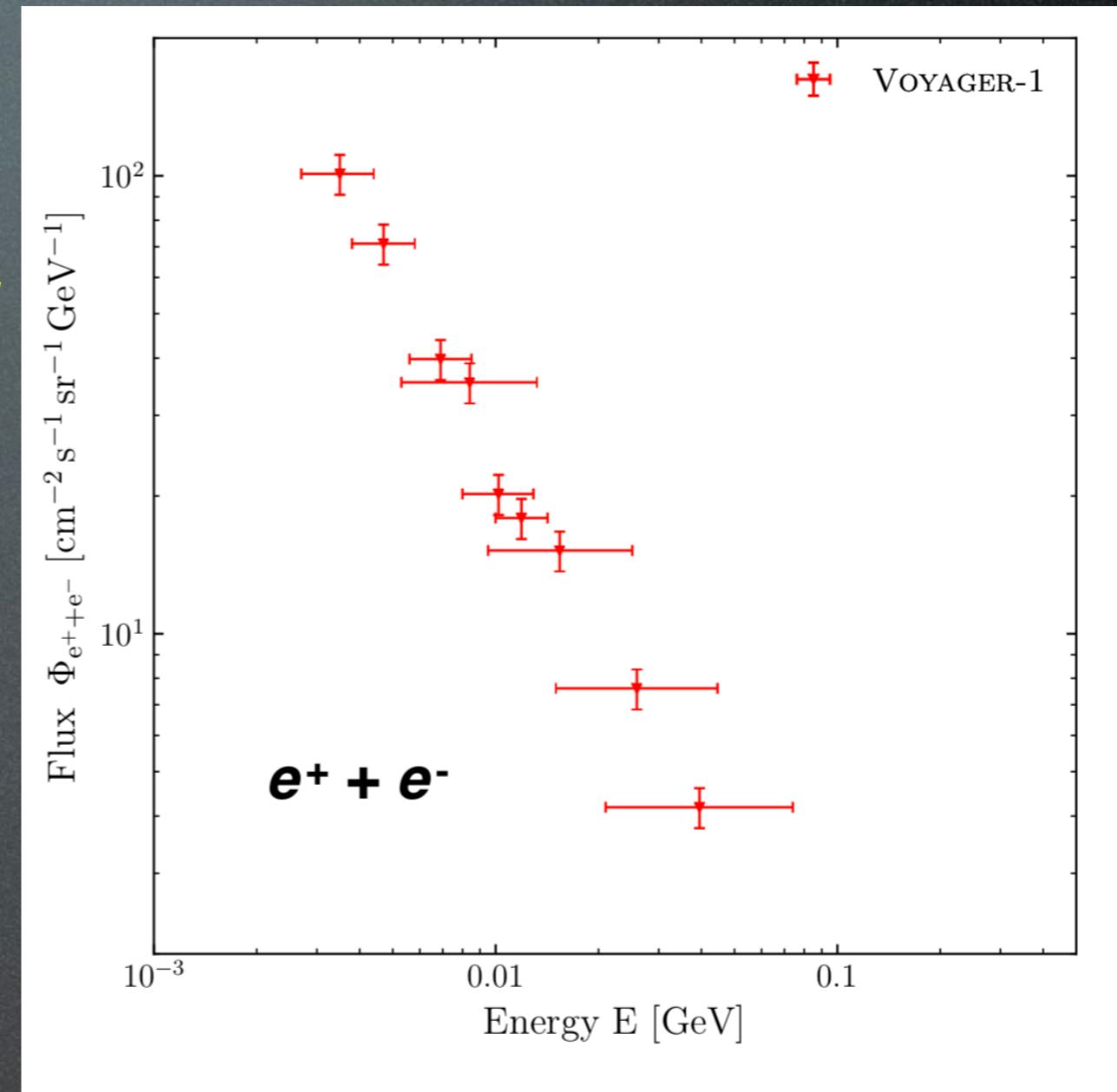
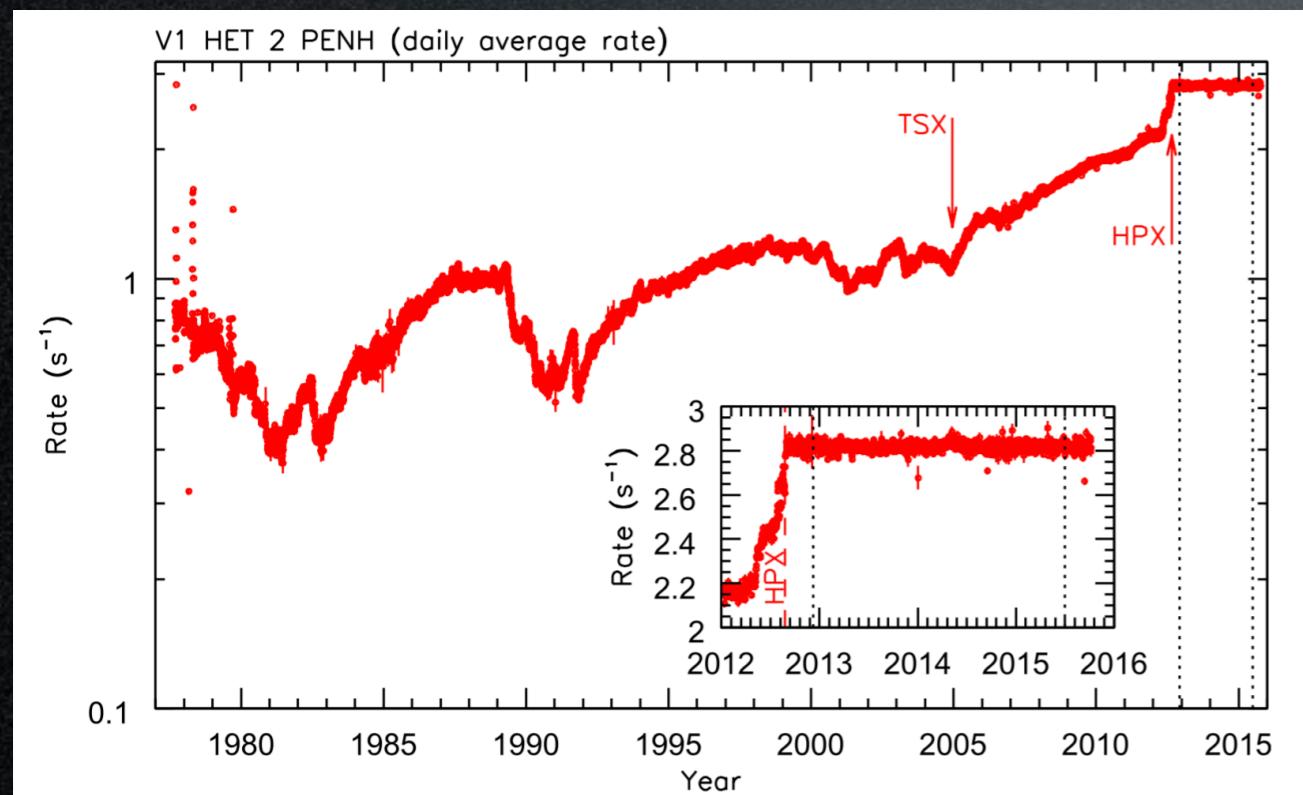
high energy



Data: leptons low energy

Voyager-1 left the heliosphere in 08.2012

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

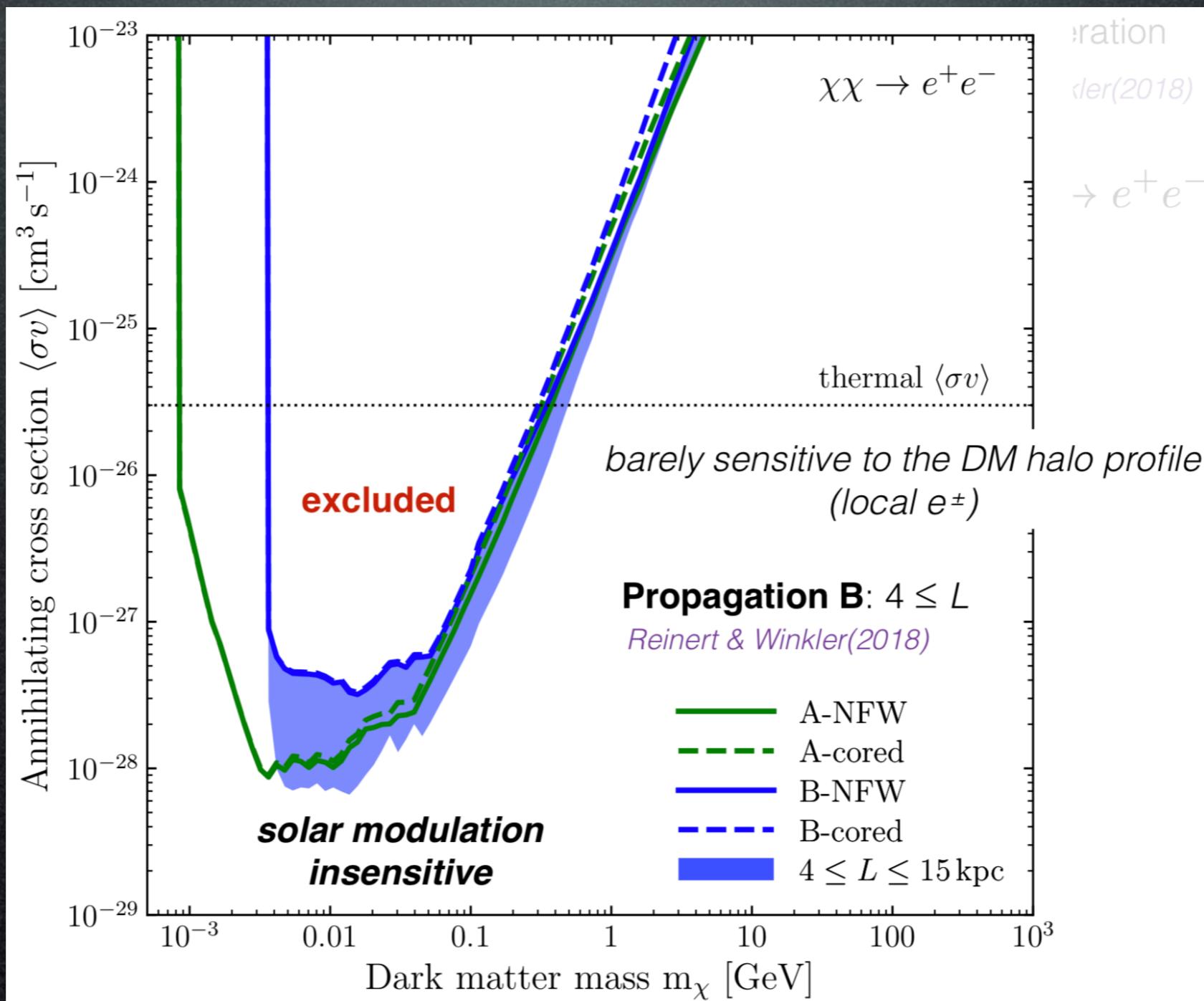


courtesy of M. Boudaud, based on
Cummings+ (Voyager-1 coll.),
The Astrophysical Journal, 831:18, 2016

Dark Matter interpretation

low energy

Constraints on sub-GeV DM



Dark Matter interpretation

low energy

Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

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

Dark Matter interpretation

low energy

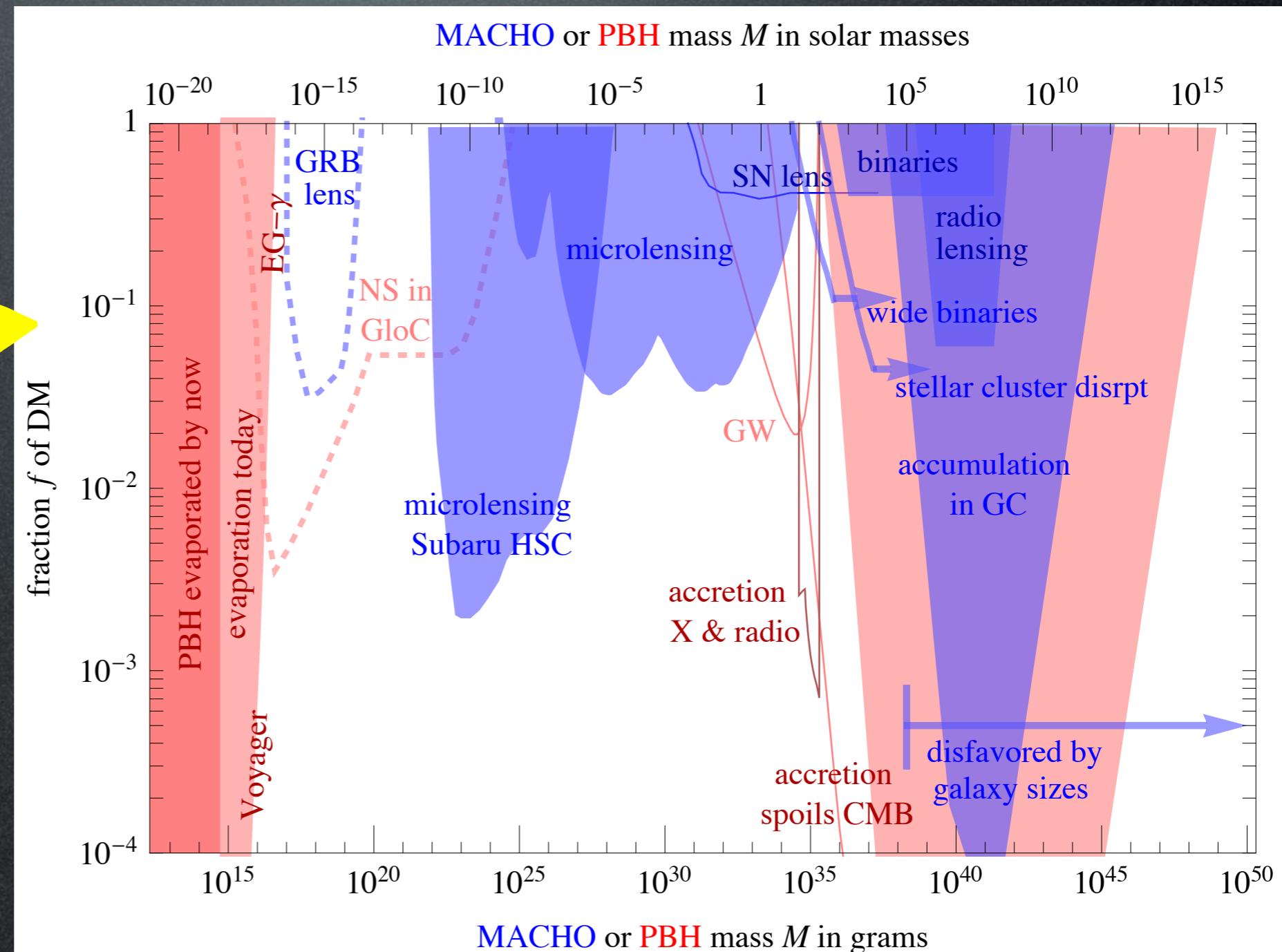
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constraints



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constraints

'small' PBHs emit today by Hawking evaporation

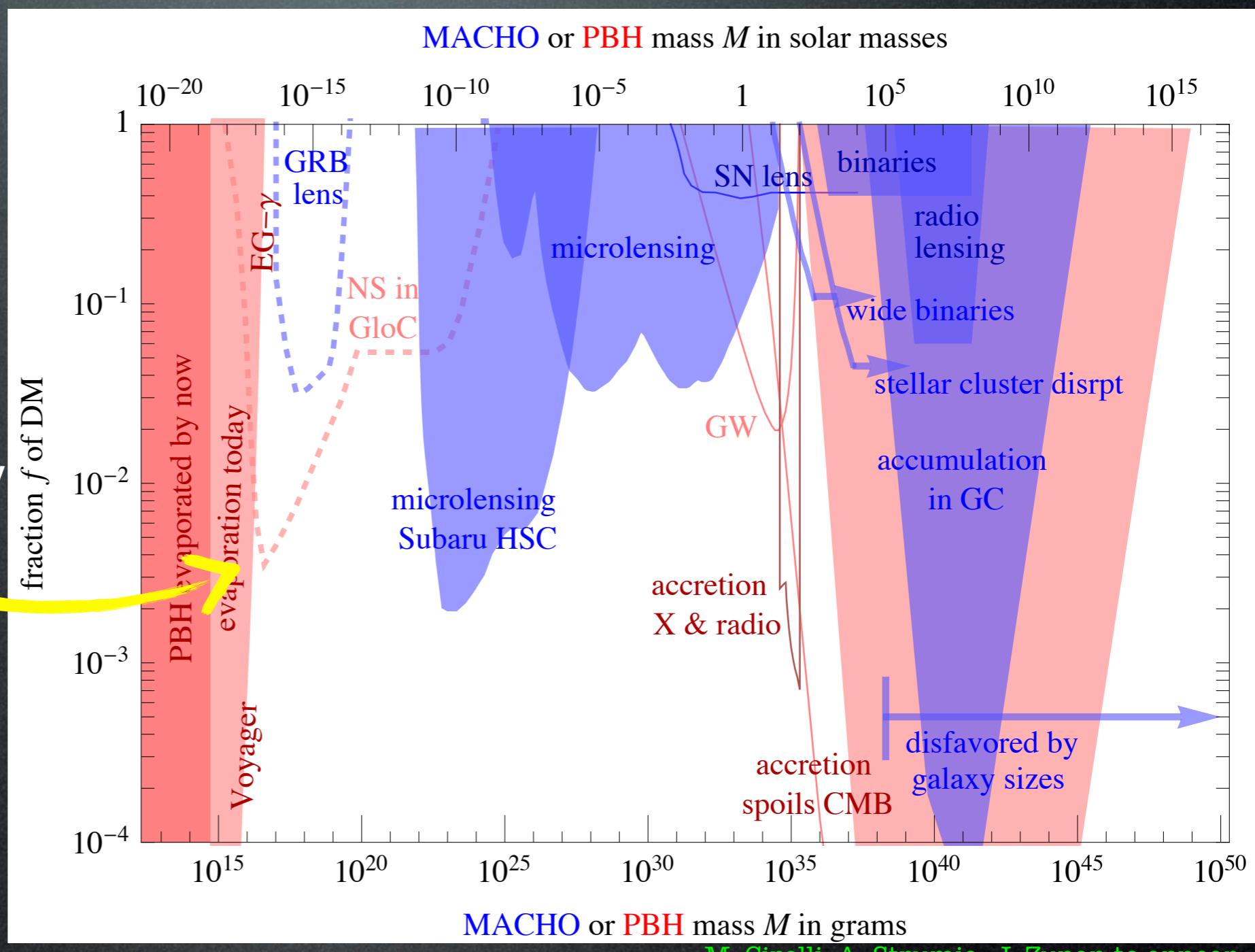
$$T = \frac{1}{8\pi G_N M}$$

rate

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

spectrum

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



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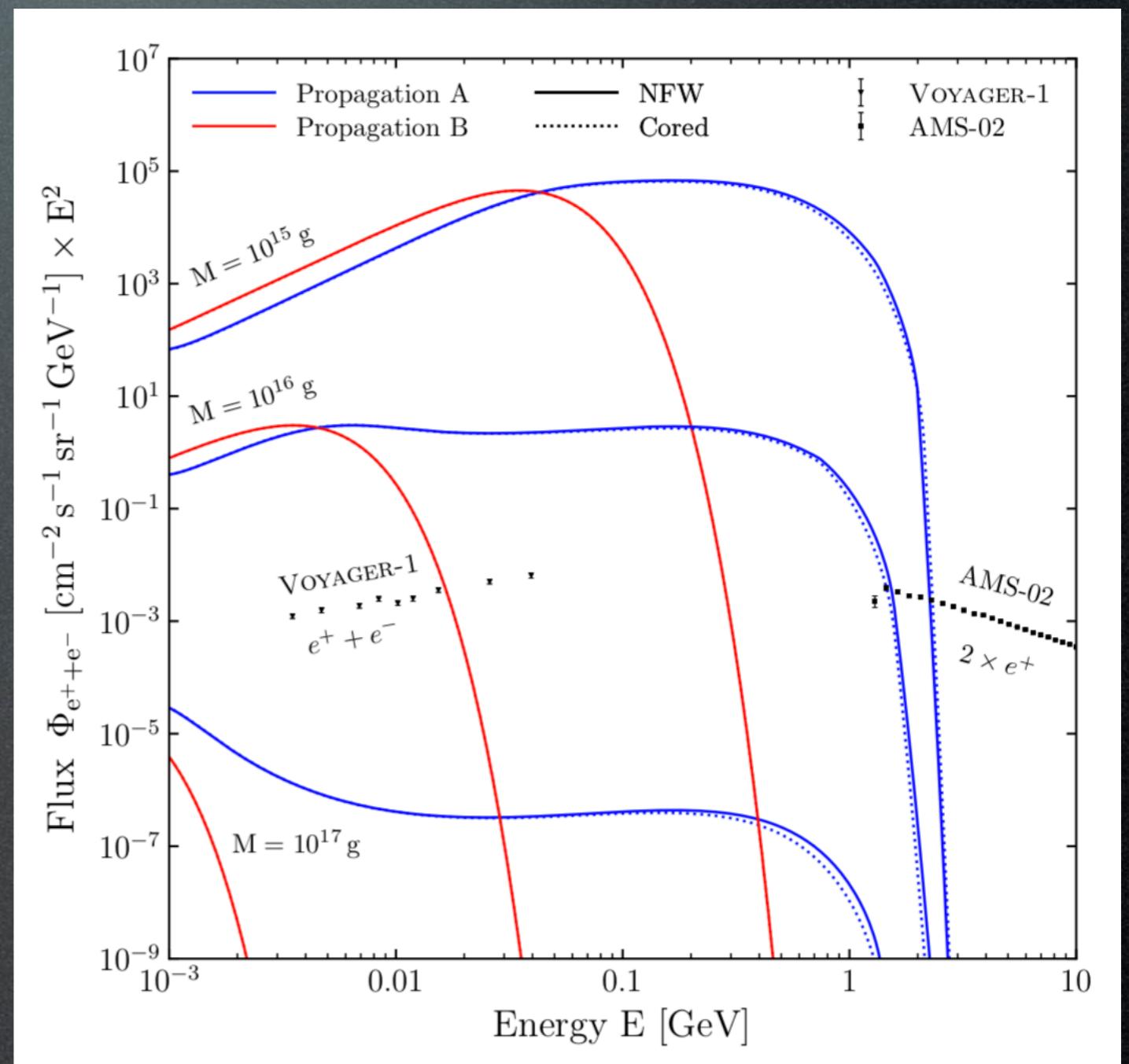
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'small' PBHs emit today by
Hawking evaporation

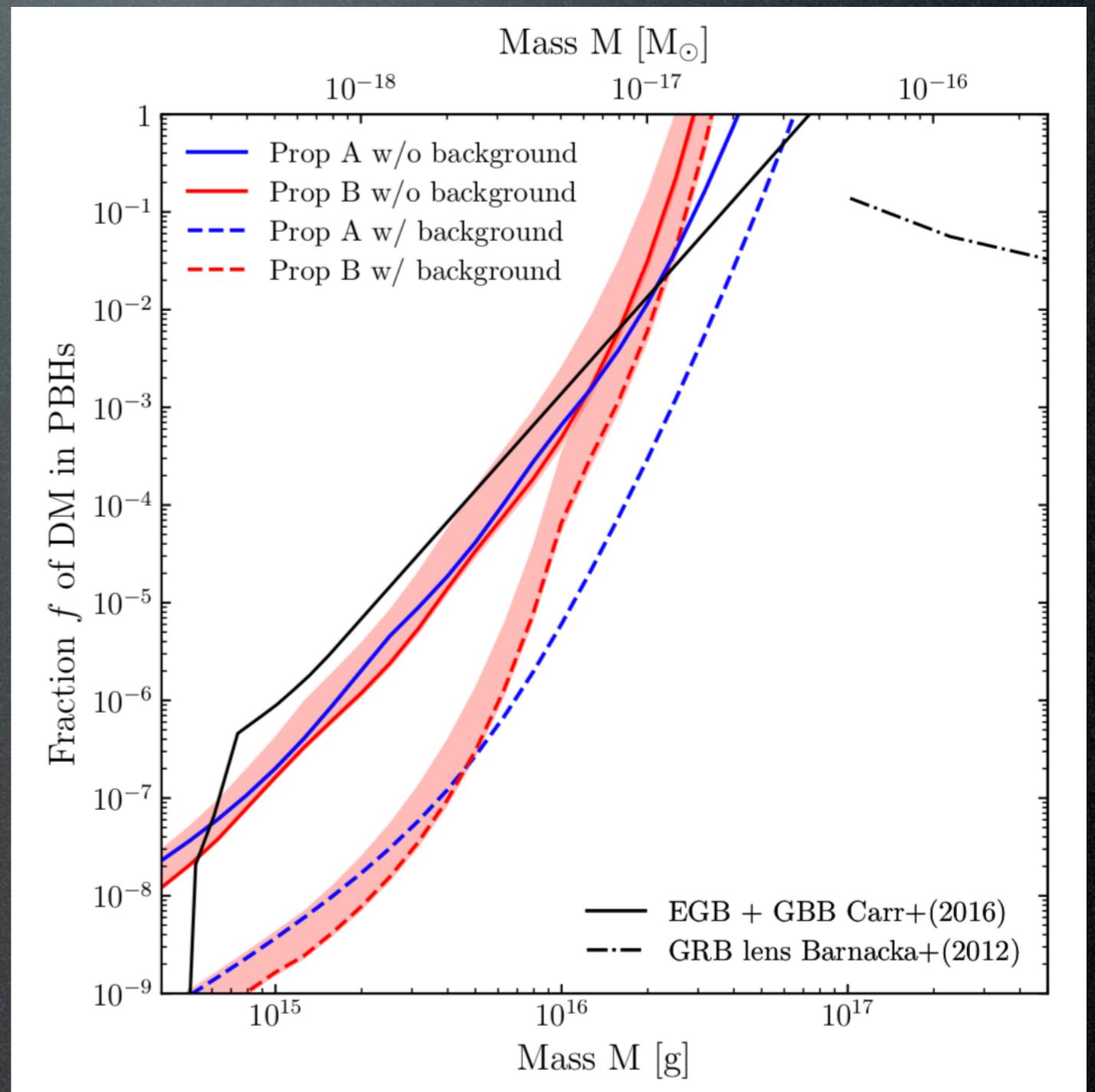
$$T = \frac{1}{8\pi G_N M}$$

rate

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

spectrum

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



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

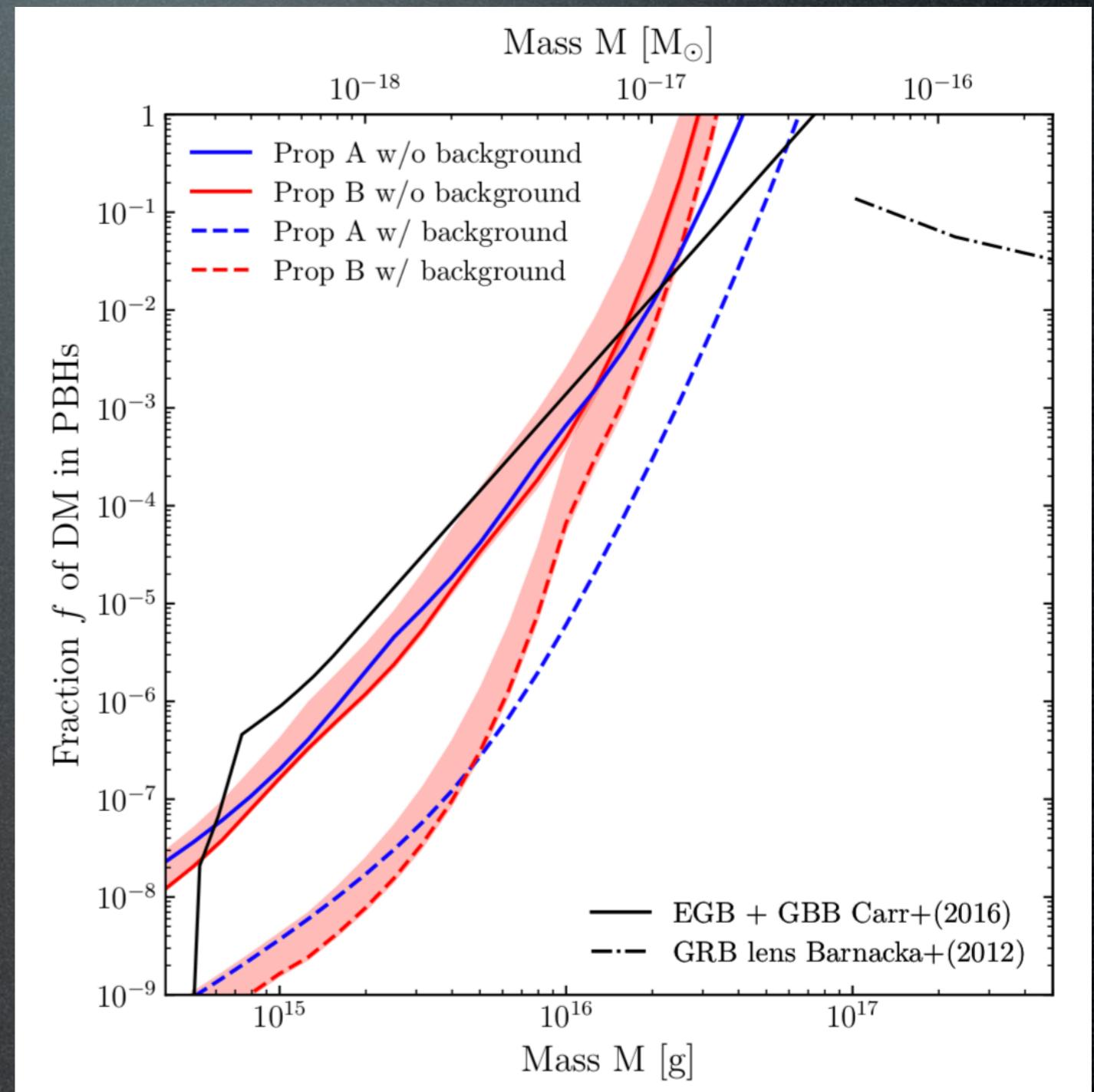
NASA's Voyager-1 Spacecraft Opens Door On New Way To Look For Dark Matter



Bruce Dorminey Contributor 

Science

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



DM detection

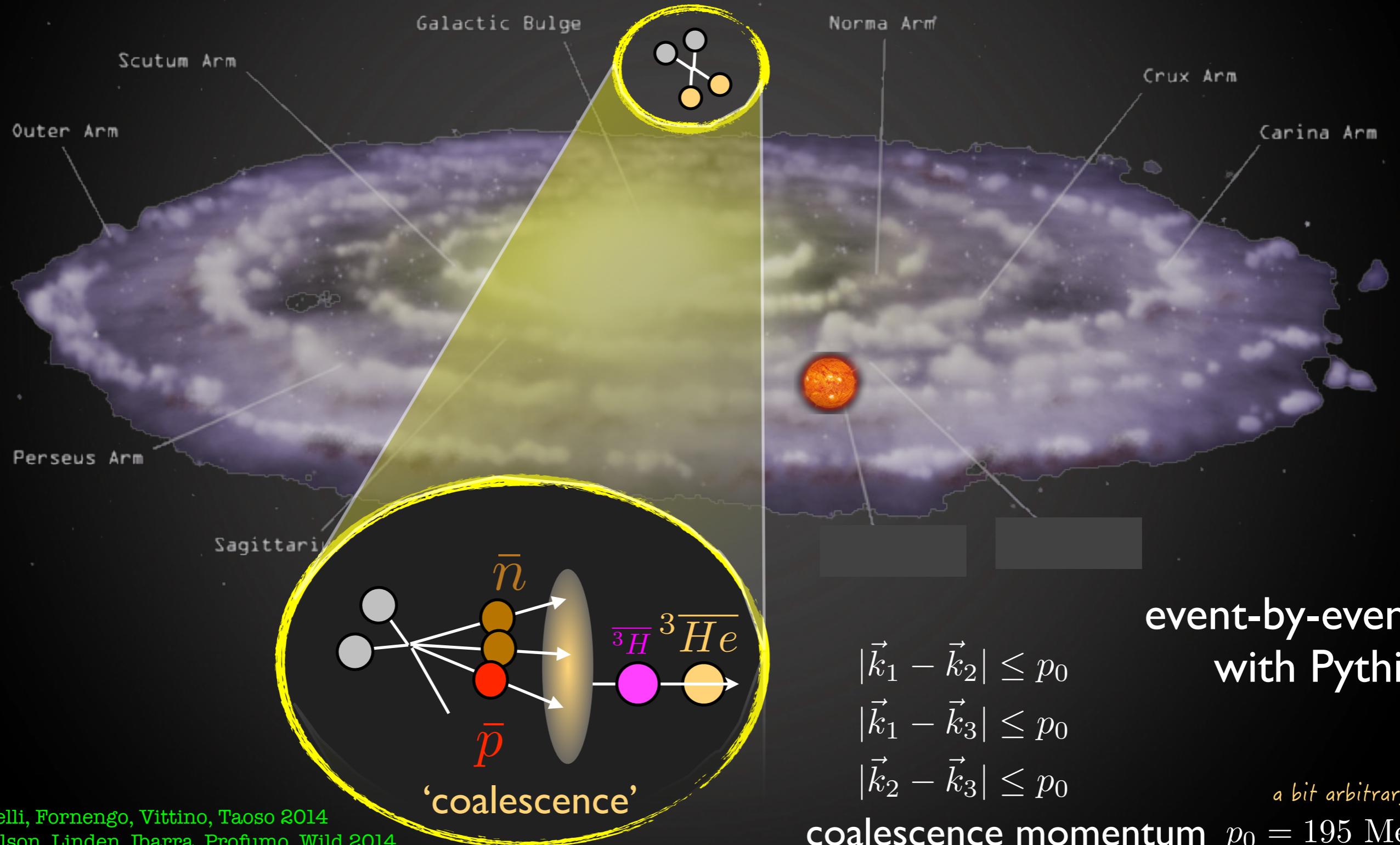
direct detection

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?

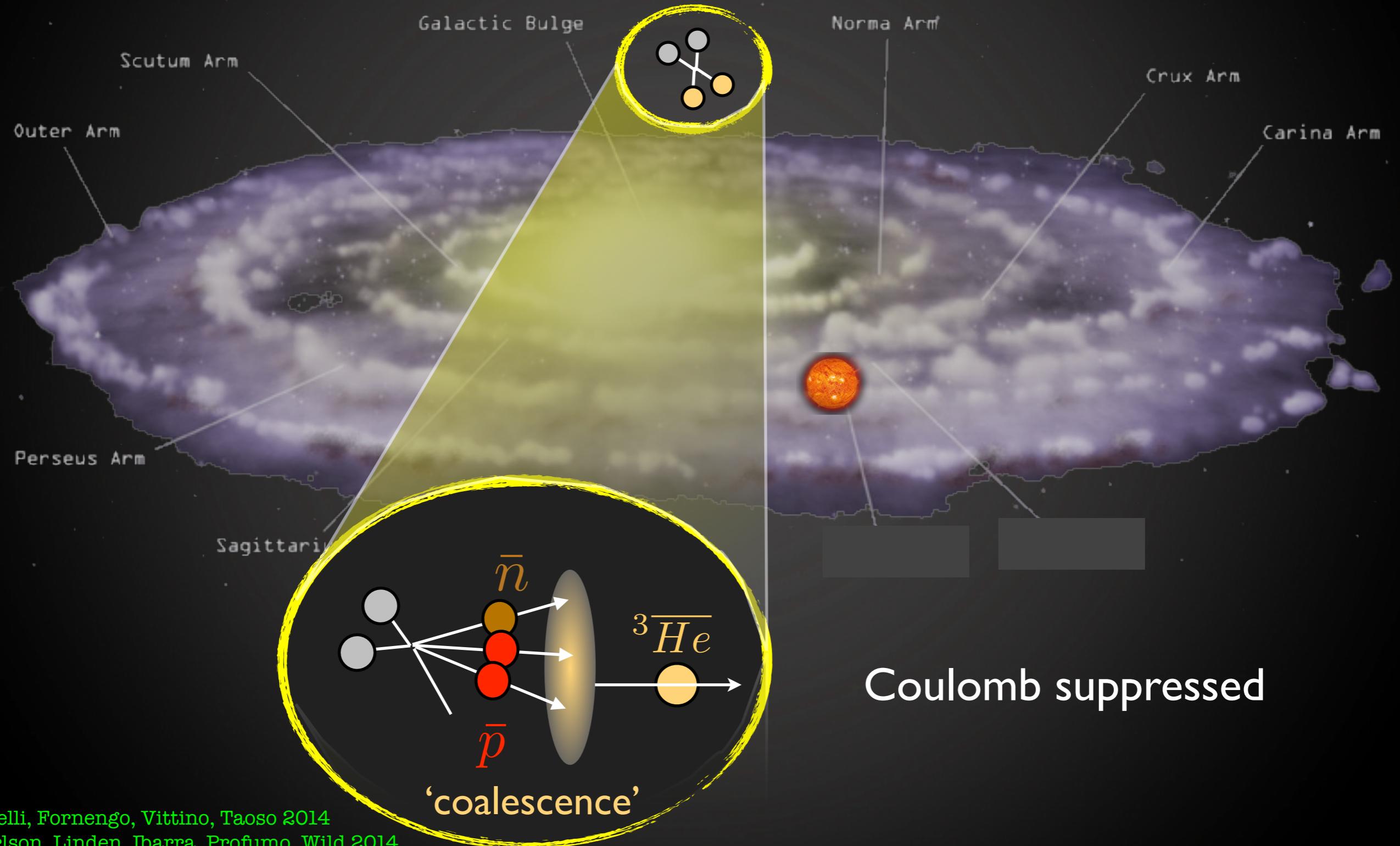
Indirect Detection

\overline{He} from DM annihilations in halo



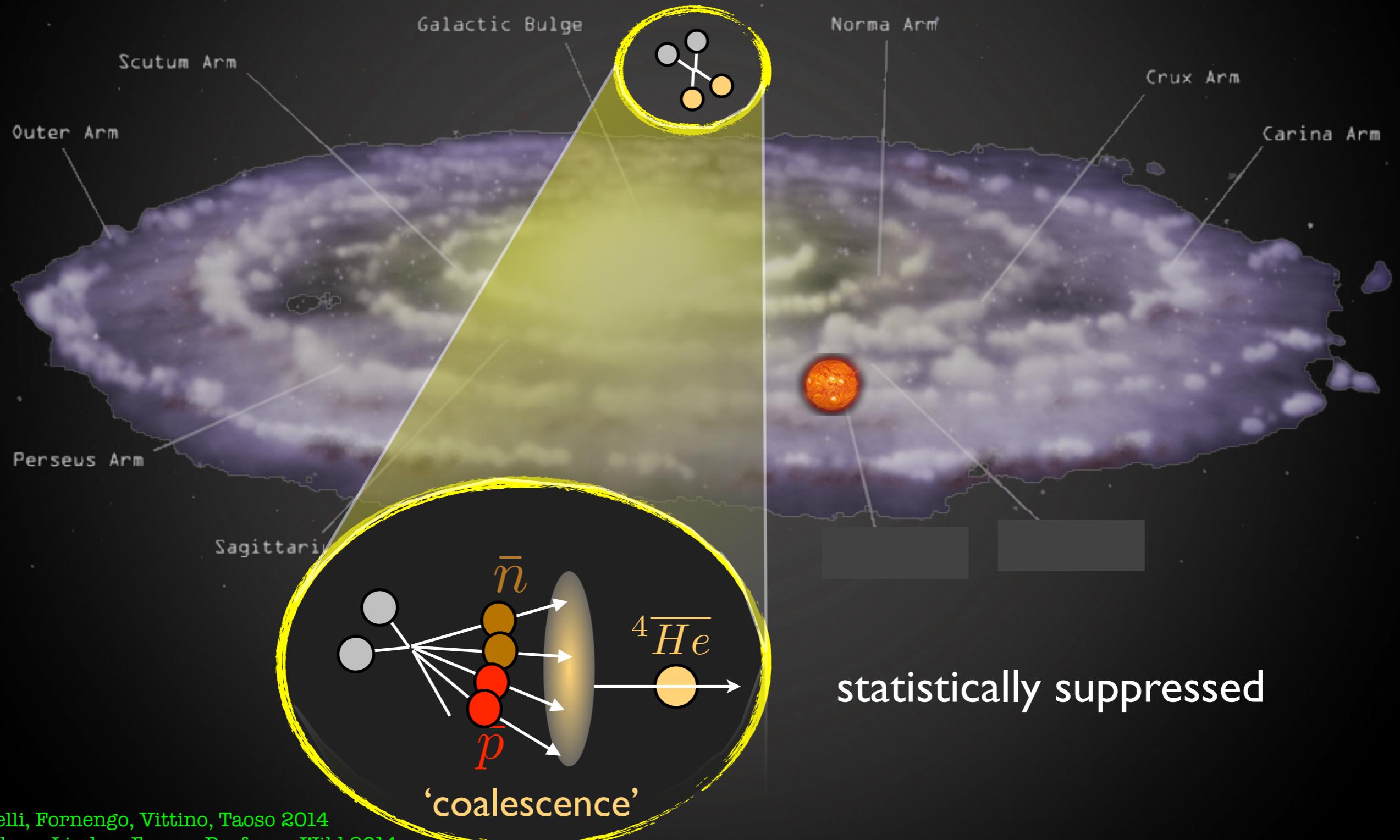
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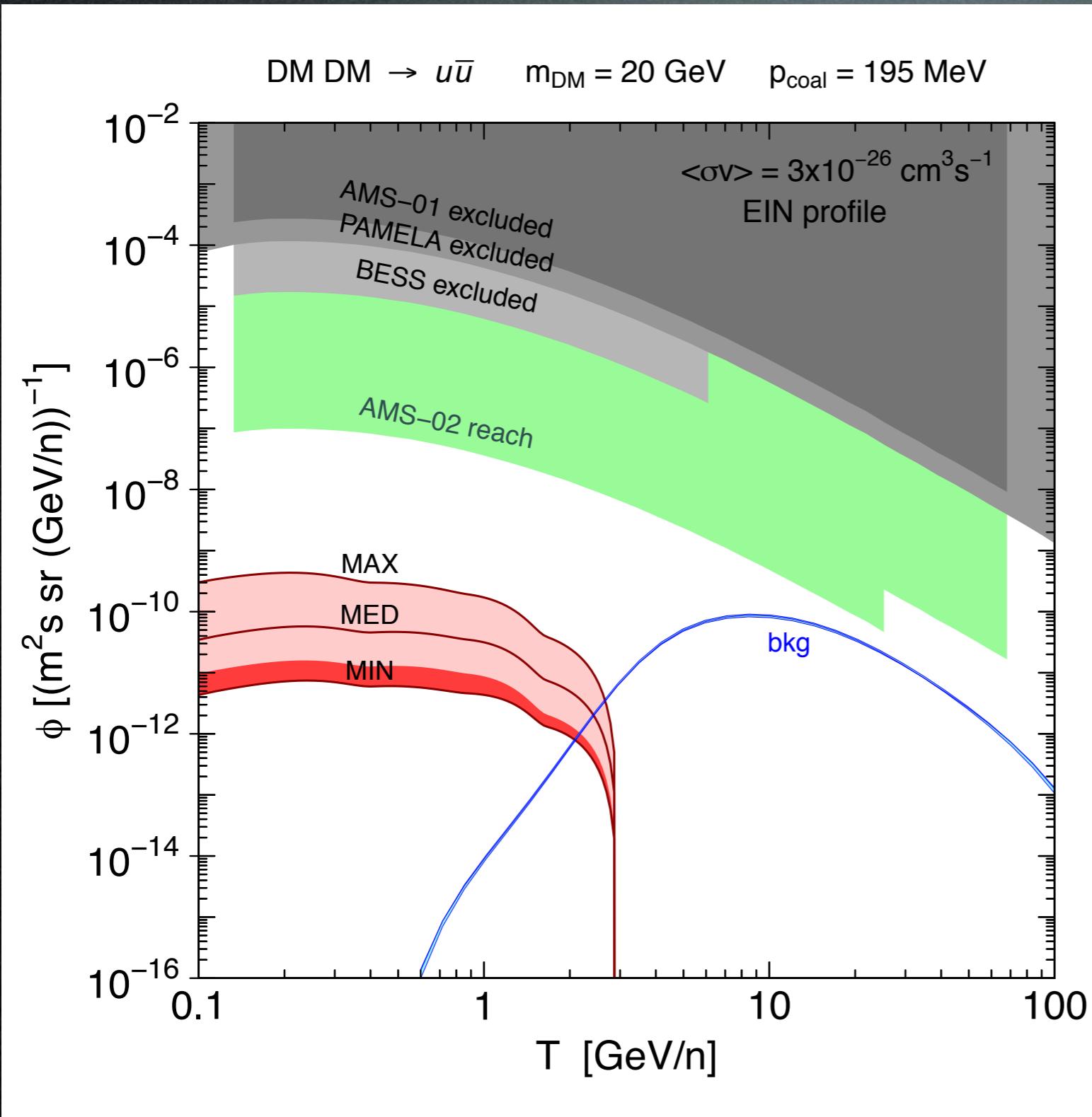
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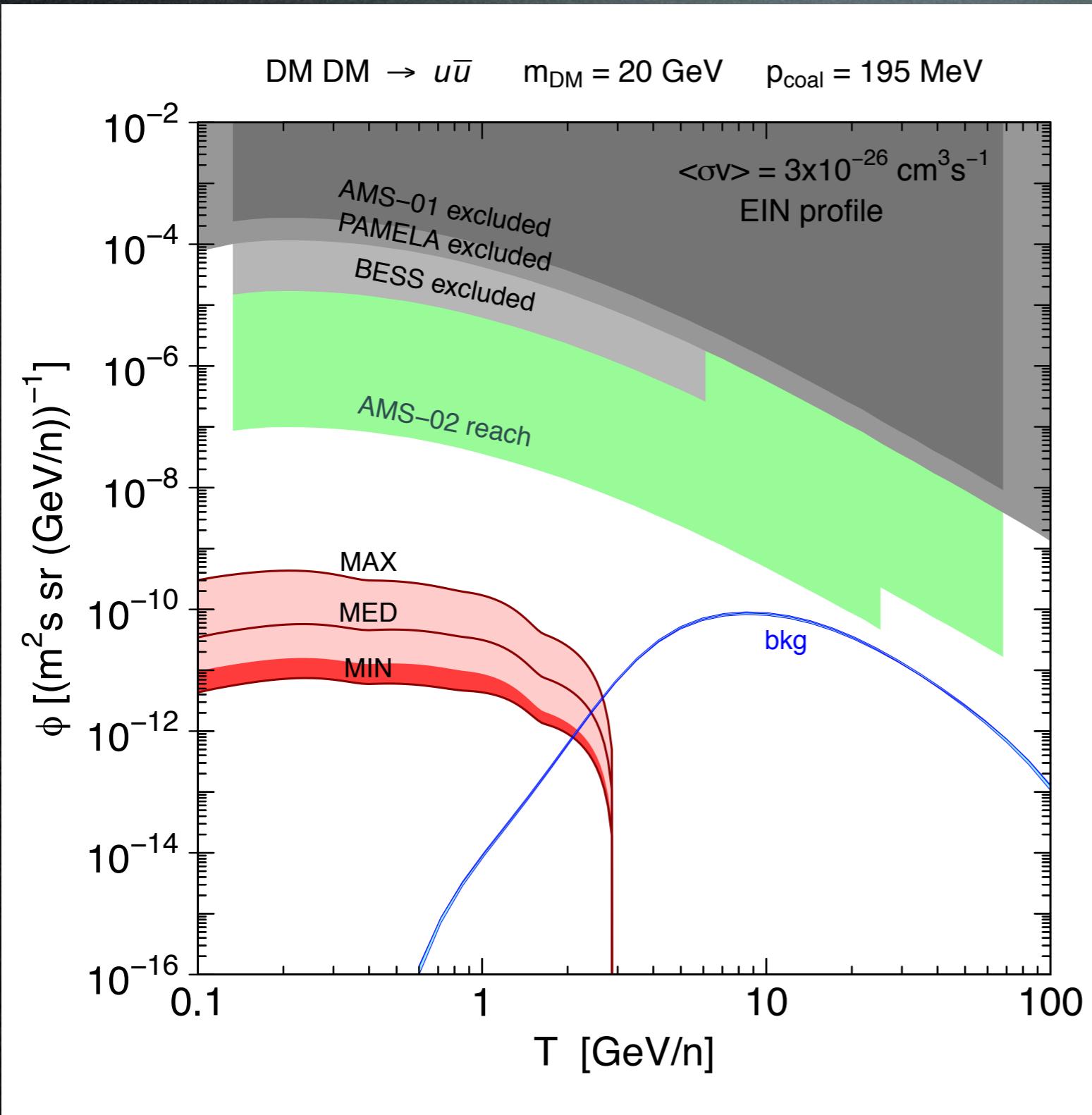
all



consistent with
antiproton bounds

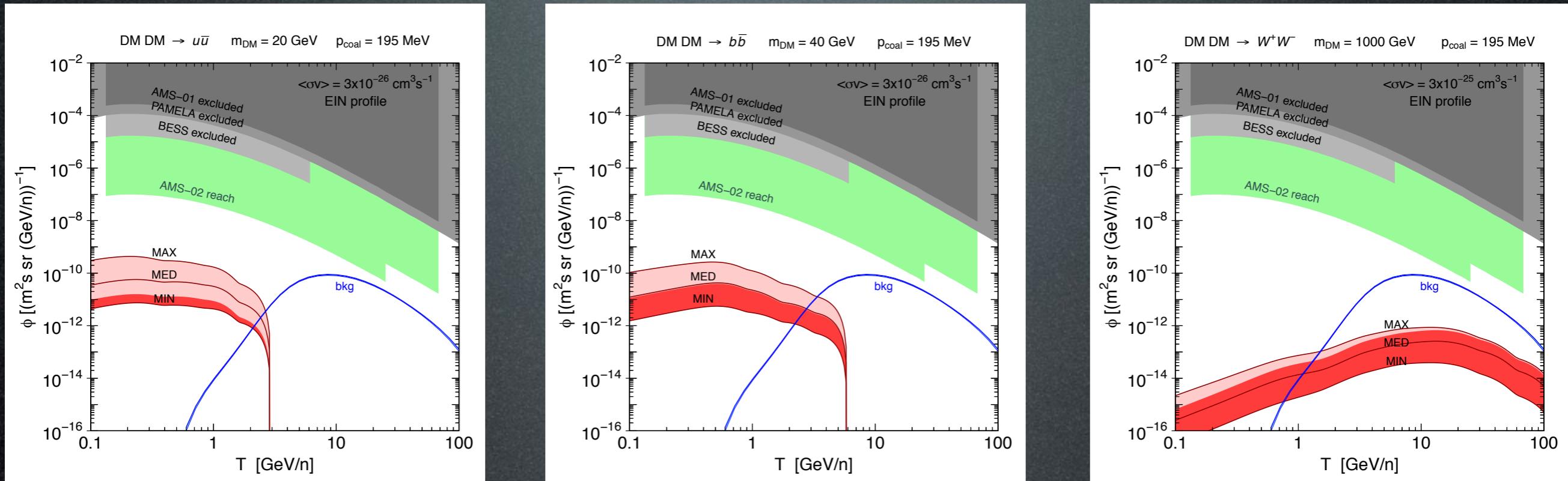
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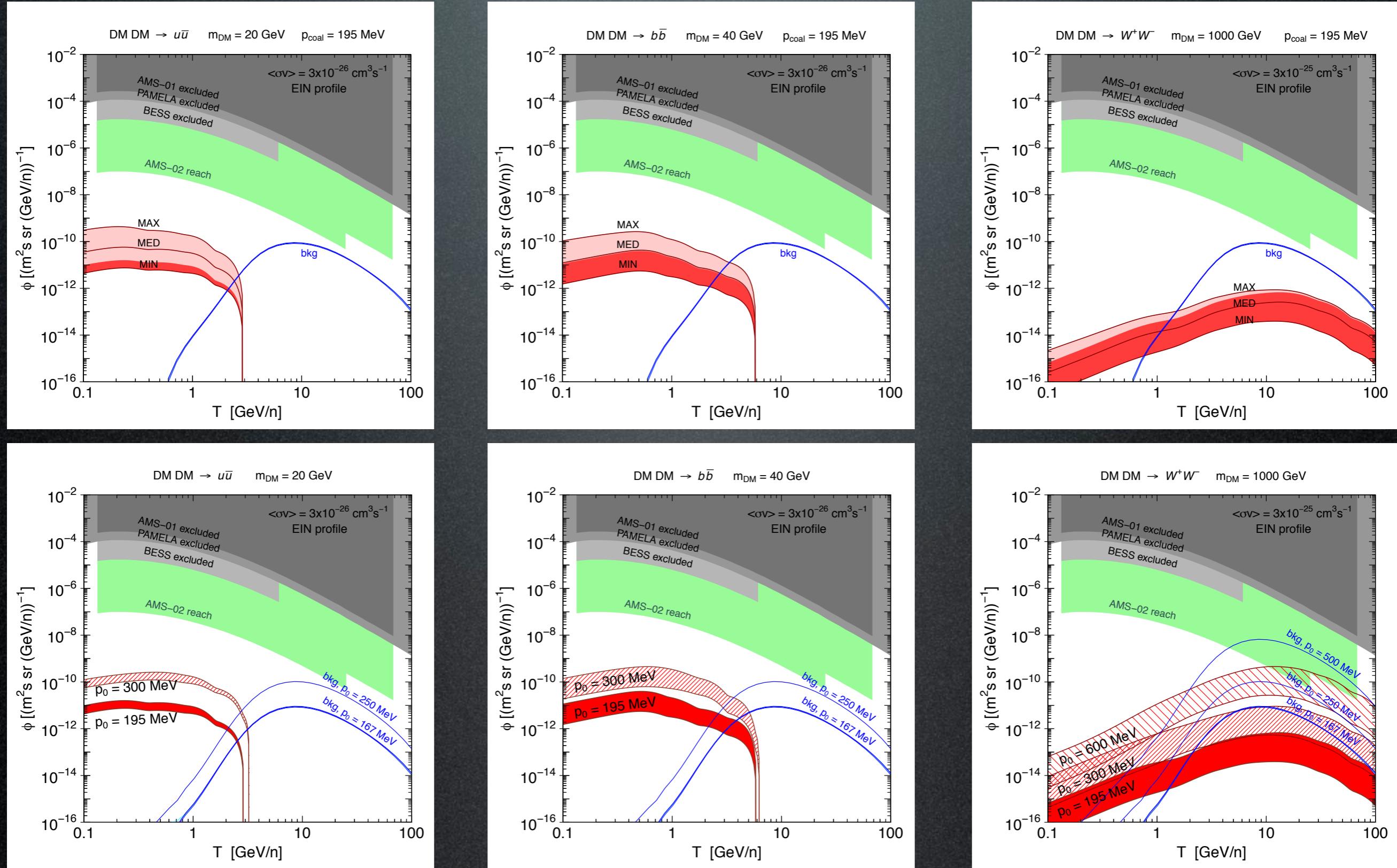
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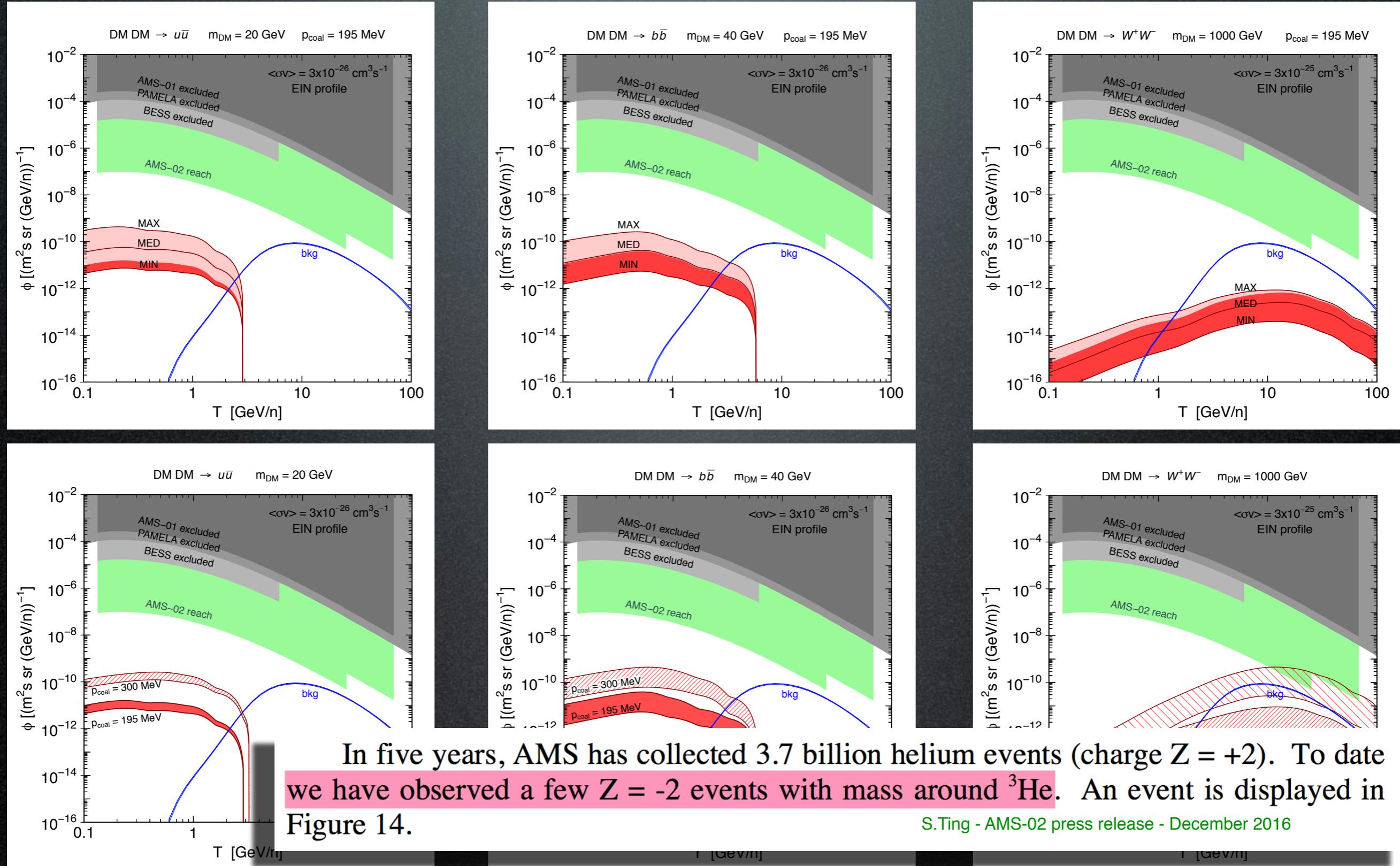
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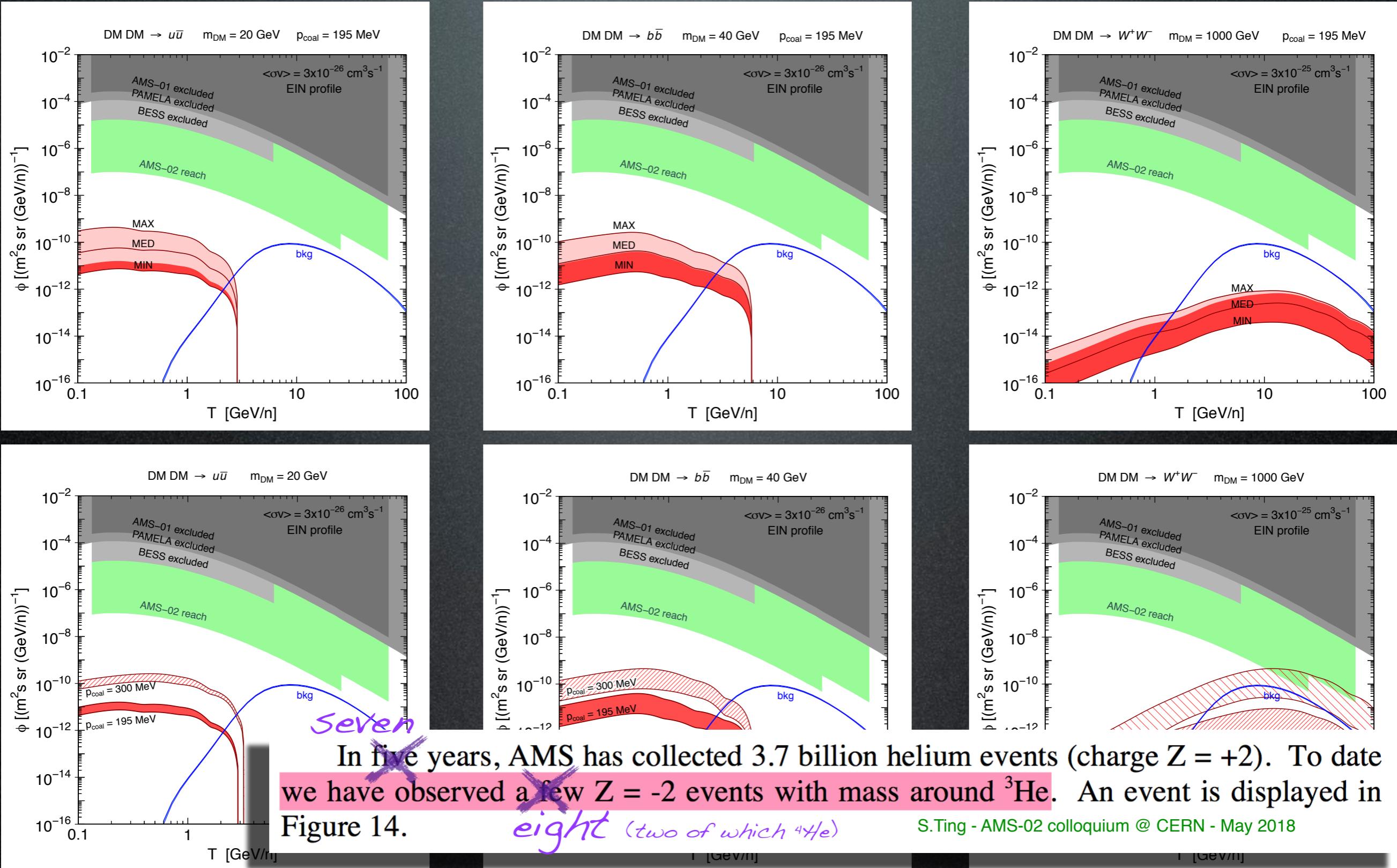
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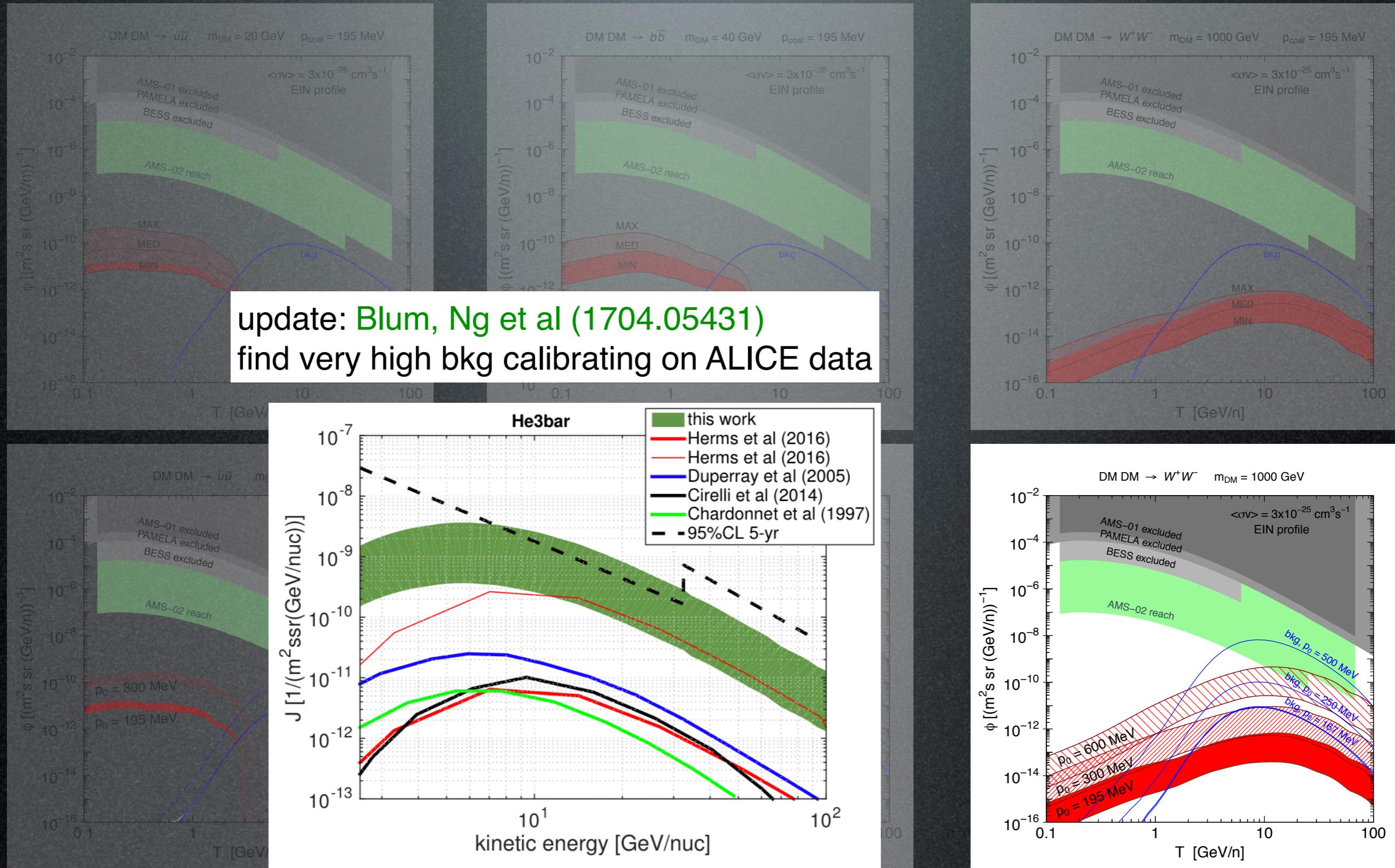
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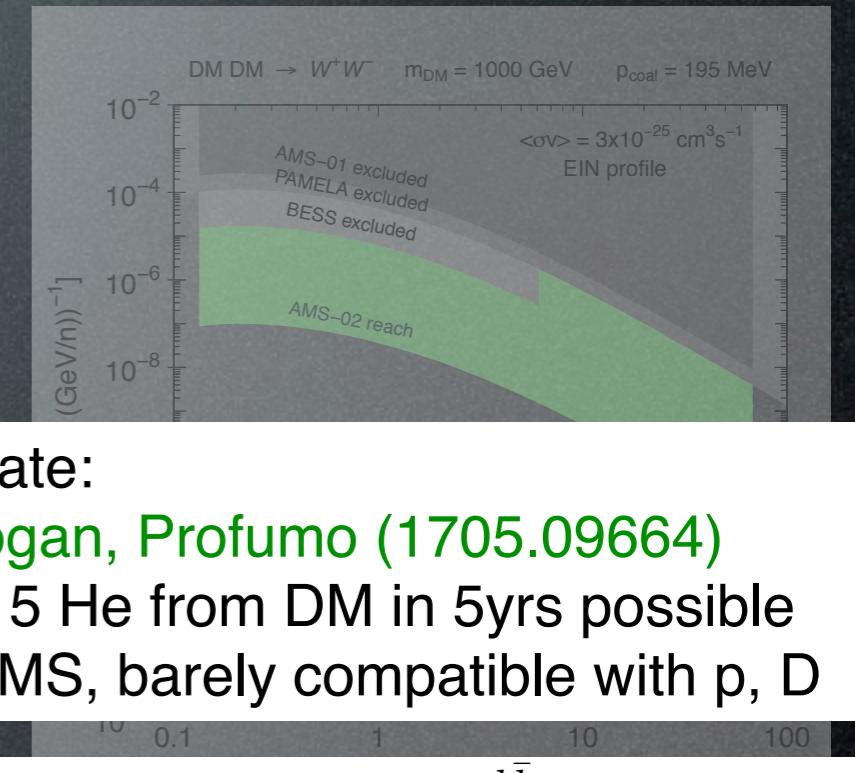
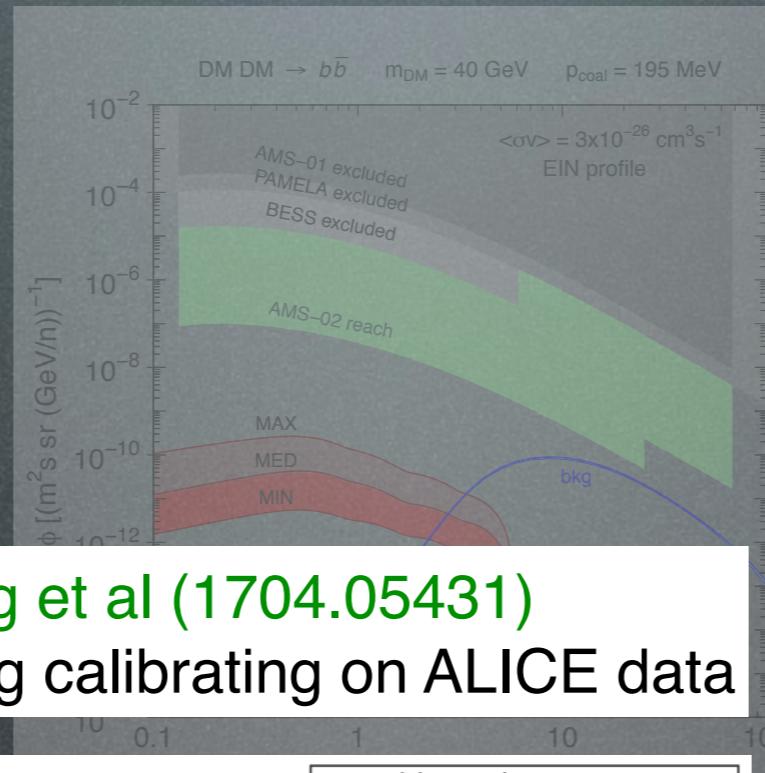
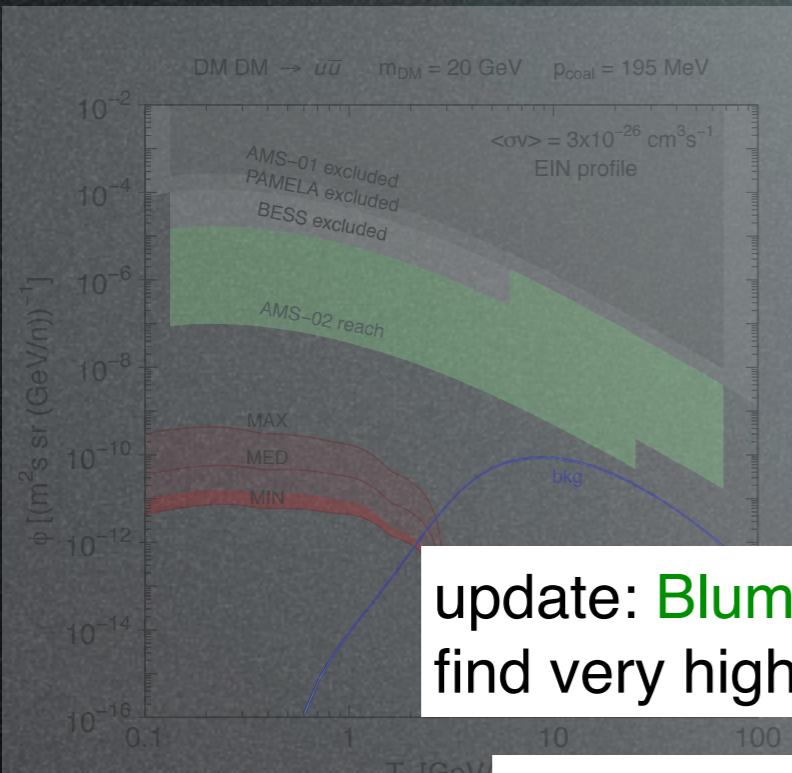
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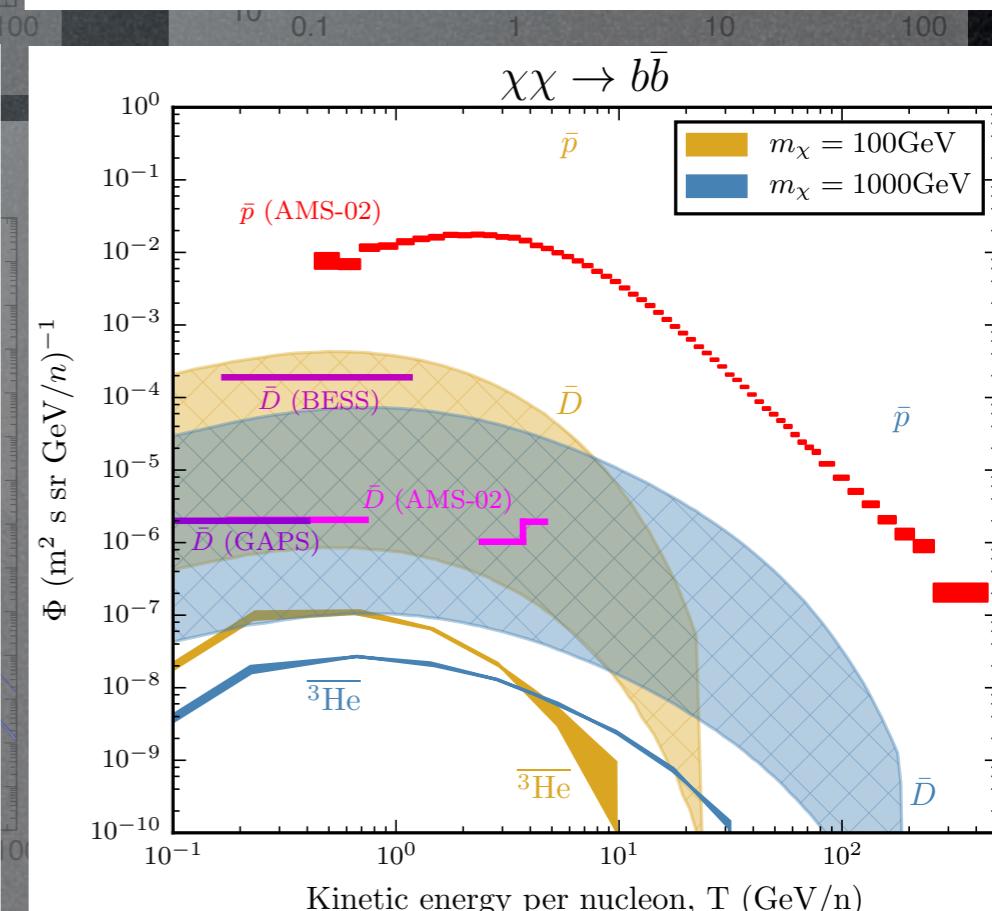
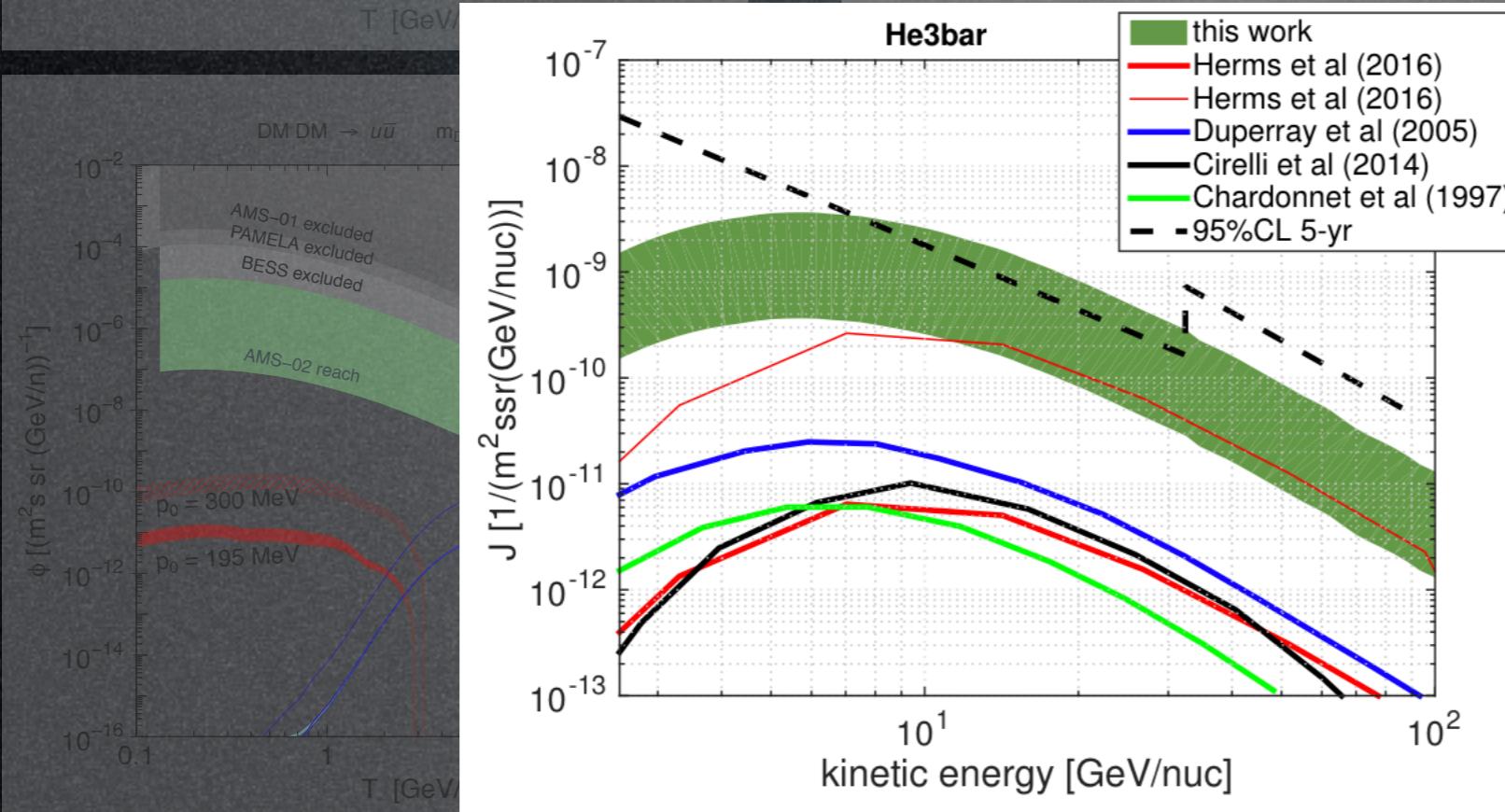
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update: Blum, Ng et al (1704.05431)
 find very high bkg calibrating on ALICE data

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



Indirect Detection

\bar{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...

also: Heck, Rajaraman (1906.01667):

\bar{He} from decay of exotic Φ carrying negative baryon number (but very fine tuned or killed by antiprotons)

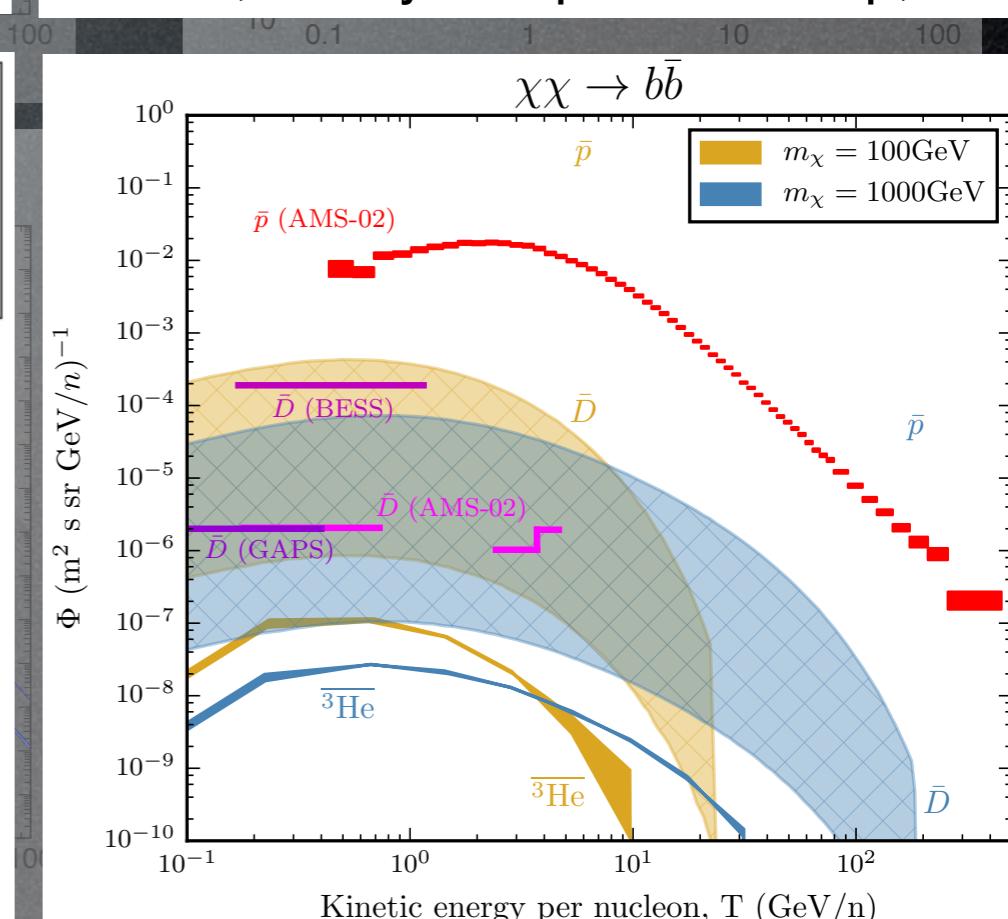
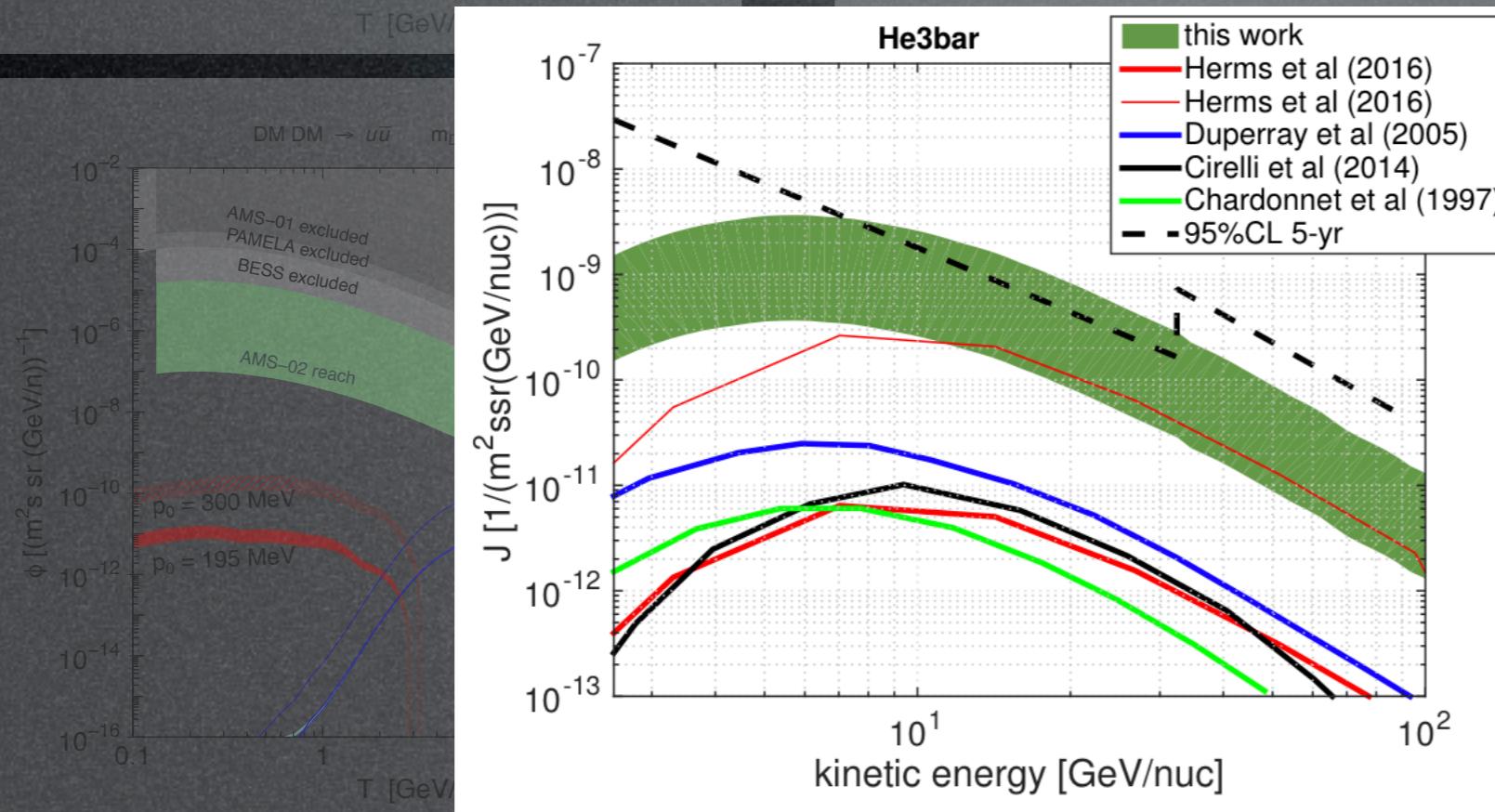
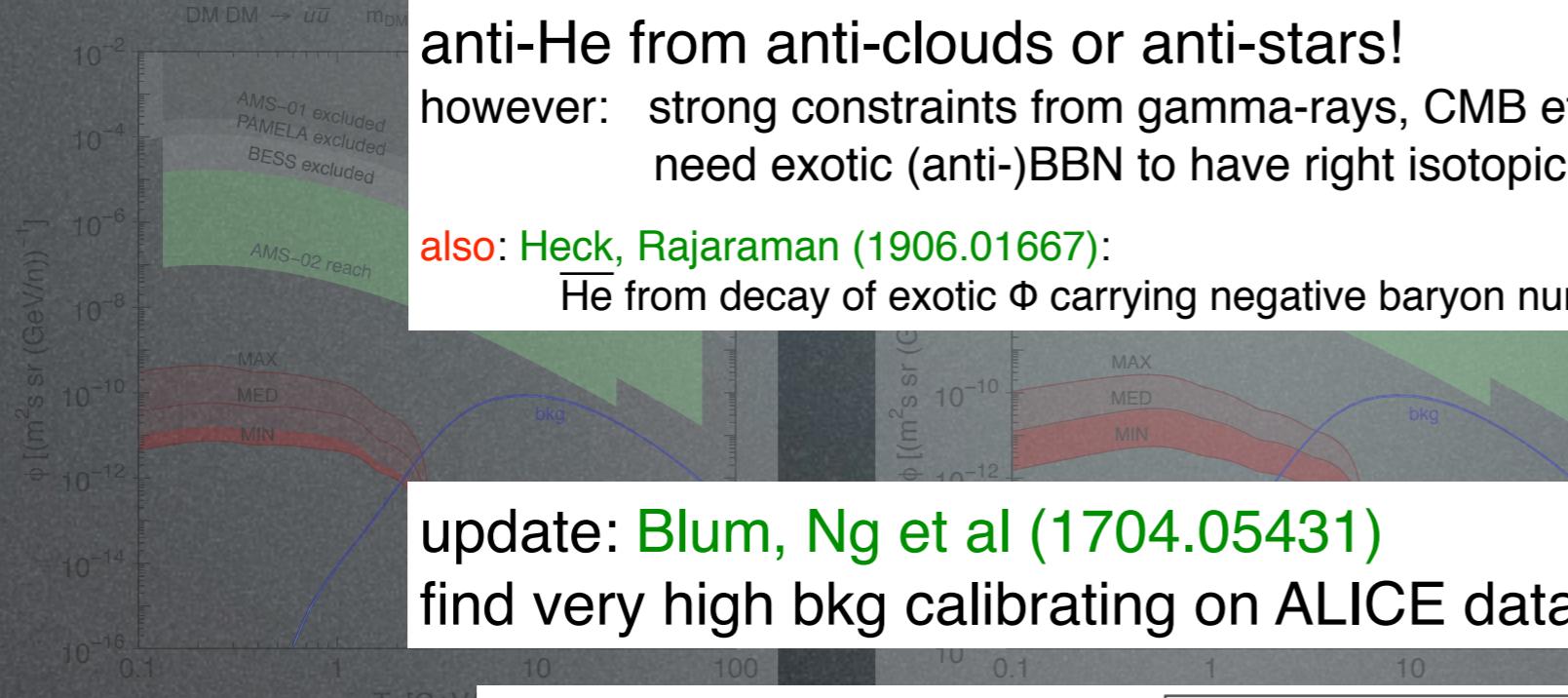
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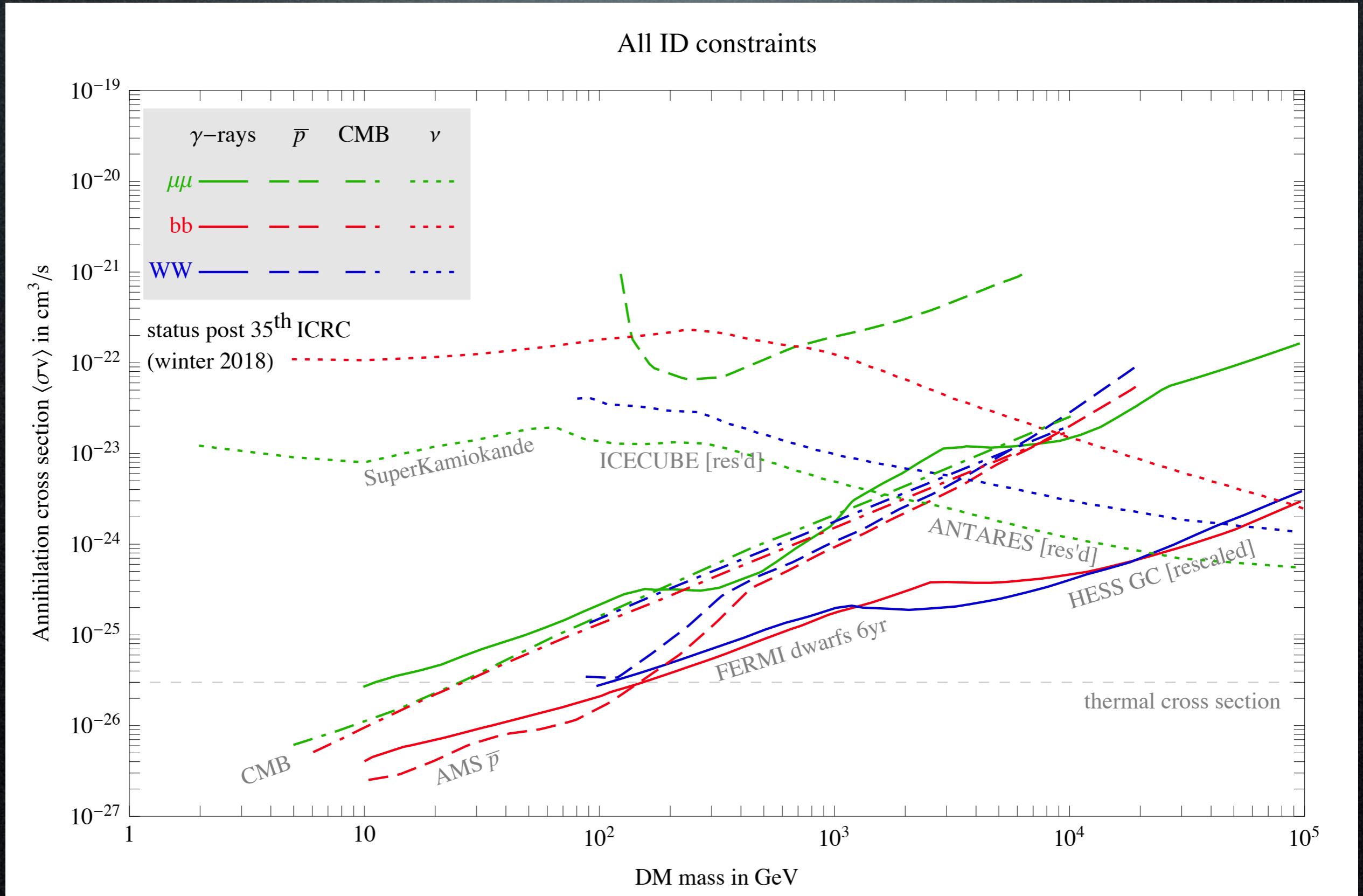
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Comparing all bounds



Conclusions

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

Conclusions

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ID with (charged) cosmic rays is in principle
a very powerful tool

Conclusions

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

ID with (charged) cosmic rays is in principle
a very powerful tool, but:

- in e^\pm : long standing ‘excesses’ at high-energies
 - new constraints at low-energies
- in \bar{p} : still large uncertainties
 - reports of excesses are greatly exaggerated
- in \bar{d} : challenging flux
- in \bar{He} : hopeless? who knows...

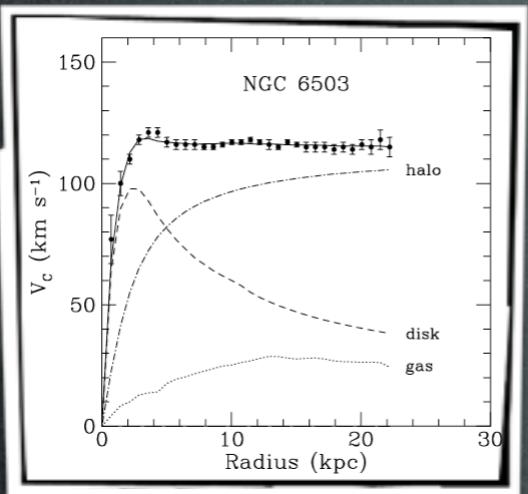
Back up slides

Introduction

DM exists

Introduction

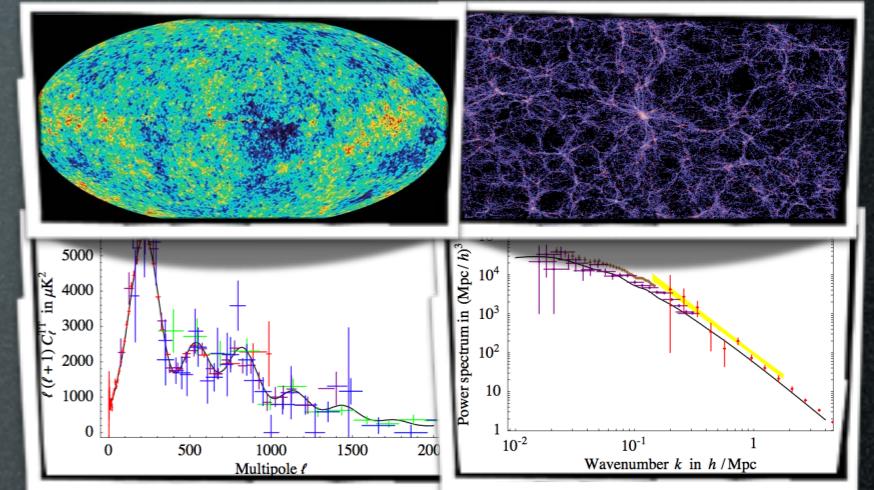
DM exists



galactic rotation curves



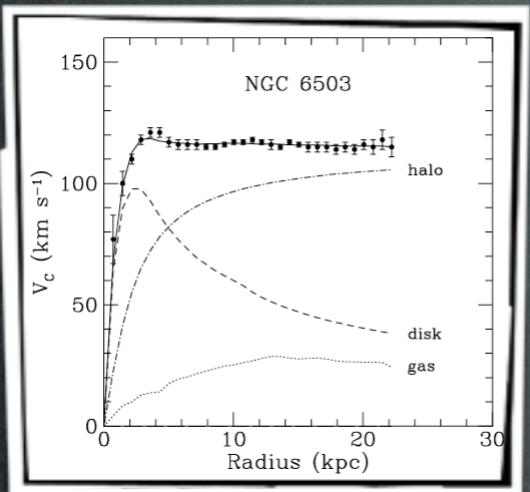
weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Introduction

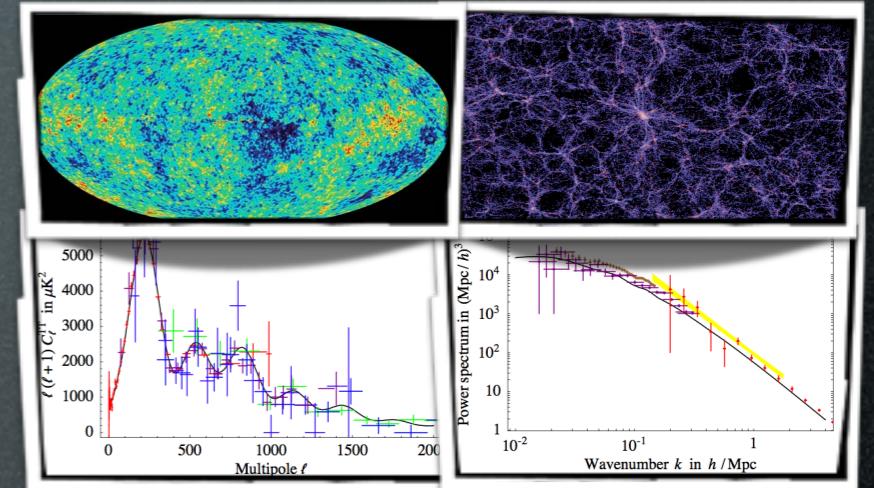
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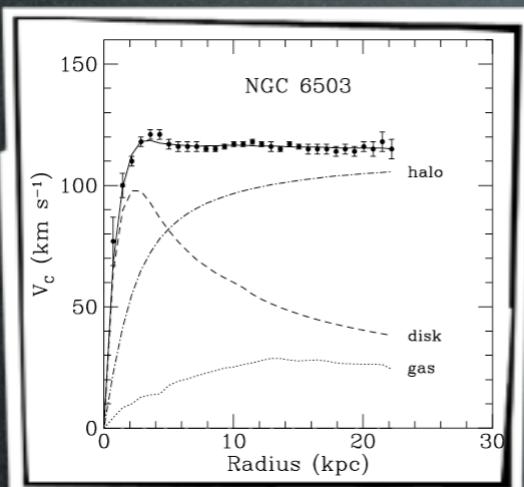


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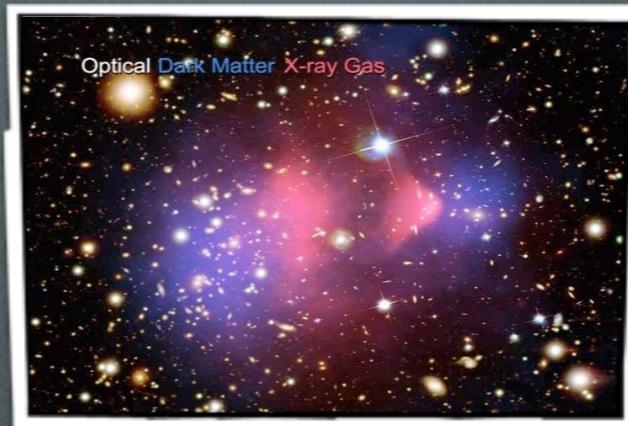
DM is a neutral, very long lived,
feebly interacting particle.

Introduction

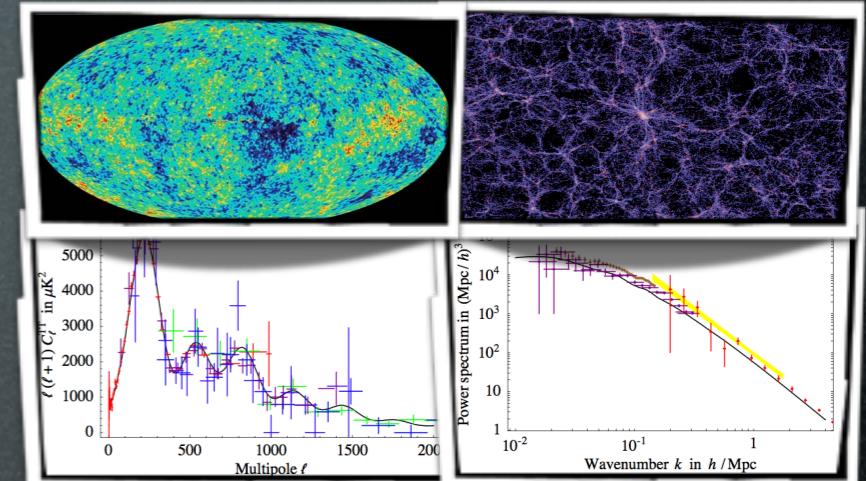
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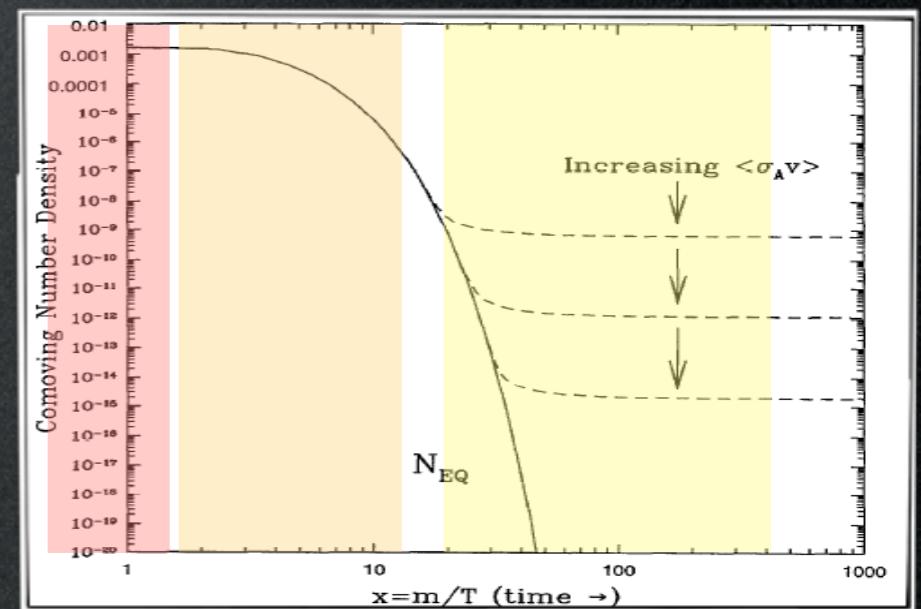


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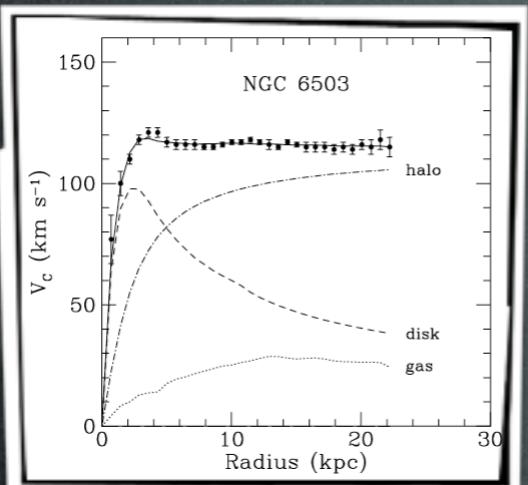
Some of us believe in
the WIMP miracle.

- 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

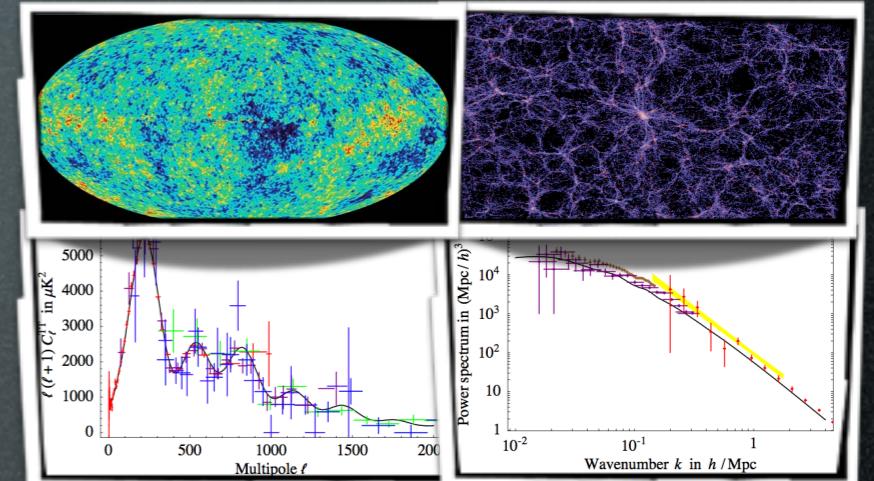
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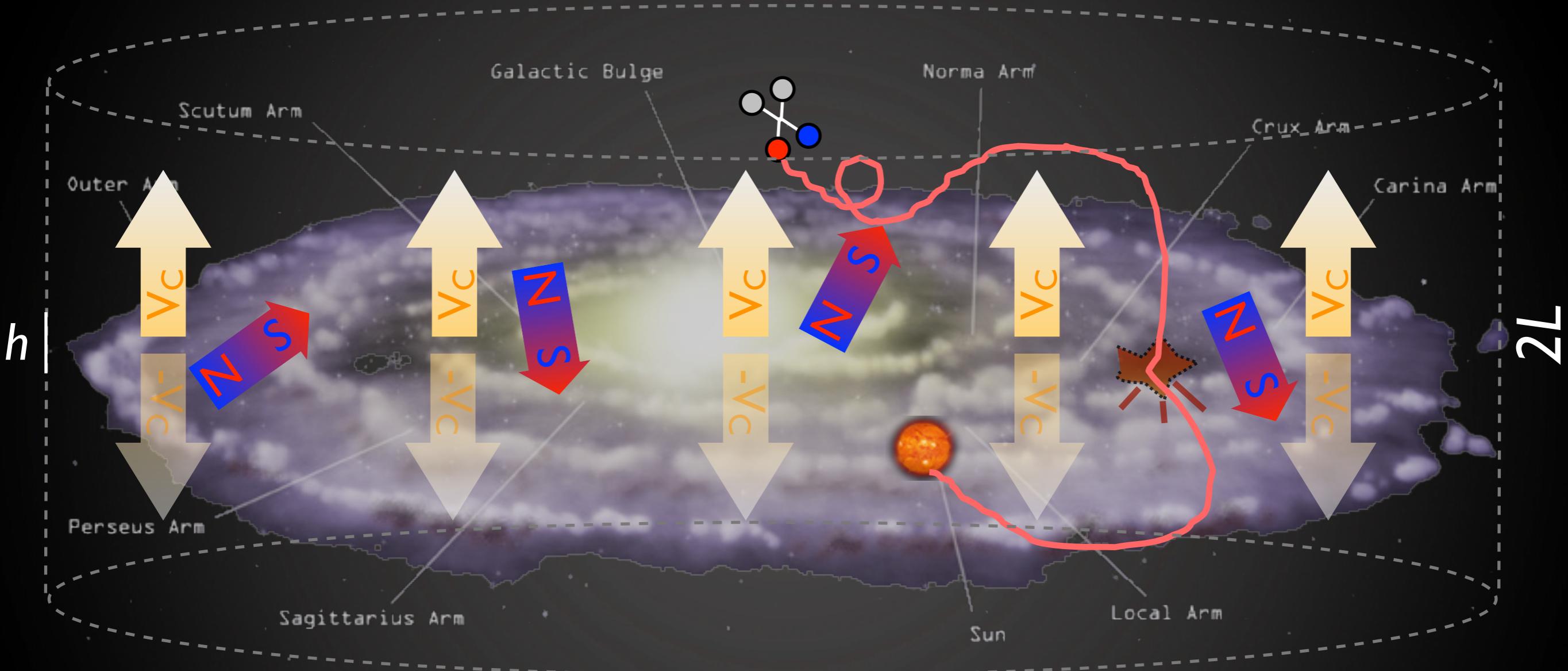
'precision cosmology' (CMB, LSS)

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

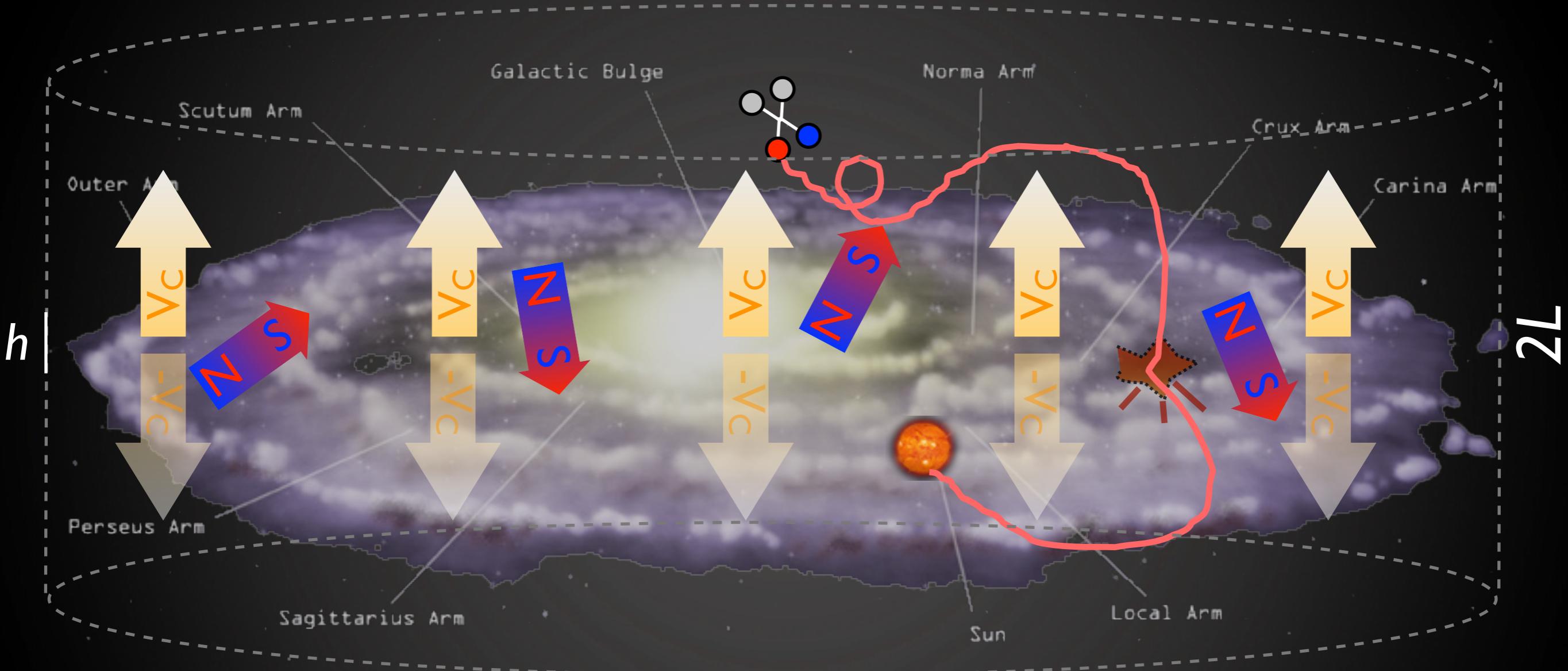


What sets the overall expected flux?

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

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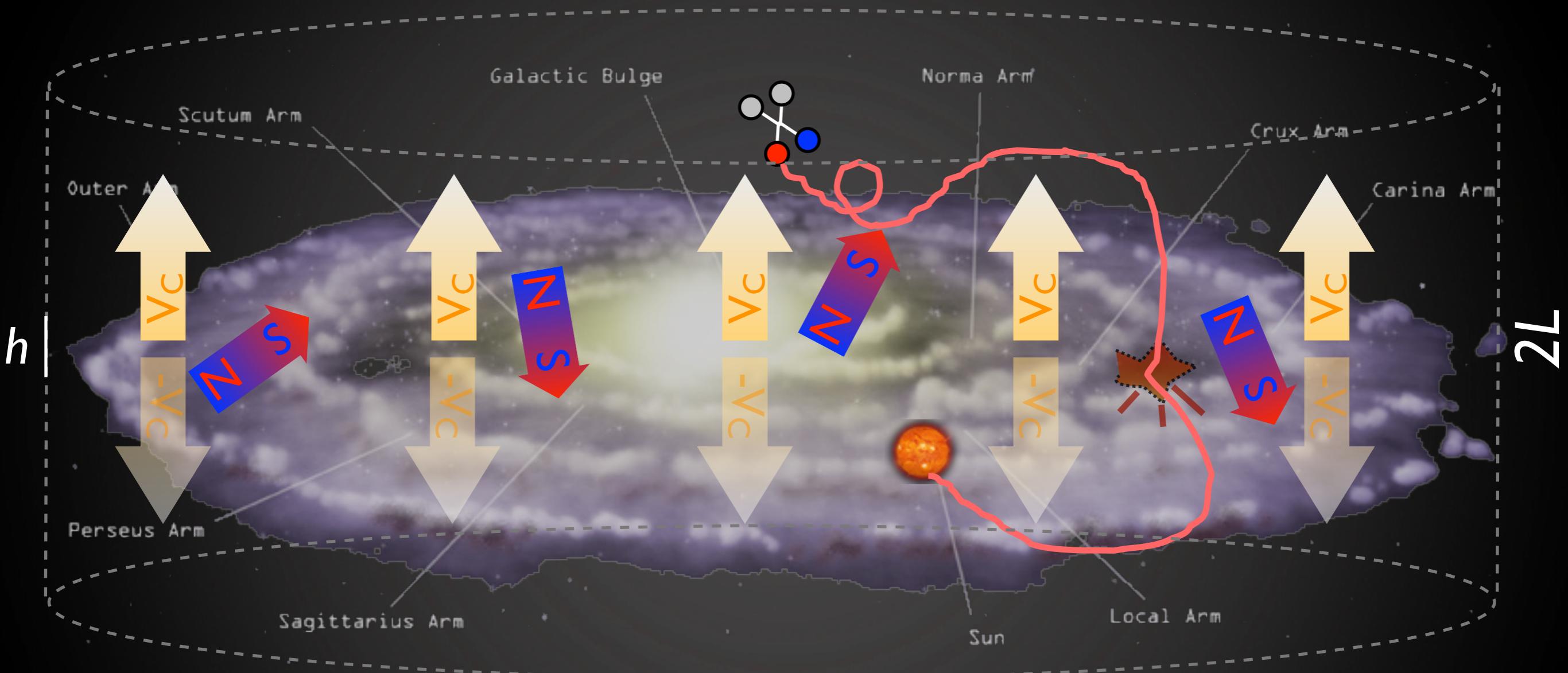
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astro&cosmo

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What sets the overall expected flux?

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

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:

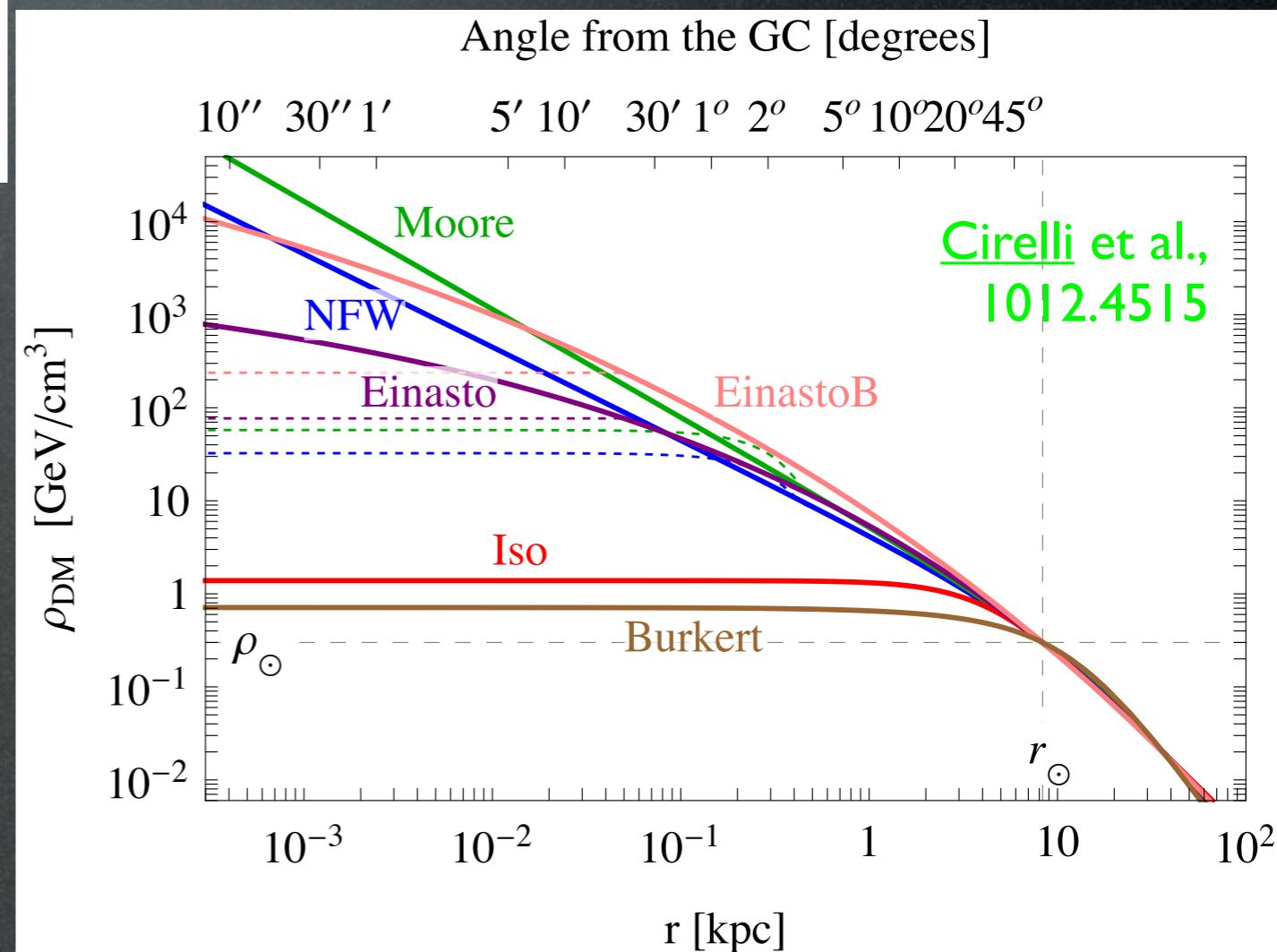
cuspy: **NFW, Moore**

mild: **Einasto**

smooth: **isothermal, Burkert**

EinastoB = steepened Einasto
(effect of baryons?)

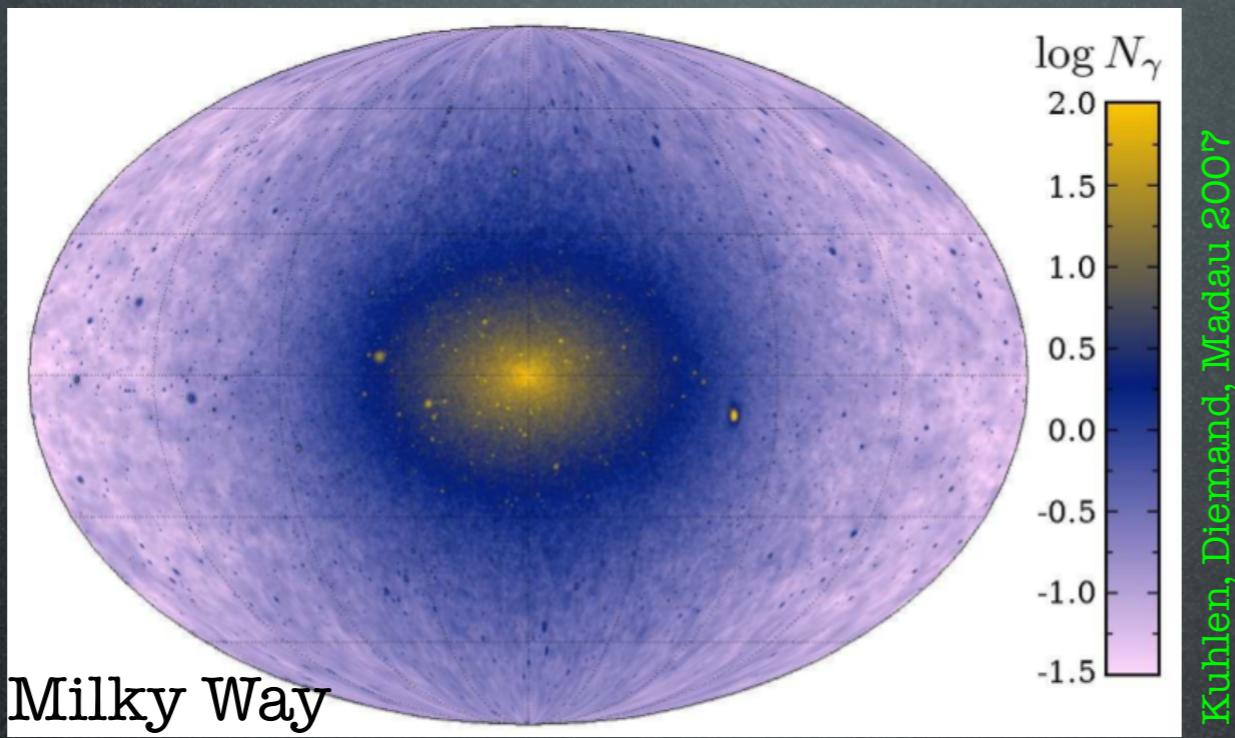
DM halo	α	r_s [kpc]	ρ_s [GeV/cm ³]
NFW	—	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	—	4.38	1.387
Burkert	—	12.67	0.712
Moore	—	30.28	0.105



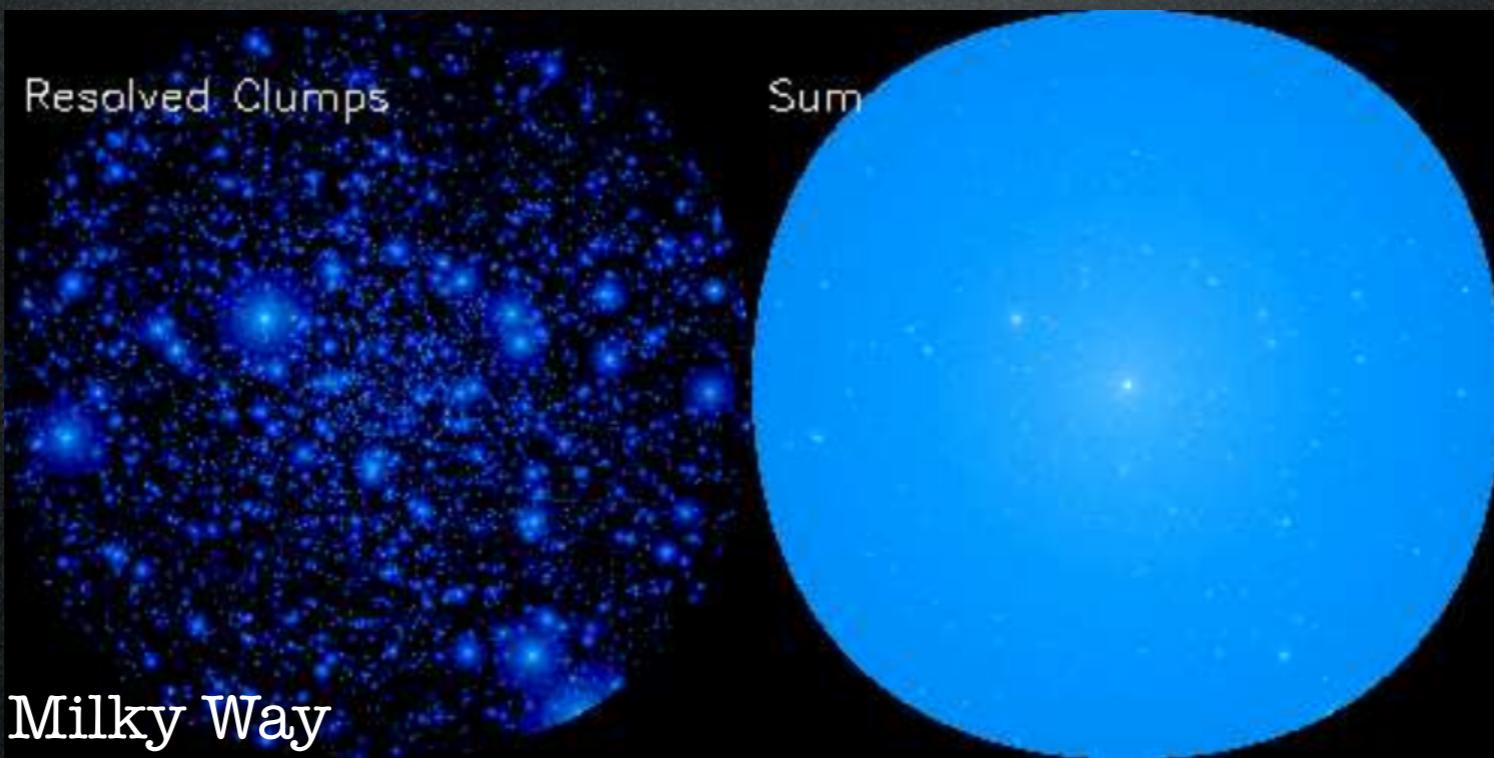
DM halo profiles

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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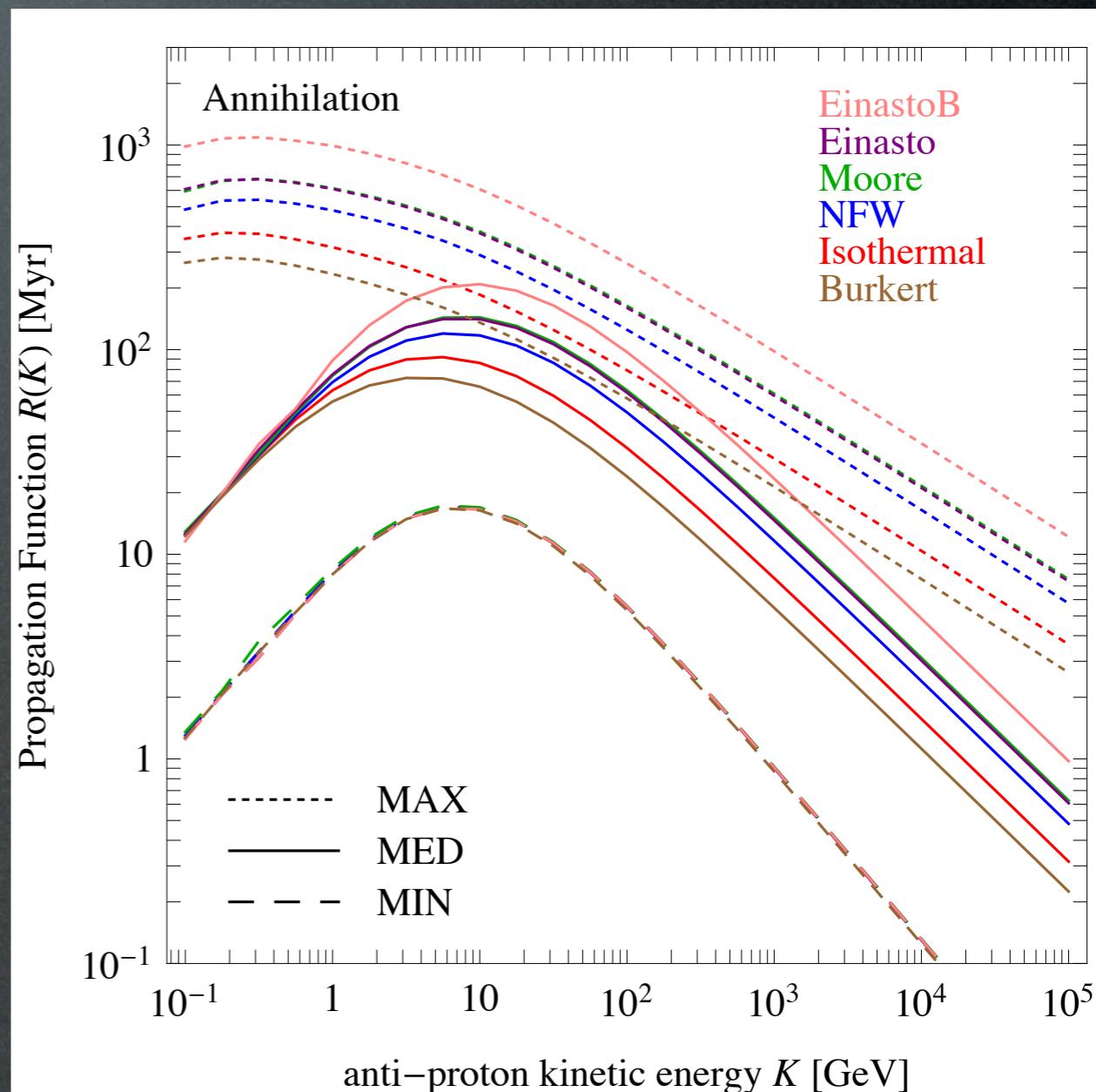
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DM detection

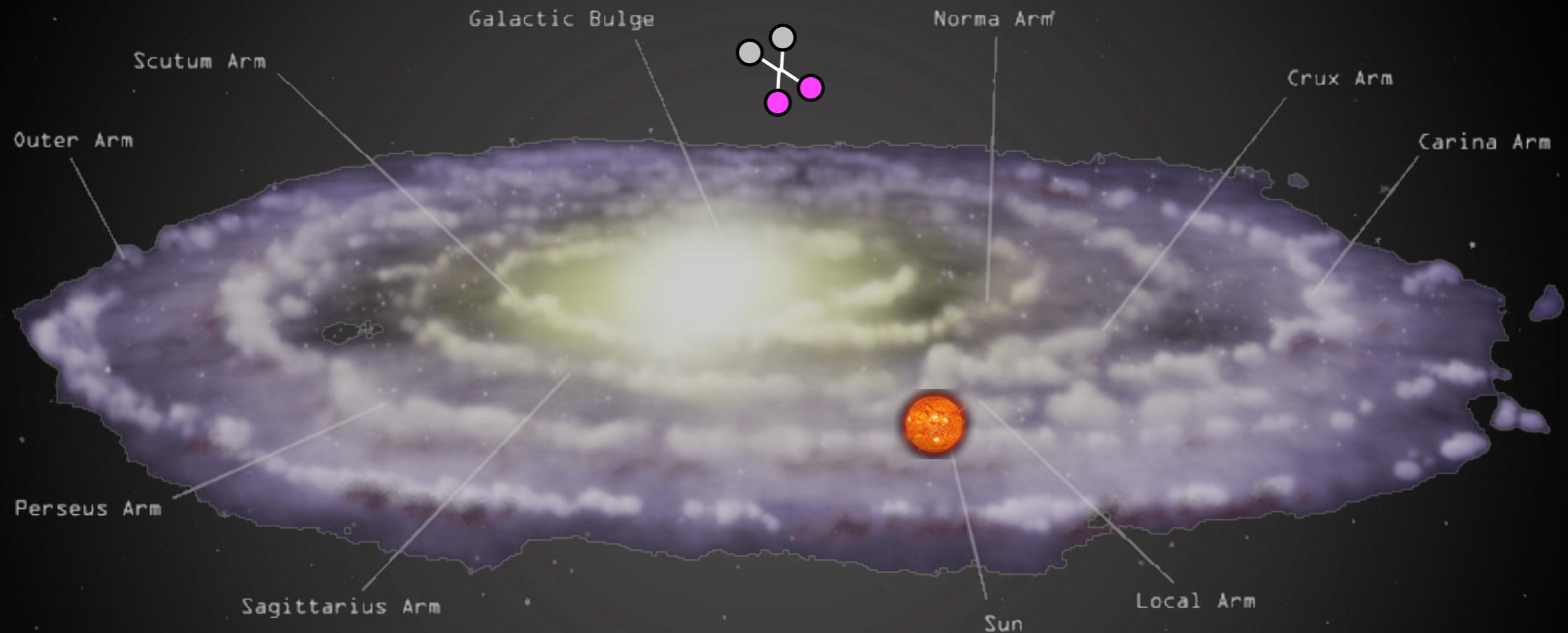
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and from secondary emission Fermi, ICT, radio telescopes...
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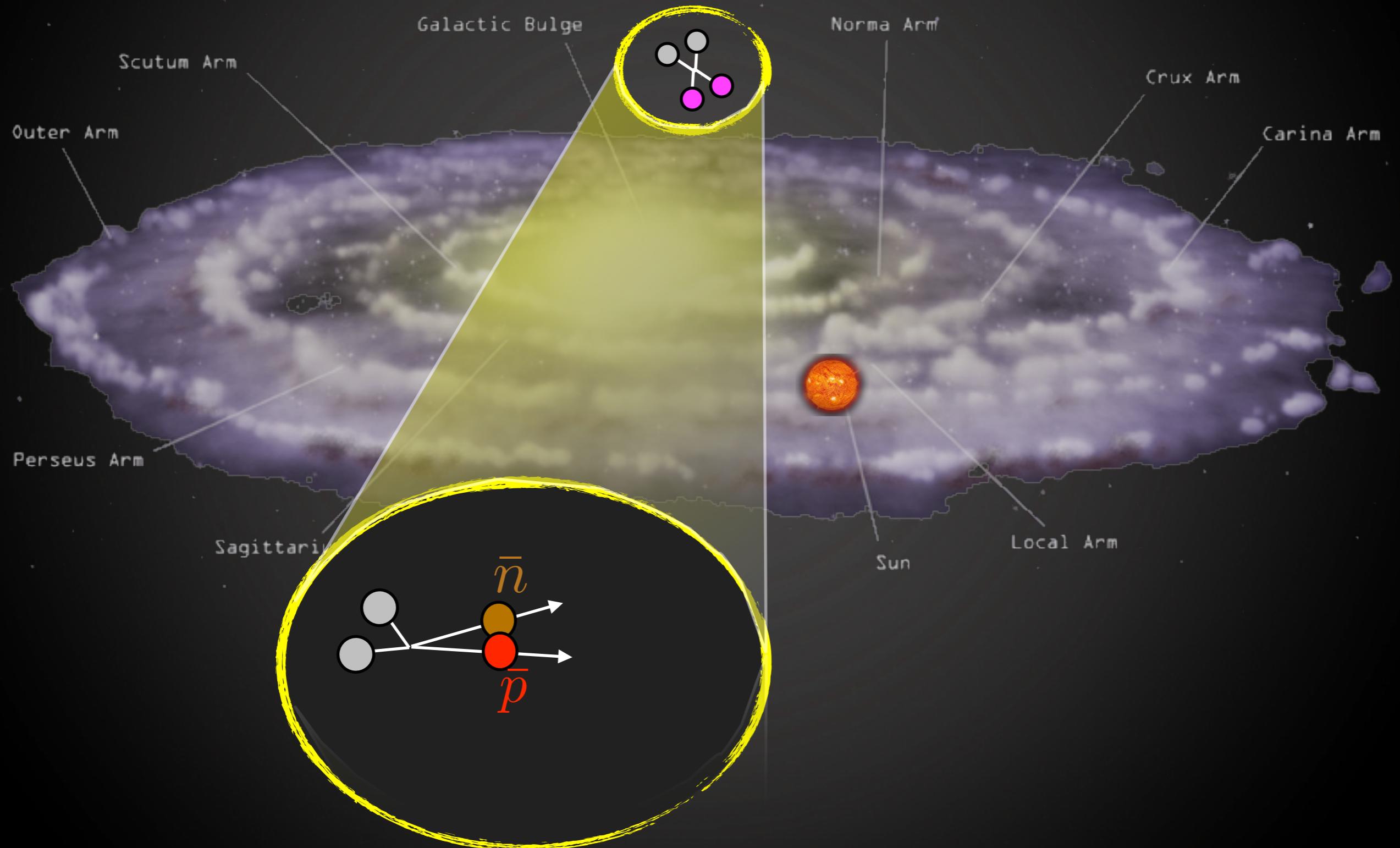
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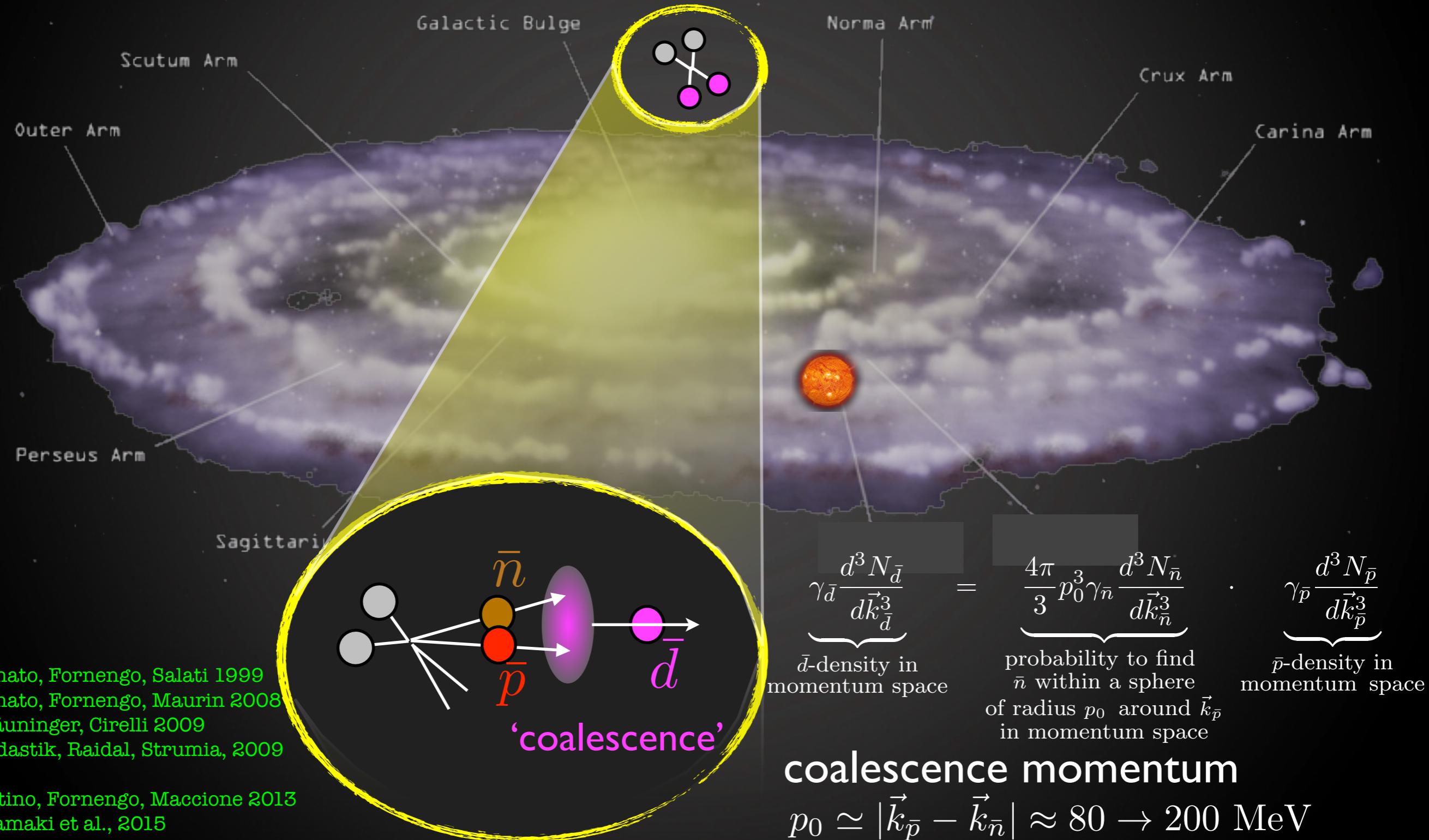
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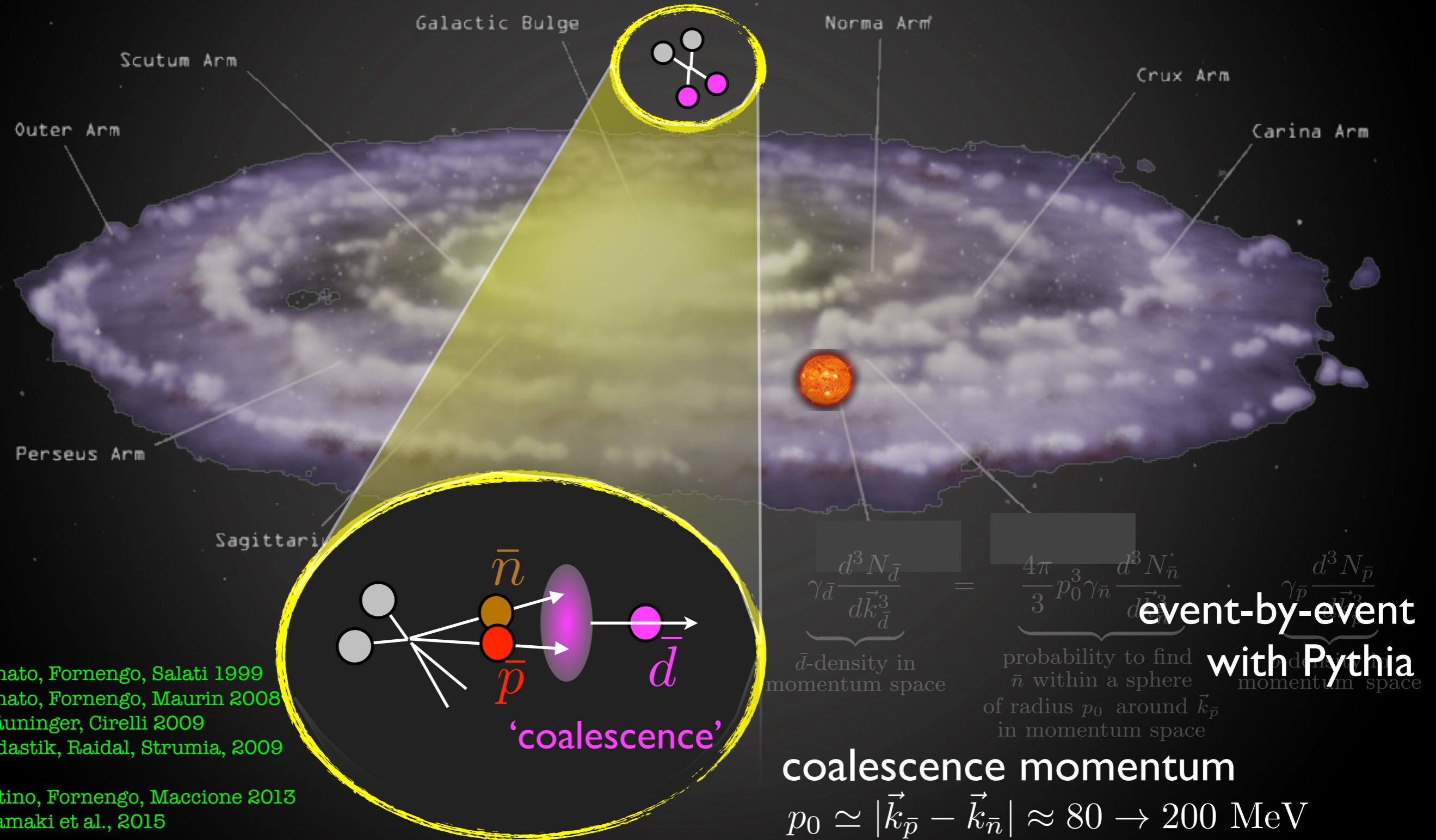
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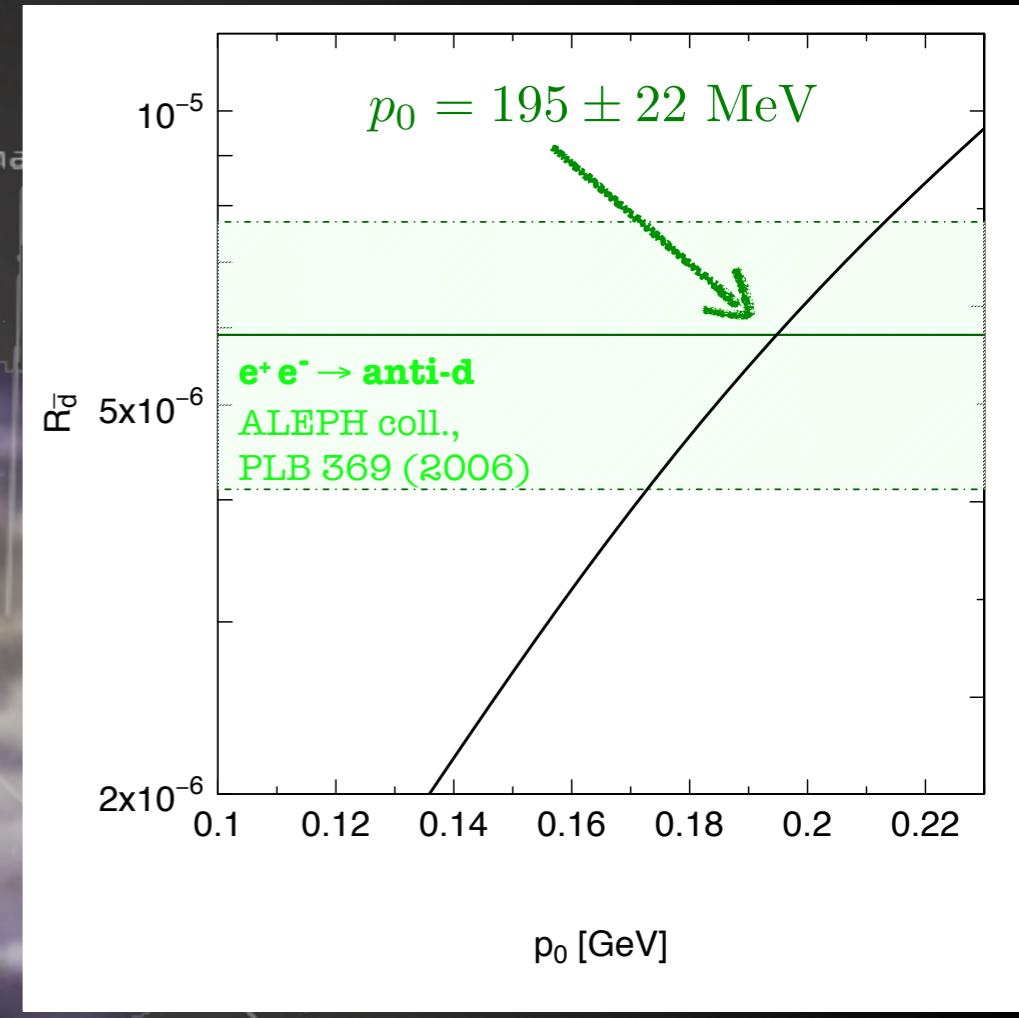
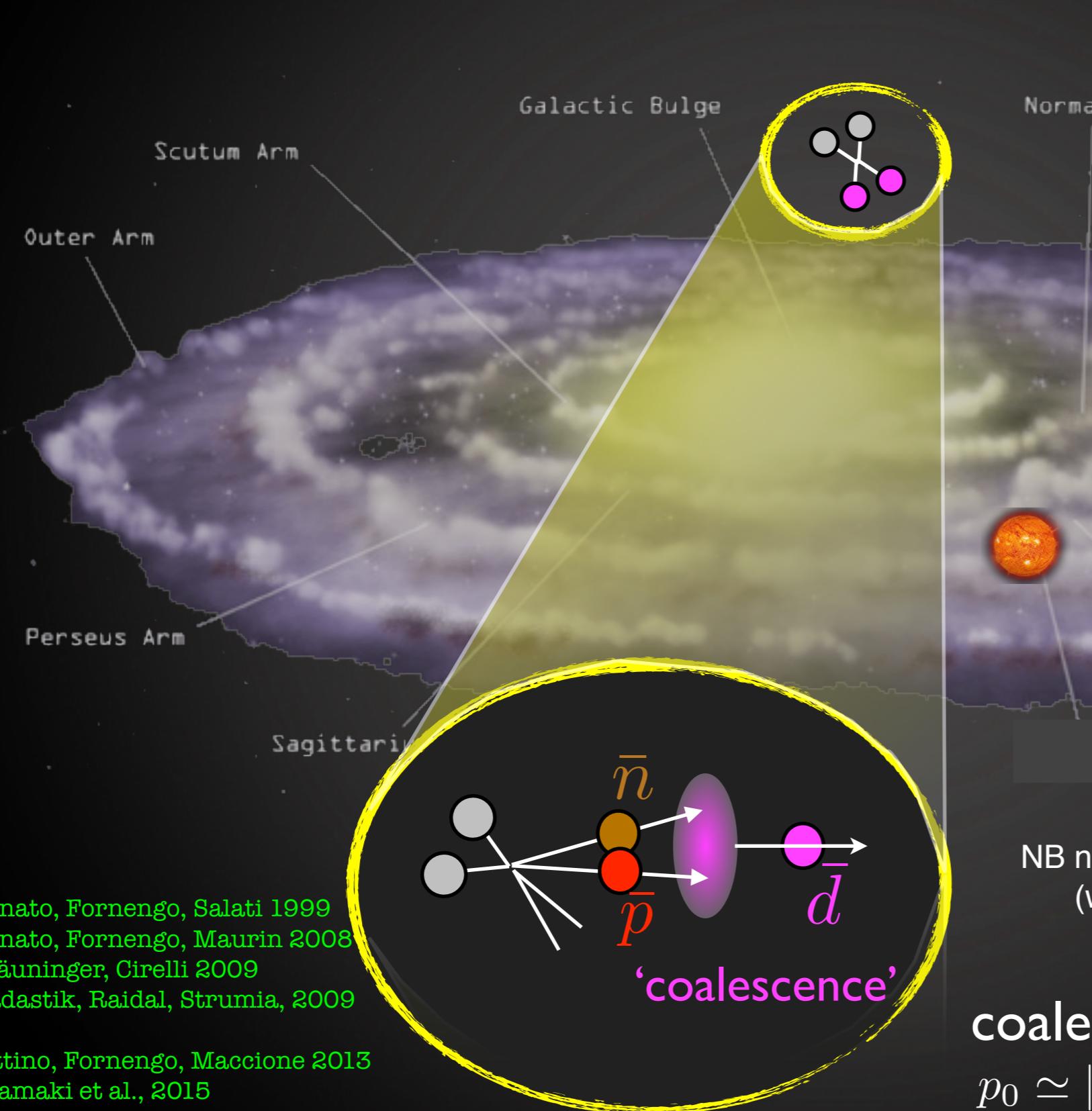
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Indirect Detection

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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...

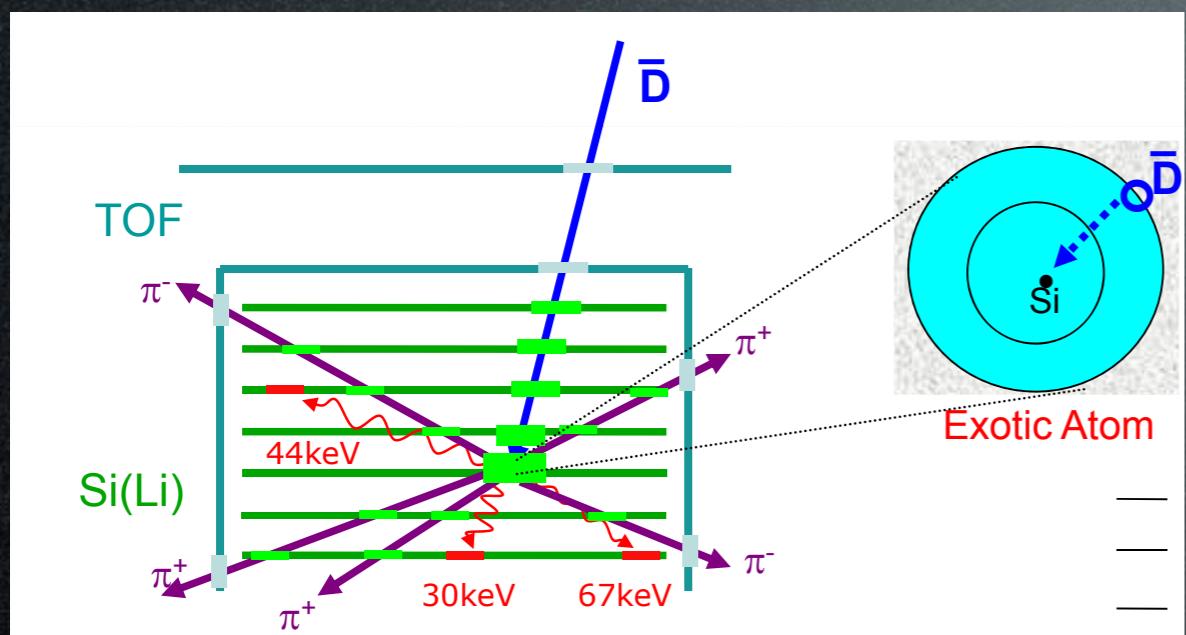
coalescence momentum

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

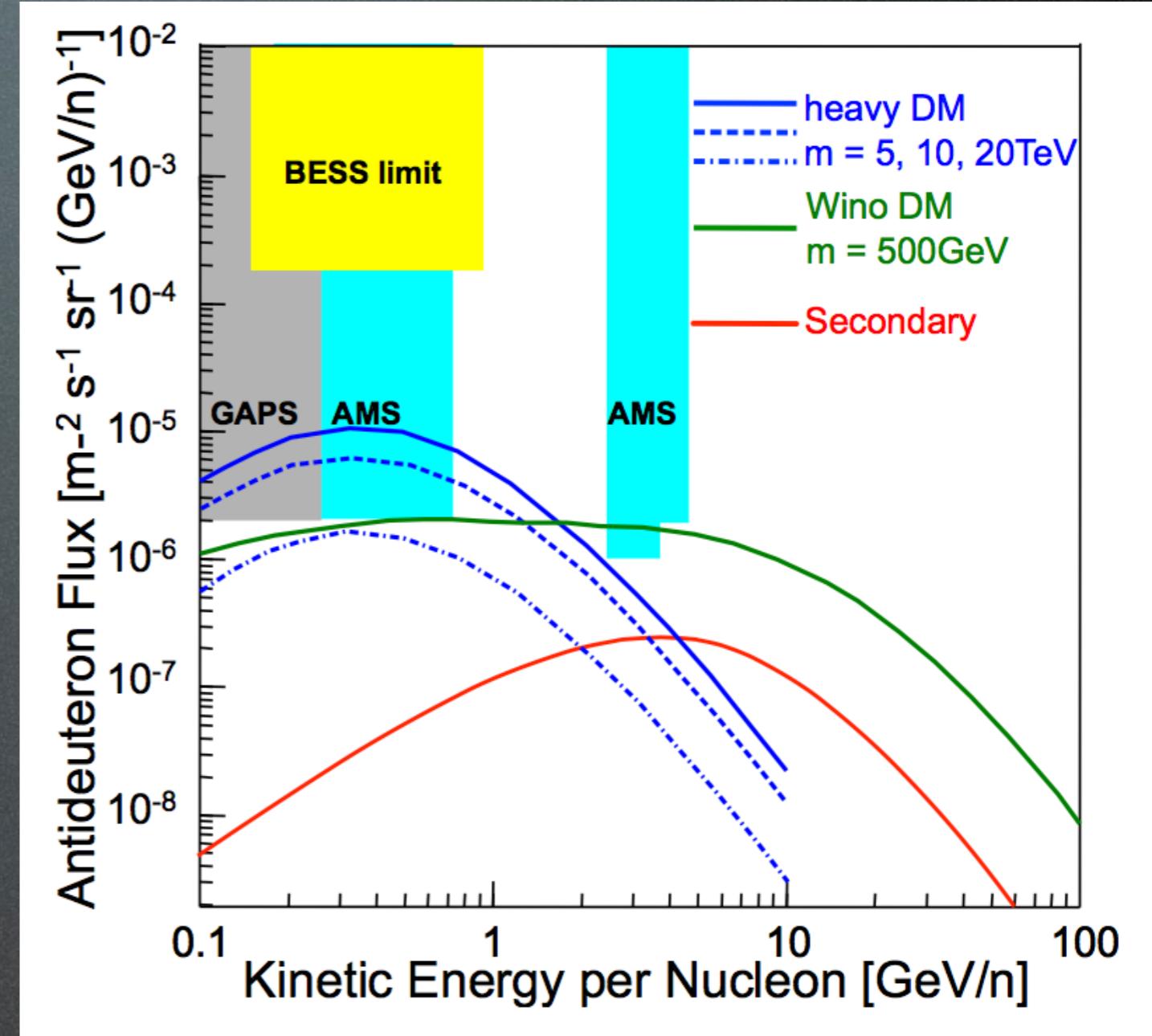
Indirect Detection

\bar{d} from DM annihilations in halo

GAPS detection principle



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



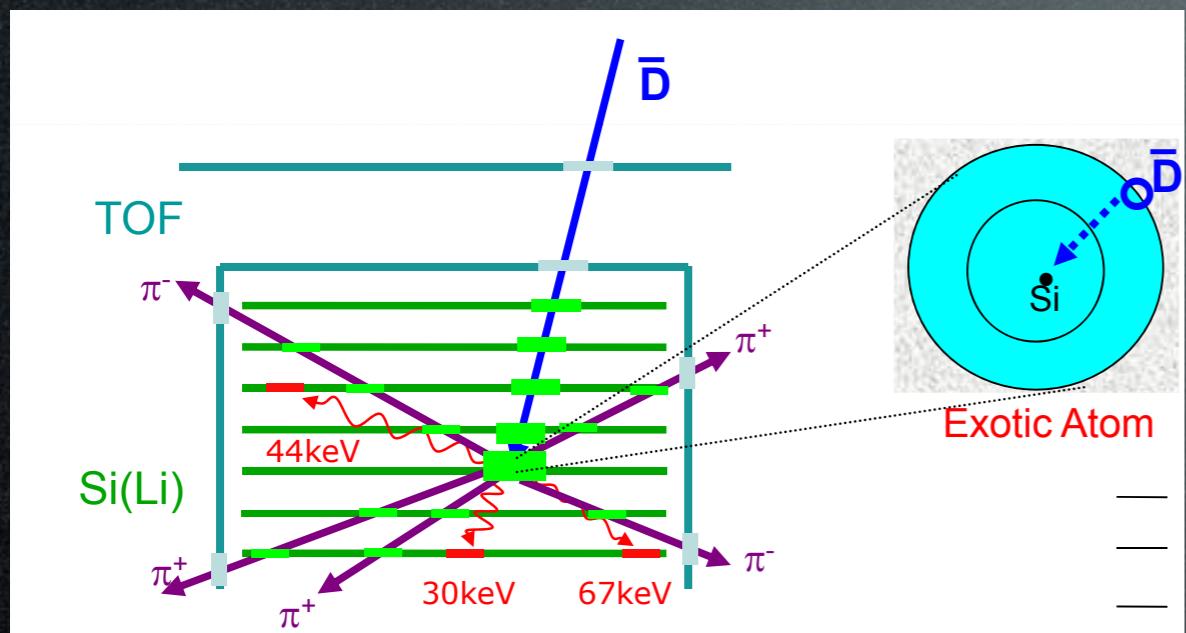
P. von Doetinchem et al., 2015

DM signal in the reach
of GAPS and AMS-02

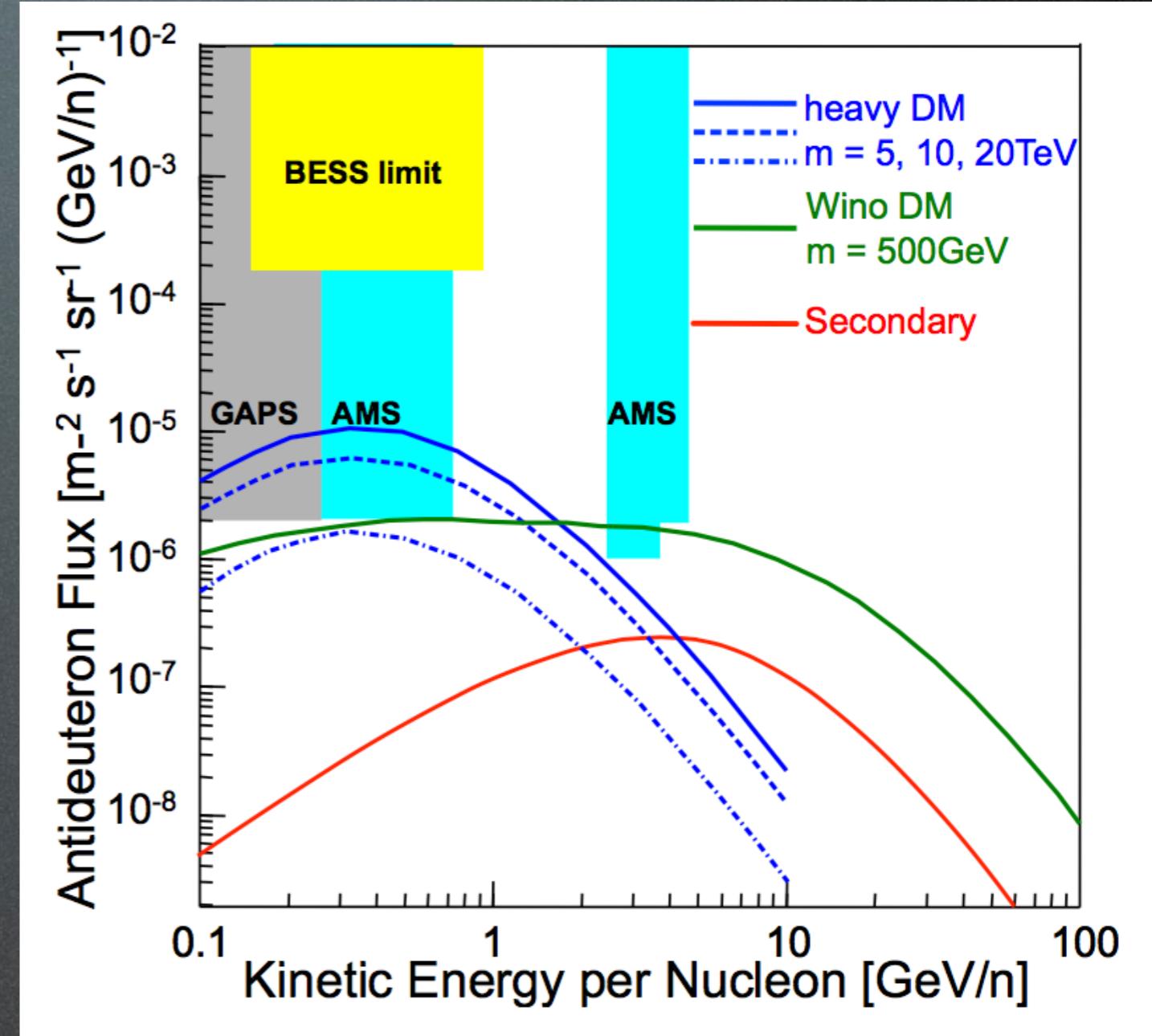
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