19 October 2021
Rencontres de Blois

Dark Matter Indirect Searches

as of 2021

Marco Cirelli

(CNRS LPTHE Jussieu)

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Selected topics in...

Dark Matter Indirect Searches

as of 2021

Marco Cirelli

(CNRS LPTHE Jussieu)

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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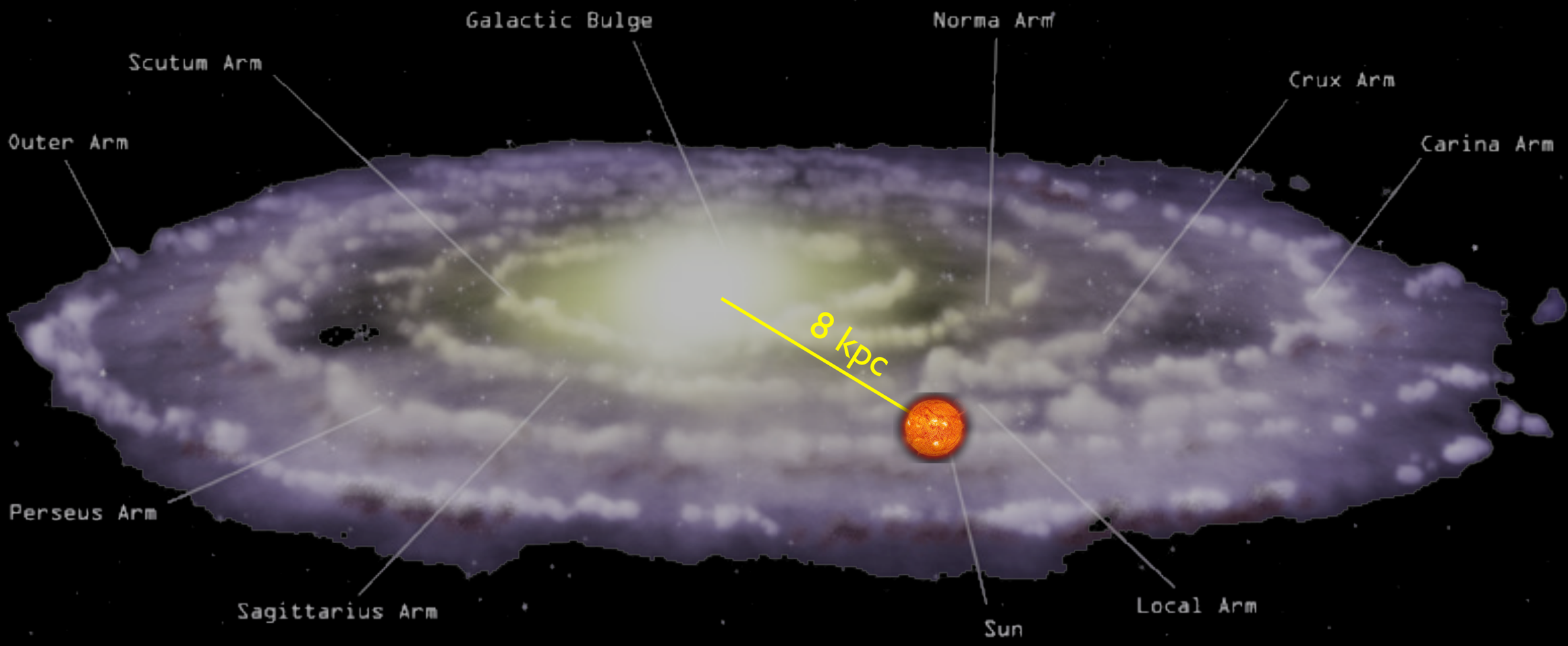
Indirect Detection: basics

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



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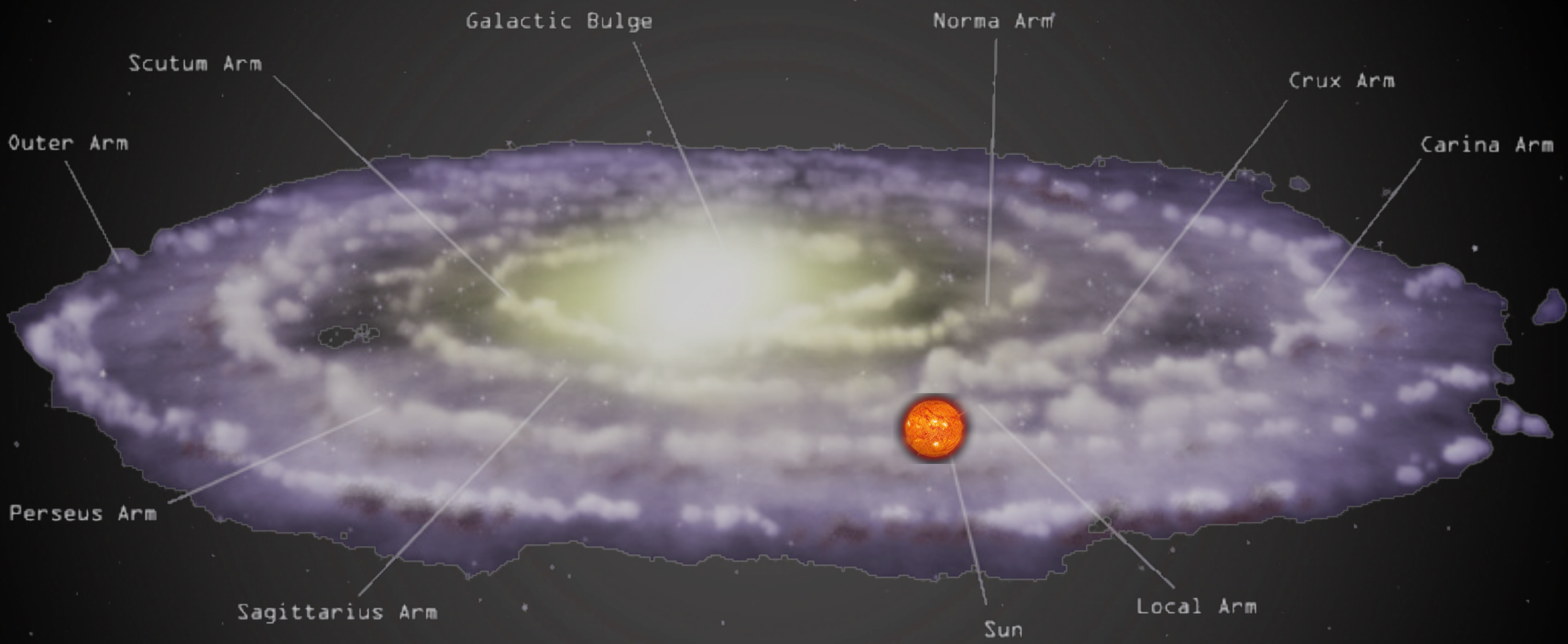

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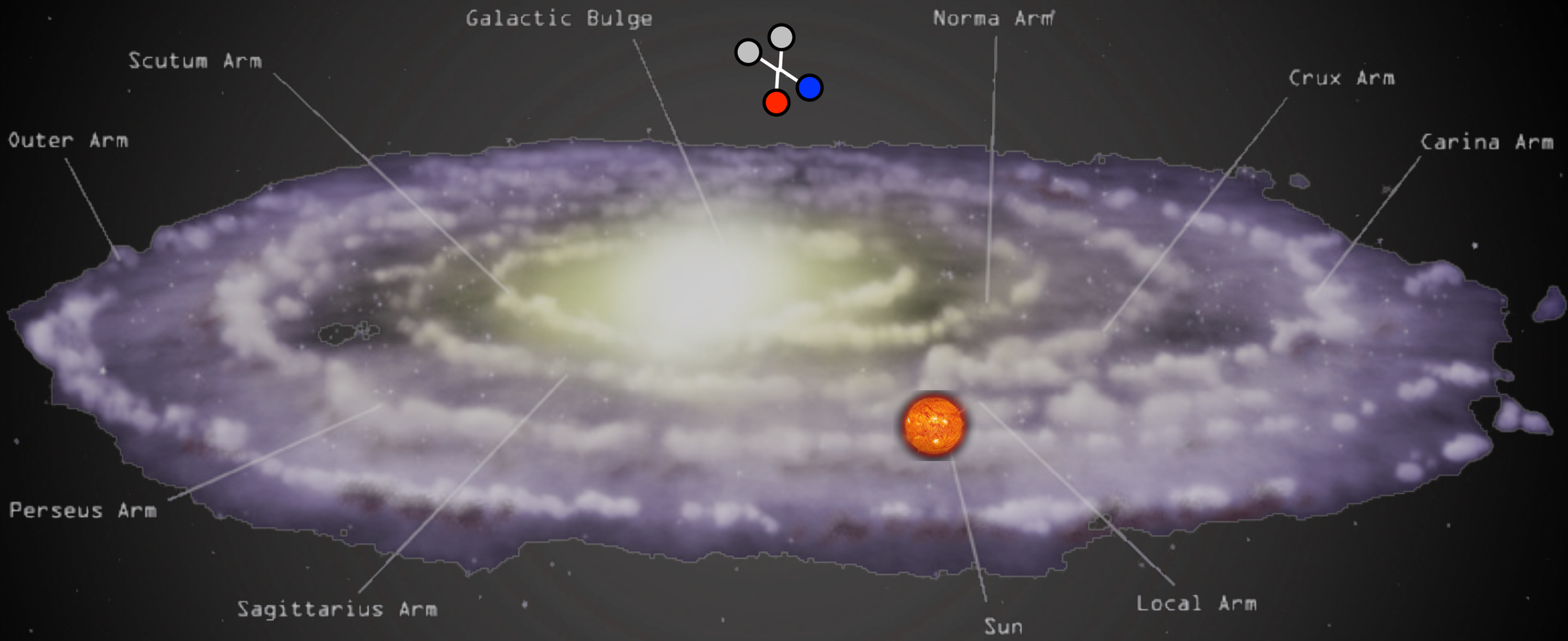

Indirect Detection: charged CRs

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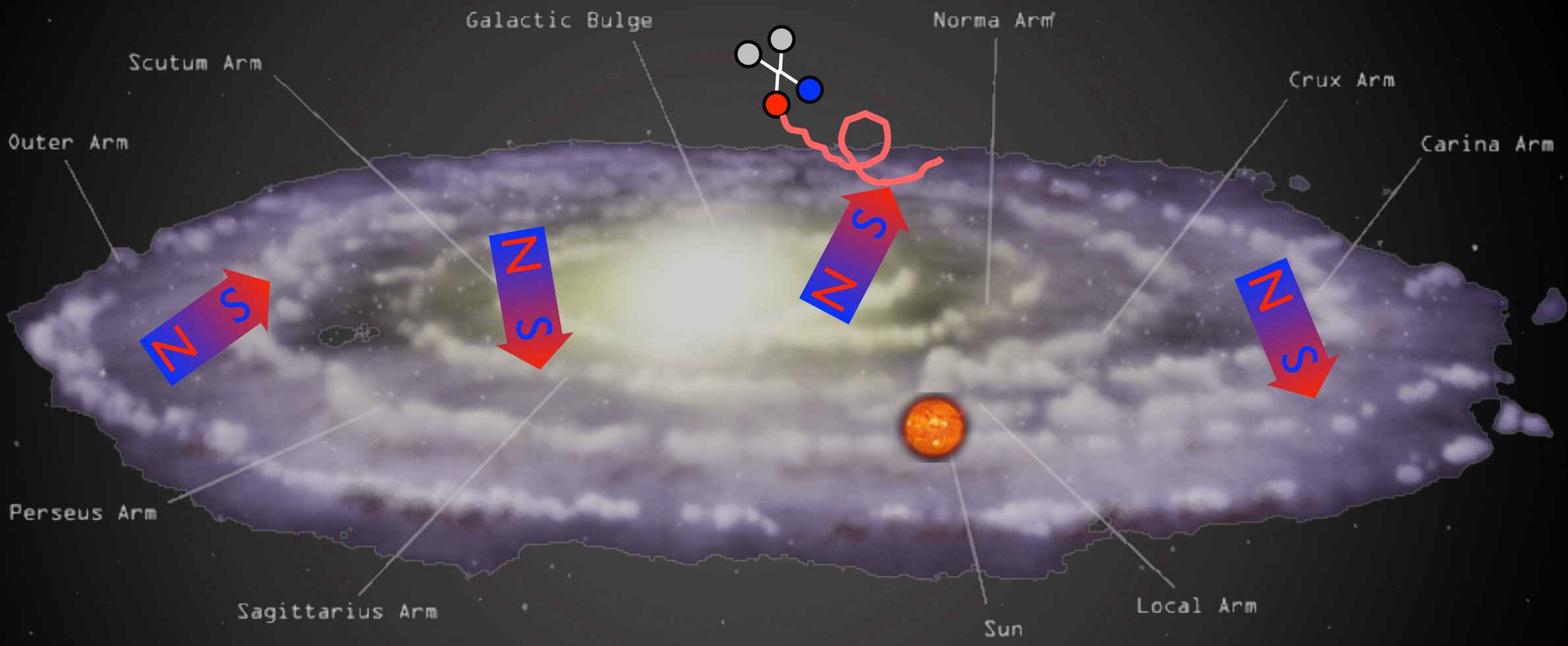

Indirect Detection: charged CRs

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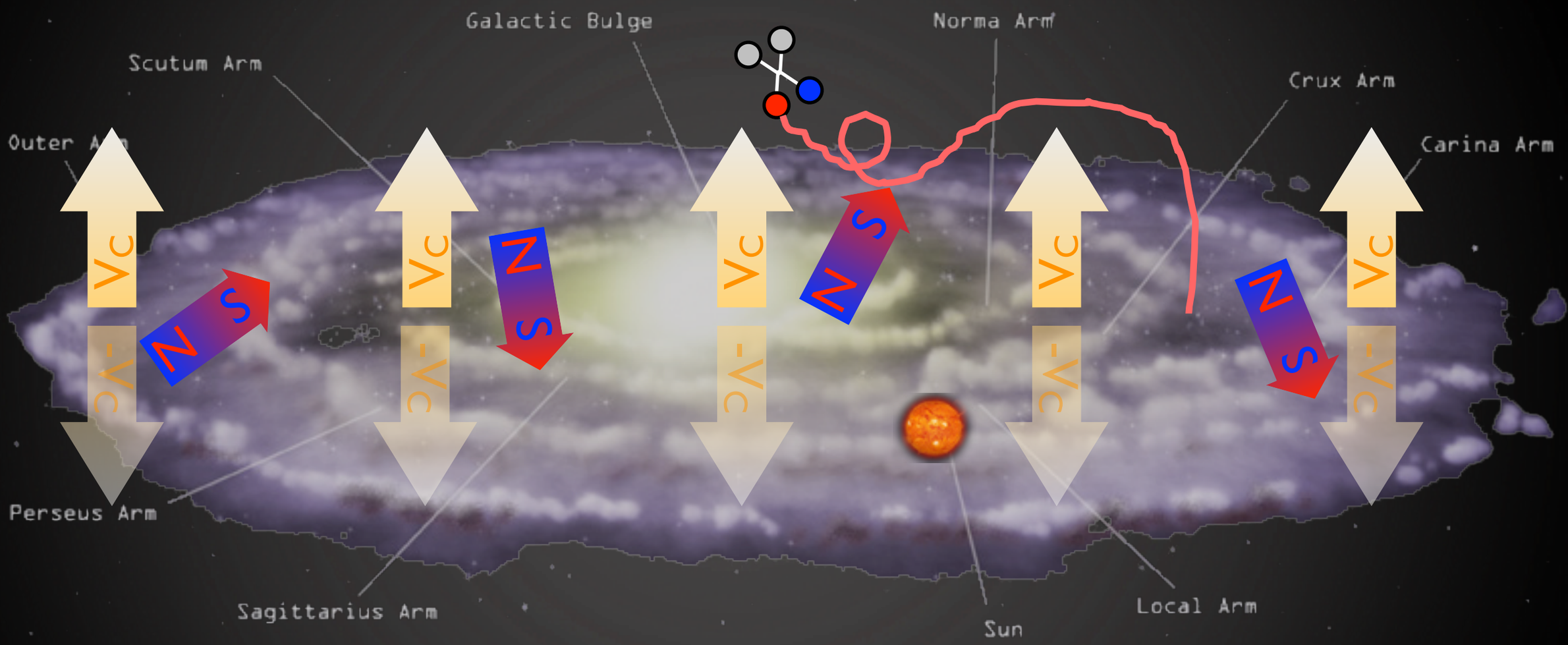

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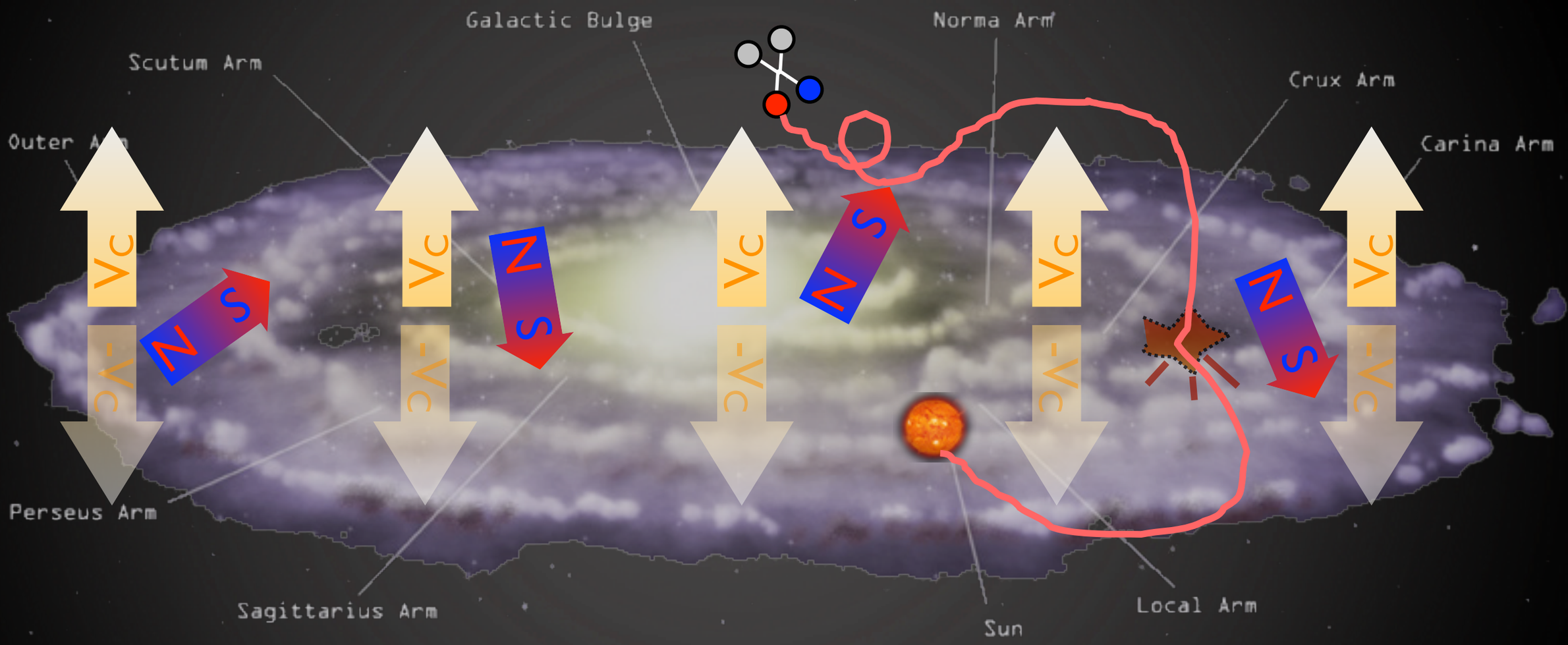

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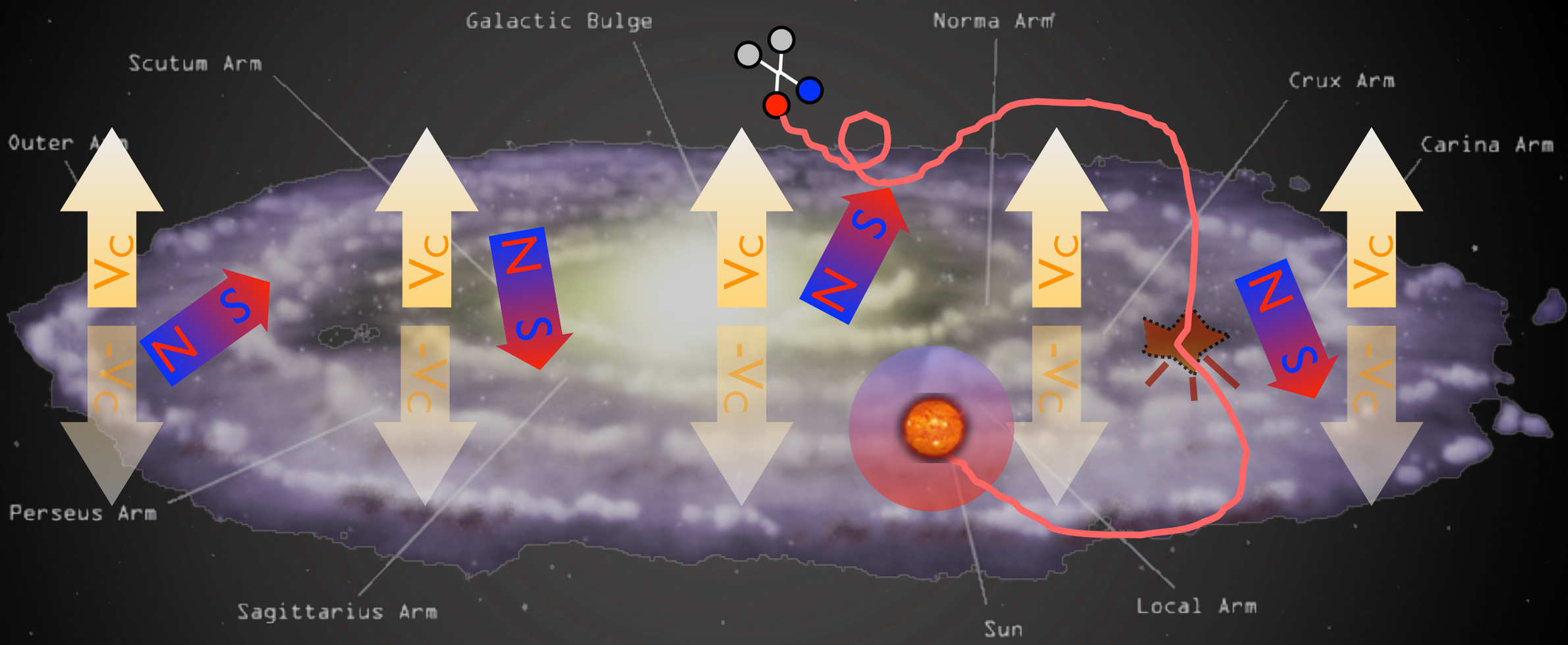

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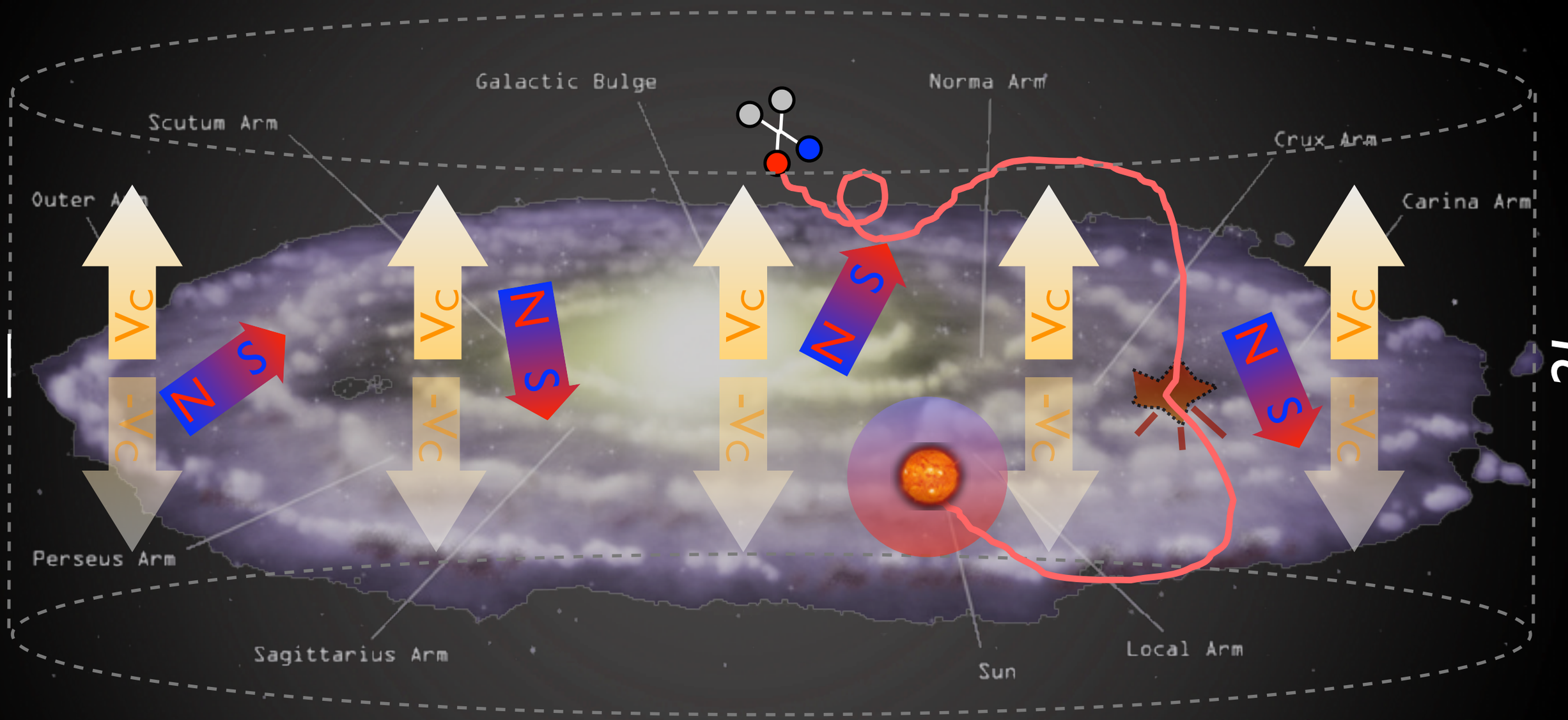


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

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

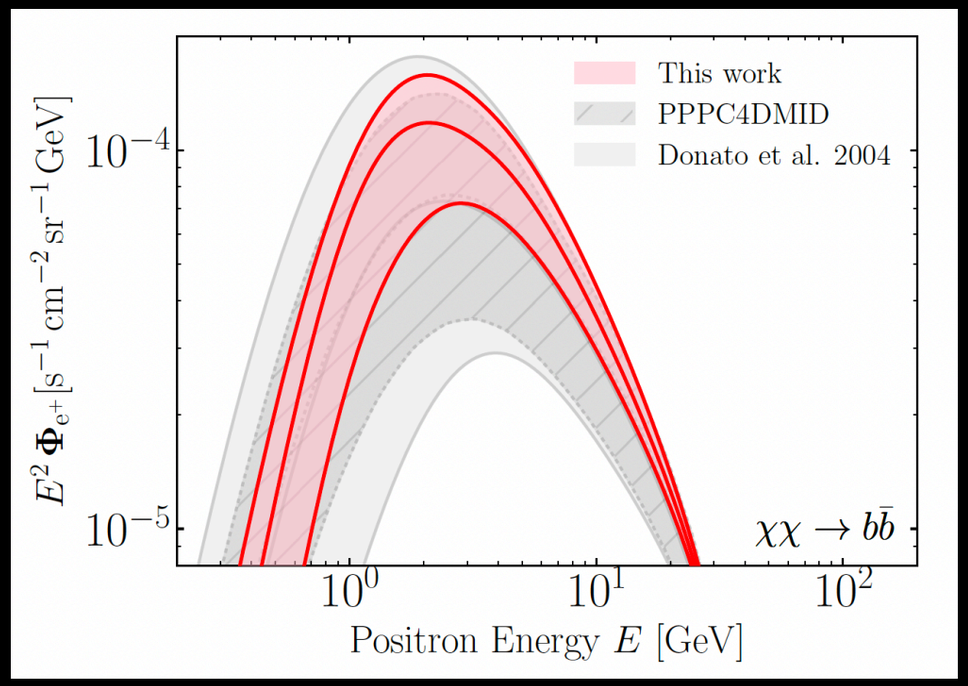
TABLE I: Propagation parameters for the MIN, MED, and MAX benchmarks for SLIM.

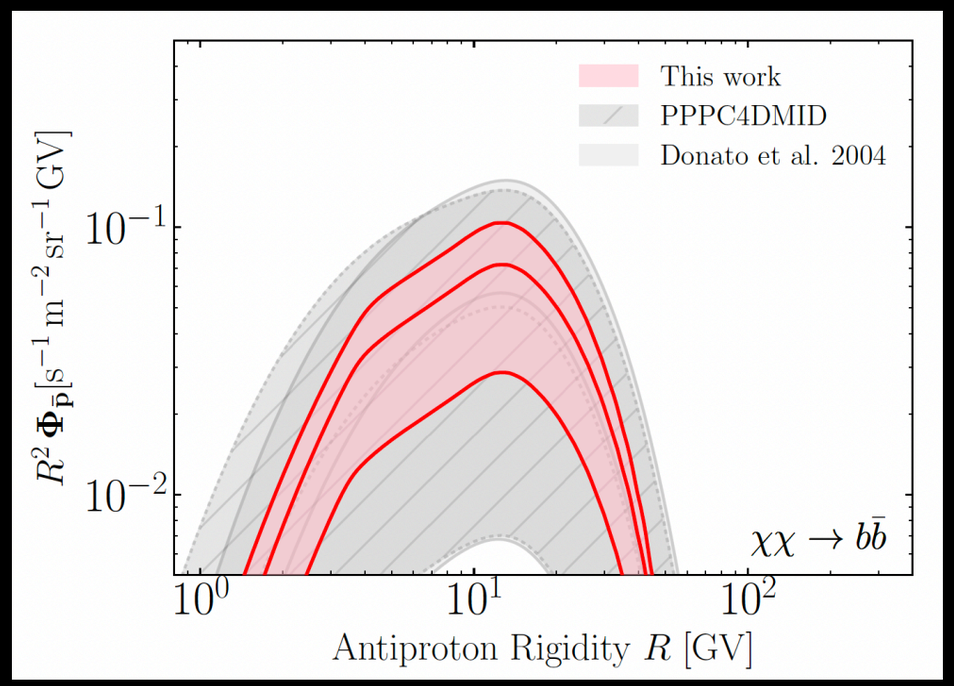
SLIM	L [kpc]	δ	$\log_{10} K_0$ [kpc^2 Myr^{-1}]	R_l [GV]	δ_l
MAX	8.40	0.490	-1.18	4.74	-0.776
MED	4.67	0.499	-1.44	4.48	-1.11
MIN	2.56	0.509	-1.71	4.21	-1.45

Previous historical determinations:
Donato et al., 2003+
Delahaye et al. 0712.2312
Cirelli et al. 1012.4515
Evoli et al. 1108.0664
…
See also:
Génolini et al. 1904.08917

Génolini, Cirelli et al. 2103.04108

Sizable reduction of the propagation uncertainties

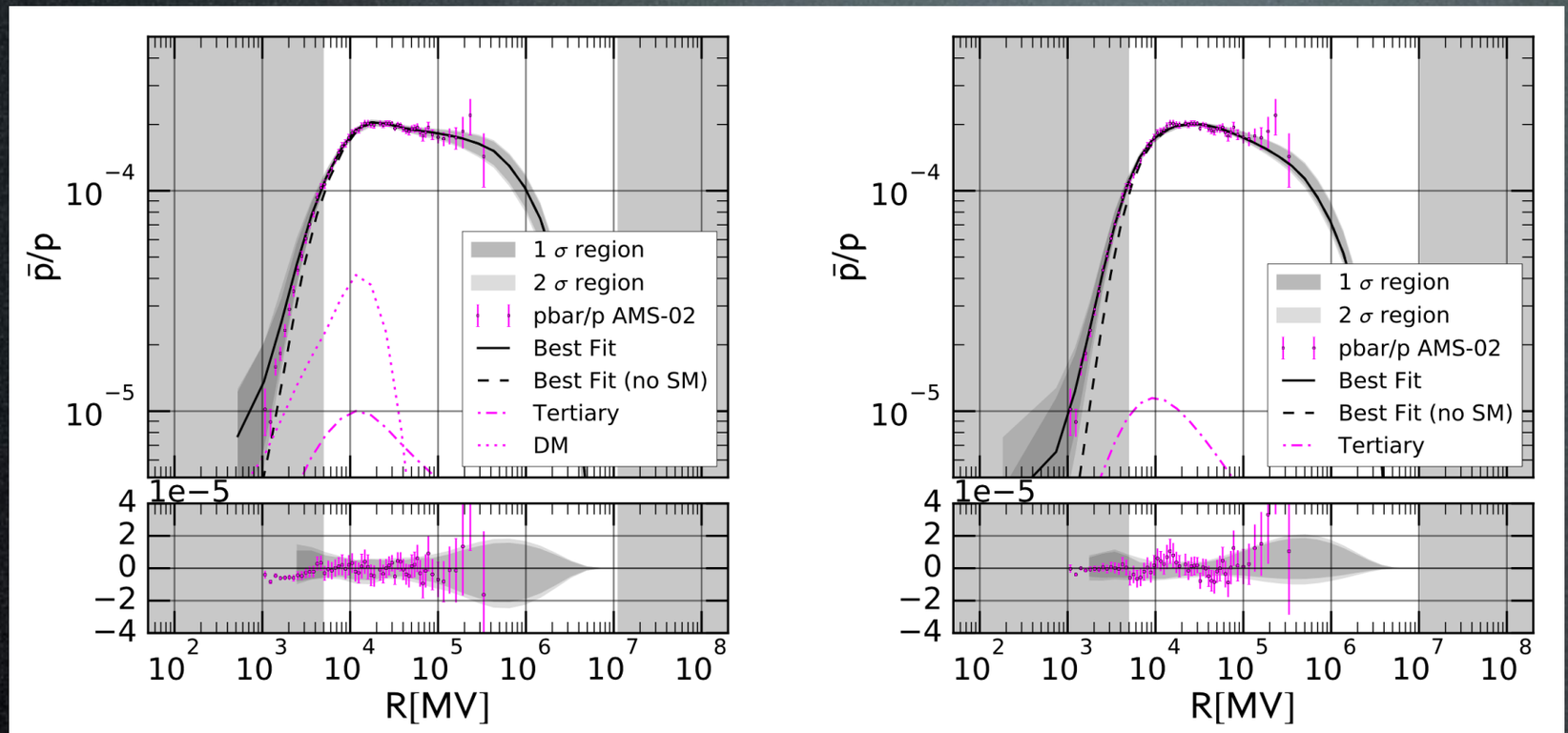




Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071



finds a possible excess

(formally ~4.5σ)

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

similarly:

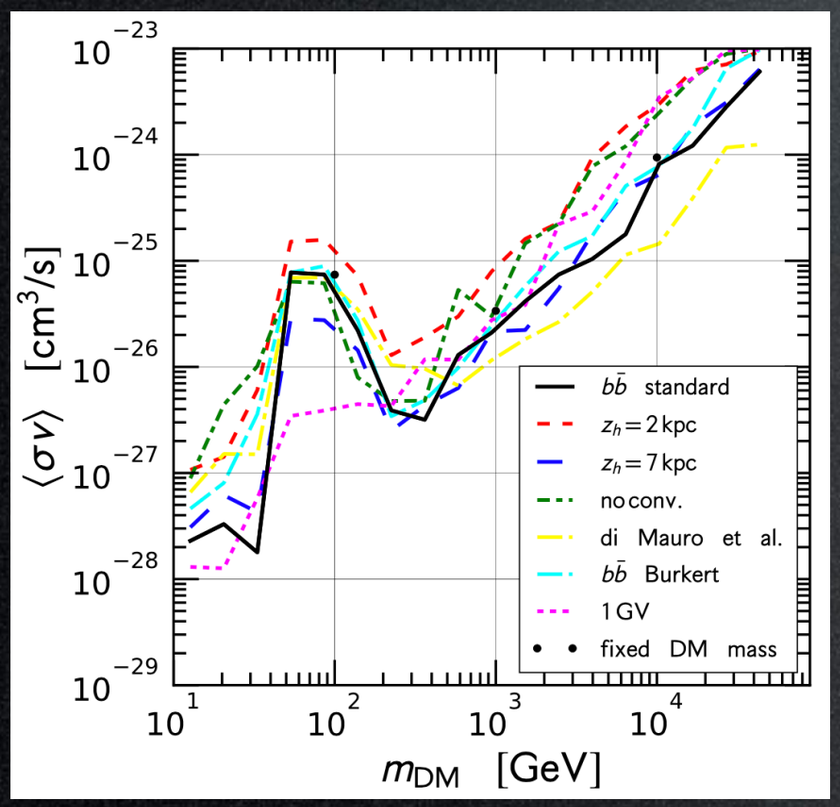
Cui, Yuan, Tsai, Fang 1610.03840

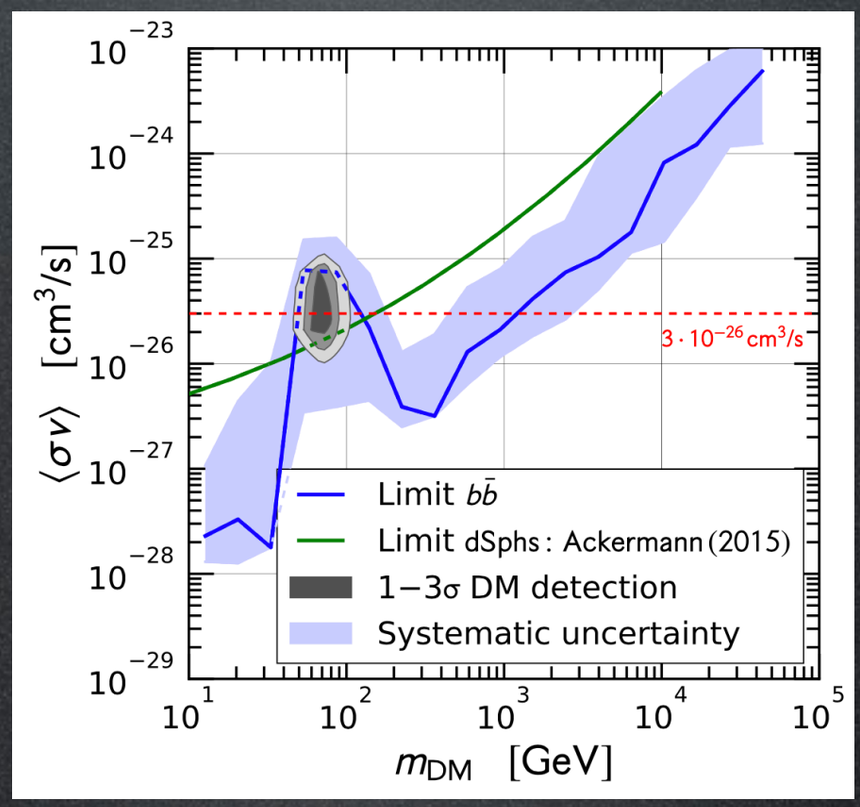
Huang + 1611.01983 (light mediators)

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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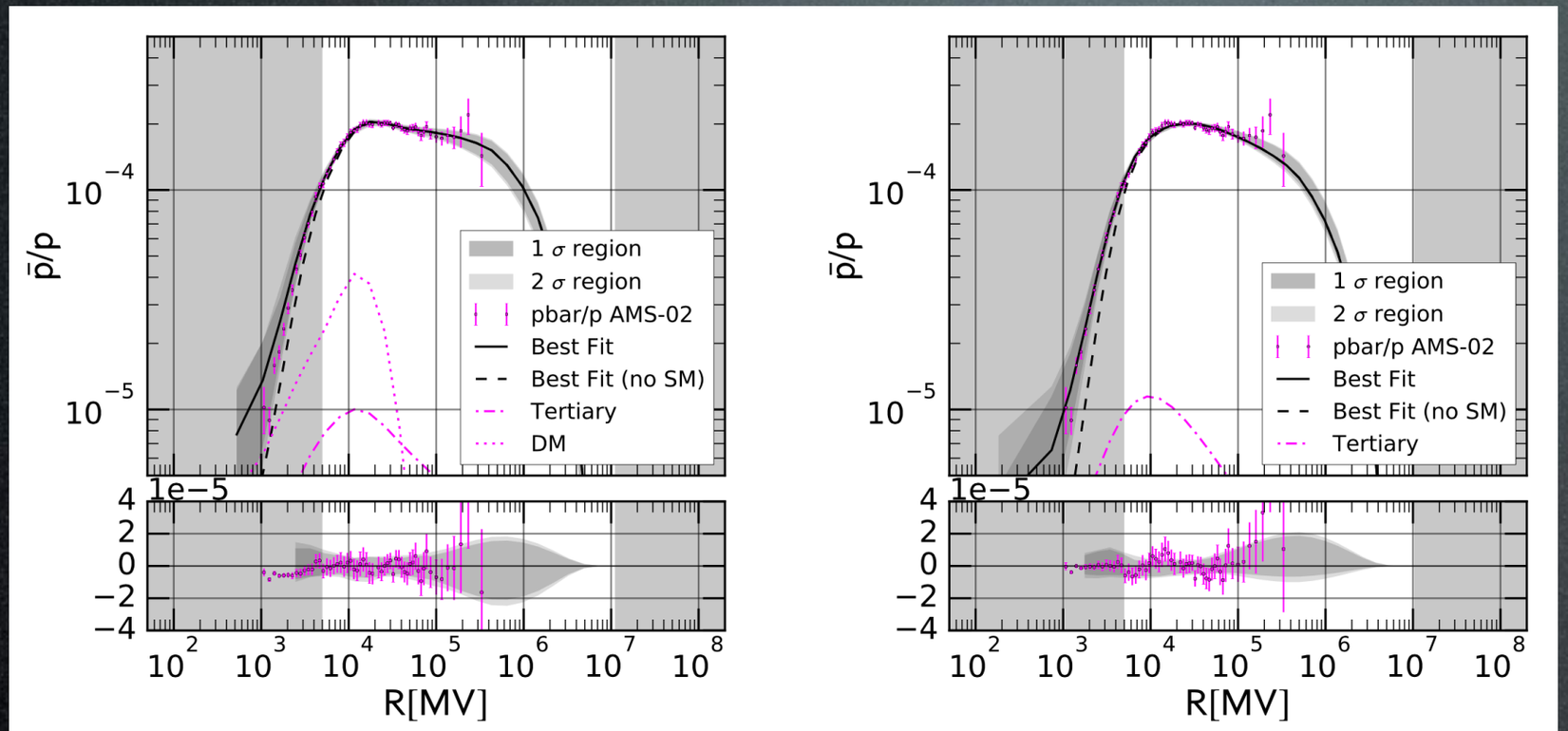

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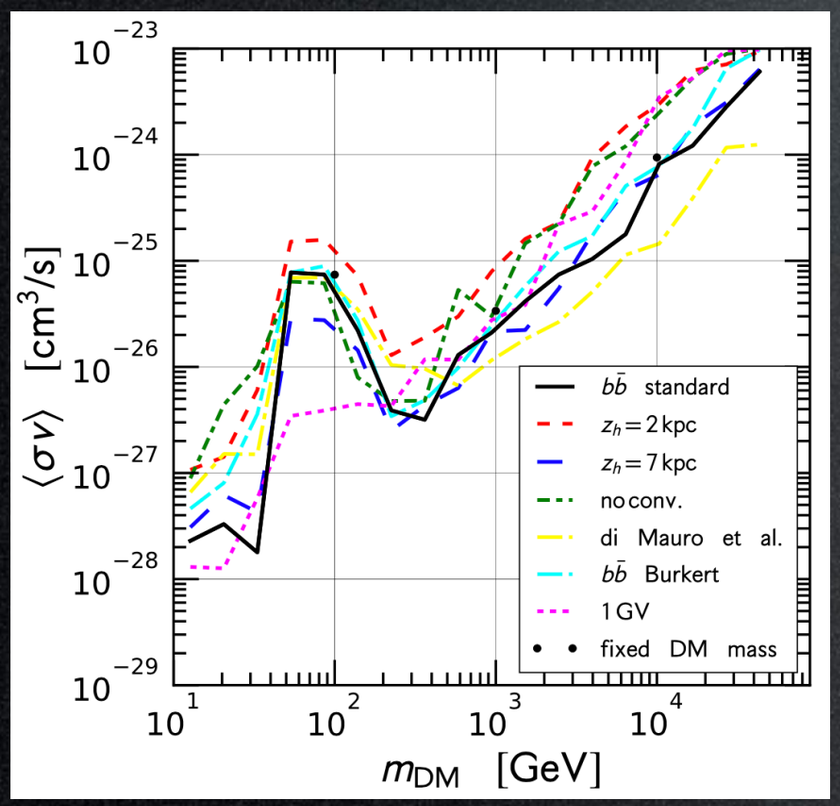

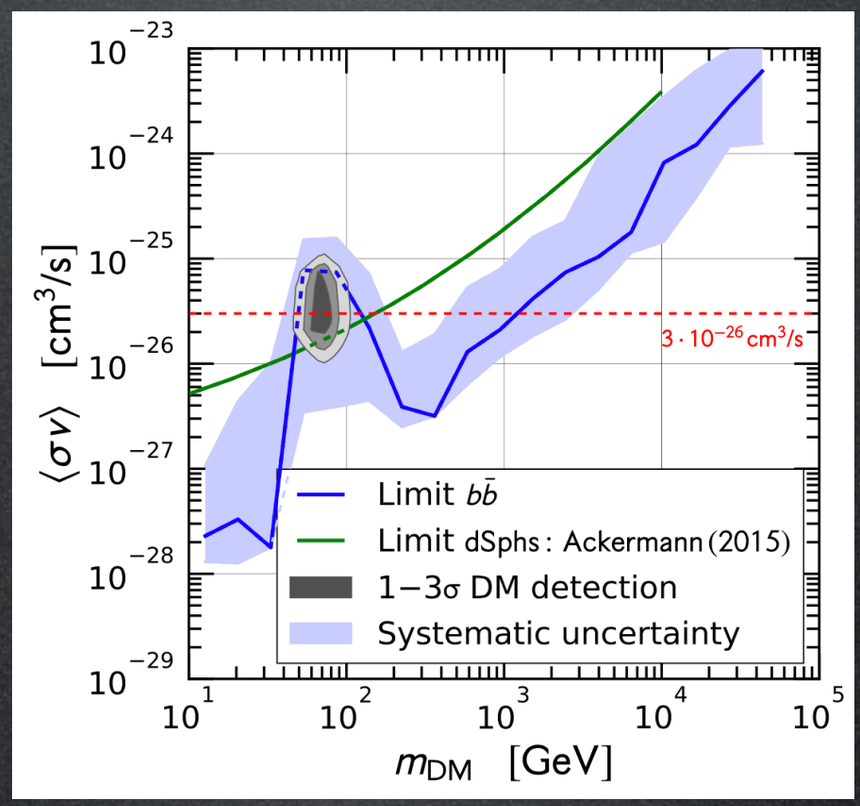

criticisms:

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

excess evaporates including low energies

Antiprotons

Recent developments

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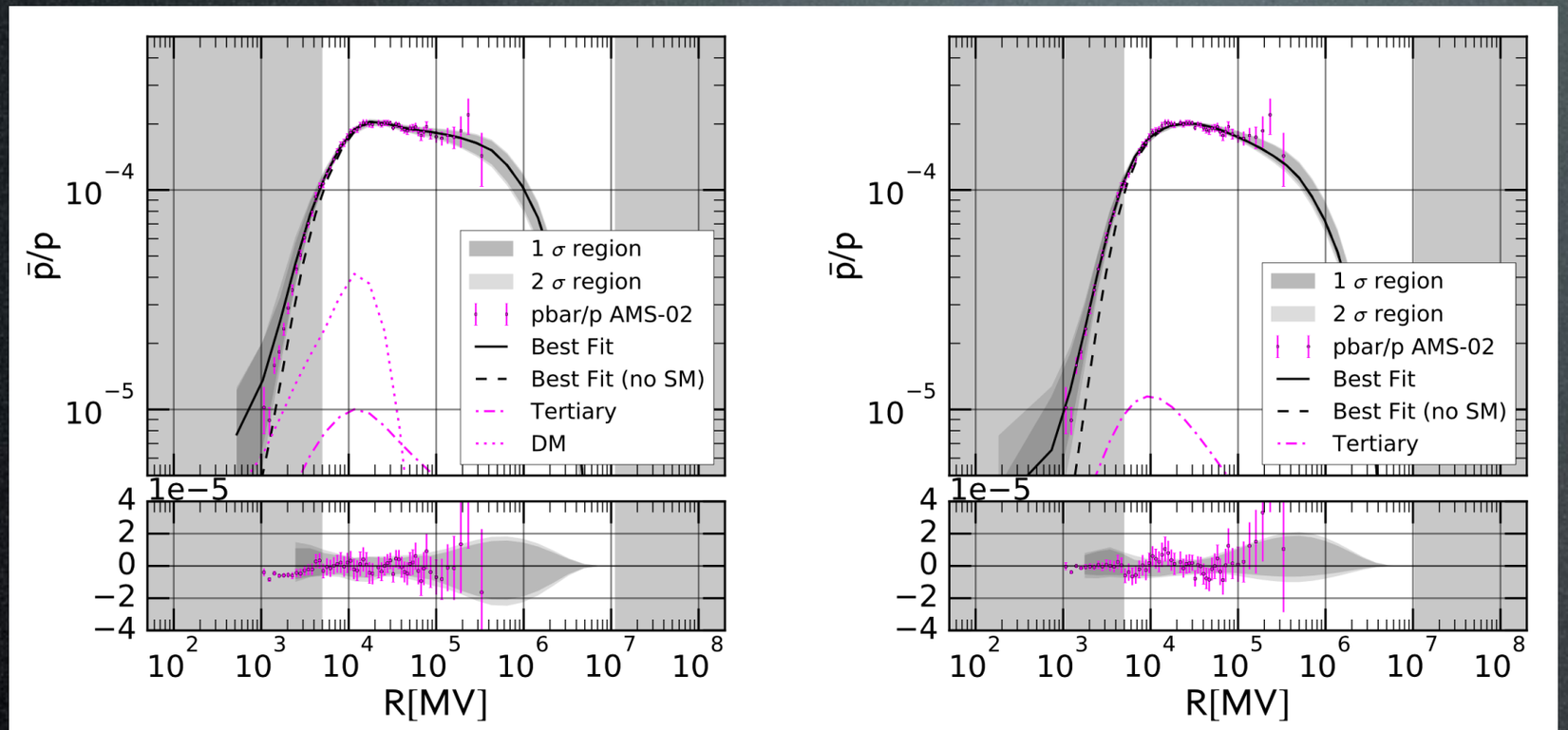

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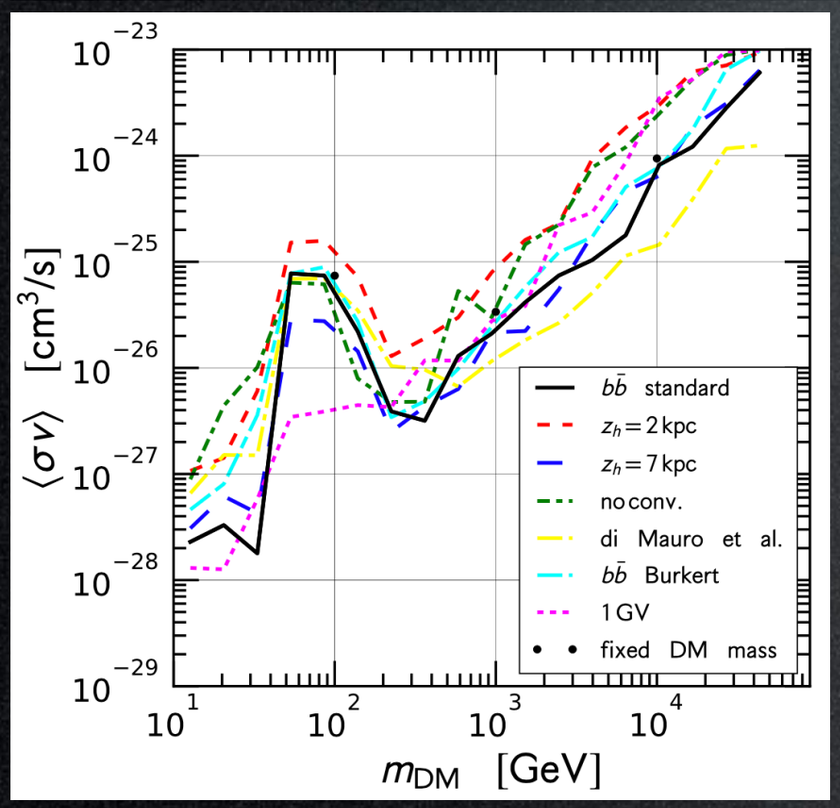

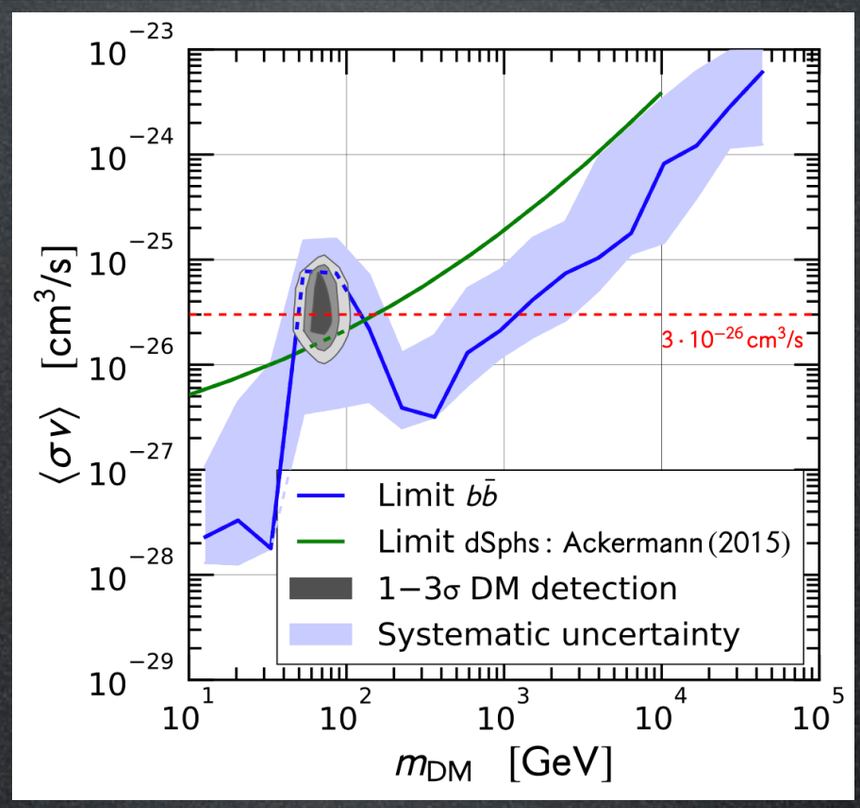

on the other hand:

B/C and p probably probe different regions

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

Antiprotons

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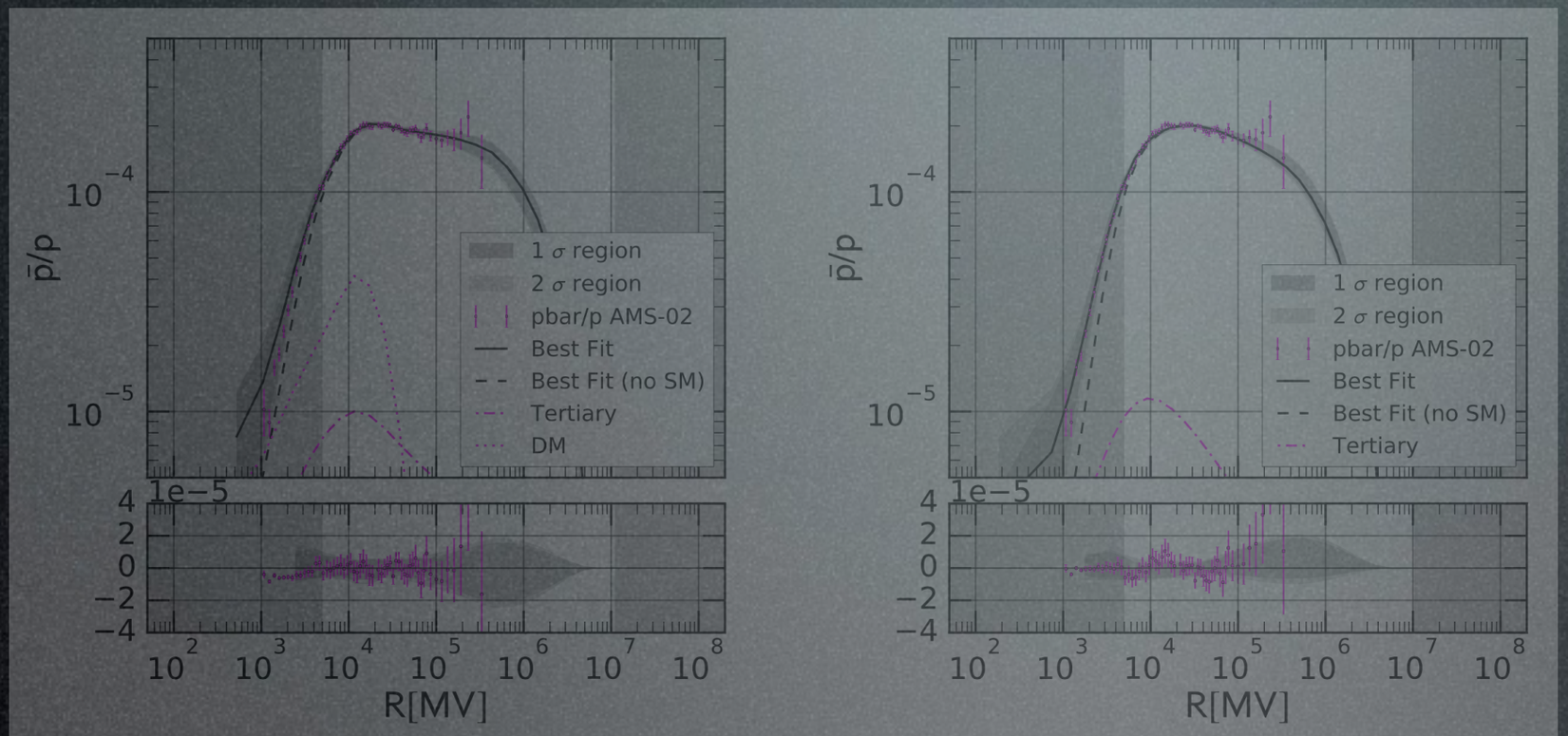

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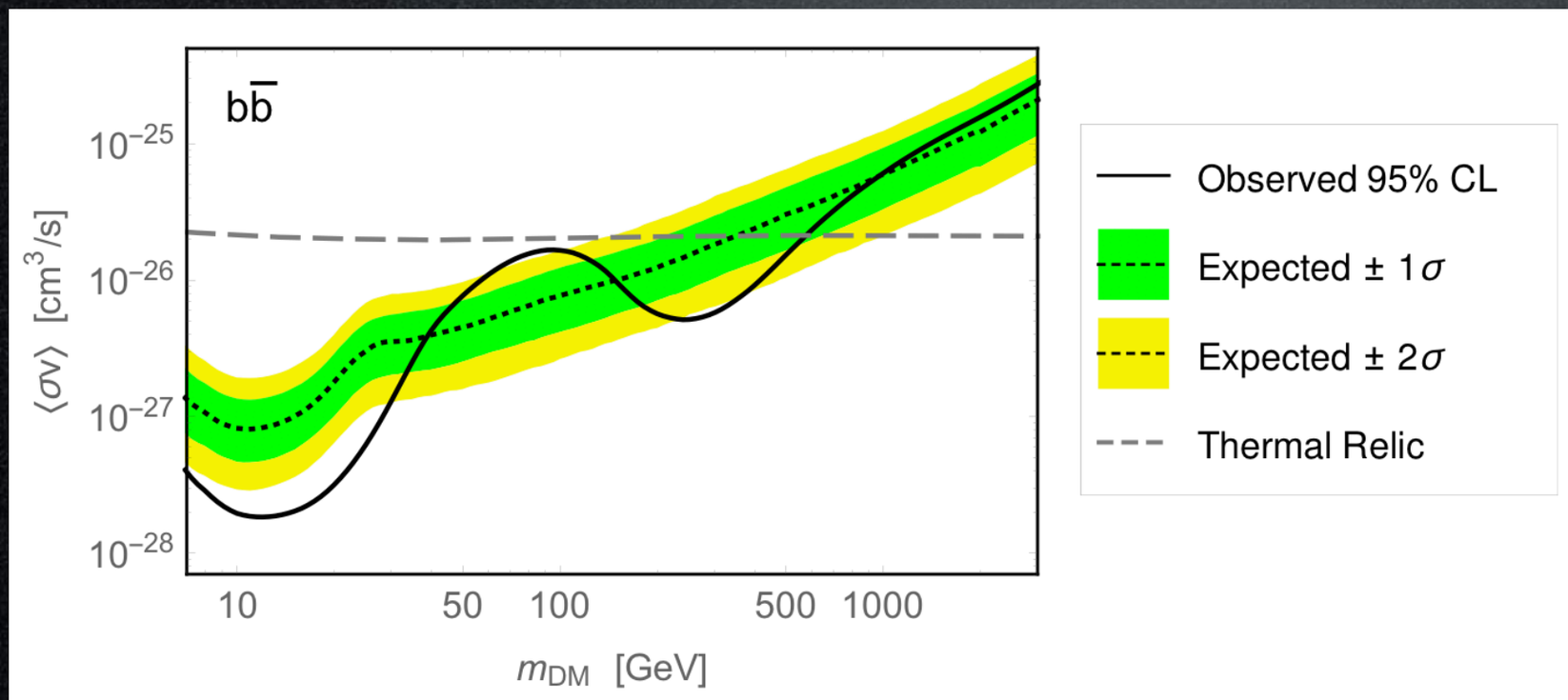


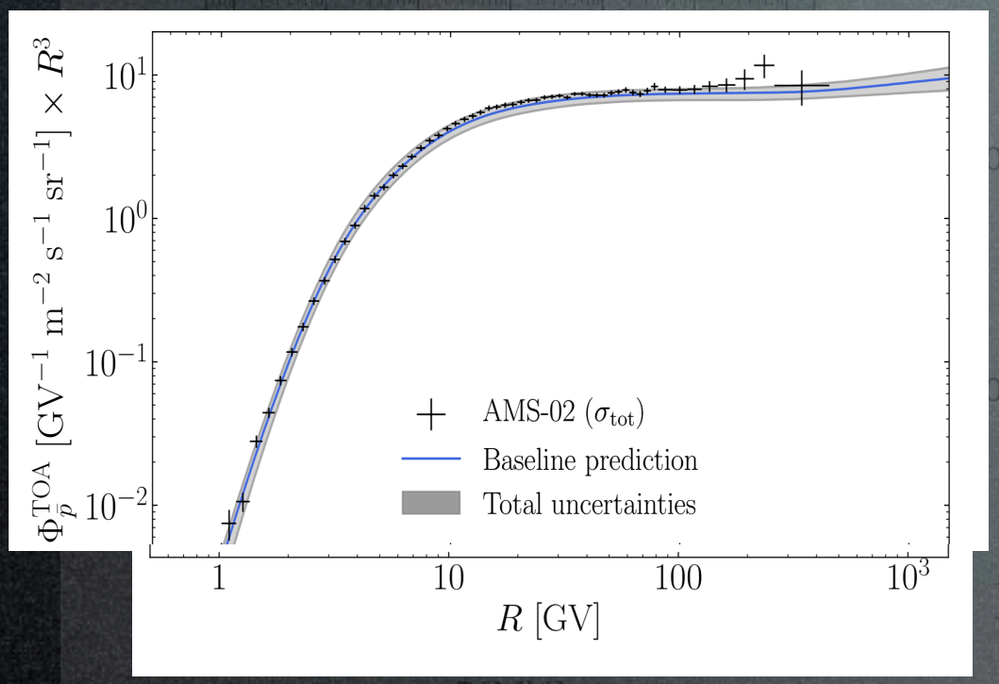
Reinert, Winkler 1712.00002

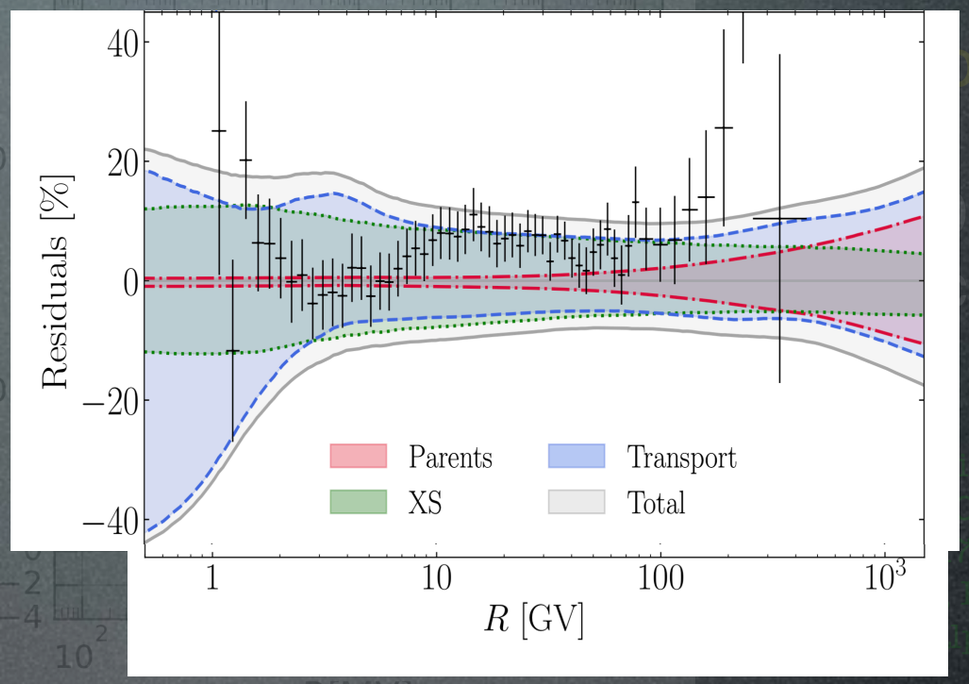
excess exists

but significance ~1σ, given all uncertainties

Antiprotons

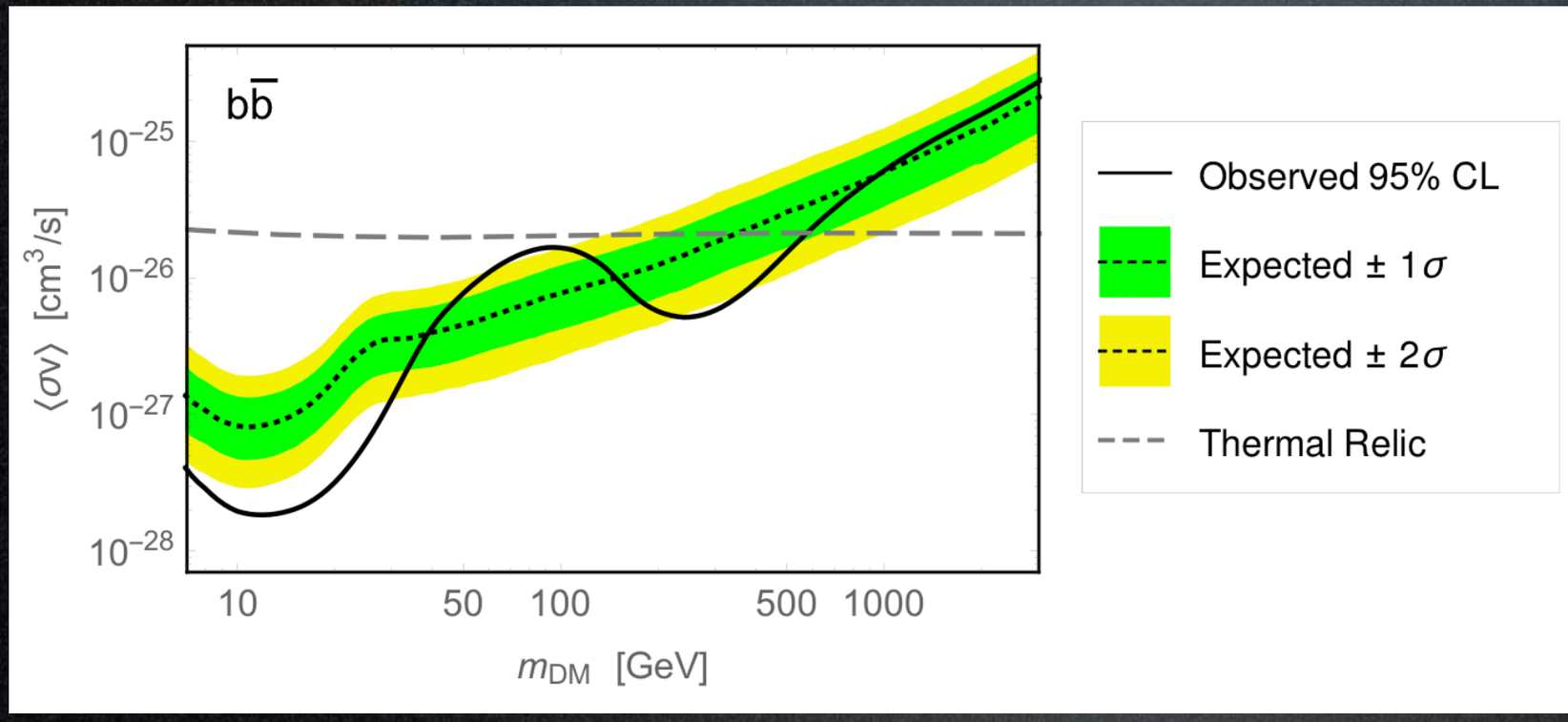
Recent developments





Boudaud et al. 1906.0719

"antiprotons are consistent with a secondary astrophysical origin"



Reinert, Winkler 1712.00002

excess exists

but significance ~1σ, given all uncertainties

Positrons (and electrons)

direct detection

production at colliders

indirect

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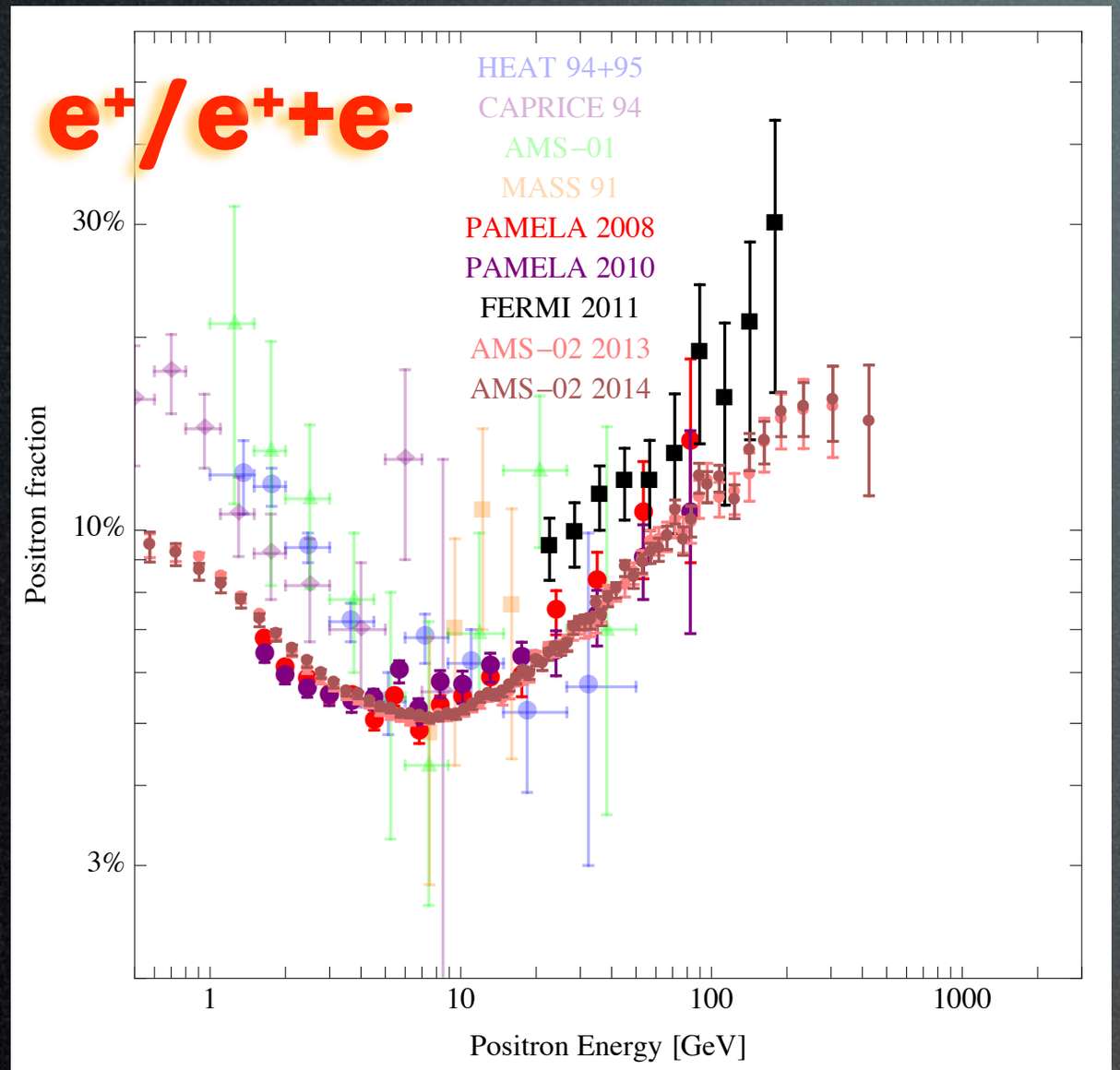
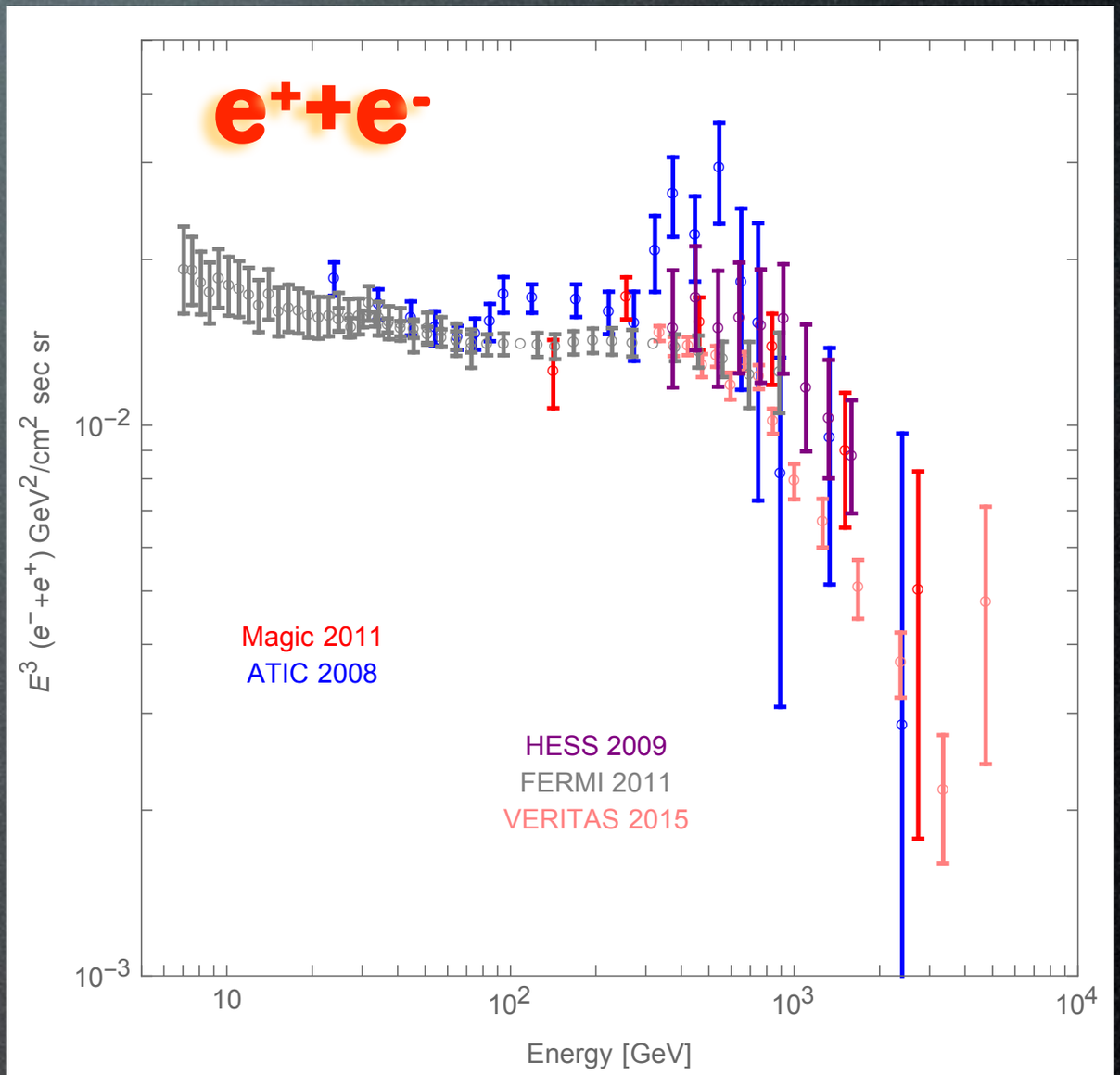
Data: leptons

high energy



M. Cirelli - compilation ICRC 2015



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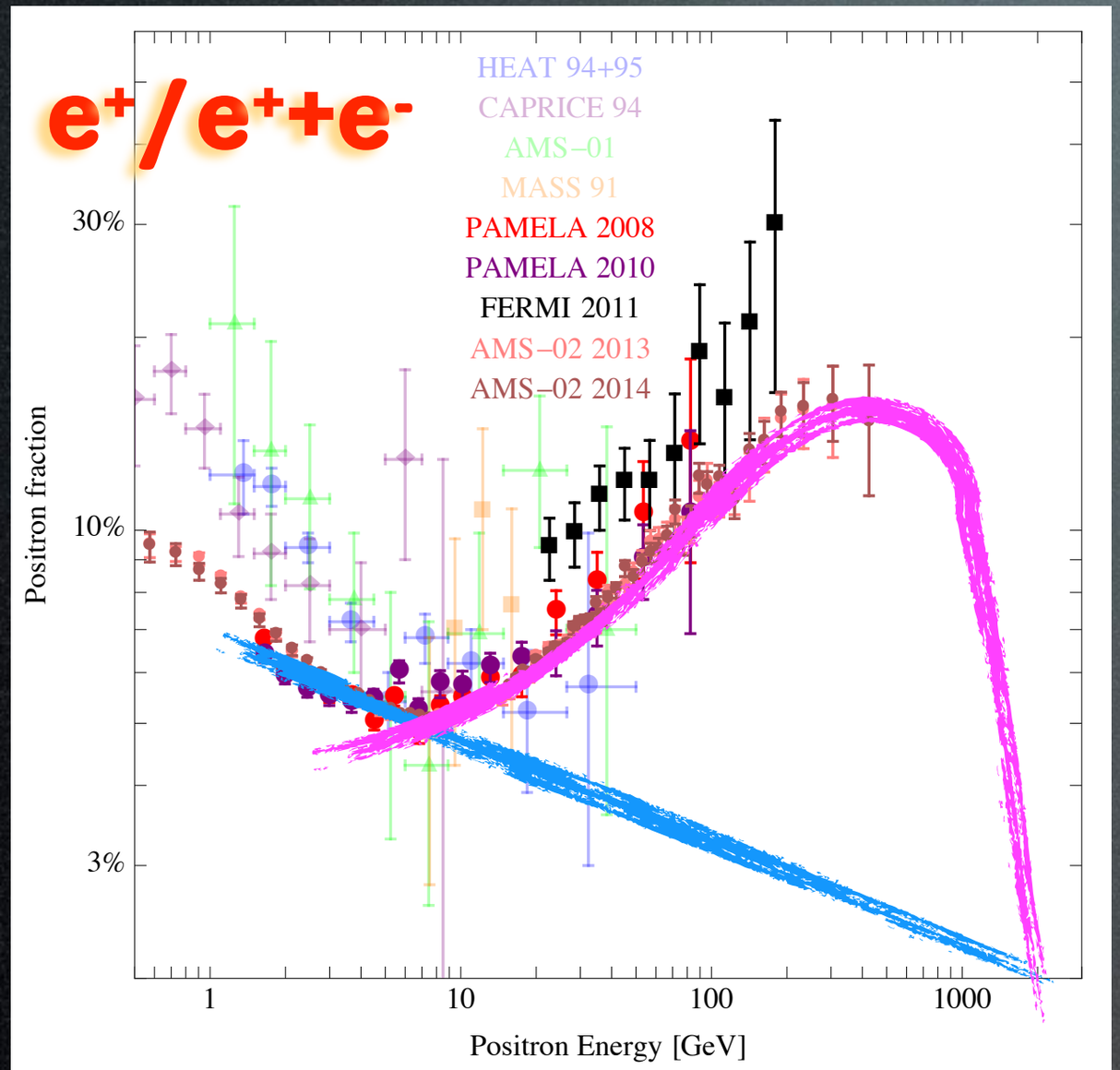

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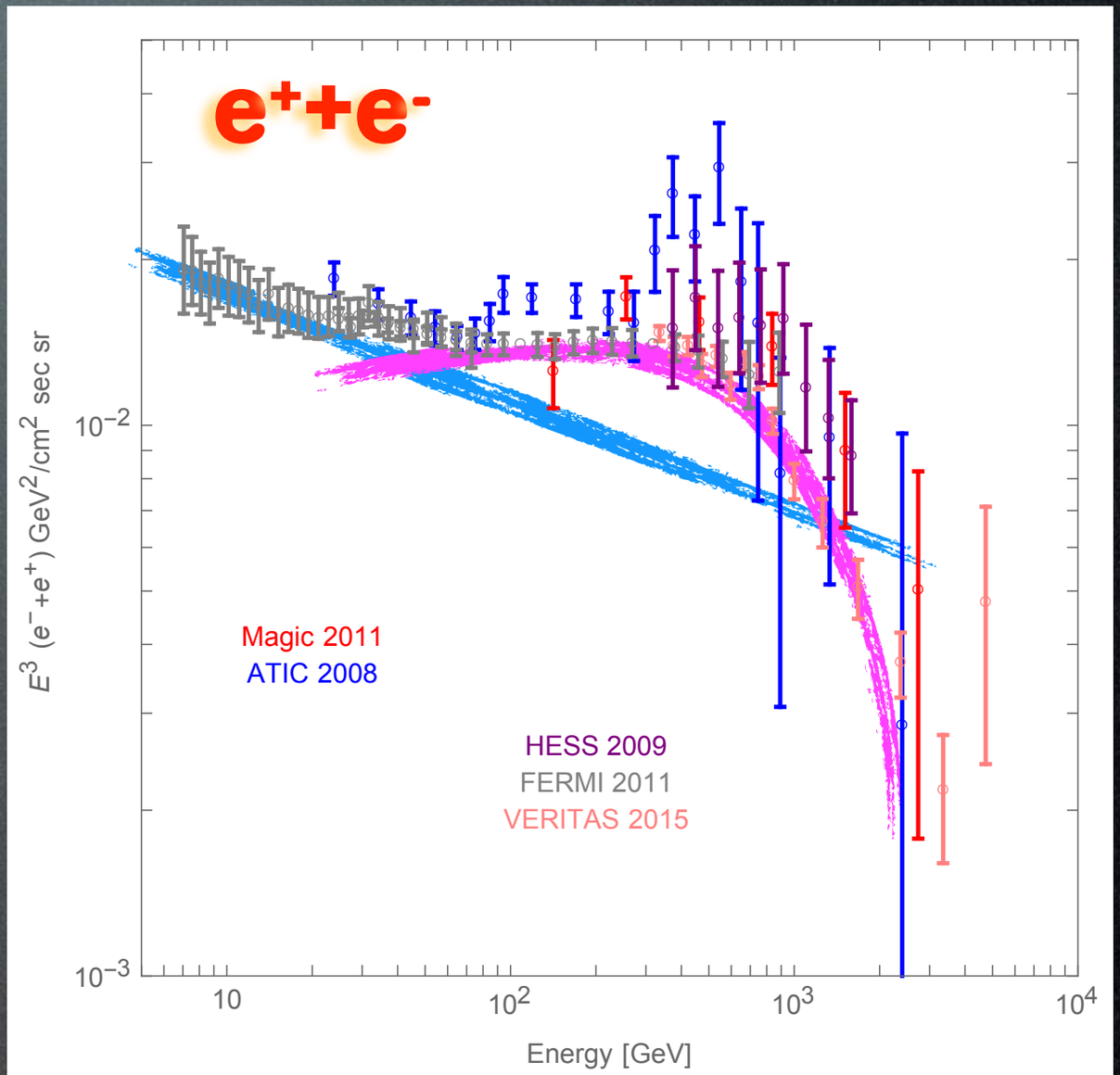


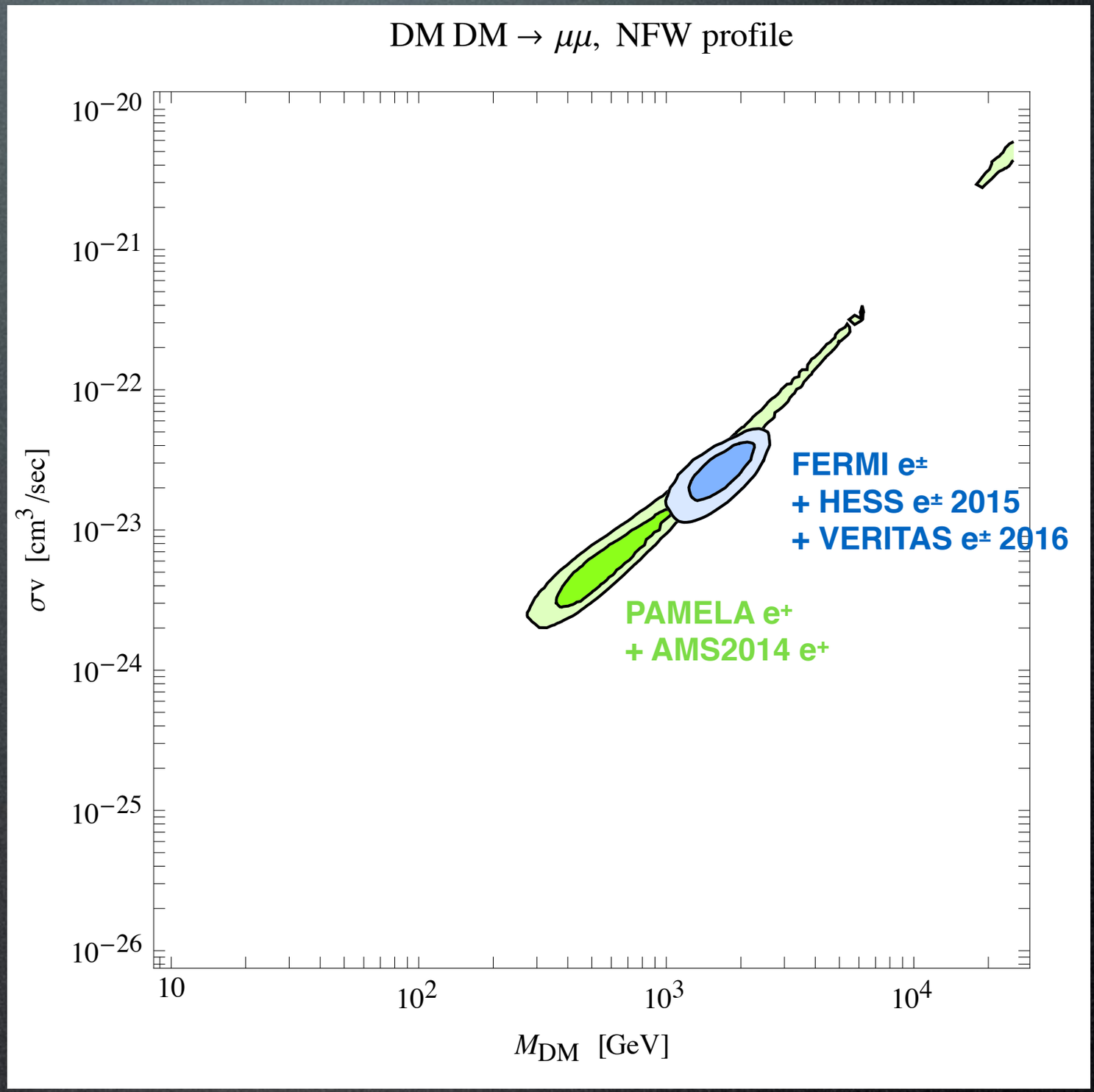
M. Cirelli - compilation ICRC 2015

Dark Matter interpretation

- leptophilic

- $m_{DM} \sim 1$ TeV

- huge annihilation cross section



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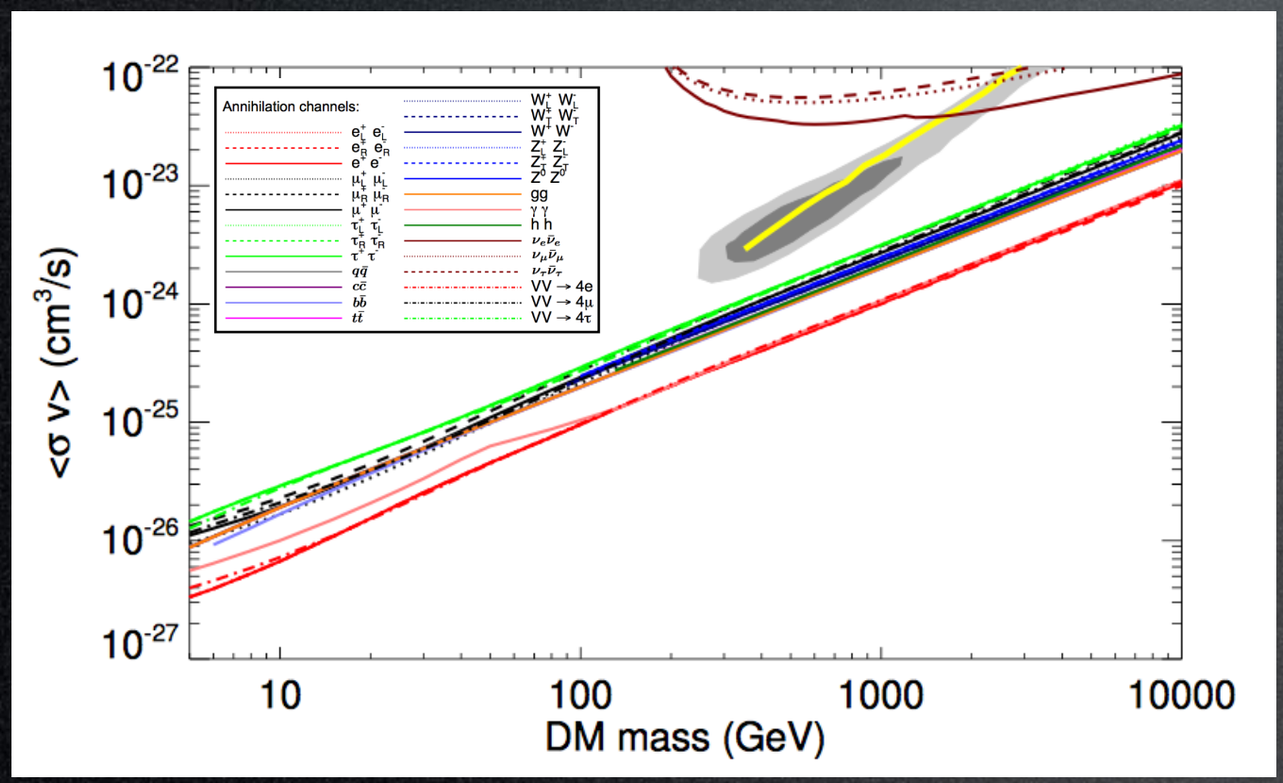
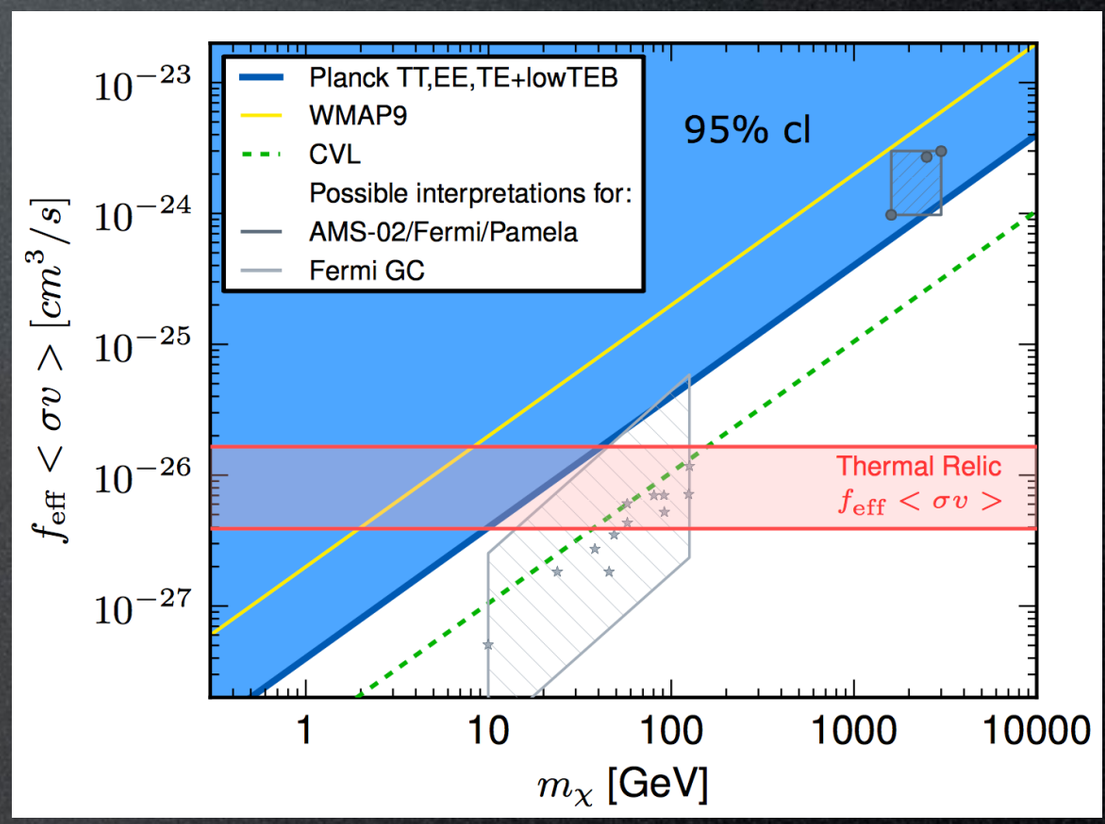
- constraints: gamma rays, neutrinos, CMB...



T.Slatyer 1506.03811

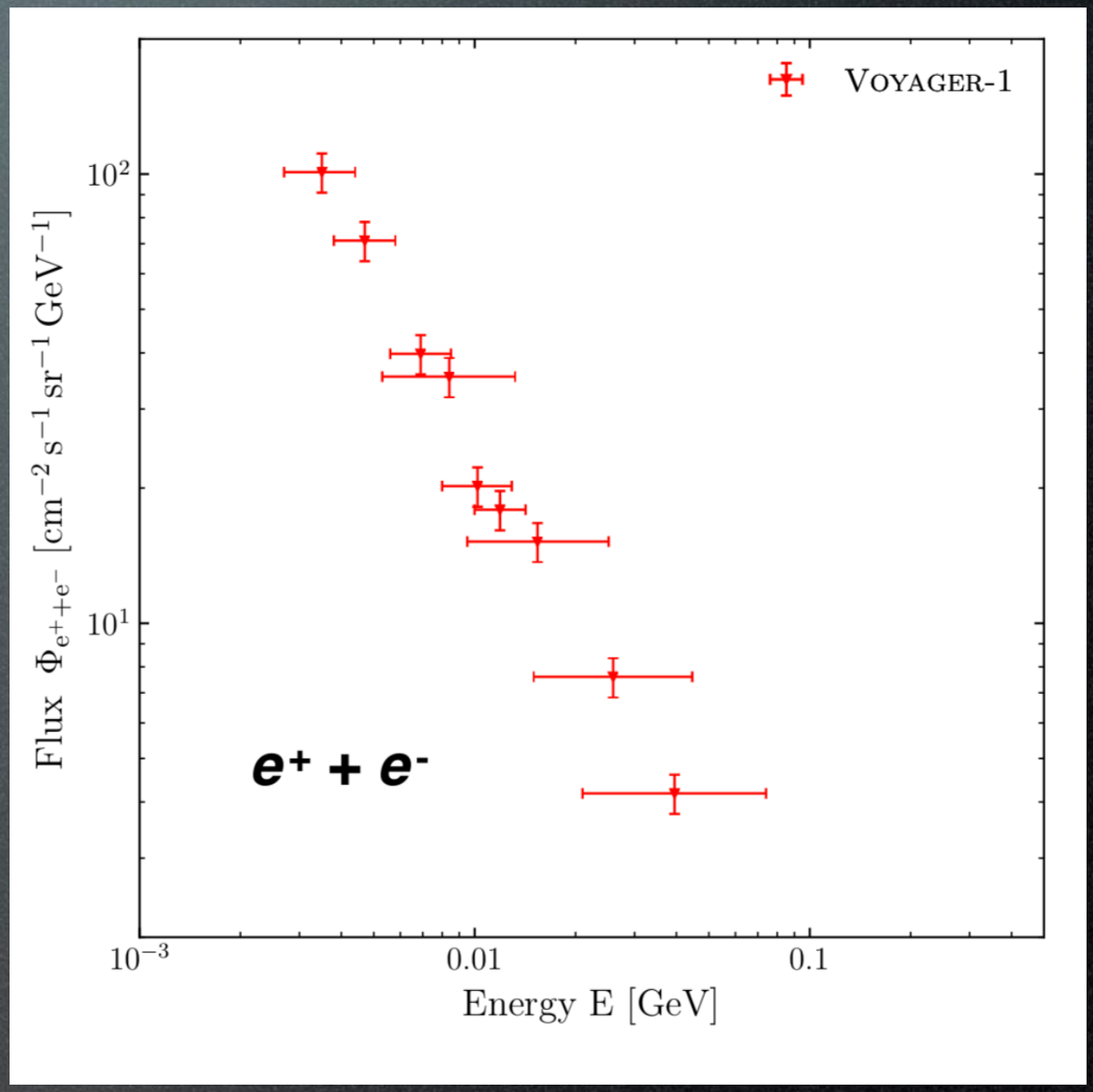


Planck 2015 (1502.01589)

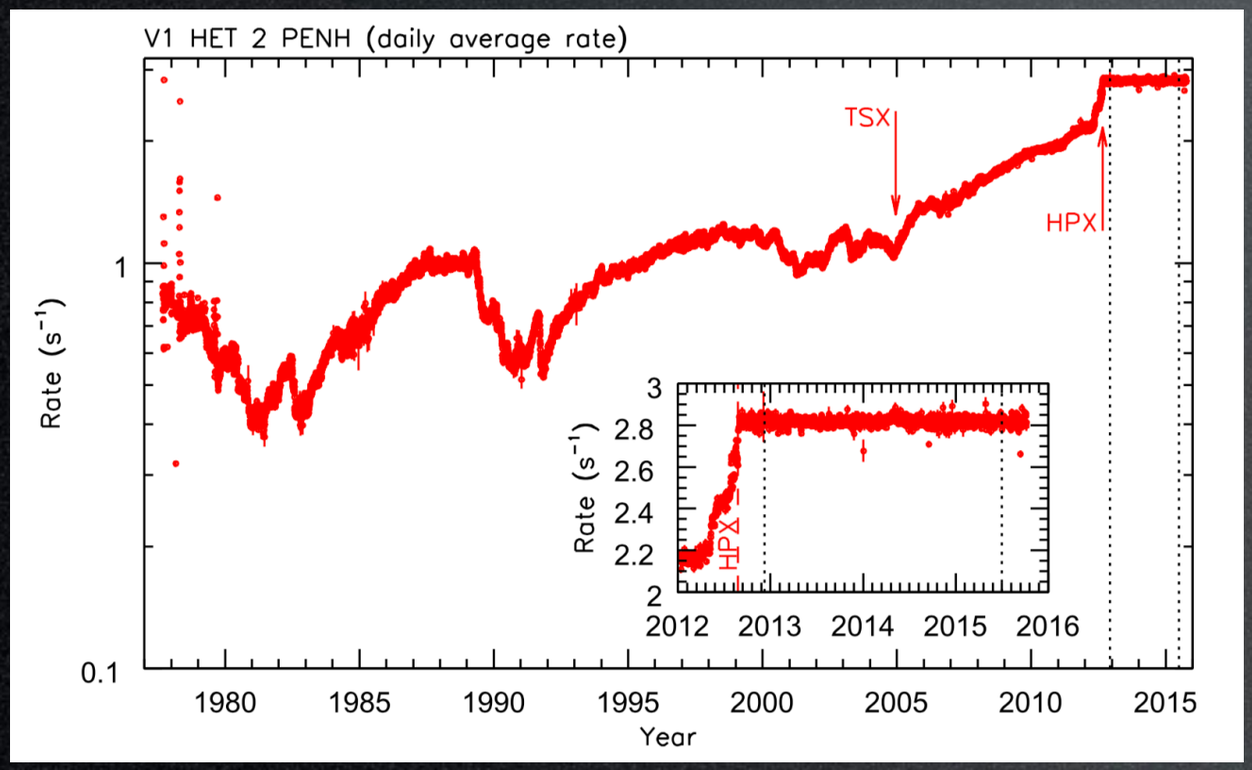
Data: leptons
low energy

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



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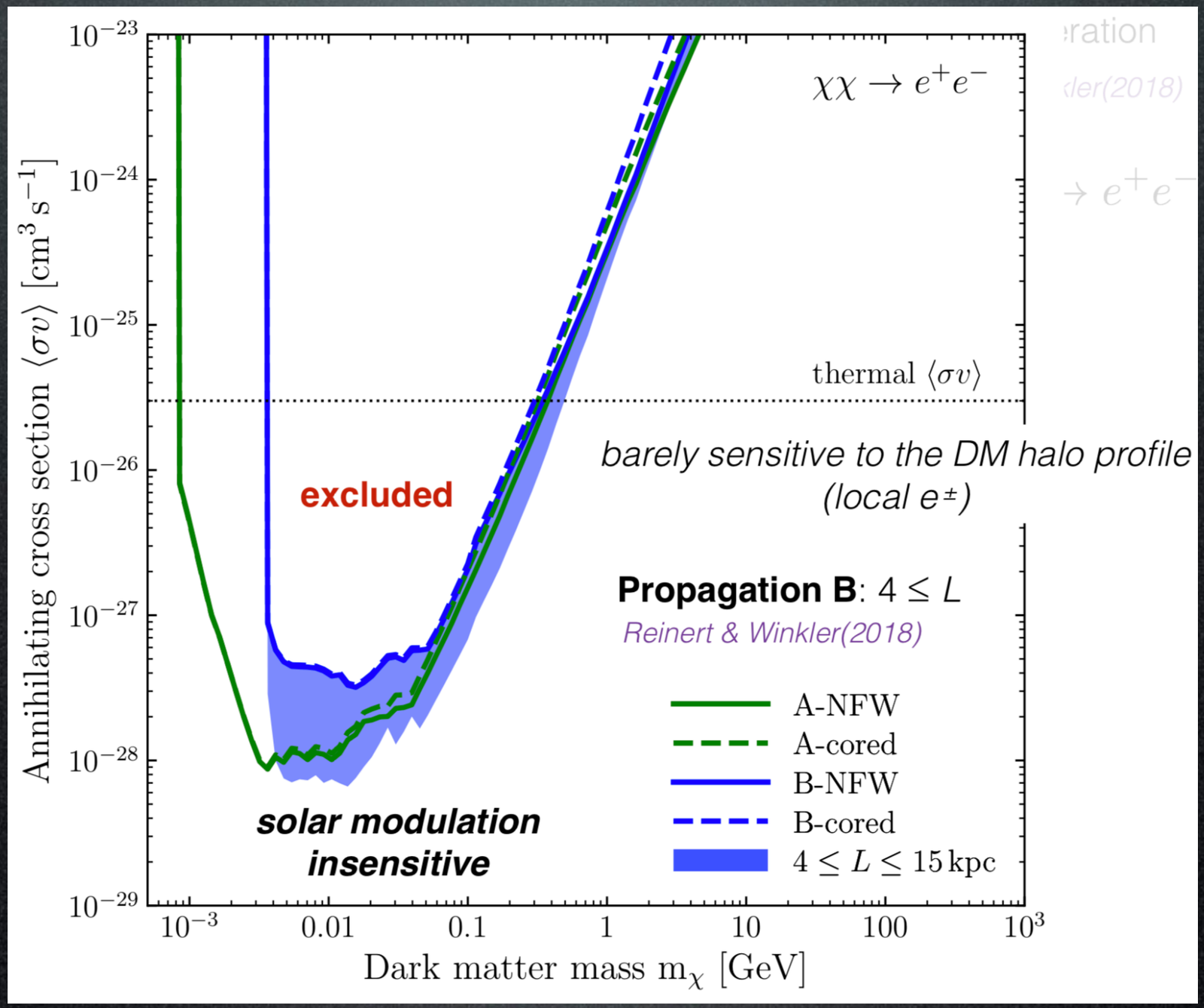
Dark Matter interpretation

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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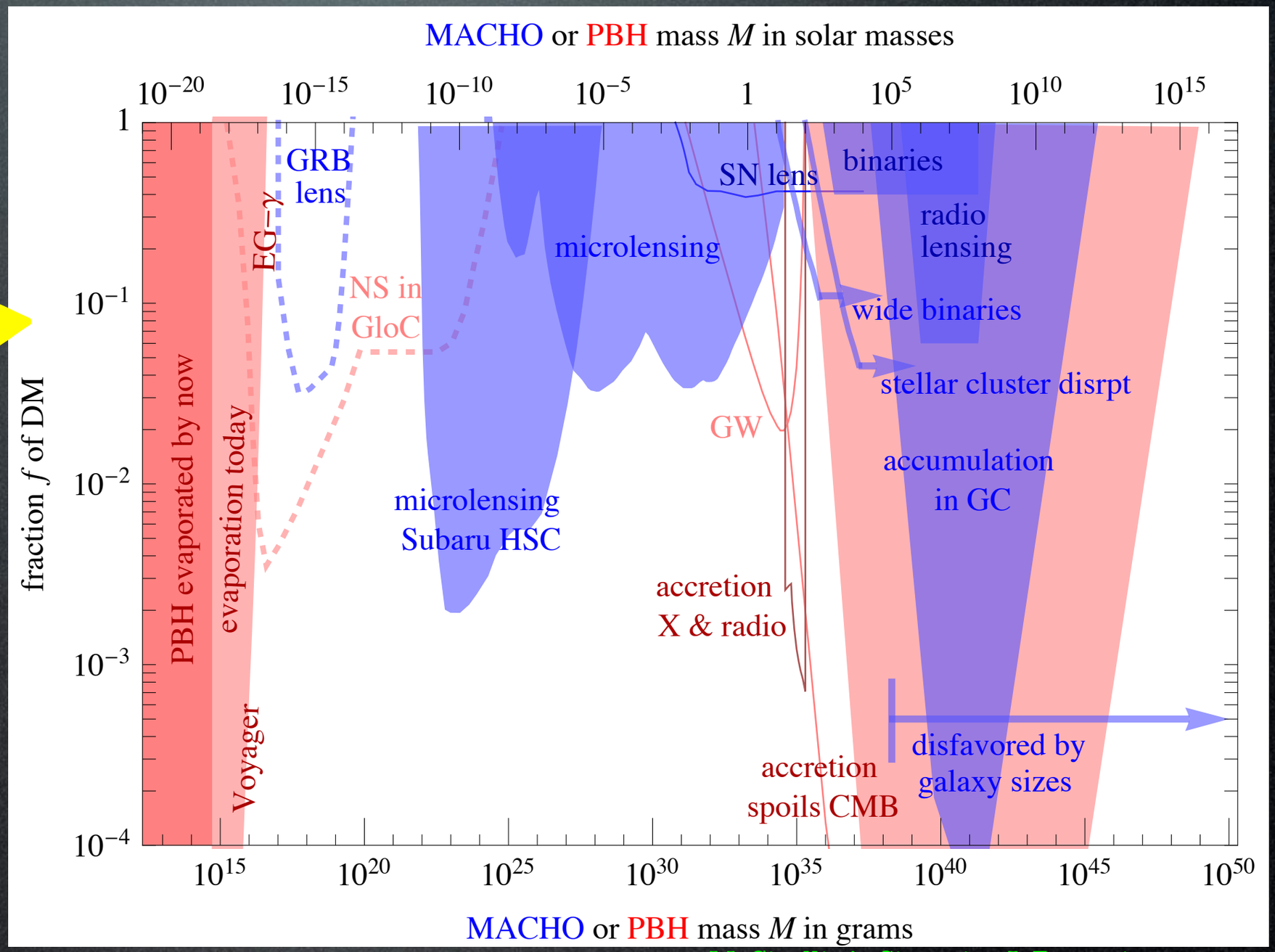

M. Cirelli, A. Strumia, J. Zupan to appear

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constraints

‘small’ PBHs emit today by Hawking evaporation

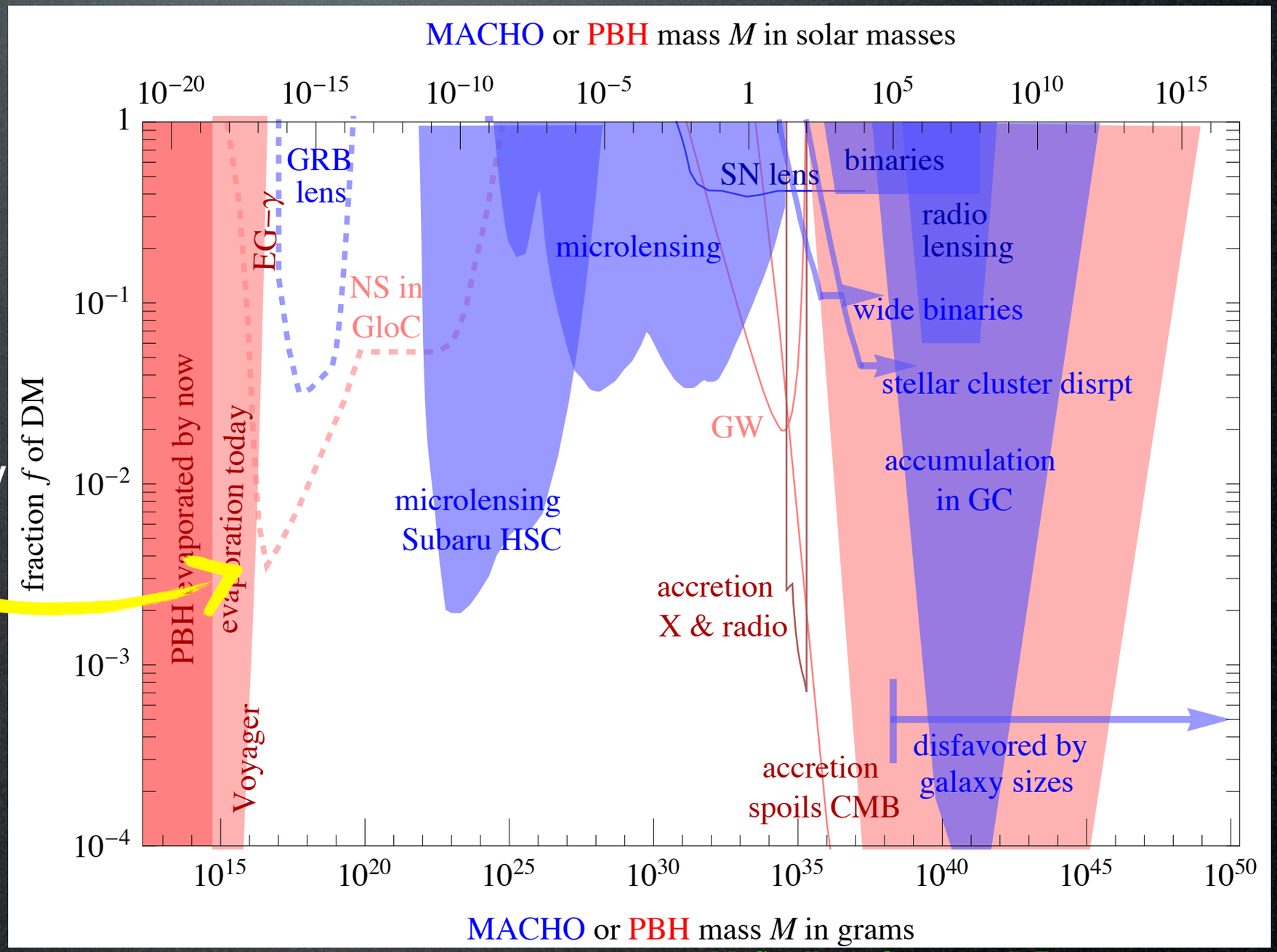
$$T = \frac{1}{8\pi G_N M}$$

rate

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

spectrum

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



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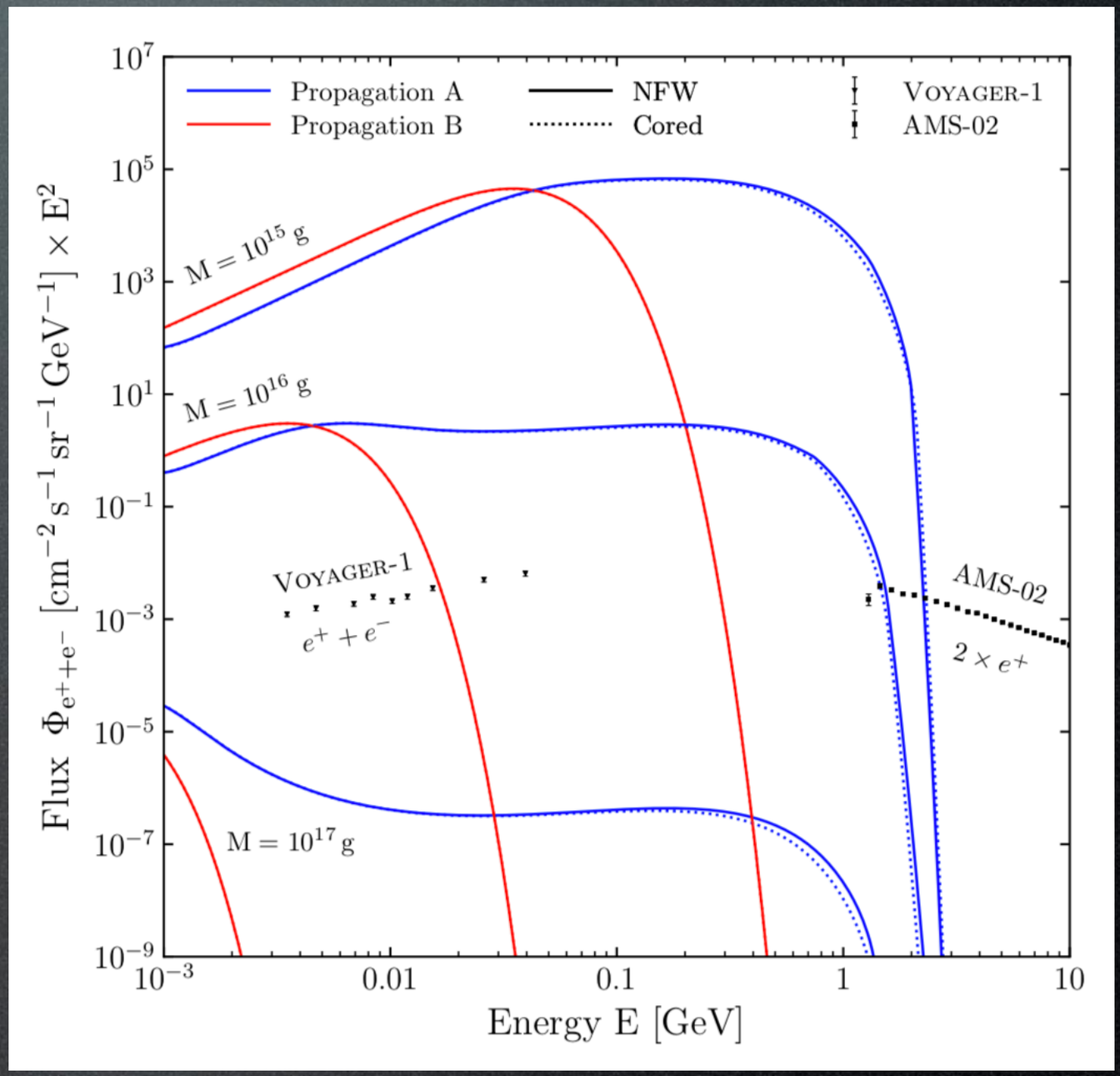

Boudaud, Cirelli 1807.03075, PRL 122 (2019)

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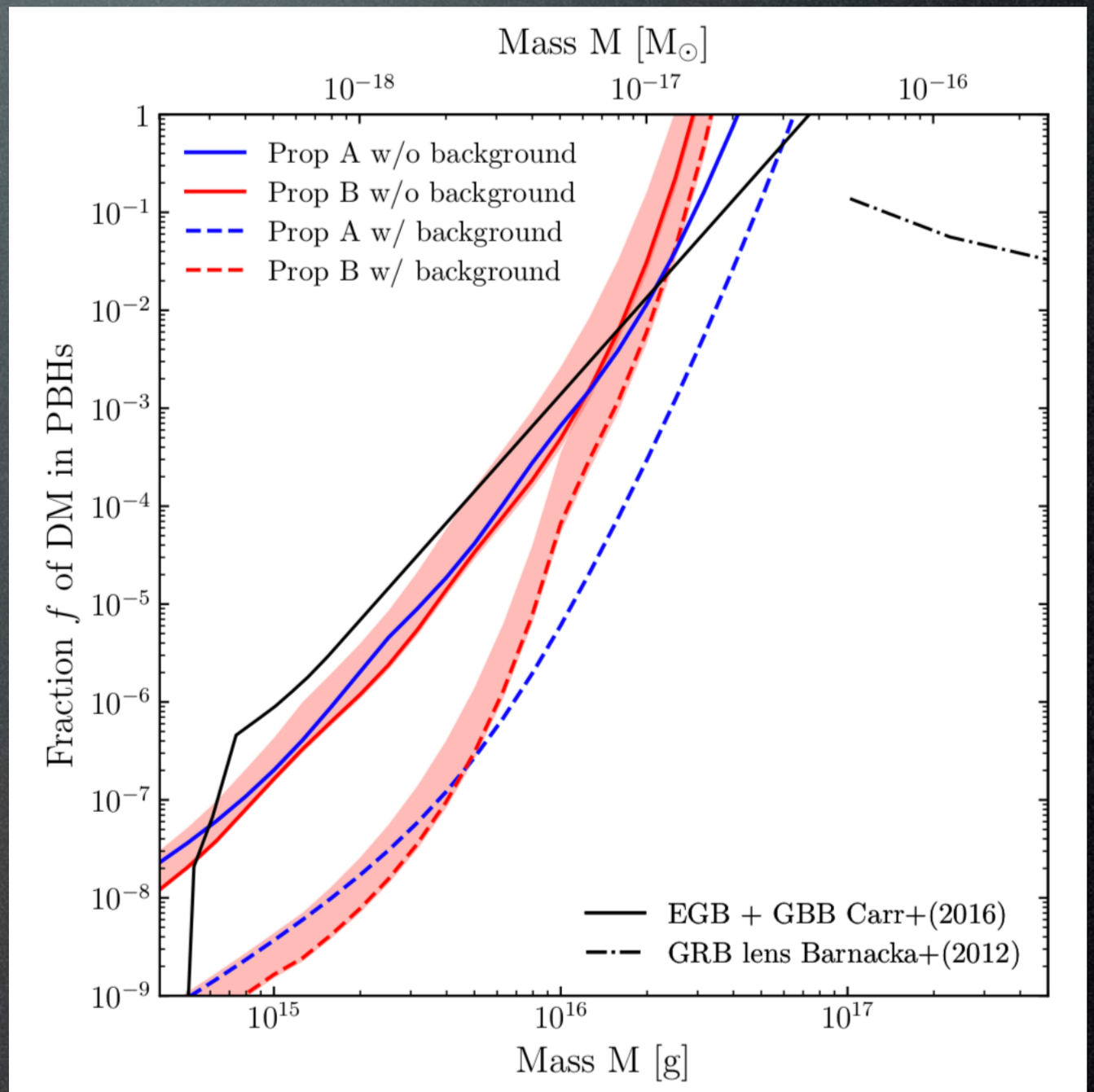

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Dark Matter interpretation

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

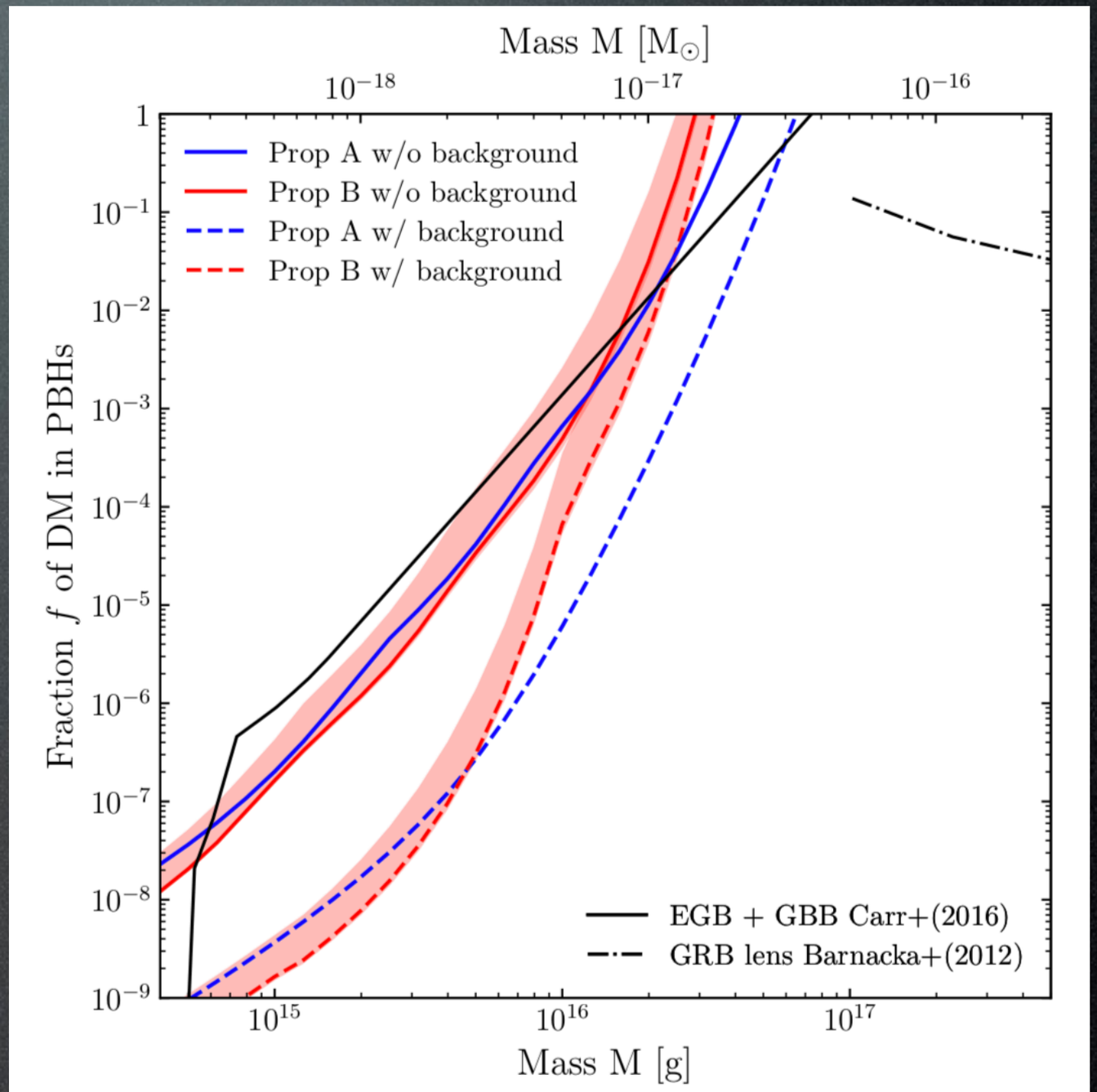
25,121 views | Jul 10, 2018, 05:59pm

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 122 (2019)

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

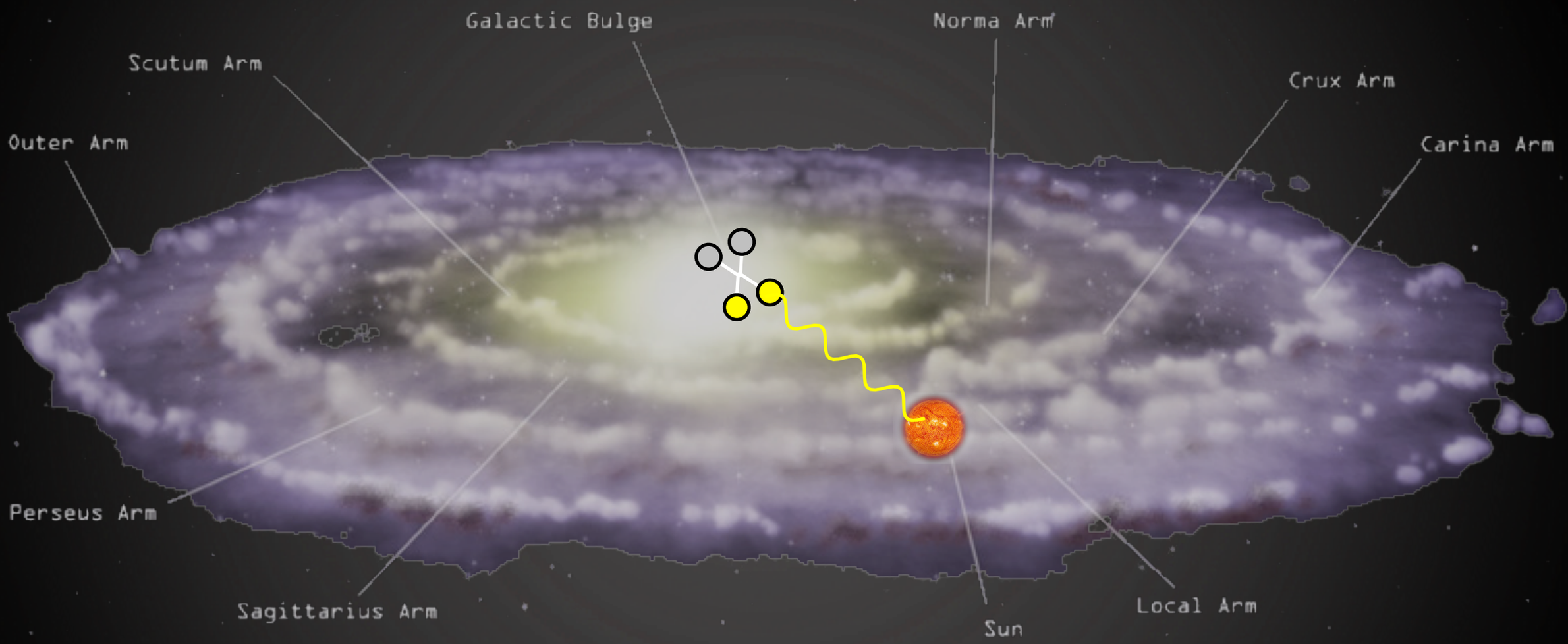
GAPS, AMS

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

SK, Icecube, Antares

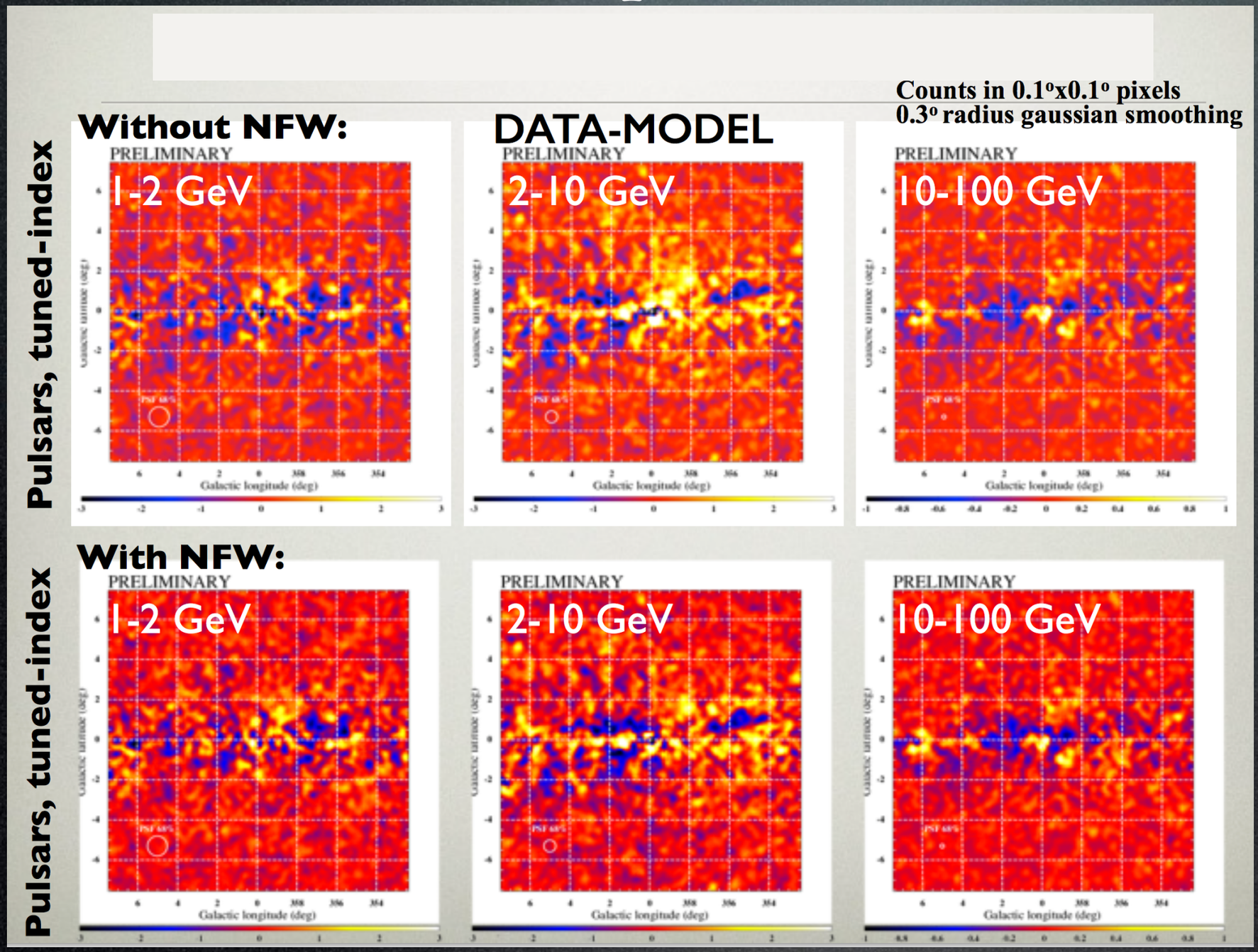
Basic picture

γ from DM annihilations in galactic center



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

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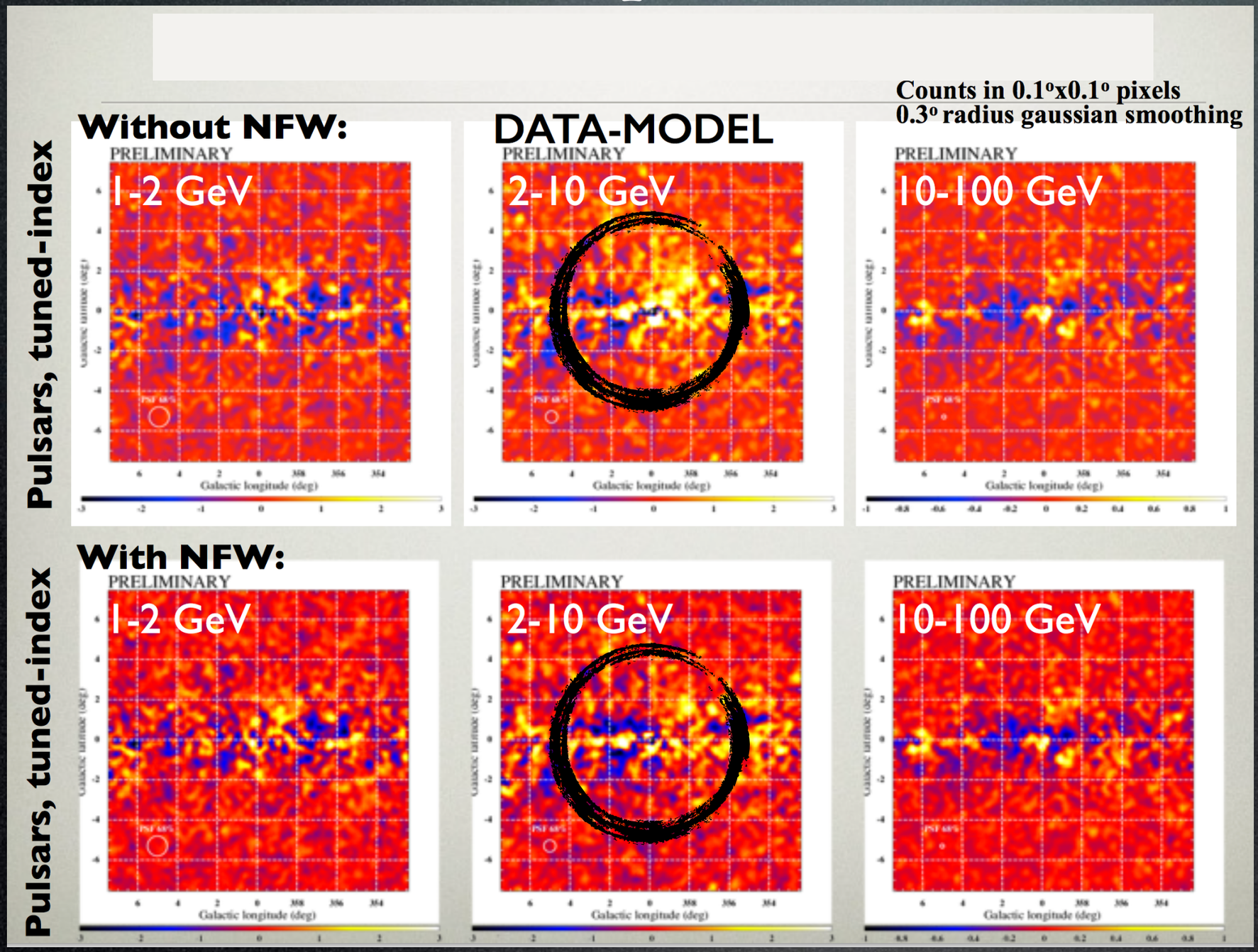

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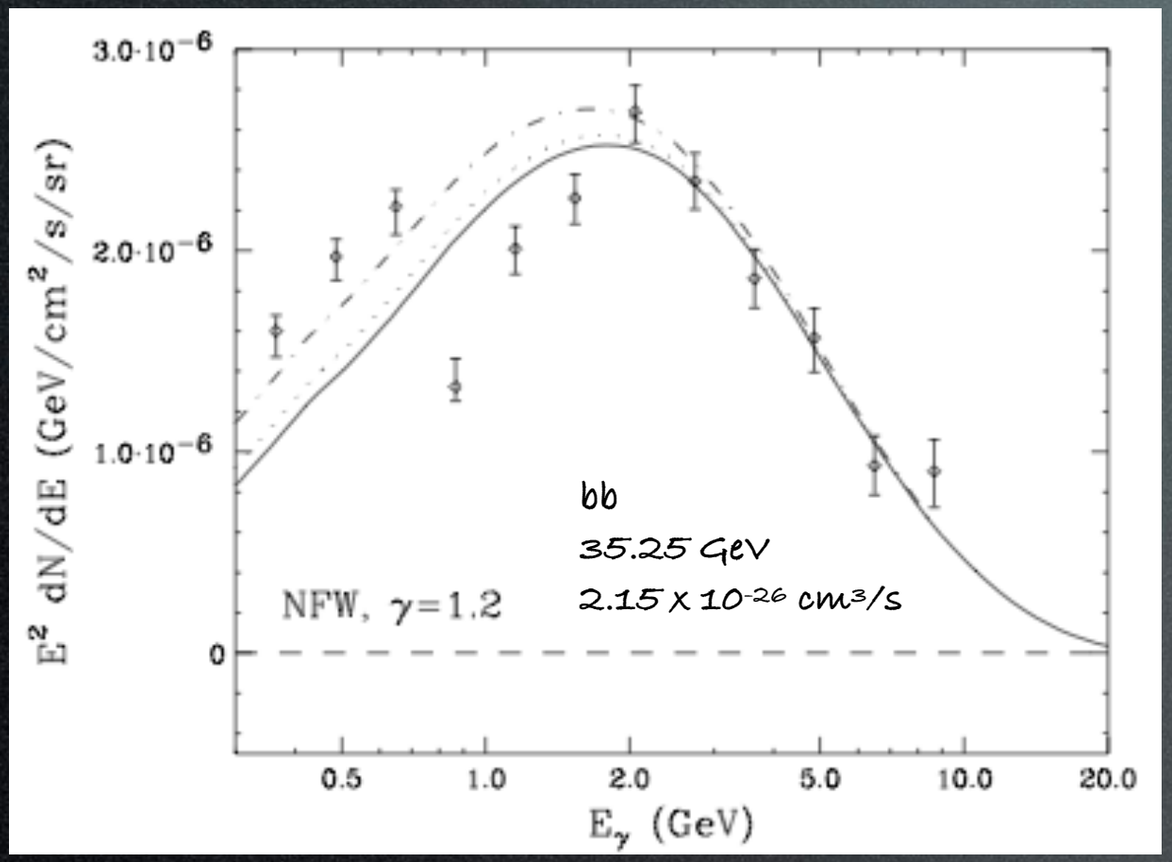
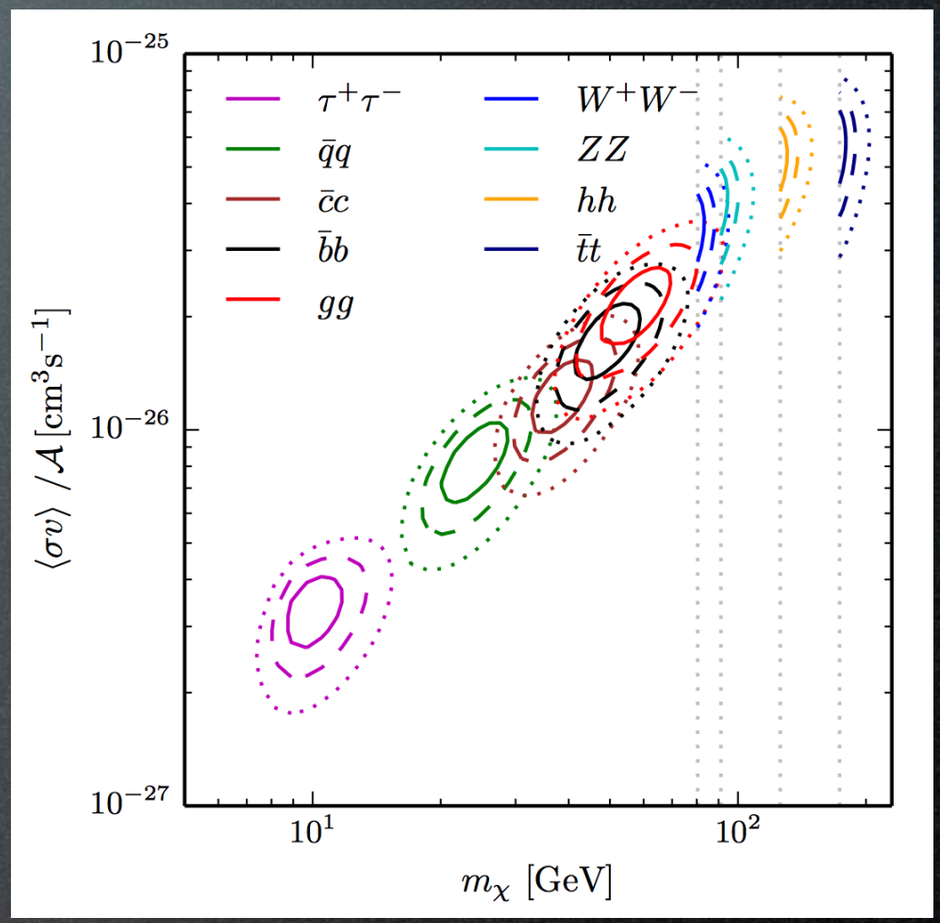
Fermi coll. 1511.02938

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

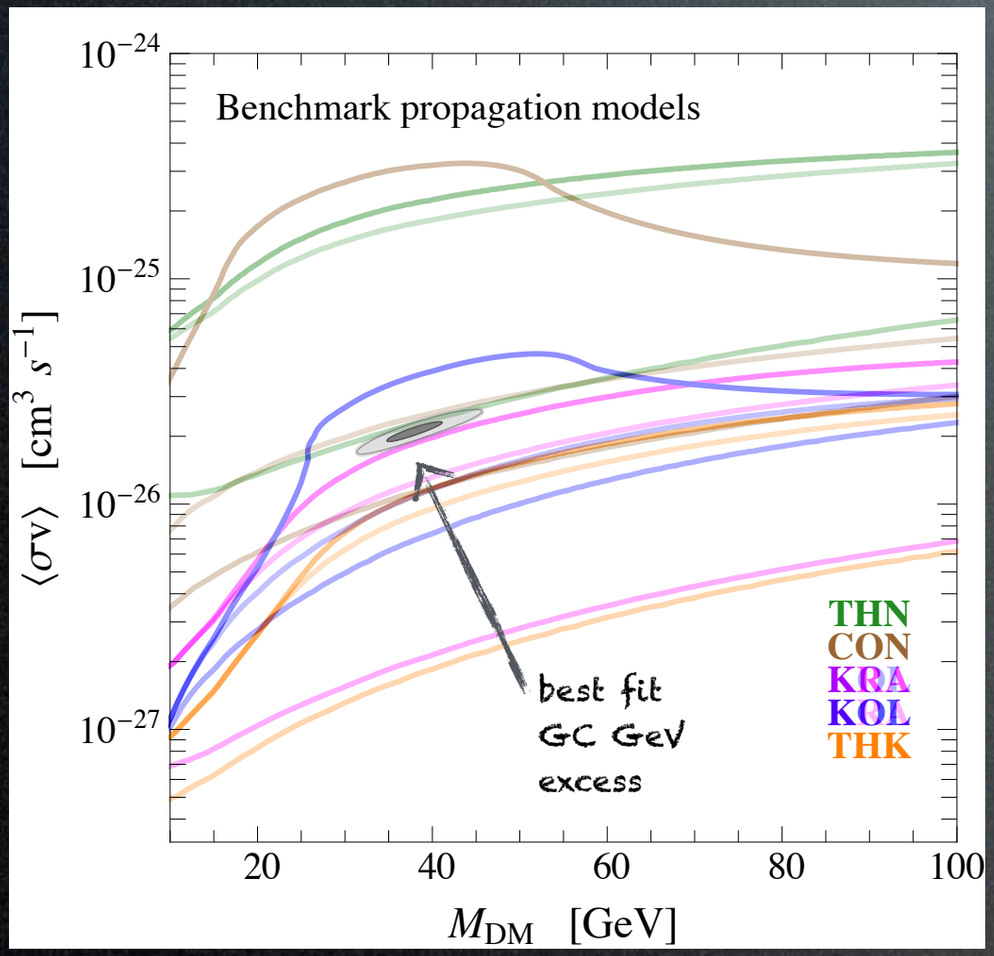
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

...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

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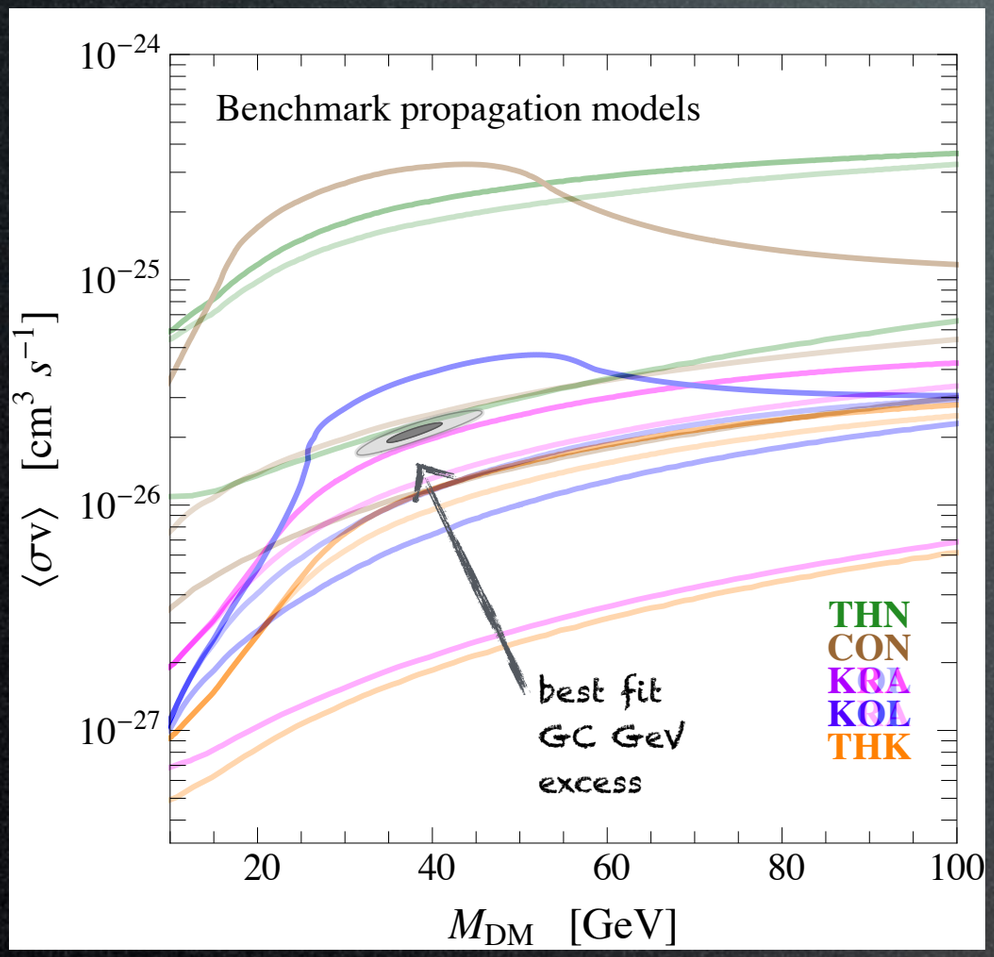
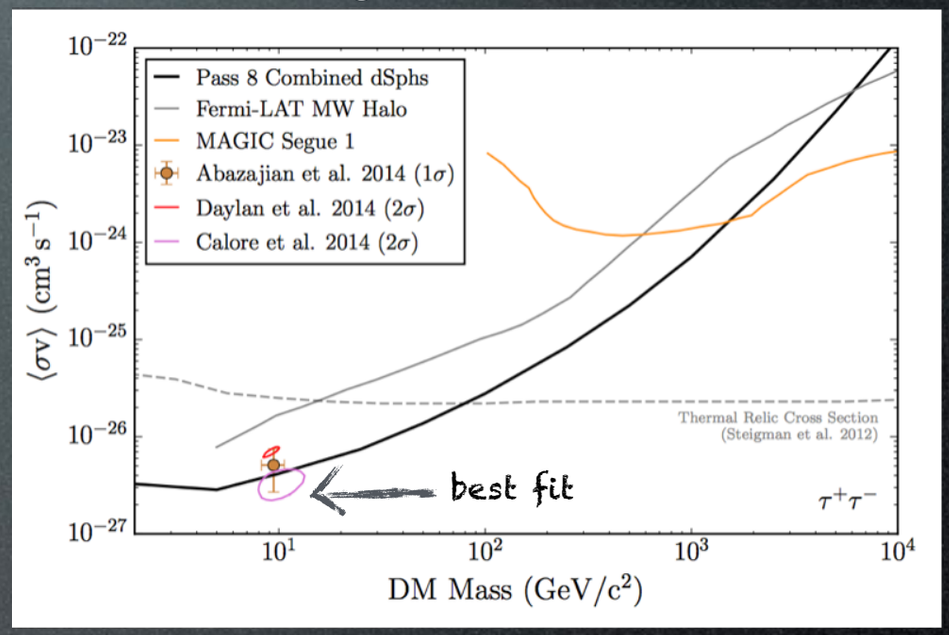


Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Gamma ray ones neither



FERMI 1503.02641

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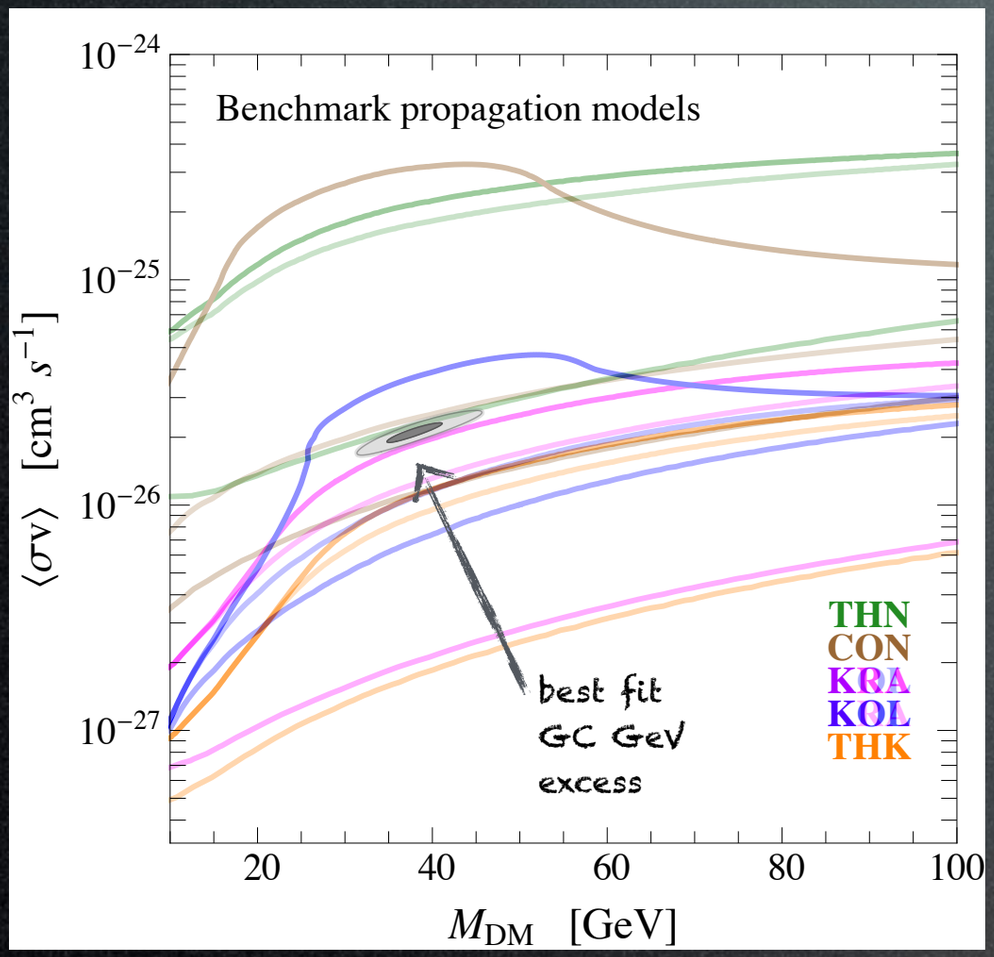

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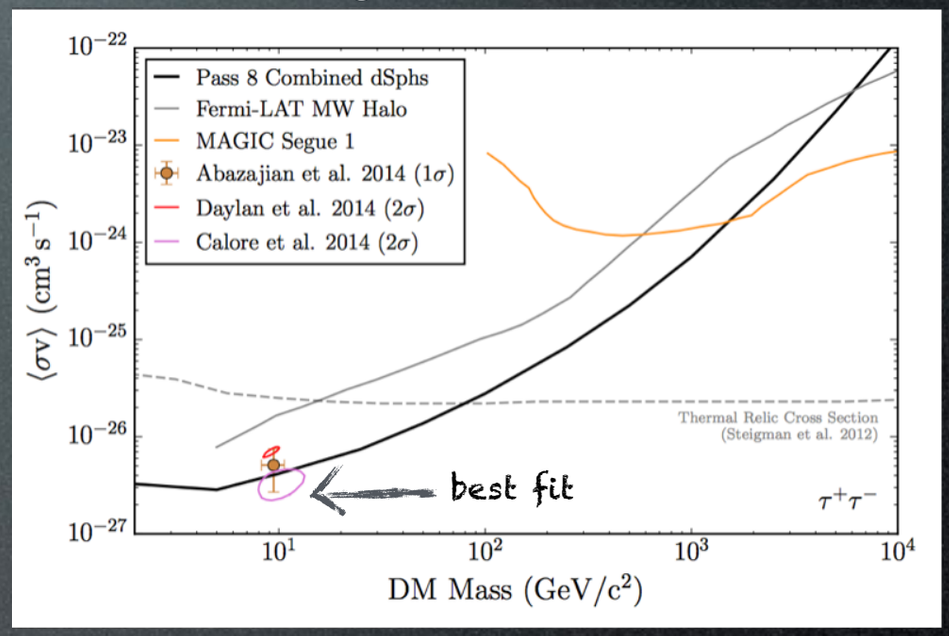
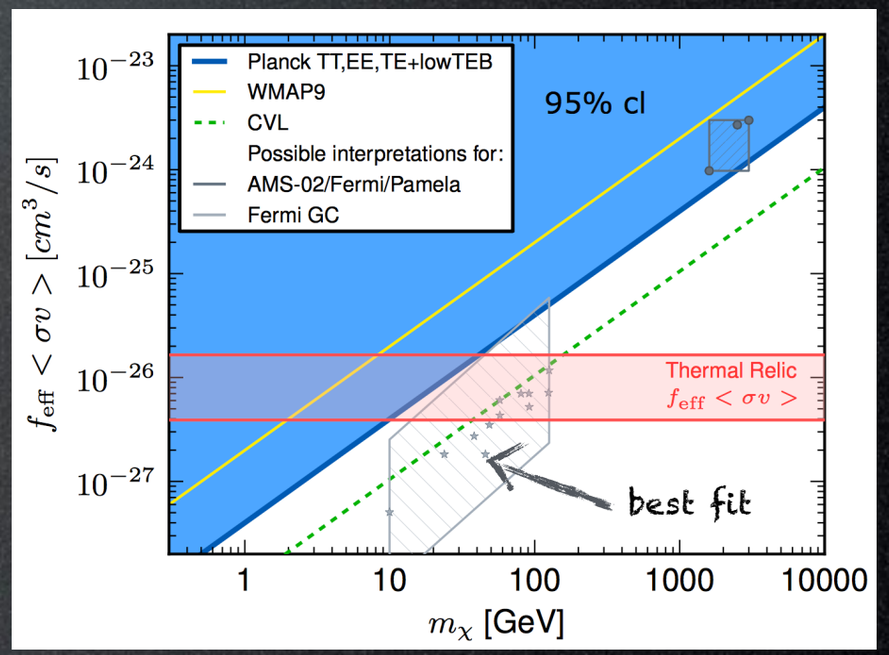


FERMI 1503.02641

Nor CMB



Planck
2015

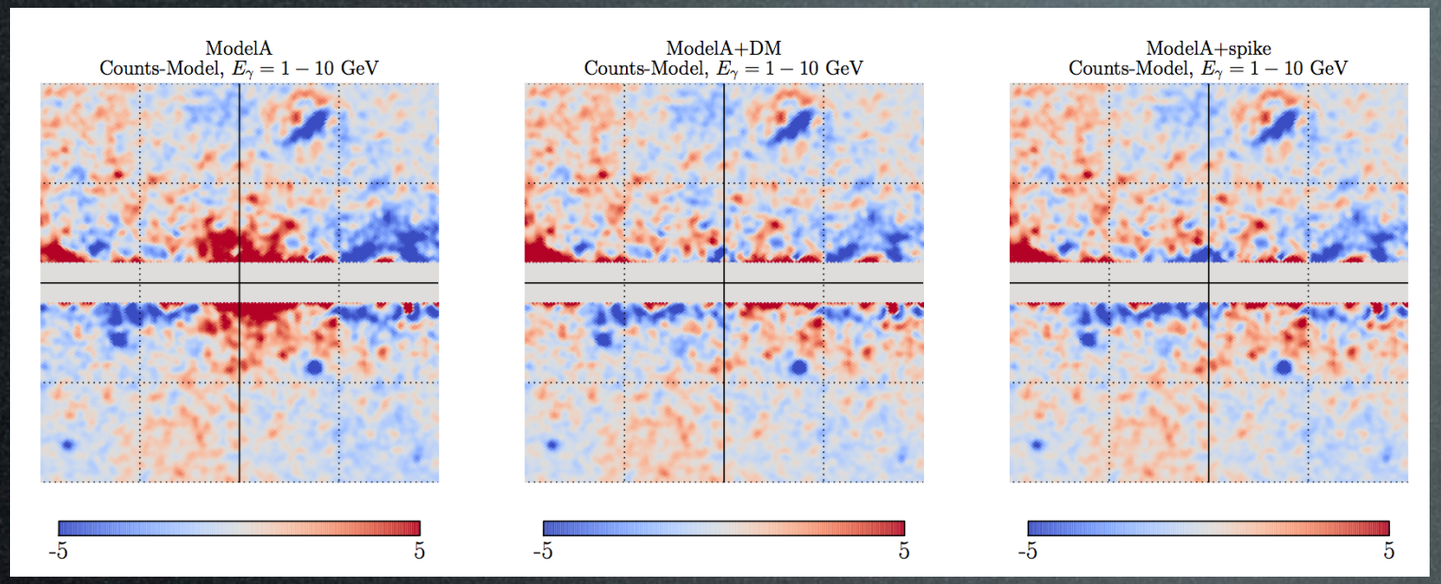
Also:

Bringmann, Vollmann,
Weniger 1406.6027

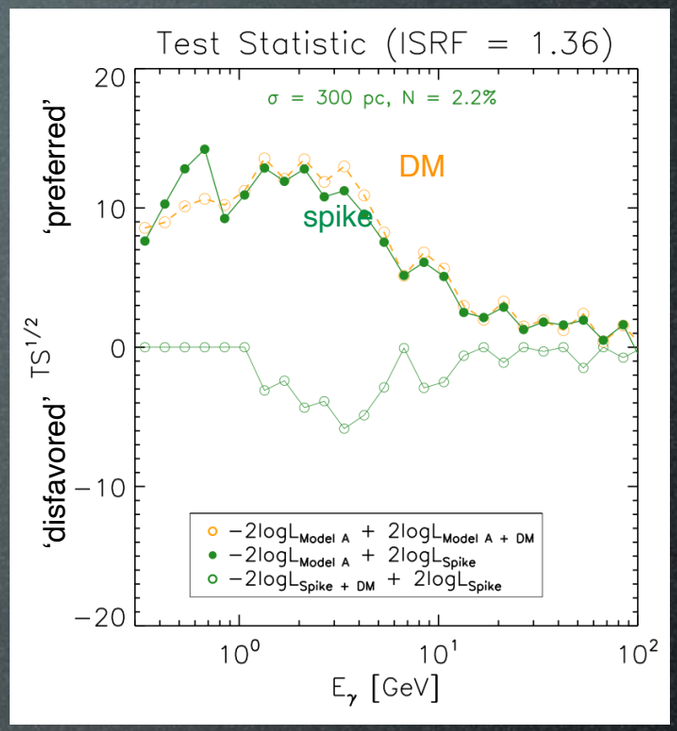
Hooper, Linden, Mertsch
1410.1527

GC GeV excess

‘Astro’ interpretation(s):

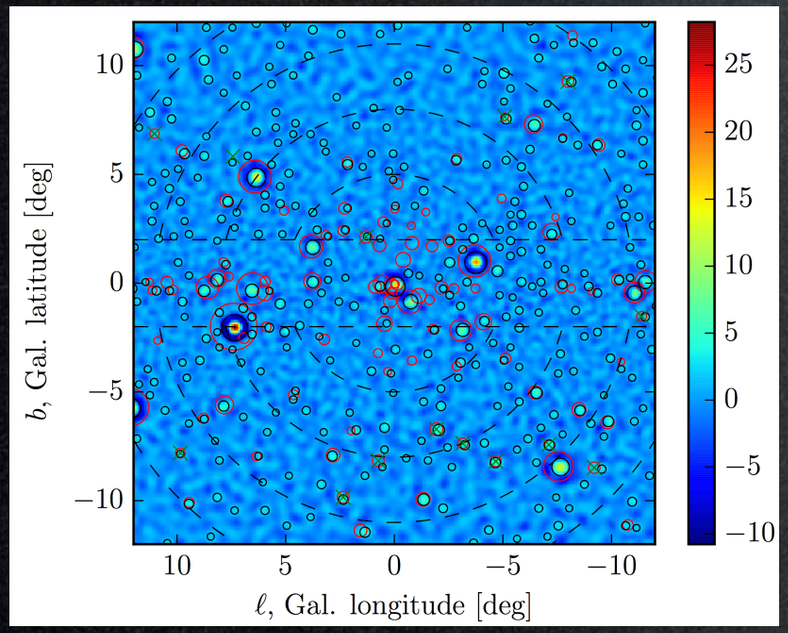


An additional steady-source spike of CRs (from SNRs?) that emit via ICS



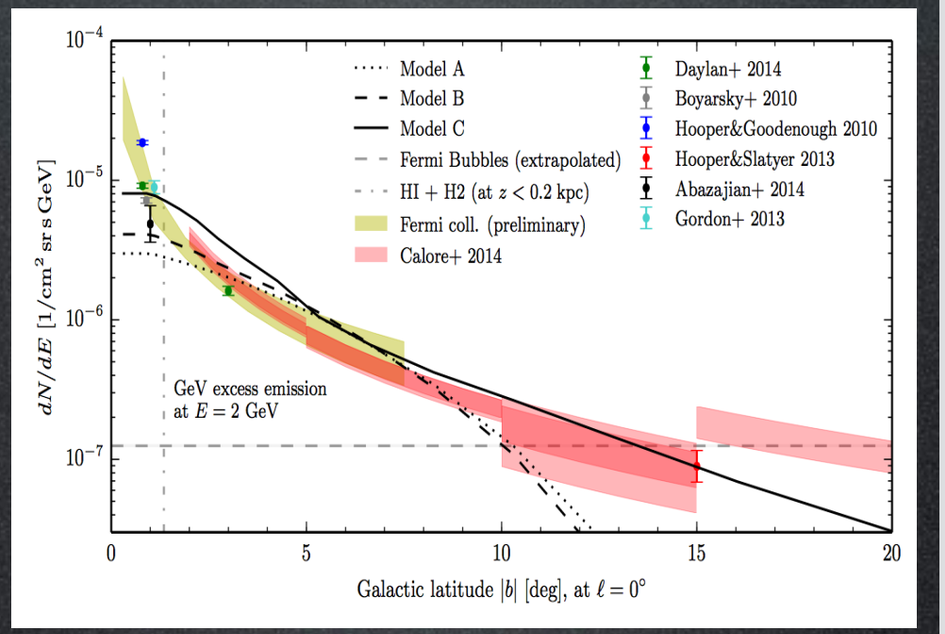
D. Gaggero et al 1507.06129

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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- We found point sources! DM ‘strongly disfavored’ (1705.00009v1).
- *Sure? (Bartels et al., 1710.10266)*
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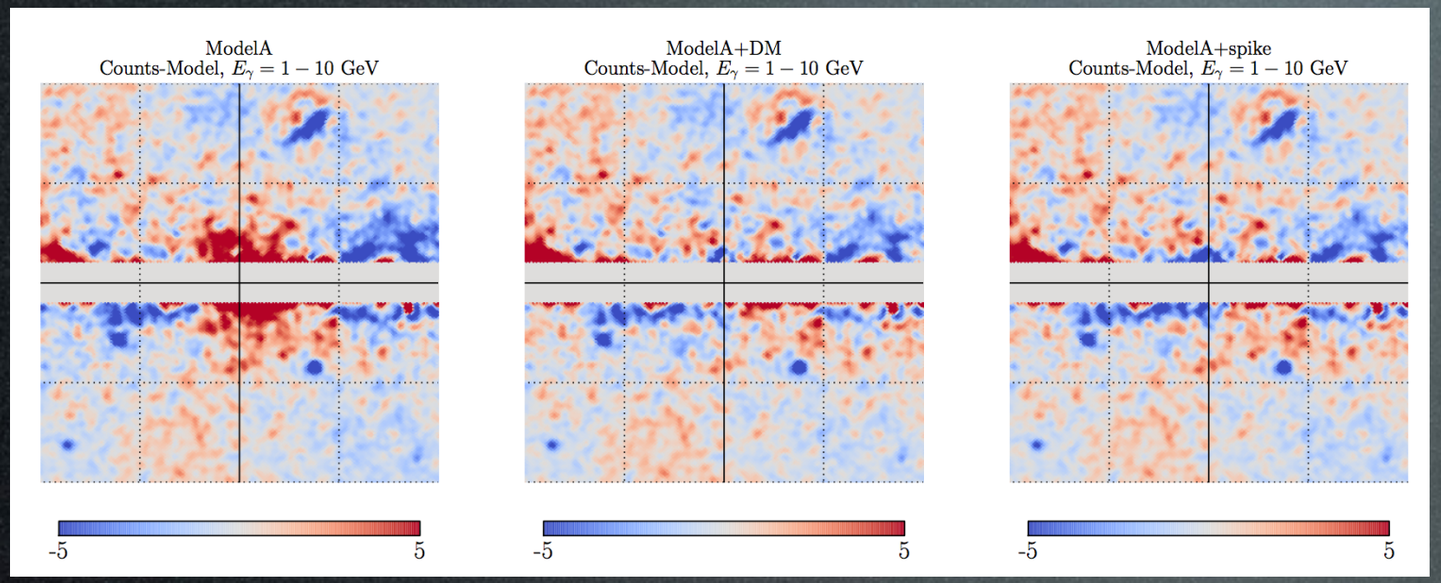

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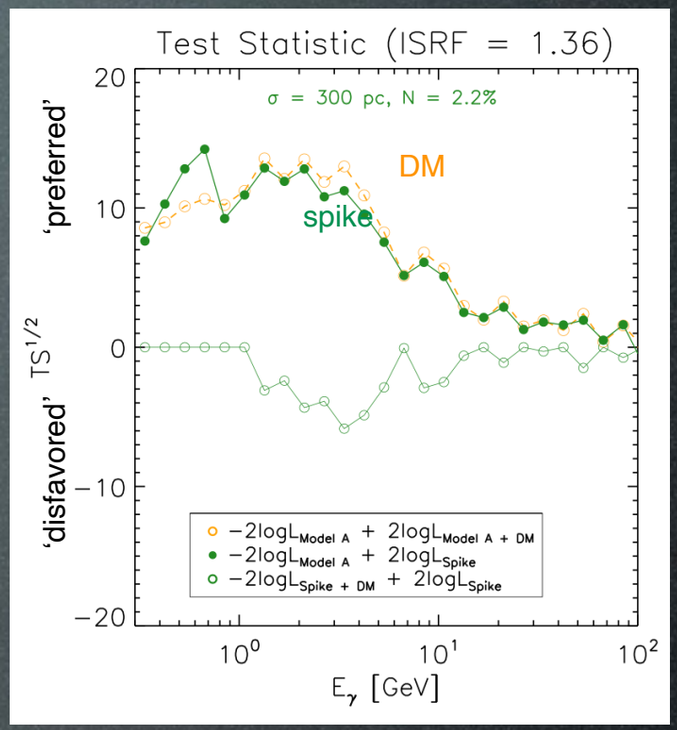

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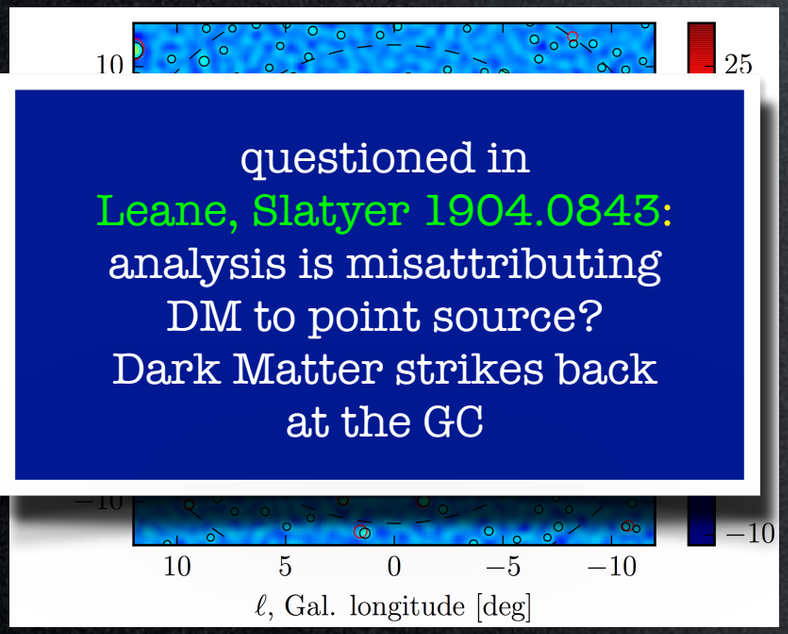

questioned in
Leane, Slatyer 1904.0843:
analysis is misattributing
DM to point source?
Dark Matter strikes back
at the GC

Bartels…Weniger 1506.05104
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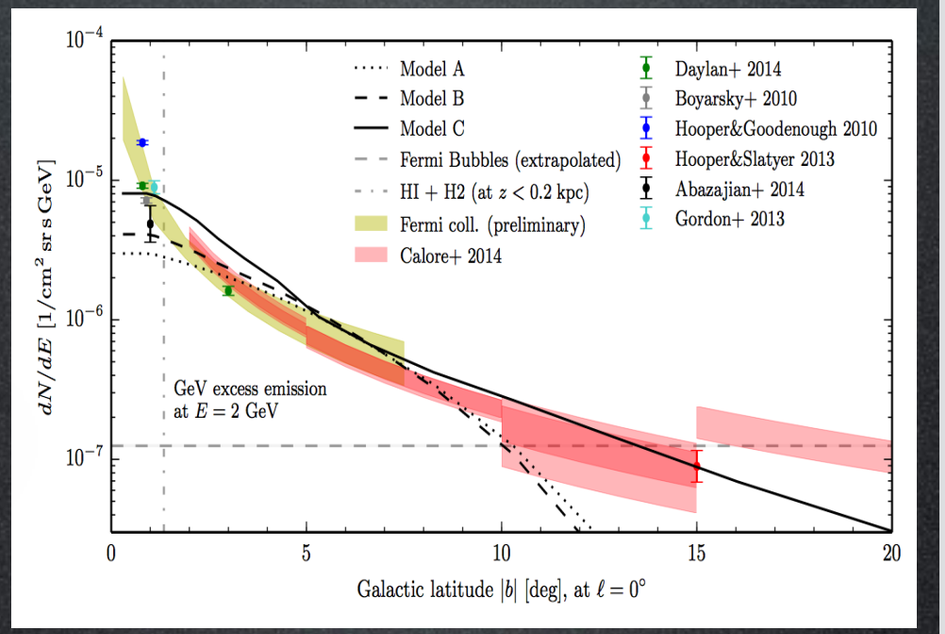

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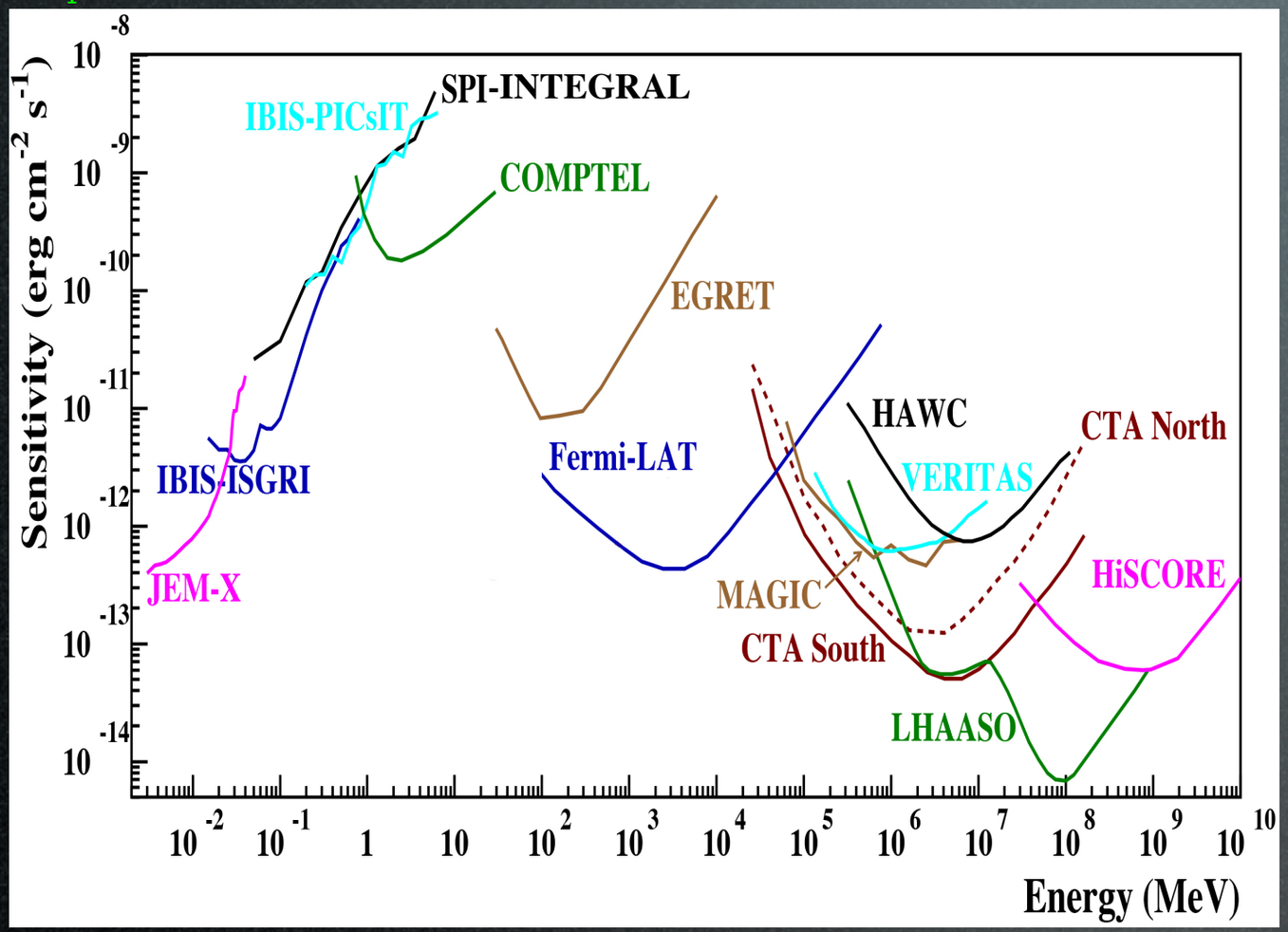
Indirect detection: photons

adapted from 1611.02232



Past/current experiments:

Integral, Comptel, Fermi

(2002⟶) *(1991-2000)* *(2009⟶)*

Planned/proposed experiments:

e-Astrogam?, Compair?, Amego?

HERD	Chinese SS	2020s?	HEP detectors	charged CRs	50 GeV – PeV
Amego	satellite	2020s?	HEP detectors	γ-rays	0.2 – 10 GeV
Compair	satellite	2020s?	HEP detectors	γ-rays	0.2 – 500 MeV
Ska	S.Africa+Australia	2020s?	radio telescope	radio	50 MHz – 30 GHz
Ino-Ical	India	2020s?	calorimeter	neutrinos	1 – 100 GeV
e-Astrogam	satellite	2030s?	HEP detectors	γ-rays	0.3 MeV – 3 GeV

Cirelli, Strumia, Zupan to appear

Indirect detection: photons

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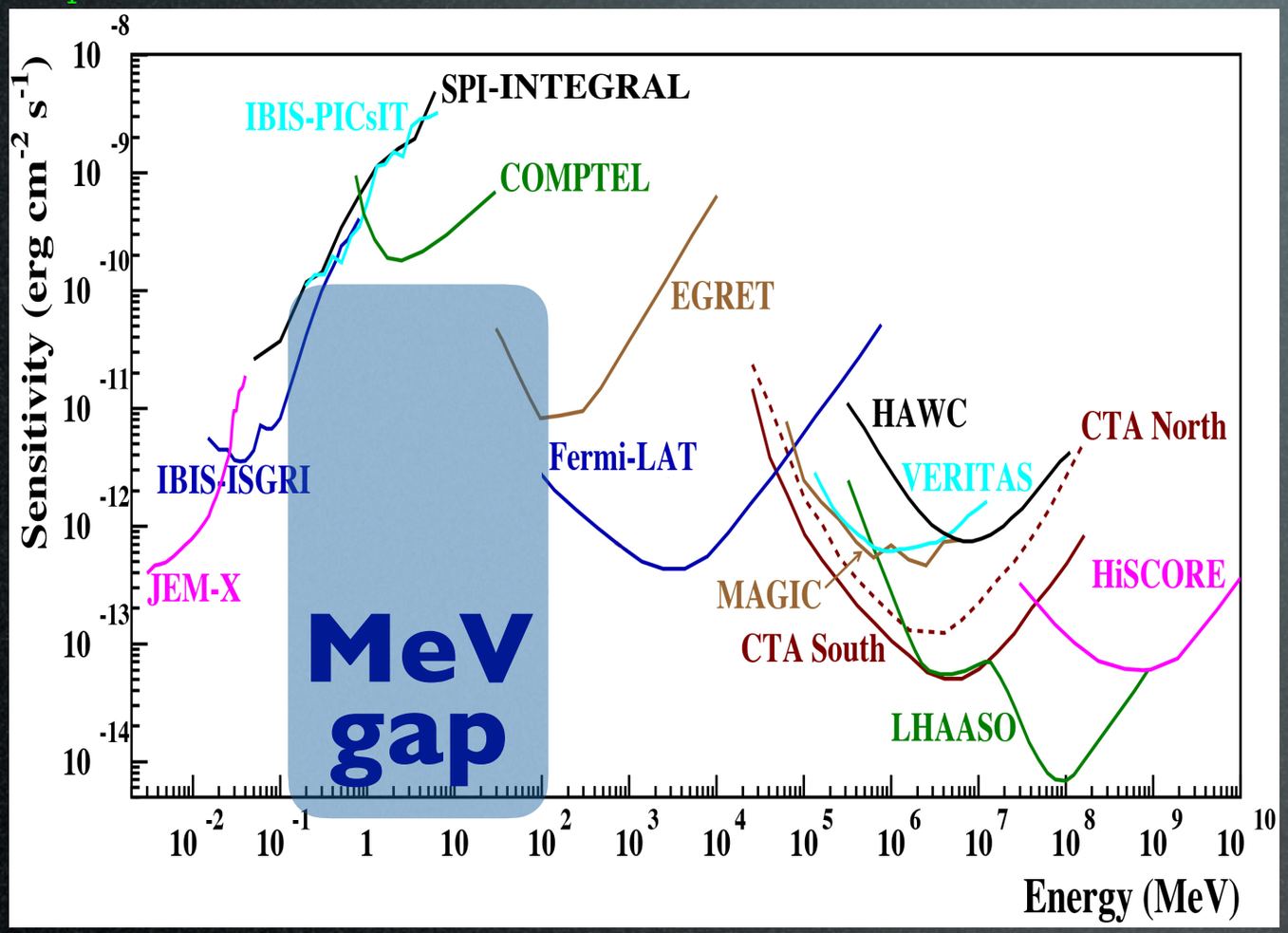

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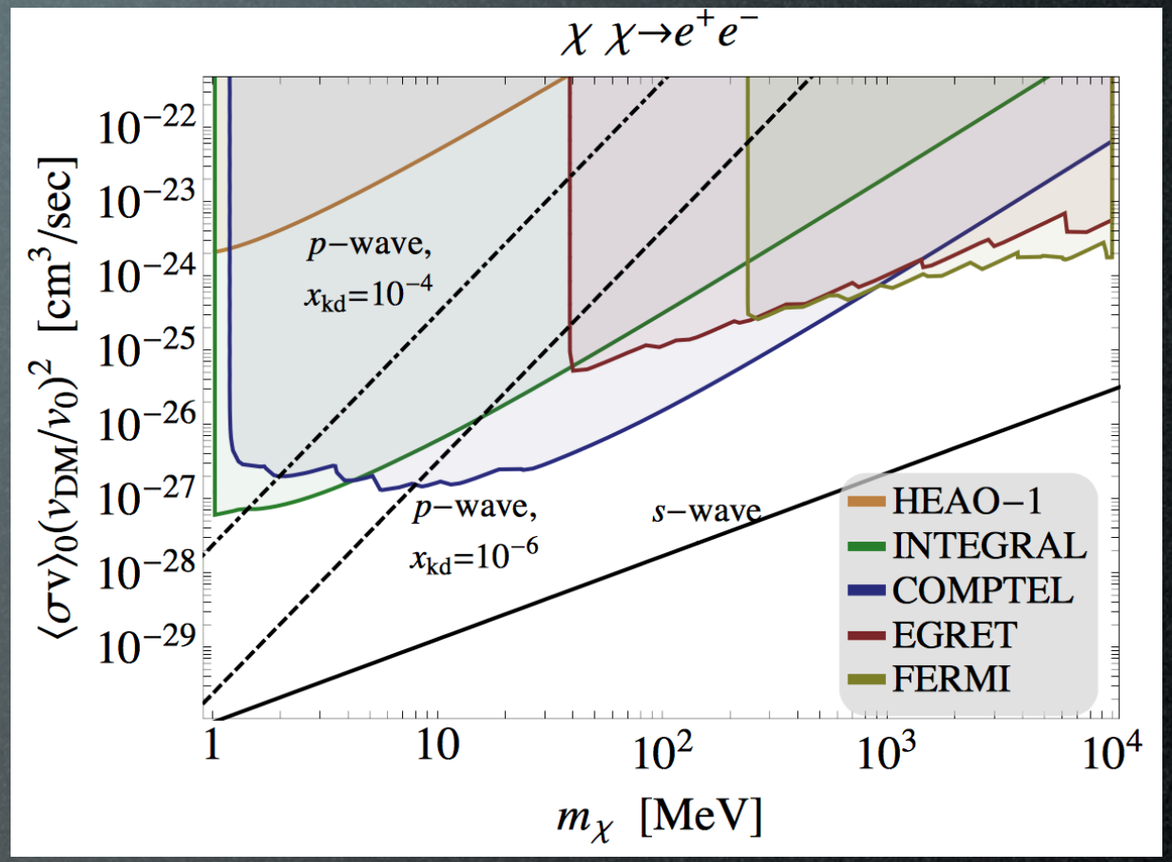
COMPAIR	satellite	2020s?	HEP detectors	γ-rays	0.2 – 500 MeV
SKA	S.Africa+Australia	2020s?	radio telescope	radio	50 MHz – 30 GHz
INO-ICAL	India	2020s?	calorimeter	neutrinos	1 – 100 GeV
E-ASTROGAM	satellite	2030s?	HEP detectors	γ-rays	0.3 MeV – 3 GeV

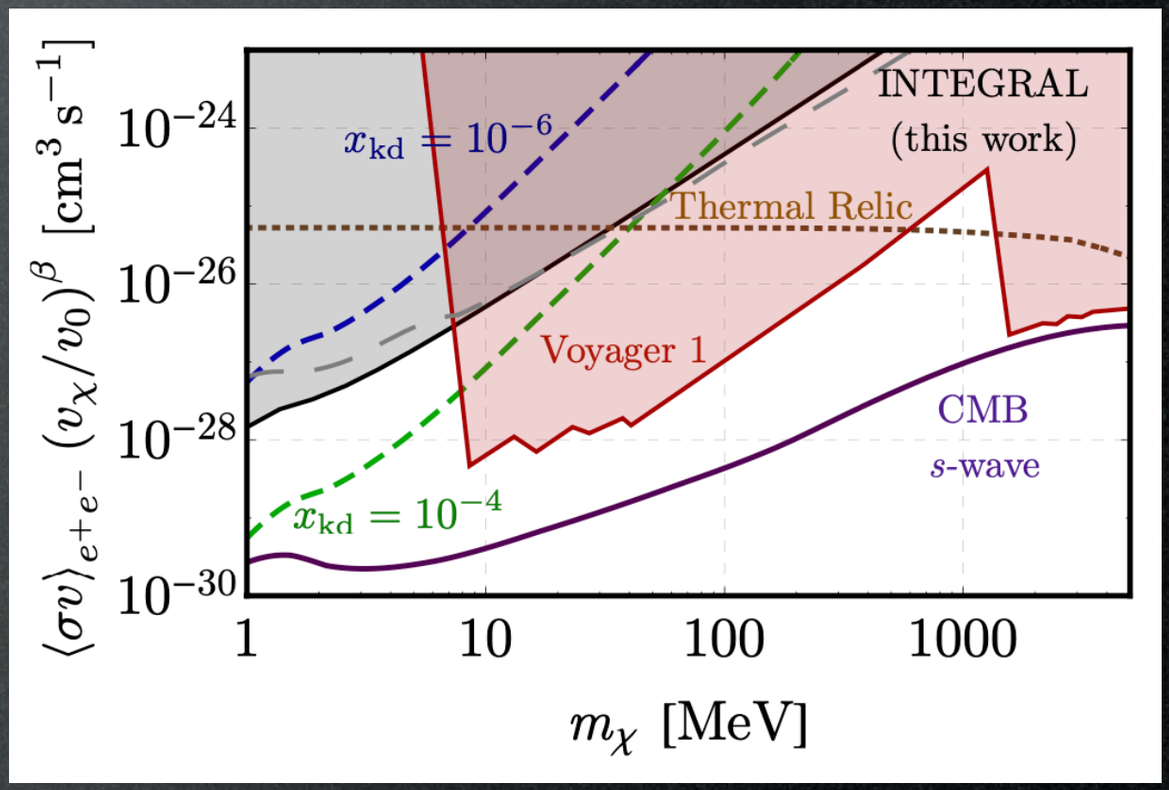
Cirelli, Strumia, Zupan to appear

Some recent studies

Essig, Kuflik, McDermott, Volansky et al., 1309.4091



Laha, Muñoz, Slatyer, 2004.00627**v1**



NB: ‘prompt’ emission only

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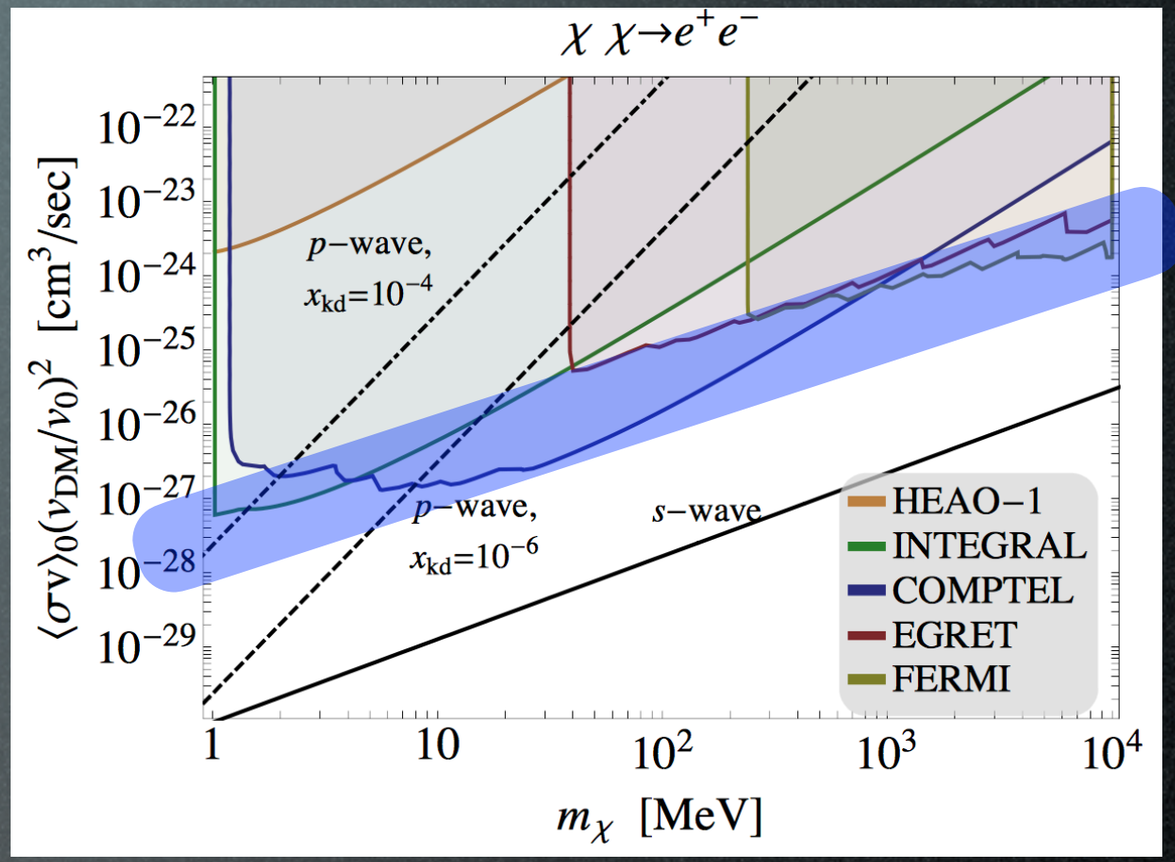

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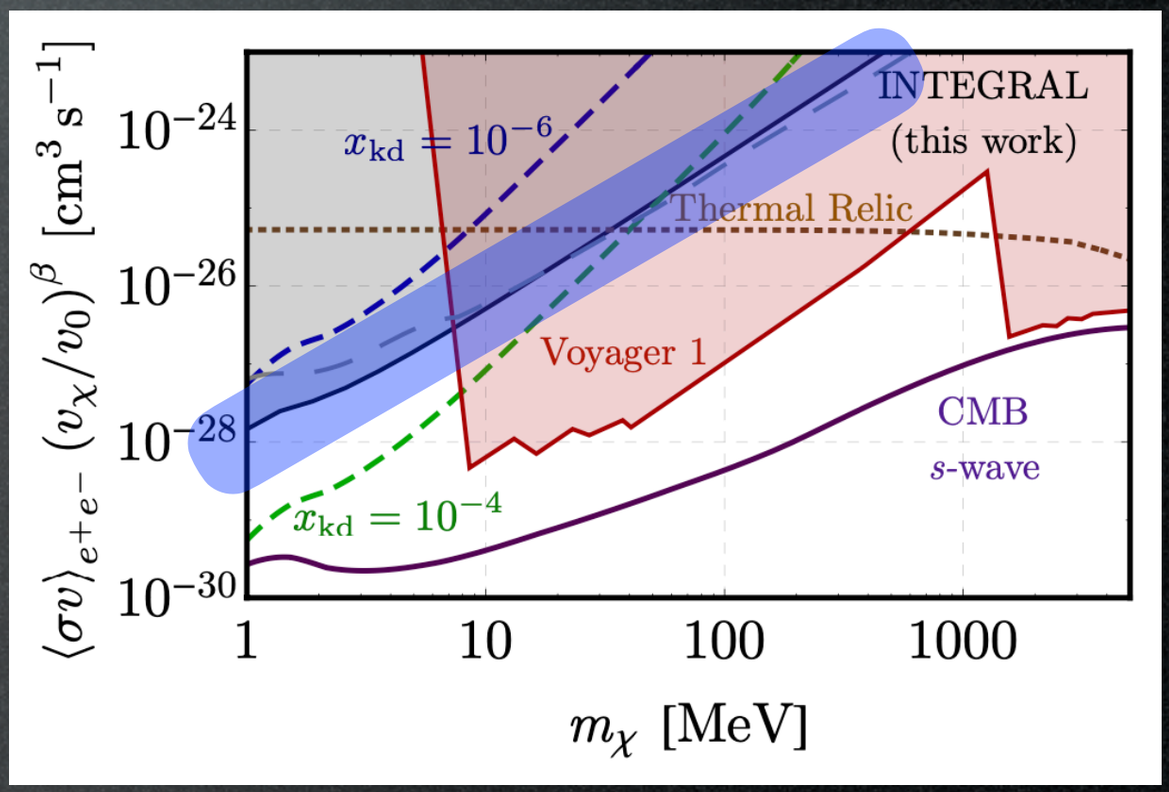

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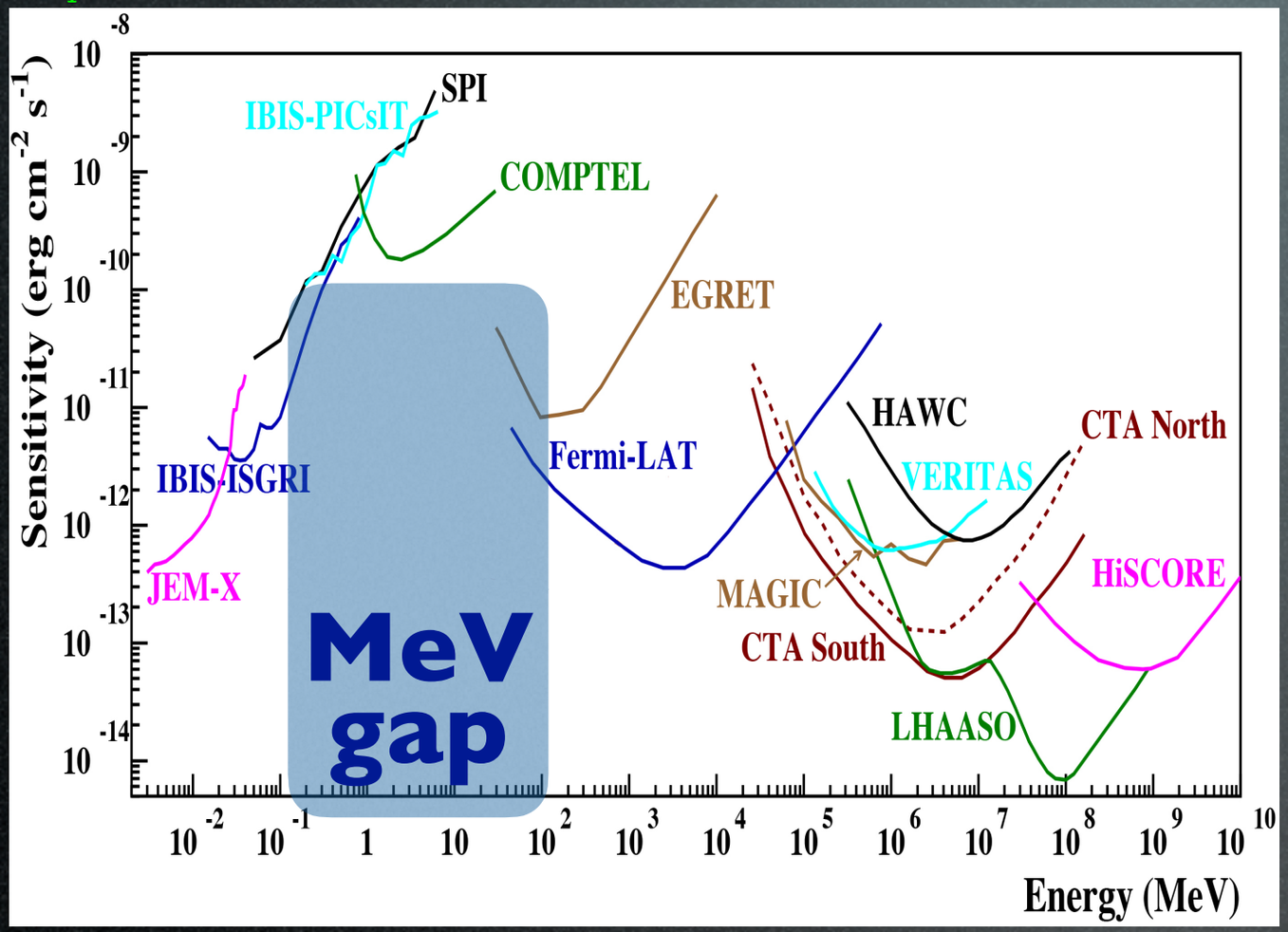

How to do better?

ICS & X-rays!

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

Sub-GeV DM & X-rays

Annihilation channels, focus on the MW (assume standard NFW profile)

$\mathrm{DM\ DM} \to e^+e^-$

$\mathrm{DM\ DM} \to \mu^+\mu^-$

$\mathrm{DM\ DM} \to \pi^+\pi^-$

Sub-GeV DM & X-rays

Annihilation channels

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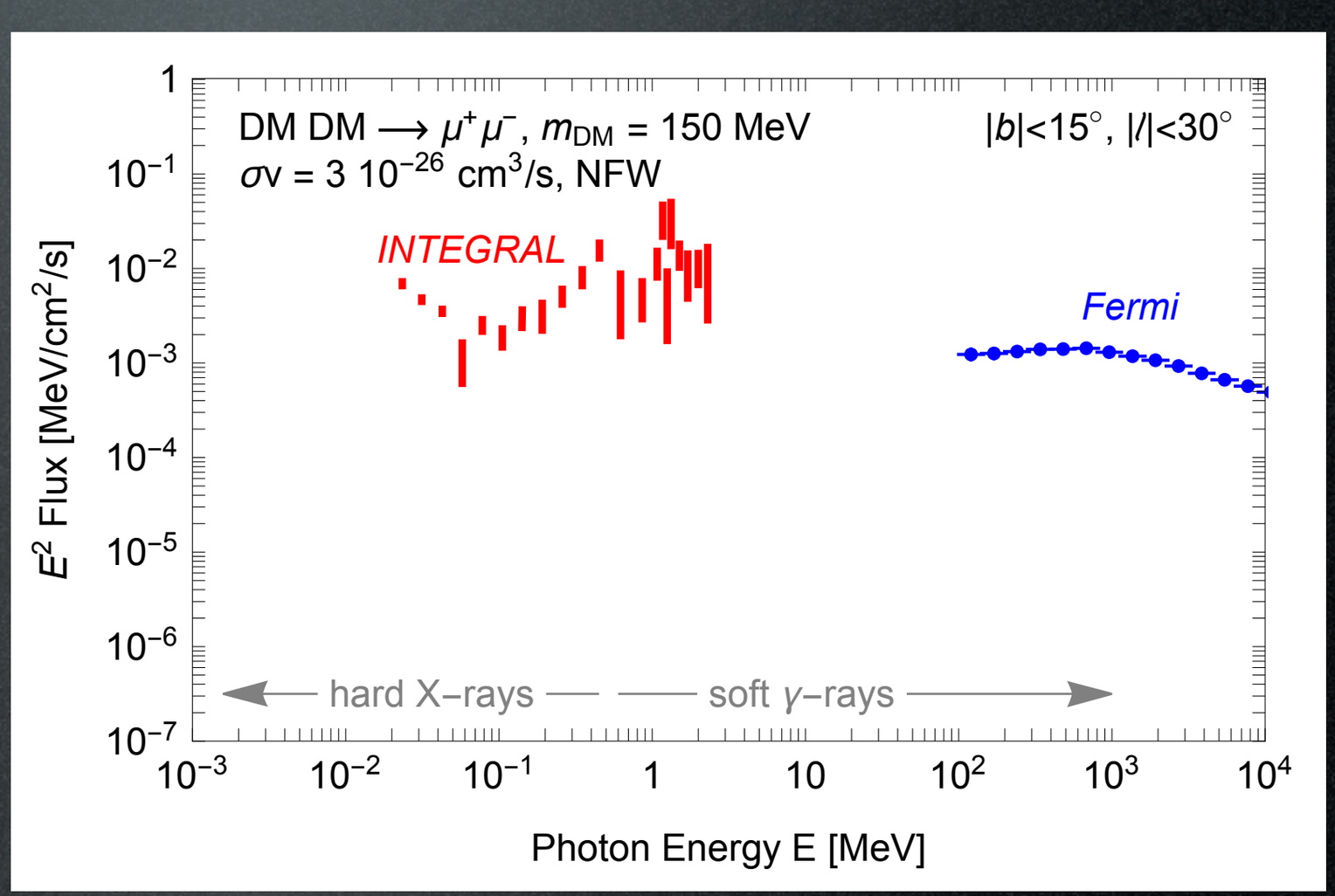

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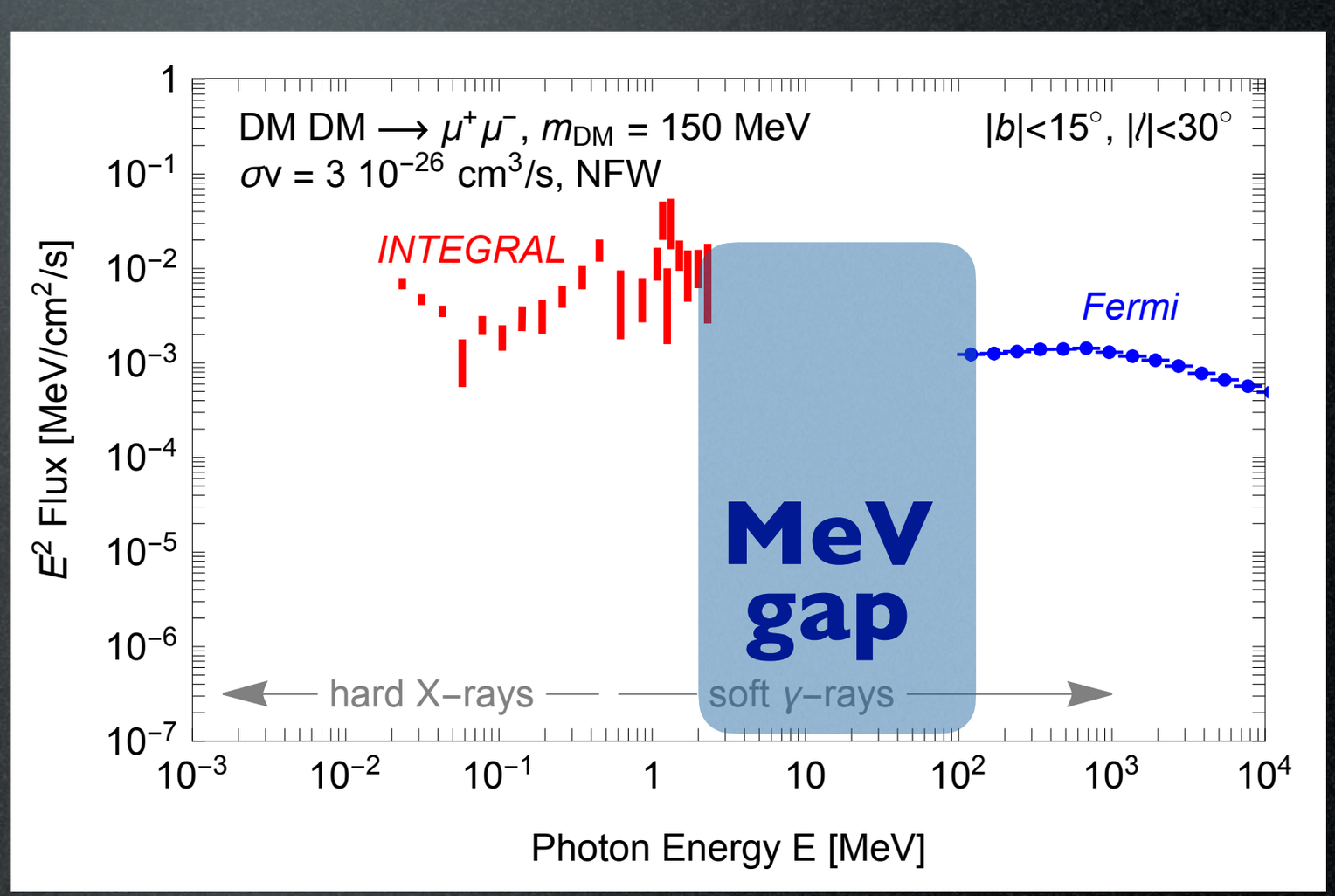

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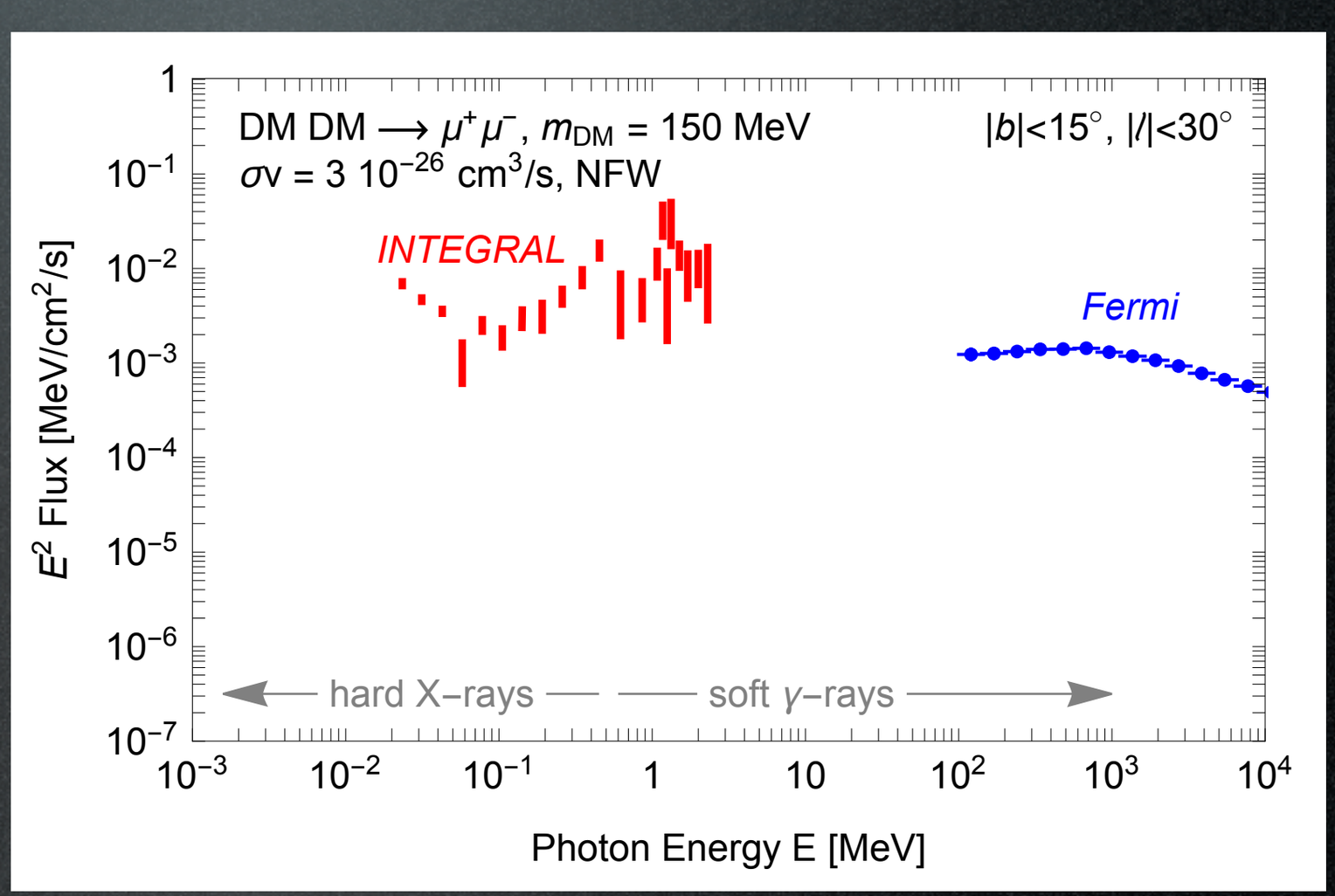

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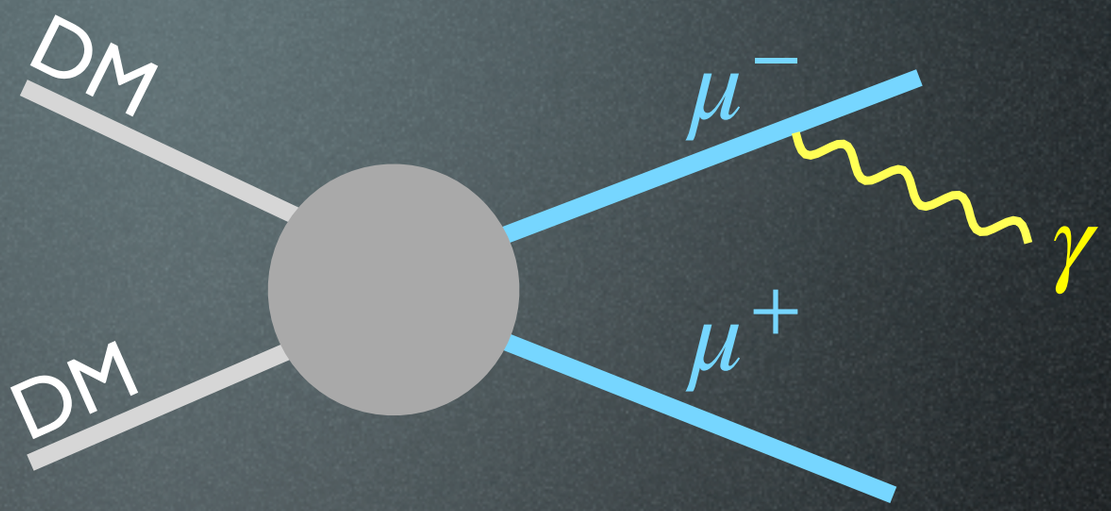
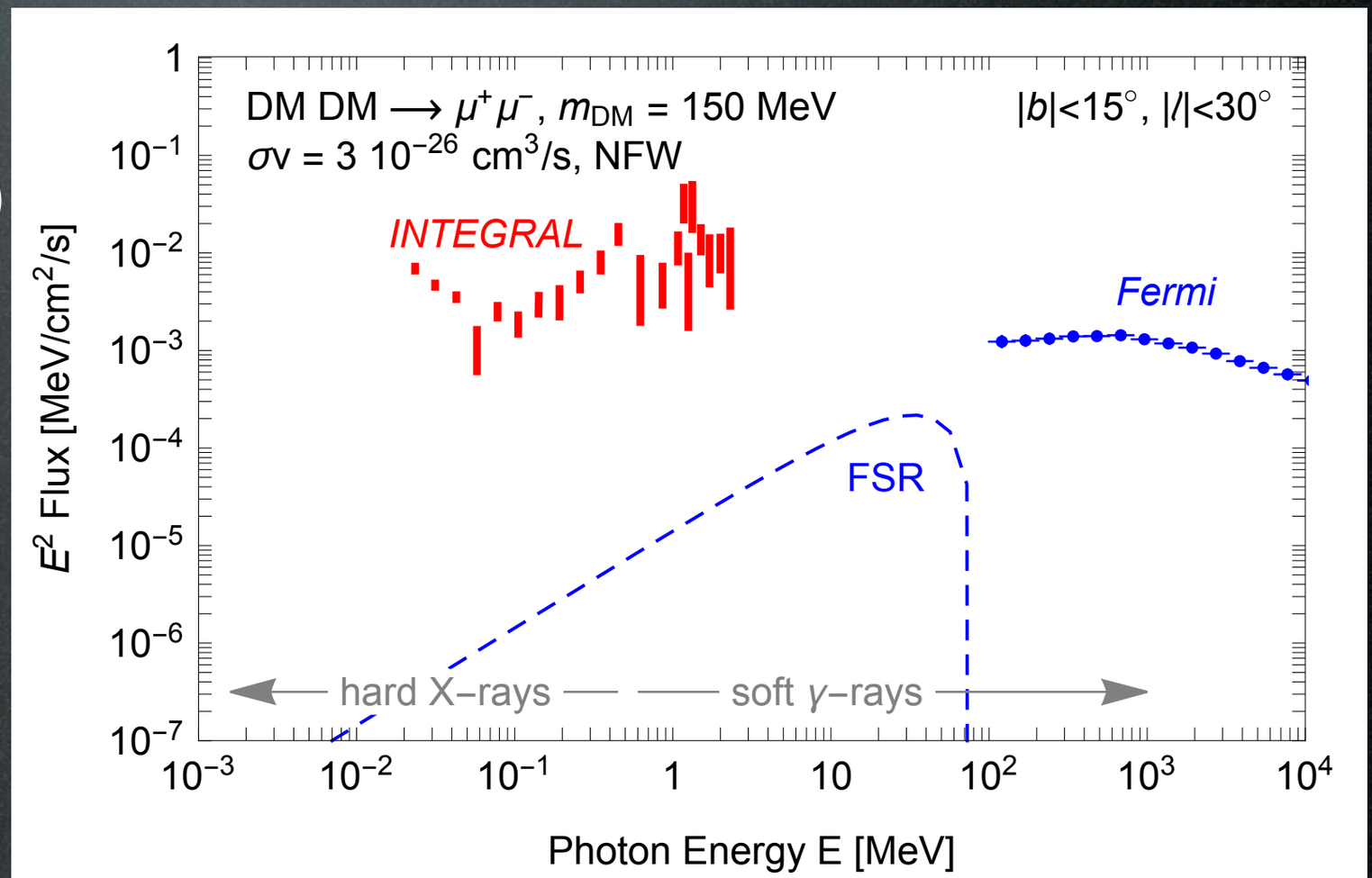


'Prompt' emission:

Final State Radiation (FSR)



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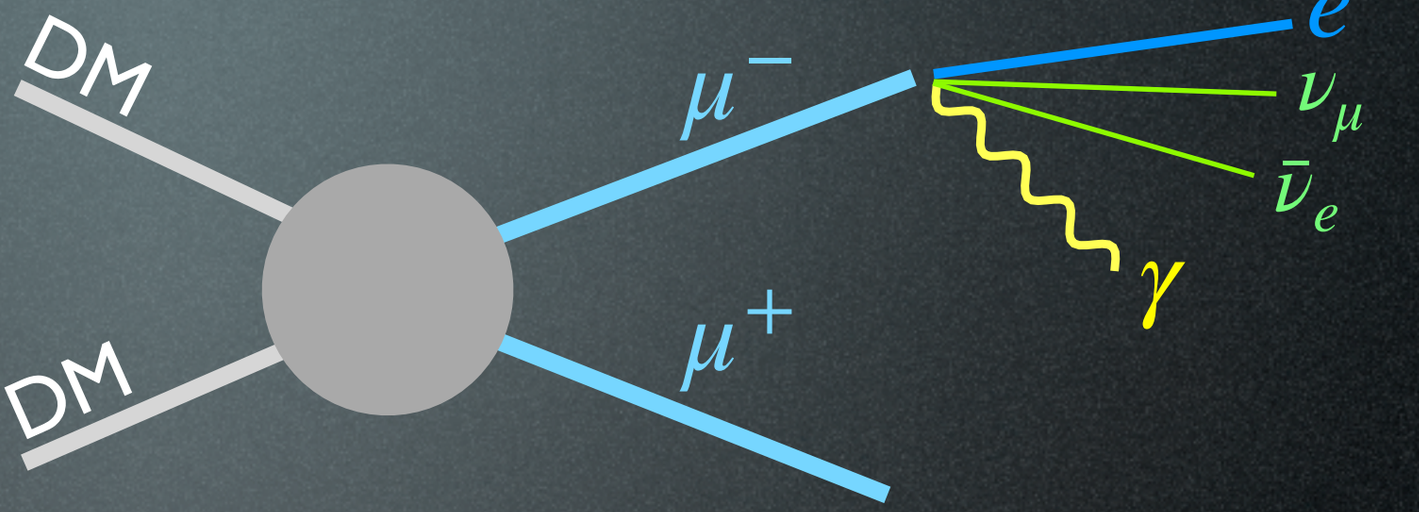
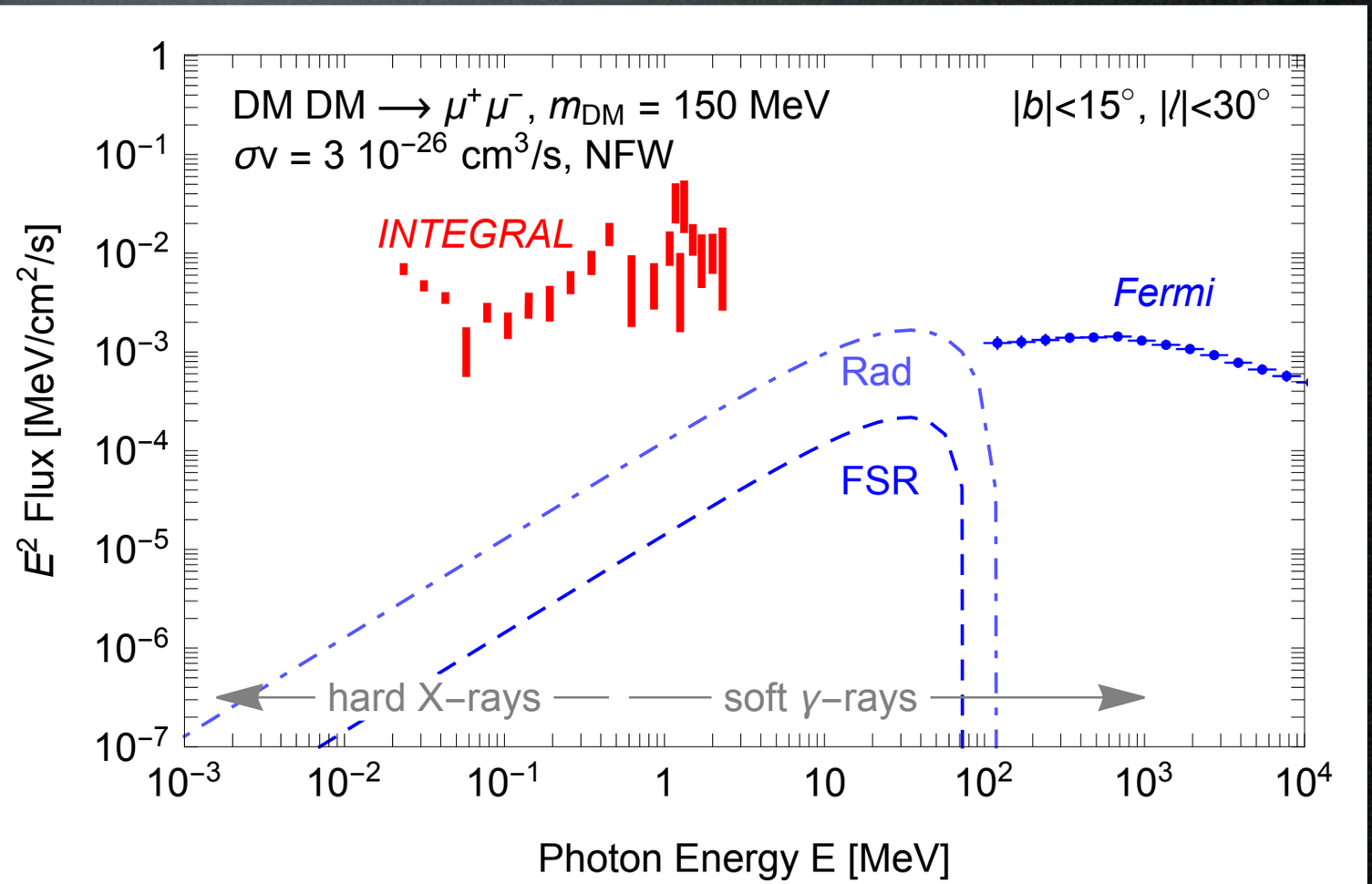


'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

Usually irrelevant, but <u>not</u> for μ decaying 'at rest'!



Sub-GeV DM & X-rays

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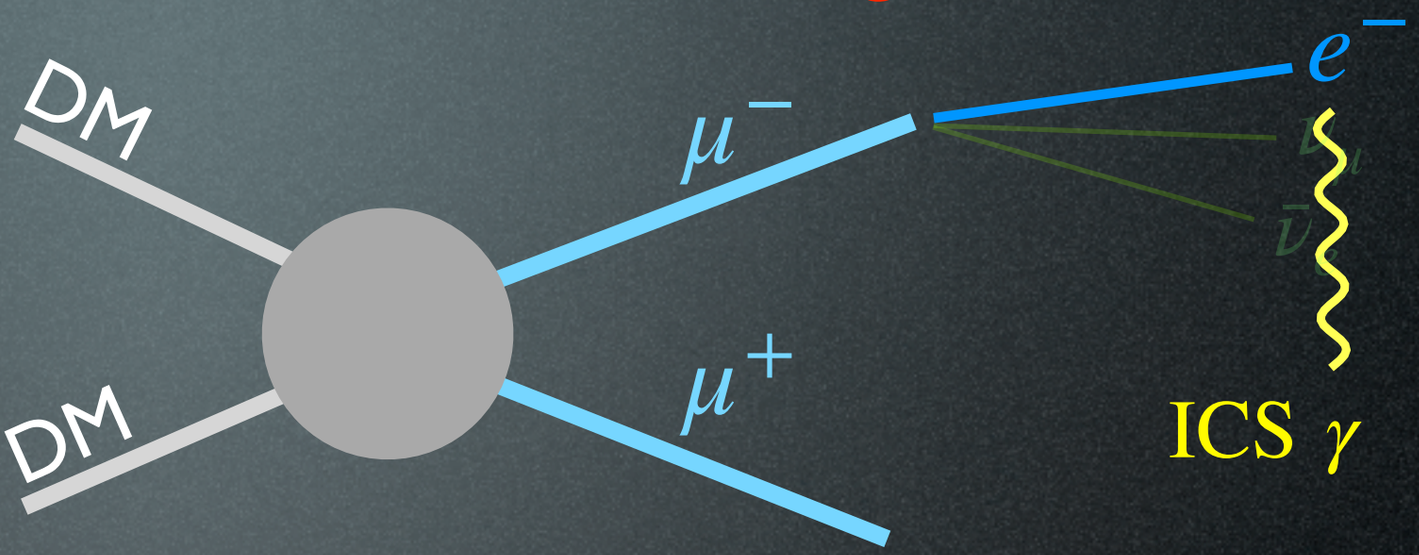


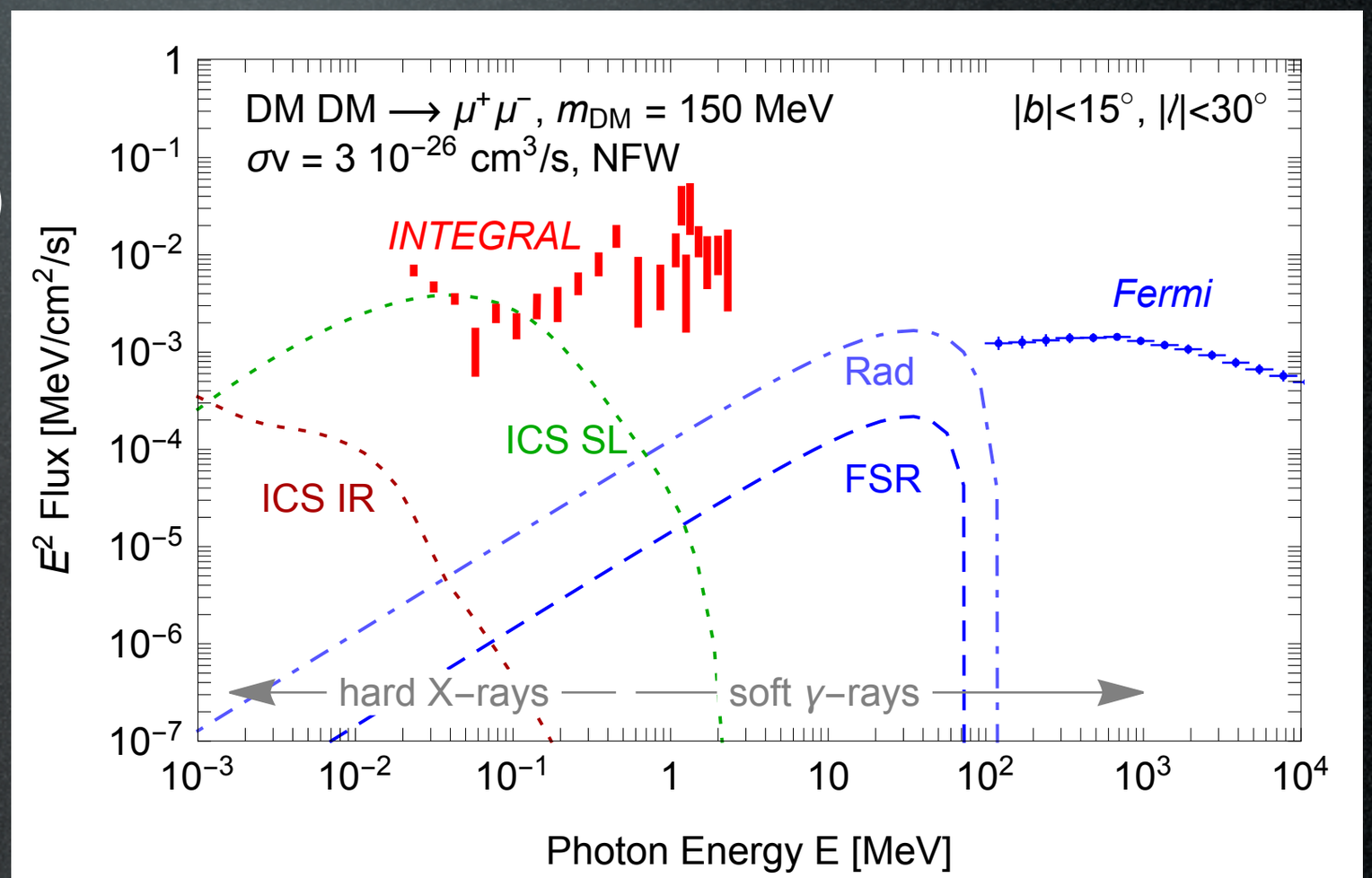
'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

Secondary emission:

ICS: inevitably associated to annihil to charged states



Sub-GeV DM & X-rays

Annihilation channels

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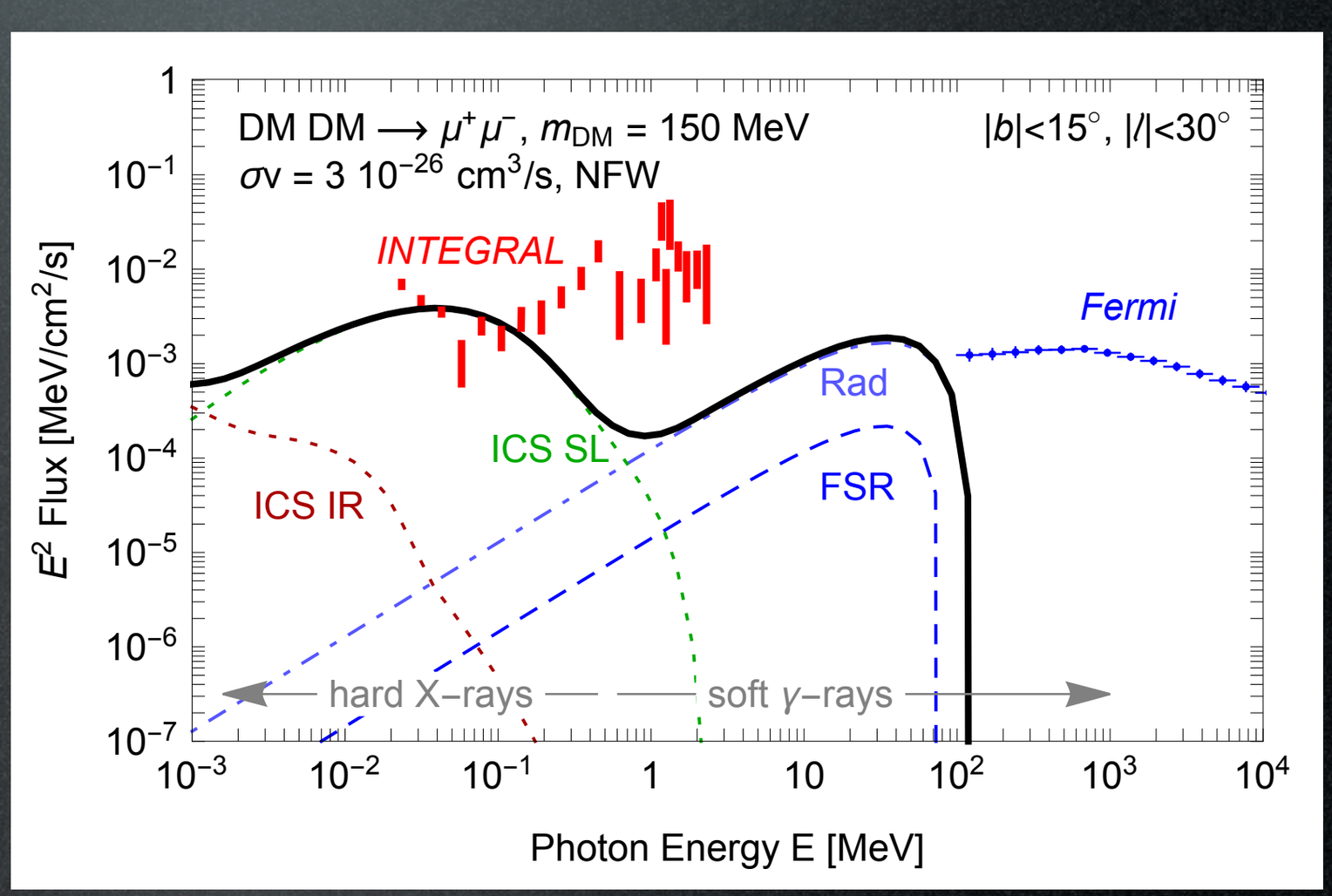
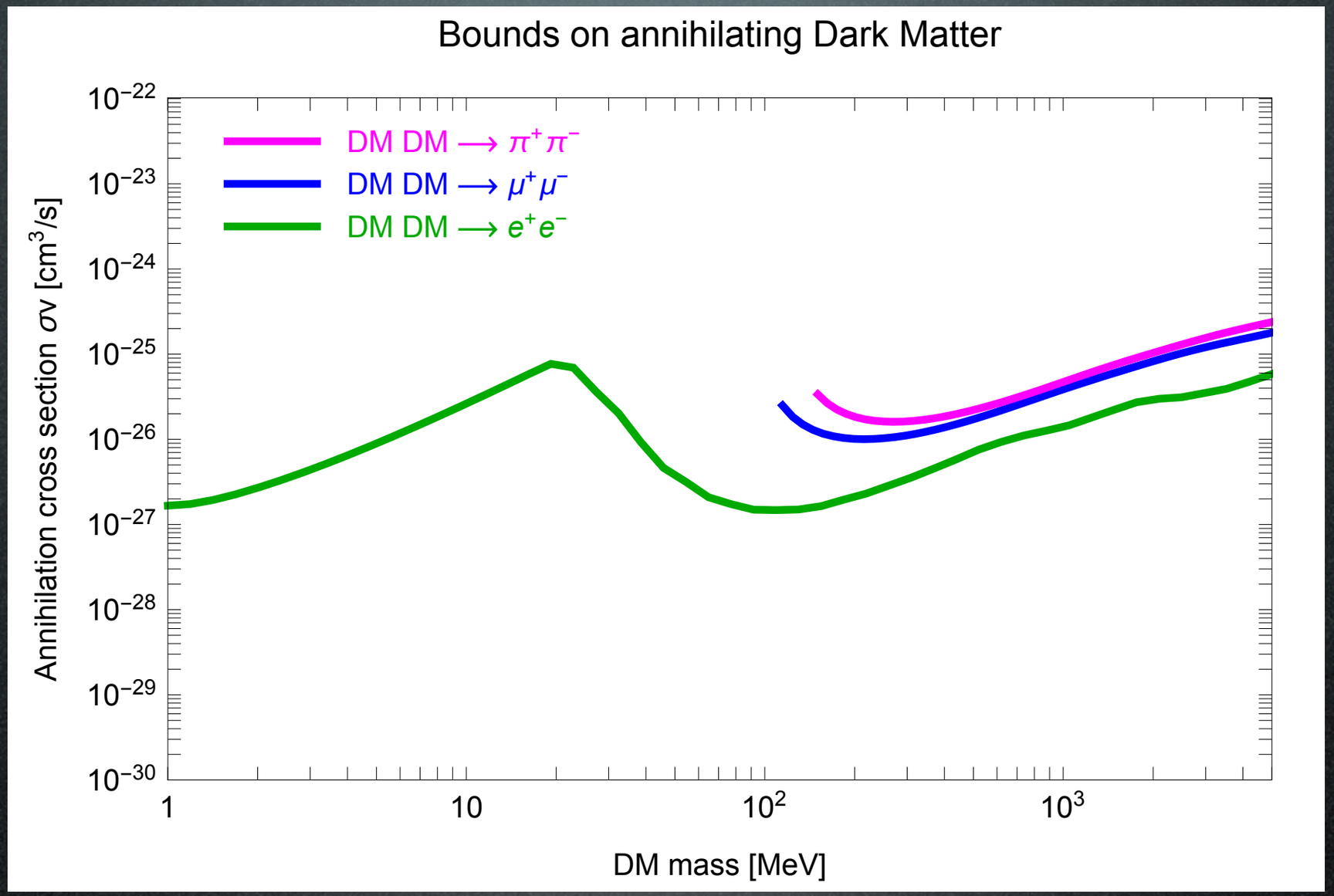
Key message:
ICS allows to probe sub-GeV DM with X-ray data

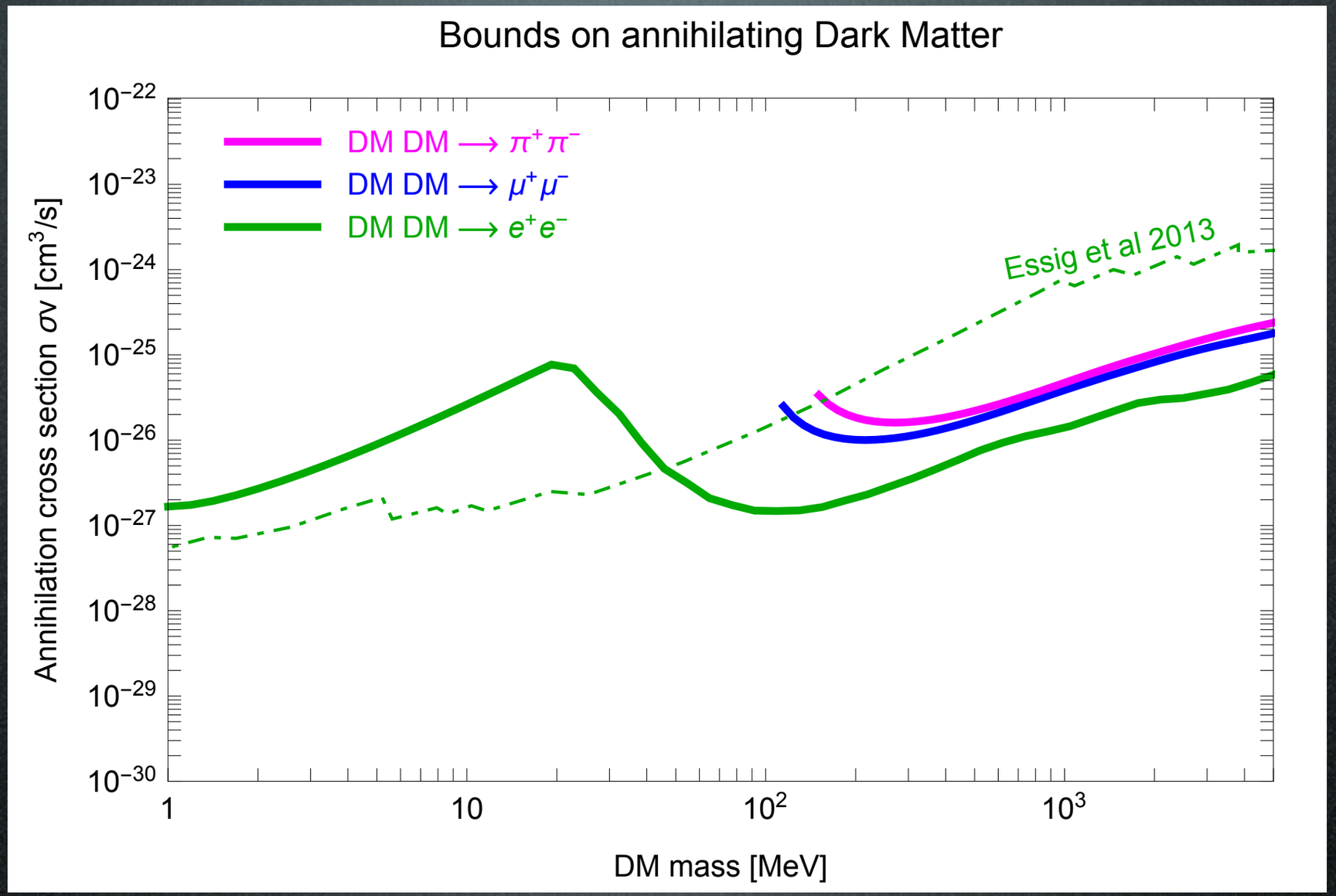


Results



Bounds on all 3 channels

Results

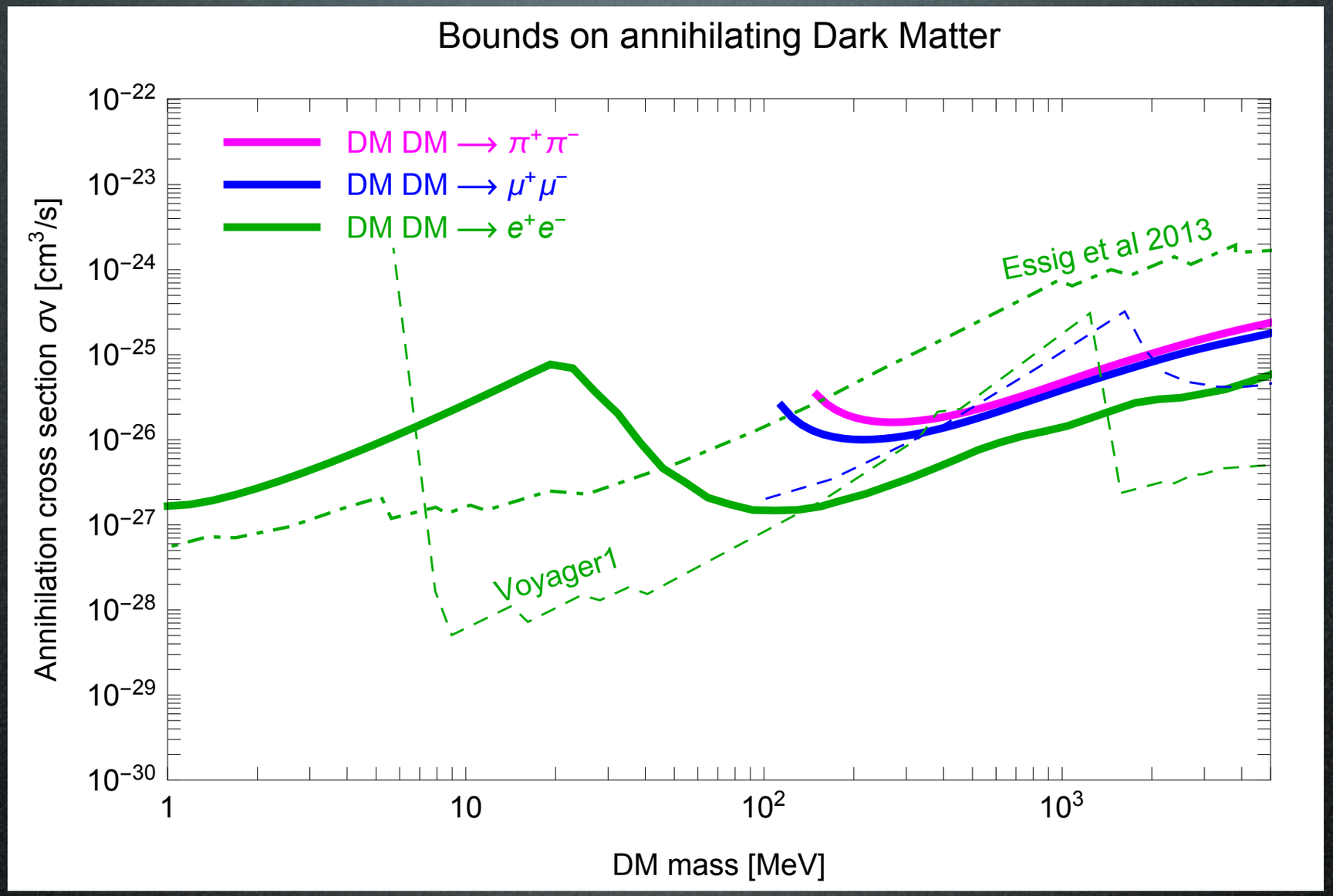


Essig+ 1309.4091

Bounds on all 3 channels

ICS allows to improve Essig+ 2013 at large m_{DM}

Results



Essig+ 1309.4091

Boudaud+ 1612.07698

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Voyager1 bounds stronger/weaker dep. on data

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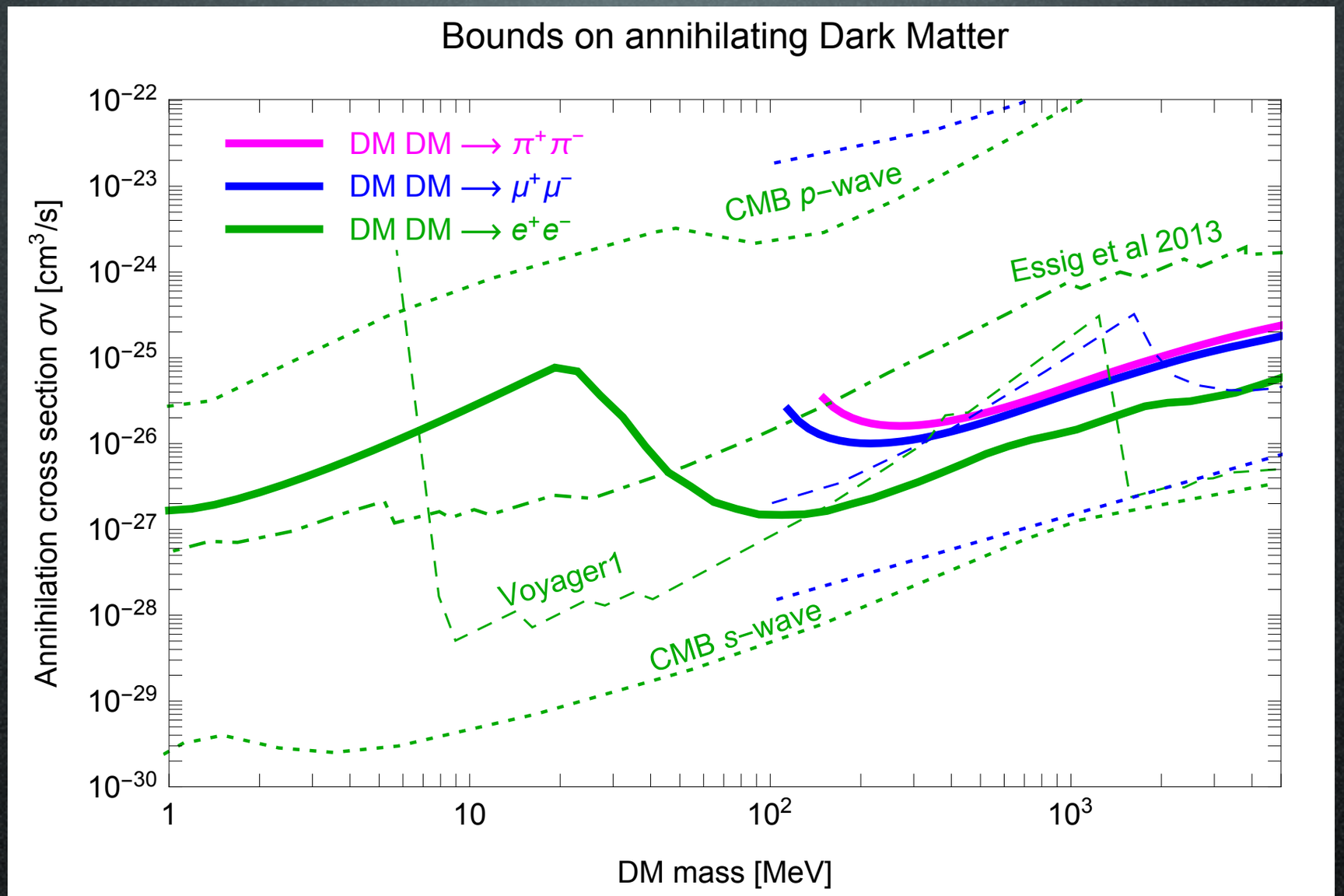


Essig+ 1309.4091

Boudaud+ 1612.07698

Slatyer+ 1506.03811

Lopez-H+ 1303.5094

Diamanti+ 1308.2578

Liu+ 2008.01084

Bounds on all 3 channels

ICS allows to improve Essig+ 2013 at large $m_{\rm DM}$

Voyager1 bounds stronger/weaker dep. on data

CMB bounds depend on s-/p-wave annihilation

DM detection

direct detection

production at colliders

indirect

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

Fermi, ICT, radio telescopes...

e^+ from annihil in galactic halo or center

PAMELA, Fermi, HESS, AMS,balloons...

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

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

GAPS, AMS

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

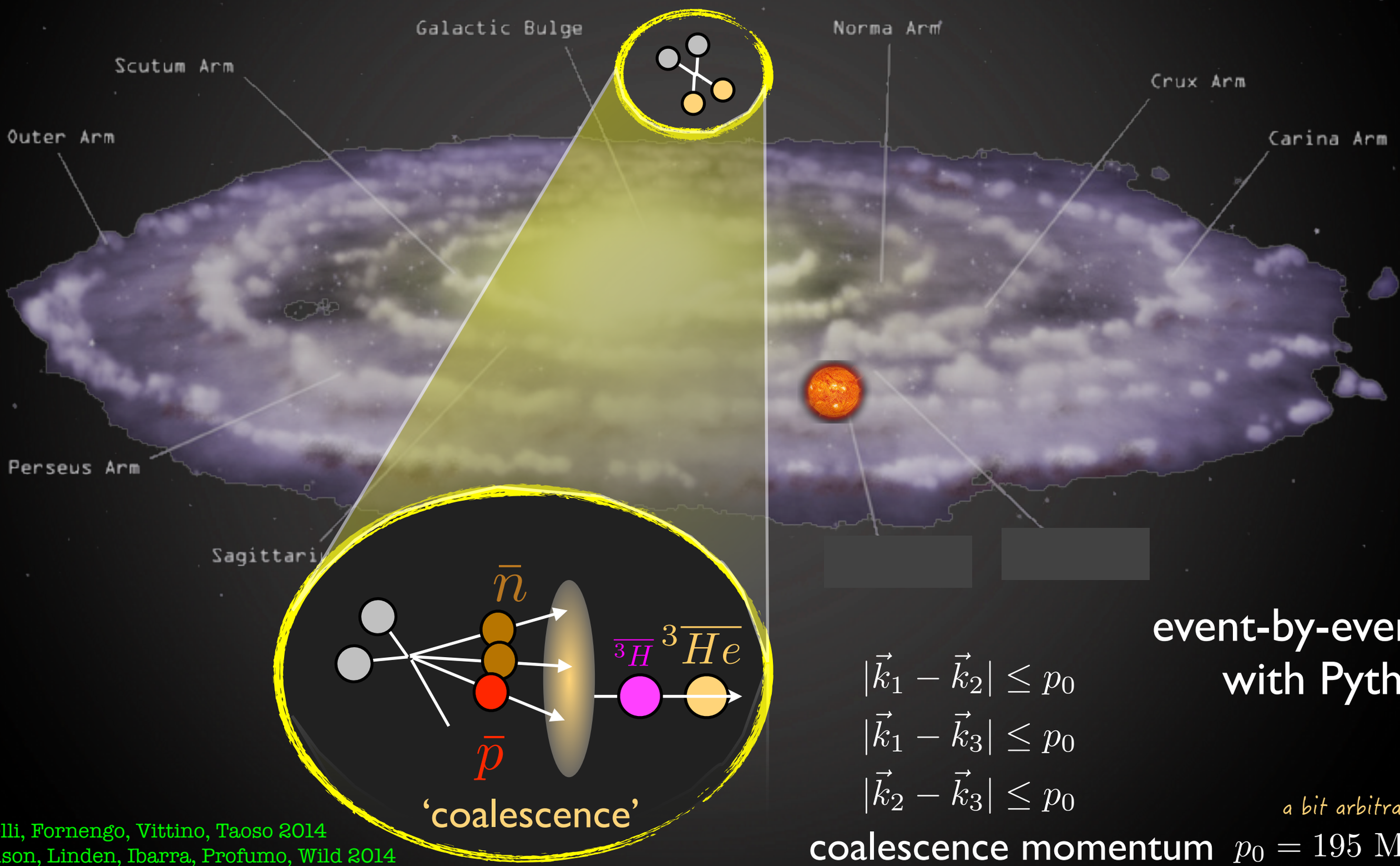
SK, Icecube, Km3Net

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

AMS?

Indirect Detection

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



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

event-by-event with Pythia

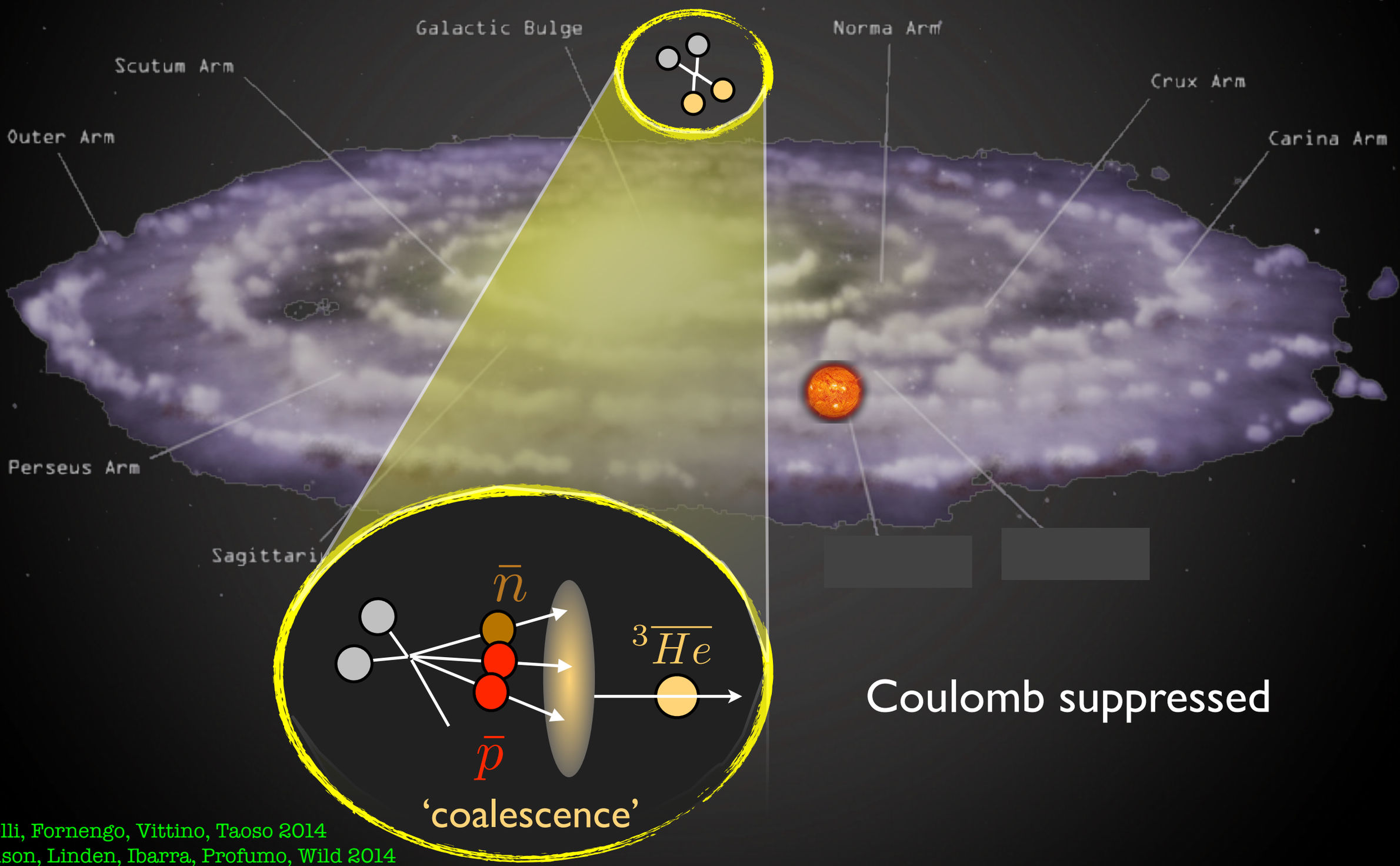
$$|\vec{k}_1 - \vec{k}_2| \leq p_0$$
$$|\vec{k}_1 - \vec{k}_3| \leq p_0$$
$$|\vec{k}_2 - \vec{k}_3| \leq p_0$$

coalescence momentum $p_0 = 195$ MeV

a bit arbitrary…

Indirect Detection

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

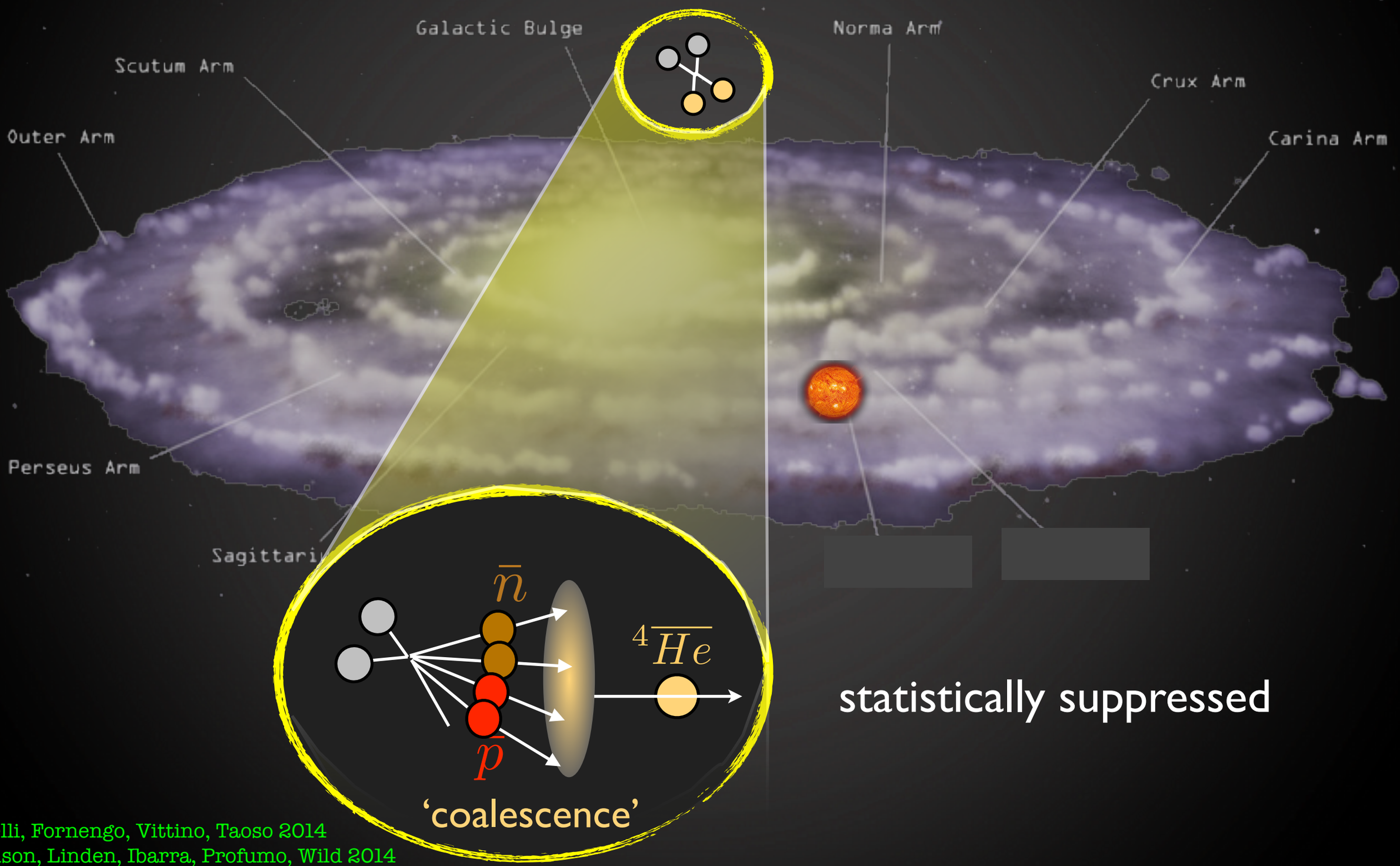


Coulomb suppressed

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

Indirect Detection

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



statistically suppressed

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

Indirect Detection

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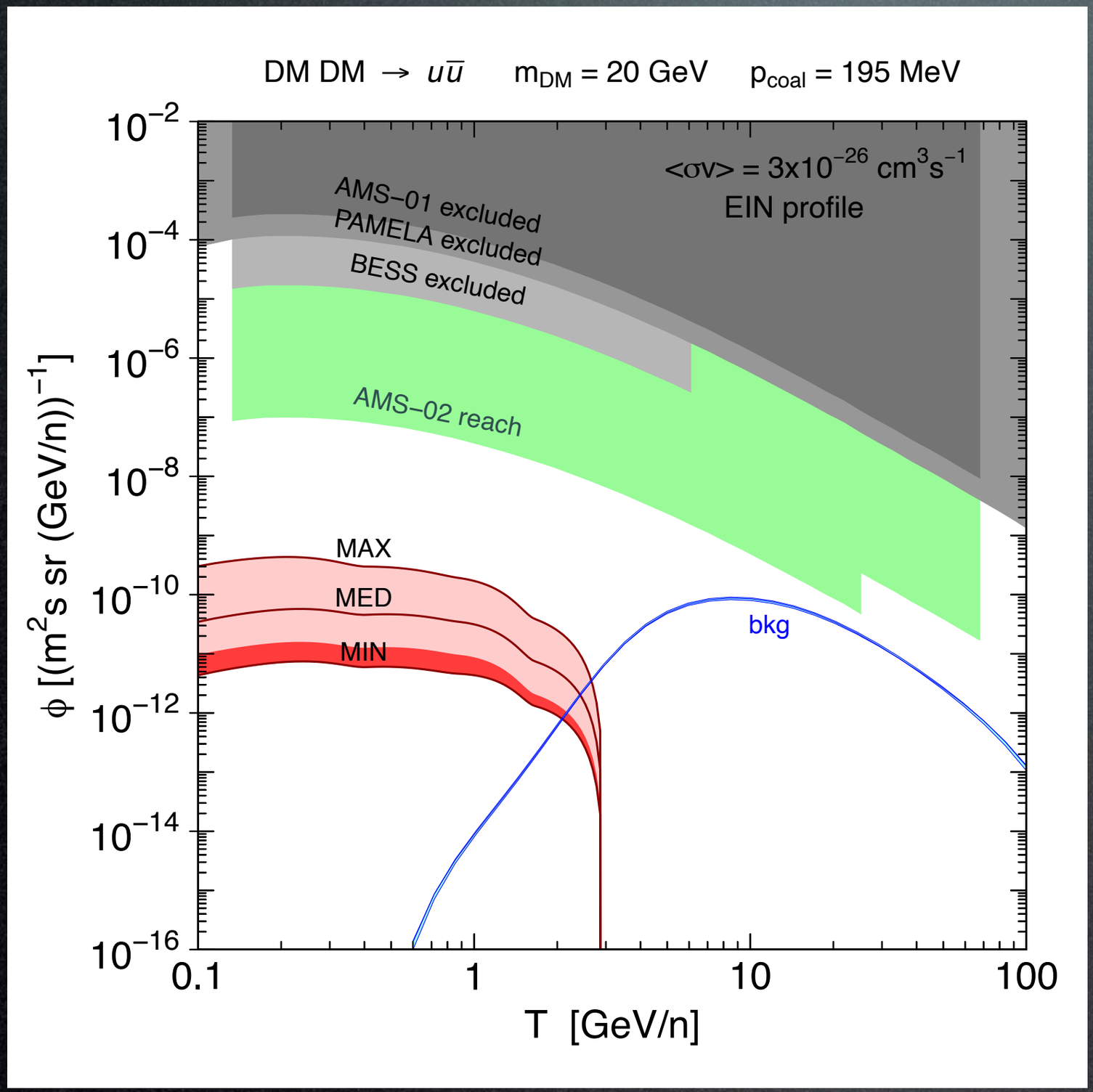
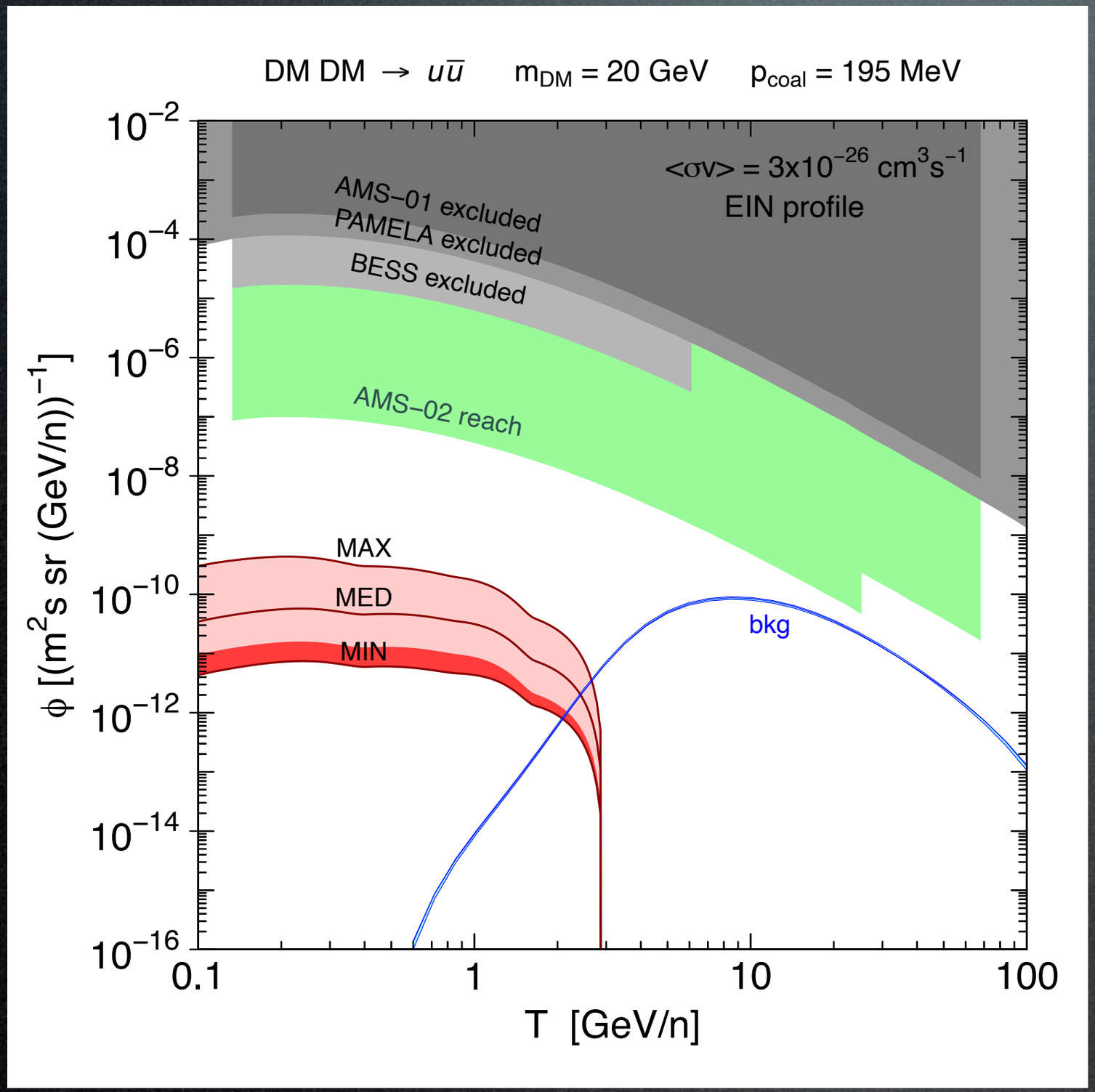


all

consistent with antiproton bounds

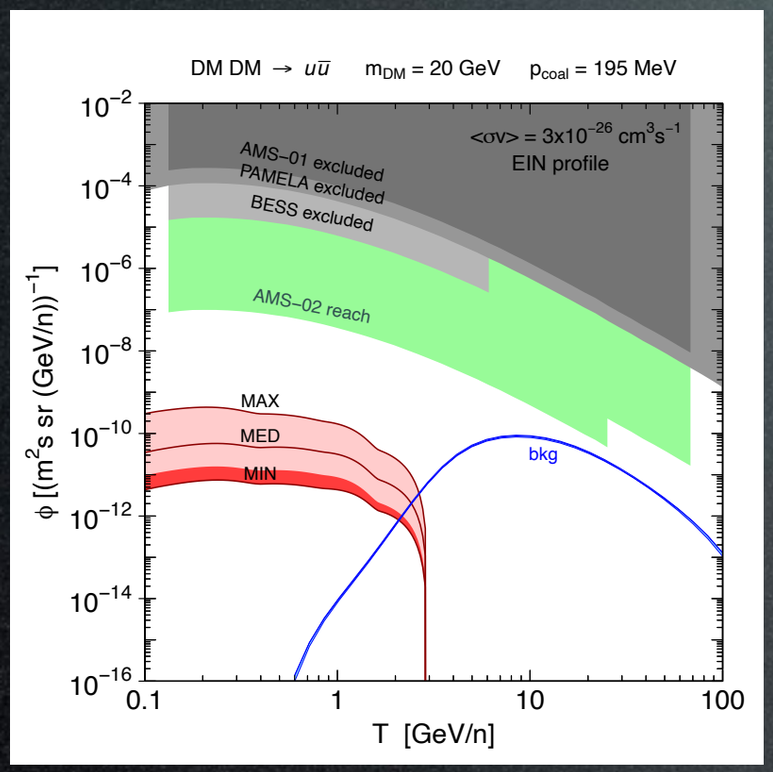
Indirect Detection

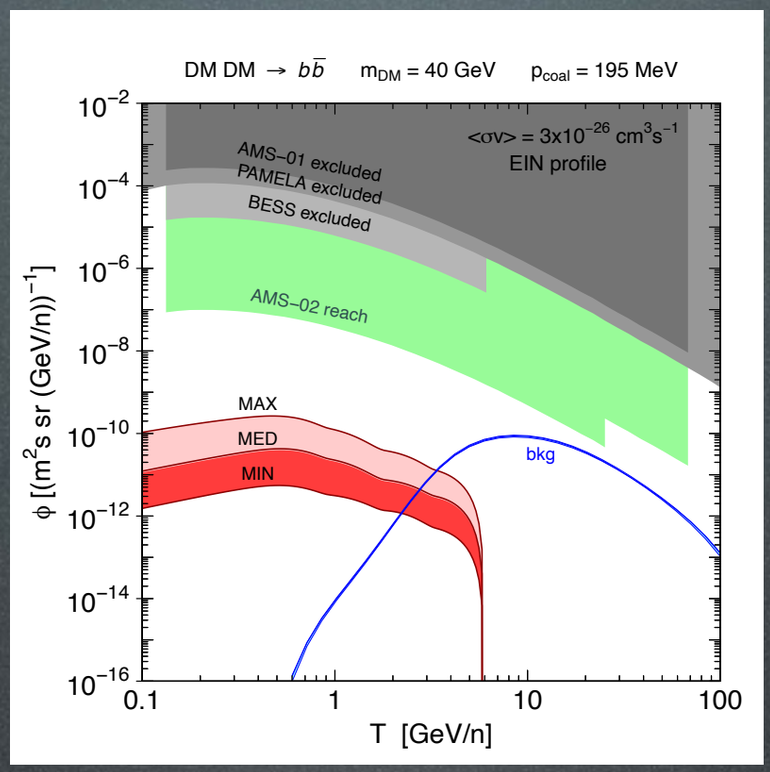
$\overline{He}$ from DM annihilations in halo

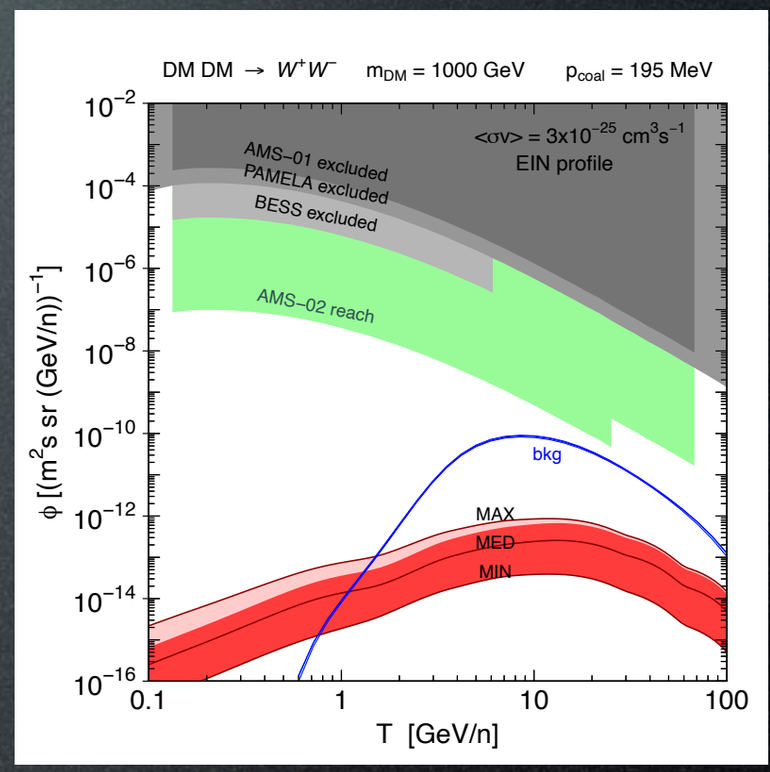


Indirect Detection

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

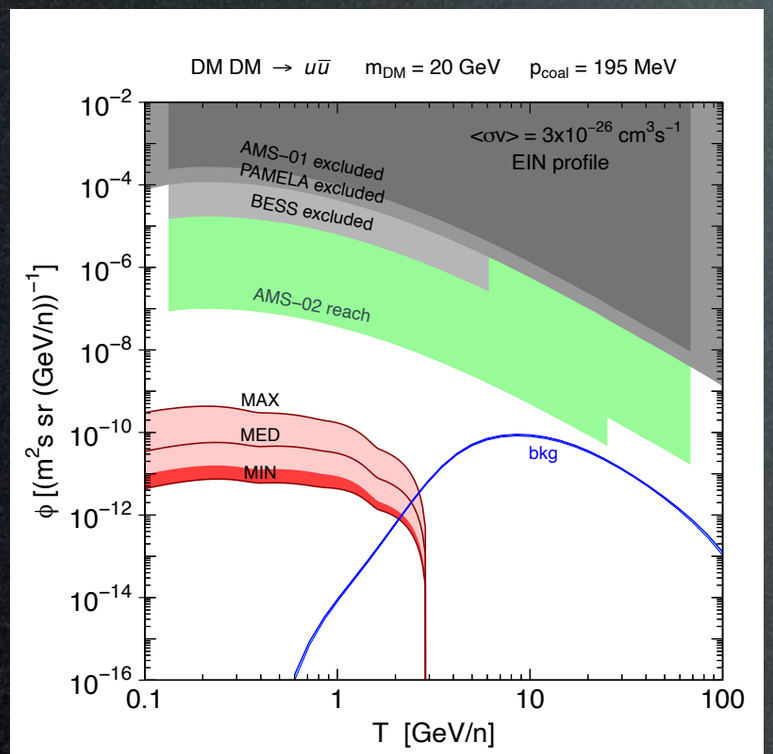


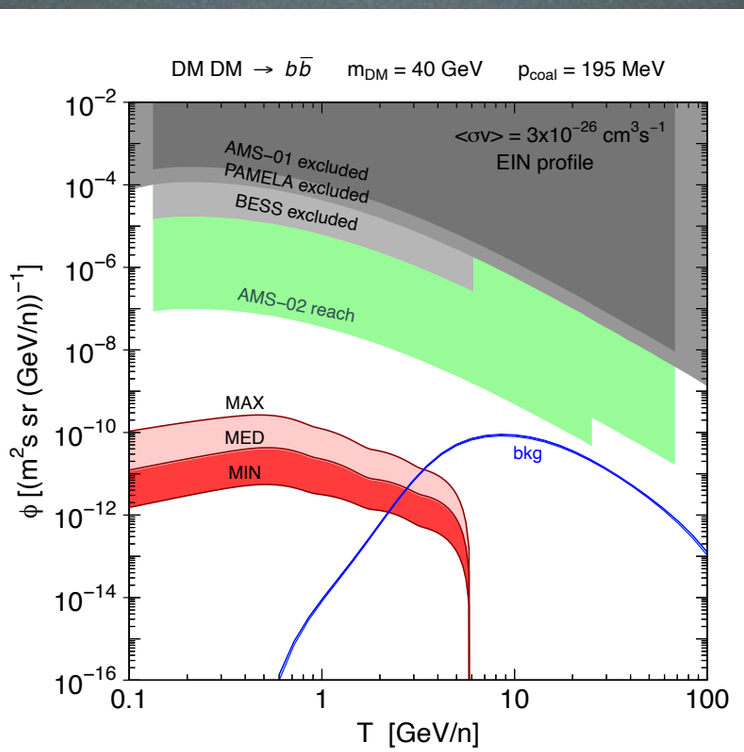


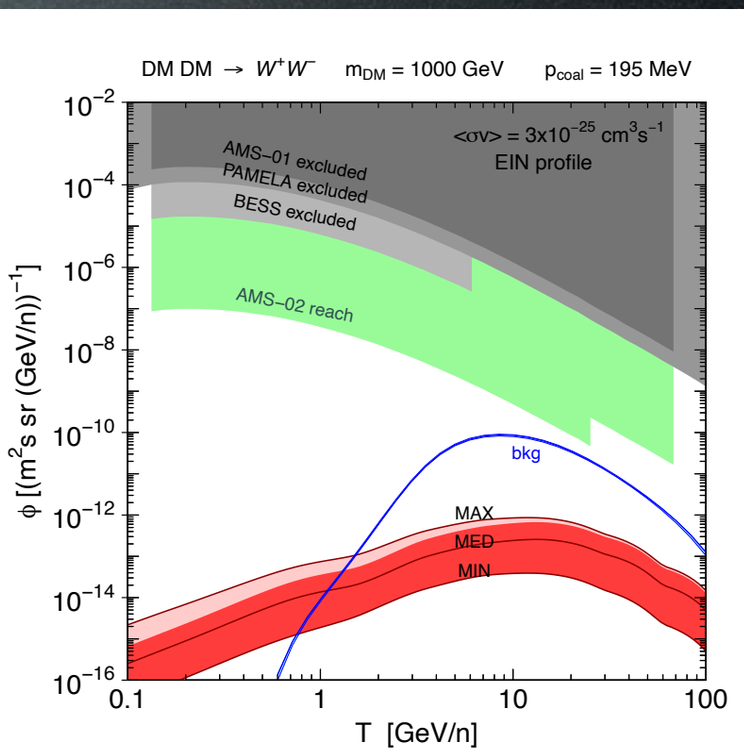


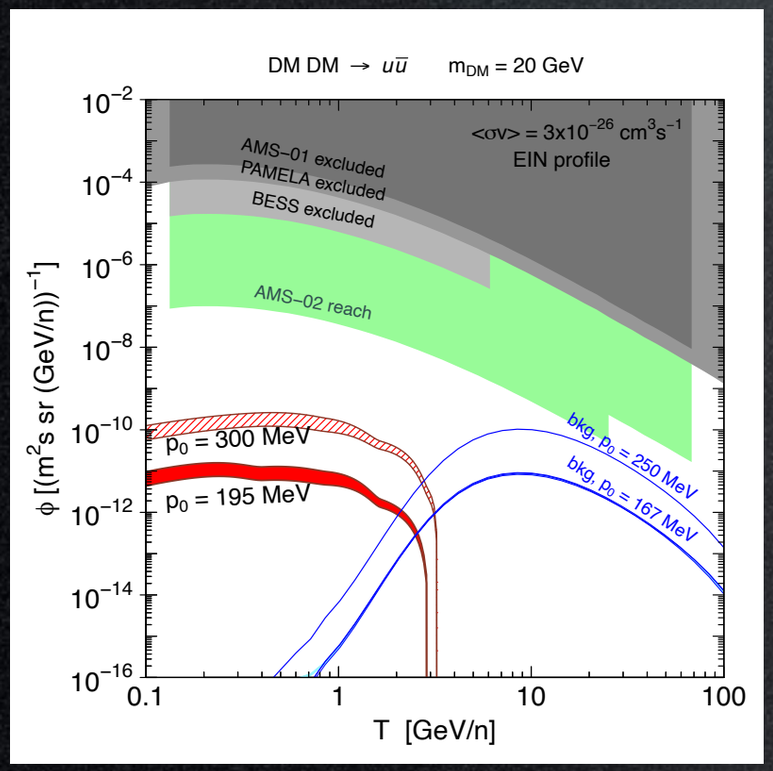
Indirect Detection

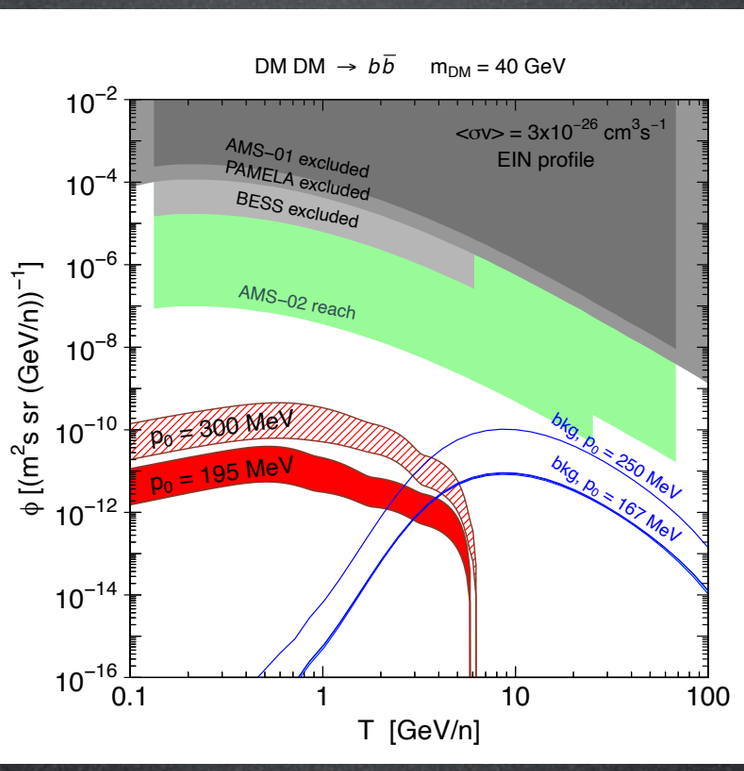
$\overline{He}$ from DM annihilations in halo

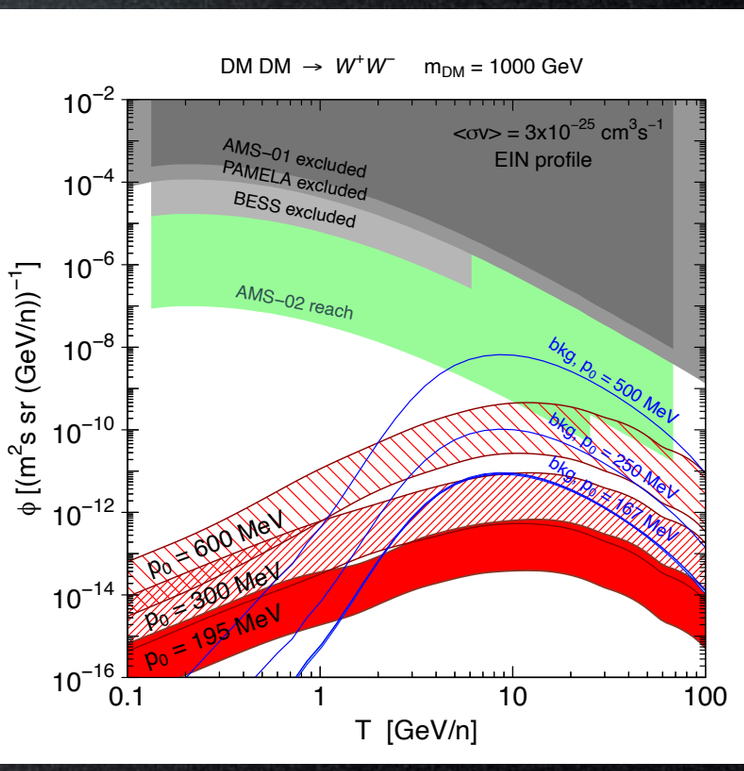












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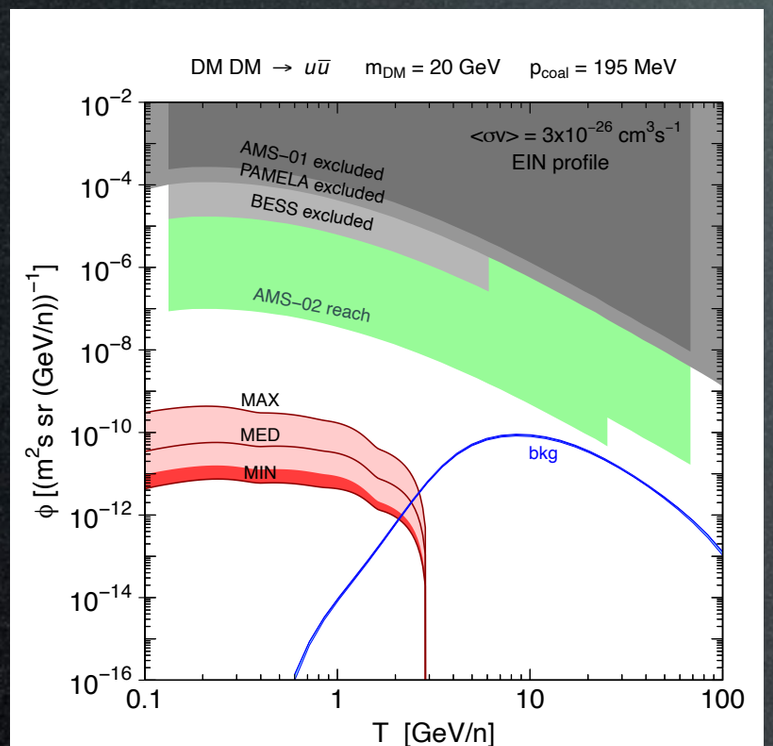
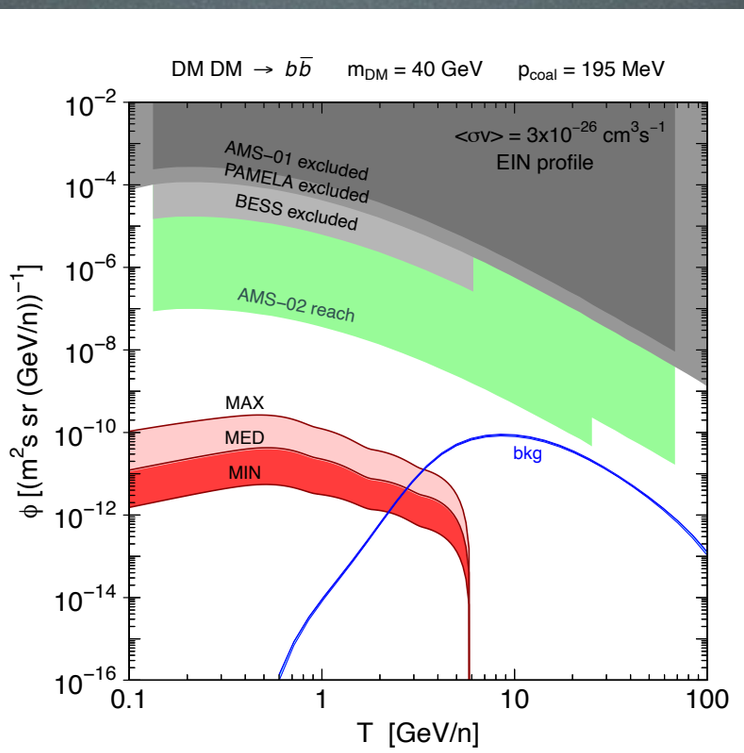
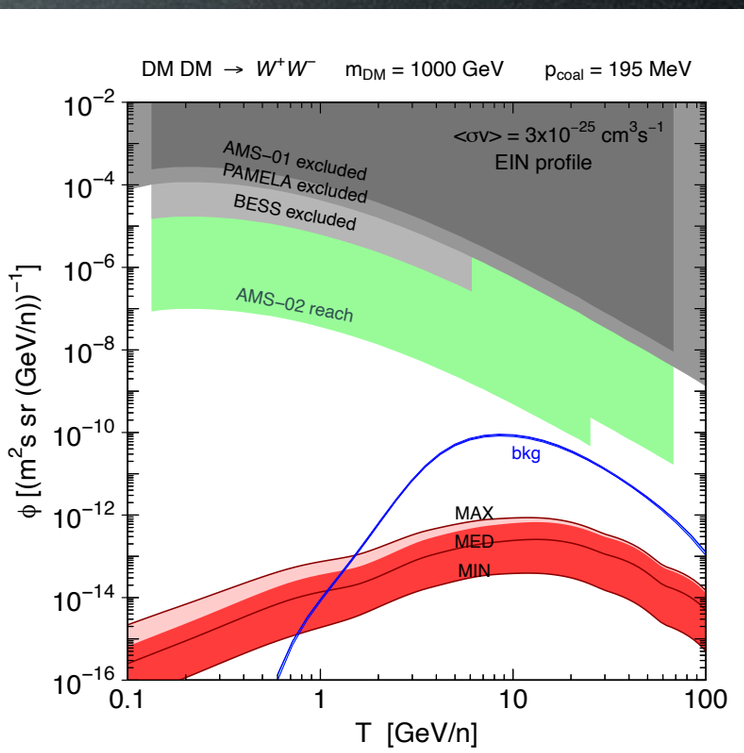
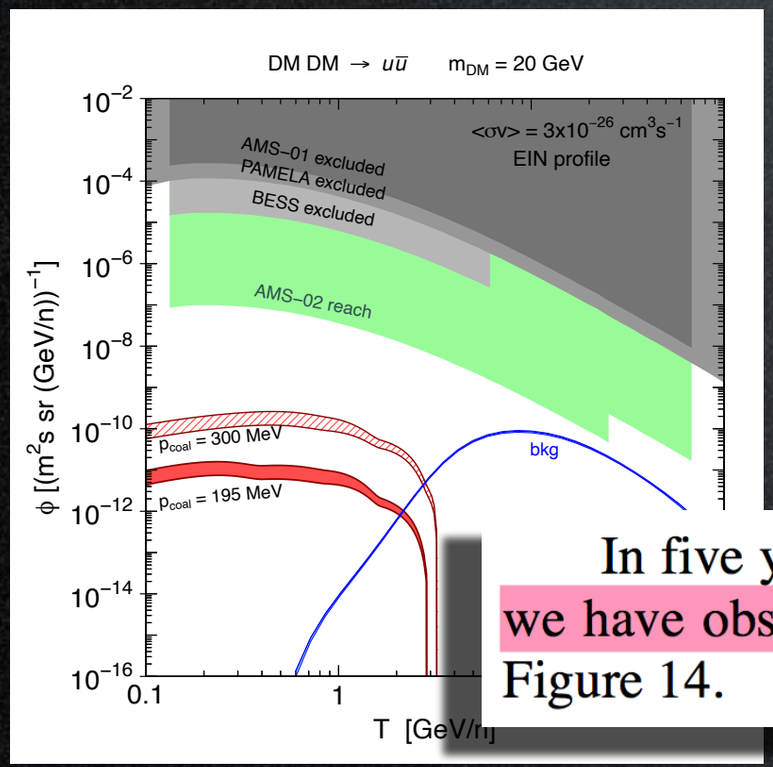
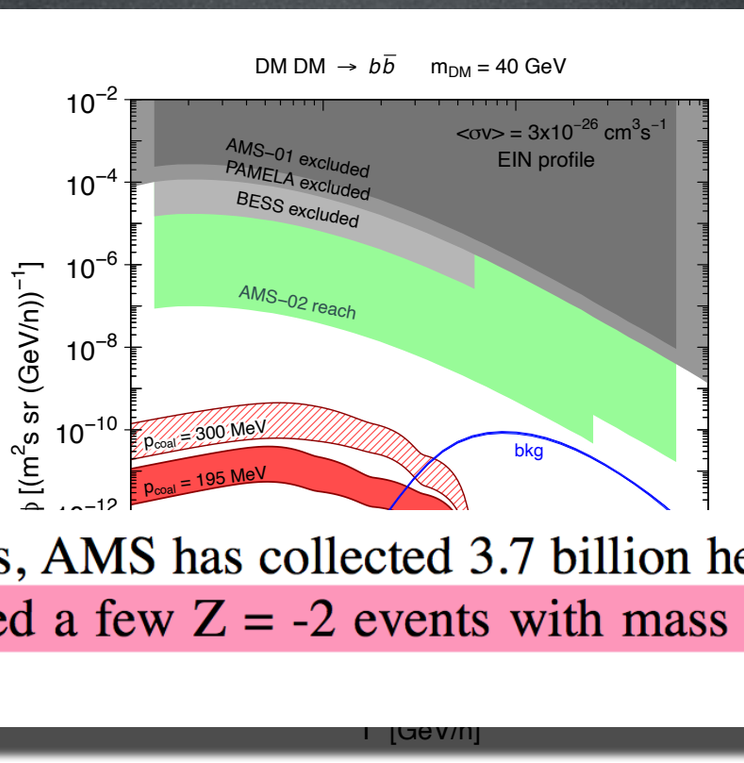
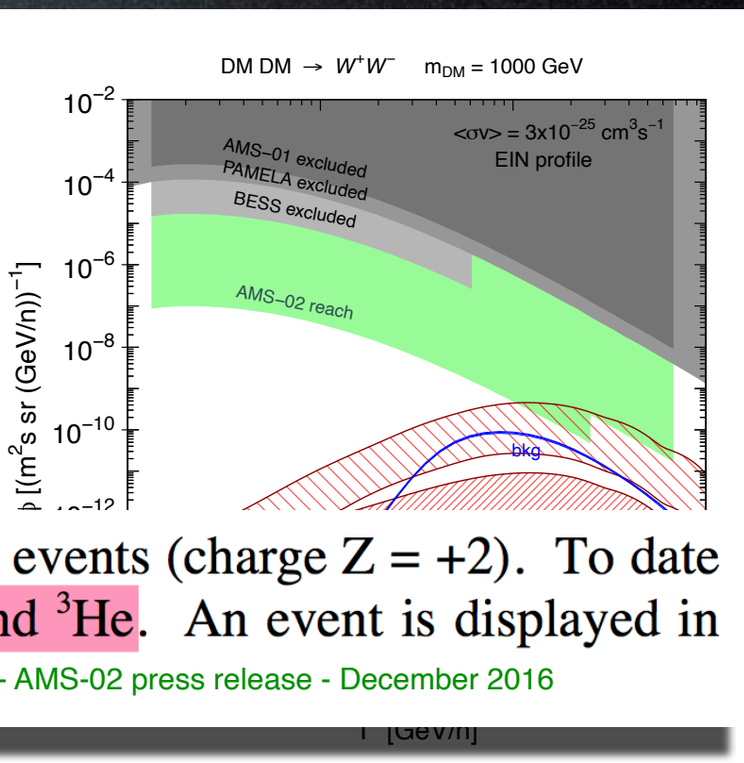










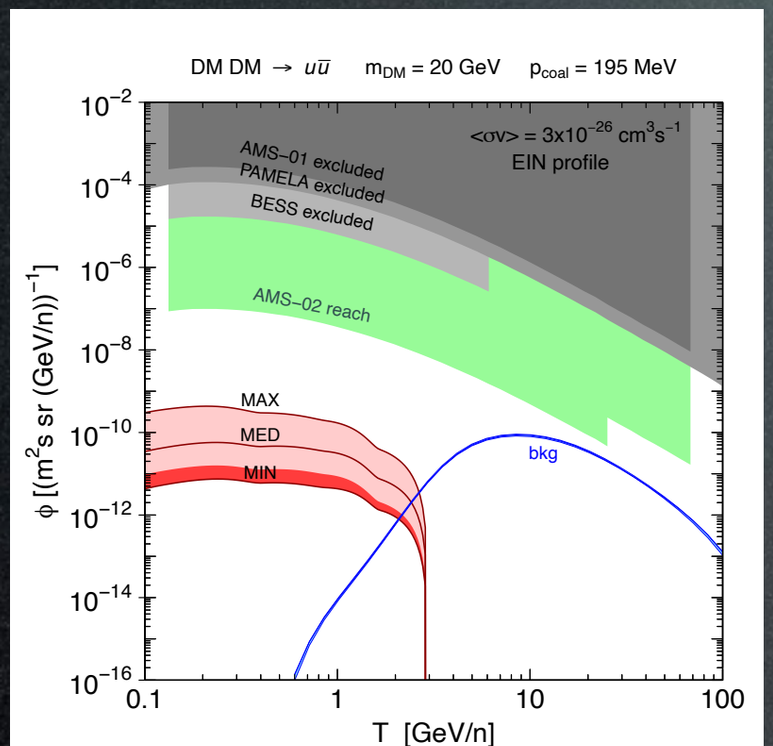


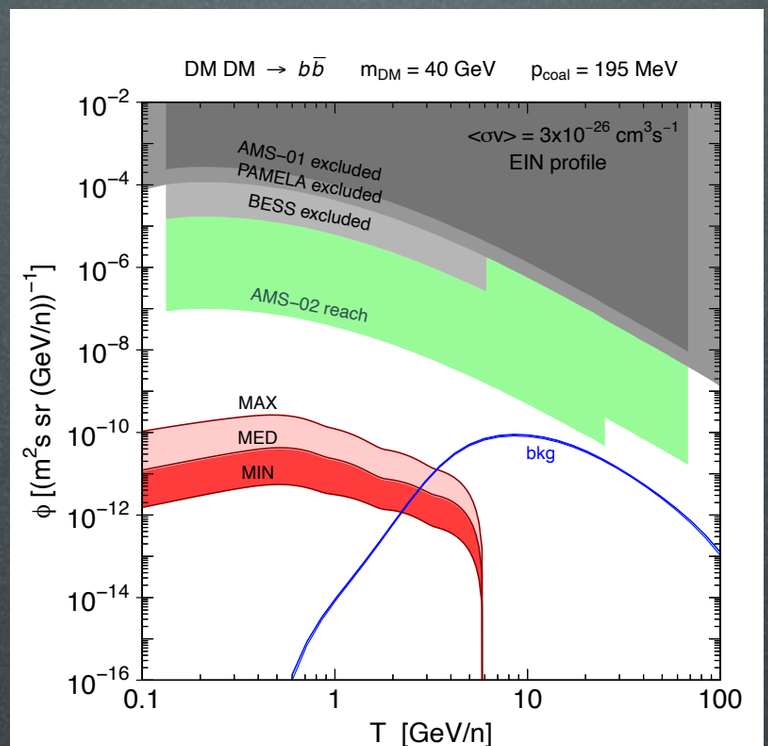
In five years, AMS has collected 3.7 billion helium events (charge Z = +2). To date we have observed a few Z = -2 events with mass around ^{3}He. An event is displayed in Figure 14.

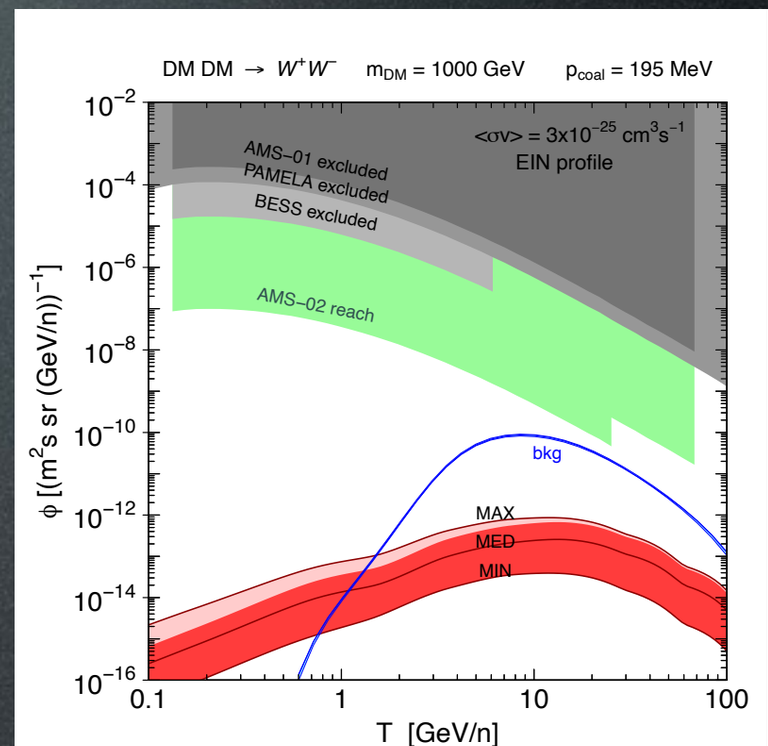
S.Ting - AMS-02 press release - December 2016

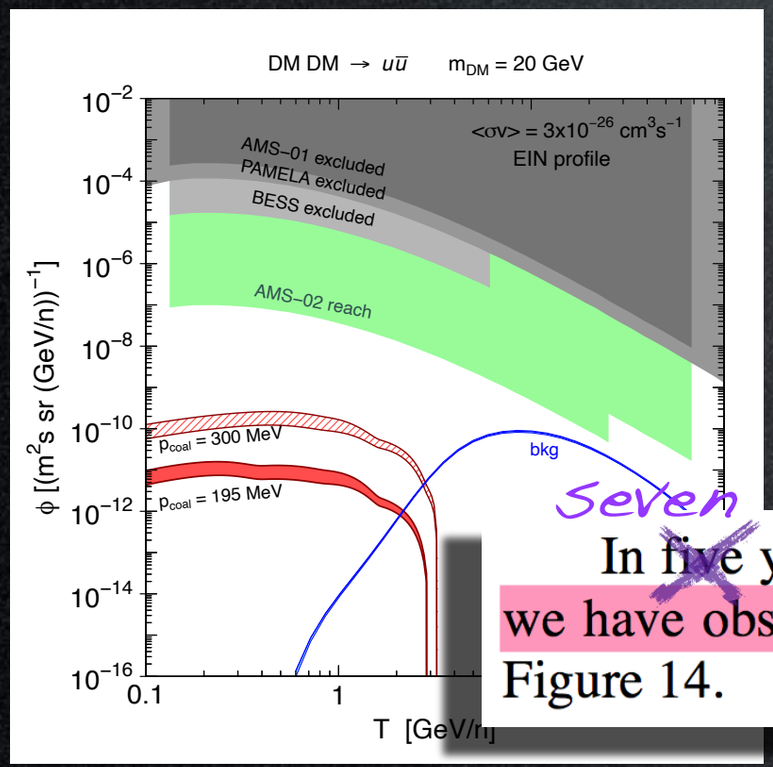
Indirect Detection

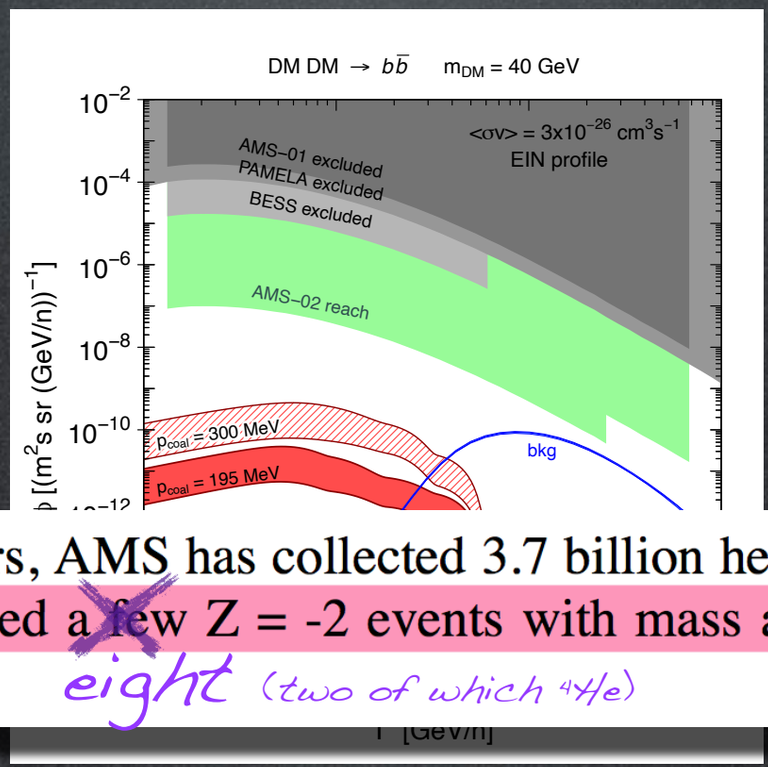
$\overline{He}$ from DM annihilations in halo

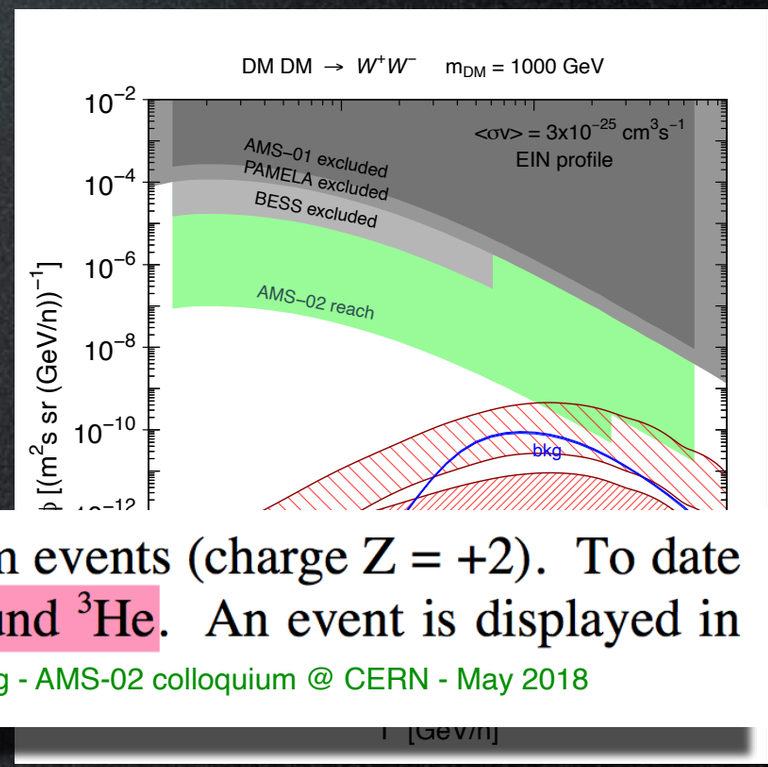












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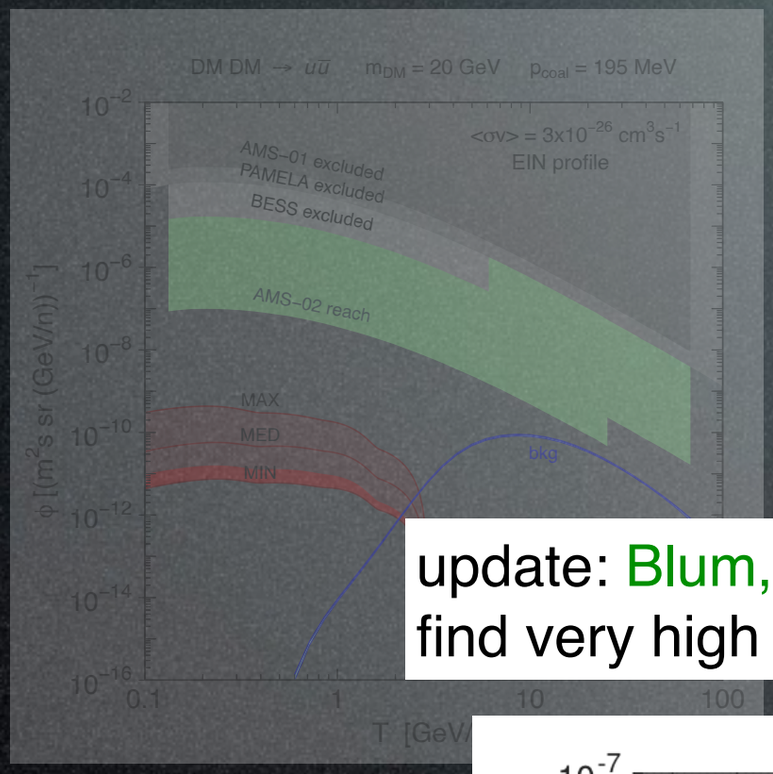
Seven

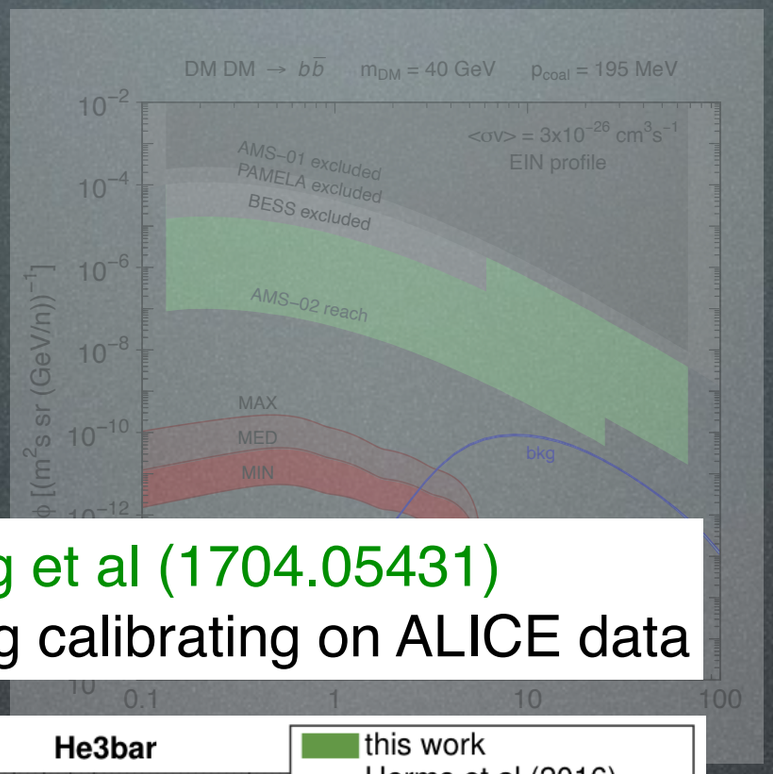
eight (two of which ^{4}He)

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

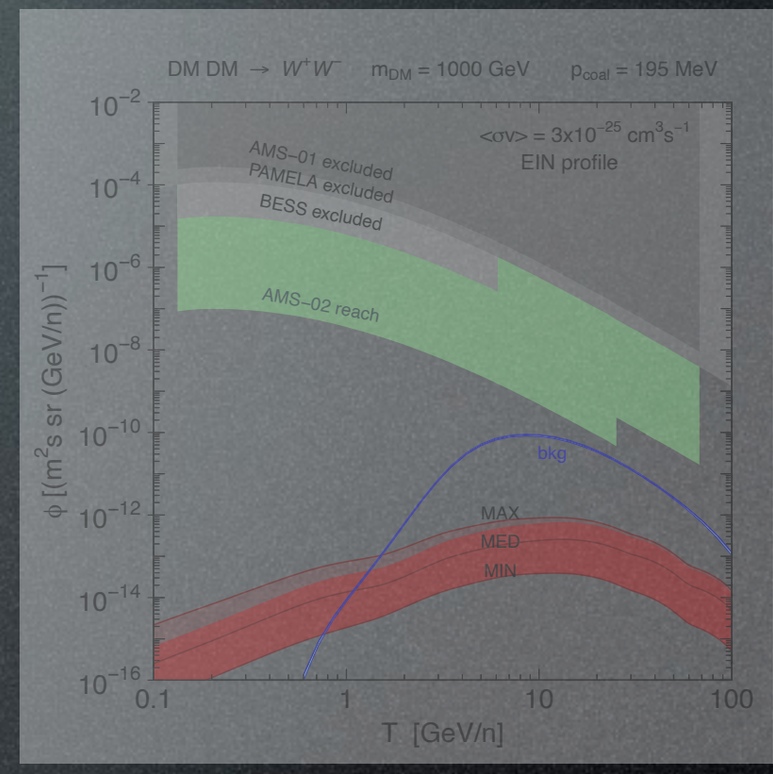
Indirect Detection

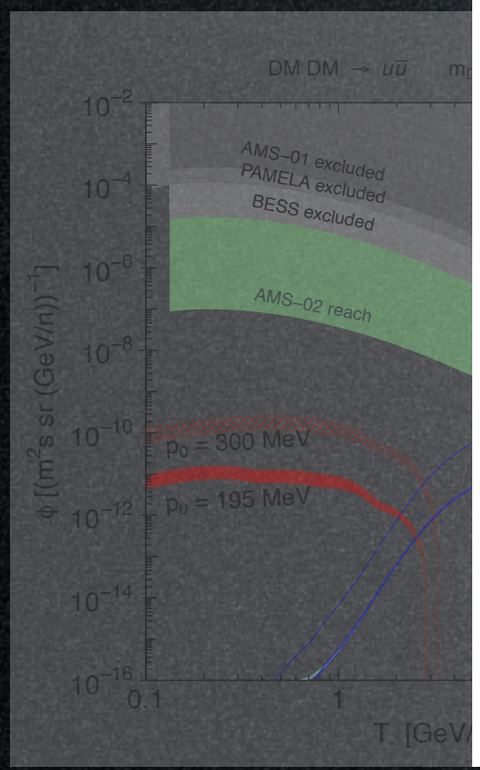
$\overline{He}$ from DM annihilations in halo

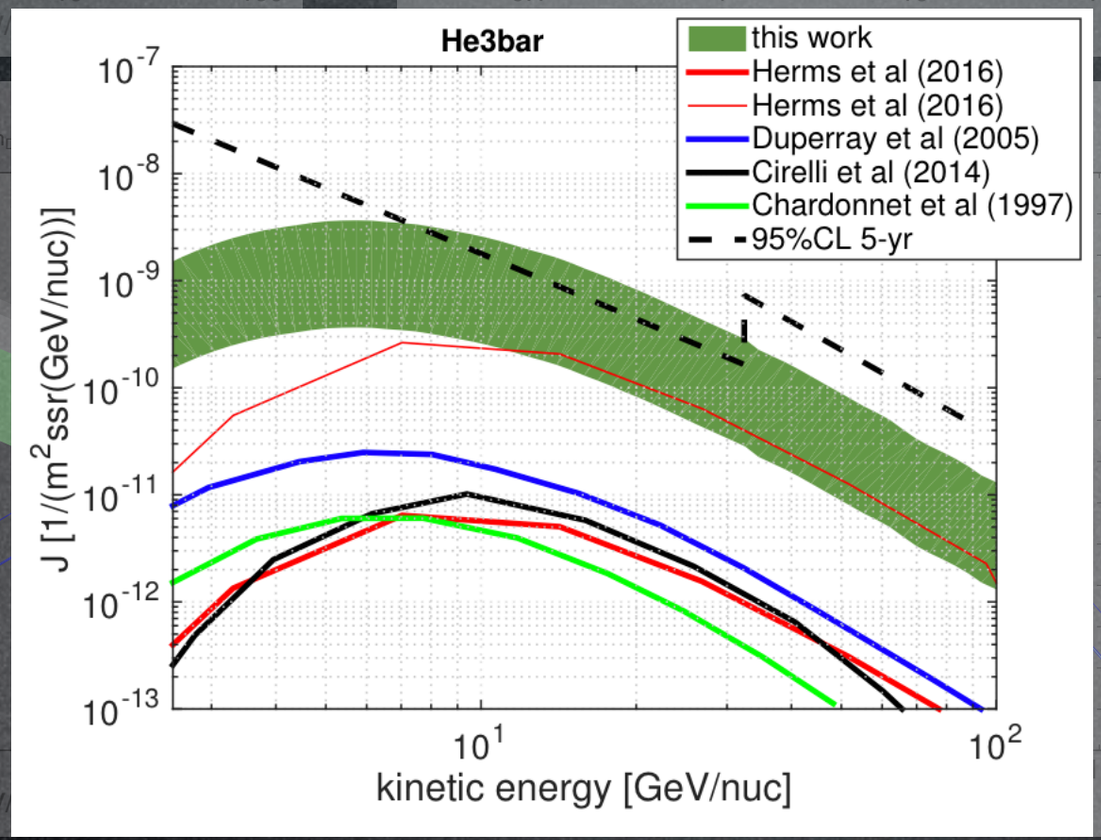


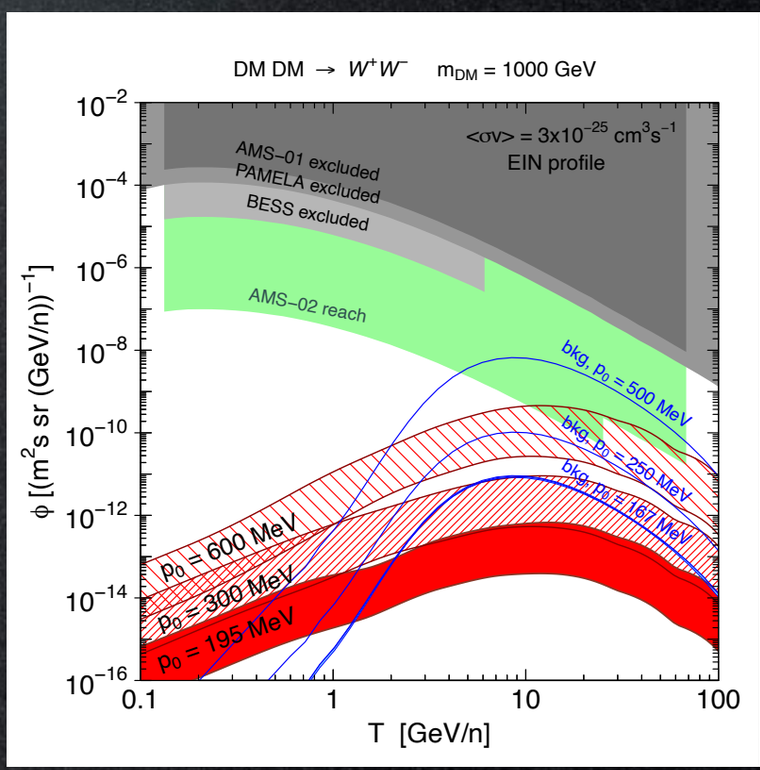


update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data



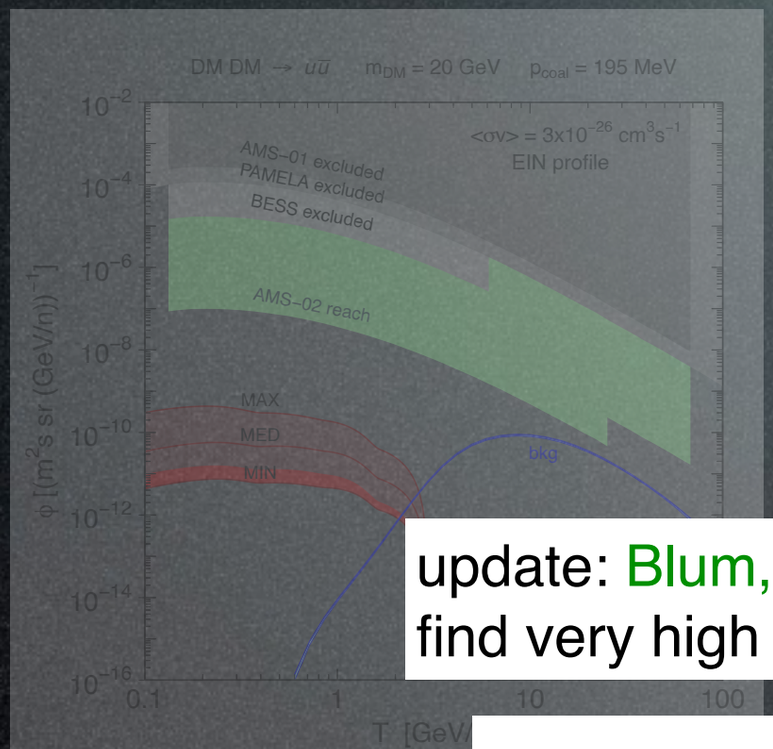


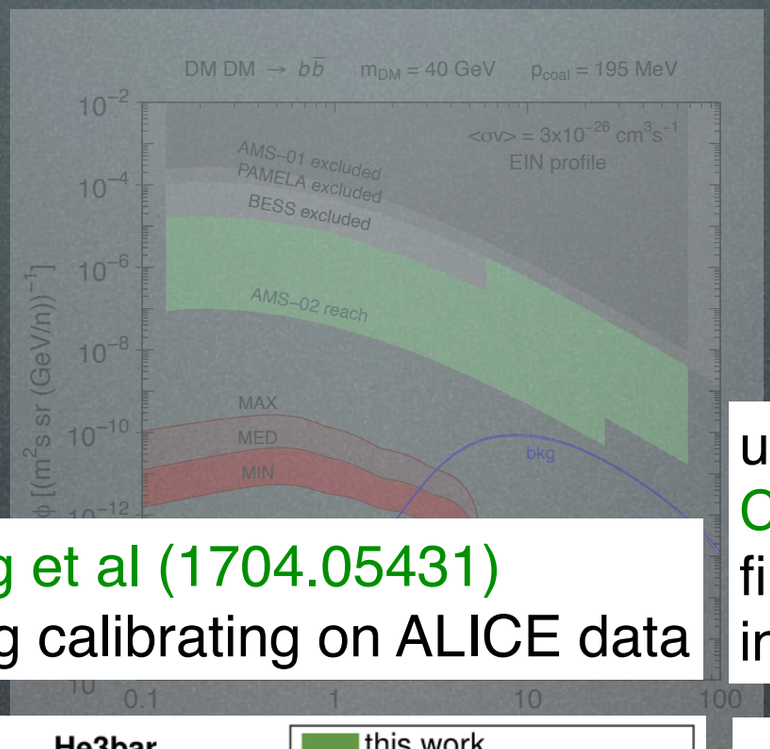


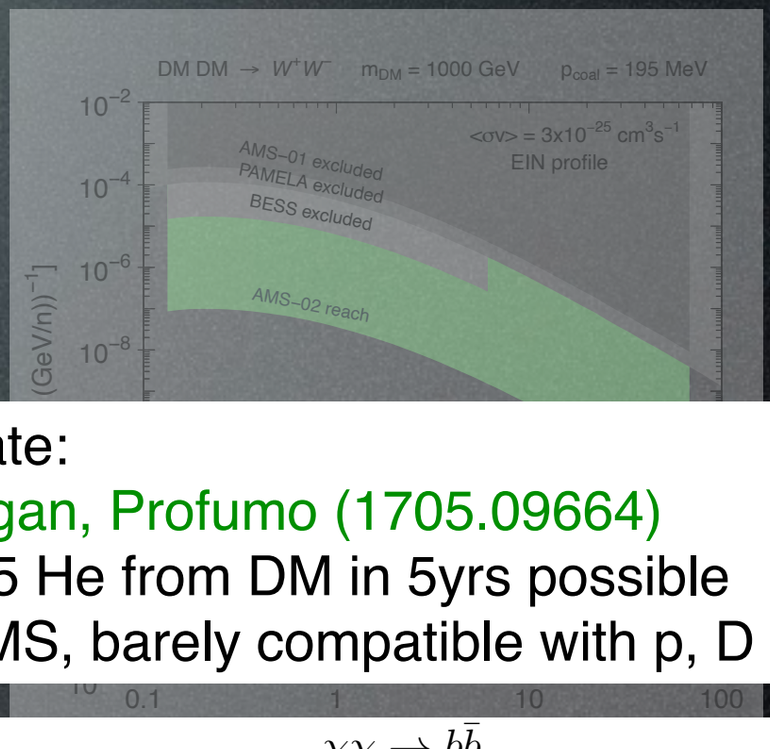


Indirect Detection

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







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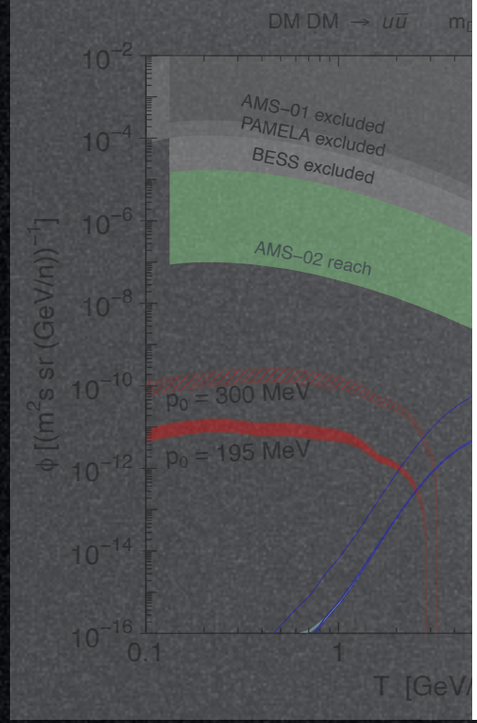
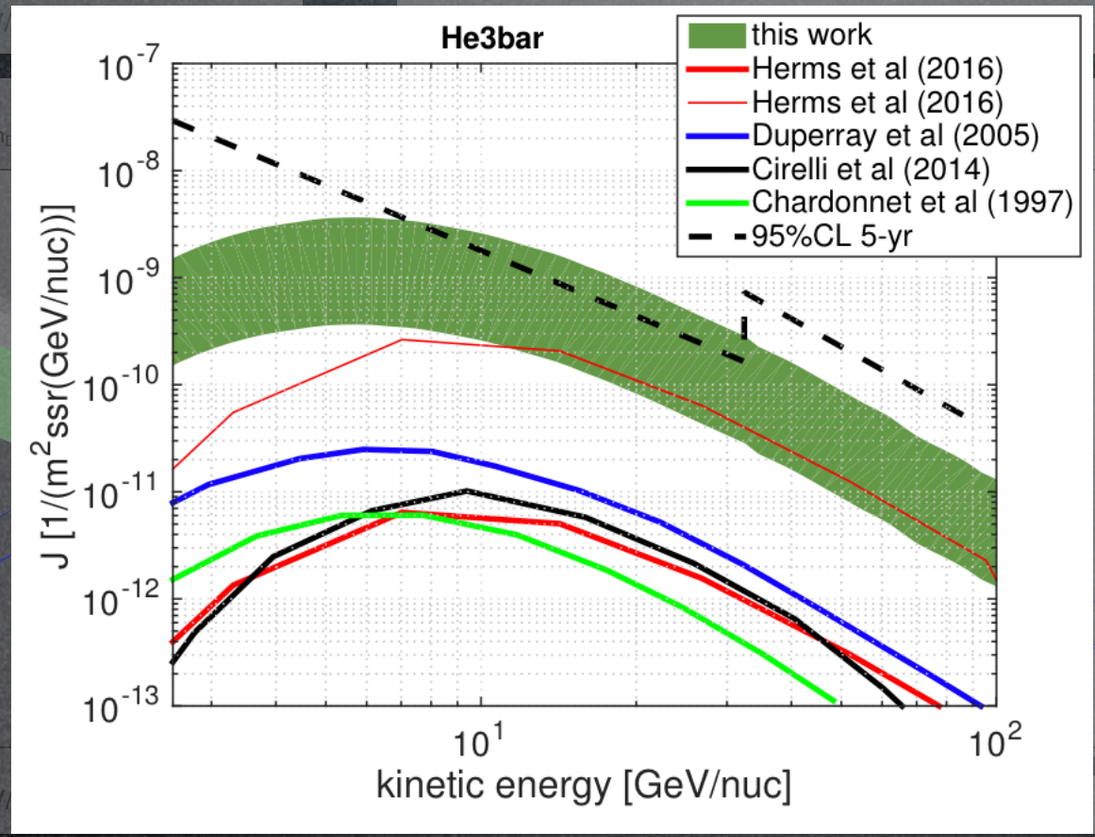
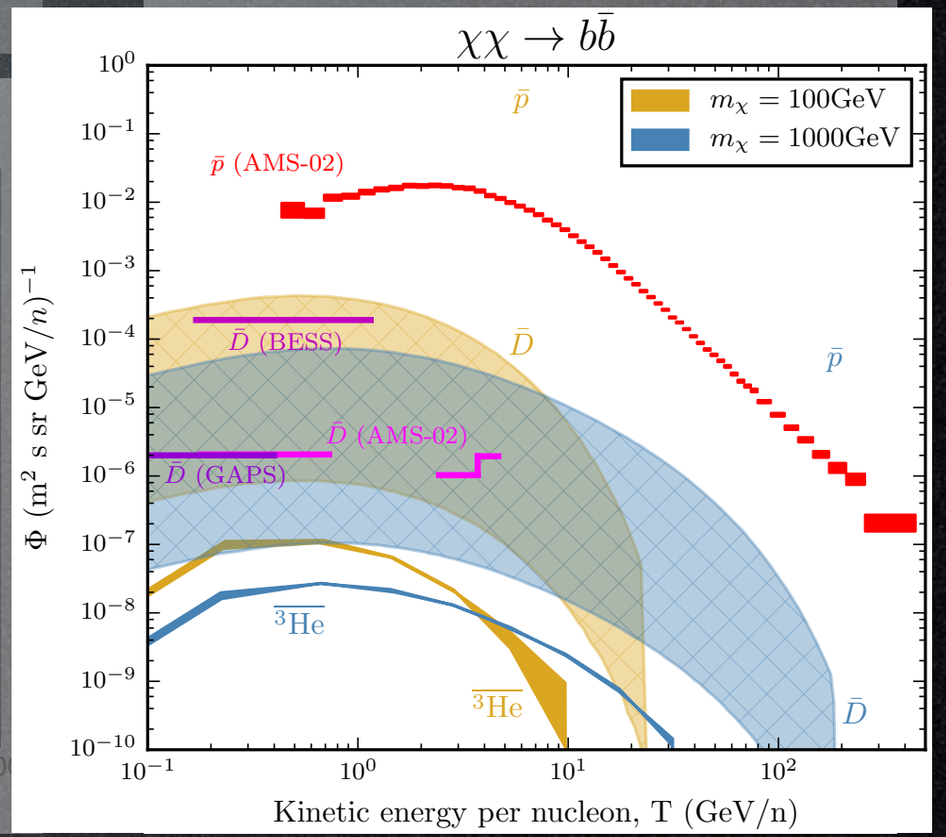
find 5 He from DM in 5yrs possible in AMS, barely compatible with p, D







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…

also: Heck, Rajaraman (1906.01667):
$\overline{\text{He}}$ from decay of exotic Φ carrying negative baryon number (but very fine tuned or killed by antiprotons)

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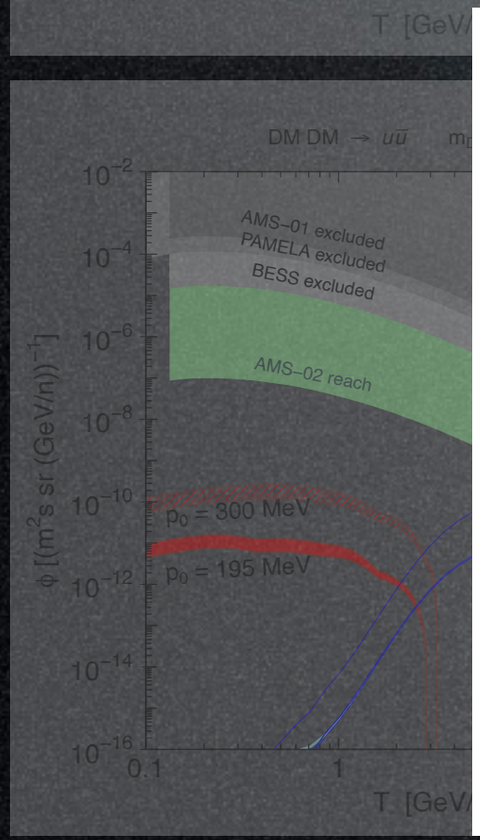

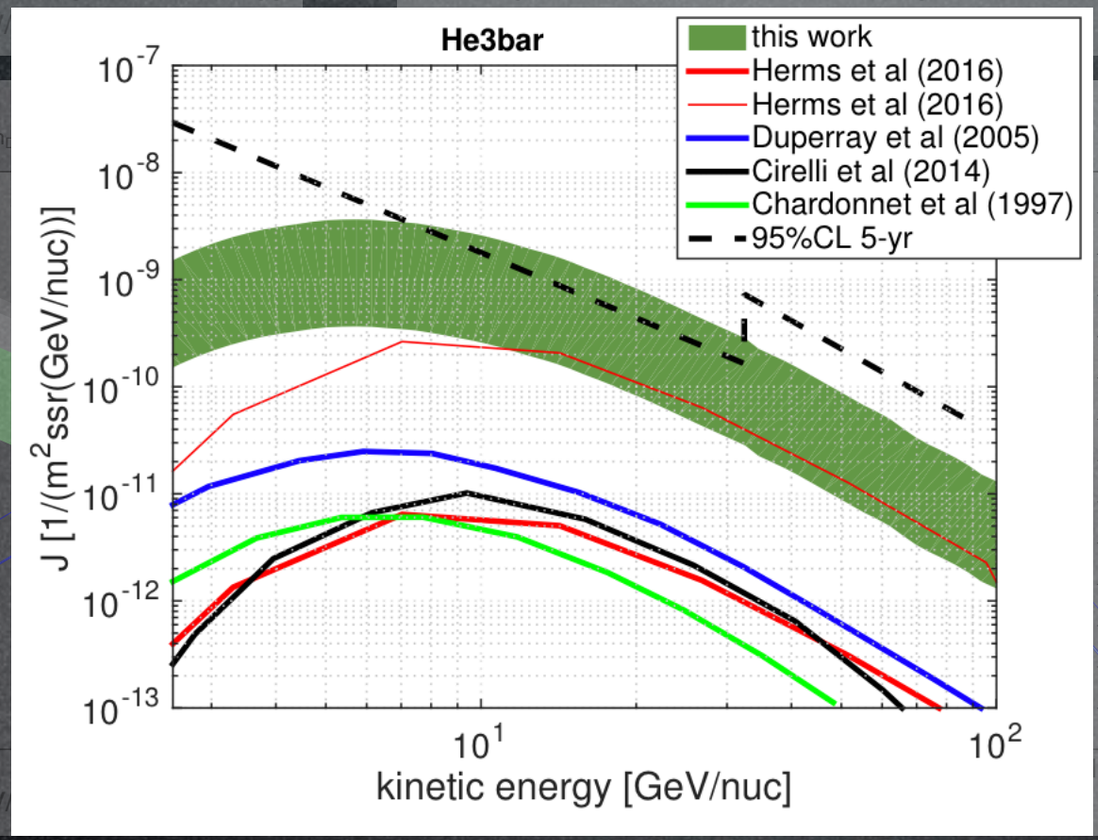

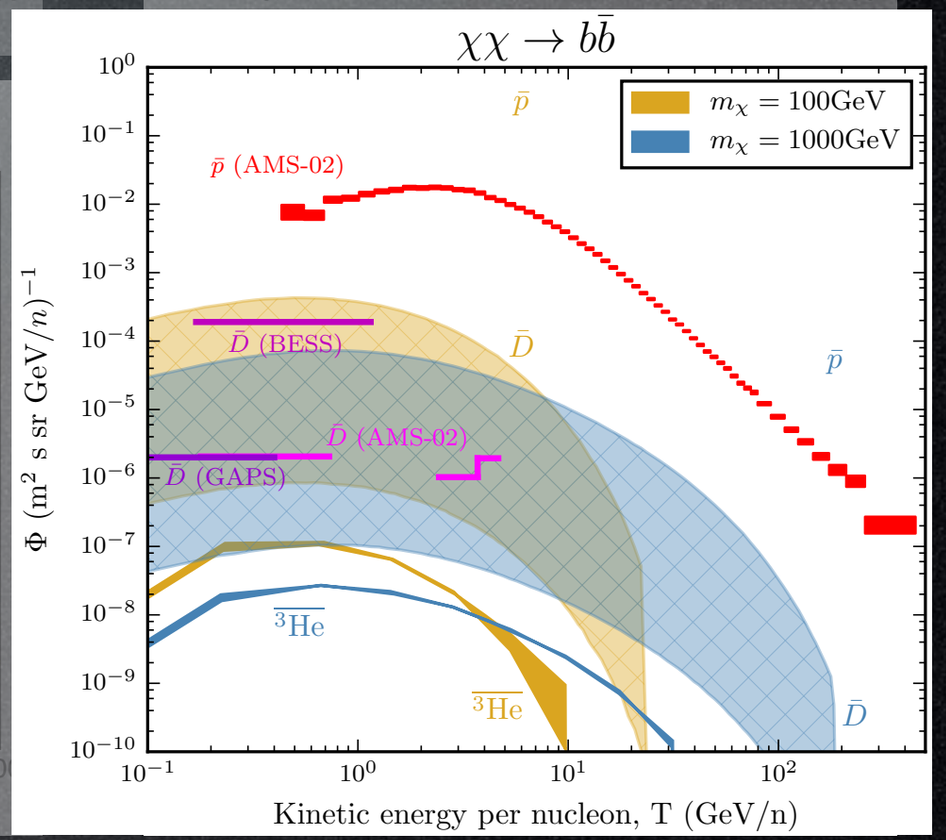

Conclusions

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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 HE 'excesses', new LE chances
in $\bar{p}$: still large uncertainties, but improving
in $\bar{d}$: challenging flux
in $\overline{He}$: hopeless? who knows!...
in ν: challenging detection
in γ: astrophysical background

Solution:

Conclusions

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- multimessenger

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Solution:

- multimessenger
- switch-off astrophysics

Back up slides