2 July 2024
Invisibles Workshop - Bologna

Dark Matter Indirect Searches

as of 2024

Marco Cirelli

(CNRS LPTHE Jussieu)

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Selected topics in...

Dark Matter Indirect Searches as of 2024

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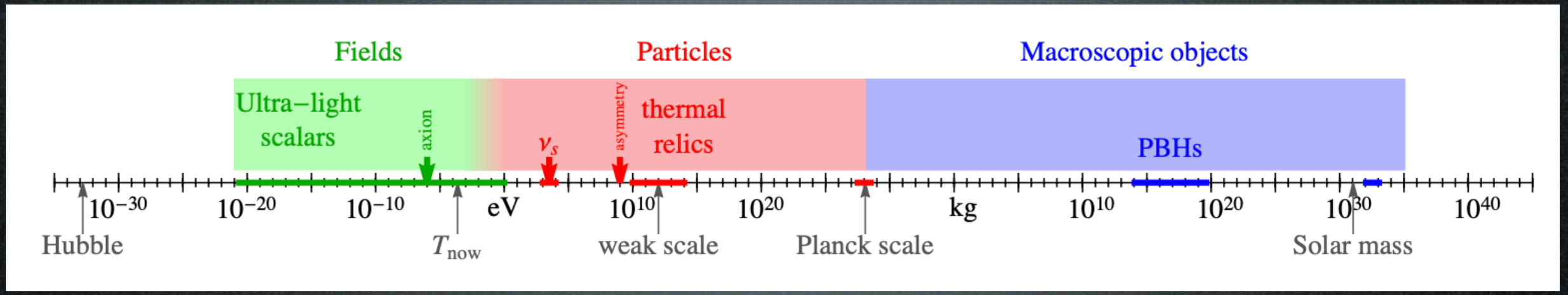
Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

Candidates

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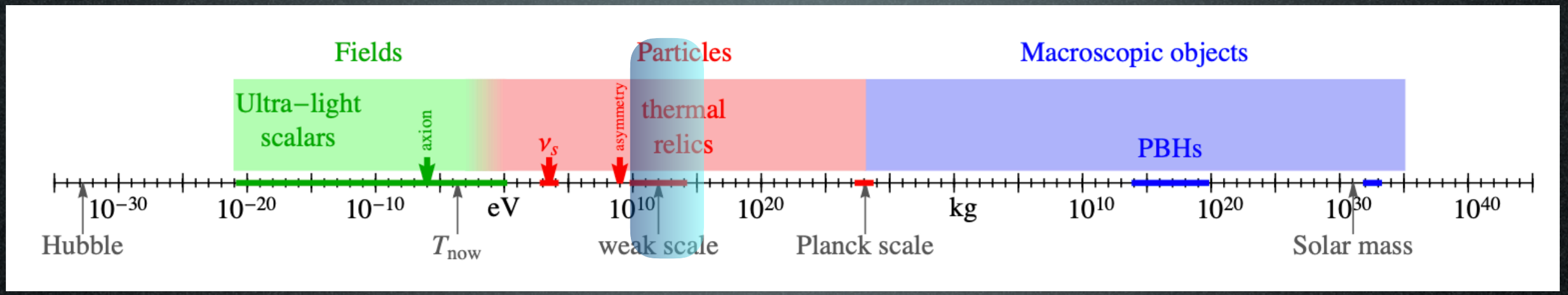

Candidates

WIMPs

Candidates

new physics at the TeV scale

thermal freeze-out

Candidates

new physics at the TeV scale

thermal freeze-out

Collider Searches

Indirect Detection

Direct Detection

Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

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Candidates

new physics at the TeV scale

thermal freeze-out

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Collider Searches

Indirect Detection

Direct Detection

DM detection

direct detection

production at colliders

indirect

- γ from annihil in galactic center or halo and from secondary emission
  Fermi, IACT, radio telescopes...
- e^+ from annihil in galactic halo or center
  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, KM3Net

DM detection

direct detection

production at colliders

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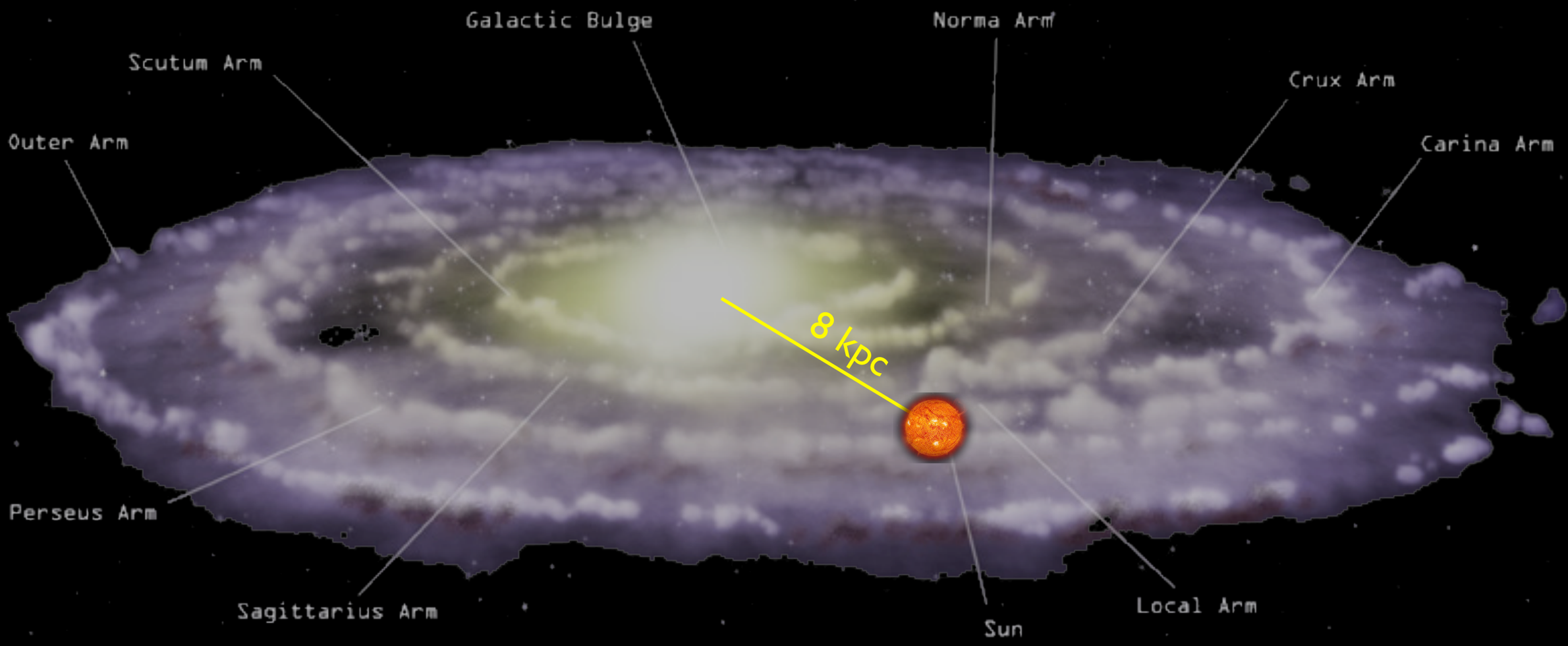
Indirect Detection: charged CRs

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



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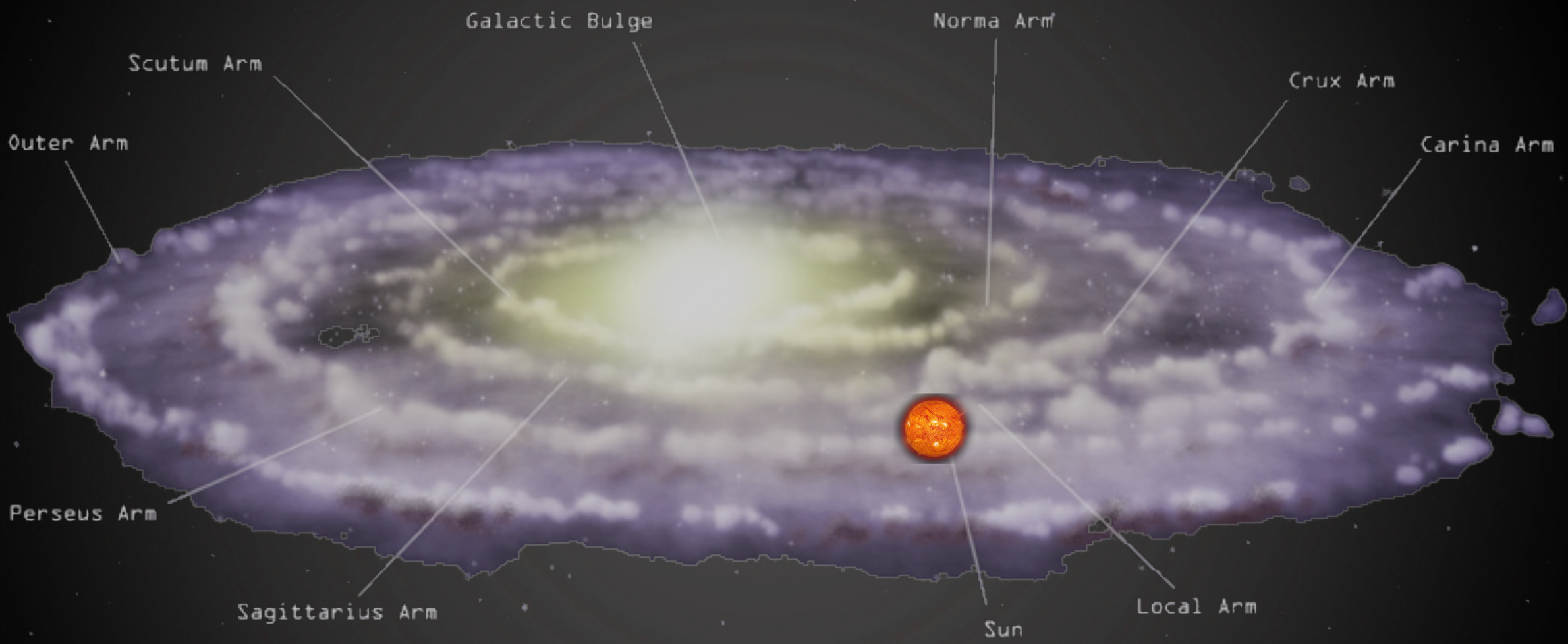

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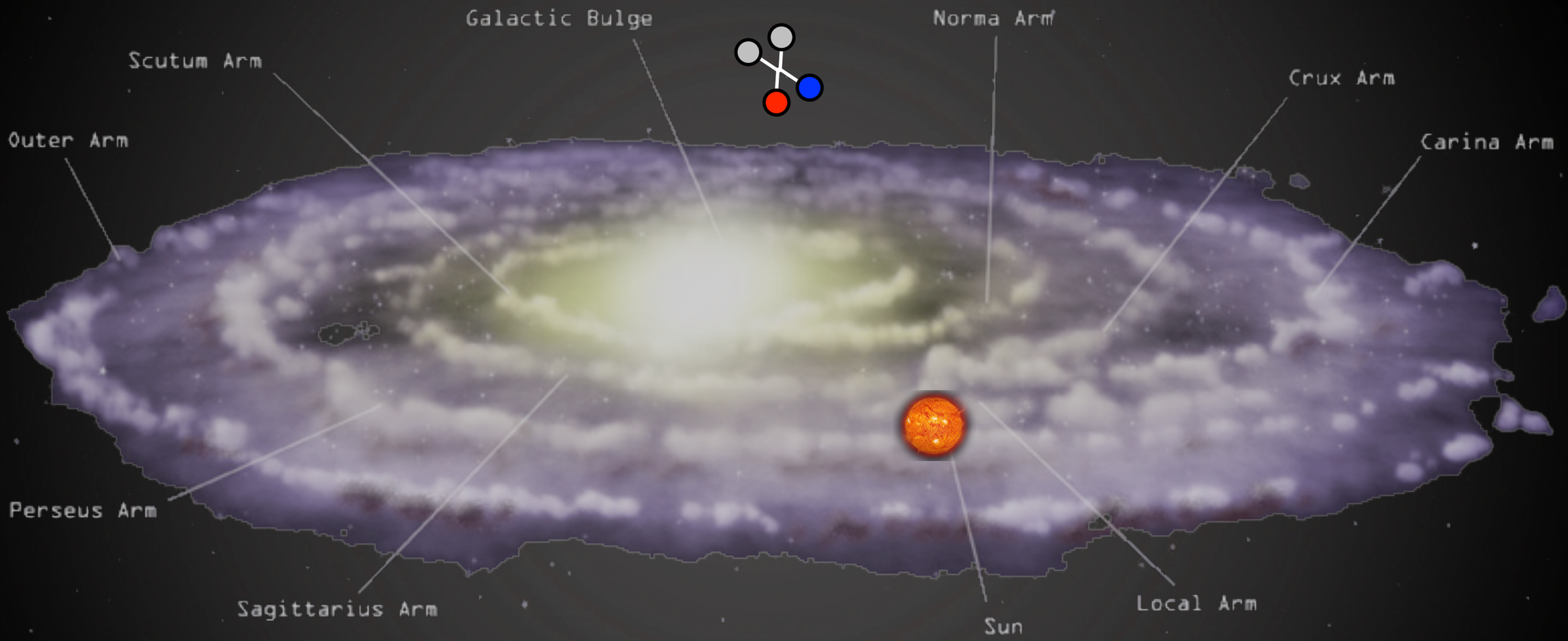

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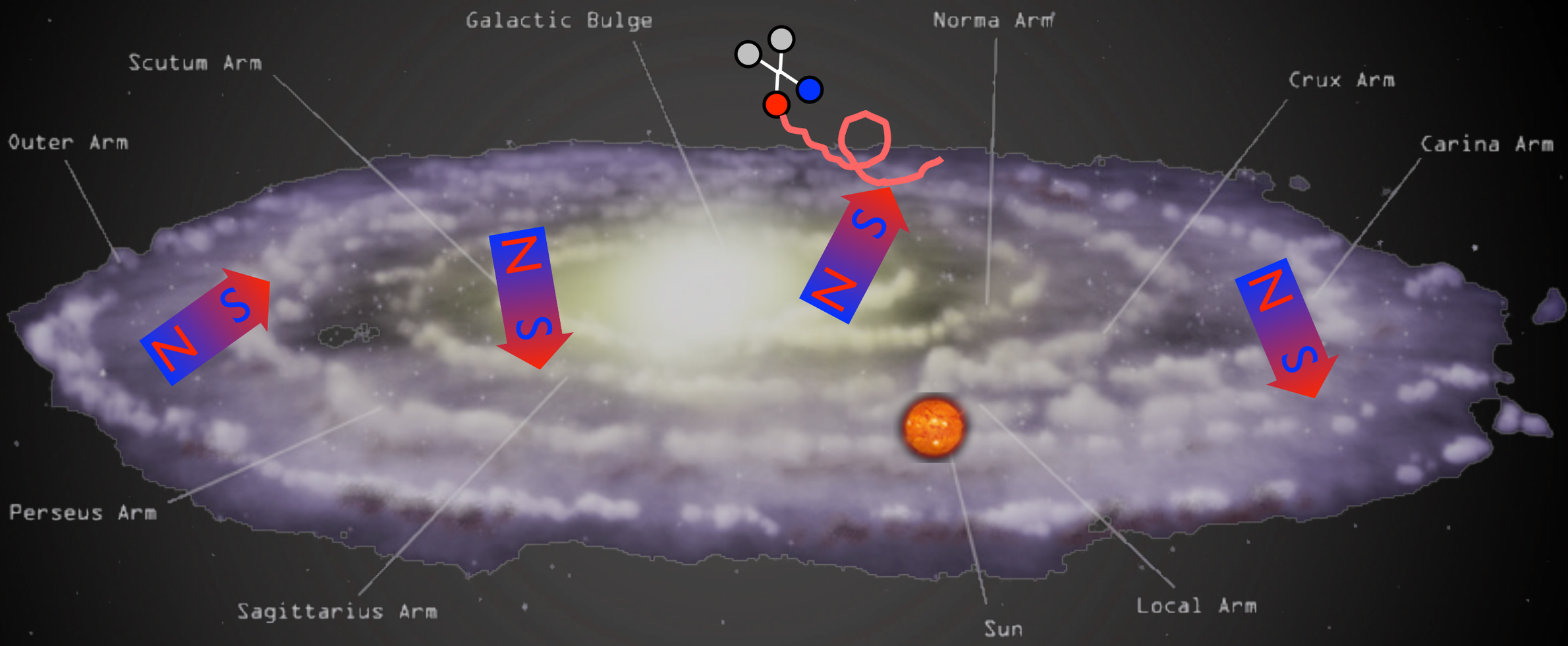

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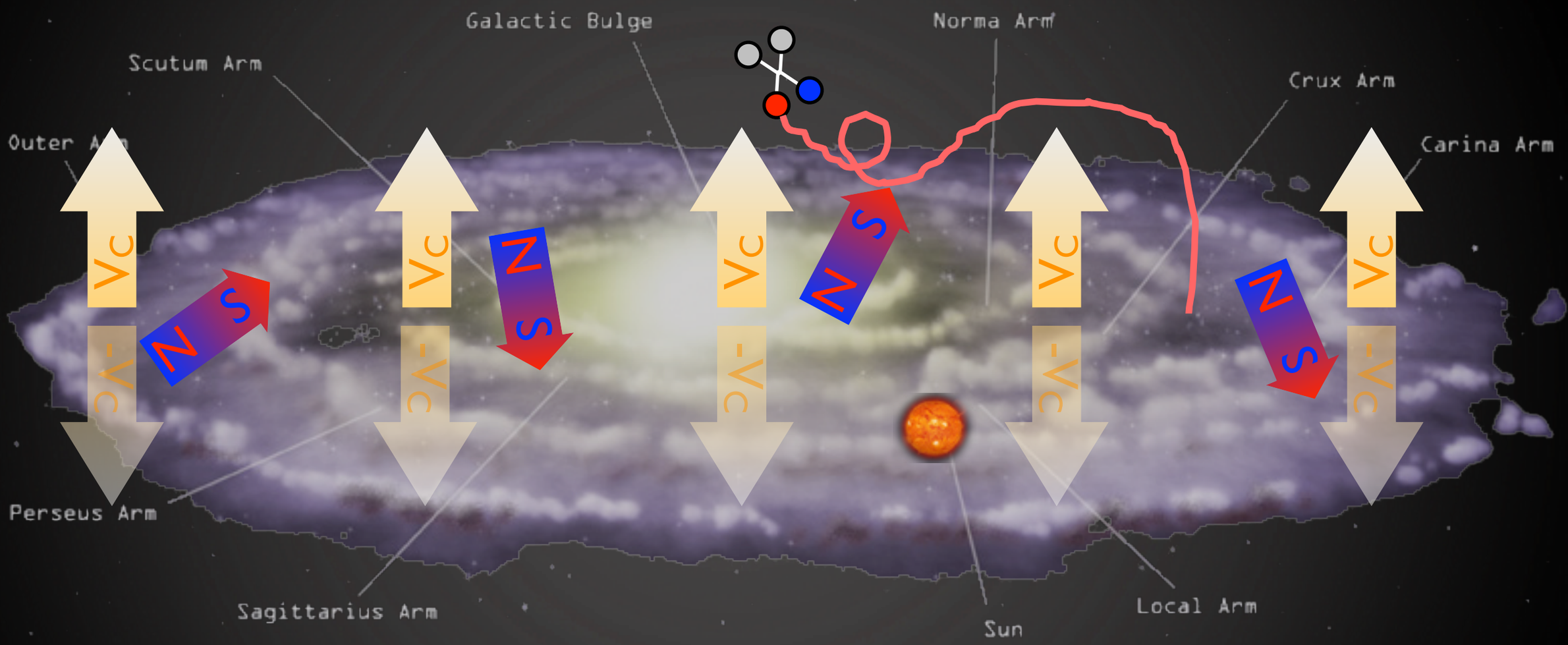

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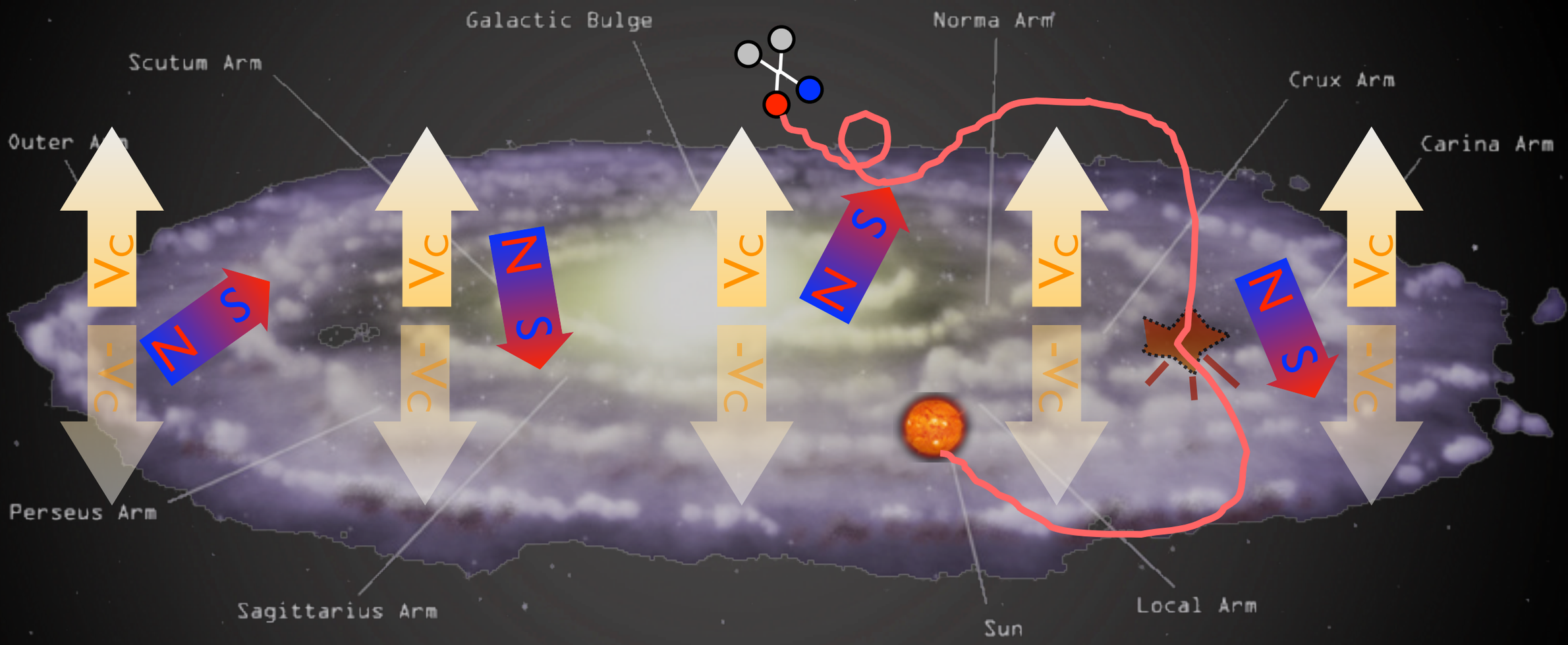

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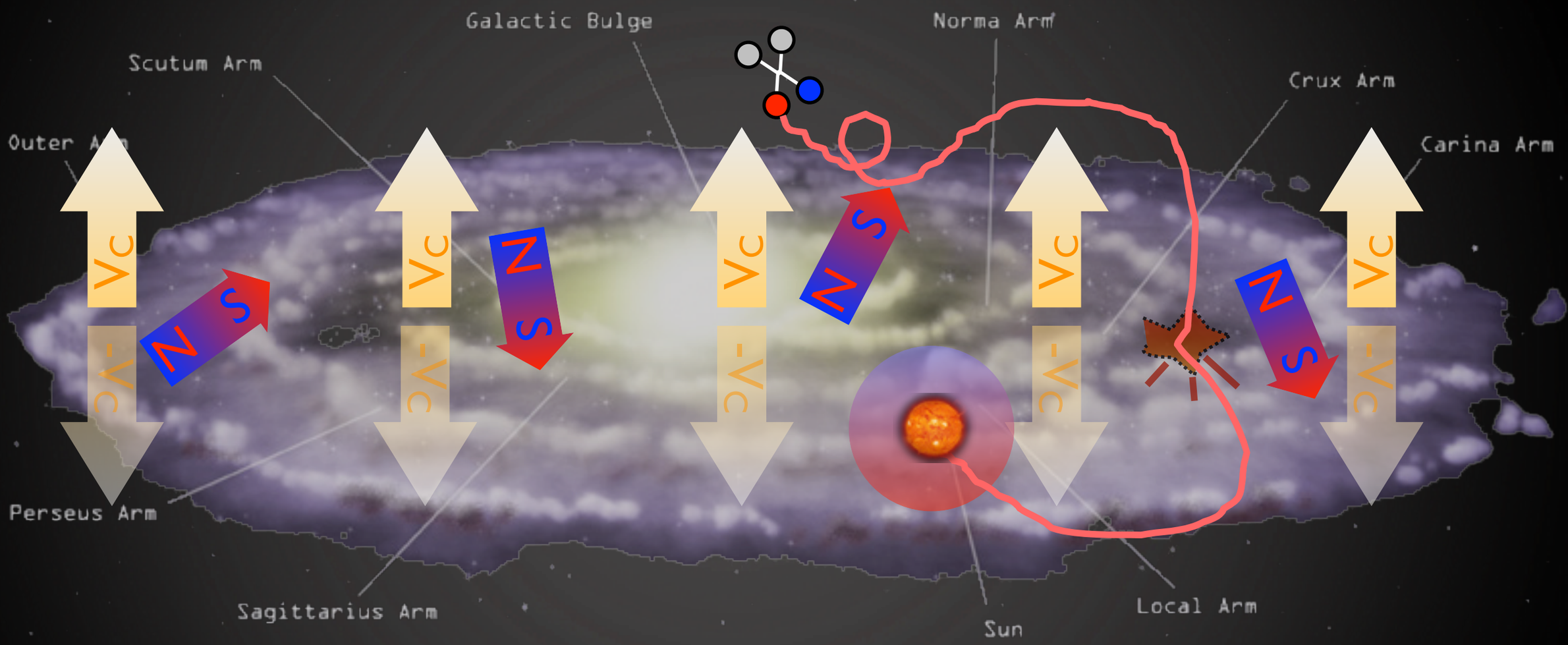

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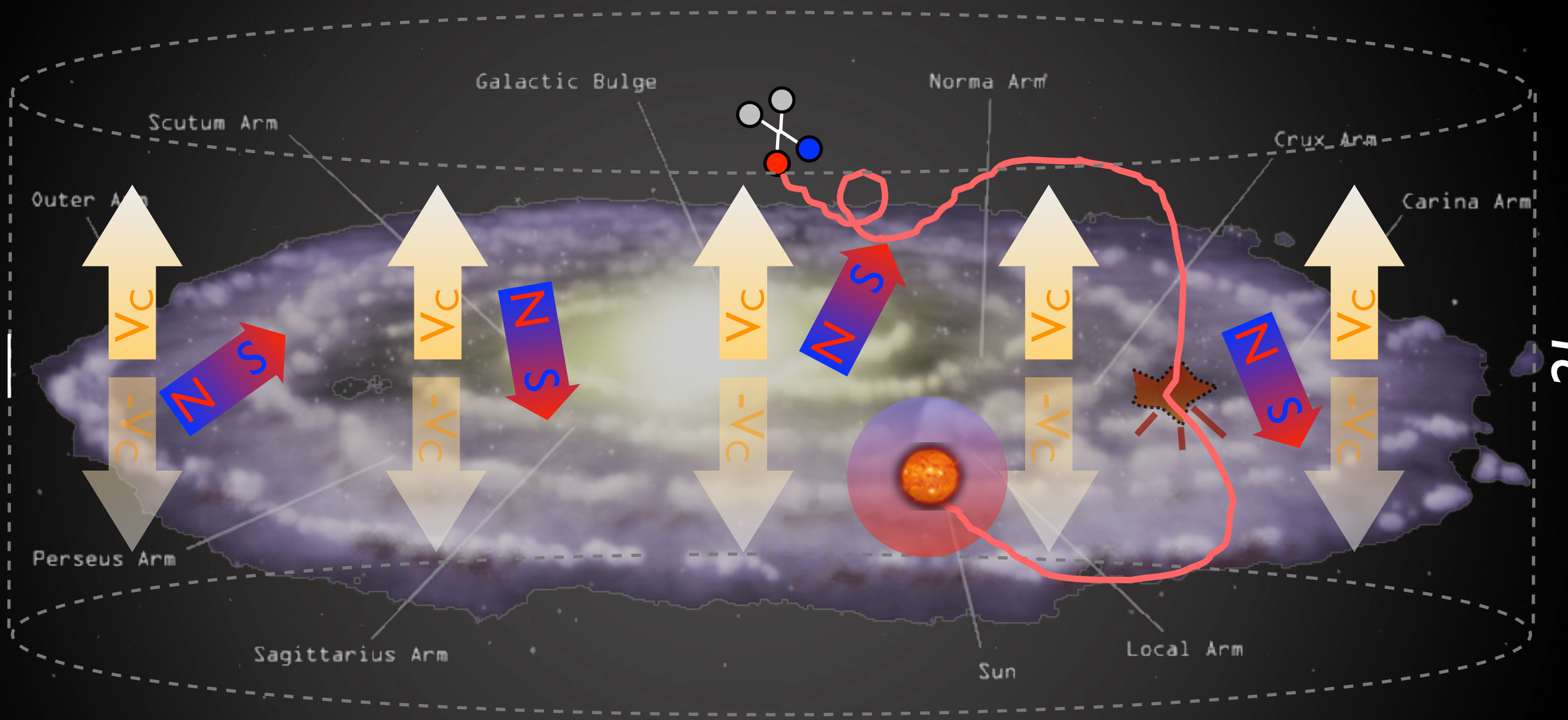


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

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

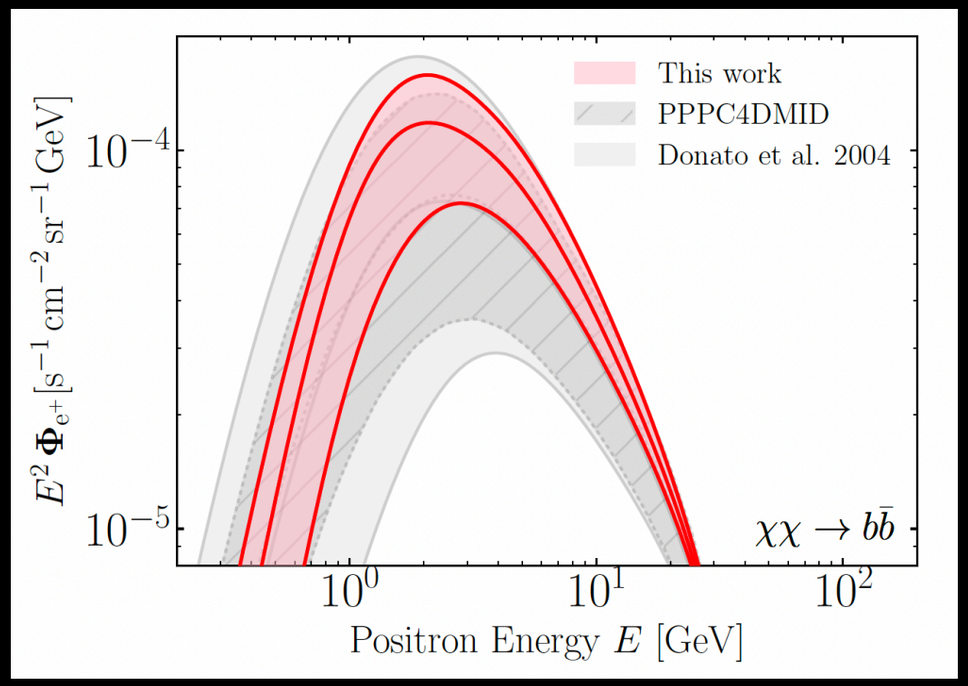
TABLE I: Propagation parameters for the MIN, MED, and MAX benchmarks for SLIM.

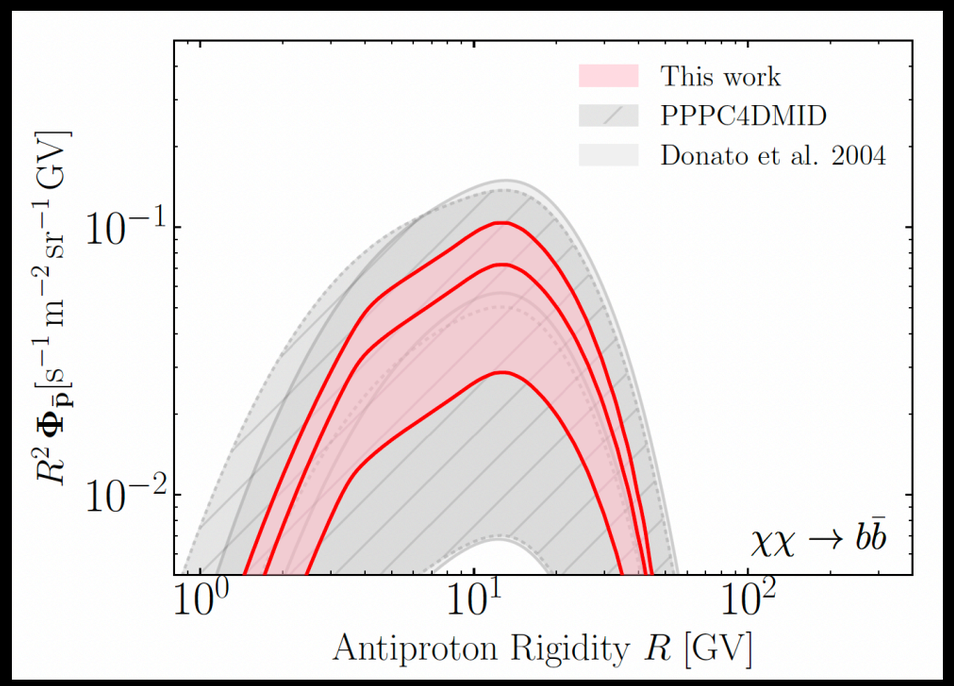
SLIM	L [kpc]	δ	$\log_{10} K_0$ [kpc^2 Myr^{-1}]	R_l [GV]	δ_l
MAX	8.40	0.490	-1.18	4.74	-0.776
MED	4.67	0.499	-1.44	4.48	-1.11
MIN	2.56	0.509	-1.71	4.21	-1.45

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

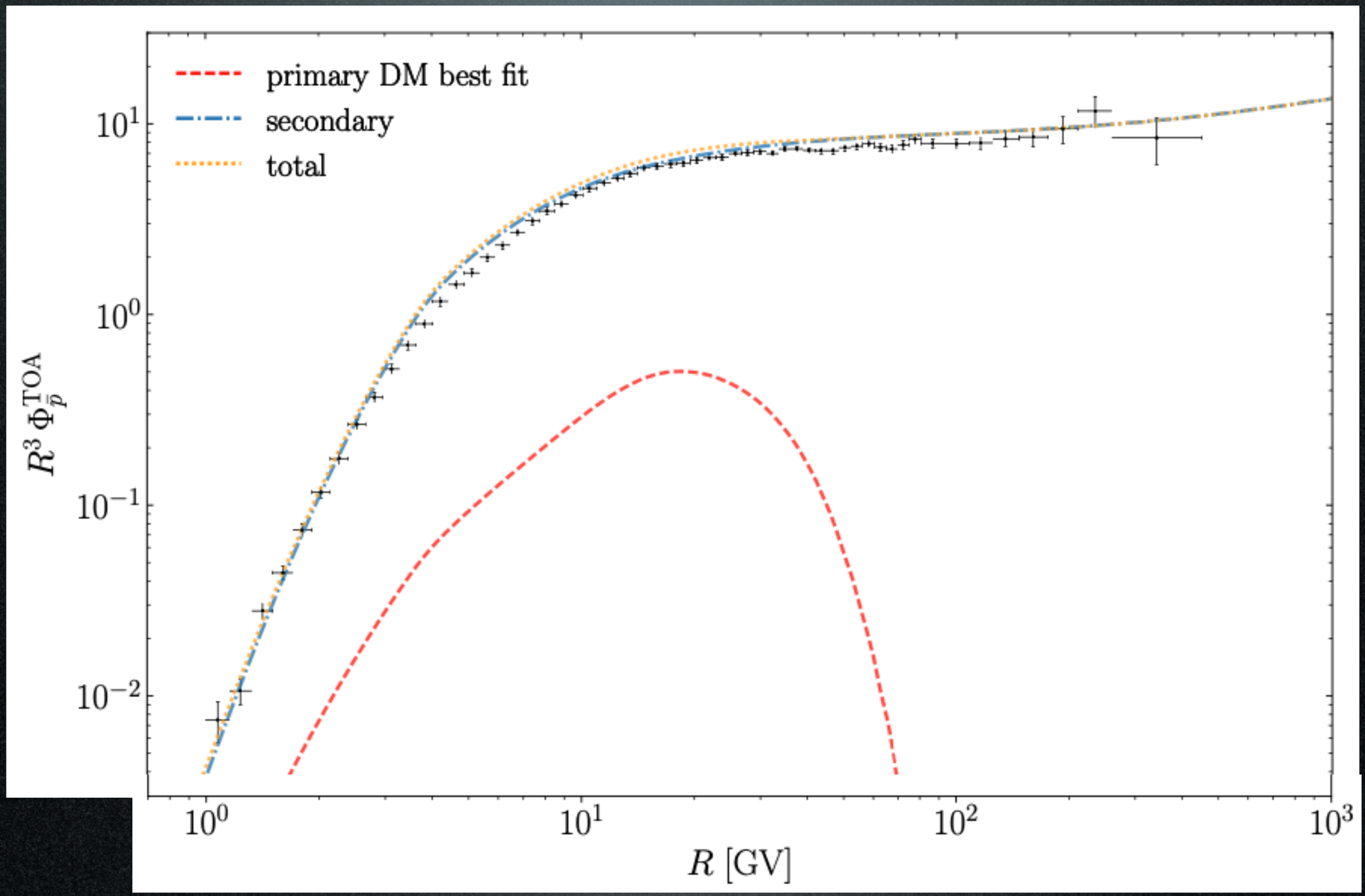
Sizable reduction of the propagation uncertainties





Model independent bounds

Based on AMS-02 $\bar{p}$ data (2016) AMS coll. Phys. Rev. Lett. 117(9), 091103 (2016)



Calore, Cirelli, Derome, Génolini, Maurin, Salati, Serpico 2202.03076

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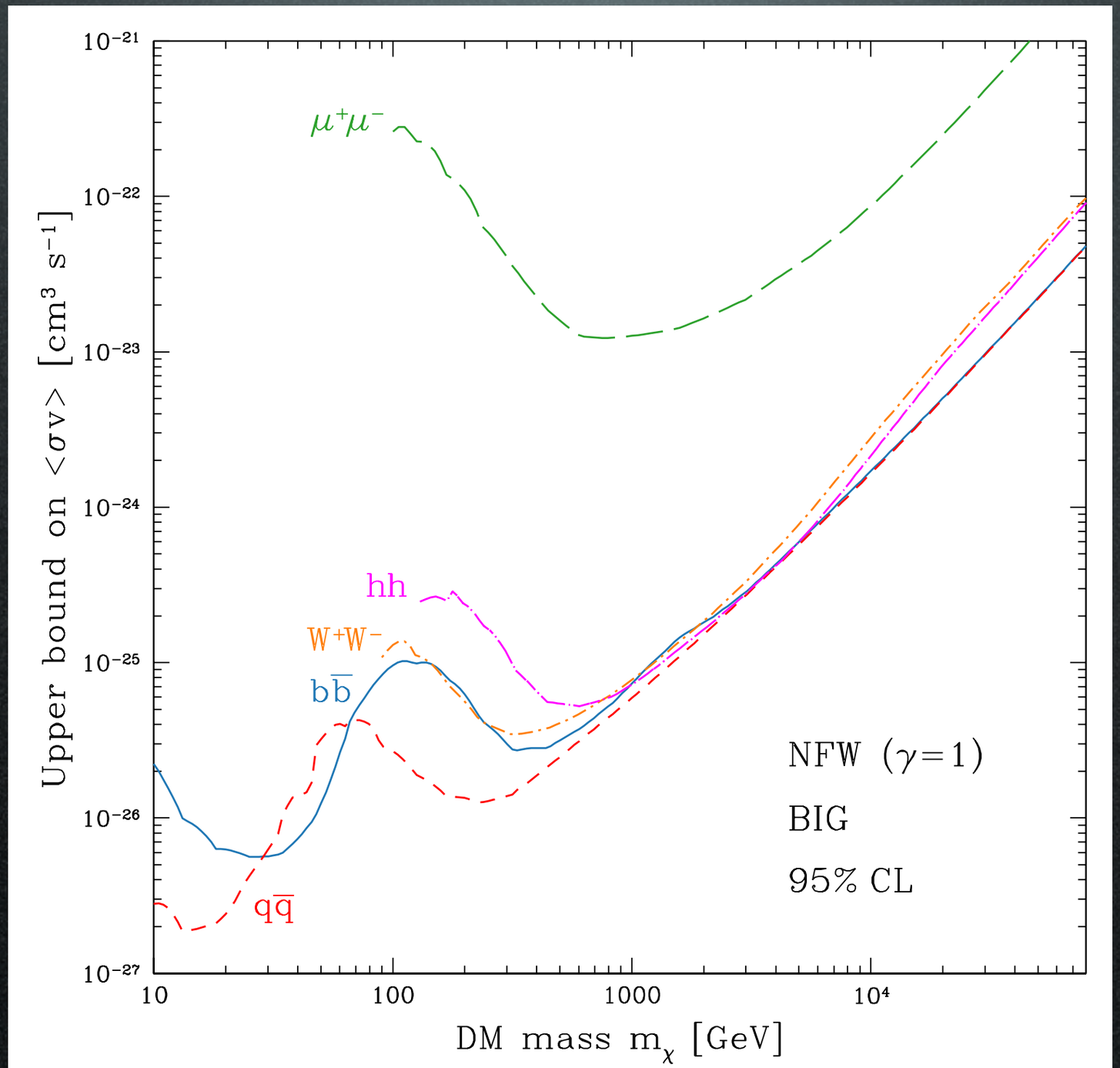

Calore, Cirelli, Derome, Génolini, Maurin, Salati, Serpico 2202.03076

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

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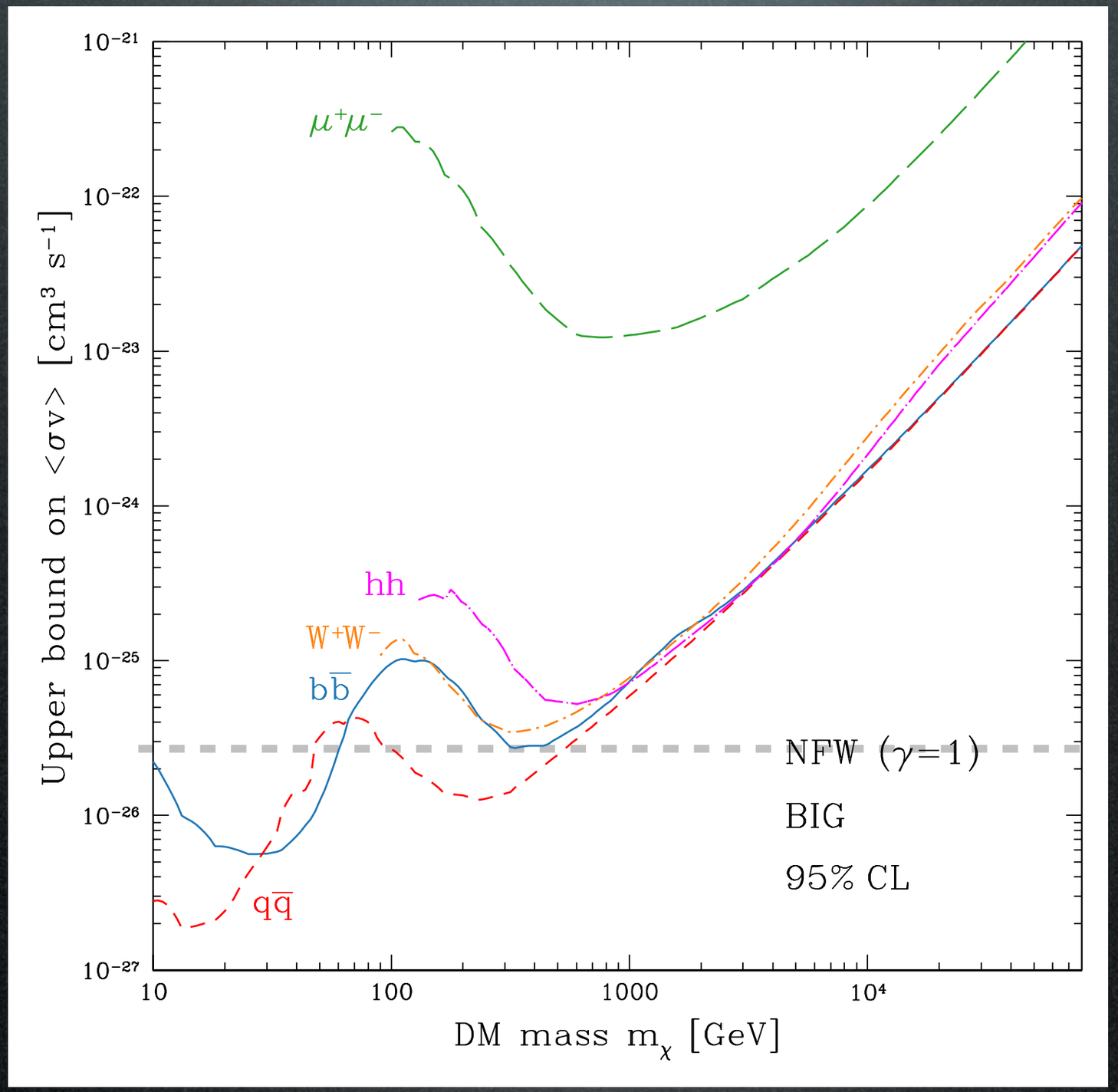


Calore, Cirelli, Derome, Génolini, Maurin, Salati, Serpico 2202.03076

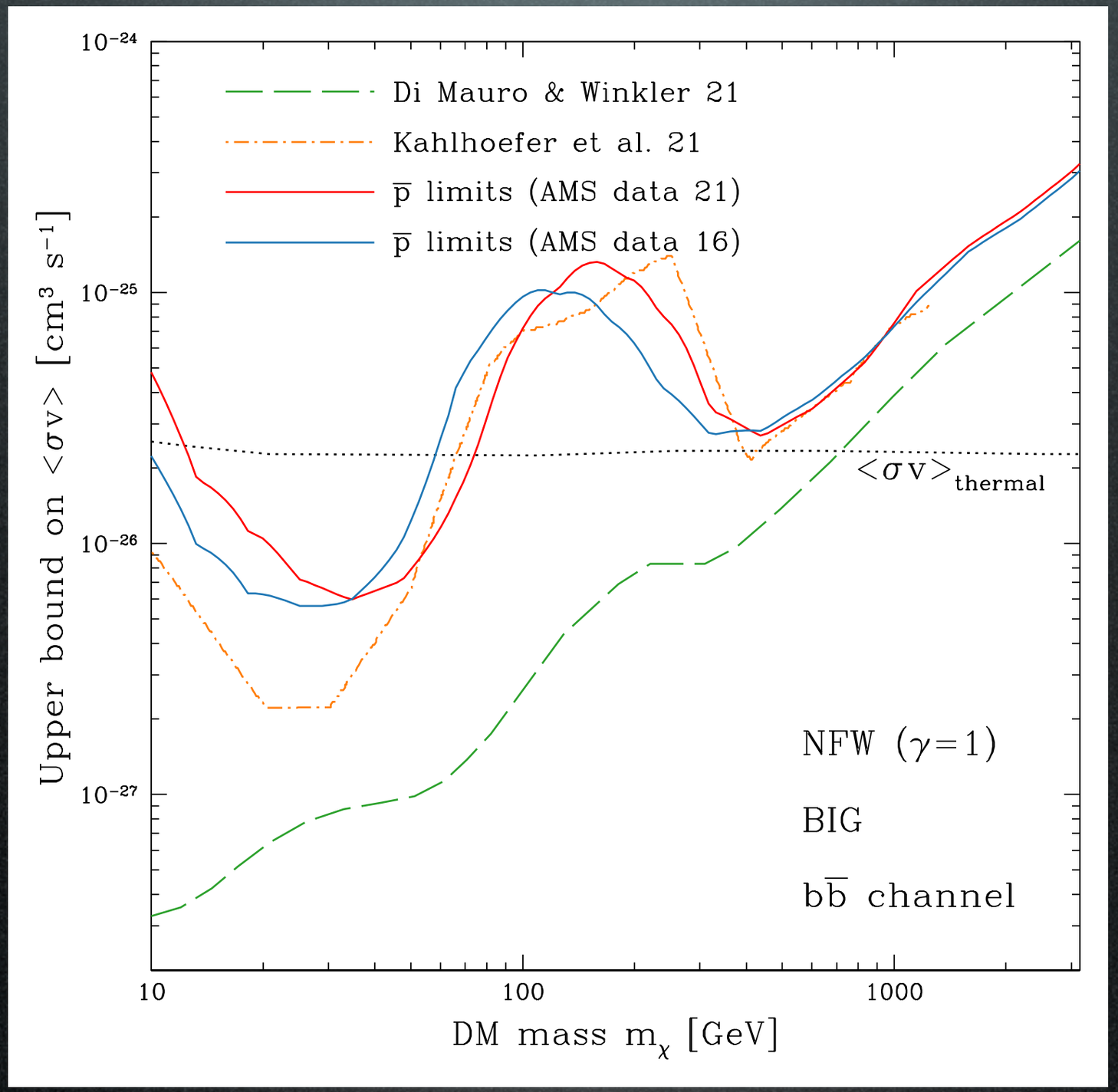
Bounds quite 'weak' because of bump

Bounds on leptonic channels

Model independent bounds

Based on **new** AMS-02 $\bar{p}$ data (2021)

(slightly inconsistent since propagation and background are based on 2016 data)



Calore, Cirelli, Derome, Génolini, Maurin, Salati, Serpico 2202.03076

Results are robust

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

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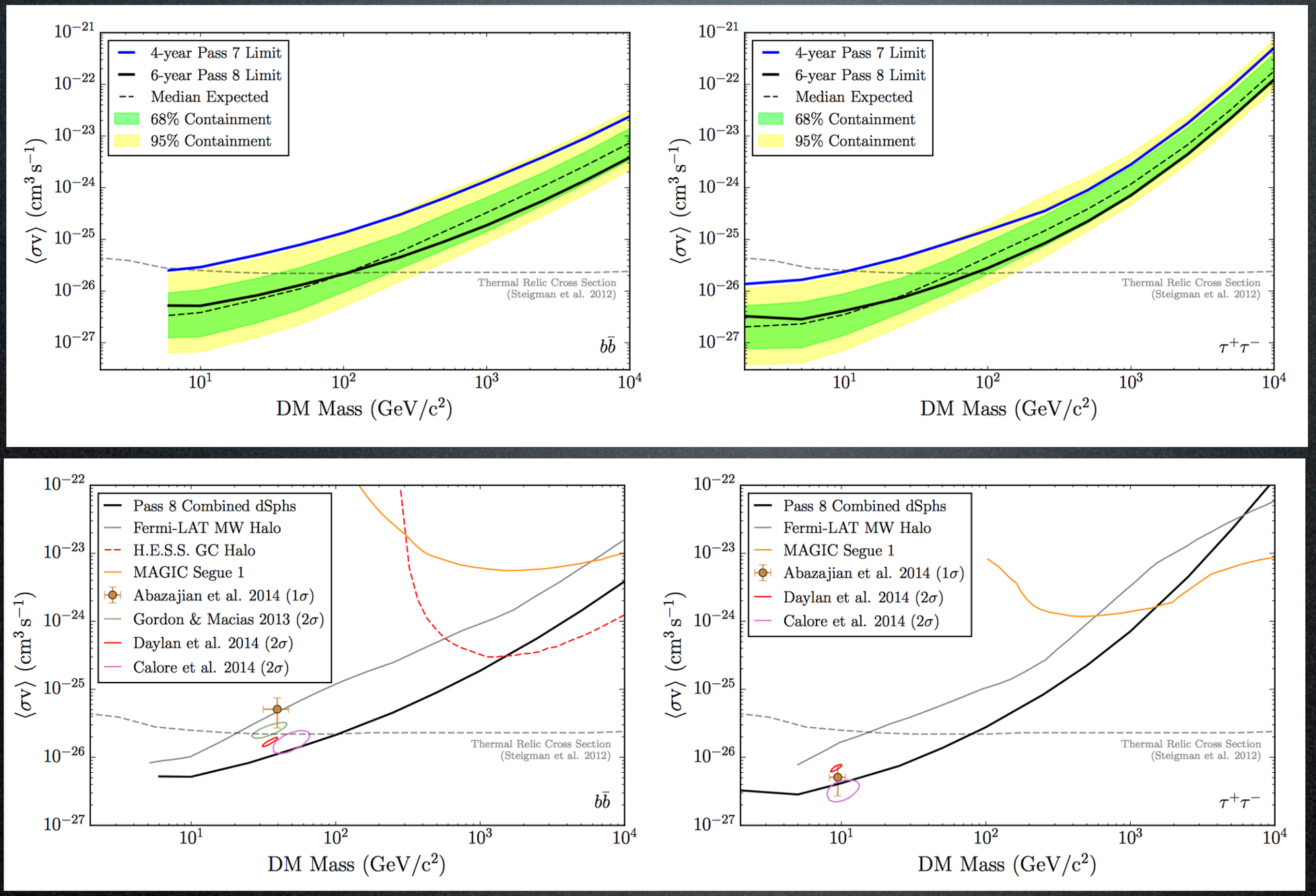
SK, Icecube, Antares

Constraints

Dwarf galaxies

FERMI

FERMI 1503.02641

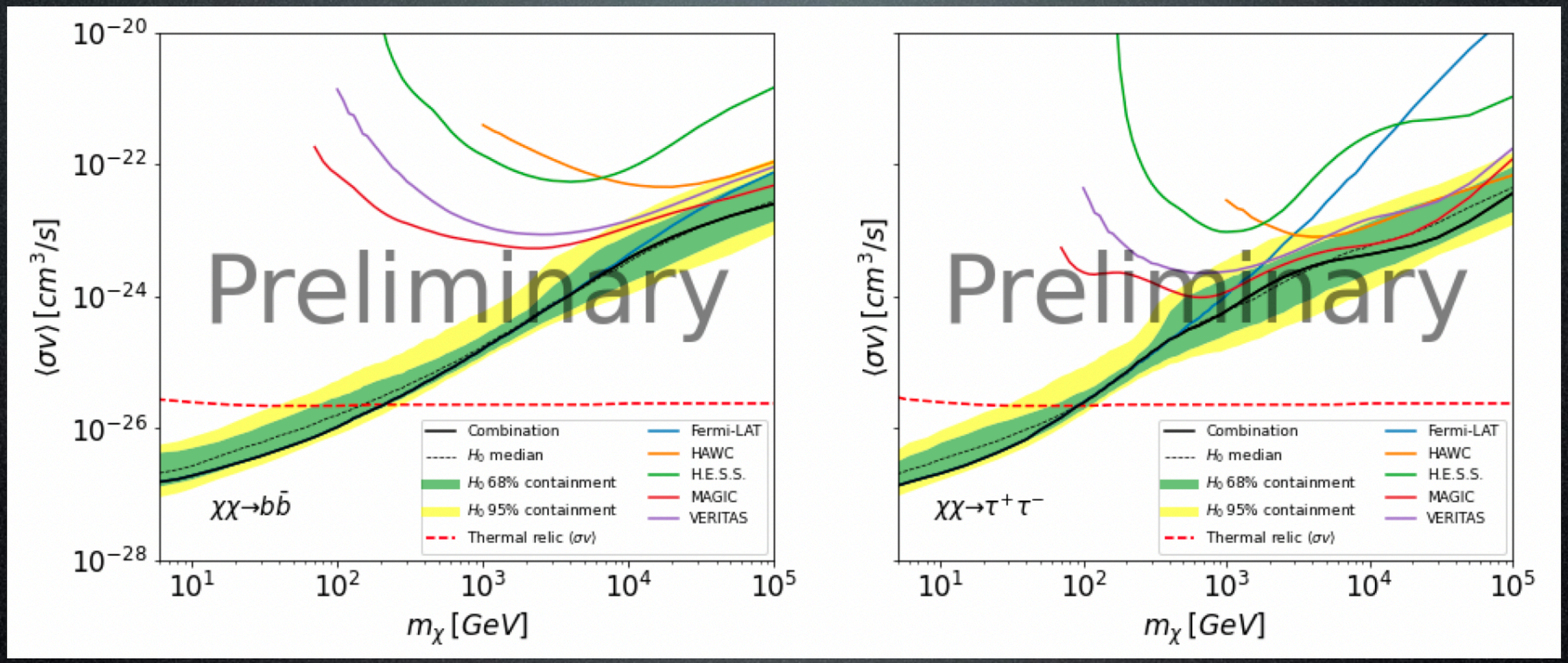


Constraints

Dwarf galaxies

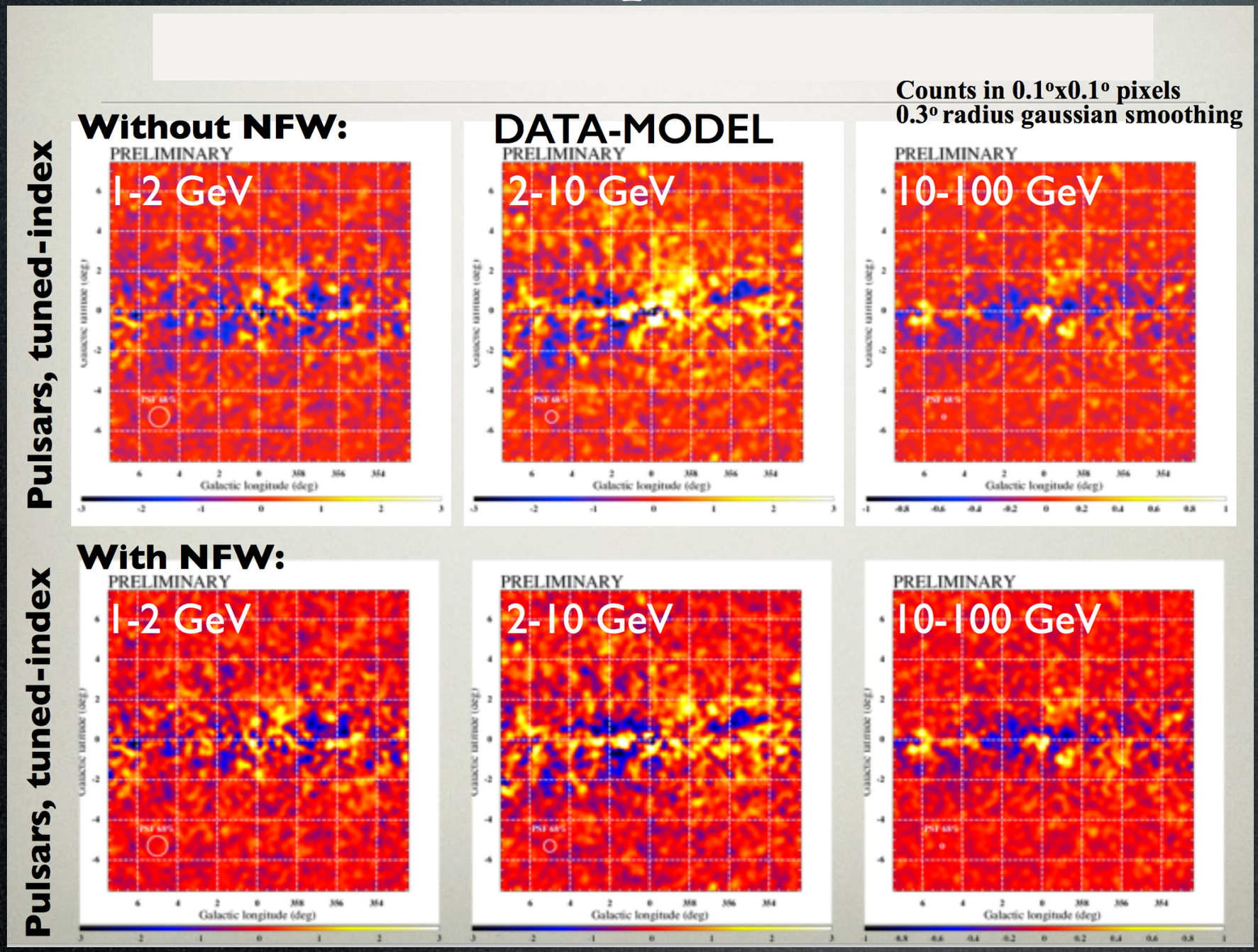
FERMI+HAWC+HESS+MAGIC+VERITAS

2108.13646



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

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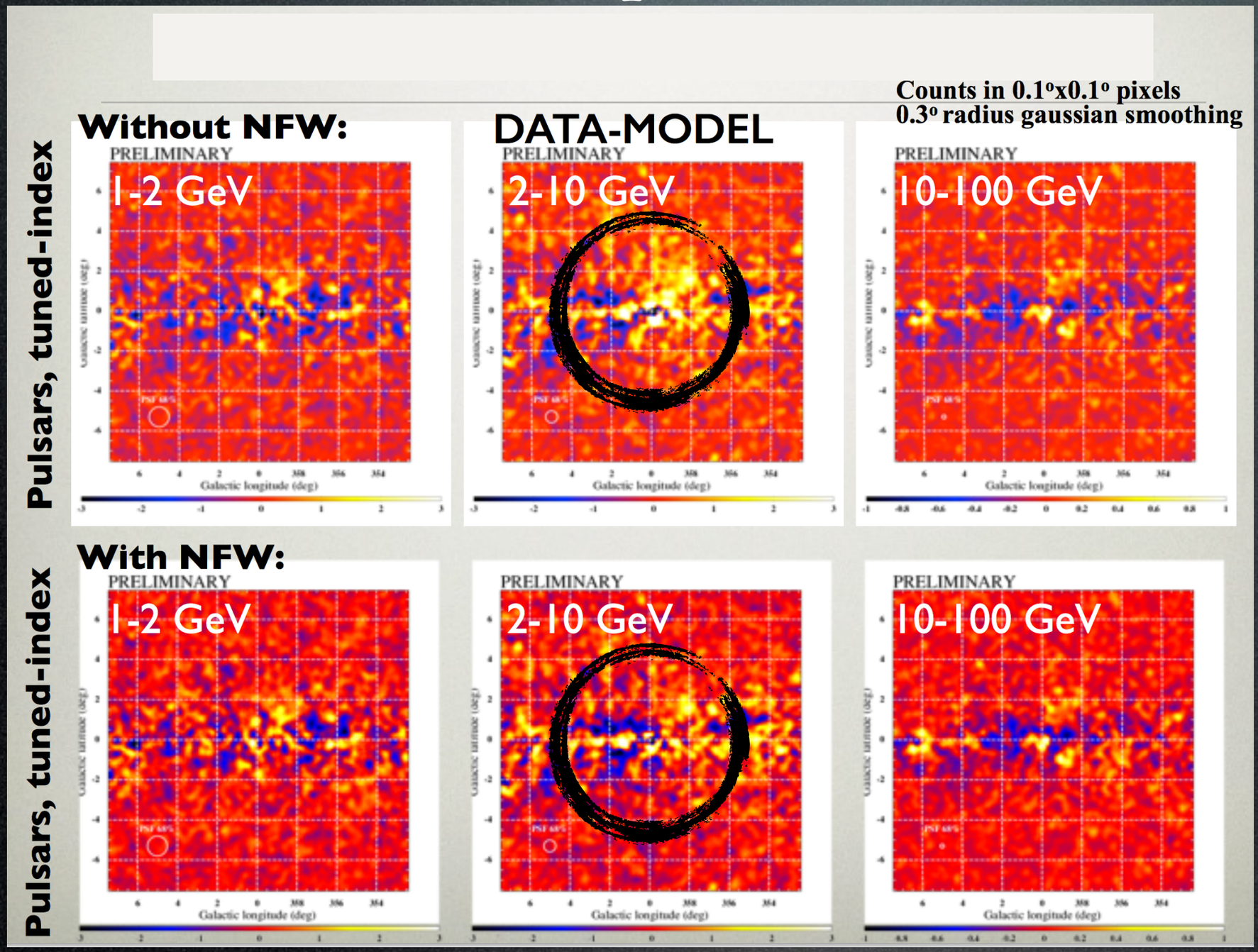

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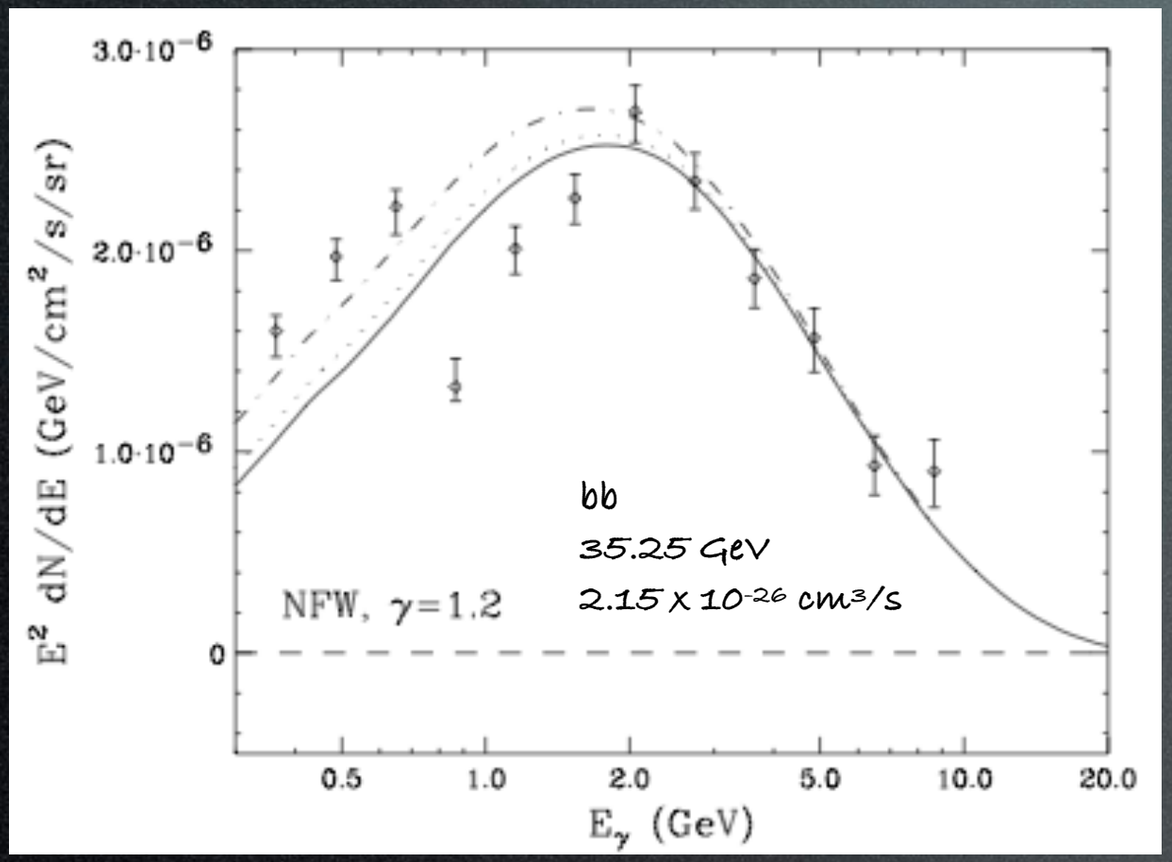
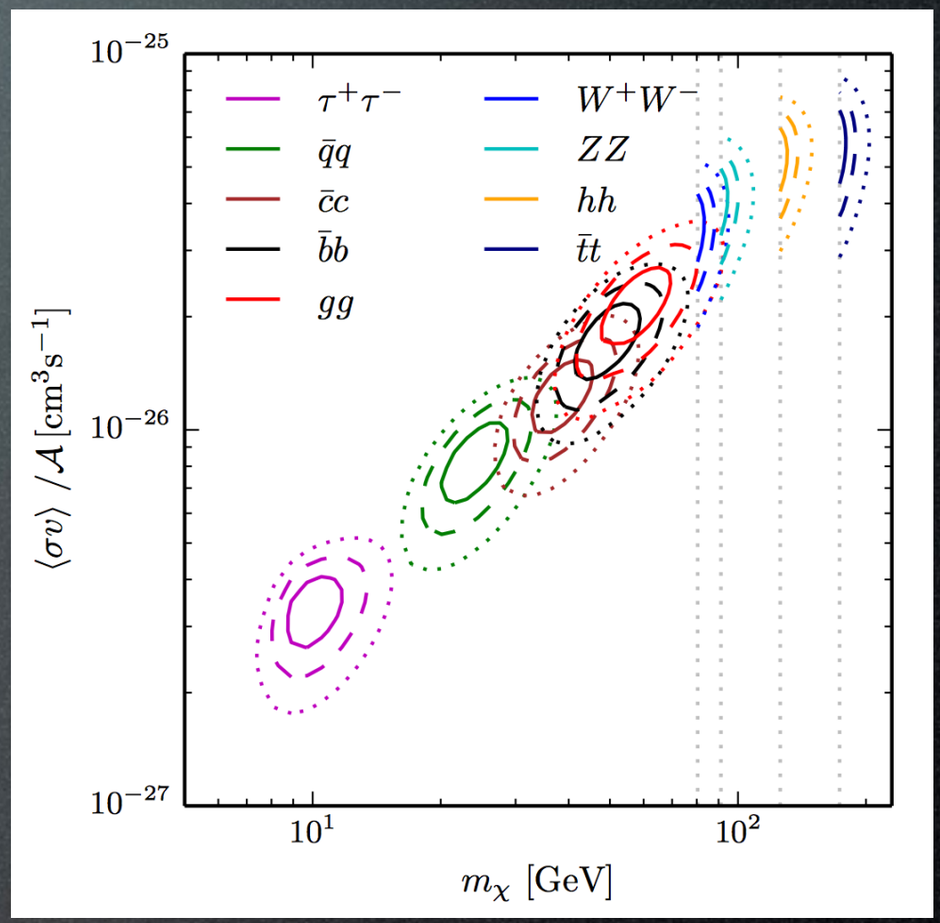
GC GeV excess

Dark Matter interpretation:

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





F. Calore et al. 1411.4647

A compelling case for annihilating DM

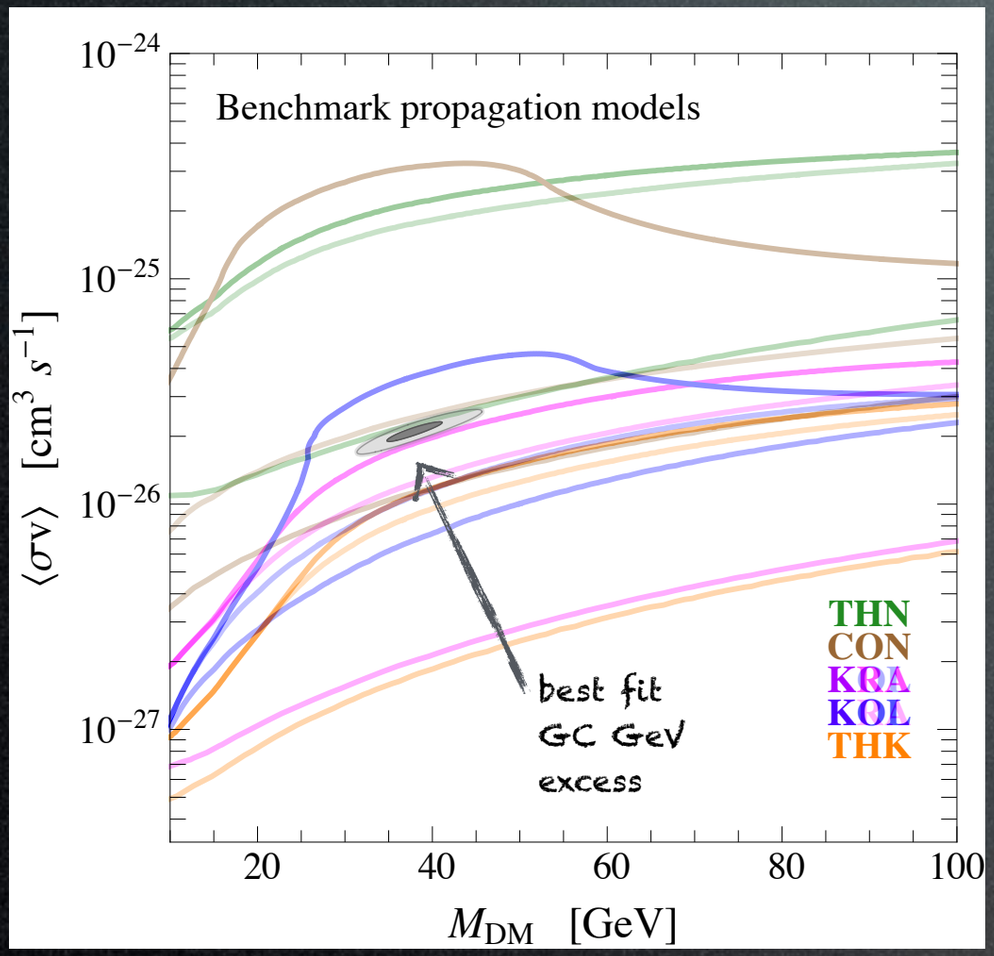
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

...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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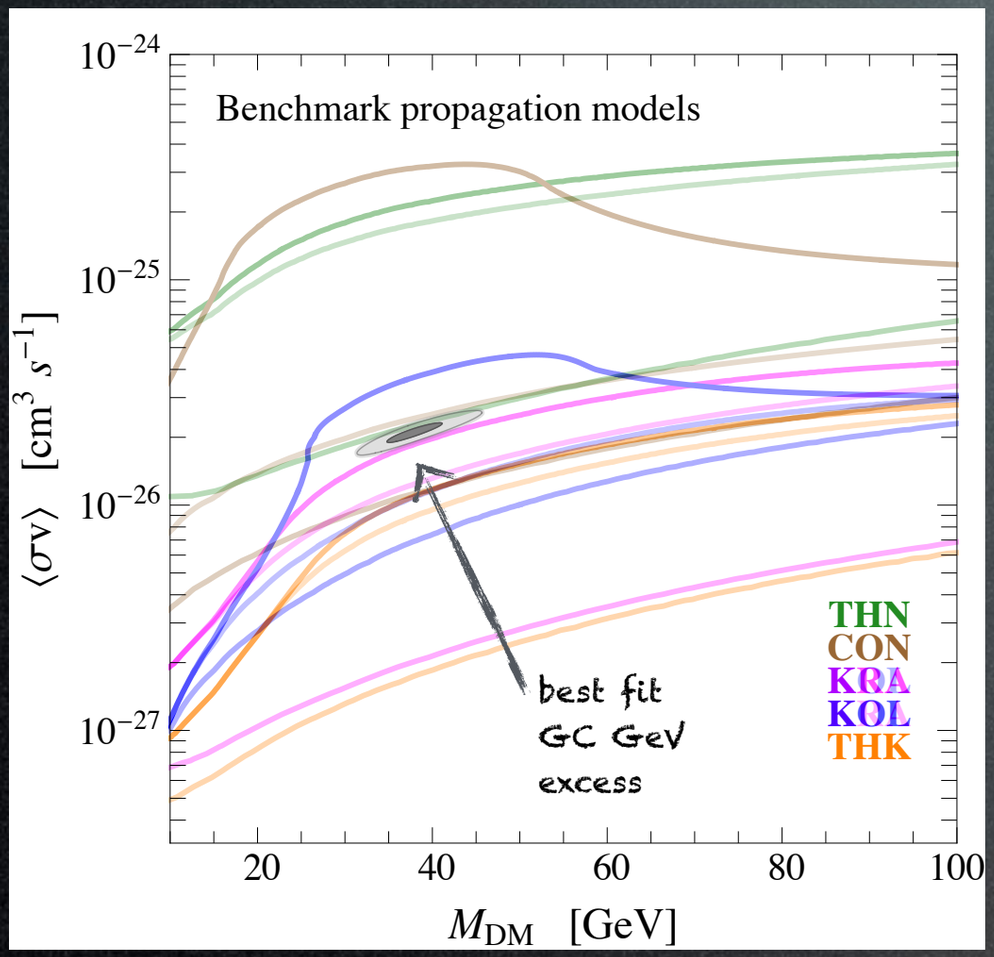
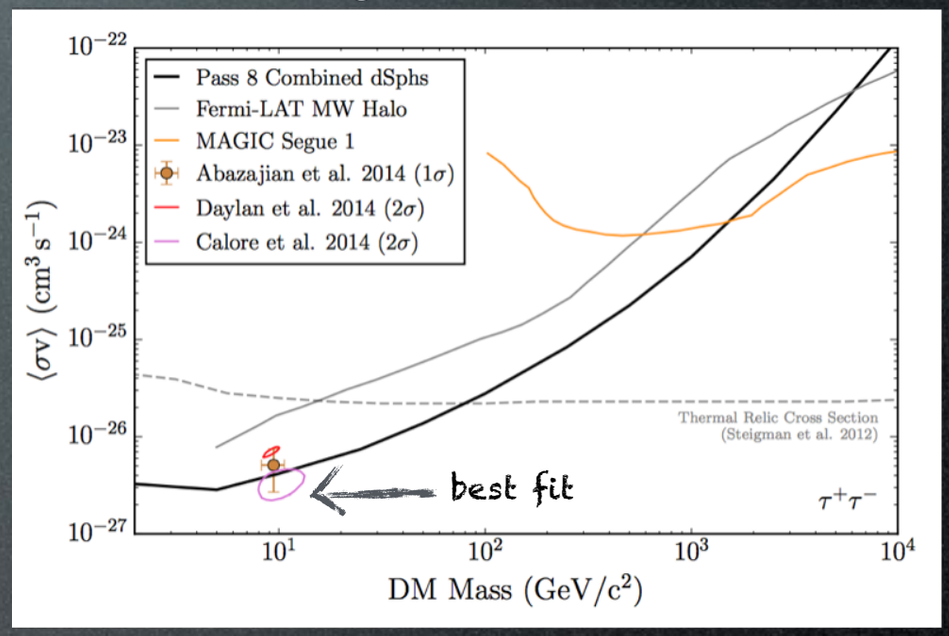


Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Gamma ray ones neither



FERMI 1503.02641

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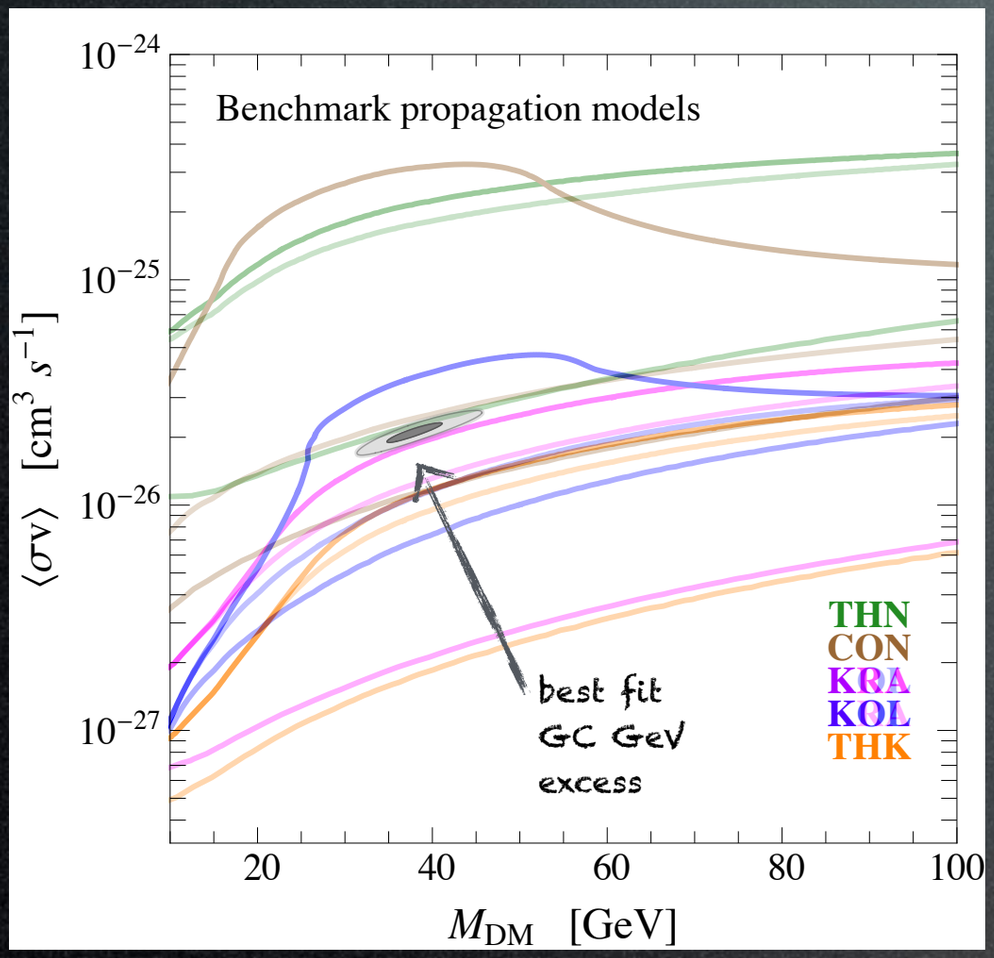

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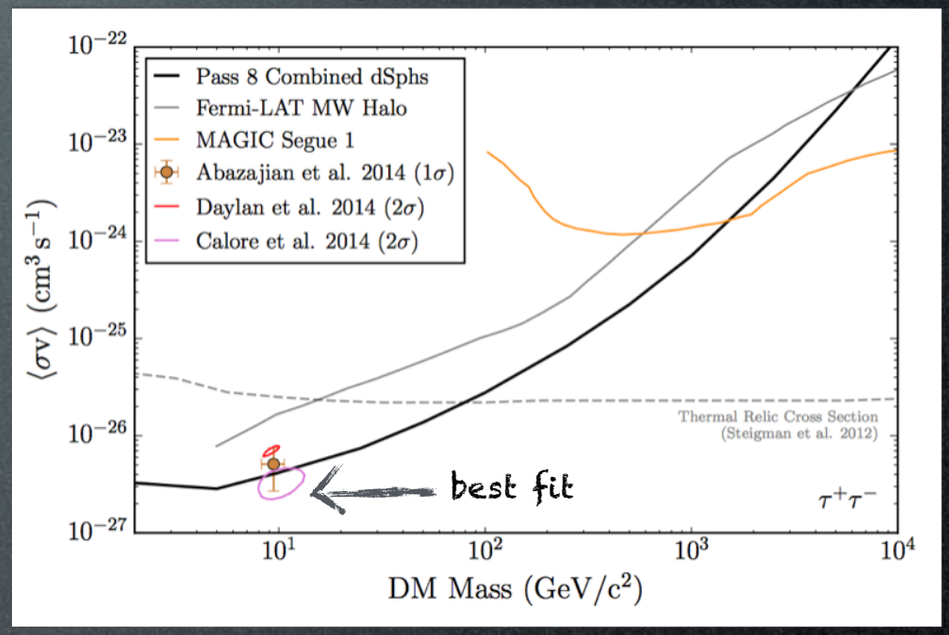
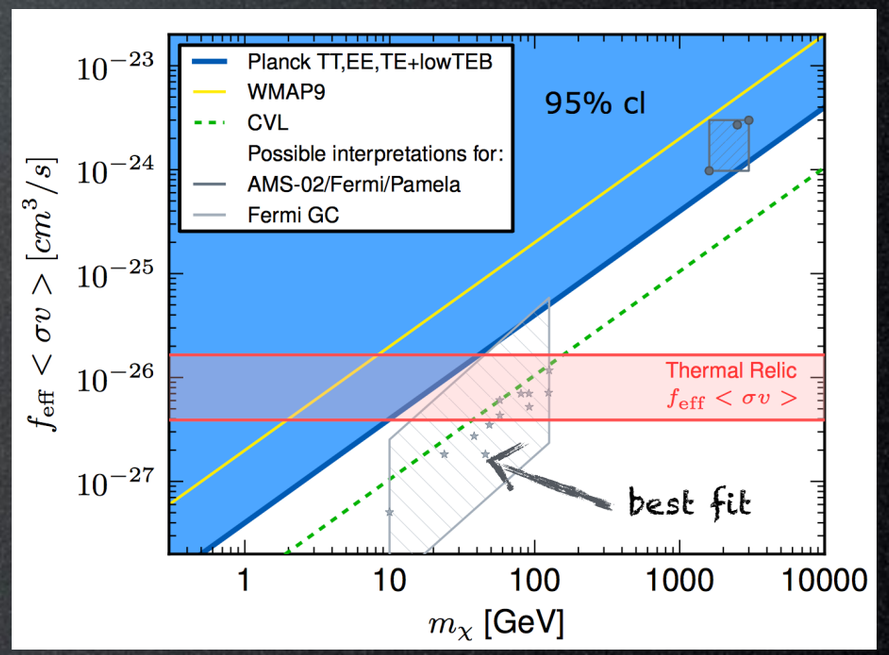


FERMI 1503.02641

Nor CMB

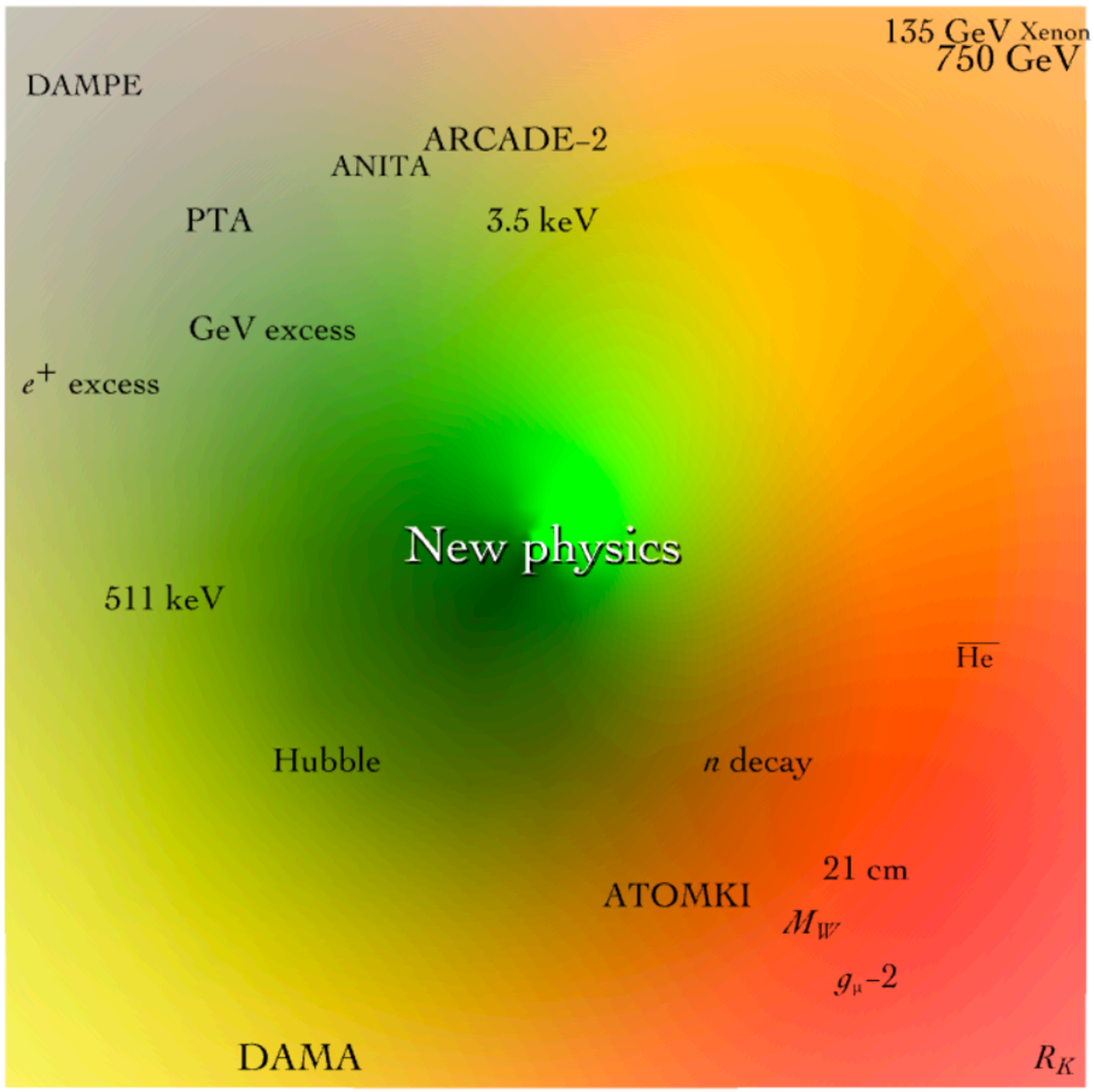


Planck 2015

DM related 'anomalies'

Astrophysics

Background

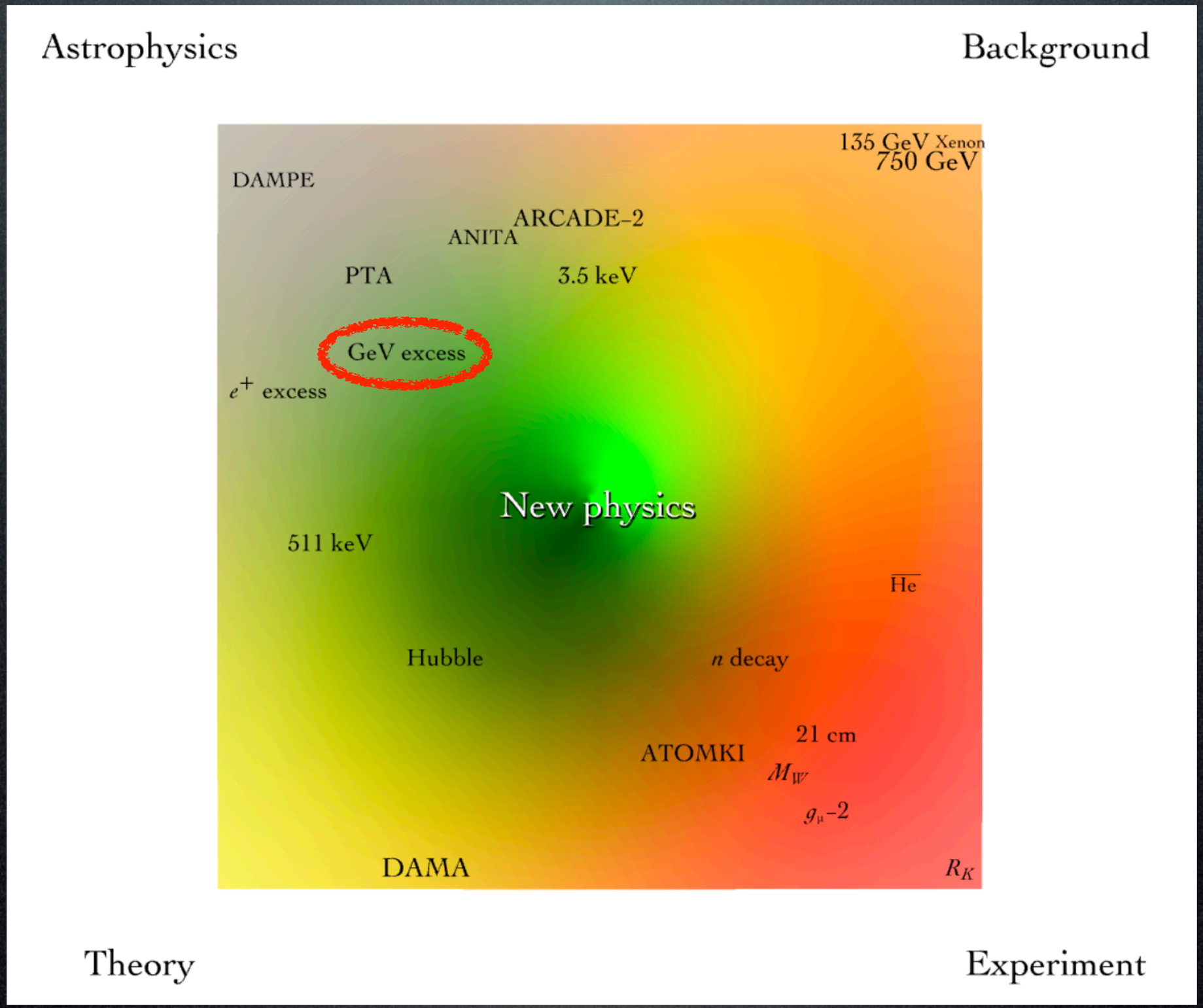


Theory

Experiment

Cirelli, Strumia, Zupan 2406.01705

DM related 'anomalies'



Cirelli, Strumia, Zupan 2406.01705

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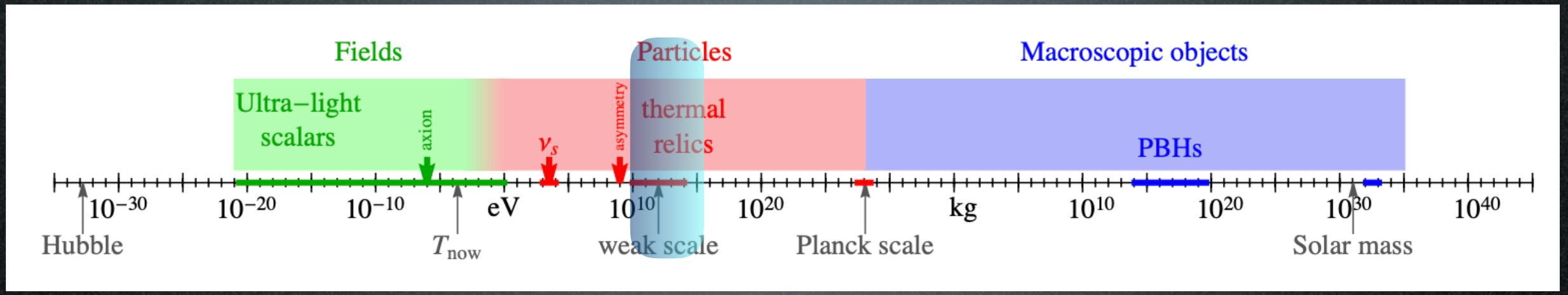

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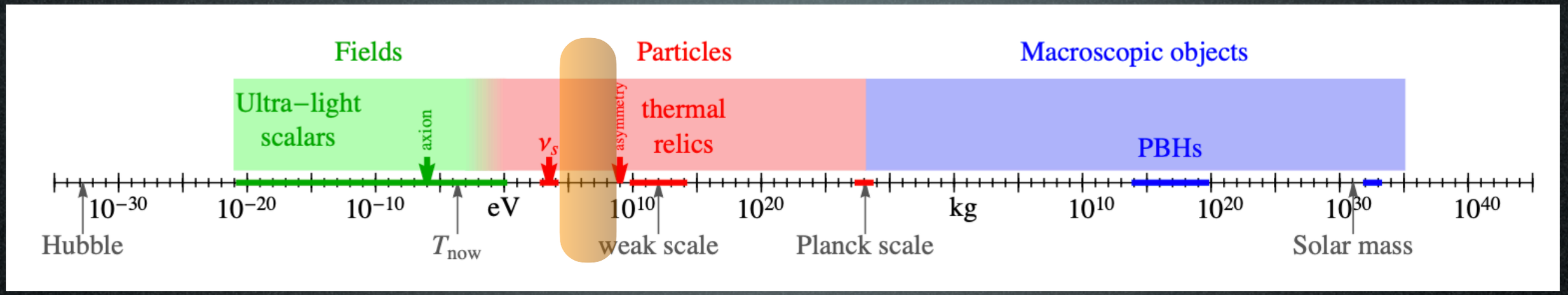

90 orders of magnitude!

Candidates

theory?

production?

Collider Searches?

Indirect Detection?

Direct Detection?

Theory

Sub-GeV DM?

- WIMPless Dark Matter
- 'SIMP miracle'
- Asymmetric DM
- 'MeV (scalar) DM' (Integral 511 KeV excess)
- 'simplified (light) DM models'
- ...

Theory

Sub-GeV DM?

Why not!

- WIMPless Dark Matter
- ‘SIMP miracle’
- Asymmetric DM
- ‘MeV (scalar) DM’ (Integral 511 KeV excess)
- ‘simplified (light) DM models’
- …

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theory

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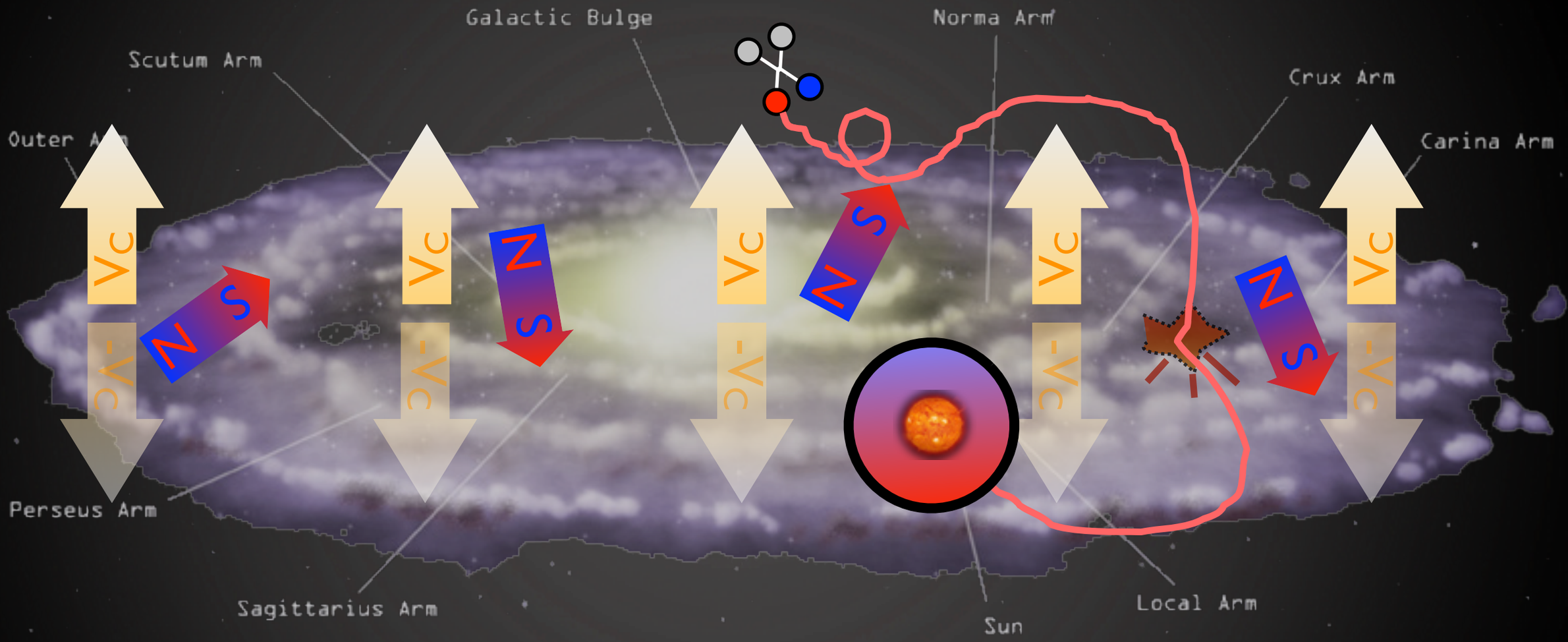
Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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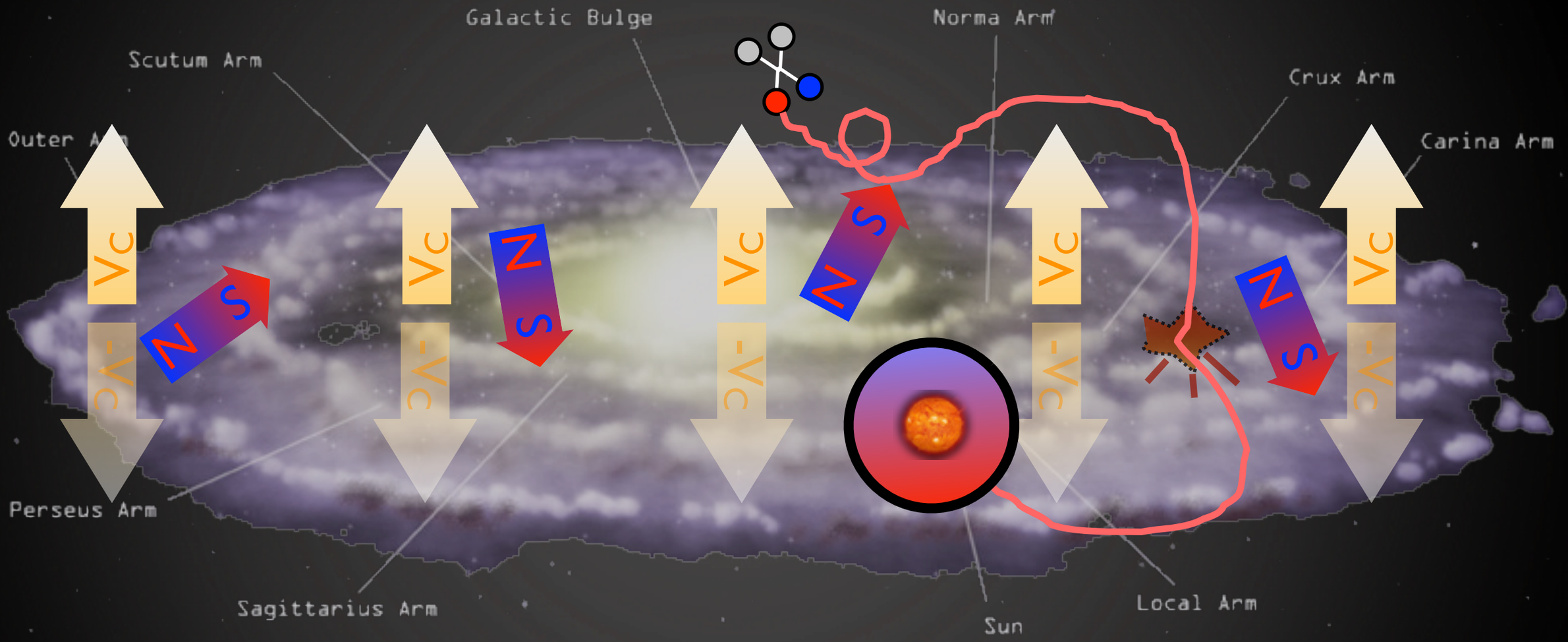

Problem:

sub-GeV charged CRs do not penetrate the heliosphere, experiments cannot collect

Indirect Detection: charged CRs

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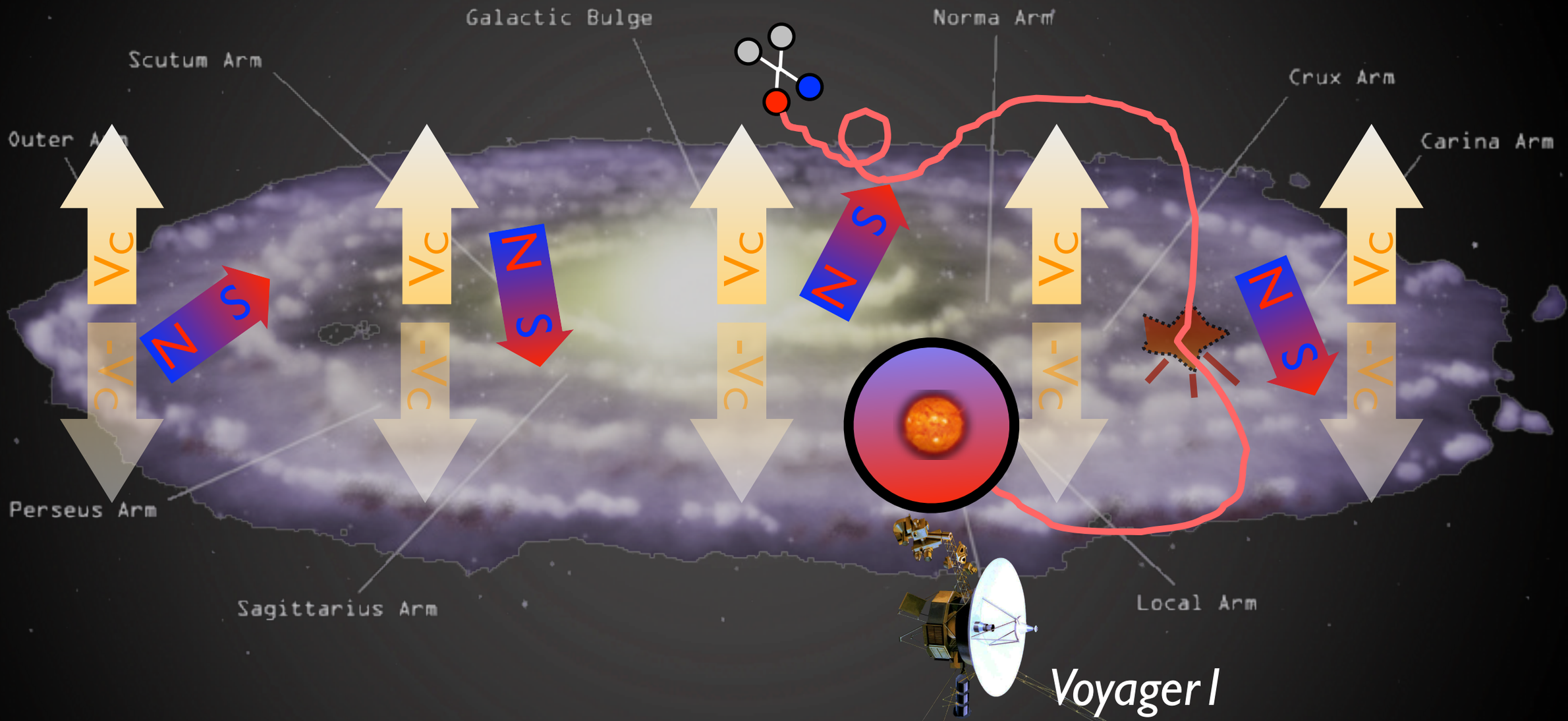


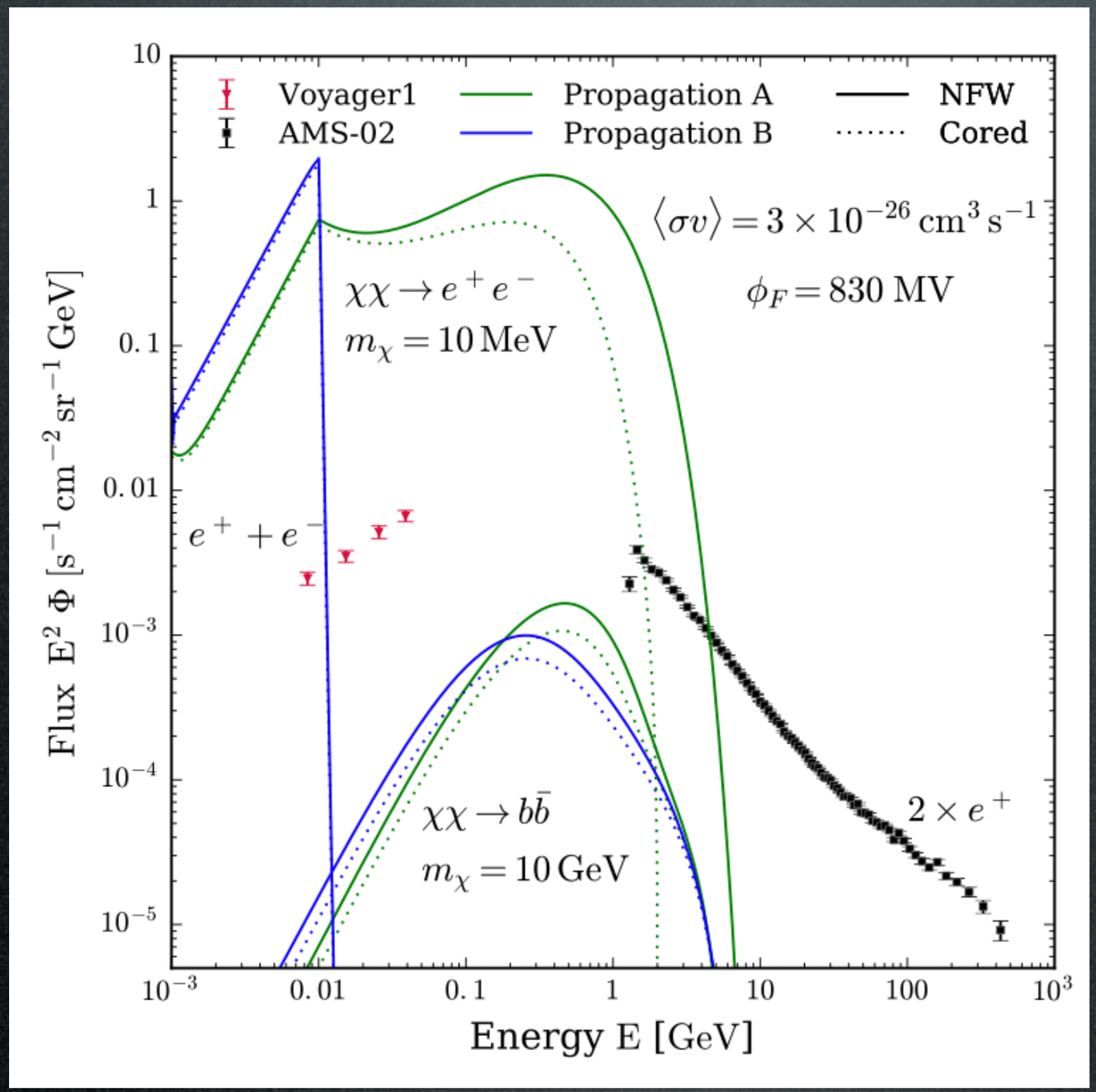
Problem:

sub-GeV charged CRs do not penetrate the heliosphere, experiments cannot collect... with one exception!

Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I



Propagation A = strong reacceleration
Propagation B = weak/no reacceleration

Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

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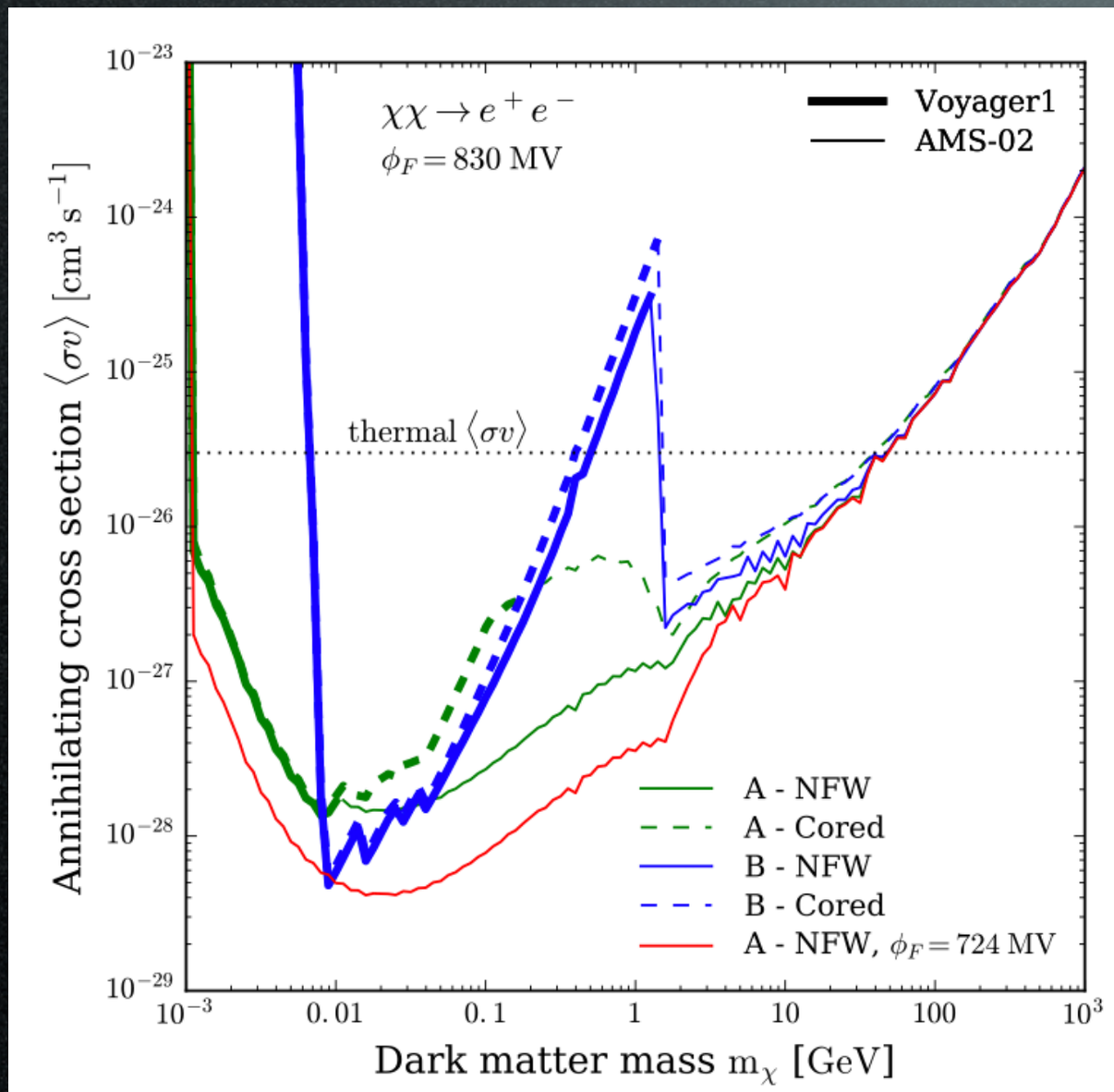
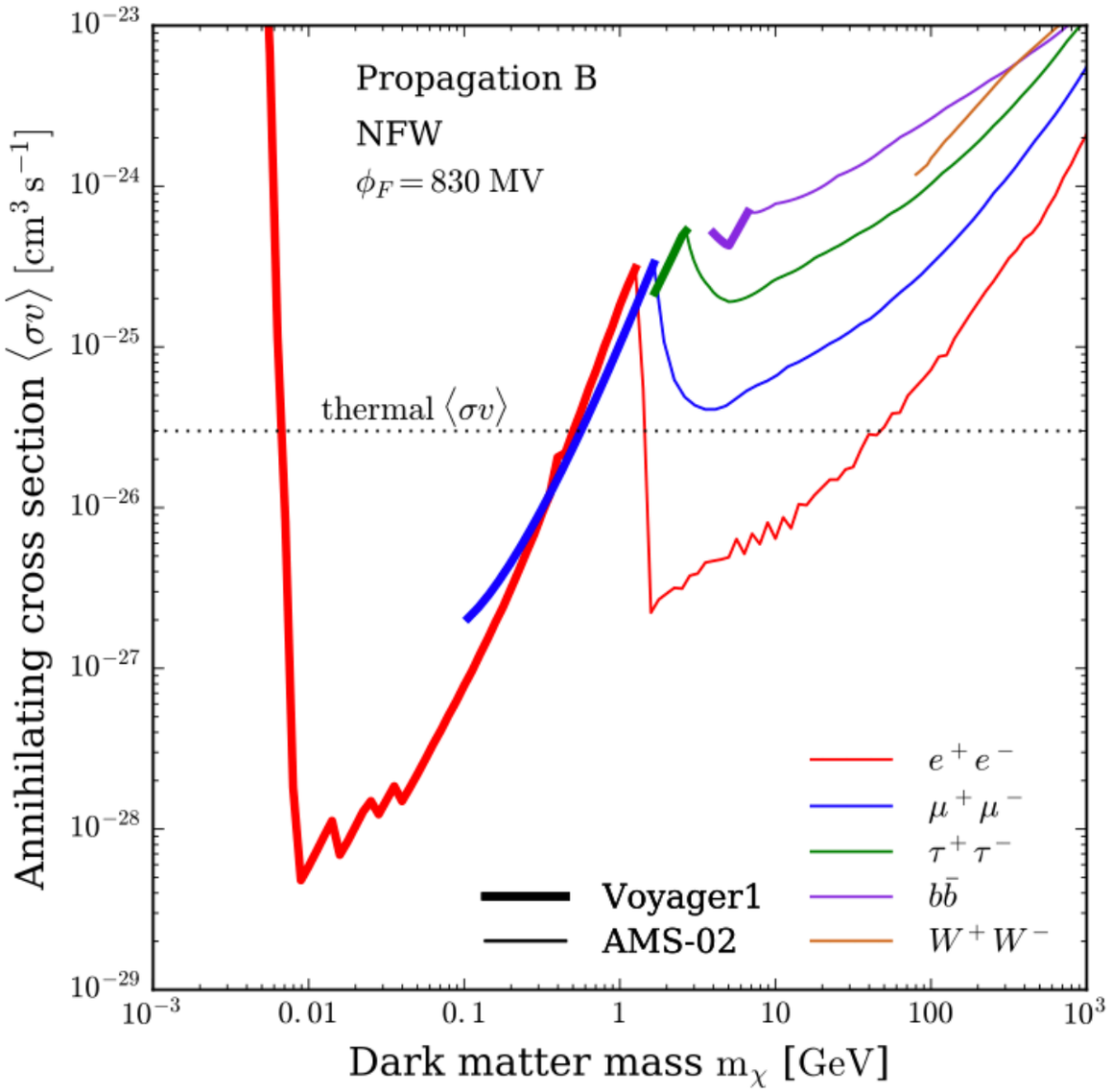
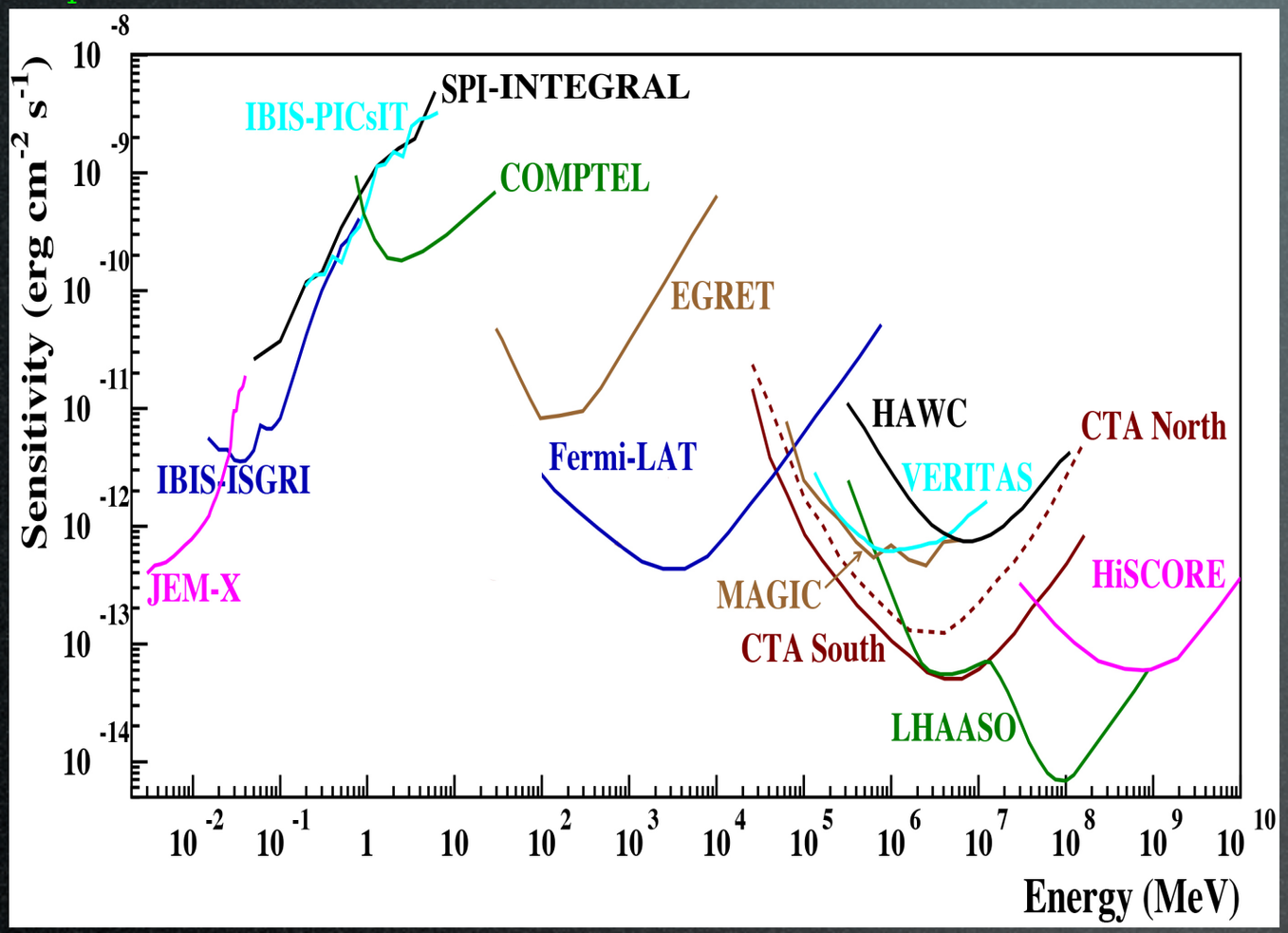




Indirect detection: photons

adapted from 1611.02232



Past/current experiments:

Integral, Comptel, Fermi

(2002⟶) *(1991-2000)* *(2009⟶)*

Planned/proposed experiments:

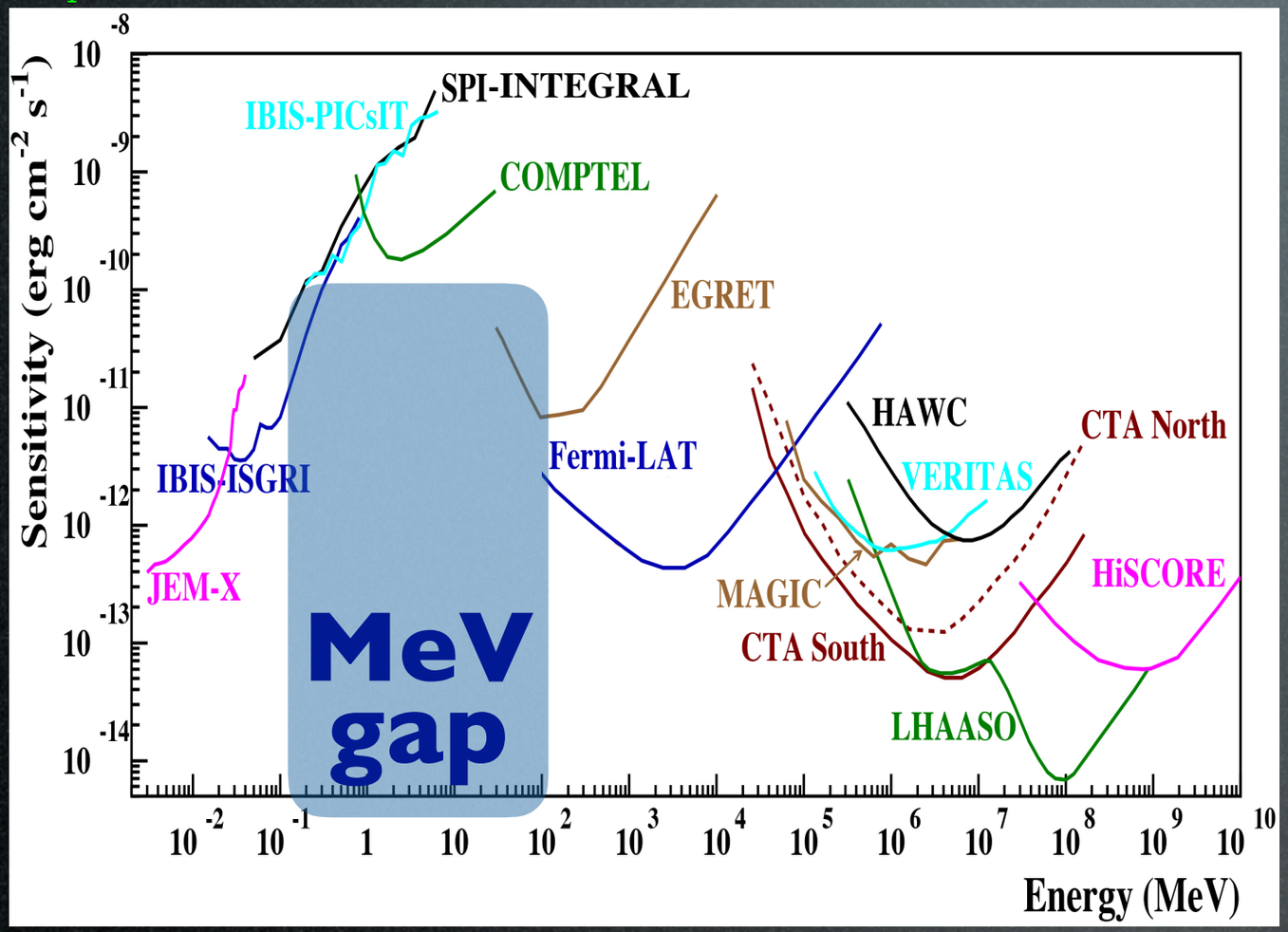
e-Astrogam?, Compair?, Amego?, COSI?

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 2406.01705

Indirect detection: photons

adapted from 1611.02232



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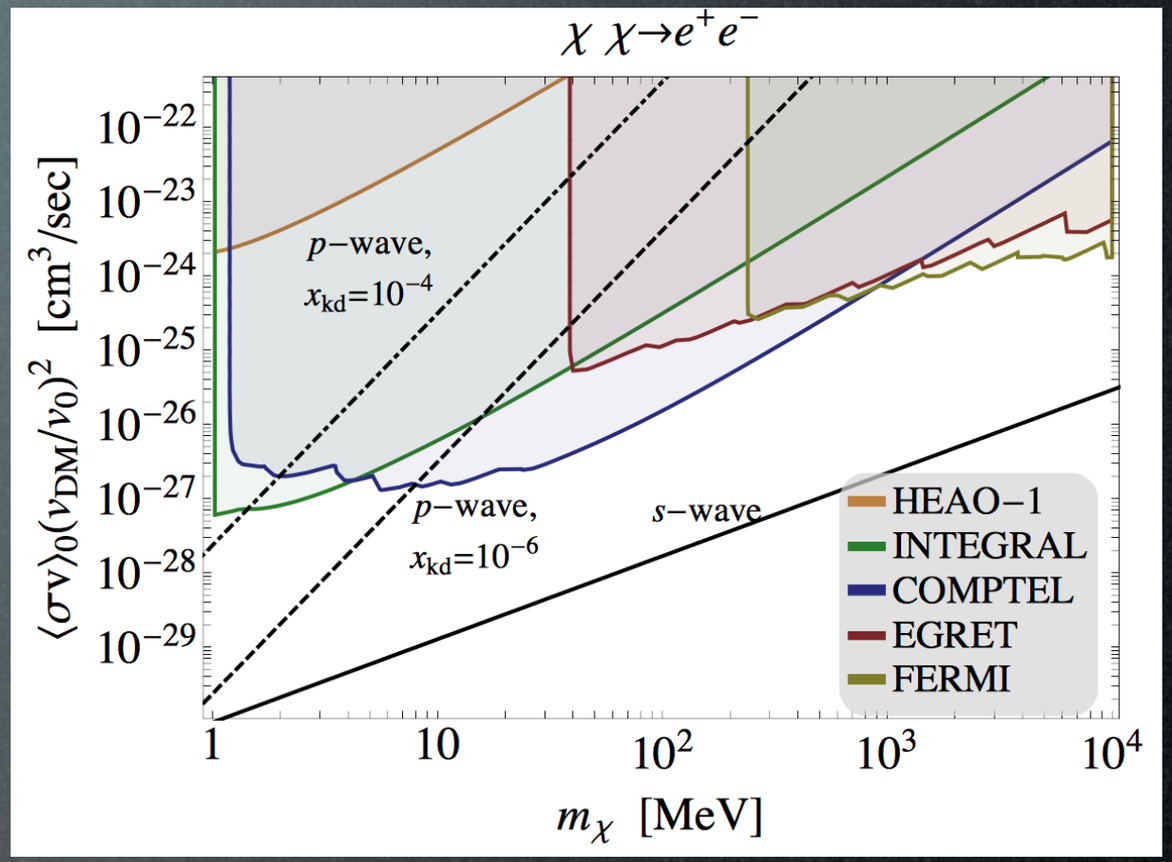
Amego?, COSI?

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

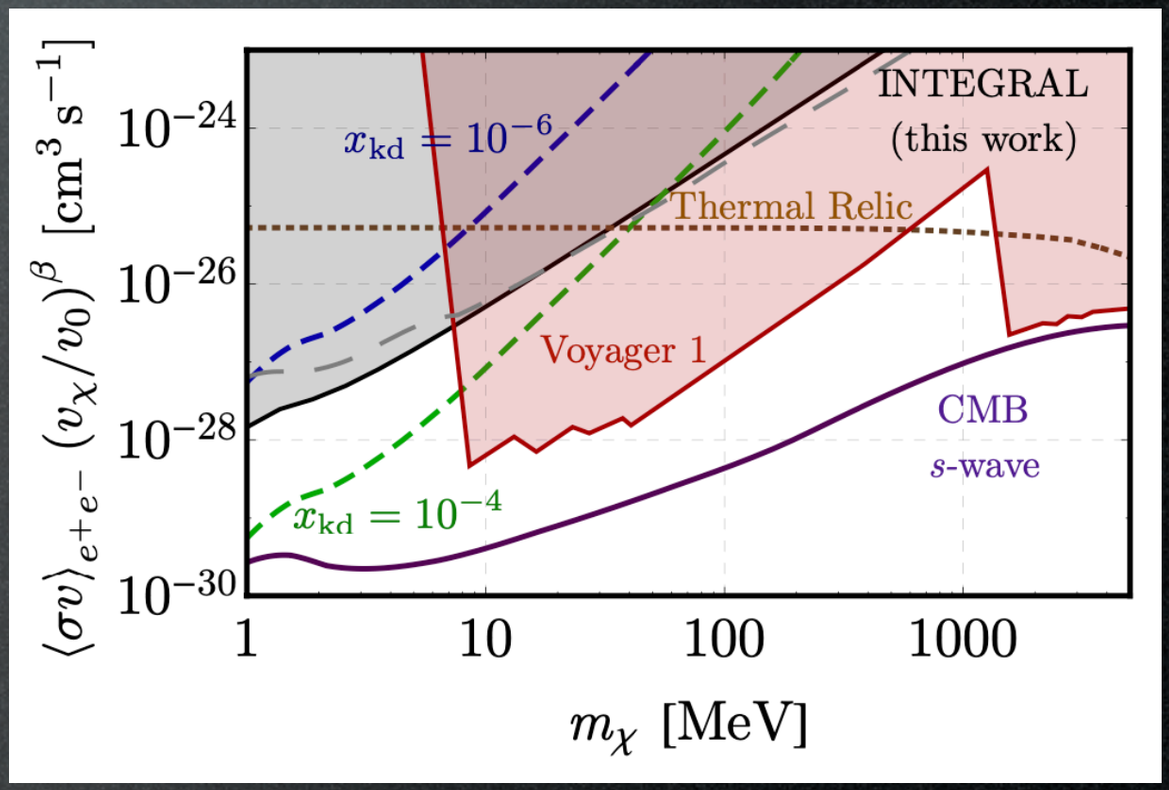
Cirelli, Strumia, Zupan 2406.01705

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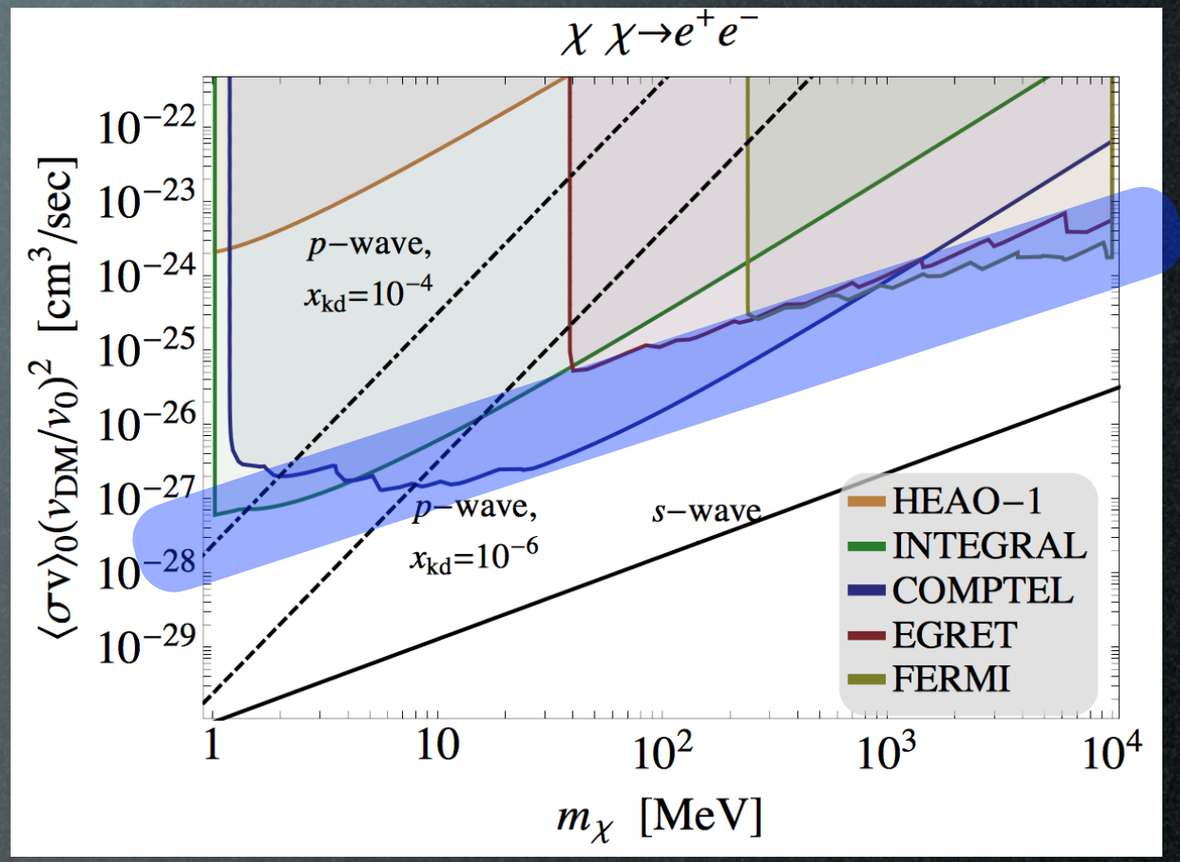
Essig, Kuflik, McDermott, Volansky et al., 1309.4091



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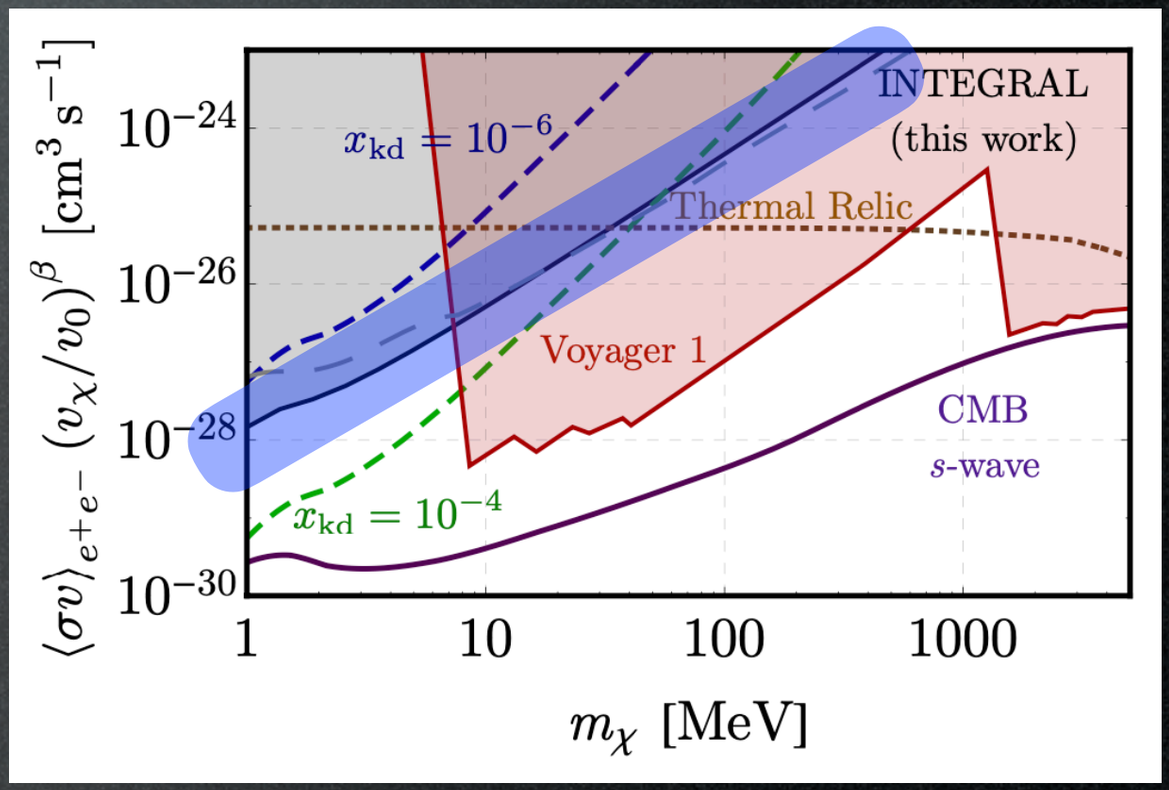
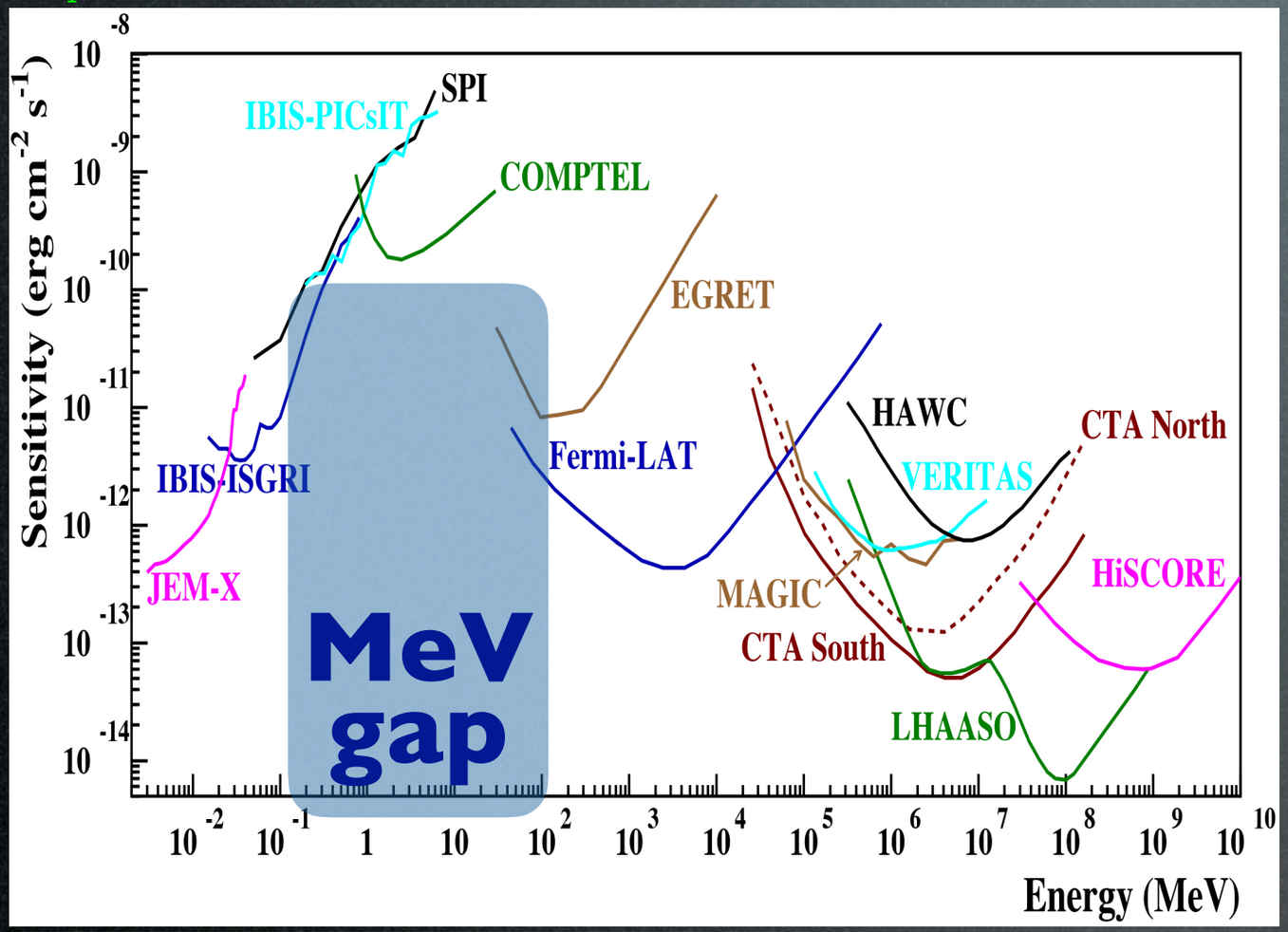


NB: ‘prompt’ emission only

Indirect detection: photons

adapted from 1611.02232



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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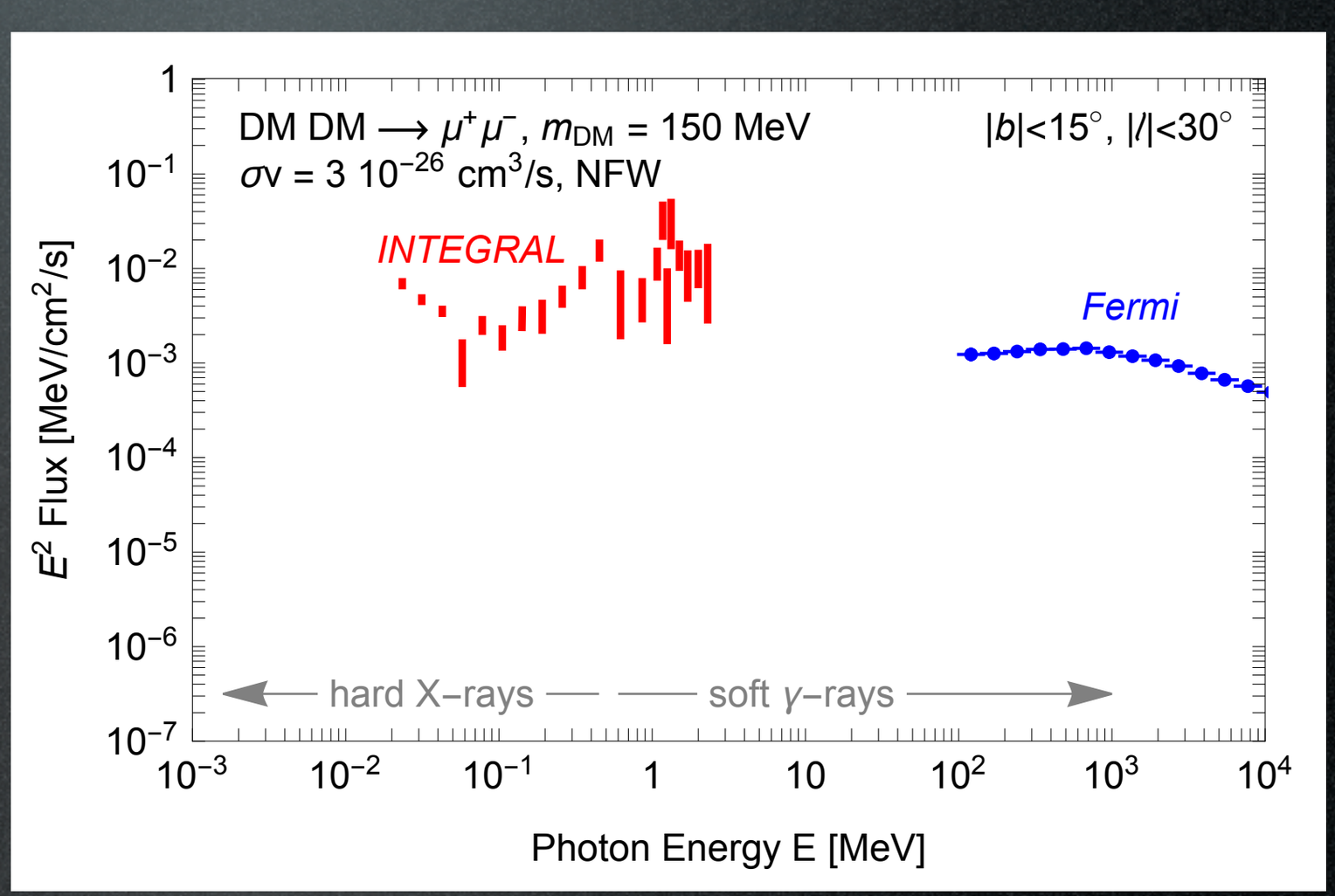

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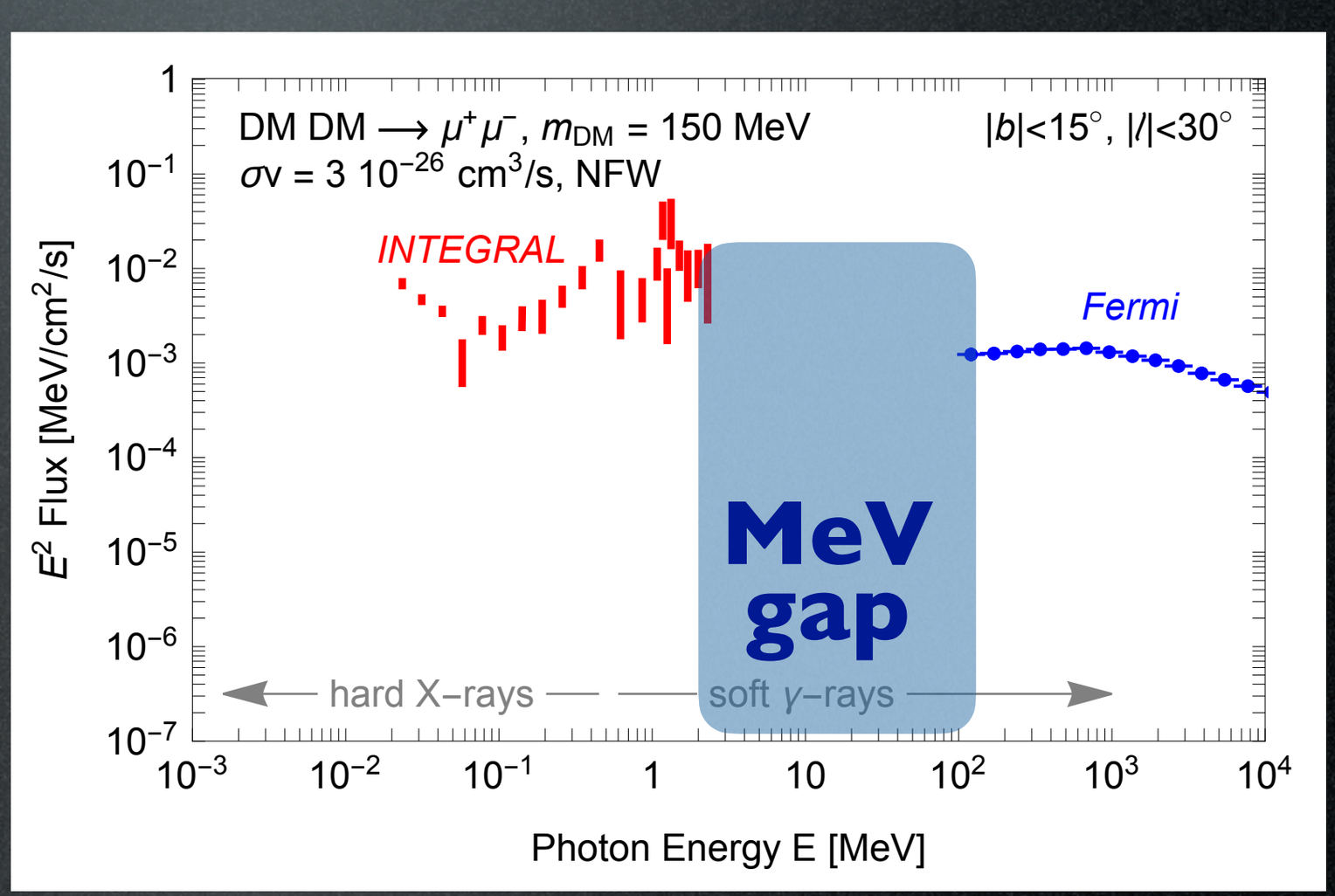

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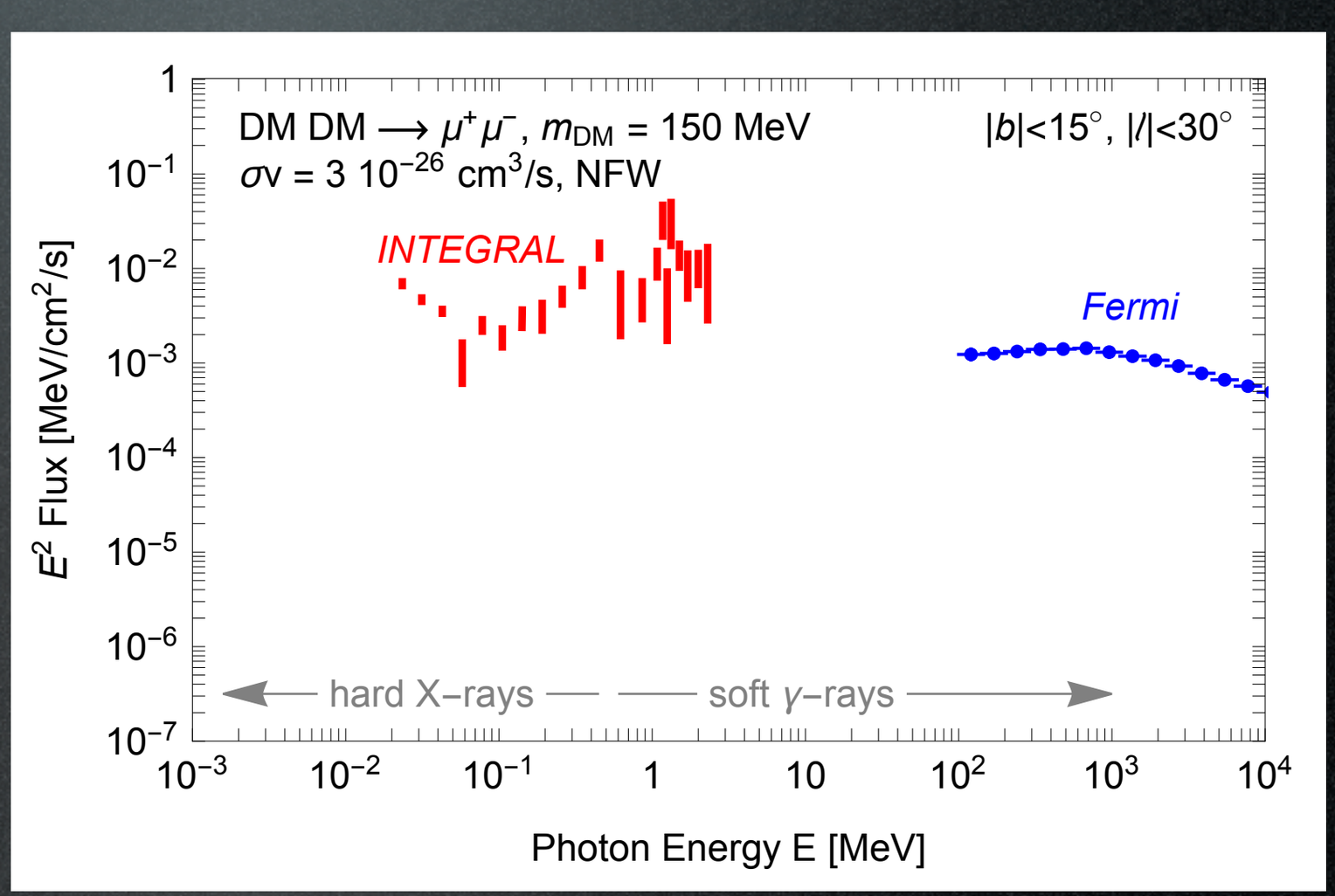

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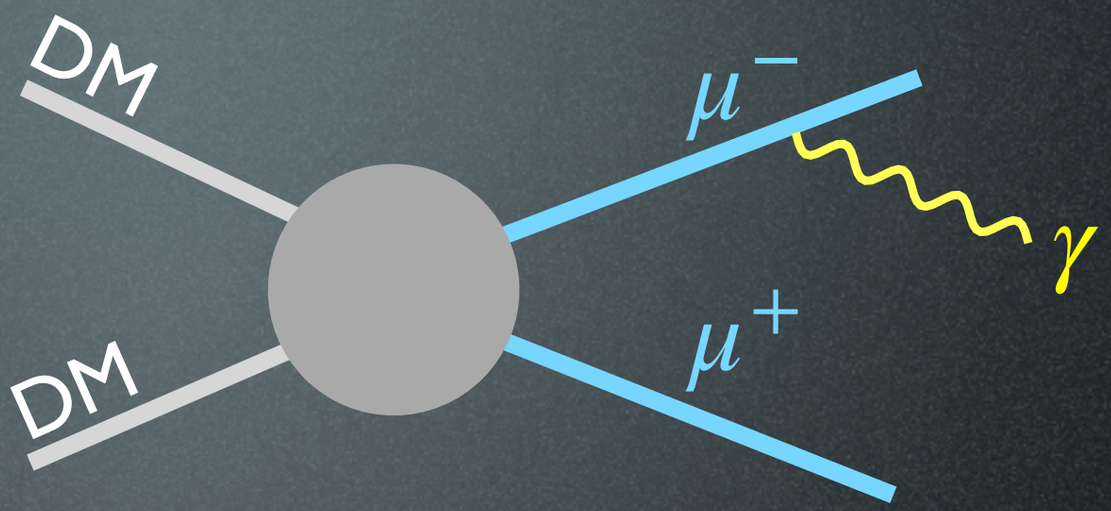
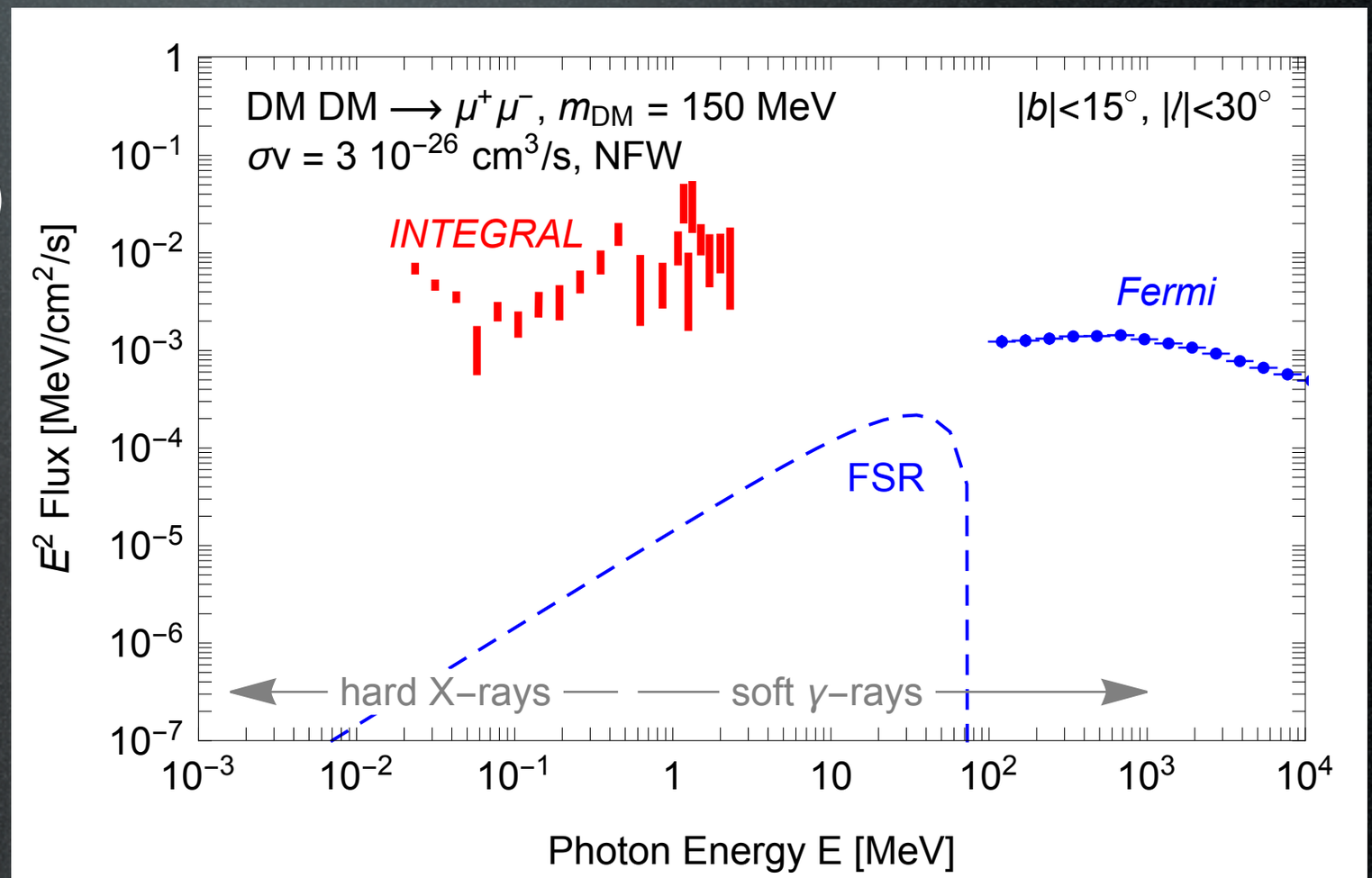


'Prompt' emission:

Final State Radiation (FSR)



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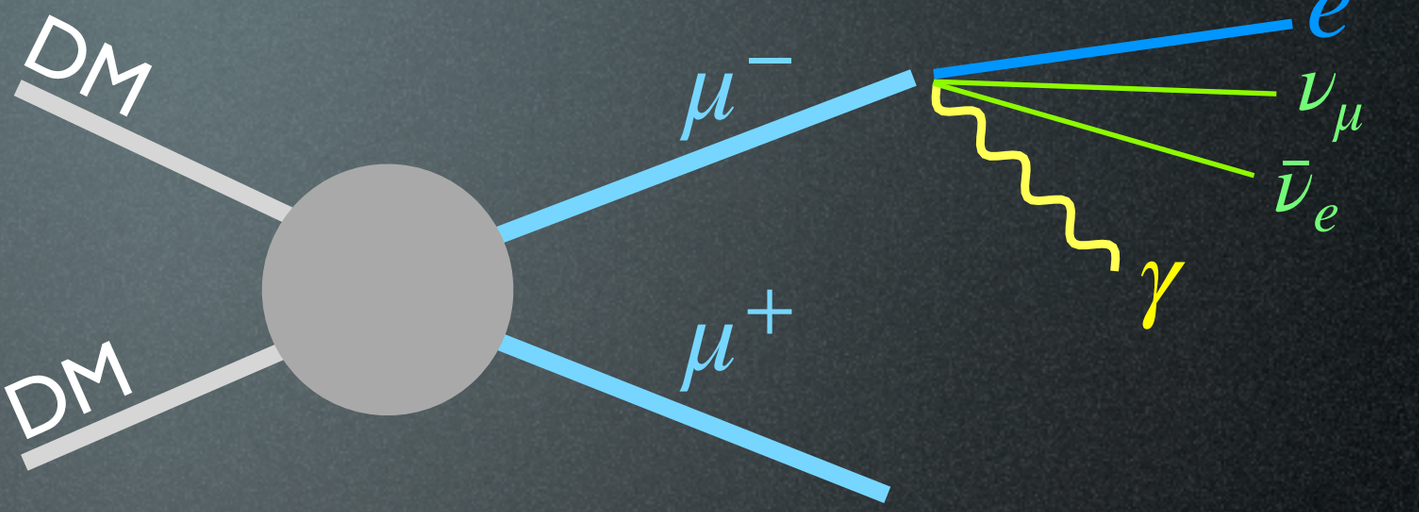
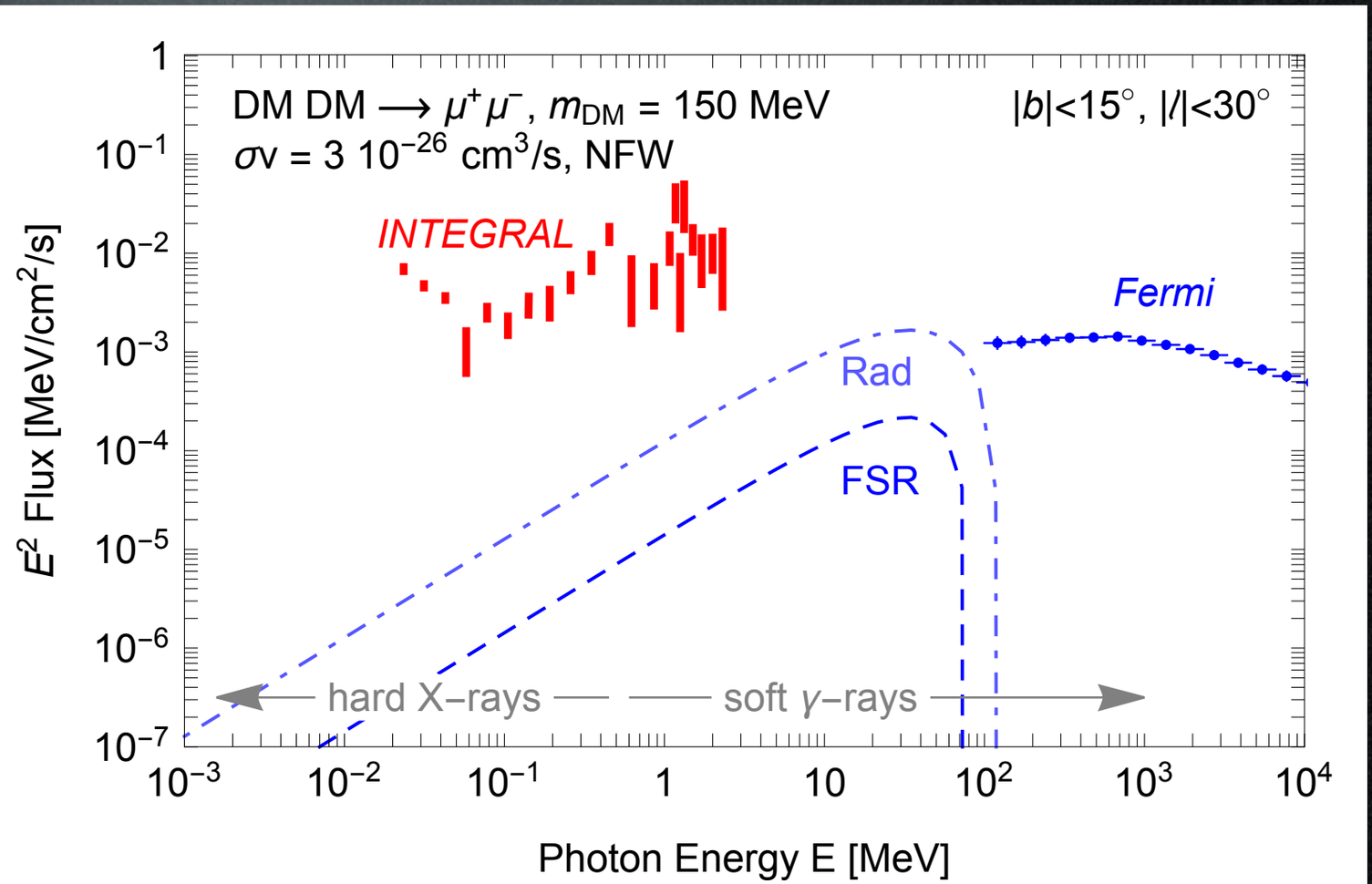


'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

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



Sub-GeV DM & X-rays

Annihilation channels

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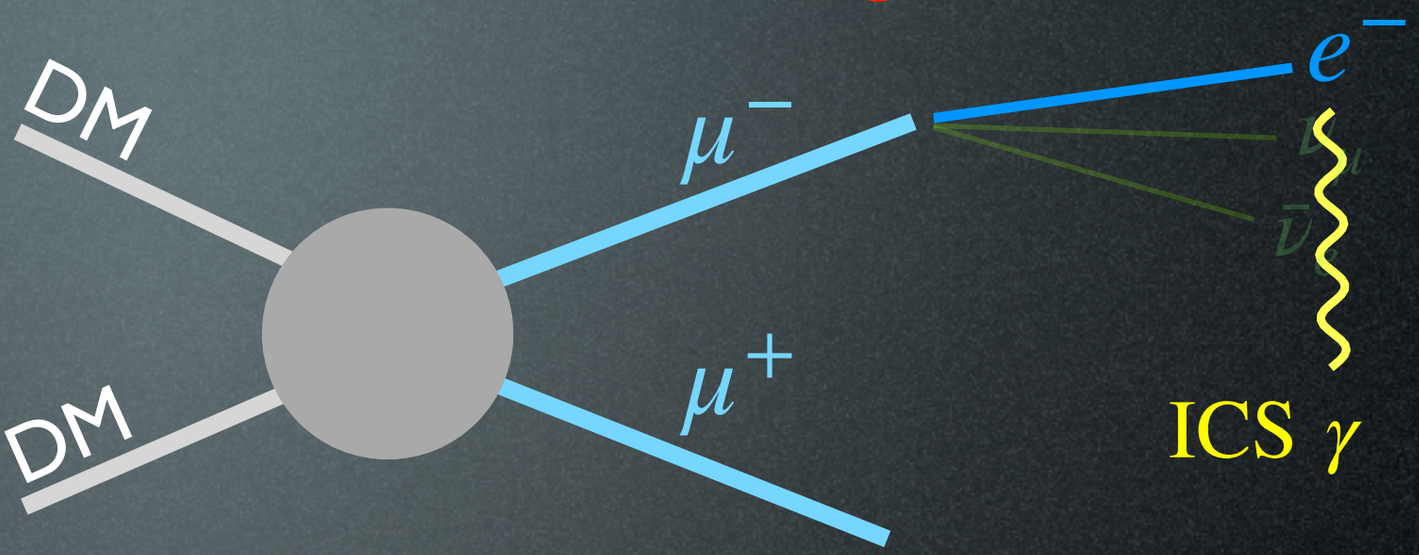


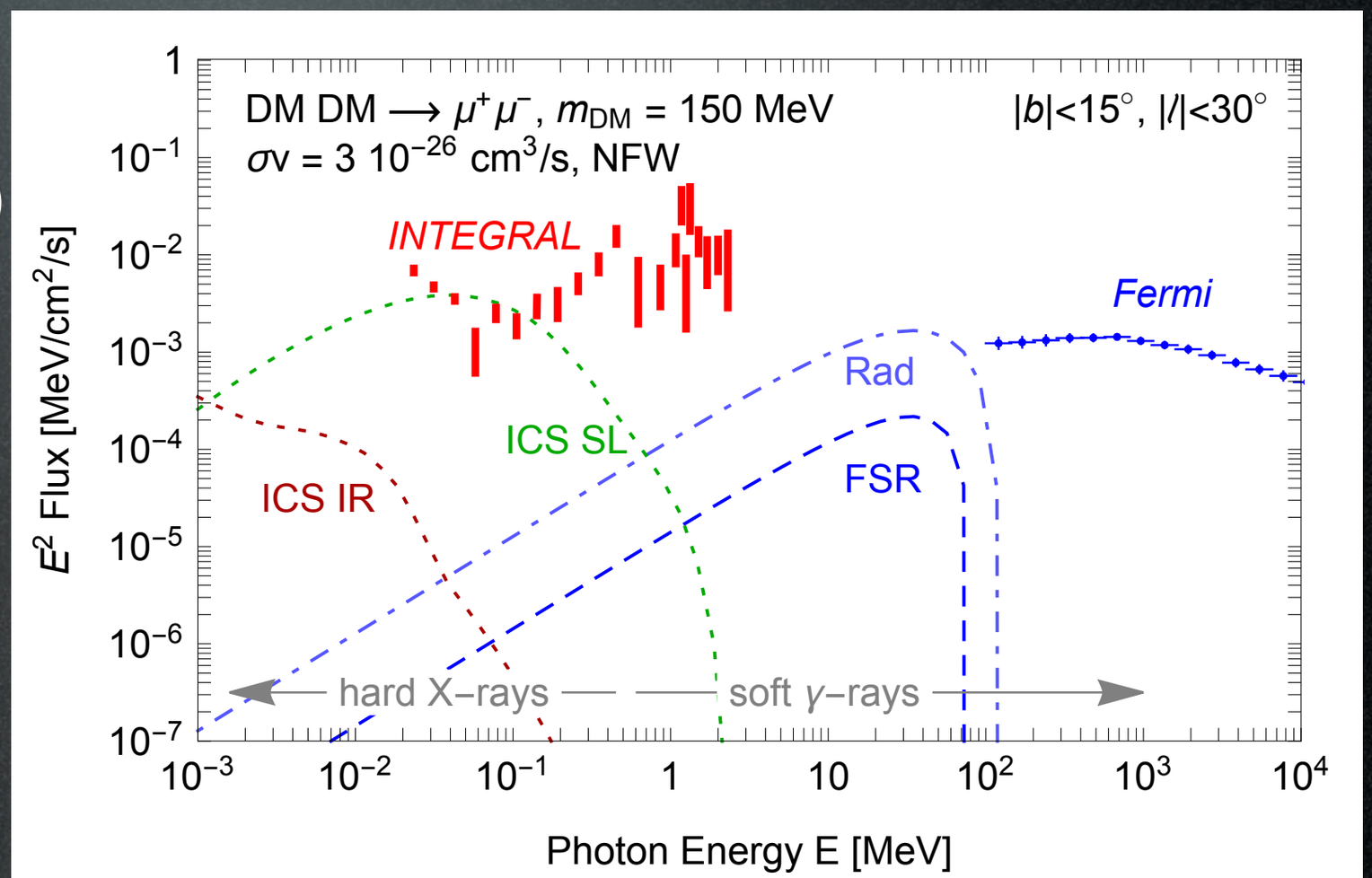
'Prompt' emission:

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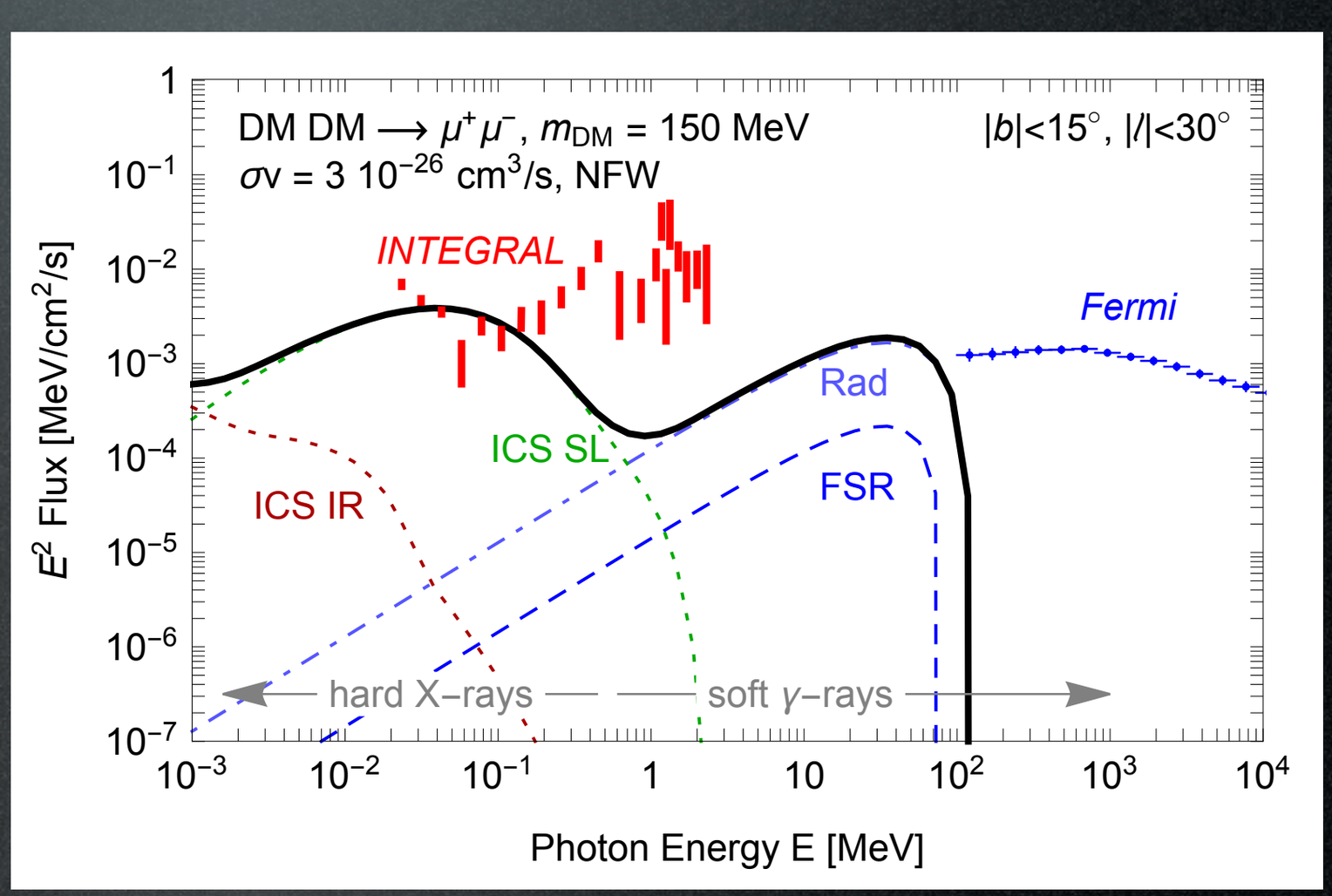
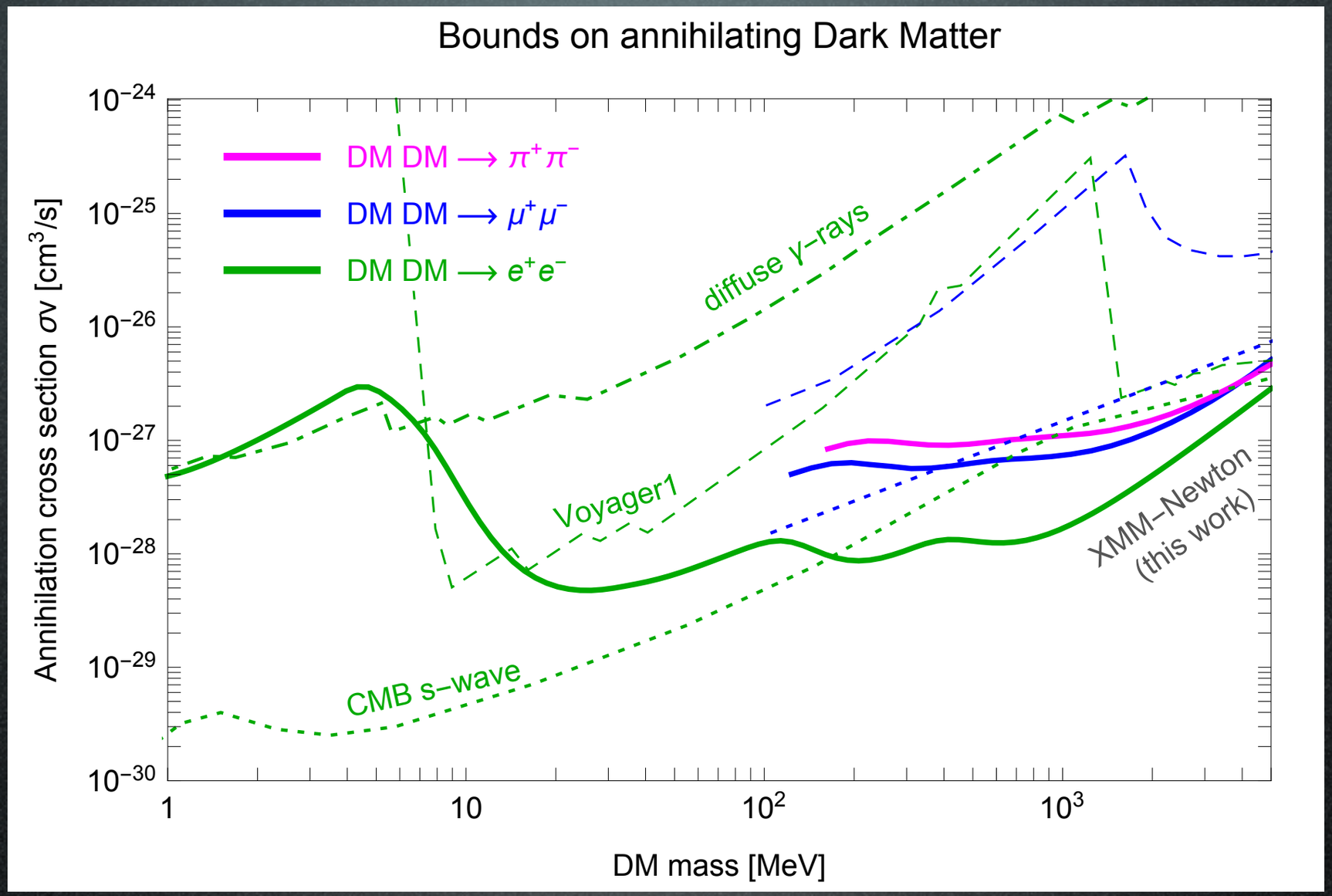
Key message:
ICS allows to probe sub-GeV DM with X-ray data



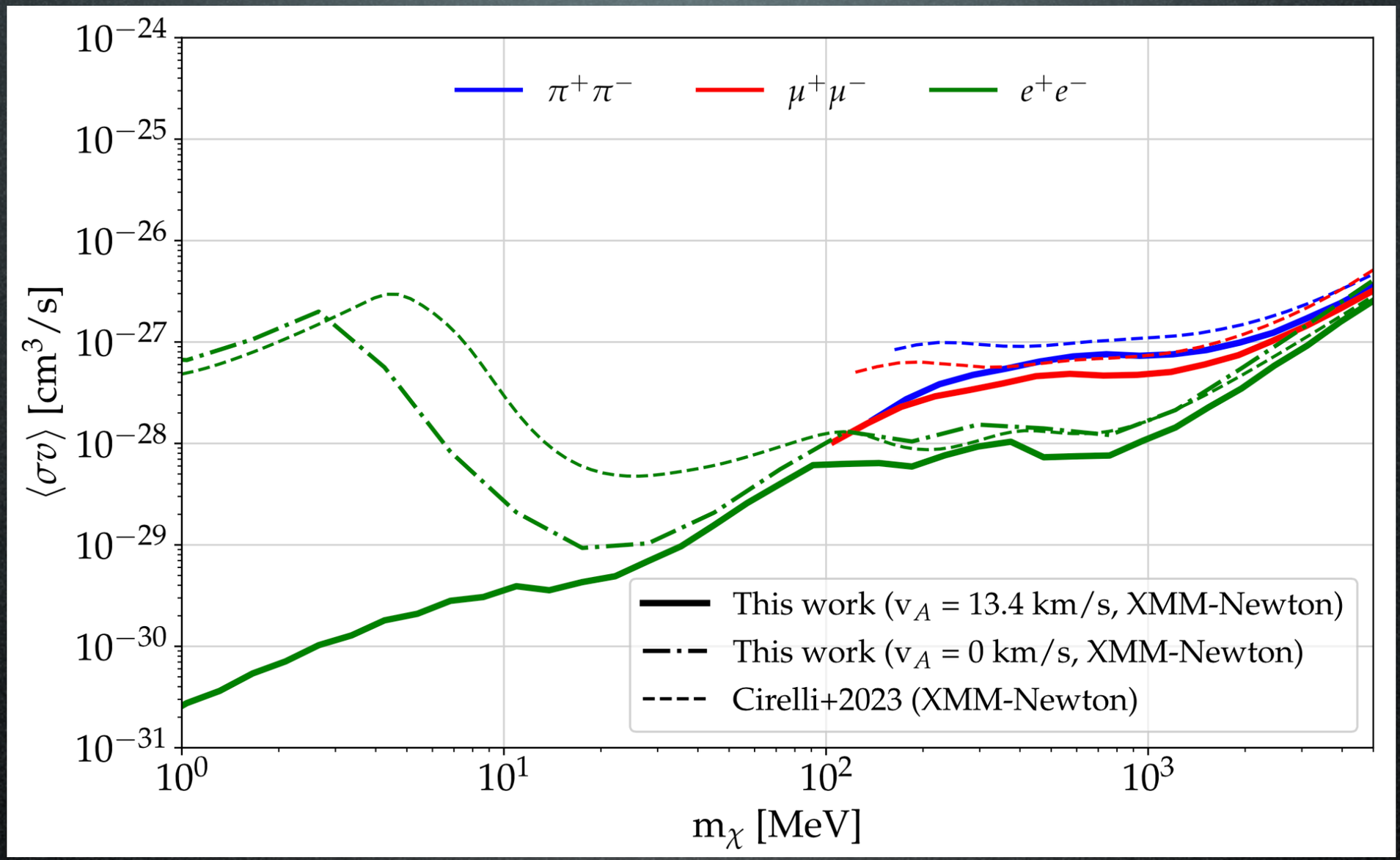
Results



Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Bounds on all 3 channels
ICS allows to vastly improve at large $m_{\rm DM}$
Deeper than the s-wave CMB bounds

Results



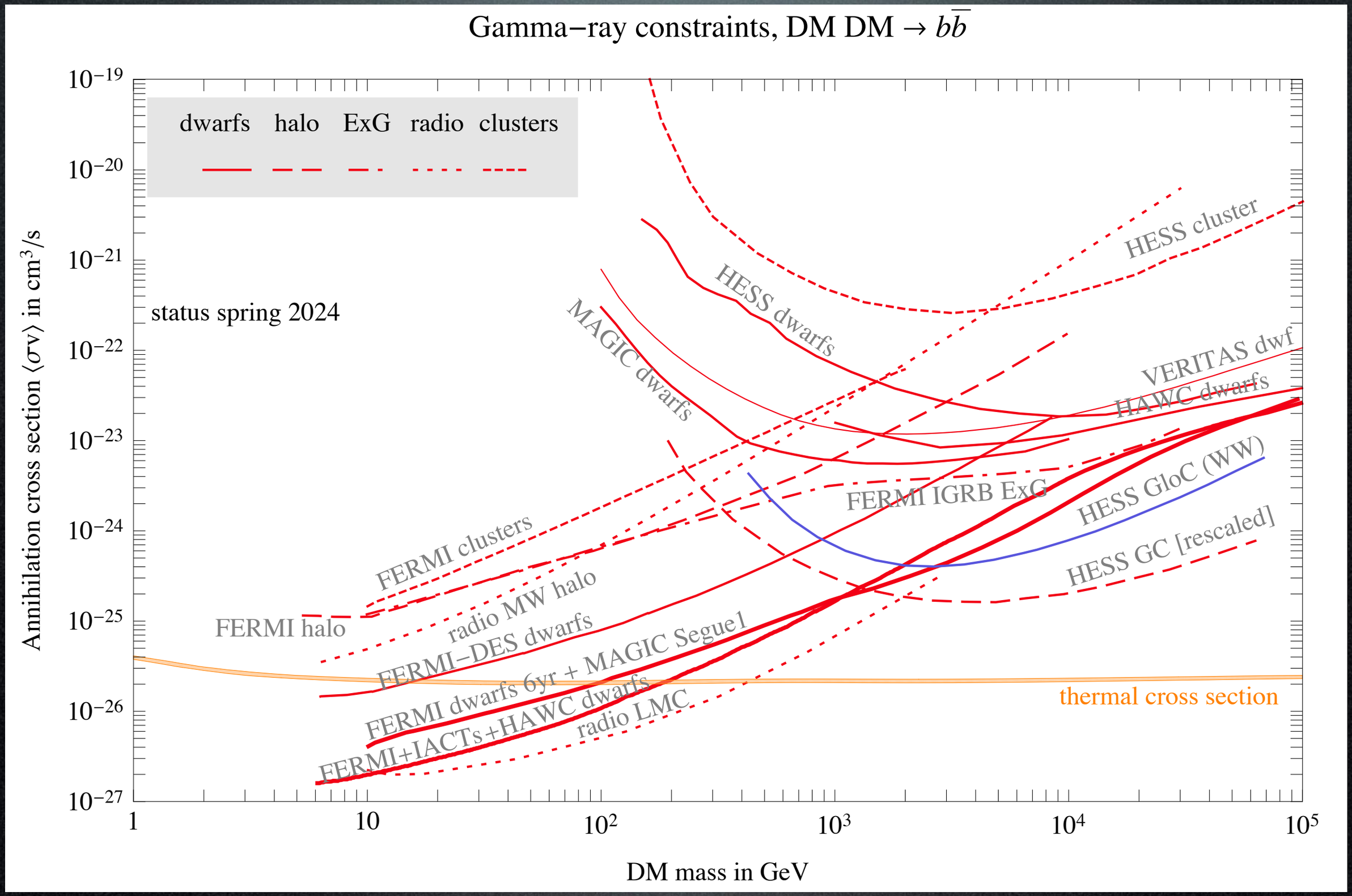
De La Torre Luque, Balaji, Koechler 2311.04979

Updated with a refined propagation (incl reacceleration)

Comparing all bounds

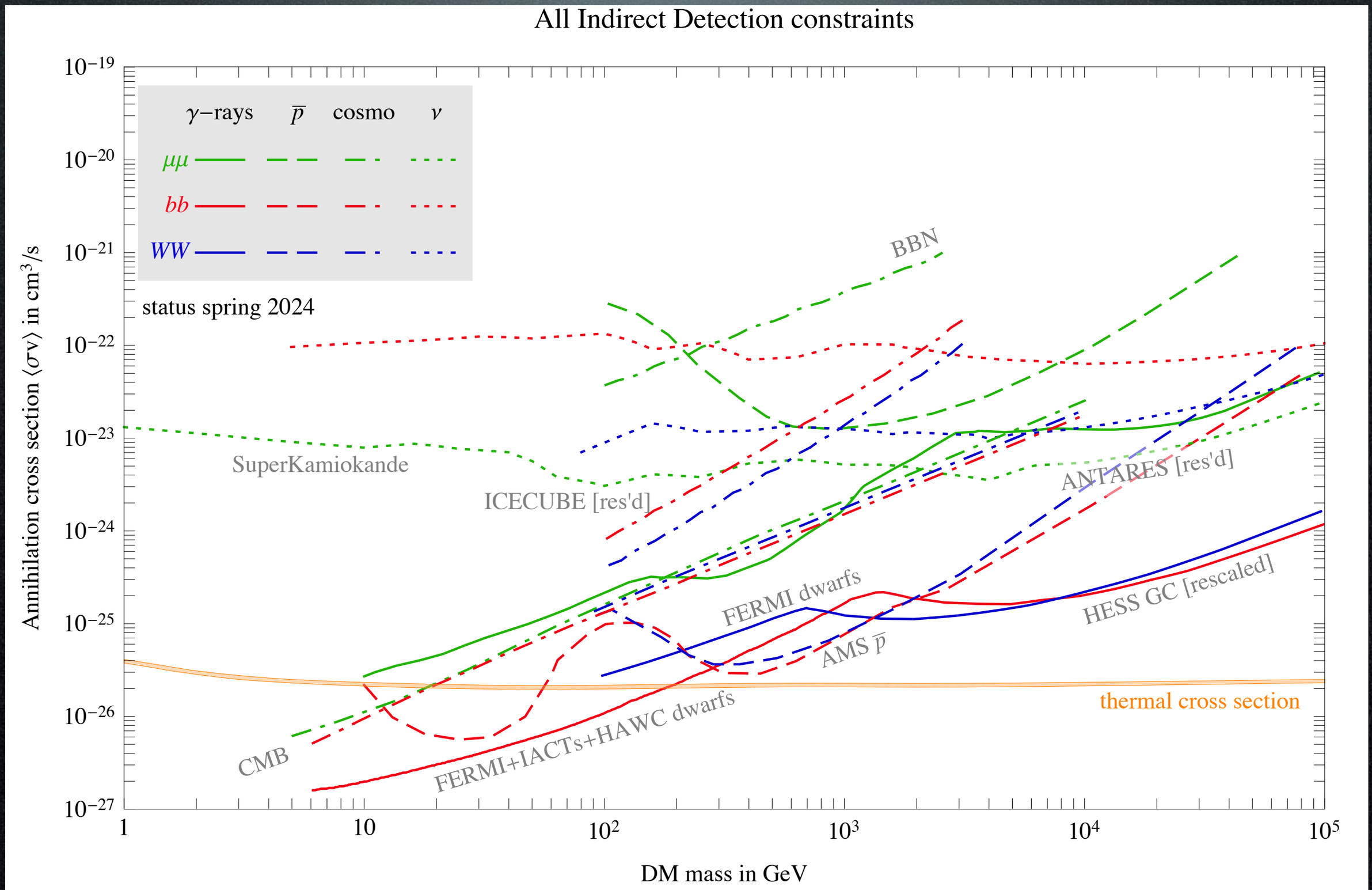
M. Cirelli, A. Strumia, J. Zupan 2406.01705

Comparing all bounds



M. Cirelli, A. Strumia, J. Zupan 2406.01705

Comparing all bounds



M. Cirelli, A. Strumia, J. Zupan 2406.01705

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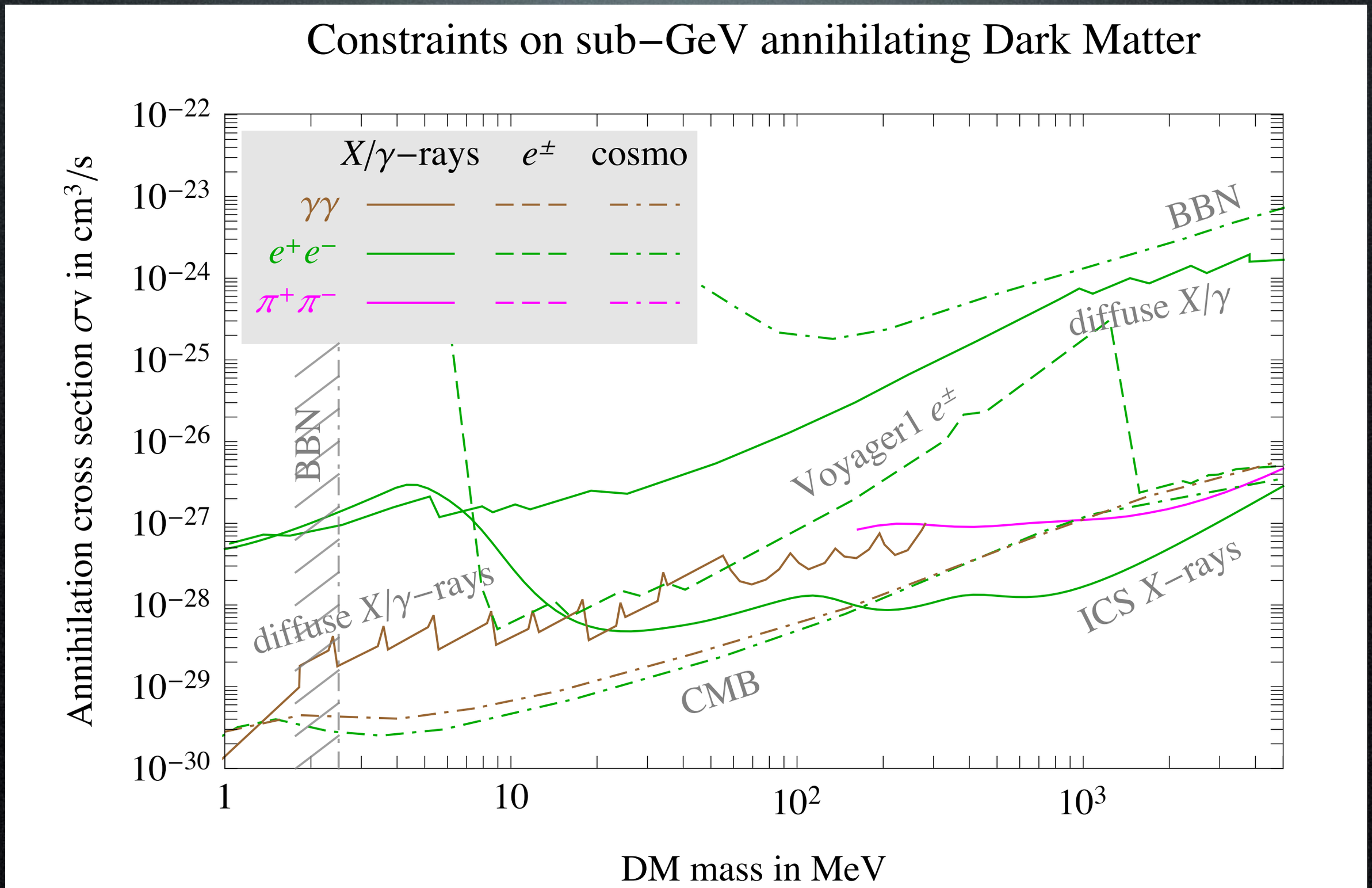

M. Cirelli, A. Strumia, J. Zupan 2406.01705

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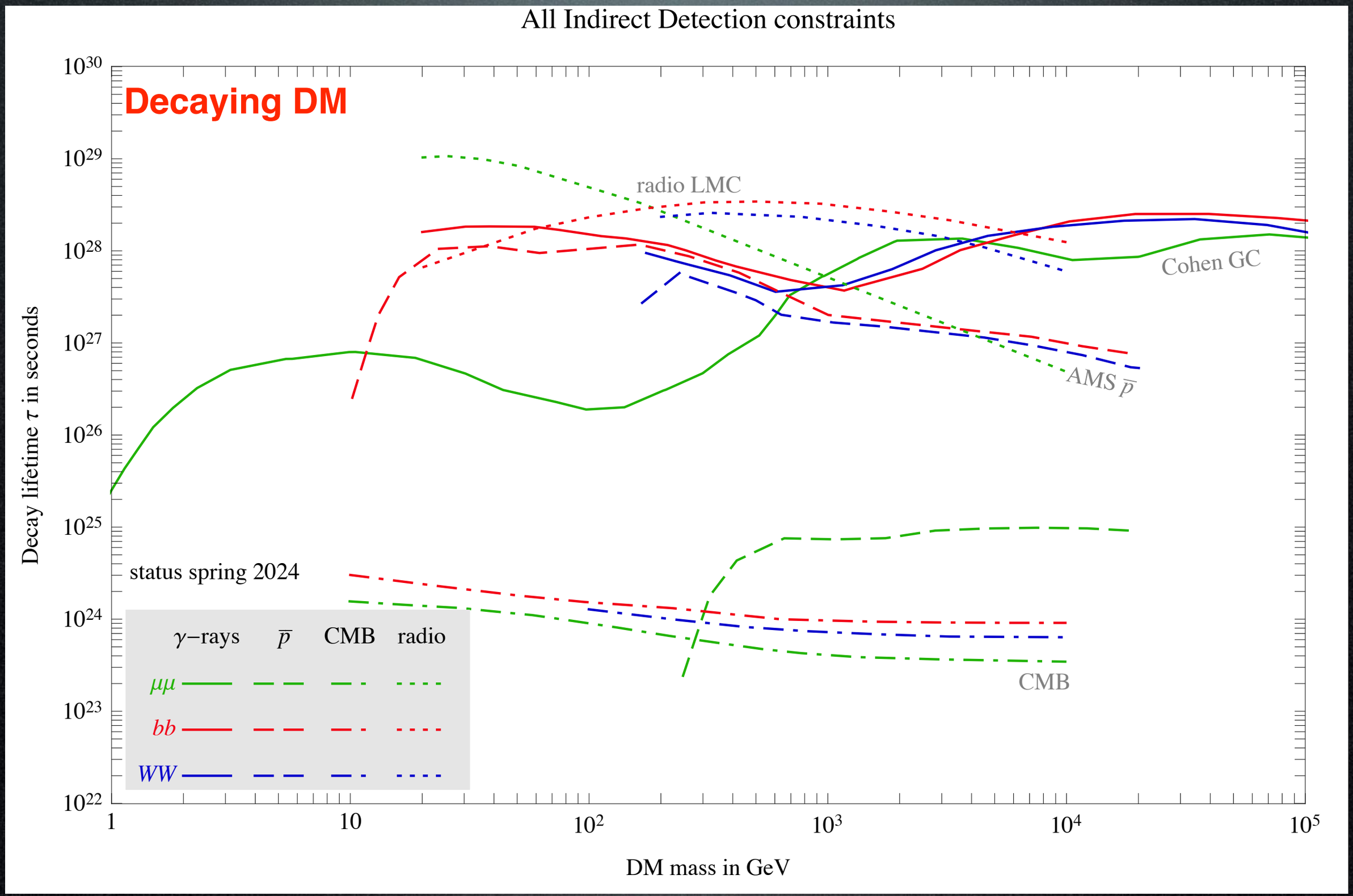
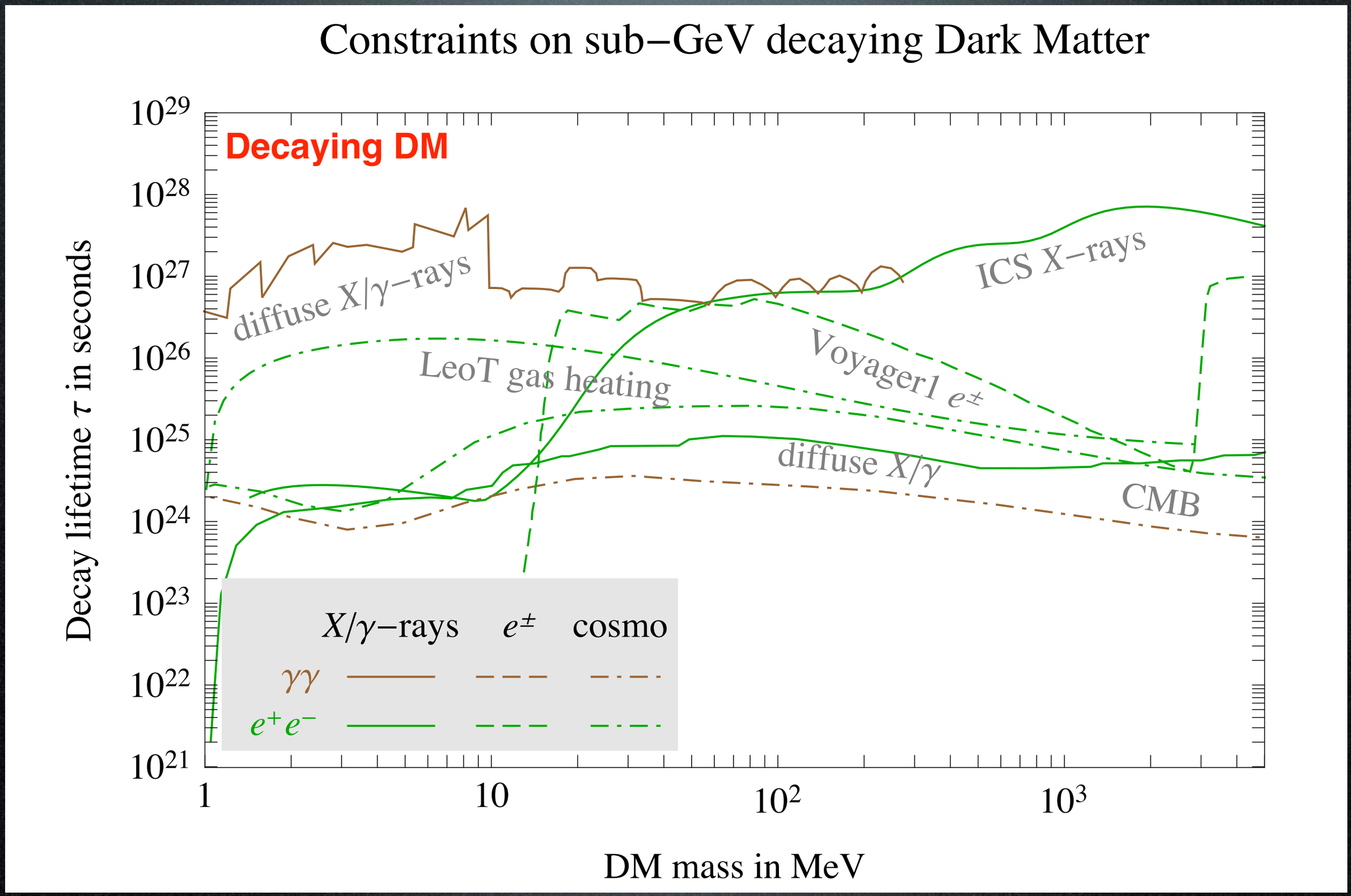


M. Cirelli, A. Strumia, J. Zupan 2406.01705

Comparing all bounds



M. Cirelli, A. Strumia, J. Zupan 2406.01705

Conclusions

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DM not seen yet (Damn!...)

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ID with cosmic rays is in principle
a very powerful tool

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DM not seen yet (Damn!...)

ID with 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 γ: astrophysical background
in $\bar{d}$: challenging flux
in $\overline{He}$: hopeless? who knows...