

20 July 2023  
SUSY 2023 - Southampton

# Dark Matter Indirect Searches as of 2023

Marco Cirelli  
(CNRS LPTHE Jussieu)



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*Selected topics in...*

# Dark Matter Indirect Searches as of 2023

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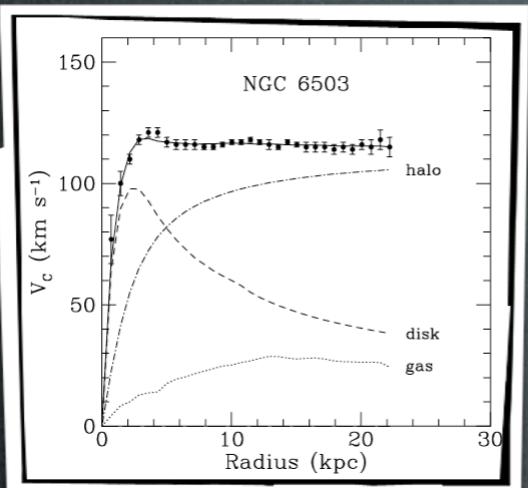


# Introduction

DM exists

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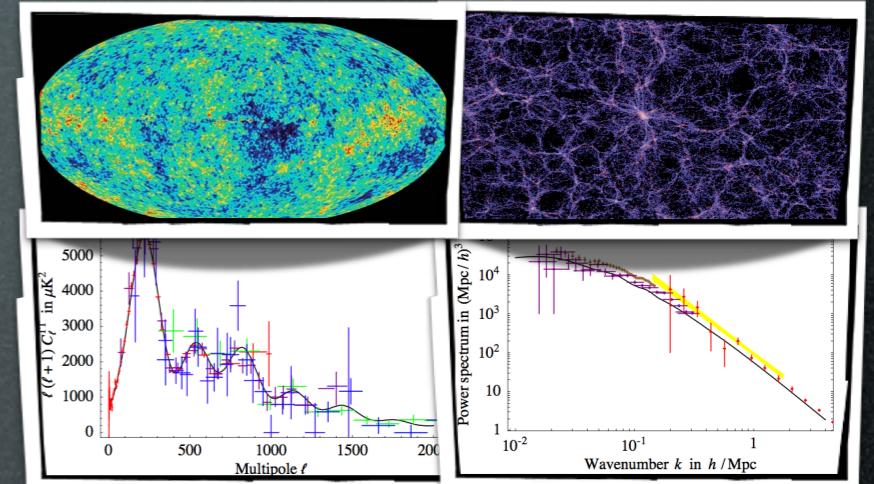
DM exists



galactic rotation curves



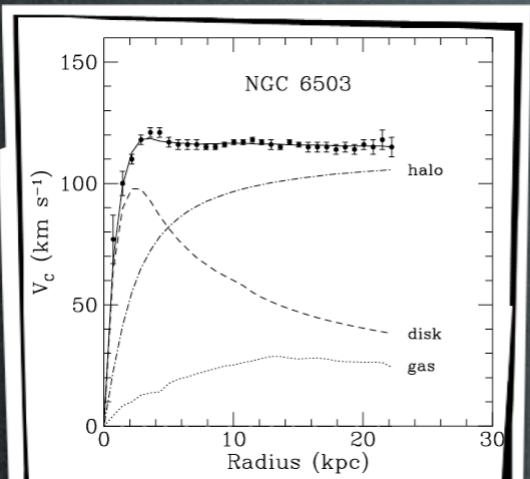
weak lensing (e.g. in clusters)



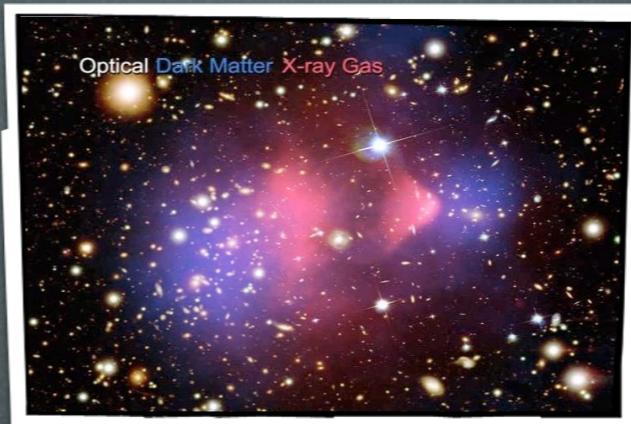
'precision cosmology' (CMB, LSS)

# Introduction

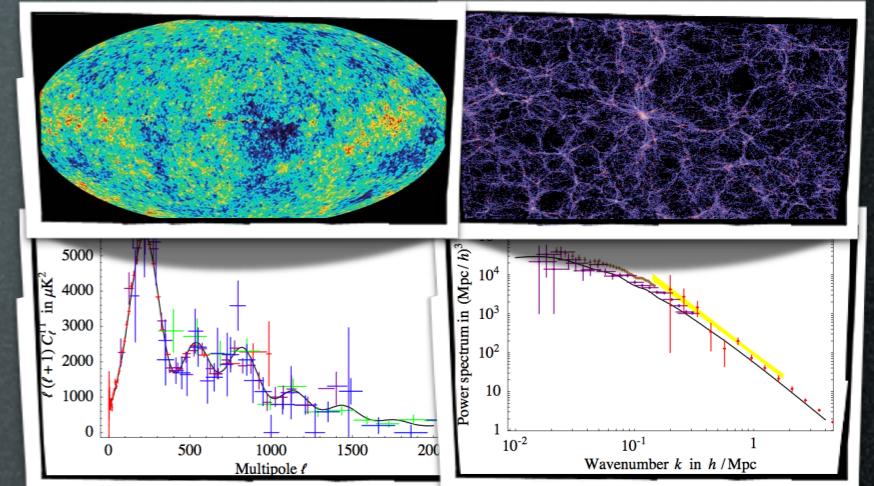
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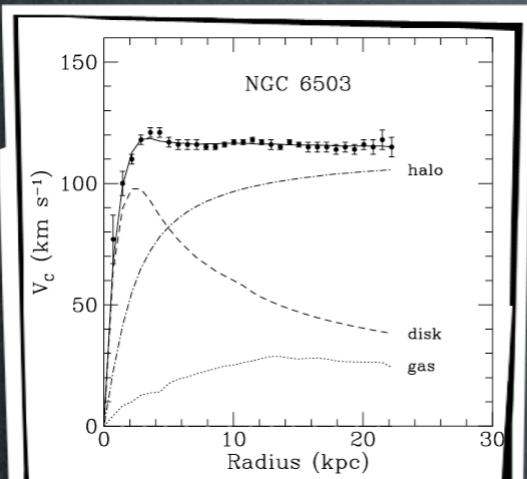


'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived,  
feebley- interacting corpuscle.

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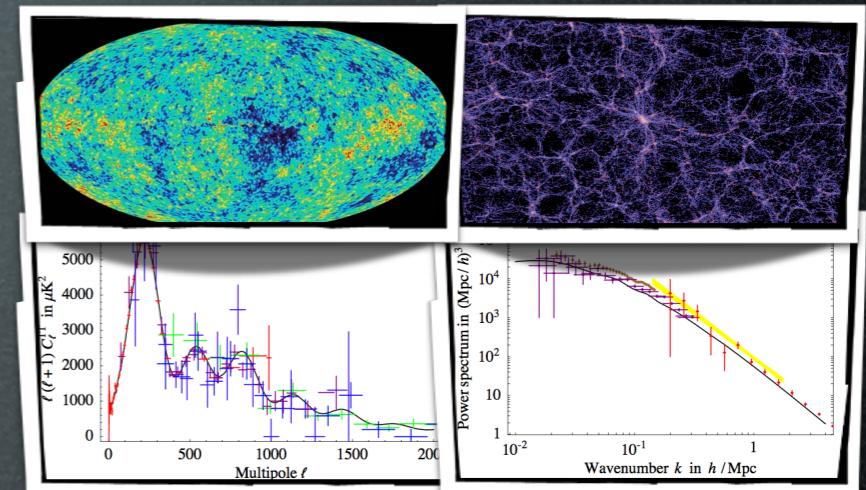
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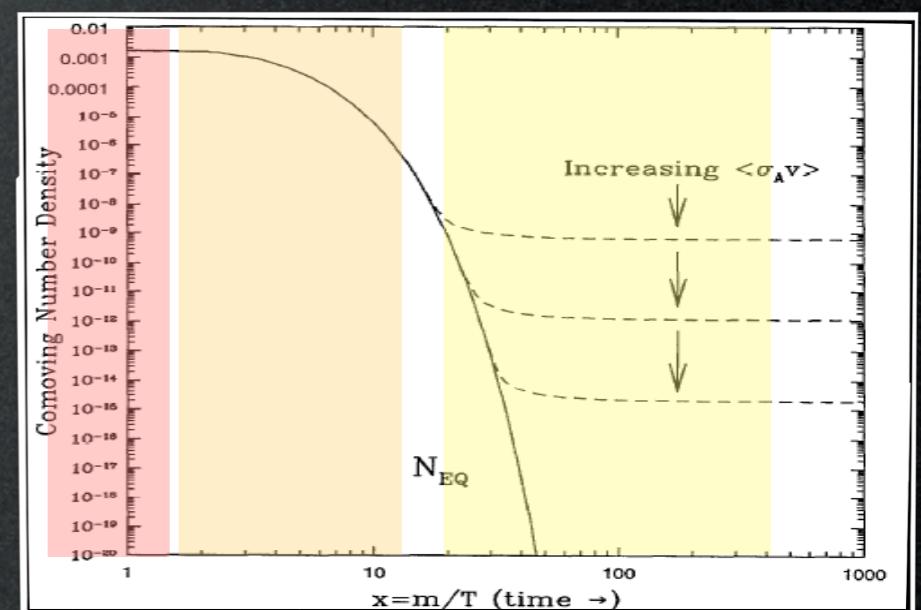


'precision cosmology' (CMB, LSS)

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

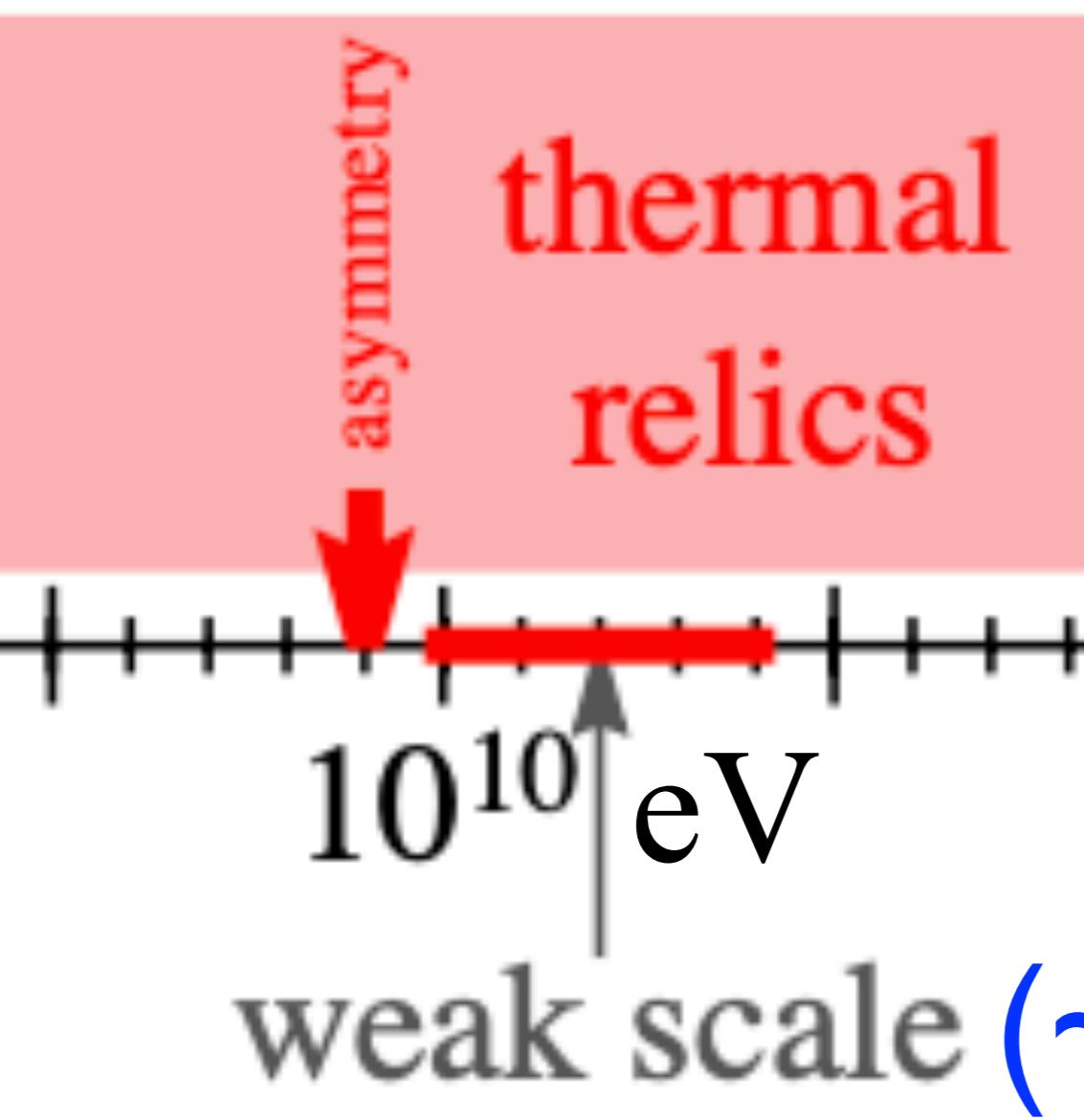
Some of us believe in  
the WIMP miracle.

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



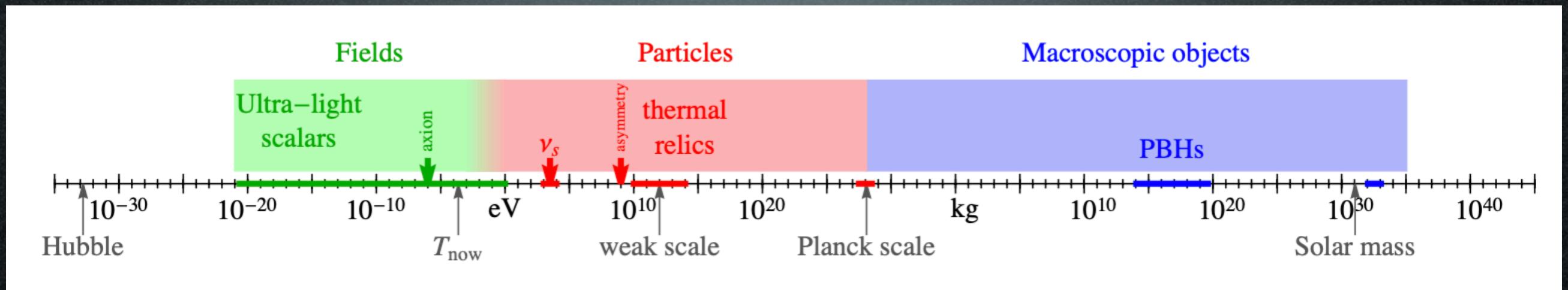
# Candidates

## Particles



# Candidates

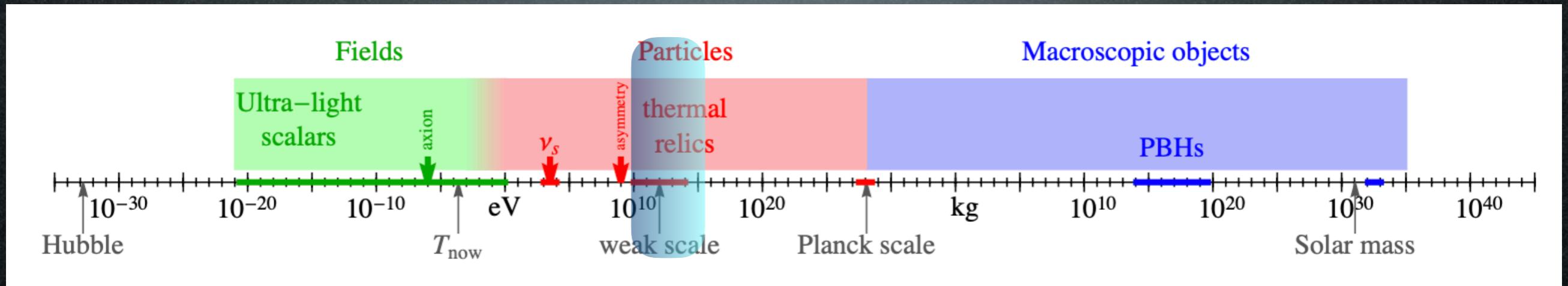
A matter of perspective: plausible mass ranges



90 orders of magnitude!

# Candidates

A matter of perspective: plausible mass ranges



# Candidates

WIMPs

# Candidates

new physics at  
the TeV scale

thermal  
freeze-out

WIMPs



# Candidates

new physics at  
the TeV scale

thermal  
freeze-out

WIMPs

Collider  
Searches

Indirect  
Detection

Direct  
Detection

# Candidates

new physics at  
the TeV scale

thermal  
freeze-out

WIMPs

Collider  
Searches

Indirect  
Detection

Direct  
Detection

# DM detection

direct detection

production at colliders

- indirect
  - $\gamma$  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

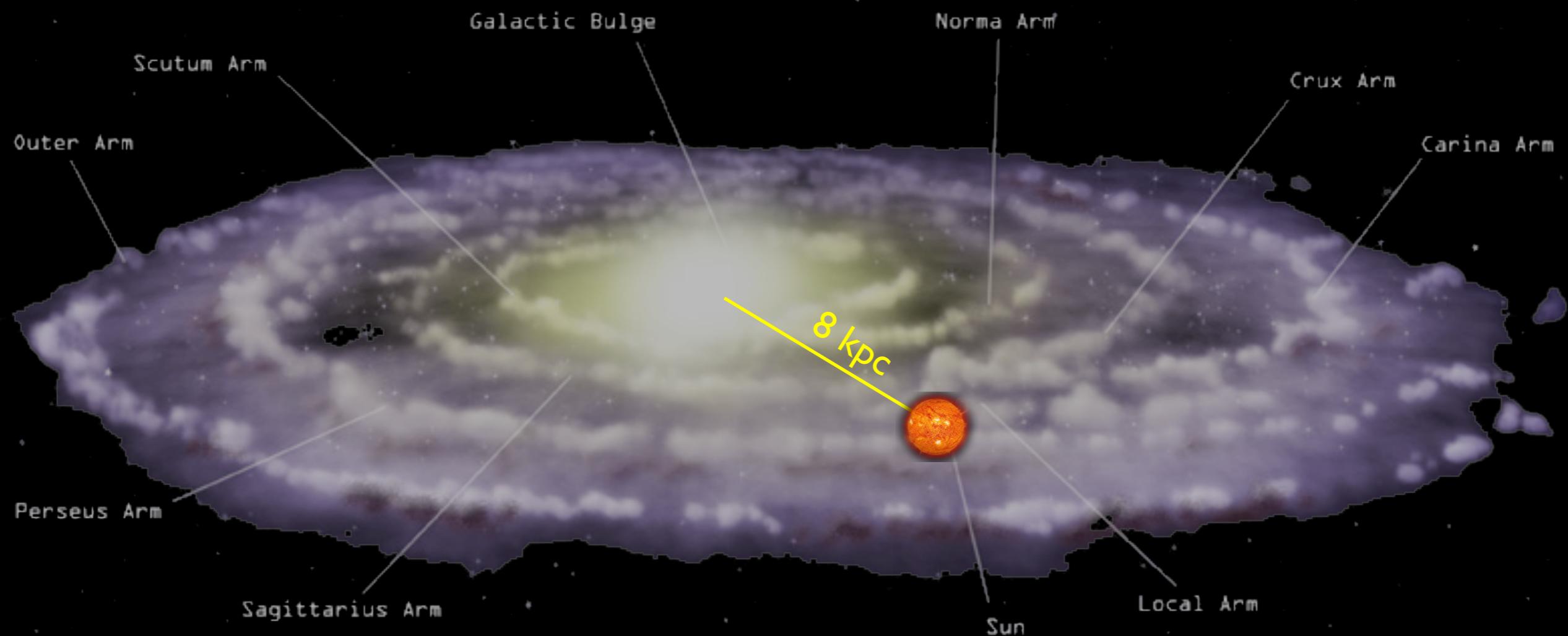
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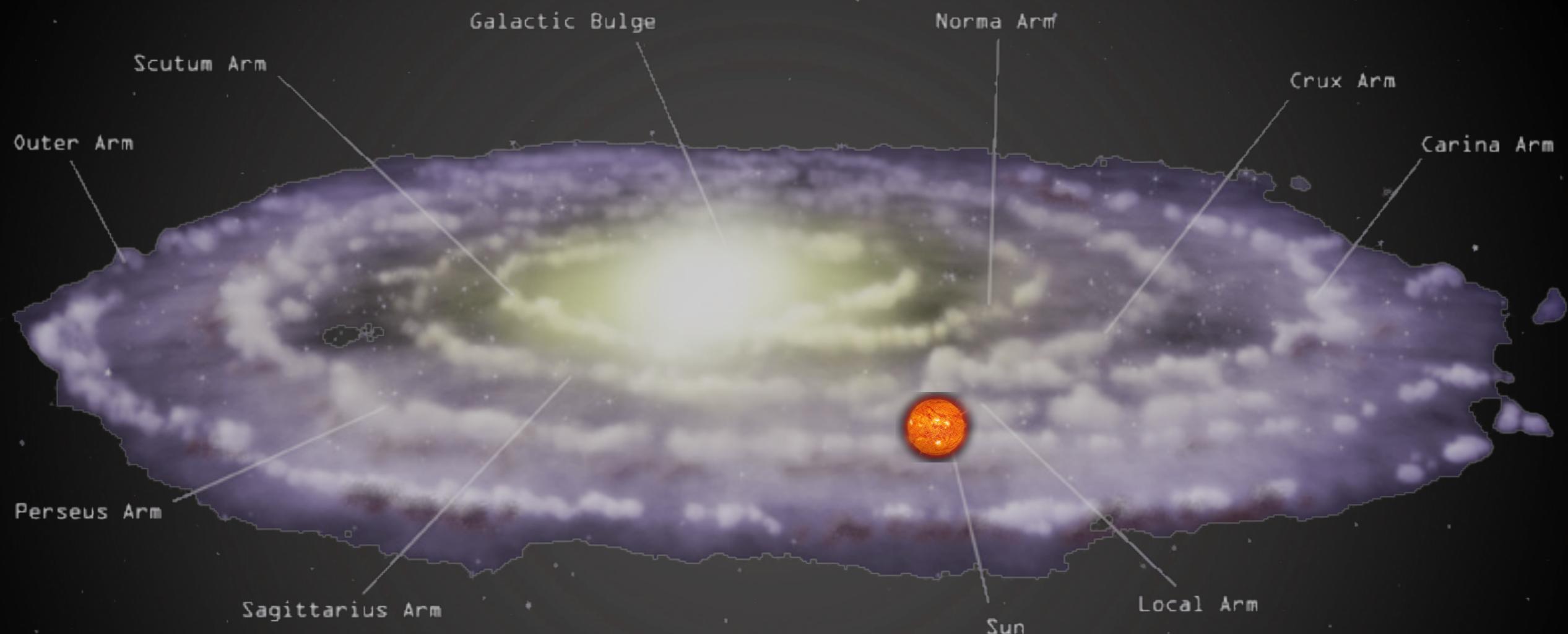
# Indirect Detection: charged CRs

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



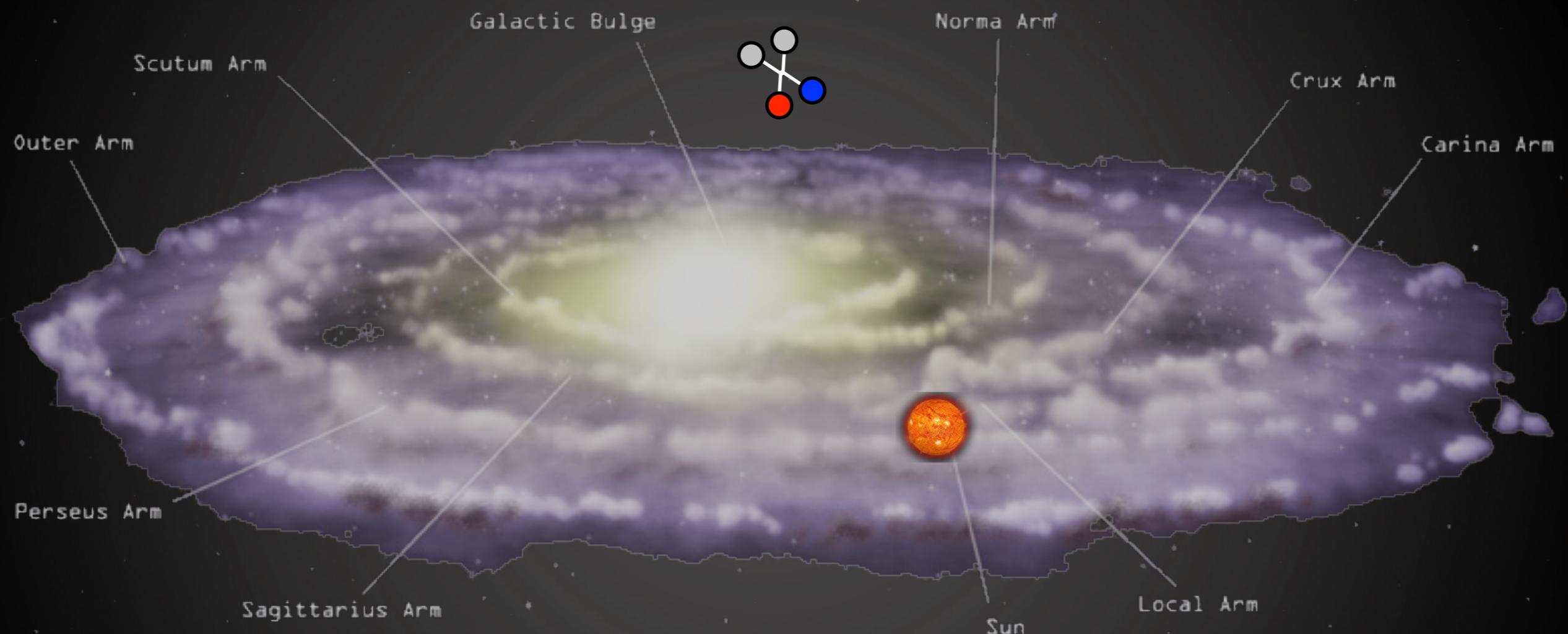
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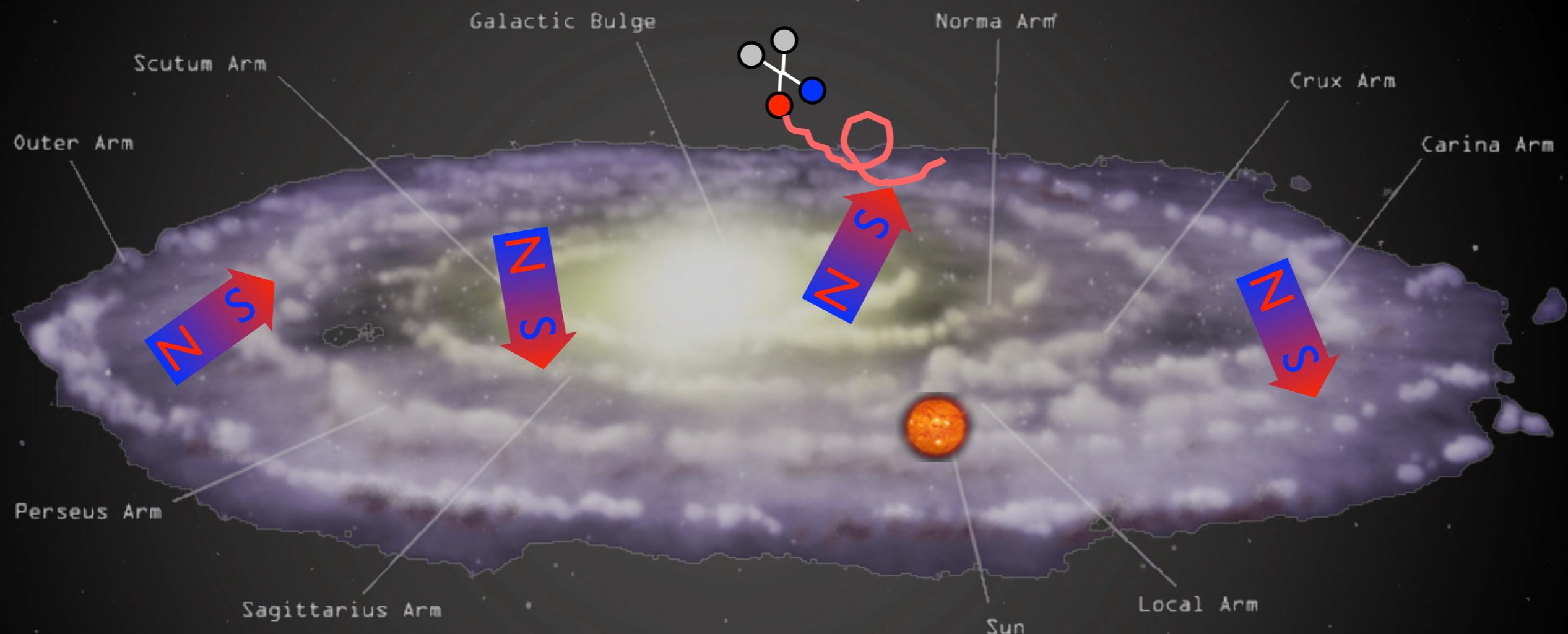
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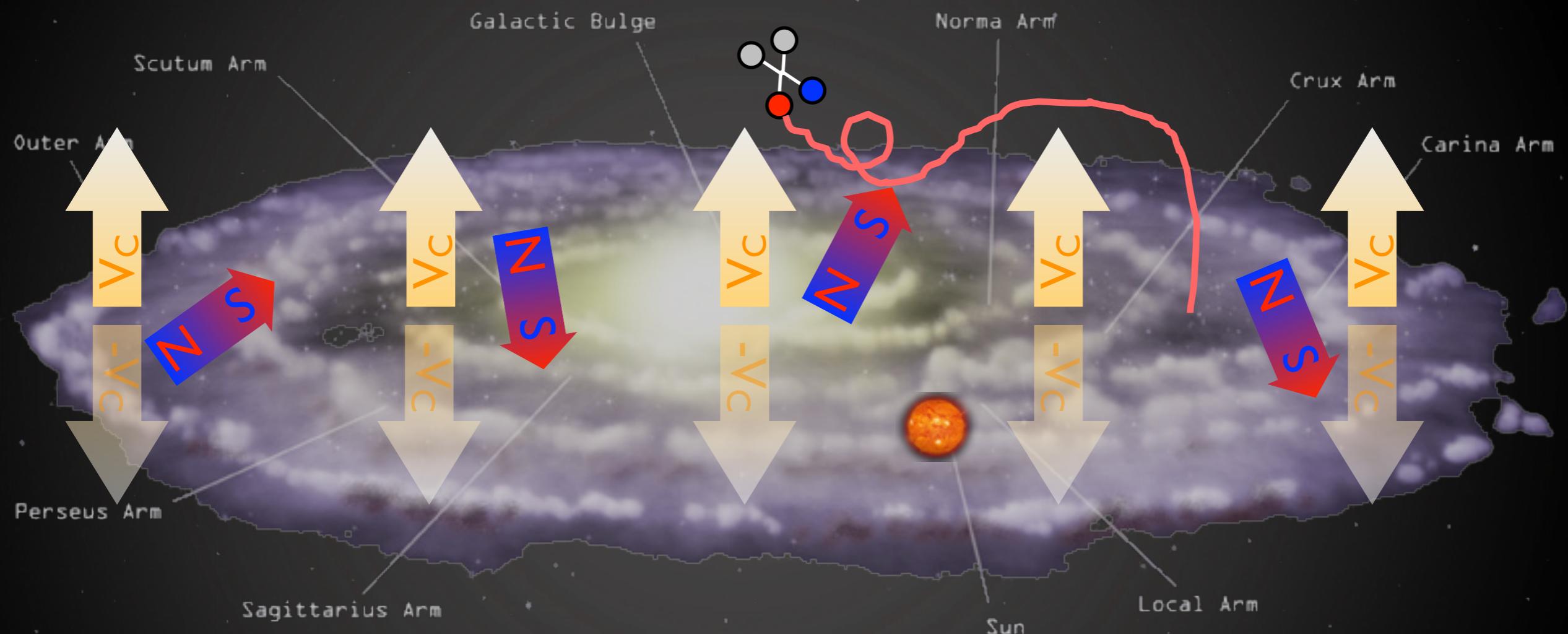
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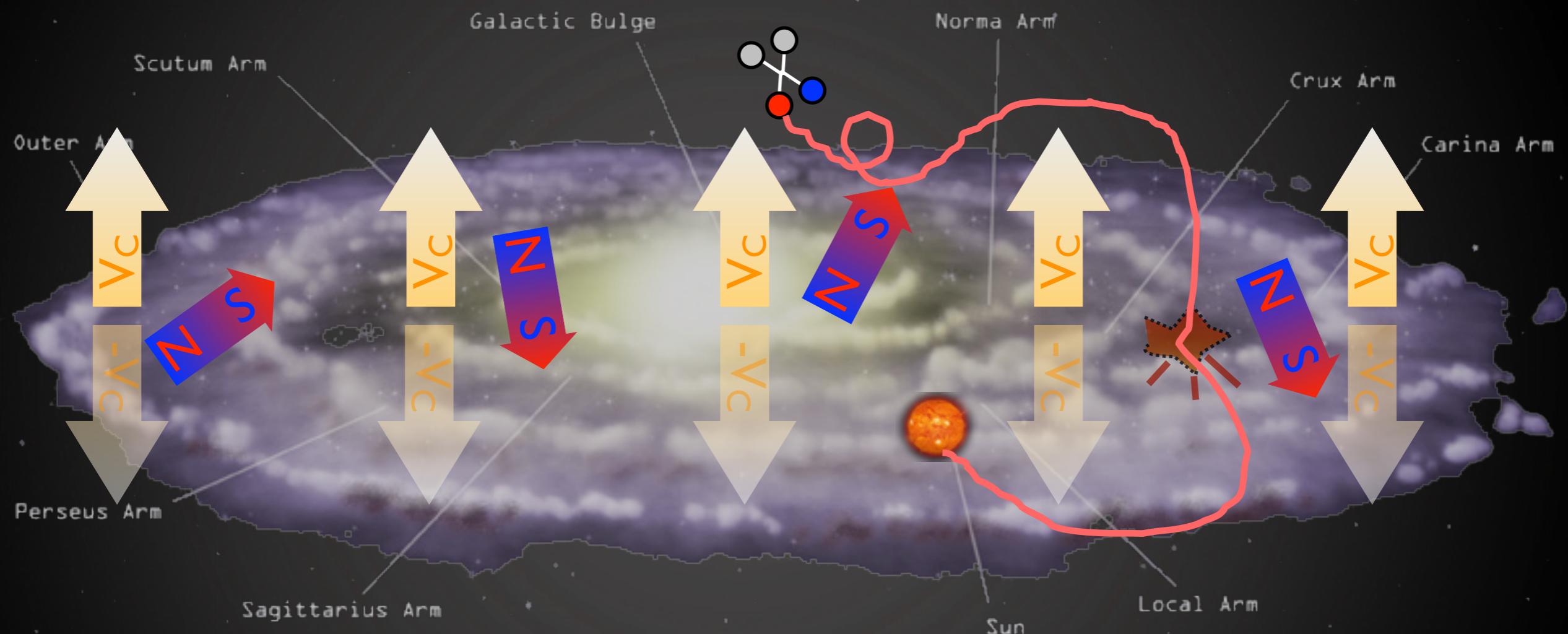
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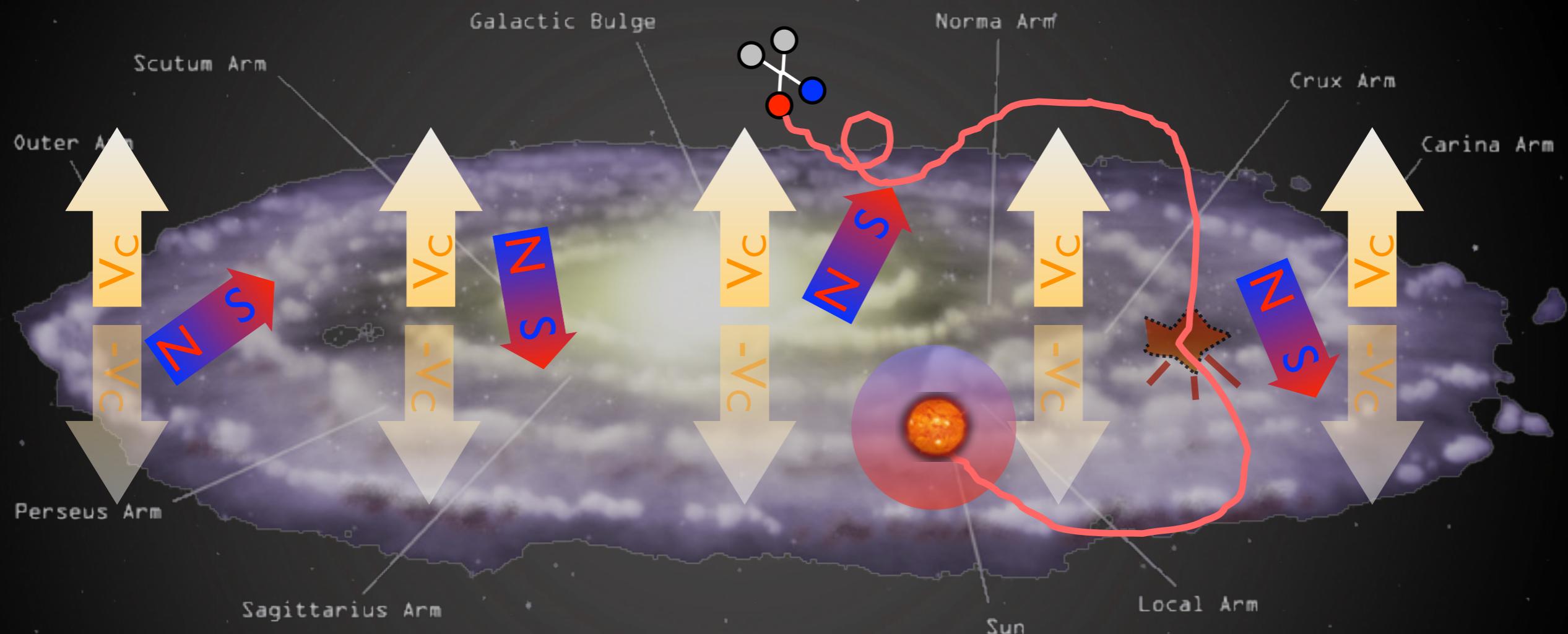
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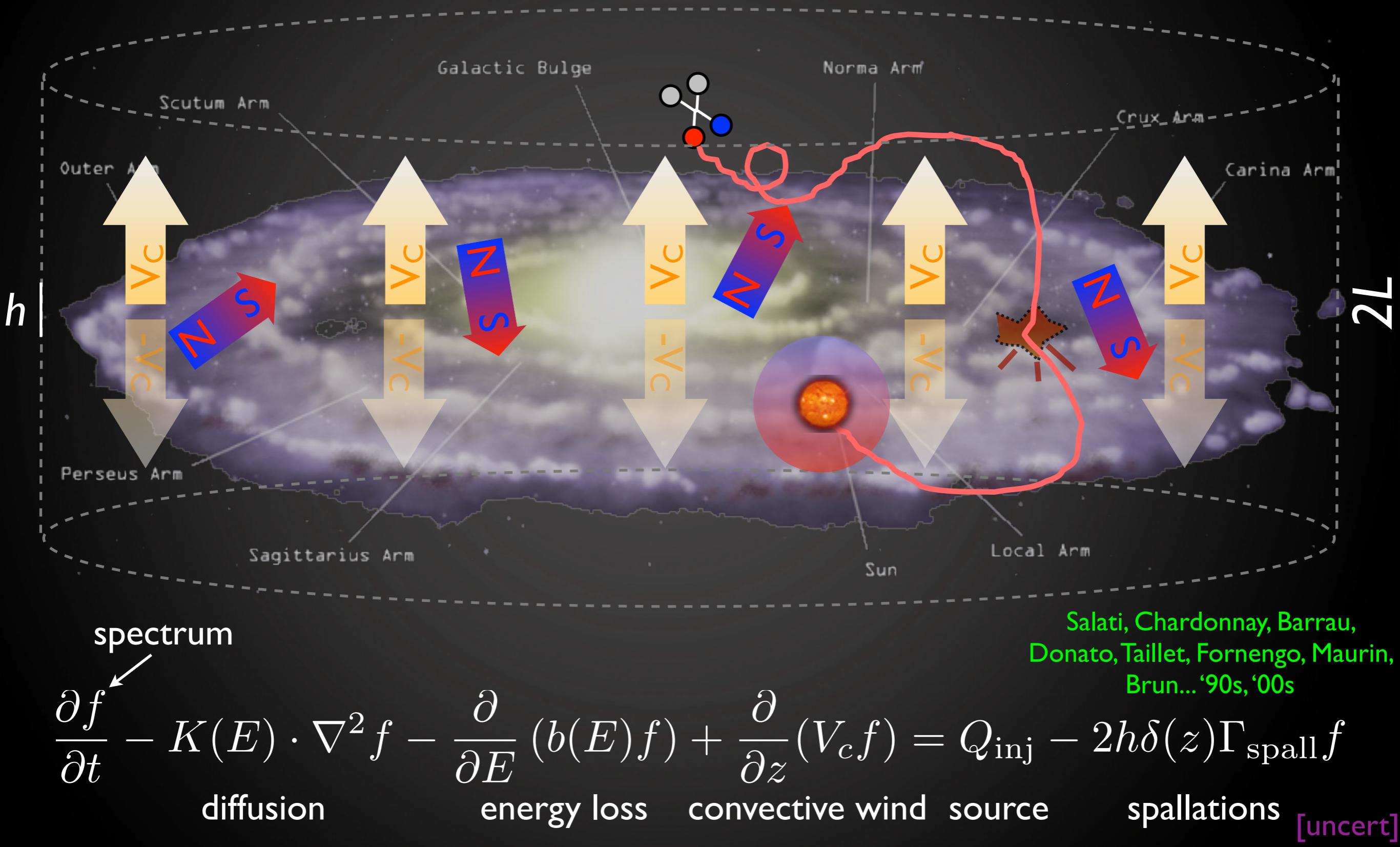
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# Indirect Detection: charged CRs

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

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

SLIM	$L$ [kpc]	$\delta$	$\log_{10} K_0$ [ $\text{kpc}^2 \text{Myr}^{-1}$ ]	$R_l$ [GV]	$\delta_l$
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

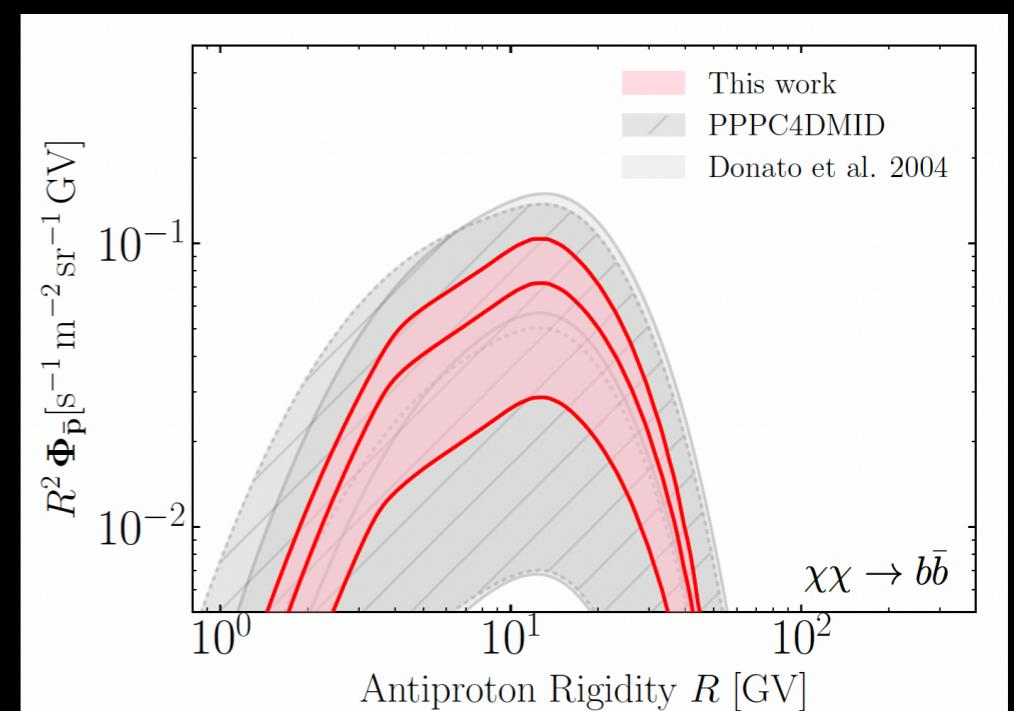
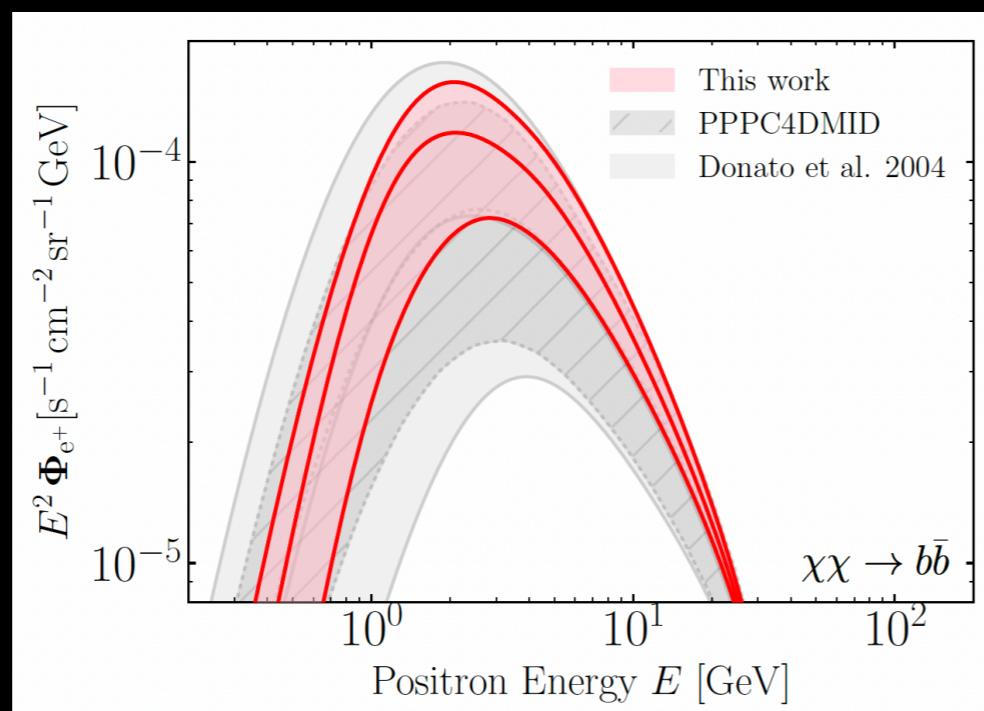
...

See also:

Génolini et al. 1904.08917

Génolini, Cirelli et al. 2103.04108

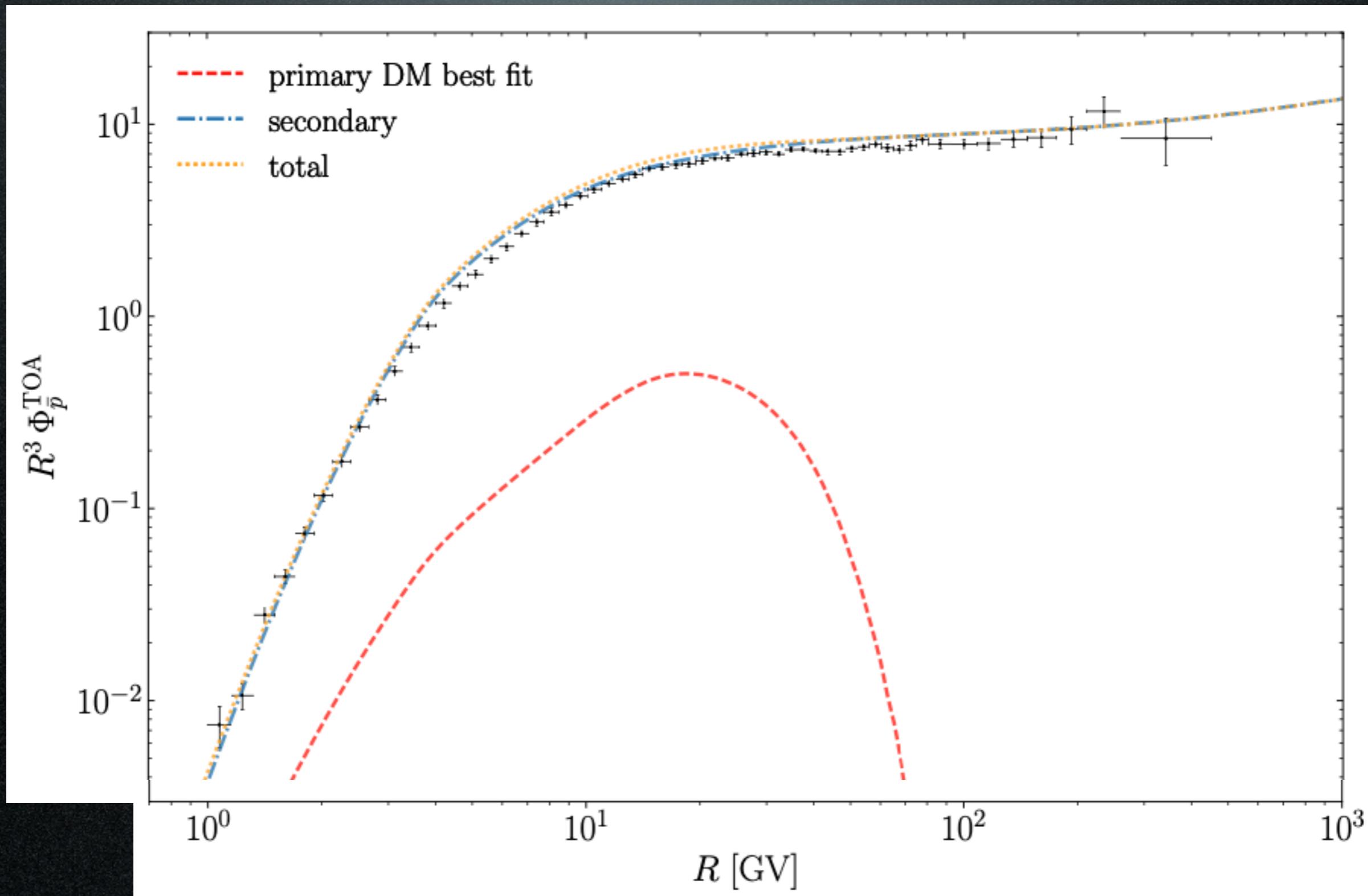
Sizable reduction of the propagation uncertainties



# Model independent bounds

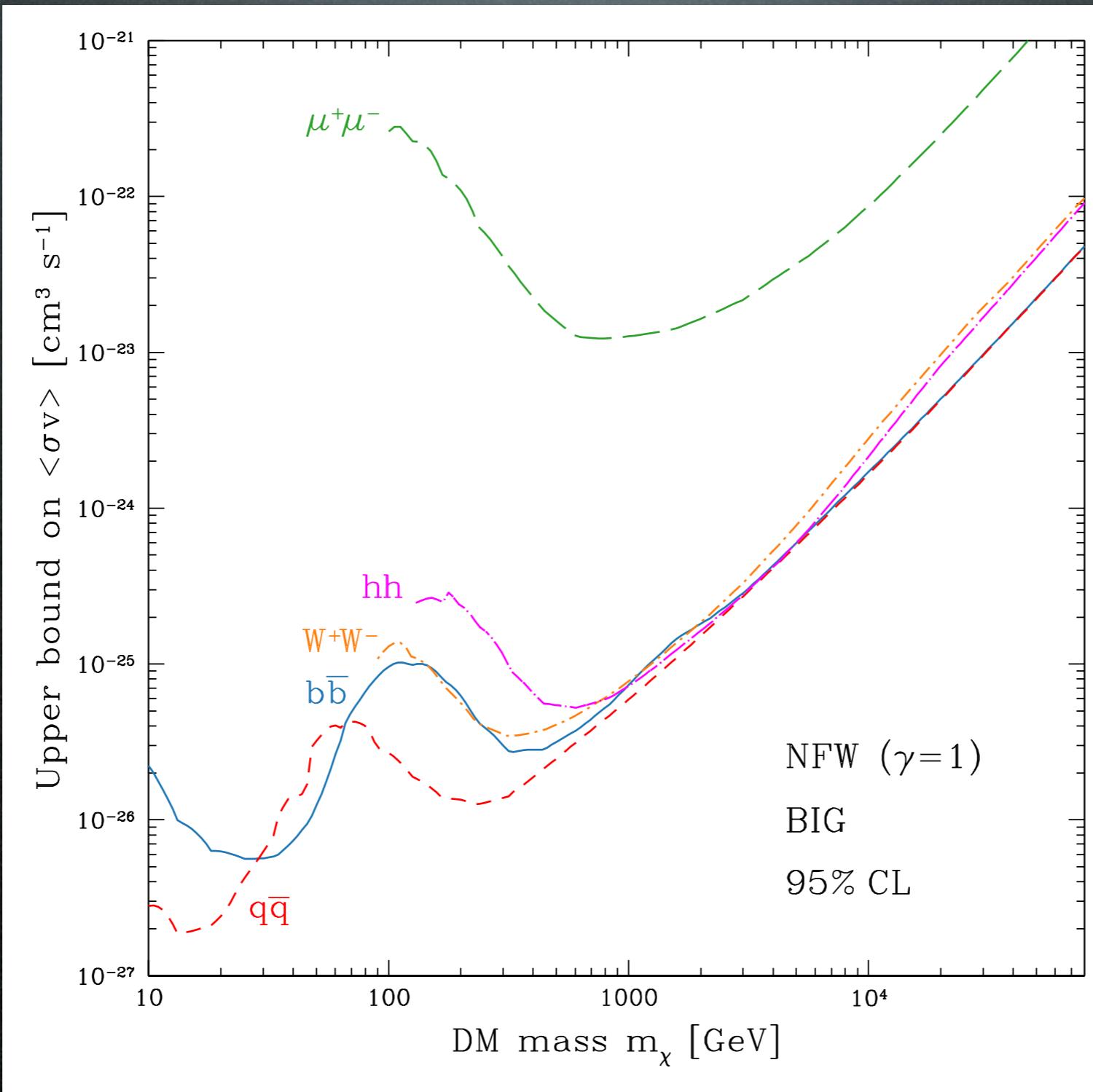
Based on AMS-02  $\bar{p}$  data (2016)

AMS coll. Phys. Rev. Lett. 117(9), 091103 (2016)



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Based on AMS-02  $\bar{p}$  data (2016)

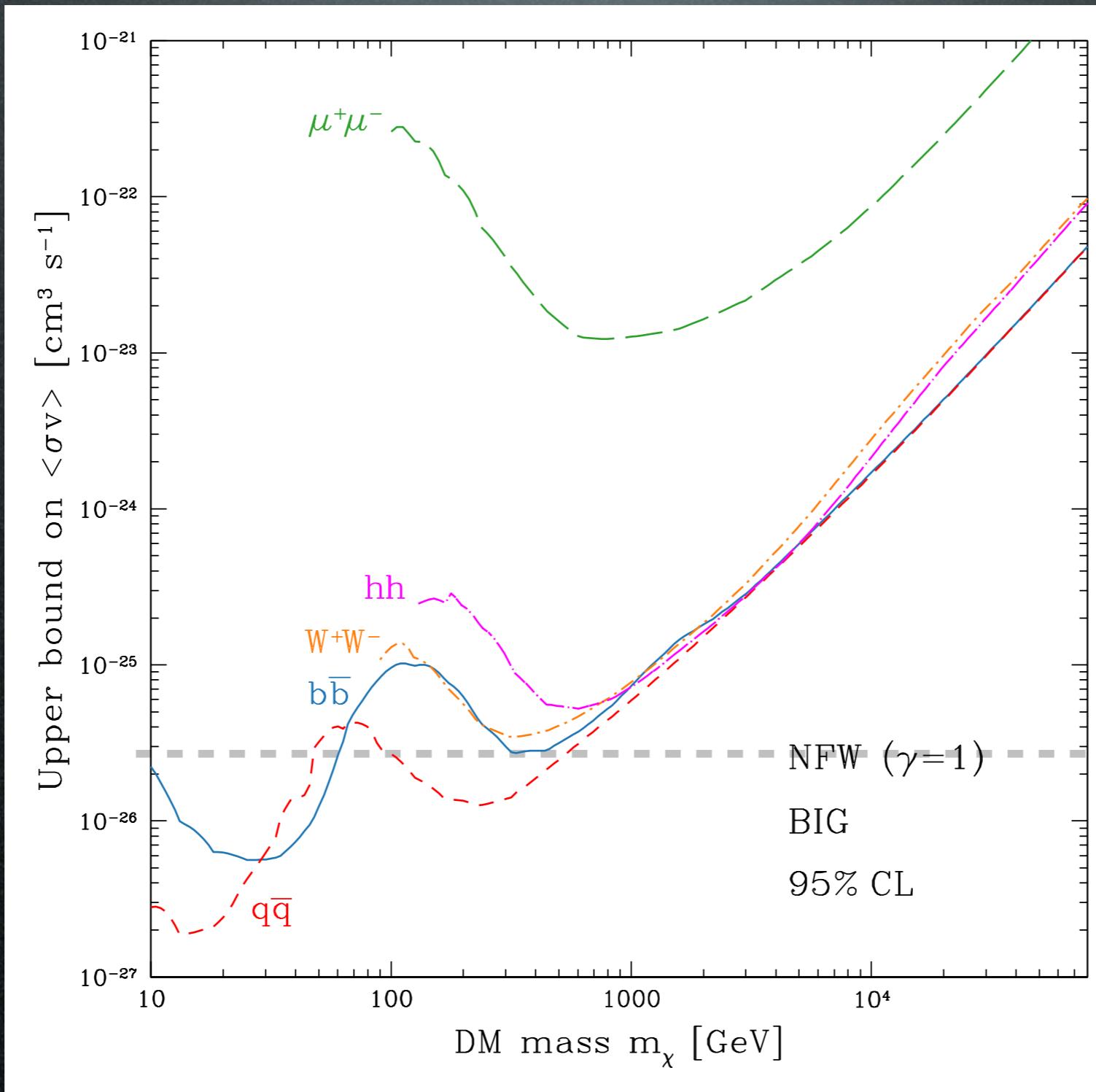


Calore, Cirelli,  
Derome, Génolini,  
Maurin, Salati, Serpico  
2202.03076

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

# Model independent bounds

Based on AMS-02  $\bar{p}$  data (2016)



Calore, Cirelli,  
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2202.03076

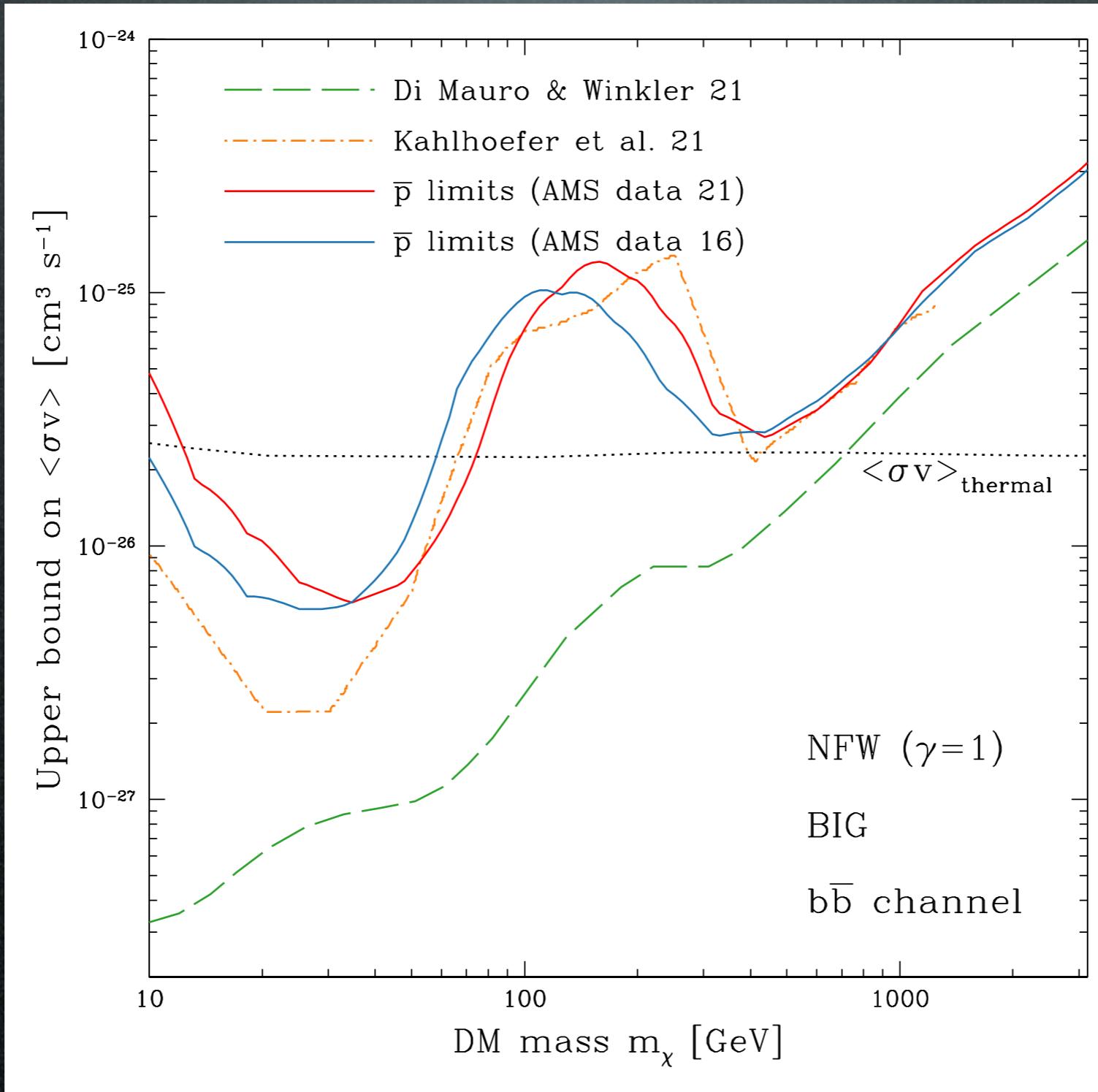
Bounds quite ‘weak’  
because of bump

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

$\gamma$  from annihil in galactic center or halo  
and from secondary emission

Fermi, ICT, radio telescopes...

indirect  $e^+$  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

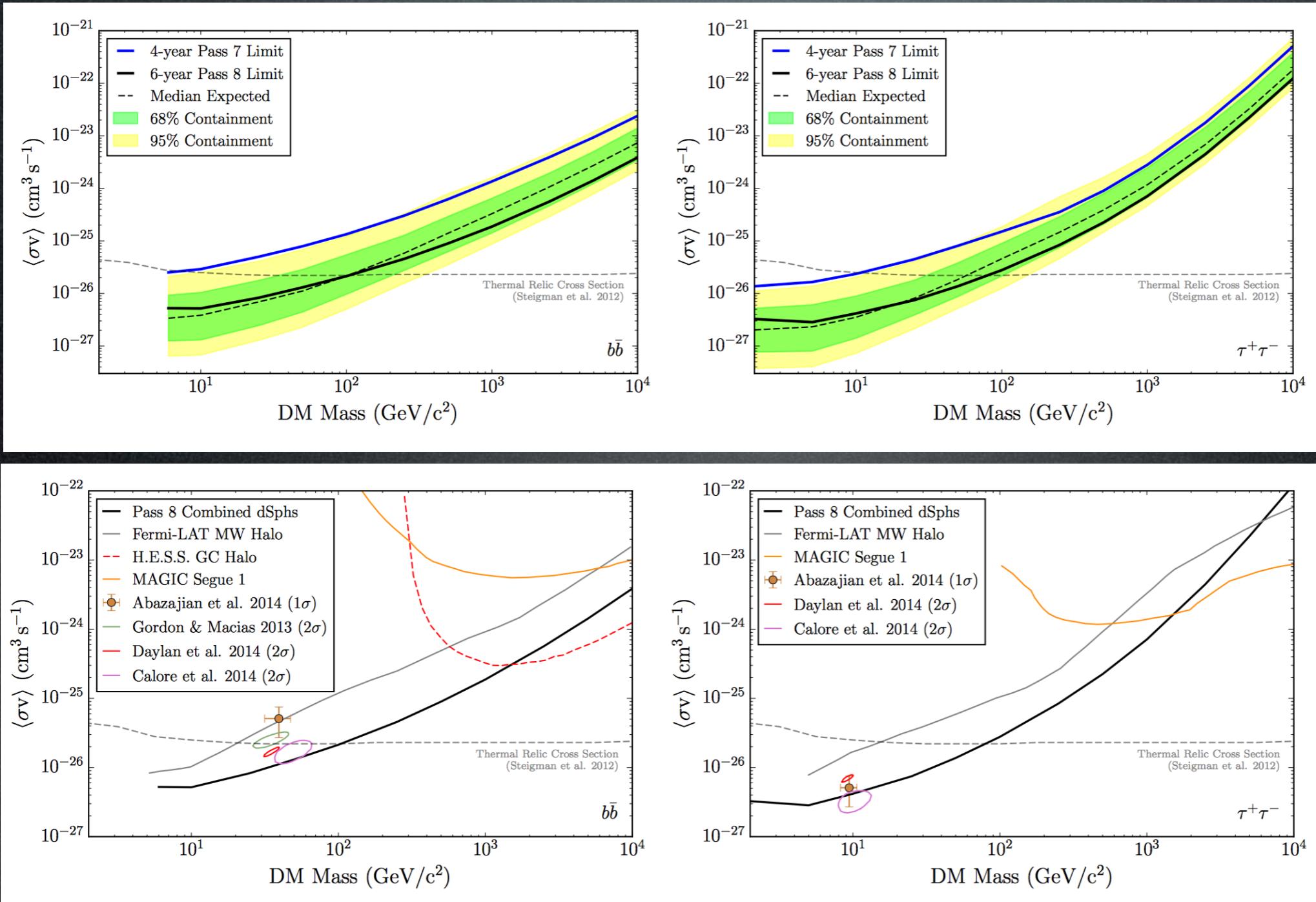
SK, Icecube, Antares

# Constraints

## Dwarf galaxies

FERMI

FERMI 1503.02641

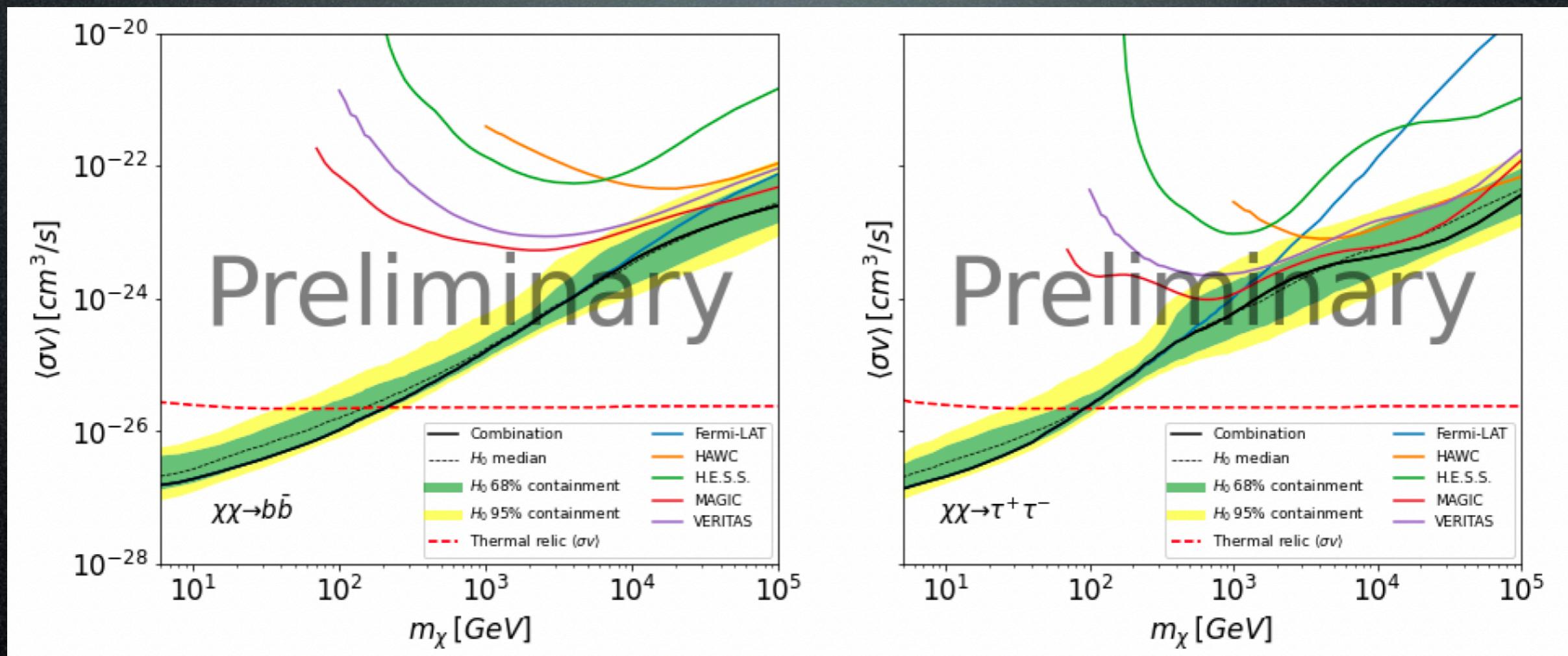


# Constraints

Dwarf galaxies

FERMI+HAWC+HESS+MAGIC+VERITAS

2108.13646

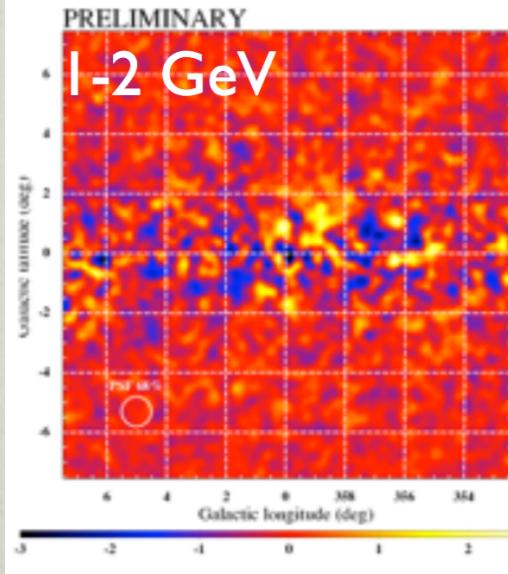


# GC GeV excess

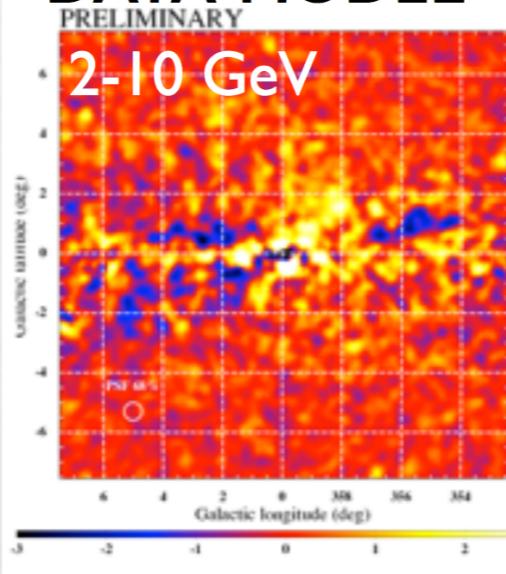
## Dark Matter interpretation:

Pulsars, tuned-index

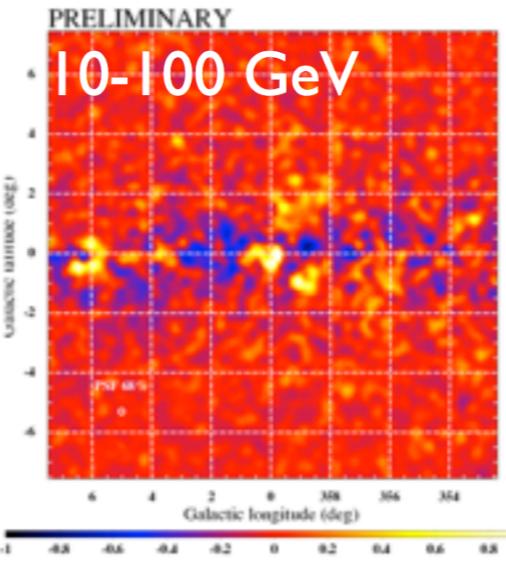
**Without NFW:**



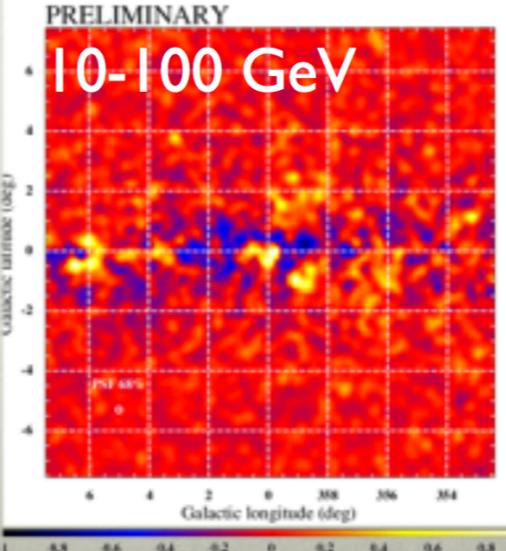
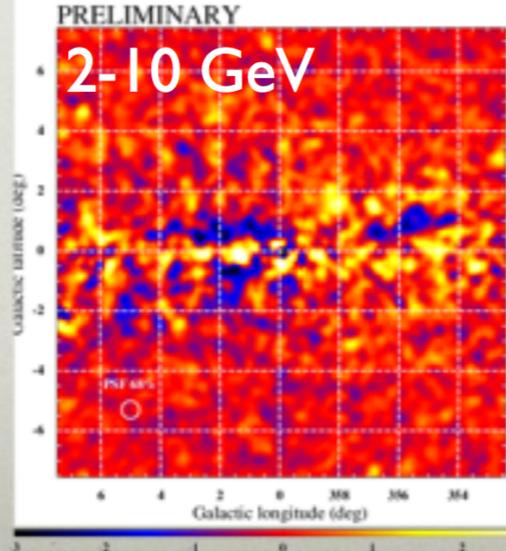
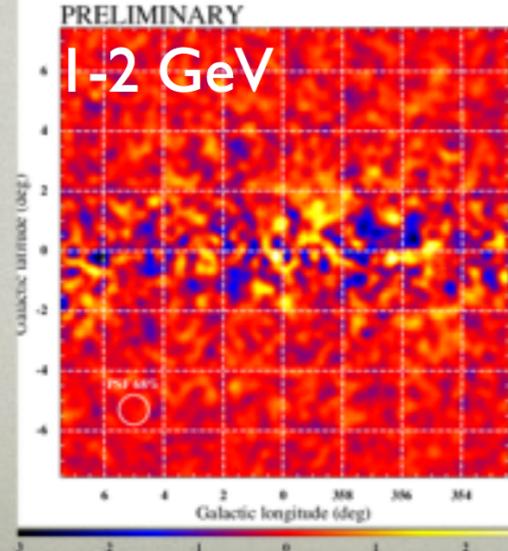
**DATA-MODEL**



Counts in  $0.1^\circ \times 0.1^\circ$  pixels  
0.3 $^\circ$  radius gaussian smoothing



**With NFW:**



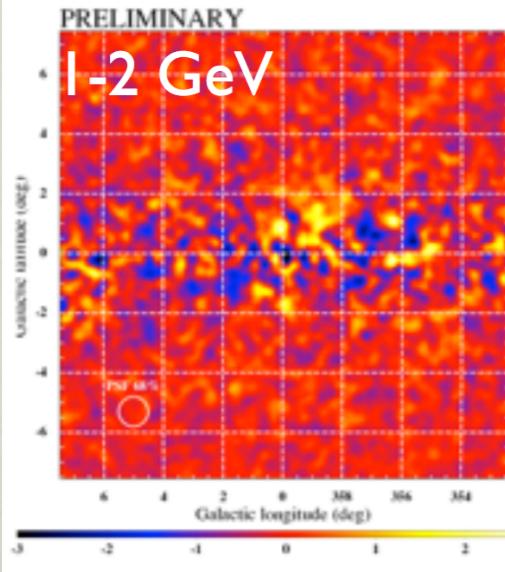
S. Murgia for FERMI-LAT - ICRC 2015  
T. Porter for FERMI-LAT - ICRC 2015 #815  
Fermi coll. 1511.02938

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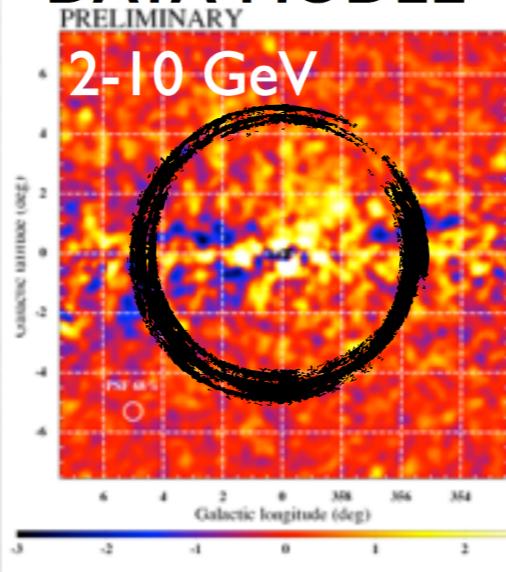
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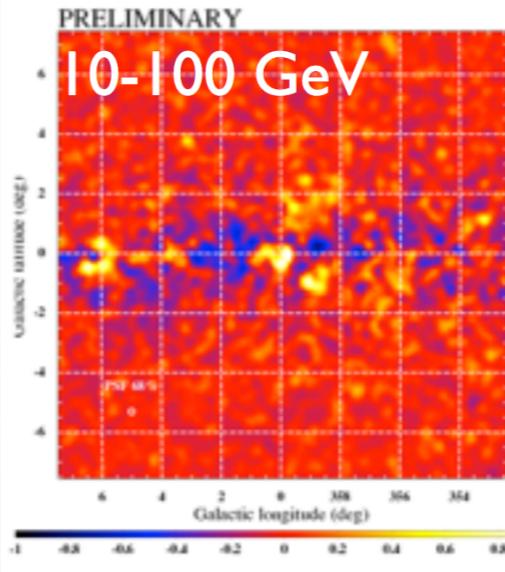
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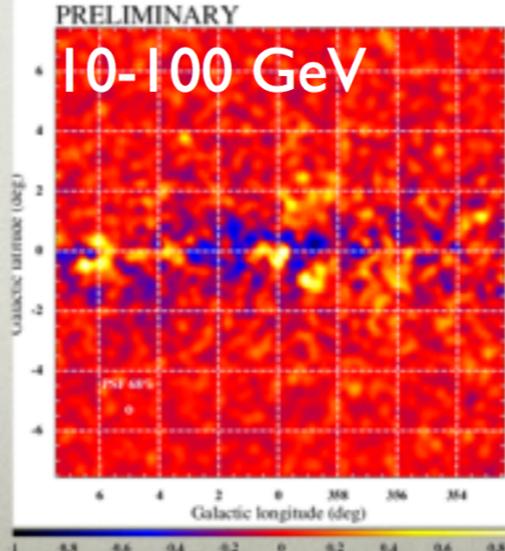
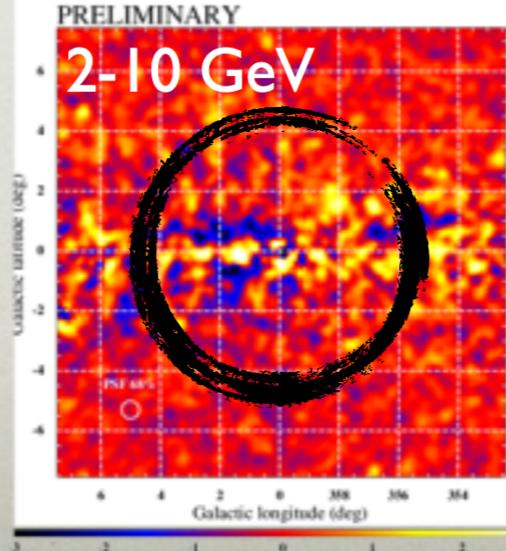
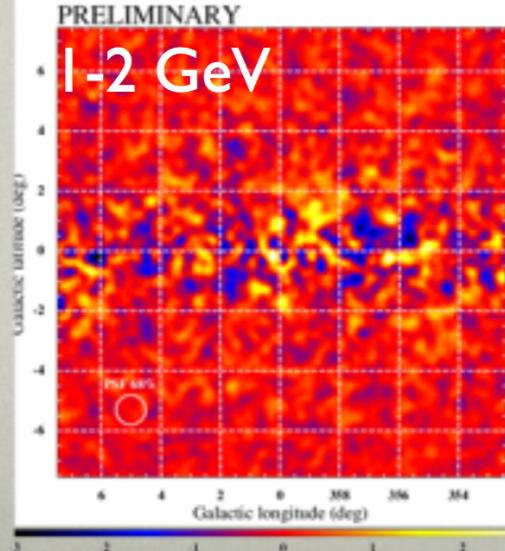
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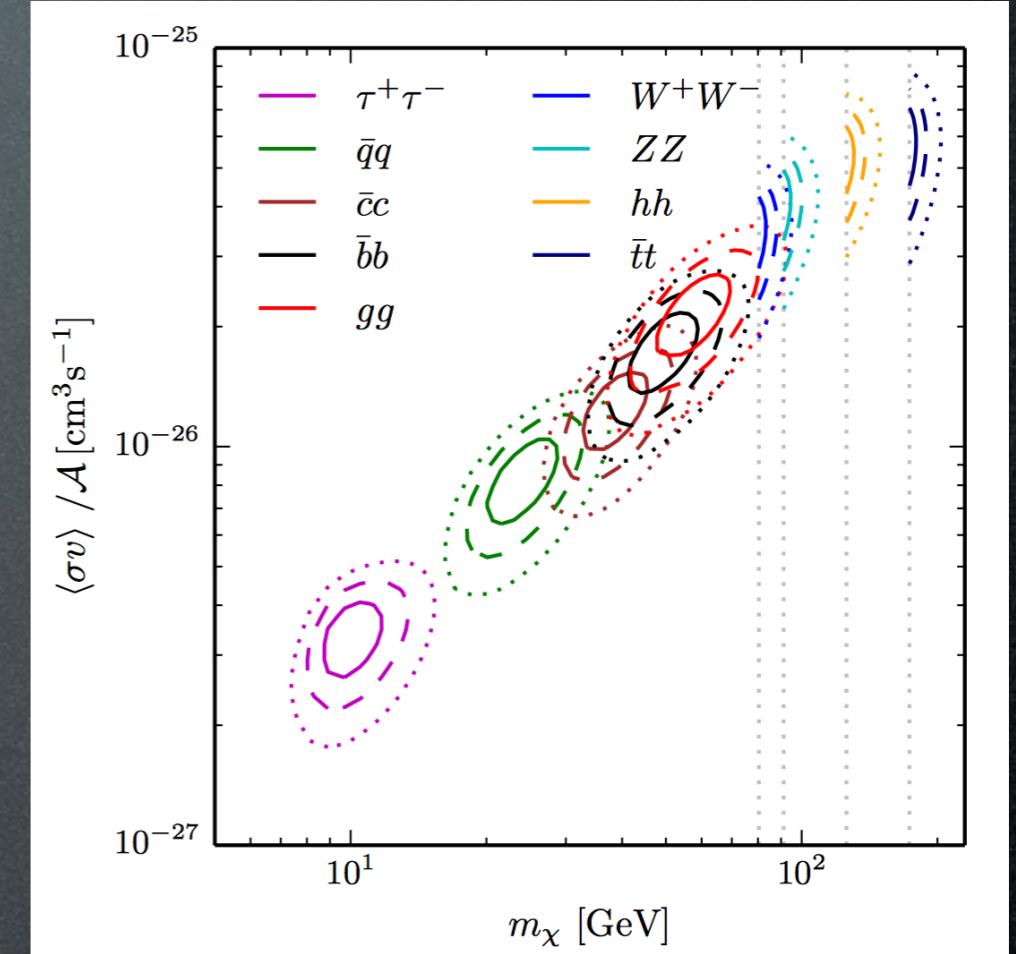
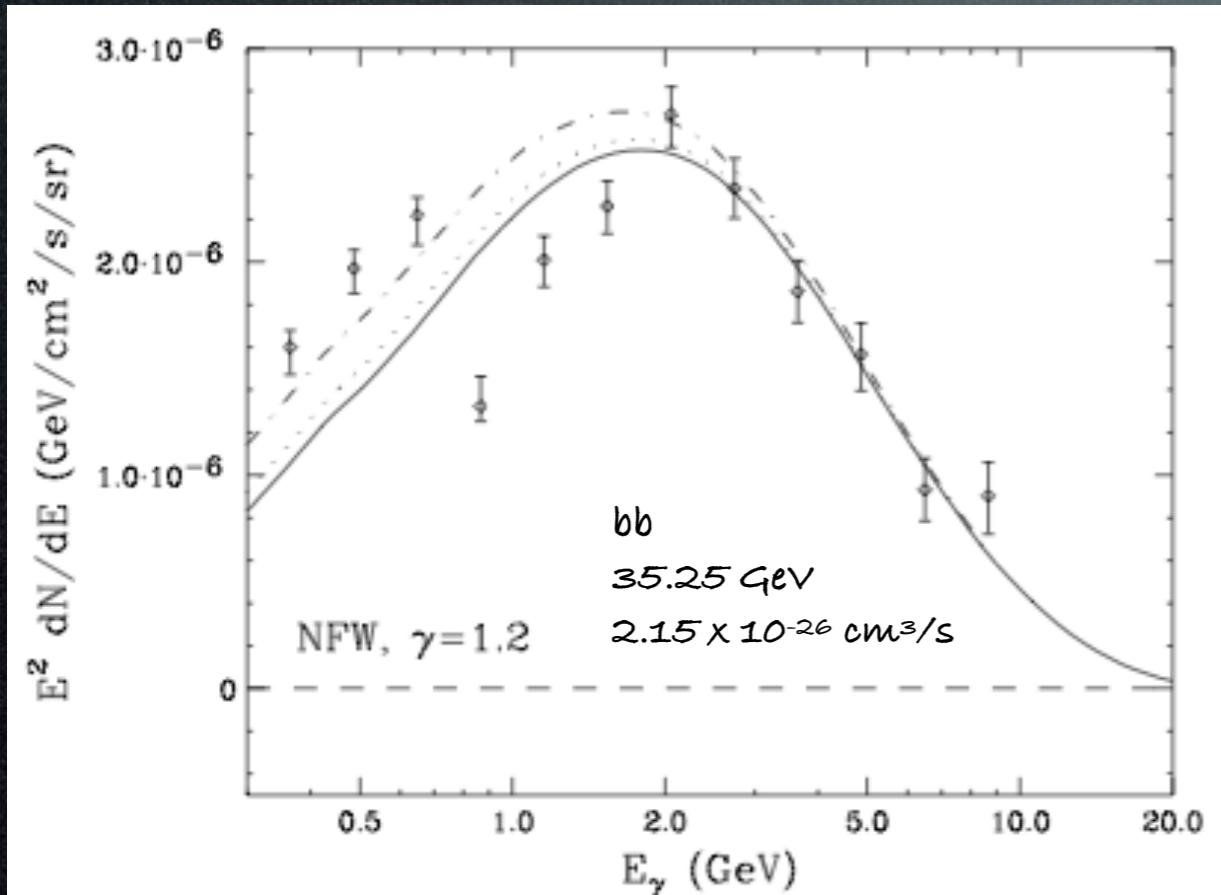
S. Murgia for FERMI-LAT - ICRC 2015  
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Fermi coll. 1511.02938

# GC GeV excess

## Dark Matter interpretation:

Best fit:

~35 GeV, quarks, ~thermal  $\sigma v$



A compelling case  
for annihilating DM

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

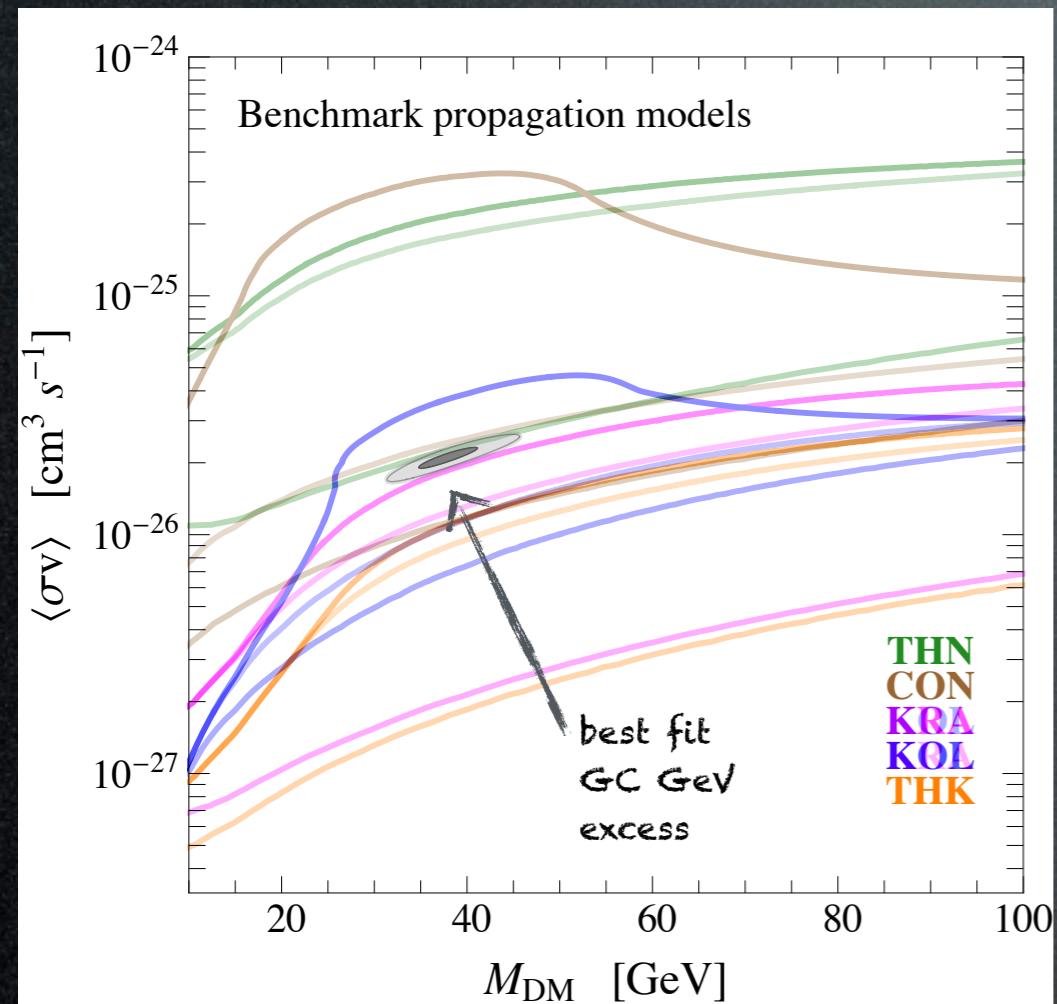
F. Calore et al. 1411.4647

...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:

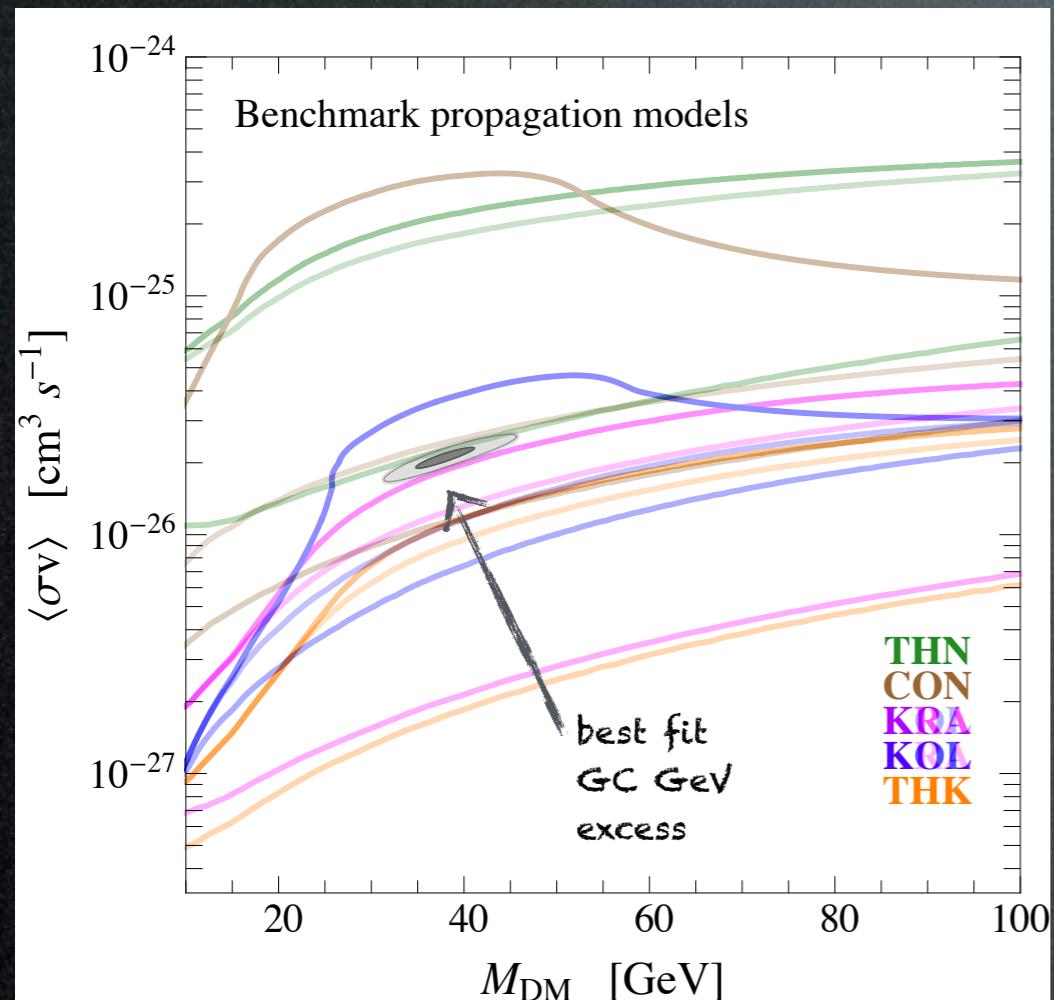
Bringmann, Vollmann,  
Weniger 1406.6027

Hooper, Linden, Mertsch  
1410.1527

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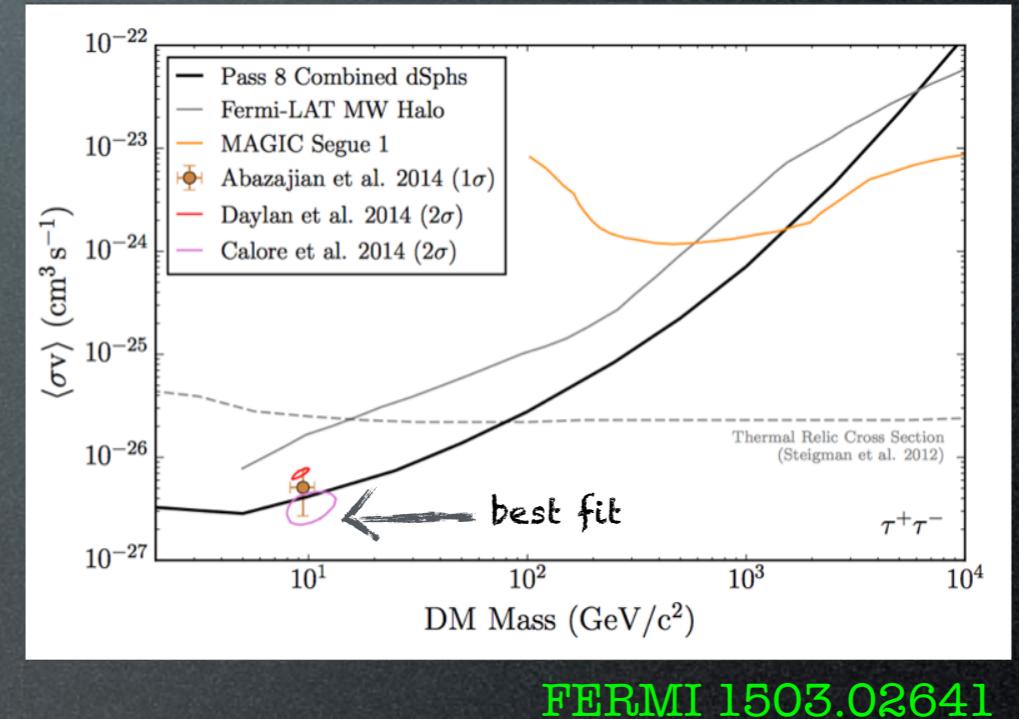
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Also:

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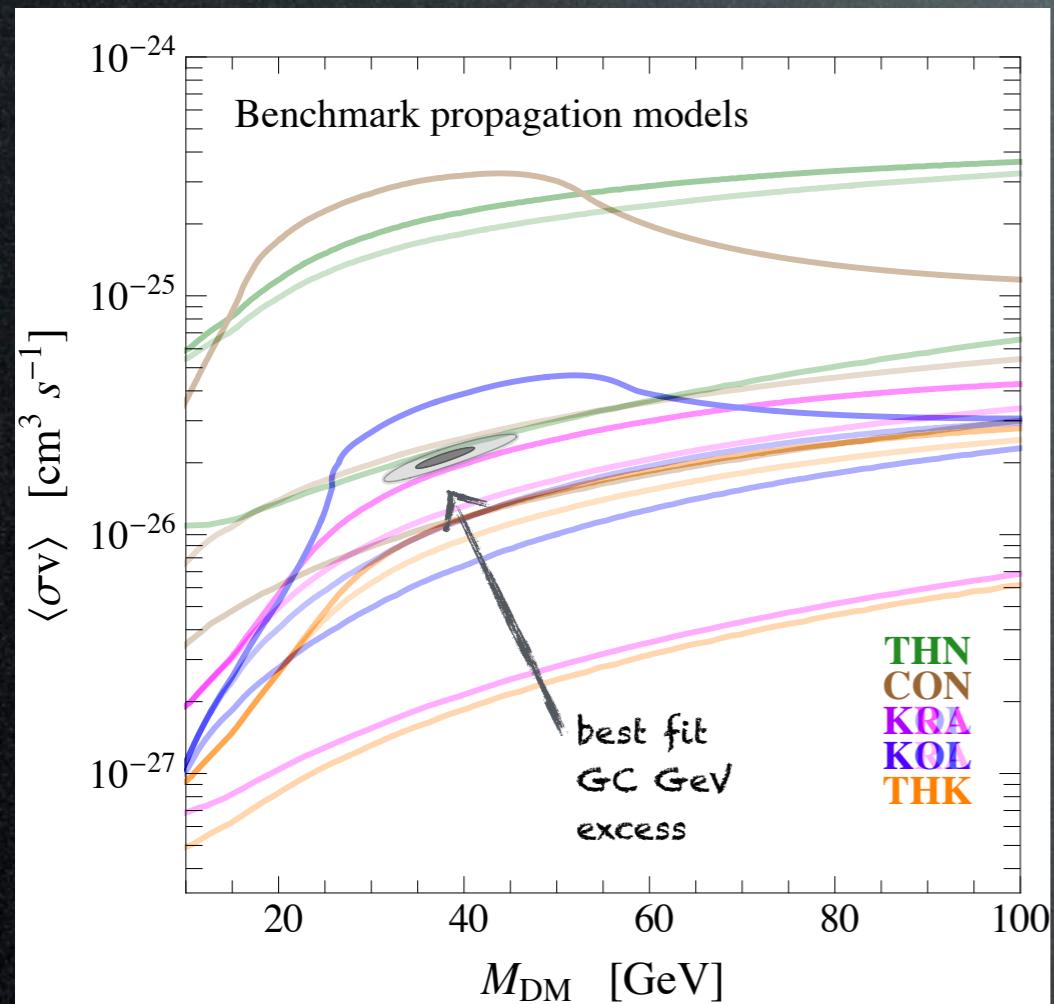
Gamma ray ones neither



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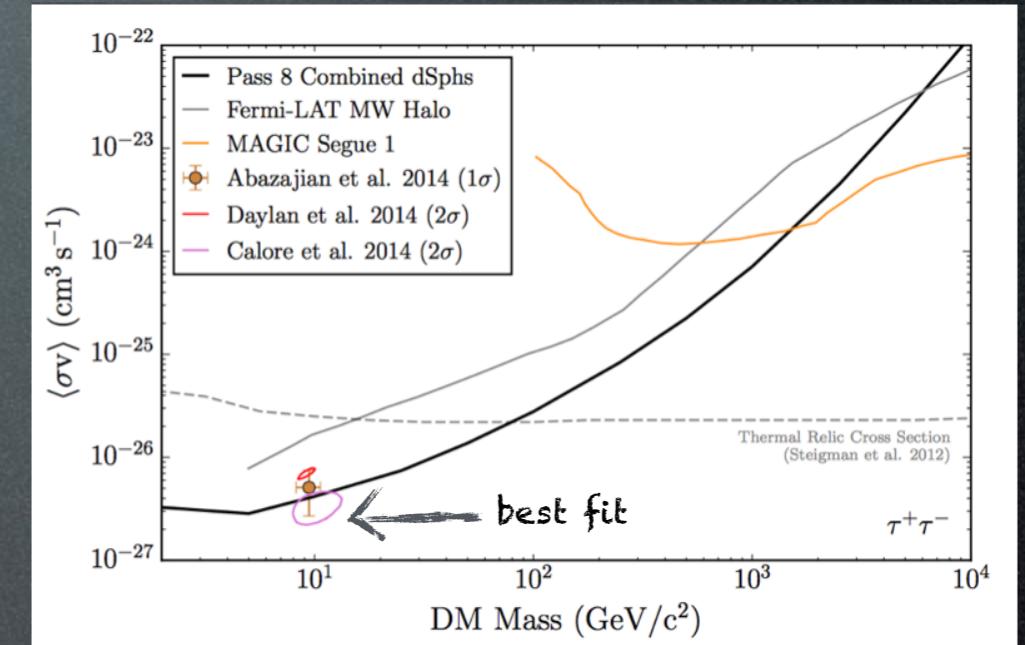


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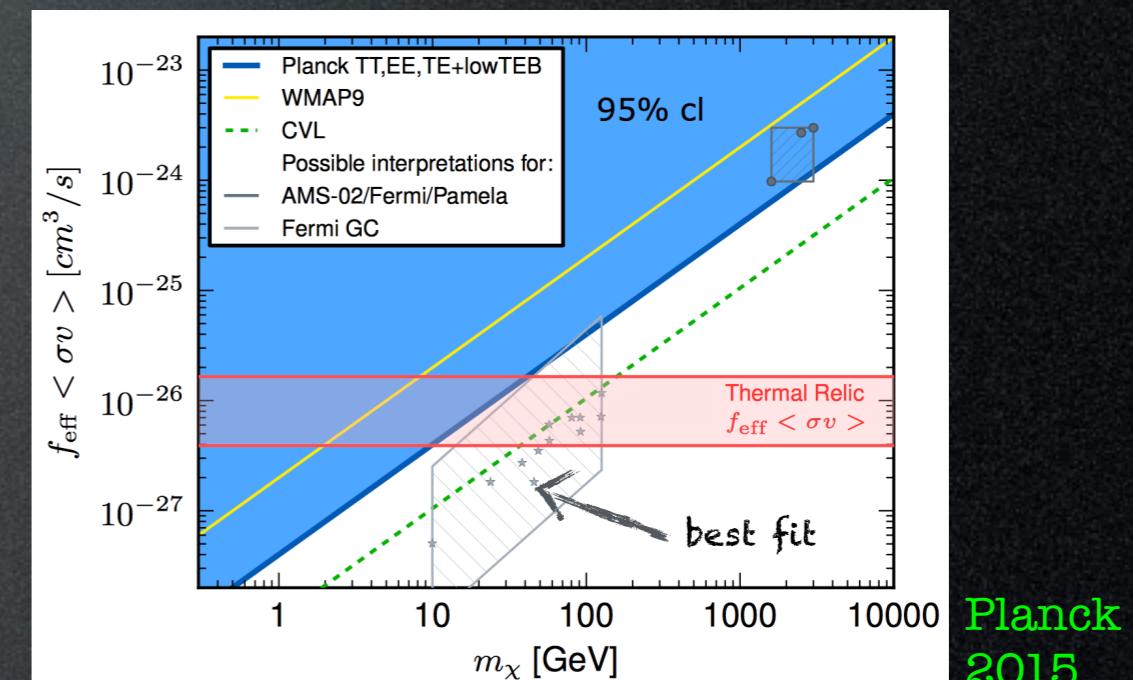
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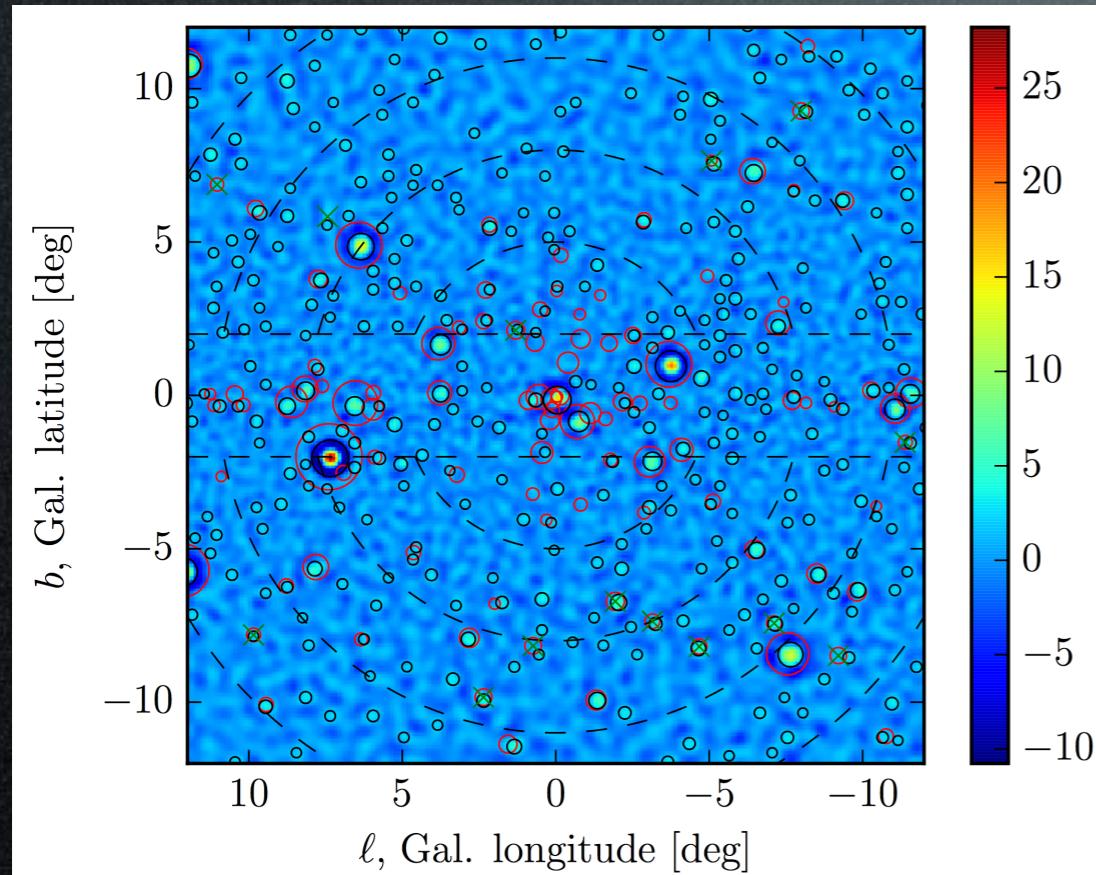
Nor CMB



# GC GeV excess

‘Astro’ interpretation(s):

Unresolved point sources (MSPs?)



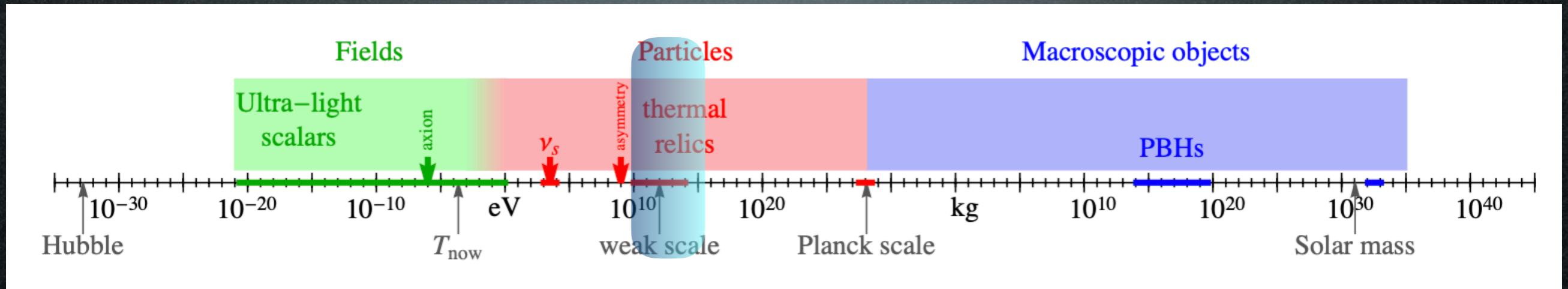
Bartels...Weniger 1506.05104  
Lee, Lisanti...Slatyer 1506.05124

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

(partly) reaffirmed in  
[List, Rodd, Lewis 2107.09070](#) :  
deep learning techniques  
suggest a substantial amount  
of the GCE flux is due to PSs

# Candidates

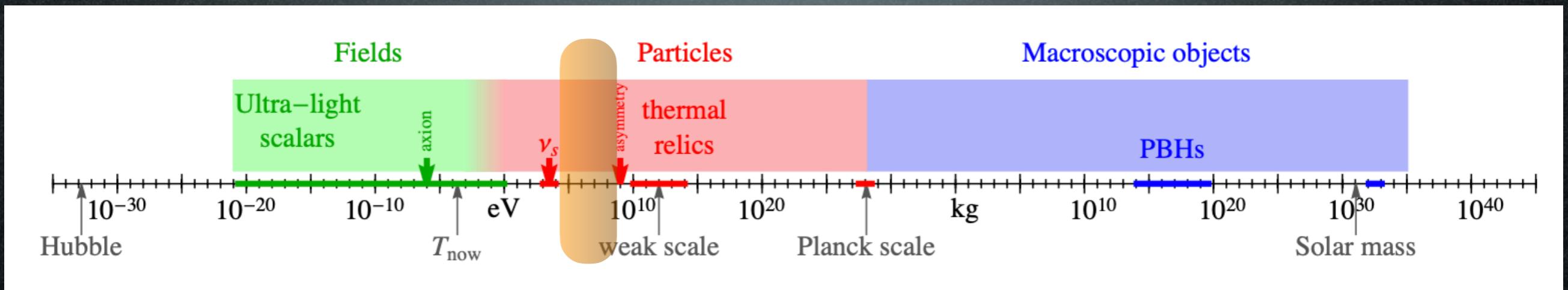
A matter of perspective: plausible mass ranges



90 orders of magnitude!

# Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

# Candidates

theory?

production?

Sub-GeV DM?

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?

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

Why not!

# Candidates

theory

production

Sub-GeV DM?

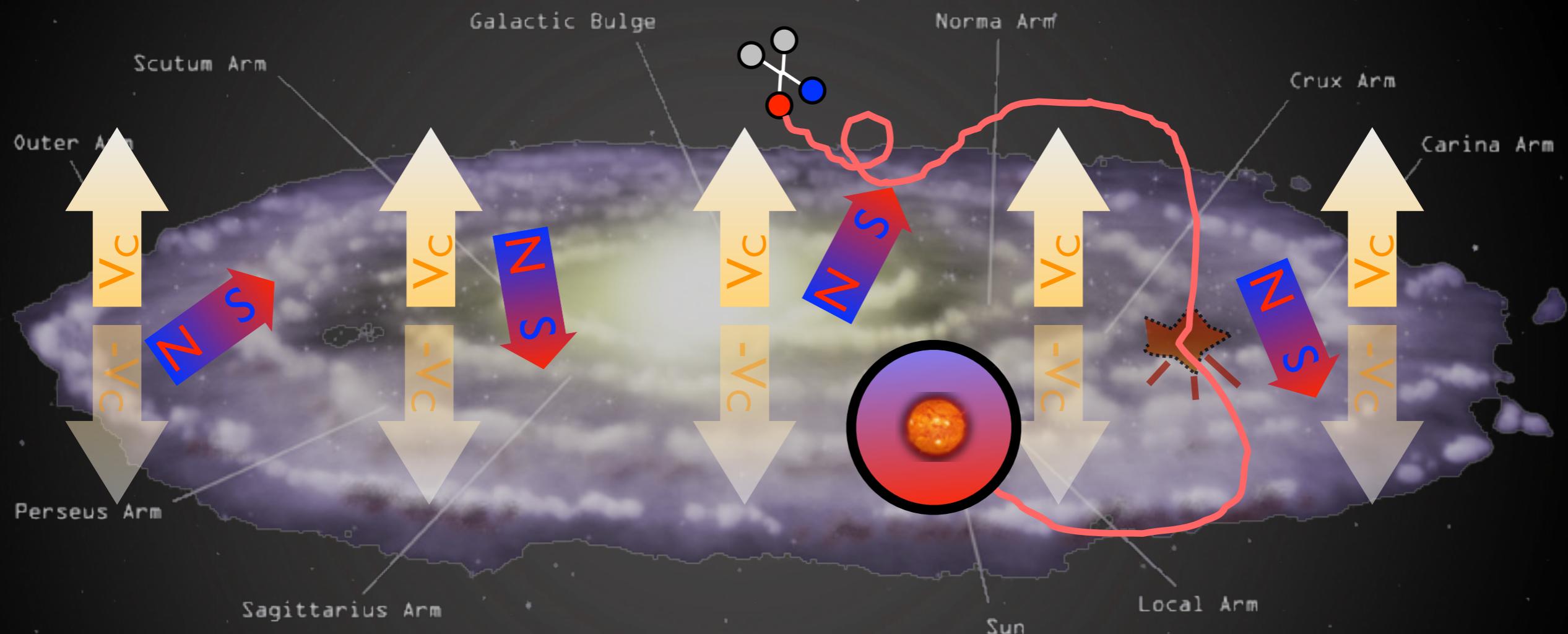
Collider  
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Indirect  
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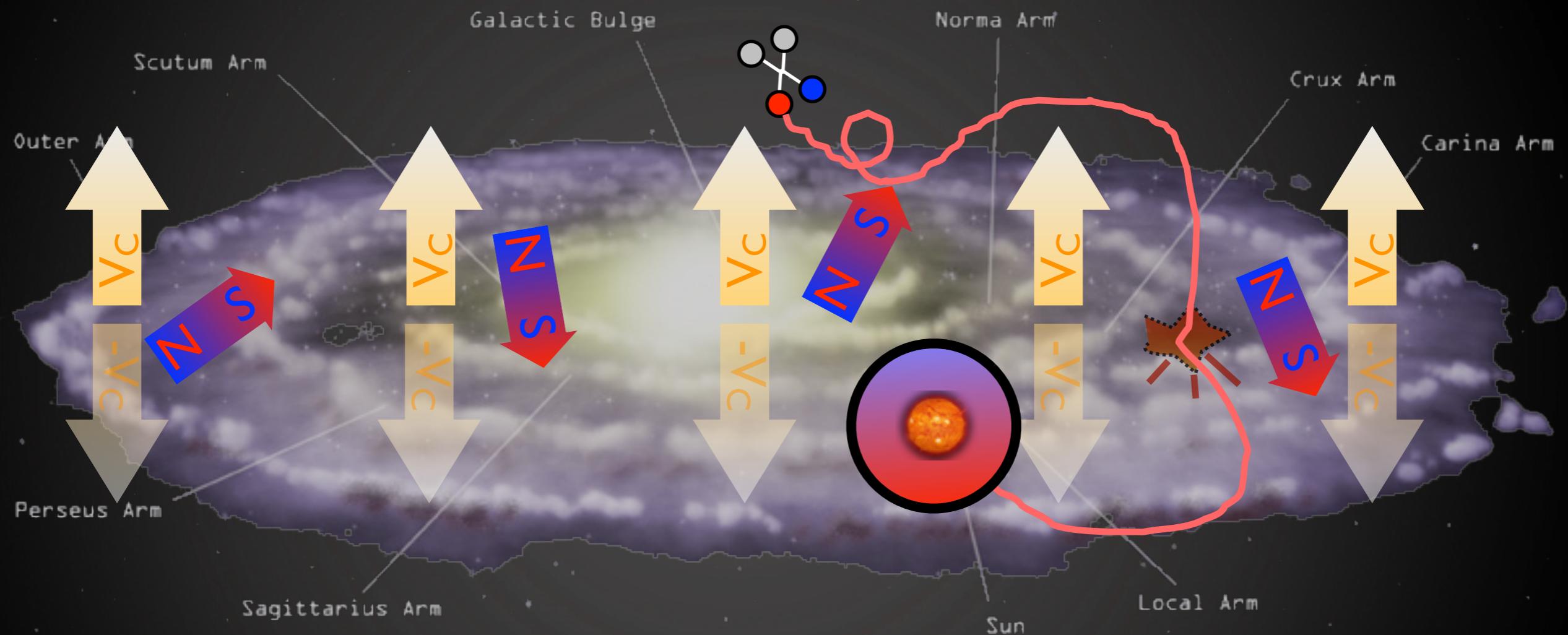
# Indirect Detection: charged CRs

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



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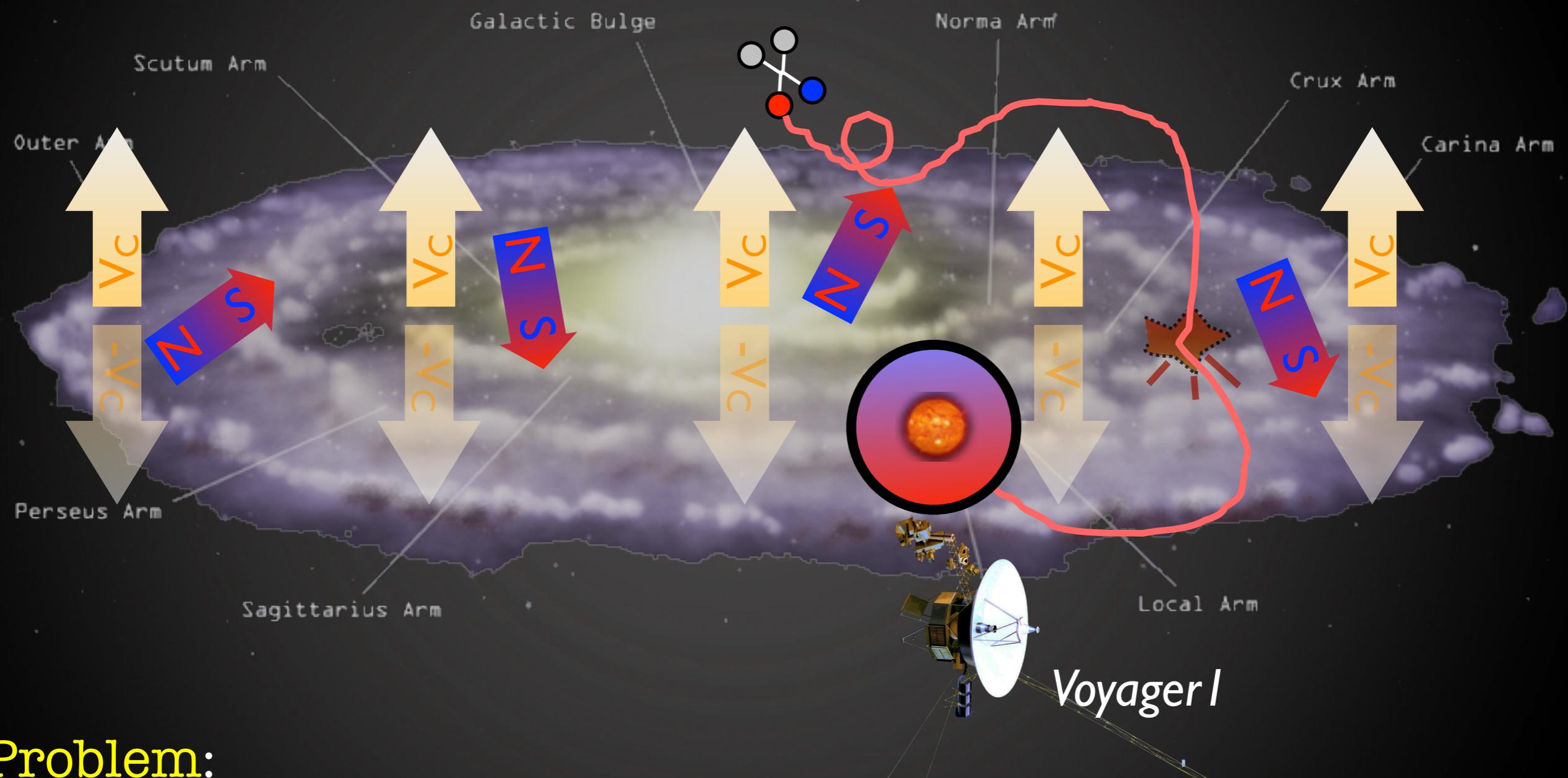


Problem:

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

# Indirect Detection: charged CRs

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



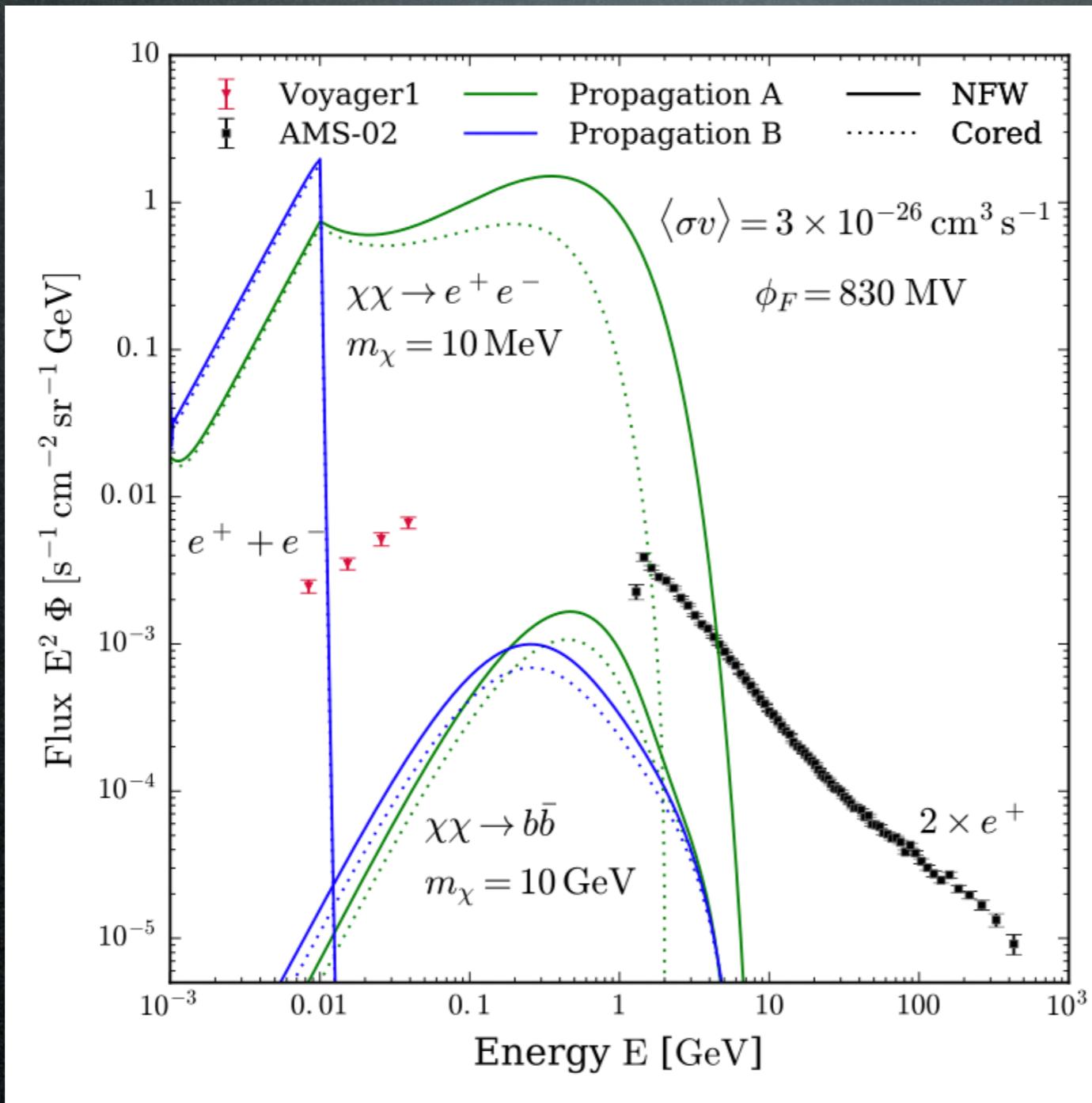
Problem:

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

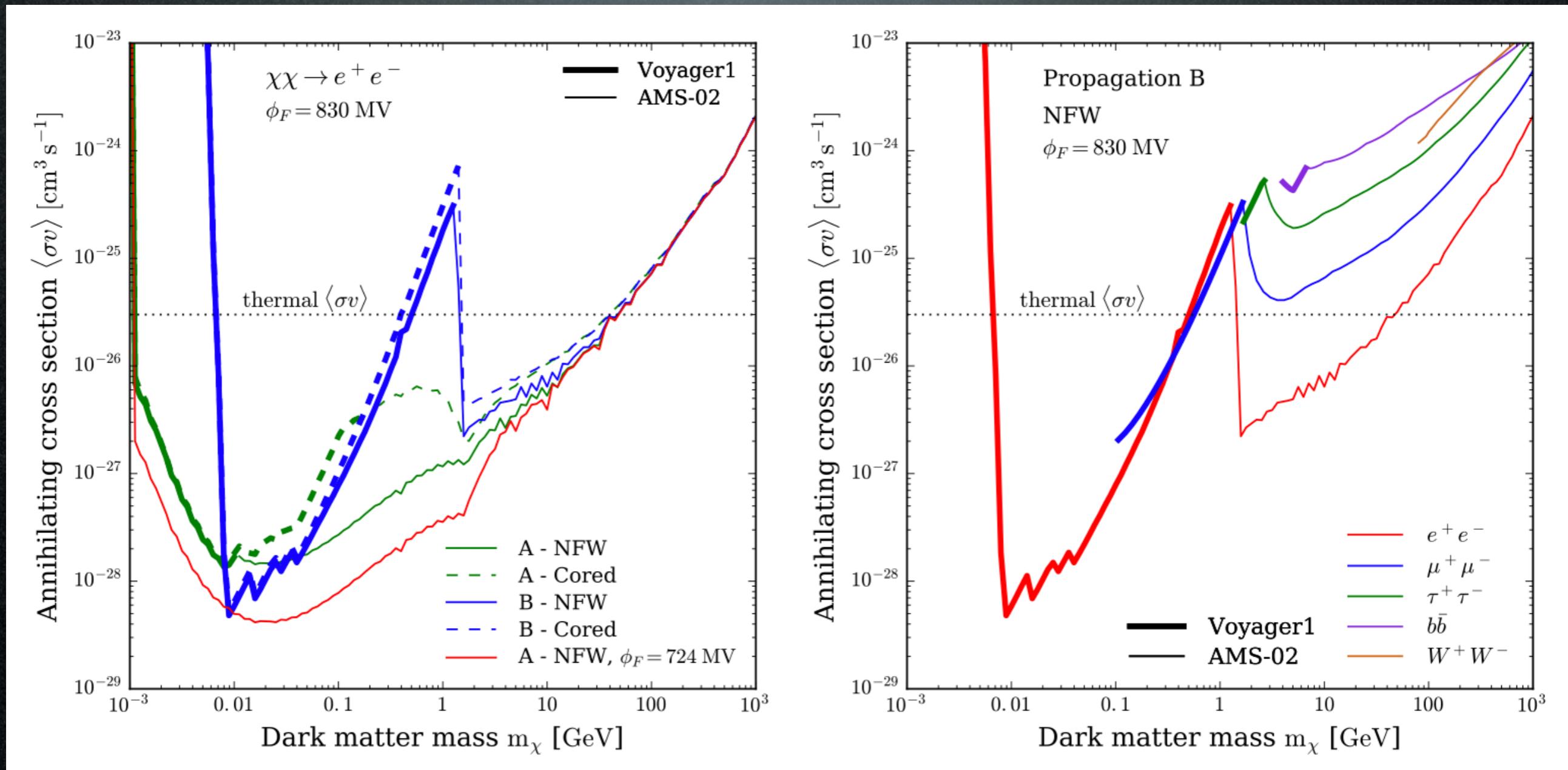


Propagation A = strong reacceleration  
Propagation B = weak/no reacceleration

# Indirect Detection: charged CRs

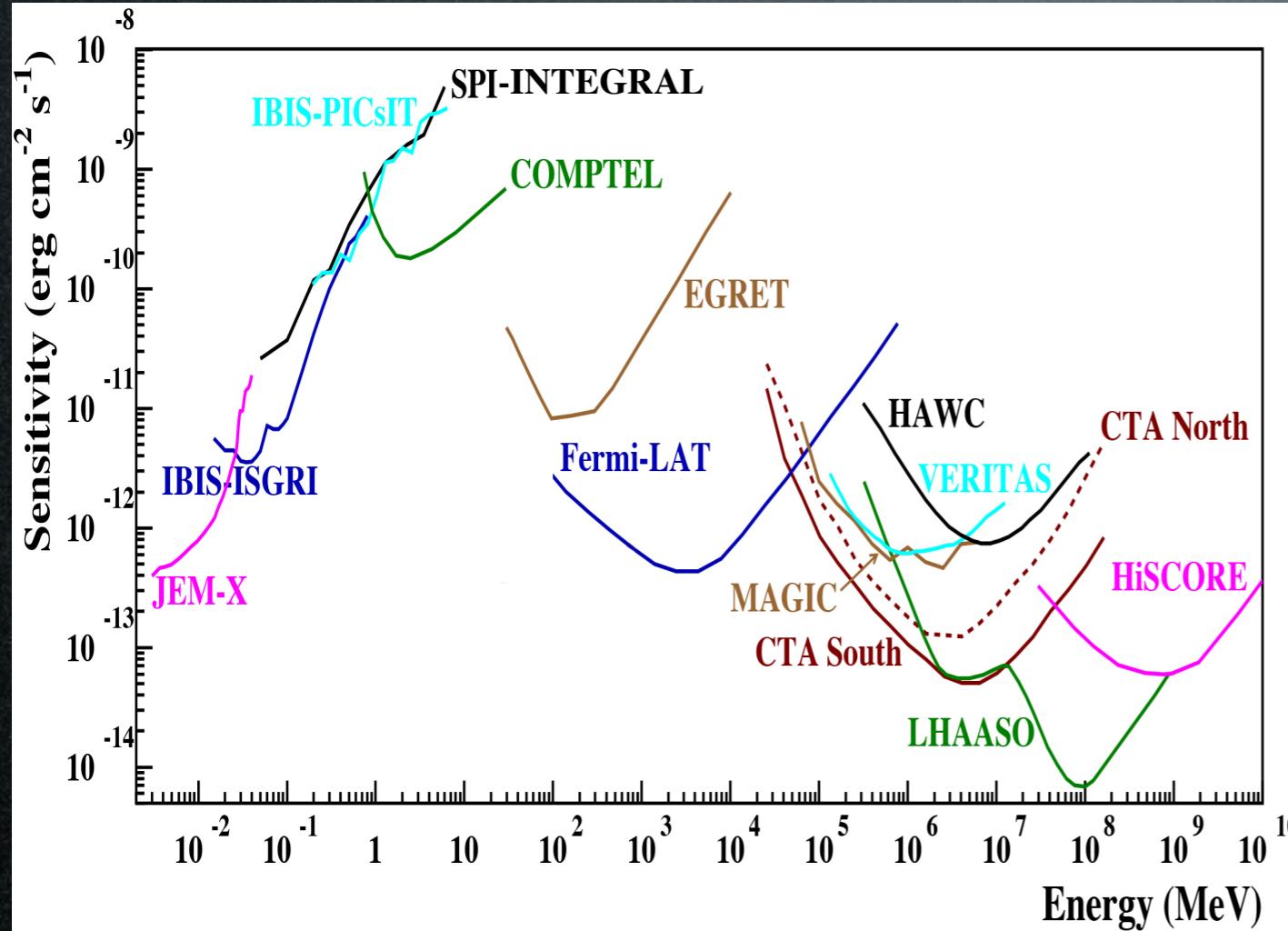
Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I



# Indirect detection: photons

adapted from 1611.02232



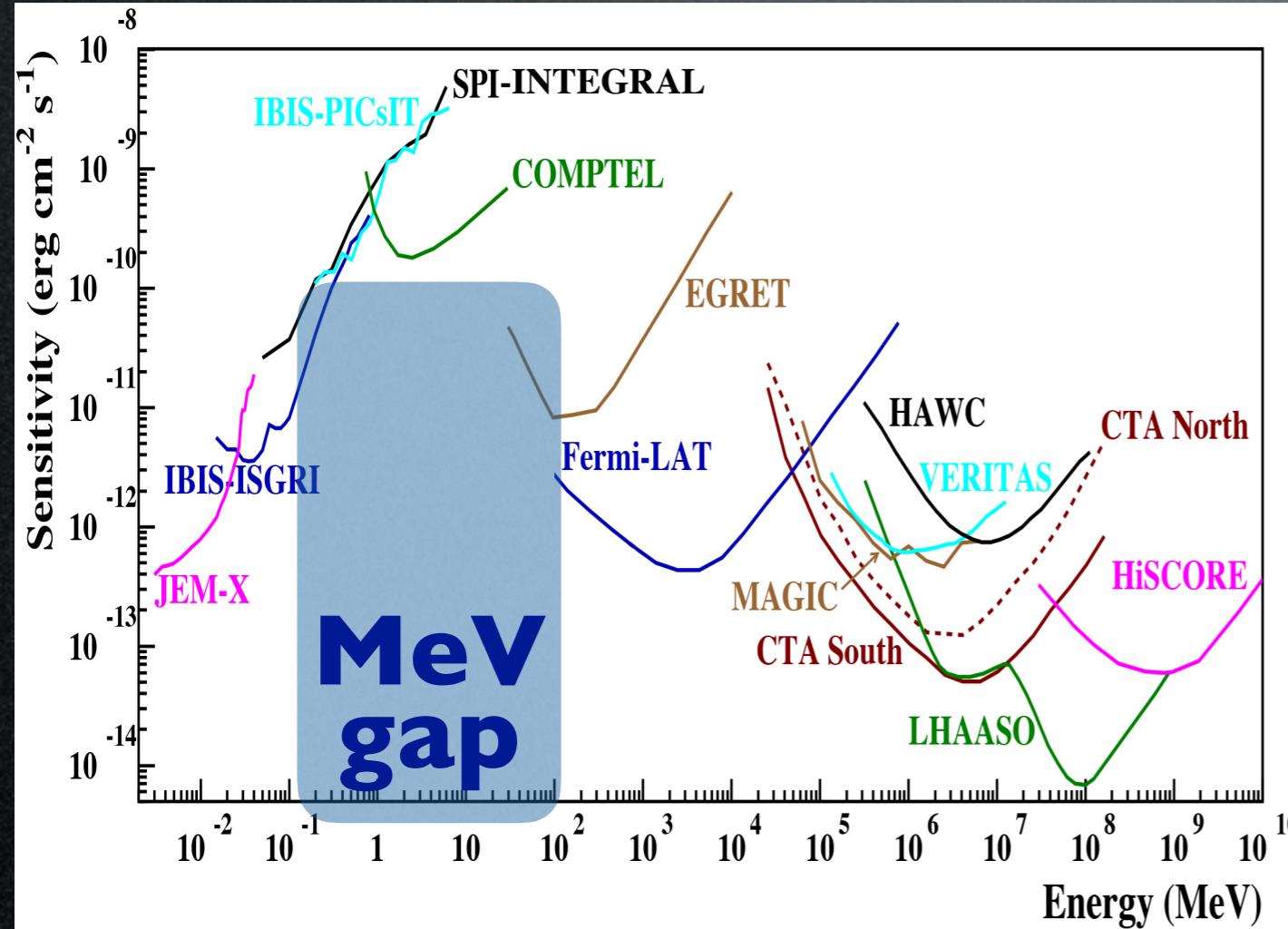
Past/current experiments:  
**Integral, Comptel, Fermi**  
(2002 →) (1991-2000) (2009 →)

Planned/proposed experiments:  
**e-Astrogam?, Compair?, Amego?, COSI?**

AMEGO	satellite	2020s?	HEP detectors	γ-rays	0.2 – 10 GeV
COMPARI	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

# Indirect detection: photons

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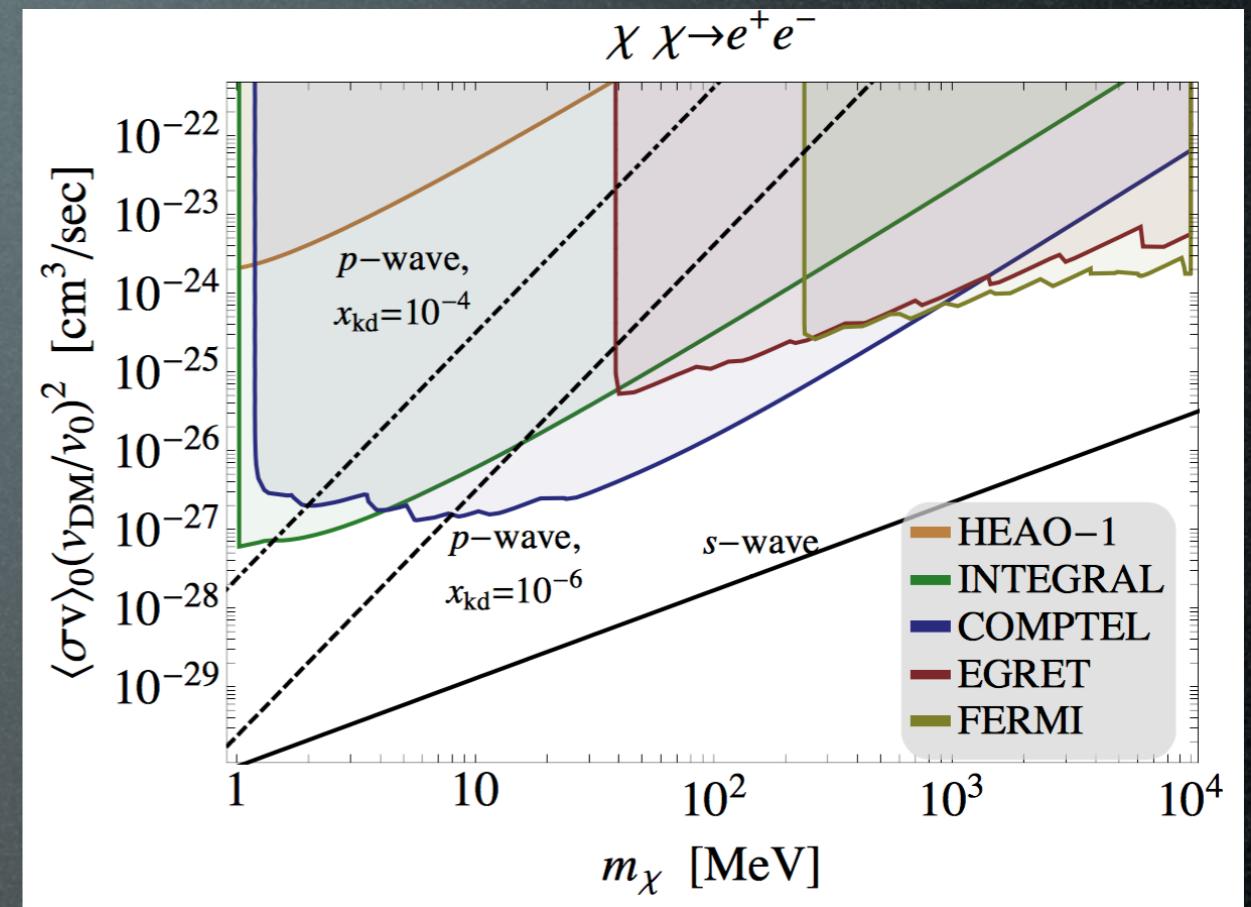
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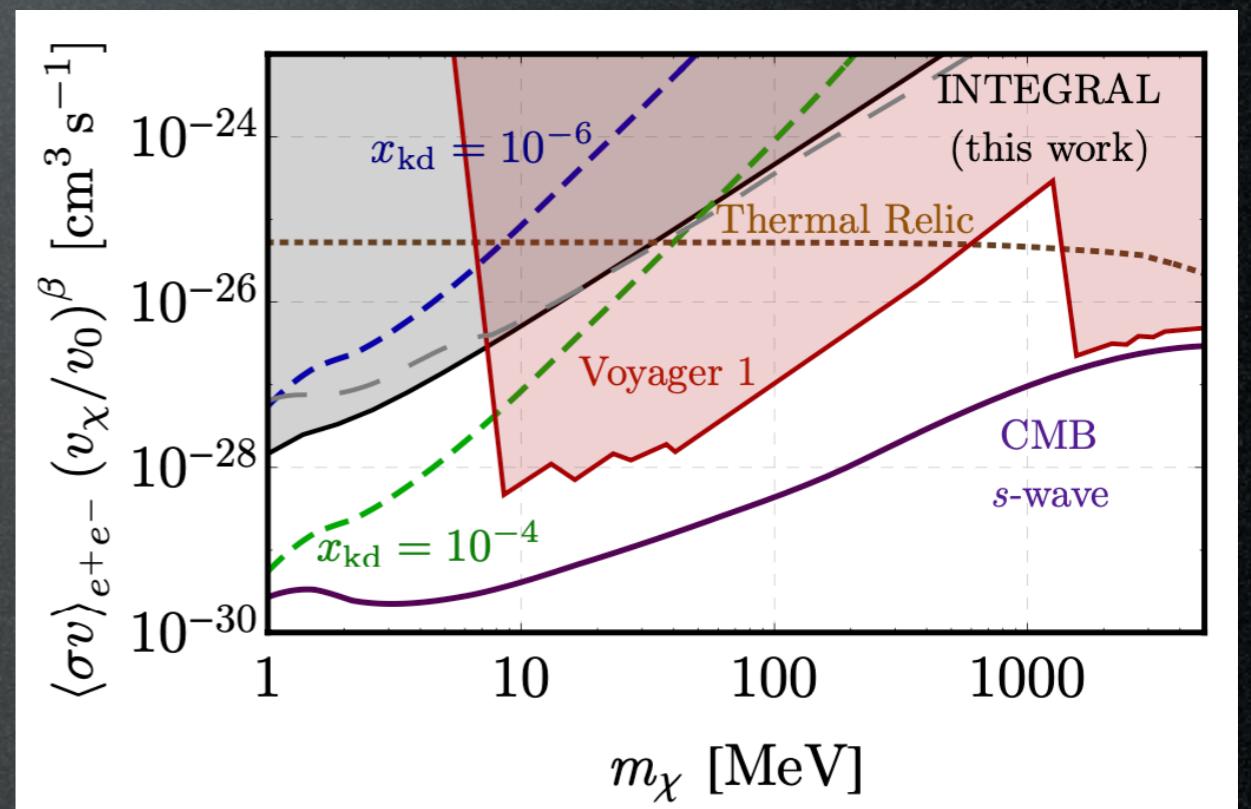
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# Some recent studies

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



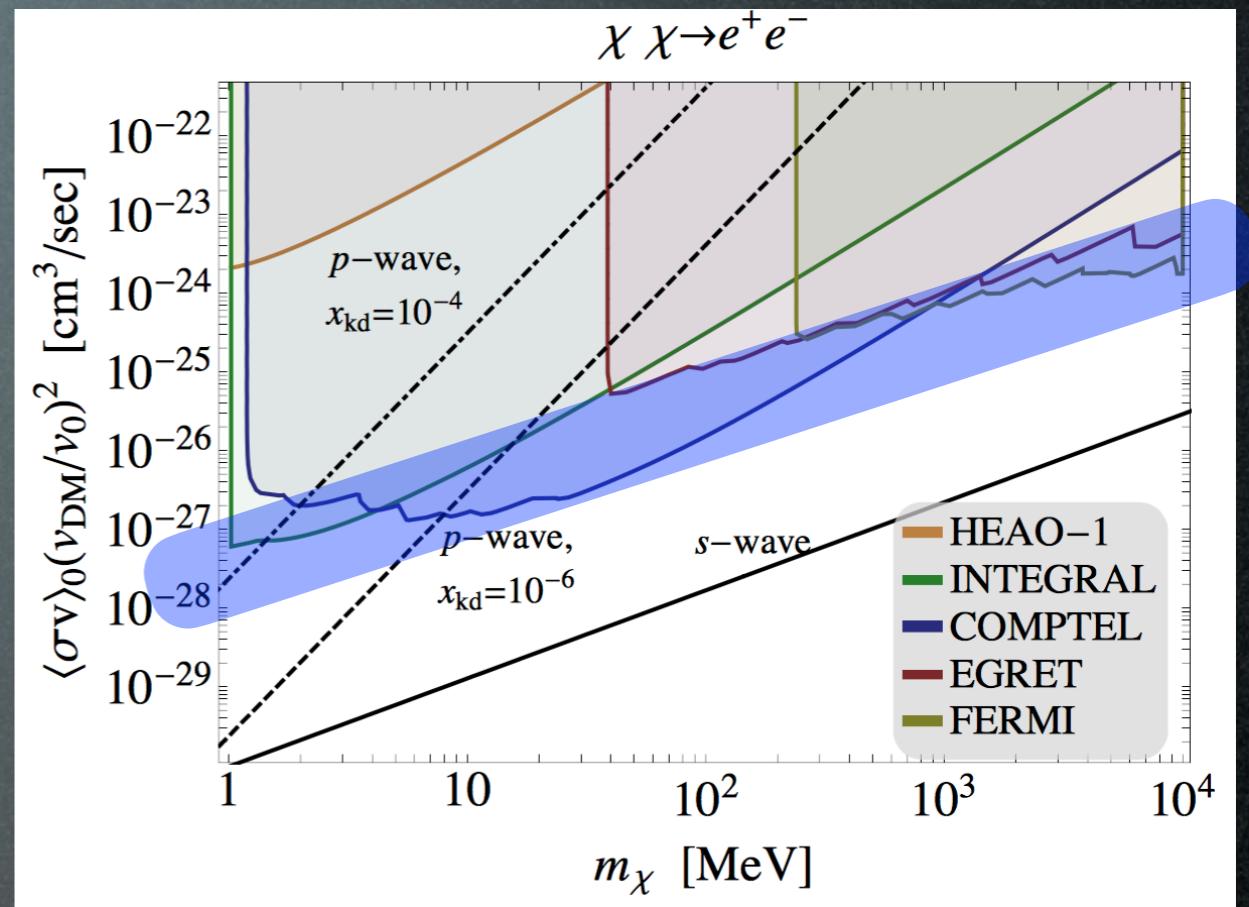
Laha, Muñoz, Slatyer, 2004.00627v1



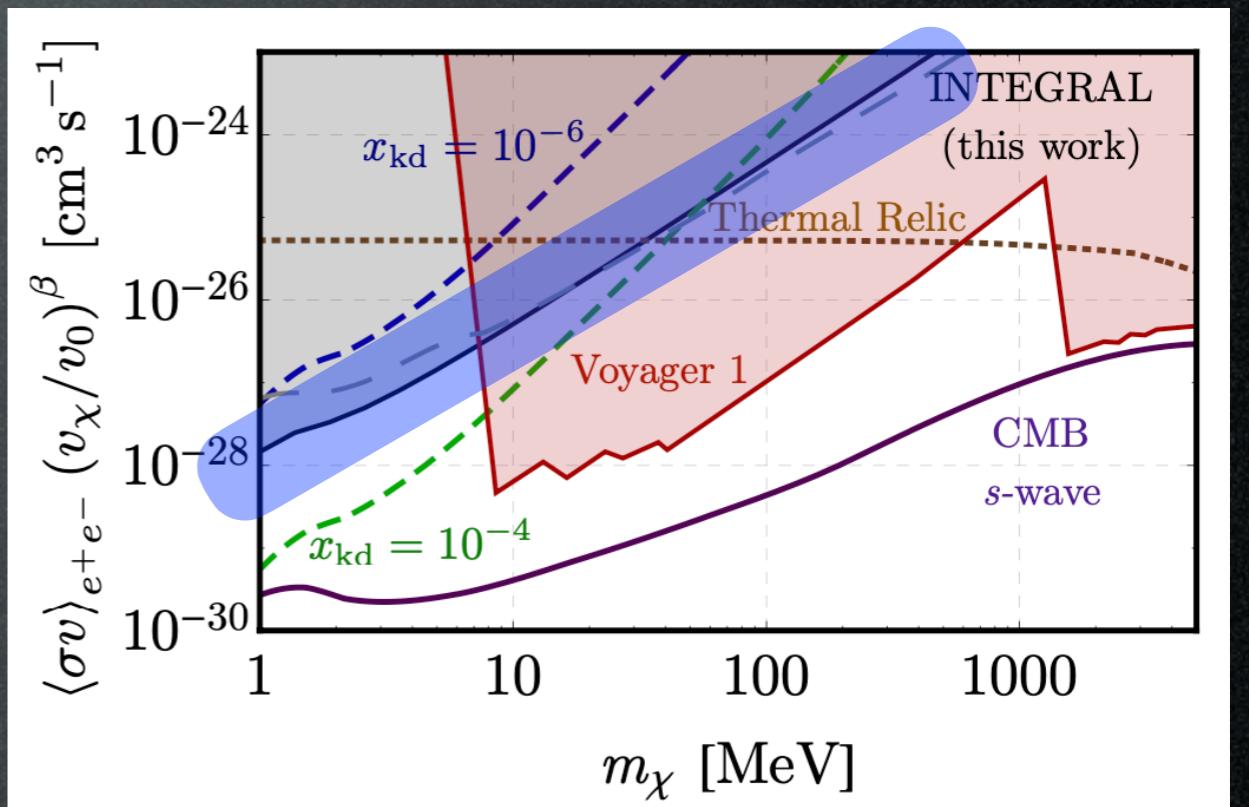
NB: ‘prompt’ emission only

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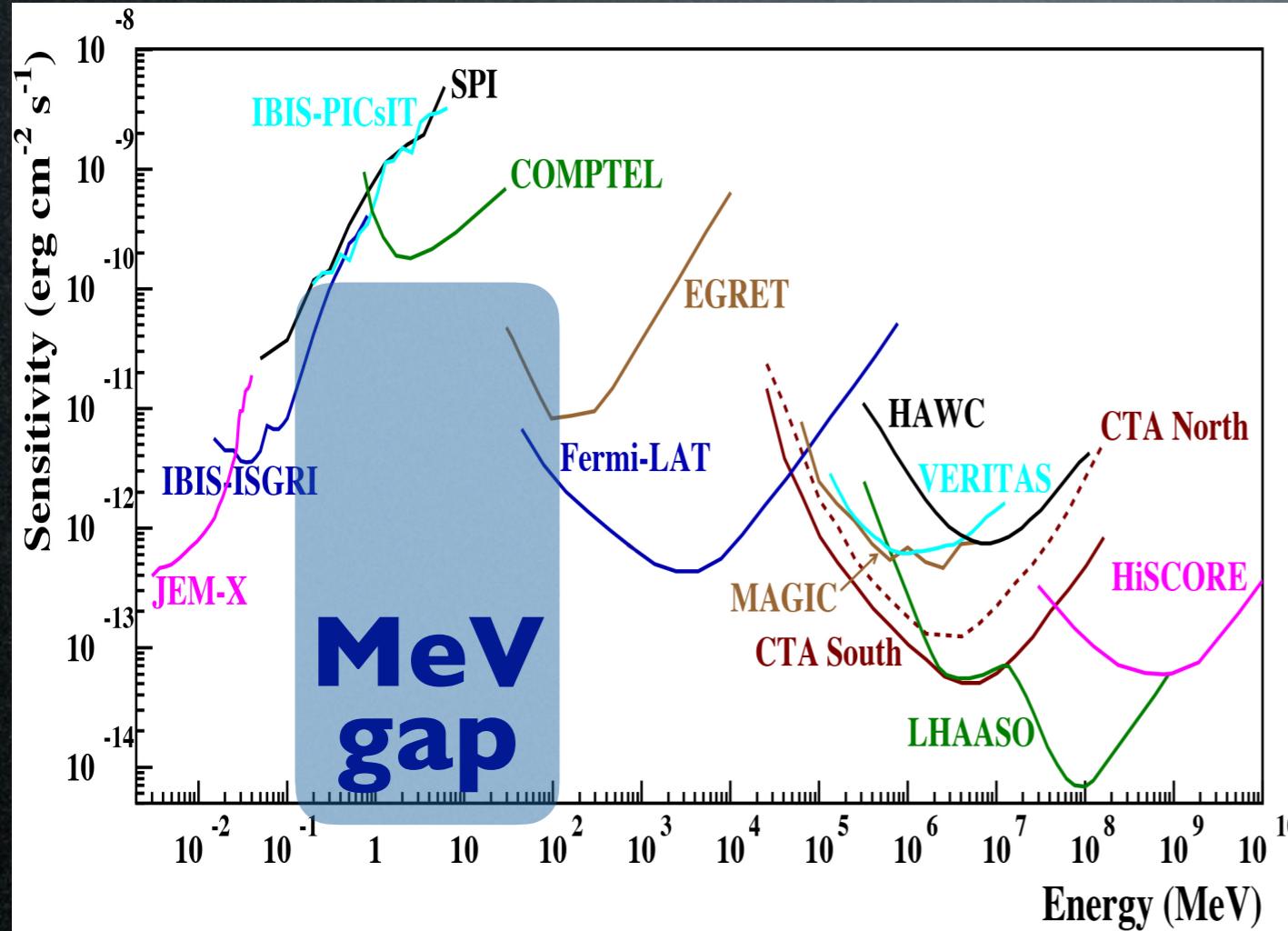
Laha, Muñoz, Slatyer, 2004.00627v1



NB: ‘prompt’ emission only

# Indirect detection: photons

adapted from 1611.02232



How to do better?  
ICS & X-rays!

# Sub-GeV DM & X-rays

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

$$\text{DM DM} \rightarrow e^+ e^-$$

$$\text{DM DM} \rightarrow \mu^+ \mu^-$$

$$\text{DM DM} \rightarrow \pi^+ \pi^-$$

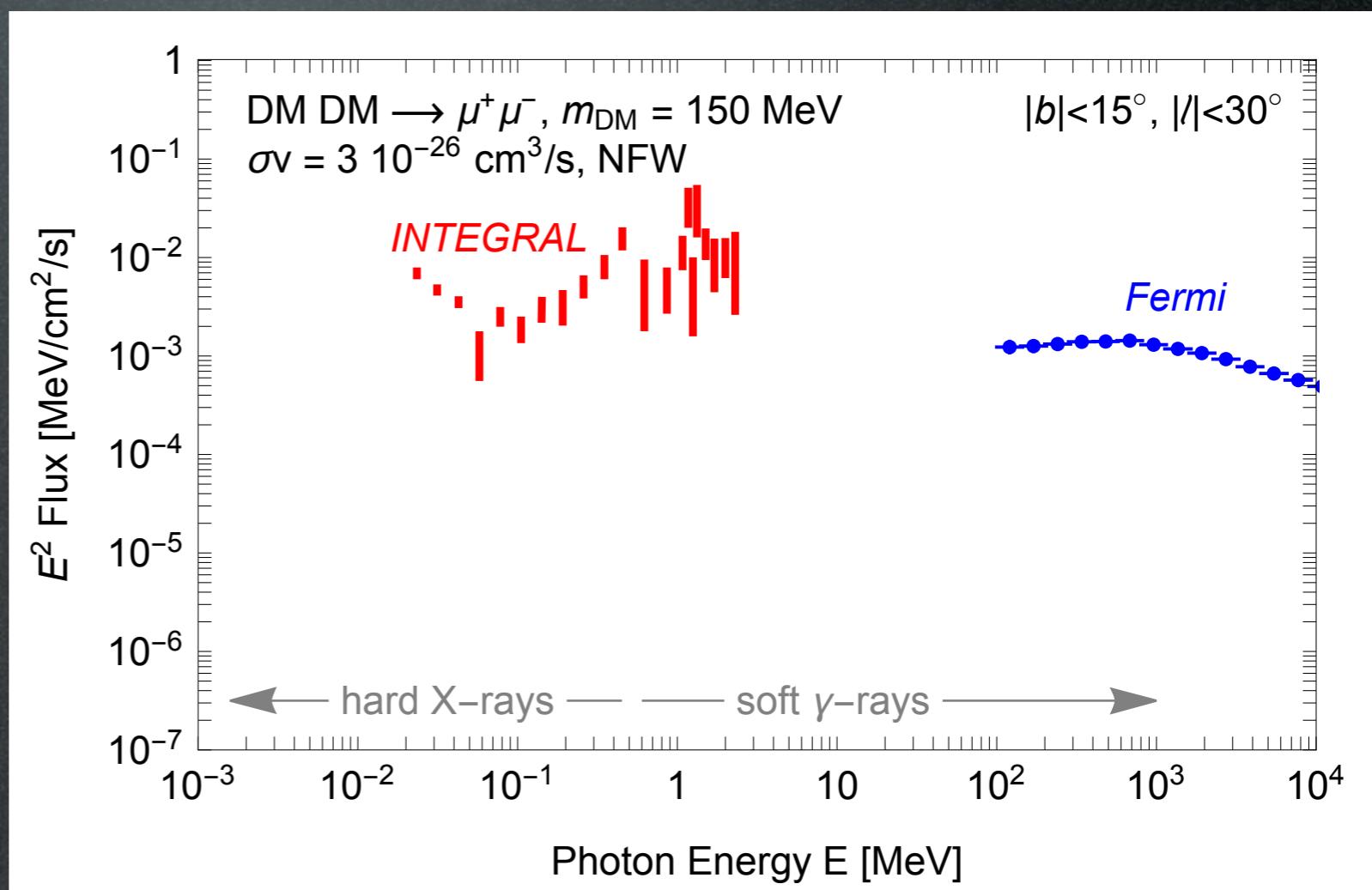
# Sub-GeV DM & X-rays

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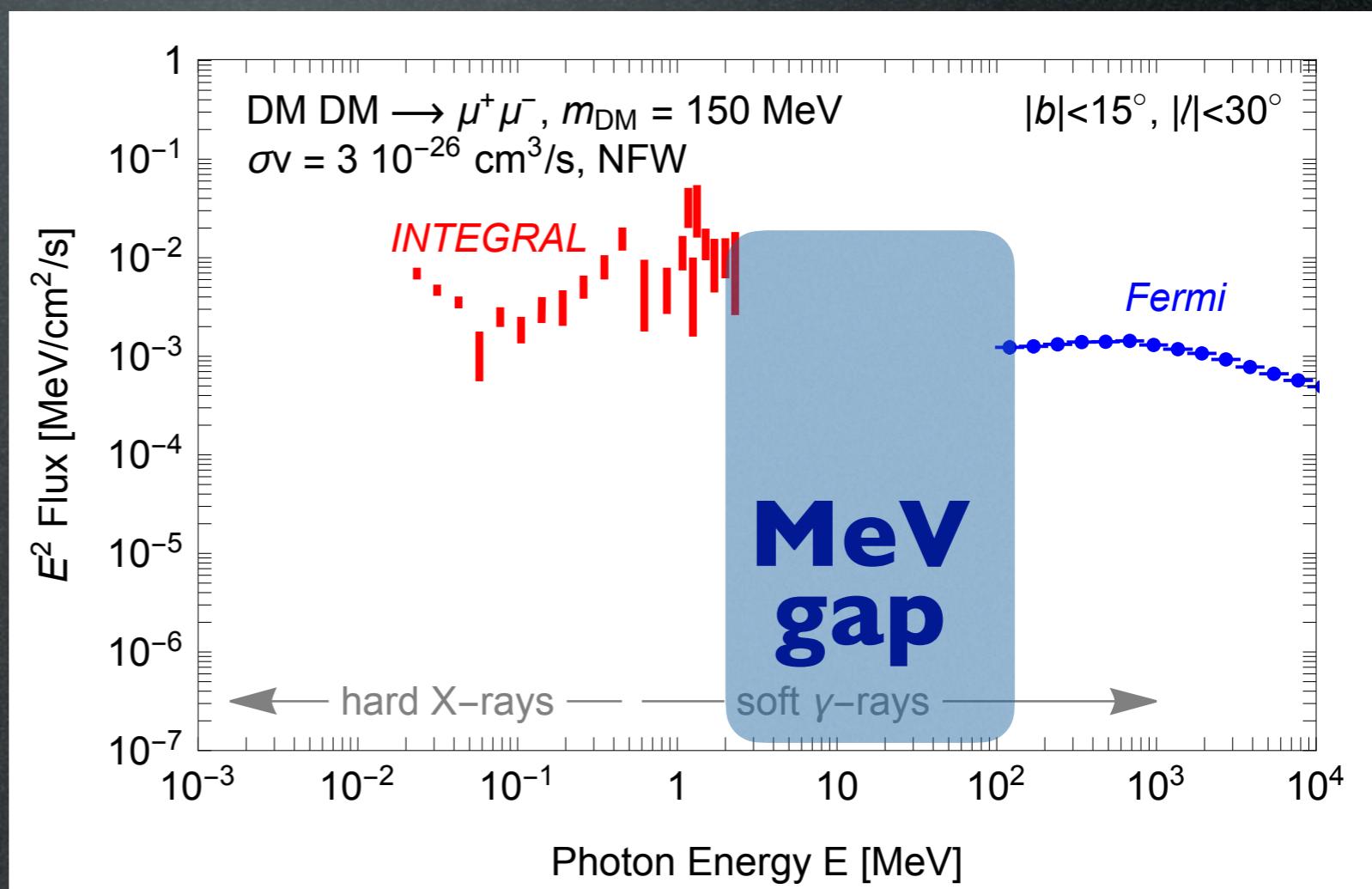
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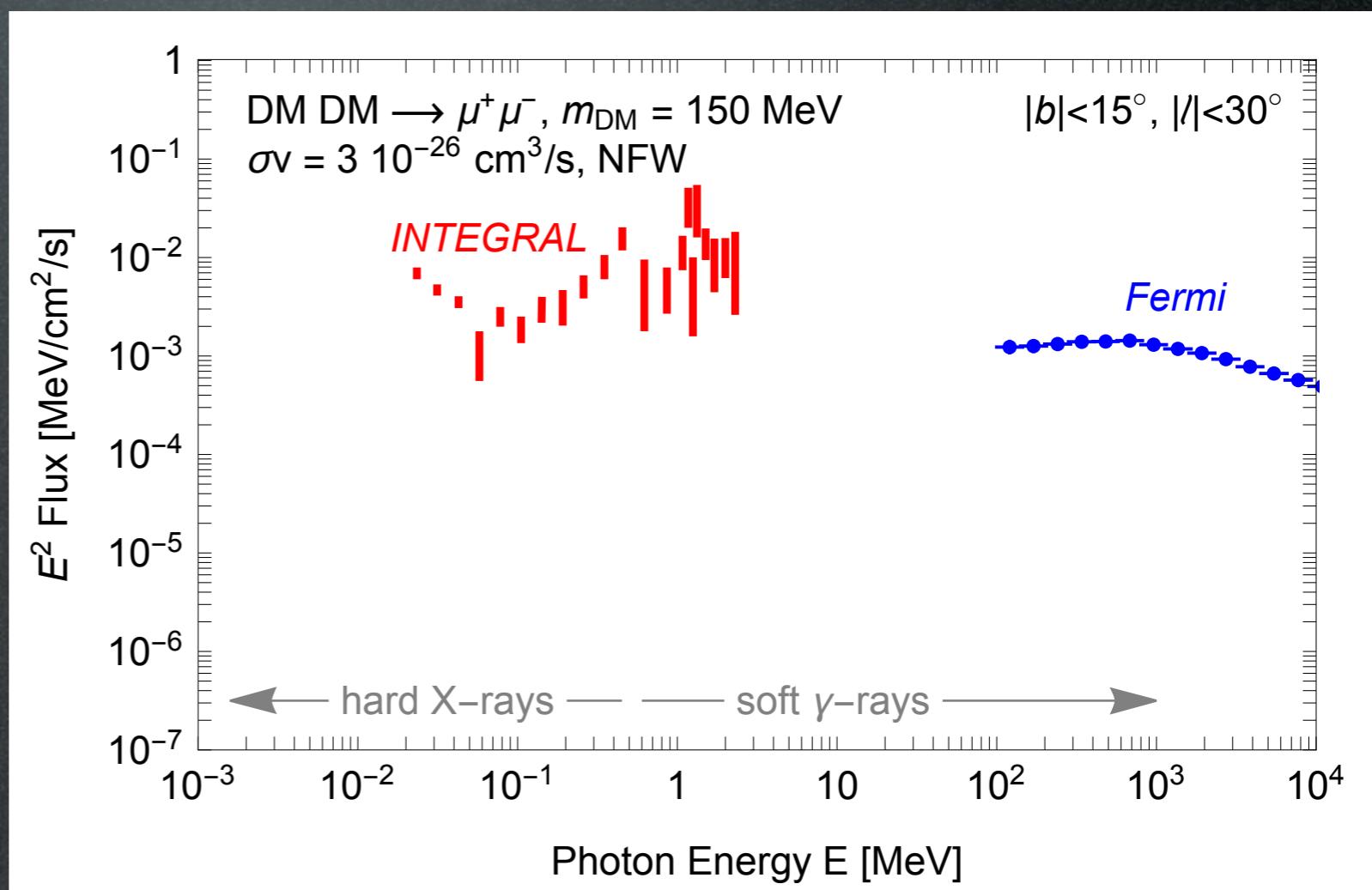
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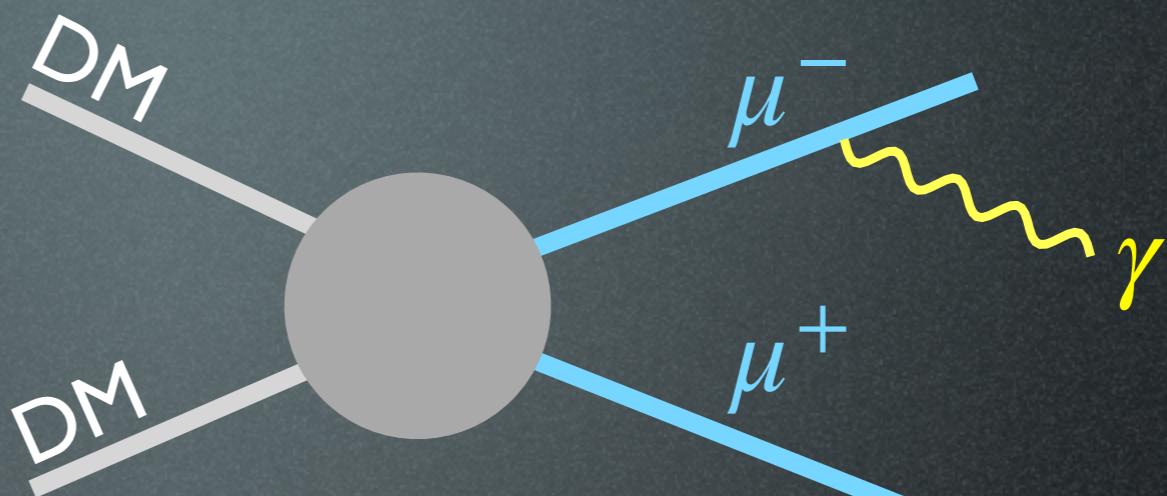
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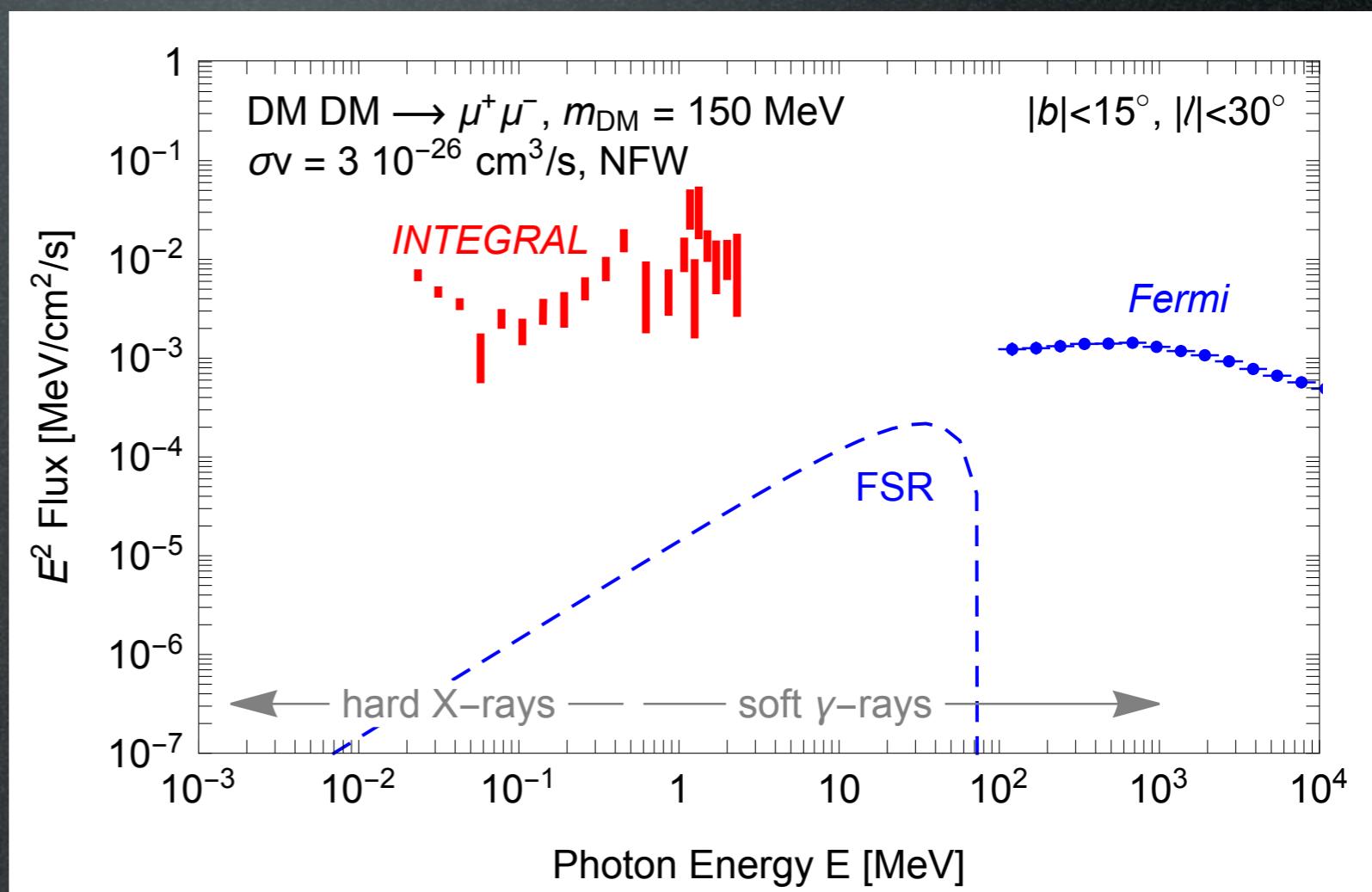
DM DM  $\rightarrow e^+e^-$

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‘Prompt’ emission:  
Final State Radiation (FSR)



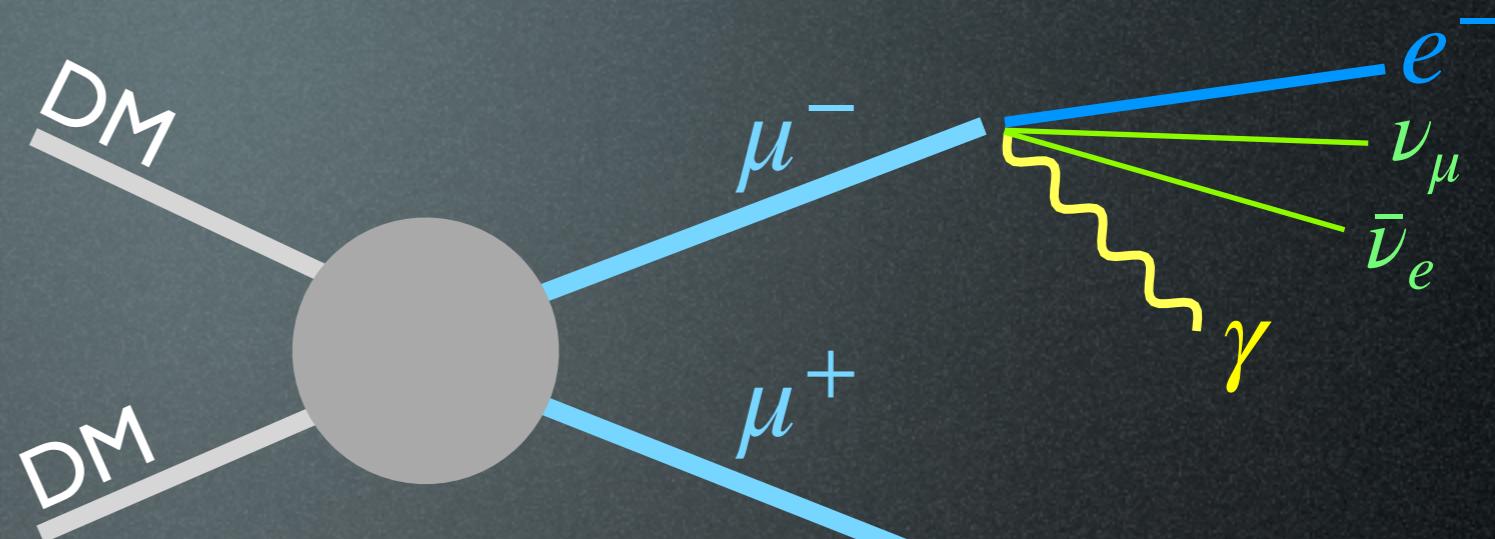
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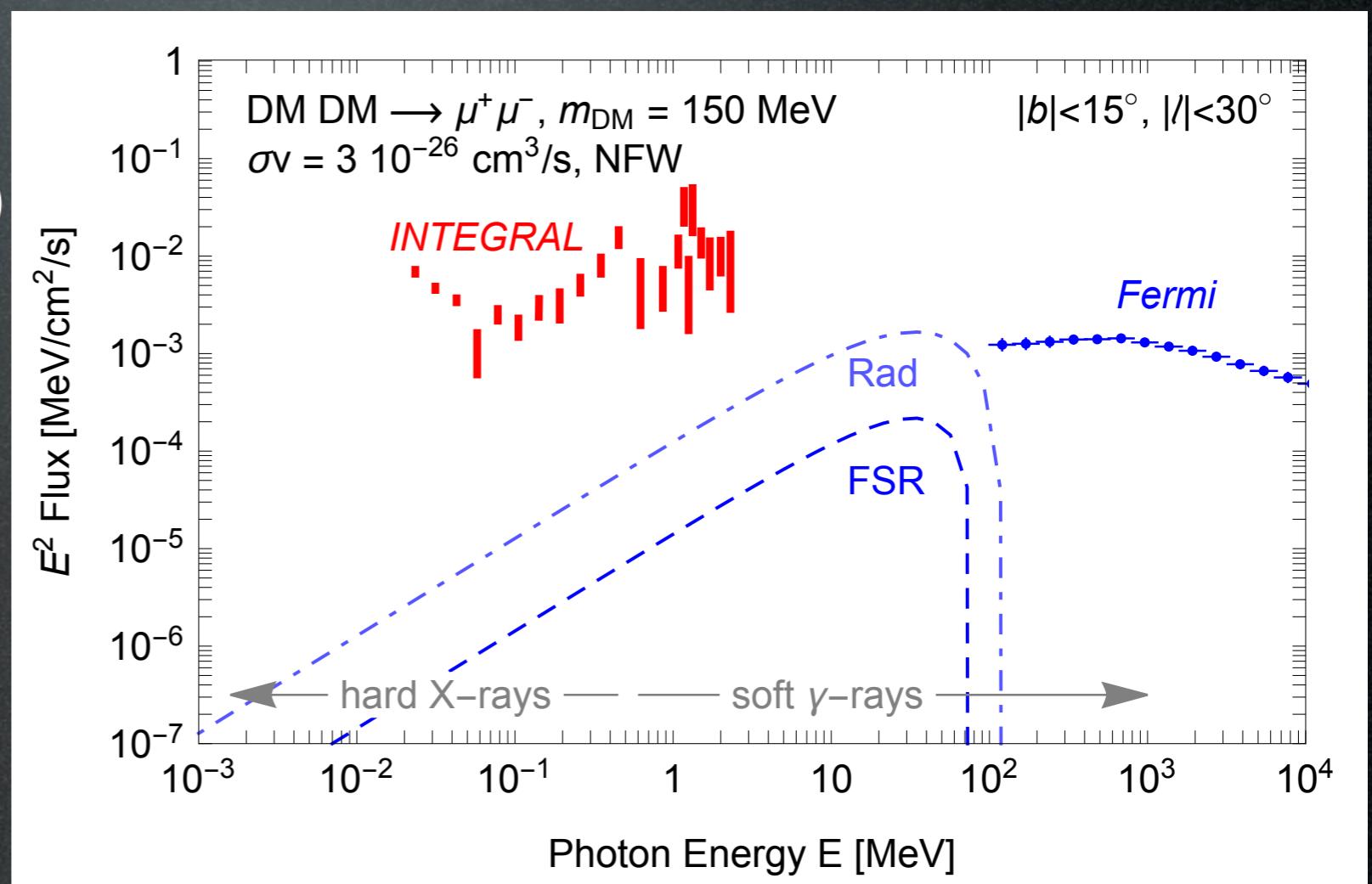
$$\text{DM DM} \rightarrow \mu^+ \mu^-$$

$$\text{DM DM} \rightarrow \pi^+ \pi^-$$



‘Prompt’ emission:  
Final State Radiation (FSR)  
Radiative  $\mu$  decay

*Usually irrelevant,  
but not for  $\mu$   
decaying ‘at rest’!*



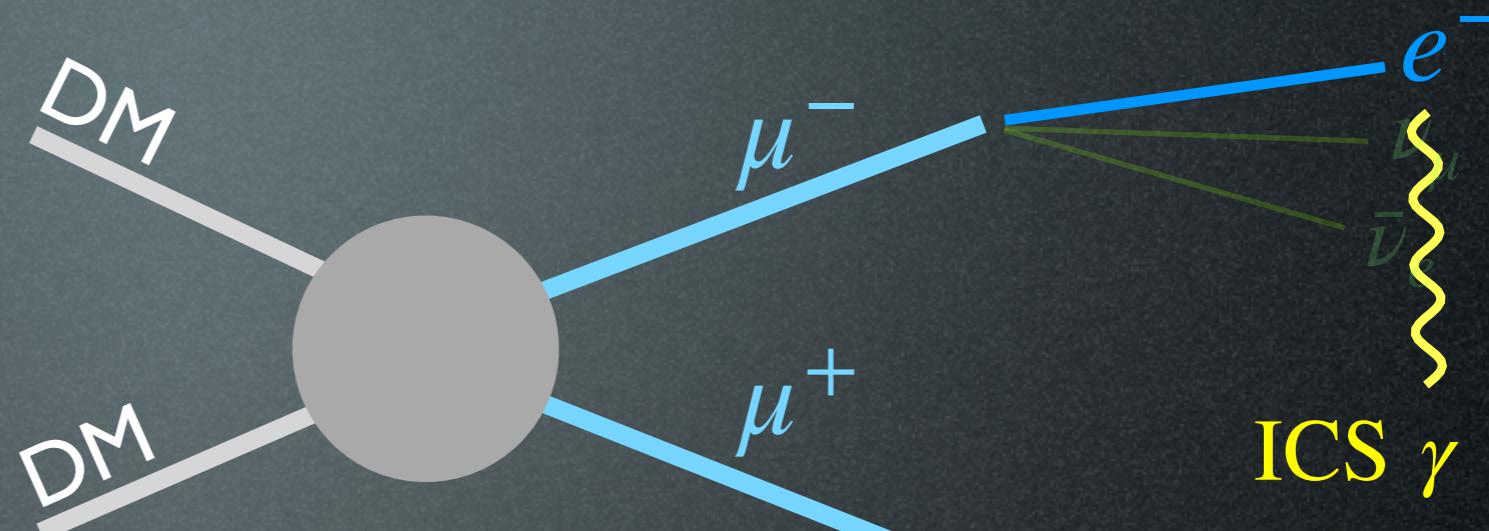
# Sub-GeV DM & X-rays

## Annihilation channels

$$\text{DM DM} \rightarrow e^+ e^-$$

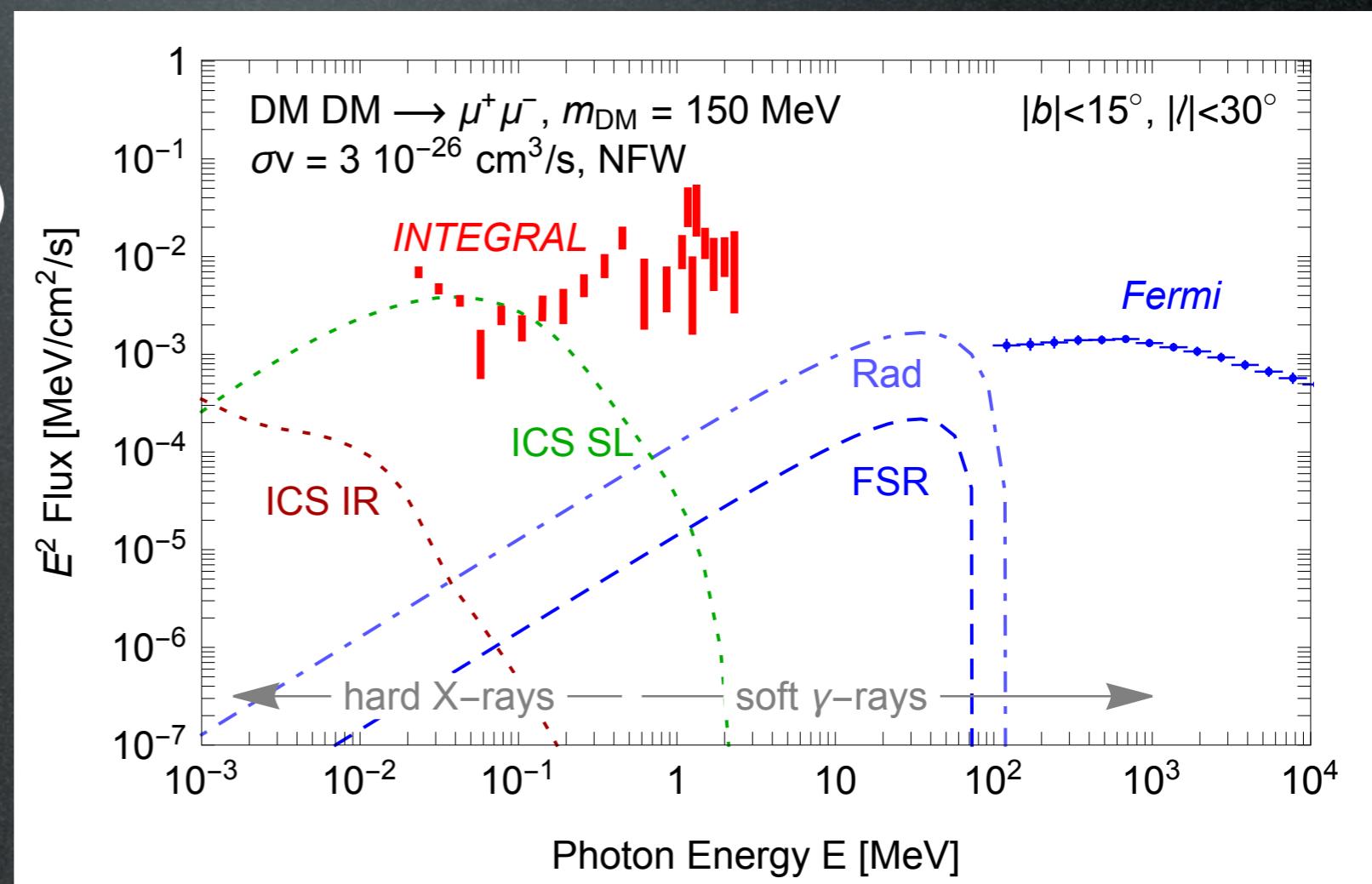
$$\text{DM DM} \rightarrow \mu^+ \mu^-$$

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‘Prompt’ emission:  
Final State Radiation (FSR)  
Radiative  $\mu$  decay

Secondary emission:  
ICS: inevitably associated  
to annihil to charged states



# Sub-GeV DM & X-rays

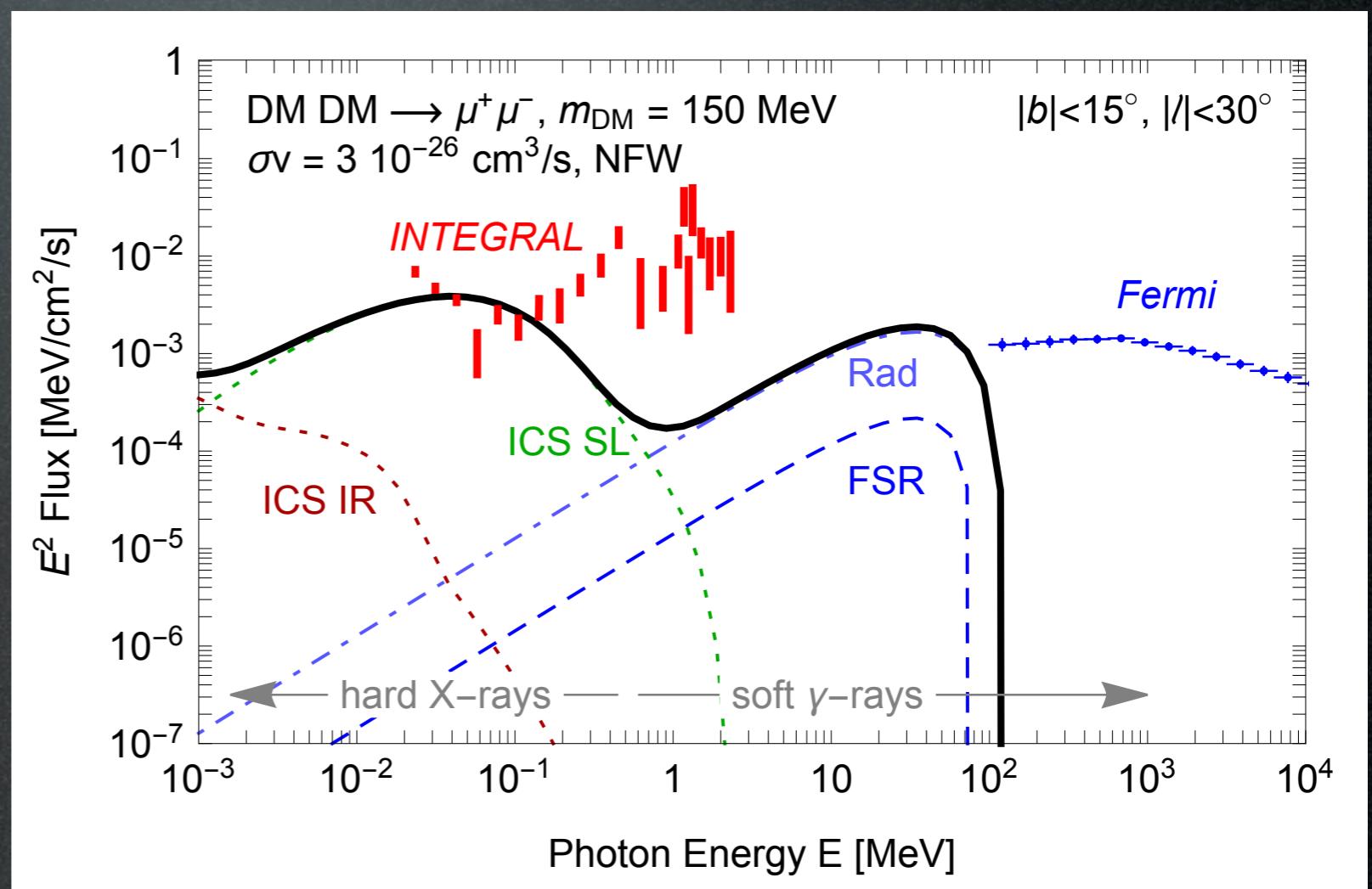
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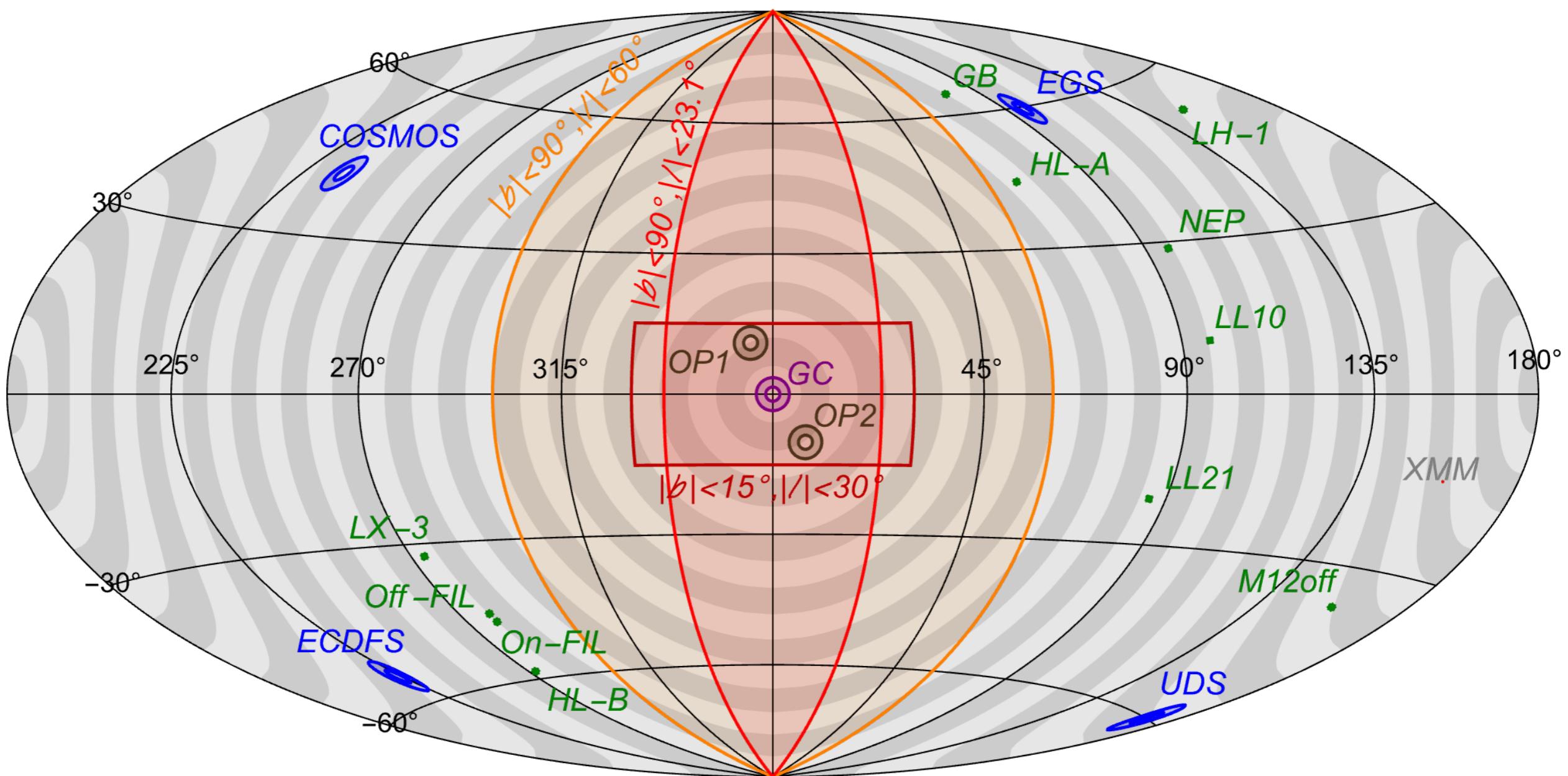
$$\text{DM DM} \rightarrow \pi^+ \pi^-$$

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



# More data !

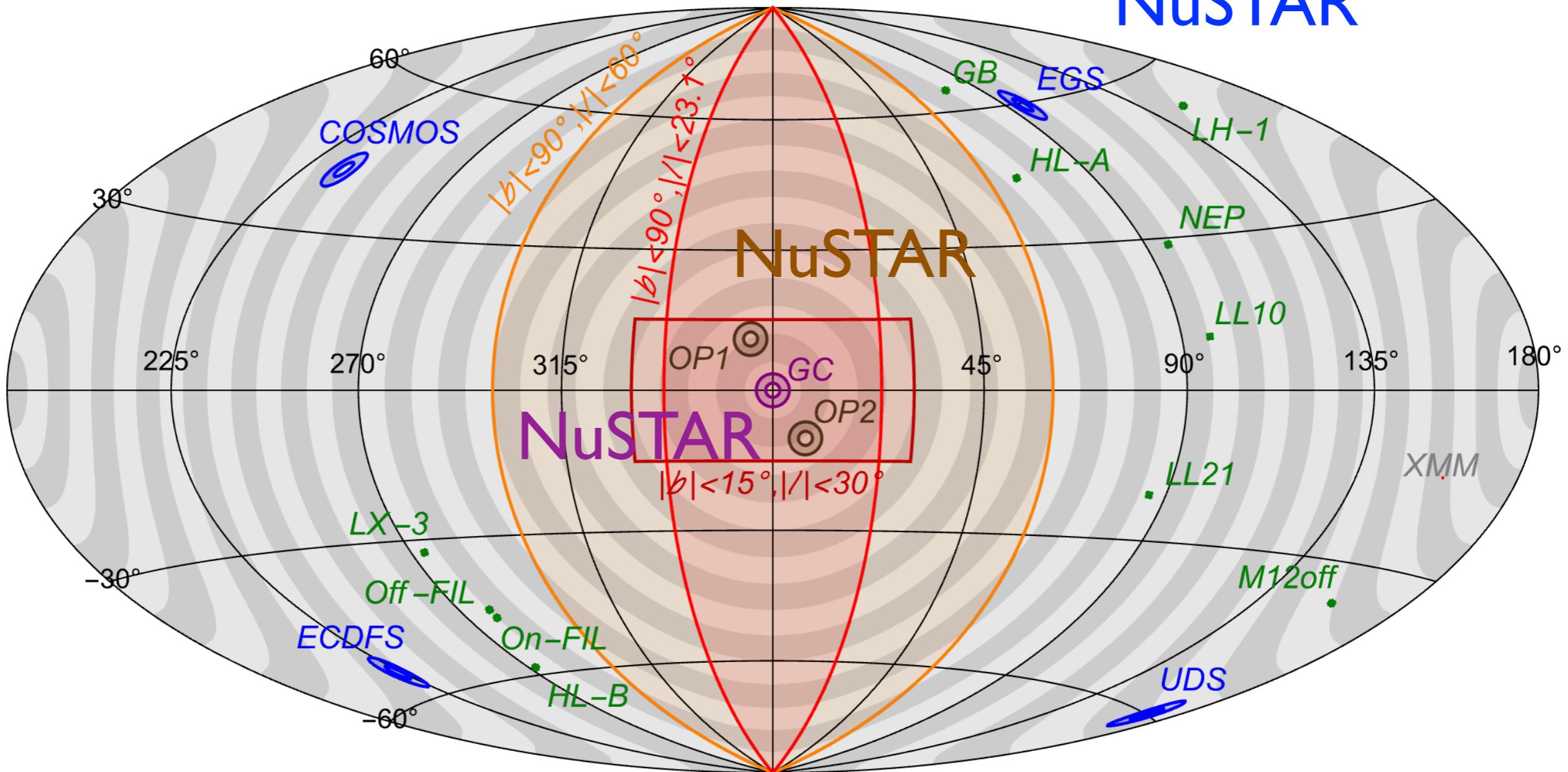
## INTEGRAL



# More data !

INTEGRAL

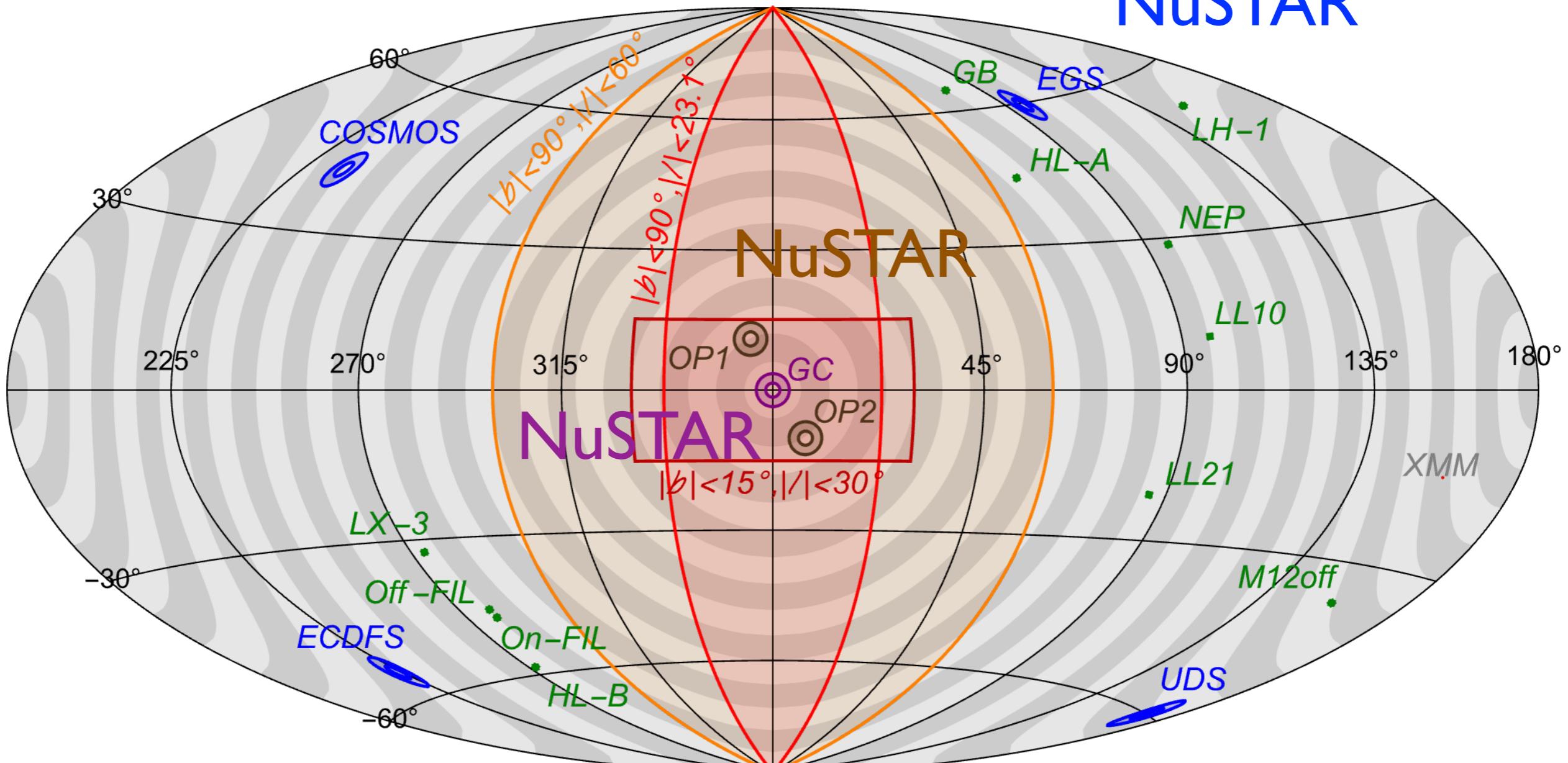
NuSTAR



# More data !

INTEGRAL

NuSTAR

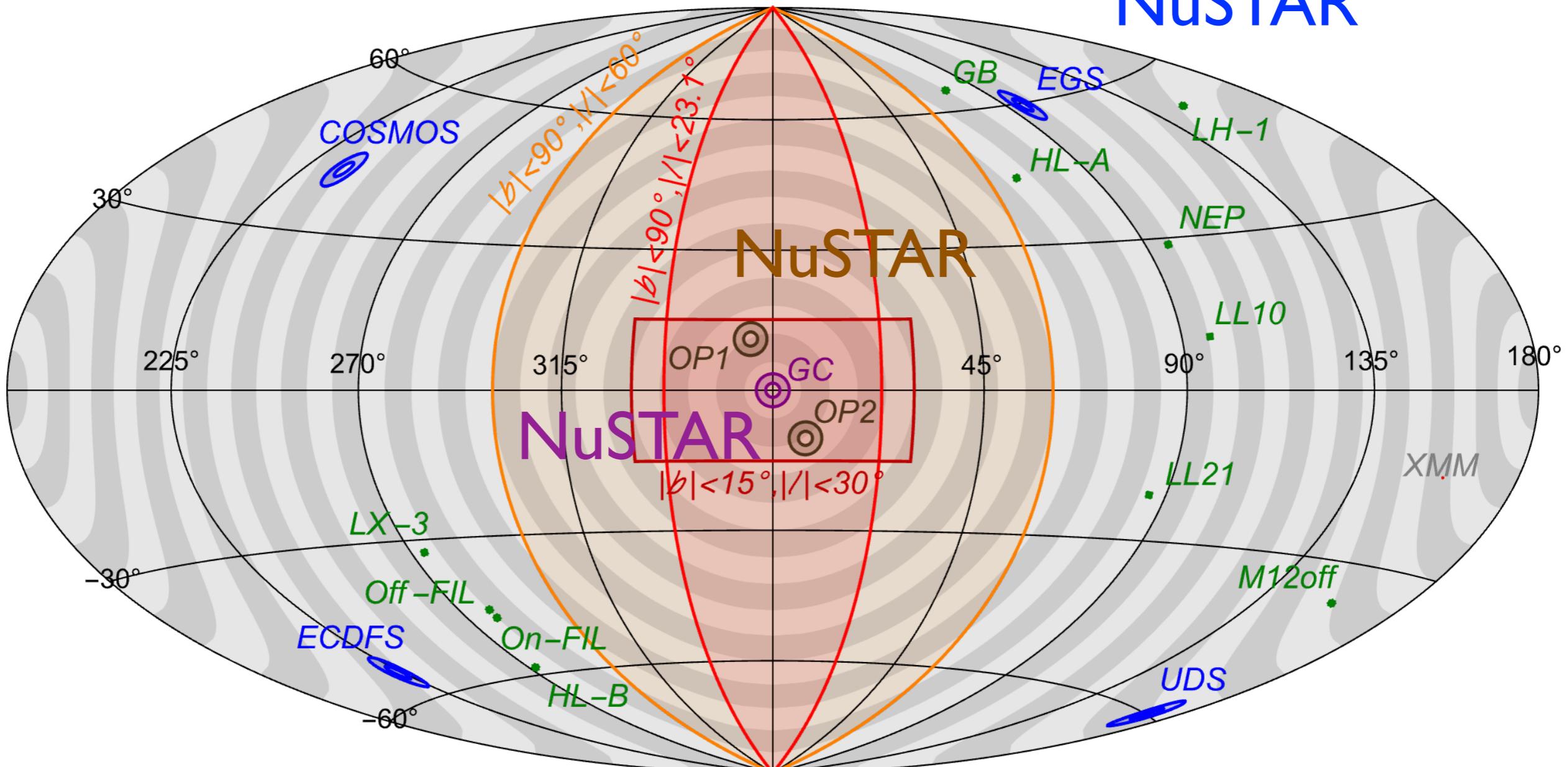


Suzaku

# More data!

INTEGRAL

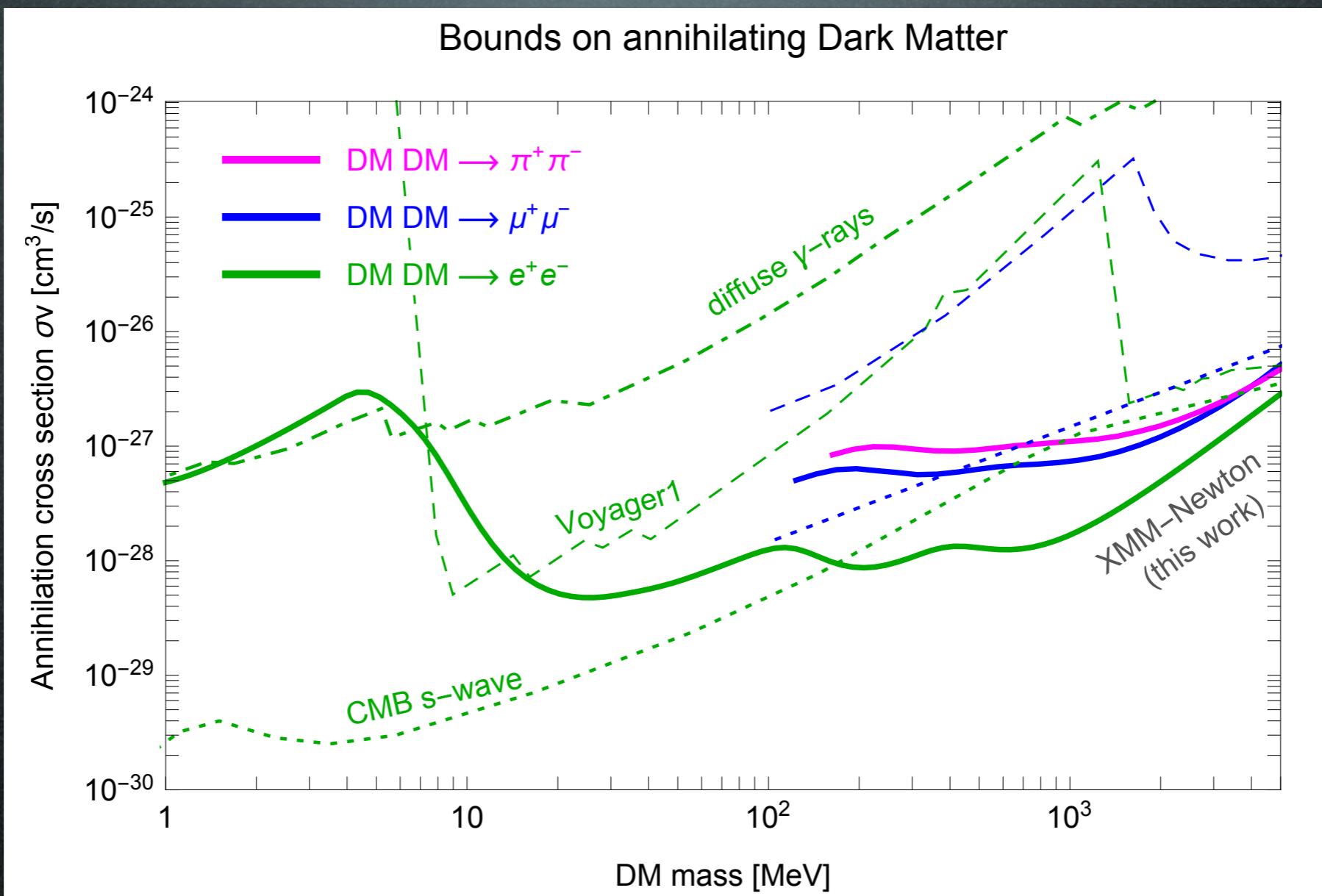
NuSTAR



Suzaku

XMM-Newton

# Results



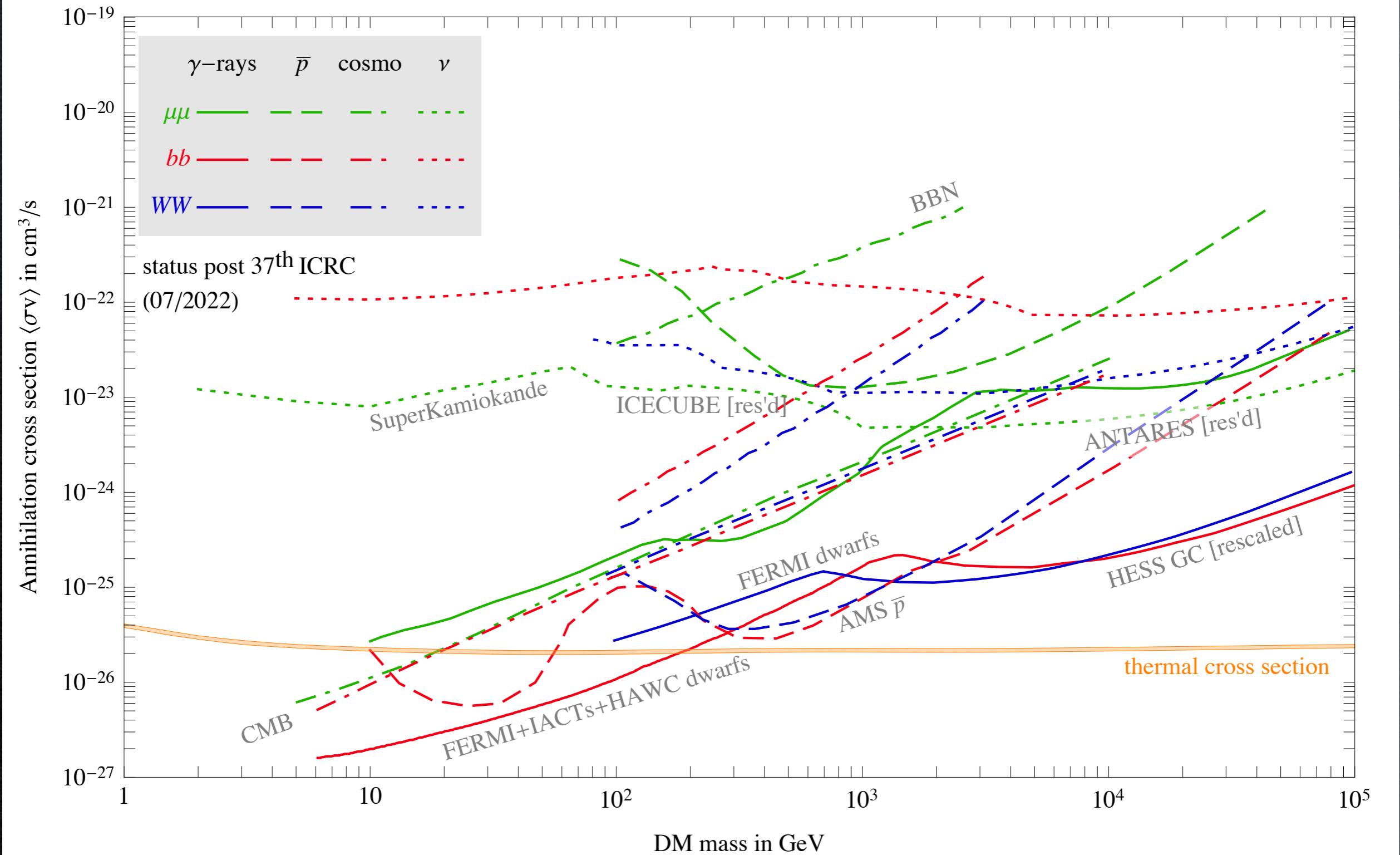
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

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



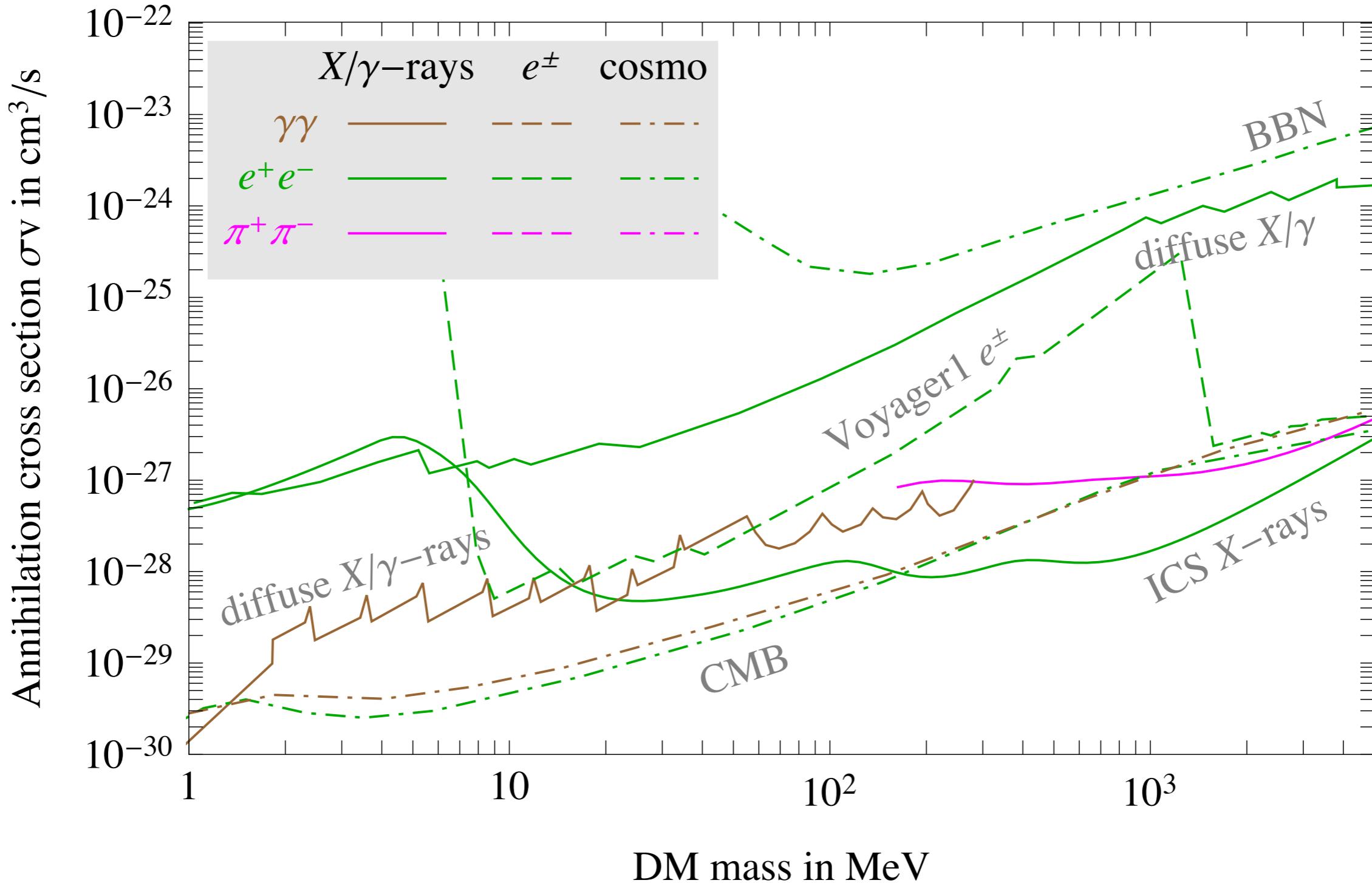
# Comparing all bounds

All Indirect Detection constraints



# Comparing all bounds

## Constraints on sub-GeV annihilating Dark Matter





# Conclusions

DM not seen yet (<sup>Damn!...</sup>)

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

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

- in  $e^\pm$ : long standing HE ‘excesses’, new LE chances
- in  $\bar{p}$ : still large uncertainties, but improving
- in  $\bar{d}$ : challenging flux
- in  $\bar{He}$ : hopeless? who knows!...
- in  $\nu$ : challenging detection
- in  $\gamma$ : astrophysical background

Solution:

# Conclusions

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

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in  $V$ : challenging detection  
in  $\gamma$ : astrophysical background

Solution:

- multimessenger

# Conclusions

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

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in  $e^\pm$ : long standing HE ‘excesses’, new LE chances  
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Solution:

- multimessenger
- switch-off astrophysics

# **Back up slides**