

29 September 2026
News from the Dark 11 - IPhT Saclay

Dark Matter Indirect Searches as of 2026

Marco Cirelli
(CNRS LPTHE Jussieu)



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News from the Dark 11 - IPhT Saclay

selected topics in...

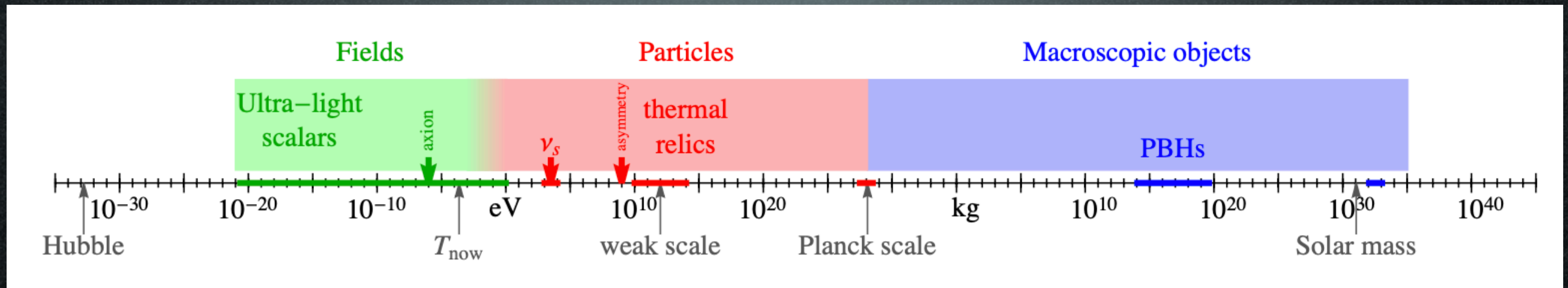
Dark Matter Indirect Searches as of 2026

Marco Cirelli
(CNRS LPTHE Jussieu)



Candidates

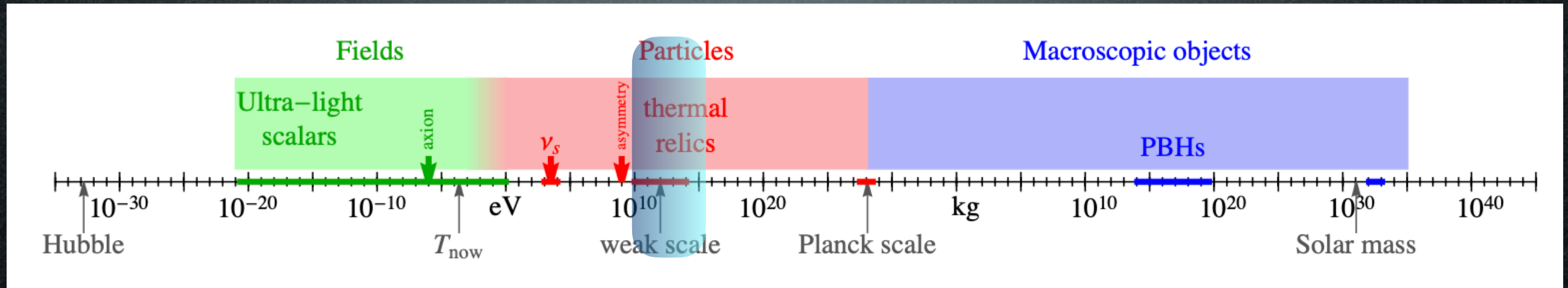
A matter of perspective: plausible mass ranges



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
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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

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

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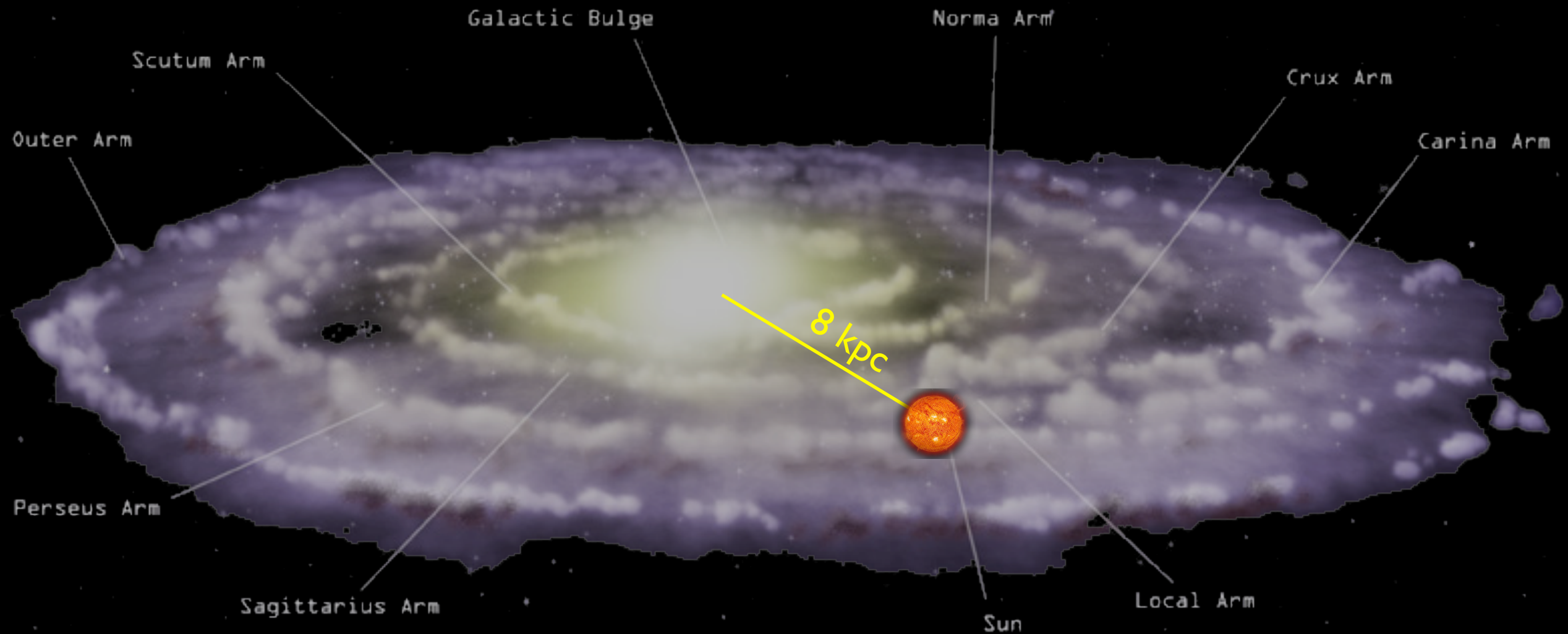
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$\nu, \bar{\nu}$ from annihil in massive bodies

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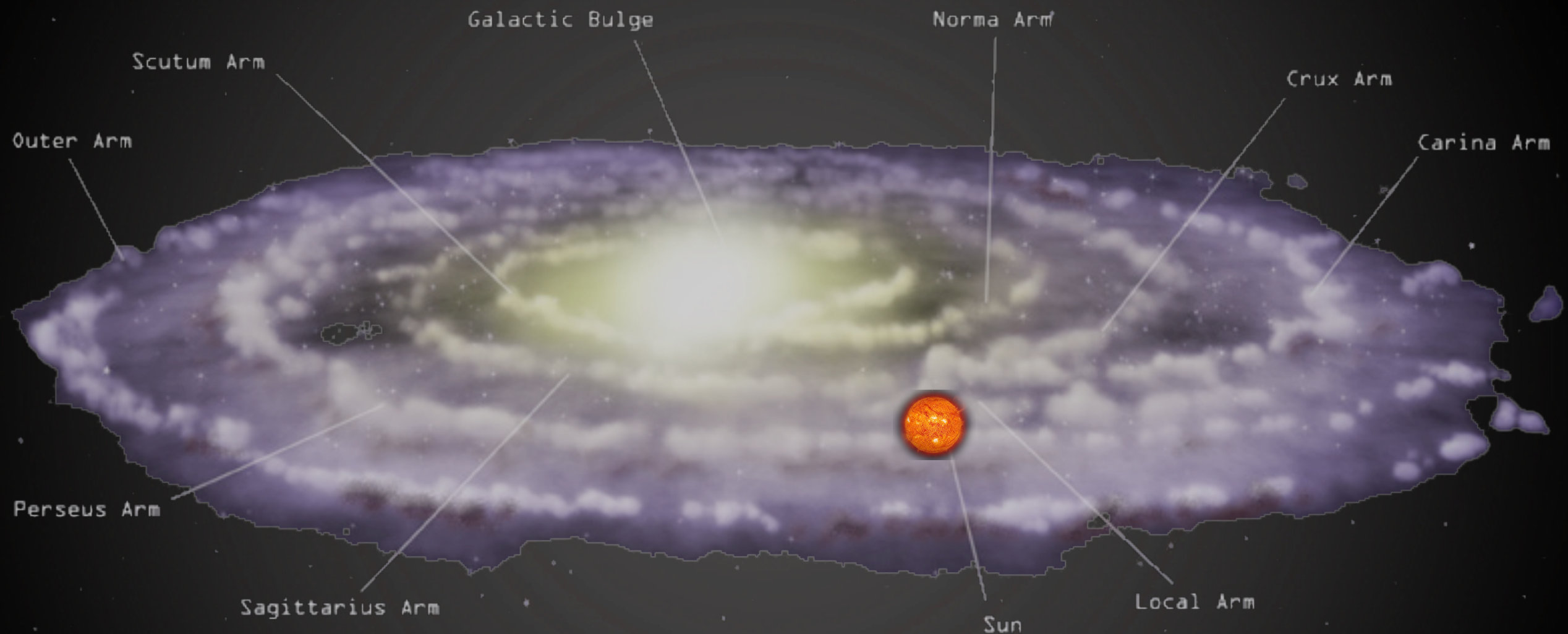
Indirect Detection: charged CRs

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



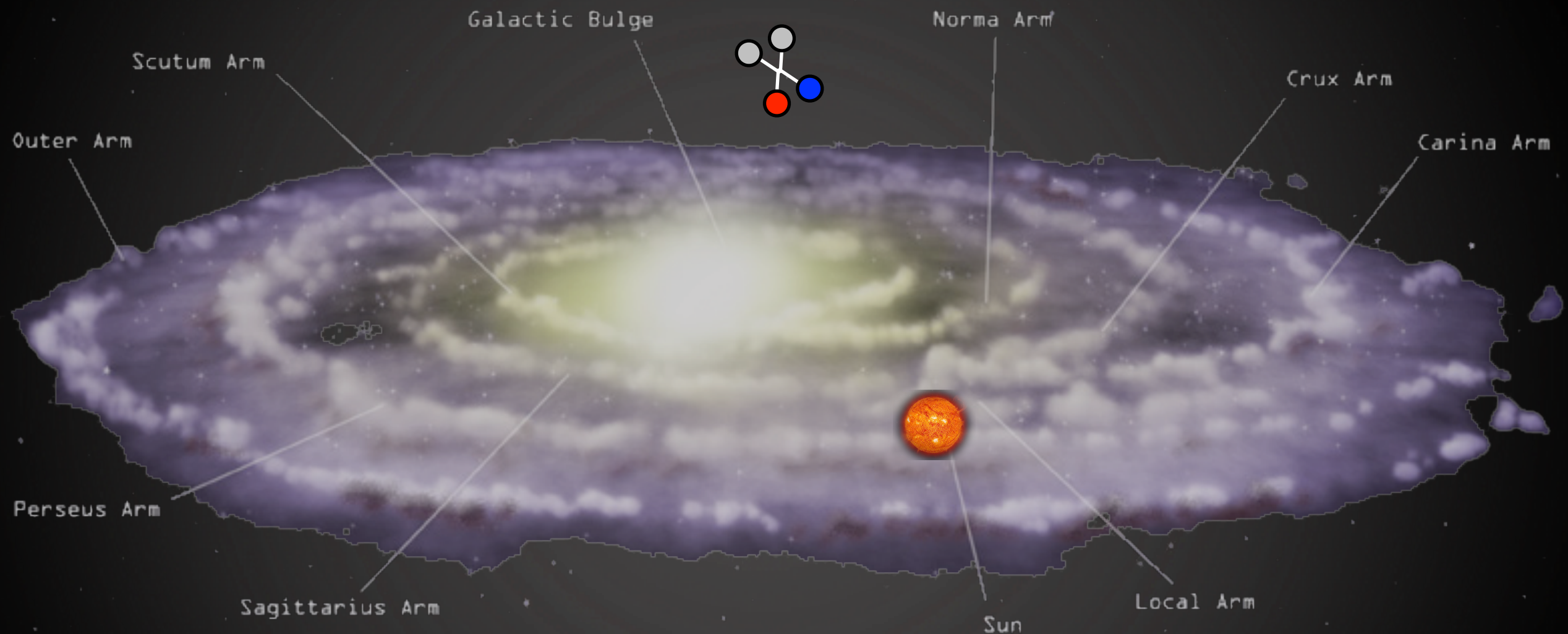
Indirect Detection: charged CRs

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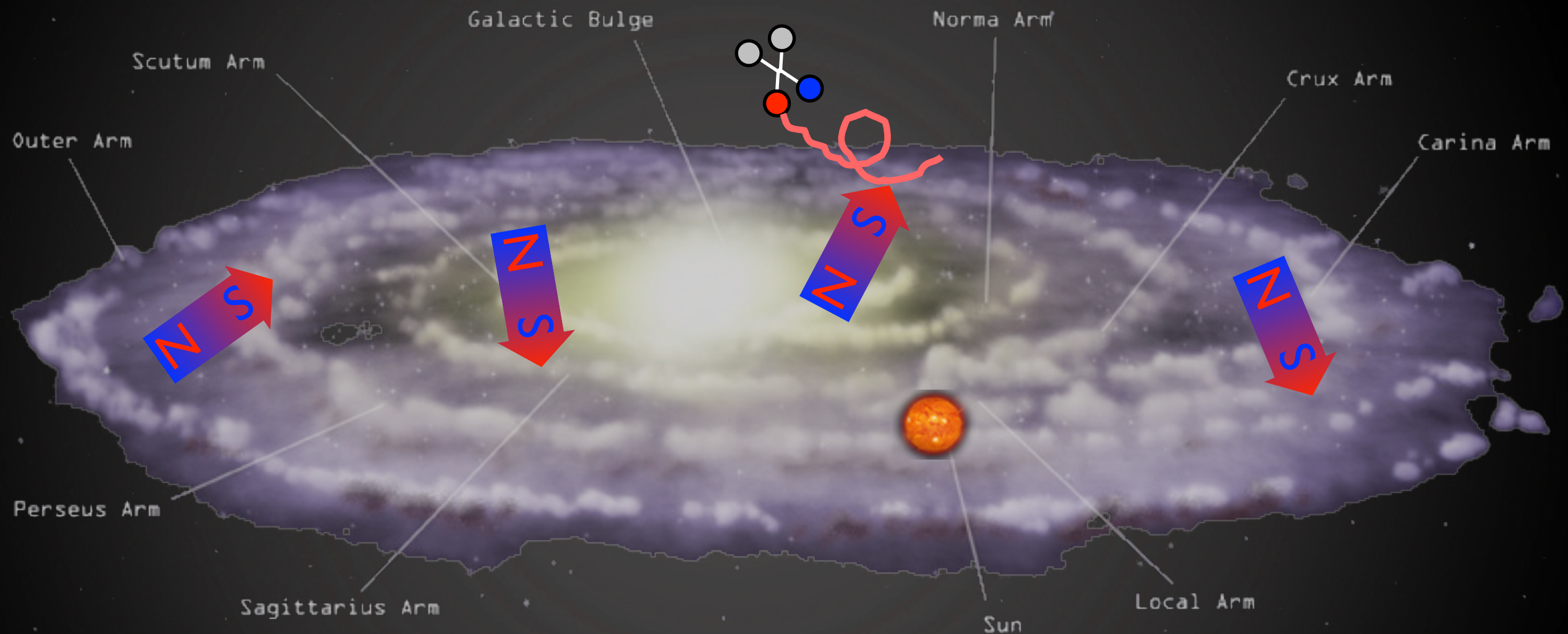
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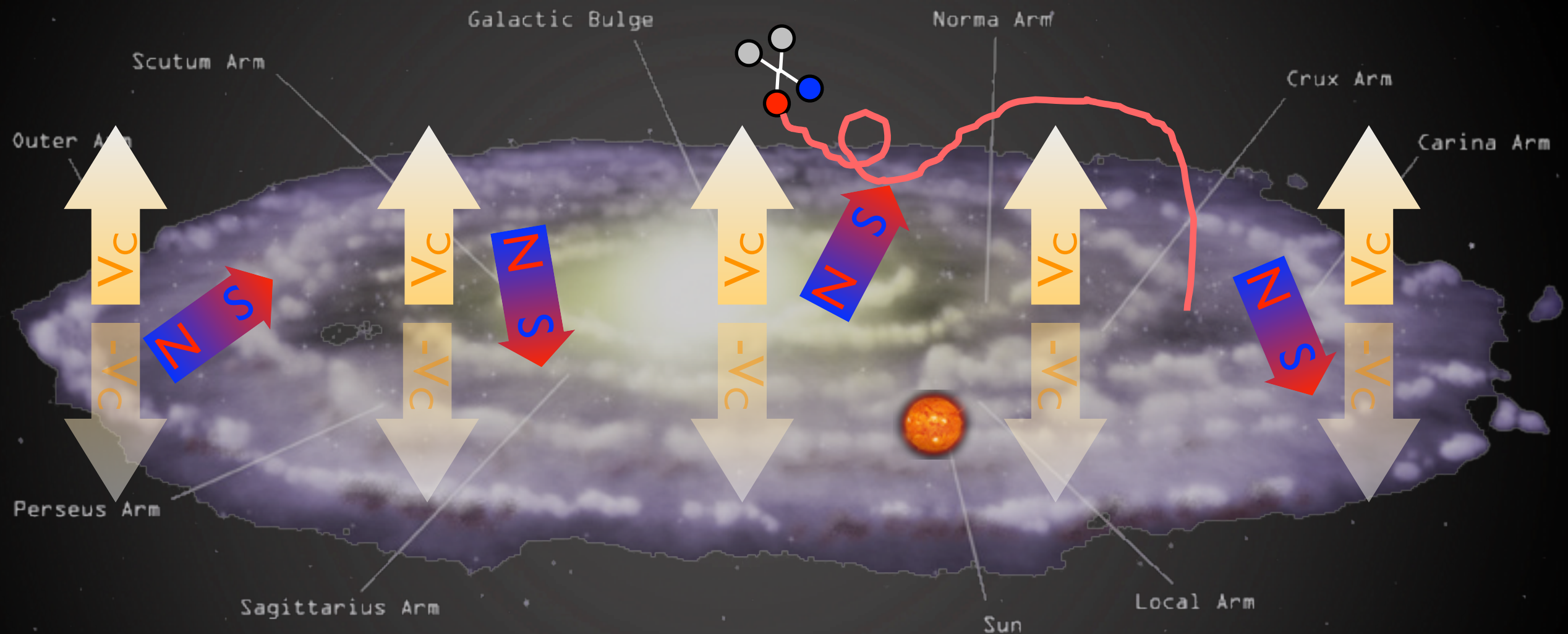
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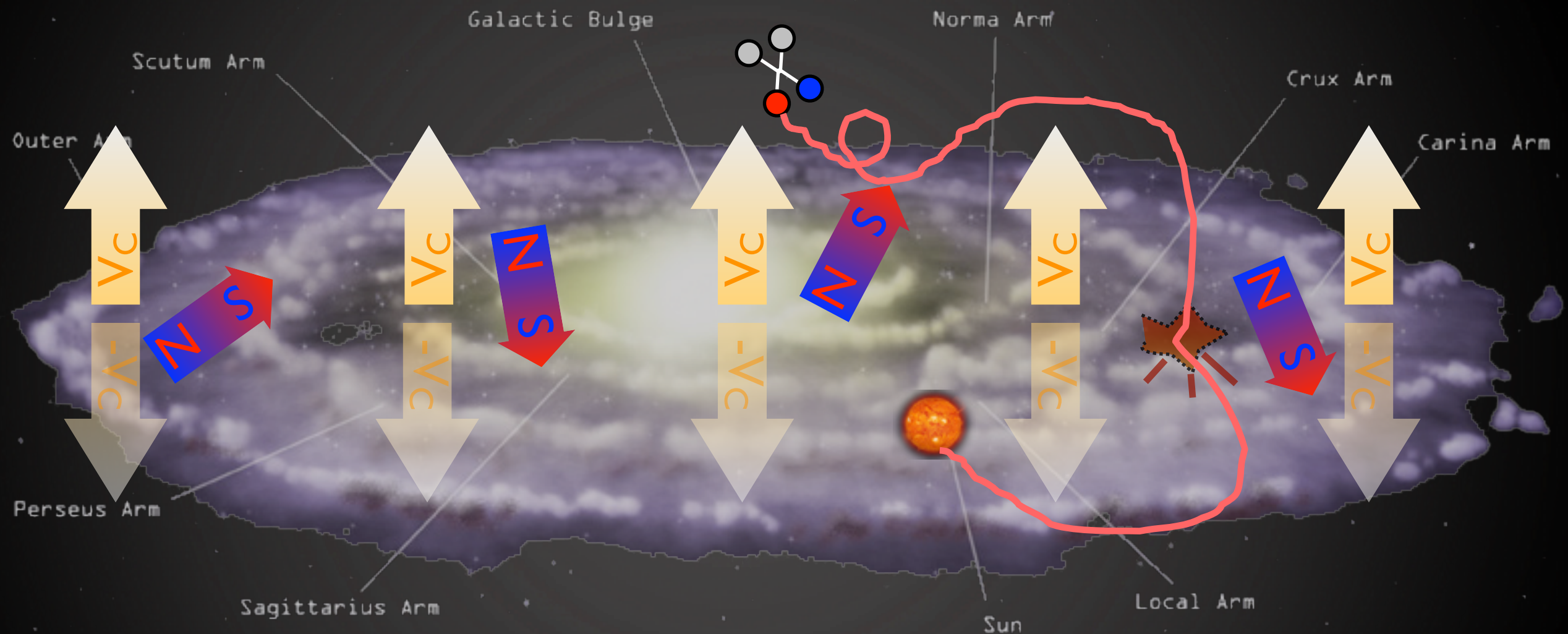
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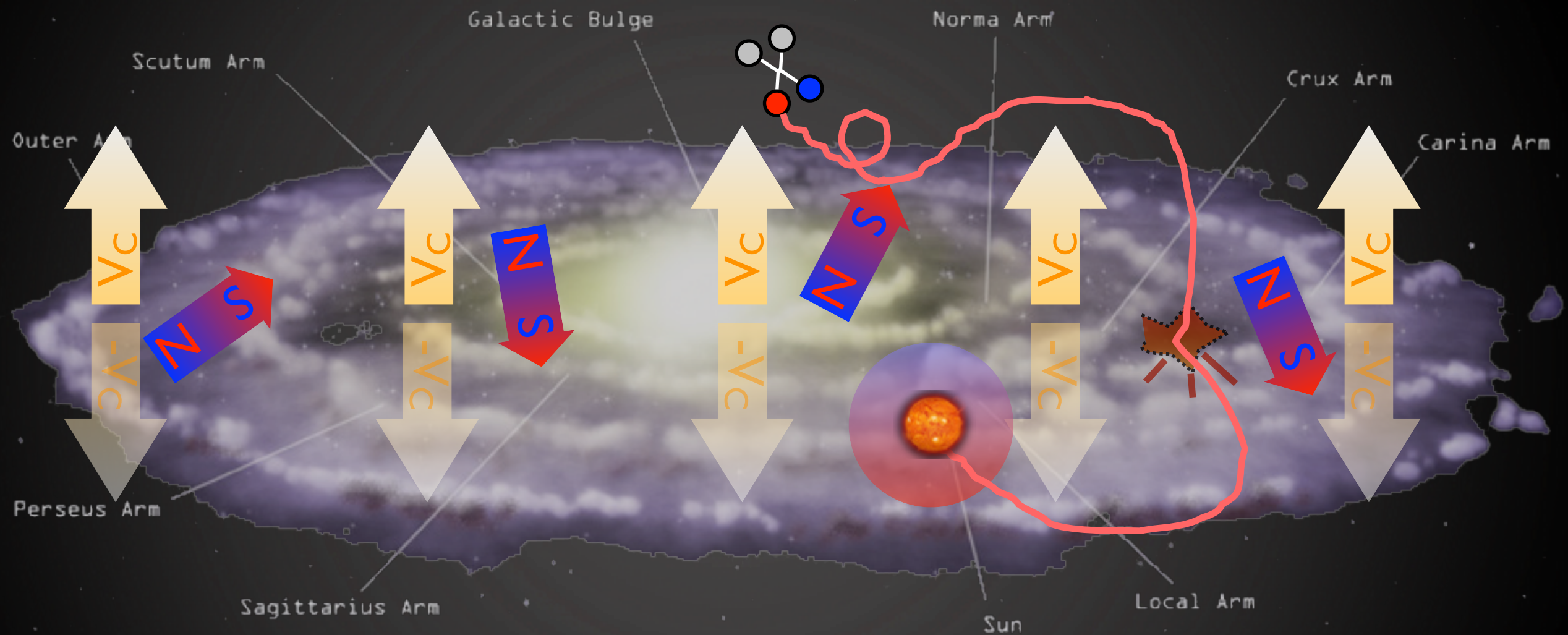
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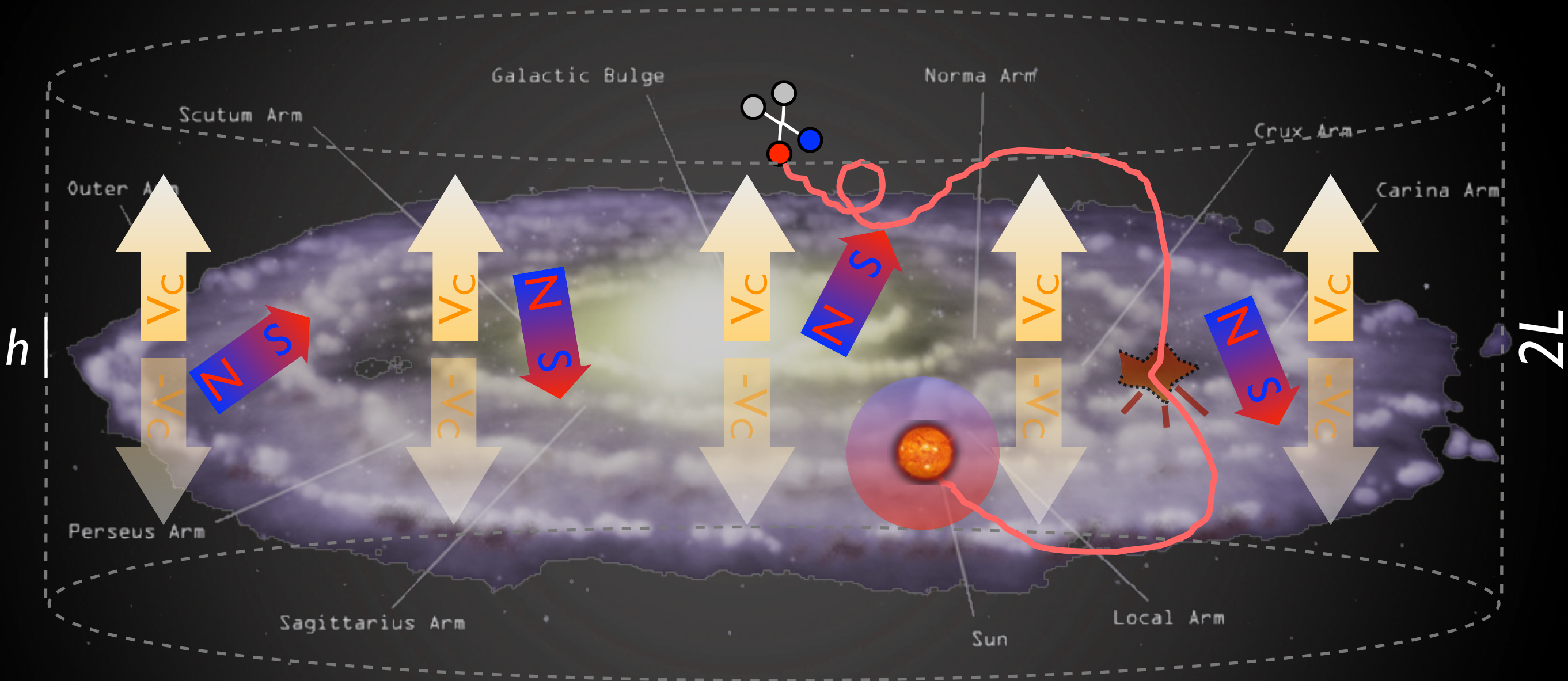
Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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



spectrum

$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E} (b(E)f) + \frac{\partial}{\partial z} (V_c f) = Q_{\text{inj}} - 2h\delta(z)\Gamma_{\text{spall}}f$$

diffusion energy loss convective wind source spallations [uncert]

Salati, Chardonay, Barrau, Donato, Taillet, Fornengo, Maurin, Laval... '90s, '00s

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_1 [GV]	δ_1
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](#)

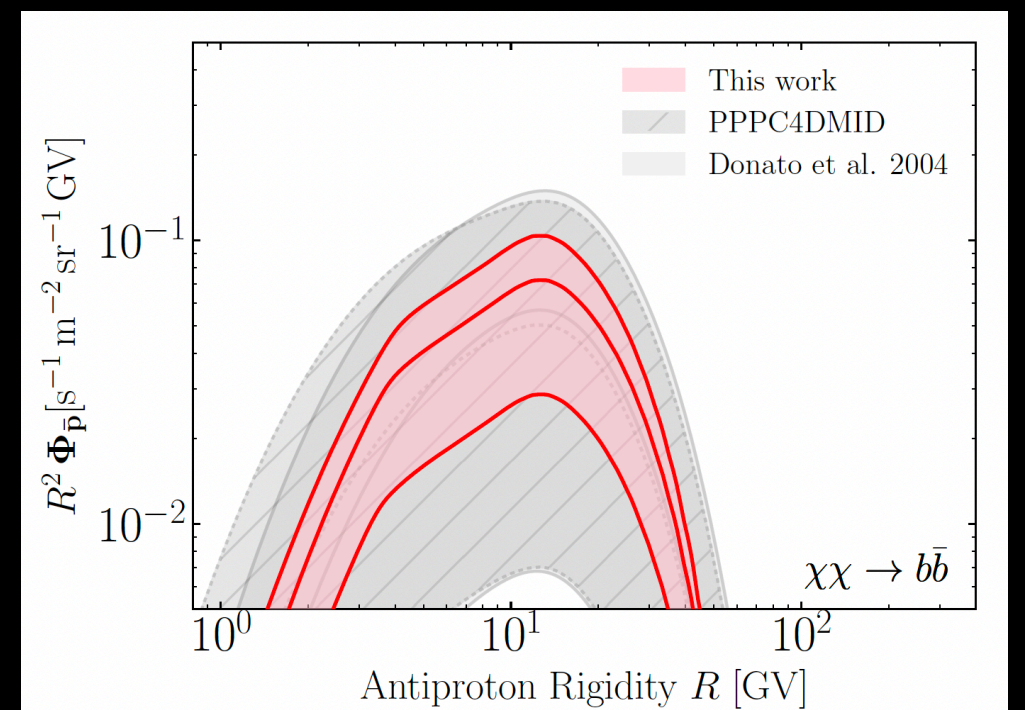
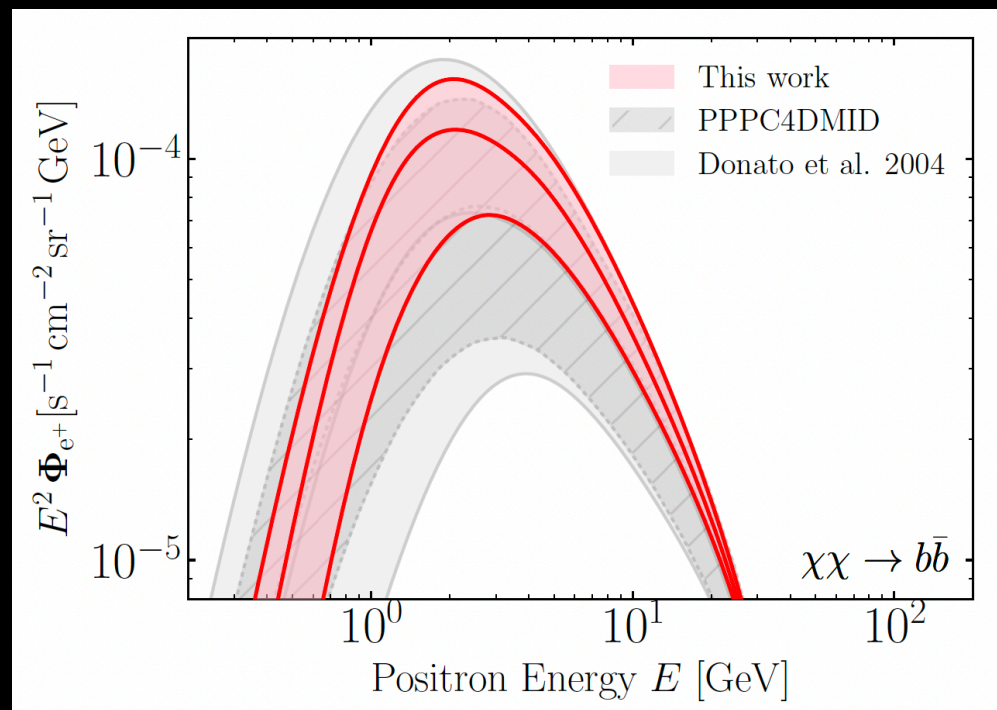
...

See also:

[Génolini et al. 1904.08917](#)

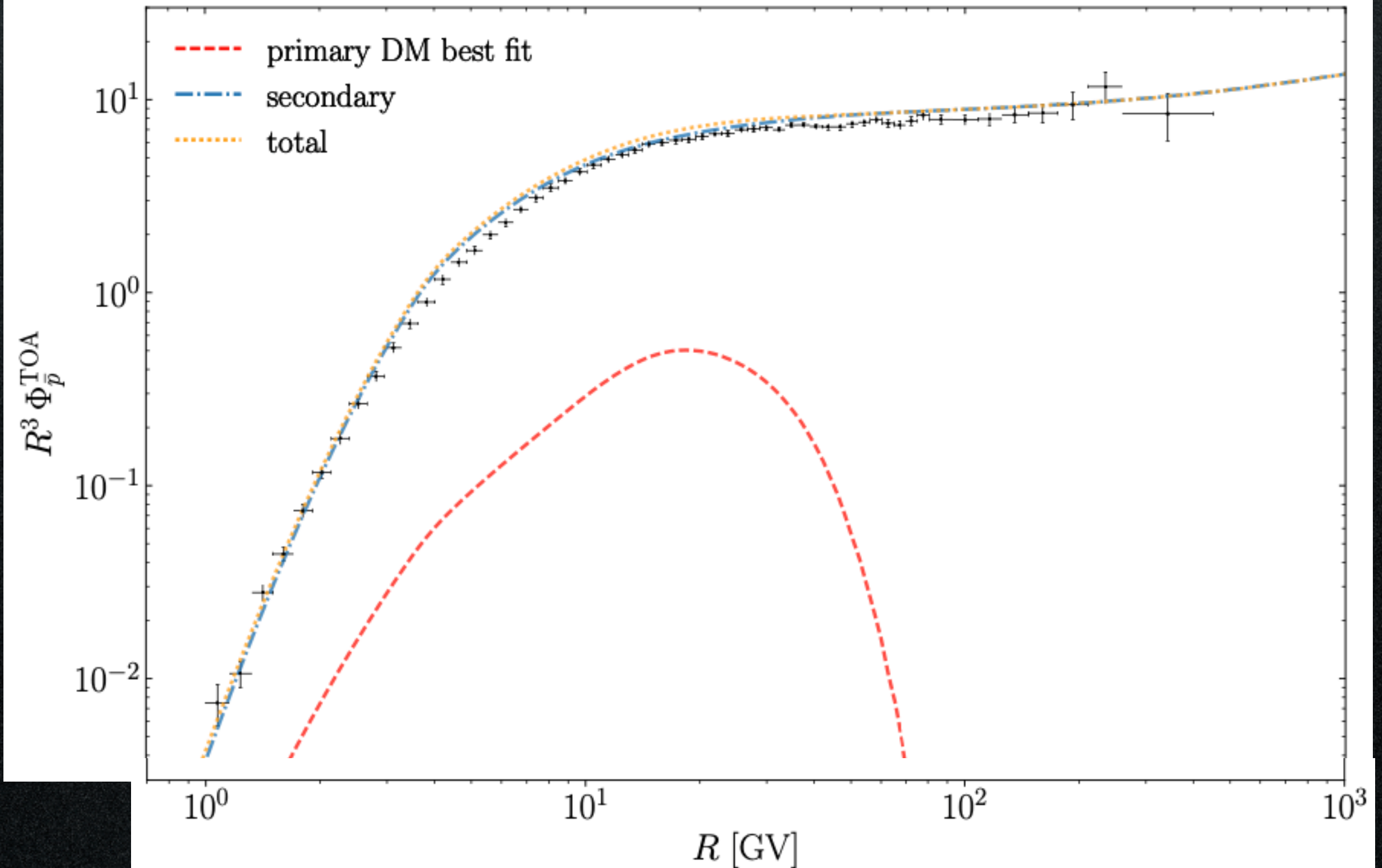
[Génolini, Cirelli et al. 2103.04108](#)

Sizable reduction of the propagation uncertainties



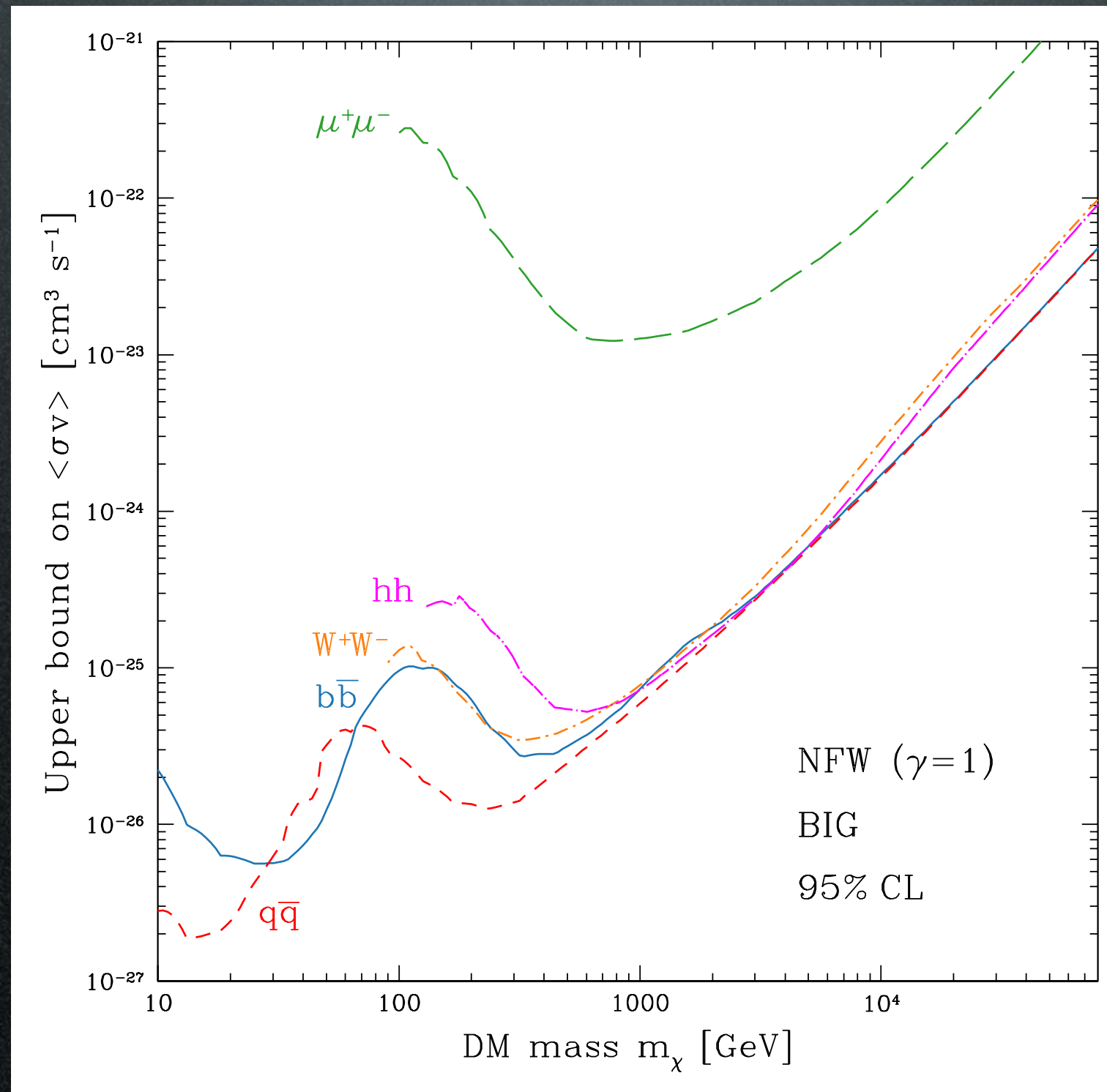
Model independent bounds

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



Model independent bounds

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

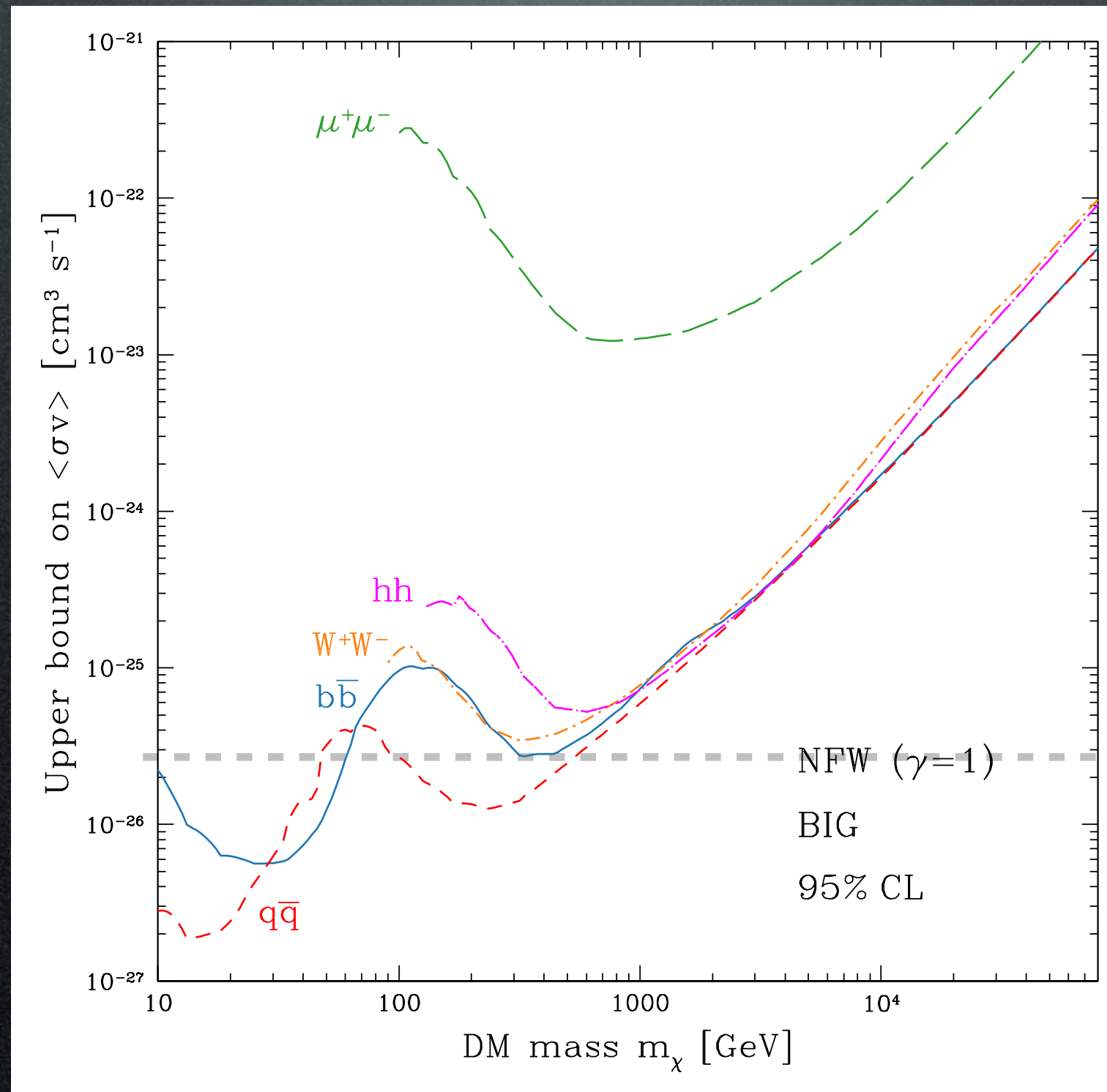


Calore, Cirelli,
Derome, Génolini,
Maurin, Salati, Serpico
2202.03076

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

Model independent bounds

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



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

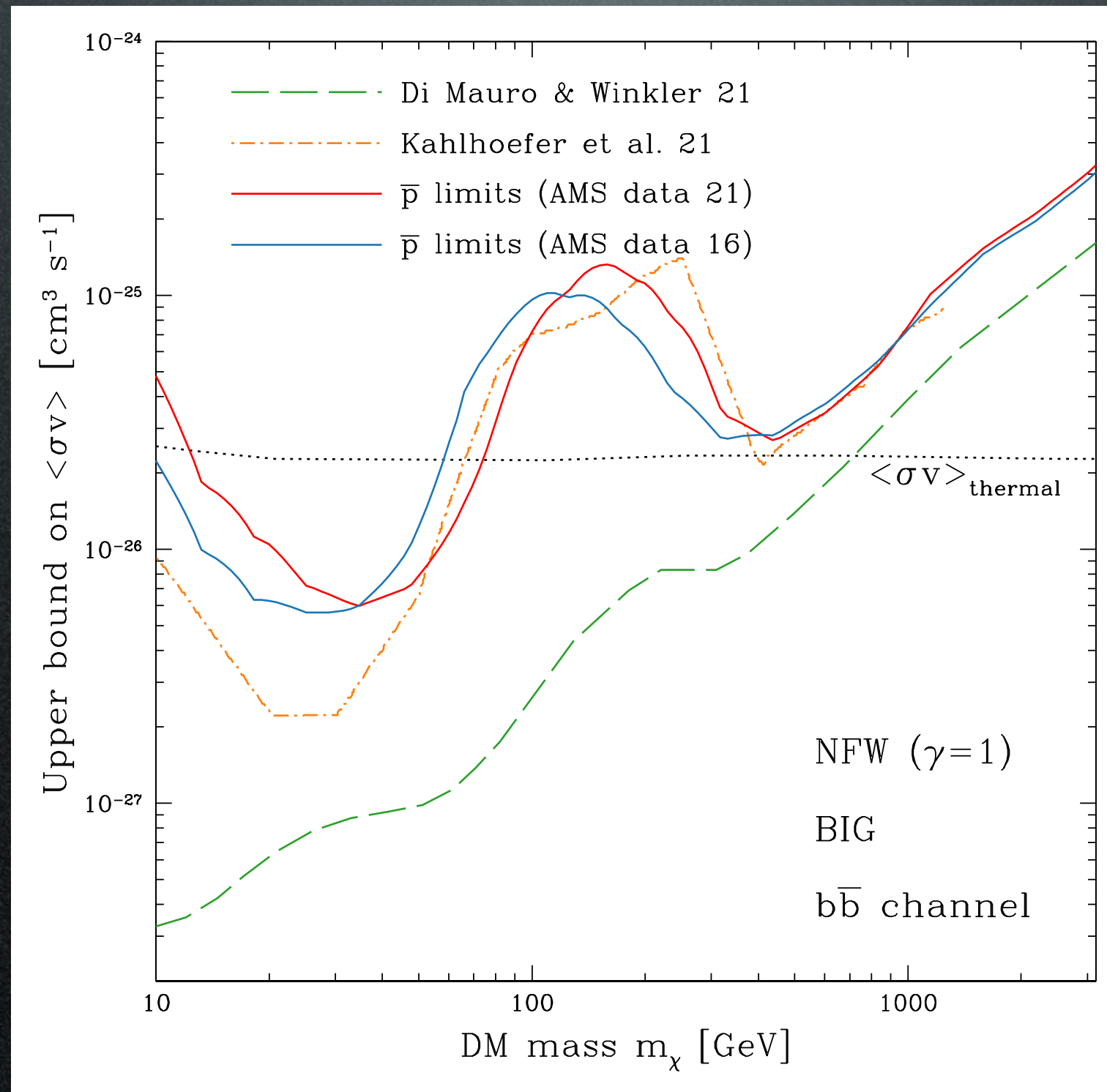
Bounds quite 'weak'
because of bump

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

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

GAPS, AMS

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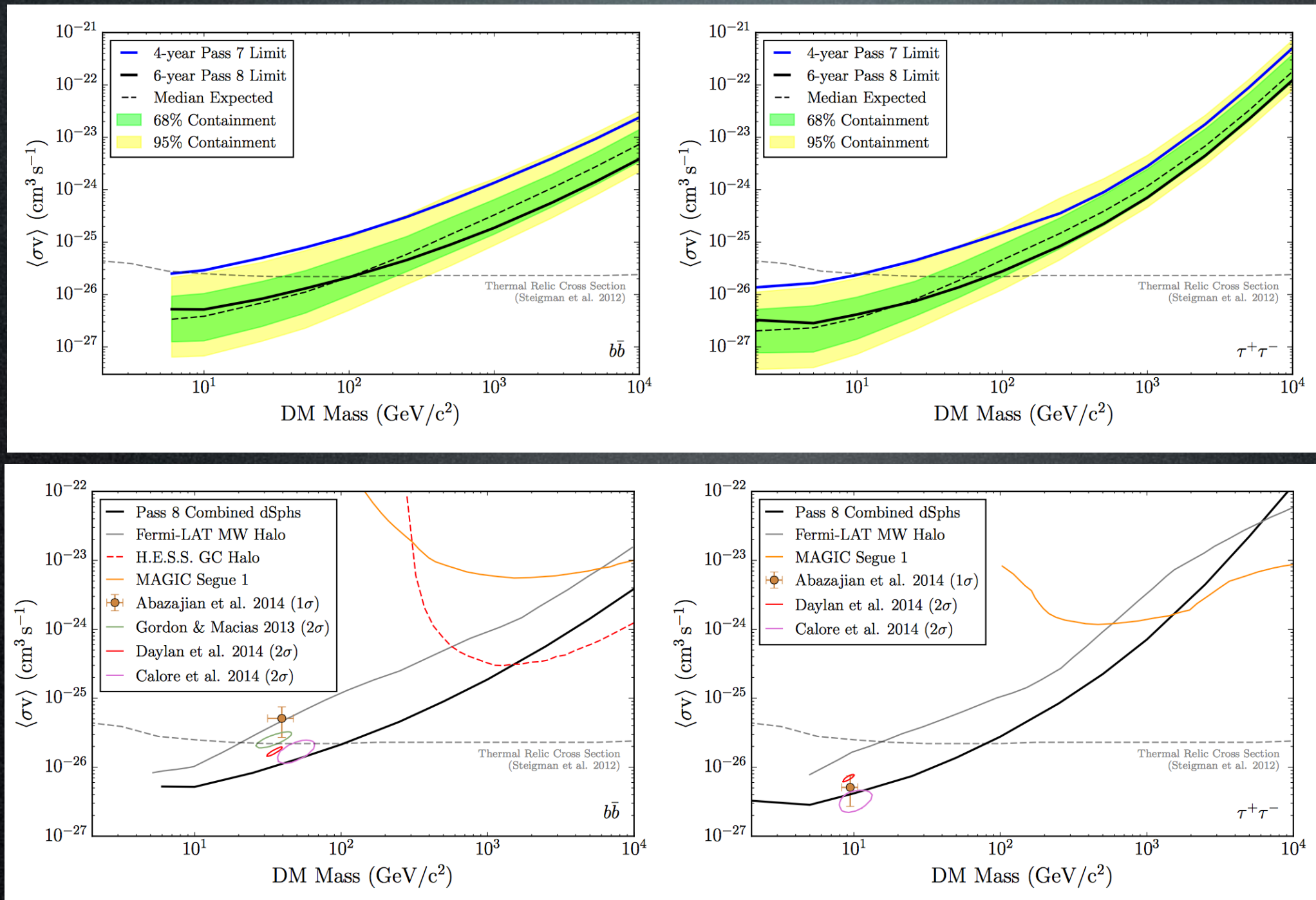
SK, Icecube, Antares

Constraints

Dwarf galaxies

FERMI

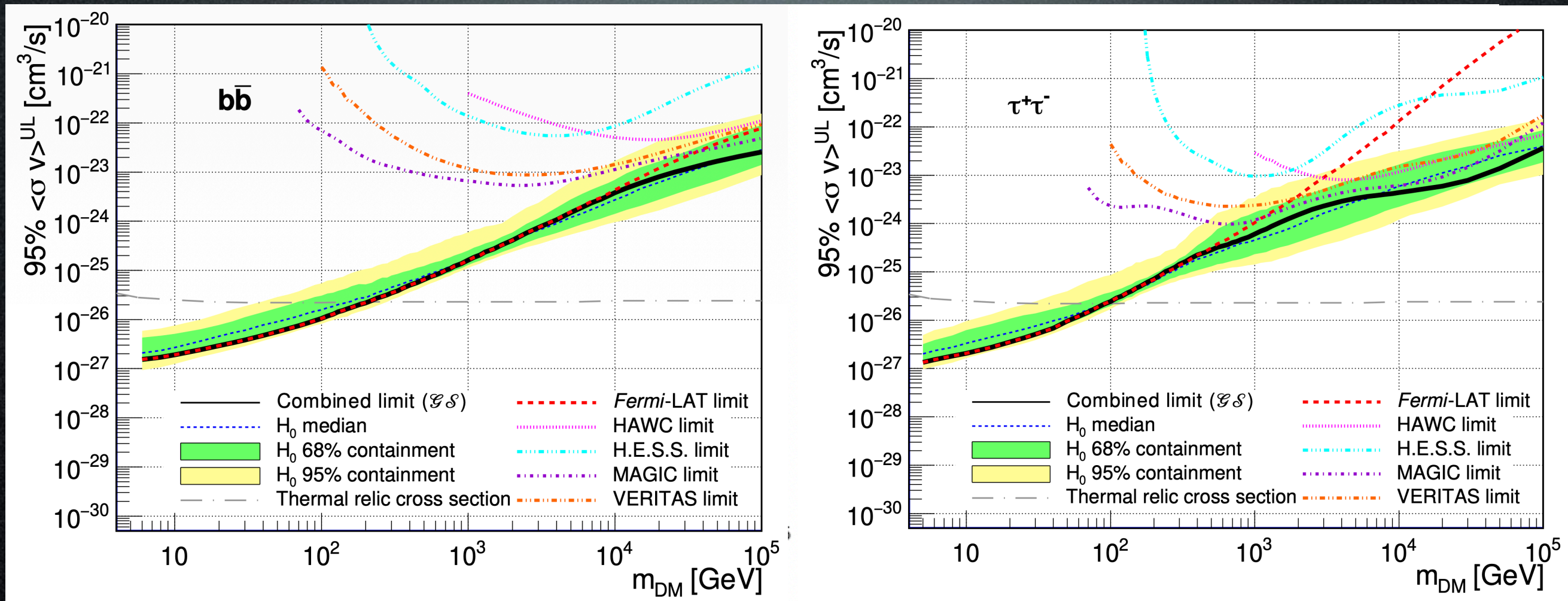
FERMI 1503.02641



Constraints

Dwarf galaxies

FERMI+HAWC+HESS+MAGIC+VERITAS



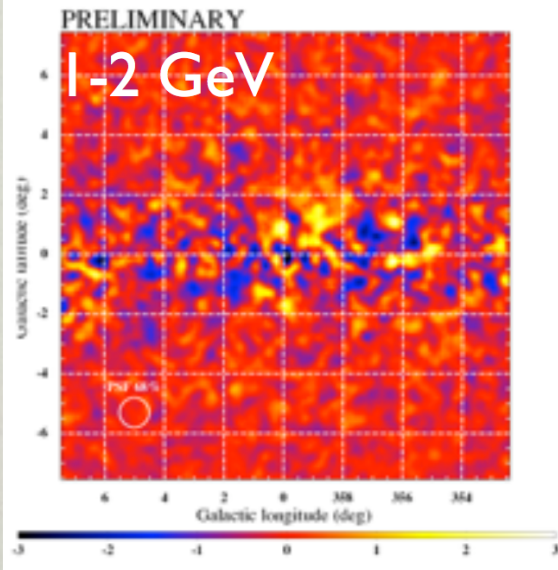
2508.20229
See also 2108.13646

GC GeV excess

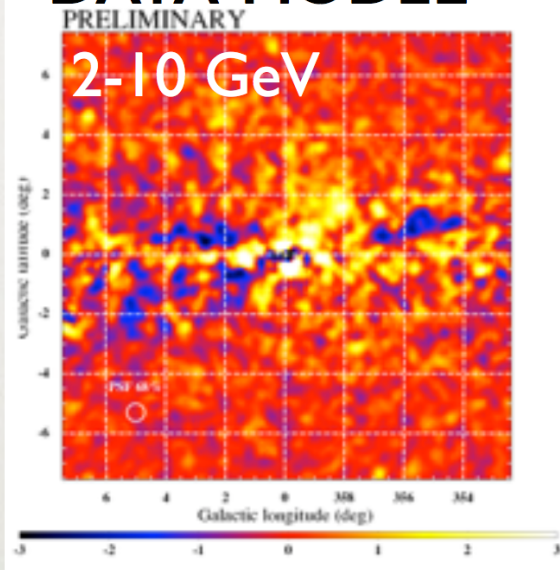
Dark Matter interpretation:

Pulsars, tuned-index

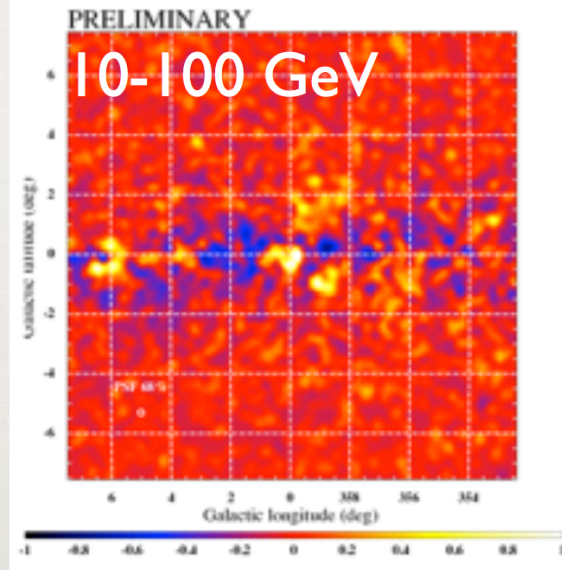
Without NFW:



DATA-MODEL

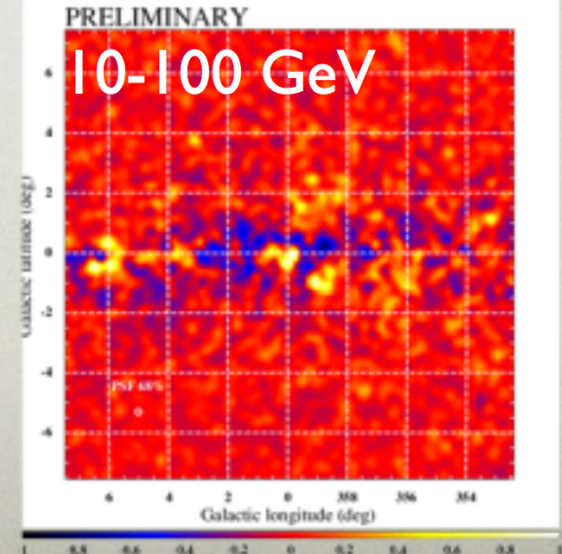
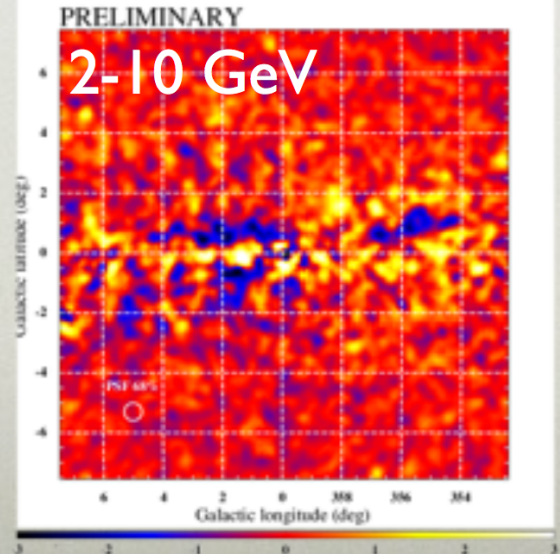
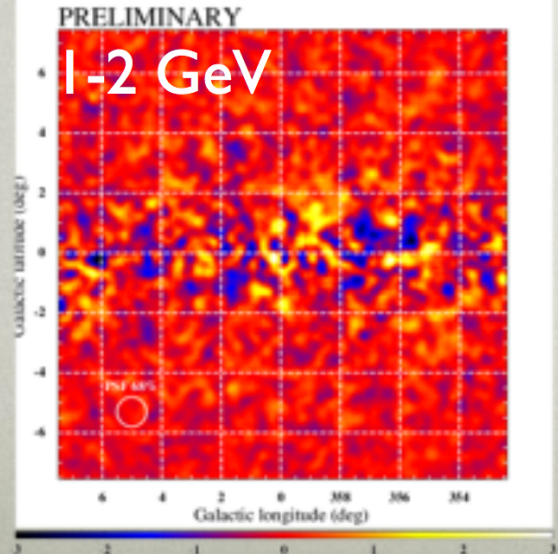


Counts in $0.1^\circ \times 0.1^\circ$ pixels
 0.3° radius gaussian smoothing



Pulsars, tuned-index

With NFW:



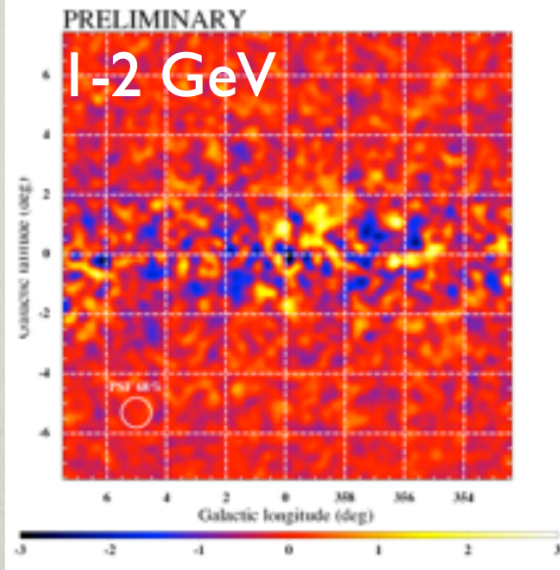
S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815
Fermi coll. 1511.02938

GC GeV excess

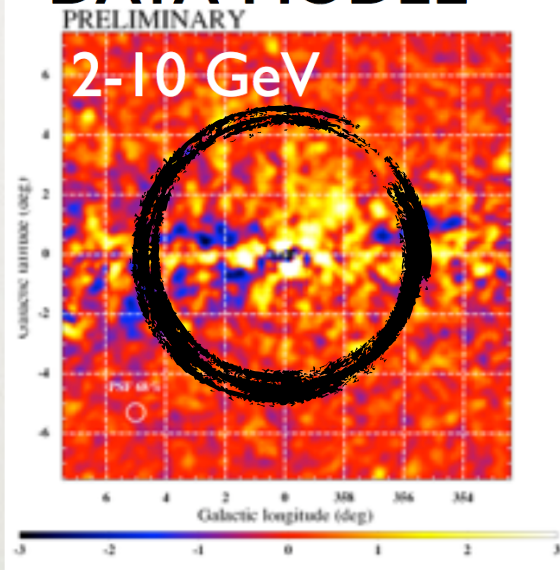
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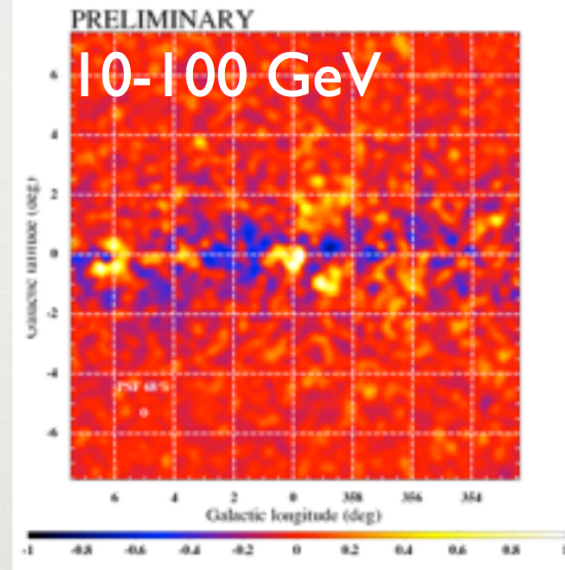
Without NFW:



DATA-MODEL

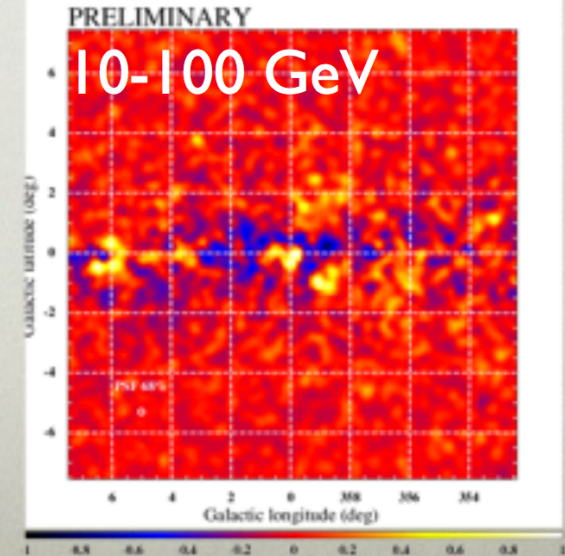
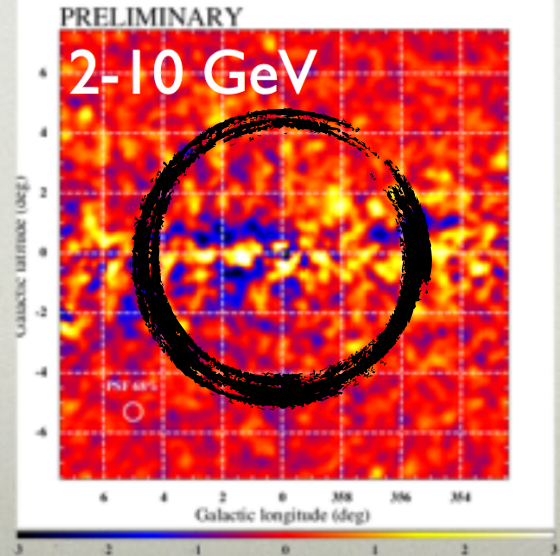
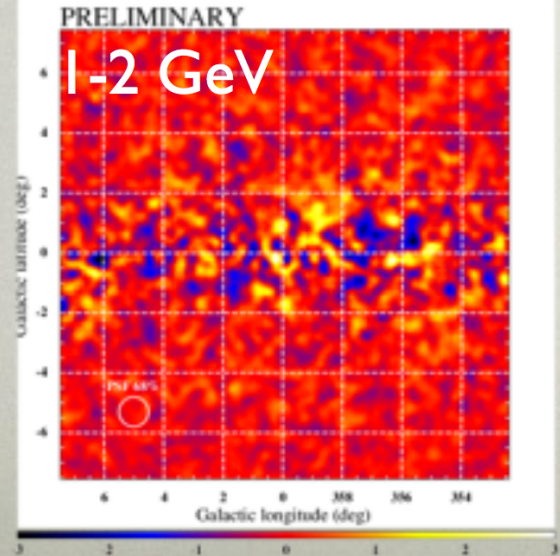


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 0.3° radius gaussian smoothing



Pulsars, tuned-index

With NFW:



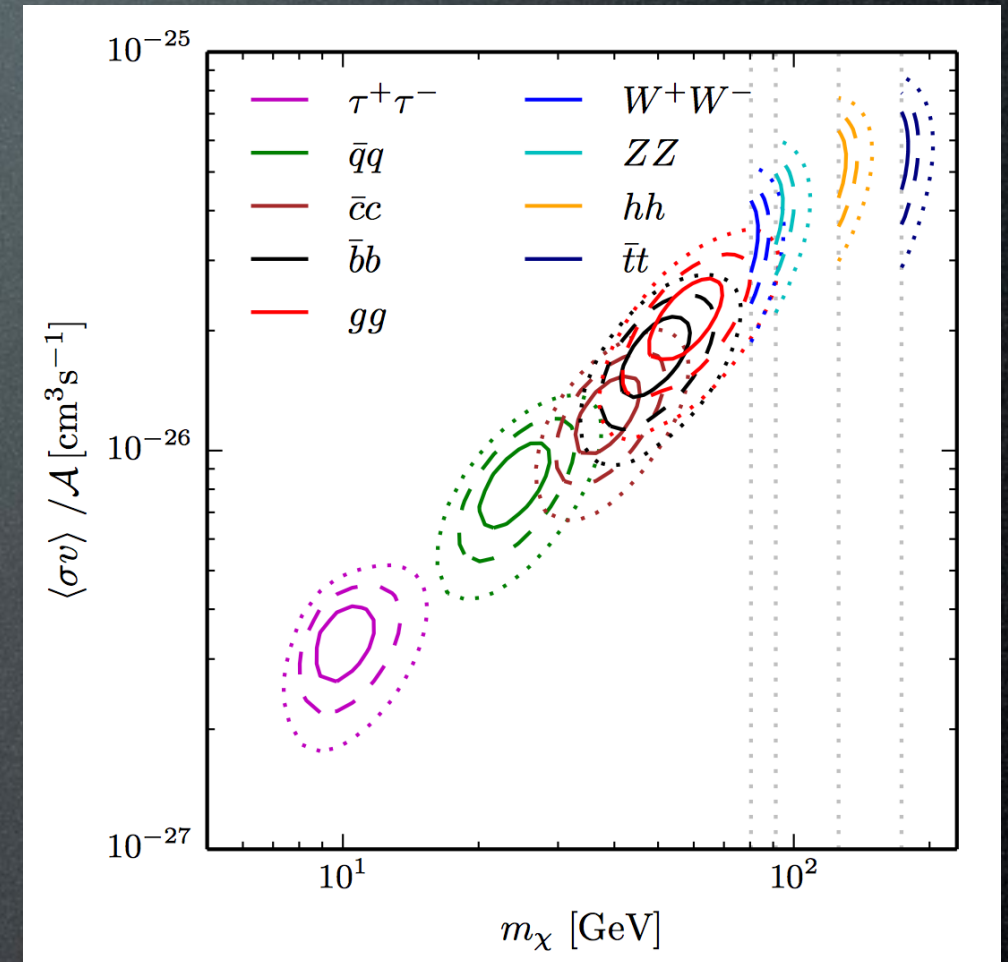
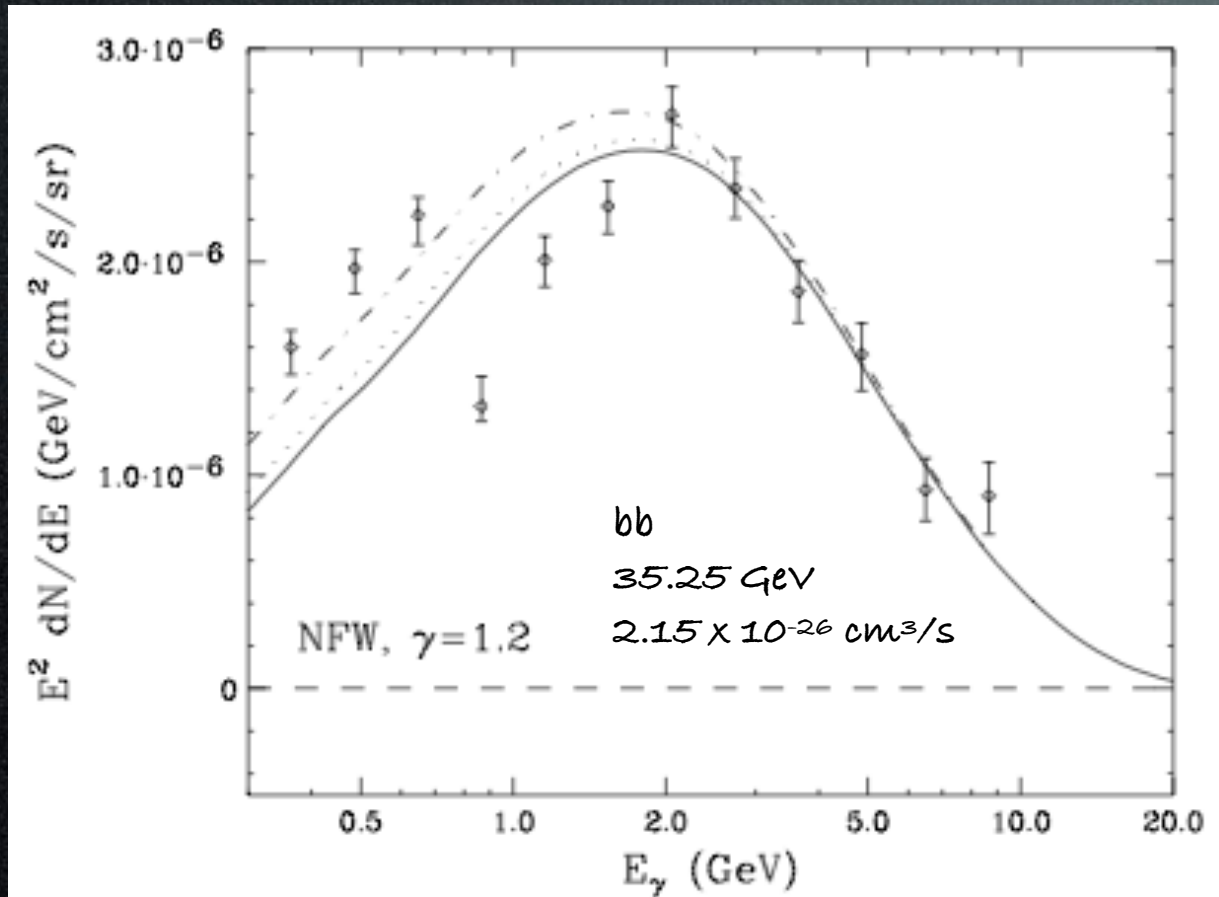
S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815
Fermi coll. 1511.02938

GC GeV excess

Dark Matter interpretation:

Best fit:

~ 35 GeV, quarks, $\sim$ thermal σv



F. Calore et al. 1411.4647

A compelling case
for annihilating DM

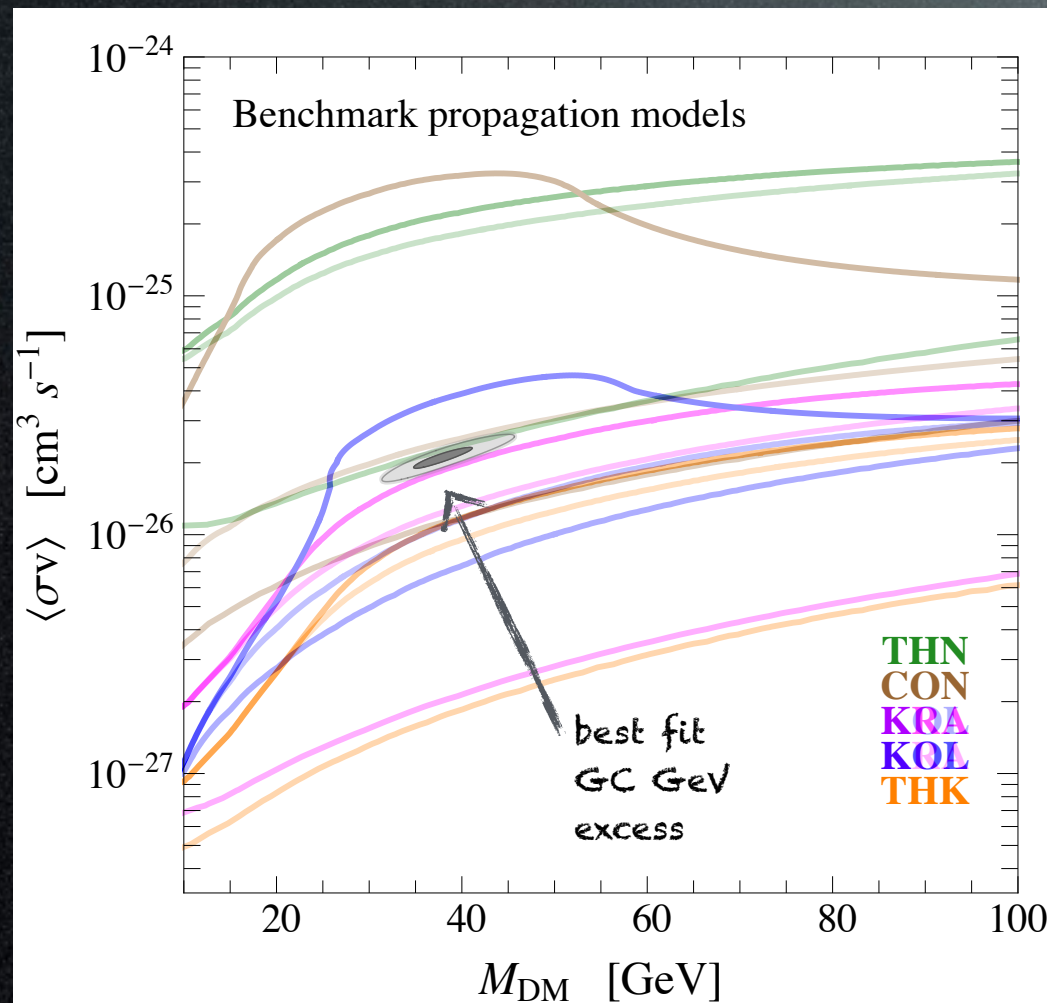
Daylan, Finkbeiner, Hooper, Linden,
Portillo, Rodd, Slatyer 1402.6703

...as good as it can get.

GC GeV excess

Dark Matter interpretation:

Antiproton constraints
are not conclusive



Cirelli, Gaggero,
Giesen, Taoso,
Urbano 1407.2173

Also:

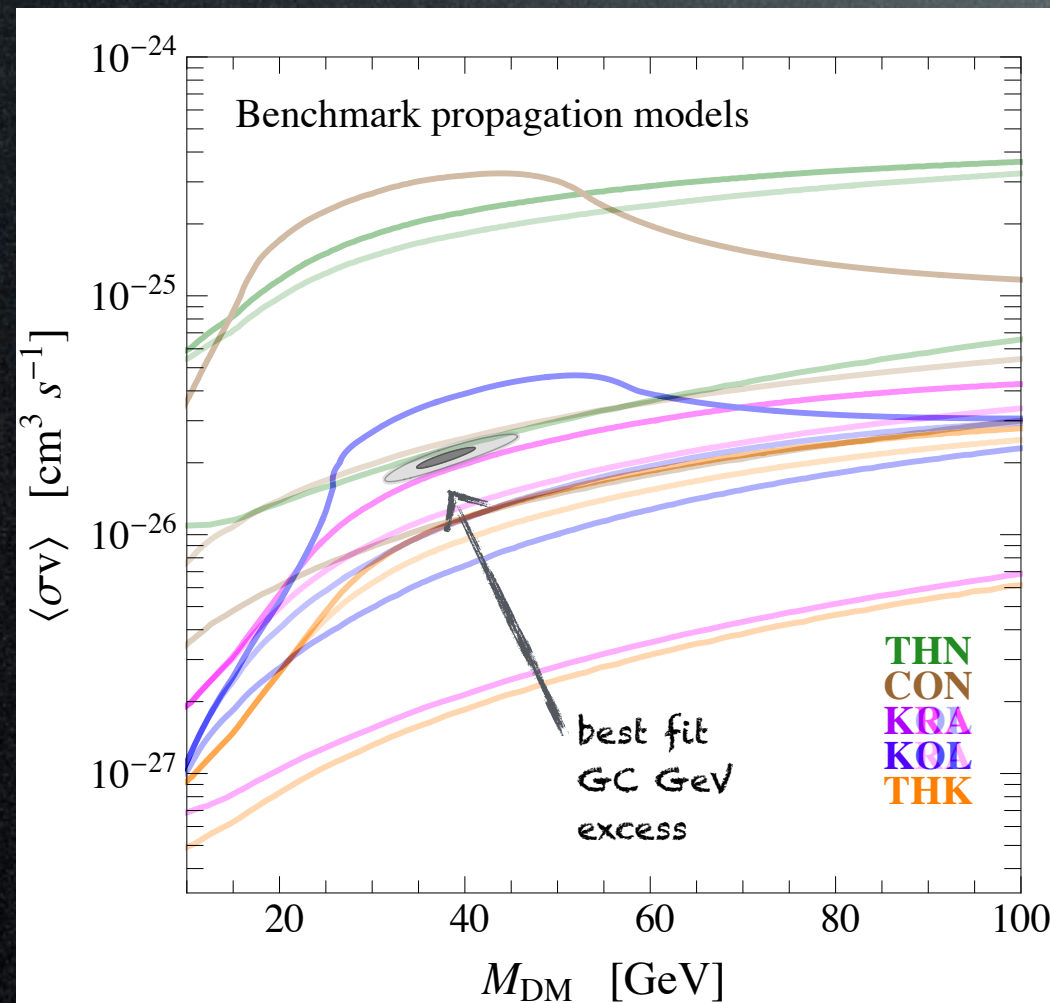
Bringmann, Vollmann,
Weniger 1406.6027

Hooper, Linden, Mertsch
1410.1527

GC GeV excess

Dark Matter interpretation:

Antiproton constraints
are not conclusive



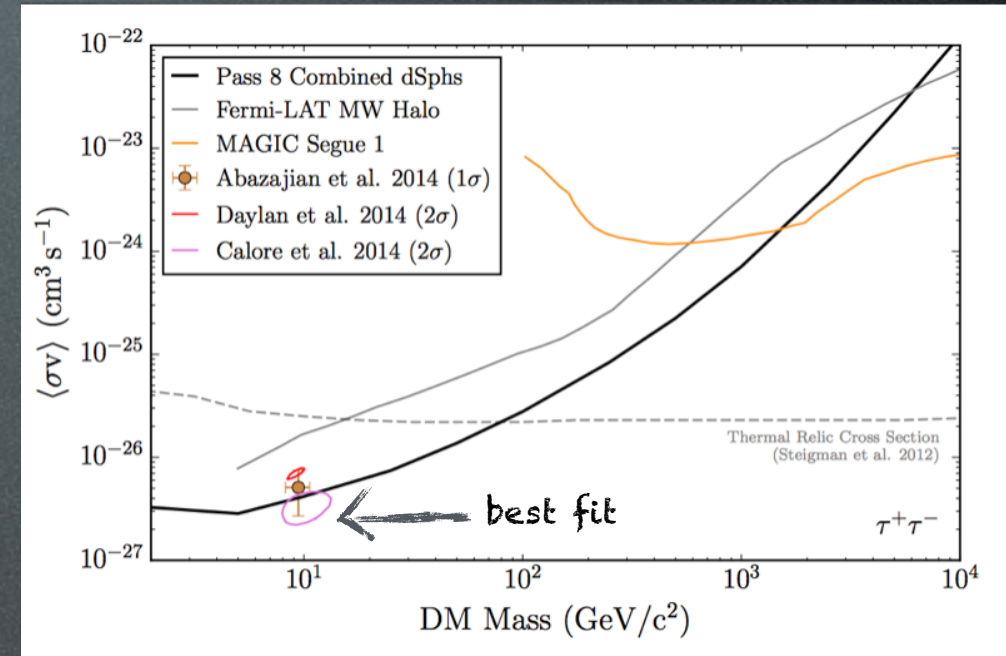
Cirelli, Gaggero,
Giesen, Taoso,
Urbano 1407.2173

Also:

Bringmann, Vollmann,
Weniger 1406.6027

Hooper, Linden, Mertsch
1410.1527

Gamma ray ones neither

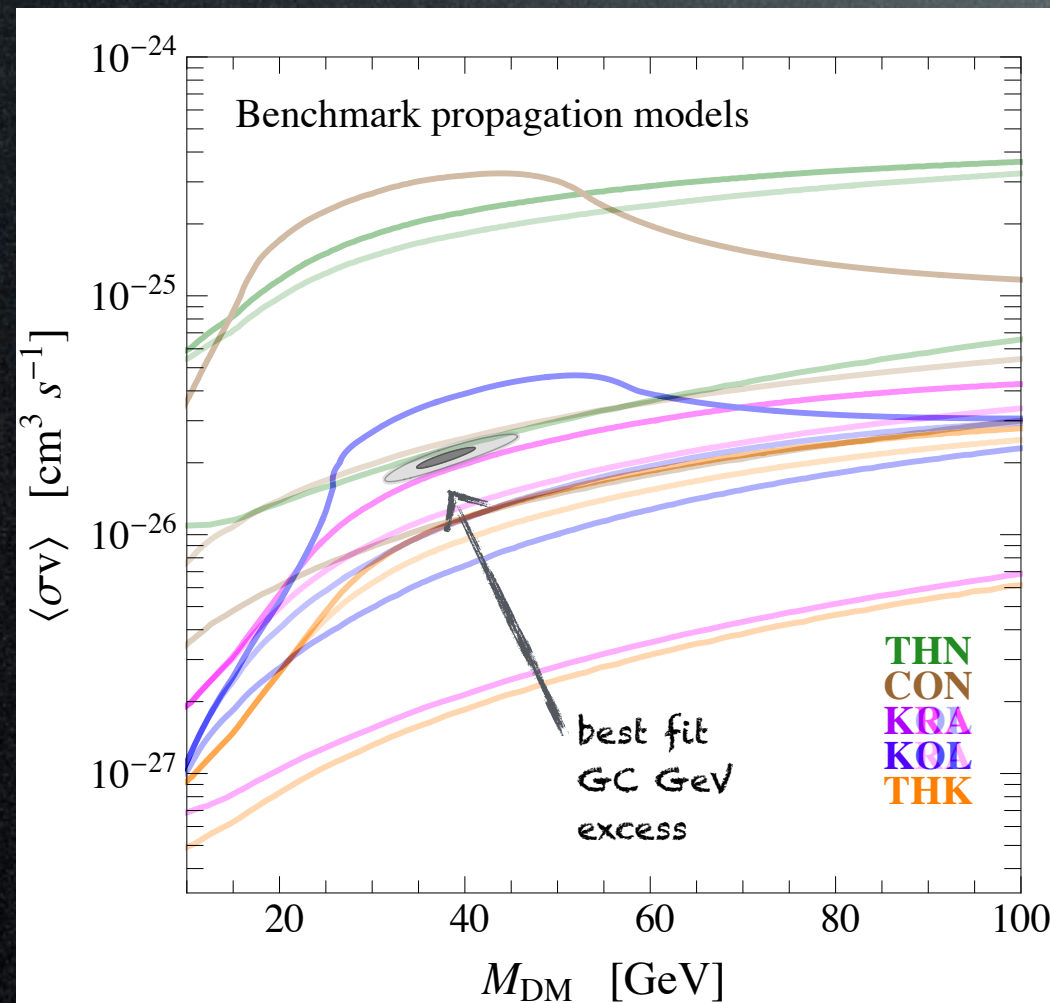


FERMI 1503.02641

GC GeV excess

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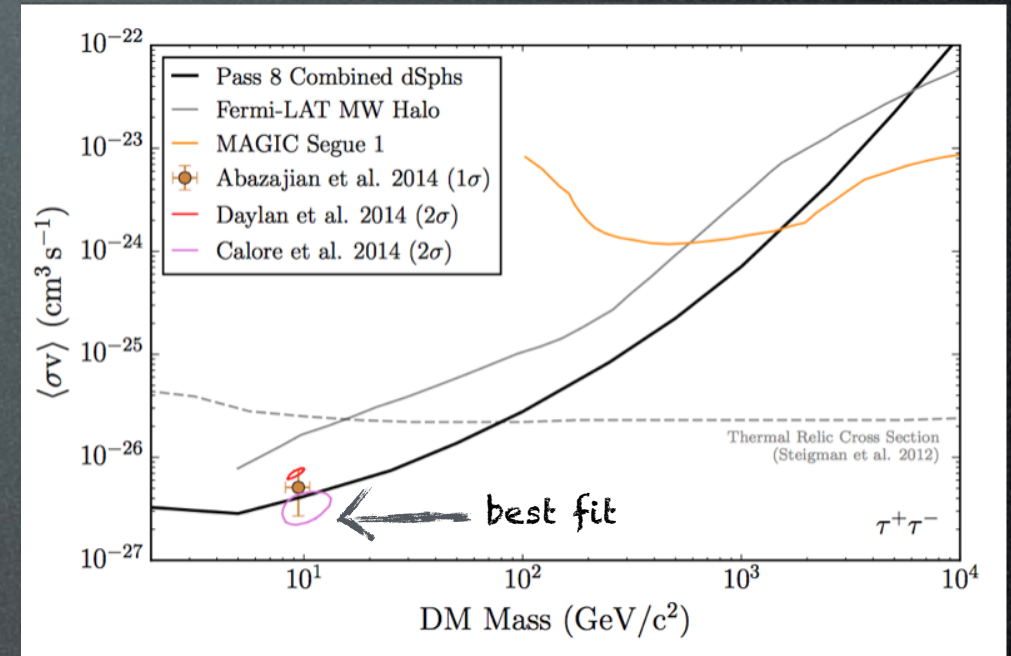
Cirelli, Gaggero,
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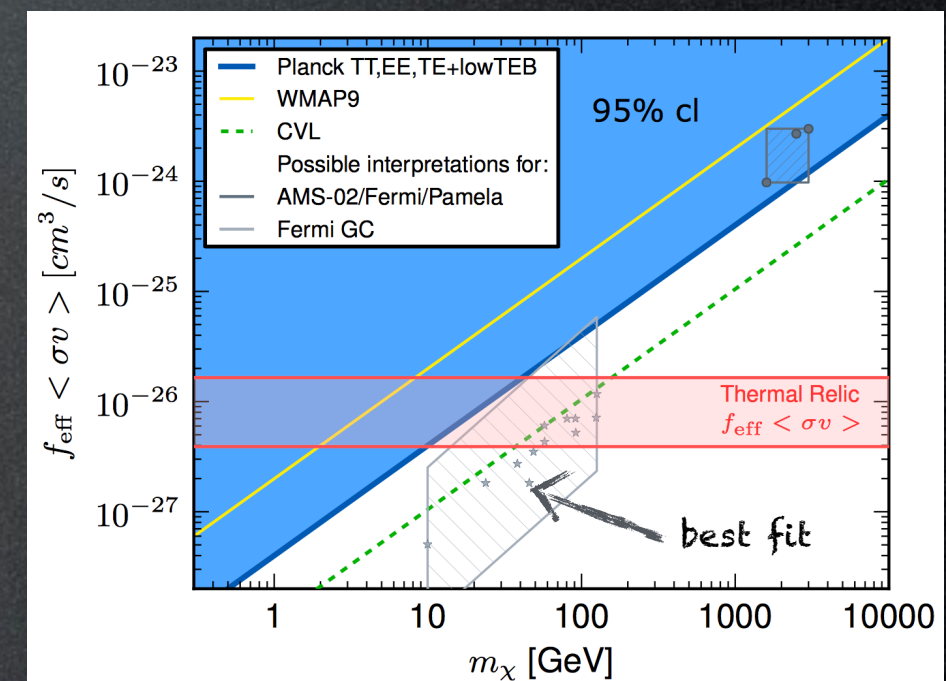
Hooper, Linden, Mertsch
1410.1527

Gamma ray ones neither



FERMI 1503.02641

Nor CMB

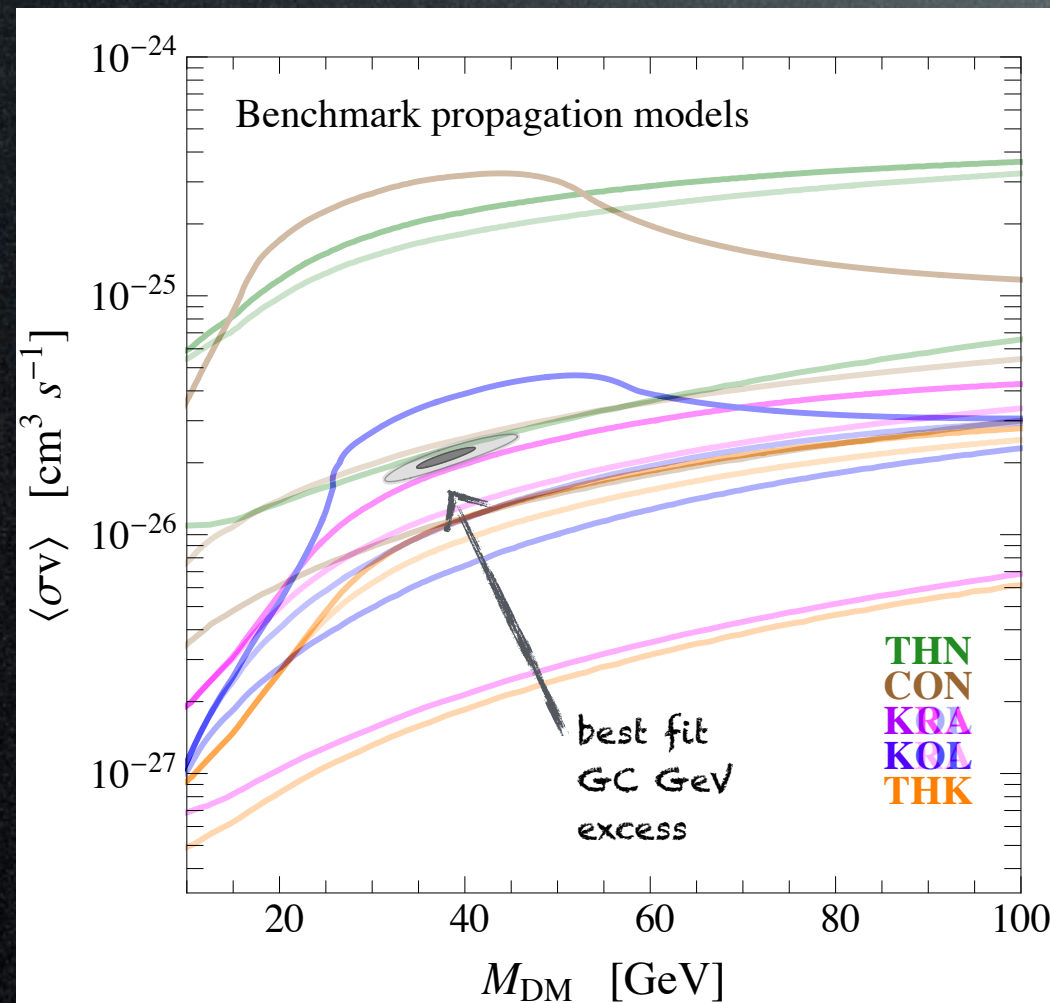


Planck
2015

GC GeV excess

Dark Matter interpretation:

Antiproton constraints
are not conclusive



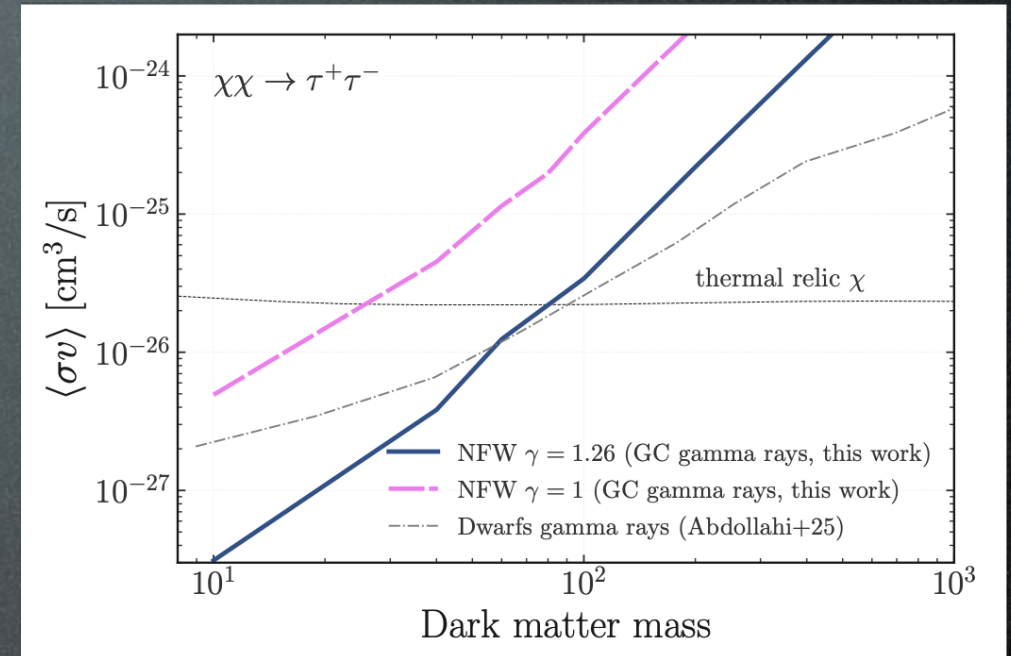
Cirelli, Gaggero,
Giesen, Taoso,
Urbano 1407.2173

Also:

Bringmann, Vollmann,
Weniger 1406.6027

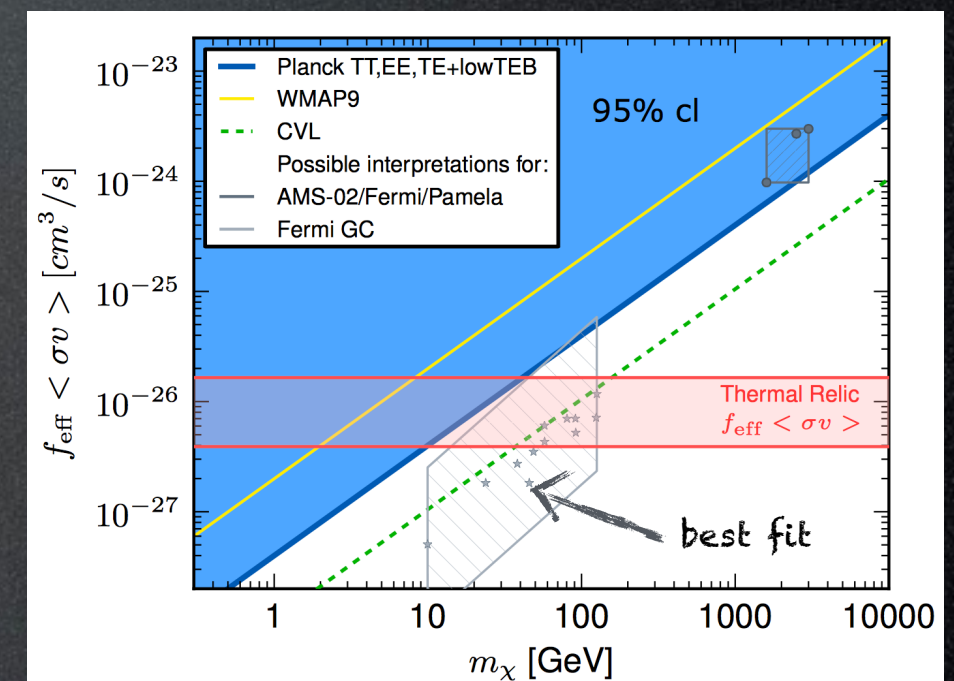
Hooper, Linden, Mertsch
1410.1527

Gamma ray ones neither



Manconi et al. 2511.03350

Nor CMB

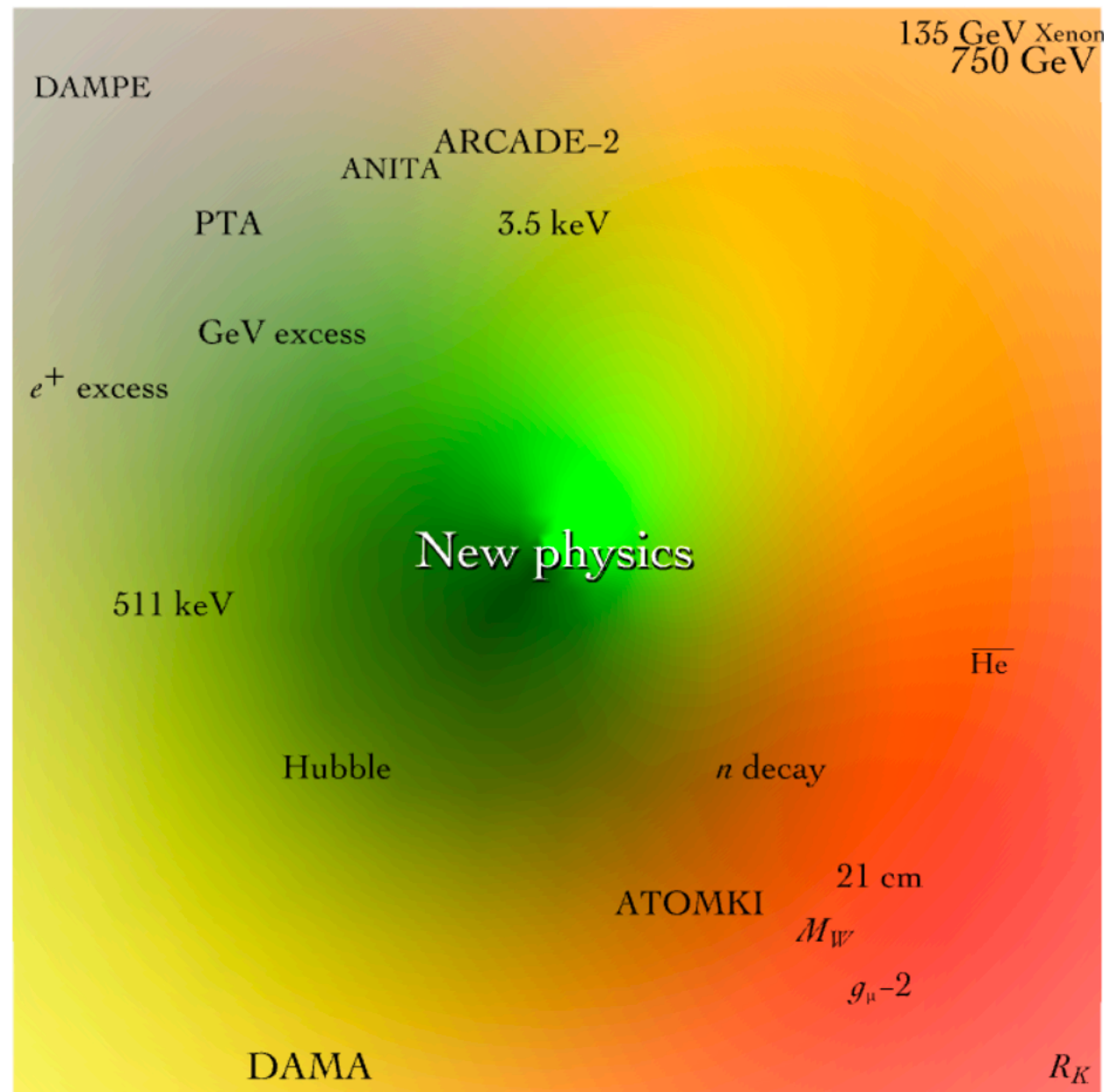


Planck
2015

DM related 'anomalies'

Astrophysics

Background



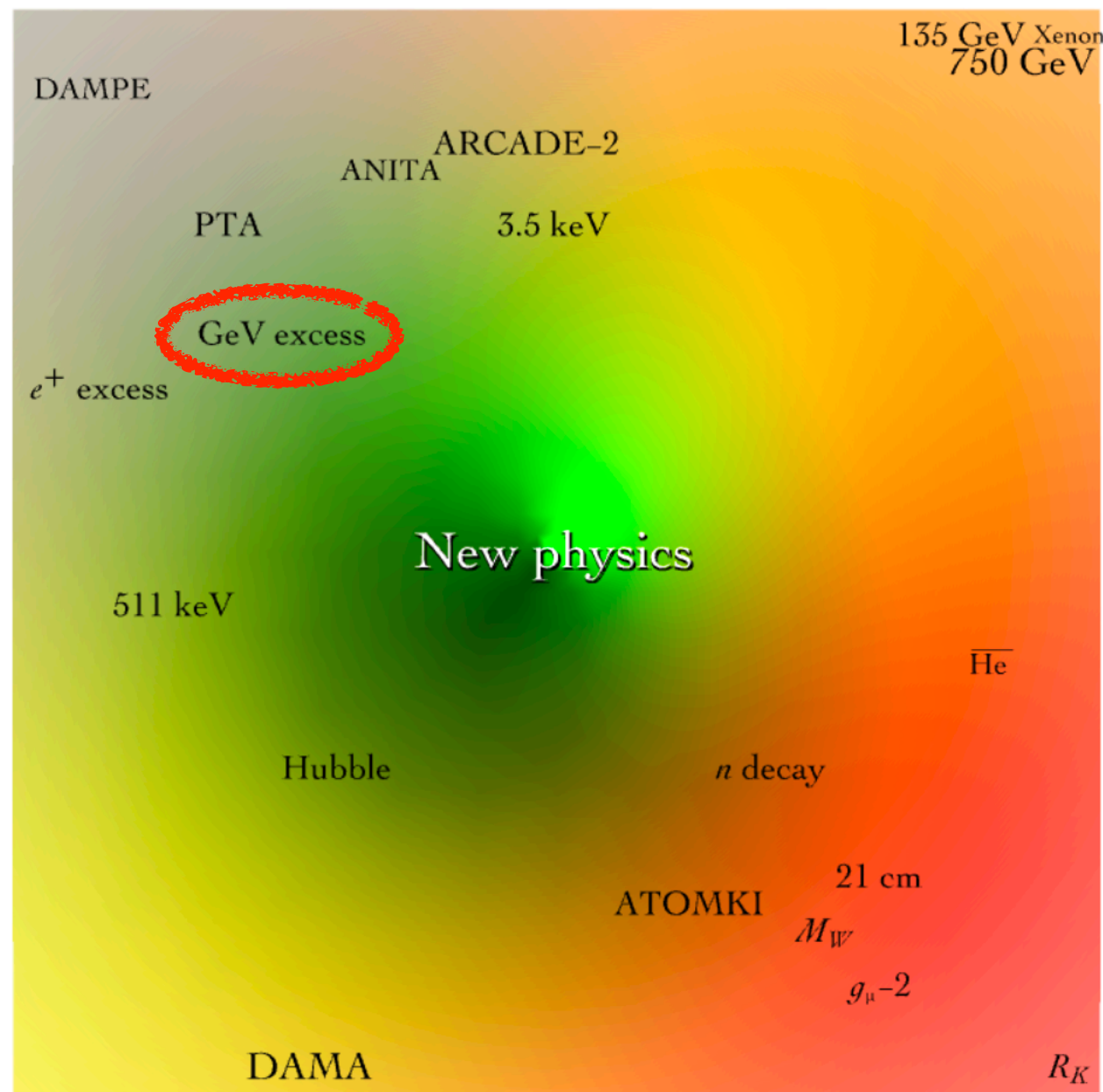
Theory

Experiment

DM related 'anomalies'

Astrophysics

Background

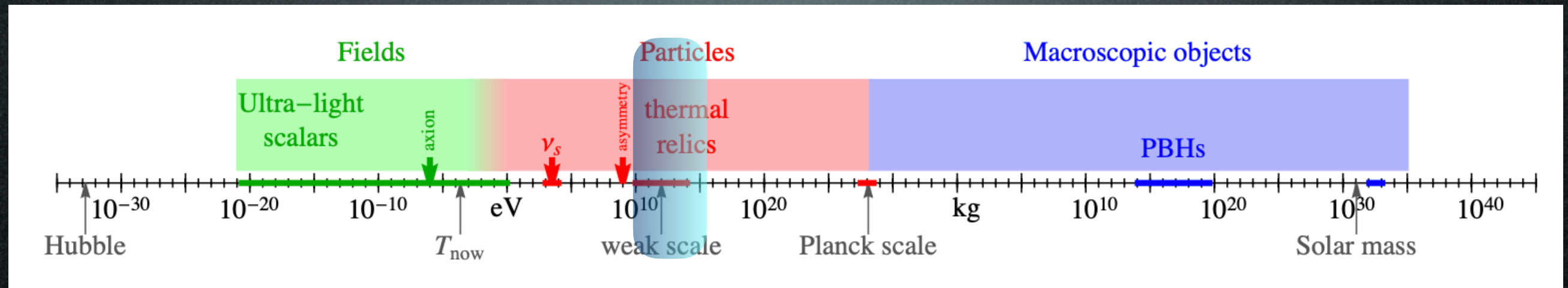


Theory

Experiment

Candidates

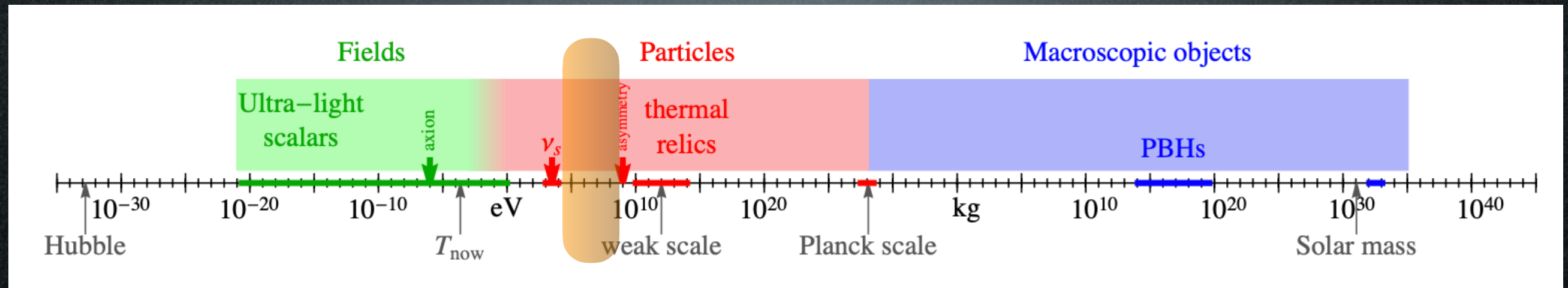
A matter of perspective: plausible mass ranges



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?

Why not!

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

Candidates

theory

production

Sub-GeV DM?

Collider
Searches

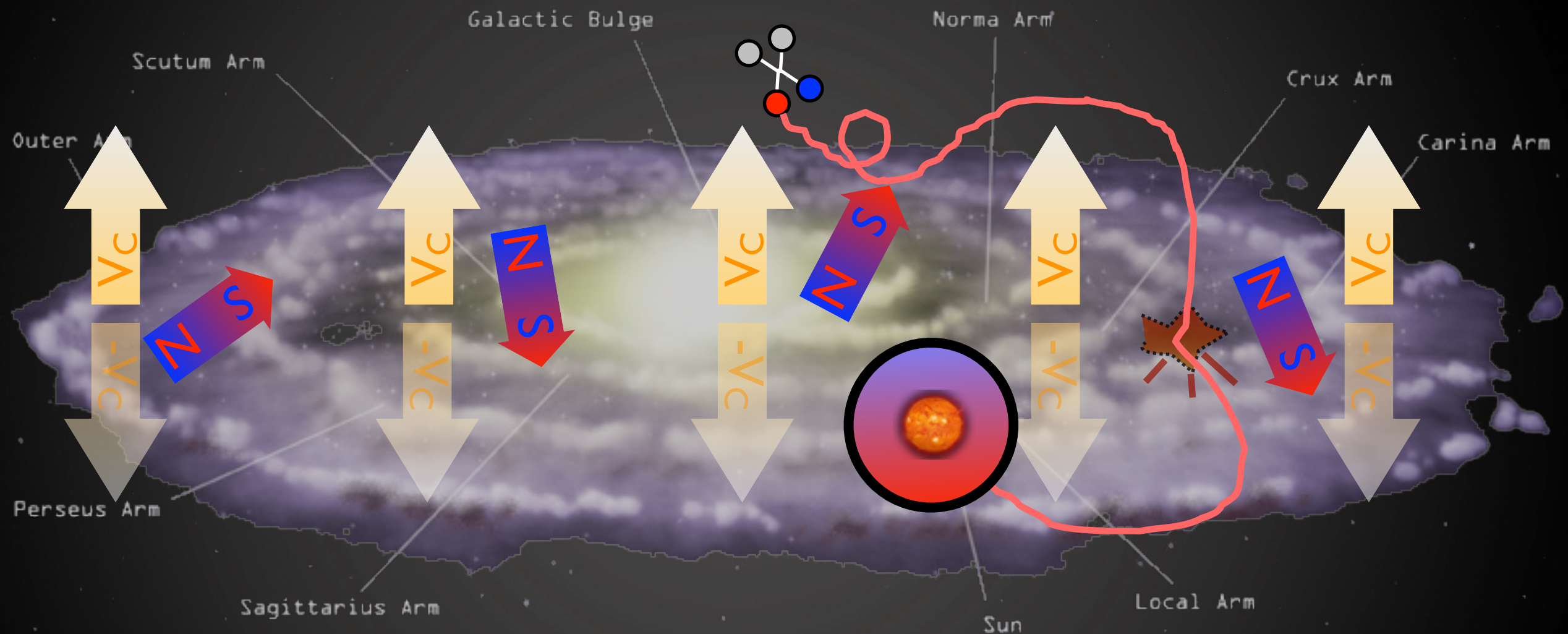
Indirect
Detection?

Direct
Detection



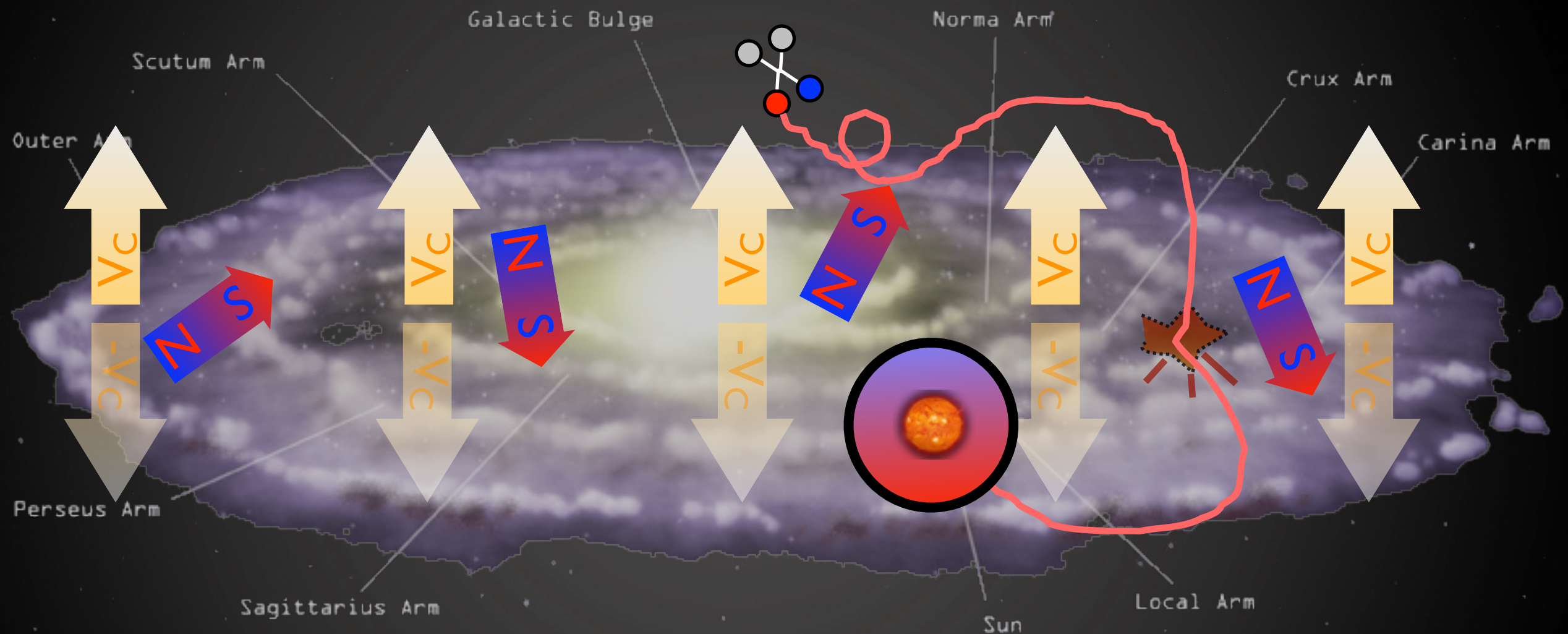
Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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

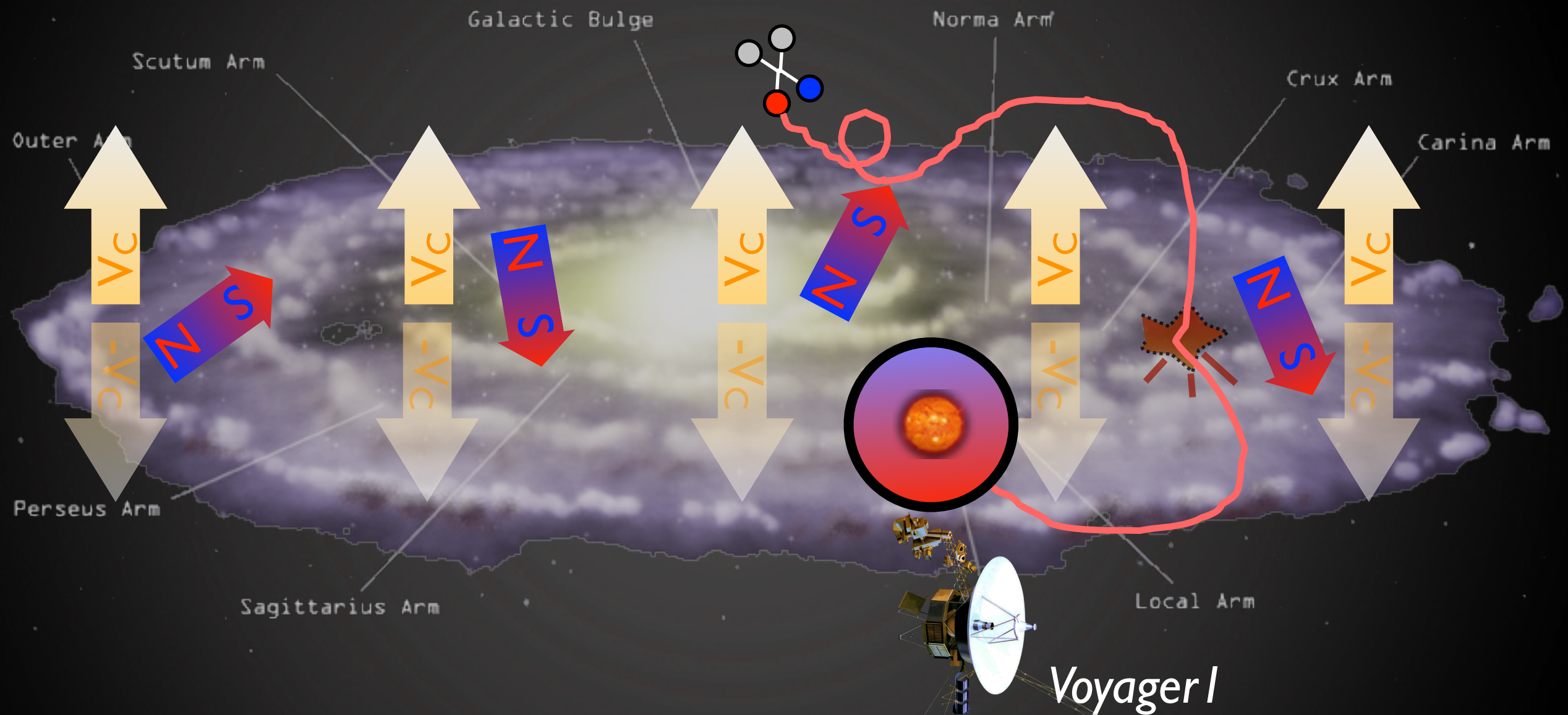


Problem:

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



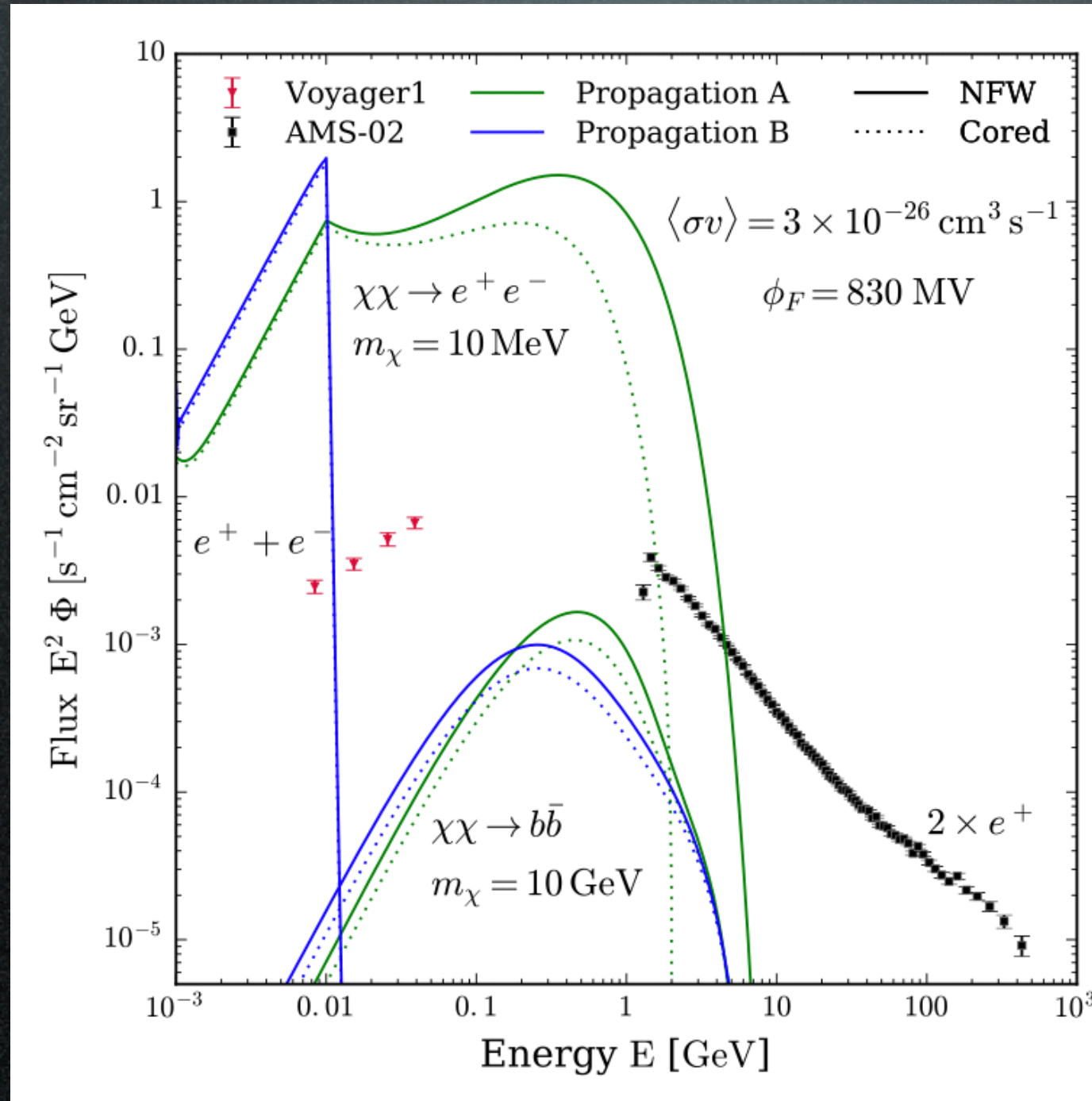
Problem:

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

Indirect Detection: charged CRs

Boudaud, Laval, Salati 1612.07698

Electron+positron measurements by **Voyager I**

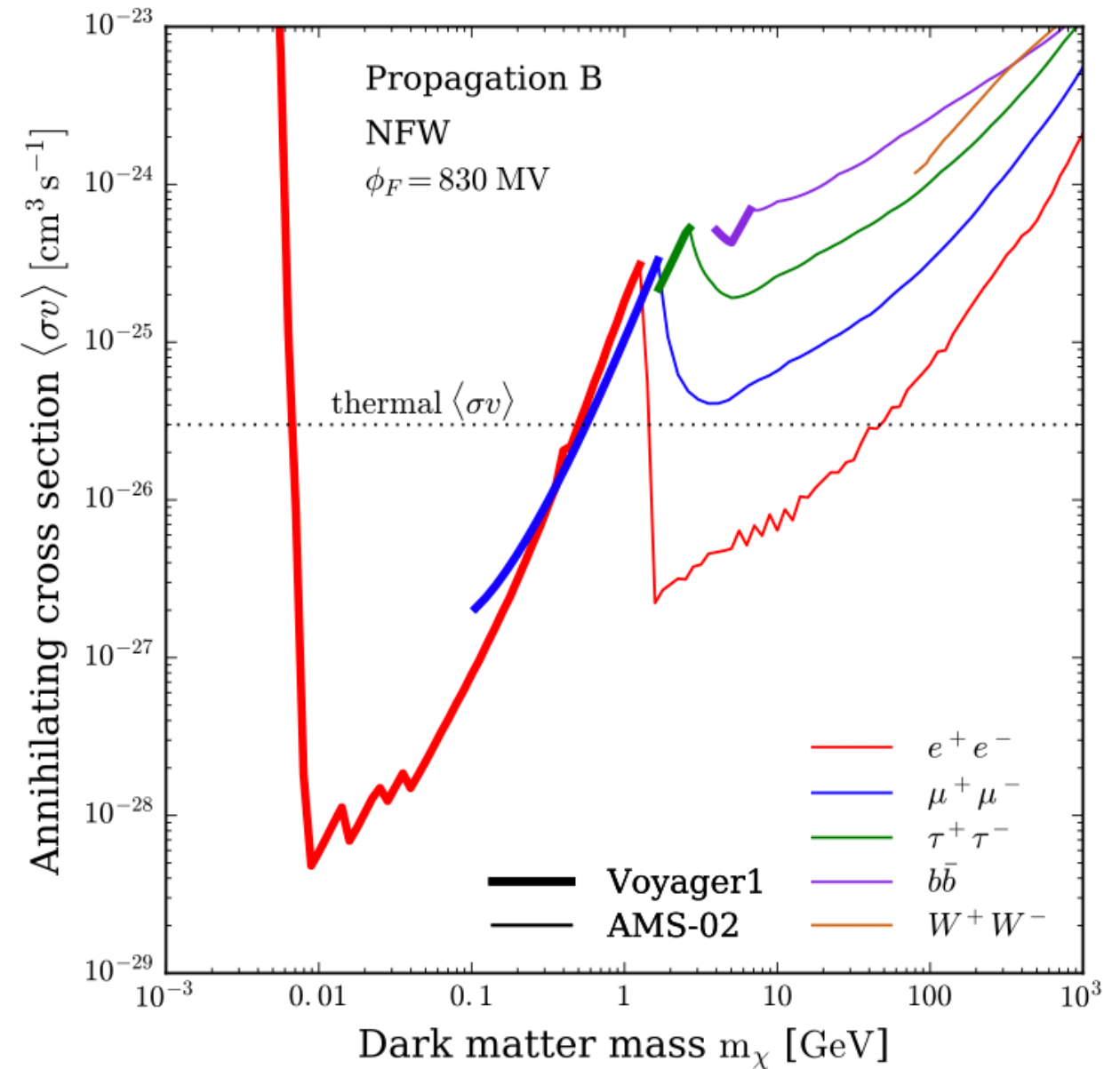
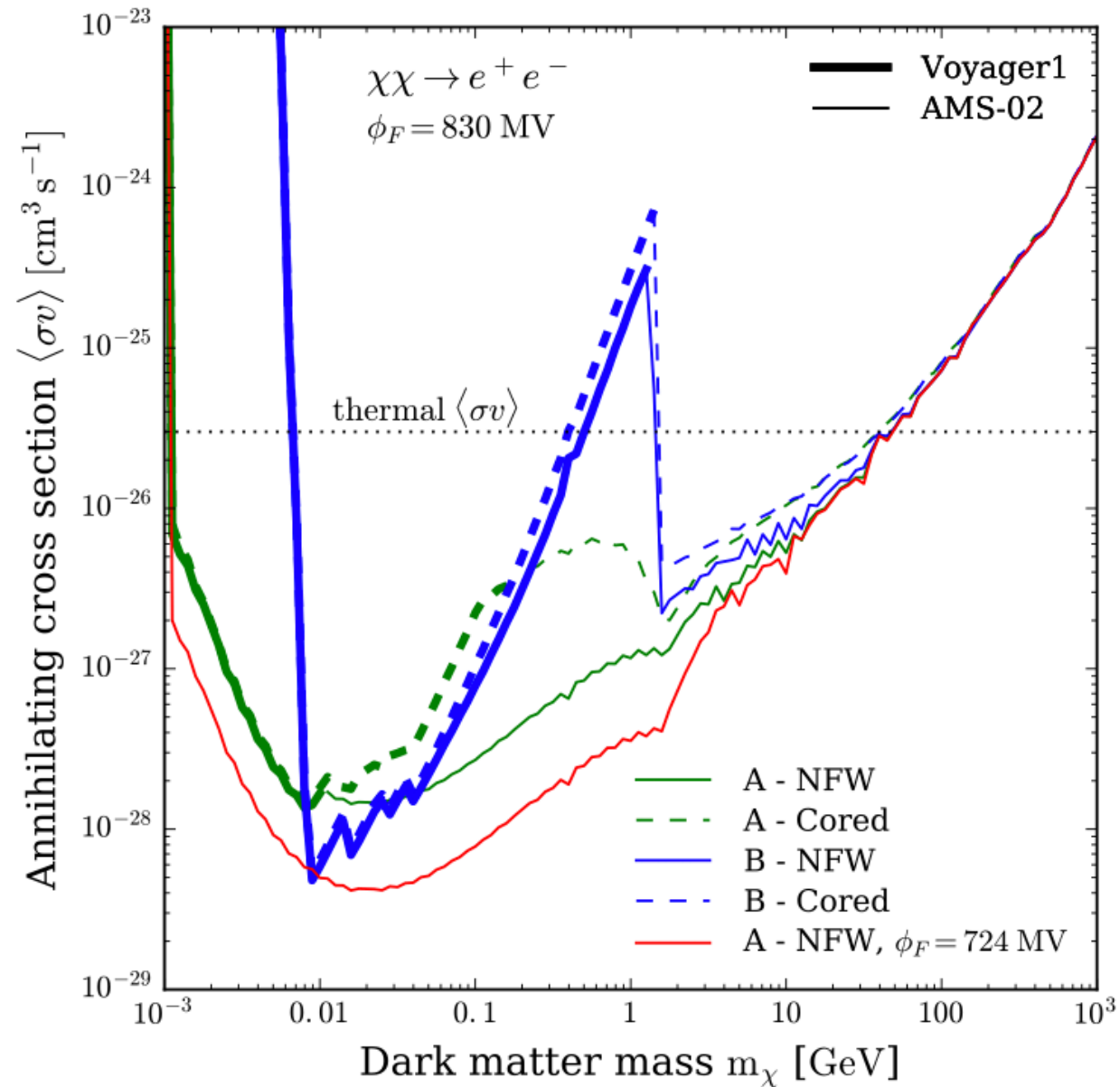


Propagation A = strong reacceleration
Propagation B = weak/no reacceleration

Indirect Detection: charged CRs

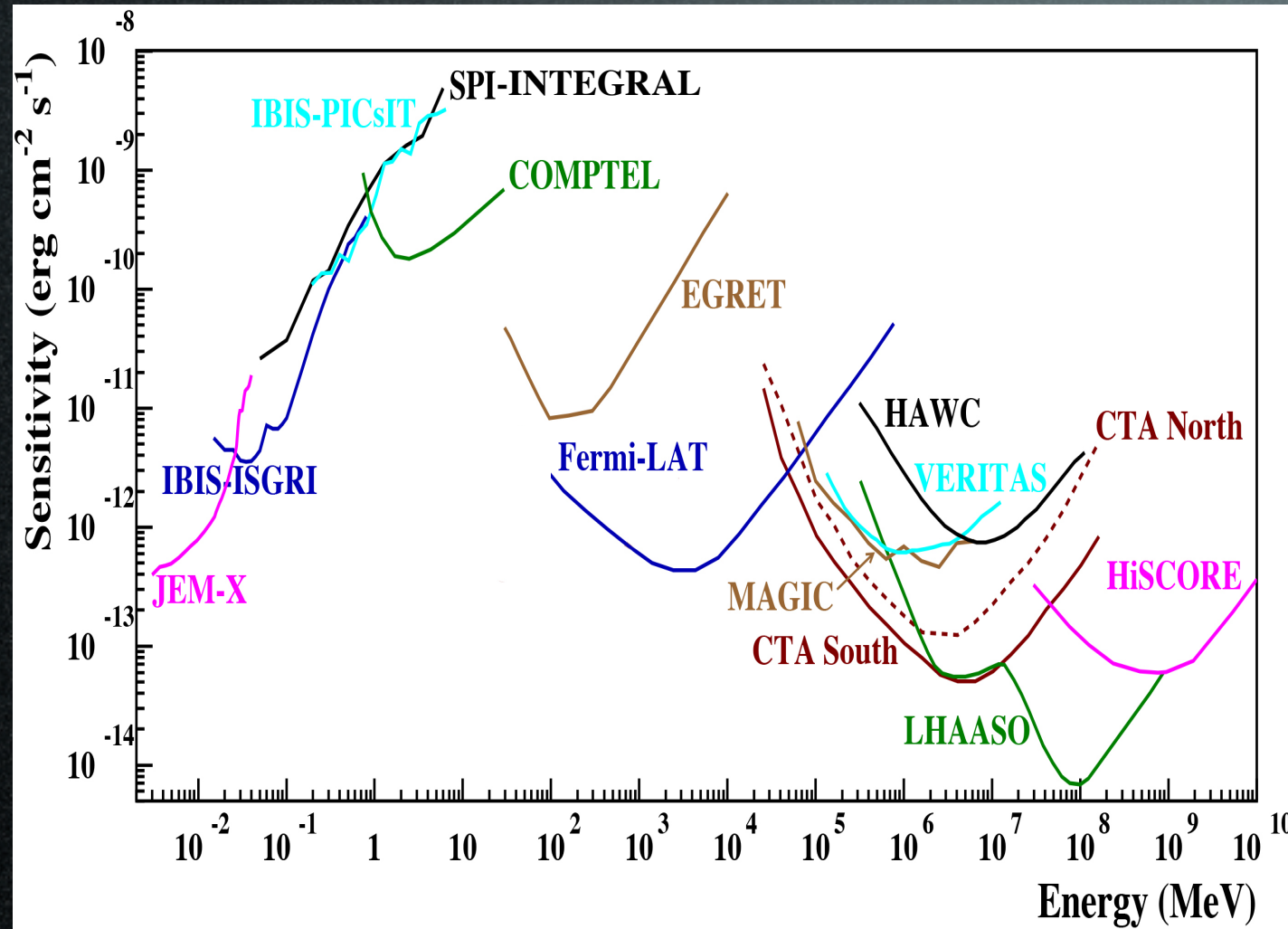
Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by **Voyager I**



Indirect detection: photons

adapted from 1611.02232



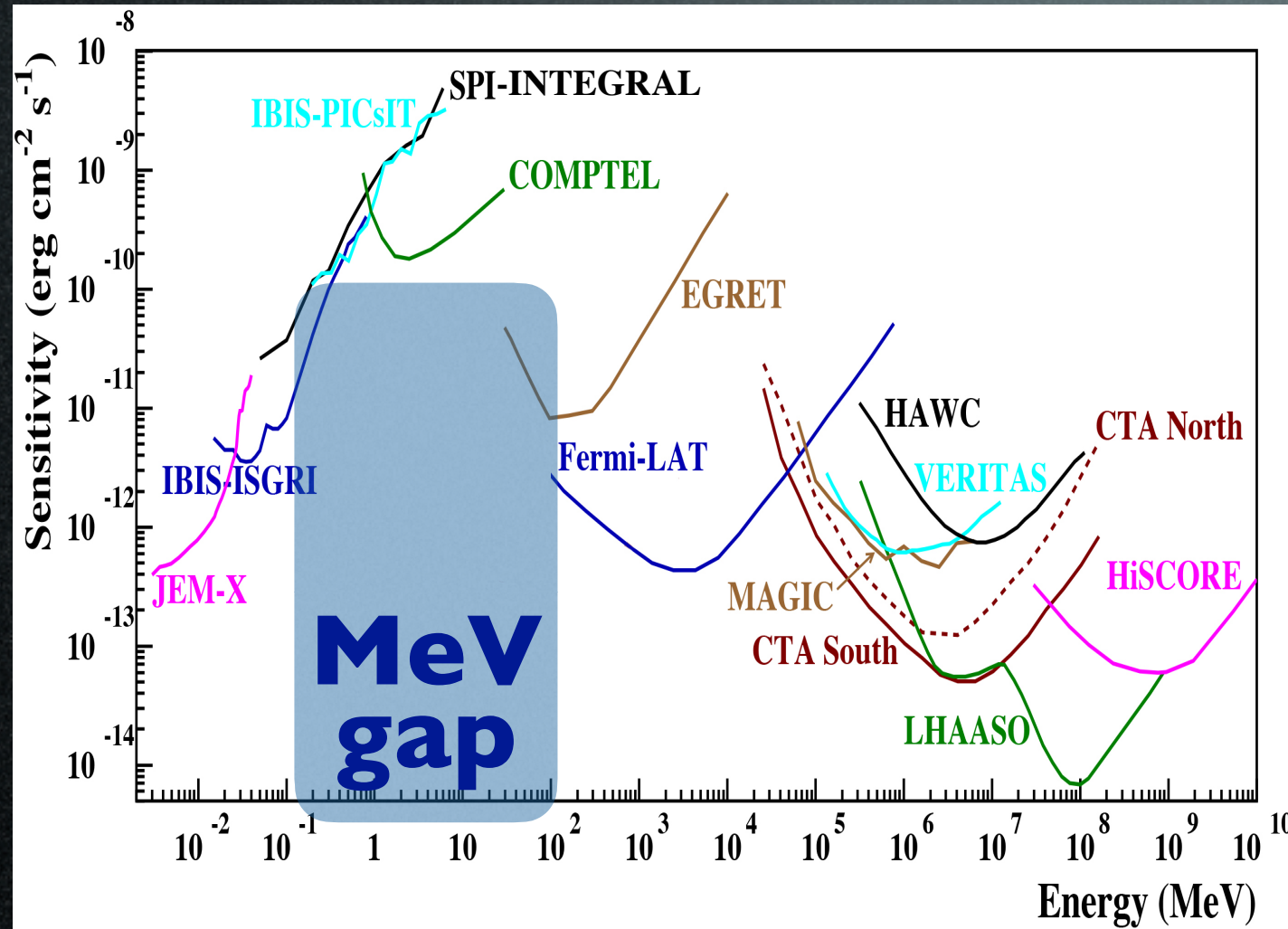
Past/current experiments:
Integral, Comptel, Fermi
 (2002 →) (1991-2000) (2009 →)

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

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

Indirect detection: photons

adapted from 1611.02232



Past/current experiments:

Integral, Comptel, Fermi

(2002 →) (1991-2000) (2009 →)

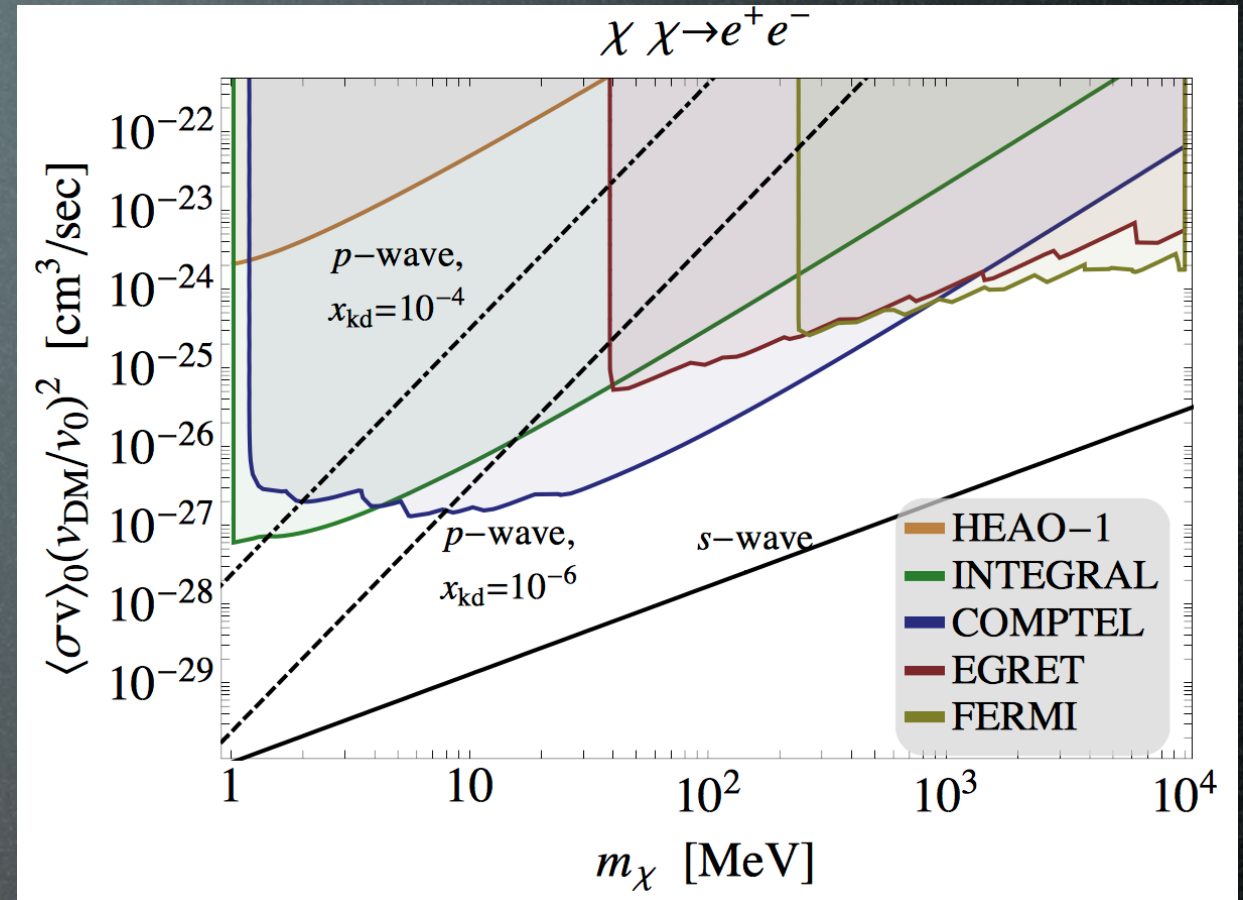
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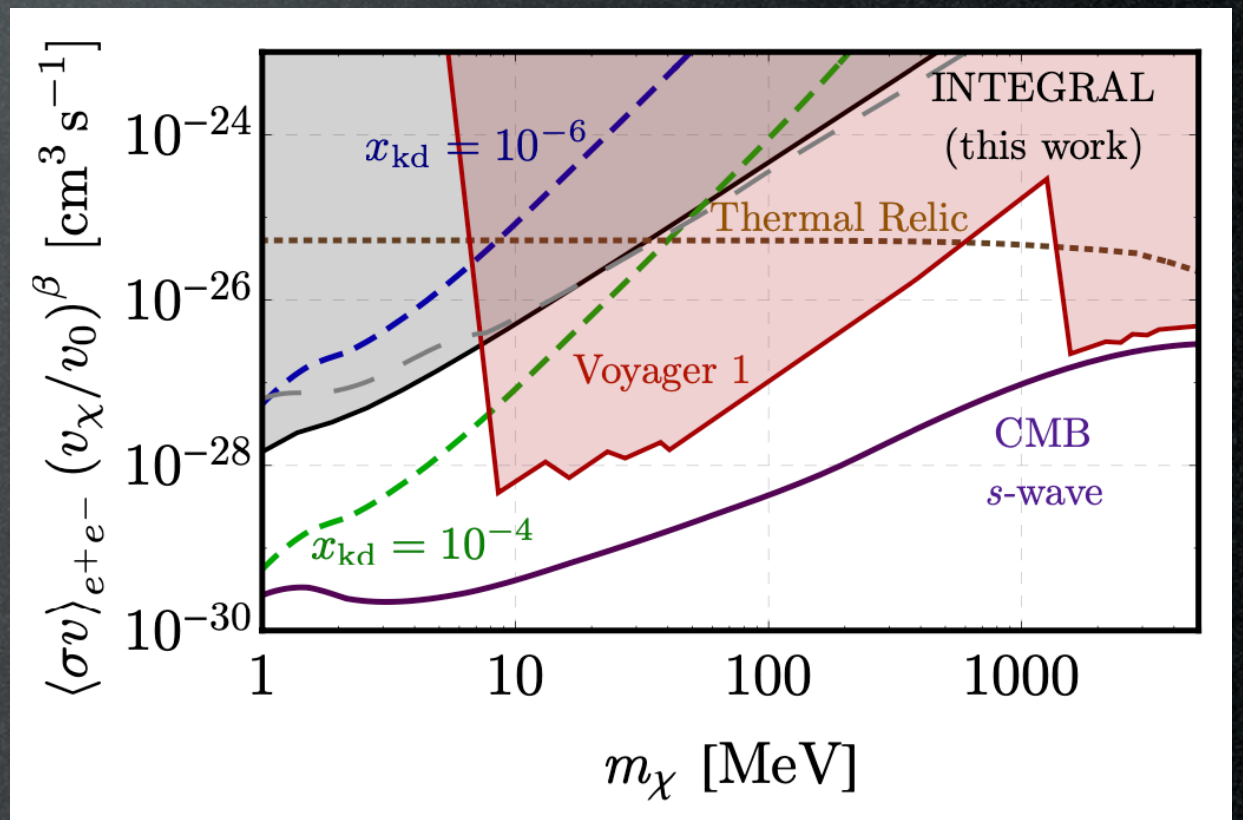
AMEGO	satellite	2020s?	HEP detectors	γ -rays	0.2 – 10 GeV
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SKA	S.Africa+Australia	2020s?	radio telescope	radio	50 MHz – 30 GHz
INO-ICAL	India	2020s?	calorimeter	neutrinos	1 – 100 GeV
E-ASTROGAM	satellite	2030s?	HEP detectors	γ -rays	0.3 MeV – 3 GeV

Some 'recent' studies

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



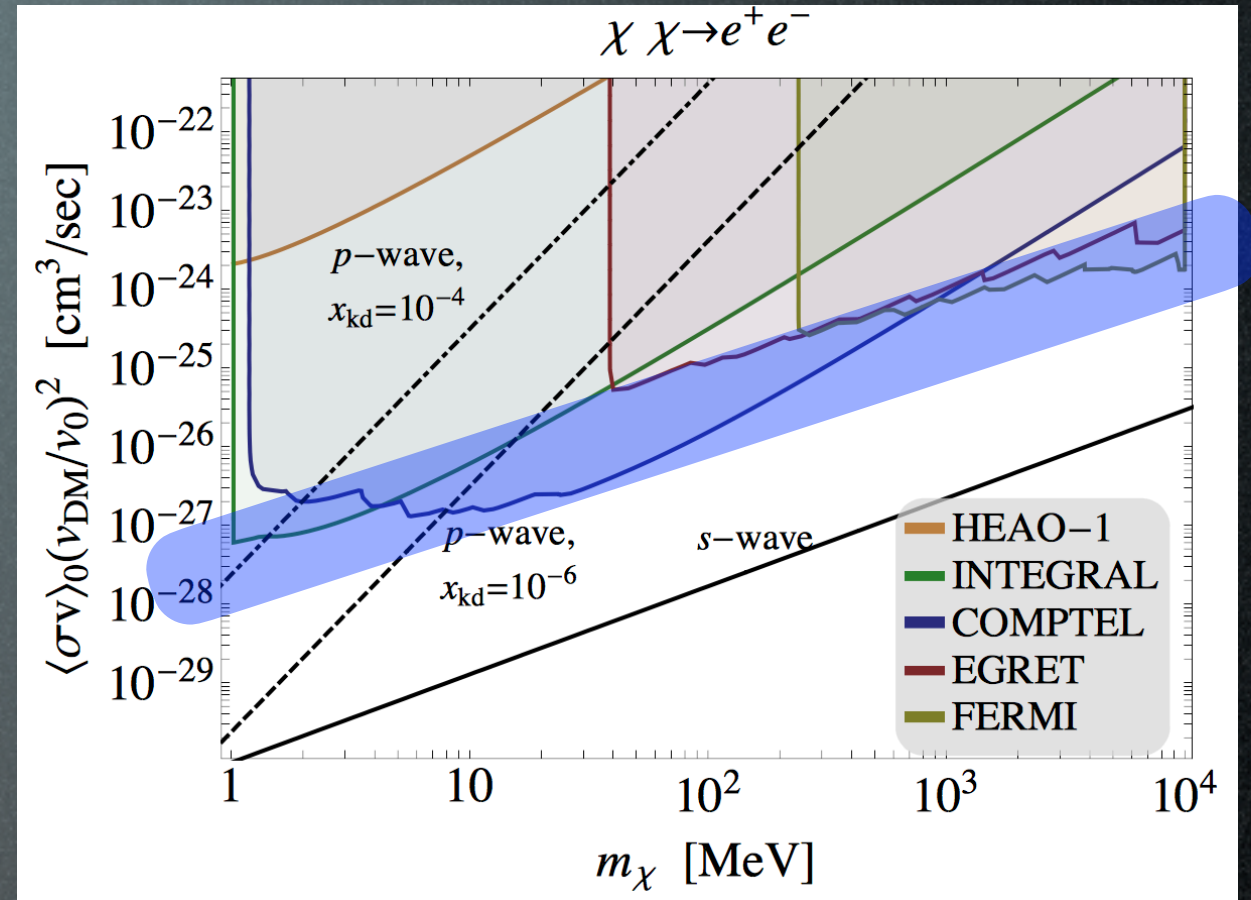
Laha, Muñoz, Slatyer, 2004.00627v1



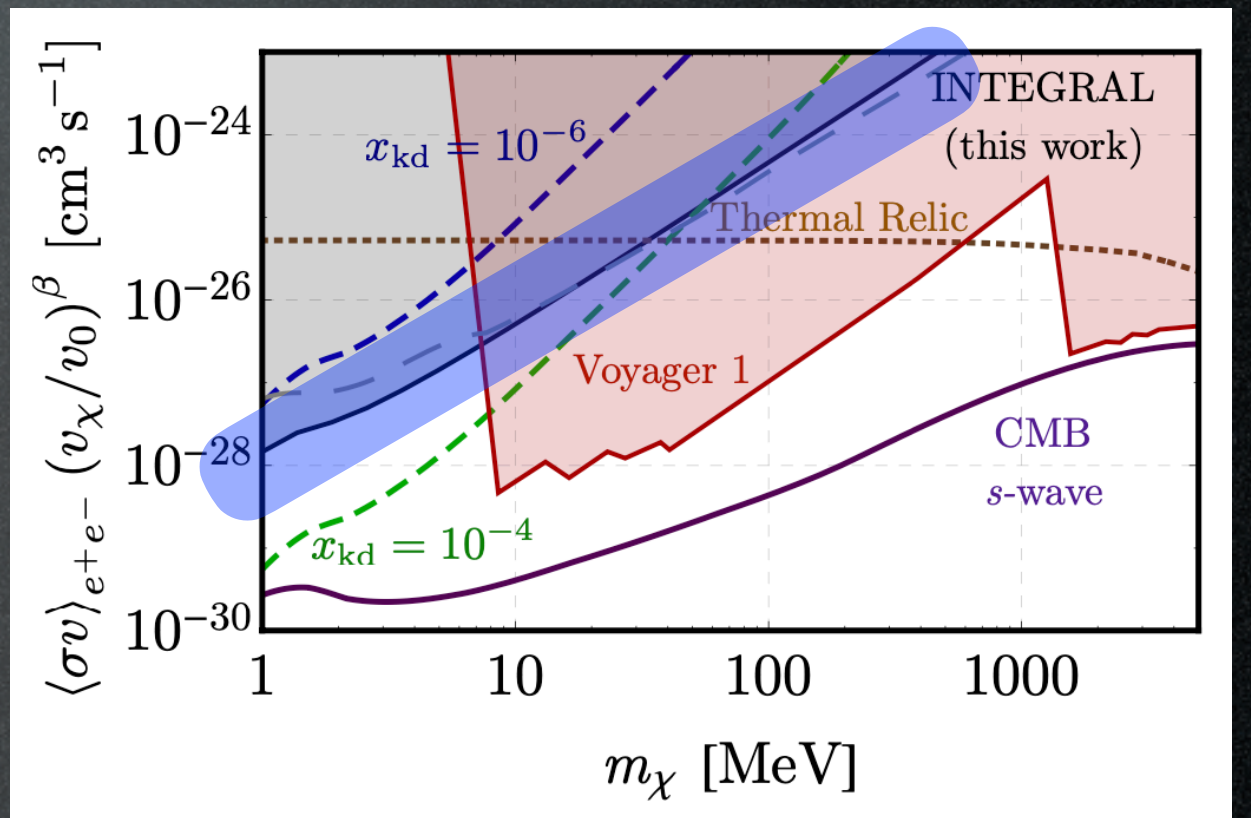
NB: 'prompt' emission only

Some 'recent' studies

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



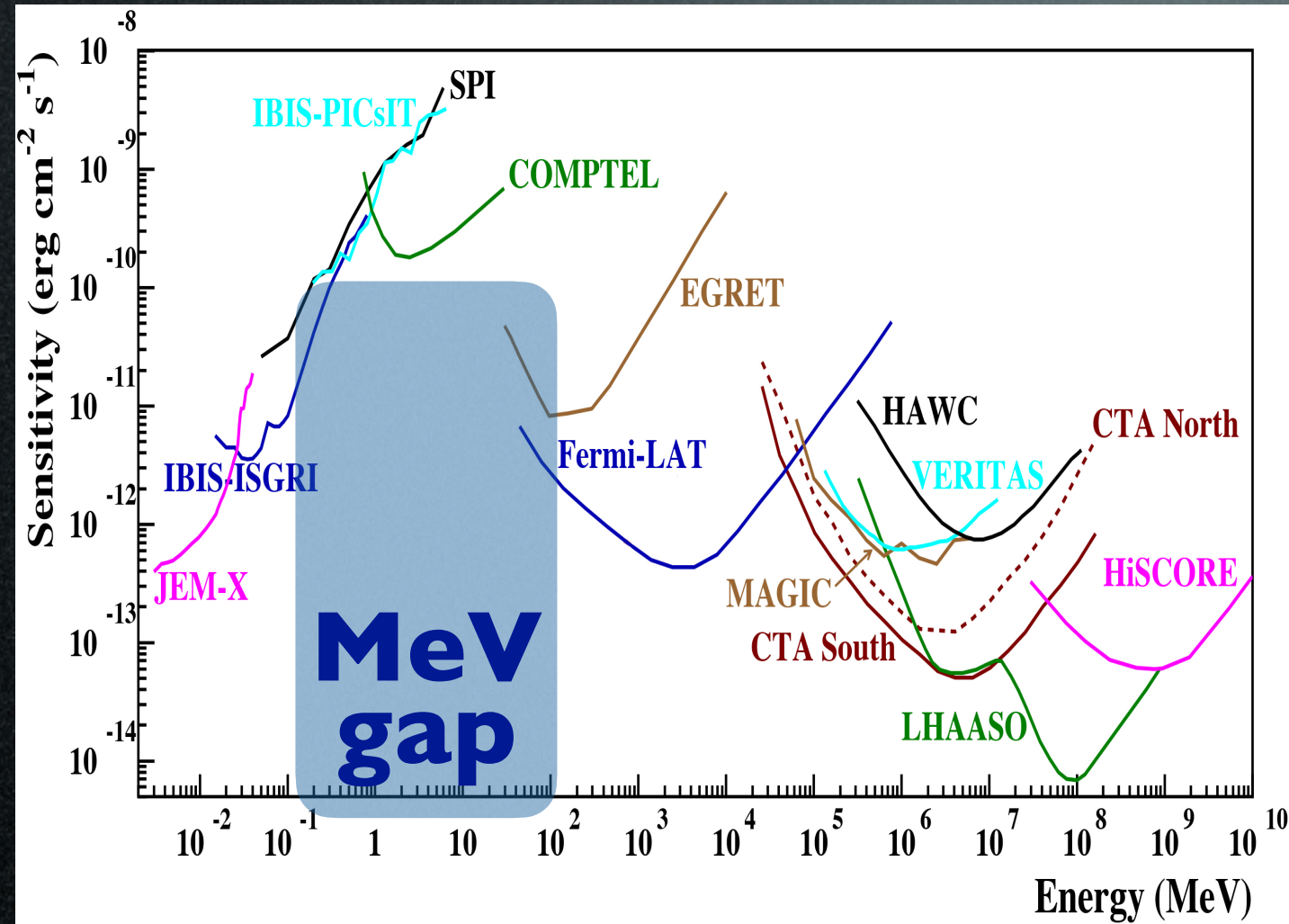
Laha, Muñoz, Slatyer, 2004.00627v1



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)

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

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

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

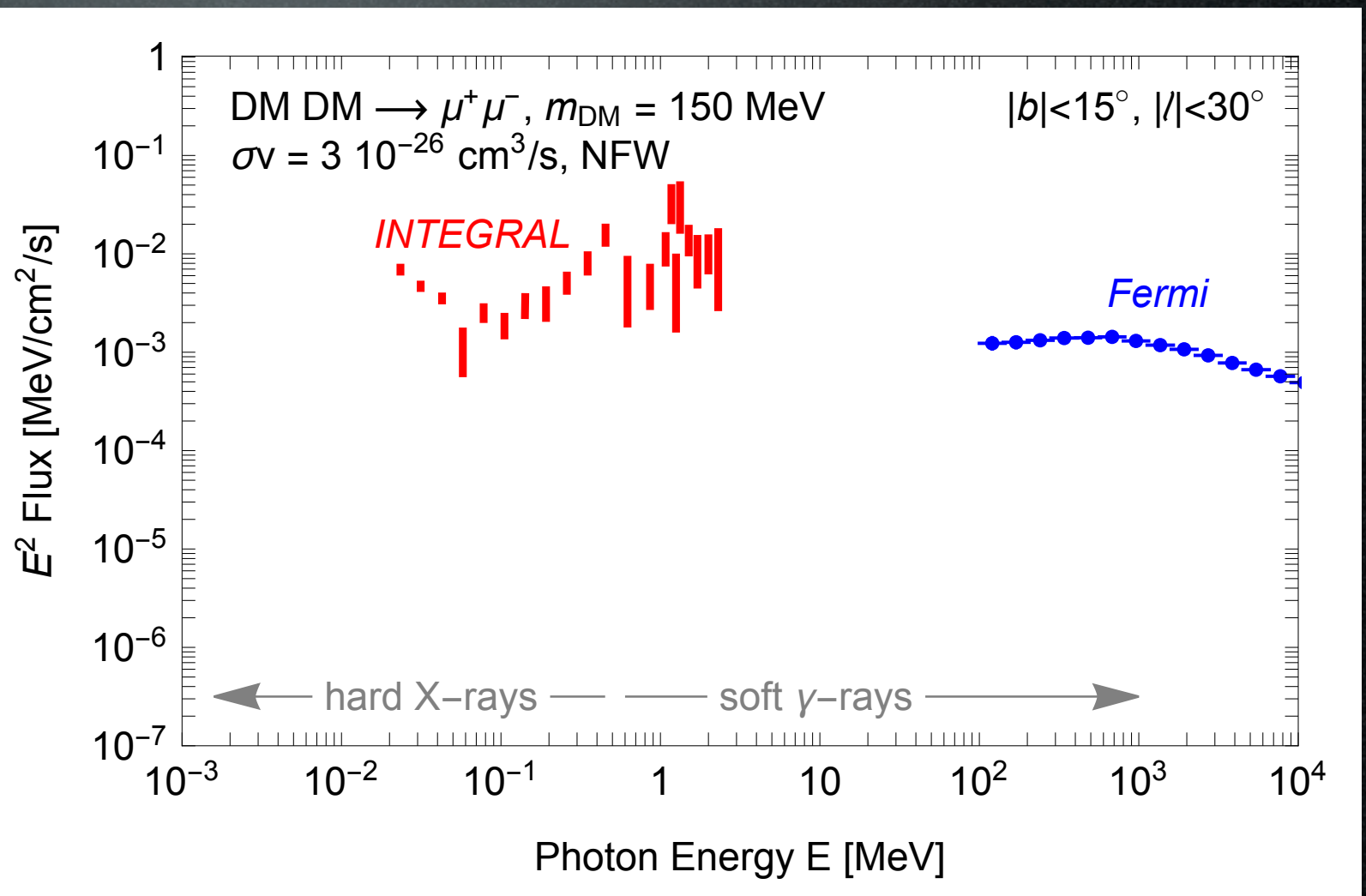
Sub-GeV DM & X-rays

Annihilation channels

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

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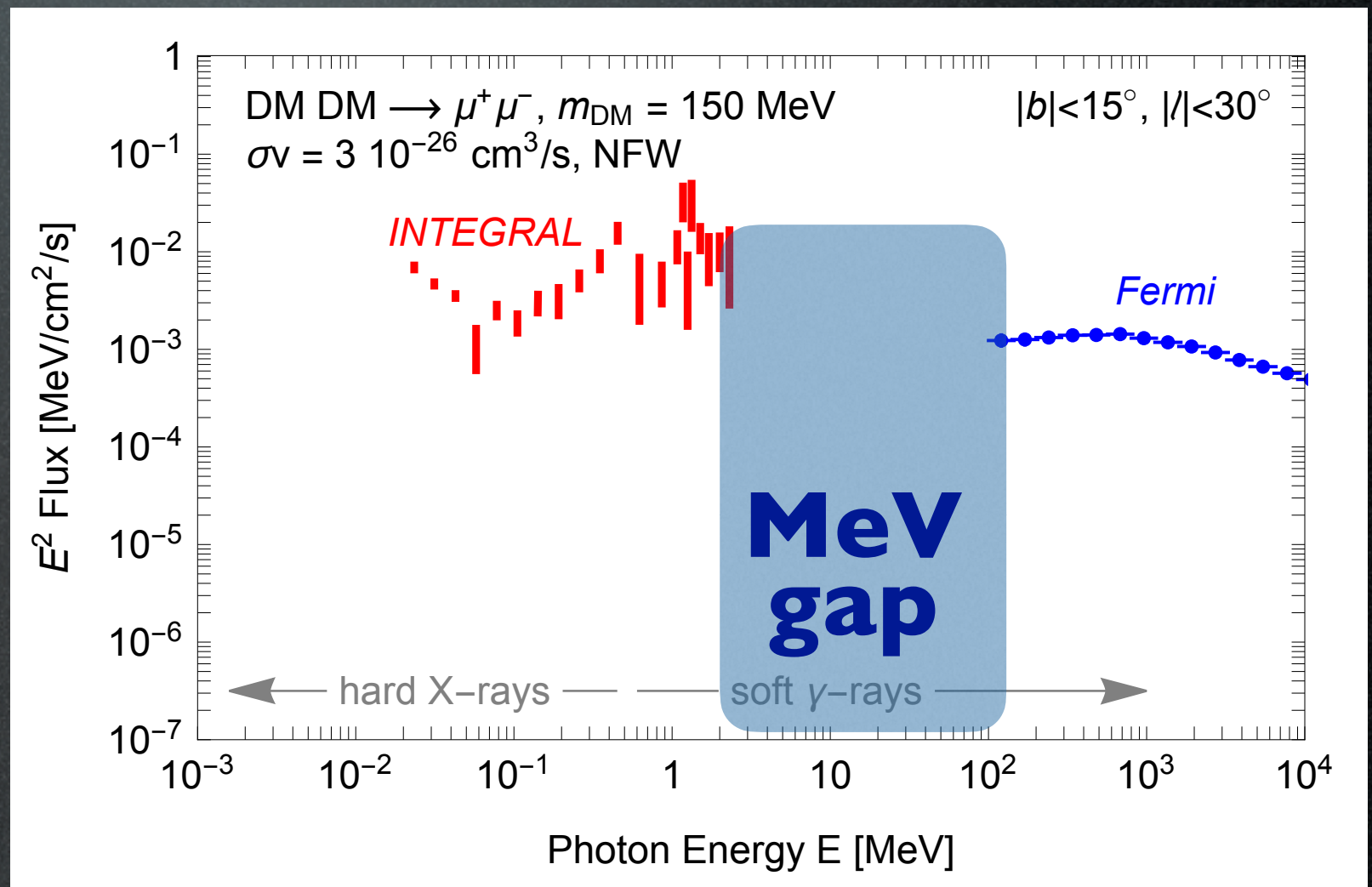
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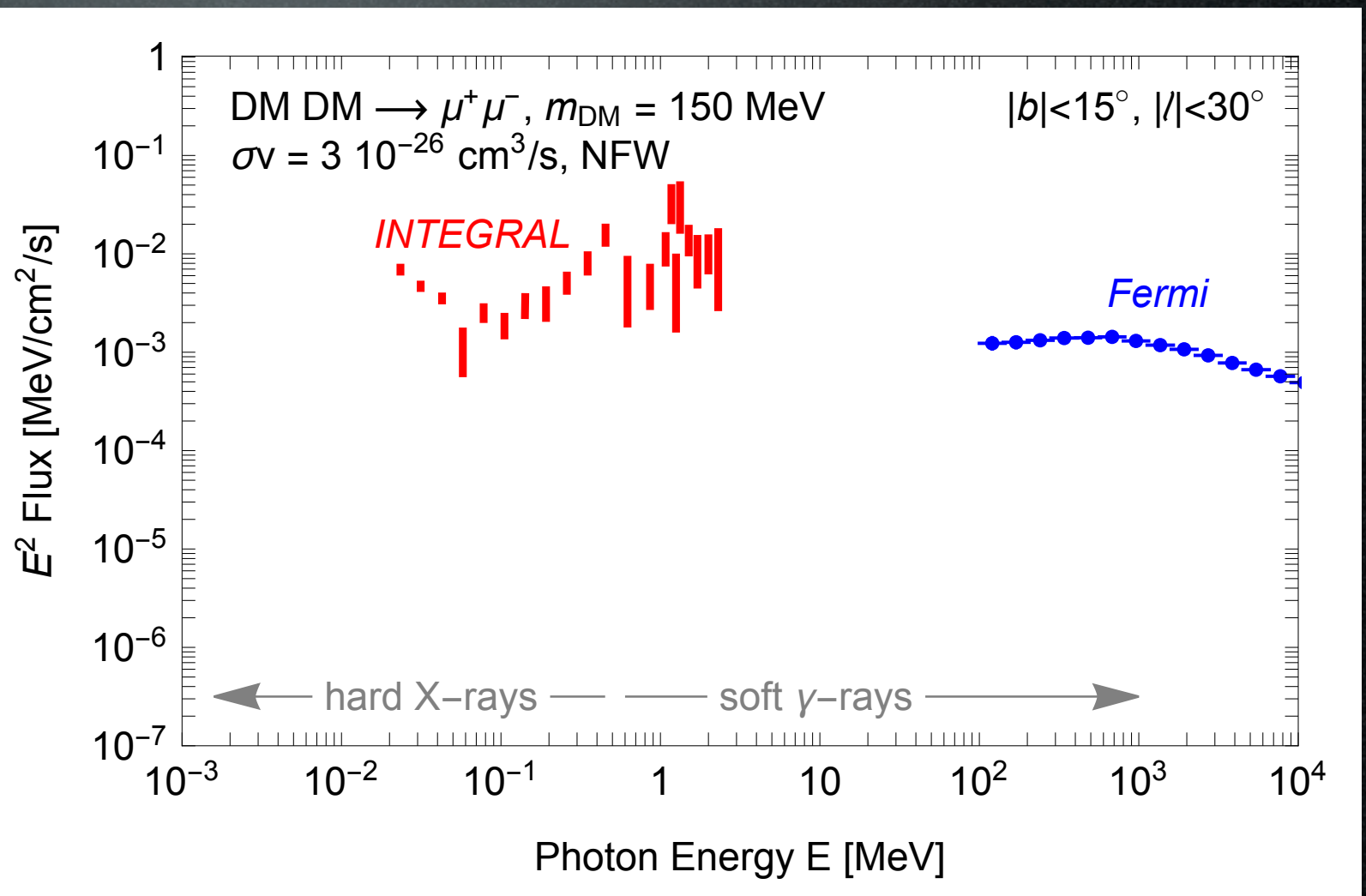
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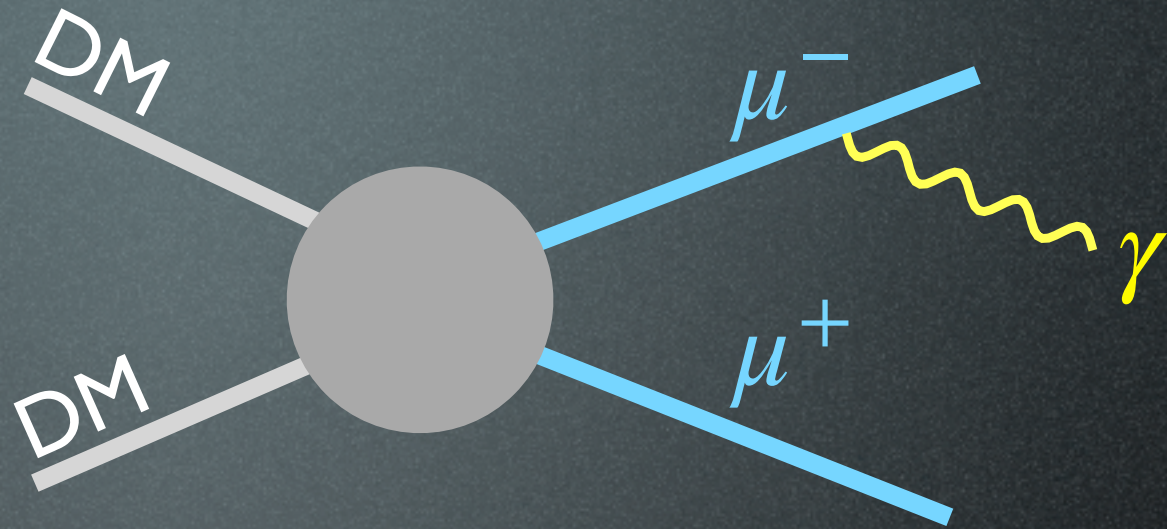
Sub-GeV DM & X-rays

Annihilation channels

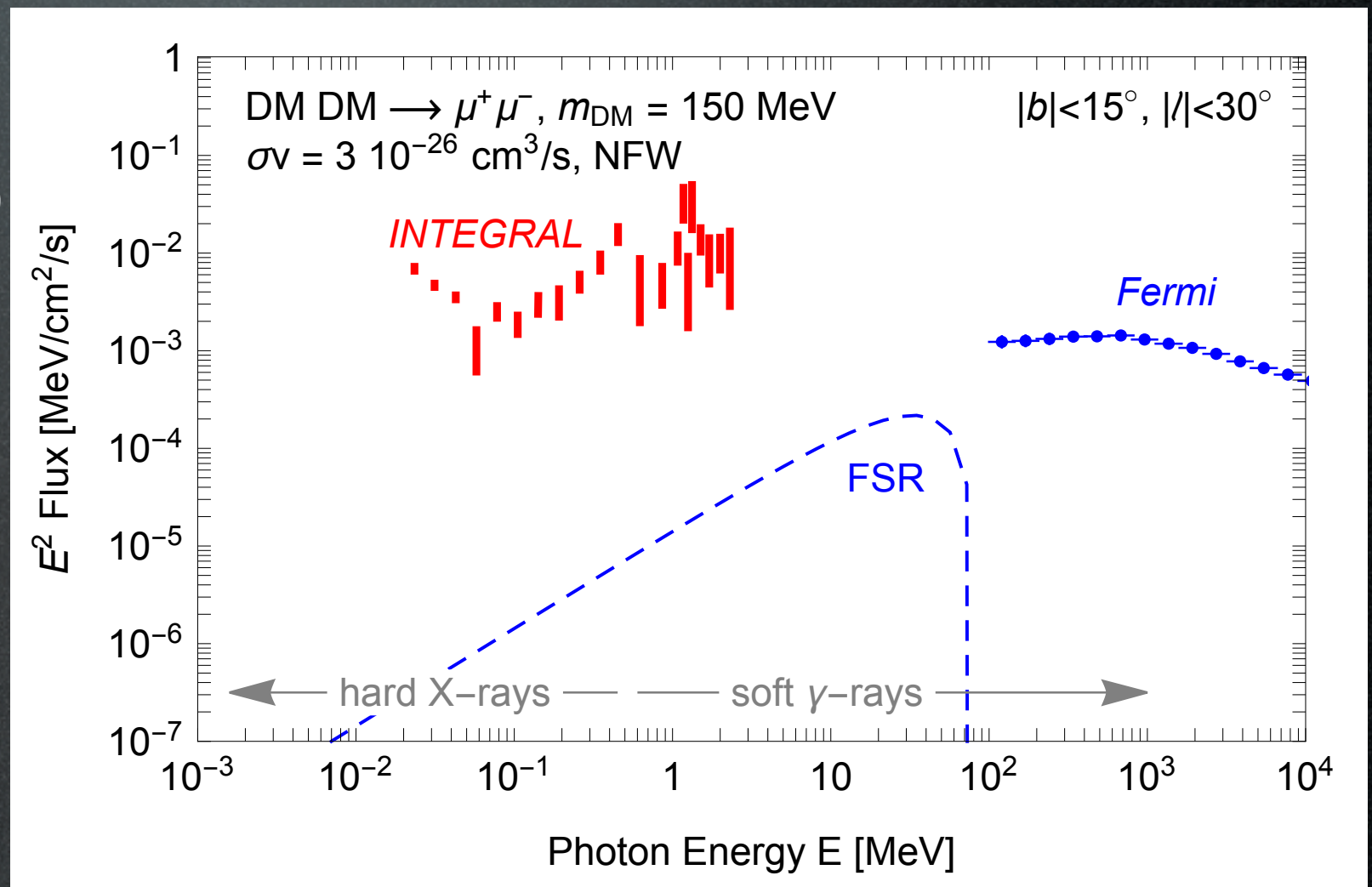
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$$\text{DM DM} \rightarrow \mu^+ \mu^-$$

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



‘Prompt’ emission:
Final State Radiation (**FSR**)



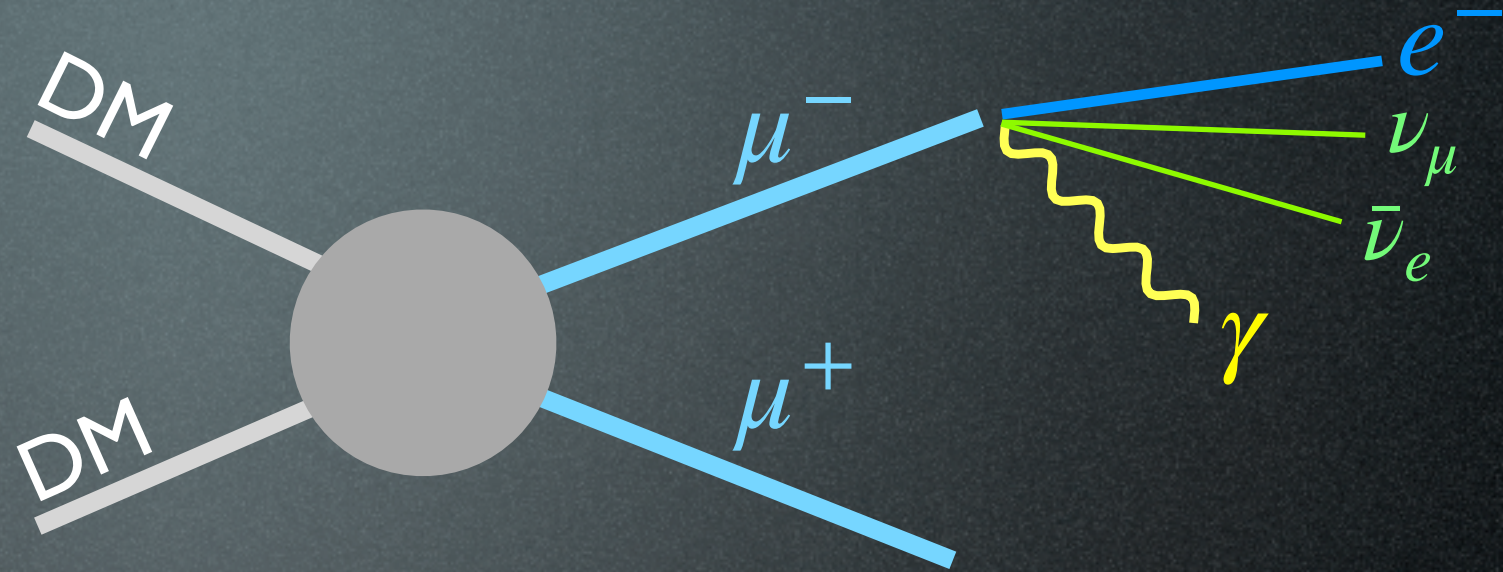
Sub-GeV DM & X-rays

Annihilation channels

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

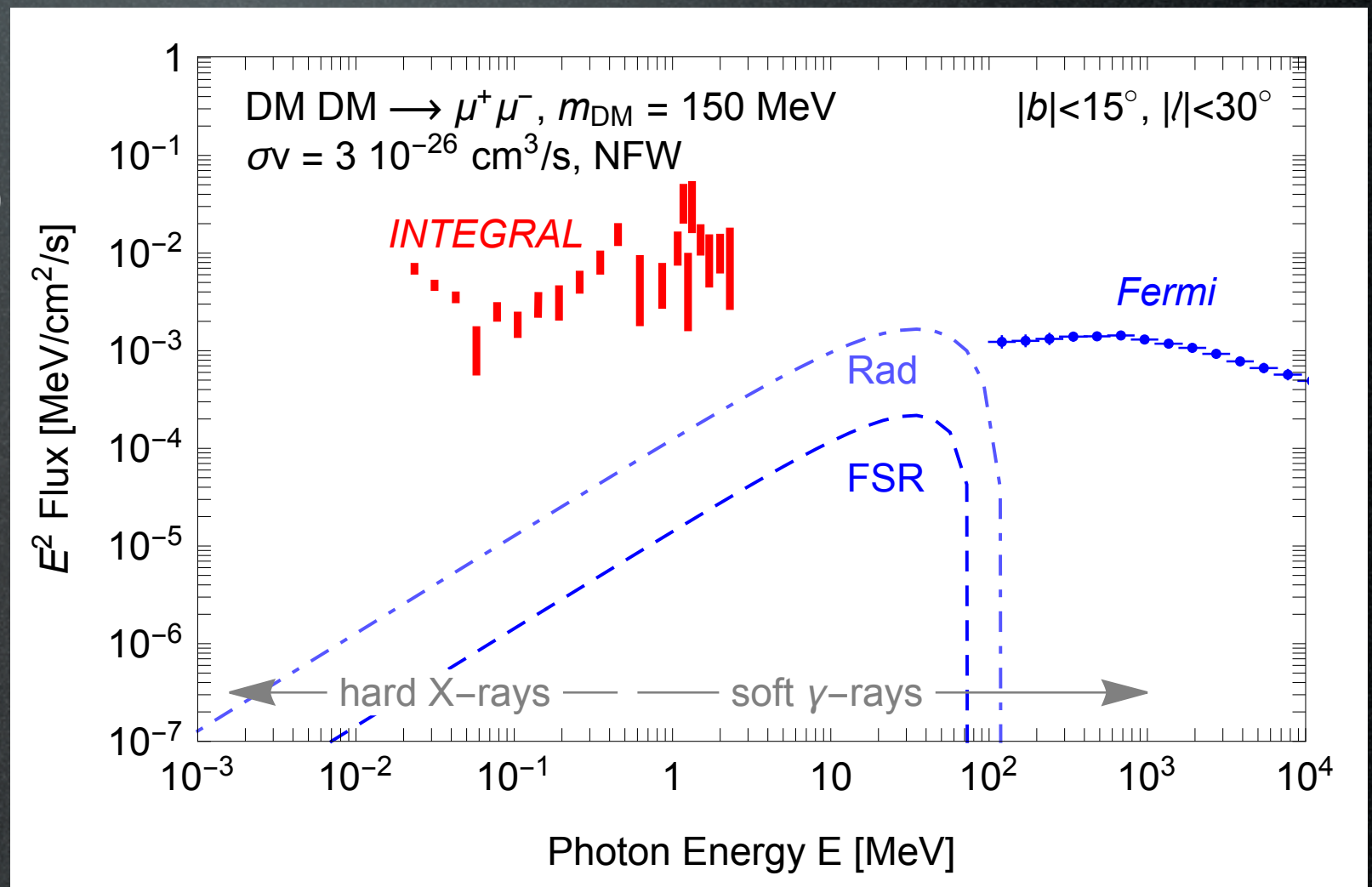
$$\text{DM DM} \rightarrow \mu^+ \mu^-$$

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



‘Prompt’ emission:
Final State Radiation (FSR)
Radiative μ decay

*Usually irrelevant,
but not for μ
decaying ‘at rest’!*



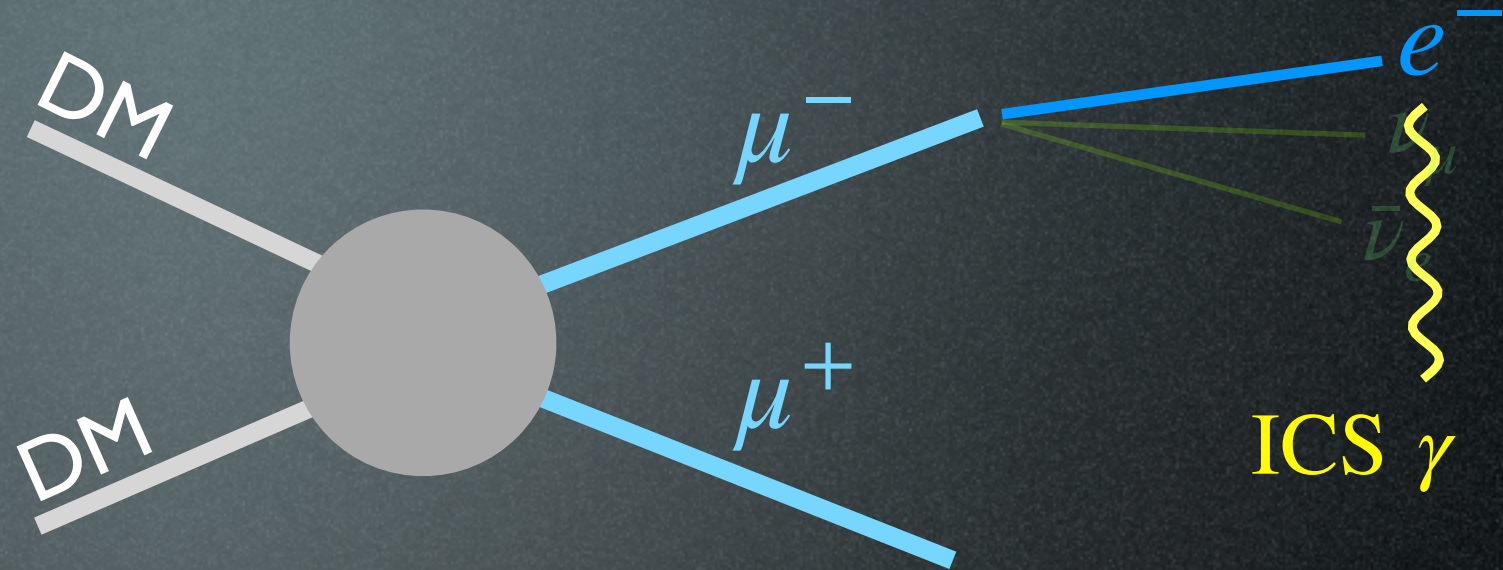
Sub-GeV DM & X-rays

Annihilation channels

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

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

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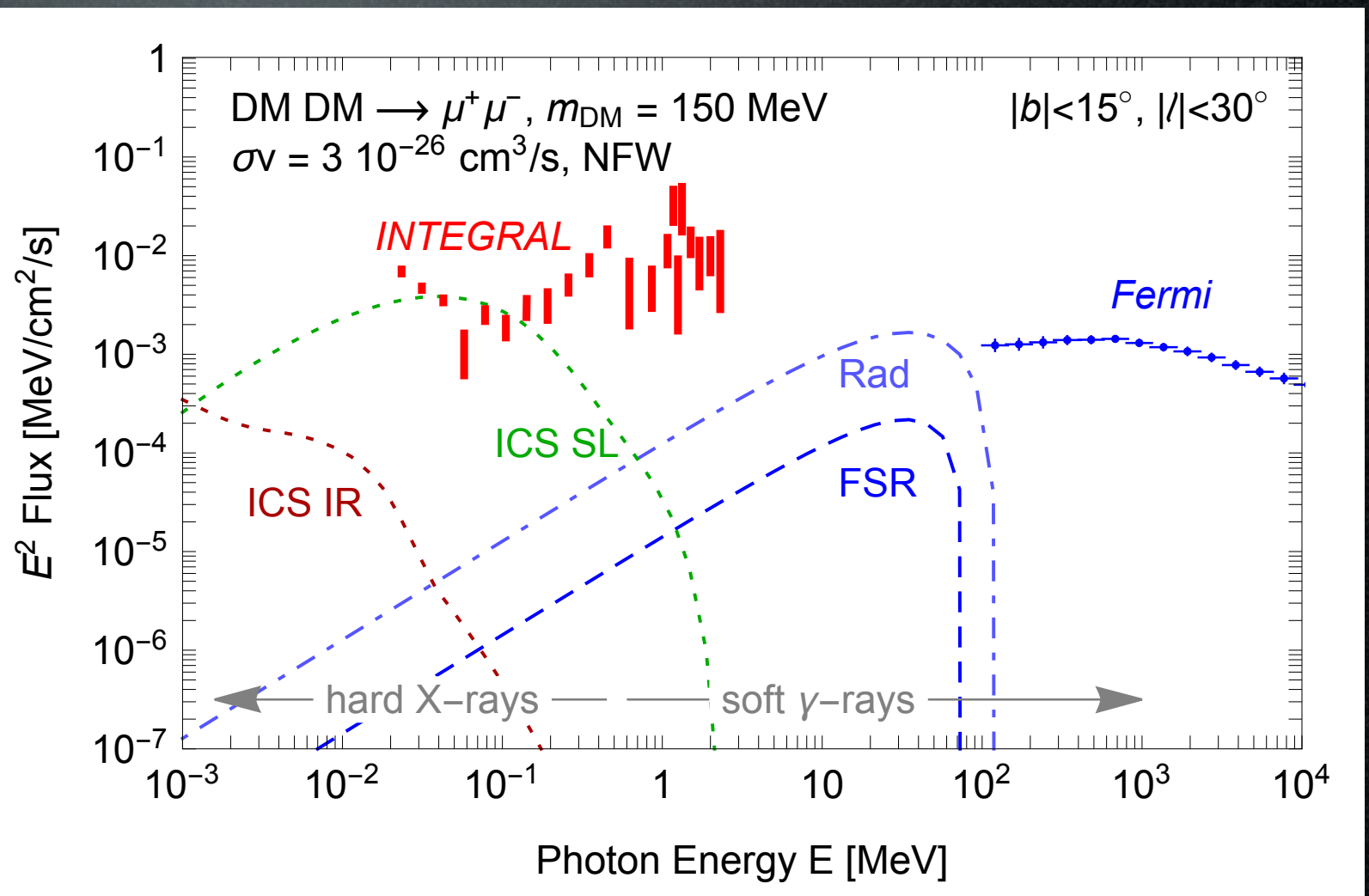
‘Prompt’ emission:

Final State Radiation (FSR)

Radiative μ decay

Secondary emission:

ICS: inevitably associated
to annihilation to charged states



Sub-GeV DM & X-rays

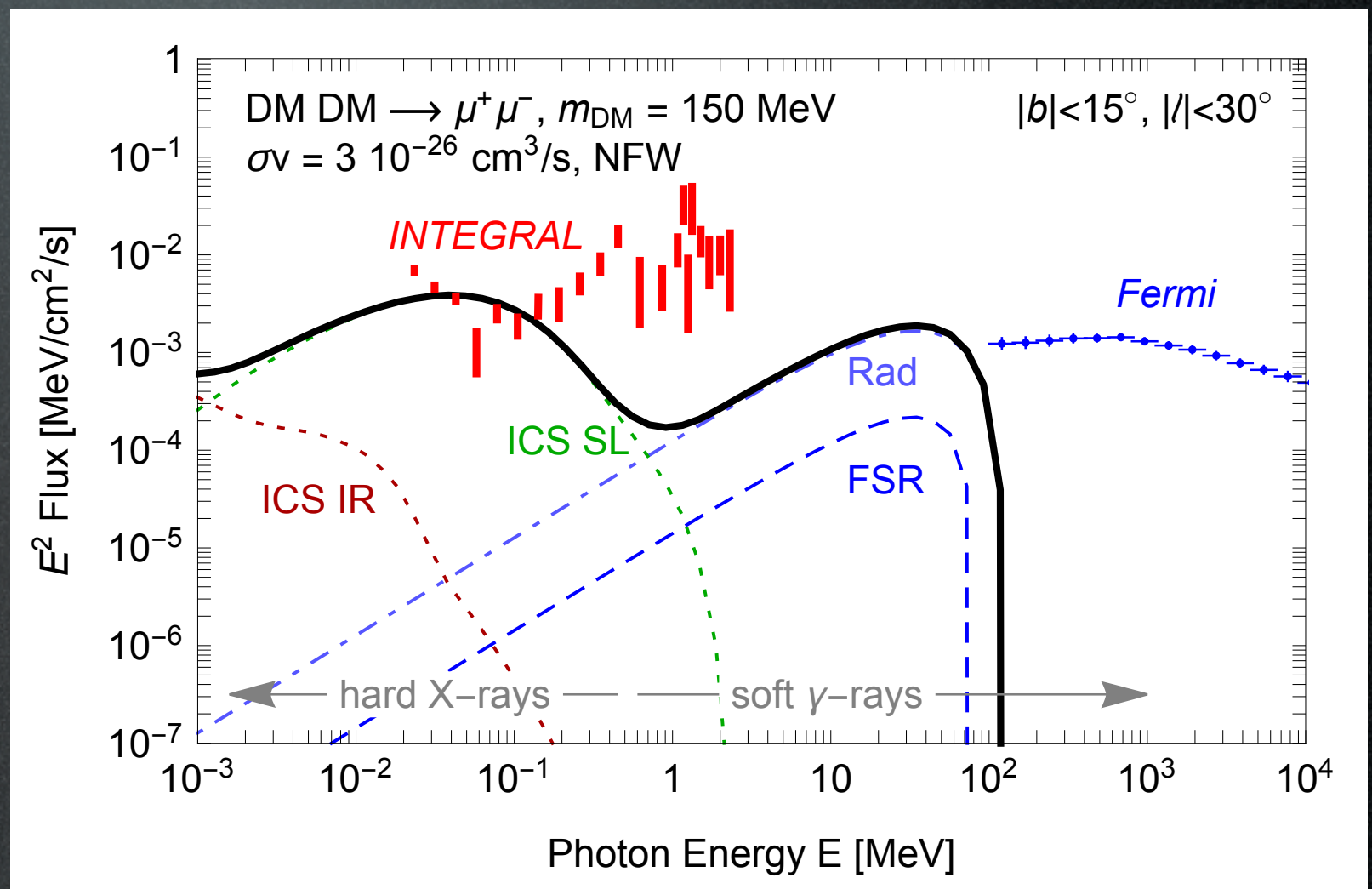
Annihilation channels

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

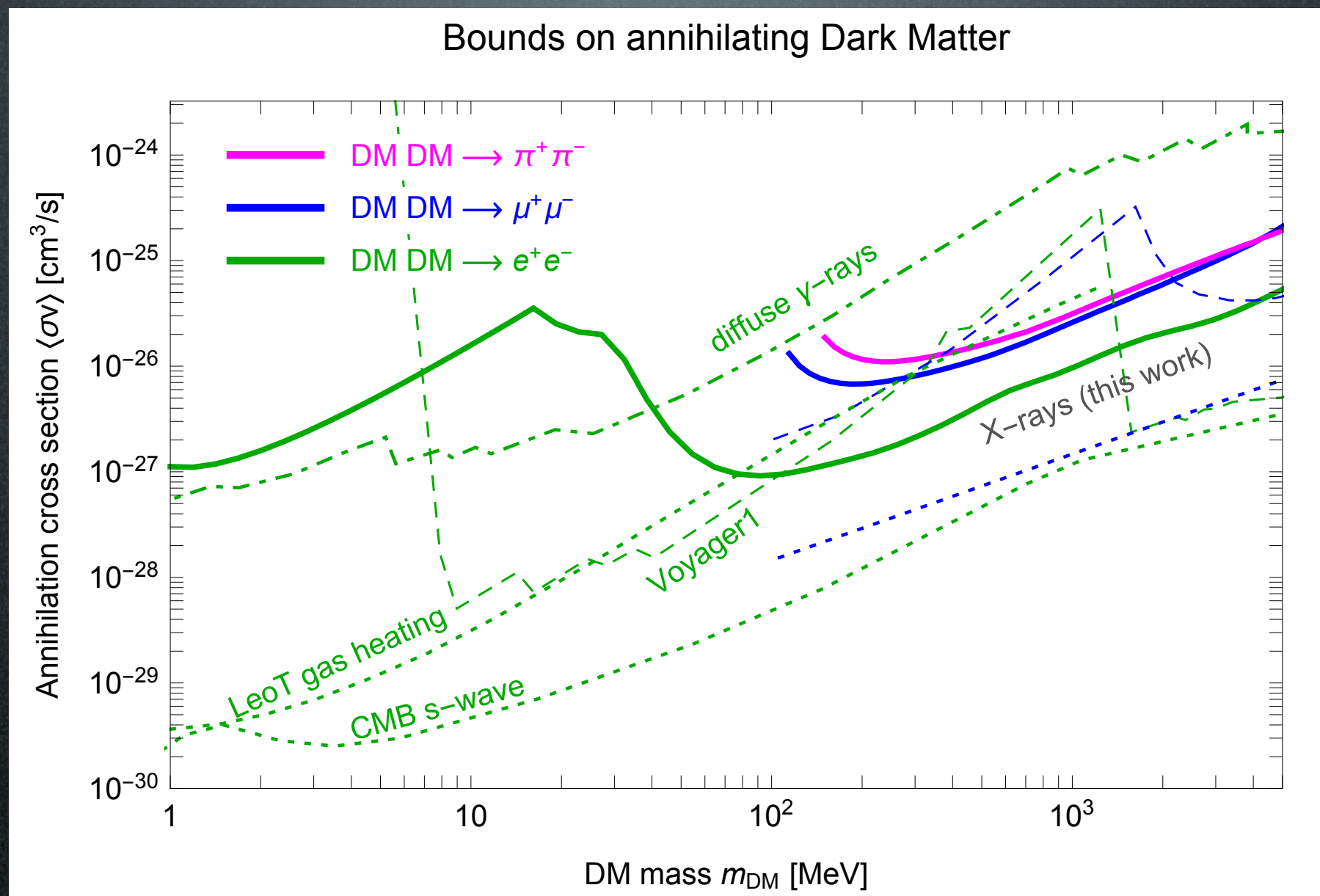
$$\text{DM DM} \rightarrow \mu^+ \mu^-$$

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



Results



Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854v3

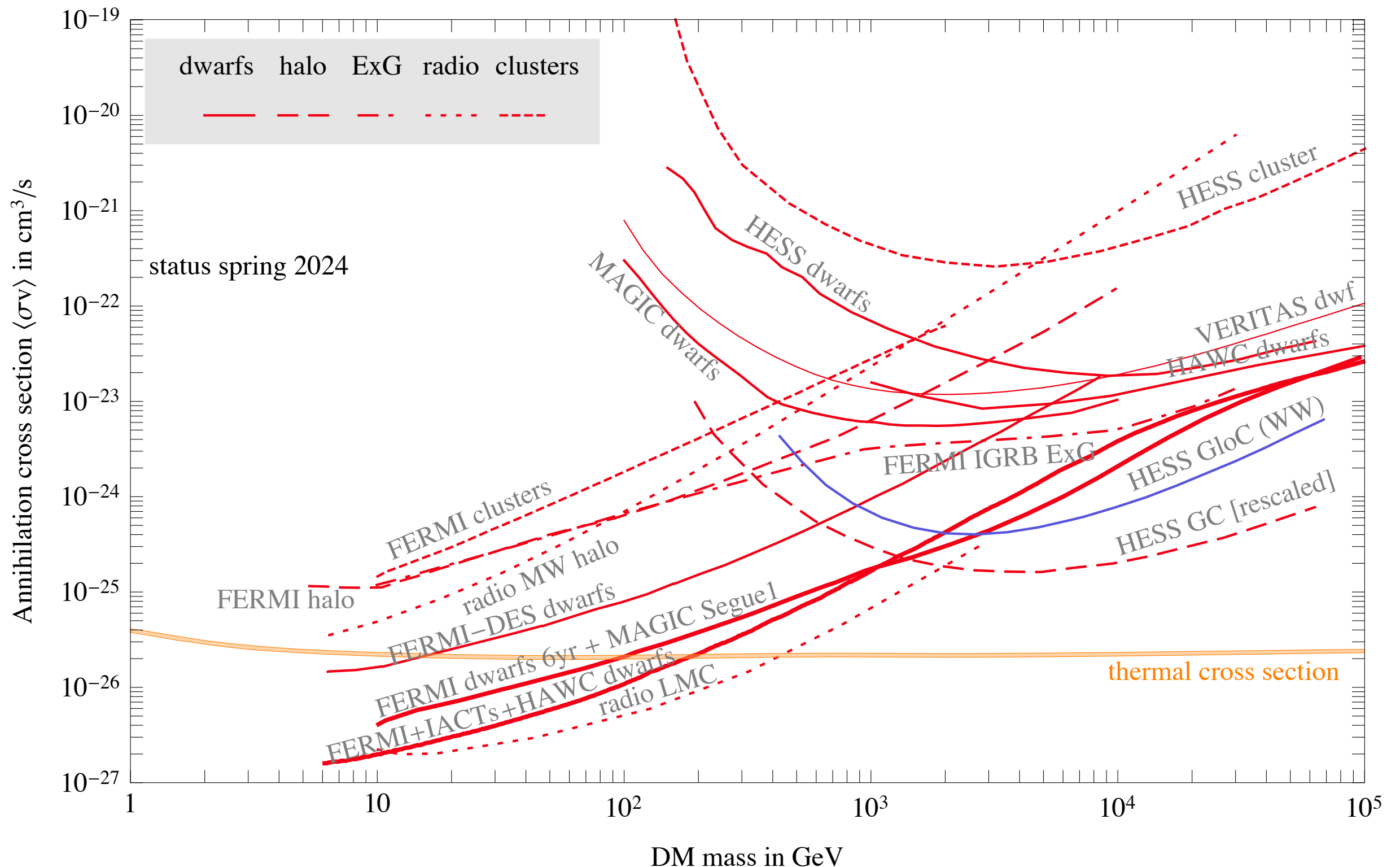
Bounds on all 3 channels

ICS allows to significantly improve at large m_{DM}

But nothing beats the s-wave CMB bounds

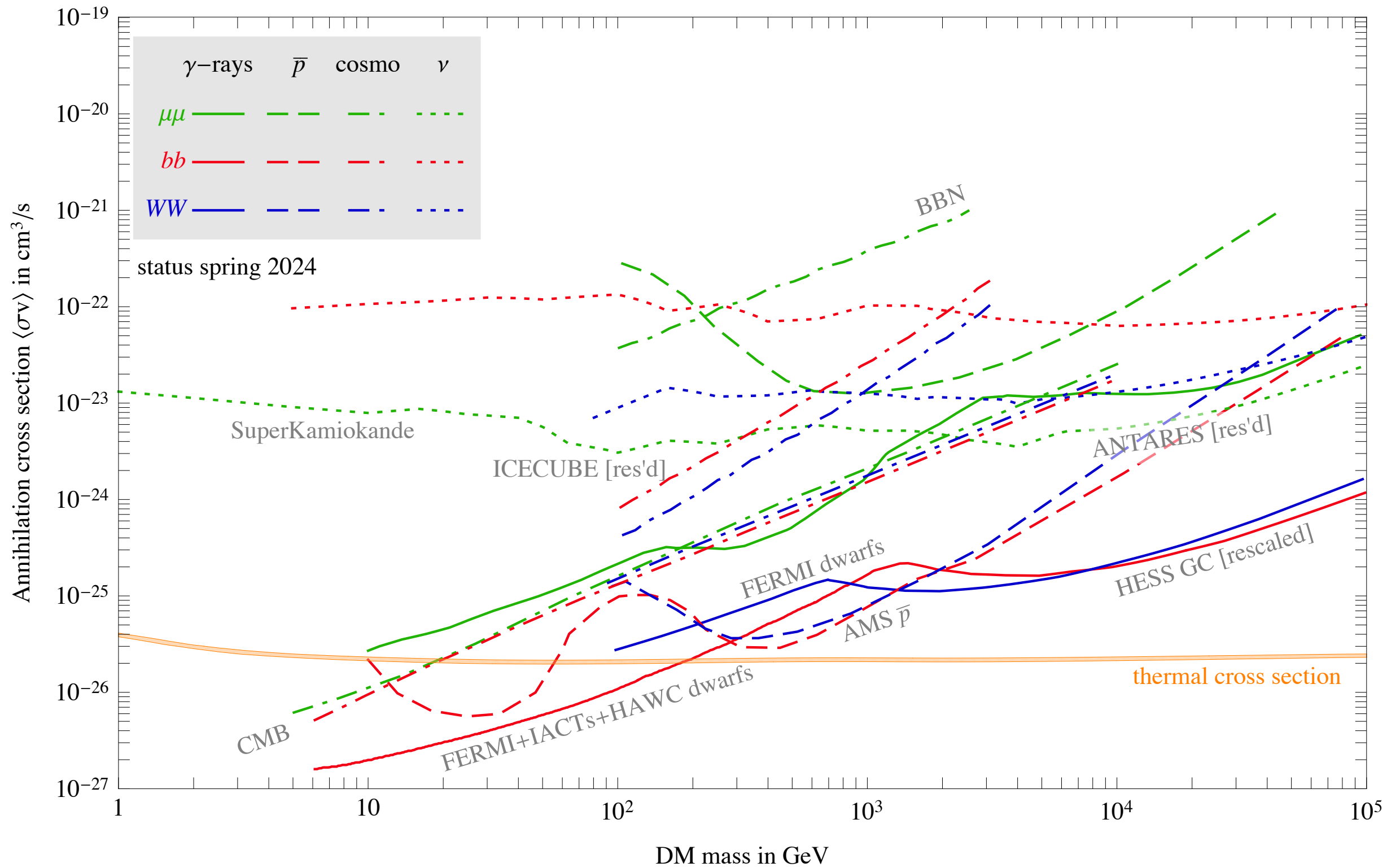
Comparing all bounds

Gamma-ray constraints, $\text{DM DM} \rightarrow b\bar{b}$



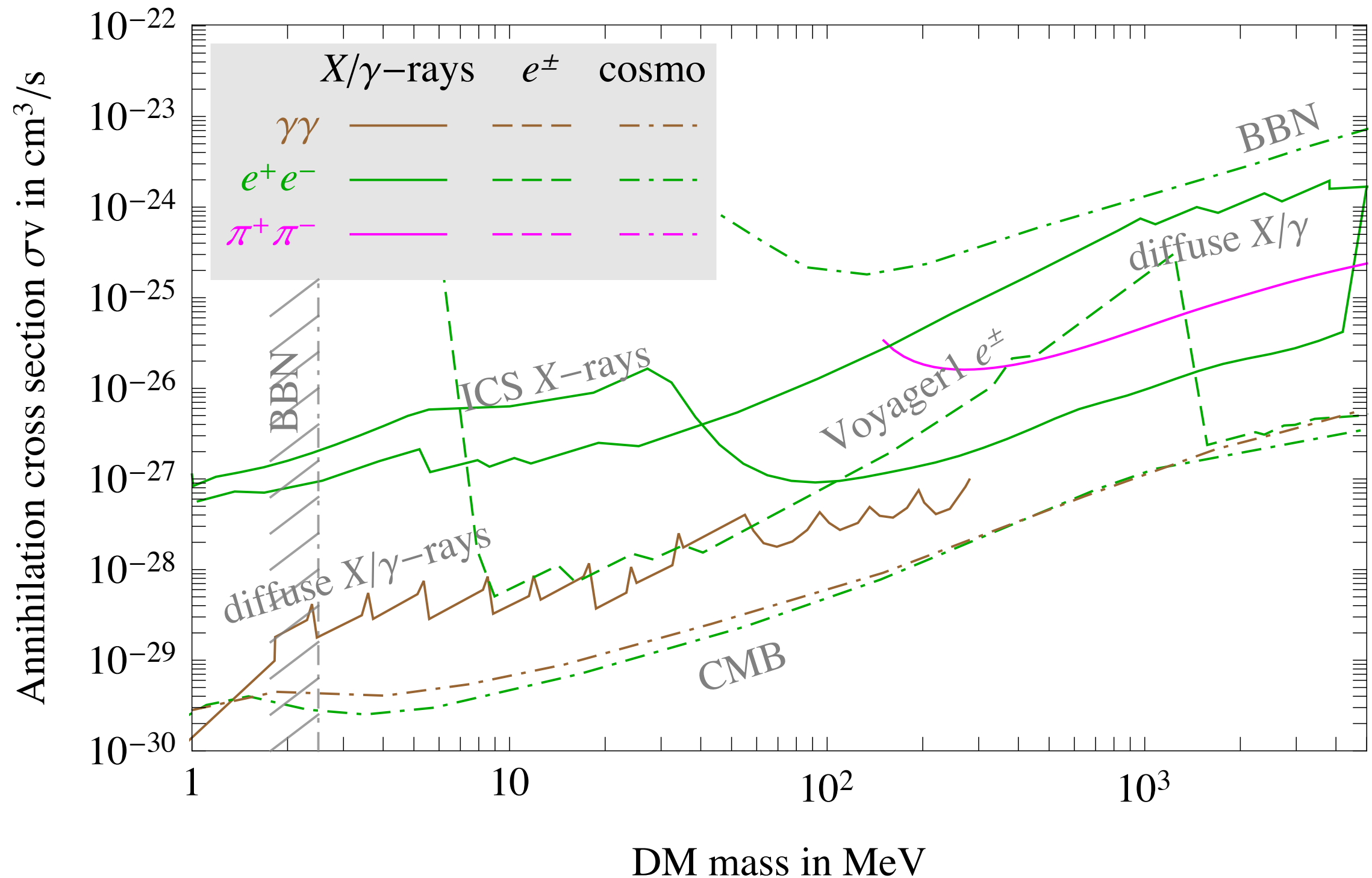
Comparing all bounds

All Indirect Detection constraints

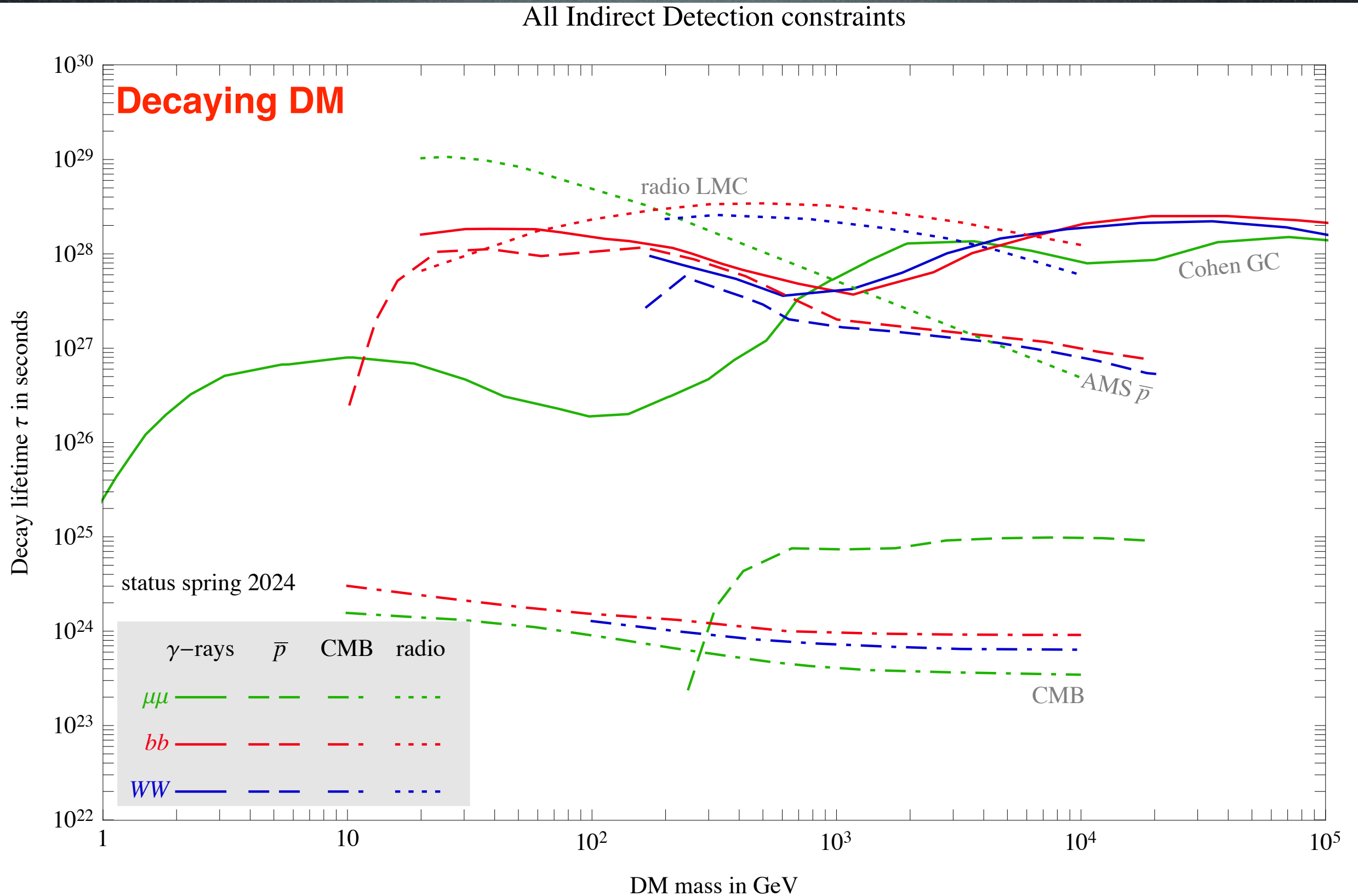


Comparing all bounds

Constraints on sub-GeV annihilating Dark Matter

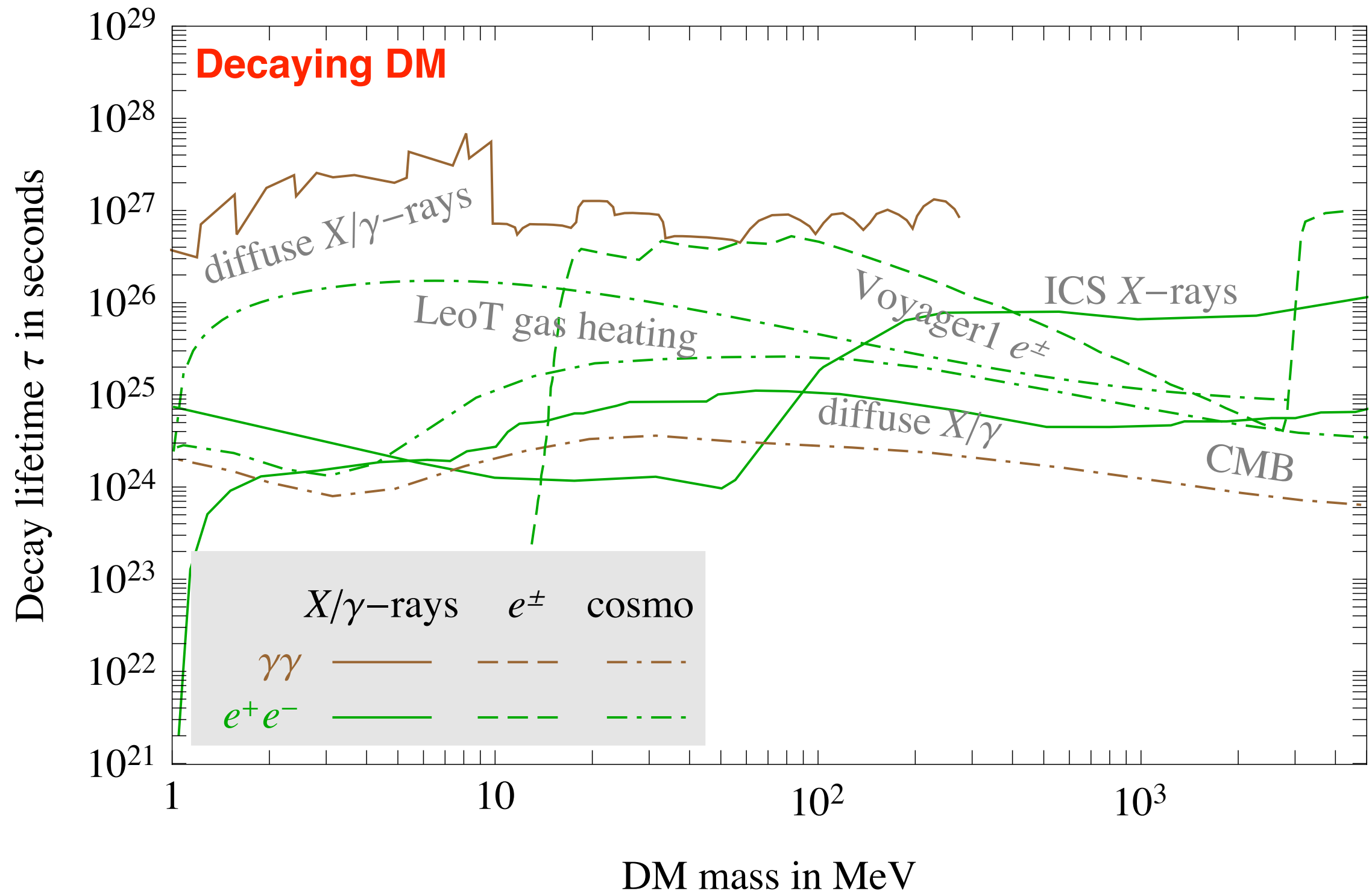


Comparing all bounds



Comparing all bounds

Constraints on sub-GeV decaying Dark Matter



Conclusions (on ID)

DM not seen yet (Damn!...)

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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!...

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in γ : astrophysical background

Solution:

- multimessenger
- switch-off astrophysics

Direct Detection: **basics**

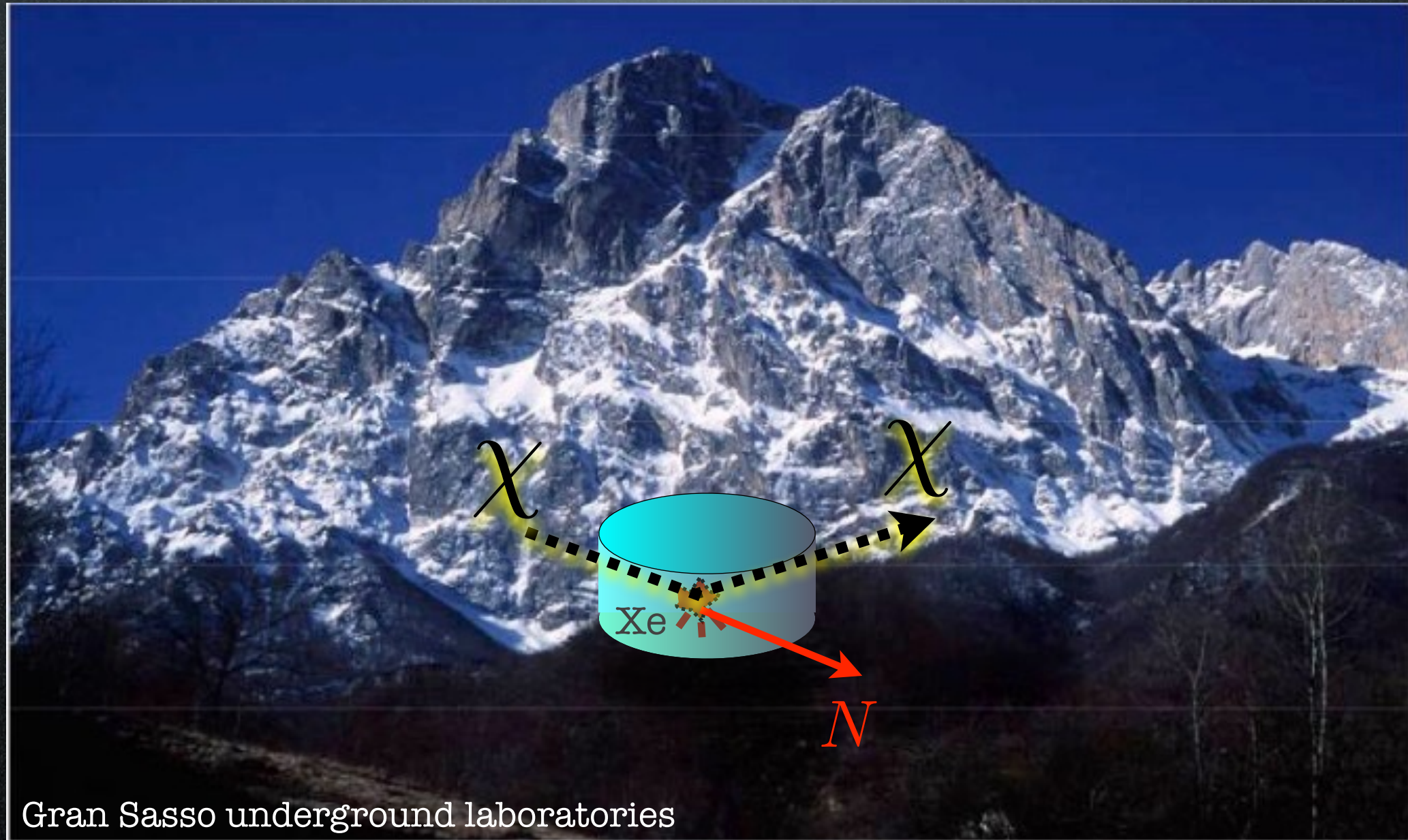


Gran Sasso underground laboratories

Direct Detection: basics



Direct Detection: basics

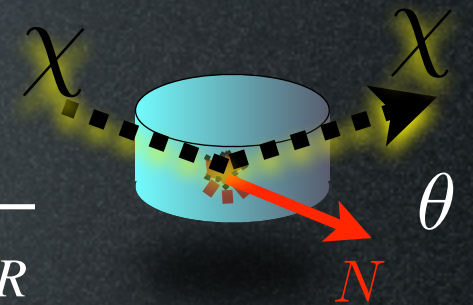


Direct Detection: basics

recoil energy $E_R = \frac{\mu_\chi^2 v^2}{m_N} (1 - \cos \theta)$

$$\mu_\chi = \frac{m_\chi m_N}{m_\chi + m_N} \rightarrow \begin{cases} m_\chi & \text{for small } m_\chi \\ m_N & \text{for large } m_\chi \end{cases}$$

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_\chi^2}}$$



recoil energy spectrum

$$\frac{dR}{dE_R} = \frac{1}{2} \frac{\rho_\odot}{m_\chi} \frac{\sigma}{\mu^2} \int_{v_{\min}(E_R)}^{v_{\text{esc}}} \frac{1}{v} f(\vec{v}) d\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth
in (static?) halo

$$\sigma \approx \sigma_n^{\text{SI}} A^4 \times \text{nuclear form factors}$$

number of events

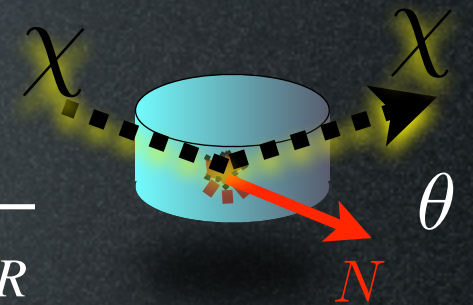
$$N = \mathcal{E} \mathcal{T} \int_{E_{\text{thres}}}^{E_{\text{max}}} \frac{dR}{dE_R} dE_R$$

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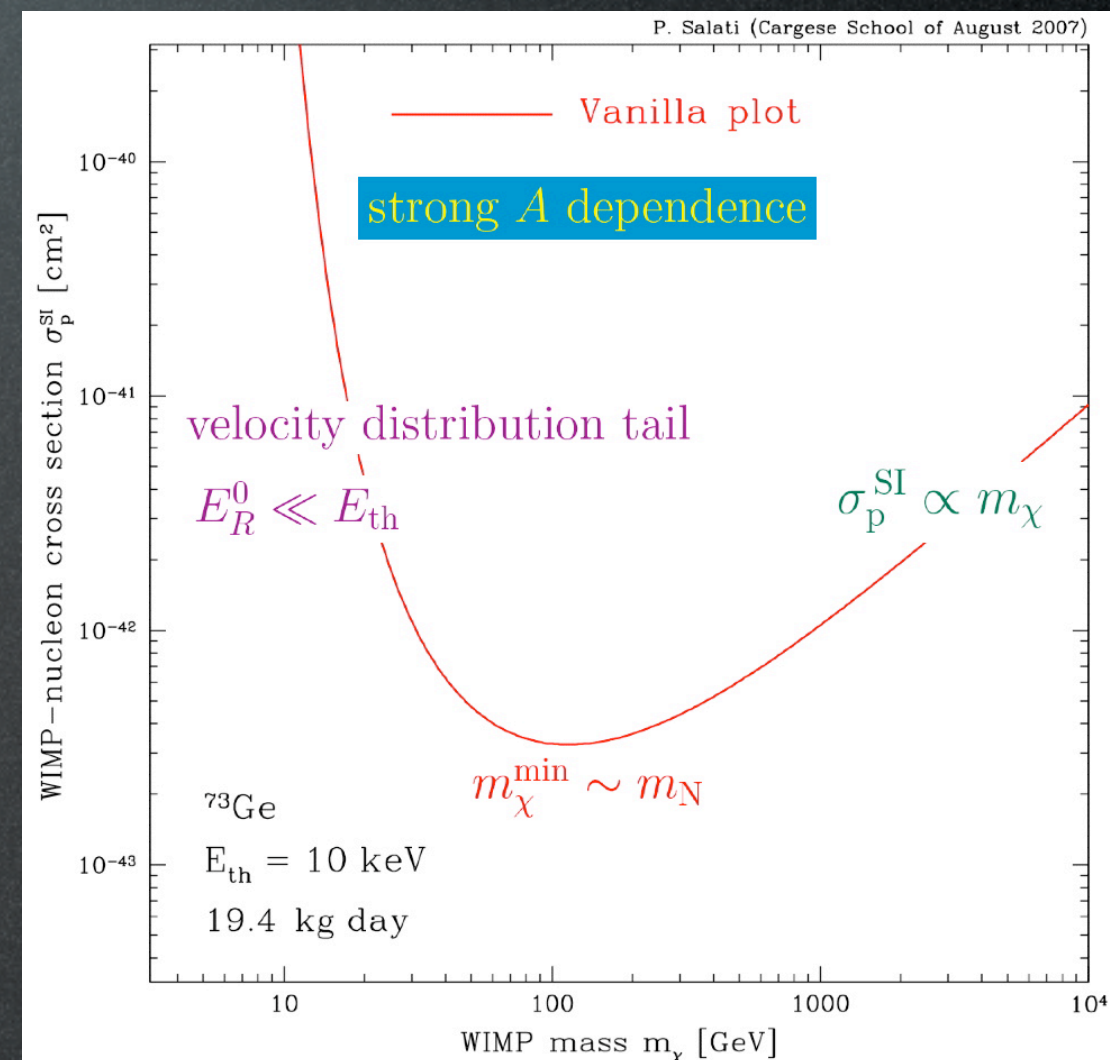
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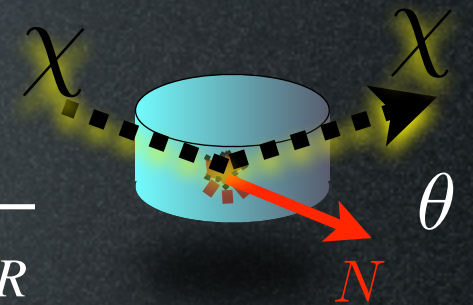


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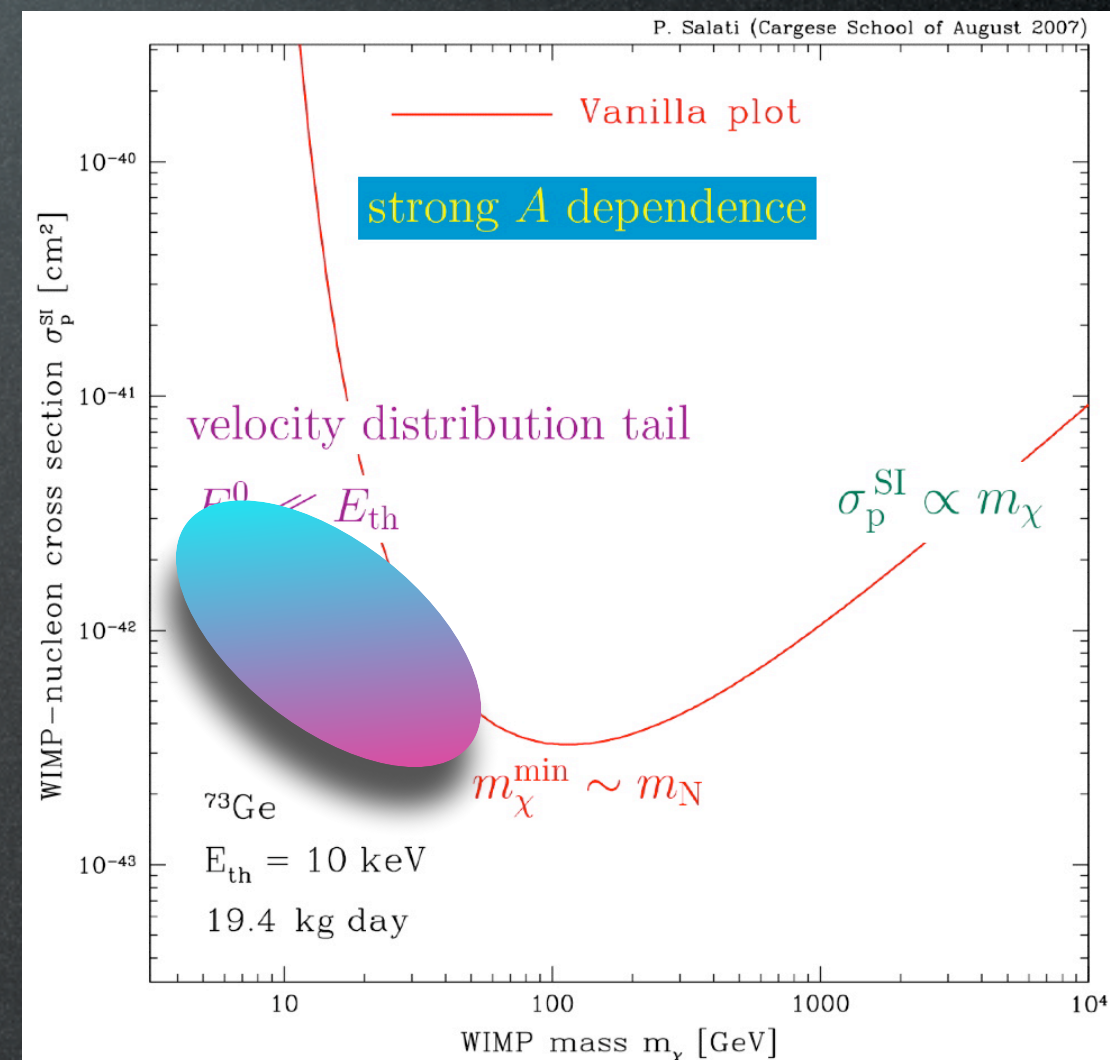
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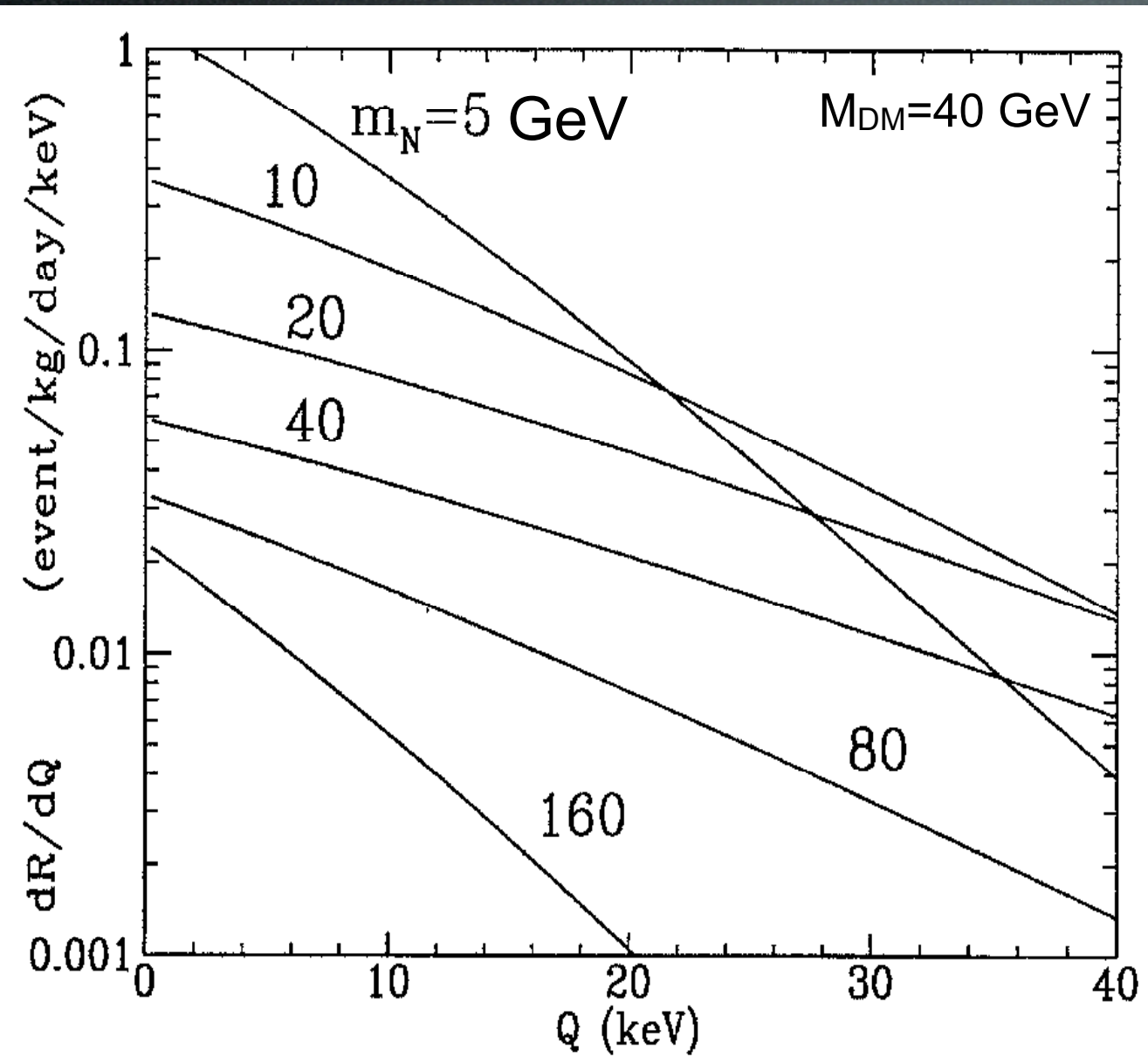
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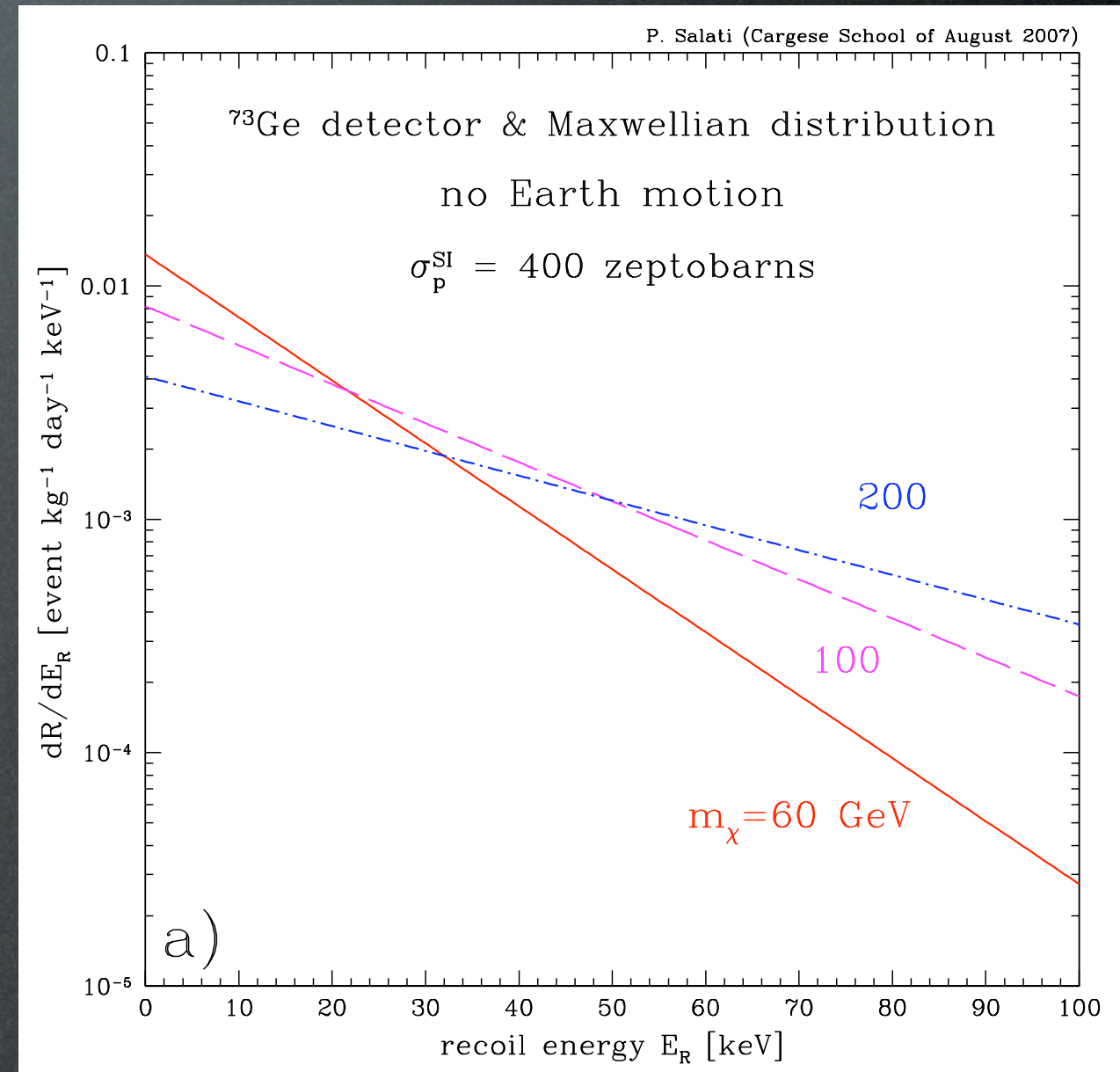
Direct Detection

Recoil spectra

fixed M_{DM}



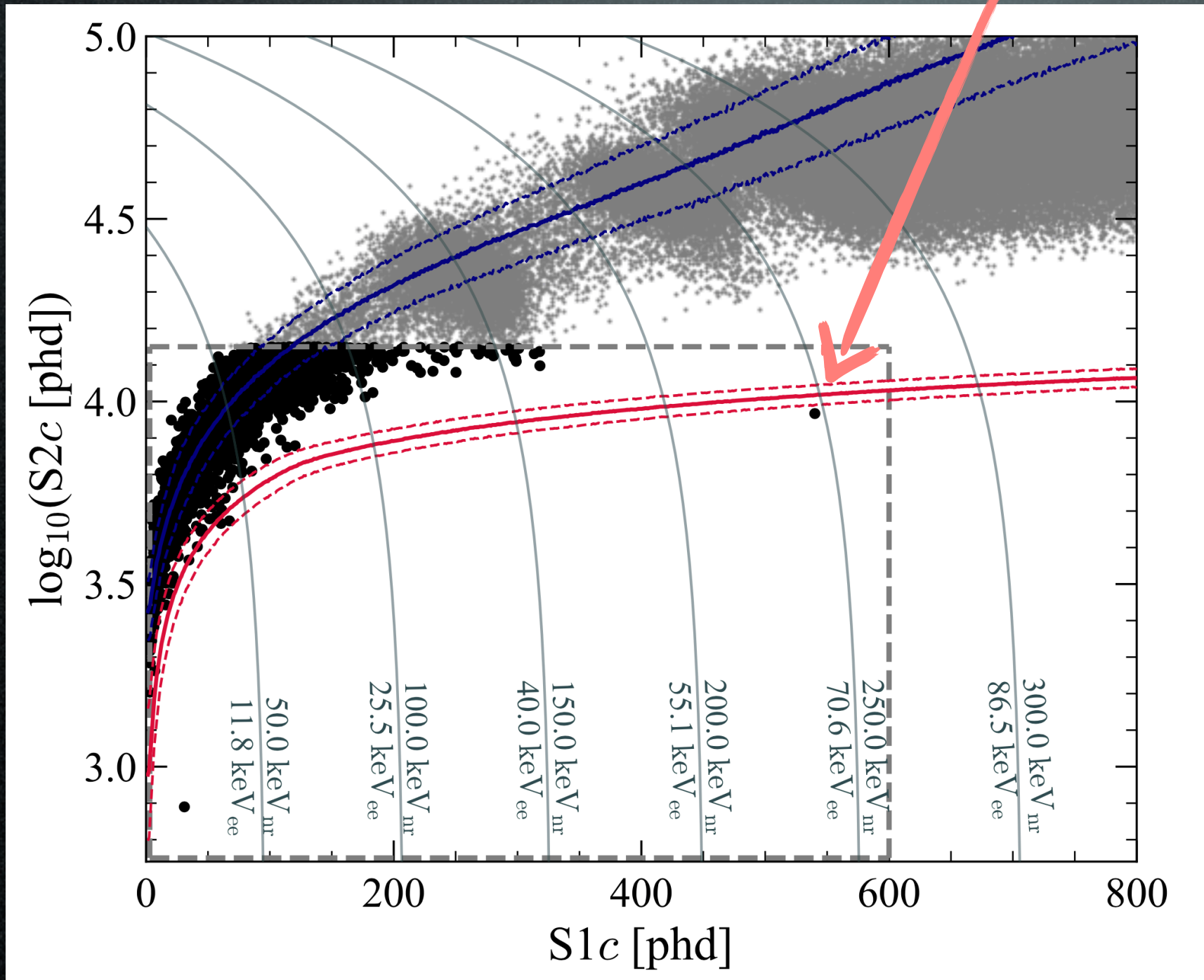
fixed M_{nucl}



LZ event

One event in the signal region

$$E_R = 248 \pm 23 \text{ (stat)} \pm 23 \text{ (sys) keV}$$



*LZ = 7 tons LXe
~1 yr data taking
2.84 ton.yr fiducial expo*

*Extended E_R window:
from 55 to 270 keV_{nr}*

2.6 σ significance

LZ 2609.02823 (appeared 3 september 2026)

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Inelastic higgsinos

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2609.11241

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Exothermic inelastic

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2609.15714, 2609.15782, 2609.17412,
2609.17935, 2609.26570

Composite DM

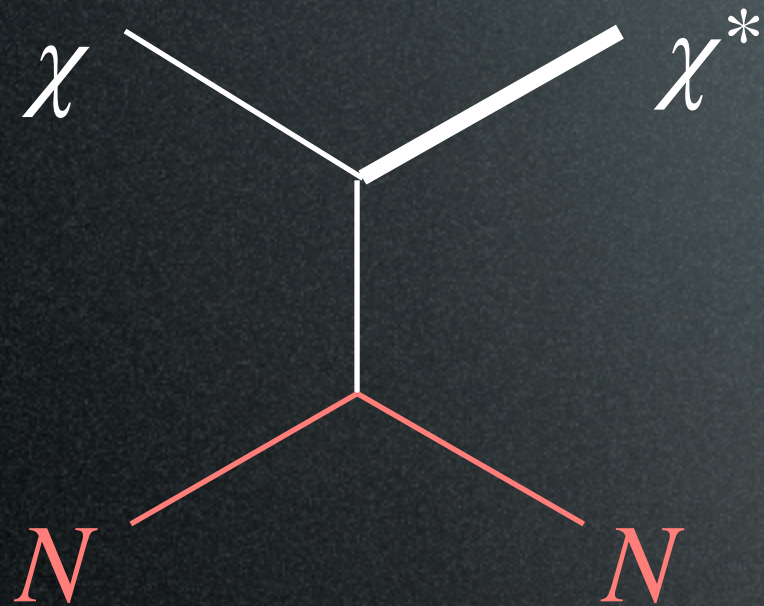
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2609.15742, 2609.15933, 2609.18564,
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Inelastic higgsinos

Why **inelastic**?

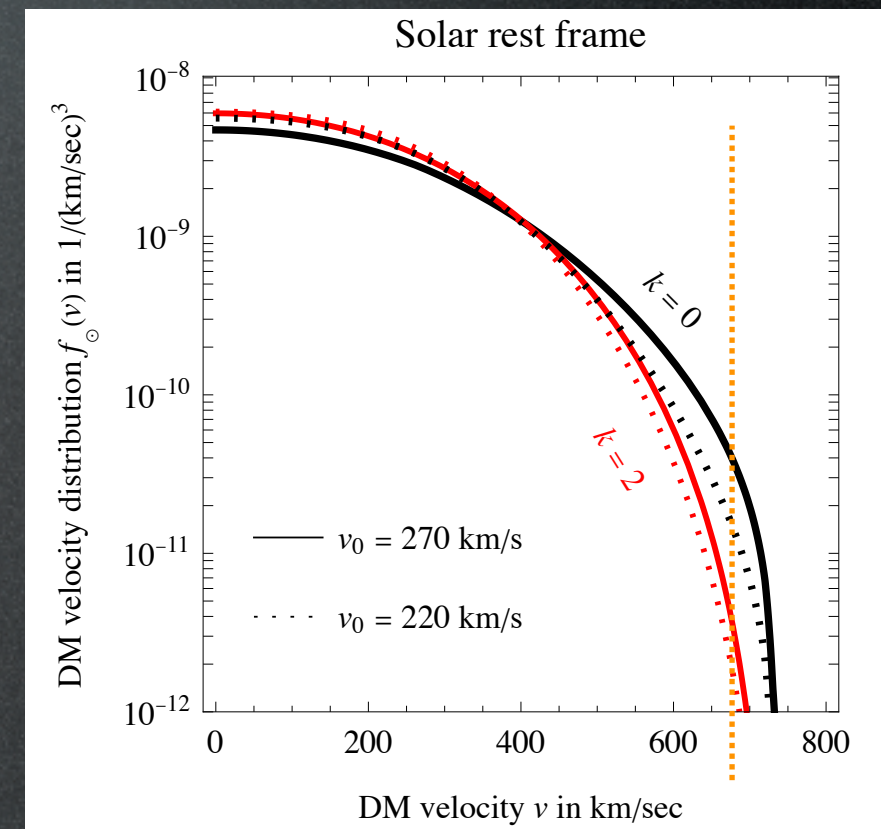
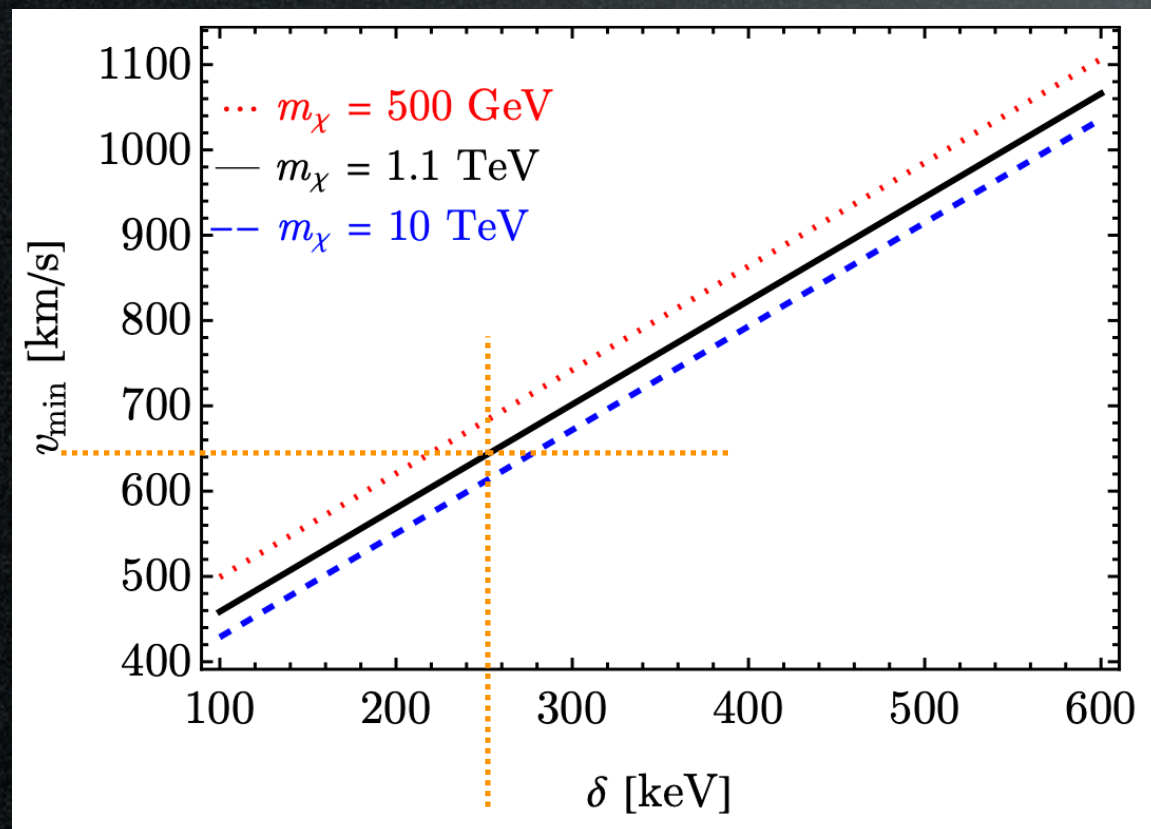


mass splitting $\delta = M_{\chi^*} - M_{\chi} \ll M_{\chi}$

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi}^2}} + \frac{\delta}{\sqrt{2E_R m_N}}$$

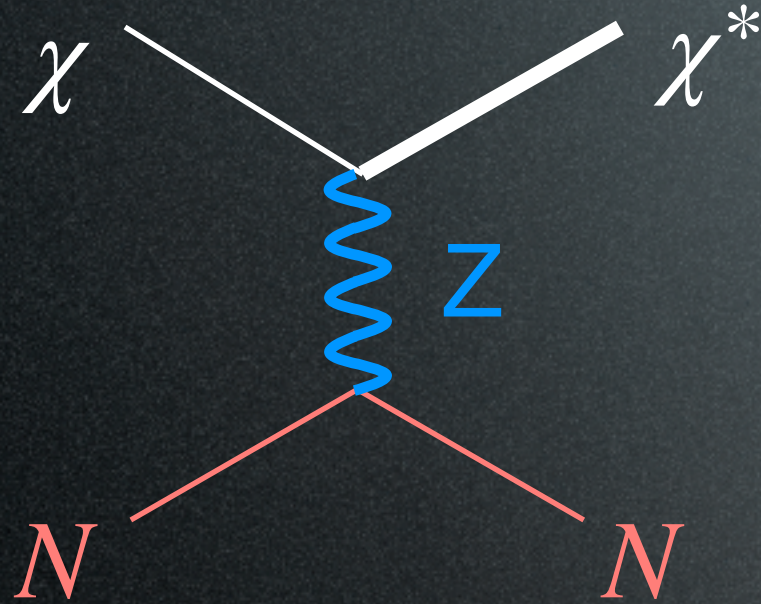
$m_N = 122 \text{ GeV}$ for Xenon

suppresses events at small E_R
probes high-speed tail of $f(v)$



Inelastic higgsinos

Why **higgsinos**?



Higgsinos are neutralinos $\tilde{B} - \tilde{W}^3 - \tilde{H}_u^0 - \tilde{H}_d^0$
neutralino mass matrix in MSSM

$$M_\chi = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

M_1 bino mass, M_2 wino mass, μ higgsino Dirac mass term ($\mu \tilde{H}_u^0 \tilde{H}_d^0$)

Upon diagonalization

$$M_{\tilde{H}_1^0, \tilde{H}_2^0} = \mu \pm \frac{\delta}{2}$$

$$M_\chi \simeq \mu$$

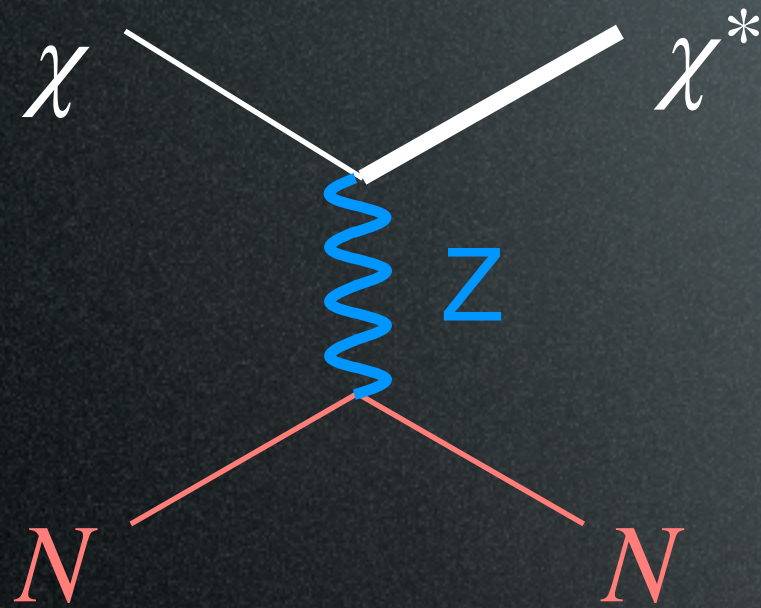
$$M_{\chi^*} \simeq \mu + \delta$$

$$\delta = m_Z^2 \left(\frac{\sin^2 \theta_W}{M_1} + \frac{\sin^2 \theta_W}{M_2} \right)$$

‘Best fit’ of the LZ event: $\mu \simeq 1.1 \text{ TeV}$, $\delta \simeq 350 \text{ keV}$ ($M_1 \approx M_2 \approx 10^7 \text{ GeV}$)

Inelastic higgsinos

Why higgsinos?



‘Best fit’ of the LZ event: $\mu \simeq 1.1 \text{ TeV}$
 $\delta \simeq 350 \text{ keV}$

Once bought that, we have a fully predictive model

Higgsino thermal mass? $m_\chi = 1.08 \pm 0.10 \text{ TeV}$ ✓

Higgsino scattering cross-section?

$$\sigma_N \simeq G_F^2 \mu_\chi^2 / 8\pi \simeq 1 \cdot 10^{-38} \text{ cm}^2 \quad \checkmark$$

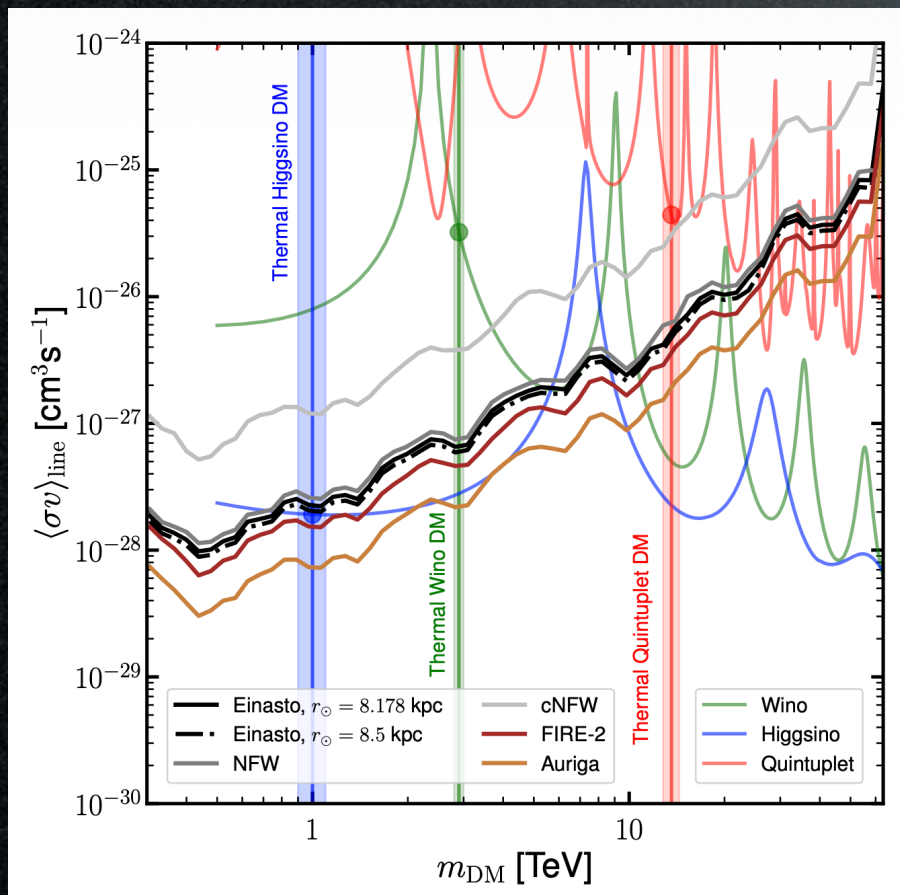
(within a few)

Freese, Theodosopoulos 2609.01583

Higgsino indirect detection?

Thanks to halo/core uncertainties ✓

...as good as it can get!



HESS 2608.07234

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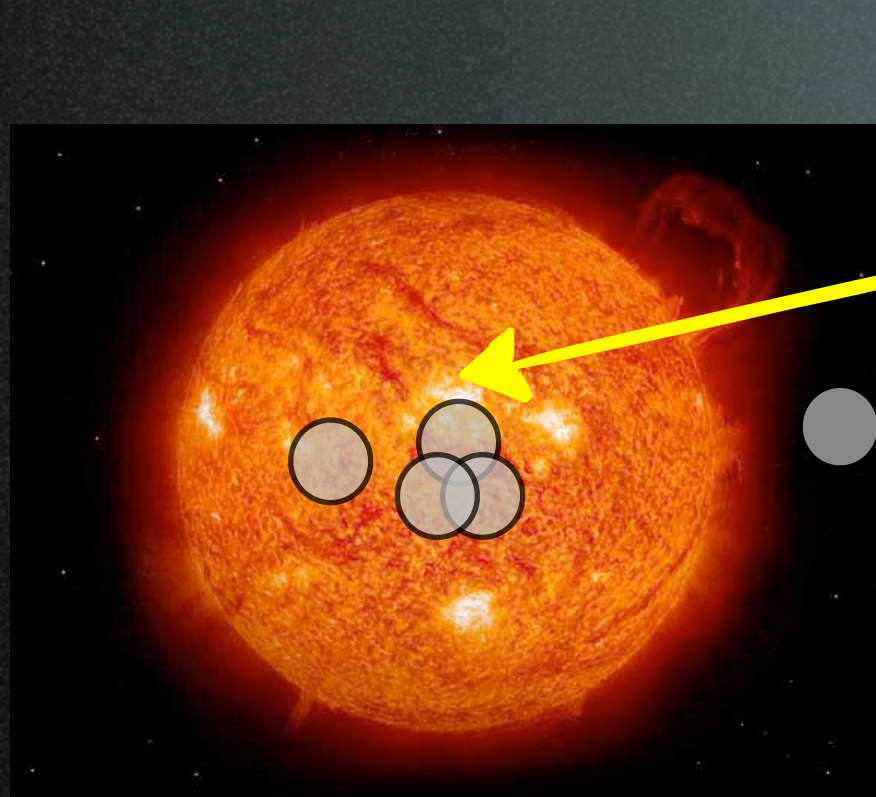
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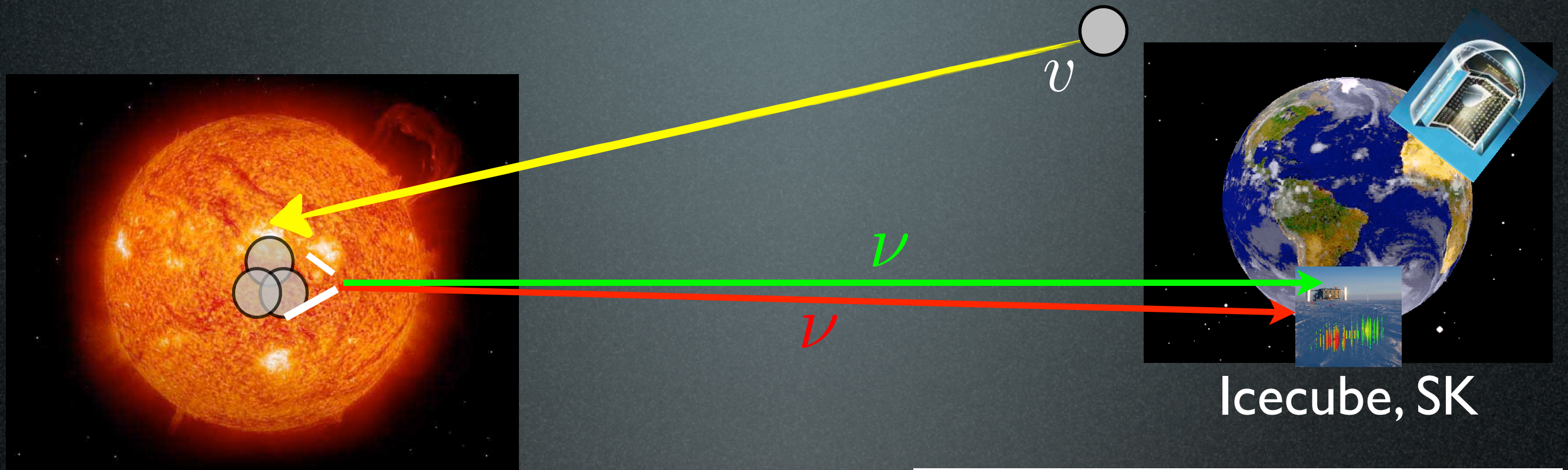
Constraints from solar capture



basics: infalling DM particles acquire large speed
they scatter with nuclei and lose energy
if $v_f < v_{\text{esc}}$, particles are gravitationally trapped
they spiral to center of body and accumulate
they annihilate

$$\begin{aligned} v_{\text{halo}} &\simeq 270 \text{ km/s} \\ v_{\text{esc}, \odot} &\simeq 620 \text{ km/s} \\ v_{\text{esc}, \oplus} &\simeq 12 \text{ km/s} \end{aligned}$$

Constraints from solar capture

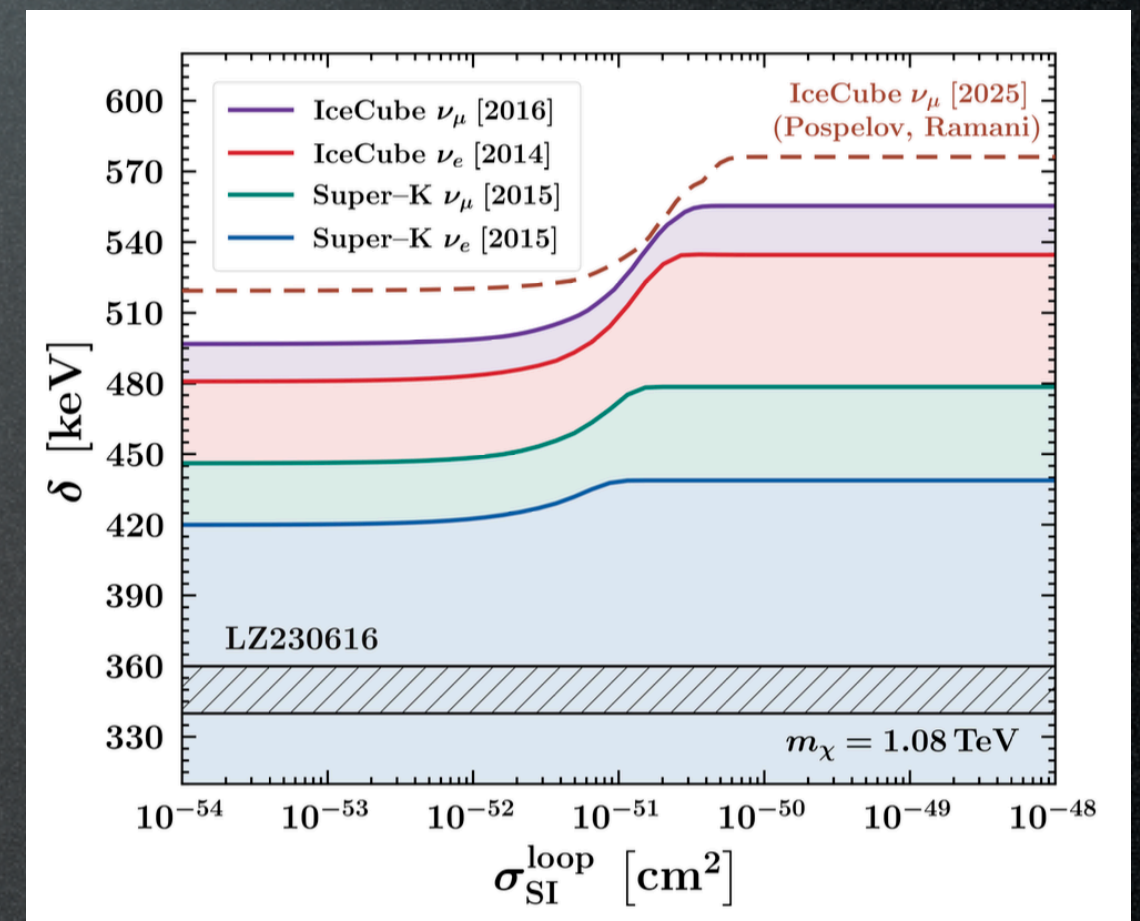


$$\chi\chi^{(*)} \rightarrow W^+W^-, ZZ \rightsquigarrow \nu$$

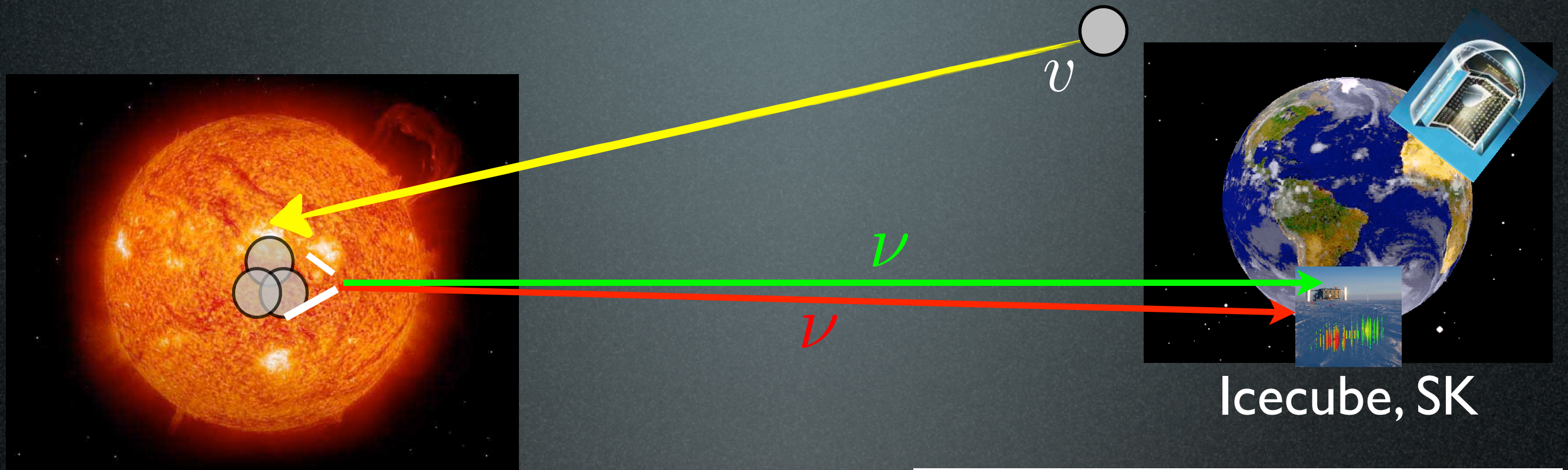
Icecube, SK imply $\delta > 557 \text{ keV}$

Details:

Large acquired speed easily provides δ :
 infalling DM is efficiently captured.
 Slowed down, inelastic scattering stops.
 But I-loop elastic takes over and
 leads to accumulation, then annihilation



Constraints from solar capture

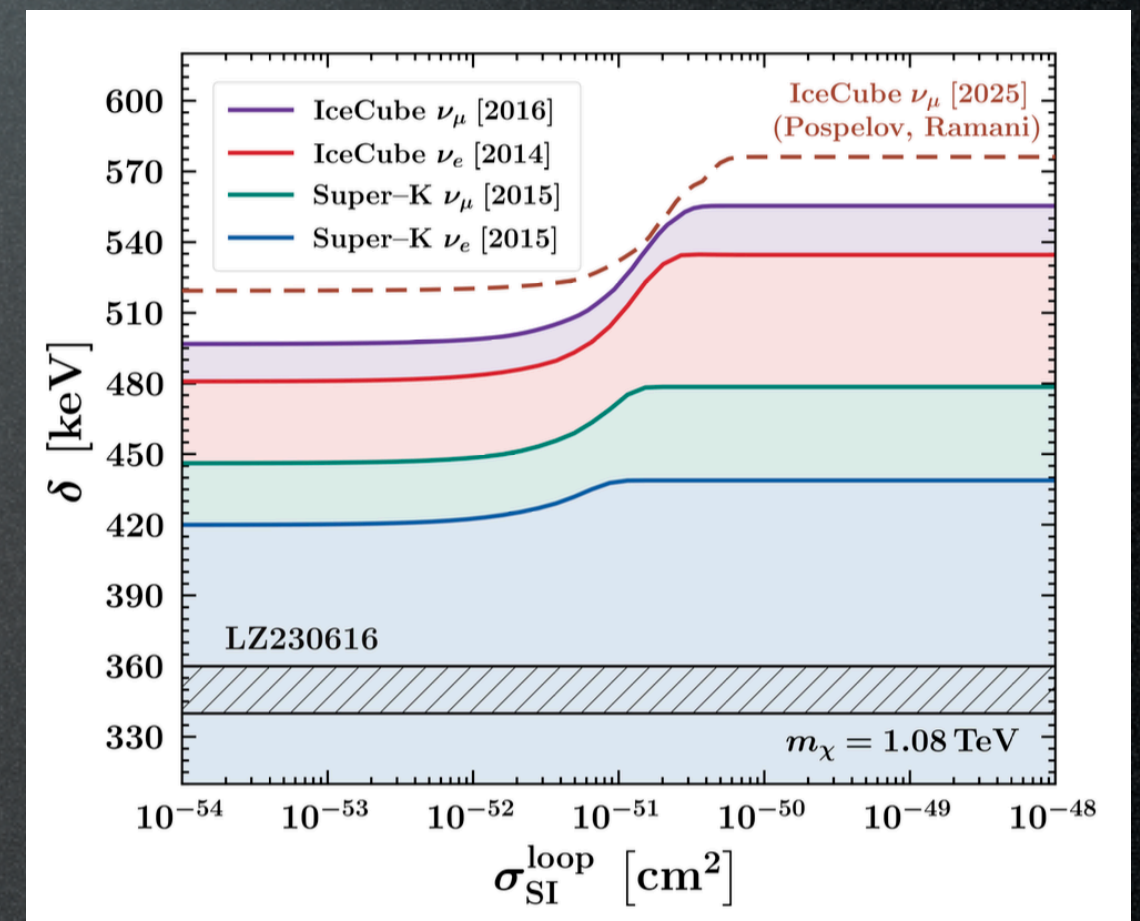


$$\chi\chi^{(*)} \rightarrow W^+W^-, ZZ \rightsquigarrow \nu$$

Icecube, SK imply $\delta > 557 \text{ keV}$

Ways-out:

Assume exotic $f(\nu)$, e.g. due to LMC,
assume exotic form factors,
relax m_χ (non-thermal production),
go beyond higgsinos...



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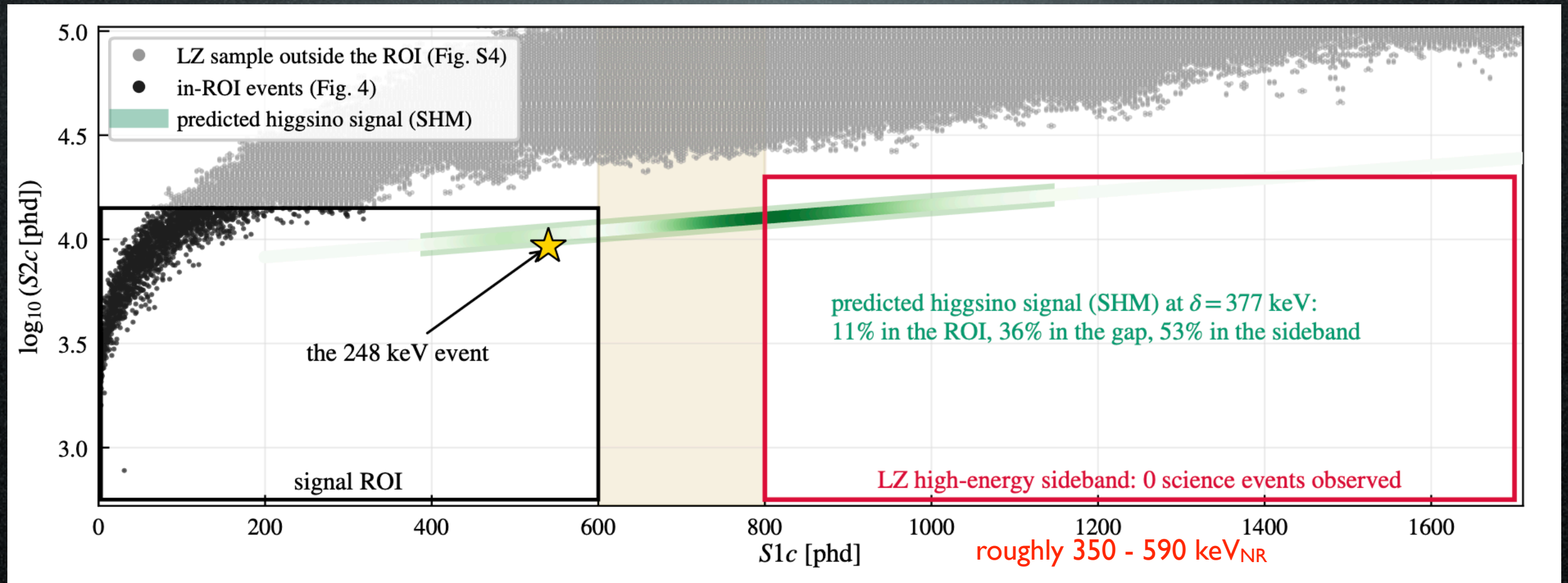
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Trouble from high-energy sideband

LZ should have seen 3-10 more events in the **high-energy band** where instead none are reported



Rodd Safdi Slatyer Xu 2609.04175

Caveats: i) assuming acceptance = 1 in HE band
ii) uncertainties due to tail of the speed distribution

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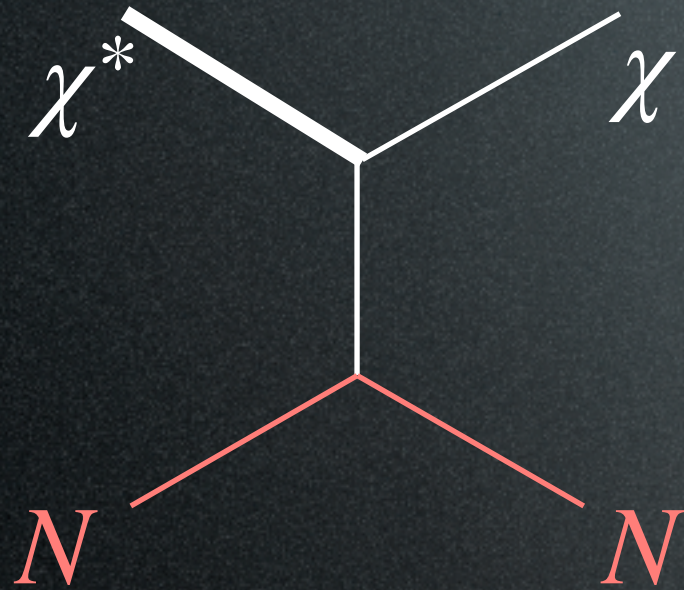
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Exothermic inelastic

Exothermic



Dent Newstead 2609.04673

De Lima 2609.05204

Baer Barger 2609.06153

mass splitting $\delta = M_{\chi^*} - M_{\chi} \ll M_{\chi}$

(Some) DM in the halo is
in the heavier χ^* state,
(meta-)stable if $\delta < 2m_e$

‘Best fit’ of the LZ event: $m_{\chi} \simeq 30 - 200 \text{ GeV}$
 $\delta \simeq 0.5 - 1 \text{ MeV}$

Much less dependent on $f(v)$

NB: Ar experiments can discriminate: no events for endothermic (too large E_R),
sharp recoil lines for exothermic

Baer Barger 2609.15782

Back up slides