7 November 2025
Astroparticle Symposium, Institut Pascal, Orsay

Sub-GeV Dark Matter and X-rays

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

7 November 2025
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1 MeV -> 5 GeV

Sub-GeV Dark Matter and X-rays

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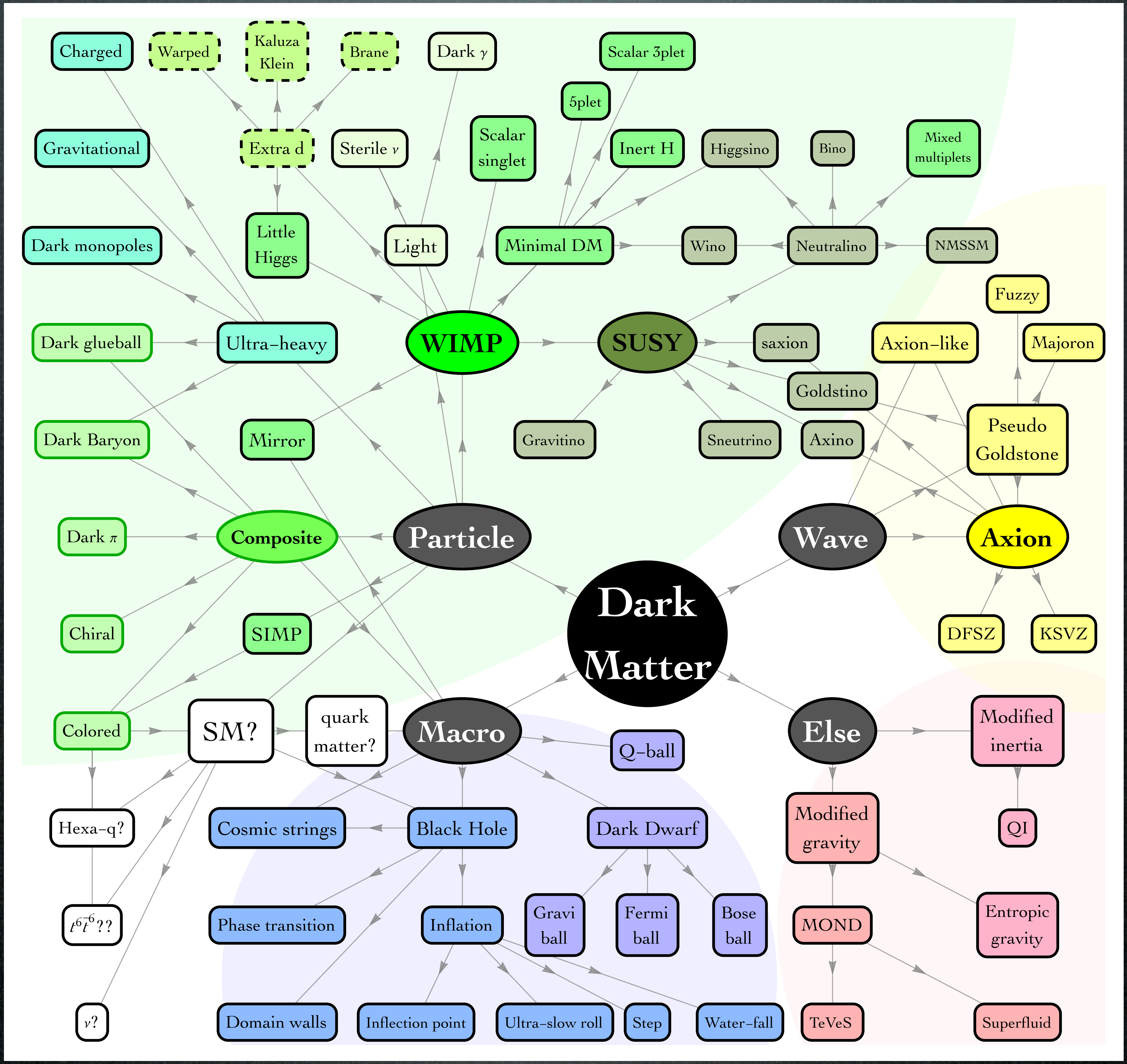
based on : Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854**v3**
De La Torre Luque, Balaji, Koechler 2311.04979
Cirelli, Kar, Shaikh 2508.03819

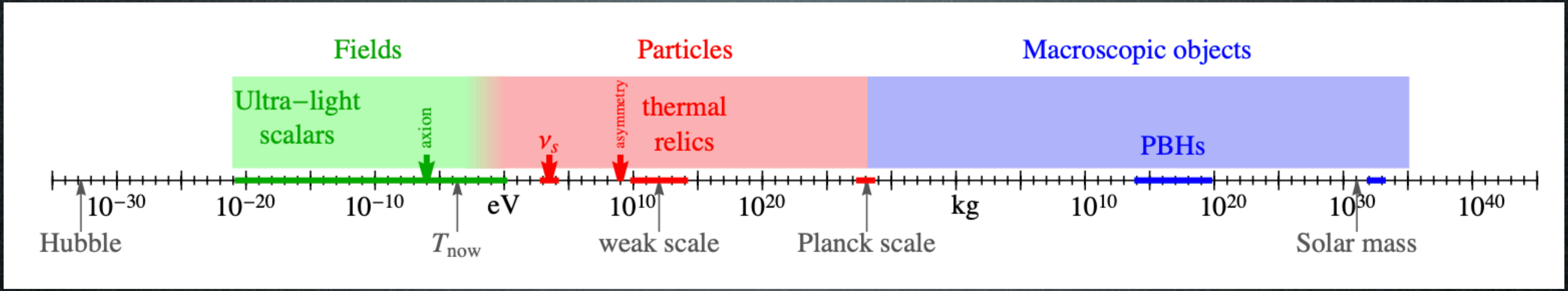
Candidates



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

Candidates

A matter of perspective: plausible mass ranges



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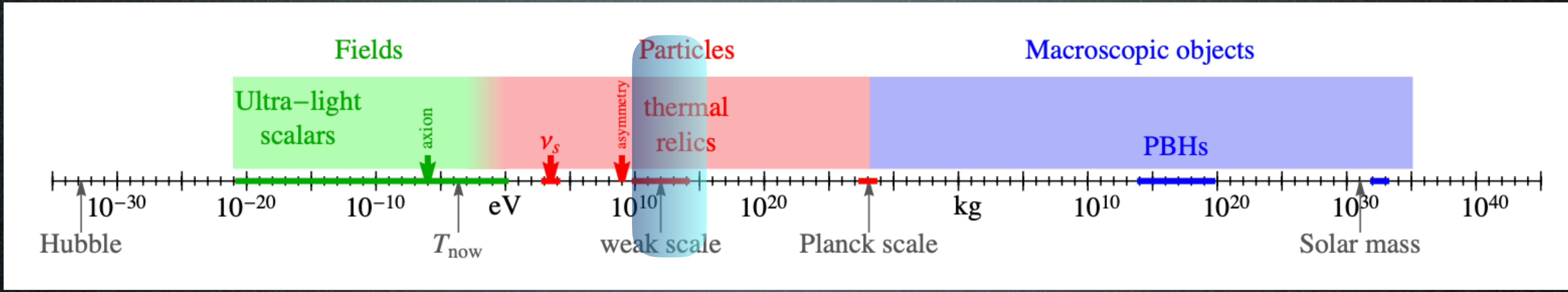
90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges



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Candidates

WIMPs

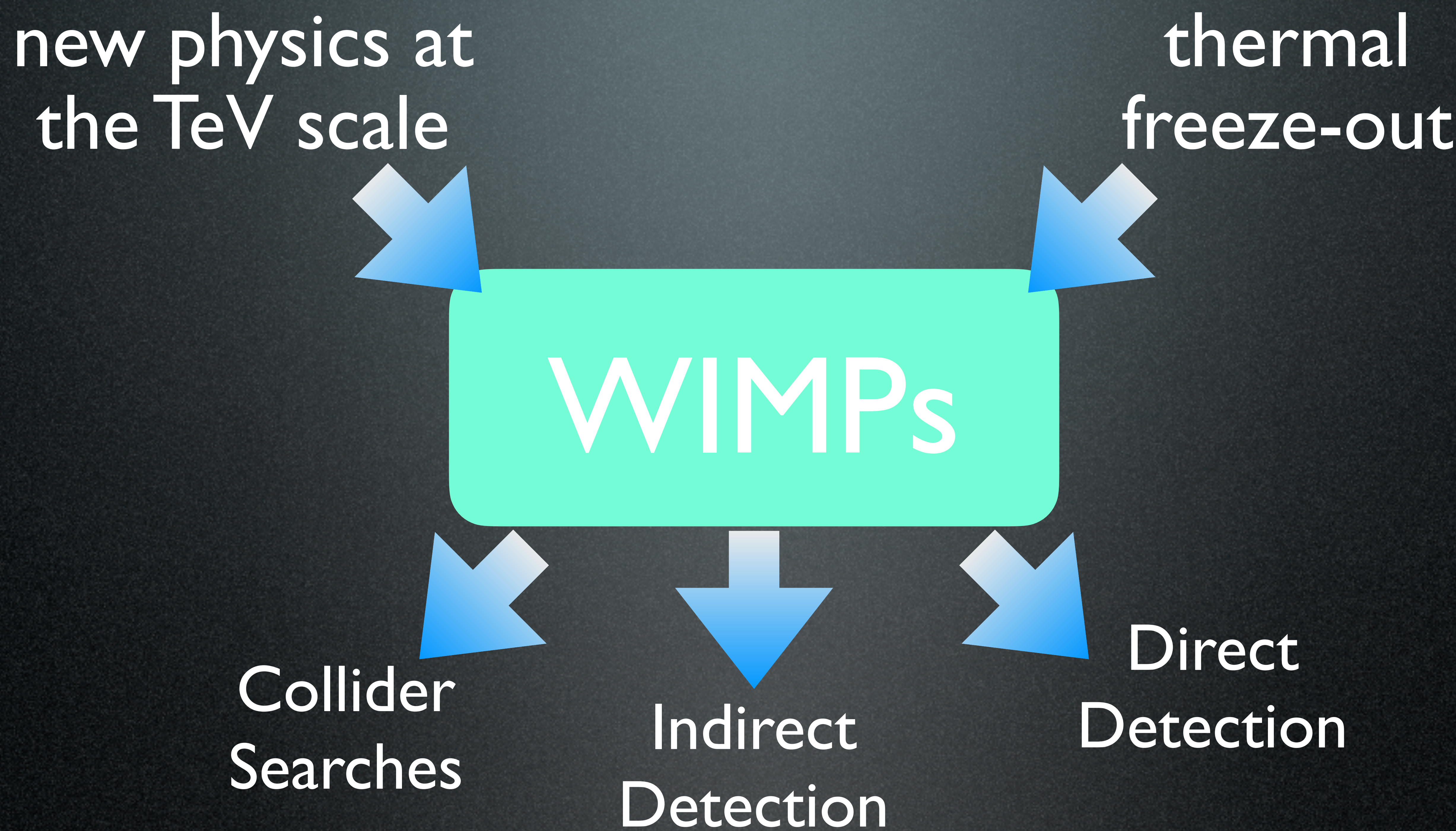
Candidates

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

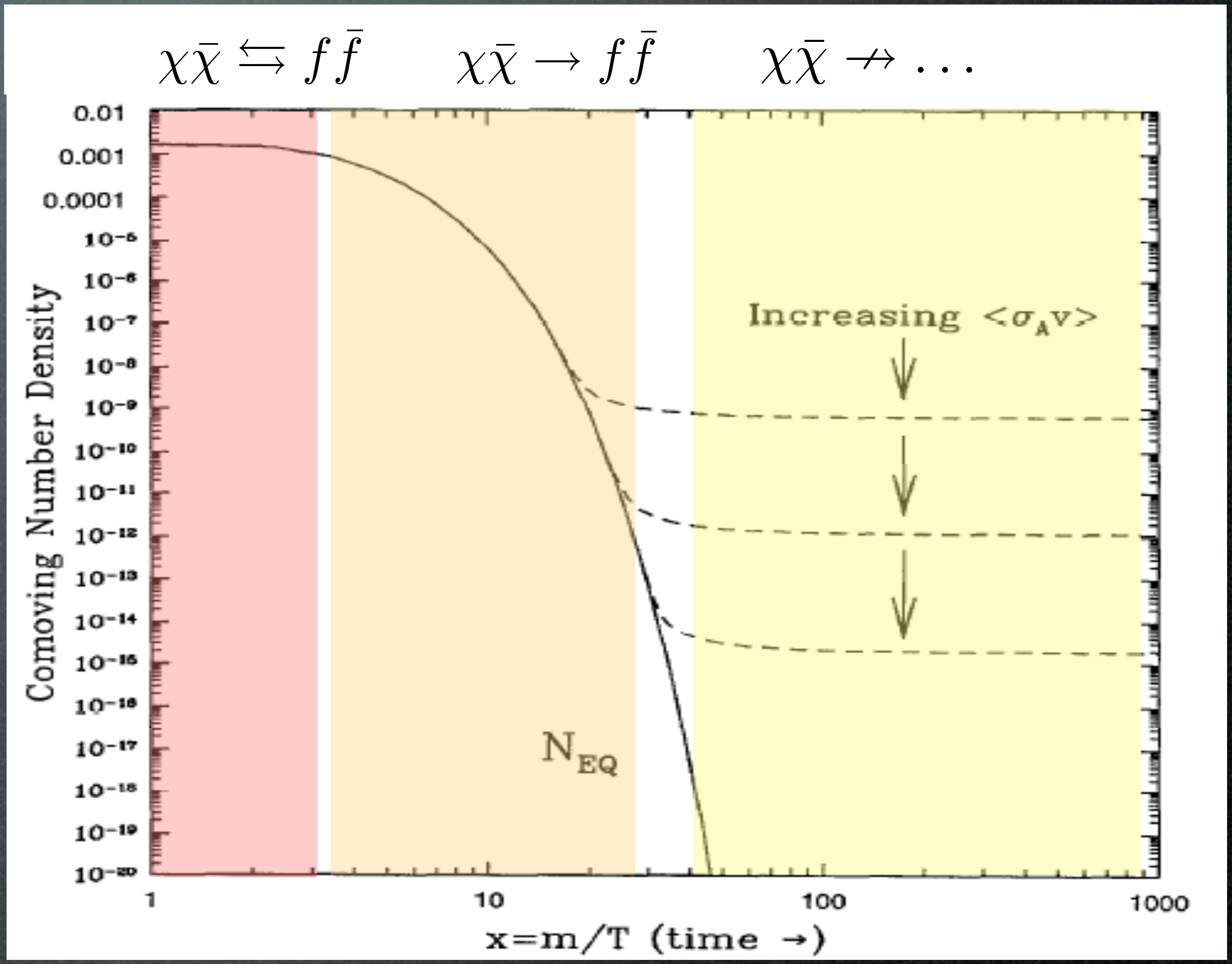
DM as a thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Relic $\Omega_{\mathrm{DM}} = 0.26$ for

$$\langle \sigma_{\mathrm{ann}} v \rangle = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

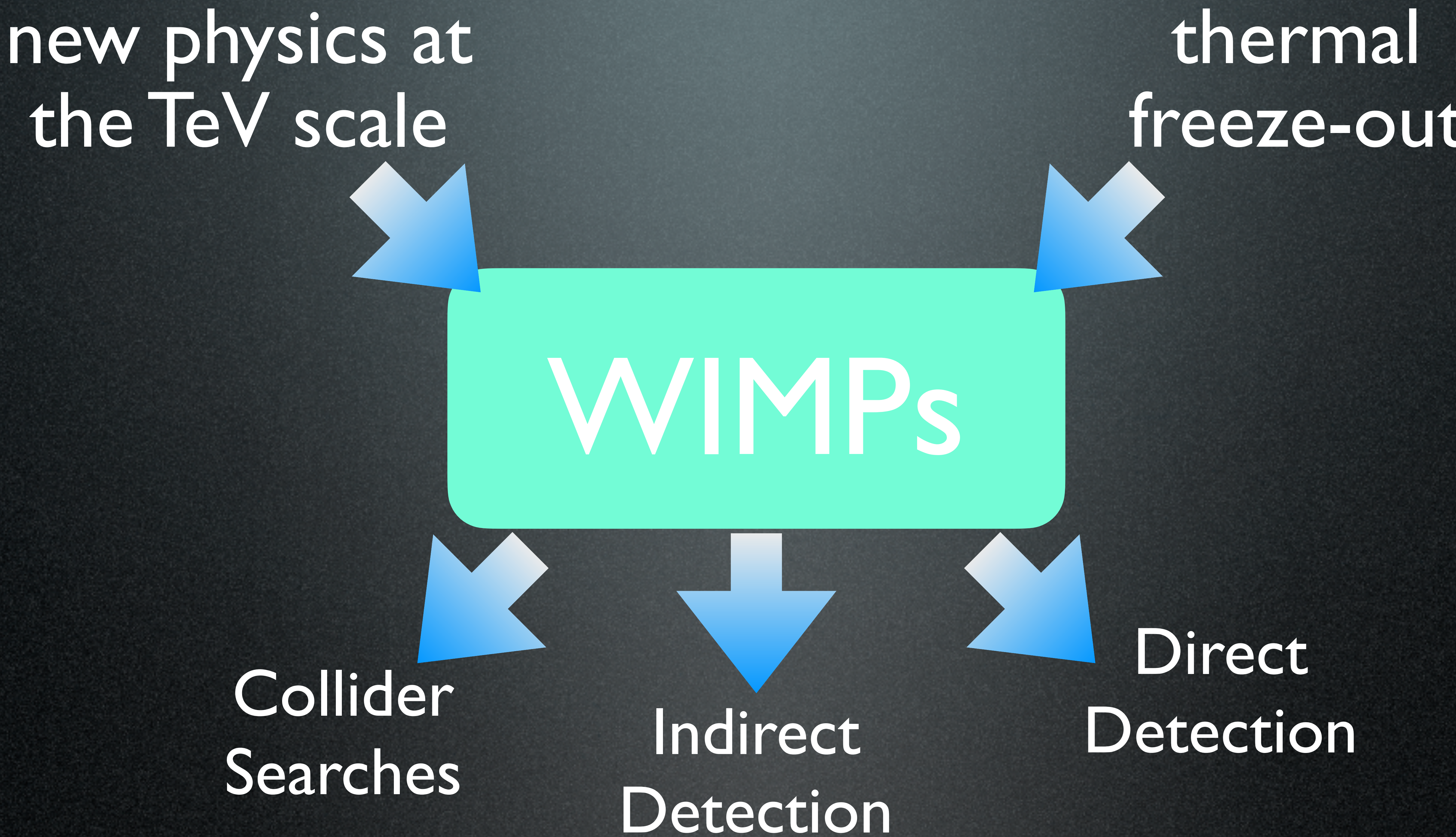


Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle \sigma_{\mathrm{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \quad \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1) \qquad \text{(WIMP)}$$

Candidates


new physics at the TeV scale
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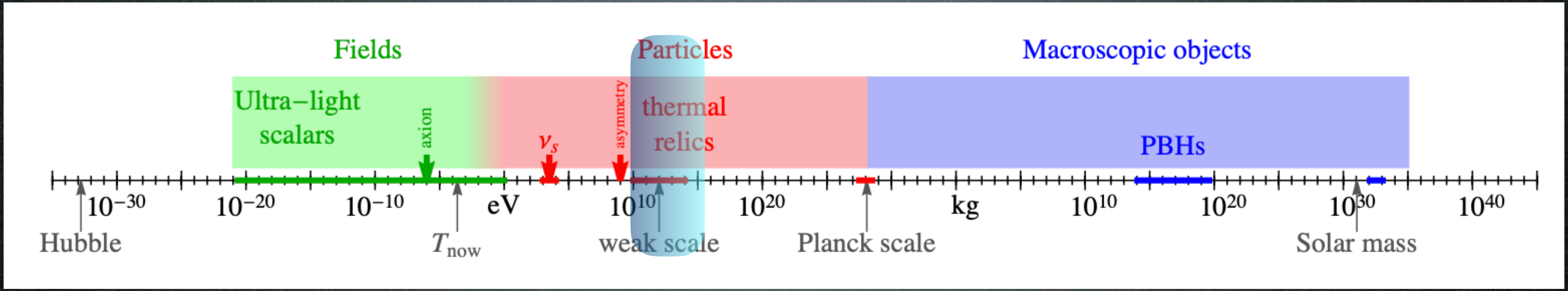

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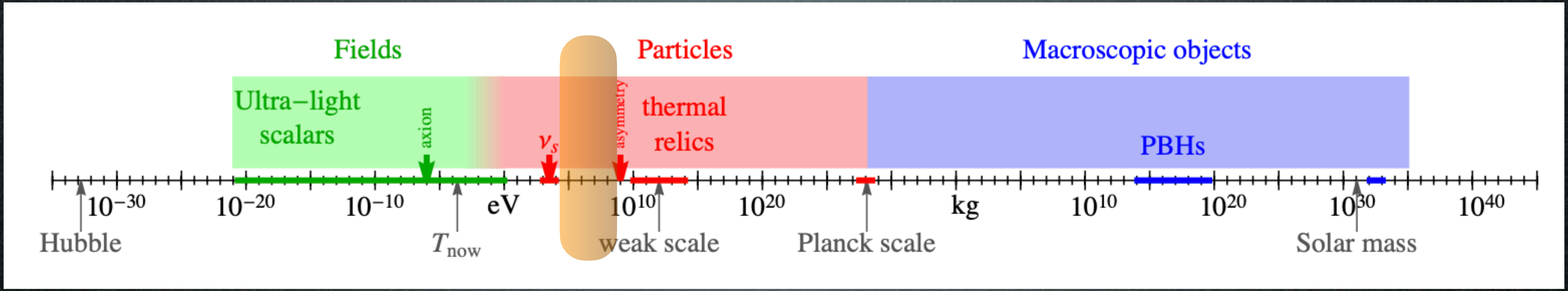

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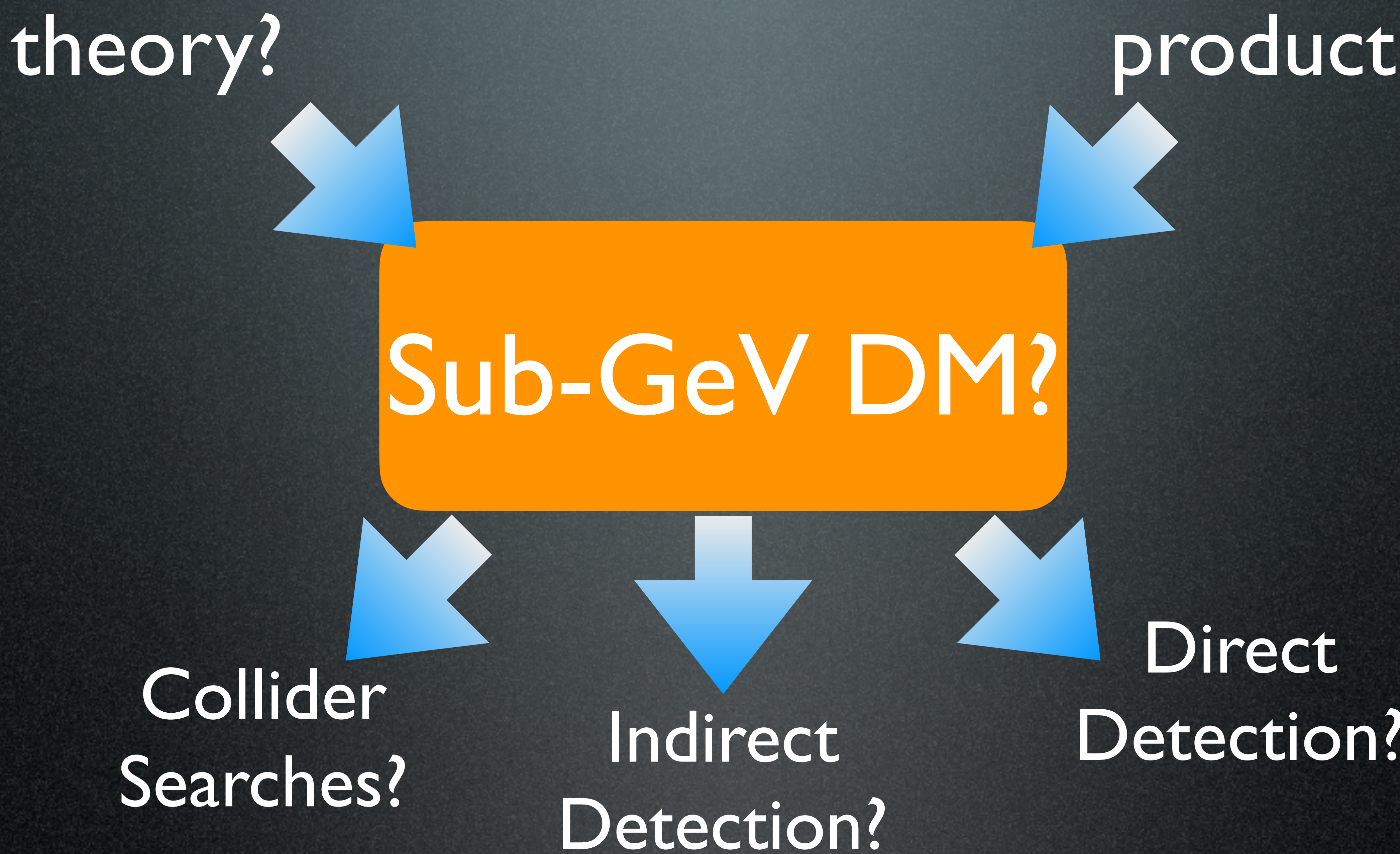

theory?
production?
Sub-GeV DM?
Collider Searches?
Indirect Detection?
Direct Detection?

Theory

Sub-GeV DM

- ‘MeV (scalar) DM’

Boehm & Fayet hep-ph/0305261

> In conclusion, scalar Dark Matter particles can be significantly lighter than a few GeV’s (thus evading the generalisation of the Lee-Weinberg limit for weakly-interacting neutral fermions) if they are coupled to a new (light) gauge boson or to new heavy fermions F (through non chiral couplings and poten-

Theory

Sub-GeV DM

- WIMPless Dark Matter

  Feng & Kumar 0803.4196

  a.k.a. hidden sector DM

  $\sim$ secluded DM

Theory

Sub-GeV DM

- WIMPless Dark Matter

Feng & Kumar 0803.4196

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\rm TeV^2}$$

a.k.a. hidden sector DM
$\sim$ secluded DM

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_x^2}{m^2}$$

Theory

Sub-GeV DM

- WIMPless Dark Matter

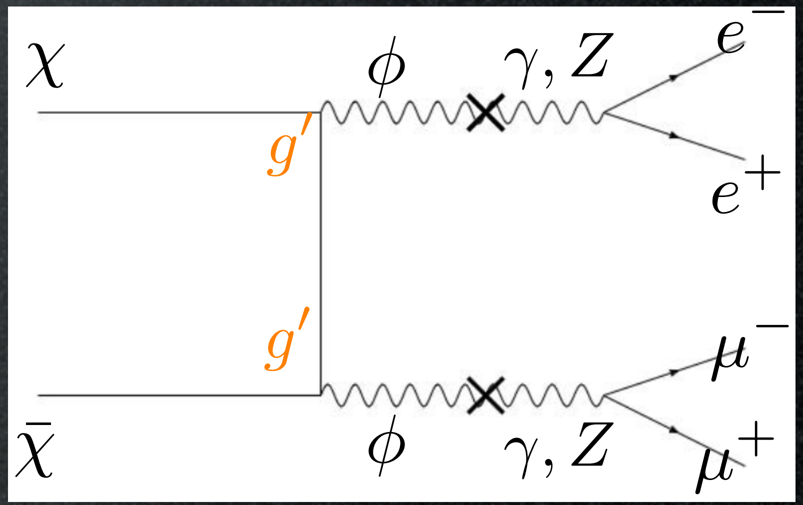
Feng & Kumar 0803.4196

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\rm TeV^2}$$

a.k.a. hidden sector DM
$\sim$ secluded DM

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_x^2}{m^2}$$

if g_x is small,
m 'naturally' small
(but nothing points to a precise value)



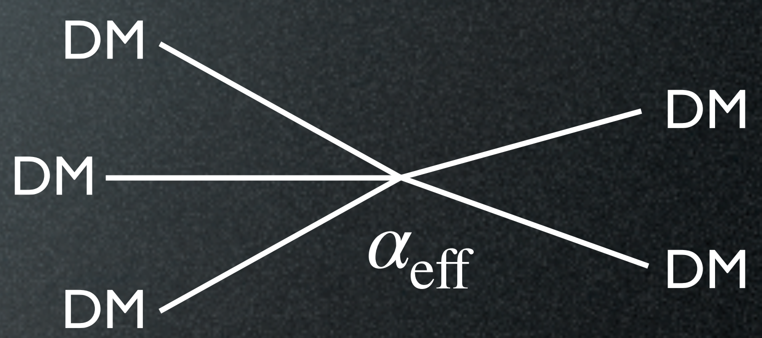
Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM

- 'SIMP miracle':

  scalar DM with relic abundance set by 3 -> 2 processes



  points to

$$m_{\text{DM}} \sim \alpha_{\text{eff}} \left(T_{\text{eq}}^2 M_{\text{Pl}}\right)^{1/3} \sim 100 \text{ MeV}$$

  Hochberg et al 1402.5143

  'naturally realized' in a dark-QCD-like setup

$$\alpha_{\text{eff}} = \mathcal{O}(1) \quad \text{i.e.} \quad g_x \sim 4\pi$$

Theory

Sub-GeV DM?

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

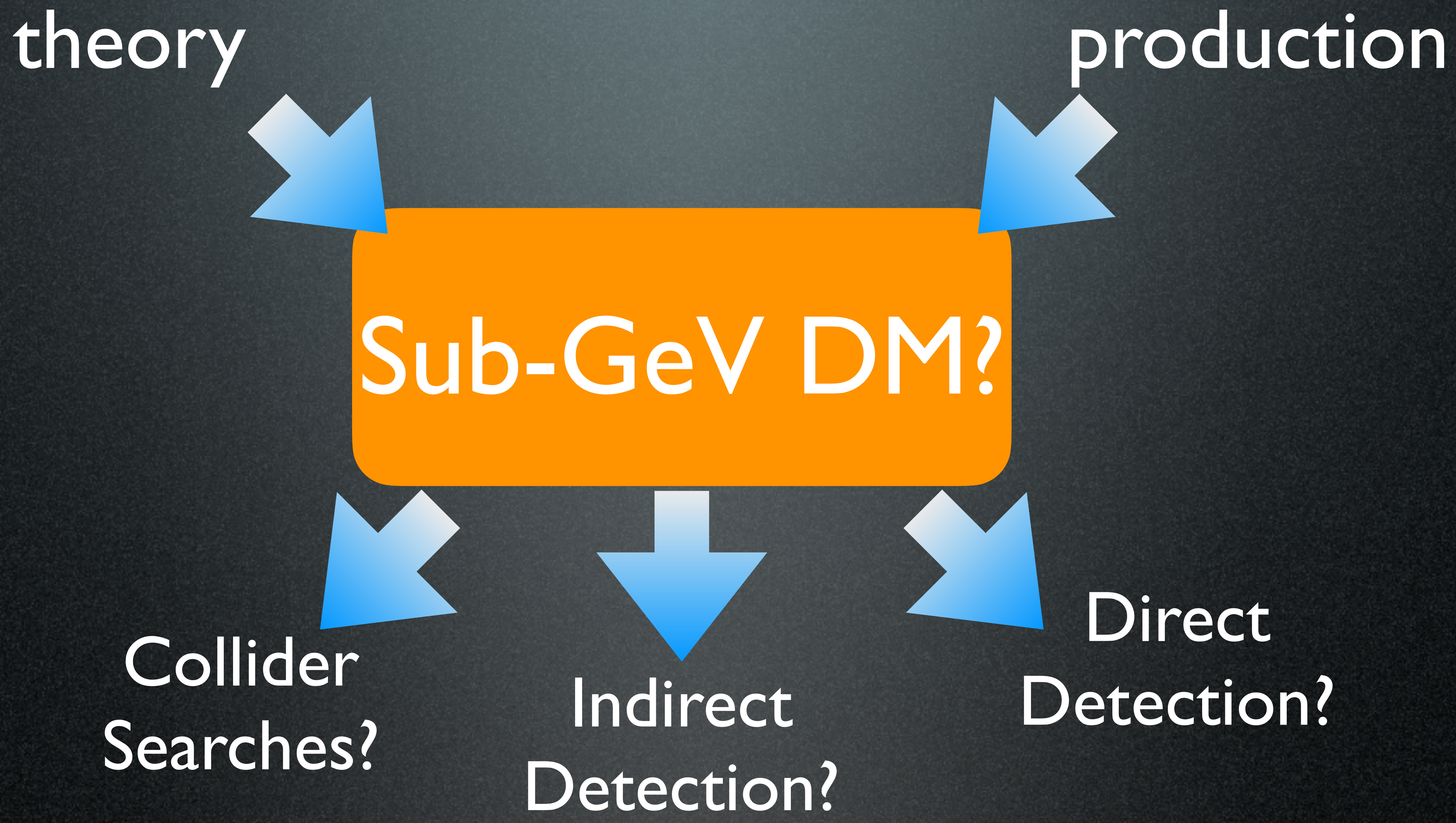
Theory

Sub-GeV DM?

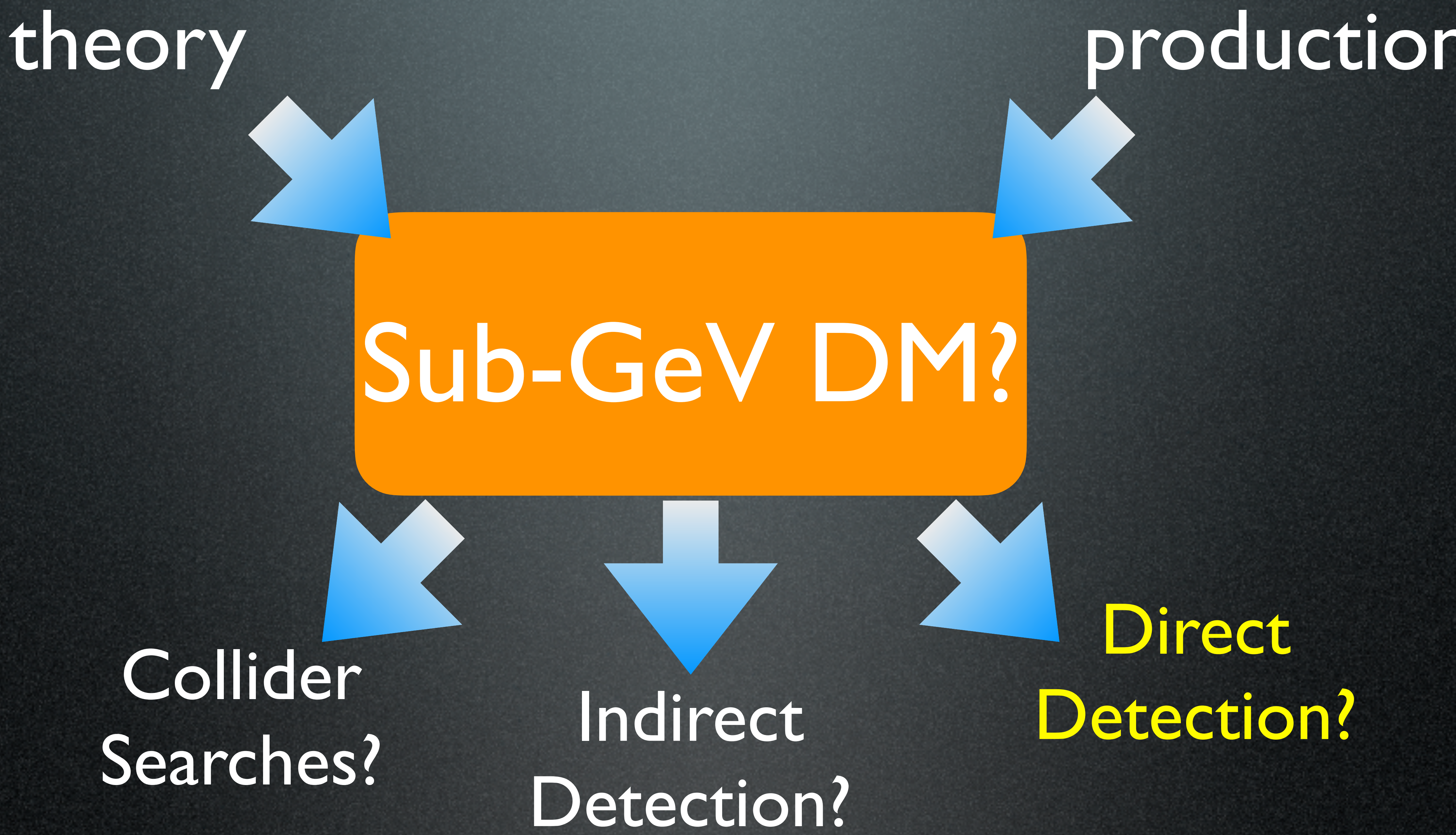
Why not!

- 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?

Candidates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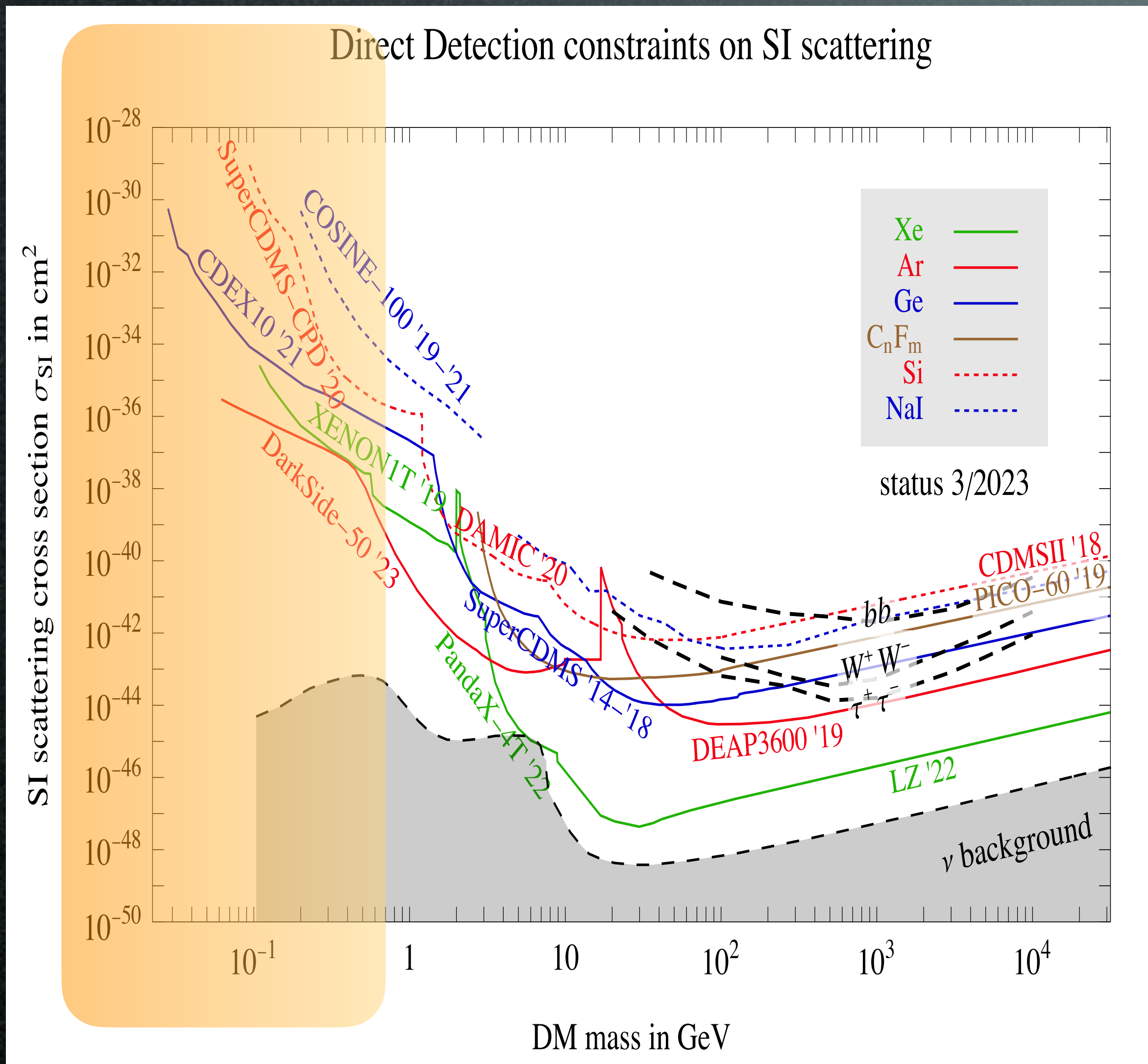
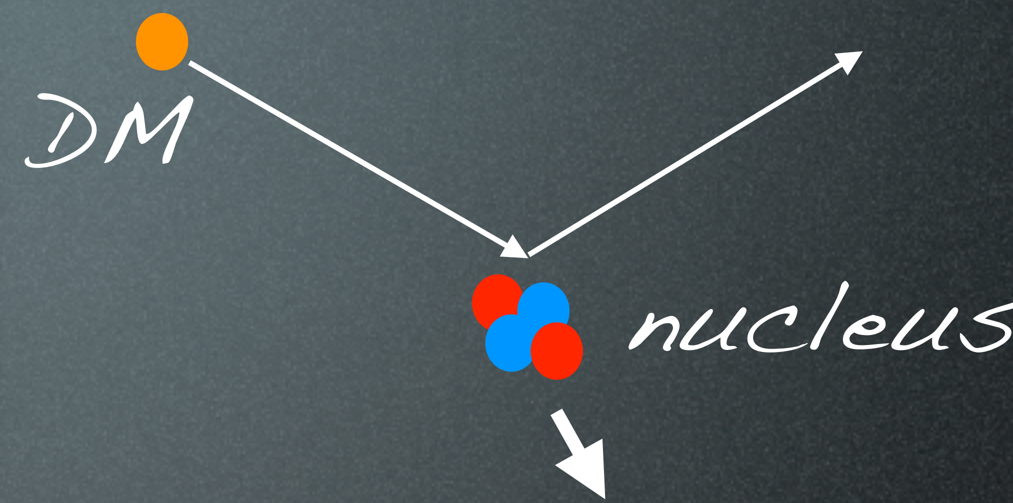
Direct Detection of sub-GeV DM



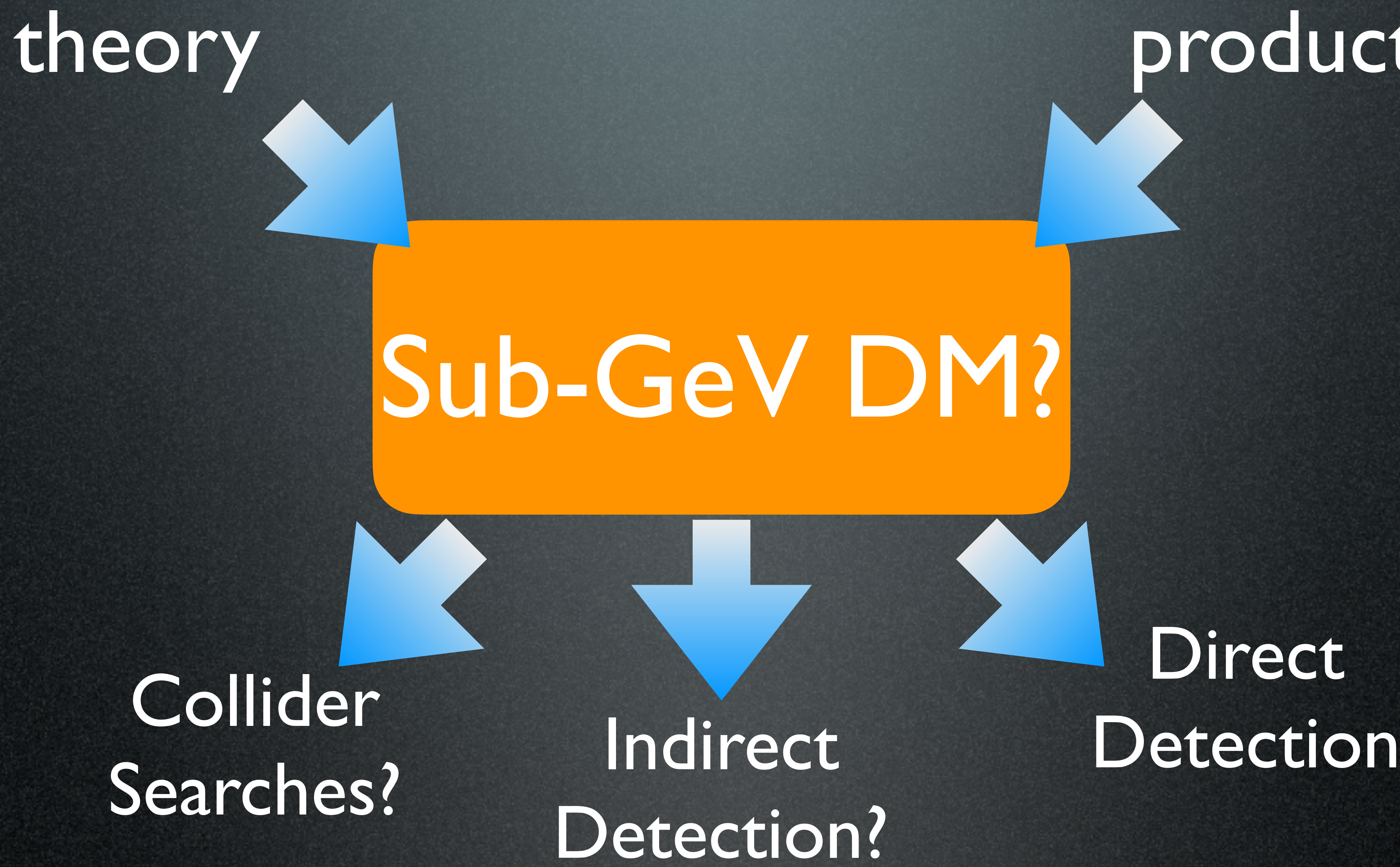
M. Cirelli, A. Strumia, J. Zupan 2406.01705



deposited energy is **below threshold** for typical <u>nuclear</u> recoil experiments

- electron recoil signal
- Migdal effect
- new experimental strategies

Candidates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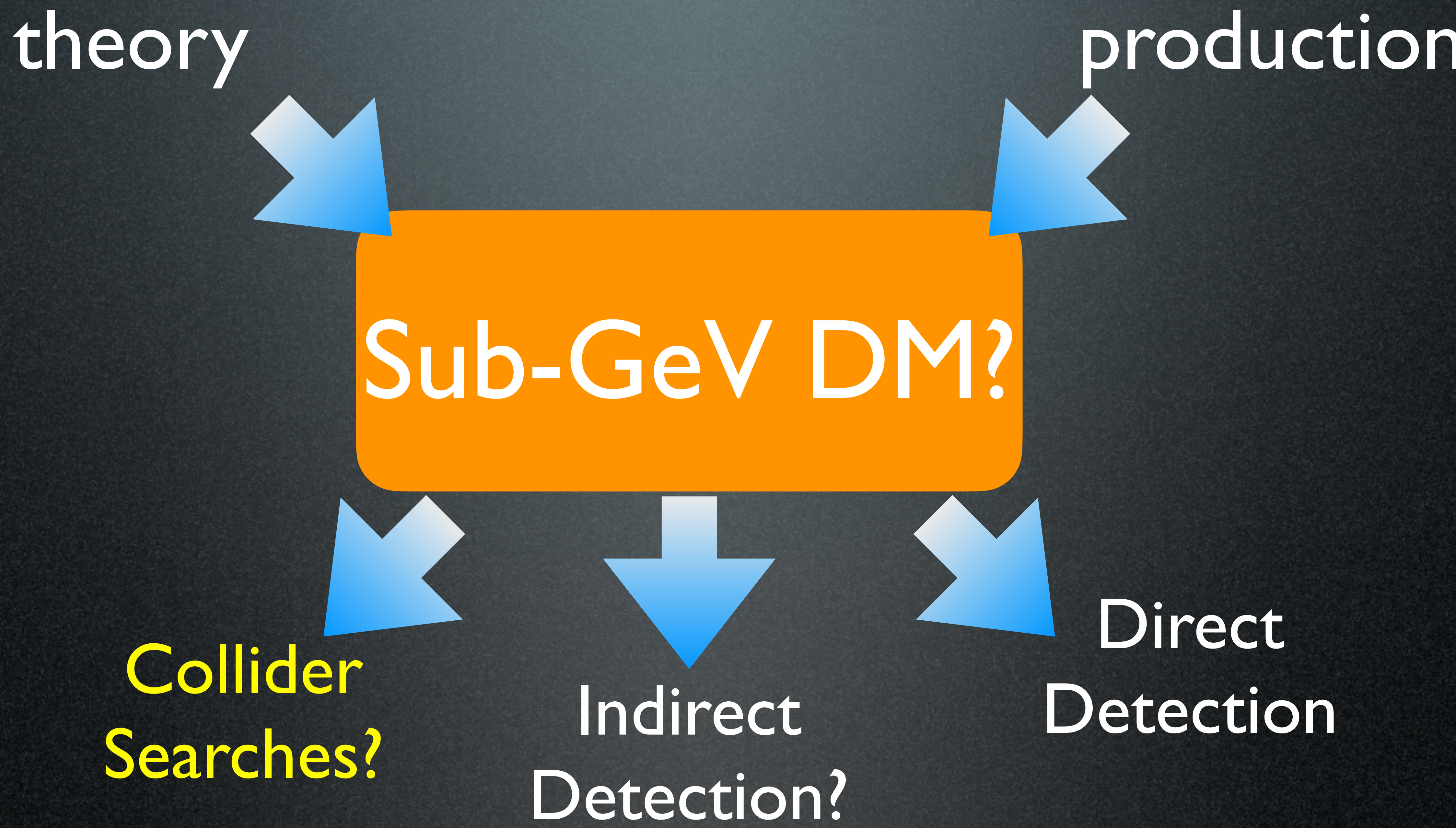
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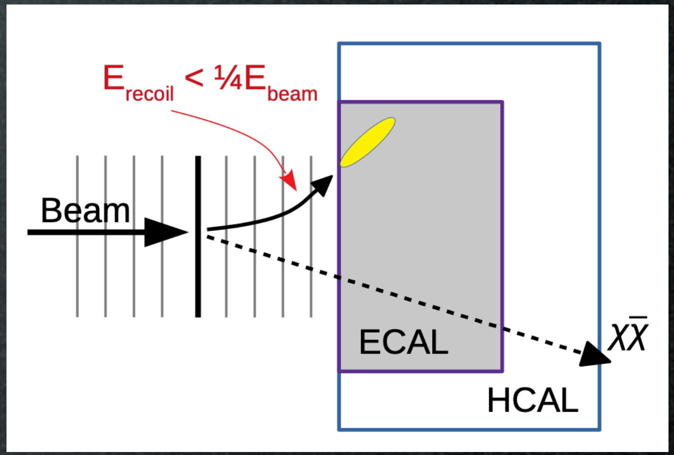
Collider searches of sub-GeV DM

Missing E_T signature is challenging for LHC experiments

- fixed target / beam dump experiments

- search for associated states, i.e. particles of a new 'dark sector'



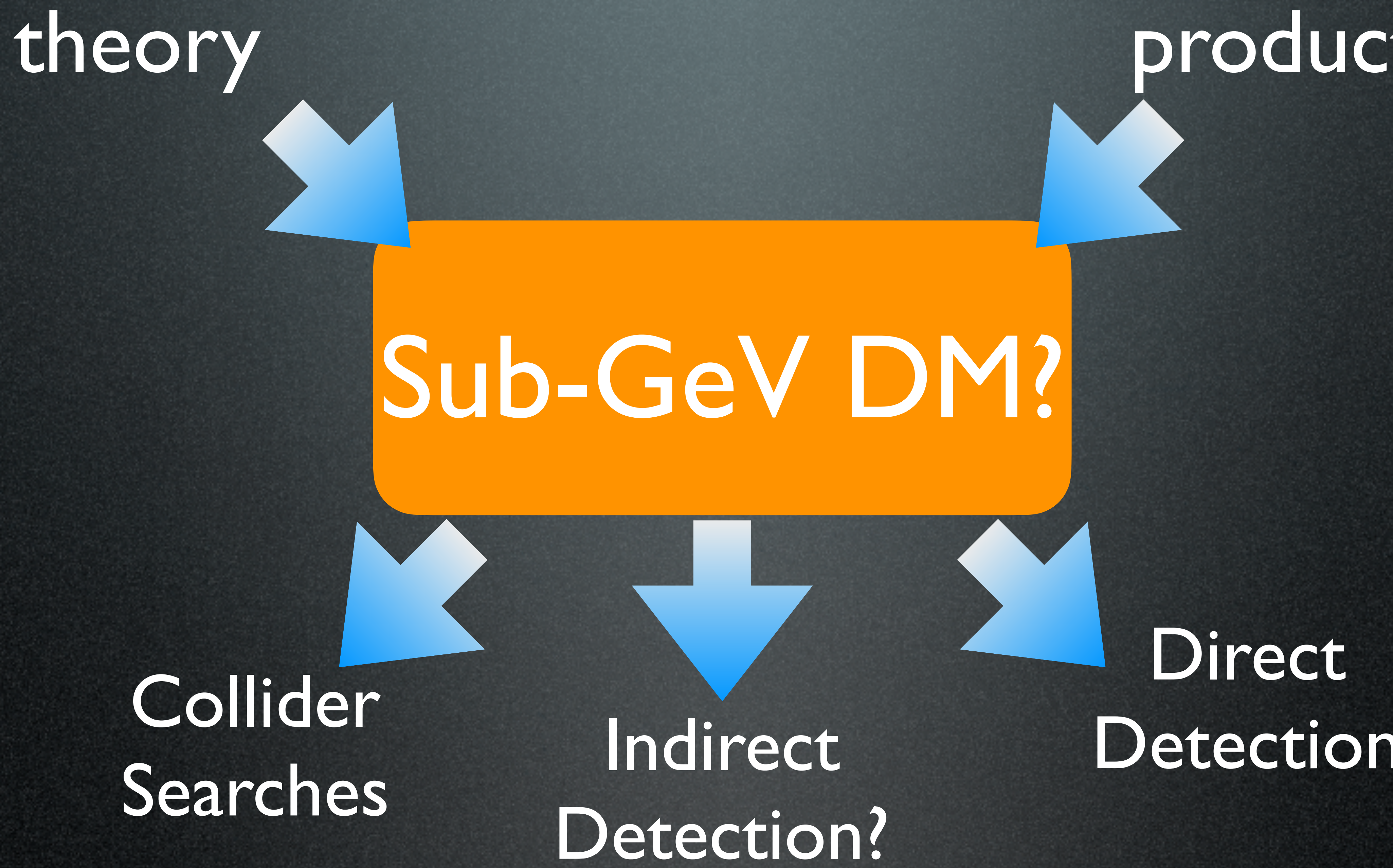
e.g. LDMX coll. 1808.05219

B. Batell, M. Pospelov and A. Ritz, Exploring Portals to a Hidden Sector Through Fixed Targets, Phys. Rev. D 80 (2009) 095024, [0906.5614].

LDMX collaboration, T. kesson et al., Light Dark Matter eXperiment (LDMX), 1808.05219.
L. Doria, P. Achenbach, M. Christmann, A. Denig, P. Glker and H. Merkel, Search for light dark matter with the MESA accelerator, in 13th Conference on the Intersections of Particle and Nuclear Physics, 9, 2018. 1809.07168.

M. Battaglieri et al., US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report, in U.S. Cosmic Visions: New Ideas in Dark Matter, 7, 2017. 1707.04591.

Candidates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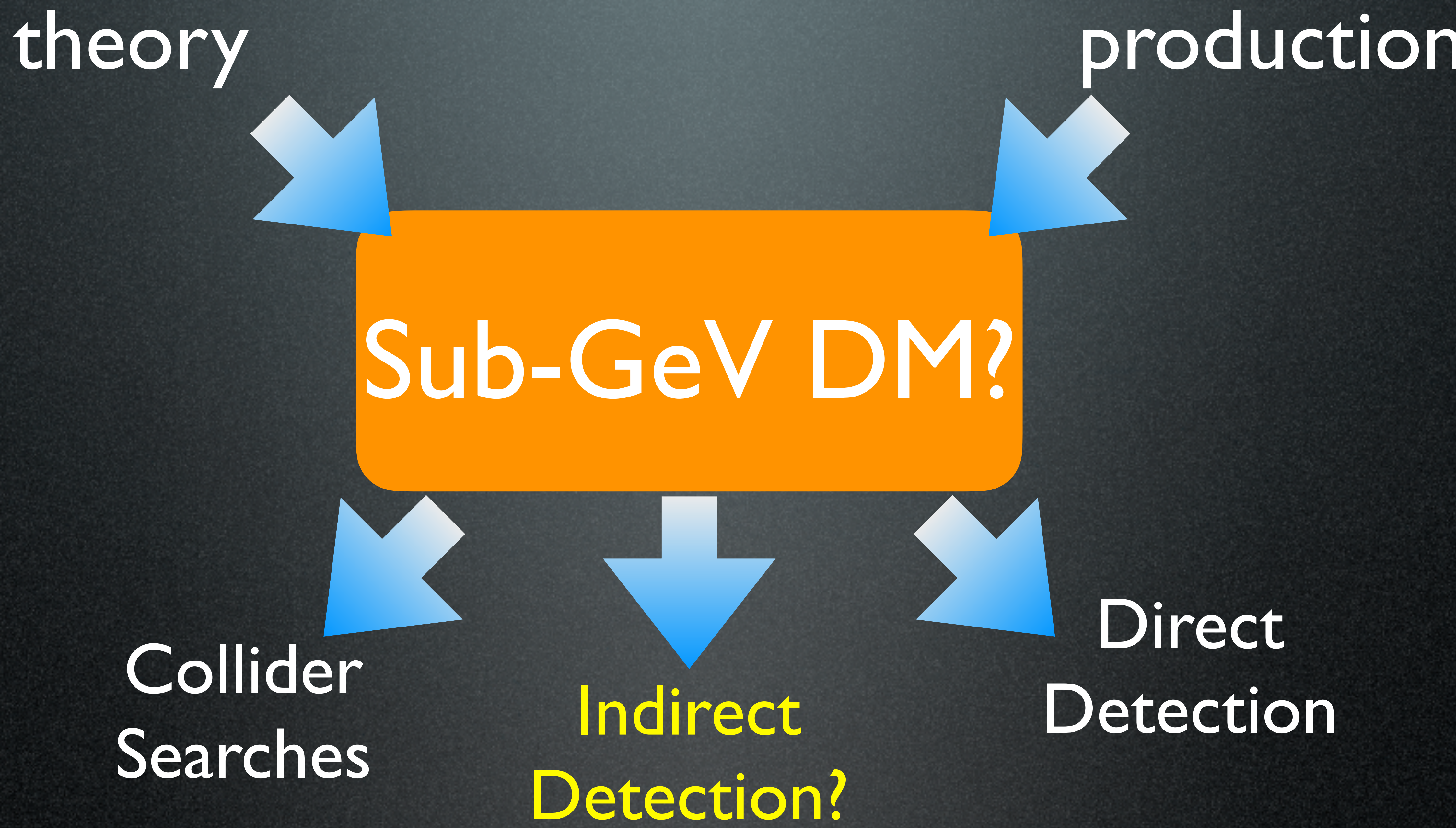
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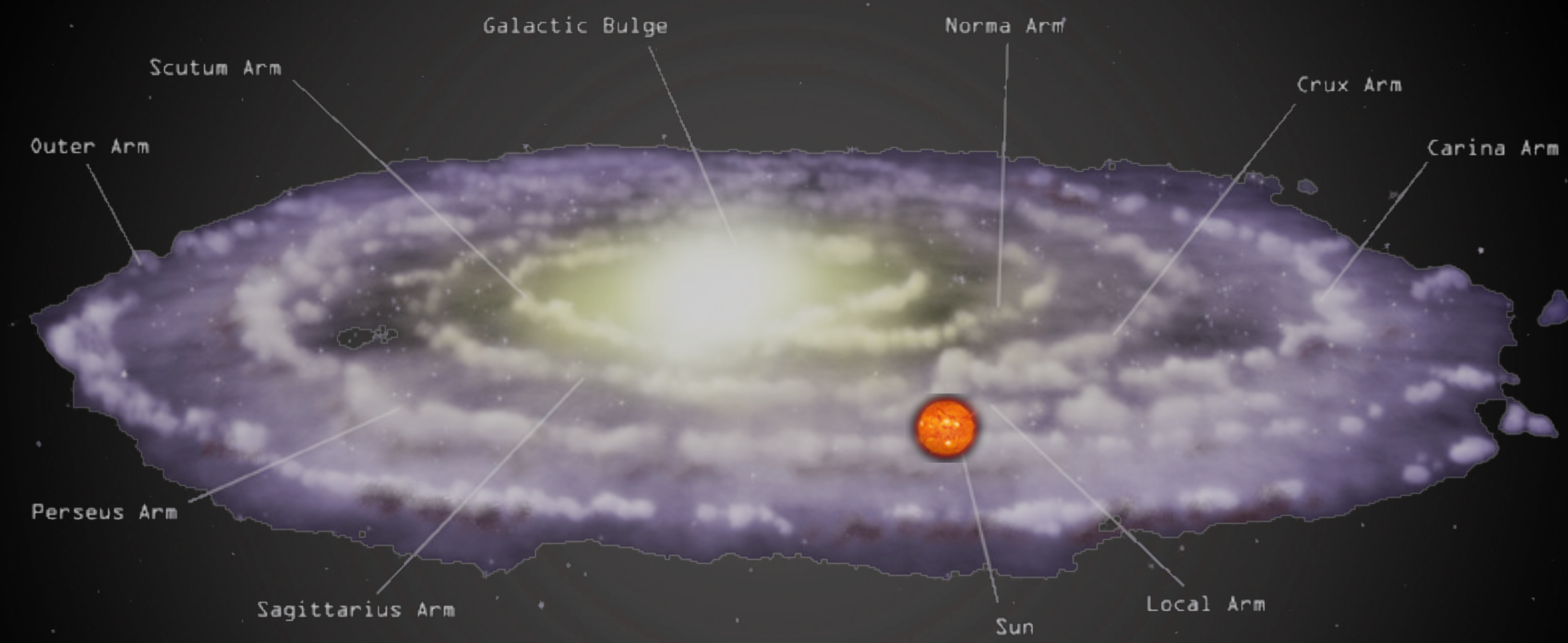
Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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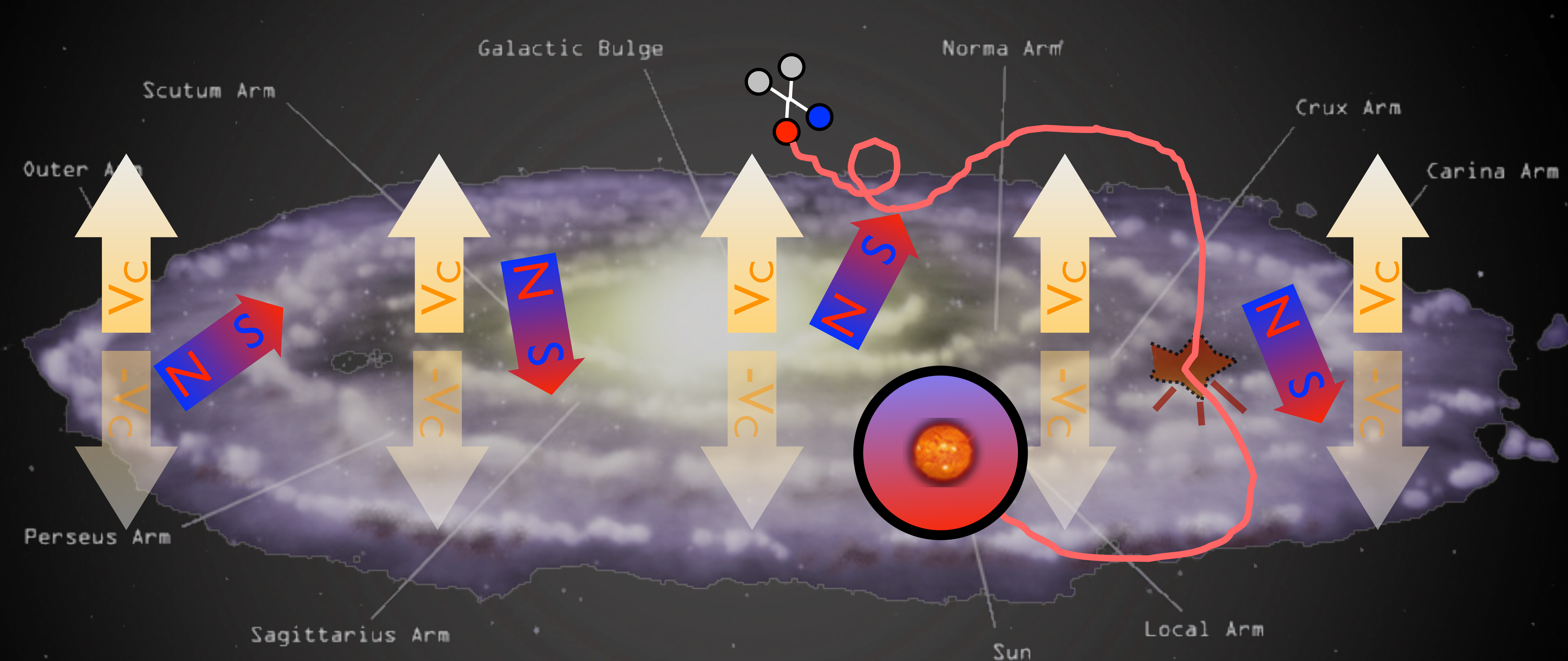

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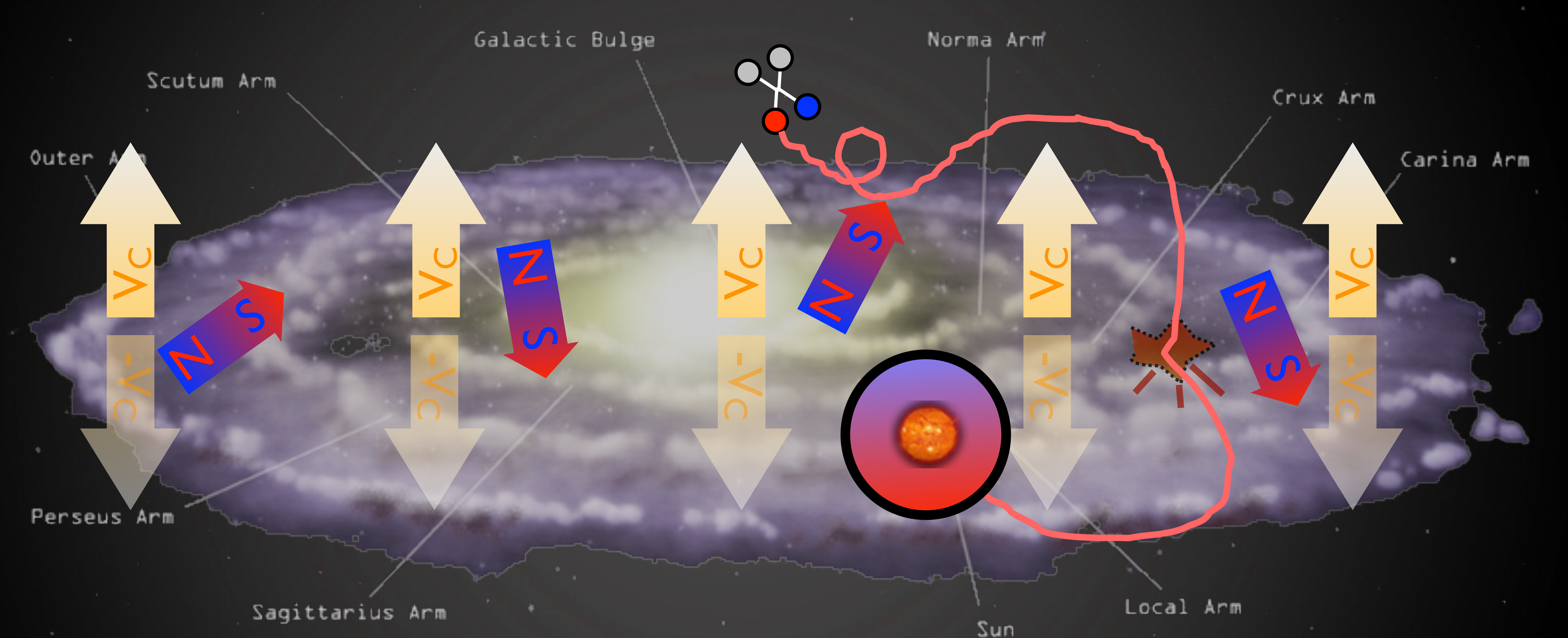

Problem:

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

Indirect Detection: charged CRs

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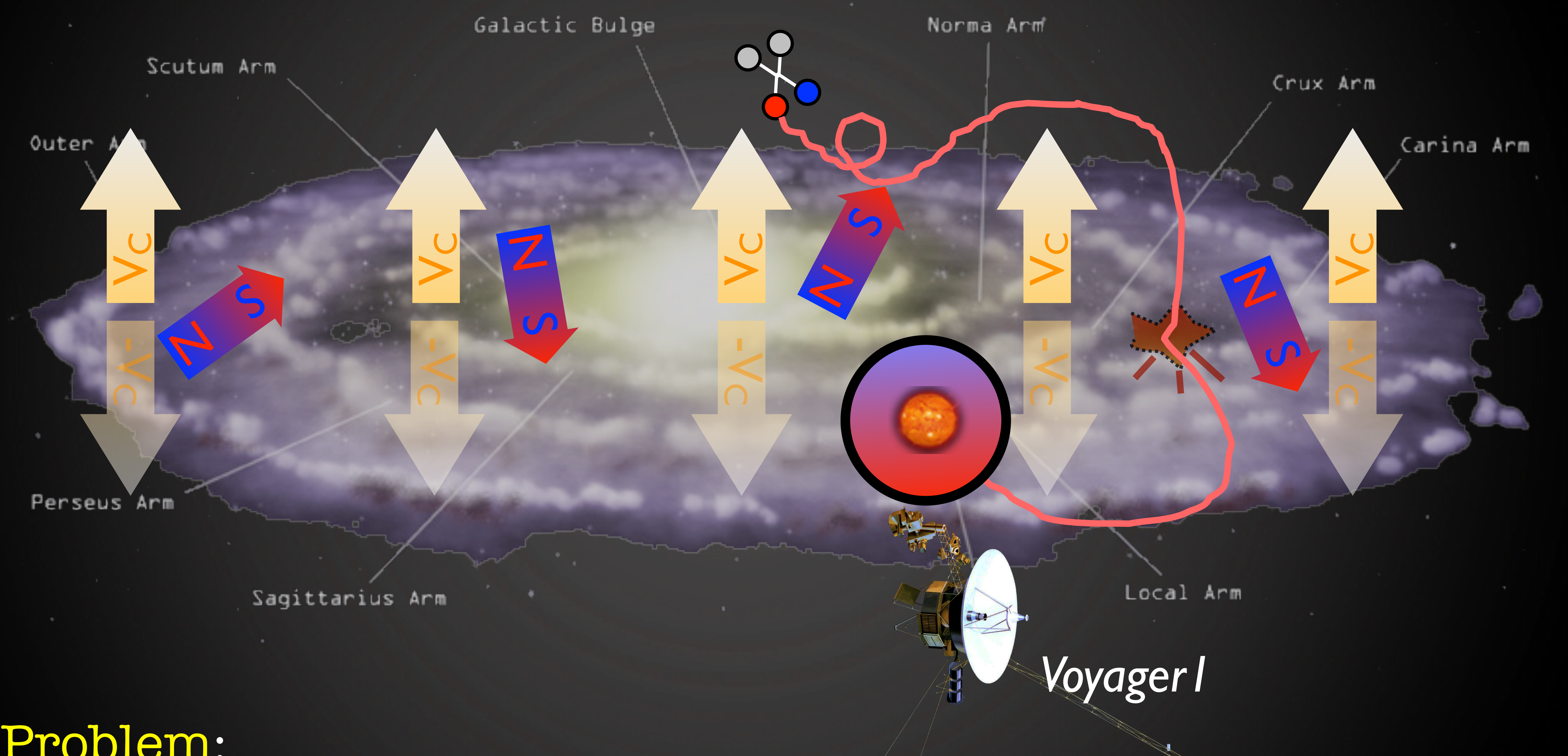


Problem:

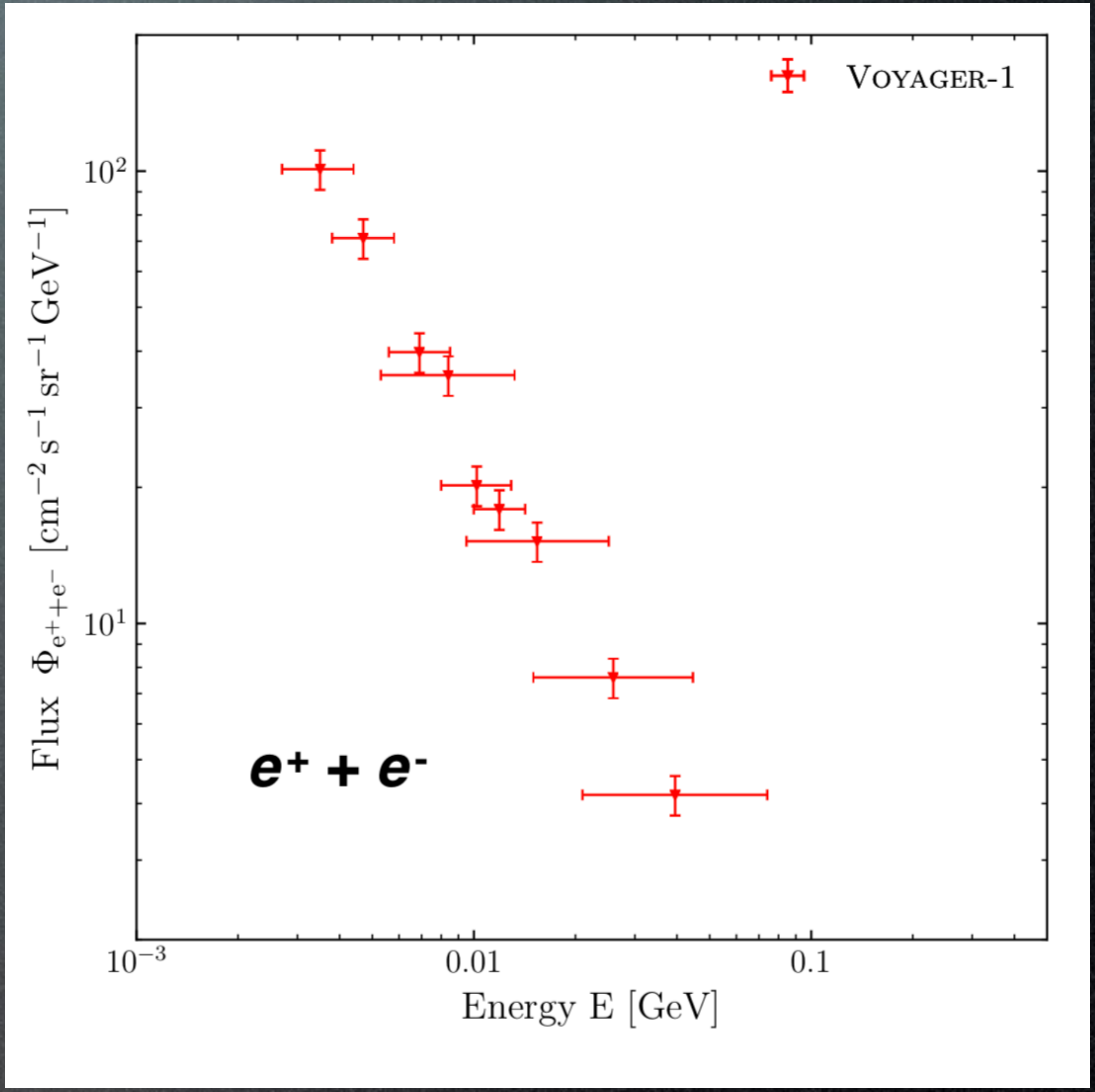
sub-GeV charged CRs do not penetrate the heliosphere, experiments cannot collect… with one exception!

Data: leptons

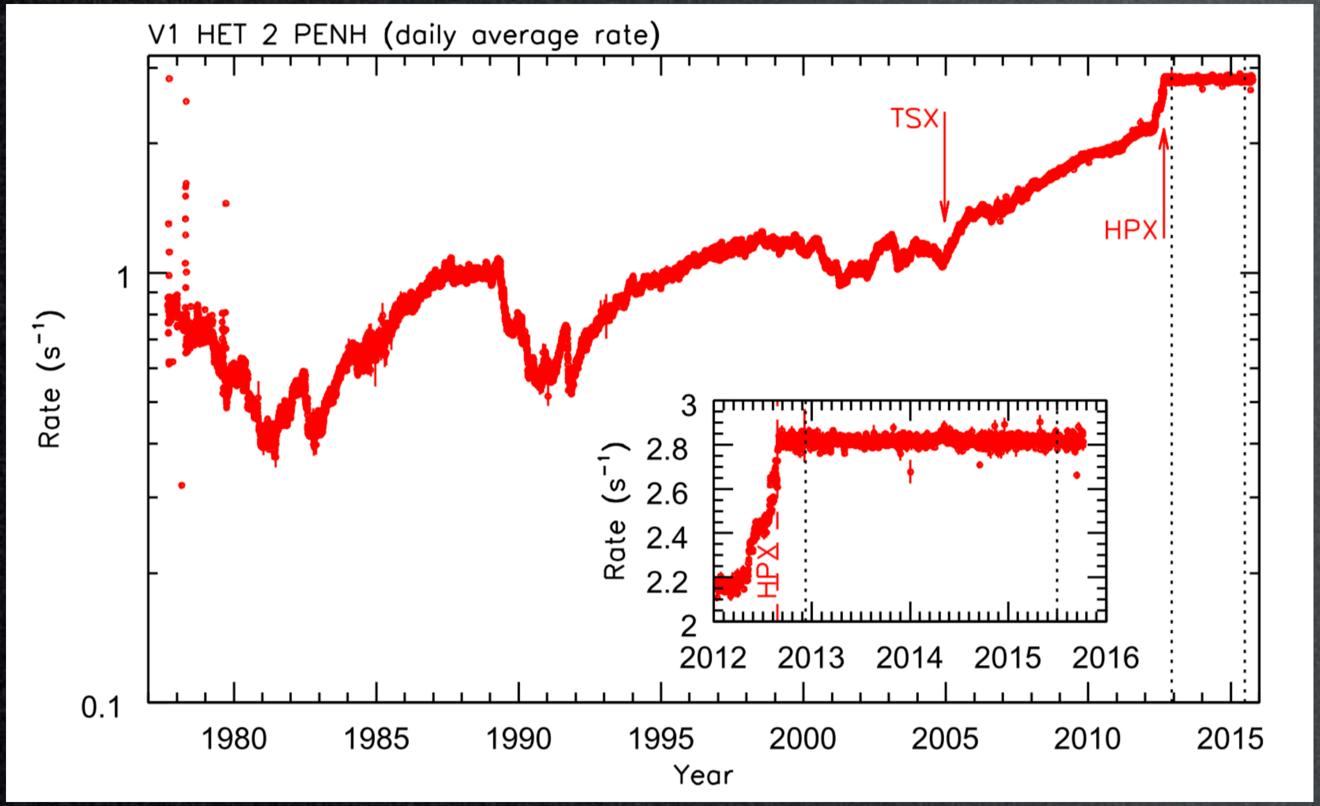
low energy

Voyager-1 left the heliosphere in 08.2012

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



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

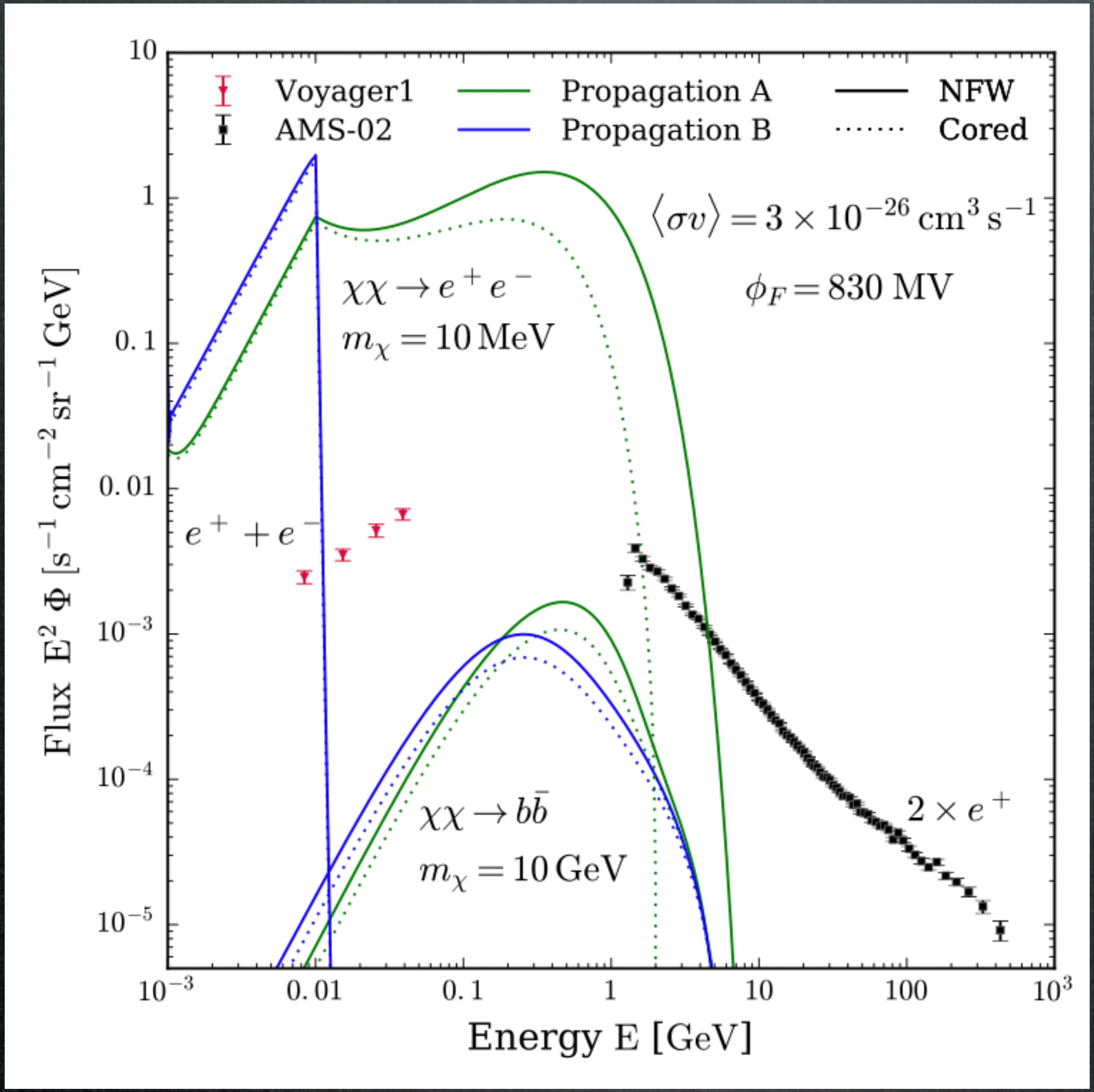


Cummings+ (Voyager-1 coll.), The Astrophysical Journal, 831:18, 2016

Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I

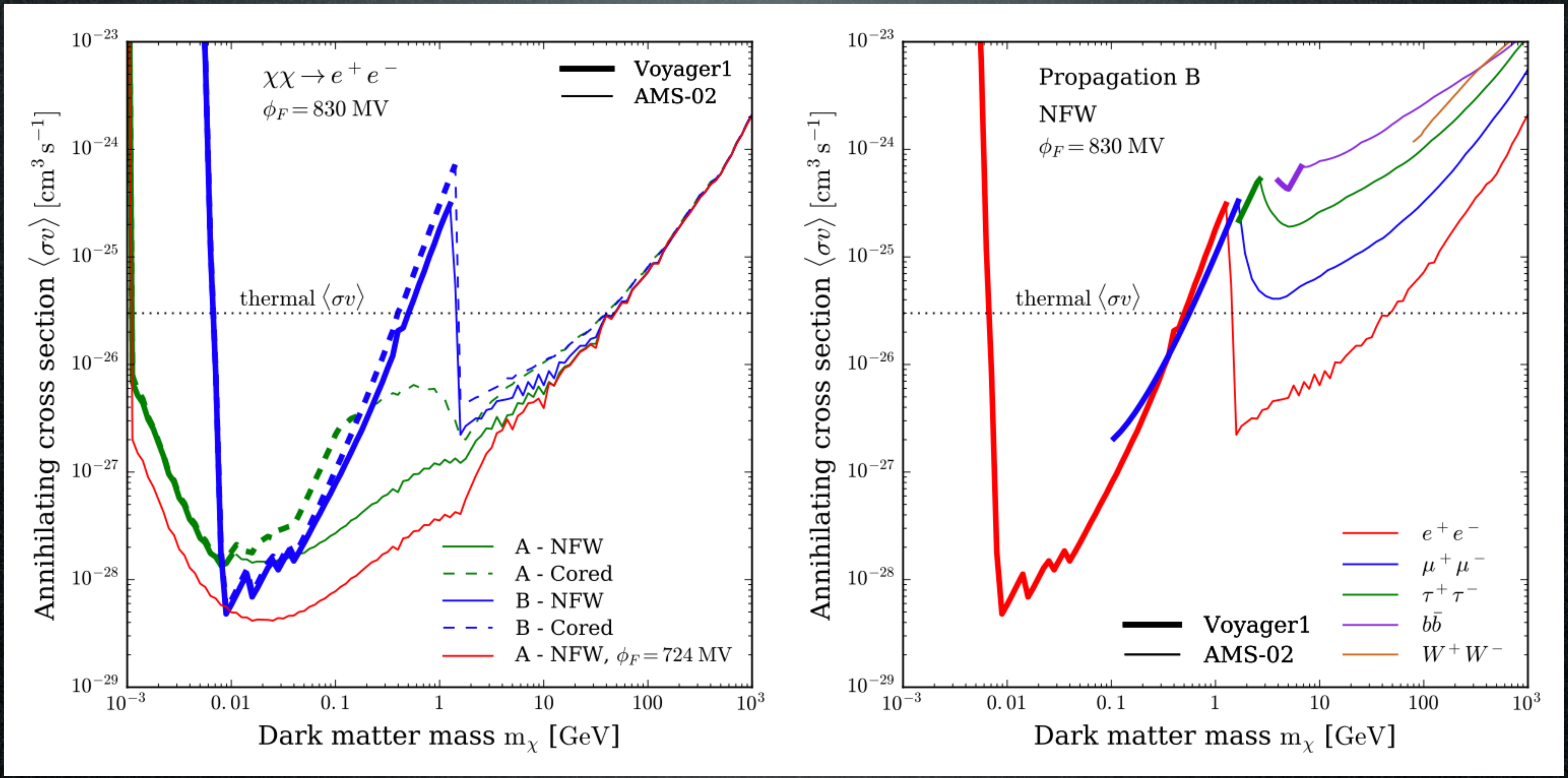


Propagation A = strong reacceleration
Propagation B = weak/no reacceleration

Indirect Detection: charged CRs

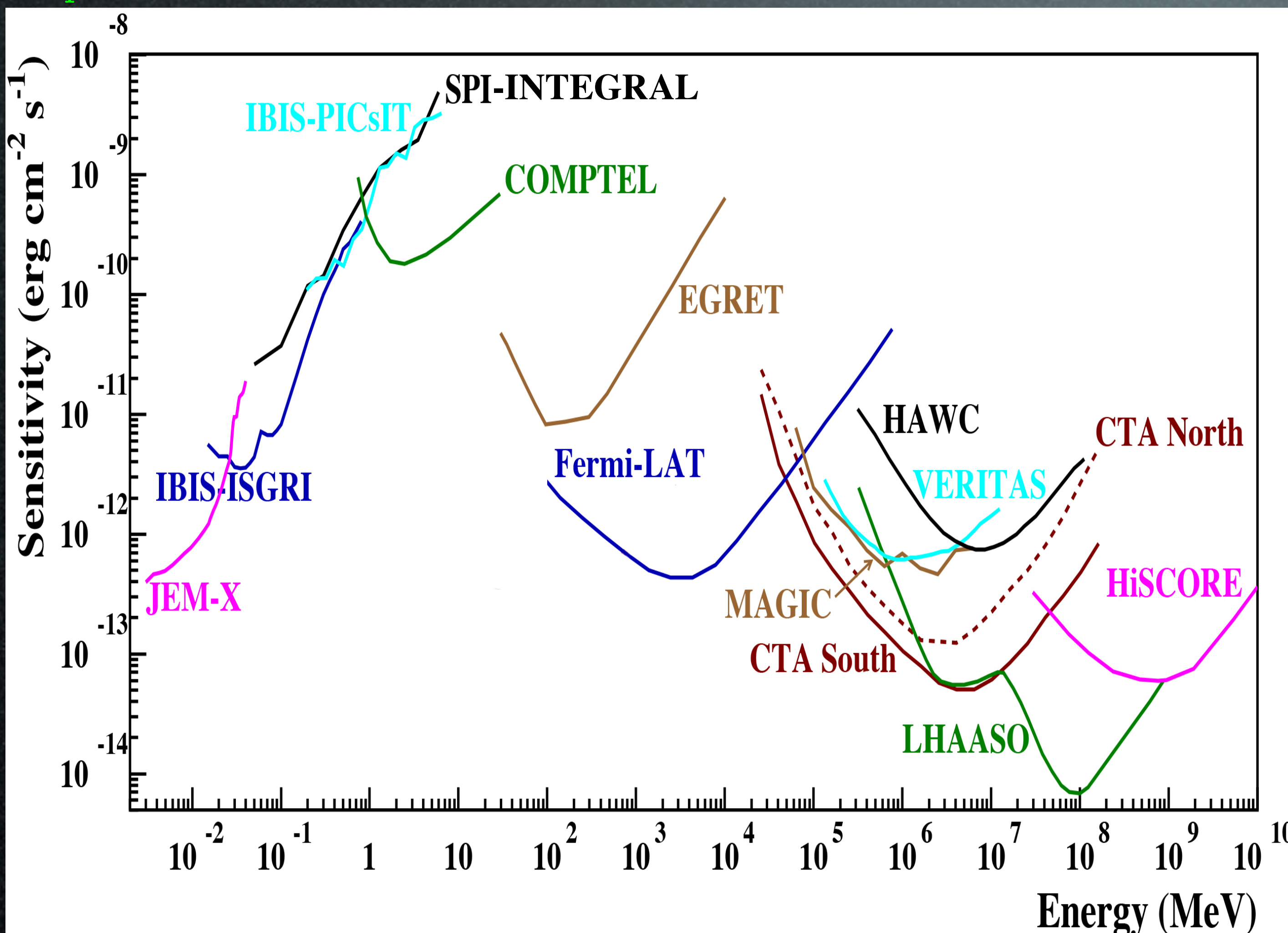
Boudaud, Lavalle, Salati 1612.07698

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?, Amego?, MAST?

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

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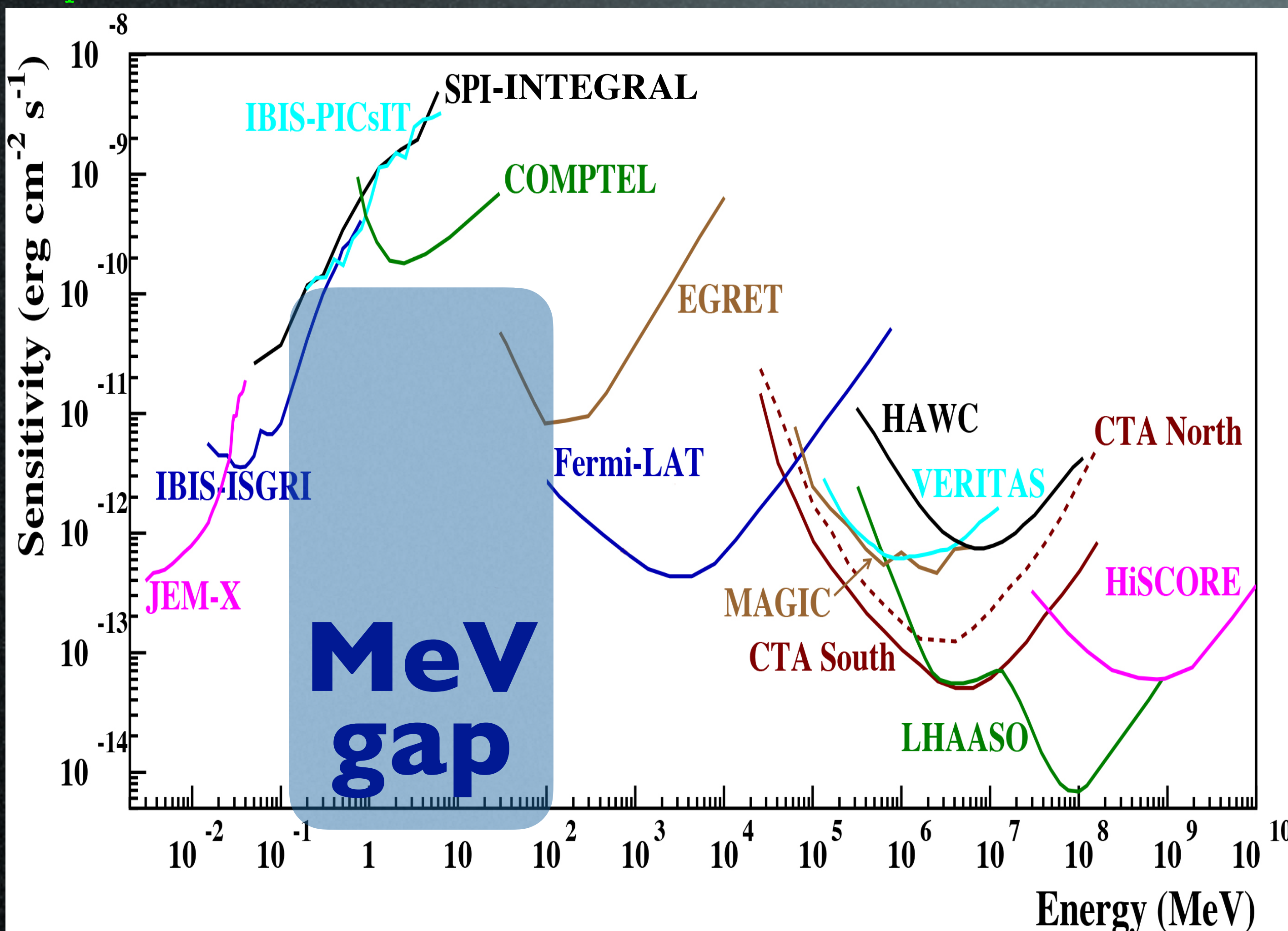

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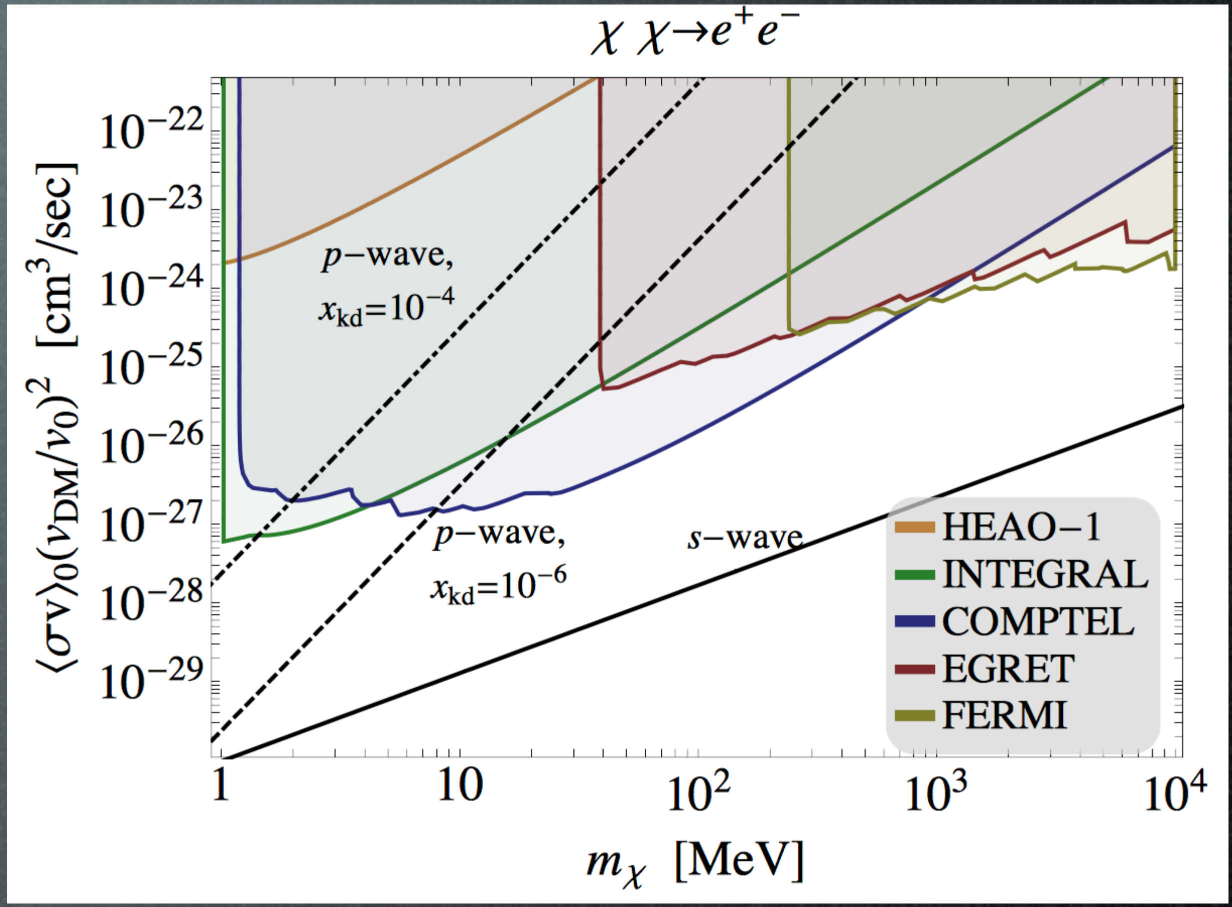
e-Astrogam	satellite	2030s?	HEP detectors	γ-rays	0.3 MeV – 3 GeV

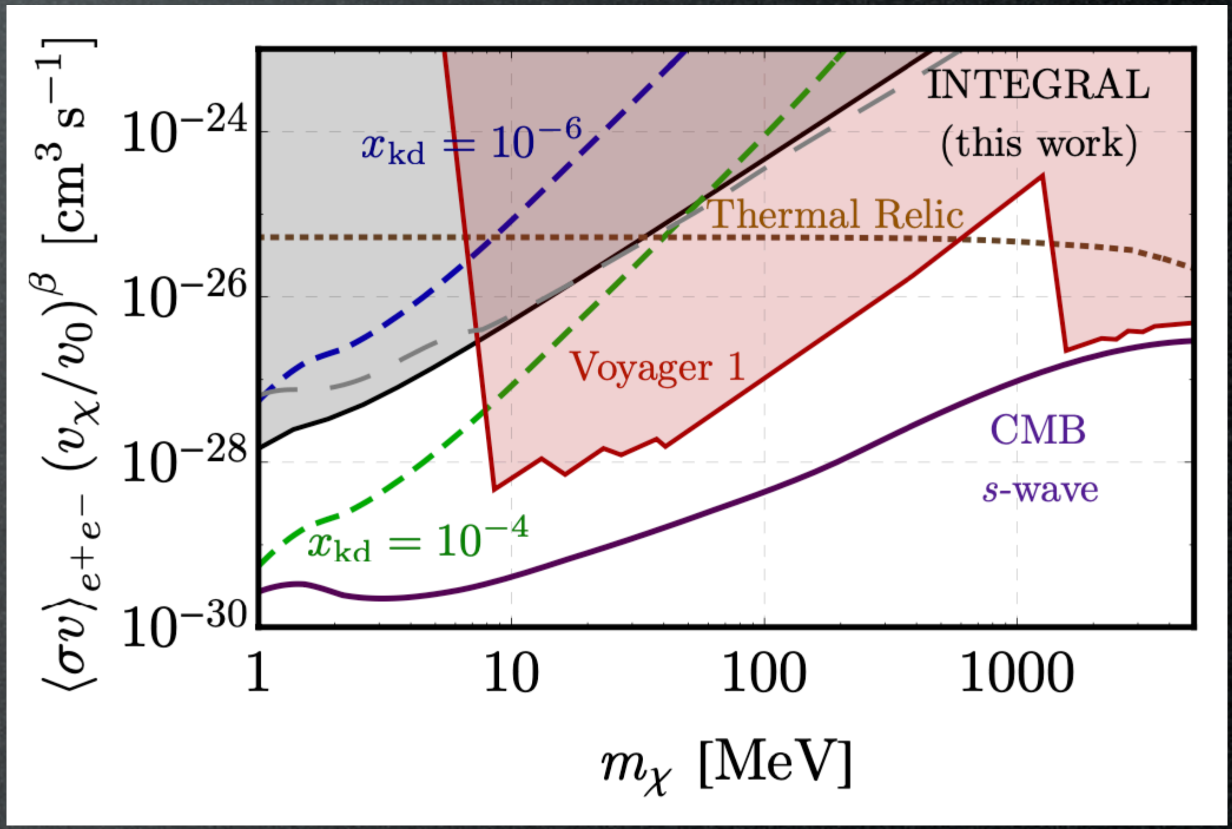
Cirelli, Strumia, Zupan 2406.01705

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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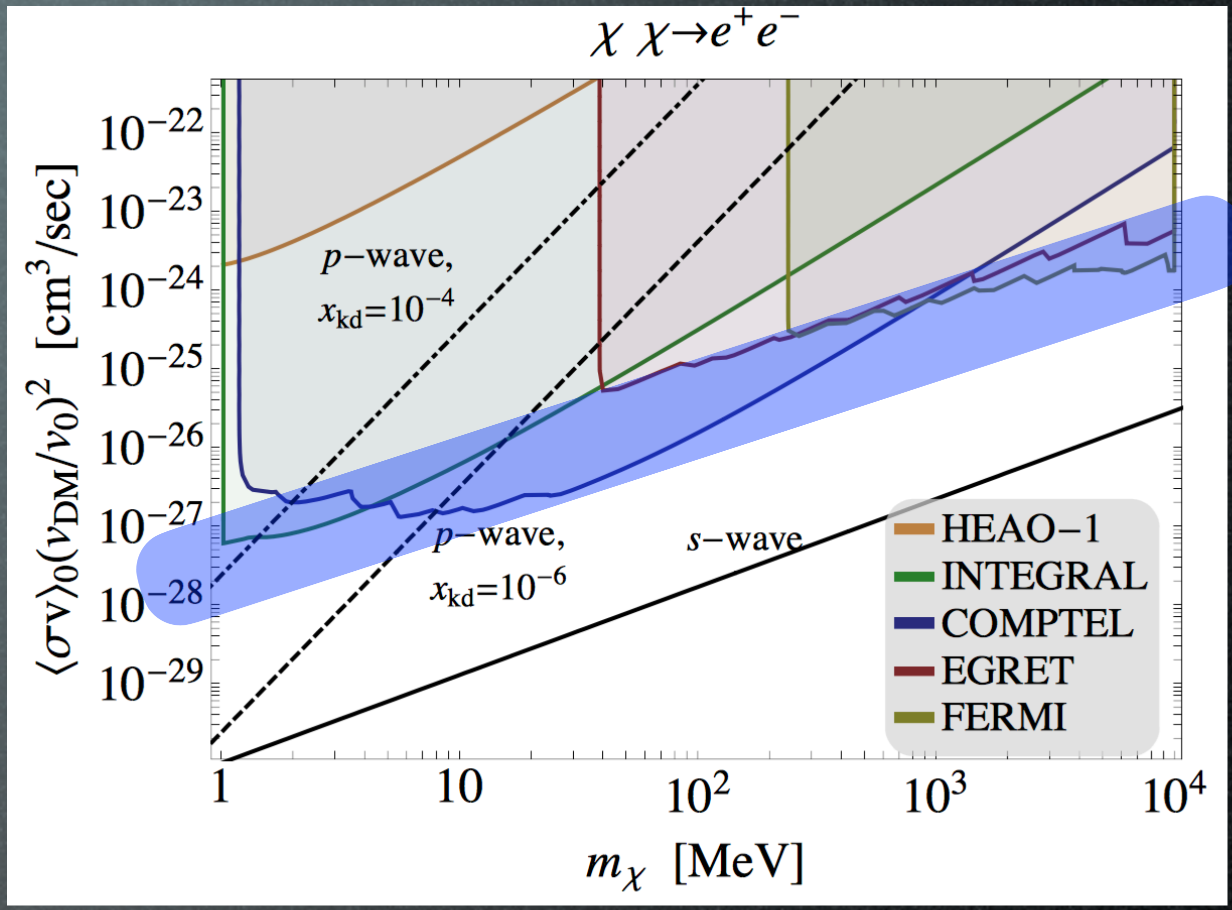

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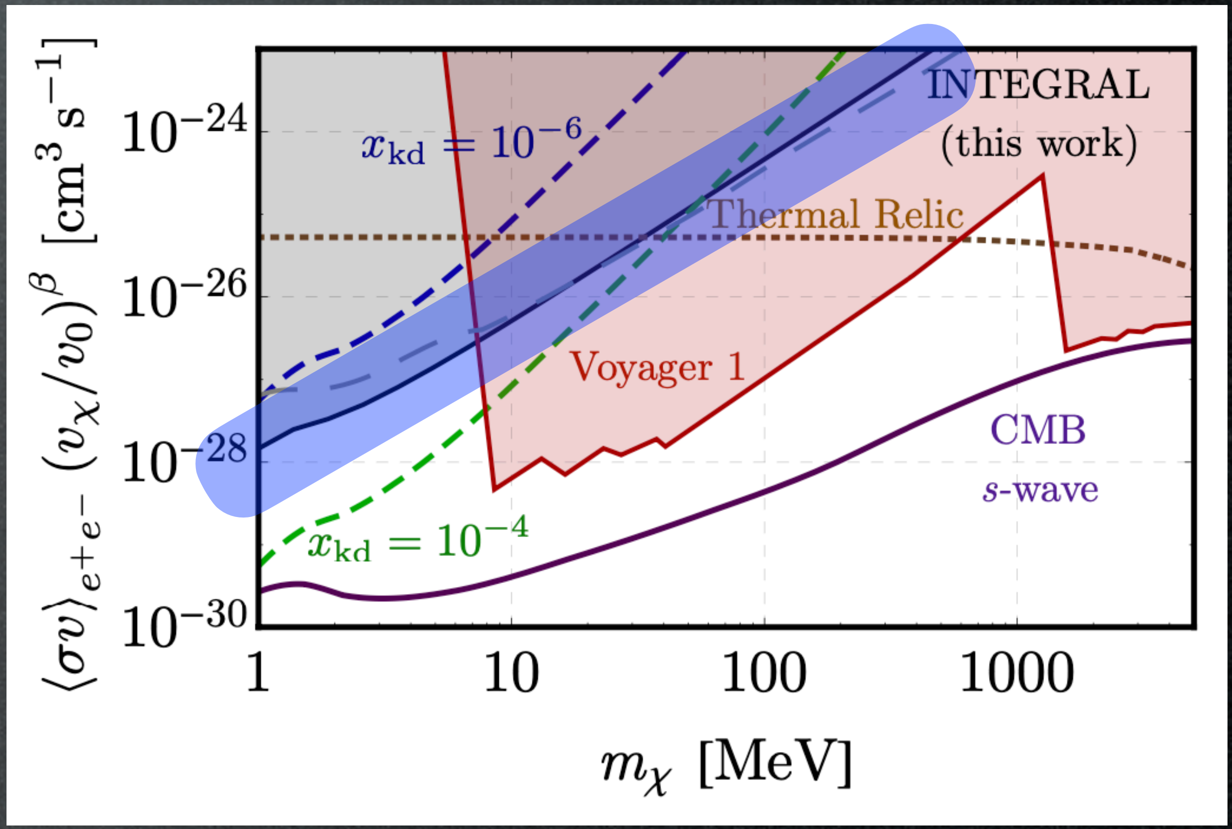

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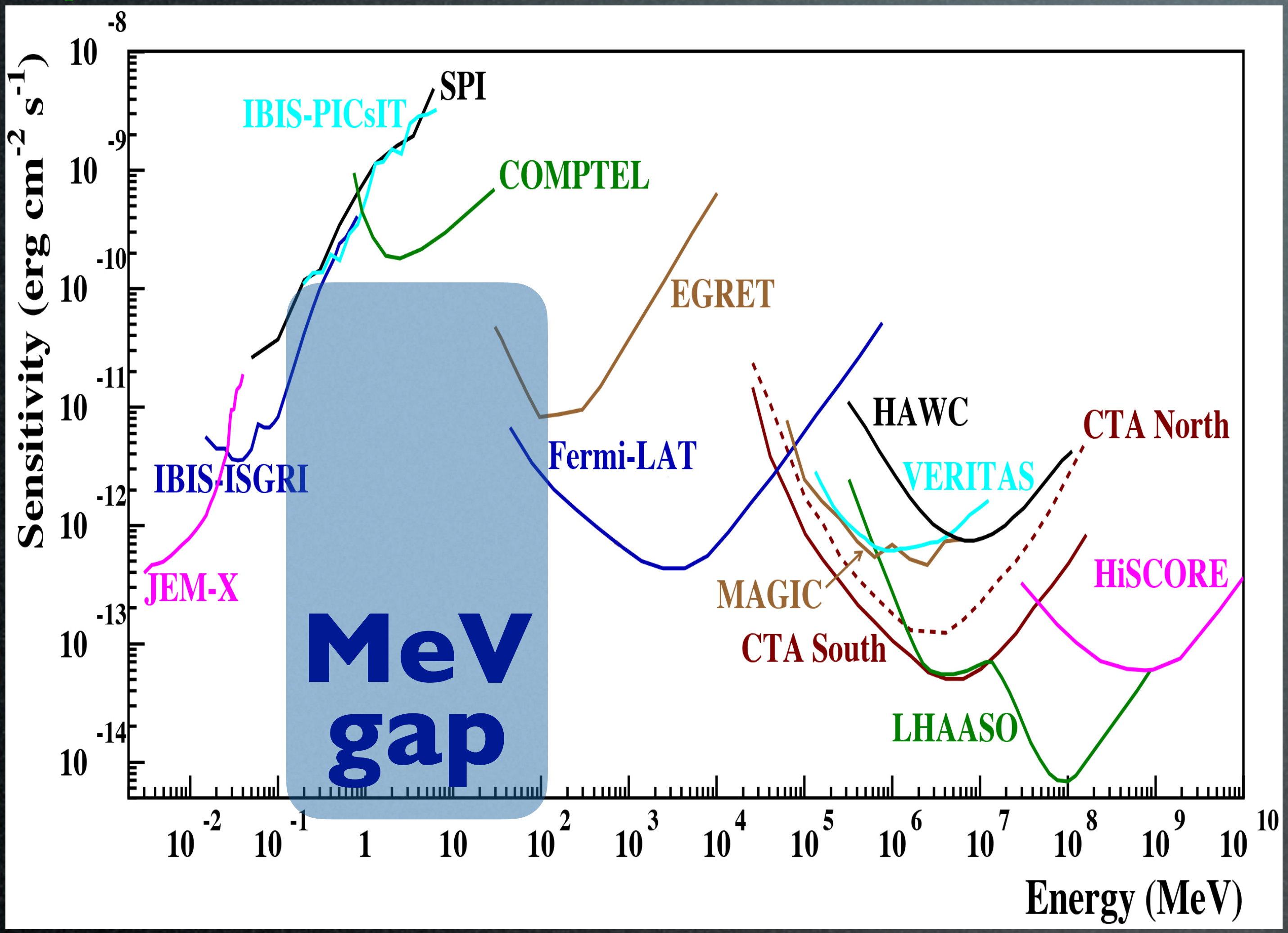
Indirect detection: photons

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)

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

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

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

Sub-GeV DM & X-rays

Annihilation channels

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

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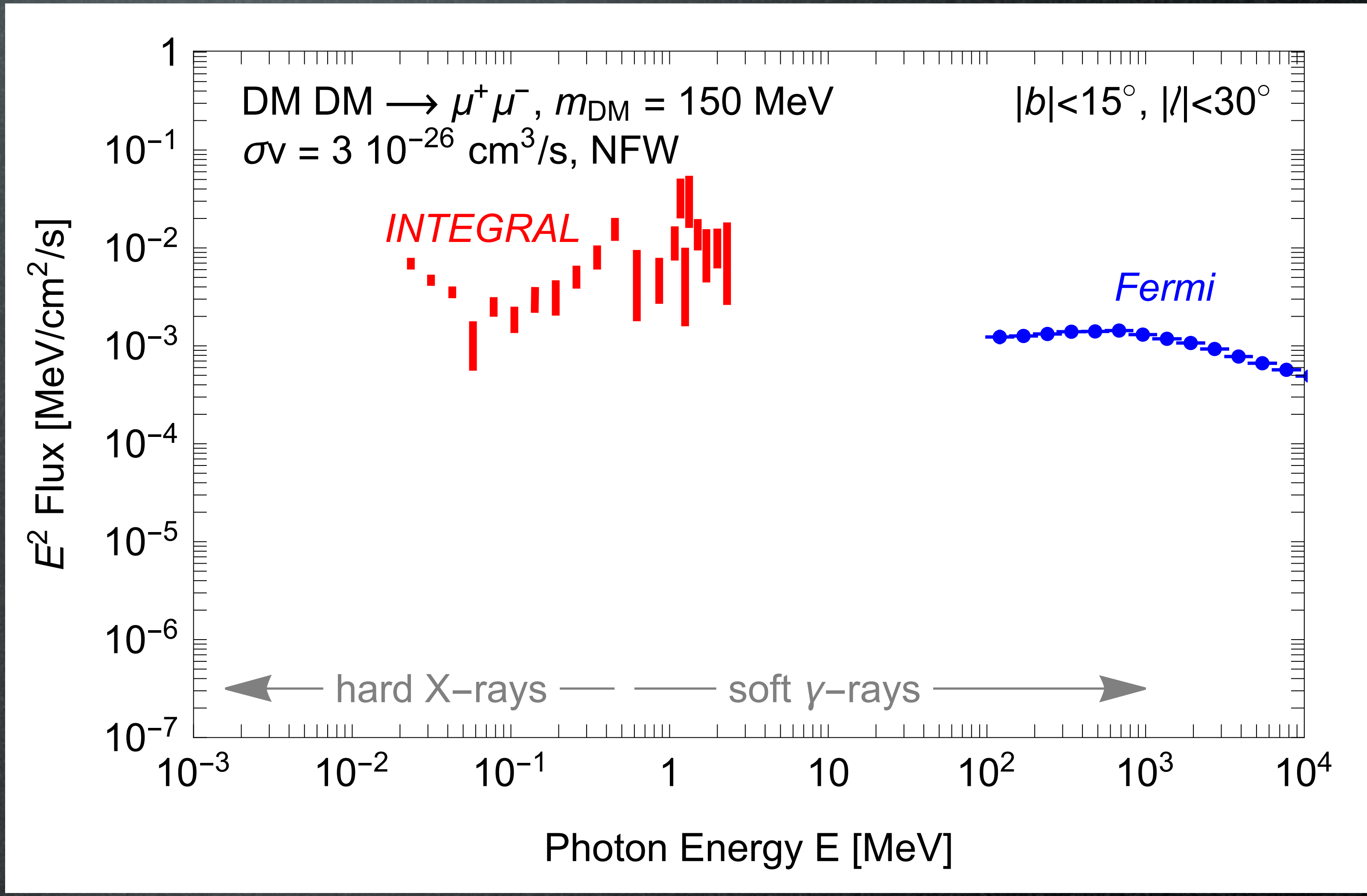

Sub-GeV DM & X-rays

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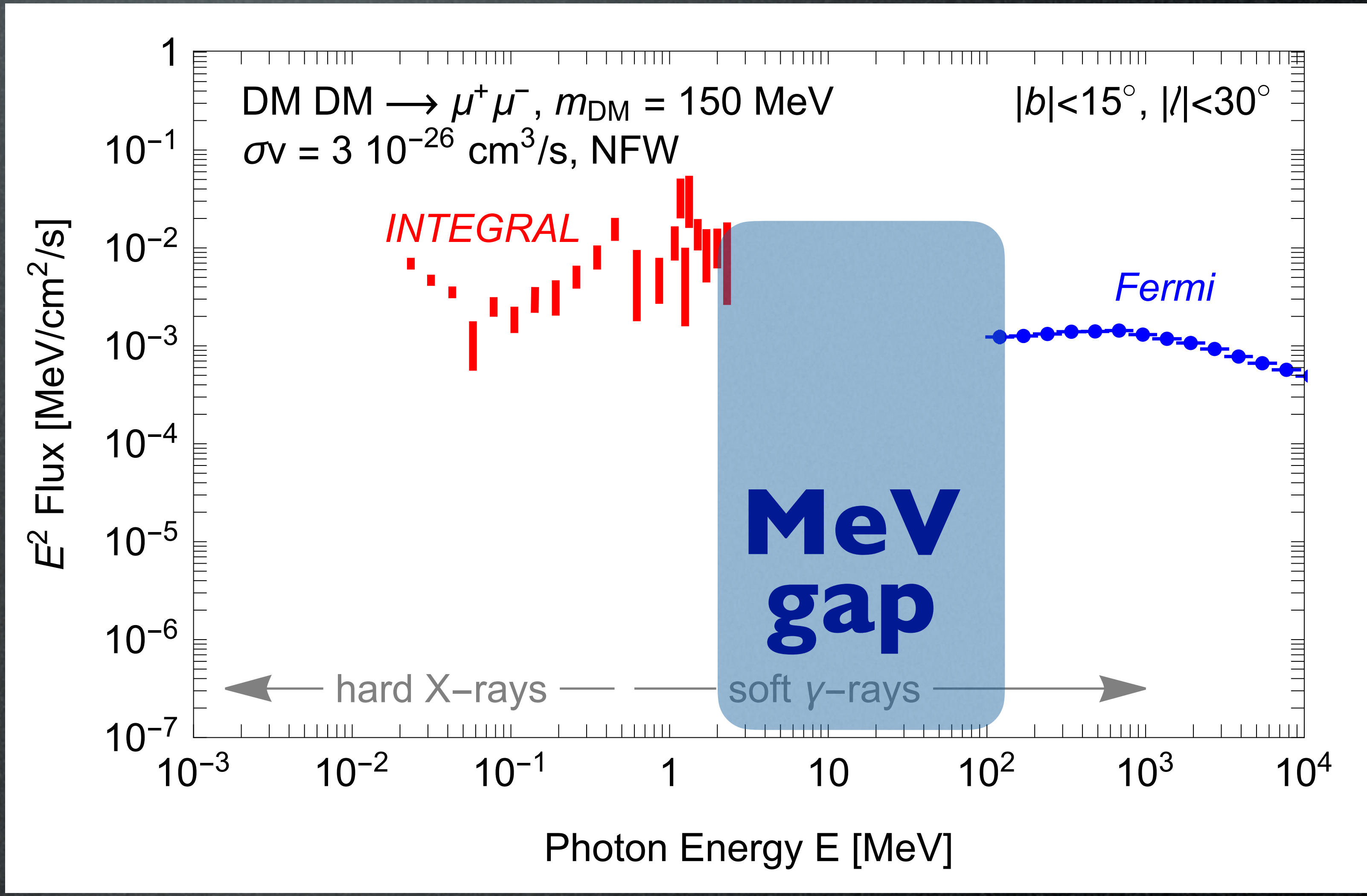

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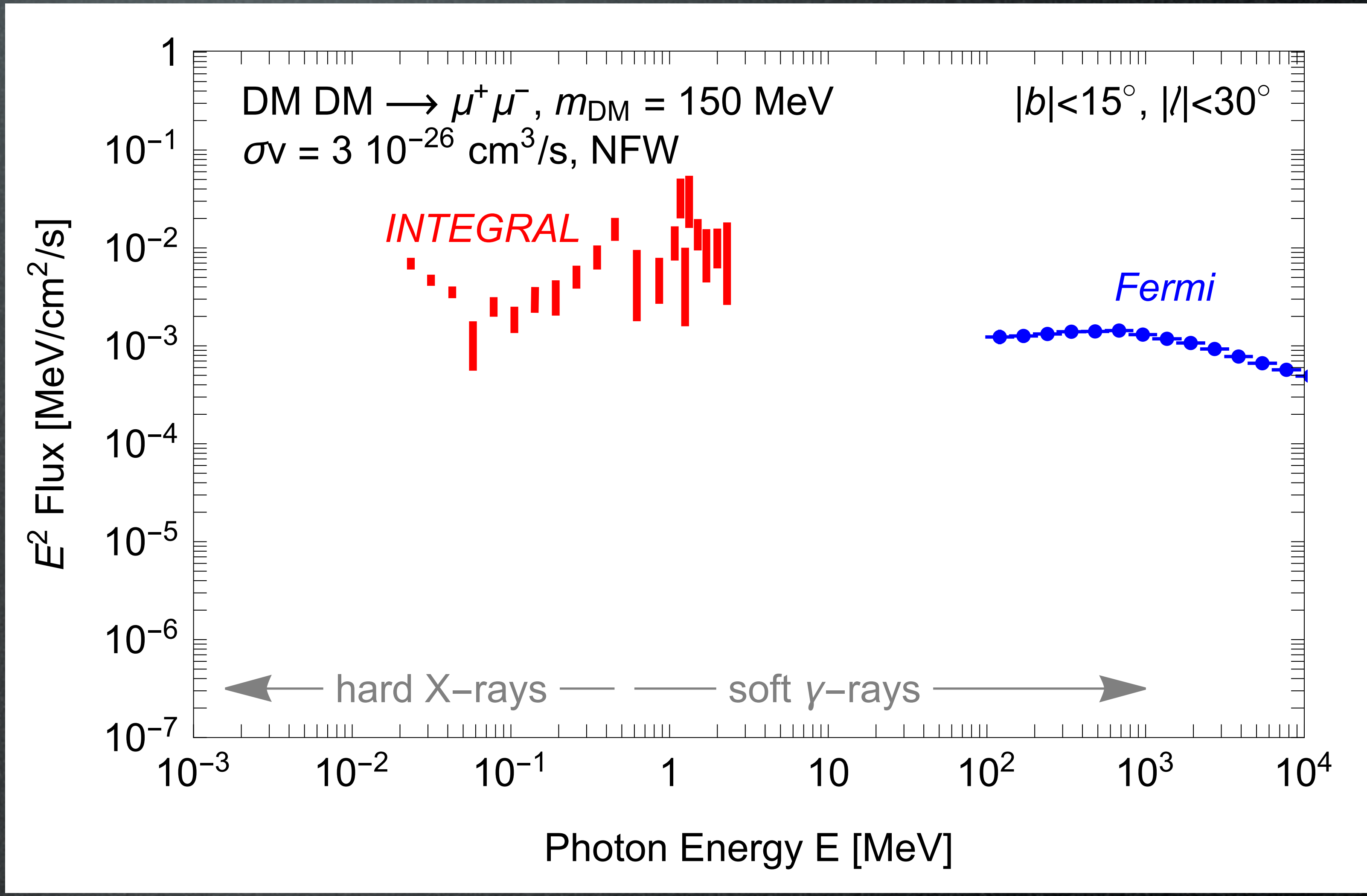

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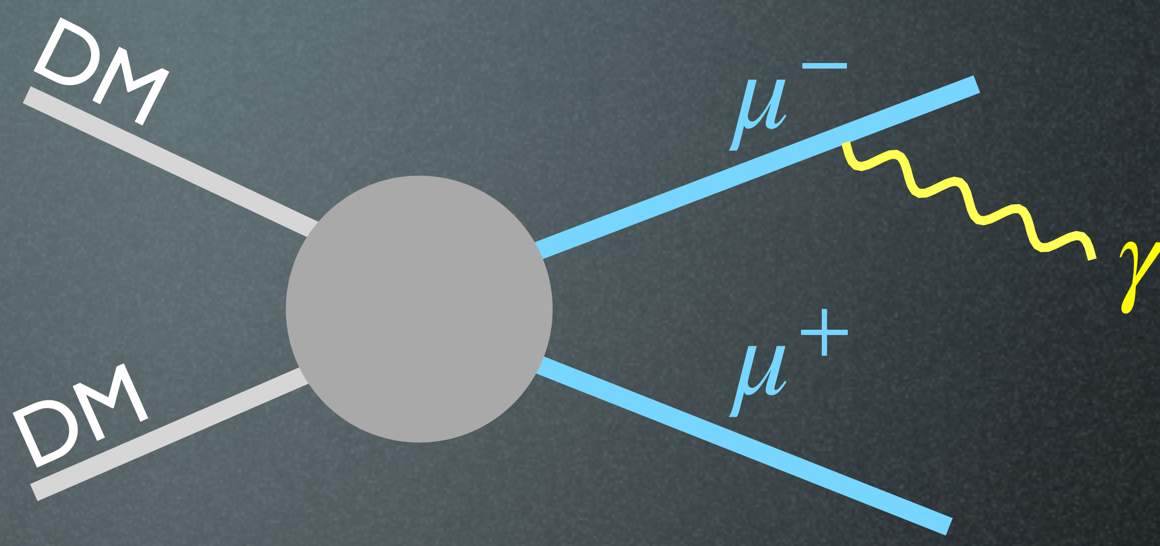
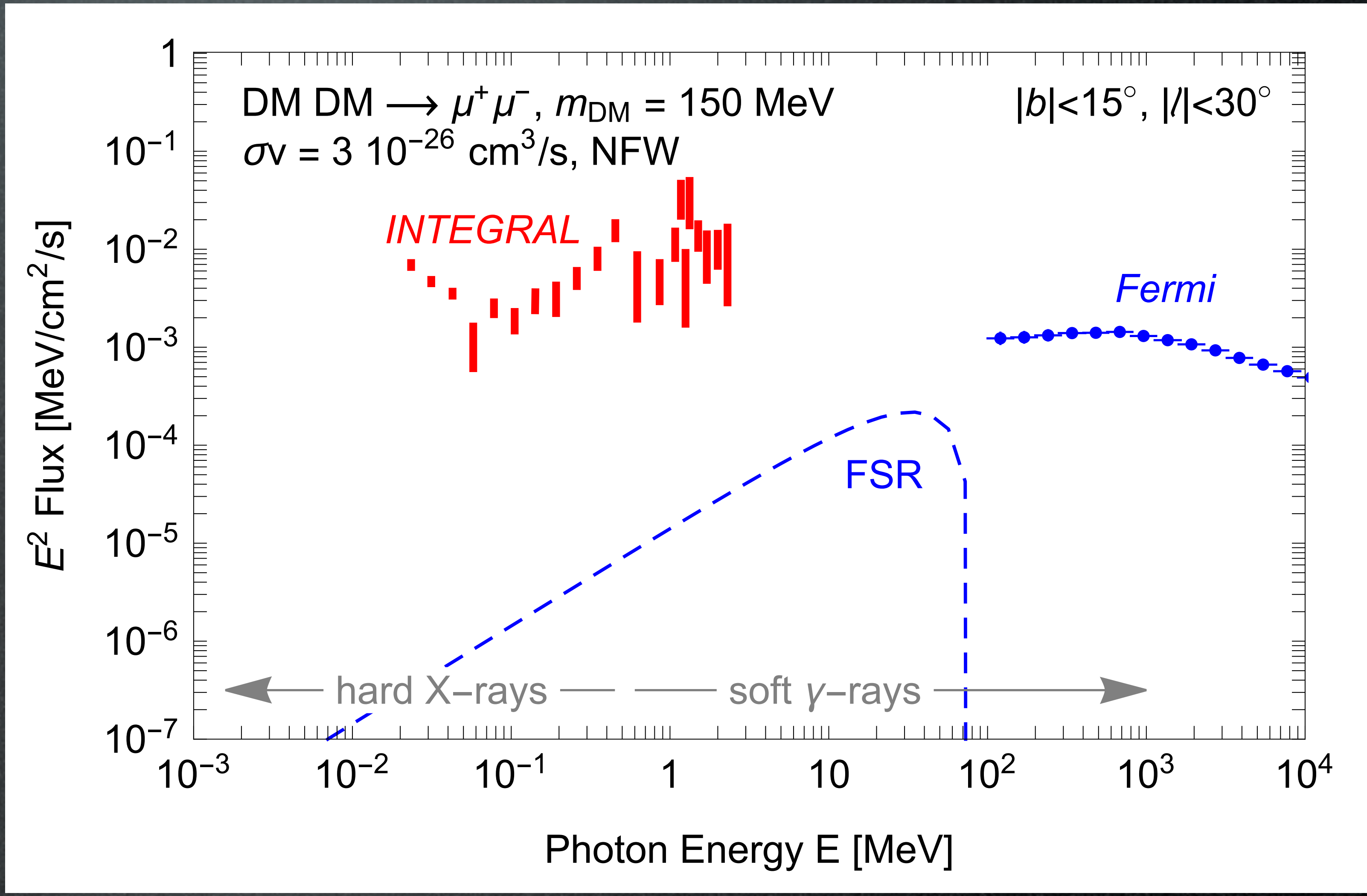


'Prompt' emission:

Final State Radiation (FSR)



Sub-GeV DM & X-rays

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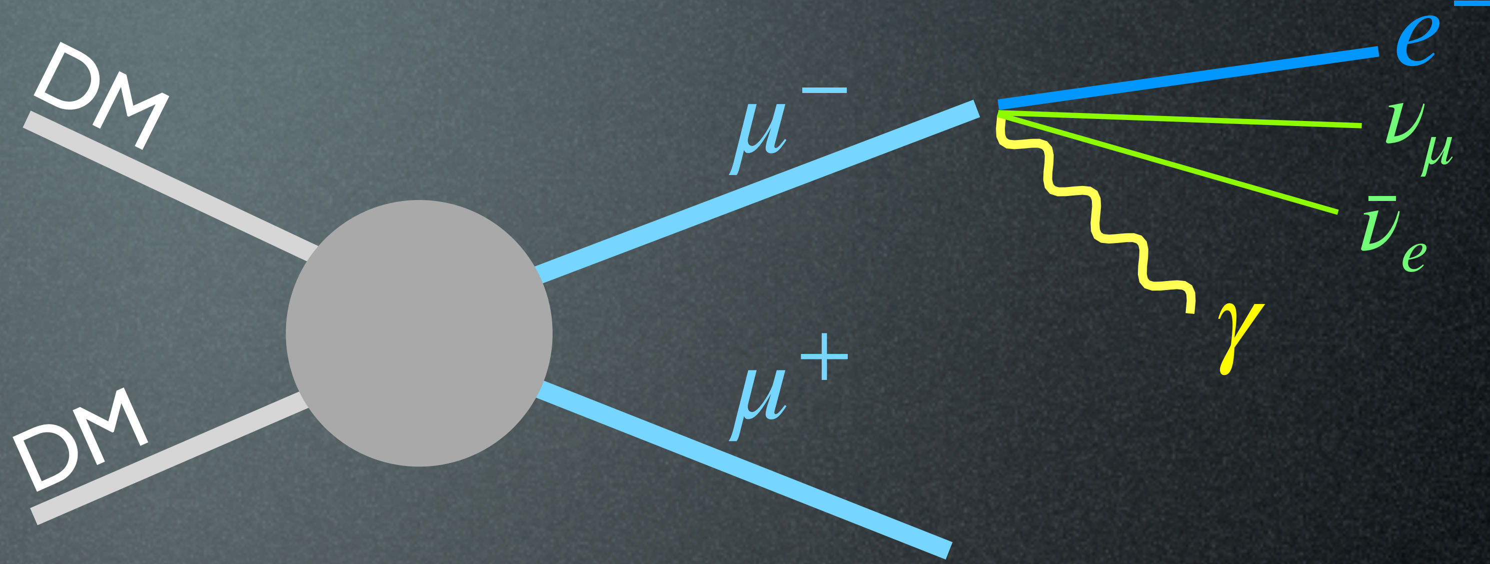
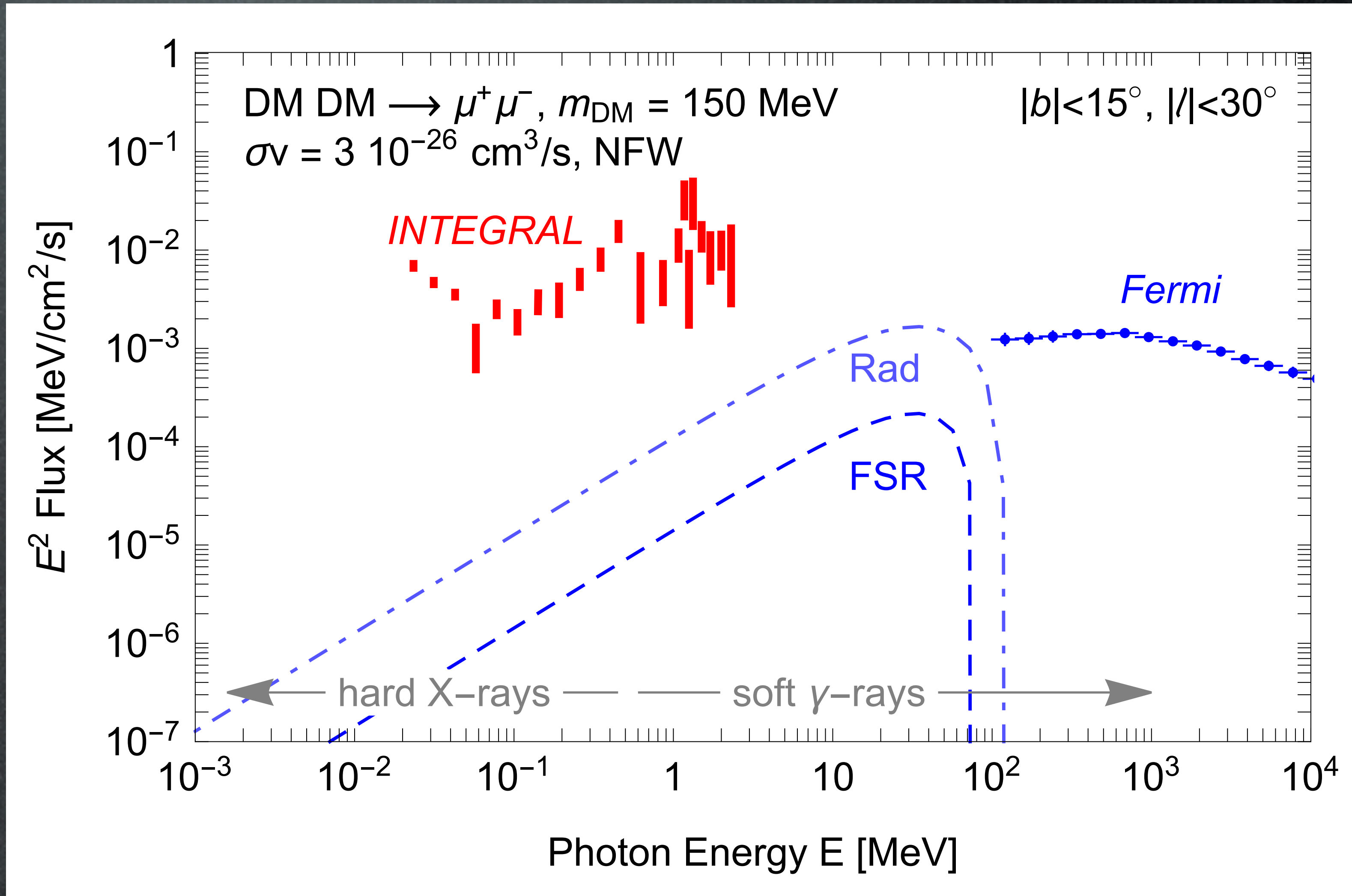


'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

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



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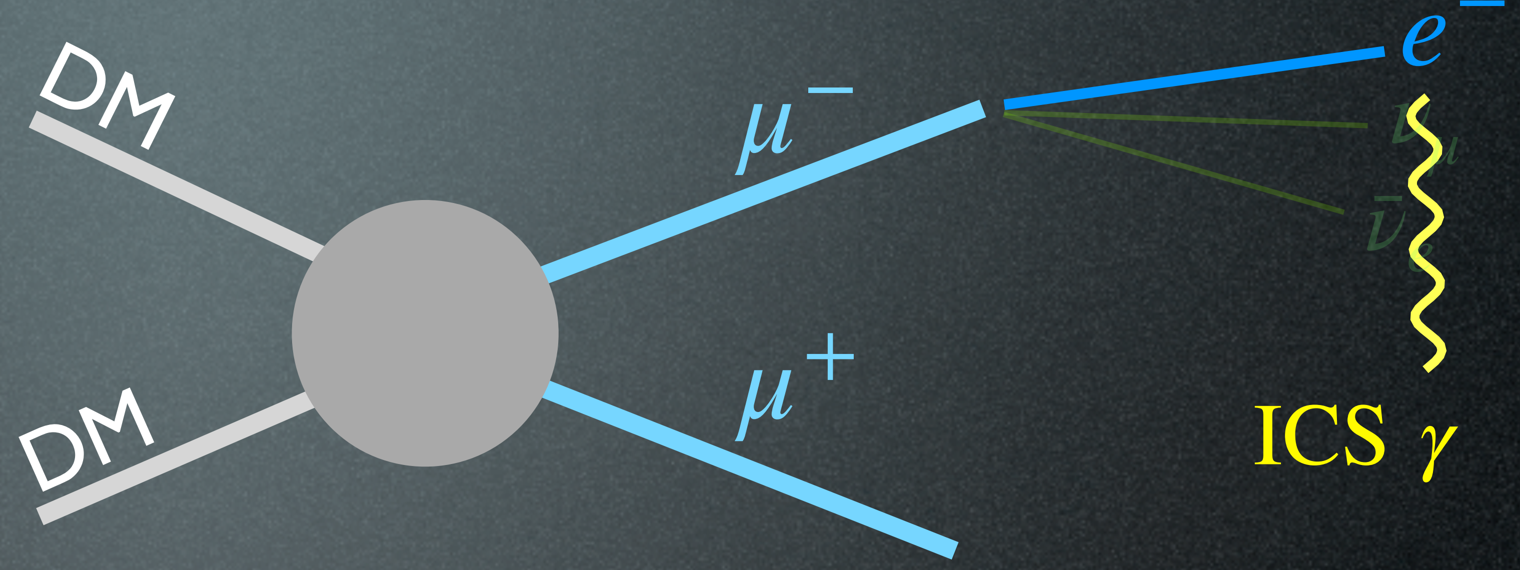


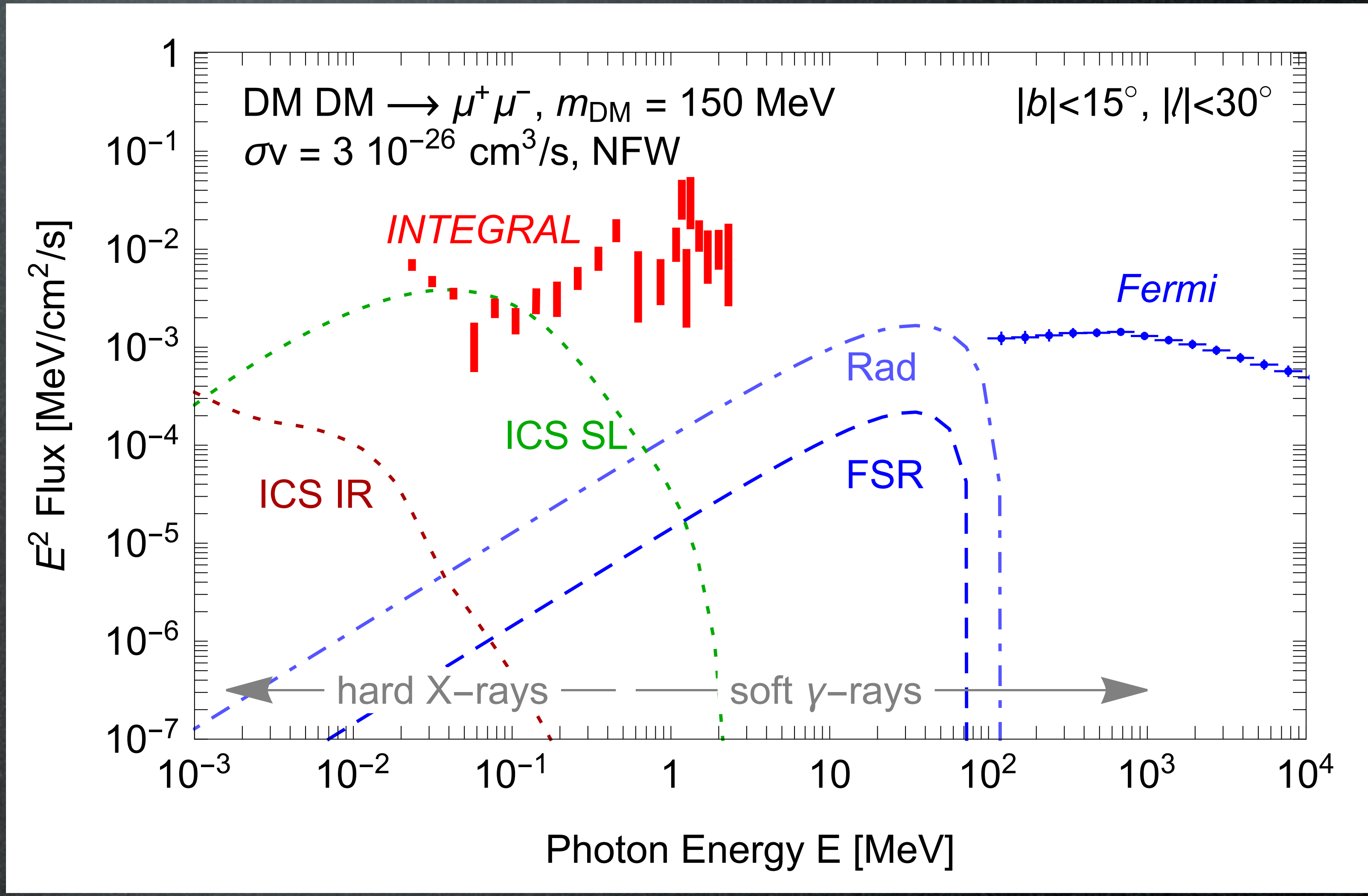
'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

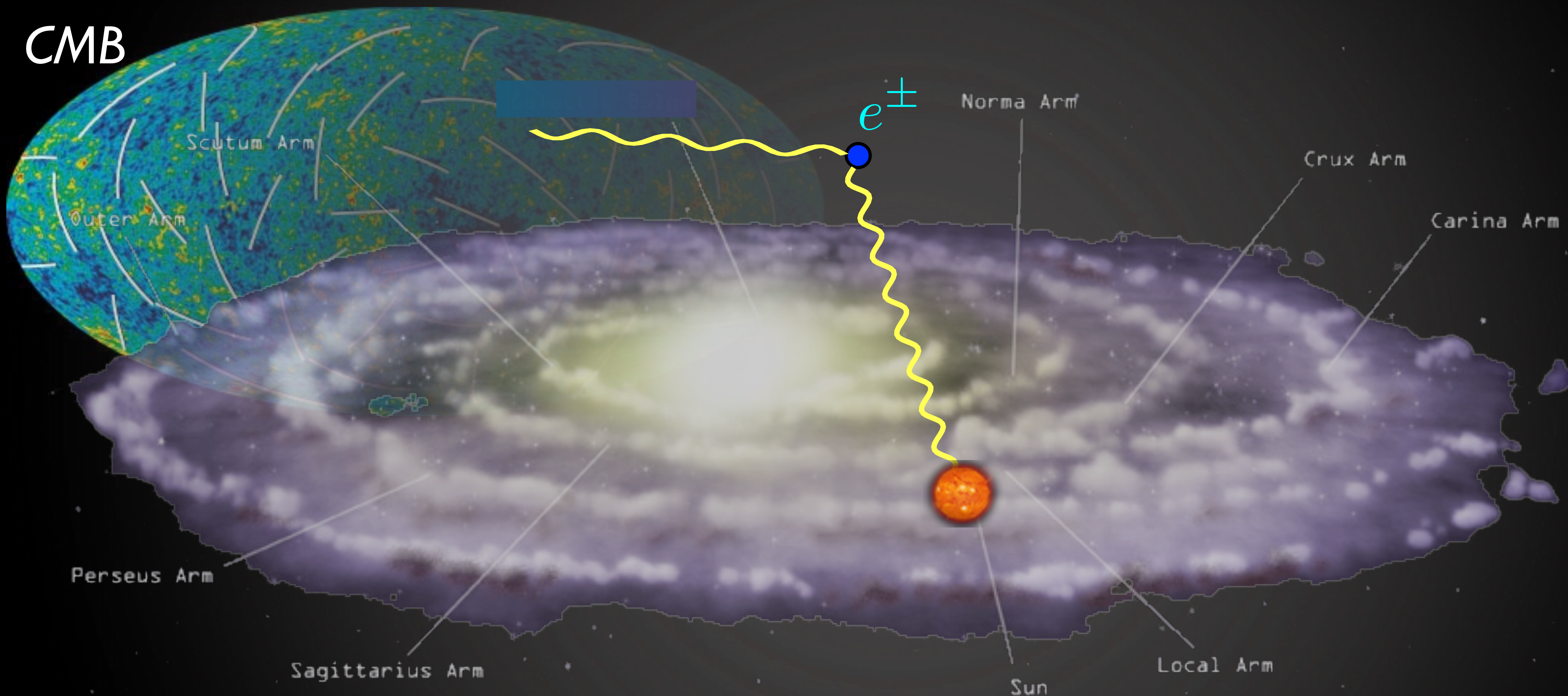
Secondary emission:

ICS: inevitably associated to annihil to charged states



Secondary emission

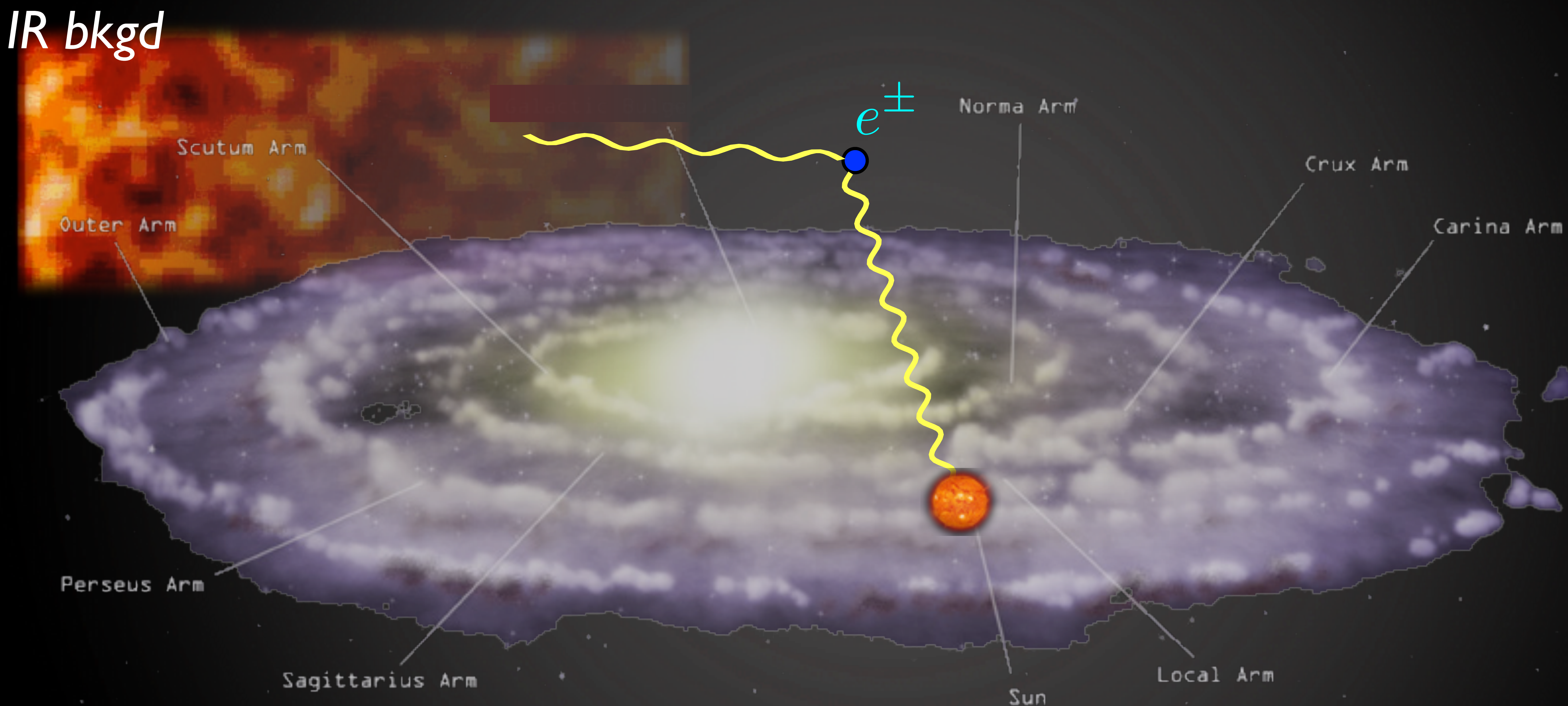
γ from Inverse Compton on $e^{\pm}$ in halo



- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Secondary emission

γ from Inverse Compton on $e^{\pm}$ in halo



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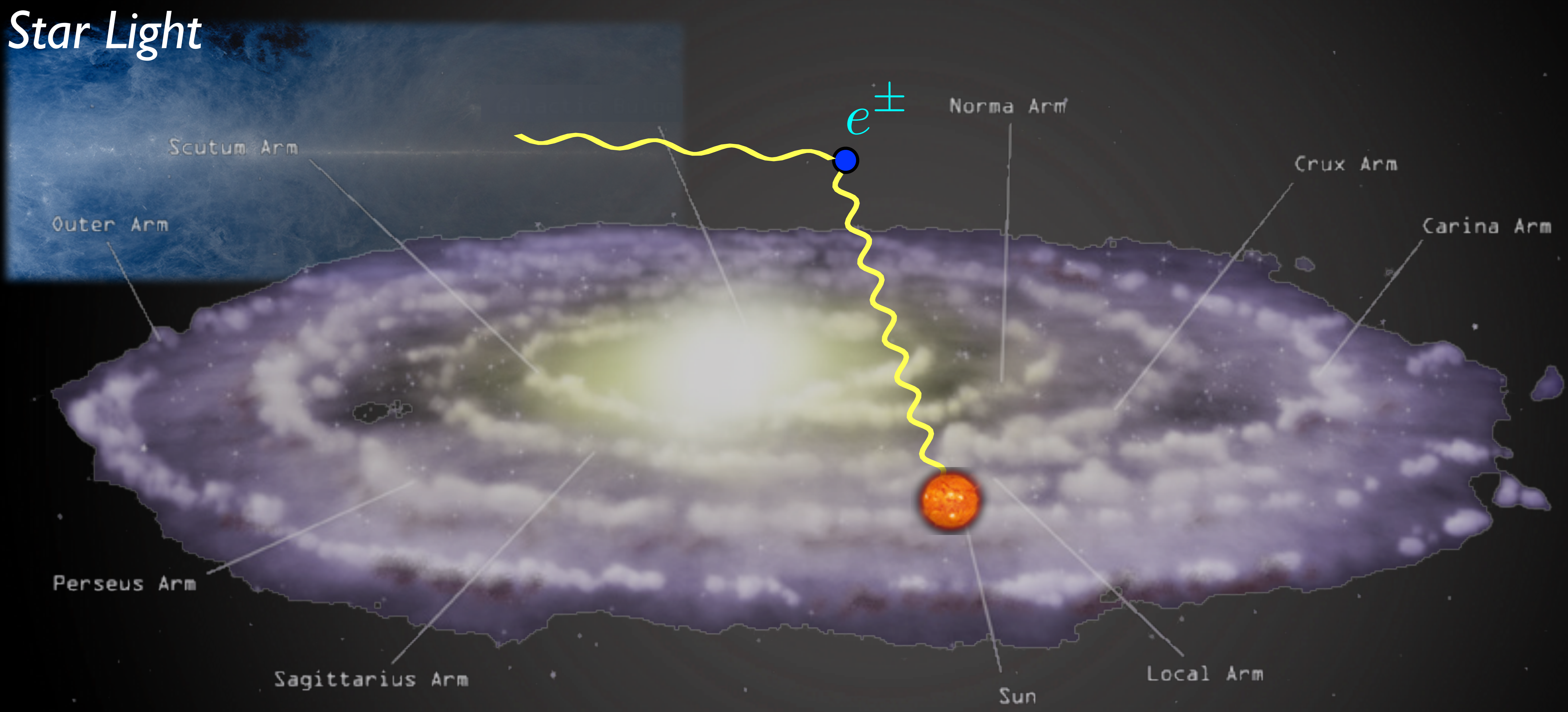
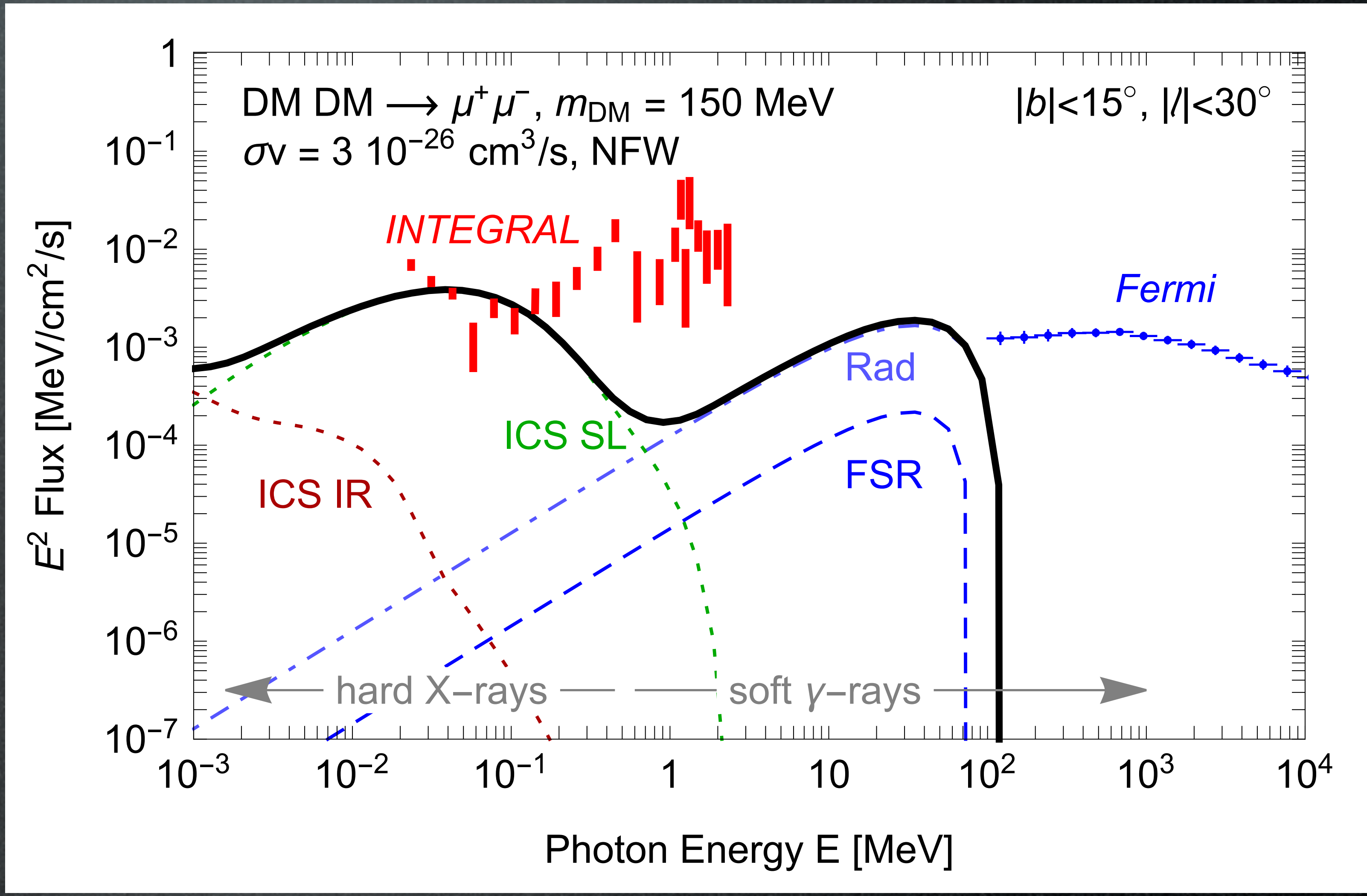


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Sub-GeV DM & X-rays

Annihilation channels

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



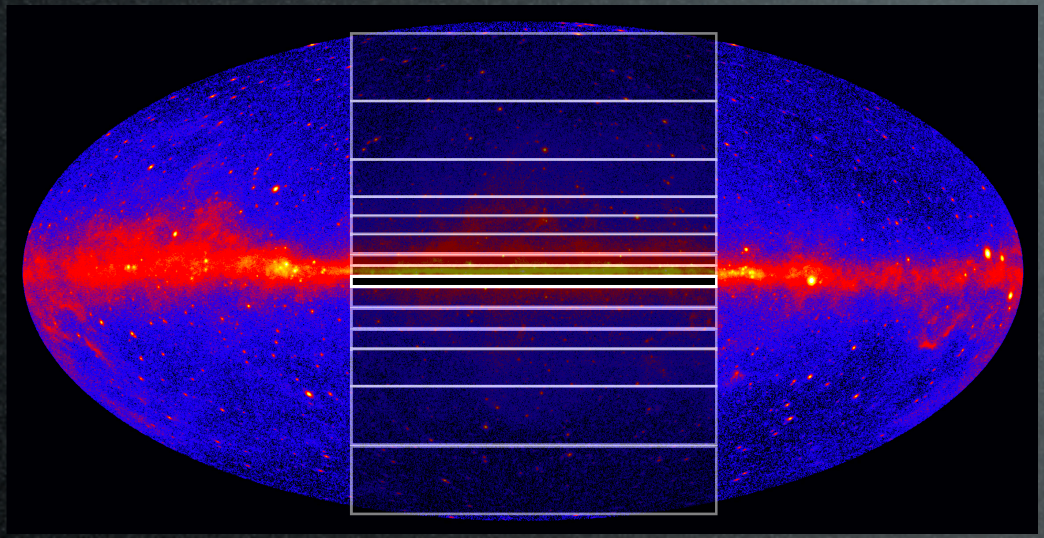
Key message:
ICS allows to probe sub-GeV DM with X-ray data

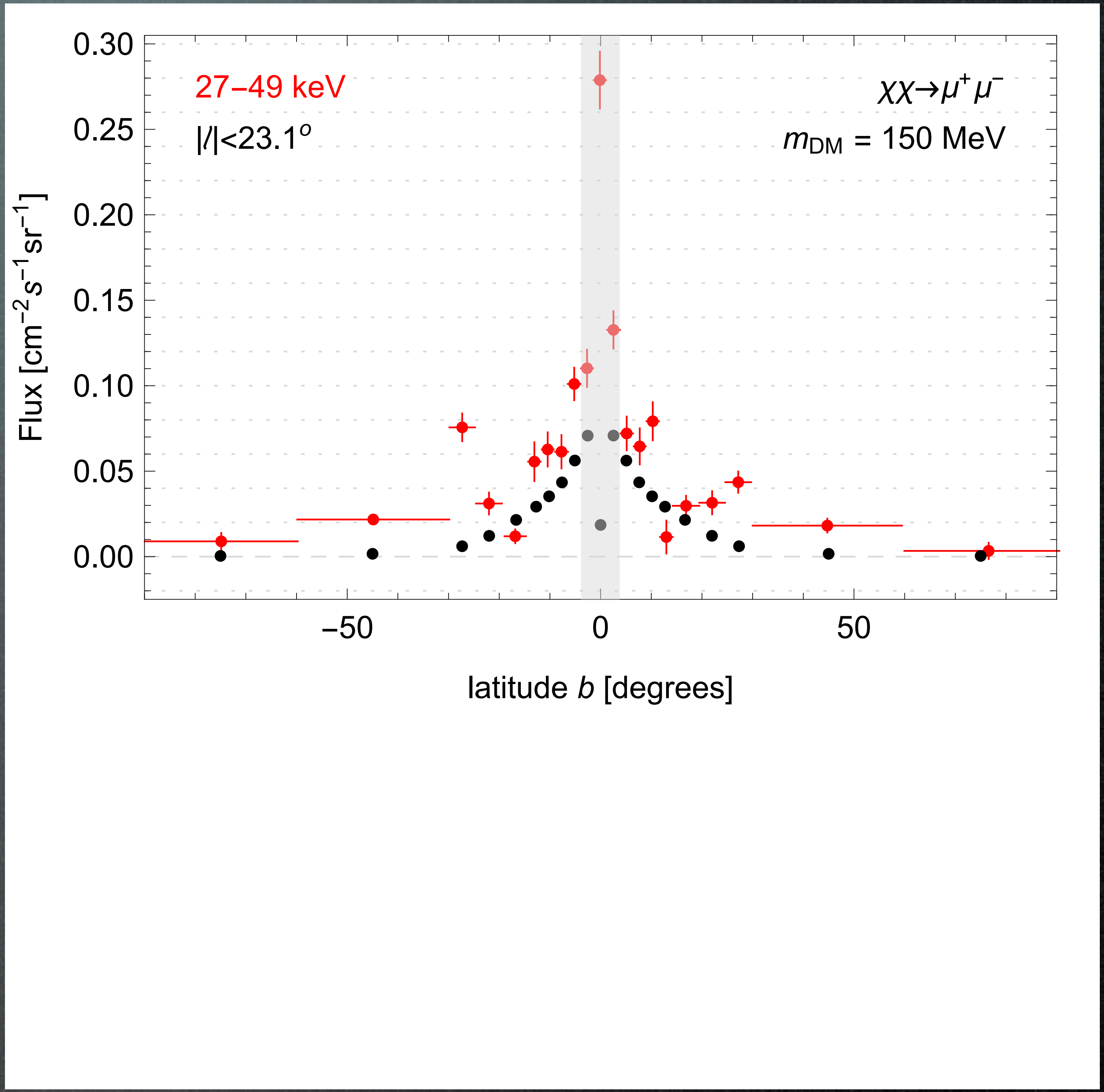
Analysis

Integral-SPI 2011 data

Bouchet et al., Integral coll. 1107.0200

latitude binned data, central MW





Analysis

Integral-SPI 2011 data

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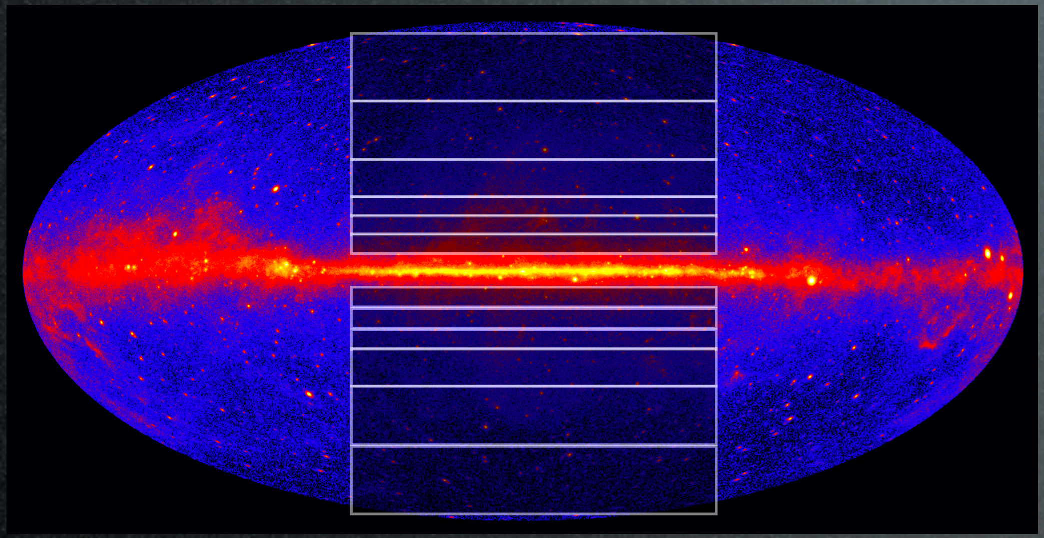
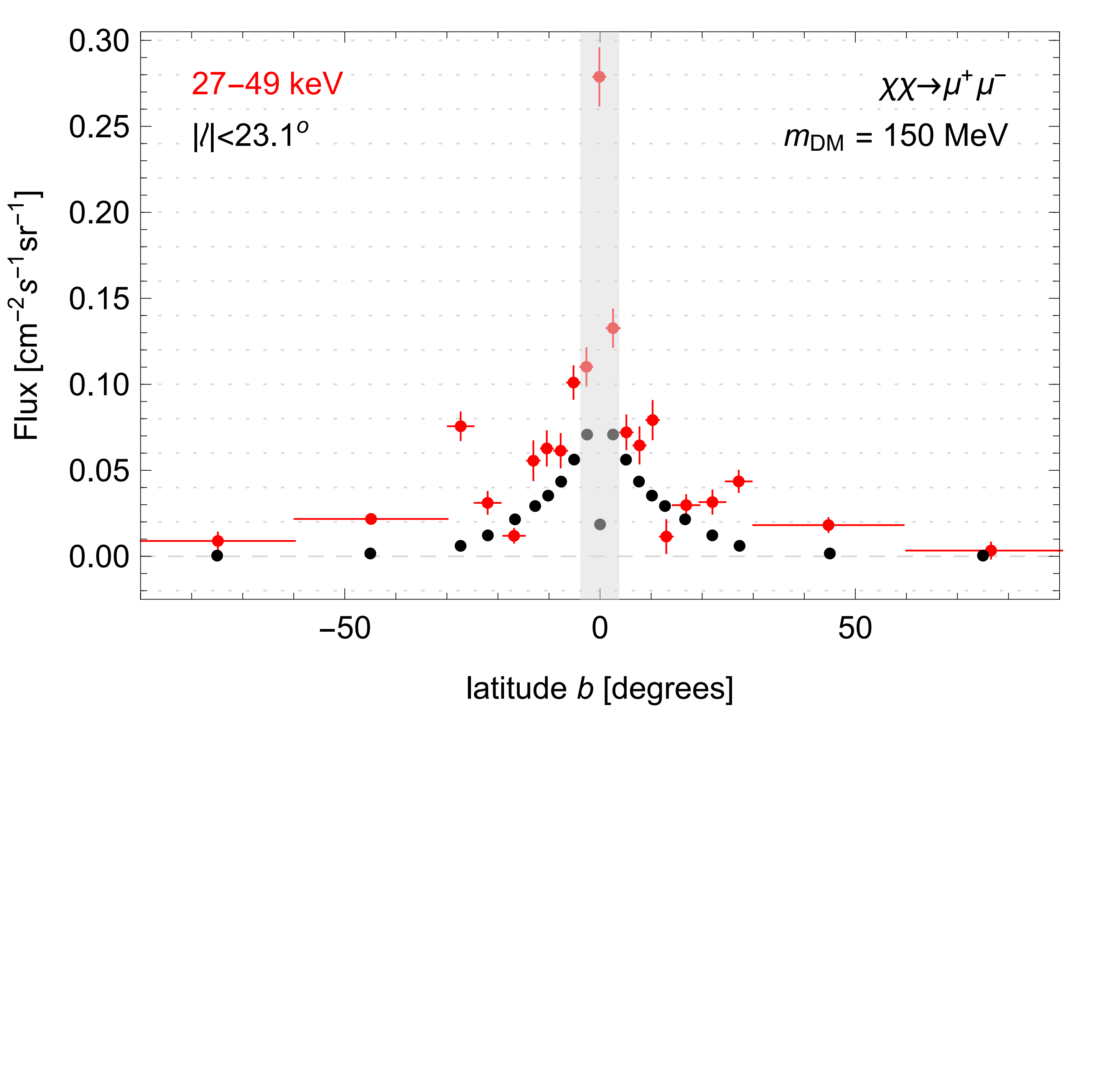
latitude binned data, central MW



remove Gal Plane



Analysis

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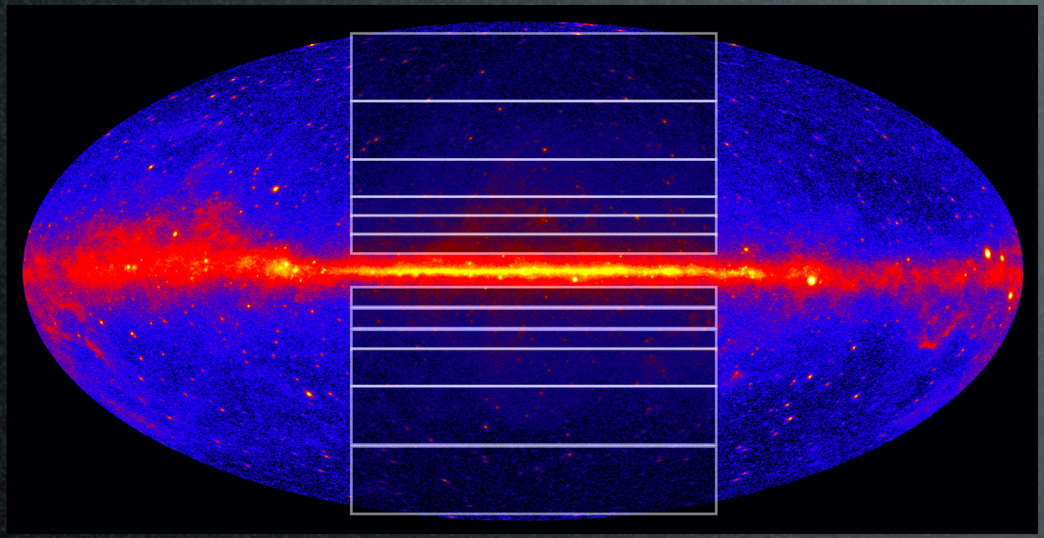
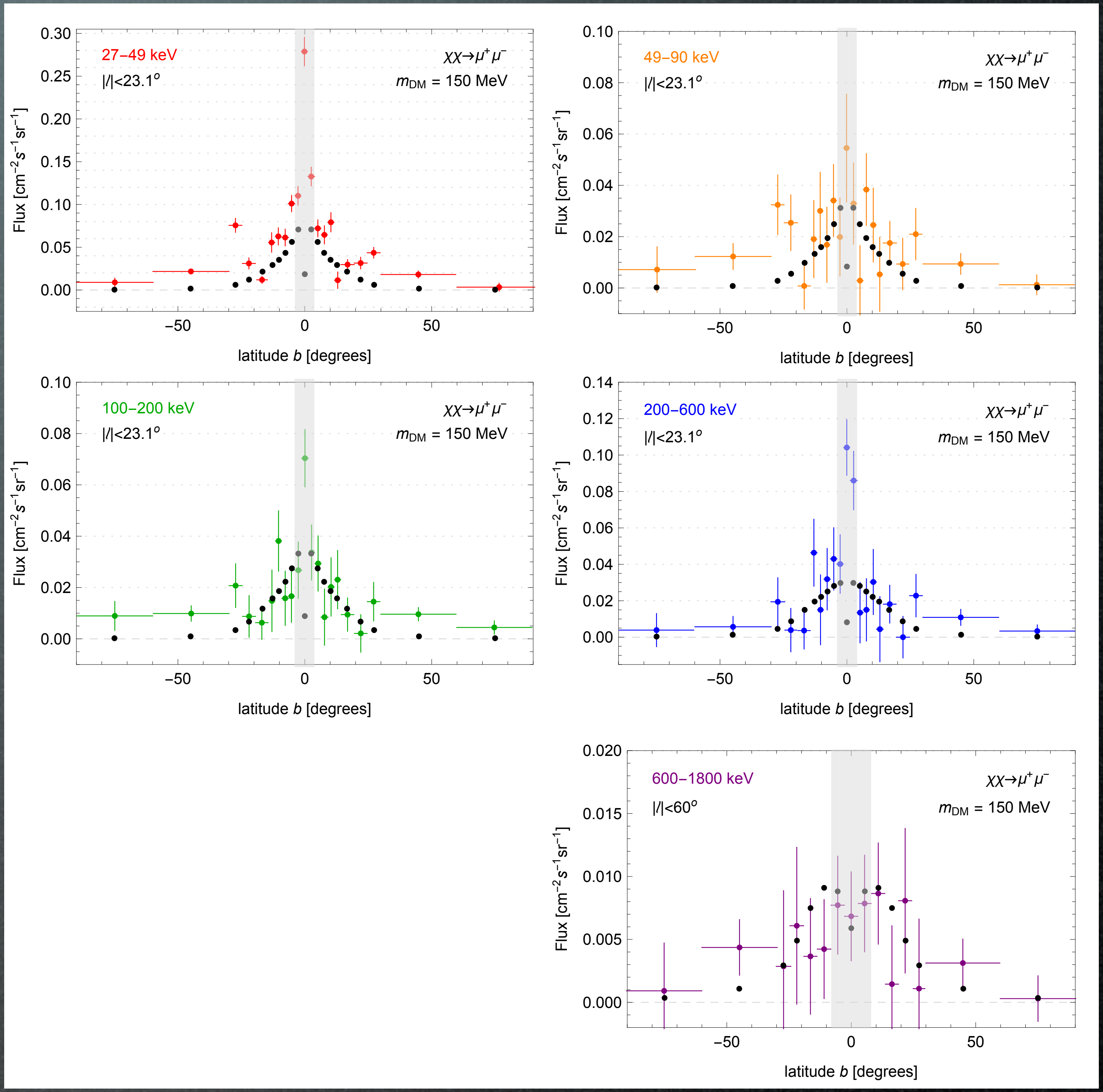


remove Gal Plane

5 energy bands



Analysis

Integral-SPI 2011 data

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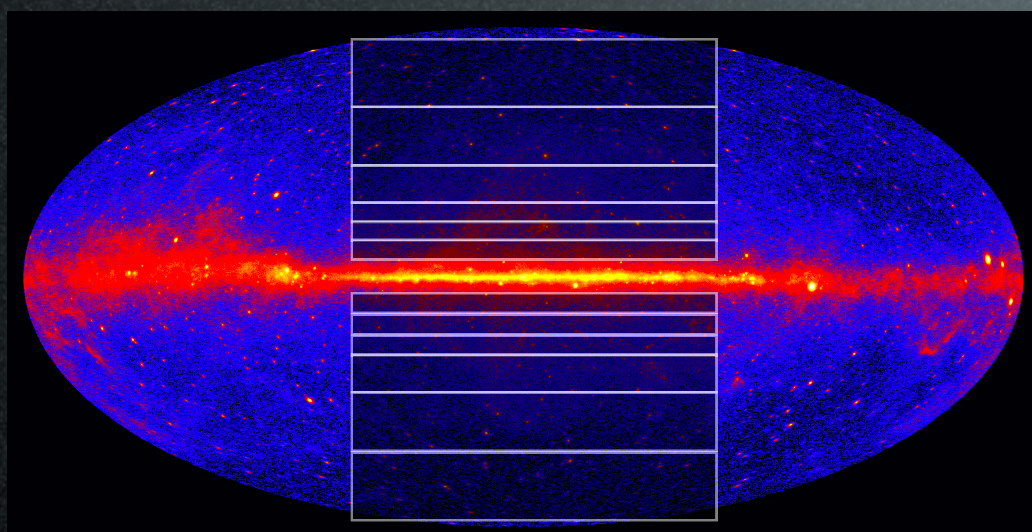
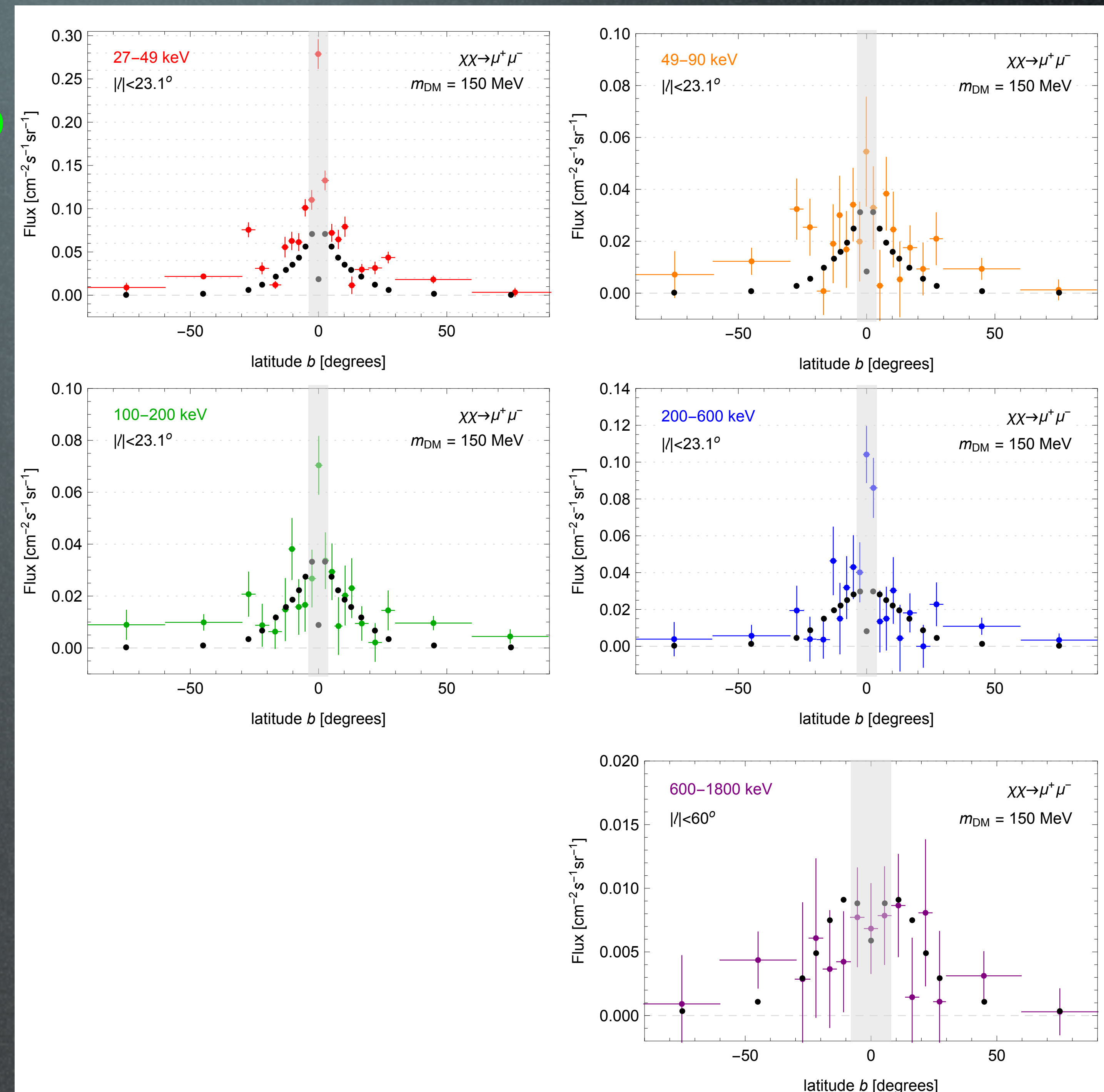




remove Gal Plane

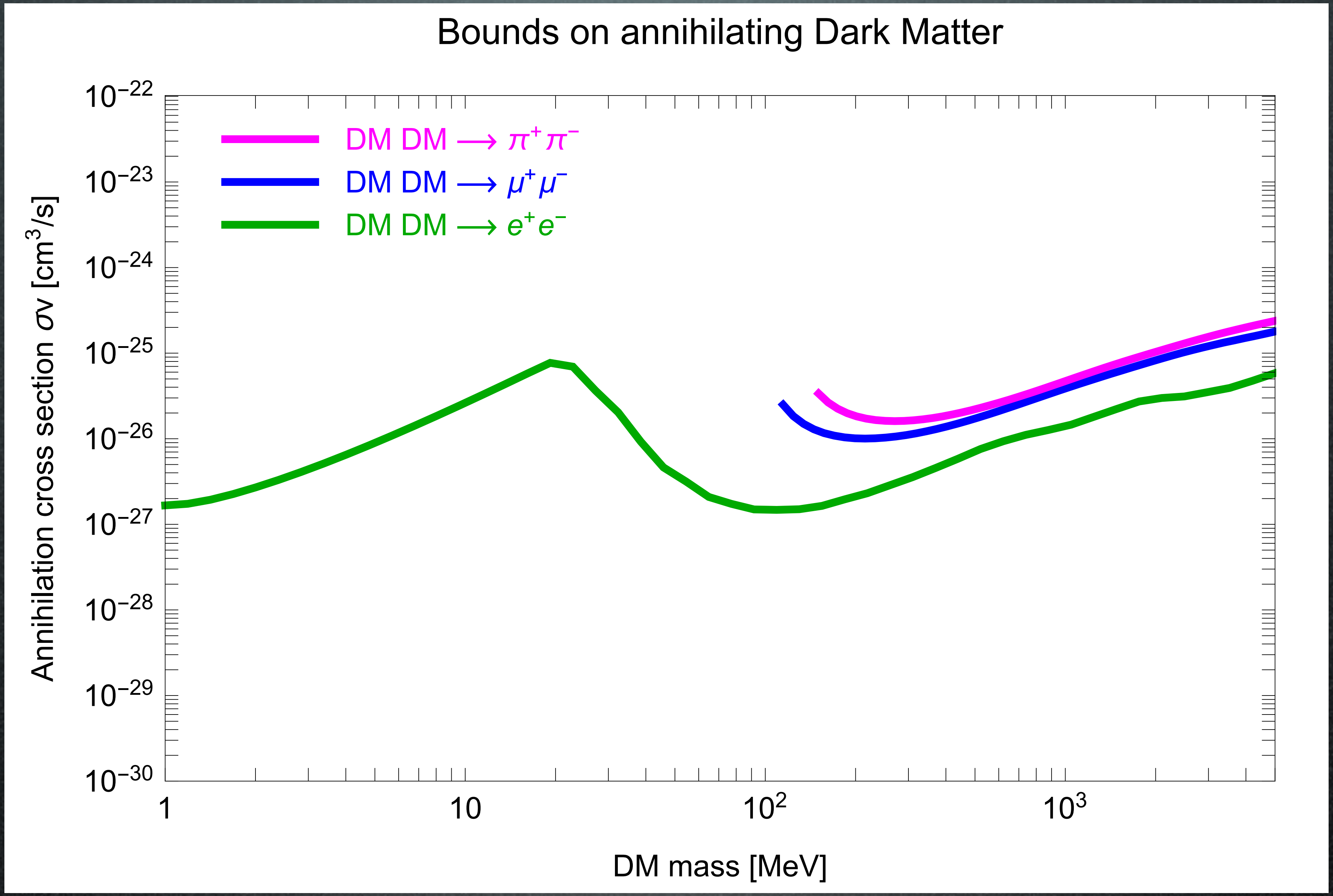
5 energy bands

Test Statistics:
exclude if DM exceeds data
by more than ~2σ global.
More precisely:

$$\chi^2_> = \sum_{\text{bands}} \sum_{i \in \{\text{b bins}\}} \frac{(\text{Max}[(\Phi_{\text{DM}\gamma,i}(\langle\sigma v\rangle) - \phi_i), 0])^2}{\sigma_i^2}$$

$$\chi^2_> \geq 4$$

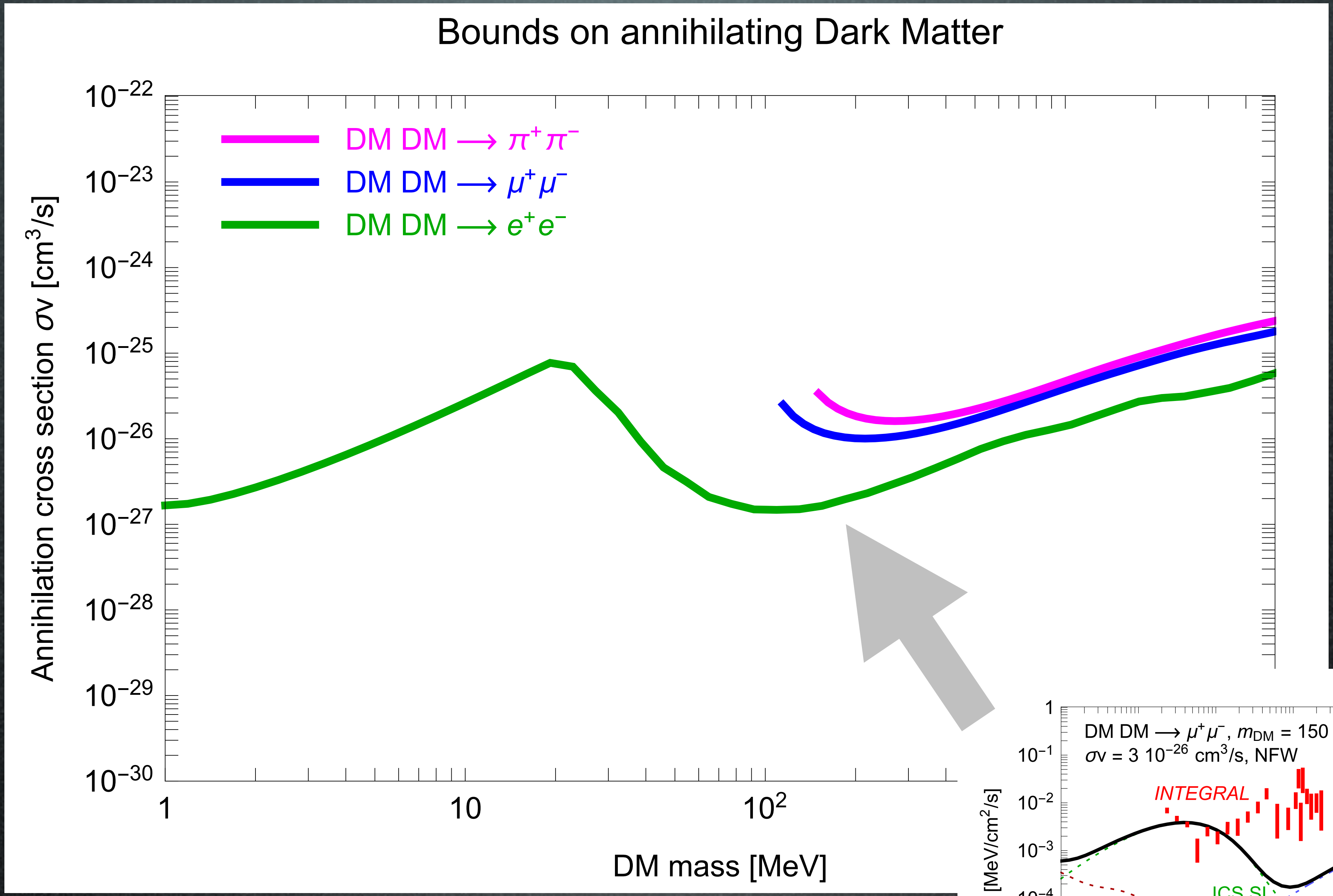
Results



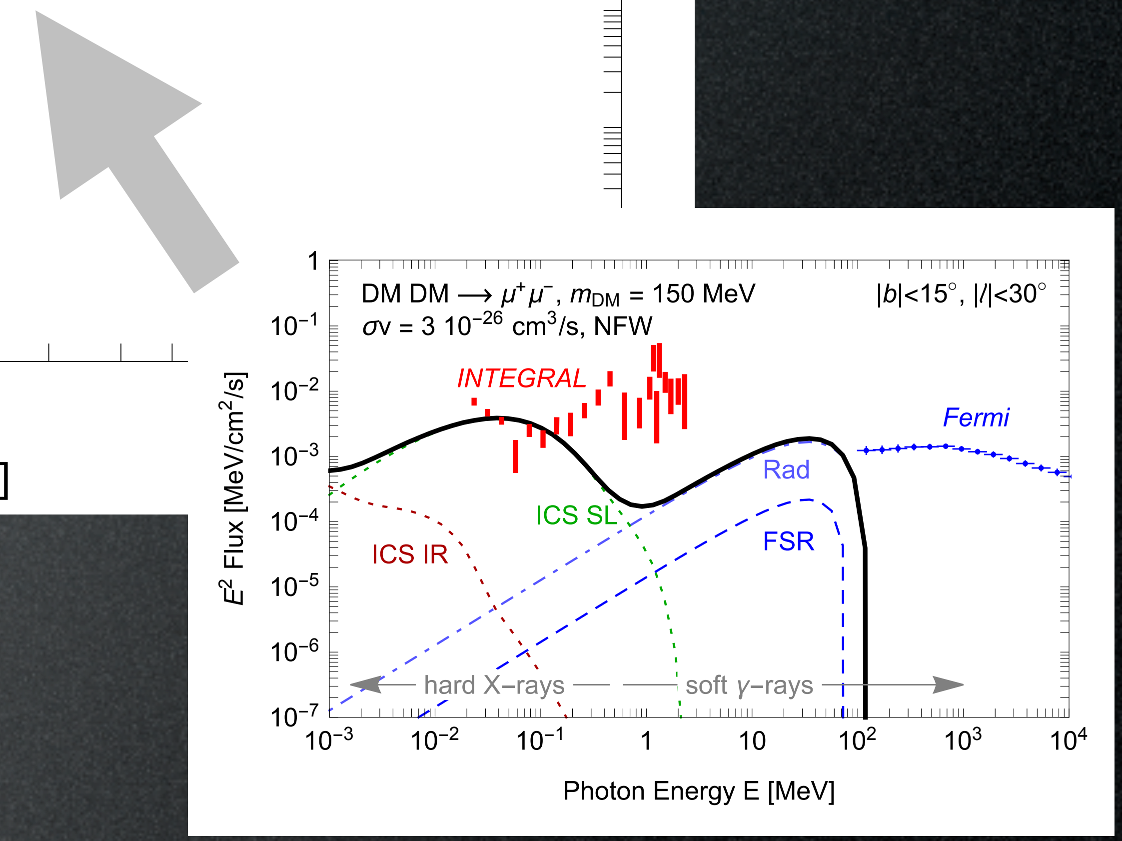
Bounds on all 3 channels

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

Results

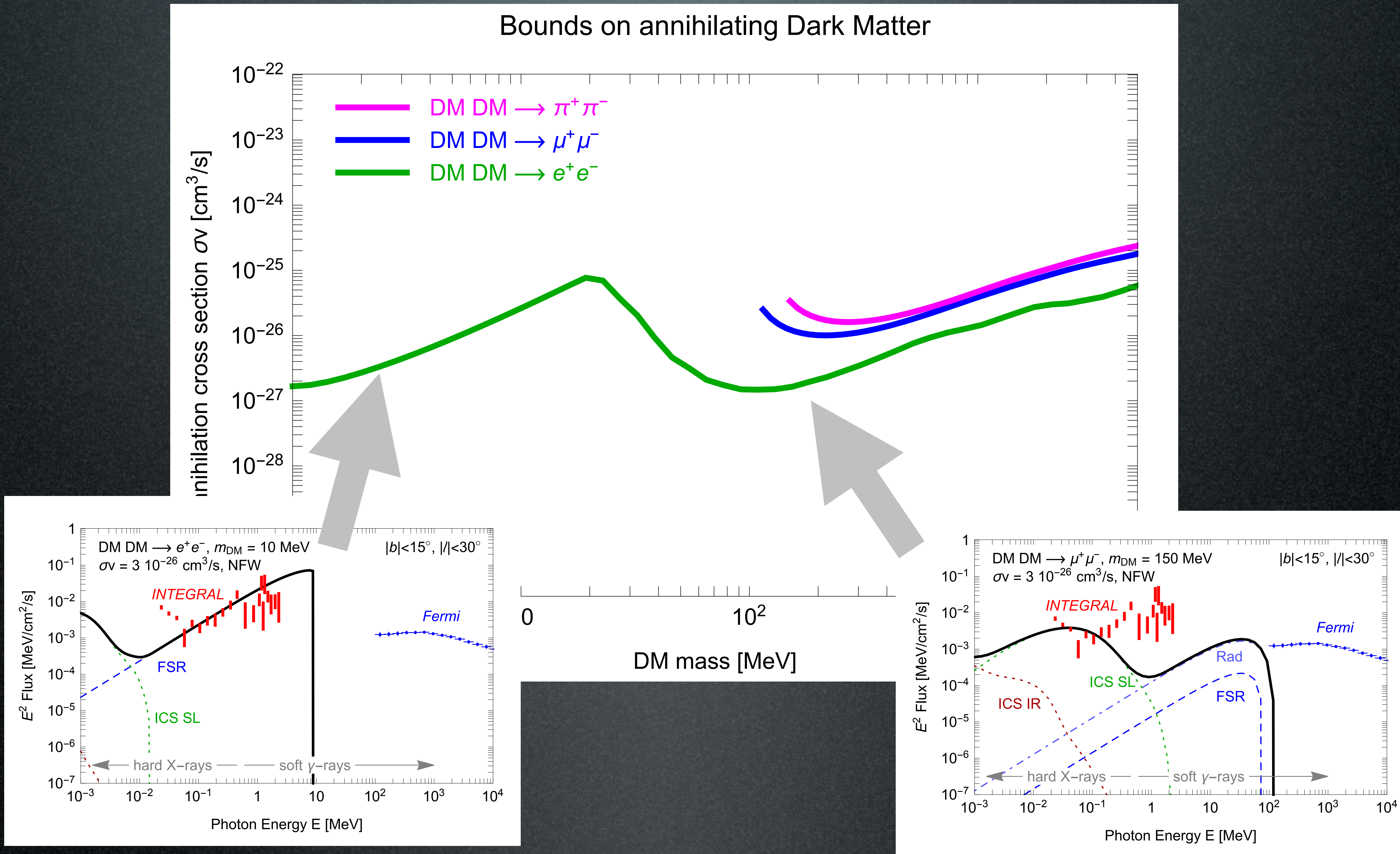


Bounds on annihilating Dark Matter
DM DM ⟶ $\pi^+\pi^-$
DM DM ⟶ $\mu^+\mu^-$
DM DM ⟶ e^+e^-
Annihilation cross section σv [cm^3/s]
DM mass [MeV]



DM DM ⟶ $\mu^+\mu^-$, m_{DM} = 150 MeV
σv = 3 10^{-26} cm^3/s, NFW
$|b|<15°$, $|l|<30°$
INTEGRAL
Fermi
Rad
ICS SL
FSR
ICS IR
hard X–rays
soft γ–rays
E^2 Flux [MeV/cm^2/s]
Photon Energy E [MeV]

Results



Bounds on annihilating Dark Matter
DM DM ⟶ π⁺π⁻
DM DM ⟶ μ⁺μ⁻
DM DM ⟶ e⁺e⁻
nihilation cross section σv [cm³/s]
DM mass [MeV]
DM DM ⟶ e⁺e⁻, m_DM = 10 MeV
σv = 3 10⁻²⁶ cm³/s, NFW
|b|<15°, |l|<30°
INTEGRAL
FSR
ICS SL
Fermi
hard X–rays
soft γ–rays
E² Flux [MeV/cm²/s]
Photon Energy E [MeV]
DM DM ⟶ μ⁺μ⁻, m_DM = 150 MeV
σv = 3 10⁻²⁶ cm³/s, NFW
|b|<15°, |l|<30°
INTEGRAL
Fermi
Rad
ICS SL
ICS IR
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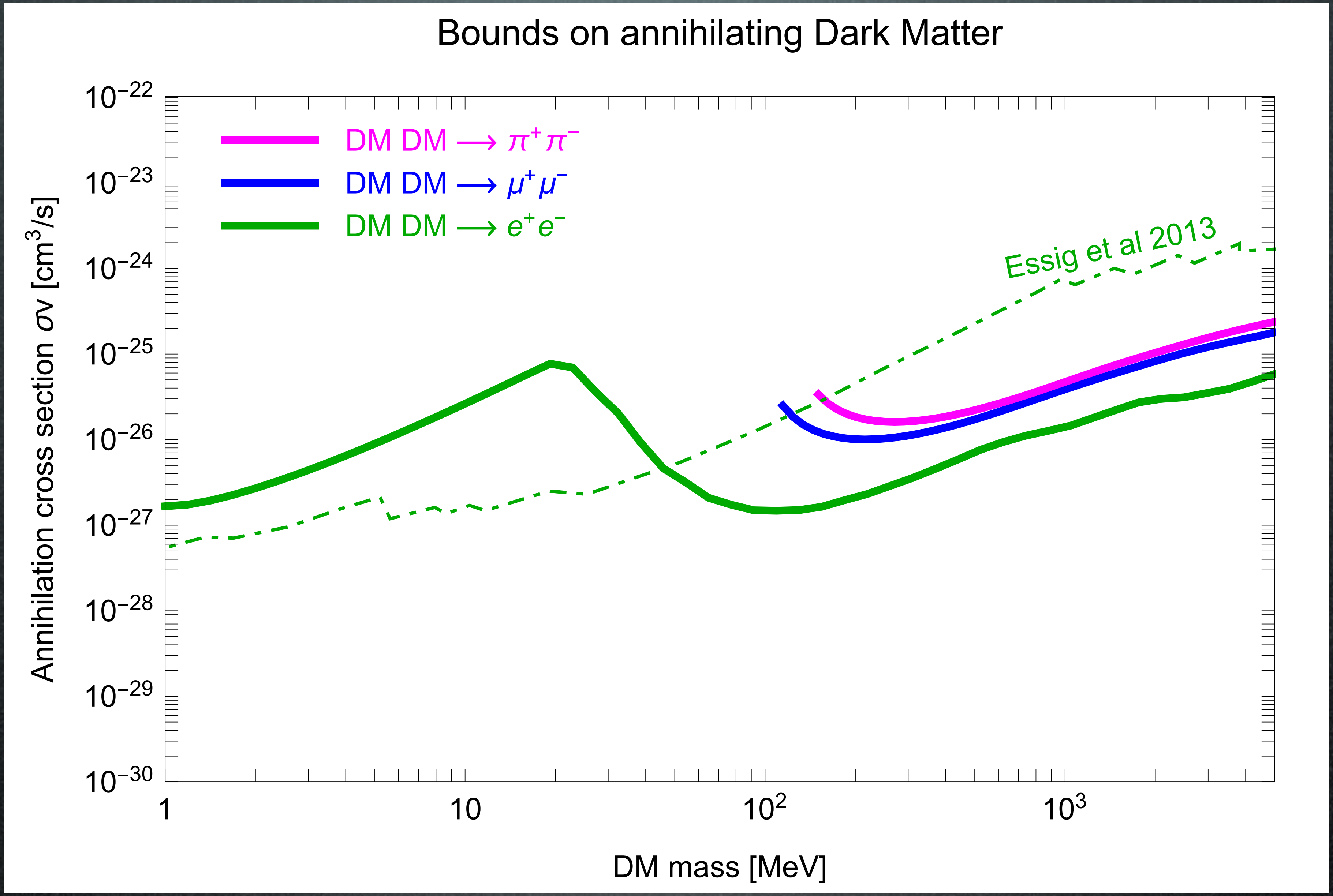
hard X–rays
soft γ–rays
E² Flux [MeV/cm²/s]
Photon Energy E [MeV]

Results

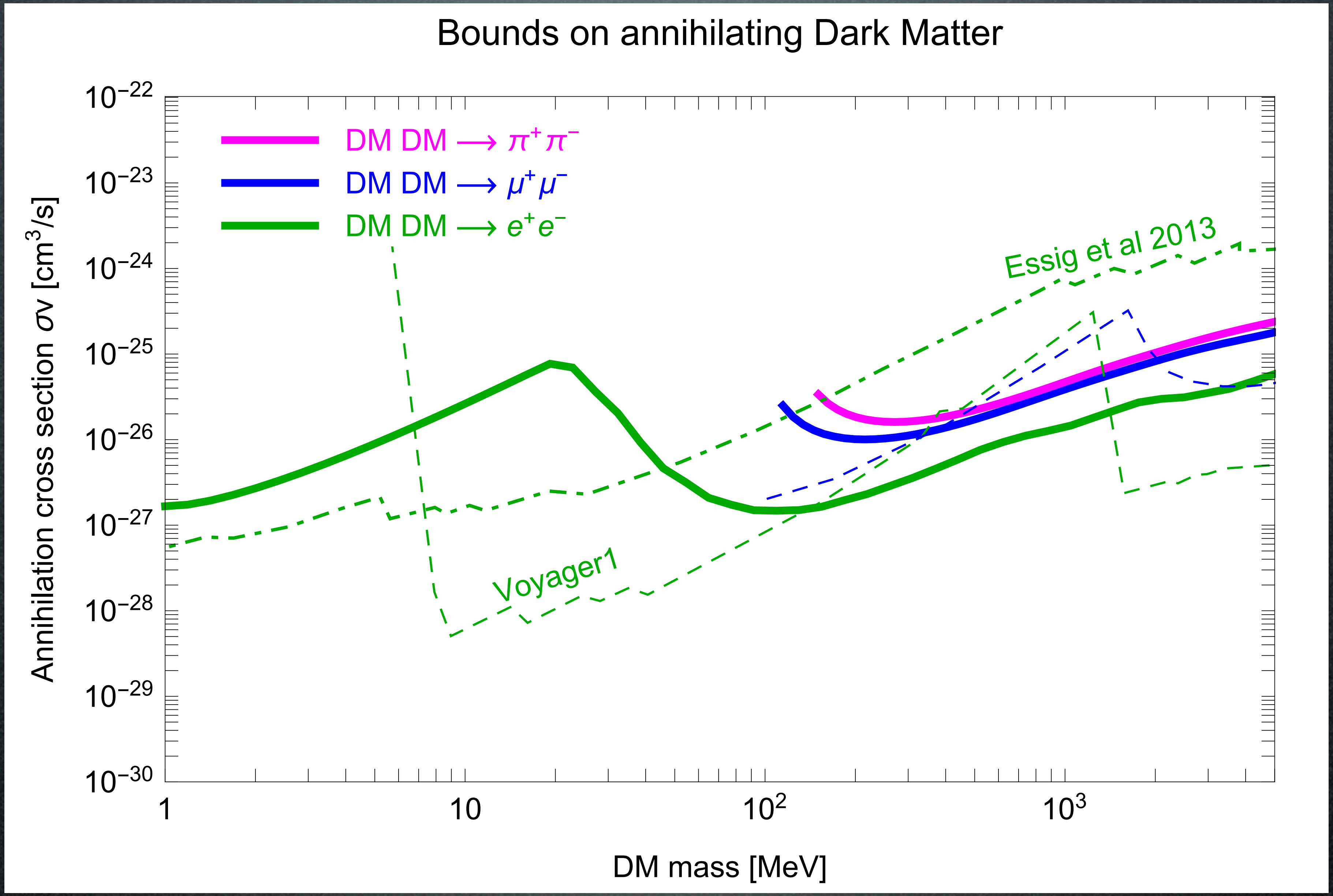


Essig+
1309.4091

Bounds on all 3 channels

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

Results



Essig+ 1309.4091

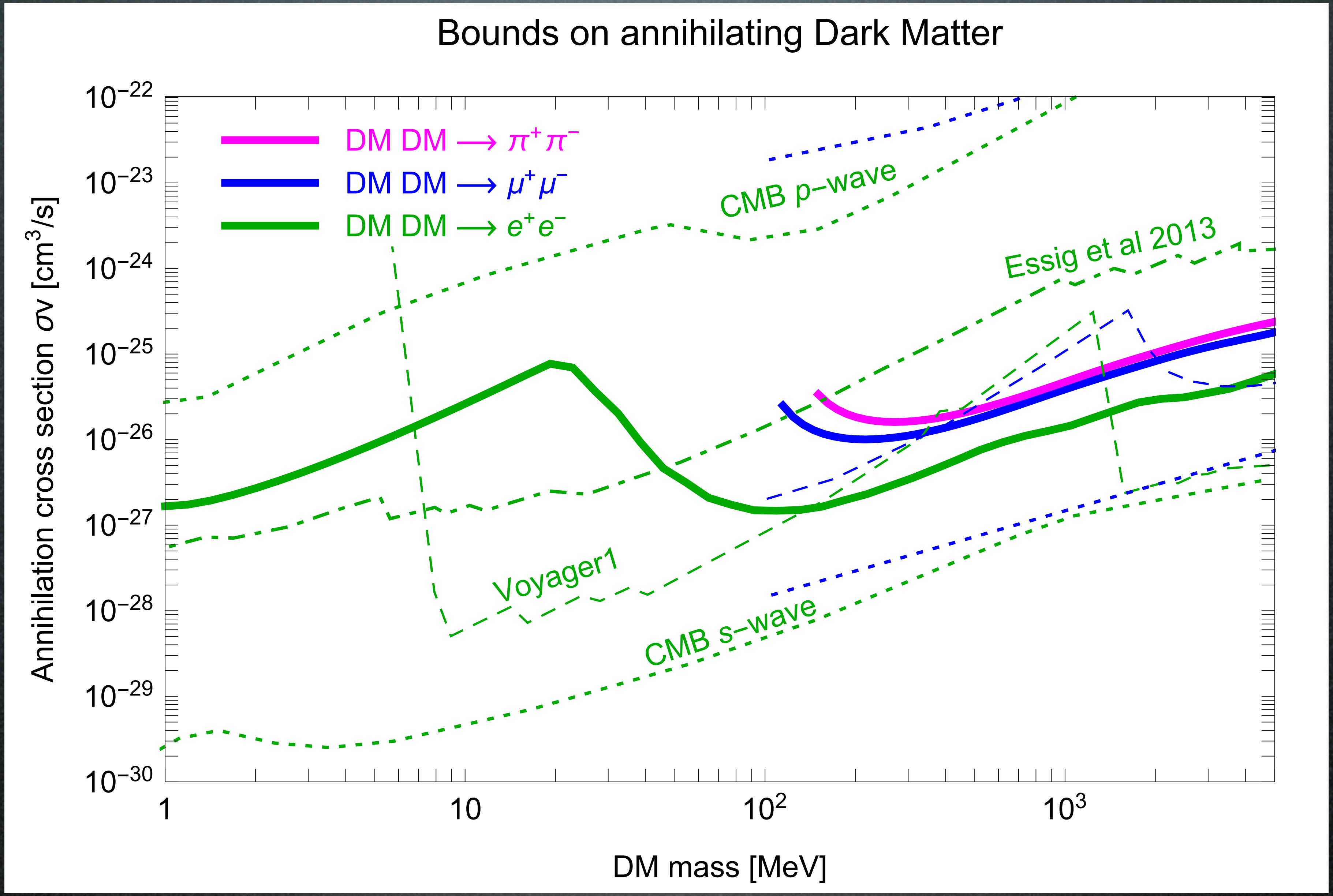
Boudaud+ 1612.07698

Bounds on all 3 channels

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

Voyager1 bounds stronger/weaker dep. on data

Results



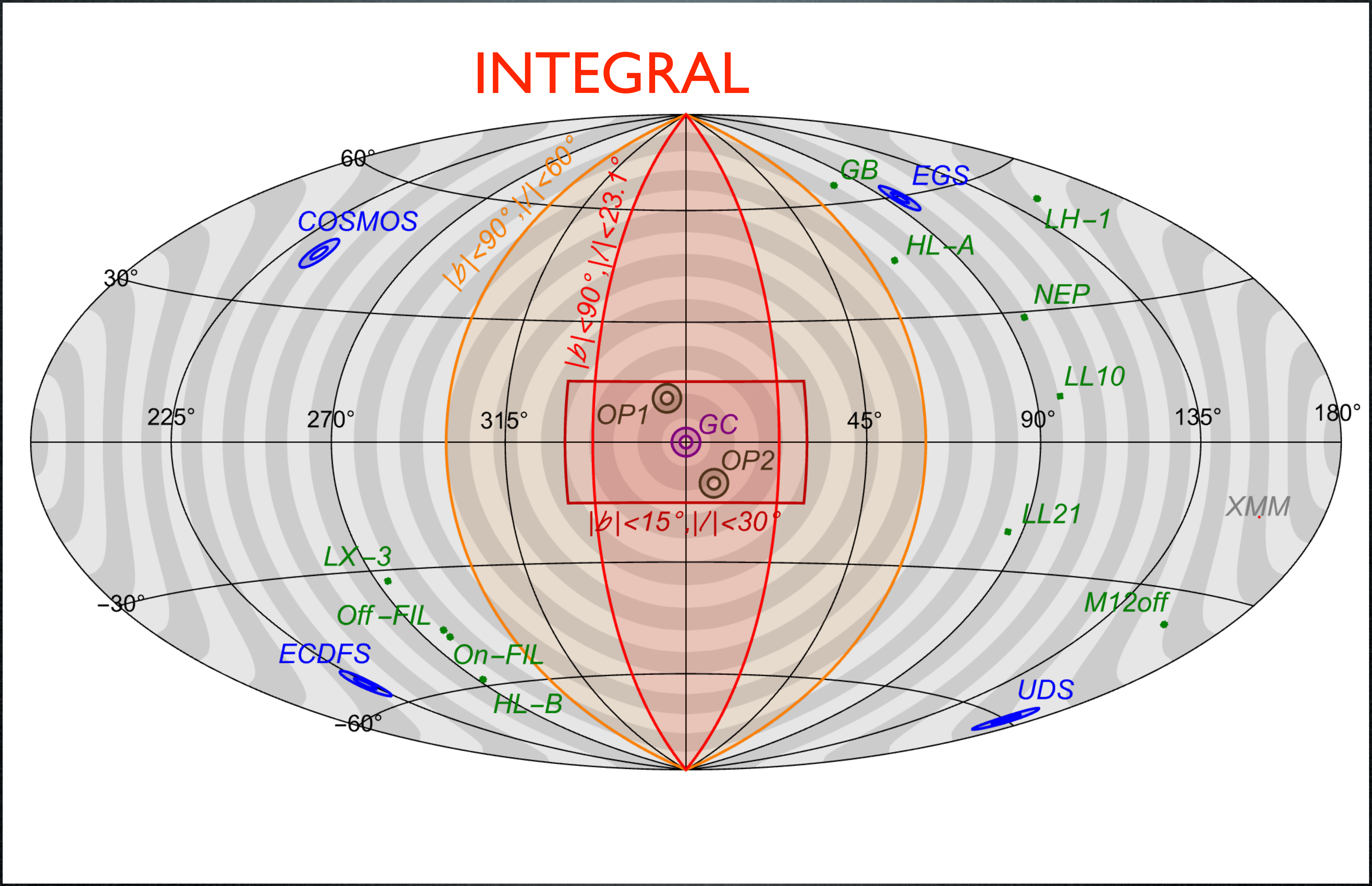
Essig+
1309.4091

Boudaud+
1612.07698

Slatyer+
1506.03811
Lopez-H+
1303.5094
Diamanti+
1308.2578
Liu+
2008.01084

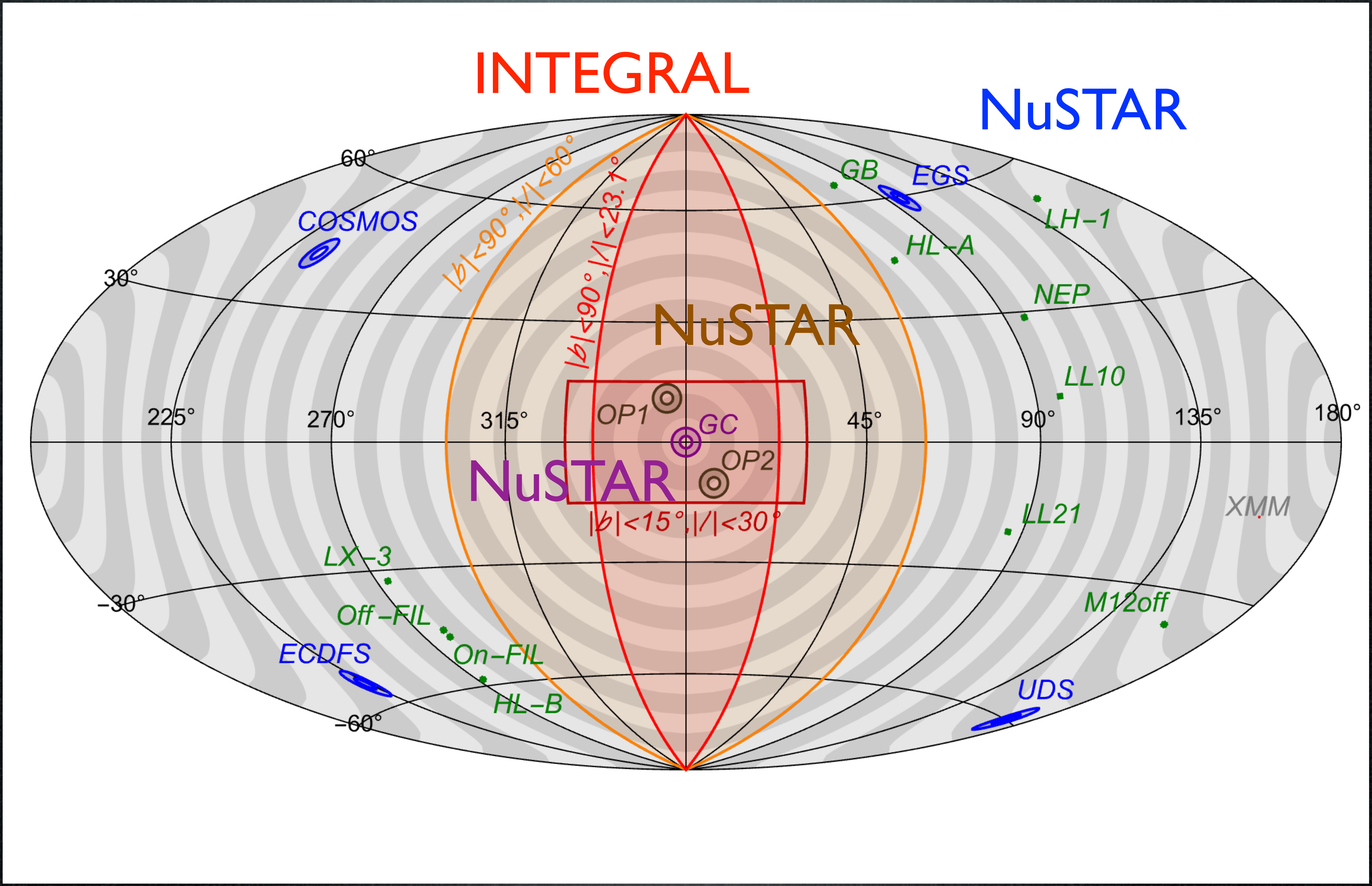
Bounds on all 3 channels
ICS allows to improve Essig+ 2013 at large $m_{\rm DM}$
Voyager1 bounds stronger/weaker dep. on data
CMB bounds depend on s-/p-wave annihilation

More data!



INTEGRAL
60°
30°
−30°
−60°
225°
270°
315°
45°
90°
135°
180°
COSMOS
|b|<90°,|l|<60°
|b|<90°,|l|<23.1°
|b|<15°,|l|<30°
OP1
GC
OP2
GB
EGS
LH−1
HL−A
NEP
LL10
LL21
XMM
LX−3
Off−FIL
On−FIL
ECDFS
HL−B
M12off
UDS

More data!


INTEGRAL
NuSTAR
NuSTAR
NuSTAR
60°
30°
−30°
−60°
225°
270°
315°
45°
90°
135°
180°
COSMOS
EGS
ECDFS
UDS
GB
LH−1
HL−A
NEP
LL10
LL21
M12off
LX−3
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XMM
OP1
GC
OP2
|b|<90°,|l|<60°
|b|<90°,|l|<23.1°
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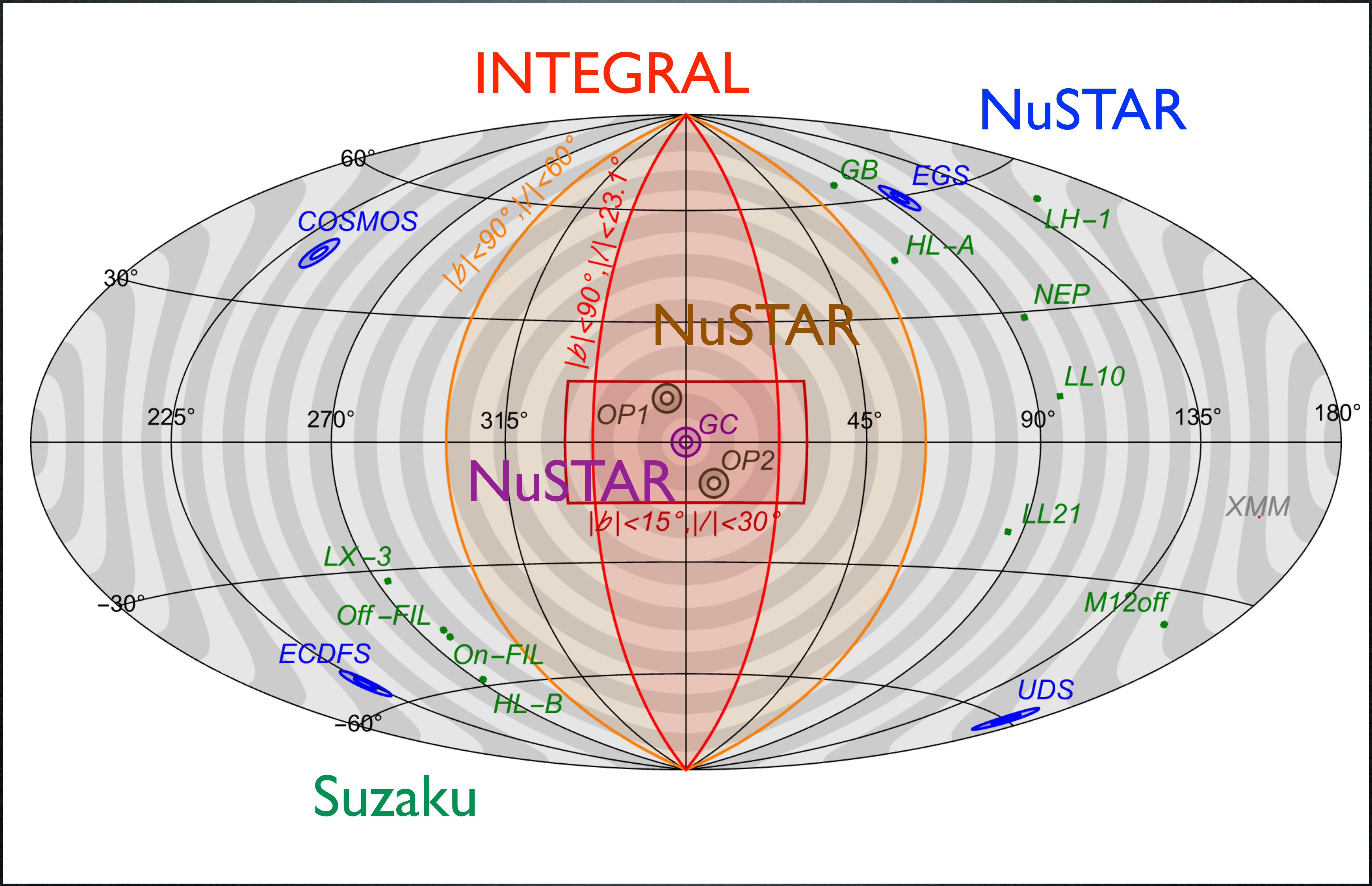
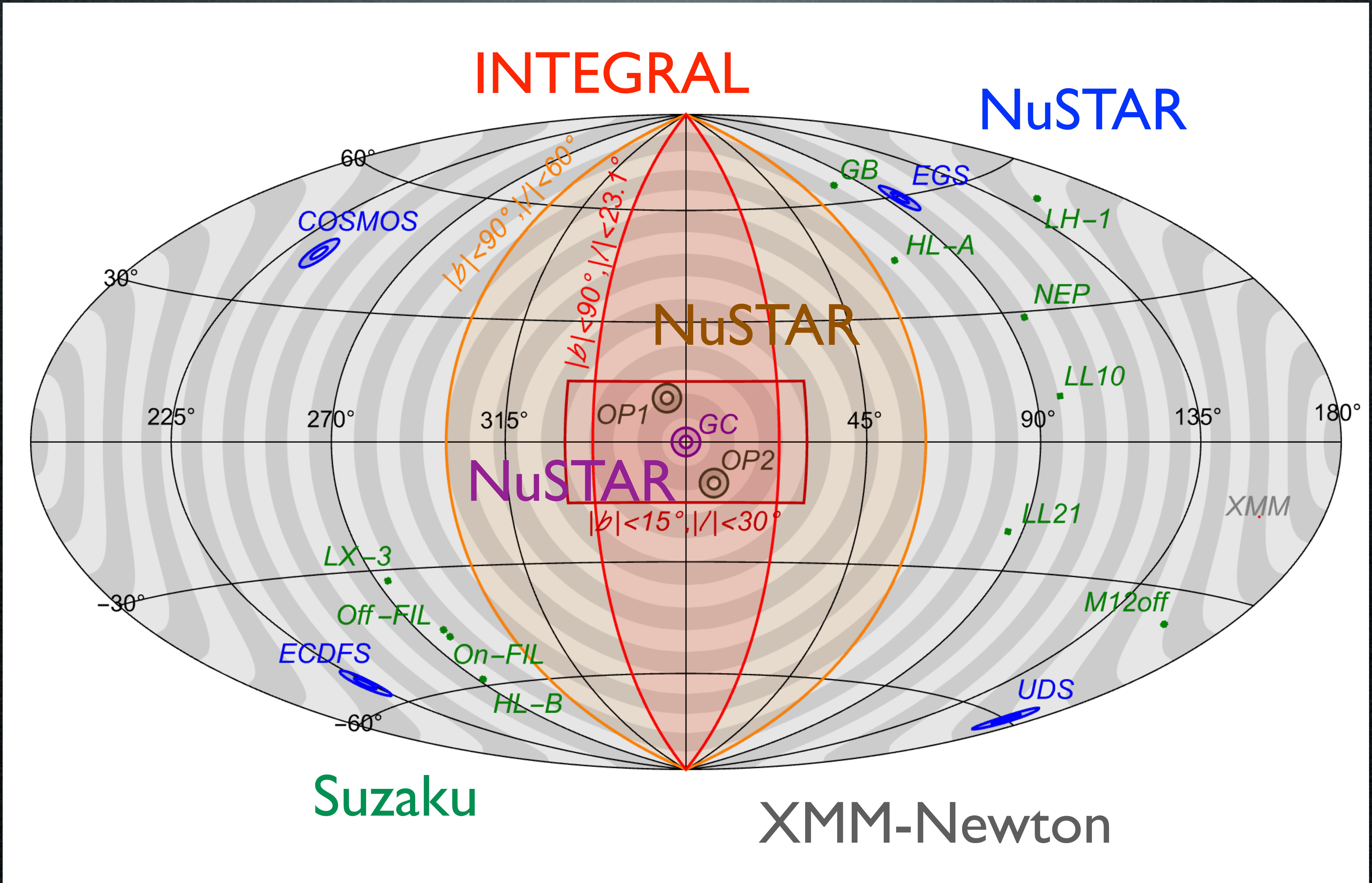
More data!



INTEGRAL
NuSTAR
NuSTAR
NuSTAR
Suzaku
COSMOS
GB
EGS
LH−1
HL−A
NEP
LL10
LL21
XMM
M12off
UDS
LX−3
Off−FIL
On−FIL
ECDFS
HL−B
OP1
GC
OP2
|b|<90°,|l|<60°
|b|<90°,|l|<23.1°
|b|<15°,|l|<30°
60°
30°
−30°
−60°
225°
270°
315°
45°
90°
135°
180°

More data!



INTEGRAL
NuSTAR
NuSTAR
NuSTAR
Suzaku
XMM-Newton
COSMOS
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LH−1
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UDS
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|b|<90°,|l|<60°
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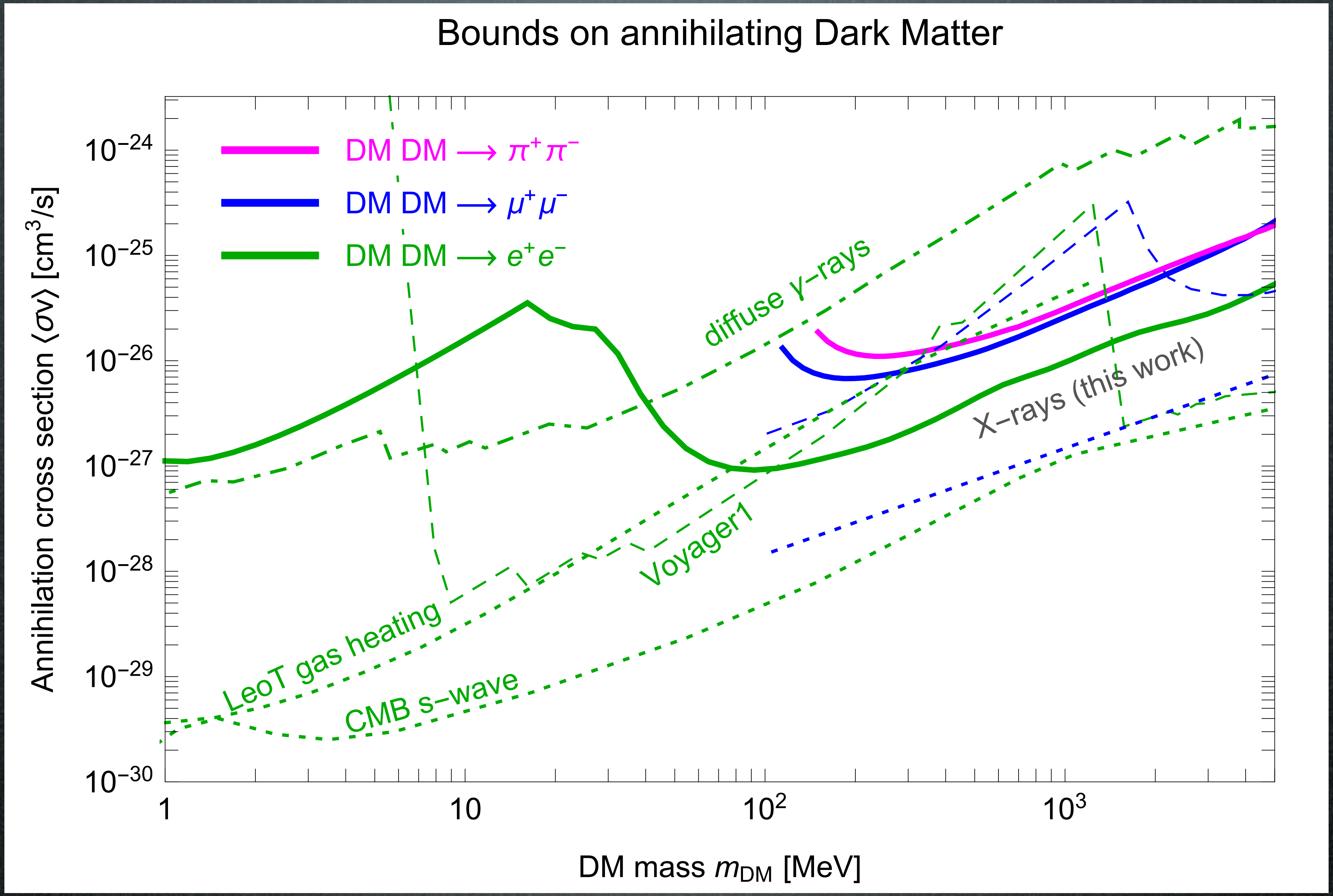
|b|<15°,|l|<30°
60°
30°
−30°
−60°
225°
270°
315°
45°
90°
135°
180°

Results



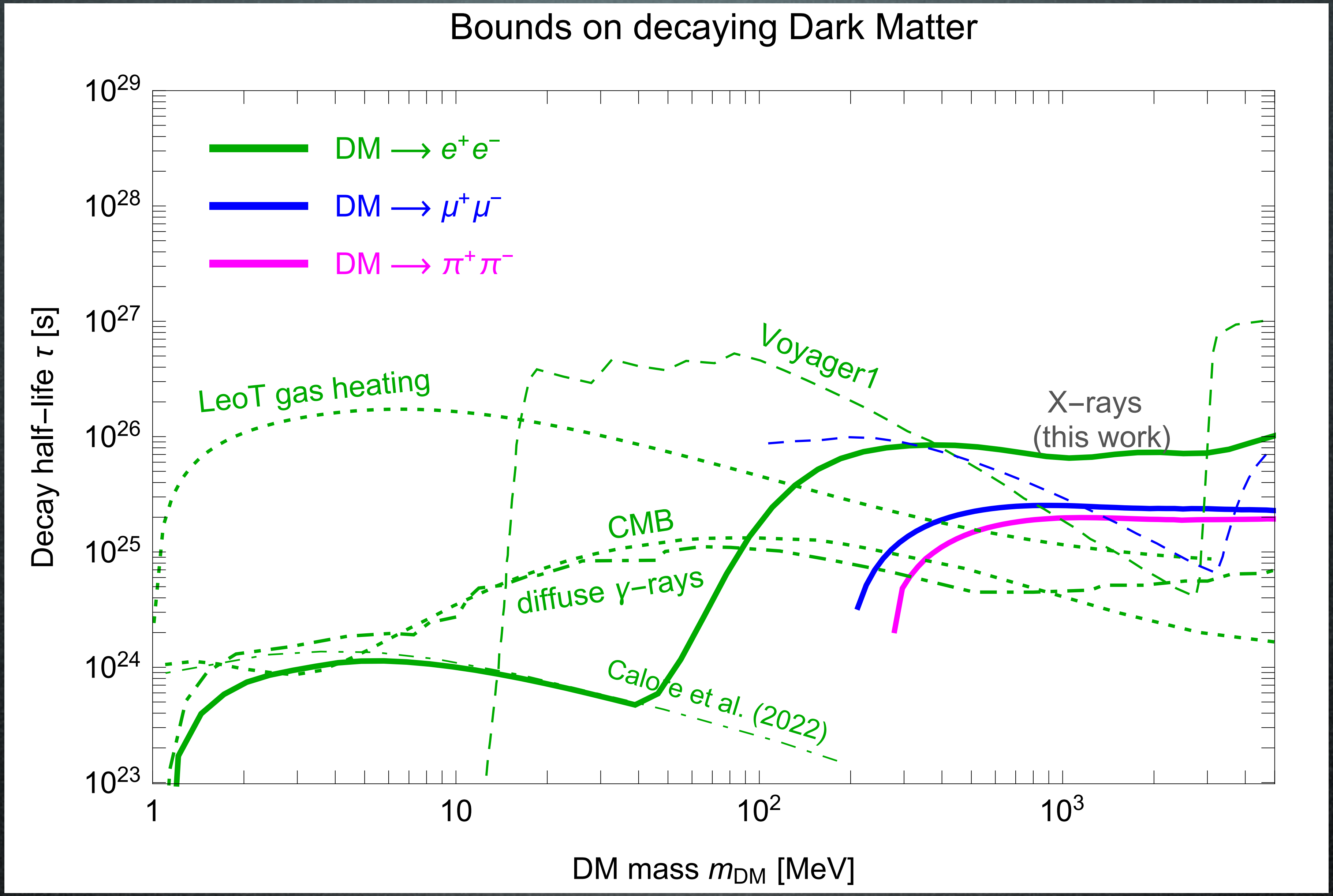
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854**v3**

Bounds on all 3 channels

ICS allows to vastly improve at large m_{DM}

But not deeper than the s-wave CMB bounds

Results



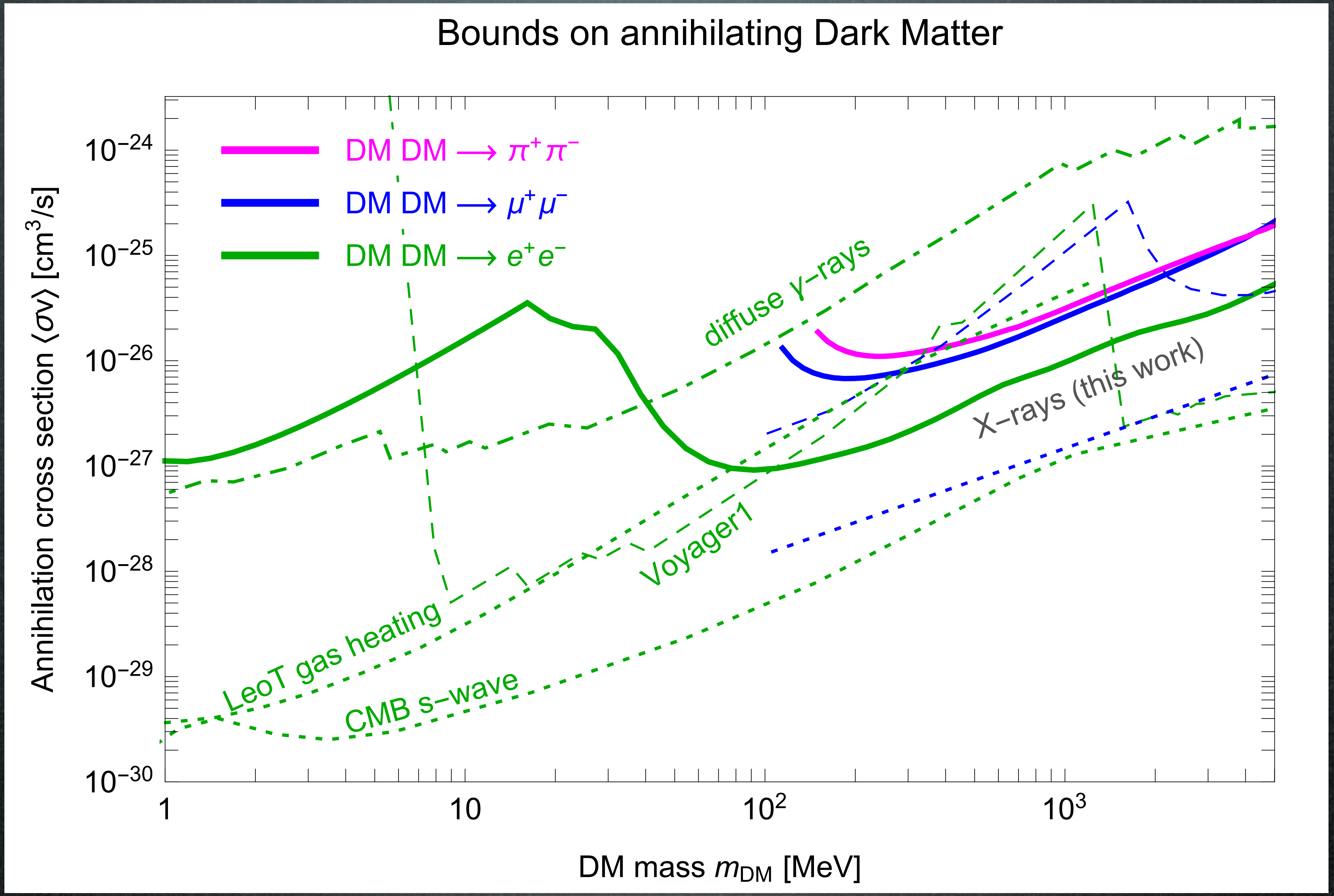
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854**v3**

Bounds on all 3 channels

ICS allows to vastly improve at large $m_{\rm DM}$

Dominant bounds above ~300 MeV

Results



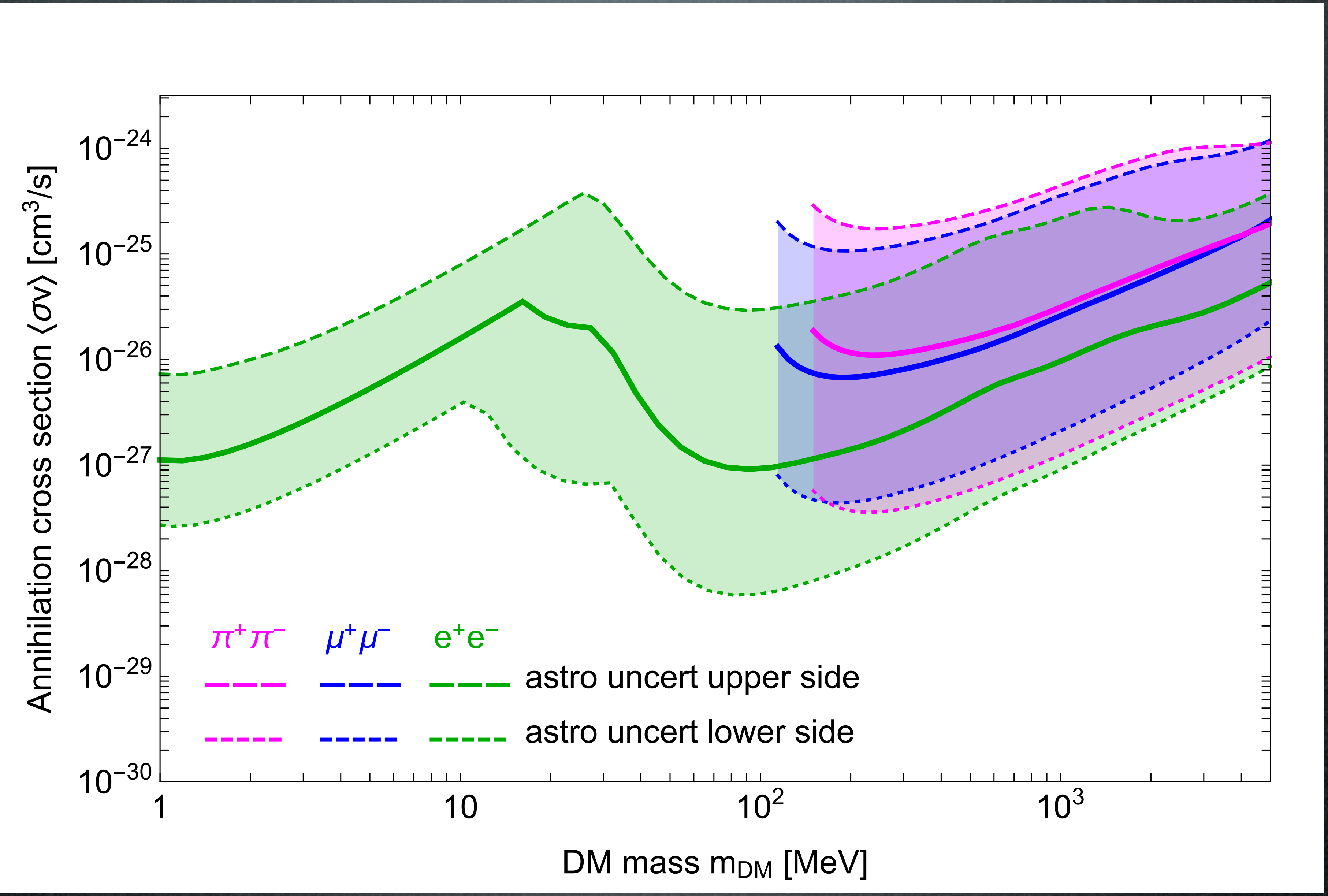
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854**v3**

Bounds on all 3 channels

ICS allows to vastly improve at large $m_{\rm DM}$

But not deeper than the s-wave CMB bounds

Results: uncertainties



Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854**v3**

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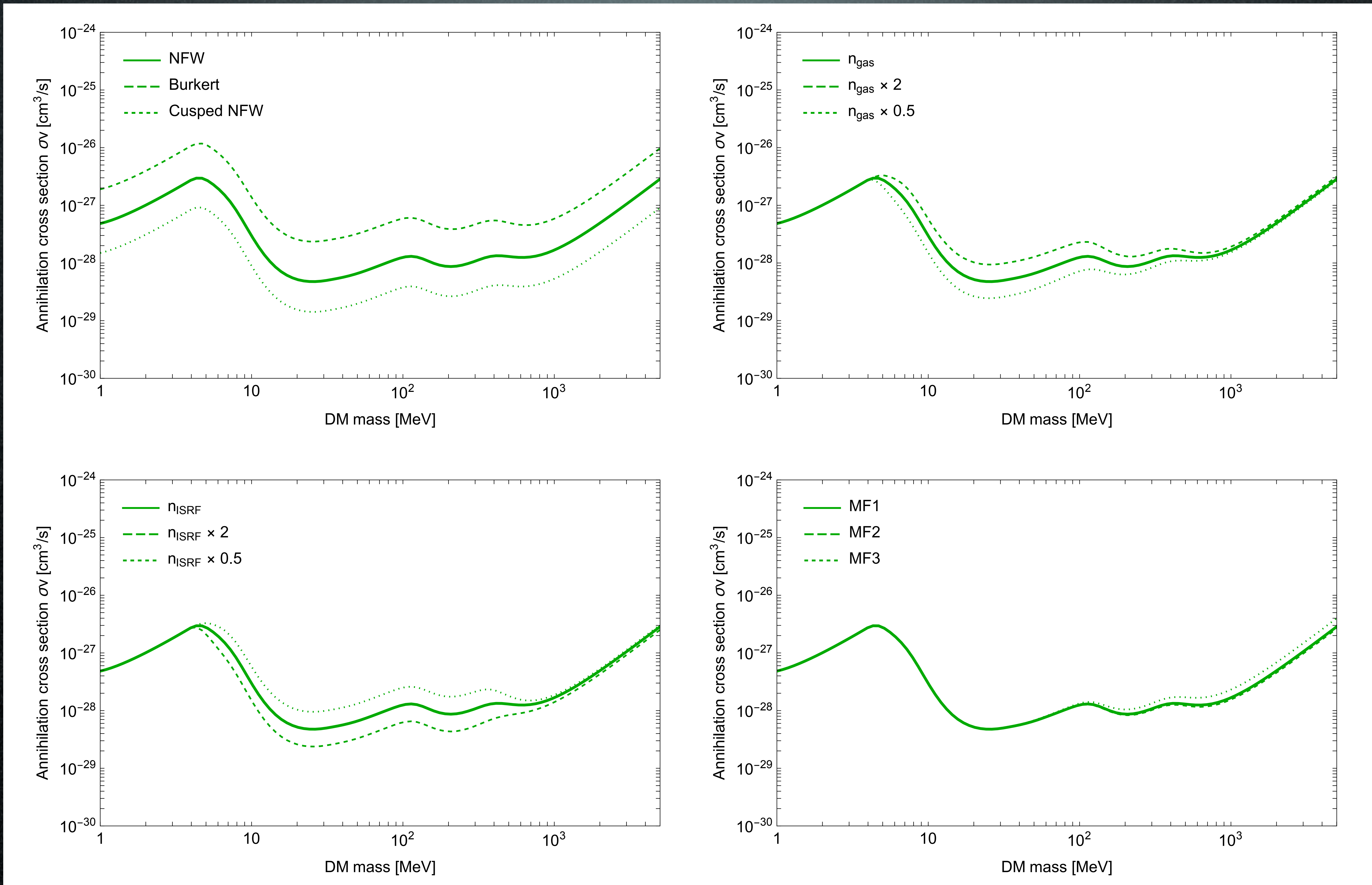
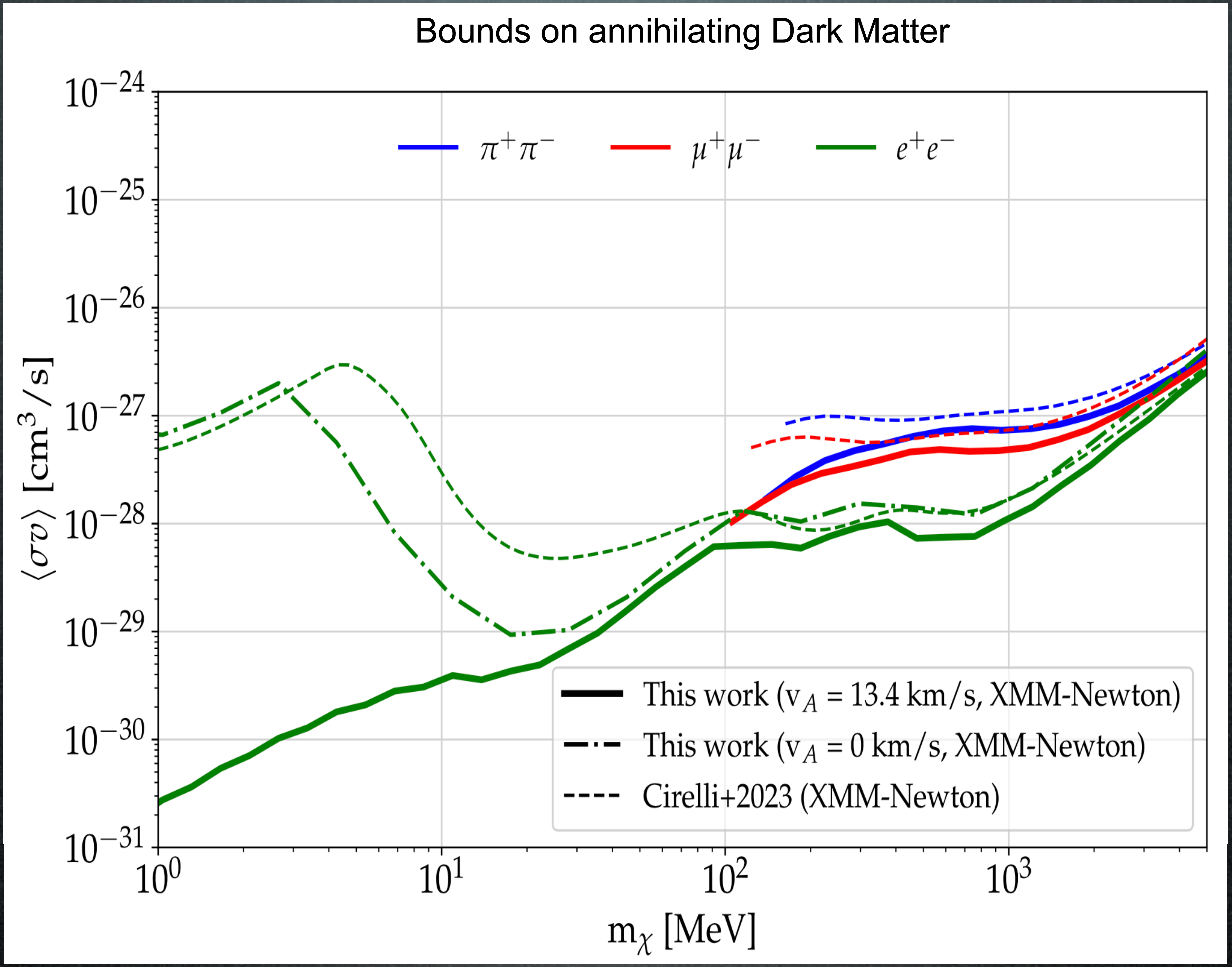


Results



Updated with a refined propagation (incl reacceleration)

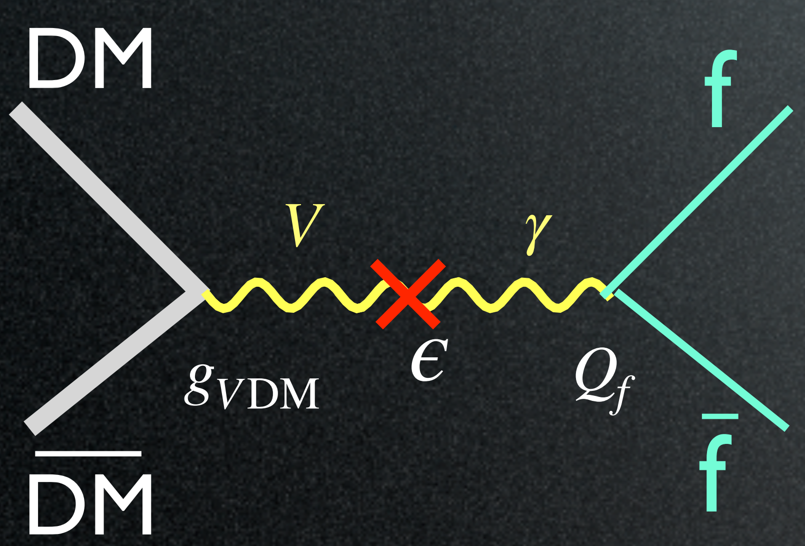
De La Torre Luque, Balaji, Koechler 2311.04979
and also Balaji et al., 2506.02310 (including eROSITA data)

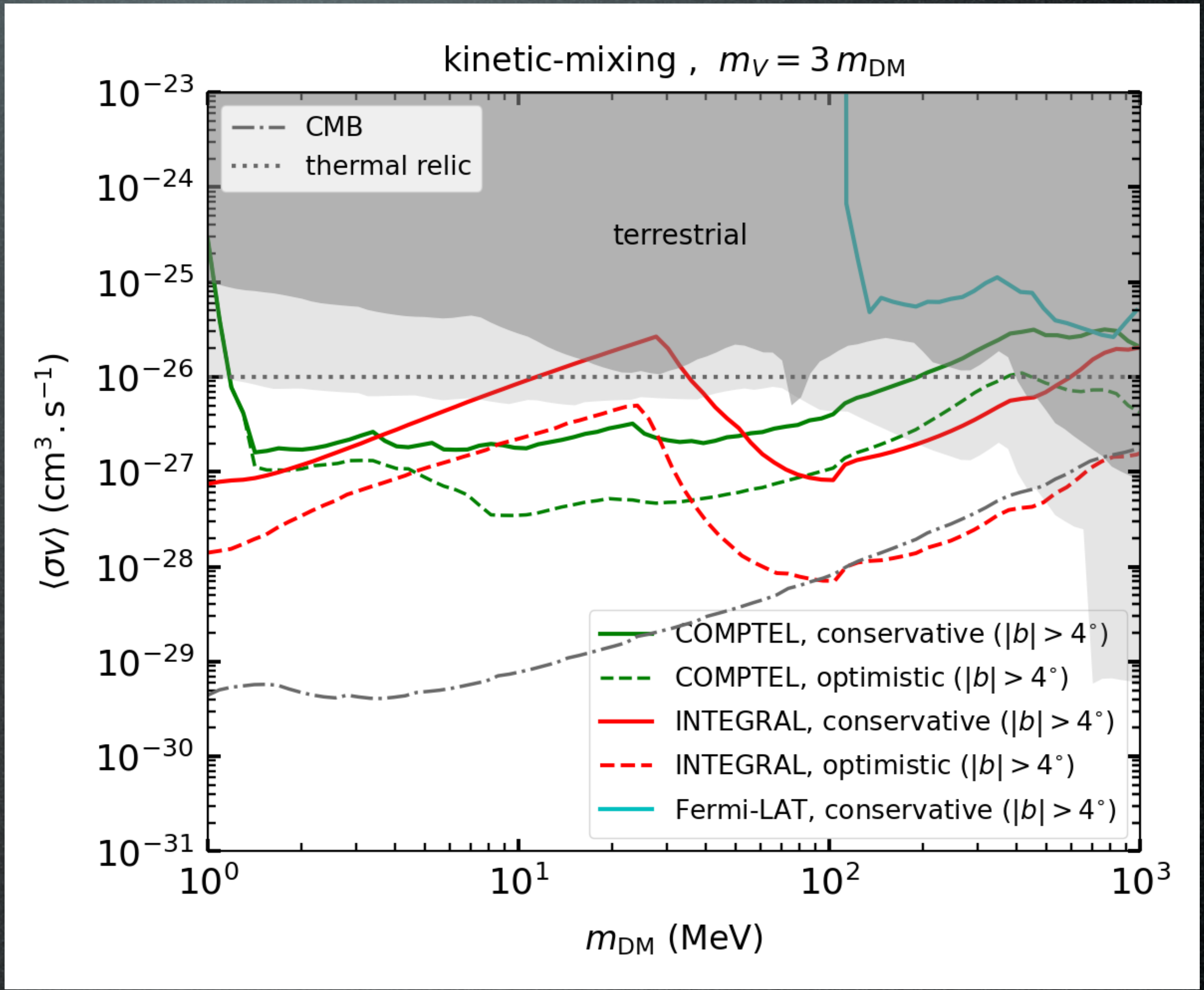
Results

Application to specific realistic models of sub-GeV DM

Cirelli, Kar, Shaikh 2508.03819

Vector-portal, kinetic mixing





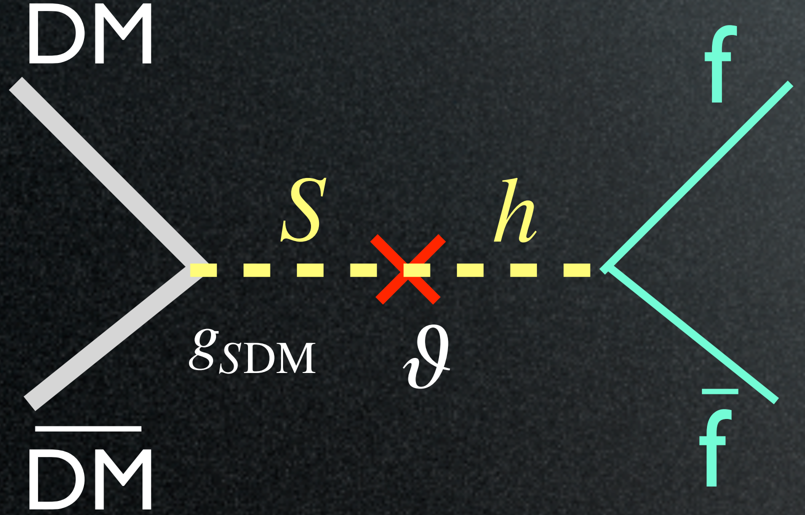
Photon bounds

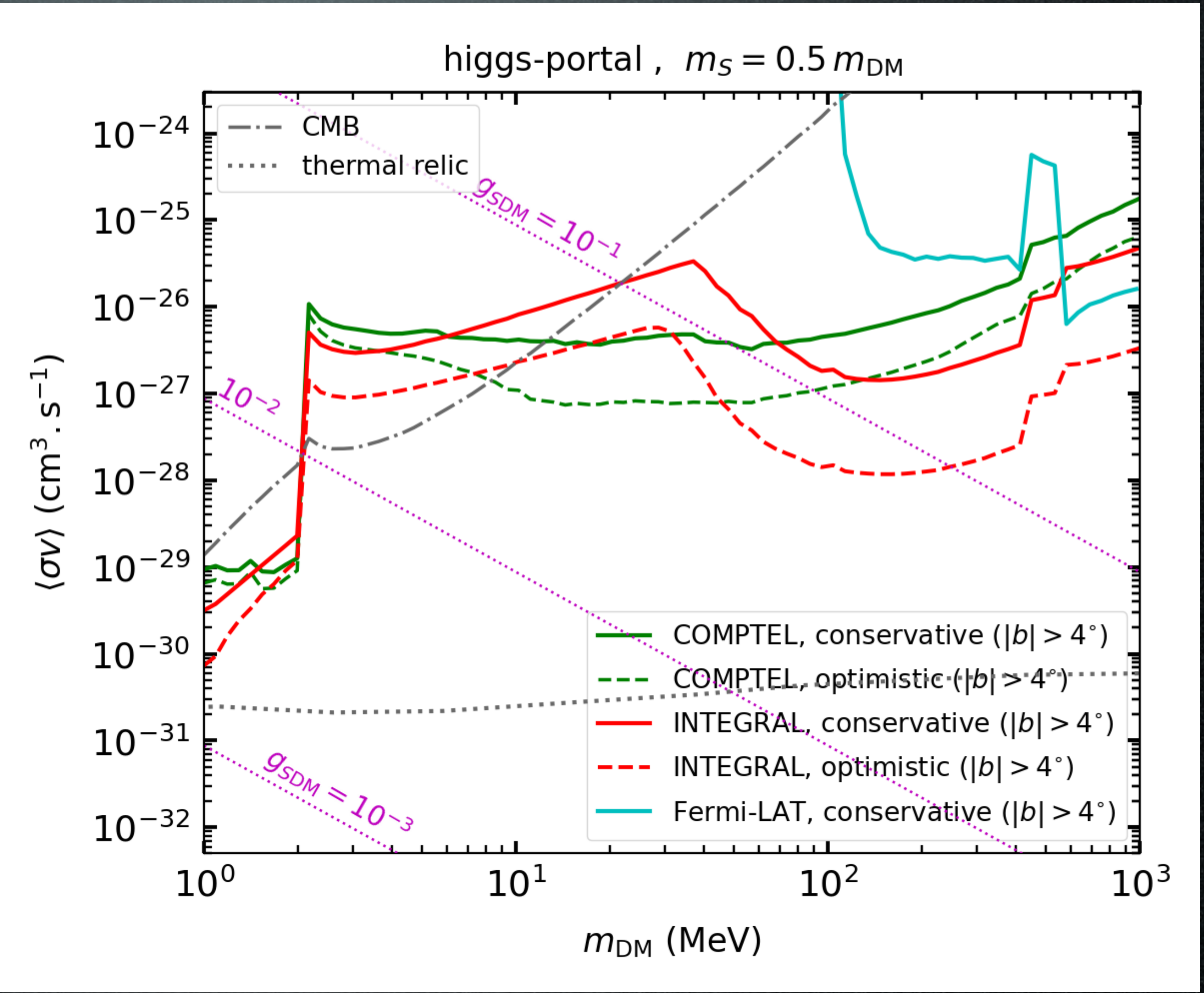
Results

Application to specific realistic models of sub-GeV DM

Cirelli, Kar, Shaikh 2508.03819

Scalar-portal,
higgs portal





Photon bounds

Conclusions

Conclusions

Sub-GeV DM is interesting
and emerging: Why not?!

Conclusions

Sub-GeV DM is interesting and emerging: Why not?!

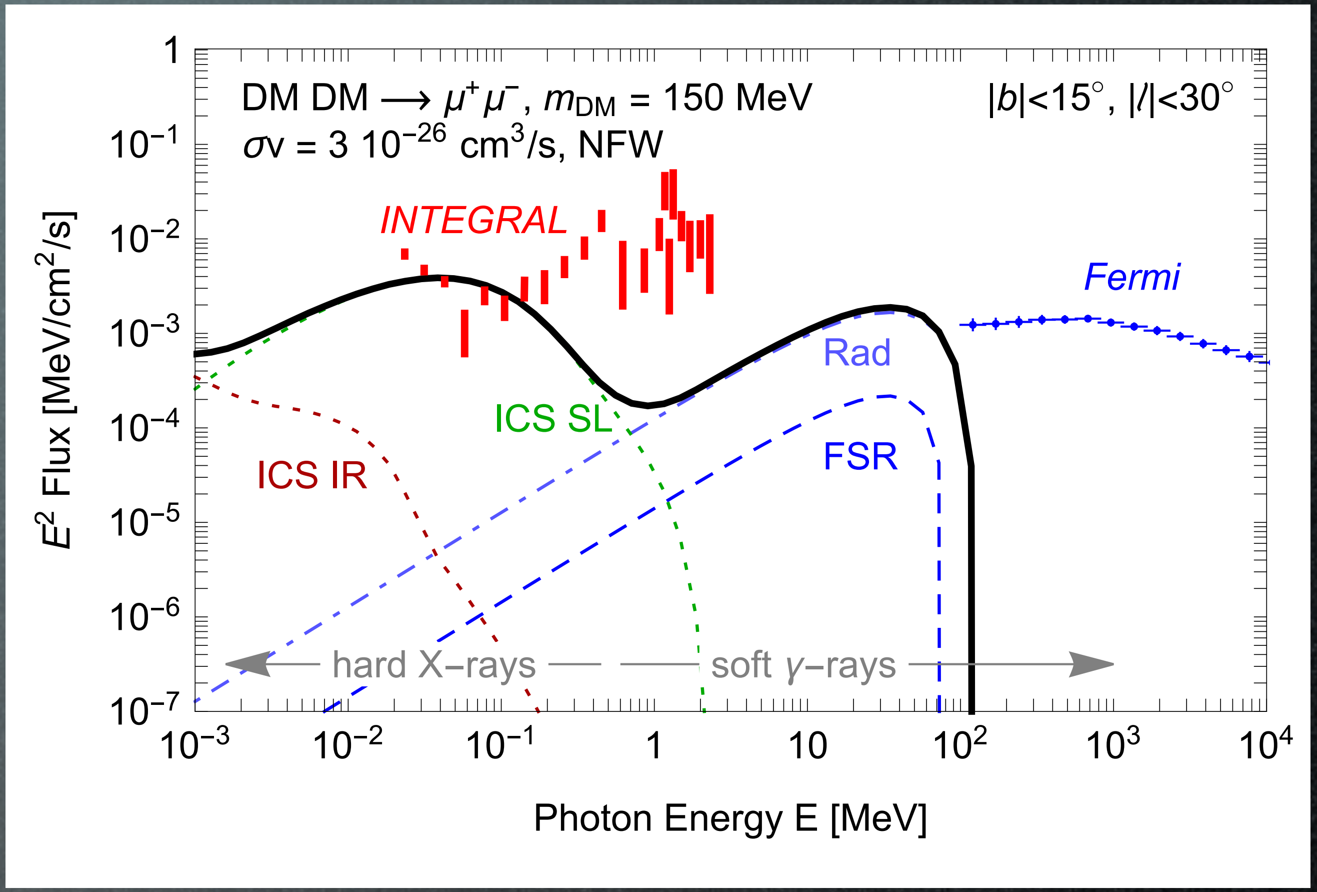
ID is (more) challenging than WIMPs

Conclusions

Sub-GeV DM is interesting and emerging: Why not?!

ID is (more) challenging than WIMPs

ICS allows to test it with X-ray data



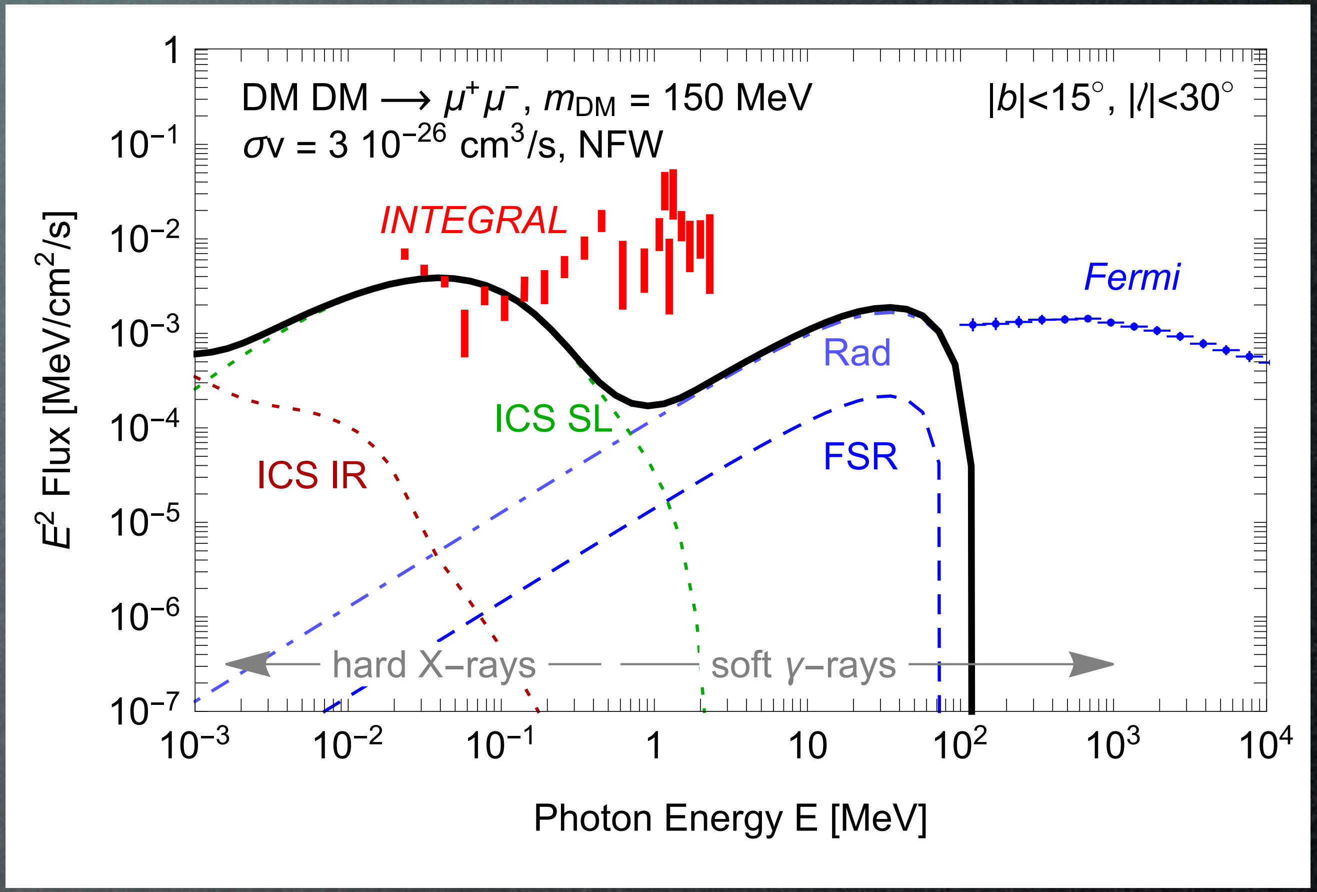
Conclusions

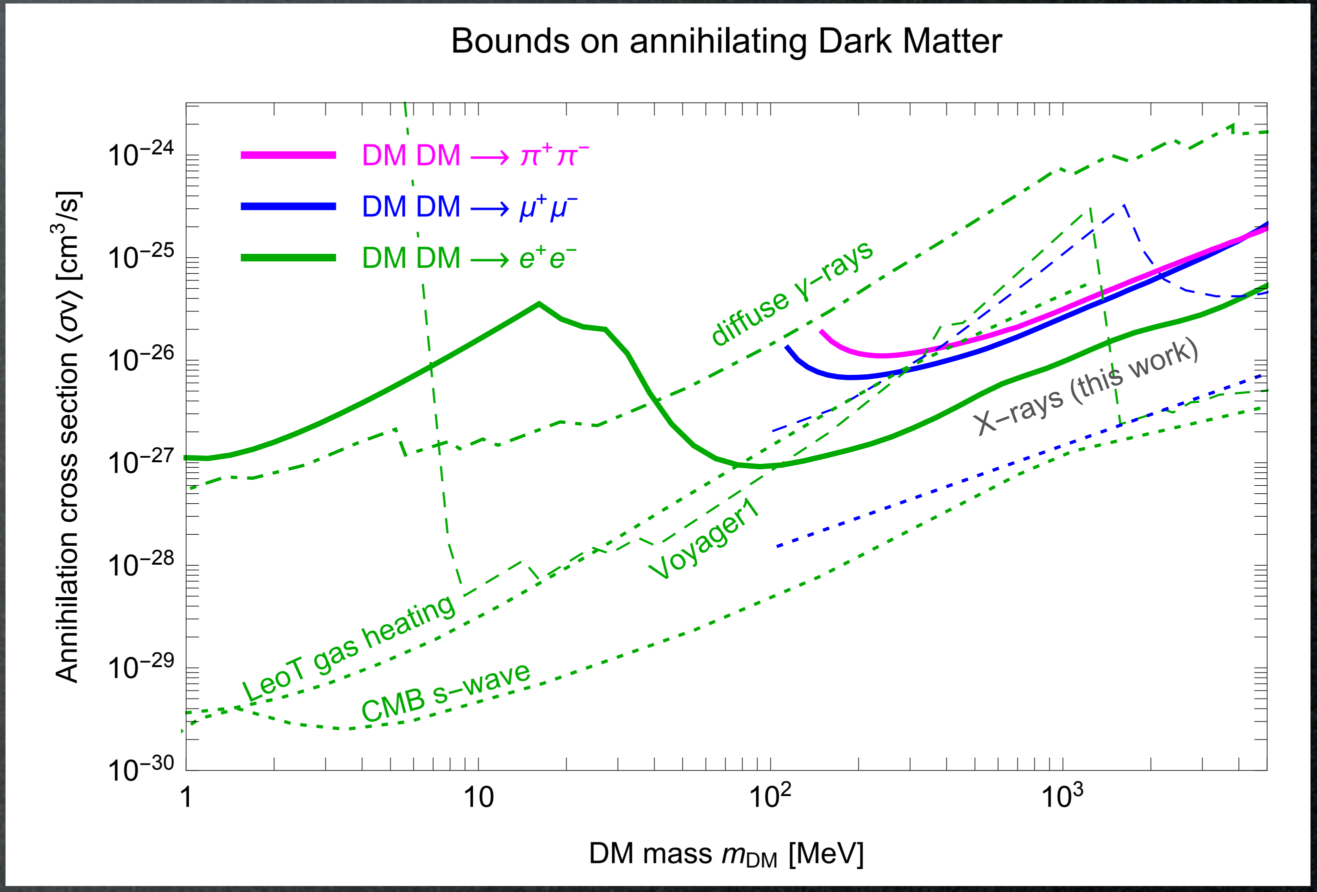
Sub-GeV DM is interesting and emerging: Why not?!

ID is (more) challenging than WIMPs

ICS allows to test it with X-ray data

Impose stringent constraints





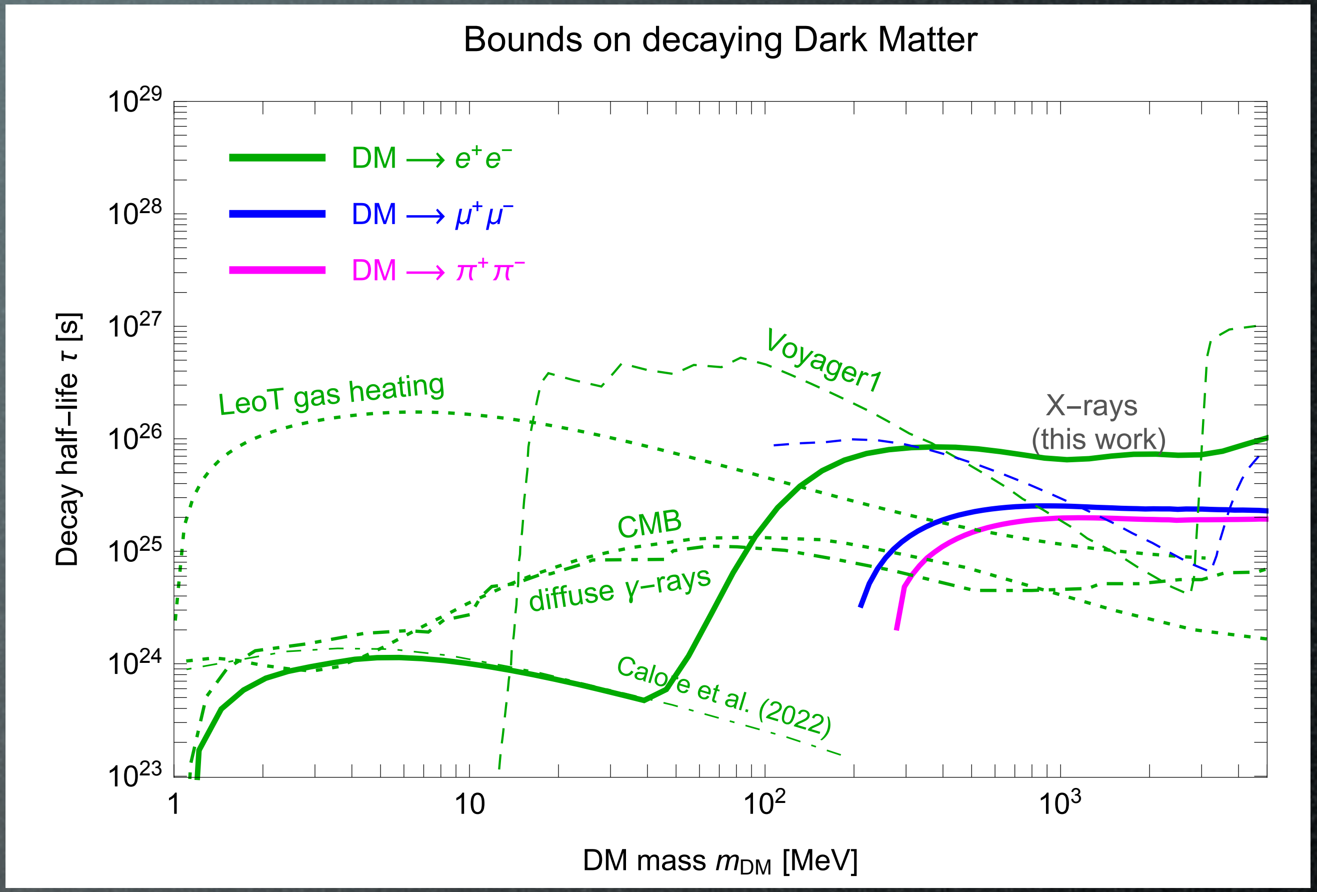
Conclusions

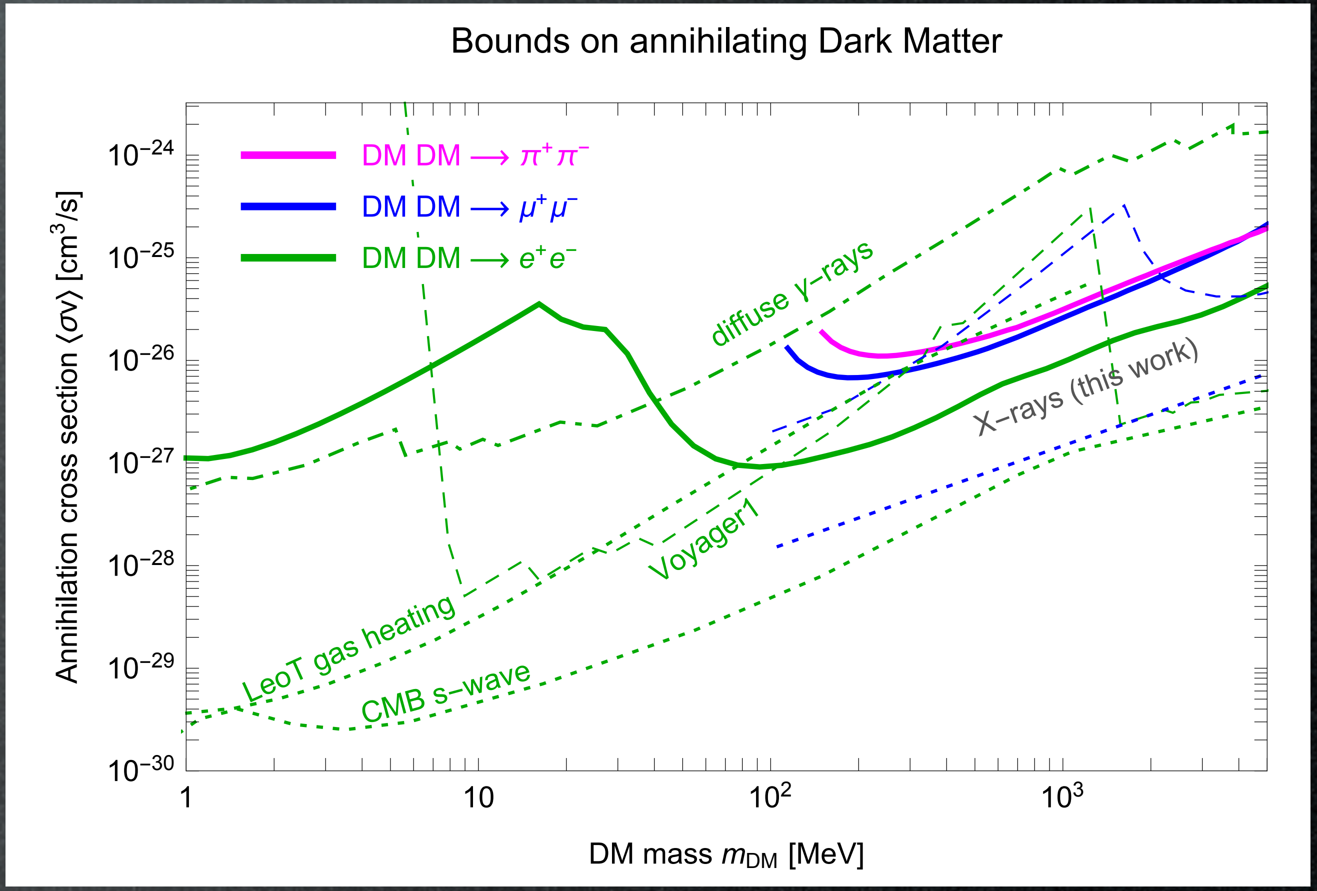
Sub-GeV DM is interesting and emerging: Why not?!

ID is (more) challenging than WIMPs

ICS allows to test it with X-ray data

Impose stringent constraints





Backup