11 December 2024
PRISMA+ colloquium, Mainz

Sub-GeV Dark Matter and X-rays

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

cnrs dépasser les frontières

SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

My career path in 2 minutes

Marco Cirelli
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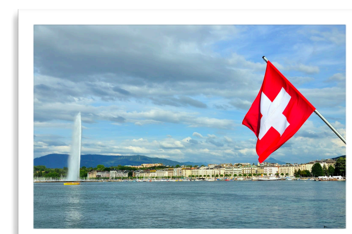

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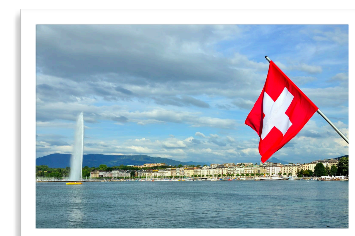
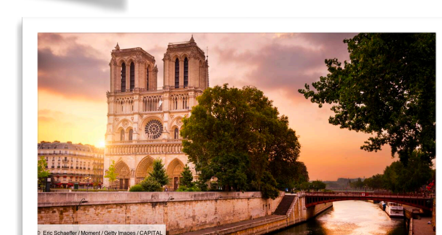

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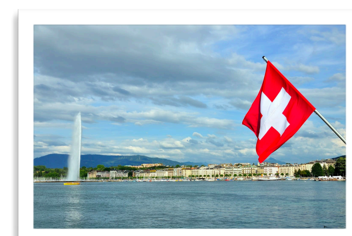

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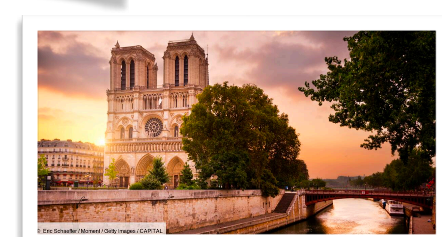

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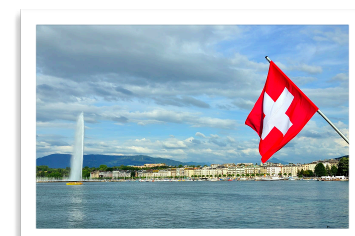

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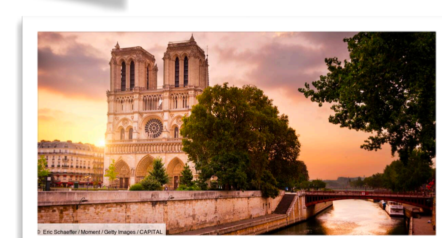

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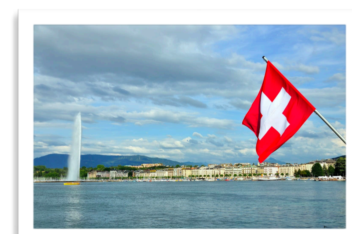

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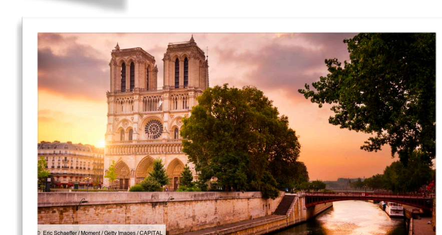

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hep-ph model building
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DM indirect detection
(Charged cosmic rays)

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(Photons, γ-rays, secondaries…)

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1 MeV -> 5 GeV

Sub-GeV Dark Matter and X-rays

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(CNRS LPTHE Jussieu Paris)

based on : Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854
De La Torre Luque, Balaji, Koechler 2311.04979
+ work in progress

Introduction

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- DM exists

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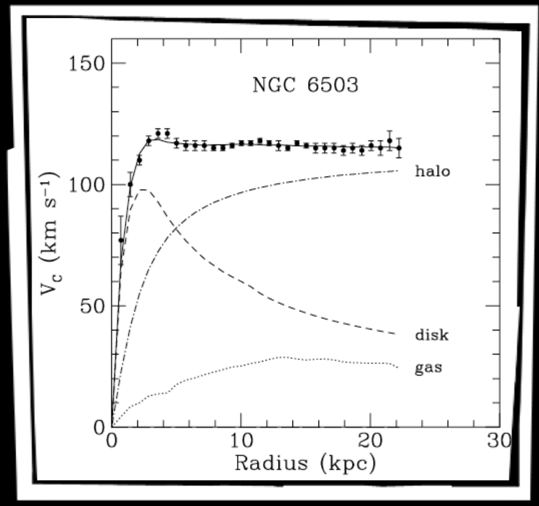
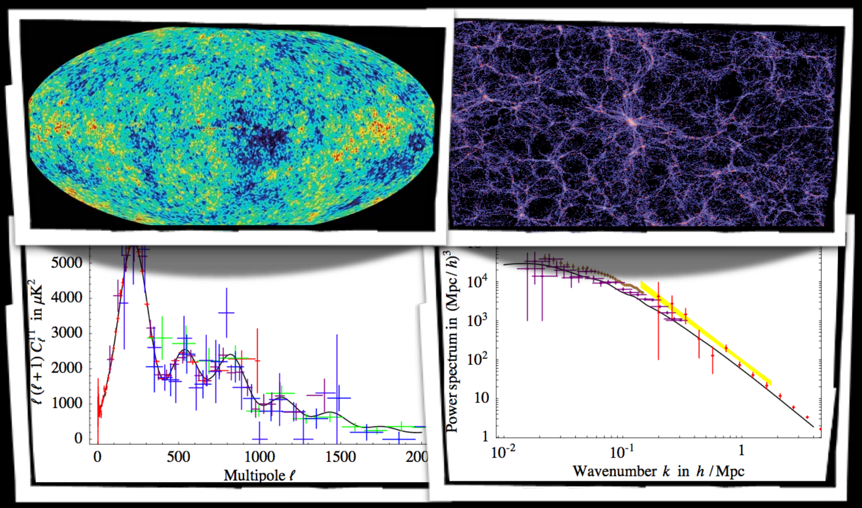


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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- it's a new, unknown corpuscle

no SM particle can fulfil

dilutes as $1/a^3$ with universe expansion

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- makes up 26% of total energy
  84% of total matter

$$\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010$$

(notice error!)

Planck 2015, 1502.01589 (tab.4)

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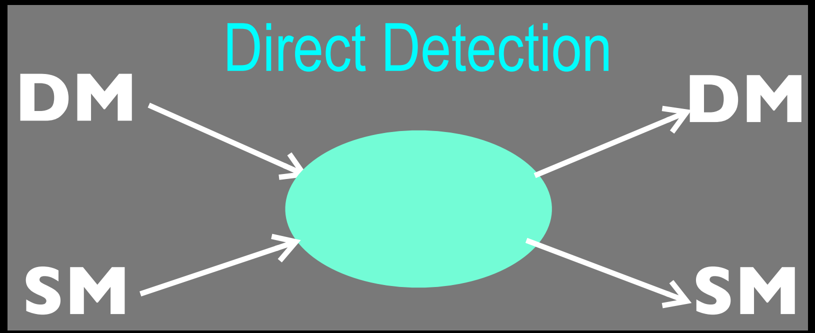

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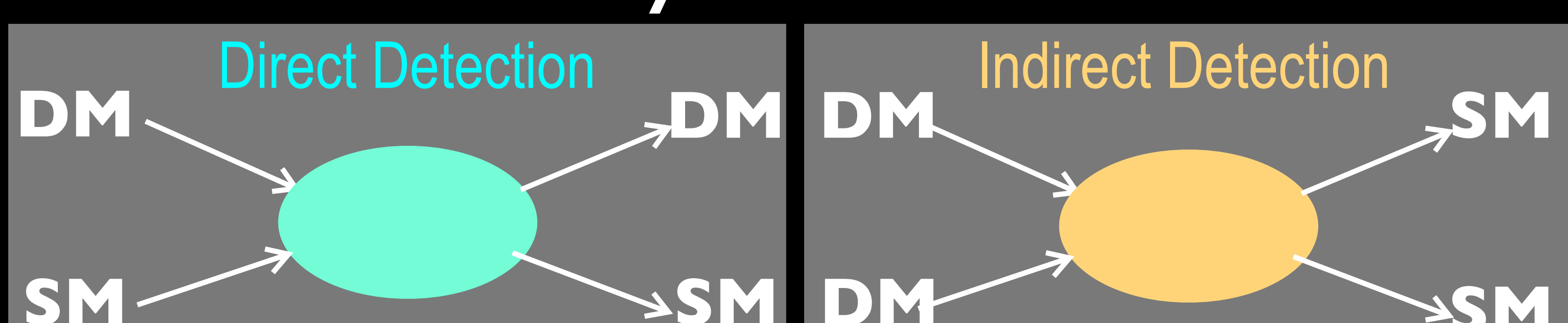

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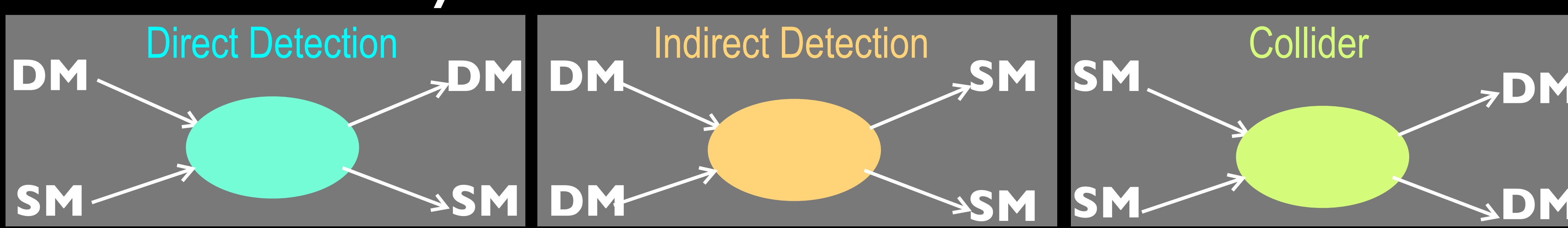

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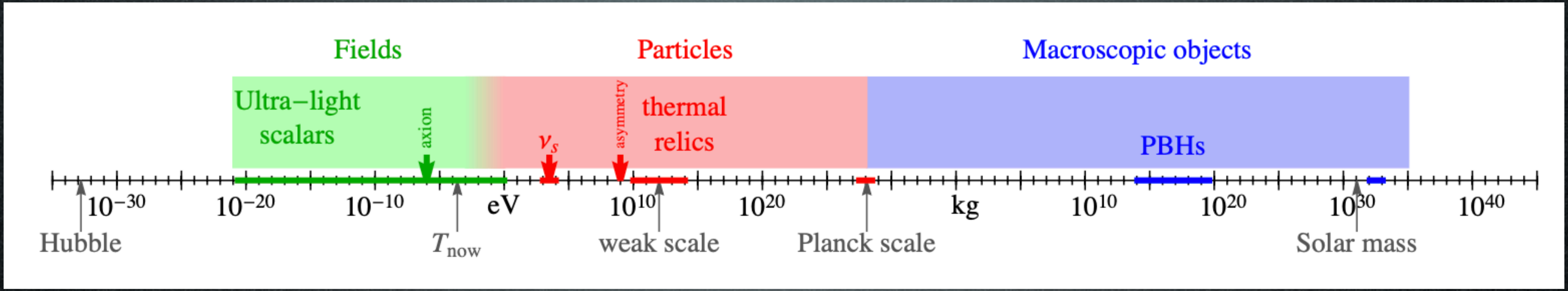
mass ???

interactions ???

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

Candidates

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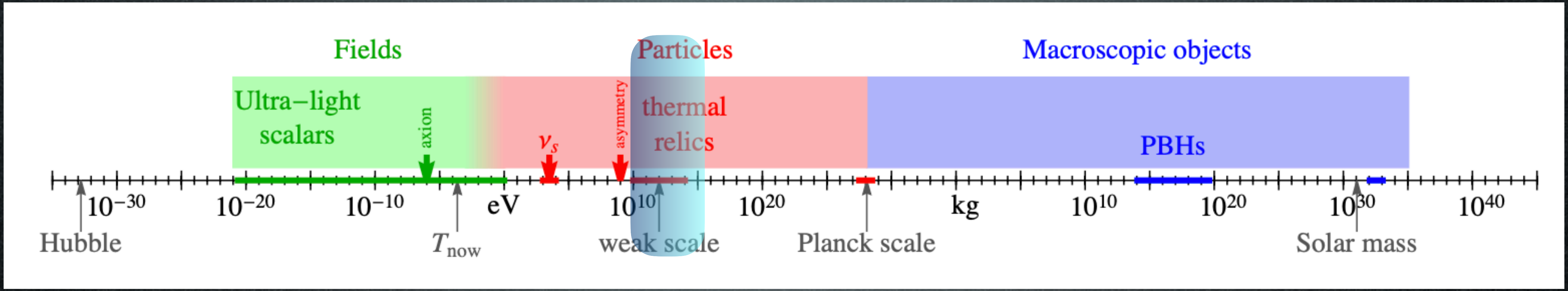


Candidates

WIMPs

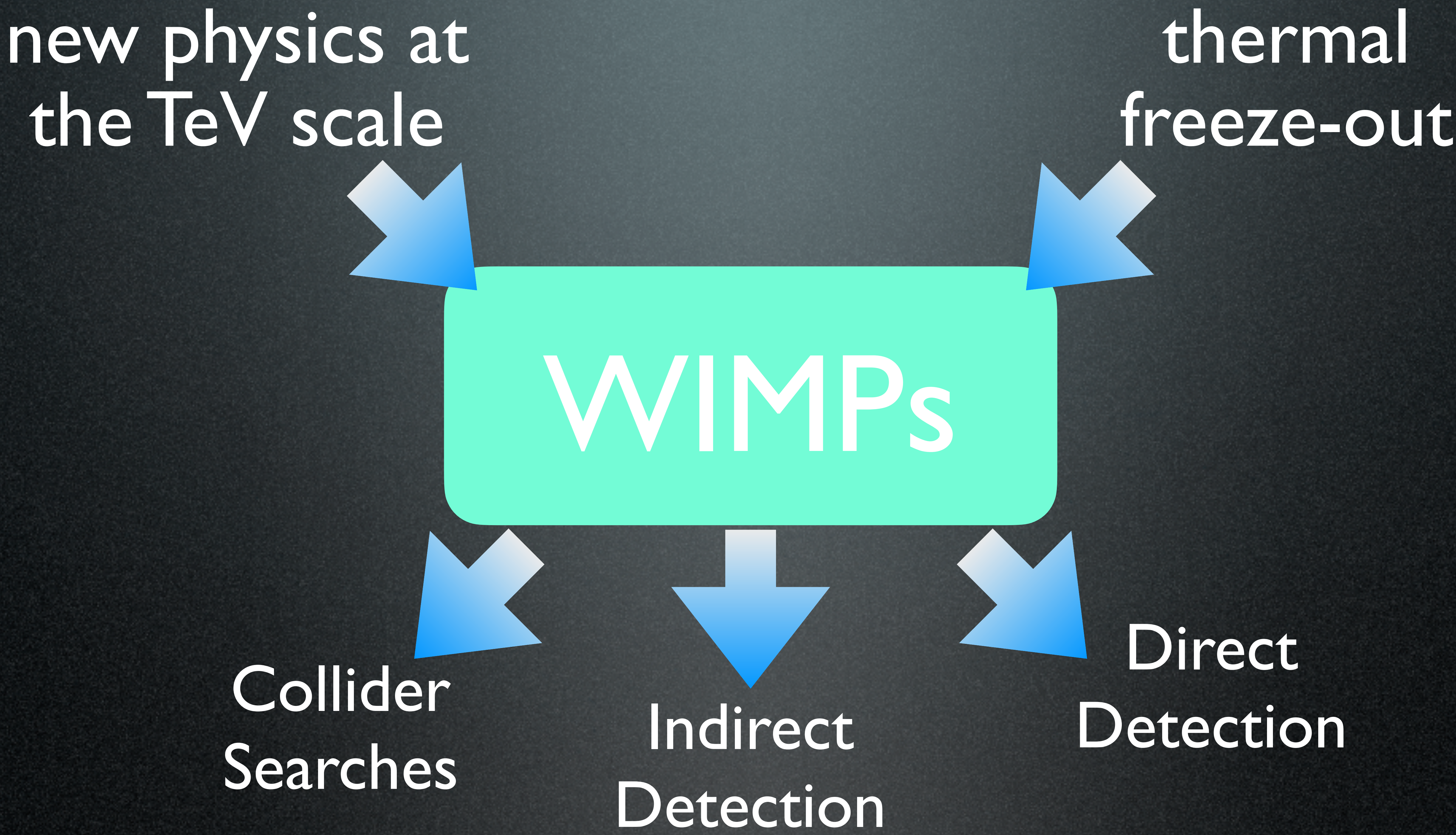
Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

Candidates


new physics at the TeV scale
thermal freeze-out
WIMPs
Collider Searches
Indirect Detection
Direct Detection

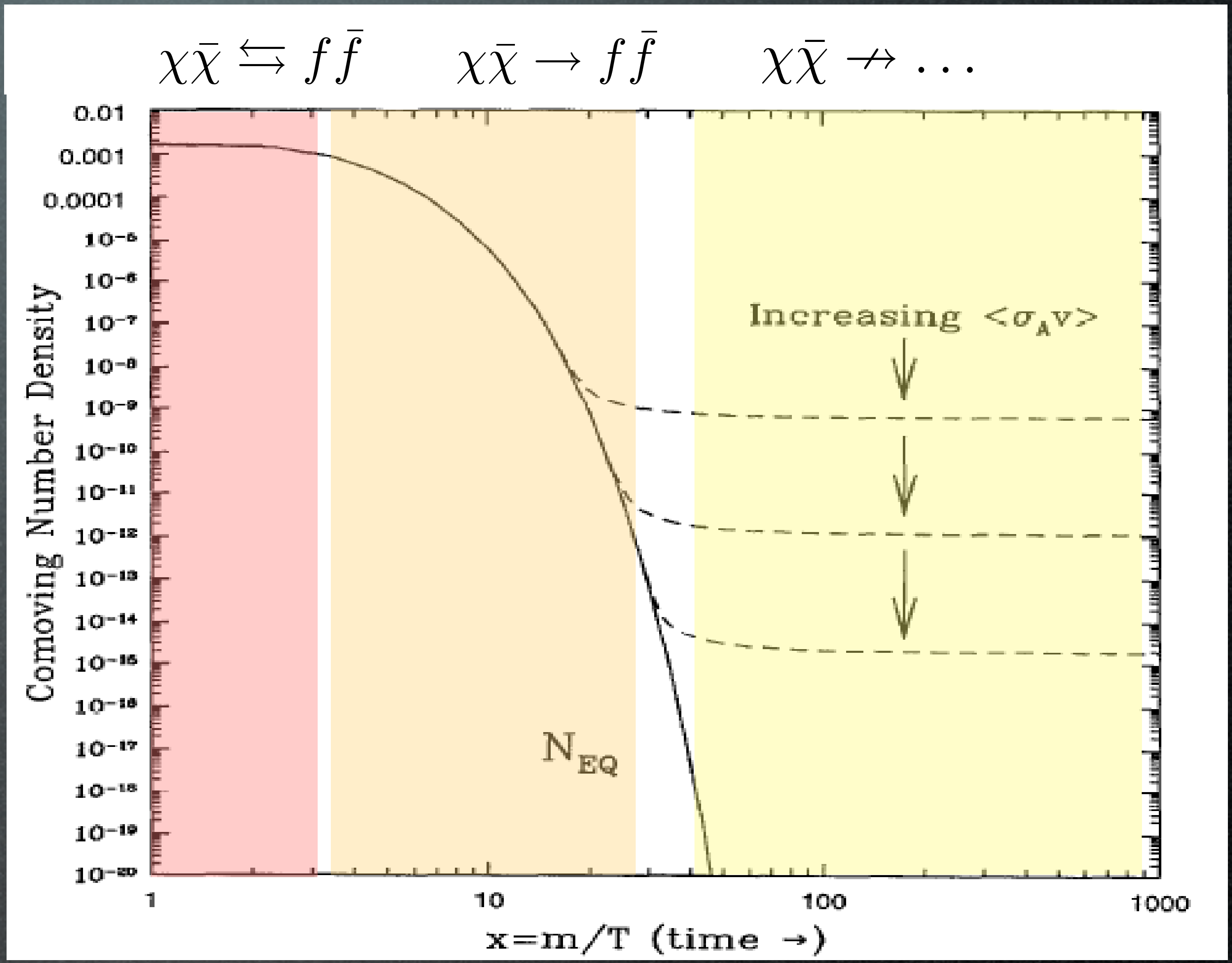
DM as a thermal relic from the Early Universe

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 $\Omega_{\mathrm{DM}} \simeq 0.23$ for

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



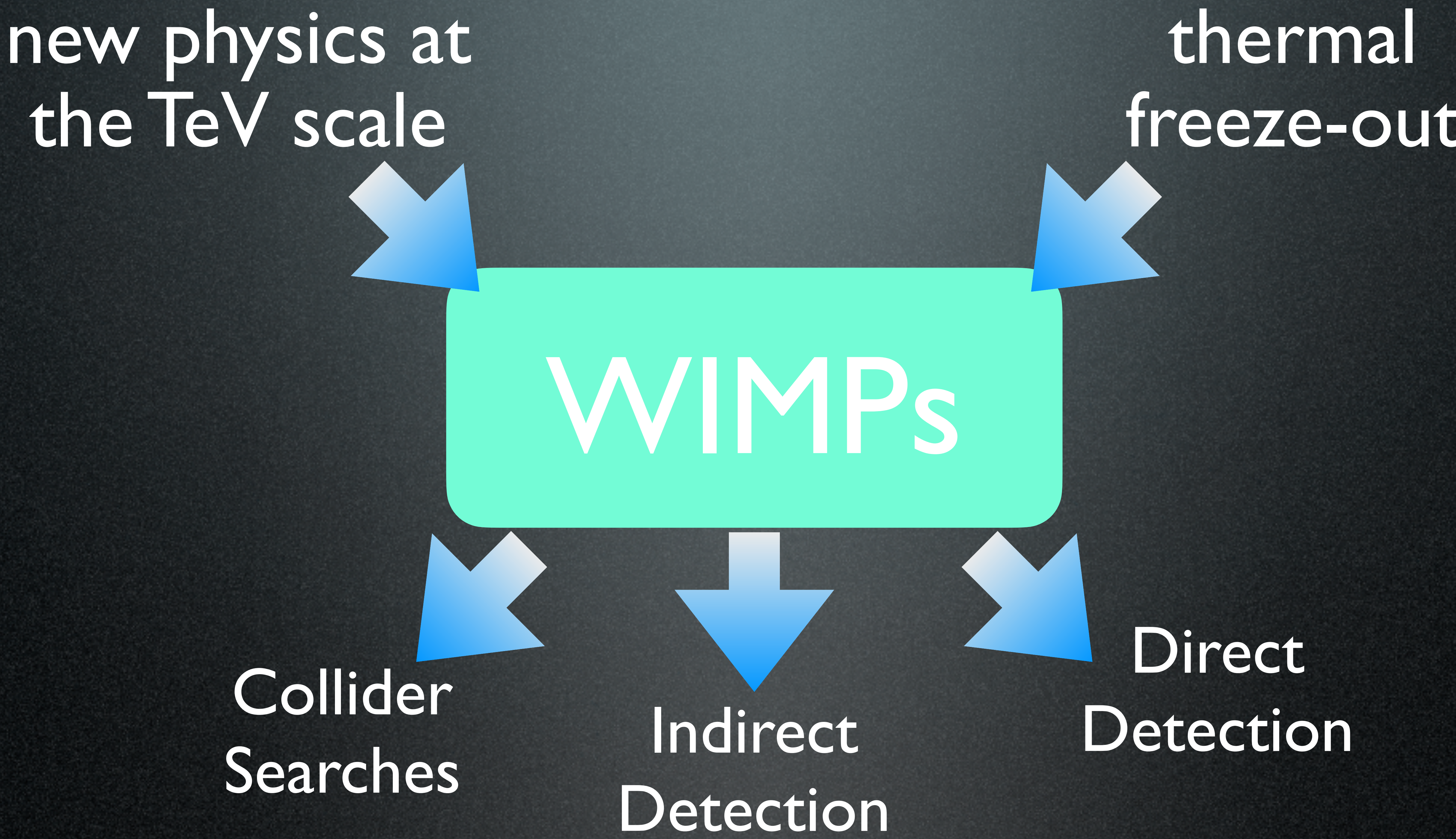
Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

Candidates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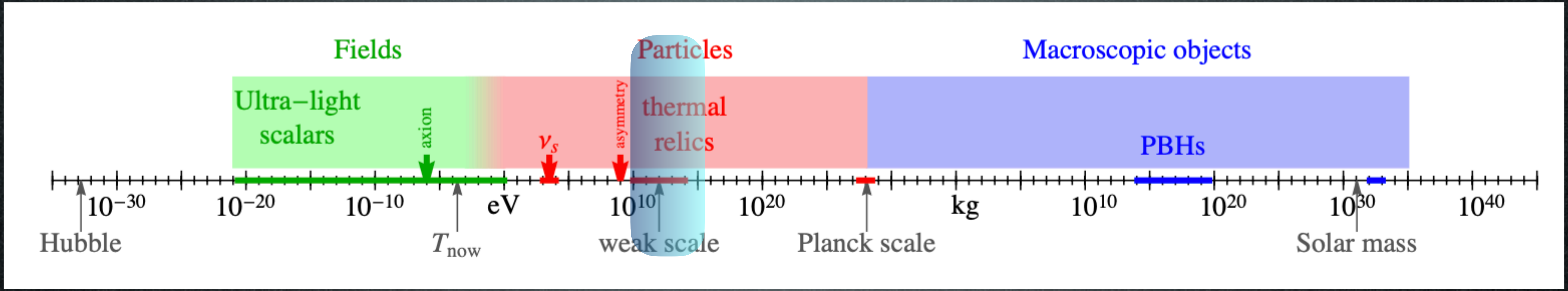

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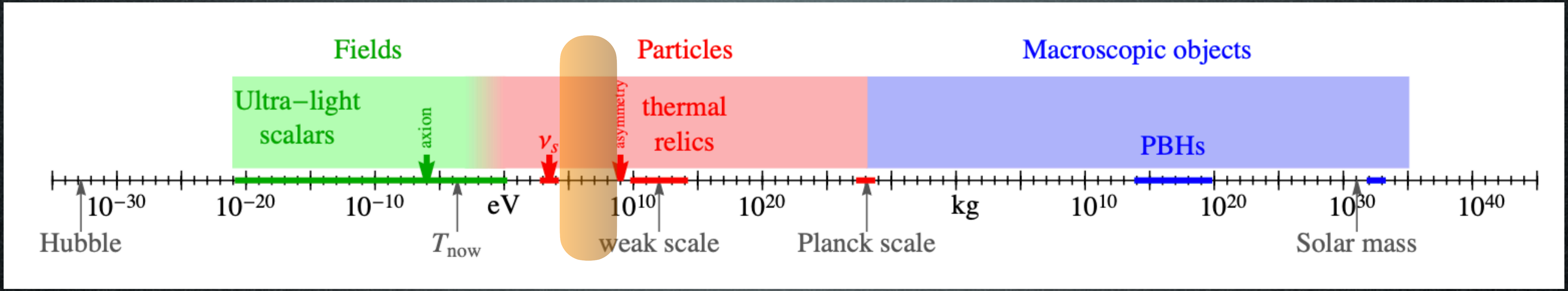

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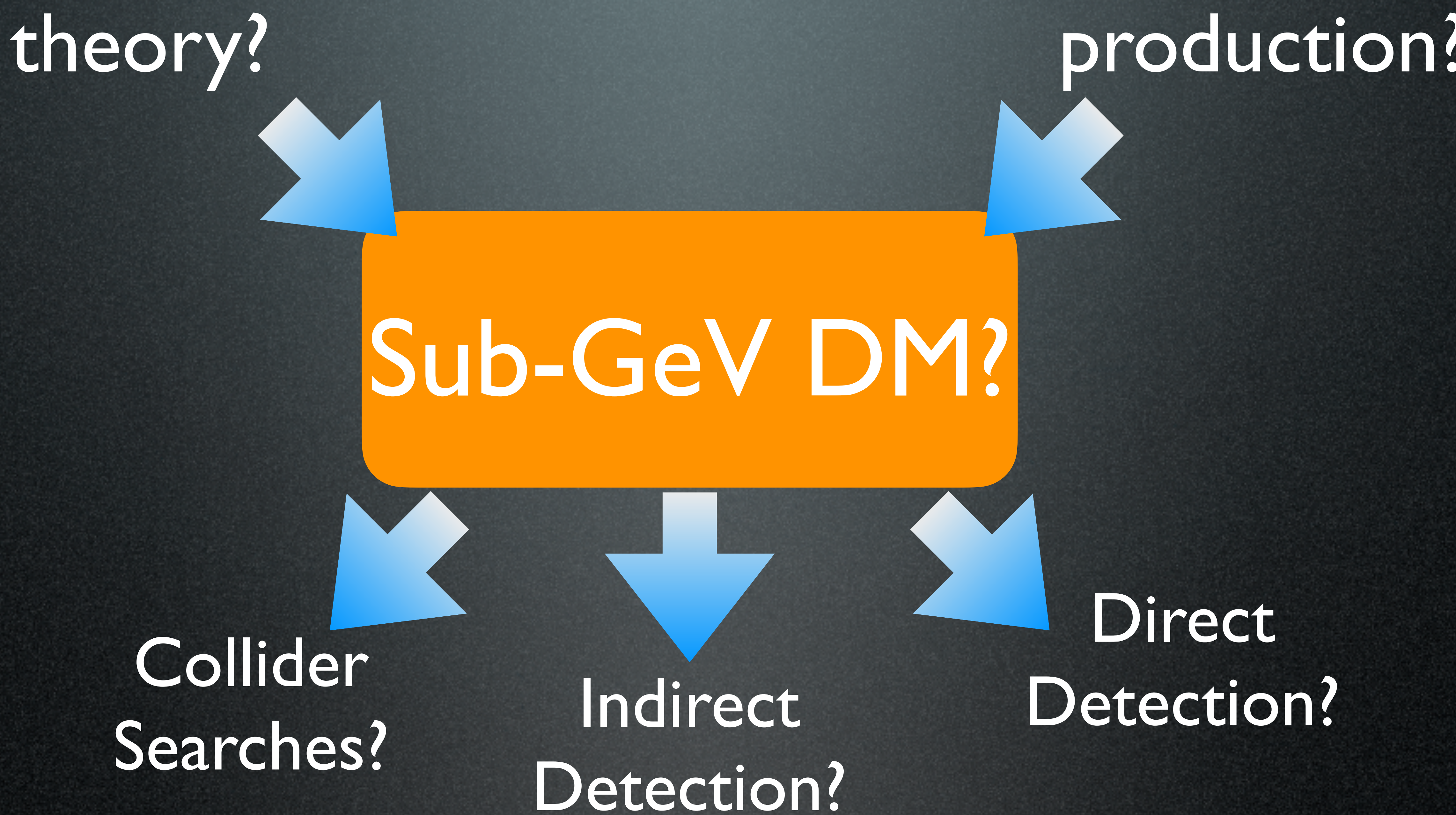
theory?
production?
Sub-GeV DM?
Collider Searches?
Indirect Detection?
Direct Detection?

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

  ∼secluded DM

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

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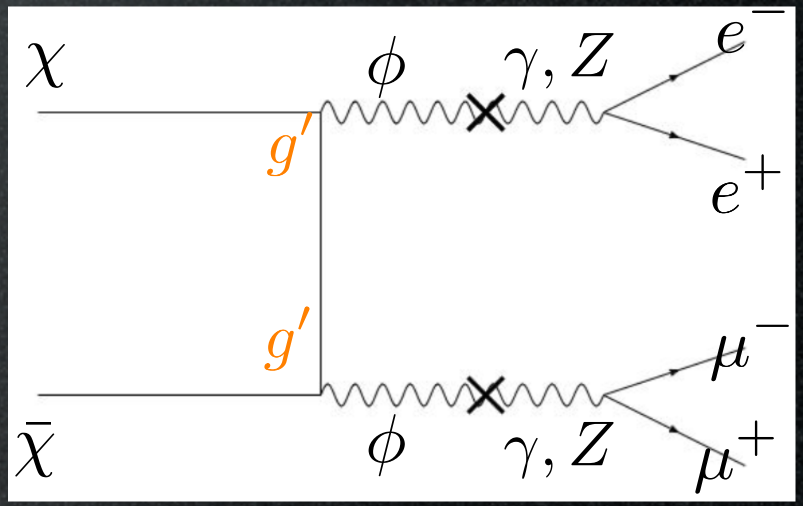
$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_x^2}{m^2}$$

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



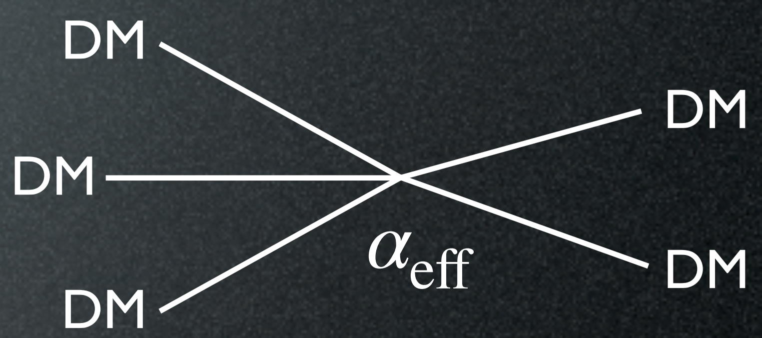
Production mechanism:
just thermal freeze-out
of these annihilations

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

- ‘simplified (light) DM models’ Knapen, Lin, Zurek 1709.07882

Theory

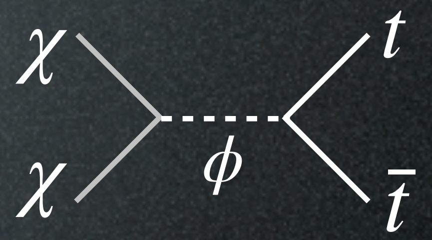
Sub-GeV DM

- 'simplified (light) DM models'

Knapen, Lin, Zurek 1709.07882

scalar DM and
hadrophilic
scalar mediator

$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n\phi\bar{n}n,$$



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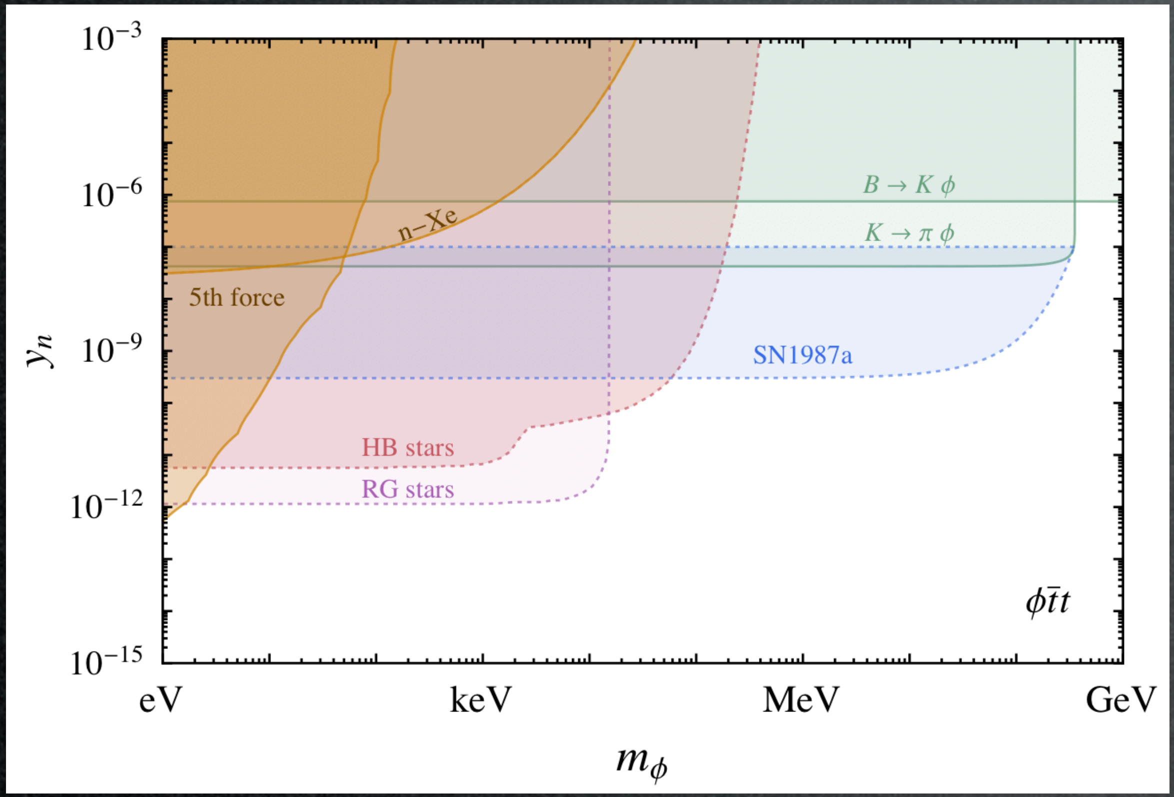

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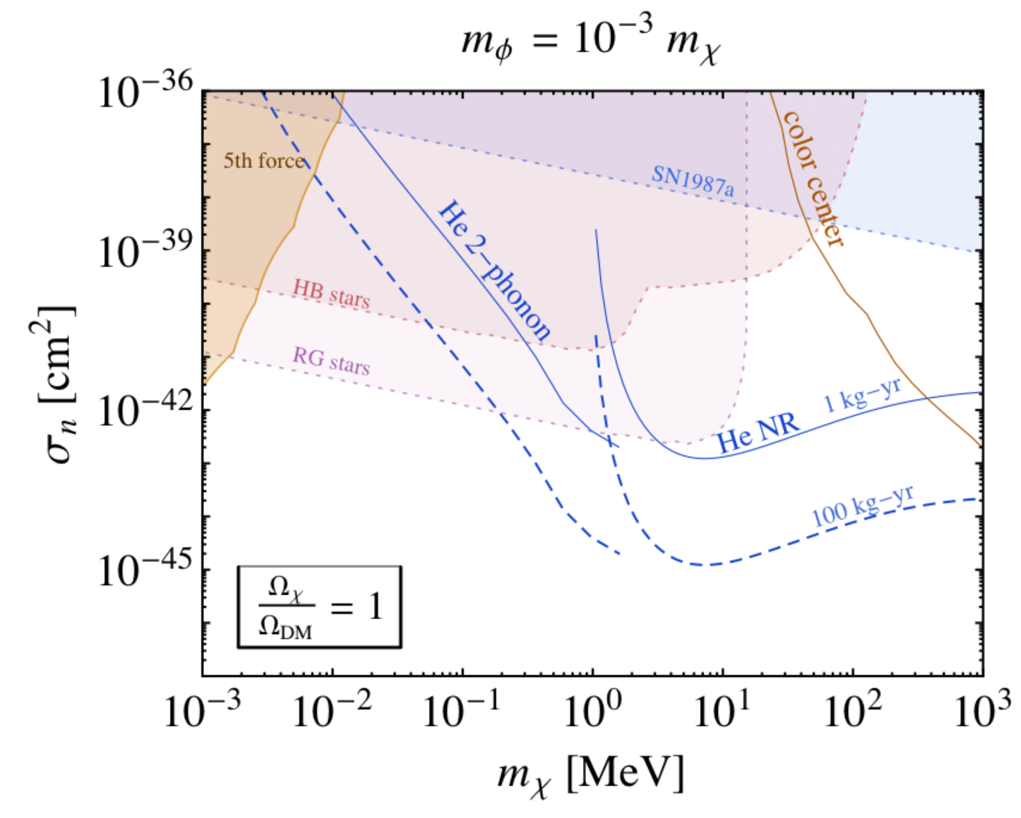

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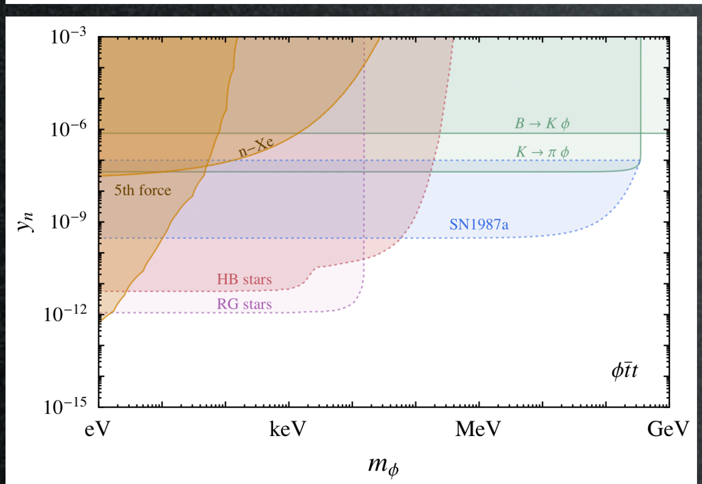
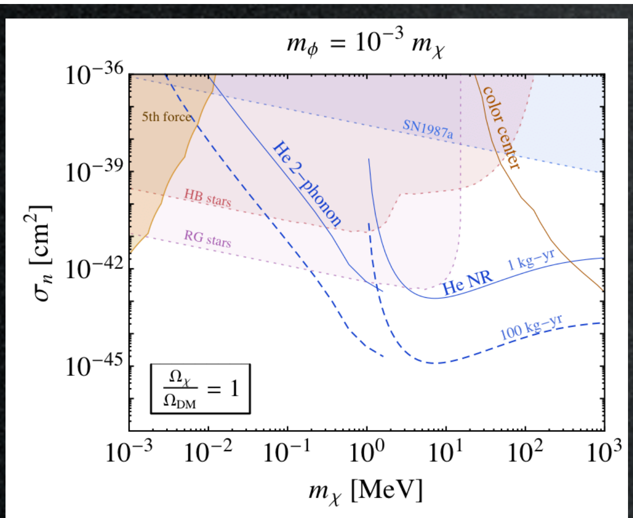




Theory

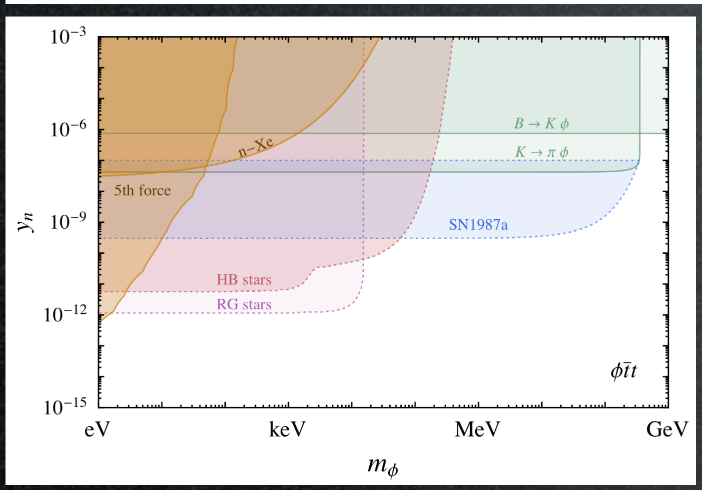
Sub-GeV DM

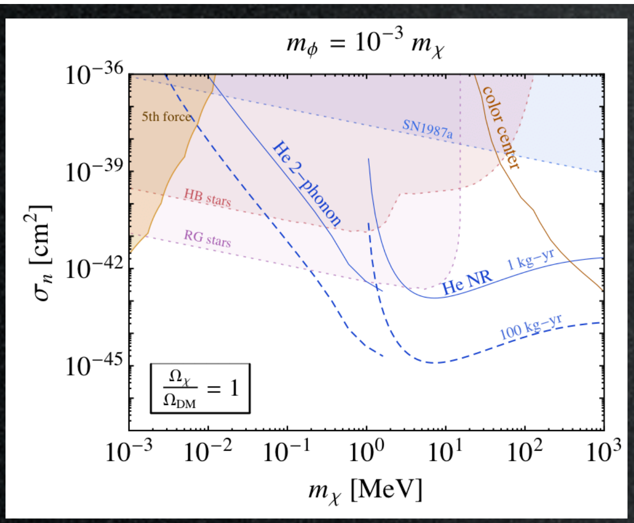
- ‘simplified (light) DM models’

Knapen, Lin, Zurek 1709.07882

scalar DM and
hadrophilic
scalar mediator

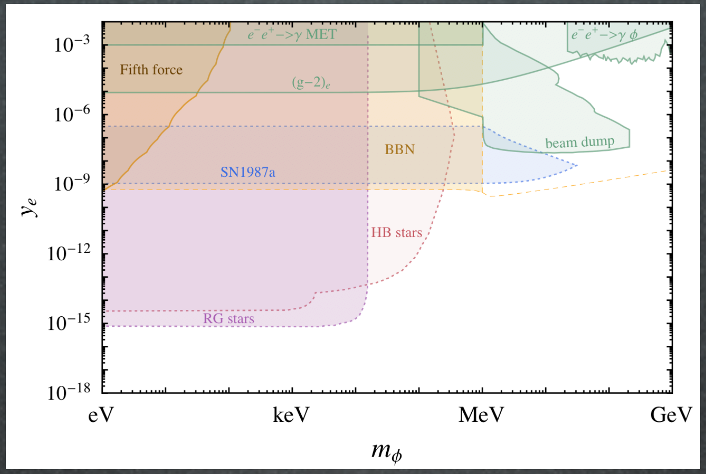
$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n\phi\bar{n}n,$$

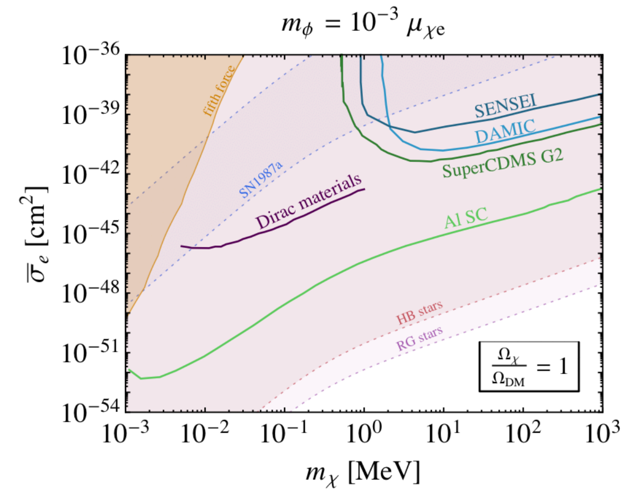




scalar DM and
leptophilic
scalar mediator

$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_e\phi\bar{e}e.$$





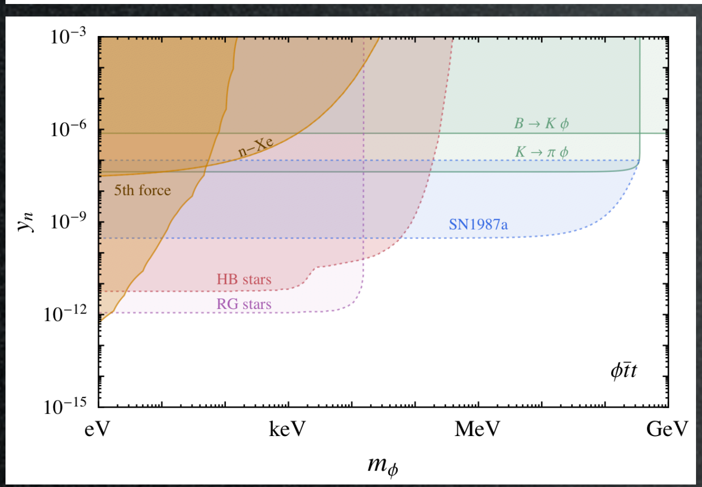
Theory

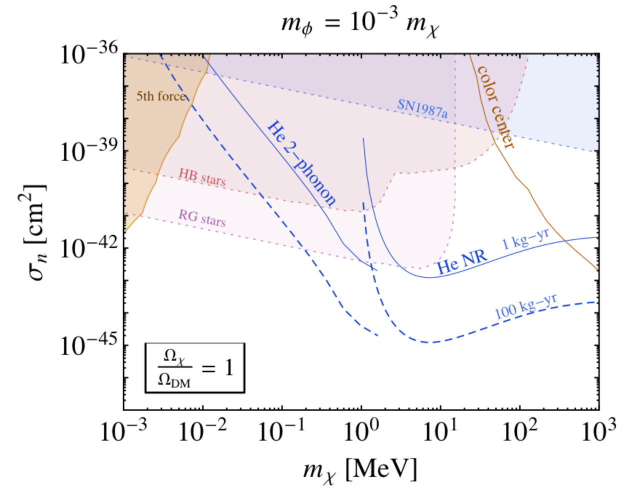
Sub-GeV DM

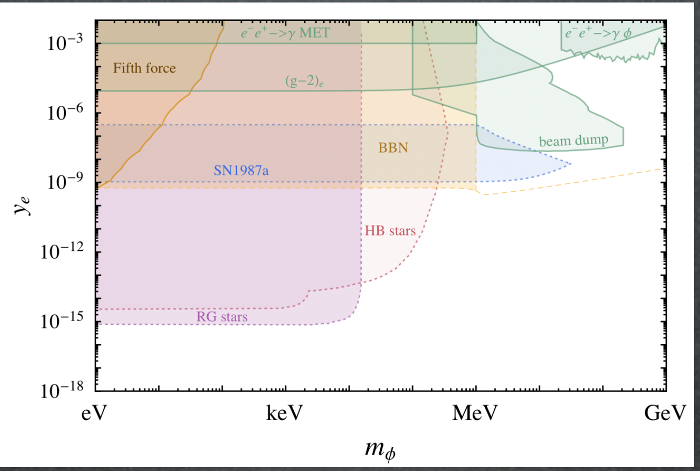
- ‘simplified (light) DM models’

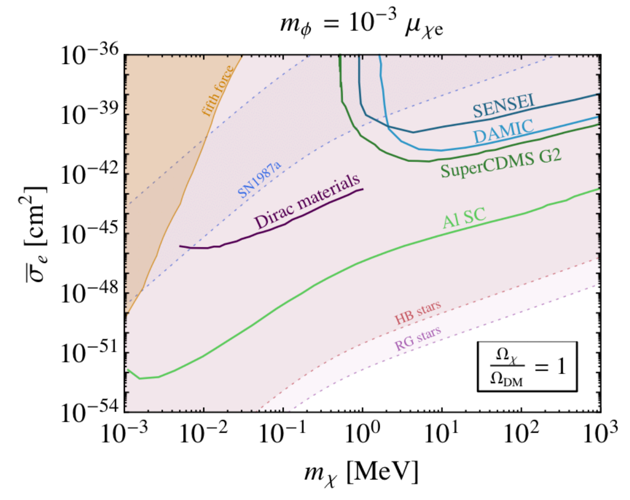
Knapen, Lin, Zurek 1709.07882

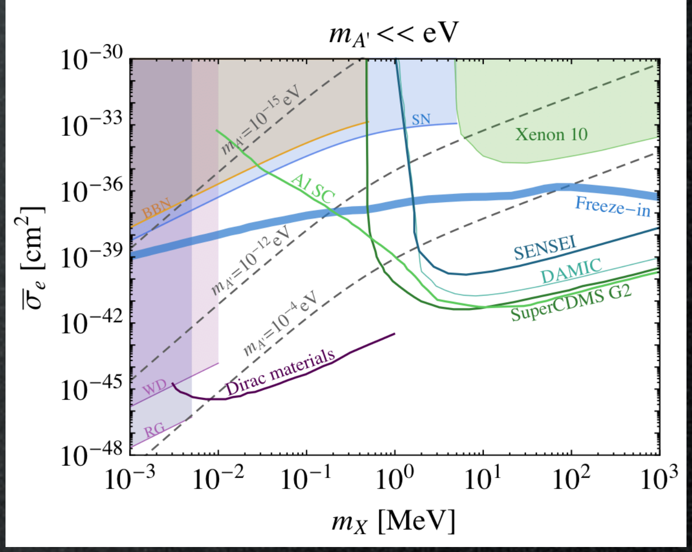
scalar DM and hadrophilic scalar mediator	scalar DM and leptophilic scalar mediator	fermionic DM and vector mediator (e.g. dark photon)
$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n\phi\bar{n}n,$	$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_e\phi\bar{e}e.$	$\mathcal{L} \supset= -\frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} - y_\chi A'_\mu \bar{\chi}\gamma^\mu\chi$

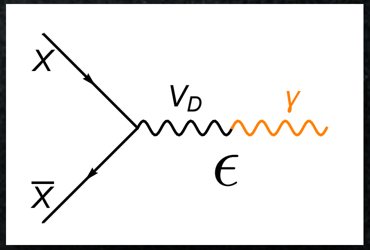












Theory

Sub-GeV DM?

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

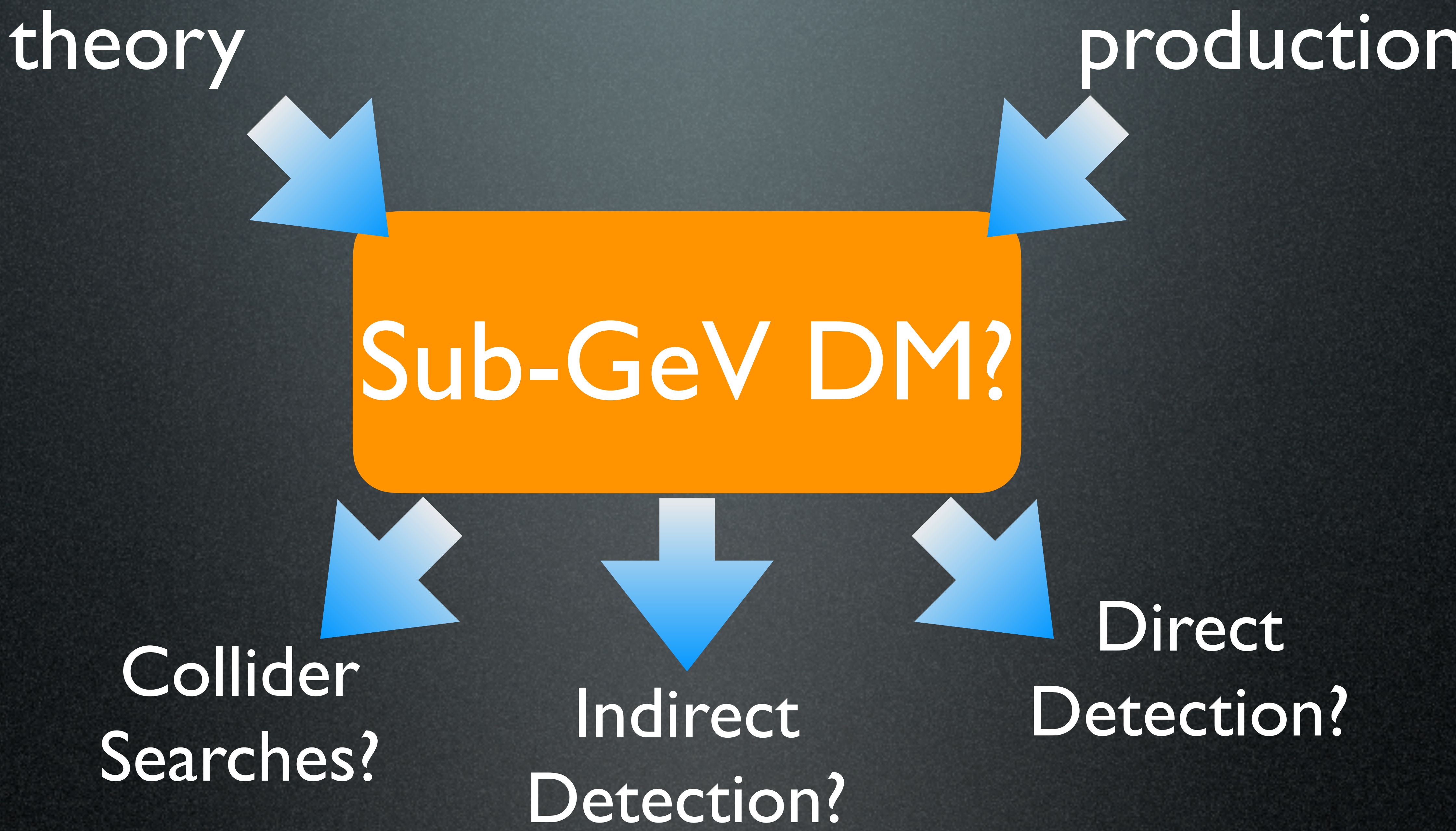
Theory

Sub-GeV DM?

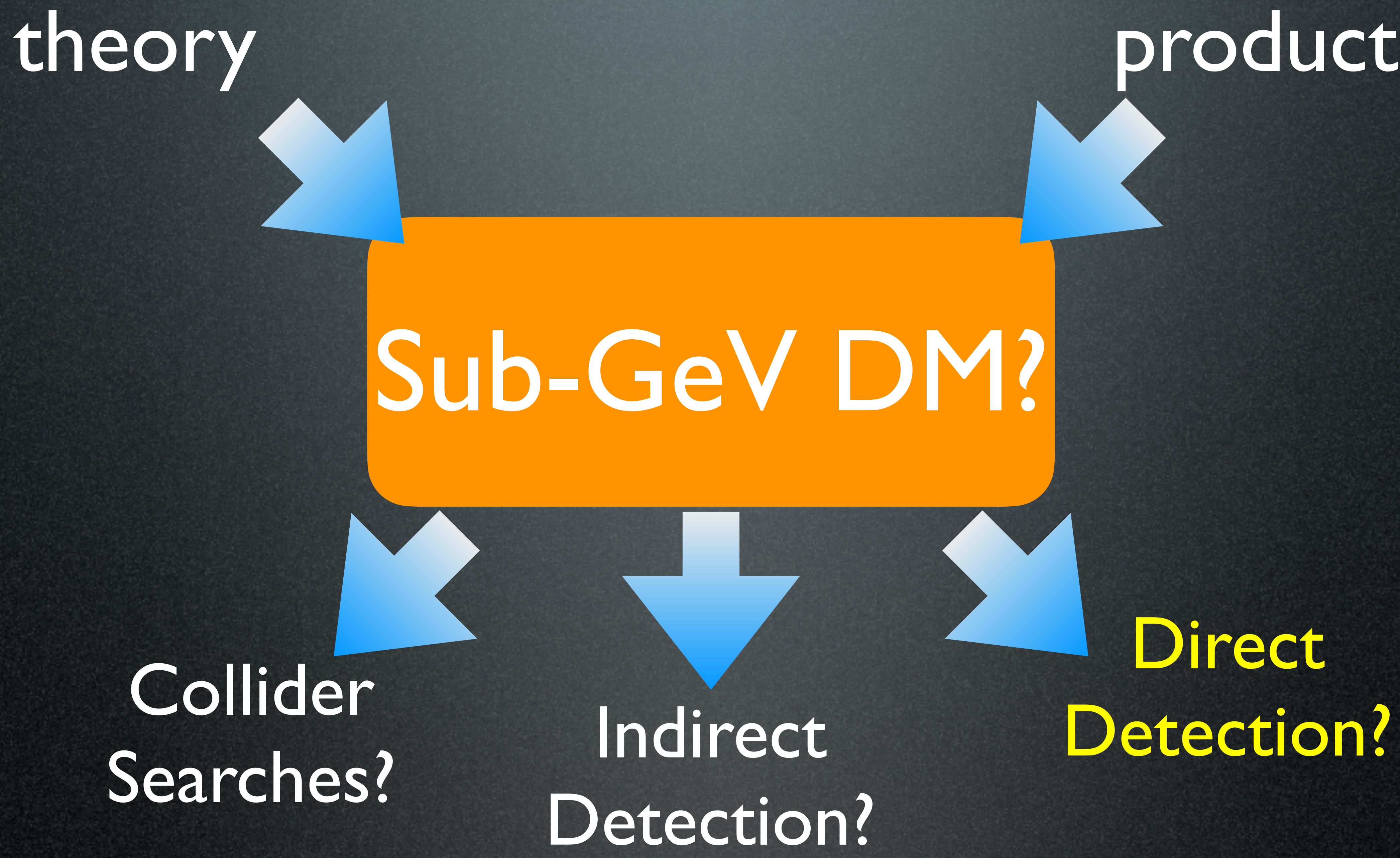
Why not!

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

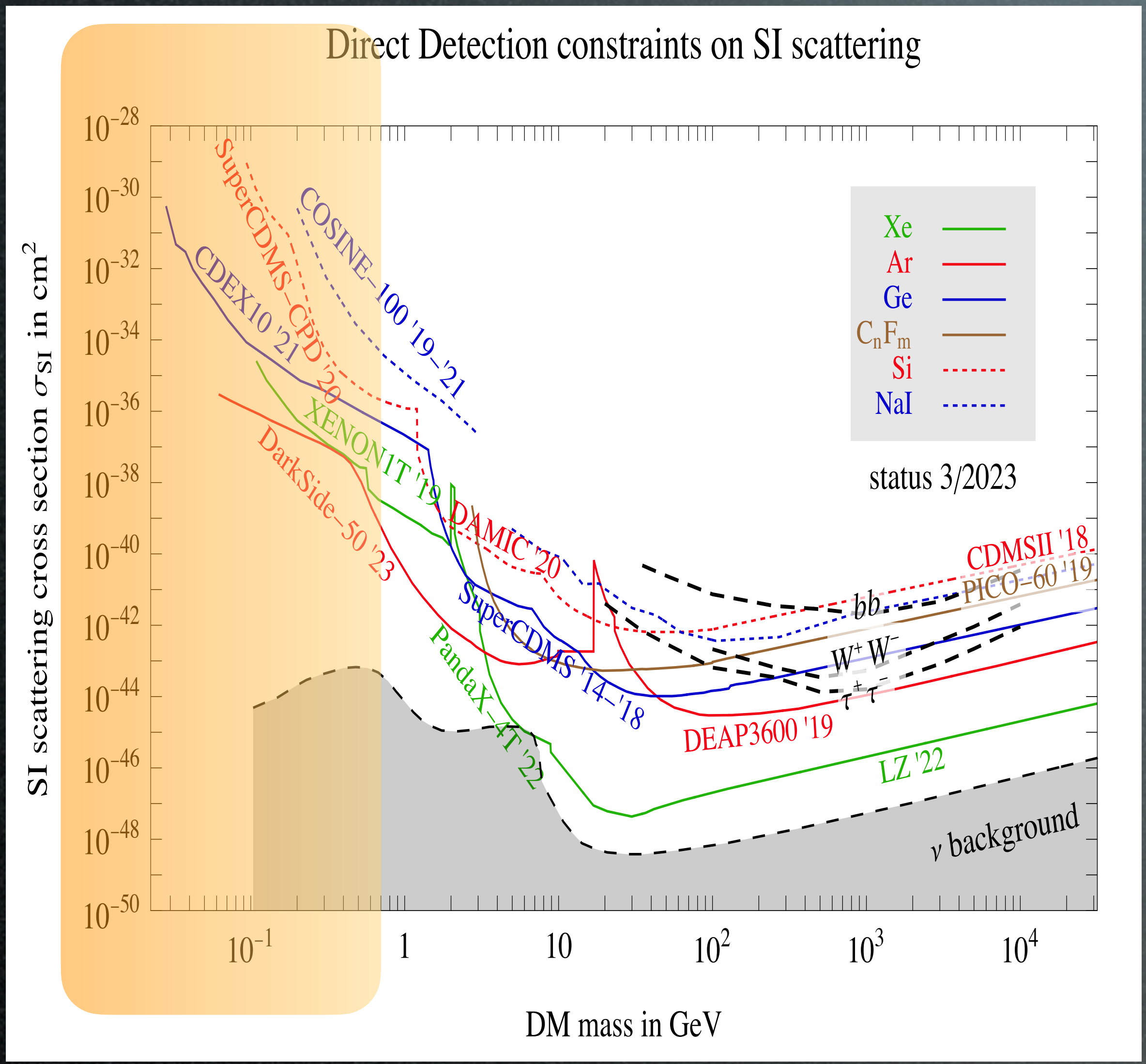
Candidates


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

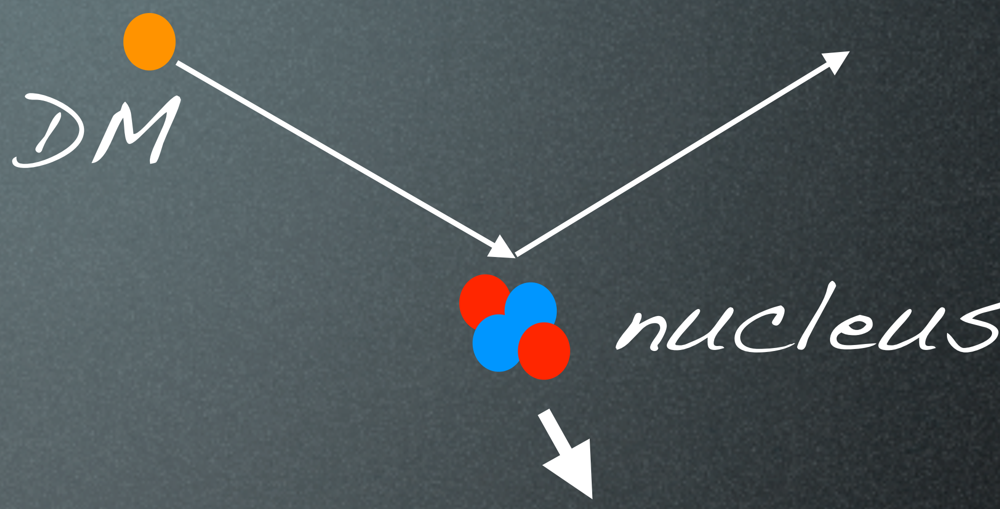
Candidates


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

Direct Detection of sub-GeV DM



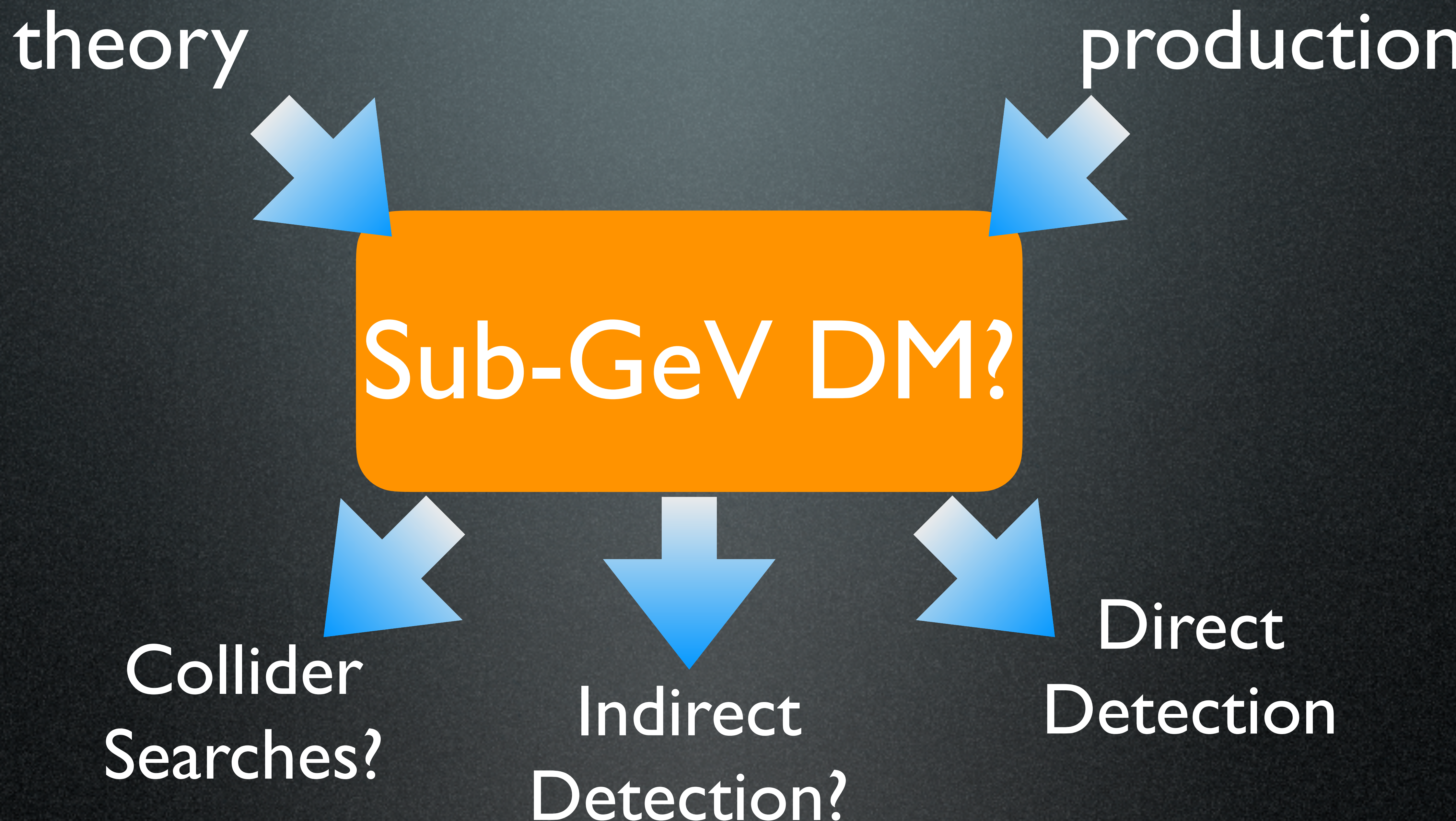
M. Cirelli, A. Strumia, J. Zupan 2406.01705



deposited energy is below threshold for typical nuclear recoil experiments

- electron recoil signal
- Migdal effect
- new experimental strategies

Candidates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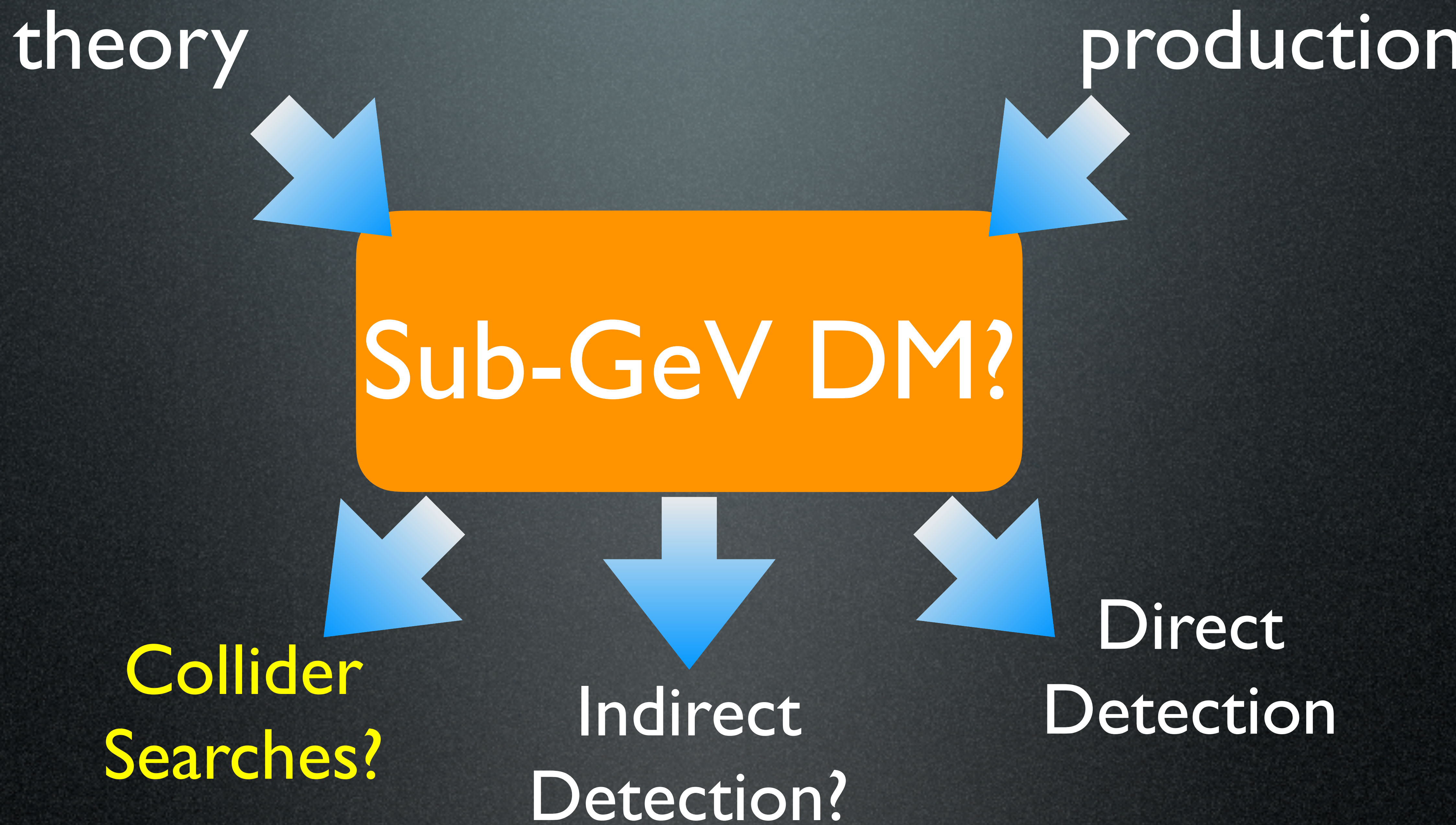
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Searches?
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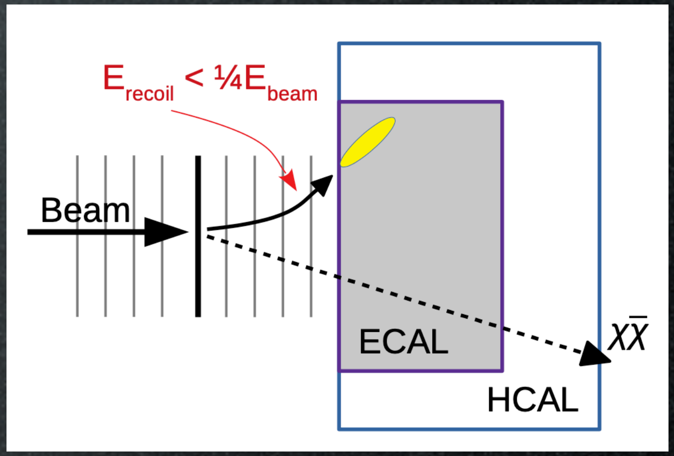
Detection?
Direct
Detection

Collider searches of sub-GeV DM

Missing $\not{E}_T$ signature is challenging for LHC experiments

- fixed target / beam dump experiments

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



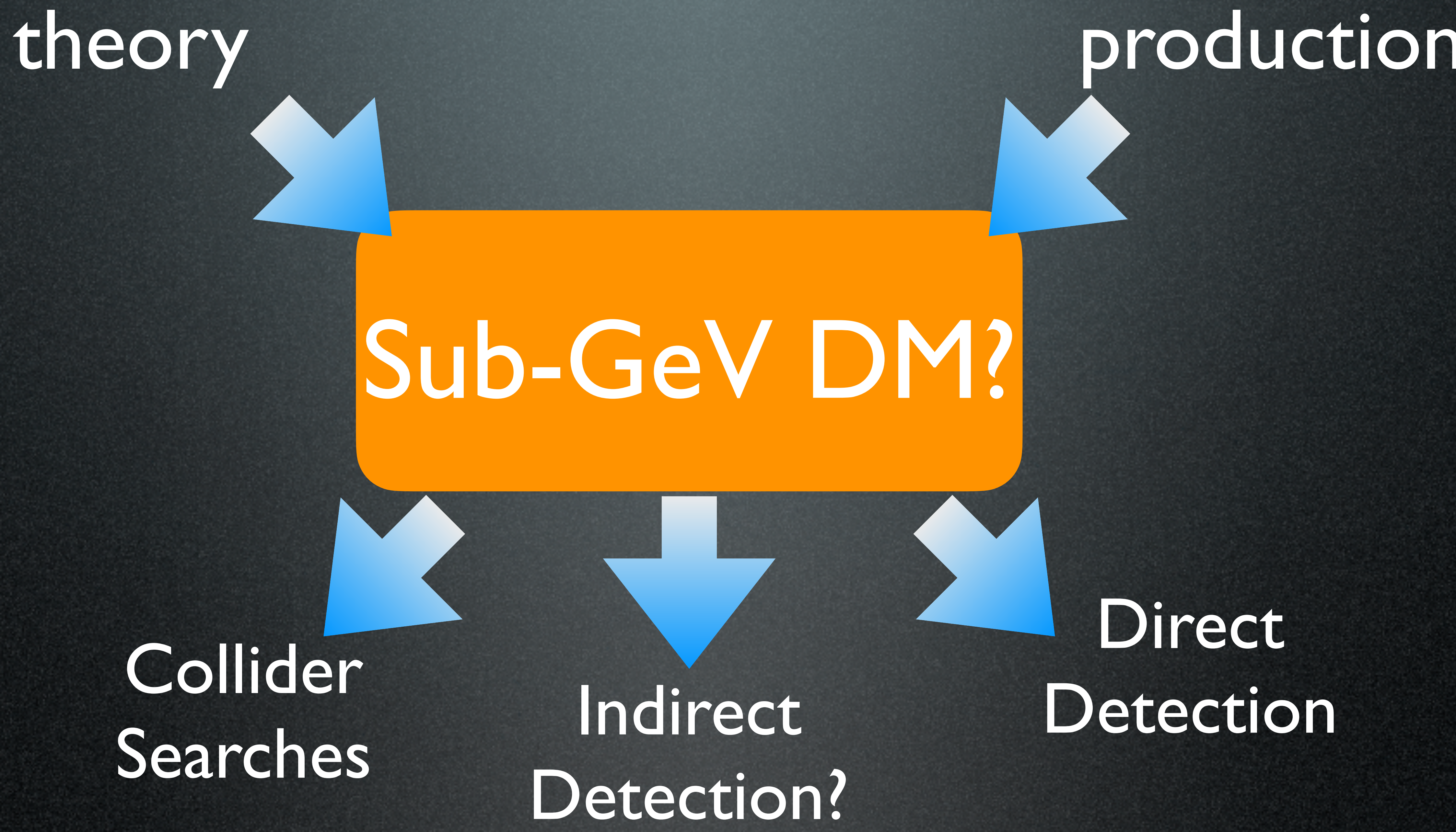
e.g. LDMX coll. 1808.05219

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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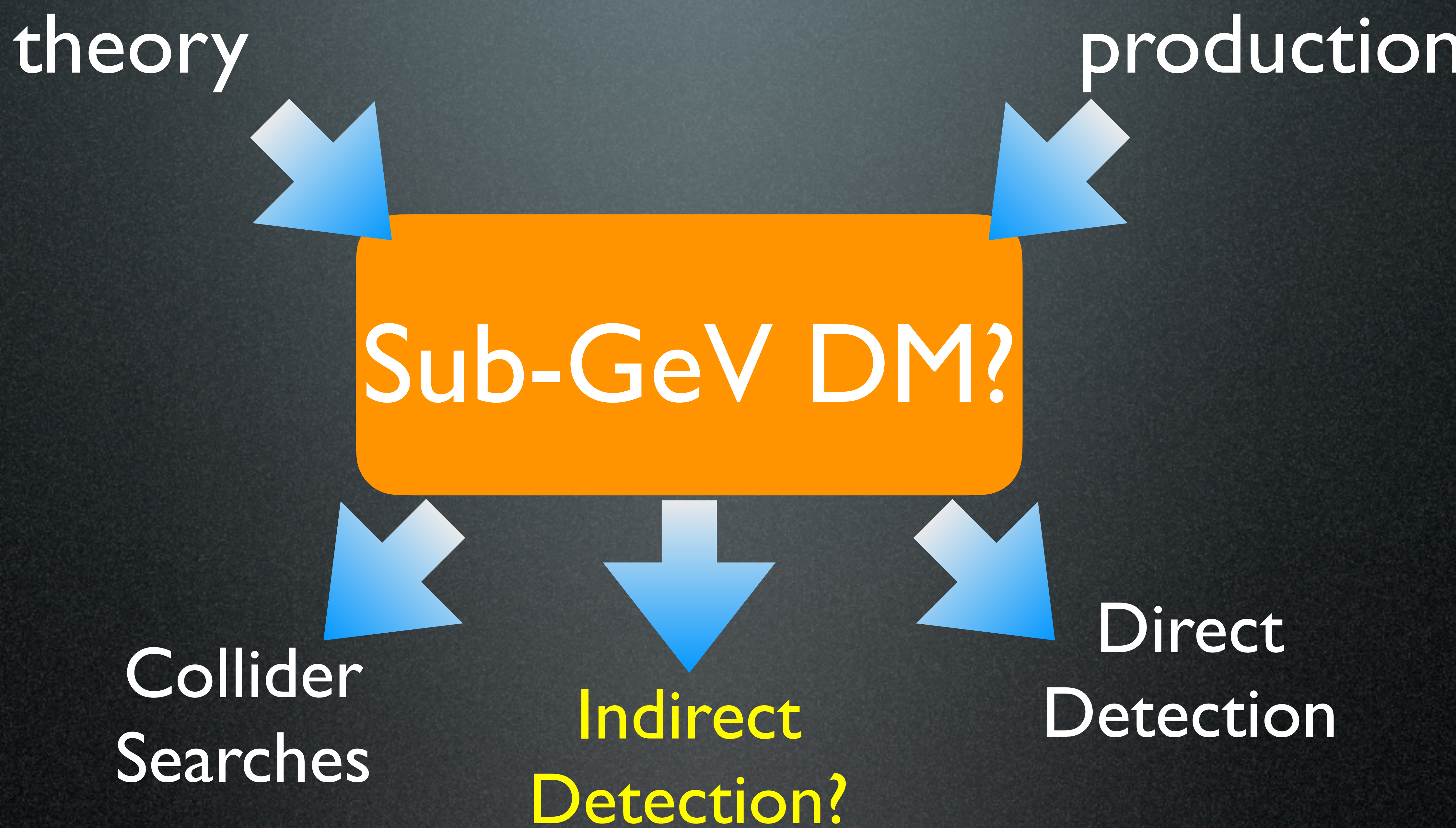
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Collider
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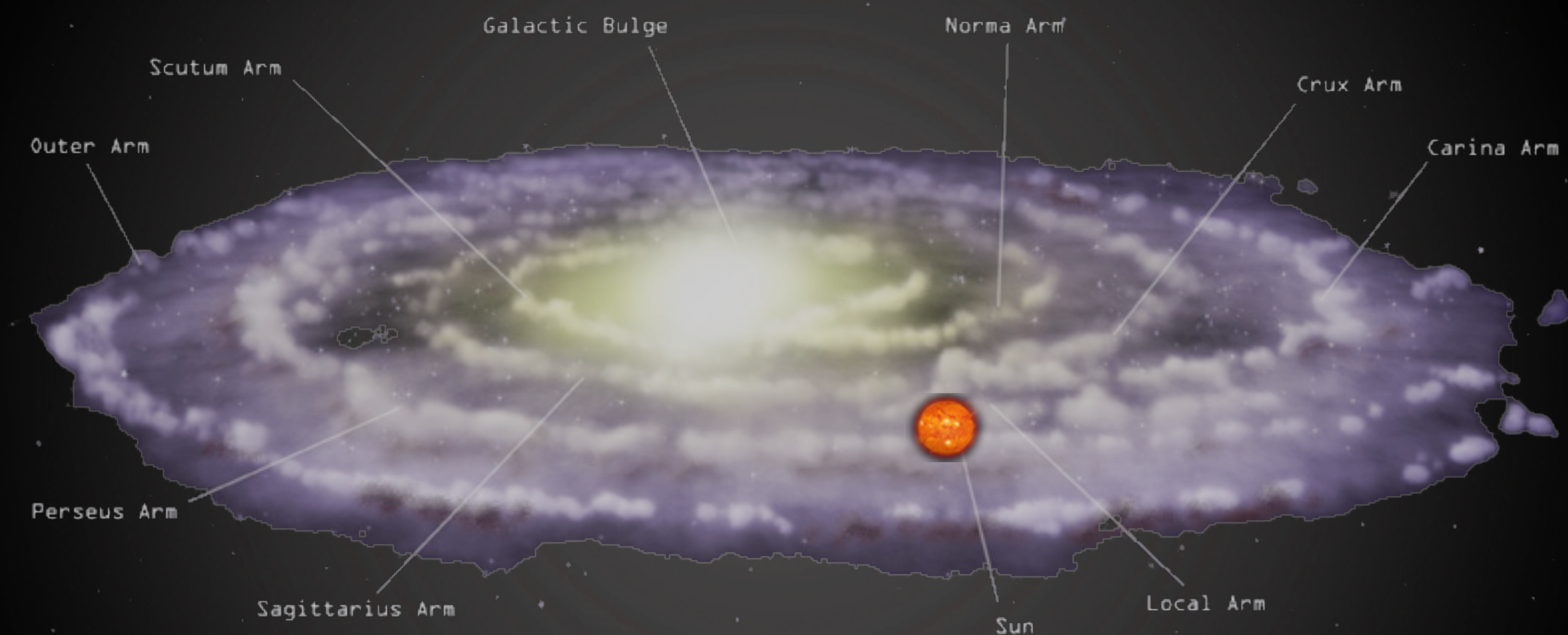
Detection?
Direct
Detection

Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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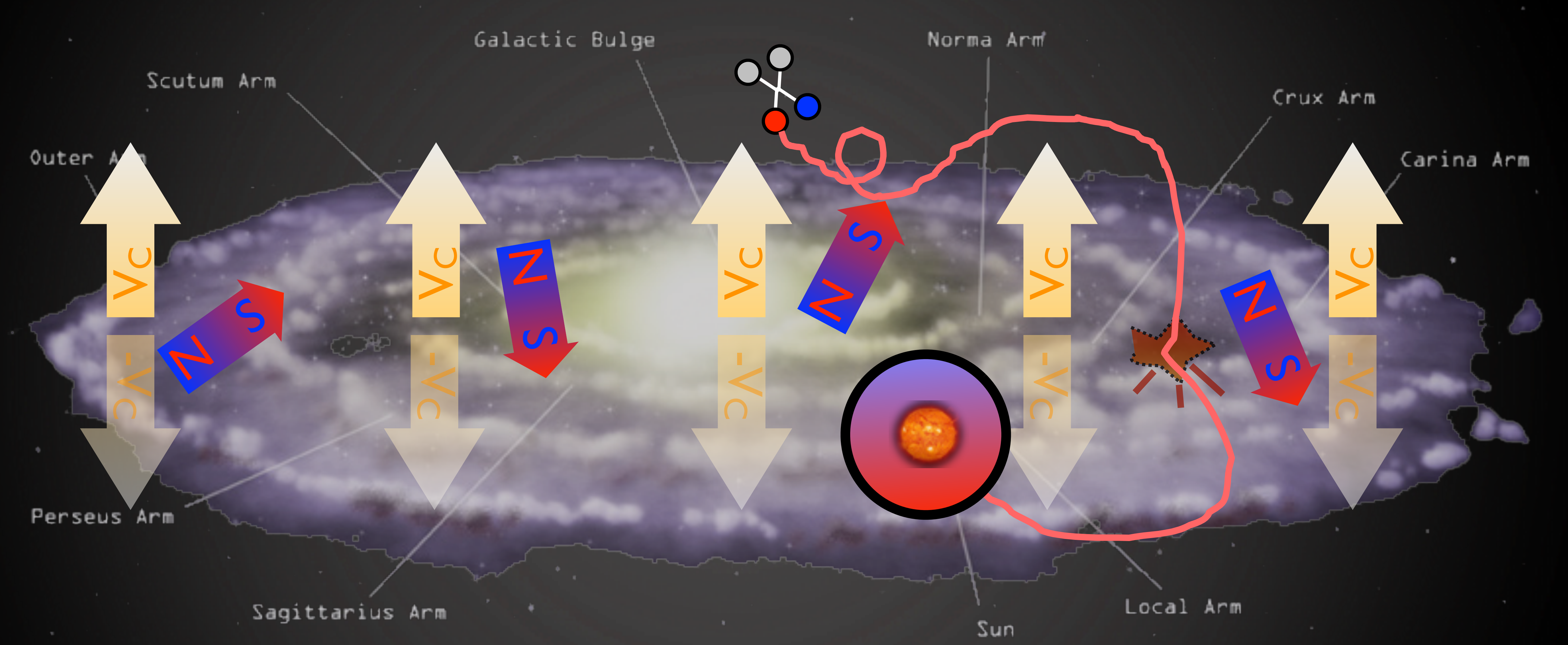

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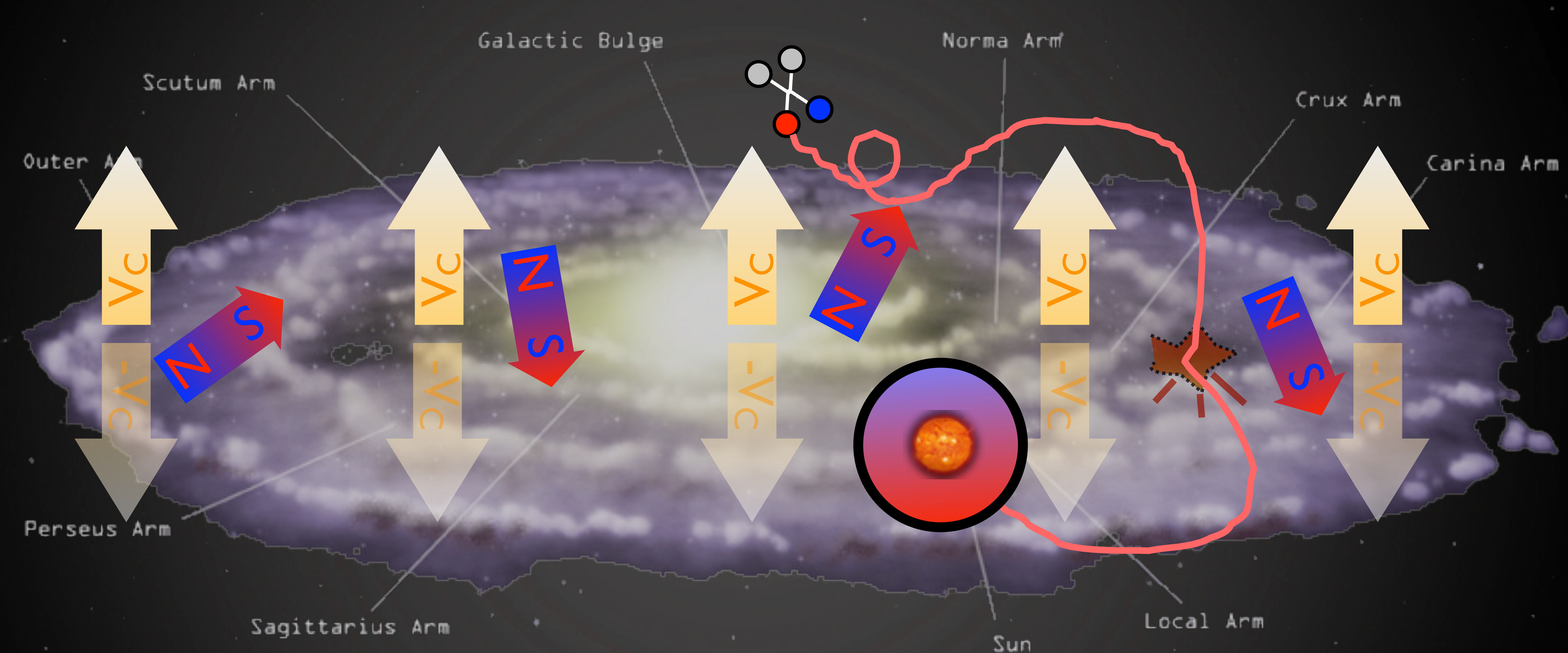
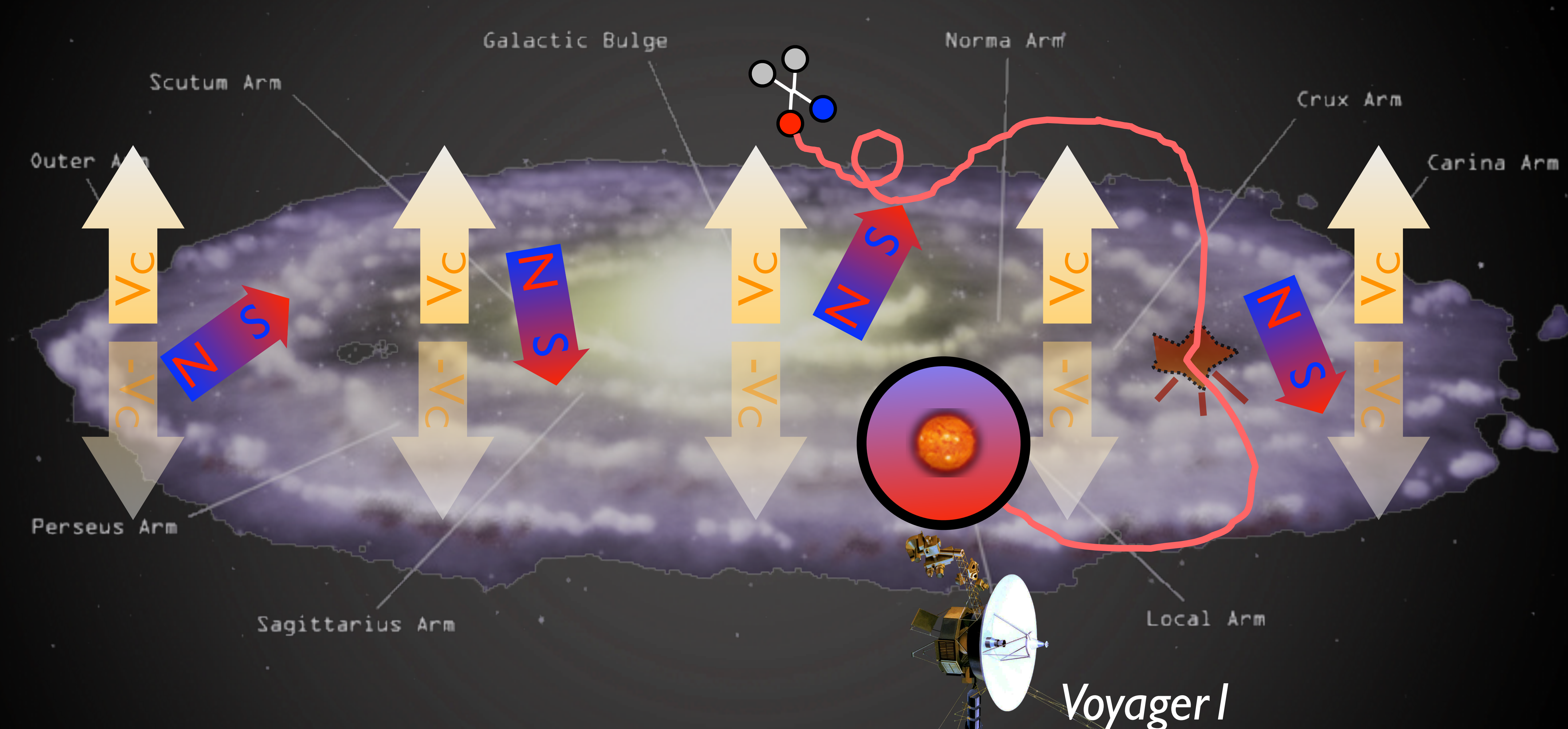


Problem:

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

Indirect Detection: charged CRs

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



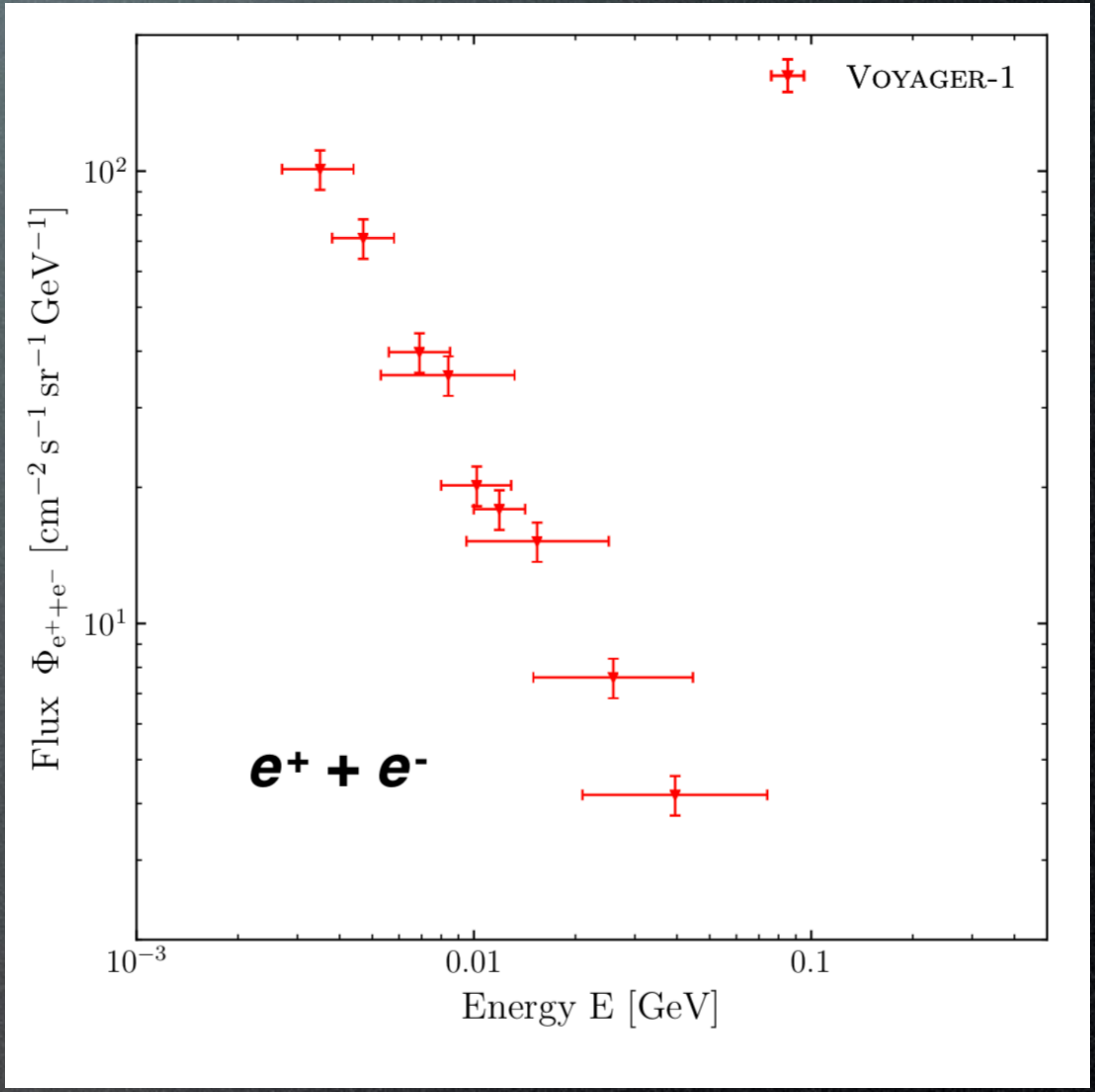
Problem:

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

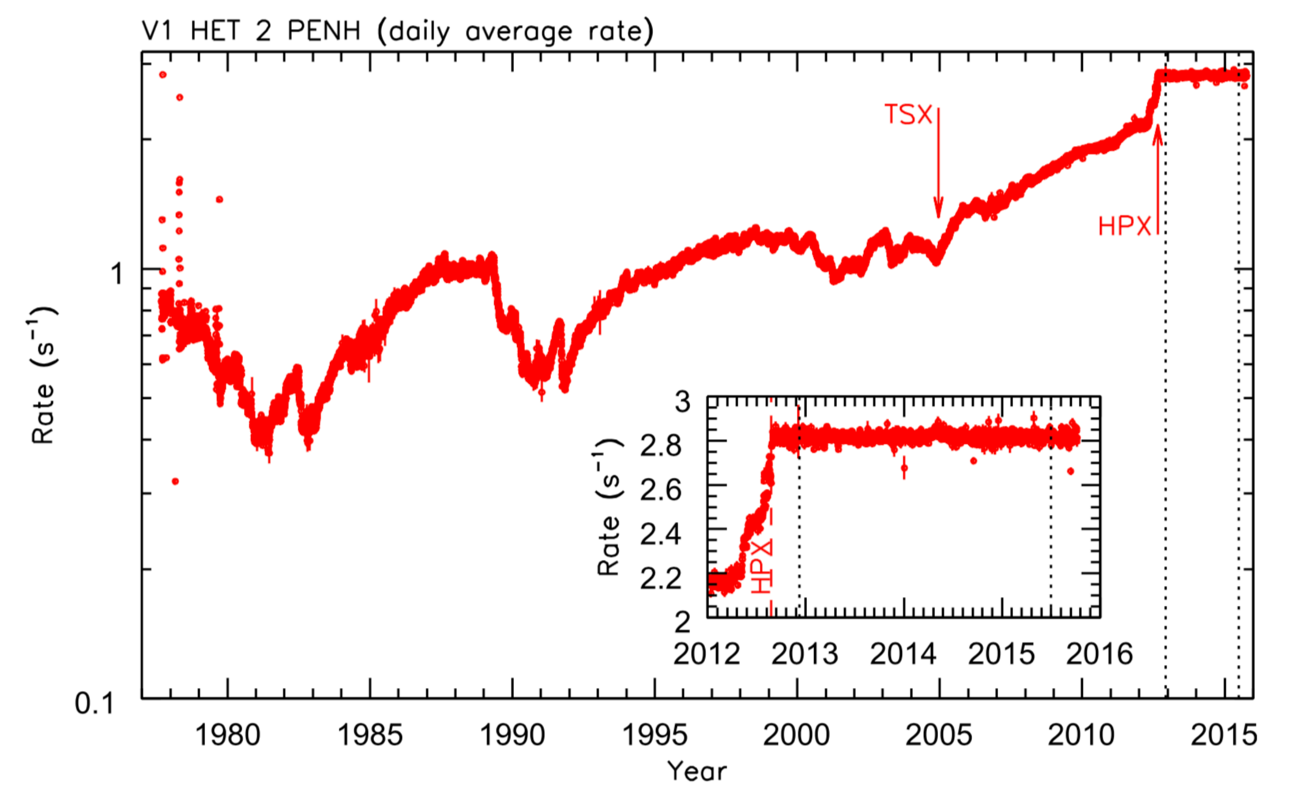
Data: leptons
low energy

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

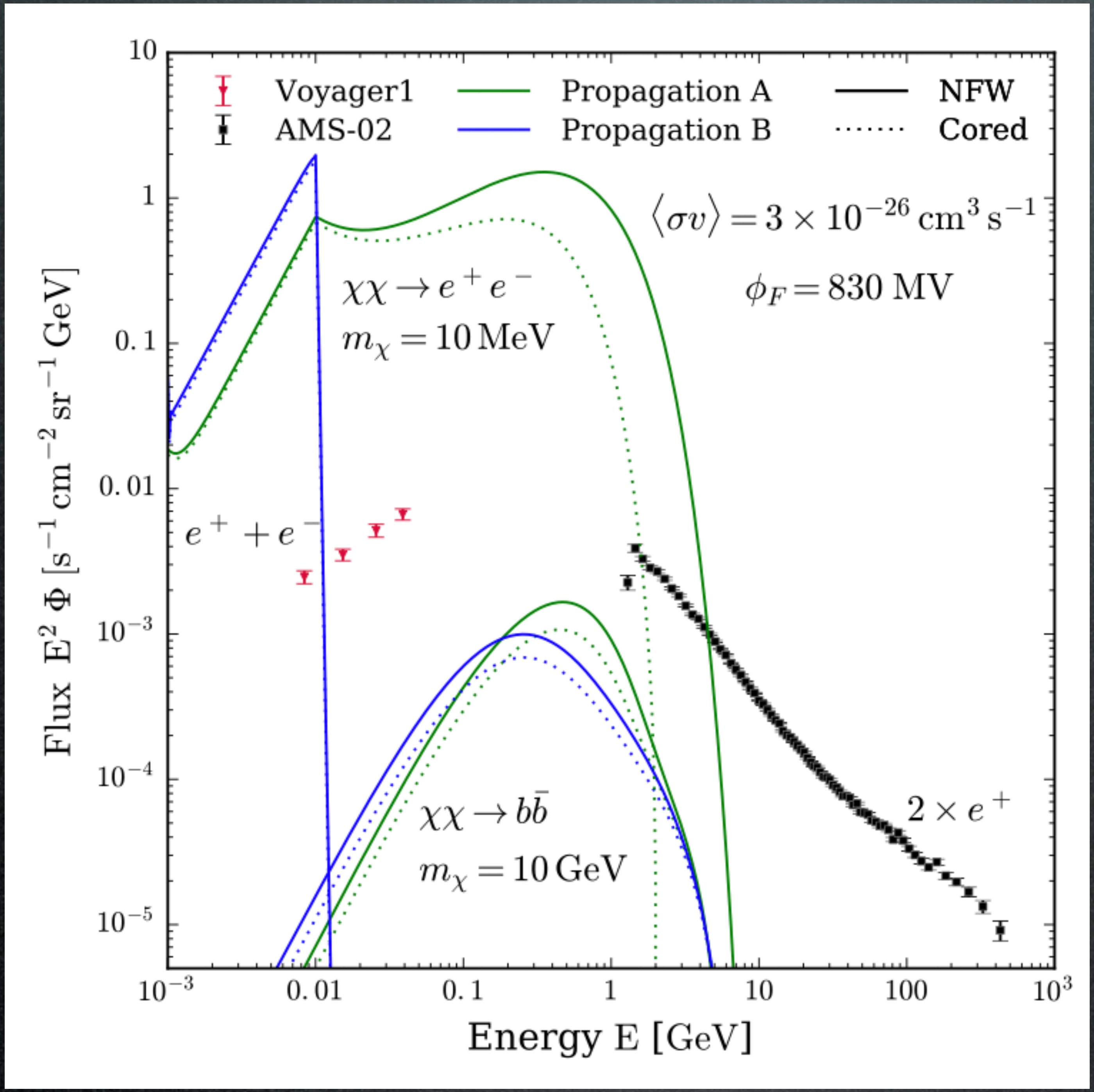


Cummings+ (Voyager-1 coll.), The Astrophysical Journal, 831:18, 2016

Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I

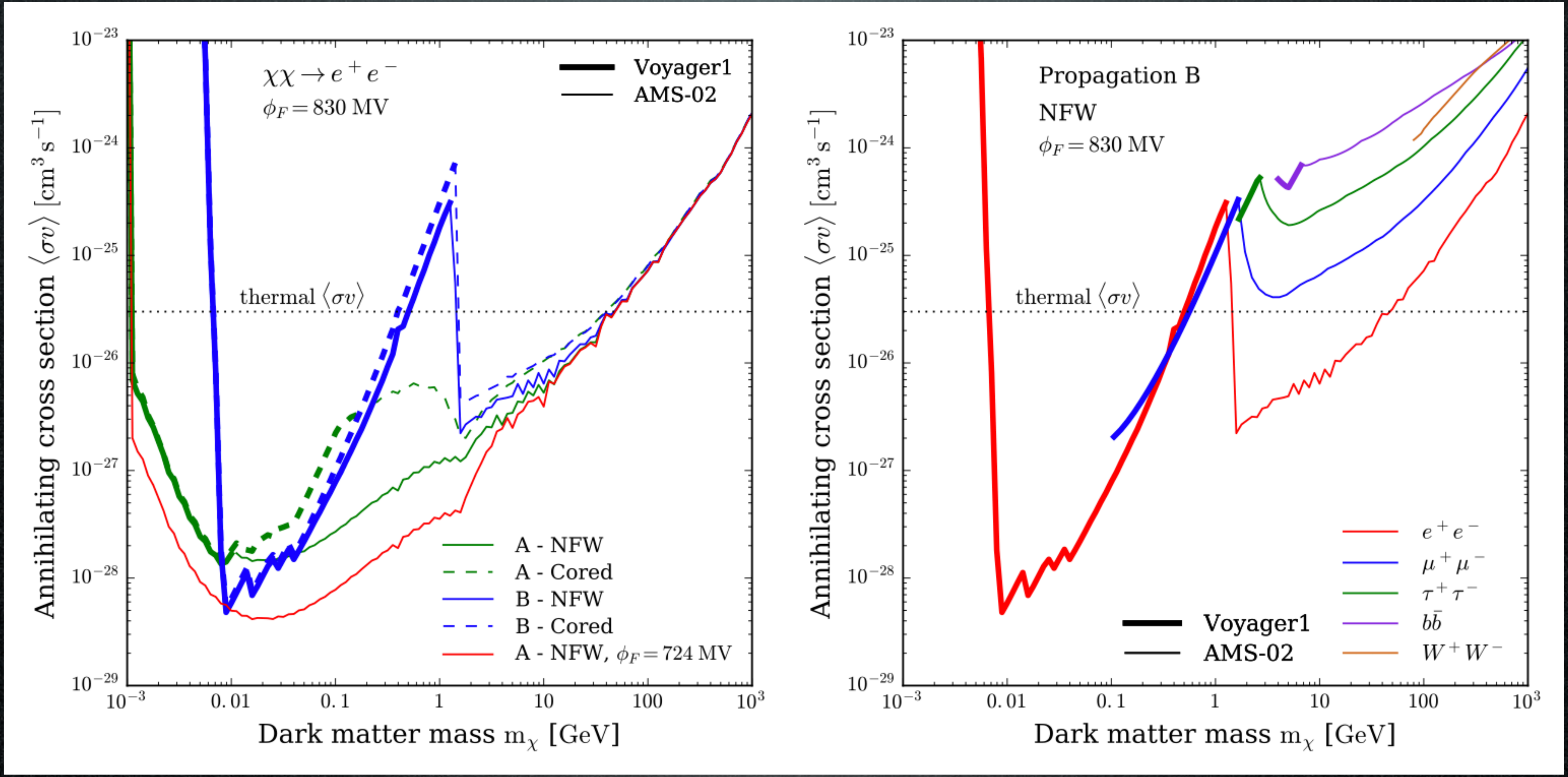


Propagation A = strong reacceleration
Propagation B = weak/no reacceleration

Indirect Detection: charged CRs

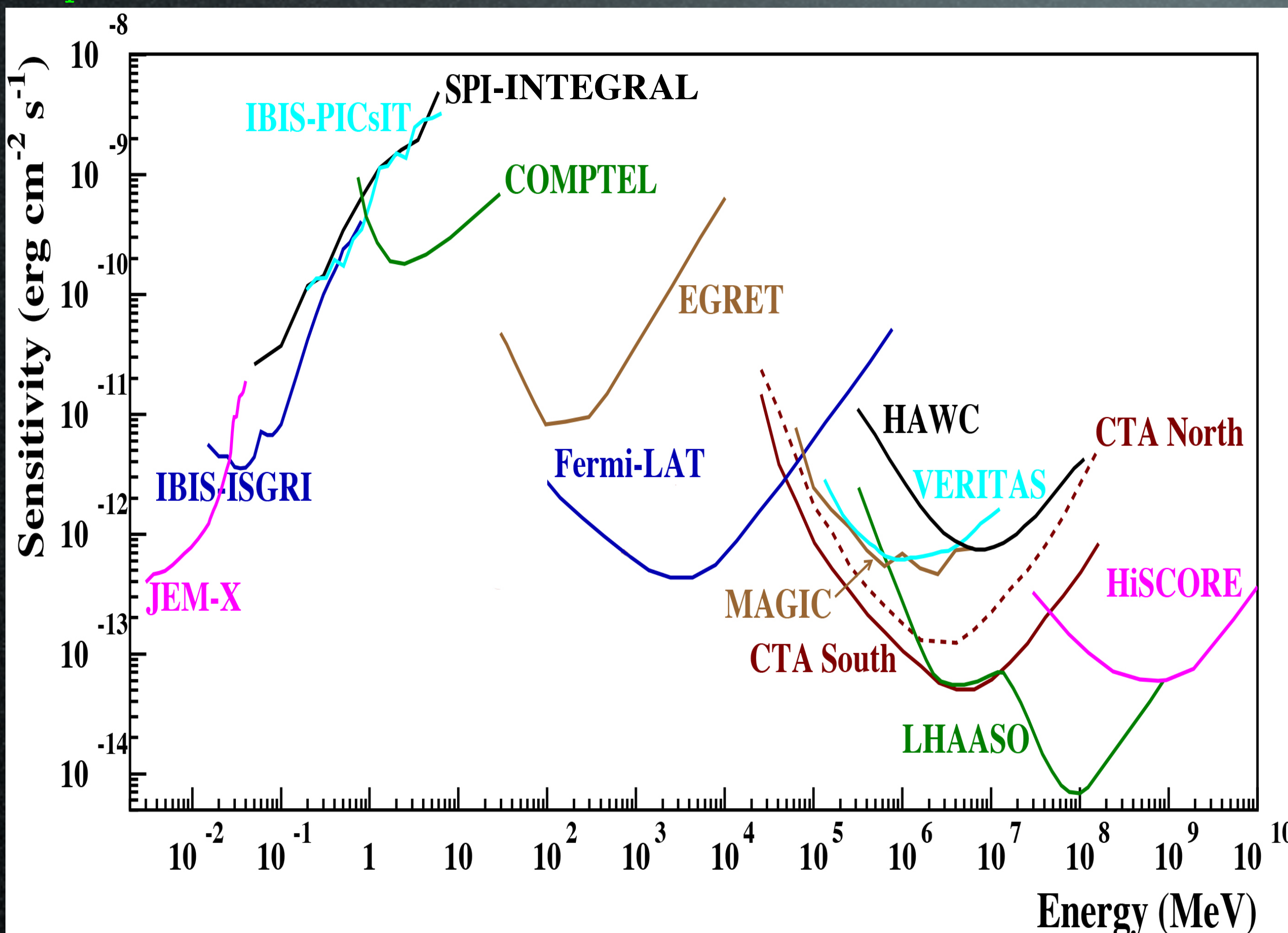
Boudaud, Lavalle, Salati 1612.07698

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?, Compair?, Amego?, COSI?

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

Cirelli, Strumia, Zupan 2406.01705

Indirect detection: photons

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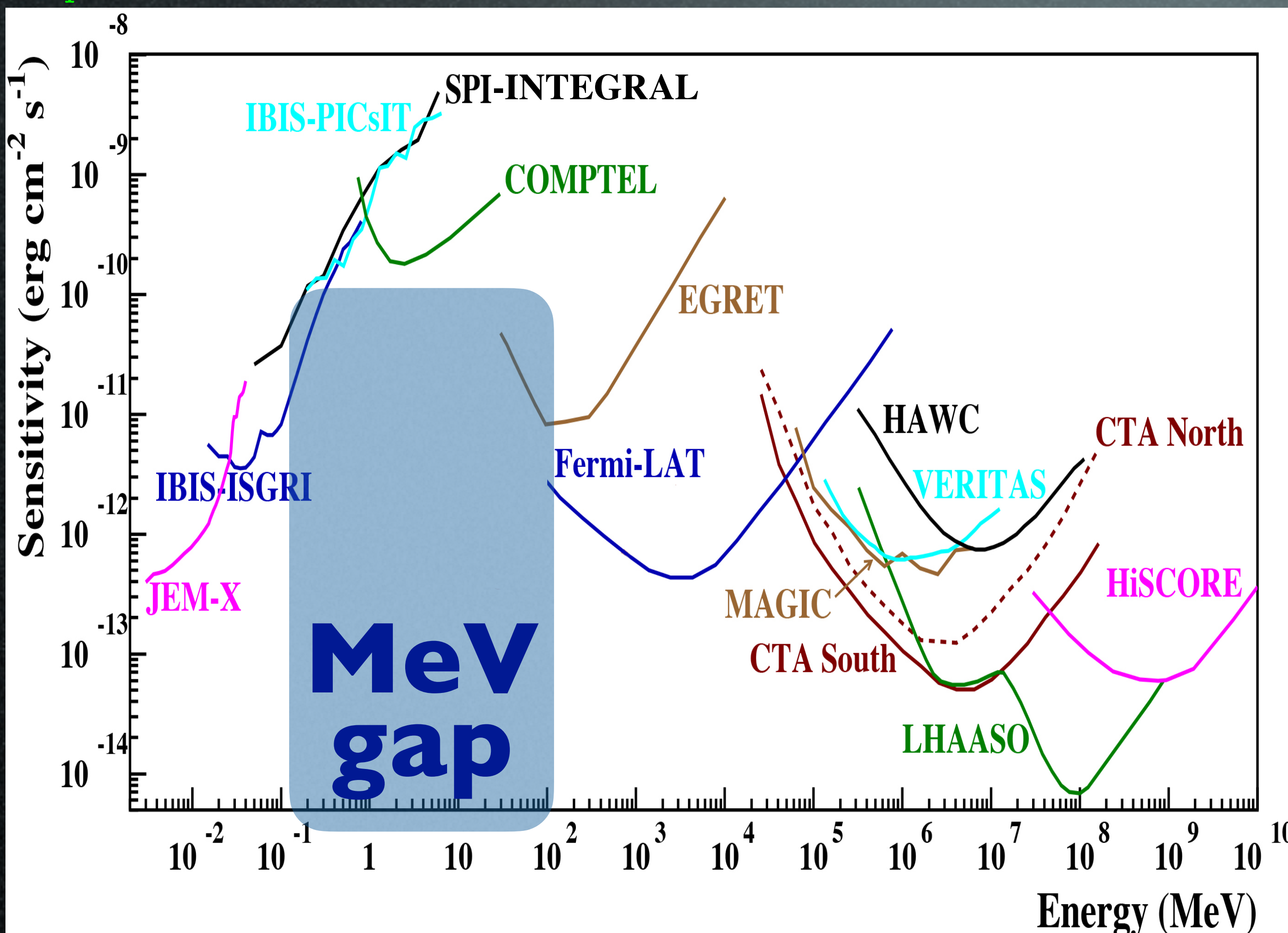

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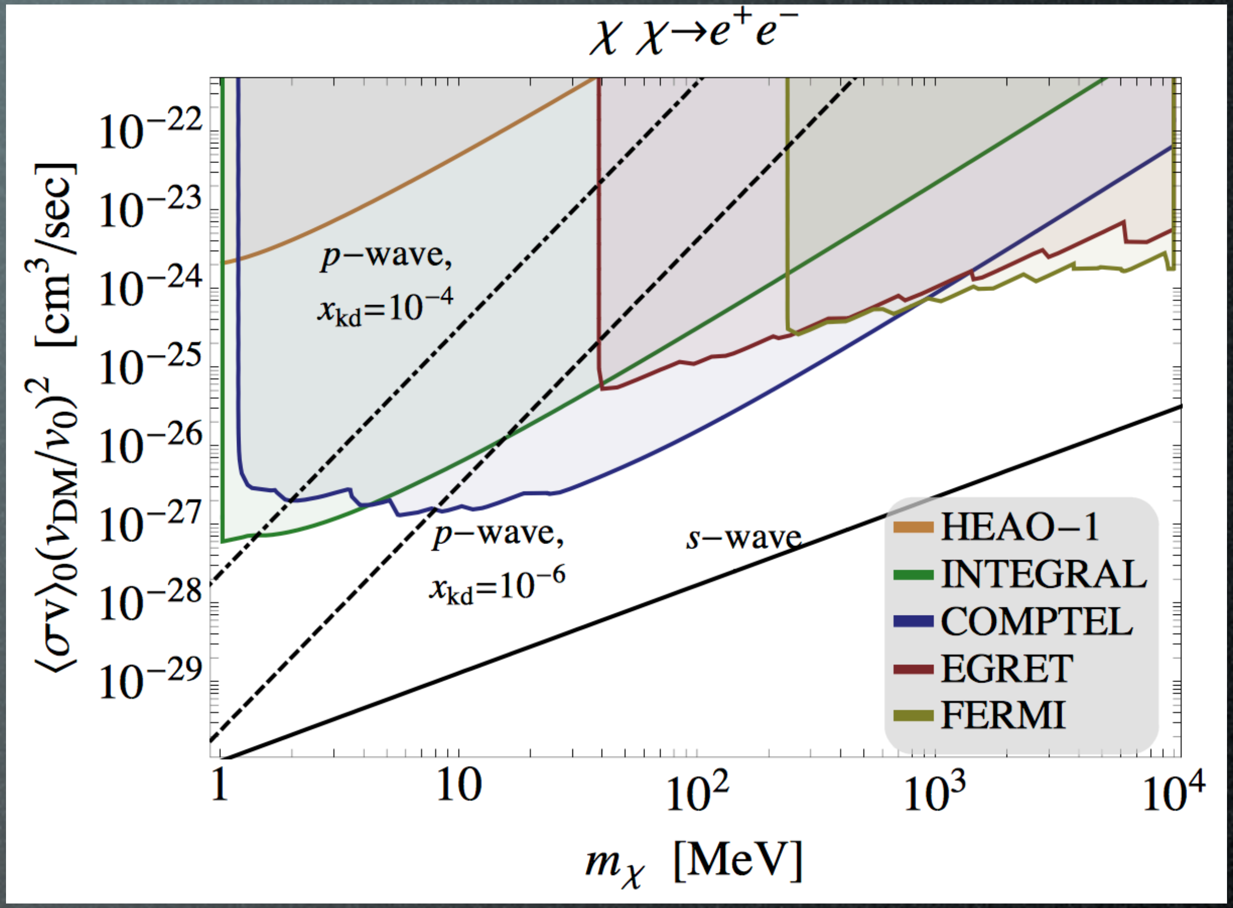
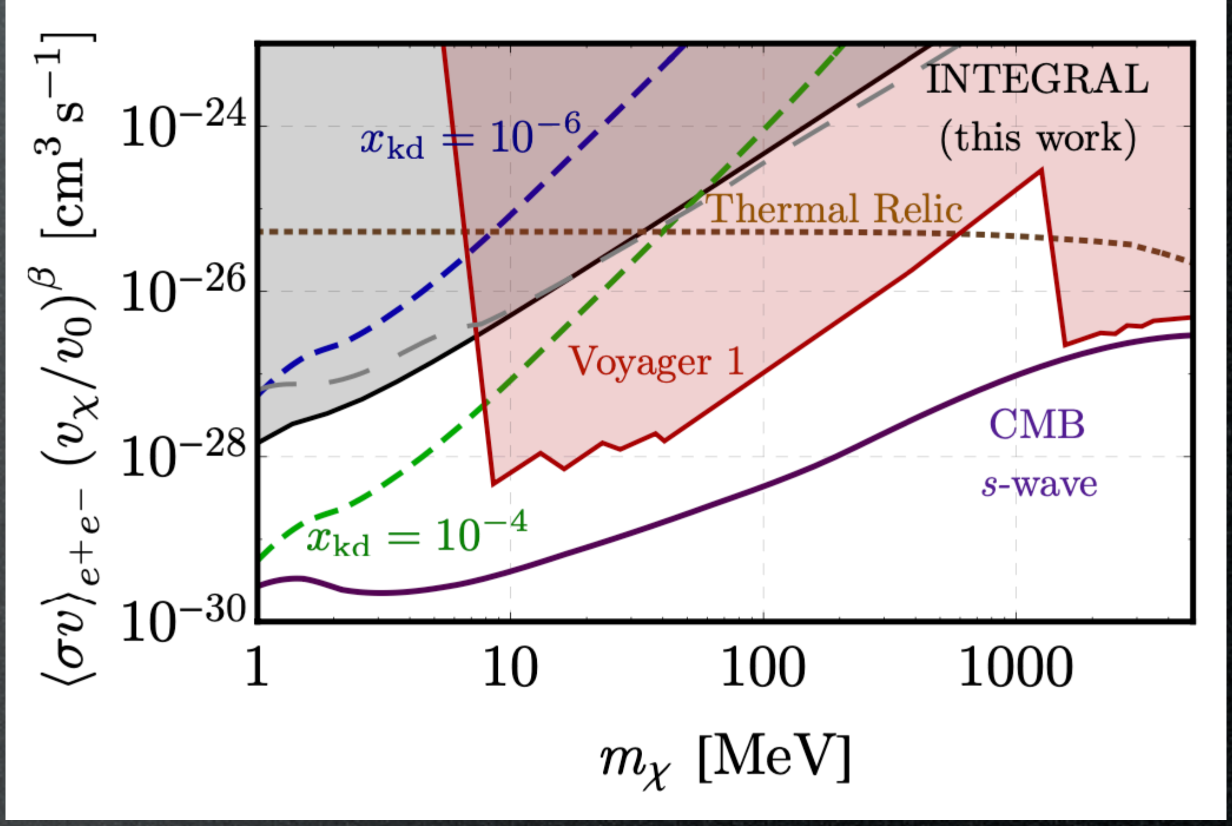
Cirelli, Strumia, Zupan 2406.01705

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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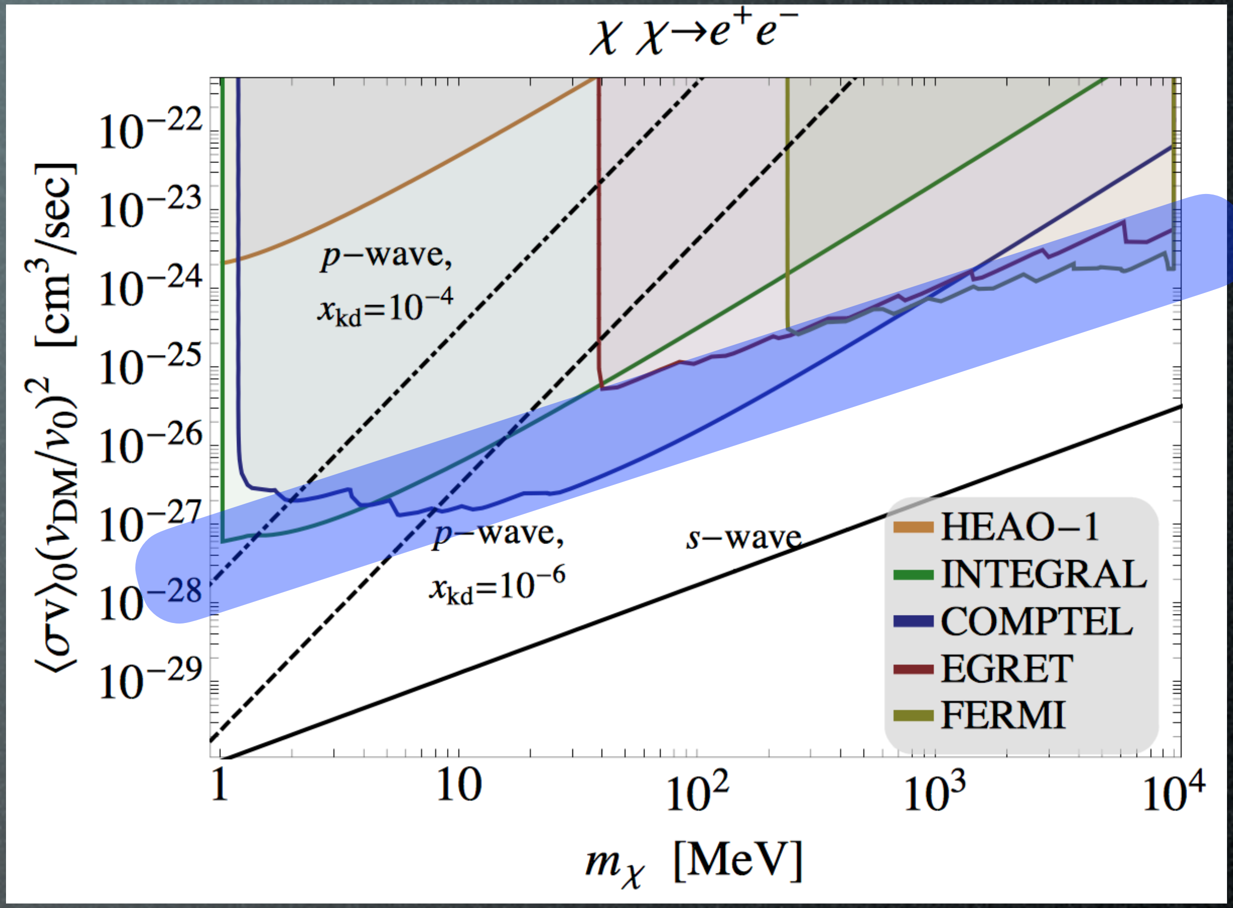

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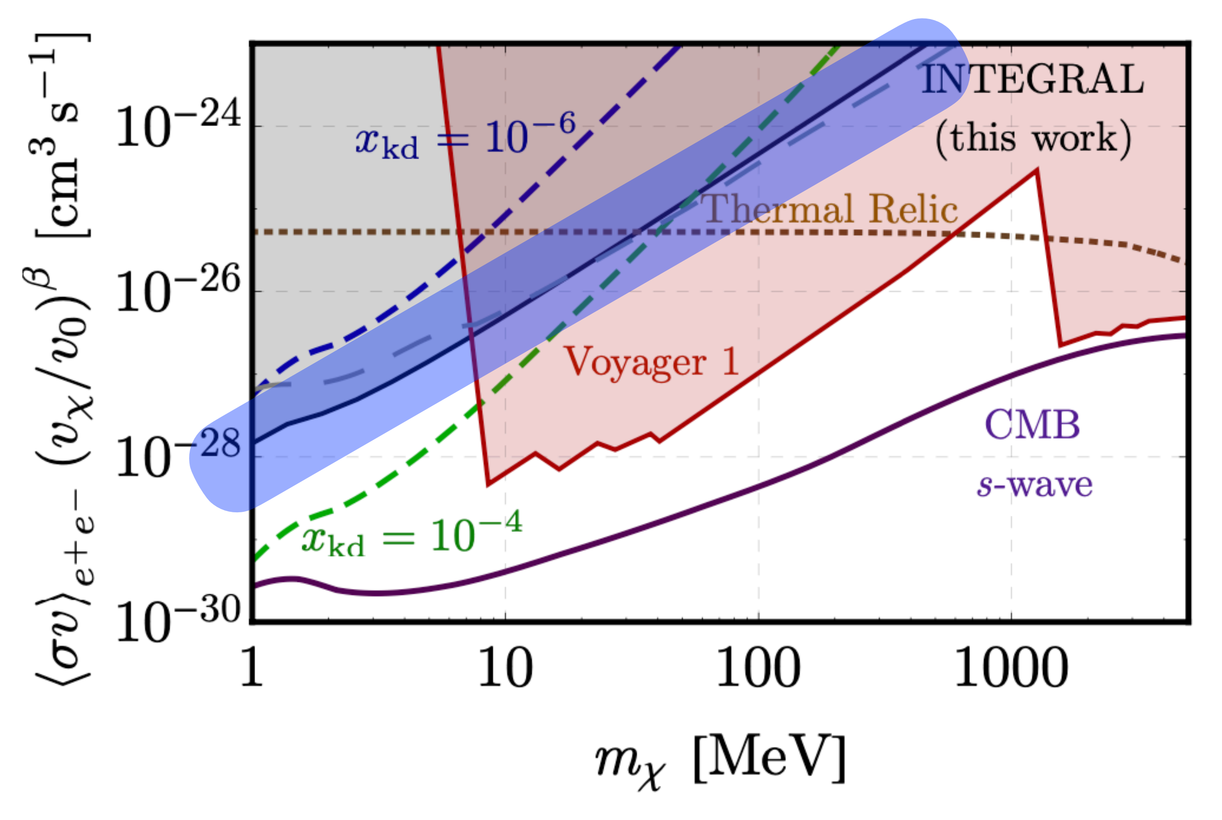

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Indirect detection: photons

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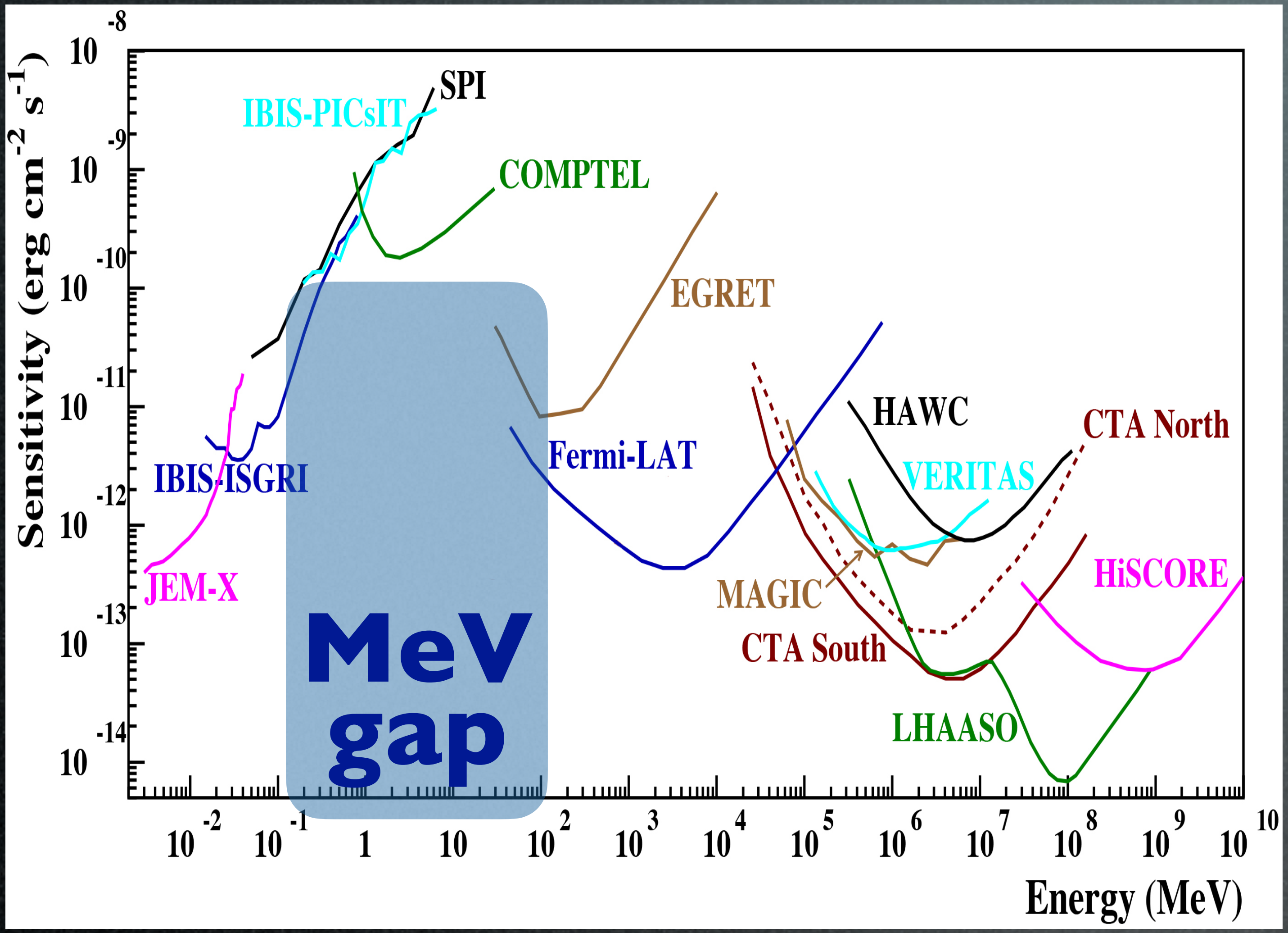

How to do better?

ICS & X-rays!

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

Sub-GeV DM & X-rays

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

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

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

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

Sub-GeV DM & X-rays

Annihilation channels

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

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

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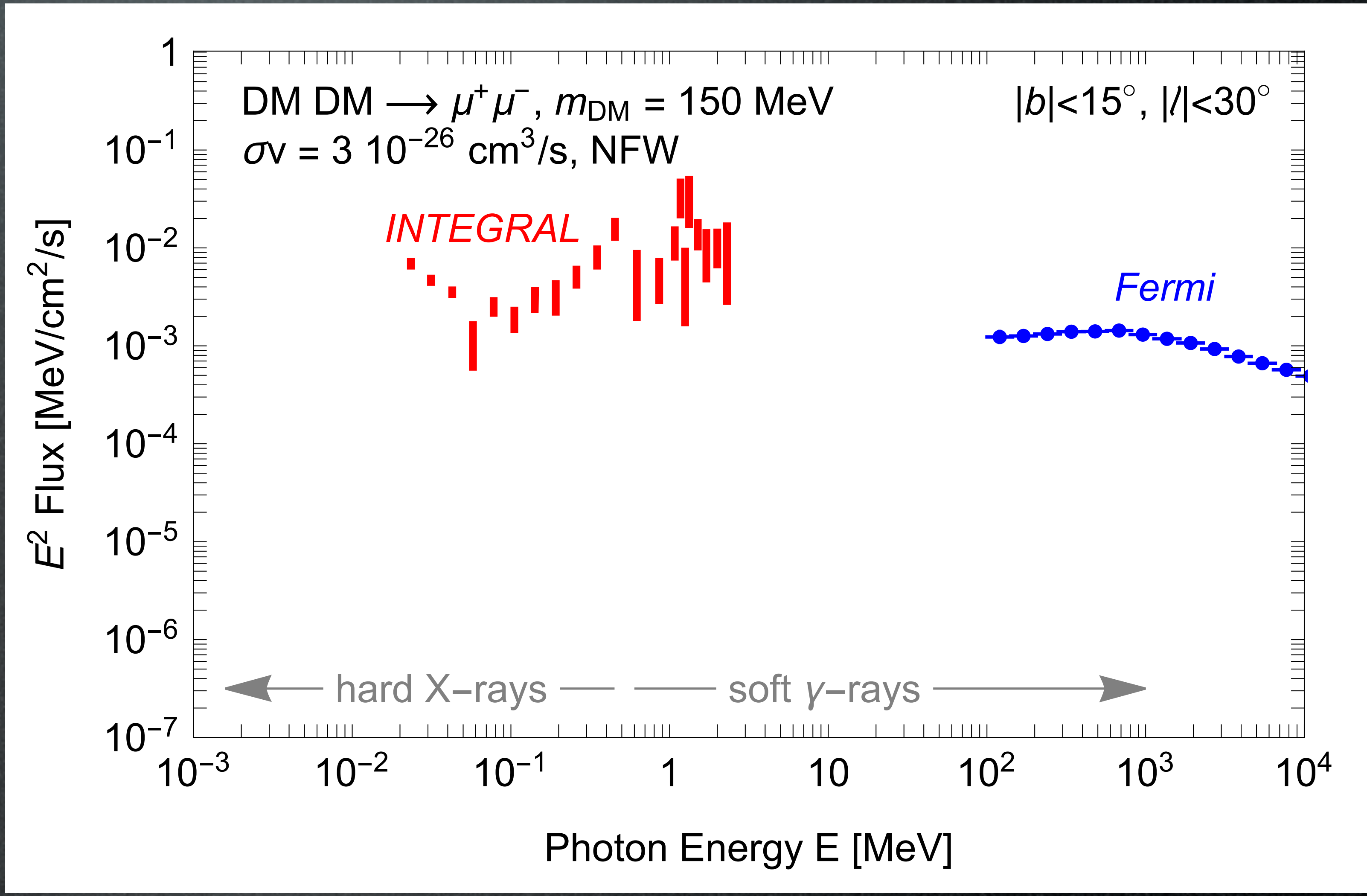

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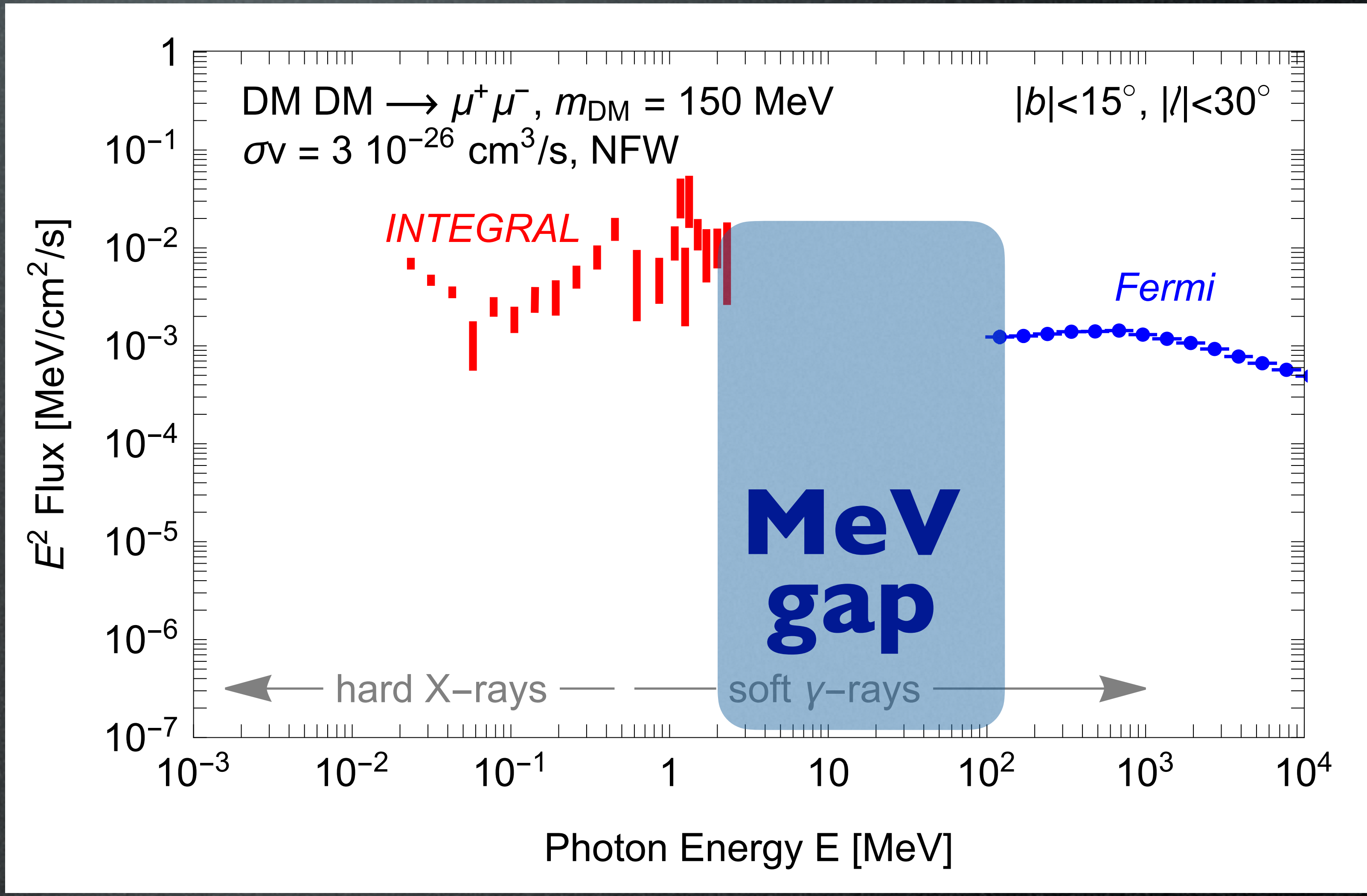

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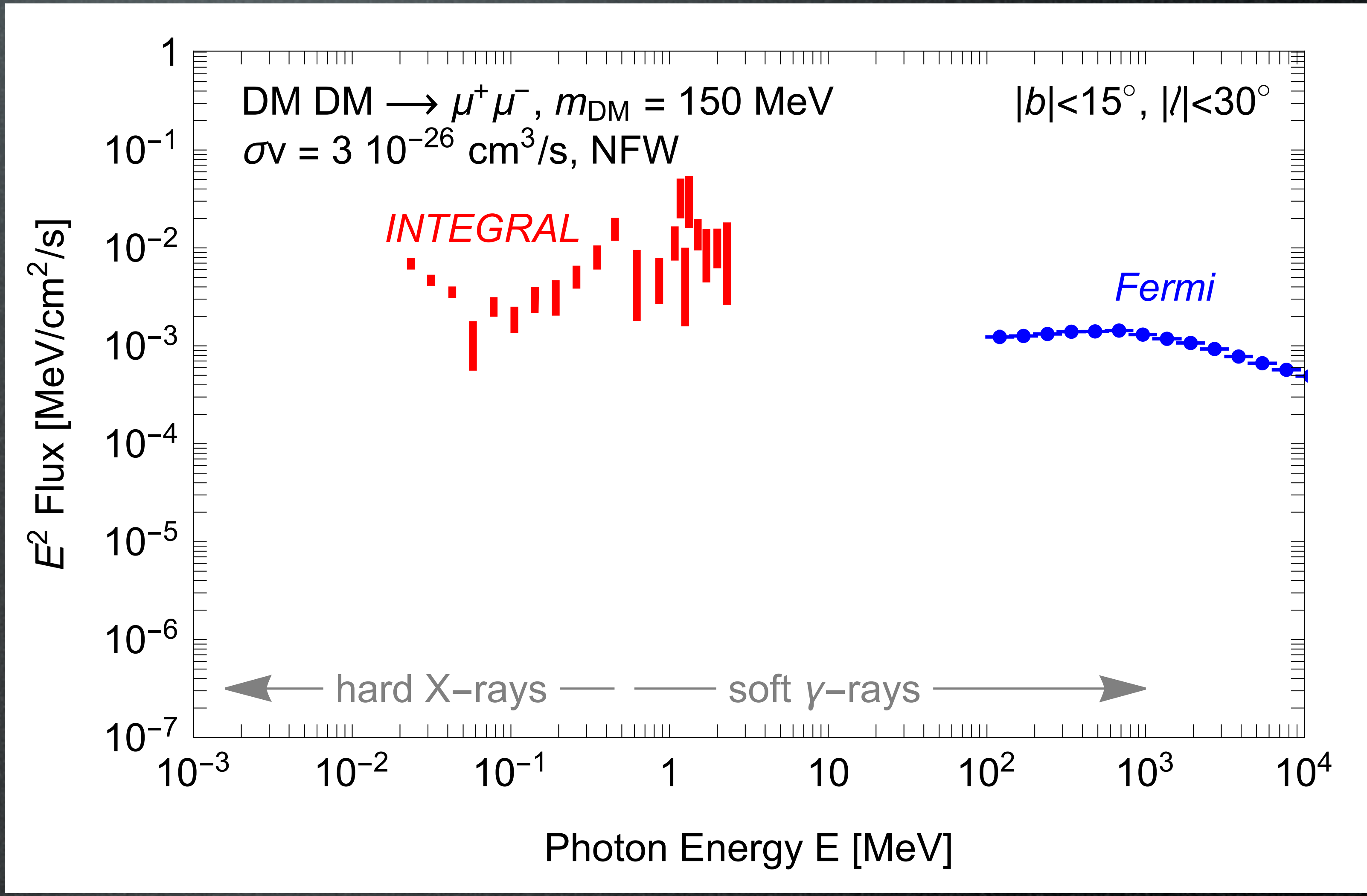

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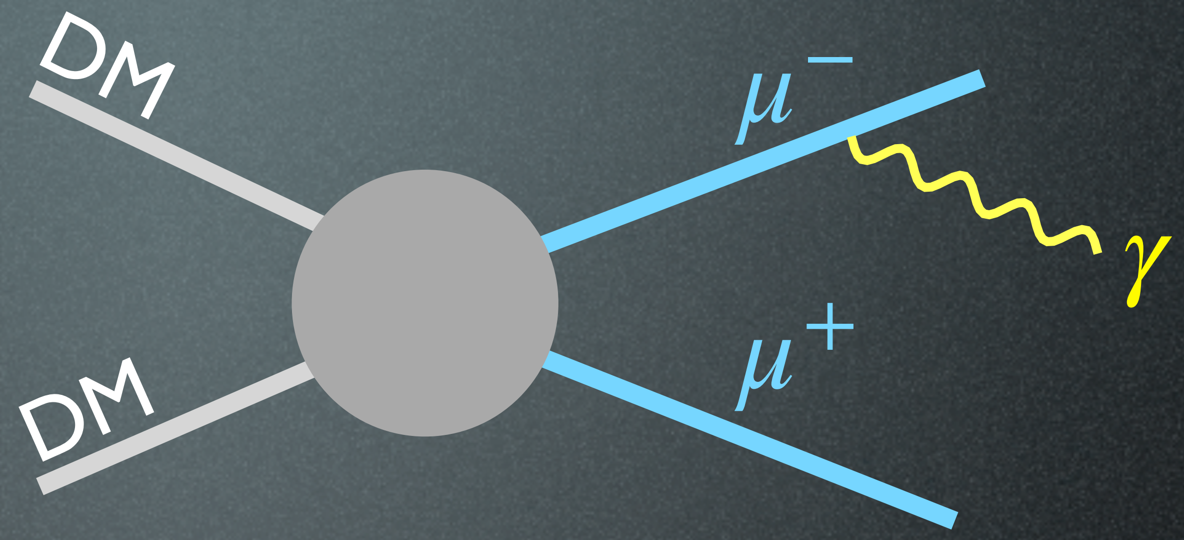
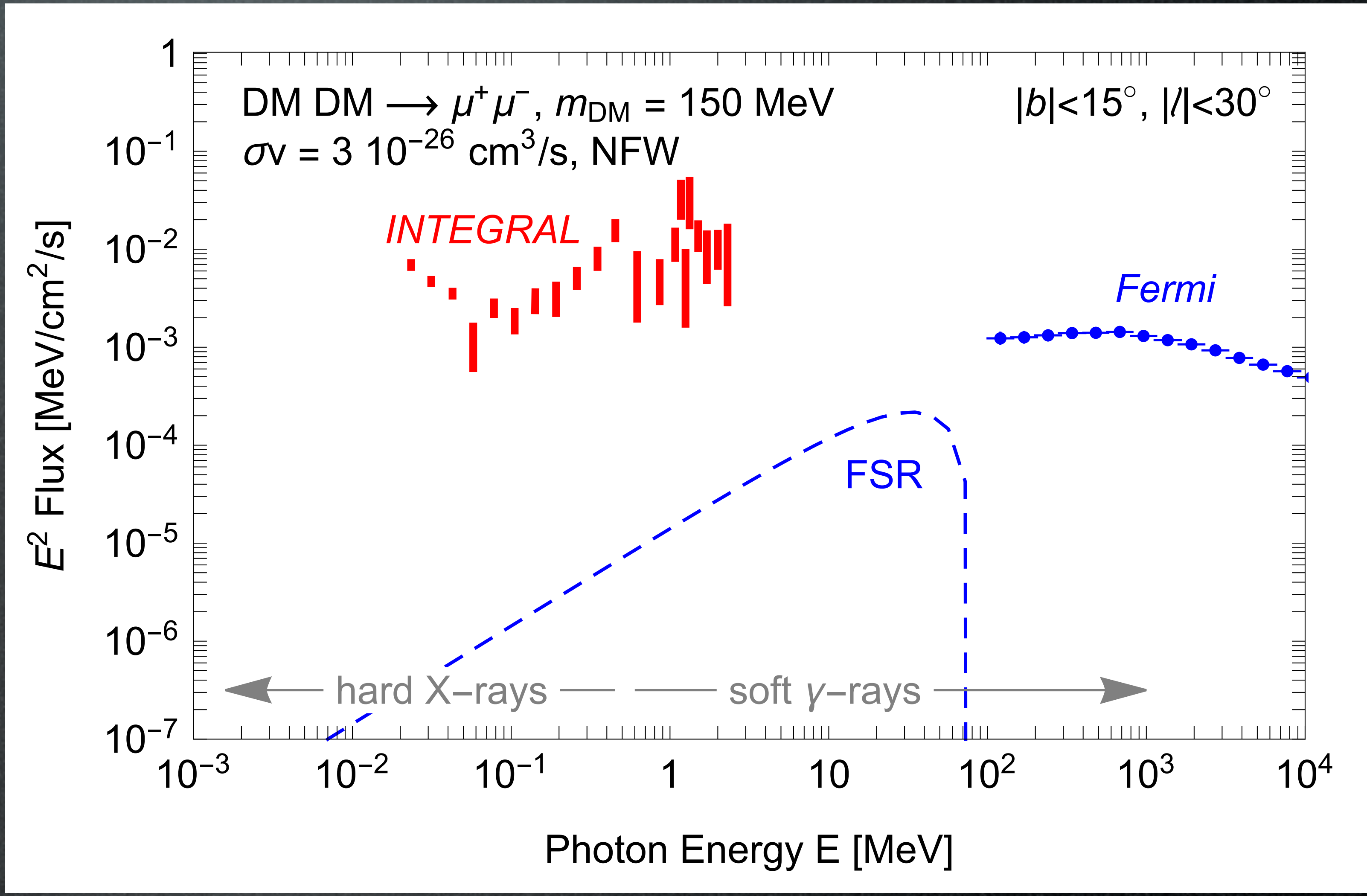


'Prompt' emission:

Final State Radiation (FSR)



Sub-GeV DM & X-rays

Annihilation channels

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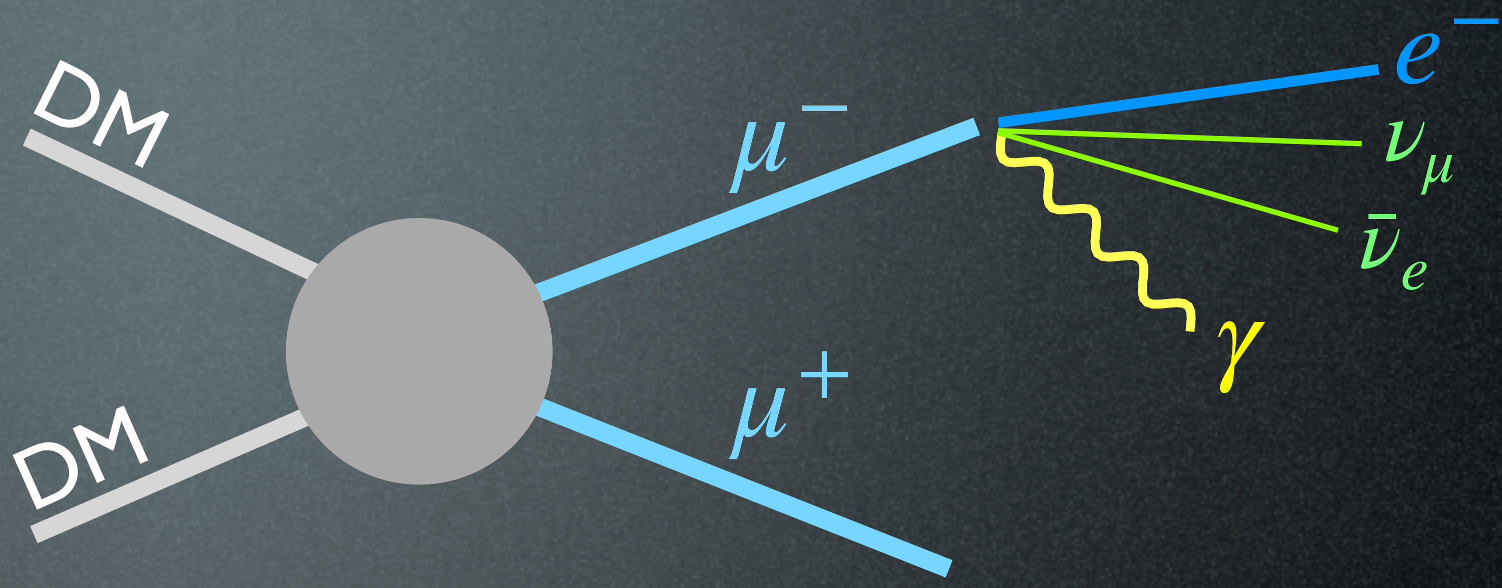
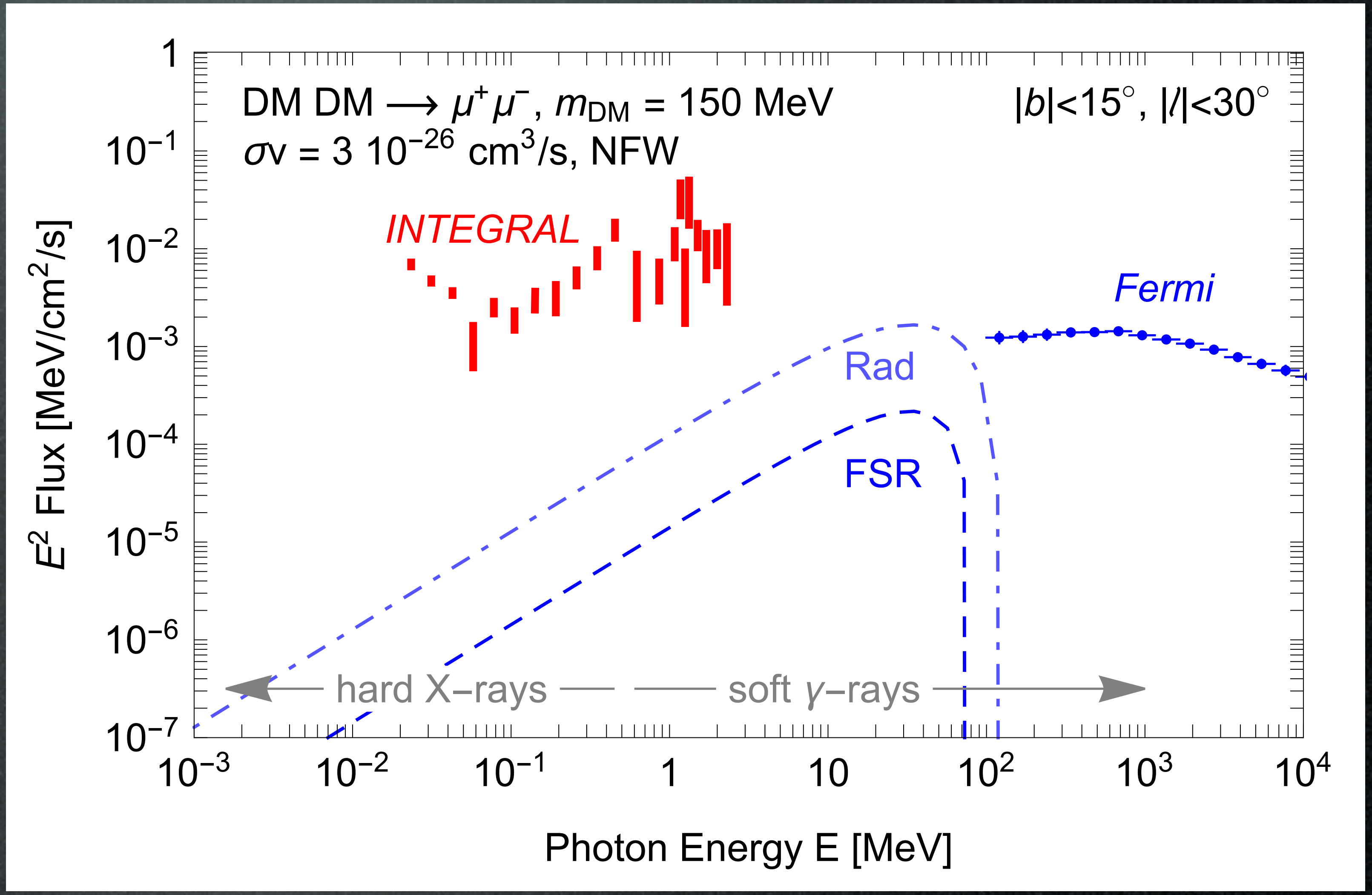


'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

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



Sub-GeV DM & X-rays

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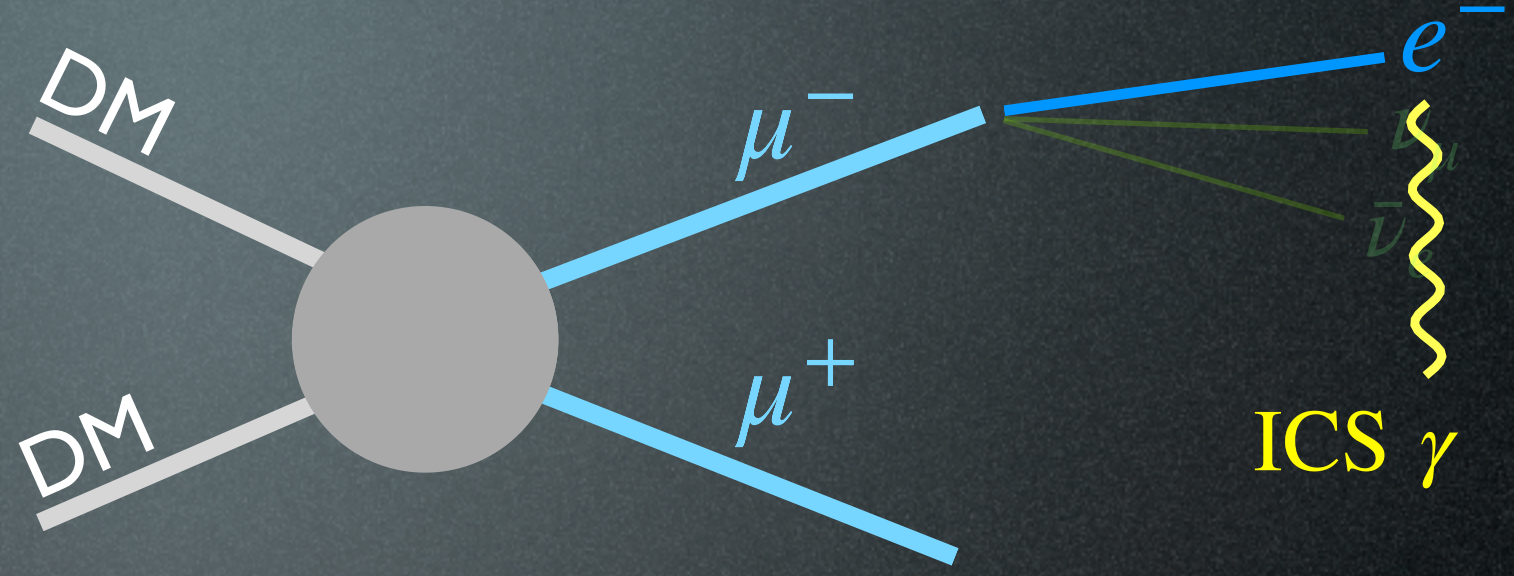


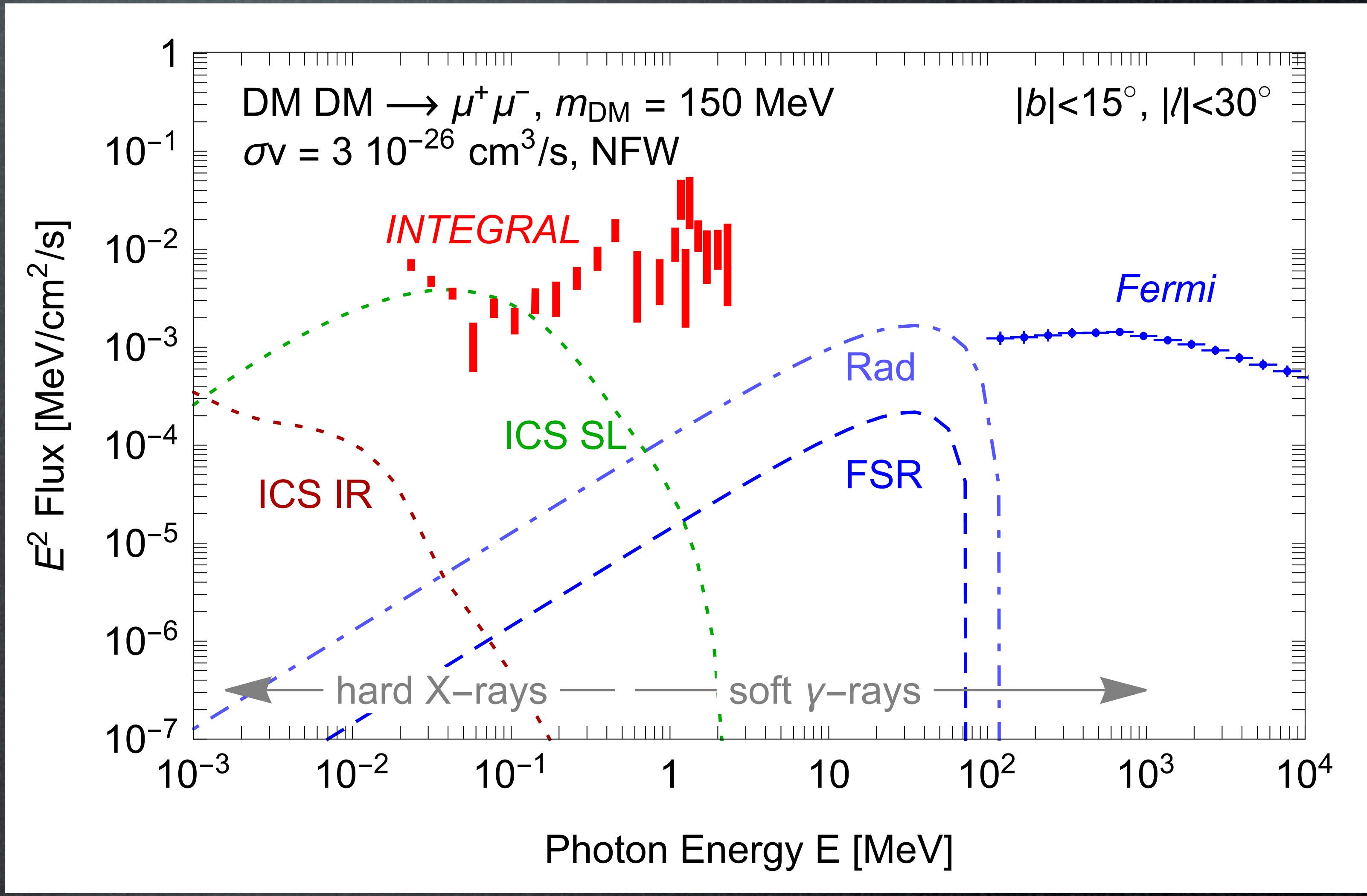
‘Prompt’ emission:

Final State Radiation (FSR)

Radiative μ decay

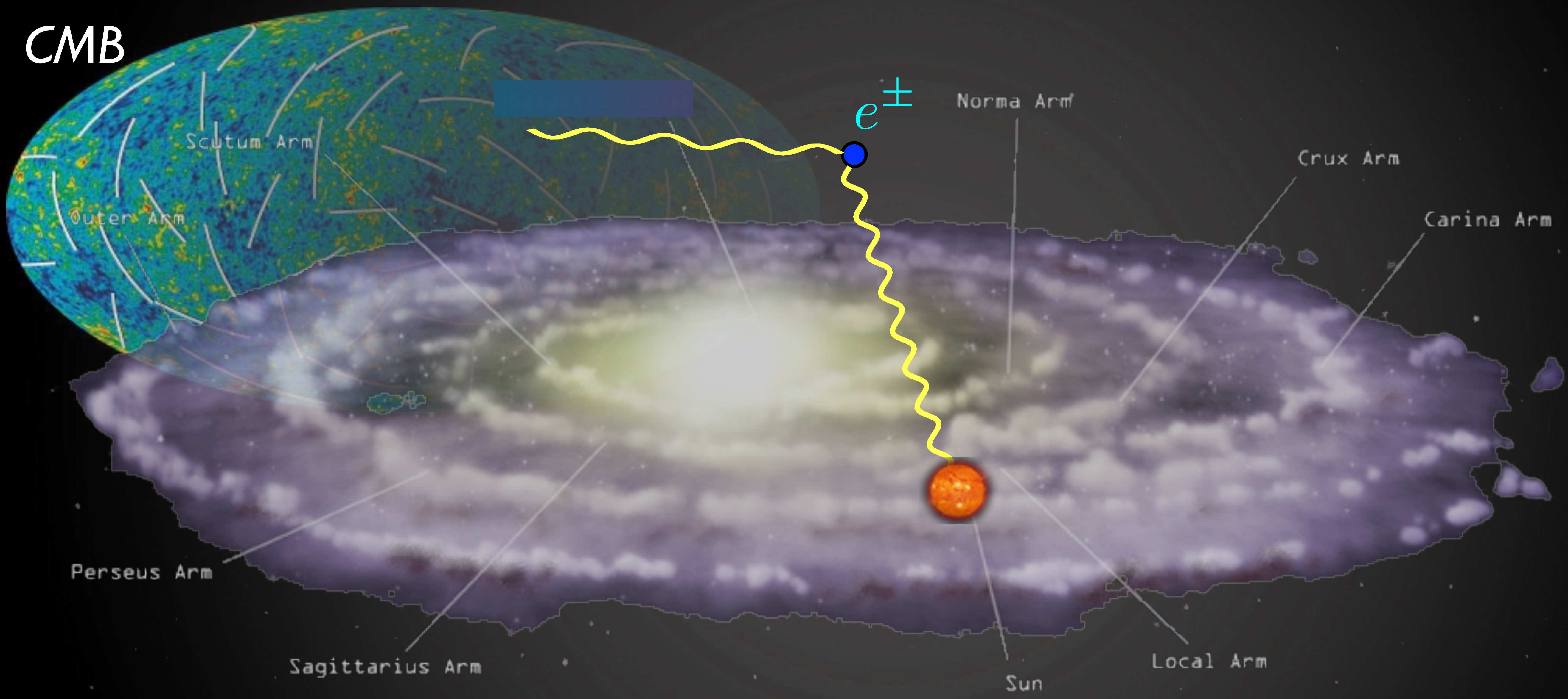
Secondary emission:

ICS: inevitably associated to annihil to charged states



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

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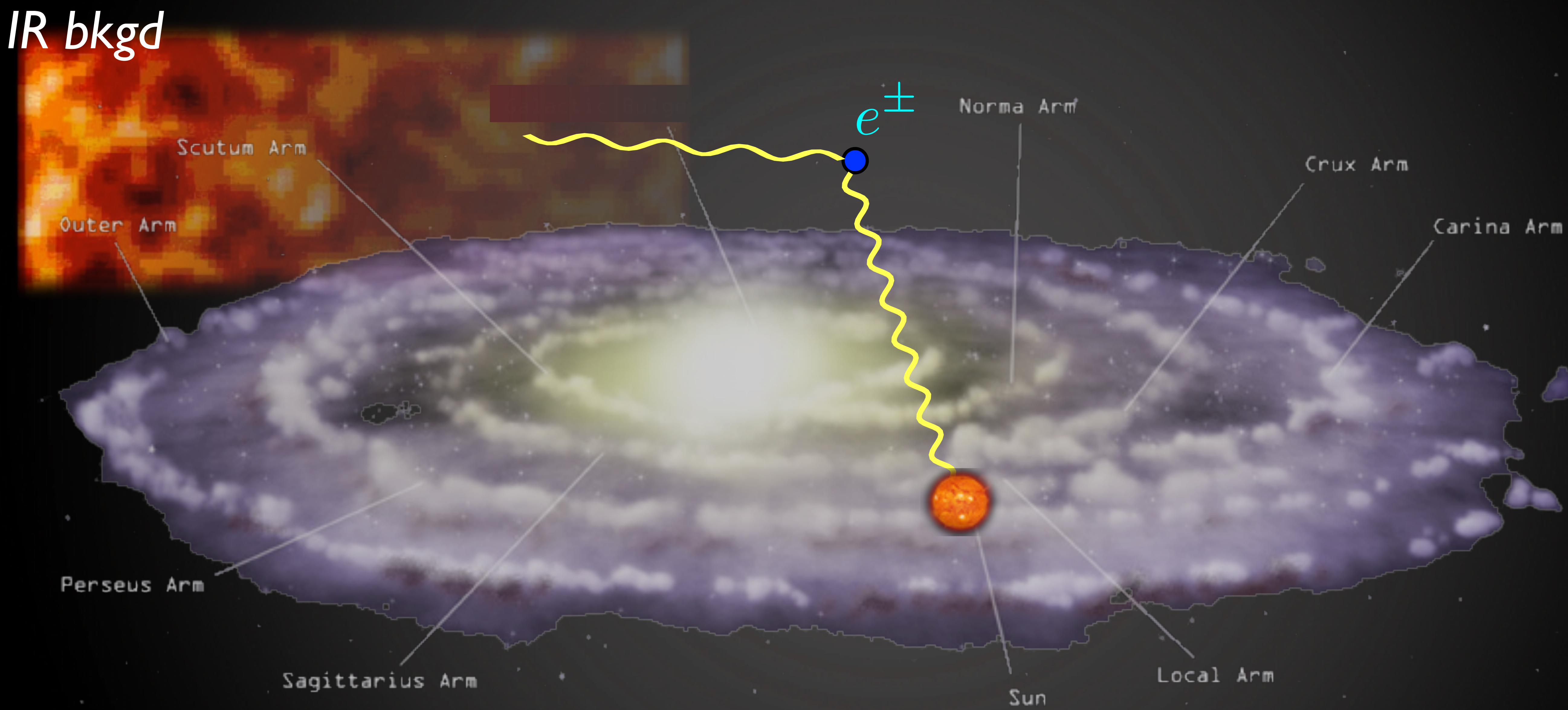

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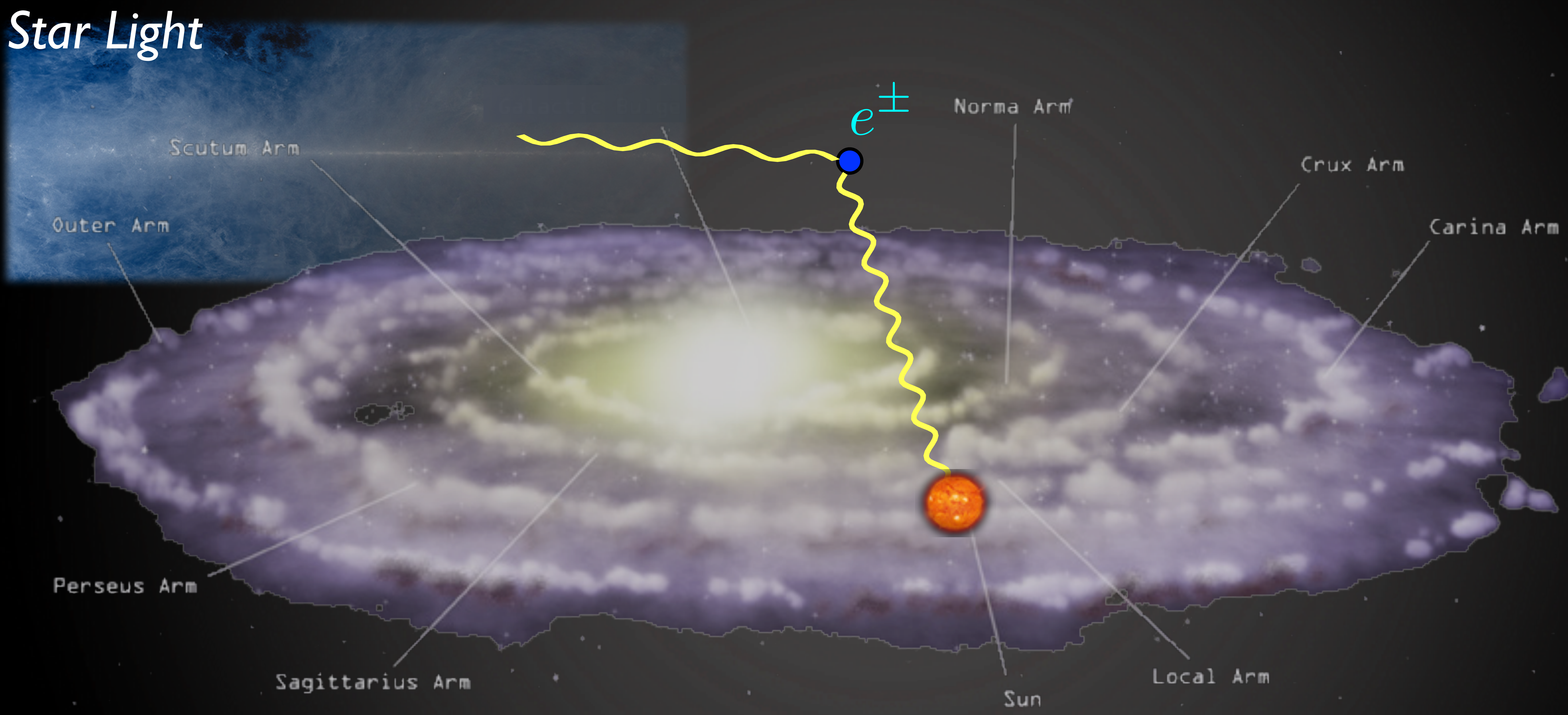

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Sub-GeV DM & X-rays

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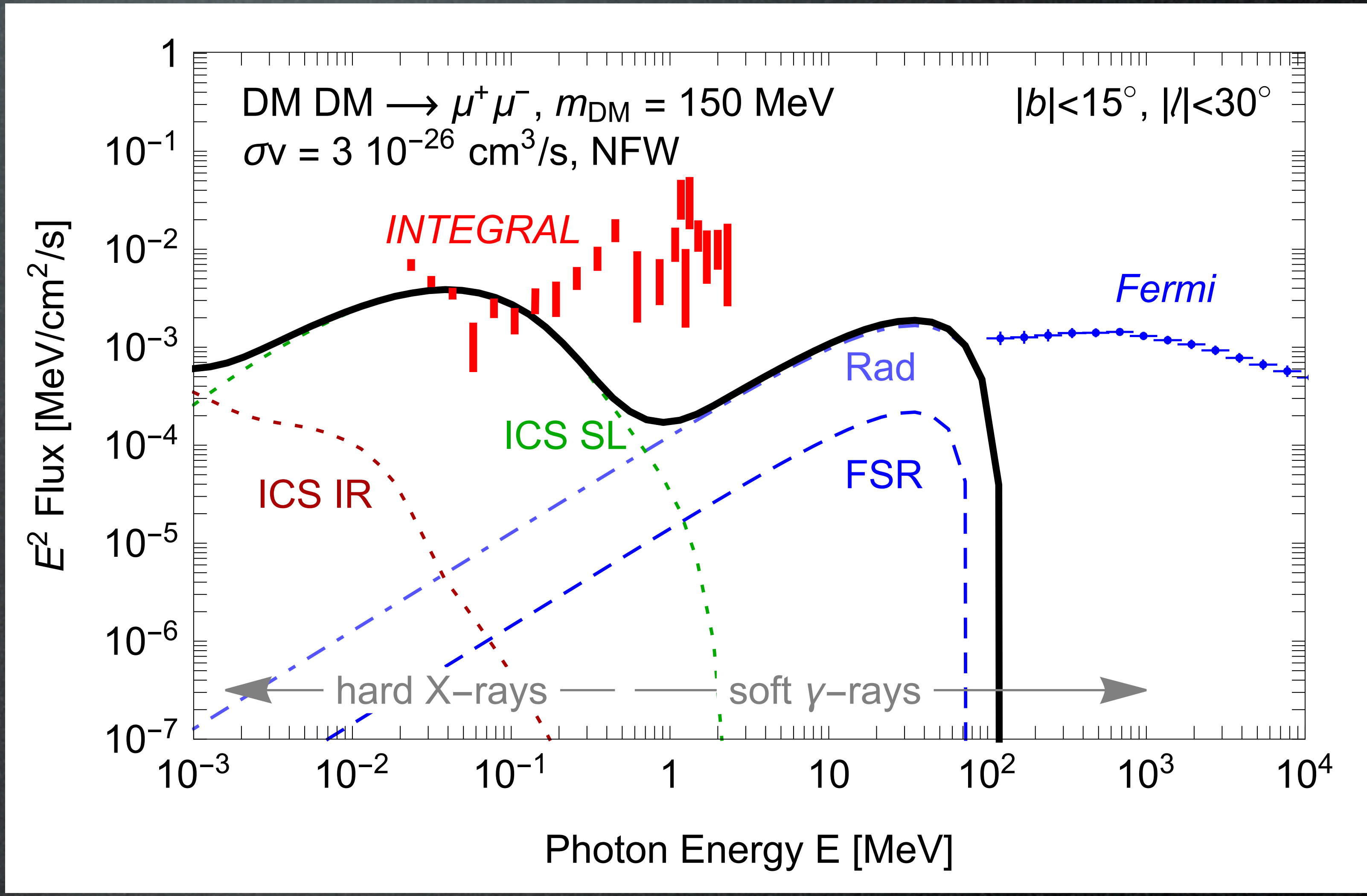


Key message:

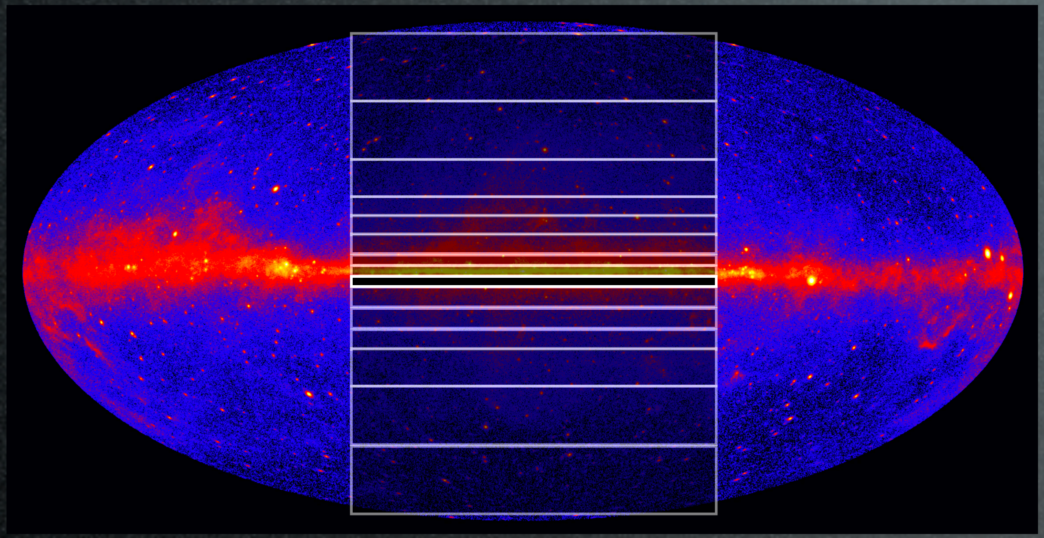
ICS allows to probe sub-GeV DM with X-ray data

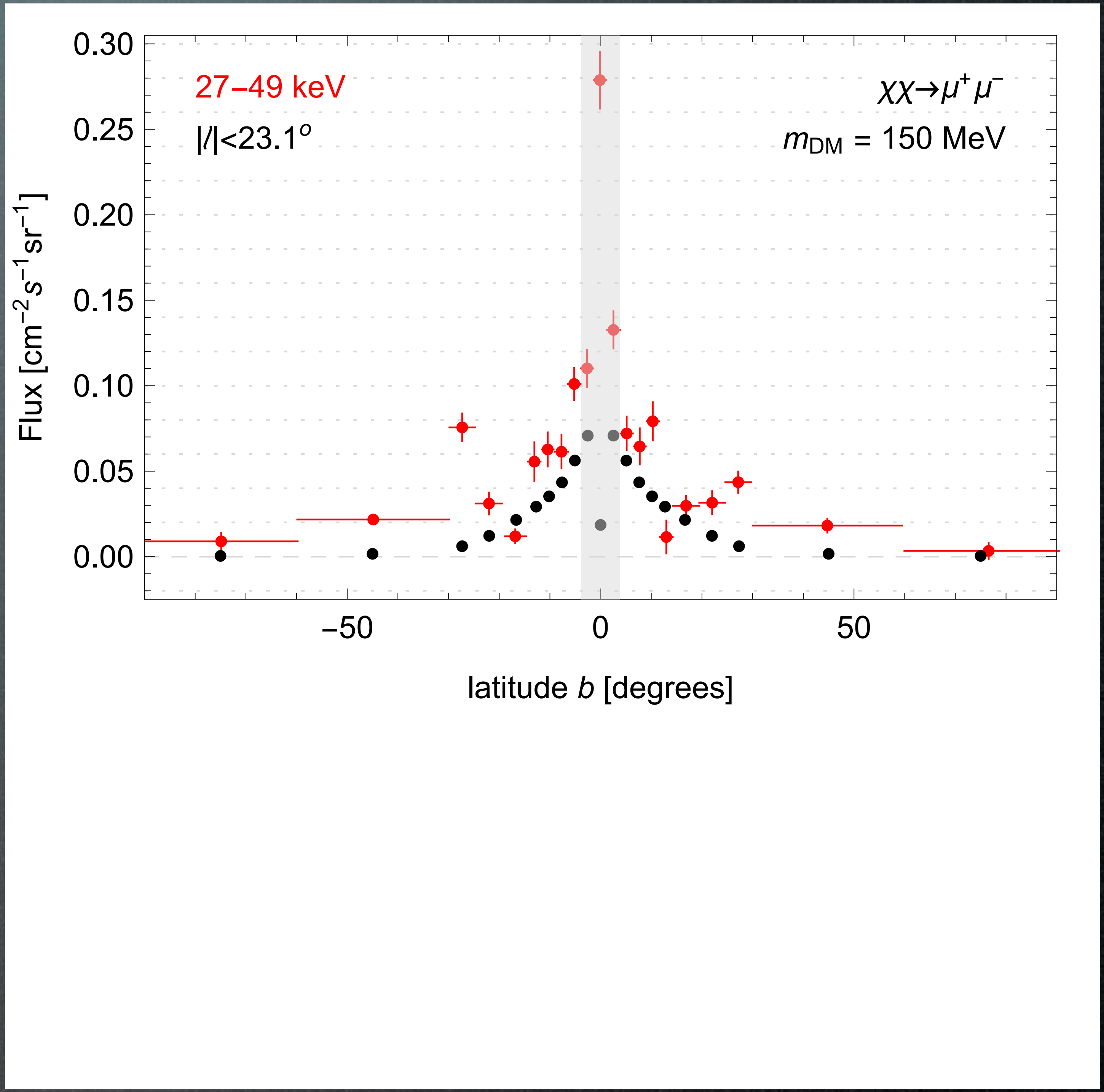
Analysis

Integral-SPI 2011 data

Bouchet et al., Integral coll. 1107.0200

latitude binned data, central MW





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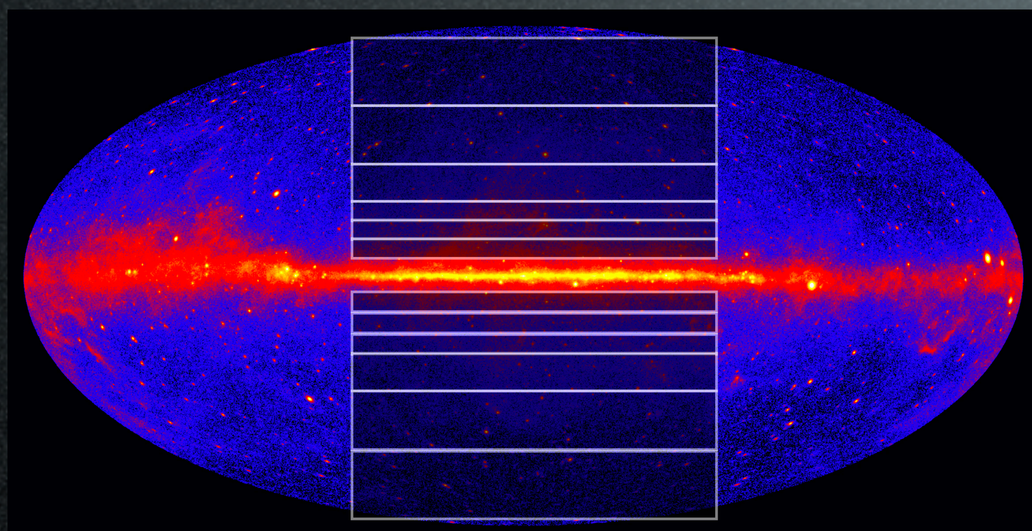
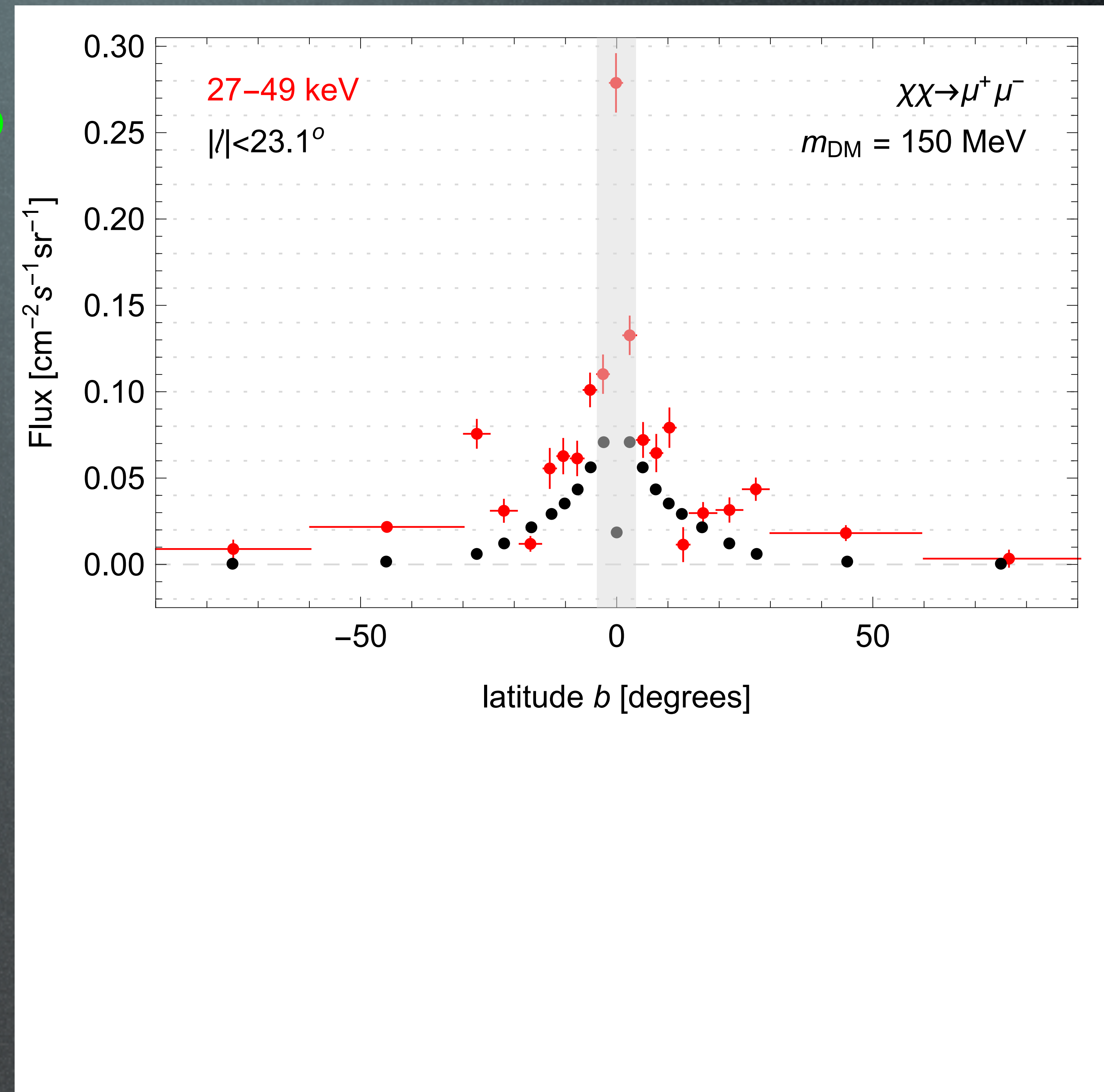


remove Gal Plane



Analysis

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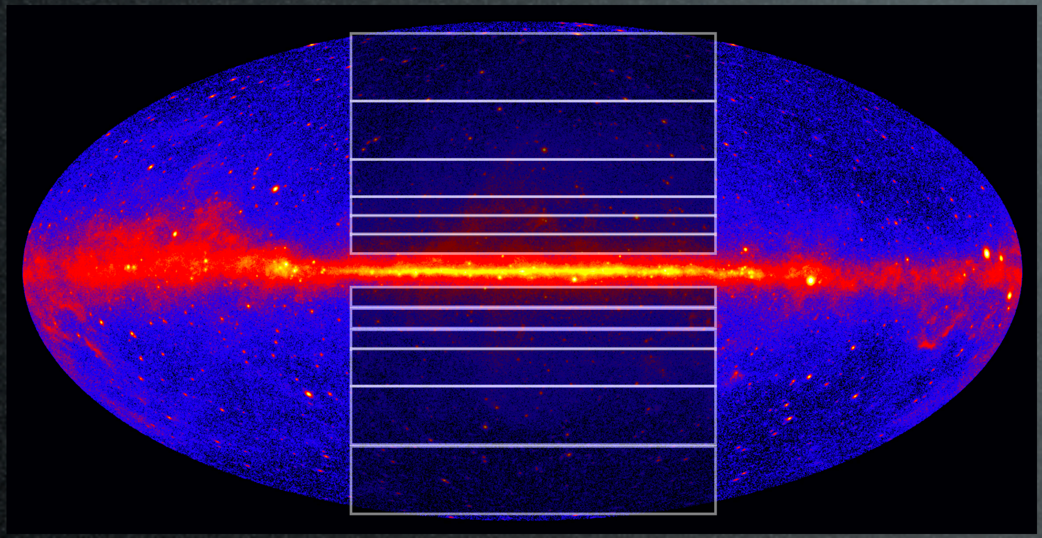
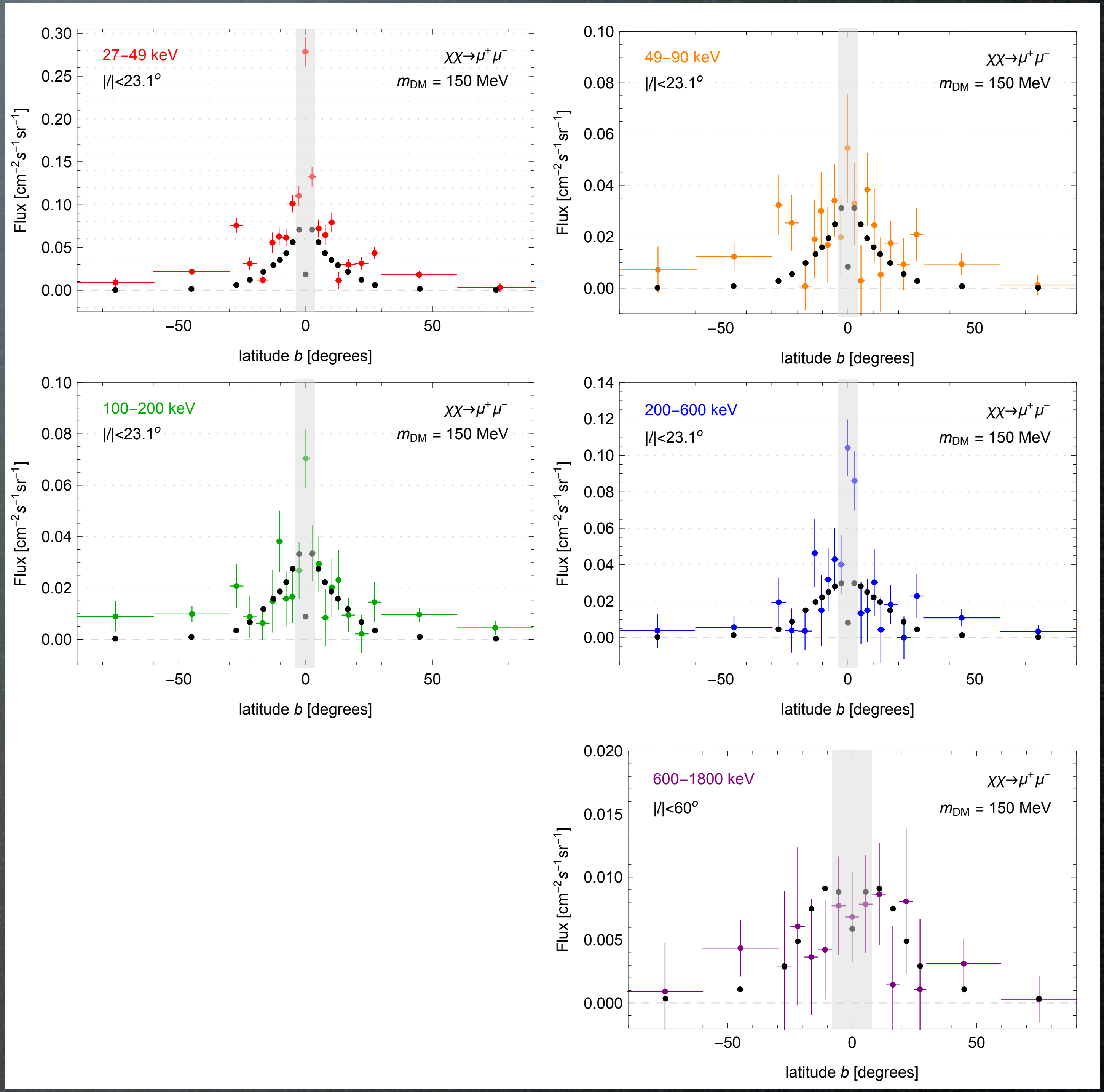


remove Gal Plane

5 energy bands



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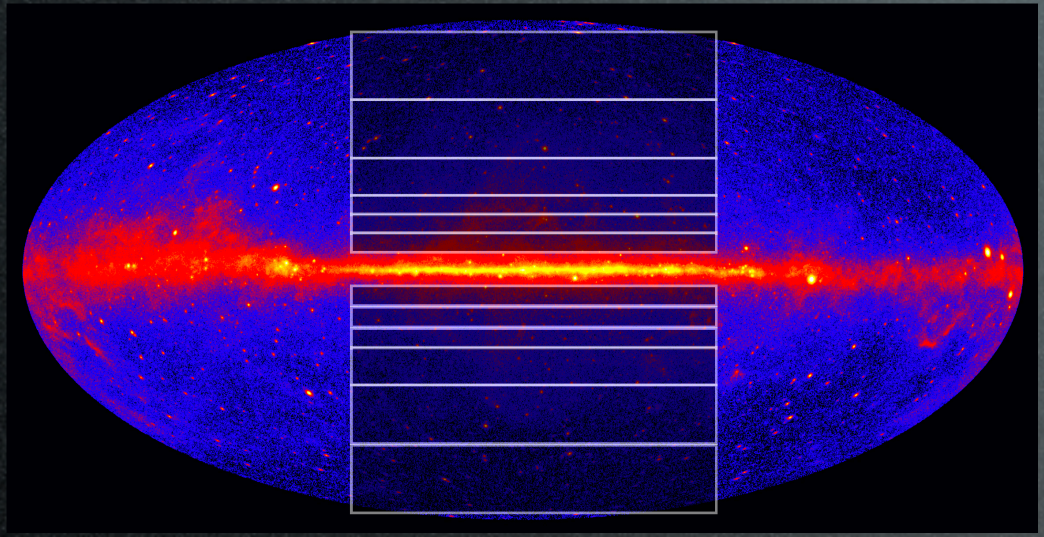
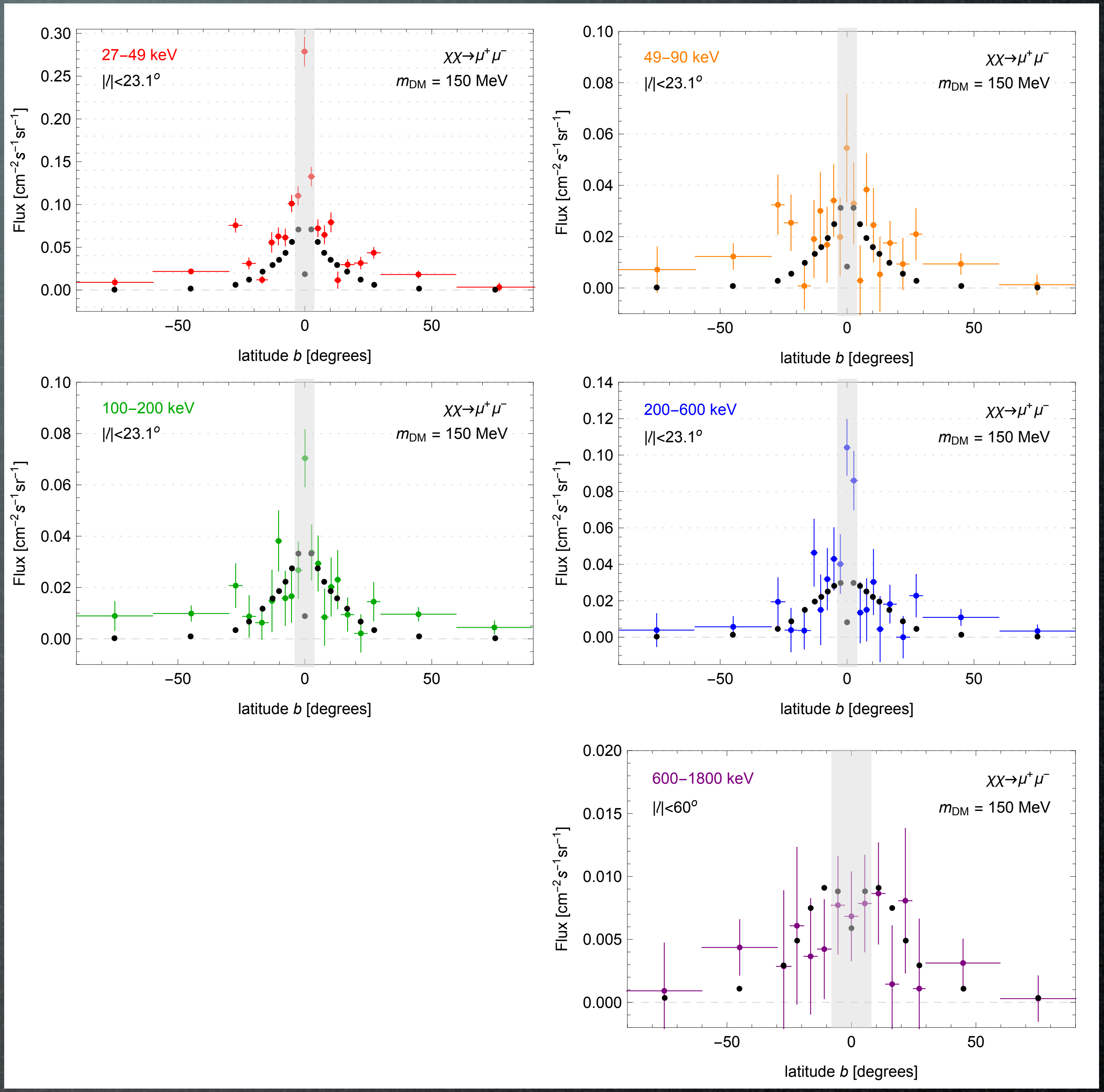
latitude binned data, central MW



remove Gal Plane

5 energy bands

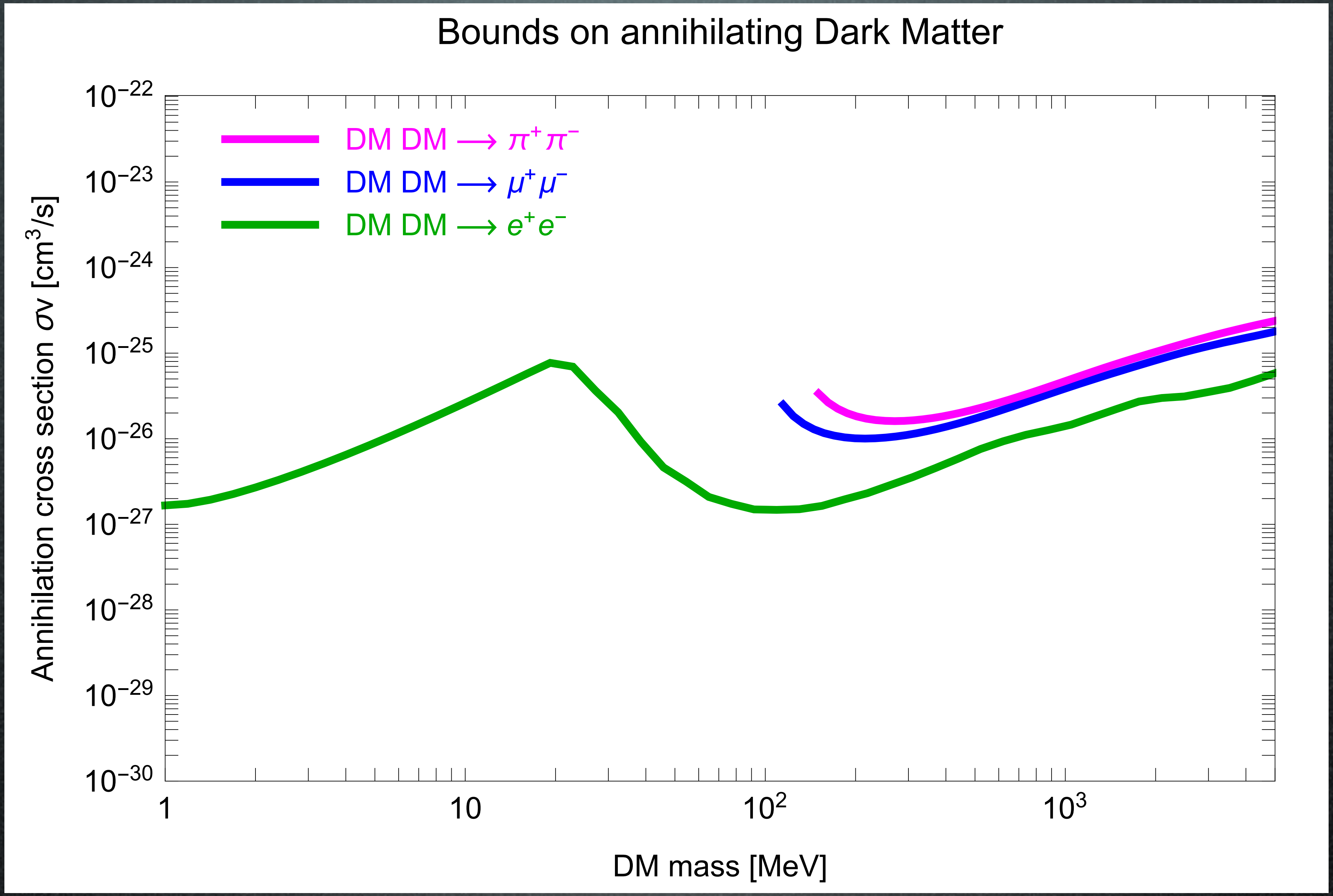


Test Statistics:
exclude if DM exceeds data
by more than ~2σ global.
More precisely:

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

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

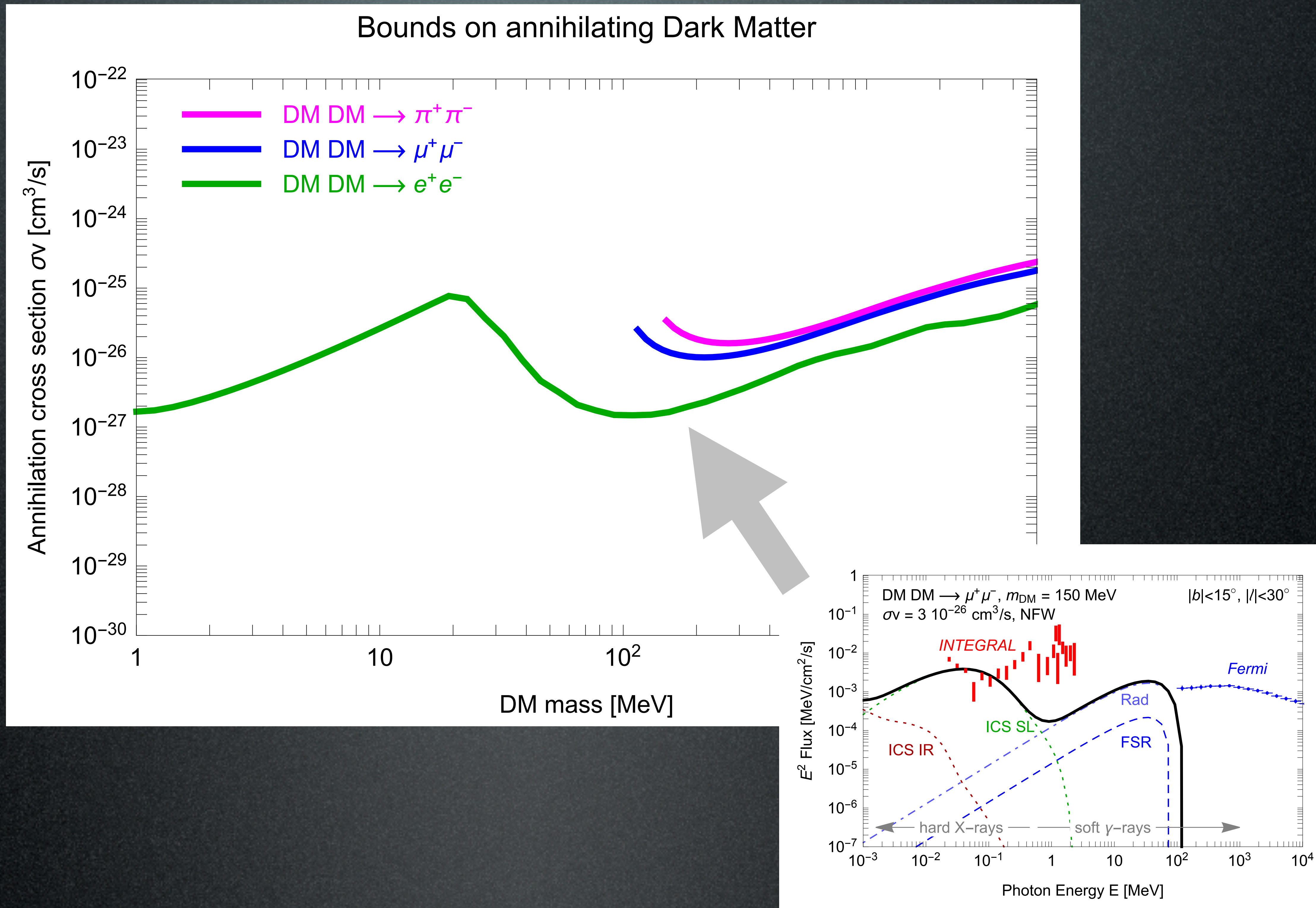
Results



Bounds on all 3 channels

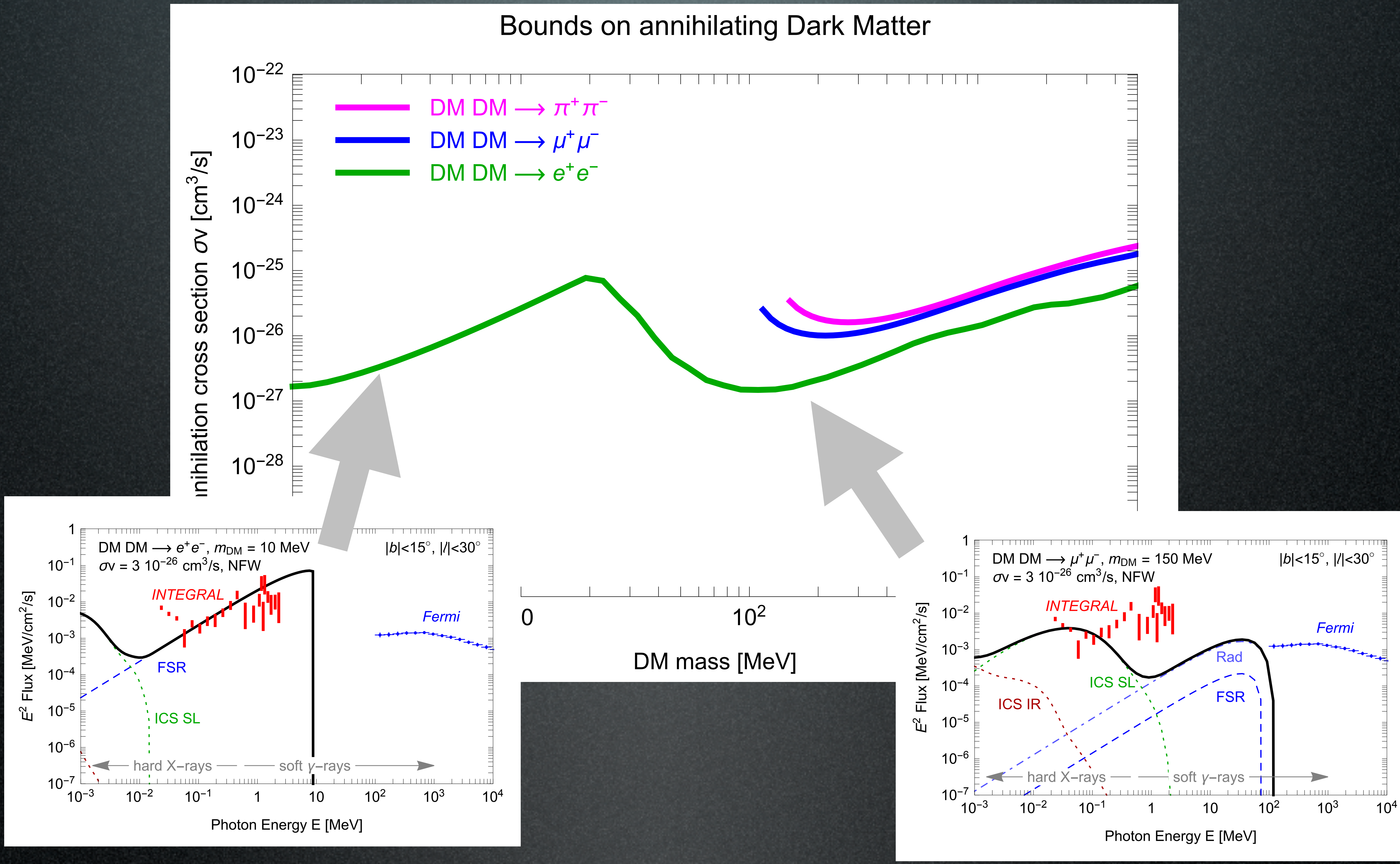
Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

Results



Bounds on annihilating Dark Matter
DM DM ⟶ π⁺π⁻
DM DM ⟶ μ⁺μ⁻
DM DM ⟶ e⁺e⁻
Annihilation cross section σv [cm³/s]
10⁻²², 10⁻²³, 10⁻²⁴, 10⁻²⁵, 10⁻²⁶, 10⁻²⁷, 10⁻²⁸, 10⁻²⁹, 10⁻³⁰
1, 10, 10²
DM mass [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
FSR
hard X–rays
soft γ–rays
E² Flux [MeV/cm²/s]
1, 10⁻¹, 10⁻², 10⁻³, 10⁻⁴, 10⁻⁵, 10⁻⁶, 10⁻⁷
10⁻³, 10⁻², 10⁻¹, 1, 10, 10², 10³, 10⁴
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]
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²⁷
10⁻²⁸
0
10²
DM mass [MeV]
DM DM ⟶ e⁺e⁻, m_DM = 10 MeV
σv = 3 10⁻²⁶ cm³/s, NFW
|b|<15°, |l|<30°
INTEGRAL
Fermi
FSR
ICS SL
hard X–rays
soft γ–rays
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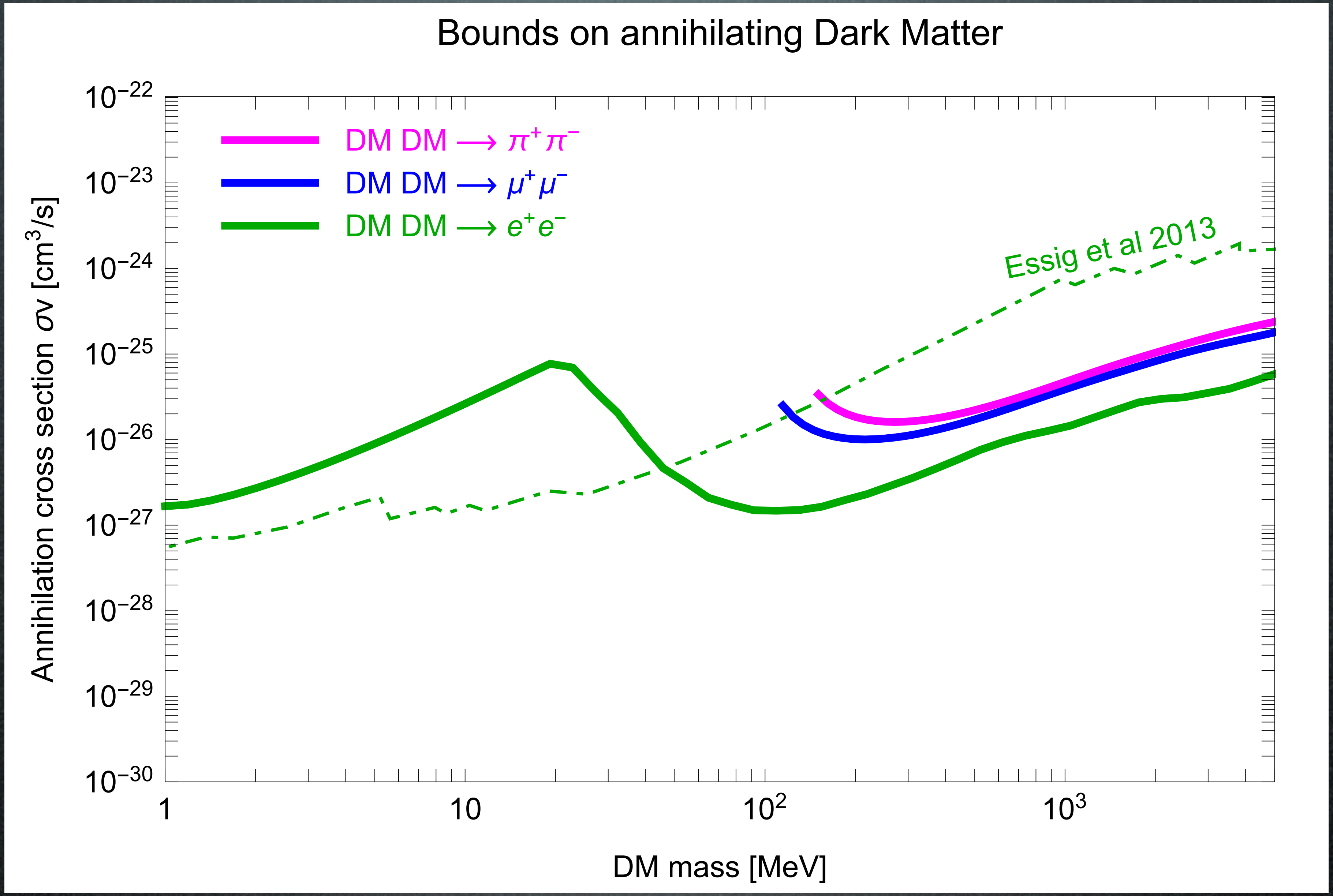
Results

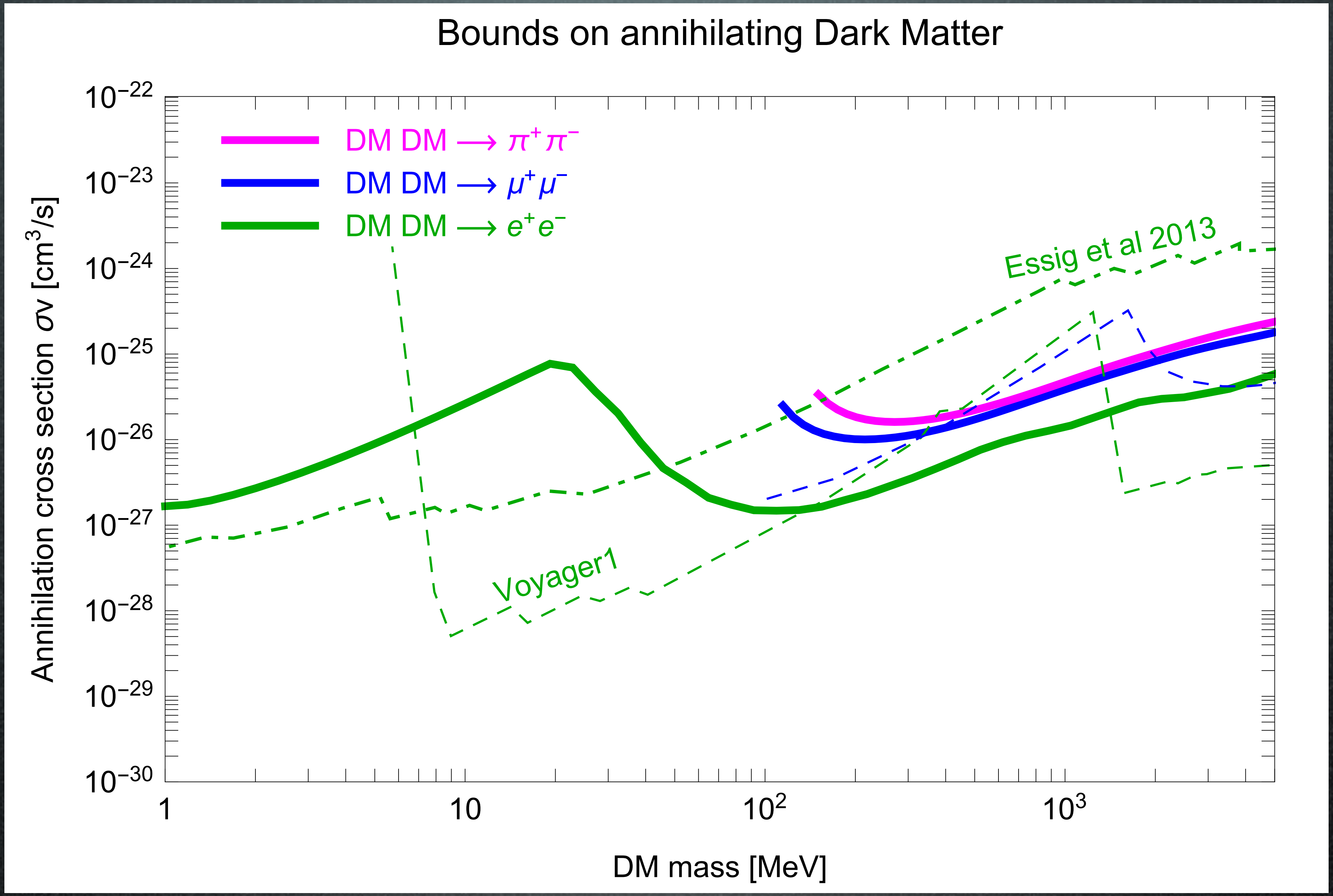


Essig+
1309.4091

Bounds on all 3 channels

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

Results



Essig+ 1309.4091

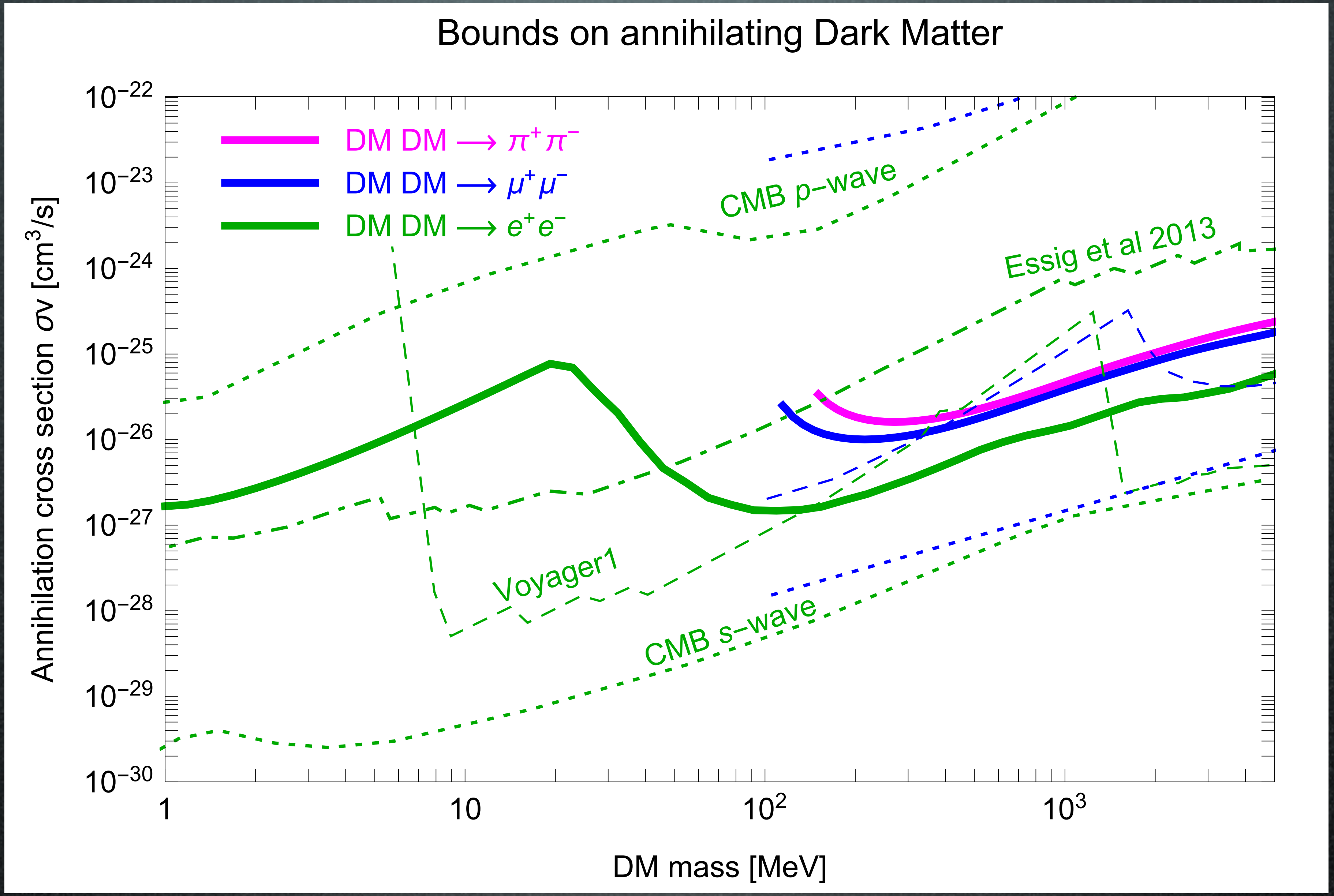
Boudaud+ 1612.07698

Bounds on all 3 channels

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

Voyager1 bounds stronger/weaker dep. on data

Results



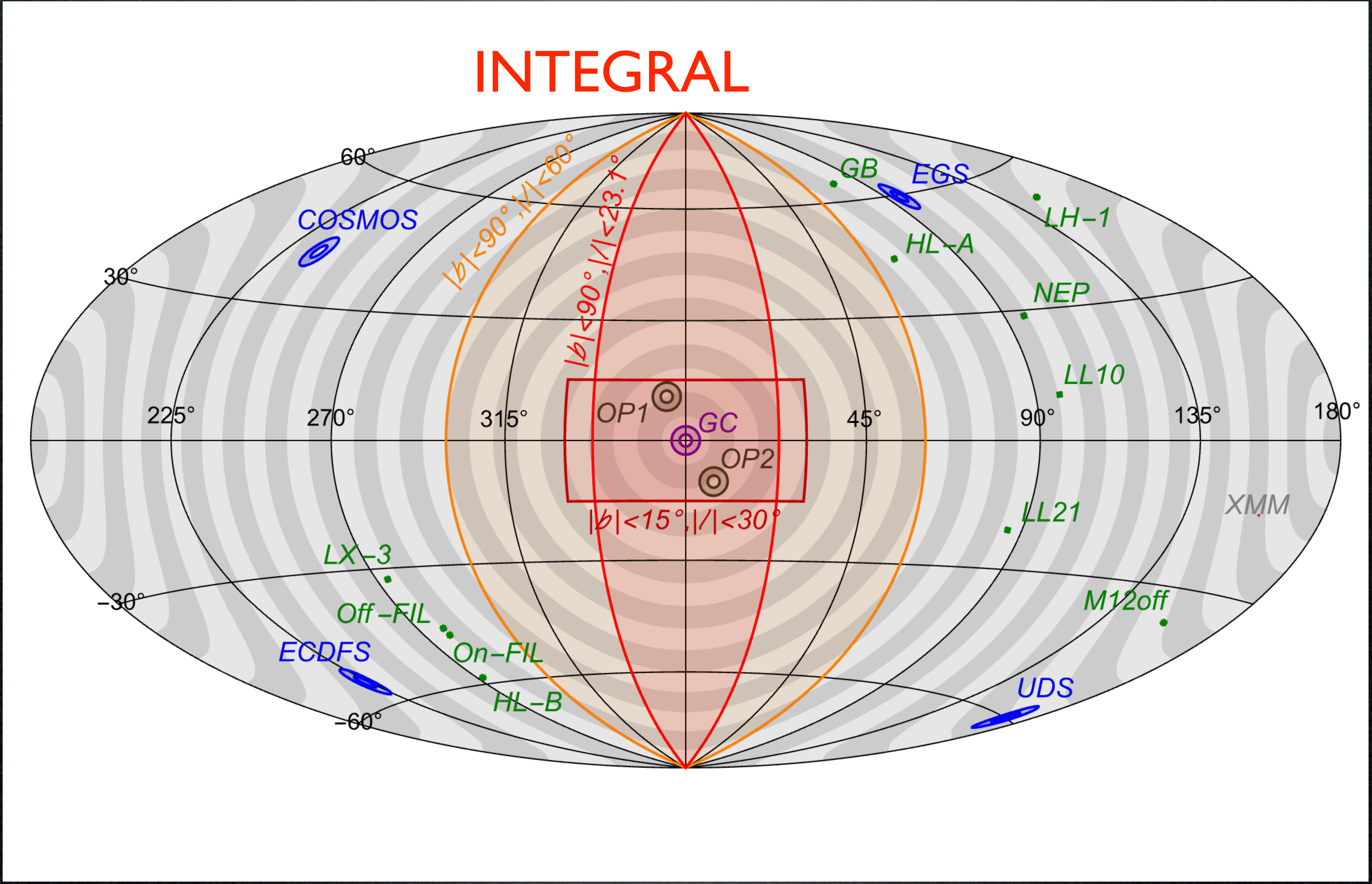
Essig+ 1309.4091

Boudaud+ 1612.07698

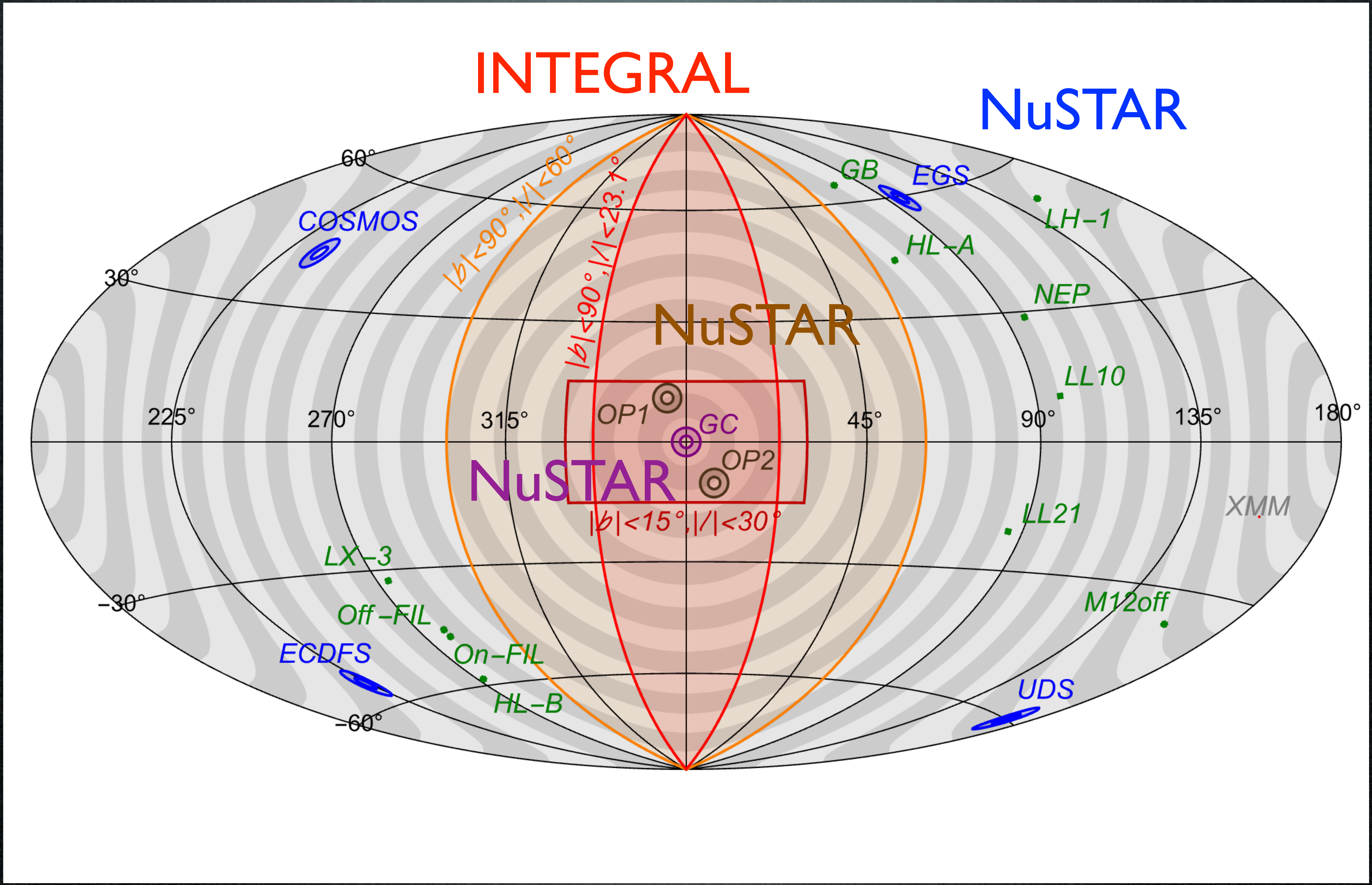
Slatyer+ 1506.03811
Lopez-H+ 1303.5094
Diamanti+ 1308.2578
Liu+ 2008.01084

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°
GB
EGS
LH–1
HL–A
NEP
LL10
OP1
GC
OP2
|b|<15°,|l|<30°
LL21
XMM
LX–3
Off–FIL
On–FIL
ECDFS
HL–B
M12off
UDS

More data!



INTEGRAL
NuSTAR
NuSTAR
NuSTAR
|b|<90°,|l|<60°
|b|<90°,|l|<23.1°
|b|<15°,|l|<30°
60°
30°
−30°
−60°
225°
270°
315°
45°
90°
135°
180°
COSMOS
GB
EGS
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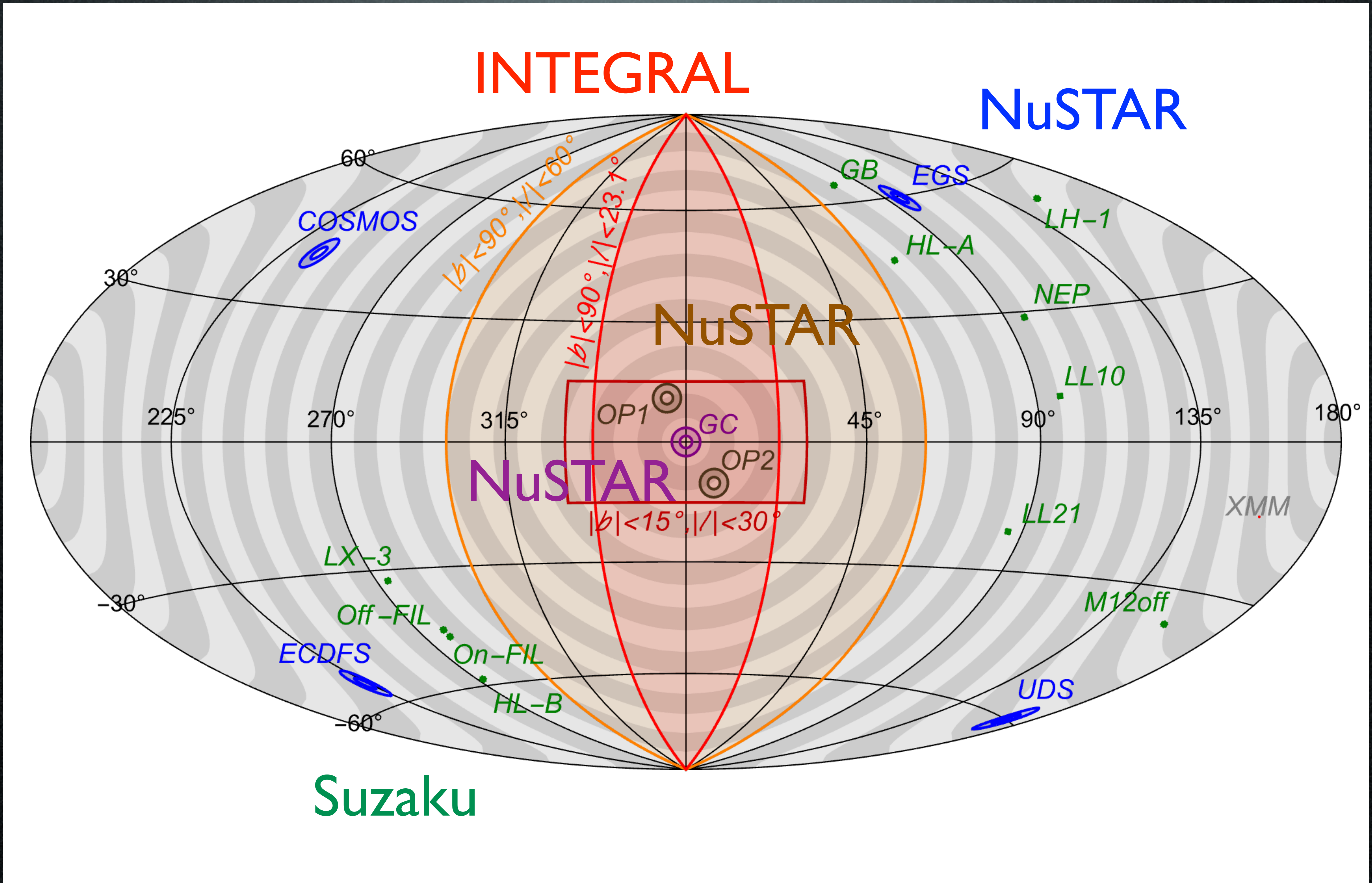
More data!



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
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|b|<90°,|l|<60°
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60°
30°
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−60°
225°
270°
315°
45°
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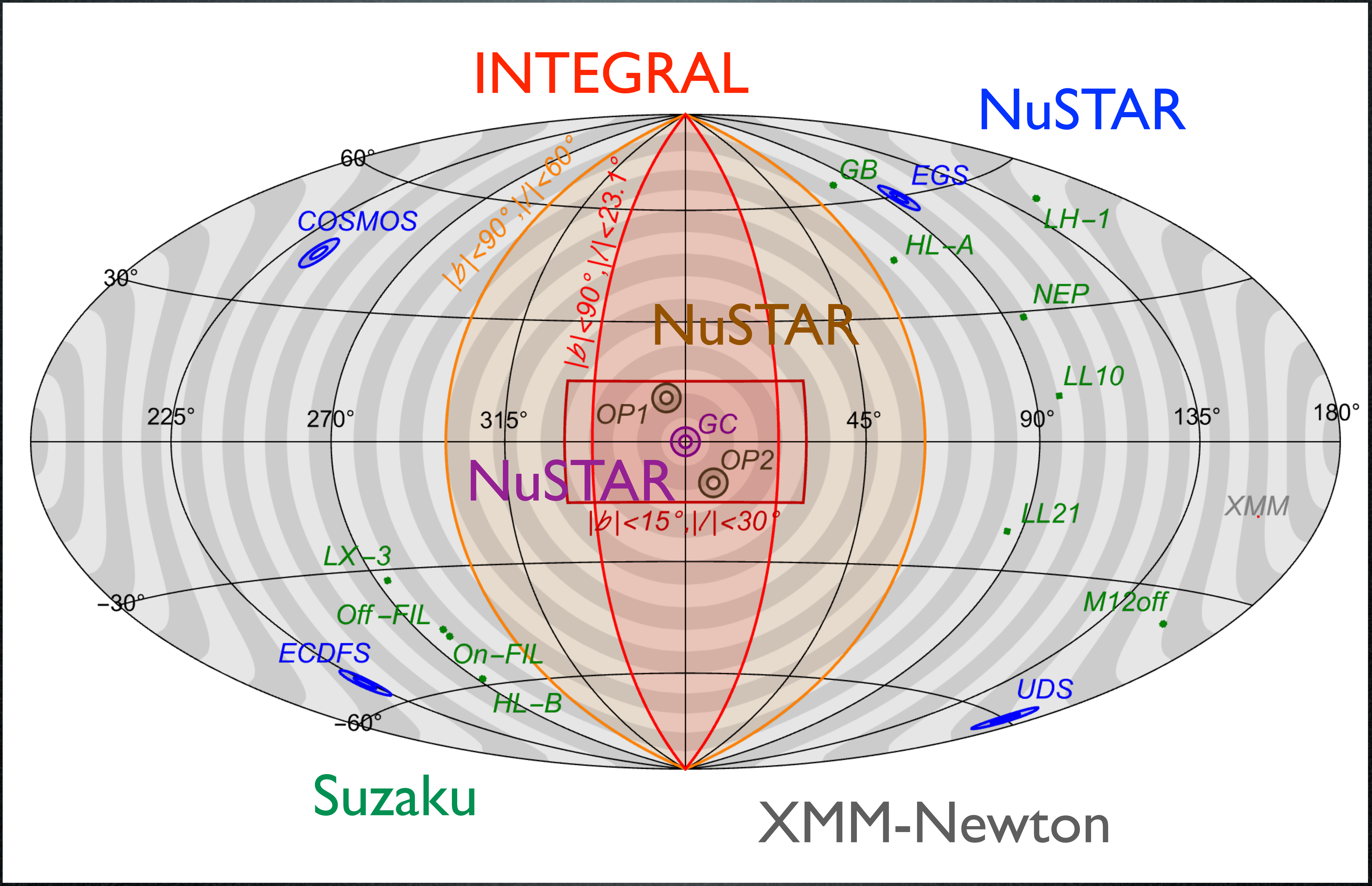
More data!



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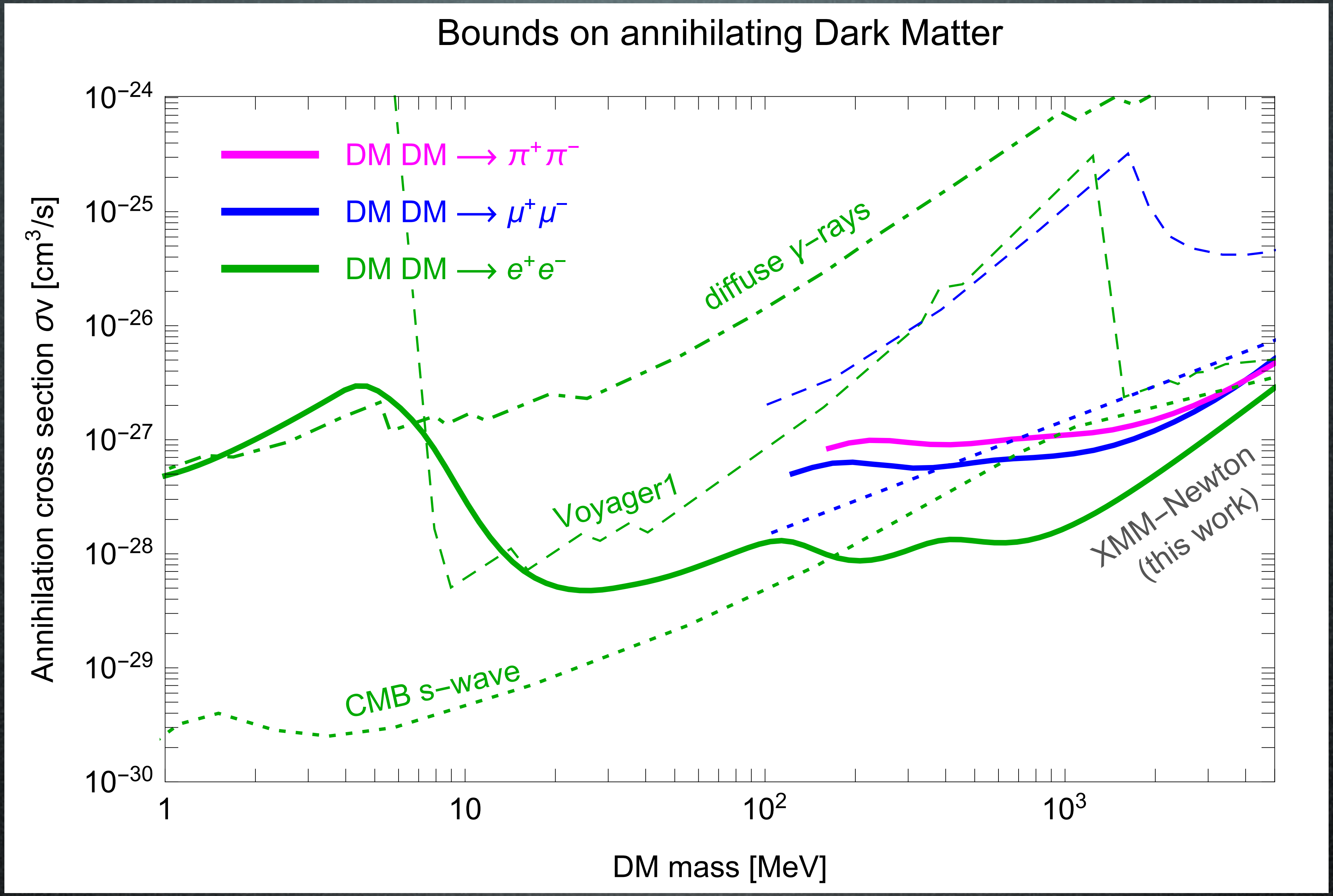
Results



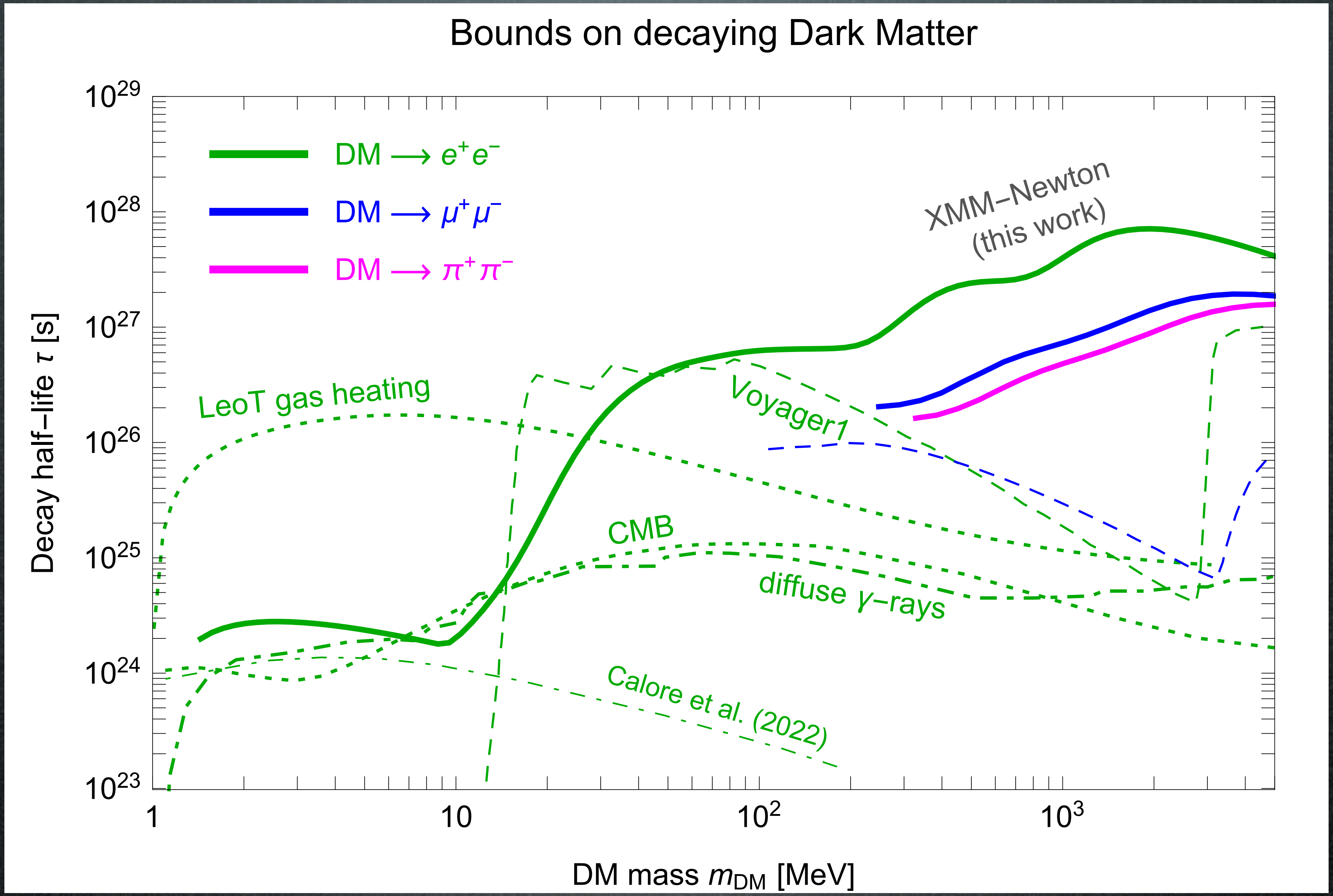
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Bounds on all 3 channels

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

Deeper than the s-wave CMB bounds

Results



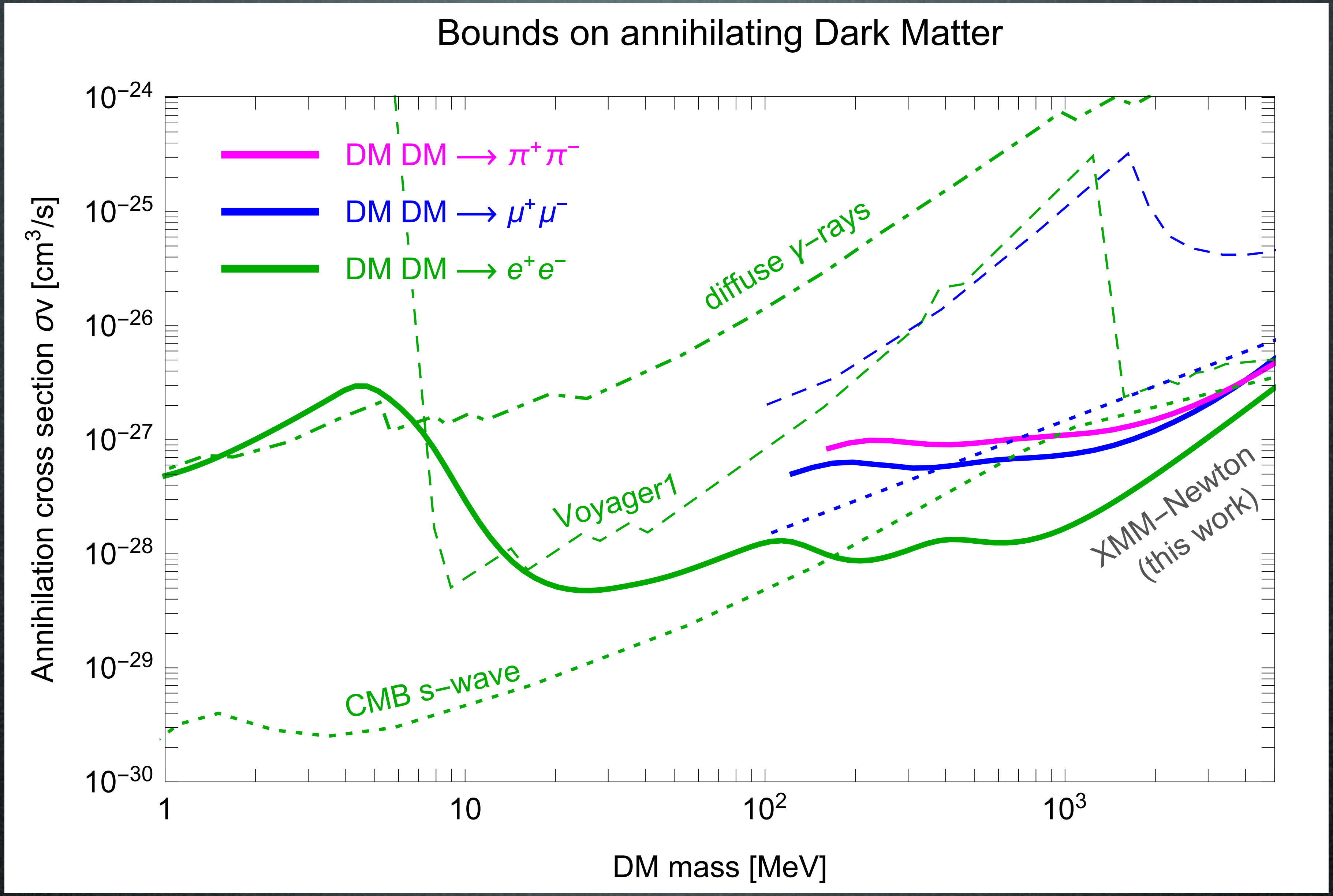
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Bounds on all 3 channels

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

Dominant bounds above 50 MeV

Results



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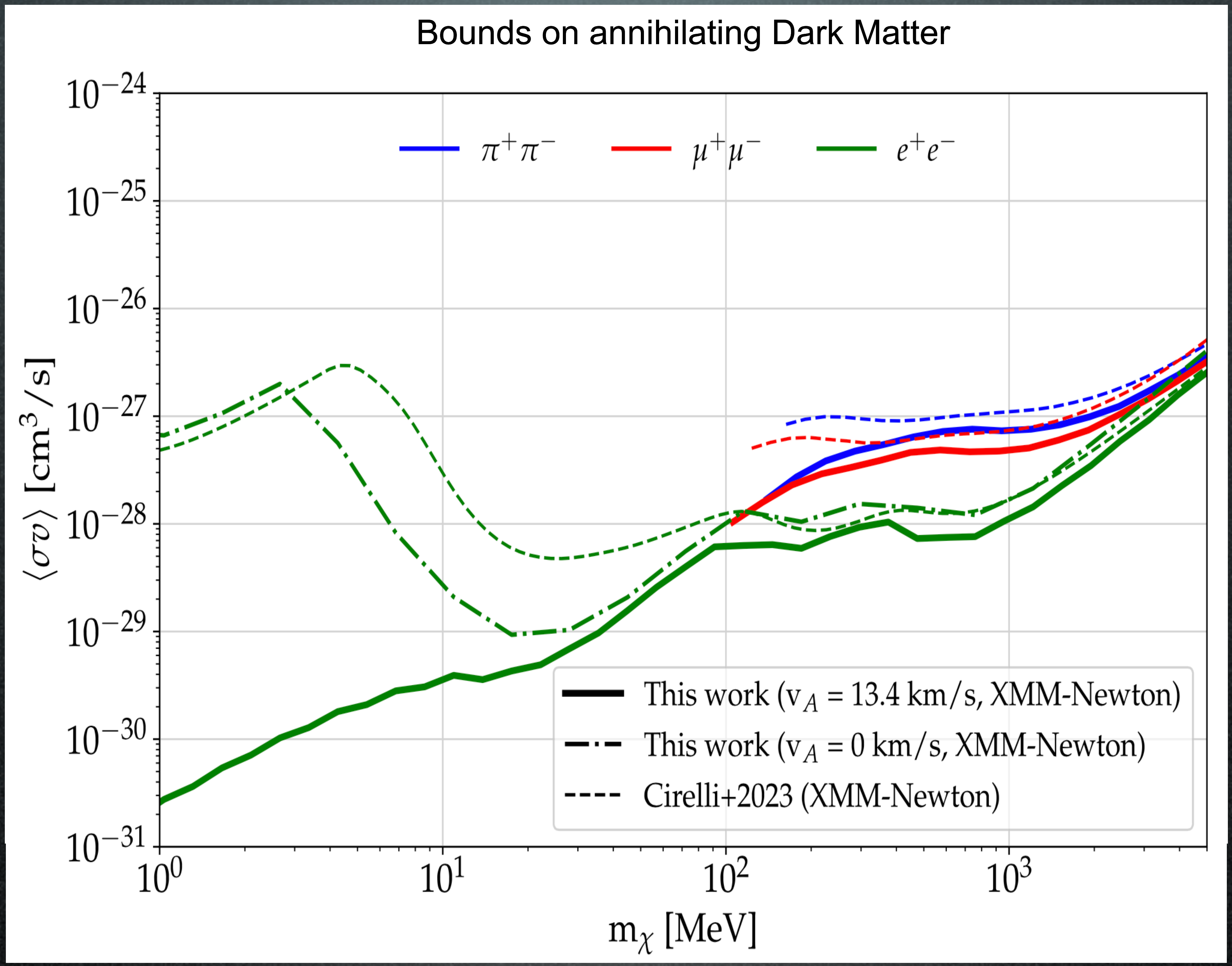
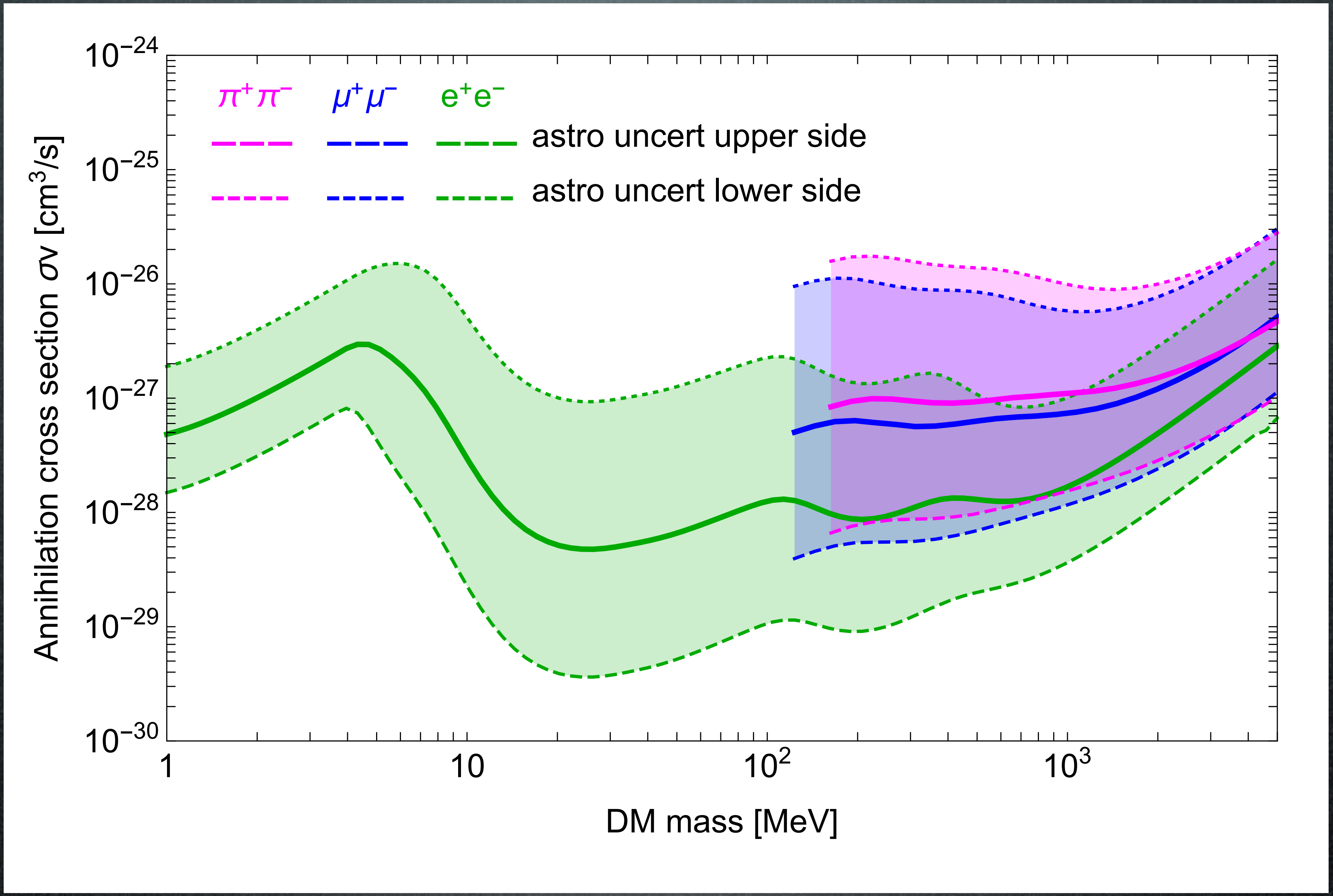


De La Torre Luque, Balaji, Koechler 2311.04979

Updated with a refined propagation (incl reacceleration)

Results: uncertainties



Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Conclusions

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

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ID is (more) challenging than WIMPs

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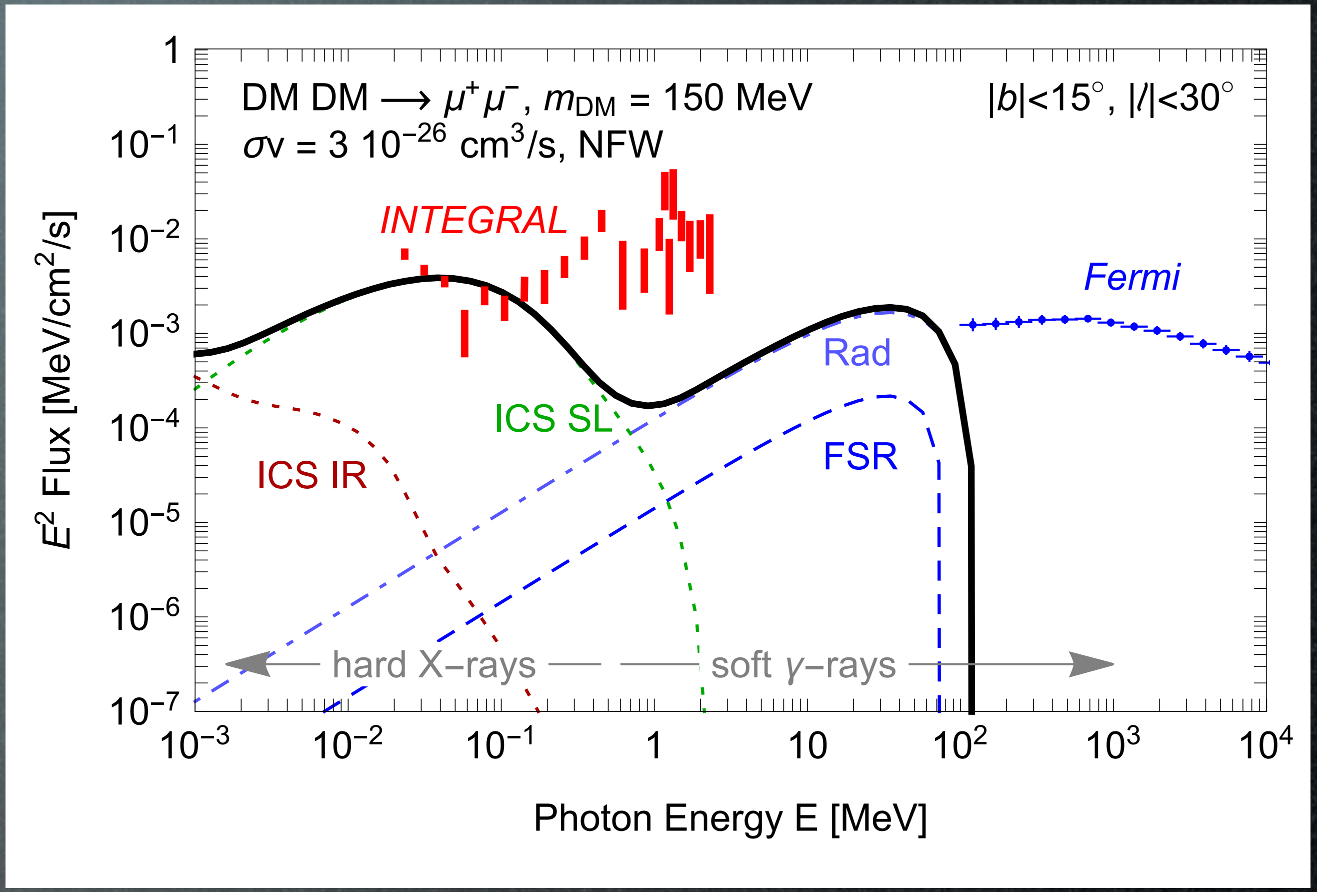
ICS allows to test it with X-ray data



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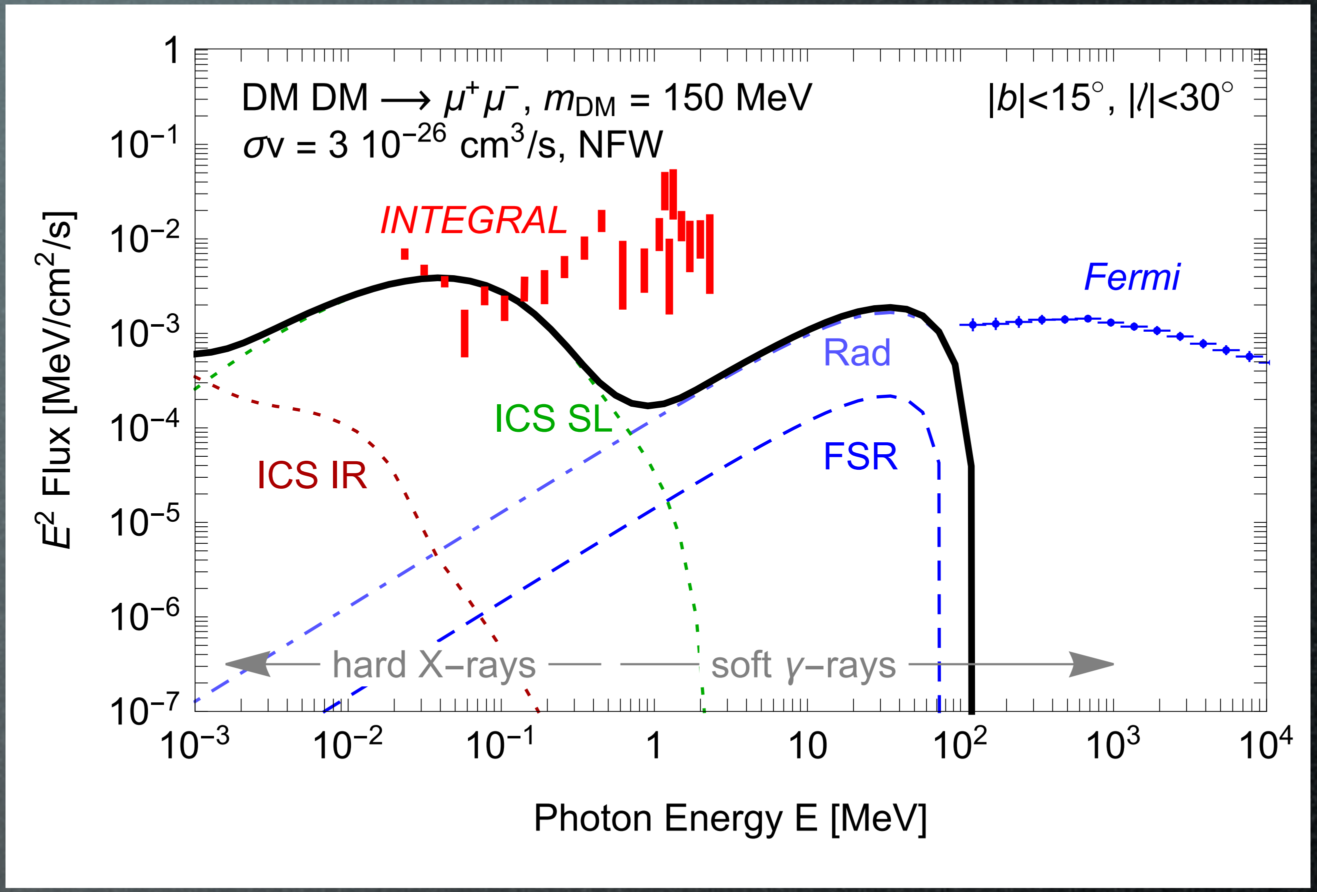
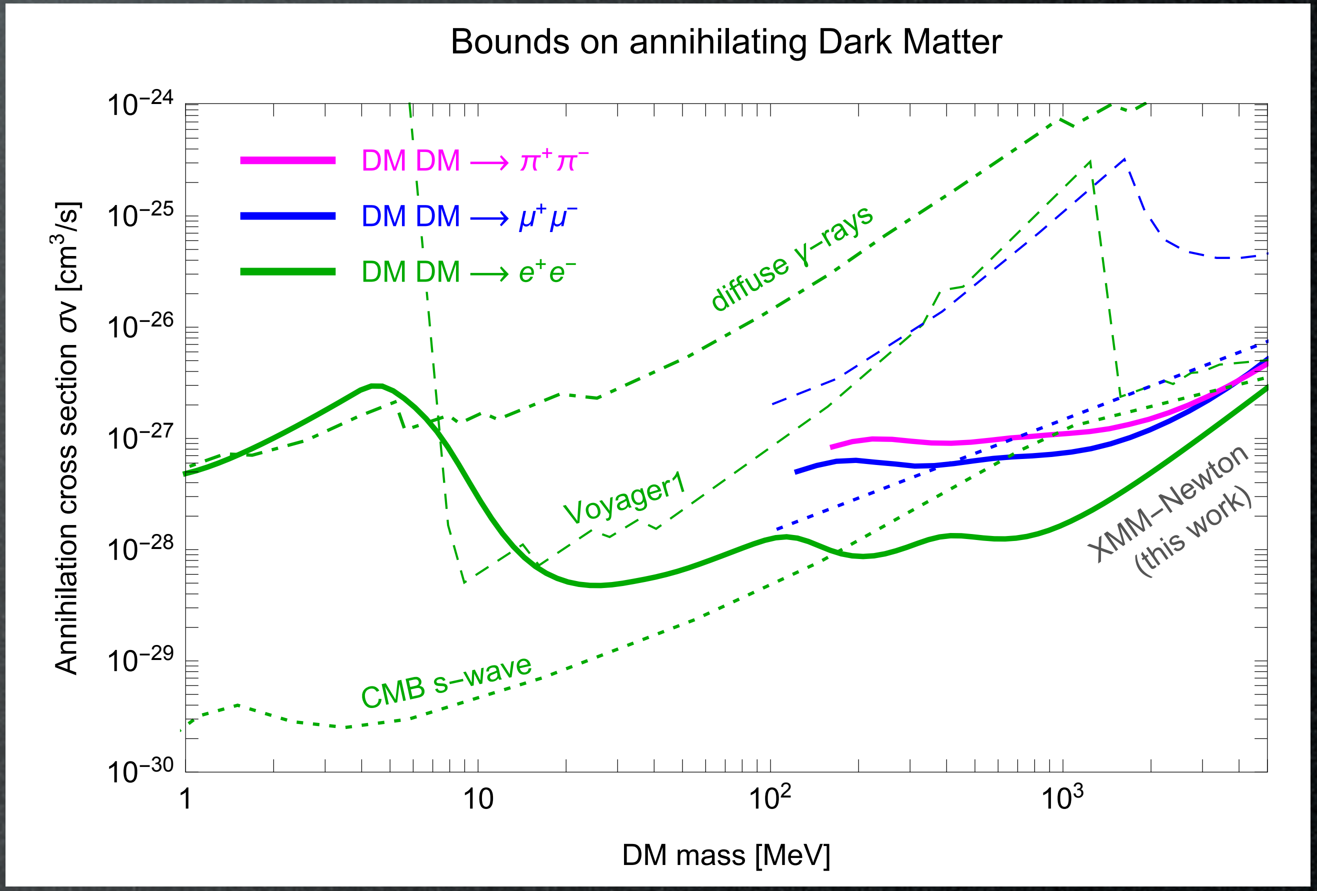
Impose stringent constraints





Conclusions

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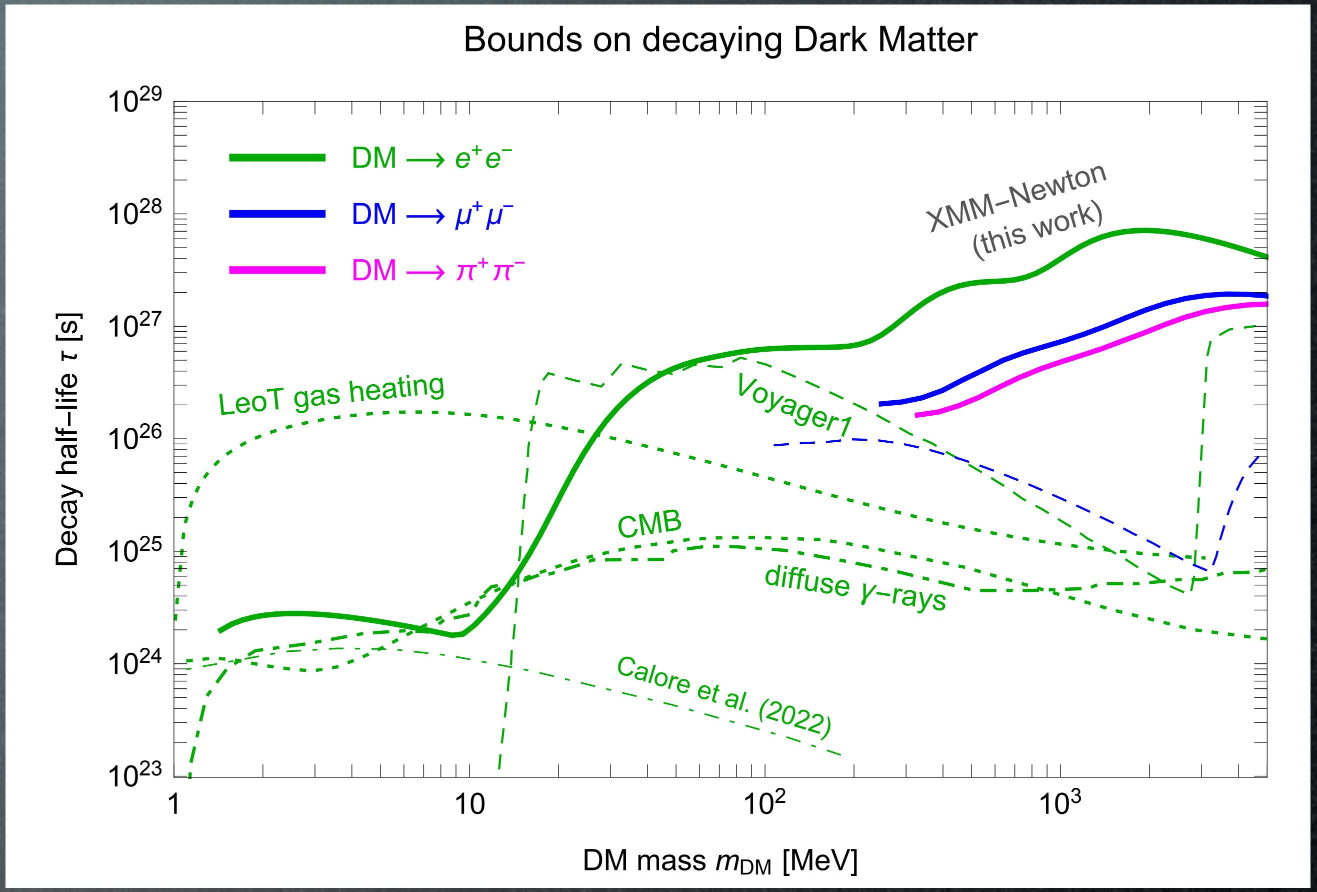
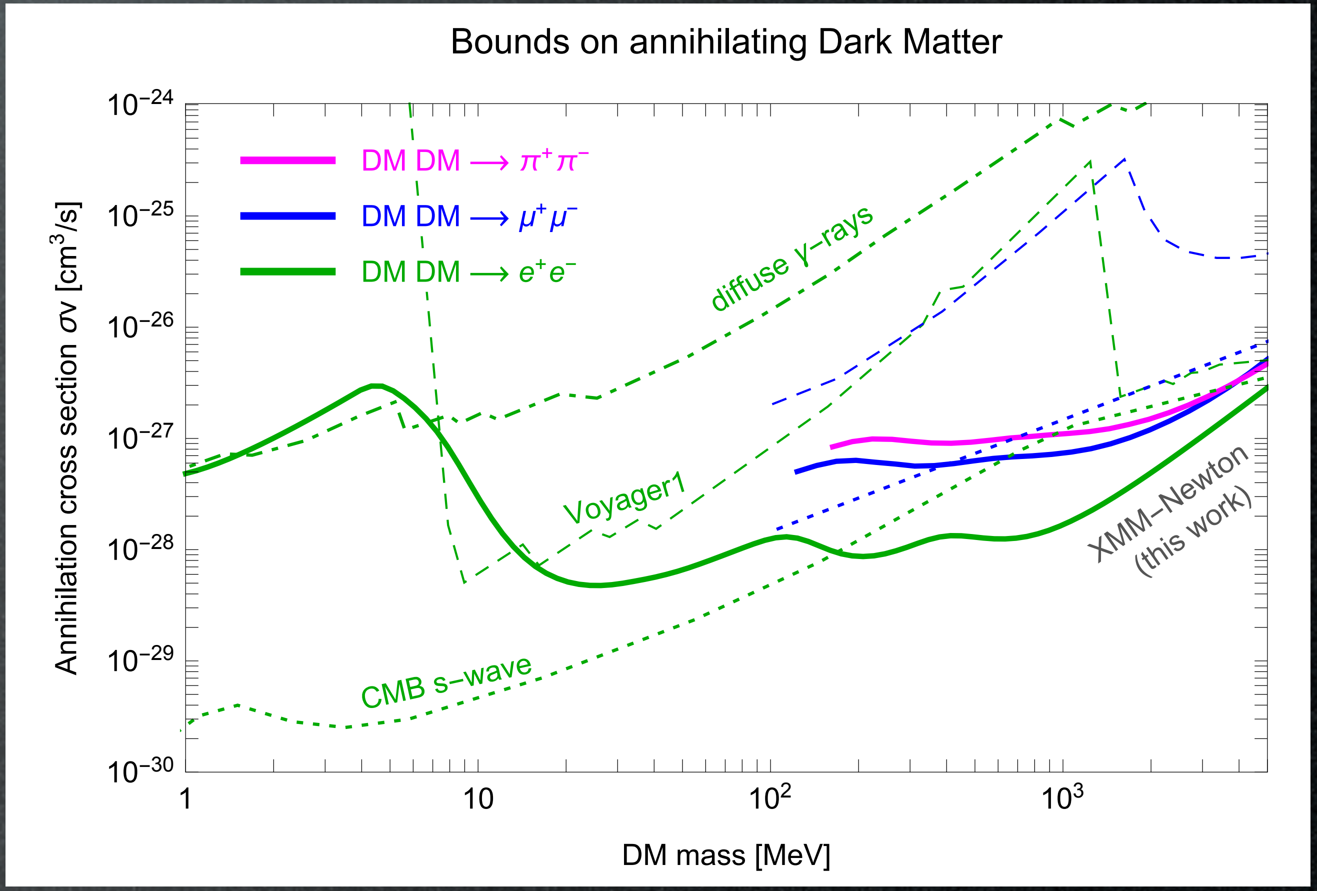




Backup

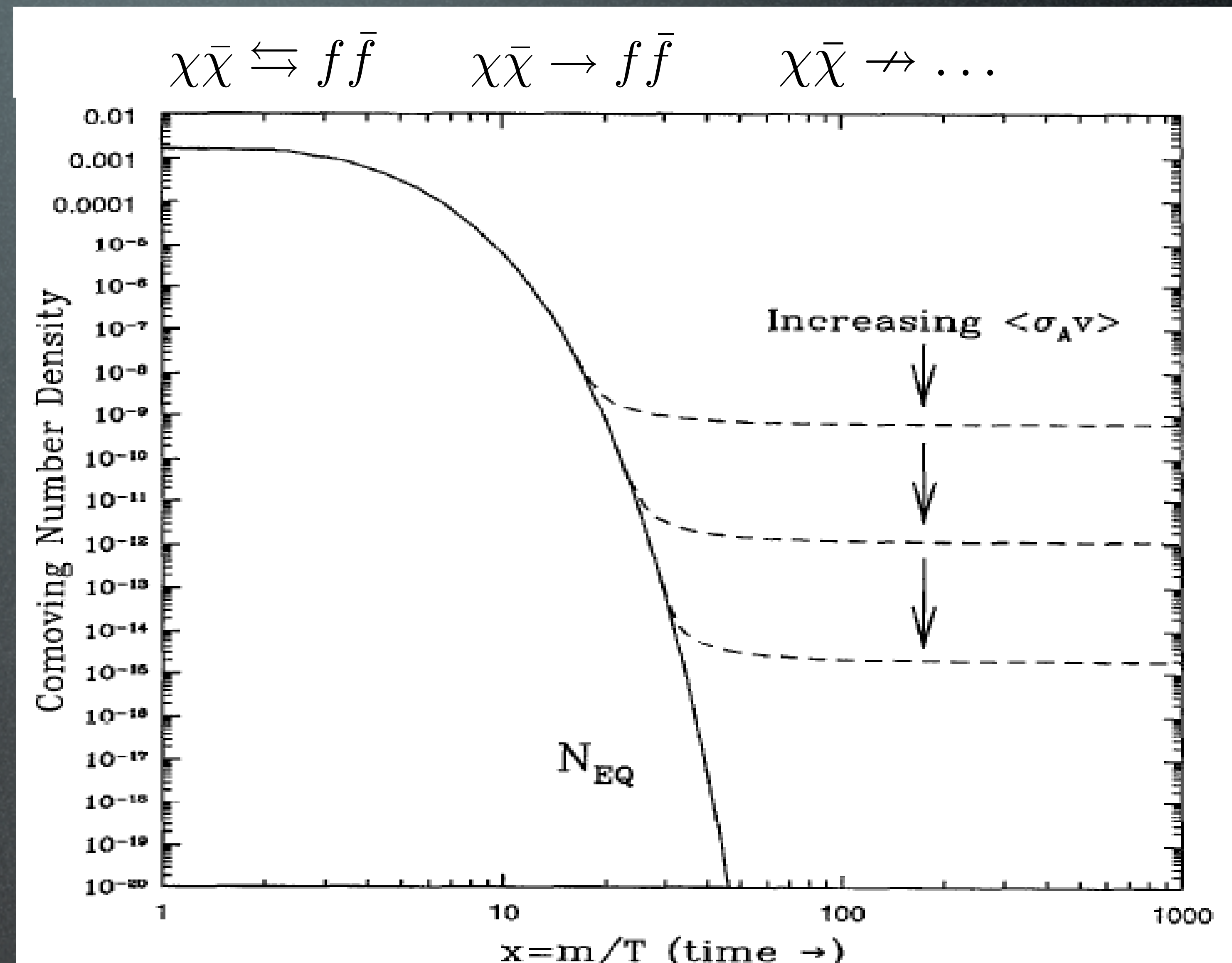
DM as a thermal relic from the Early Universe

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 $\Omega_{\mathrm{DM}} \simeq 0.23$ 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:

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

(WIMP)

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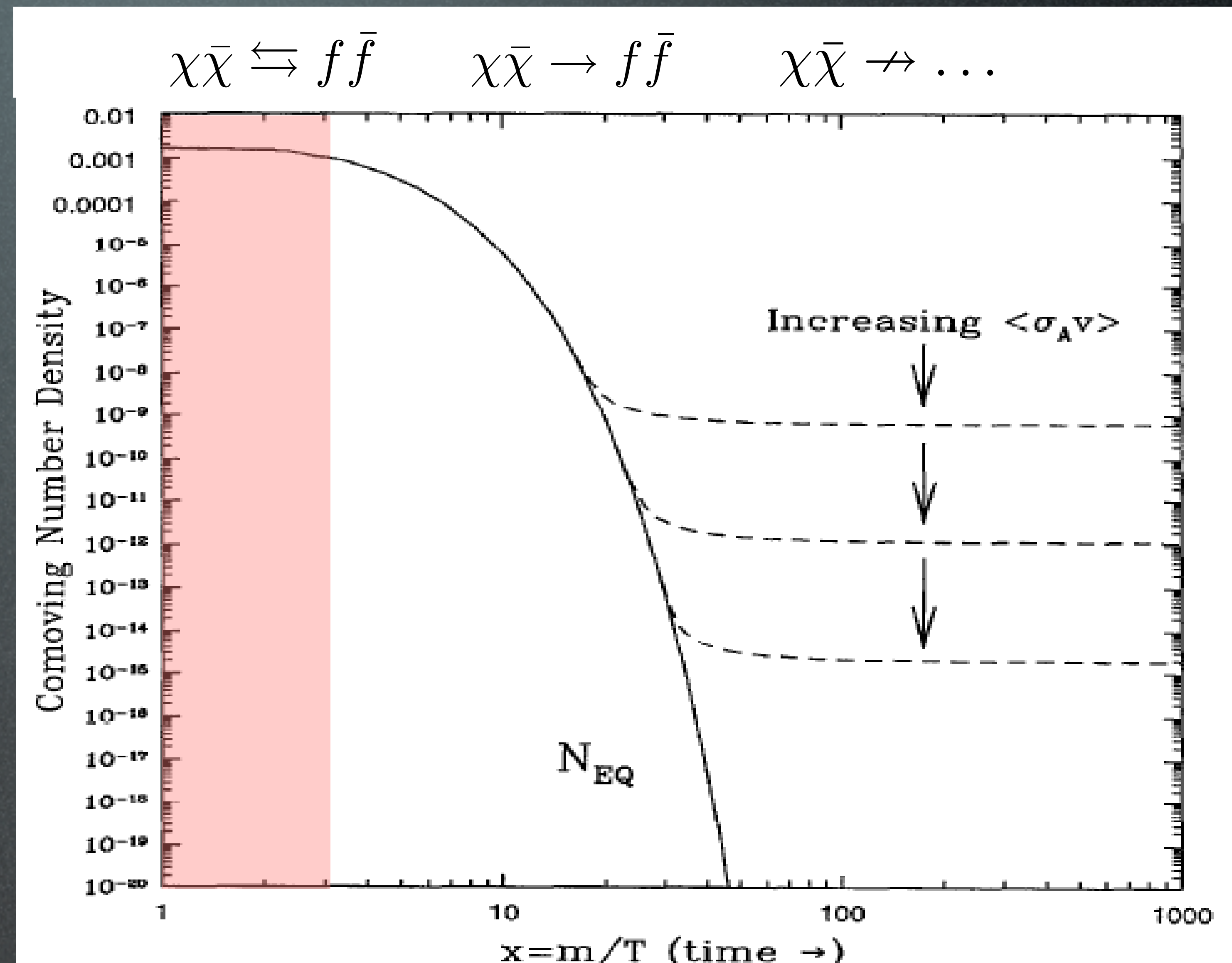

Kolb,Turner, The Early Universe, 1995

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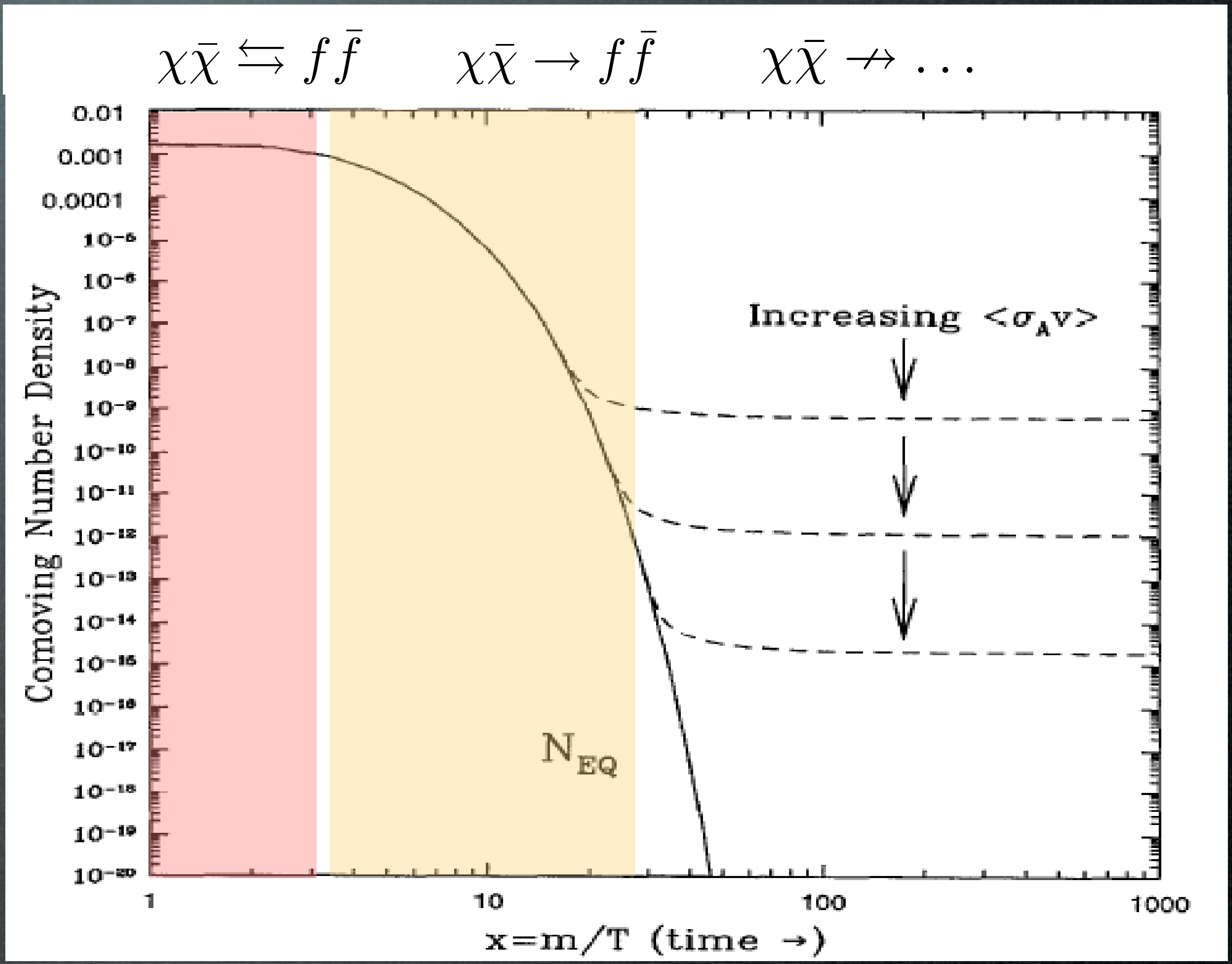

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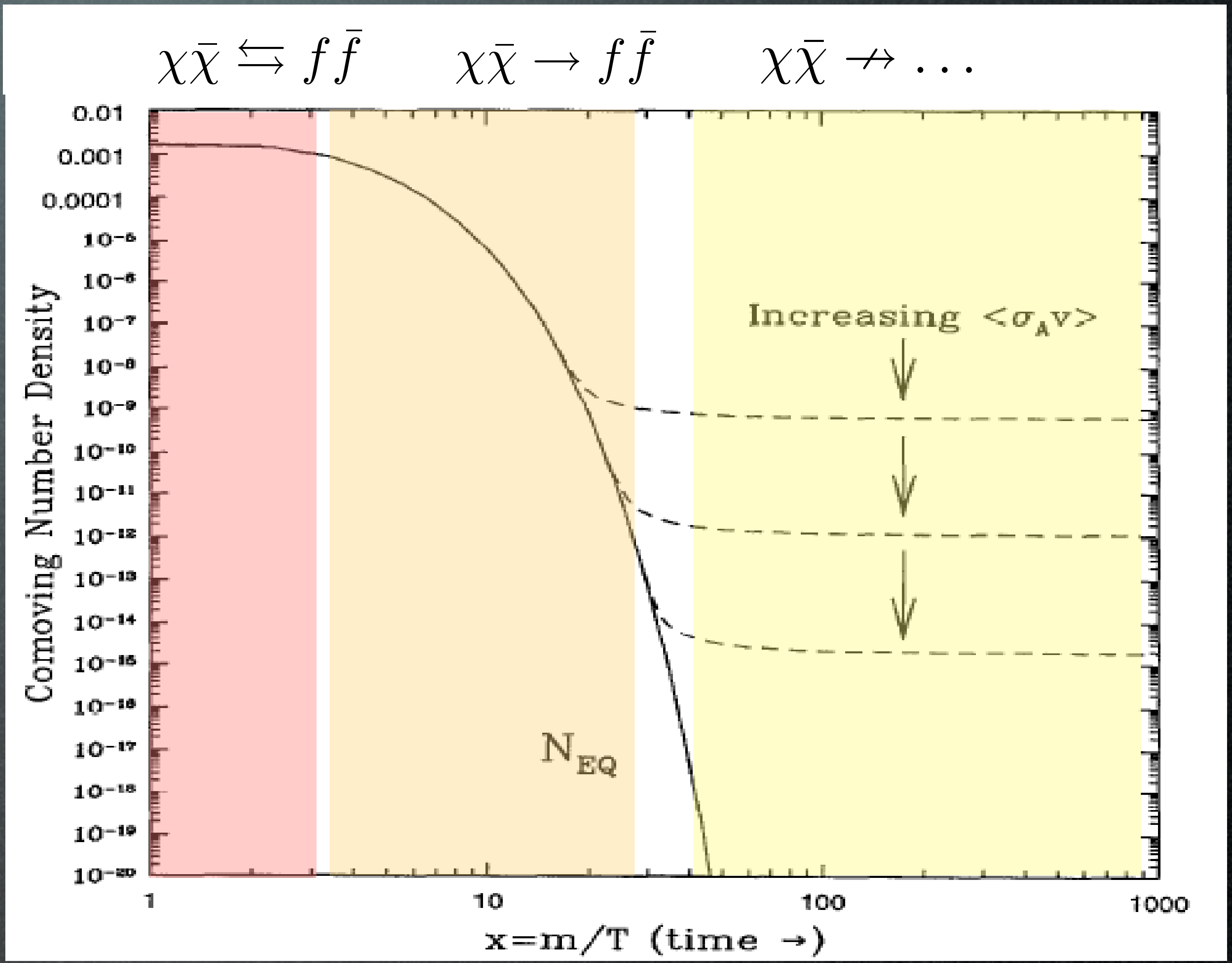

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Weak cross section:

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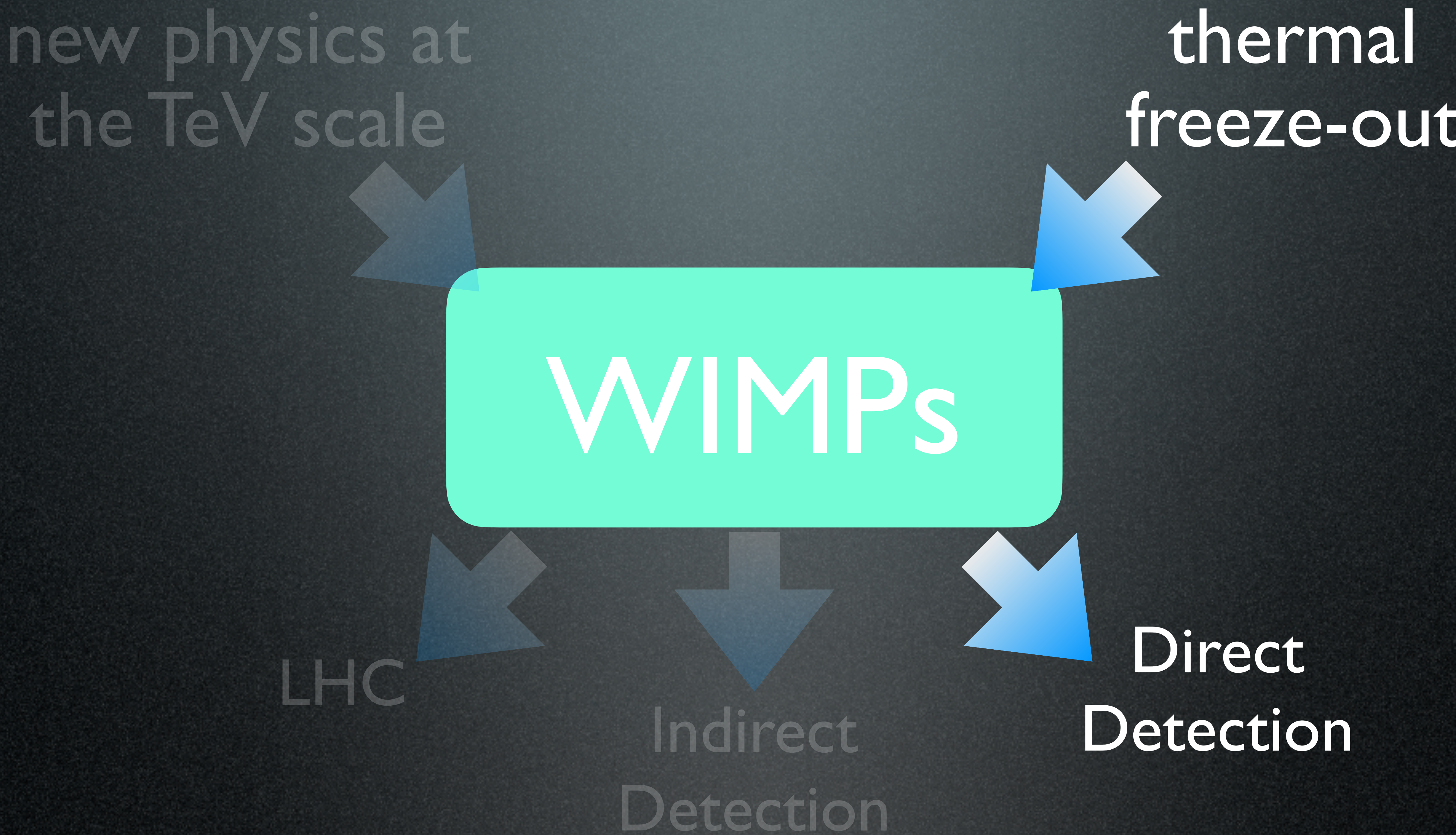
(WIMP)

Candidates

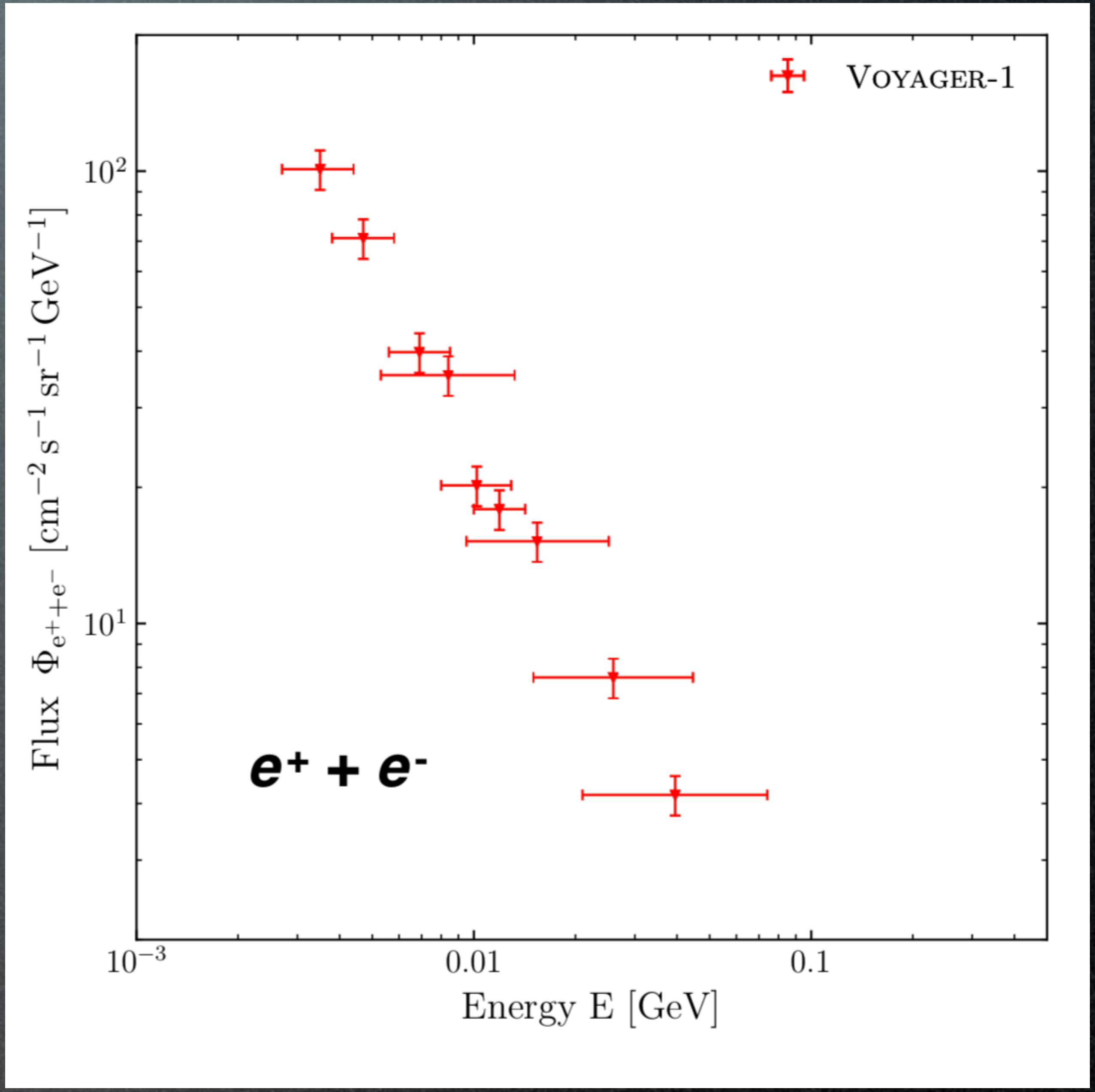


1. even without a larger framework, WIMPs are still appealing
2. the three search strategies are complementary

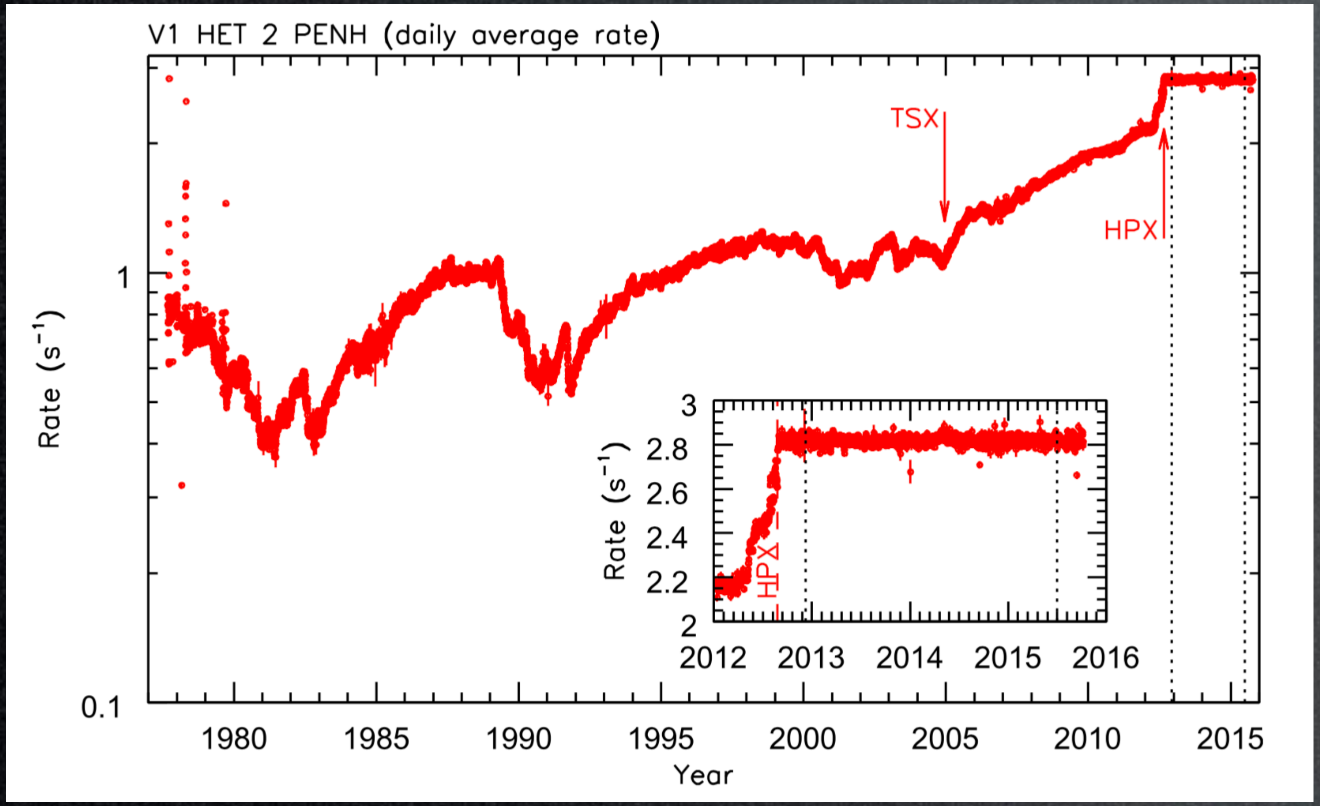
Data: leptons
low energy

Voyager-1 left the heliosphere in 08.2012

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



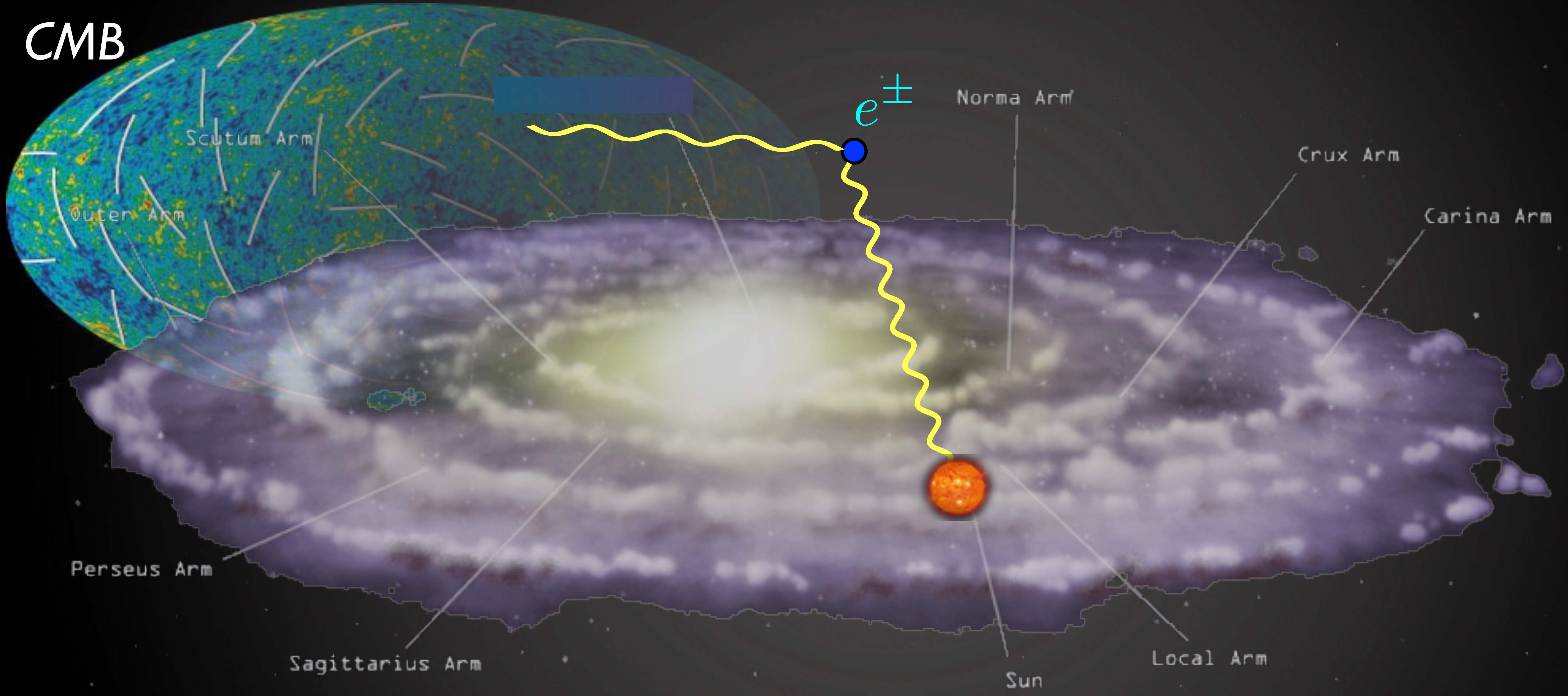
courtesy of M. Boudaud, based on Cummings+ (Voyager-1 coll.), The Astrophysical Journal, 831:18, 2016



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

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

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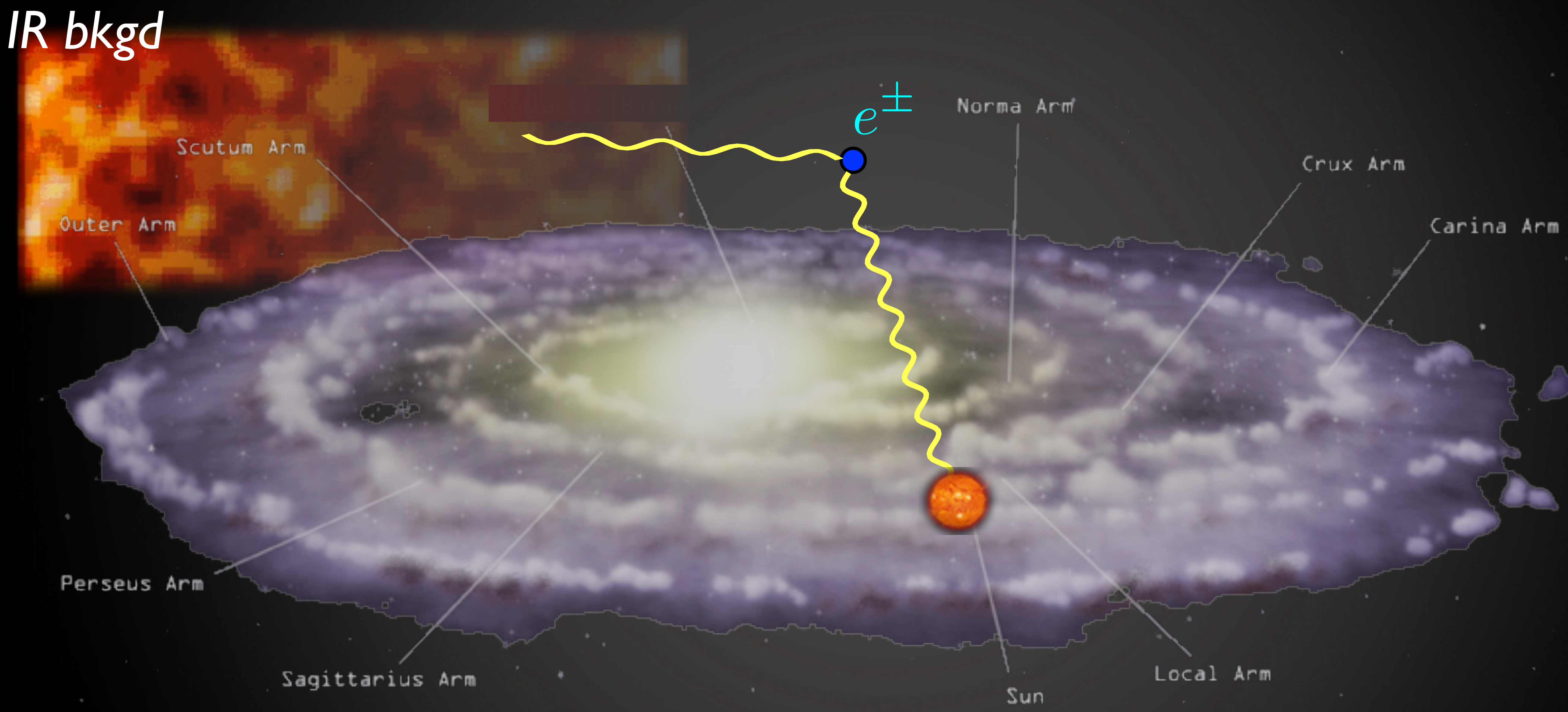

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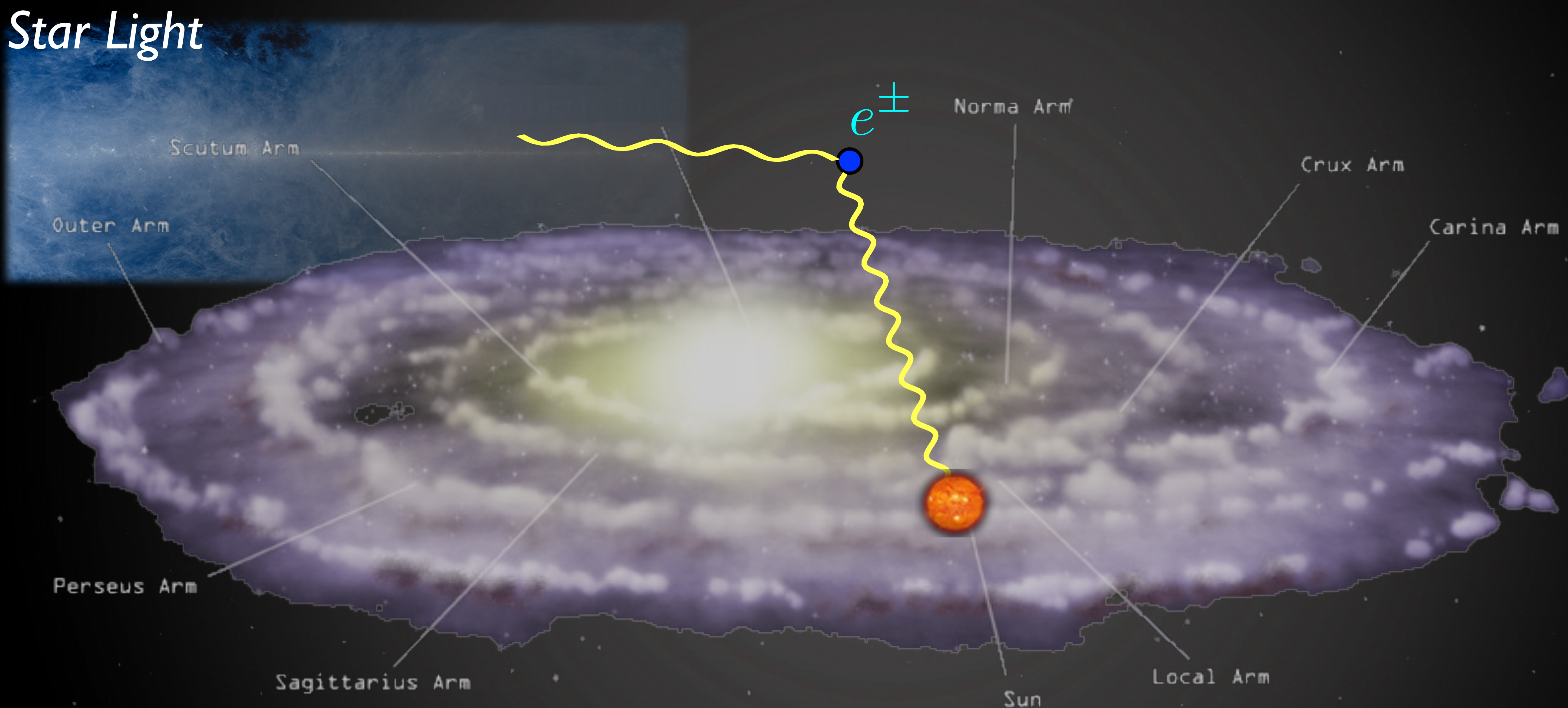

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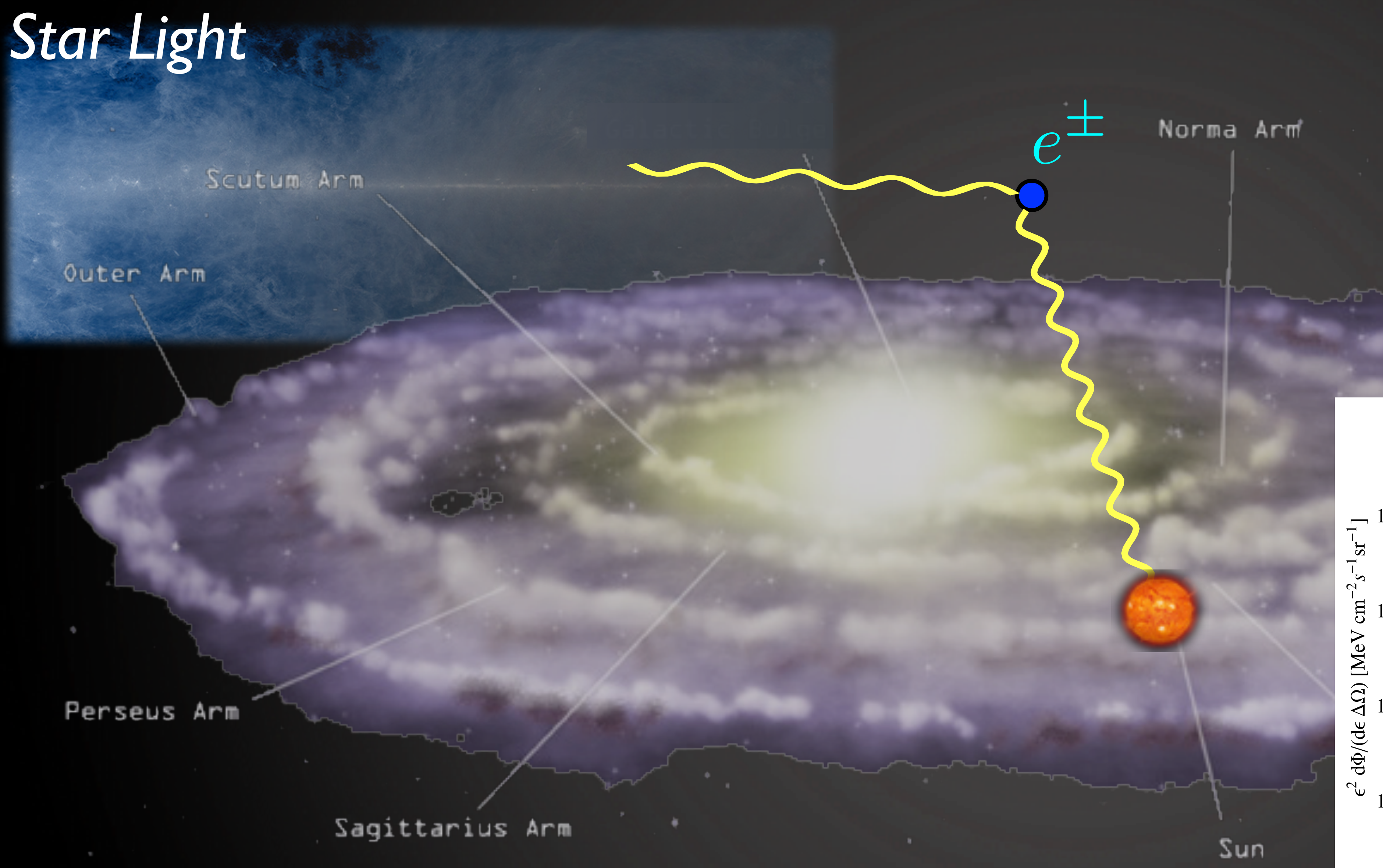

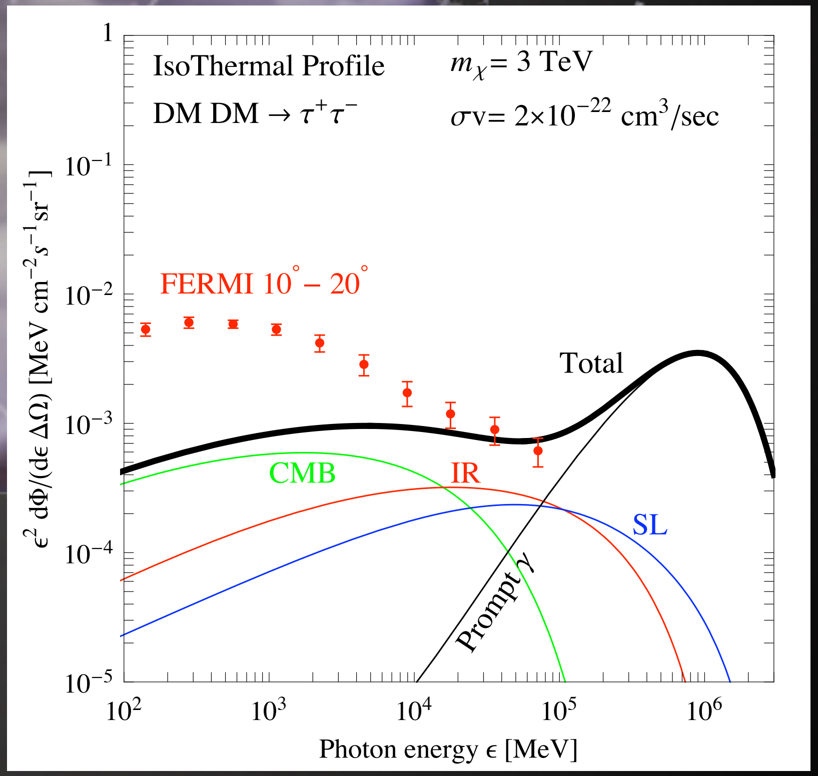

Cirelli, Panci, Serpico 0912.0663

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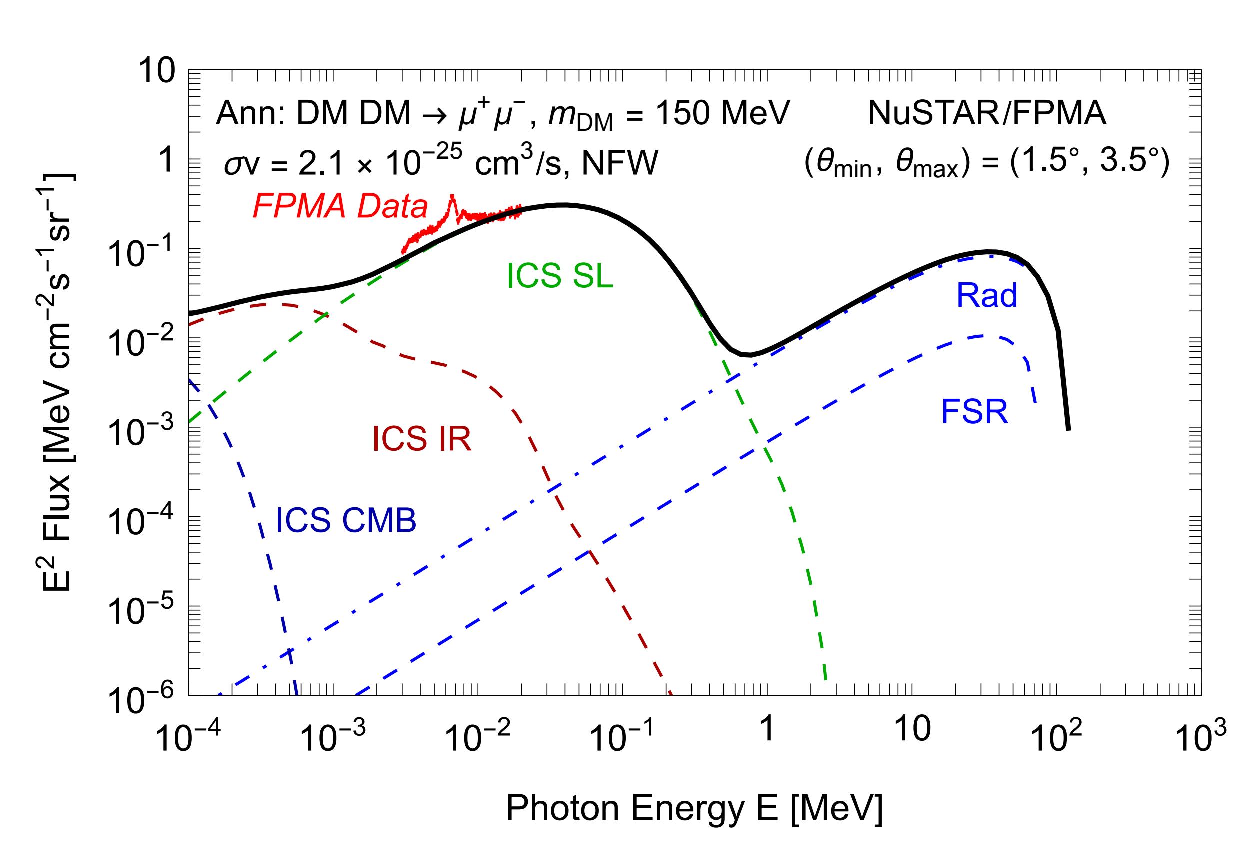
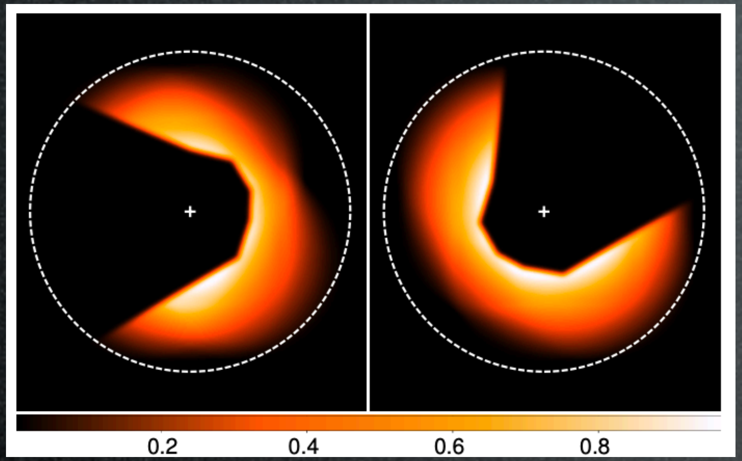
More analysis!

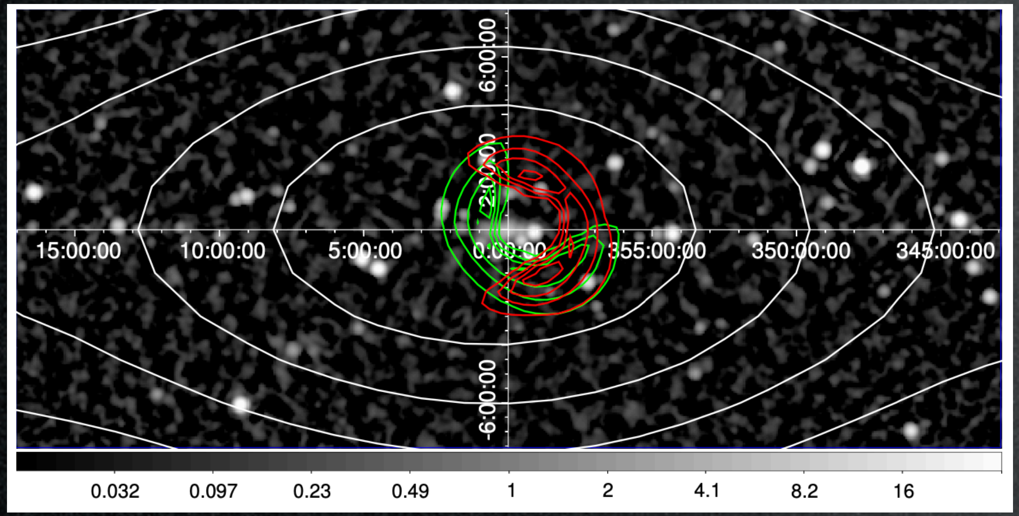
NuSTAR 2015-2020 data

Krivonos et al.2011.11469
Mori et al., 1510.04631
Hong et al., 1605.03882
Perez et al., 1609.00667
Roach et al., 1908.09037

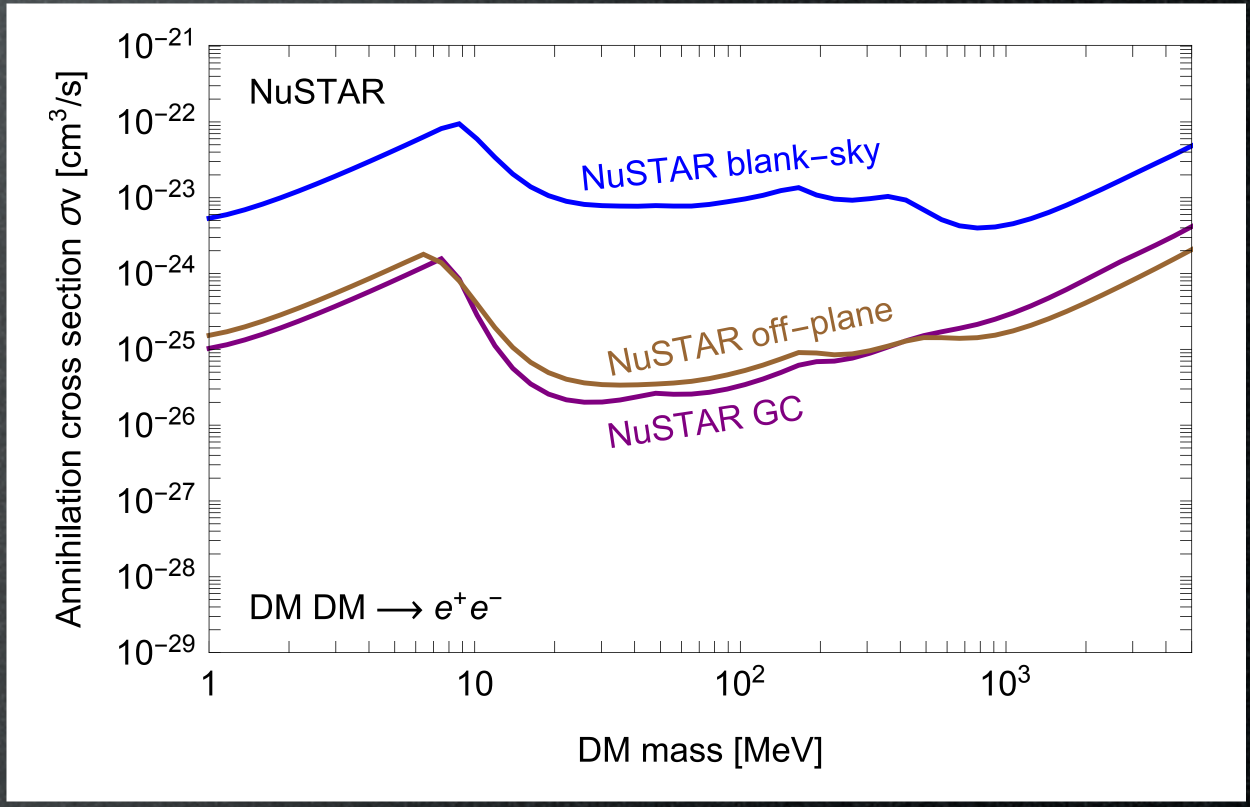


Rather complex field of view…





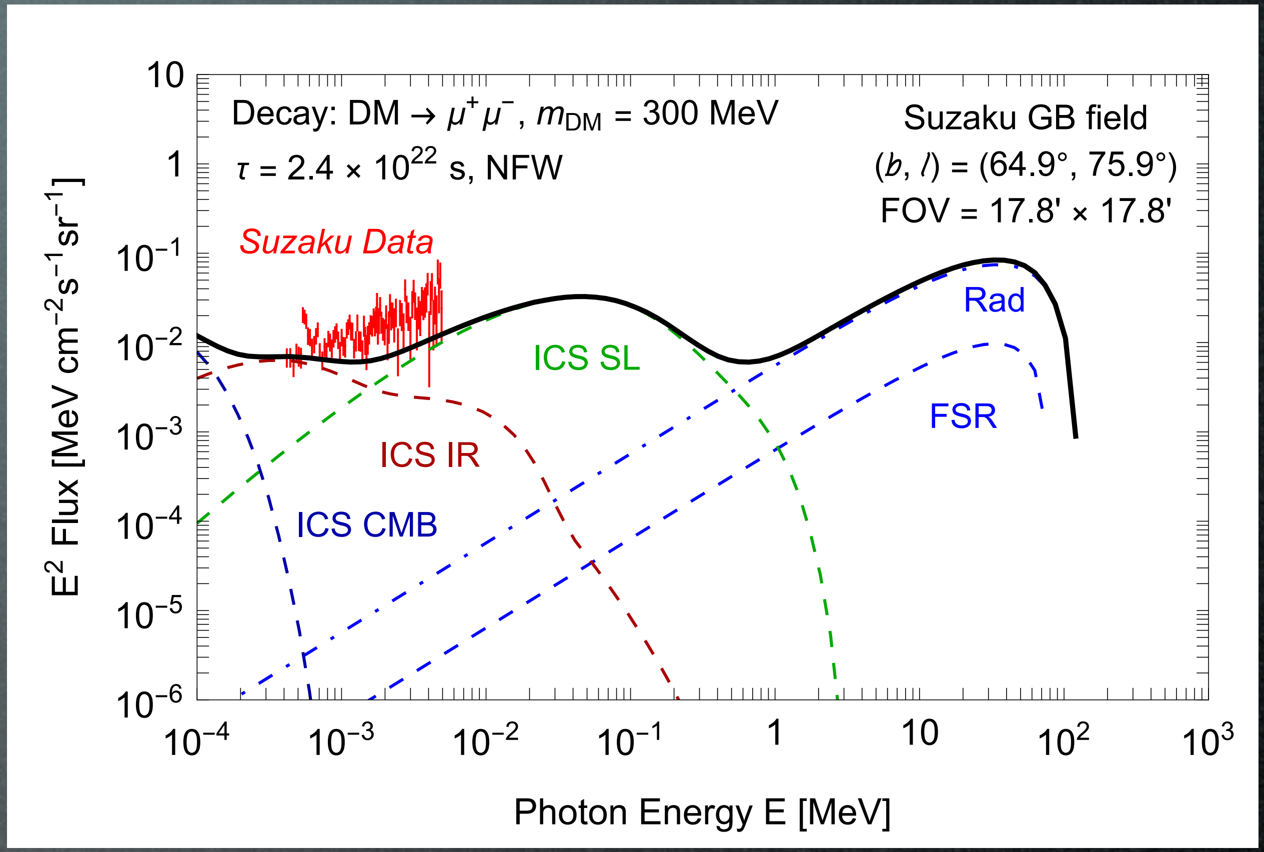
Results



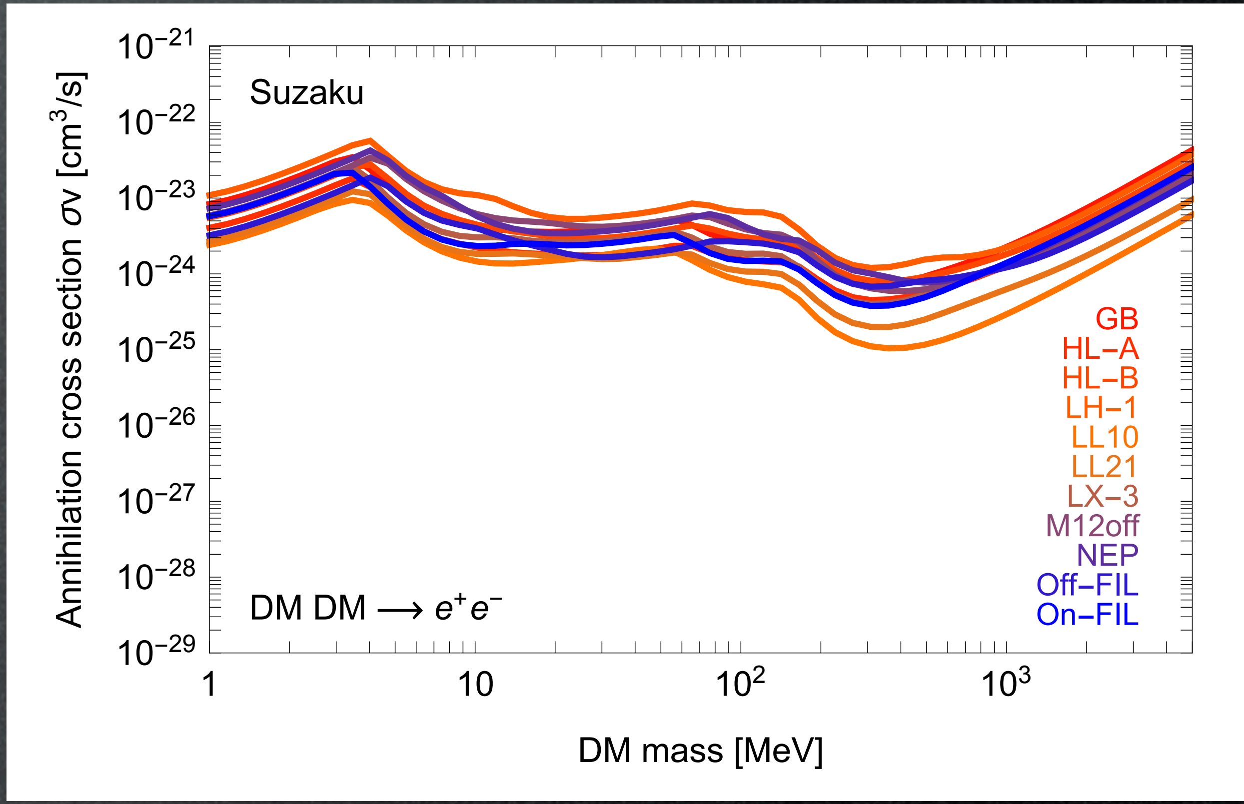
More analysis!

Suzaku 2009 data

Yoshino et al., 0903.2981



Results

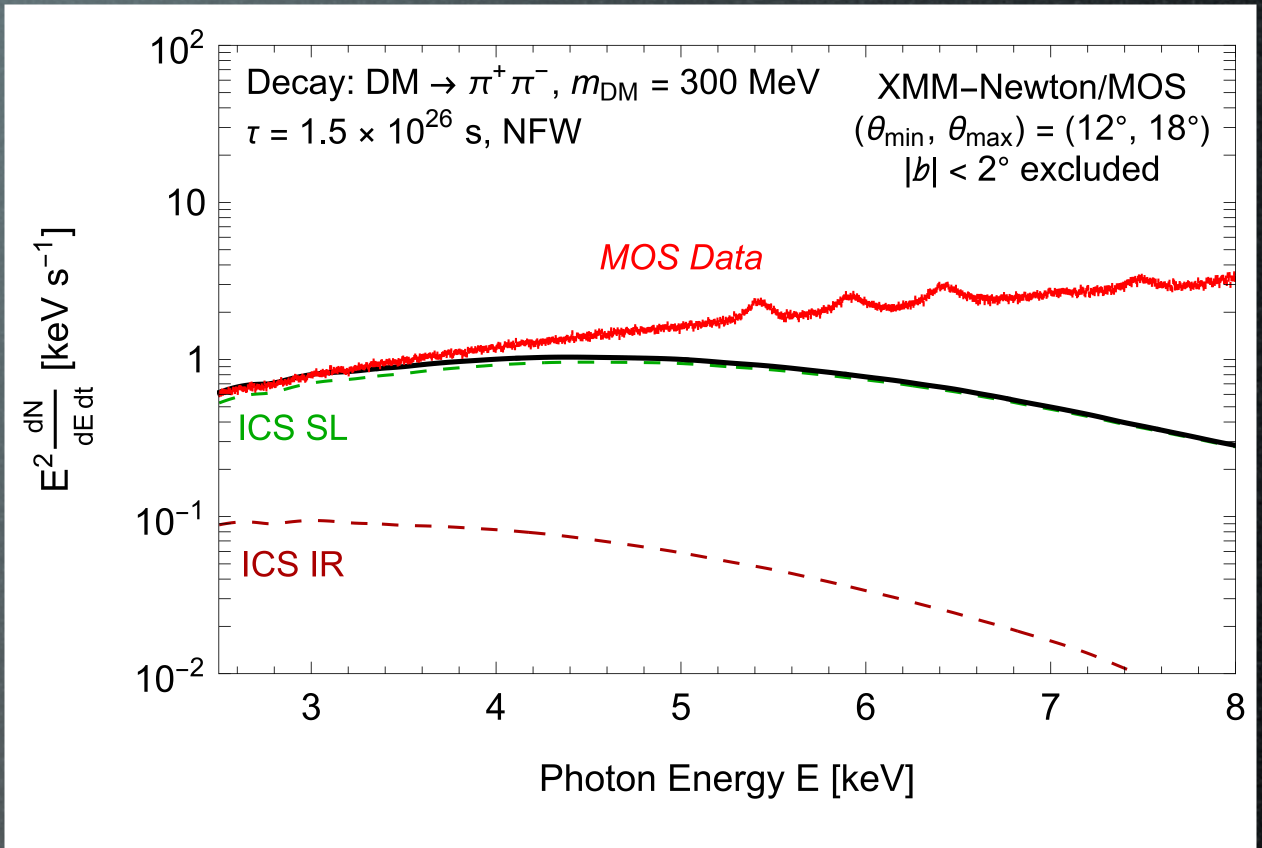


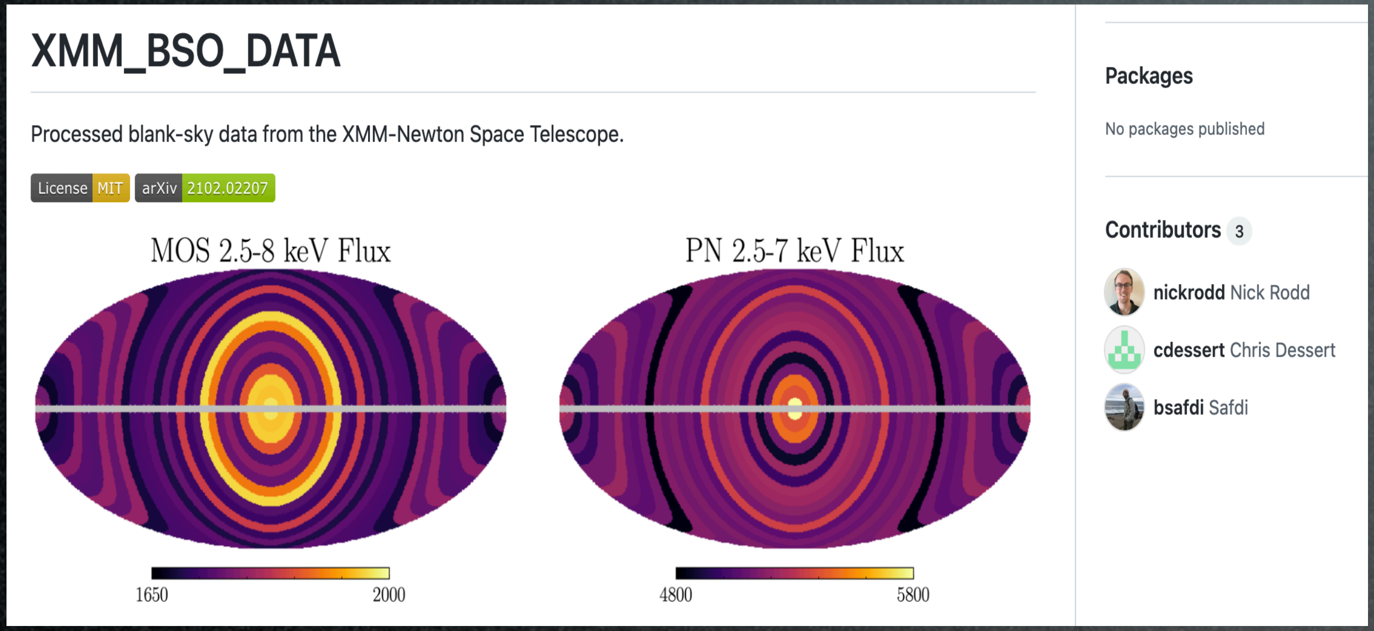
More analysis!

XMM-Newton 1999-2018 data

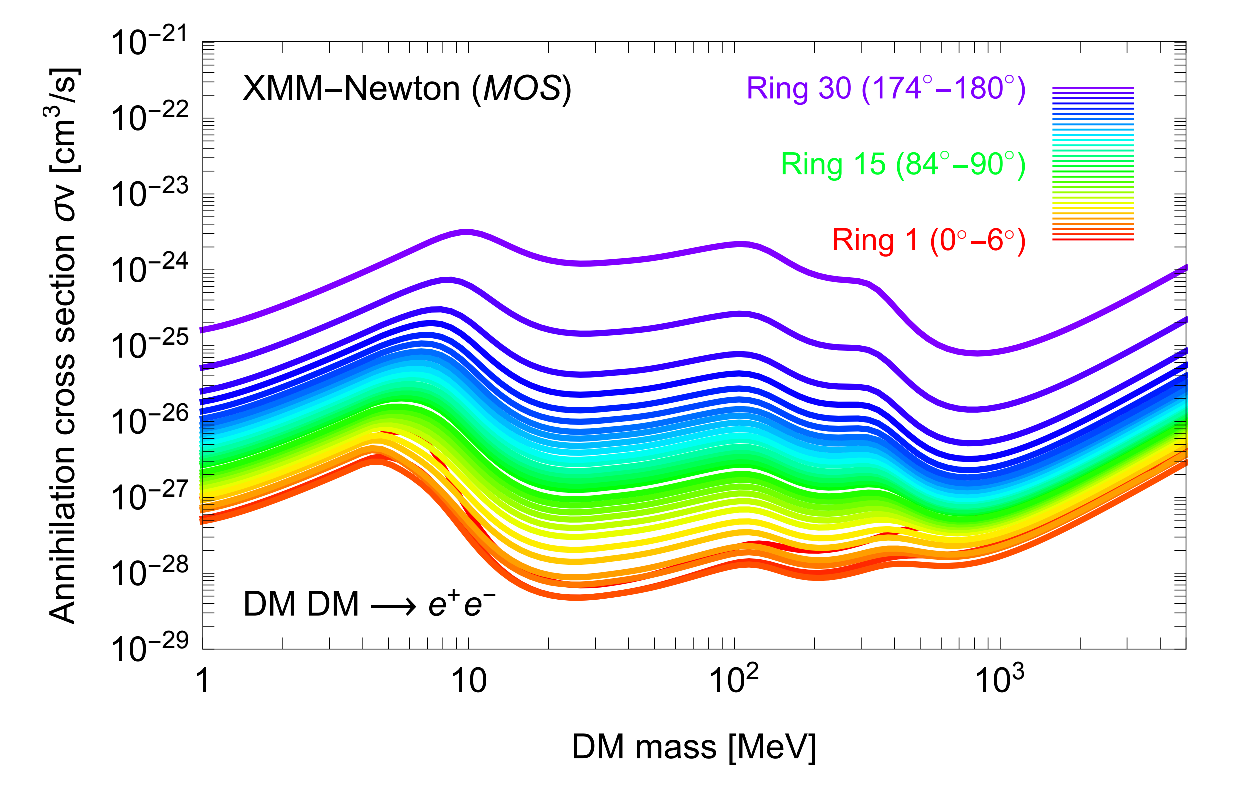
Dessert et al., 1812.06976
Foster et al., 2102.02207

https://github.com/bsafdi/XMM_BSO_DATA
Kudos to Safdi, Rodd etc!





Results



More analysis!

XMM-Newton 1999-2018 data

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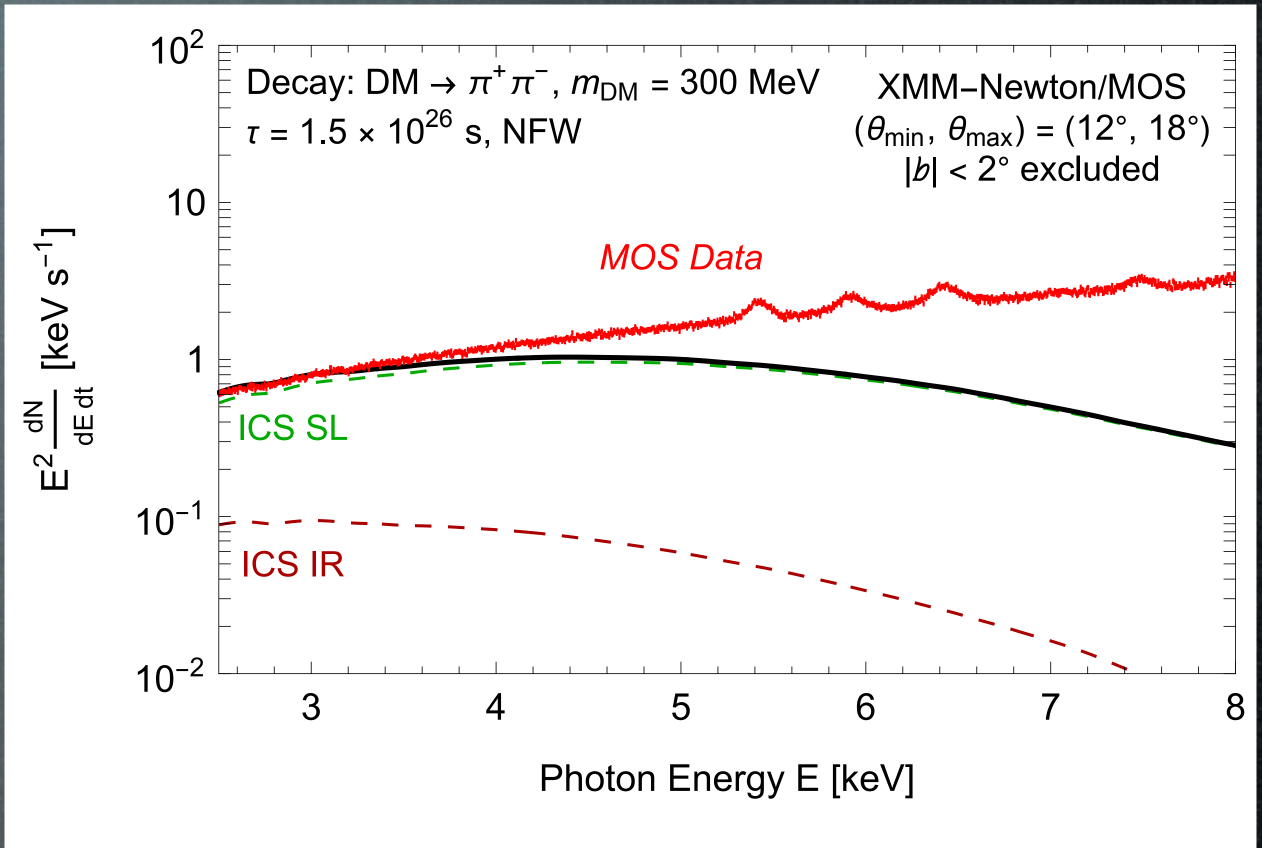
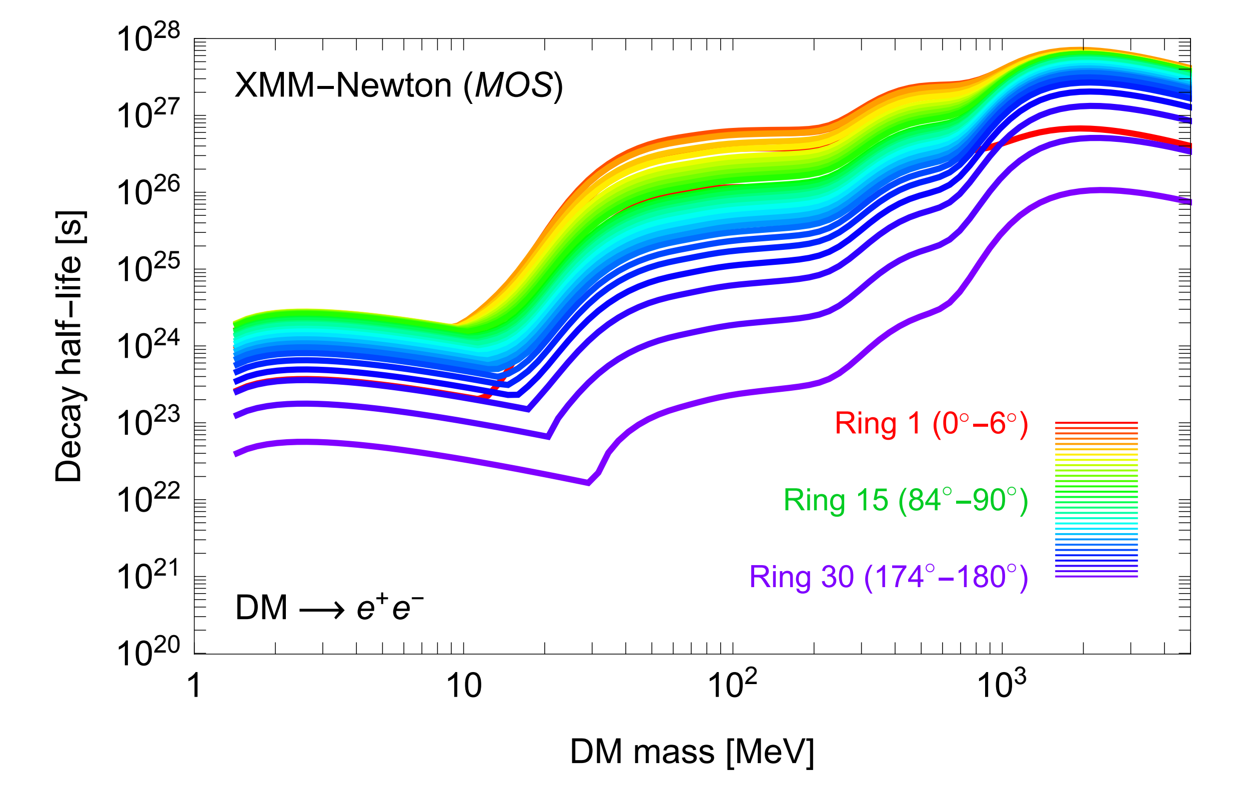
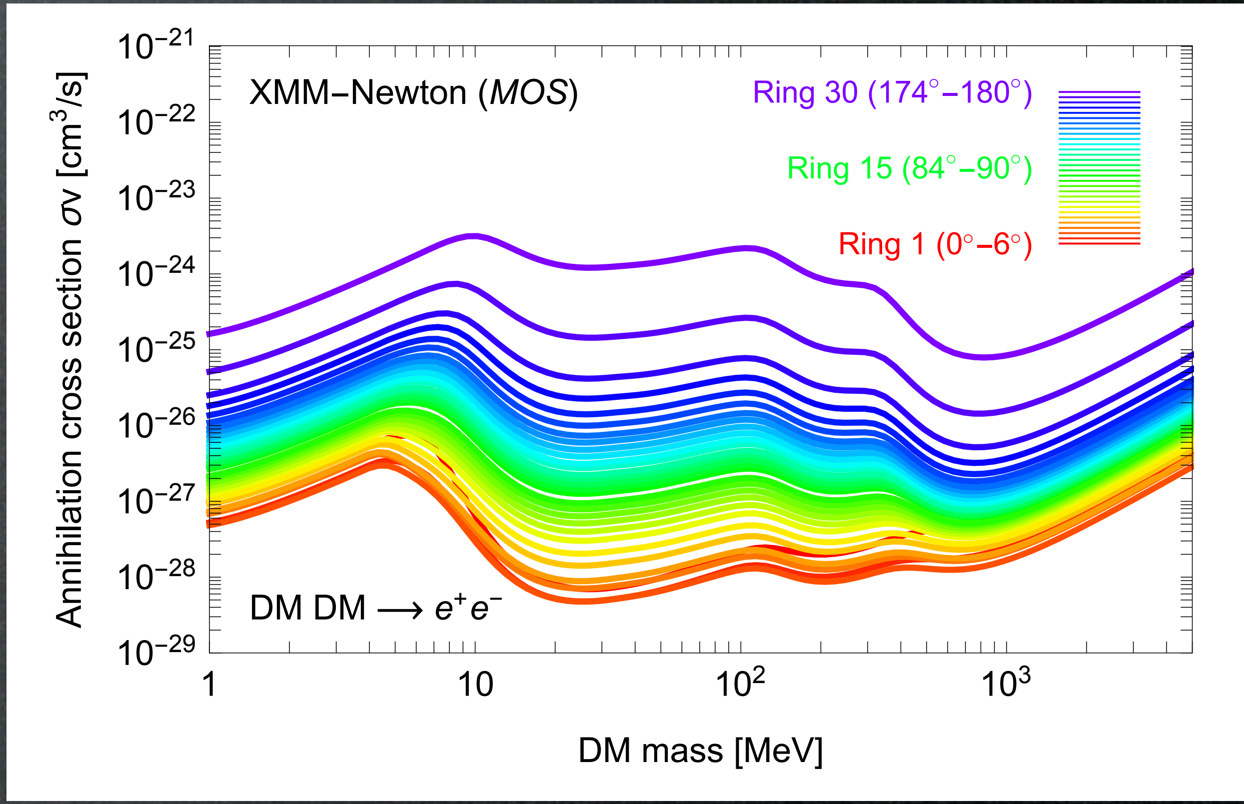


Results decay



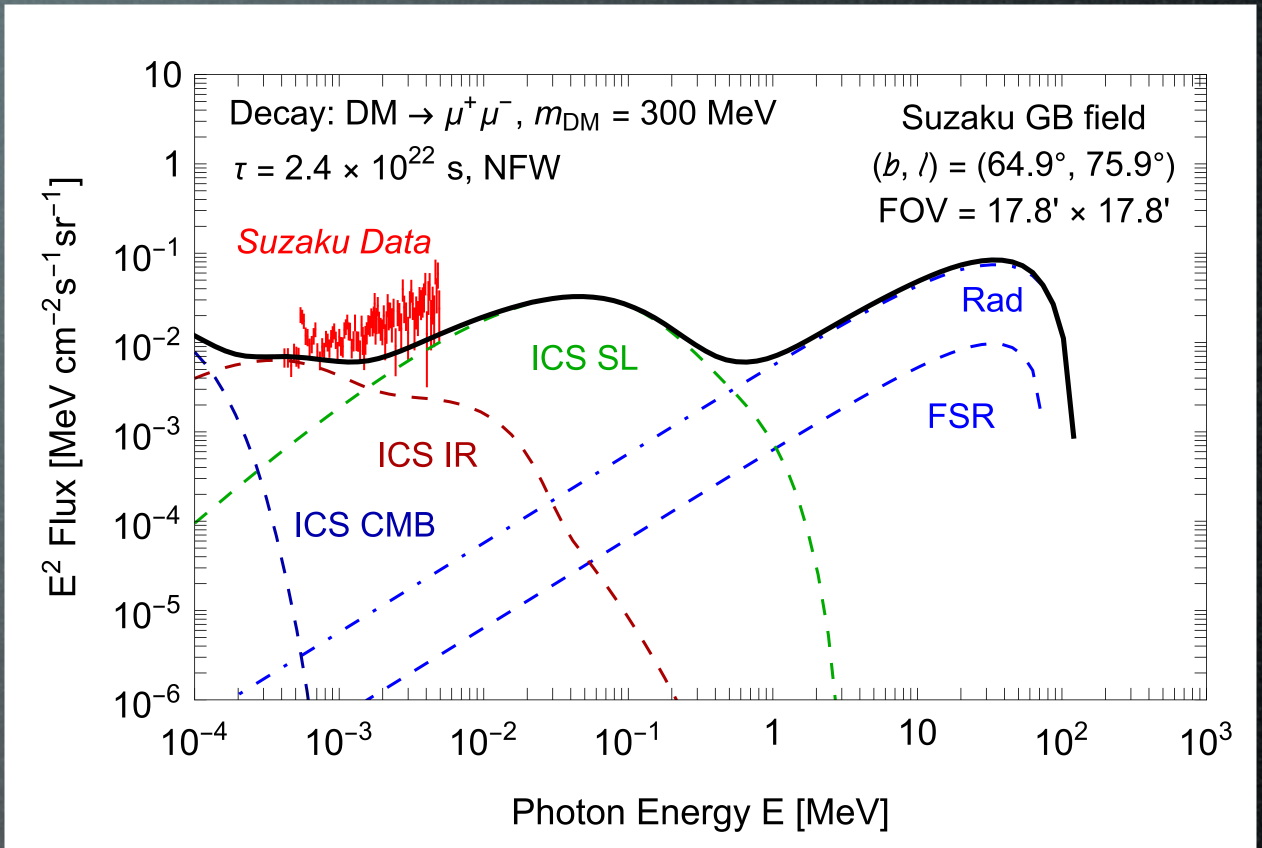
Results annihilation



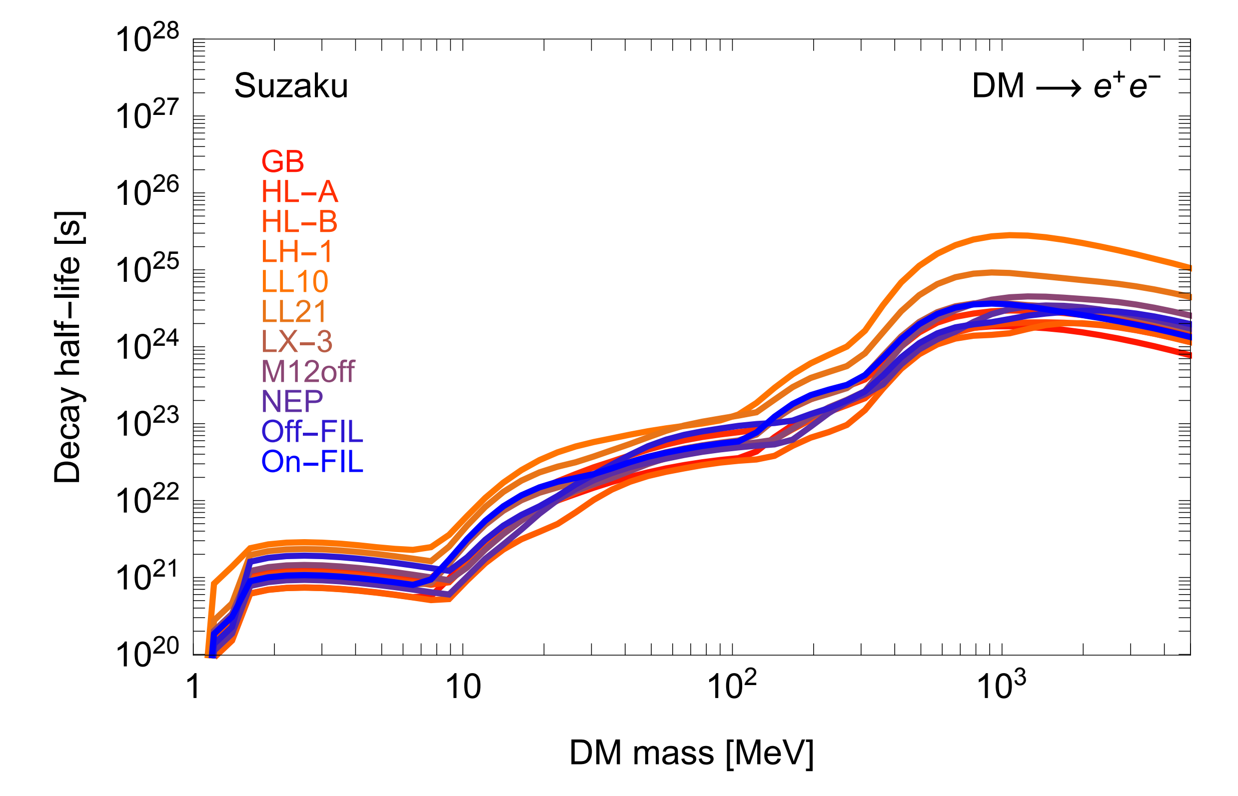
More analysis!

Suzaku 2009 data

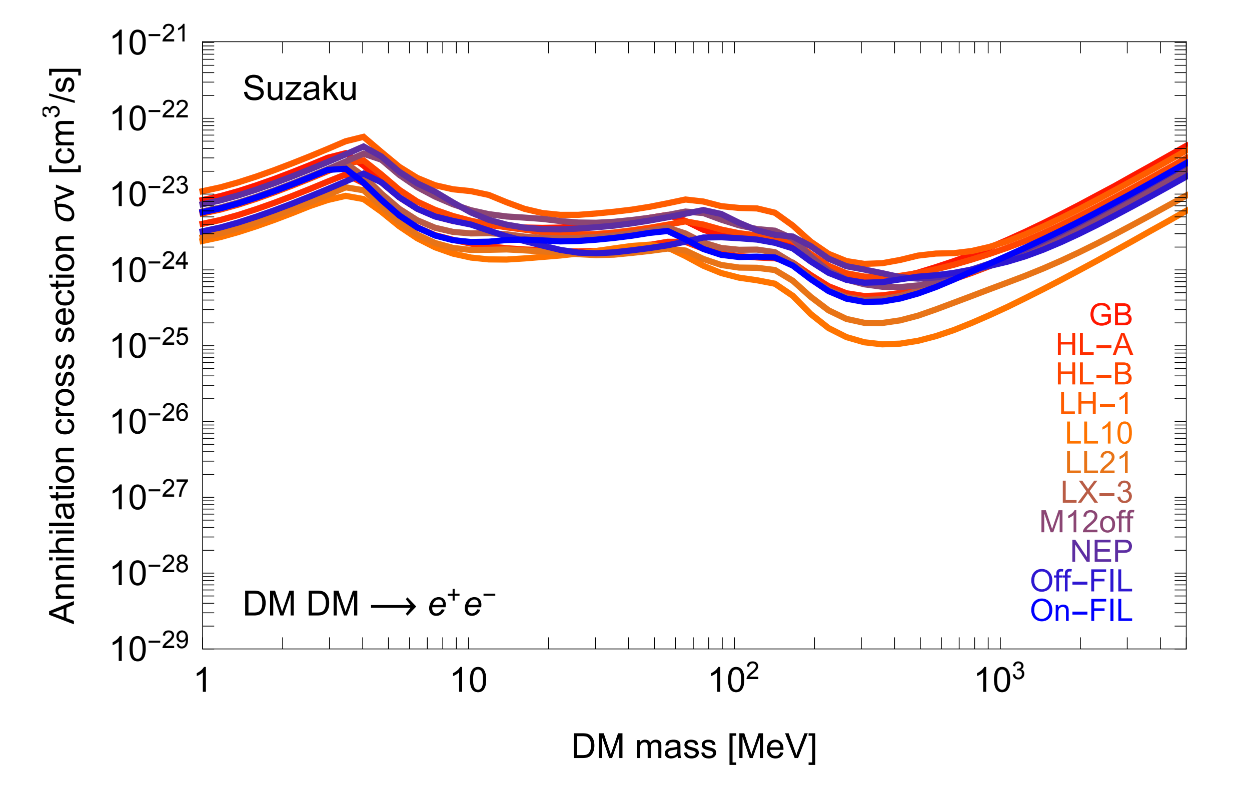
Yoshino et al., 0903.2981



Results decay



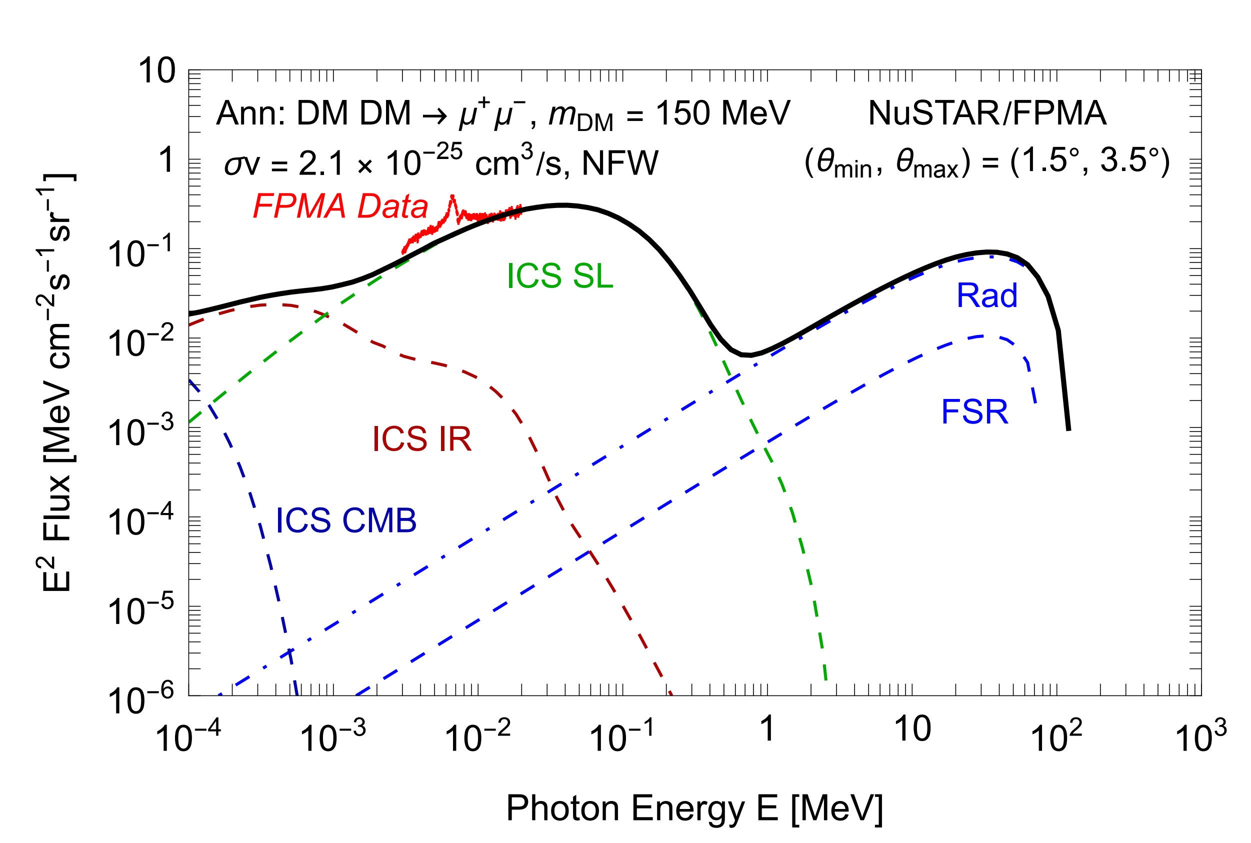
Results annihilation



More analysis!

NuSTAR 2015-2020 data

Krivonos et al.2011.11469
Mori et al., 1510.04631
Hong et al., 1605.03882
Perez et al., 1609.00667
Roach et al., 1908.09037



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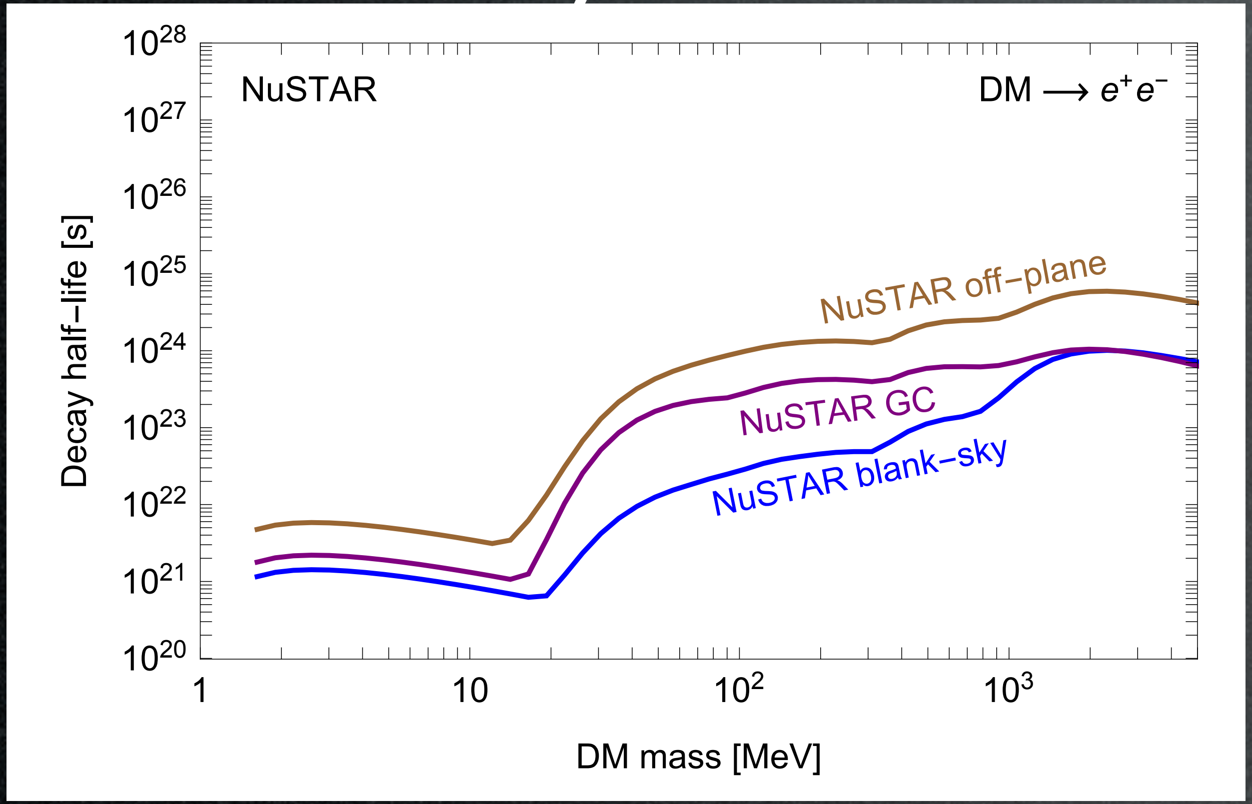
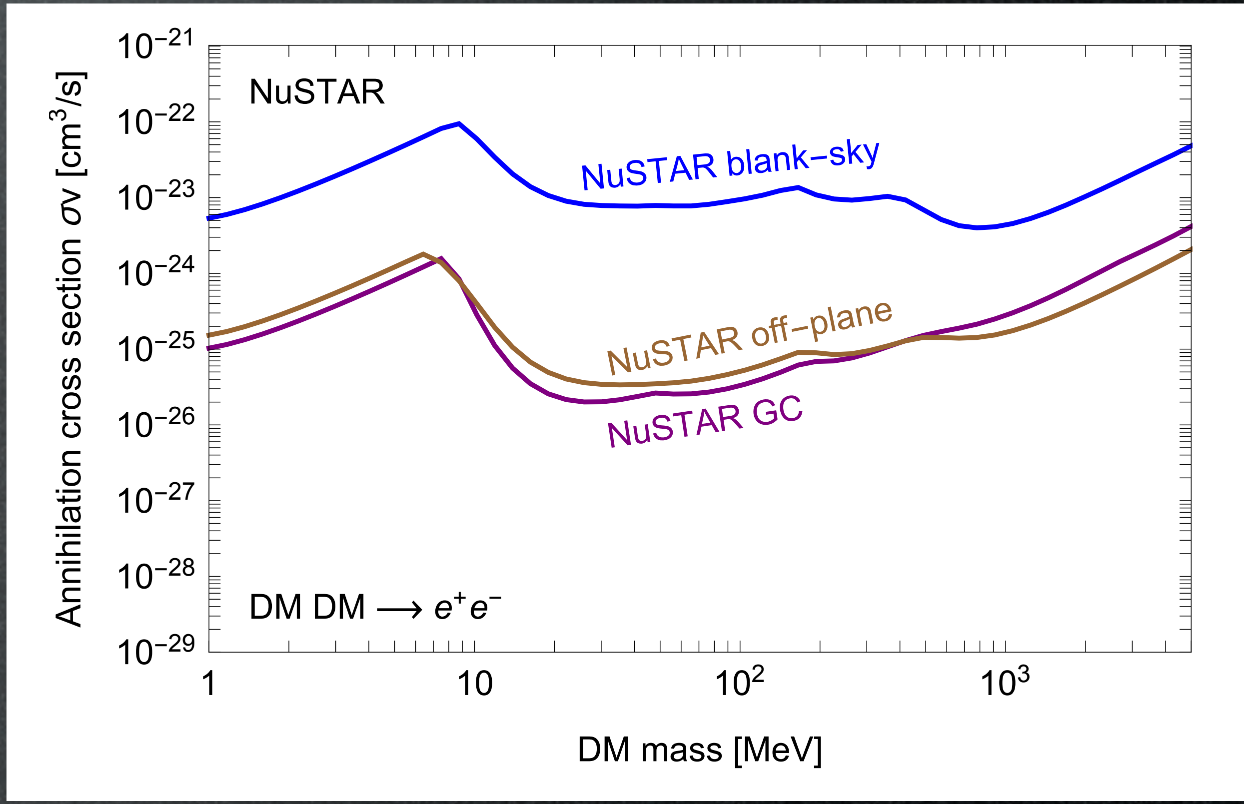


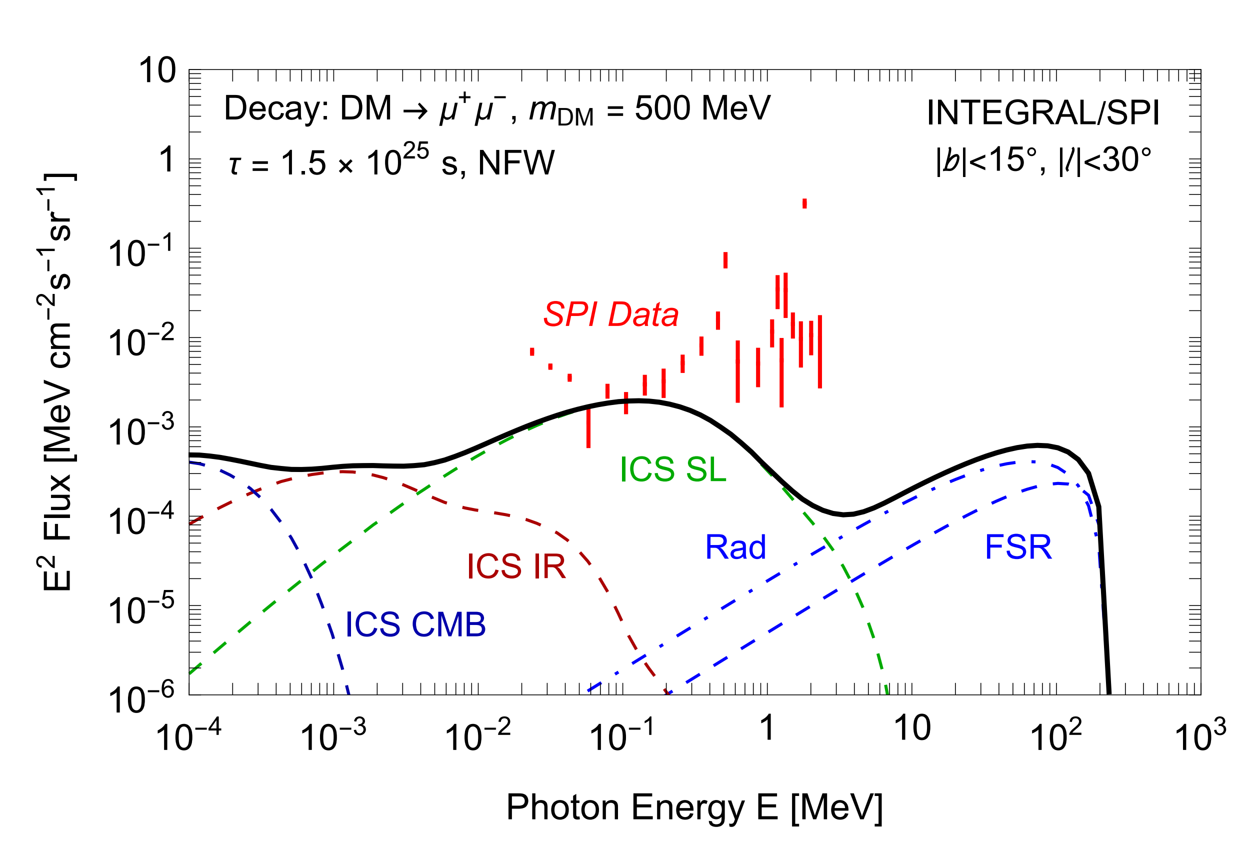
Results annihilation



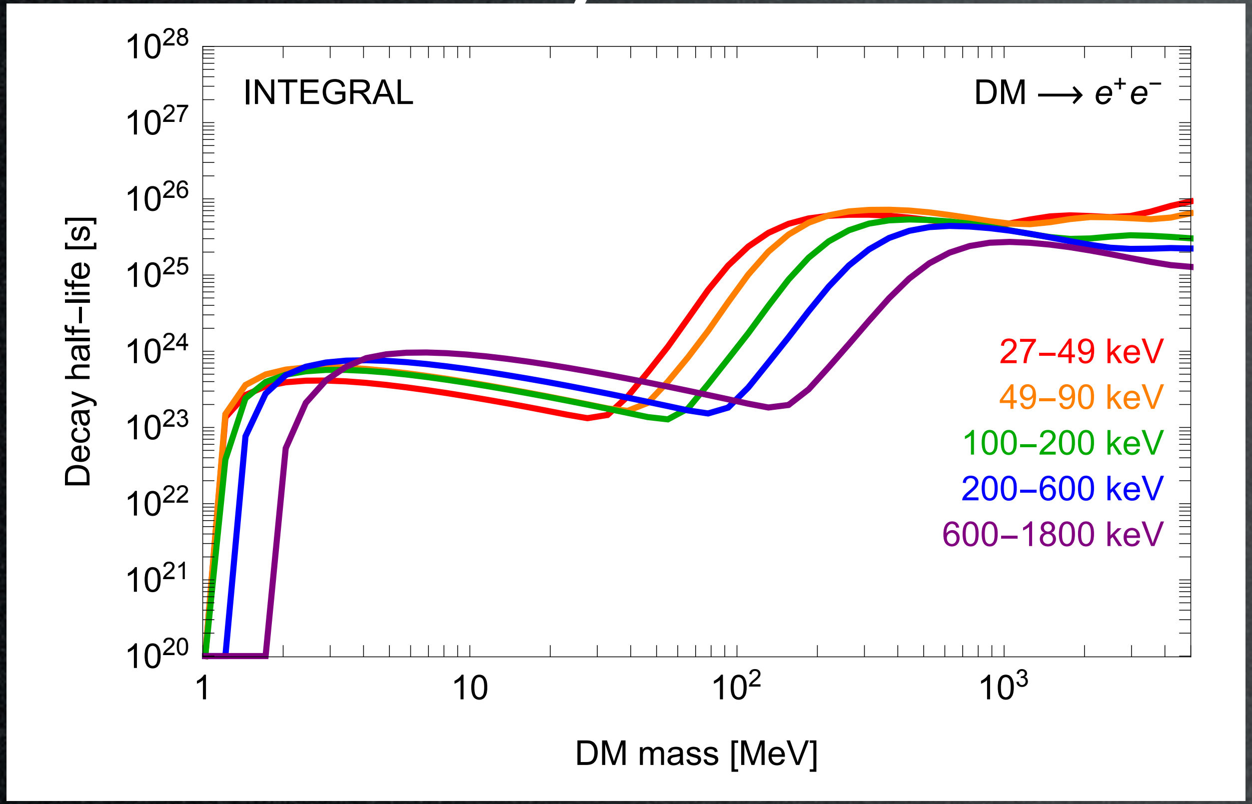
More analysis!

Integral-SPI 2011 data

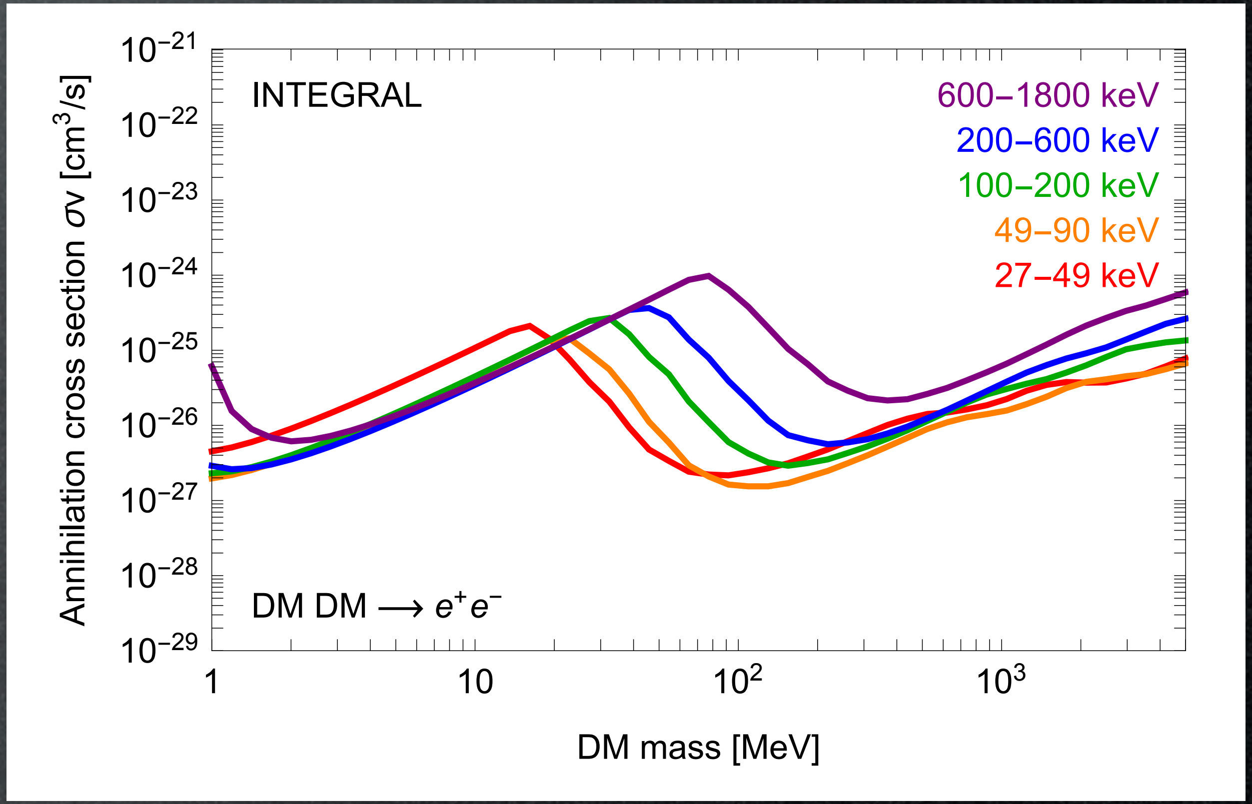
Bouchet et al., Integral coll. 1107.0200



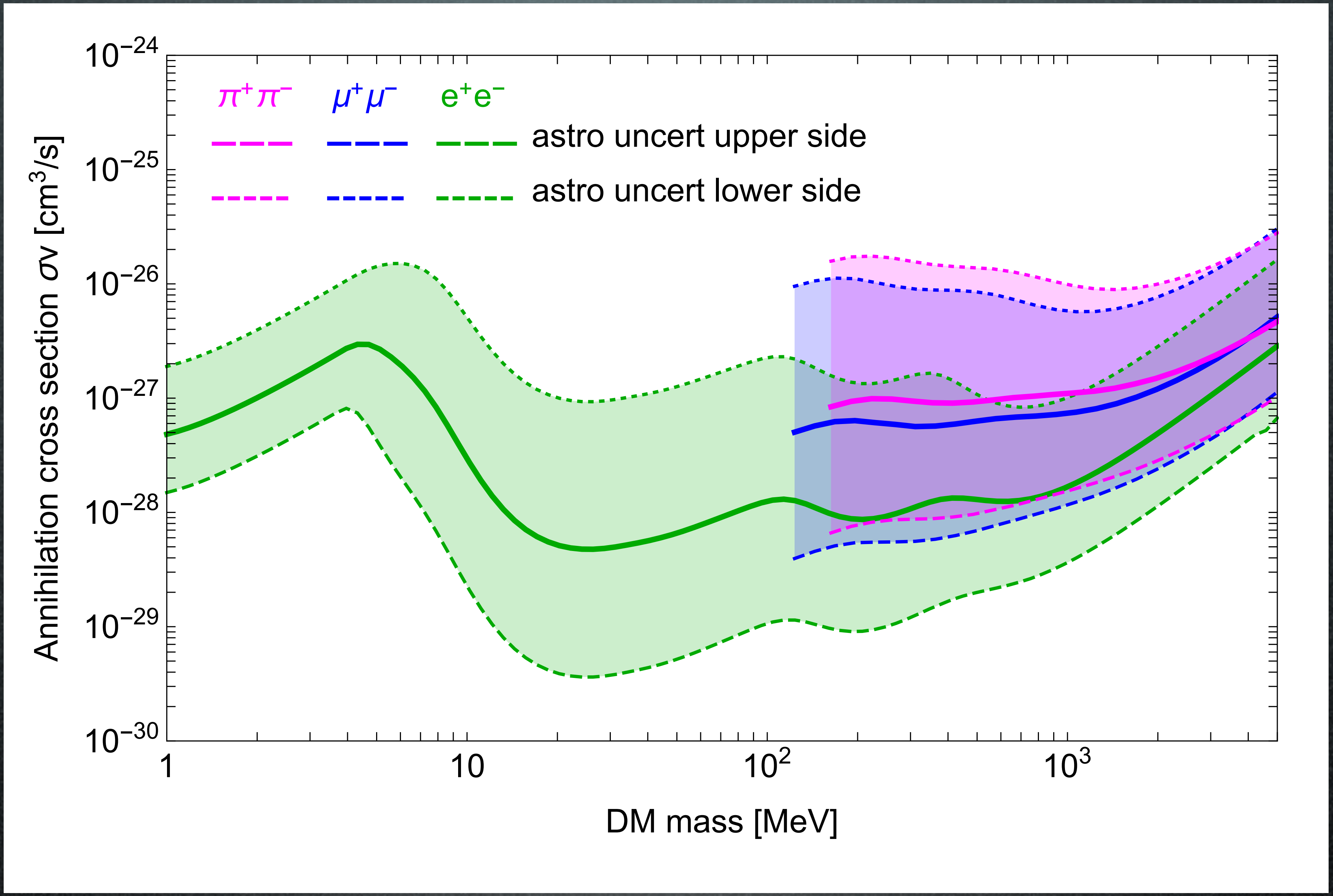
Results decay



Results annihilation

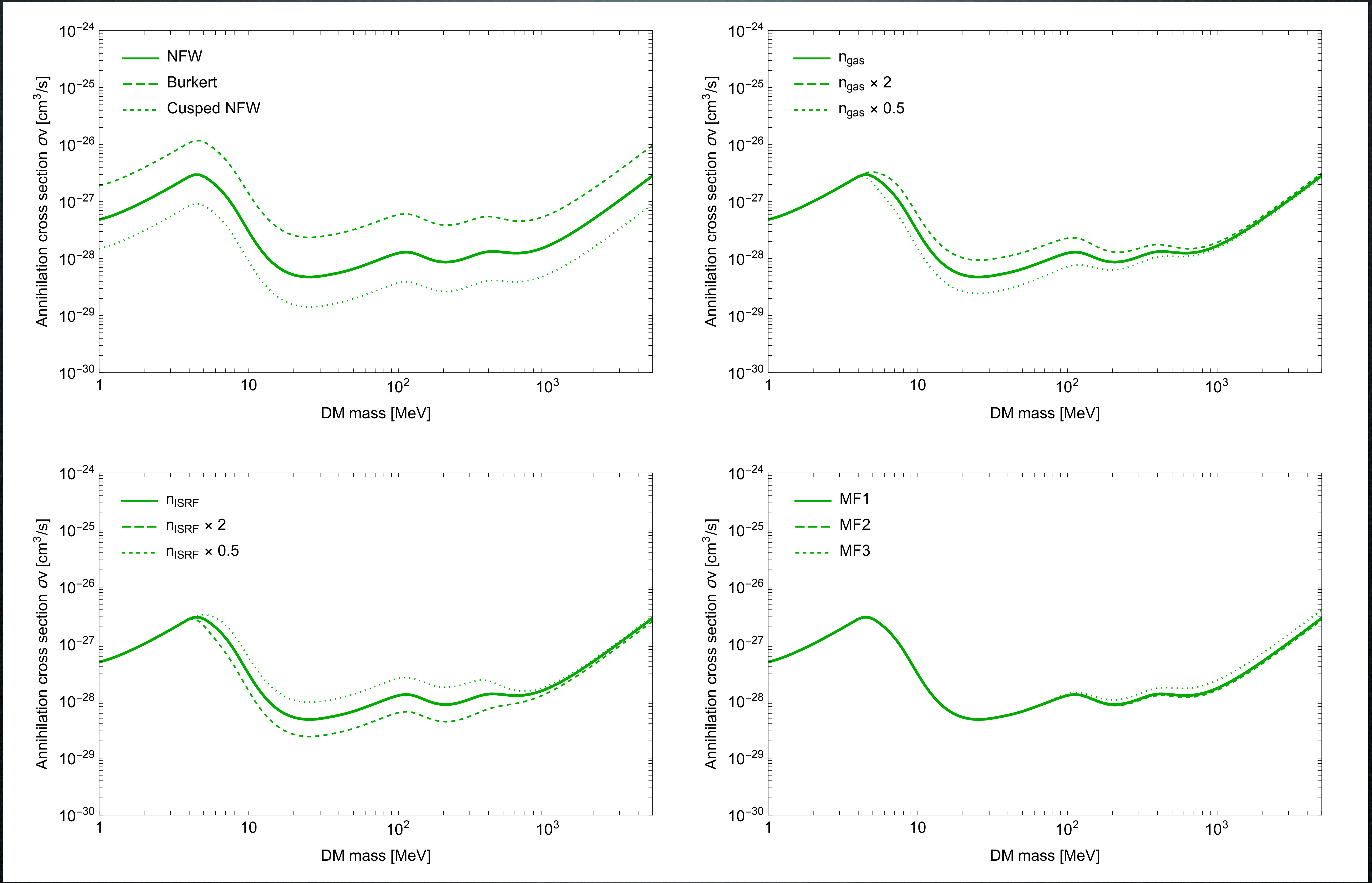


Results: uncertainties

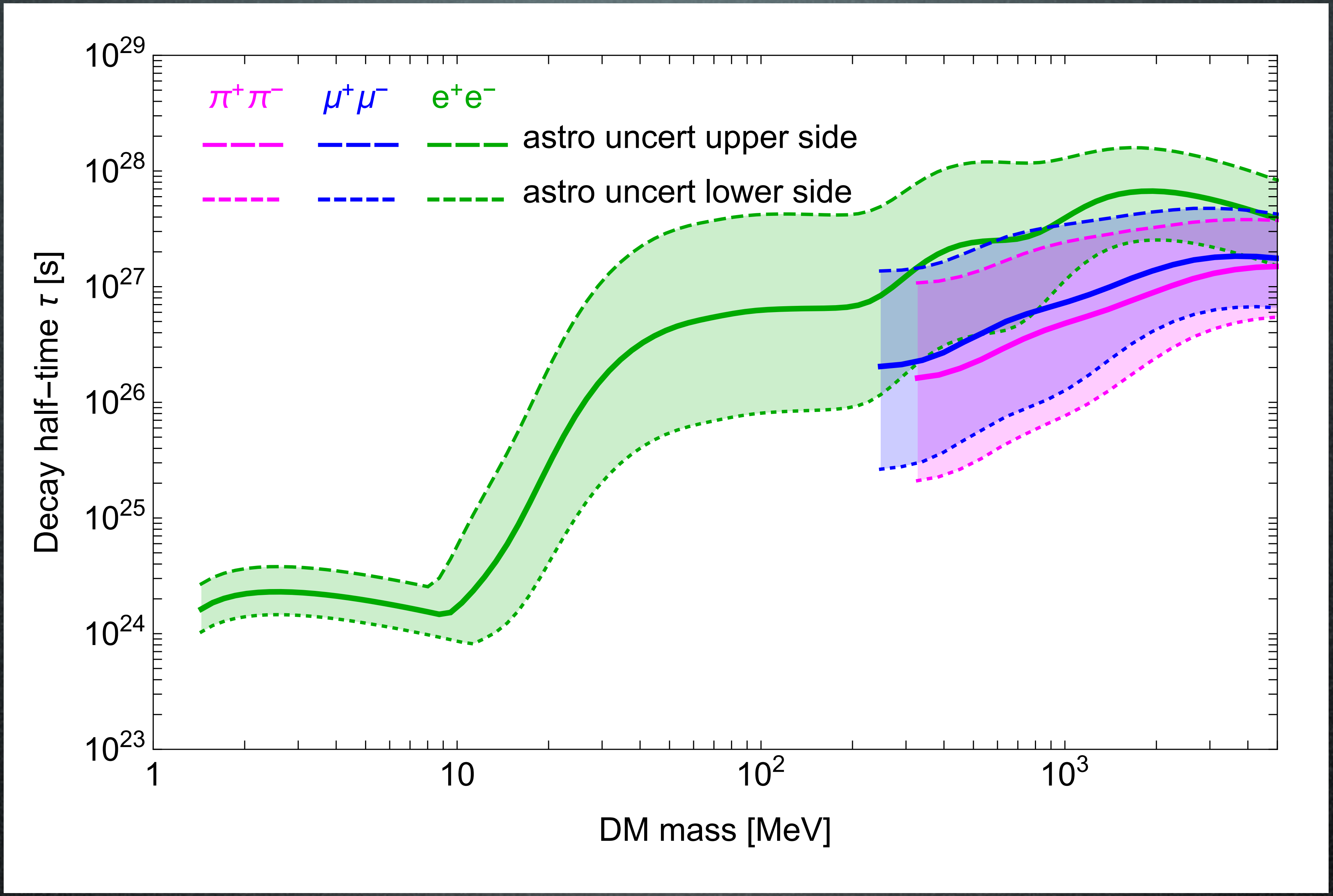


Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Results: uncertainties



Results: uncertainties



Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Results: uncertainties