6 September 2021
Corfu Summer Institute - Workshop on SM and beyond

# Sub-GeV Dark Matter and X-rays

Marco Cirelli
(CNRS LPTHE Jussieu Paris)

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1 MeV -> 10 GeV

# Sub-GeV Dark Matter and X-rays


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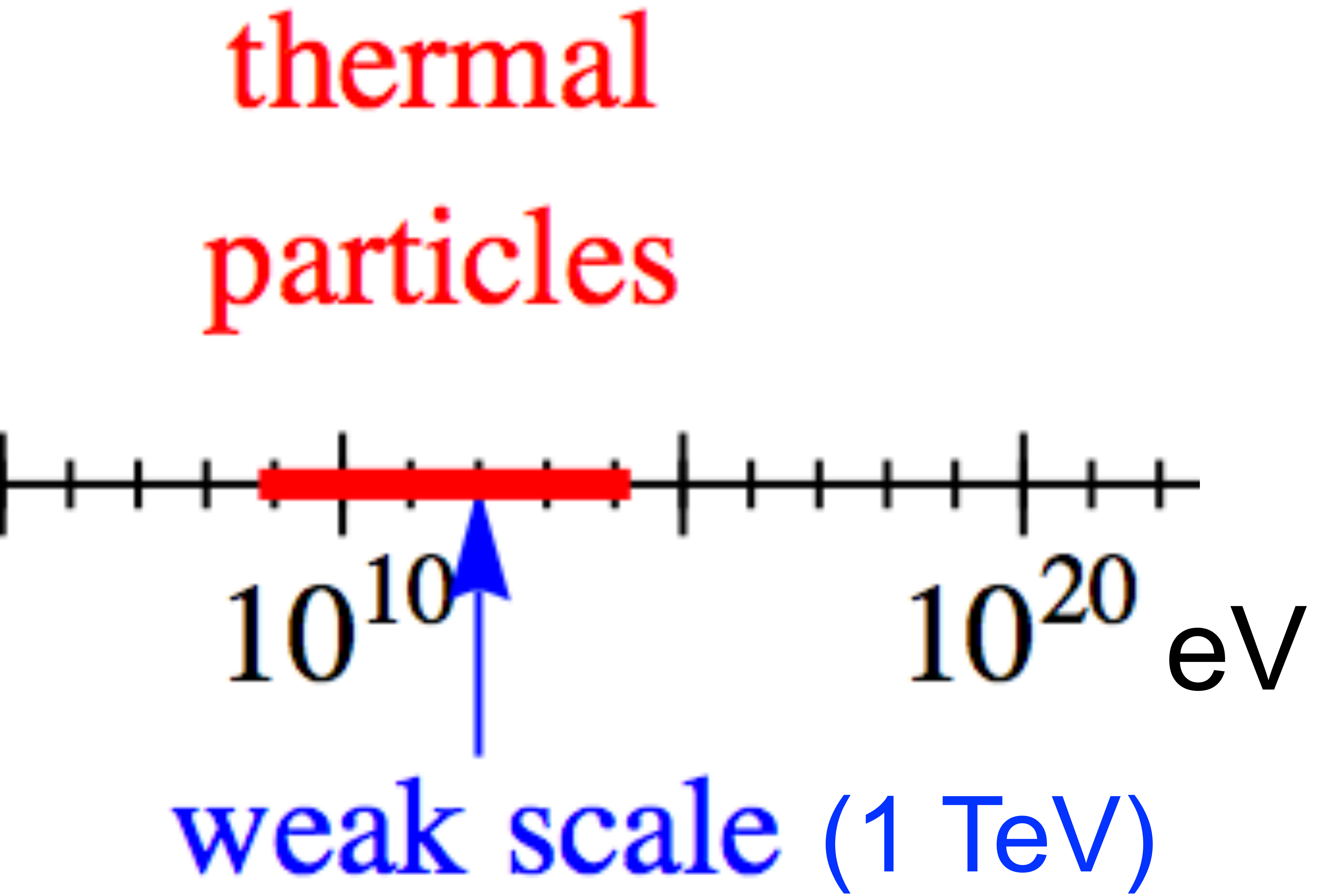
(CNRS LPTHE Jussieu Paris)


based on : Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

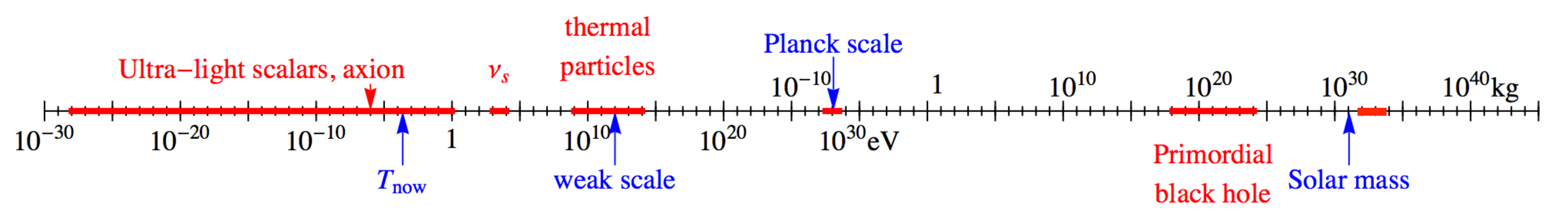
# Candidates

A matter of perspective: plausible mass ranges



# Candidates

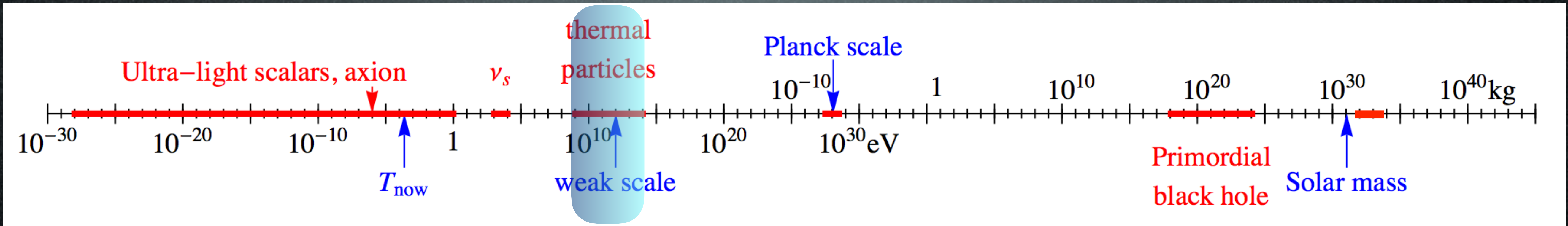
A matter of perspective: plausible mass ranges




90 orders of magnitude!

# Candidates

A matter of perspective: plausible mass ranges




90 orders of magnitude!

# Candidates

WIMPs

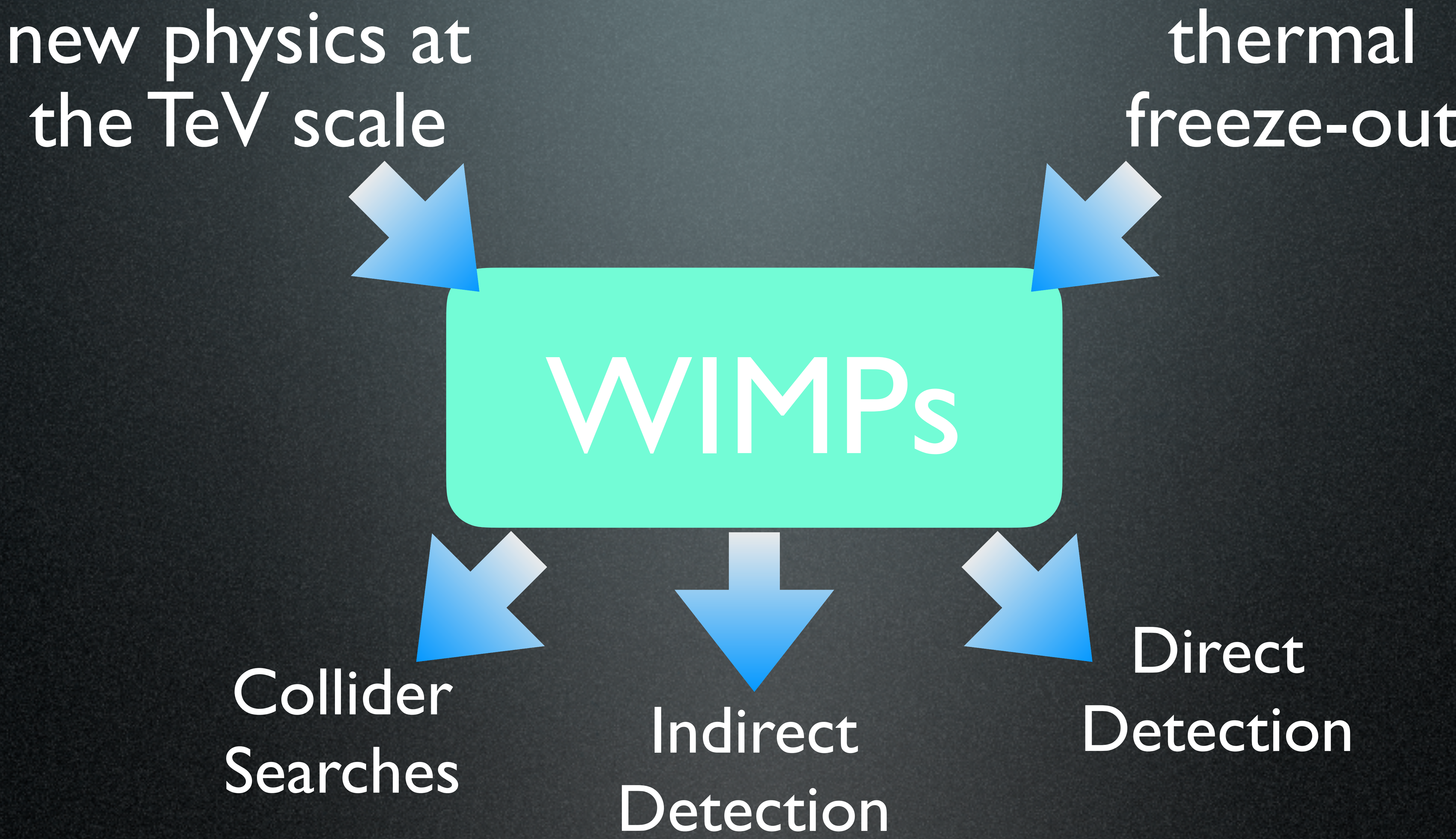
# Candidates

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

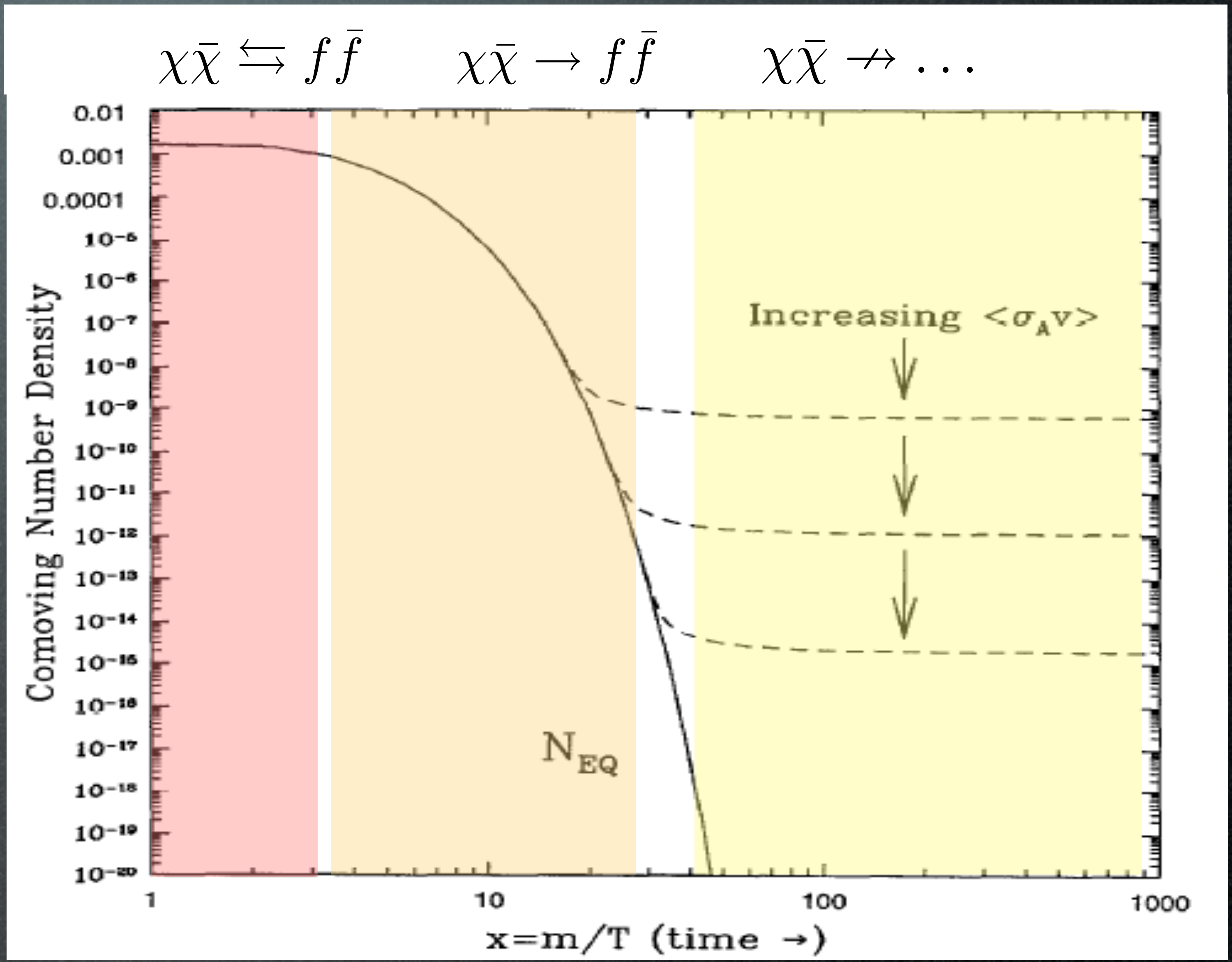
# DM as a thermal relic from the Early Universe

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

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



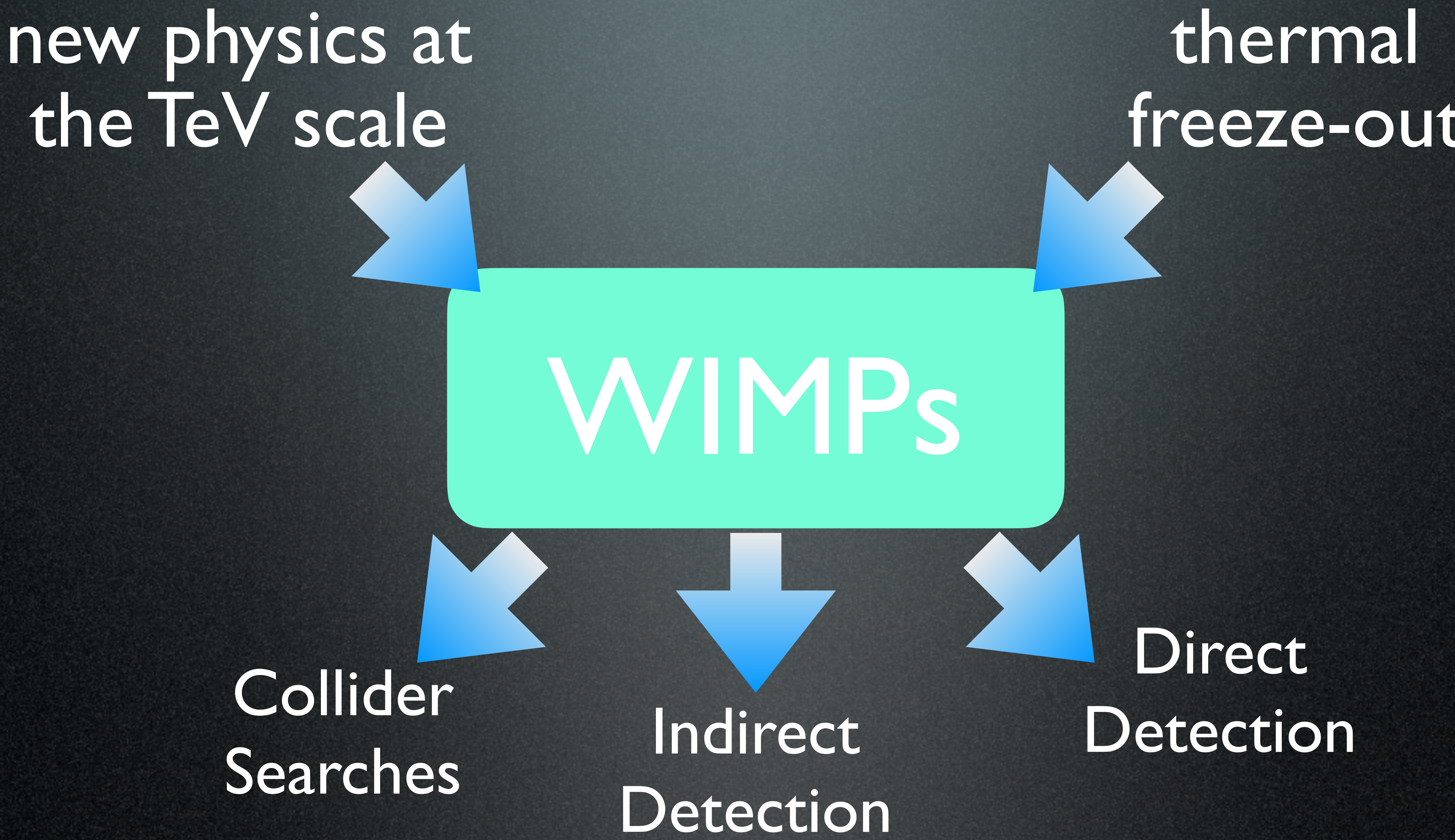

Kolb,Turner, The Early Universe, 1995

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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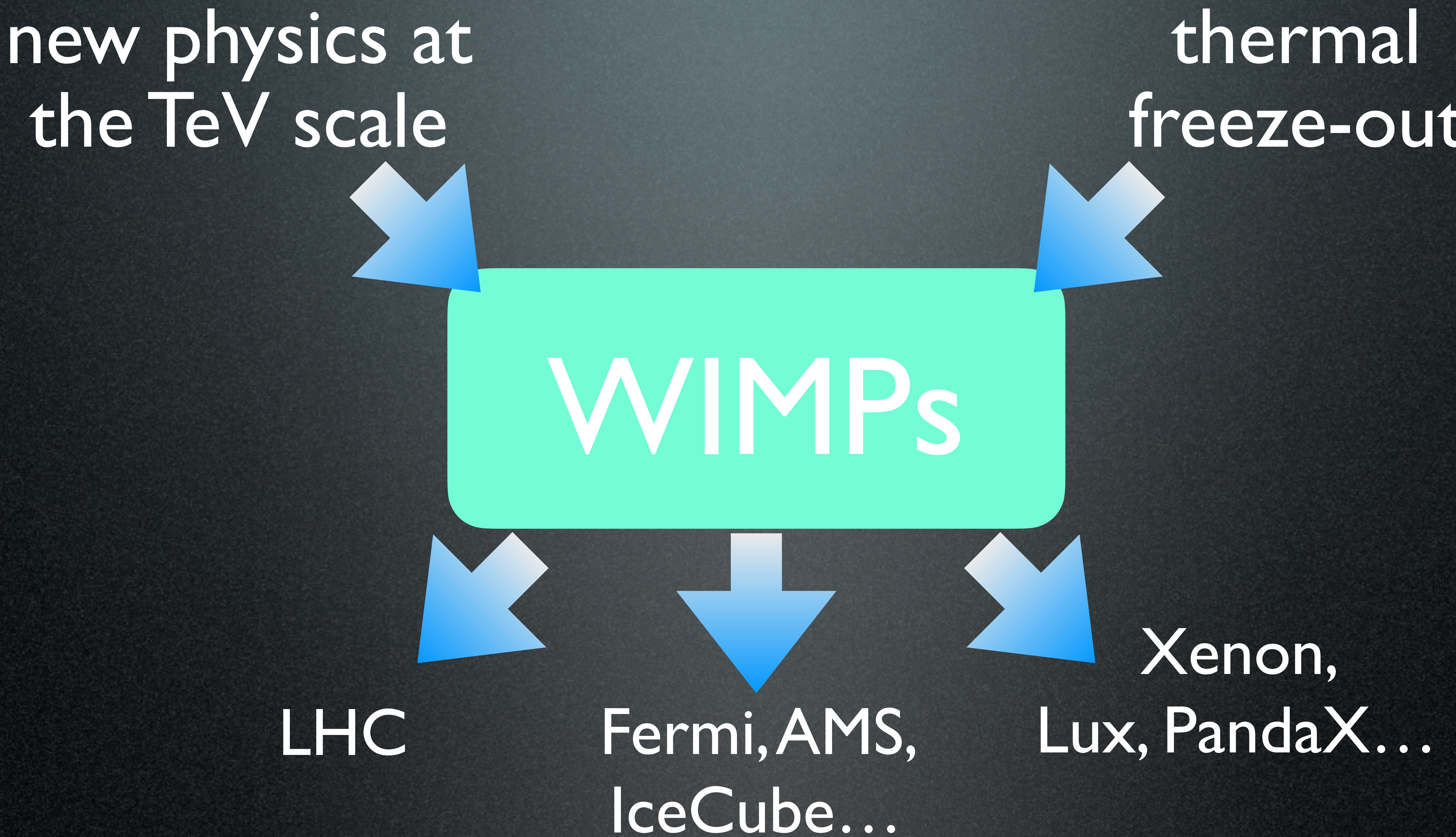
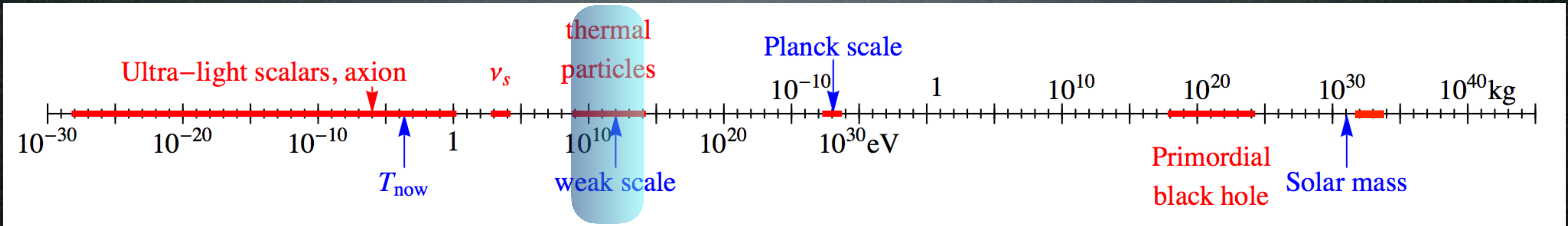

new physics at
the TeV scale
thermal
freeze-out
WIMPs
LHC
Fermi, AMS,
IceCube…
Xenon,
Lux, PandaX…

# Candidates

A matter of perspective: plausible mass ranges

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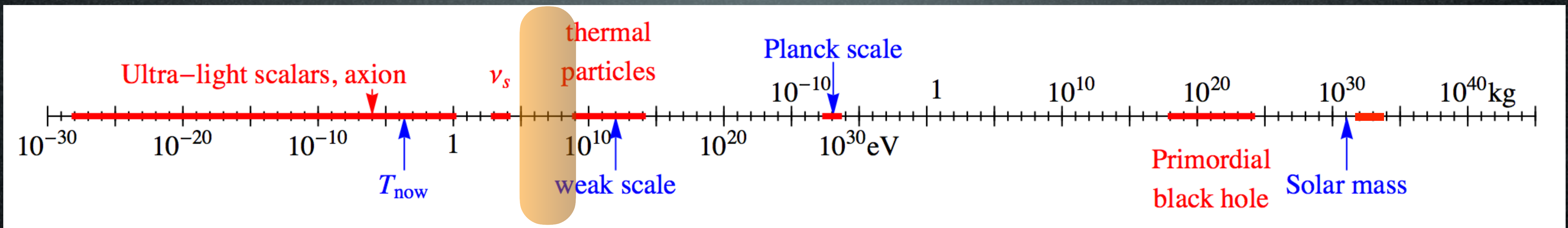


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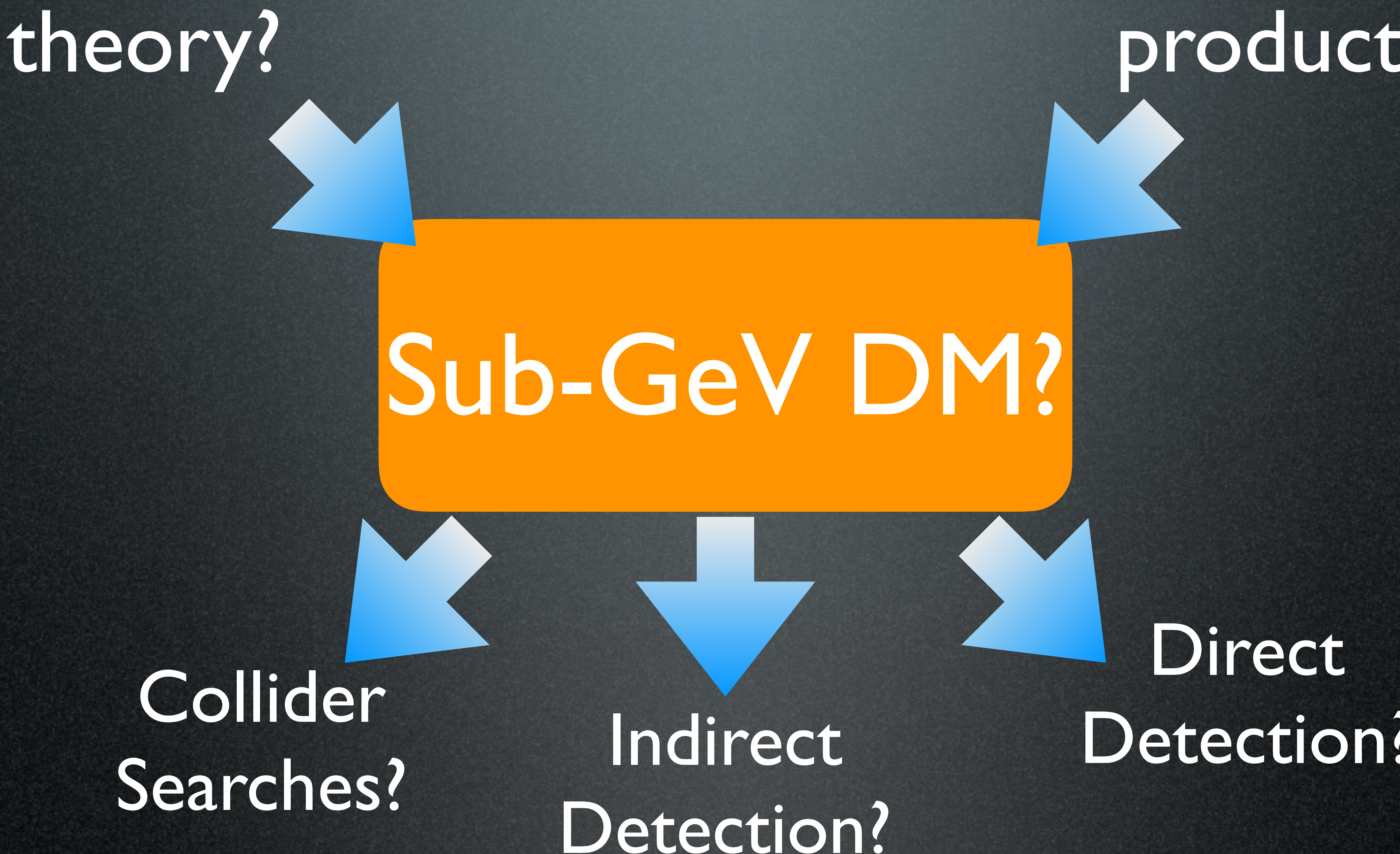

theory?
production?
Sub-GeV DM?
Collider Searches?
Indirect Detection?
Direct Detection?

# Theory

## Sub-GeV DM

- WIMPless Dark Matter

  Feng & Kumar 0803.4196

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

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

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

# Theory

## Sub-GeV DM

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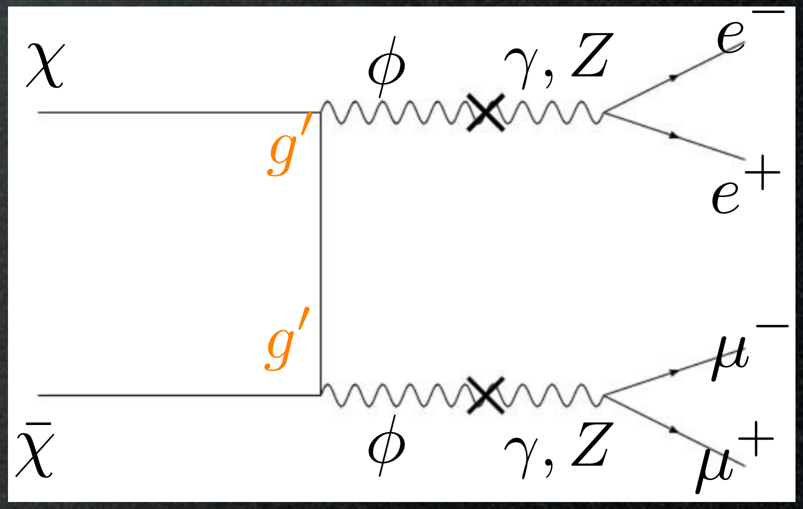
a.k.a. hidden sector DM
$\sim$ secluded DM

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

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



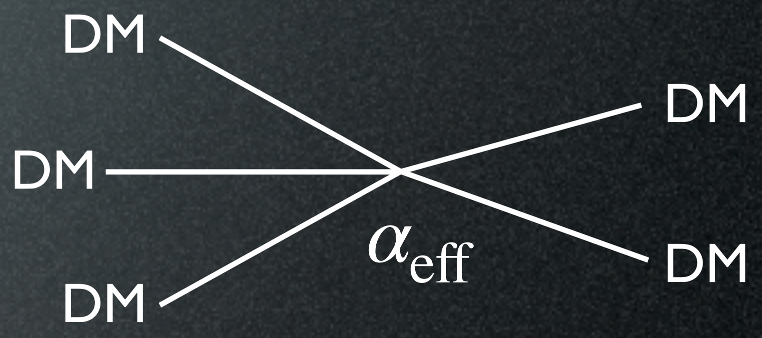

Production mechanism:
just thermal freeze-out
of these annihilations

# 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

- 'MeV (scalar) DM' (for the Integral 511 KeV excess?)

  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

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

# Theory

## Sub-GeV DM

- 'simplified (light) DM models'

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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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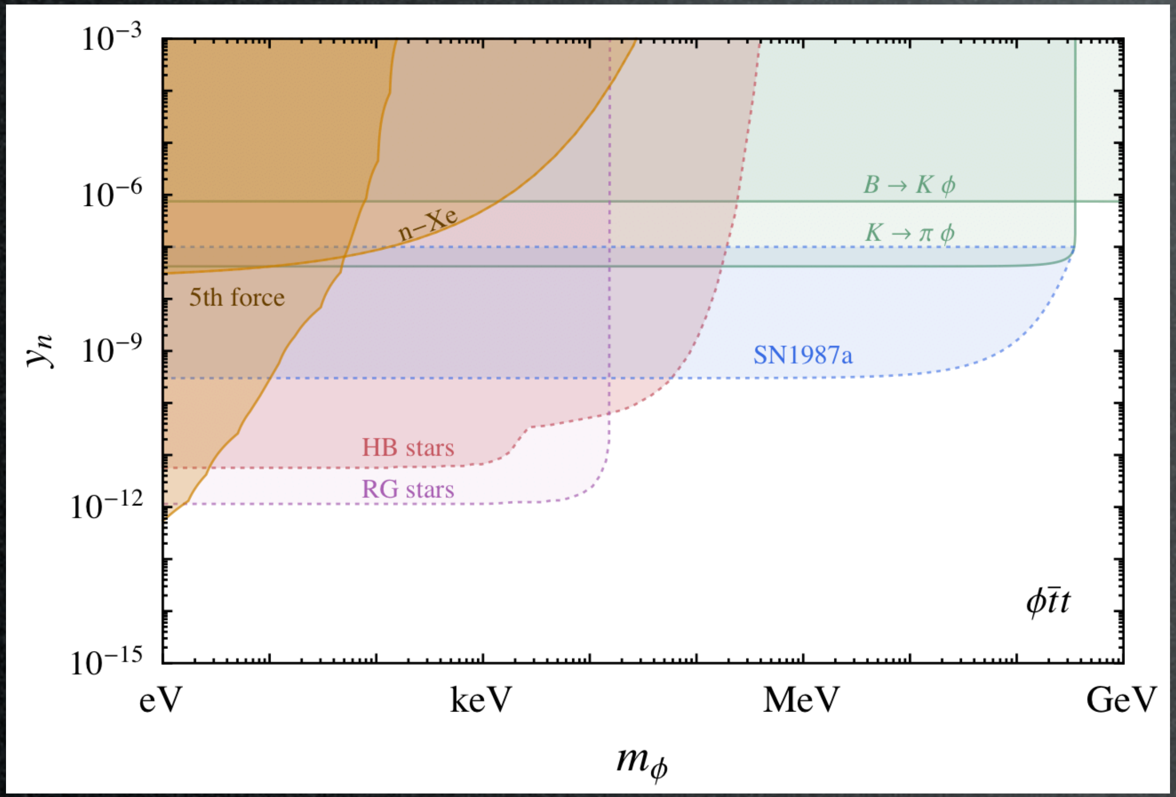
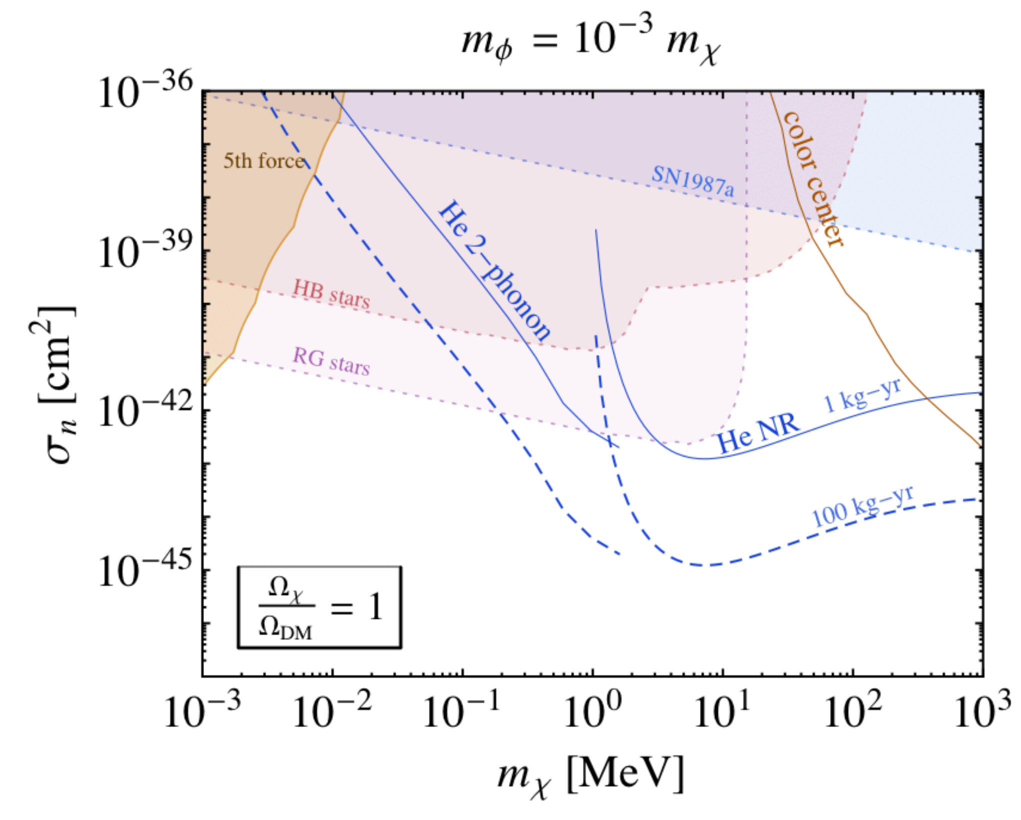
constraints on the mediator




constraints on the DM



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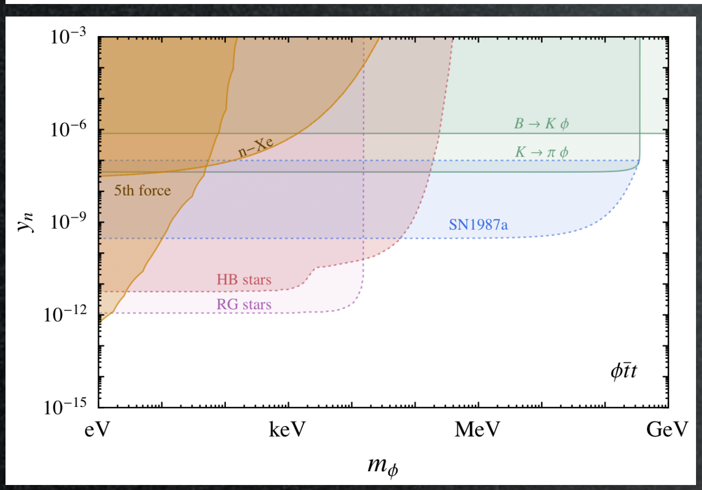


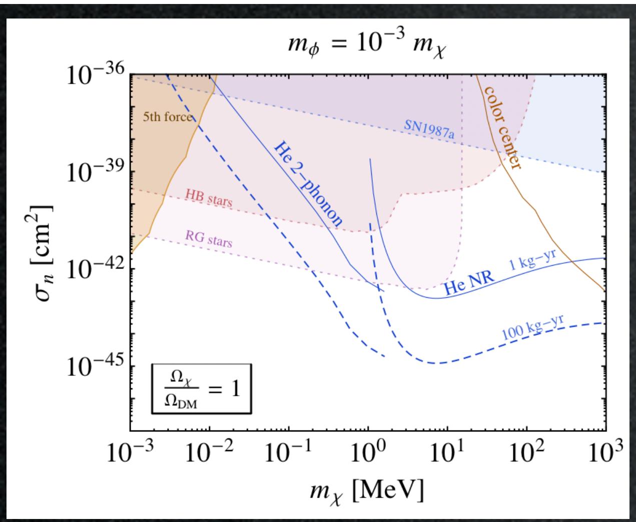

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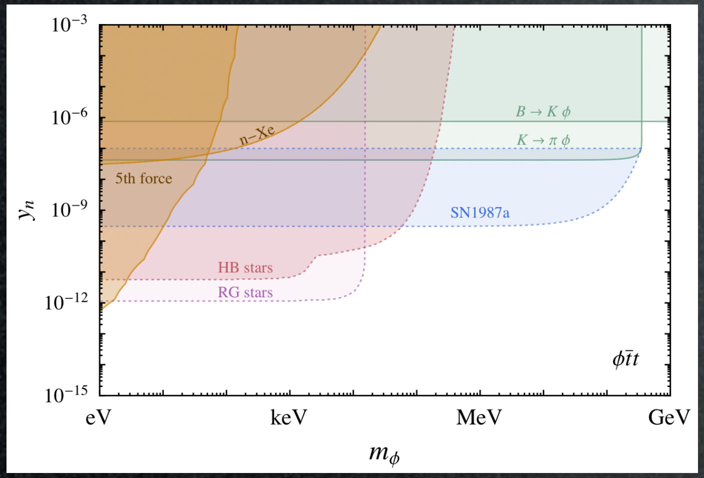


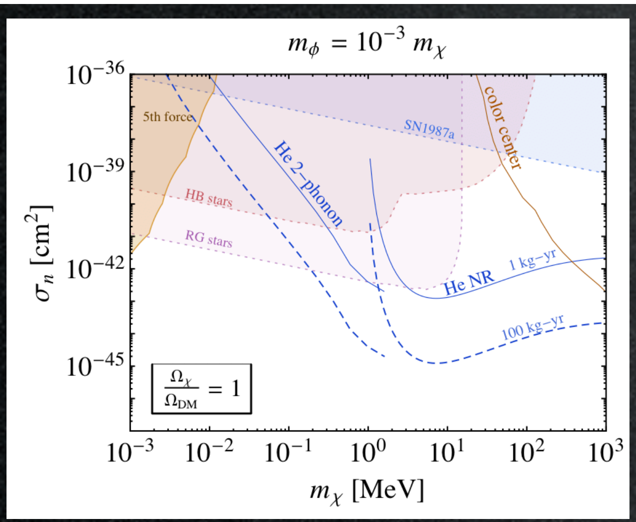


scalar DM and
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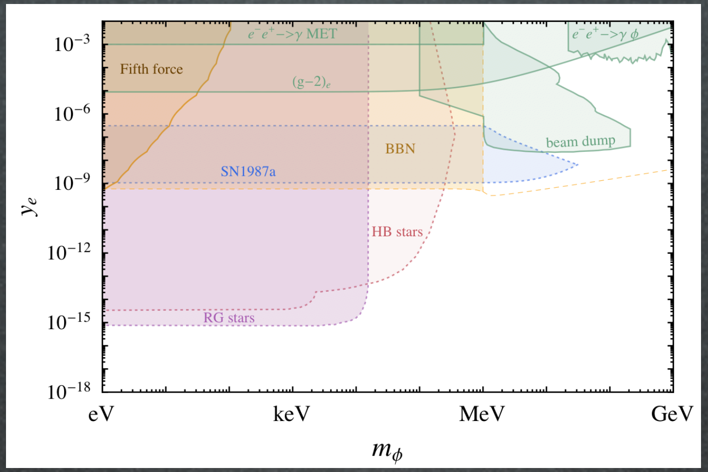


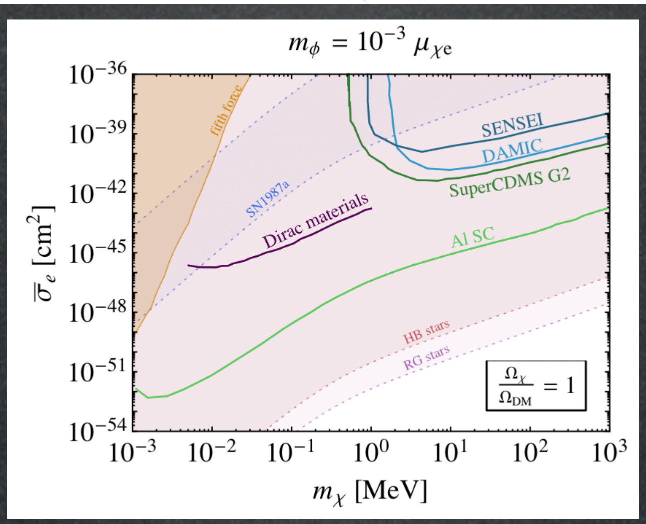

# Theory

## Sub-GeV DM

- ‘simplified (light) DM models’

Knapen, Lin, Zurek 1709.07882

**scalar DM and hadrophilic scalar mediator**

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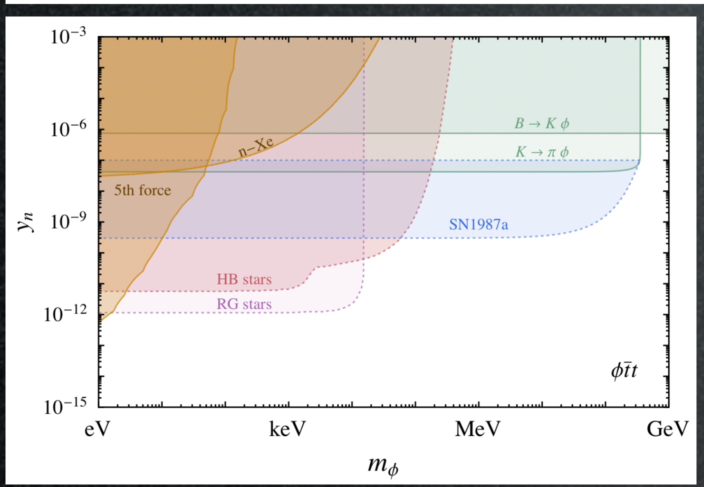
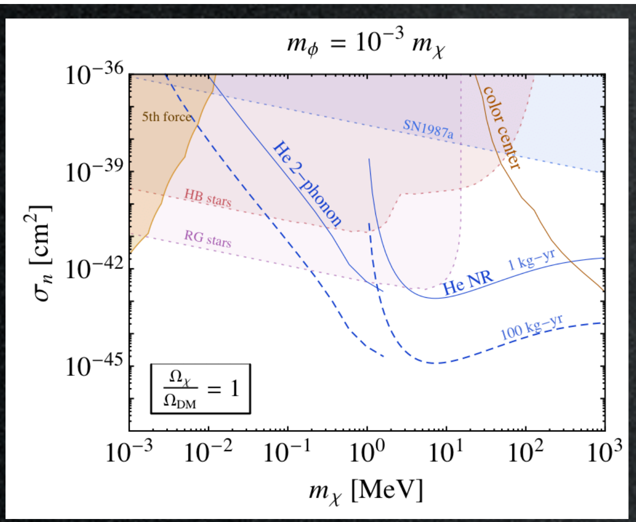
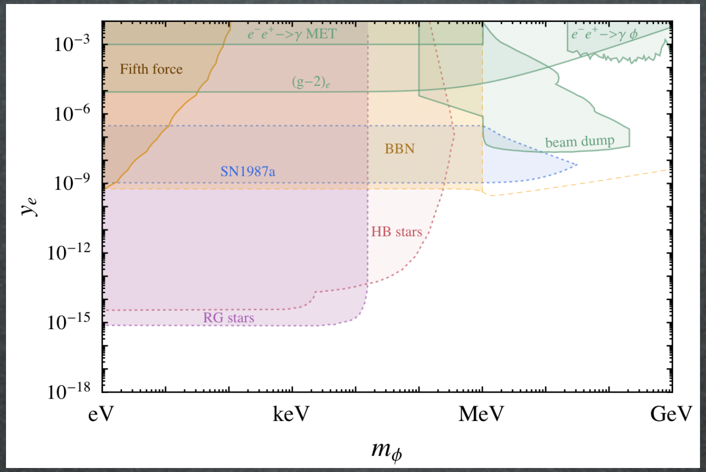
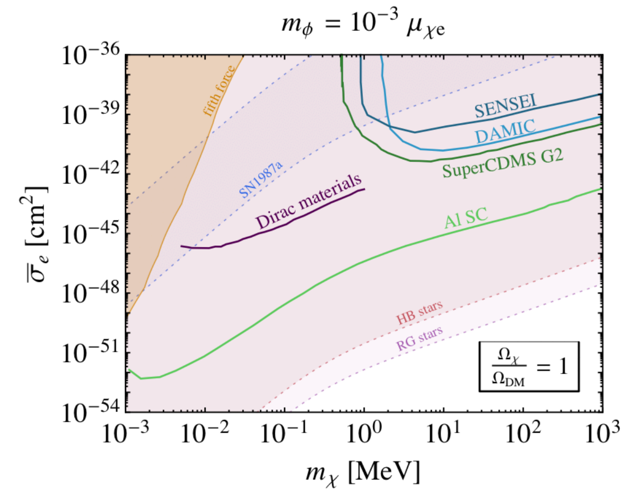



**scalar DM and leptophilic scalar mediator**

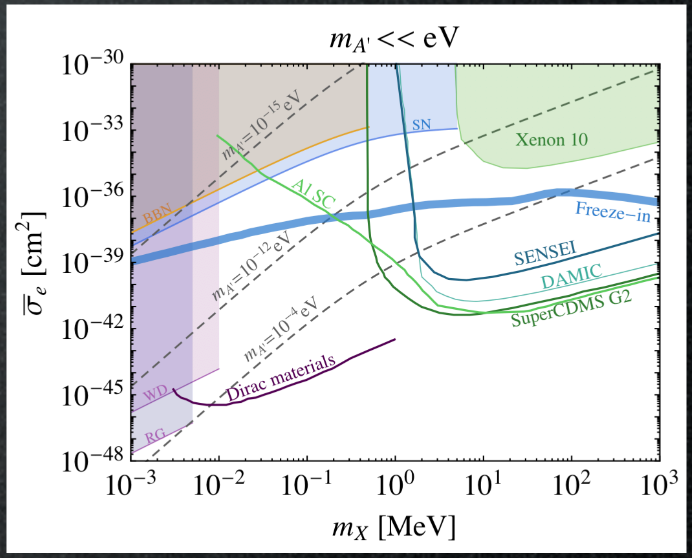
$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_e\phi\bar{e}e.$$

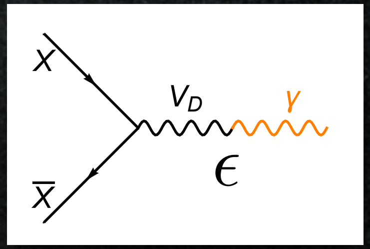



**fermionic DM and vector mediator (e.g. dark photon)**

$$\mathcal{L} \supset= -\frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} - y_\chi A'_\mu \bar{\chi}\gamma^\mu\chi$$



# Theory

## Sub-GeV DM?

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

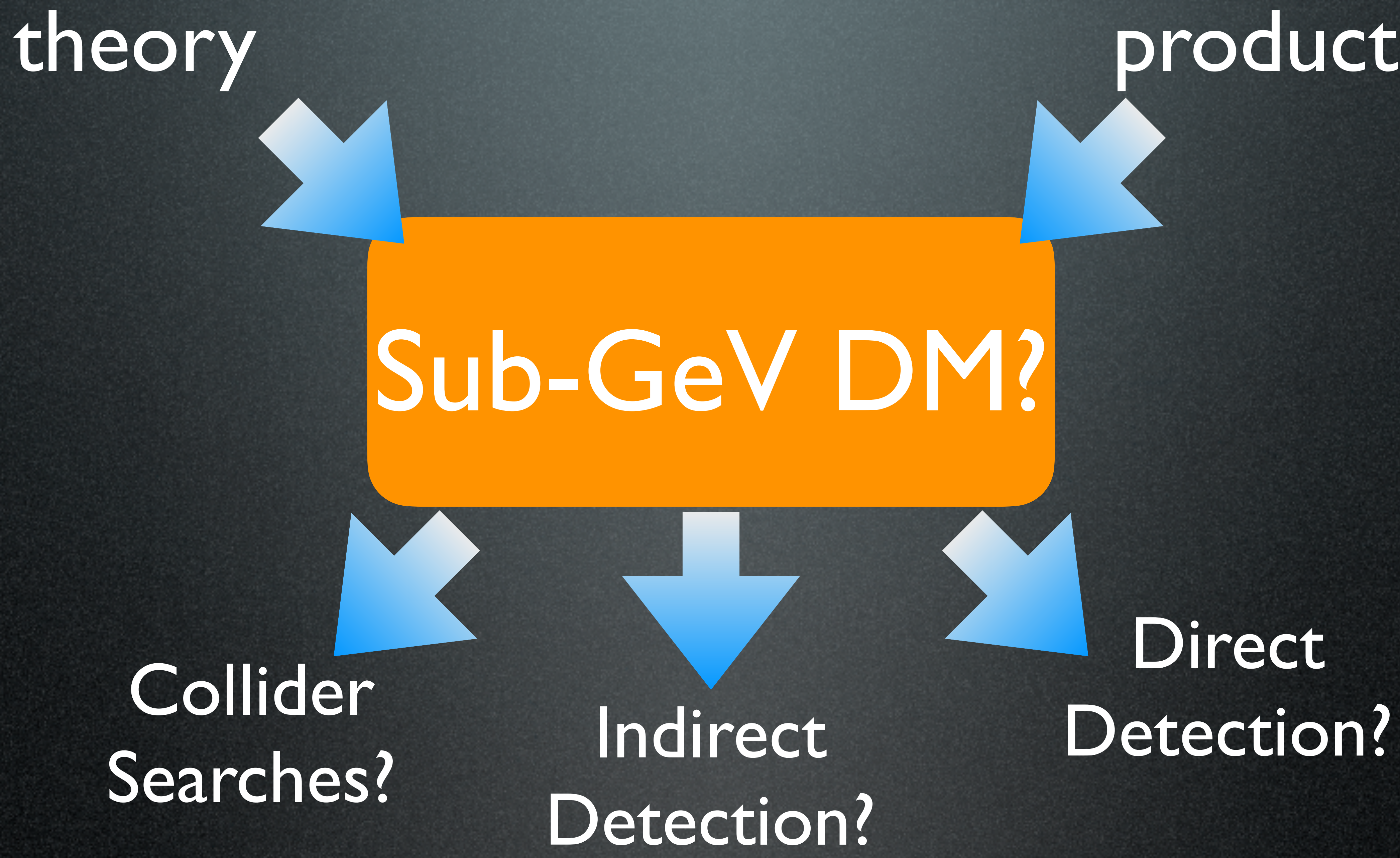
# Theory

## 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
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Sub-GeV DM?
Collider Searches?
Indirect Detection?
Direct Detection?

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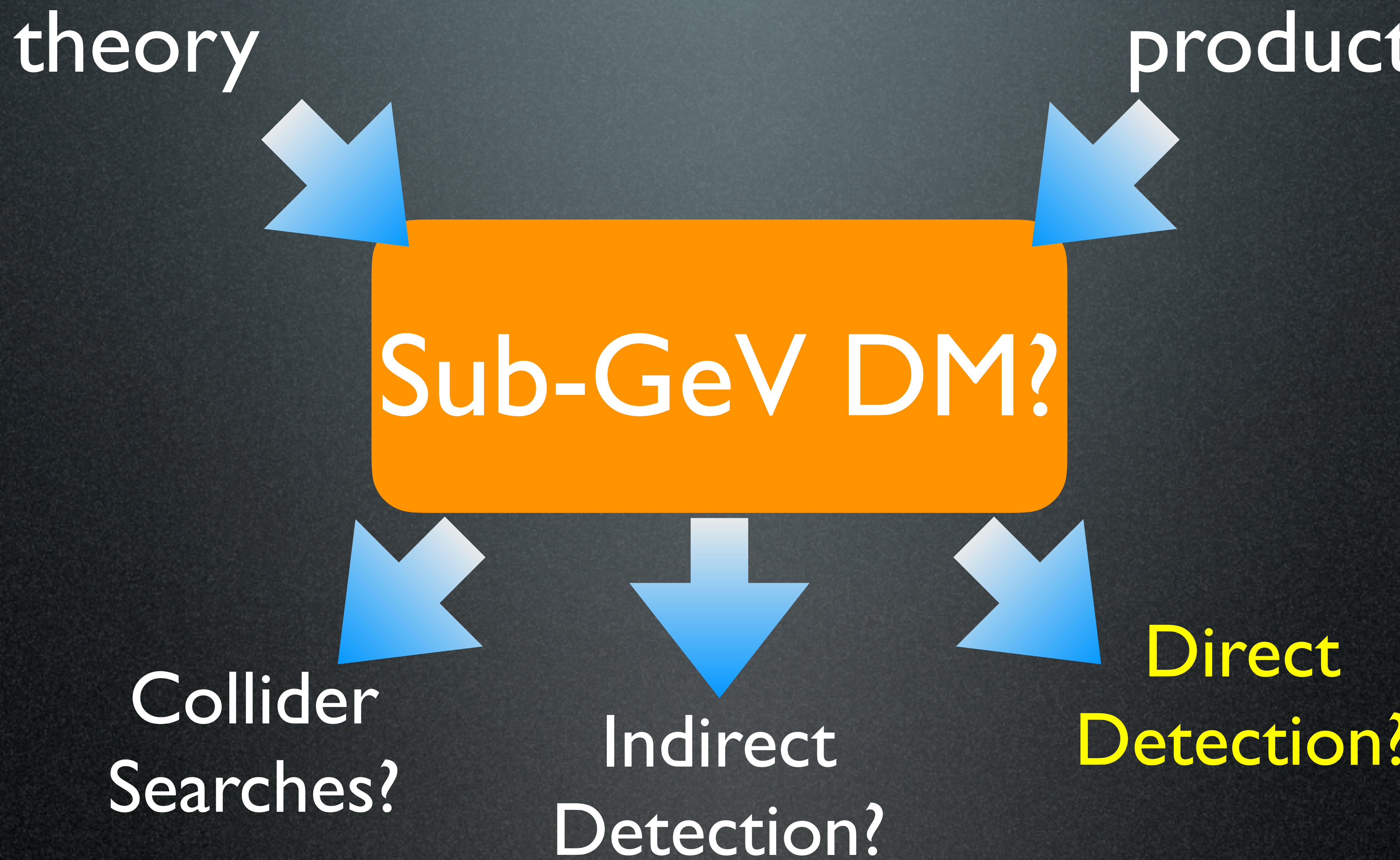
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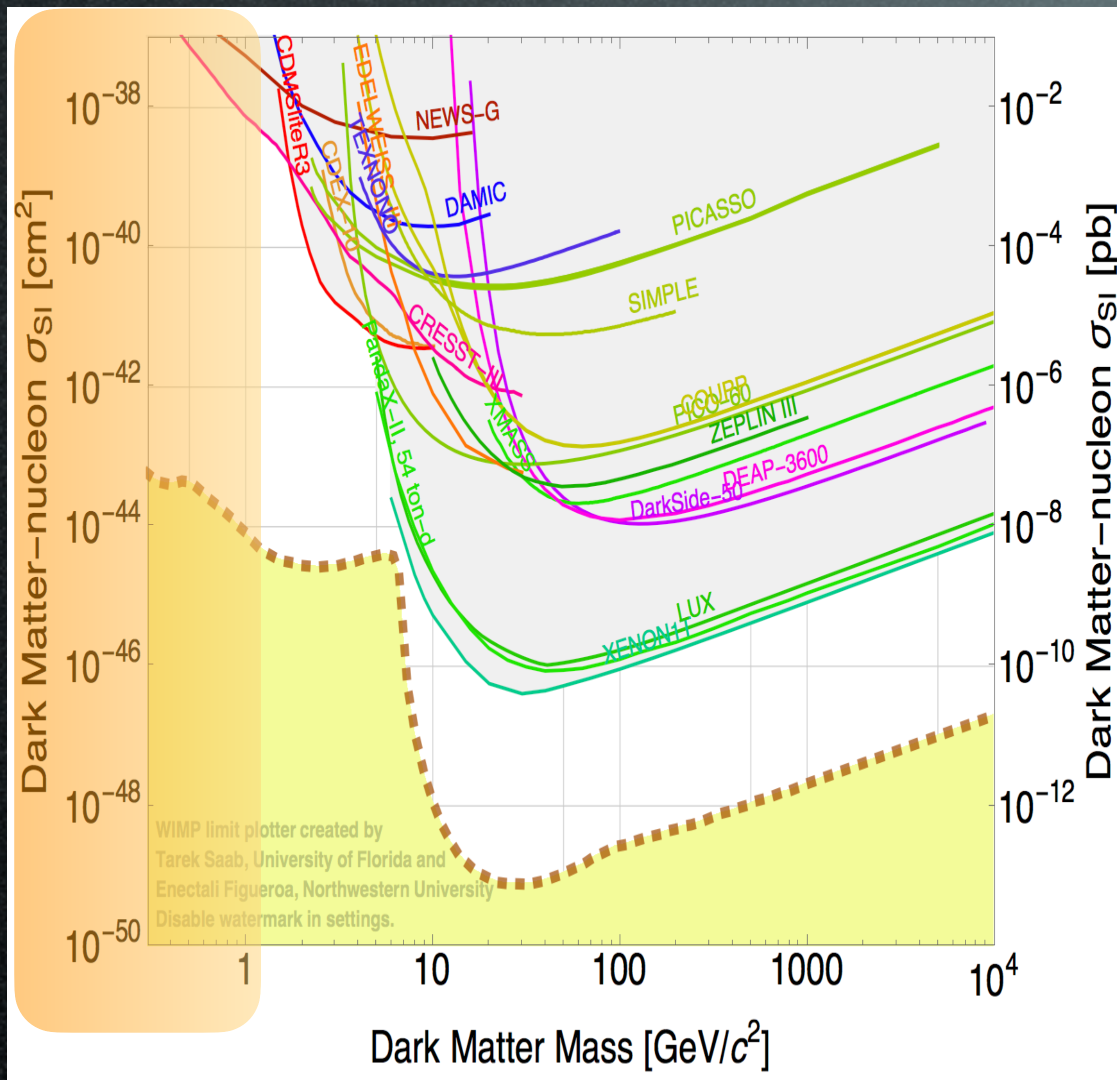
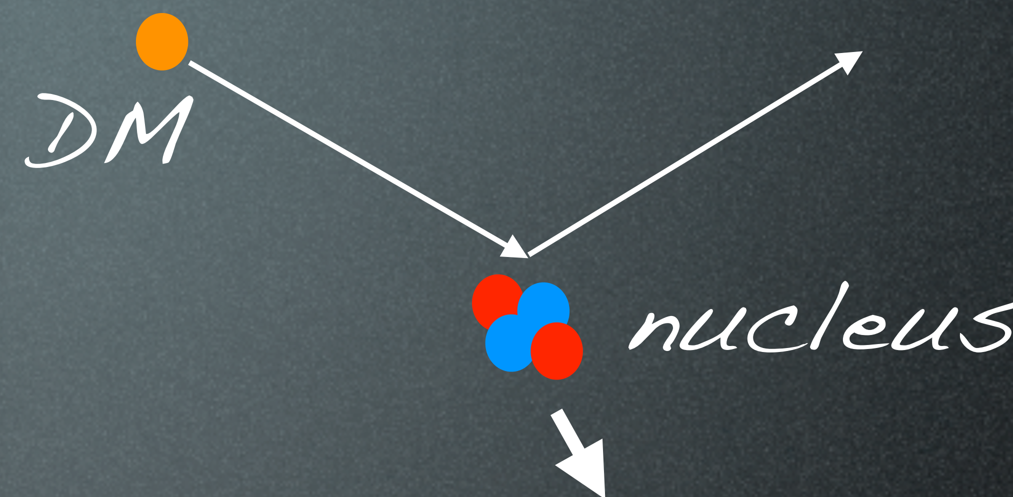
# Direct Detection of sub-GeV DM




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

- electron recoil signal
- Migdal effect
- new experimental strategies

# Direct Detection of sub-GeV DM

R. Essig, J. Mardon, T. Volansky ‘Direct Detection of Sub-GeV Dark Matter’ 1108.5383
R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky ‘First Direct Detection Limits on sub-GeV Dark Matter from XENON10’ 1206.2644
C. Kouvaris, J. Pradler ‘Probing sub-GeV Dark Matter with conventional detectors’ 1607.01789
C. McCabe ‘New constraints and discovery potential of sub-GeV dark matter with xenon detectors’ 1702.04730
R. Essig, T. Volansky, T.-T. Yu ‘New Constraints and Prospects for sub-GeV Dark Matter Scattering off Electrons in Xenon’ 1703.00910
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R. Bernabei et al. ‘On electromagnetic contributions in WIMP quests’ 0706.1421
R. Essig, J. Pradler et al. ‘Relation between the **Migdal Effect** and DM-Electron Scattering in Isolated Atoms and Semiconductors’ 1908.10881
R. Essig et al. ‘Direct Detection of sub-GeV Dark Matter with **Semiconductor Targets**’ 1509.01598
Y. Hochberg et al. ‘Directional Detection of Dark Matter with **2D Targets**’ 1606.08849
S. Derenzo et al. ‘Direct Detection of sub-GeV Dark Matter with **Scintillating Targets**’ 1607.01009
Y. Hochberg et al. ‘Detection of sub-MeV Dark Matter with **Three-Dimensional Dirac Materials**’ 1708.08929
S. Knapen et al. ‘Detection of Light Dark Matter With **Optical Phonons in Polar Materials**’ 1712.06598
S. Griffin et al. ‘Directional Detection of Light Dark Matter with **Polar Materials**’ 1807.10291
S. M. Griffin et al. ‘Multichannel direct detection of light dark matter: Target comparison’ 1910.10716
T. Trickle et al. ‘Multi-Channel Direct Detection of Light Dark Matter: Theoretical Framework’ 1910.08092
P. W. Graham et al. ‘Semiconductor Probes of Light Dark Matter’ Phys. Dark Univ. 1 (2012) 32-49 1203.2531
E. Andersson et al. ‘Projected sensitivity to sub-GeV dark matter of next-generation semiconductor detectors’ 2001.08910.
SENSEI collaboration Single-electron and single-photon sensitivity with a silicon Skipper CCD Phys. Rev. Lett. 119 (2017) 131802 1706.00028
DAMIC collaboration Constraints on Light Dark Matter Particles Interacting with Electrons from DAMIC at SNOLAB 1907.12628
Y. Hochberg et al. Superconducting Detectors for Superlight Dark Matter Phys. Rev. Lett. 116 (2016) 011301 1504.07237
Y. Hochberg et al. Detecting Superlight Dark Matter with Fermi-Degenerate Materials JHEP 08 (2016) 057 1512.04533
W. Guo et al. Concept for a dark matter detector using liquid helium-4 Phys. Rev. D 87 (2013) 115001 1302.0534
S. Knapen et al. Light Dark Matter in Superfluid Helium: Detection with Multi-excitation Production Phys. Rev. D 95 (2017) 056019 1611.06228
S. Hertel et al. Direct detection of sub-GeV dark matter using a superfluid 4He target Phys. Rev. D 100 (2019) 092007 1810.06283
F. Acanfora et al. Sub-GeV Dark Matter in Superfluid He-4: an Effective Theory Approach Eur. Phys. J. C 79 (2019) 549 1902.02361
H. J. Maris et al. Dark Matter Detection Using Helium Evaporation and Field Ionization Phys. Rev. Lett. 119 (2017) 181303 1706.00117
Y. Hochberg et al. Directional detection of dark matter with two-dimensional targets Phys. Lett. B 772 (2017) 239-246 1606.08849
Y. Hochberg et al. Detecting Sub-GeV Dark Matter with Superconducting Nanowires, Phys. Rev. Lett. 123 (2019) 151802 1903.05101
R. Essig et al. Detection of sub-GeV Dark Matter and Solar Neutrinos via Chemical-Bond Breaking Phys. Rev. D 95 (2017) 056011 1608.02940
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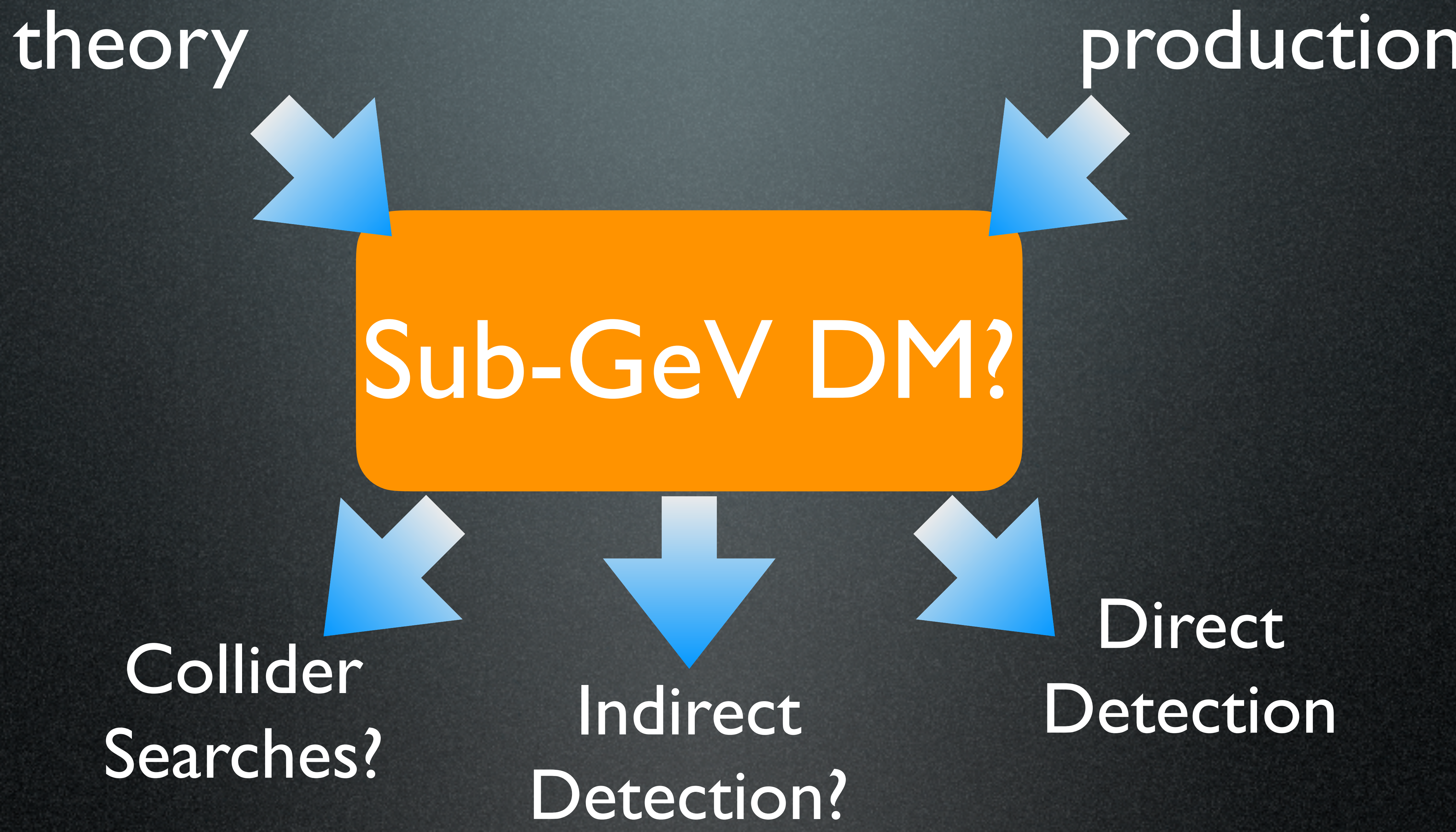
S. Knapen et al. Detection of Light Dark Matter With Optical Phonons in Polar Materials Phys. Lett. B 785 (2018) 386-390 1712.06598
S. Griffin et al. Directional Detection of Light Dark Matter with Polar Materials Phys. Rev. D 98 (2018) 115034 1807.10291
S. Baum et al. Searching for Dark Matter with Paleo-Detectors Phys. Lett. B 803 (2020) 135325 1806.05991
P. C. Bunting et al. Magnetic Bubble Chambers and Sub-GeV Dark Matter Direct Detection Phys. Rev. D 95 (2017) 095001 1701.06566
C. Blanco et al. Dark Matter-Electron Scattering from Aromatic Organic Targets Phys. Rev. D 101 (2020) 056001 1912.02822
R. Essig et al. DD of Spin-(In)dependent Nuclear Scattering of Sub-GeV DM Using Molecular Excitations Phys. Rev. Res. 1 (2019) 033105, 1907.07682
N. A. Kurinsky et al. Diamond Detectors for Direct Detection of Sub-GeV Dark Matter Phys. Rev. D 99 (2019) 123005 1901.07569
...

# Candidates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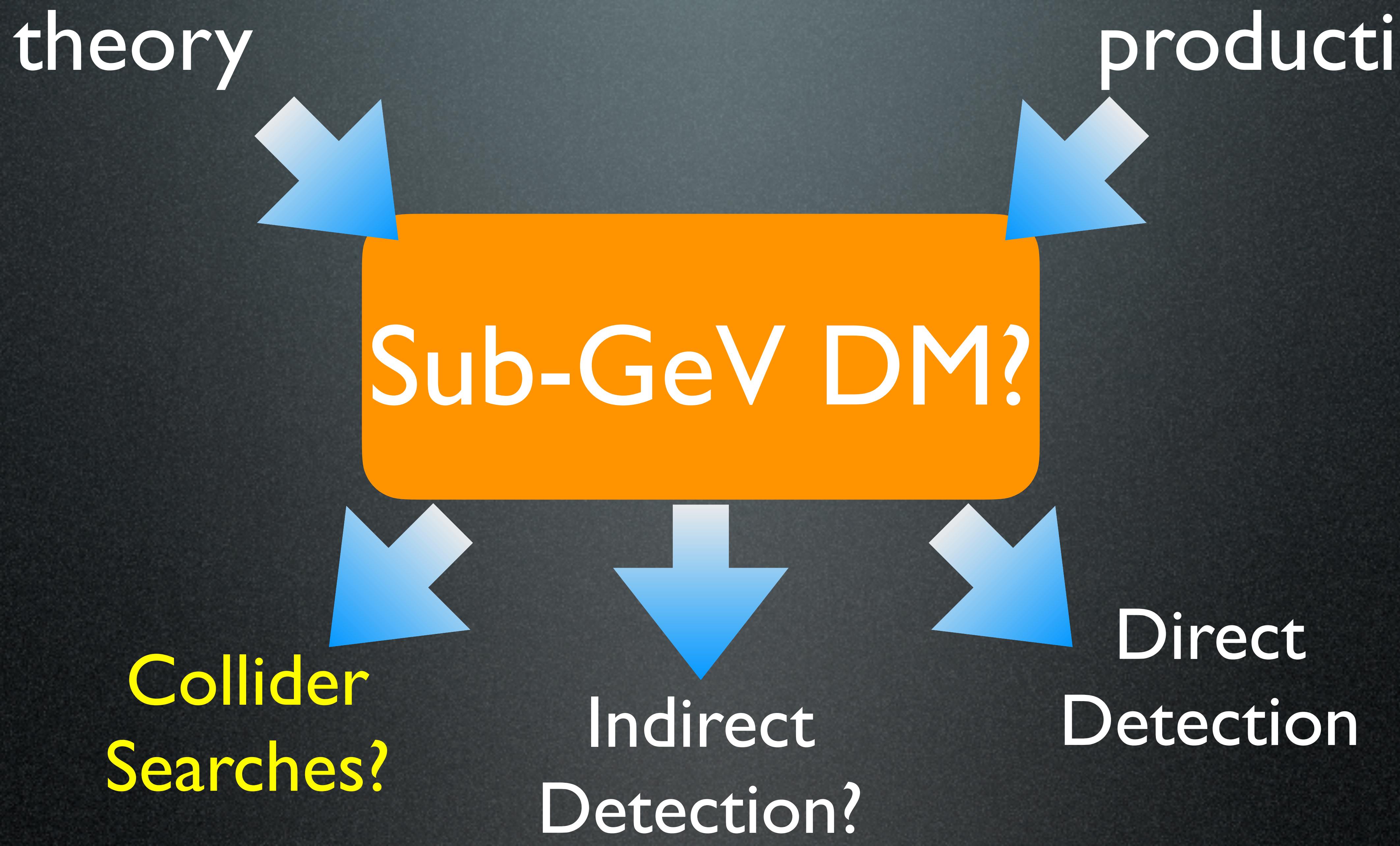
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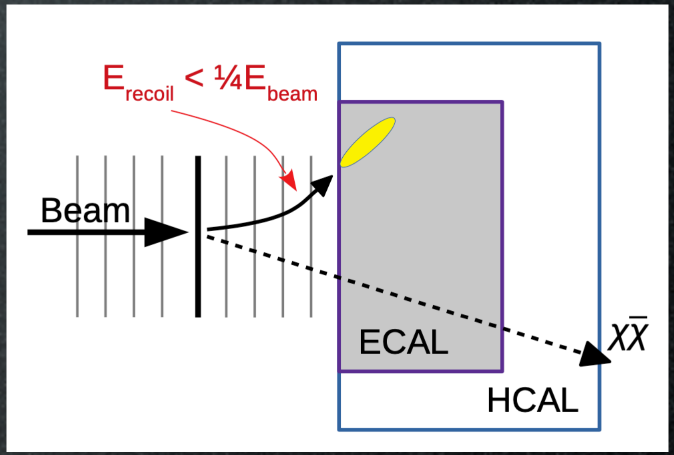
# Collider searches of sub-GeV DM

Missing $E_T$ signature is below threshold for LHC experiments

- fixed target / beam dump experiments

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



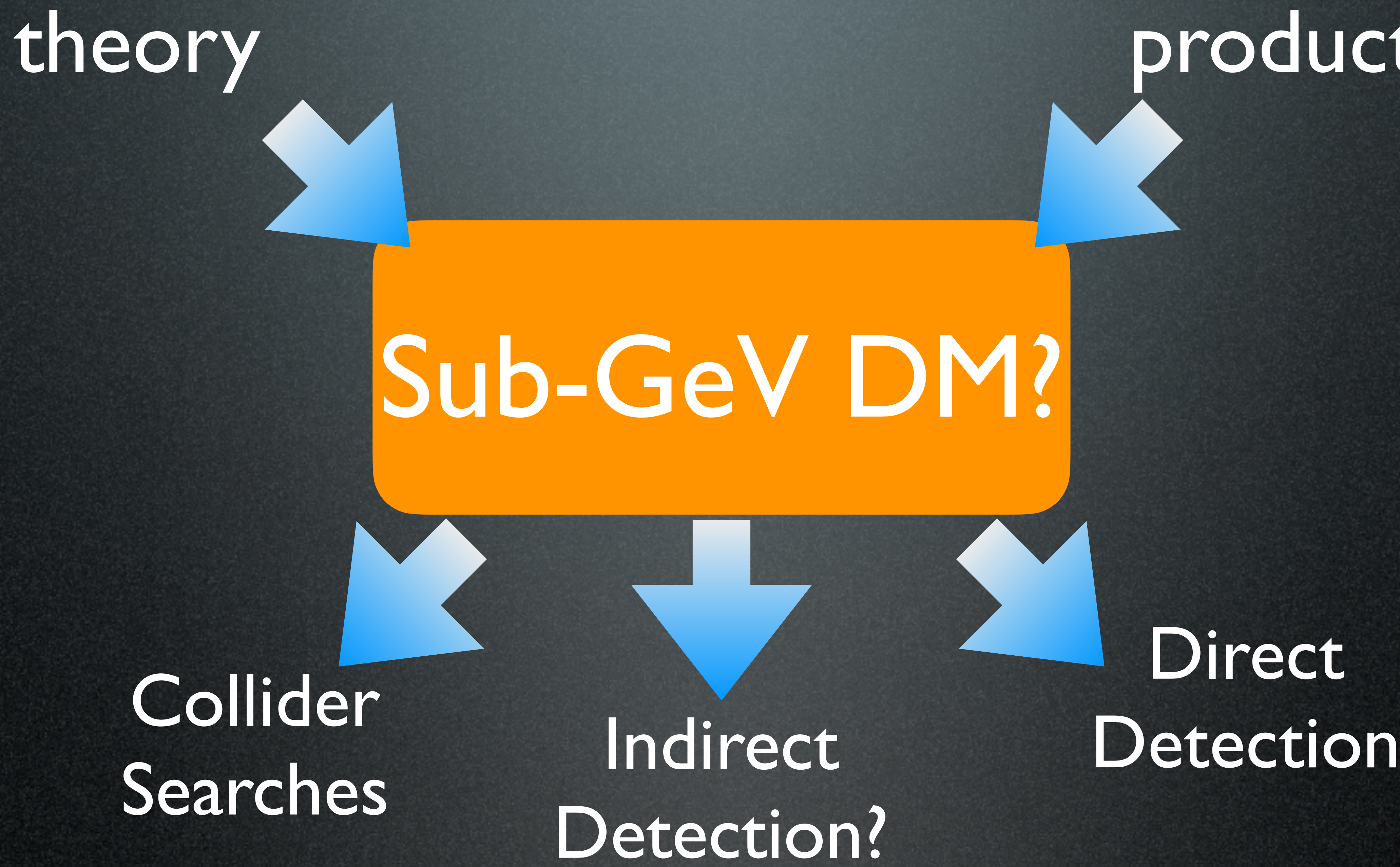

e.g. LDMX coll. 1808.05219


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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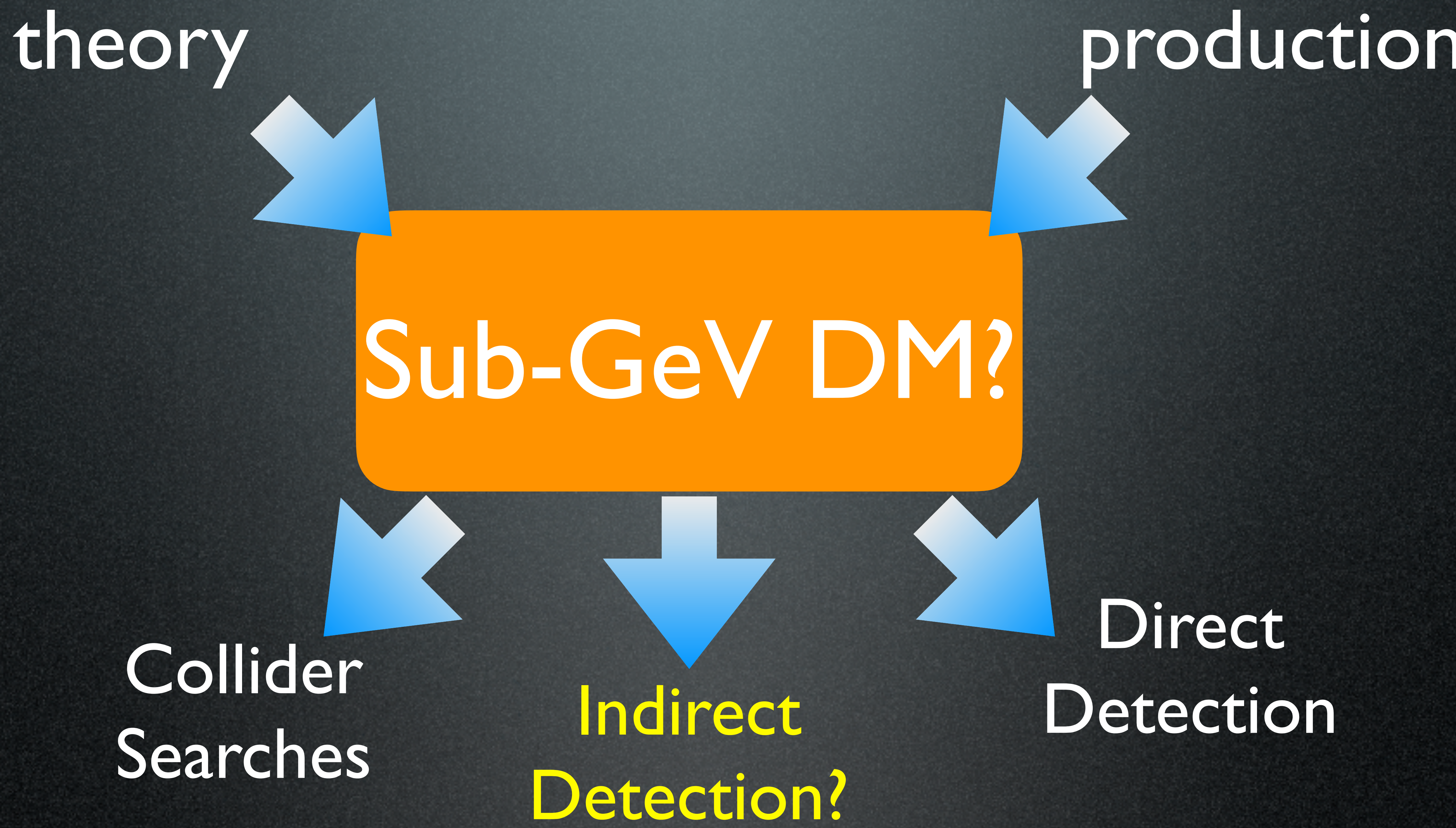
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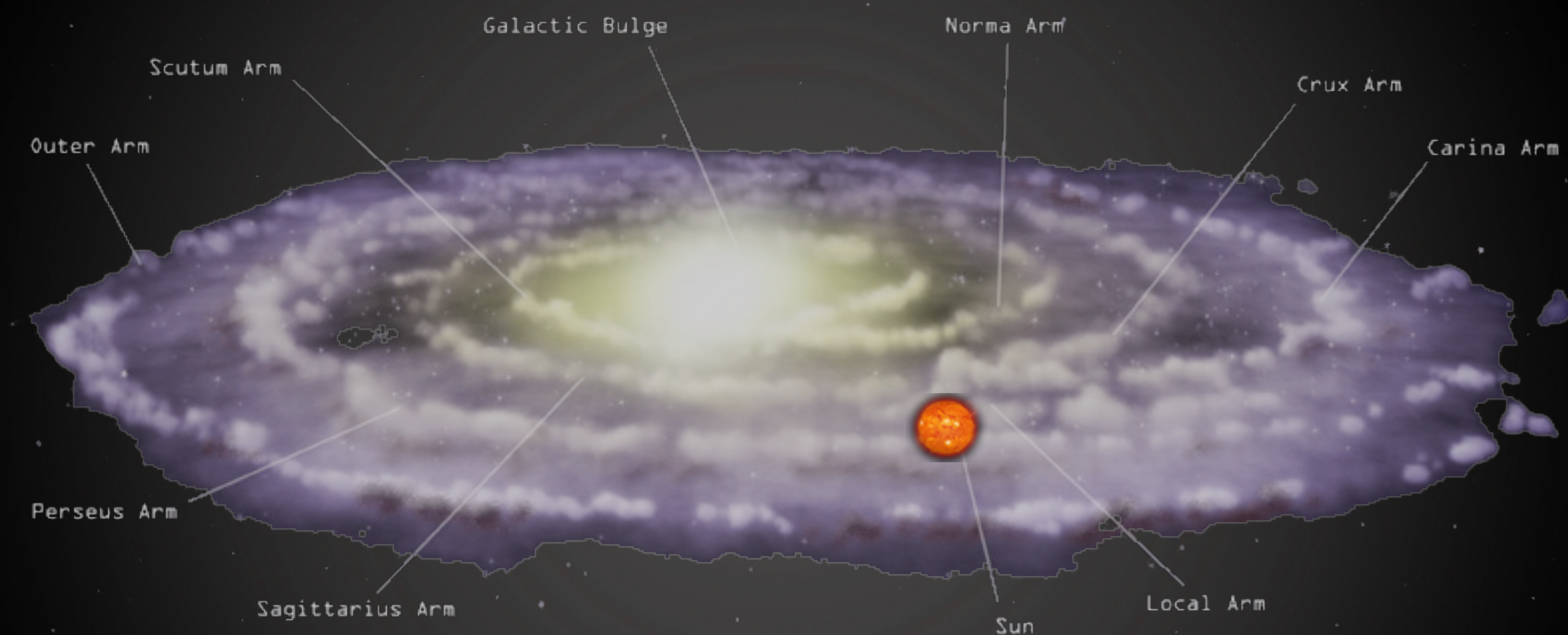
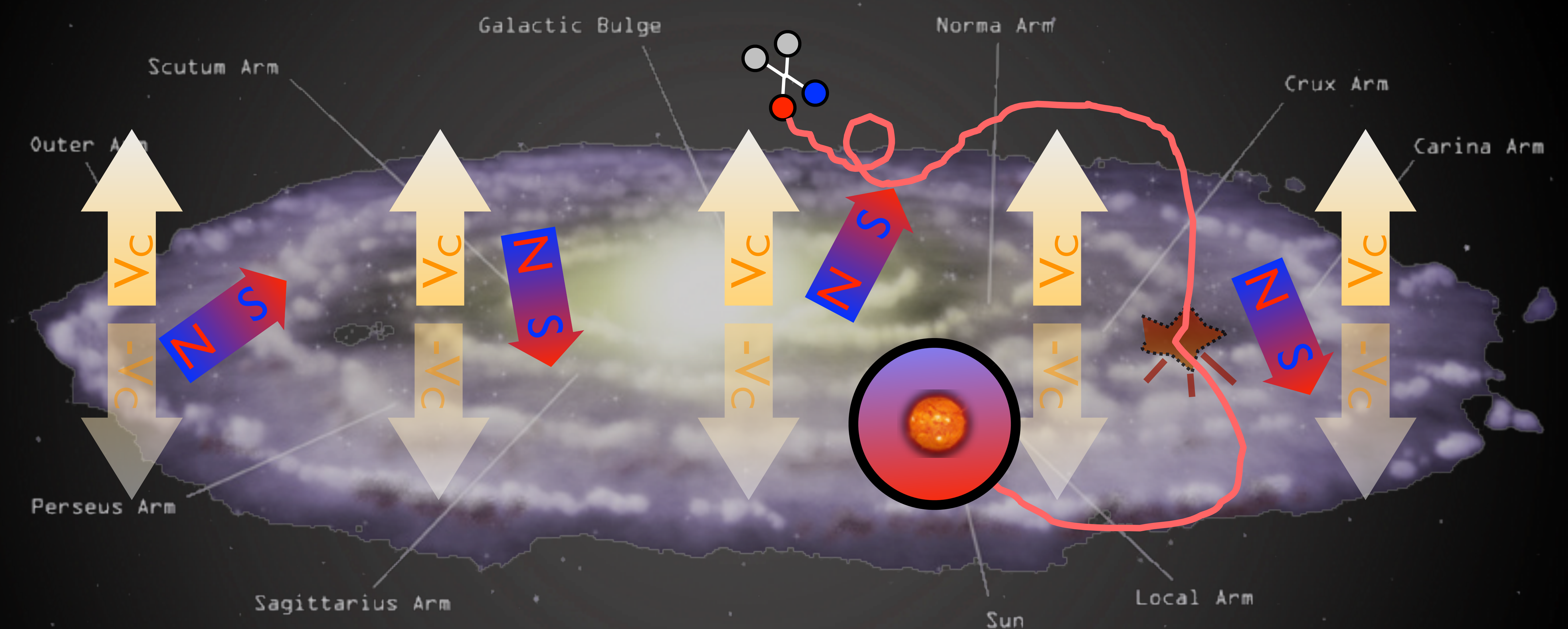
# Indirect Detection: charged CRs

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



# Indirect Detection: charged CRs

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



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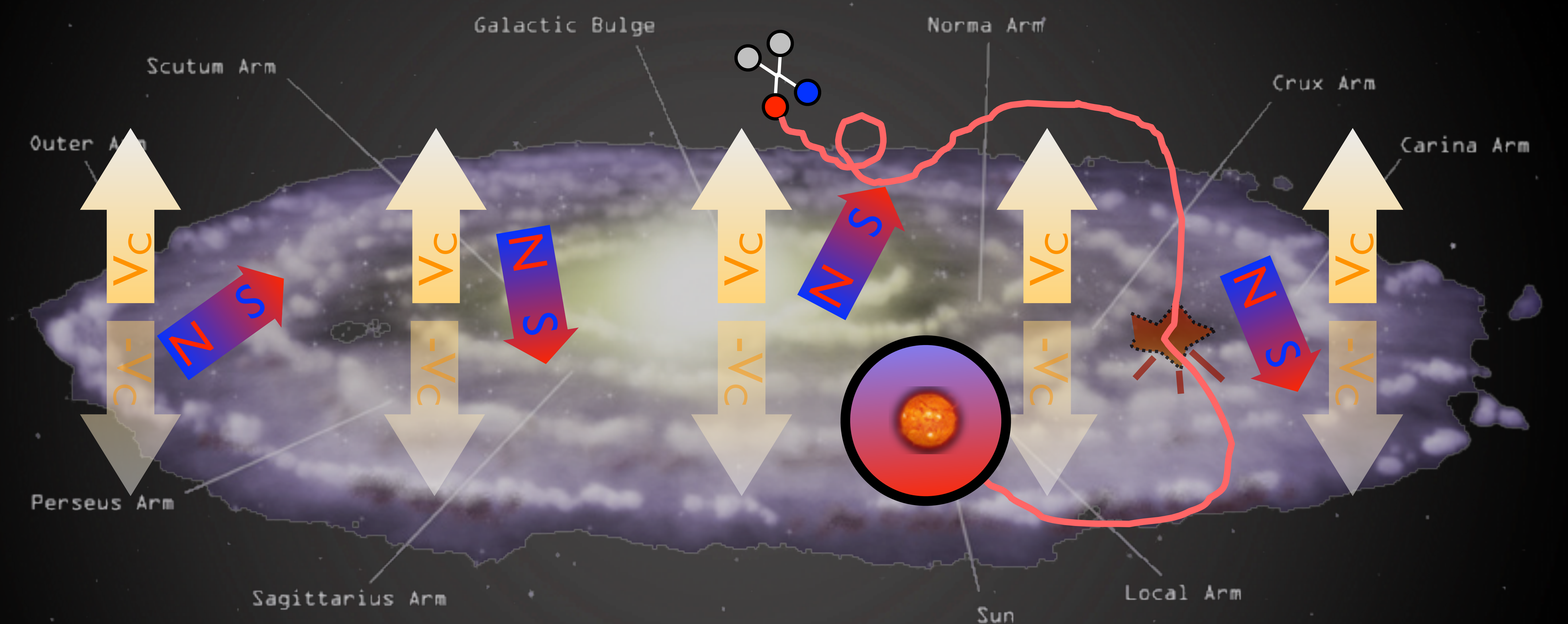


Problem:

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

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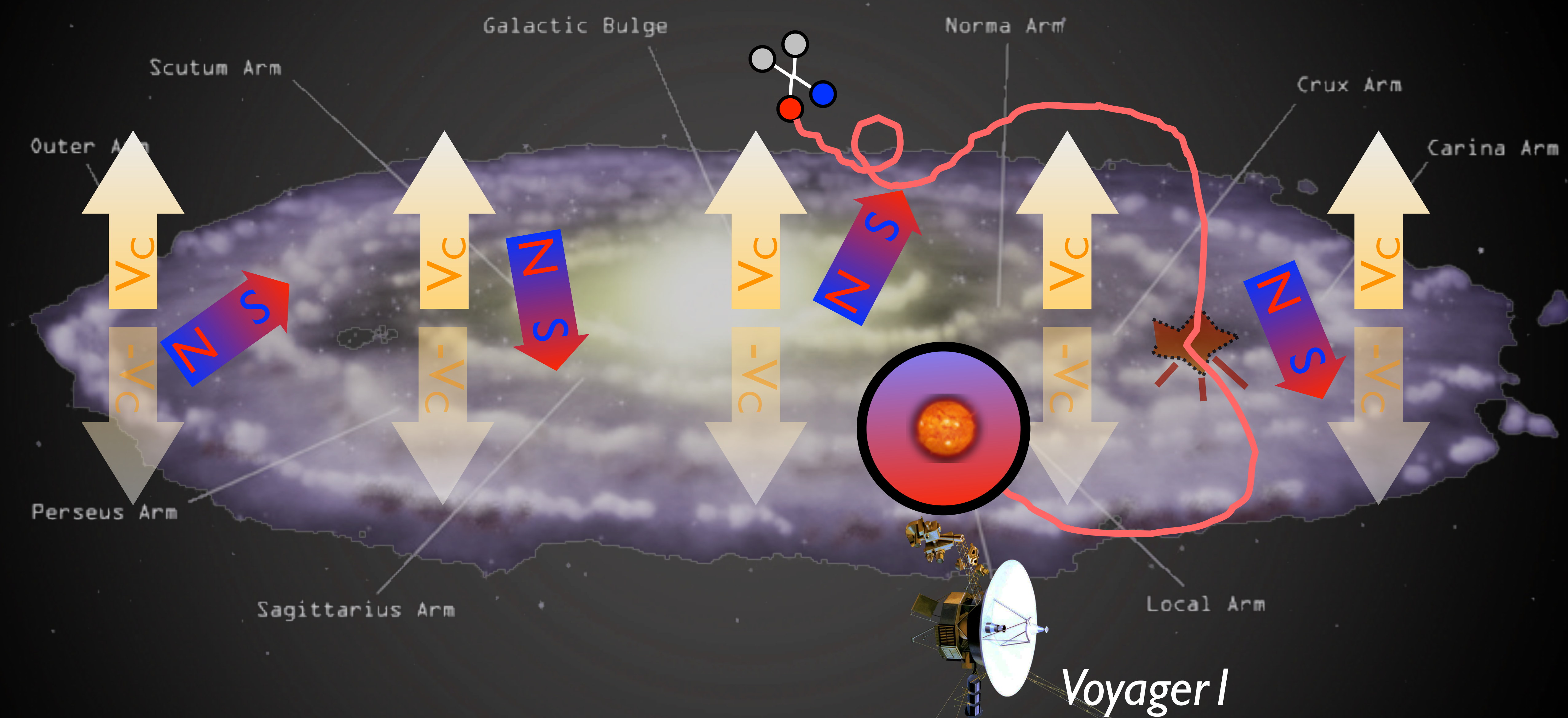


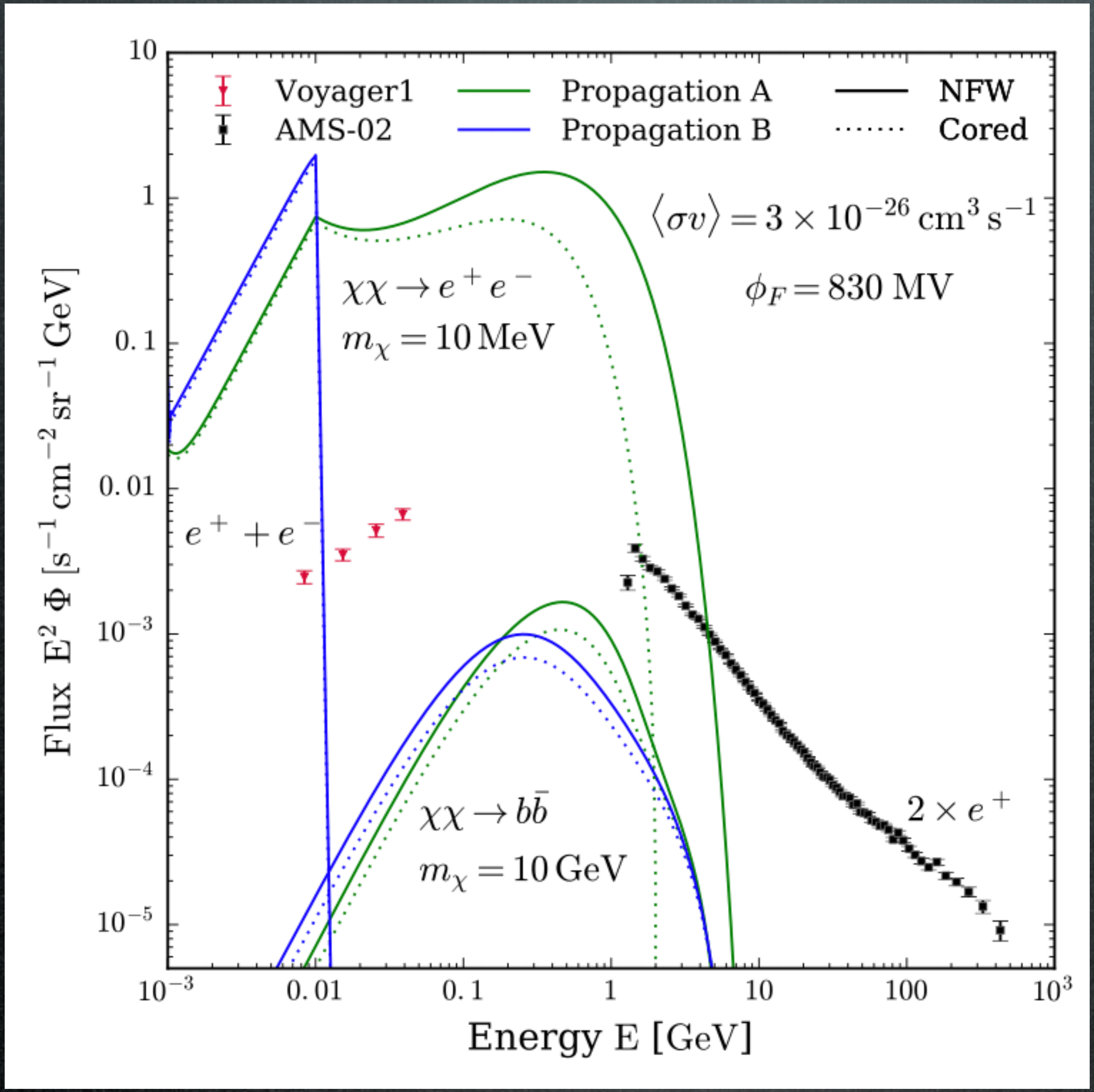

Problem:

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

# Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I




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

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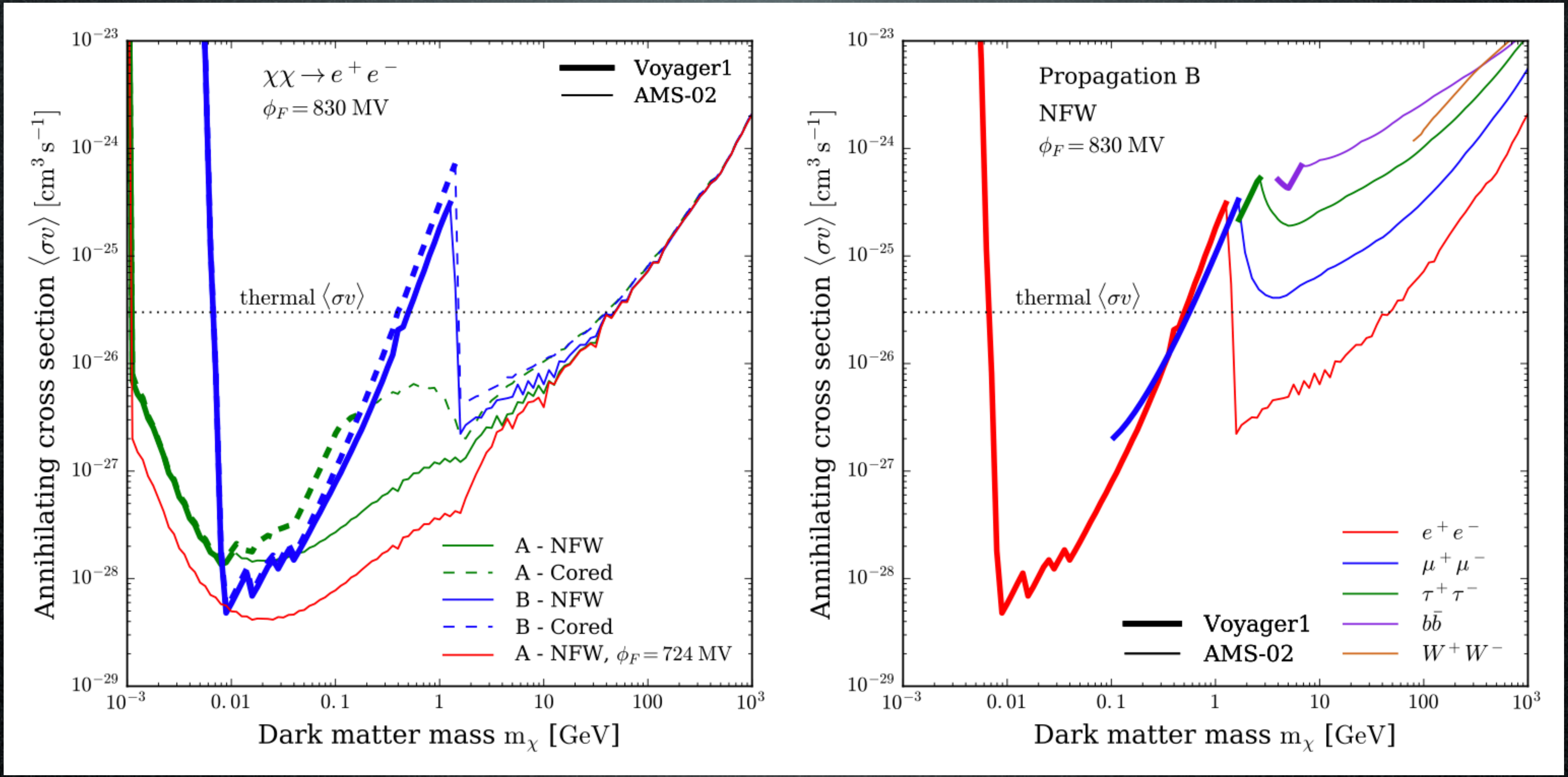
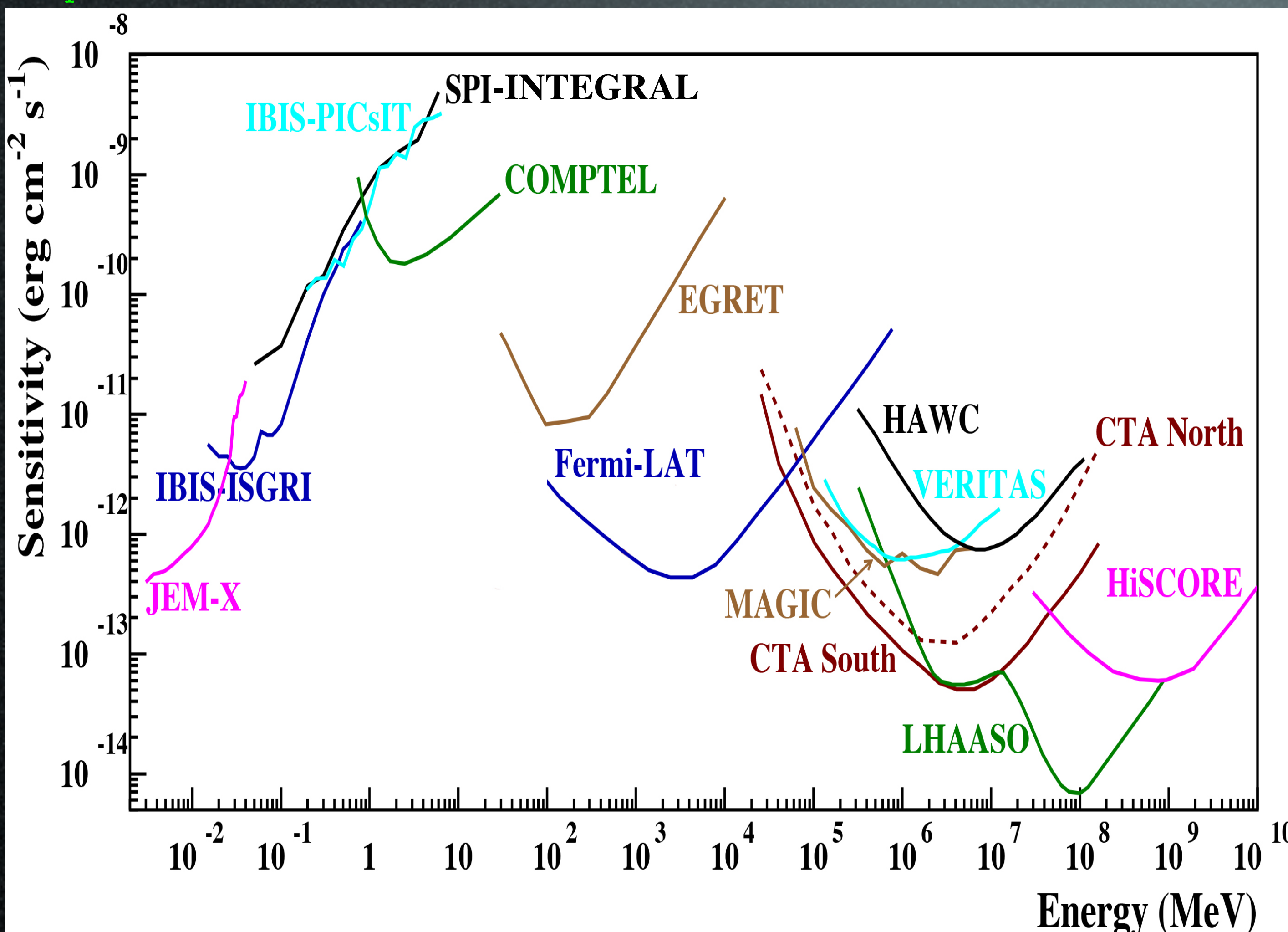


# Indirect detection: photons

adapted from 1611.02232




Past/current experiments:

Integral, Comptel, Fermi

(2002 ⟶ ) (1991-2000) (2009 ⟶ )

Planned/proposed experiments:

e-Astrogam?, Compair?, Amego?

| | | | | | |
|---|---|---|---|---|---|
| Amego | satellite | 2020s? | HEP detectors | $\gamma$-rays | 0.2 – 10 GeV |
| Compair | satellite | 2020s? | HEP detectors | $\gamma$-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 |
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Cirelli, Strumia, Zupan to appear

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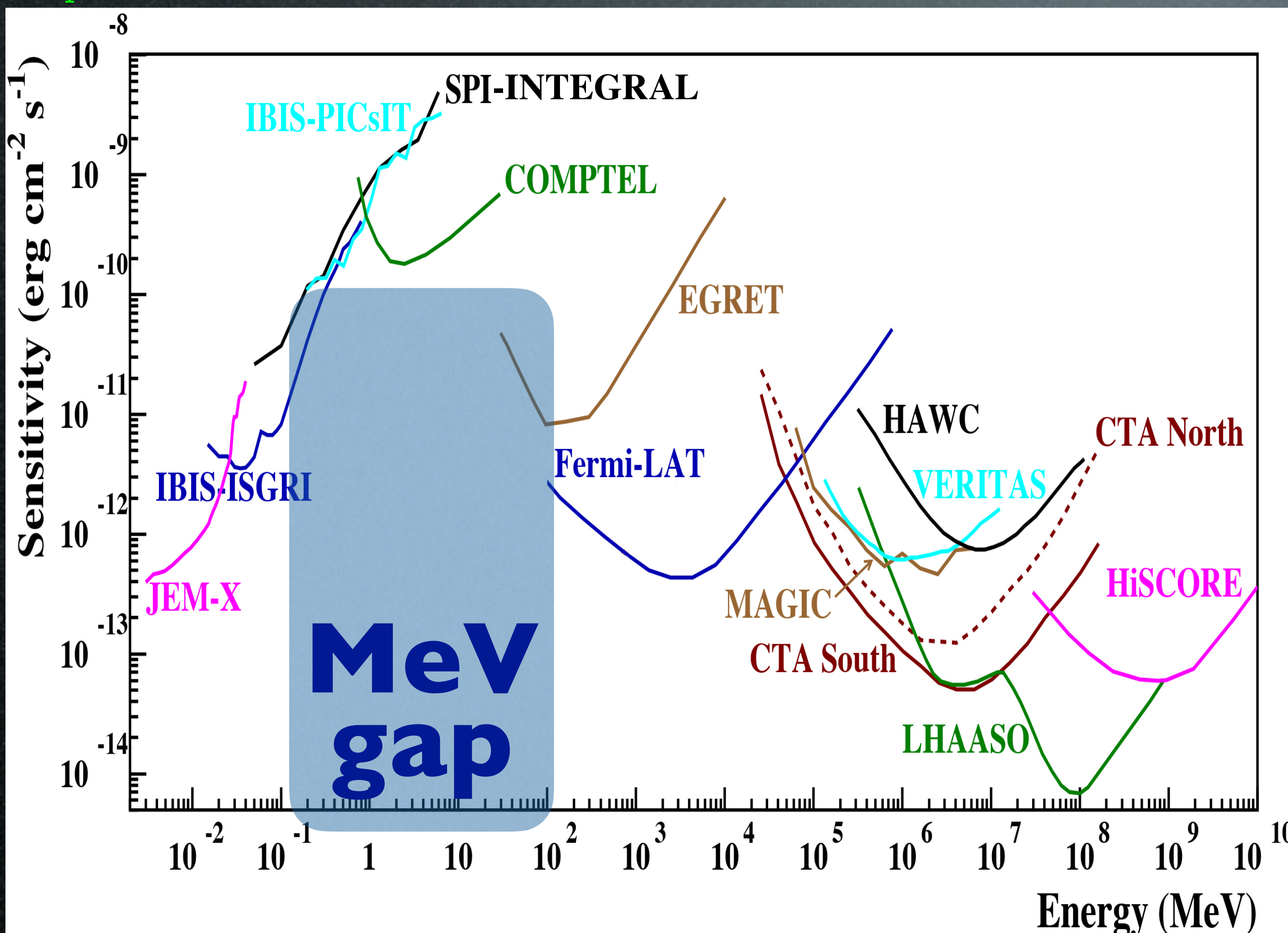


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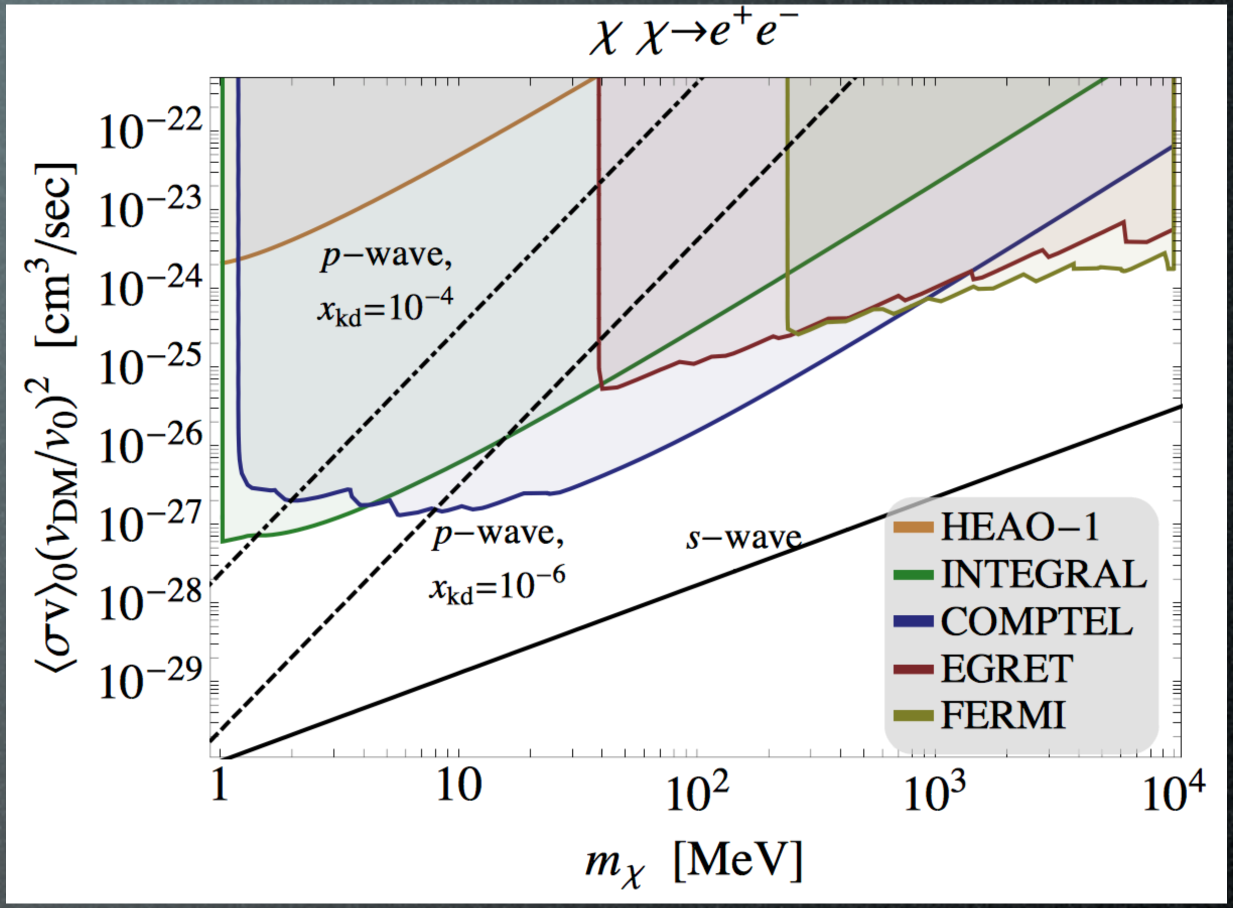
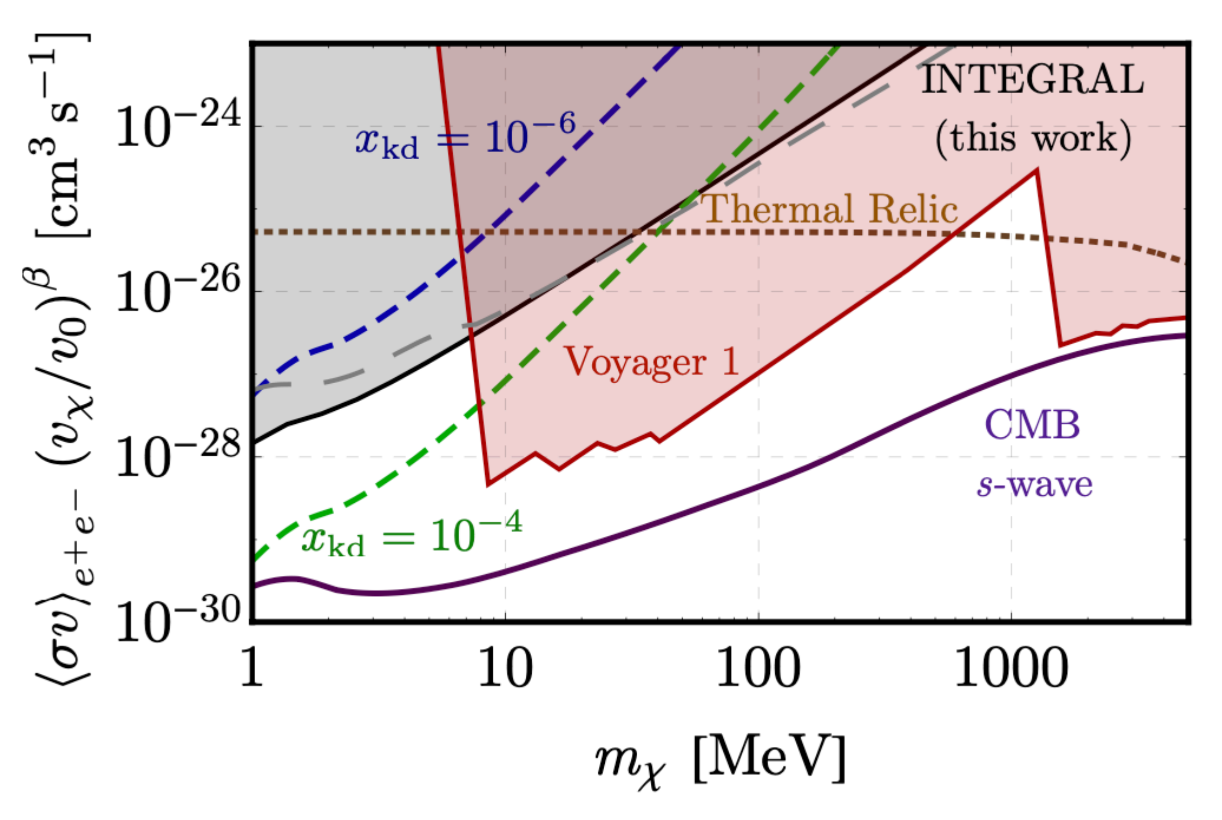
# Some recent studies

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




Laha, Muñoz, Slatyer, 2004.00627**v1**




NB: 'prompt' emission only

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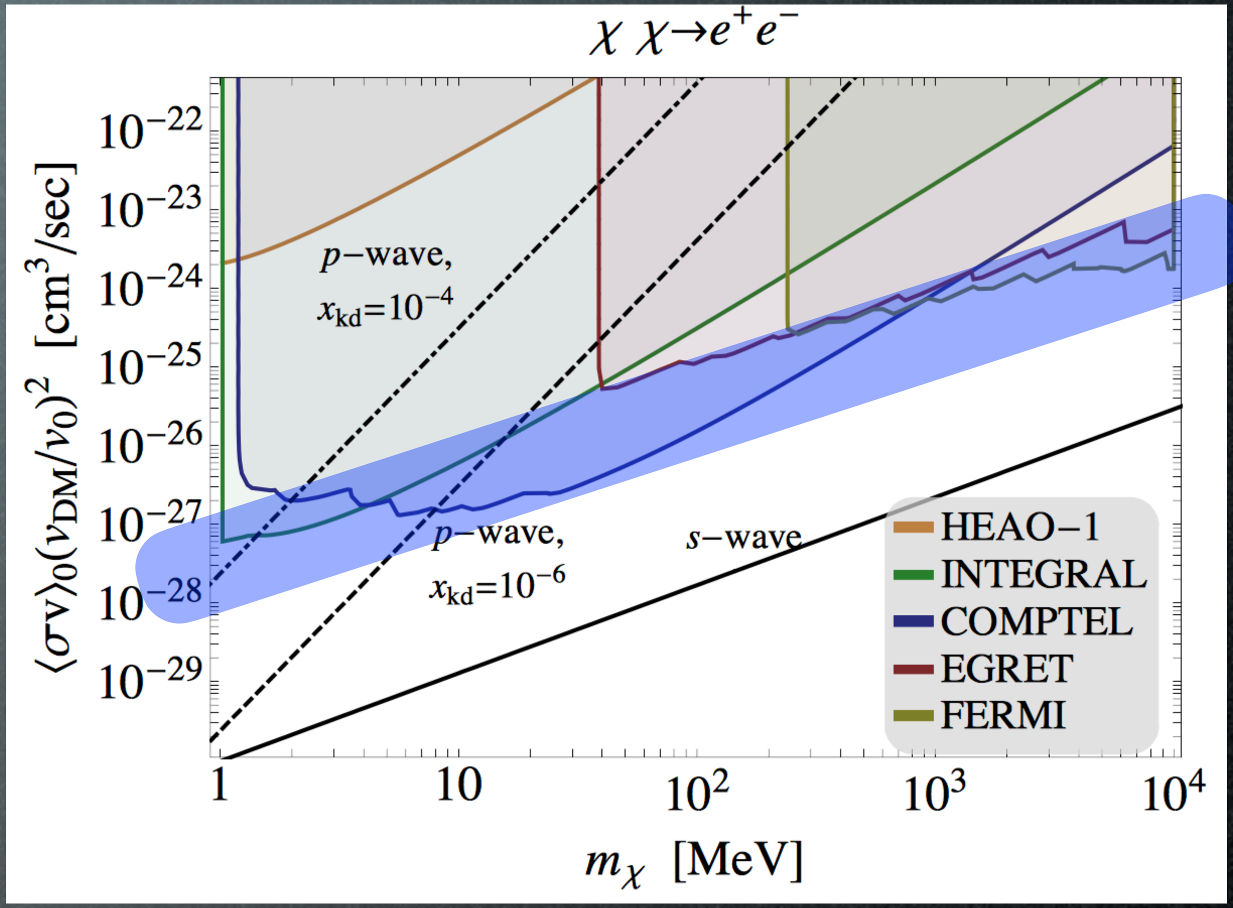


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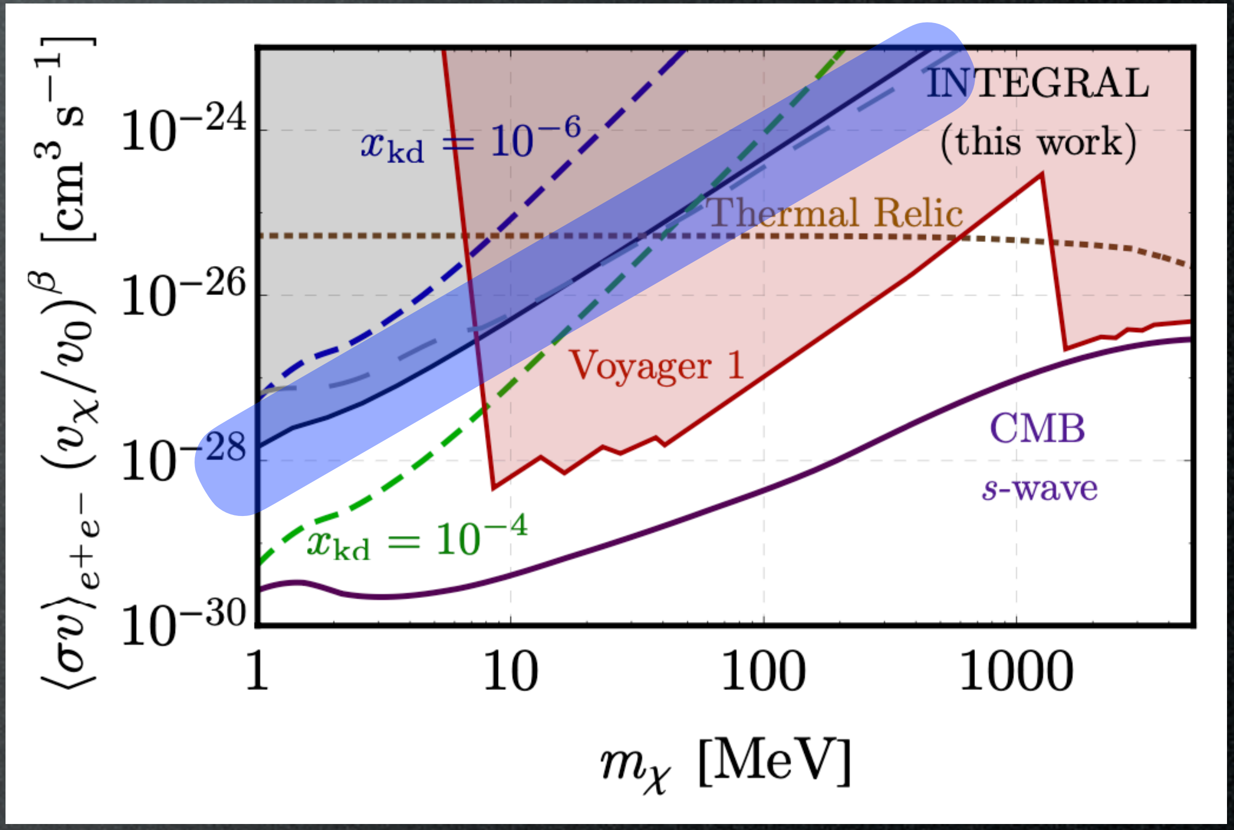


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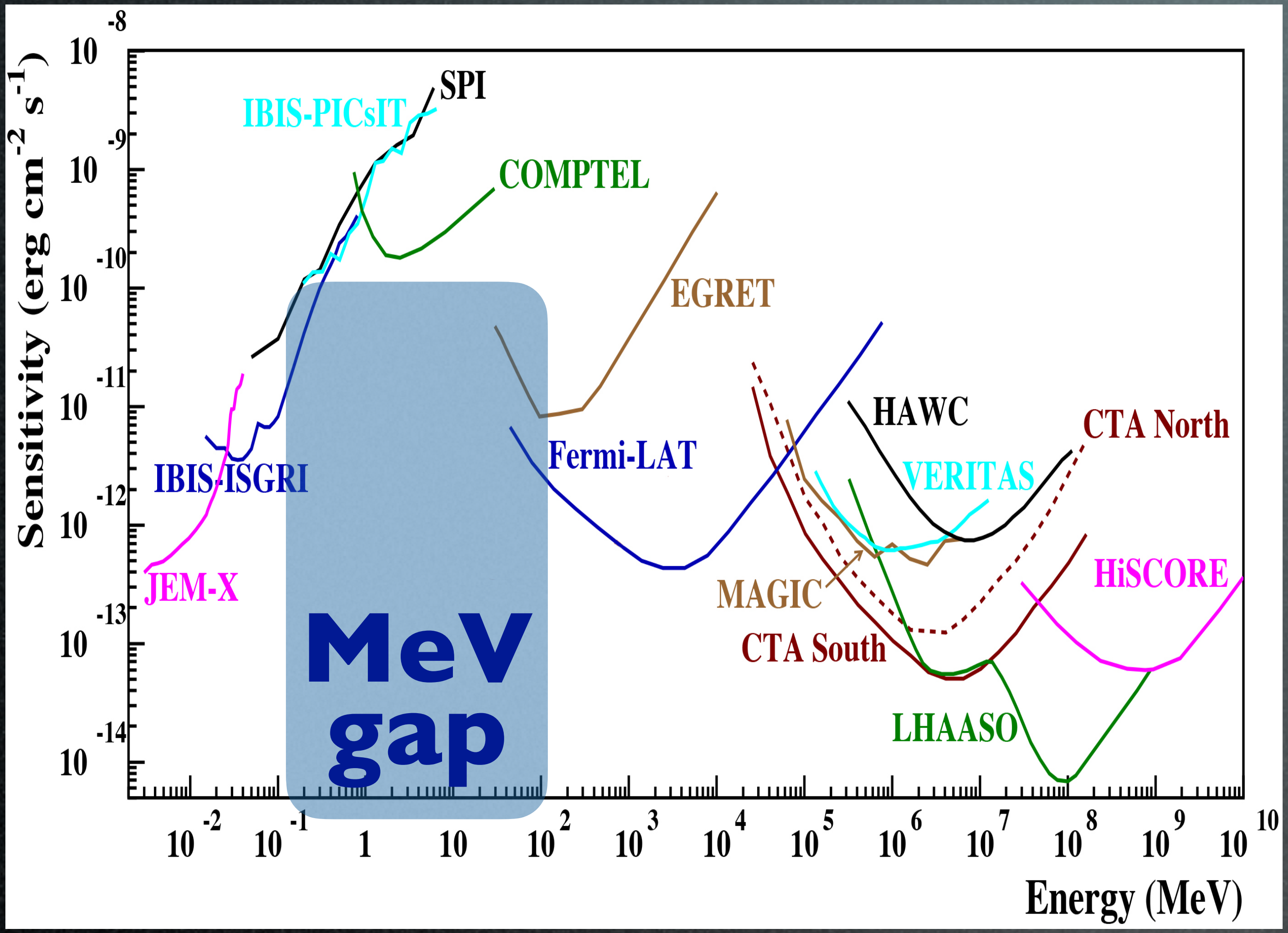


How to do better?

ICS & X-rays!

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

# Sub-GeV DM & X-rays

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

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

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

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

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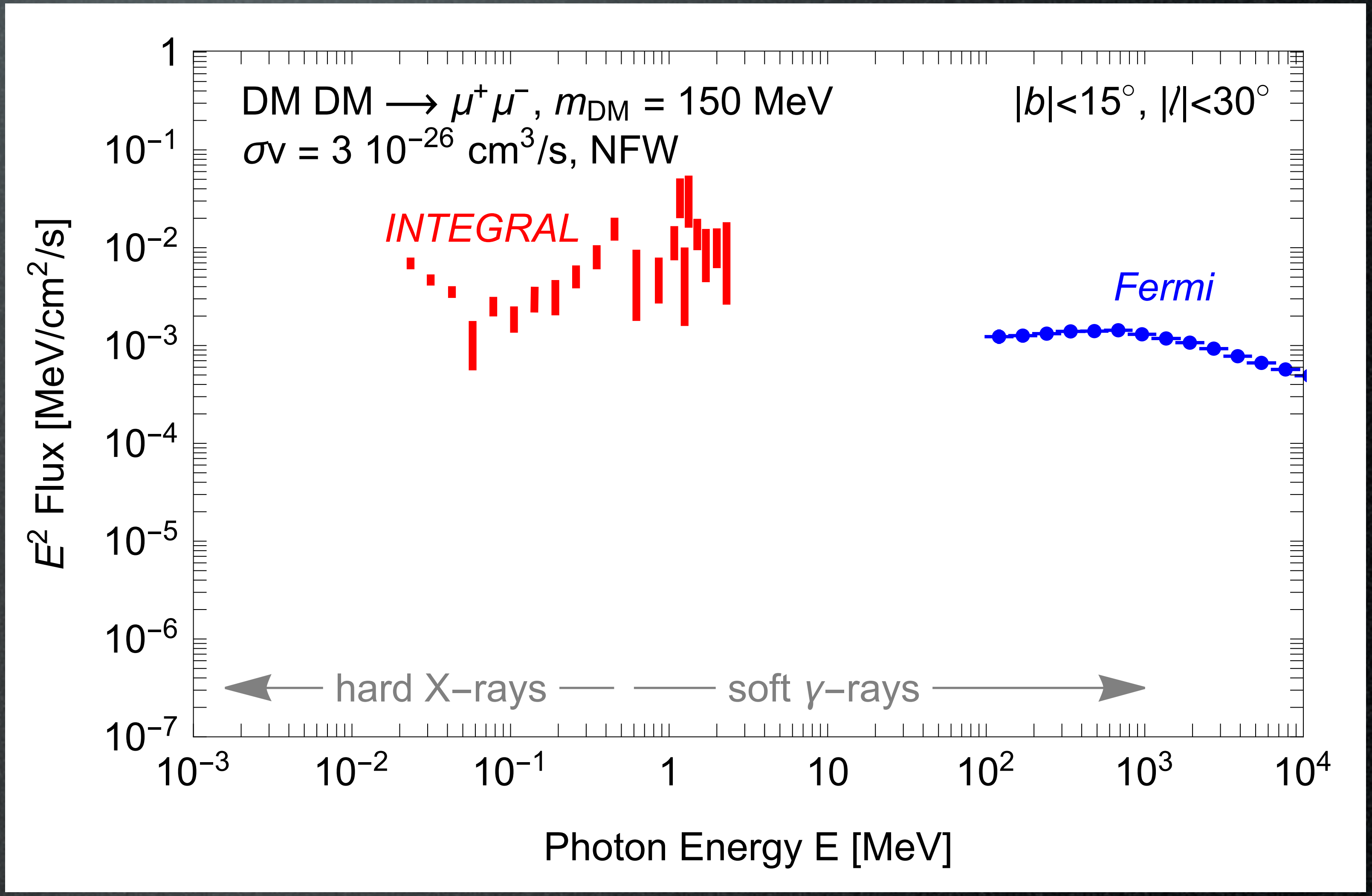

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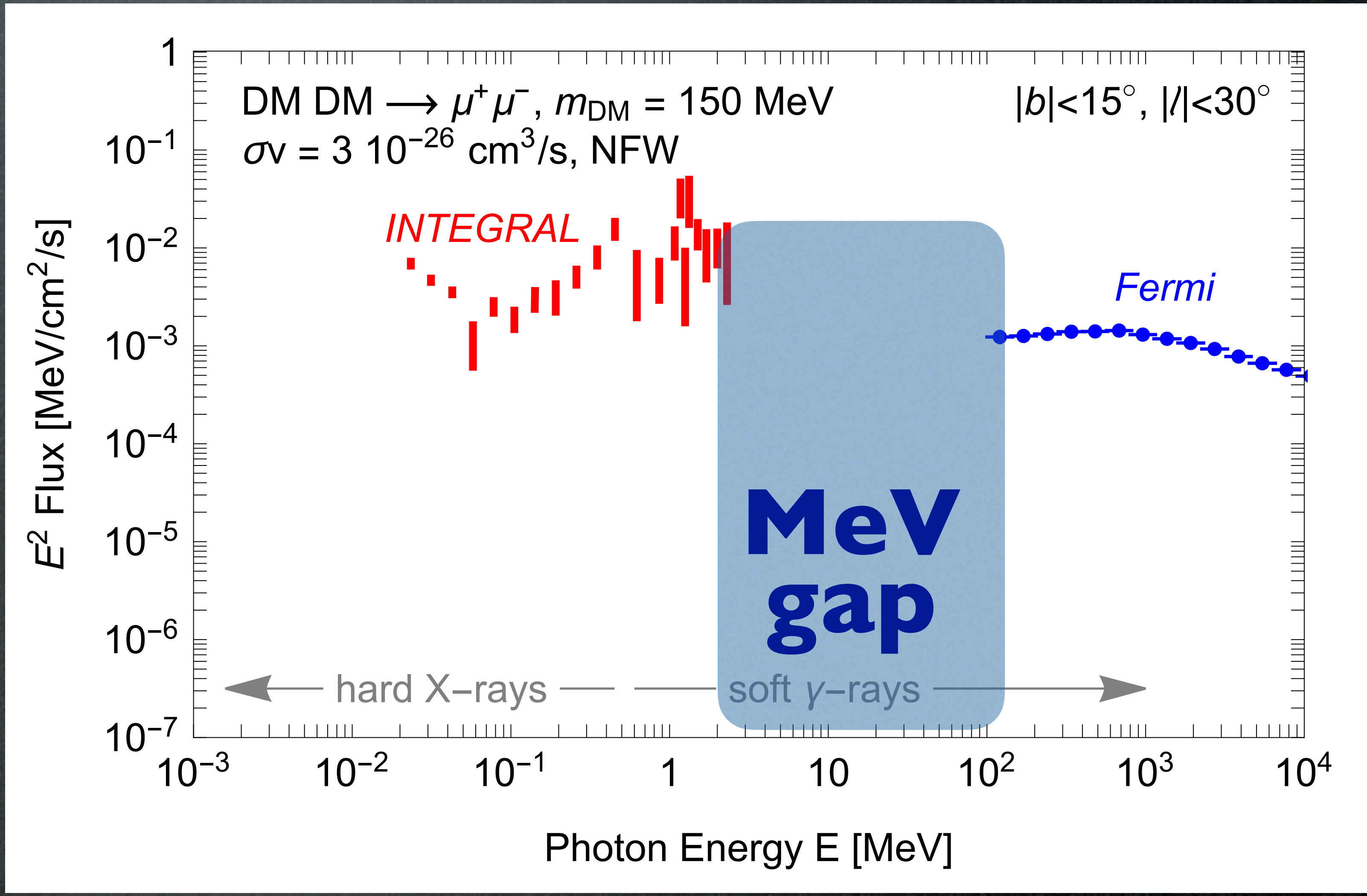

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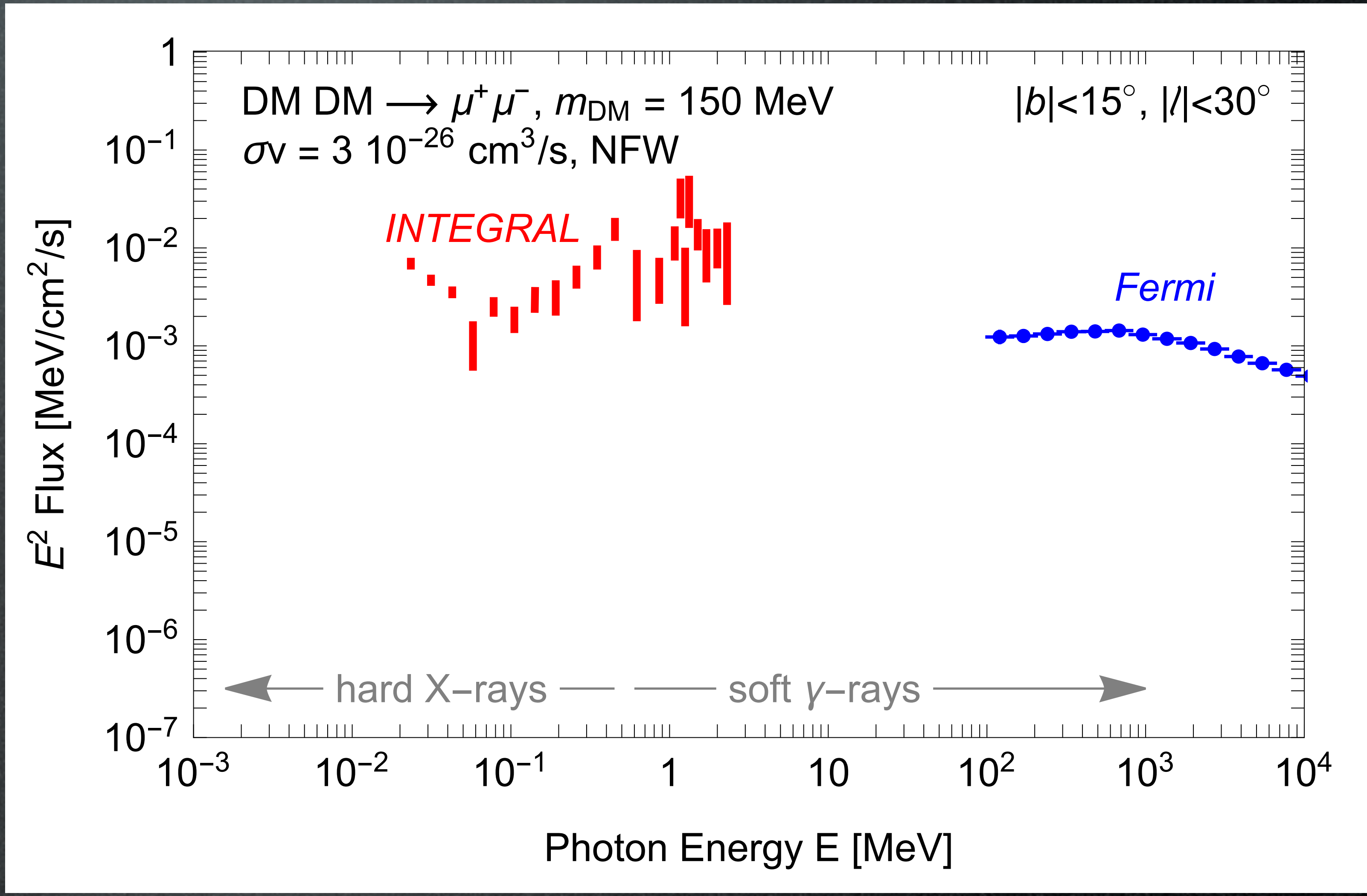

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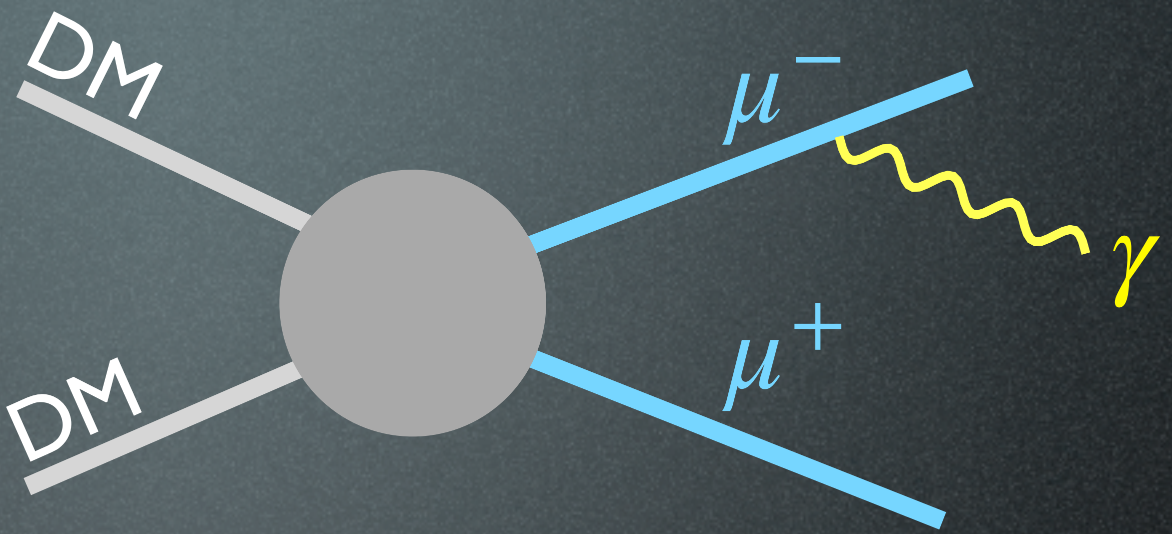
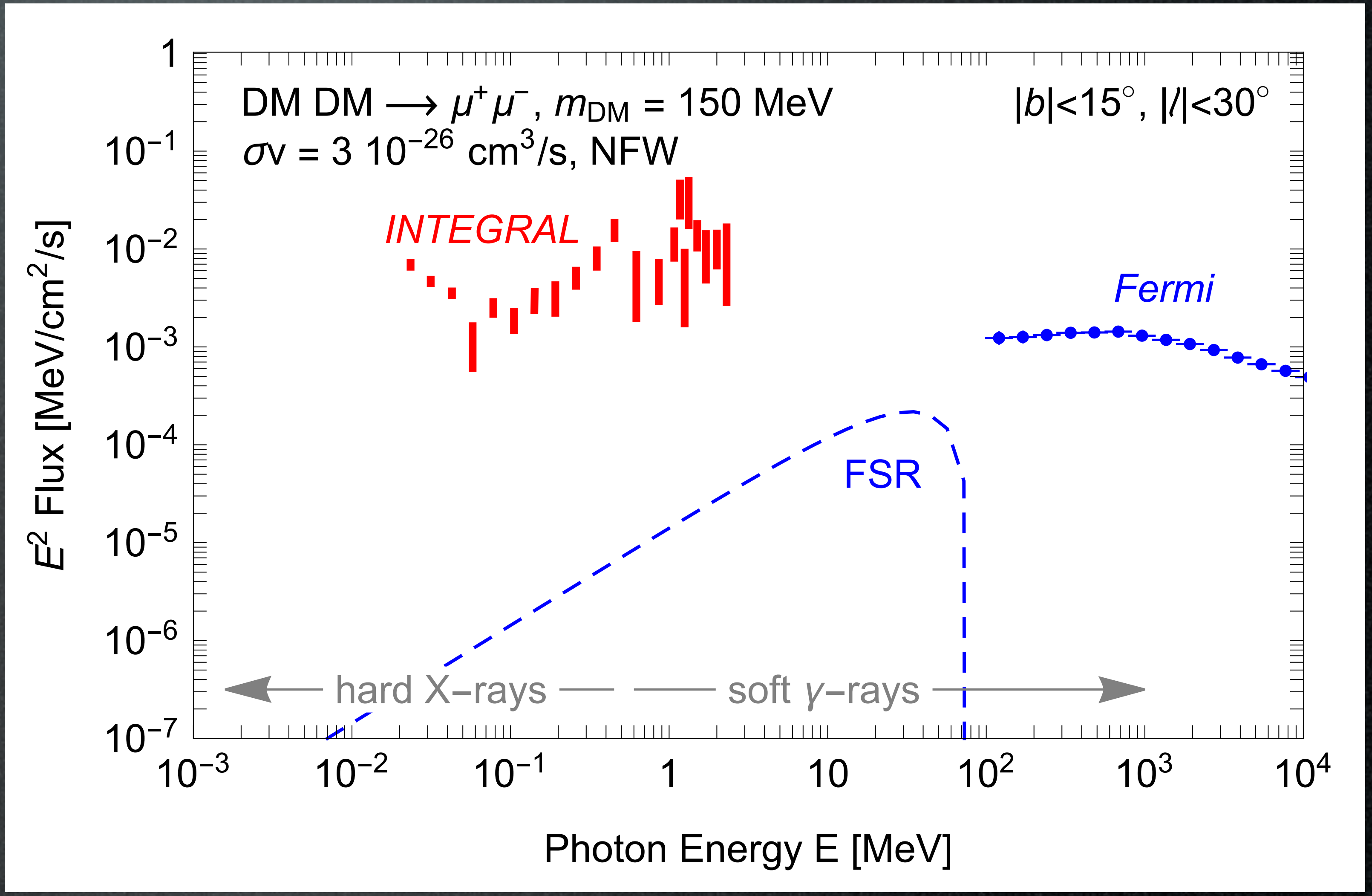



'Prompt' emission:

Final State Radiation (FSR)



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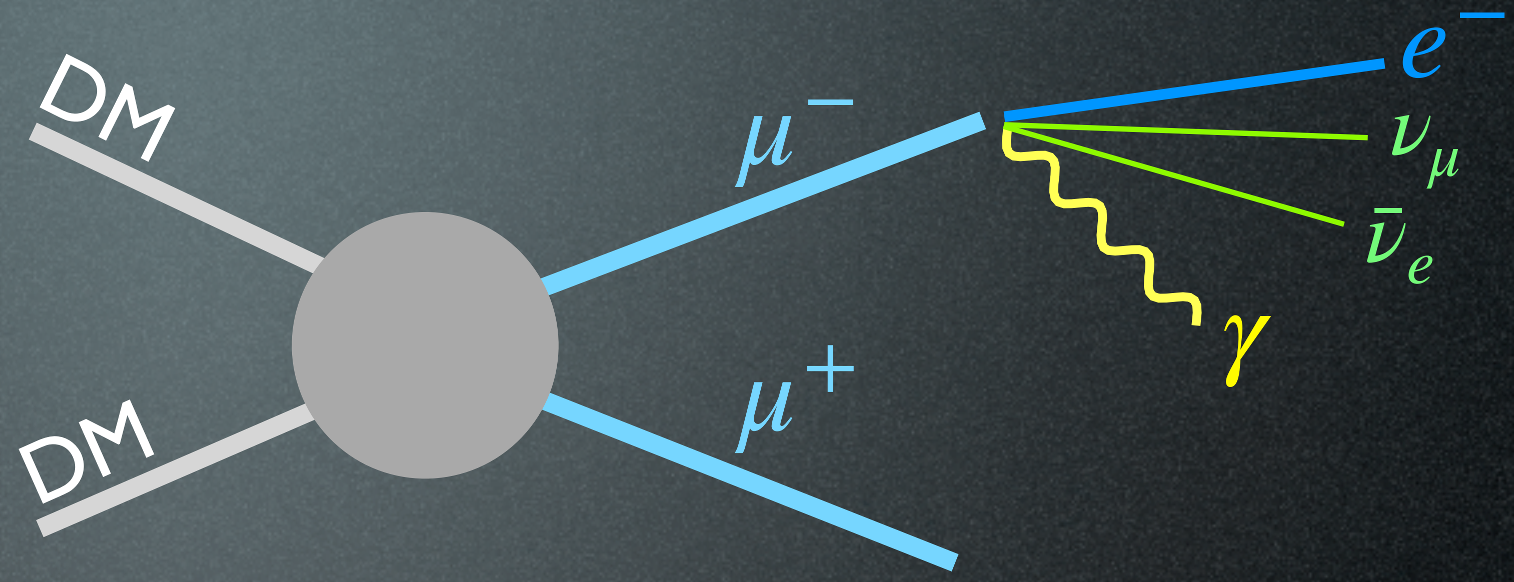
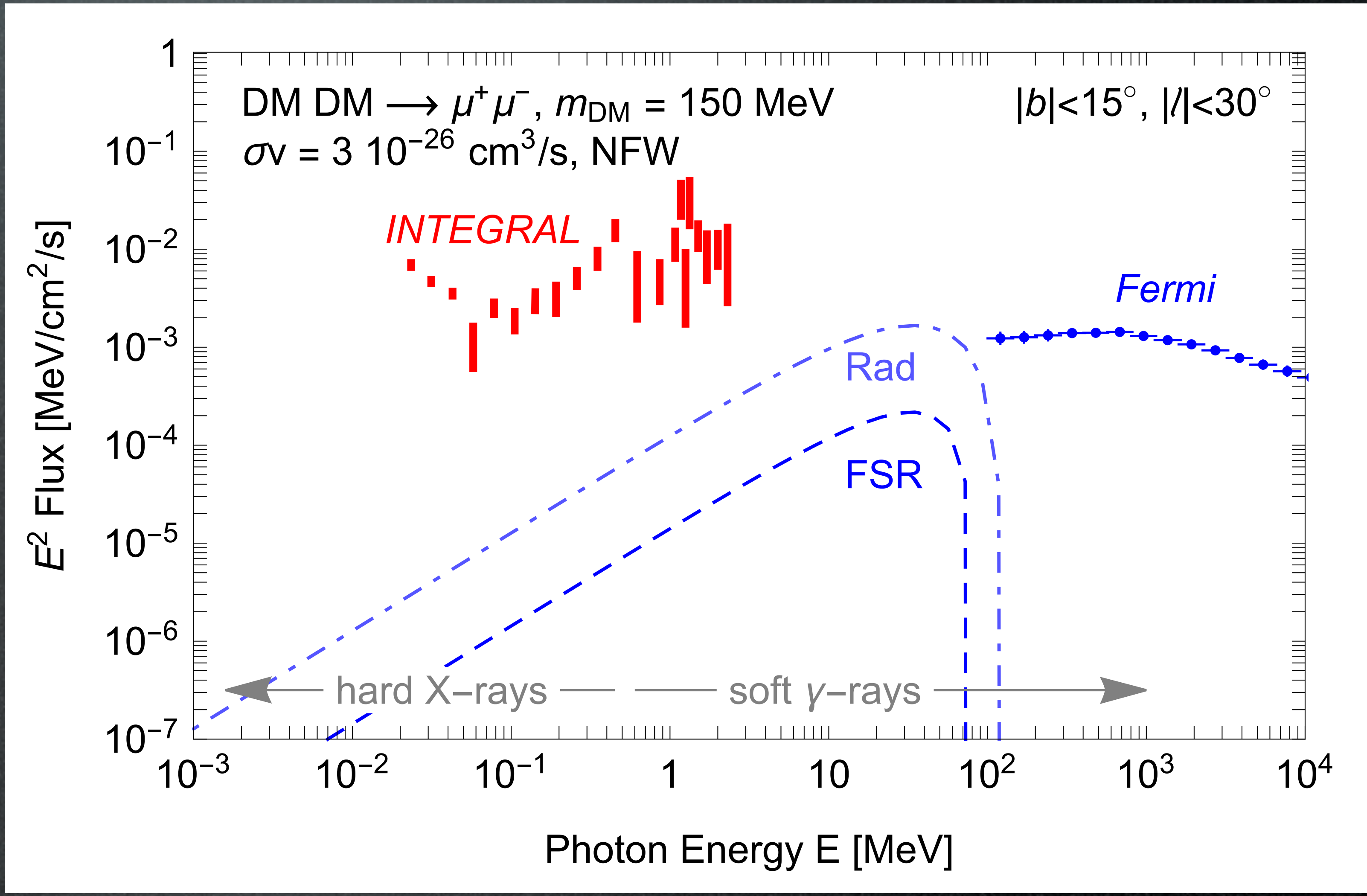



‘Prompt’ emission:

Final State Radiation (FSR)

Radiative $\mu$ decay

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



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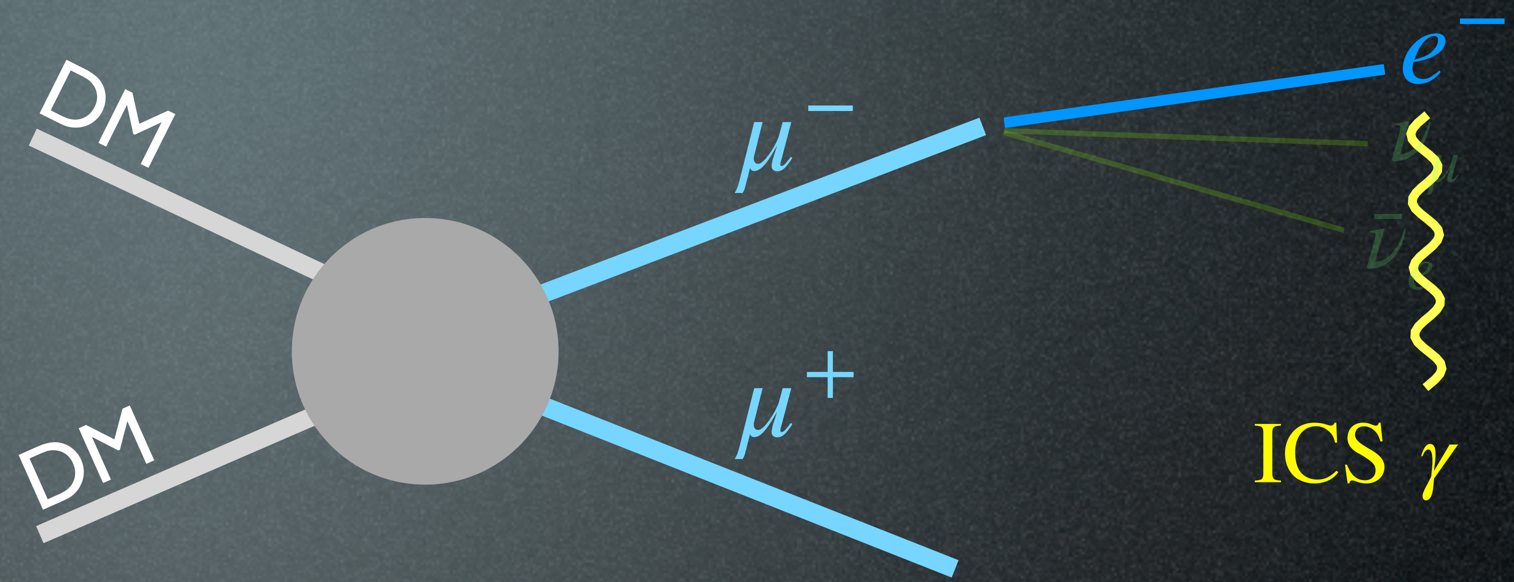


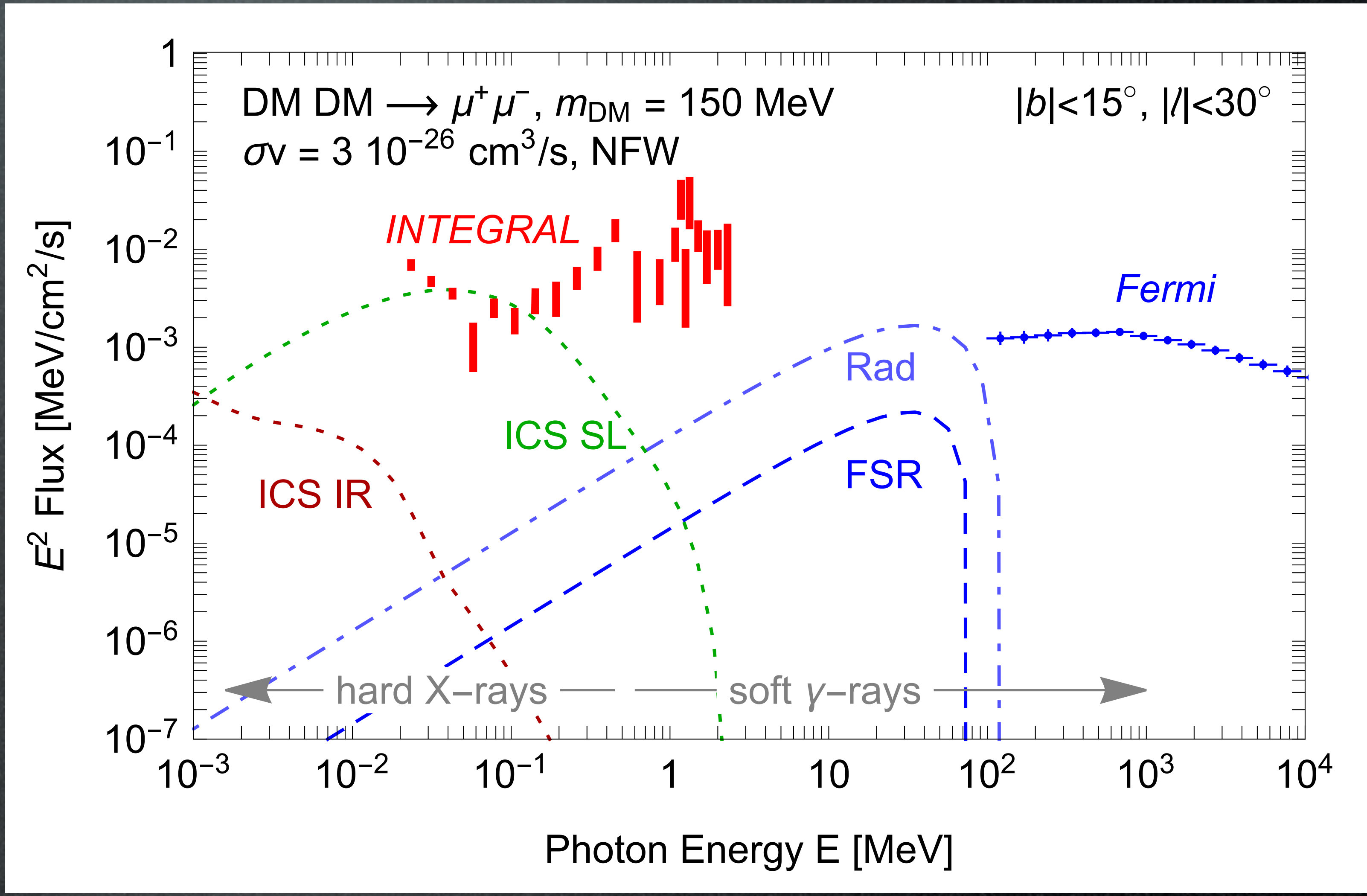

‘Prompt’ emission:

Final State Radiation (FSR)

Radiative $\mu$ decay

Secondary emission:

ICS: inevitably associated to annihil to charged states



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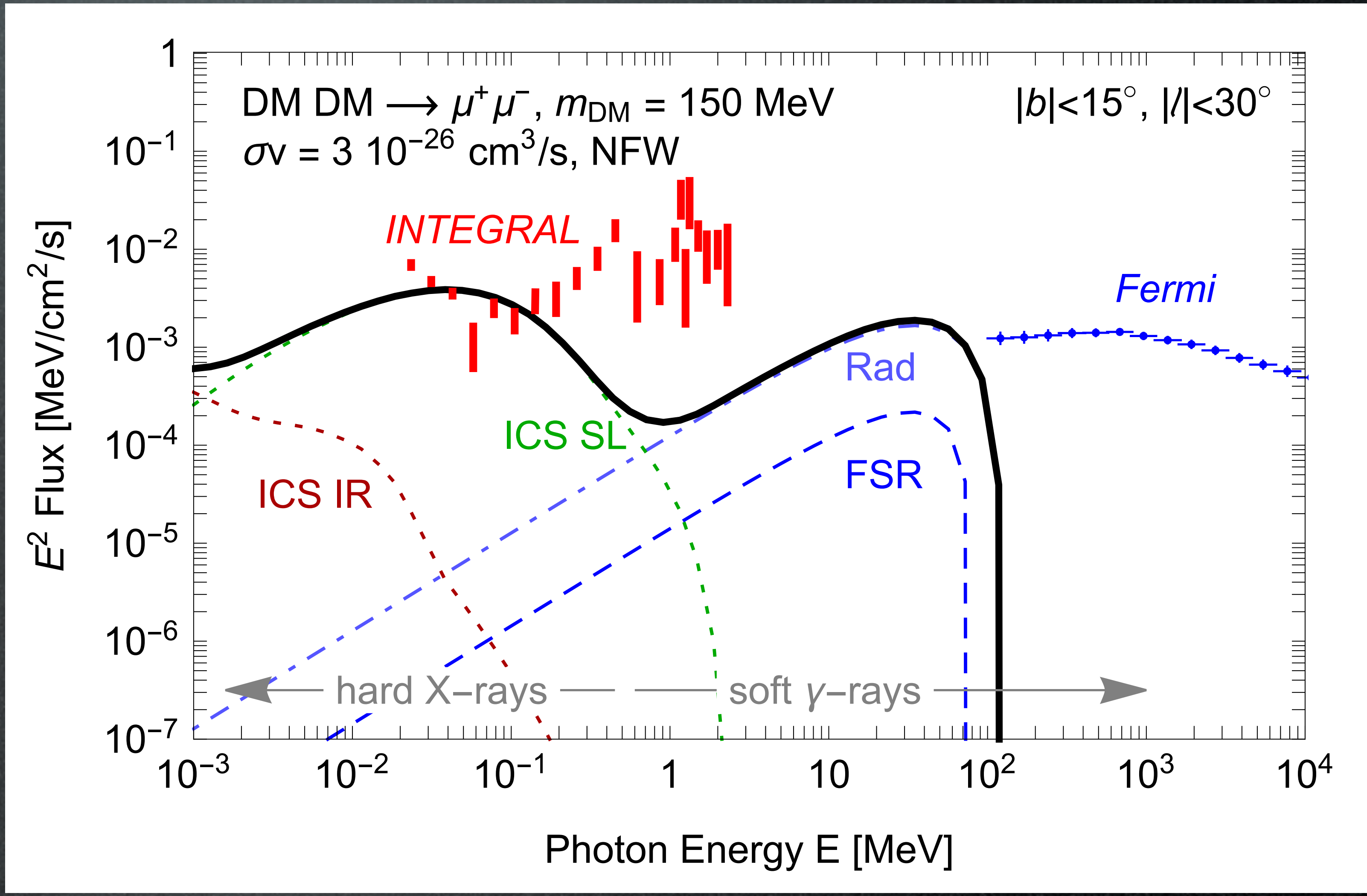


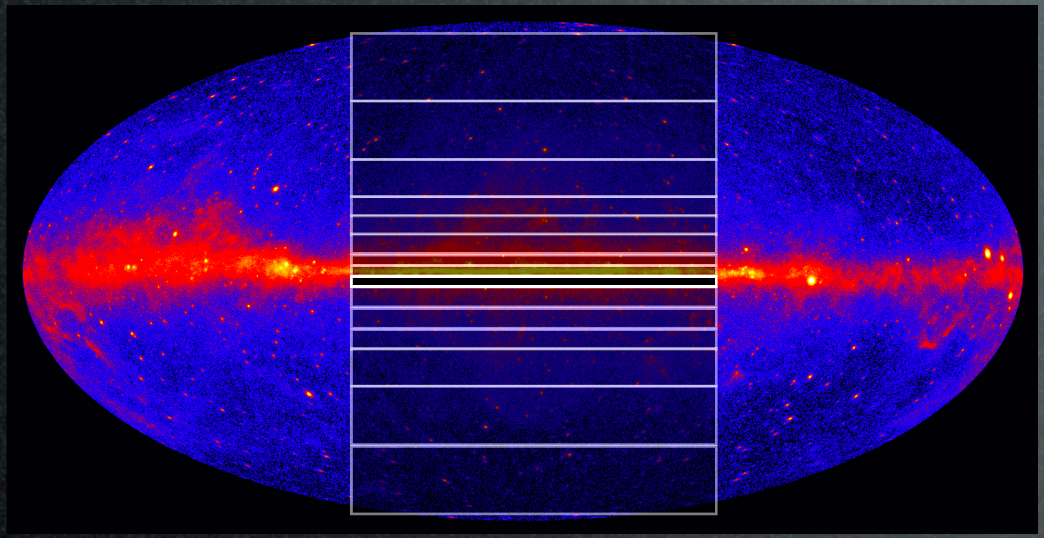

**Key message:**
ICS allows to probe sub-GeV DM with X-ray data

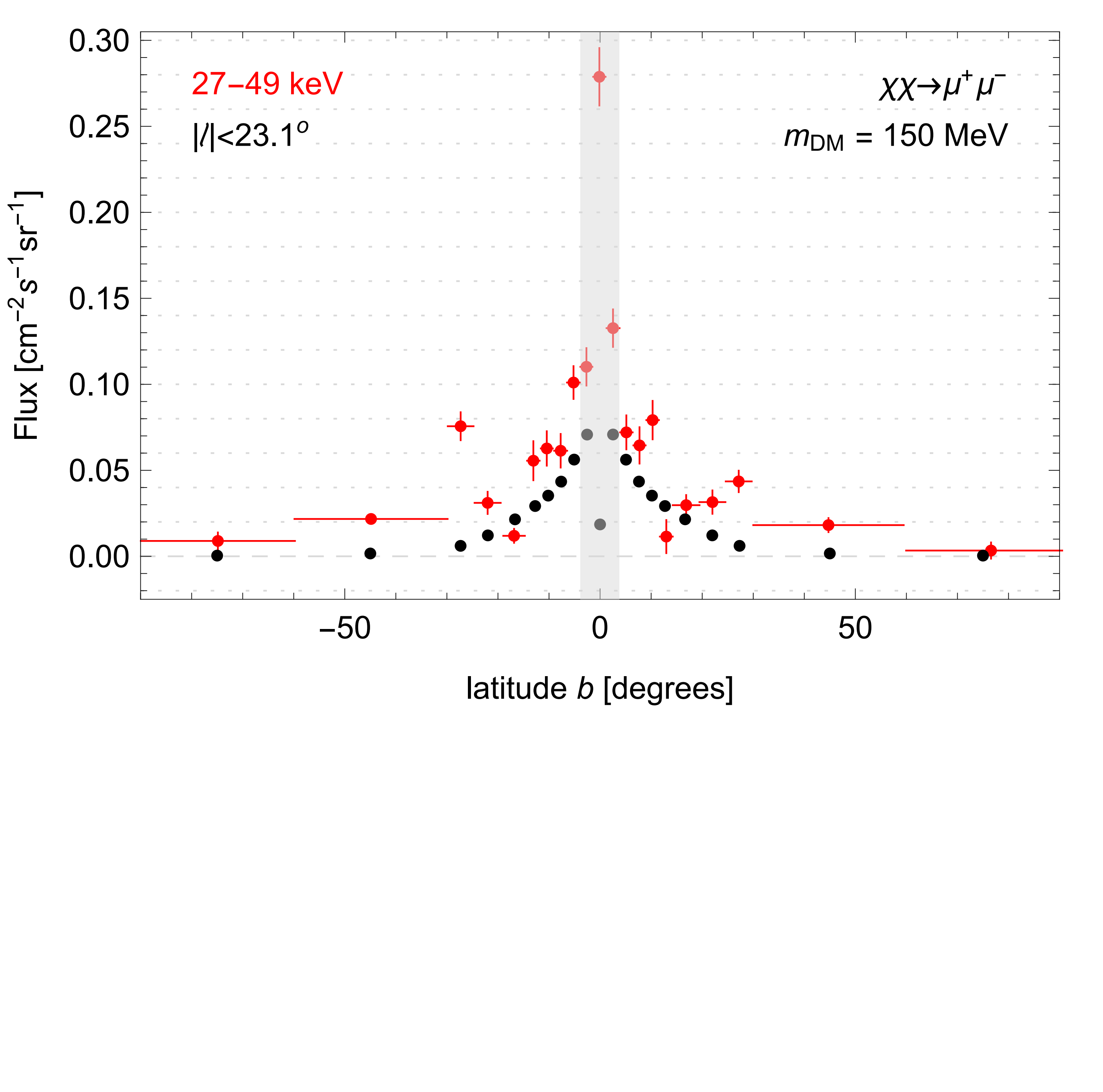
# Analysis

Integral-SPI 2011 data

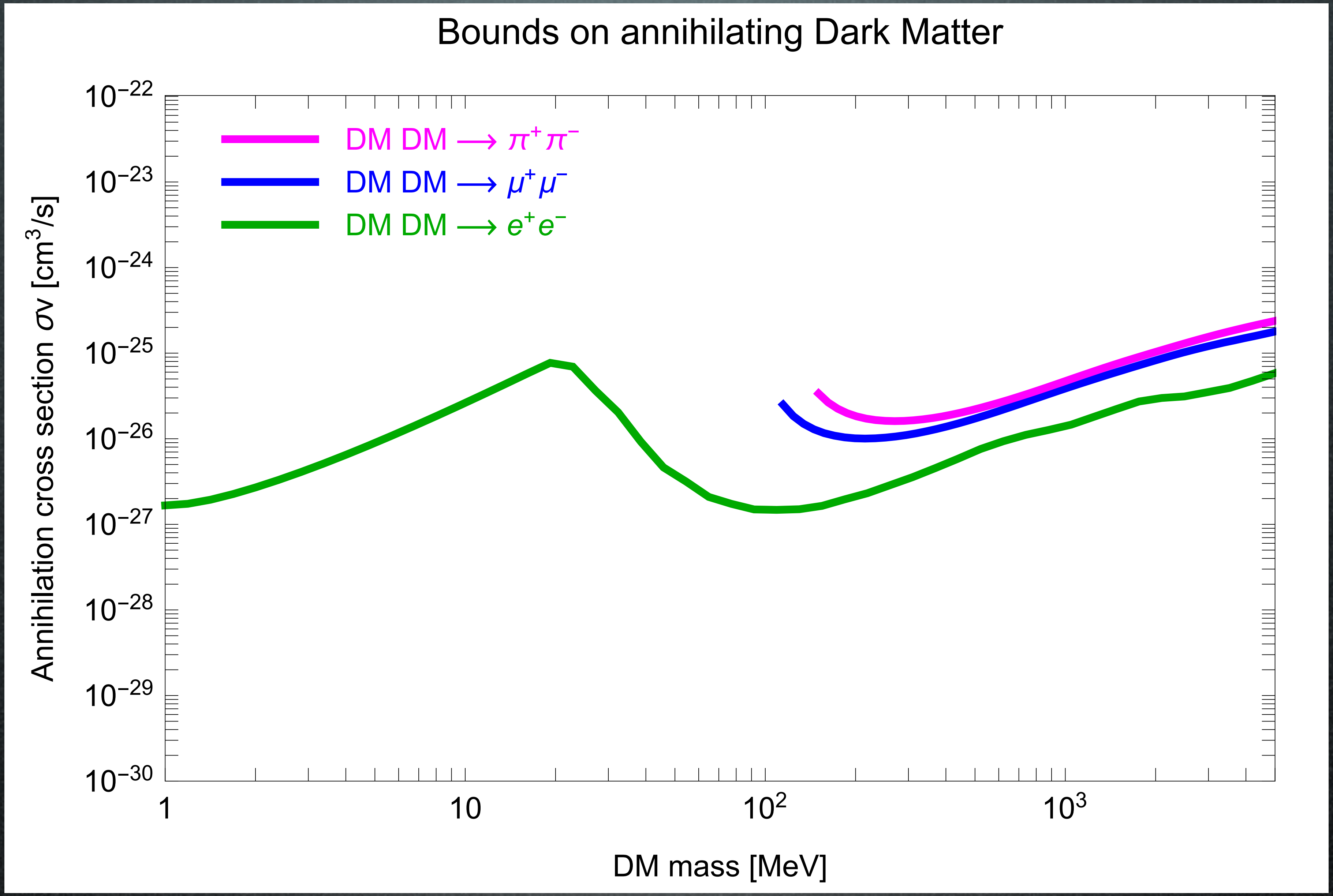
Bouchet et al., Integral coll. 1107.0200

latitude binned data, central MW





# Results




Bounds on all 3 channels

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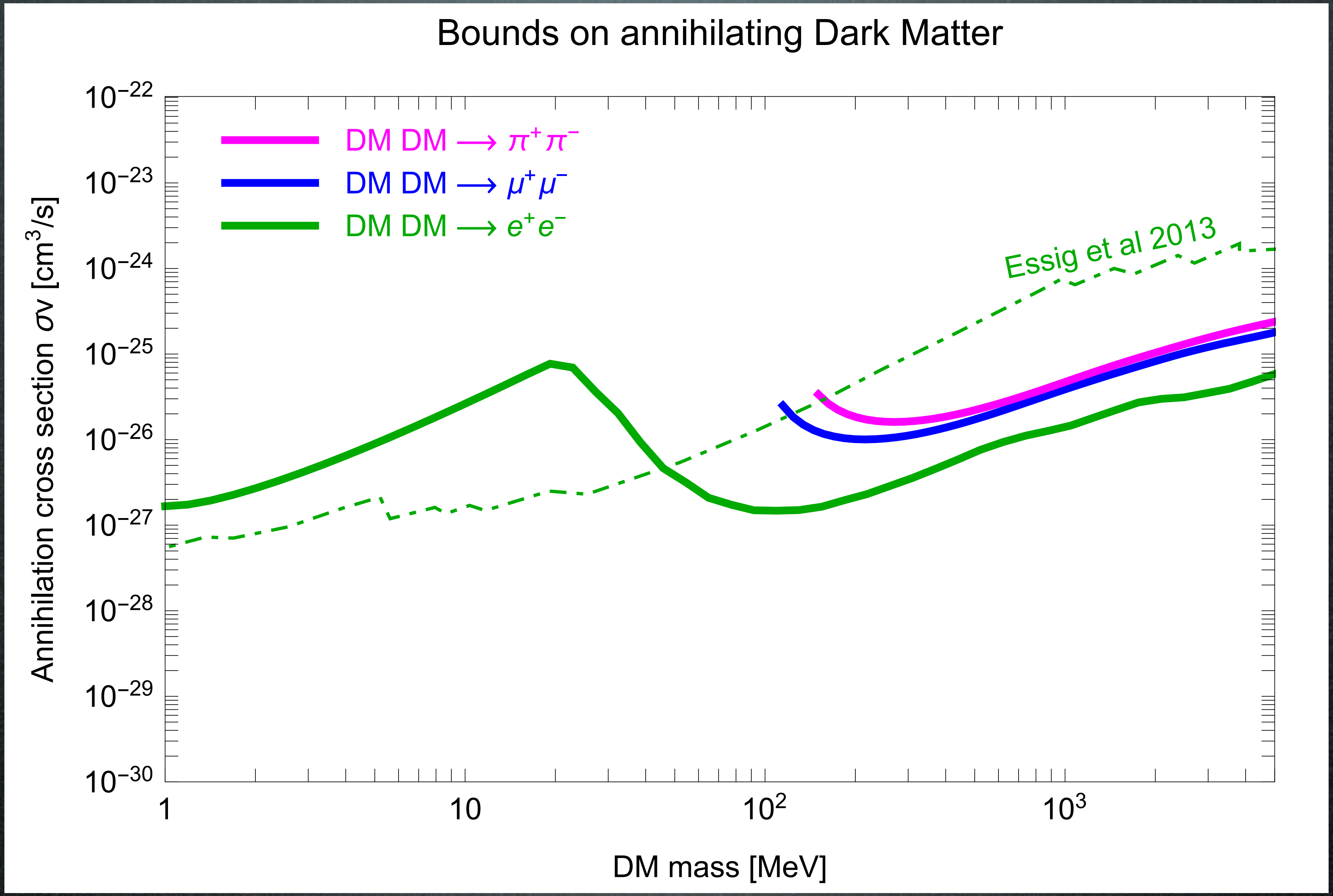


Essig+
1309.4091

Bounds on all 3 channels

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

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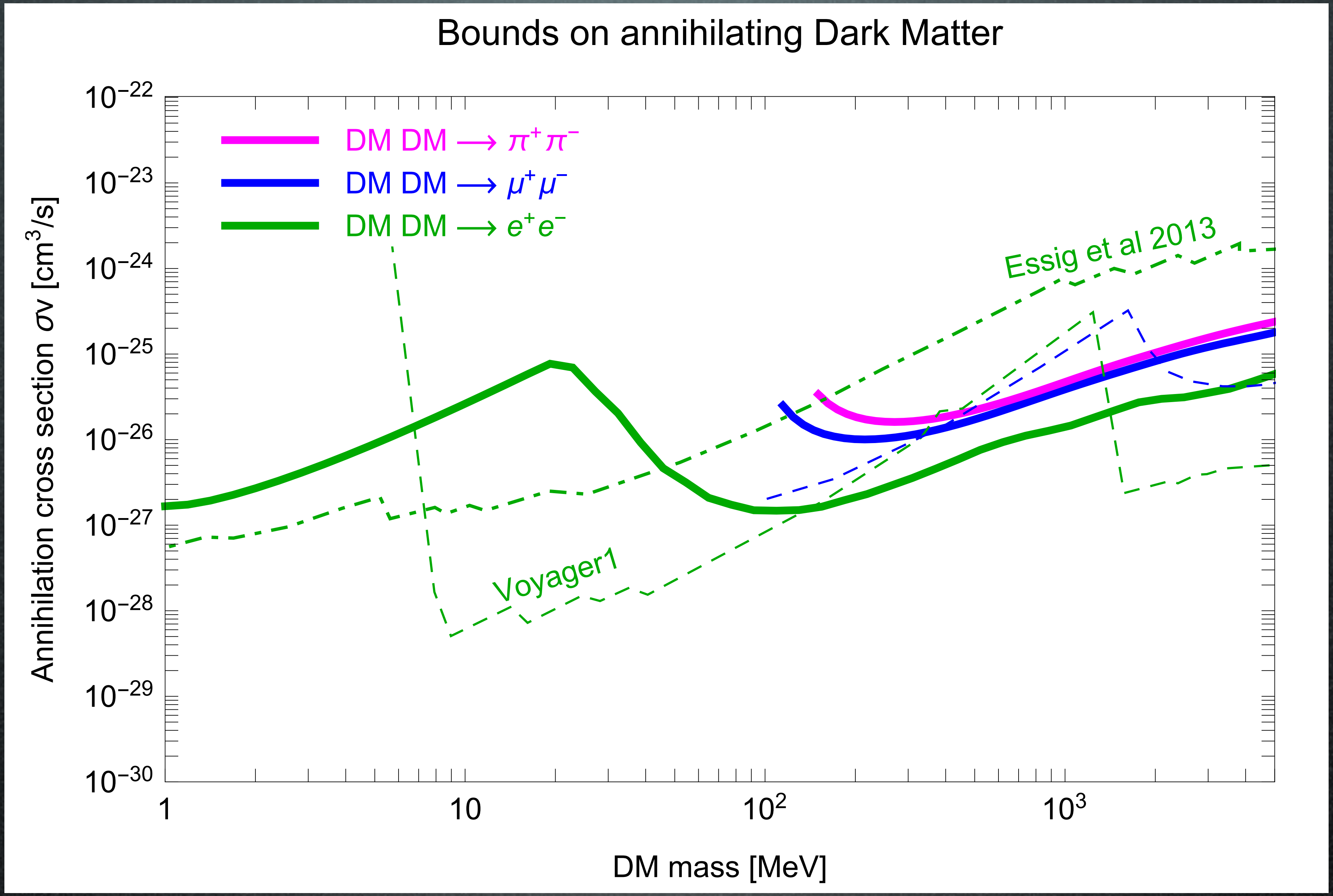


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Voyager1 bounds stronger/weaker dep. on data

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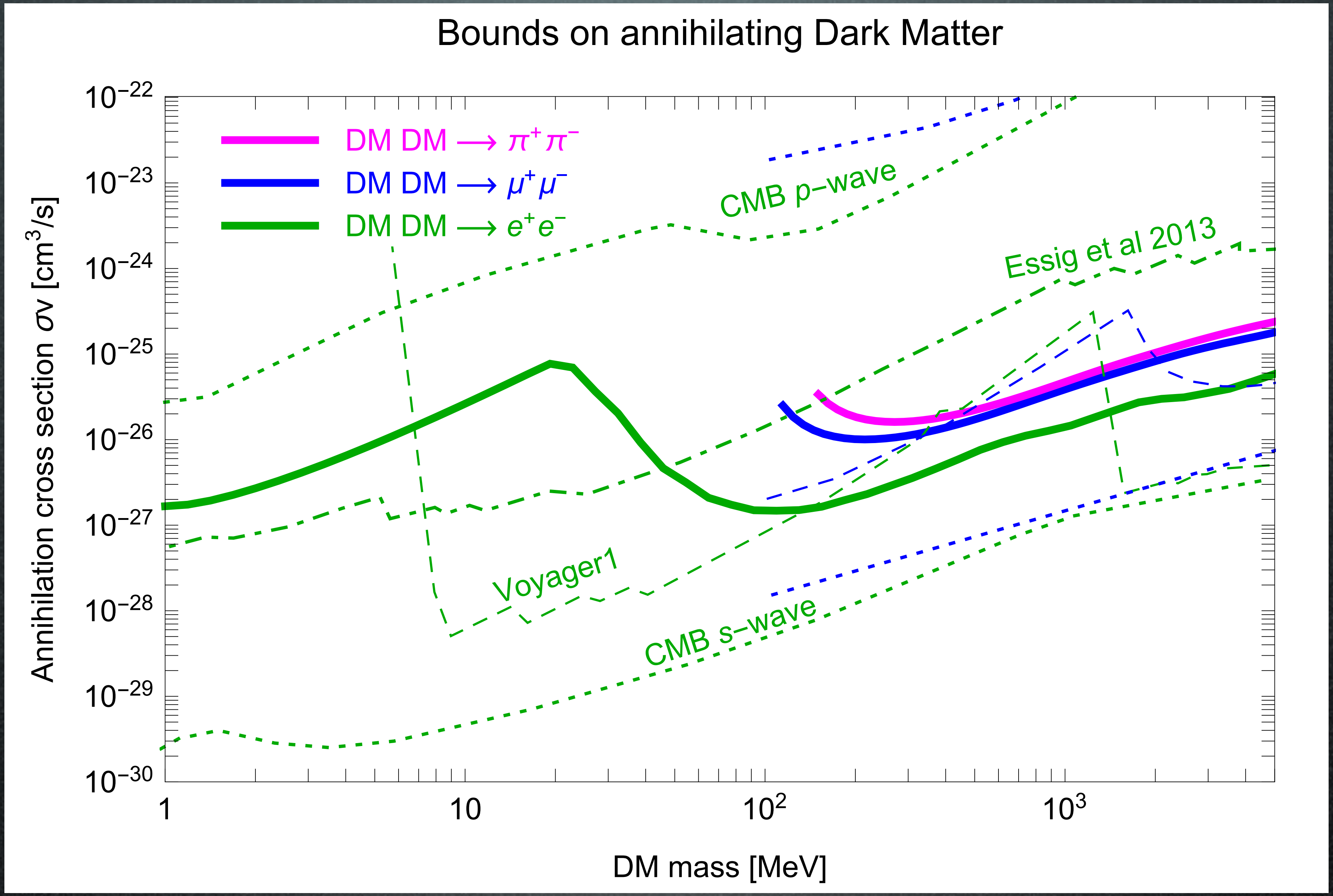


Essig+ 1309.4091

Boudaud+ 1612.07698

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

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CMB bounds depend on s-/p-wave annihilation

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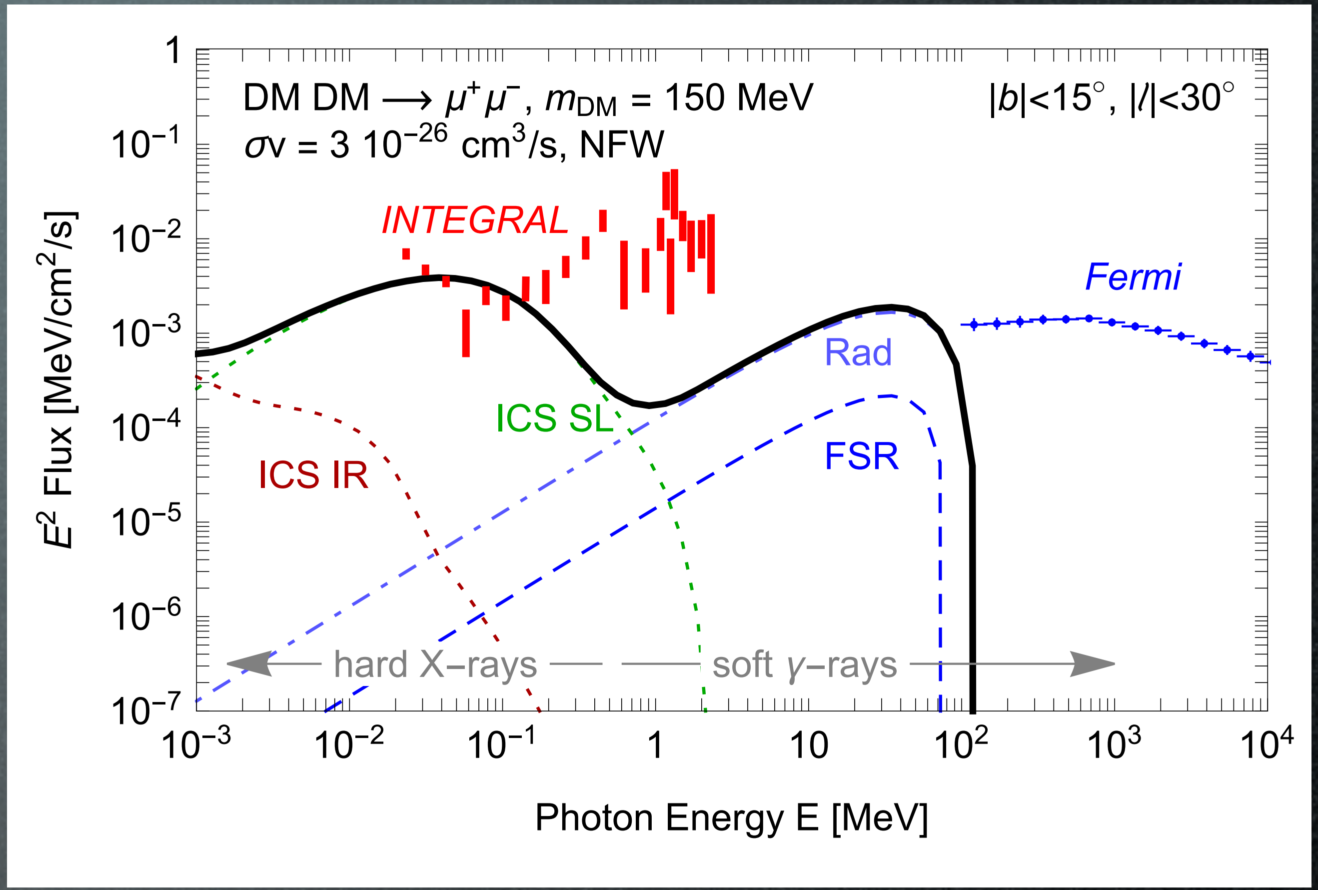

# Conclusions

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