

25 September 2022

NuDM International Conference - Sharm El-Sheikh

Sub-GeV Dark Matter and X-rays

Marco Cirelli

(CNRS LPTHE Jussieu Paris)



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1 MeV \rightarrow 10 GeV

Sub-GeV \leftarrow

Dark Matter and X-rays

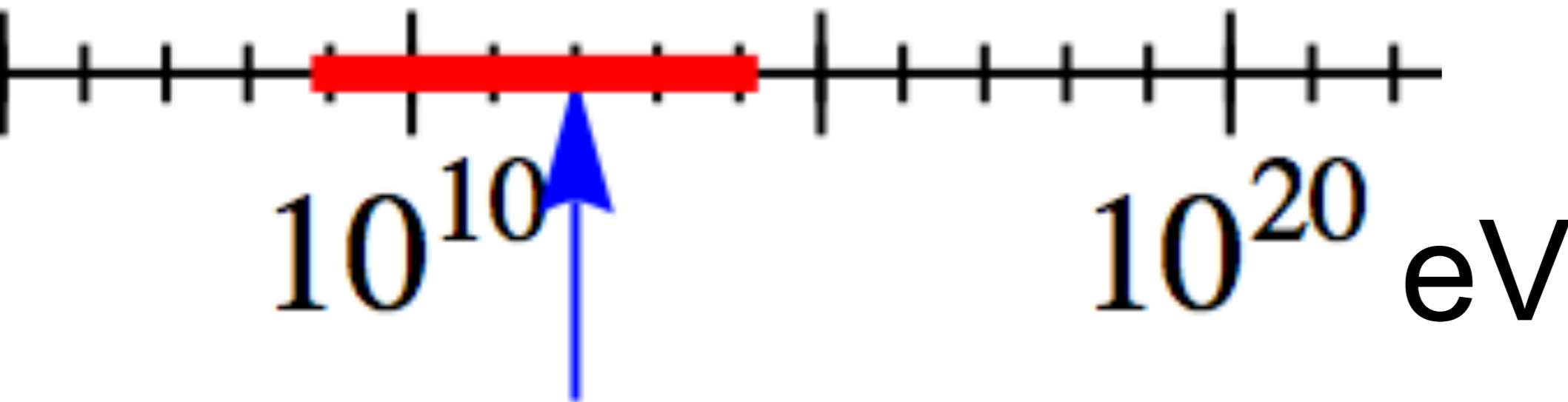
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Candidates

A matter of perspective: plausible mass ranges

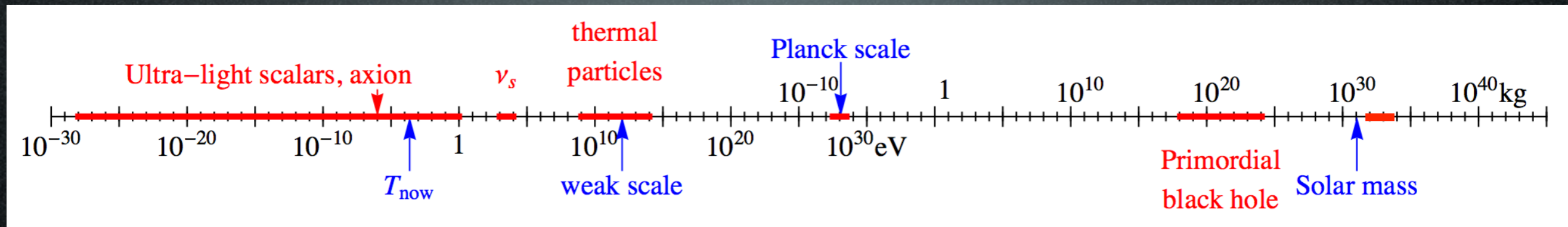
thermal
particles



weak scale (1 TeV)

Candidates

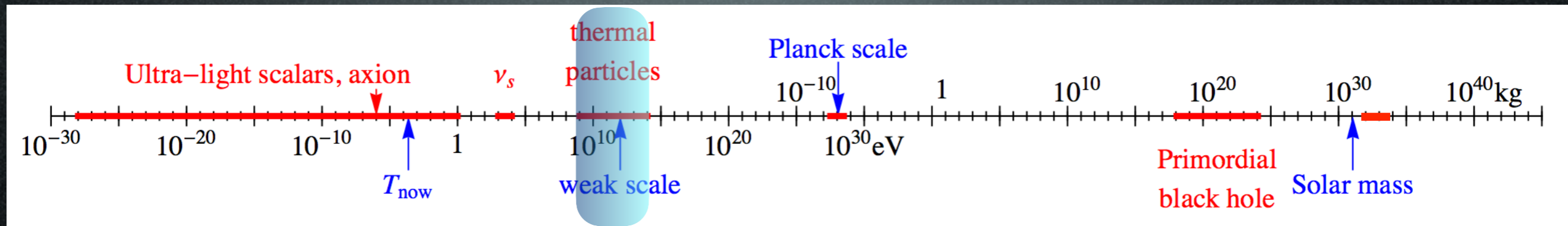
A matter of perspective: plausible mass ranges



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

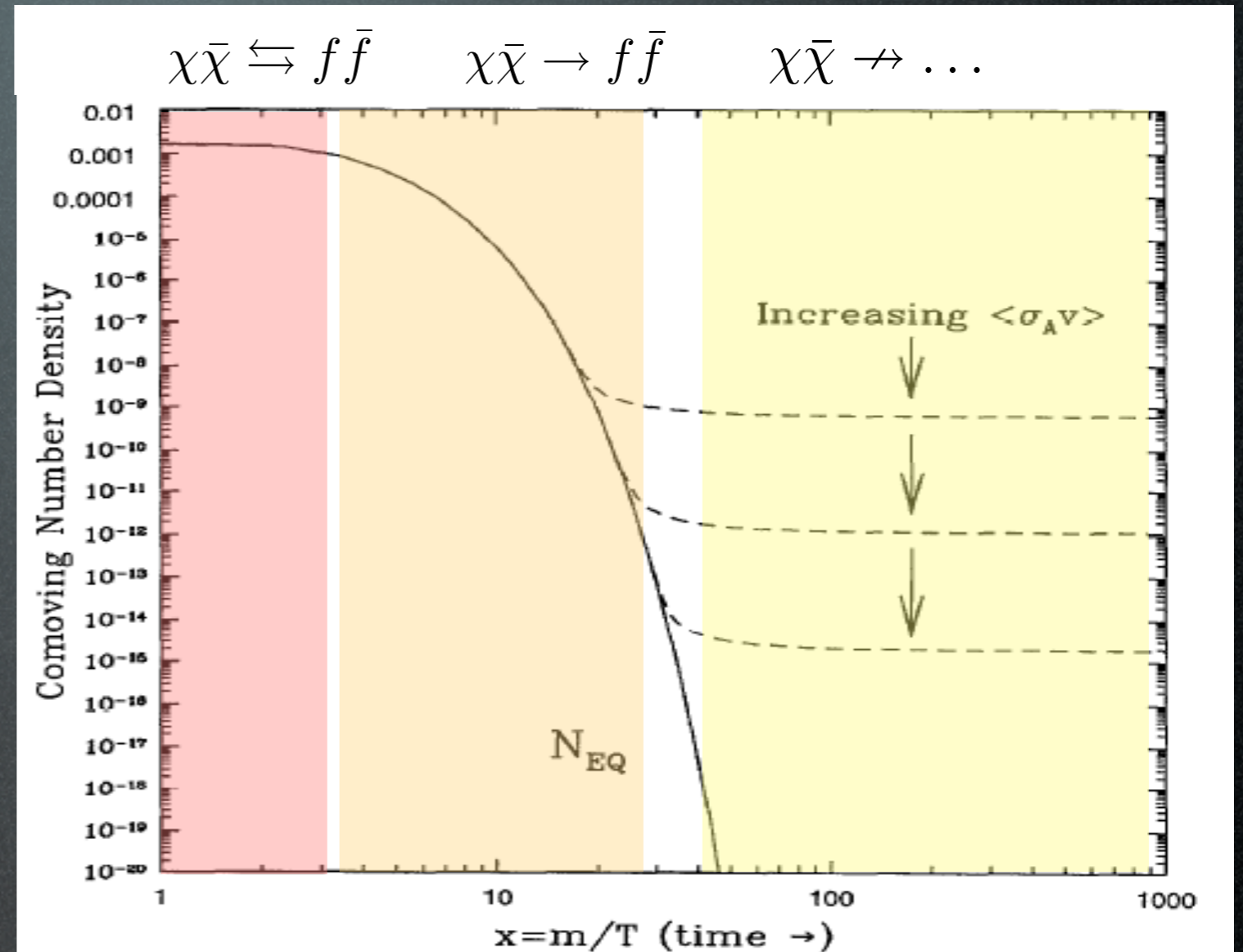
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

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

Relic $\Omega_{\text{DM}} \simeq 0.23$ for

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



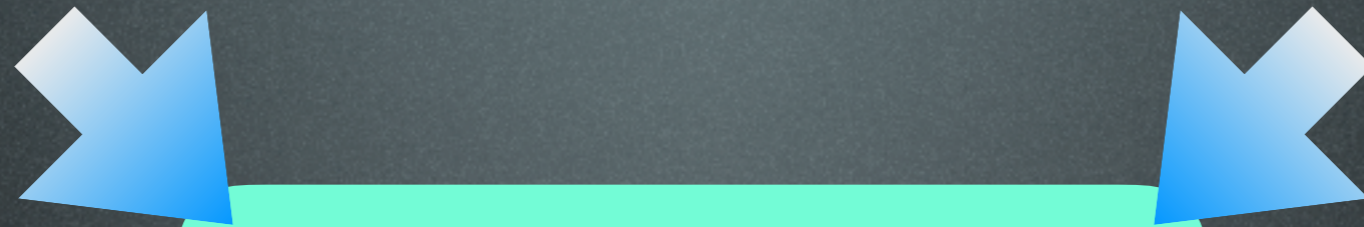
Weak cross section:

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

Candidates

new physics at
the TeV scale

thermal
freeze-out



WIMPs



Collider
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Indirect
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Direct
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WIMPs



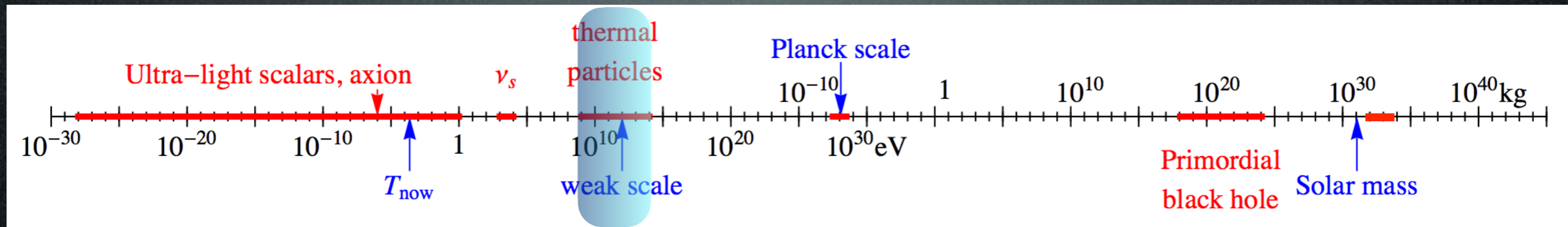
LHC

Fermi, AMS,
IceCube...

Xenon,
Lux, PandaX...

Candidates

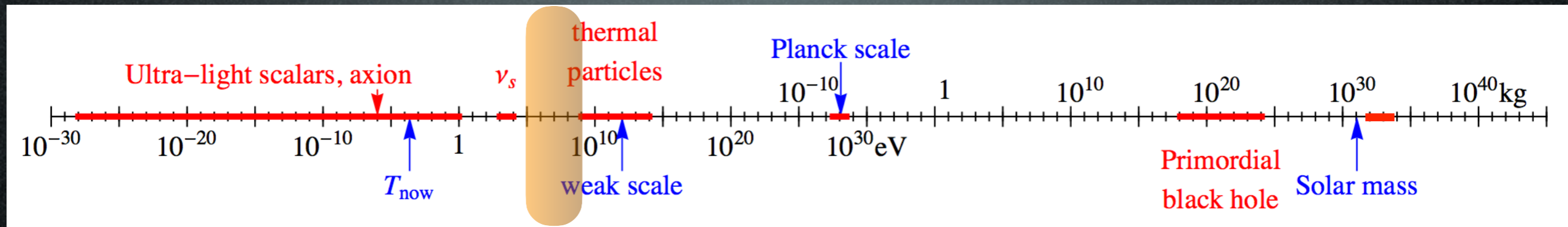
A matter of perspective: plausible mass ranges



90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

Candidates

theory?

production?

Sub-GeV DM?

Collider
Searches?

Indirect
Detection?

Direct
Detection?



Theory

Sub-GeV DM

- WIMPless Dark Matter

Feng & Kumar 0803.4196

a.k.a. hidden sector DM

~ secluded DM

Theory

Sub-GeV DM

- **WIMPless** Dark Matter

Feng & Kumar 0803.4196

a.k.a. **hidden sector** DM

~ **secluded** DM

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

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

Theory

Sub-GeV DM

- **WIMPLess** Dark Matter

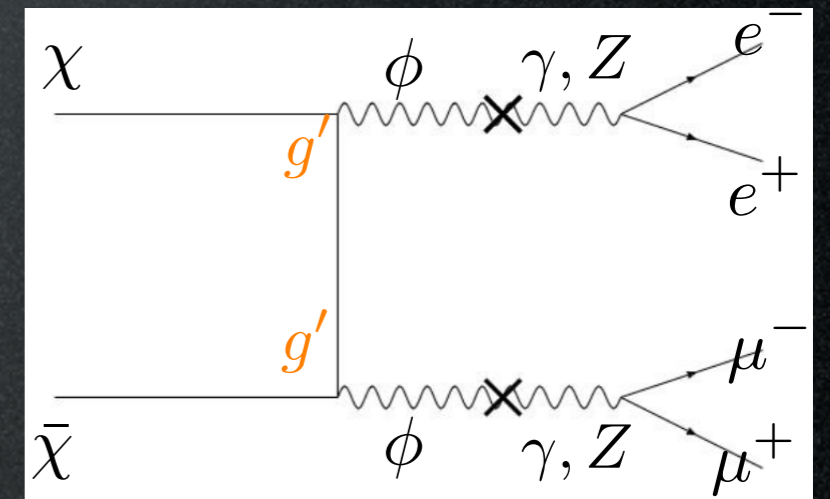
Feng & Kumar 0803.4196

a.k.a. **hidden sector** DM
~ **secluded** DM

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

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

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 $3 \rightarrow 2$ processes

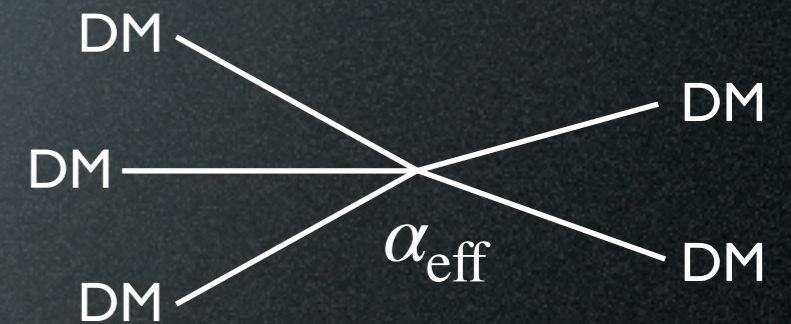
points to

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

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’

Knapen, Lin, Zurek 1709.07882

scalar DM and
hadrophilic
scalar mediator

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



Theory

Sub-GeV DM

‘simplified (light) DM models’

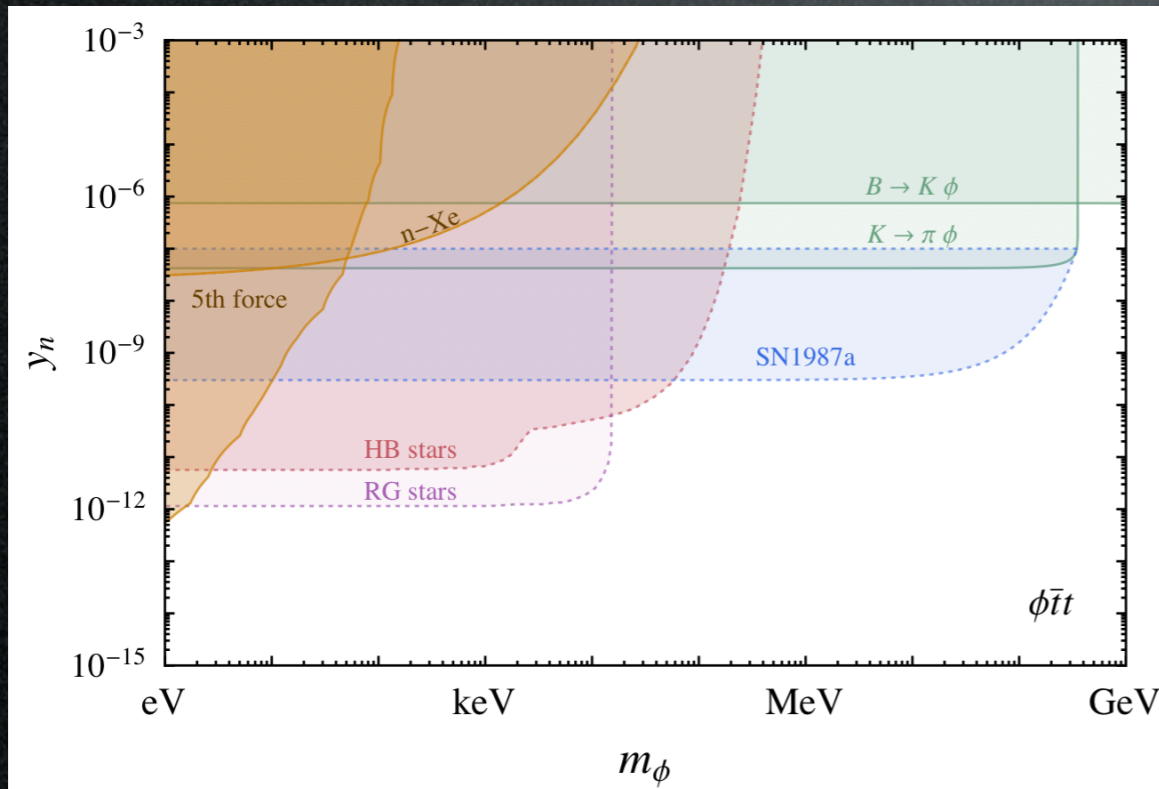
Knapen, Lin, Zurek 1709.07882

scalar DM and
hadrophilic
scalar mediator

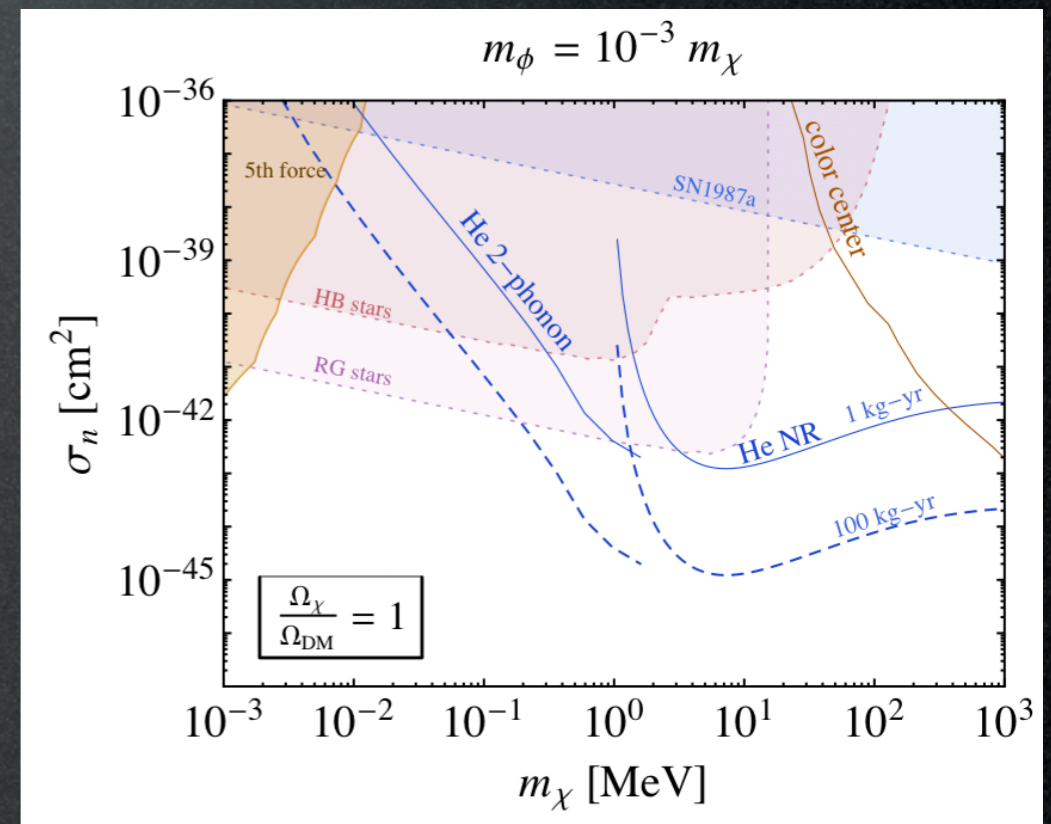
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constraints on the mediator



constraints on the DM



Theory

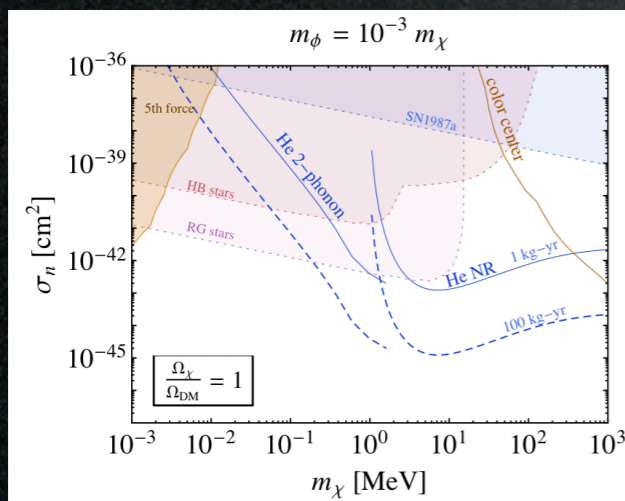
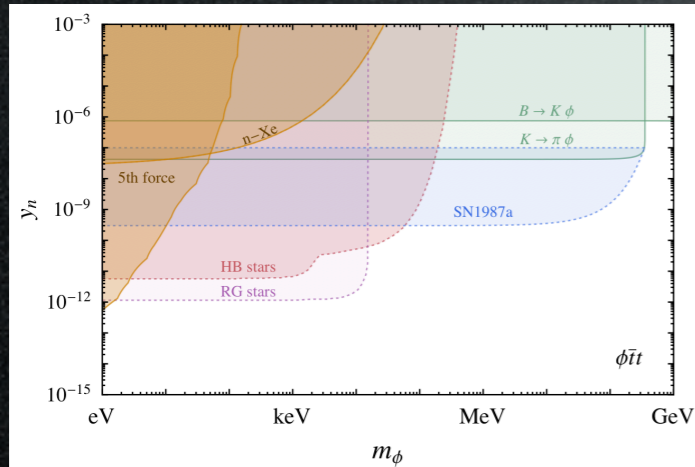
Sub-GeV DM

‘simplified (light) DM models’

Knapen, Lin, Zurek 1709.07882

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Theory

Sub-GeV DM

‘simplified (light) DM models’

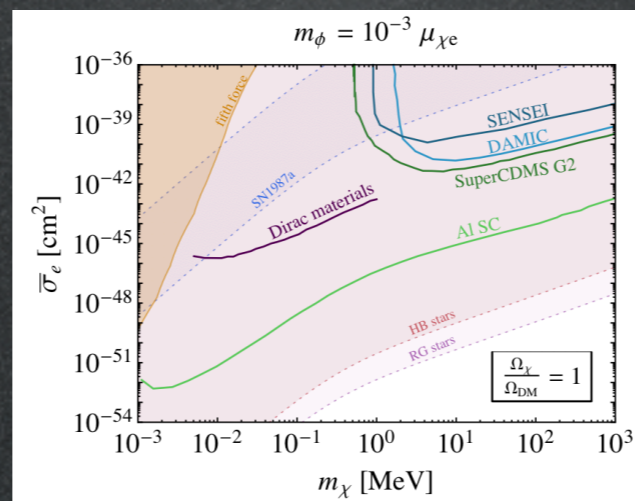
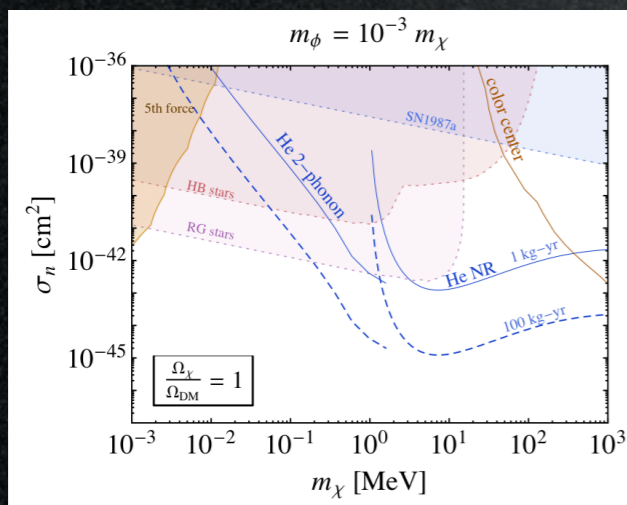
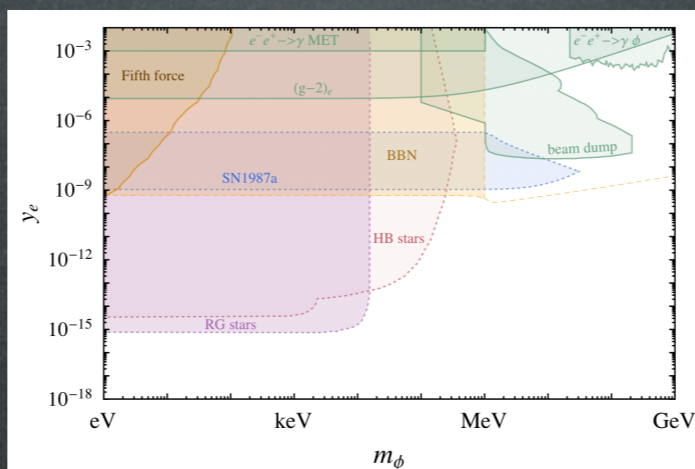
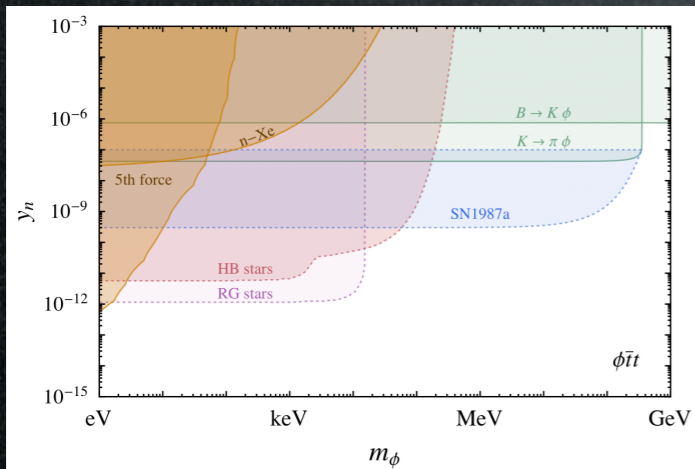
scalar DM and
hadrophilic
scalar mediator

scalar DM and
leptophilic
scalar mediator

Knapen, Lin, Zurek 1709.07882

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

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Theory

Sub-GeV DM

‘simplified (light) DM models’

scalar DM and
hadrophilic
scalar mediator

scalar DM and
leptophilic
scalar mediator

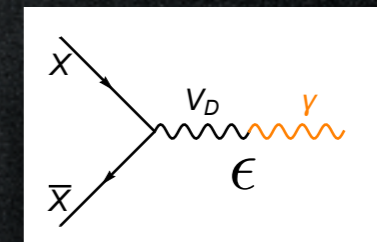
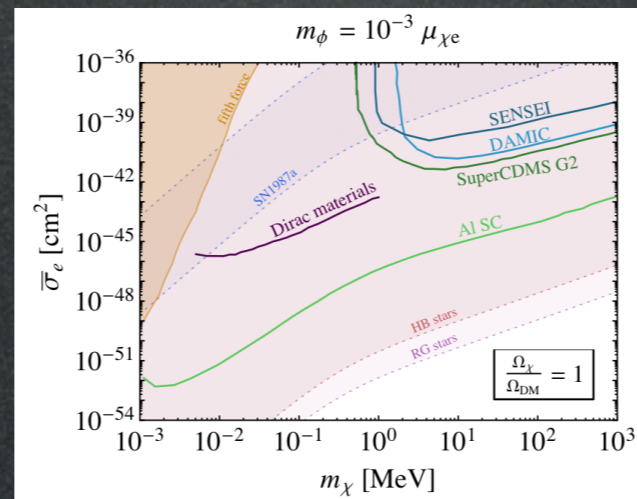
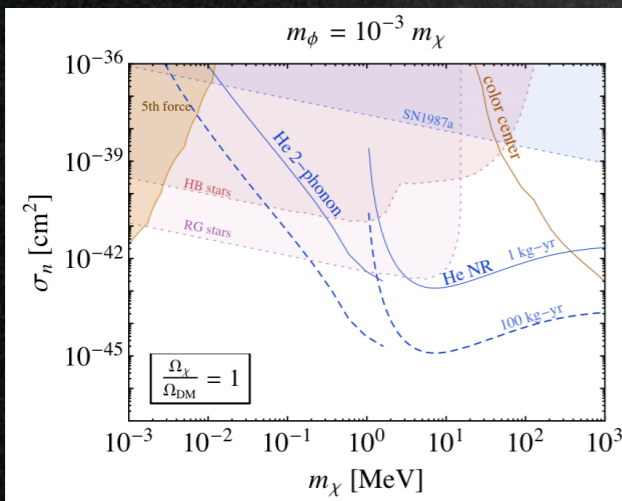
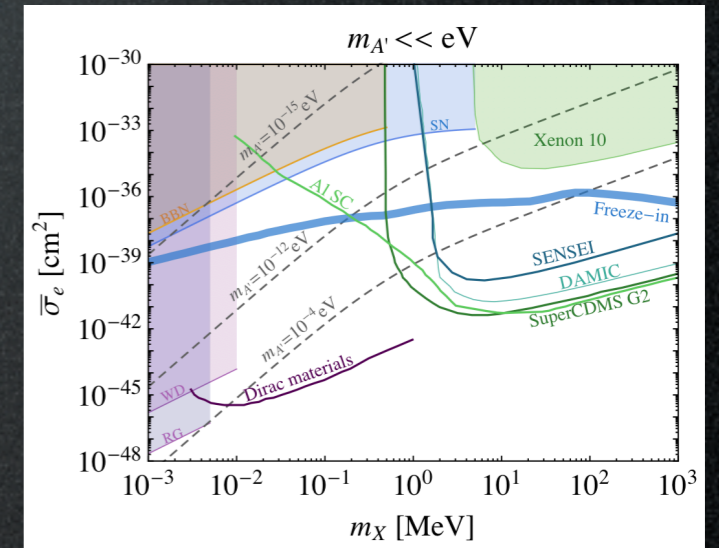
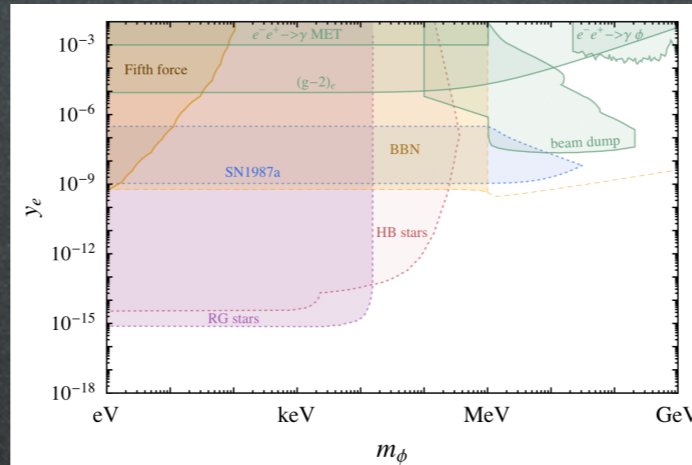
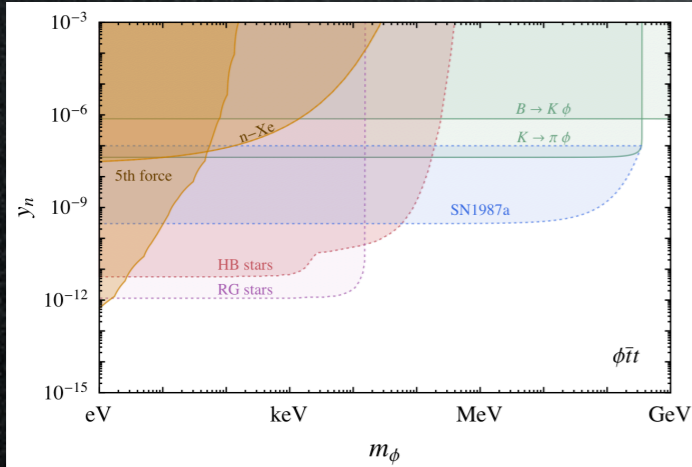
fermionic DM and
vector mediator
(e.g. dark photon)

Knapen, Lin, Zurek 1709.07882

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

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

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



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?

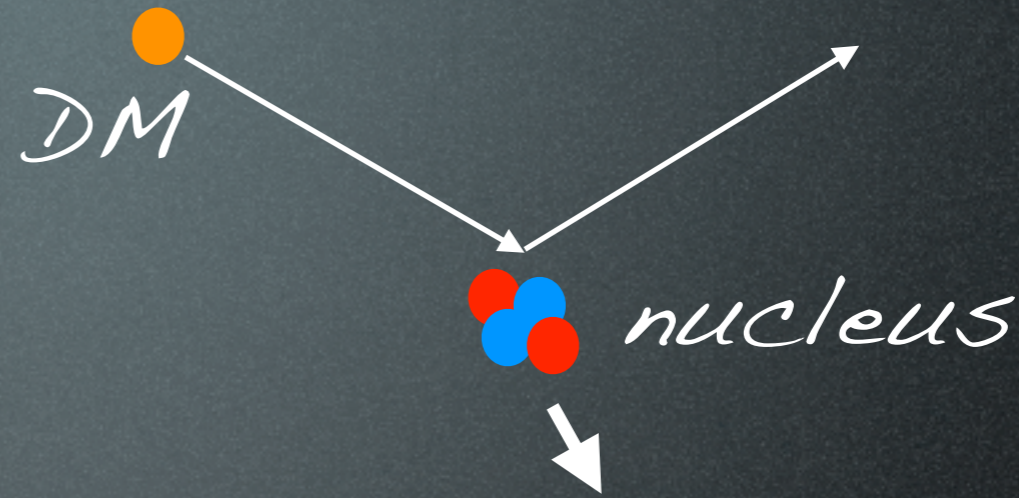
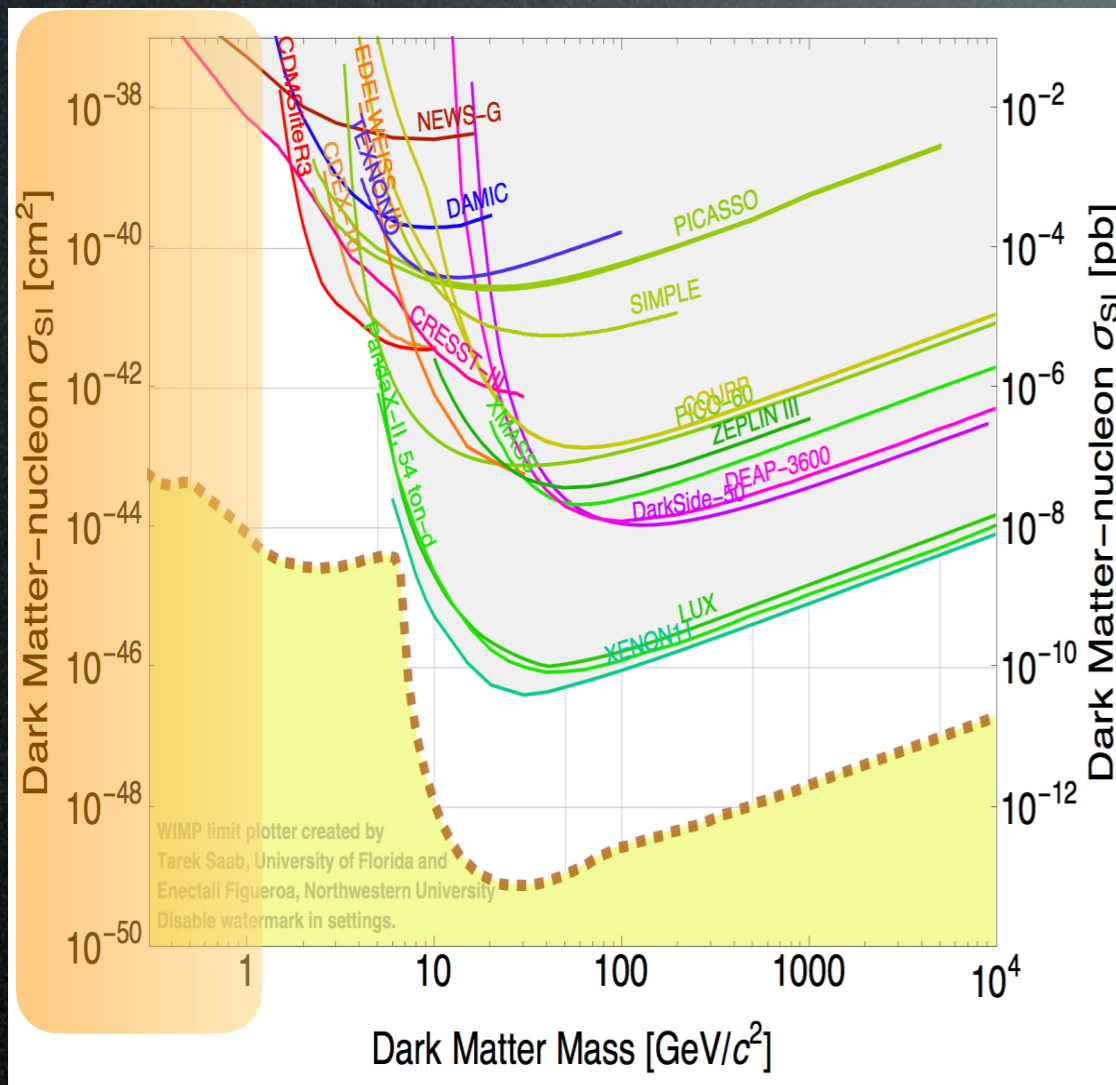
Collider
Searches?

Indirect
Detection?

Direct
Detection?



Direct Detection of sub-GeV DM



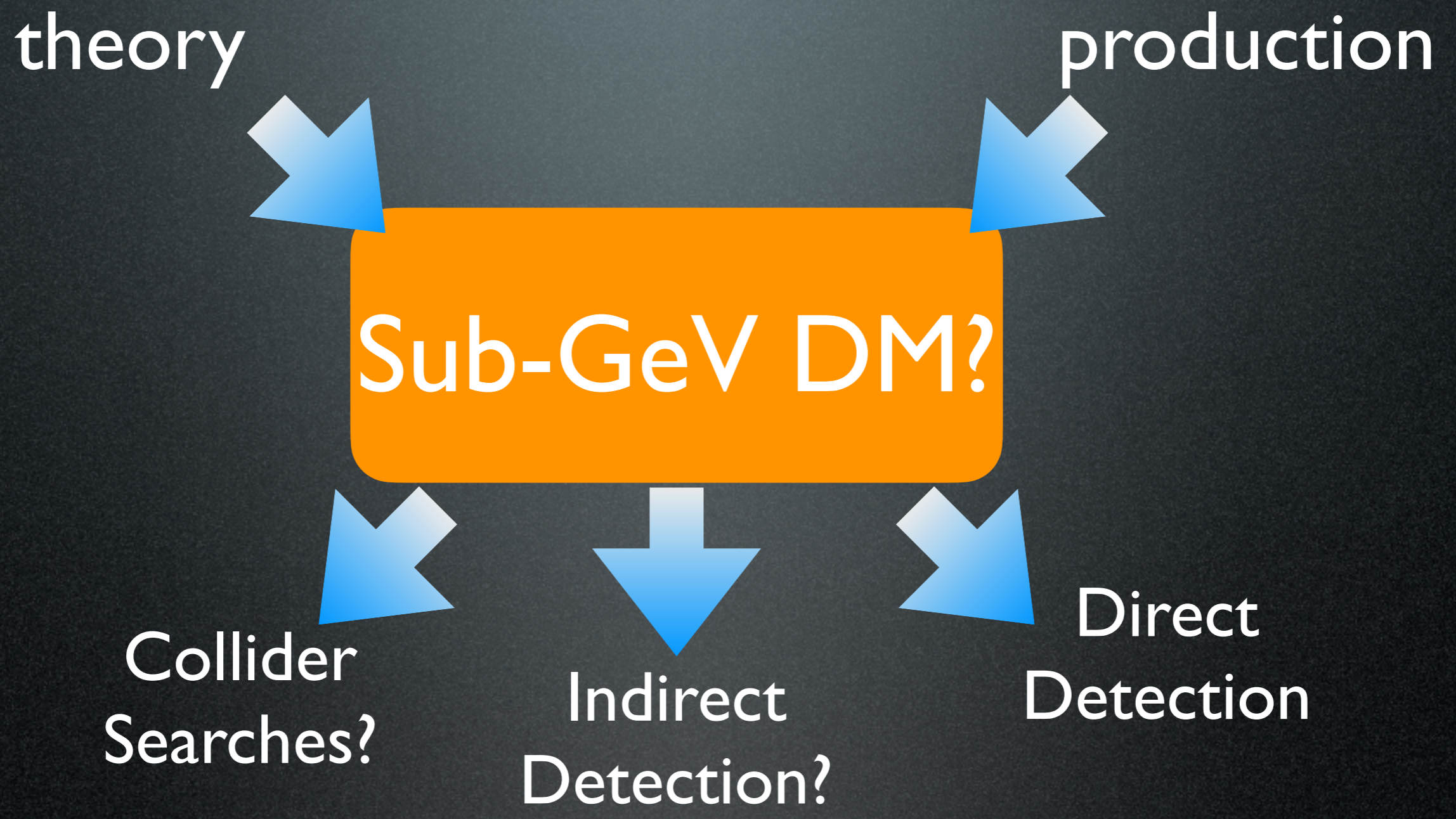
deposited energy is **below threshold** for typical nuclear recoil experiments

- 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
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- 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
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- 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
- Budnik et al. 'DD of Light Dark Matter and Solar Neutrinos via Color Center Production in Crystals' Phys. Lett. B 782 (2018) 242-250, 1705.03016
- 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



Candidates

theory

production

Sub-GeV DM?

Collider
Searches?

Indirect
Detection?

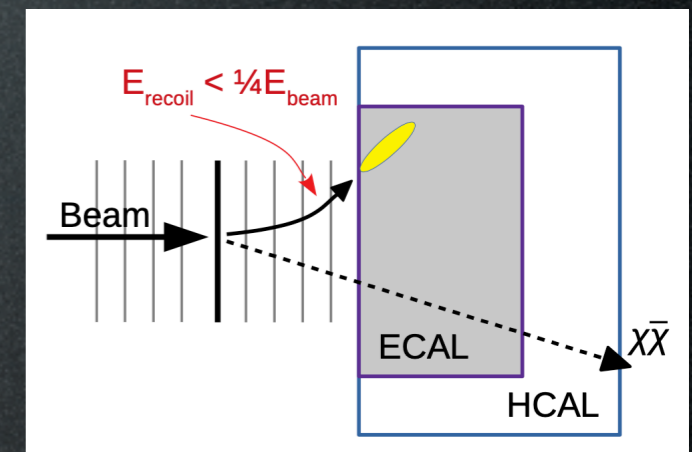
Direct
Detection



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

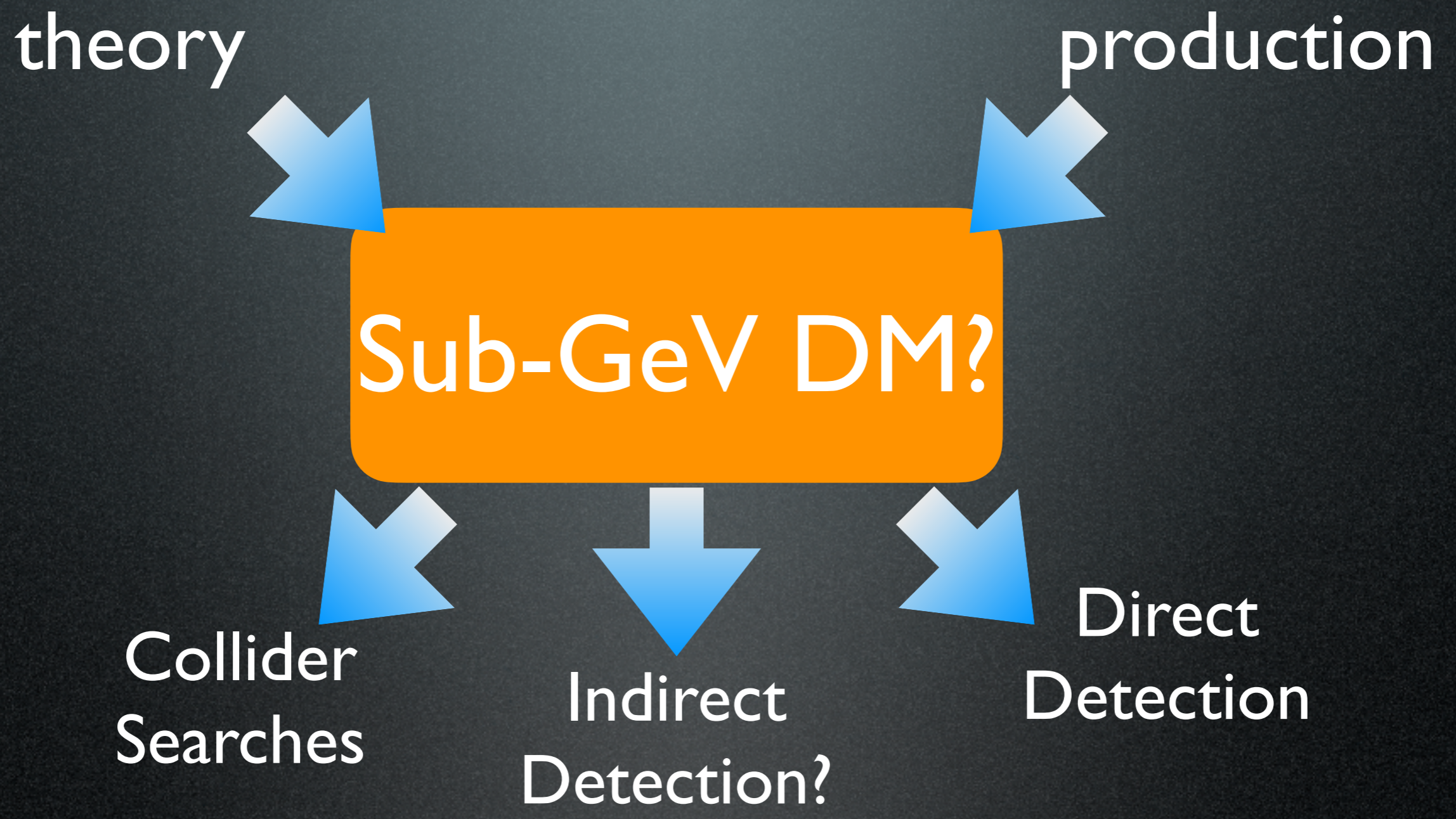
B. Batell, M. Pospelov and A. Ritz, Exploring Portals to a Hidden Sector Through Fixed Targets, Phys. Rev. D 80 (2009) 095024, [0906.5614].

LDMX collaboration, T. Kesson et al., Light Dark Matter eXperiment (LDMX), 1808.05219.

L. Doria, P. Achenbach, M. Christmann, A. Denig, P. Glöckler 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



Candidates

theory

production



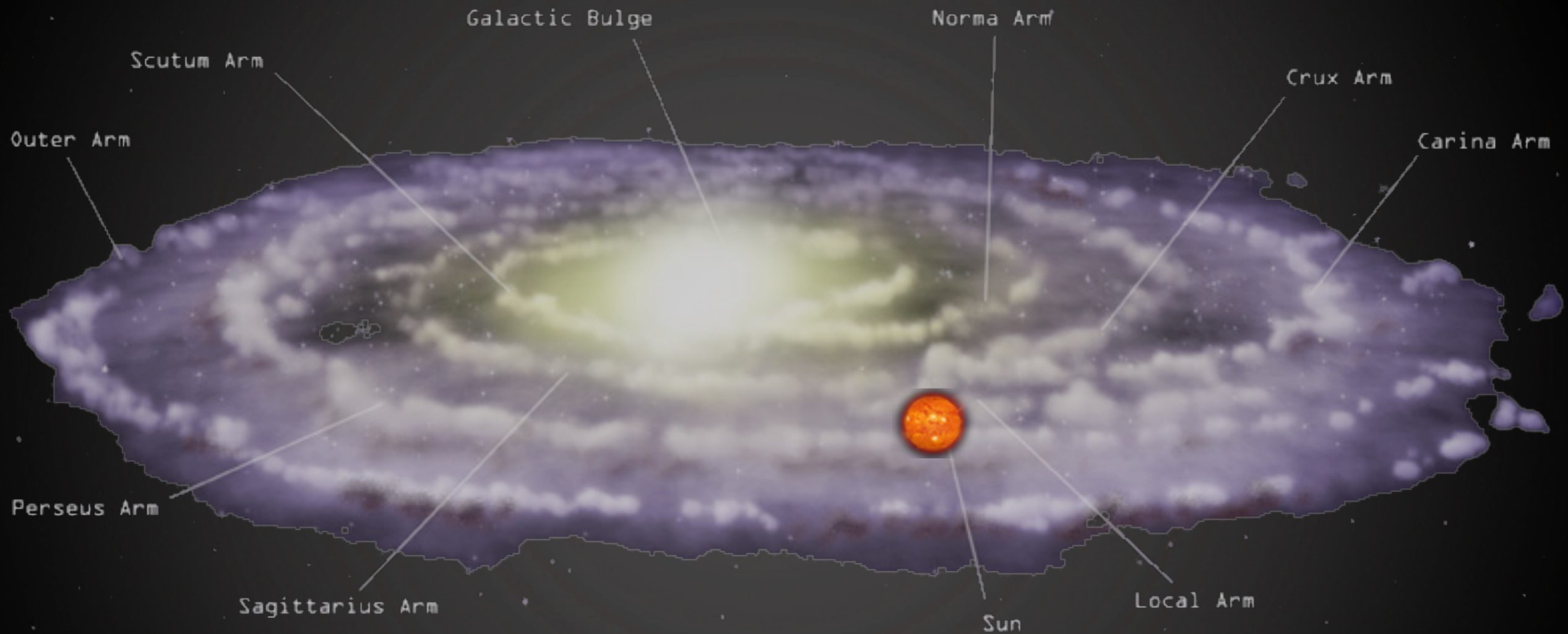
Collider Searches

Indirect Detection?

Direct Detection

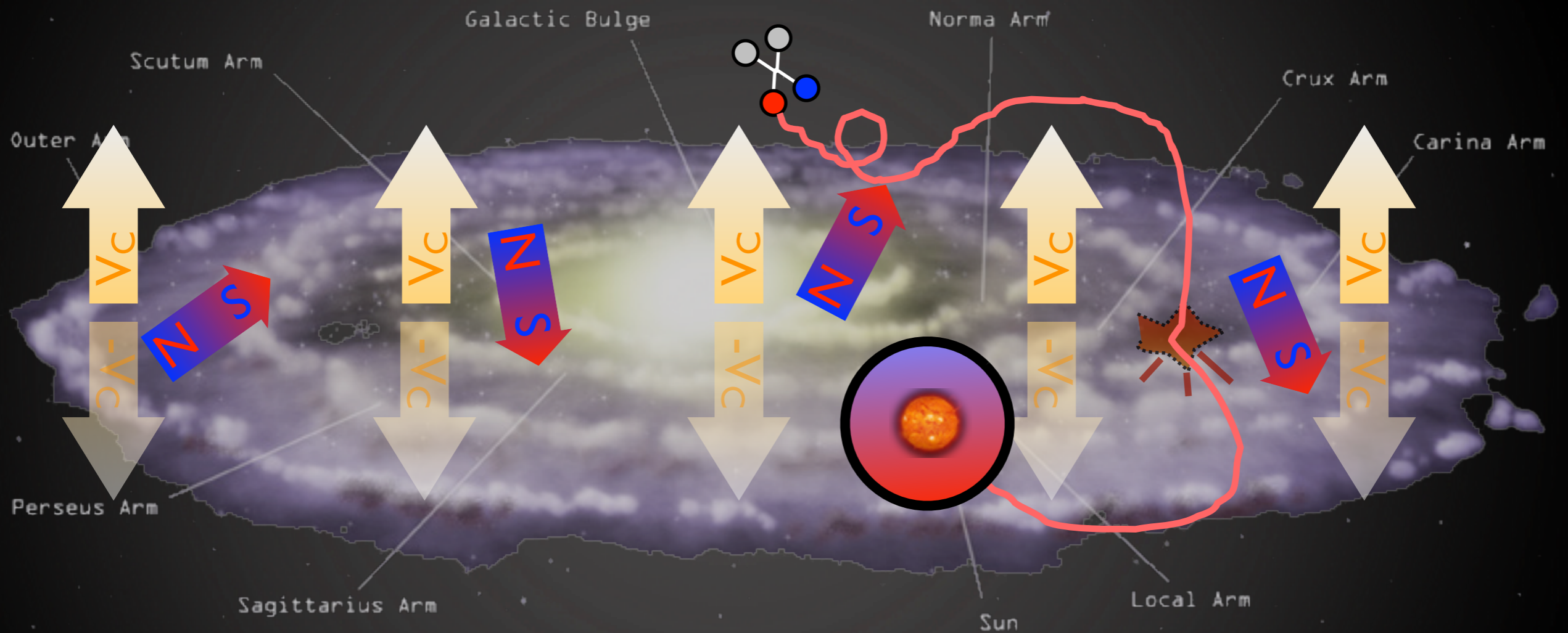
Indirect Detection: charged CRs

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



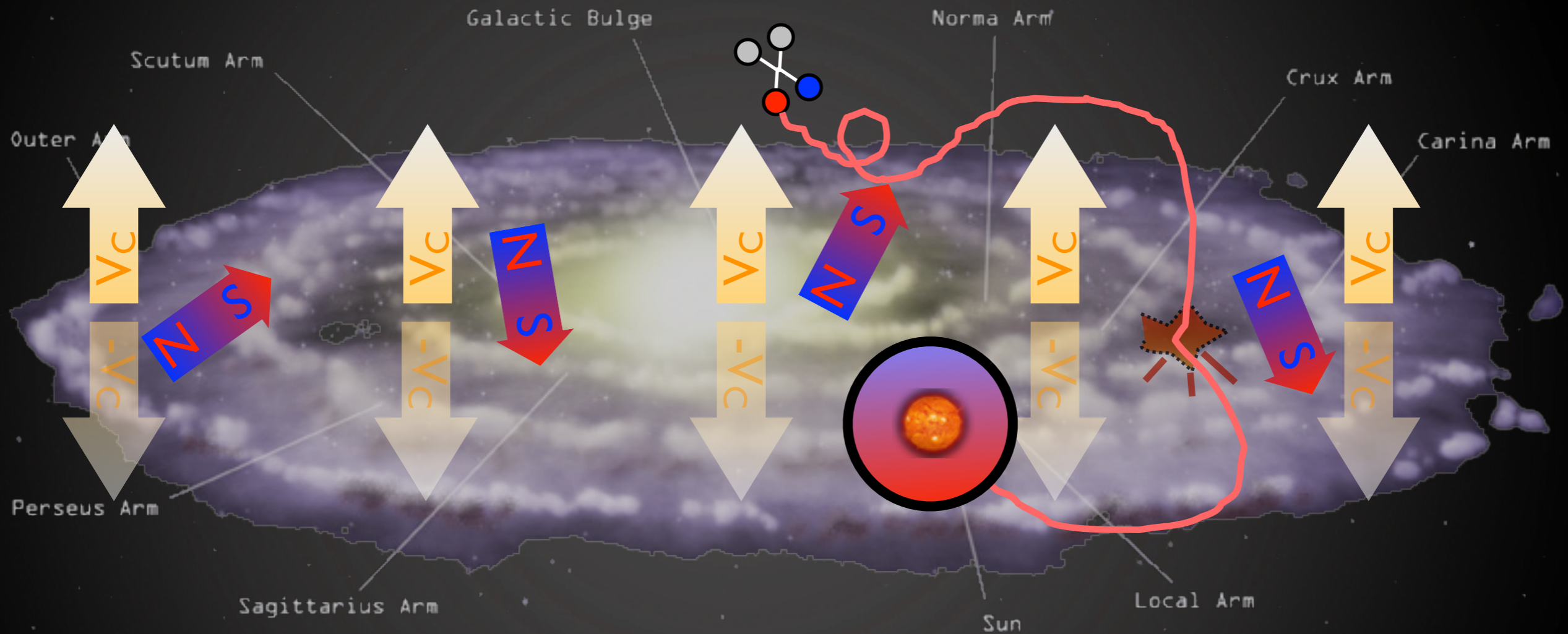
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Indirect Detection: charged CRs

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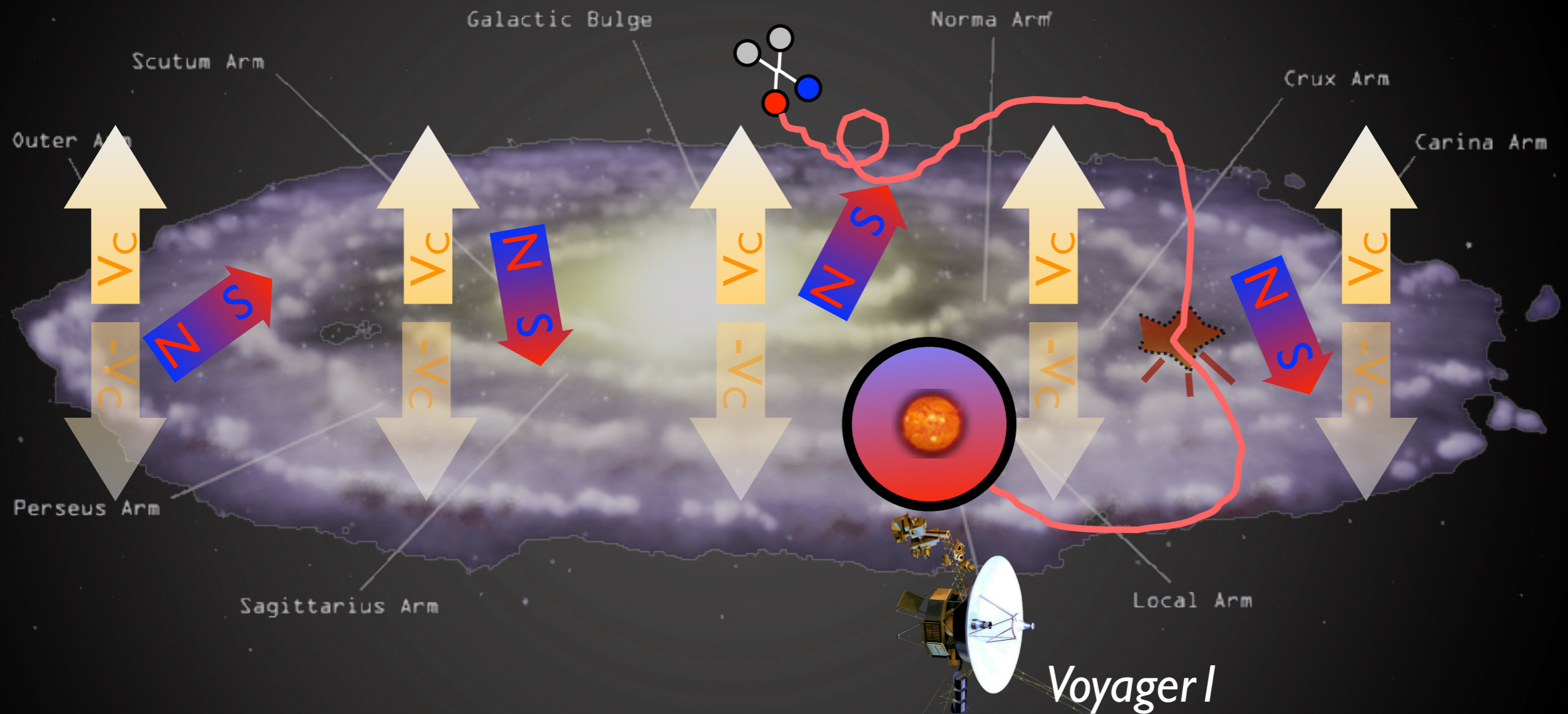


Problem:

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

Indirect Detection: charged CRs

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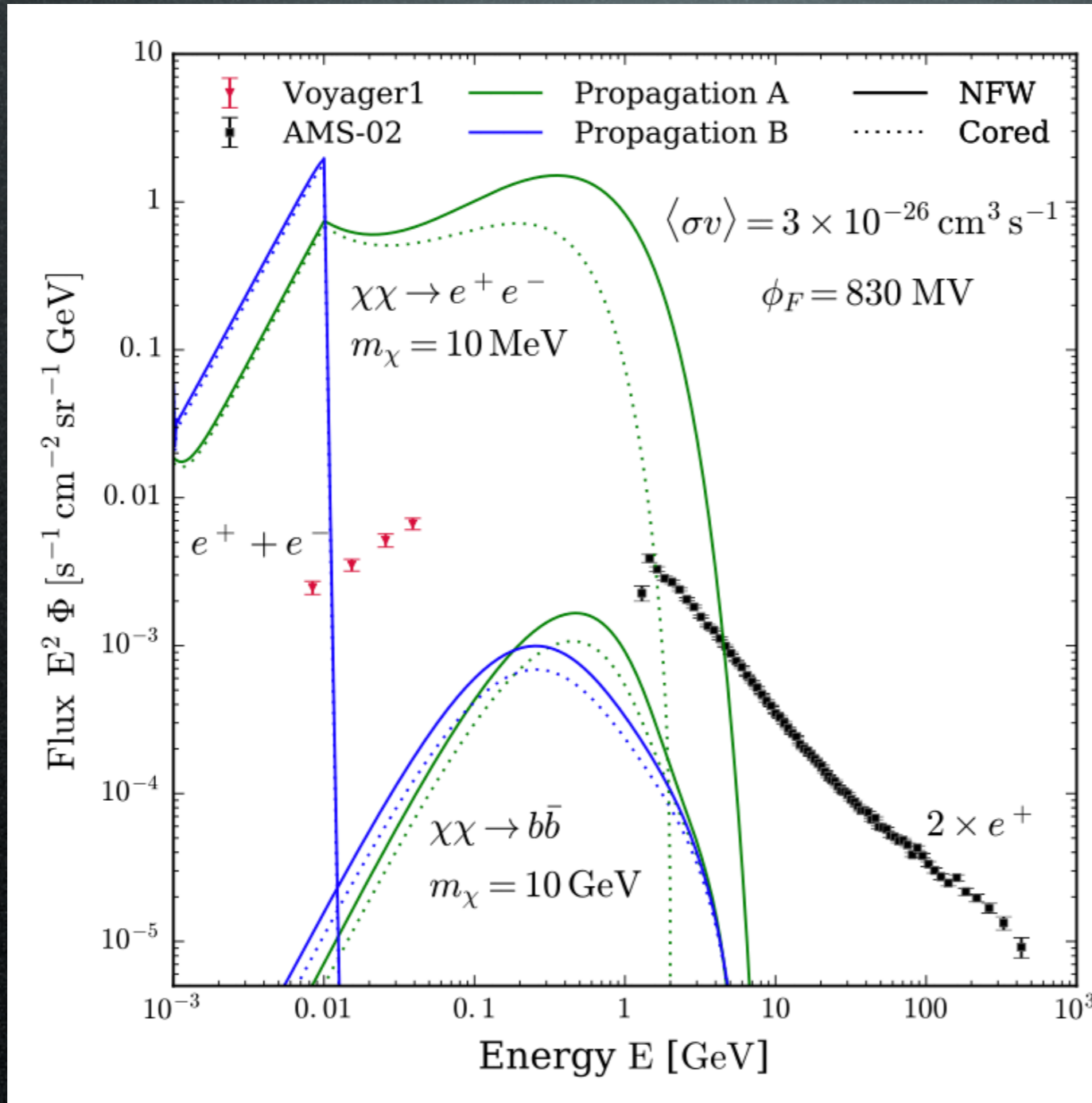
Problem:

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

Indirect Detection: charged CRs

Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by **Voyager I**

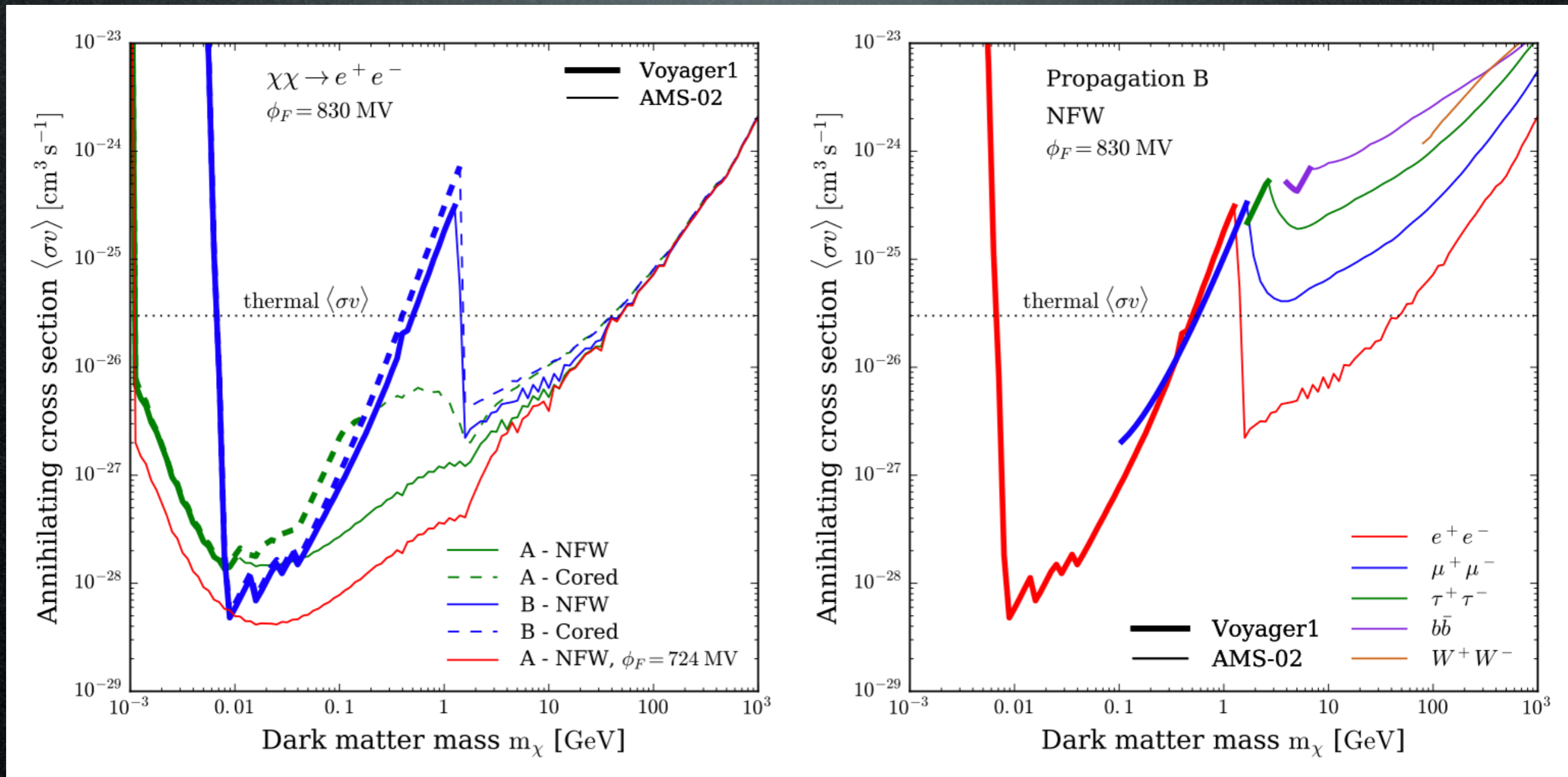


Propagation A = strong reacceleration
Propagation B = weak/no reacceleration

Indirect Detection: charged CRs

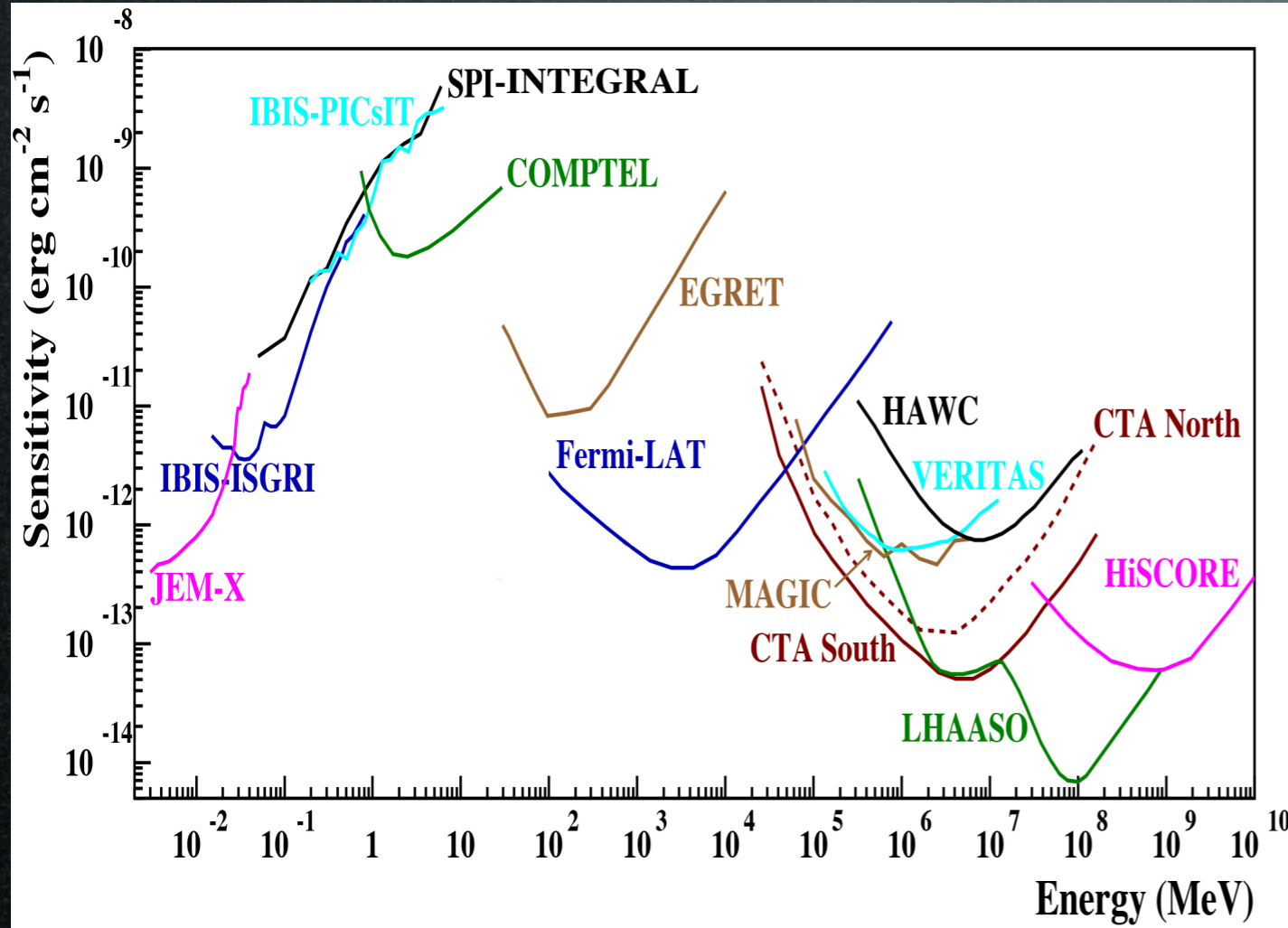
Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by **Voyager I**



Indirect detection: photons

adapted from 1611.02232



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

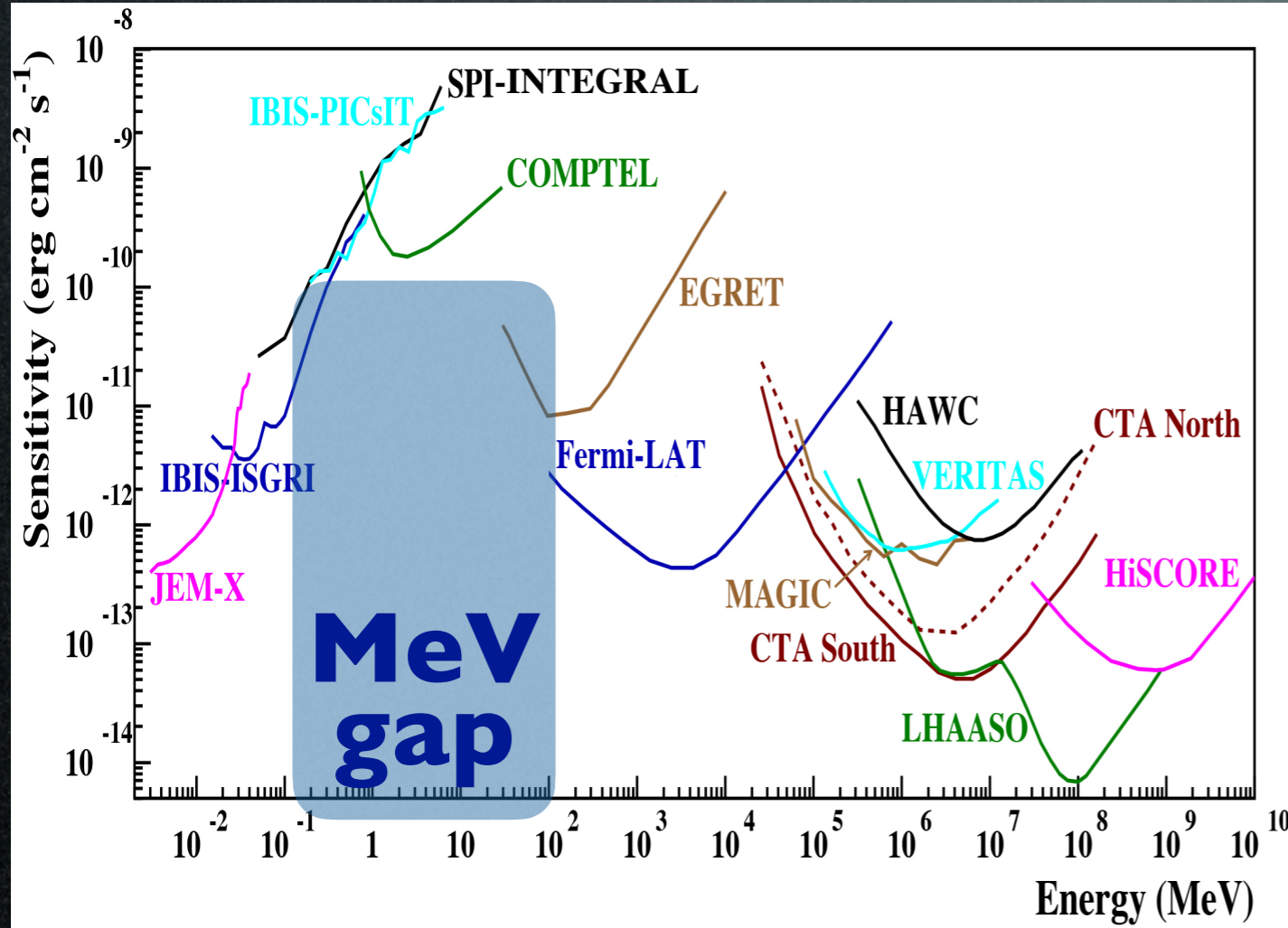
Planned/proposed experiments:
e-Astrogam?, Compair?, Amego?

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 to appear

Indirect detection: photons

adapted from 1611.02232



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

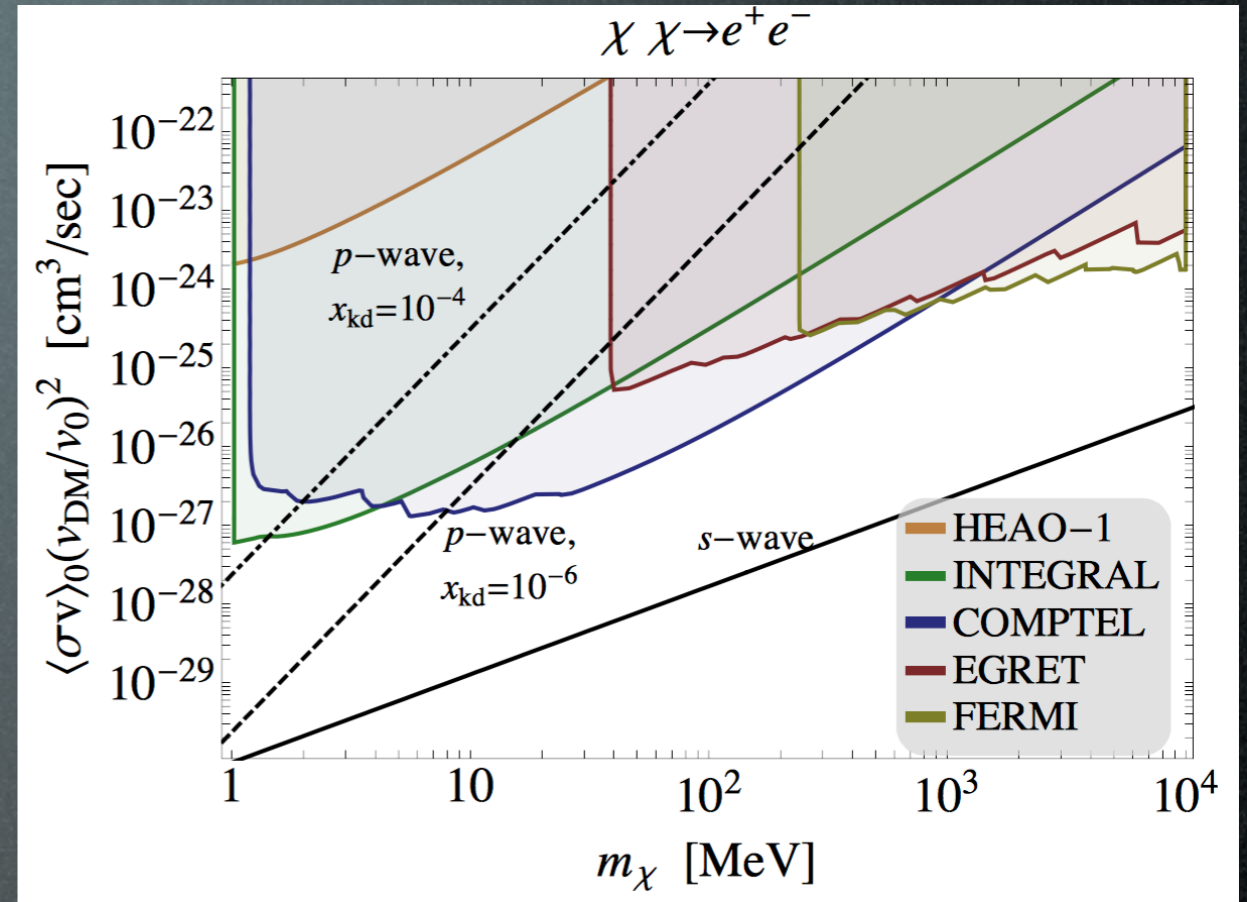
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INO-ICAL	India	2020s?	calorimeter	neutrinos	1 – 100 GeV
E-ASTROGAM	satellite	2030s?	HEP detectors	γ -rays	0.3 MeV – 3 GeV

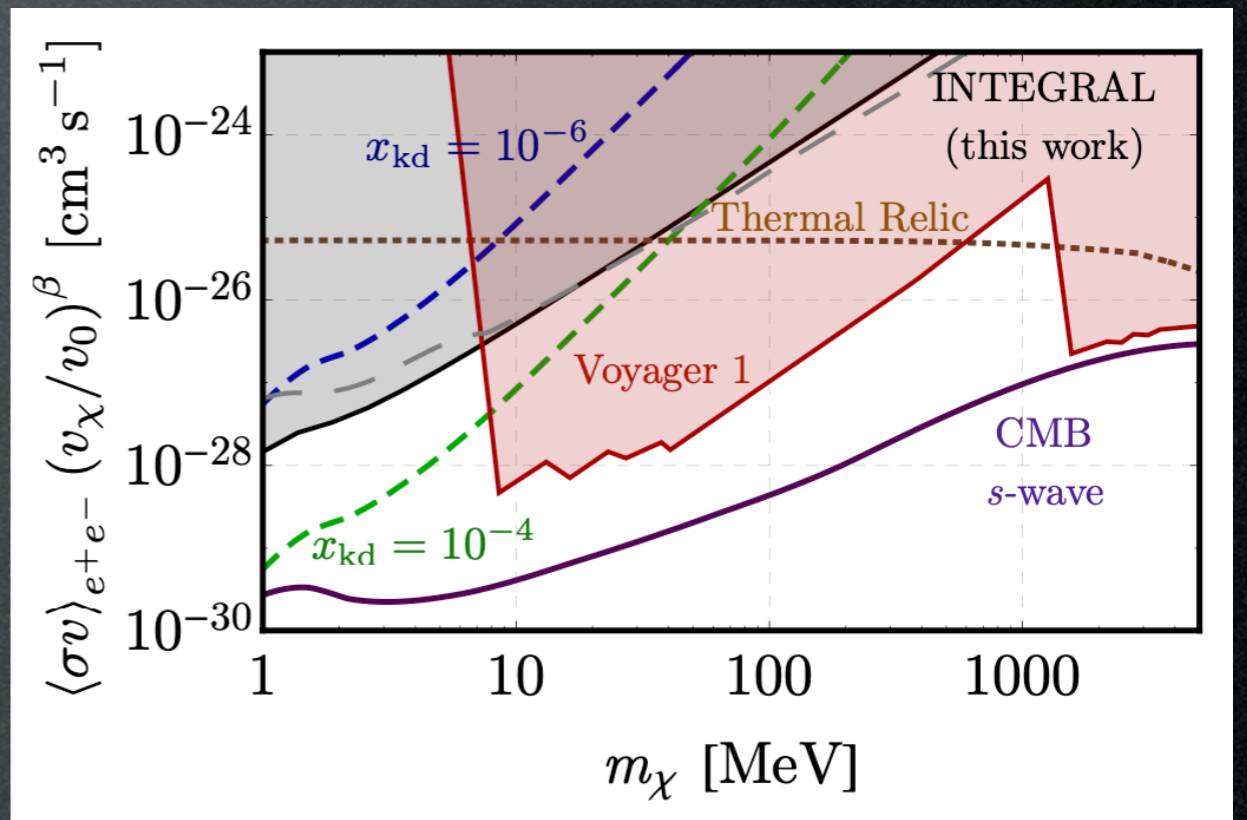
Cirelli, Strumia, Zupan to appear

Some recent studies

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



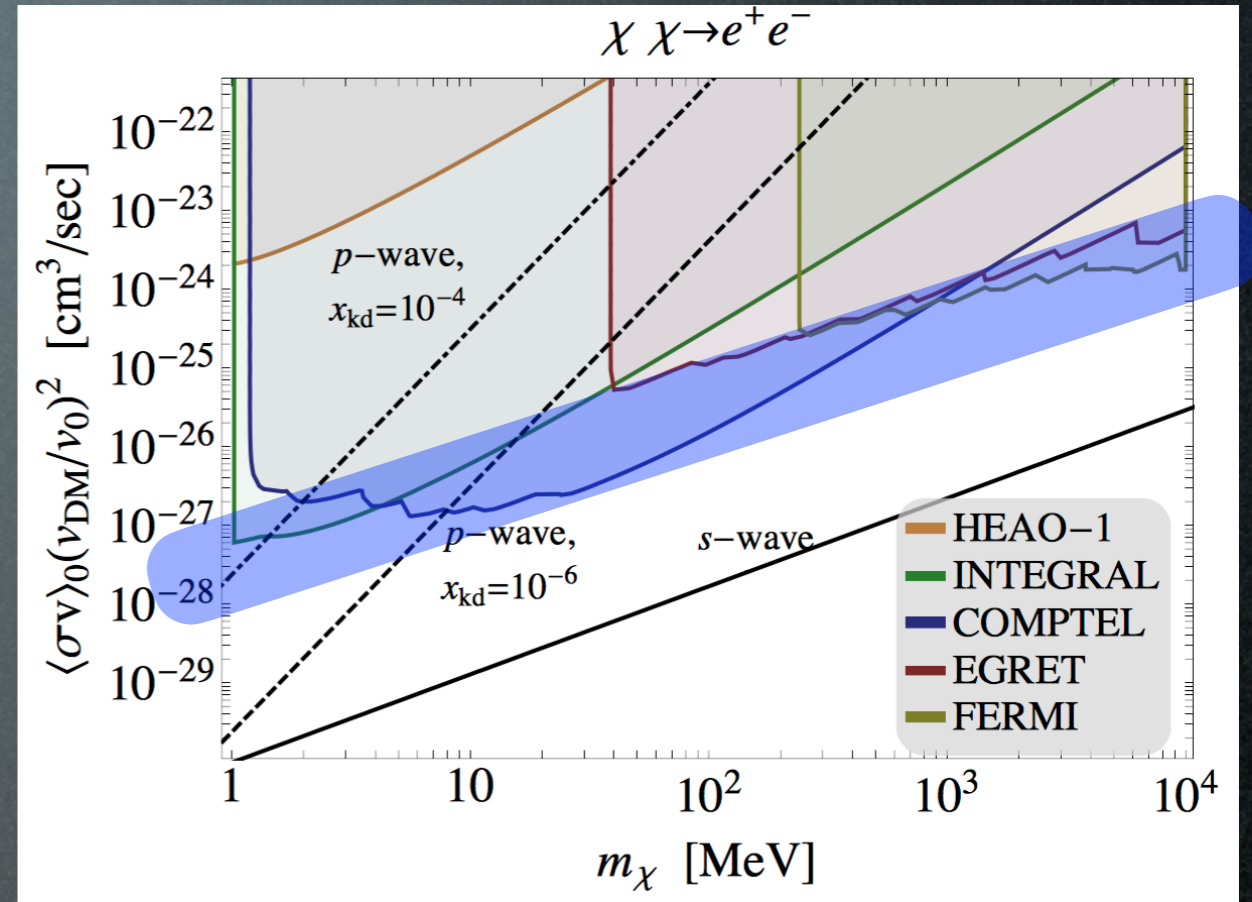
Laha, Muñoz, Slatyer, 2004.00627v1



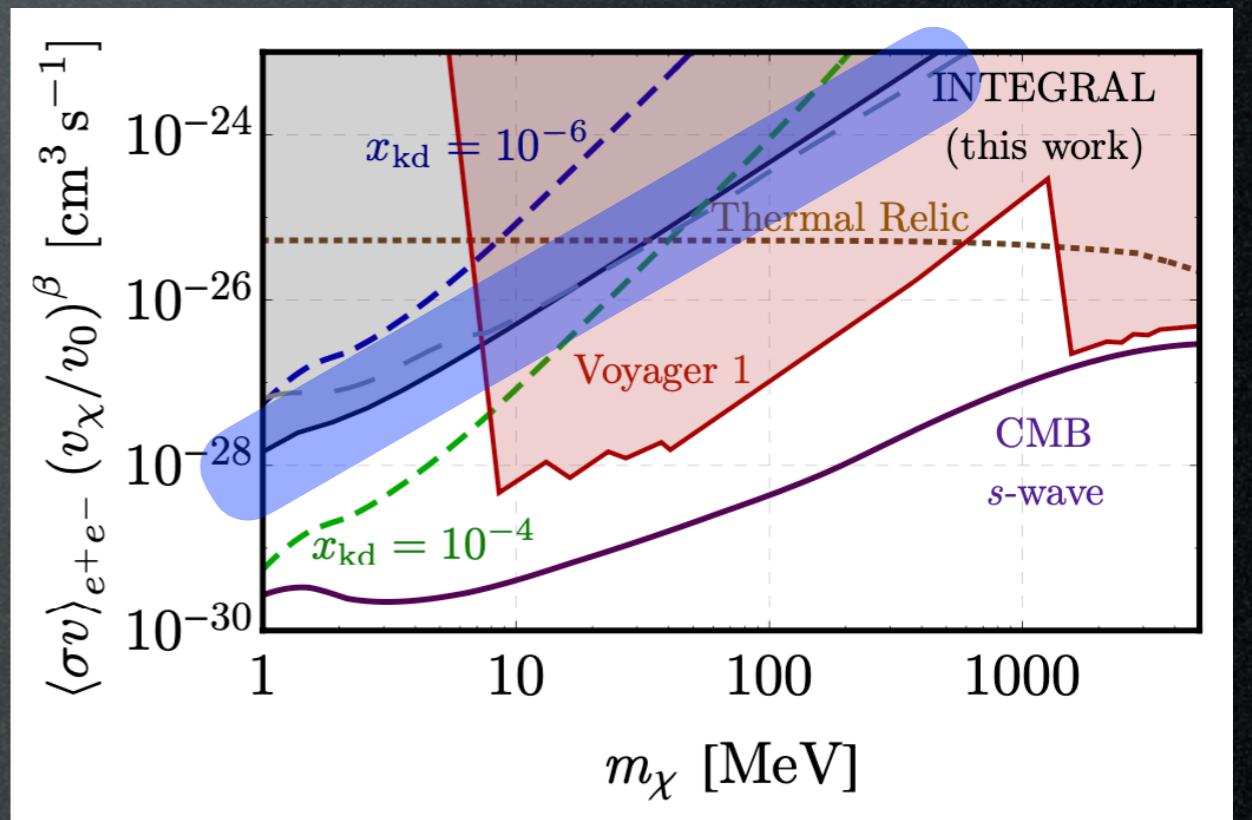
NB: 'prompt' emission only

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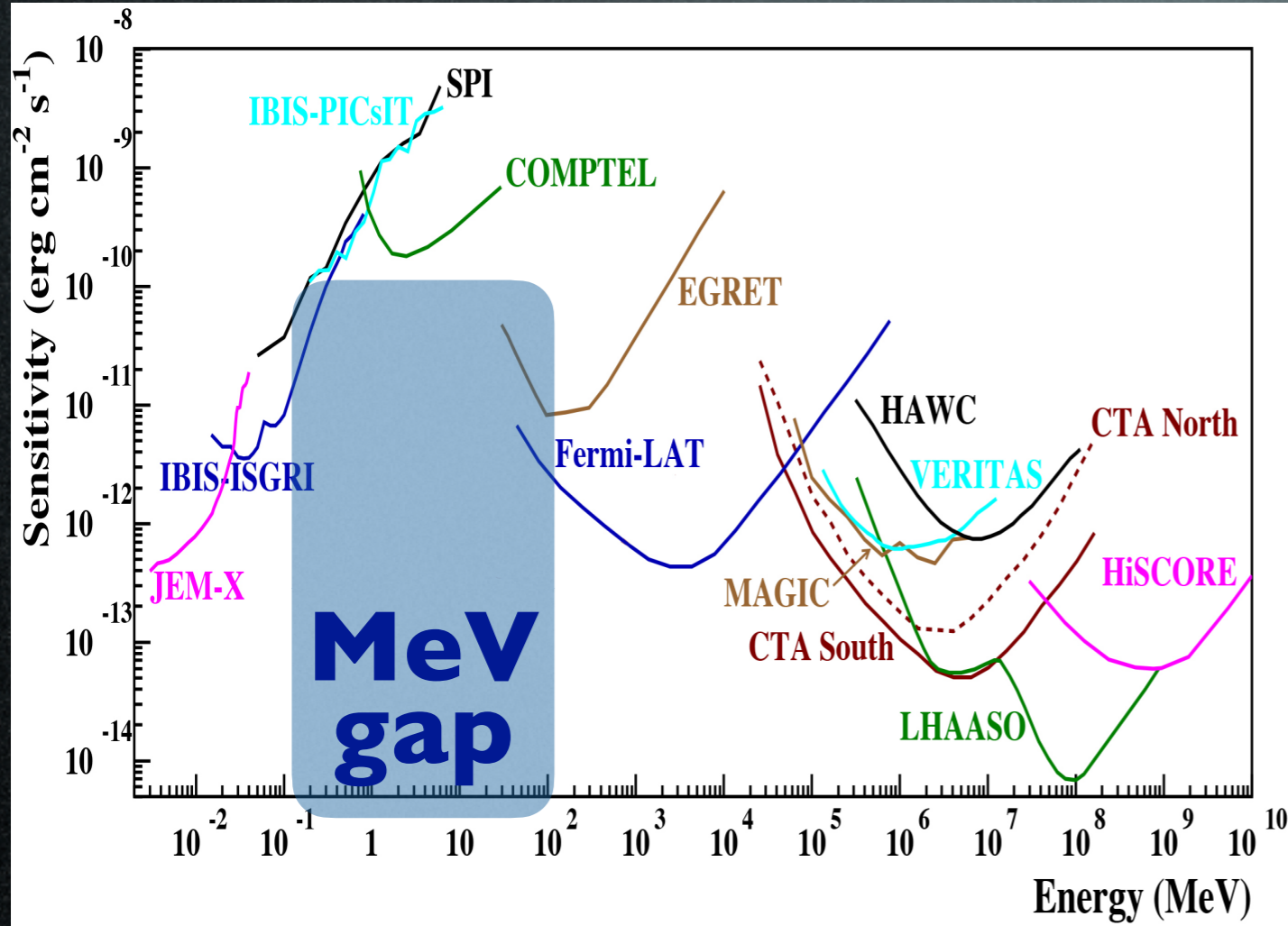
Laha, Muñoz, Slatyer, 2004.00627v1



NB: 'prompt' emission only

Indirect detection: photons

adapted from 1611.02232



How to do better?
ICS & X-rays!

Sub-GeV DM & X-rays

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

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

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

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

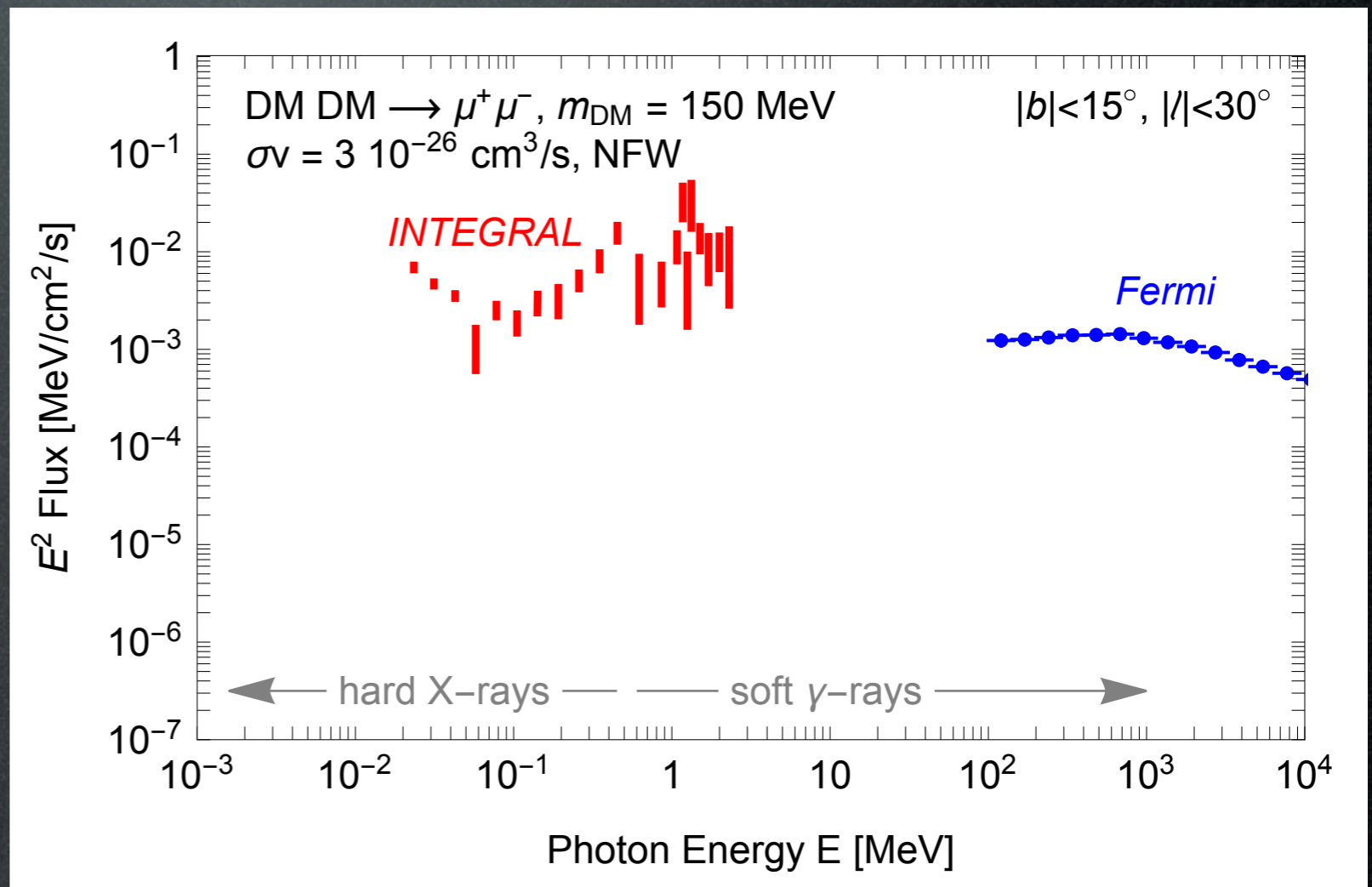
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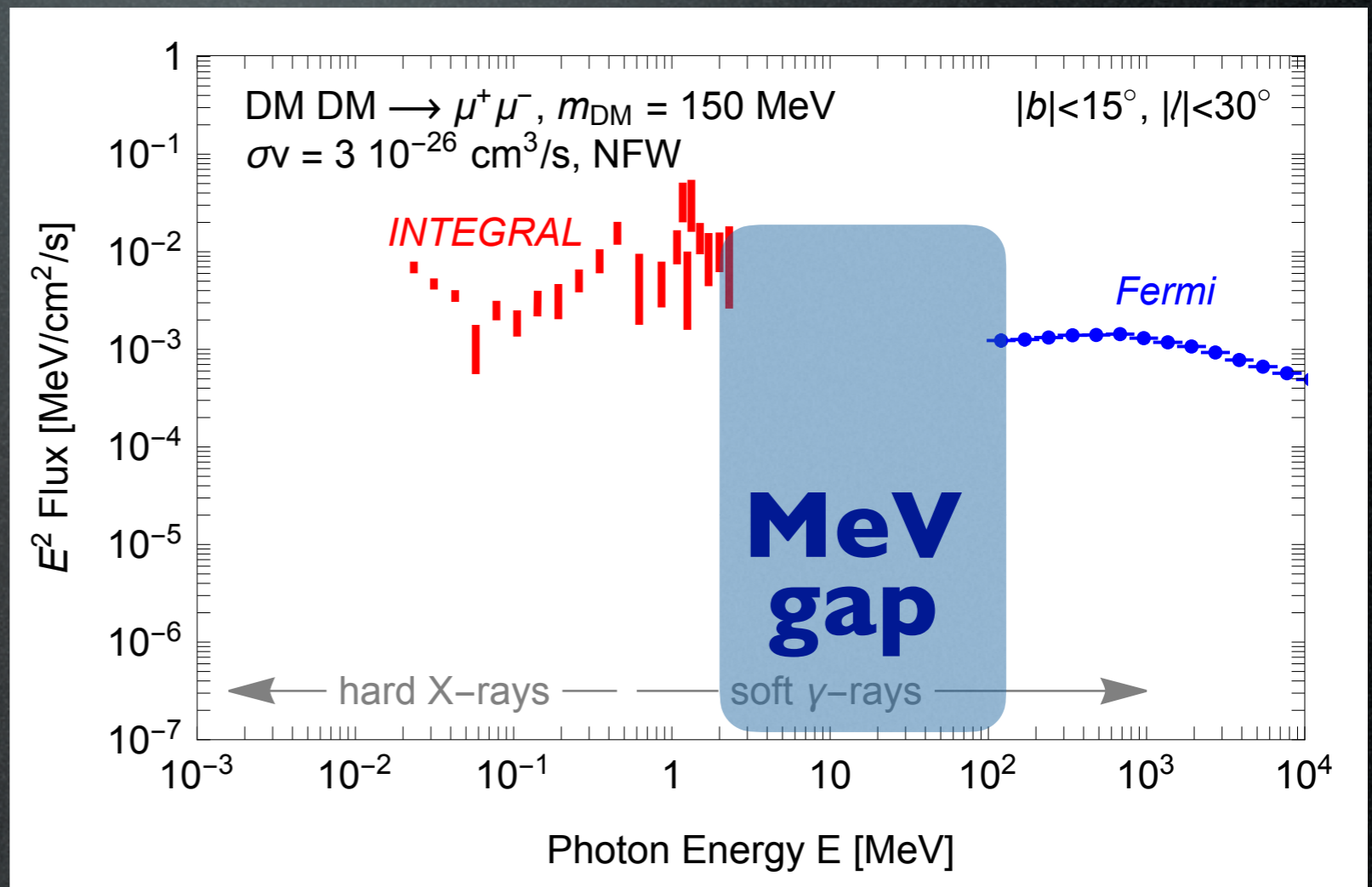
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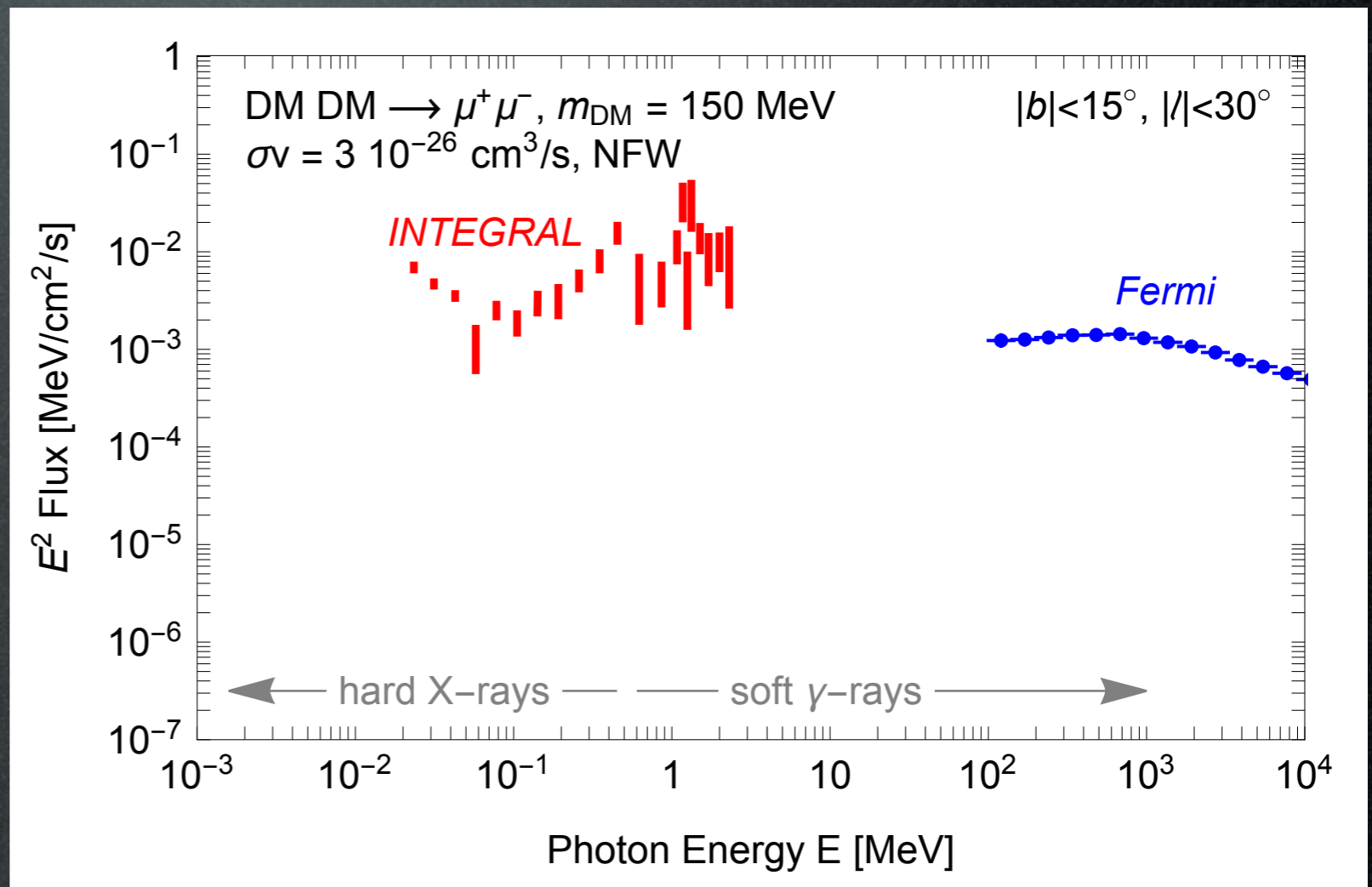
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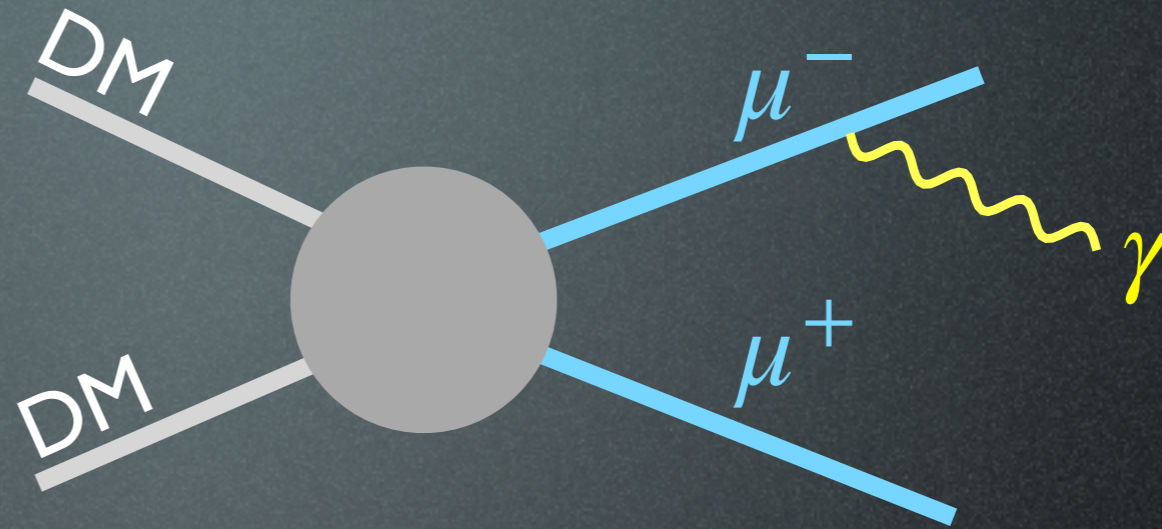
Sub-GeV DM & X-rays

Annihilation channels

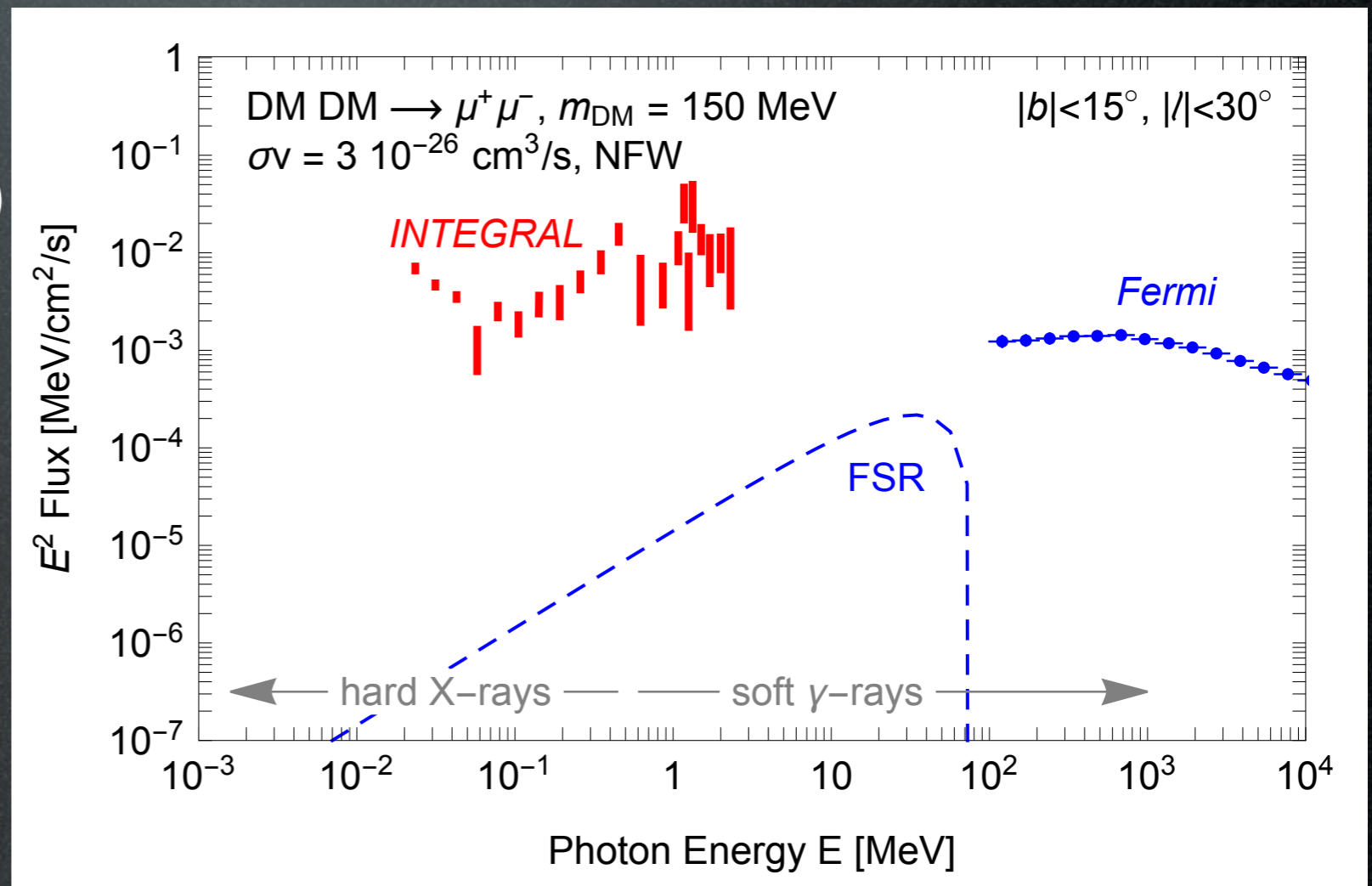
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‘Prompt’ emission:
Final State Radiation (FSR)



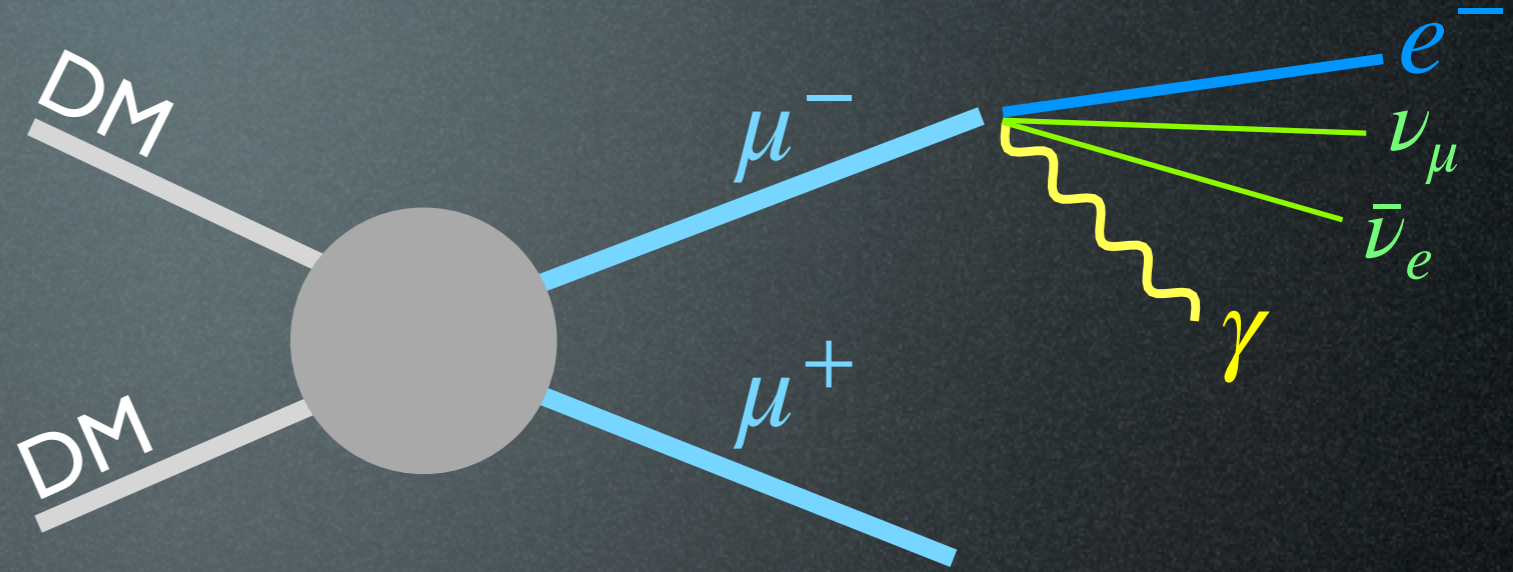
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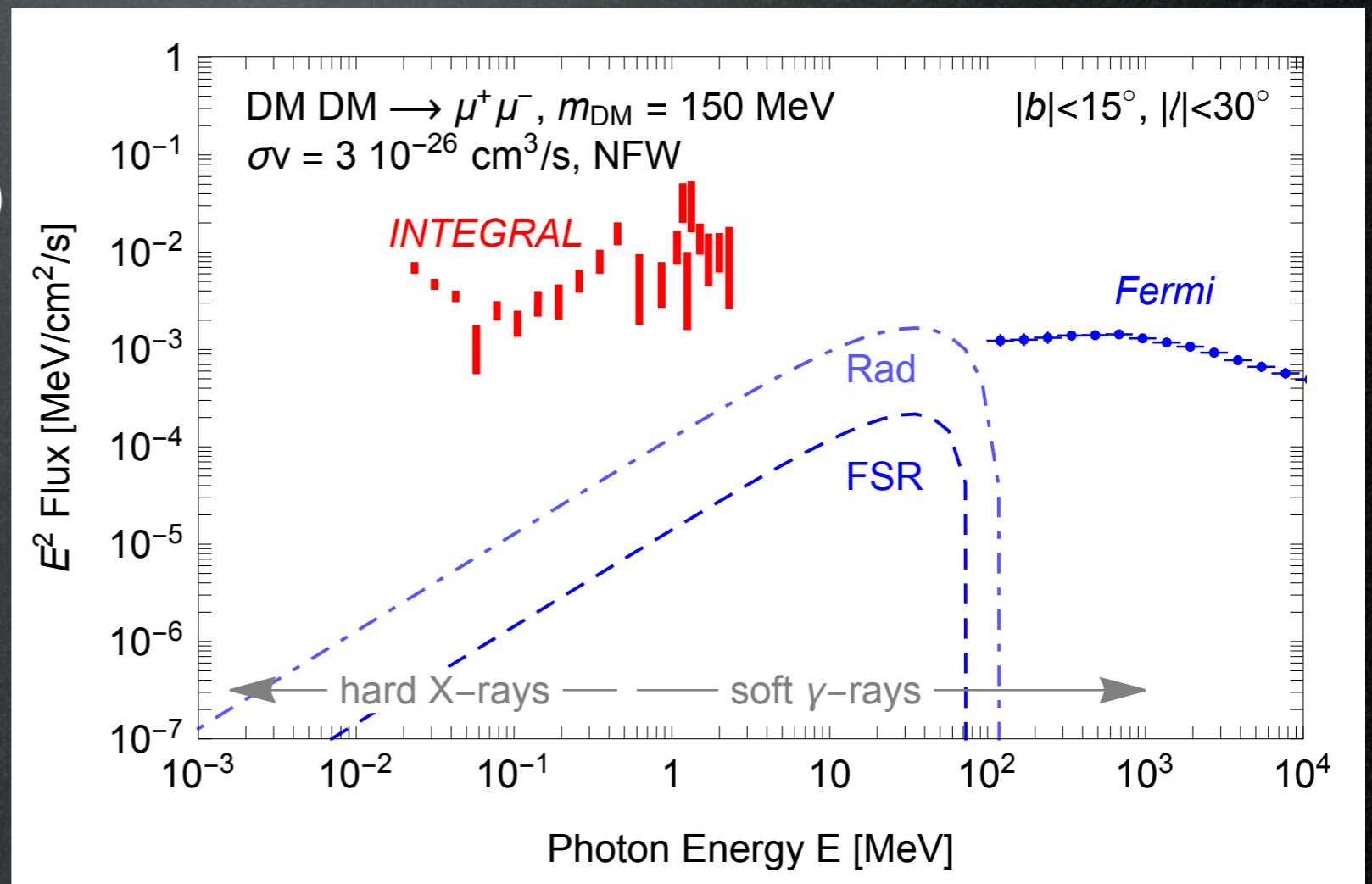


‘Prompt’ emission:

Final State Radiation (FSR)

Radiative μ decay

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



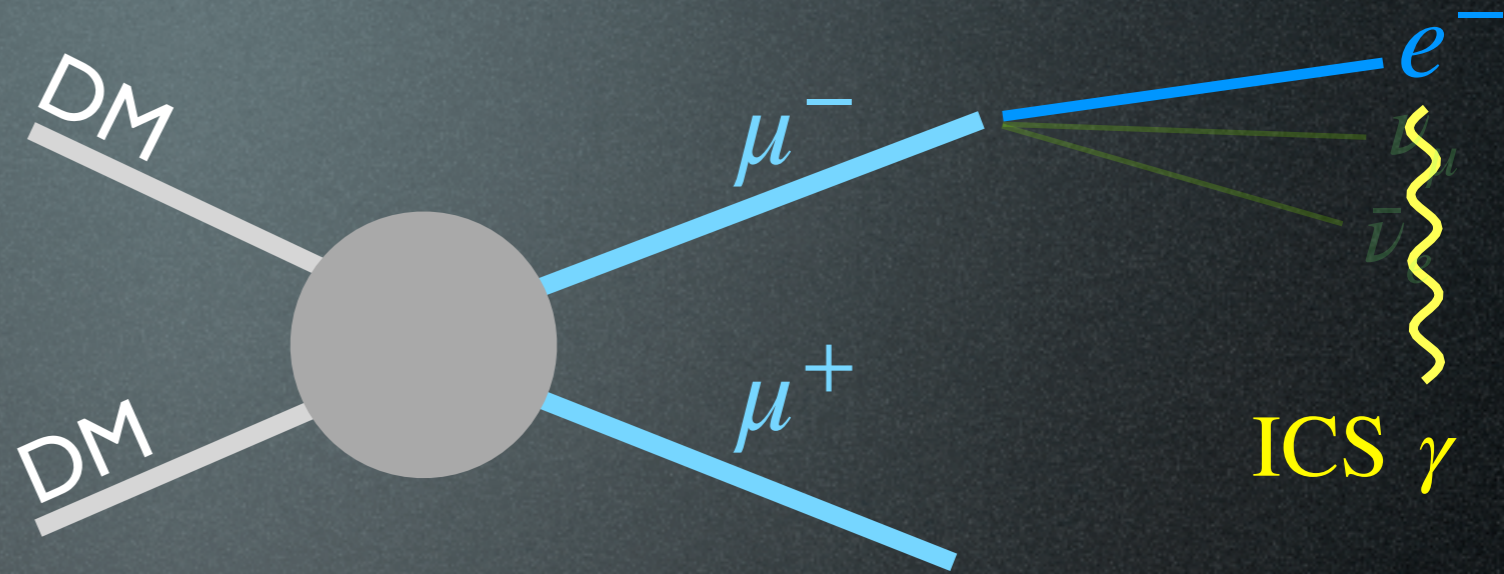
Sub-GeV DM & X-rays

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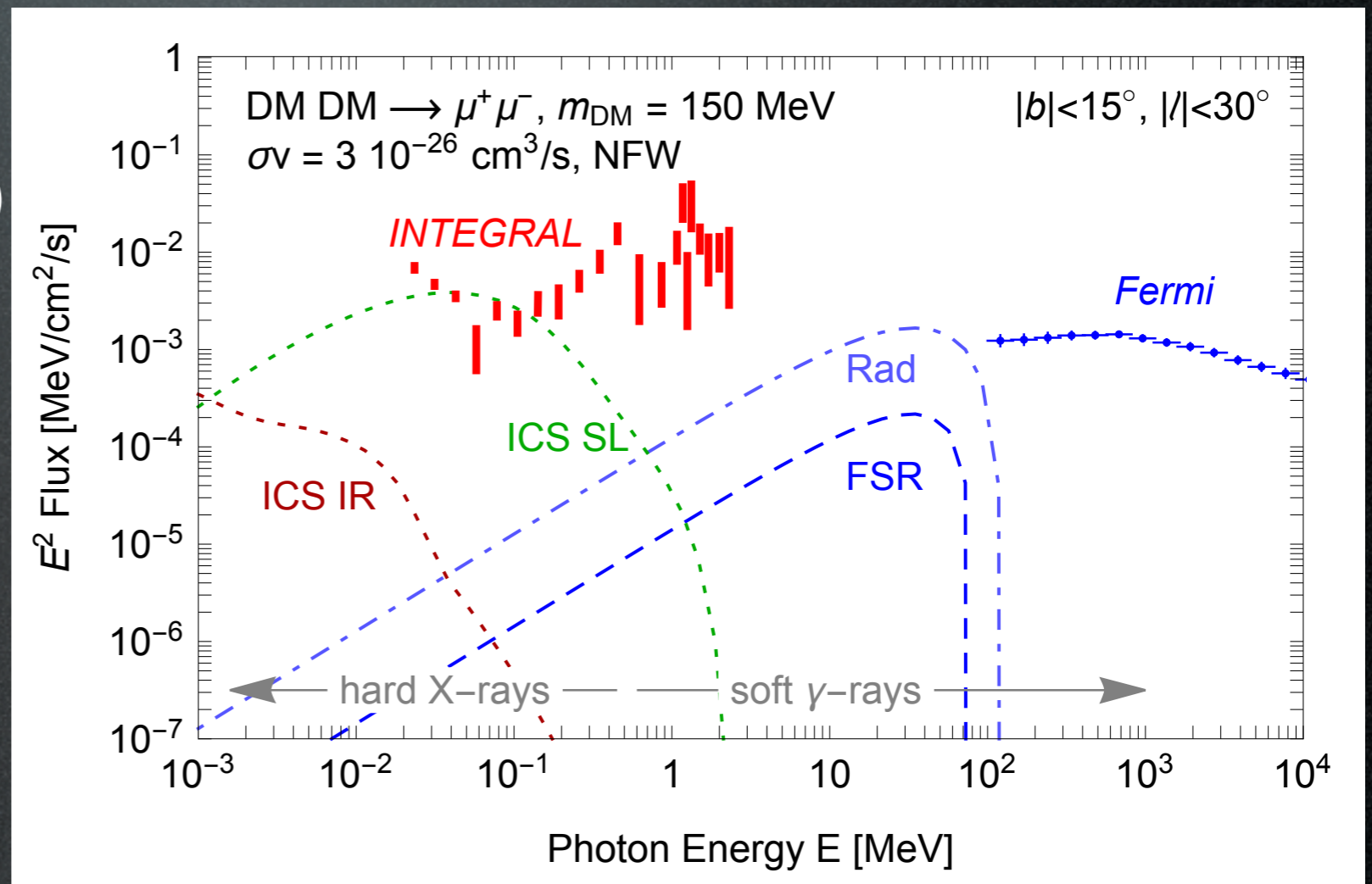
‘Prompt’ emission:

Final State Radiation (FSR)

Radiative μ decay

Secondary emission:

ICS: inevitably associated to annihil to charged states



Sub-GeV DM & X-rays

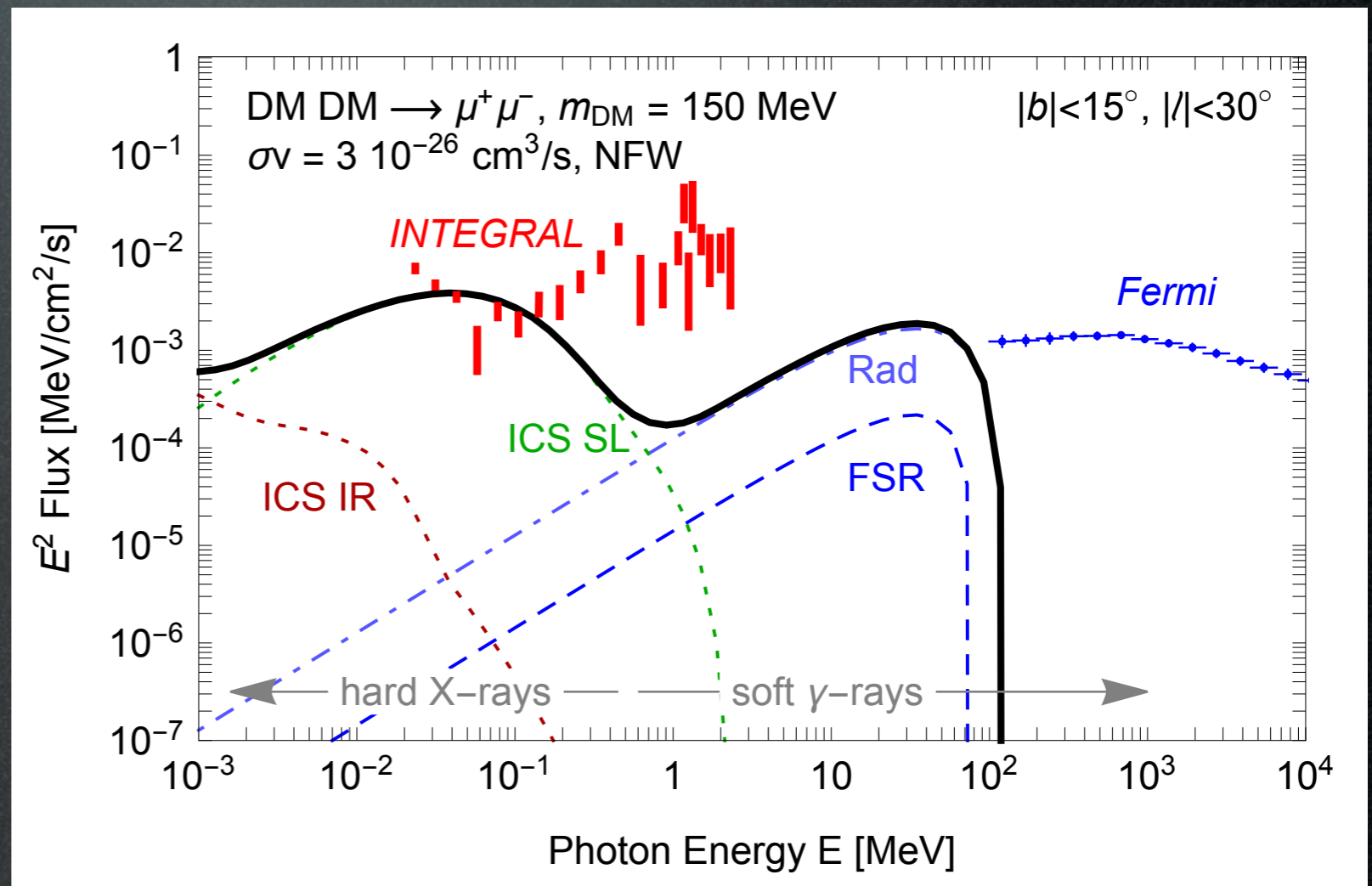
Annihilation channels

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

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

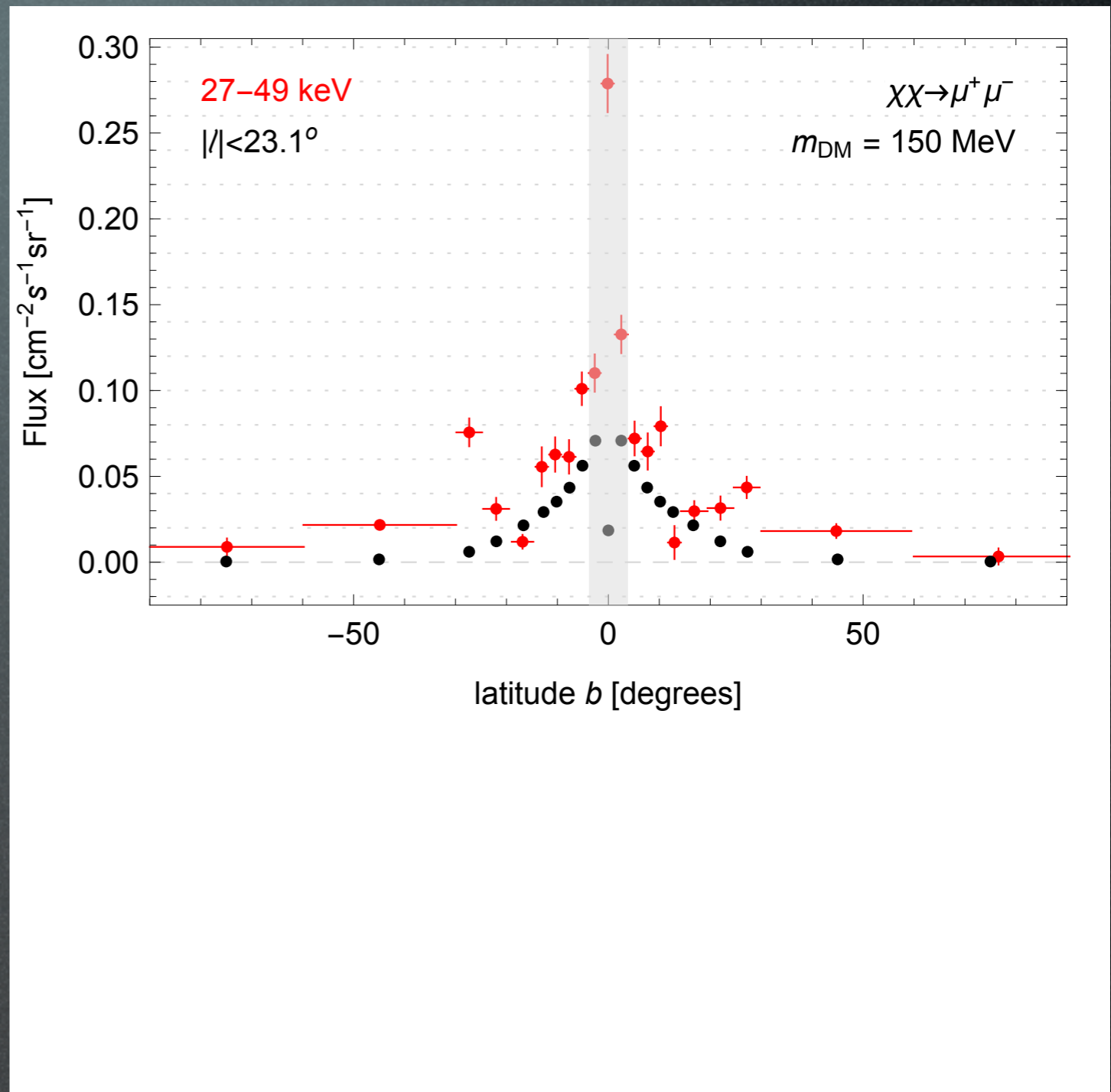
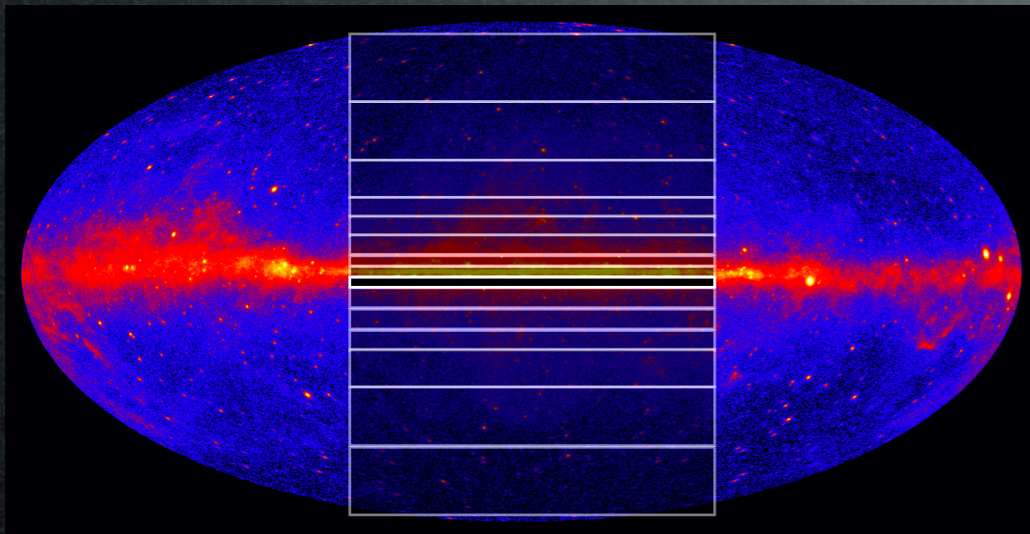


Analysis

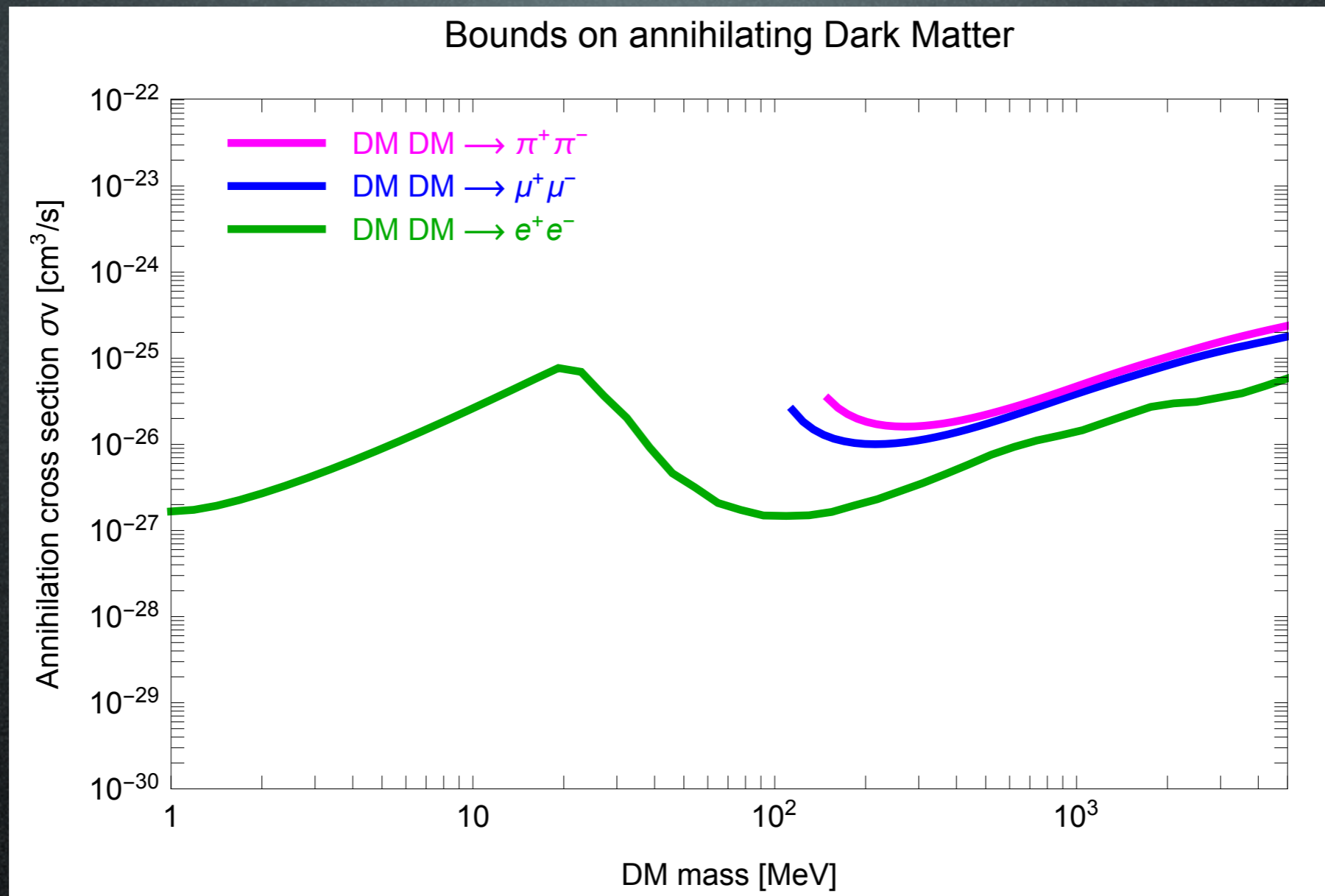
Integral-SPI 2011 data

Bouchet et al., Integral coll. 1107.0200

latitude binned data, central MW

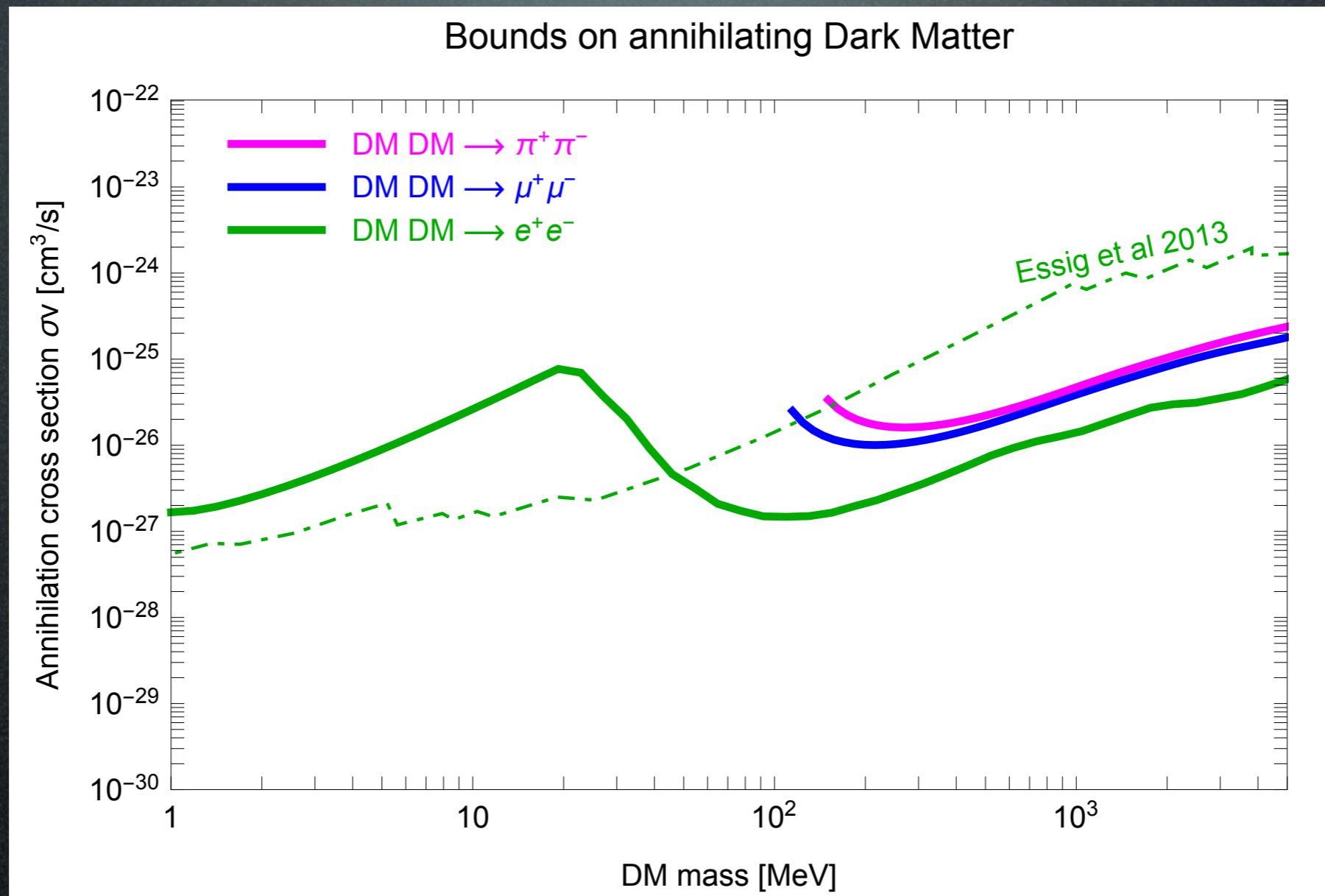


Results



Bounds on all 3 channels

Results

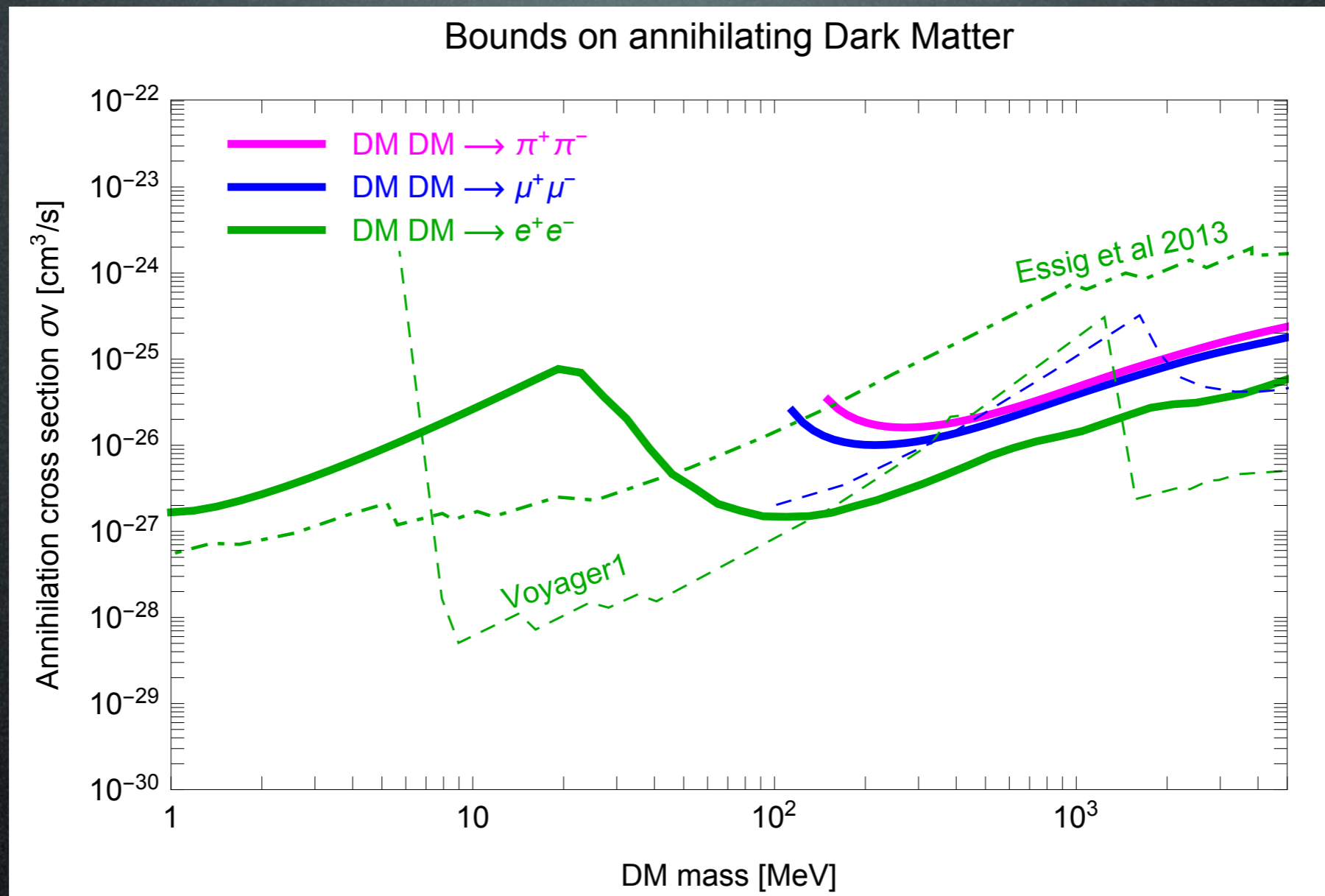


Essig+
1309.4091

Bounds on all 3 channels

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

Results



Essig+
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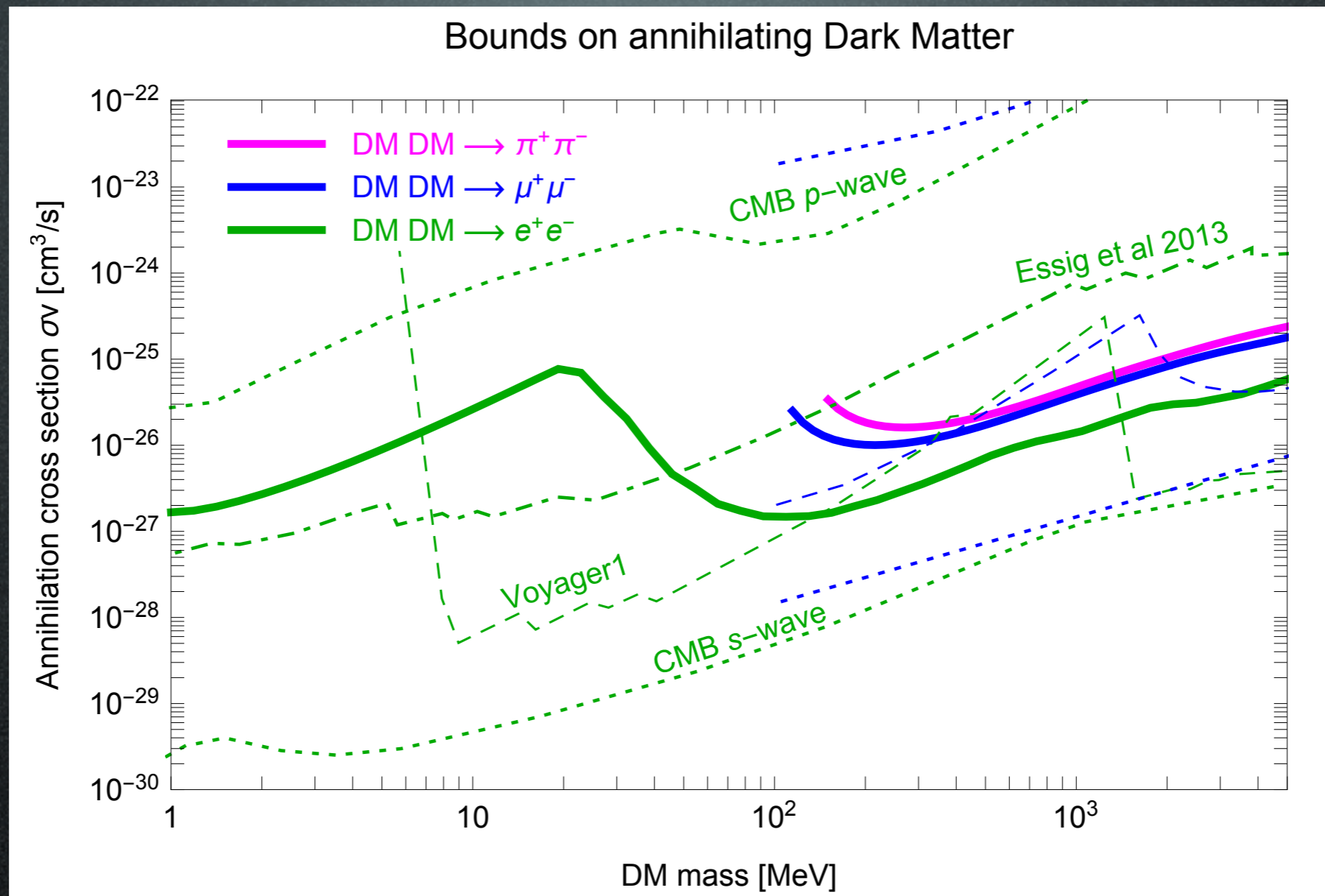
Boudaud+
1612.07698

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Results



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

Conclusions

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

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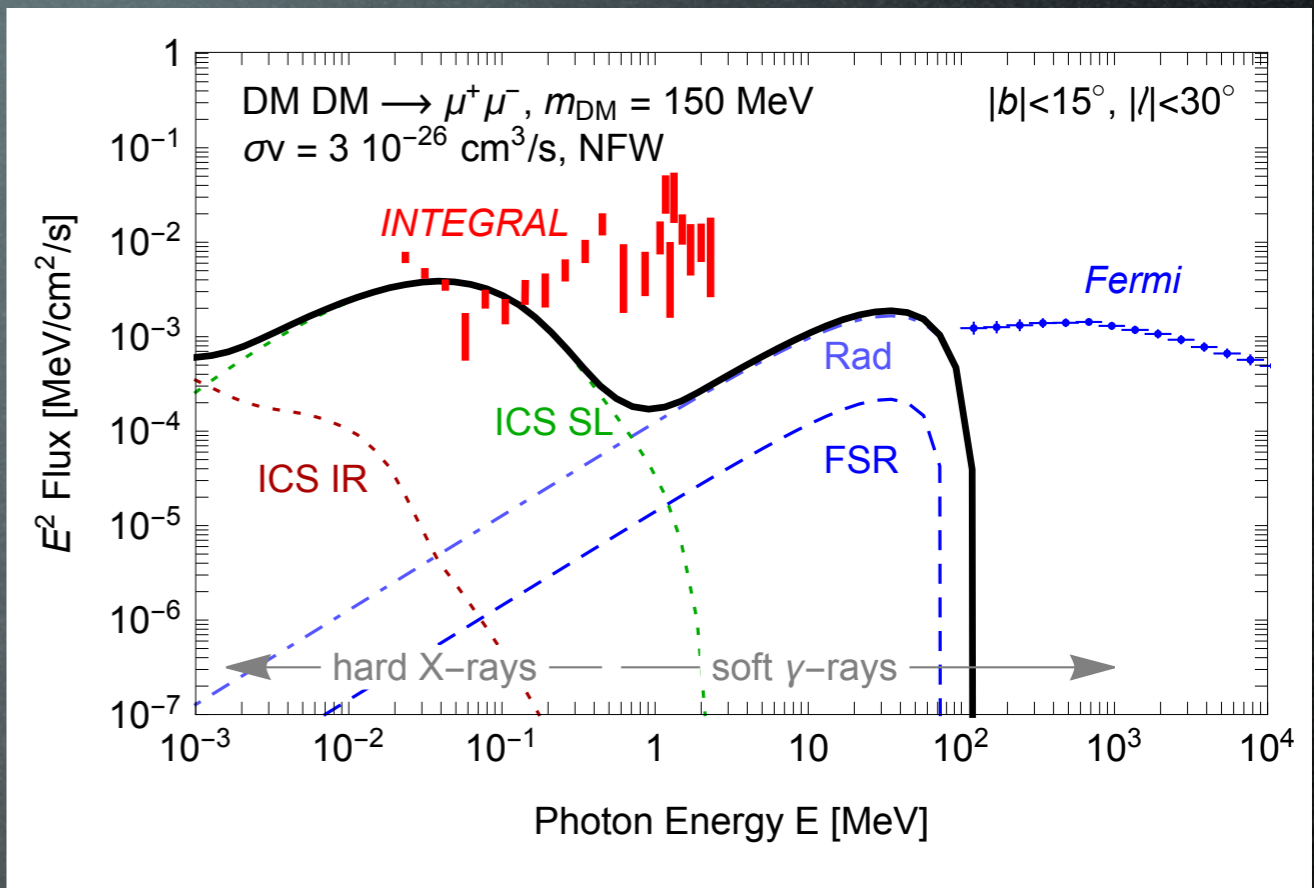
ID is (more) challenging
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Conclusions

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

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ICS allows to test it with **X-ray data**



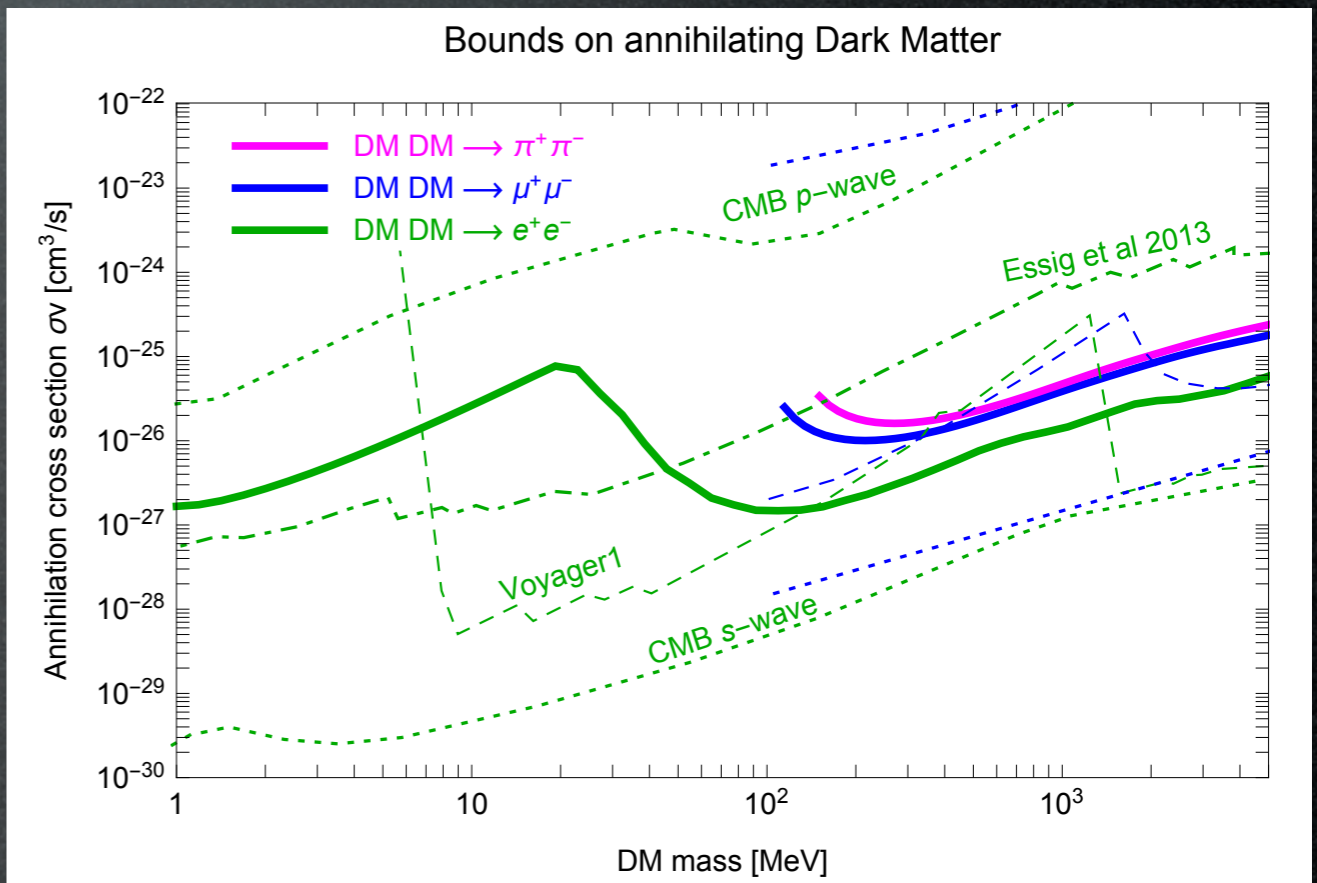
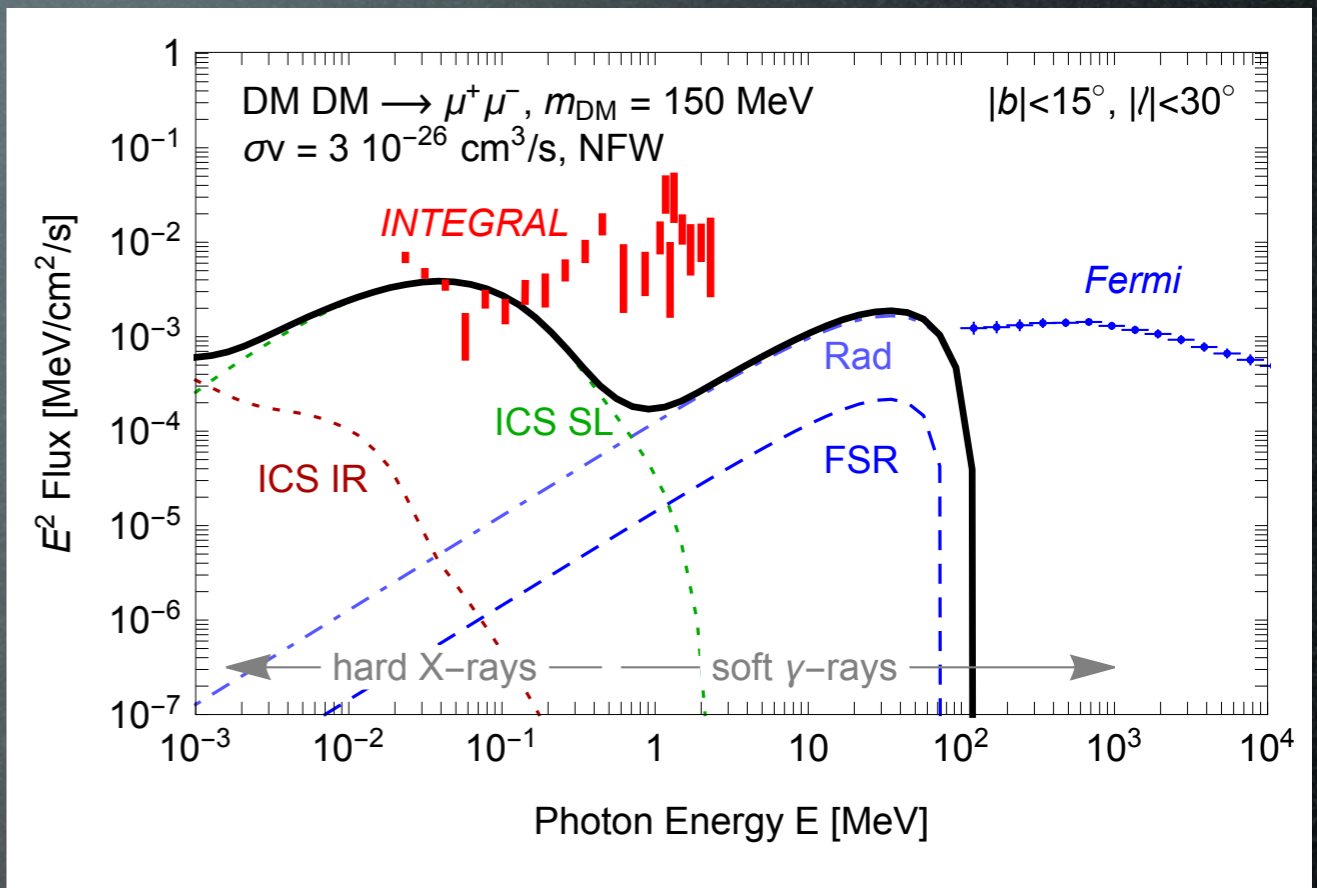
Conclusions

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



Backup

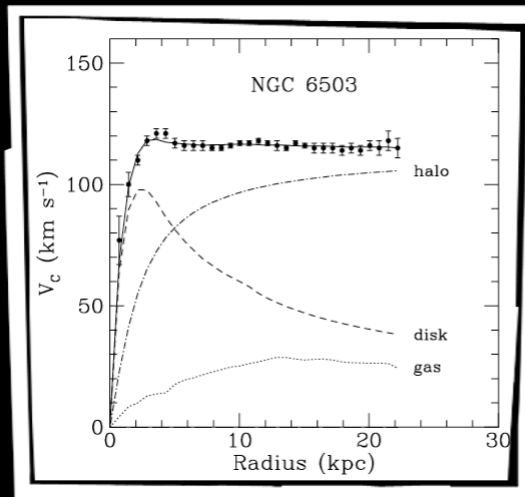
Dark Matter factsheet

Dark Matter factsheet

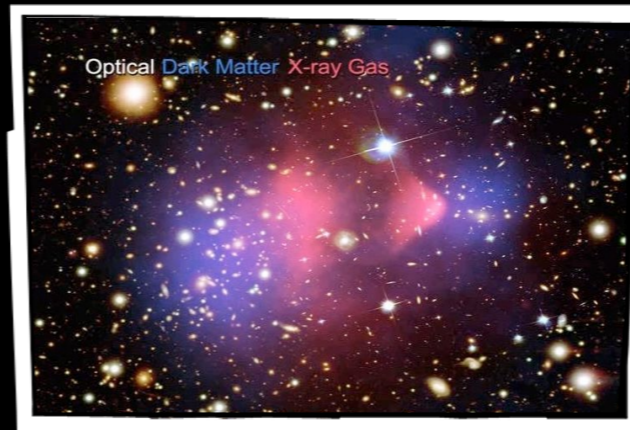
- DM exists

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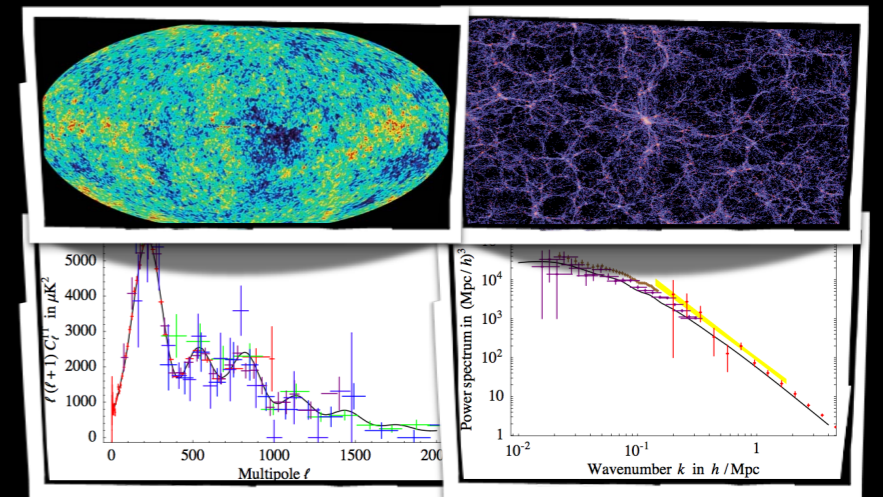
DM exists



galactic rotation curves



weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Dark Matter factsheet

- DM exists
- it's a **new, unknown** corpuscule

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

Dark Matter factsheet

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*no SM particle
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- makes up **26%** of total energy
82% of total matter

$$\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$$

(notice error!)

[Planck 2015, 1502.01589]

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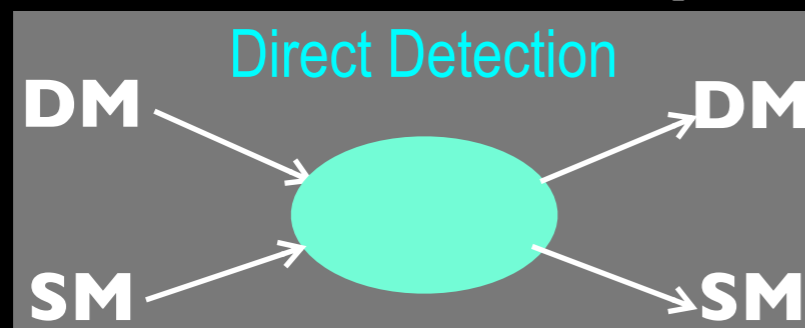
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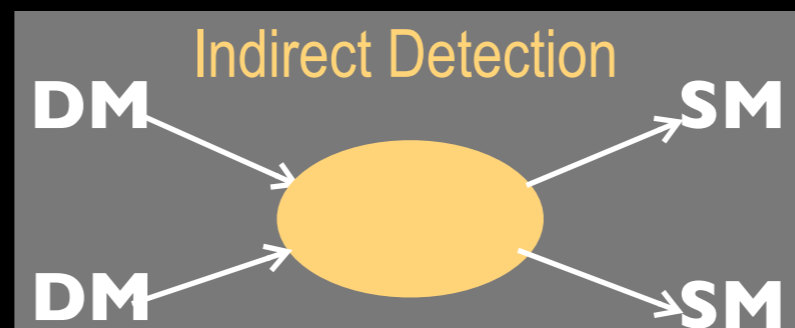
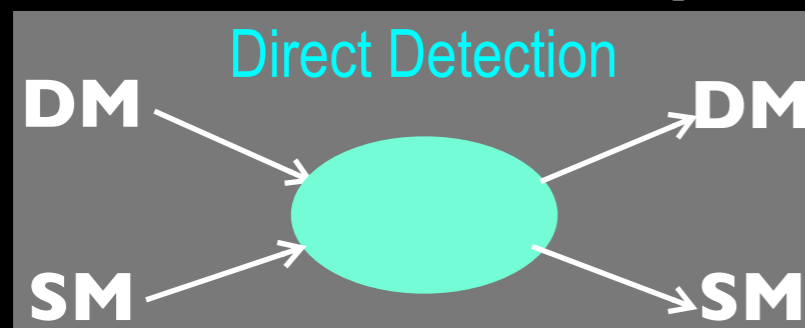
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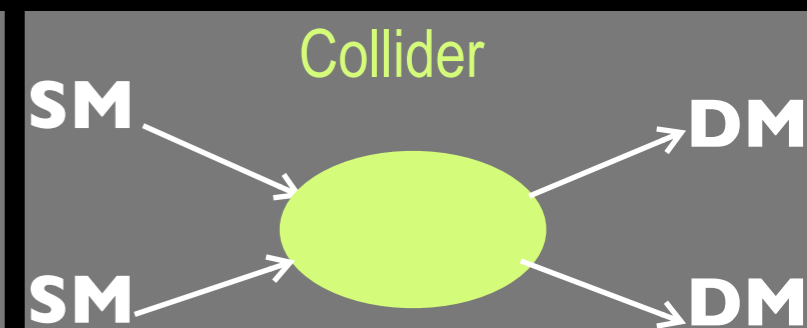
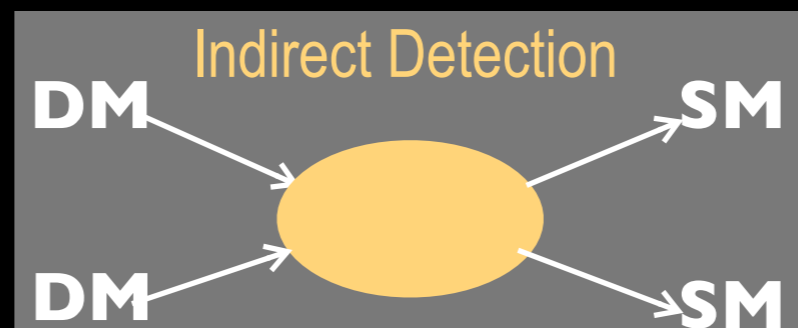
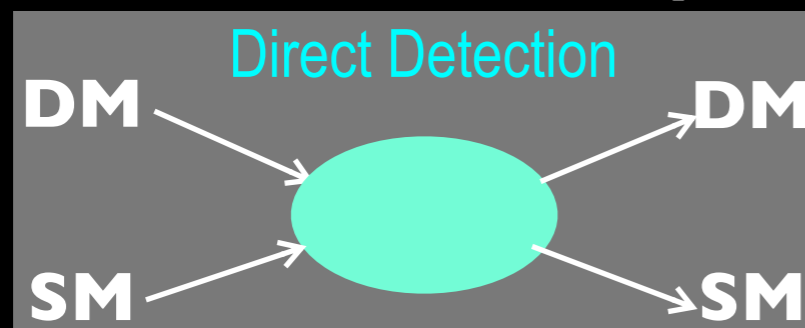
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Mass??

Charge??
Interactions??

Candidates

The Dark Matter
theory space:

Candidates

The Dark Matter
theory space:

**SuSy
DMI**

**Non
SuSy
DMI**

Candidates

The Dark Matter
theory space:

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DMI**

**Non
SuSy
DMI**



?

Candidates

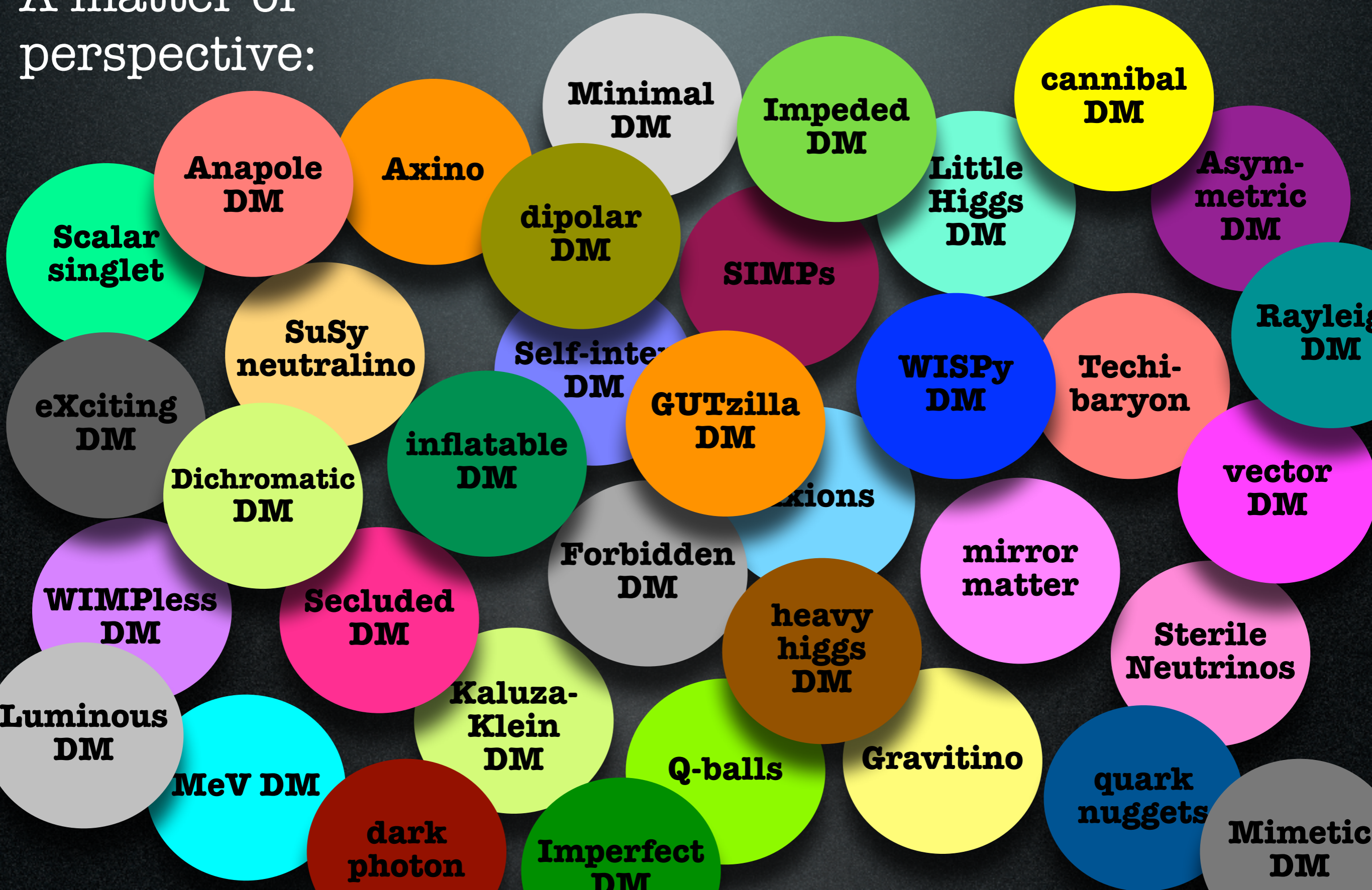
The Dark Matter
theory space:

**SuSy
neutralino**

other
exotic
candi-
dates

Candidates

A matter of perspective:



Candidates

The Dark Matter
theory space:



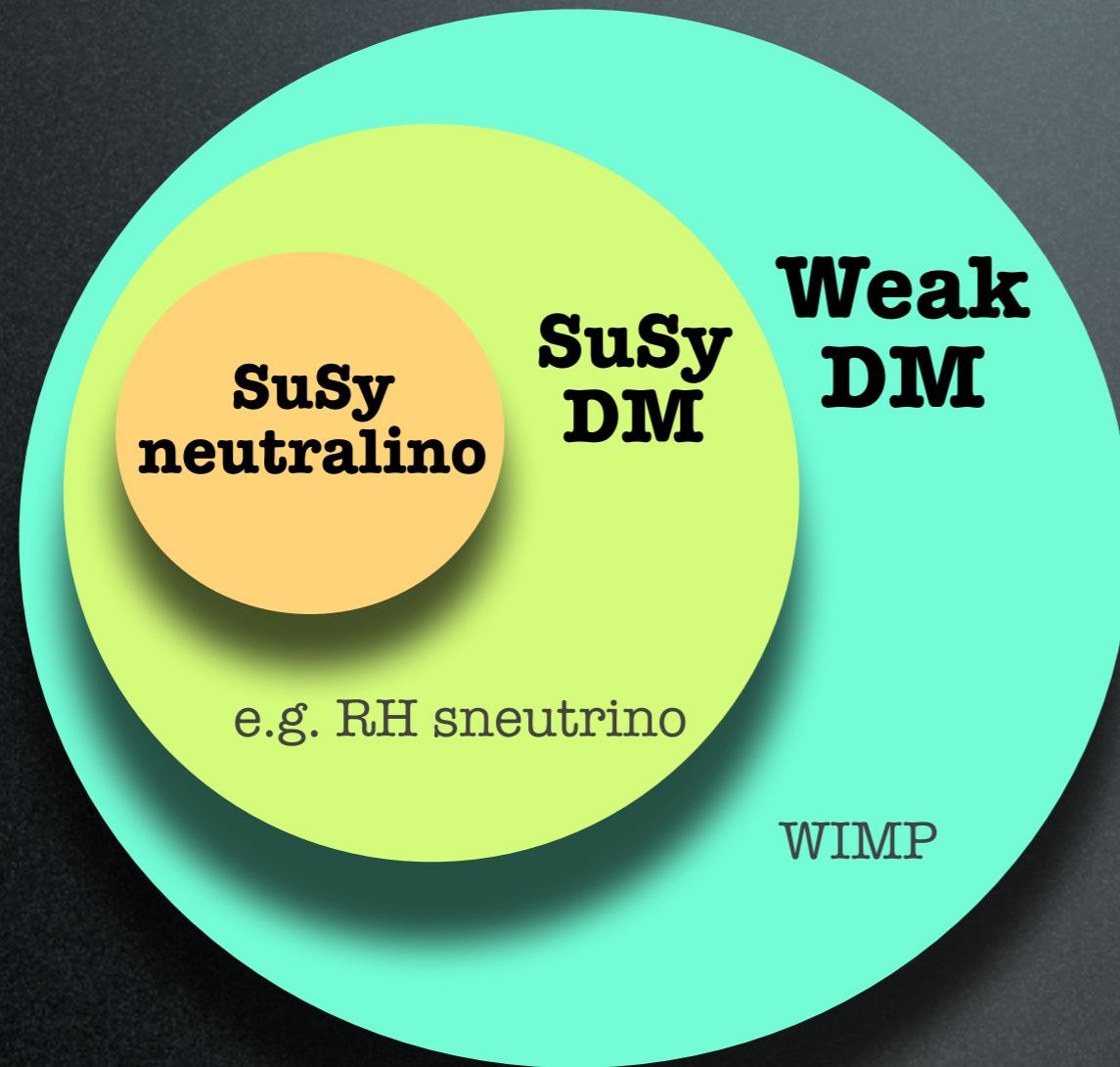
Candidates

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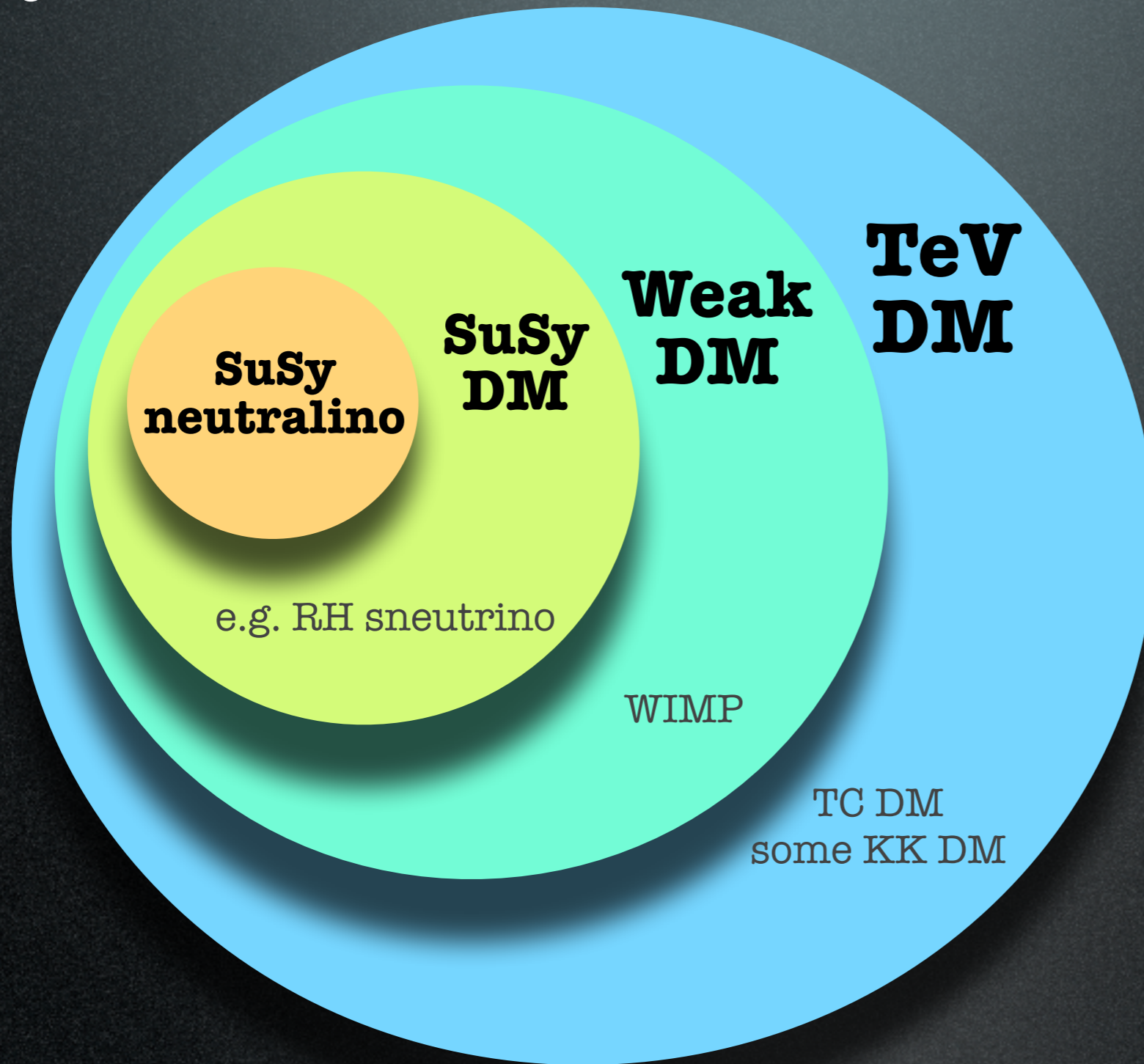
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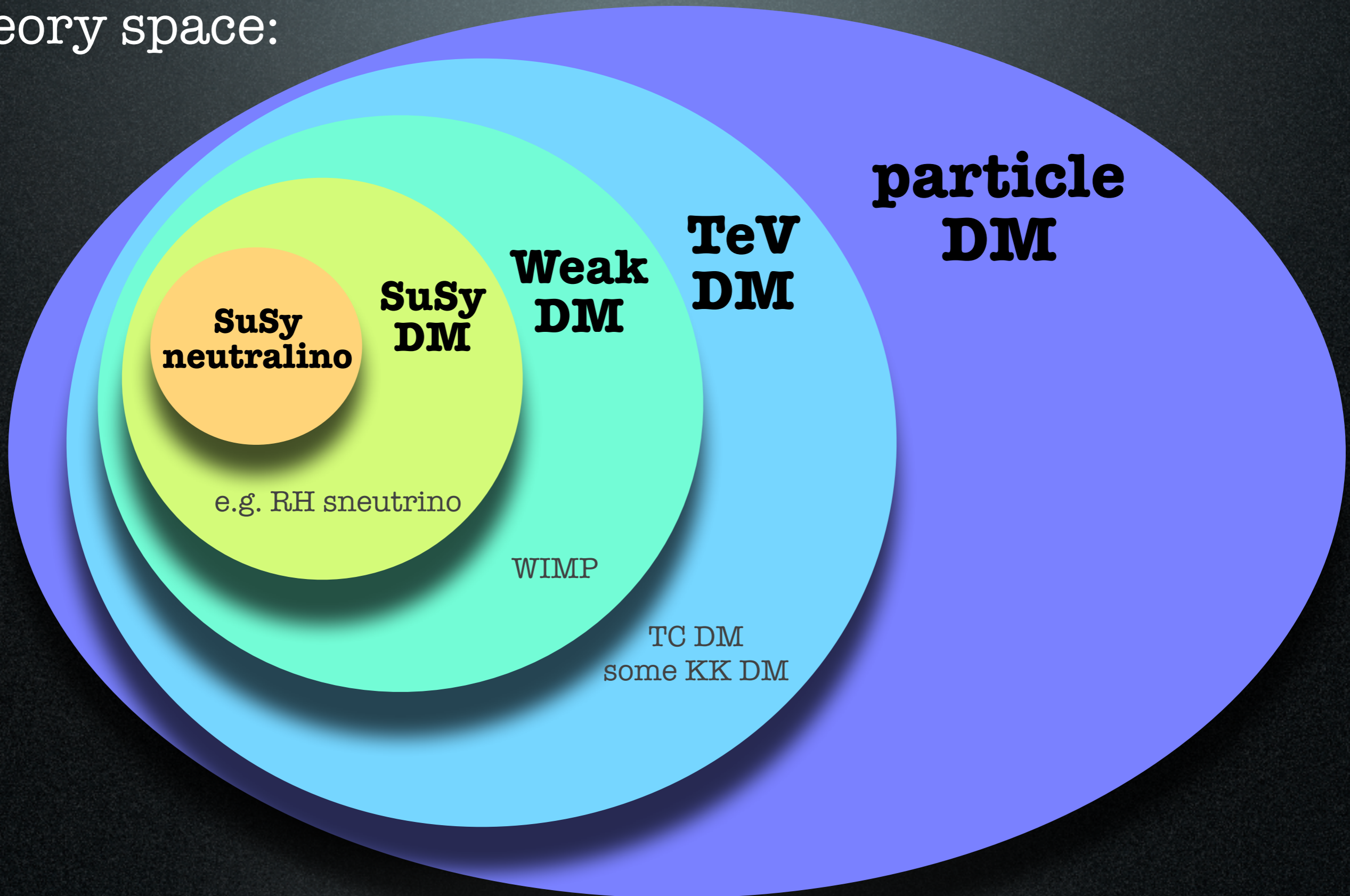
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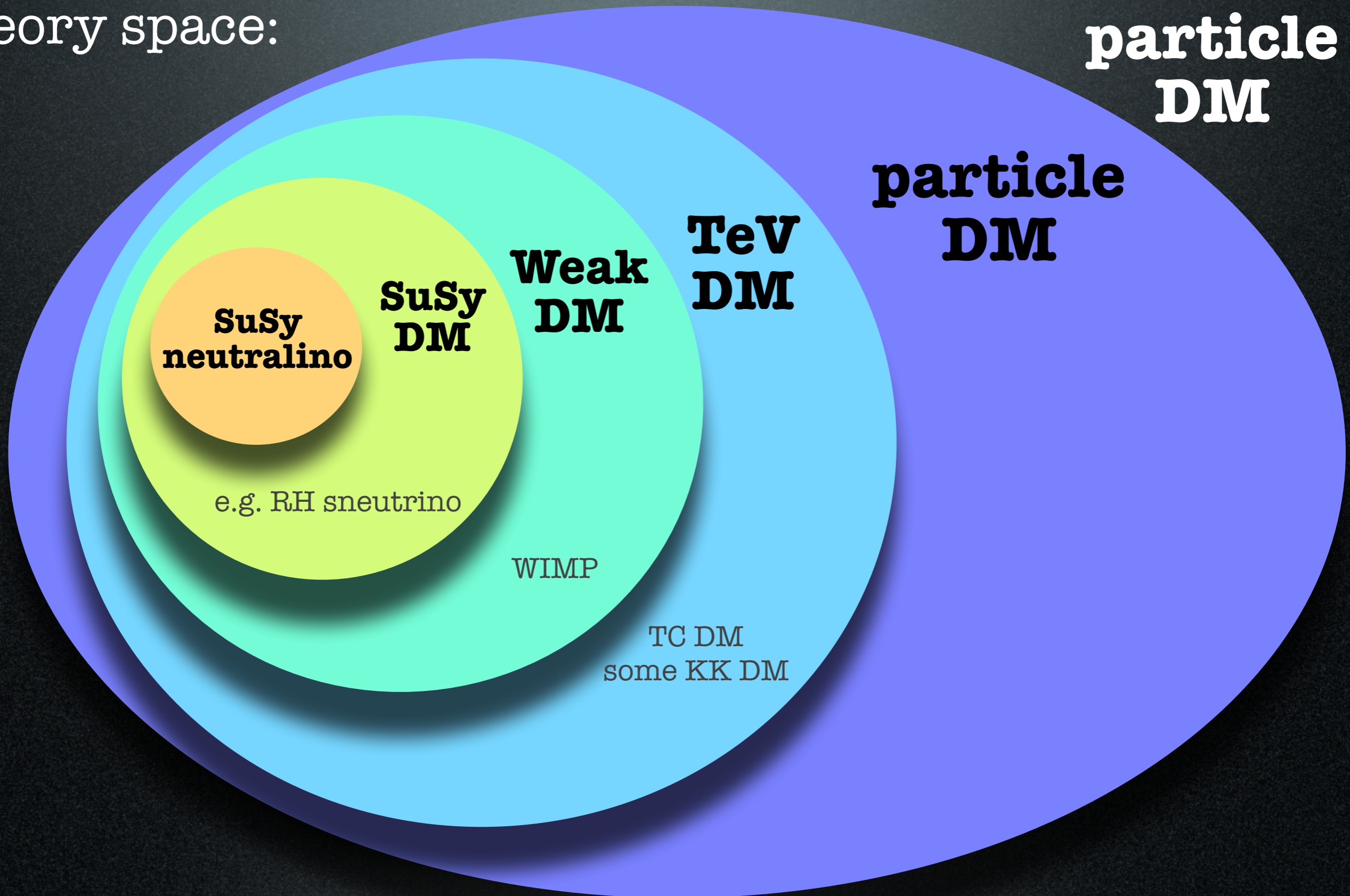
Candidates

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Candidates

The Dark Matter theory space:



Candidates

new physics at
the TeV scale

thermal
freeze-out



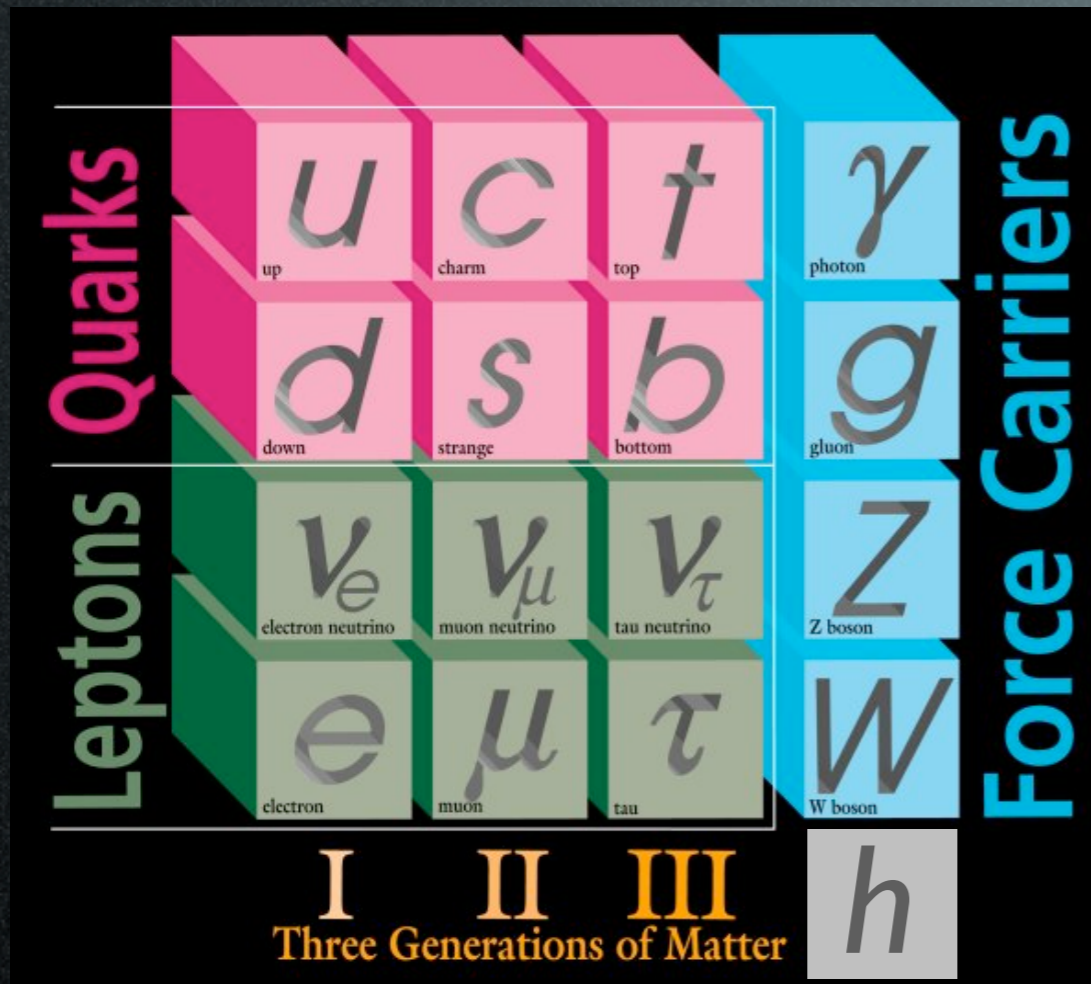
WIMPs

LHC

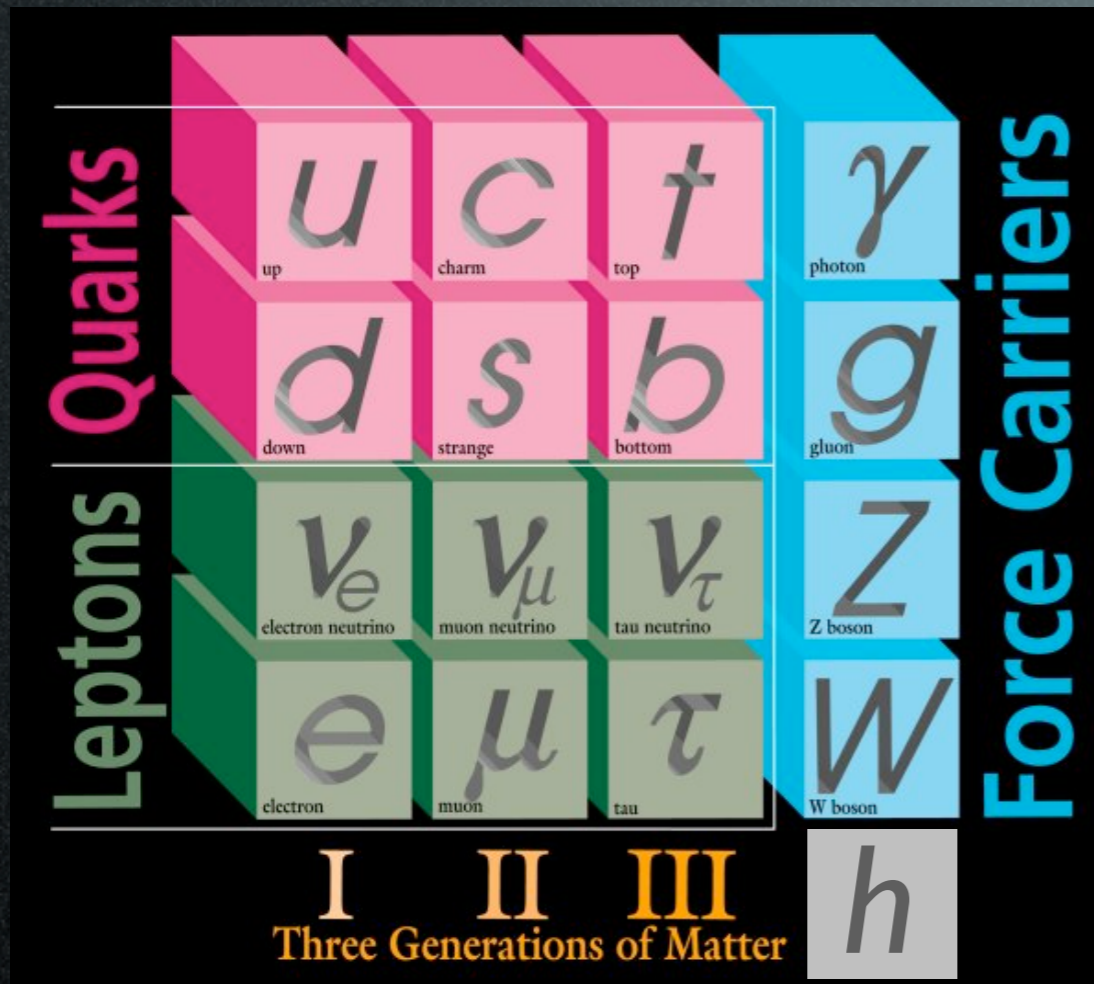
Indirect
Detection

Direct
Detection

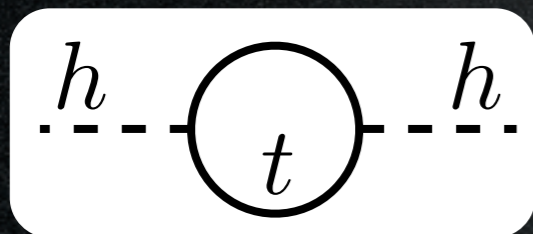
SuSy DM in 2 minutes



SuSy DM in 2 minutes

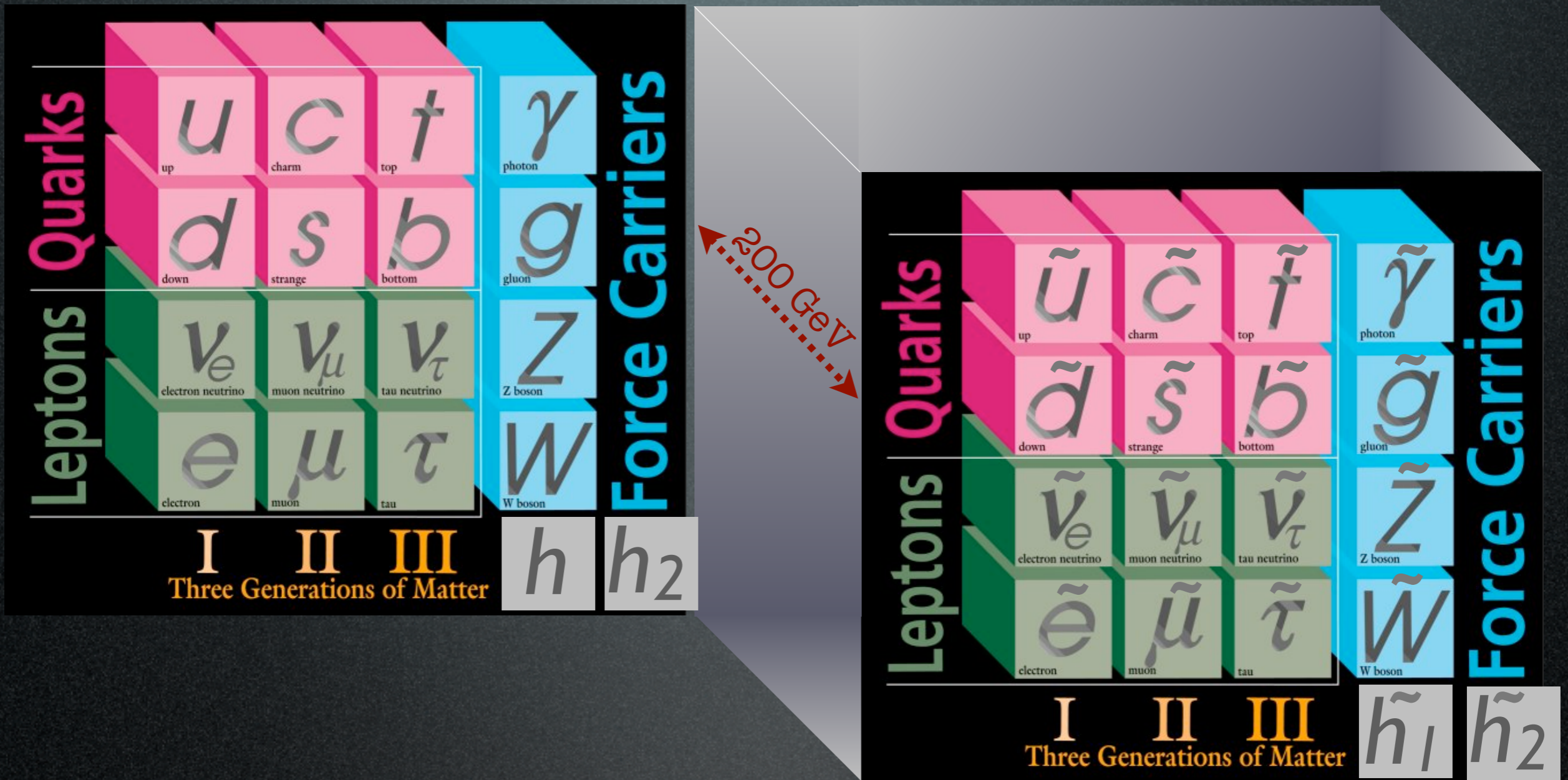


$$m_h \simeq 125 \text{ GeV}$$

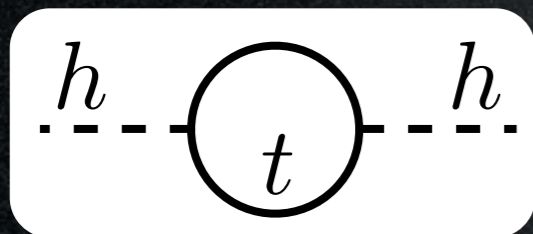


$$\Delta m_h \propto 10^{19} \text{ GeV}$$

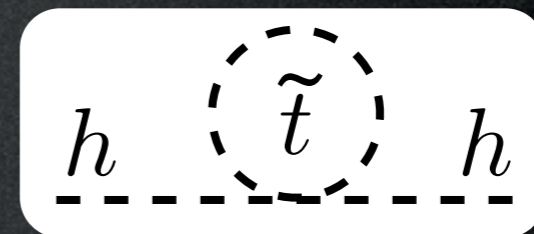
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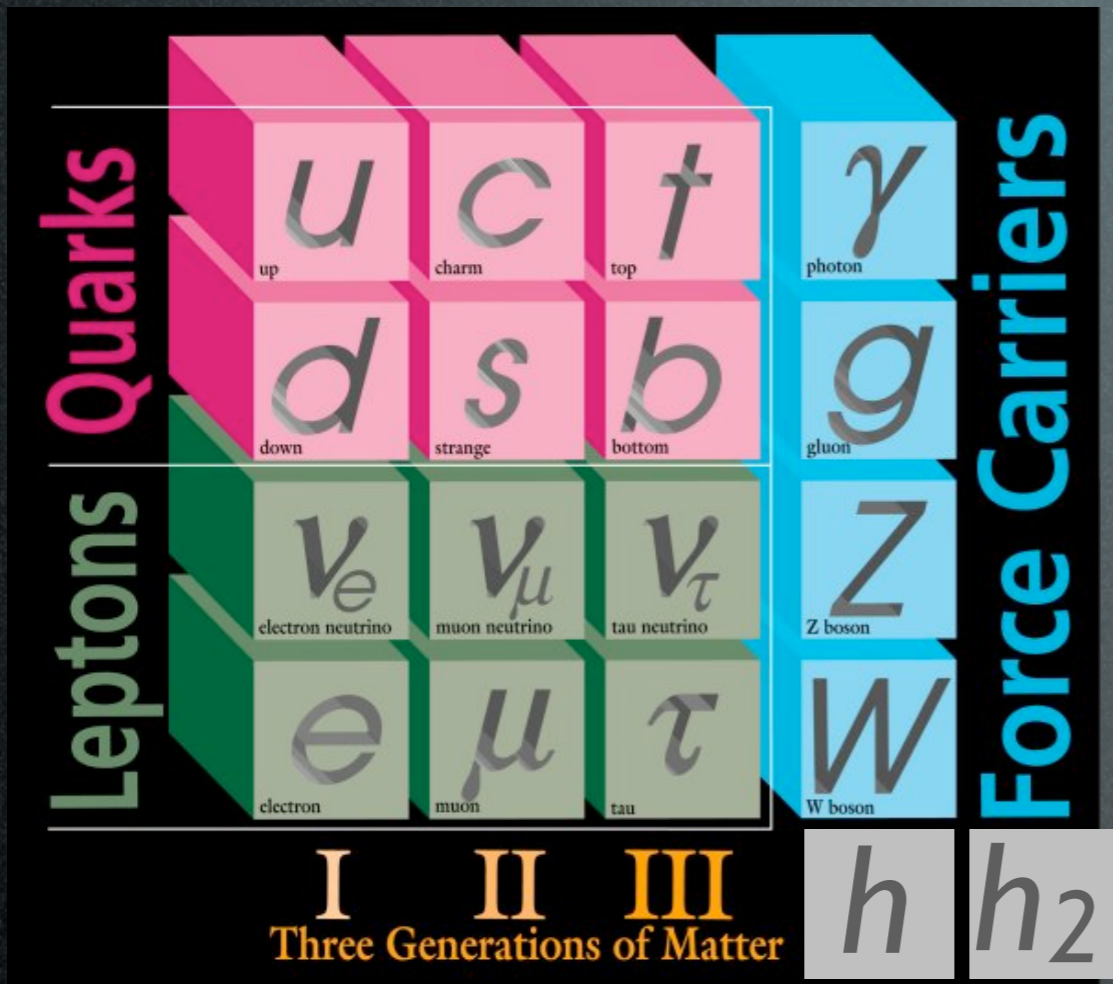


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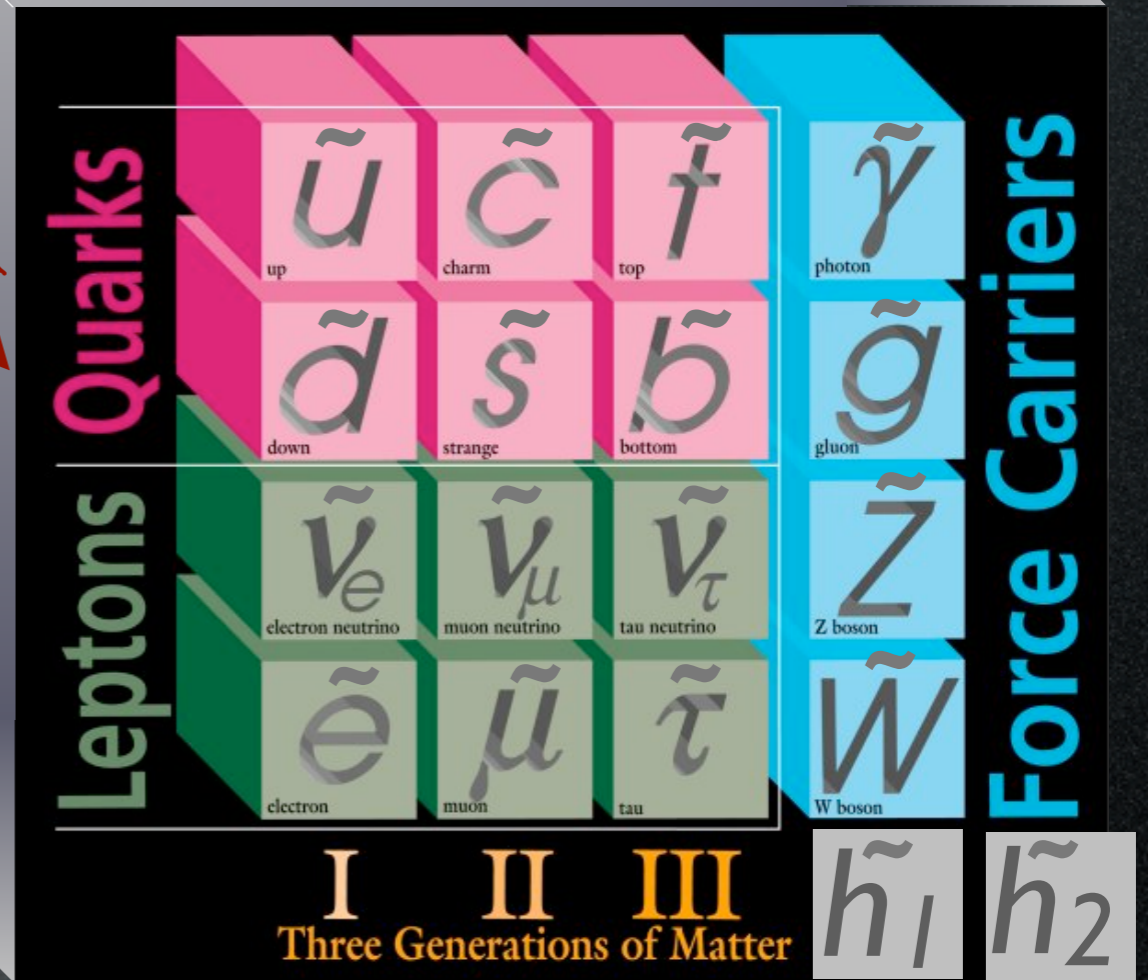


$$\Delta m_h \propto -10^{19} \text{ GeV}$$

SuSy DM in 2 minutes

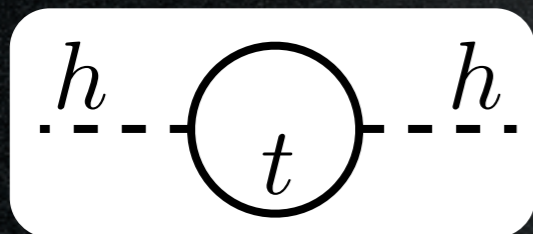


200 GeV



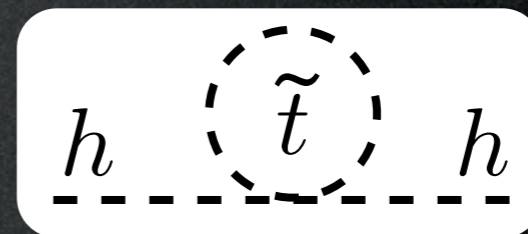
$$R = +1$$

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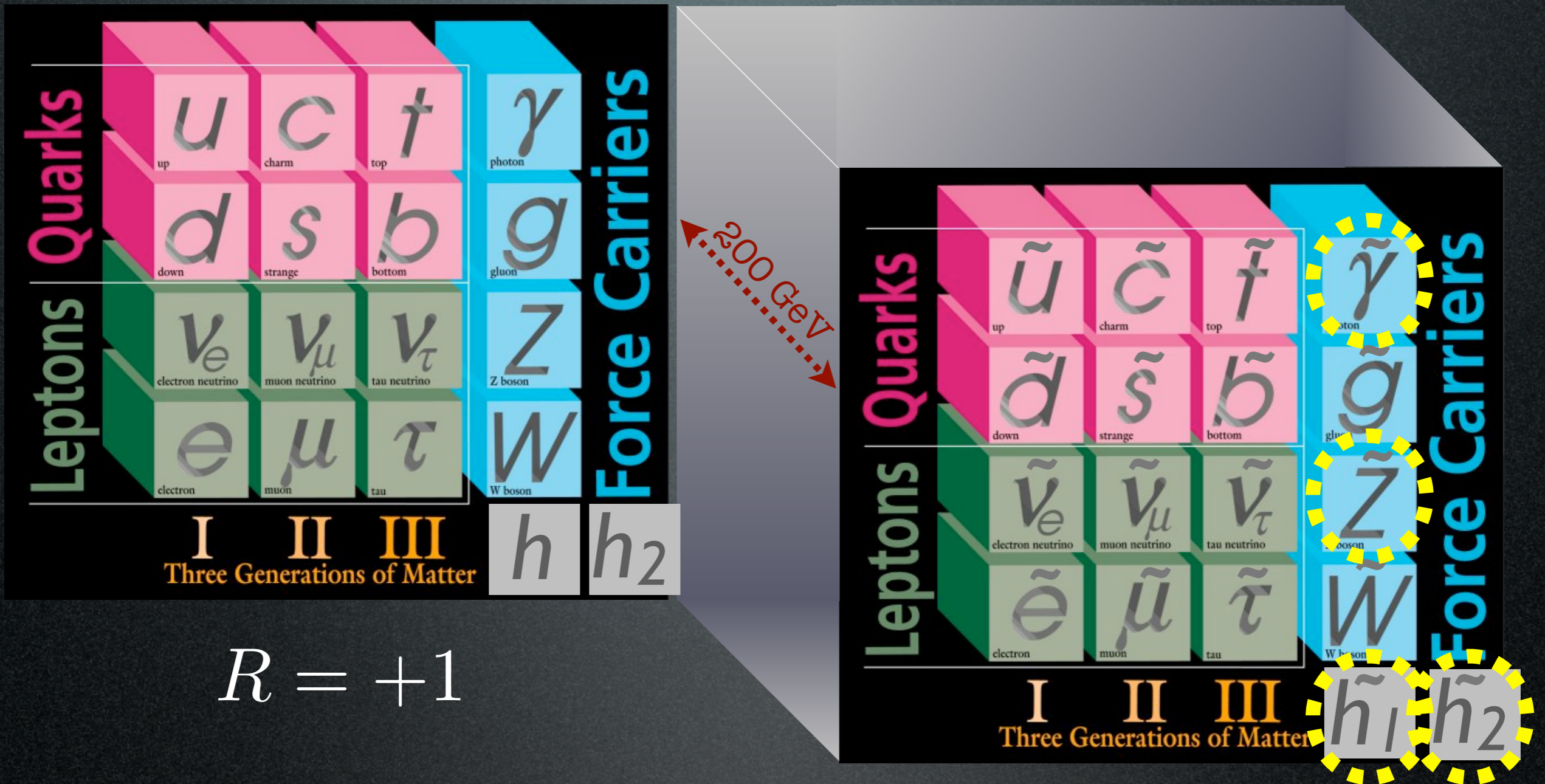
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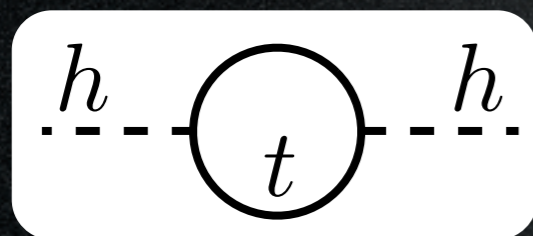
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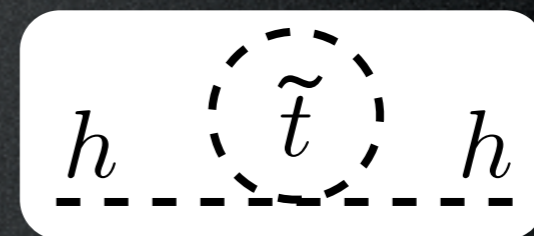
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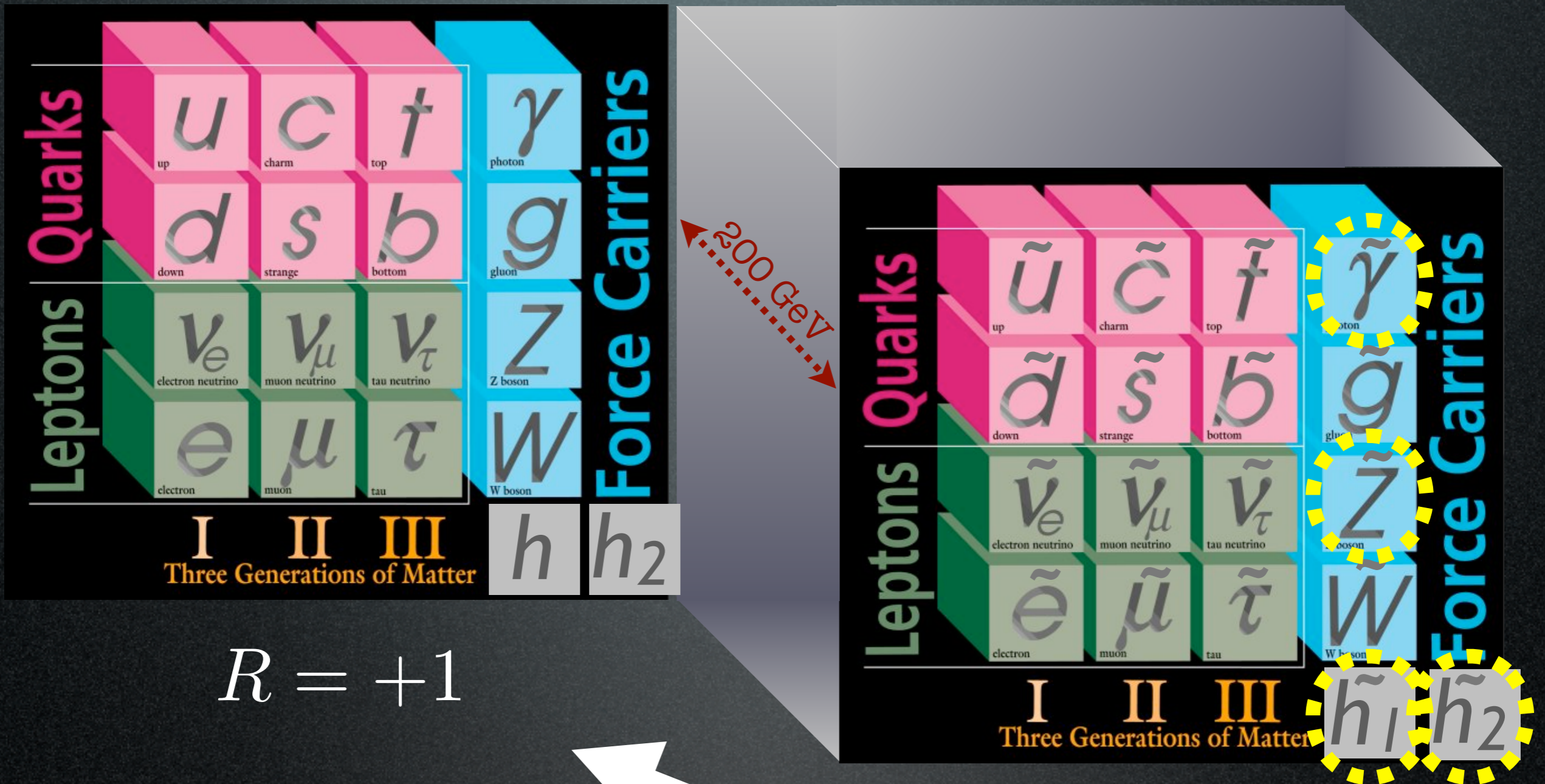
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$$R = -1$$



$$\Delta m_h \propto -10^{19} \text{ GeV}$$

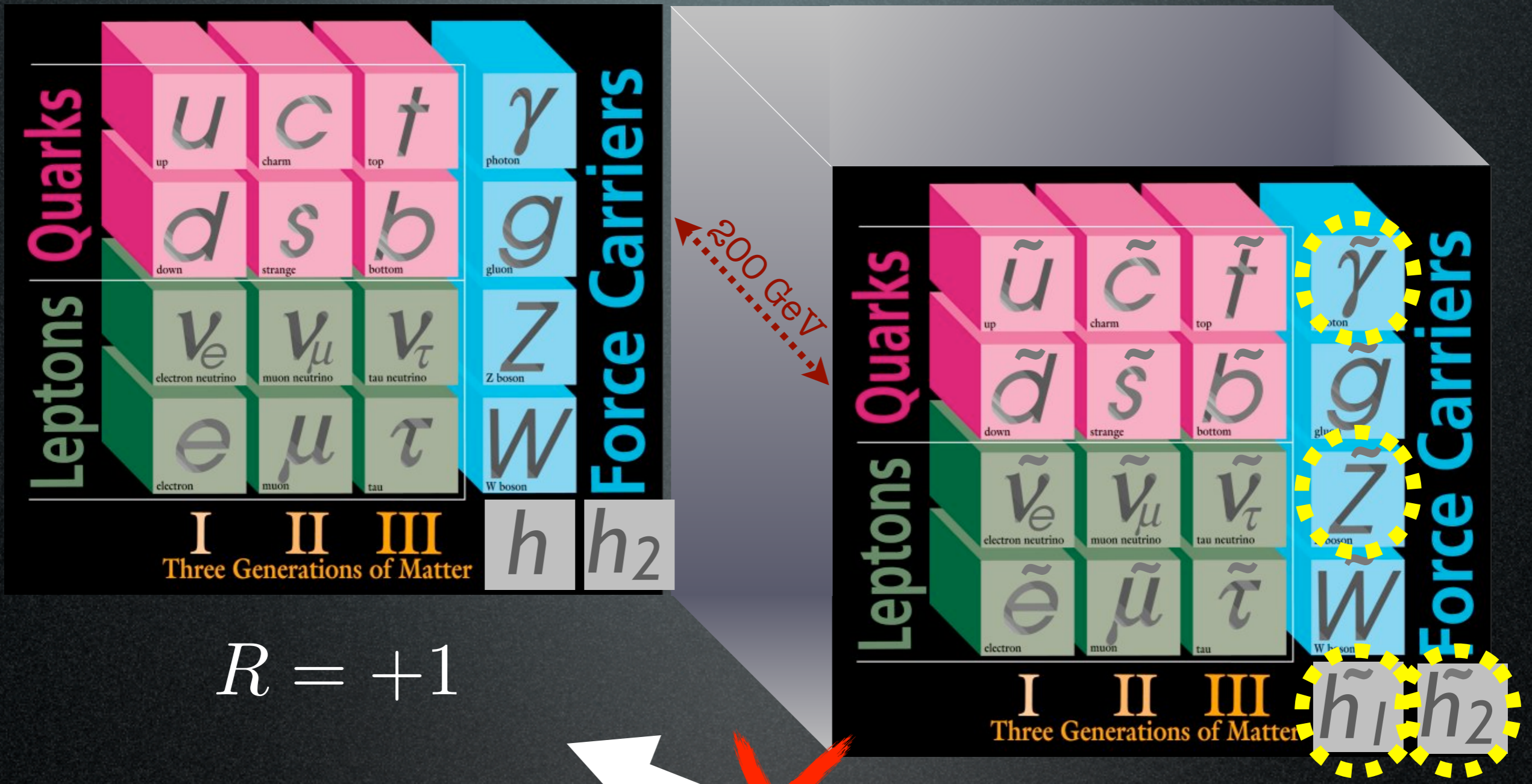
SuSy DM in 2 minutes



$$R = +1$$

$$R = -1$$

SuSy DM in 2 minutes



$$R = +1$$

$$R = -1$$

prevent proton decay