8 September 2022
RADPyC - XXXVI Annual Meeting of the Division of Particles and Fields, Mexico (remote)

Sub-GeV Dark Matter and X-rays

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

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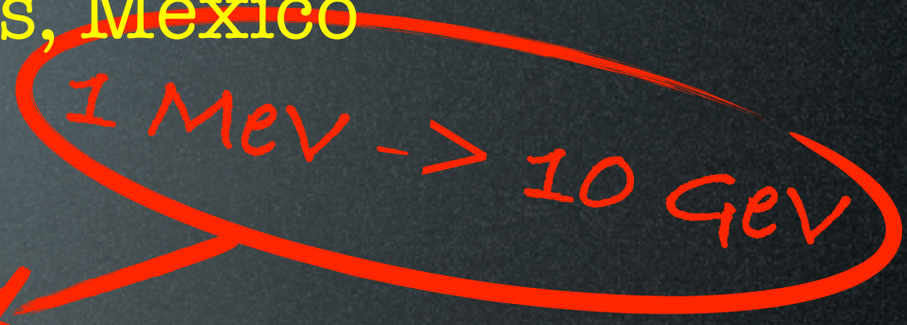


Sub-GeV Dark Matter and X-rays

Marco Cirelli
(CNRS LPTHE Jussieu Paris)

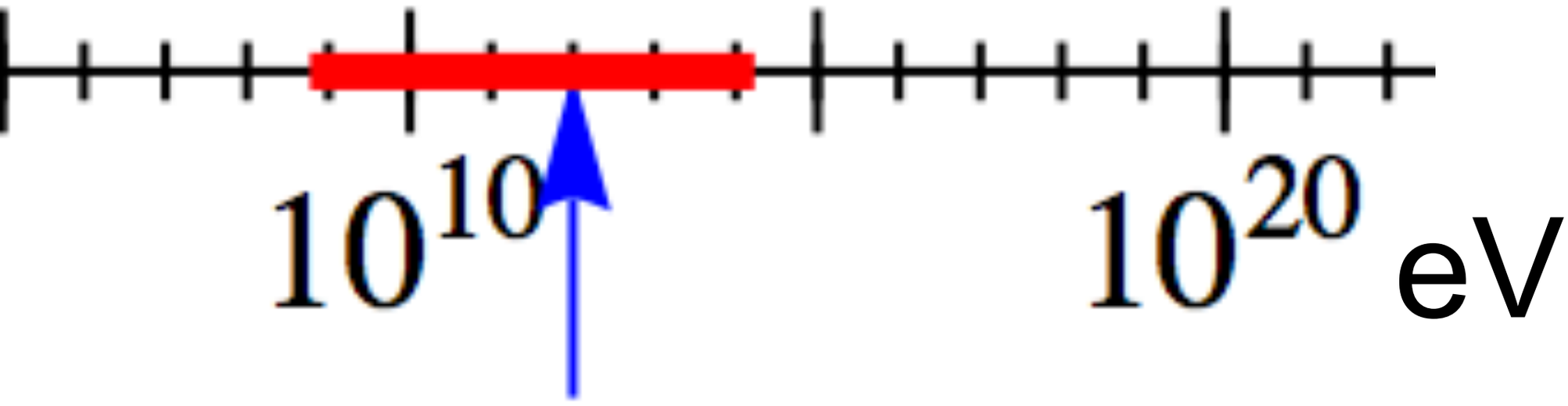
based on : Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493
+ work in progress

Candidates

A matter of perspective: plausible mass ranges

thermal

particles



weak scale (1 TeV)

Candidates

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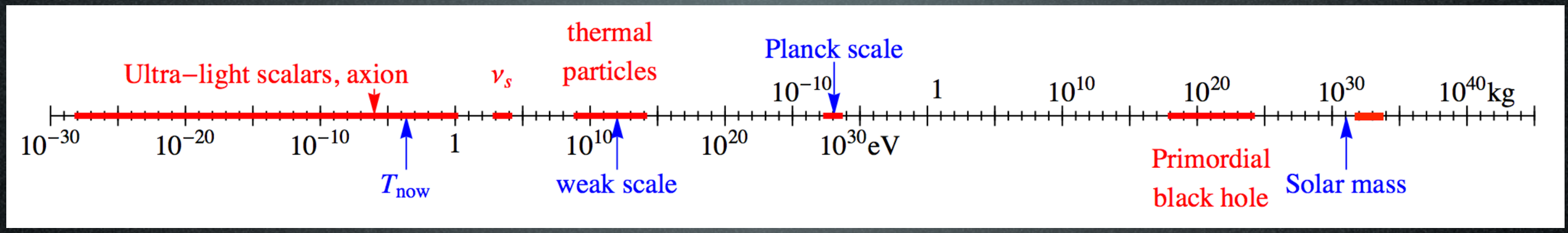

90 orders of magnitude!

Candidates

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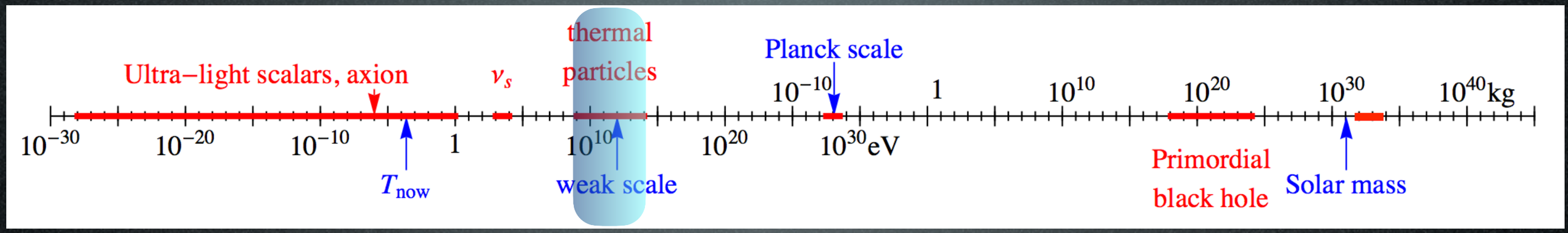

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Candidates

WIMPs

Candidates

new physics at the TeV scale

thermal freeze-out

Candidates

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thermal freeze-out

Collider Searches

Indirect Detection

Direct Detection

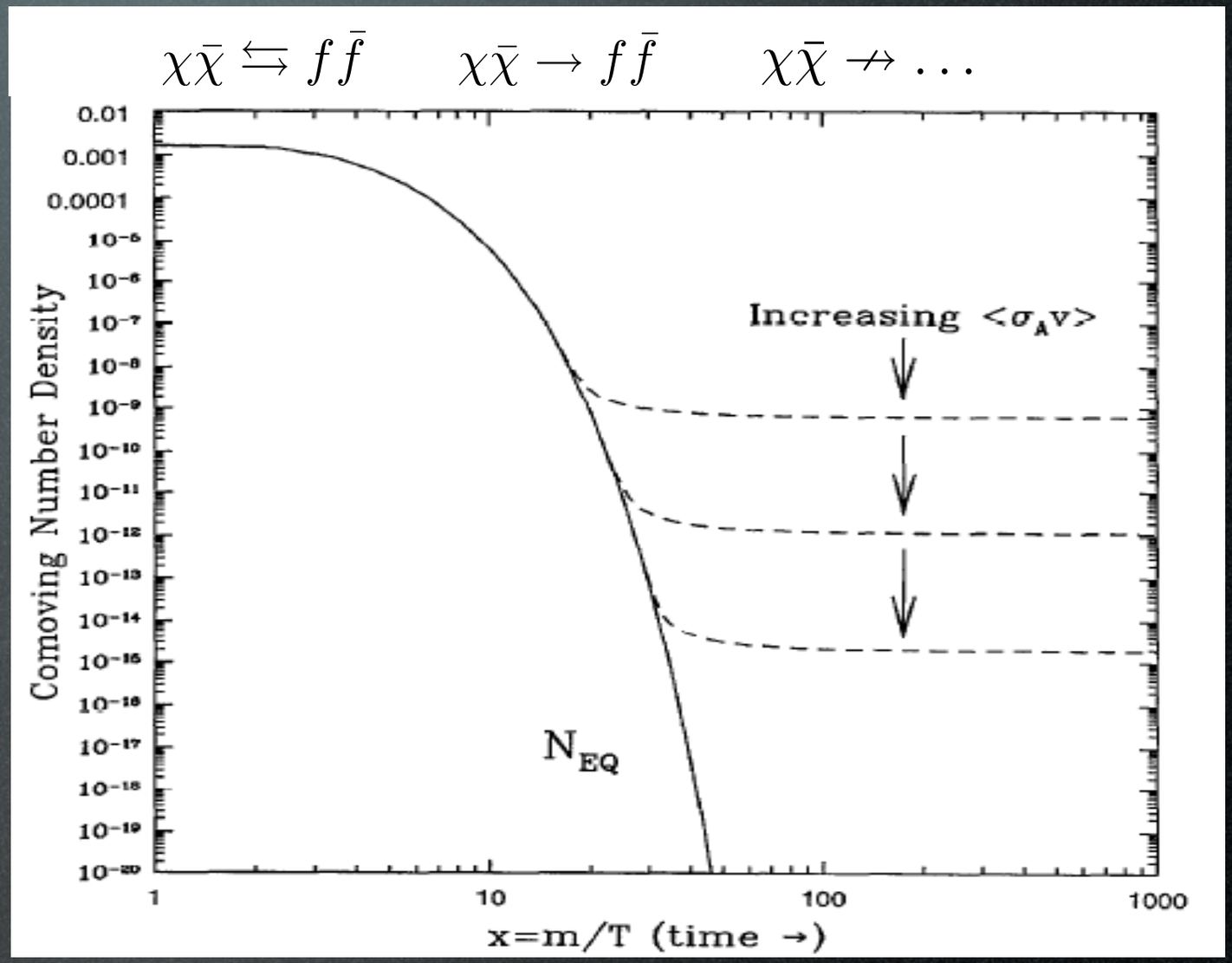
DM as a thermal relic from the Early Universe

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:

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

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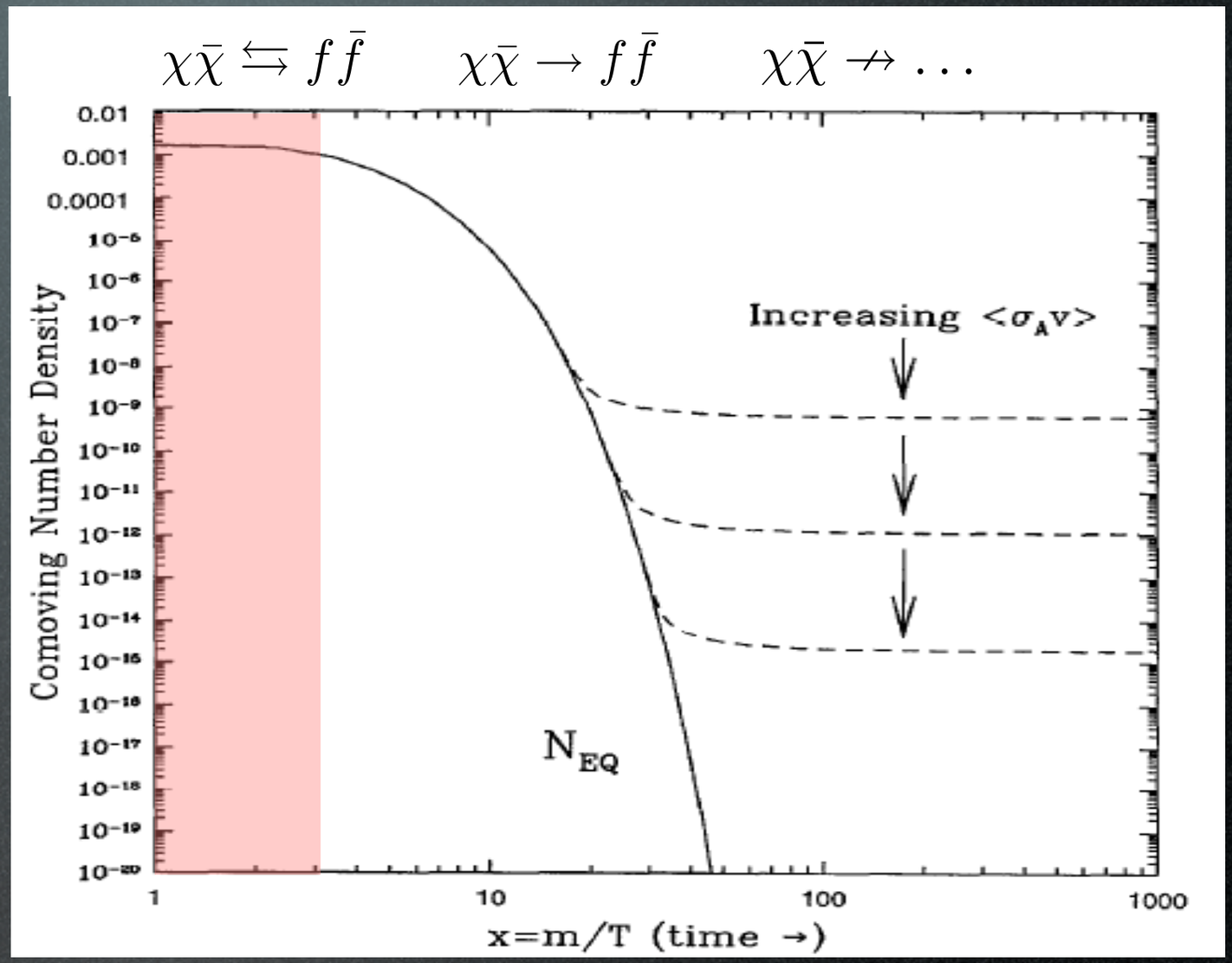

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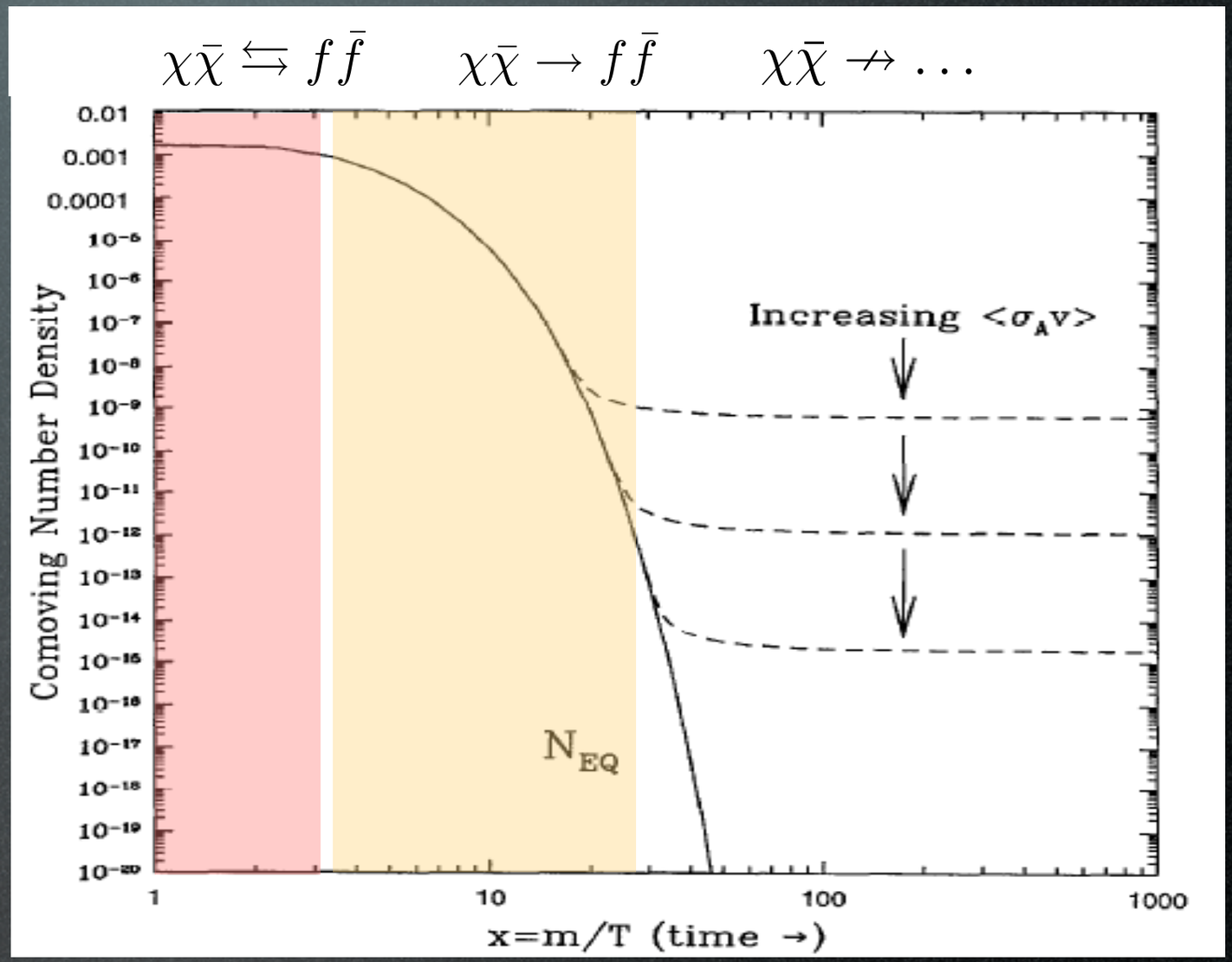

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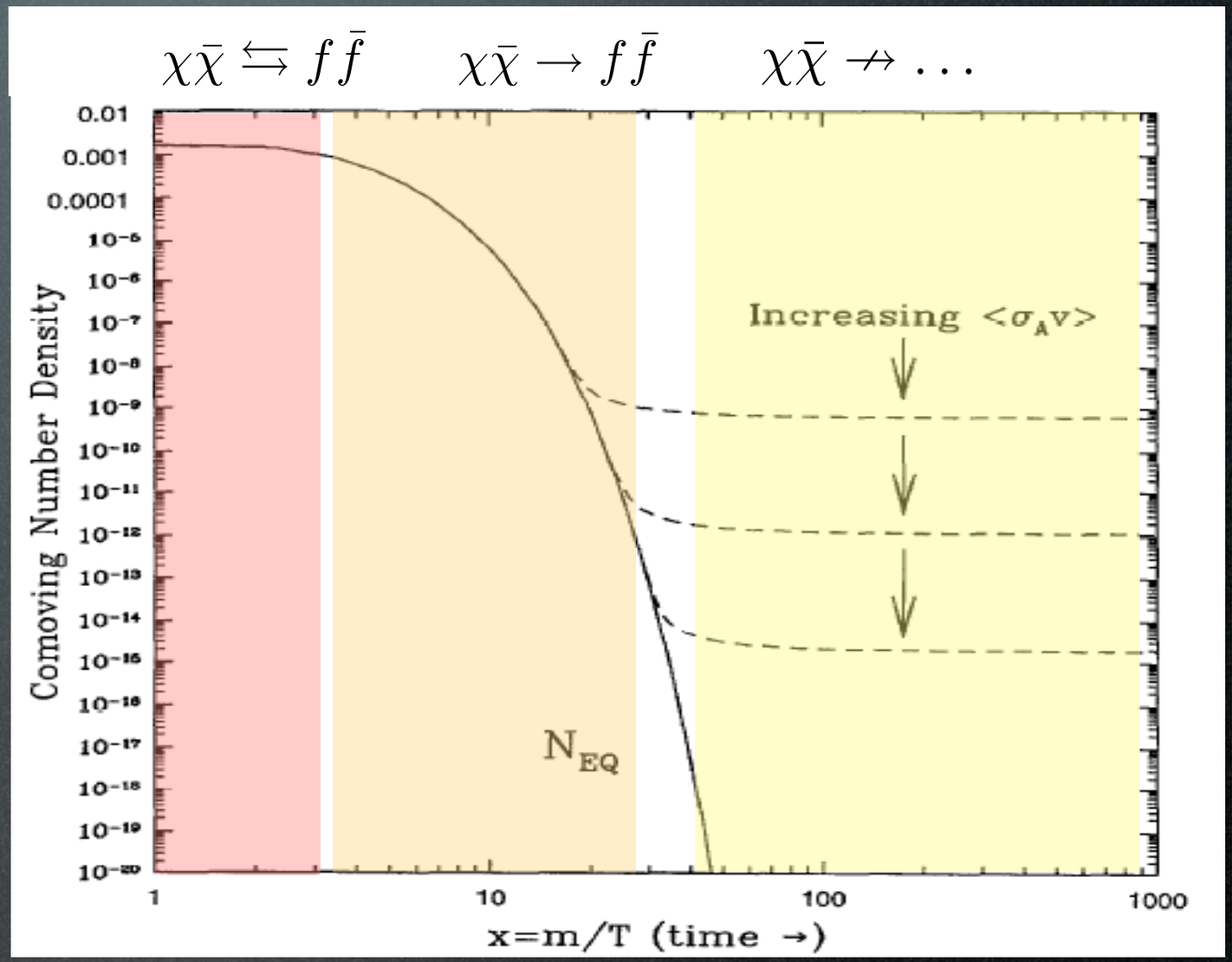

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(WIMP)

Candidates

new physics at the TeV scale

thermal freeze-out

Collider Searches

Indirect Detection

Direct Detection

Candidates

new physics at the TeV scale

thermal freeze-out

LHC

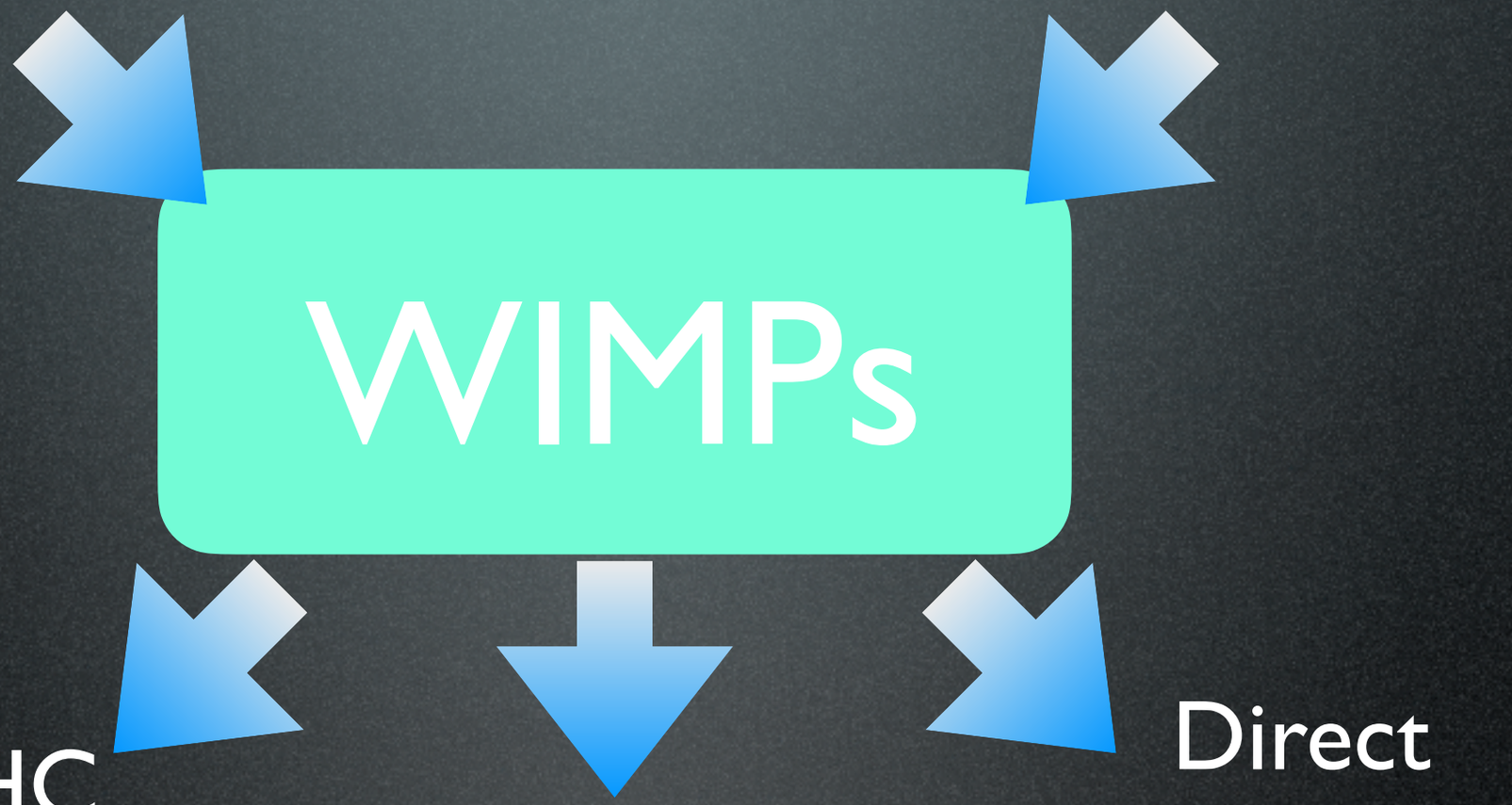
Fermi, AMS, IceCube…

Xenon, Lux, PandaX…

Candidates

new physics at the TeV scale

thermal freeze-out



LHC

Indirect Detection

Direct Detection

1.
2.

Candidates

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thermal freeze-out

1. even without a larger framework, WIMPs are still appealing
2.

Candidates

new physics at the TeV scale

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WIMPs

LHC

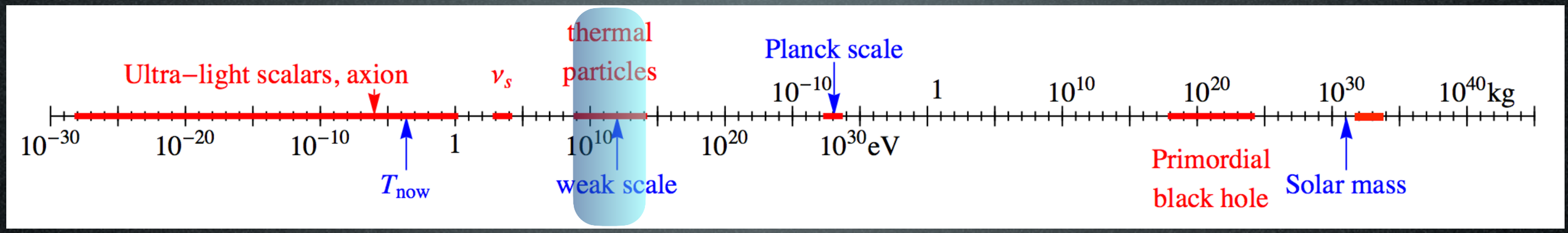
Indirect Detection

Direct Detection

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

Candidates

A matter of perspective: plausible mass ranges



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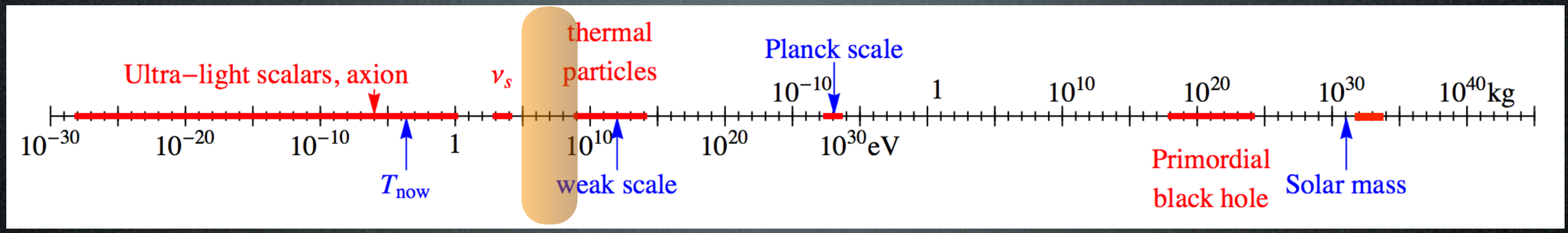

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Candidates

theory?

production?

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

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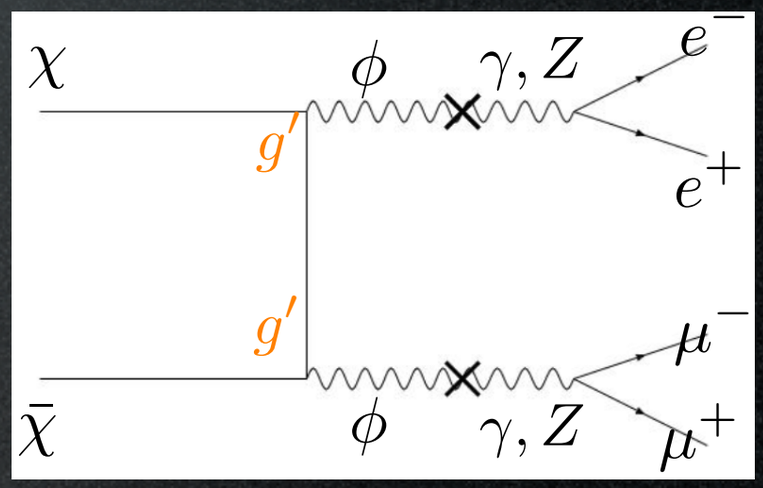
$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_x^2}{m^2}$$

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



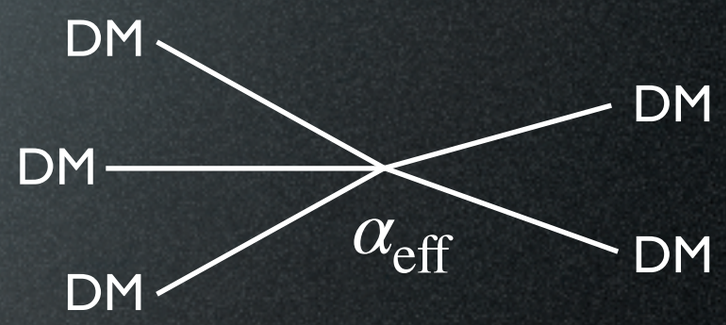
Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM

- ‘SIMP miracle’:

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



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

  Hochberg et al 1402.5143

‘naturally realized’ in a dark-QCD-like setup

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

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’

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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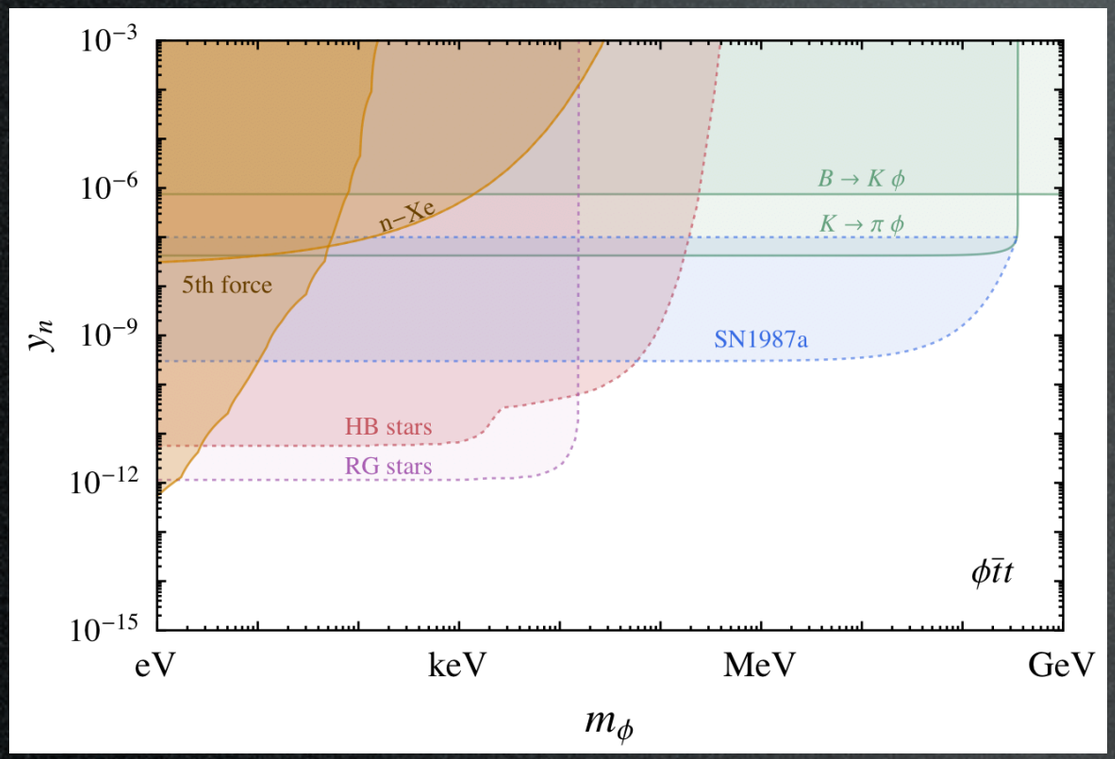

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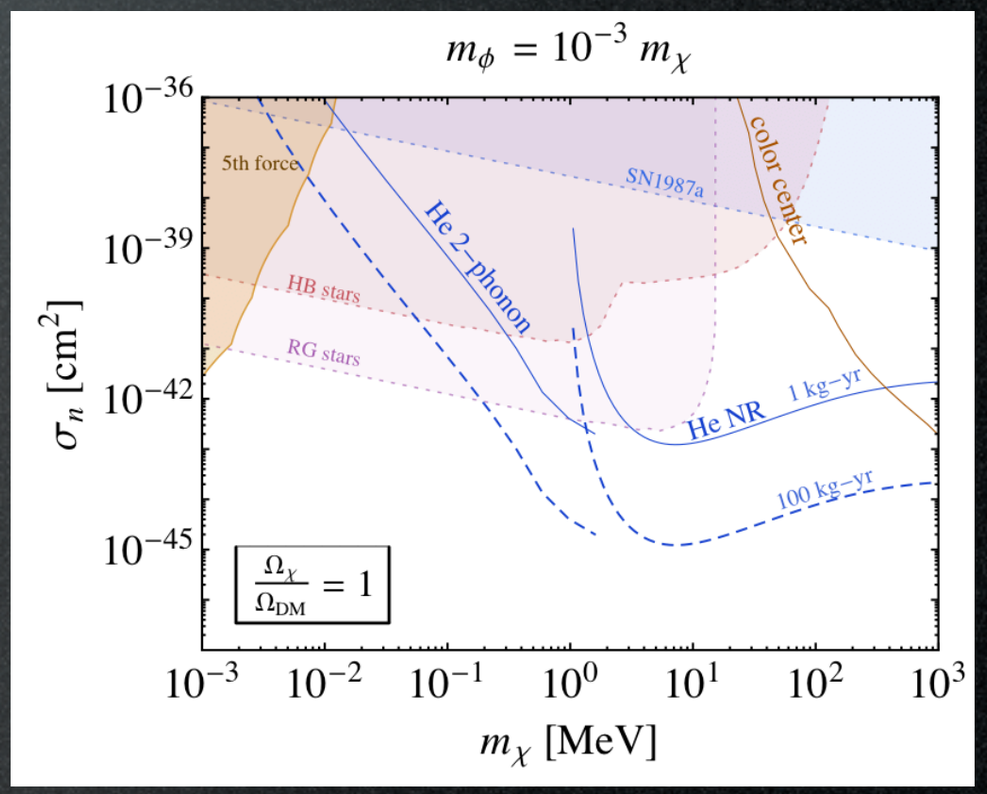

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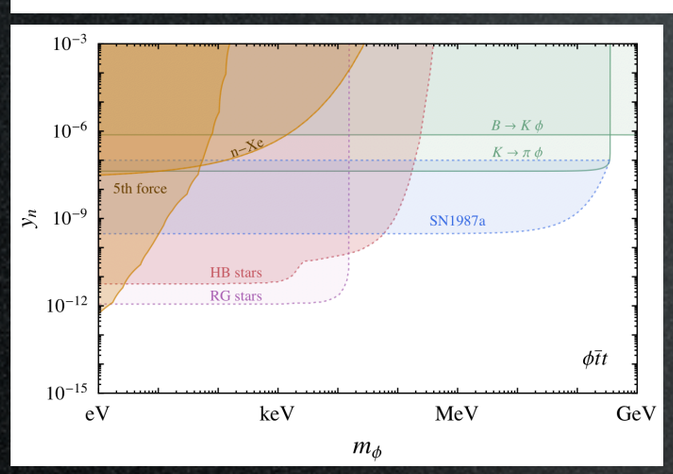

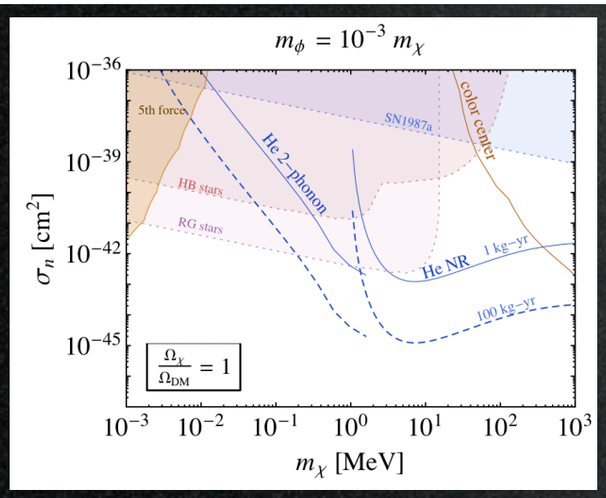

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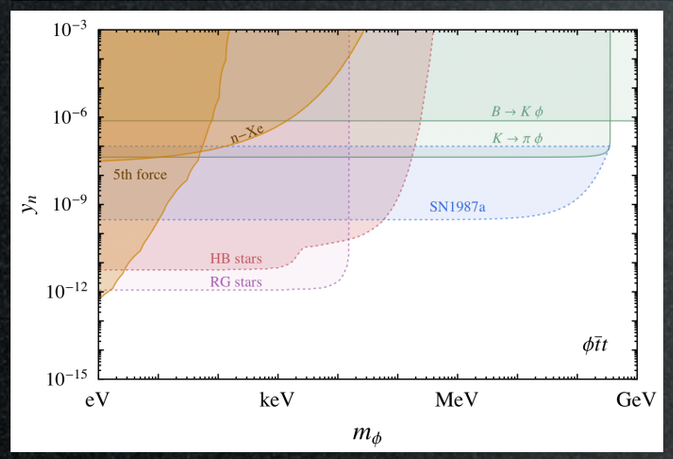

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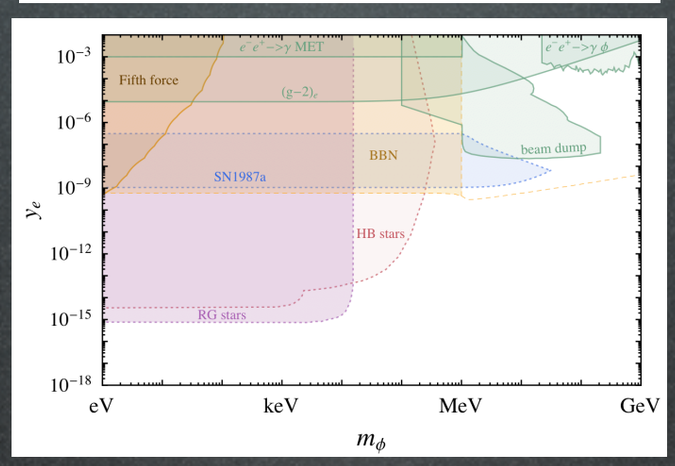

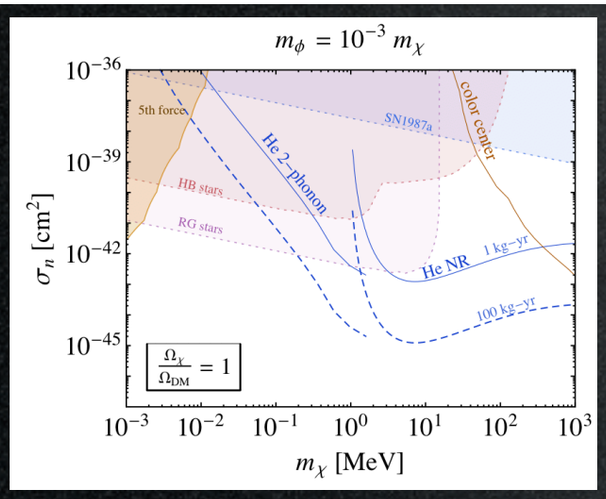

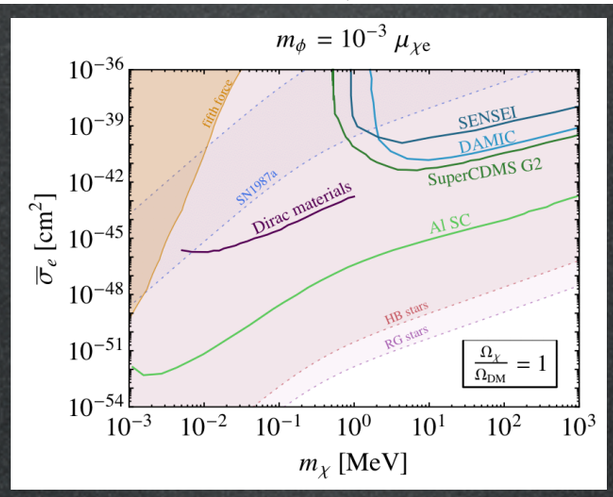

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Sub-GeV DM

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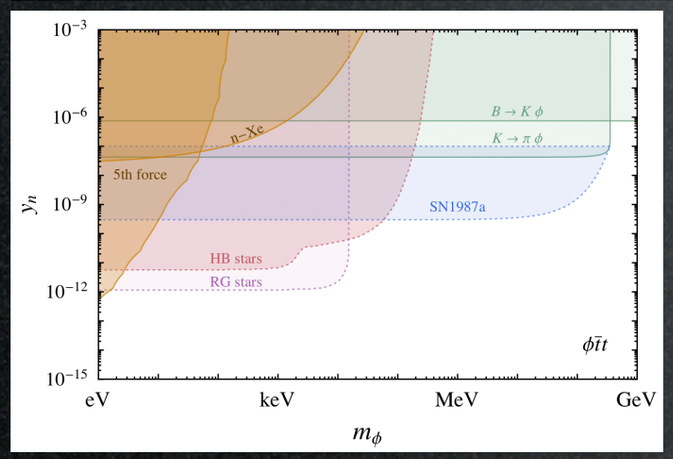

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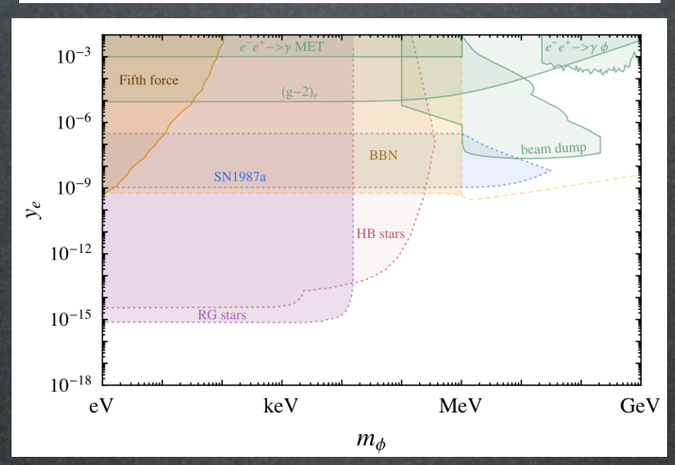
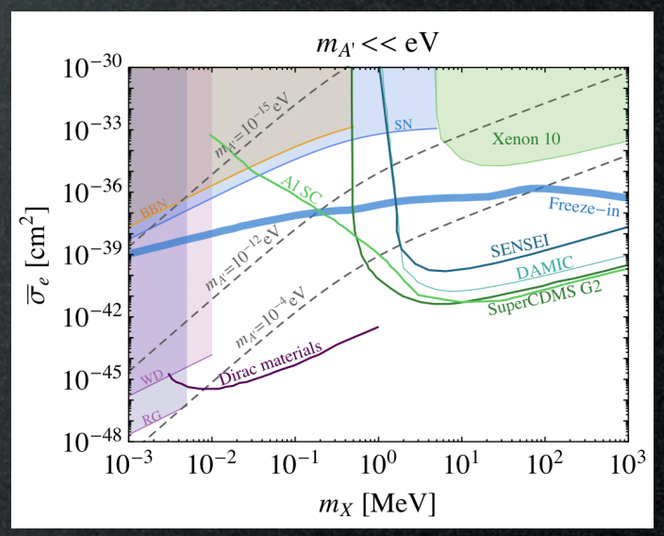
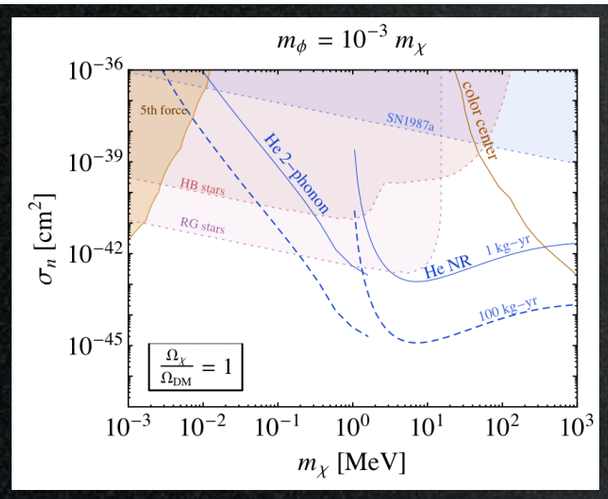
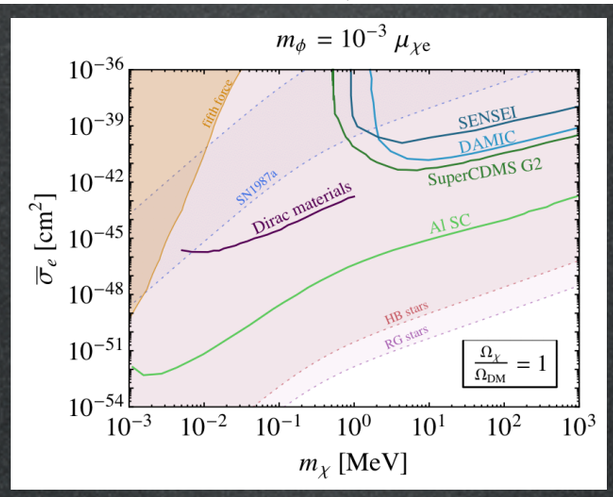


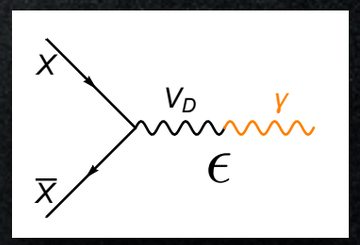
fermionic DM and vector mediator (e.g. dark photon)

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









Asymmetric DM: a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

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BBN, CMB...

$$\Omega_{\rm B} \propto m_{\rm B}\, \eta_{\rm B}$$

'Darko'genesis:

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$$m_{\rm DM} \simeq 5 \text{ GeV}$$

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!

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Candidates

theory

production

Sub-GeV DM?

Collider Searches?

Indirect Detection?

Direct Detection?

Candidates

theory

production

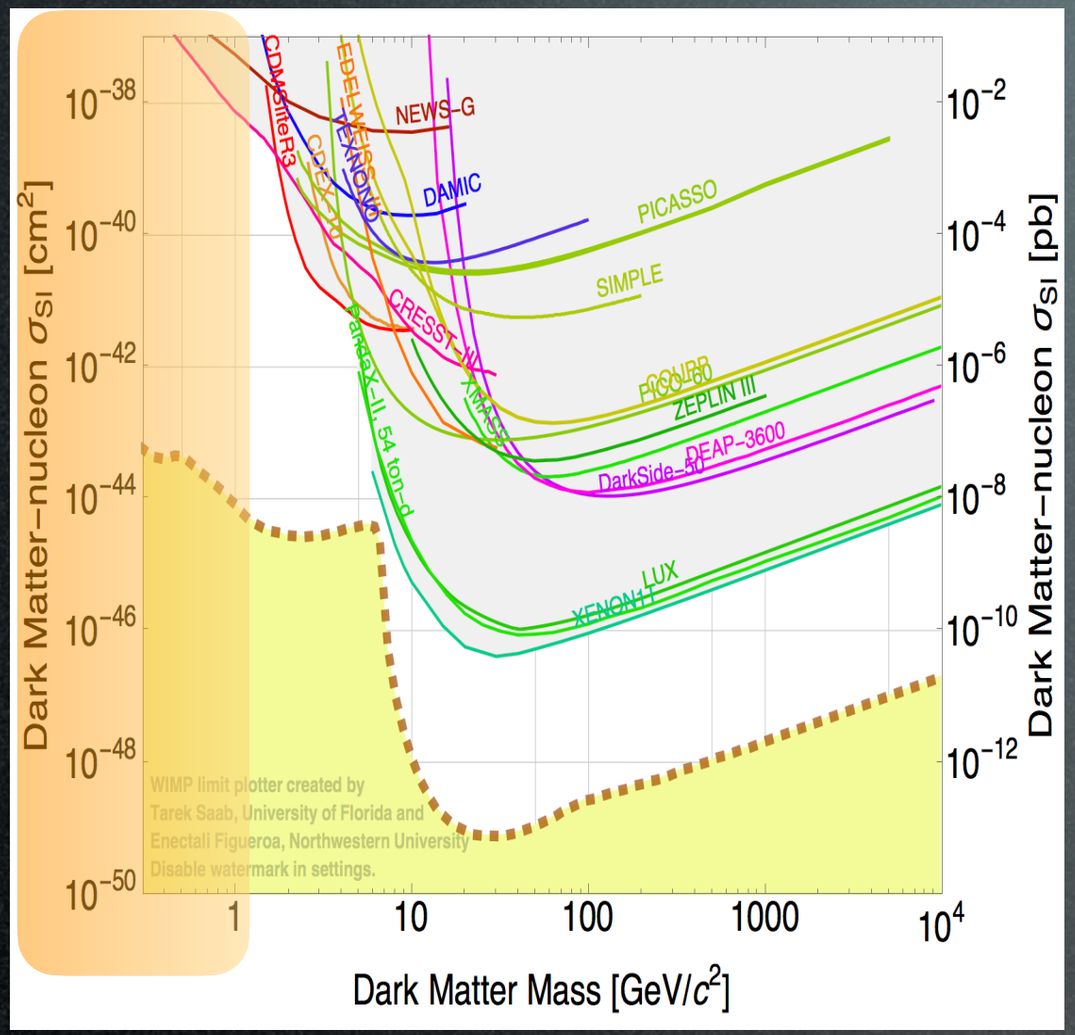
Sub-GeV DM?

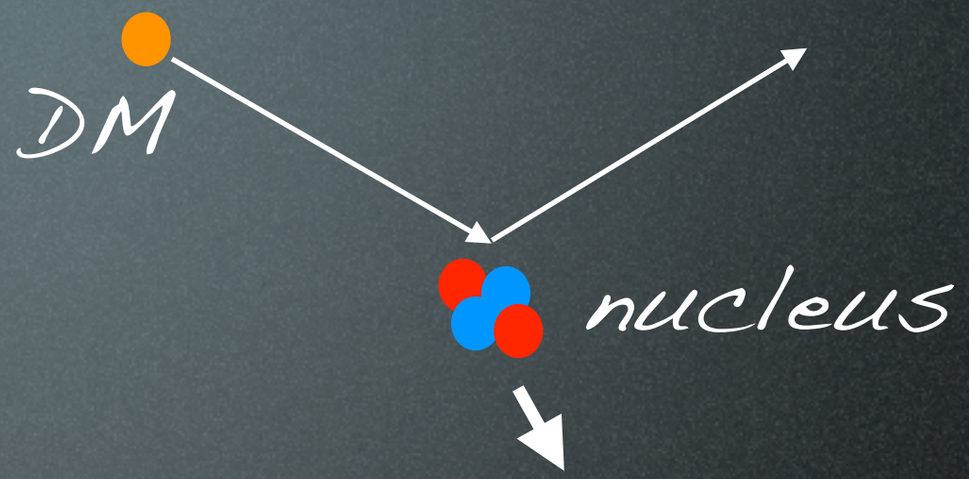
Collider Searches?

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

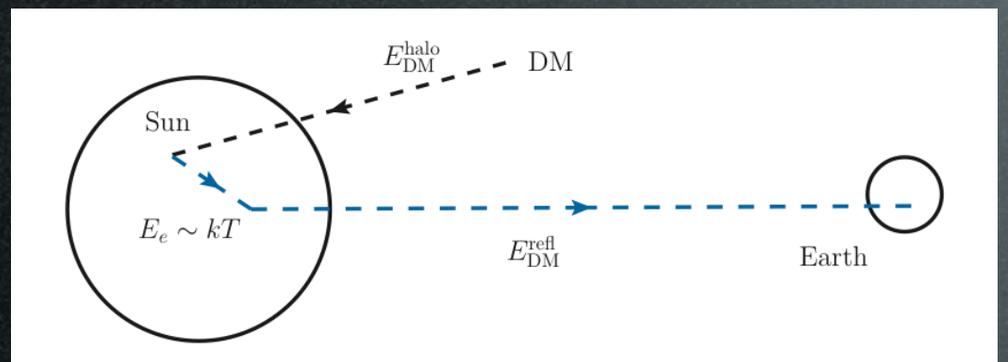
Direct Detection of sub-GeV DM

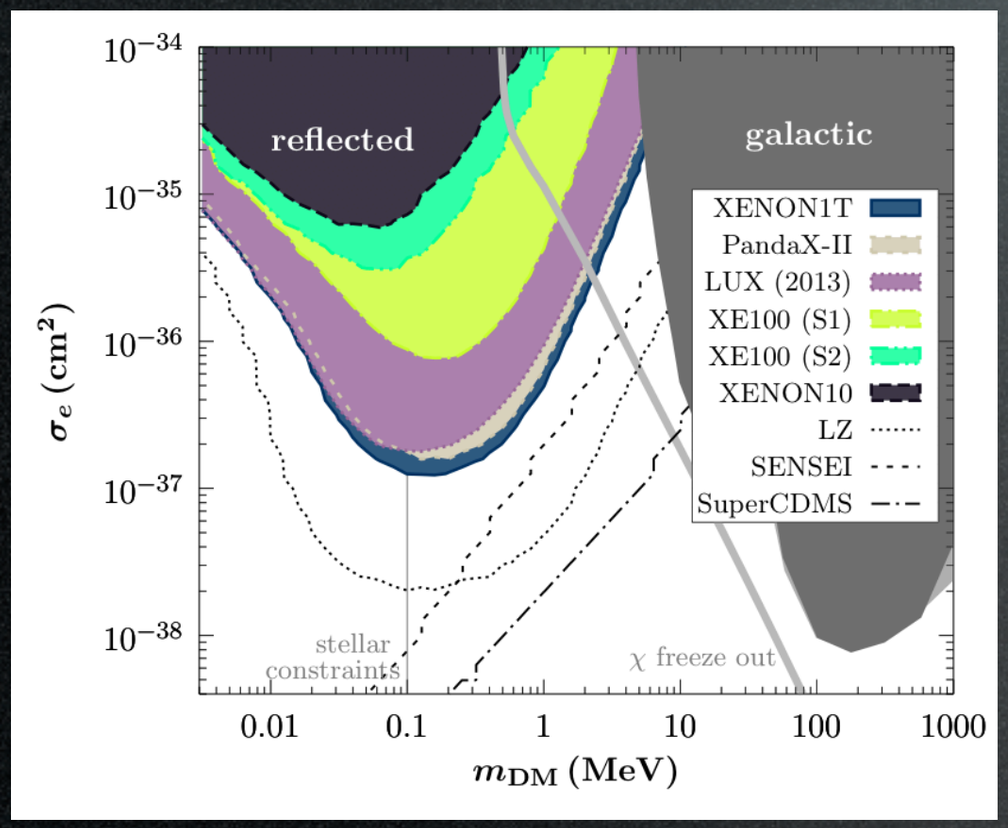
R. Essig, J. Mardon, T. Volansky 'Direct Detection of Sub-GeV Dark Matter' 1108.5383
R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky 'First Direct Detection Limits on sub-GeV Dark Matter from XENON10' 1206.2644
C. Kouvaris, J. Pradler 'Probing sub-GeV Dark Matter with conventional detectors' 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
J. H. Davis 'Probing Sub-GeV Mass Strongly Interacting Dark Matter with a Low-Threshold Surface Experiment' 1708.01484
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
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
...

“Direct Detection” of sub-GeV DM

‘Reflected DM’

light DM upscattered by hot e^- in the Sun gives signal above threshold
(DM-e scattering, twice)



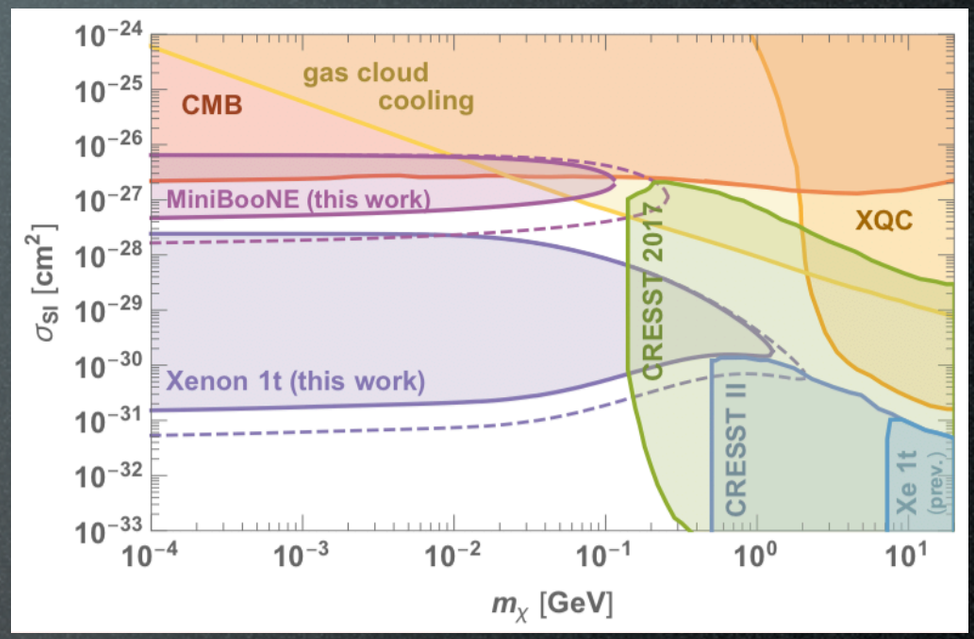


An, Pospelov, Pradler, Ritz 1708.03642

original idea with DM-nucleon scattering:
Kouvaris+ 1506.04316, 1709.06573

‘CR DM’

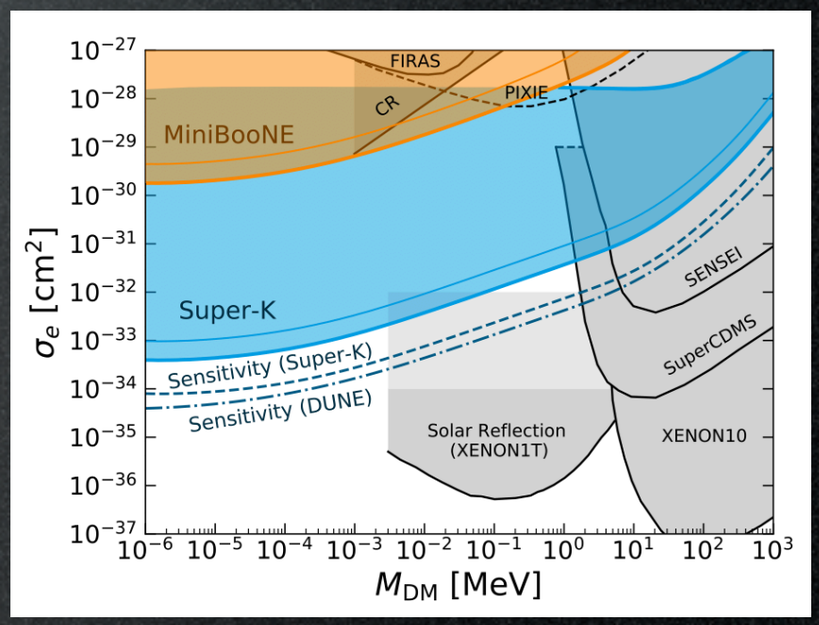
DM upscattered by HE CRs gives signal above threshold in DD even if light



Bringmann, Pospelov 1810.10543

same idea with electron scattering and signal in SK

Ema, Sala, Sato 1810.10543



improvements: Cappiello & Beacom 1906.11283

another incarnation: light DM produced in spallations of CR on atmosphere
Alvis, Fairbairn+ 1905.05776

Candidates

theory

production

Sub-GeV DM?

Collider Searches?

Indirect Detection?

Direct Detection

Candidates

theory

production

Sub-GeV DM?

Collider Searches?

Indirect Detection?

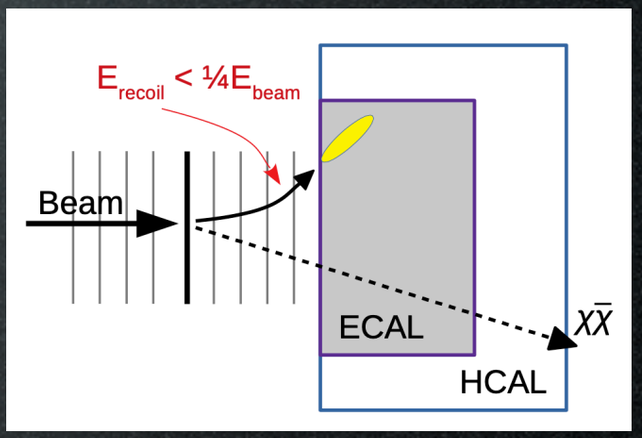
Direct Detection

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. 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.

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theory

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Collider Searches

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Candidates

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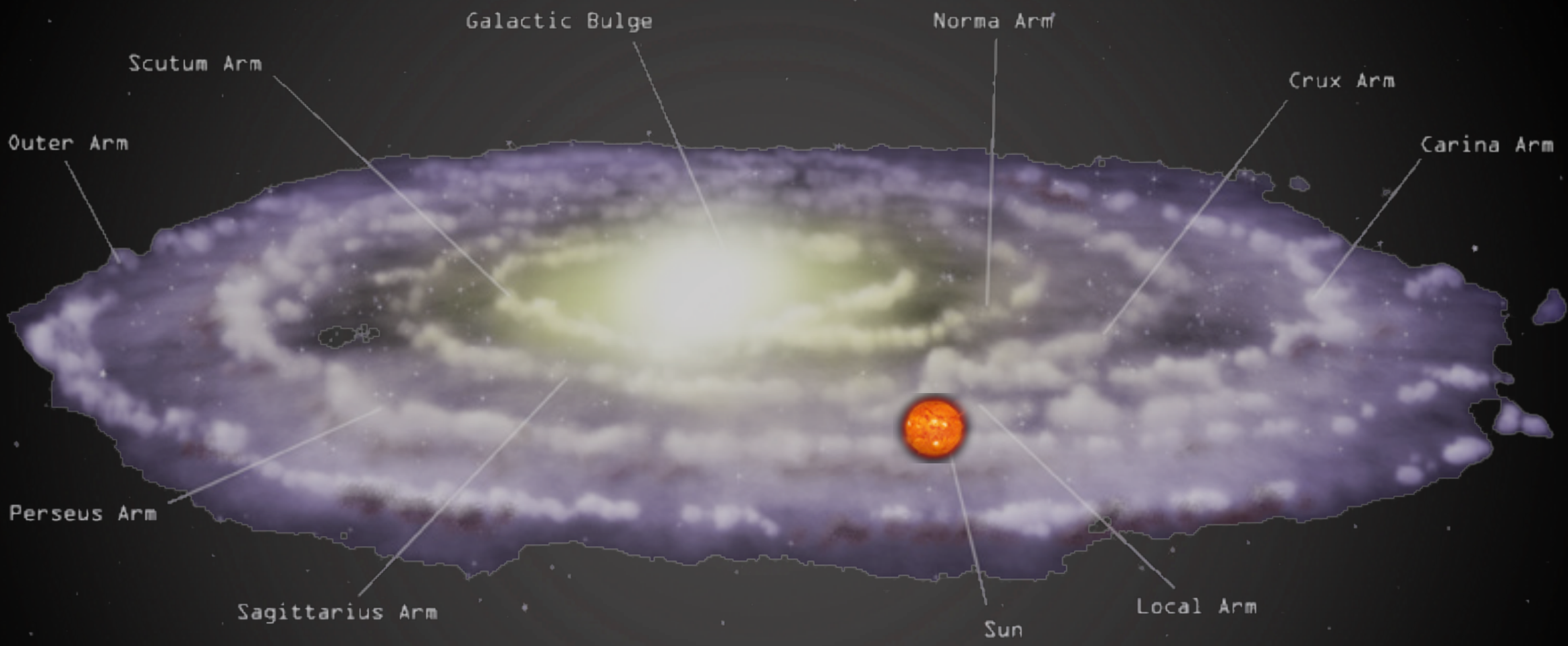
Direct Detection

Indirect Detection: charged CRs

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



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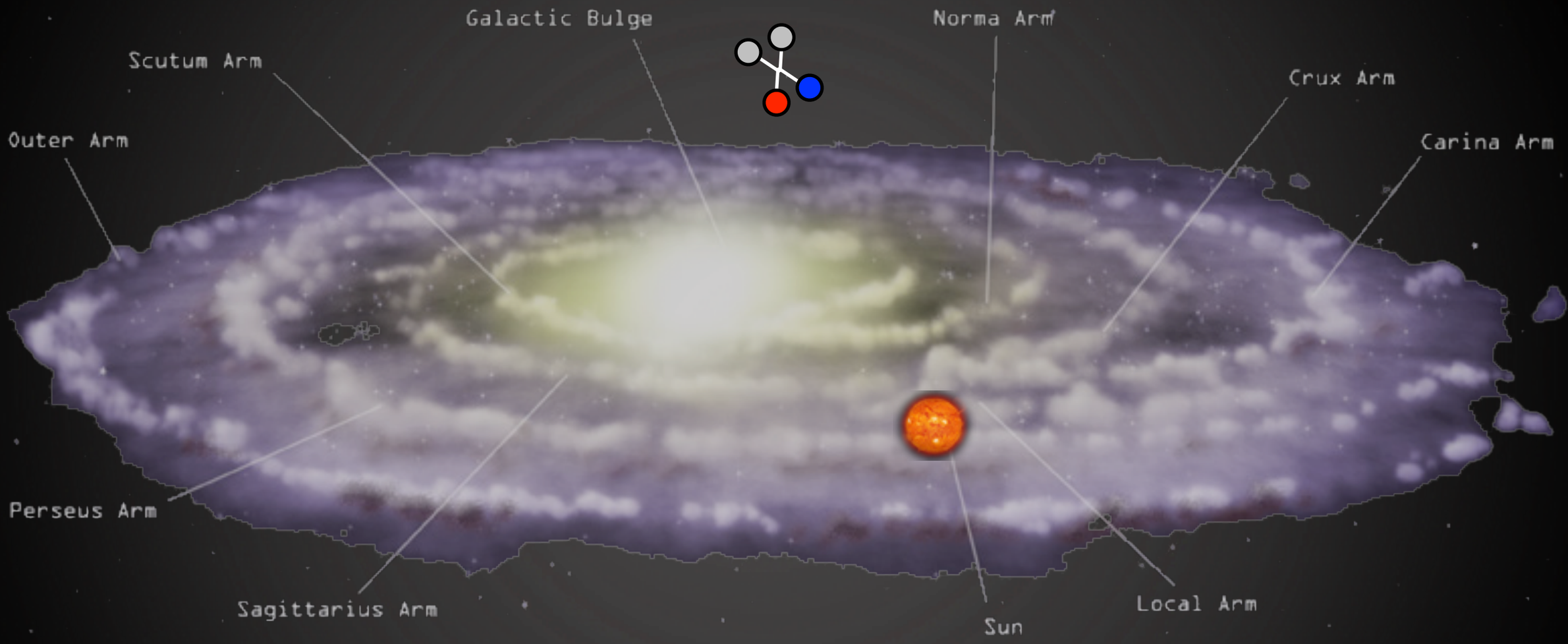

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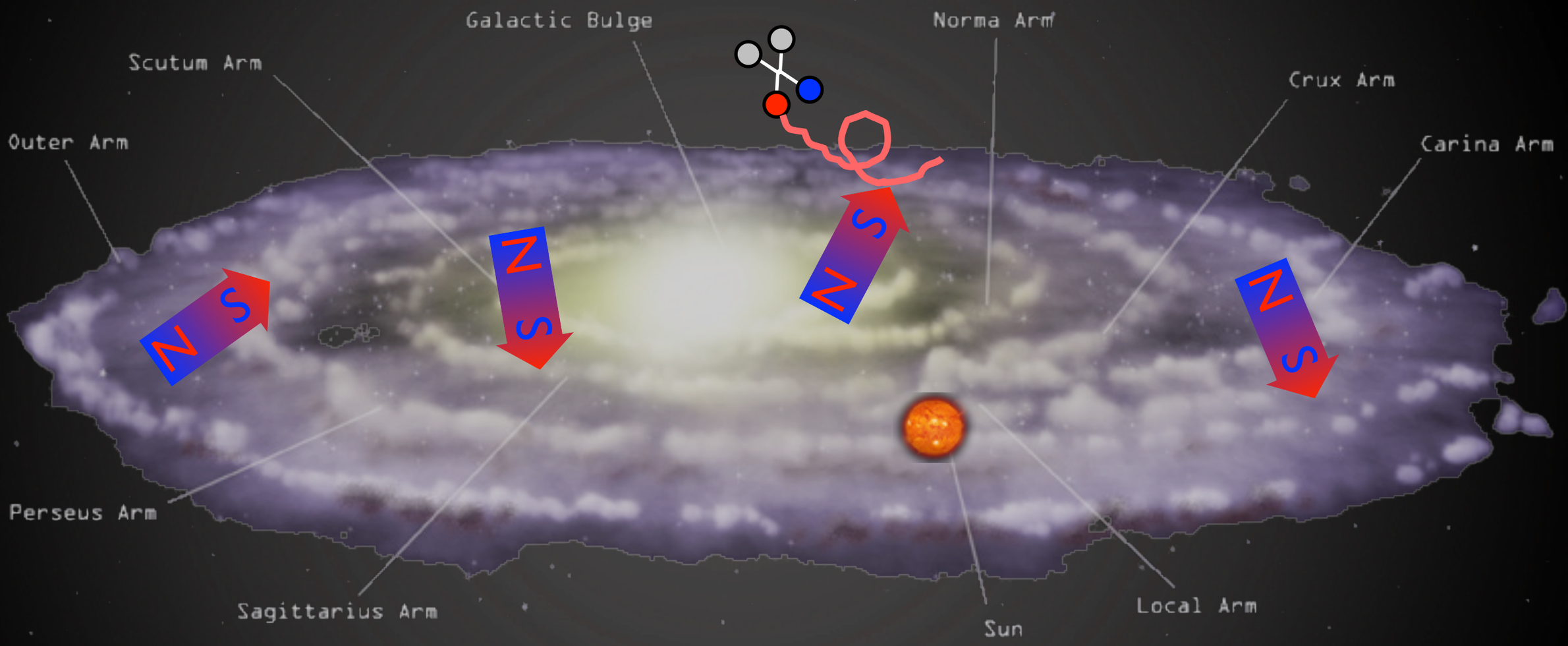

Indirect Detection: charged CRs

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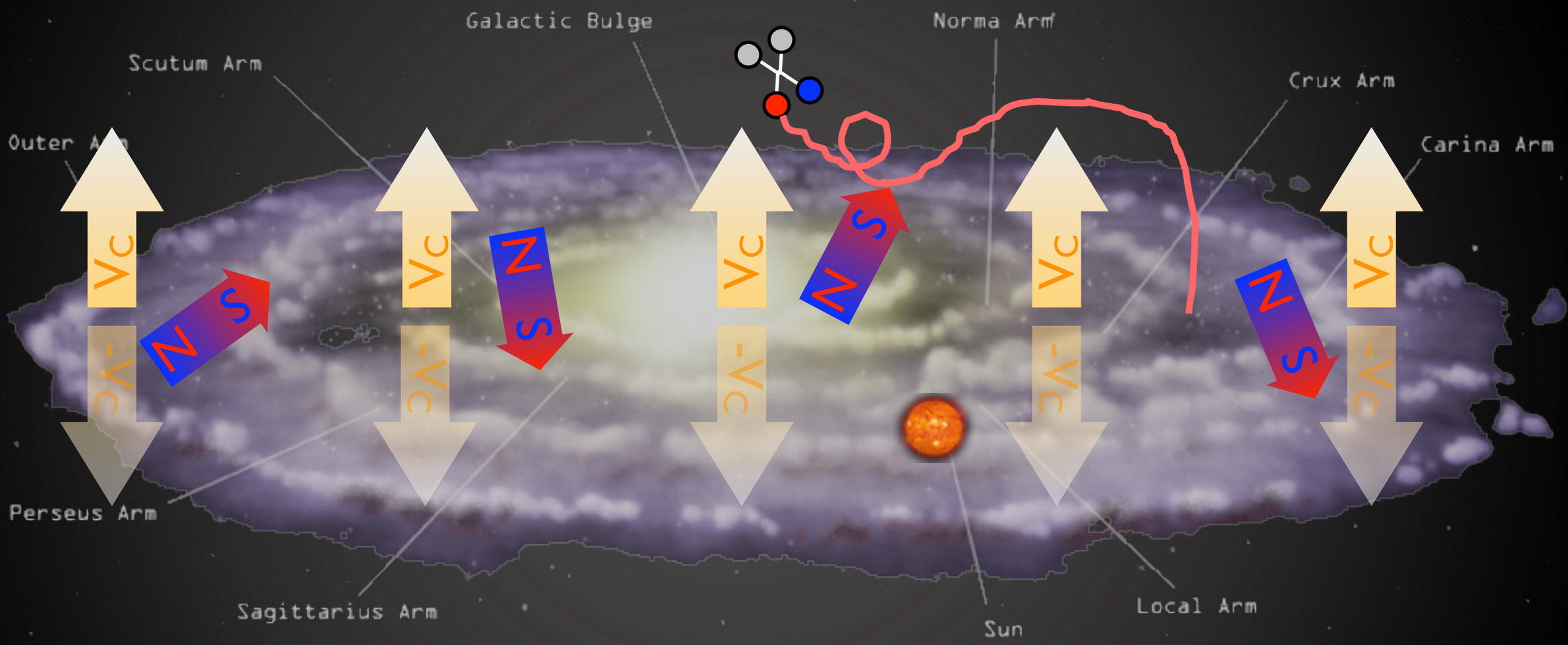

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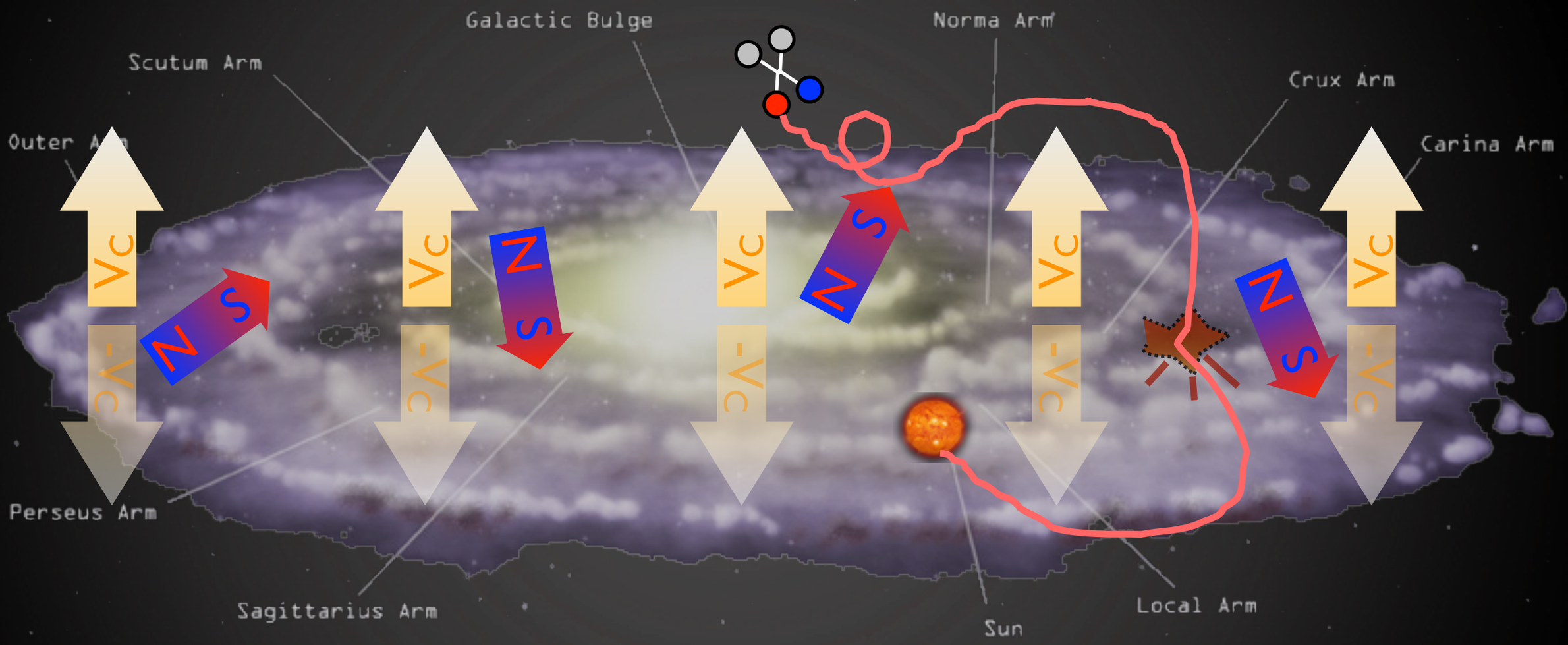

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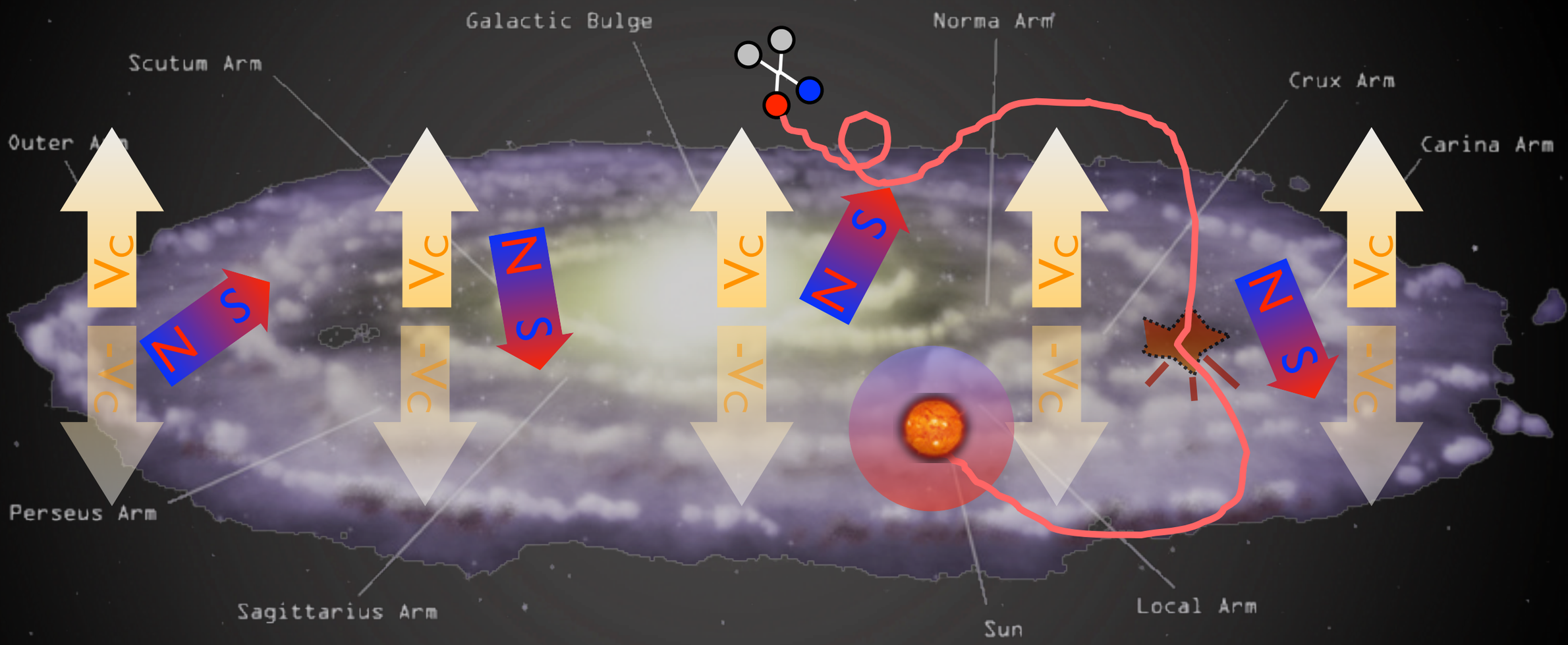

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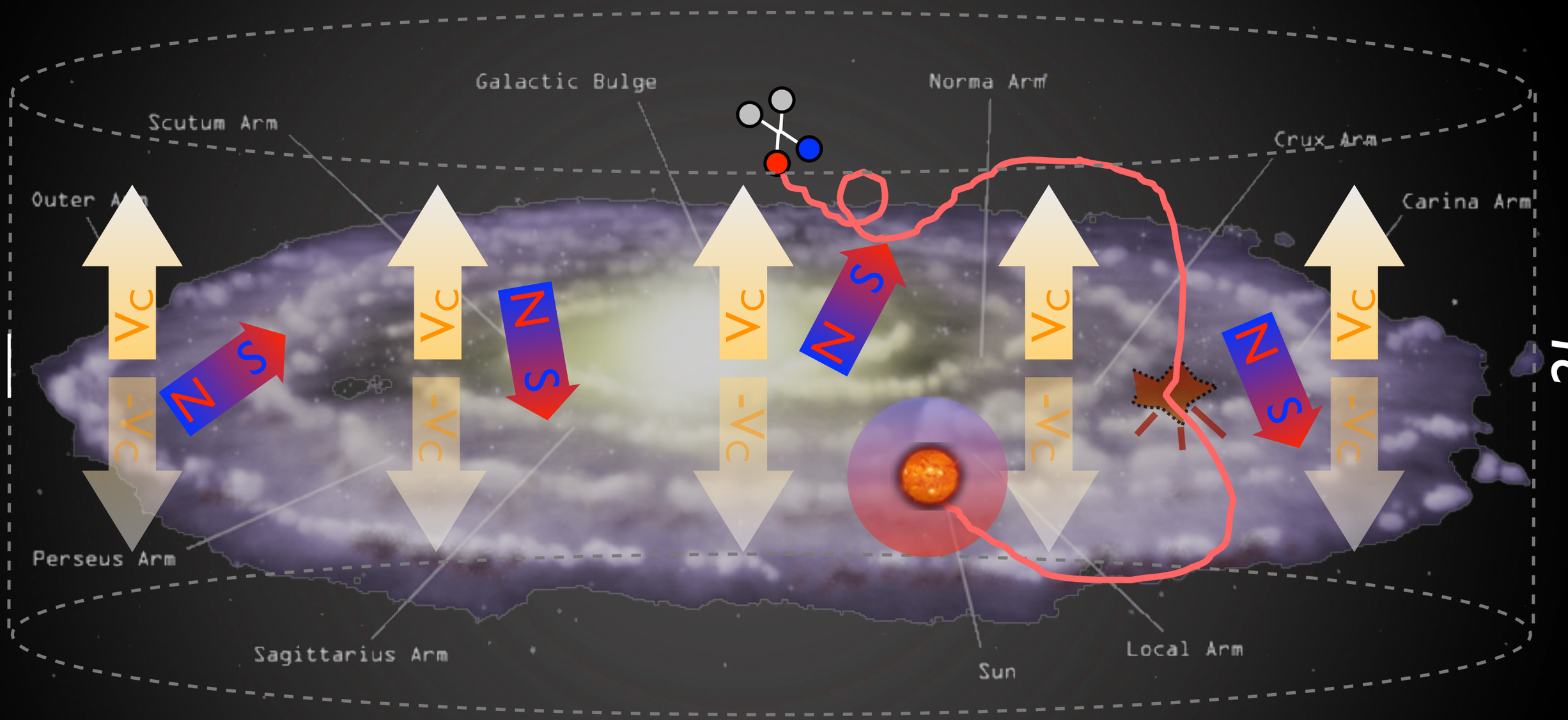


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

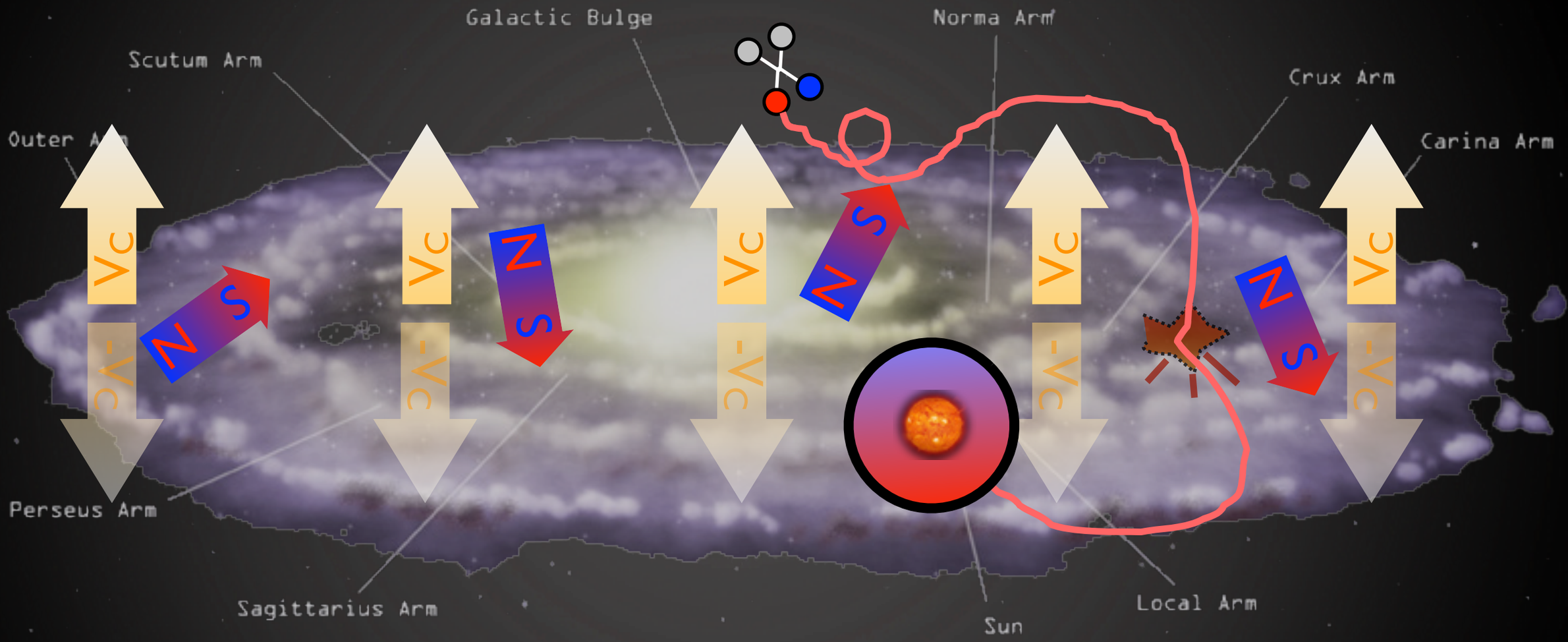
spectrum

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

diffusion | energy loss | convective wind | source | spallations

Indirect Detection: charged CRs

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



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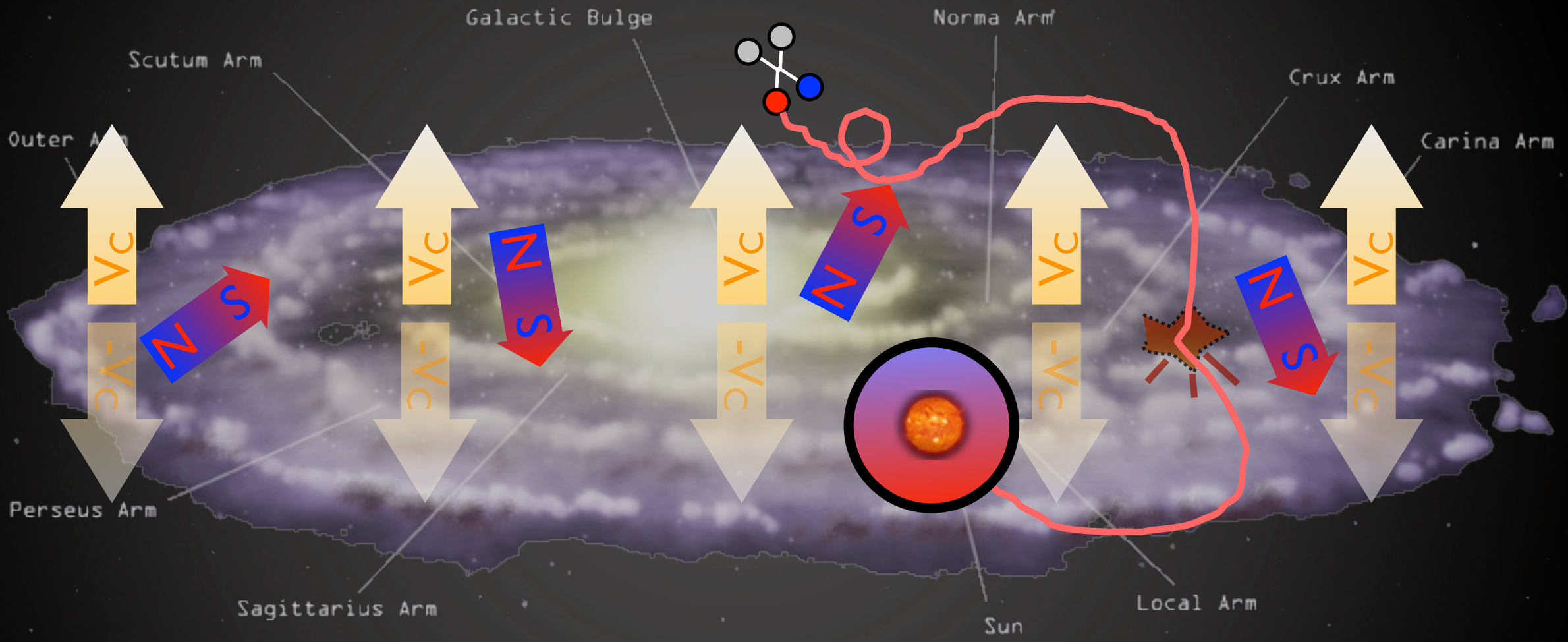

Problem:

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

Indirect Detection: charged CRs

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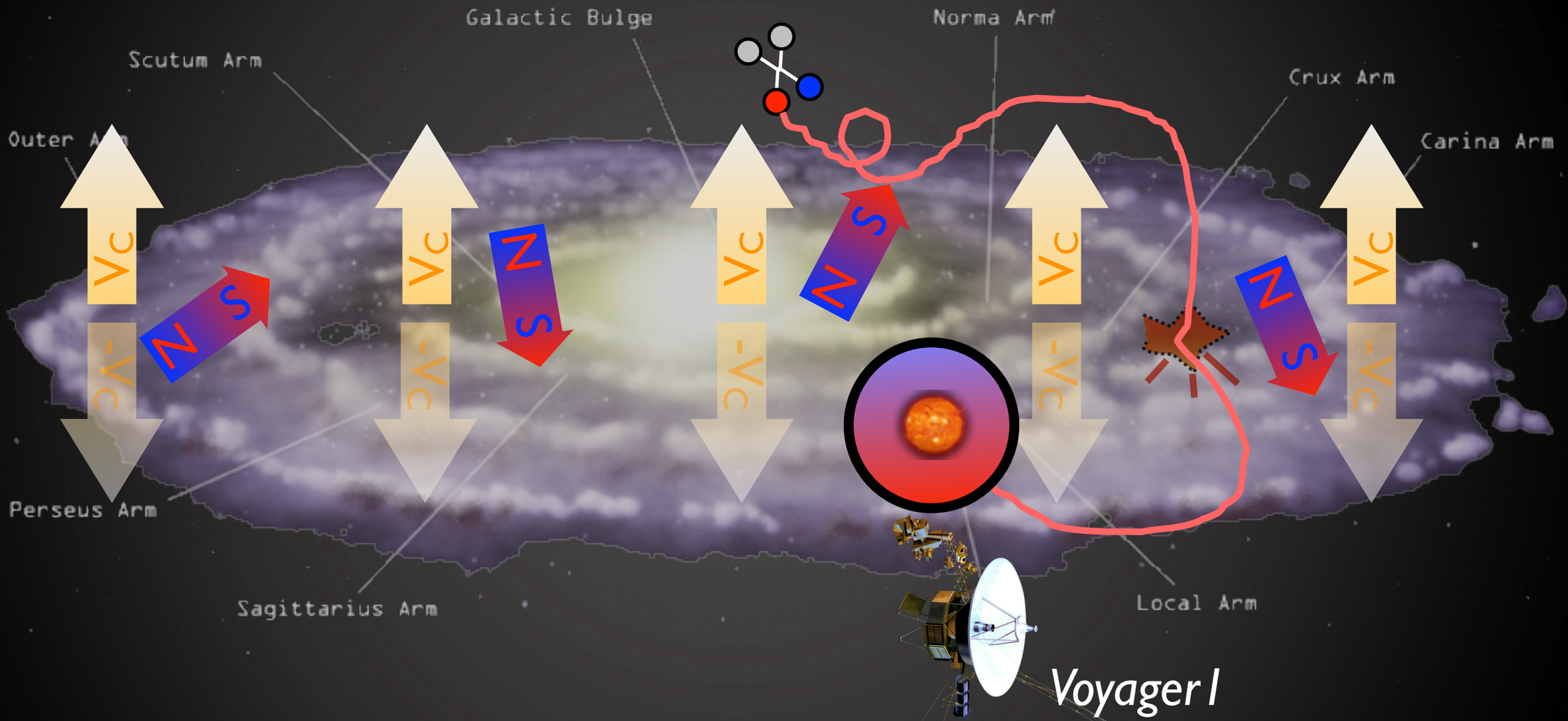


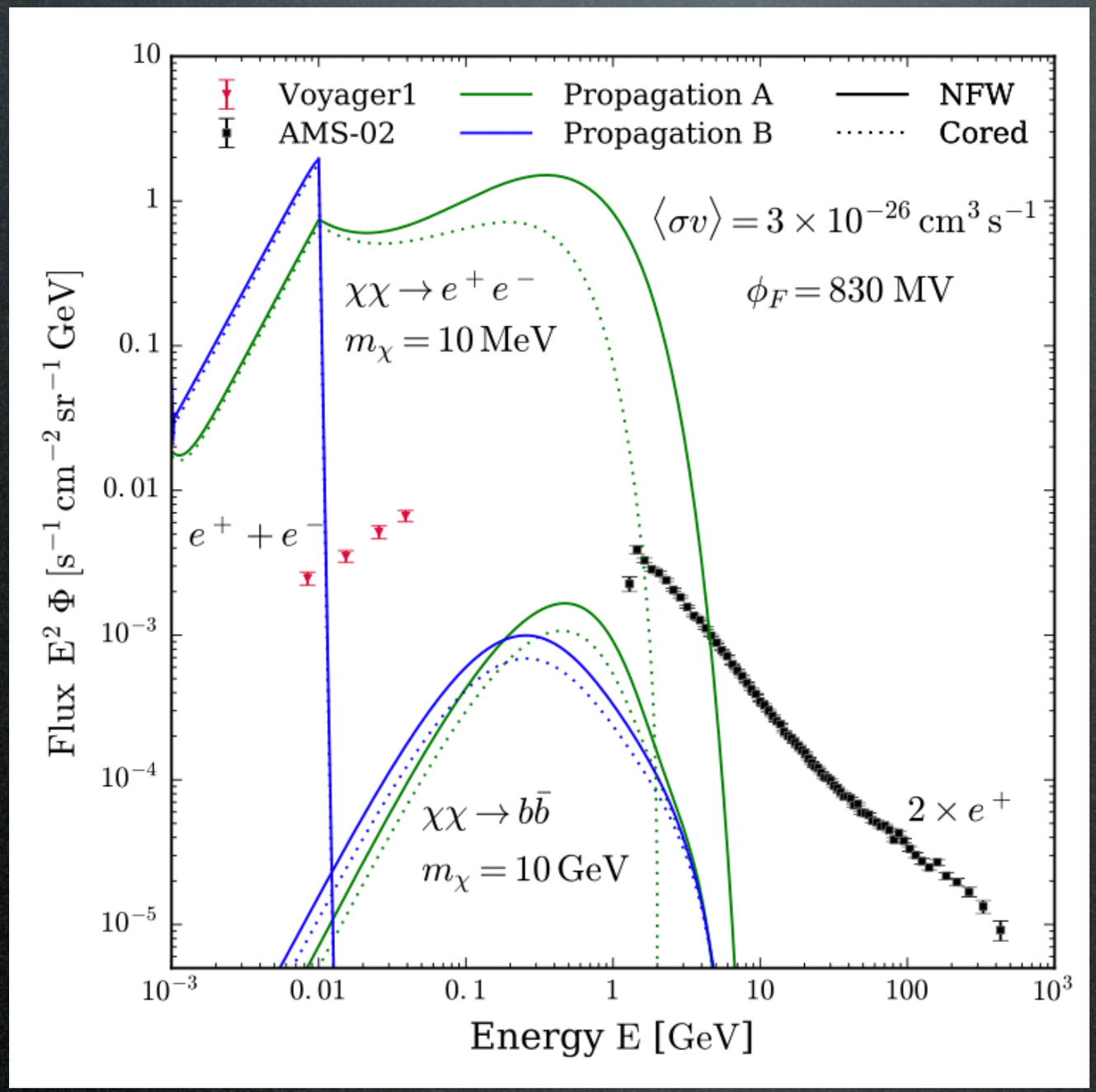
Problem:

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

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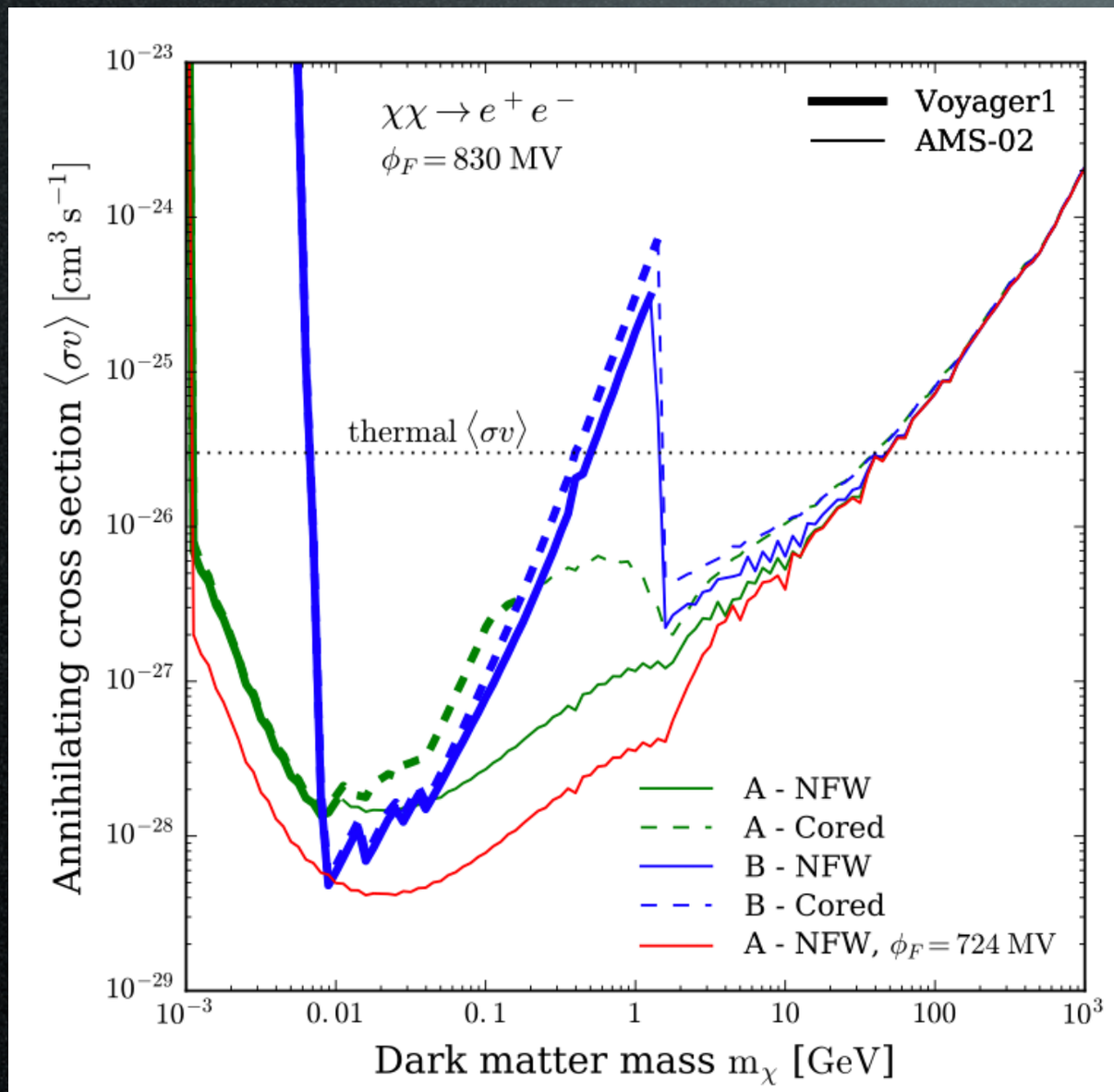
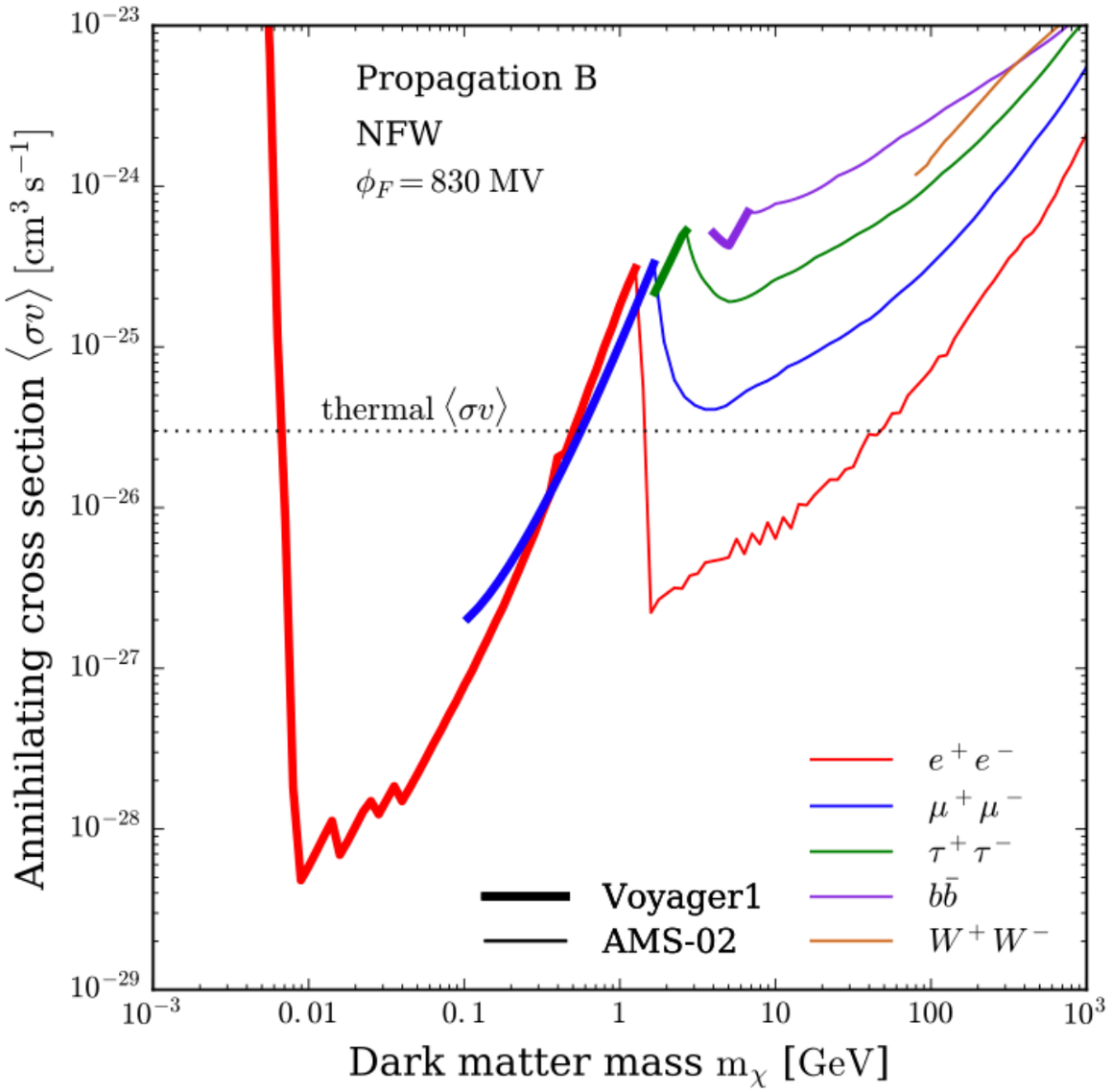
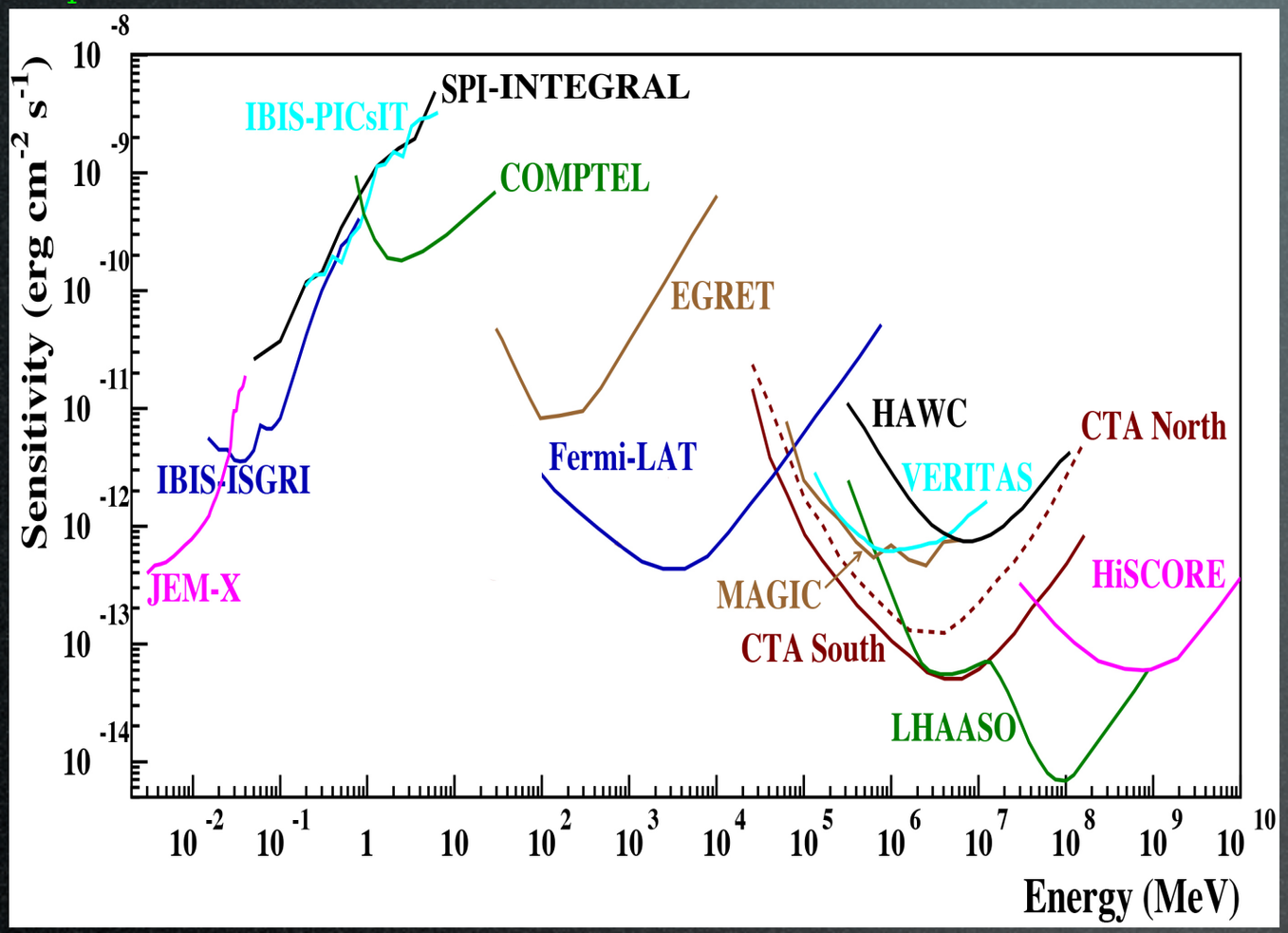




Indirect detection: photons

adapted from 1611.02232



Past/current experiments:

Integral, Comptel, Fermi

(2002⟶) *(1991-2000)* *(2009⟶)*

Planned/proposed experiments:

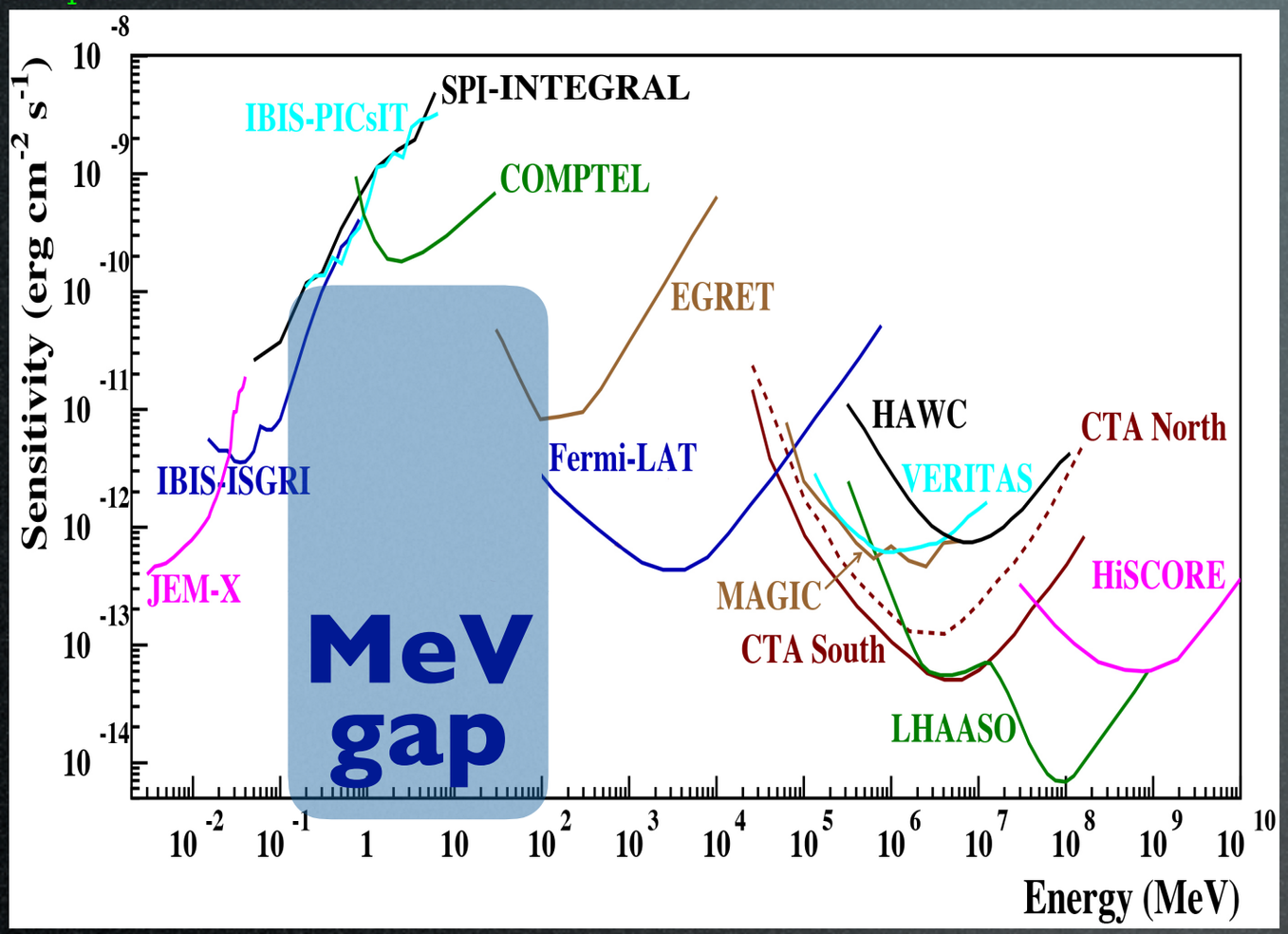
e-Astrogam?, Compair?, Amego?

Amego	satellite	2020s?	HEP detectors	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



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INO-ICAL	India	2020s?	calorimeter	neutrinos	1 – 100 GeV
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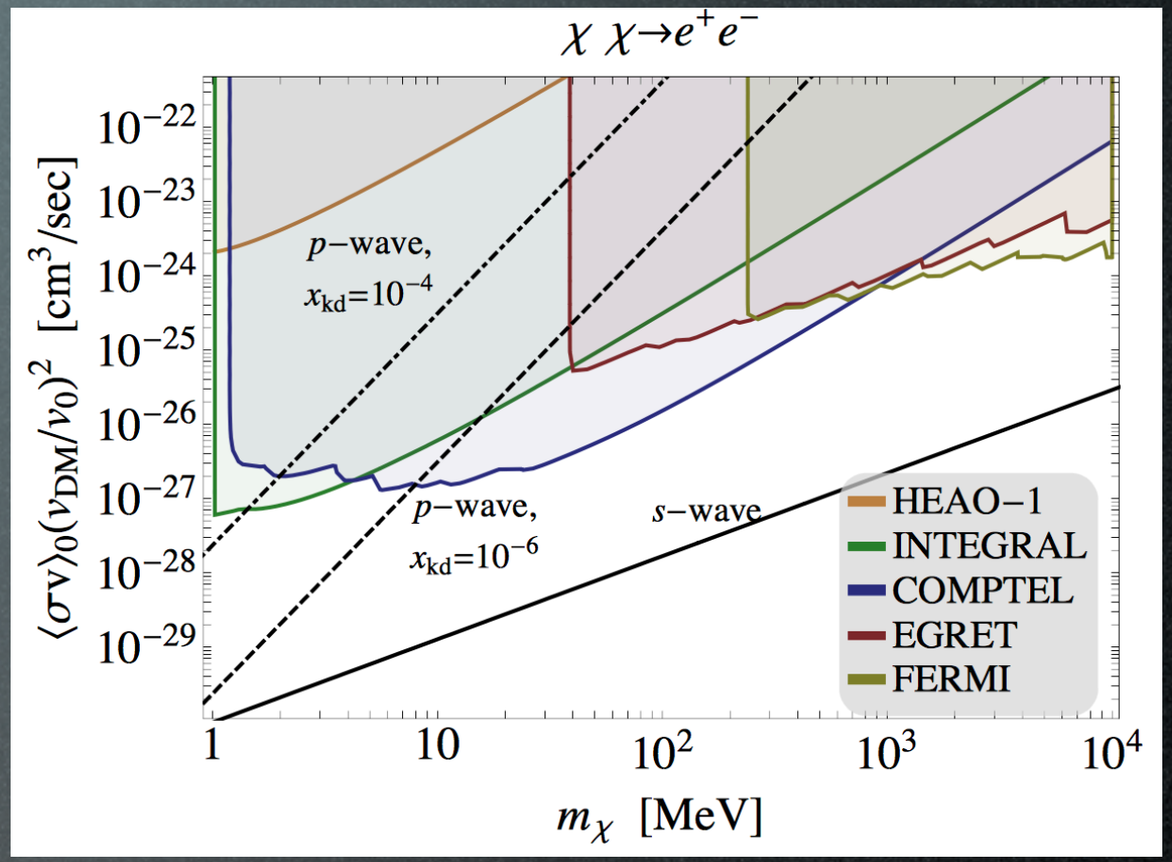
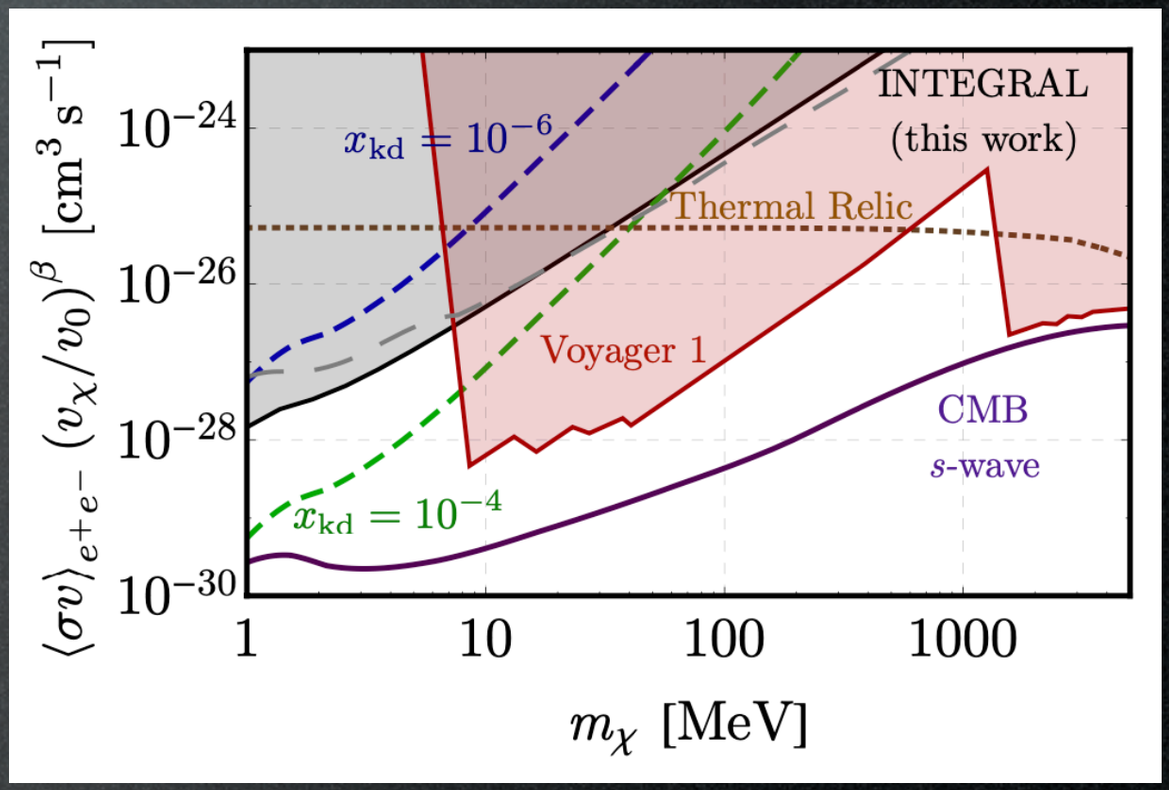
Some recent studies

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



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



NB: ‘prompt’ emission only

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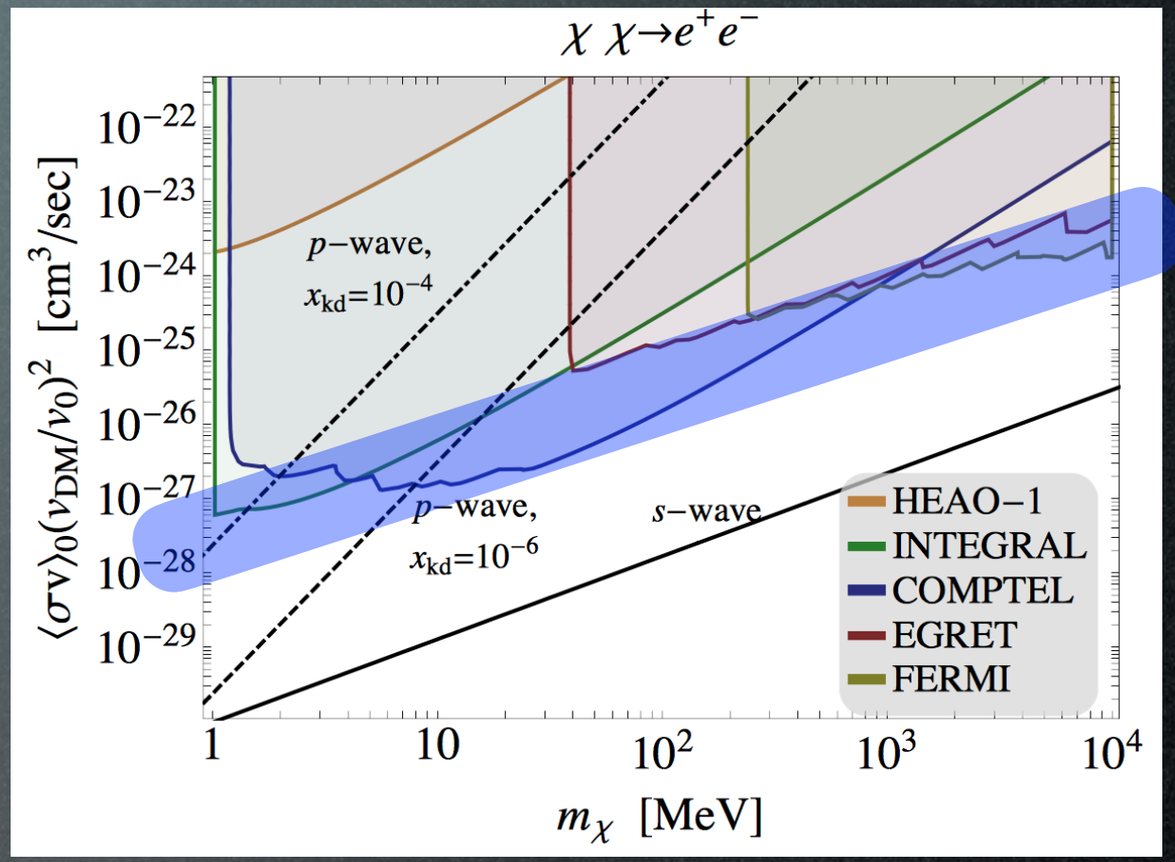

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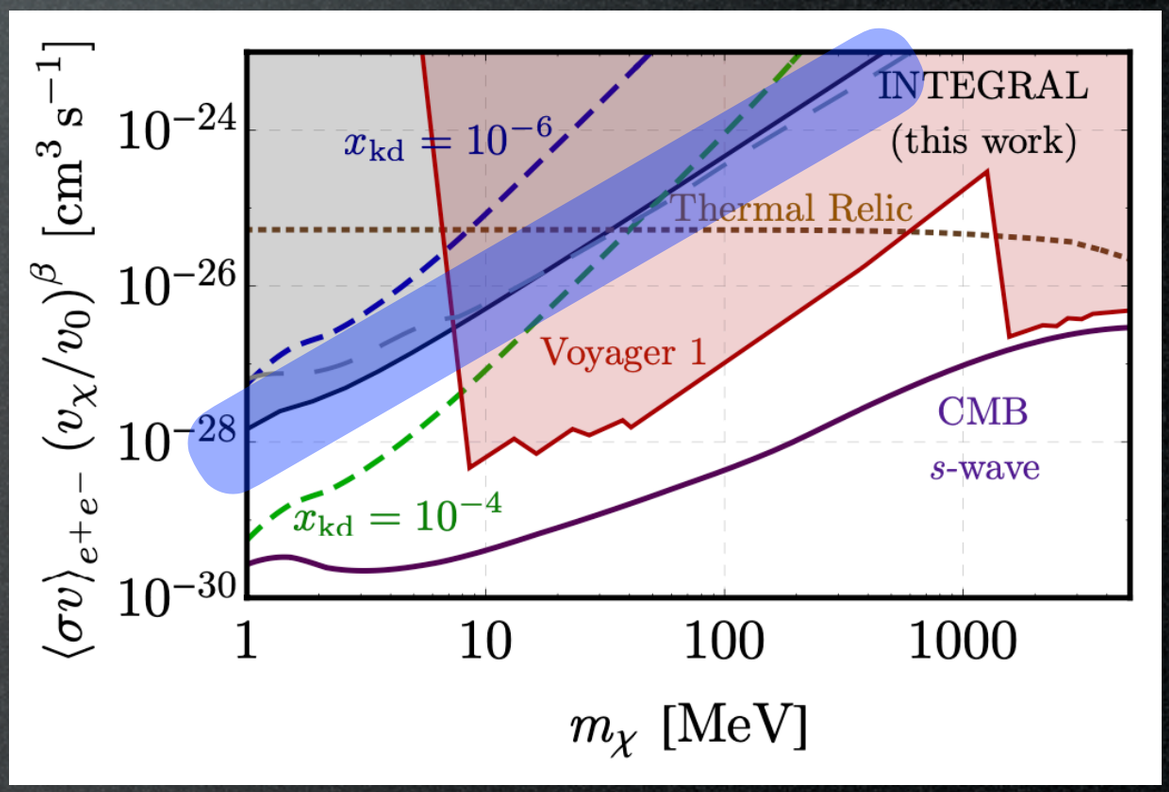

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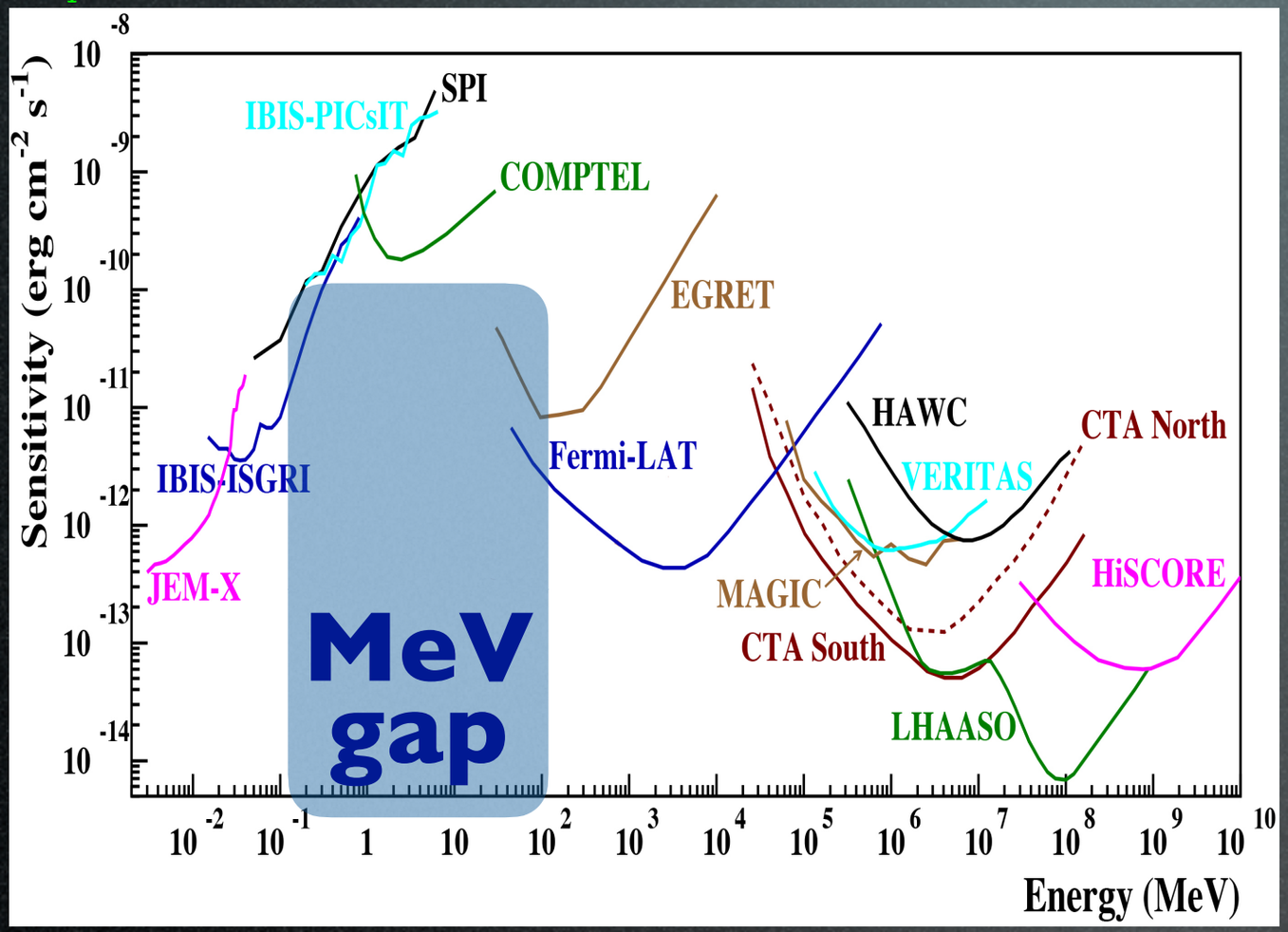
Indirect detection: photons

adapted from 1611.02232



How to do better?

ICS & X-rays!

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

Sub-GeV DM & X-rays

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

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

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

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

Sub-GeV DM & X-rays

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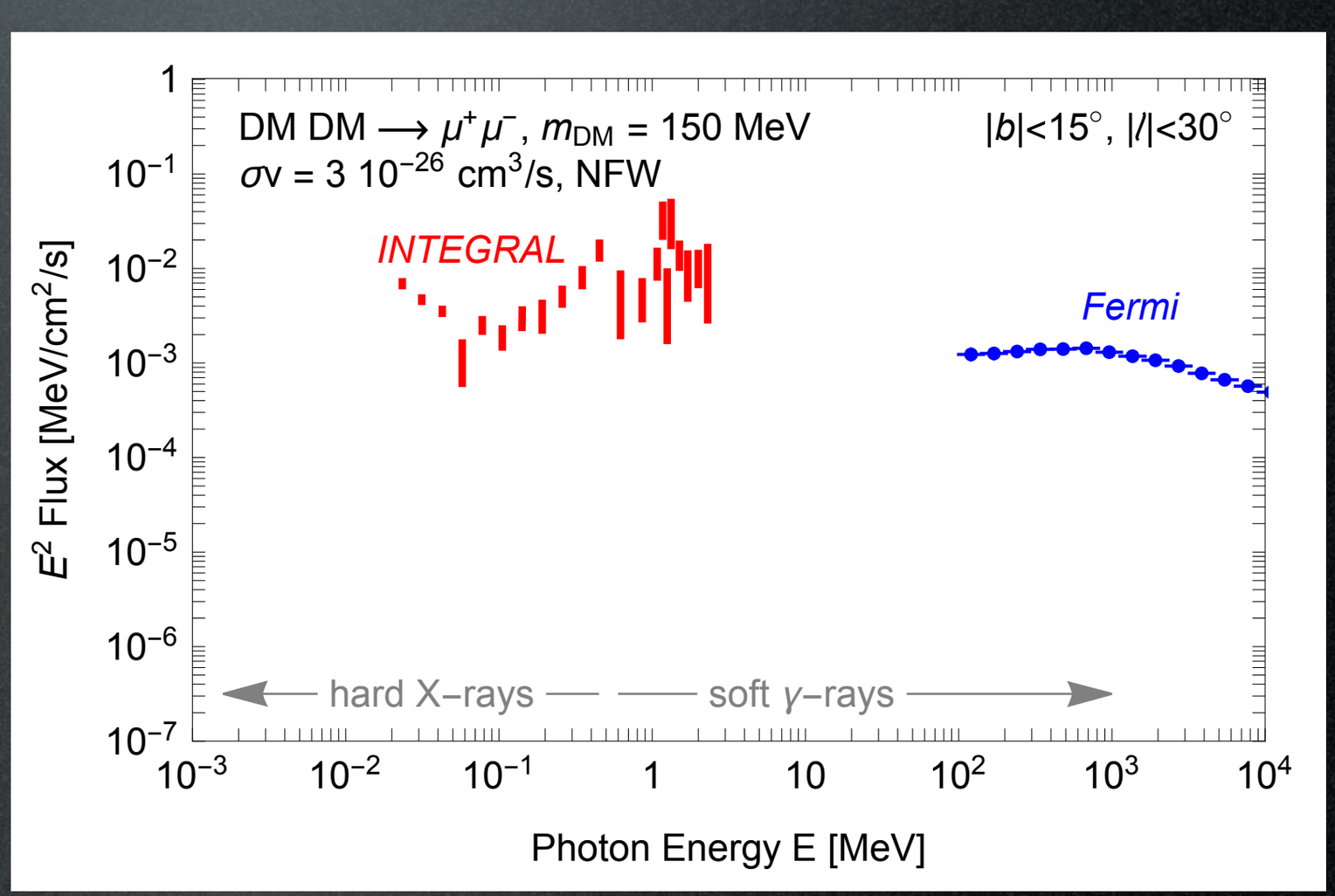

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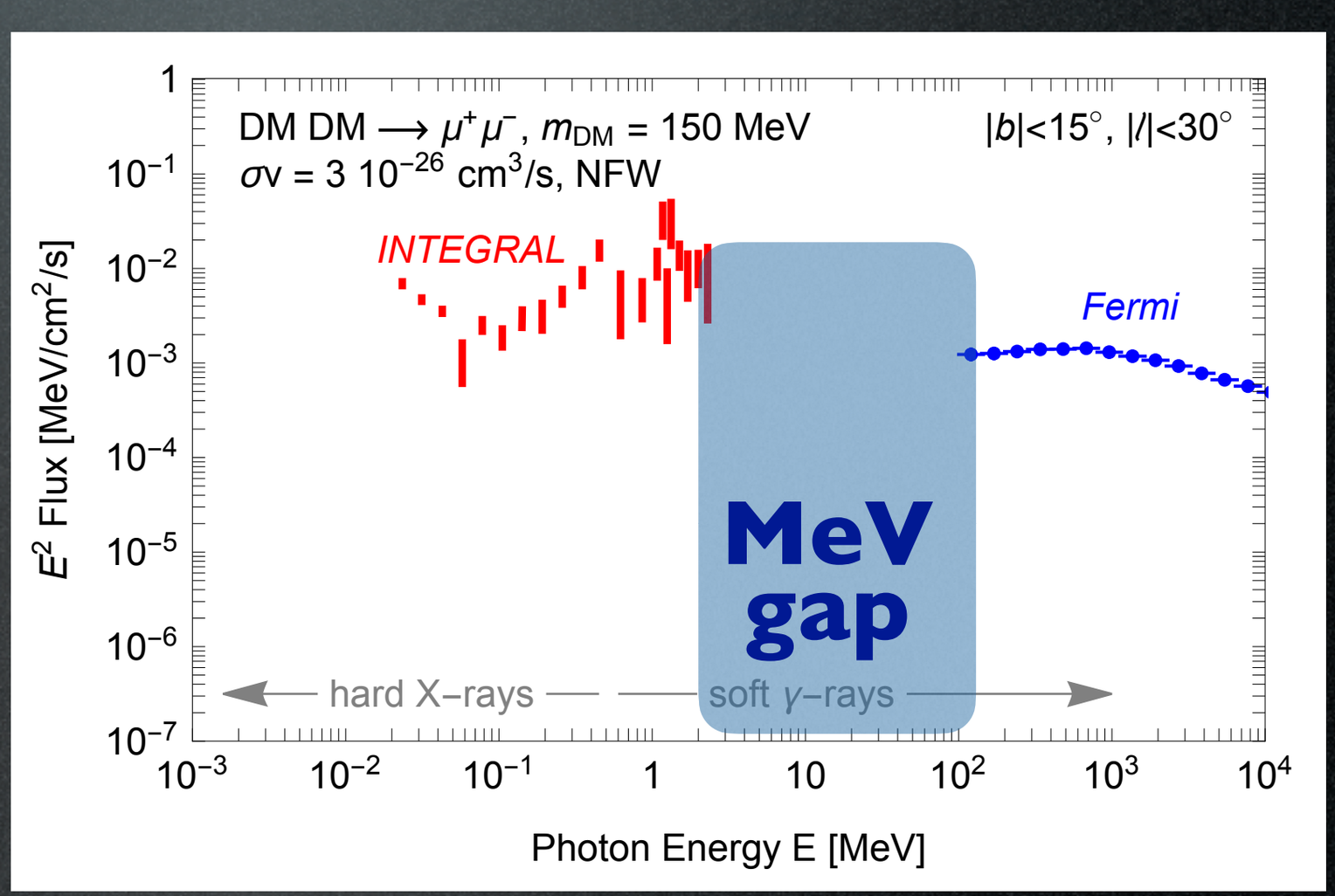

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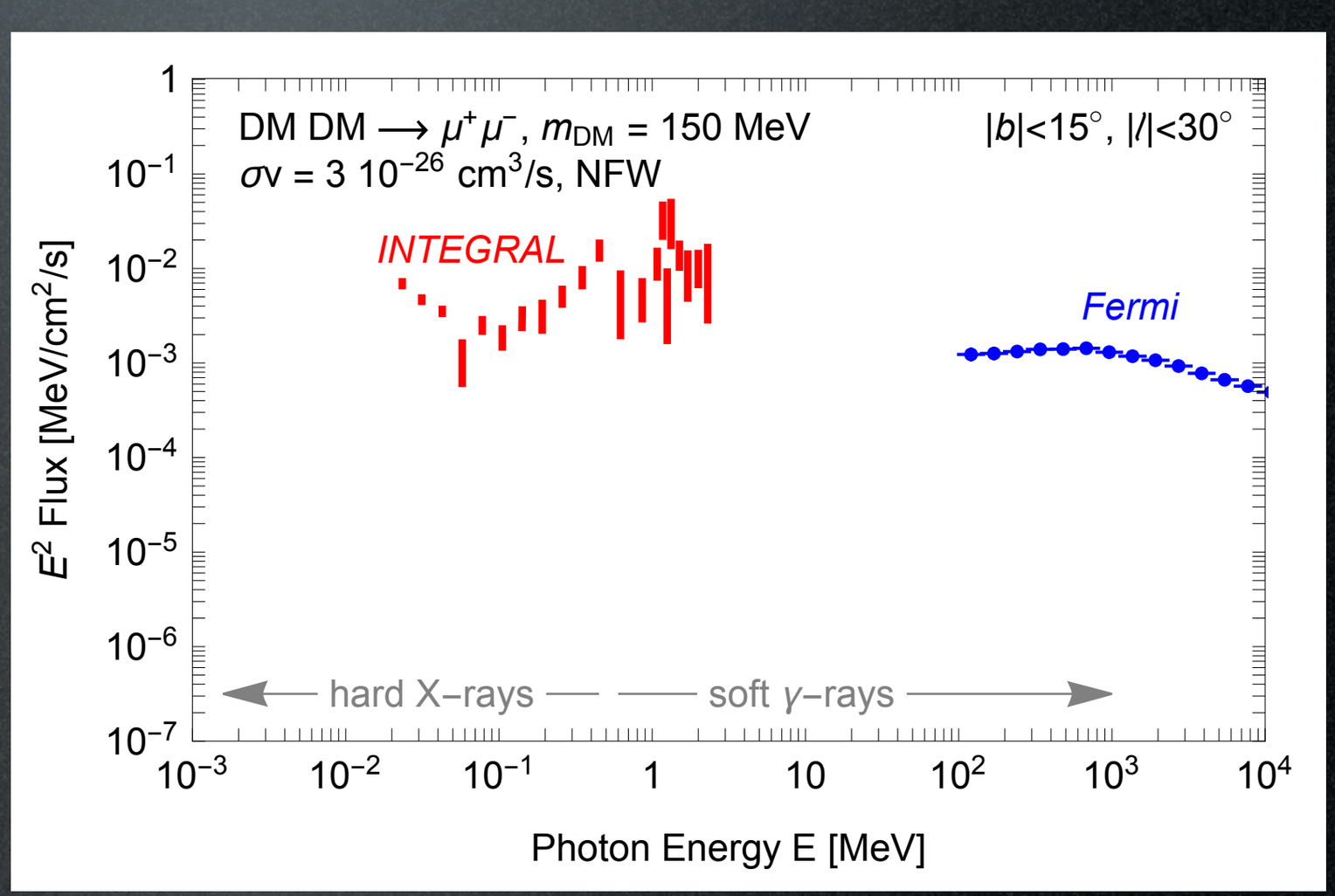

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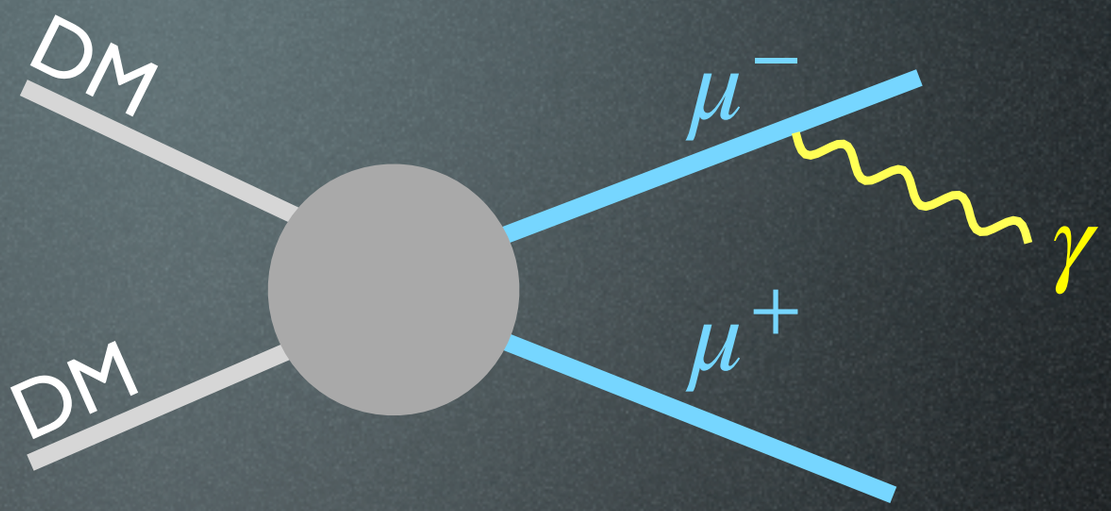
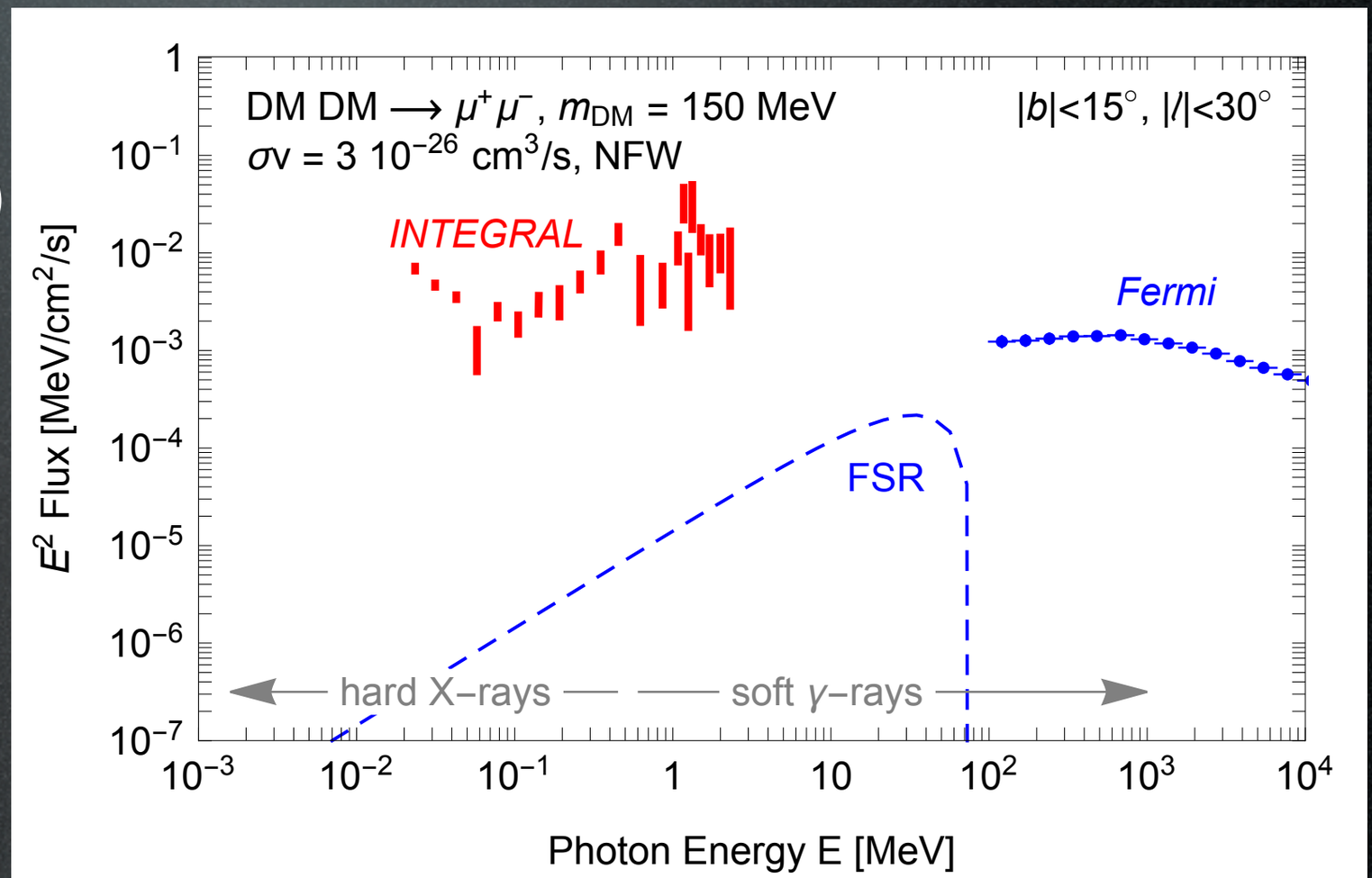


'Prompt' emission:

Final State Radiation (FSR)



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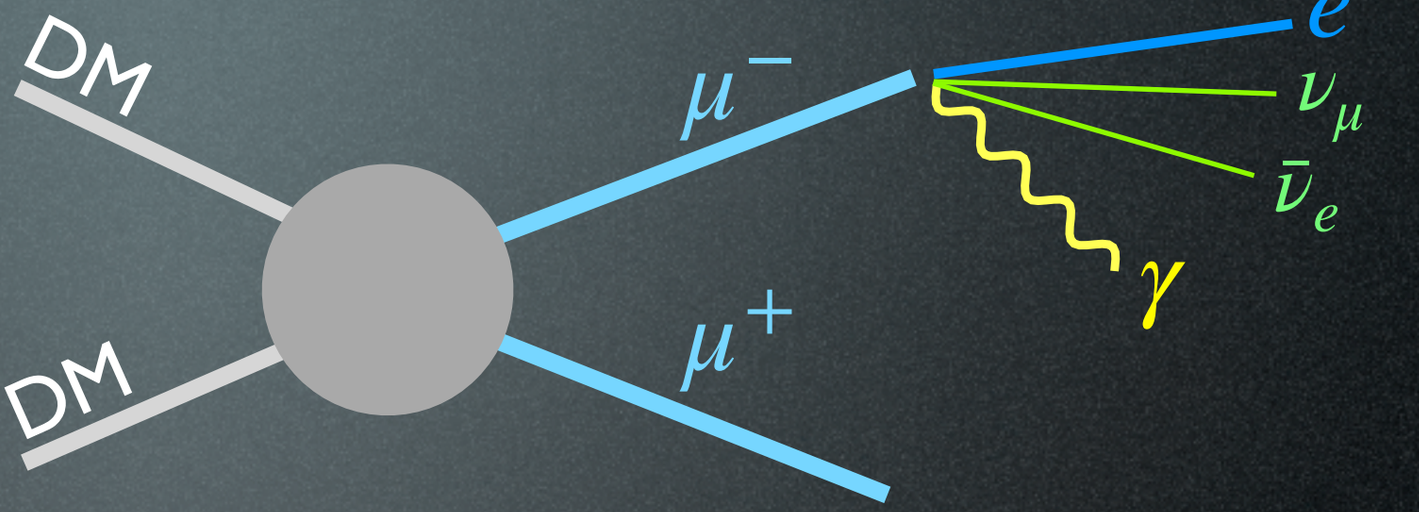
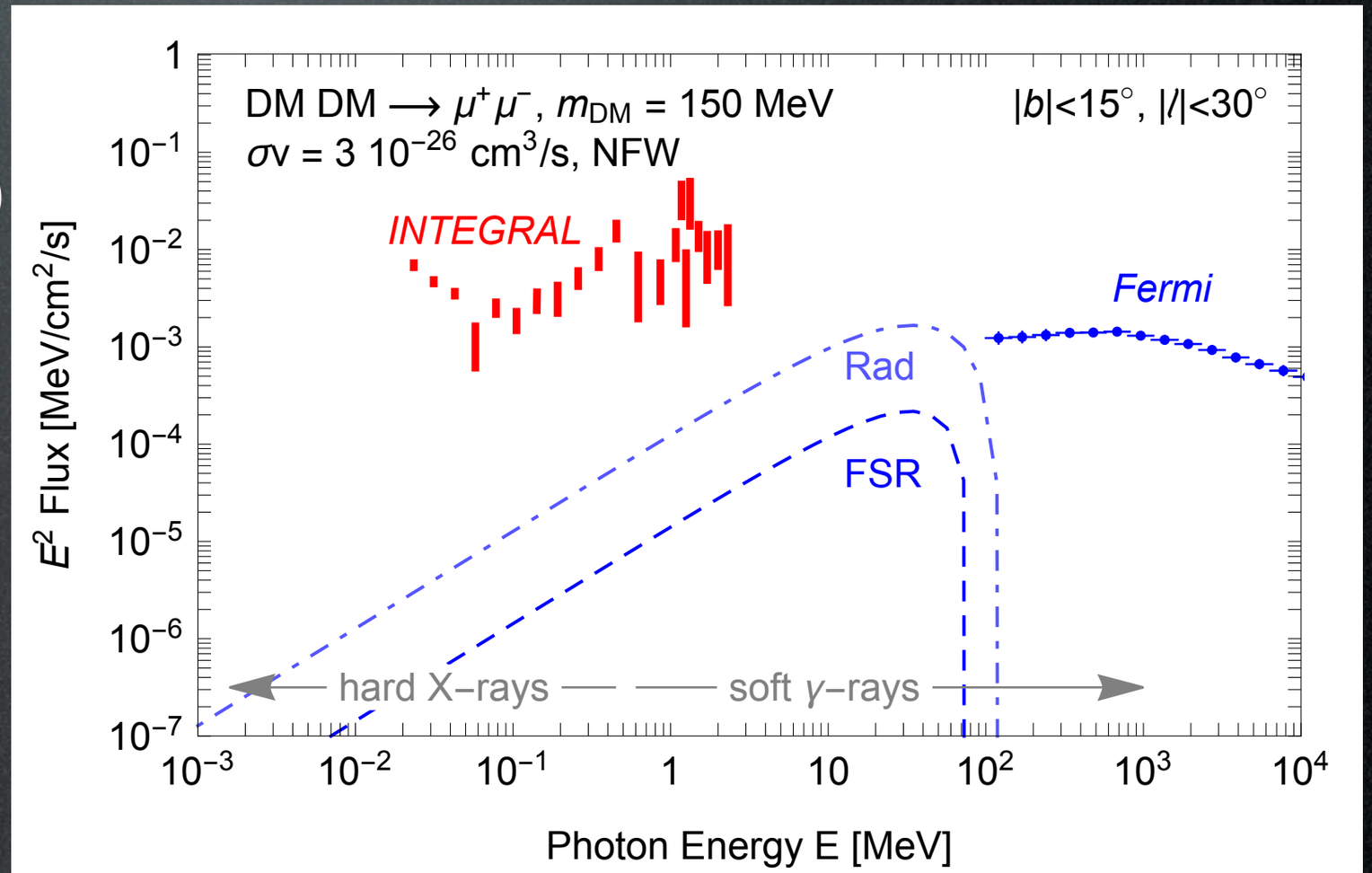


'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

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



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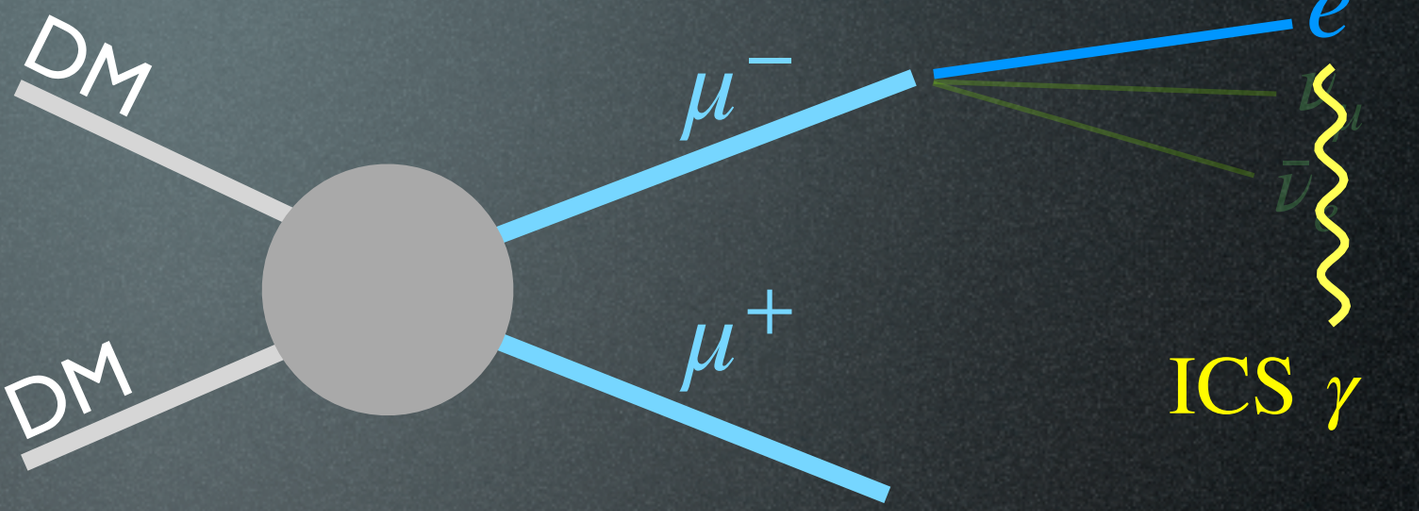

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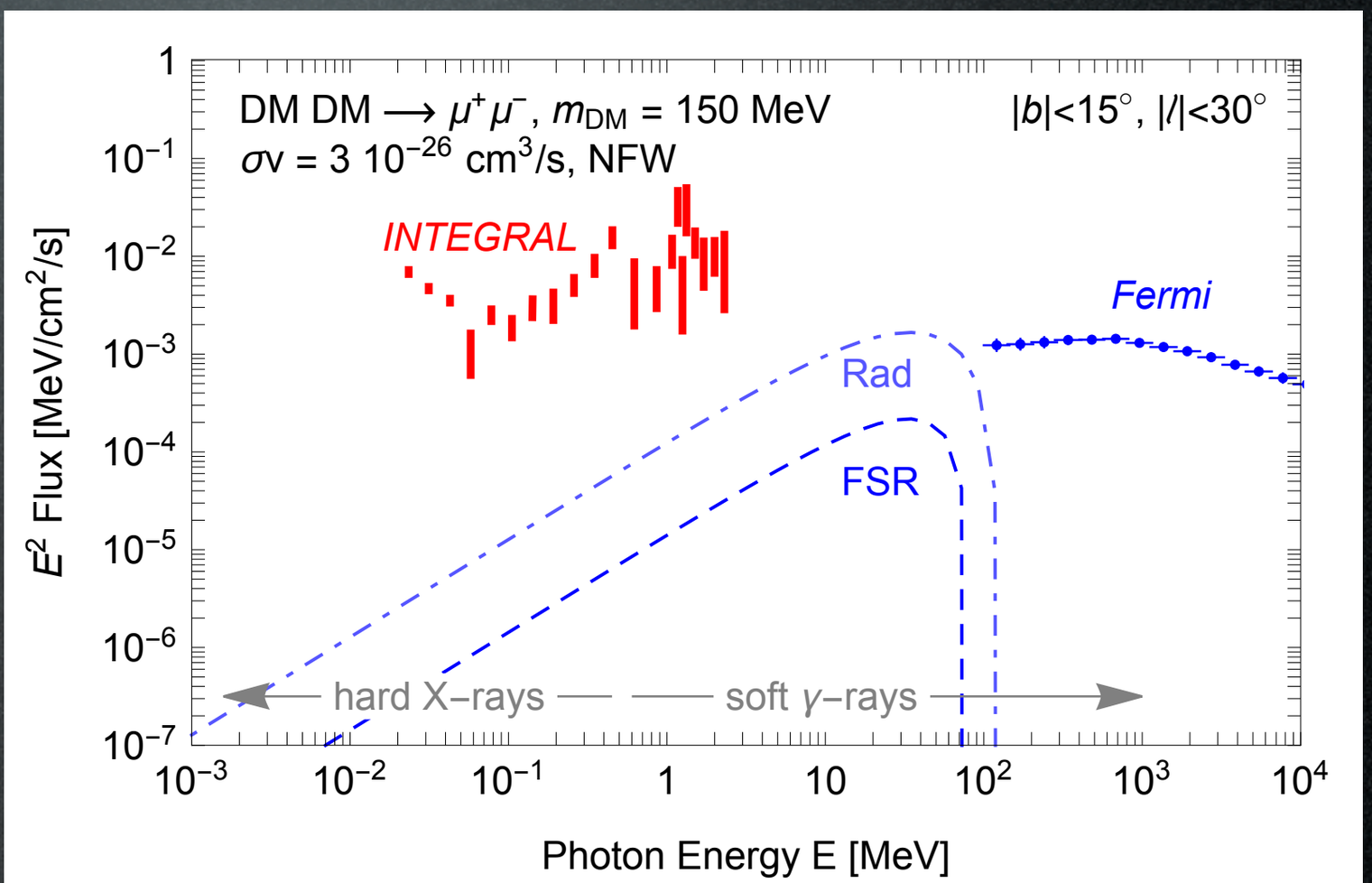
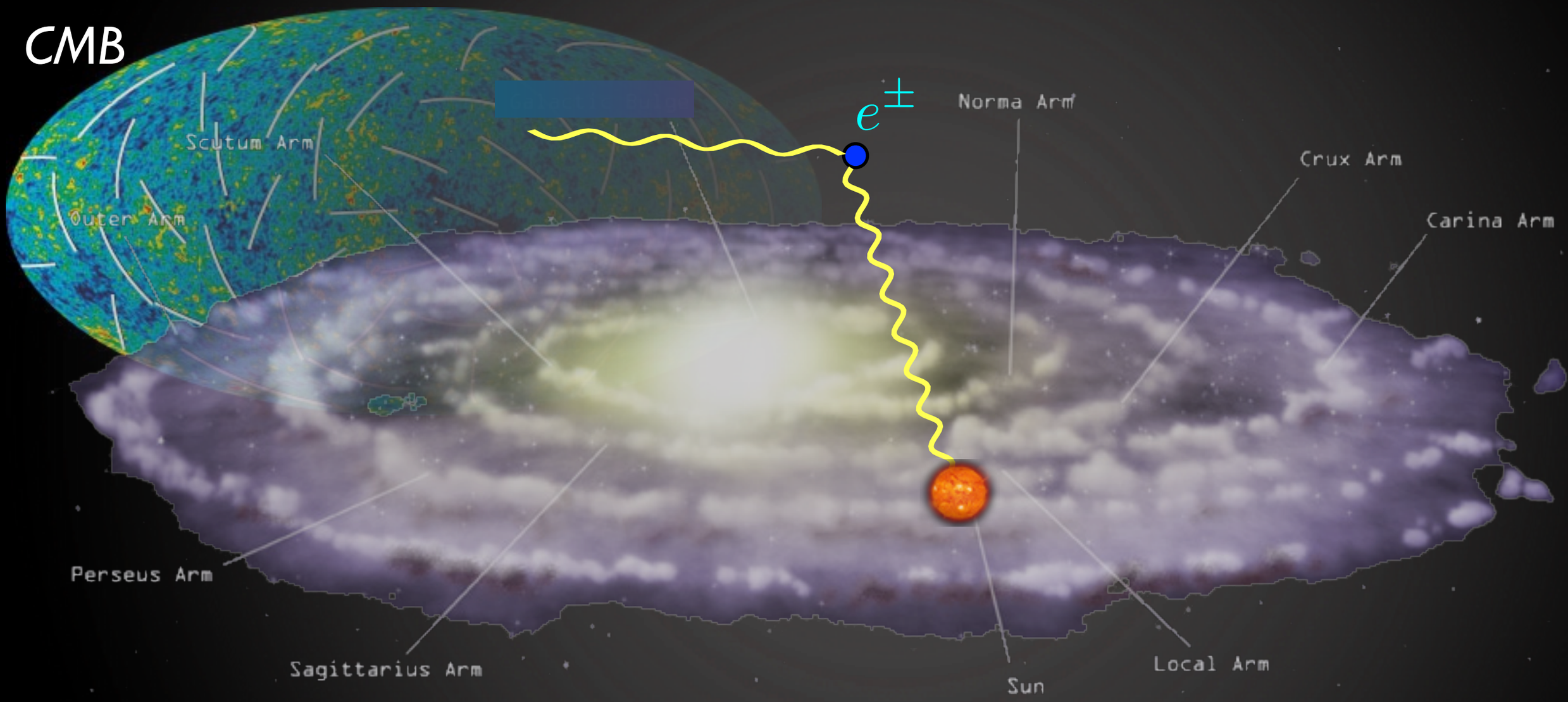


Secondary emission

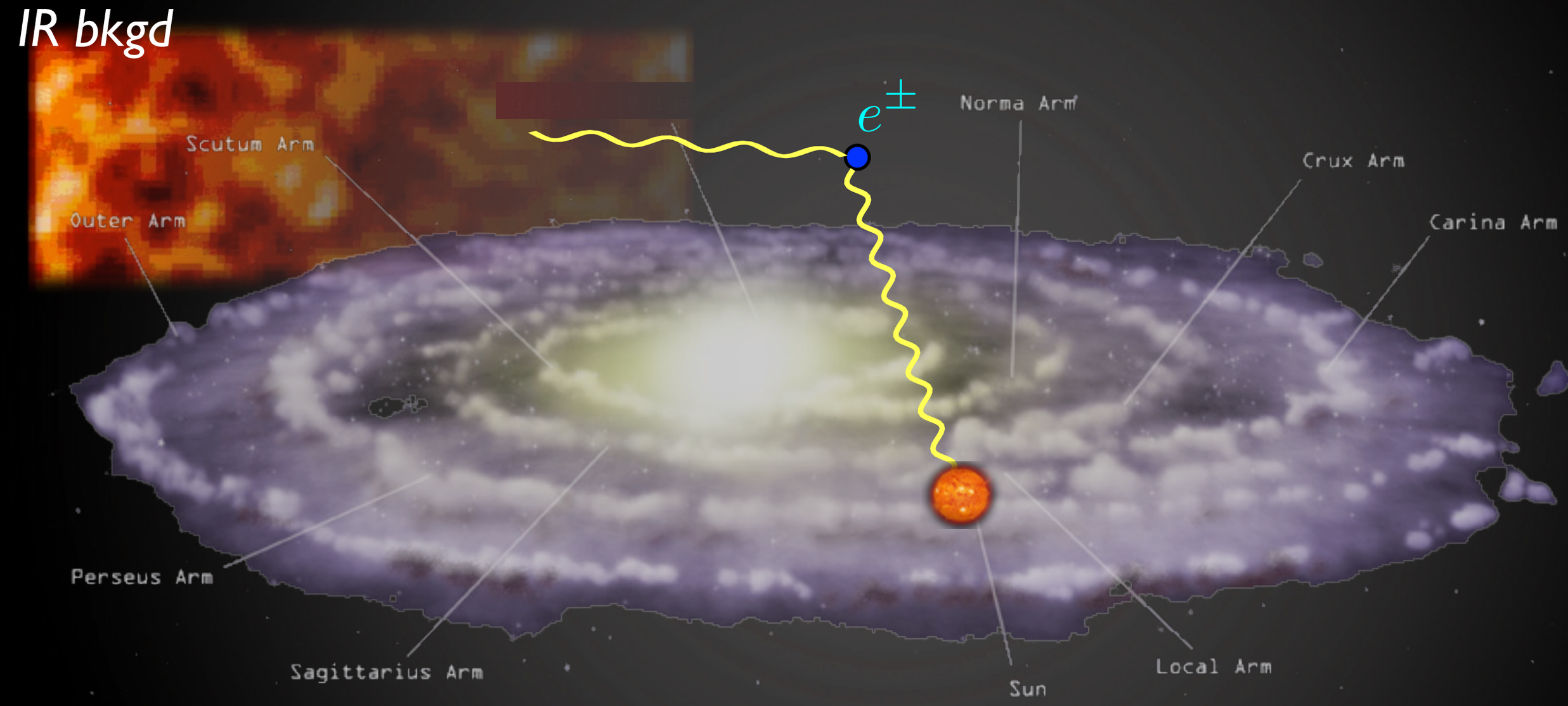
γ from Inverse Compton on $e^{\pm}$ in halo



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

Secondary emission

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



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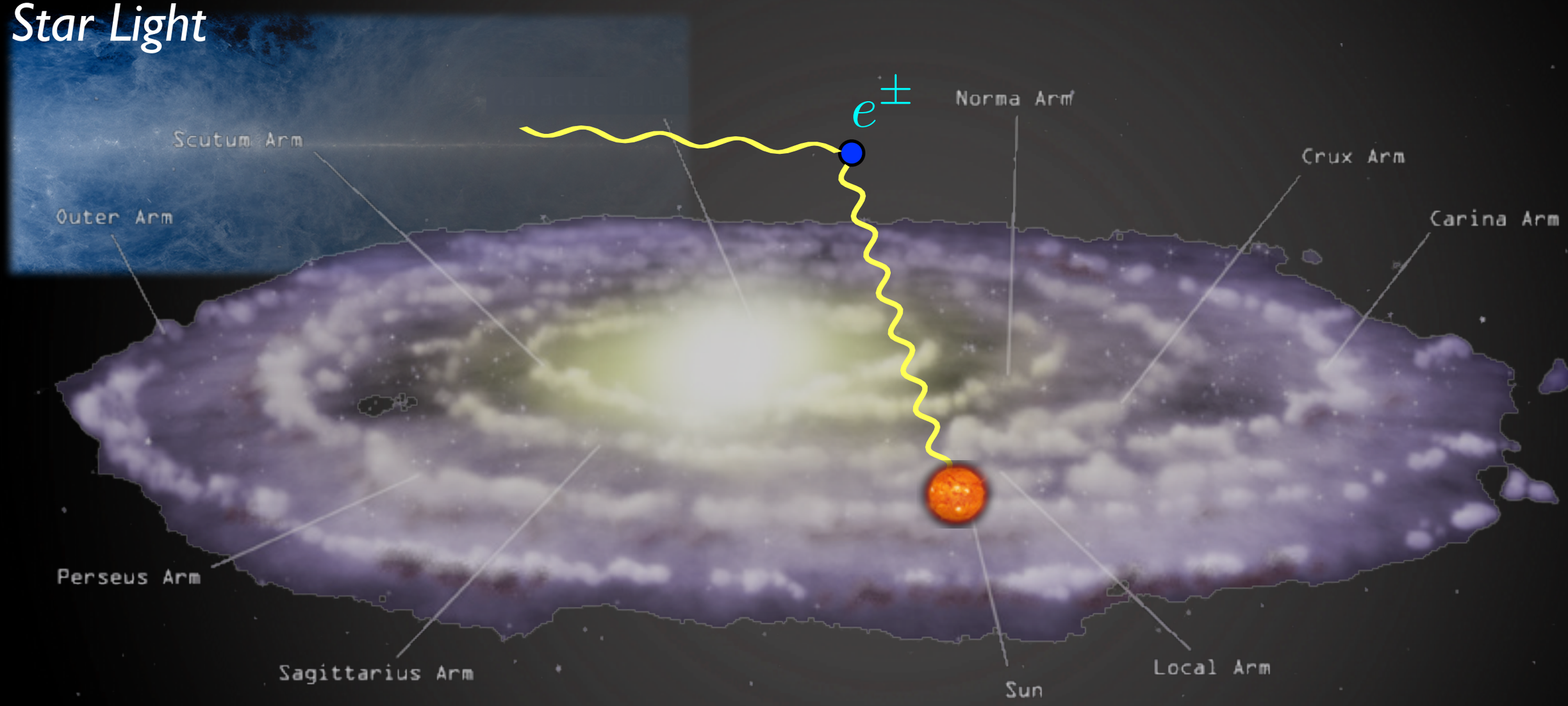

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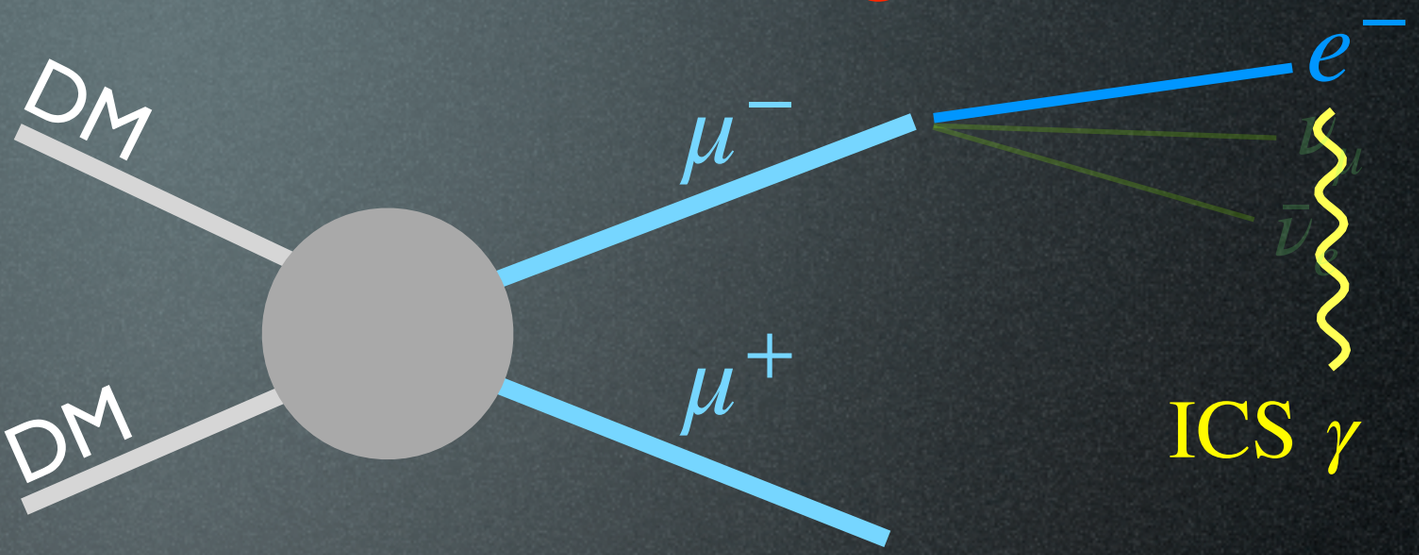


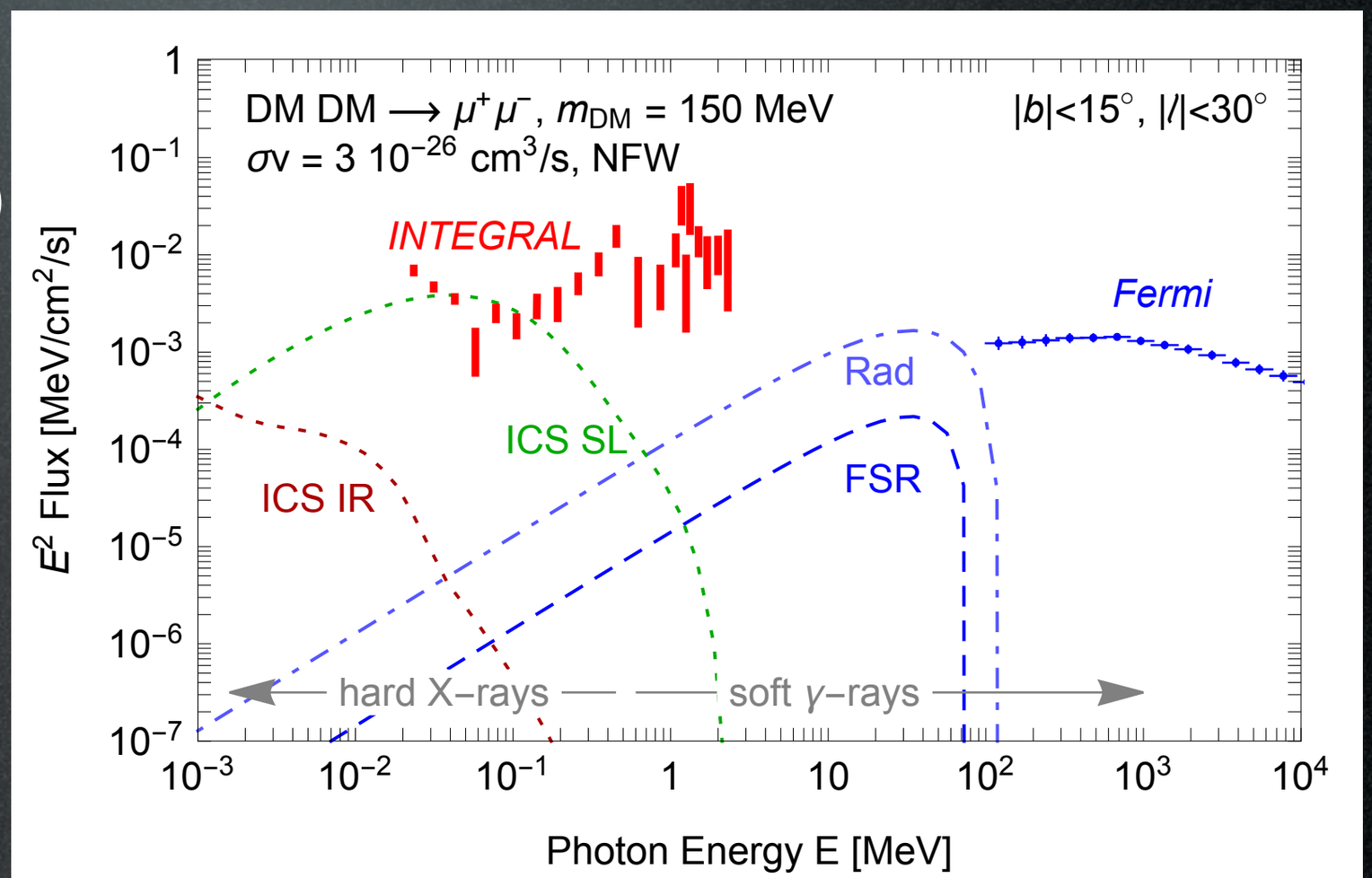
'Prompt' emission:

Final State Radiation (FSR)

Radiative μ decay

Secondary emission:

ICS: inevitably associated to annihil to charged states



Sub-GeV DM & X-rays

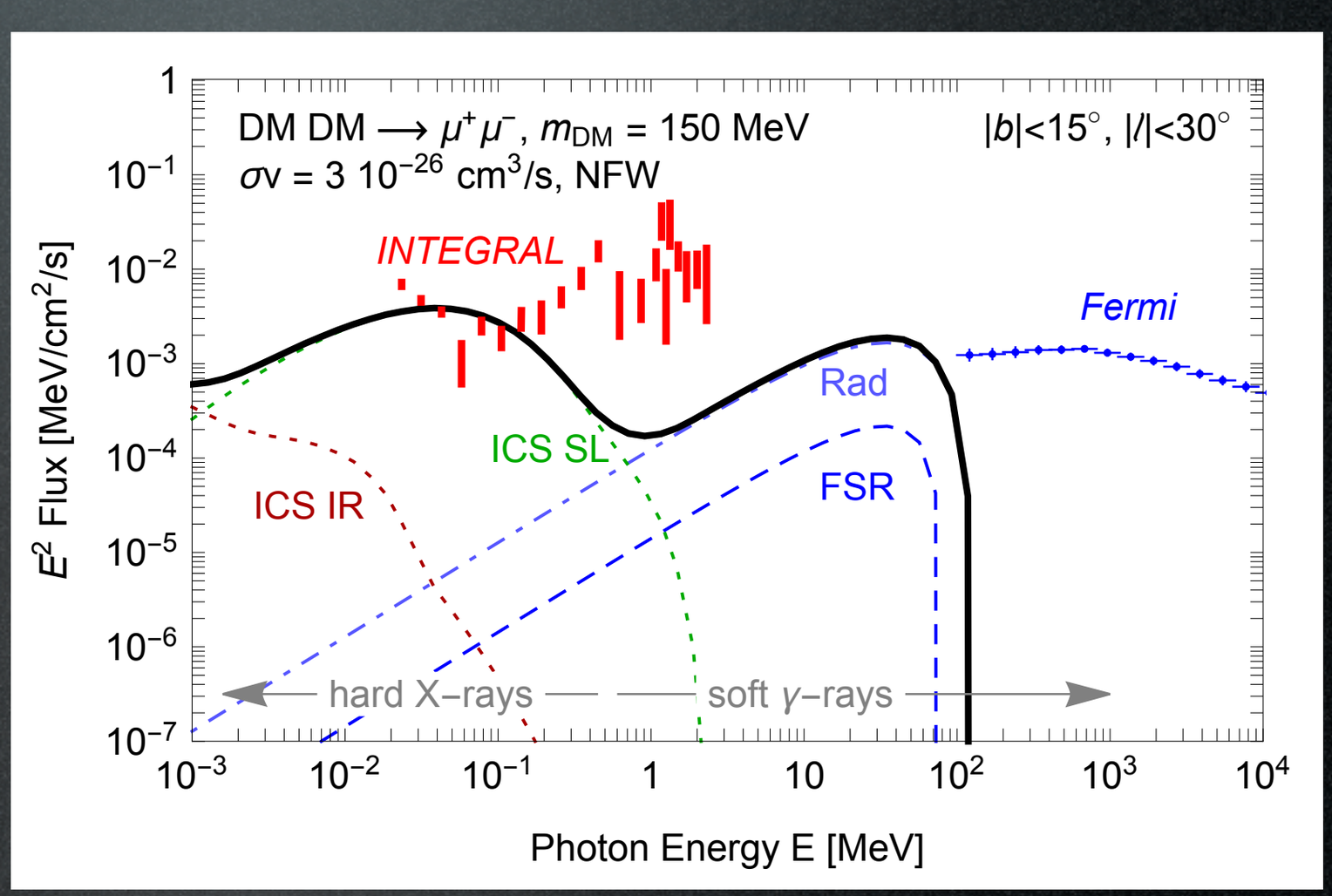
Annihilation channels

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

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

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

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

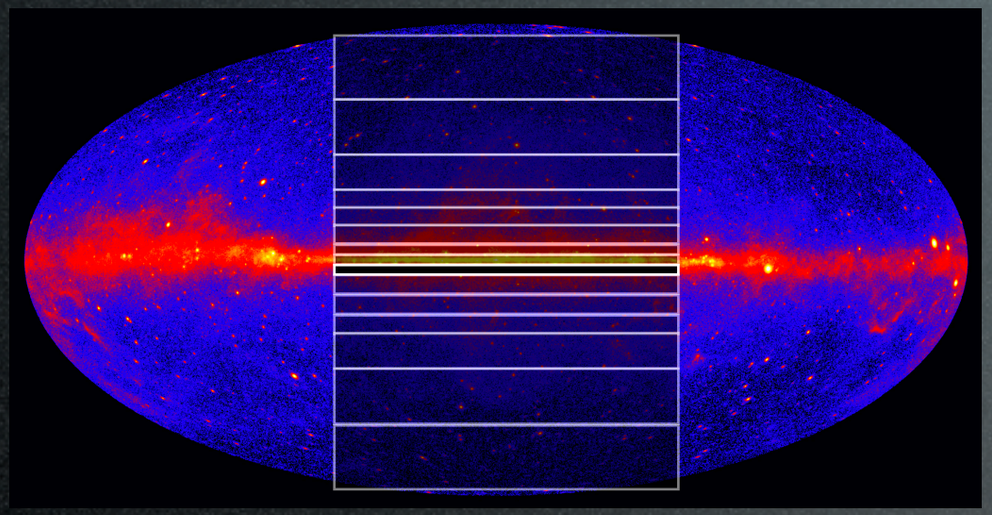


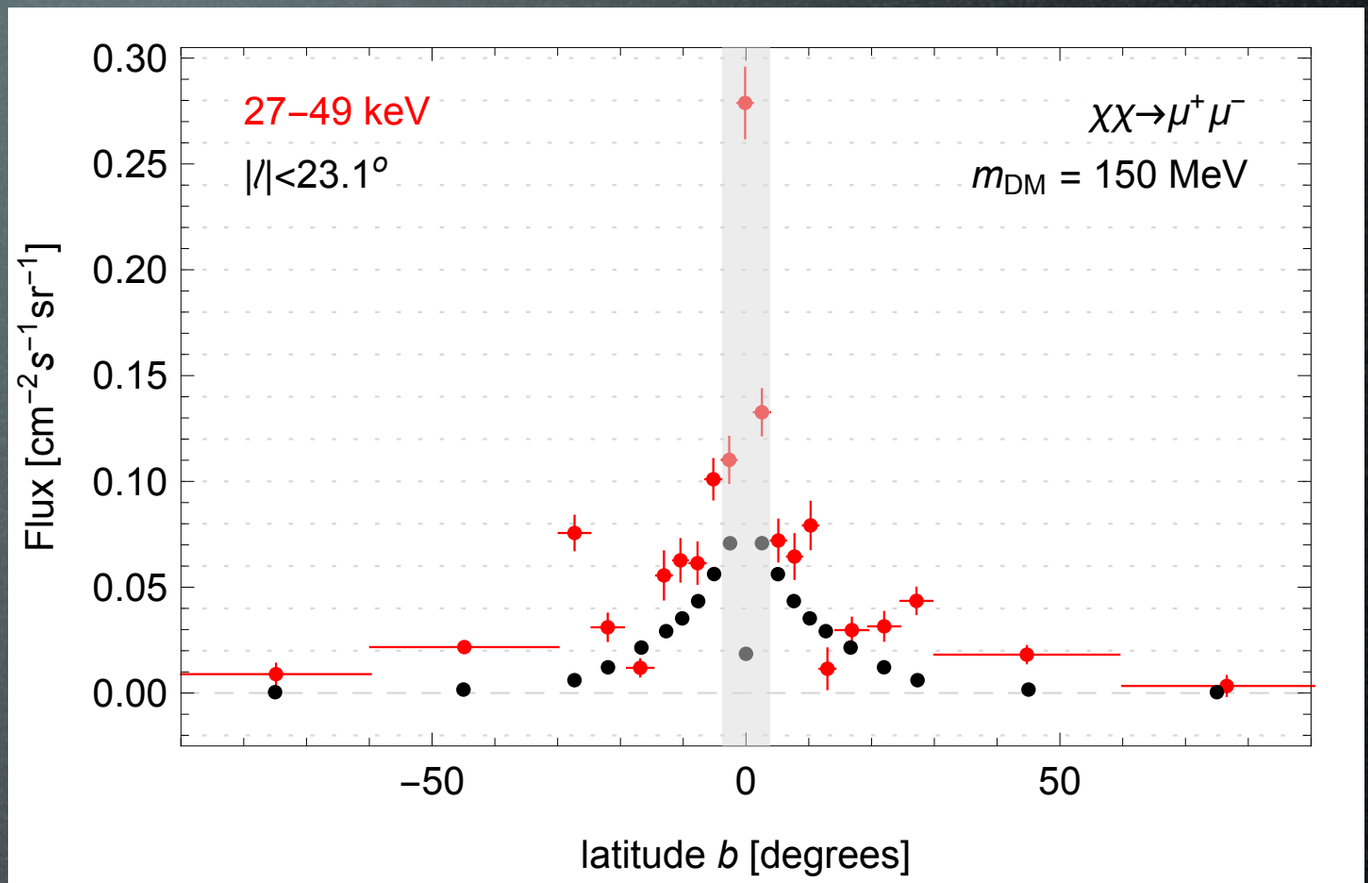
Analysis

Integral-SPI 2011 data

Bouchet et al., Integral coll. 1107.0200

latitude binned data, central MW





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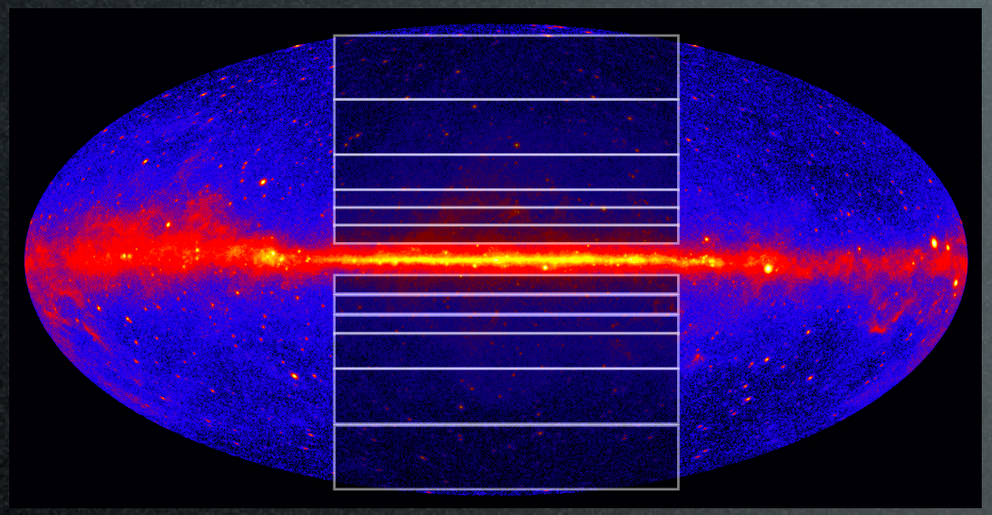
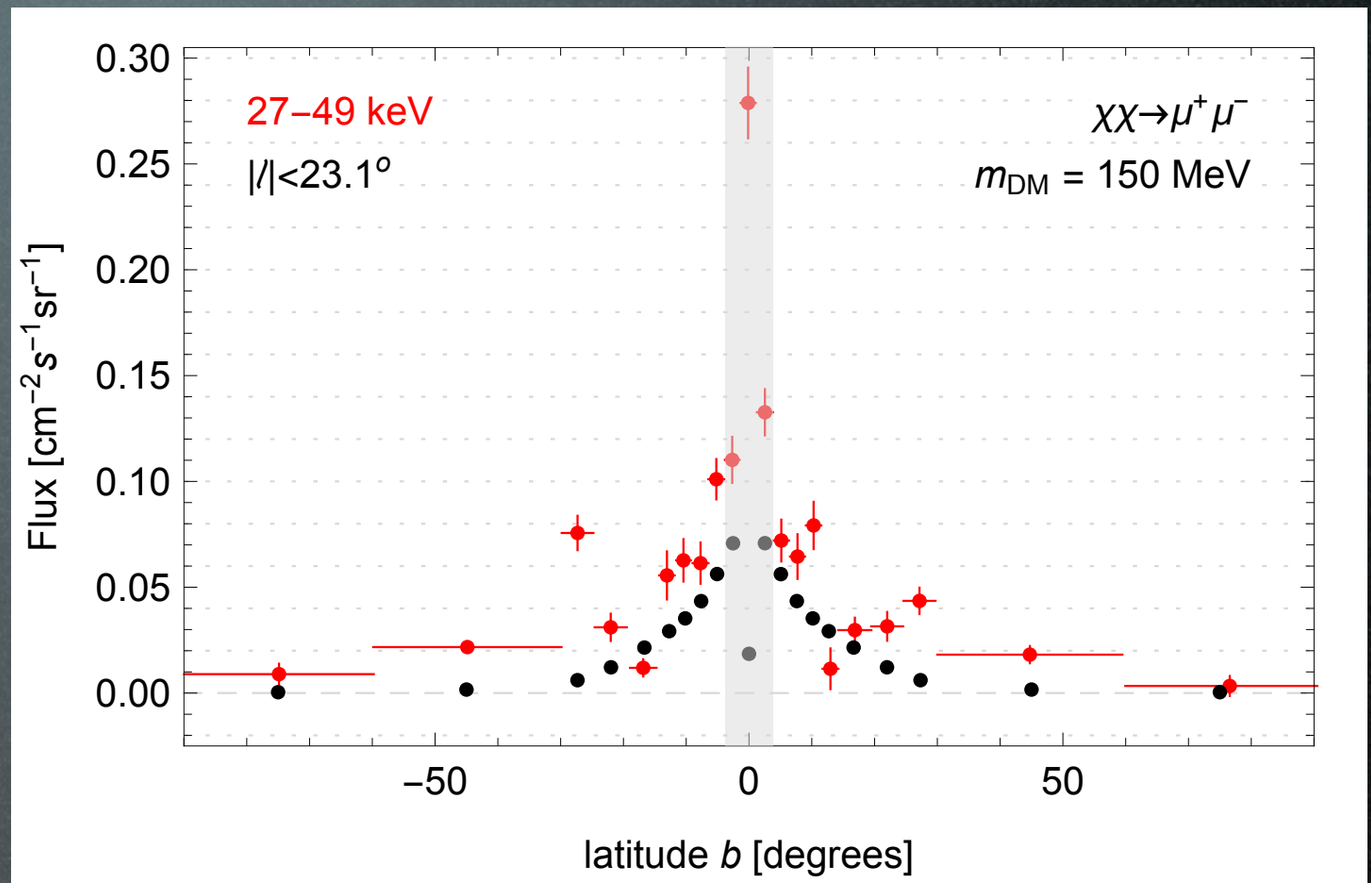


remove Gal Plane



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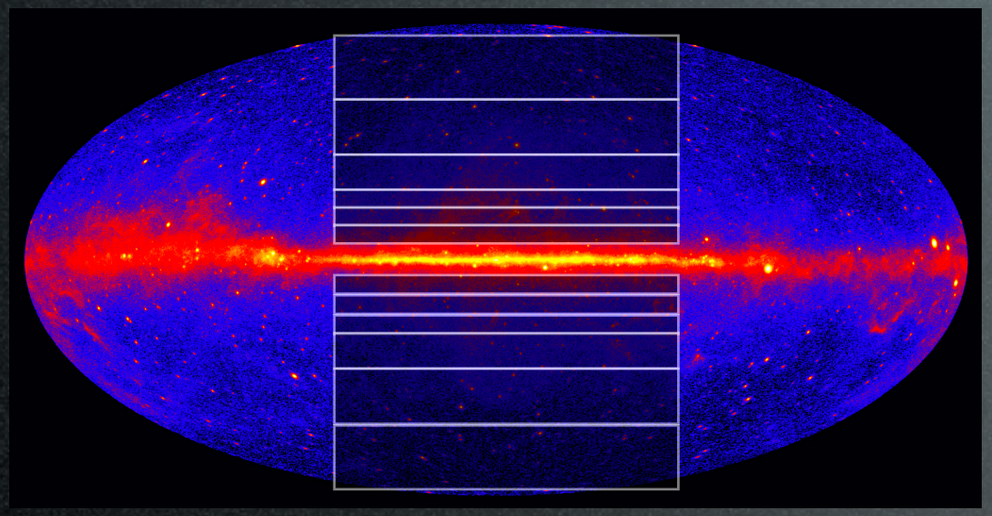
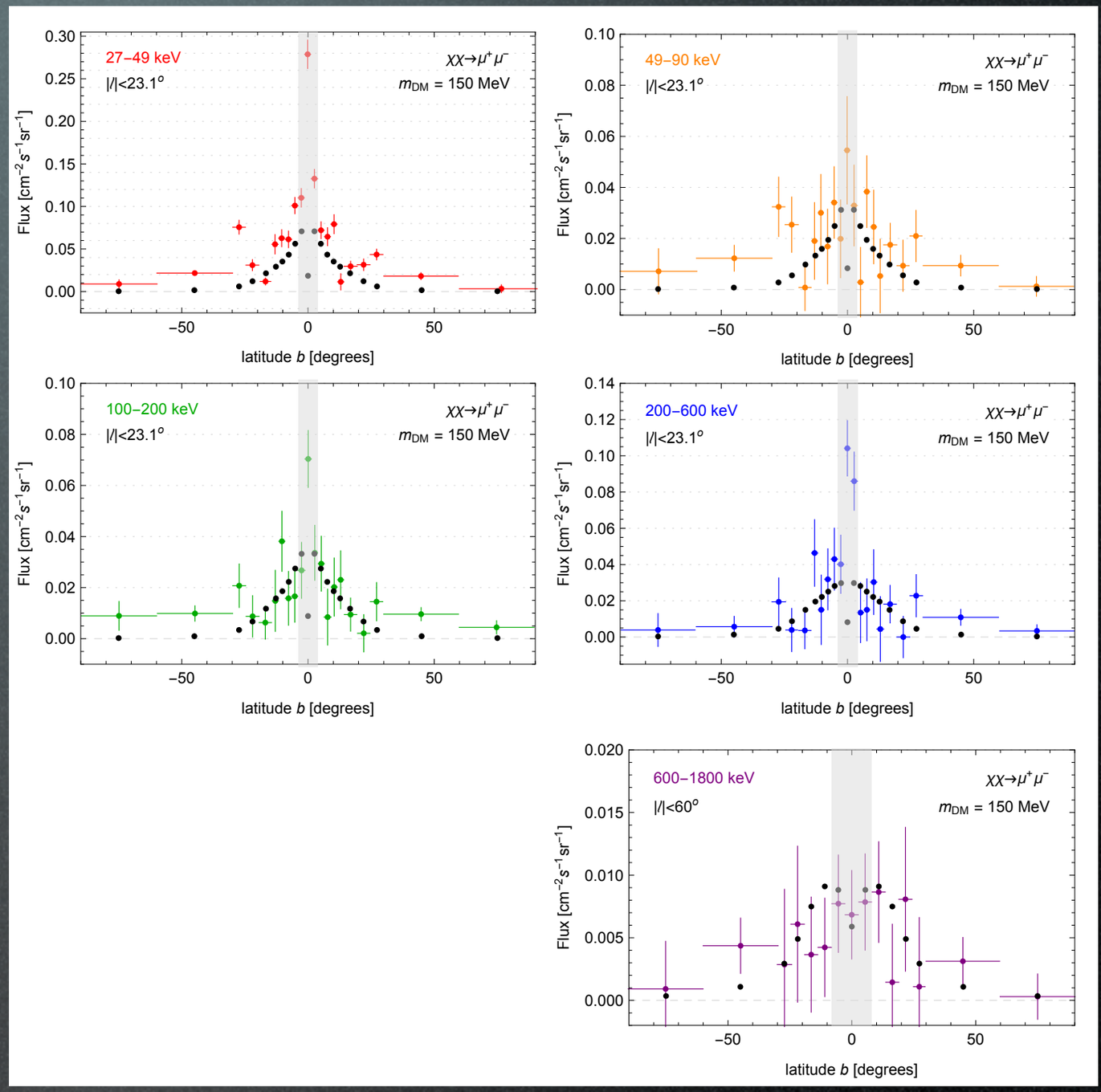


remove Gal Plane

5 energy bands



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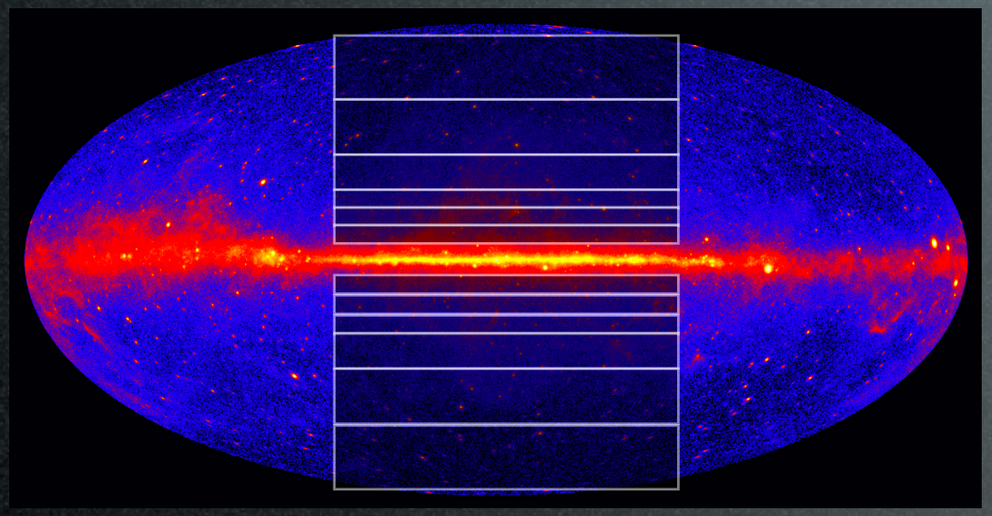

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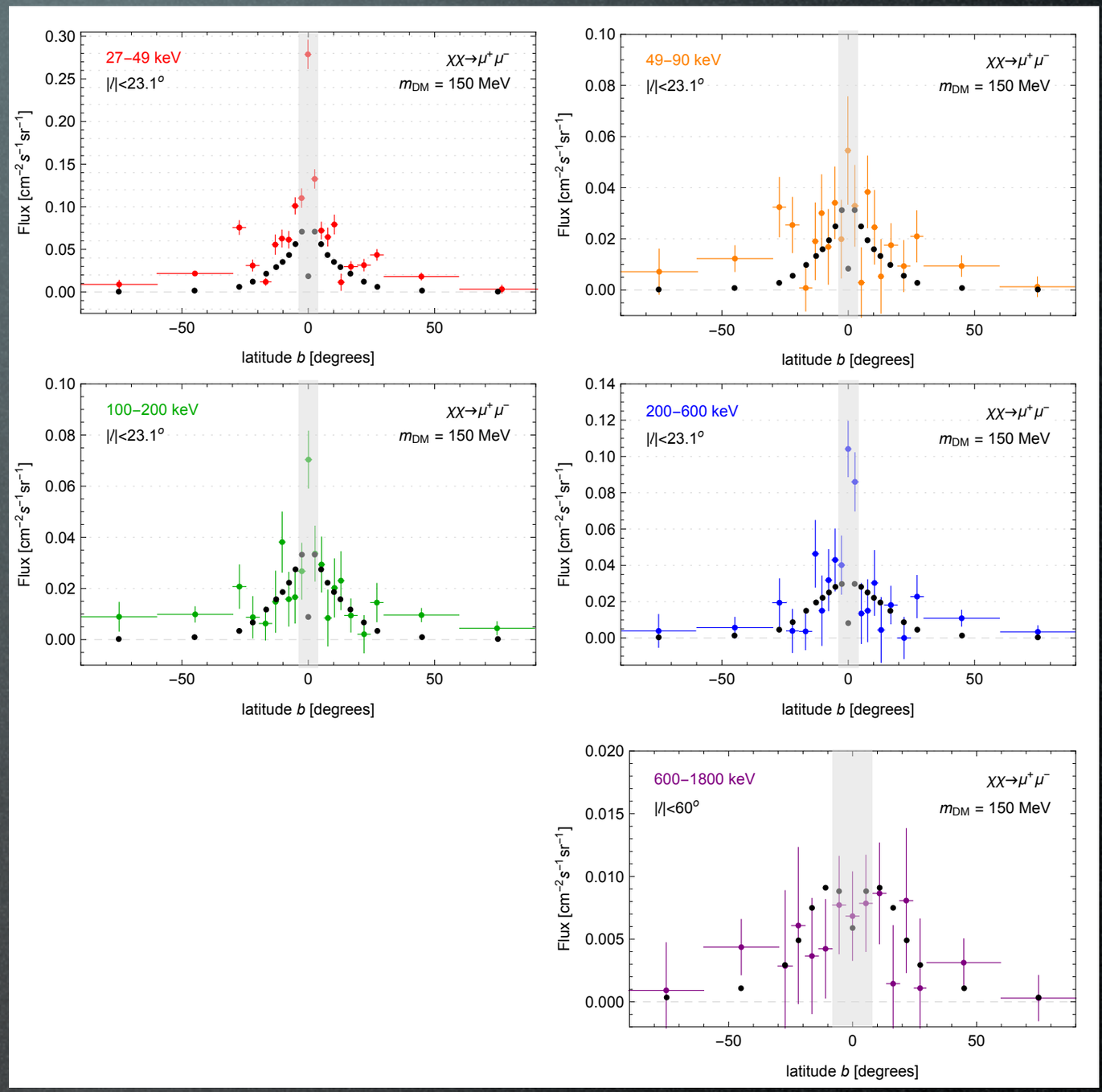
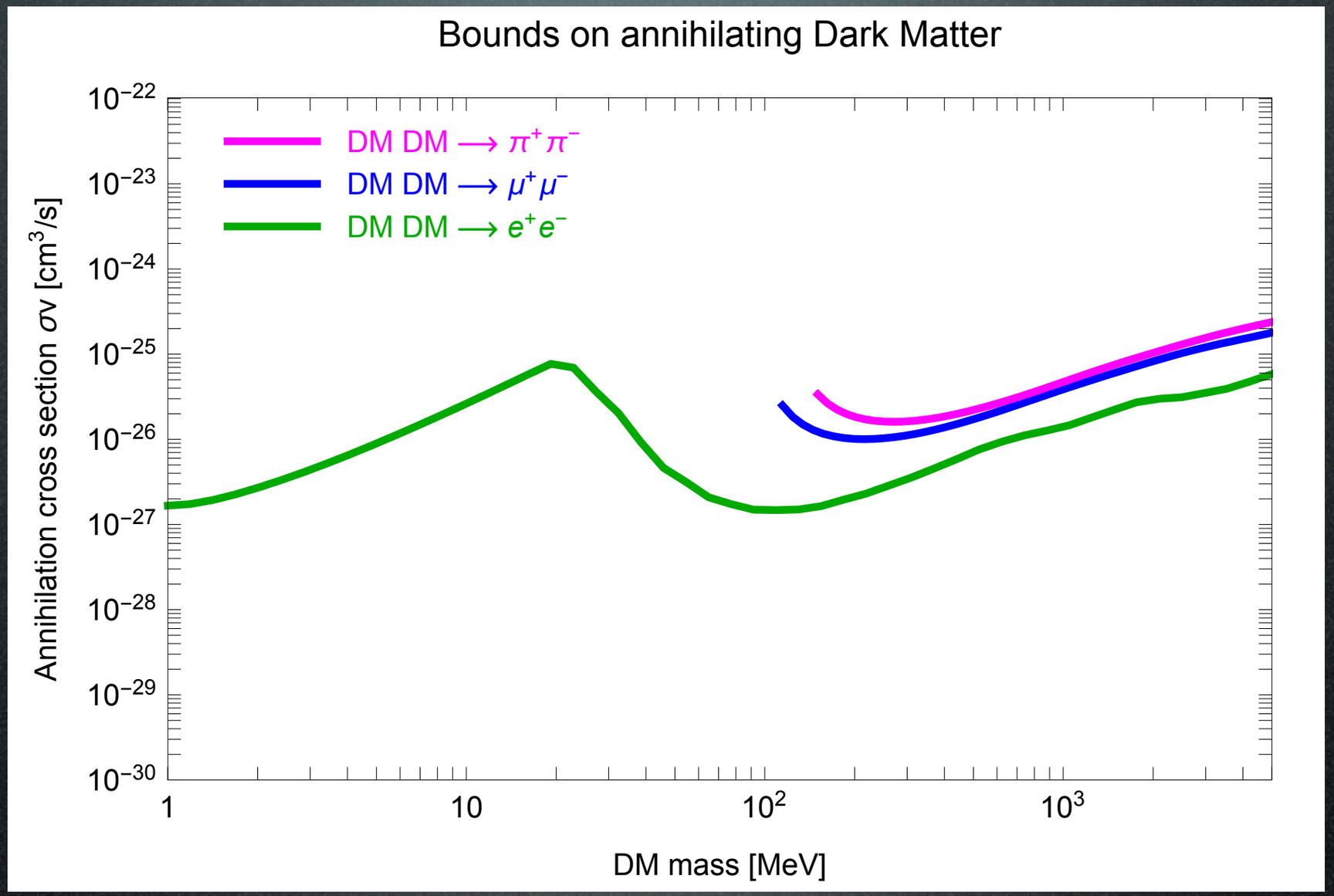


Test Statistics:
exclude if DM exceeds data by more than ~2σ global.
More precisely:

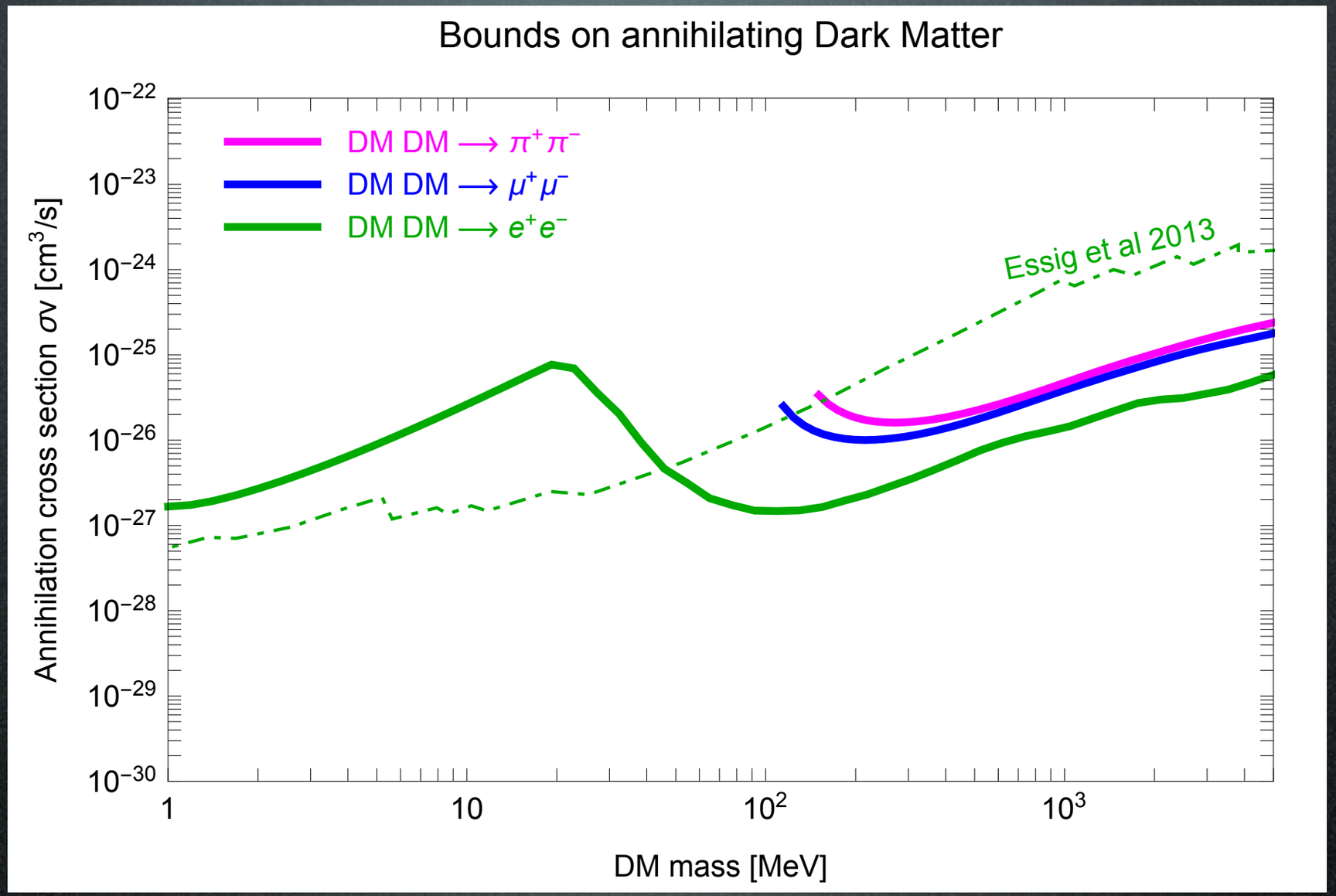
$$\chi^2_> = \sum_{\text{bands}} \sum_{i \in \{\text{b bins}\}} \frac{(\text{Max}[(\Phi_{\text{DM}\gamma,i}(\langle\sigma v\rangle) - \phi_i), 0])^2}{\sigma_i^2} \qquad \chi^2_> \geq 4$$

Results



Bounds on all 3 channels

Results

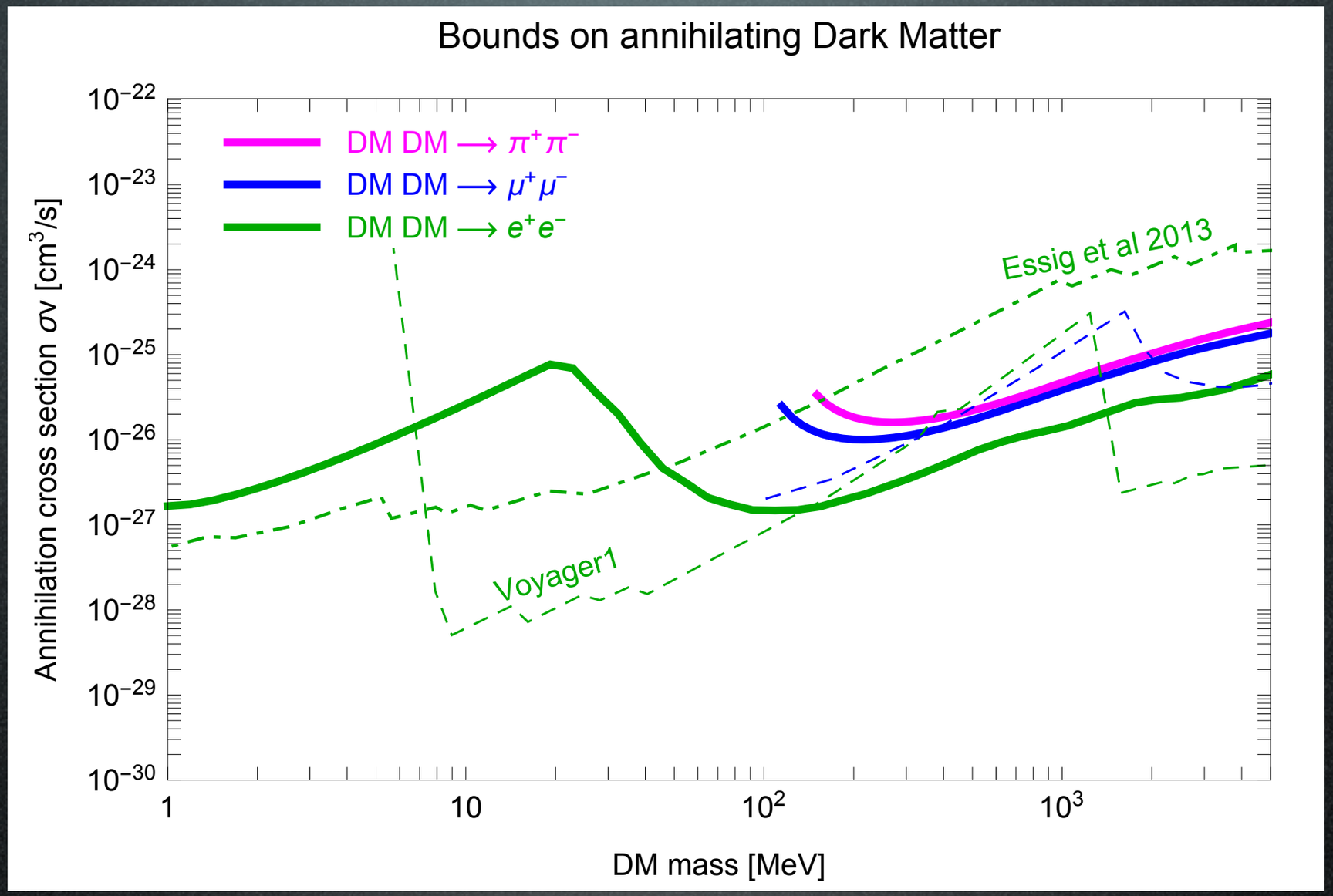


Essig+ 1309.4091

Bounds on all 3 channels

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

Results



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Voyager1 bounds stronger/weaker dep. on data

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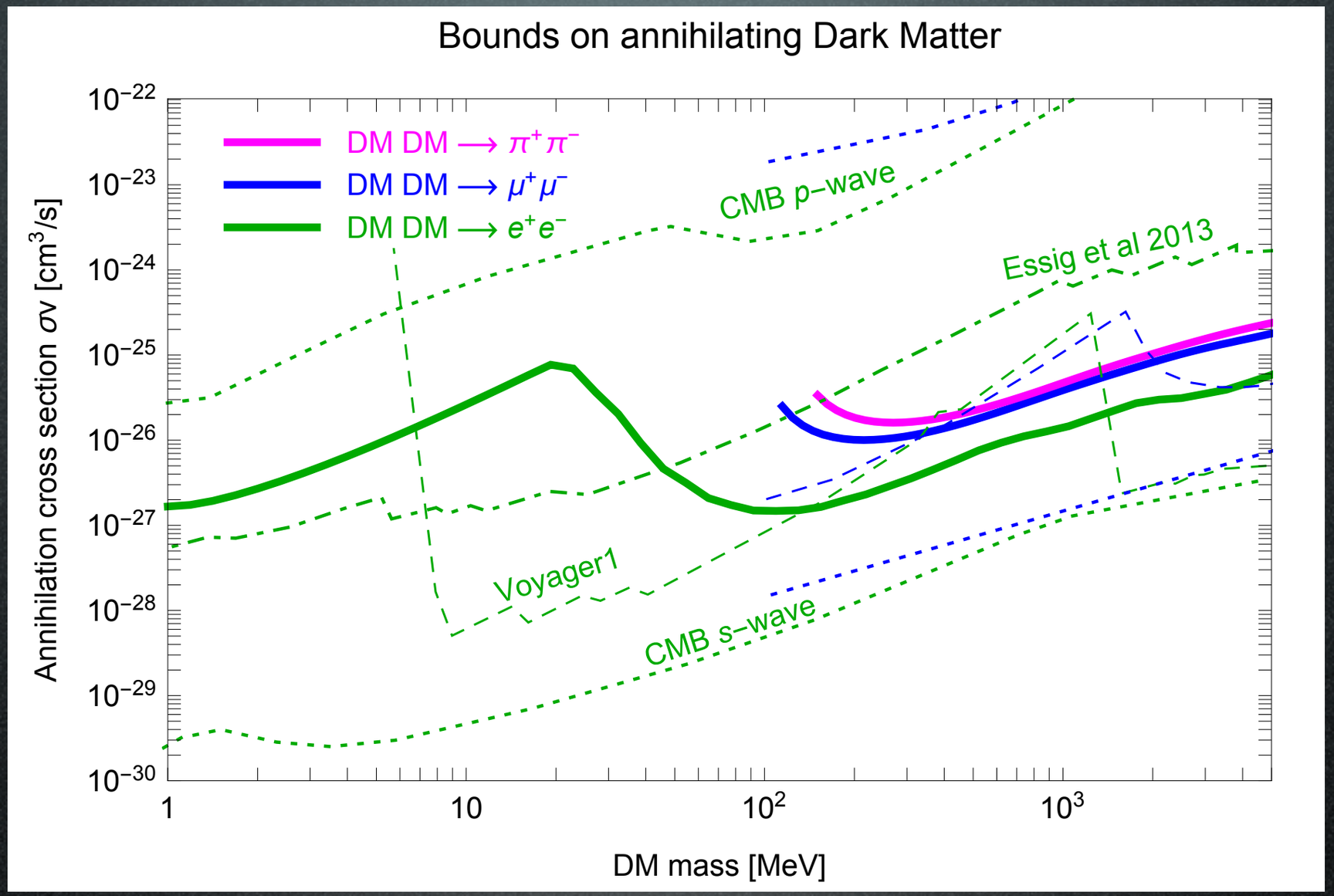


Essig+ 1309.4091

Boudaud+ 1612.07698

Slatyer+ 1506.03811

Lopez-H+ 1303.5094

Diamanti+ 1308.2578

Liu+ 2008.01084

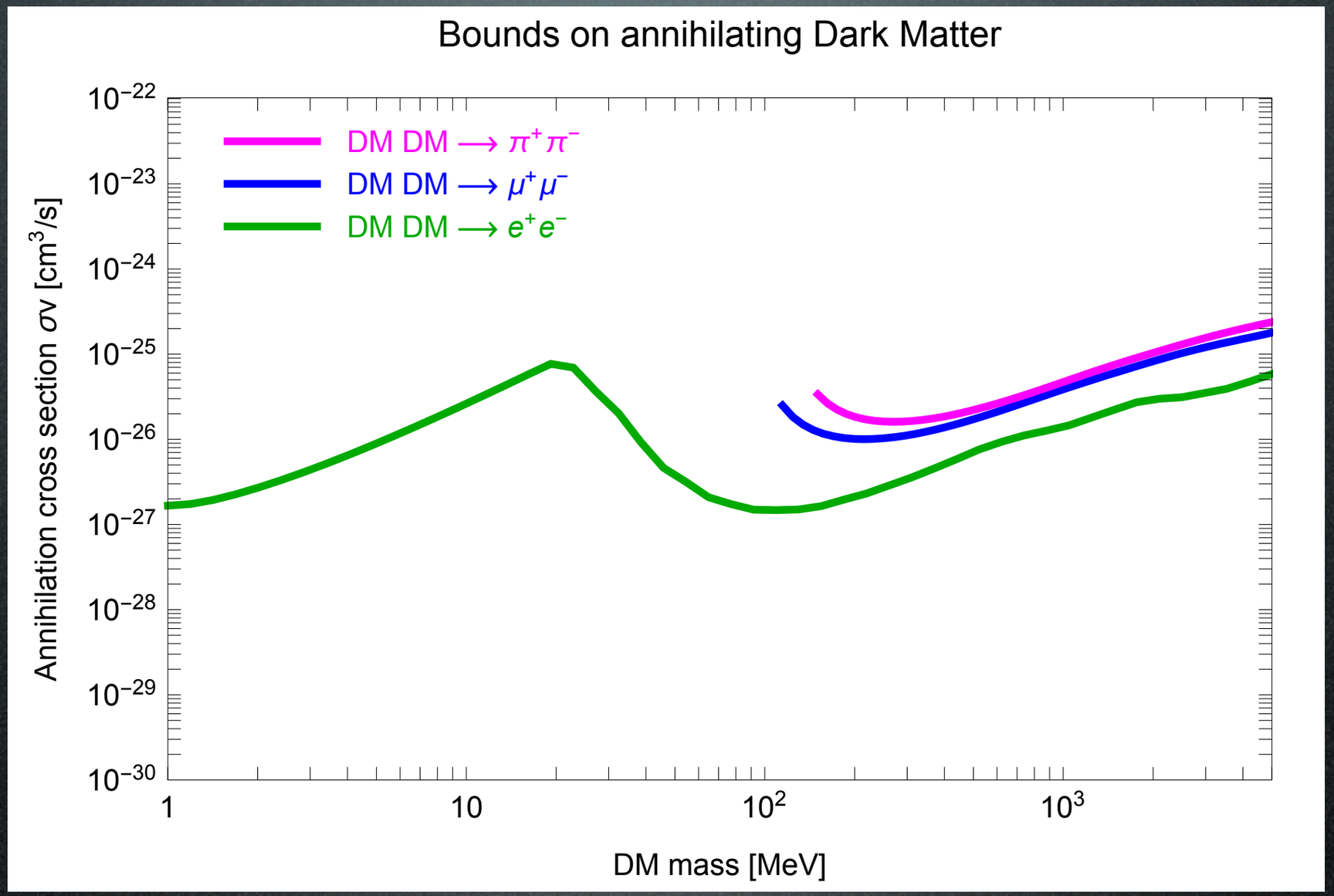
Bounds on all 3 channels

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

Voyager1 bounds stronger/weaker dep. on data

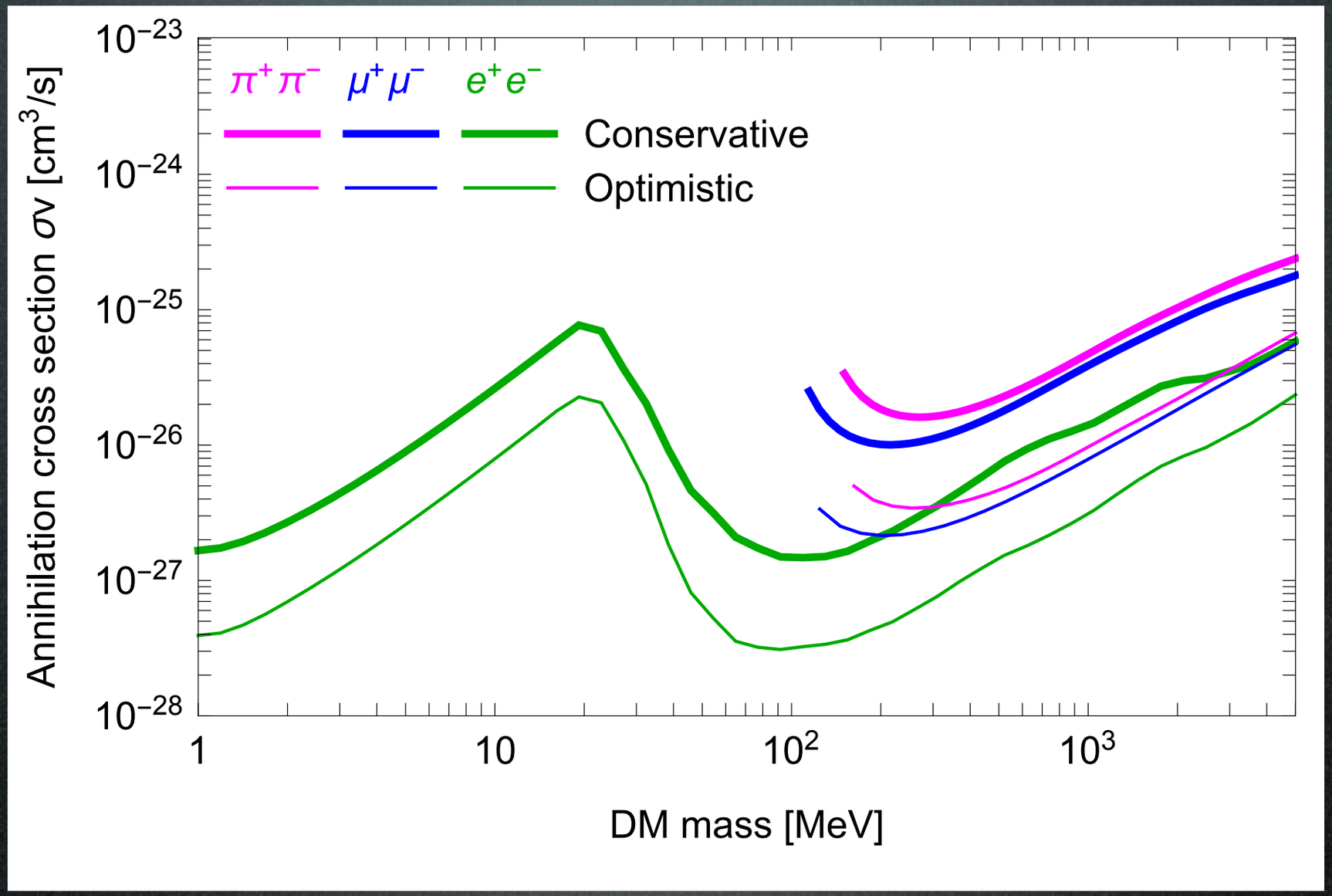
CMB bounds depend on s-/p-wave annihilation

Results



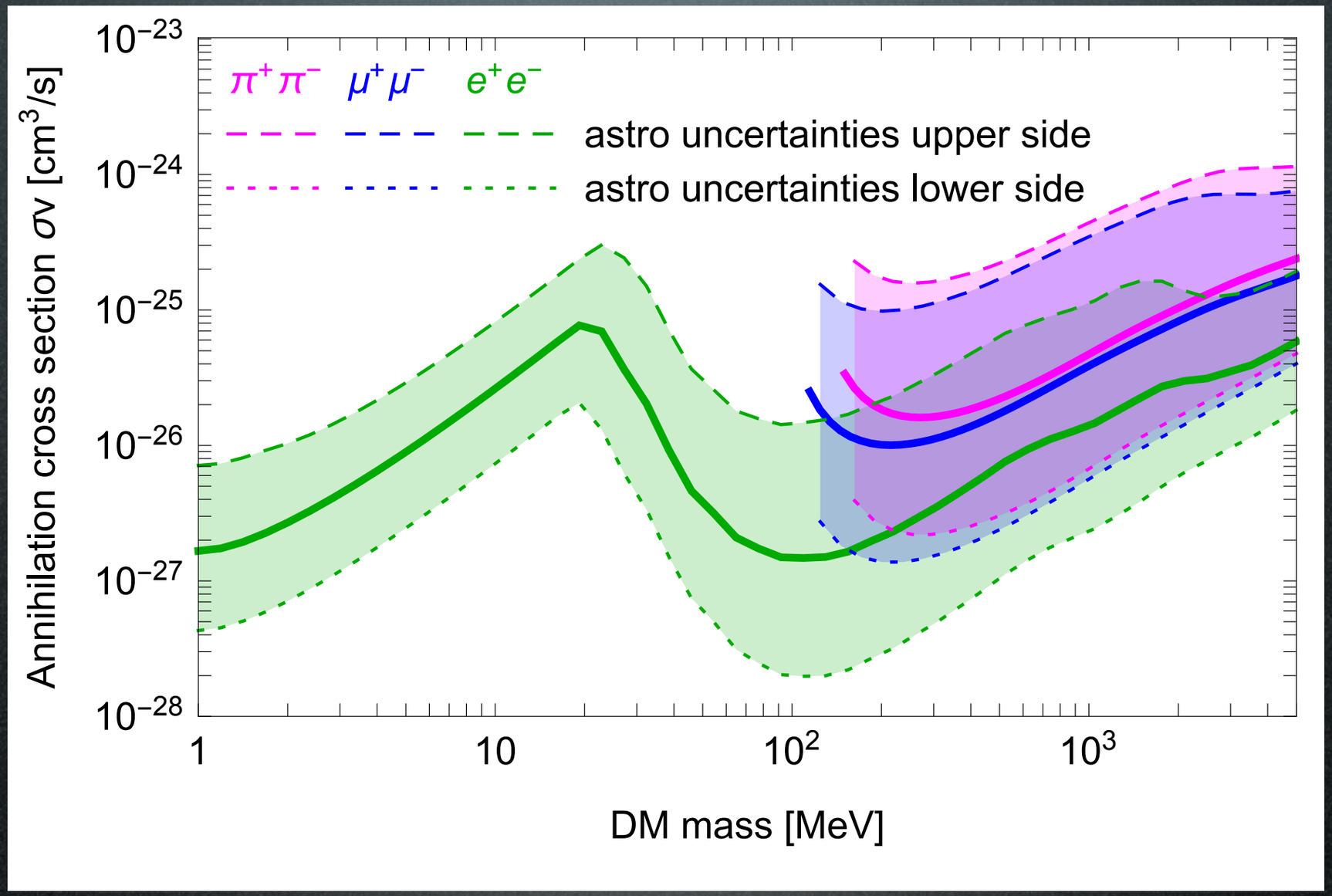
Bounds on all 3 channels

Results

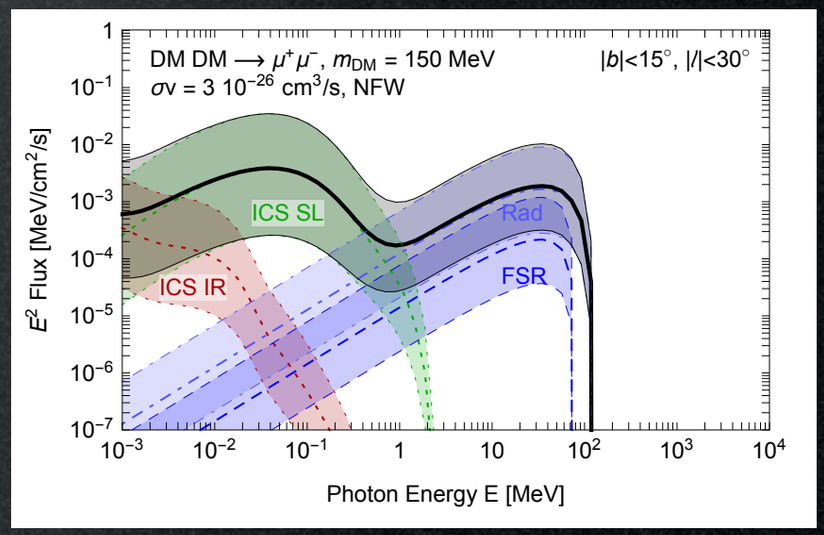


Bounds including an astrophysical background

Results



Uncertainties:
- DM galactic profile
- Gas density
- ISRF
- Galactic magnetic field



Conclusions

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

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ID is (more) challenging
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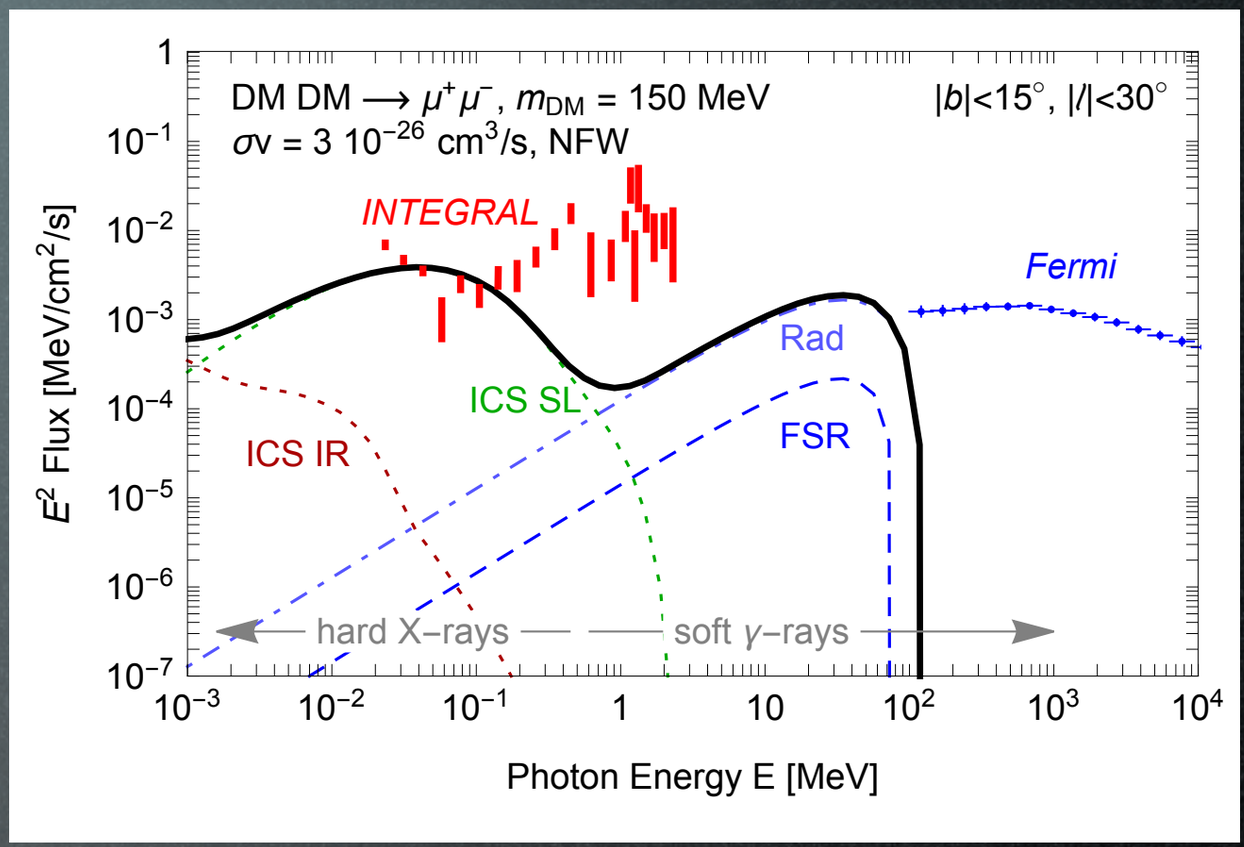
ID is (more) challenging than WIMPs

ICS allows to test it with X-ray data



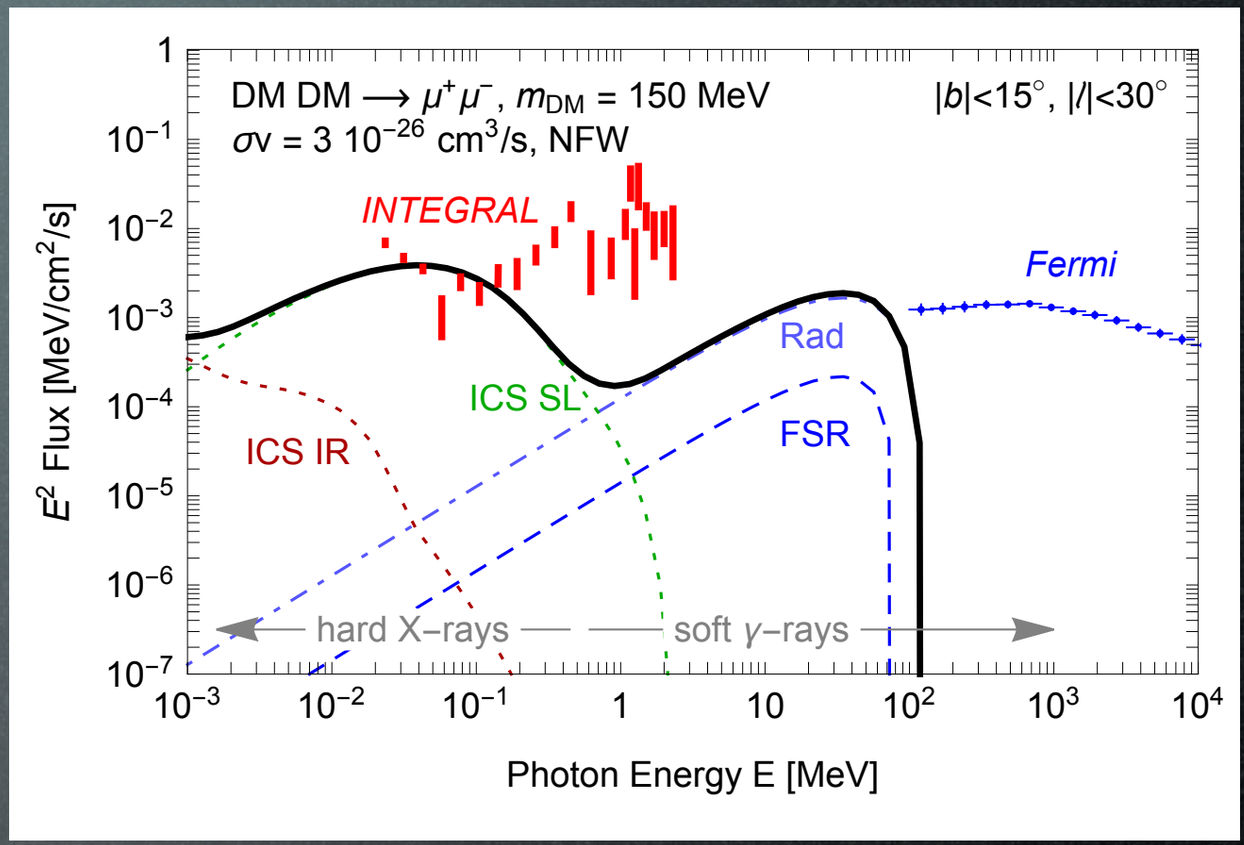
Conclusions

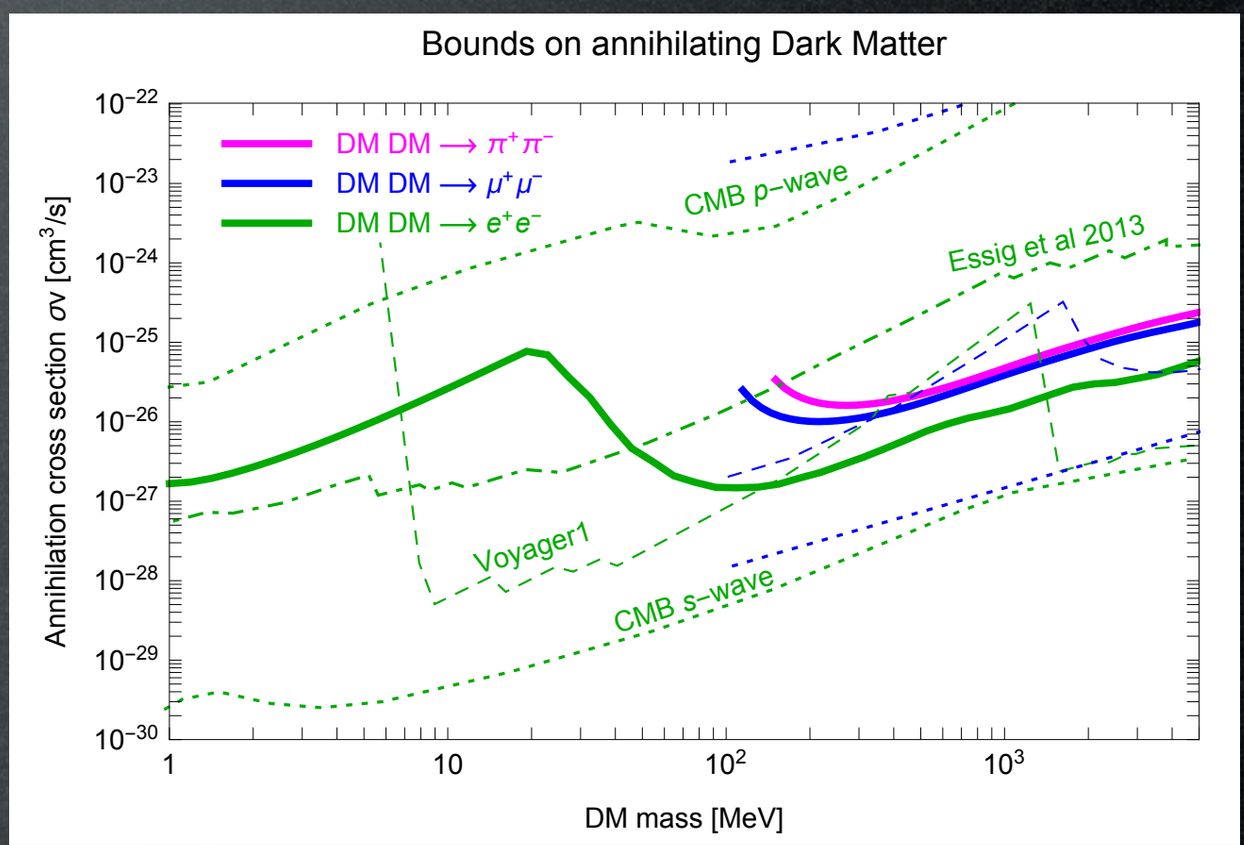
Sub-GeV DM is interesting and emerging: Why not?!

ID is (more) challenging than WIMPs

ICS allows to test it with X-ray data

Impose stringent constraints





Backup

Dark Matter factsheet

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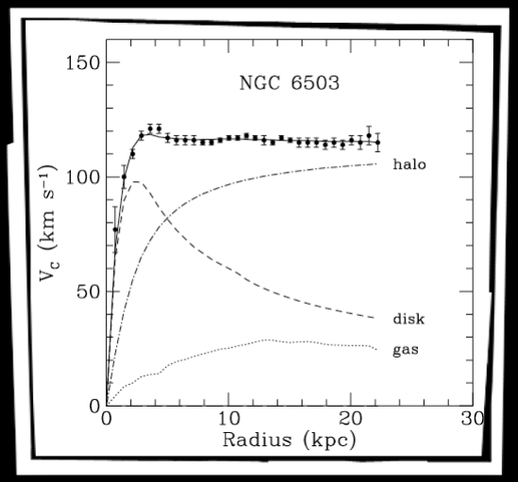
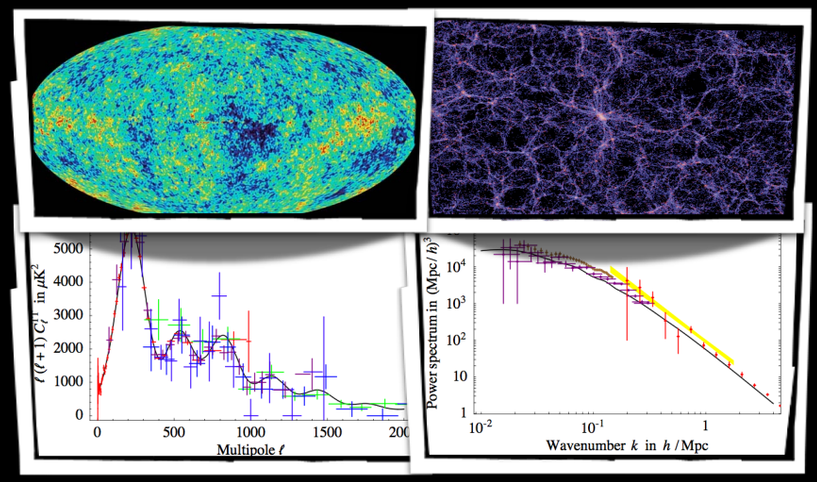


galactic rotation curves

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

- DM exists
- it's a new, unknown particle

no SM particle can fulfill

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Dark Matter factsheet

- DM exists
- it's a new, unknown particle
- makes up 26% of total energy
  82% of total matter

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

(notice error!)

[Planck 2015, 1502.01589]

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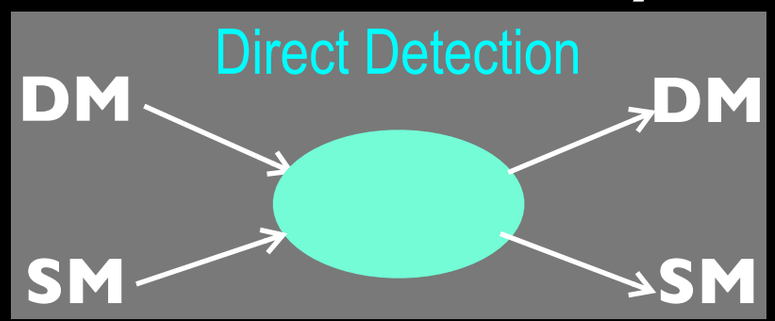

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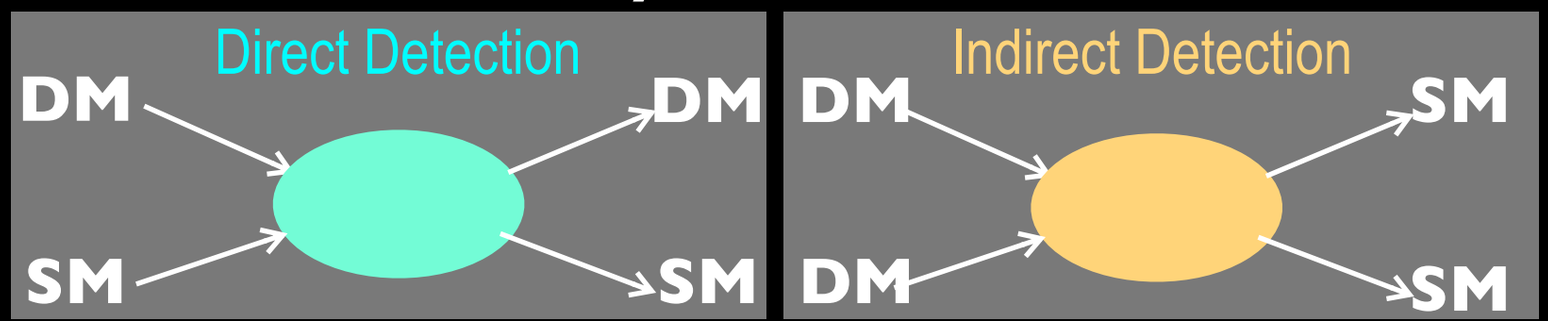

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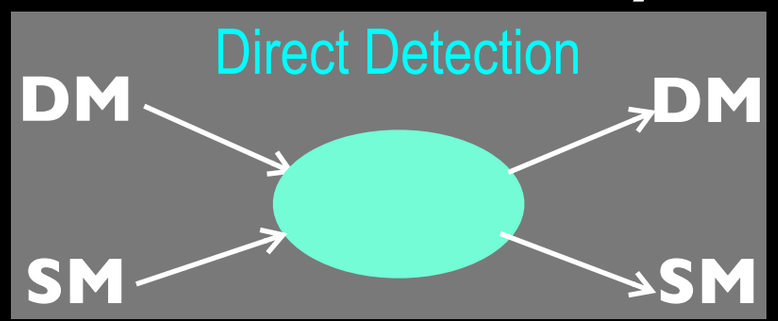

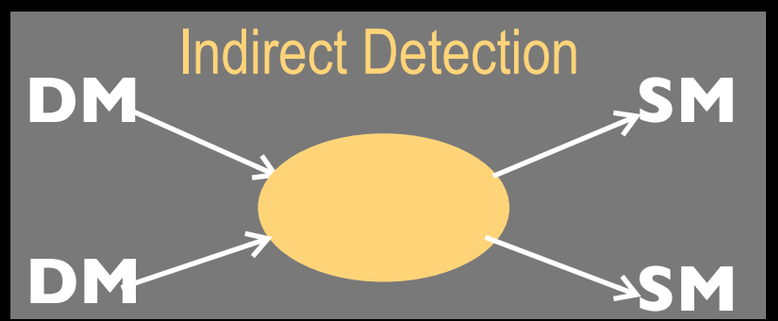

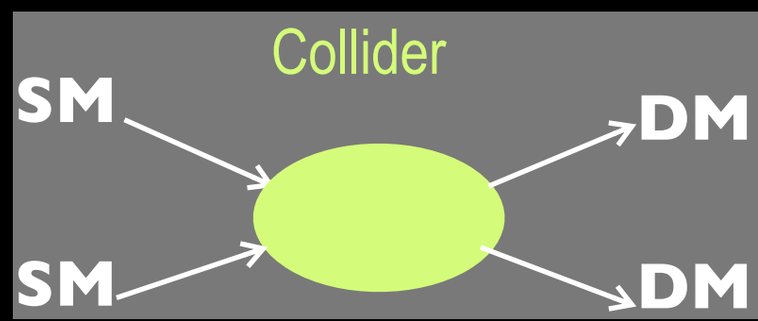

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Mass??

Charge??
Interactions??

Candidates

The Dark Matter theory space:

Candidates

The Dark Matter theory space:

SuSy DM

Non SuSy DM

Candidates

The Dark Matter theory space:

SuSy DM

Non SuSy DM

?

Candidates

The Dark Matter theory space:

SuSy neutralino

other exotic candi-dates

Candidates

A matter of perspective:

Scalar singlet
Anapole DM
Axino
Minimal DM
dipolar DM
Impeded DM
SIMPs
Little Higgs DM
cannibal DM
Asym-metric DM
Rayleig DM
eXciting DM
SuSy neutralino
Self-inte DM
GUTzilla DM
WISPy DM
Techi-baryon
vector DM
Dichromatic DM
inflatable DM
xions
Forbidden DM
mirror matter
WIMPless DM
Secluded DM
heavy higgs DM
Sterile Neutrinos
Luminous DM
Kaluza-Klein DM
Q-balls
Gravitino
quark nuggets
MeV DM
dark photon
Imperfect DM
Mimetic DM

Candidates

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SuSy neutralino

Candidates

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Candidates

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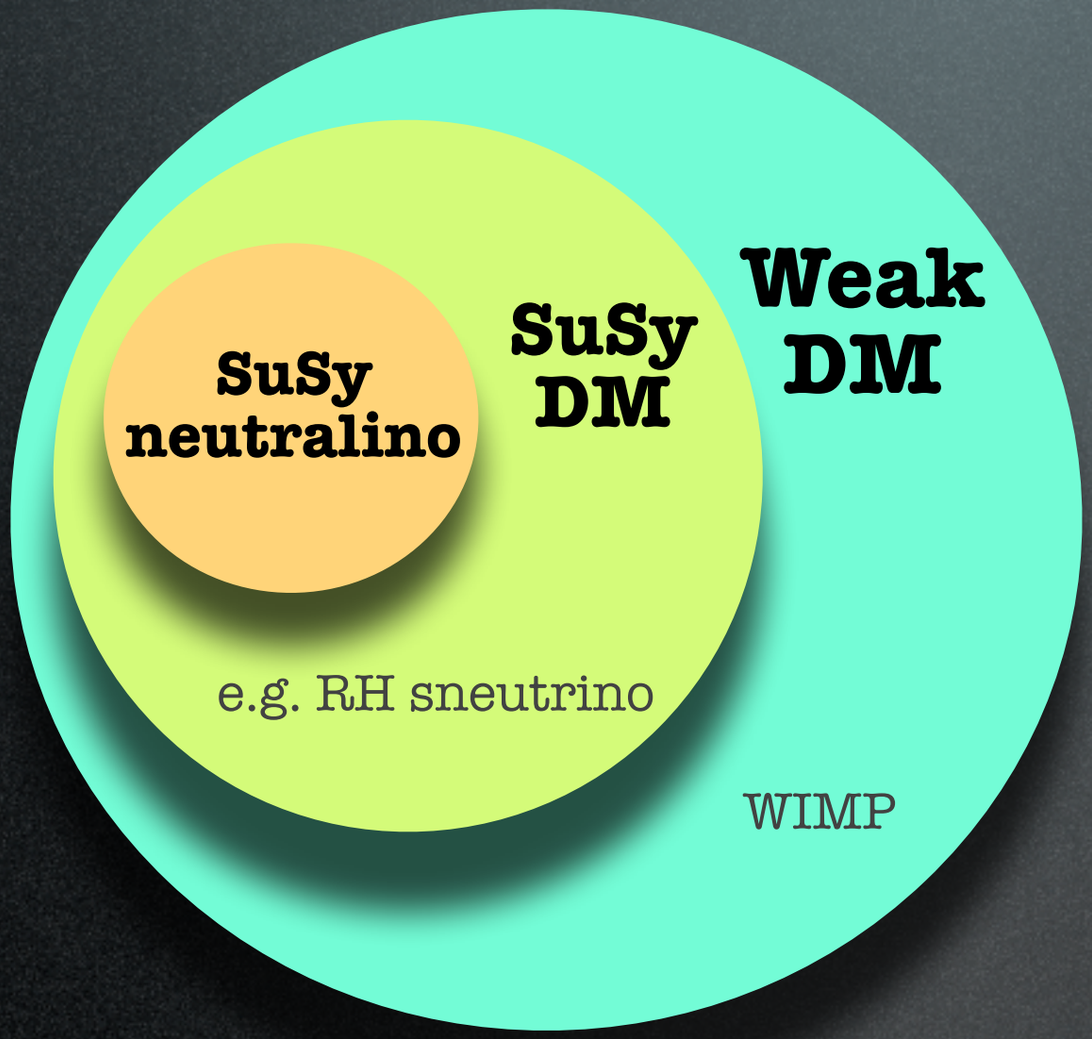

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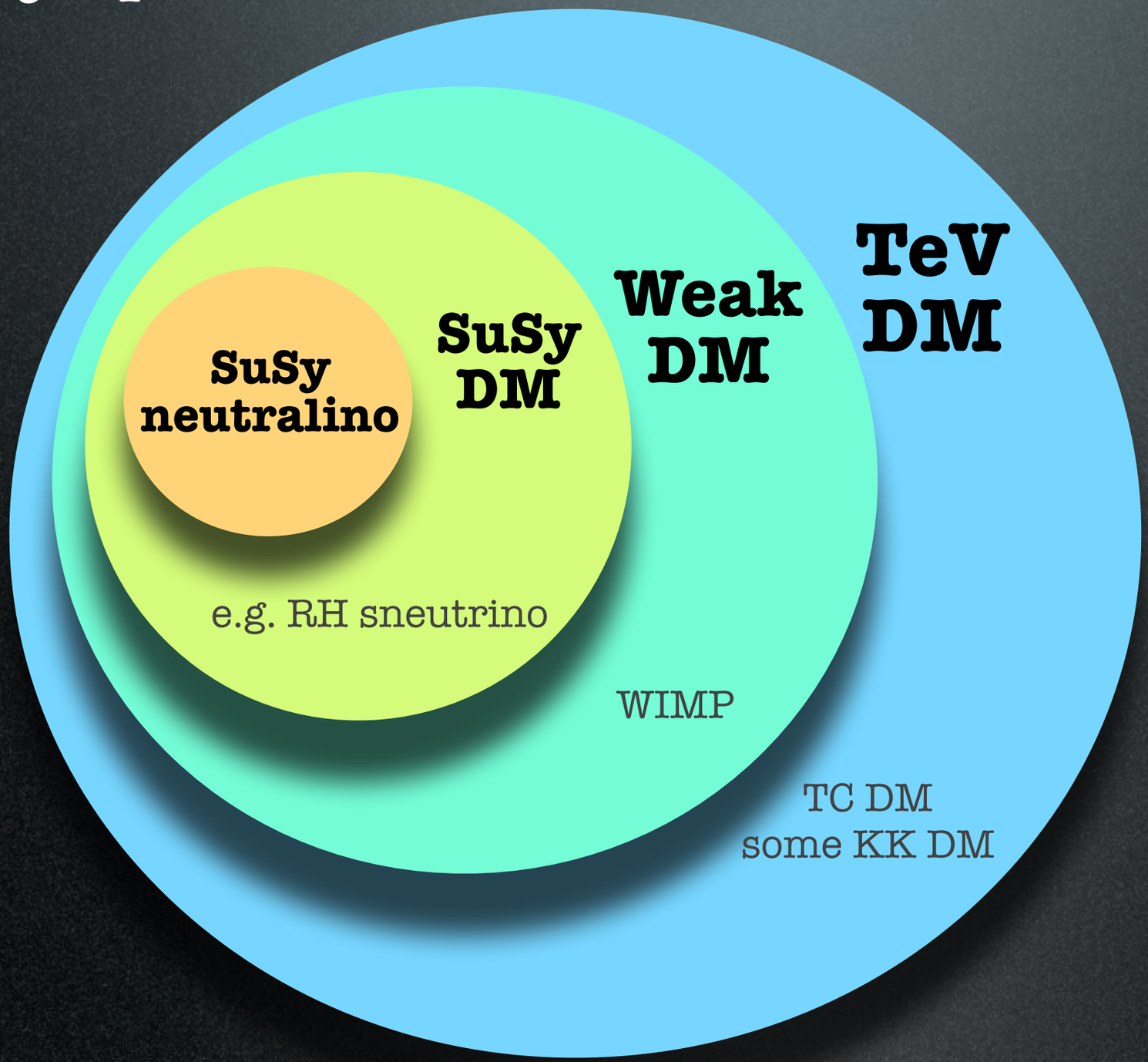

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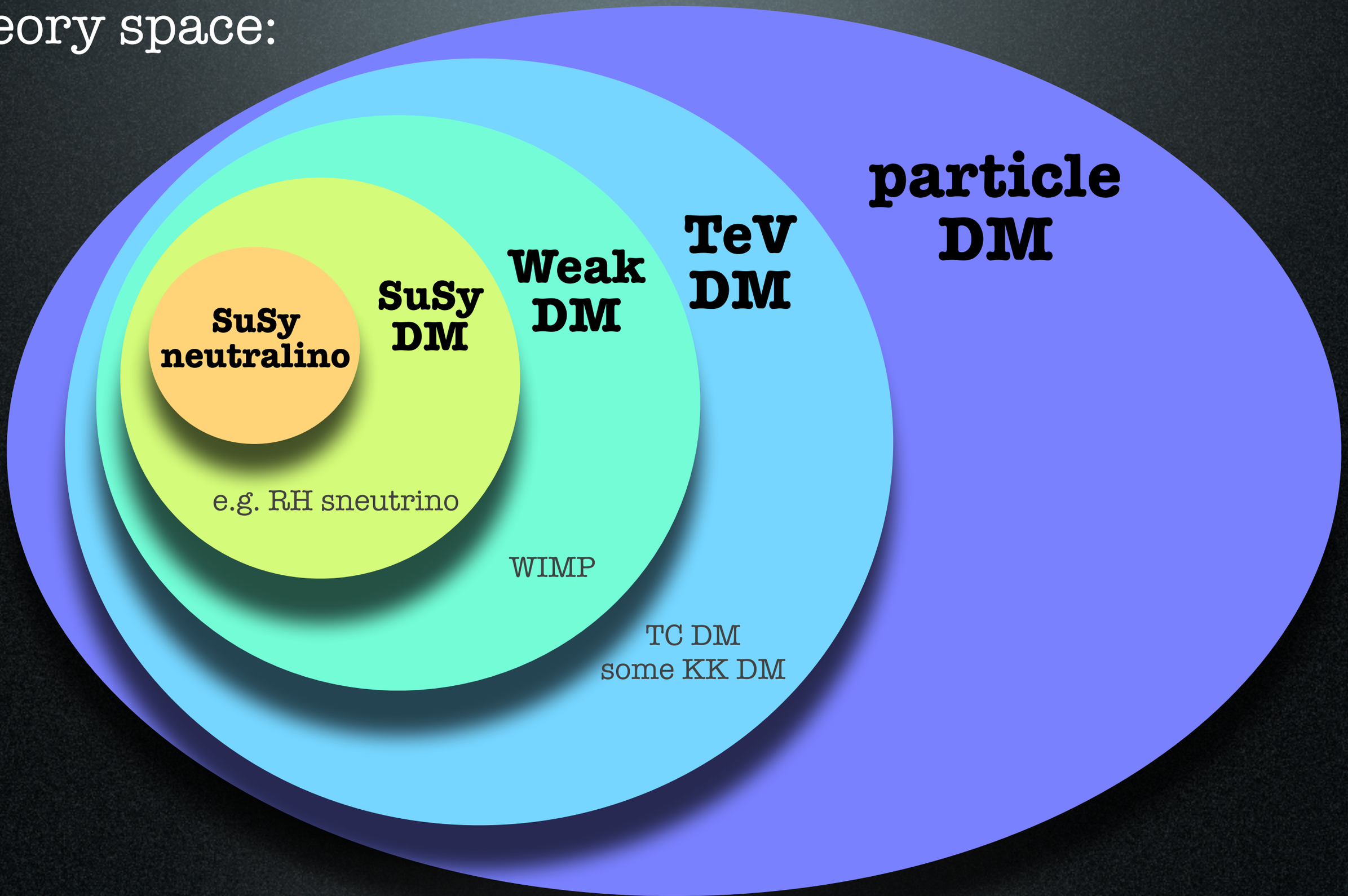

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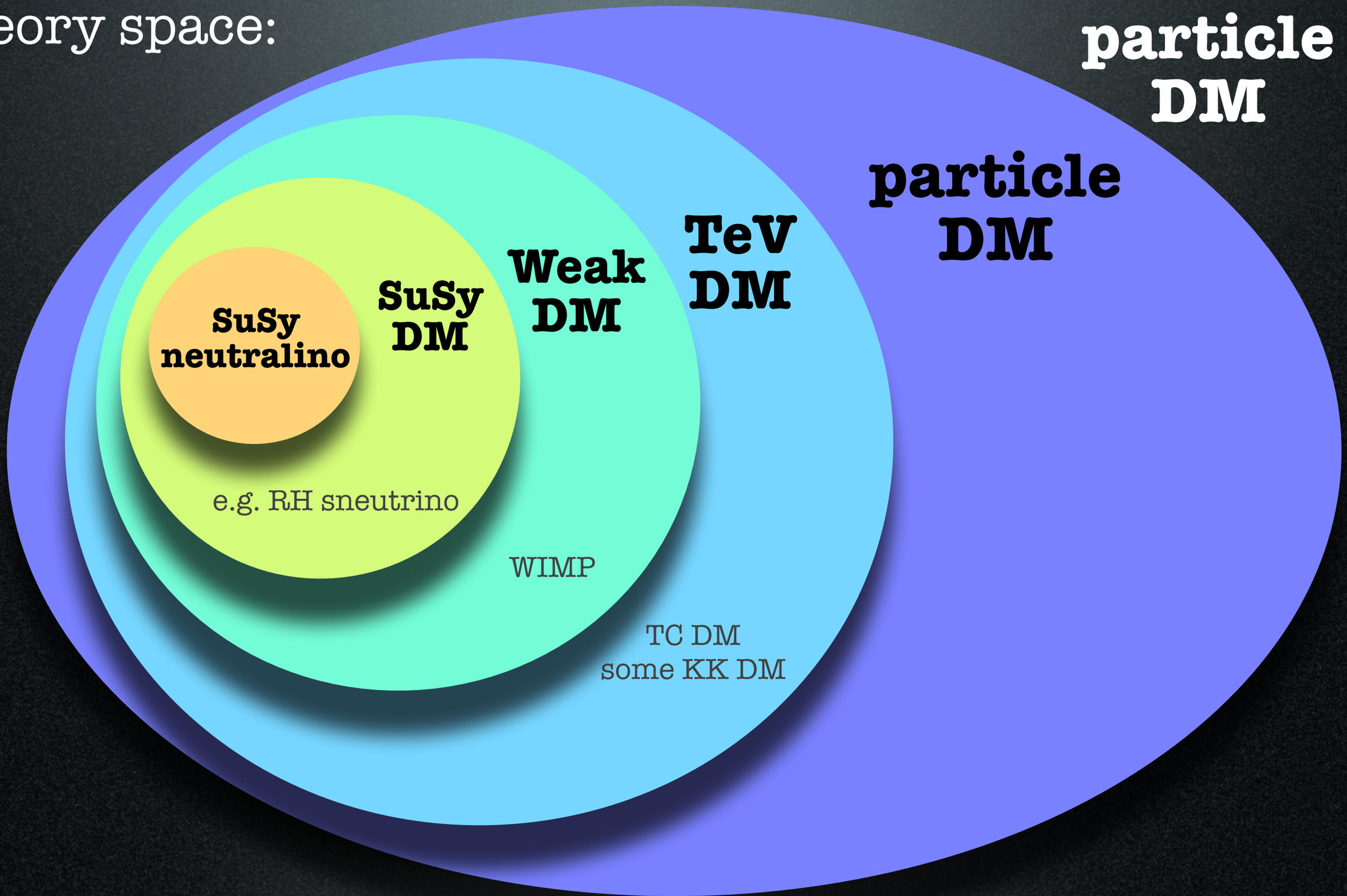
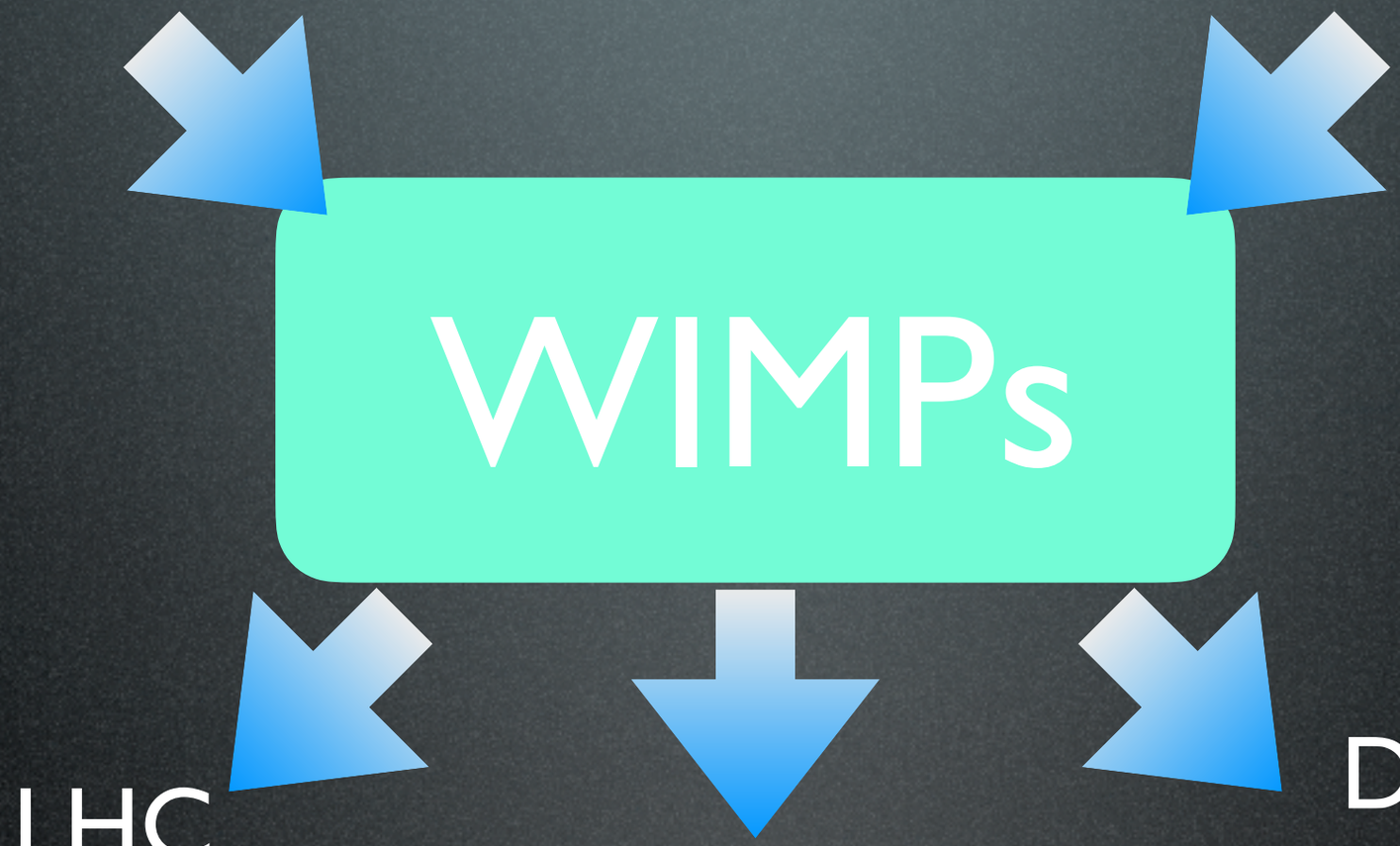


Candidates

new physics at the TeV scale

thermal freeze-out

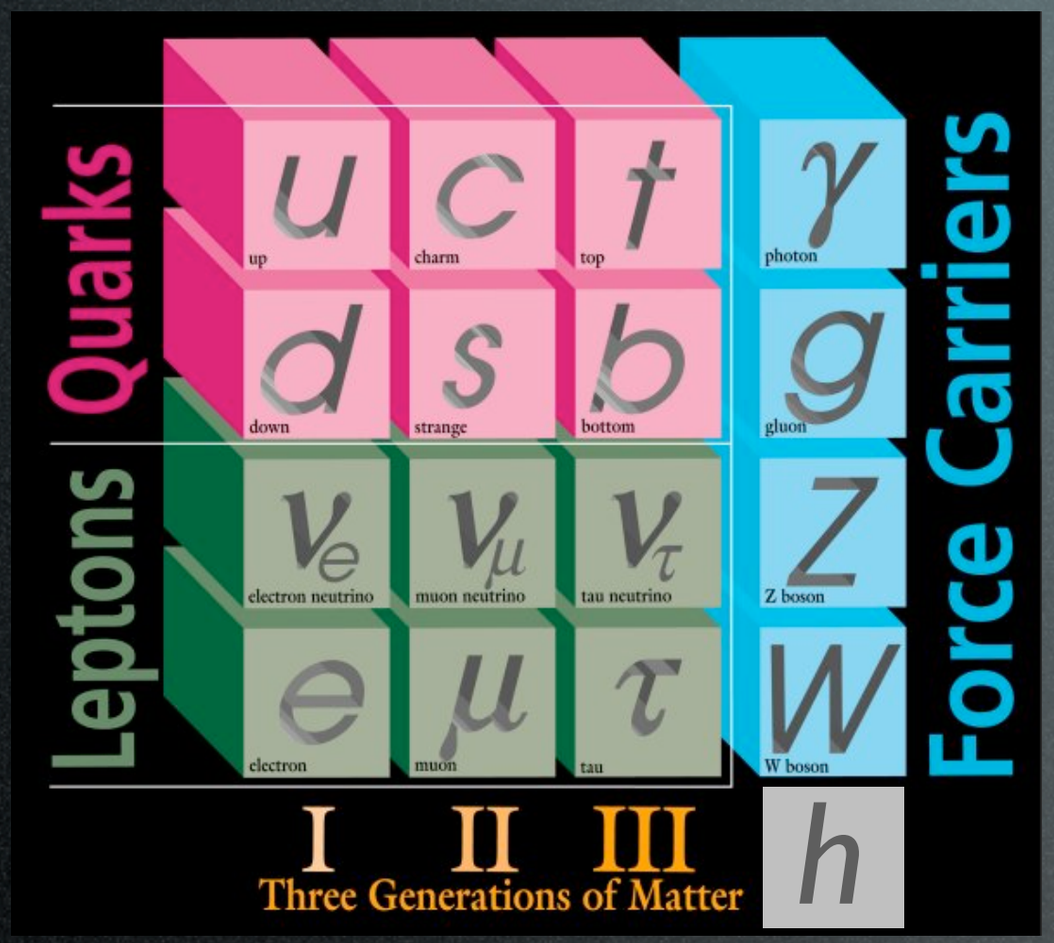


LHC

Indirect Detection

Direct Detection

SuSy DM in 2 minutes



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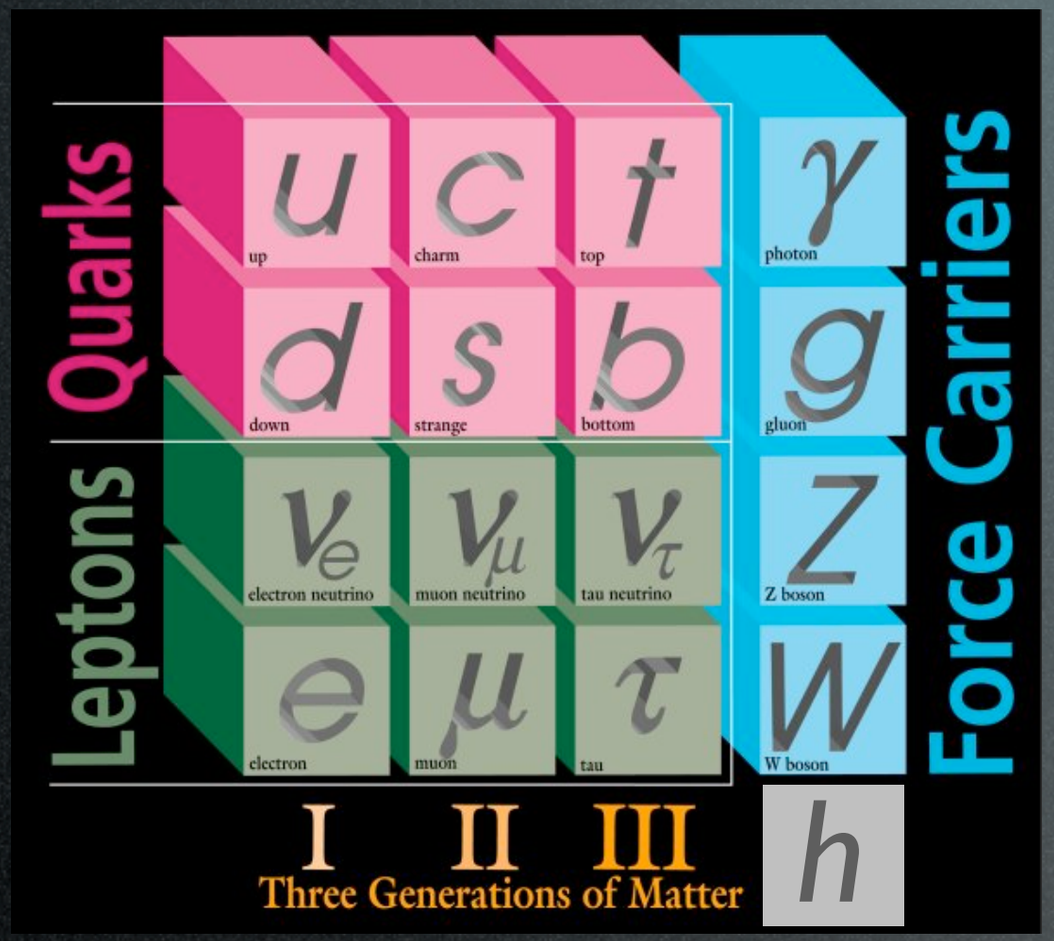
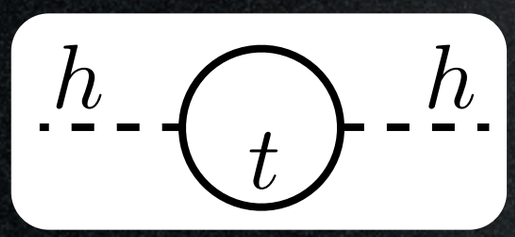
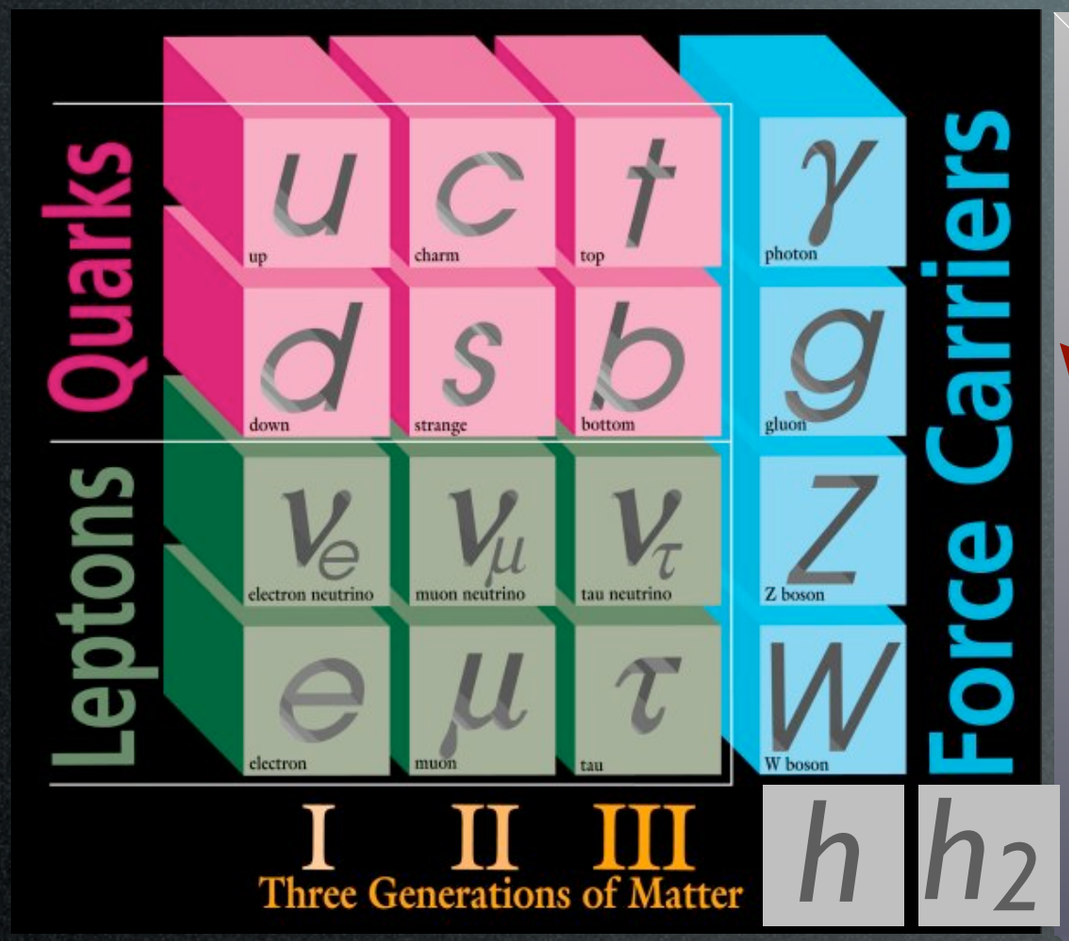


$$m_{\rm h} \simeq 125 \text{ GeV}$$

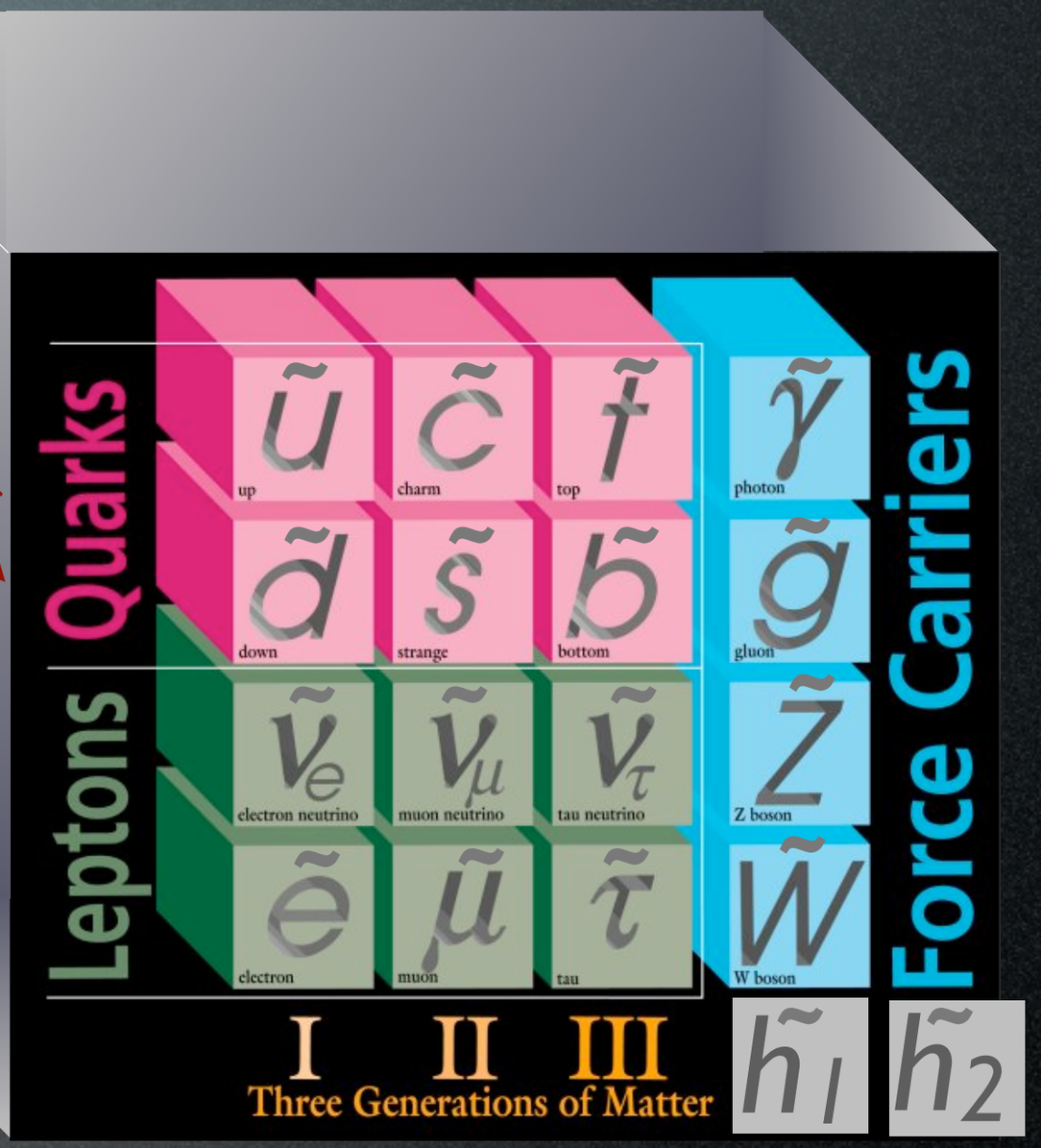


$$\Delta m_{\rm h} \propto 10^{19} \text{ GeV}$$

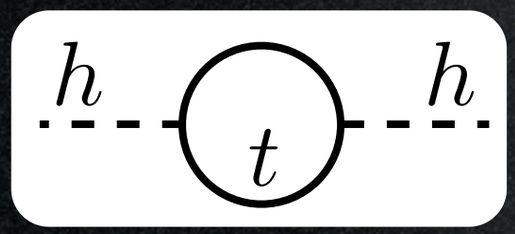
SuSy DM in 2 minutes



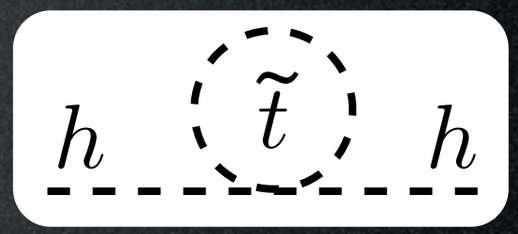
200 GeV



$m_{\rm h} \simeq 125$ GeV

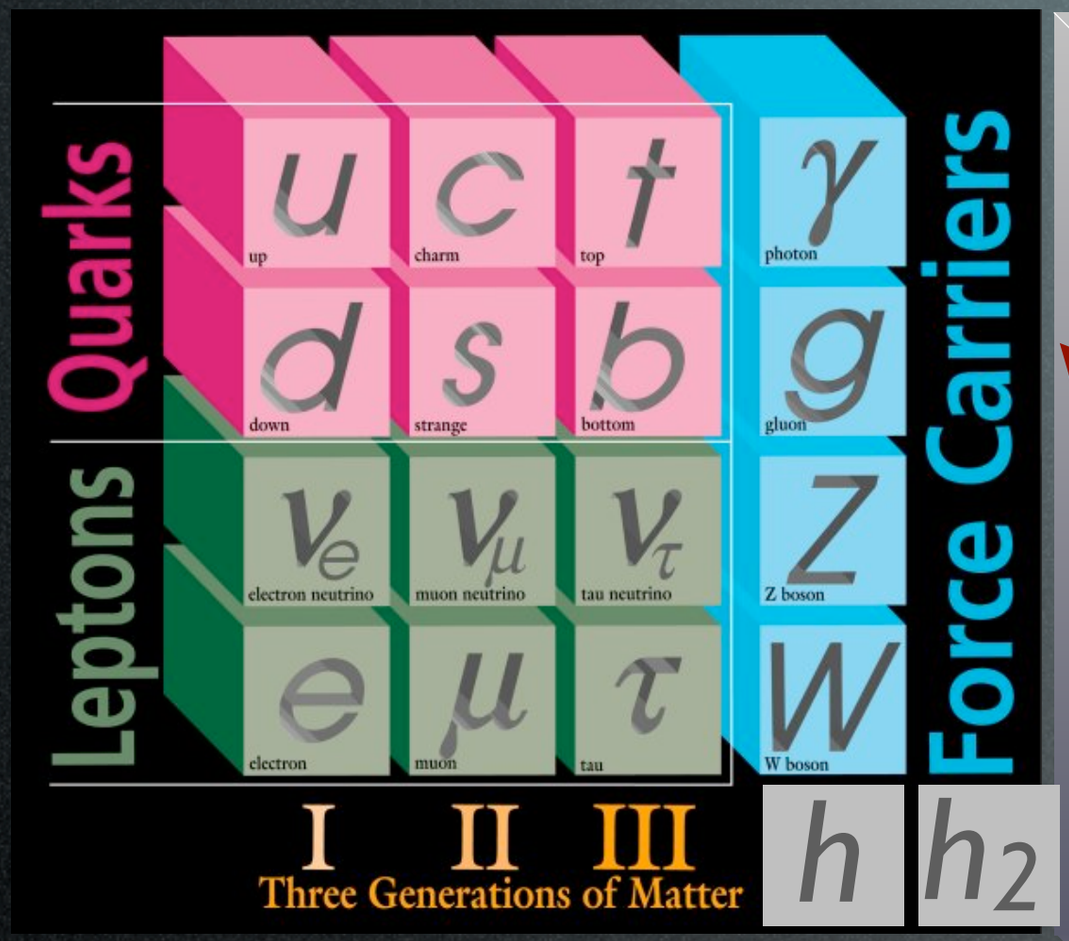


$\Delta m_{\rm h} \propto 10^{19}$ GeV



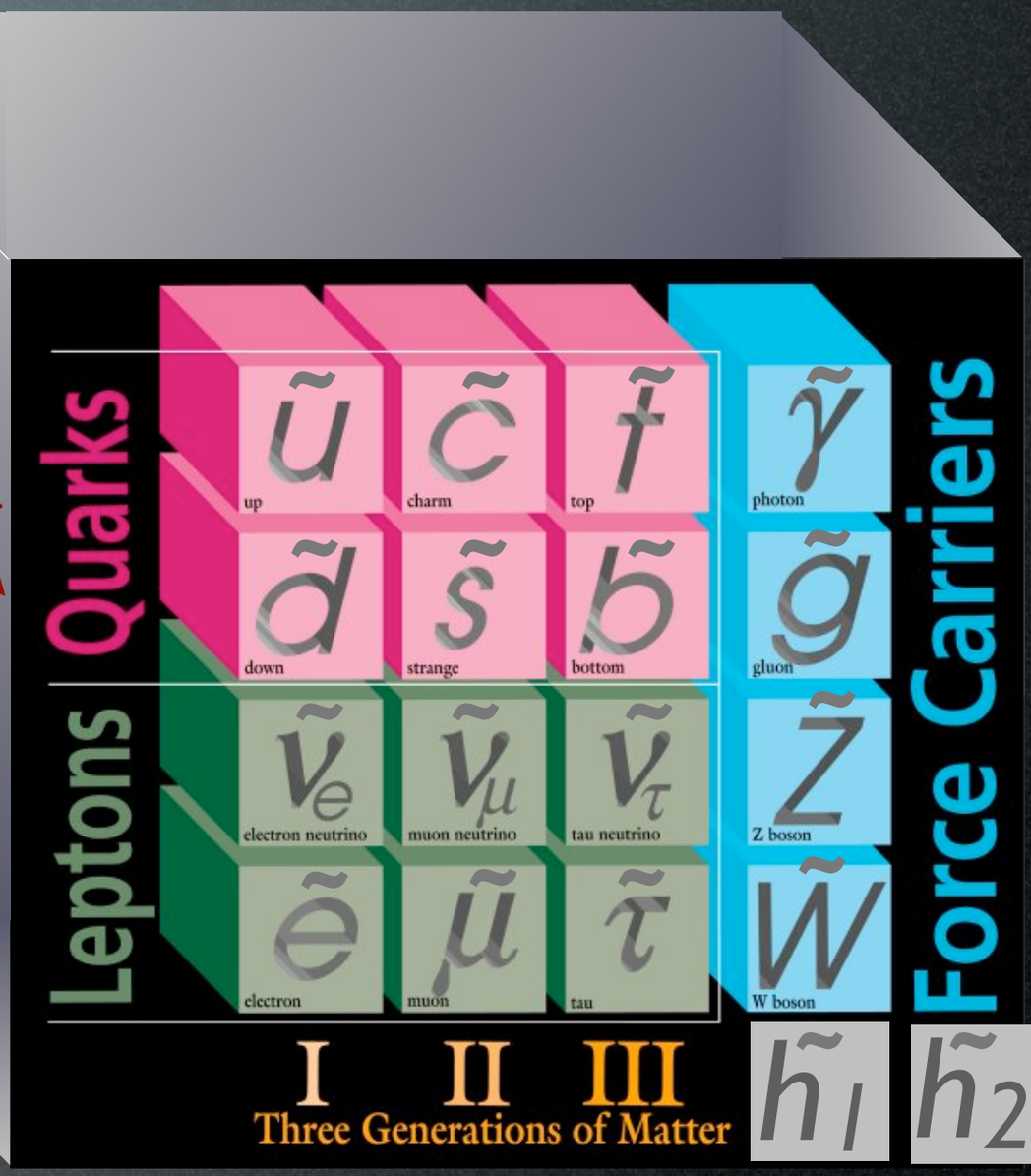
$\Delta m_{\rm h} \propto -10^{19}$ GeV

SuSy DM in 2 minutes

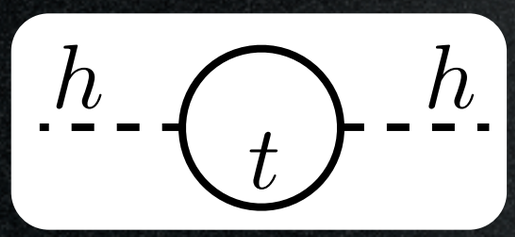


$R = +1$

200 GeV

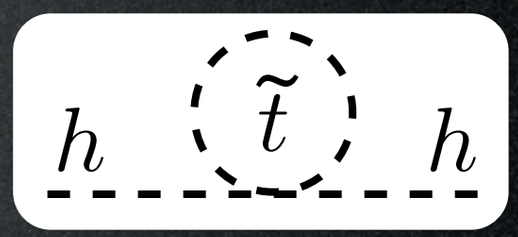


$m_{\mathrm{h}} \simeq 125\ \mathrm{GeV}$



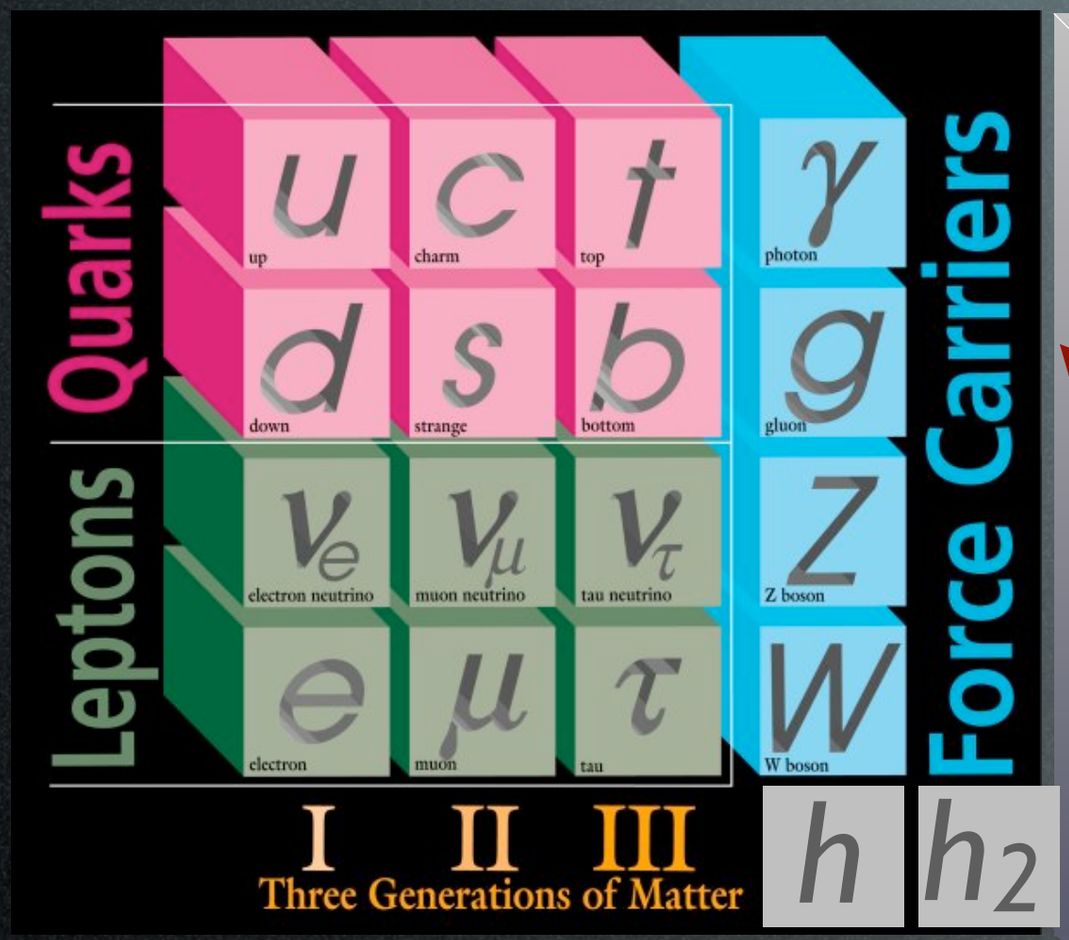
$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$

$R = -1$



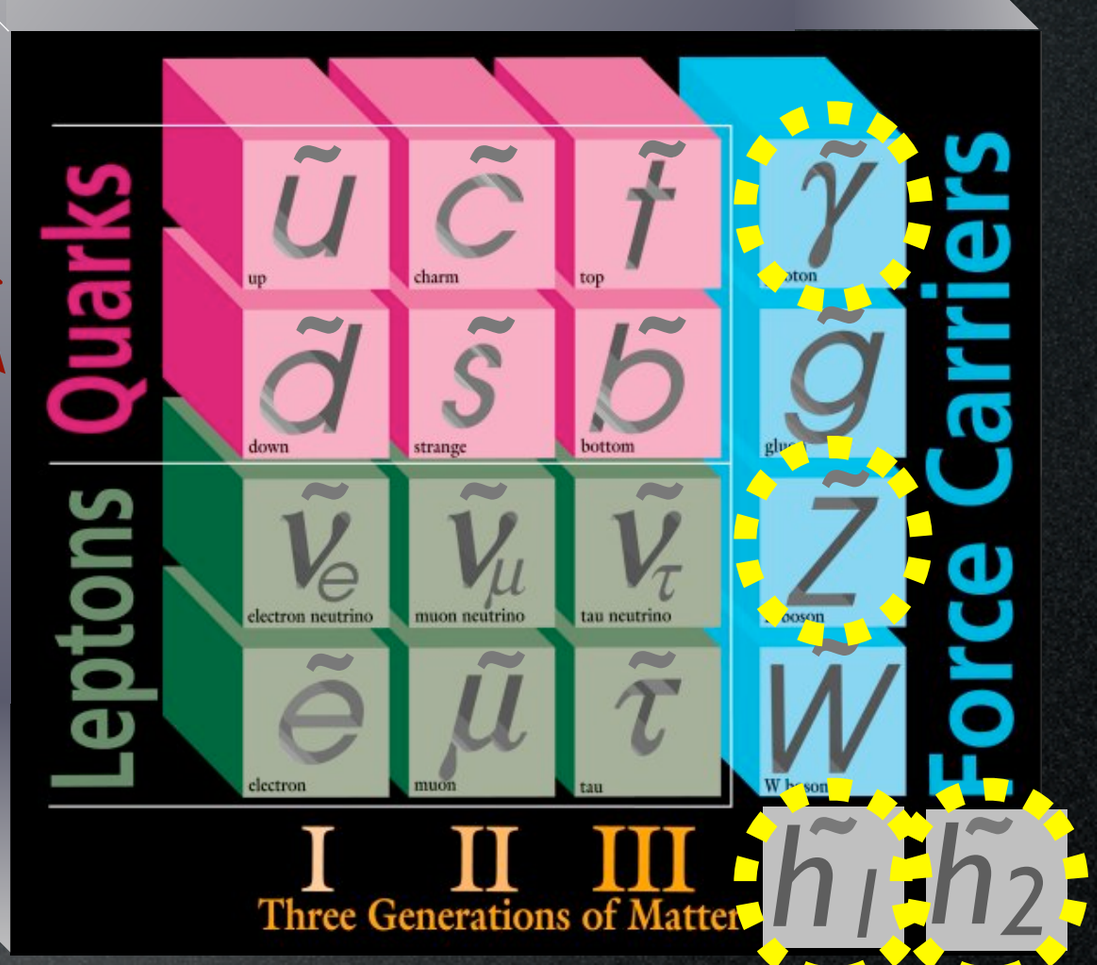
$\Delta m_{\mathrm{h}} \propto -10^{19}\ \mathrm{GeV}$

SuSy DM in 2 minutes



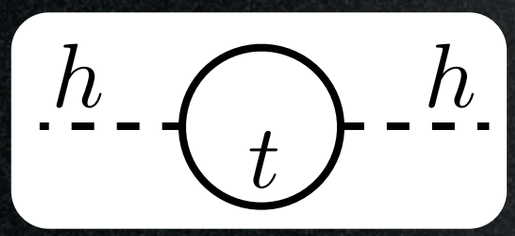
$R = +1$

200 GeV

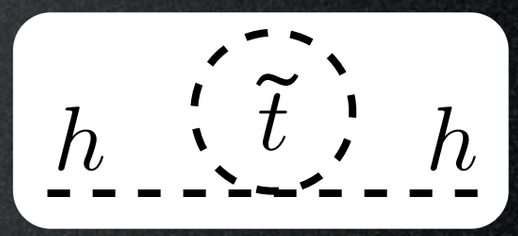


$R = -1$

$m_{\mathrm{h}} \simeq 125\ \mathrm{GeV}$

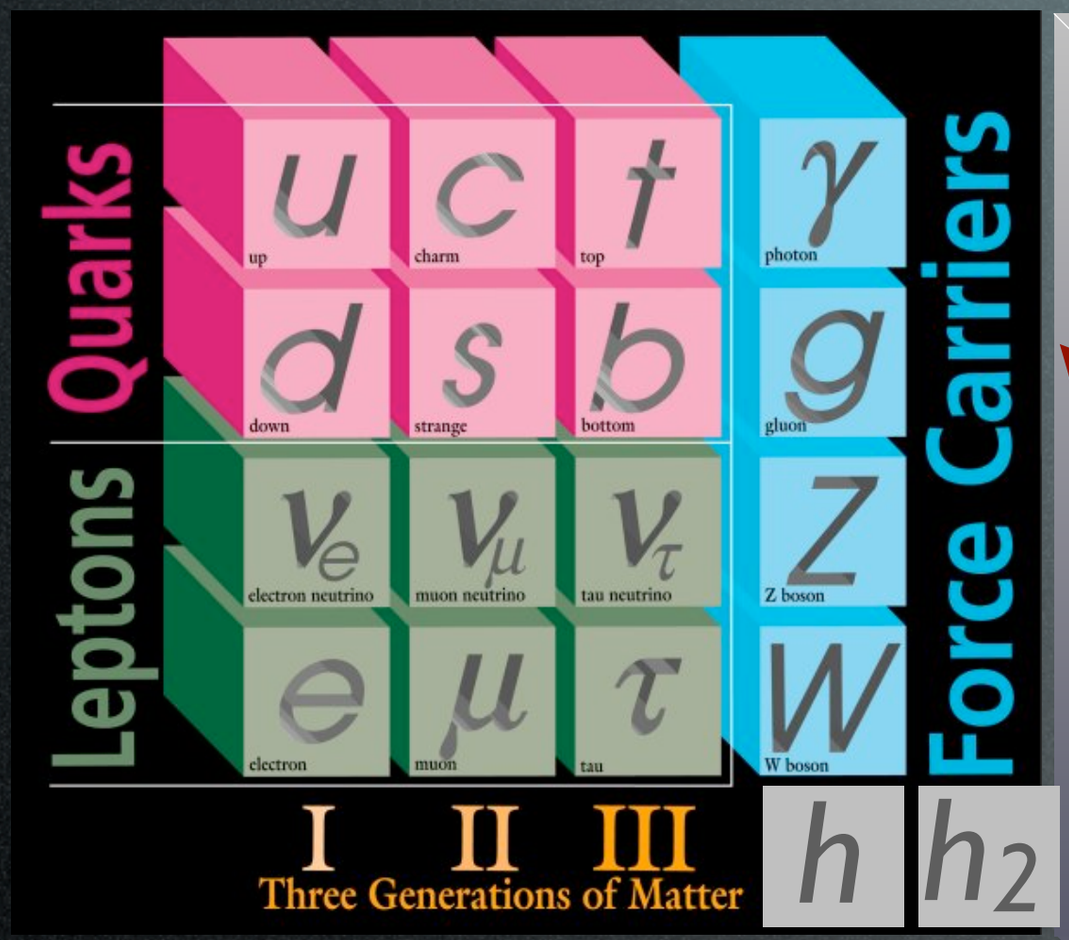


$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$

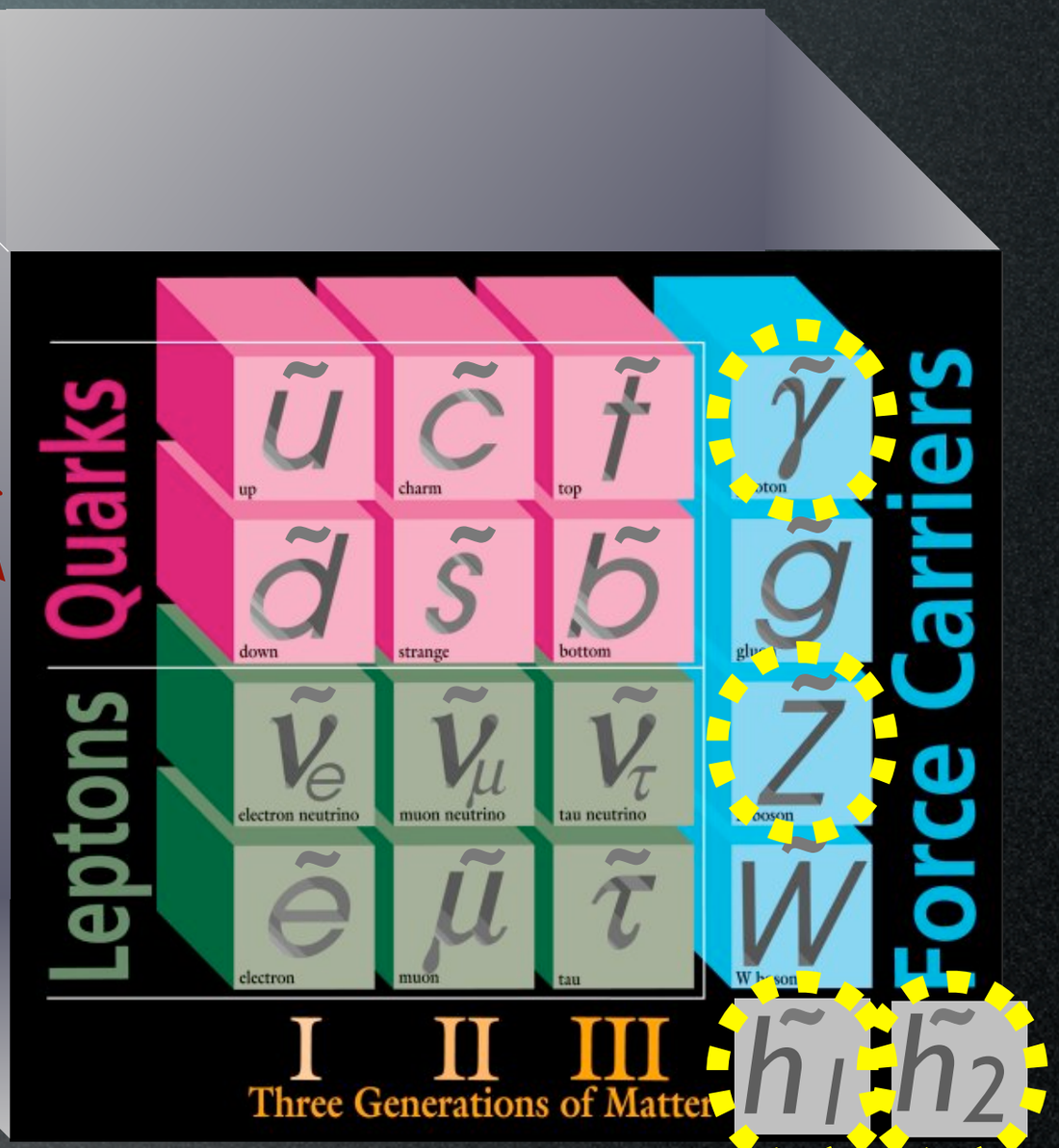


$\Delta m_{\mathrm{h}} \propto -10^{19}\ \mathrm{GeV}$

SuSy DM in 2 minutes



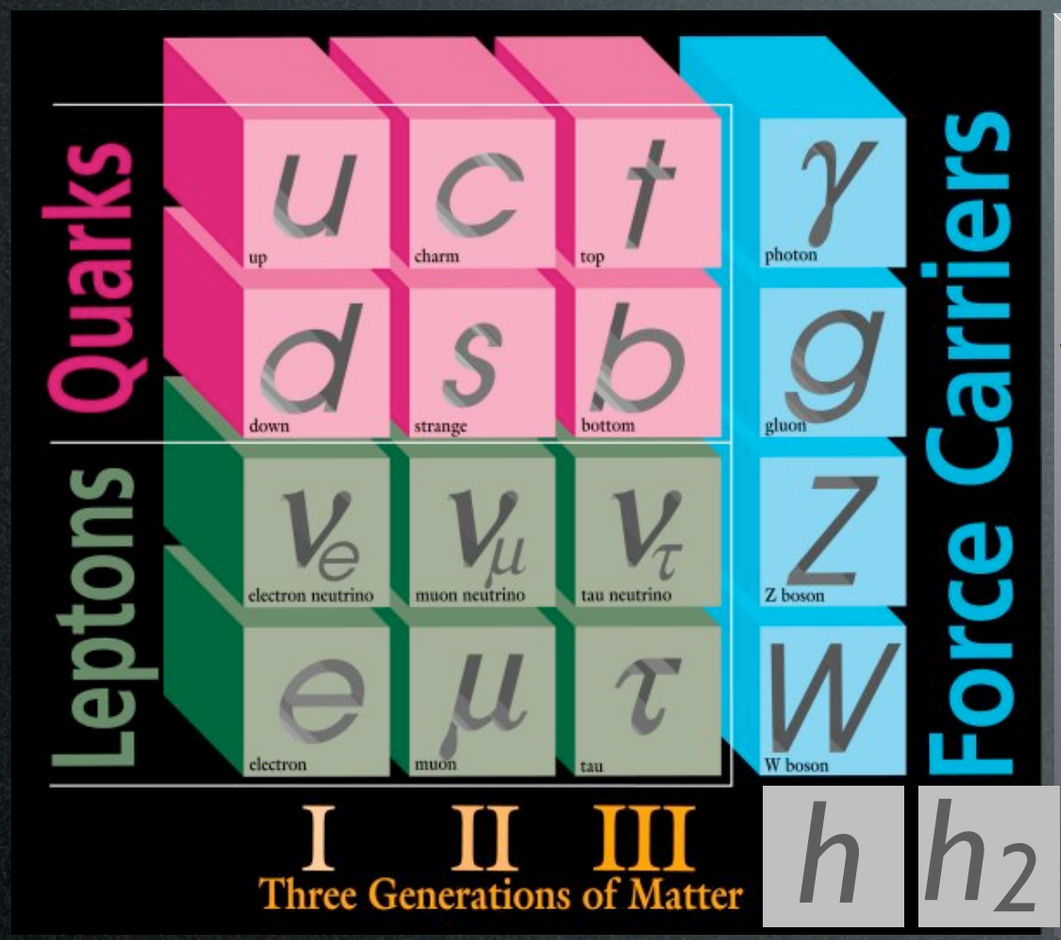
200 GeV



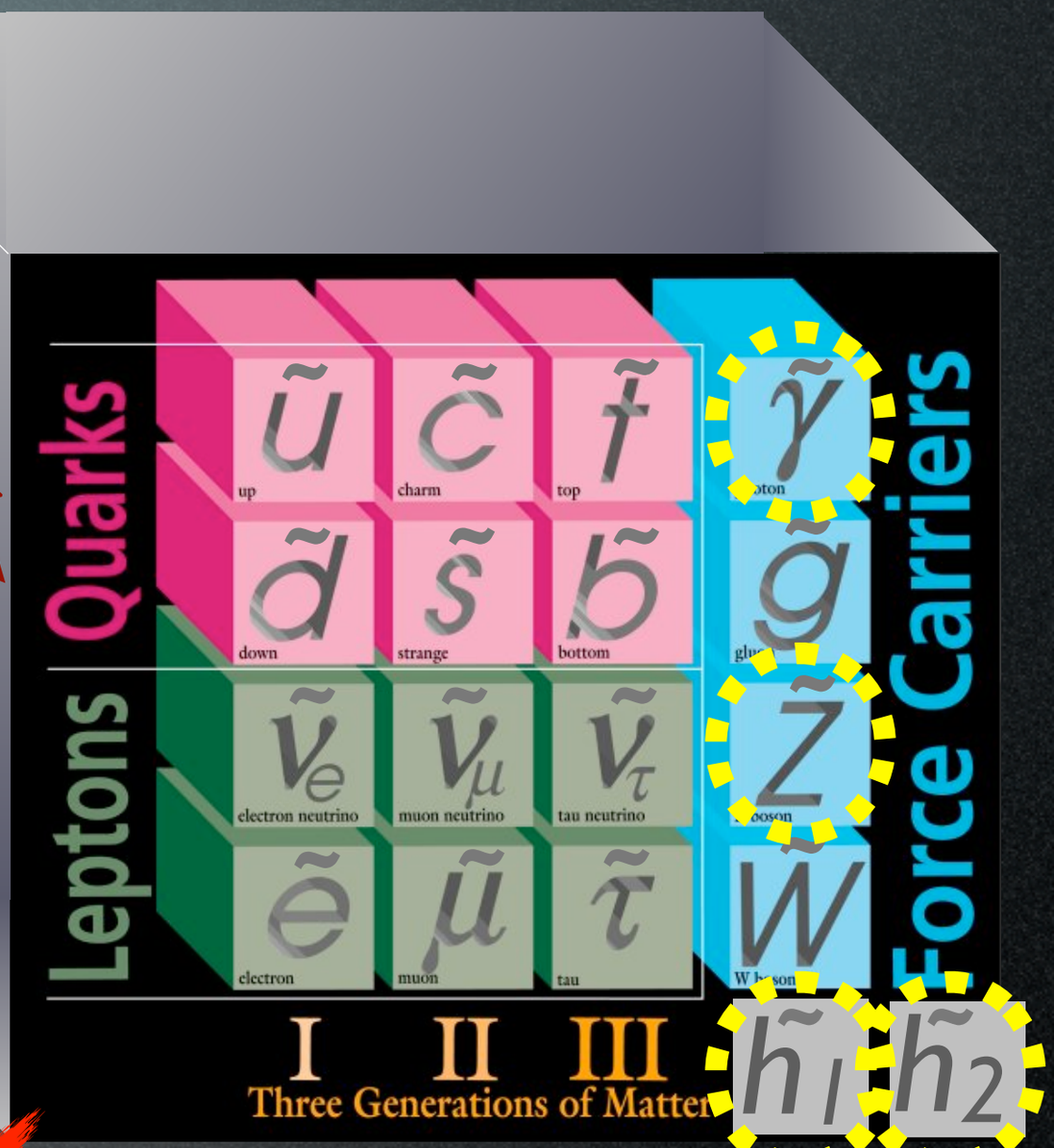
$R = +1$

$R = -1$

SuSy DM in 2 minutes



200 GeV



$R = +1$

$R = -1$

prevent
proton decay