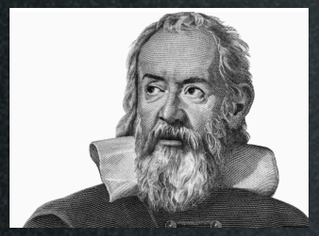
17 march 2026
GGI Firenze



Io stimo più il trovare un vero, benché di cosa leggera,
che i disputare lungamente delle massime questioni
senza conseguire verità nessuna.

Dark Matter circa 2026:
the WIMPs and beyond the WIMPs

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

LPTHE
LABORATOIRE DE PHYSIQUE
THEORIQUE ET HAUTES ENERGIES

cnrs
dépasser les frontières

SORBONNE
UNIVERSITÉ
CRÉATEURS DE FUTURS
DEPUIS 1257

17 march 2026
GGI Firenze

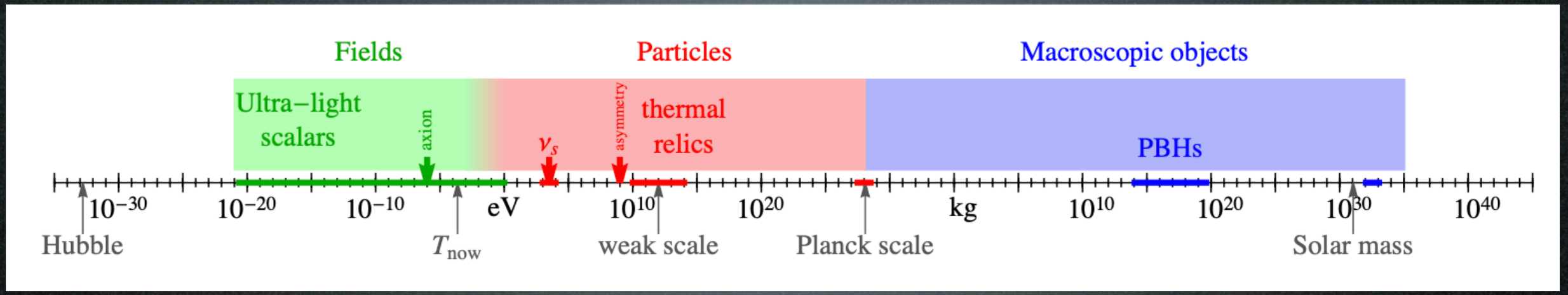
Dark Matter, where art thou?

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

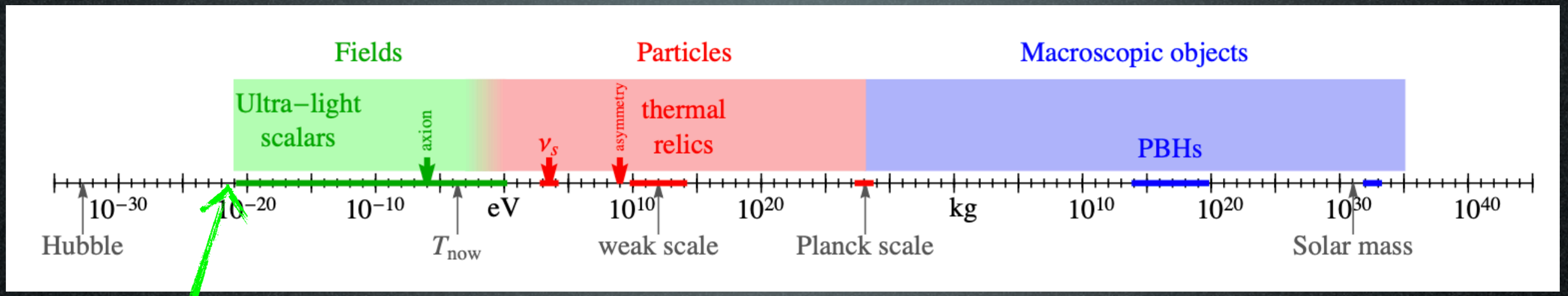
Answer

Somewhere on this plot:



90 orders of magnitude!

Candidates



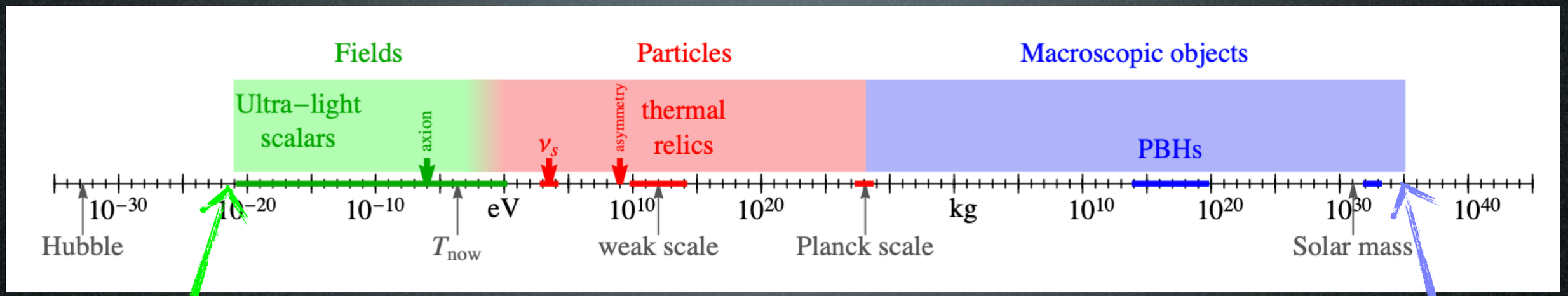
90 orders of magnitude!

as diffuse as a dwarf galaxy

DM de Broglie wavelength

$$\lambda = 2\pi/Mv \lesssim 1 \text{ kpc}$$

Candidates



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as diffuse as a dwarf galaxy

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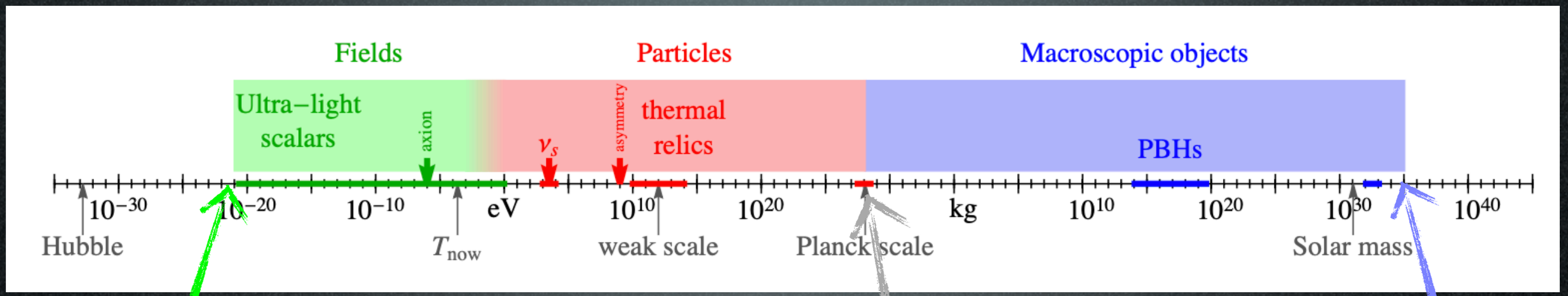
as big as a dwarf galaxy

DM mass

$M \lesssim 10^4\ M_\odot$

Candidates



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most likely elementary | most likely composite

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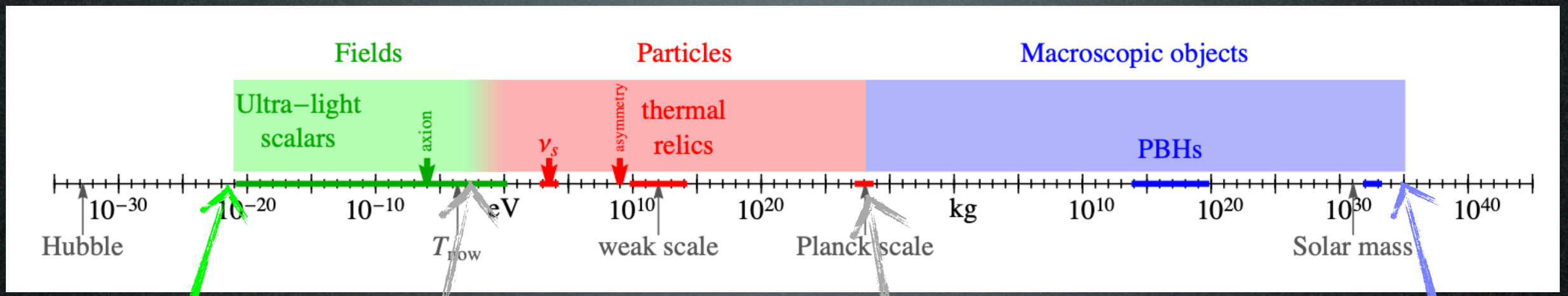

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as diffuse as a dwarf galaxy

DM de Broglie wavelength

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best described as classical field

most likely elementary | most likely composite

best described as particle

as big as a dwarf galaxy

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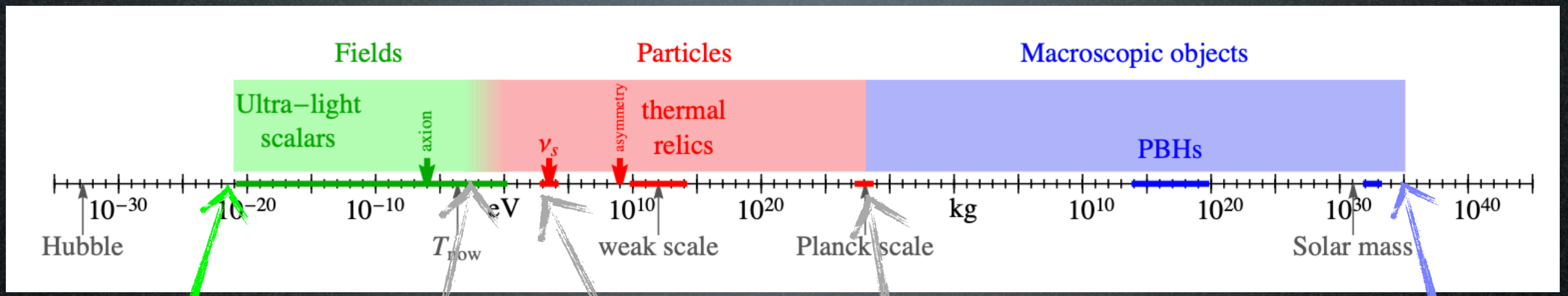
Candidates



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as big as a dwarf galaxy

DM de Broglie wavelength

$$\lambda = 2\pi/Mv \lesssim 1 \text{ kpc}$$

DM mass

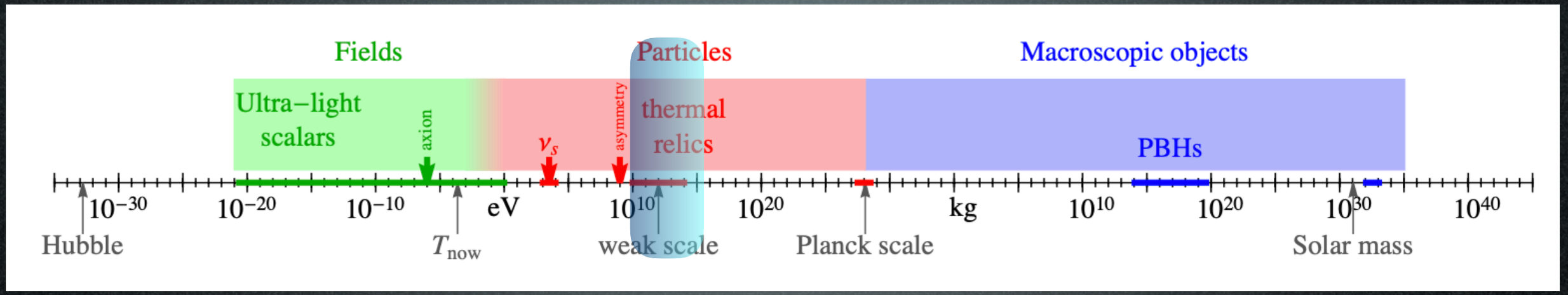
$$M \lesssim 10^4 \, M_\odot$$

occupation number

$$N \simeq \frac{\rho}{M/\lambda^3}$$

most likely	most likely
elementary	composite
best described as	best described as
classical field	particle
$M \lesssim 0.1\,\text{keV}$ necessarily *bosonic*	$M \gtrsim 0.1\,\text{keV}$ *bosonic* or *fermionic*

Candidates


Fields
Particles
Macroscopic objects
Ultra–light scalars
axion
ν_s
asymmetry
thermal relics
PBHs
10^{-30}
10^{-20}
10^{-10}
eV
10^{10}
10^{20}
kg
10^{10}
10^{20}
10^{30}
10^{40}
Hubble
$T_{\rm now}$
weak scale
Planck scale
Solar mass

Candidates

WIMPs

Candidates

new physics at the TeV scale

thermal freeze-out

Candidates

new physics at the TeV scale

thermal freeze-out

Collider Searches

Indirect Detection

Direct Detection

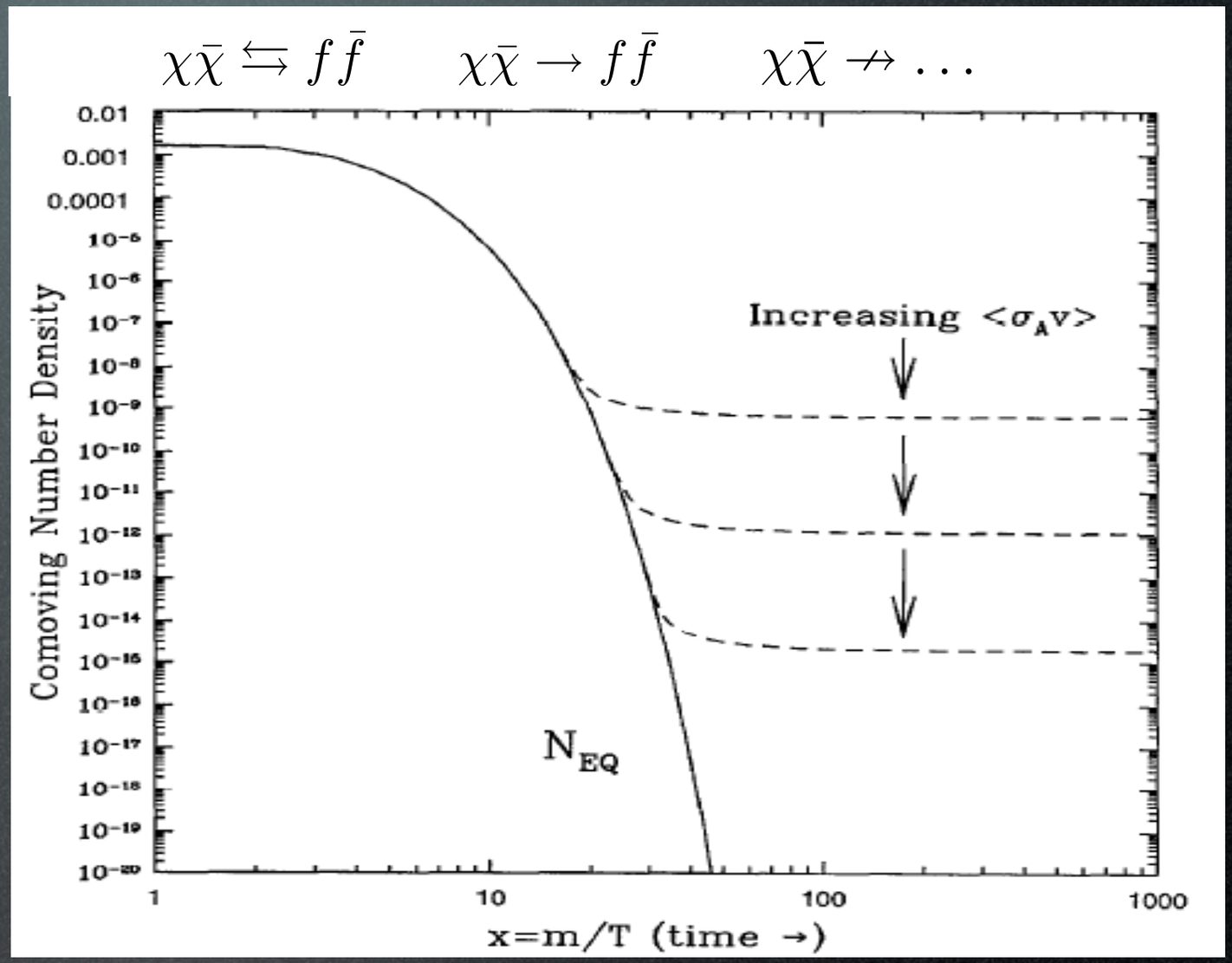
DM as a thermal relic from the Early Universe

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 $\Omega_{\mathrm{DM}} \simeq 0.26$ for

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



Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

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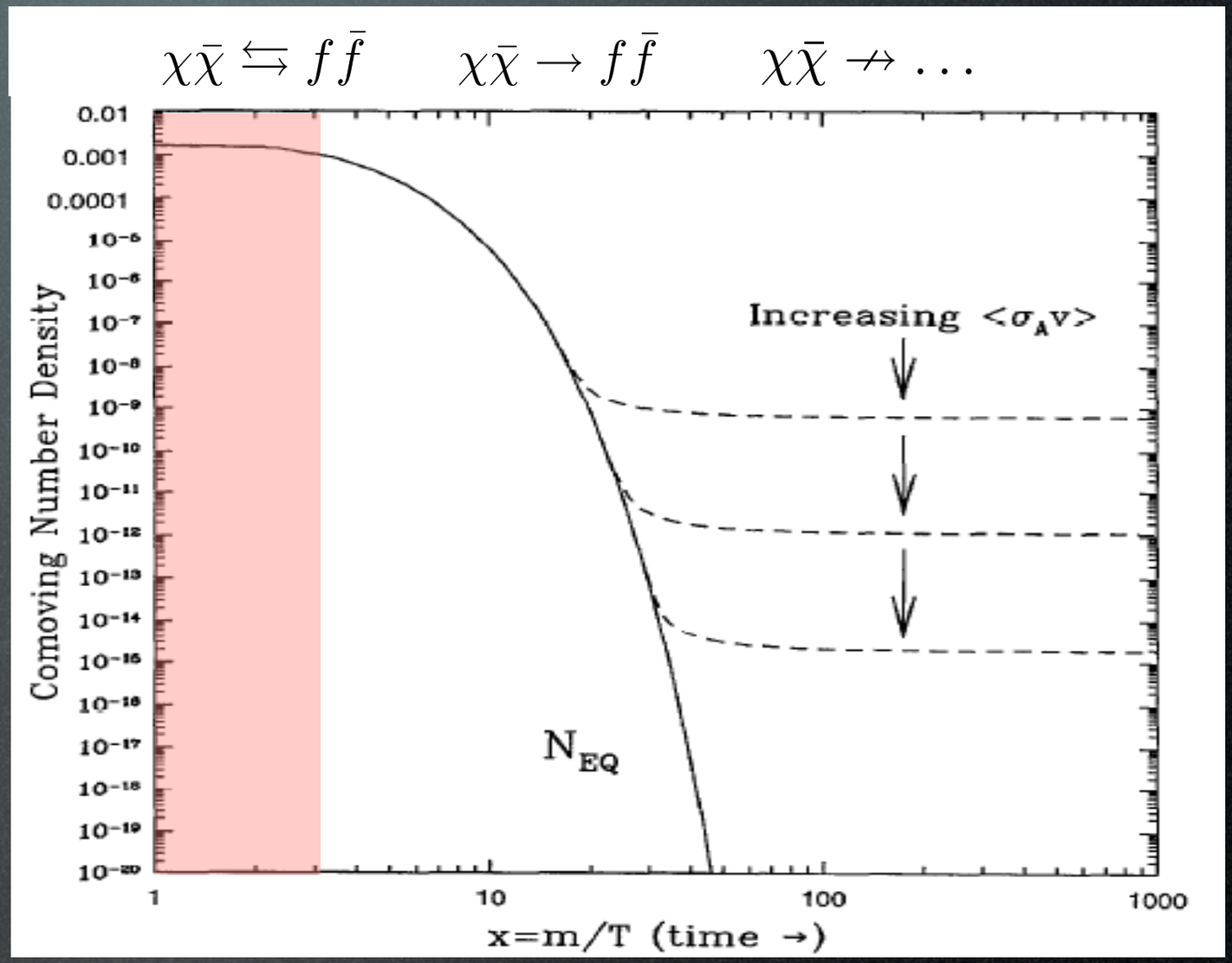

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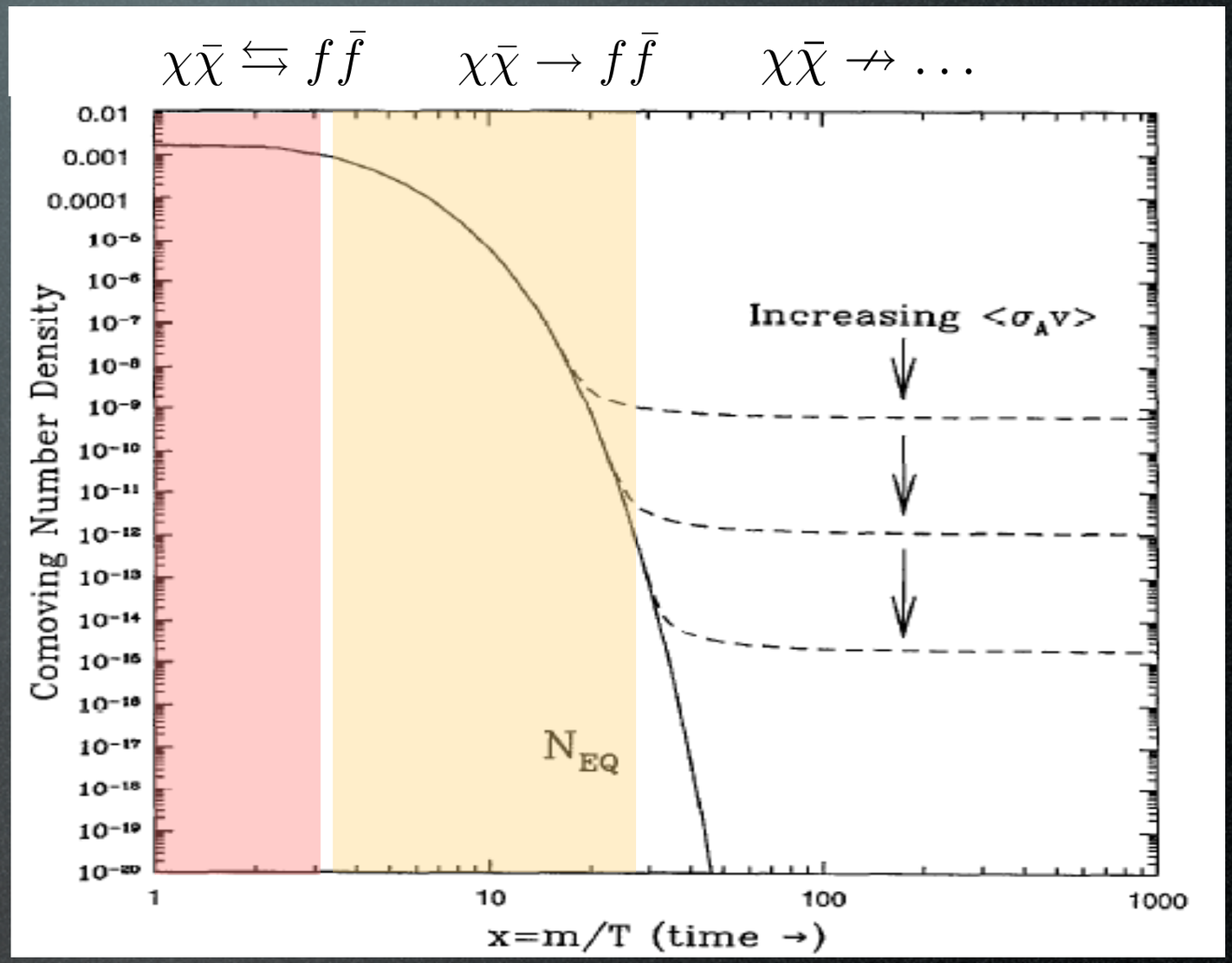

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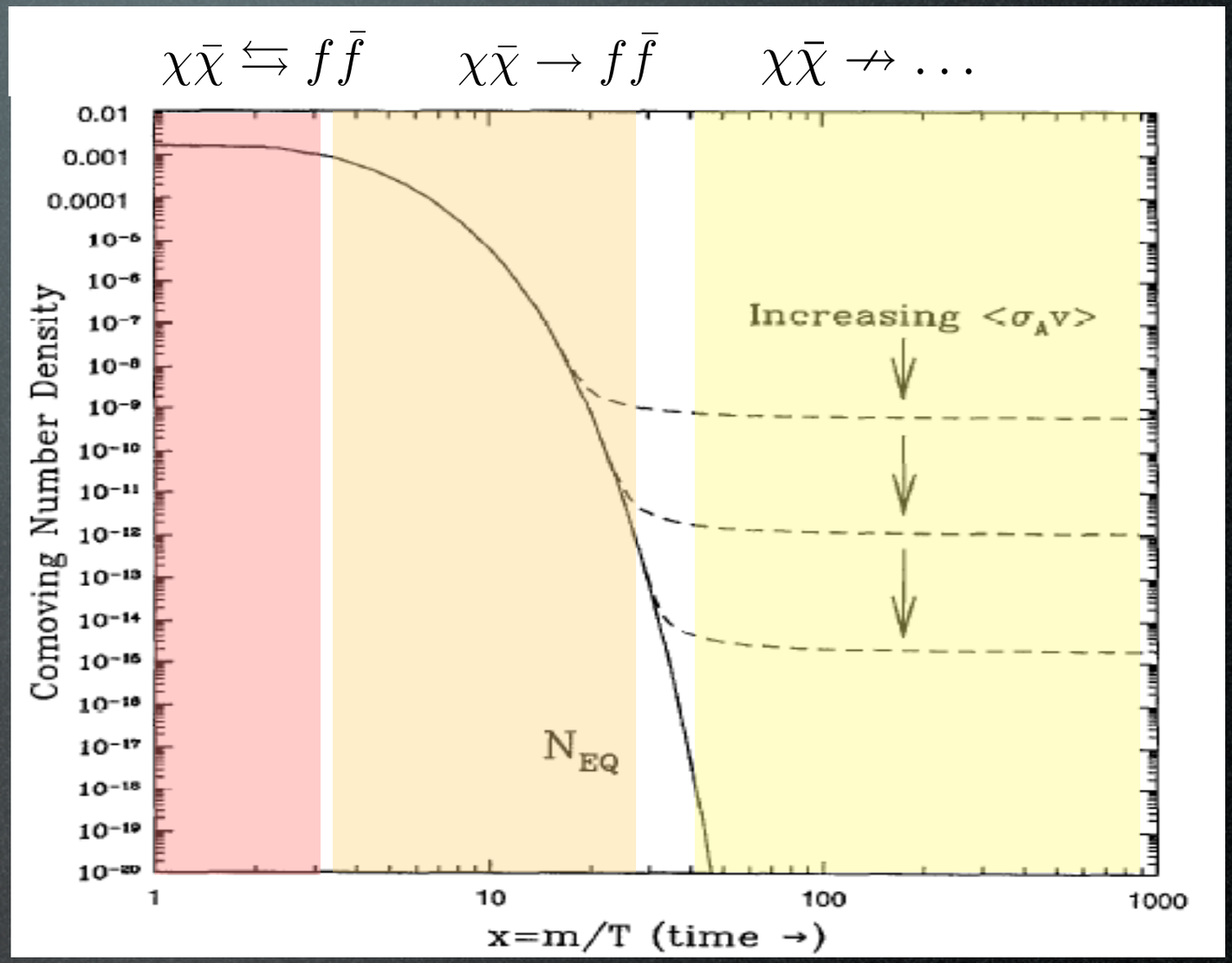

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new physics at the TeV scale

thermal freeze-out

WIMPs

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2.

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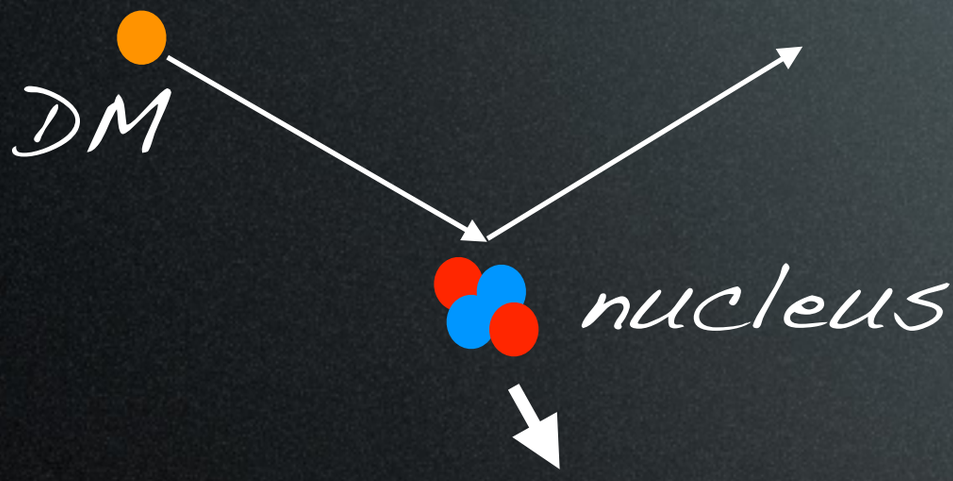
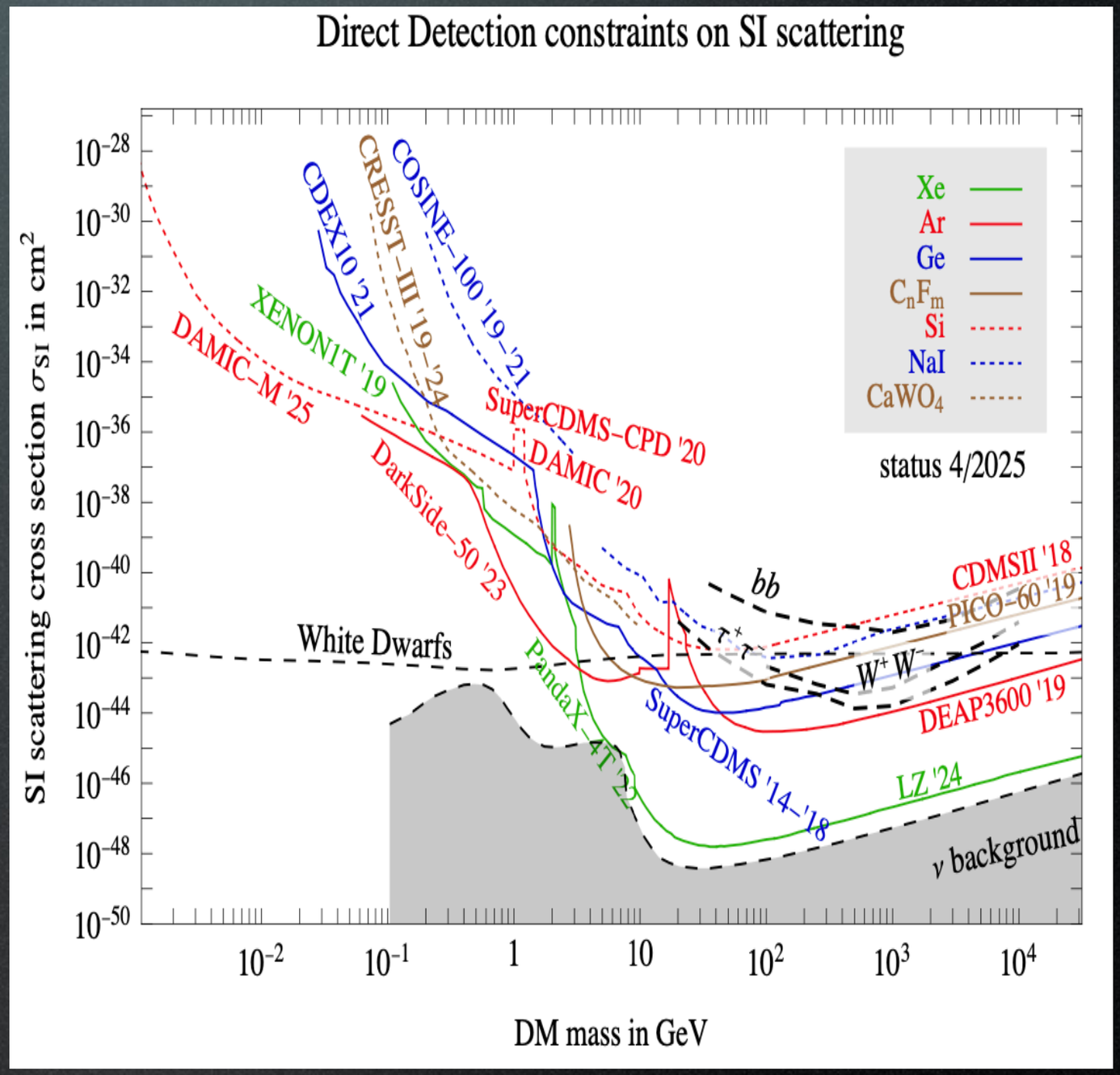
WIMP Direct Detection

SM weak scale SI interactions





M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705

WIMP Direct Detection

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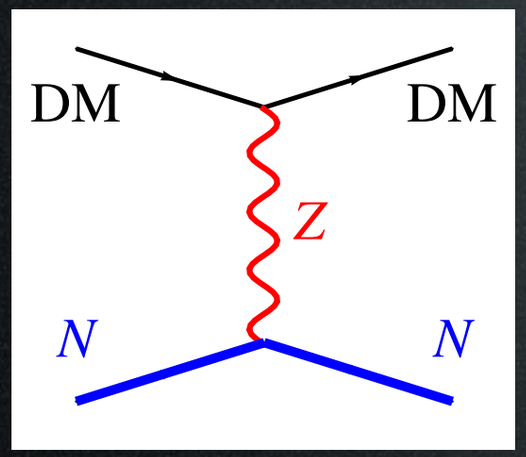
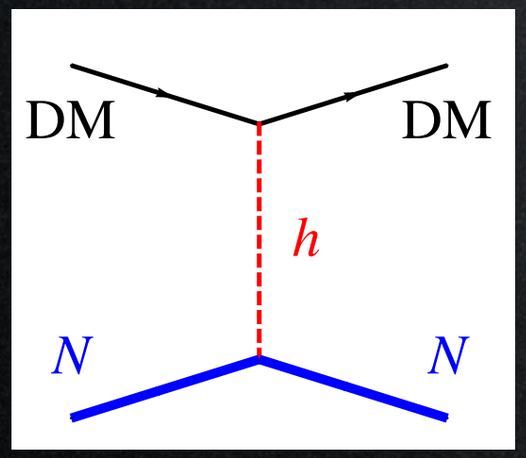
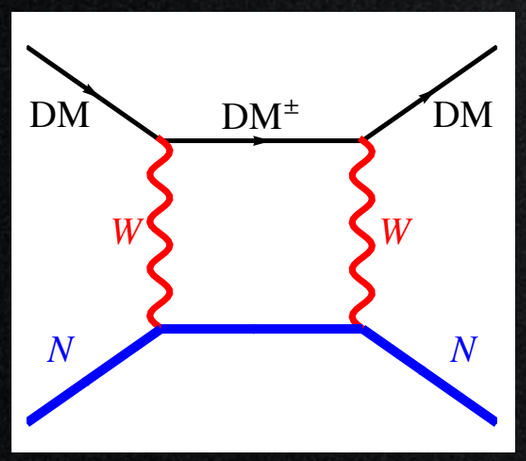


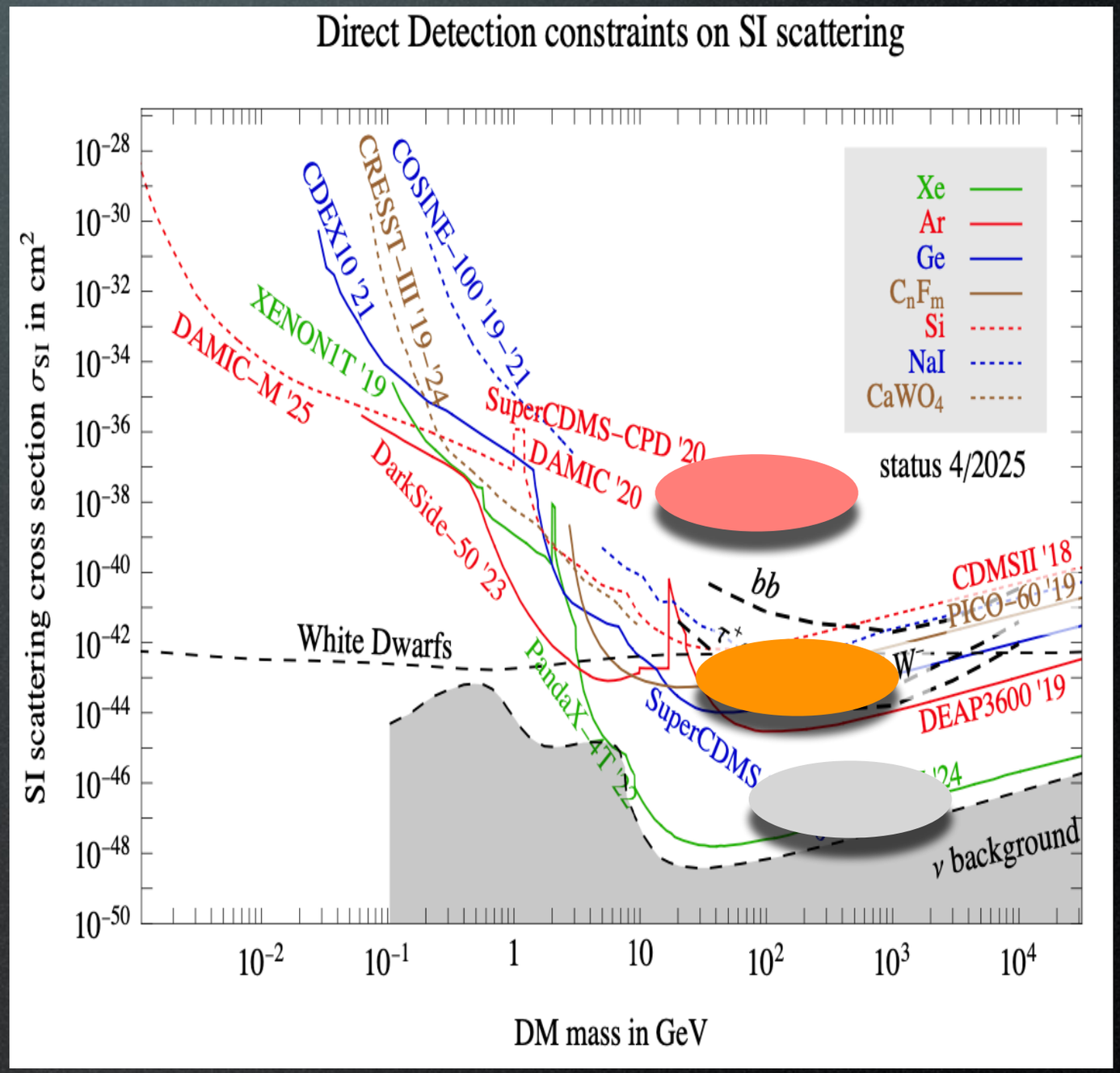
tree level, vector



tree level, scalar



one loop



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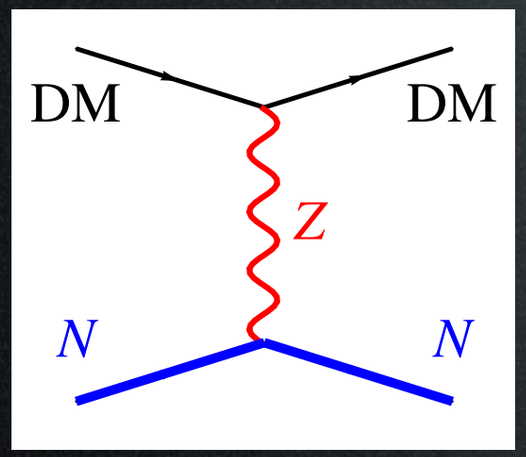
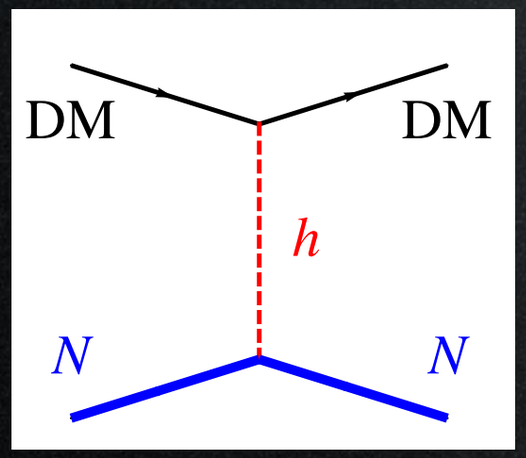
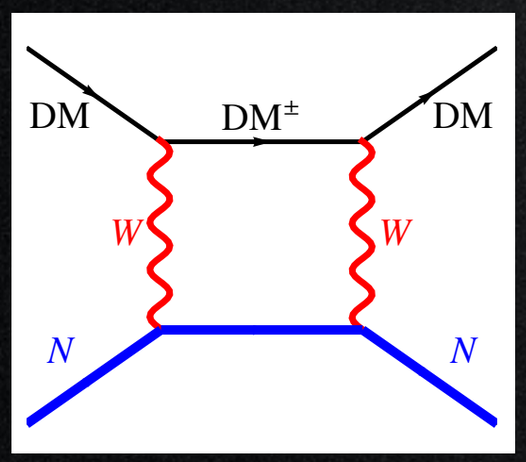


tree level, vector



tree level, scalar



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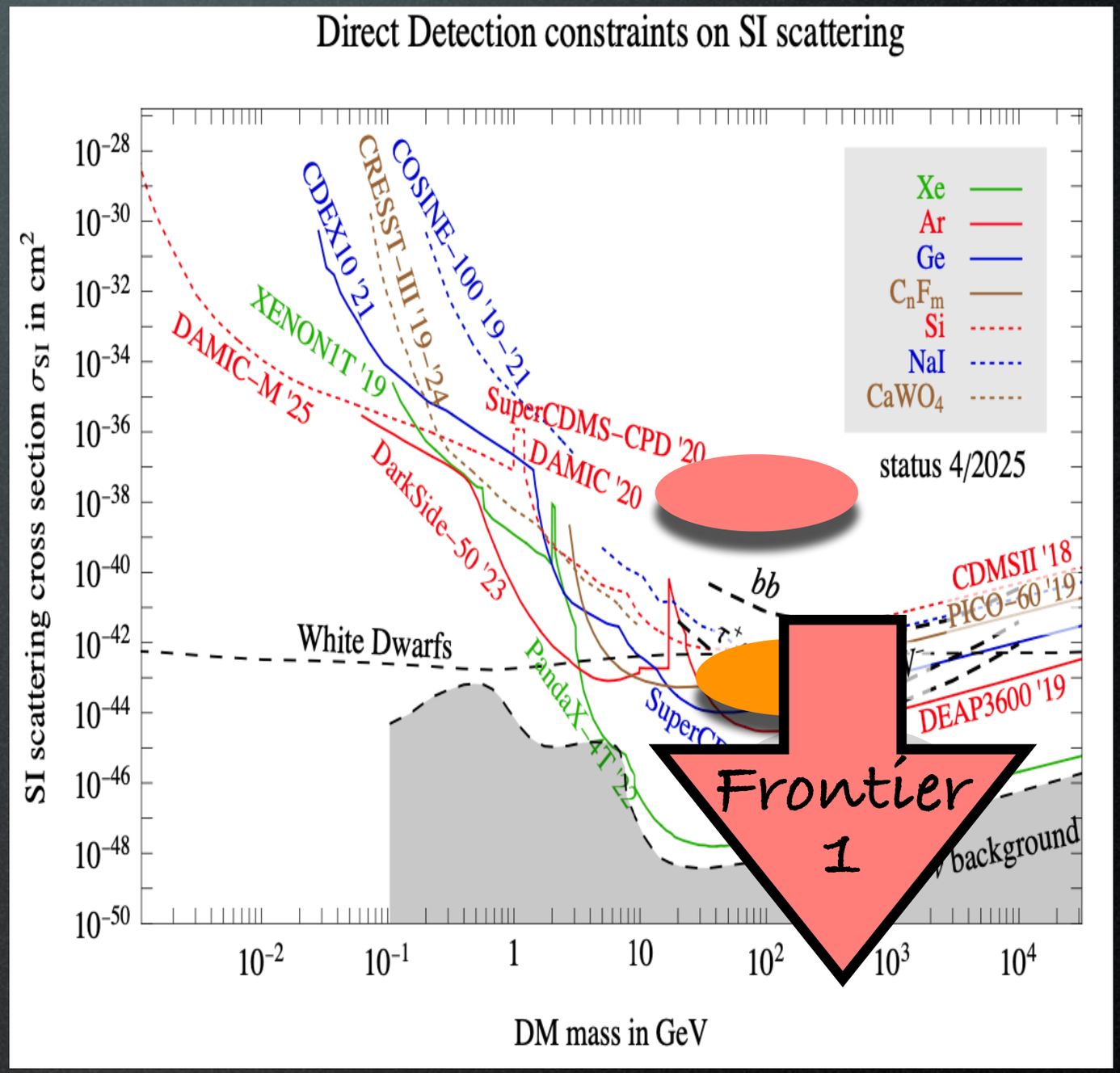

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new physics at the TeV scale

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1. even without a larger framework, WIMPs are still appealing
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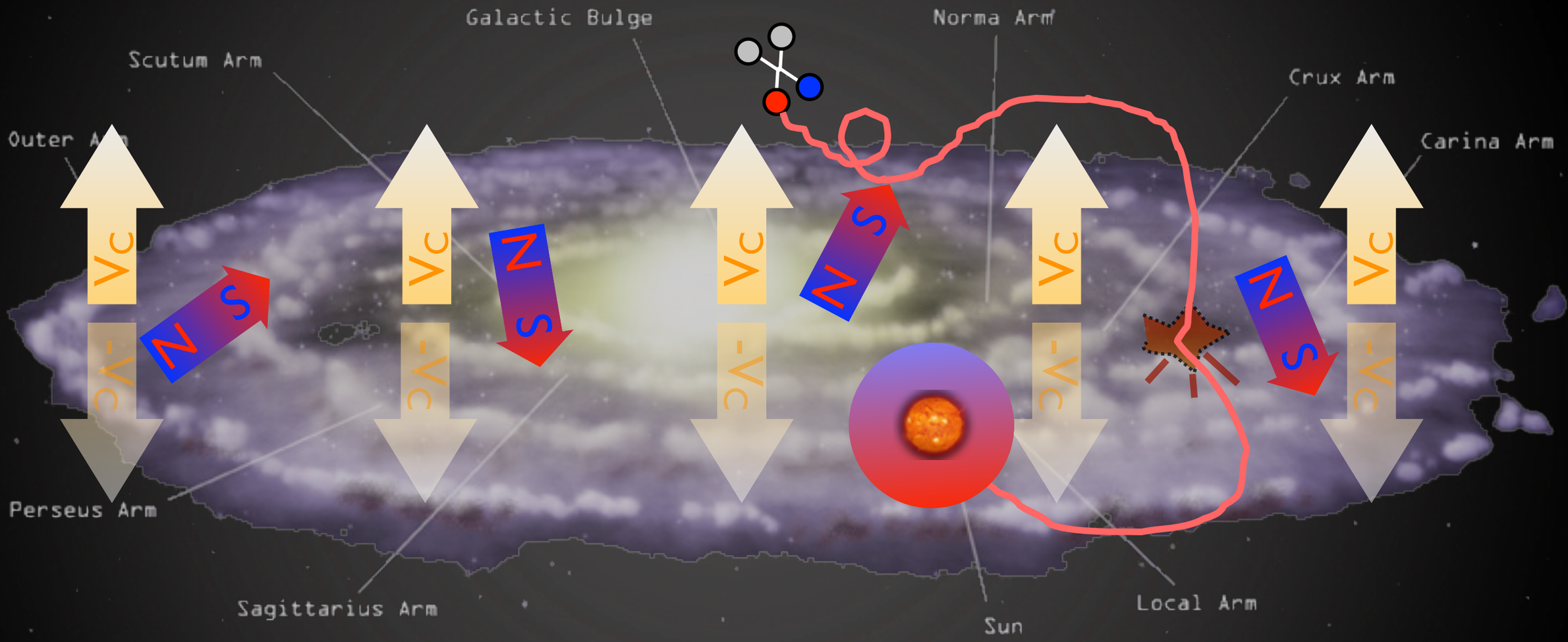
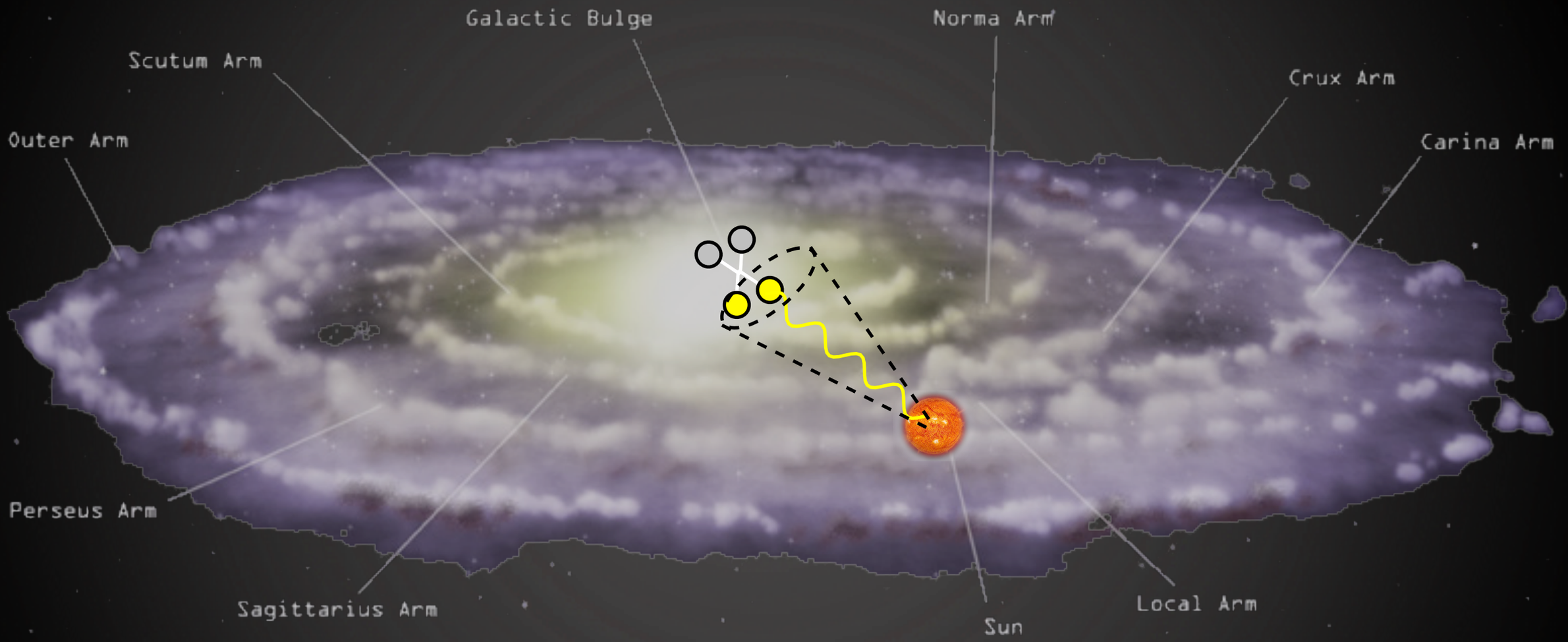
Indirect Detection: charged CRs

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



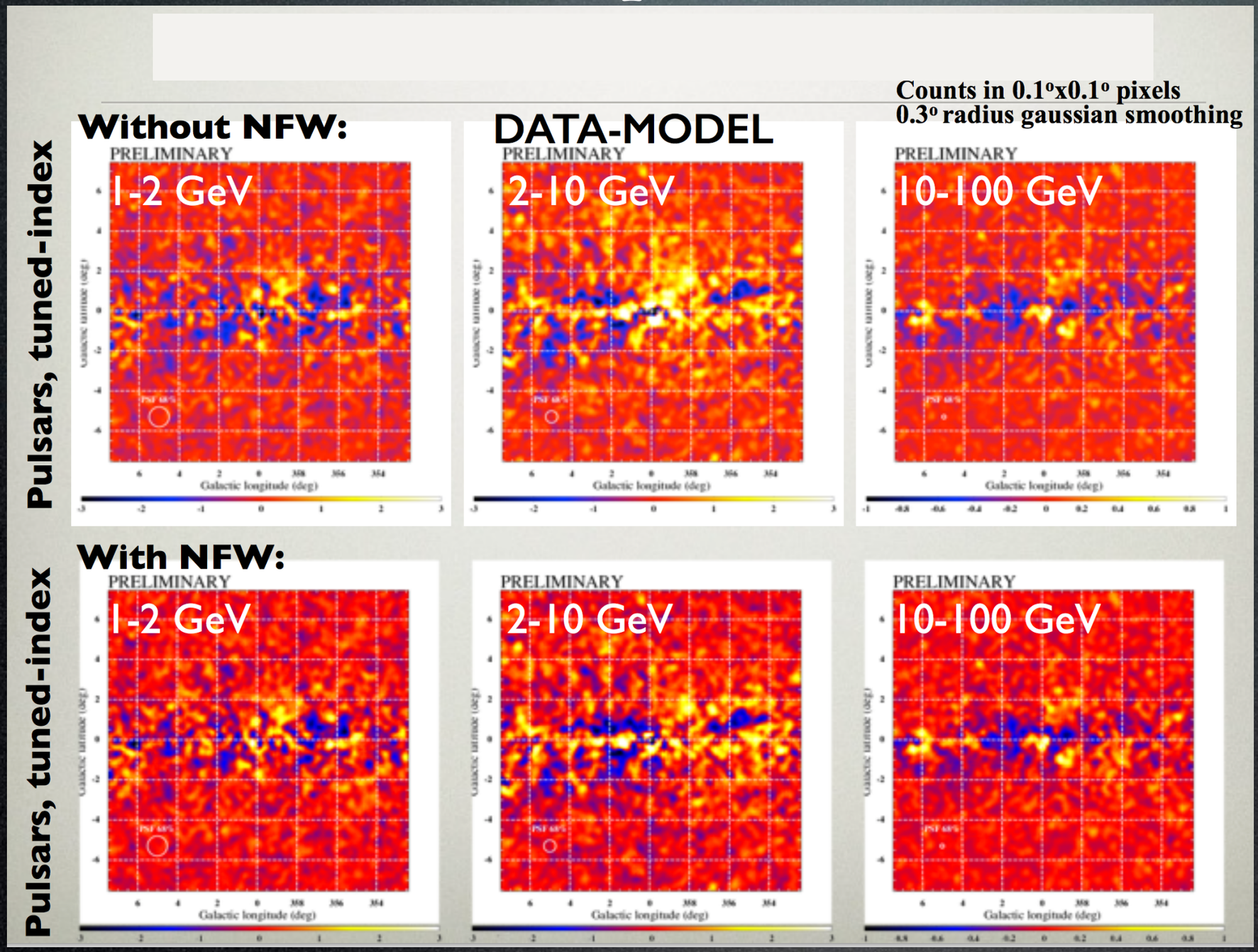
Indirect Detection: photons

γ from DM annihilations (e.g. in the GC)



GC GeV excess

Dark Matter interpretation:



S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815
Fermi coll. 1511.02938

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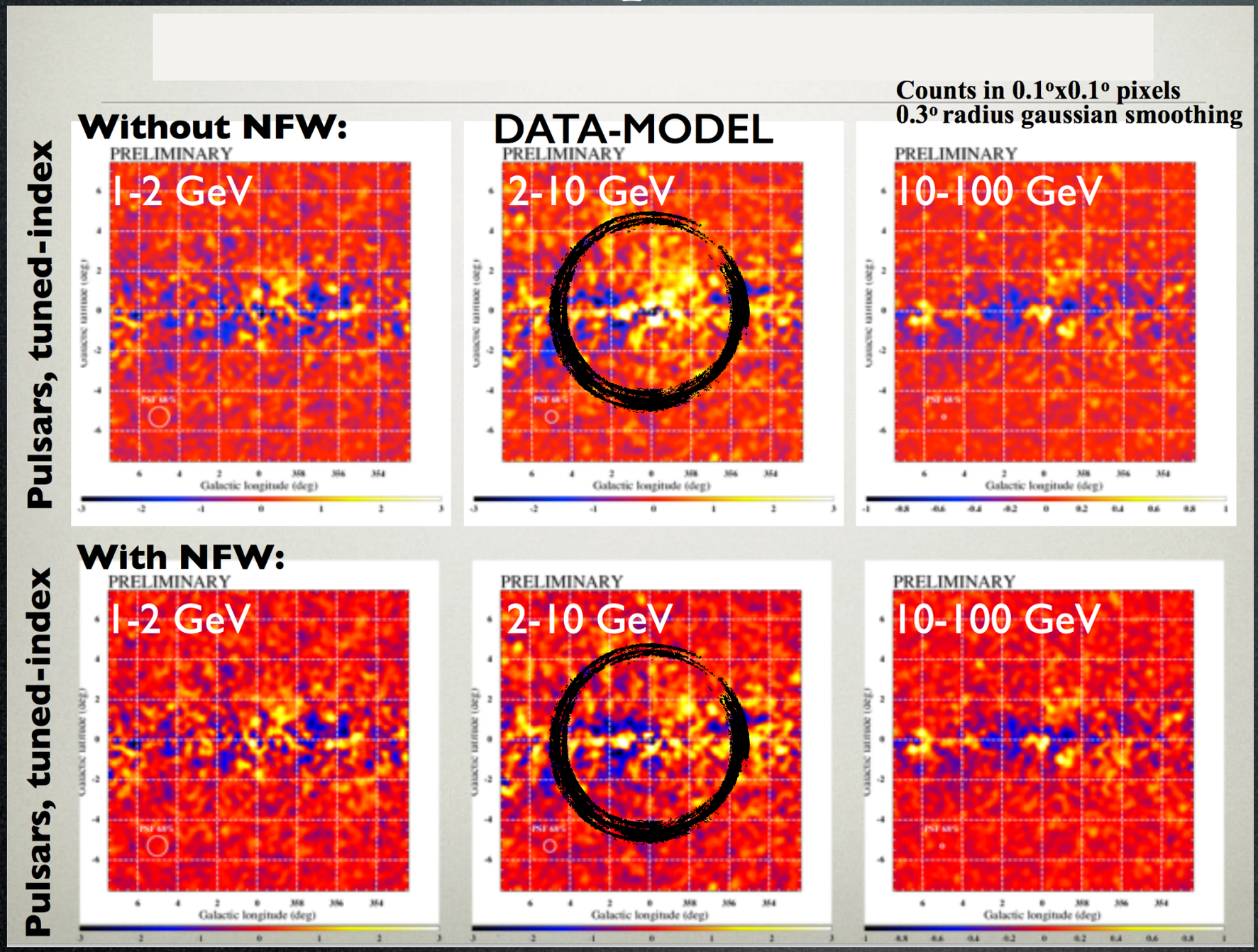

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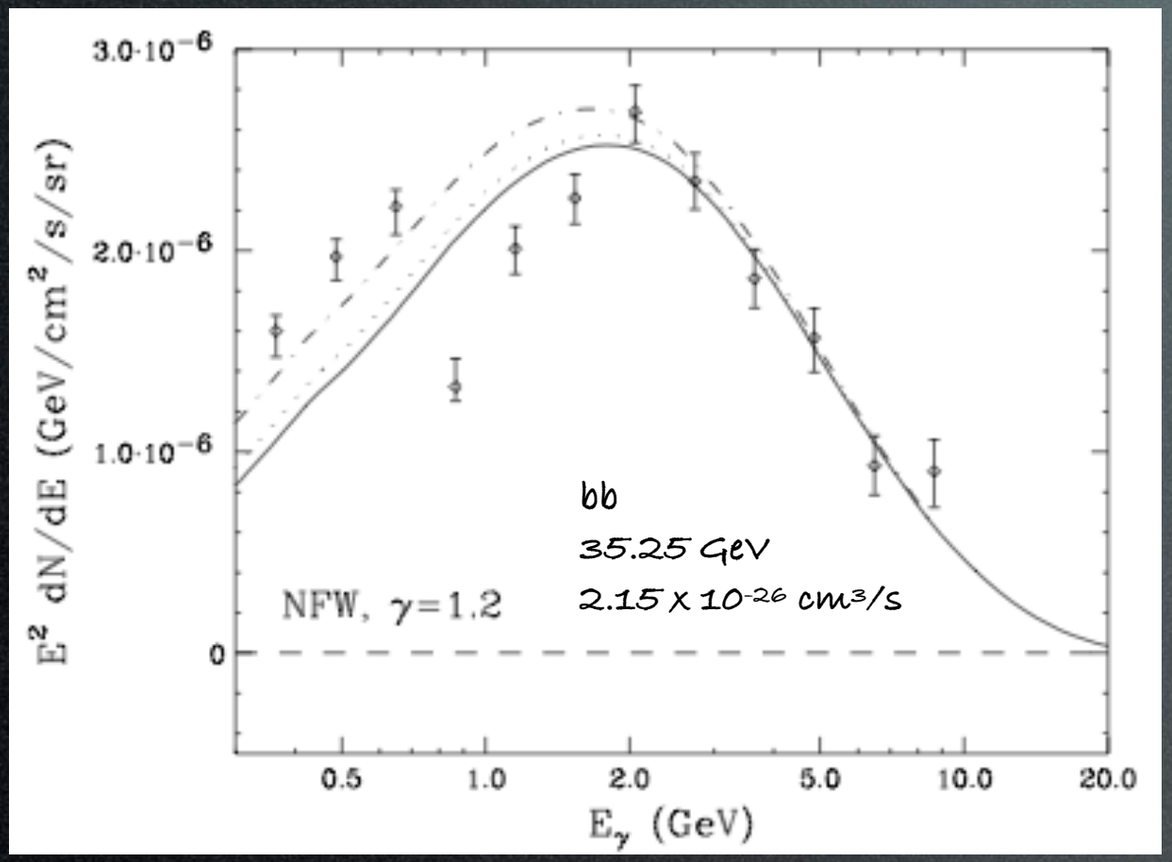
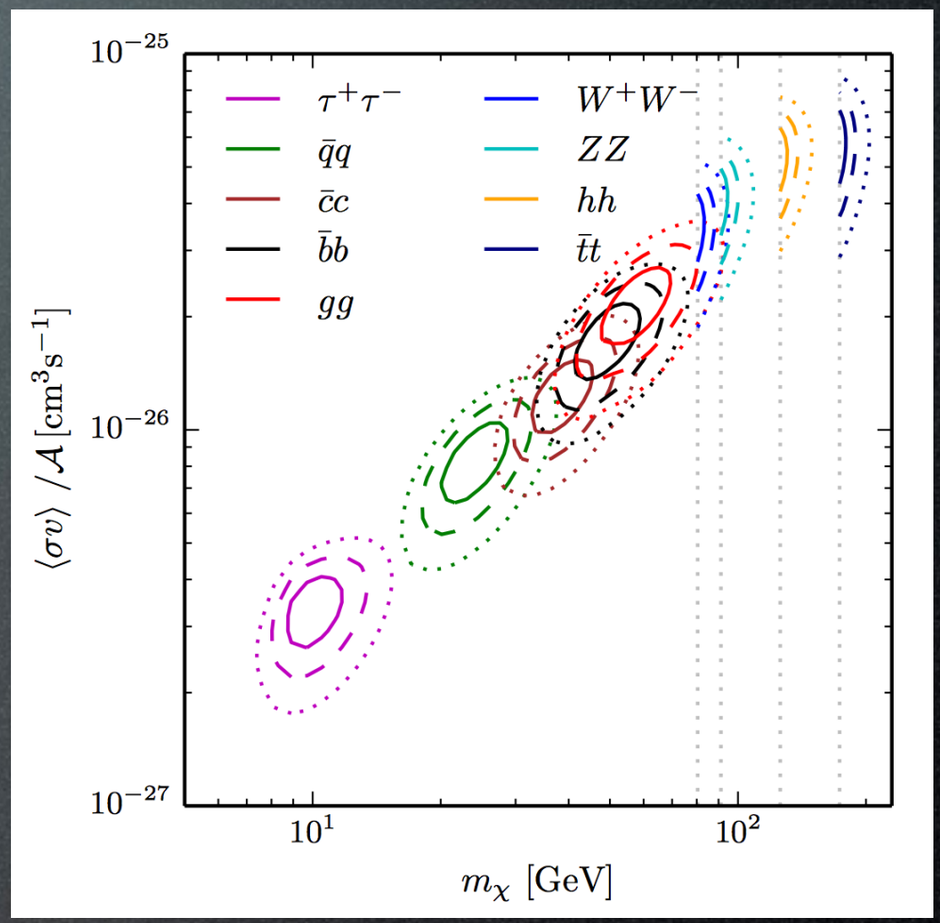
Fermi coll. 1511.02938

GC GeV excess

Dark Matter interpretation:

Best fit:
~35 GeV, quarks, ~thermal σv





F. Calore et al. 1411.4647

A compelling case for annihilating DM

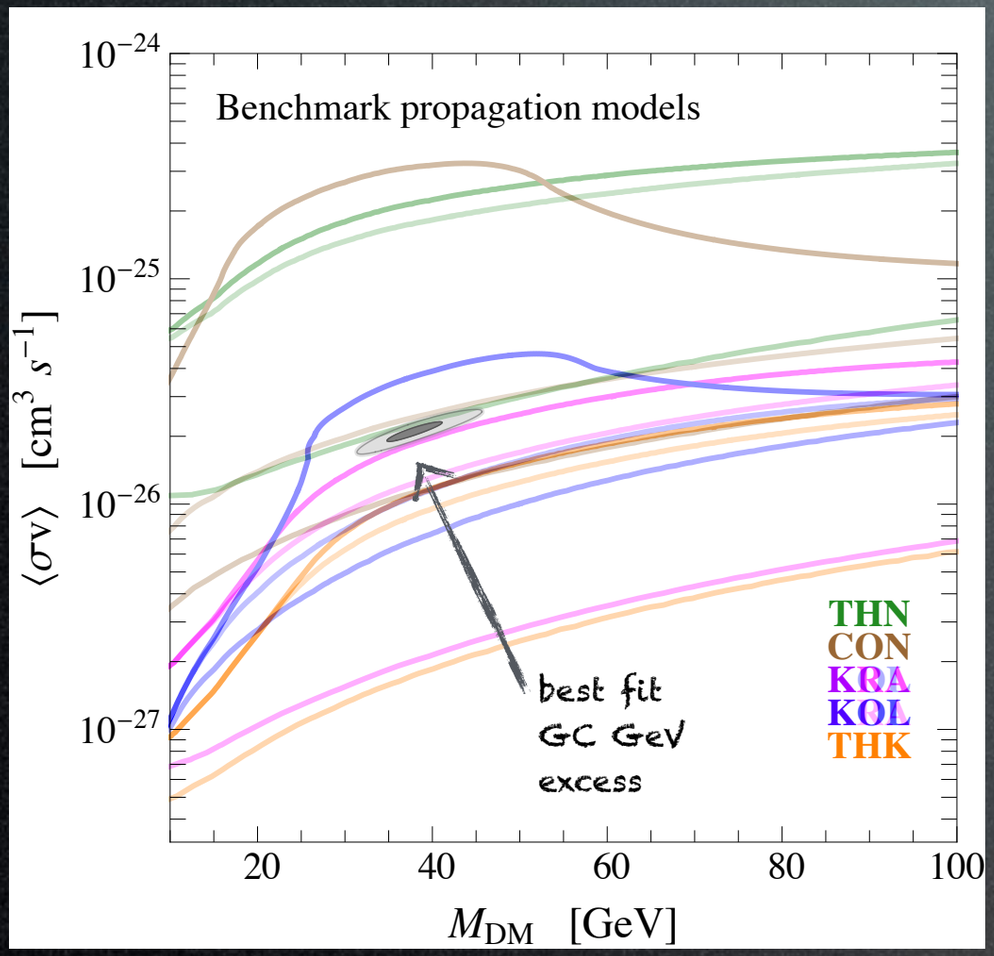
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

...as good as it can get.

GC GeV excess

Dark Matter interpretation:

Antiproton constraints
are not conclusive



Cirelli, Gaggero,
Giesen, Taoso,
Urbano 1407.2173

Also:

Bringmann, Vollmann,
Weniger 1406.6027

Hooper, Linden, Mertsch
1410.1527

GC GeV excess

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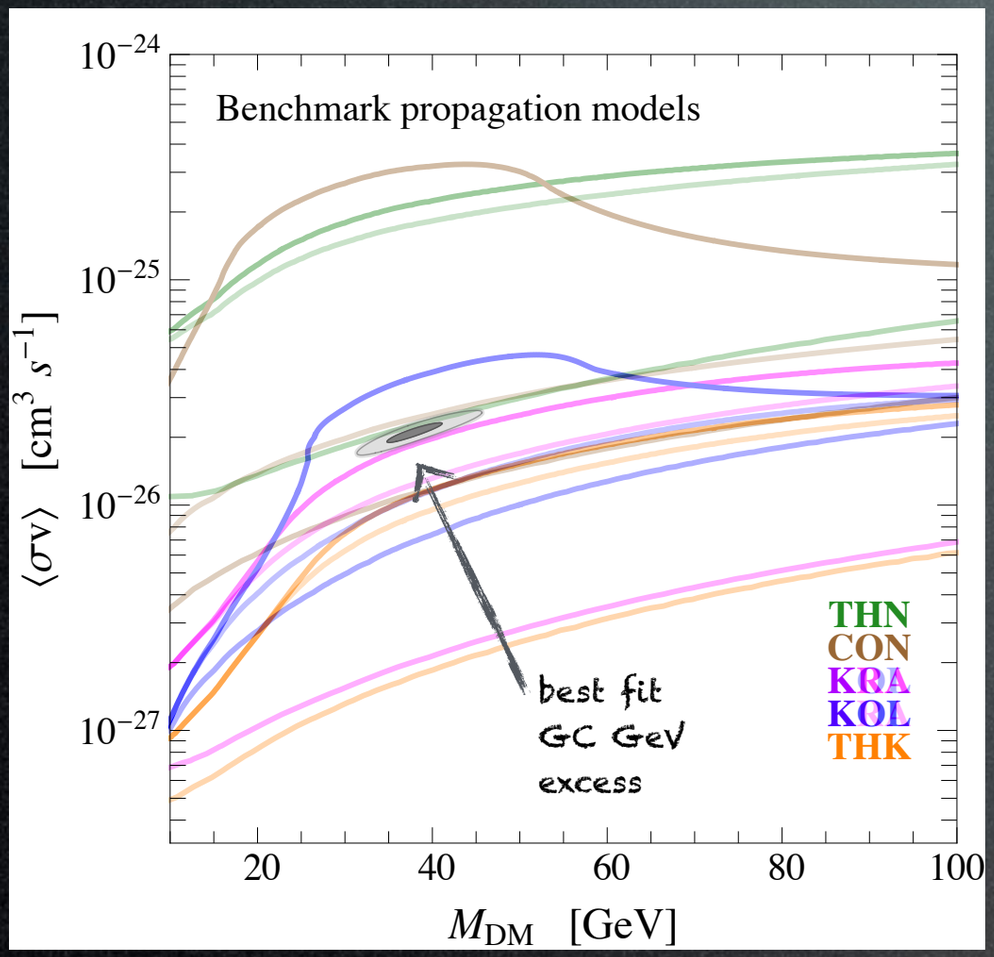
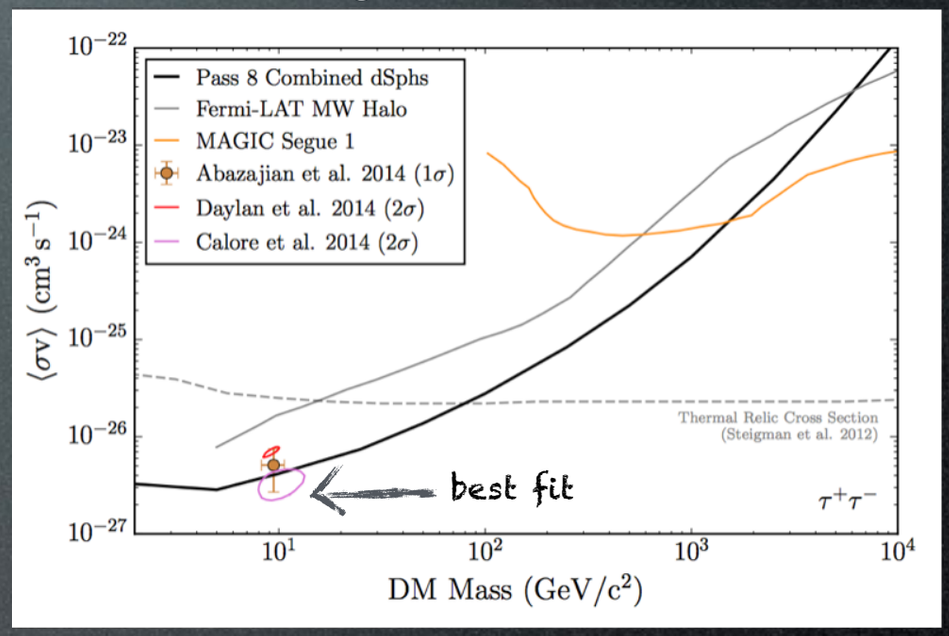


Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Gamma ray ones neither



FERMI 1503.02641

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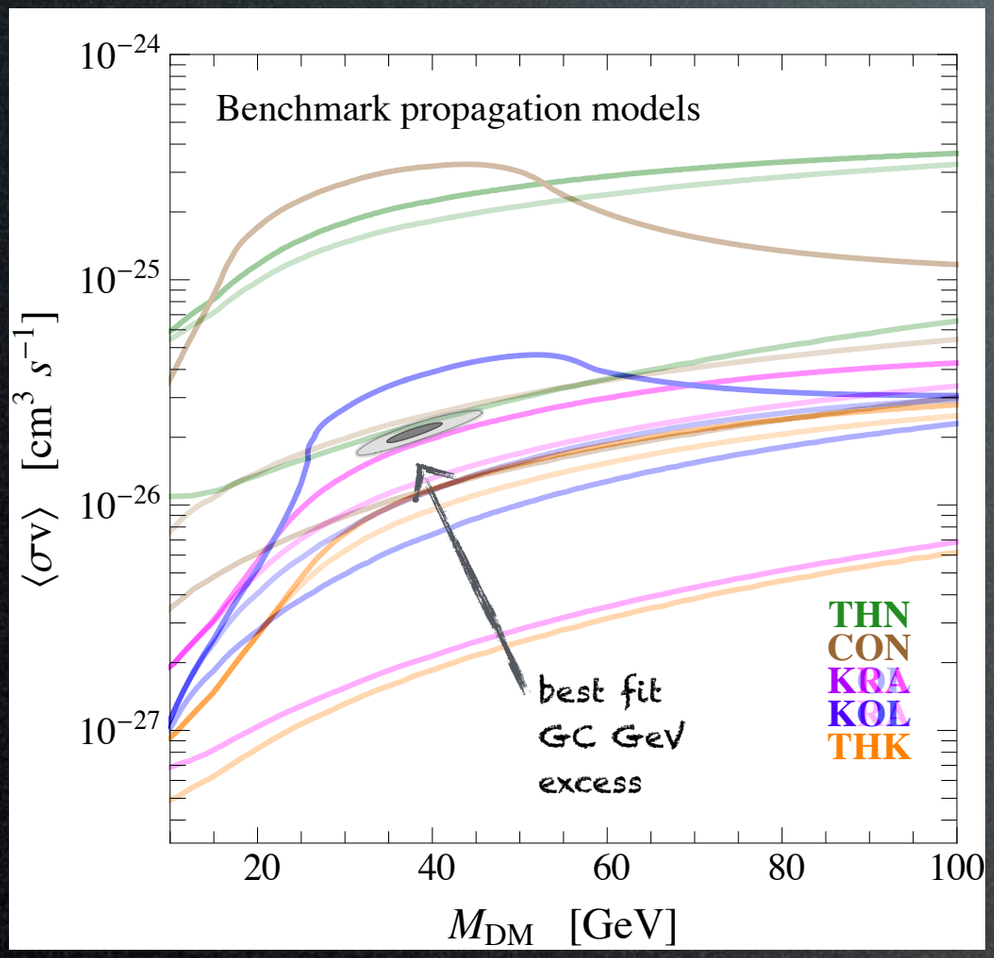

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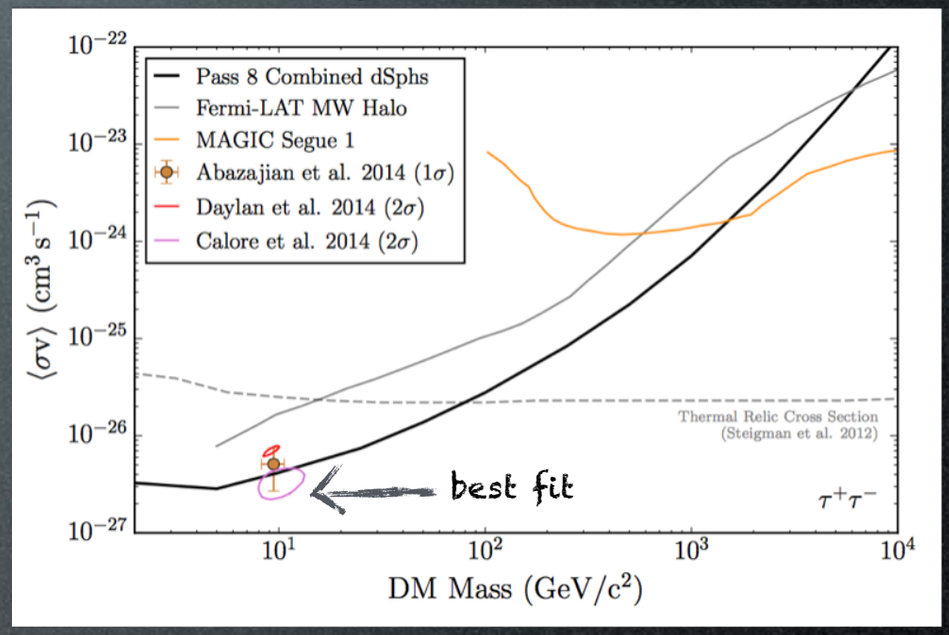
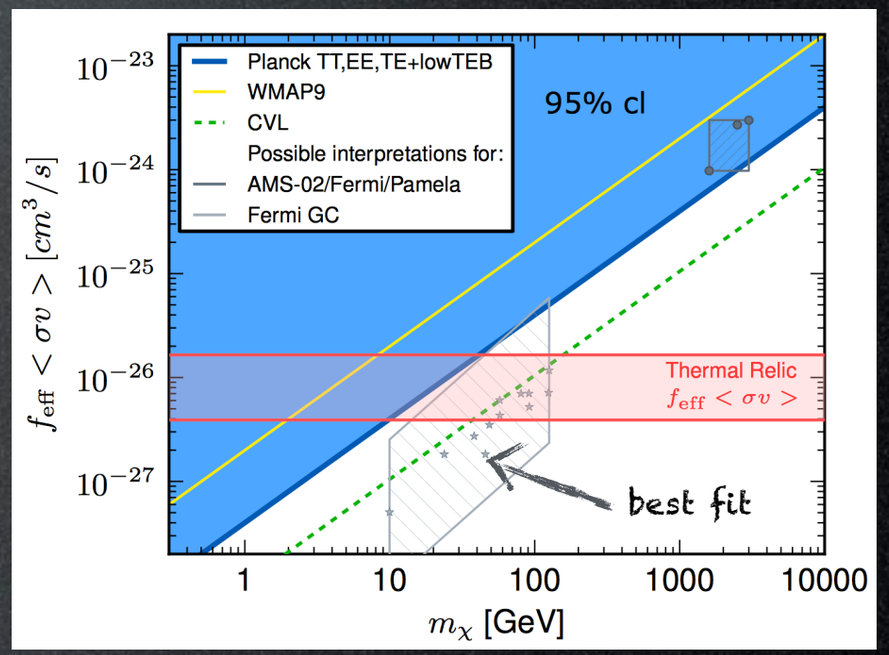


FERMI 1503.02641

Nor CMB



Planck 2015

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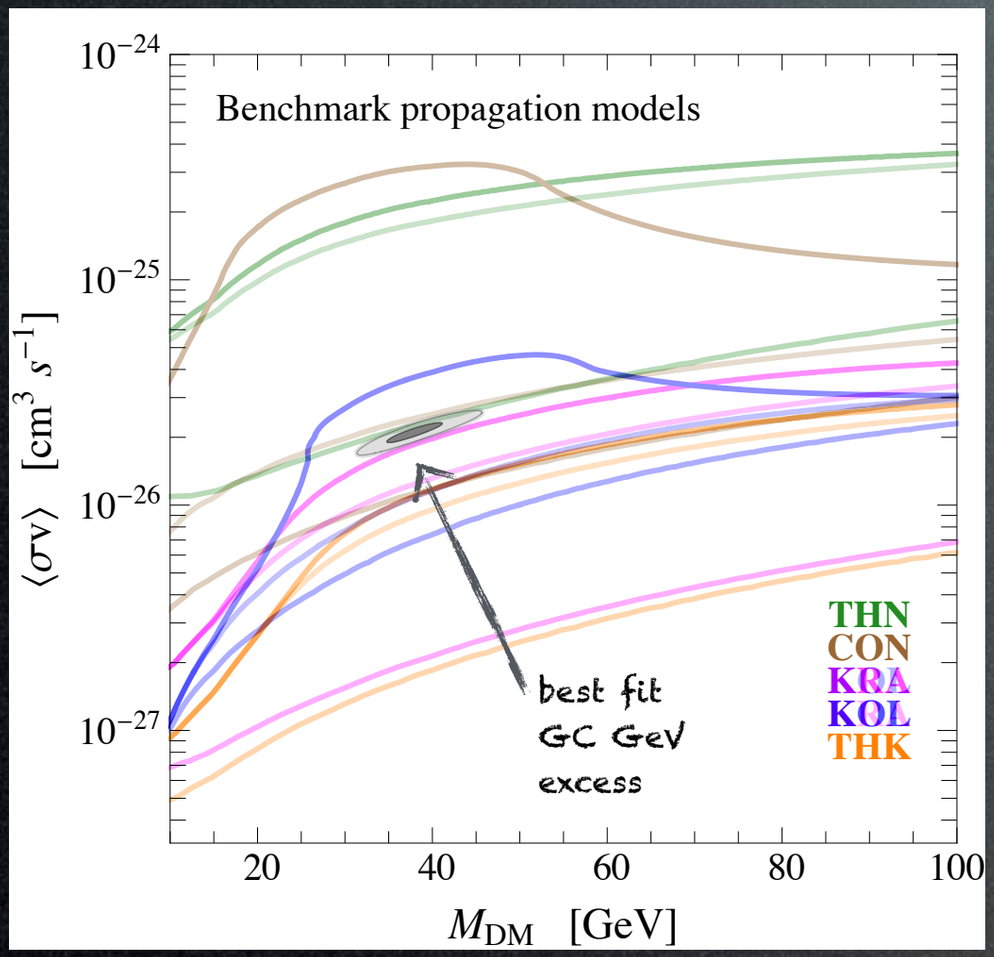

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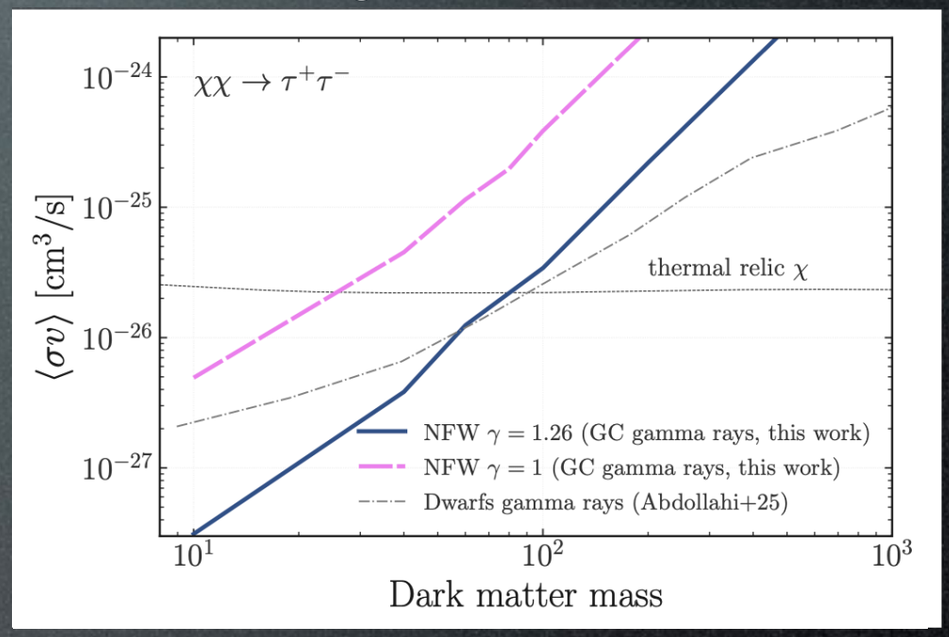

Manconi et al. 2511.03350

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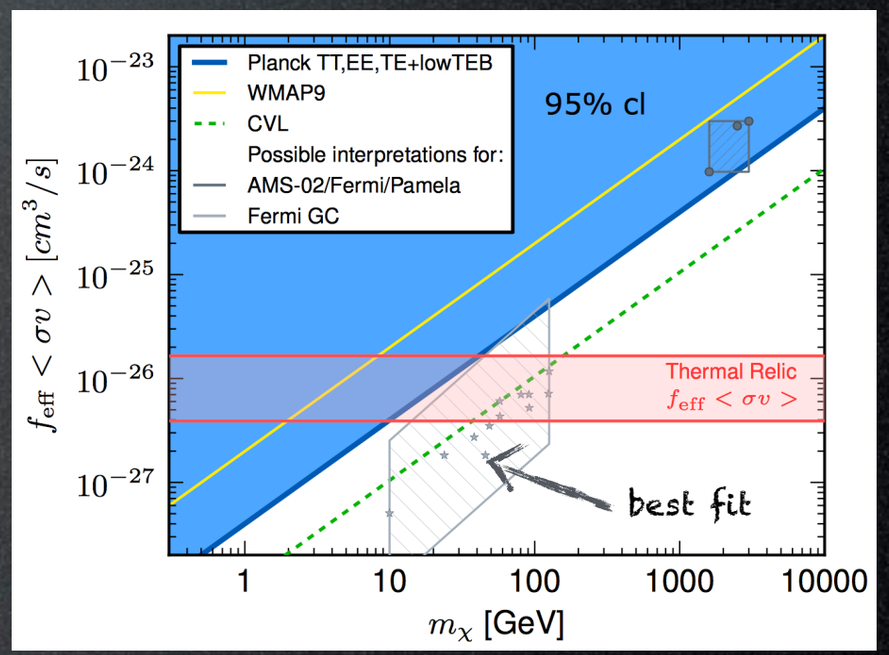
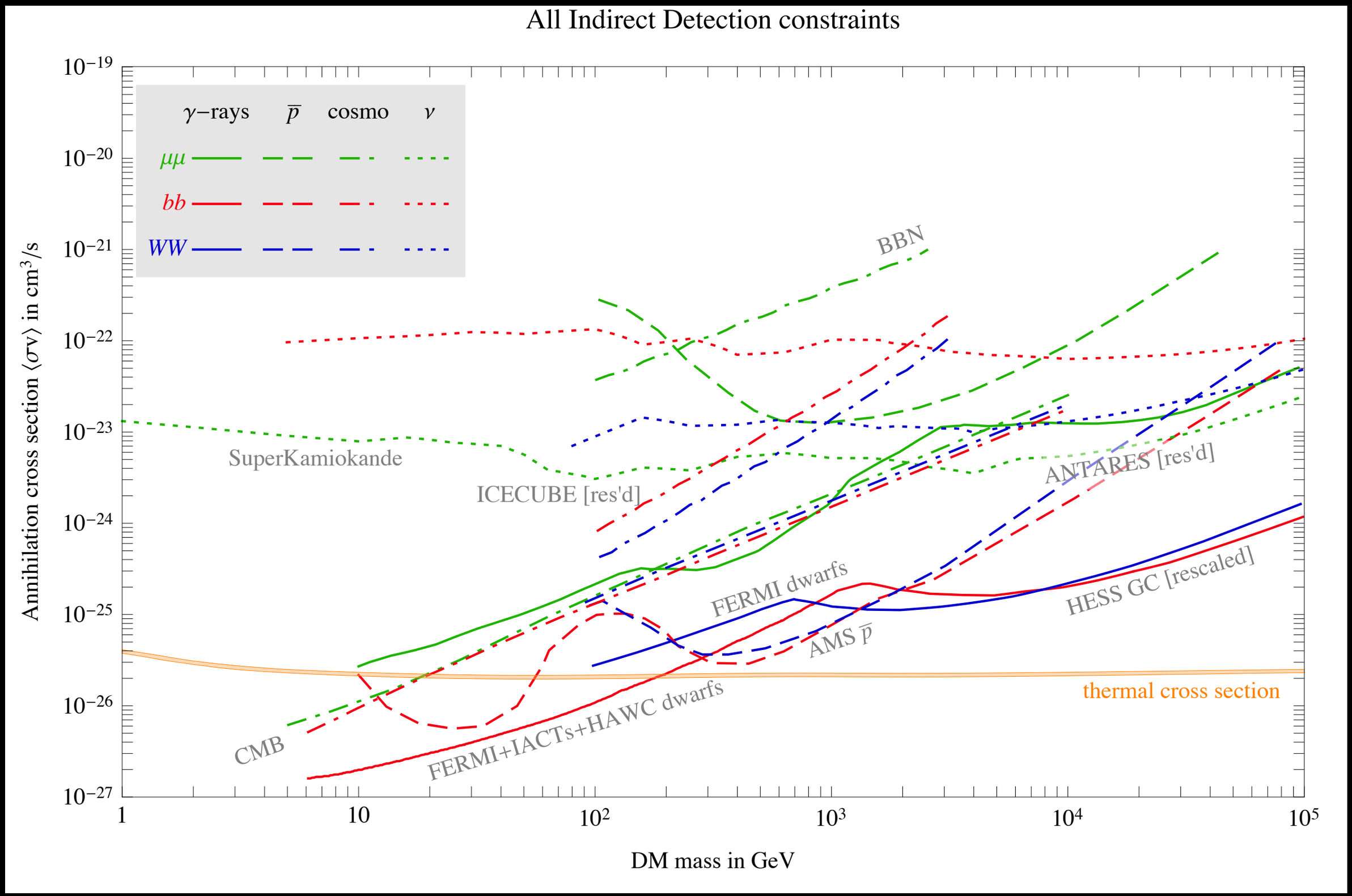


Planck 2015

WIMP Indirect Detection



M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705

WIMP Indirect Detection

All Indirect Detection constraints

γ−rays $\bar{p}$ cosmo ν

$\mu\mu$ bb WW

BBN

SuperKamiokande

ICECUBE [res'd]

ANTAR

FERMI dwarfs

AMS $\bar{p}$

thermal cross section

CMB

FERMI+IACTs+HA

Annihilation cross section $\langle\sigma v\rangle$ in cm^3/s

10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27}

1 10 10^2 10^3 10^4 10^5

Frontier 3

heavy (PeV) DM

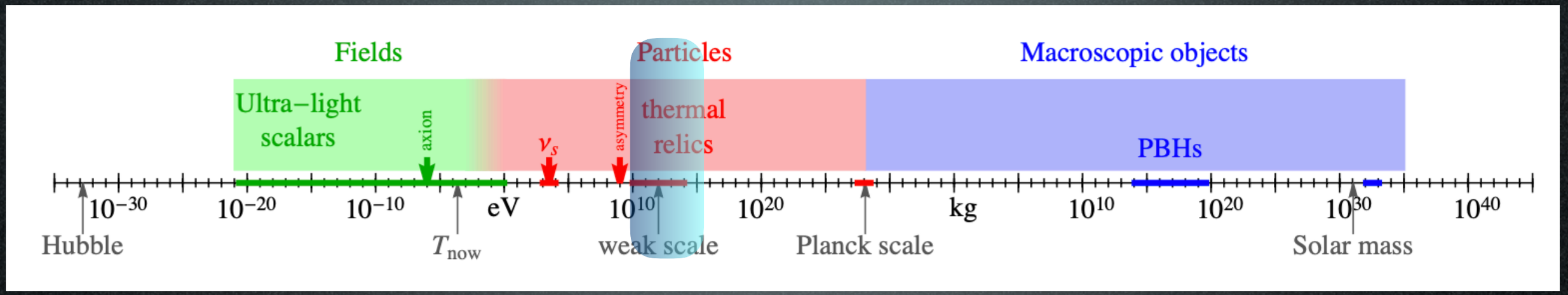
Frontier 2

WIMPs & very weakly coupled DM

M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705

Candidates

A matter of perspective: plausible mass ranges



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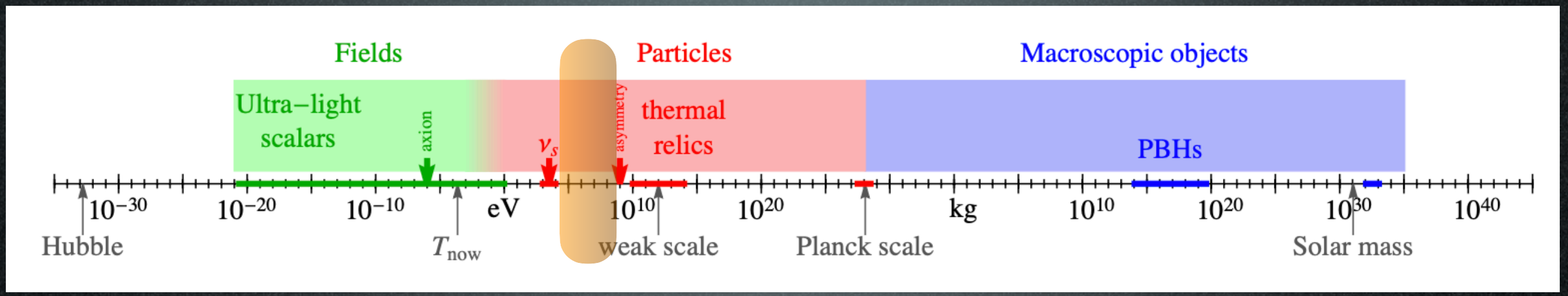

Sub-GeV DM?

Candidates

theory?

production?

Collider Searches?

Indirect Detection?

Direct Detection?

Theory

Sub-GeV DM

- 'MeV (scalar) DM'

Boehm & Fayet hep-ph/0305261

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

Theory

Sub-GeV DM

- WIMPless Dark Matter

  Feng & Kumar 0803.4196

  a.k.a. hidden sector DM

  ~secluded DM

Theory

Sub-GeV DM

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

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

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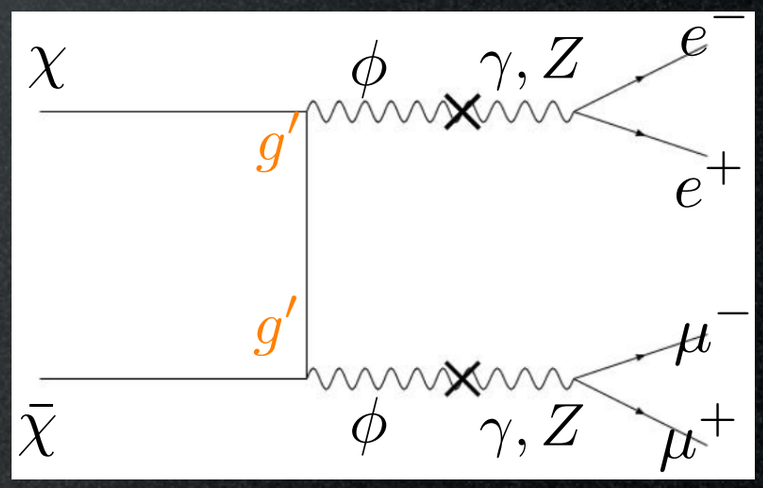
$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_x^2}{m^2}$$

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



Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM?

- 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’
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- …

Candidates

theory

production

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Candidates

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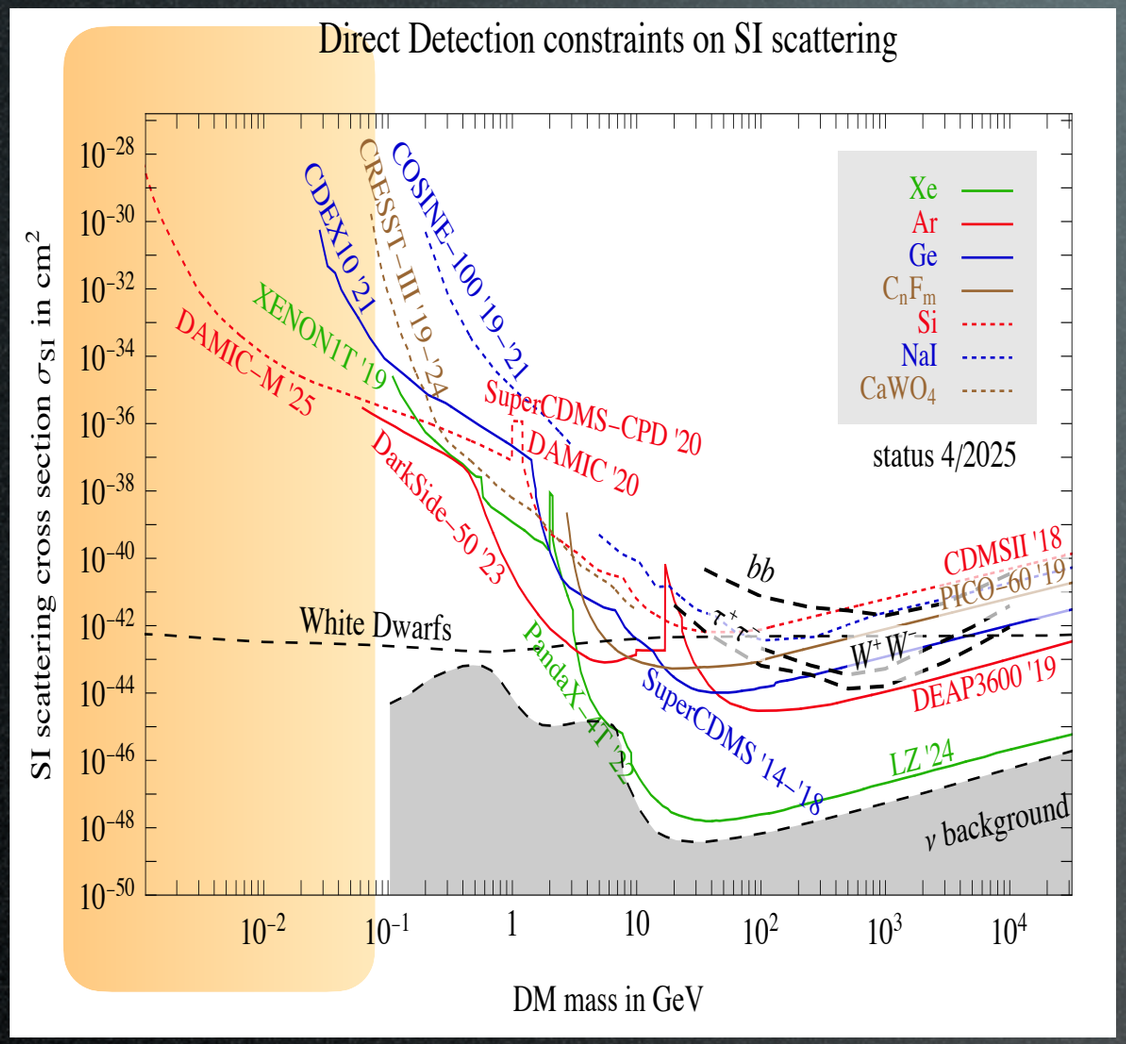
Collider Searches?

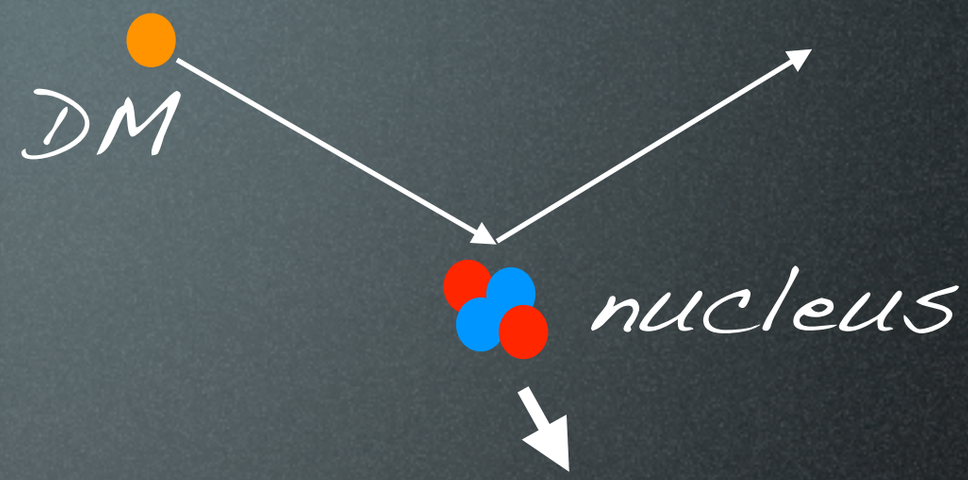
Indirect Detection?

Direct Detection?

Direct Detection of sub-GeV DM



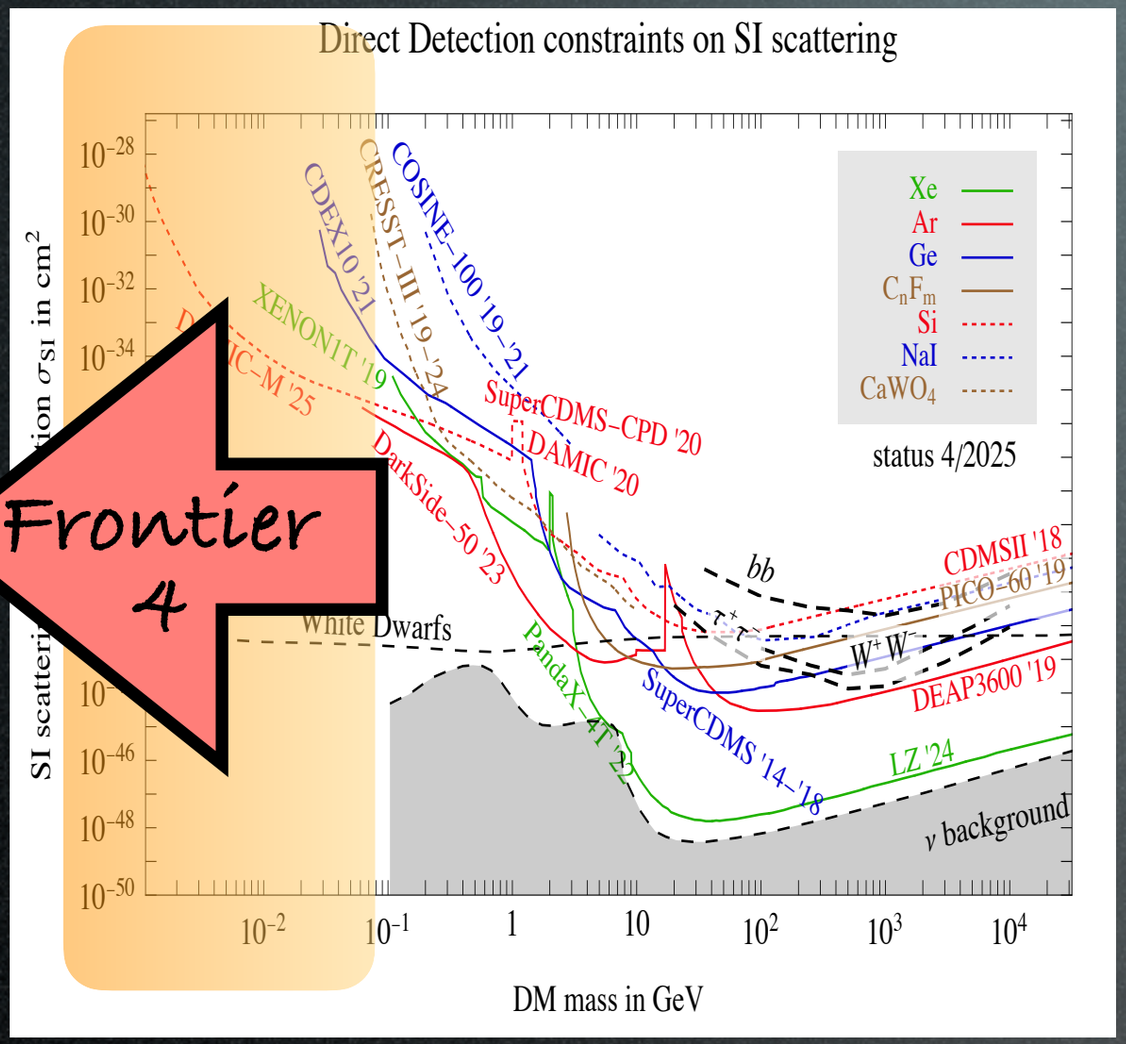
M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705



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

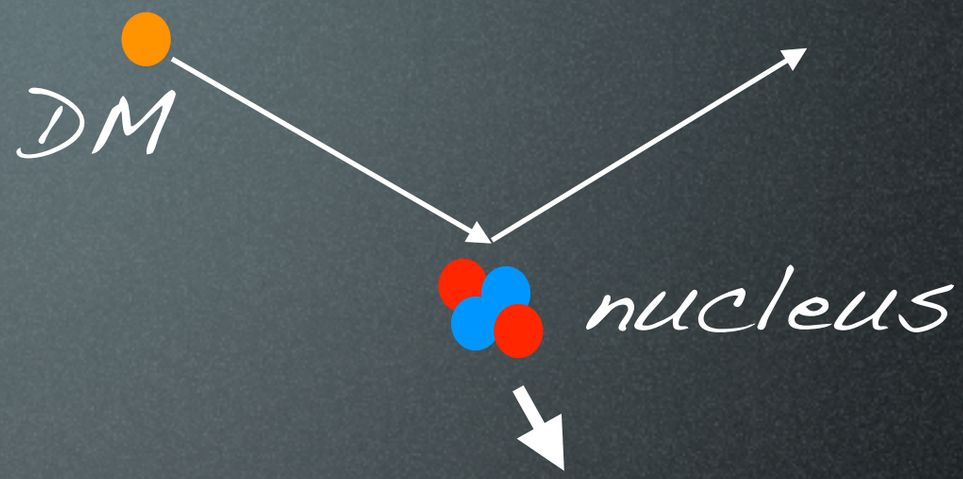
- electron recoil signal
- Migdal effect
- new experimental strategies

Direct Detection of sub-GeV DM



Frontier 4

M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705



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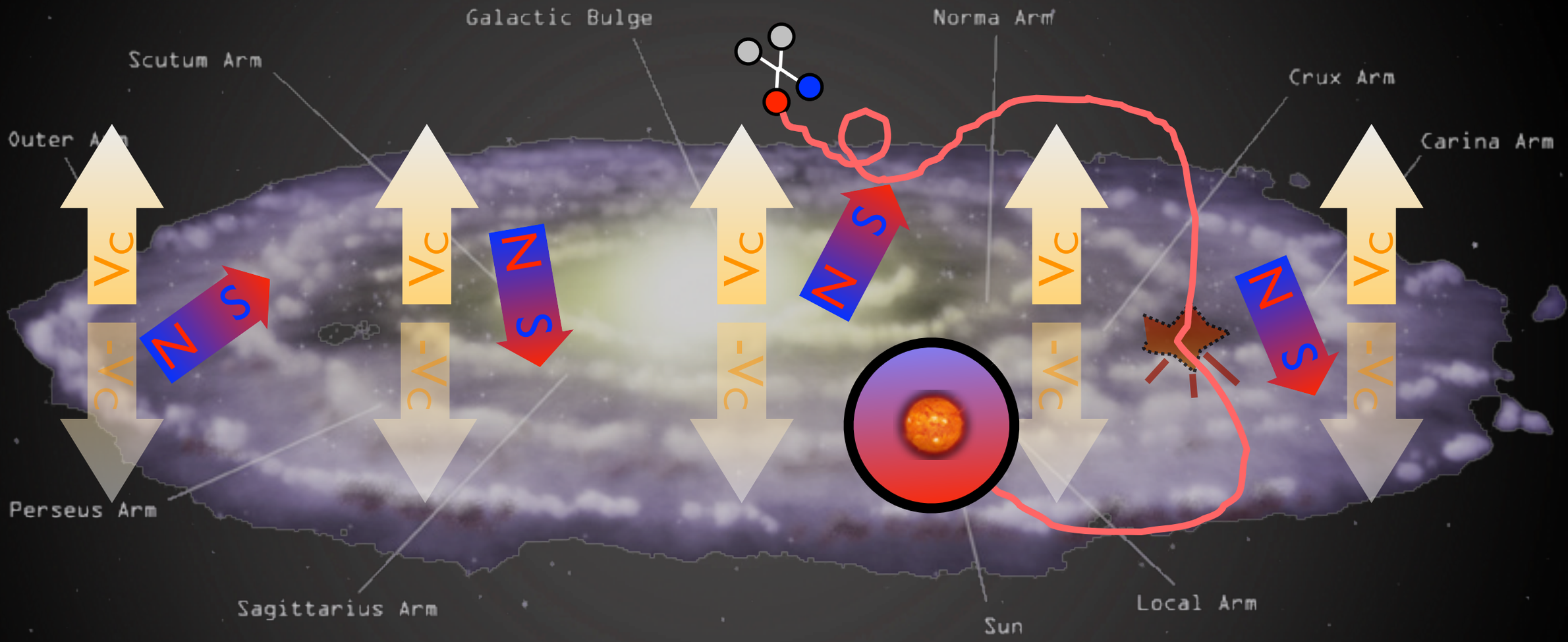
Collider Searches

Indirect Detection?

Direct Detection

Indirect Detection: charged CRs

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



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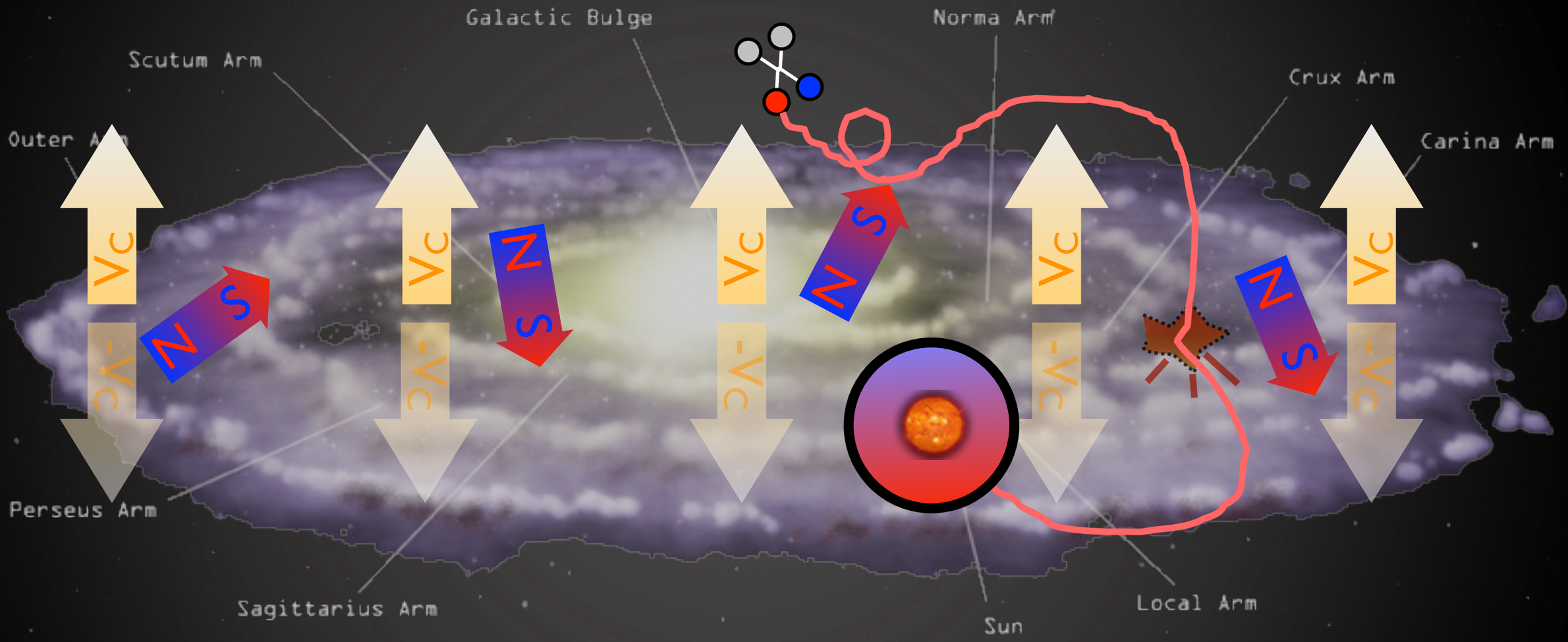

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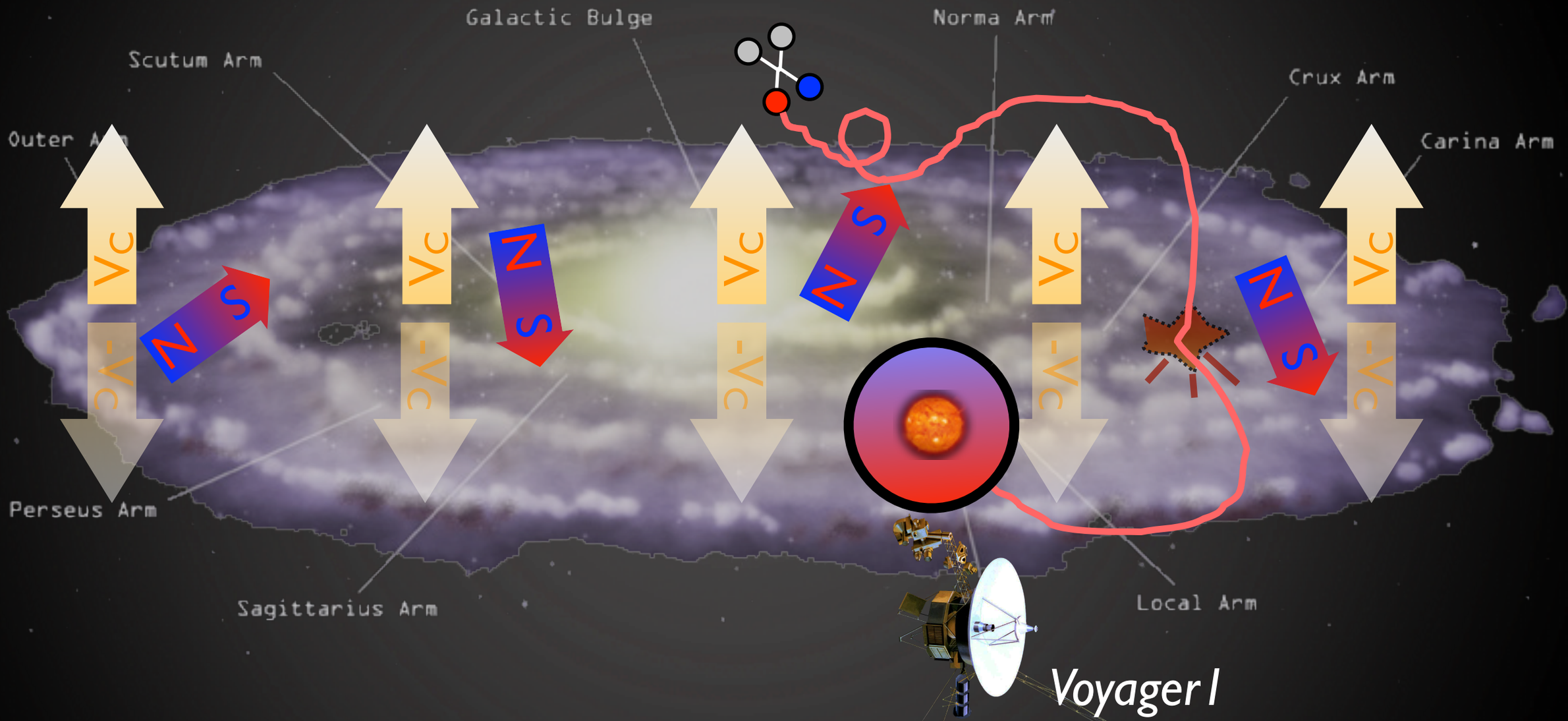


Problem:

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

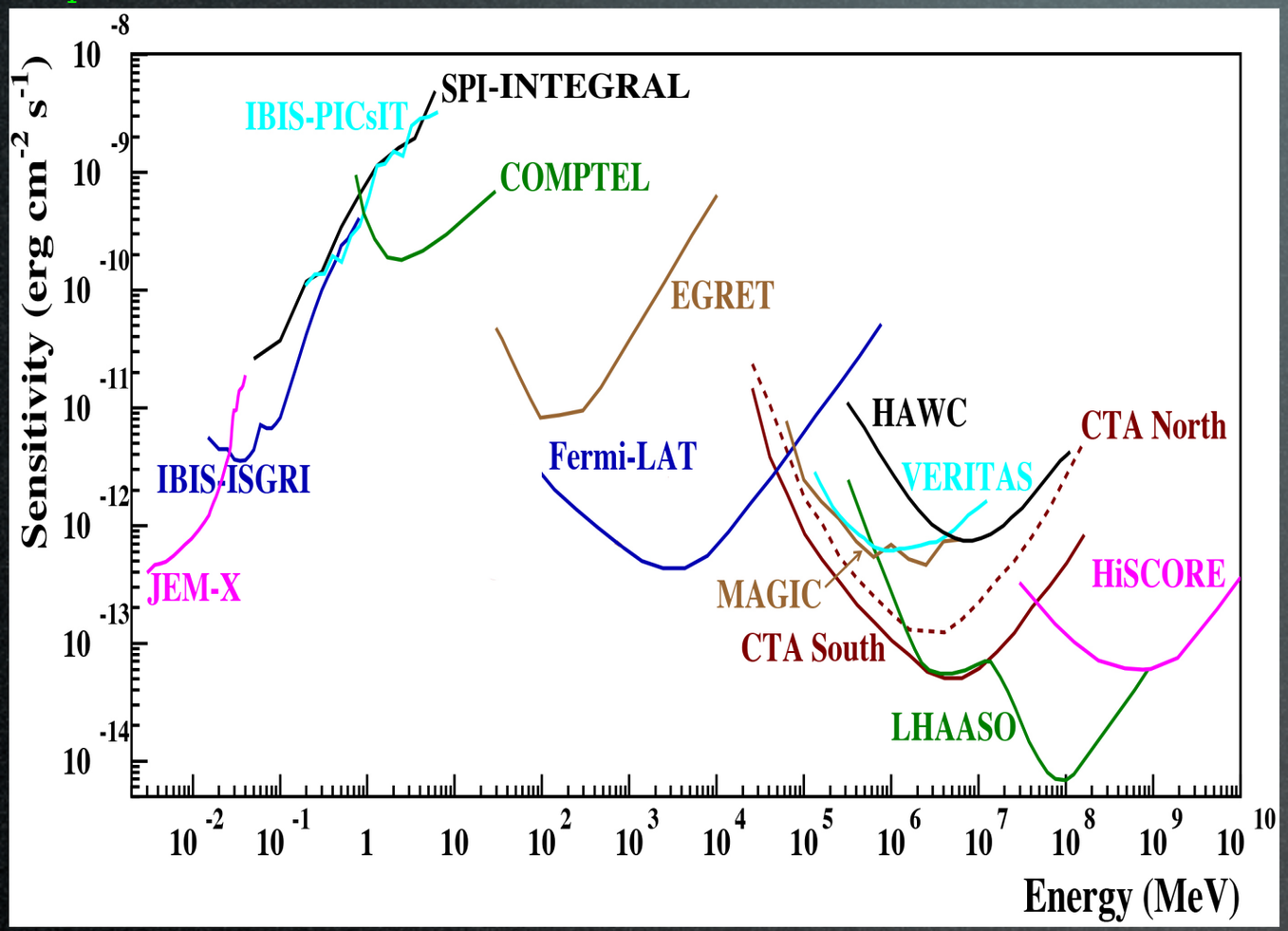
Indirect detection: photons

Sub-GeV DM produces sub-GeV γ-rays

Indirect detection: photons

Sub-GeV DM produces sub-GeV γ-rays

adapted from 1611.02232



Past/current experiments:
Integral, Comptel, Fermi
(2002 → 2025) (1991-2000) (2009 →)

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

AMEGO	satellite	2020s?	HEP detectors	γ-rays	0.2 – 10 GeV
COMPAIR	satellite	2020s?	HEP detectors	γ-rays	0.2 – 500 MeV
SKA	S.Africa+Australia	2020s?	radio telescope	radio	50 MHz – 30 GHz
INO-ICAL	India	2020s?	calorimeter	neutrinos	1 – 100 GeV
E-ASTROGAM	satellite	2030s?	HEP detectors	γ-rays	0.3 MeV – 3 GeV

Cirelli, Strumia, Zupan 2406.01705

Indirect detection: photons

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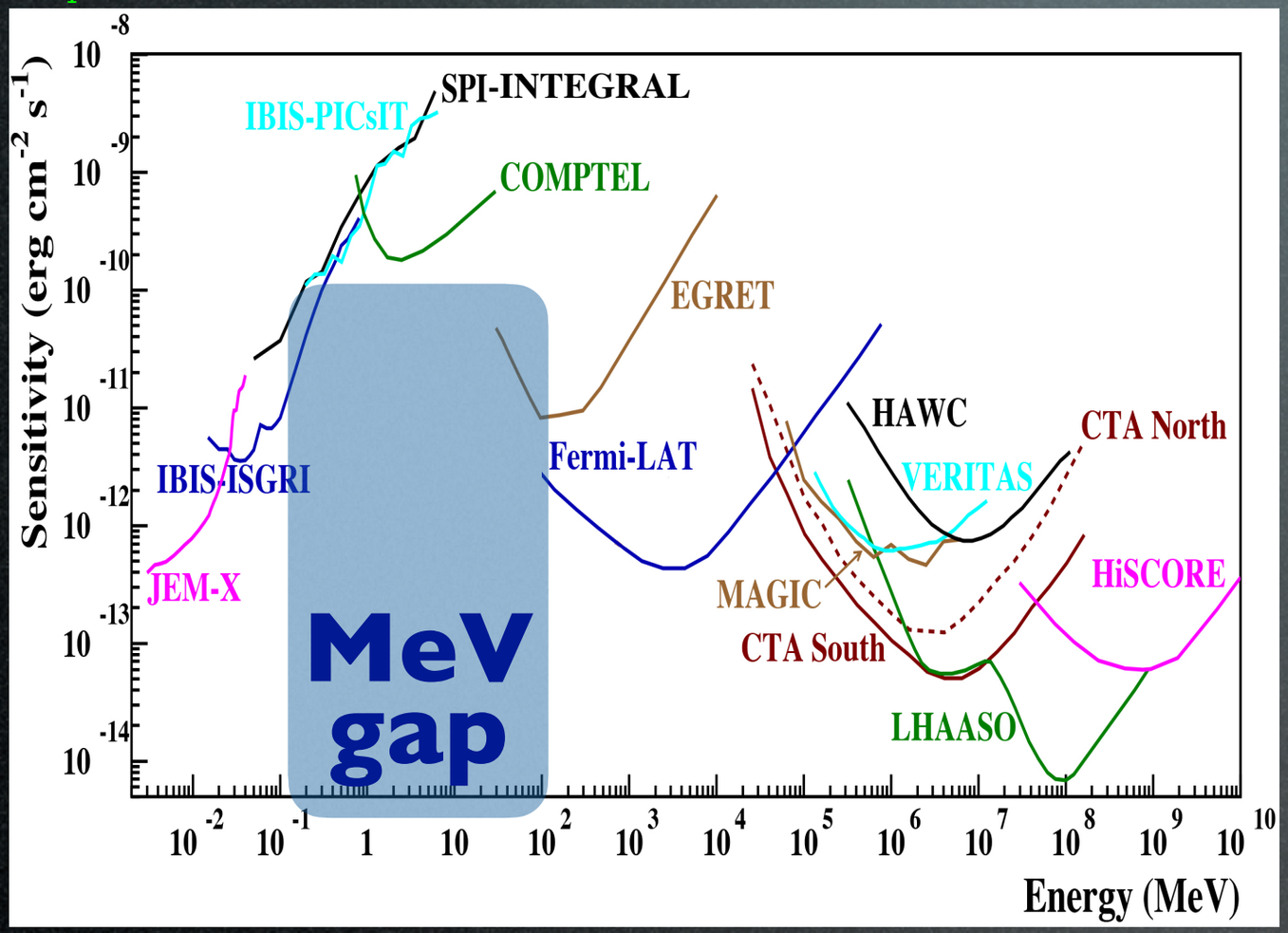

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Cirelli, Strumia, Zupan 2406.01705

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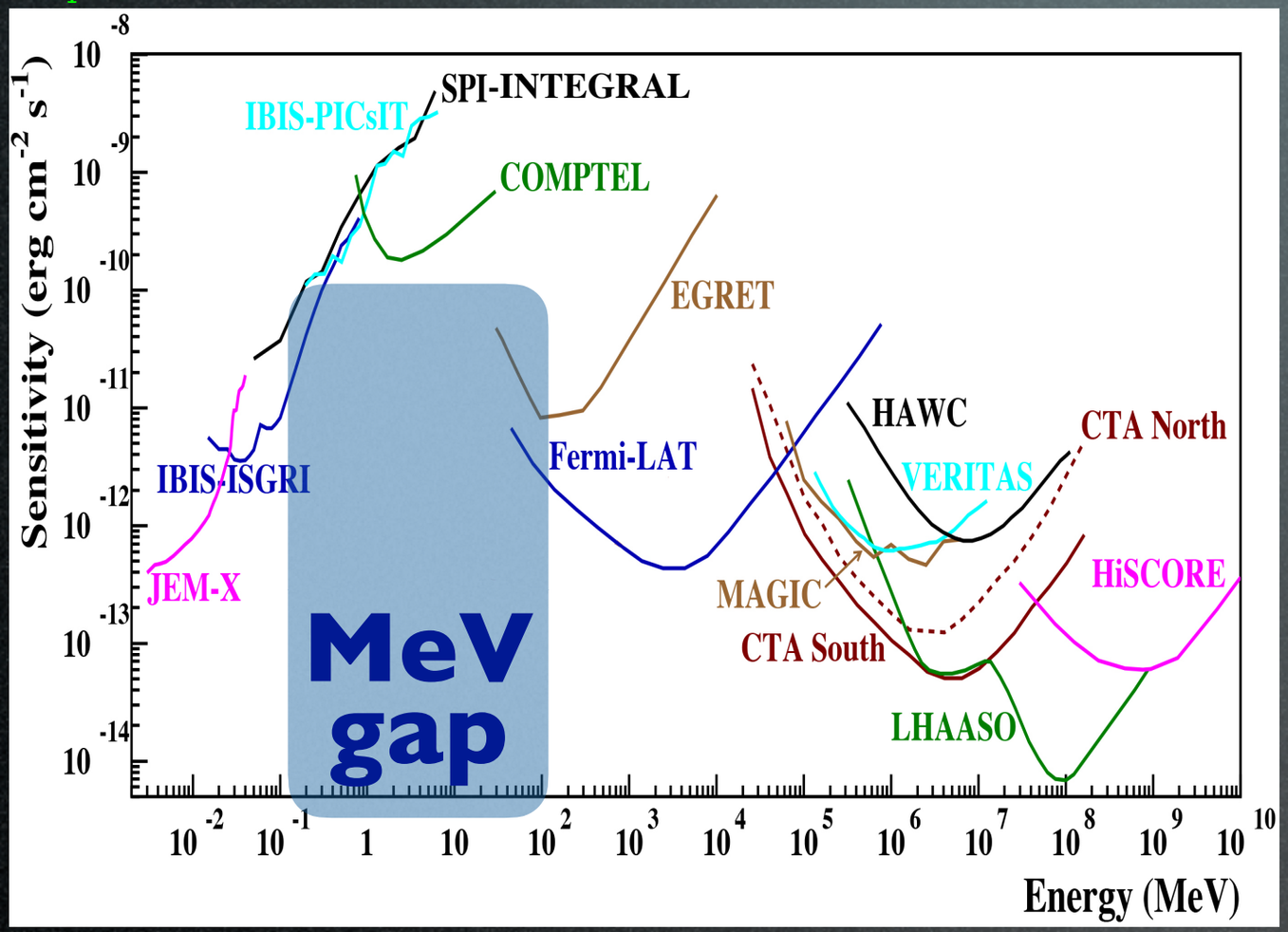


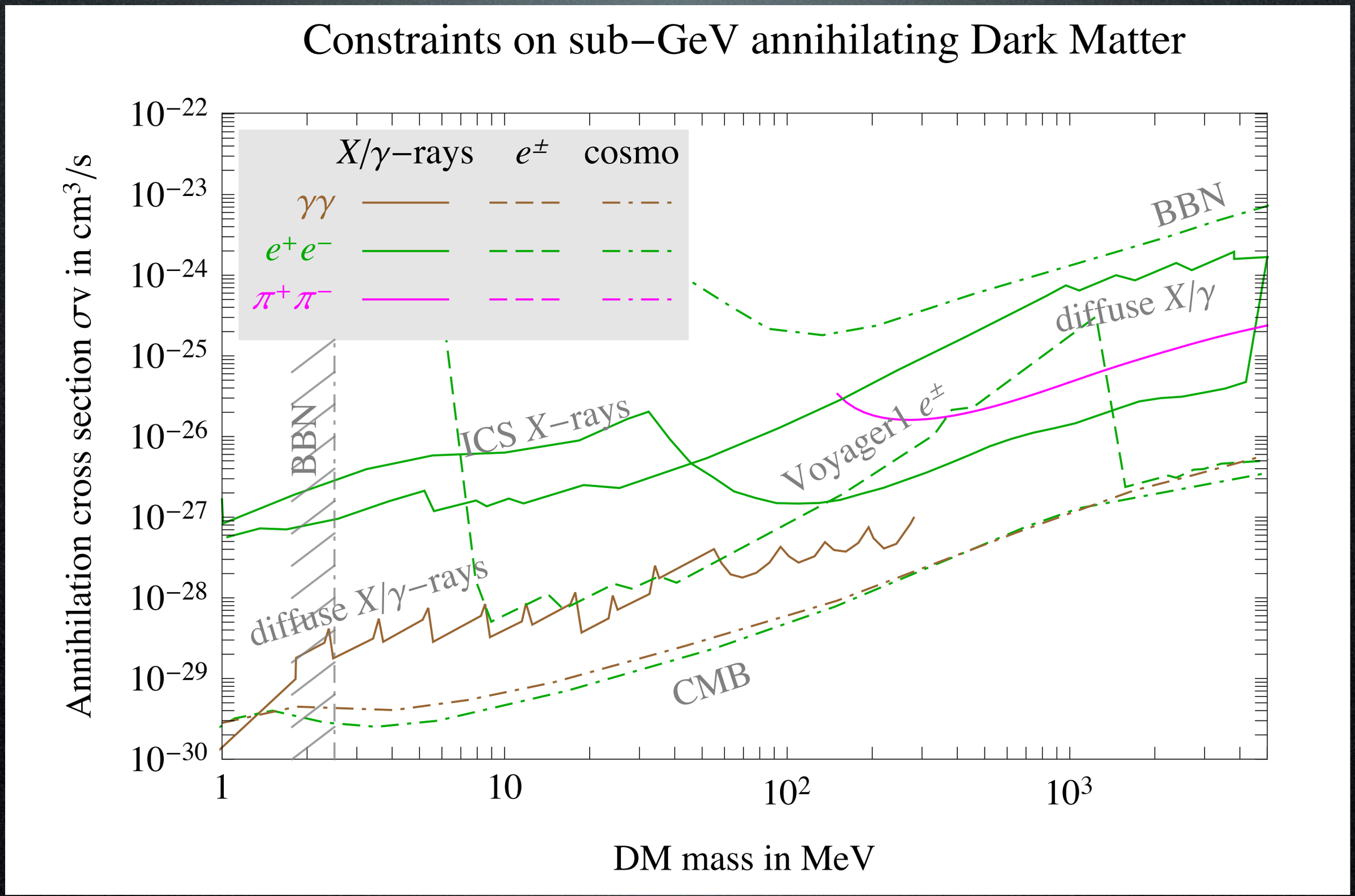
How to do better?

ICS & X-rays!

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Comparing all bounds



M. Cirelli, A. Strumia, J. Zupan 2406.01705 **v3** (includes eROSITA from 2506.02310)

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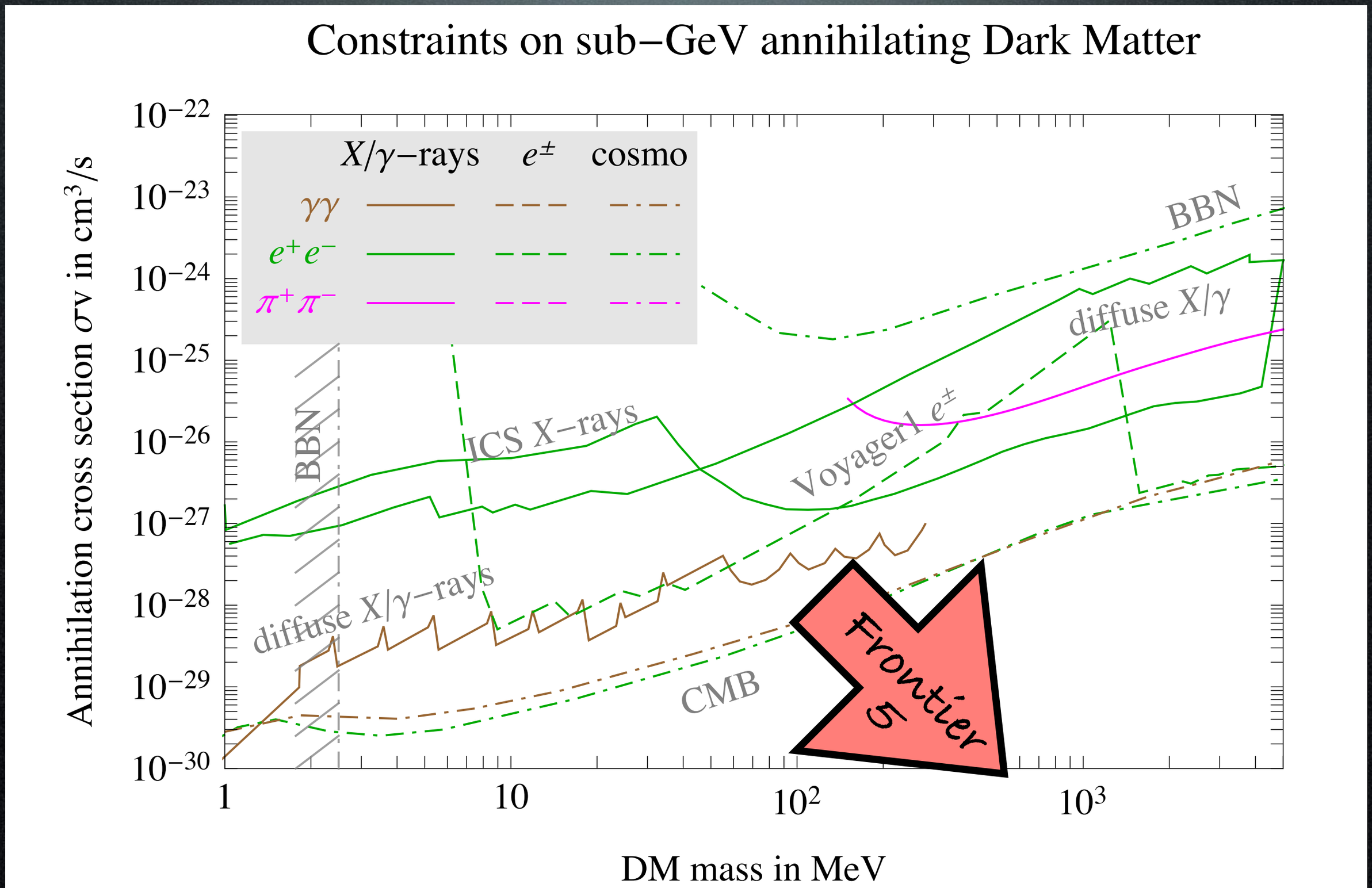
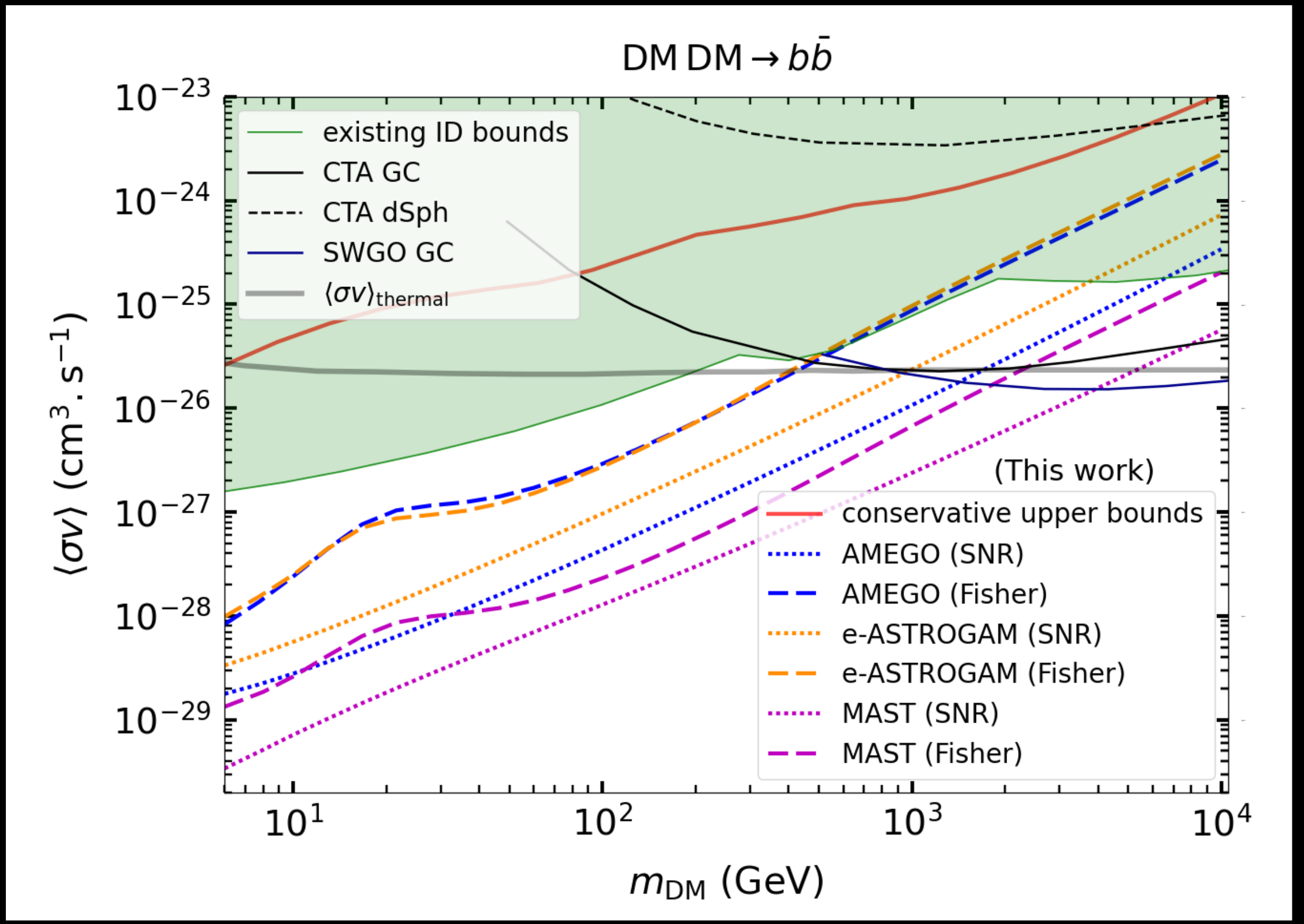


M. Cirelli, A. Strumia, J. Zupan 2406.01705 **v3** (includes eROSITA from 2506.02310)

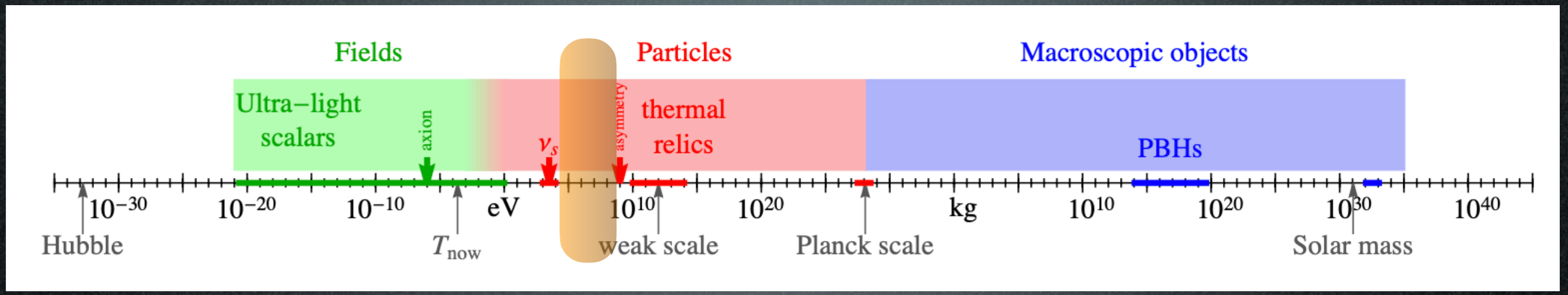
WIMP ID - future prospects



M. Cirelli, A. Kar, 2503.04907

Candidates

A matter of perspective: plausible mass ranges



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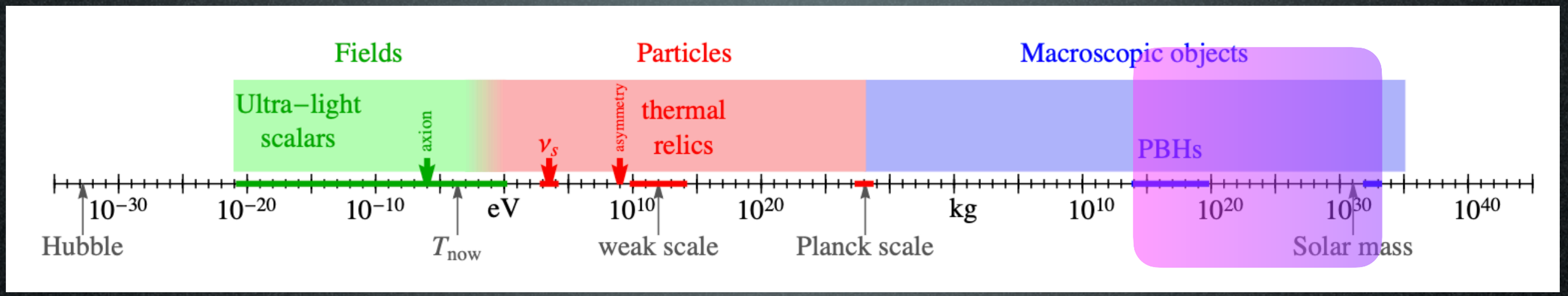

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an astro *je ne sais pas quoi*:

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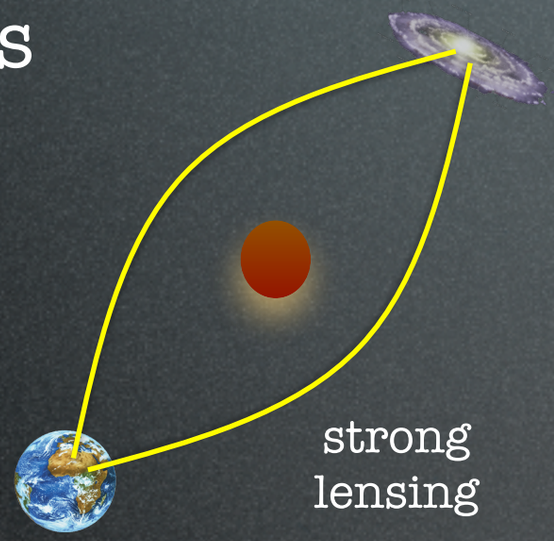
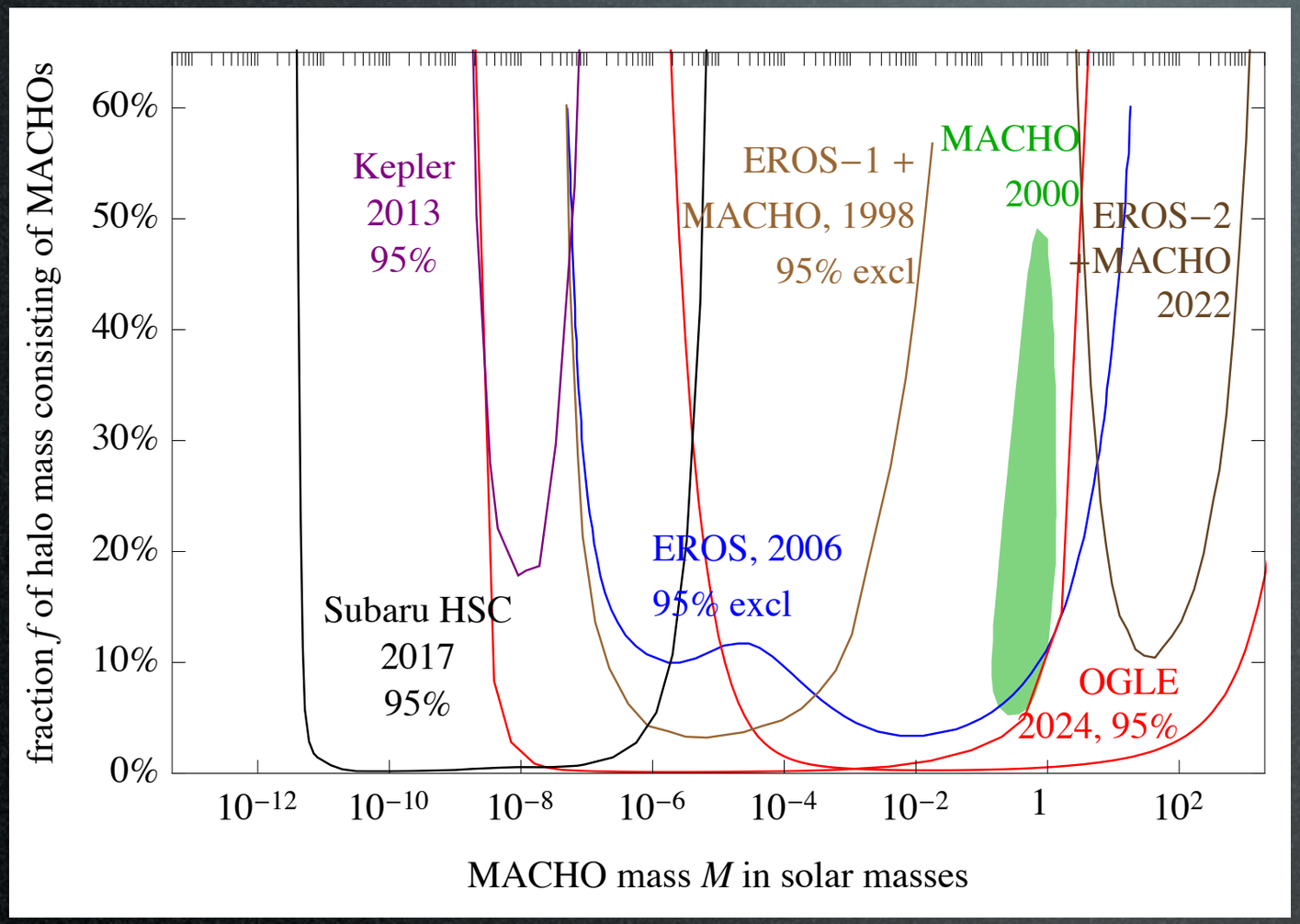


strong
lensing

MACHOs or PBHs as DM



M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705

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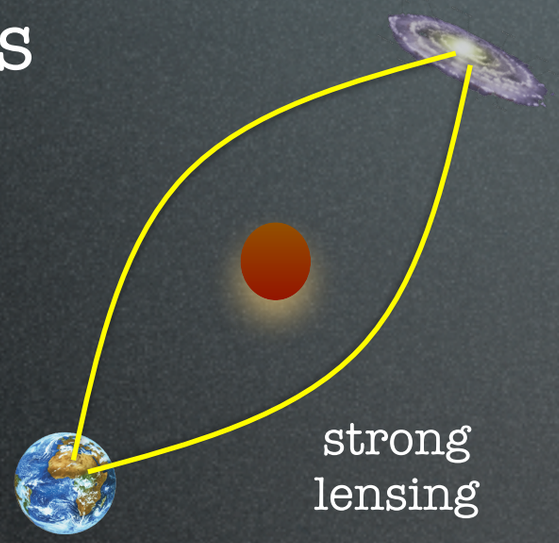

a baryon of the SM:

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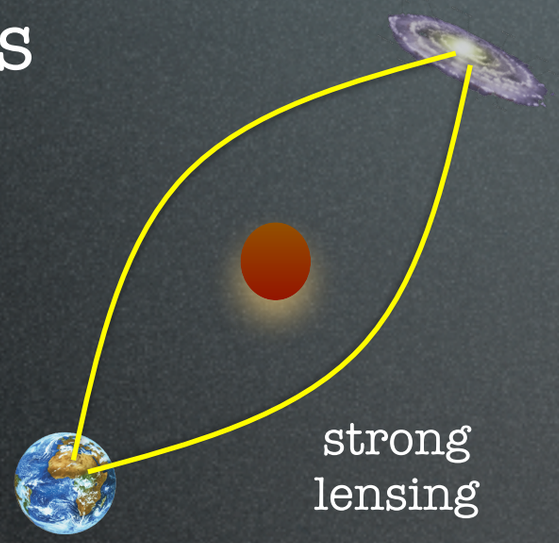

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- BBN computes the abundance of He in terms of primordial baryons:
  too much baryons => Universe full of Helium
- CMB says baryons are 4% max

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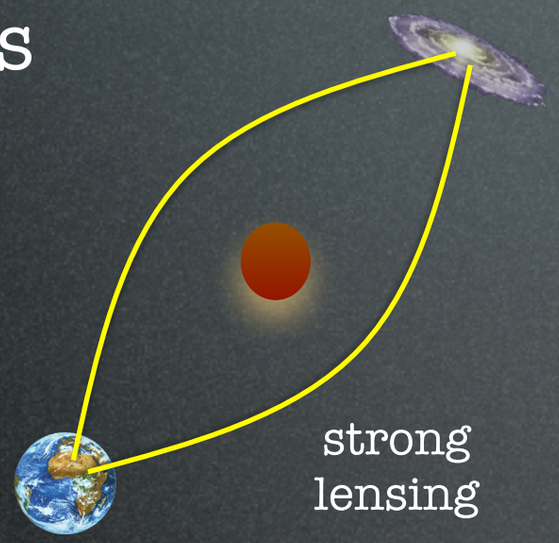

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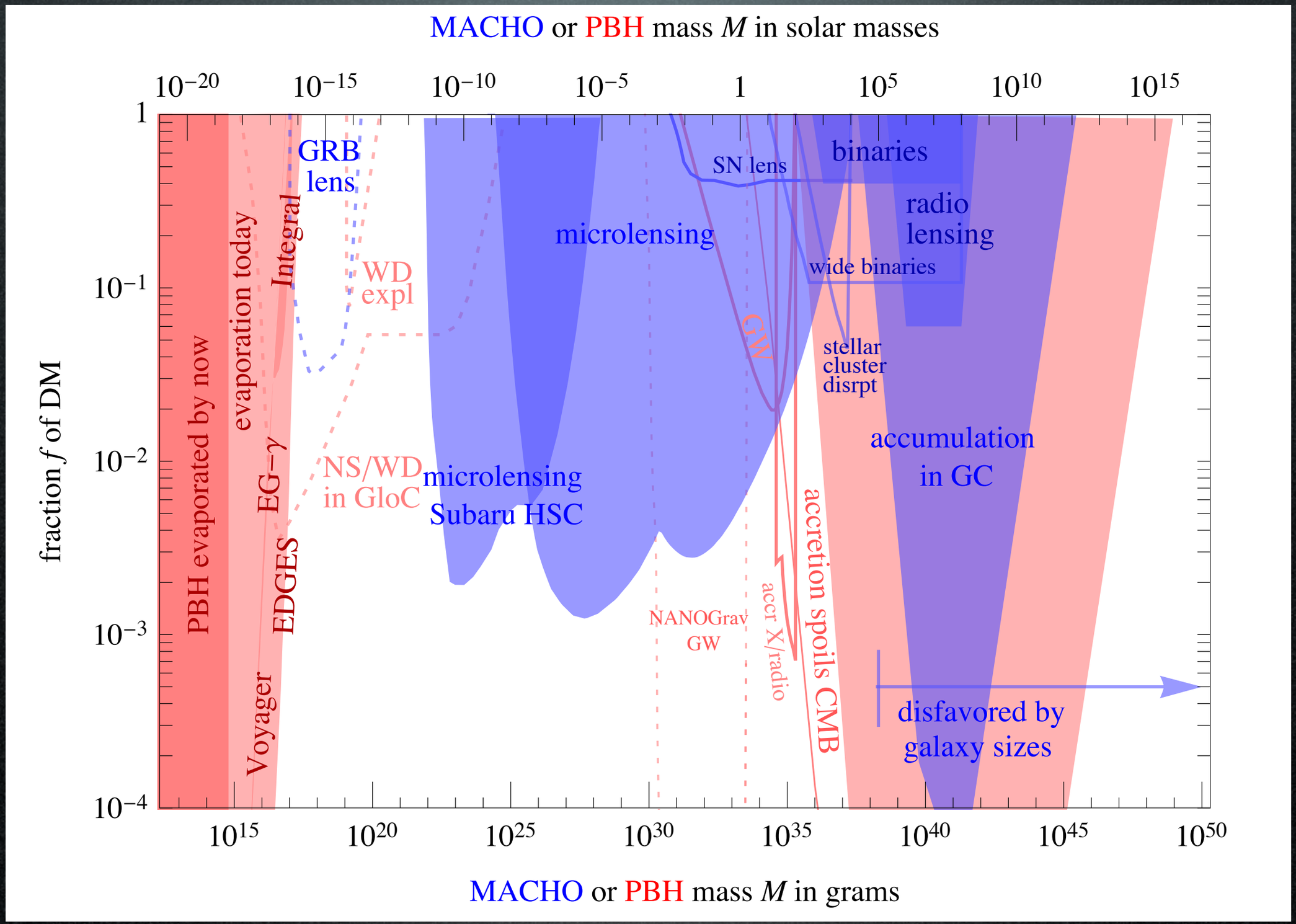
A loophole: Primordial Black Holes!

- produced before BBN
- with masses too small/large to lens
- perhaps LIGO-VIRGO have seen them?

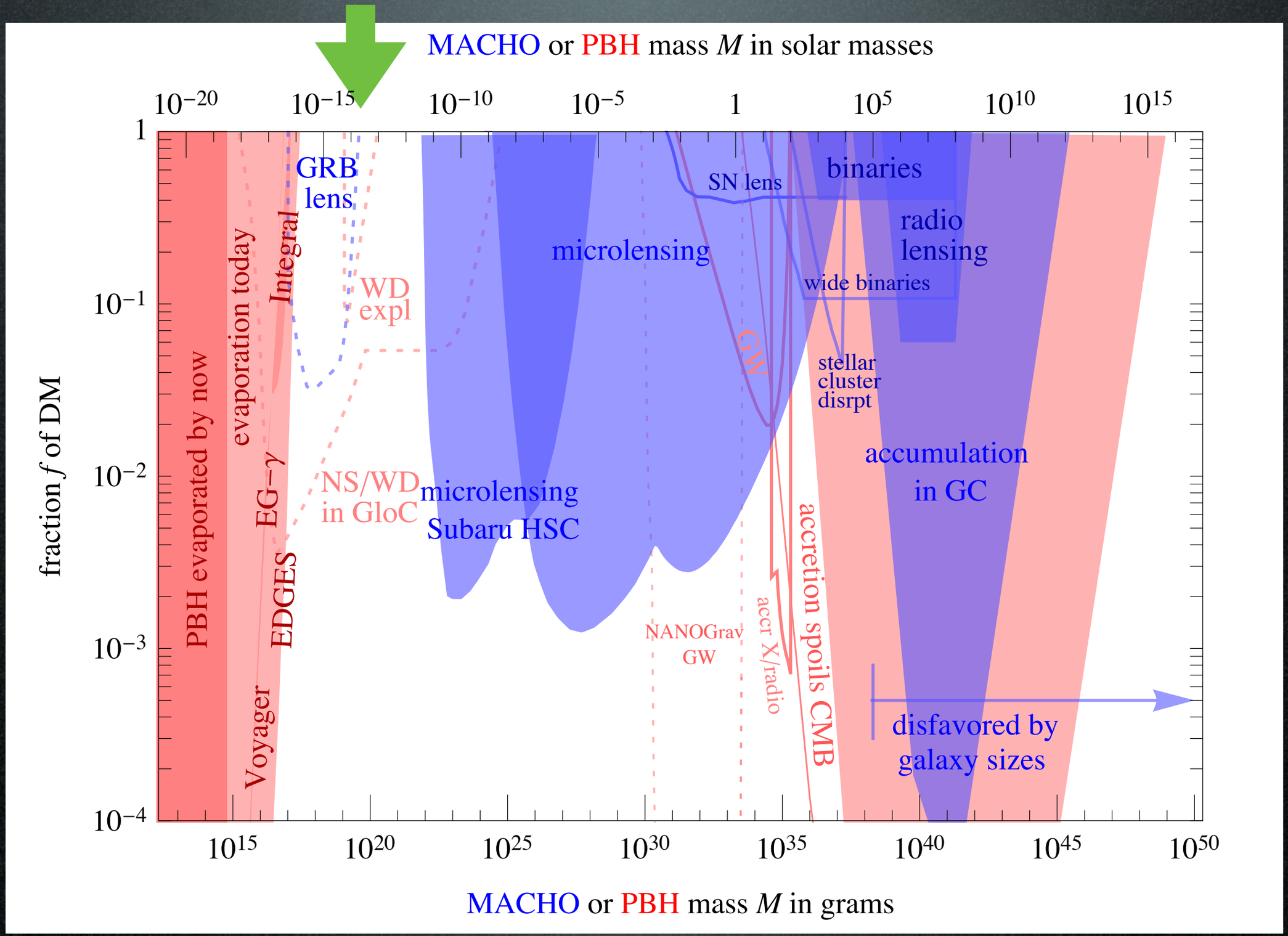
PBHs as DM



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

PBHs as DM

window still open?



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

PBHs as DM

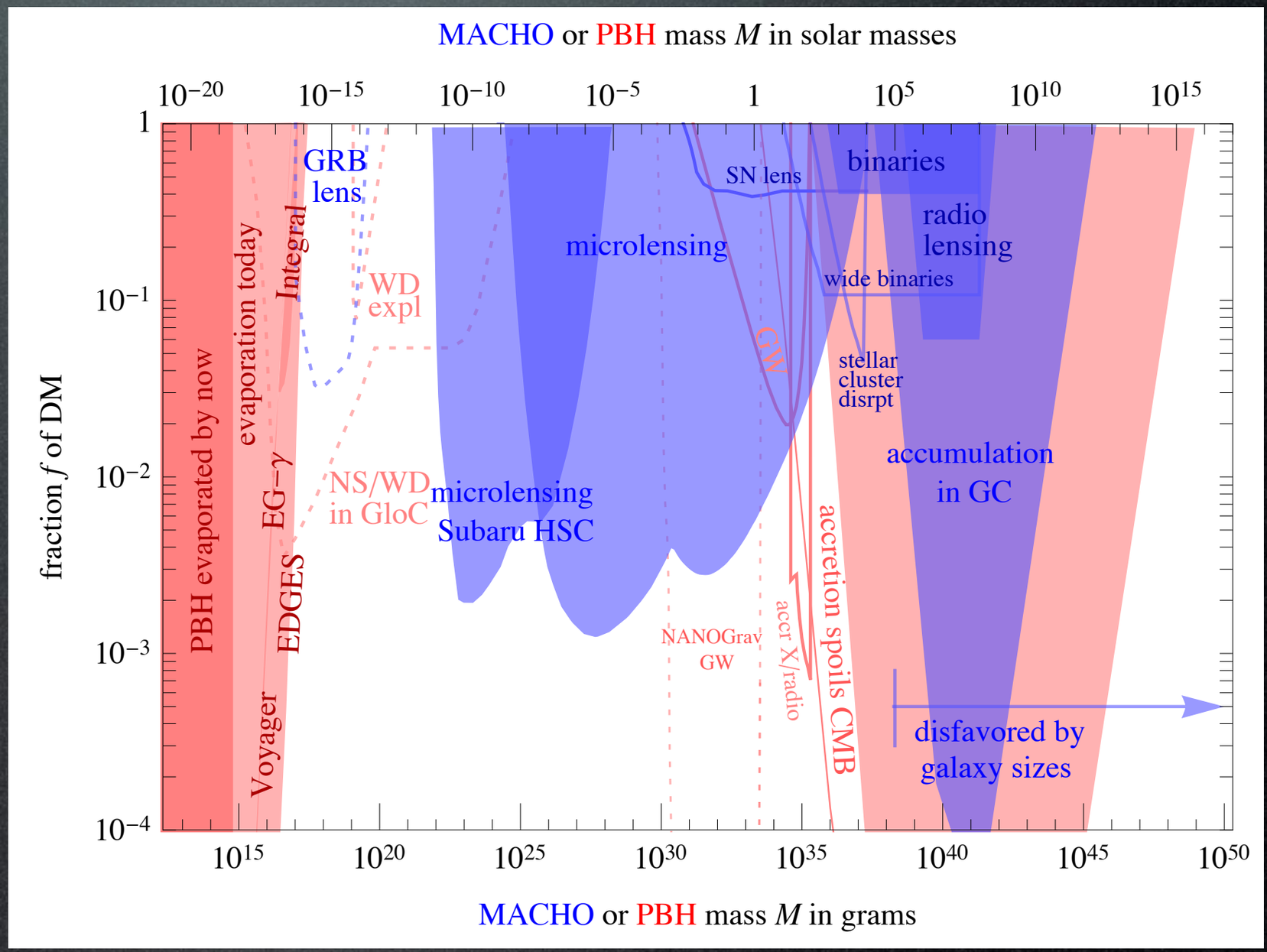
Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints



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

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‘small’ PBHs emit today by Hawking evaporation

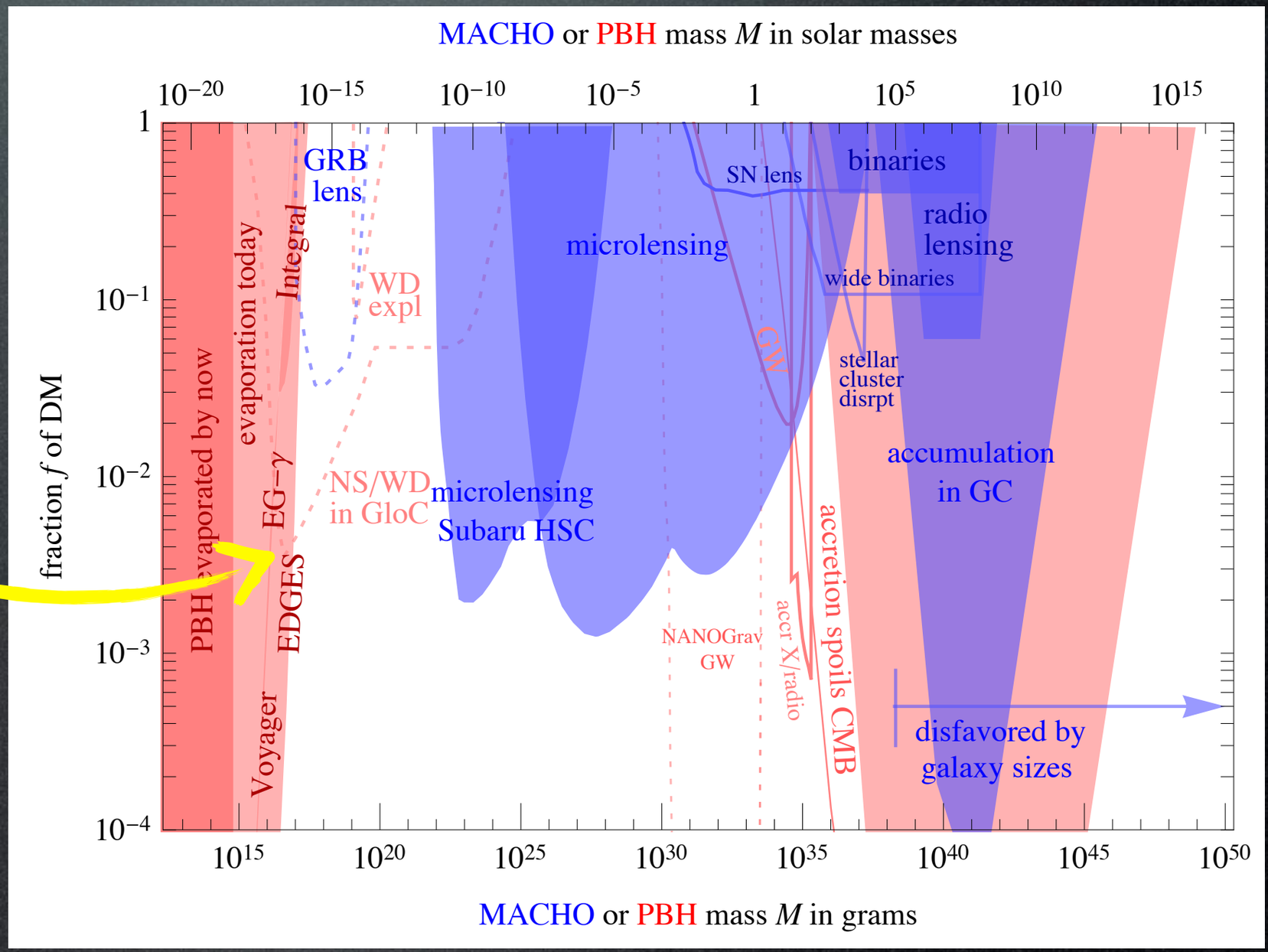
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



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

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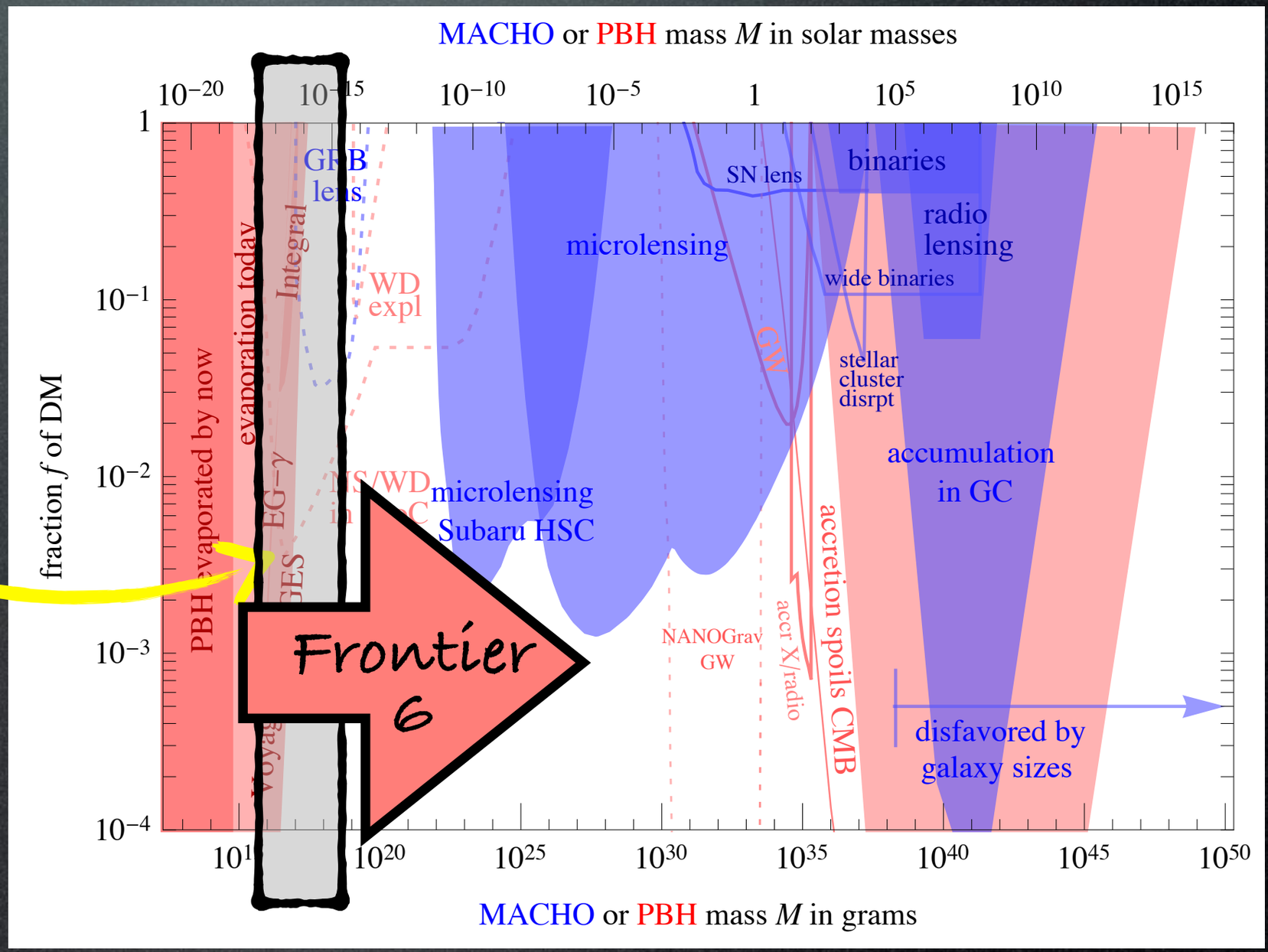

M. Cirelli, A. Strumia, J. Zupan 2406.01705

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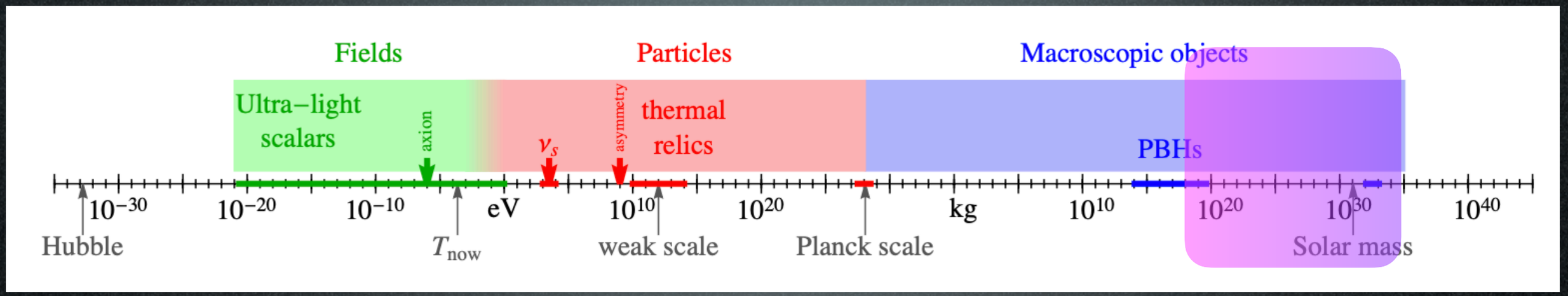

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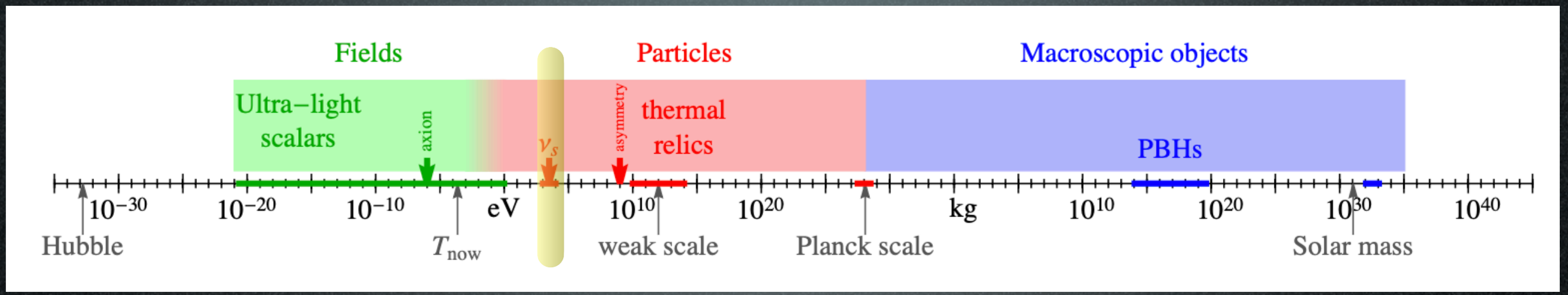


KeV DM?

X-ray line

Bulbul et al., 1402.2301

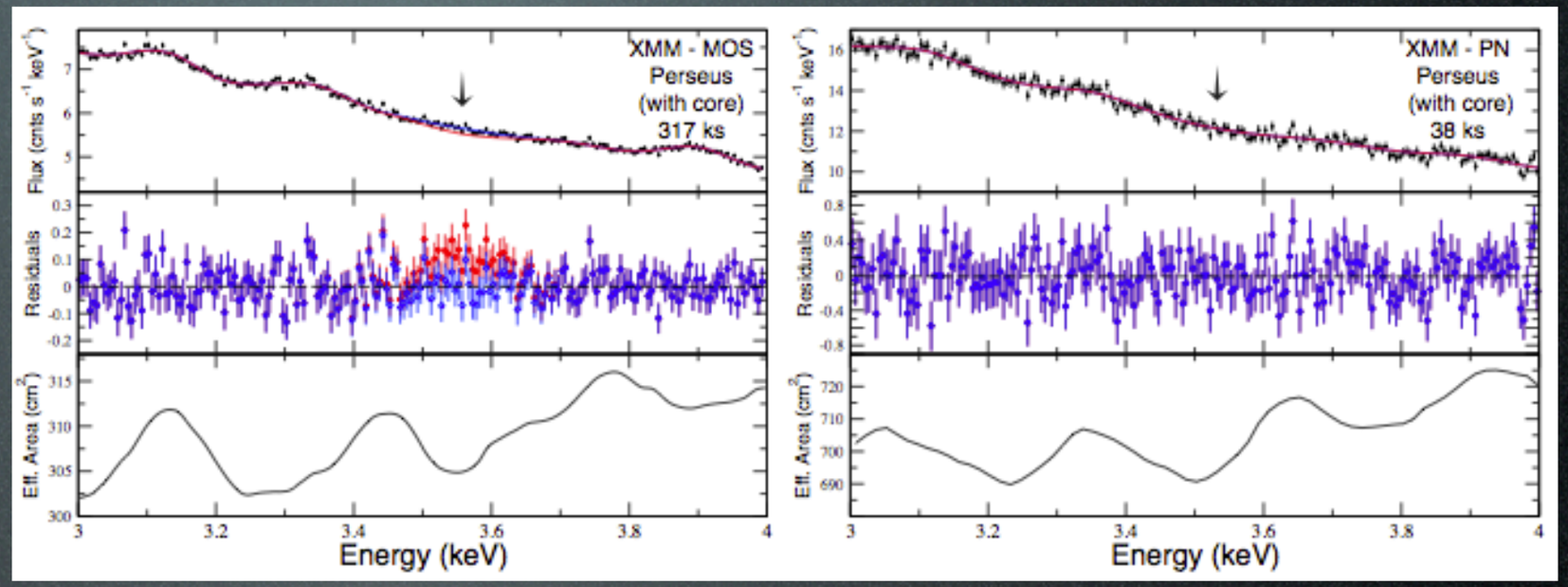
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

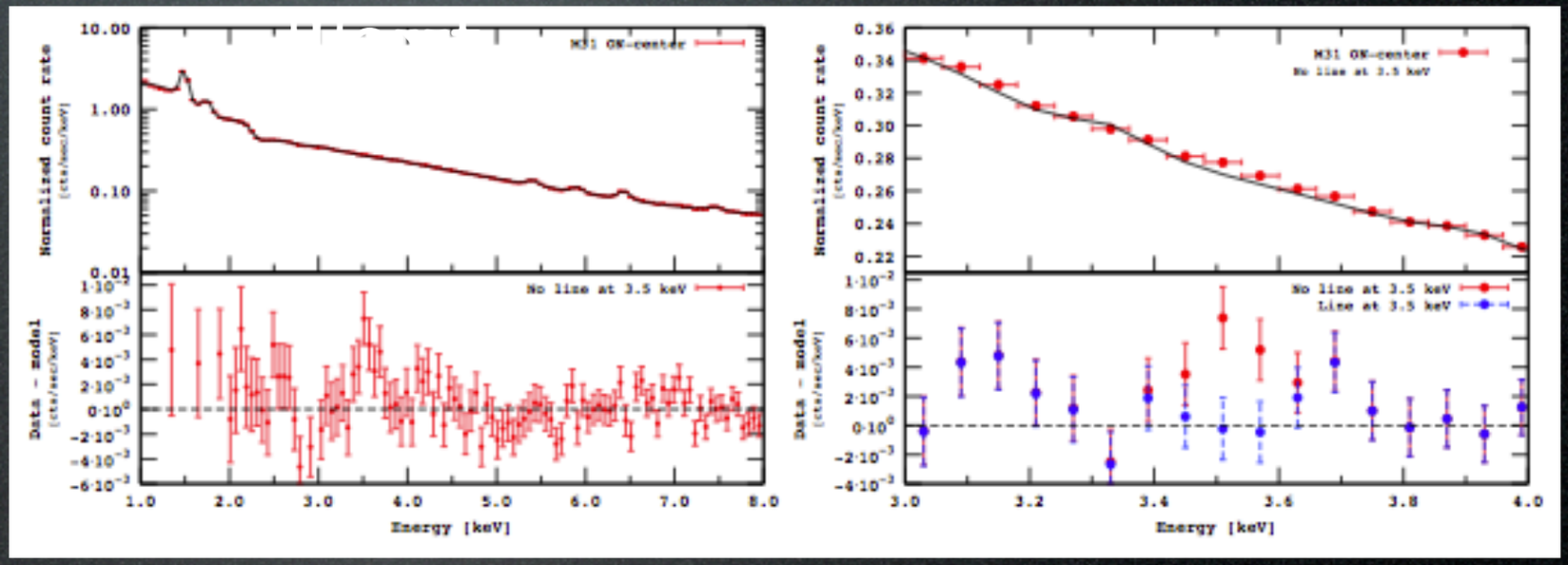
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

z = 0 and 0.0179

4.4σ



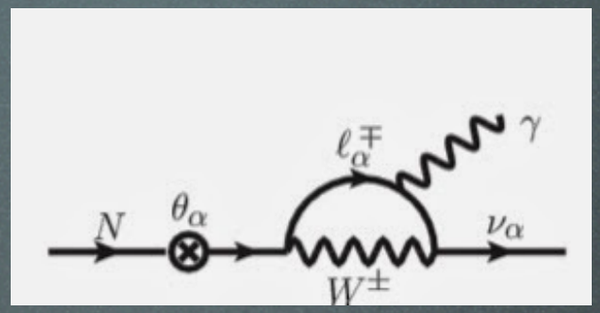
X-ray line

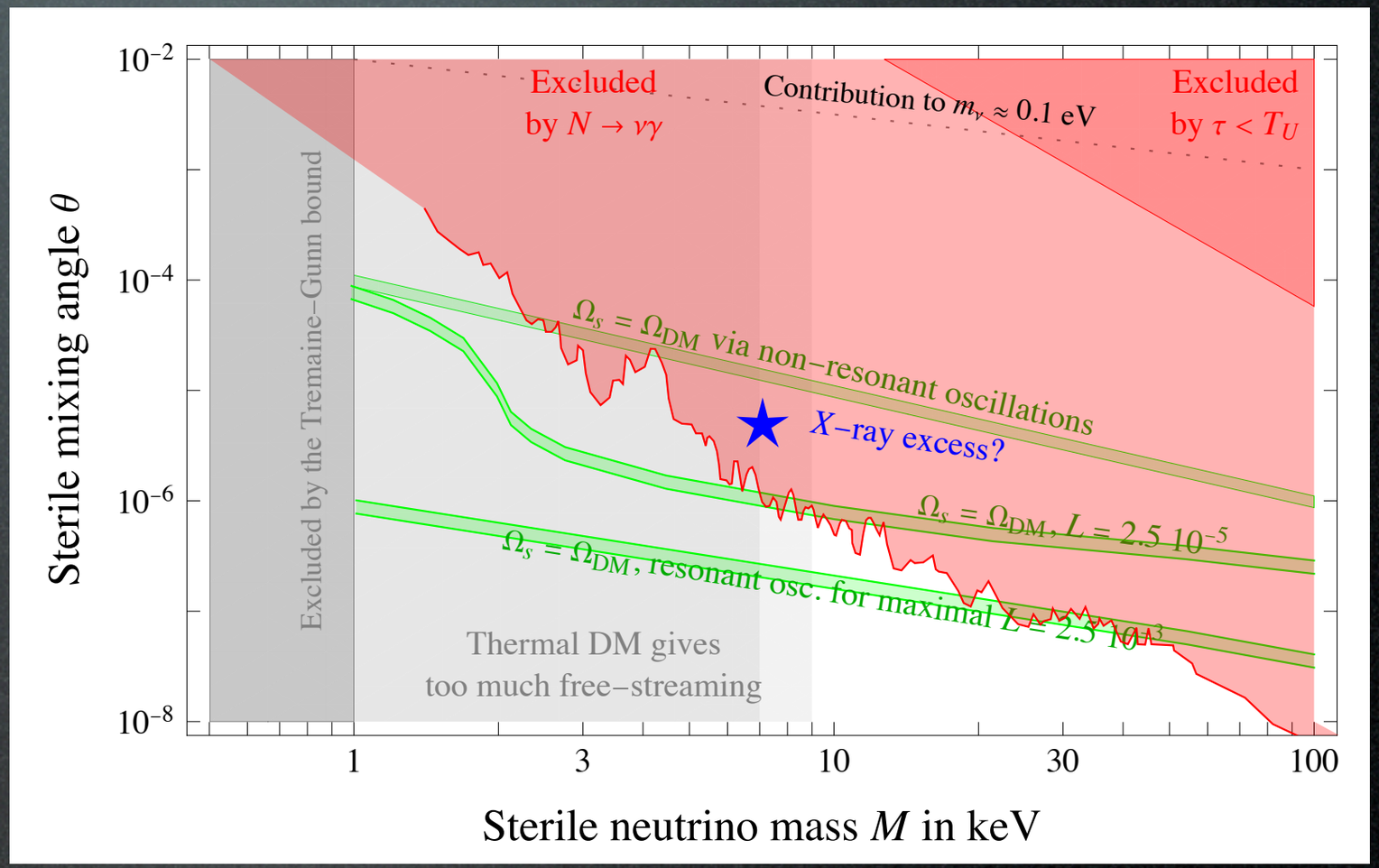
Sterile neutrino decay

$m_\nu = 7.1$ KeV

$\tau \simeq 10^{29}$ sec

$\sin^2 2\theta \sim$ few 10^{-11}





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

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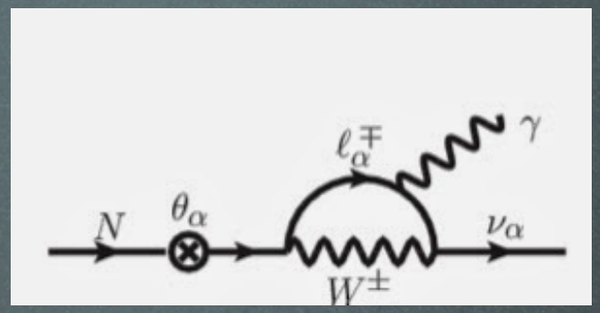

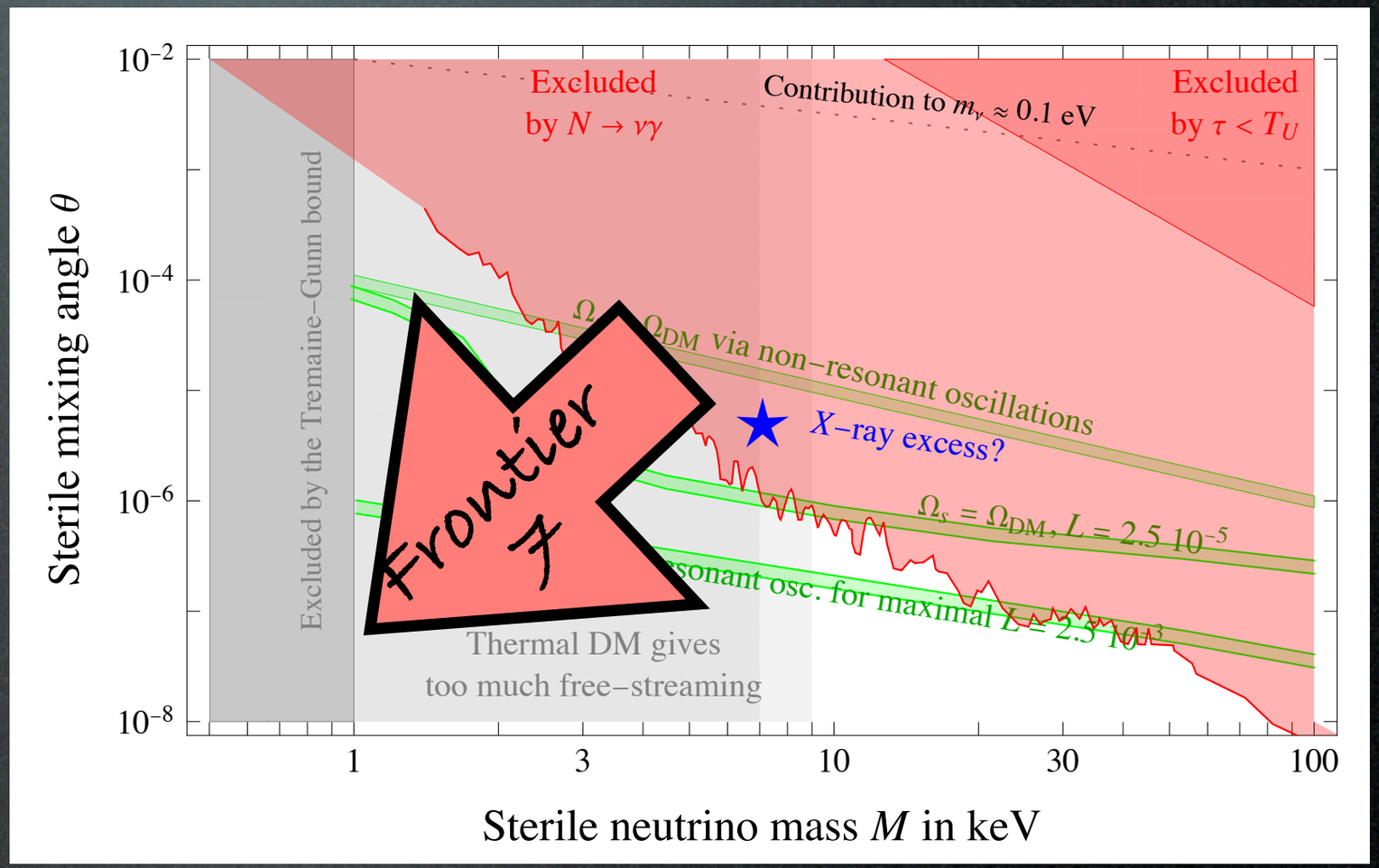

M. Cirelli, A. Strumia, J. Zupan 2406.01705

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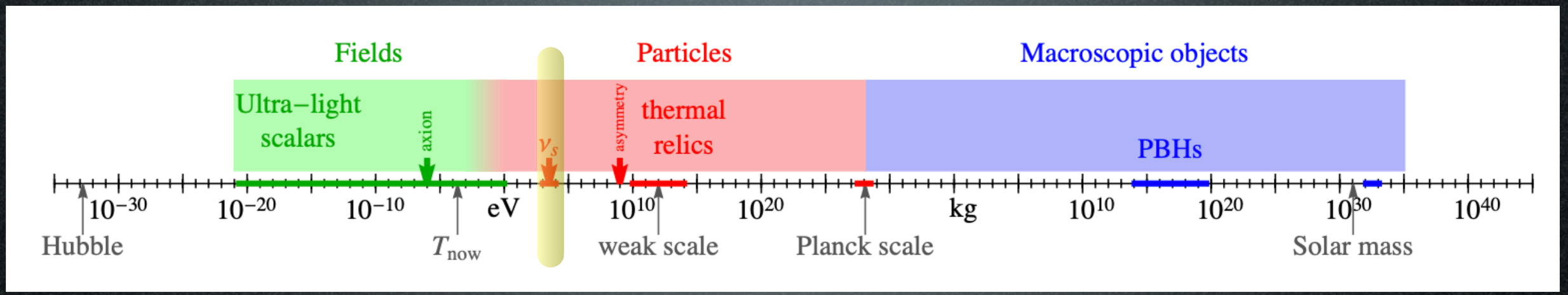

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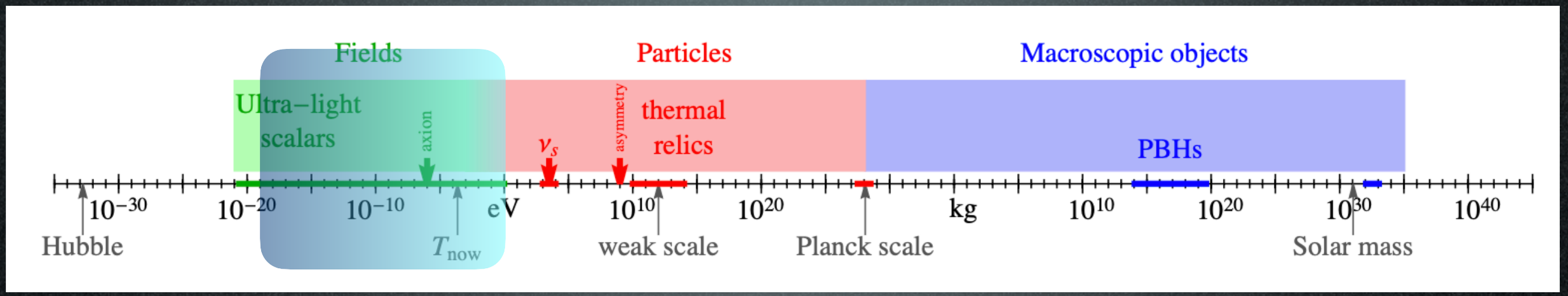


Axions

Theoretically motivated:

one can add to the SM $\mathscr{L} = \mathscr{L}_{\rm SM} - \theta \dfrac{g_3^2}{64\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$ $\left(\tilde{G}^a_{\mu\nu} \equiv \dfrac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^a_{\alpha\beta} \right)$

which induces $d_n \approx \theta \; e \; m_\pi^2 / m_N^2 \approx 10^{-16} \; \theta \; e\,\text{cm}$

but experimentally $|d_n| \lesssim 3 \; 10^{-26} \; e\,\text{cm}$

so why is $|\theta| \lesssim 10^{-11}$?

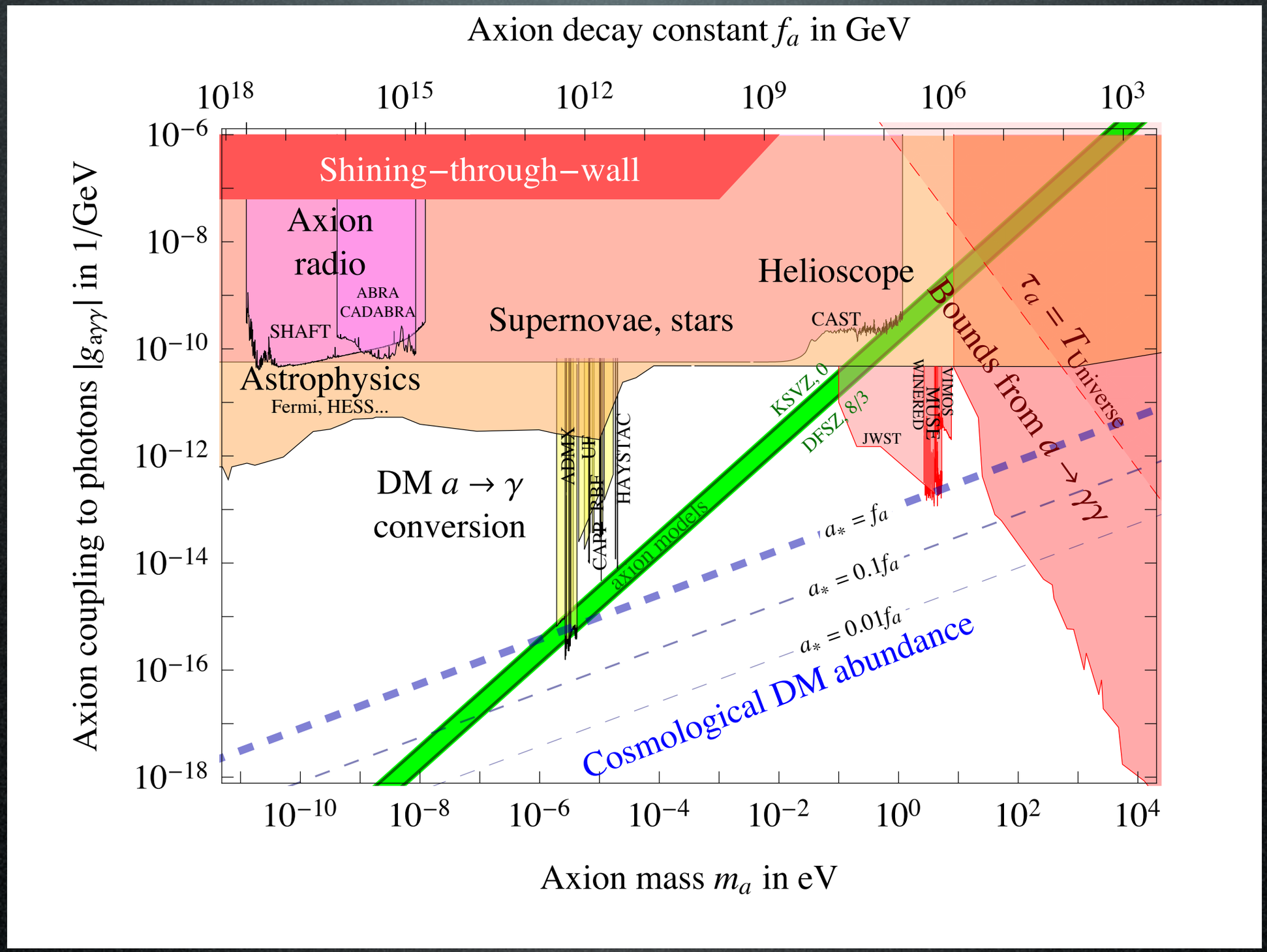
Perhaps because θ is dynamical (a field)

and driven to (almost) zero by its potential (symmetrical under $\mathrm{U(1)_{PQ}}$).

In this case $m_a \approx 0.6\,\text{meV} \dfrac{10^{10}\ \text{GeV}}{f_a}$

Axions

Searches:



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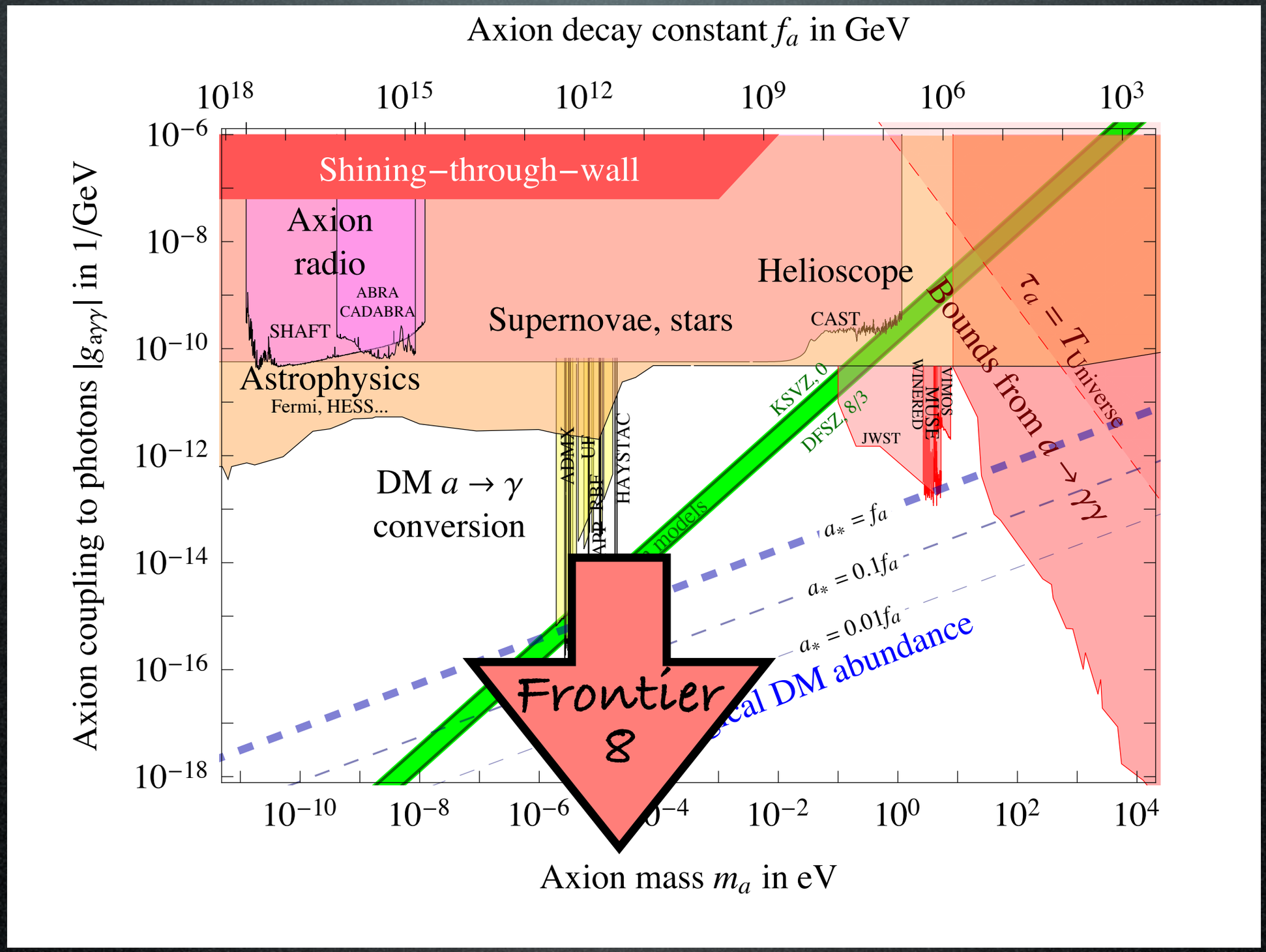

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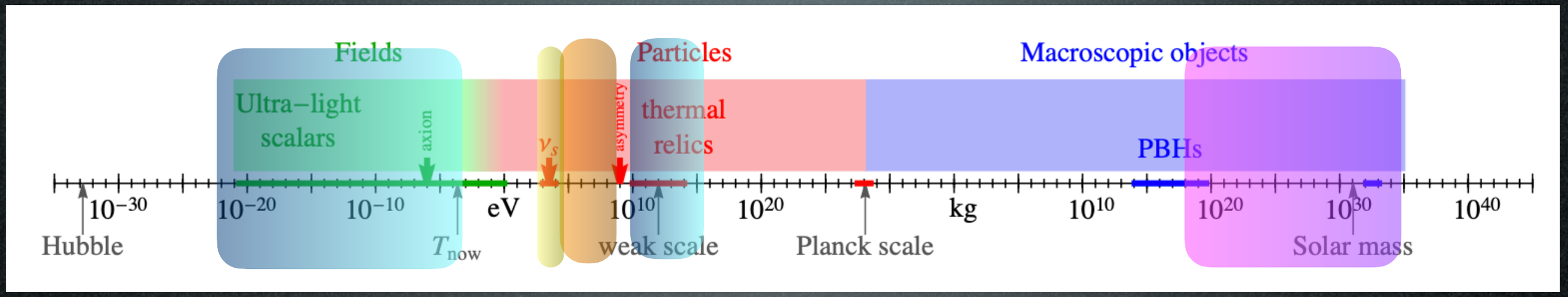
Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

Thermal DM?
Sub-GeV DM?
PBH DM?
KeV DM?
Ultralight DM?

Conclusions

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in an experiment driven phase

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but actually too many...

Thermal DM?	still motivated, frontier is heavy DM
Sub-GeV DM?	why not? Challenging detection
PBH DM?	old idea with new vibes
KeV DM?	phenomenological
Ultralight DM?	old idea with new vibes

Conclusions

The physics of Dark Matter is
in an experiment driven phase

Theory can (does) point to prefe ctions,
but ac to many...

Frontier 4

Frontier 6

Frontier 3

Frontier 2

Frontier 7

Frontier 1

Frontier 8

Frontier 5

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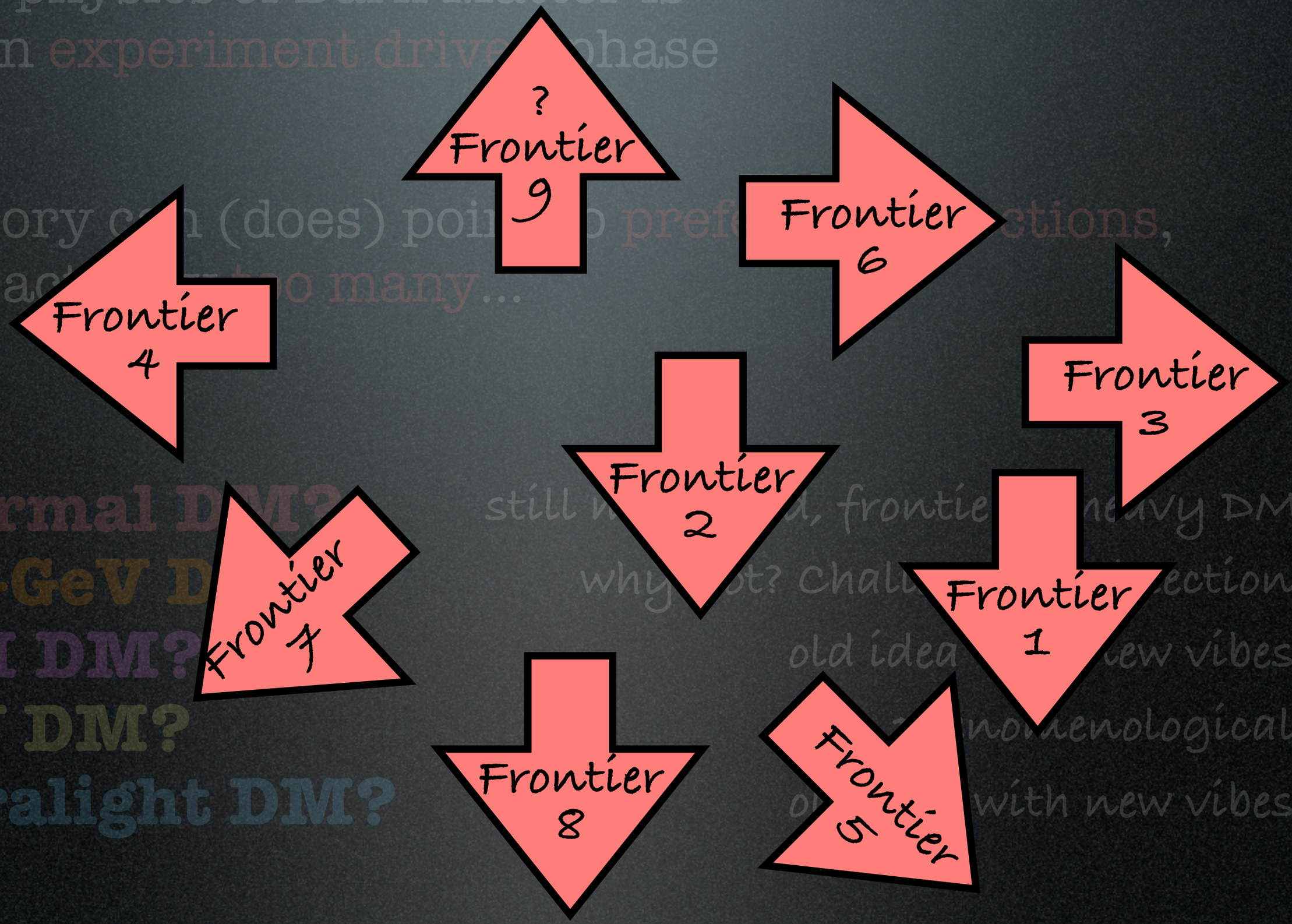
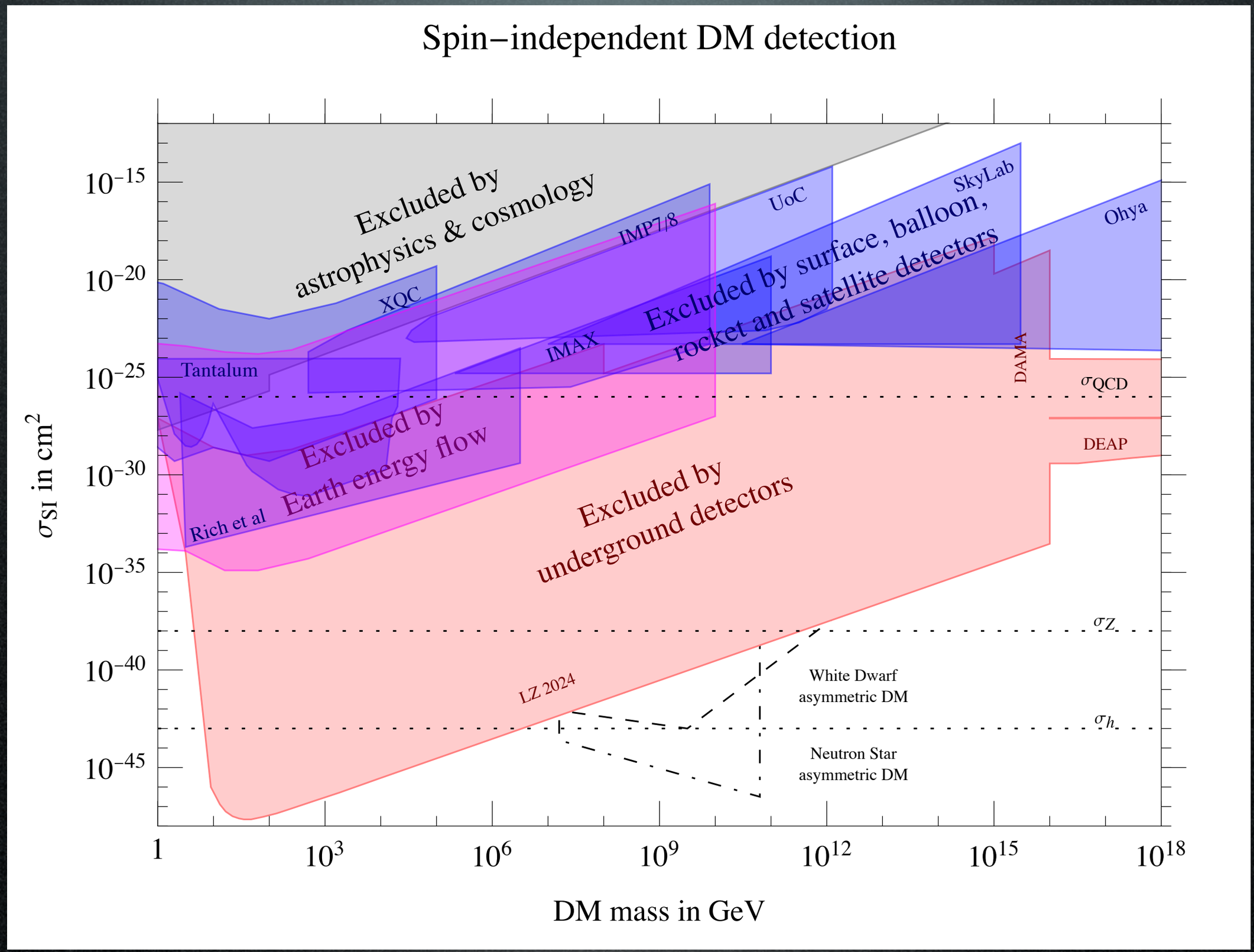


DD of strongly int DM



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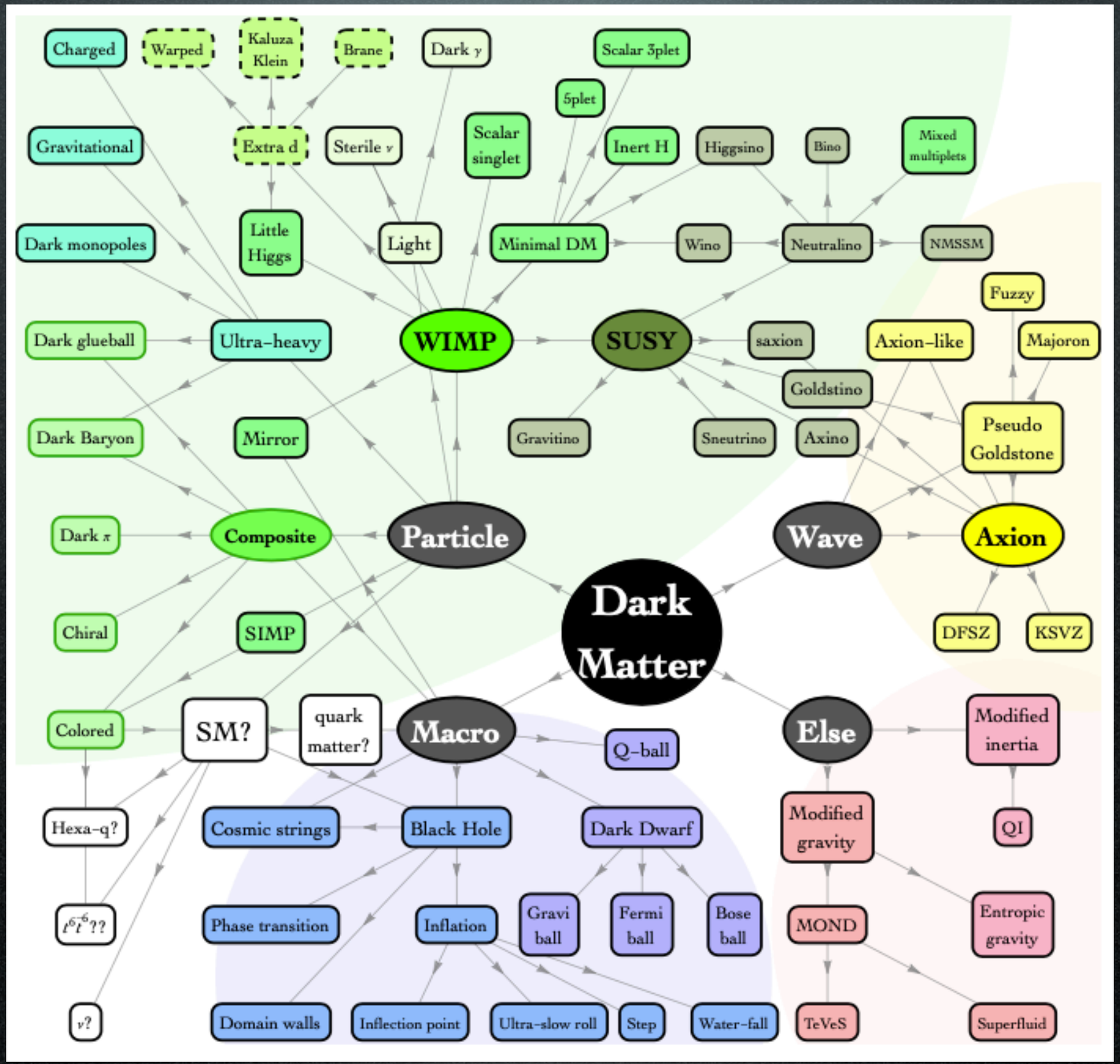
A map of DM candidates



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