16 June 2025
Dark Tools workshop, Torino

General Review about DM:
evidences, candidates, searches

Marco Cirelli
(CNRS LPTHE Jussieu Paris)

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

cnrs dépasser les frontières

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CRÉATEURS DE FUTURS DEPUIS 1257

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Executive summary

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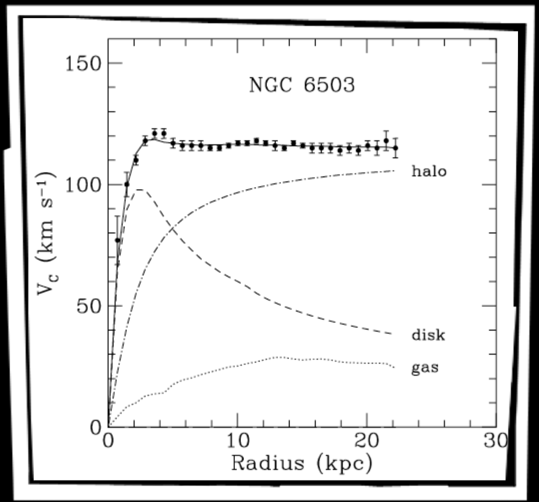
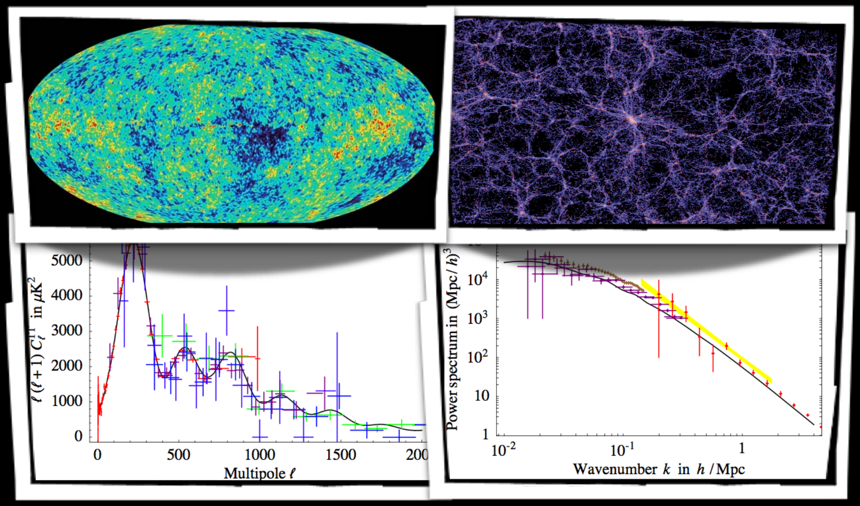


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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- it's a new, unknown particle

no SM particle can fulfill

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

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

$$\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$$

(notice error!)

Planck 2015, 1502.01589 (tab.4)

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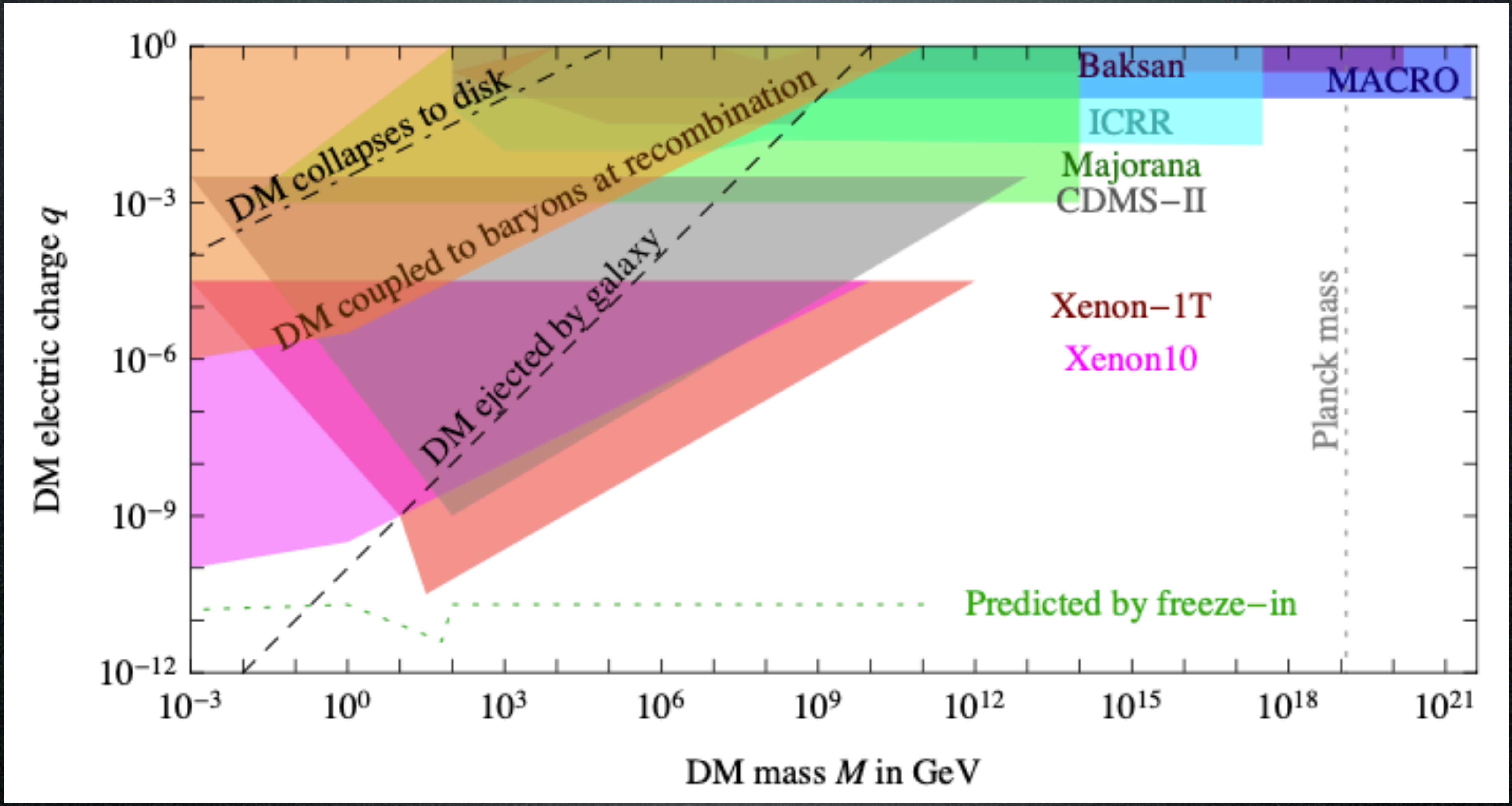
Charged DM limits



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

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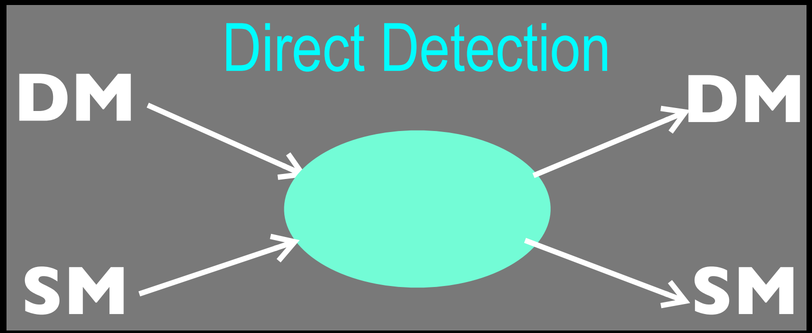

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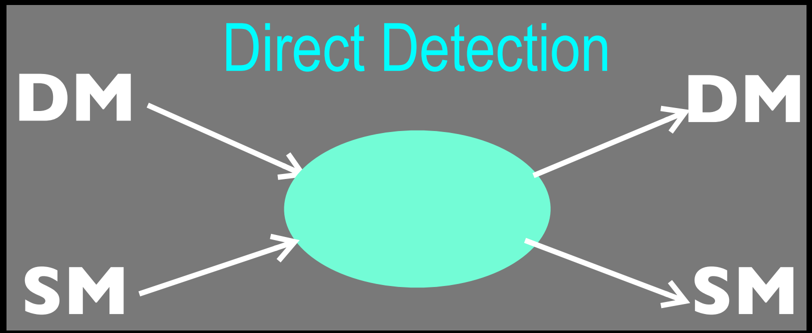

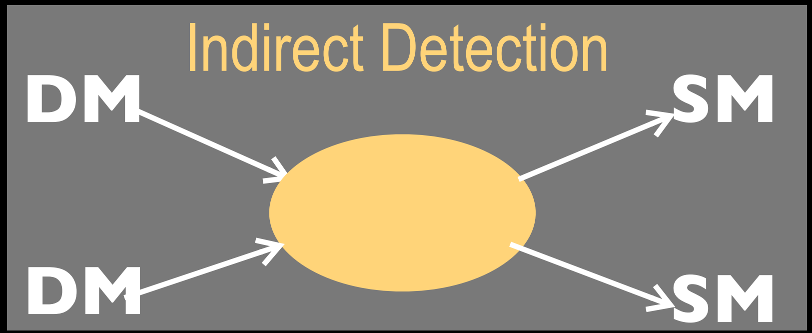

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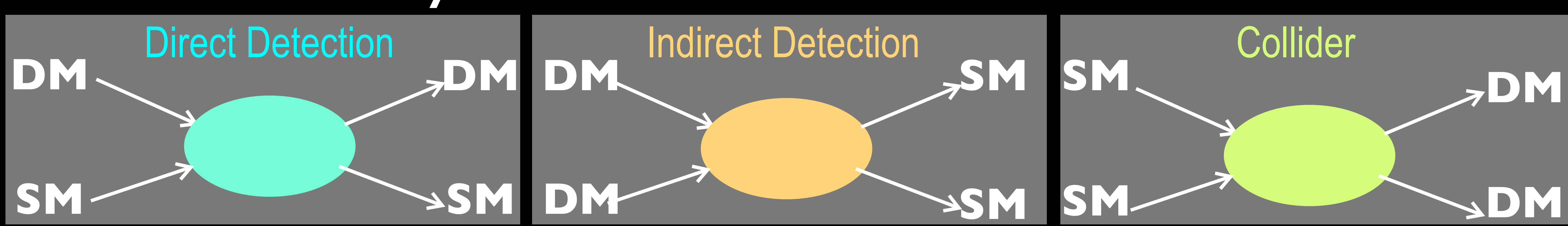

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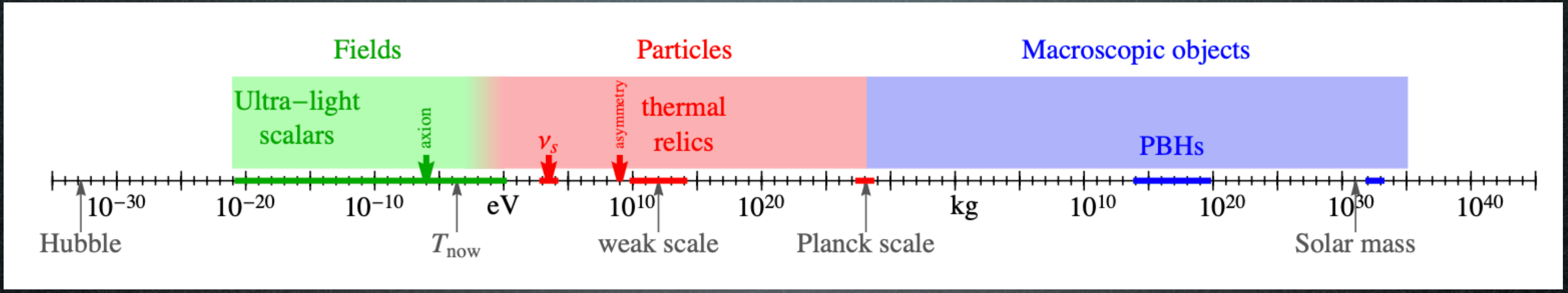
Mass??

Charge??
Interactions??

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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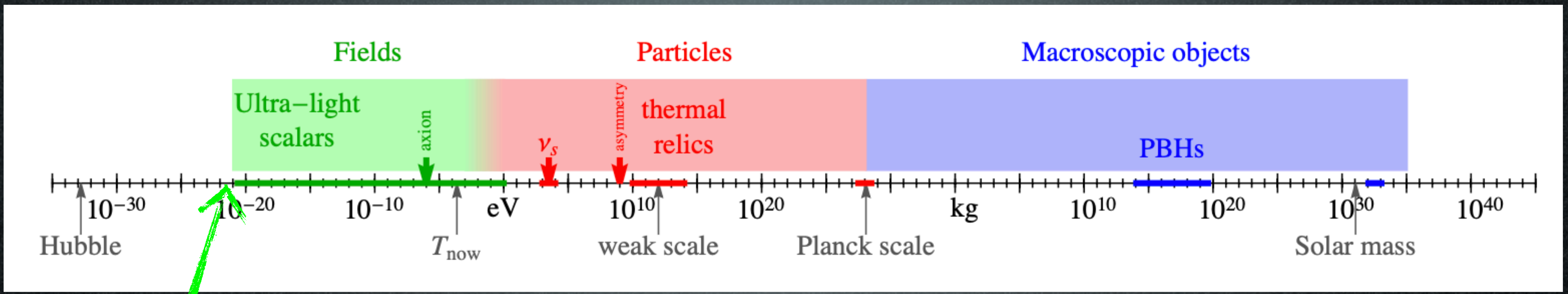

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as diffuse as a dwarf galaxy

DM de Broglie wavelength

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

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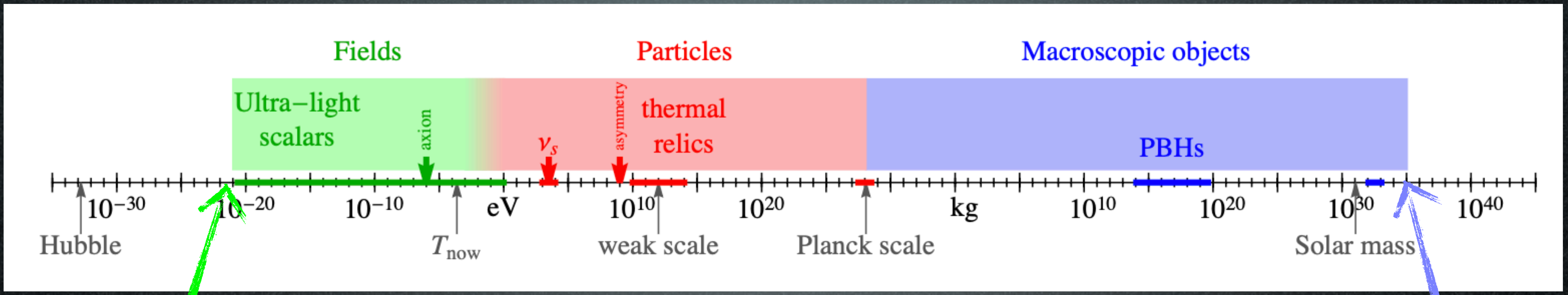

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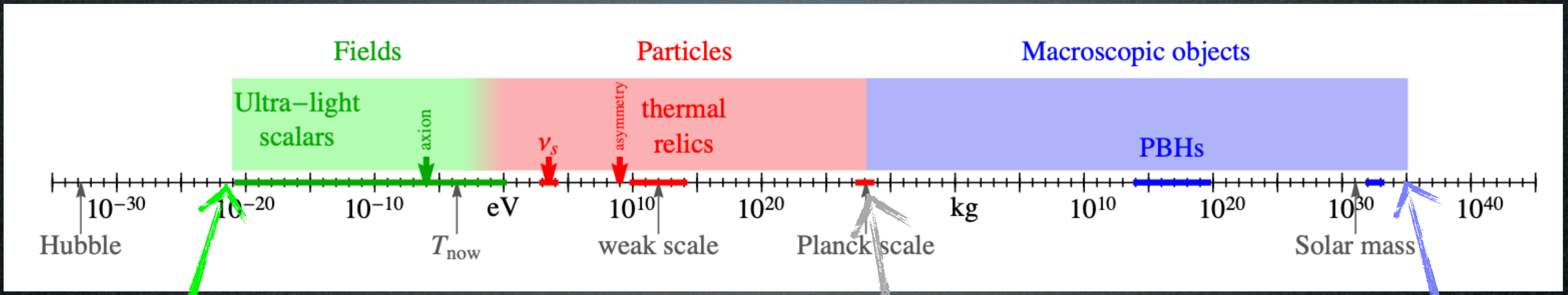

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most likely elementary | most likely composite

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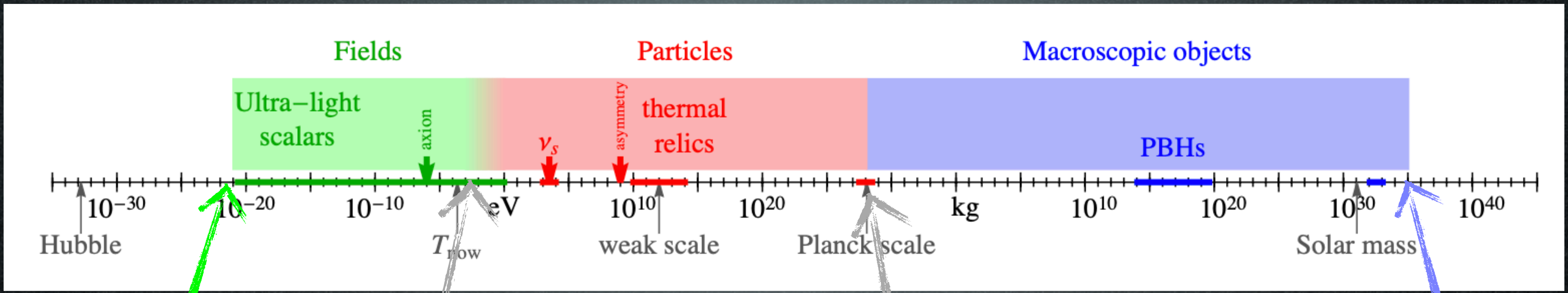

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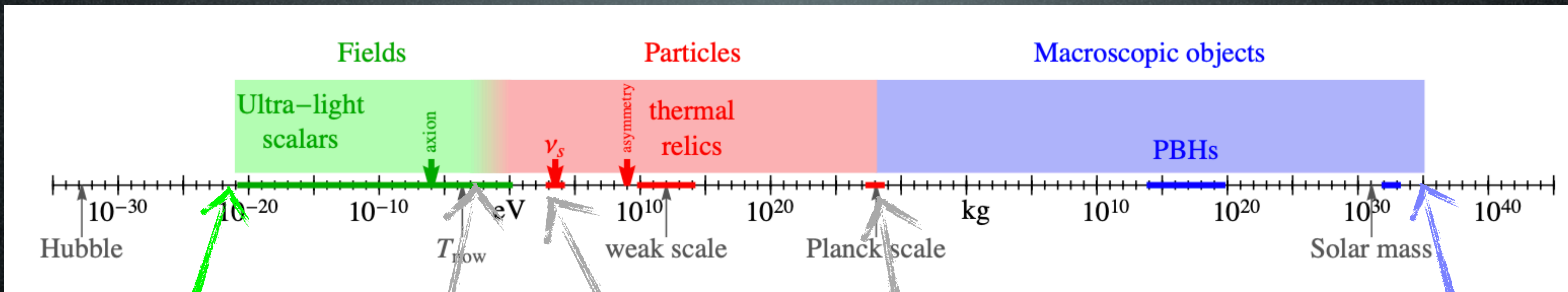

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occupation number

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

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$M \lesssim 0.1\,\mathrm{keV}$ necessarily *bosonic* | $M \gtrsim 0.1\,\mathrm{keV}$ *bosonic* or *fermionic*

Candidates

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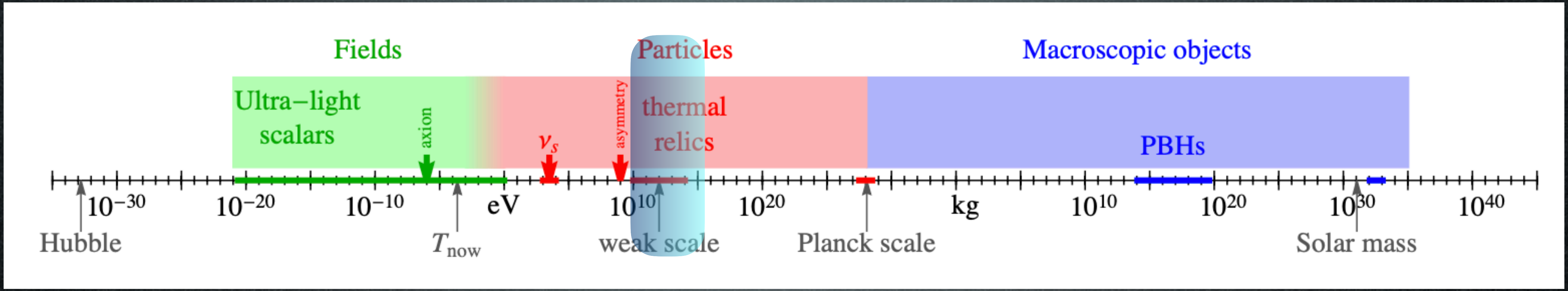


Candidates

WIMPs

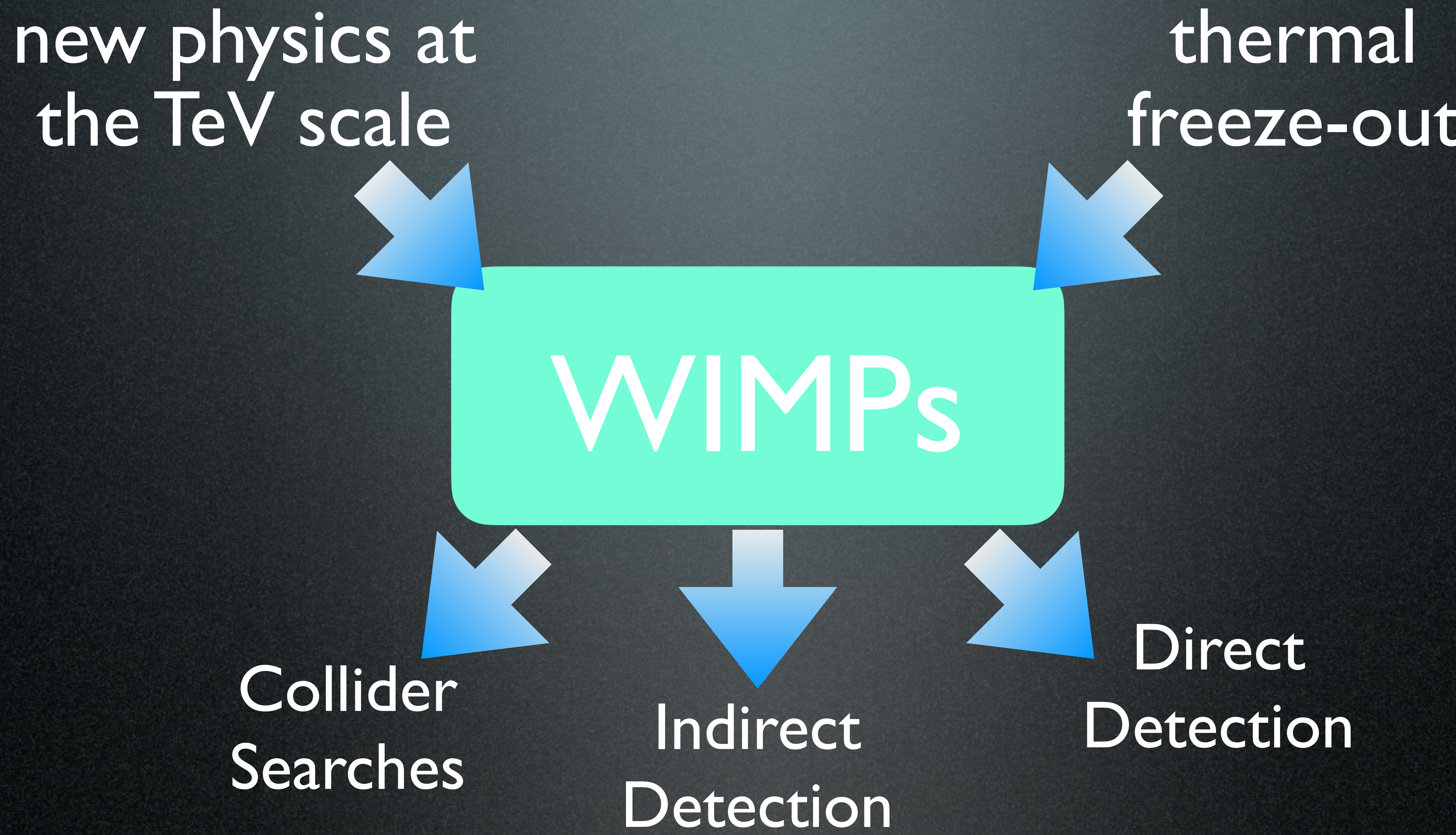
Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

Candidates


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

DM as a thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

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

Relic $\Omega_{\rm DM} \simeq 0.26$ for

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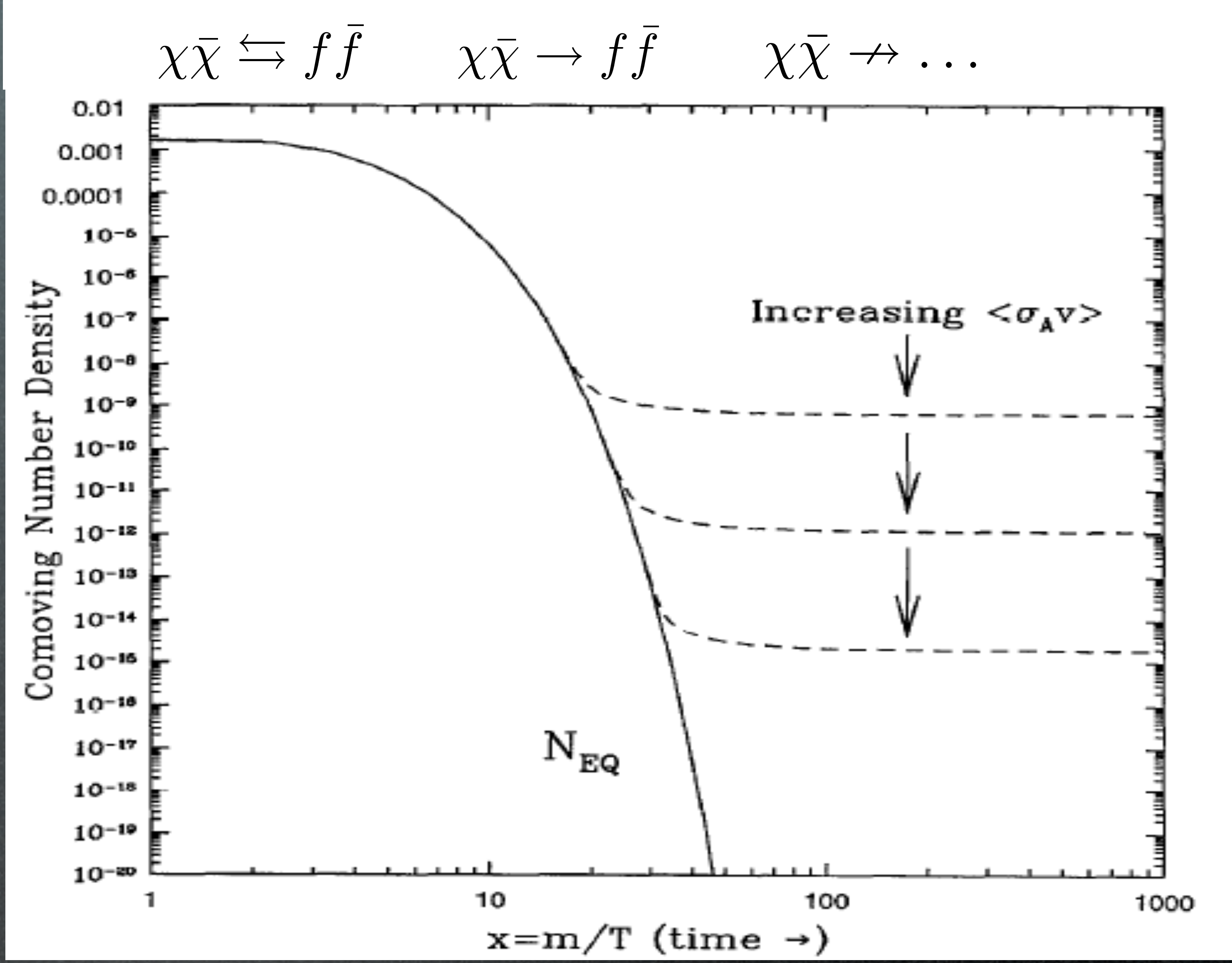

Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

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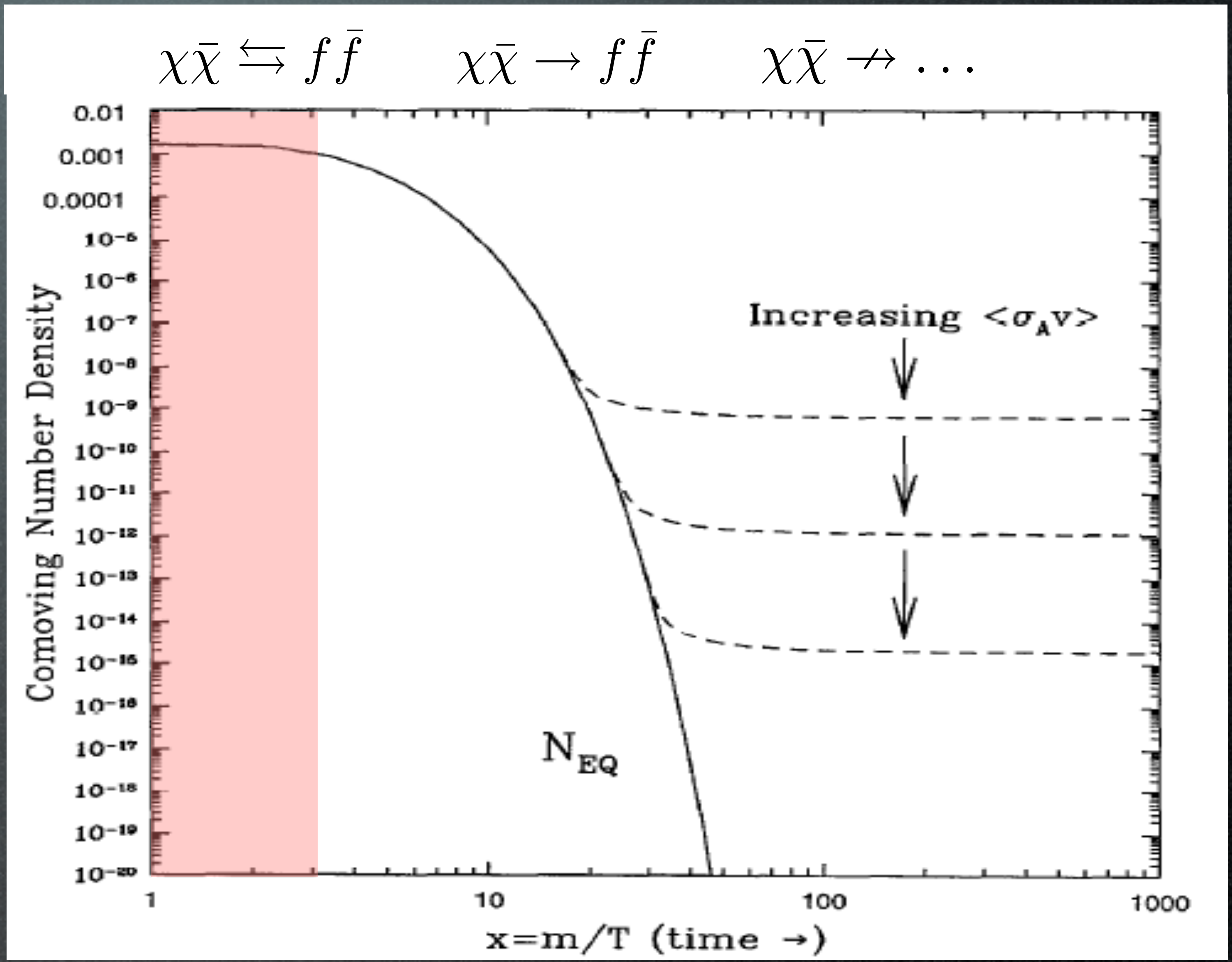

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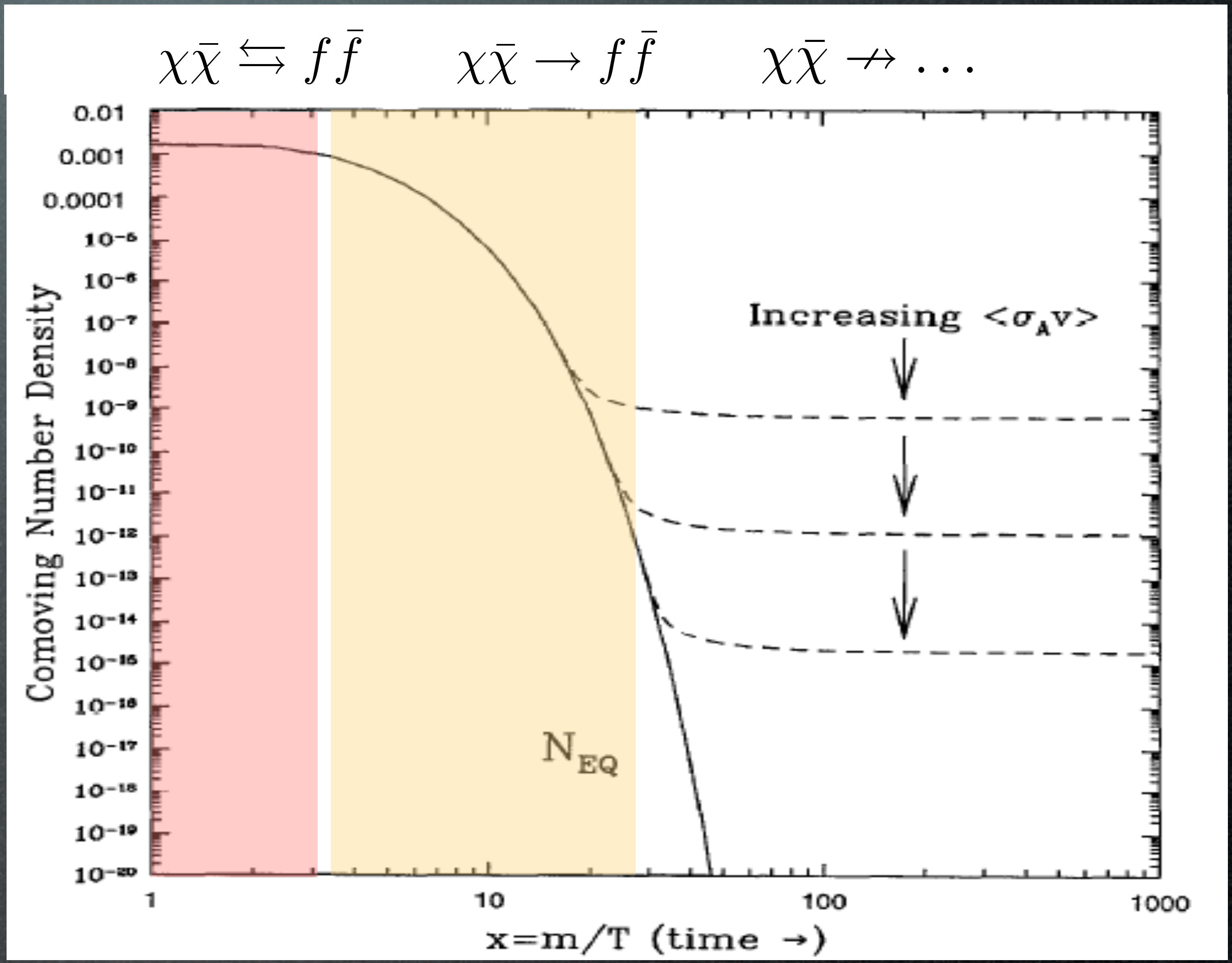

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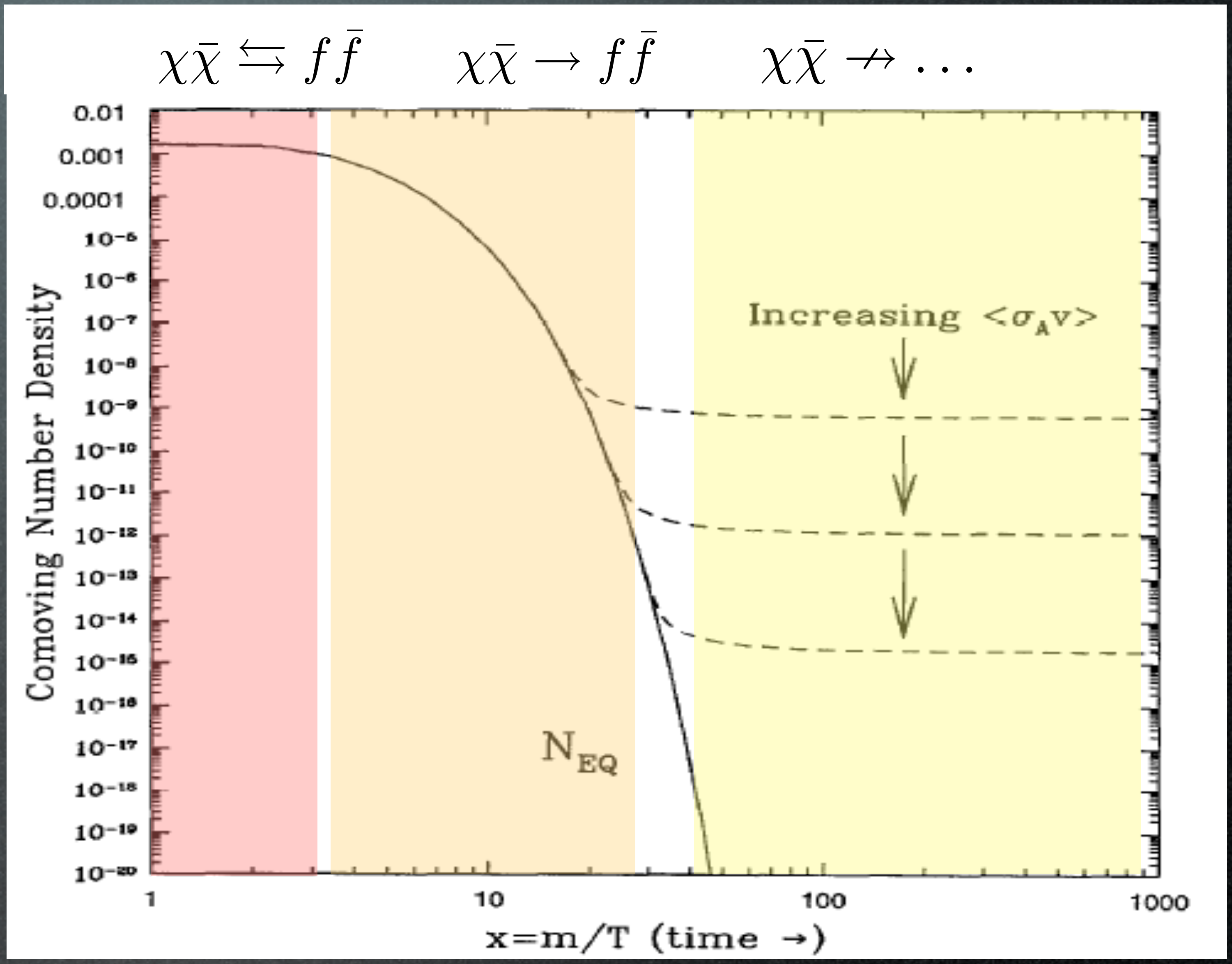

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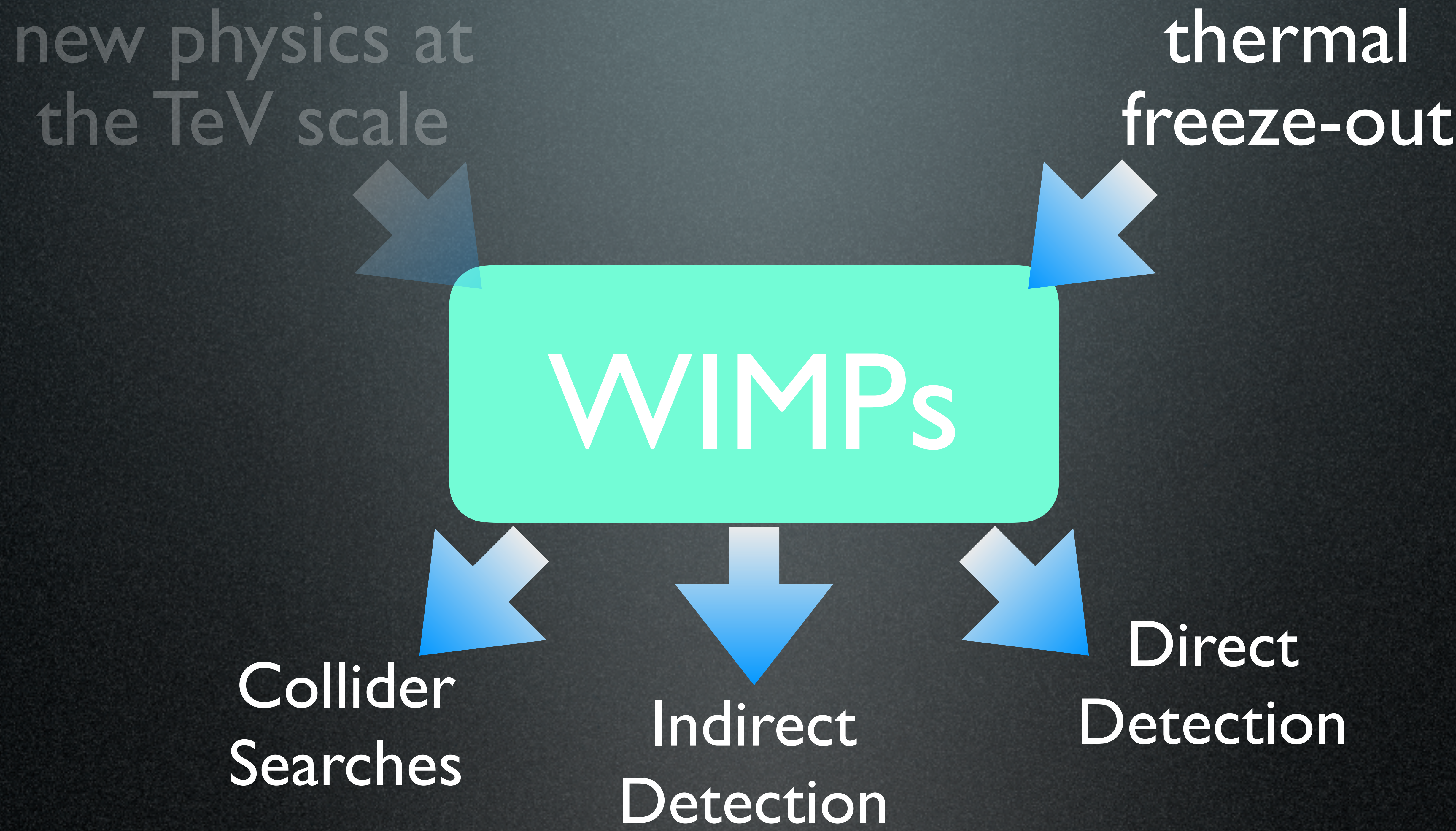
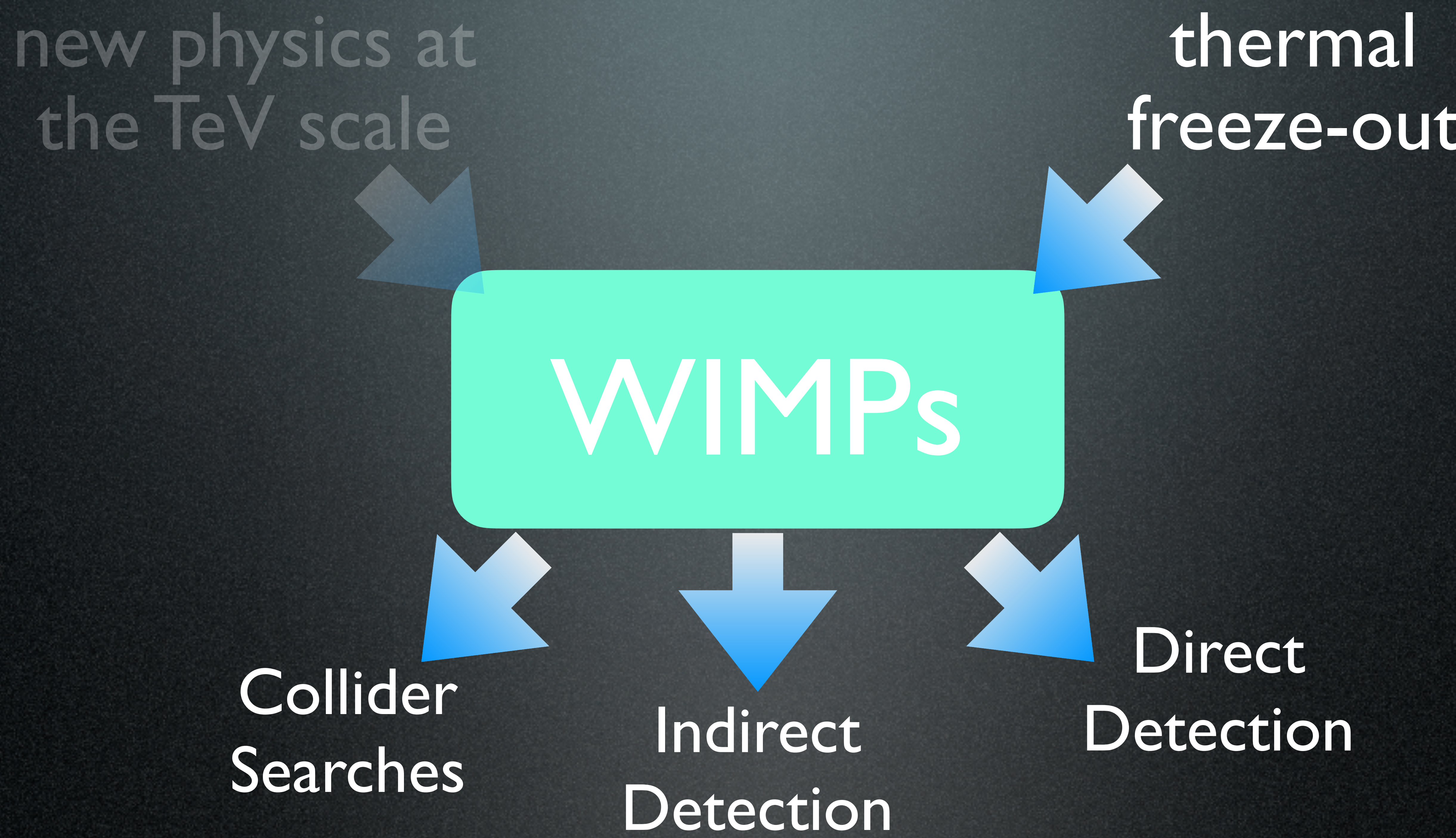

new physics at the TeV scale
thermal freeze-out
WIMPs
Collider Searches
Indirect Detection
Direct Detection

Candidates



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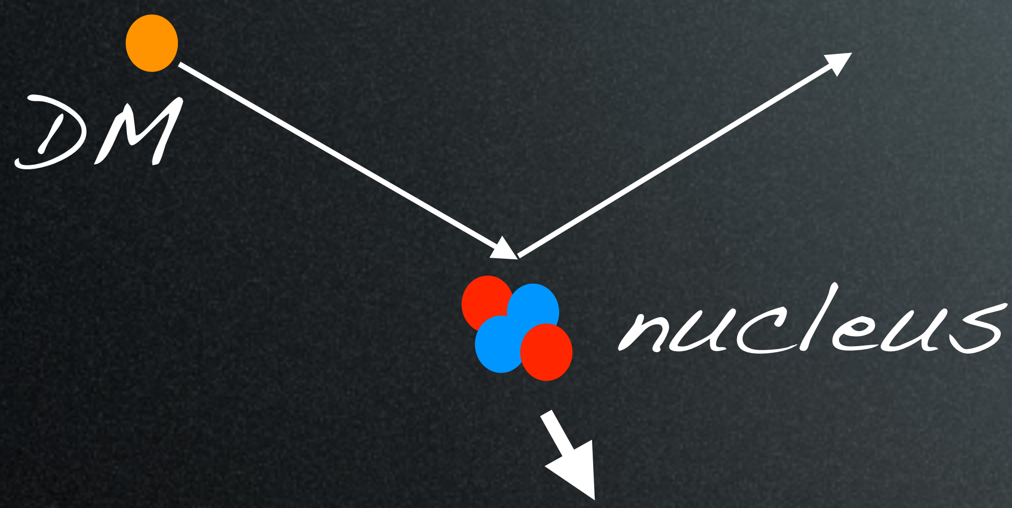
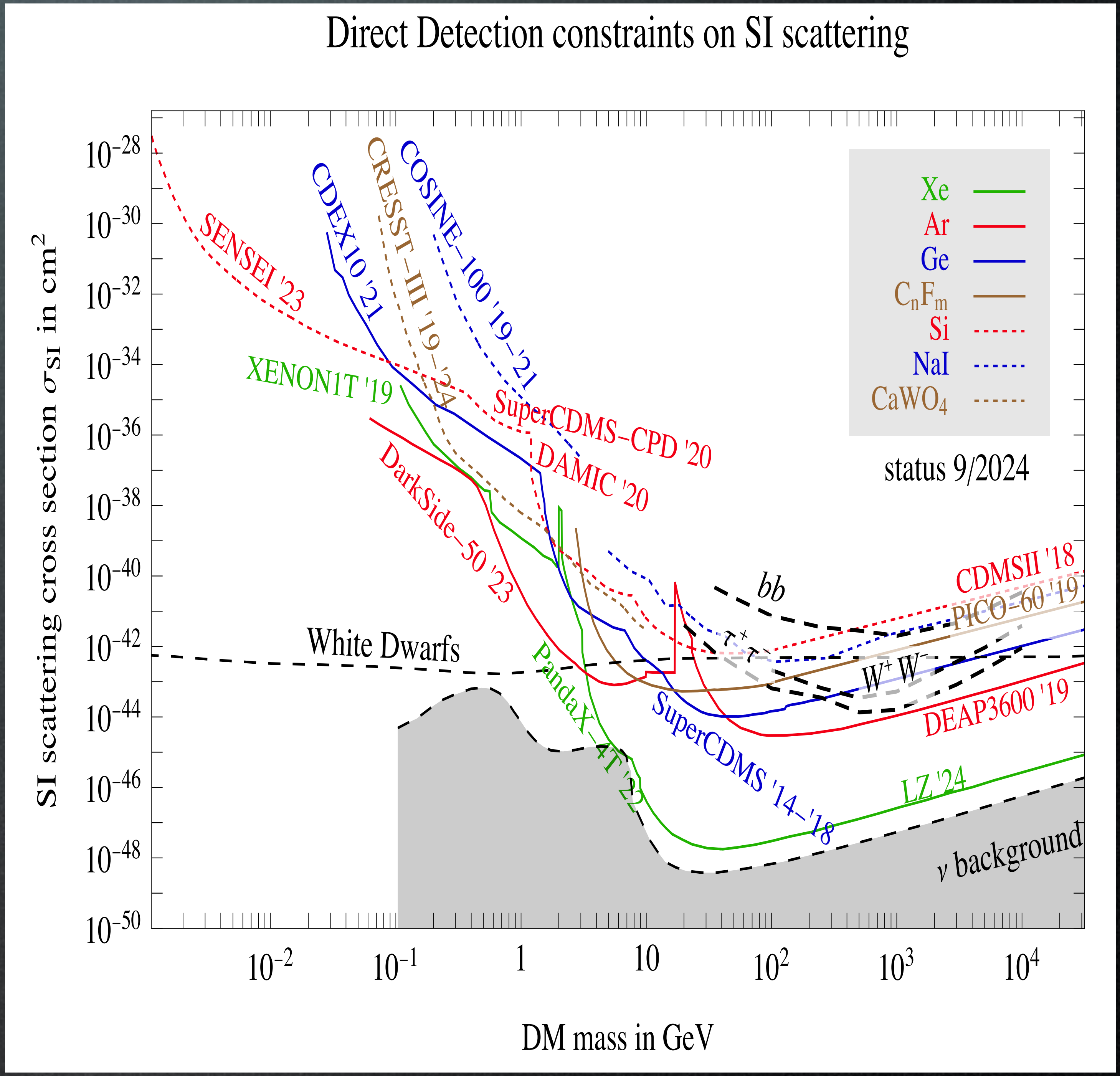
WIMP Direct Detection

SM weak scale SI interactions





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

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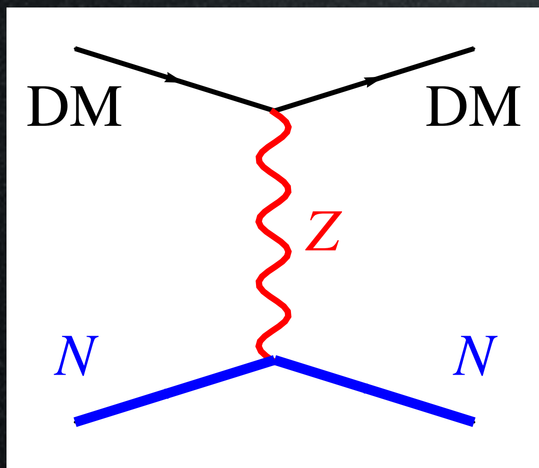
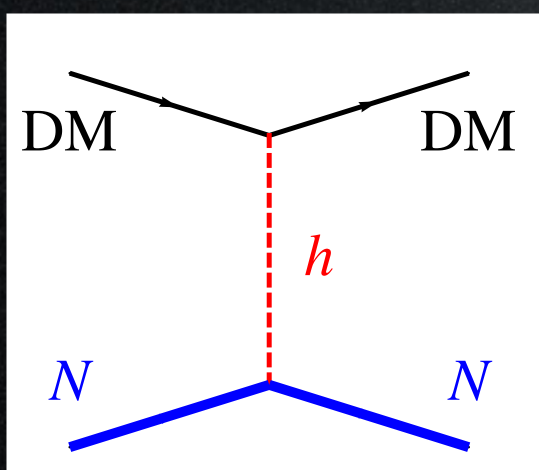
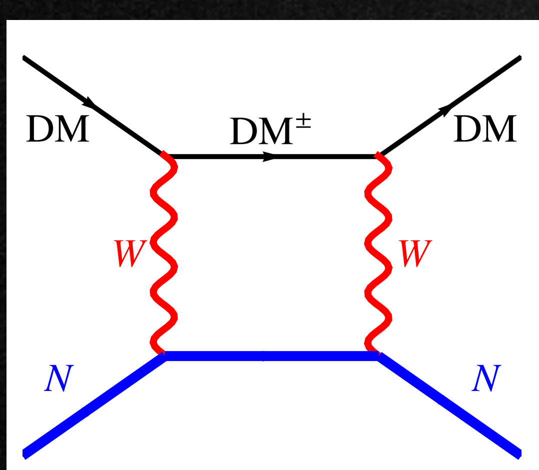


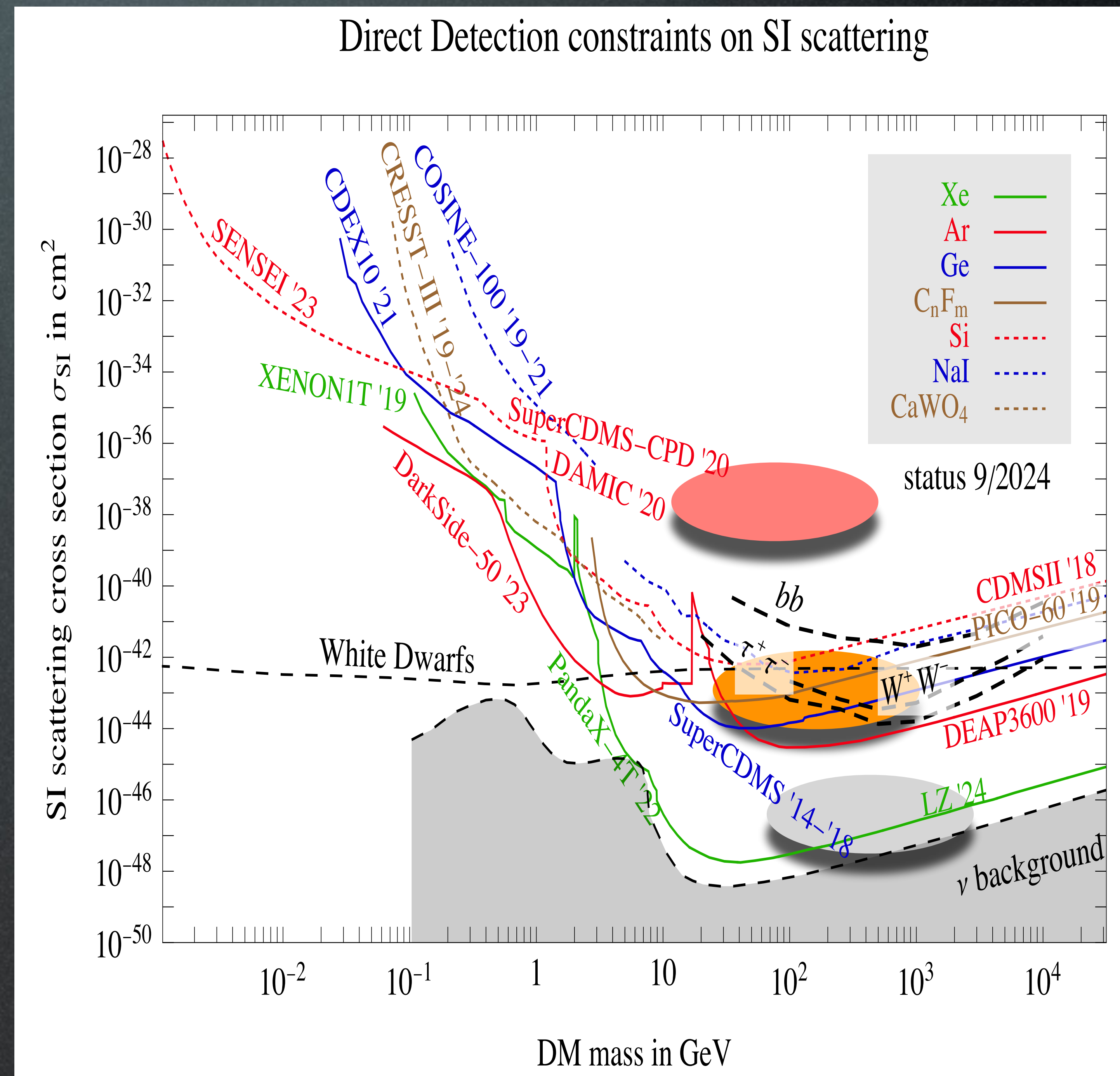
tree level, vector



tree level, scalar



one loop



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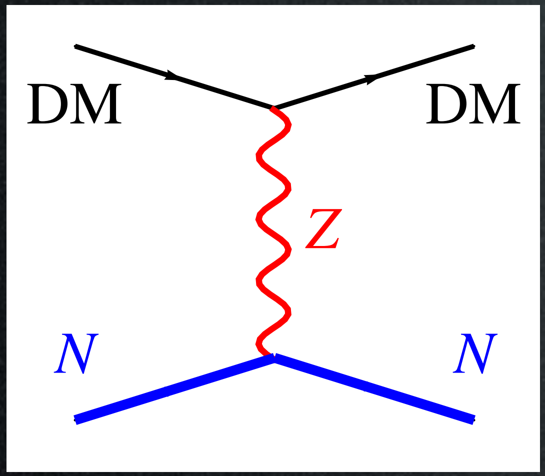

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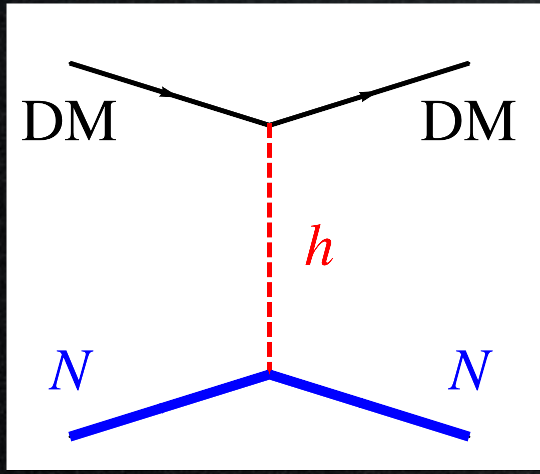

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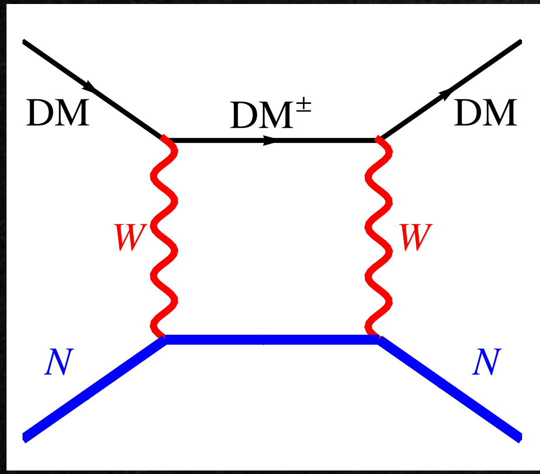

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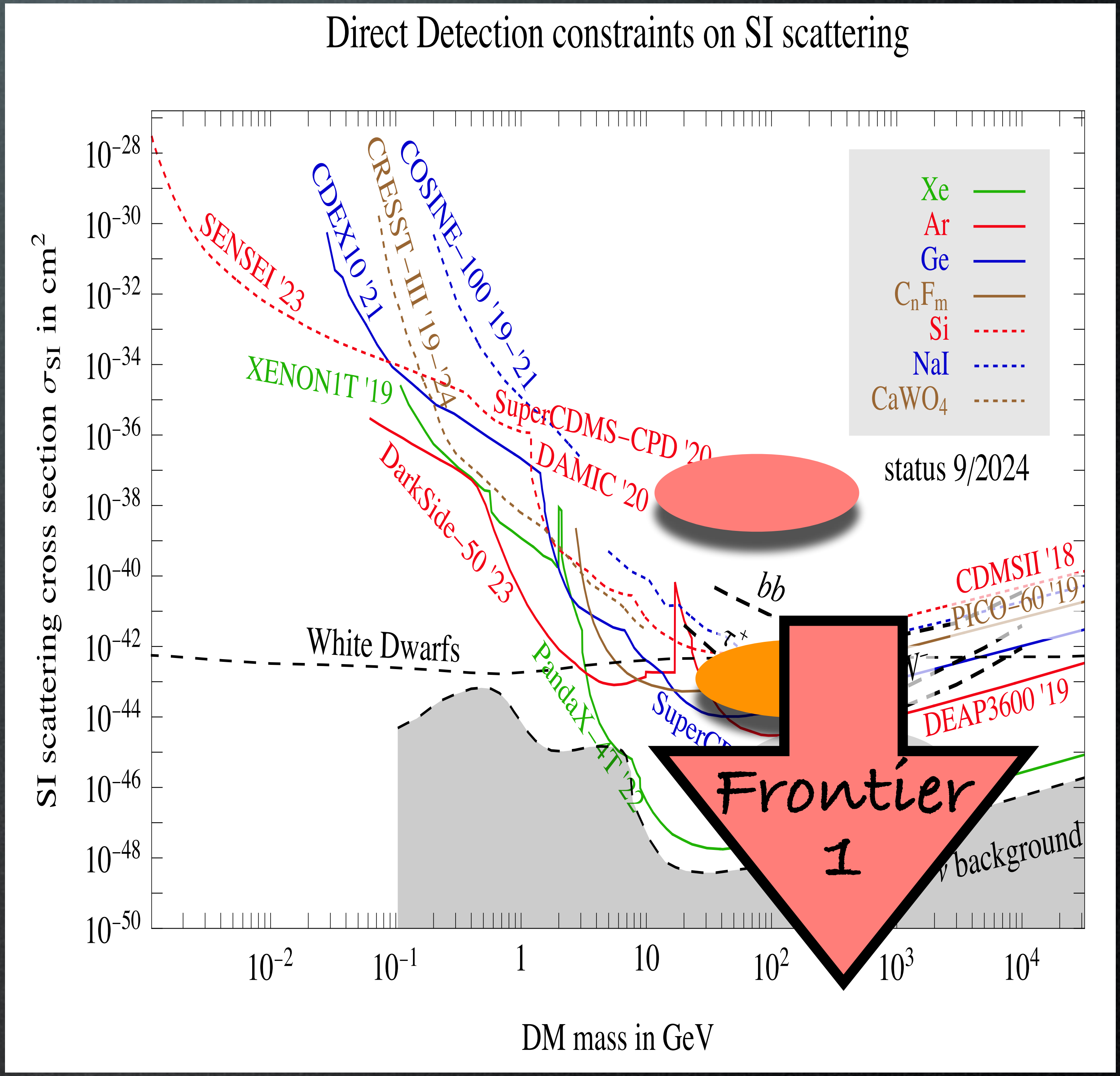

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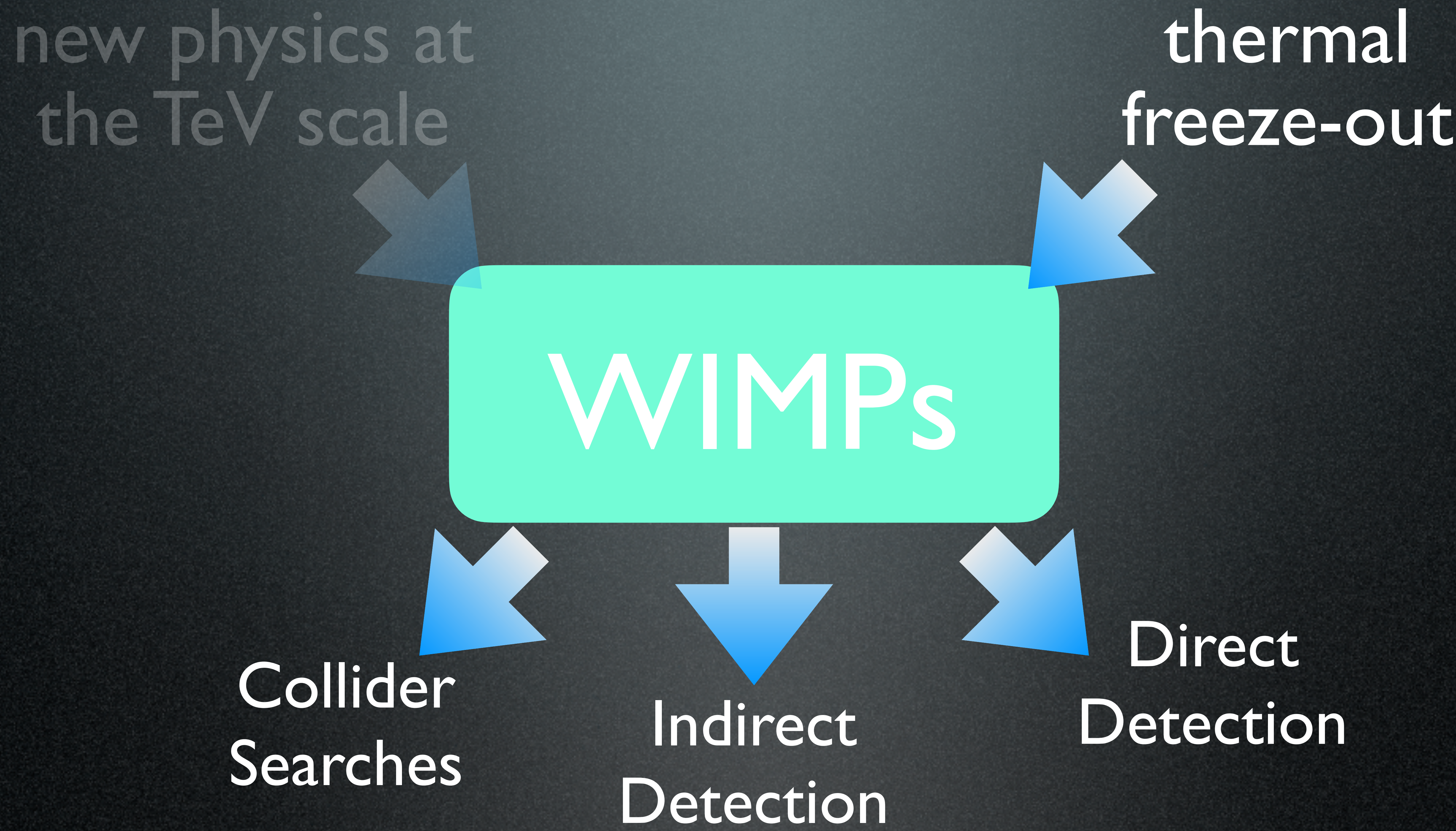

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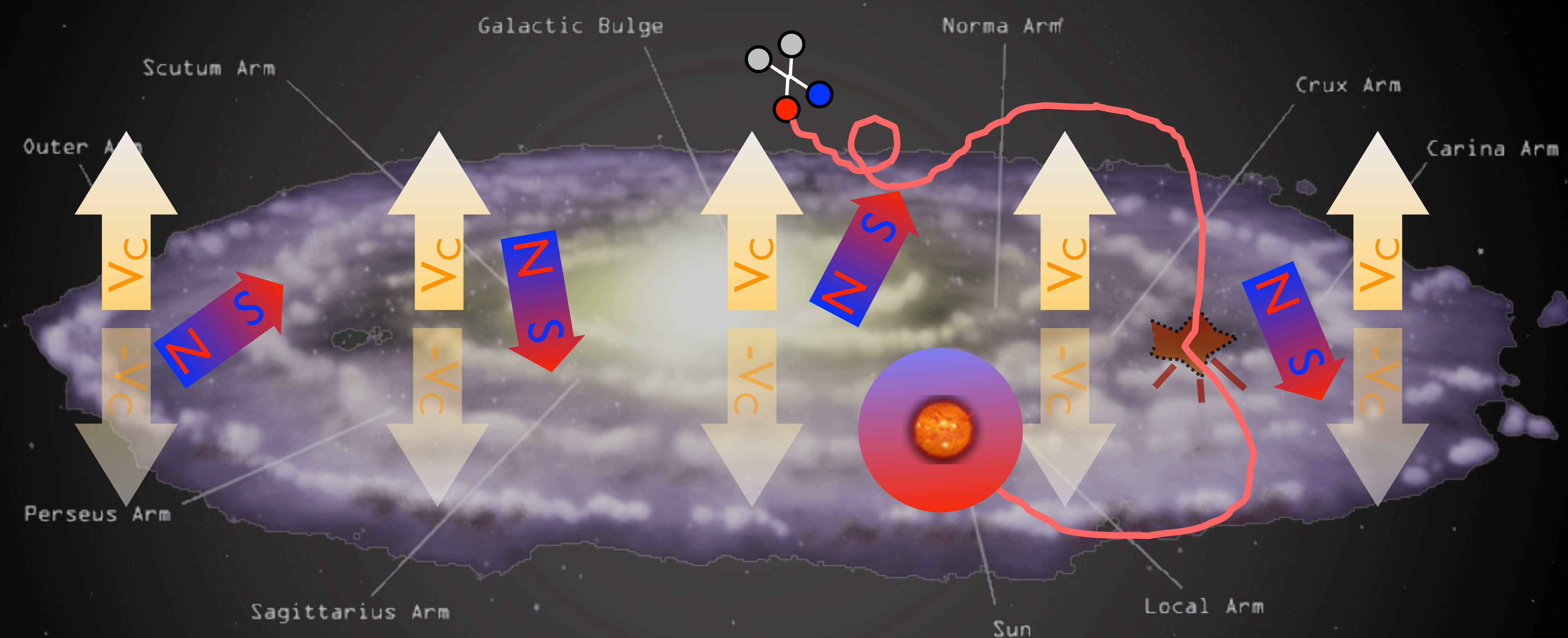
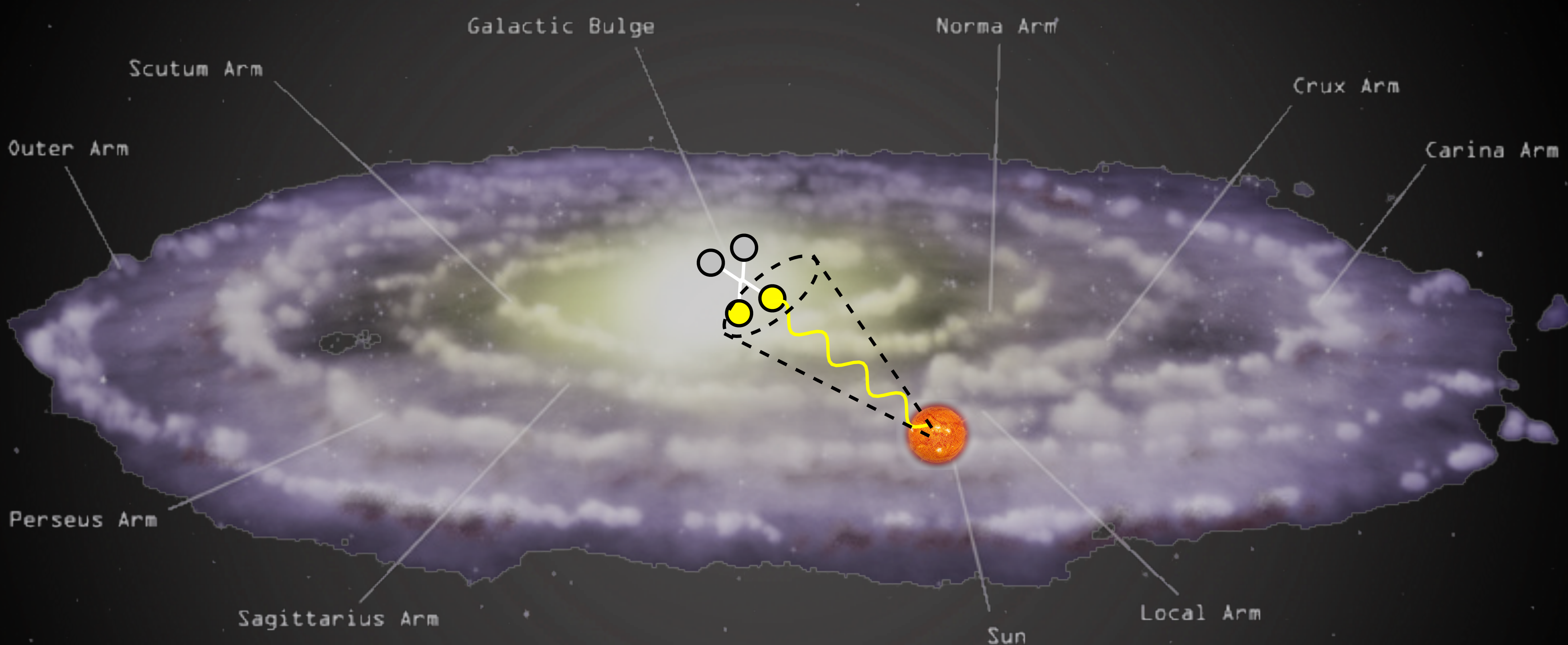
Indirect Detection: charged CRs

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

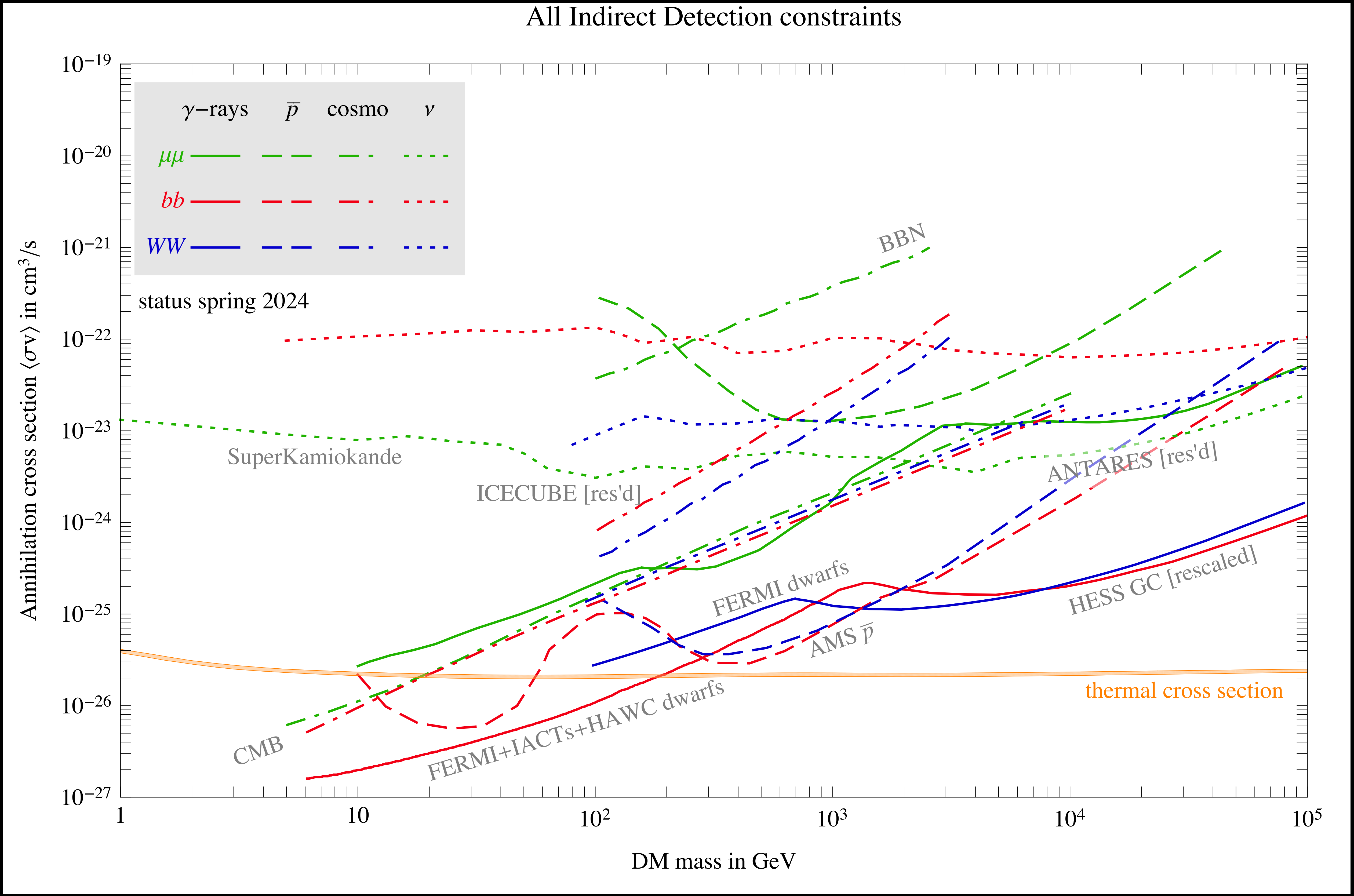


Indirect Detection: photons

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



WIMP Indirect Detection



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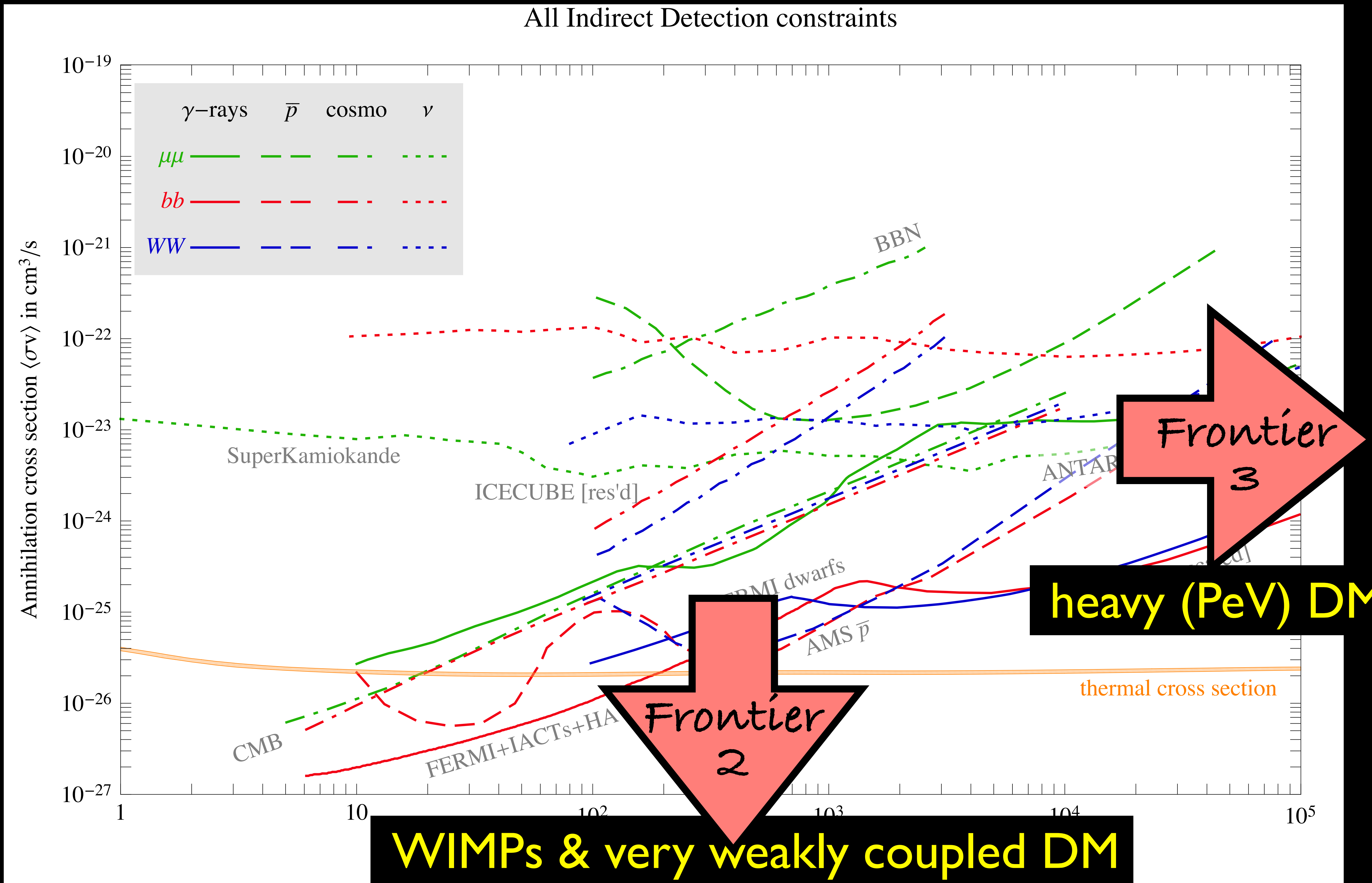

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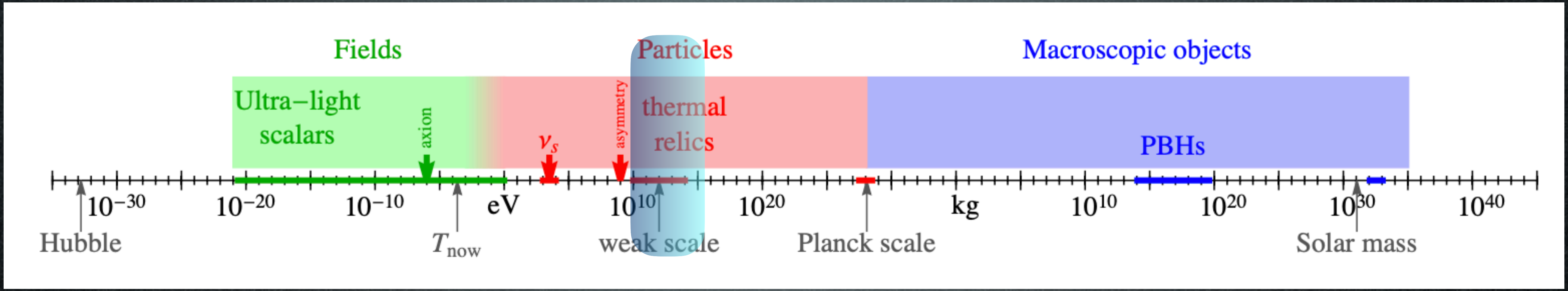
A matter of perspective: plausible mass ranges



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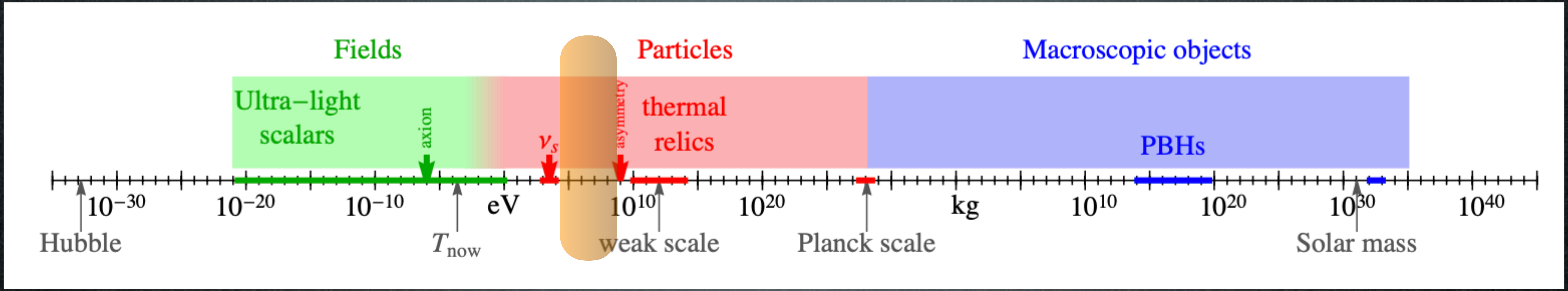
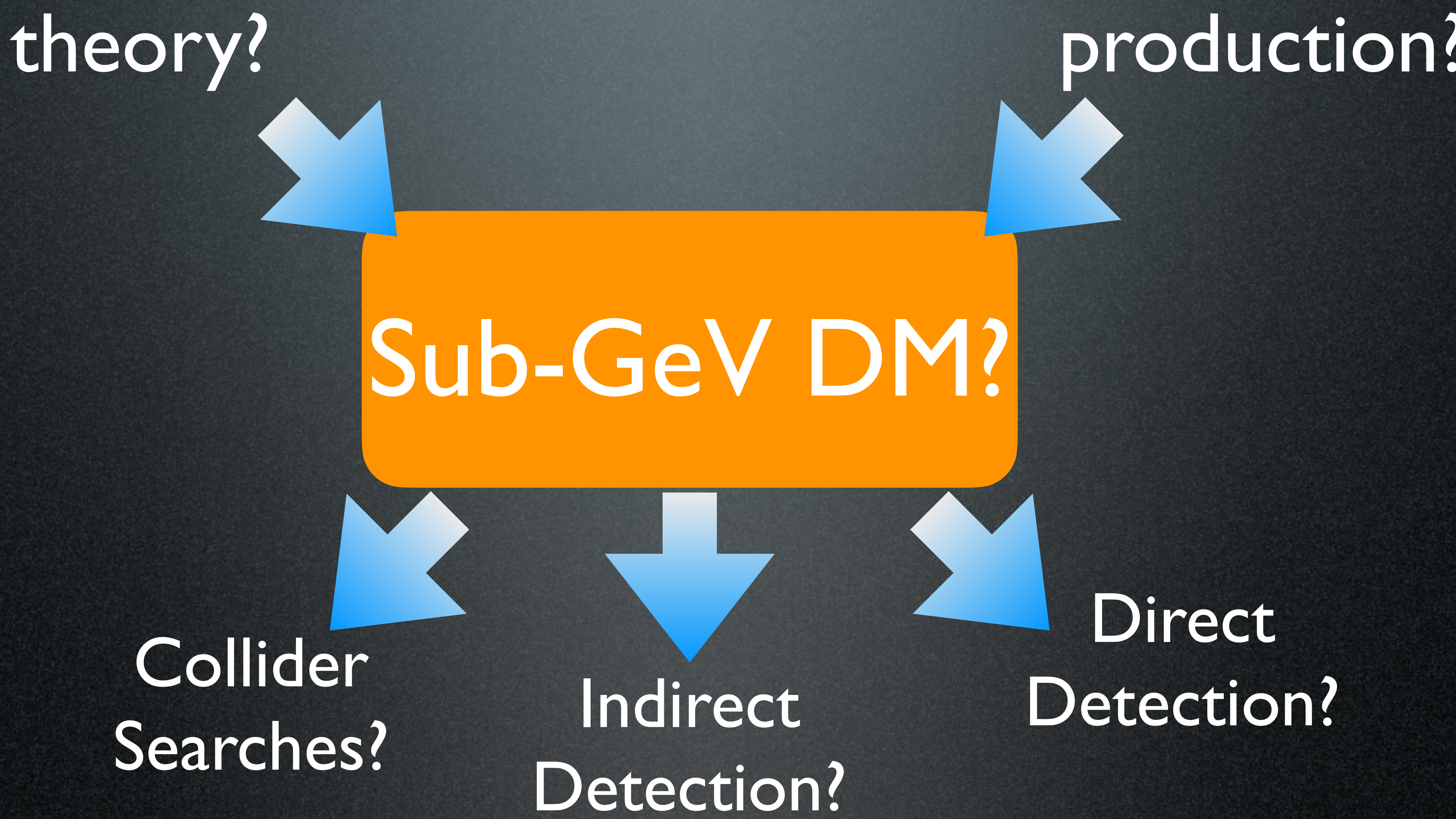


Sub-GeV DM?

Candidates


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

Theory

Sub-GeV DM

- 'MeV (scalar) DM'

Boehm & Fayet hep-ph/0305261

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

Theory

Sub-GeV DM

- WIMPless Dark Matter

  Feng & Kumar 0803.4196

  a.k.a. hidden sector DM

  $\sim$ secluded DM

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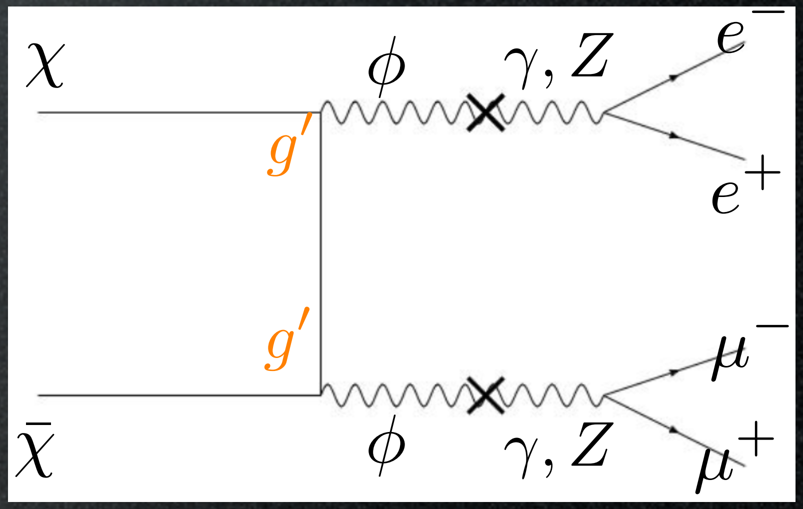
if g_x is small,
m 'naturally' small
(but nothing points to a precise value)



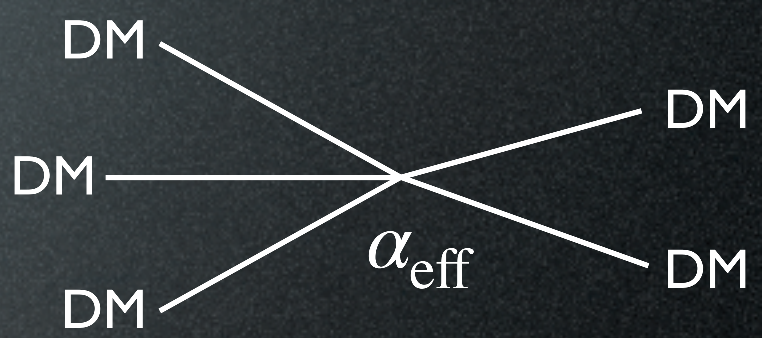
Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM

- 'SIMP miracle':

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



  points to

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

  Hochberg et al 1402.5143

  'naturally realized' in a dark-QCD-like setup

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

Theory

Sub-GeV DM?

- 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
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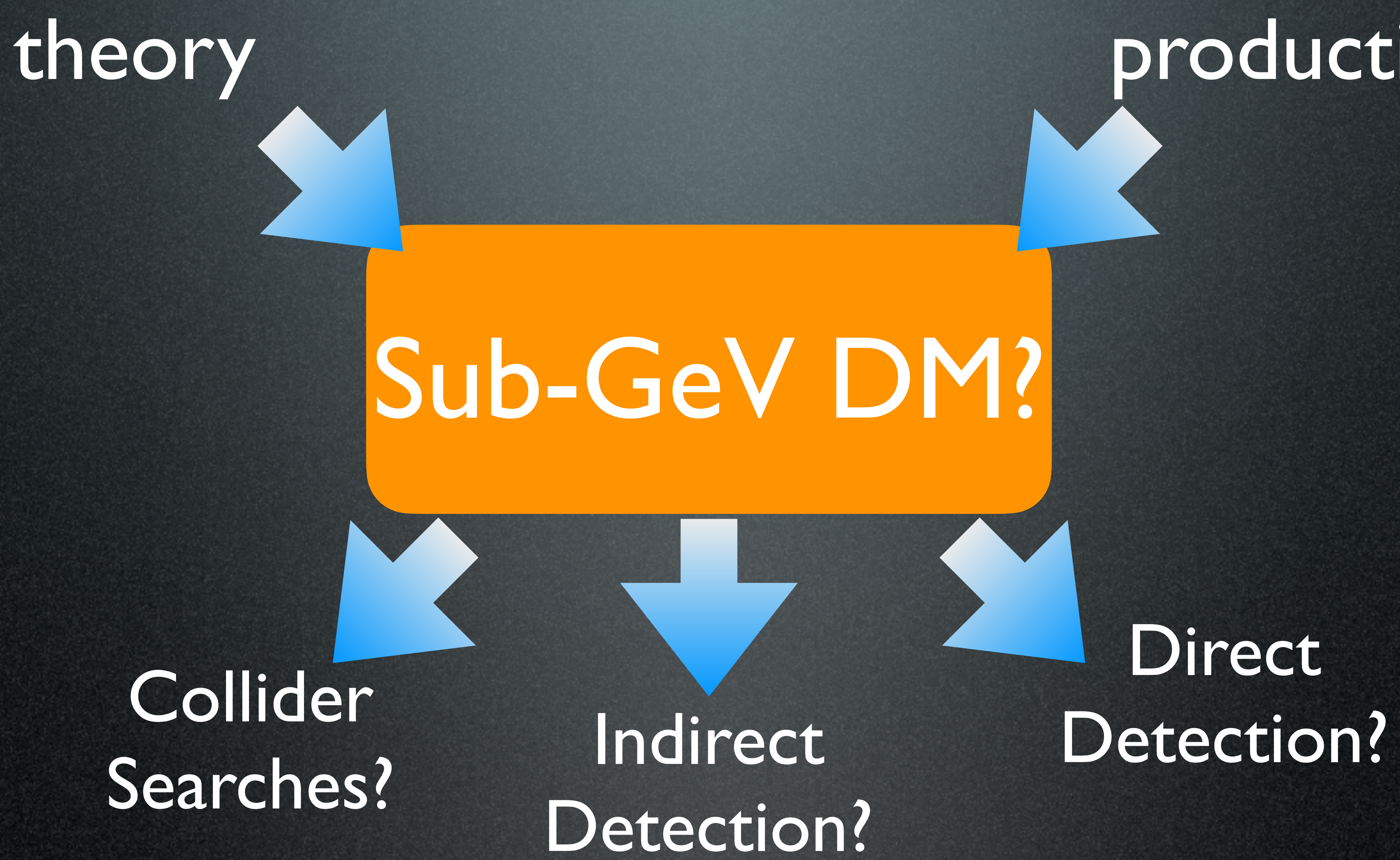
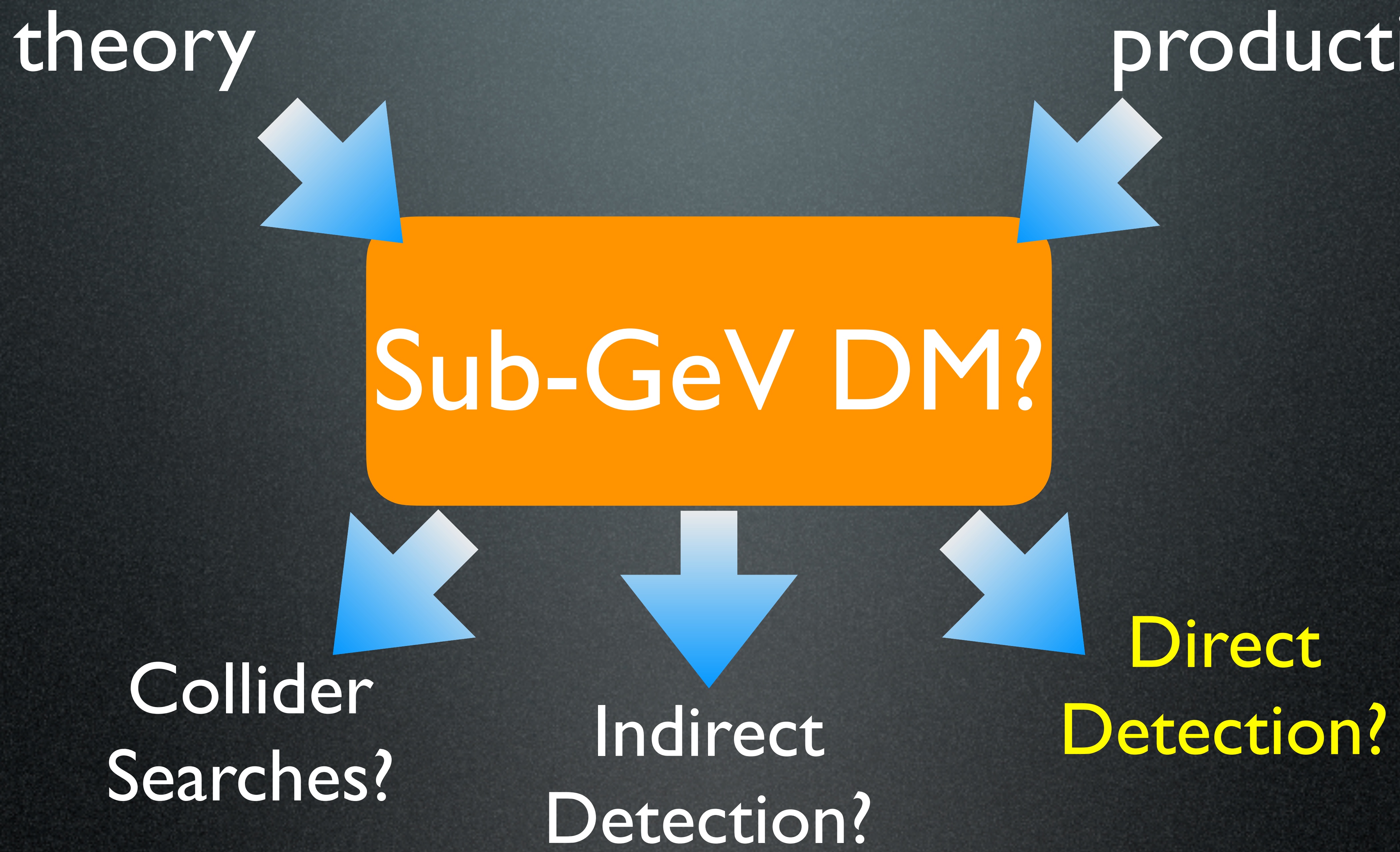
- ...

Candidates


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

Candidates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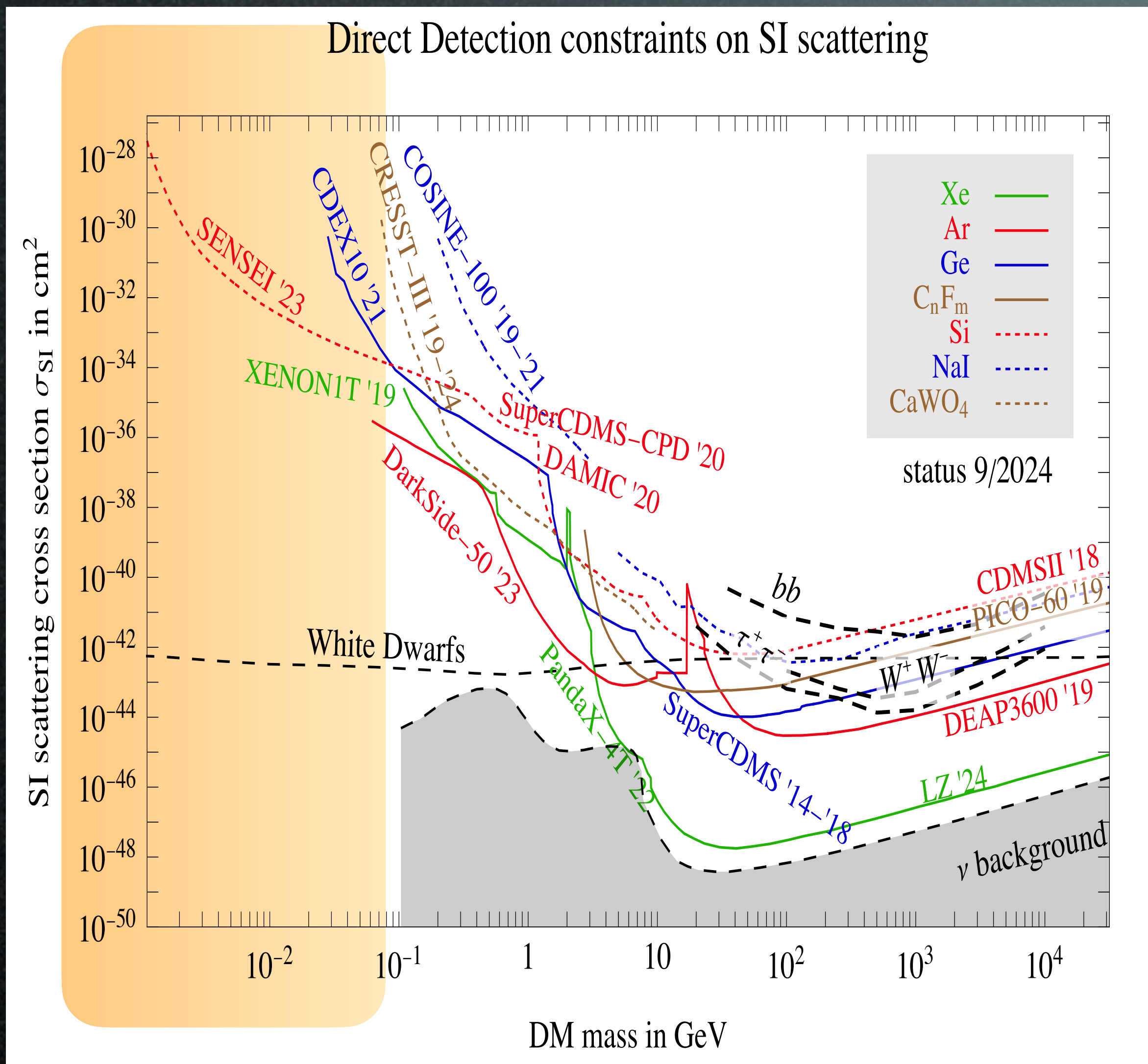
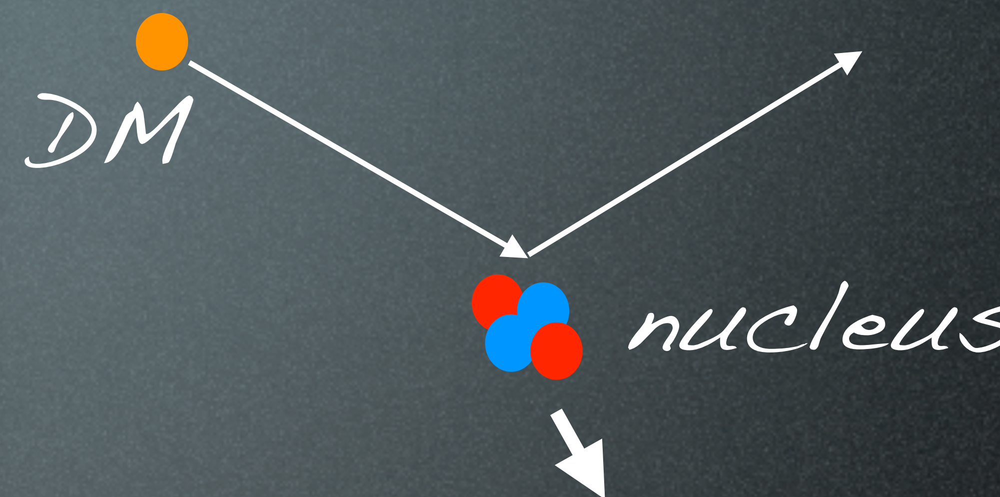
Direct Detection of sub-GeV DM



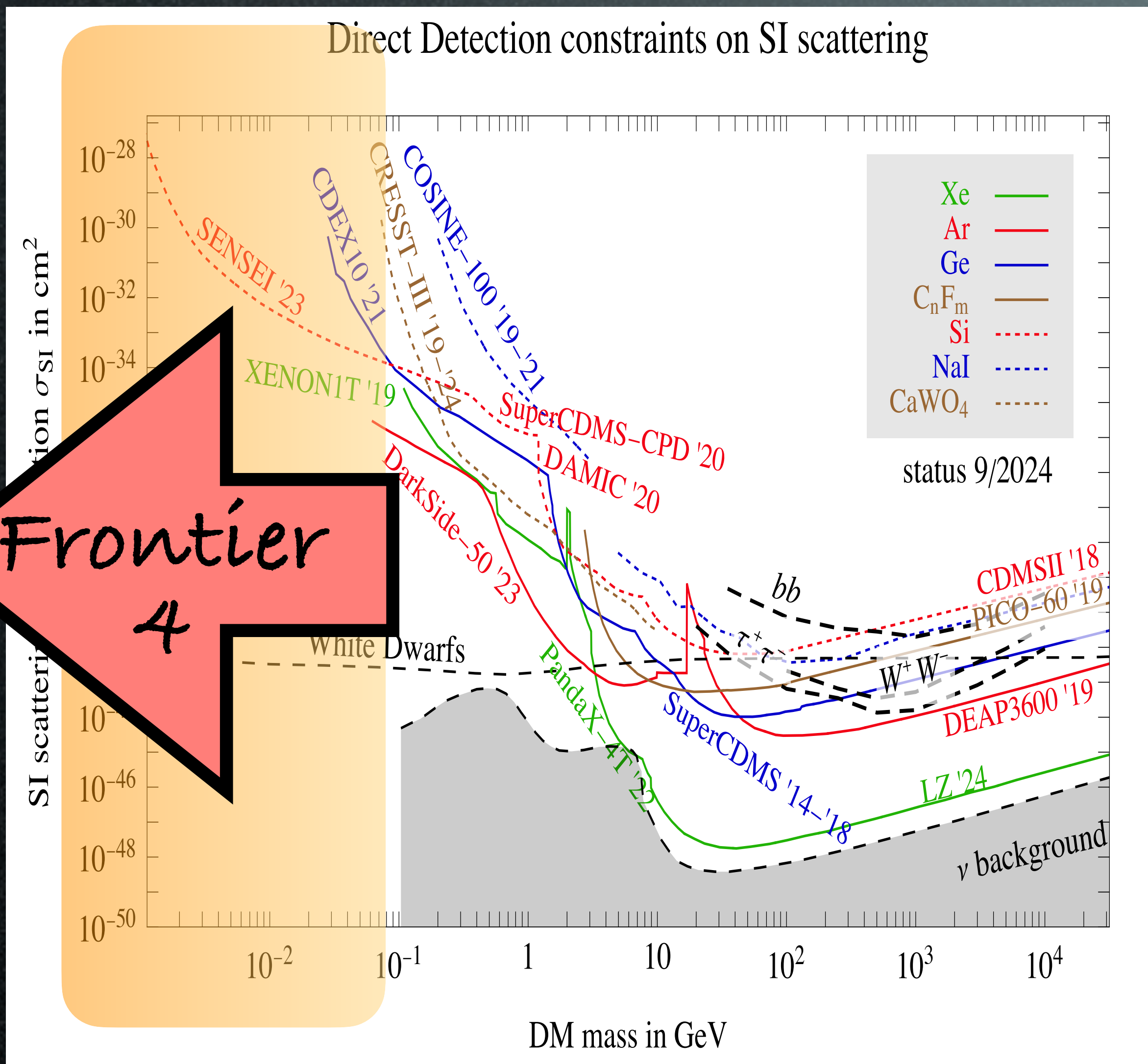
M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705



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

- electron recoil signal
- Migdal effect
- new experimental strategies

Direct Detection of sub-GeV DM



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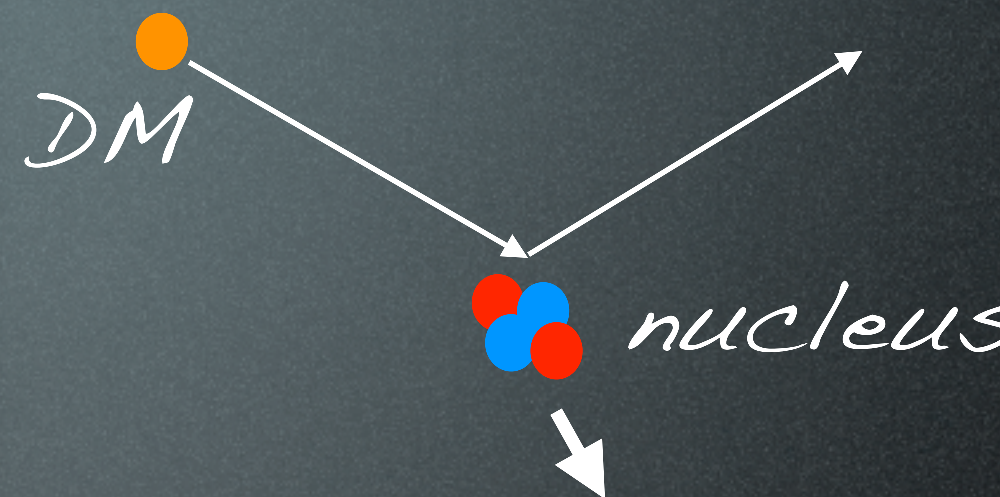

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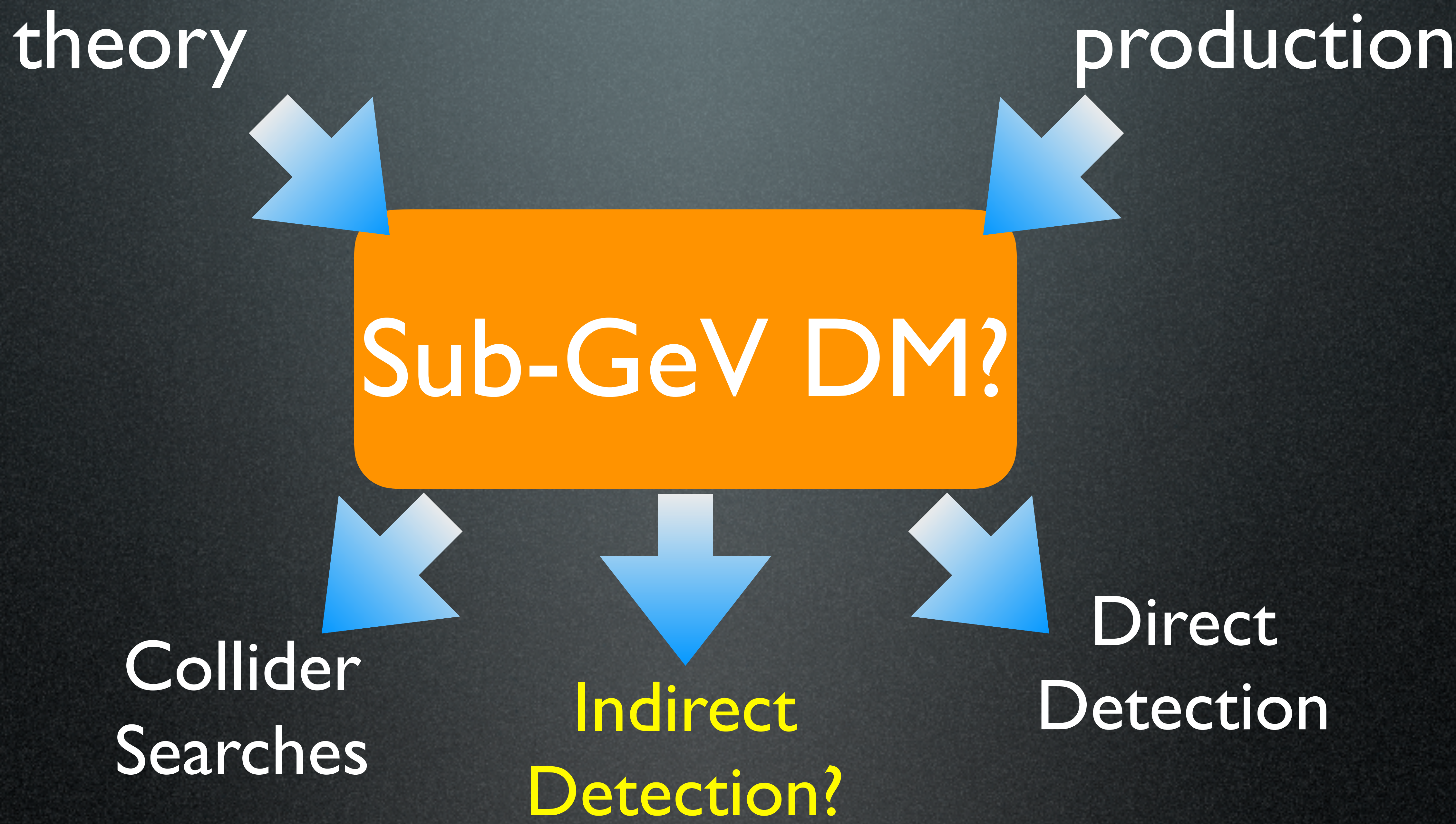
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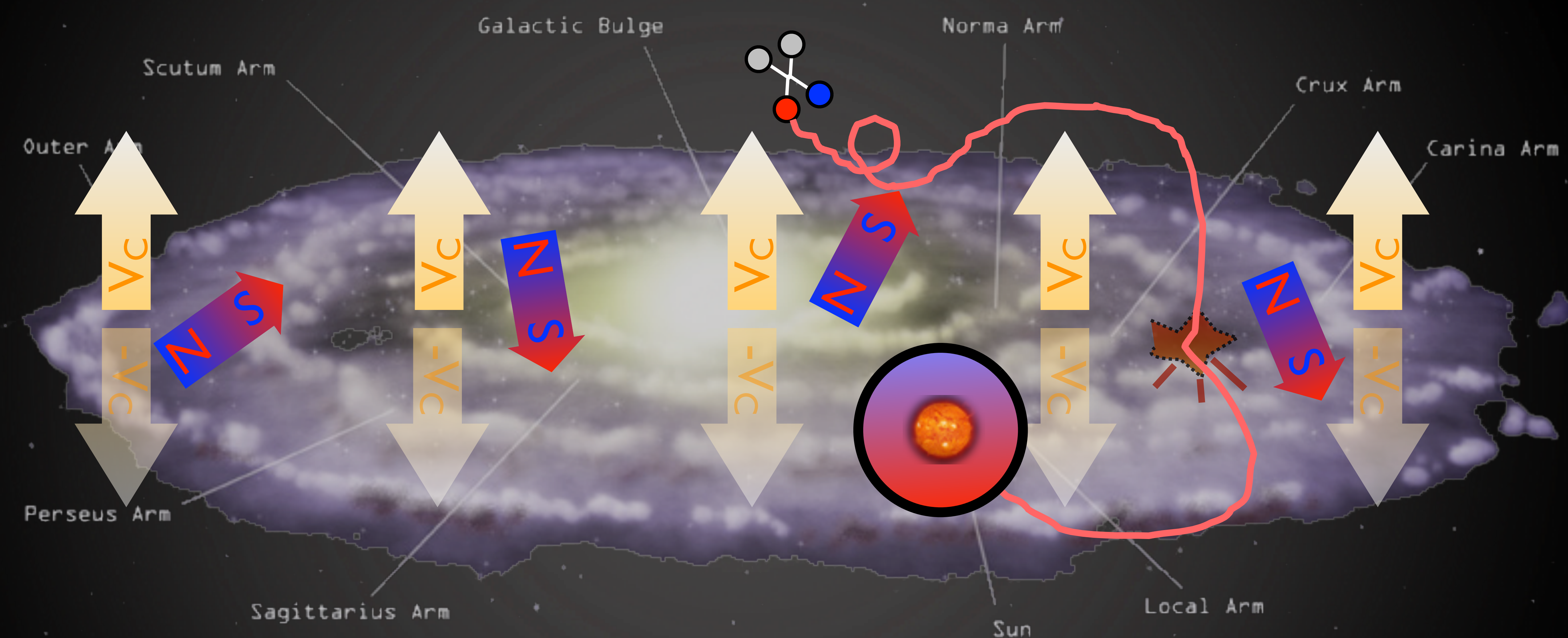
Indirect Detection: charged CRs

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



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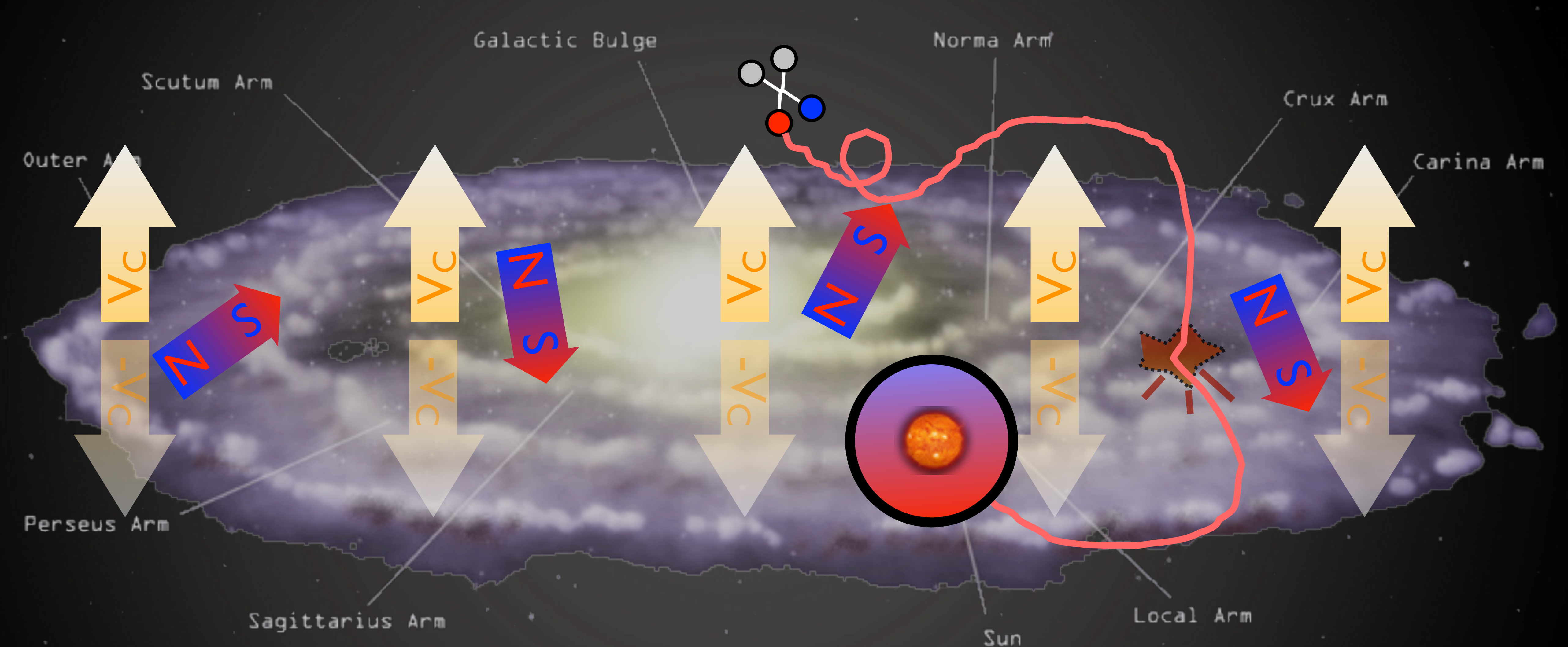

Problem:

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

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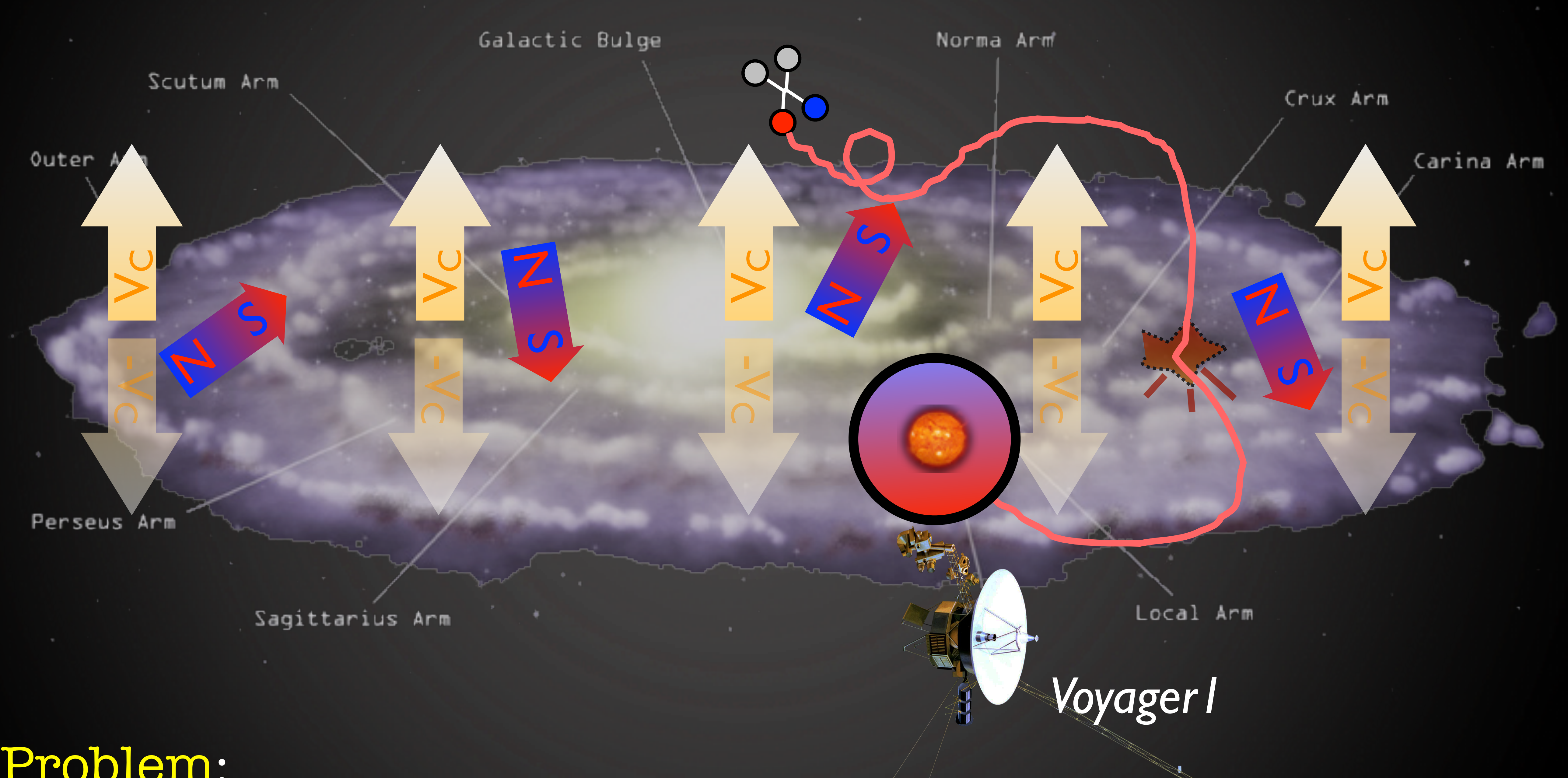


Problem:

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

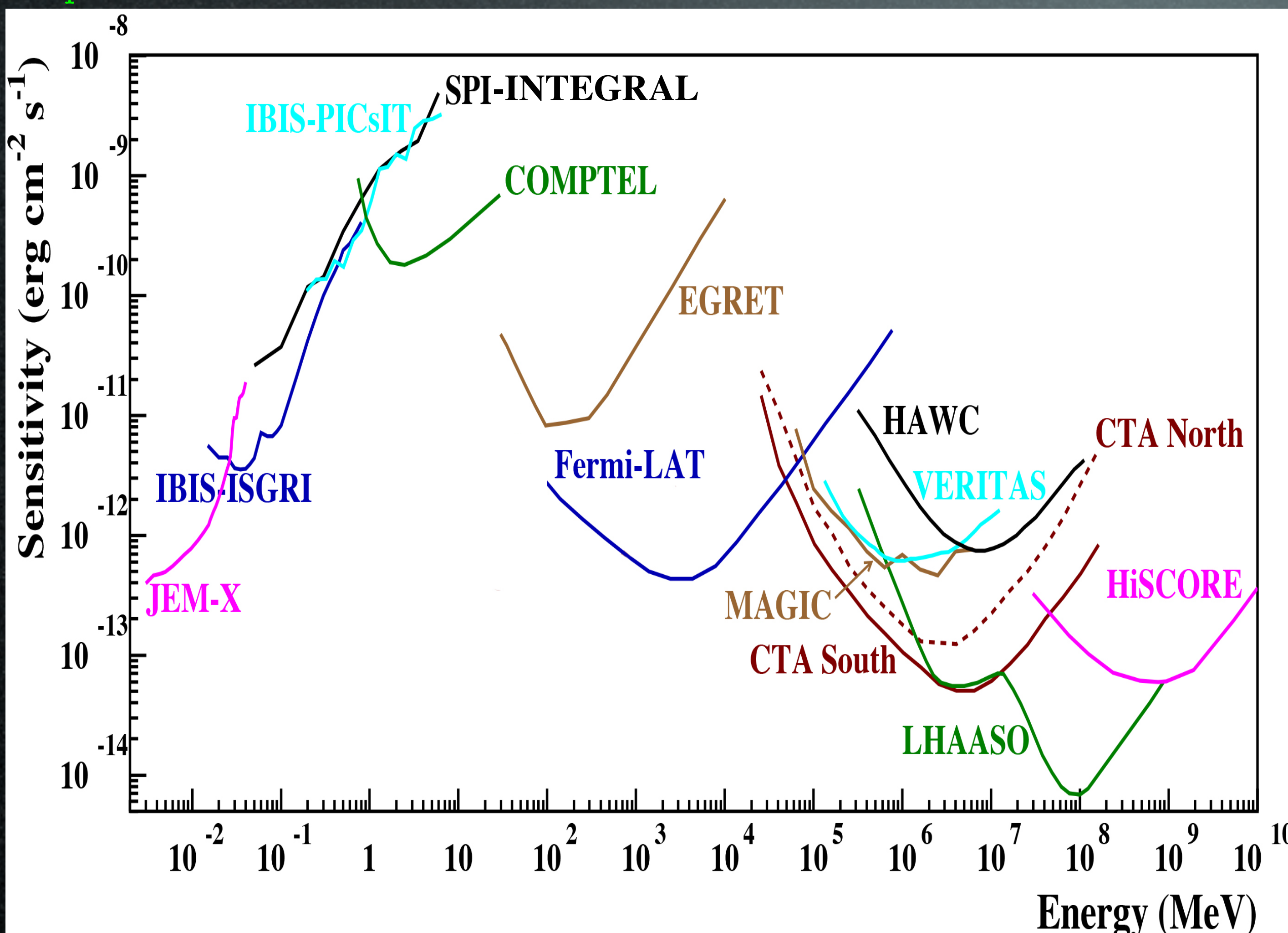
Indirect detection: photons

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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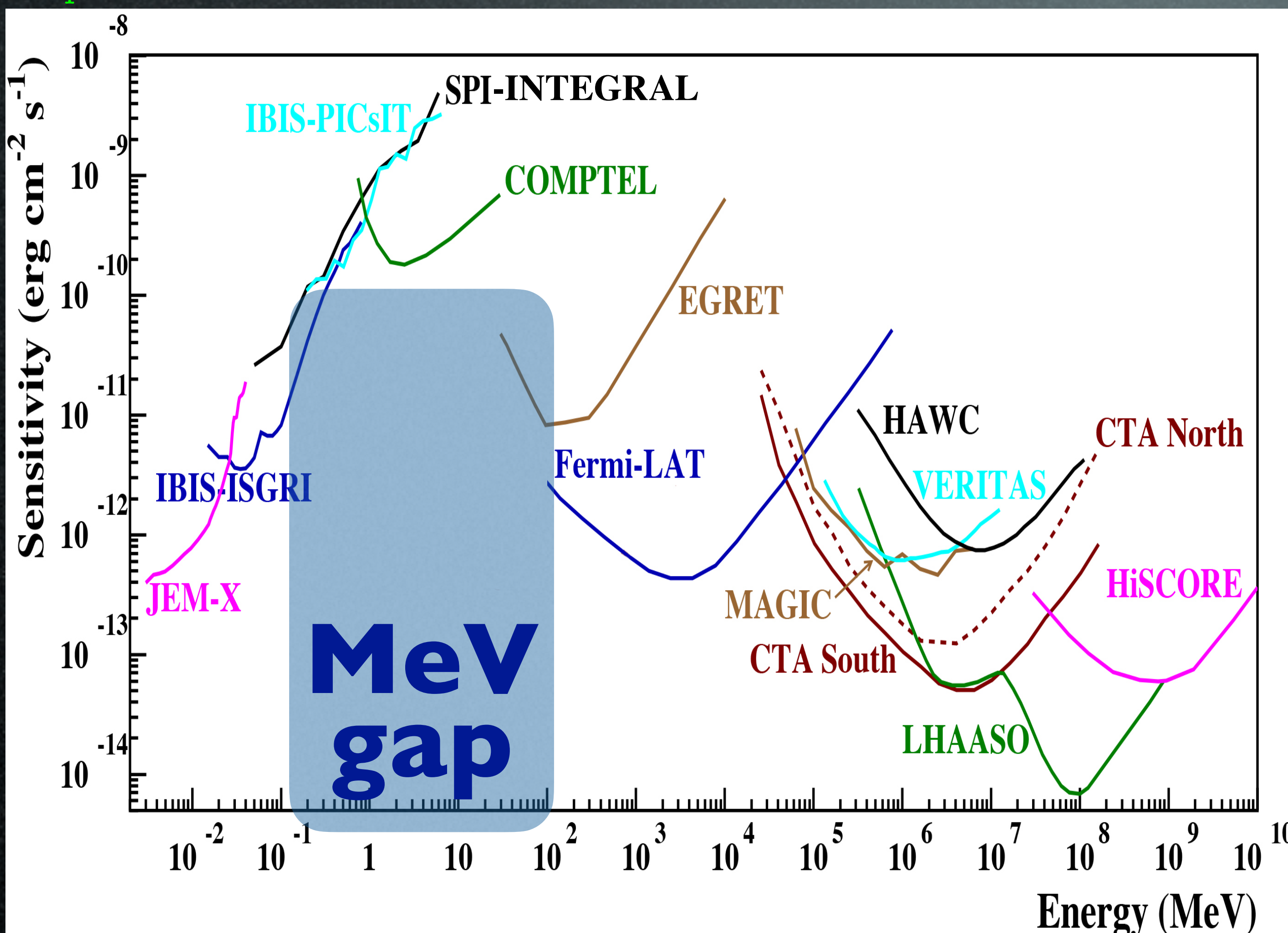

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Cirelli, Strumia, Zupan 2406.01705

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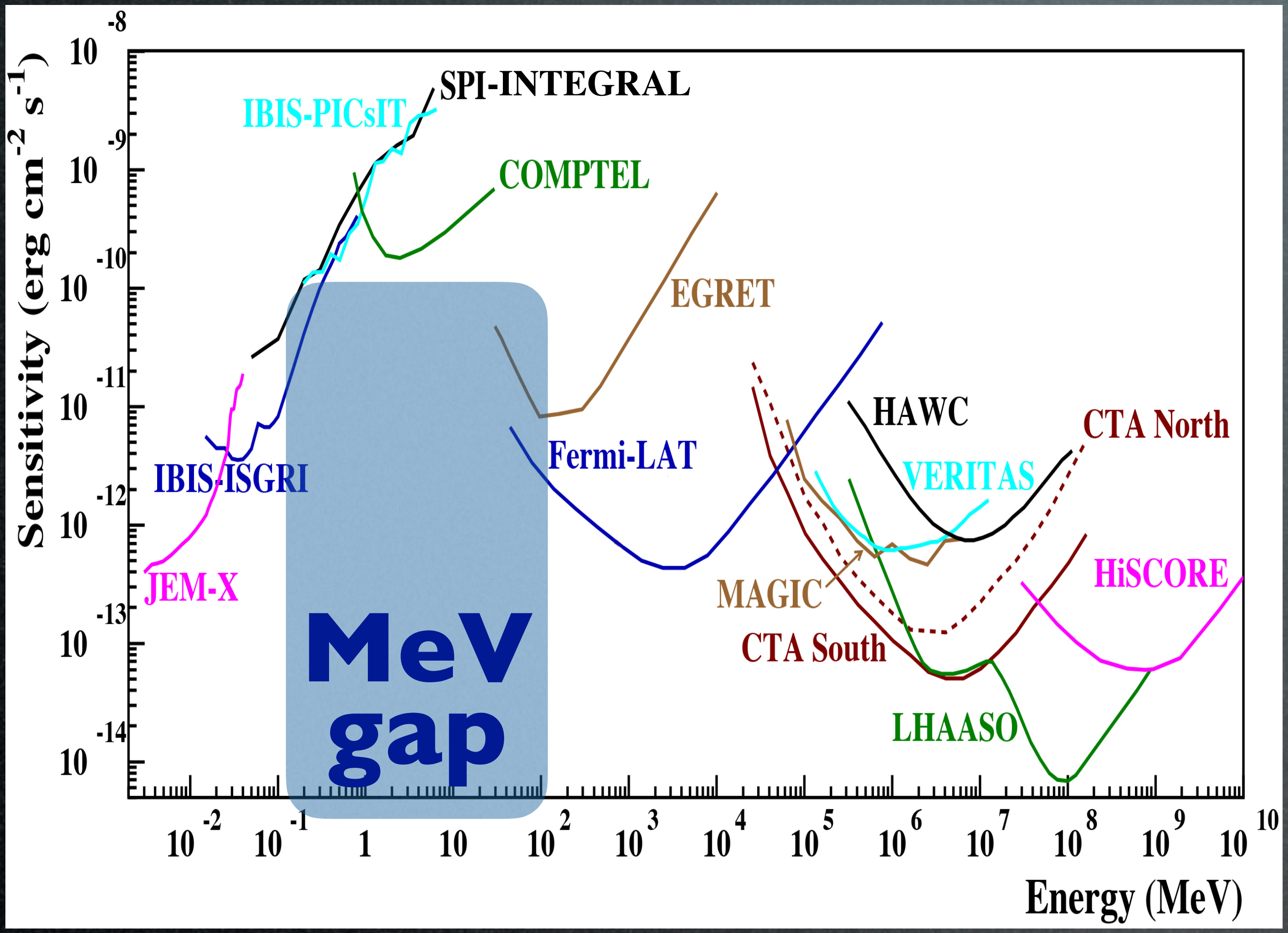


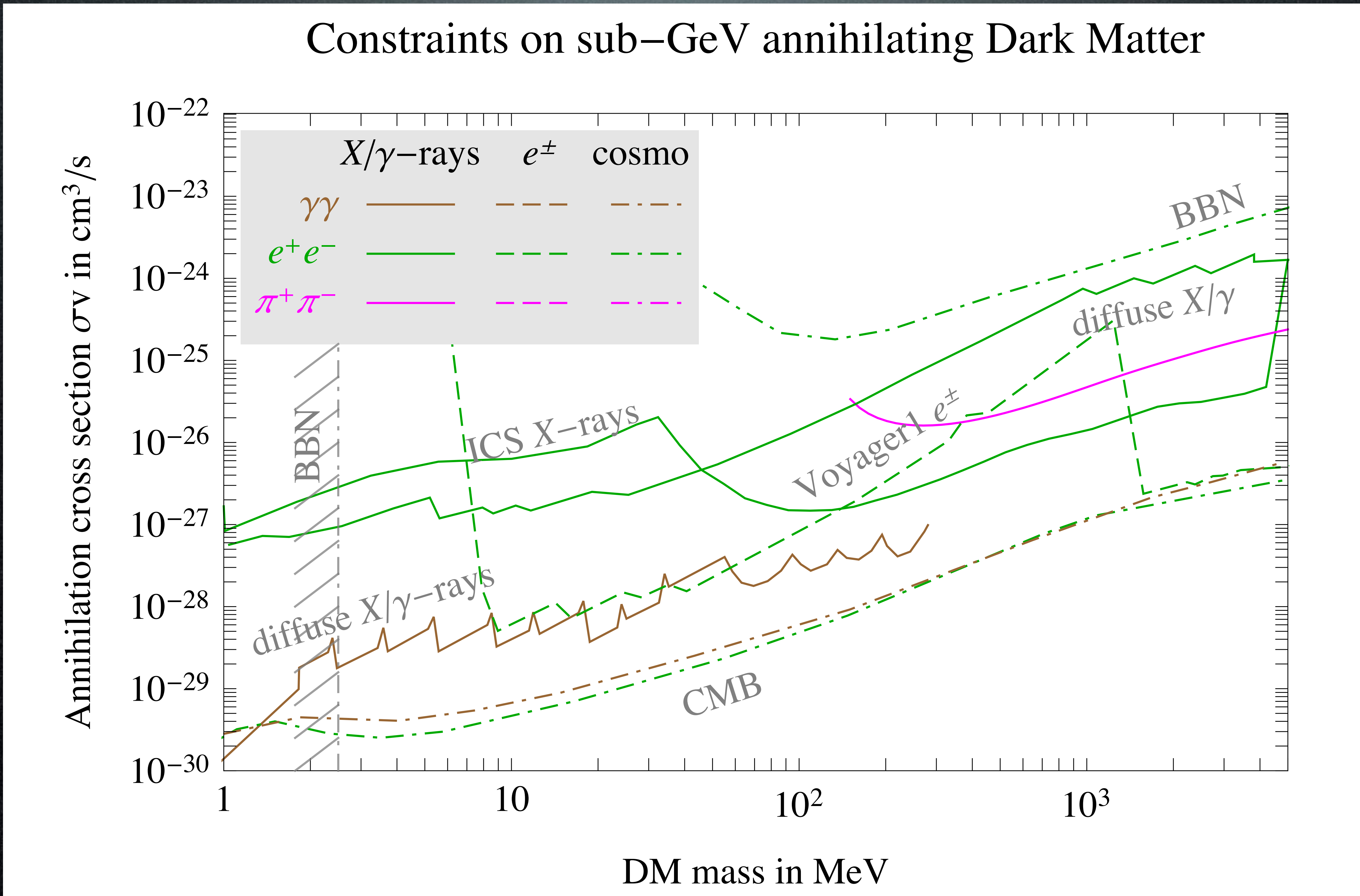
How to do better?

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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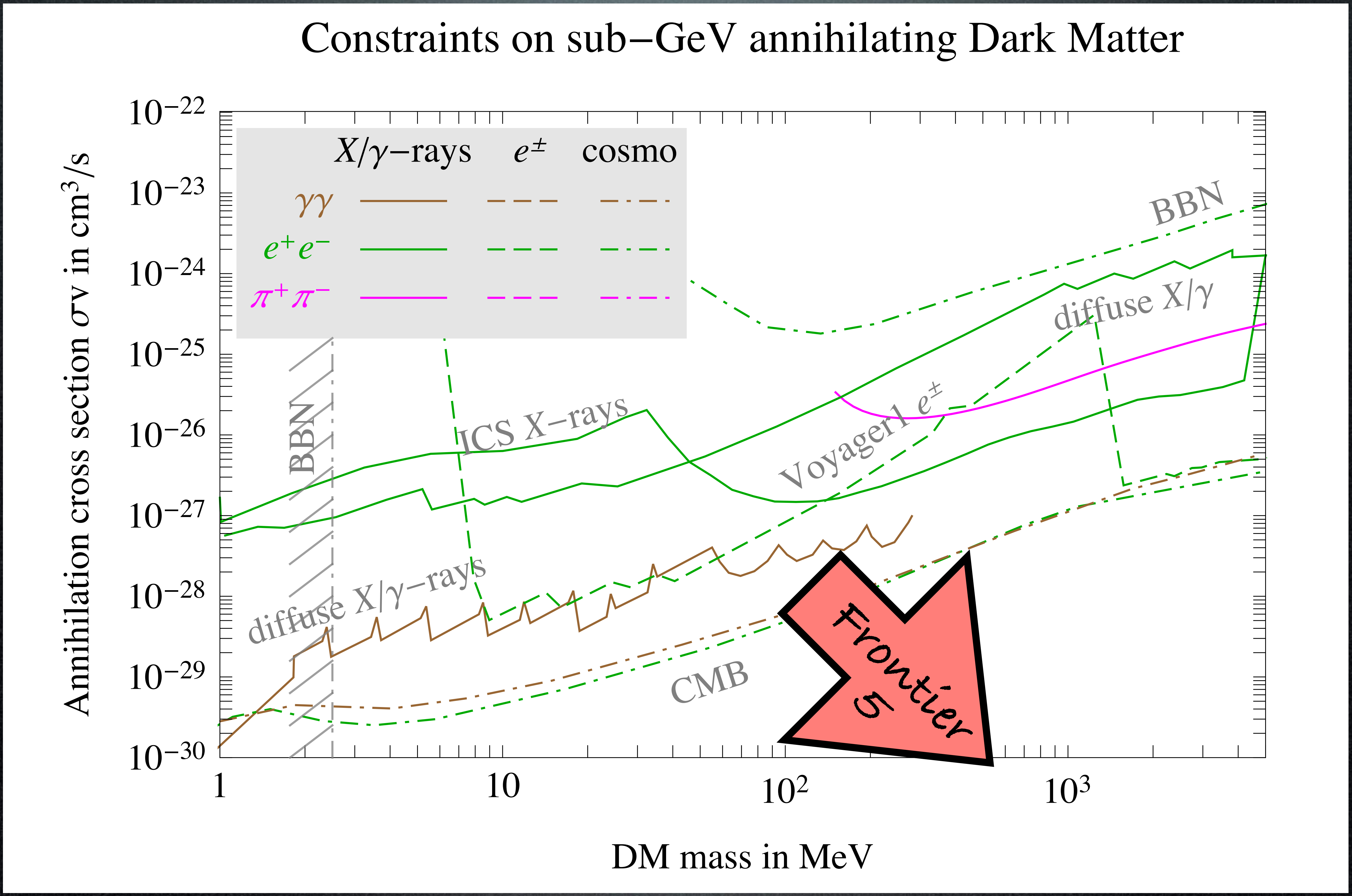
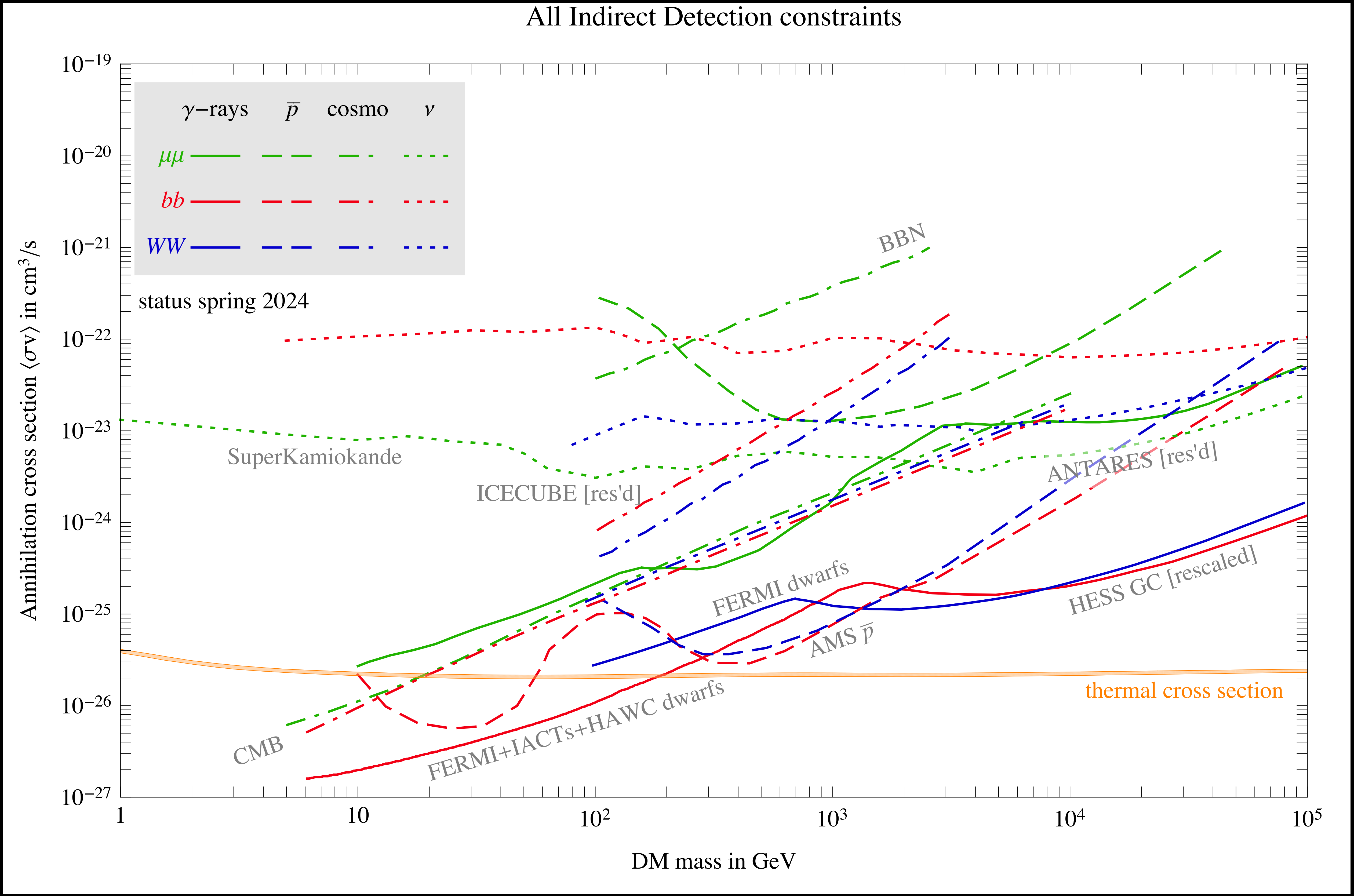


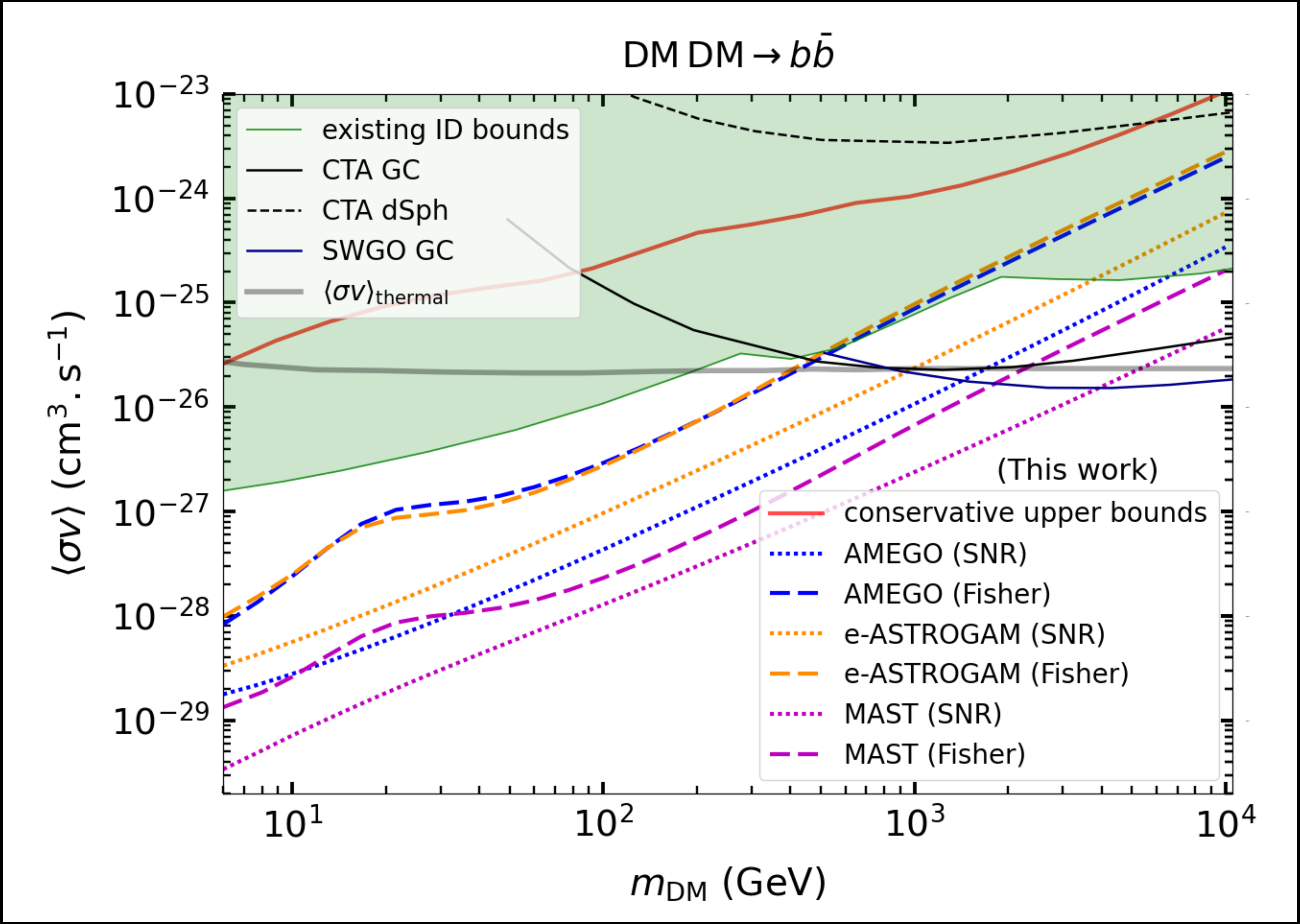
M. Cirelli, A. Strumia, J. Zupan 2406.01705 **v3** (includes eROSITA from 2506.02310)

WIMP Indirect Detection



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

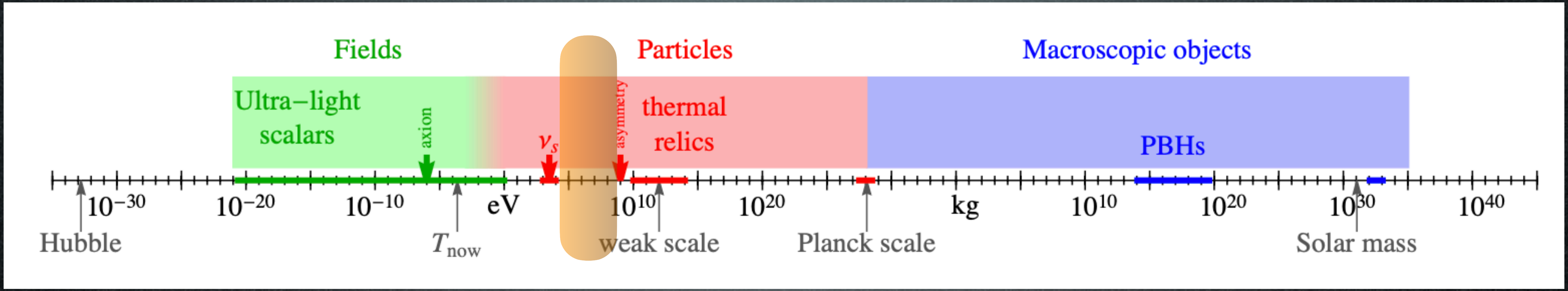
WIMP ID - future prospects



M. Cirelli, A. Kar, 2503.04907

Candidates

A matter of perspective: plausible mass ranges



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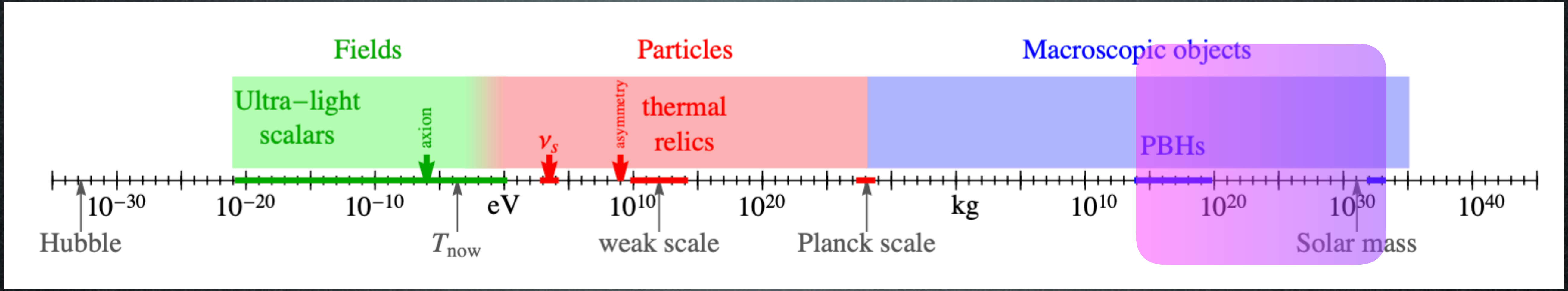

DM can **NOT** be:

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- brown dwarves

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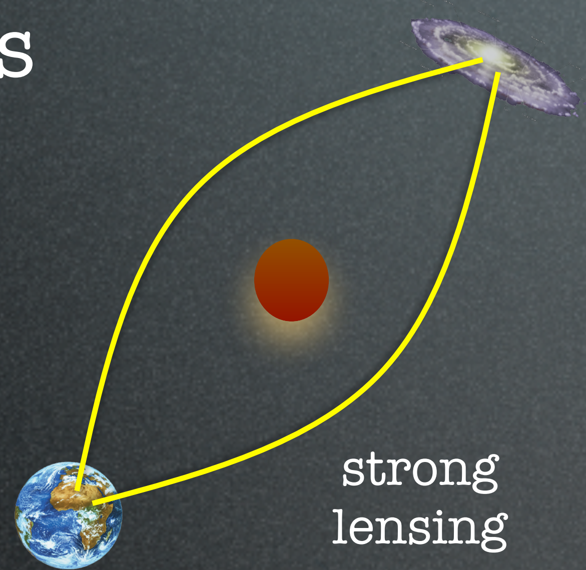
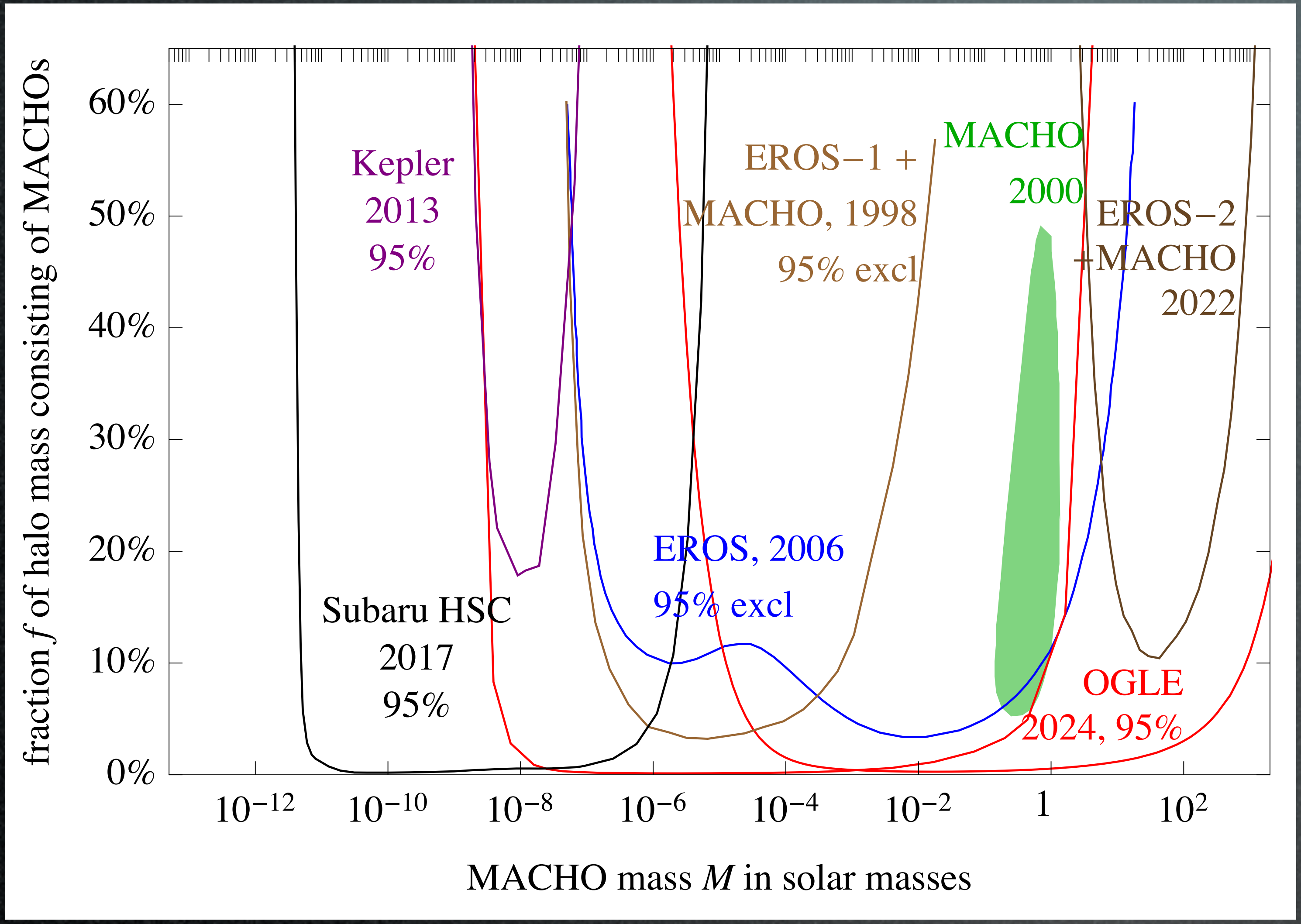


MACHOs or PBHs as DM



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

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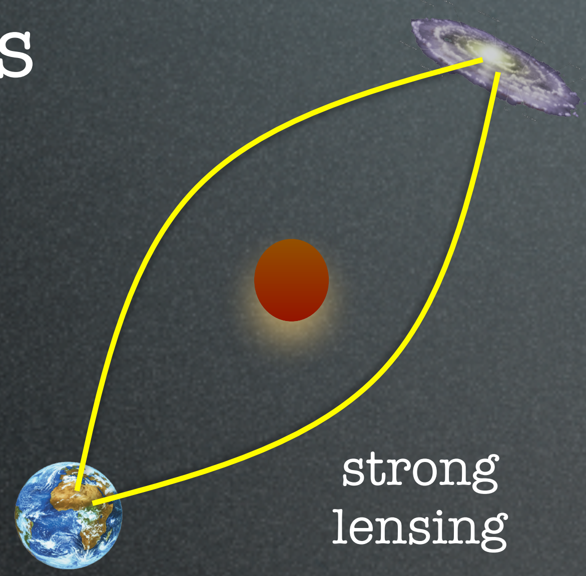

a baryon of the SM:

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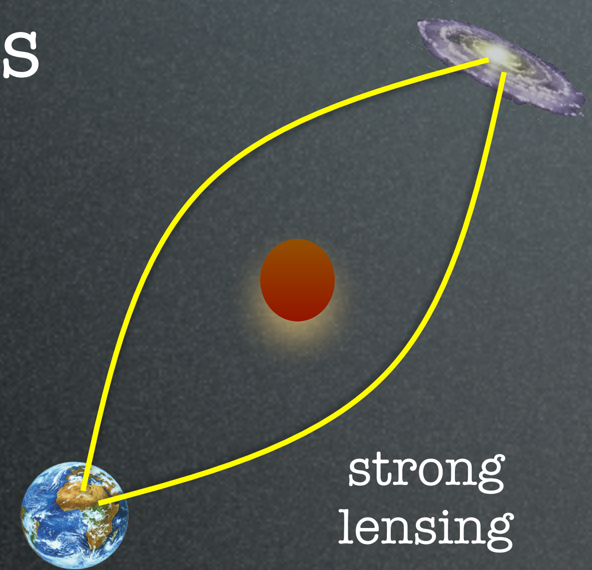

a ~~baryon of the SM~~:

- 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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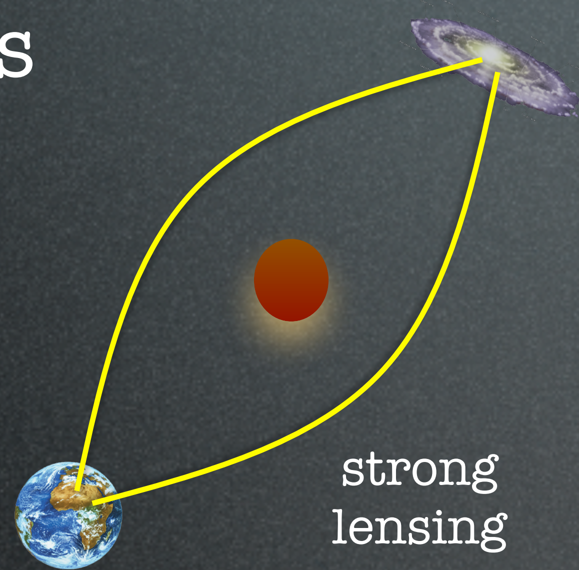

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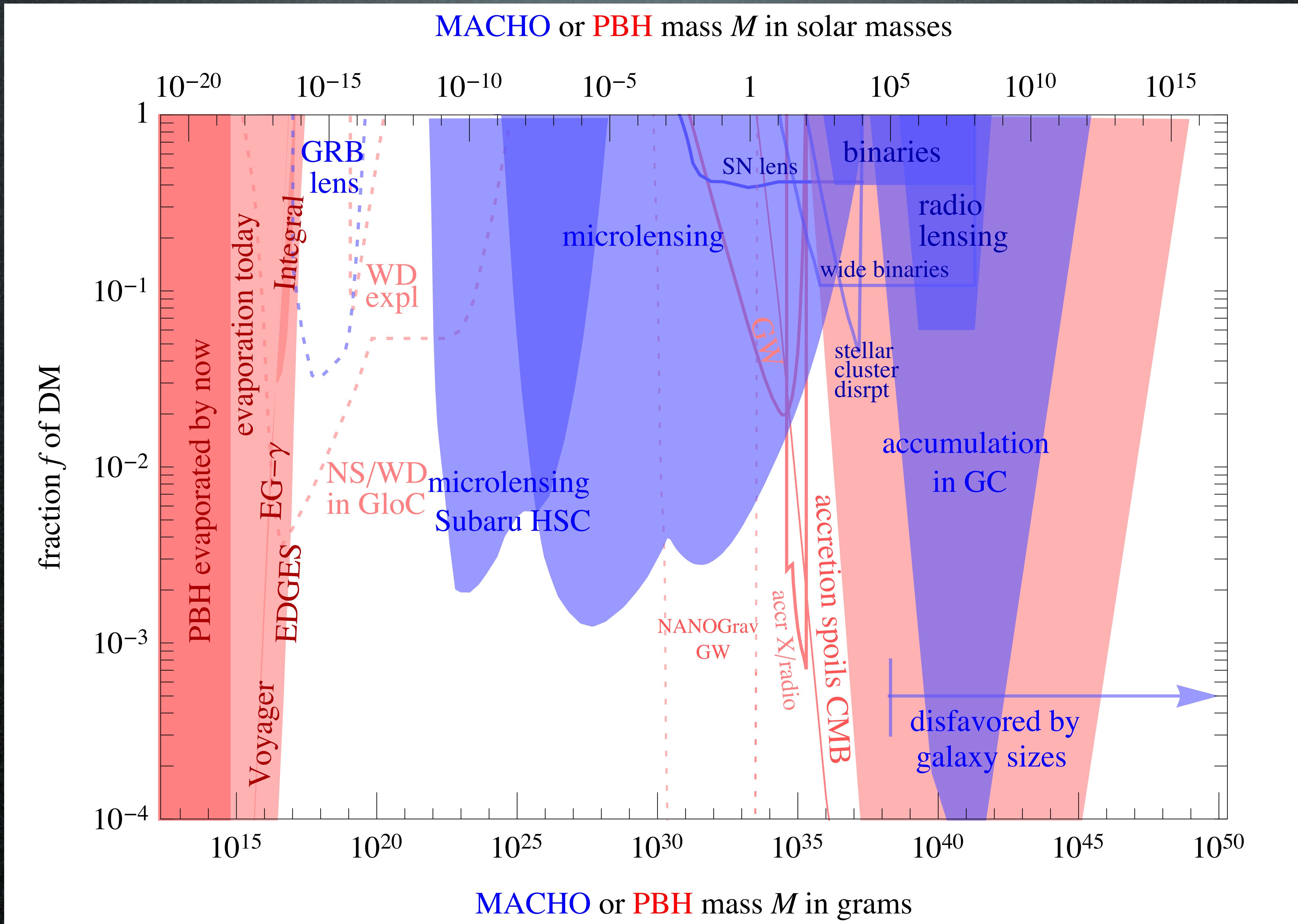
A loophole: Primordial Black Holes!

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

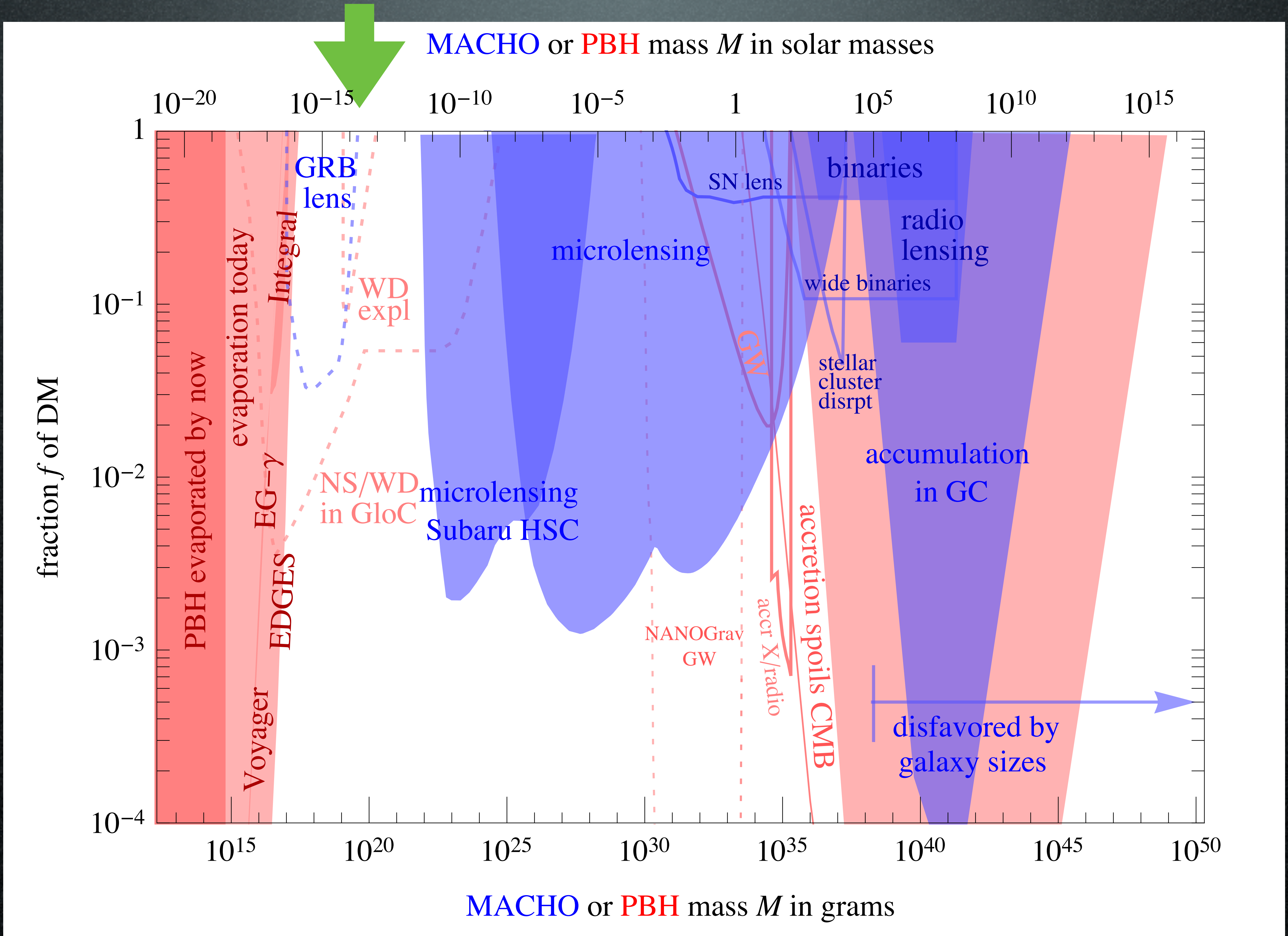
PBHs as DM



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

PBHs as DM

window still open?



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PBHs as DM

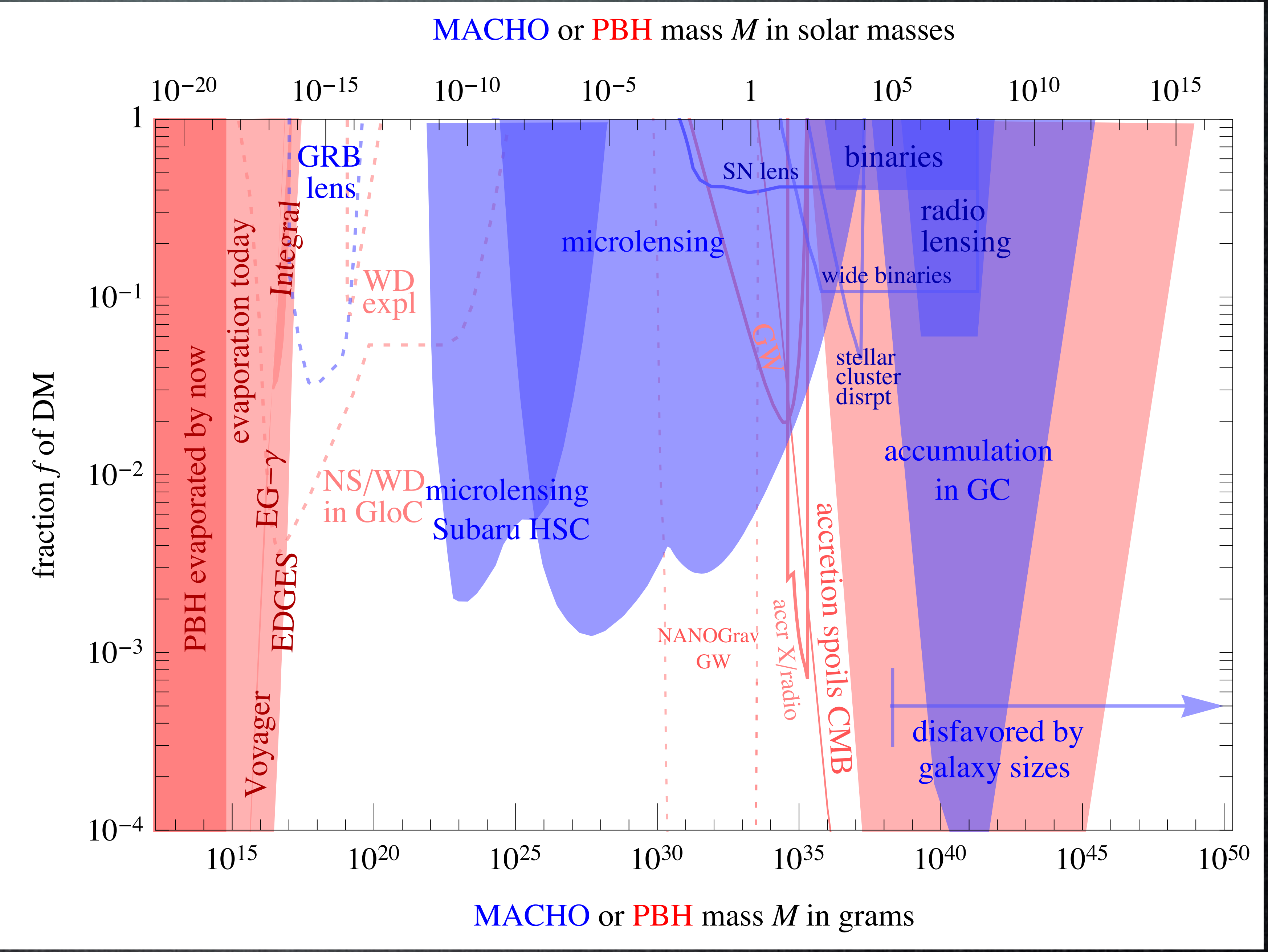
Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

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

constraints



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'small' PBHs emit today by Hawking evaporation

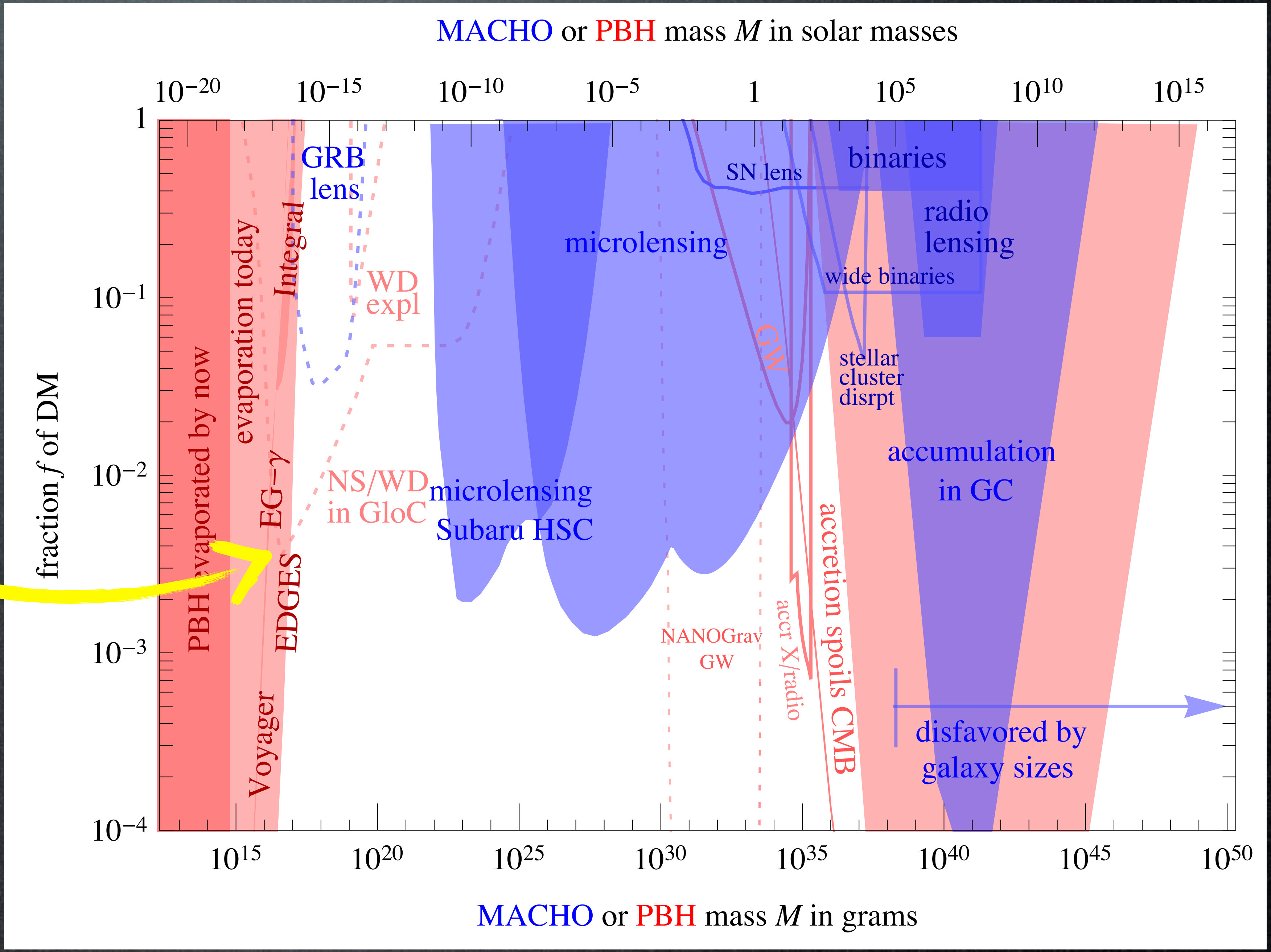
$$T = \frac{1}{8\pi\, G_N M}$$

rate

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

spectrum

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



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

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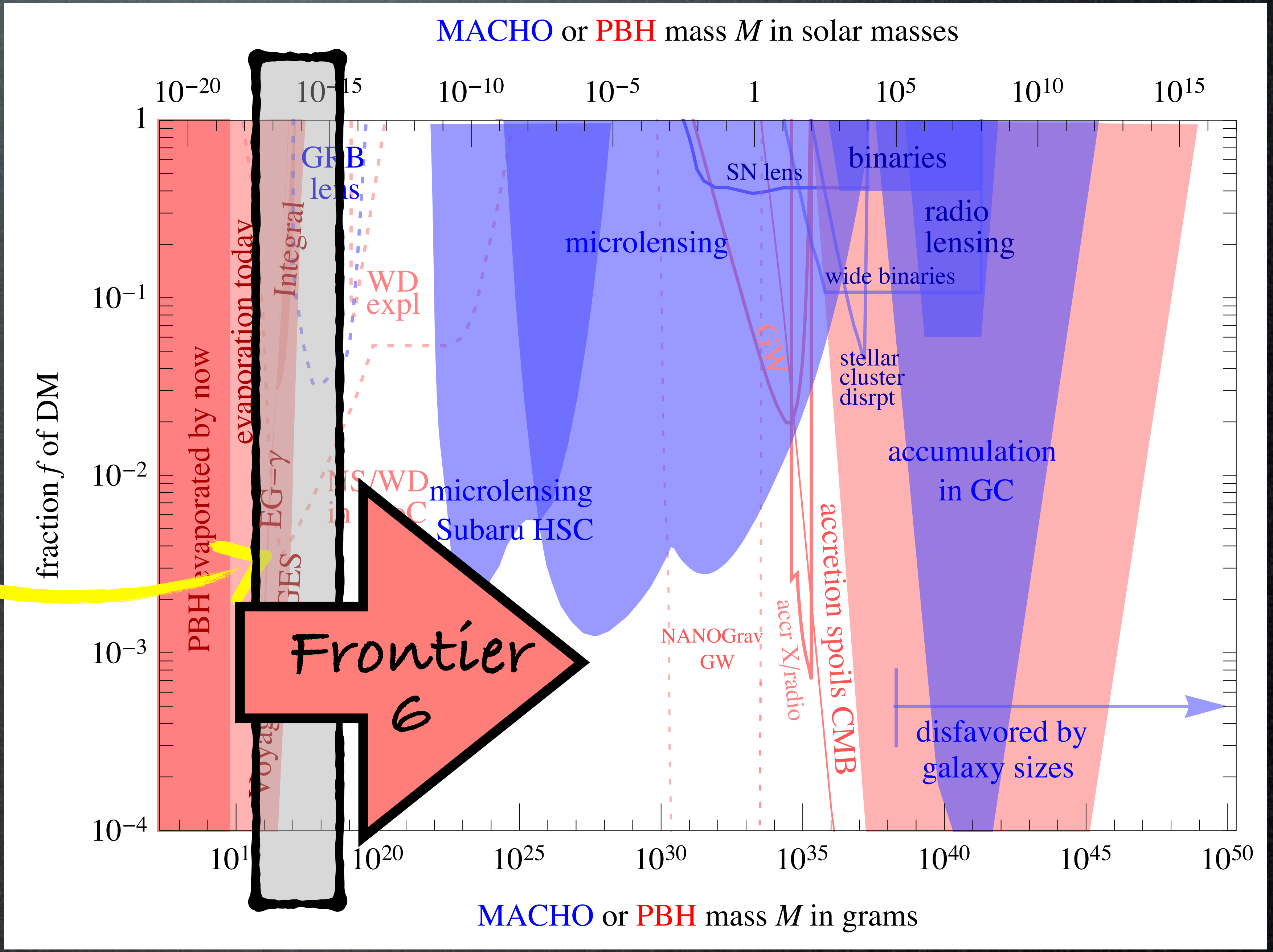
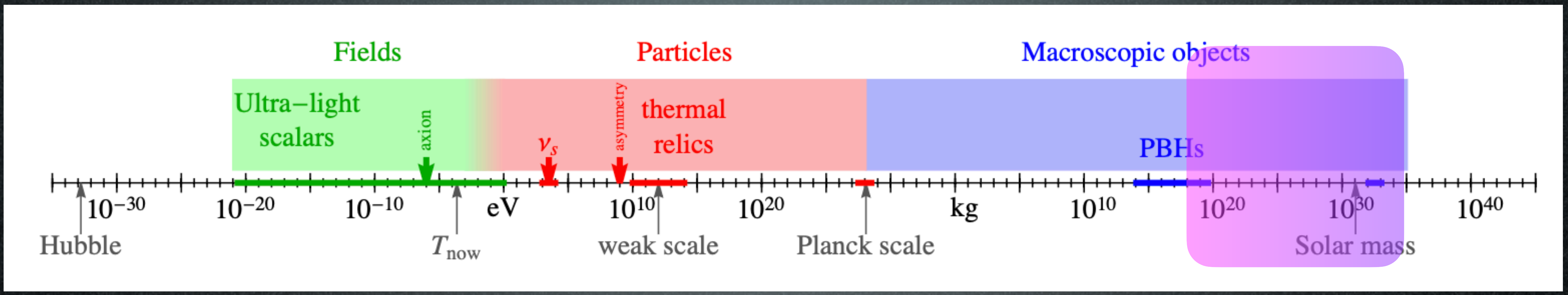


M. Cirelli, A. Strumia, J. Zupan 2406.01705

Candidates

A matter of perspective: plausible mass ranges



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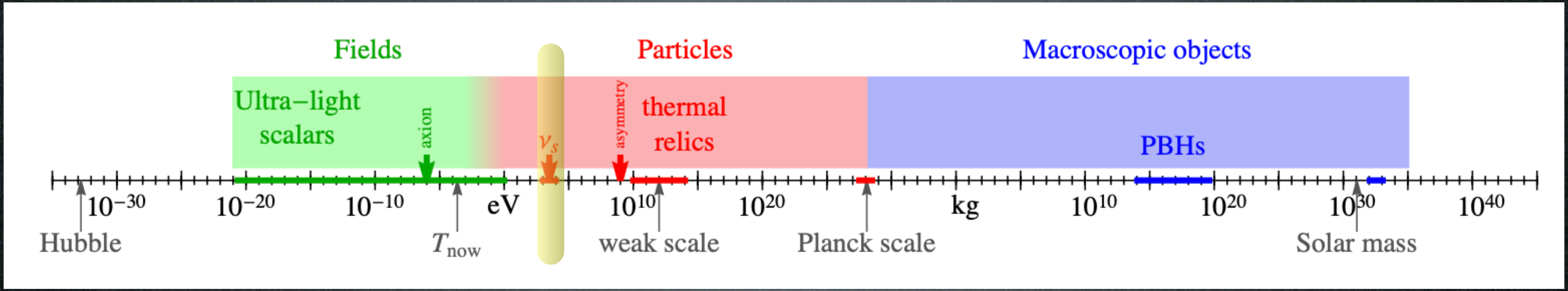


KeV DM?

X-ray line

Bulbul et al., 1402.2301

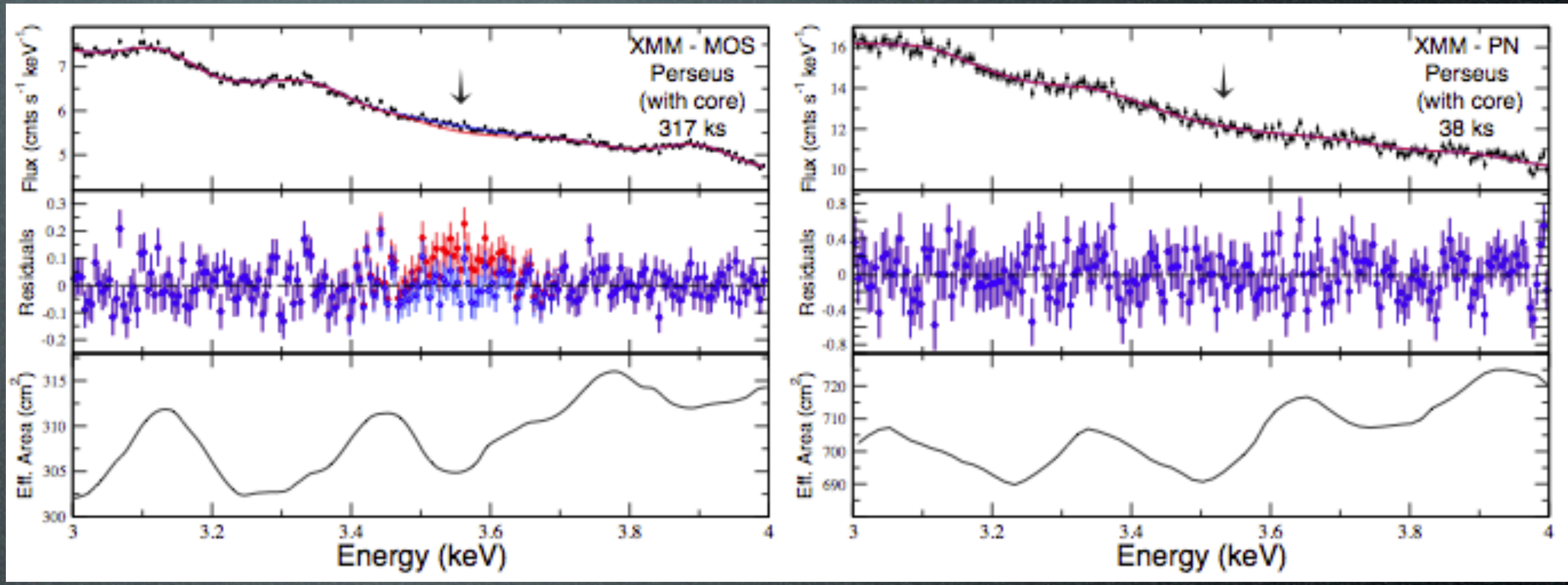
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

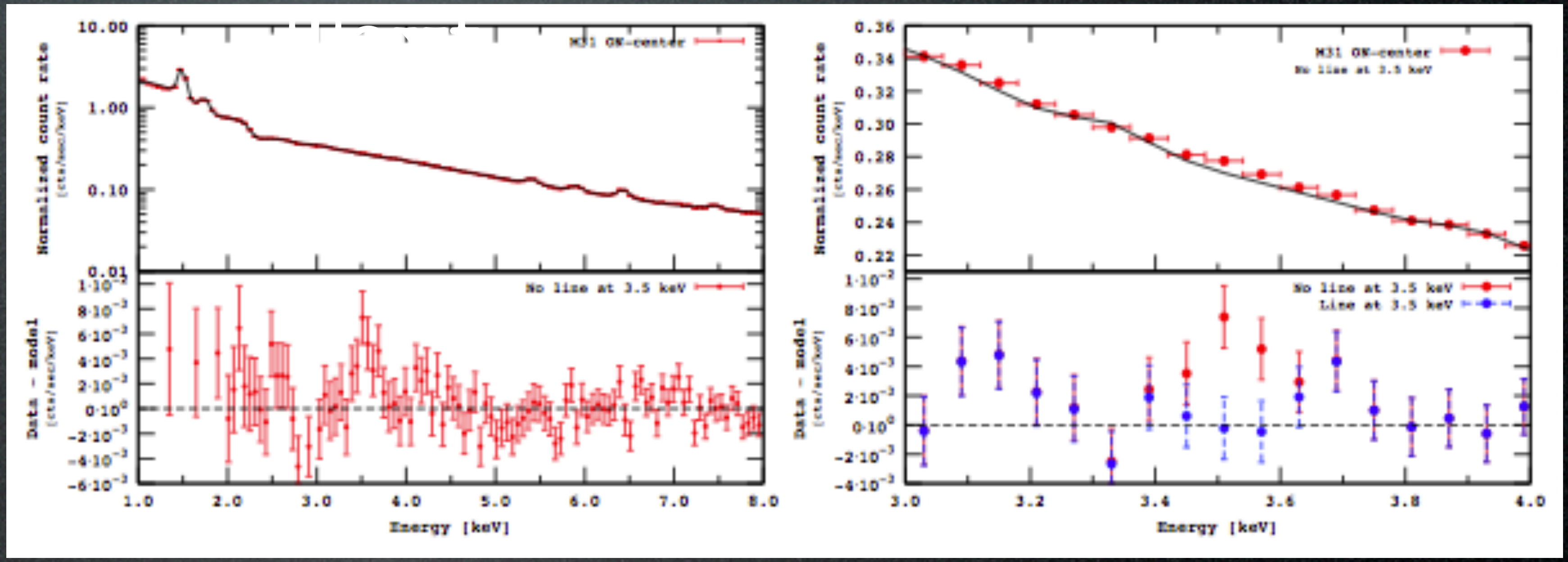
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

z = 0 and 0.0179

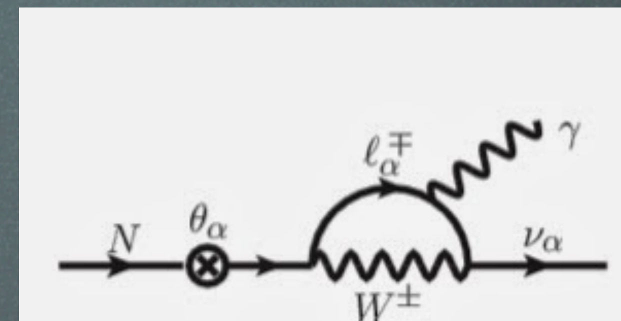
4.4σ

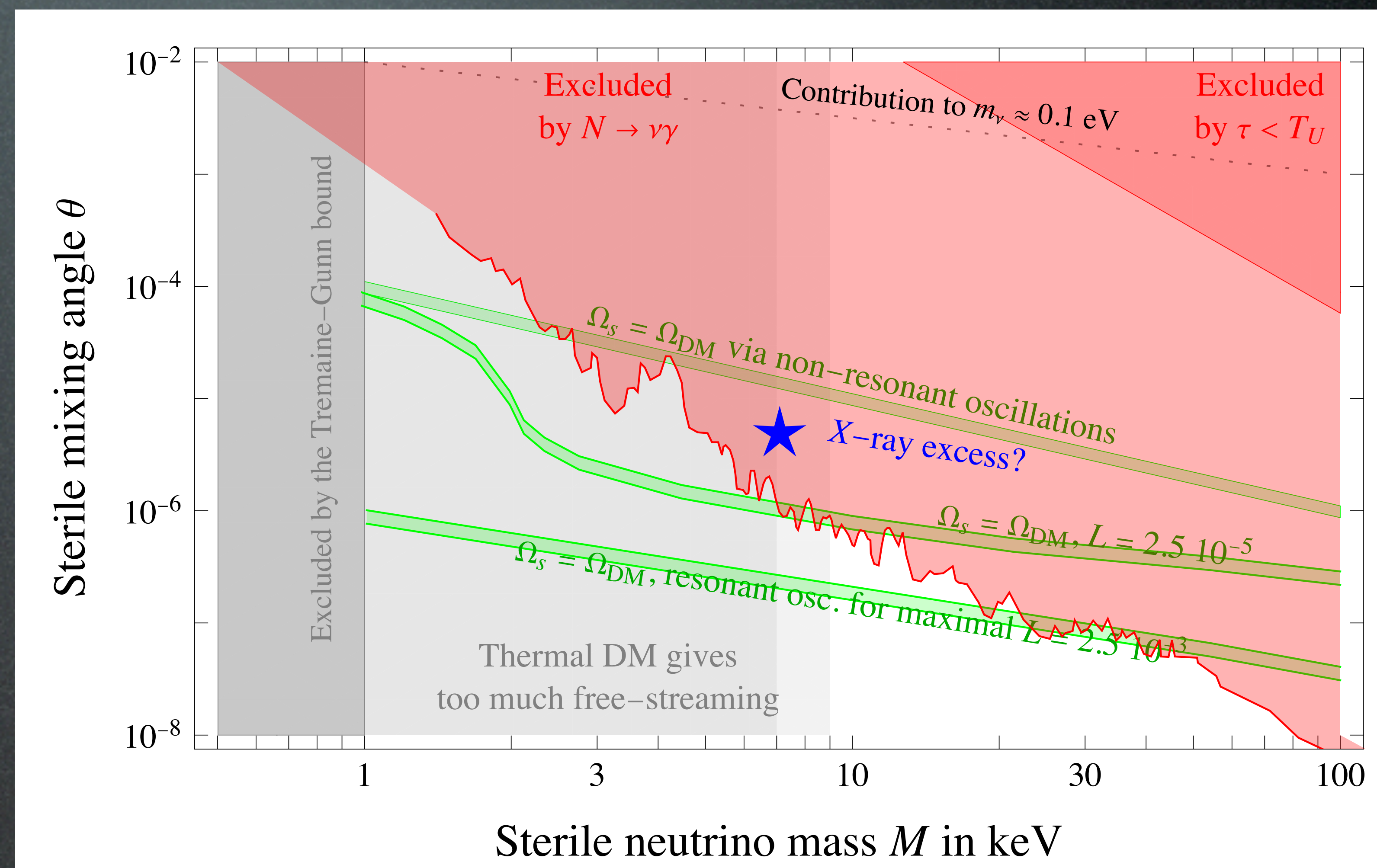


X-ray line

Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$





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

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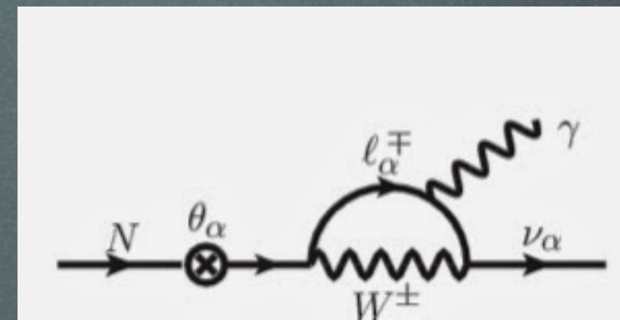

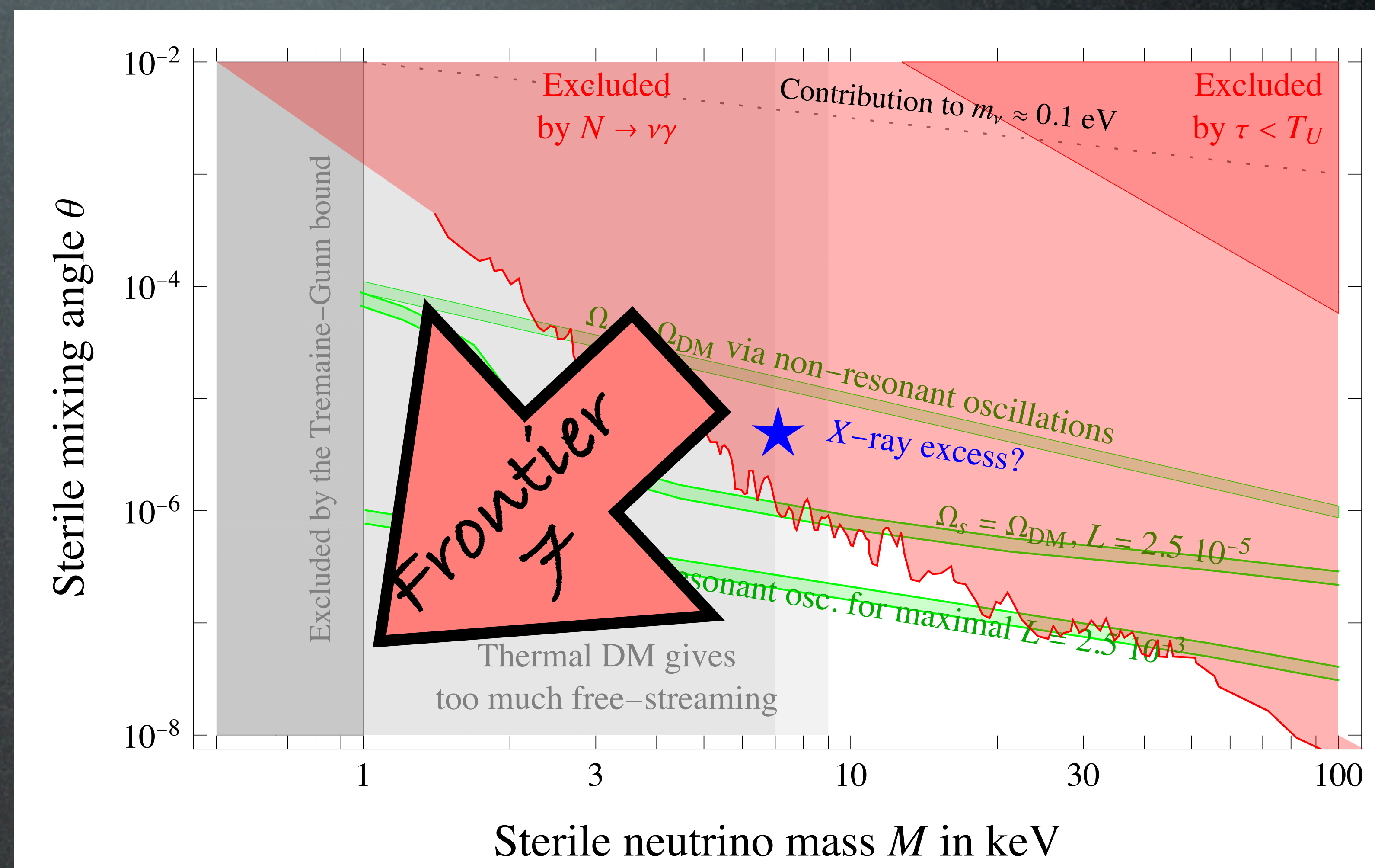

M. Cirelli, A. Strumia, J. Zupan 2406.01705

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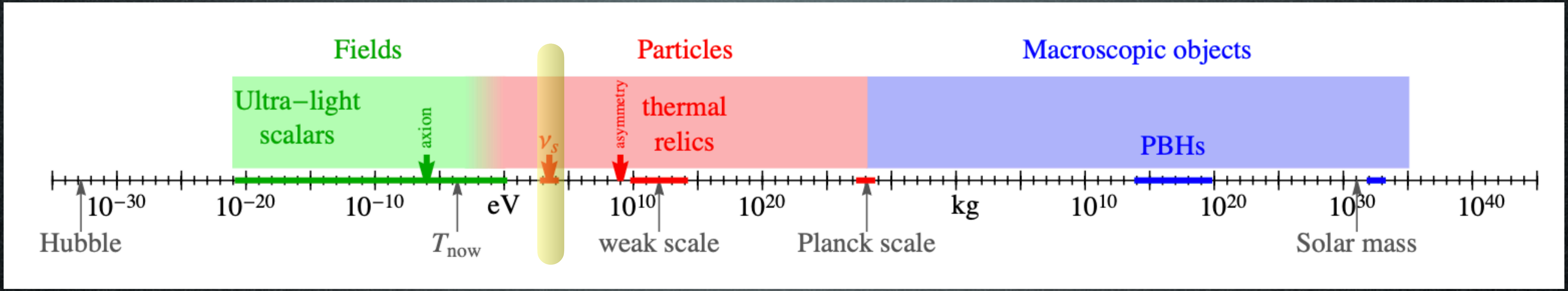

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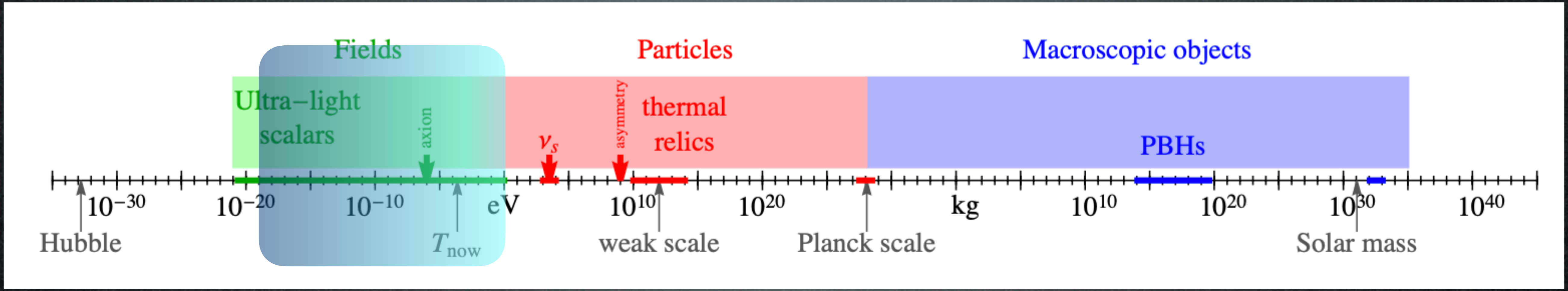


Axions

Theoretically motivated:

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

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

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

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

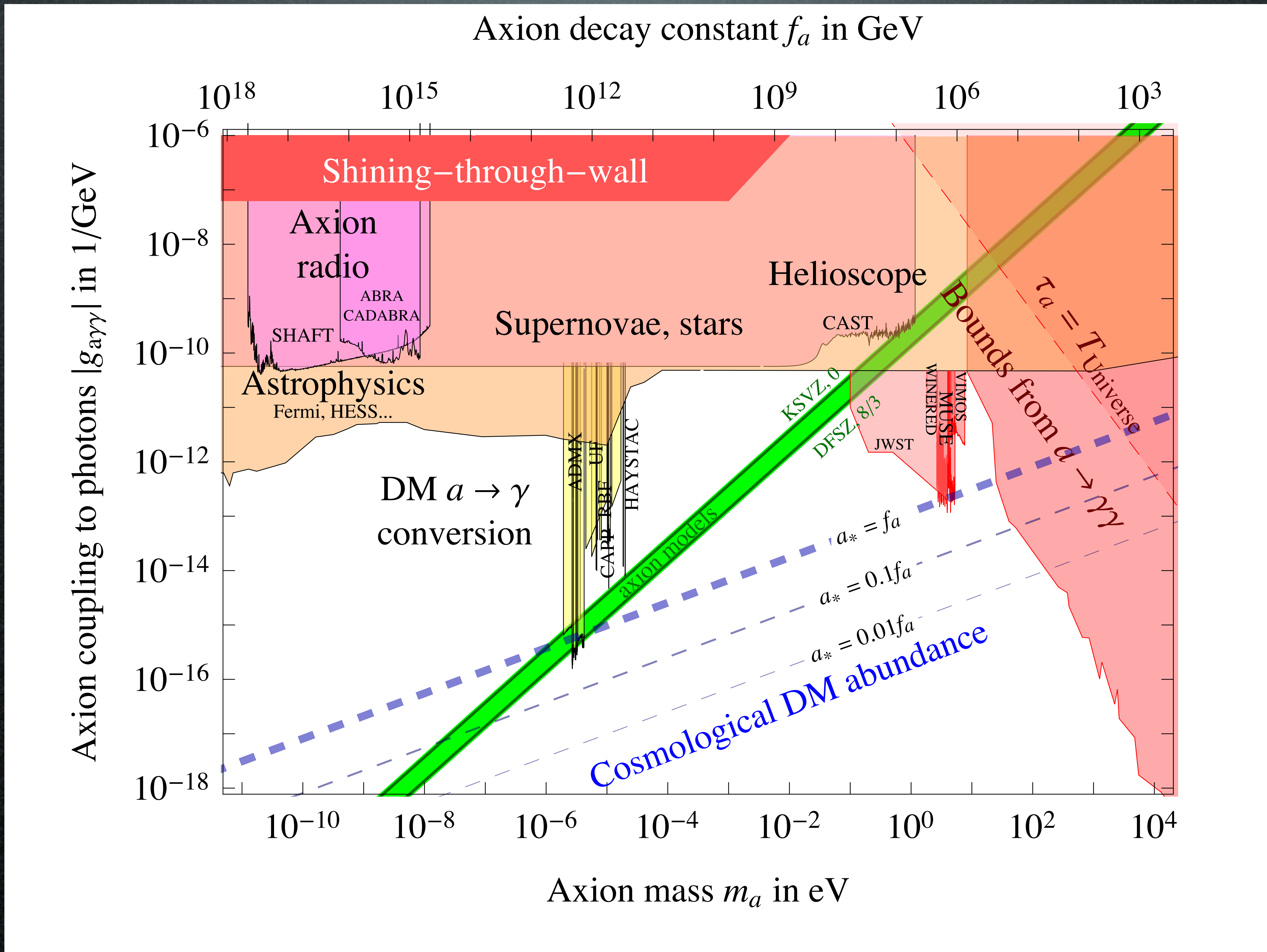
Perhaps because θ is dynamical (a field)

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

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

Axions

Searches:



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

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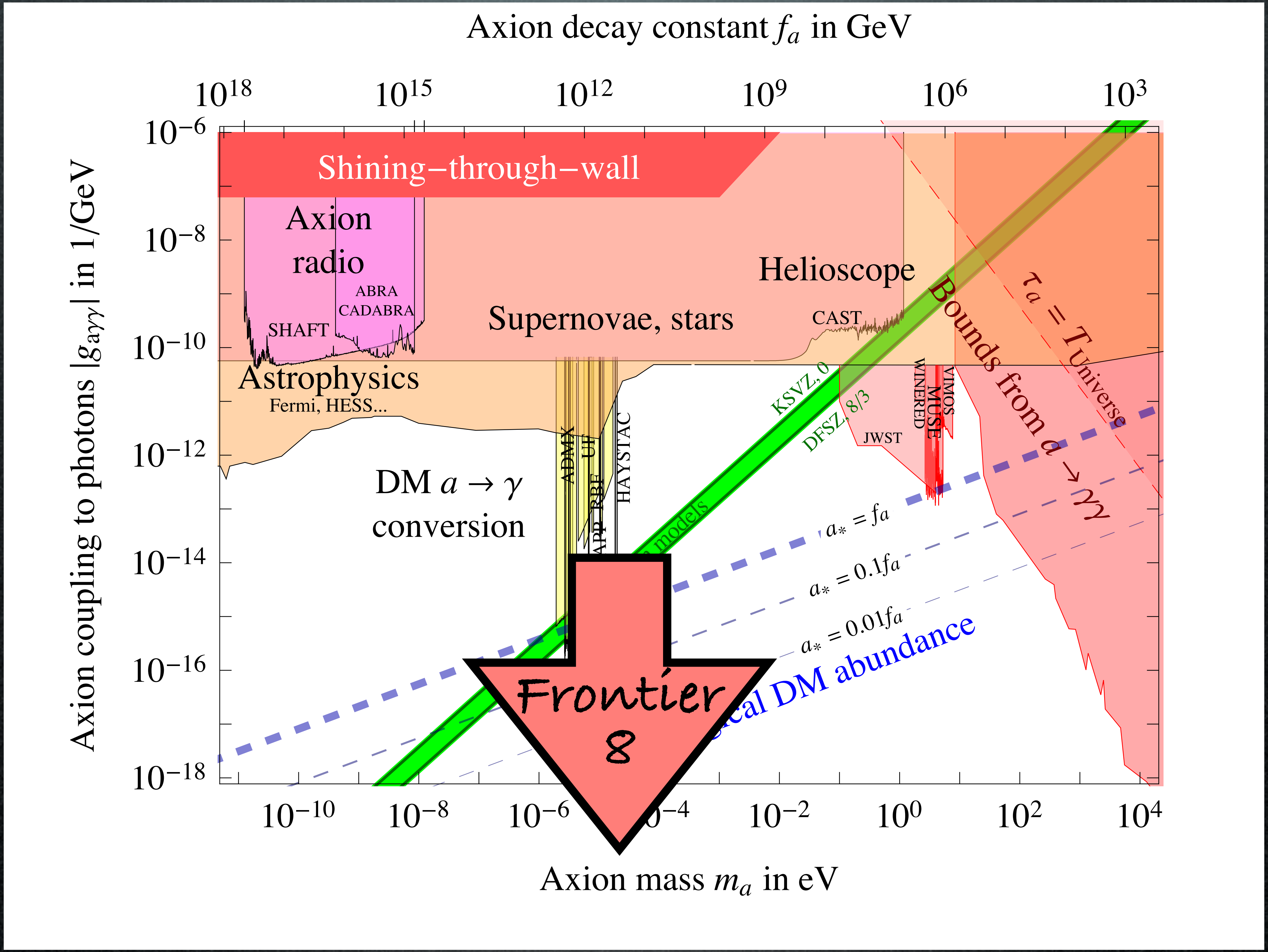

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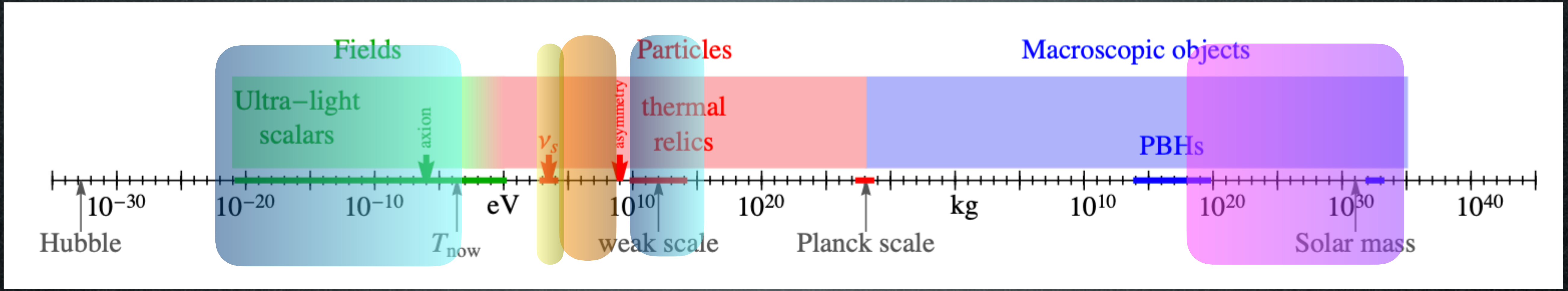

90 orders of magnitude!

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

Conclusions

Conclusions

The physics of Dark Matter is in an experiment driven phase

Conclusions

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

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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

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Frontier 6

Frontier 4

Frontier 3

Frontier 2

Frontier 1

Frontier 7

Frontier 8

Frontier 5

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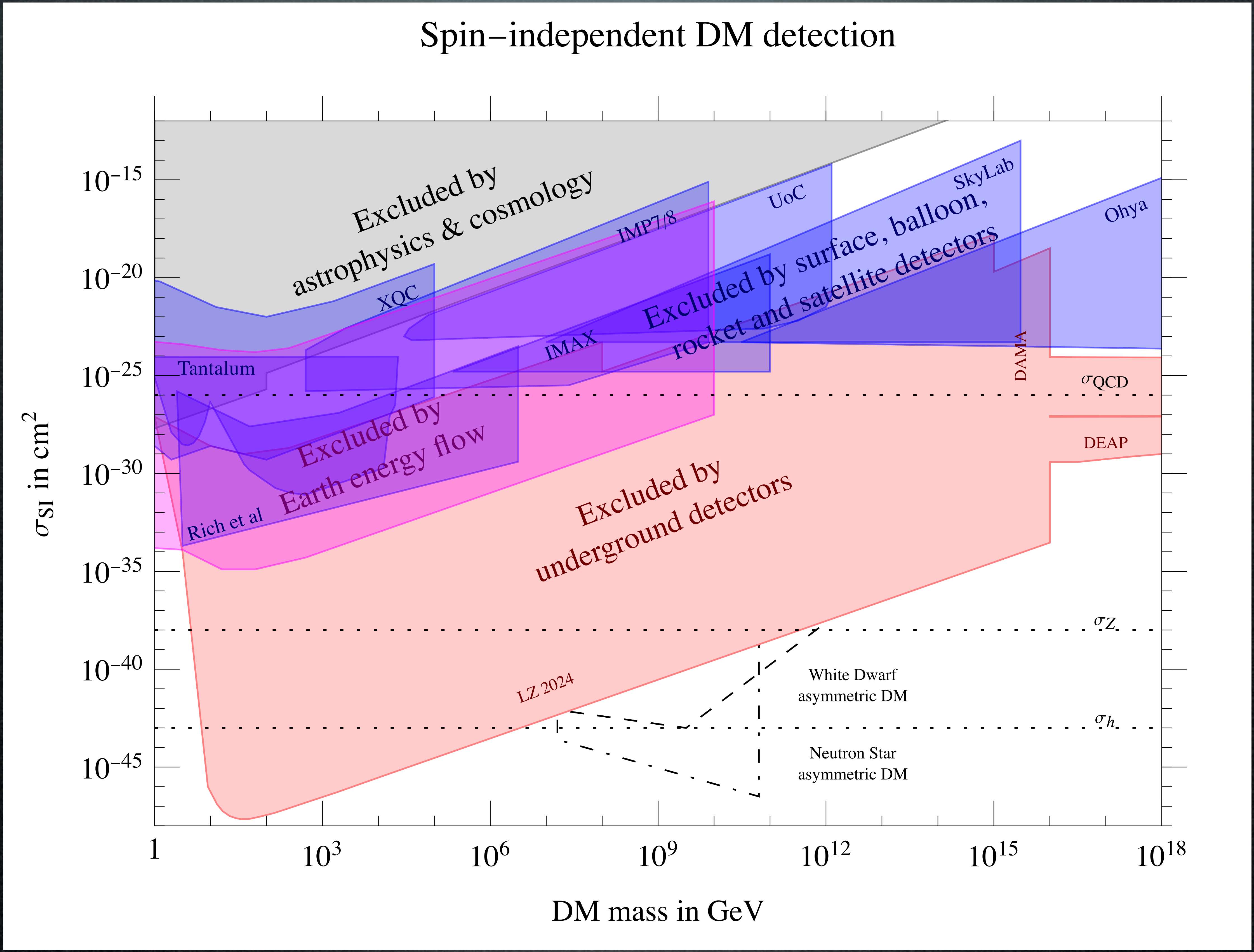
DD of strongly int DM



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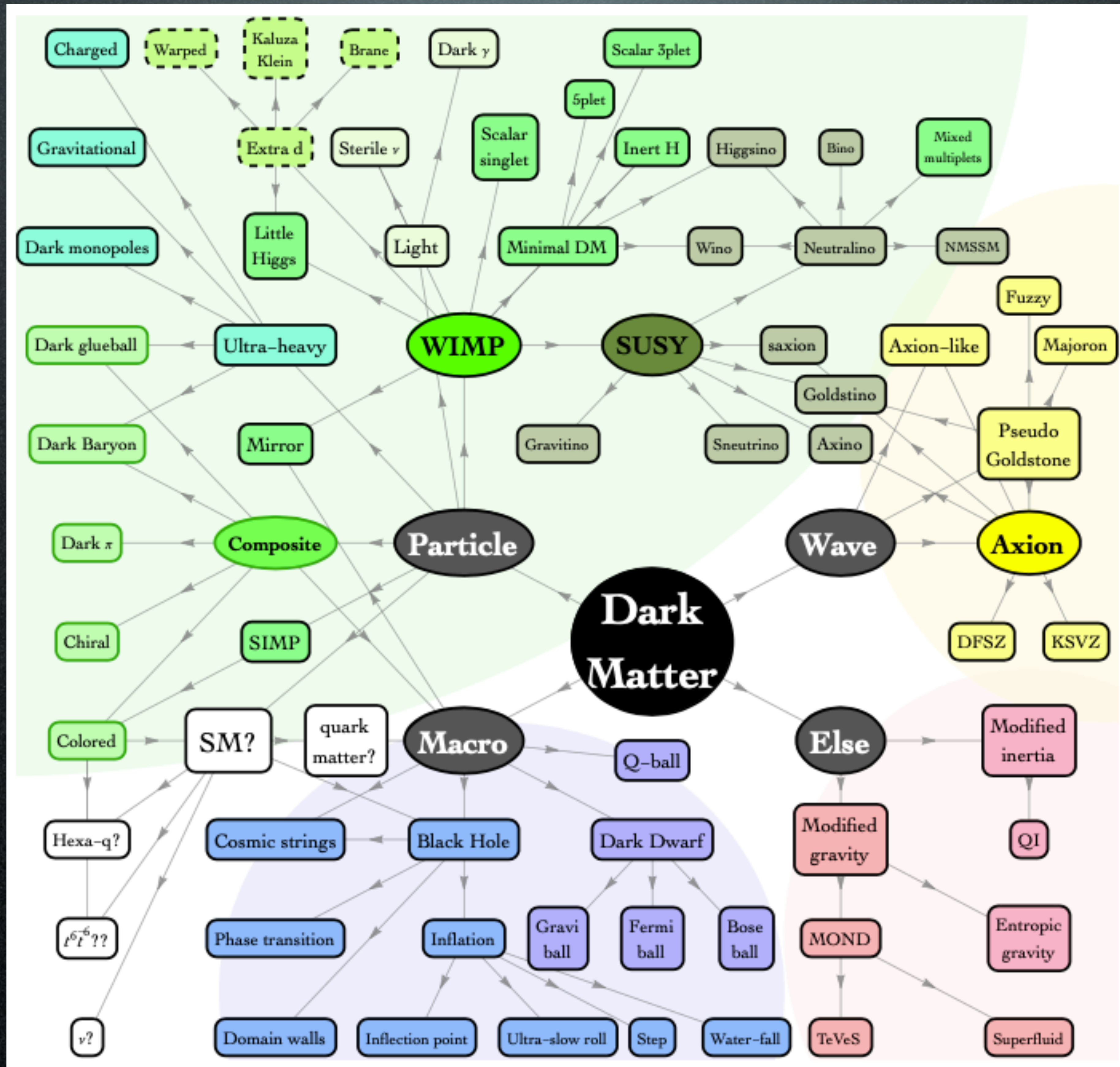
A map of DM candidates



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