

30 August 2023
TAUP 2023 Conference - Vienna, Austria

Dark Matter candidates (light and heavy)

Marco Cirelli
(CNRS LPTHE Jussieu Paris)



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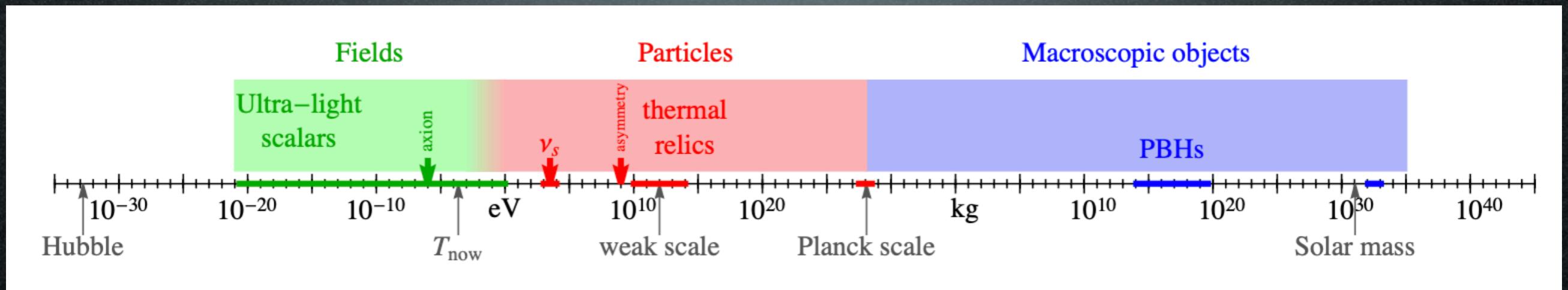
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Candidates

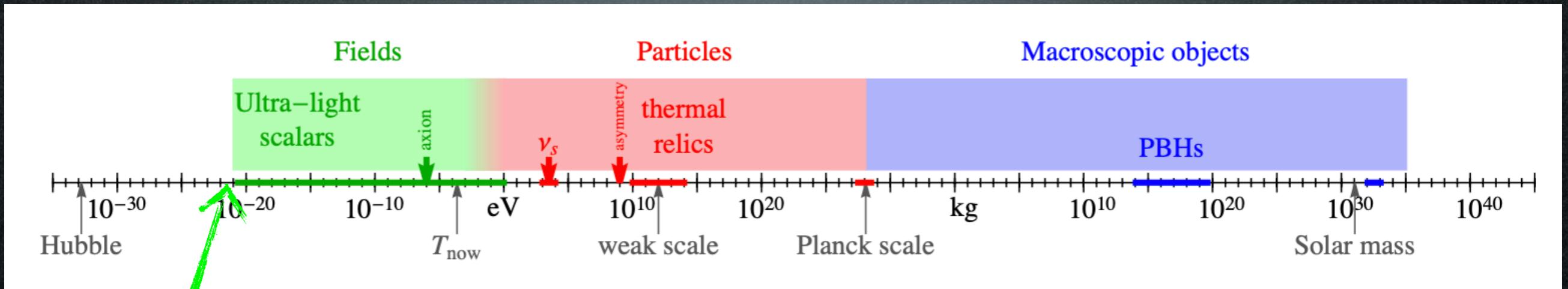
A matter of perspective: plausible mass ranges



90 orders of magnitude!

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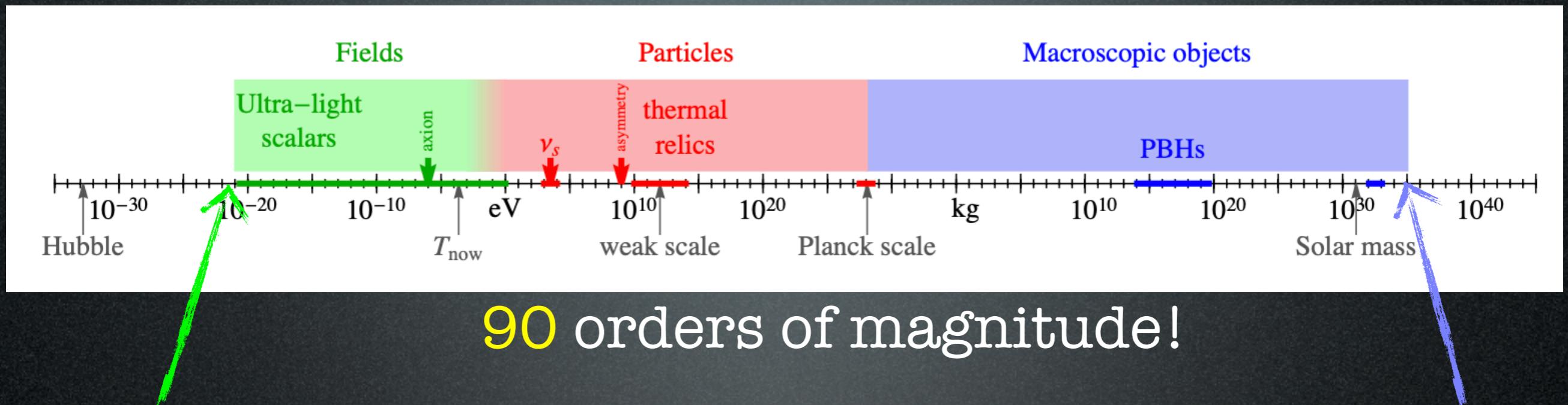
as **diffuse** as a
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DM de Broglie wavelength

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

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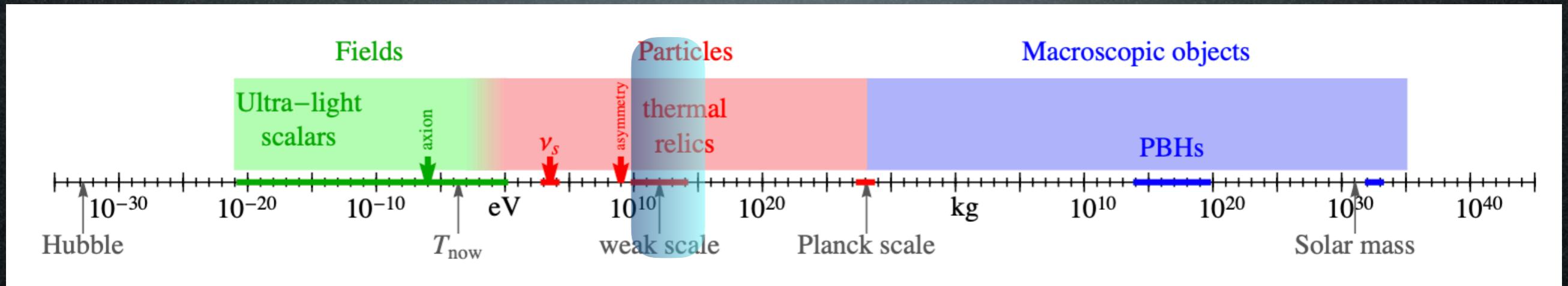
as **big** as a
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DM de Broglie wavelength
 $\lambda = 2\pi/Mv \lesssim 1 \text{ kpc}$

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

Candidates

A matter of perspective: plausible mass ranges



Candidates

WIMPs

Candidates

new physics at
the TeV scale

thermal
freeze-out

WIMPs



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WIMPs

Collider
Searches

Indirect
Detection

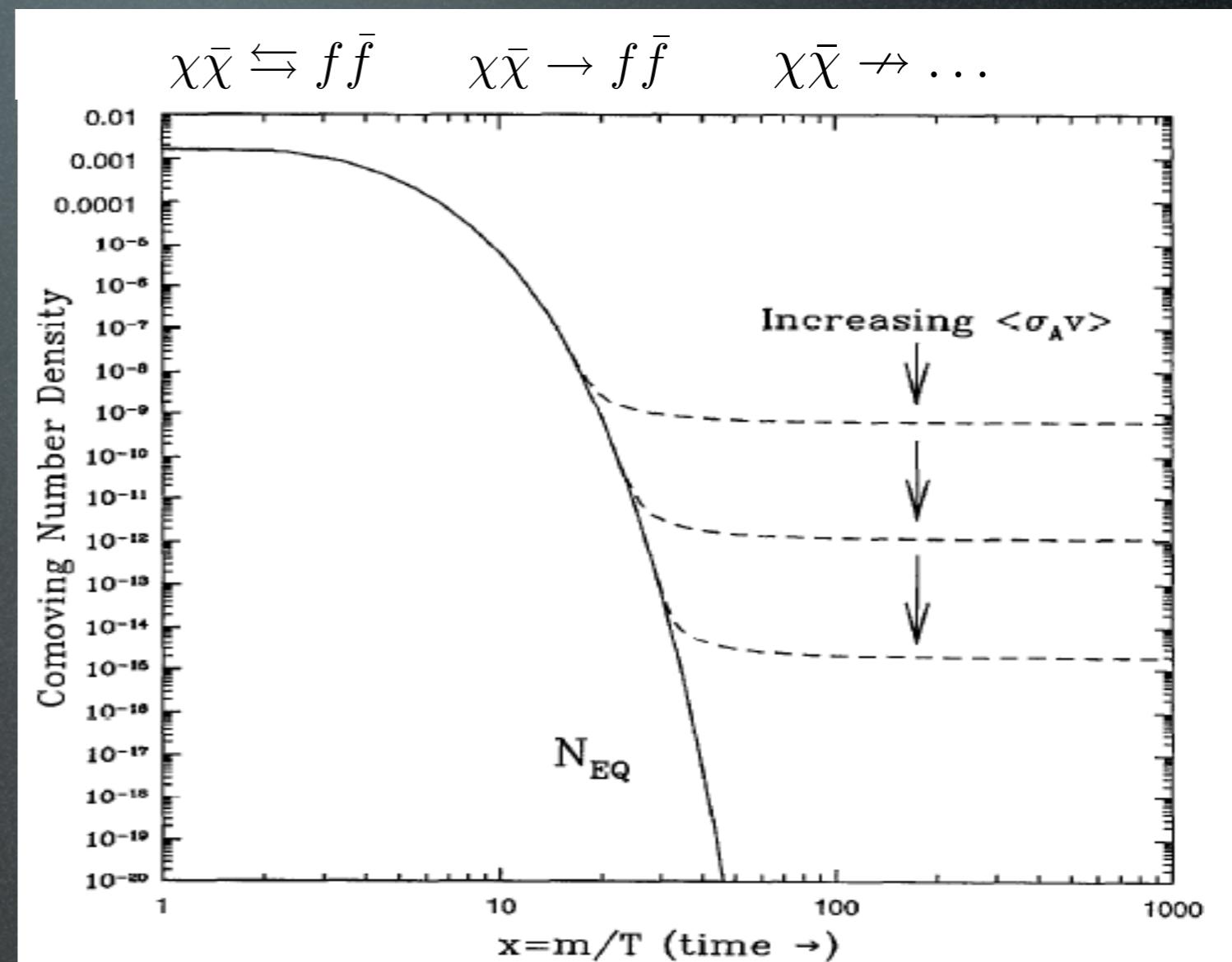
Direct
Detection

DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

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

Relic $\Omega_{\text{DM}} \simeq 0.23$ for
 $\langle \sigma_{\text{ann}} v \rangle = 3 \cdot 10^{-26} \text{ cm}^3/\text{sec}$



Weak cross section:

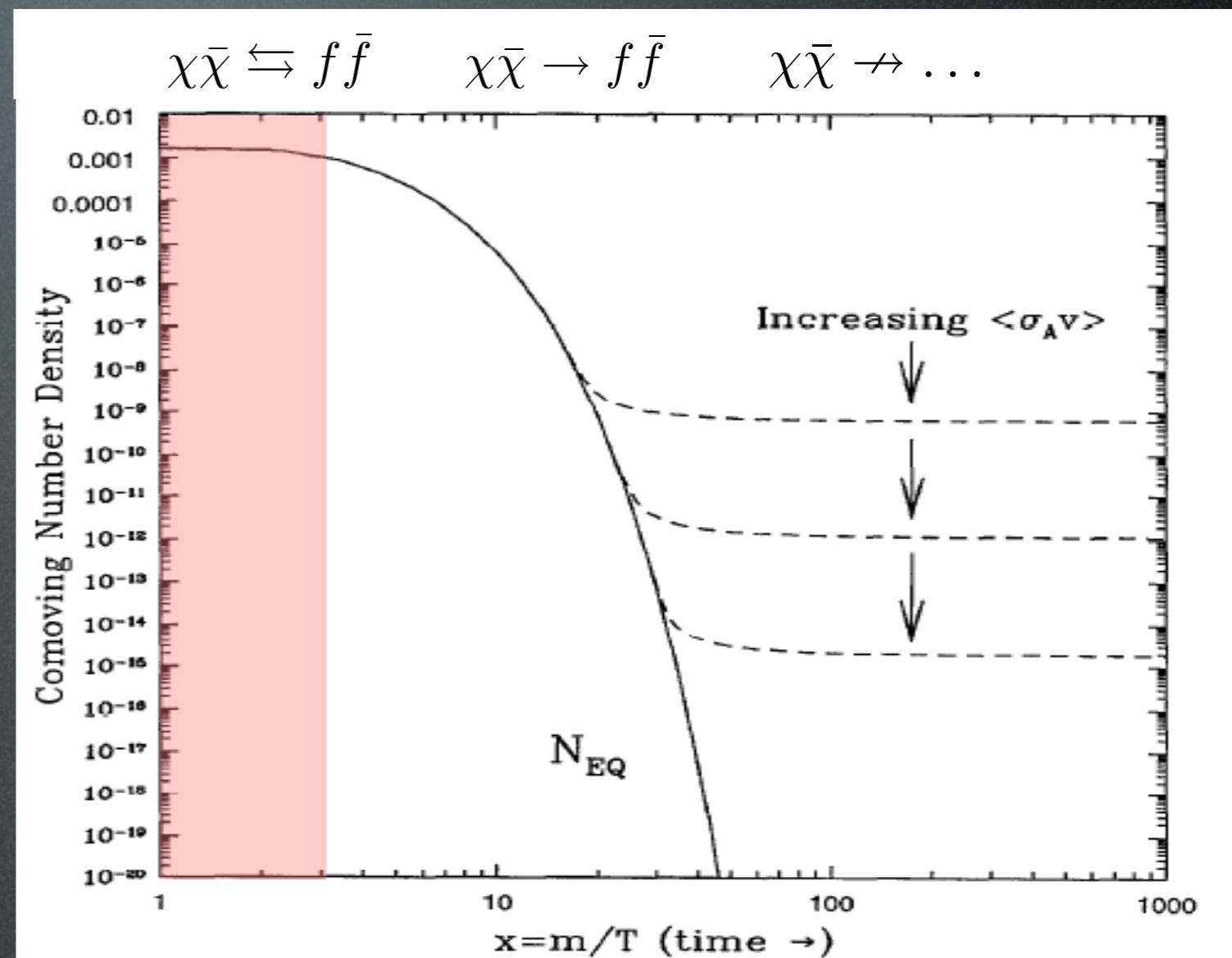
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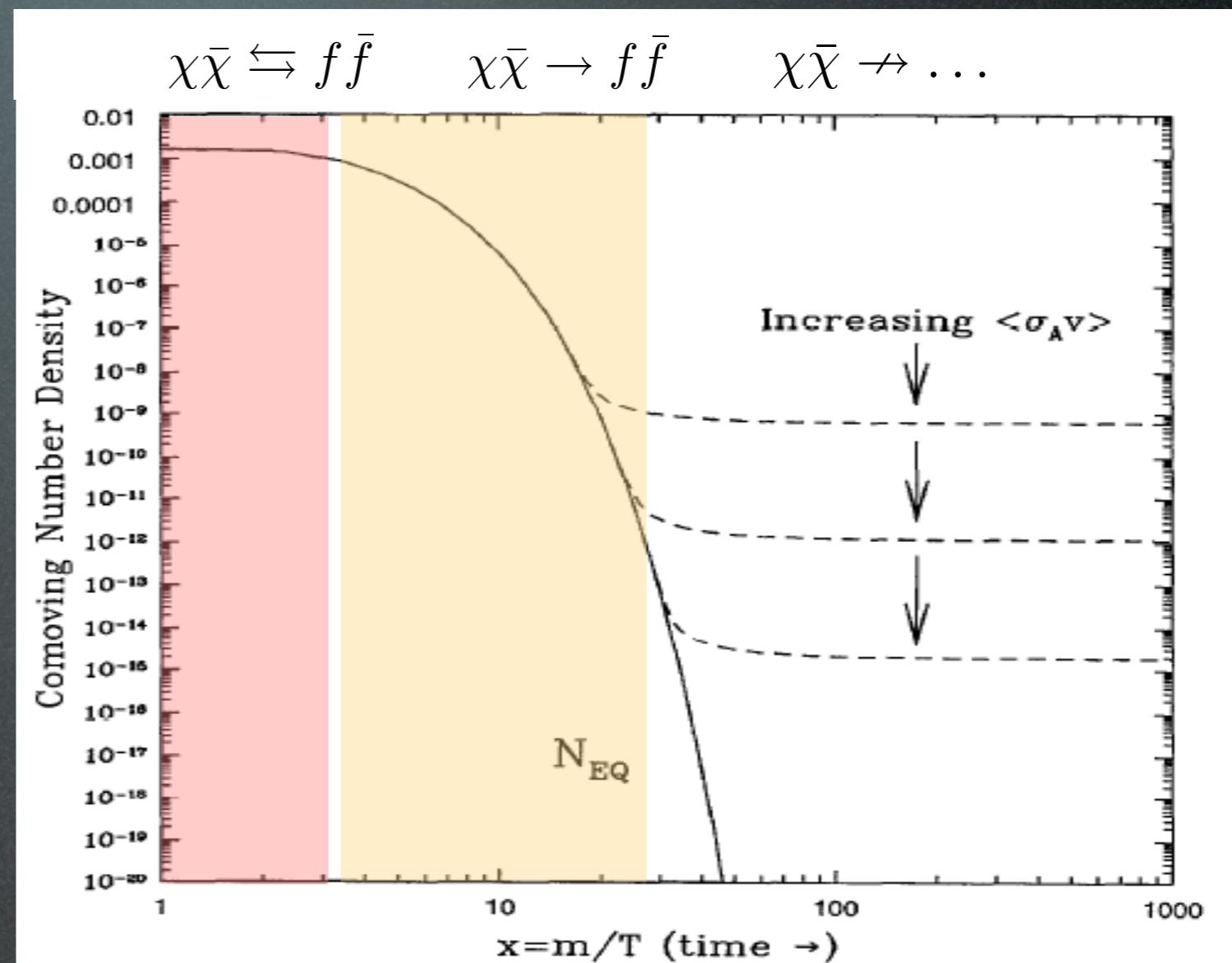
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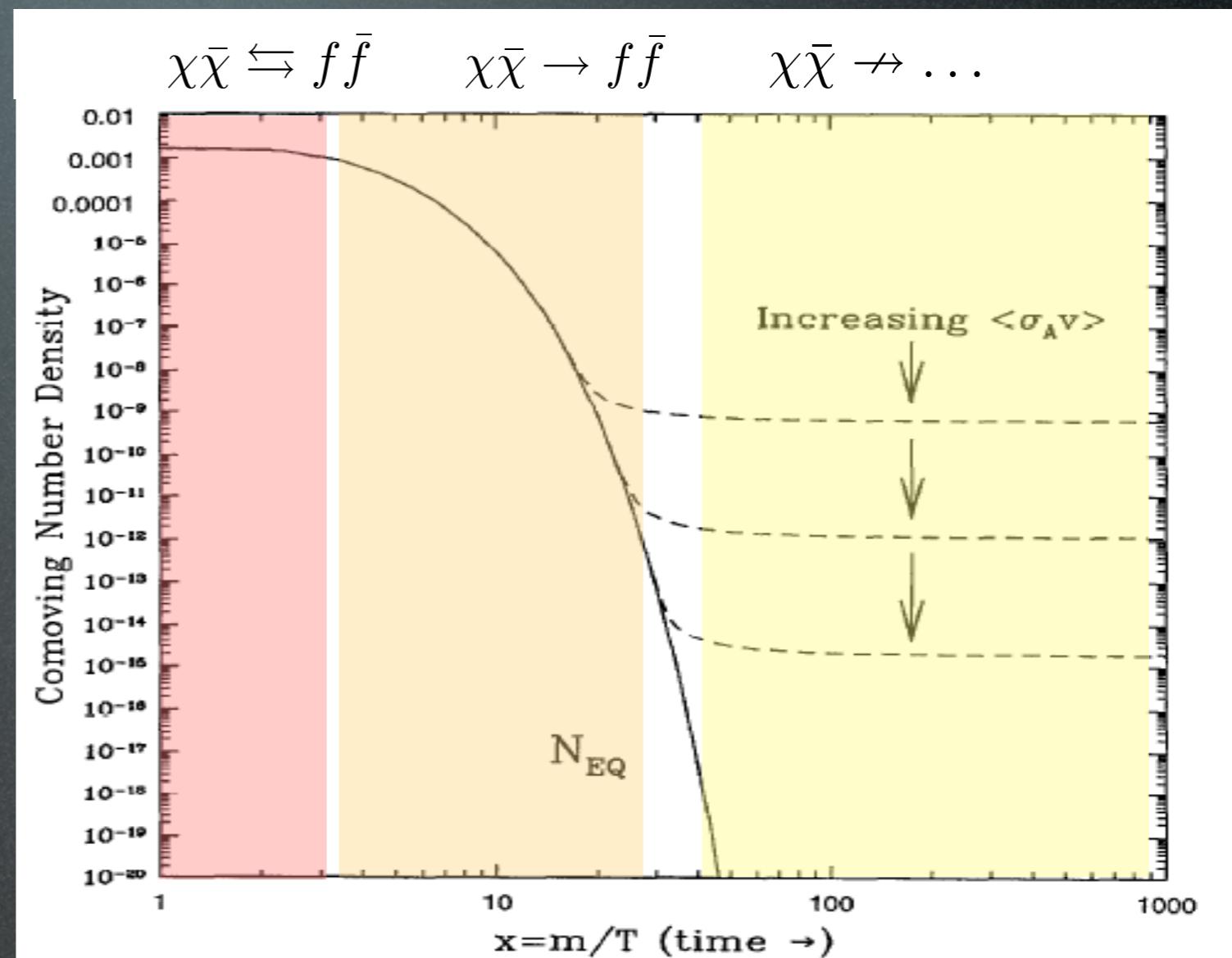
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new physics at
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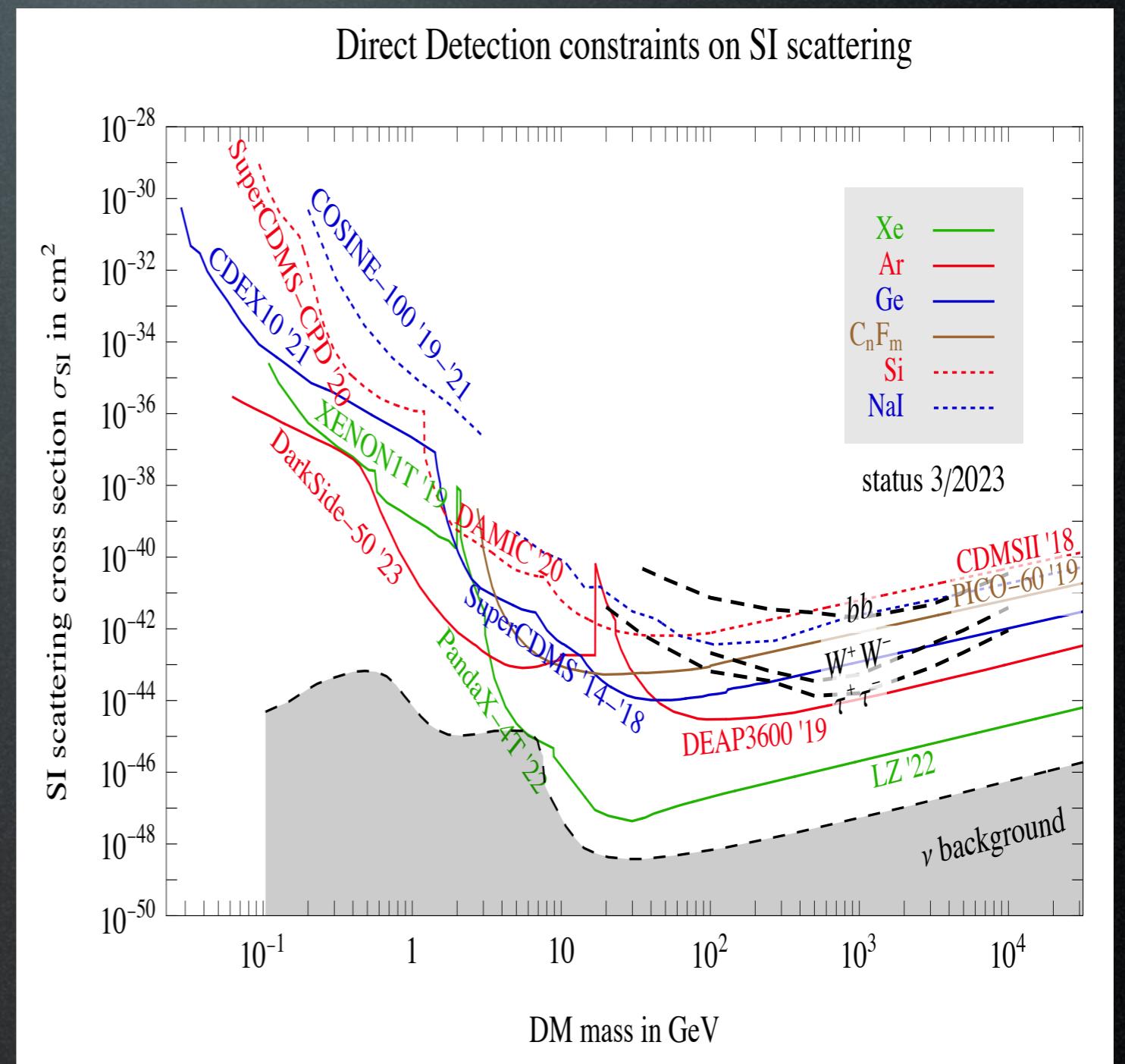
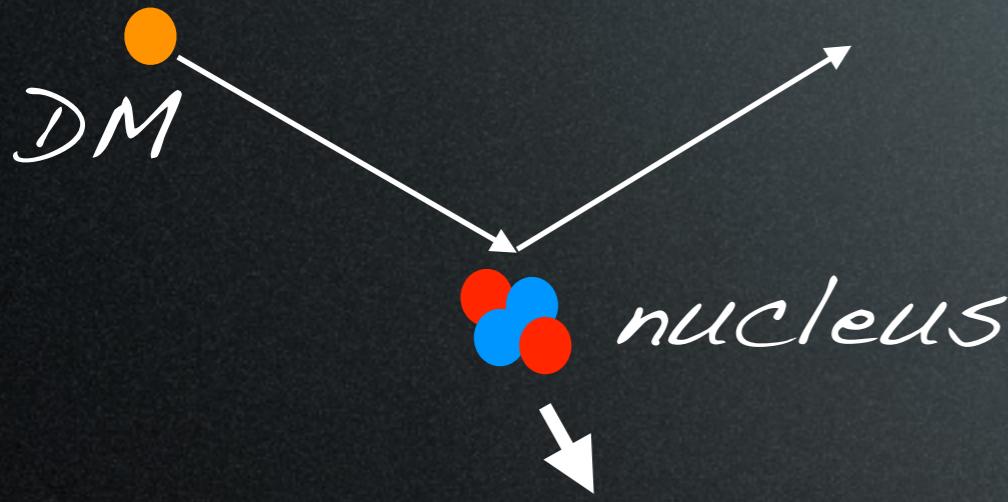
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2. the three search strategies are **complementary**

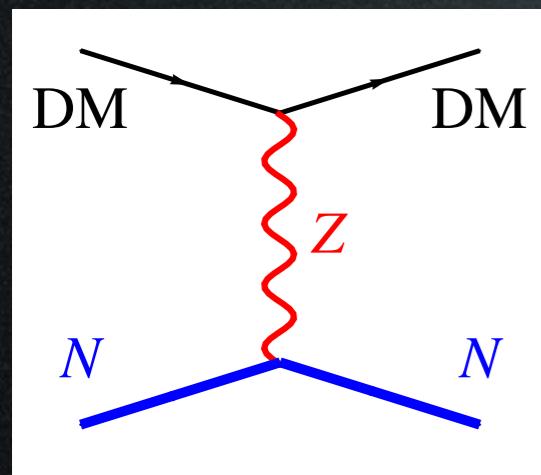
WIMP Direct Detection

SM weak scale SI interactions

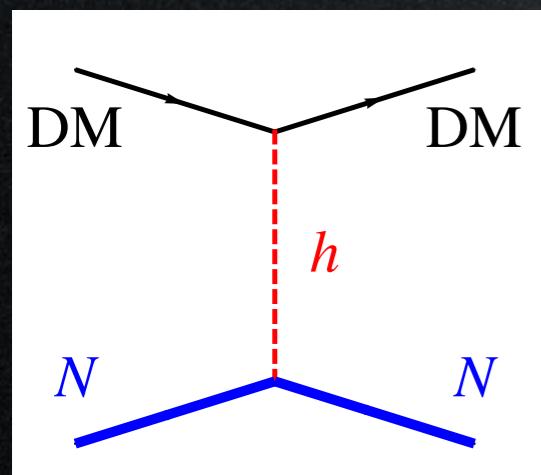


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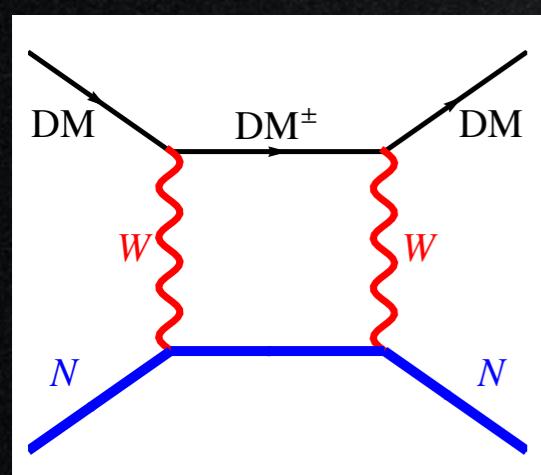
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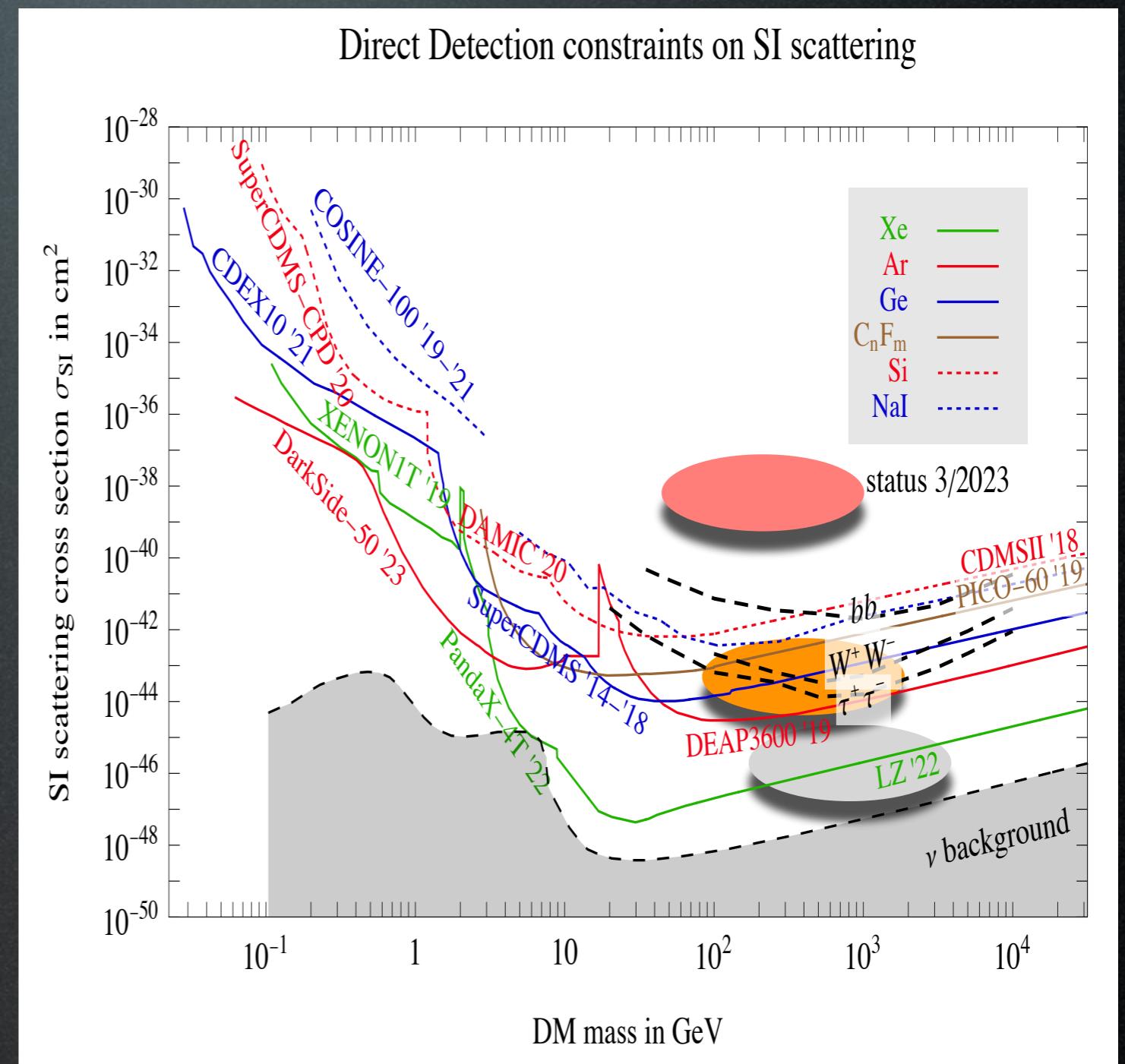
tree level,
vector



tree level,
scalar



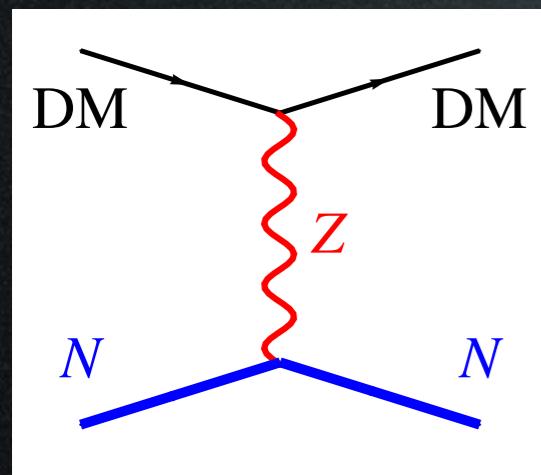
one loop



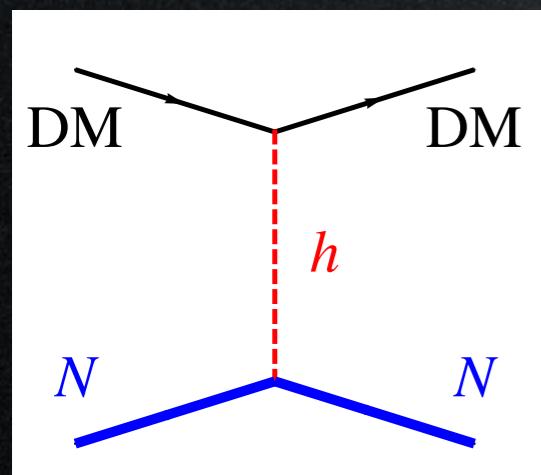
M. Cirelli, A. Strumia, J. Zupan to appear

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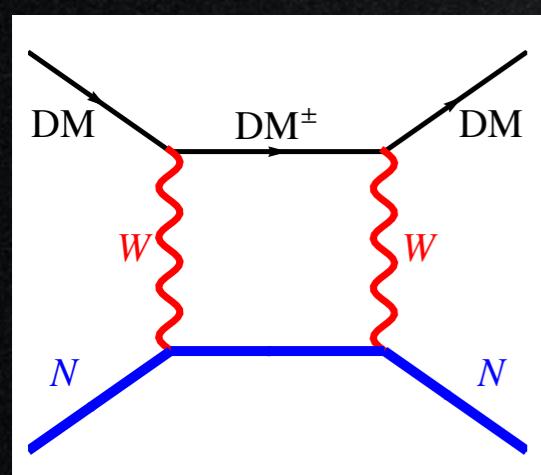
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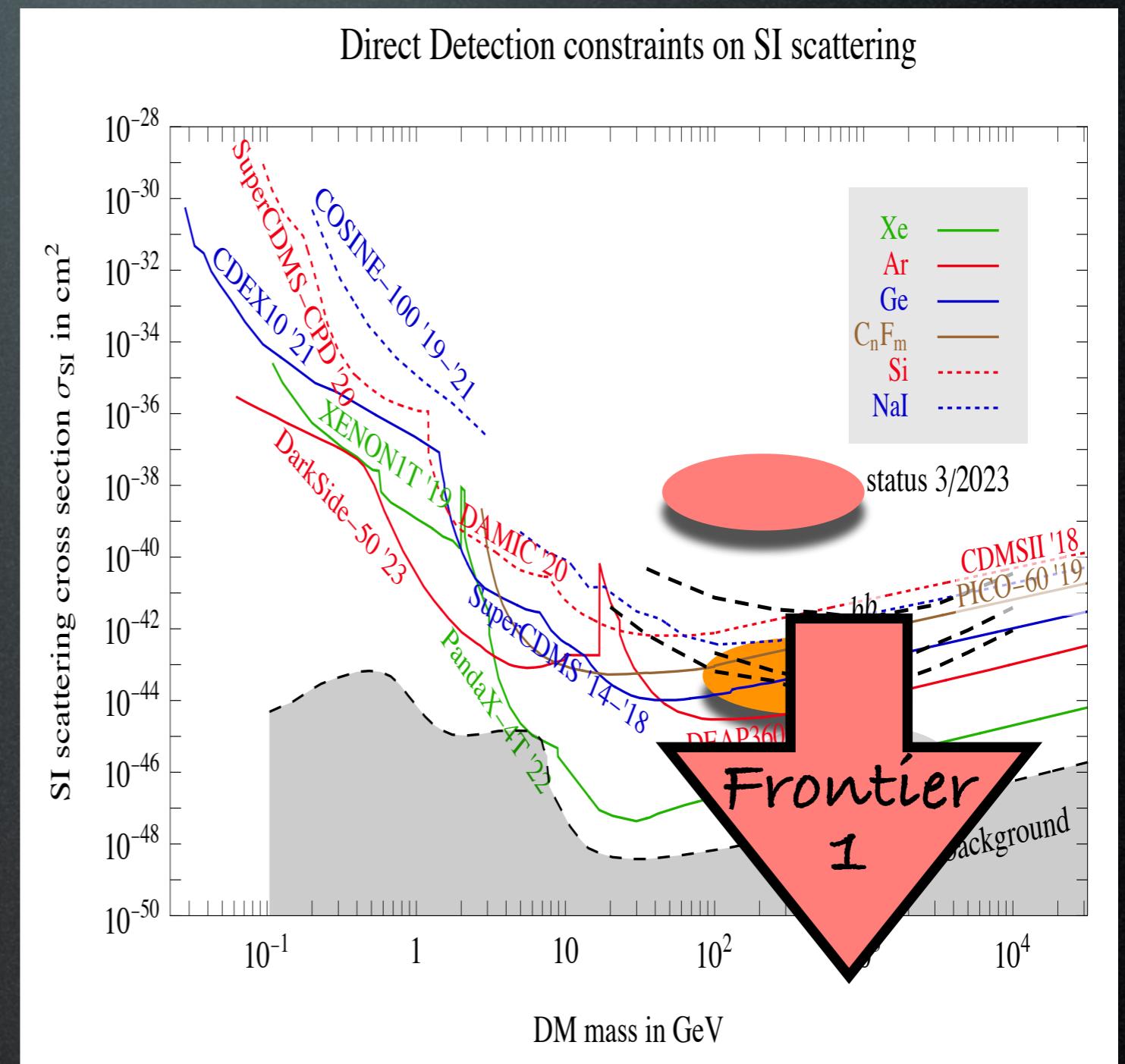
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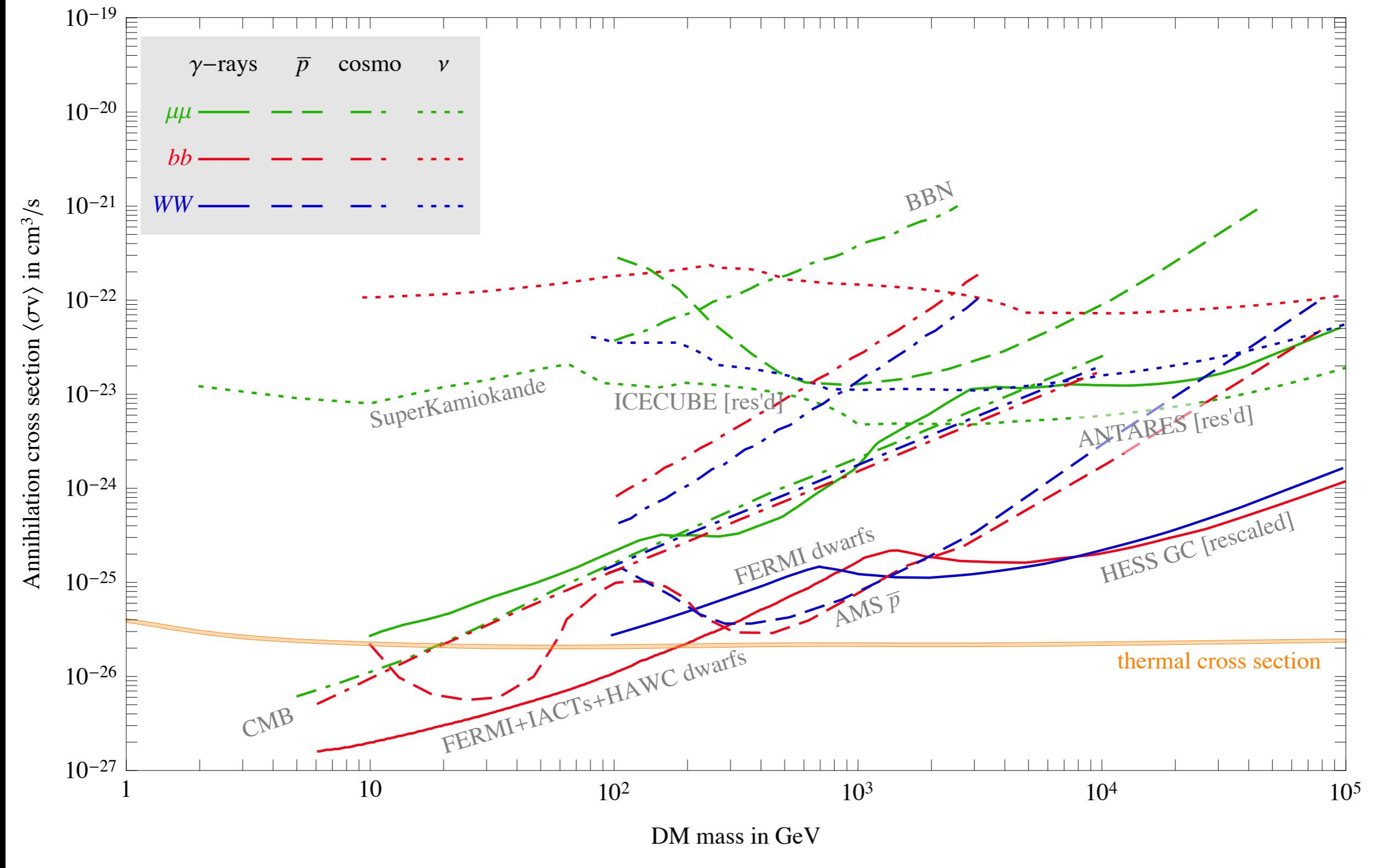
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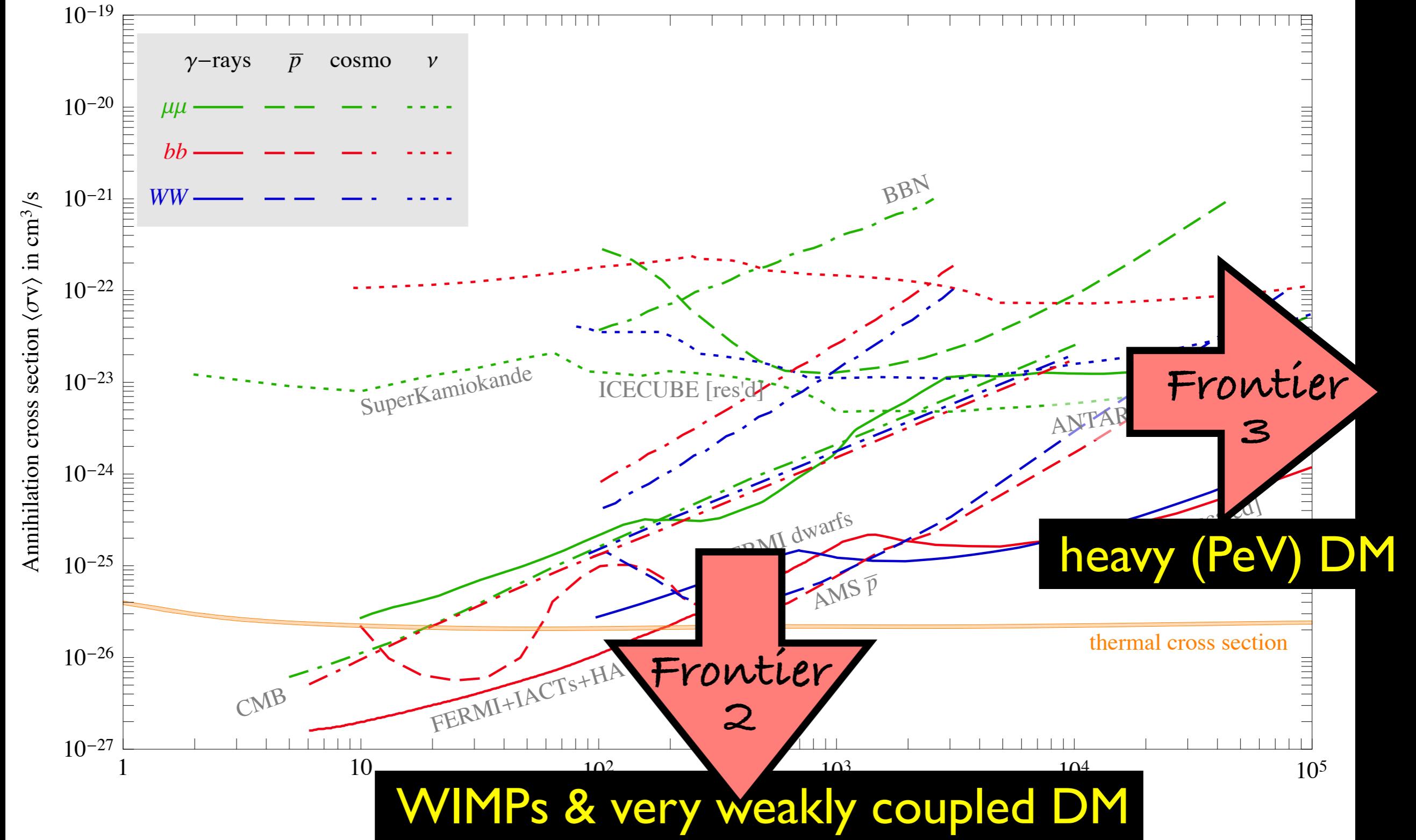
WIMP Indirect Detection

All Indirect Detection constraints



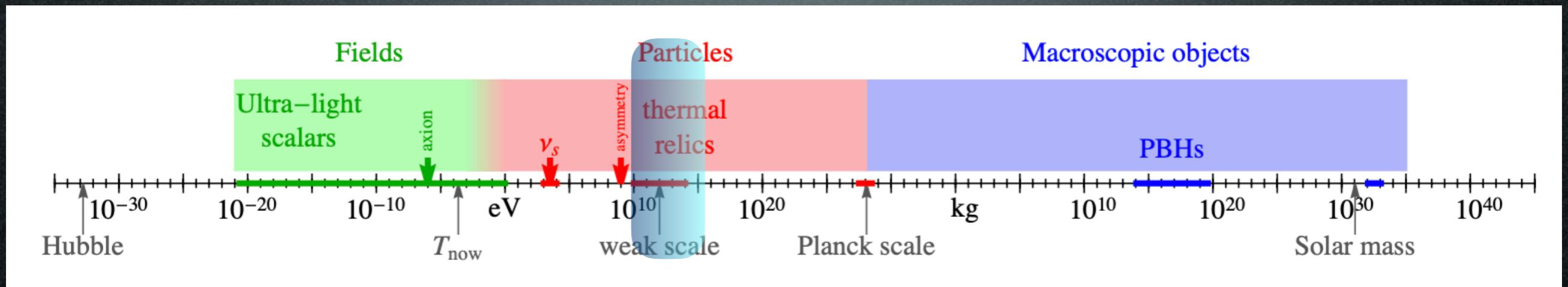
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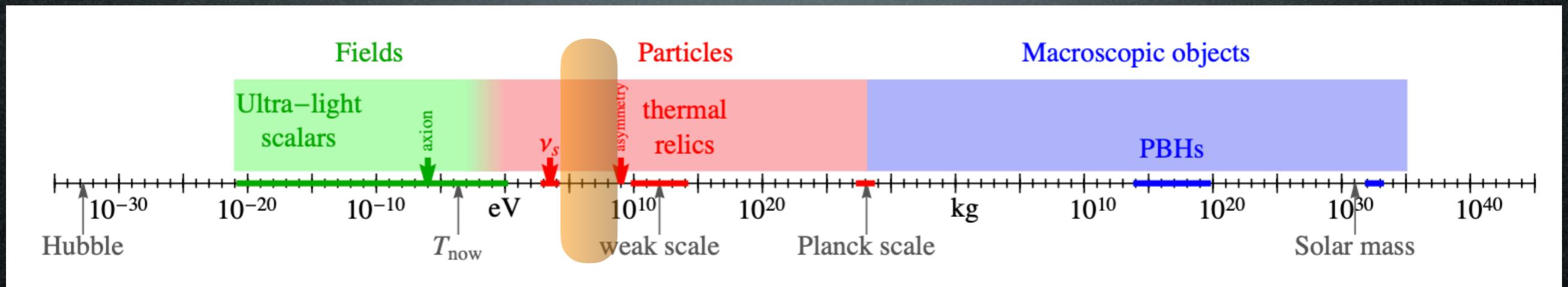
Candidates

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Sub-GeV DM?

Candidates

theory?

production?

Sub-GeV DM?

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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

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- WIMPless Dark Matter

Feng & Kumar 0803.4196

a.k.a. hidden sector DM
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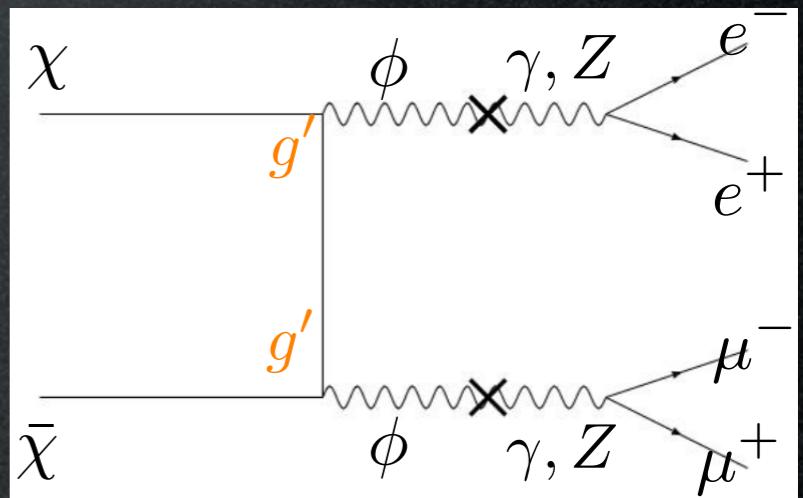
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if g_x is small,
 m ‘naturally’ small
(but nothing points to a precise value)



Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM

- ‘SIMP miracle’: scalar DM with relic abundance set by $3 \rightarrow 2$ processes

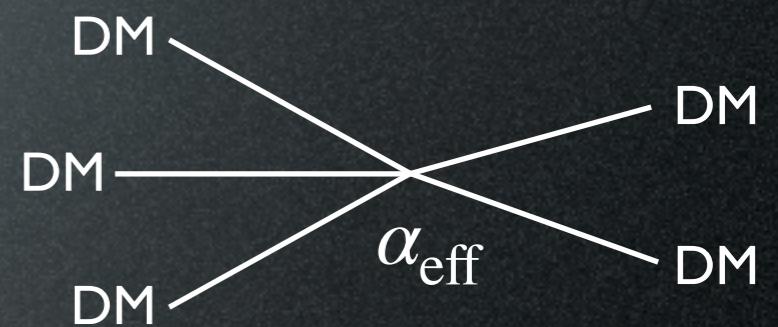
points to

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

Hochberg et al 1402.5143

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

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



Theory

Sub-GeV DM

- ‘simplified (light) DM models’

Knapen, Lin, Zurek 1709.07882

Theory

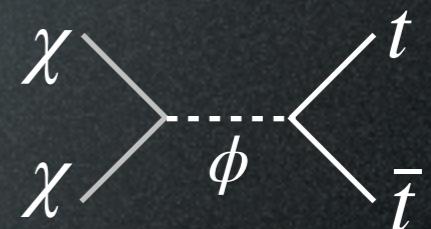
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scalar DM and
hadrophilic
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Knapen, Lin, Zurek 1709.07882

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



Theory

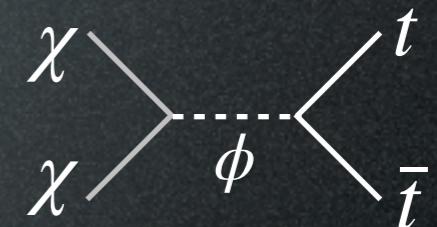
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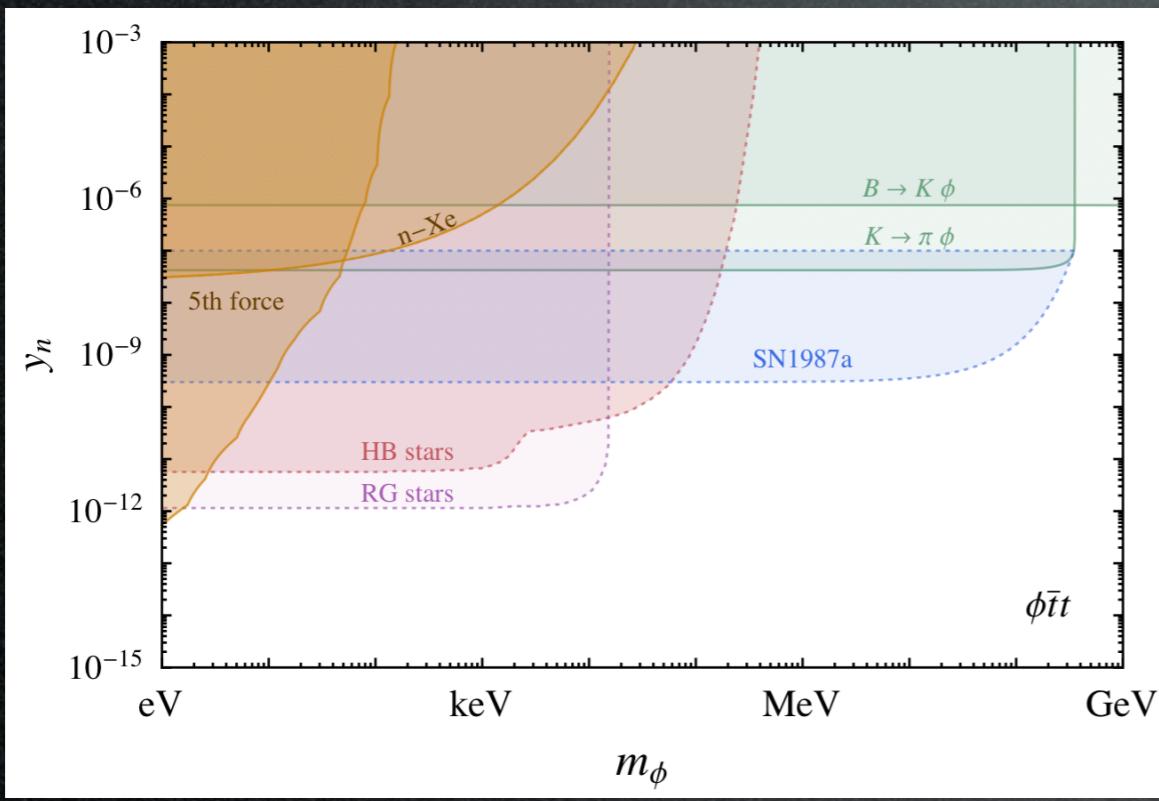
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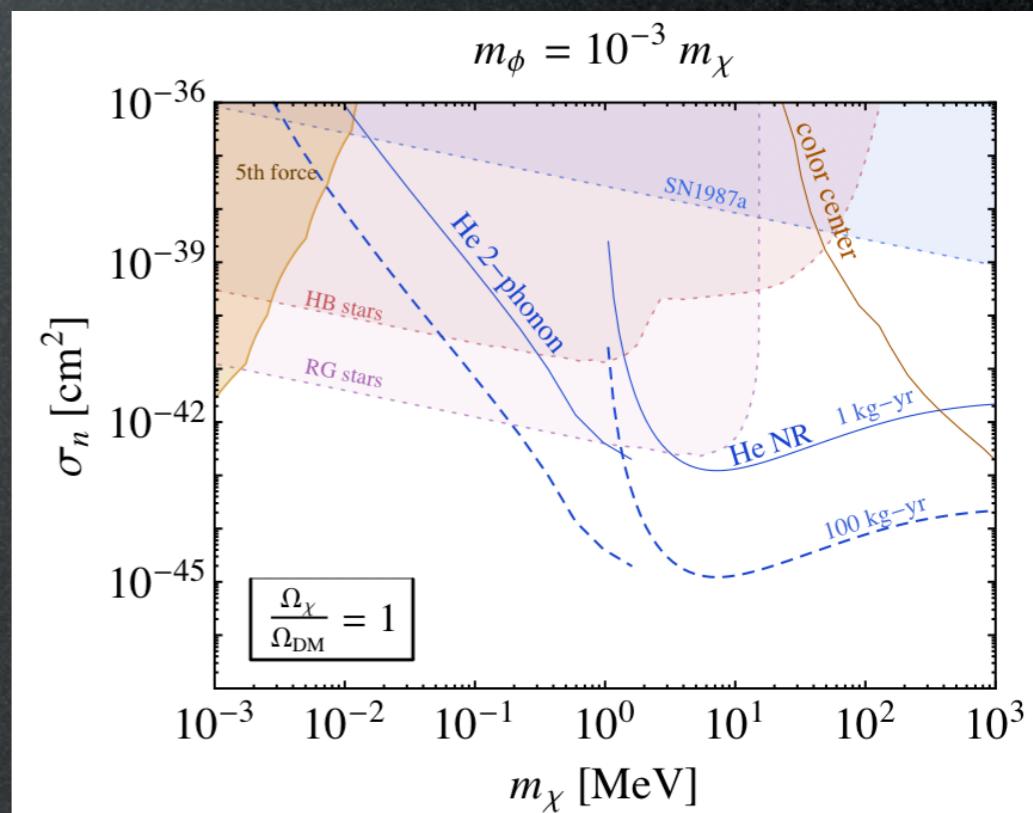
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constraints on the mediator



constraints on the DM



Theory

Sub-GeV DM?

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

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Why not!

Candidates

theory

production

Sub-GeV DM?

Collider
Searches?

Indirect
Detection?

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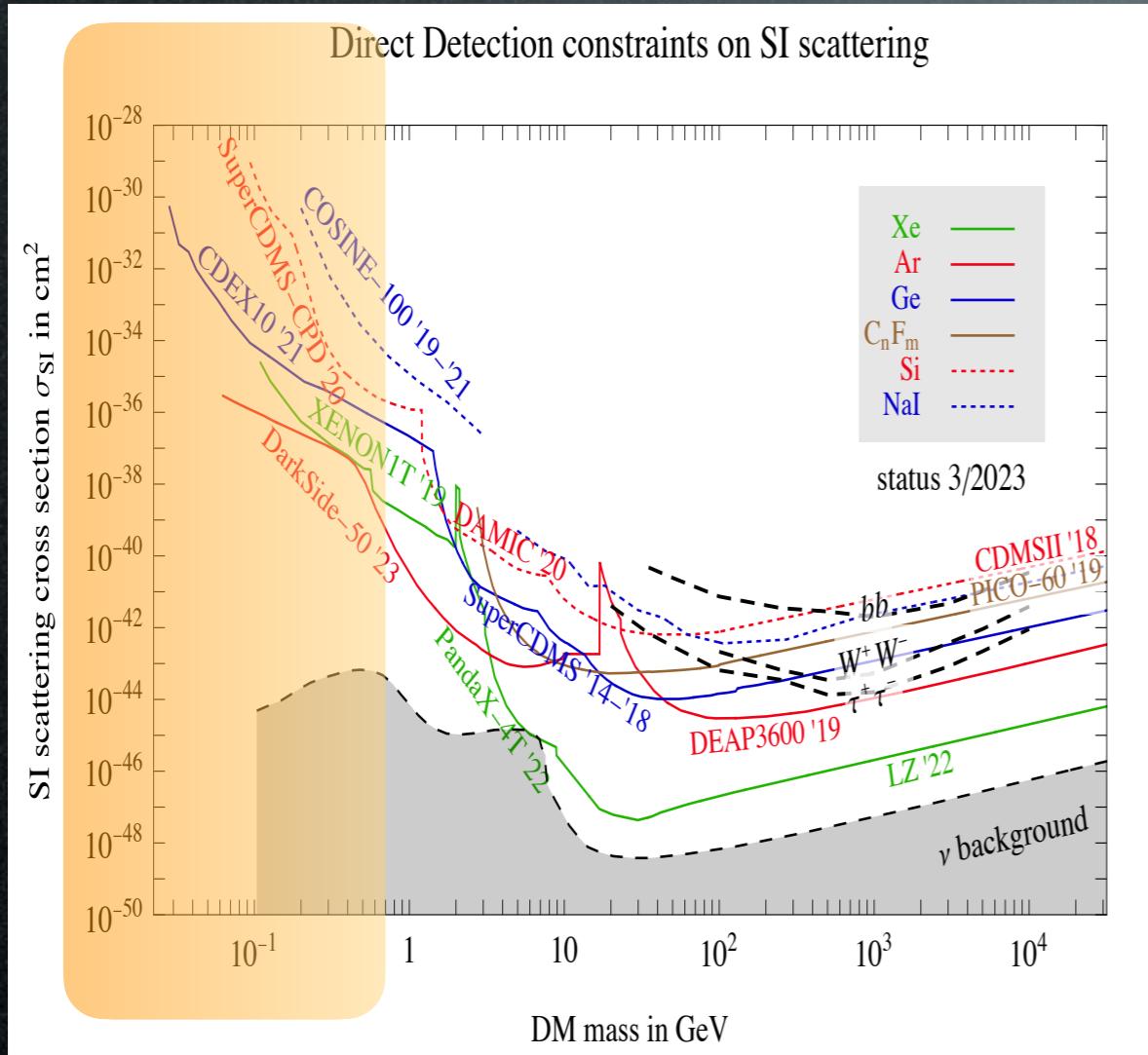
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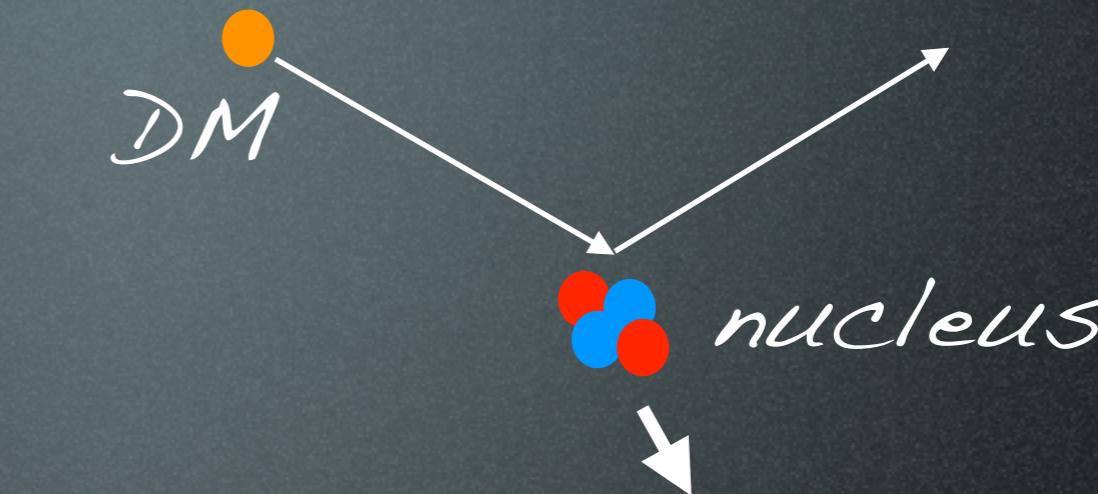
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Direct Detection of sub-GeV DM



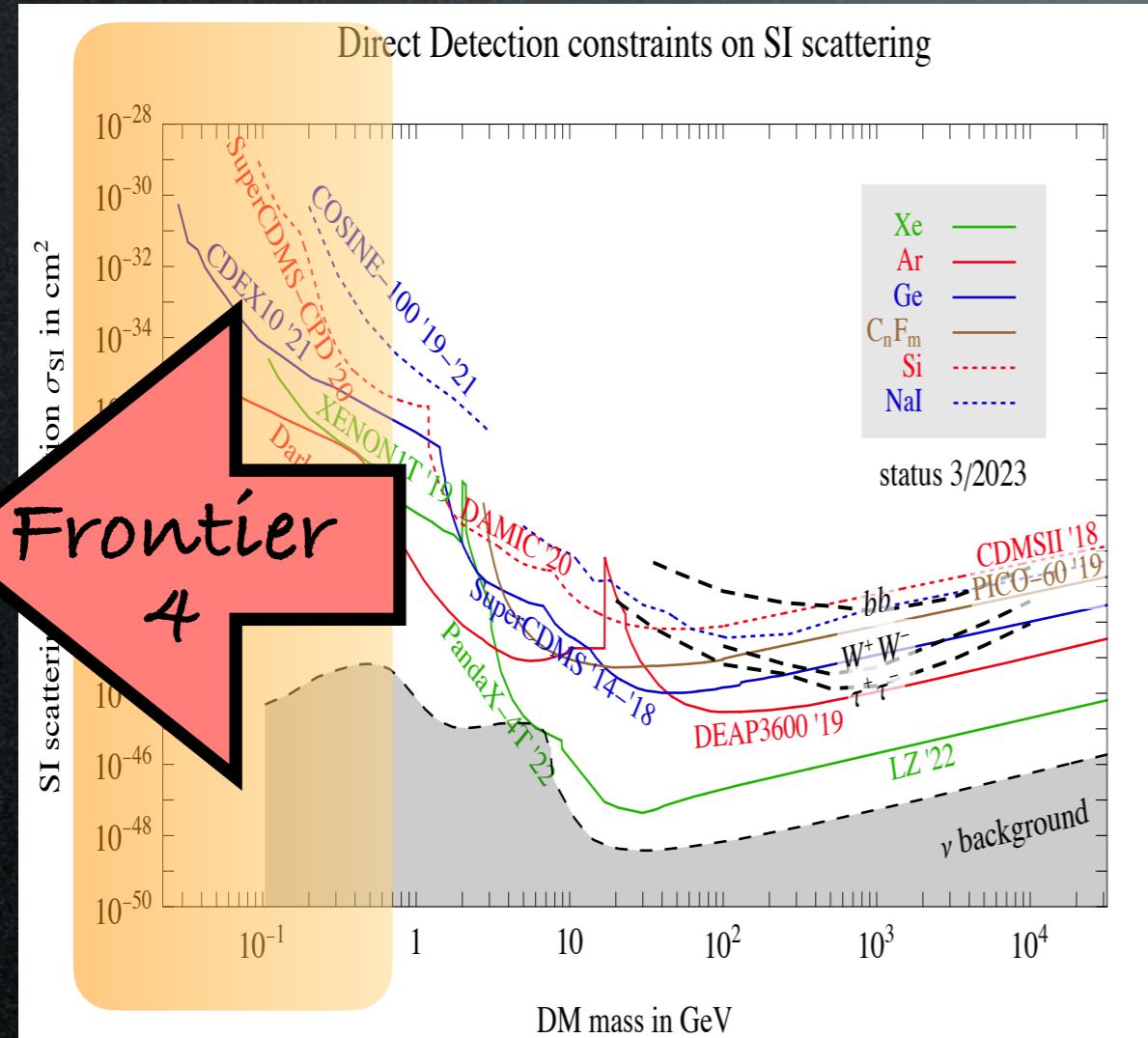
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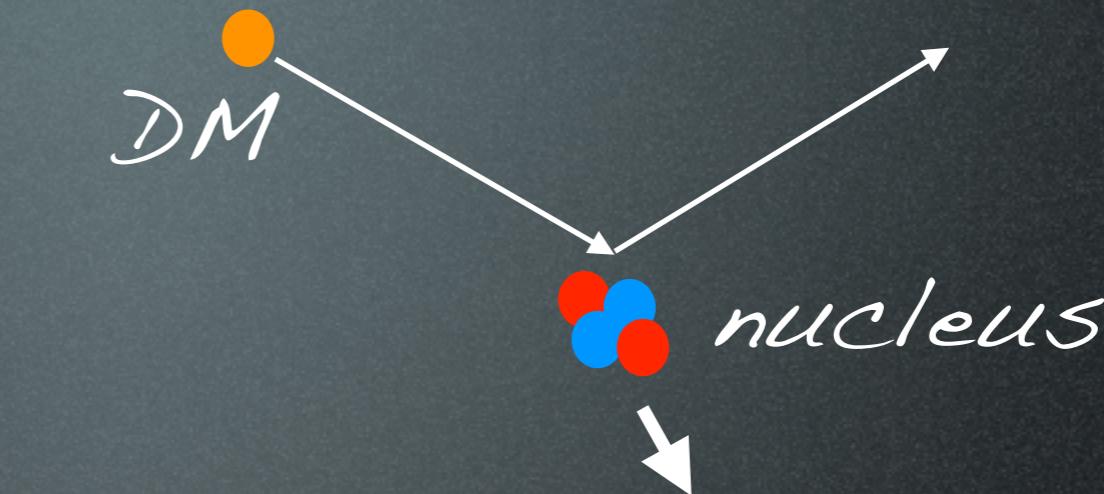
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below threshold for typical
nuclear recoil experiments

- electron recoil signal
- Migdal effect
- new experimental strategies

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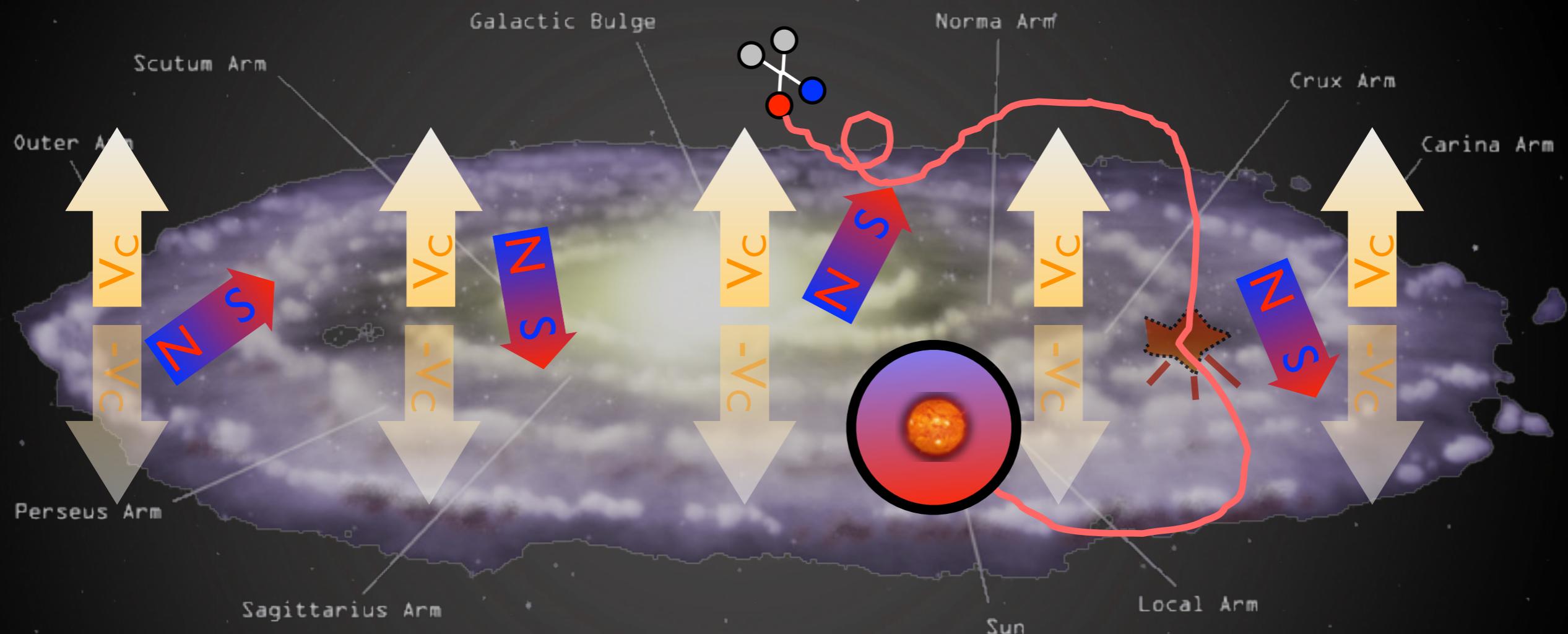
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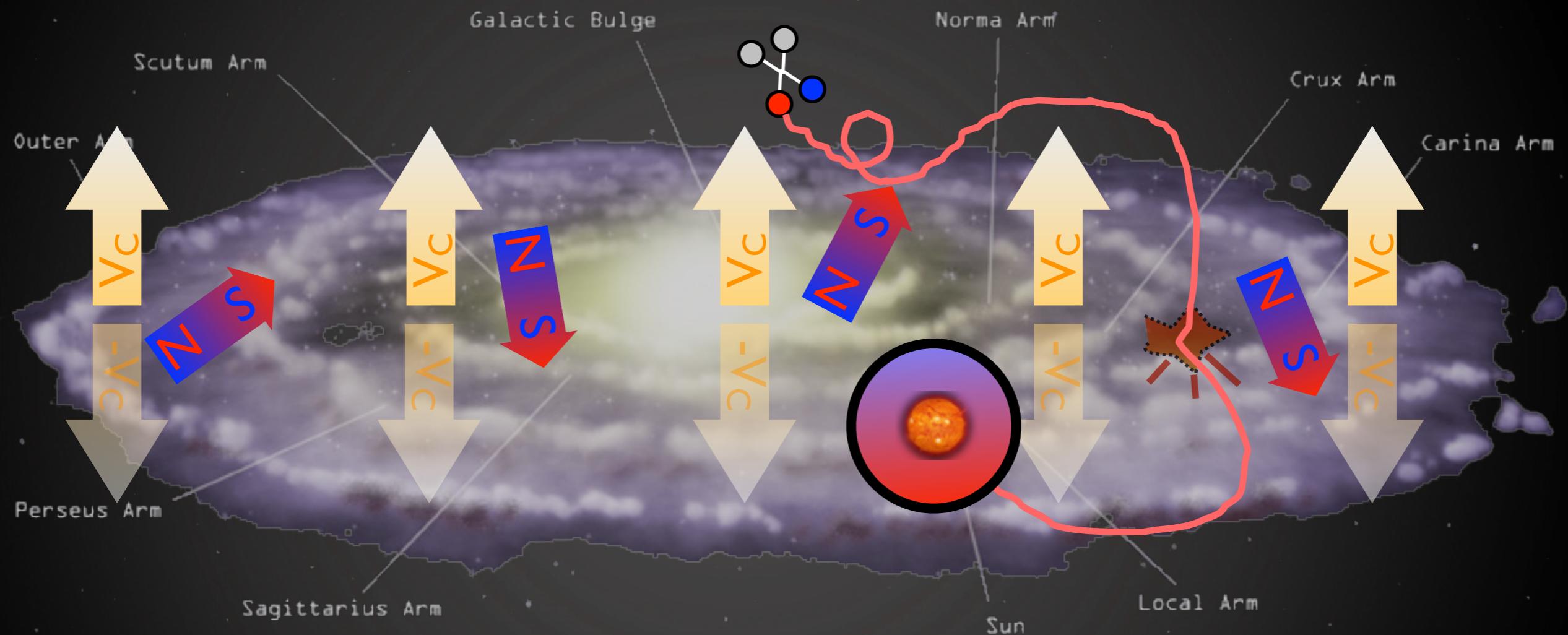
Indirect Detection: charged CRs

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



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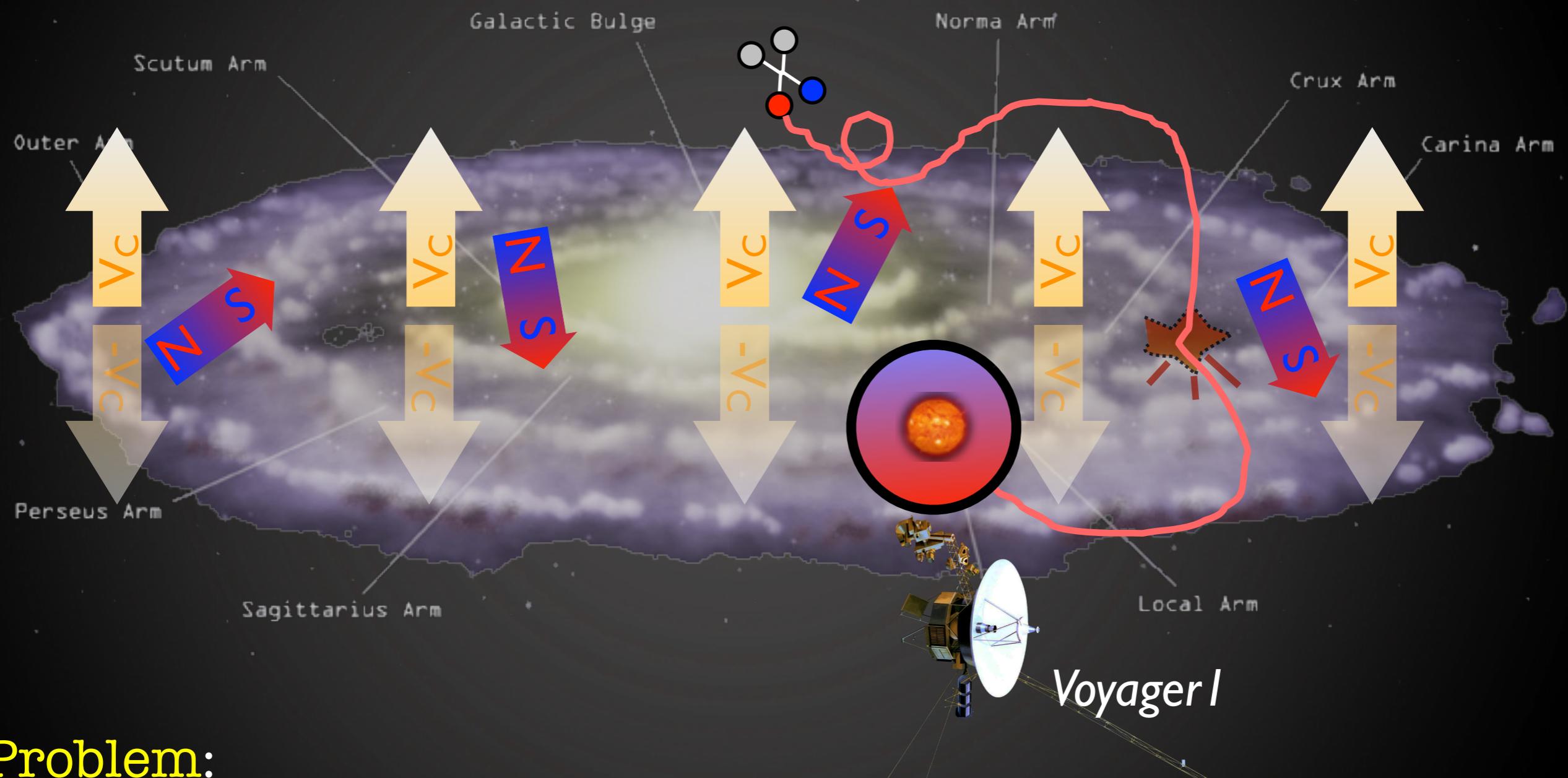


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sub-GeV charged CRs do not penetrate the heliosphere,
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Indirect Detection: charged CRs

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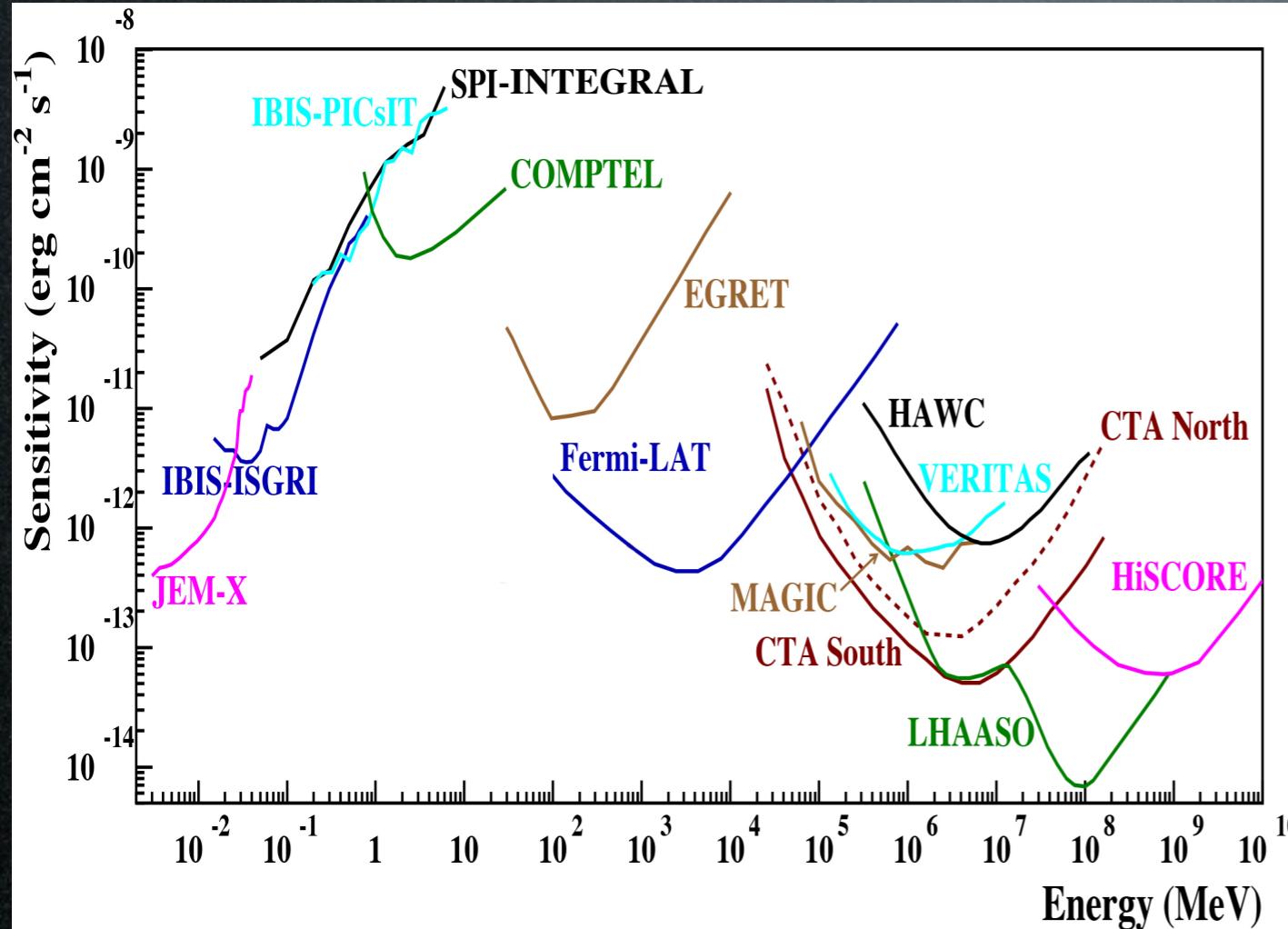


Problem:

sub-GeV charged CRs do not penetrate the heliosphere,
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Indirect detection: photons

adapted from 1611.02232



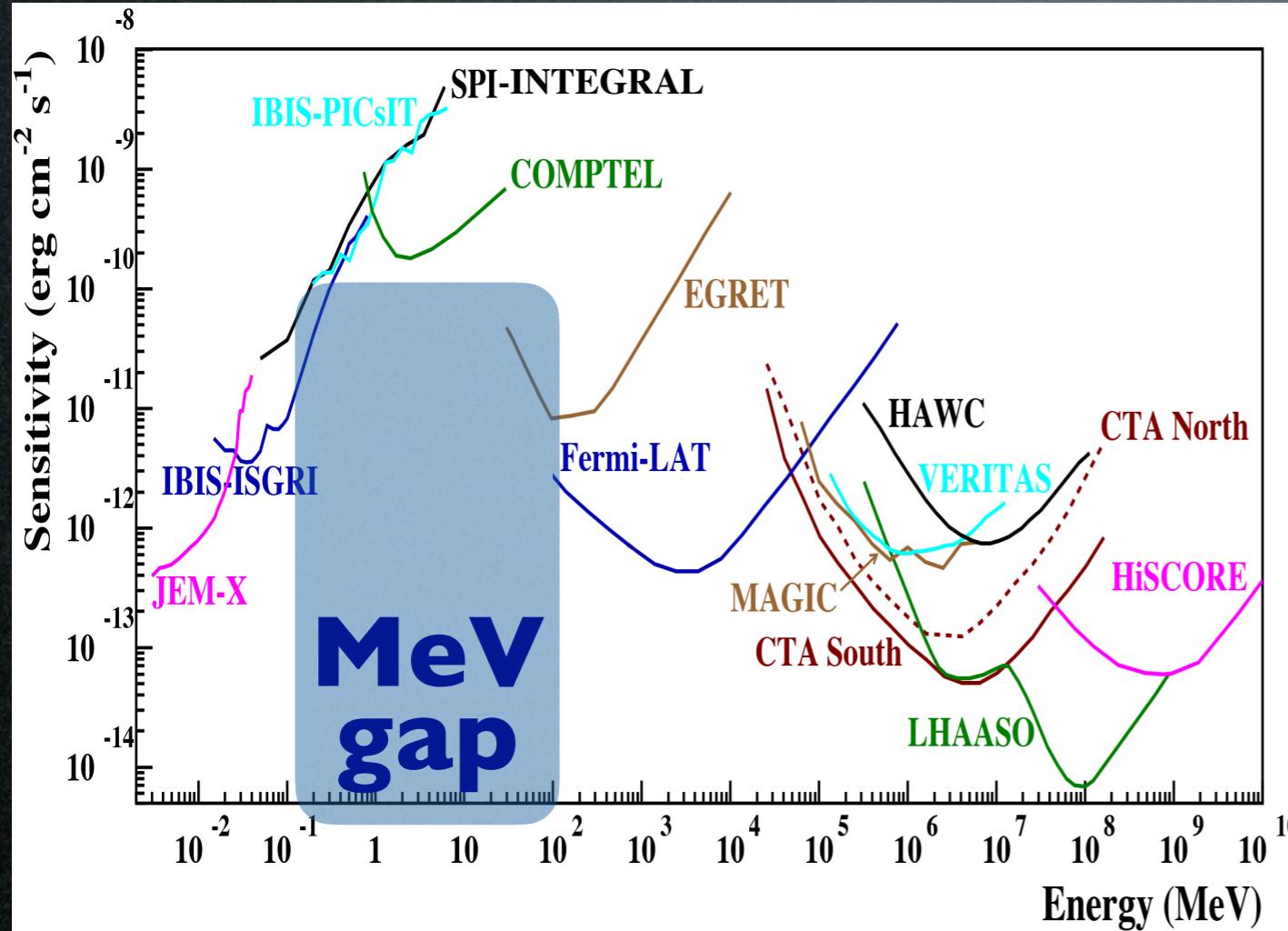
Past/current experiments:
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(2002 →) (1991-2000) (2009 →)

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

AMEGO	satellite	2020s?	HEP detectors	γ-rays	0.2 – 10 GeV
COMPARI	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

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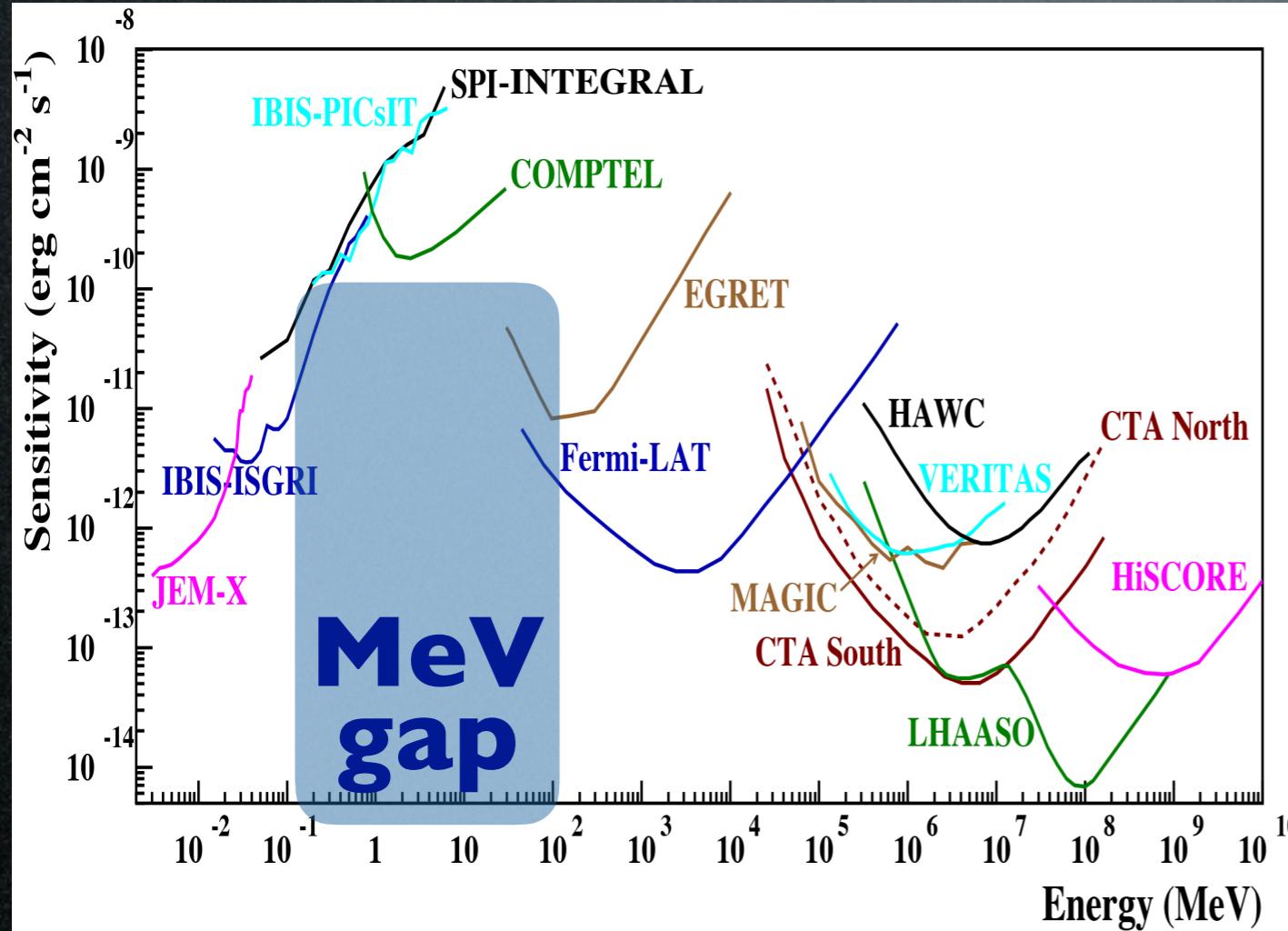
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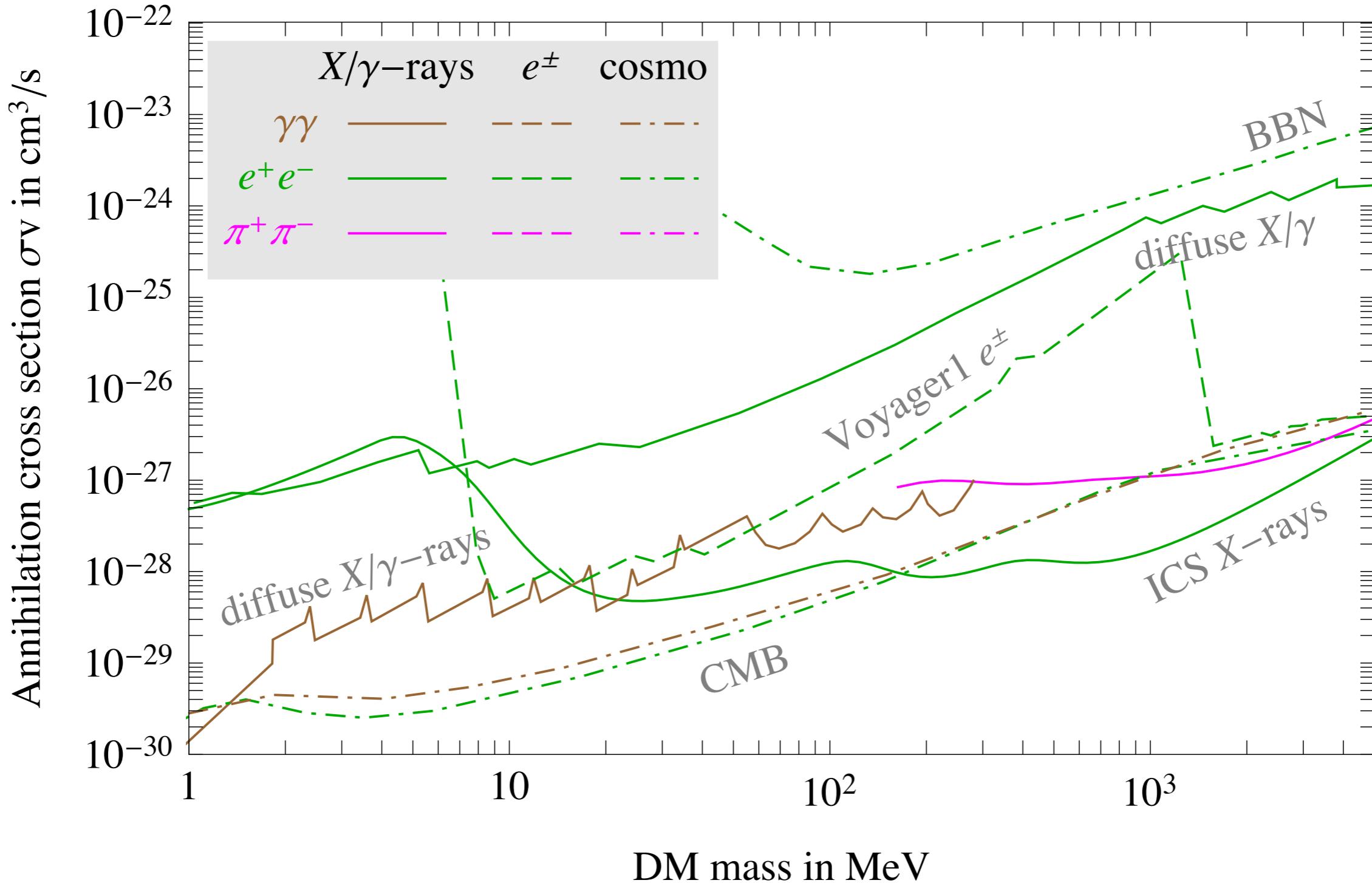
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How to do better?
ICS & X-rays!

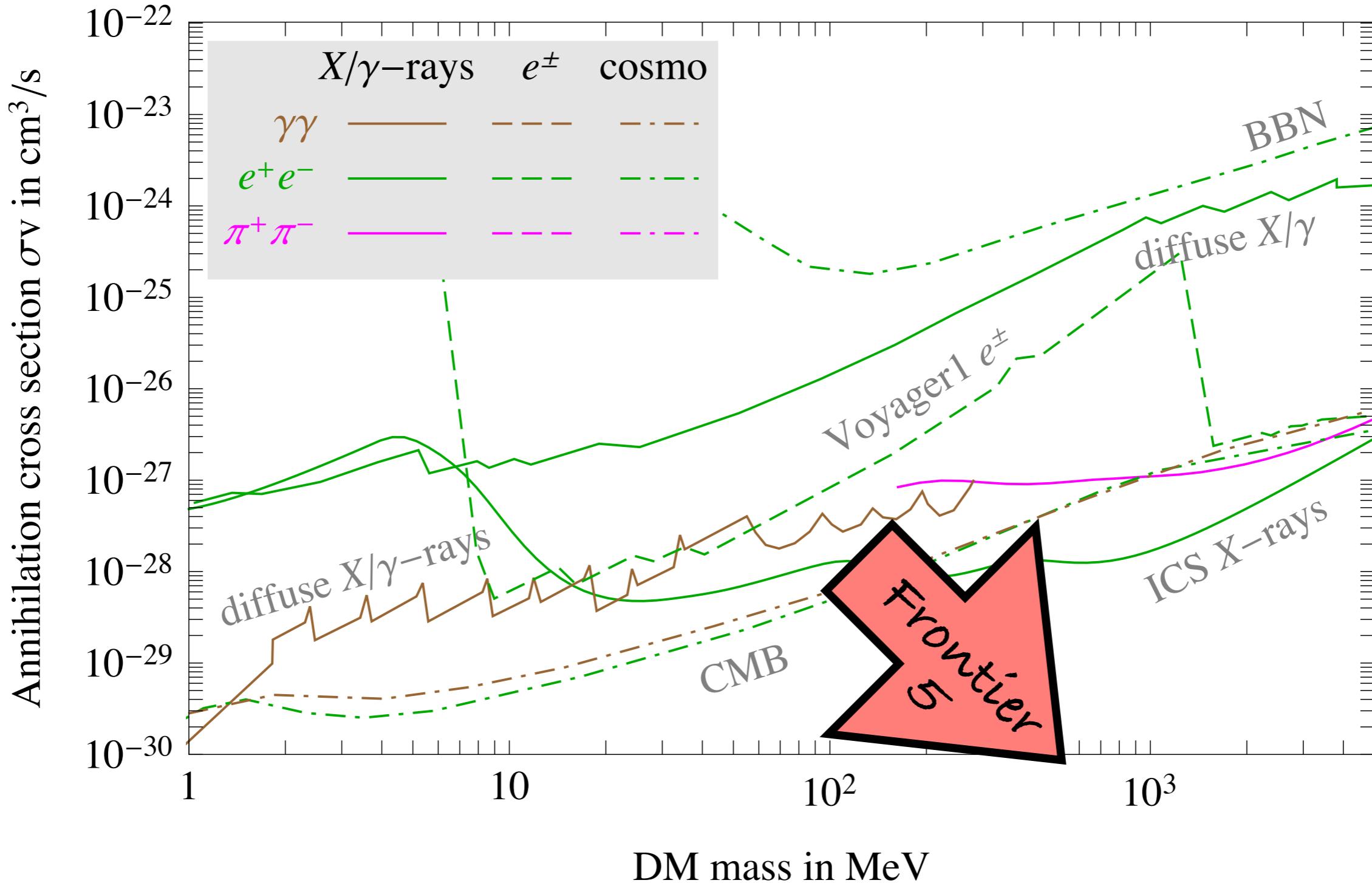
Comparing all bounds

Constraints on sub-GeV annihilating Dark Matter



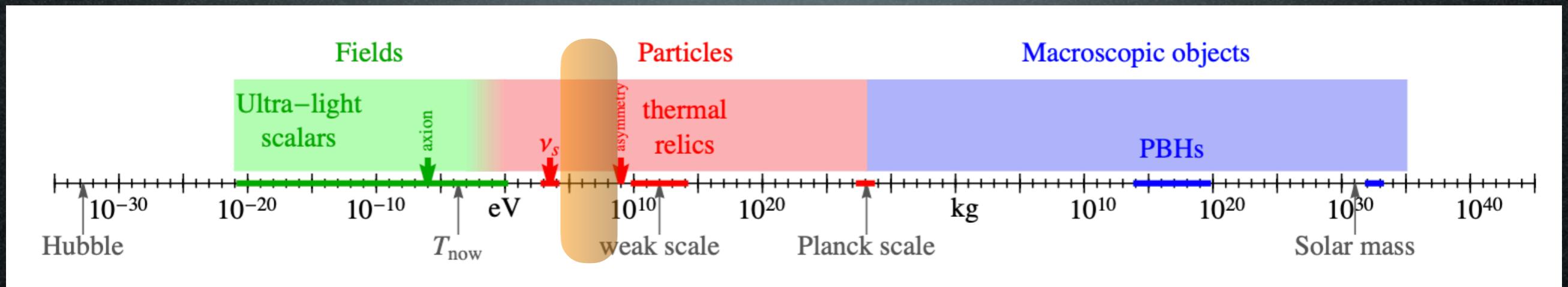
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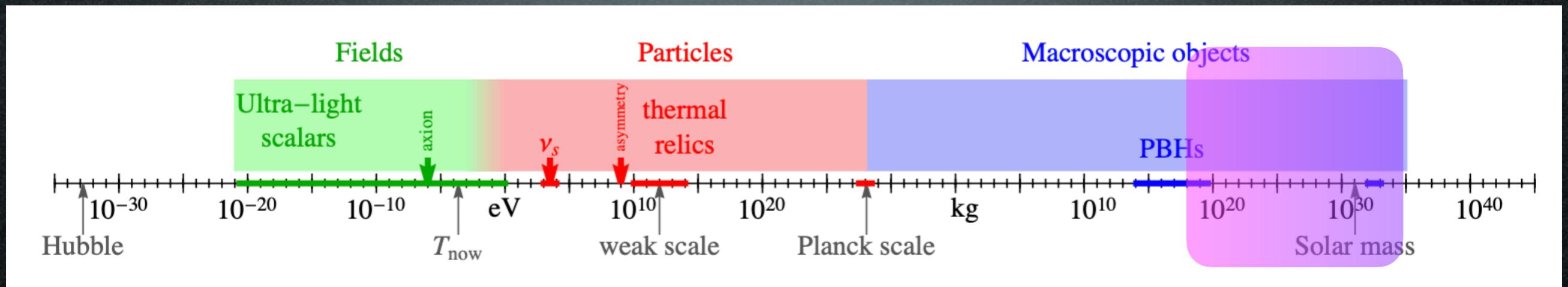
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an astro *je ne sais pas quoi*:

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- gas
- Black Holes
- brown dwarves

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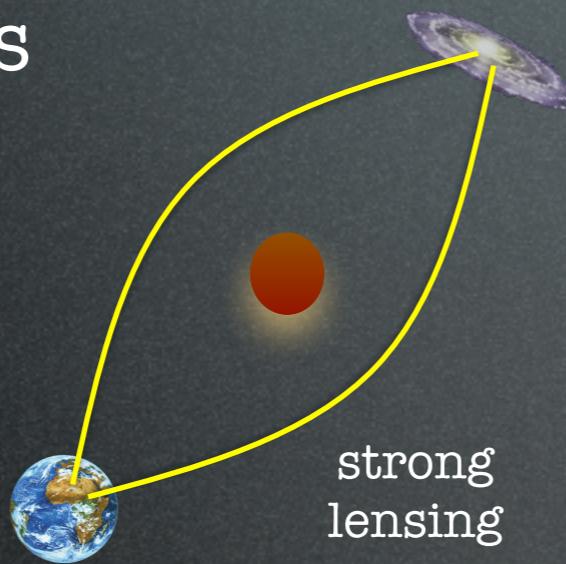
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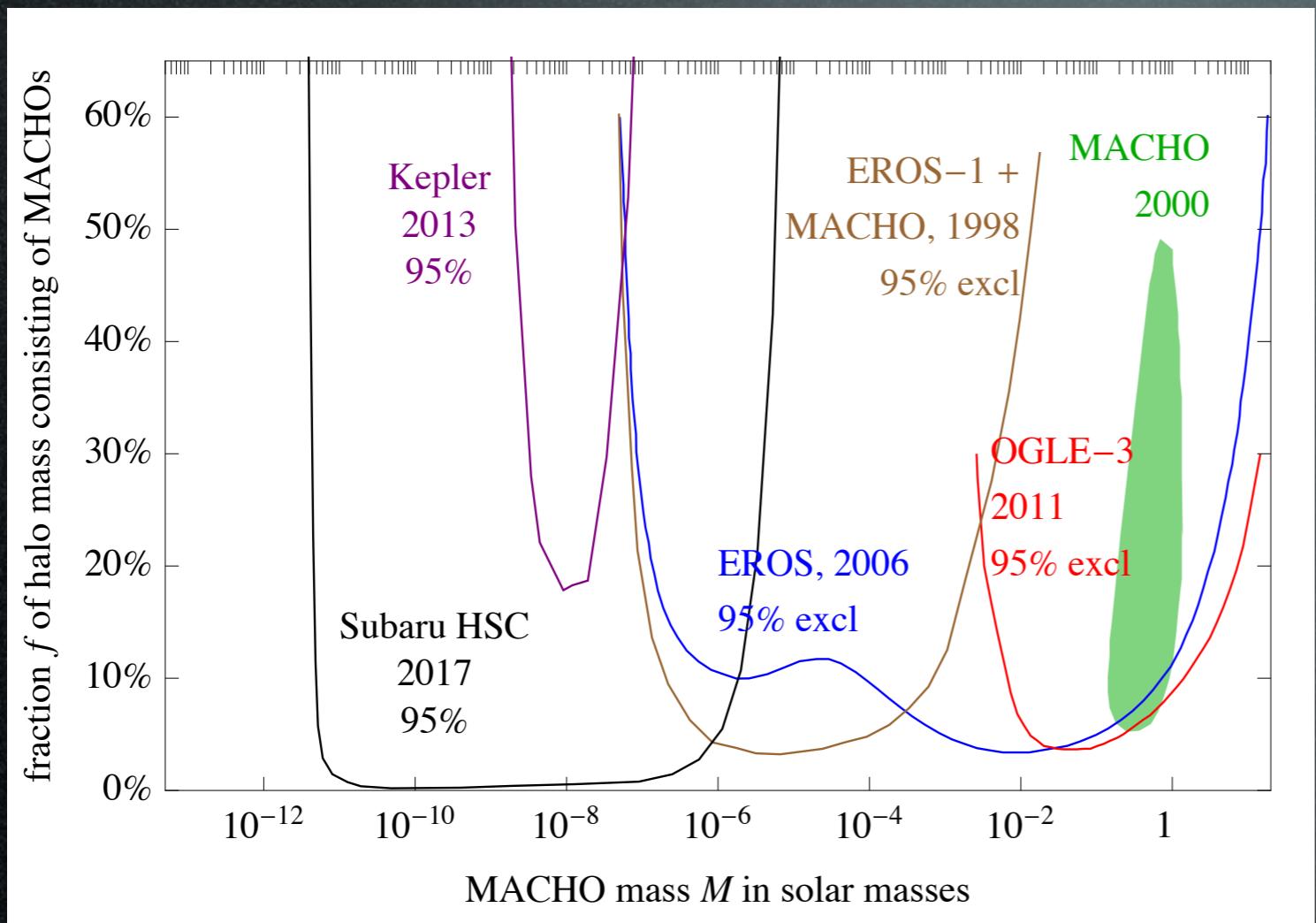
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MACHOs or PBHs as DM

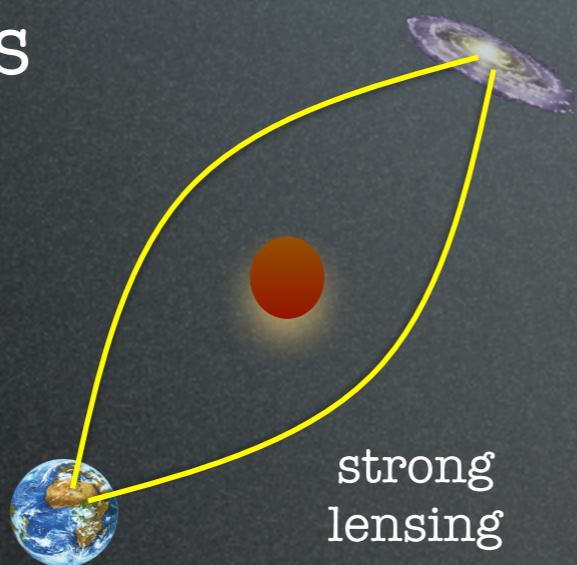


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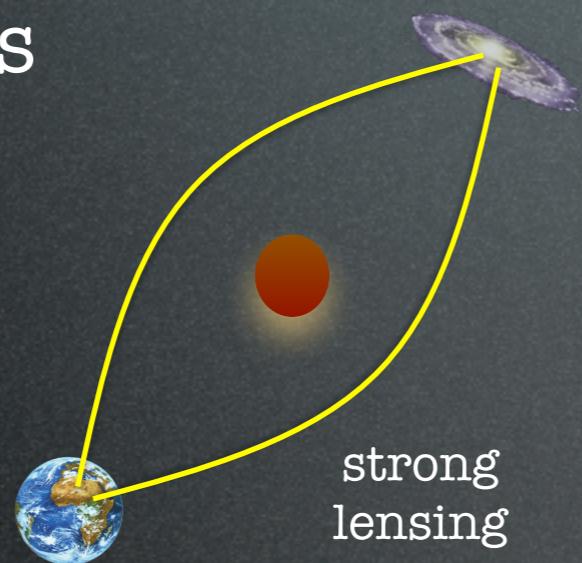
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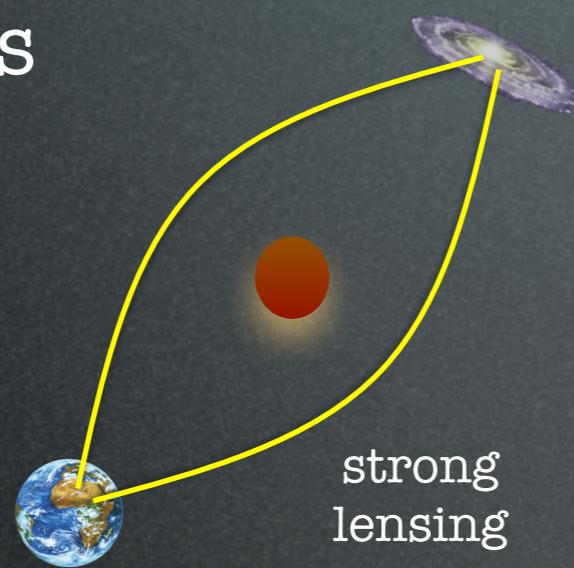
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- BBN computes the abundance of He in terms of primordial baryons:
too much baryons => Universe full of Helium
- CMB says baryons are 4% max

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- ~~Black Holes~~
- ~~brown dwarves~~



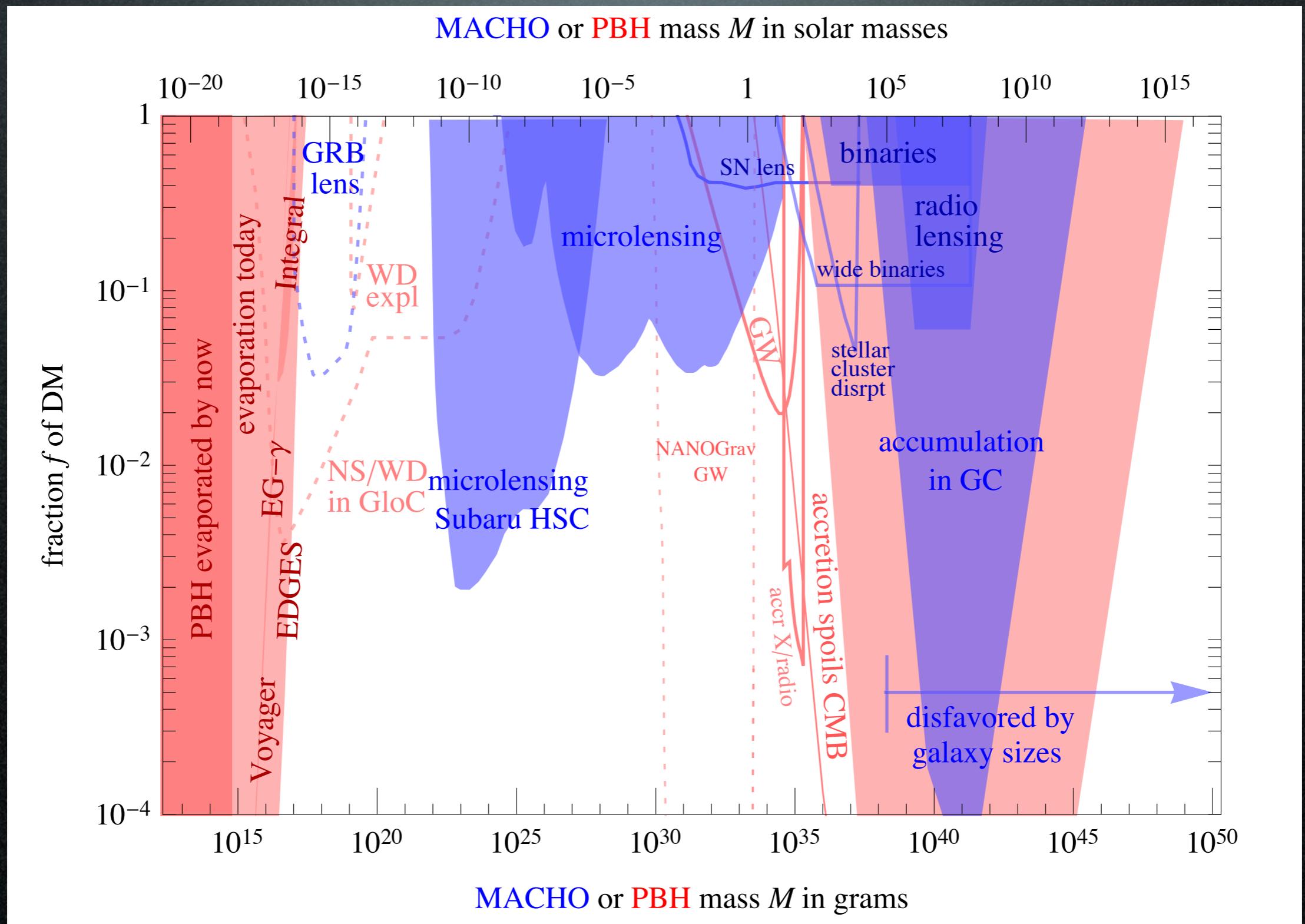
~~a baryon of the SM:~~

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

A loophole: Primordial Black Holes!

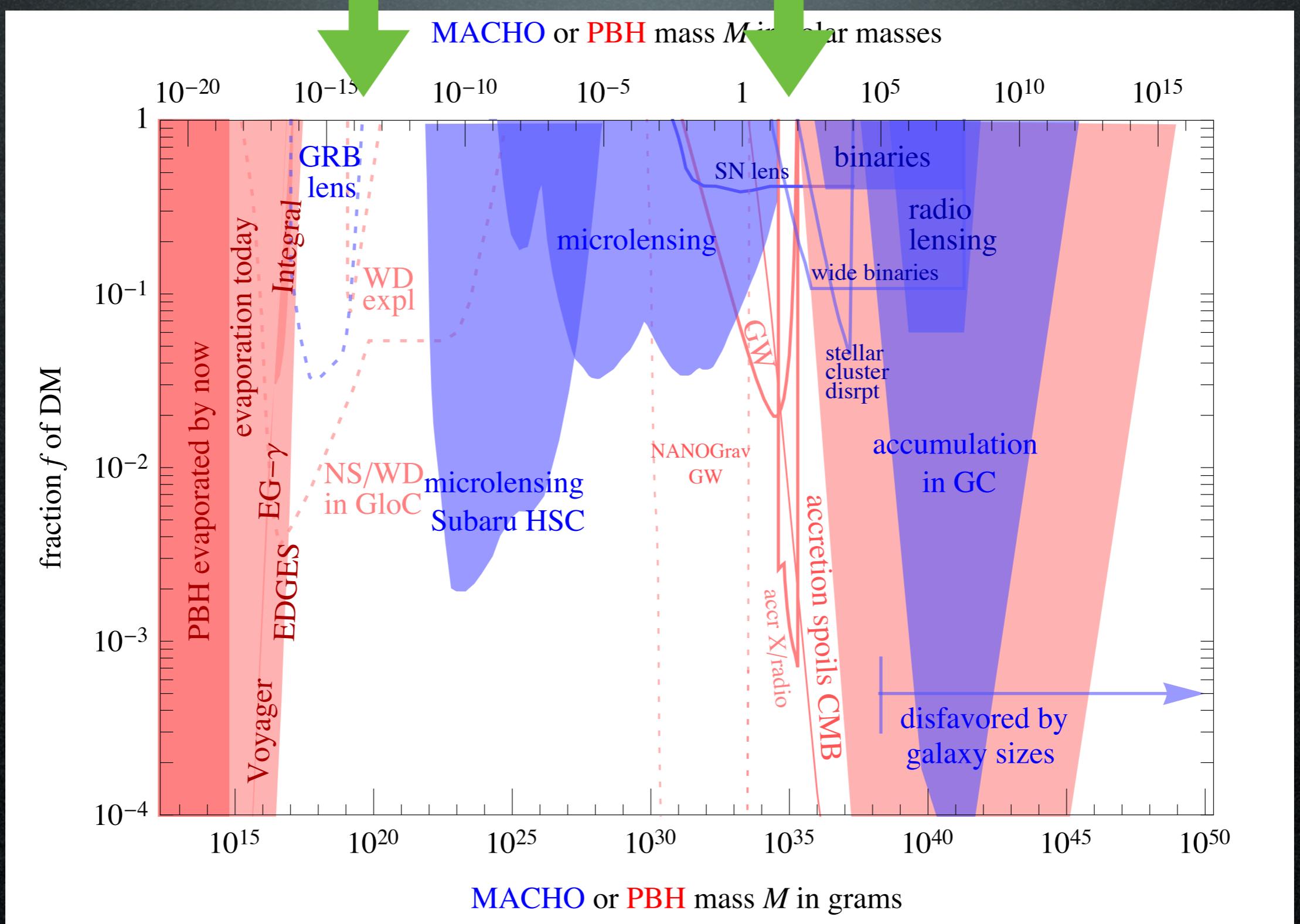
- produced before BBN
- with masses too small/large to lens
- perhaps LIGO-VIRGO have seen them?

PBHS as DM



PBHS as DM

slivers still open?



PBHS as DM

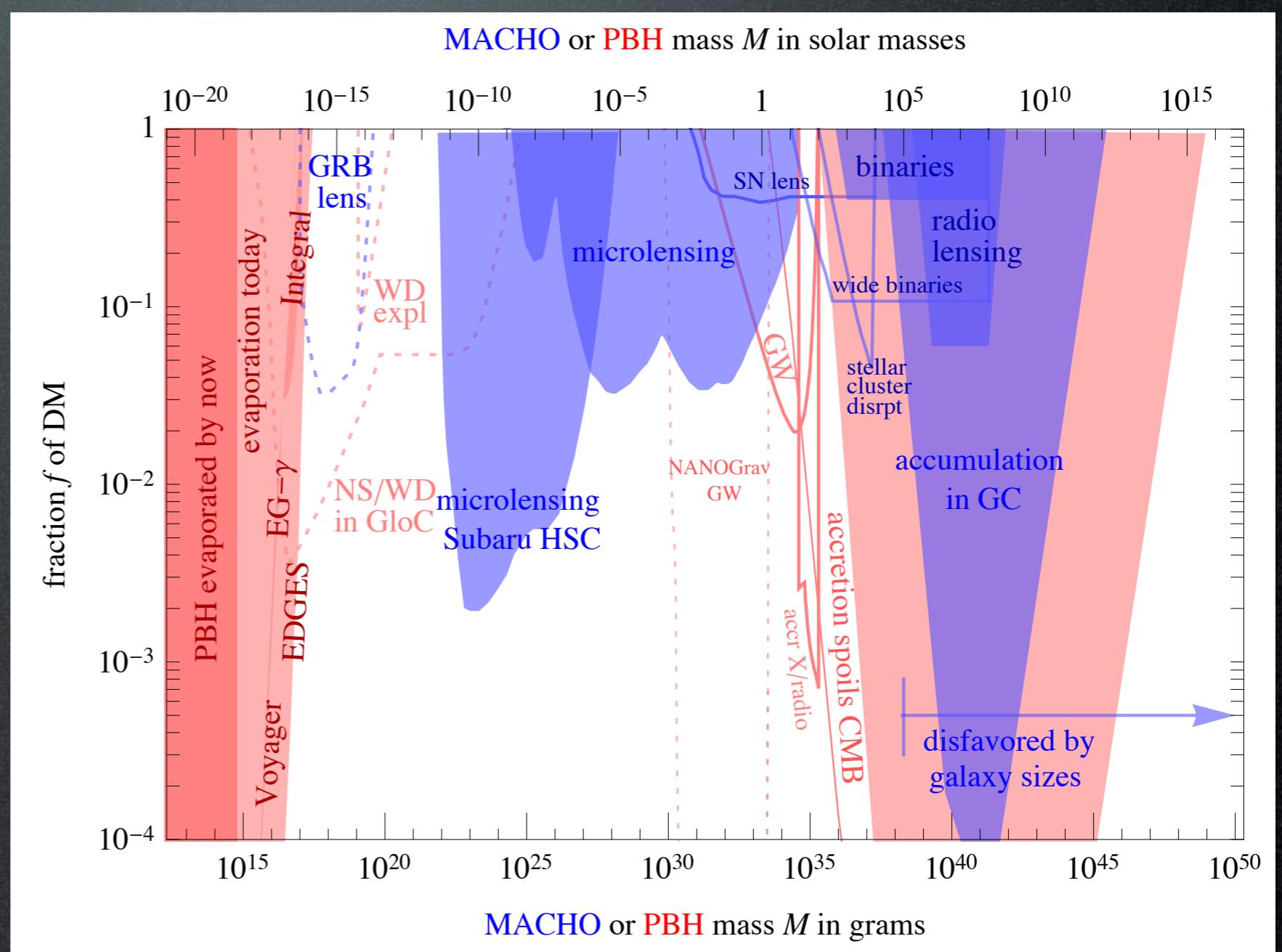
Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

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

constraints



PBHS as DM

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'small' PBHs emit today by Hawking evaporation

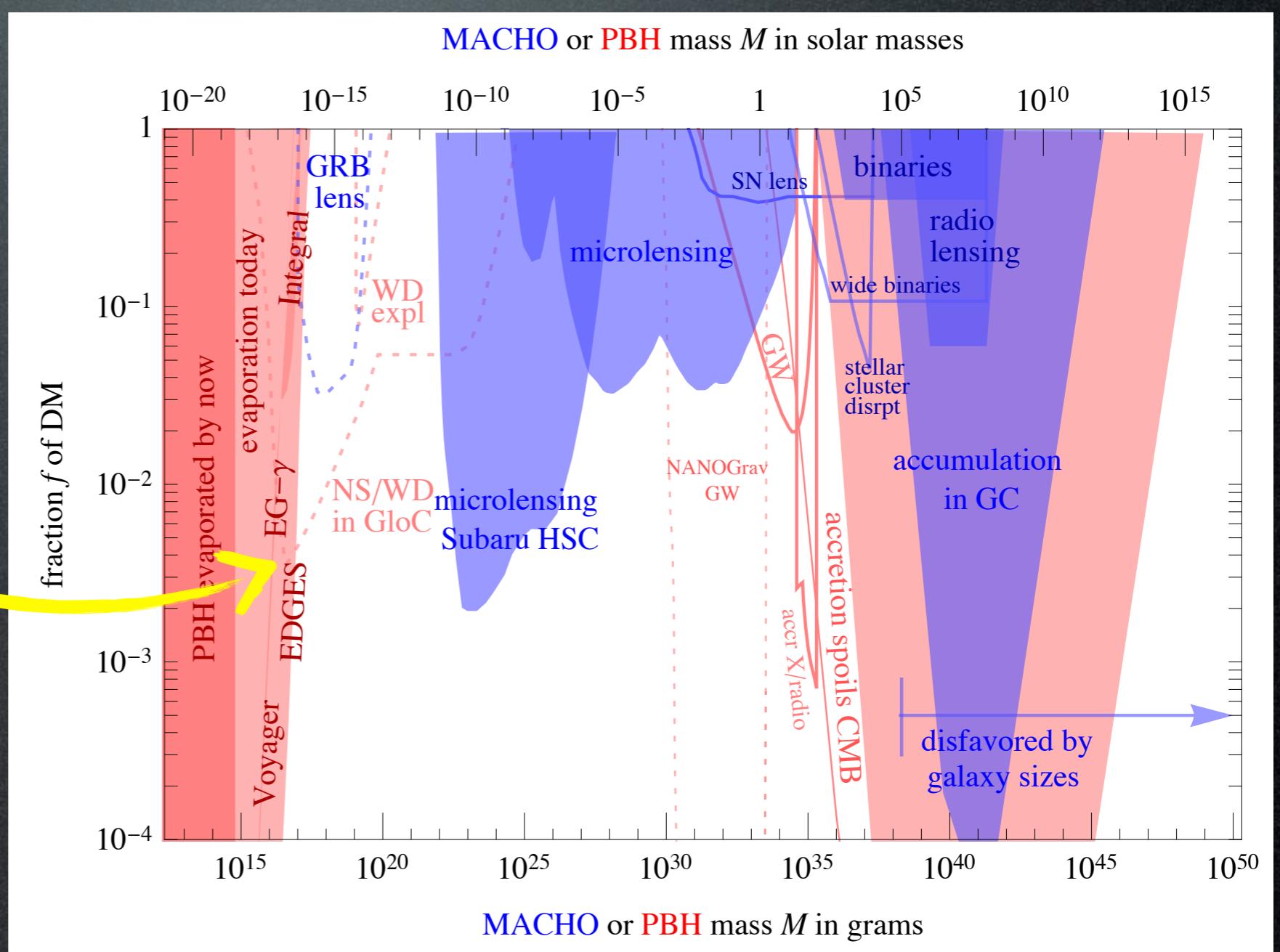
$$T = \frac{1}{8\pi G_N M}$$

rate

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

spectrum

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



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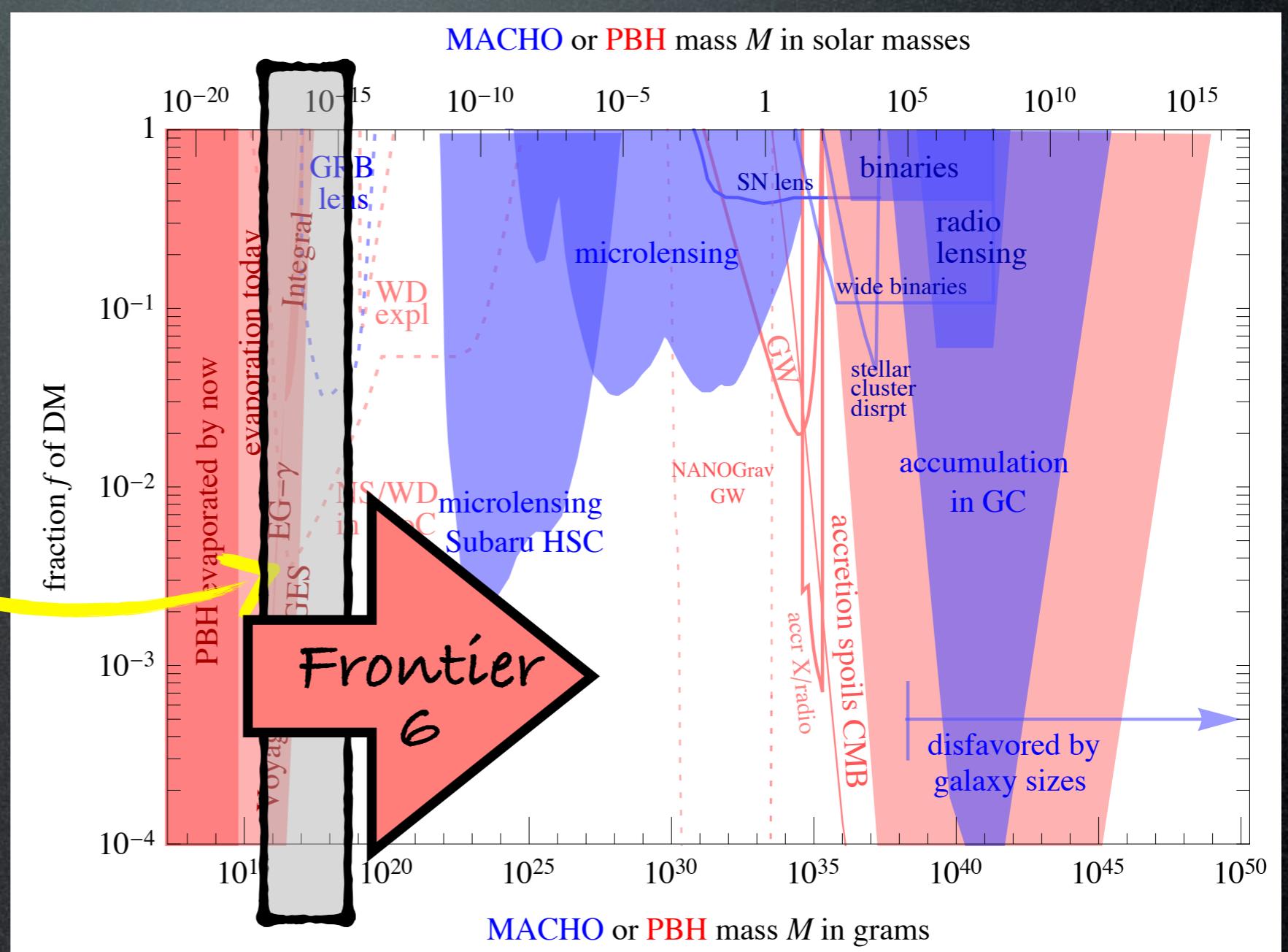
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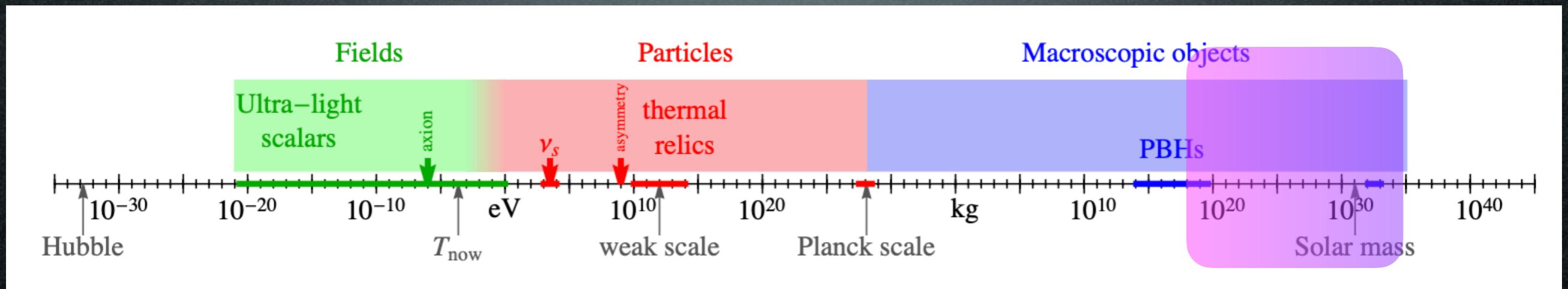
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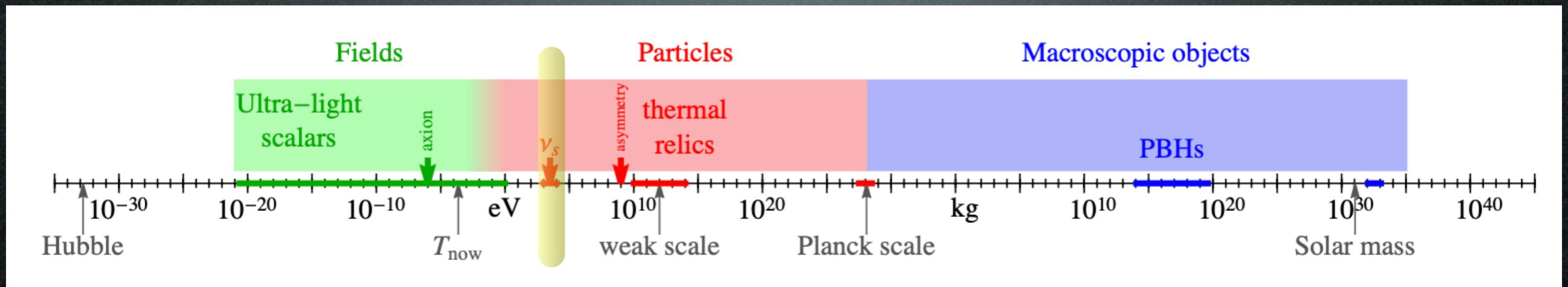
Candidates

A matter of perspective: plausible mass ranges



Candidates

A matter of perspective: plausible mass ranges



KeV DM?

X-ray line

Bulbul et al., 1402.2301

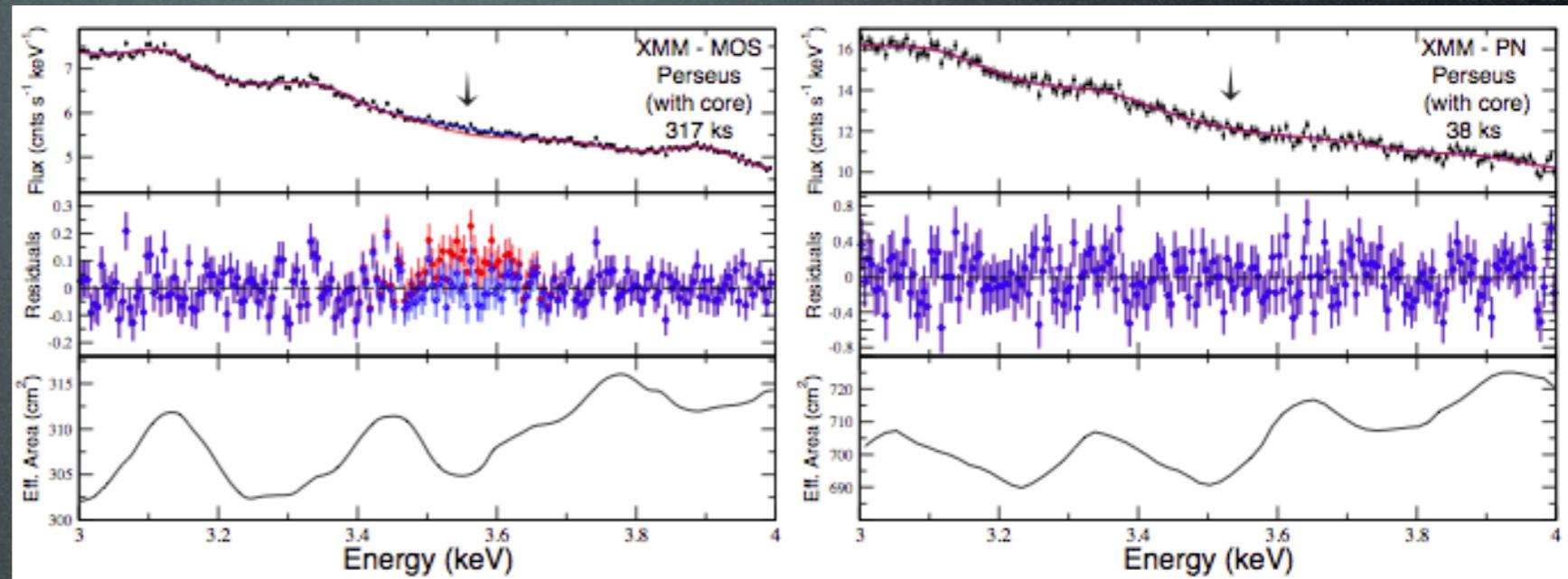
$3.55 - 3.57 \pm 0.03$ KeV

73 clusters

(Chandra & XMM-Newton)

$z = 0.01 - 0.35$

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy,
1402.4119

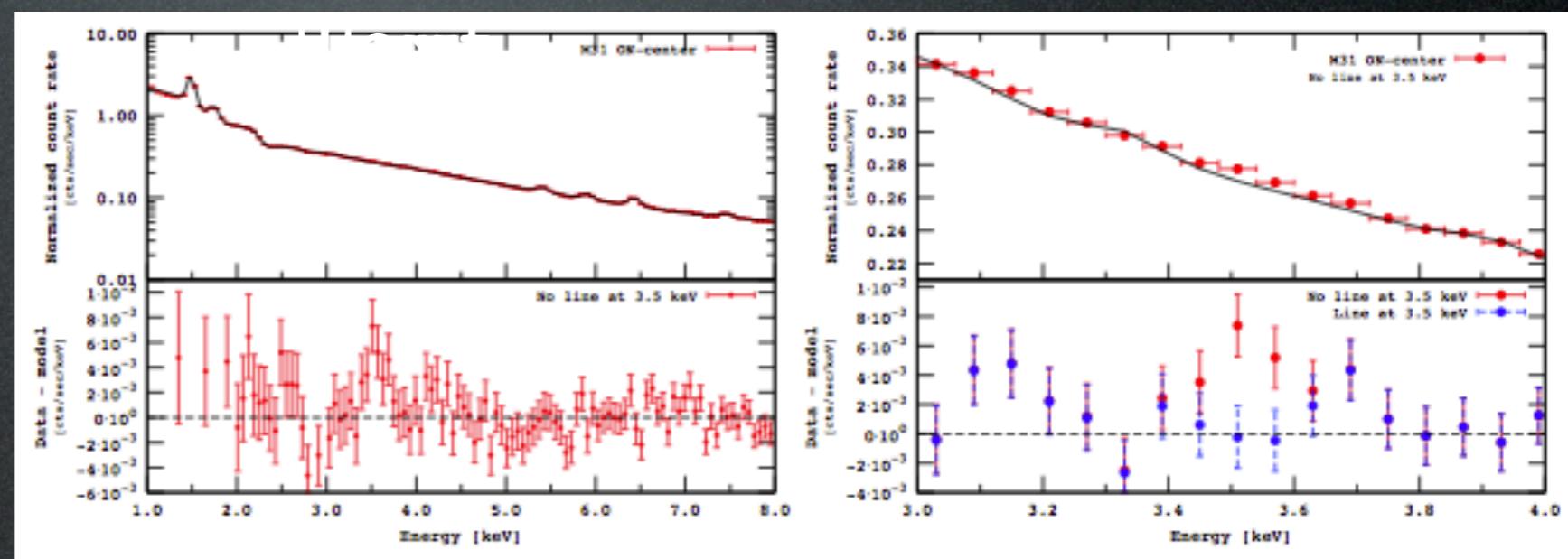
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

$z = 0$ and 0.0179

4.4σ



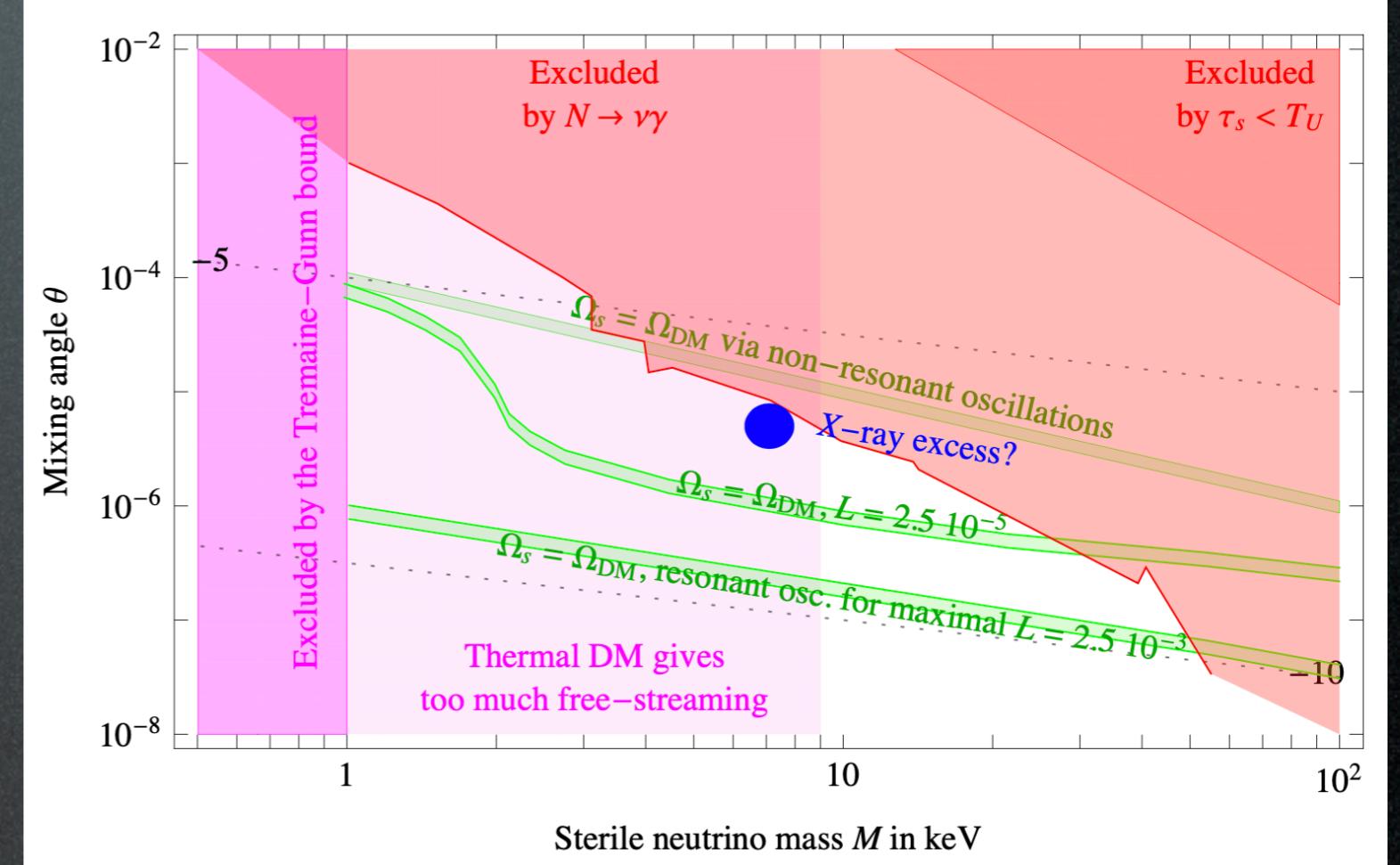
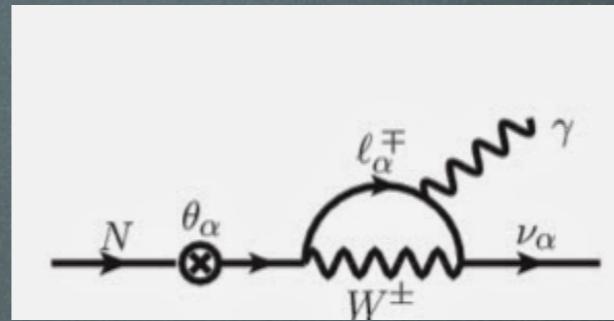
X-ray line

Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$

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

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



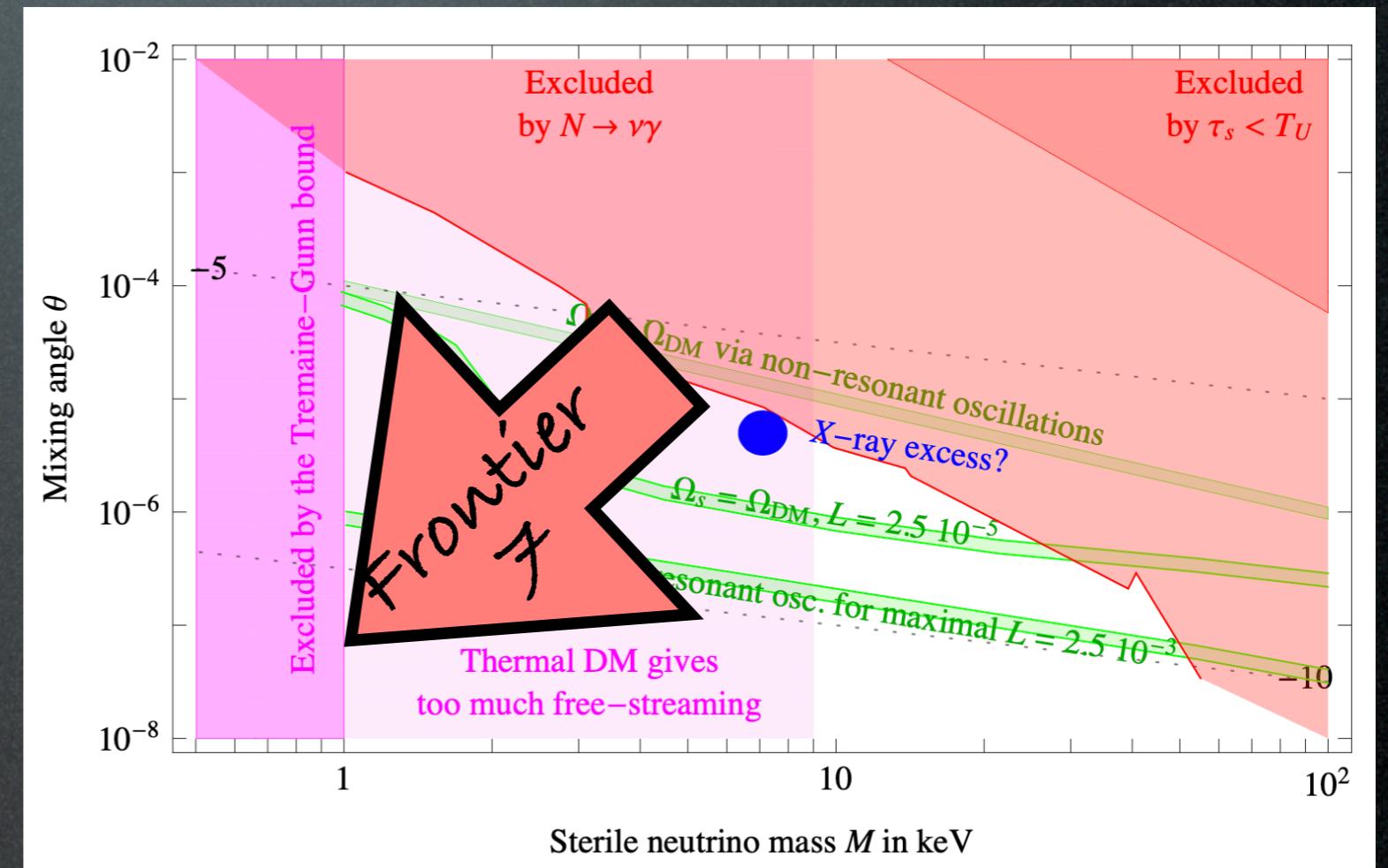
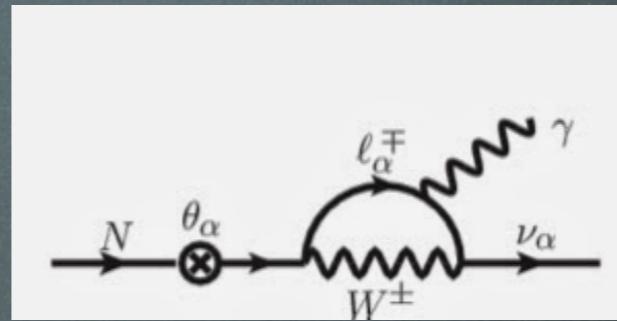
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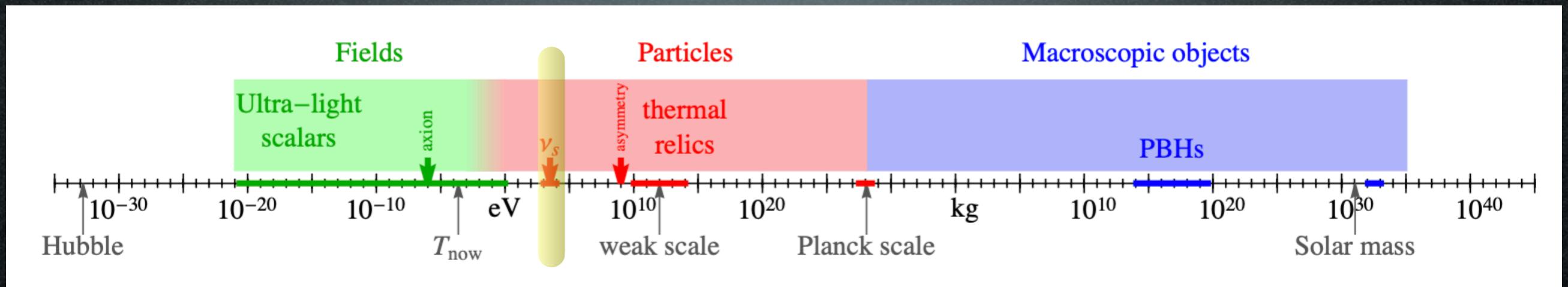
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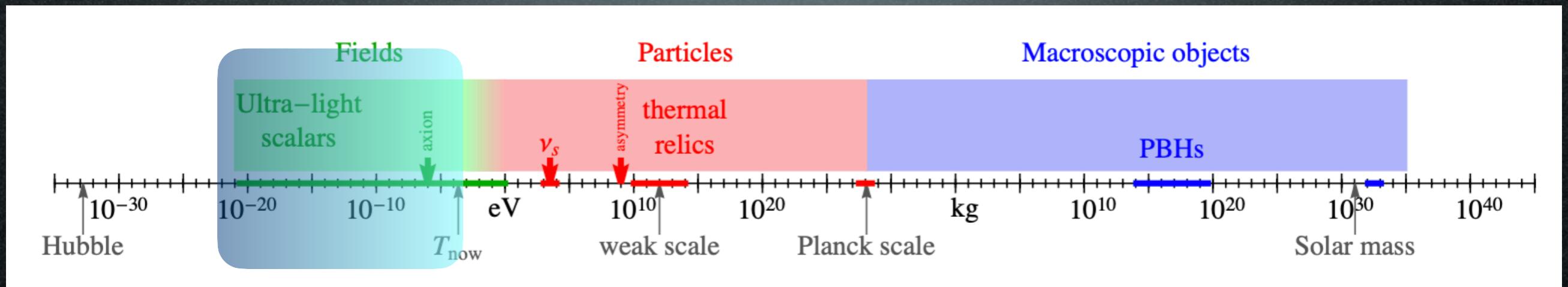
Candidates

A matter of perspective: plausible mass ranges



Candidates

A matter of perspective: plausible mass ranges



Axions

Theoretically motivated:

one can add to the SM $\mathcal{L} = \mathcal{L}_{\text{SM}} - \theta \frac{g_3^2}{64\pi^2} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a$ $\left(\tilde{G}_{\mu\nu}^a \equiv \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G_{\alpha\beta}^a \right)$
which induces $d_n \approx \theta e m_\pi^2 / m_N^2 \approx 10^{-16} \theta e \text{ cm}$

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

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

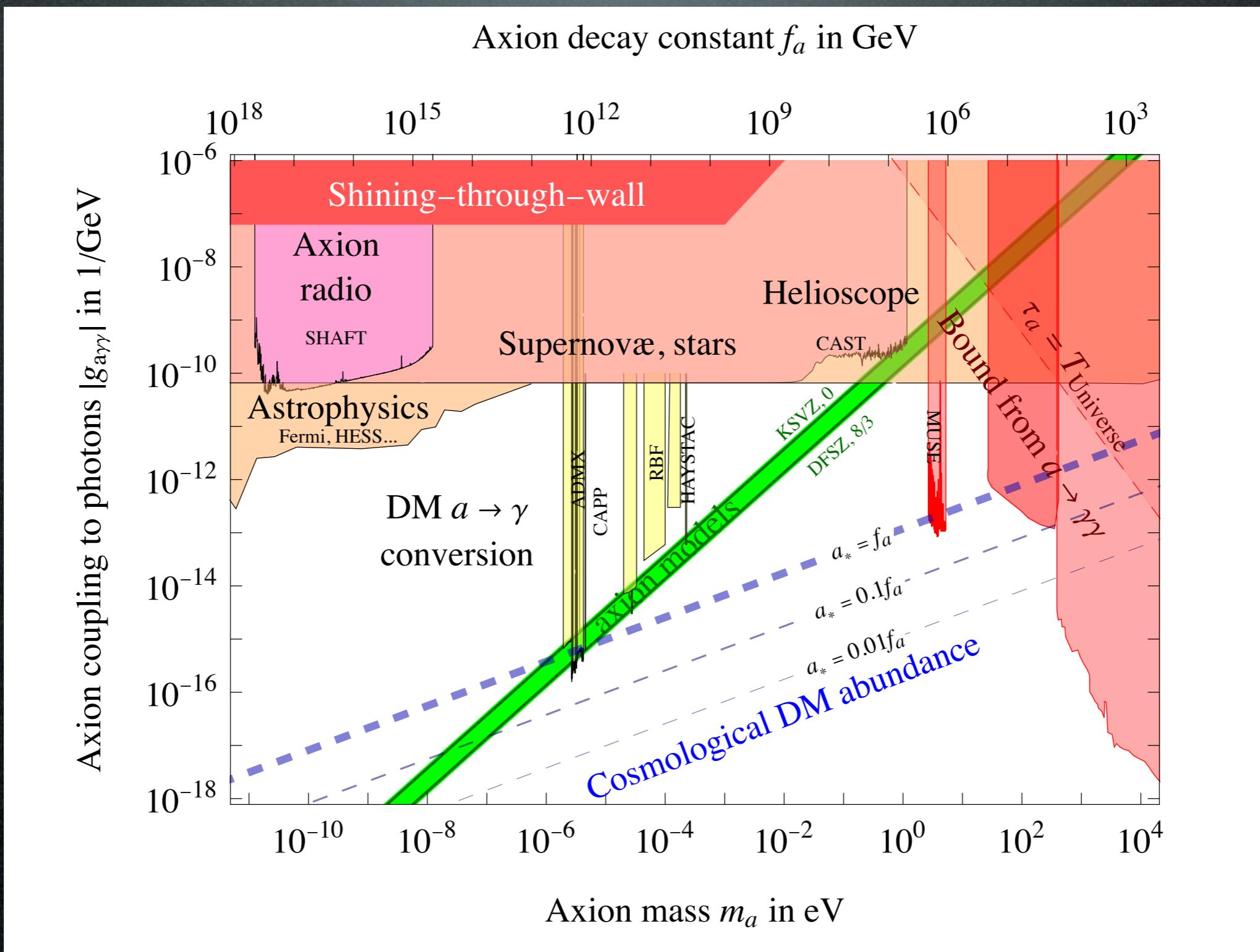
Perhaps because θ is dynamical (a field)

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

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

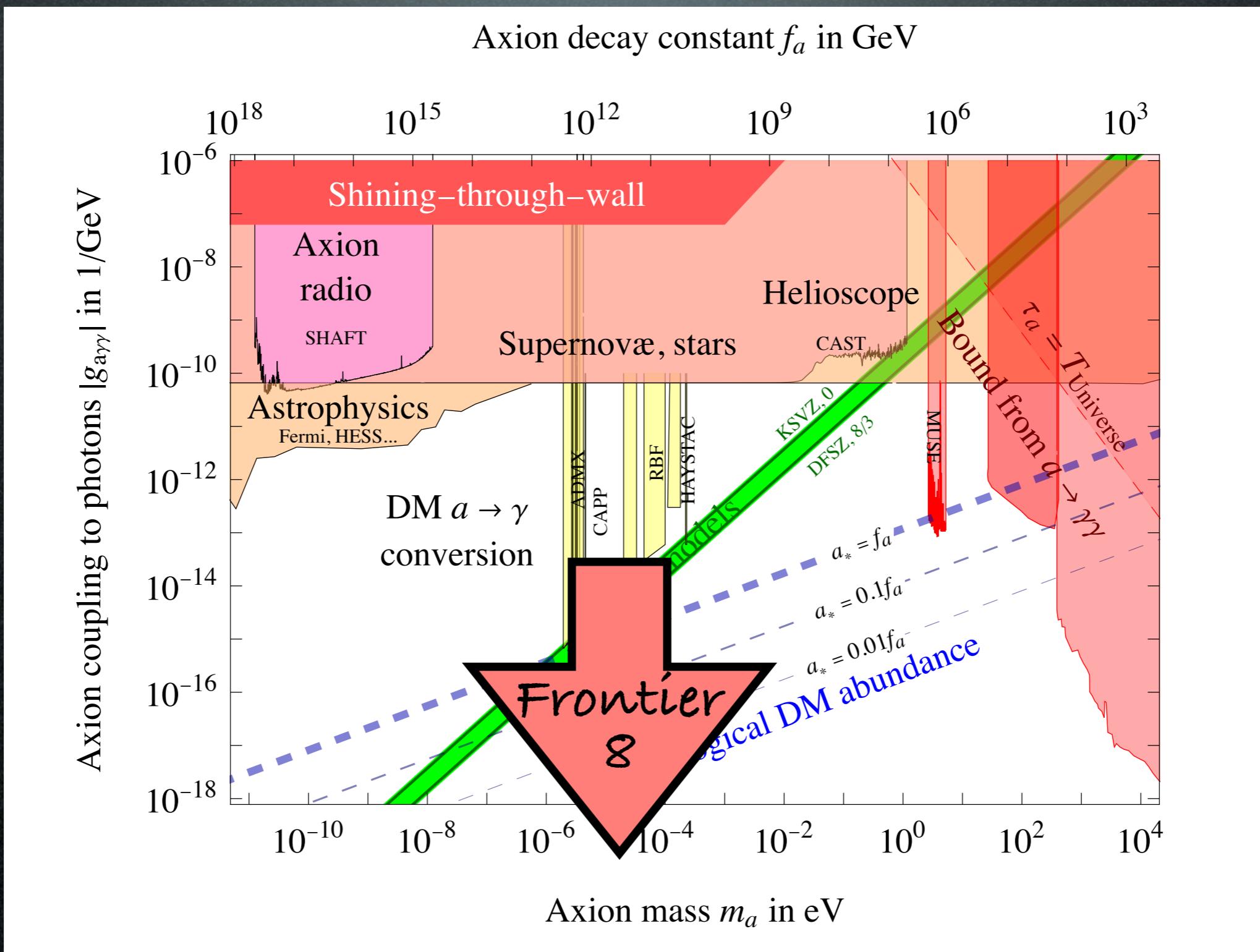
Axions

Searches:



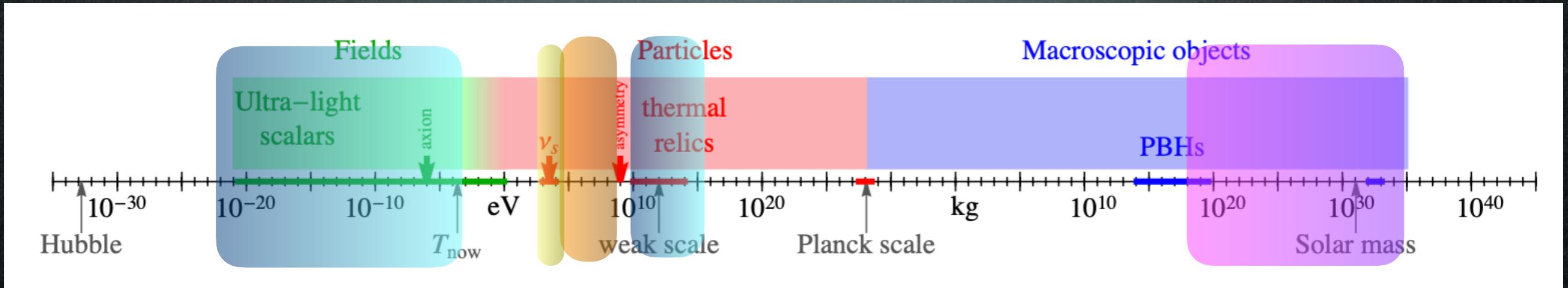
Axions

Searches:



Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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

Conclusions

The physics of Dark Matter is
in an experiment driven phase

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Theory can (does) point to preferred directions,
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?

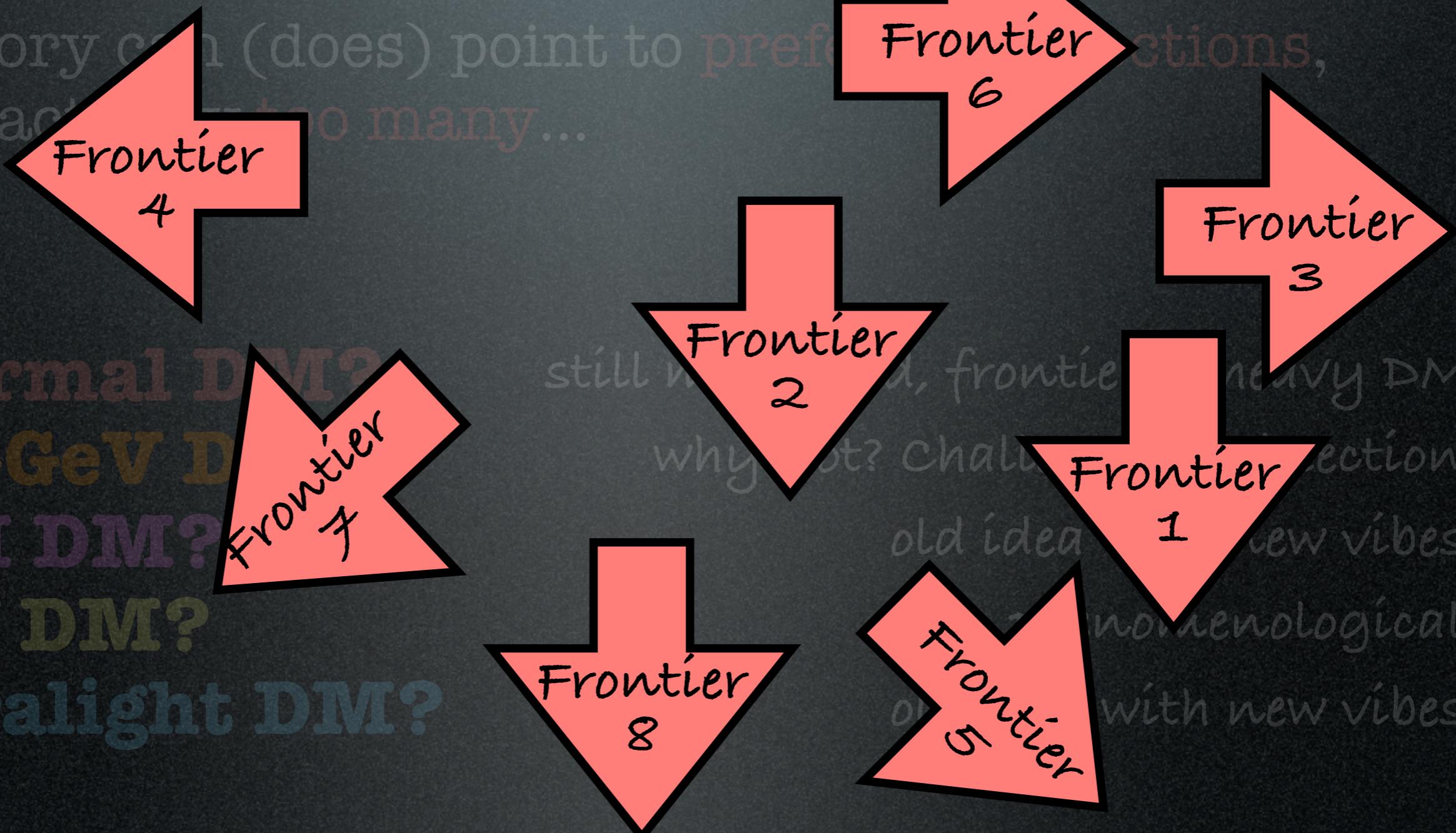
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