23 Octobre 2023
CS IN2P3

La phénoménologie de la matière noire

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

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Executive summary

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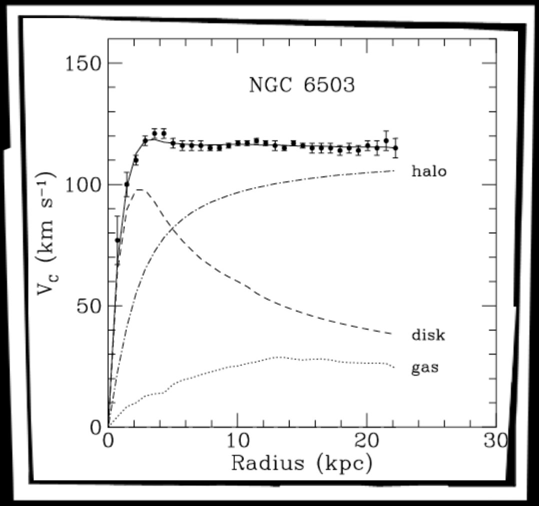
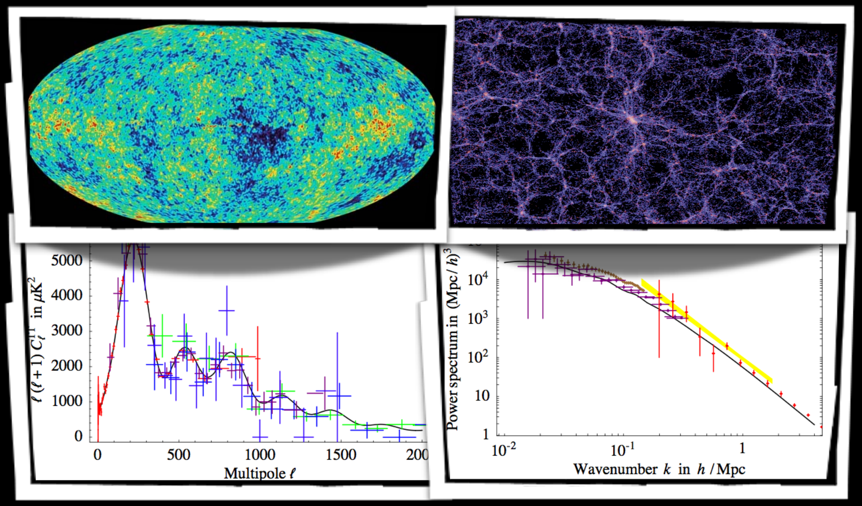


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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no SM particle can fulfil

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

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  84% of total matter

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(notice error!)

Planck 2015, 1502.01589 (tab.4)

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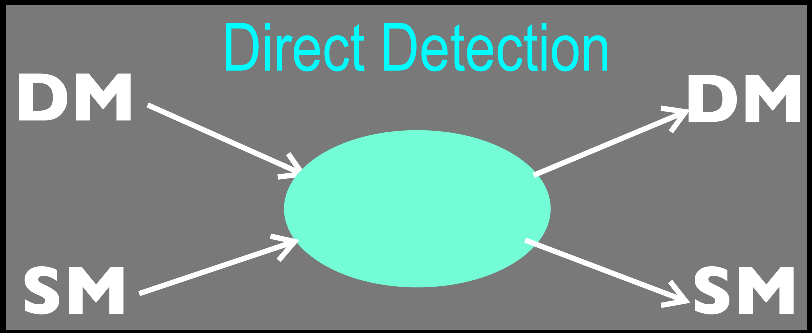

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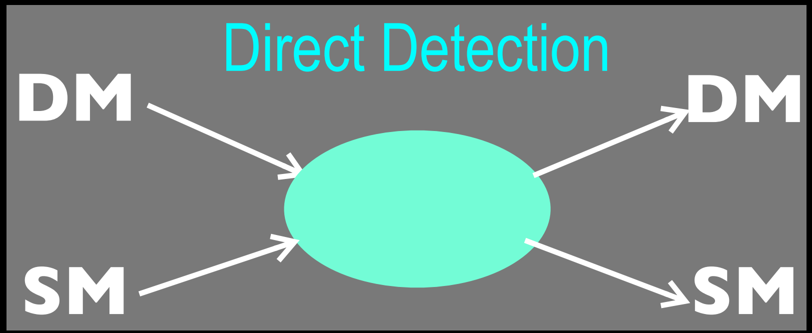

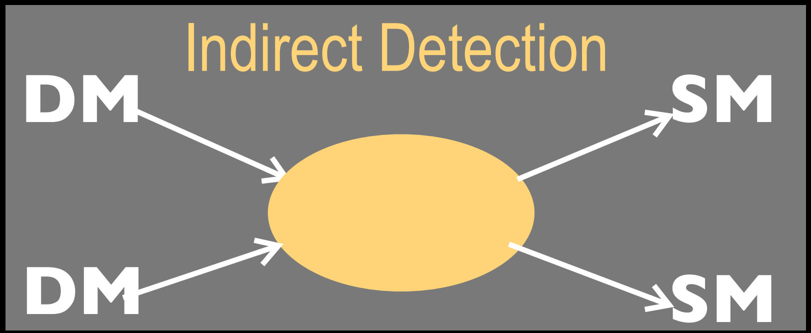

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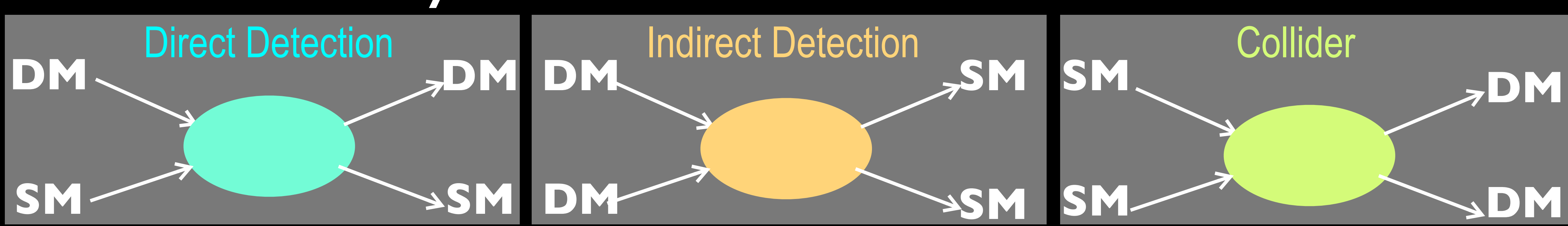

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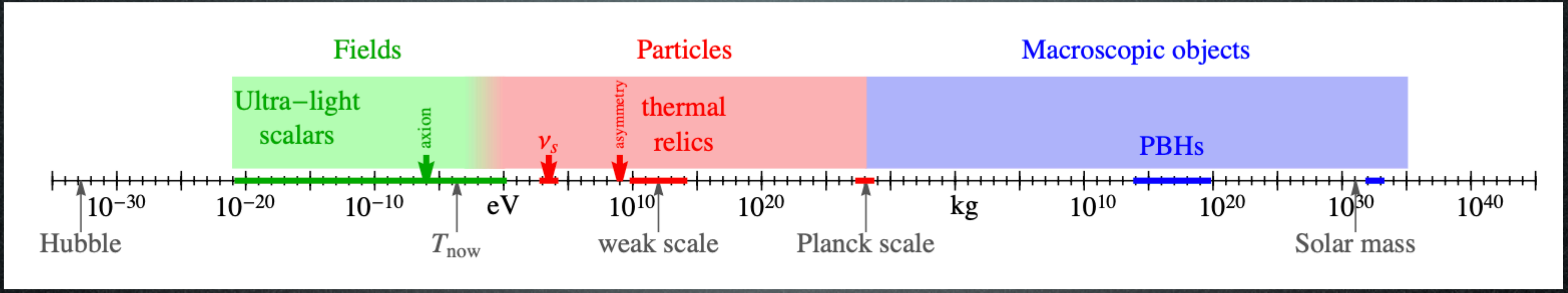
Mass??

Charge??
Interactions??

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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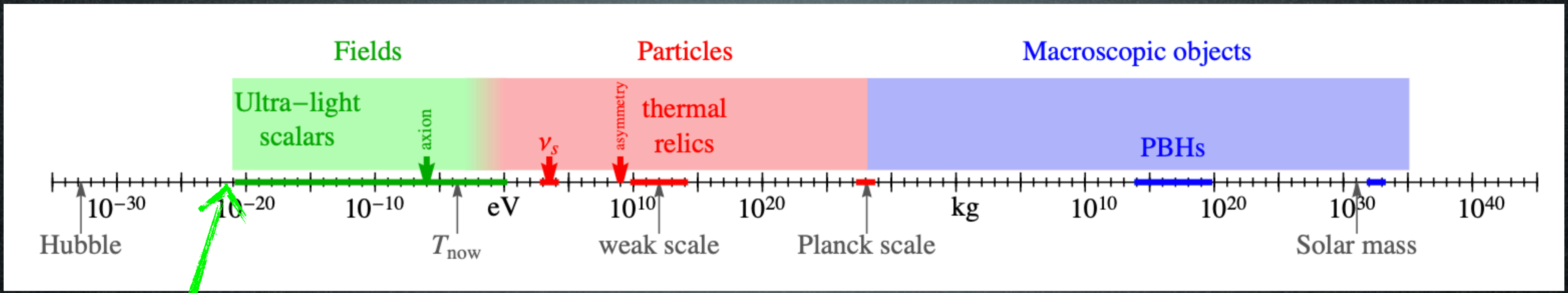

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as diffuse as a dwarf galaxy

DM de Broglie wavelength

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

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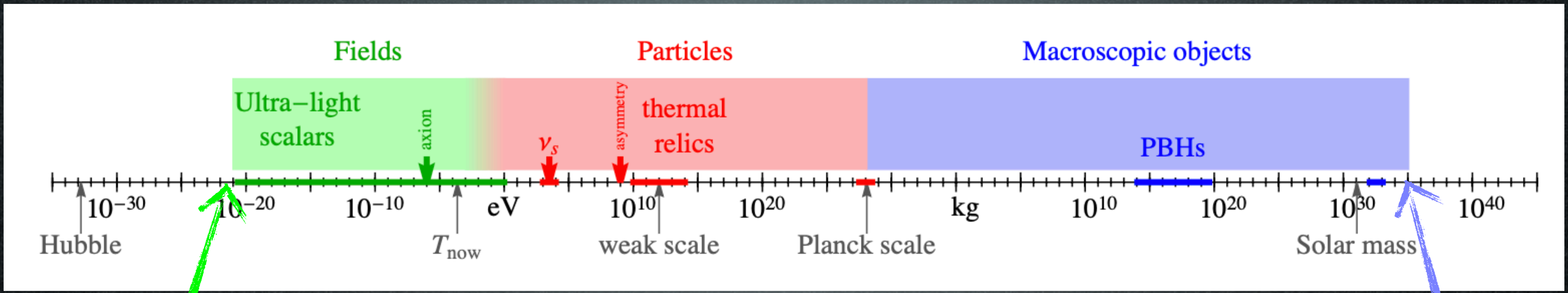

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as big as a dwarf galaxy

DM mass

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

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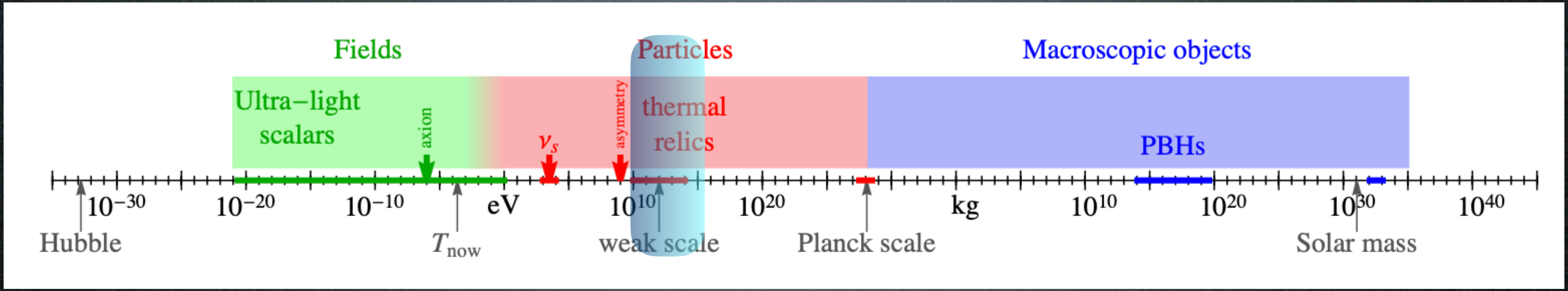

Candidates

WIMPs

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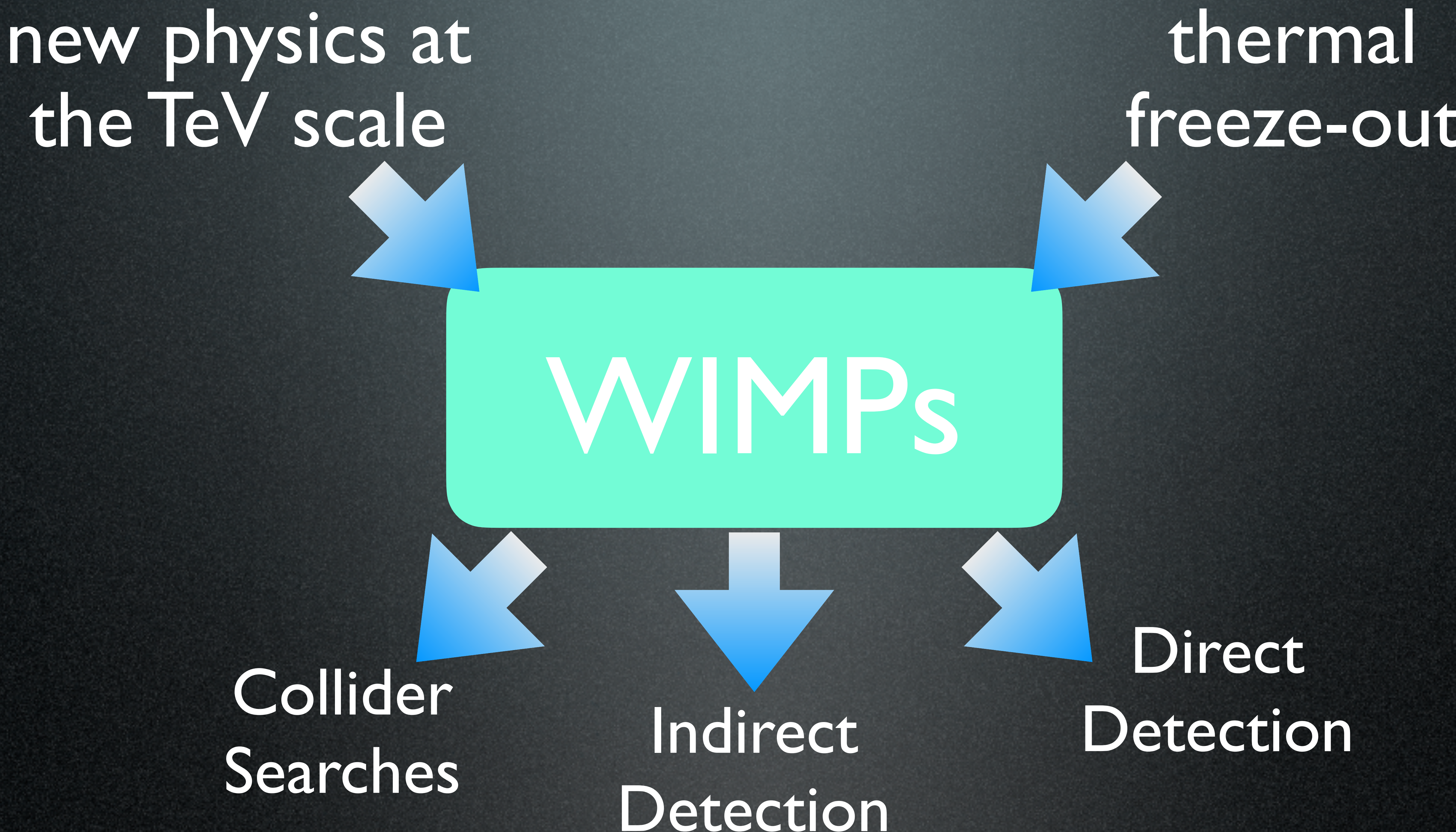
new physics at the TeV scale
thermal freeze-out
WIMPs
Collider Searches
Indirect Detection
Direct Detection

DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

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

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

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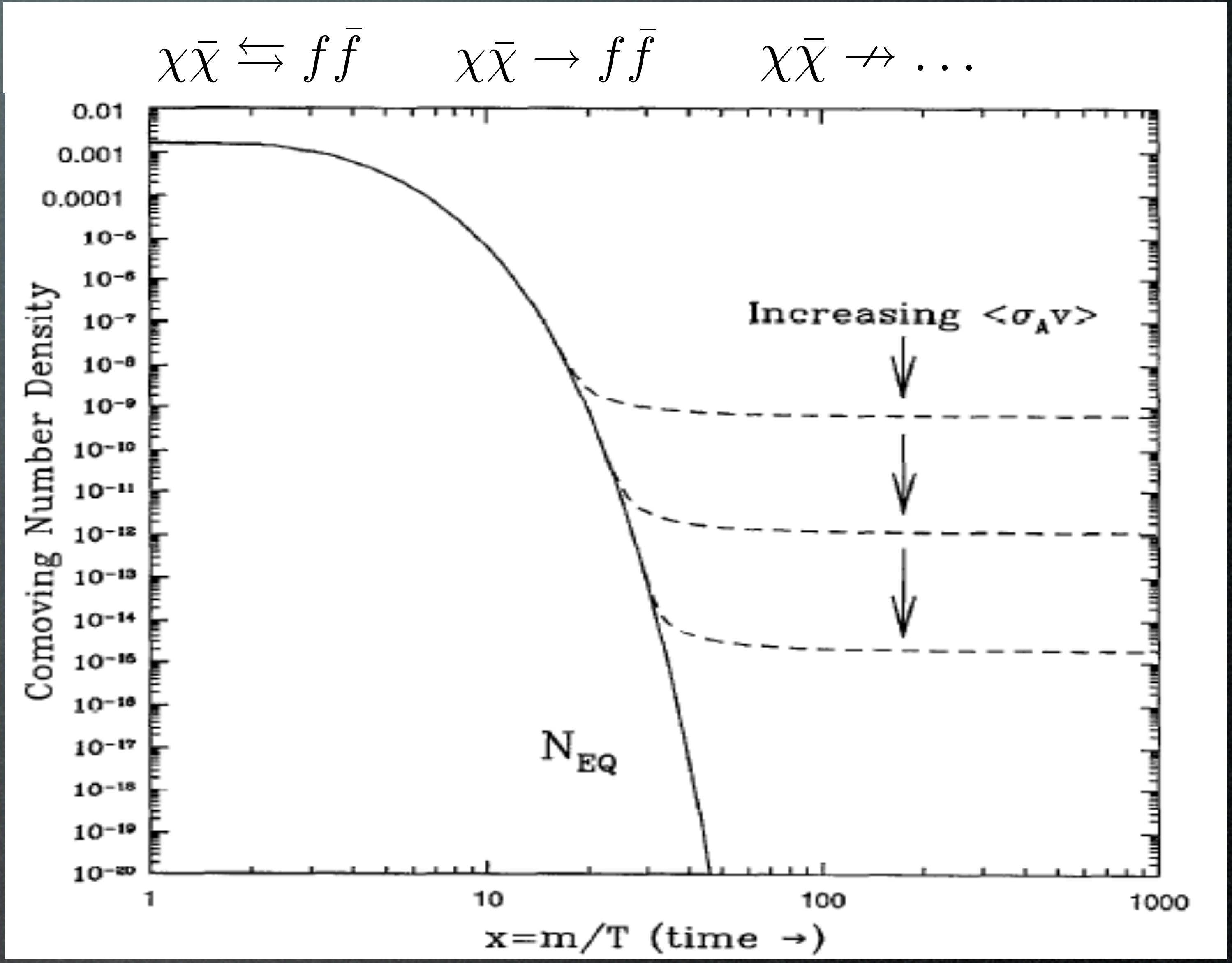

Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

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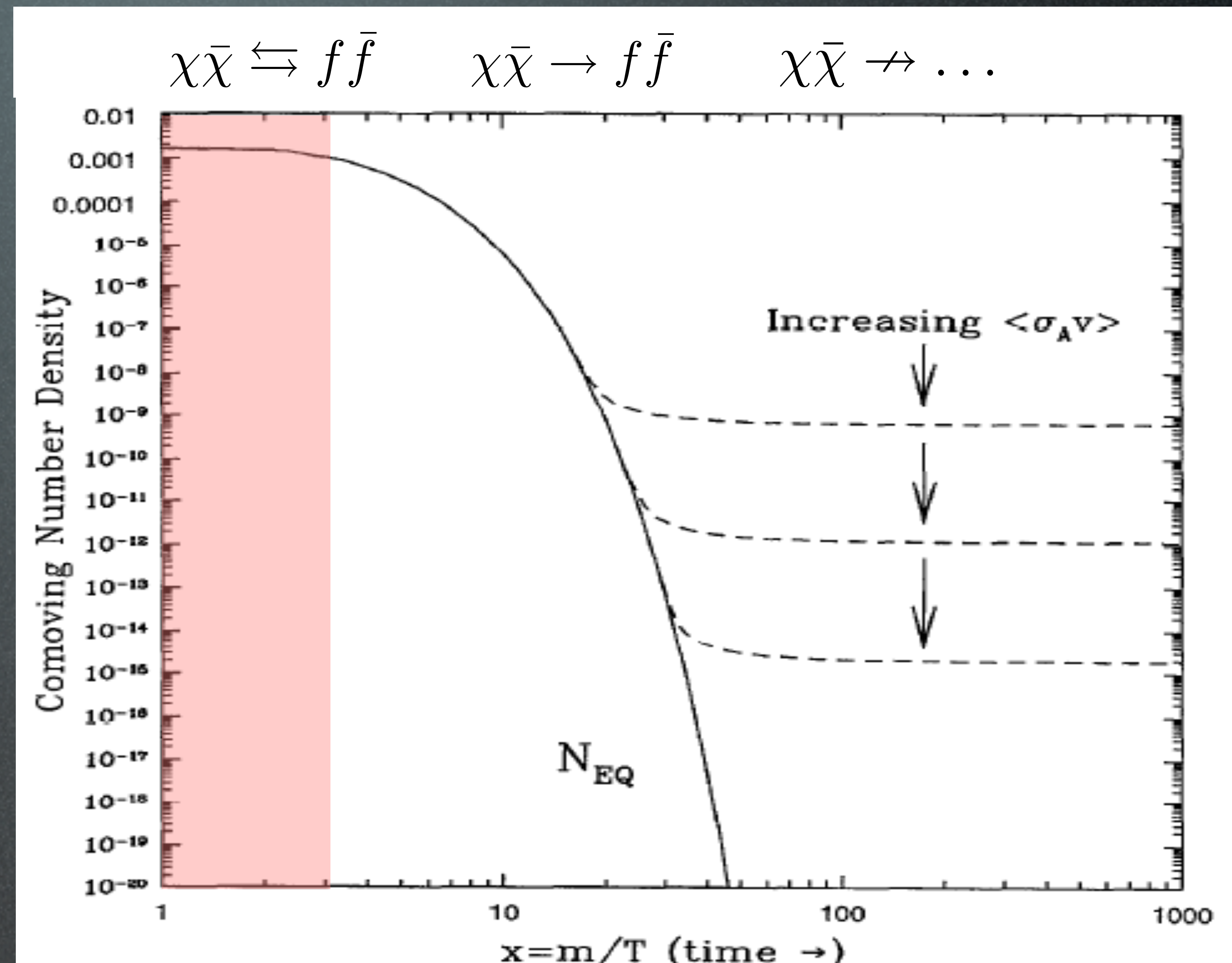

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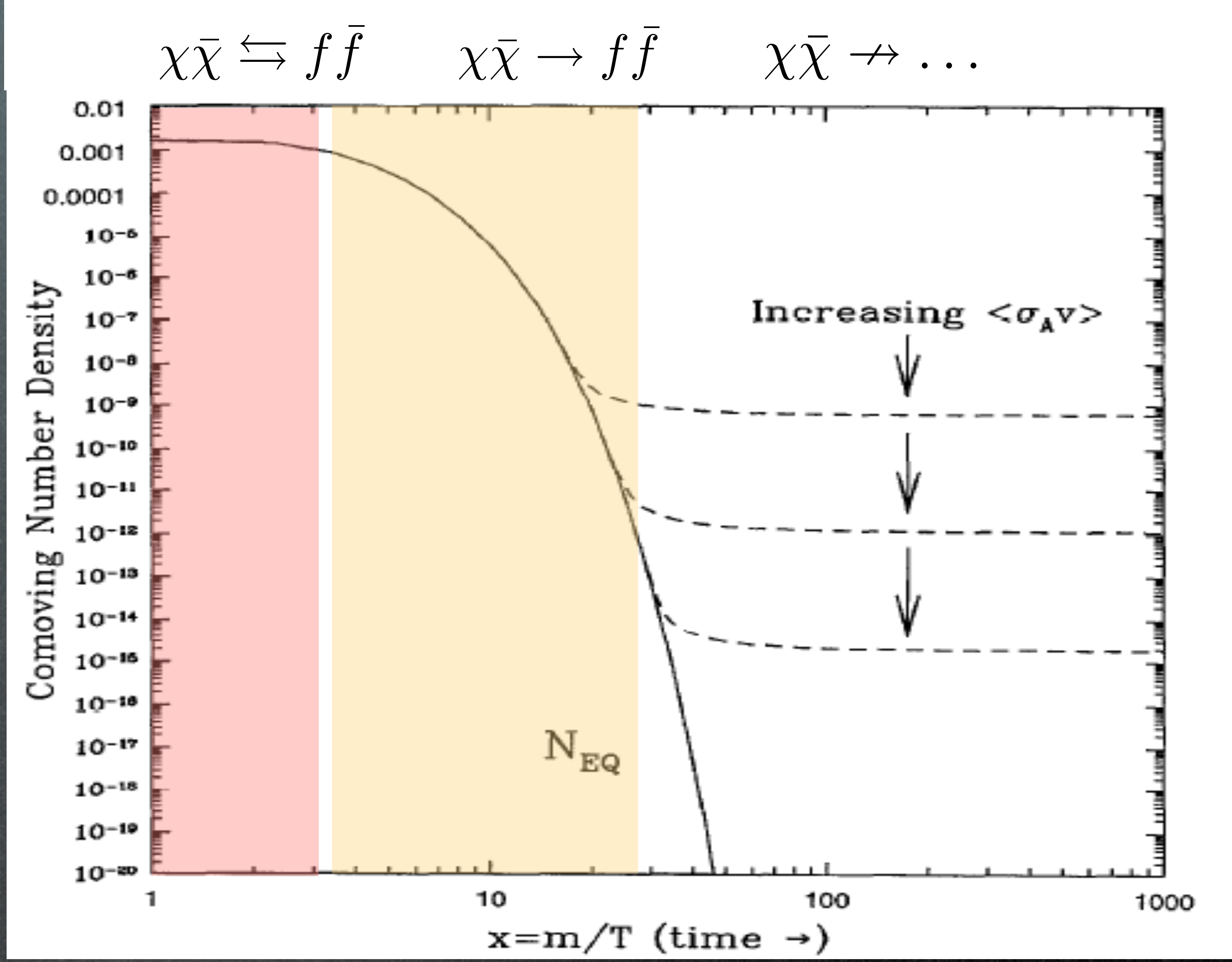

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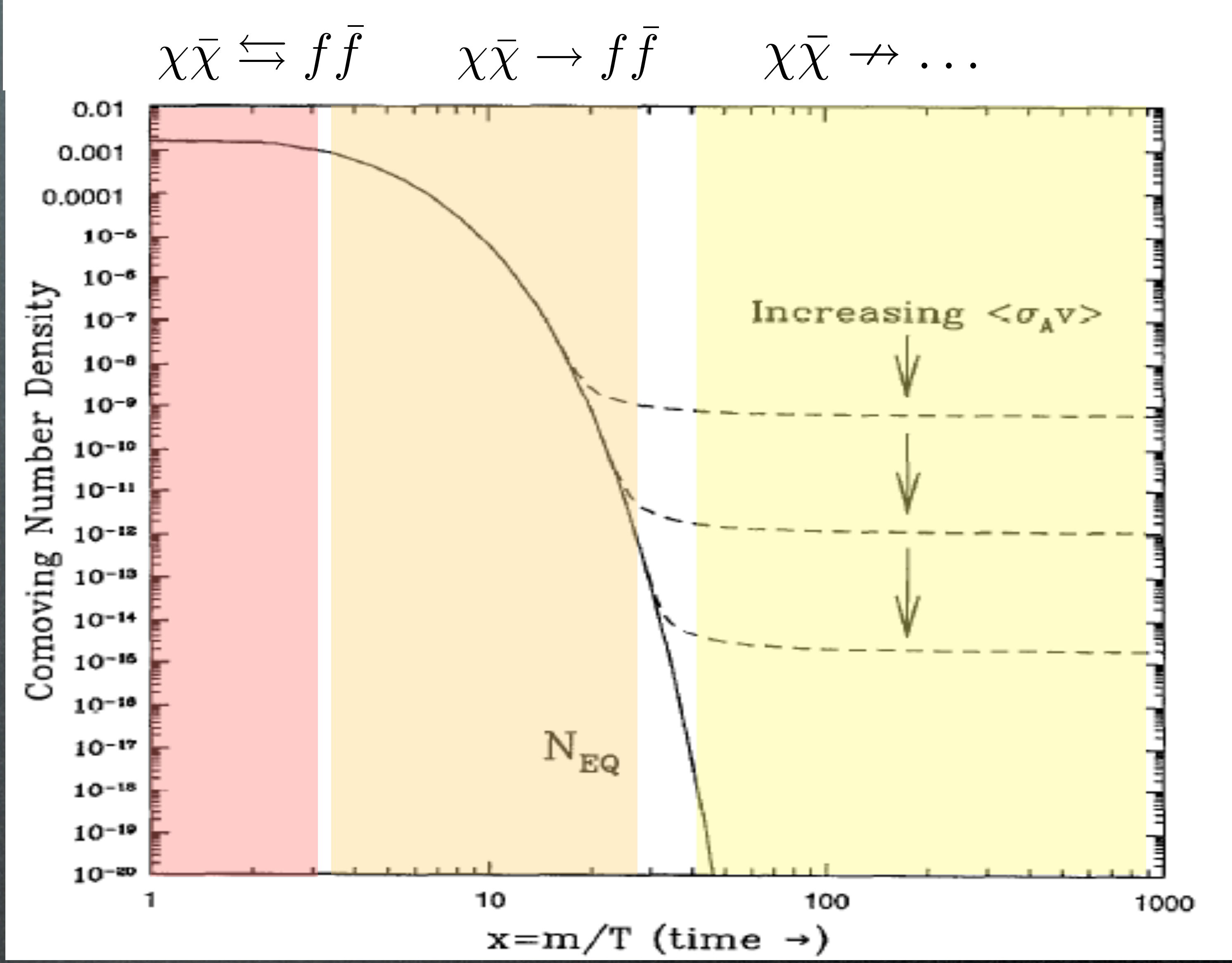

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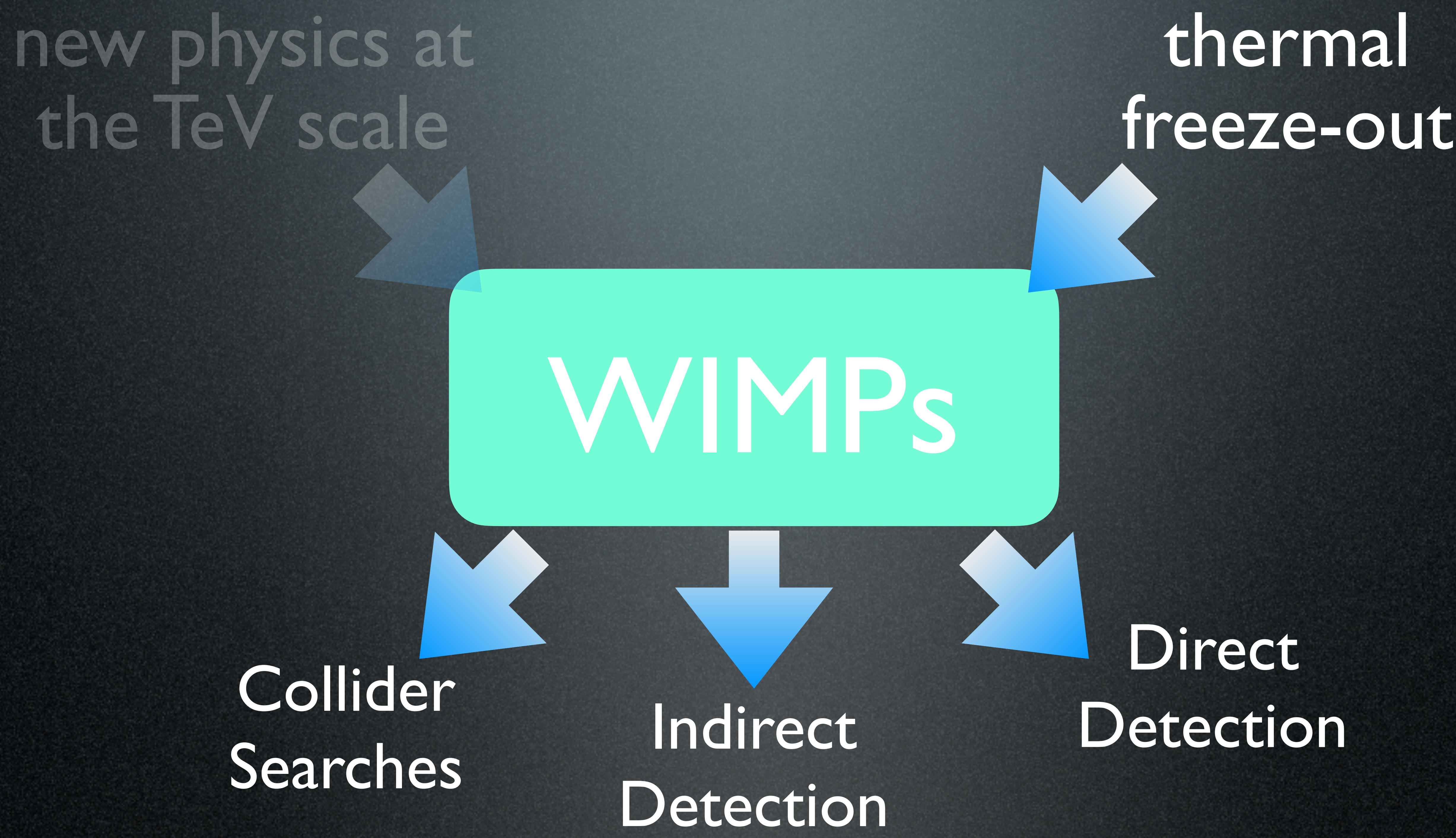
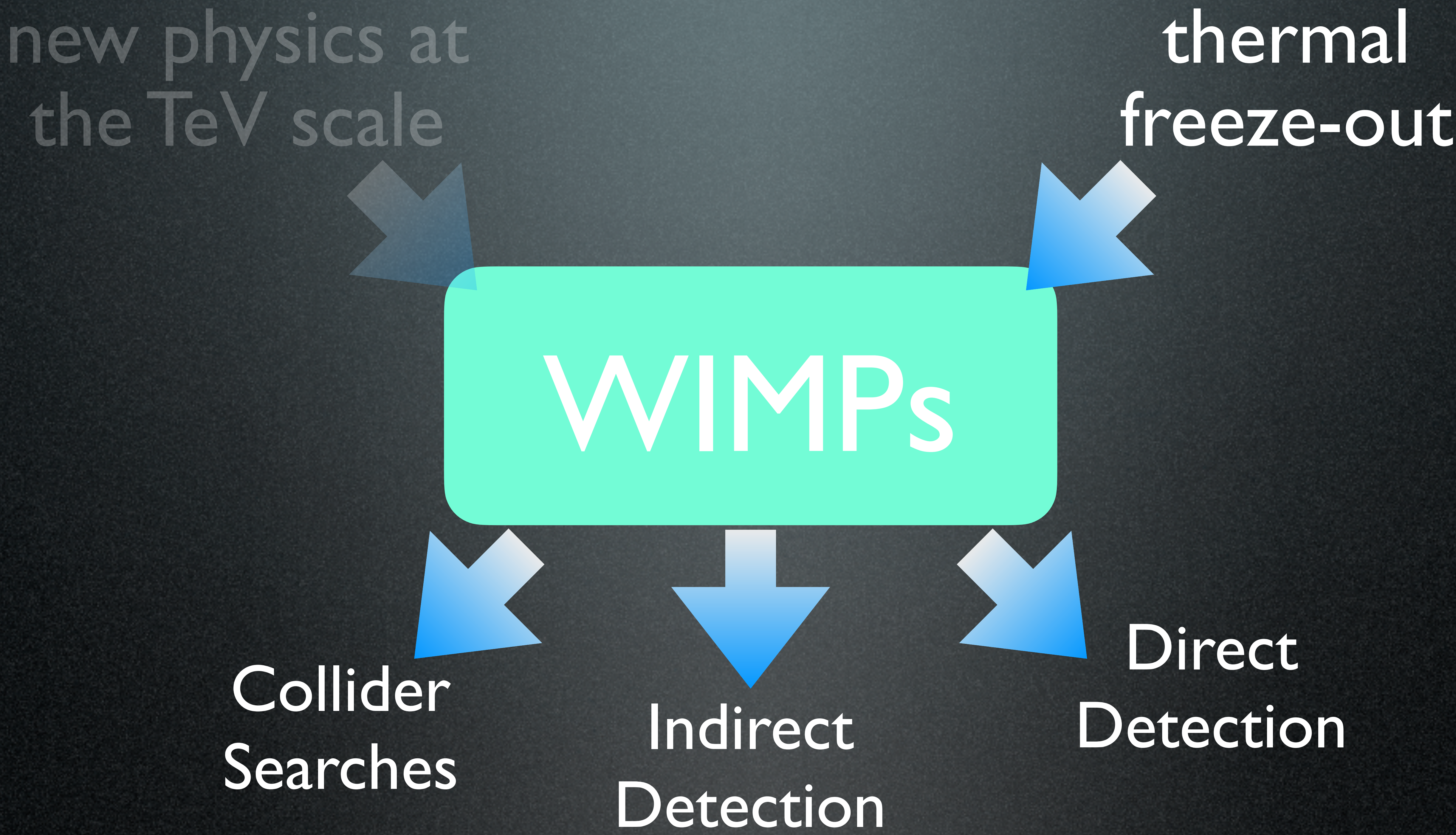


1. even without a larger framework, WIMPs are still appealing
2.

Candidates



1. even without a larger framework, WIMPs are still appealing
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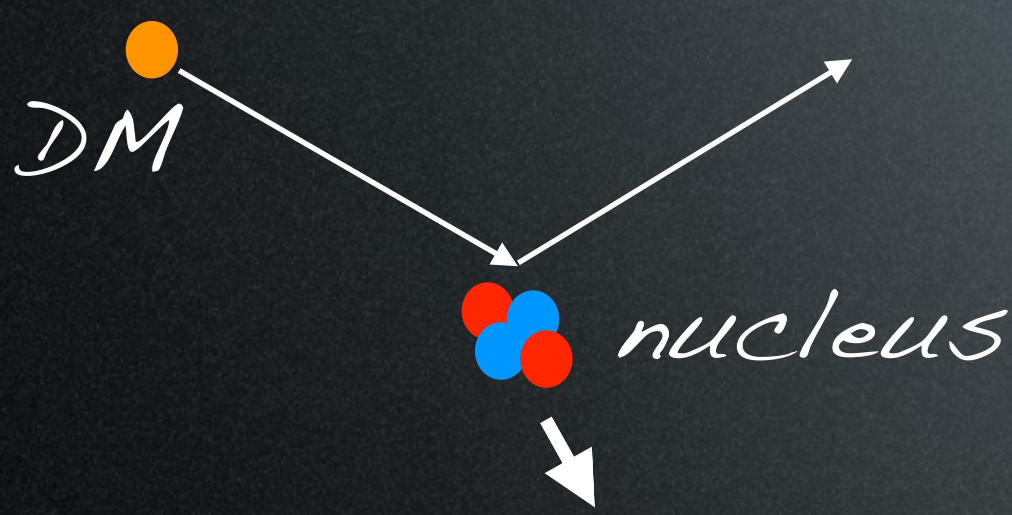
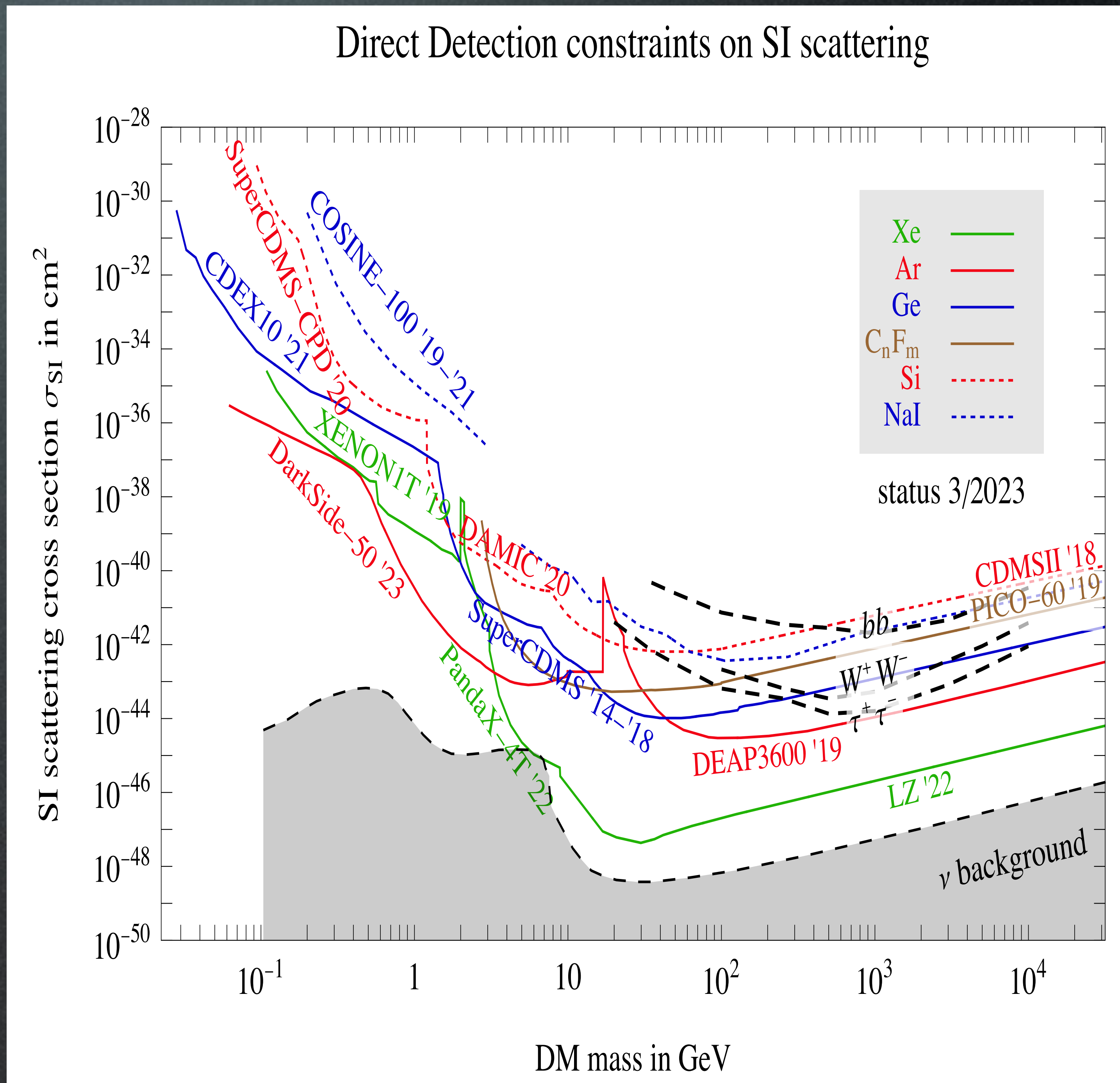
WIMP Direct Detection

SM weak scale SI interactions





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

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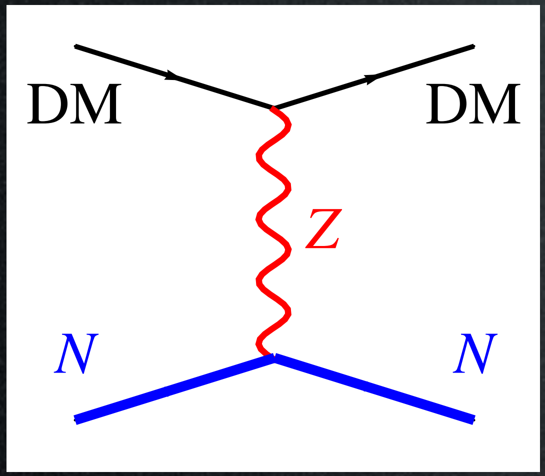
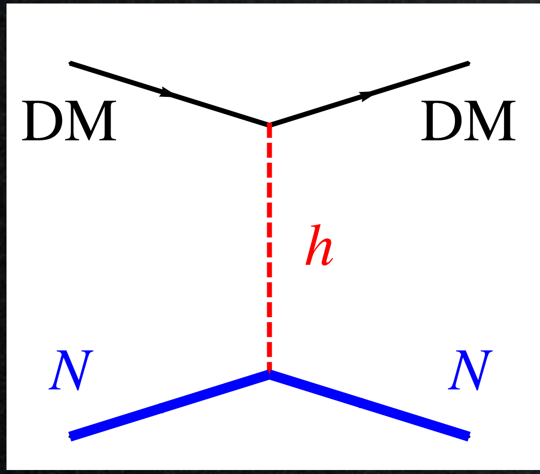
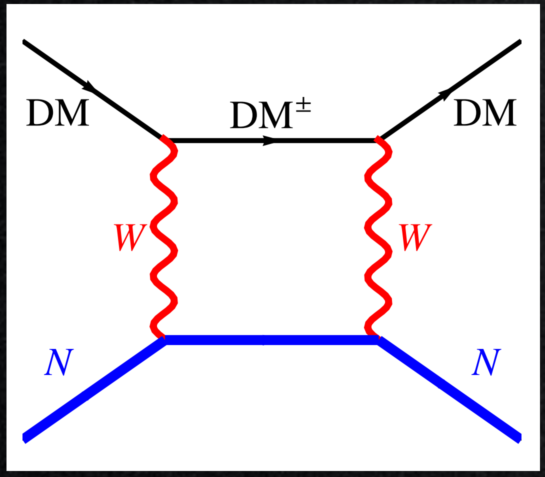


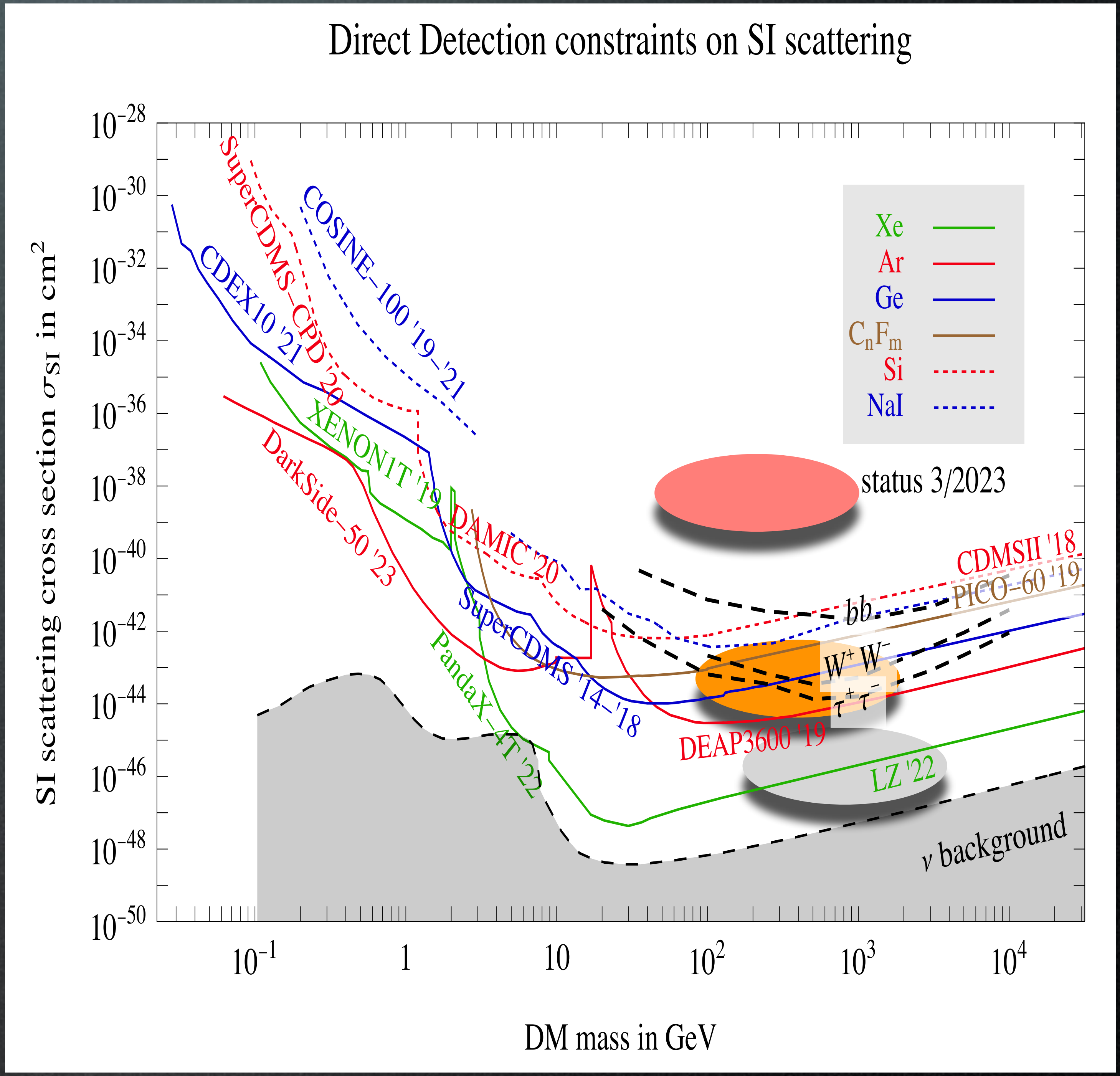
tree level, vector



tree level, scalar



one loop



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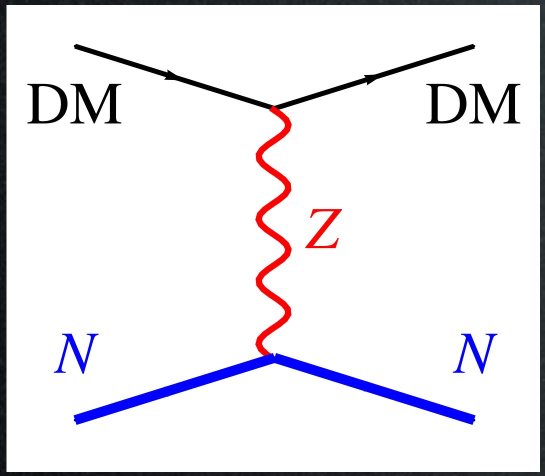

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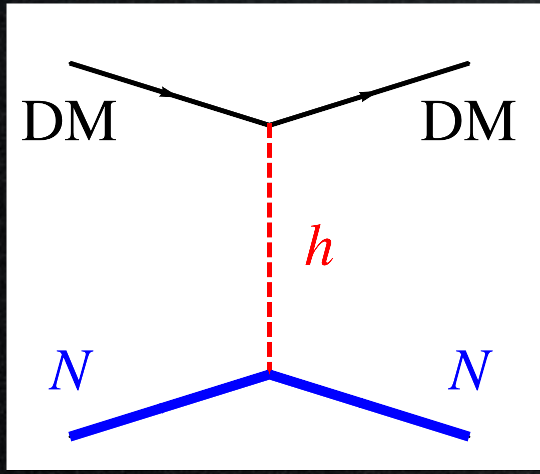

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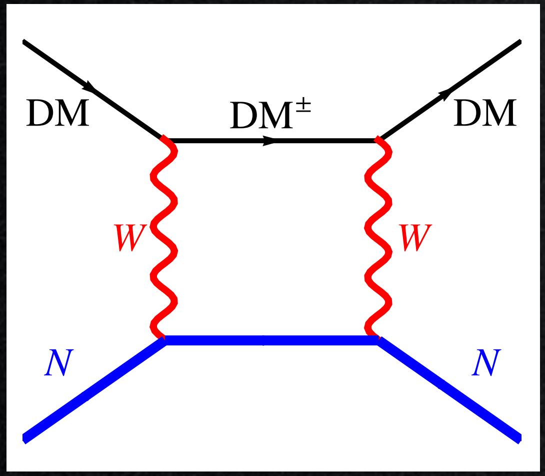

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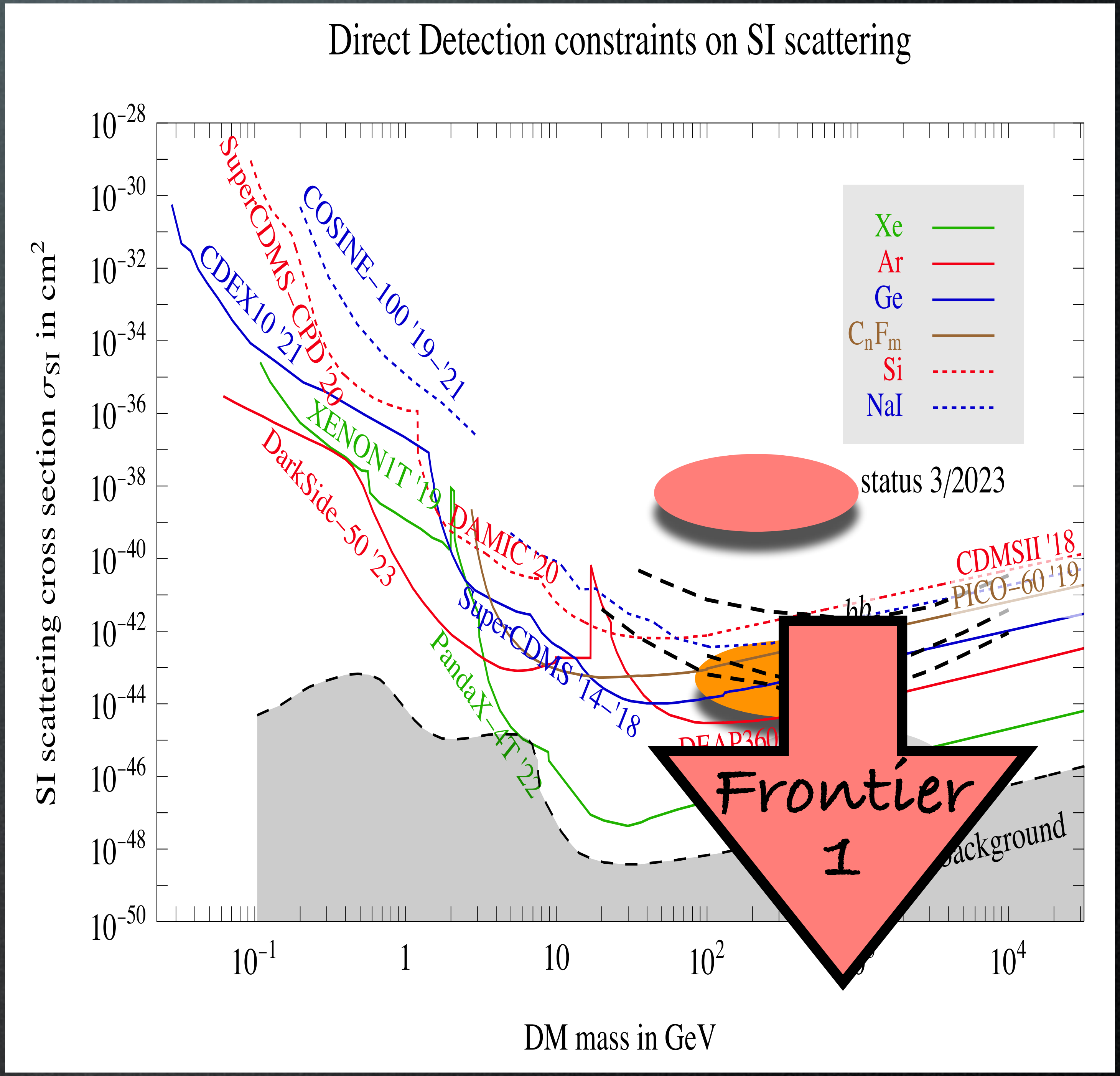

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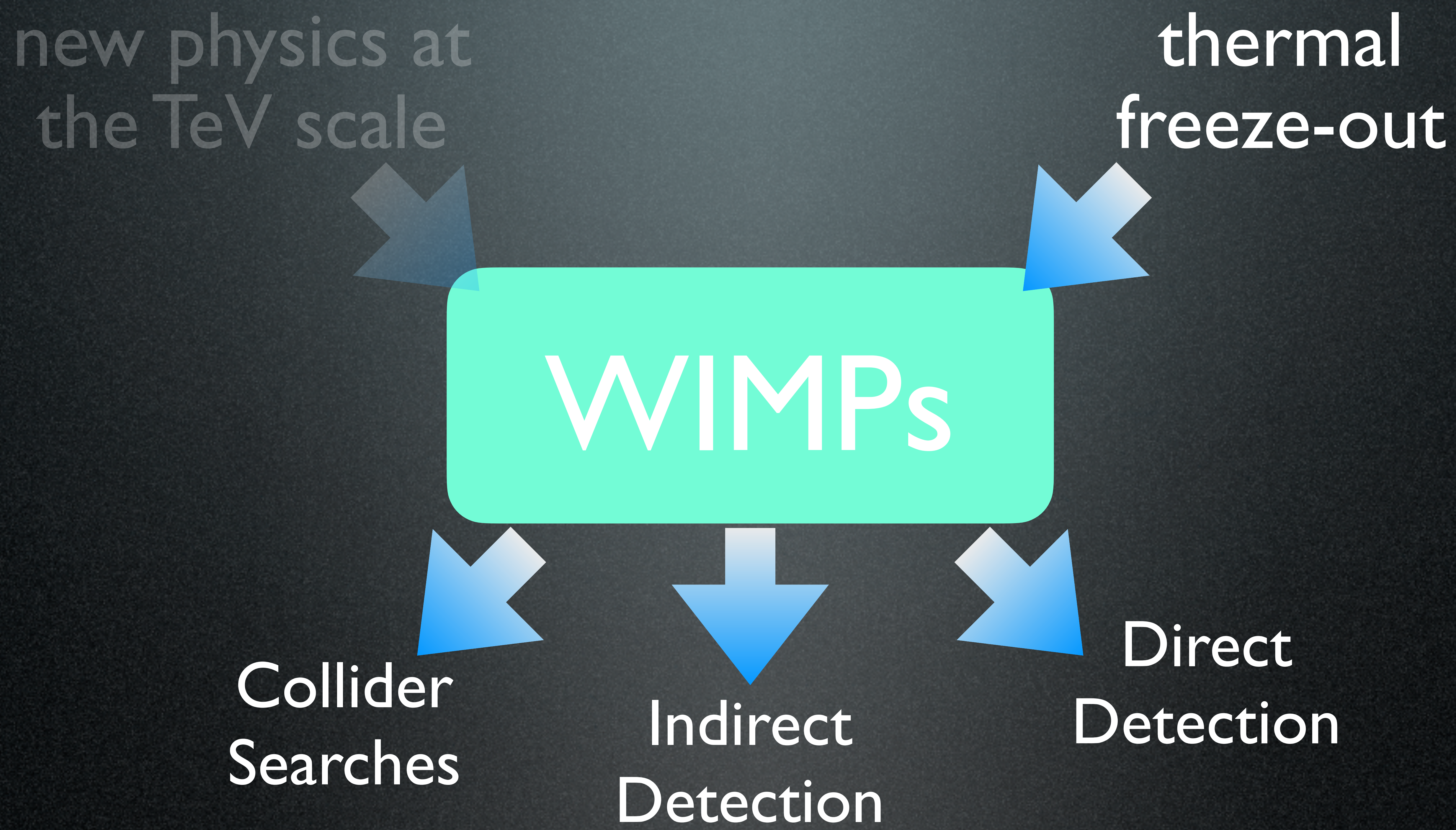
Candidates



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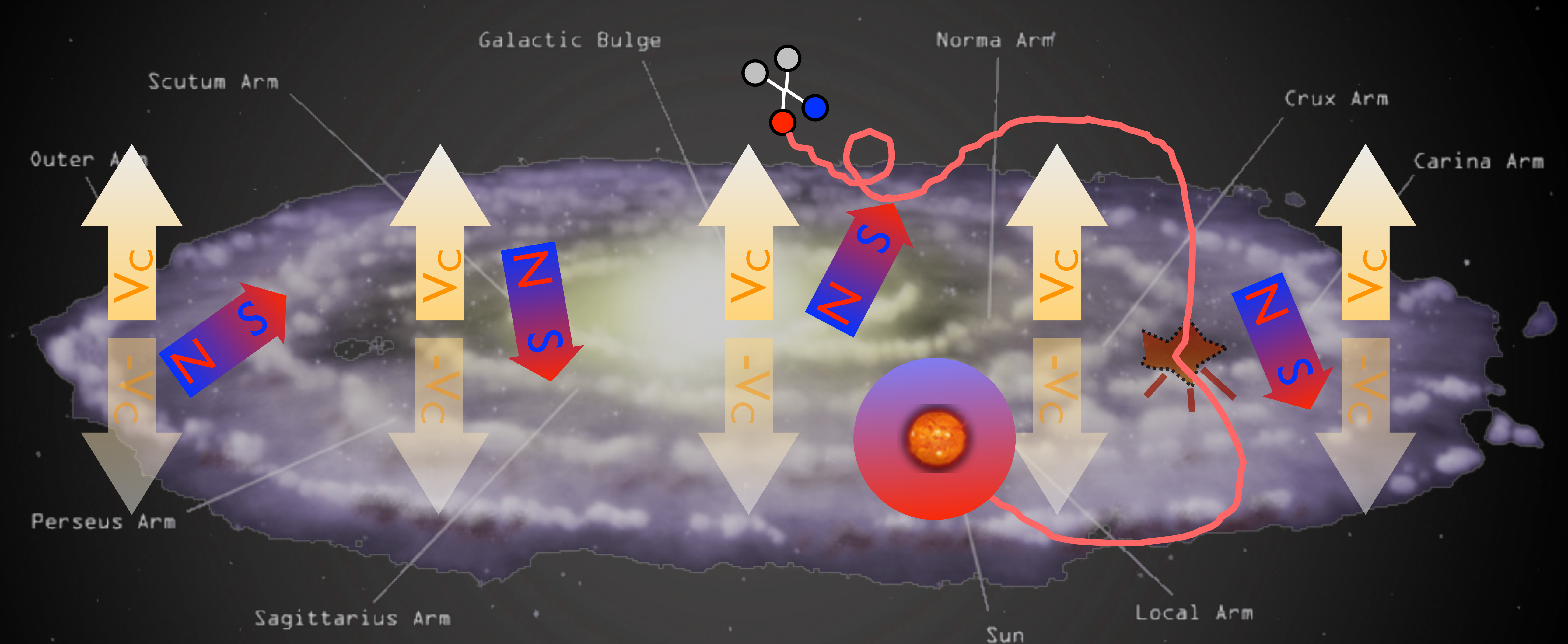
Indirect Detection: charged CRs

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



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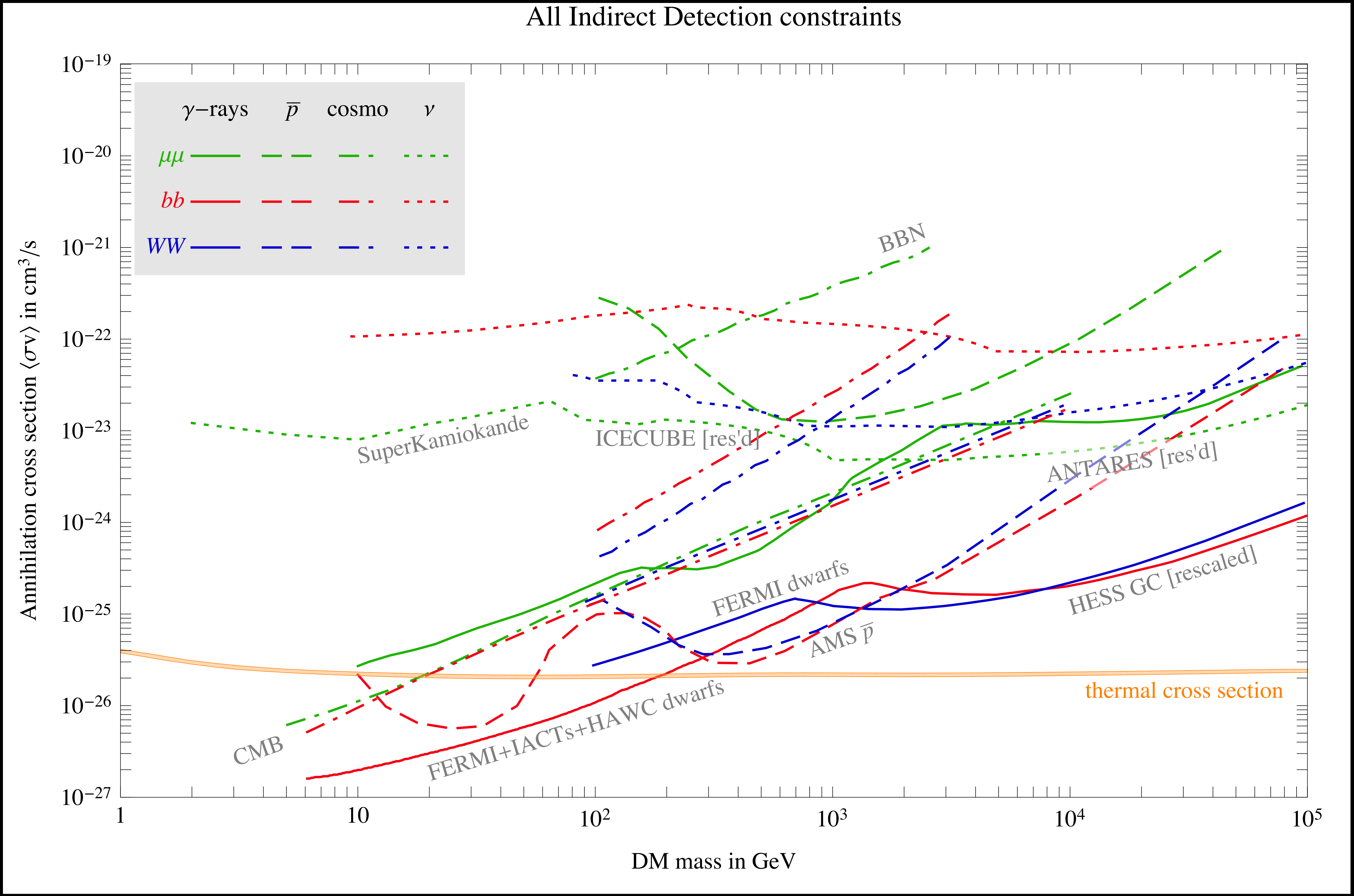

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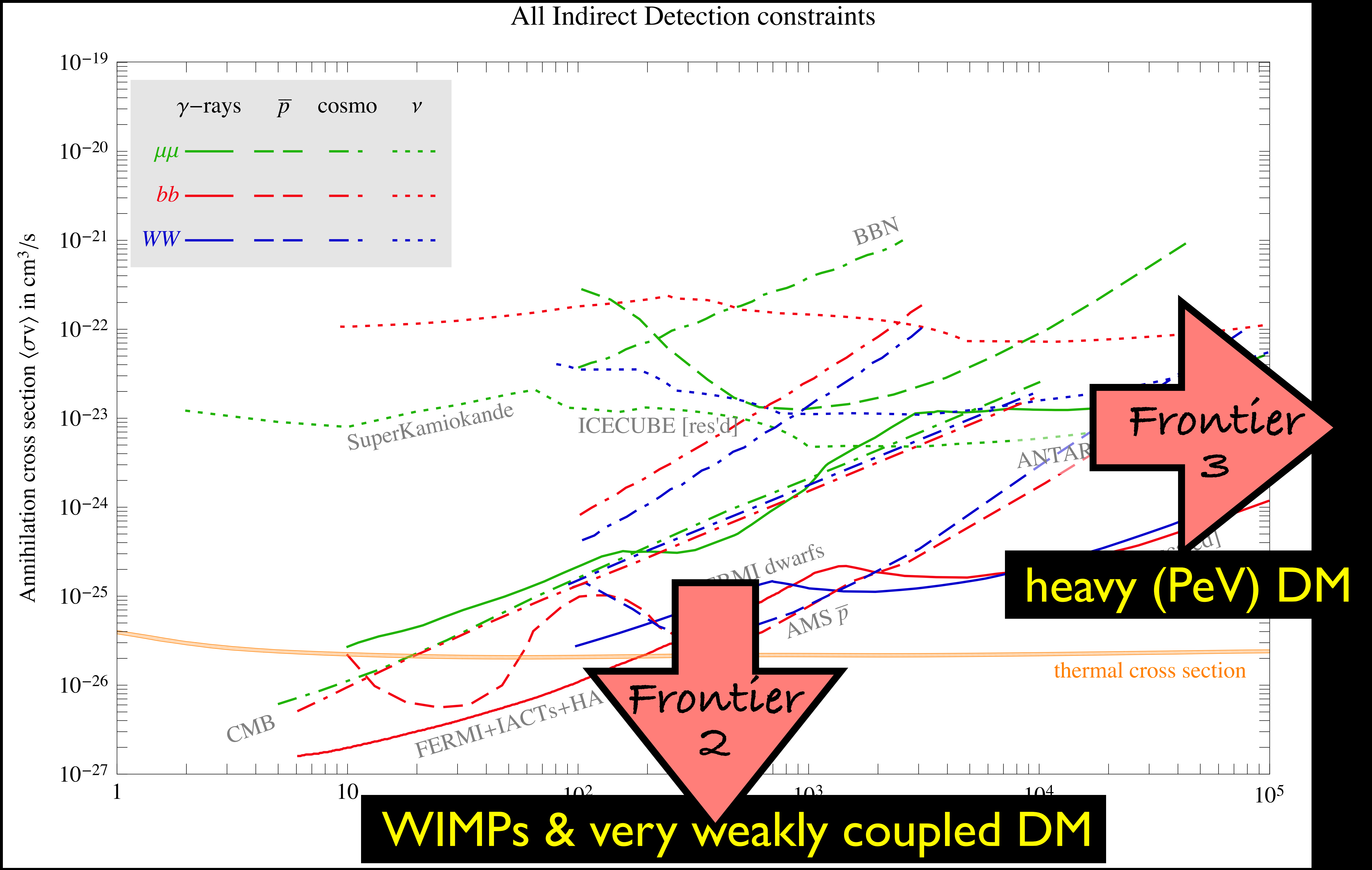

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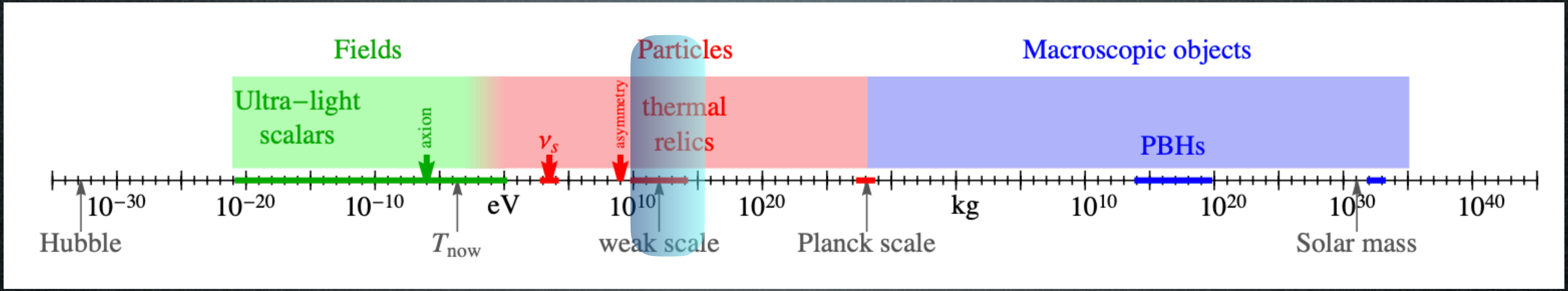
Candidates

A matter of perspective: plausible mass ranges



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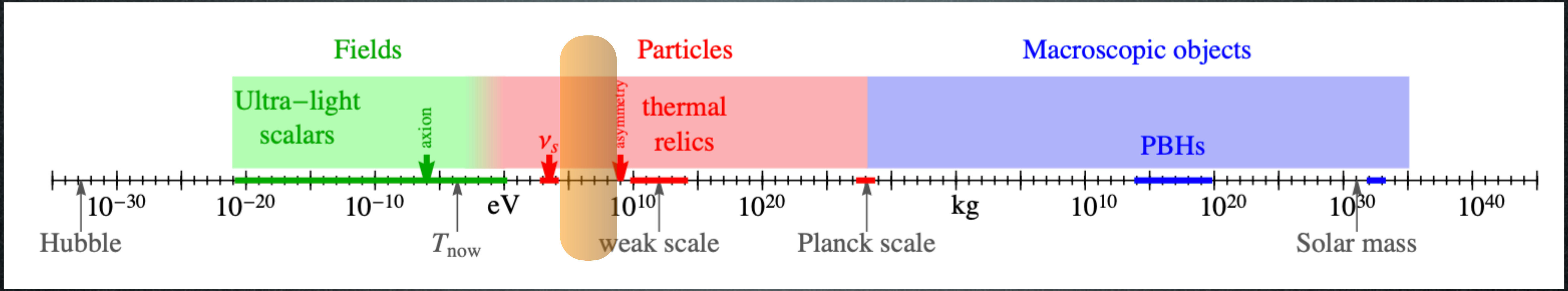
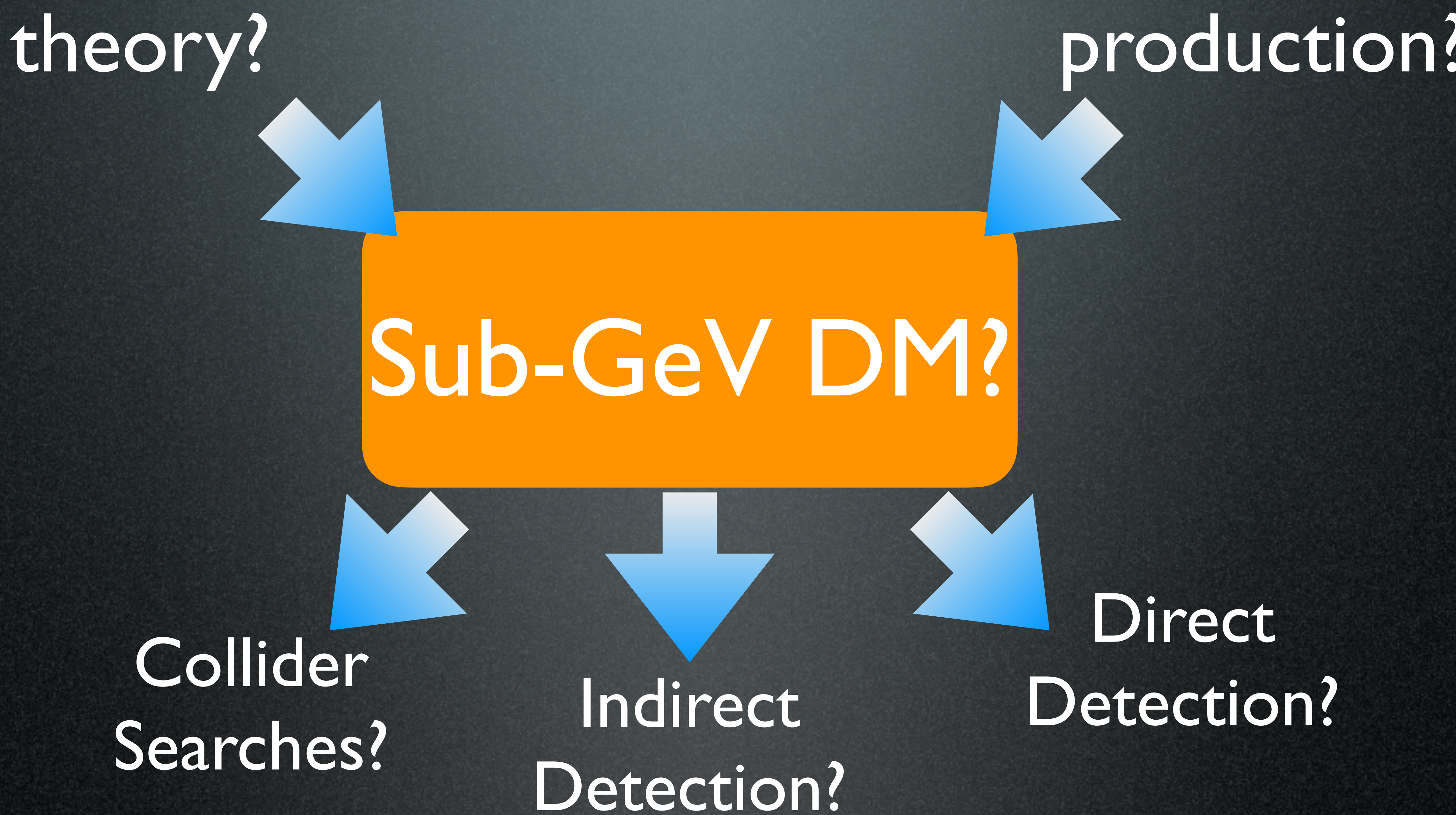


Sub-GeV DM?

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

Theory

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

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

Theory

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$\sim$ secluded DM

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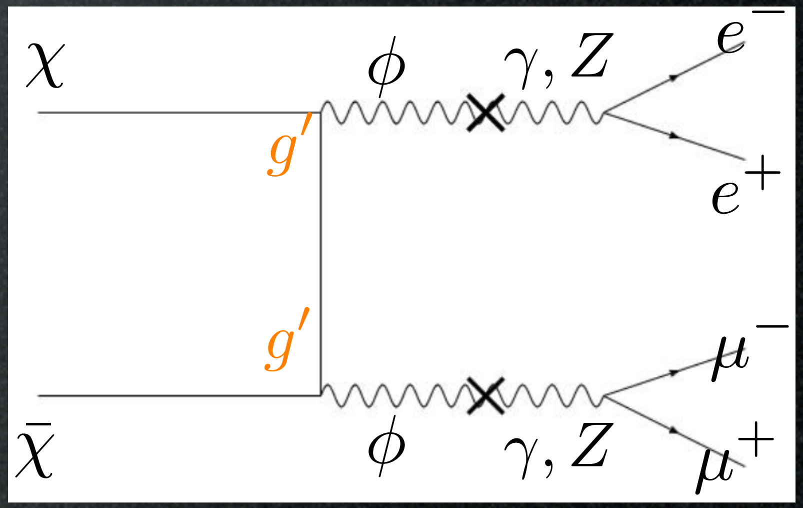
if g_x is small,

m 'naturally' small

(but nothing points to a precise value)



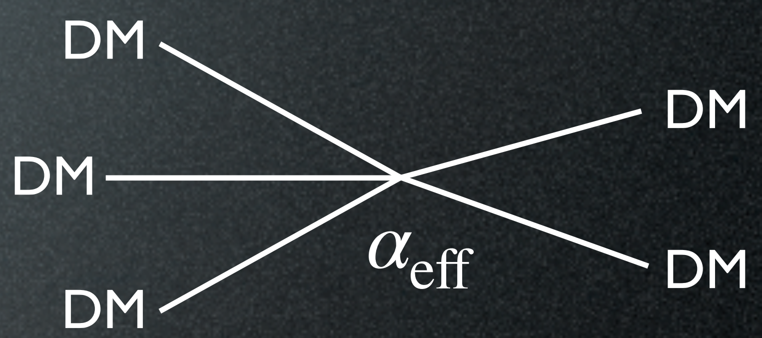
Production mechanism:

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

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

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

- ‘simplified (light) DM models’ Knapen, Lin, Zurek 1709.07882

Theory

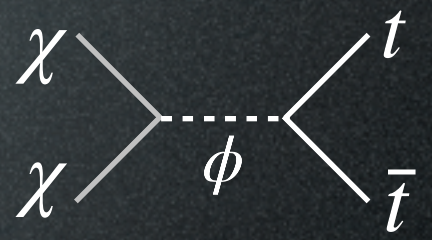
Sub-GeV DM

- ‘simplified (light) DM models’

Knapen, Lin, Zurek 1709.07882

scalar DM and
hadrophilic
scalar mediator

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



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Knapen, Lin, Zurek 1709.07882

scalar DM and hadrophilic scalar mediator

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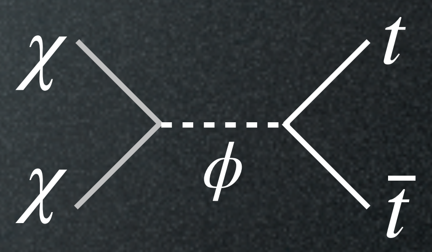
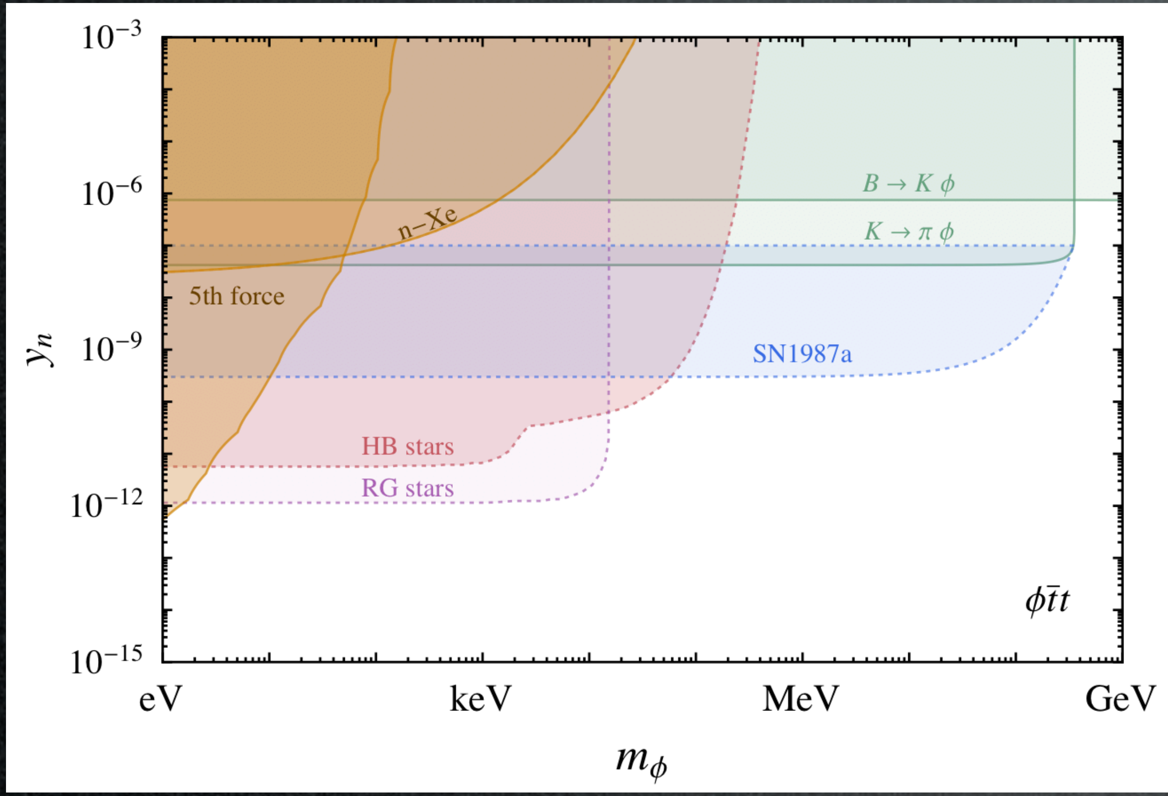
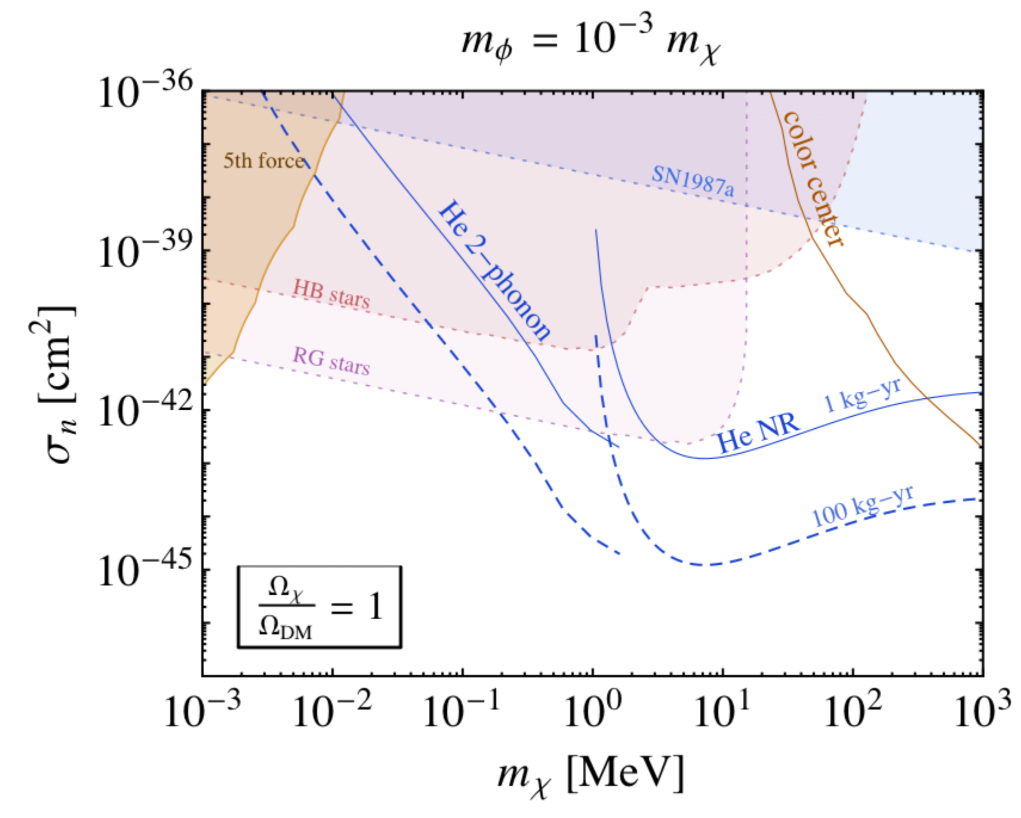


constraints on the mediator



constraints on the DM



Theory

Sub-GeV DM?

- 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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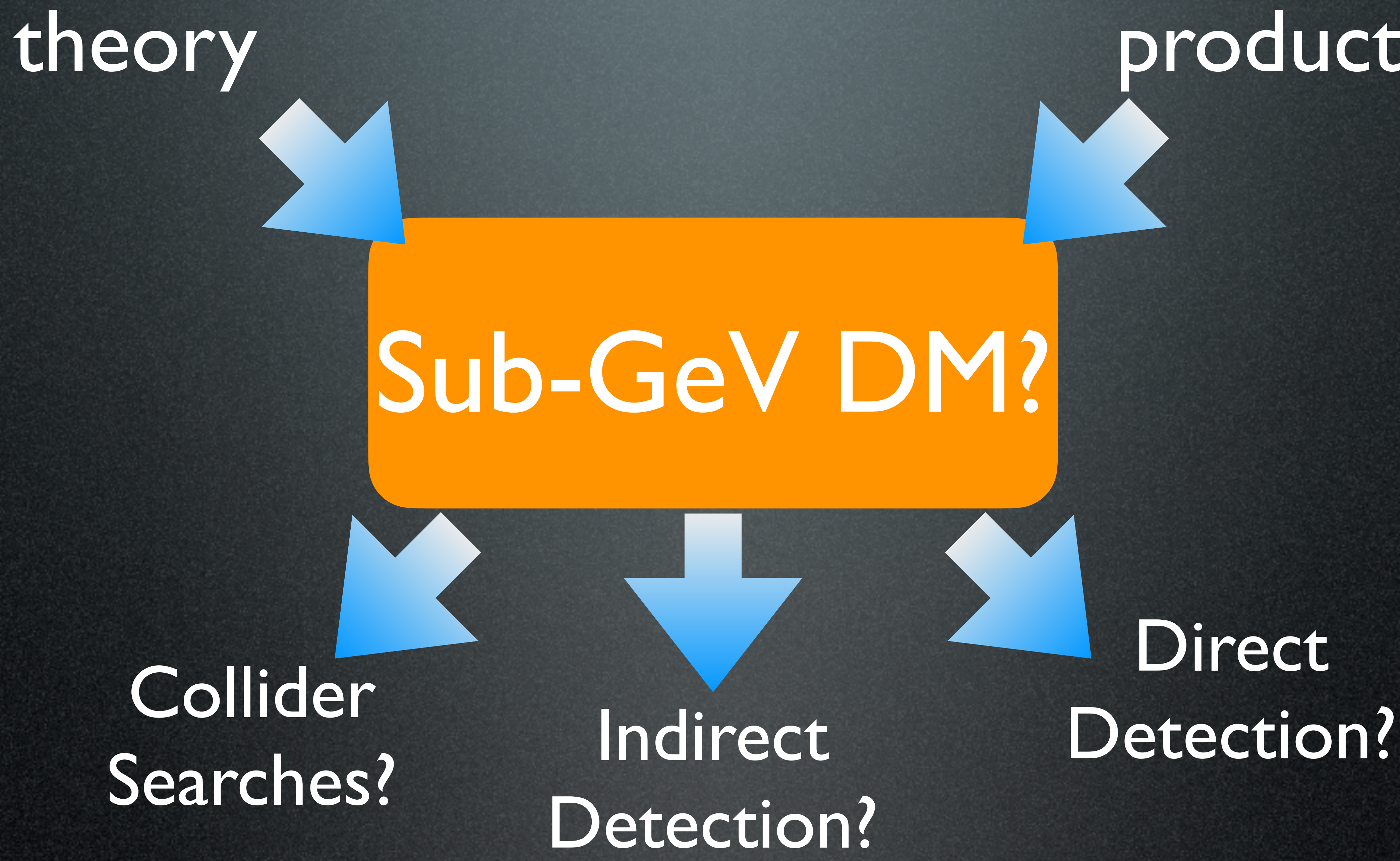
Candidates


theory
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Collider
Searches?
Indirect
Detection?
Direct
Detection?

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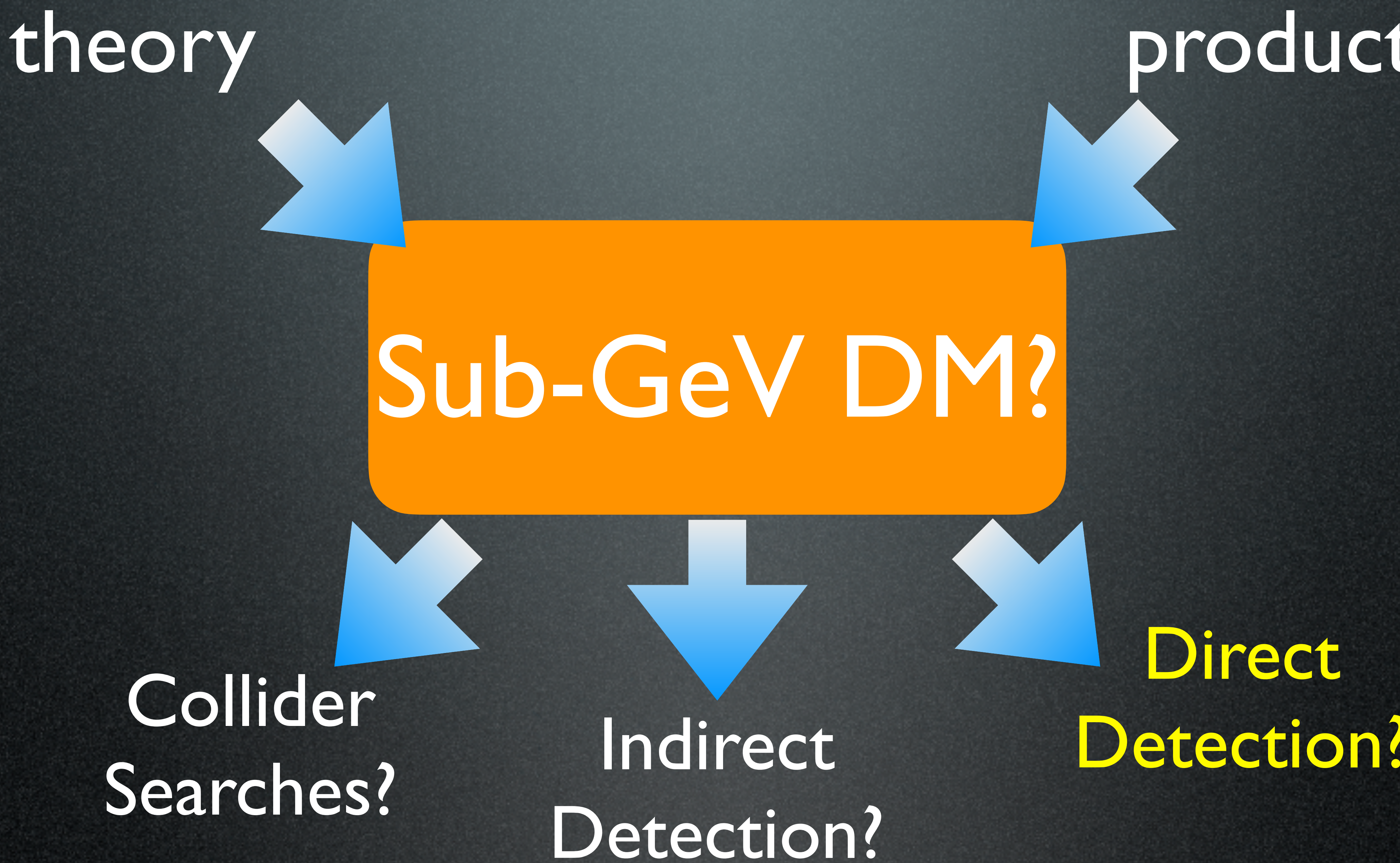
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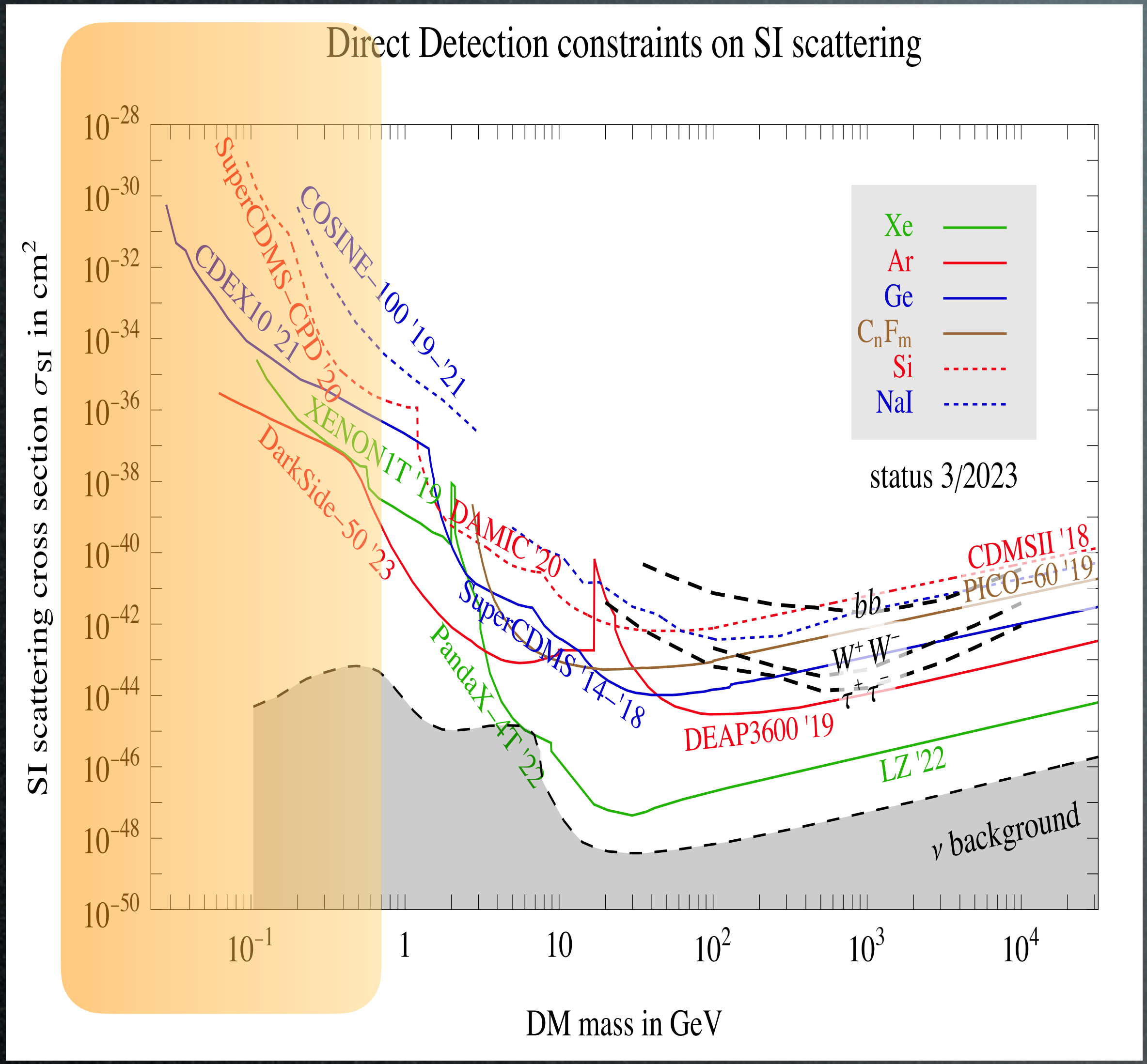
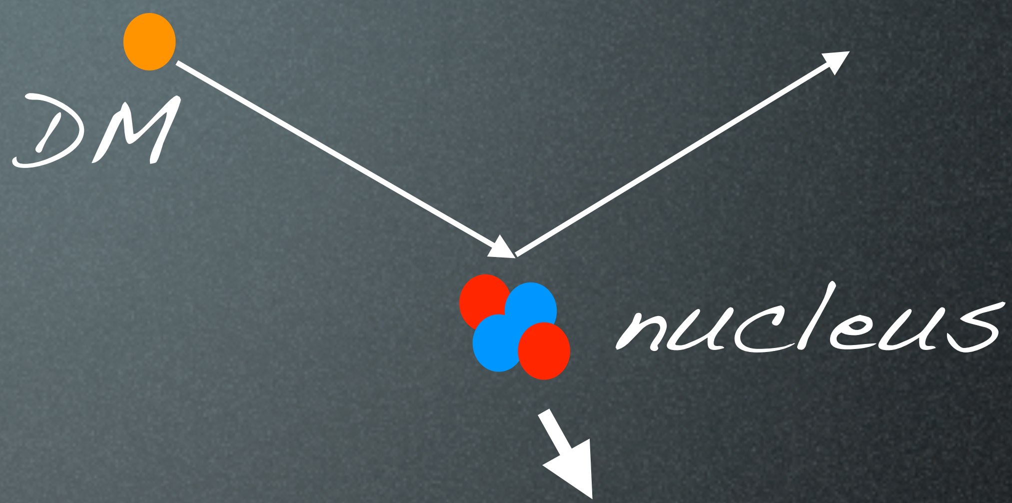
Direct Detection of sub-GeV DM



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



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

- electron recoil signal
- Migdal effect
- new experimental strategies

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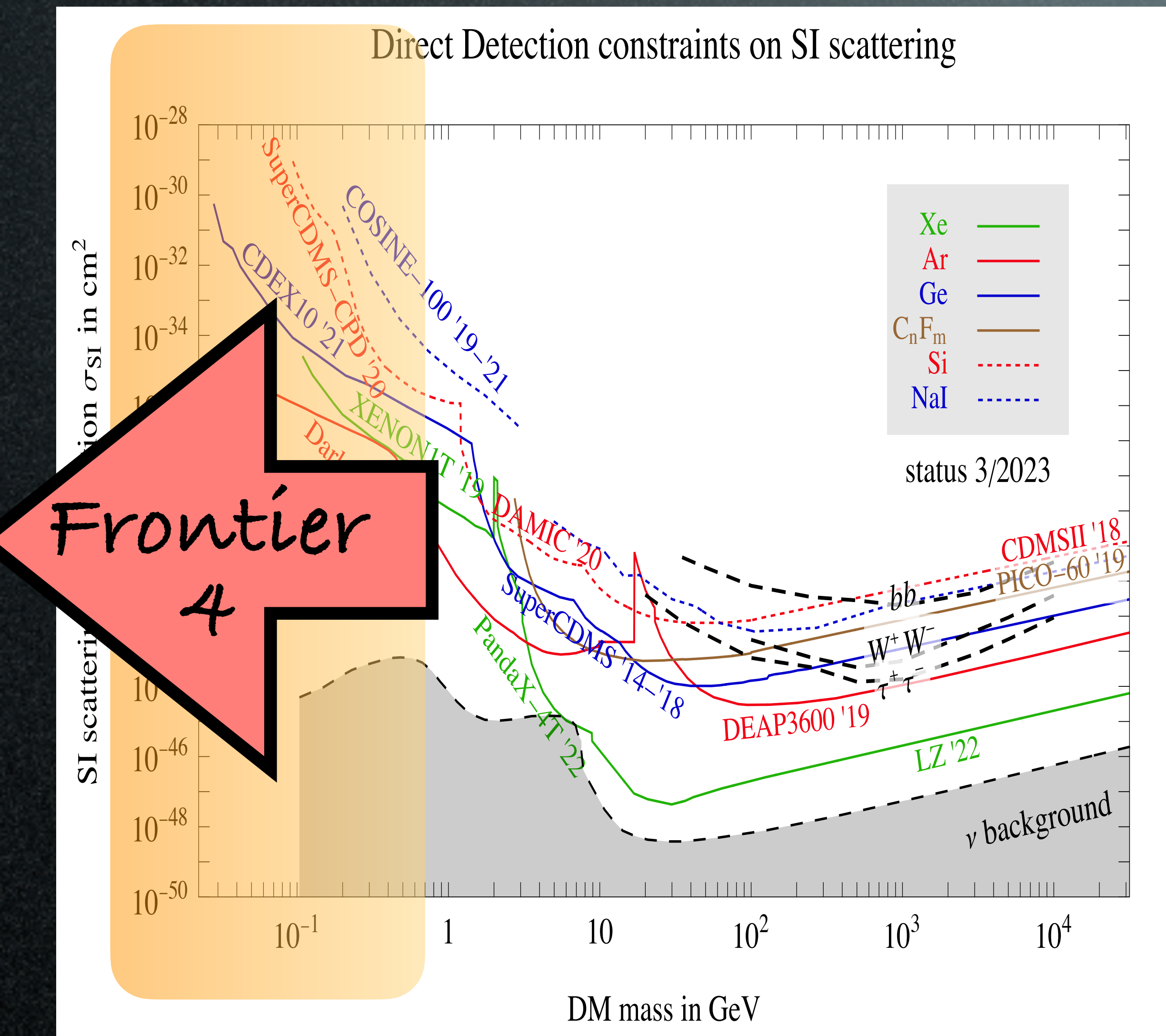

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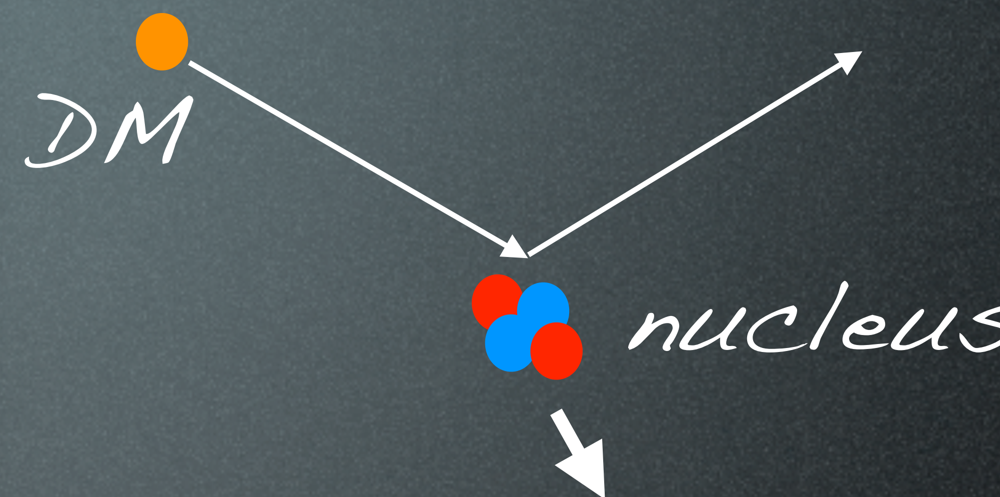

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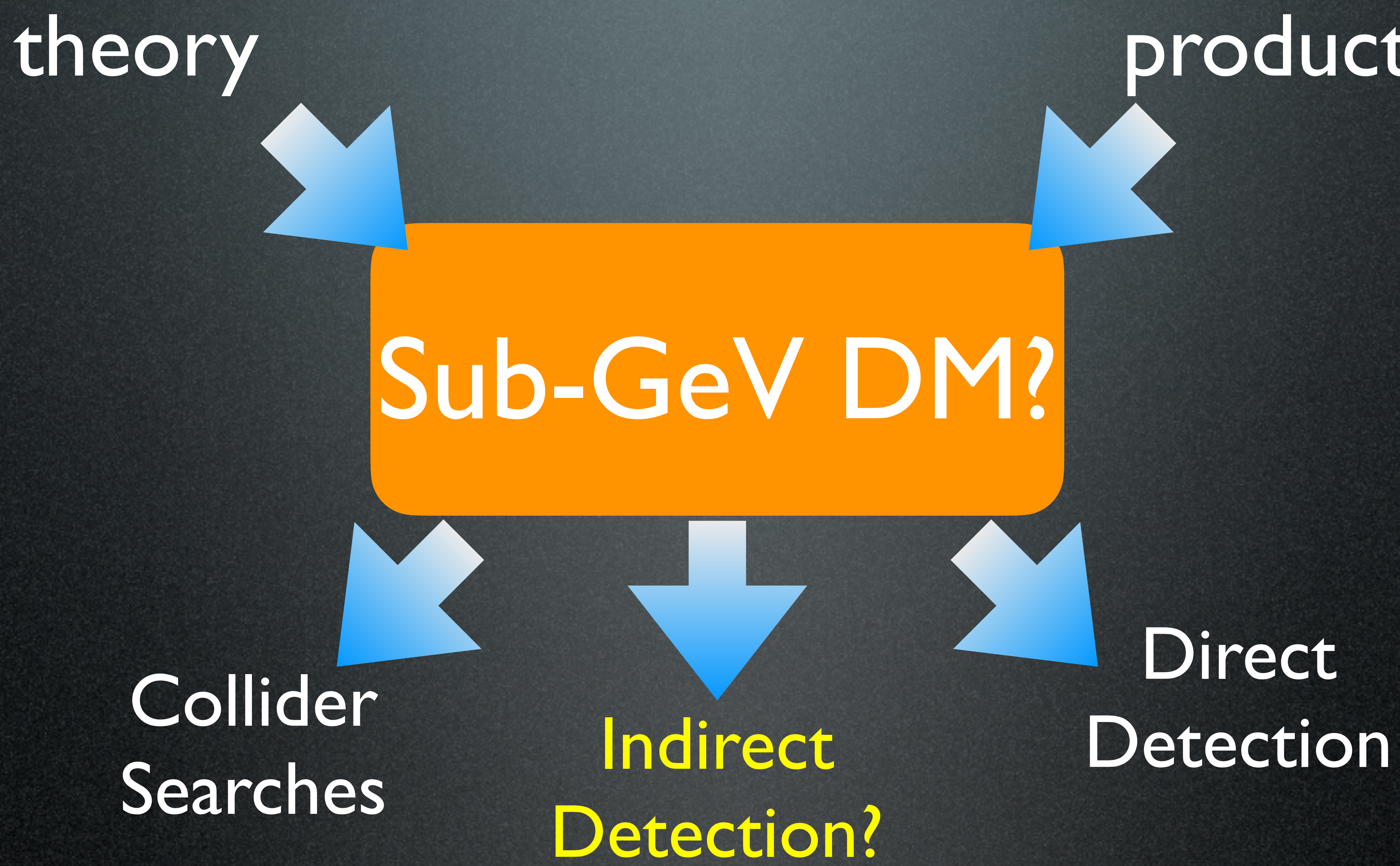
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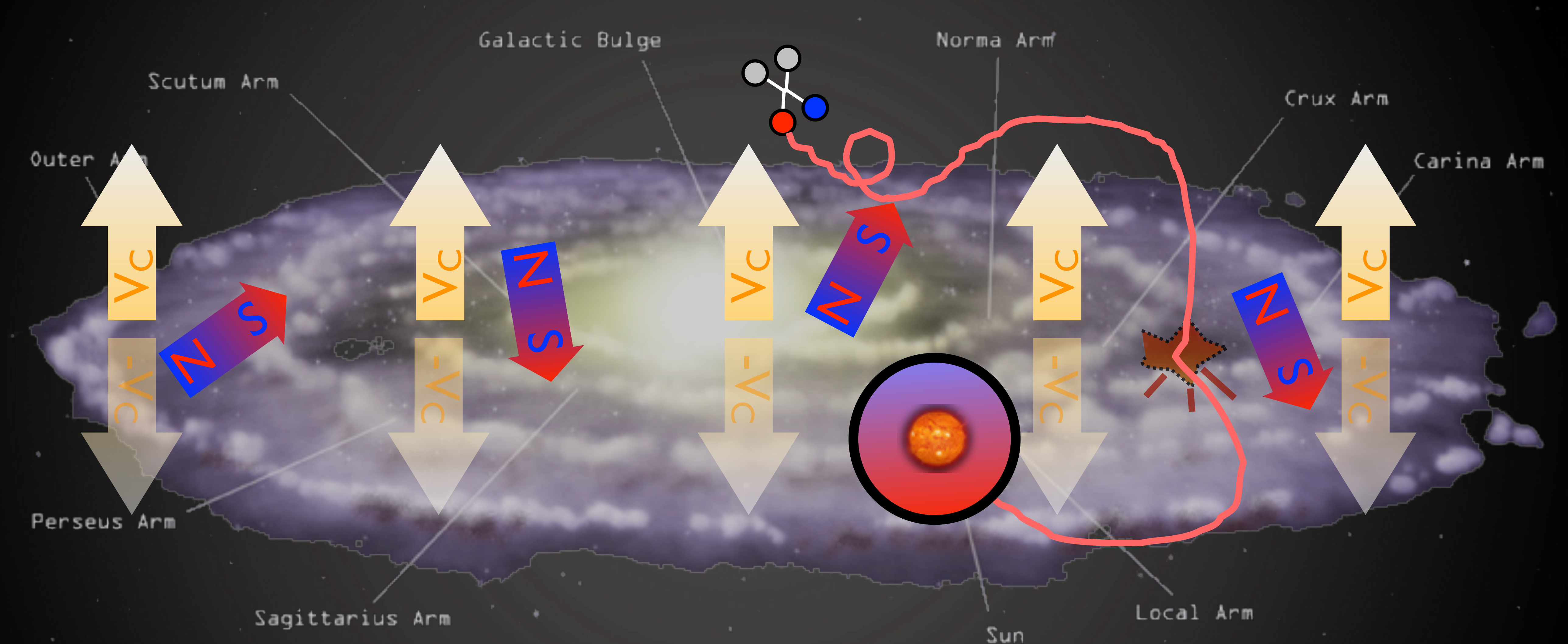
Indirect Detection: charged CRs

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



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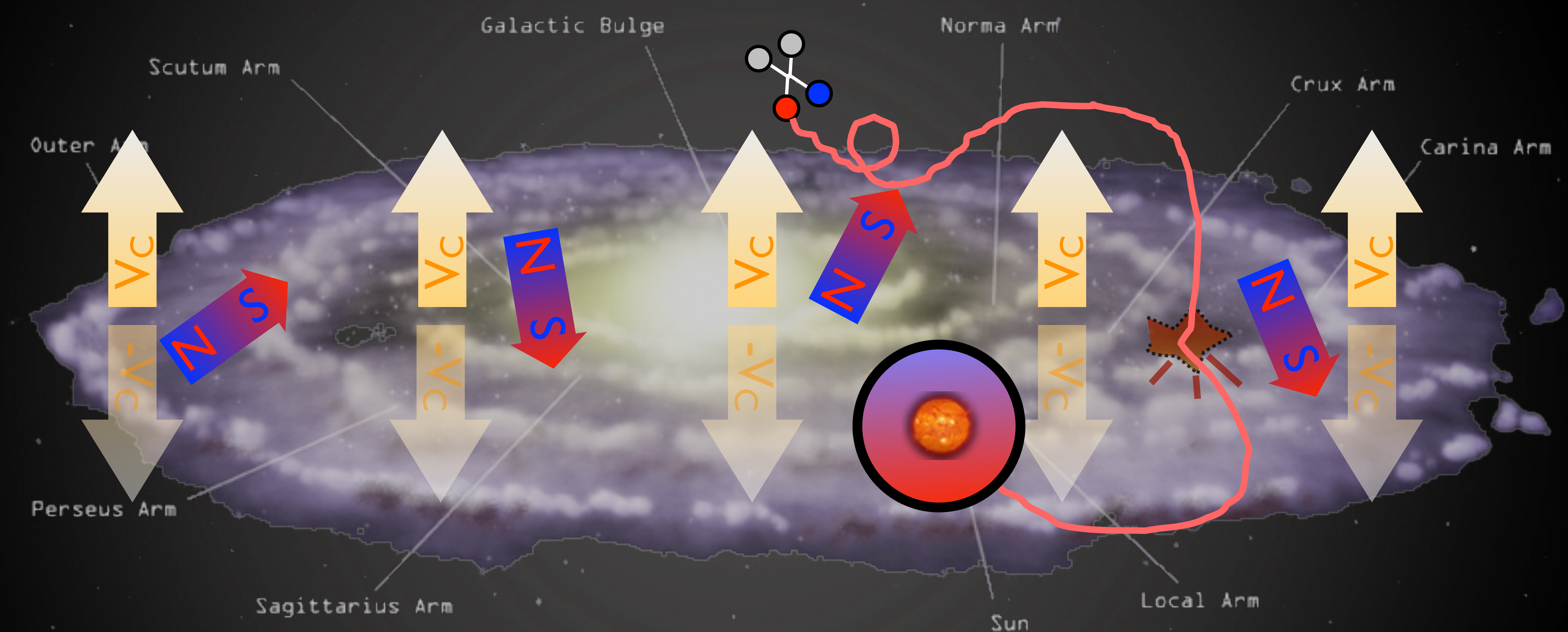

Problem:

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

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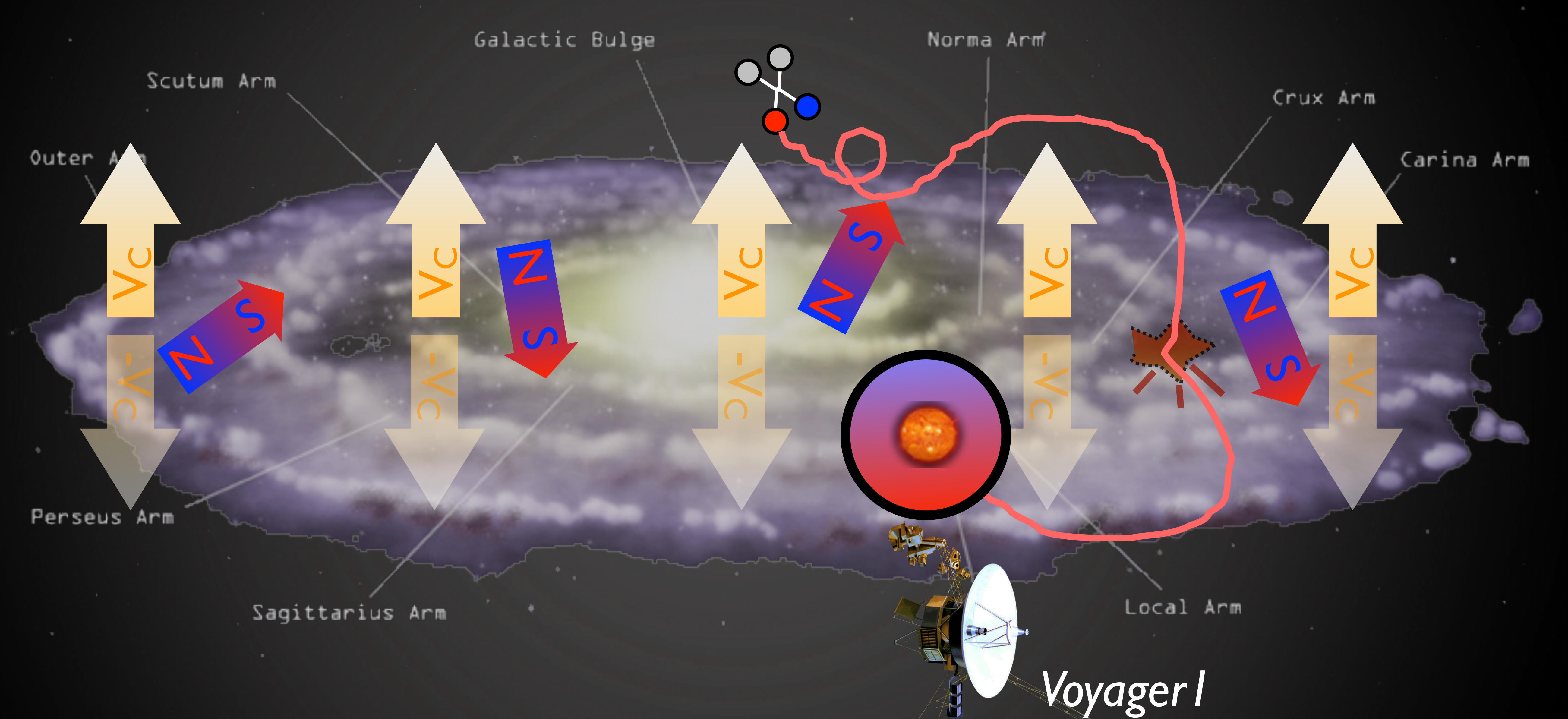
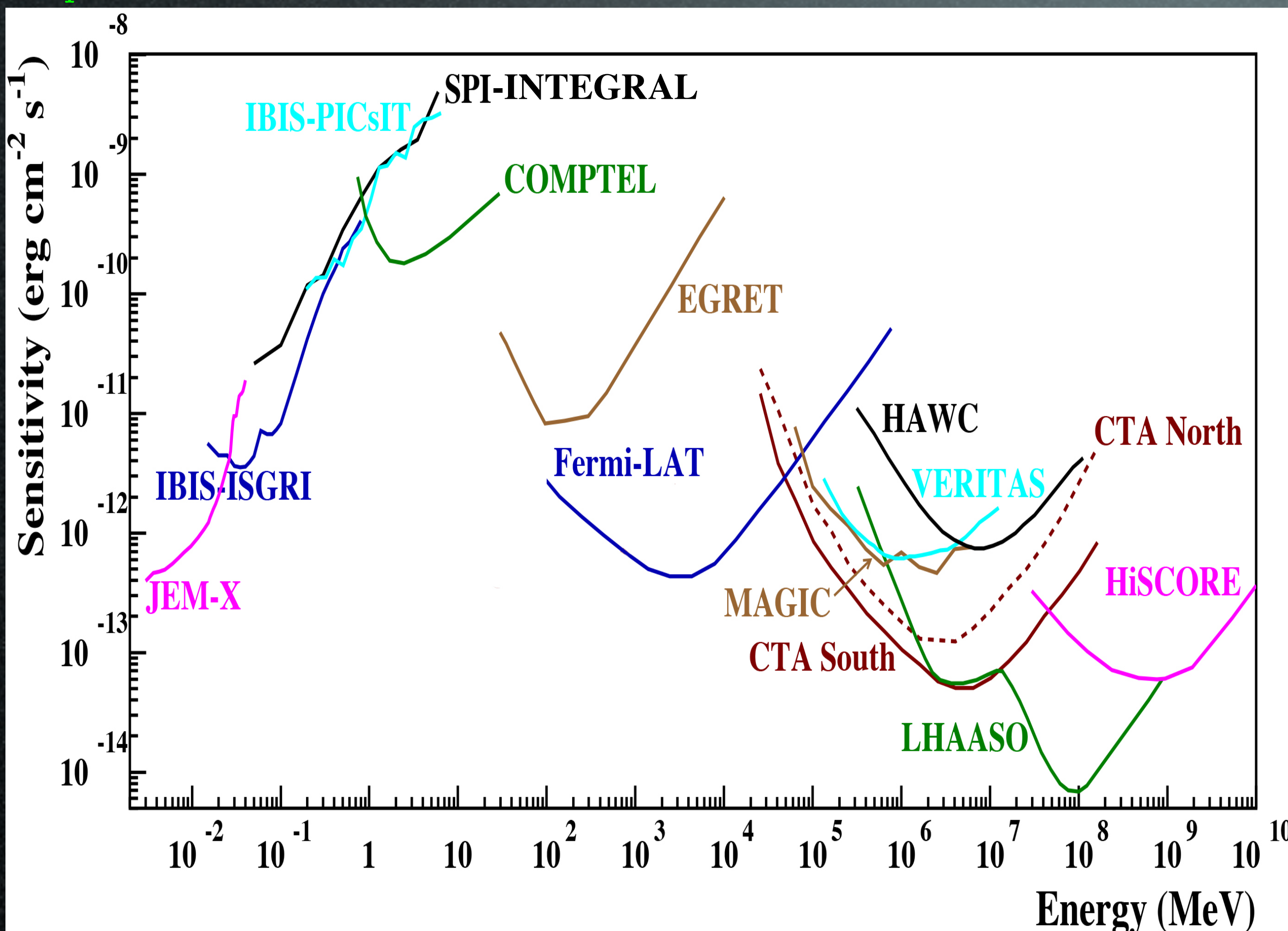


Problem:

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

Indirect detection: photons

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

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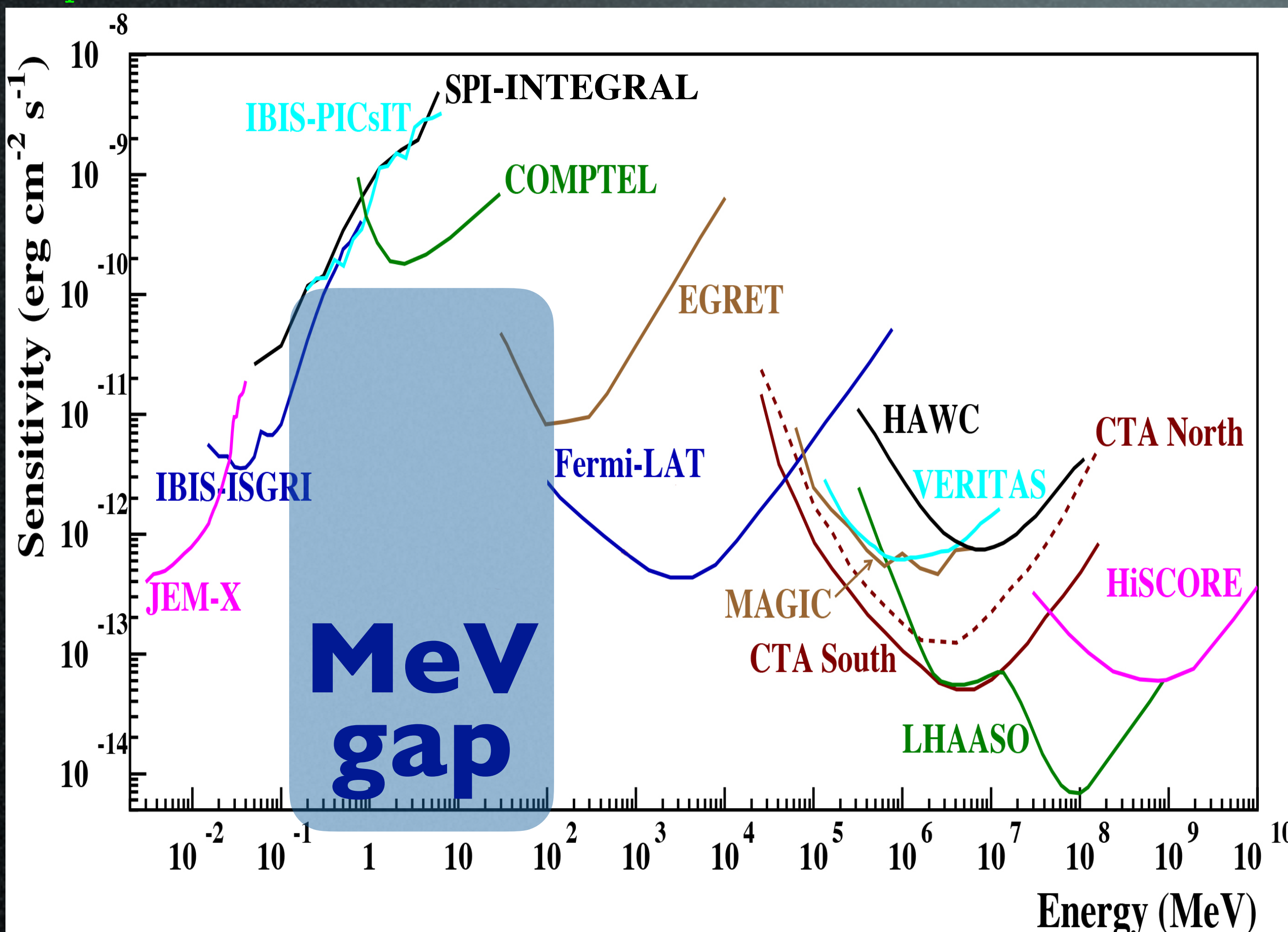

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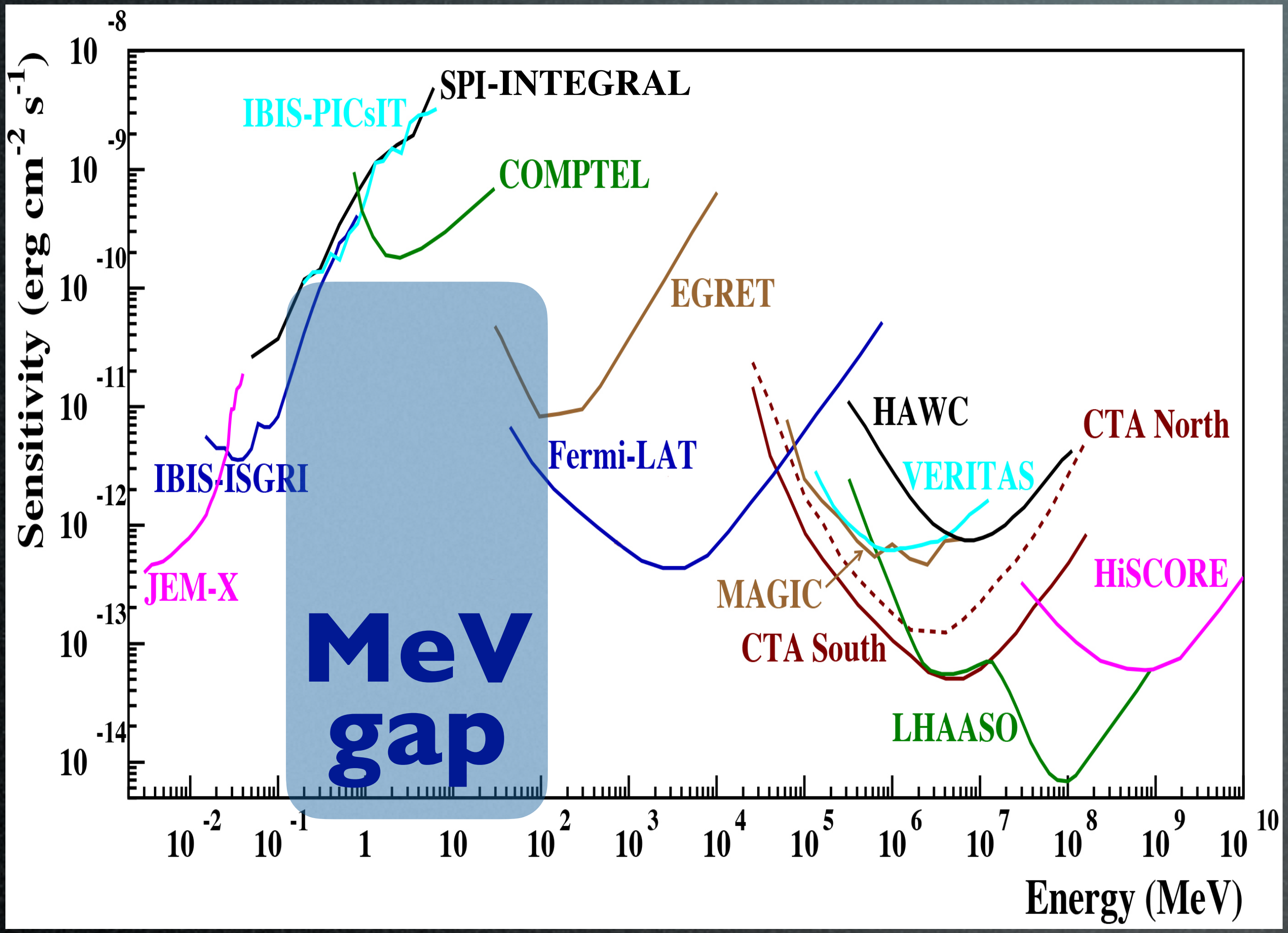
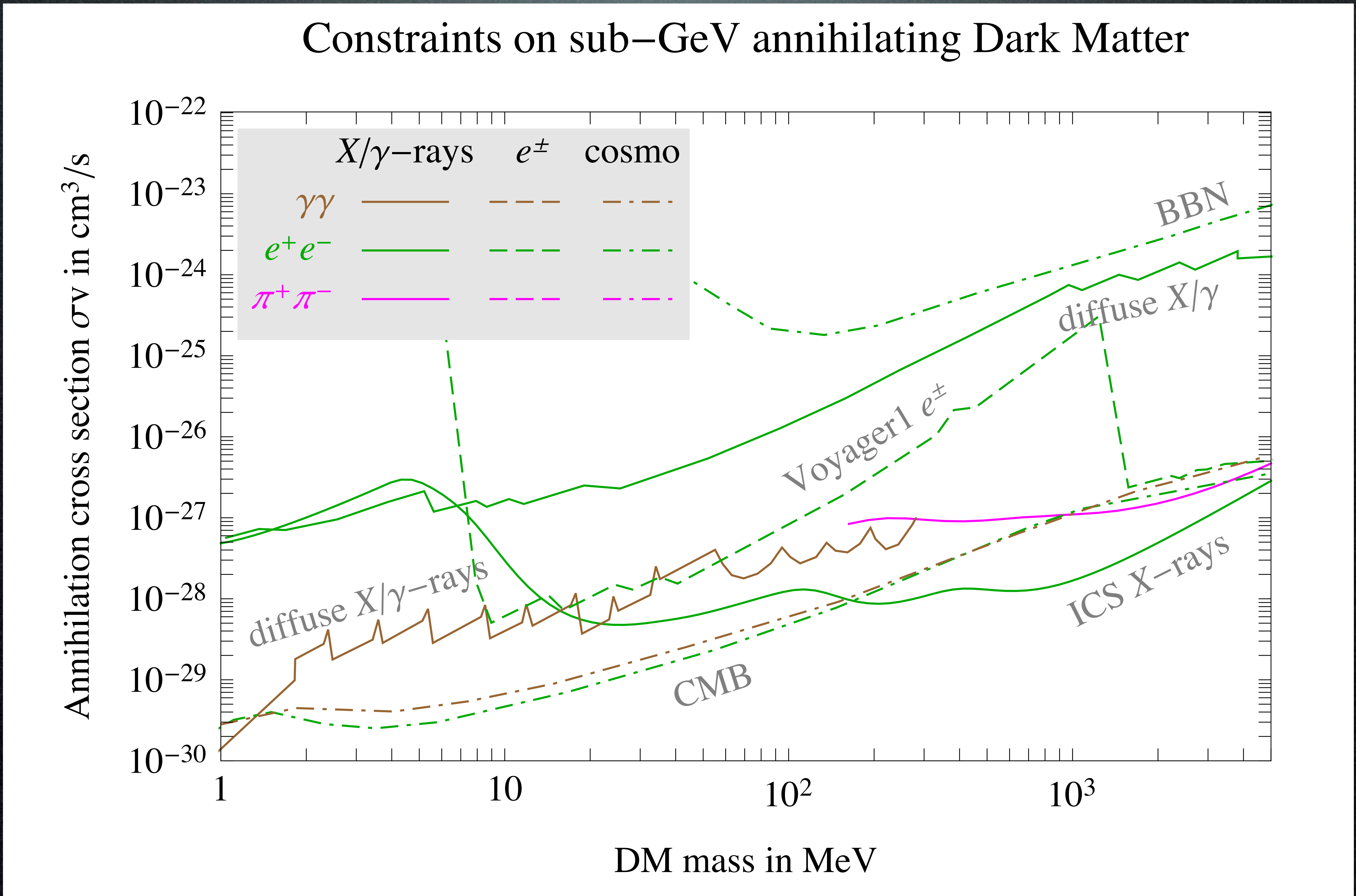


How to do better?

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 to appear

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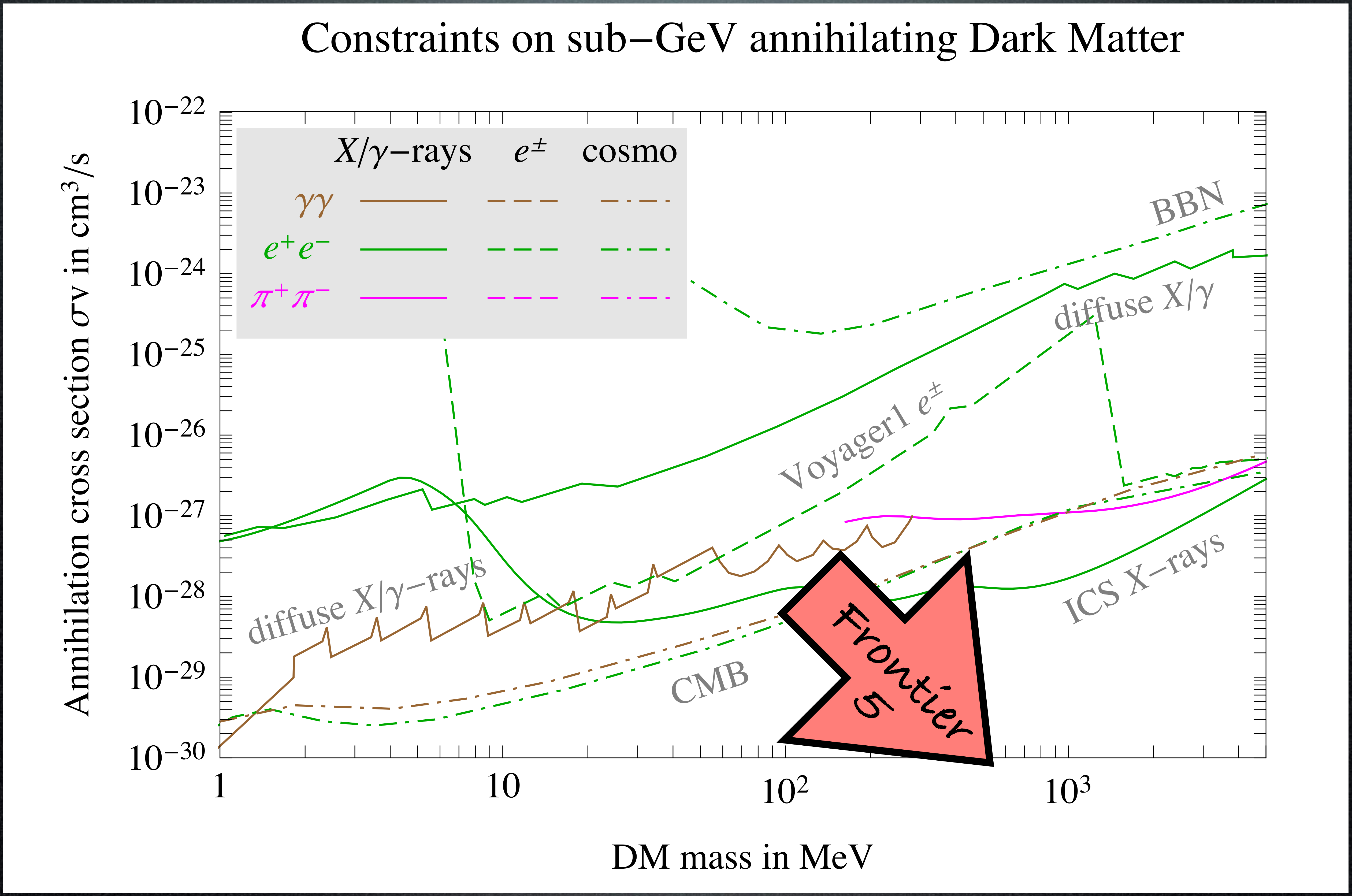

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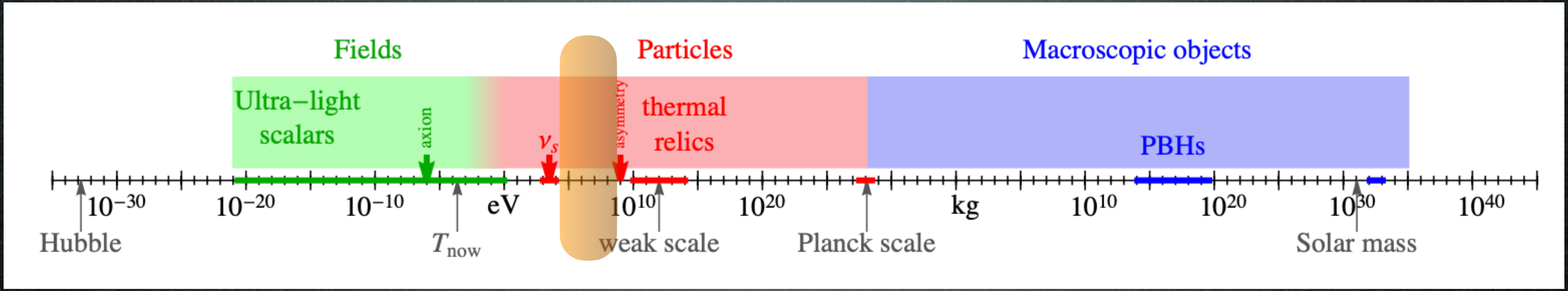
Candidates

A matter of perspective: plausible mass ranges



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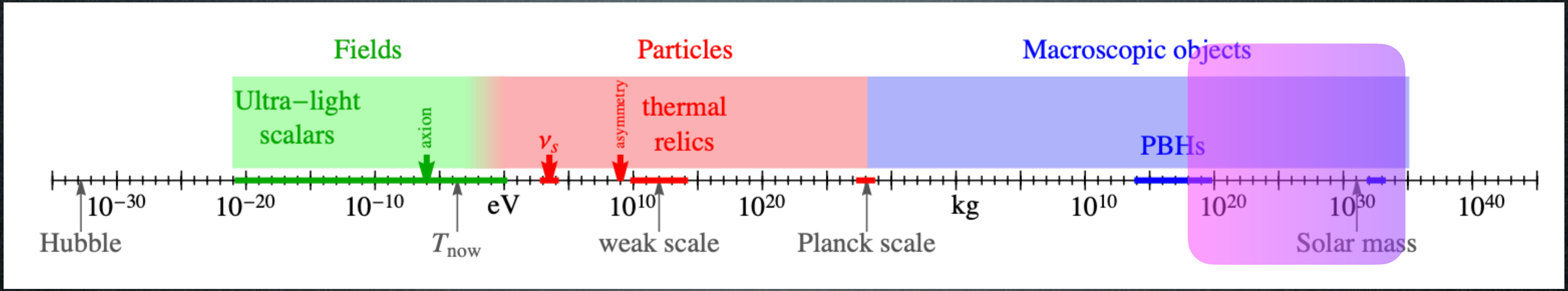

DM can **NOT** be:

an astro *je ne sais pas quoi*:

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- gas

- Black Holes
- brown dwarves

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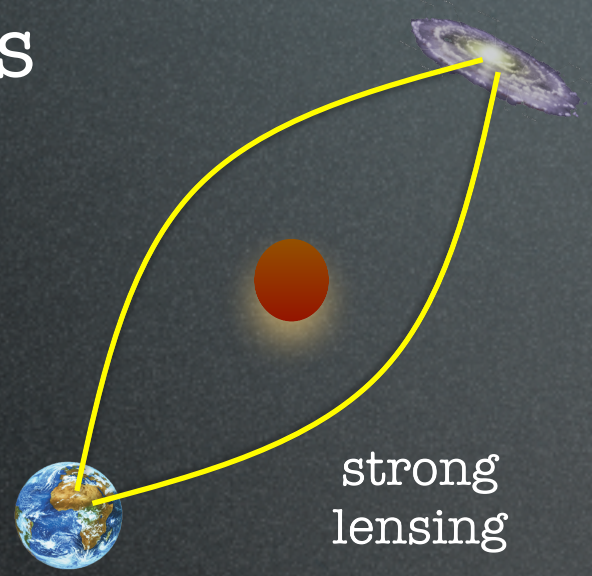
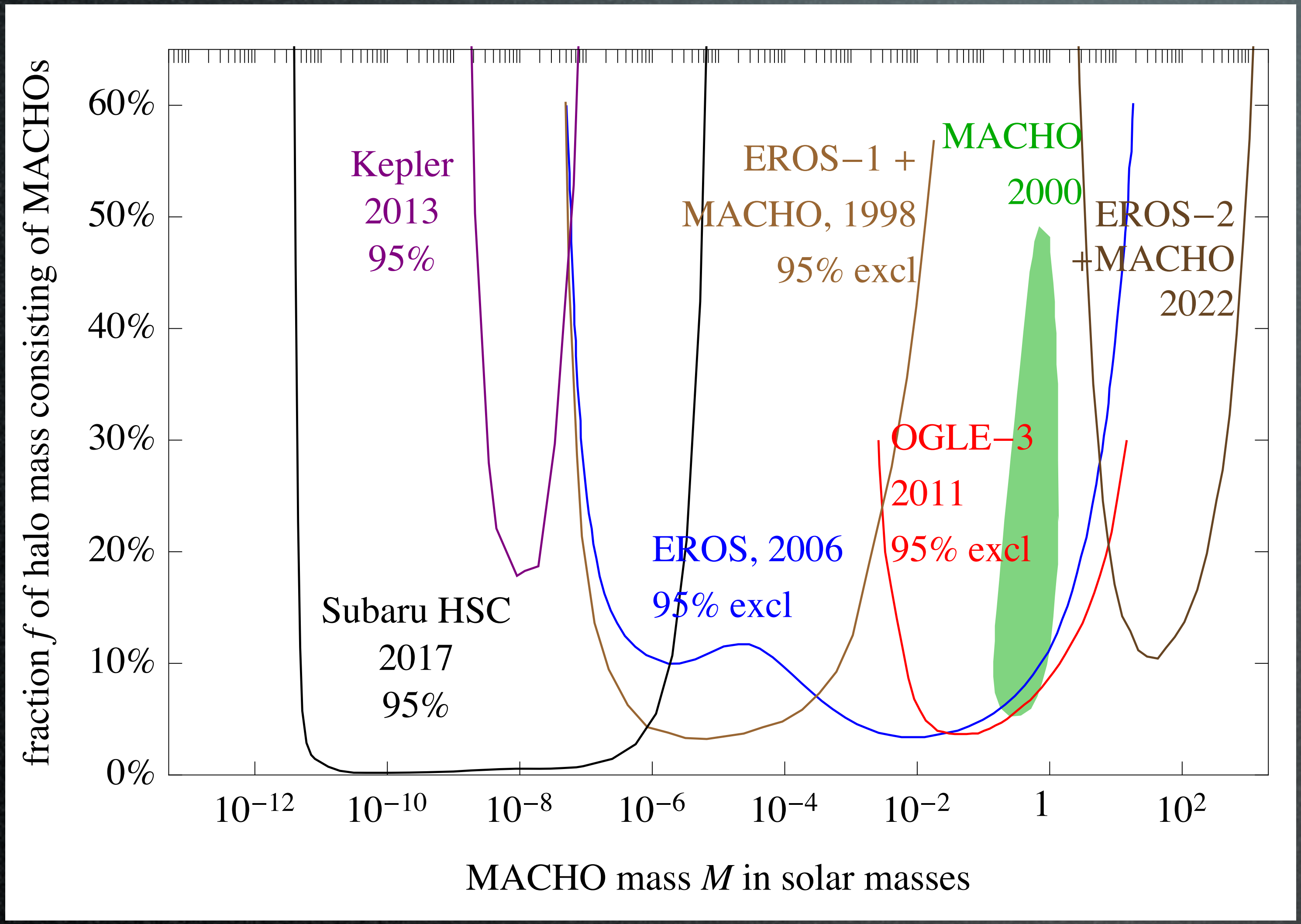


MACHOs or PBHs as DM



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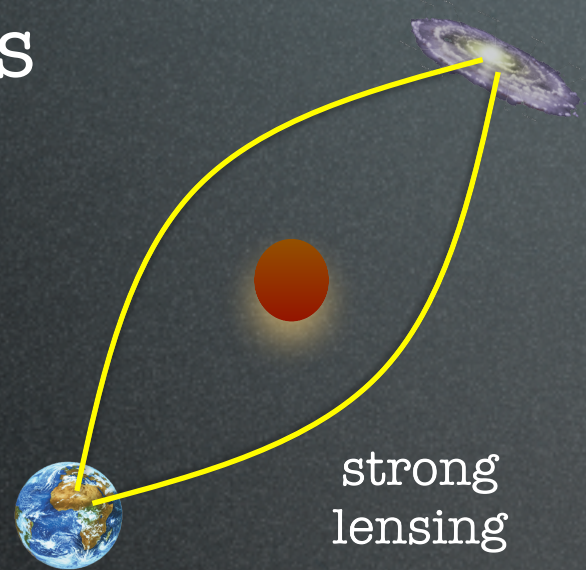

a baryon of the SM:

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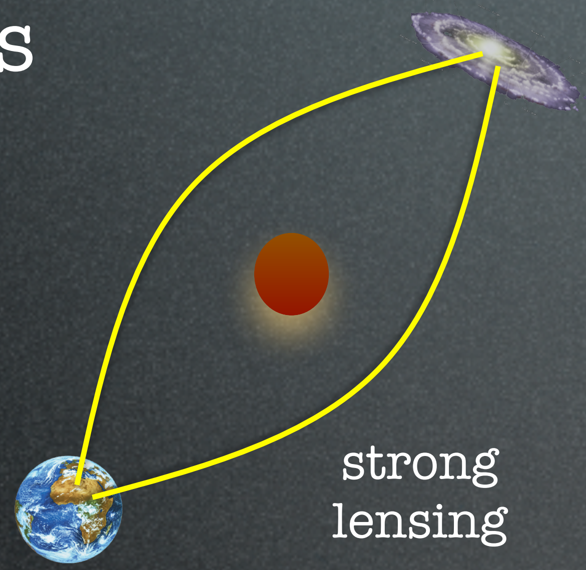

a baryon of the SM:

- 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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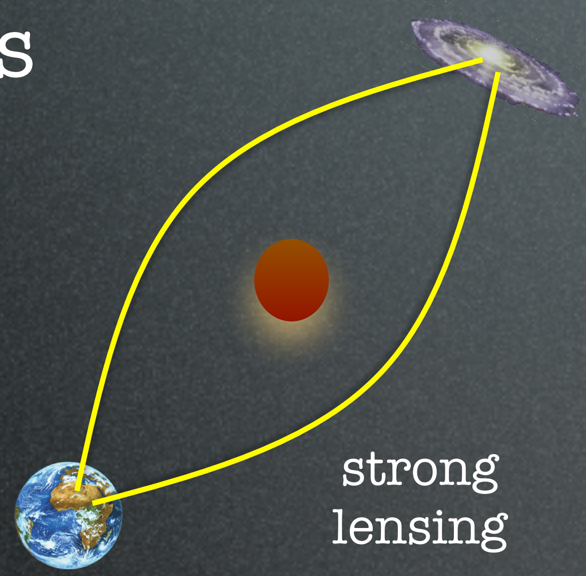

a ~~baryon of the SM~~:

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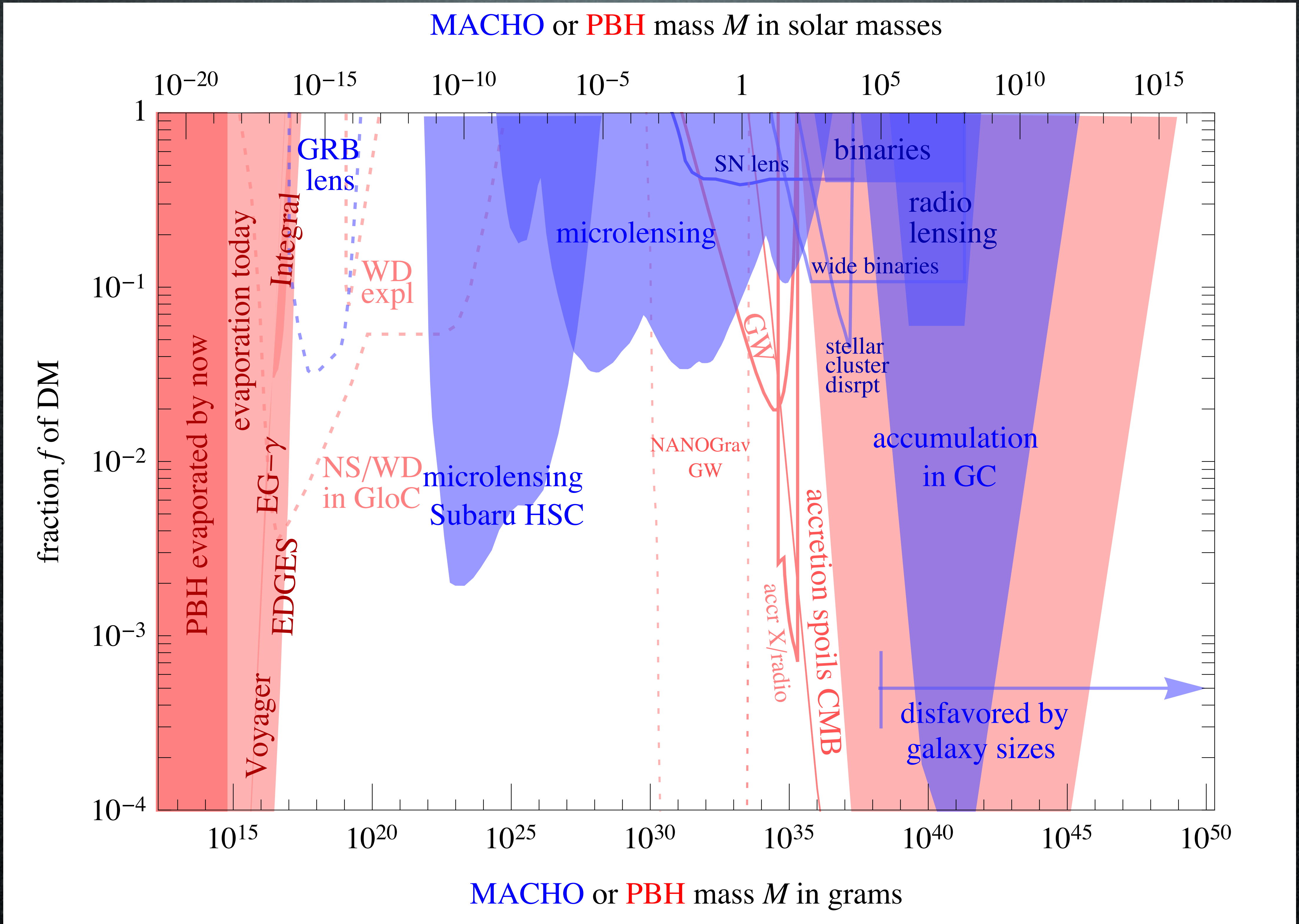
A loophole: Primordial Black Holes!

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

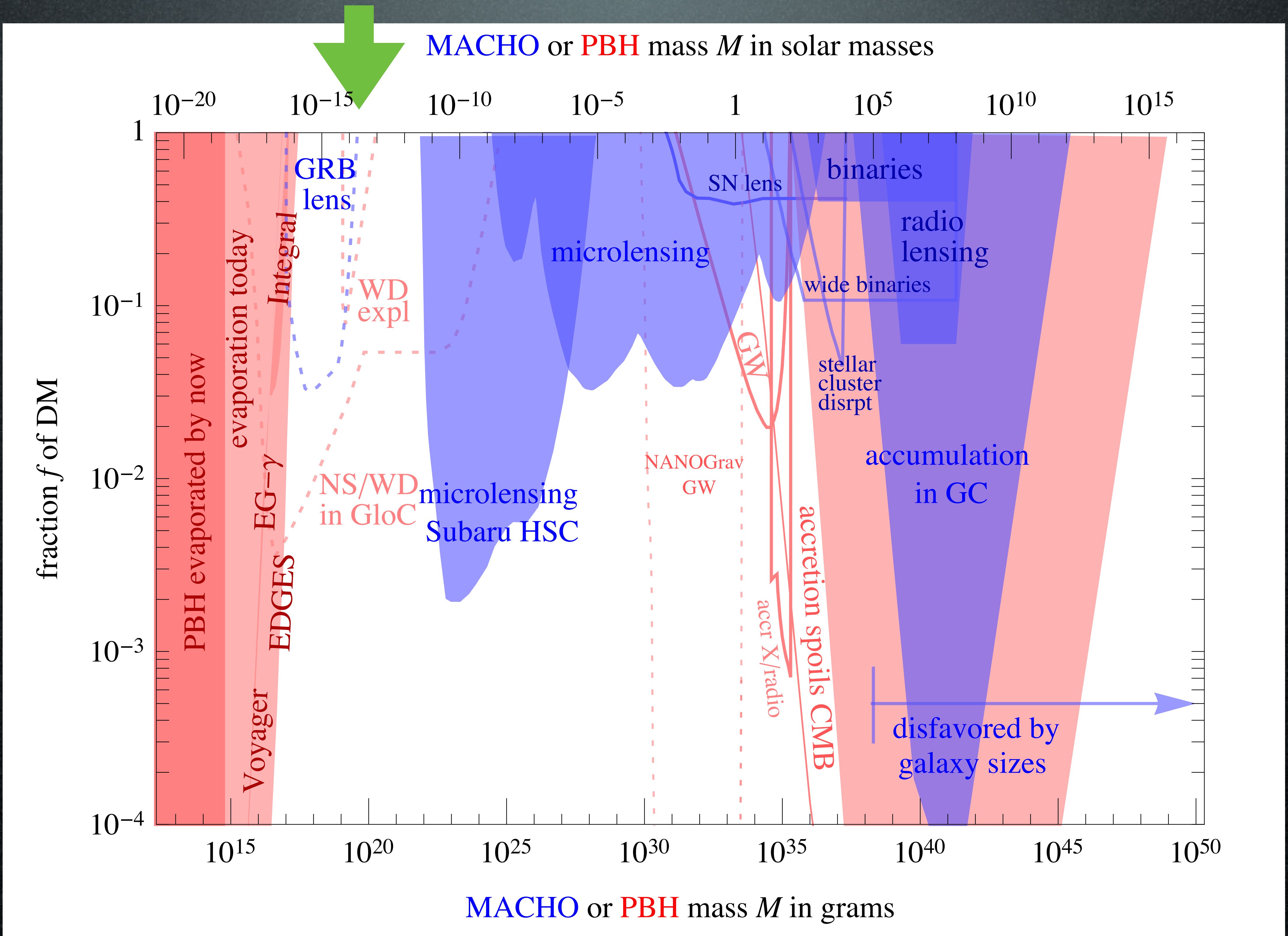
PBHs as DM



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

PBHs as DM

window still open?



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

PBHs as DM

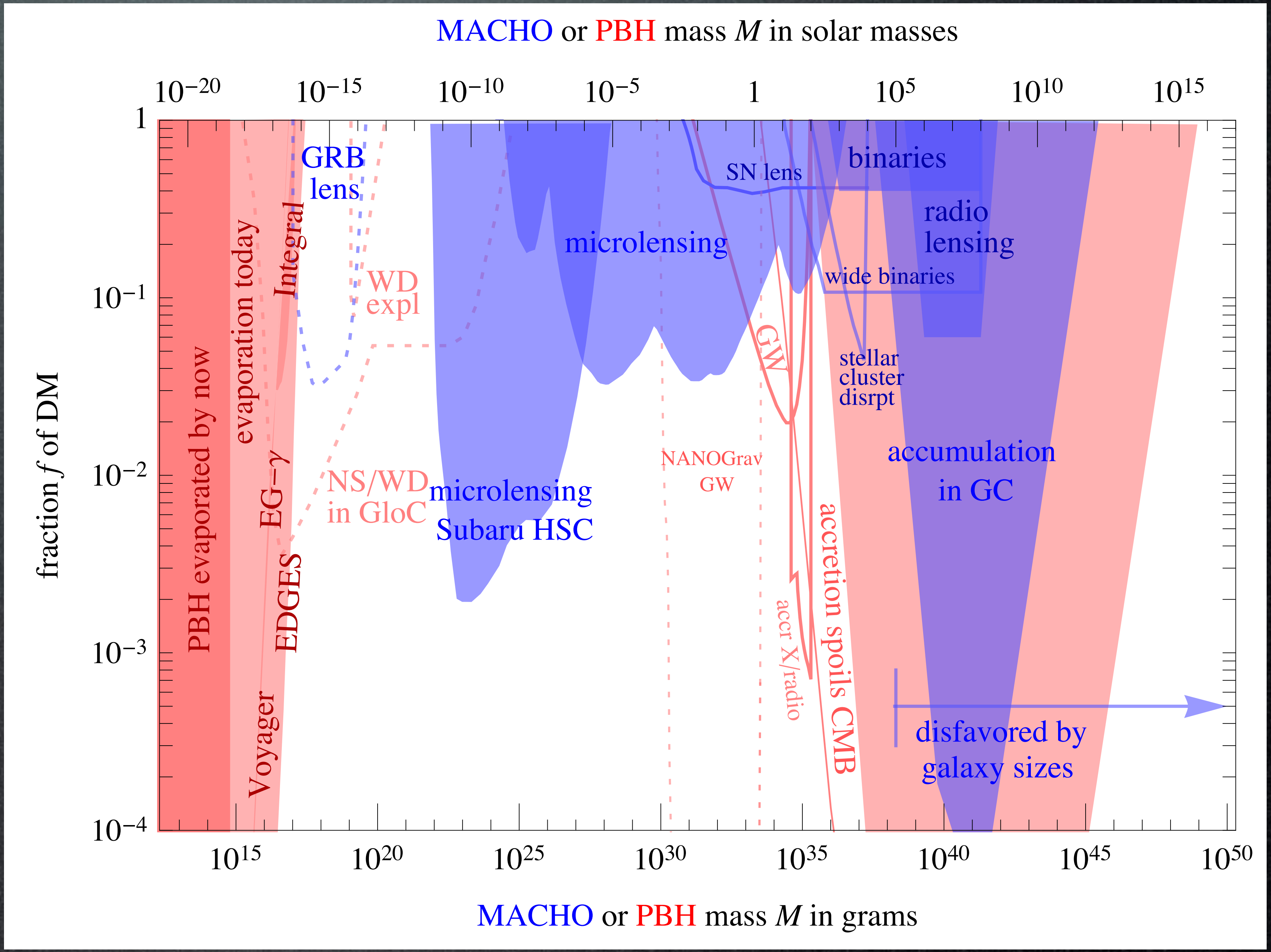
Constraints on Primordial Black Holes

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

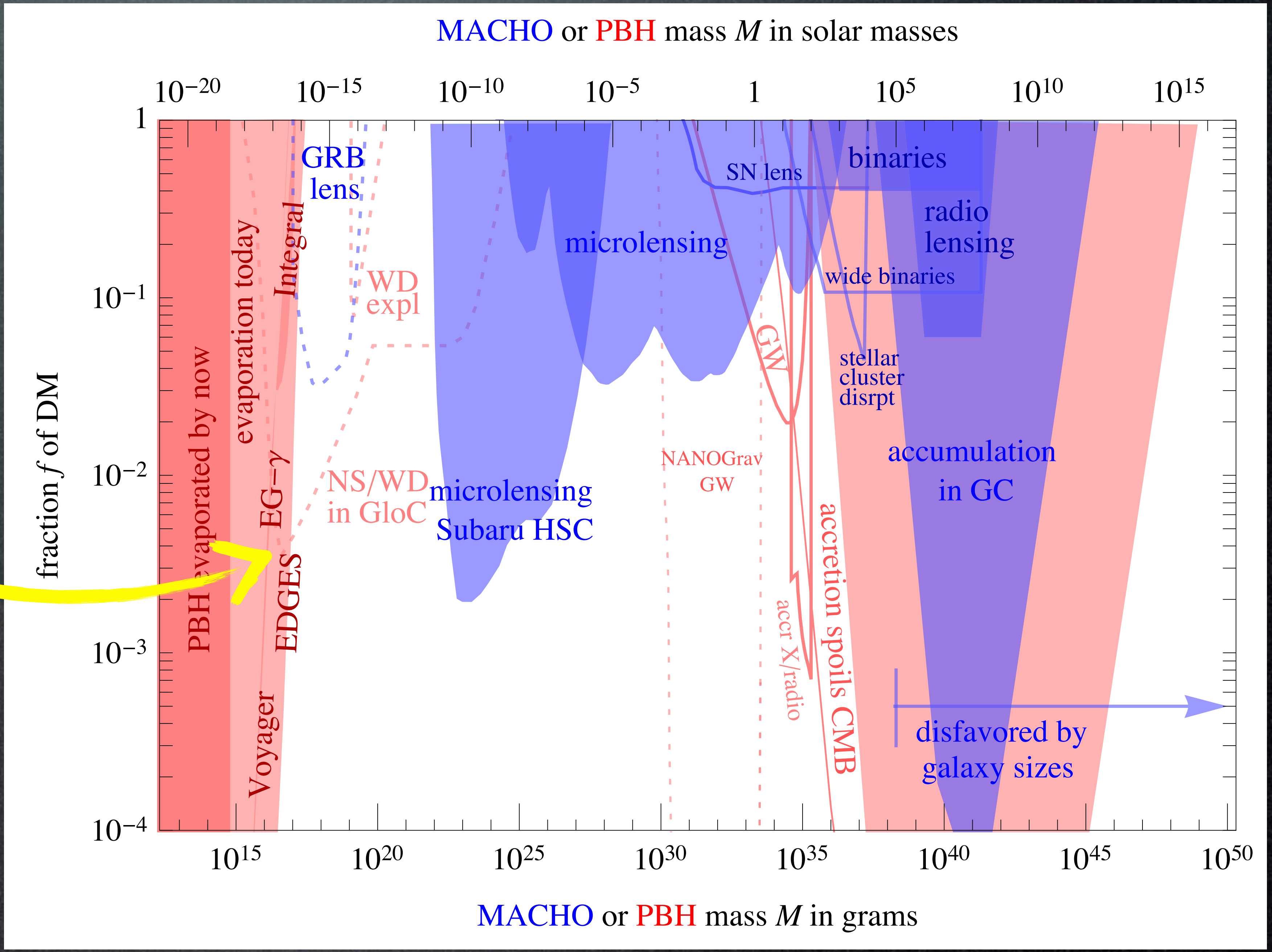
$$T = \frac{1}{8\pi\, G_N M}$$

rate

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

spectrum

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



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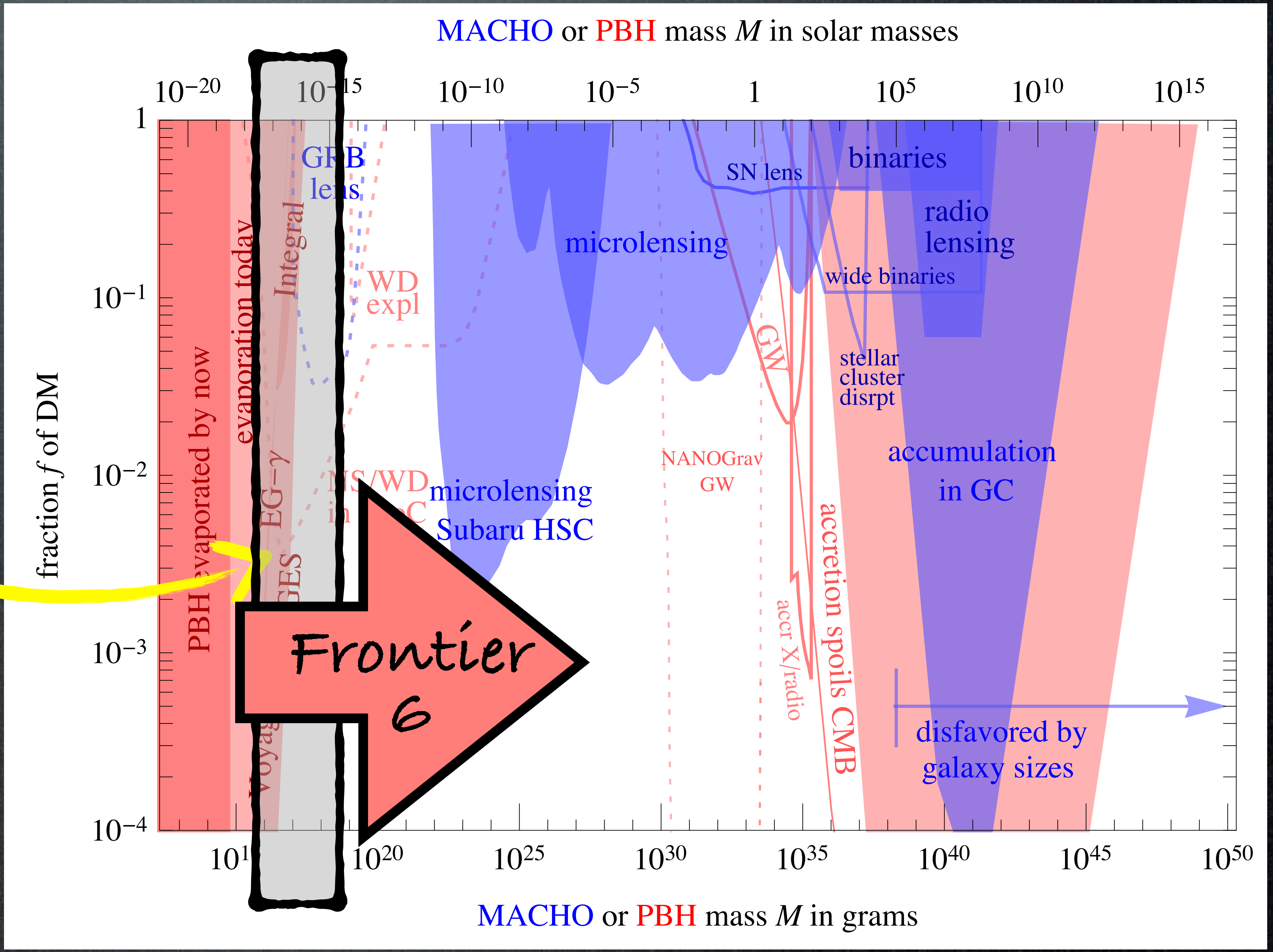

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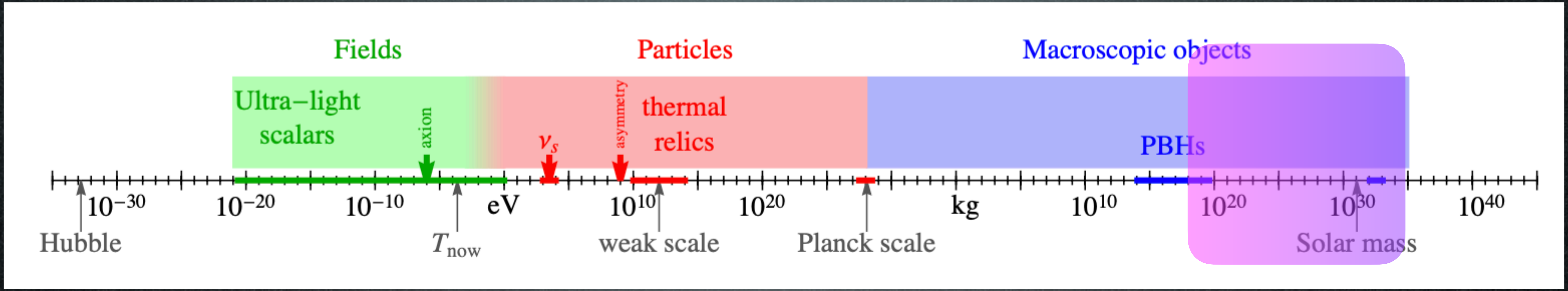
A matter of perspective: plausible mass ranges



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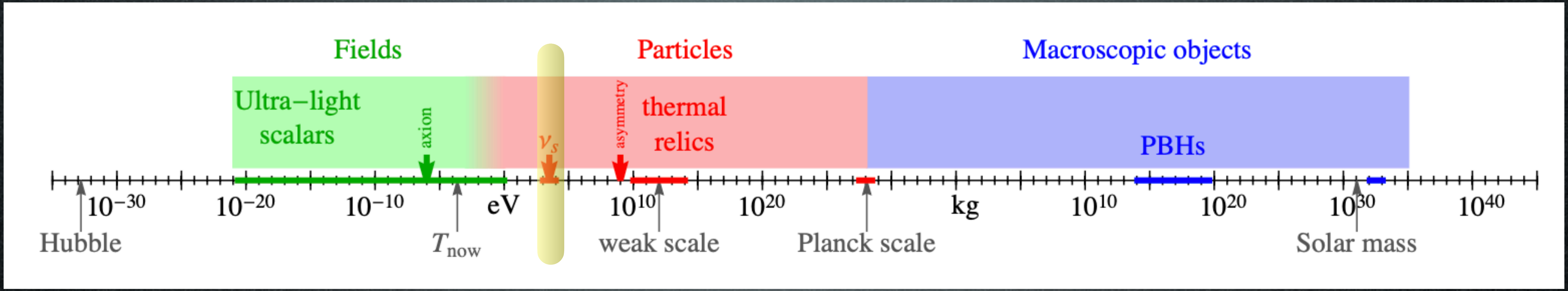


KeV DM?

X-ray line

Bulbul et al., 1402.2301

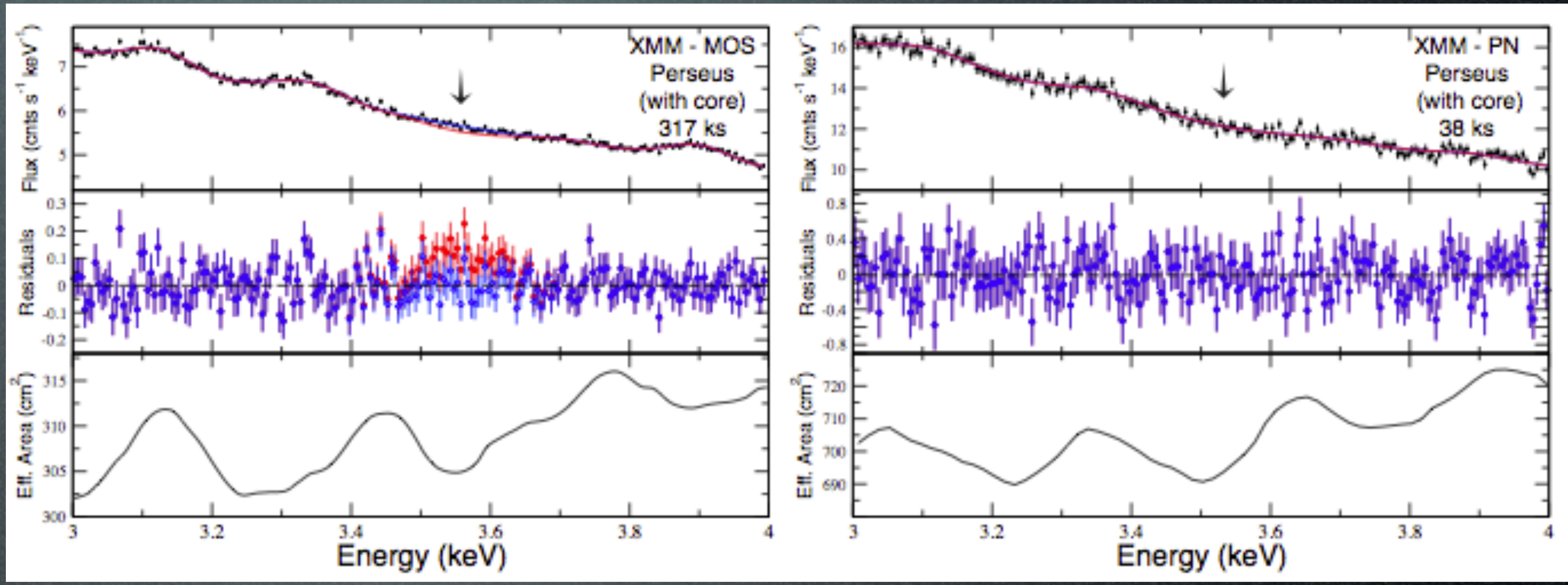
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

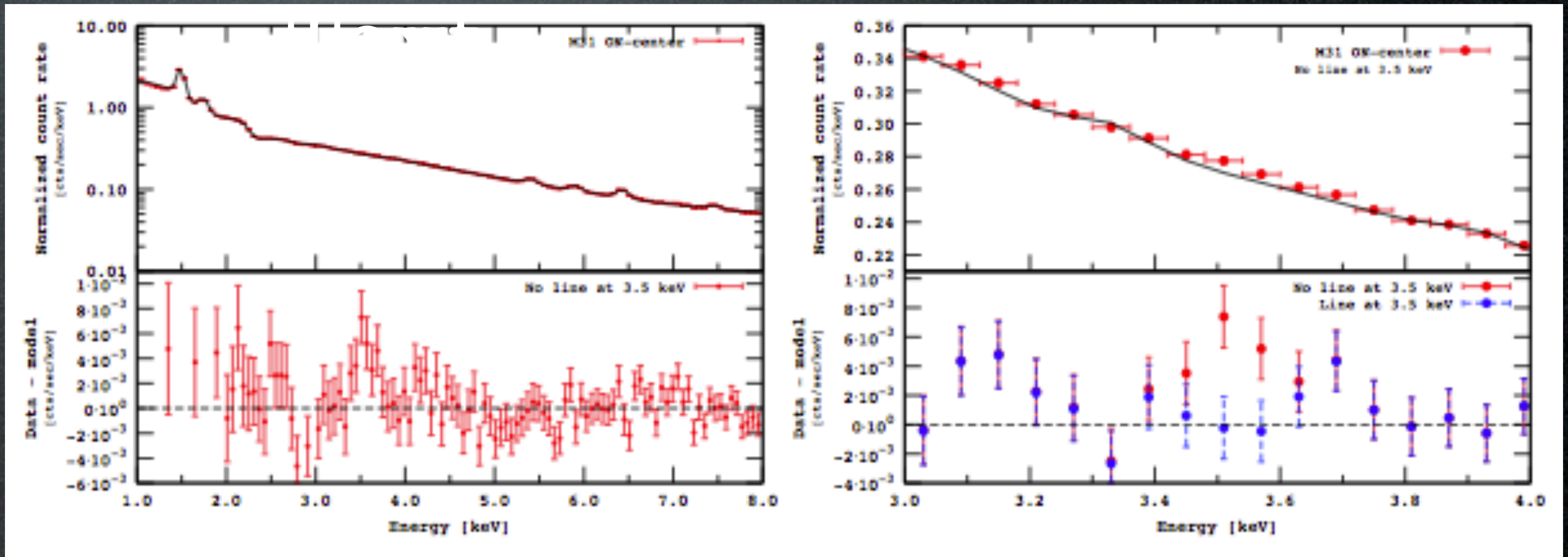
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

z = 0 and 0.0179

4.4σ



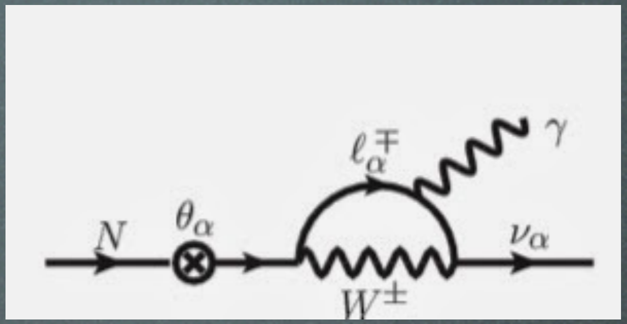
X-ray line

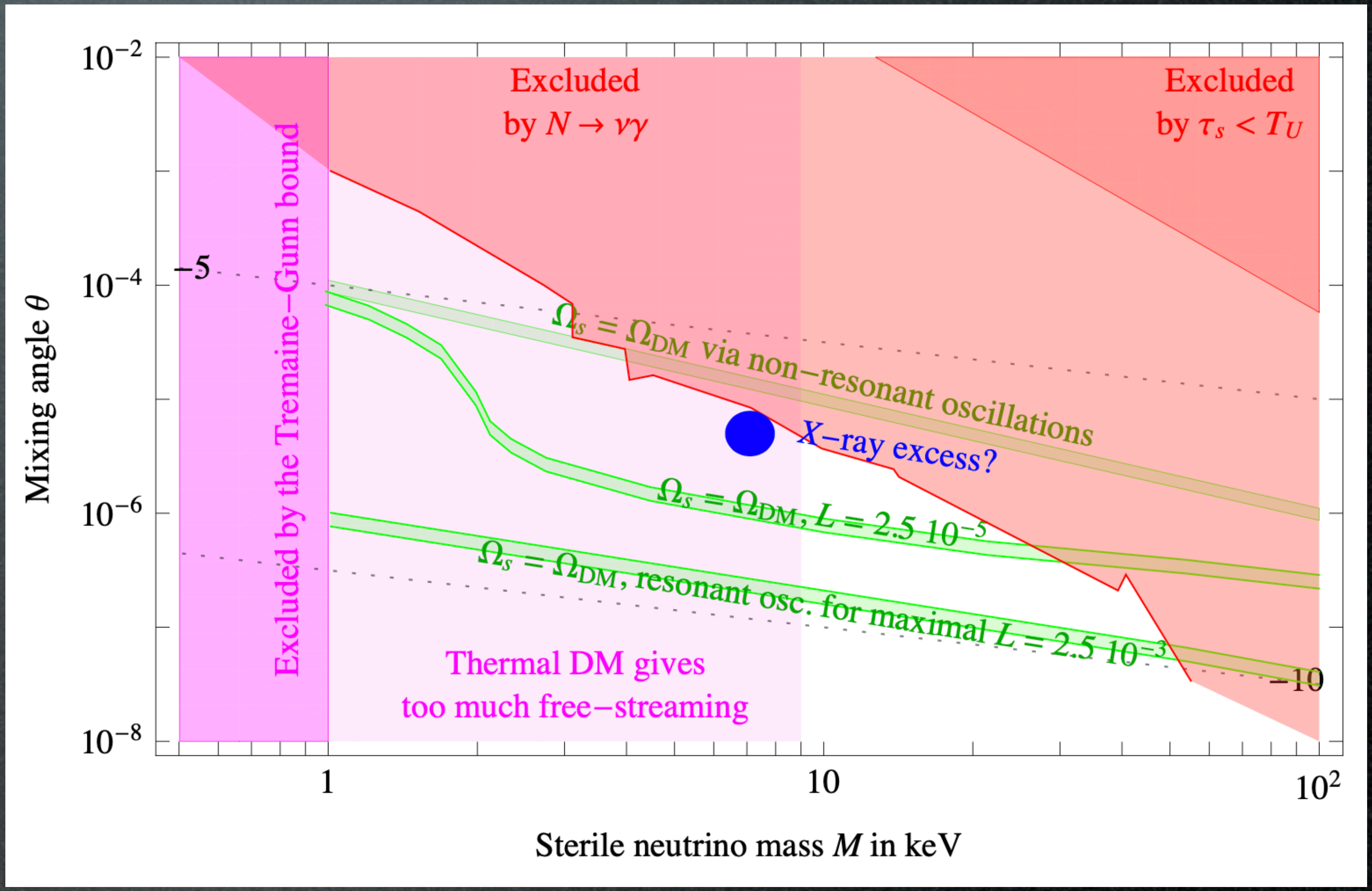
Sterile neutrino decay

$m_\nu = 7.1$ KeV

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

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





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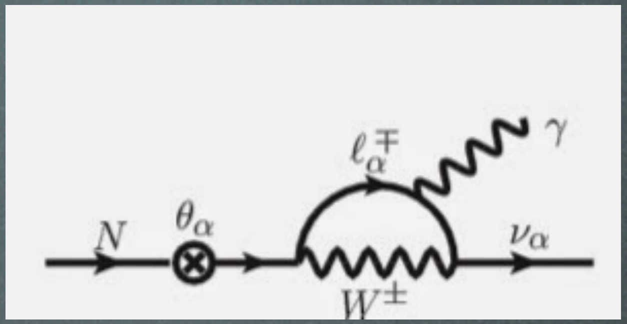

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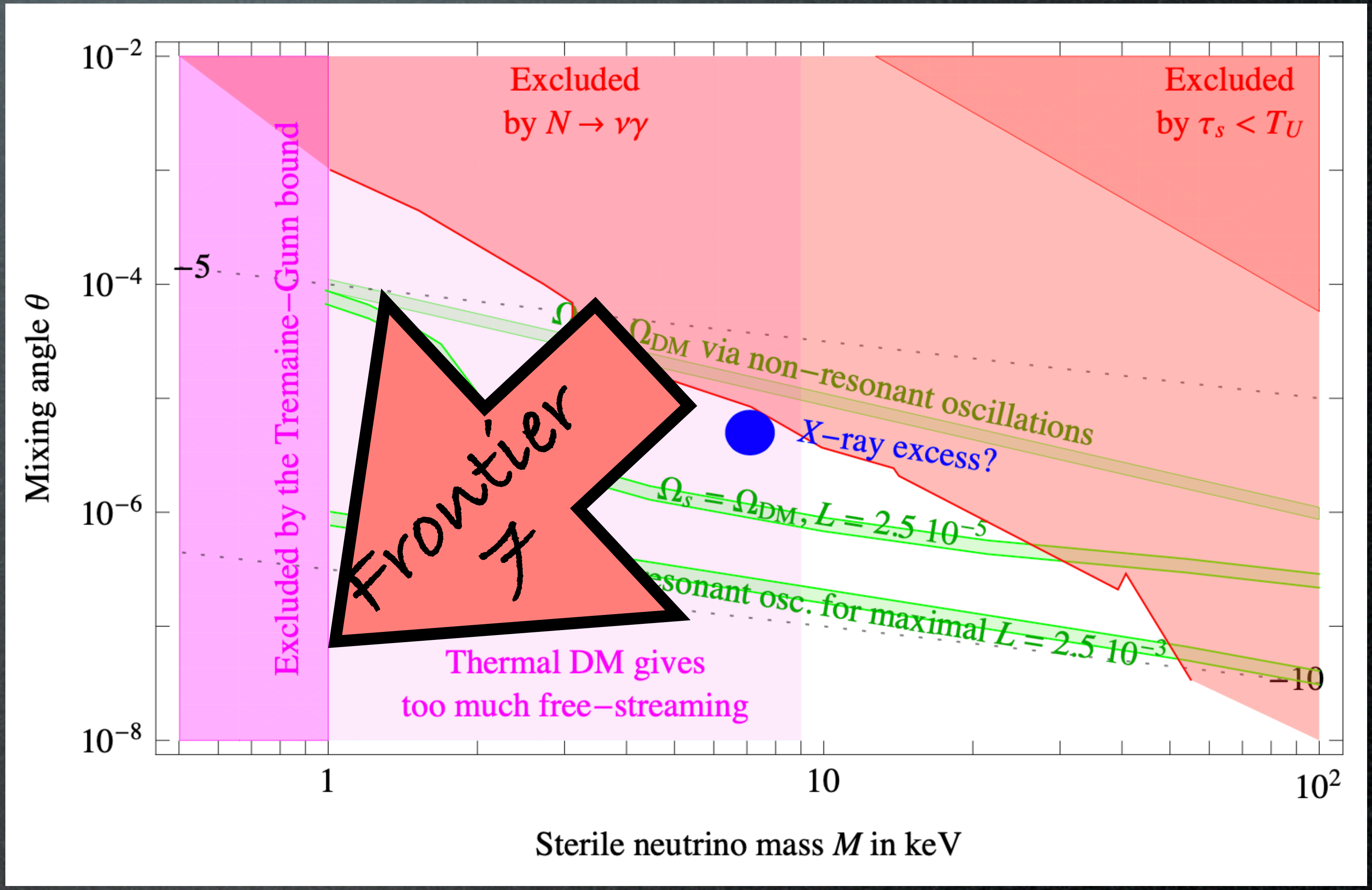

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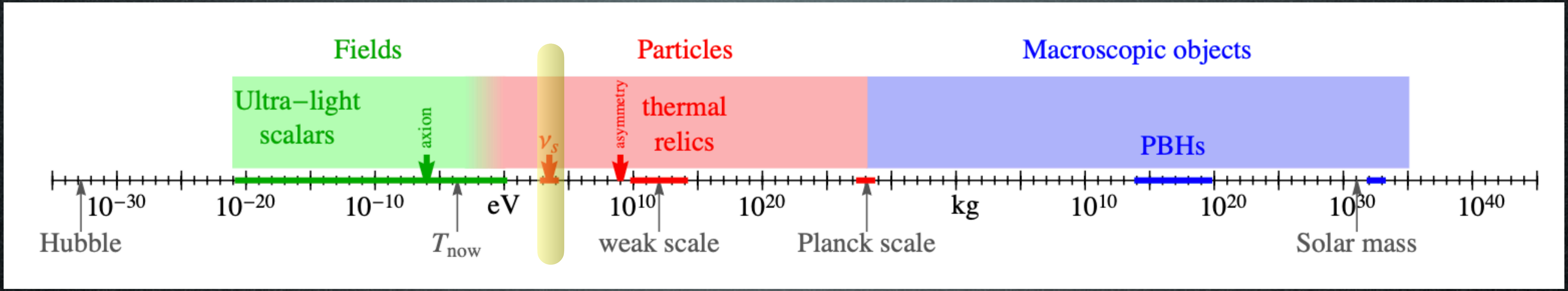

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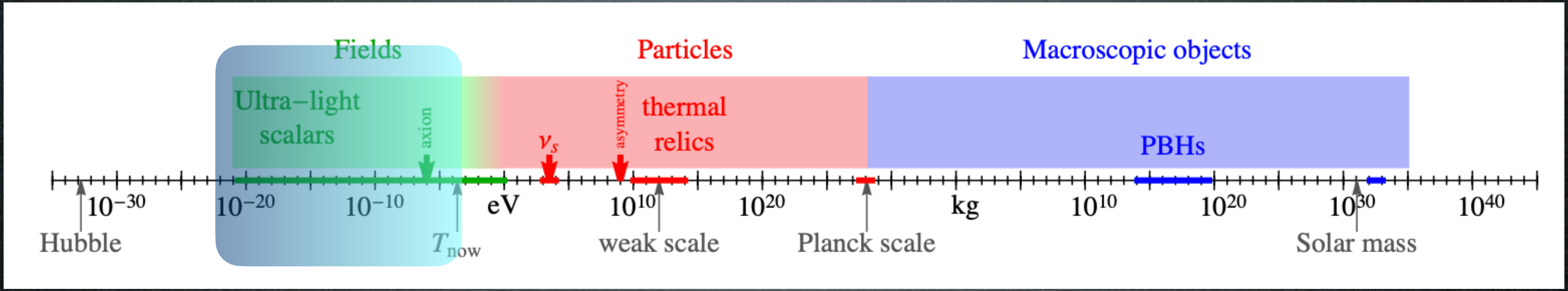


Axions

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

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

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

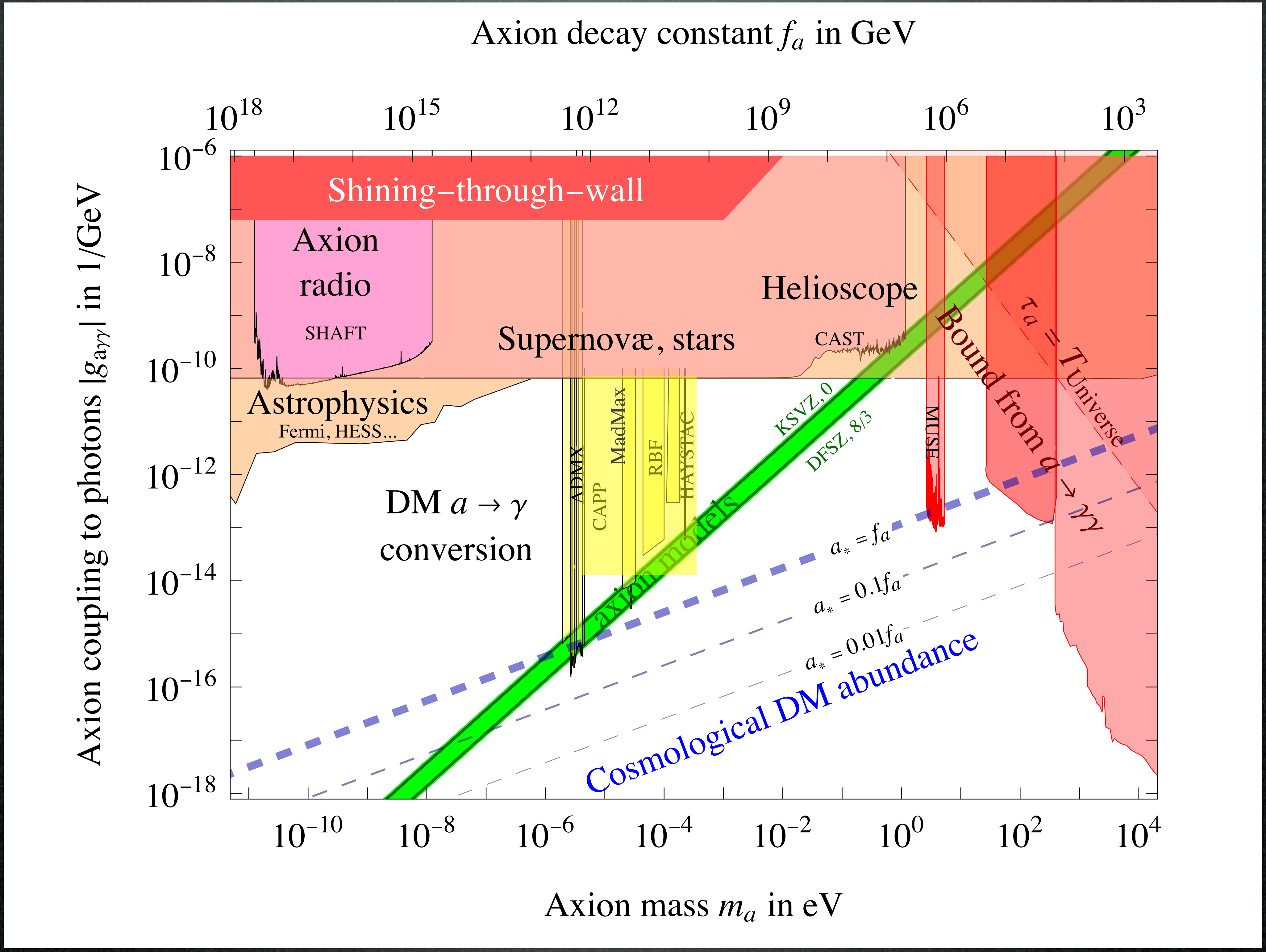
Perhaps because θ is dynamical (a field)

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

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

Axions

Searches:



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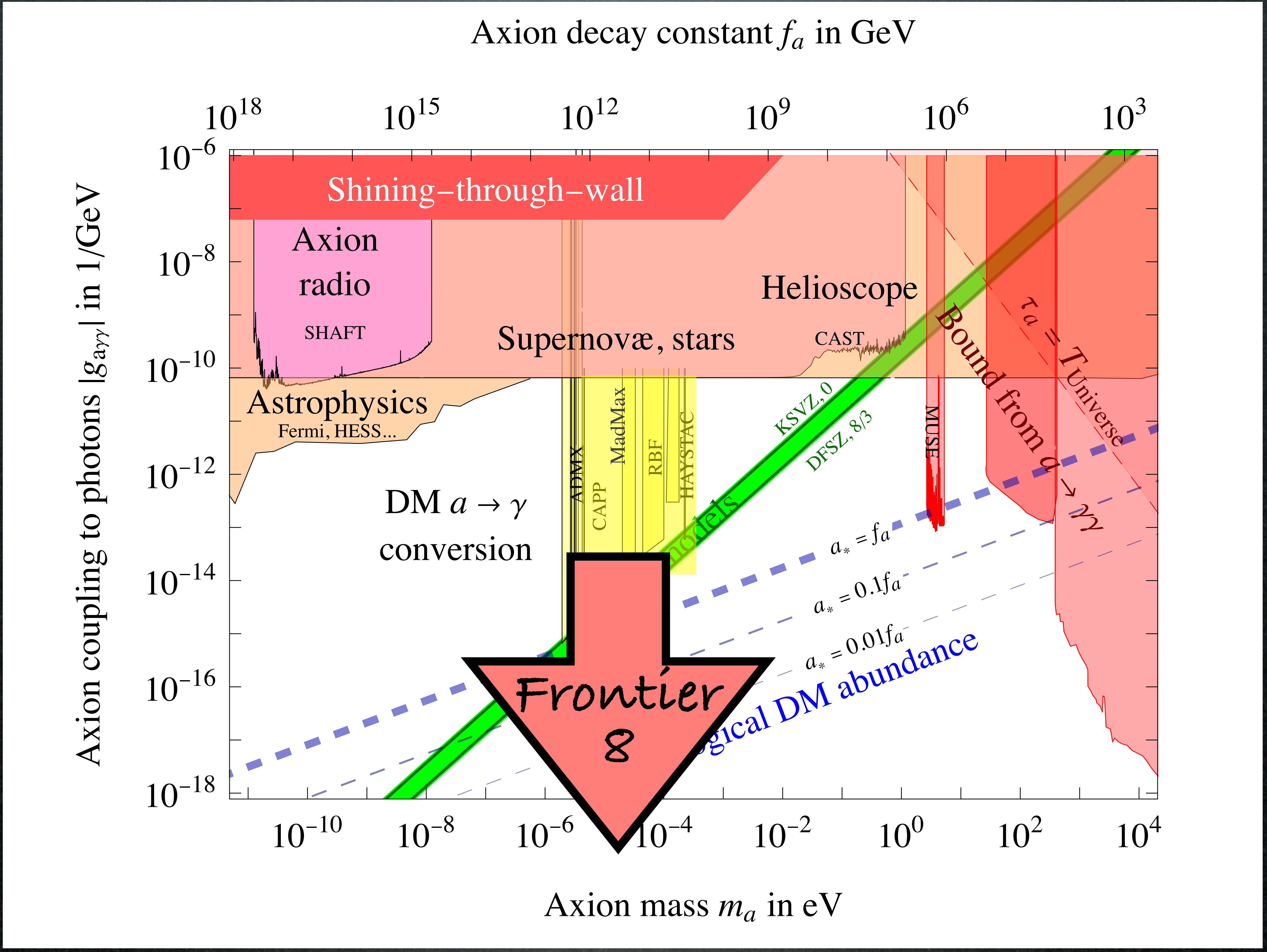

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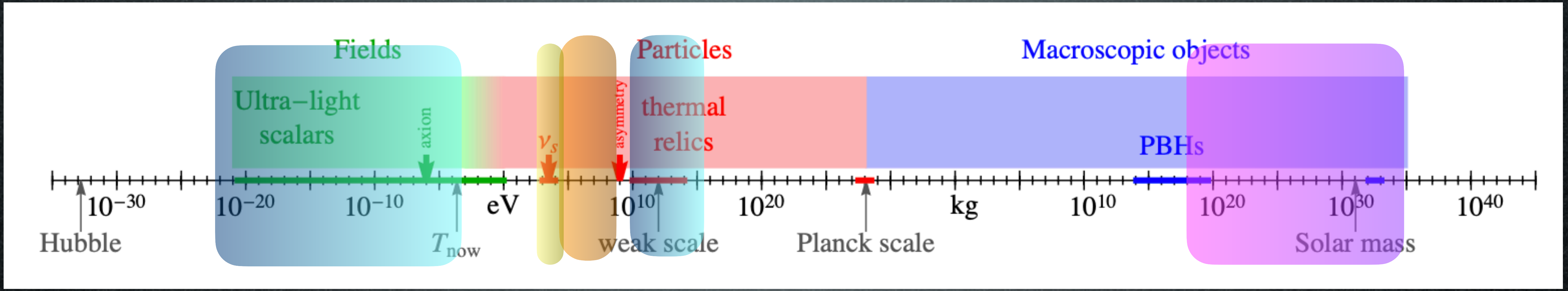

90 orders of magnitude!

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

Conclusions

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The physics of Dark Matter is in an experiment driven phase

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Conclusions

The physics of Dark Matter is
in an experiment driven phase

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? old idea with new vibes

Conclusions

The physics of Dark Matter is
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Theory c… (does) point to prefe… …ctions,
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Thermal DM?
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still w… …d, frontie… …eavy DM
why …ot? Chall… …ection
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…nomenological
o… with new vibes

Frontier 6
Frontier 4
Frontier 3
Frontier 2
Frontier 7
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Frontier 8
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? Frontier 9

Frontier 6

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Frontier 8

Frontier 5

DD of strongly int DM