16-17 June 2024

Cracow school of Theoretical Physics- Zakopane

Dark Matter

candidates, searches

Marco Cirelli

(LPTHE Jussieu CNRS Paris)

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LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

cnrs dépasser les frontières

SORBONNE UNIVERSITÉ CRÉATEURS DE FUTURS DEPUIS 1257

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Introduction

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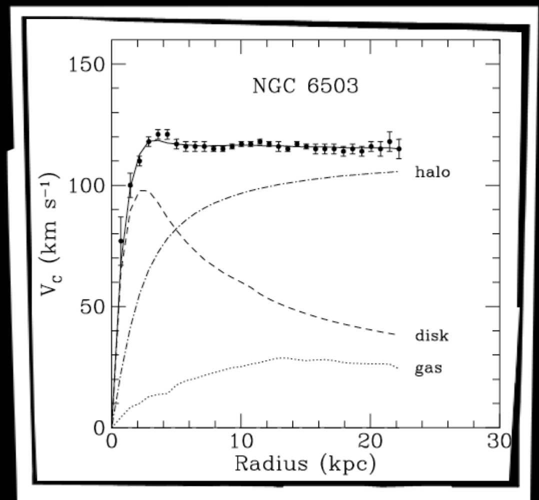
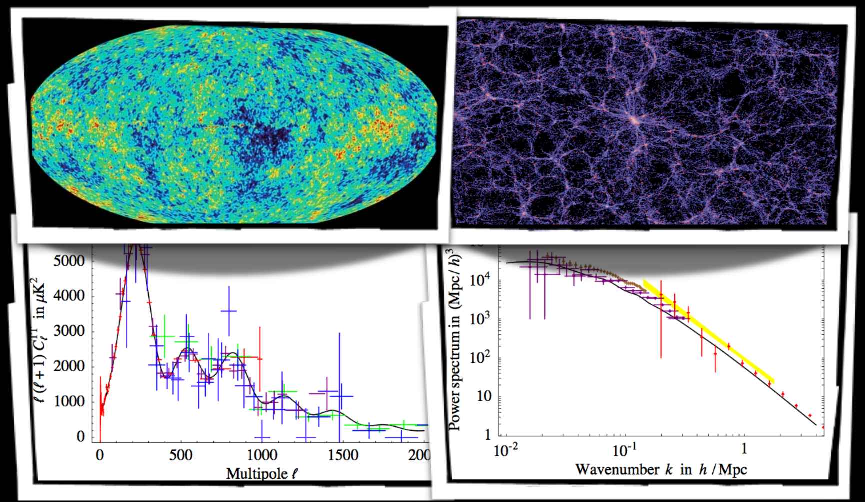


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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- it's a new, unknown corpuscle

no SM particle can fulfil

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

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(notice error!)

Planck 2015, 1502.01589 (tab.4)

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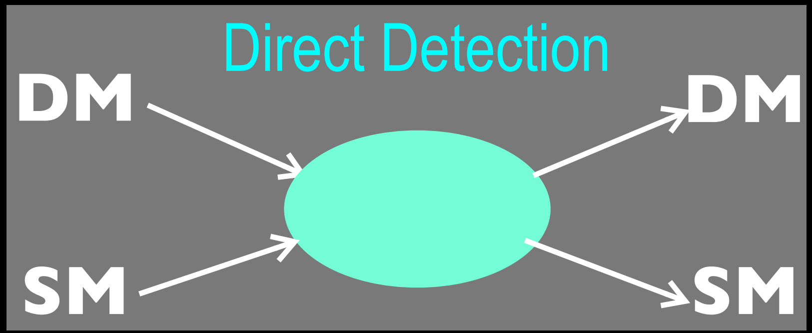

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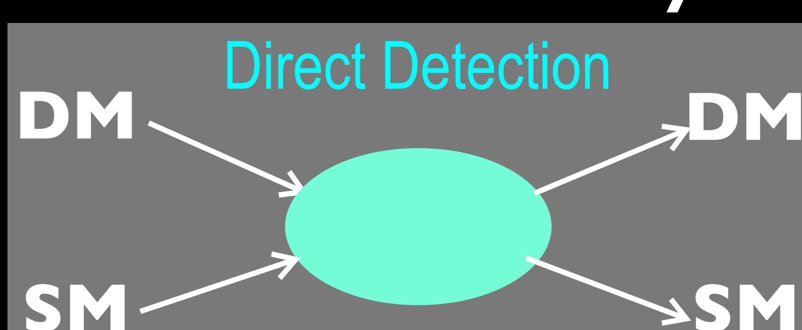

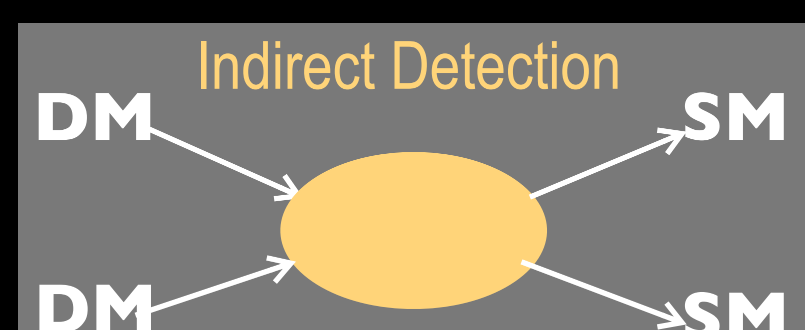

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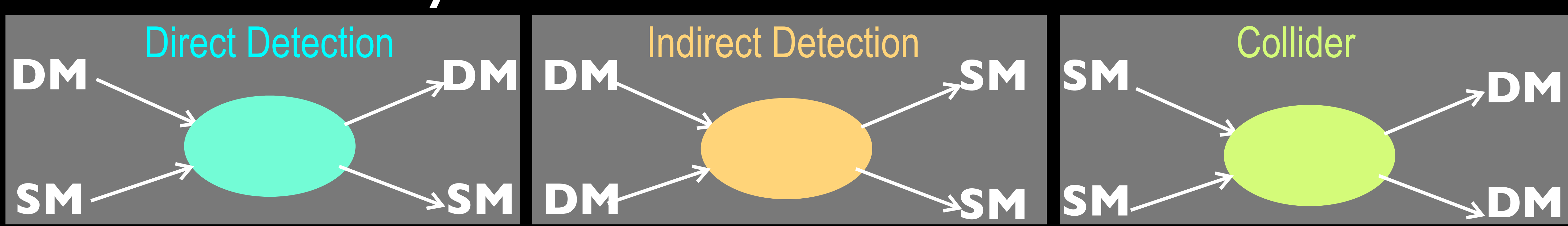

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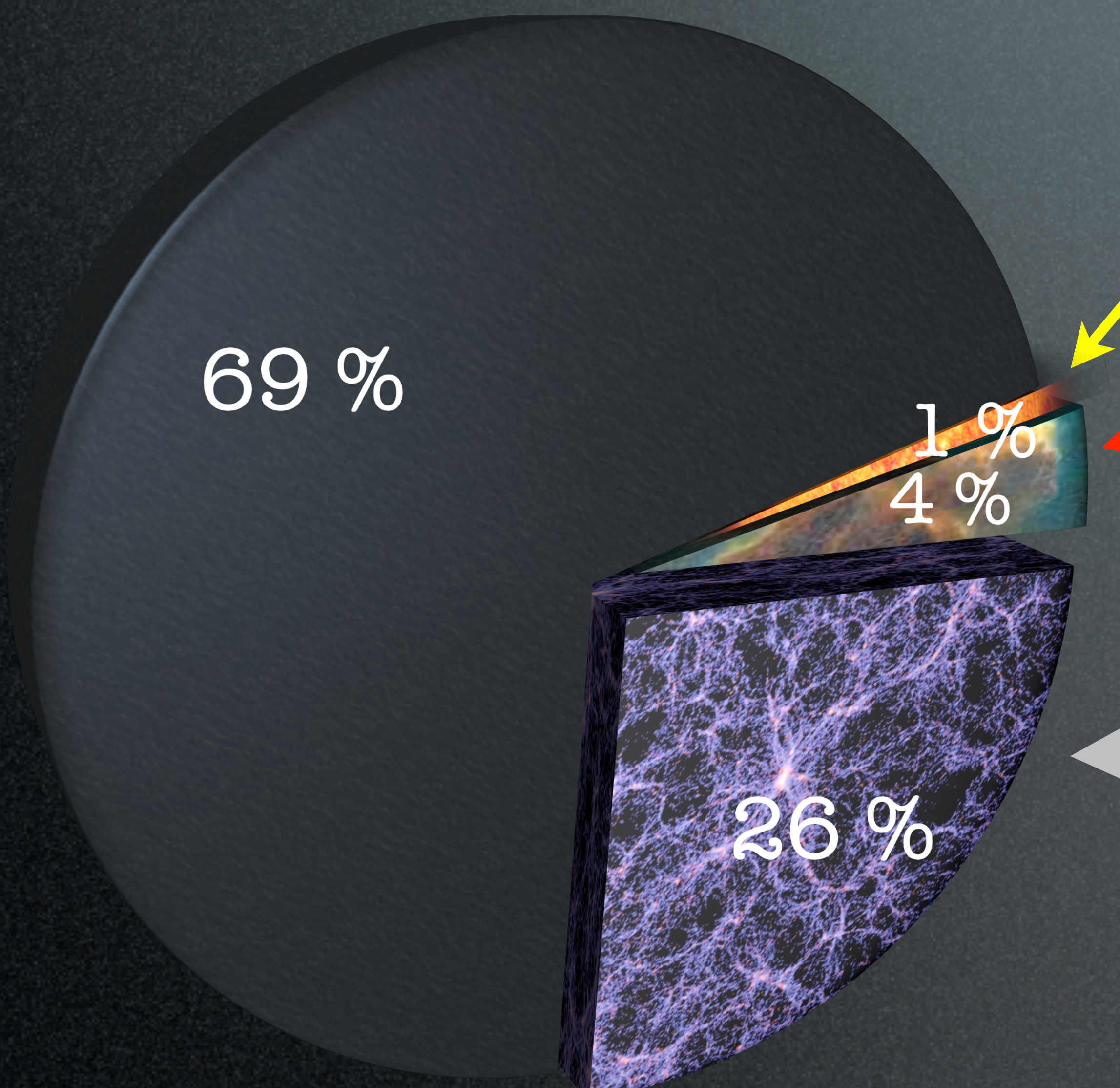
The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

$\Omega_{\rm DM} \sim 0.26$

$\Omega_{\rm de} \sim 0.69$

$\left(\Omega_x = \frac{\rho_x}{\rho_c}; \quad h = 0.67 \text{ or } 0.71 \right)$

what's the difference
between DM and DE?

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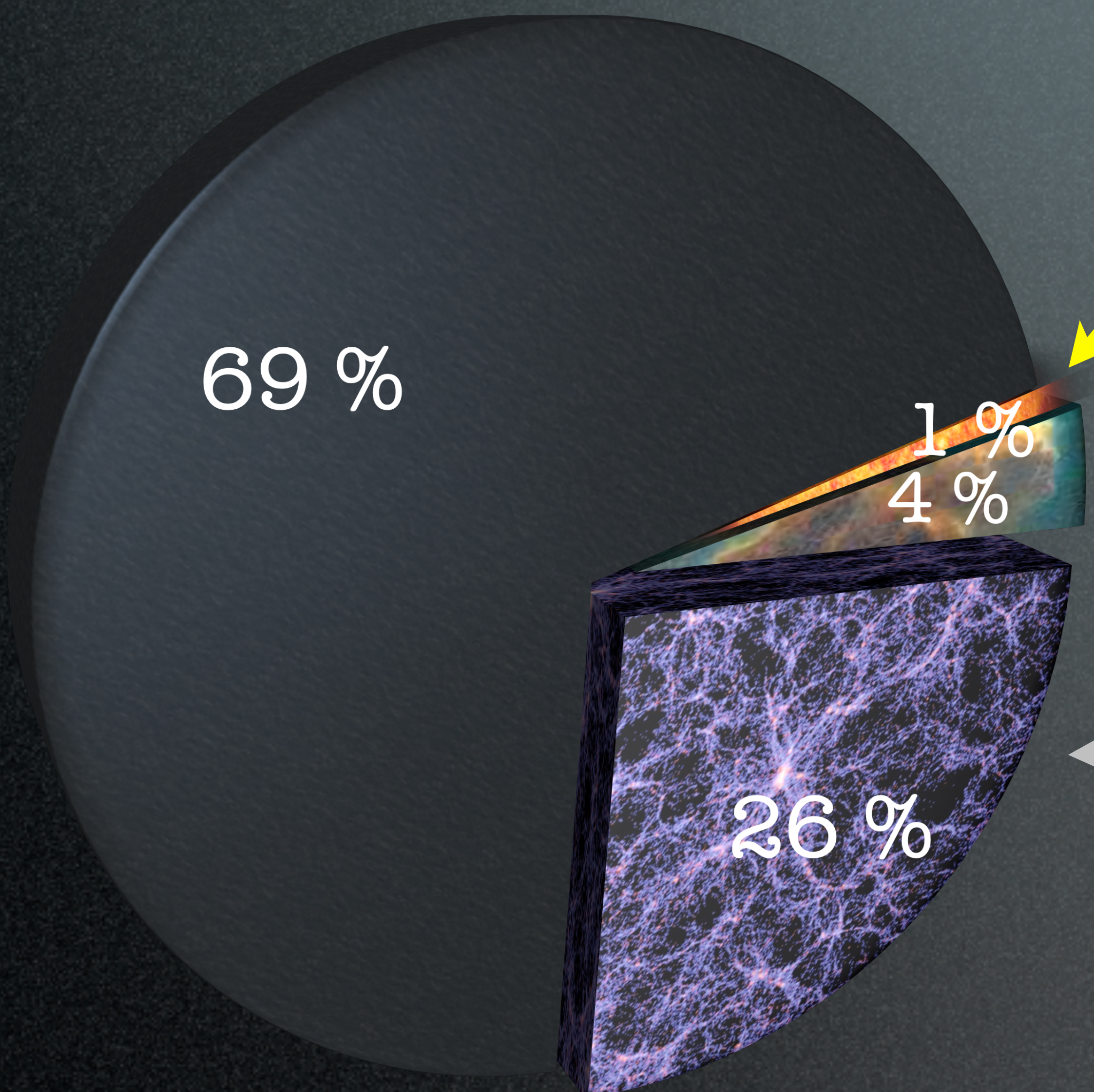

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particle physics $\cap$ cosmology

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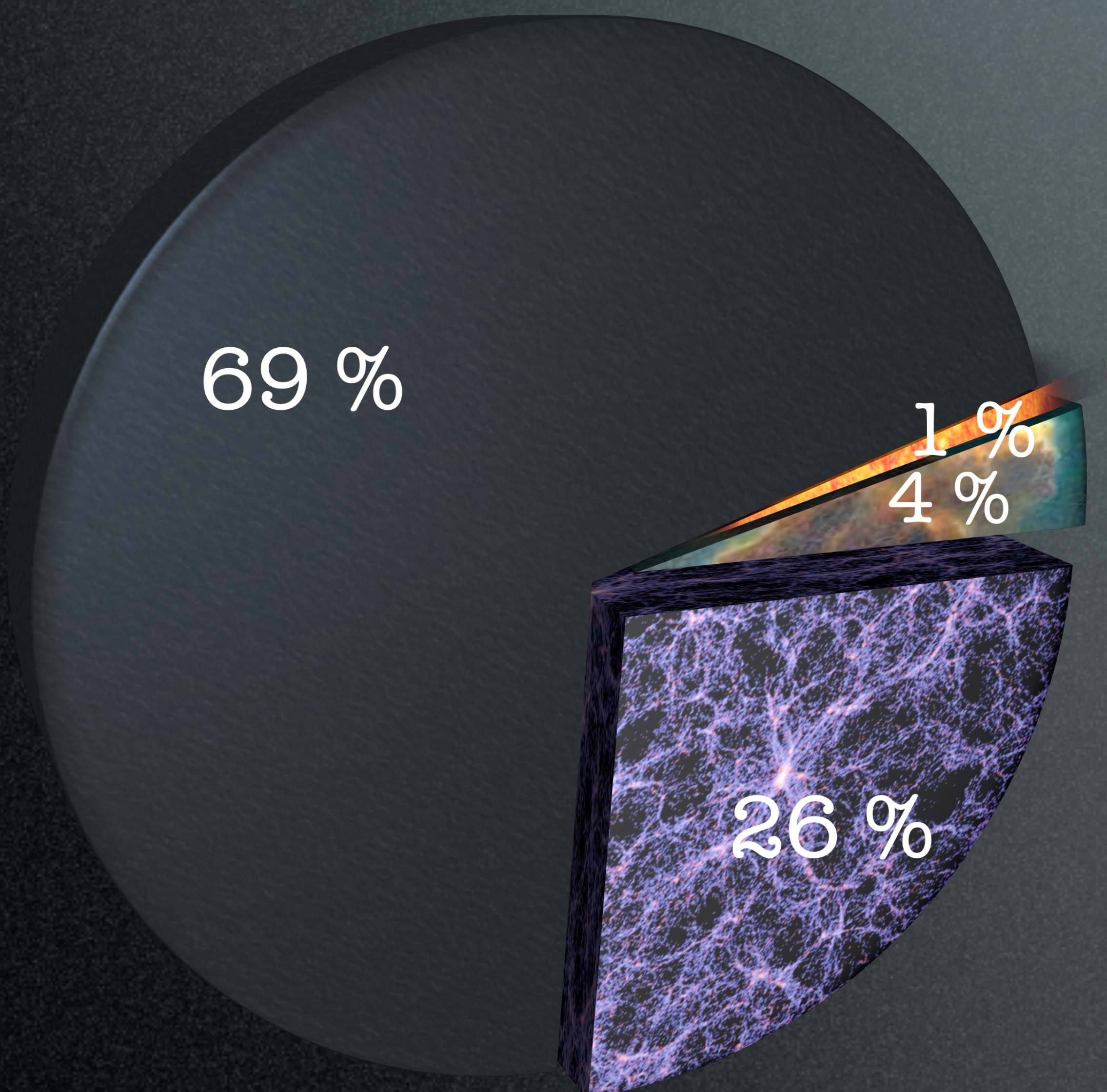


FAvgQ: what's the difference between DM and DE?

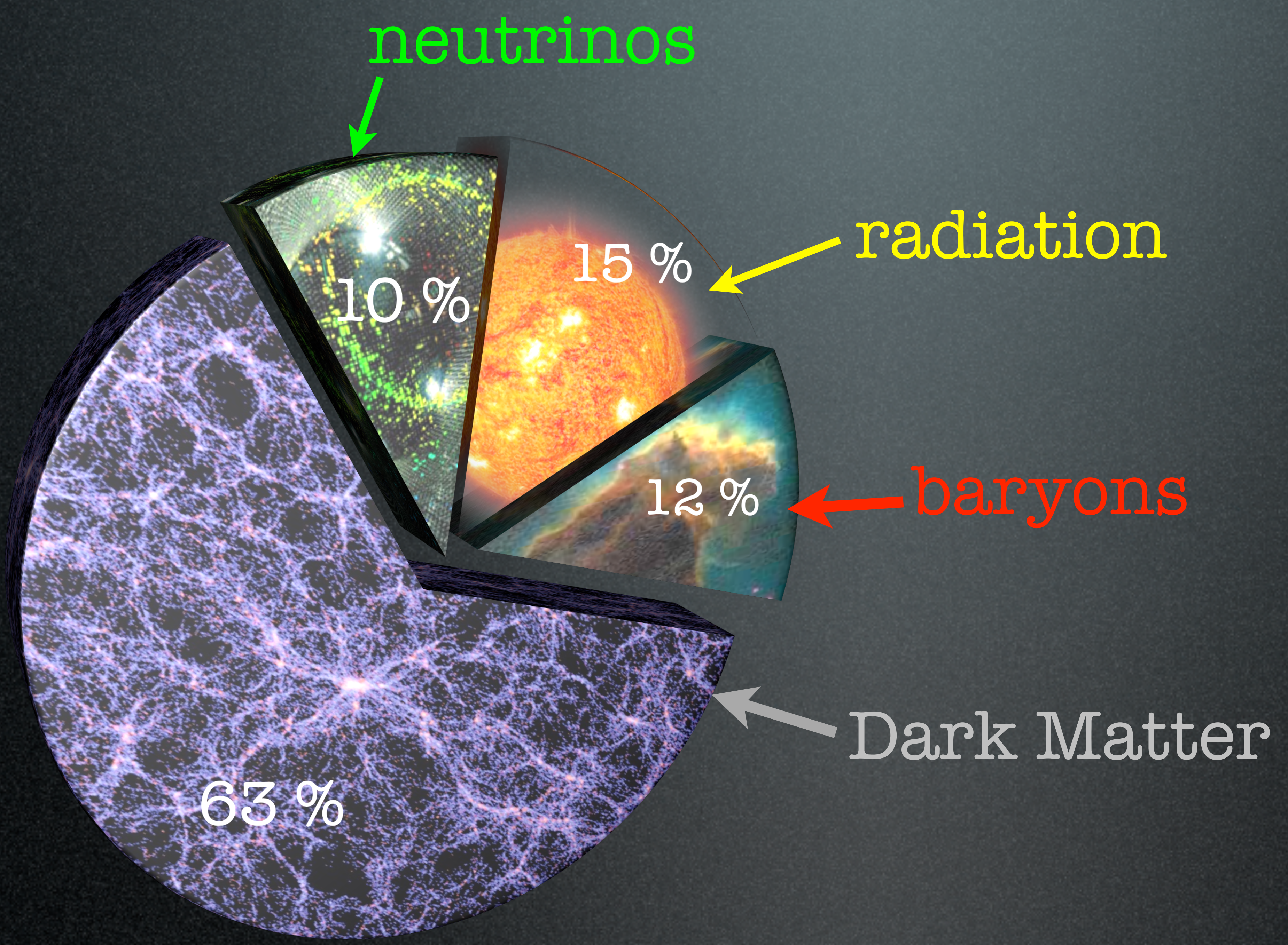
DM behaves like matter

- overall it dilutes as volume expands
- clusters gravitationally on small scales
- $w = P/\rho = 0$ (NR matter)
  (radiation has $w = -1/3$)

DE behaves like a constant

- it does not dilute
- does not cluster, it is prob homogeneous
- $w = P/\rho \simeq -1$
- pulls the acceleration, FRW eq. $\frac{\ddot{a}}{a} = -\frac{4\pi G_{\rm N}}{3}(1-3w)\rho$

The cosmic inventory



At the time of CMB formation (380 Ky)

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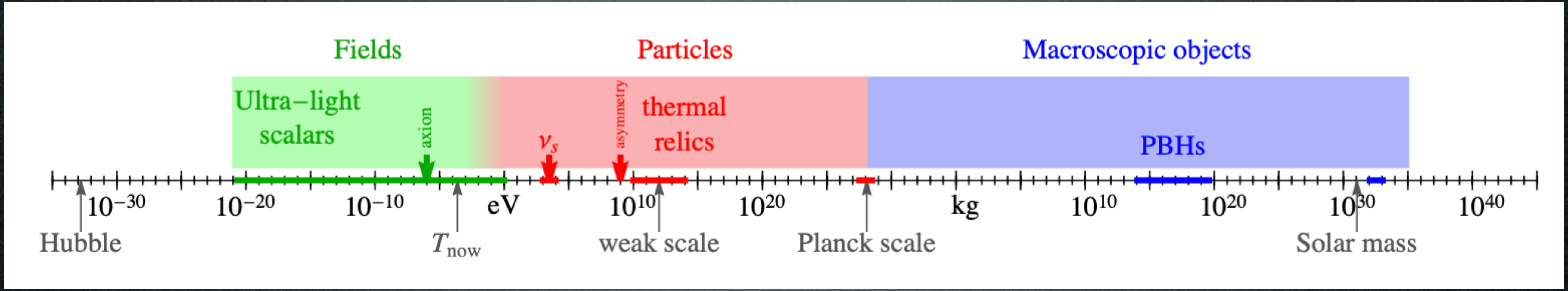
mass ???   interactions ???

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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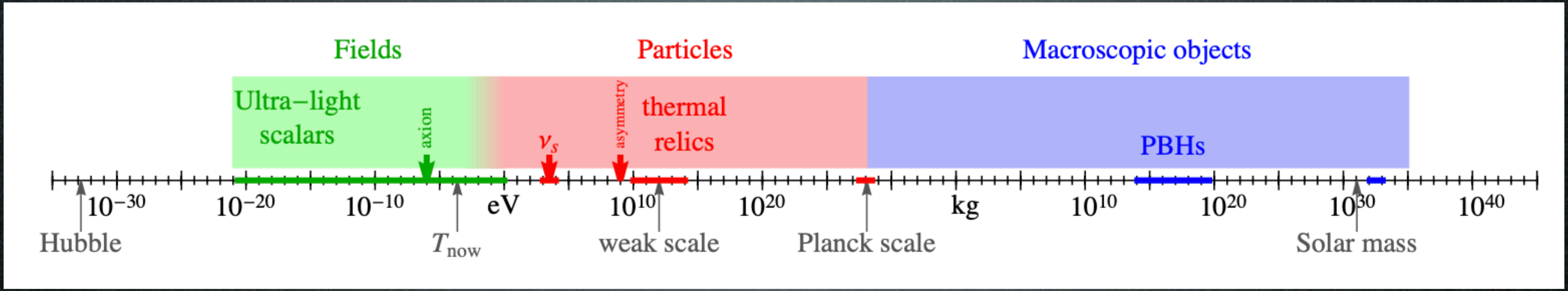

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DM can be made
by a huge number of very light 'particles'
or
a tiny number of very heavy 'particles'
as long as it is:
neutral, cold, stable and feebly interacting

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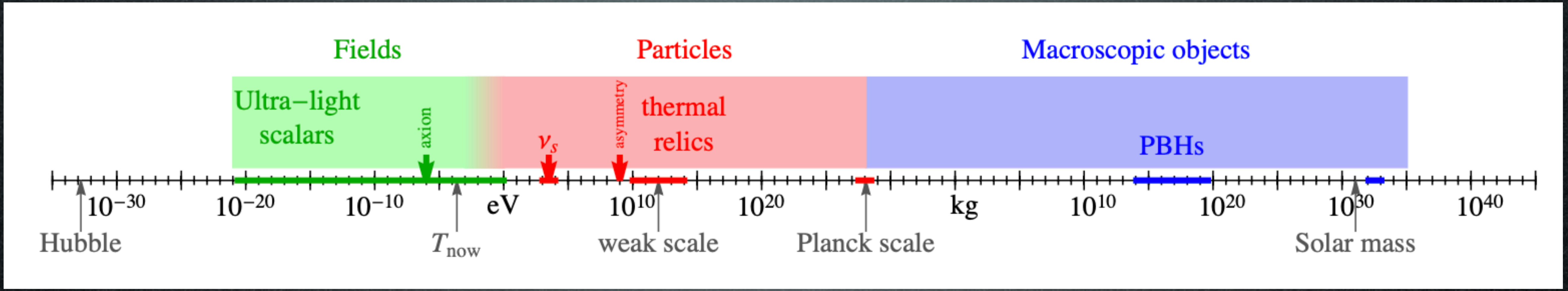

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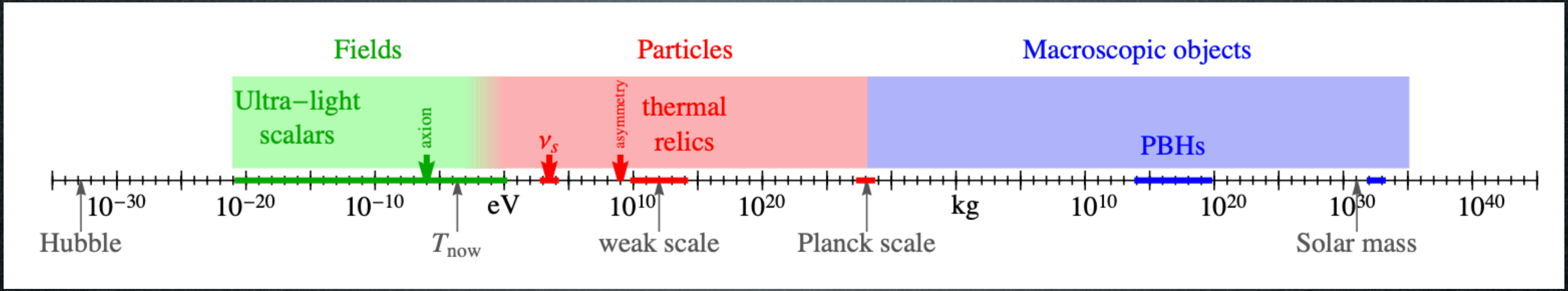

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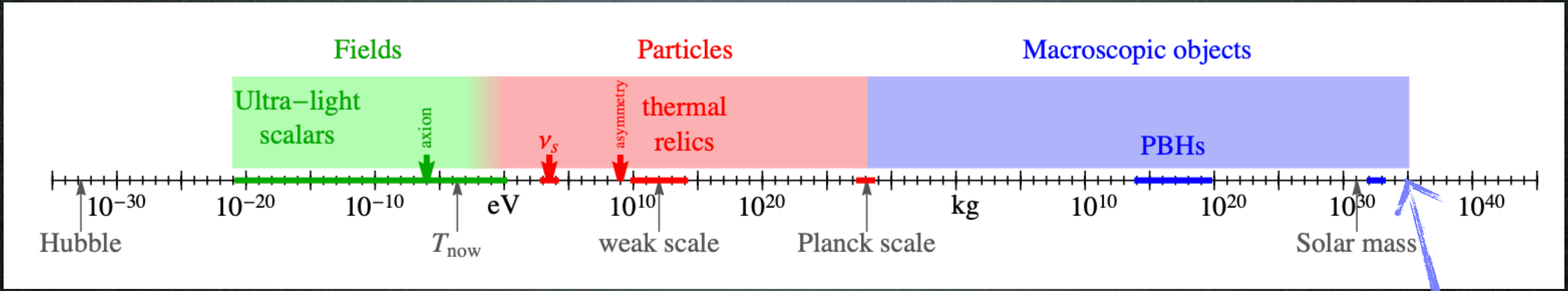

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as big as a dwarf galaxy

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

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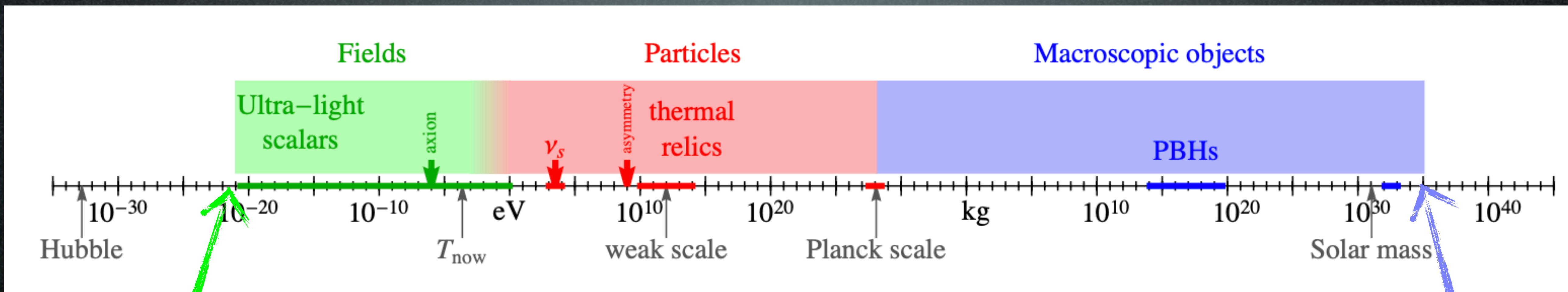

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DM de Broglie wavelength

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

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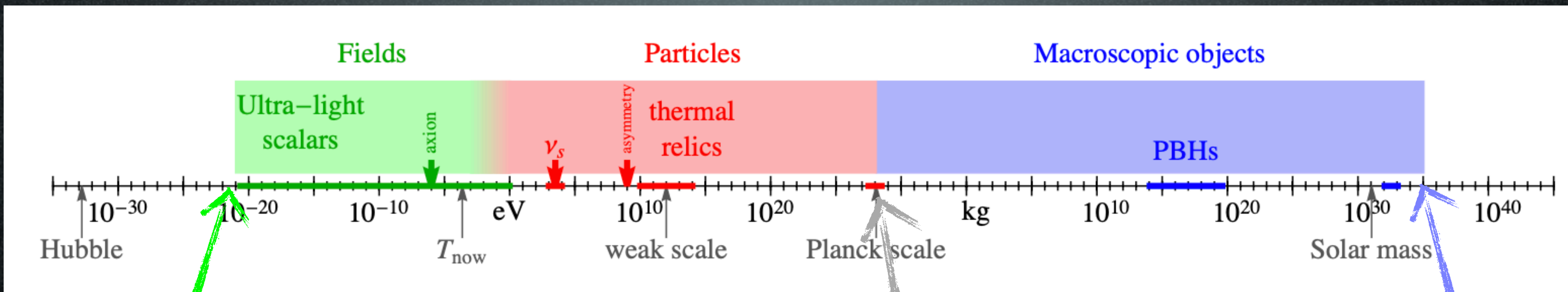

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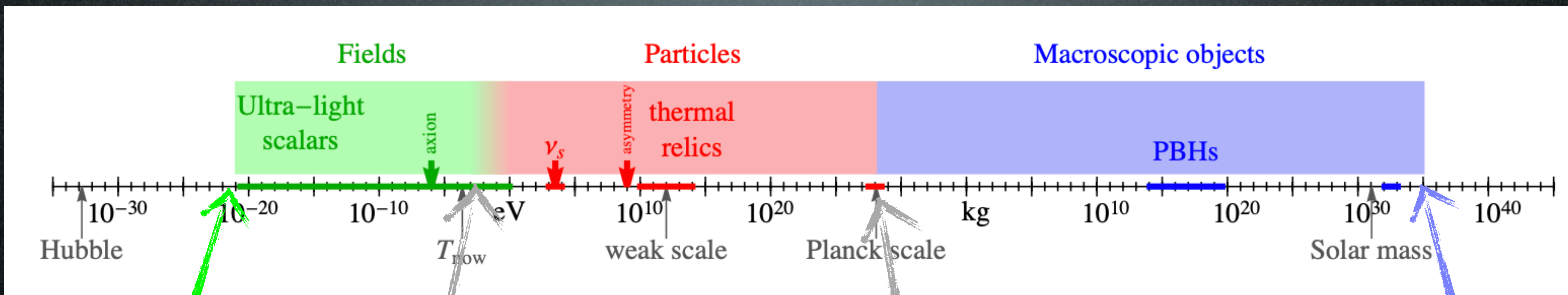

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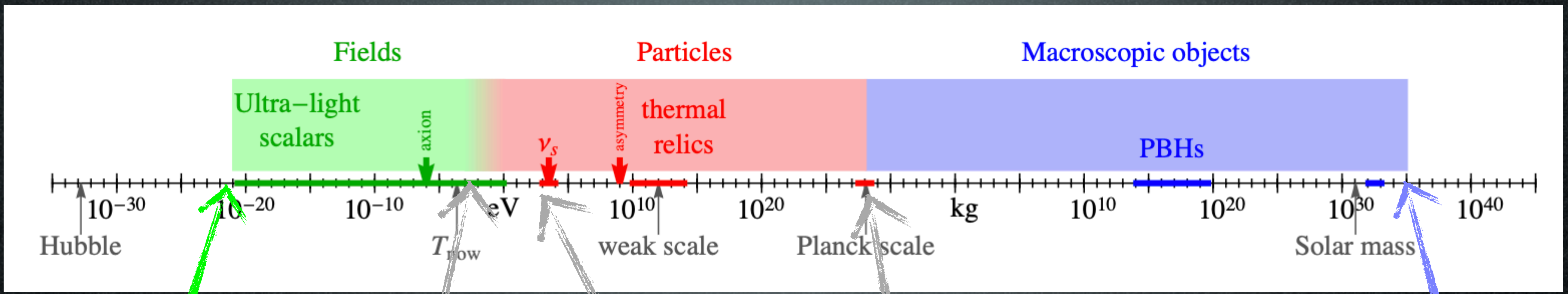

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$M \lesssim 0.1\,\text{keV}$ necessarily *bosonic* | $M \gtrsim 0.1\,\text{keV}$ *bosonic* or *fermionic*

Overview of Particle Physics candidates for Dark Matter

Candidates

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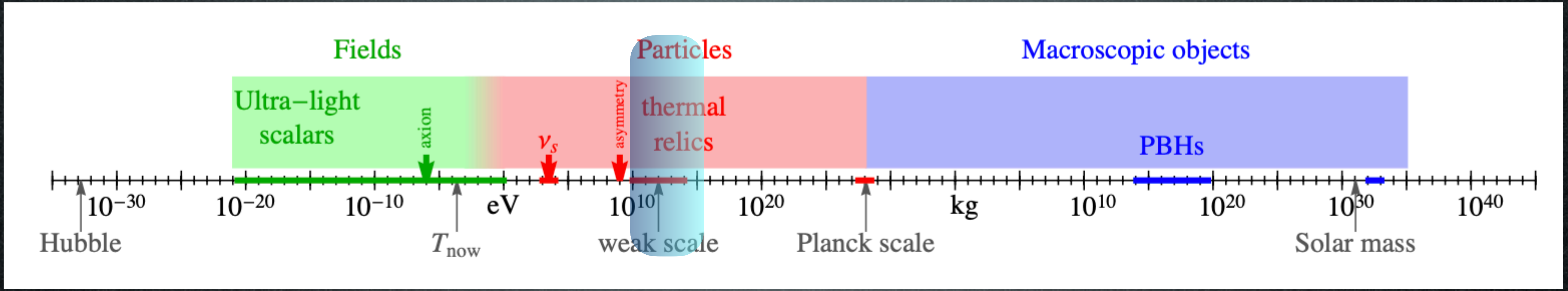

Thermal DM

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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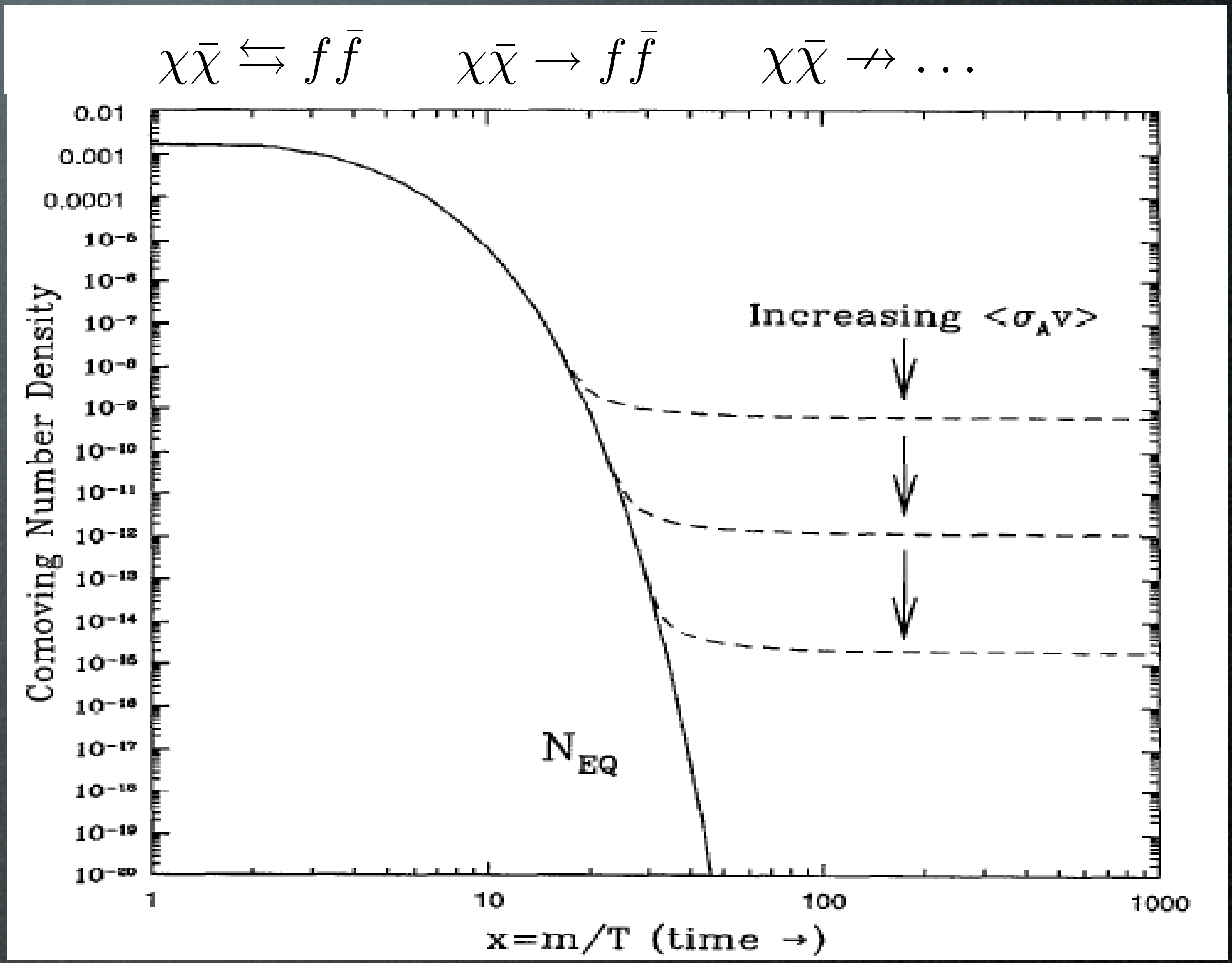

Kolb,Turner, The Early Universe, 1995

Weak cross section:

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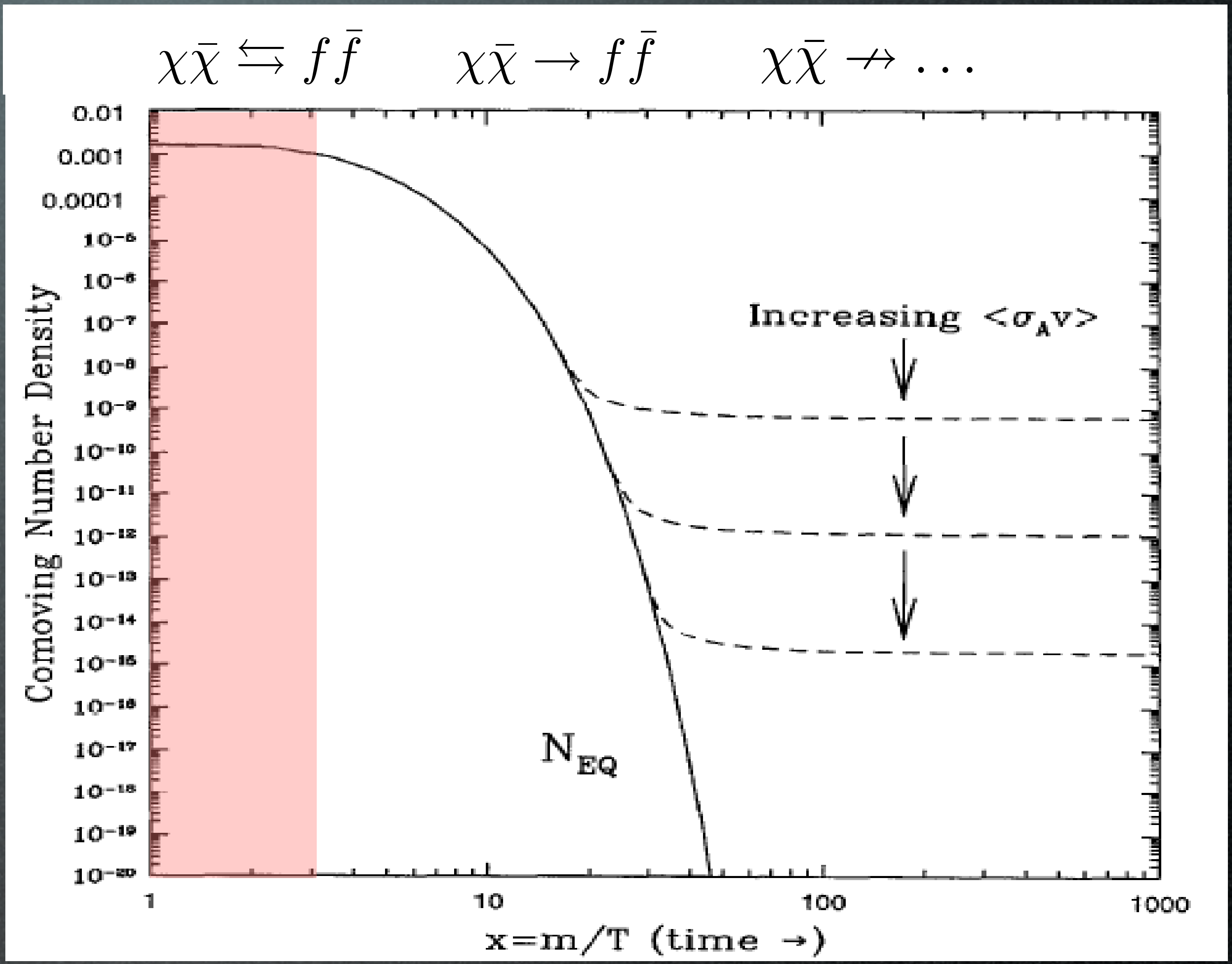

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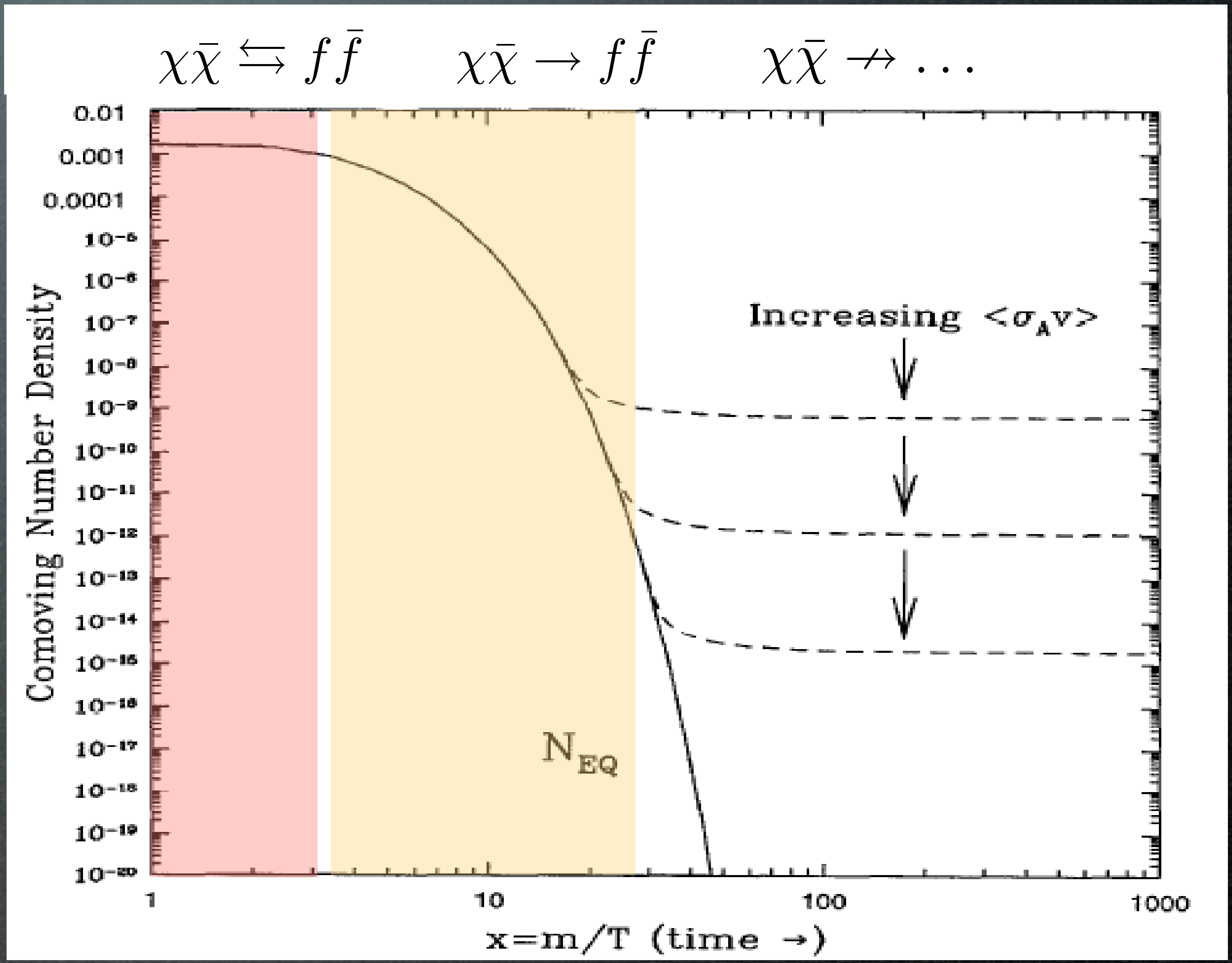

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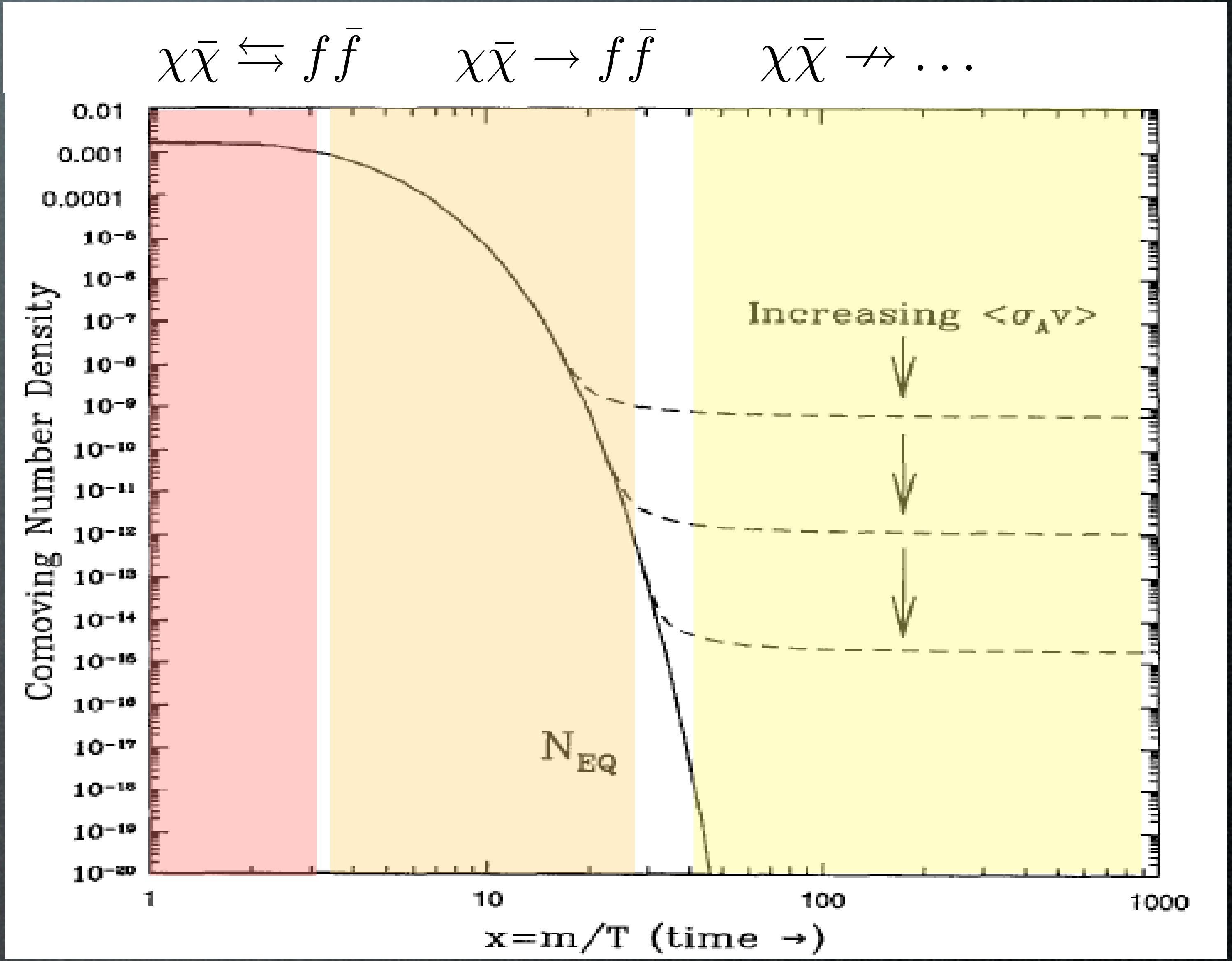

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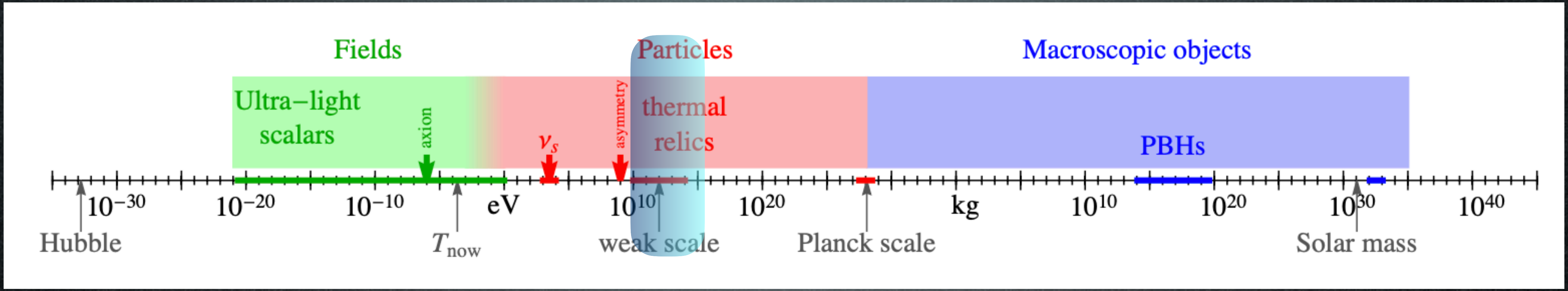

Thermal DM

Candidates

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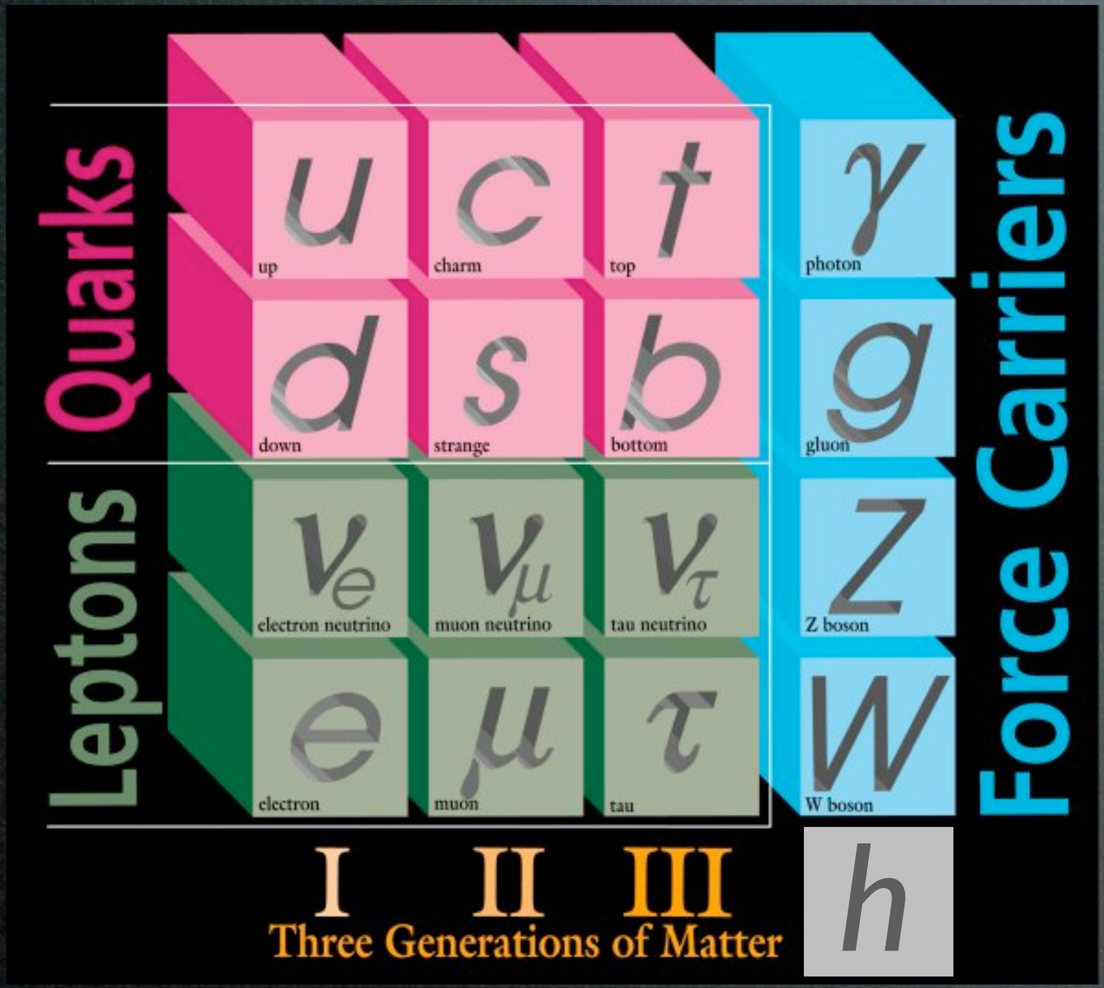
SuSy neutralino

other exotic candi-dates

SuSy DM in 2 minutes



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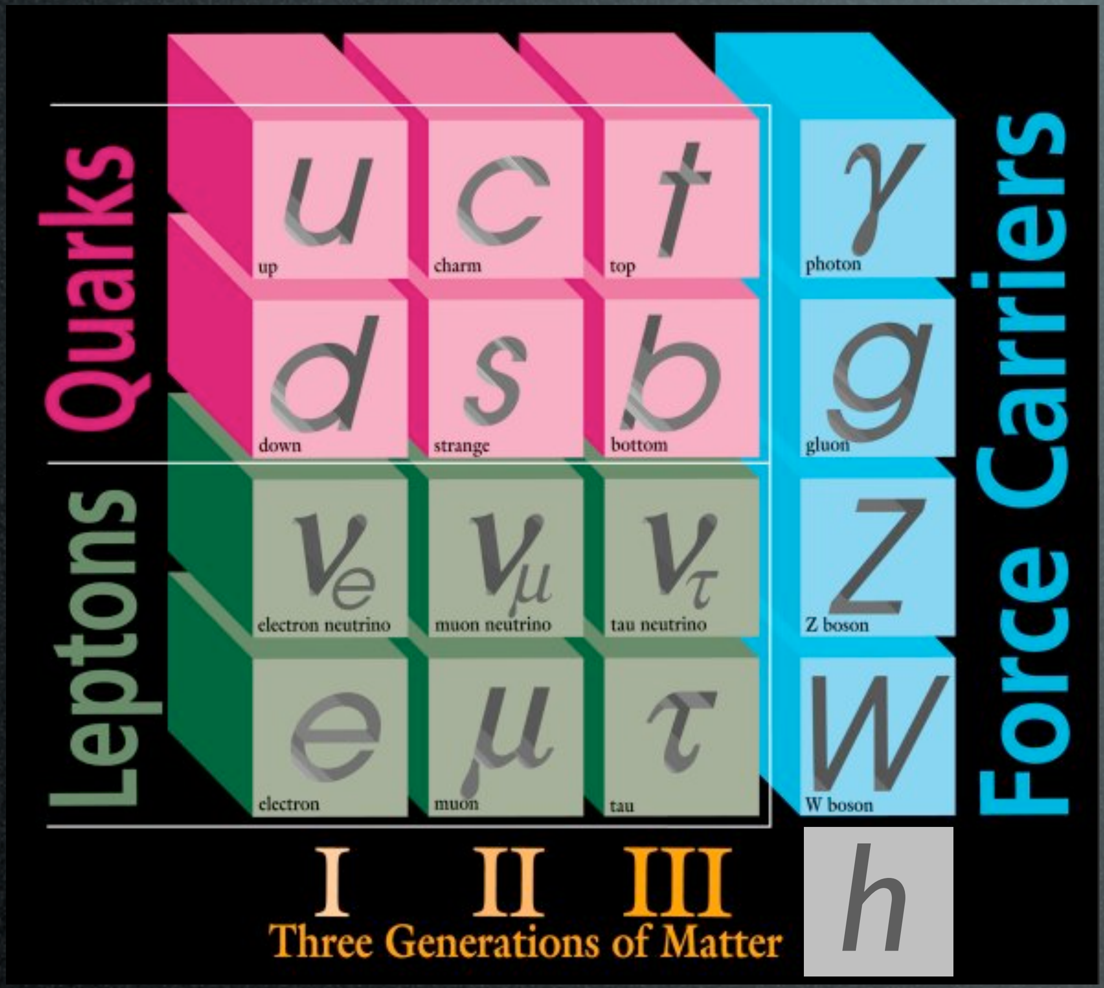

$m_{\rm h} \simeq 125\ {\rm GeV}$

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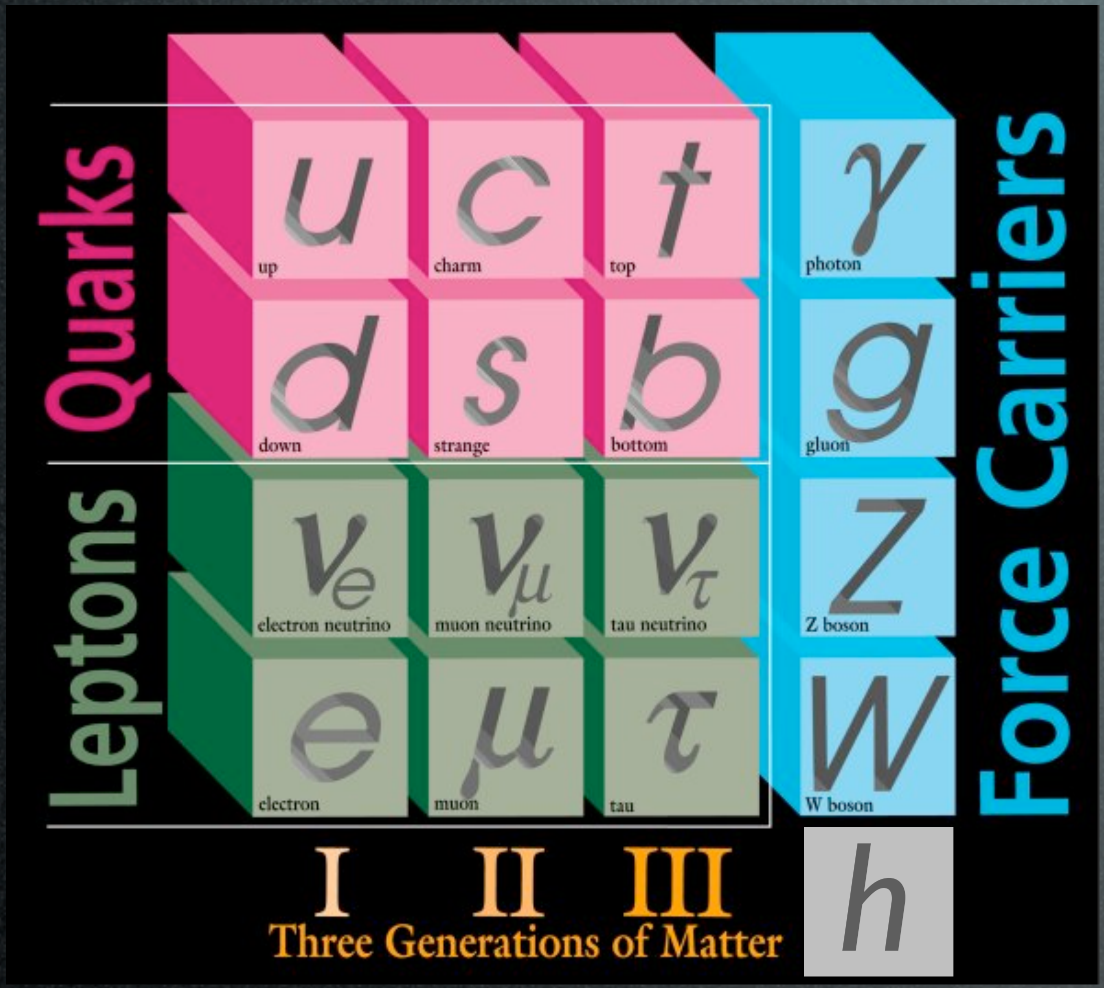

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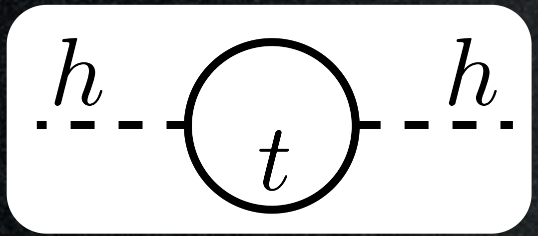

$\Delta m_{\mathrm{h}} \propto 10^{19}$ GeV

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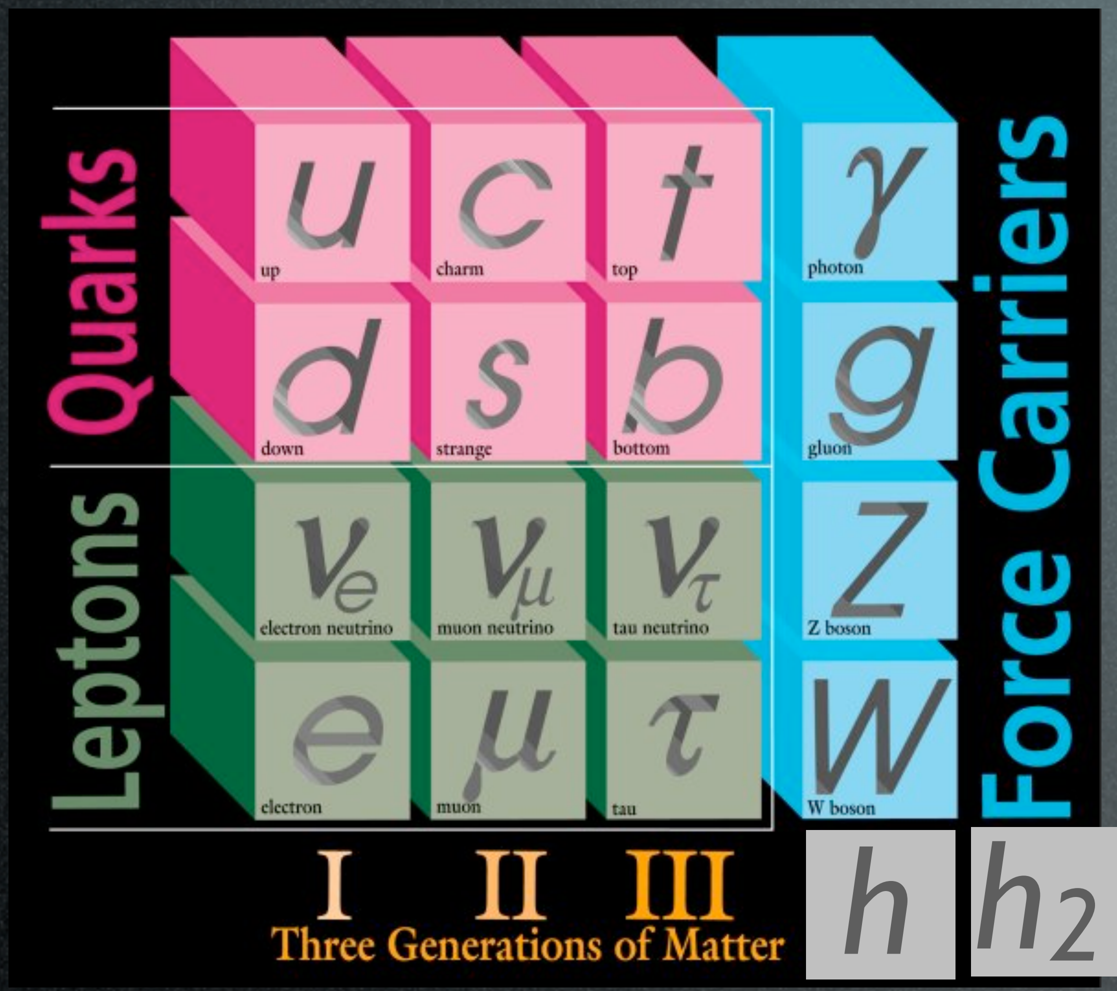

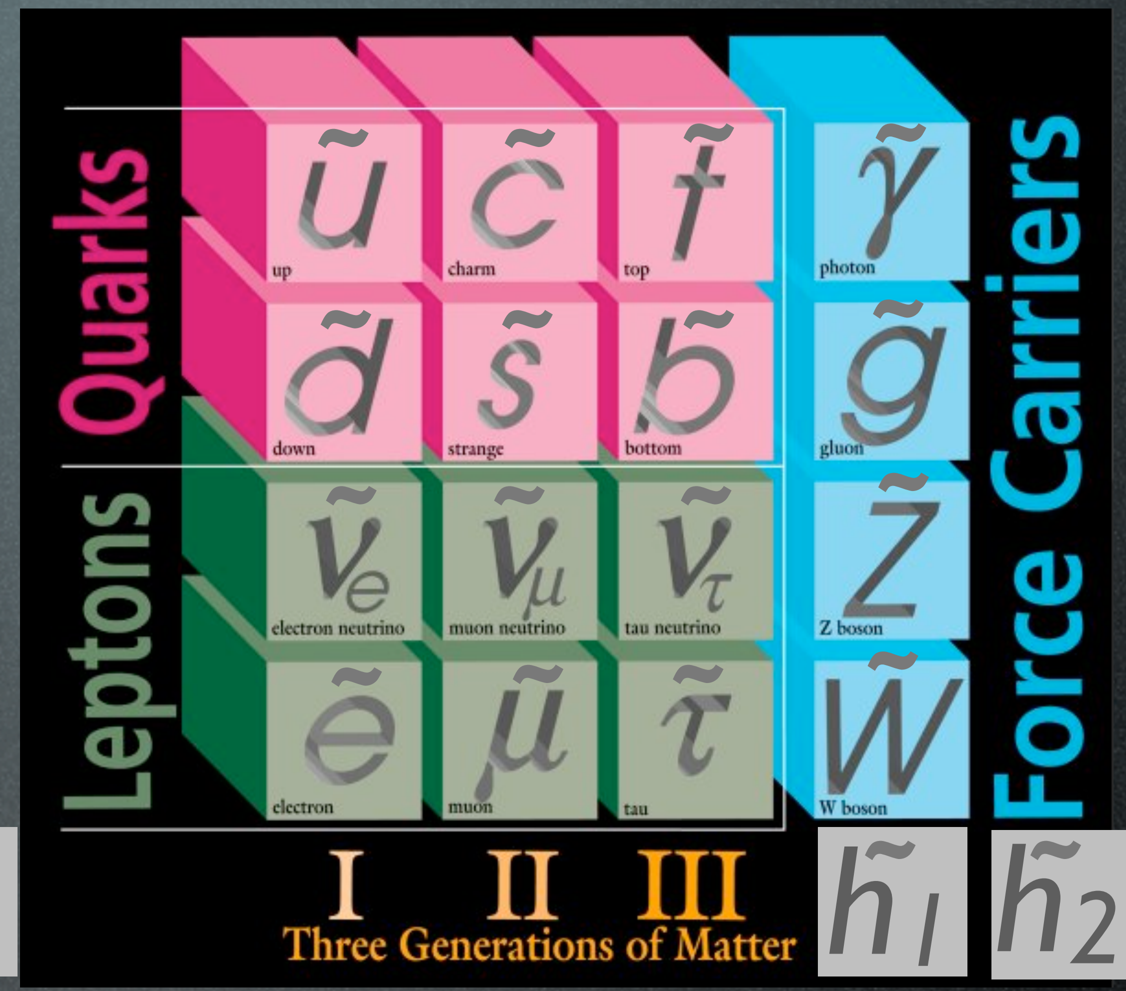

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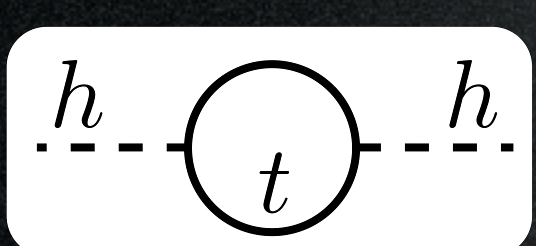

$\Delta m_{\rm h} \propto 10^{19} \text{ GeV}$

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

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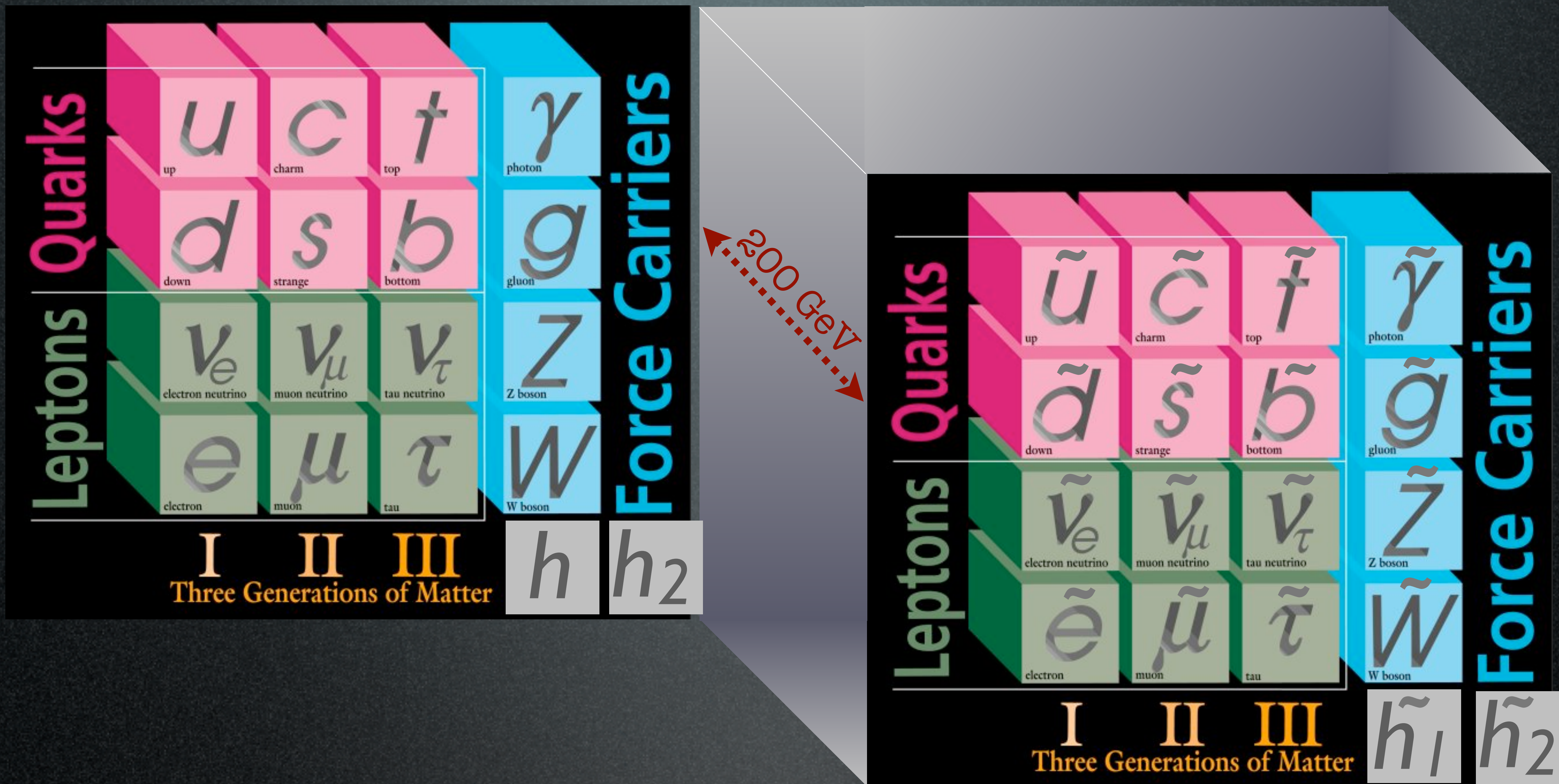

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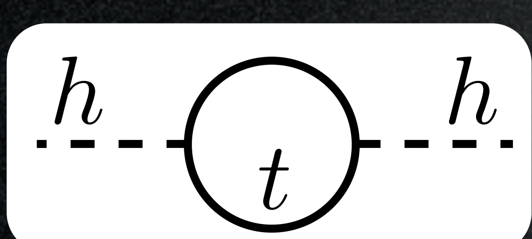
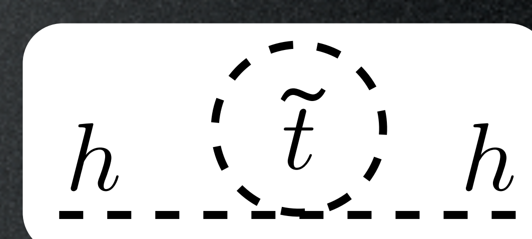
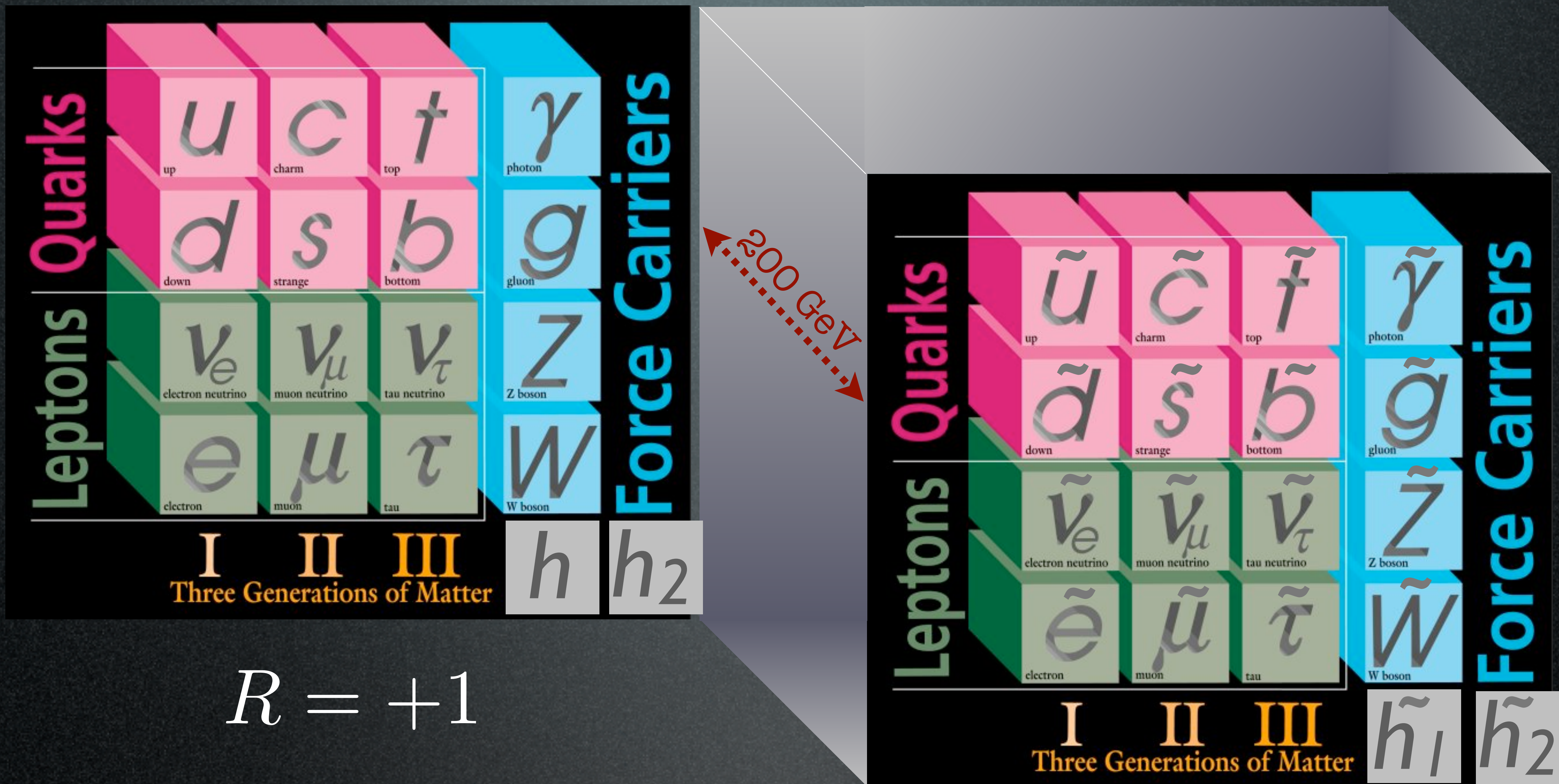


$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$



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

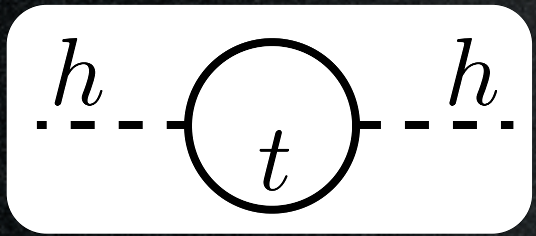
SuSy DM in 2 minutes



$$R = +1$$

$$R = -1$$

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



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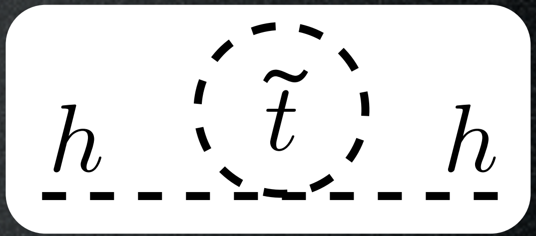

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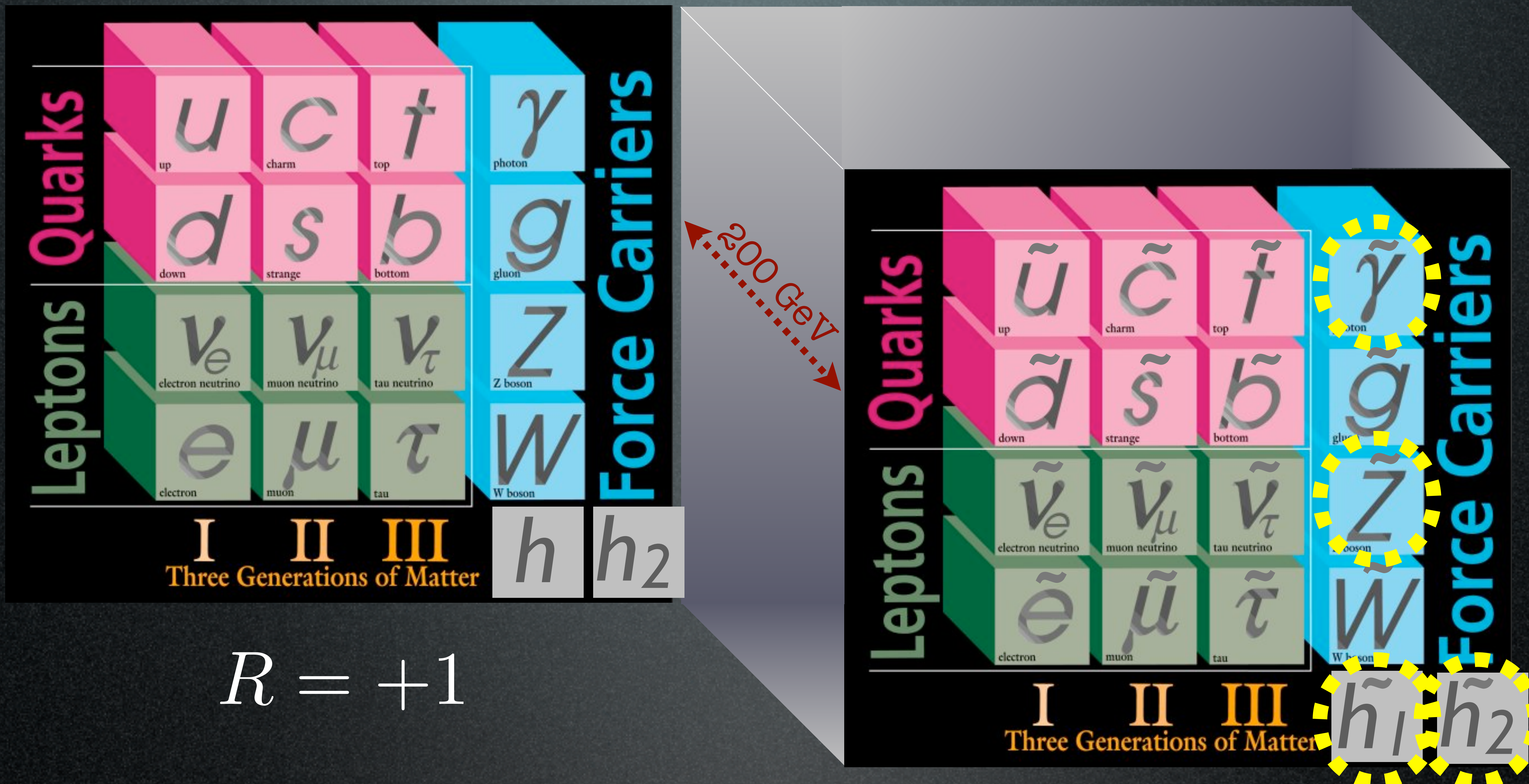

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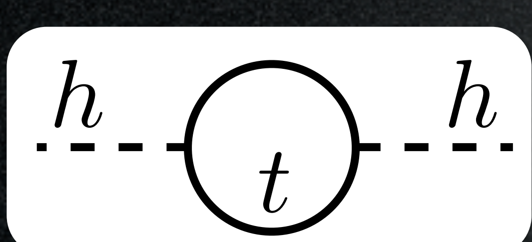
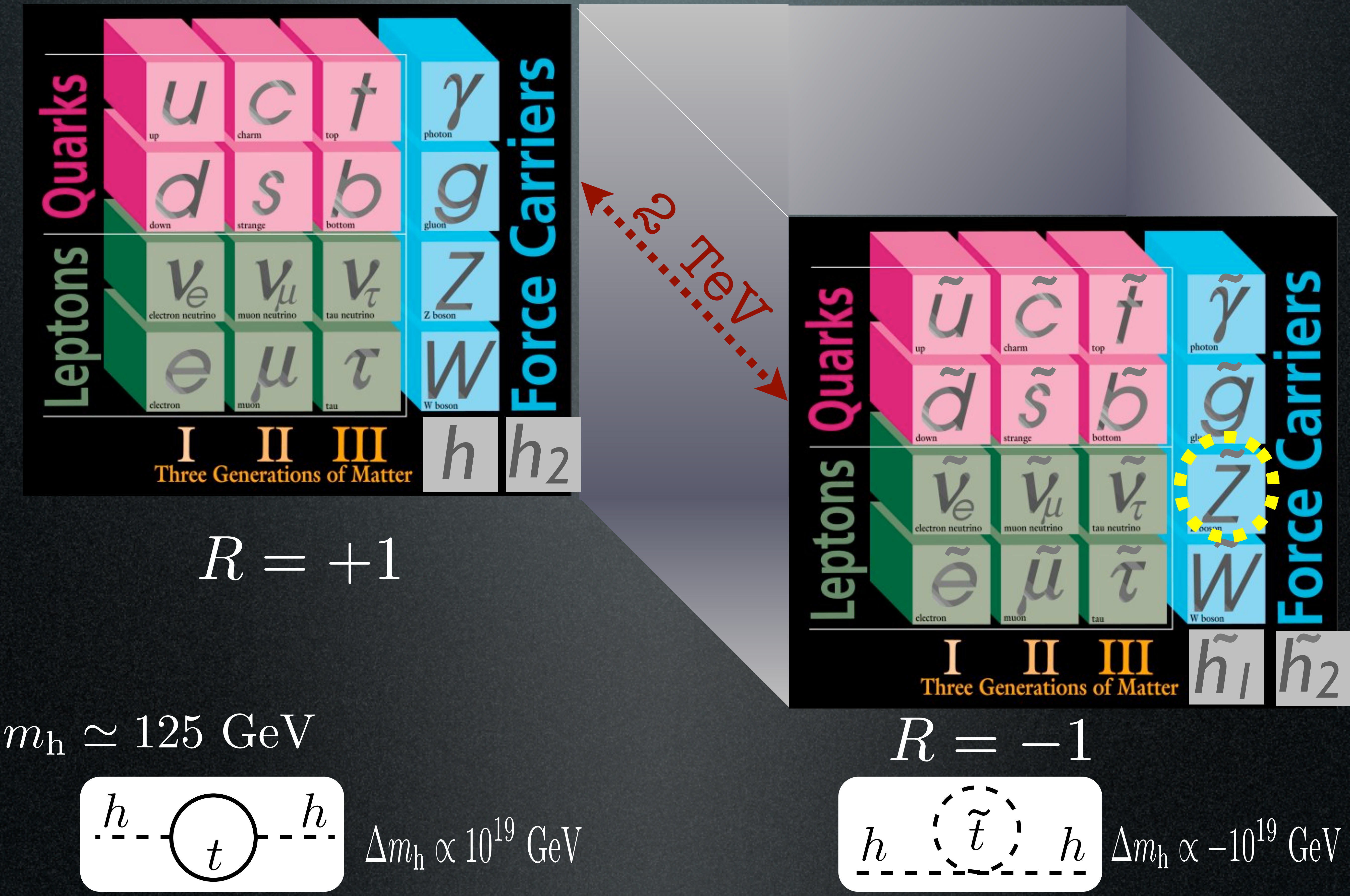


$\Delta m_{\mathrm{h}} \propto 10^{19}$ GeV

$R = -1$

neutral ✓
cold ✓
stable ✓
feebly int. ✓

SuSy DM in 2 minutes

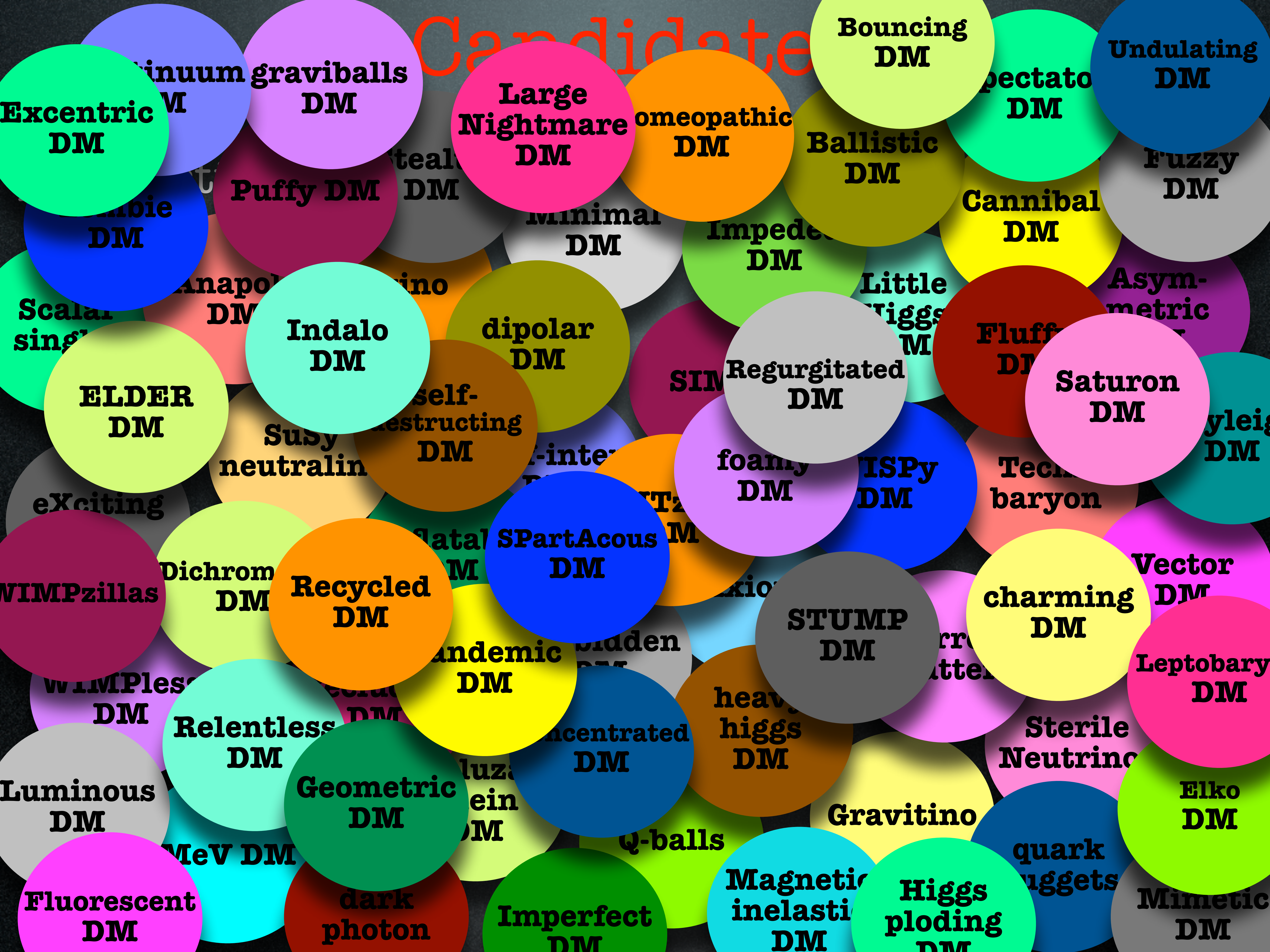


Candidates

A matter of perspective:

SuSy neutralino

other exotic candi- dates



Bouncing DM
Undulating DM
Excentric DM
graviballs DM
Large Nightmare DM
Puffy DM
Ballistic DM
Cannibal DM
Fuzzy DM
Minimal DM
Indalo DM
dipolar DM
ELDER DM
Regurgitated DM
Saturon DM
SPartAcous DM
Recycled DM
STUMP DM
charming DM
Vector DM
Relentless DM
Geometric DM
Luminous DM
MeV DM
Fluorescent DM
dark photon
Imperfect
Q-balls
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Elko DM
Mimetic DM

Scalar singlet DM

On top of the SM, add one extra scalar singlet S
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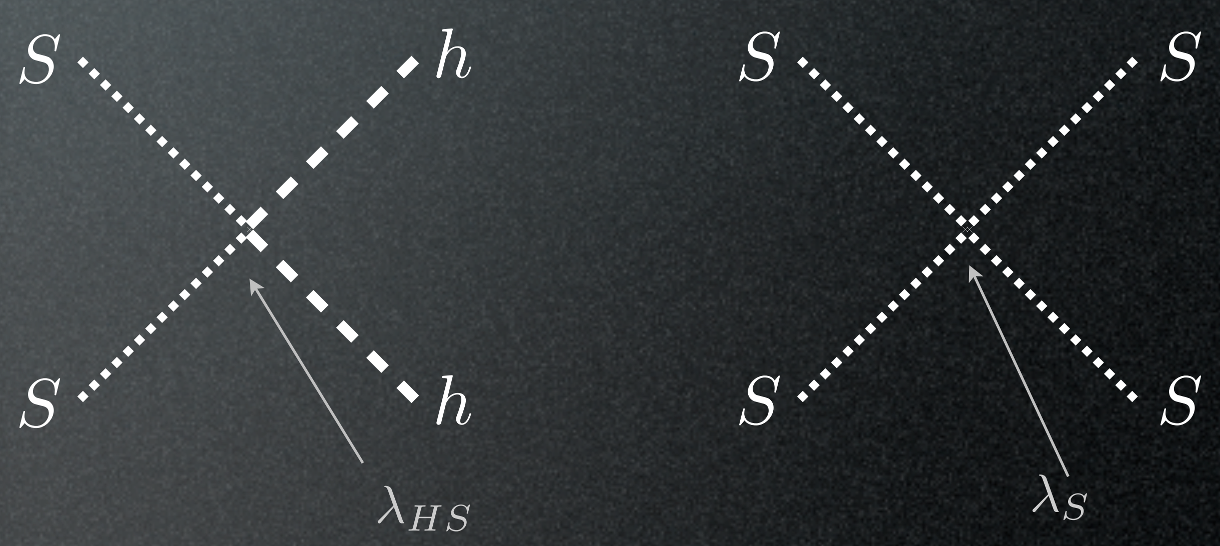
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{|\partial_\mu S|^2}{2} - \frac{m_S^2}{2} S^2 - \lambda_{HS} S^2 |H|^2 - \frac{\lambda_S}{4} S^4$$

parameters are: $m_S, \lambda_{HS}, (\lambda_S)$



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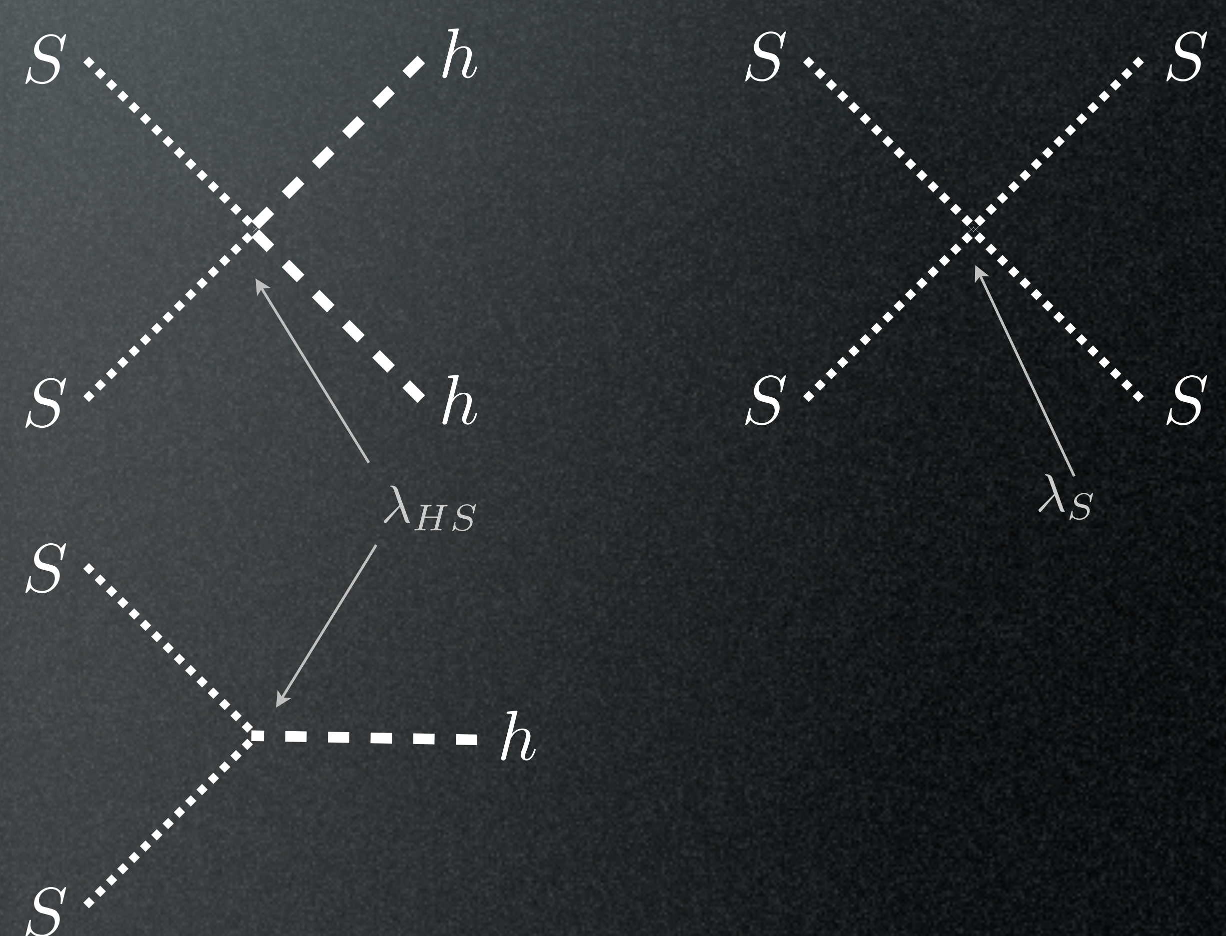

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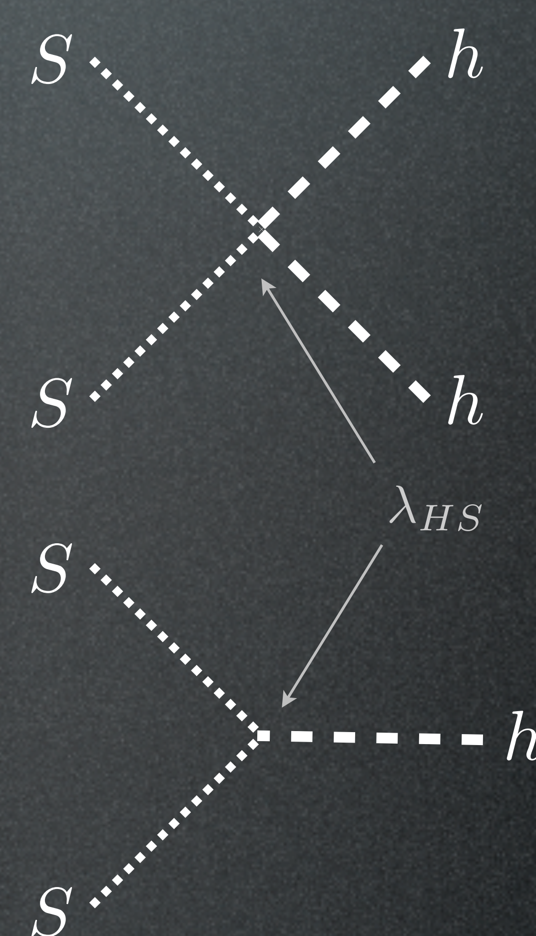

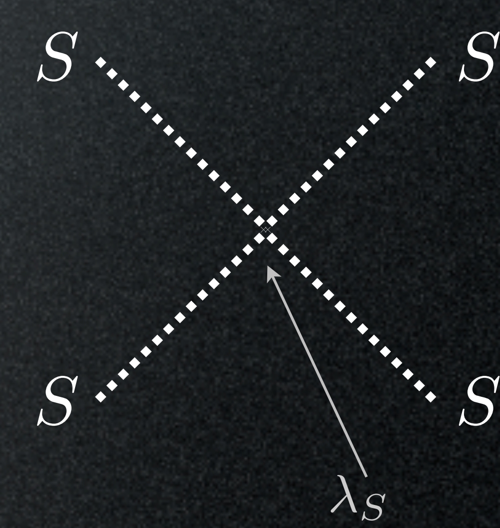

neutral ☑
cold ☑
stable ☑
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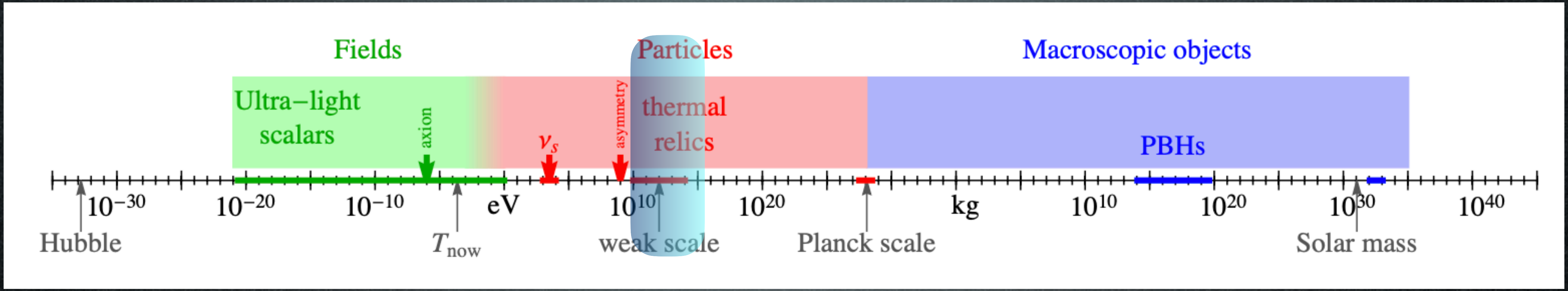
Candidates

A matter of perspective: plausible mass ranges



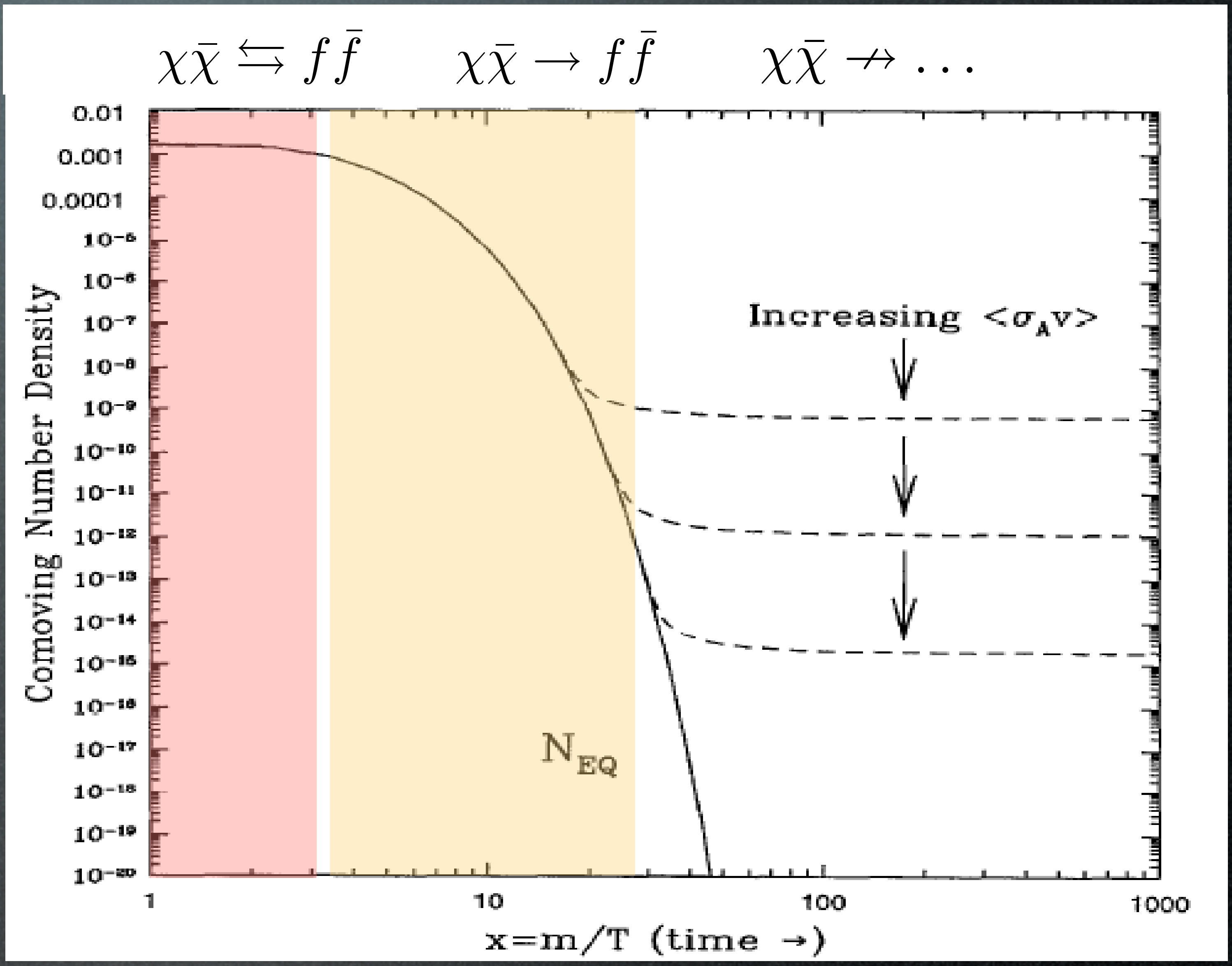
DM as a thermal relic from the Early Universe

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

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



Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

Candidates

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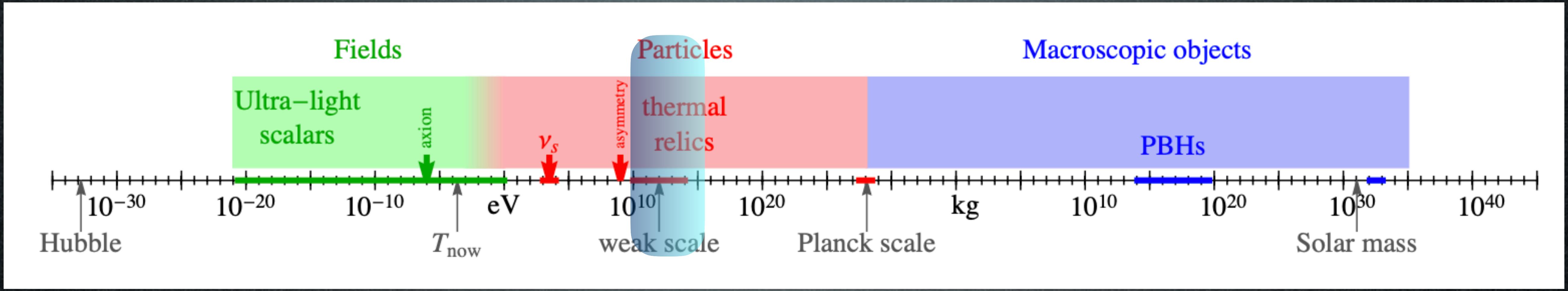

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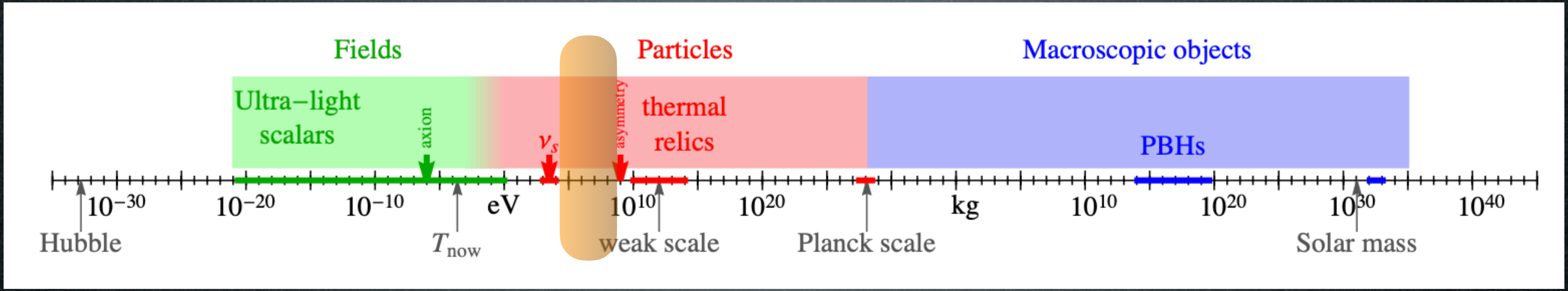

Sub-GeV DM?

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

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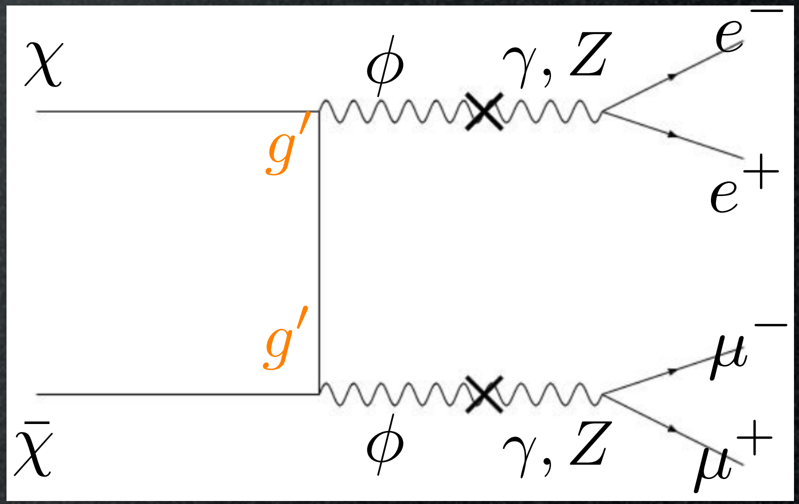
$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_x^2}{m^2}$$

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



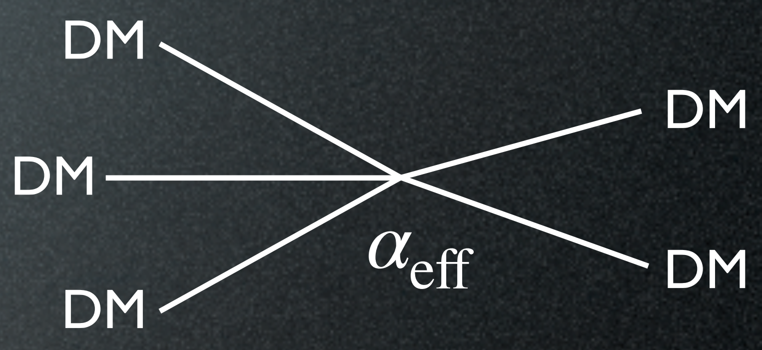
Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM

- ‘SIMP miracle’:

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



points to

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

Hochberg et al 1402.5143

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

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

Theory

Sub-GeV DM?

- 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'
- Asymmetric DM
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- ...

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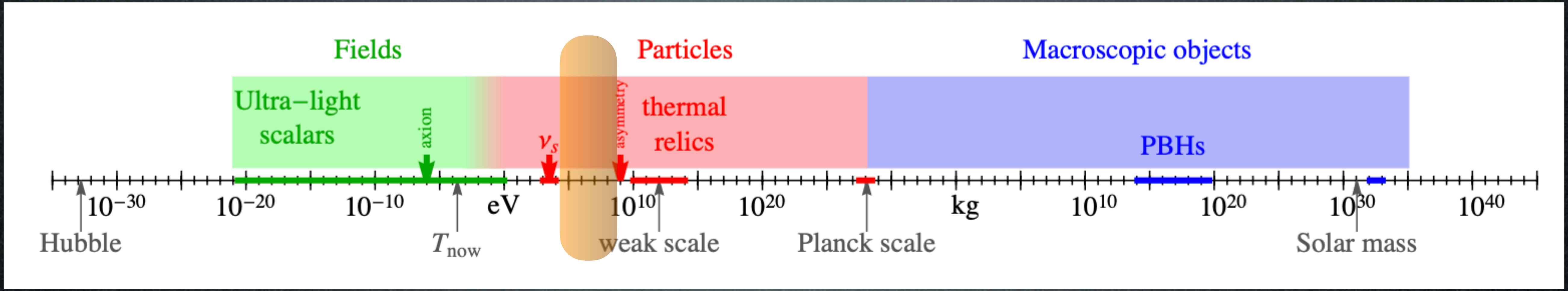

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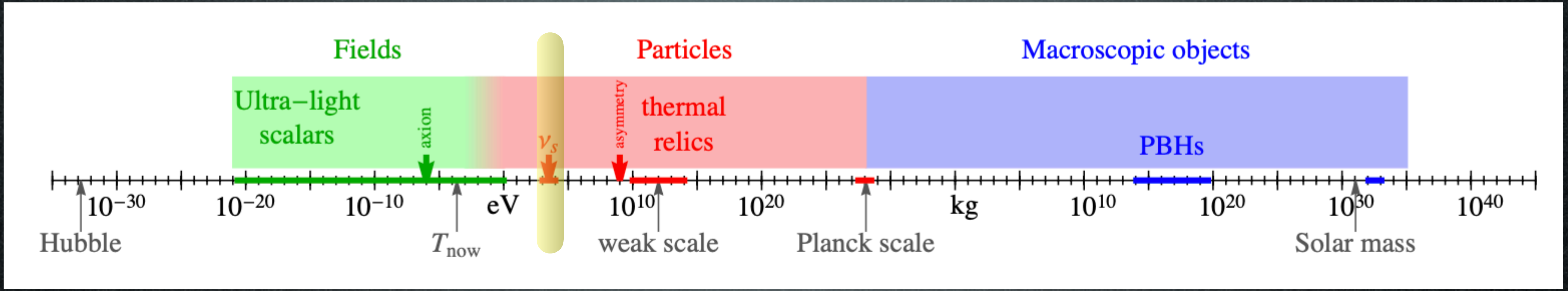


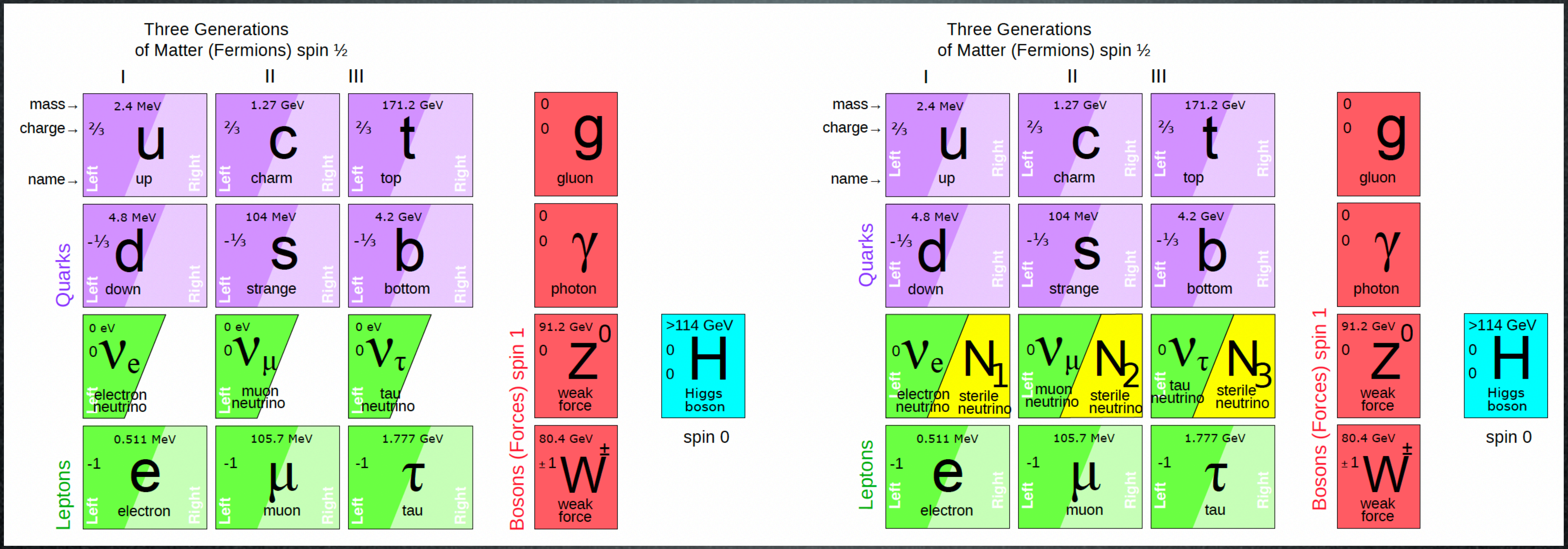
KeV DM

Sterile neutrinos

Sterile neutrinos

Theoretically ‘motivated’:

one can complete the SM lepton sector



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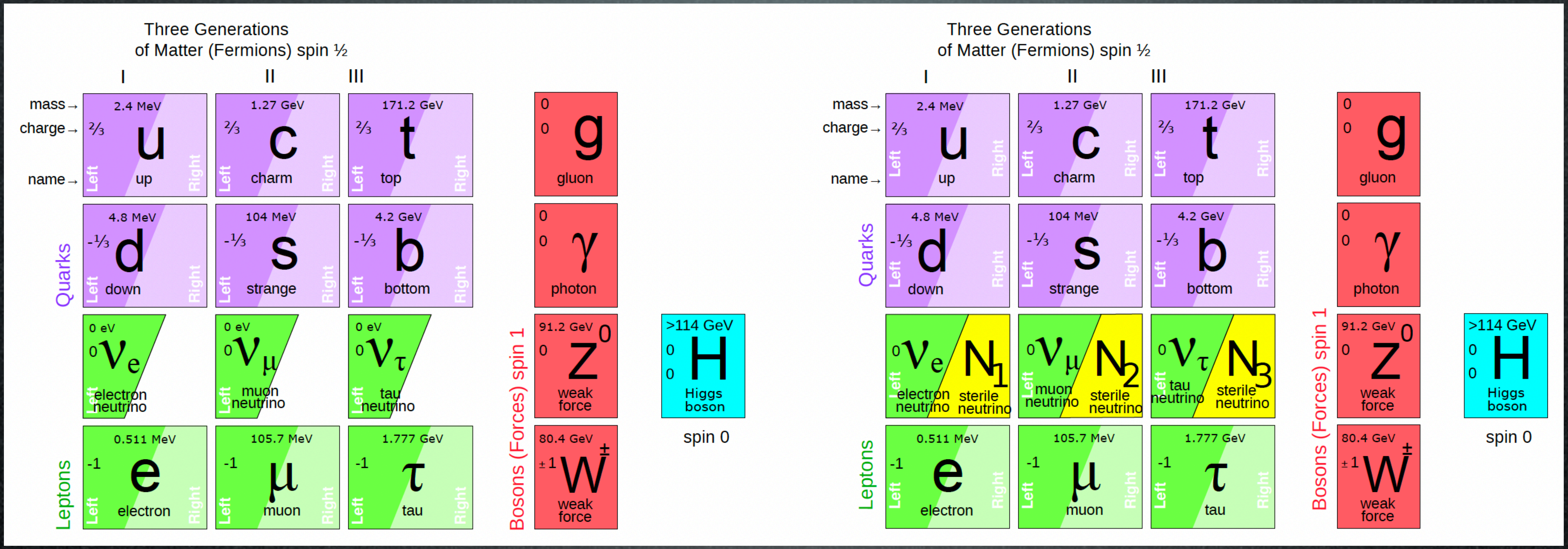

$m_\nu \gtrsim$ few KeV to be cold enough

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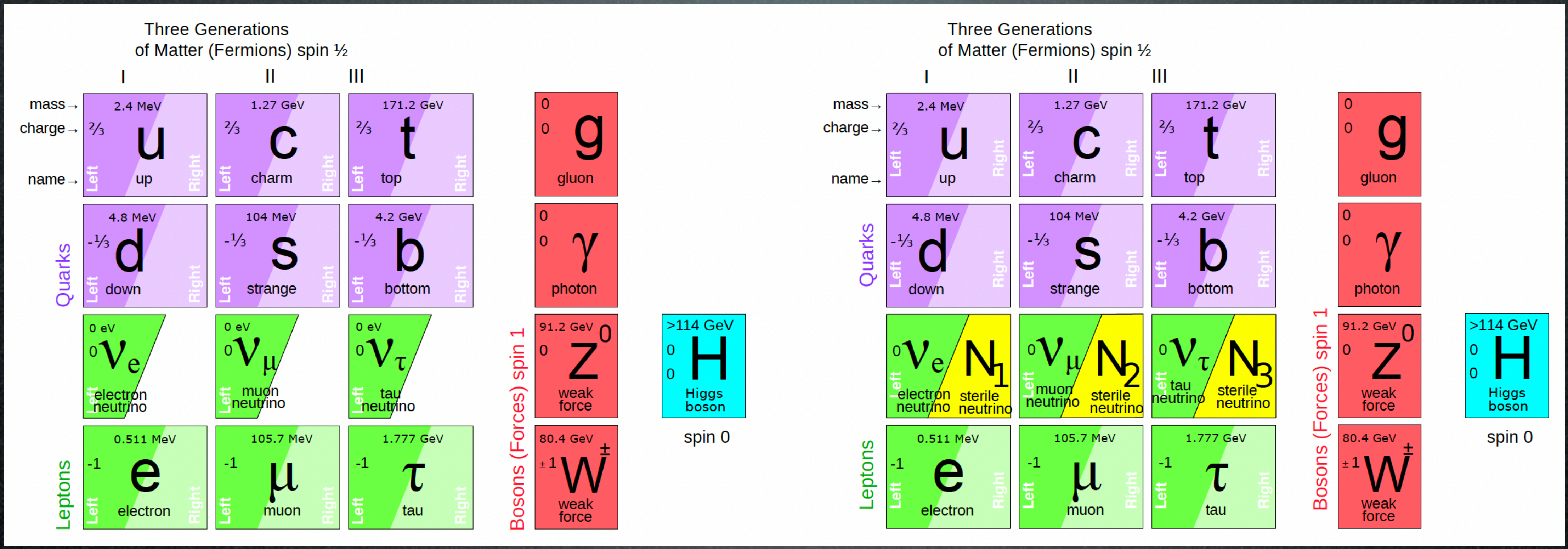


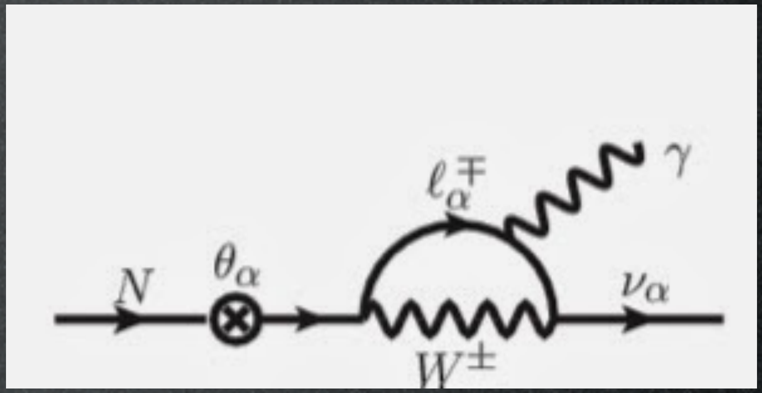
$m_\nu \gtrsim \text{few KeV}$ to be cold enough

Sterile neutrino decay

$m_\nu = 7.1$ KeV

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

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



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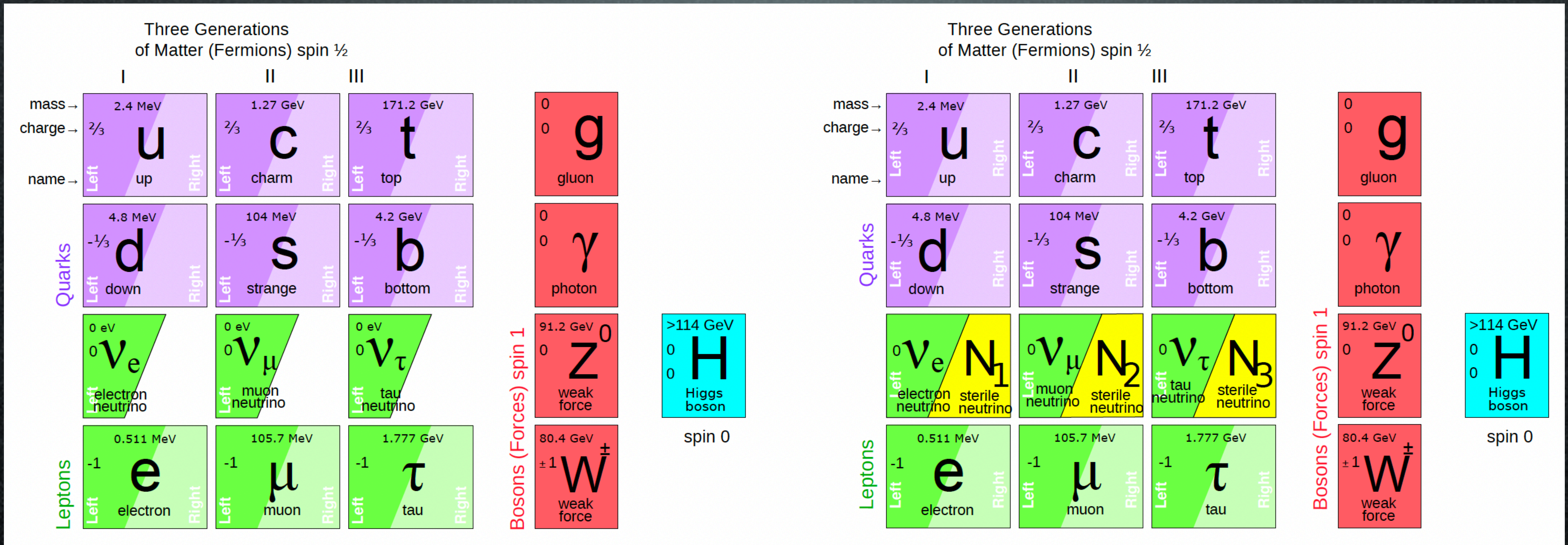

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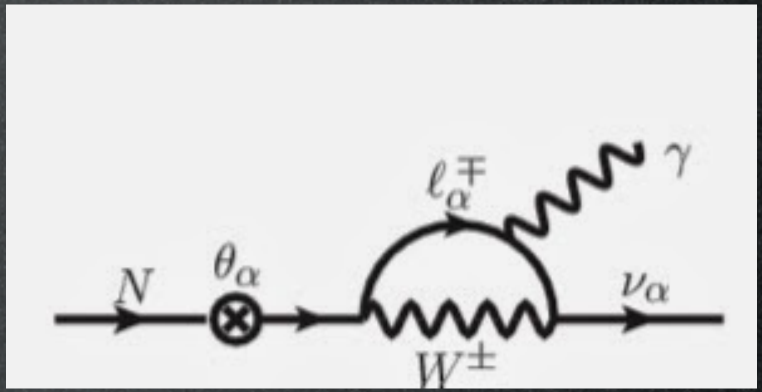

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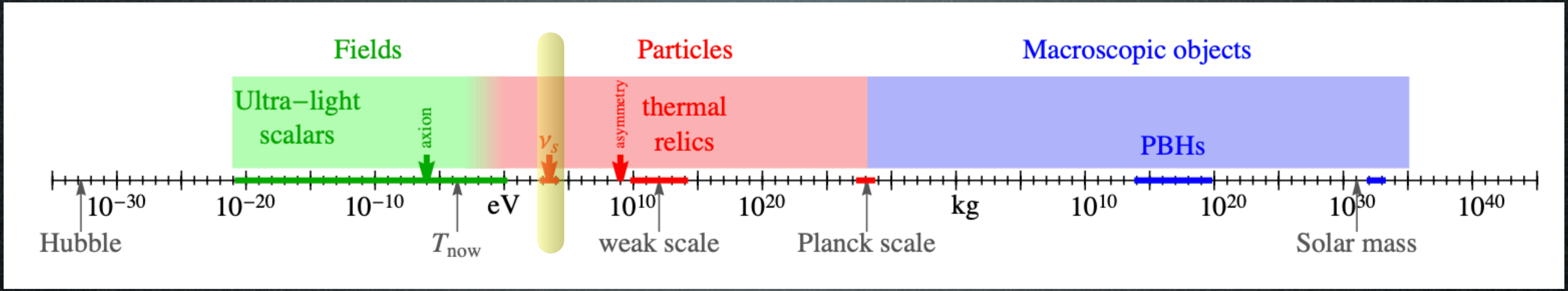

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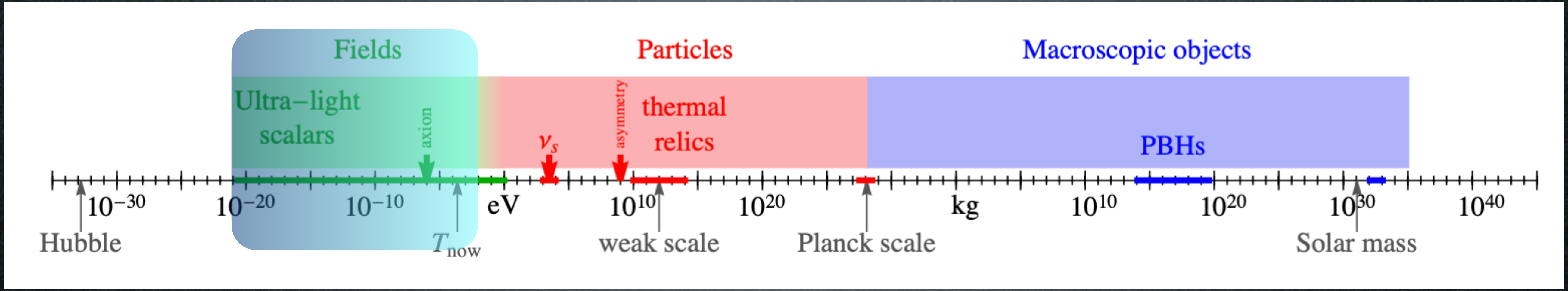

Ultralight DM

Axions

Axions

Theoretically motivated:

one can add to the SM $\mathscr{L} = \mathscr{L}_{\rm SM} - \theta \frac{g_3^2}{64\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$

$$\left(\tilde{G}^a_{\mu\nu} \equiv \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^a_{\alpha\beta} \right)$$

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Perhaps because θ is dynamical (a field)

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

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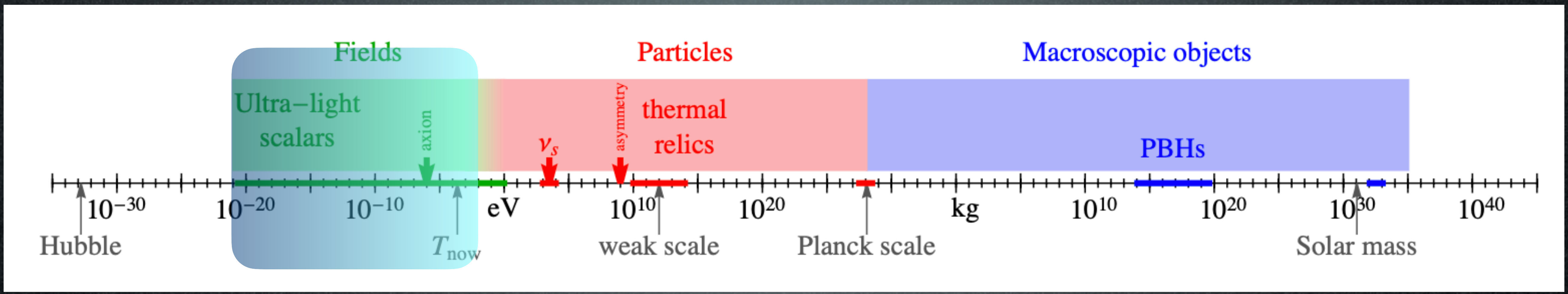
Candidates

A matter of perspective: plausible mass ranges



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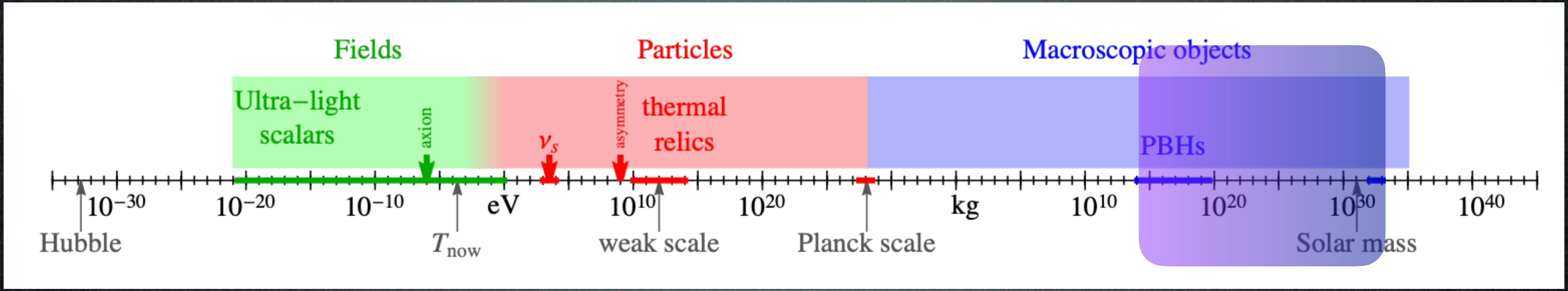

PBH DM

Primordial Black Holes

DM can **NOT** be:

an astro *je ne sais pas quoi*:

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- gas

- Black Holes
- brown dwarves

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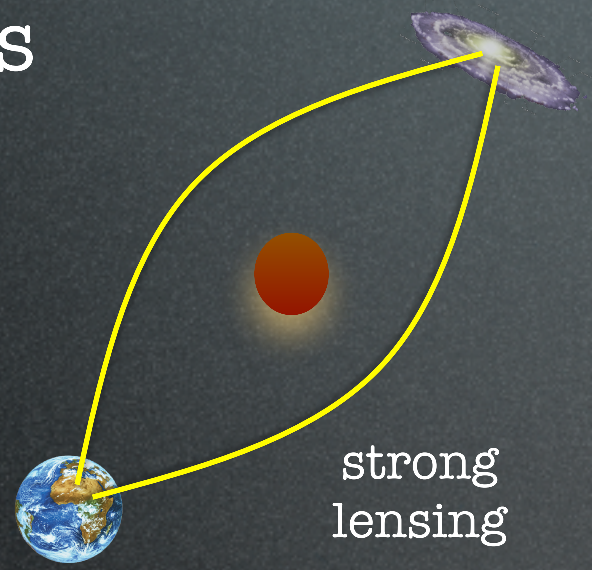
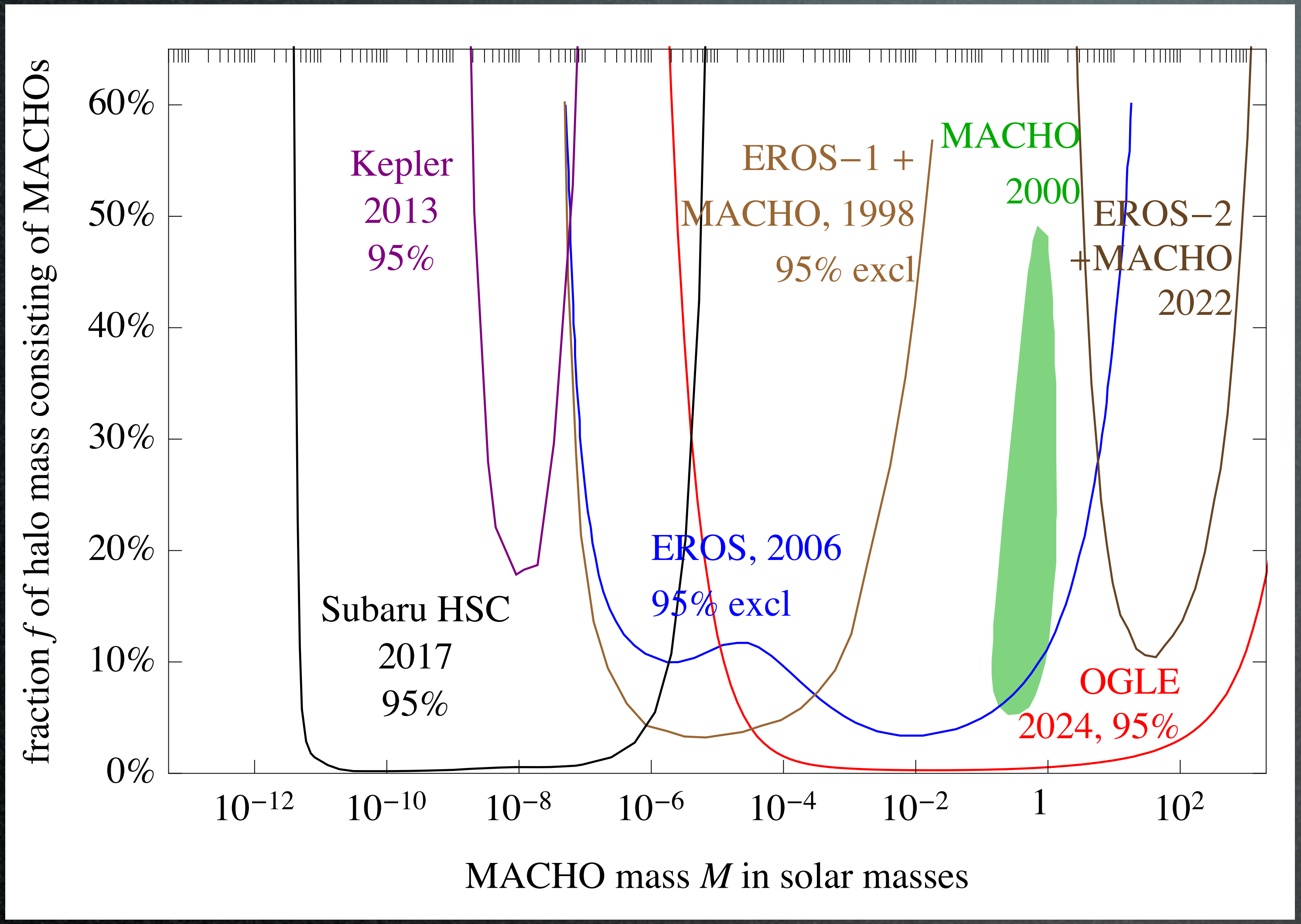


MACHOs or PBHs as DM



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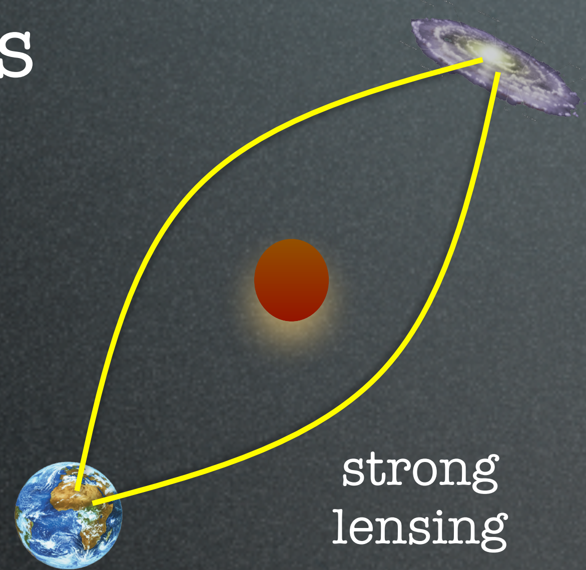

a baryon of the SM:

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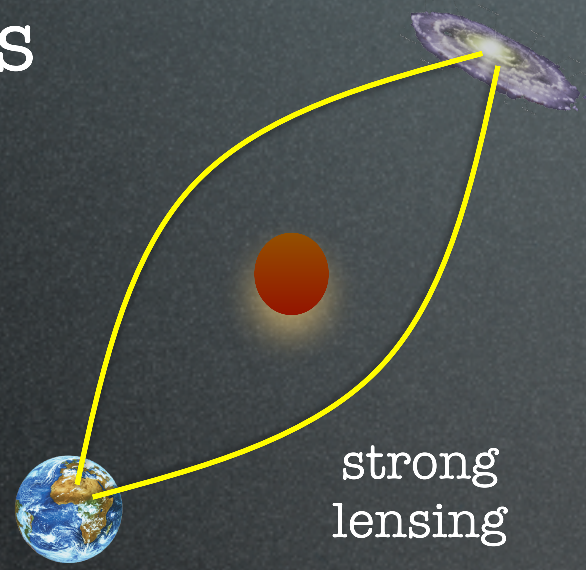

a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium

- CMB says baryons are 4% max

Primordial Black Holes

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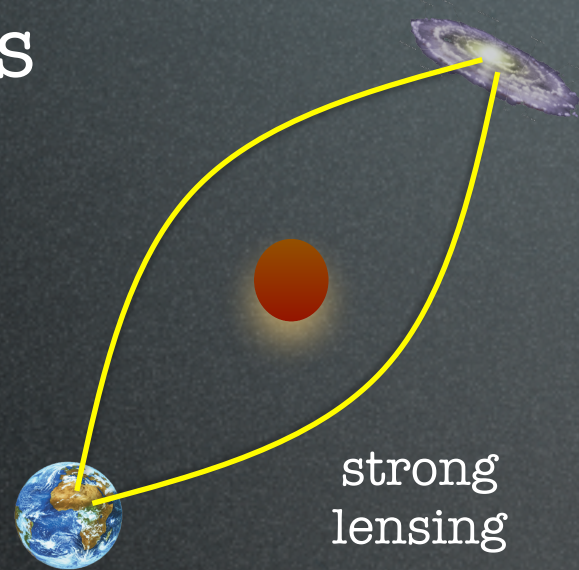
- ~~gas~~

- ~~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

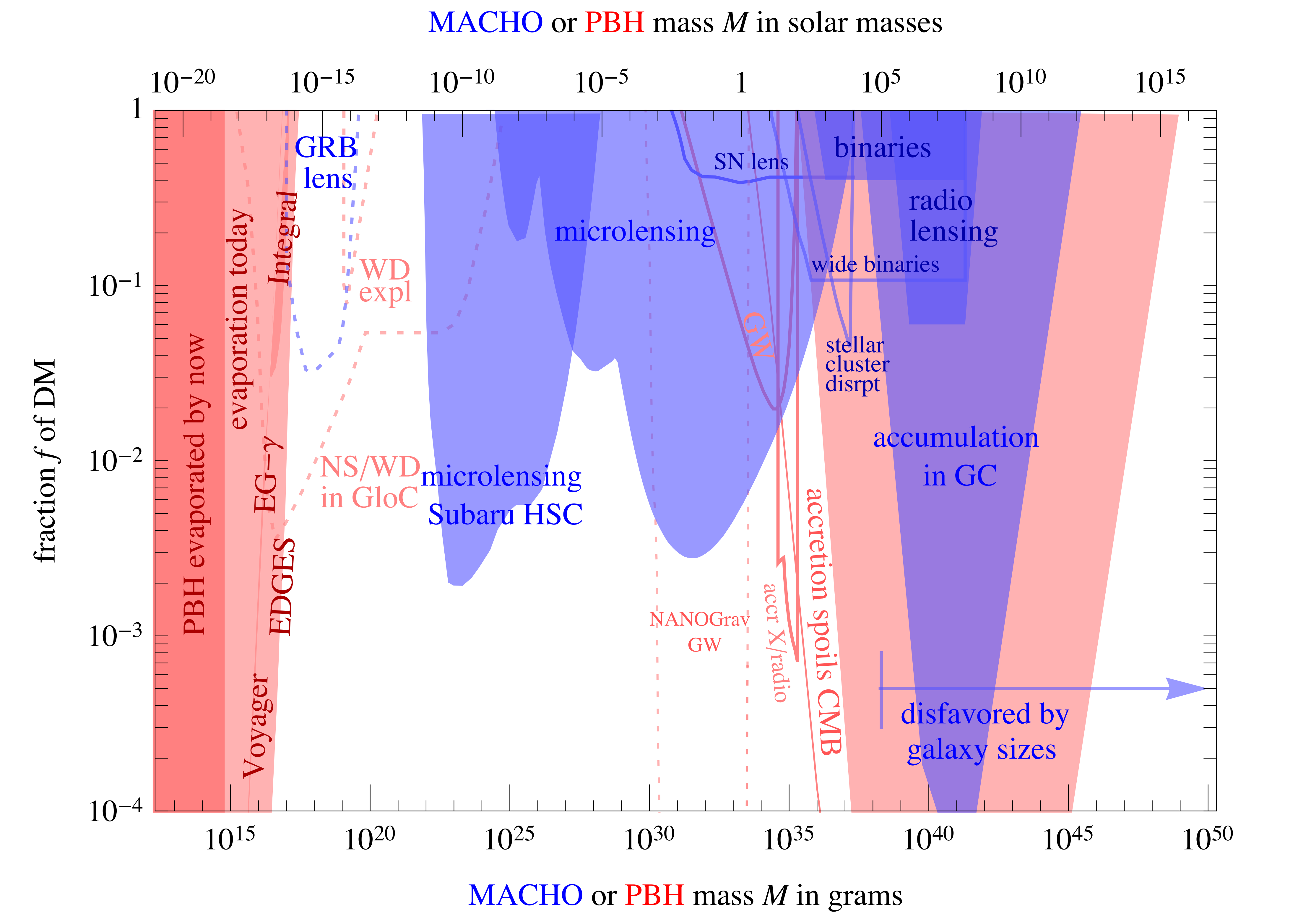
- CMB says baryons are 4% max

A loophole: Primordial Black Holes!

- produced before BBN
- with masses too small/large to lens
- perhaps GW observatories are seeing them?

PBHs as DM

huge range of sizes: $M \simeq 10^{15}(t/10^{-23}\ \text{sec})\ \text{g}$ (with many constraints)



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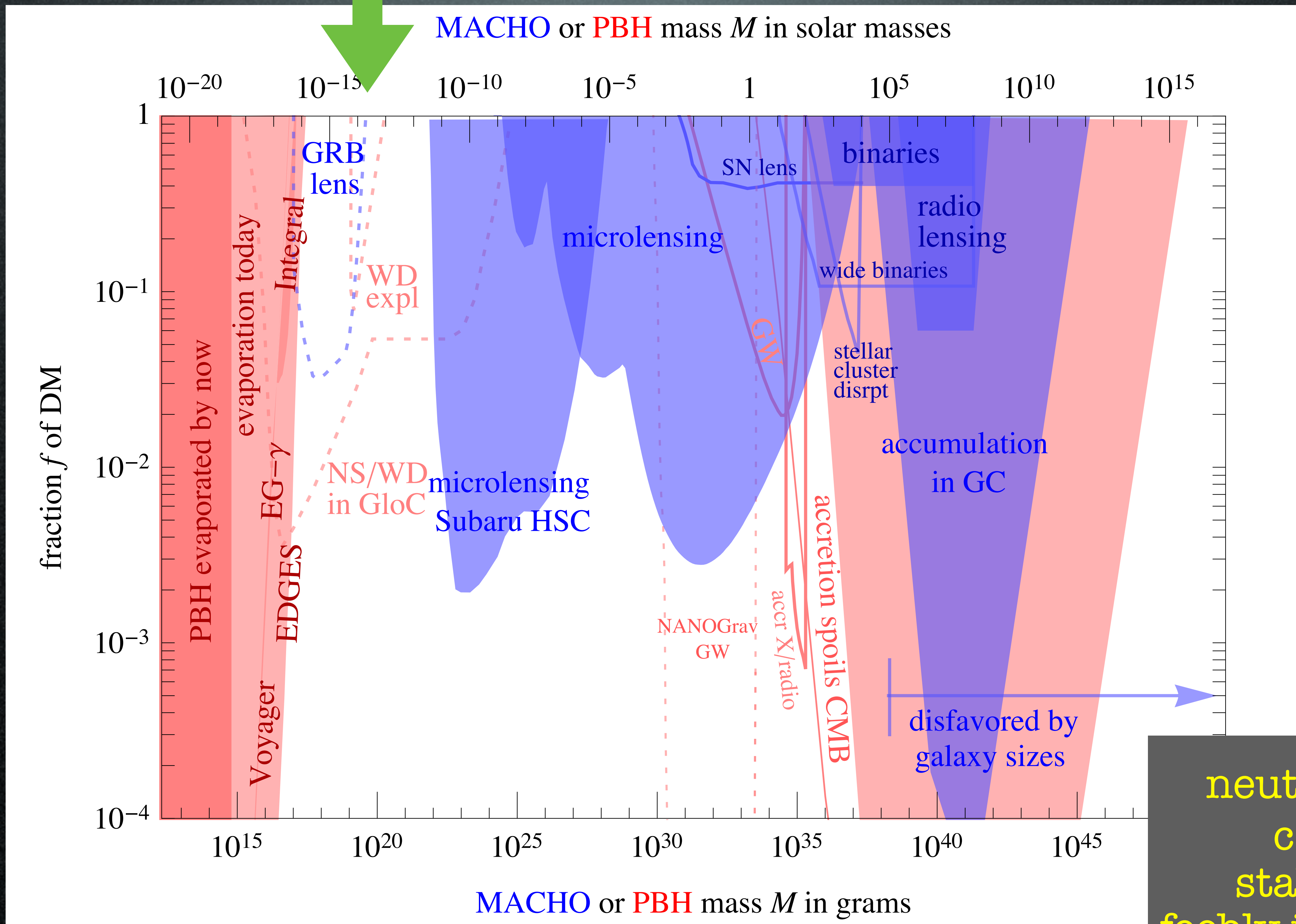
PBHs as DM

window still open?



neutral ☑
cold ☑
stable ☑
feebly int. ☑

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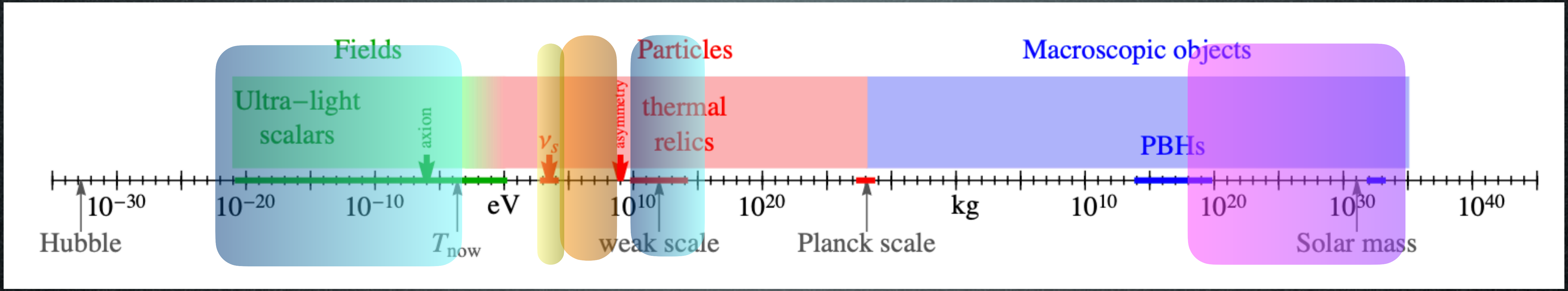
Conclusions

A matter of perspective: plausible mass ranges



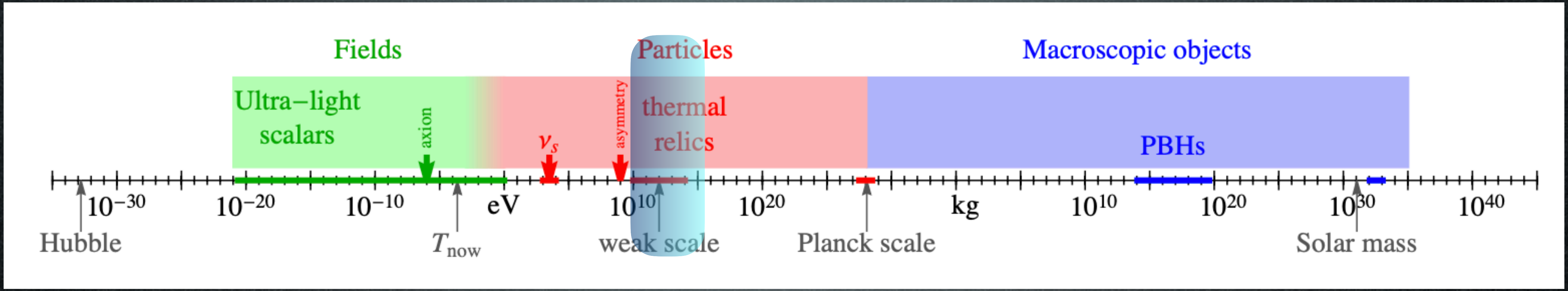
90 orders of magnitude!

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

How do we search for Dark Matter?

Candidates

A matter of perspective: plausible mass ranges



Thermal DM

(WIMP) DM detection

- direct detection
  Xenon, LZ, DarkSide, CDMS (Dama/Libra?)
- production at colliders
  LHC
- indirect
  - γ from annihil in galactic center or halo and from synchrotron emission
    Fermi, HESS, X-ray satellites, radio telescopes
  - e^+ from annihil in galactic halo or center
    AMS, Fermi
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{d}$ from annihil in galactic halo or center
    GAPS
  - $\nu, \bar{\nu}$ from annihil in massive bodies
    Icecube, Km3Net

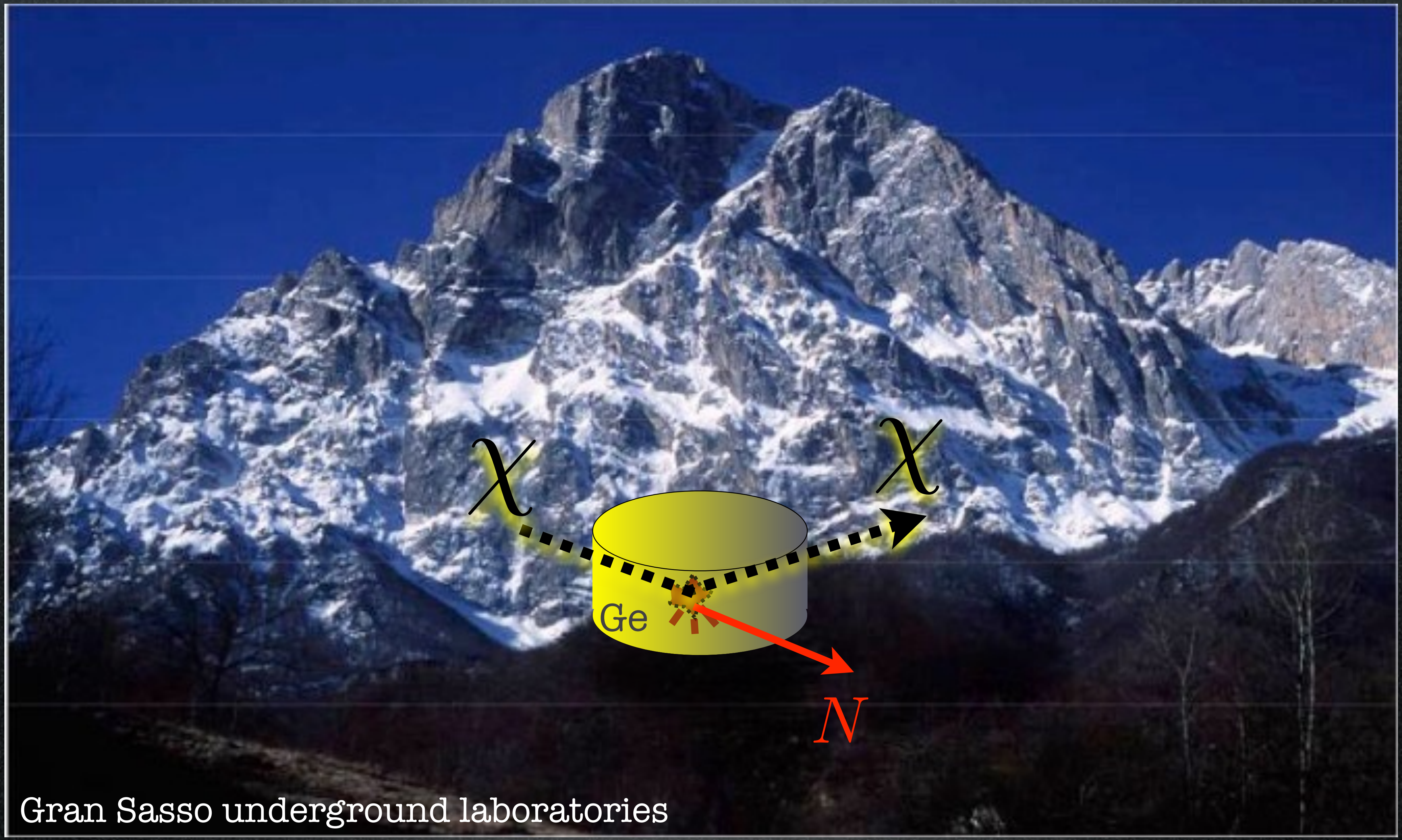
Direct Detection

Direct Detection: **basics**

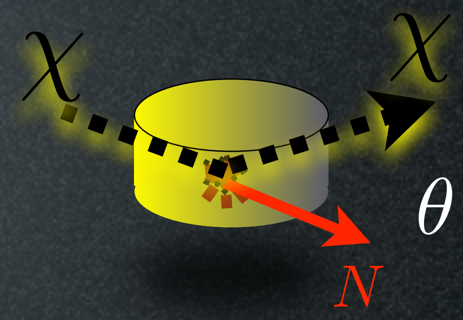

Gran Sasso underground laboratories

Direct Detection: basics

Direct Detection: basics



Direct Detection: basics



recoil energy $$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$

$$\mu_\chi = \frac{m_\chi m_N}{m_\chi + m_N} \to \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\rho_\odot}{m_\chi}\frac{\sigma}{\mu^2}\int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v})\, \mathrm{d}\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

$\sigma \approx \sigma_n^{\rm SI} A^4$ $\times$ nuclear form factors

number of events

$$N = \mathcal{E}\,\mathcal{T}\int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R}\, dE_R$$

Direct Detection: basics

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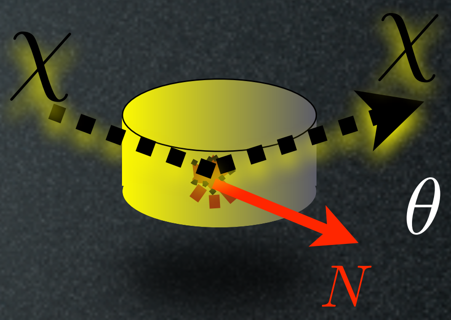

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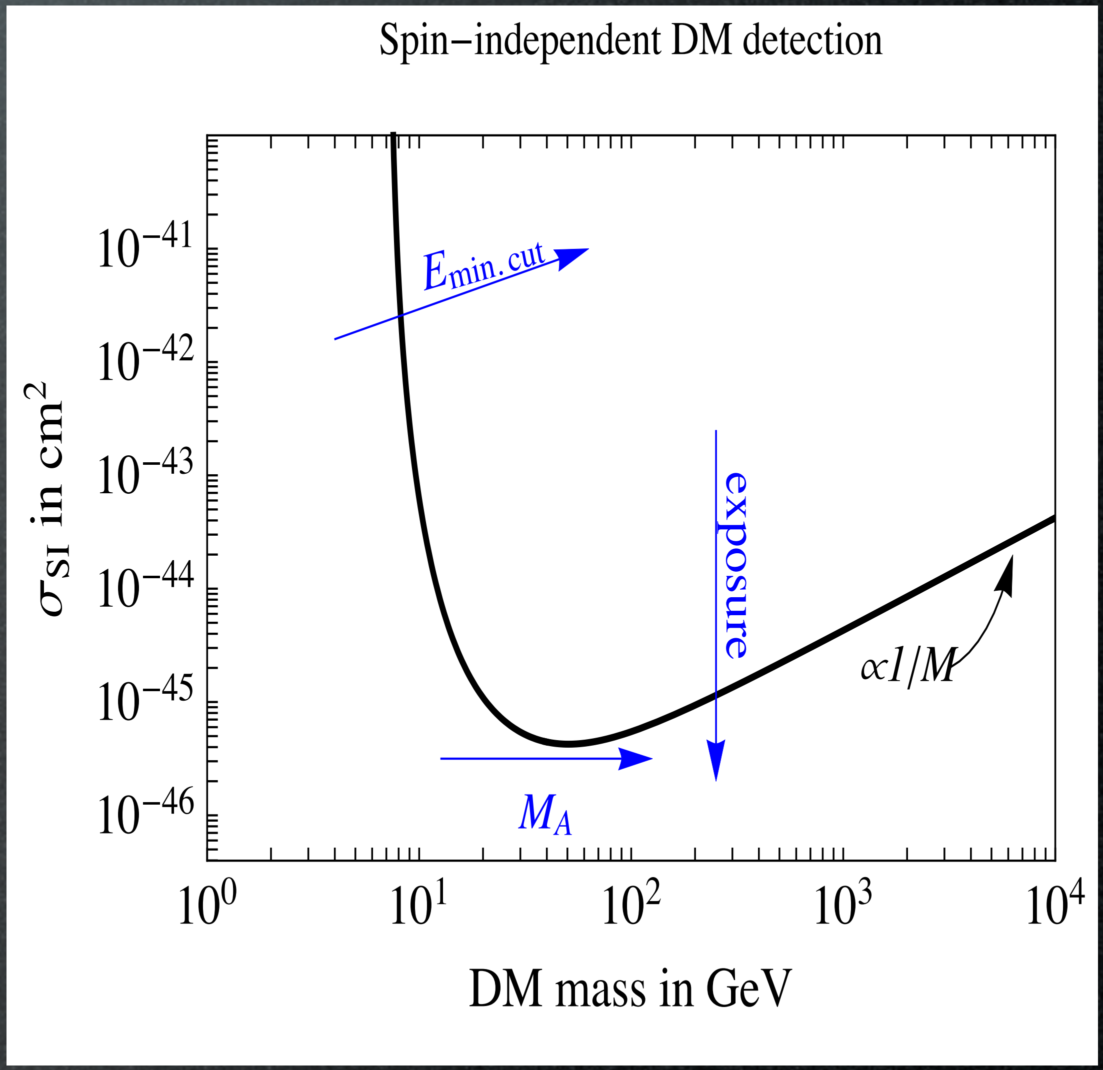

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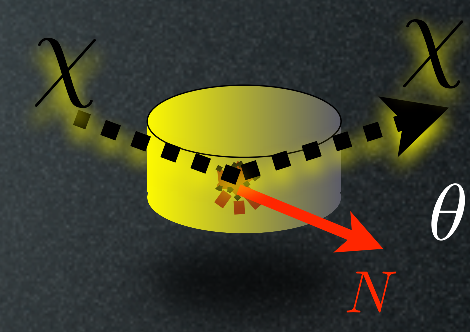
Direct Detection: basics



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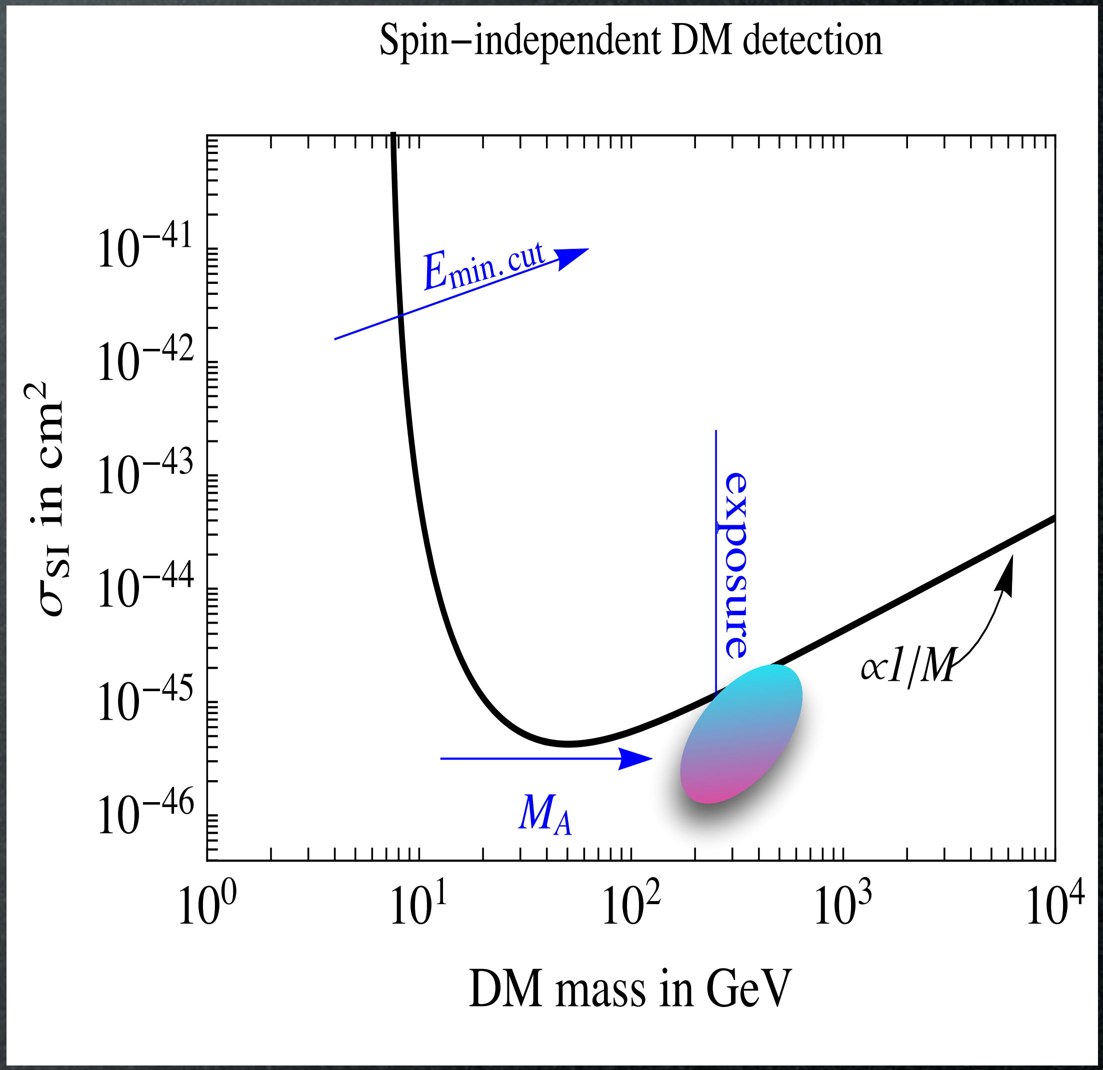

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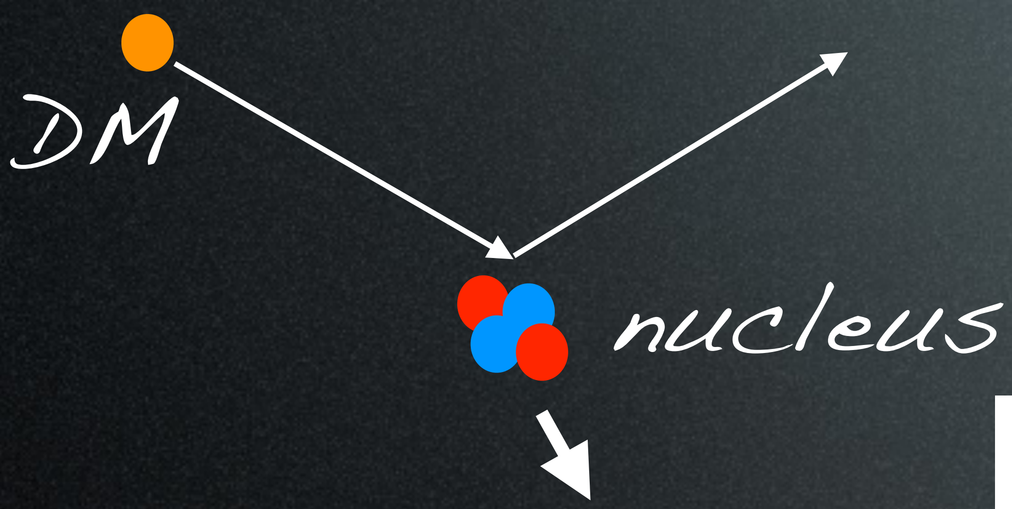
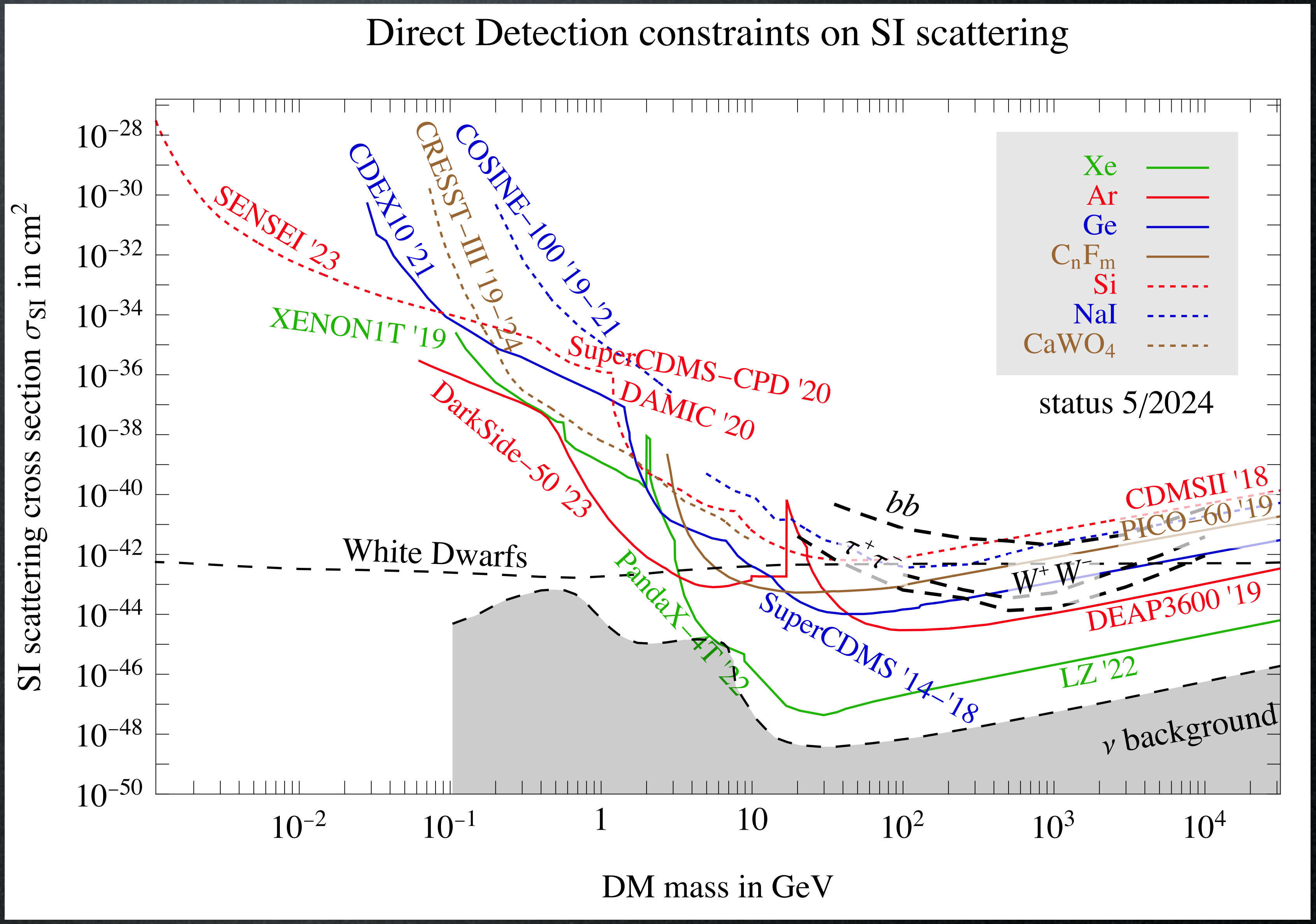
WIMP Direct Detection

SI interactions





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Indirect Detection

DM detection

direct detection

Xenon, LZ, DarkSide, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

- γ from annihil in galactic center or halo and from synchrotron emission
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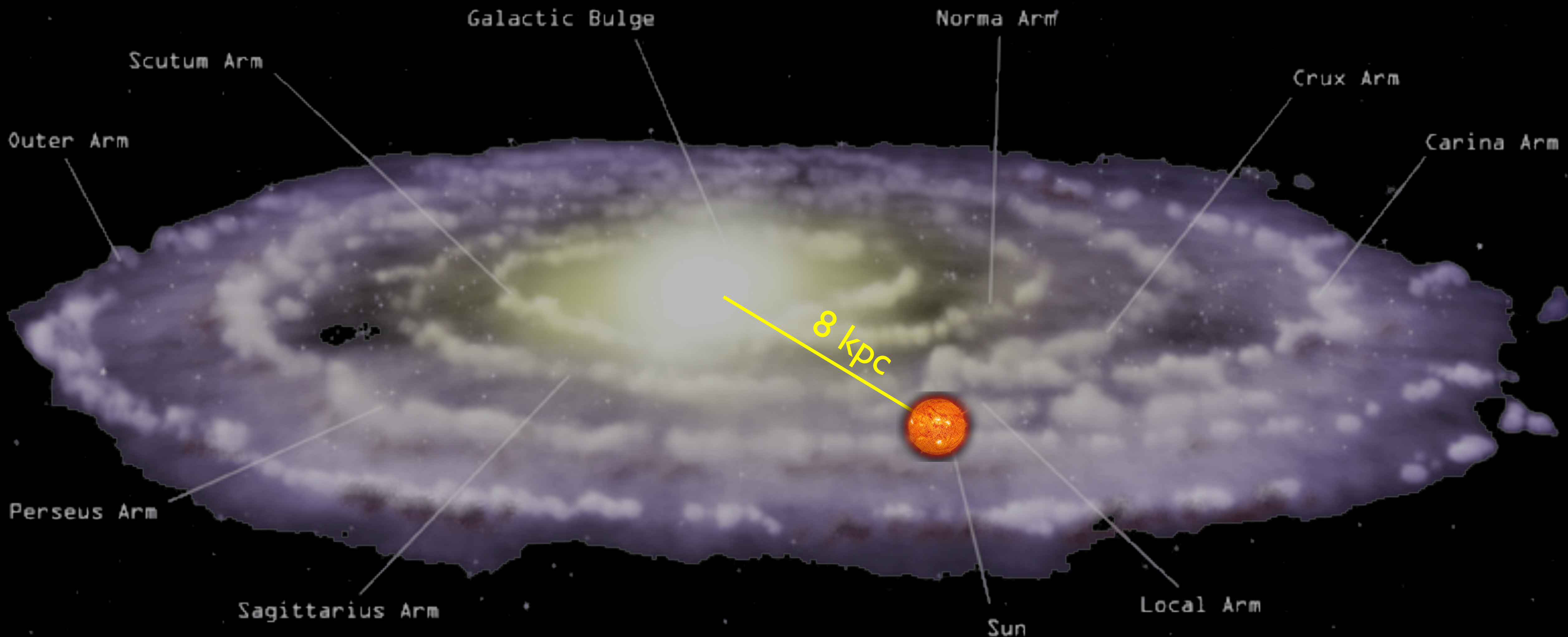
- $\nu, \bar{\nu}$ from annihil in massive bodies
  Icecube, Km3Net

Indirect Detection: basics

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



Indirect Detection: basics

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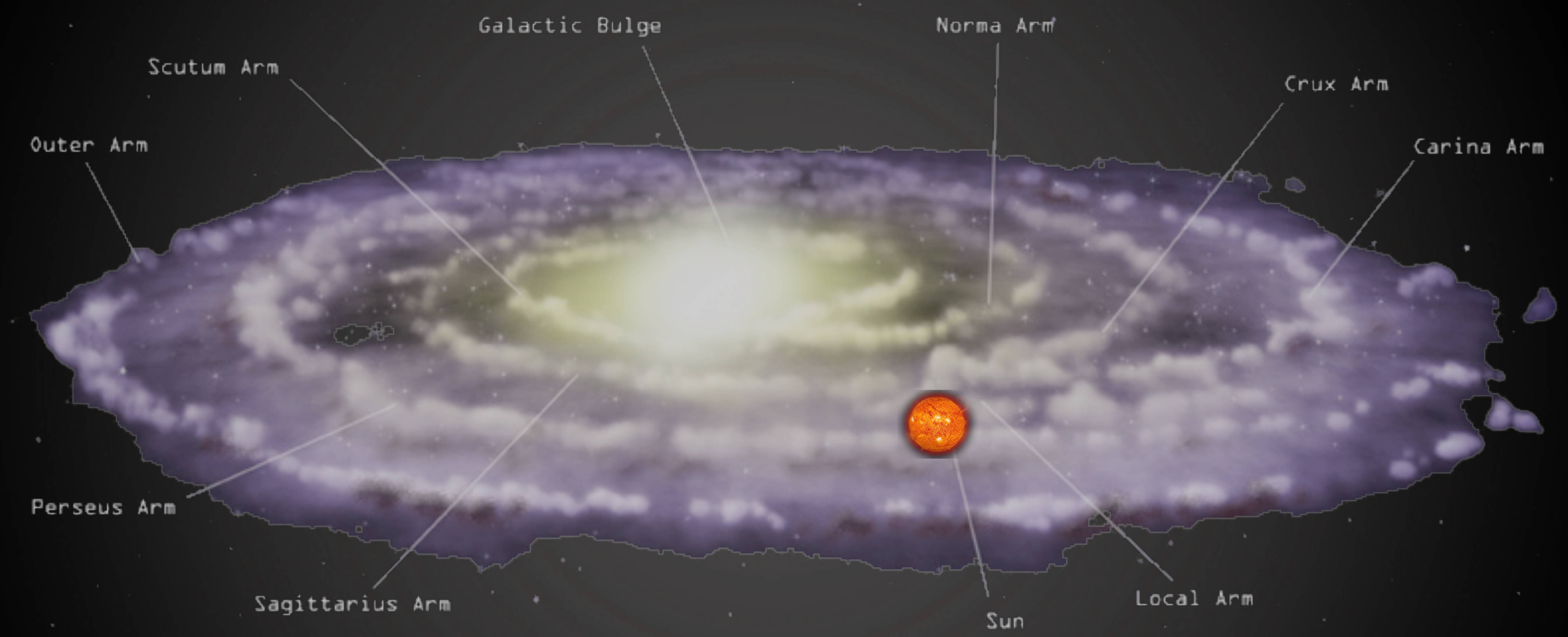

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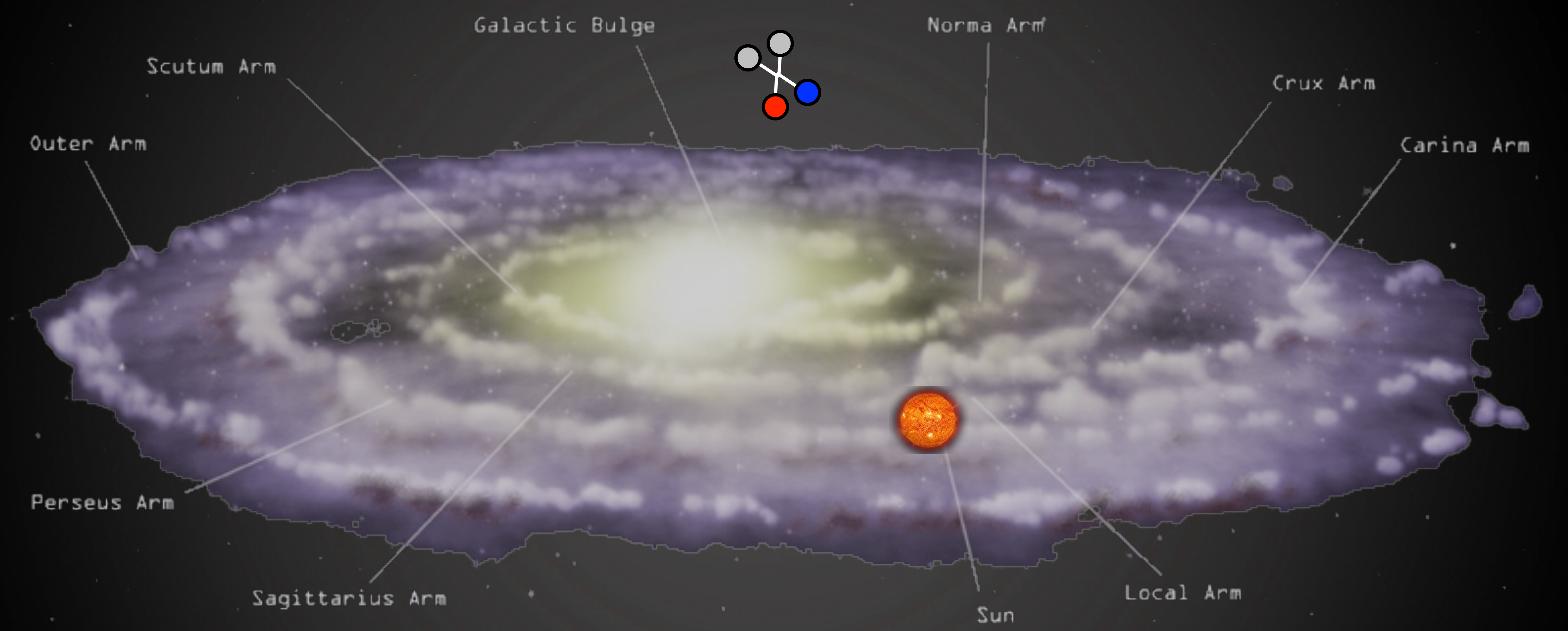

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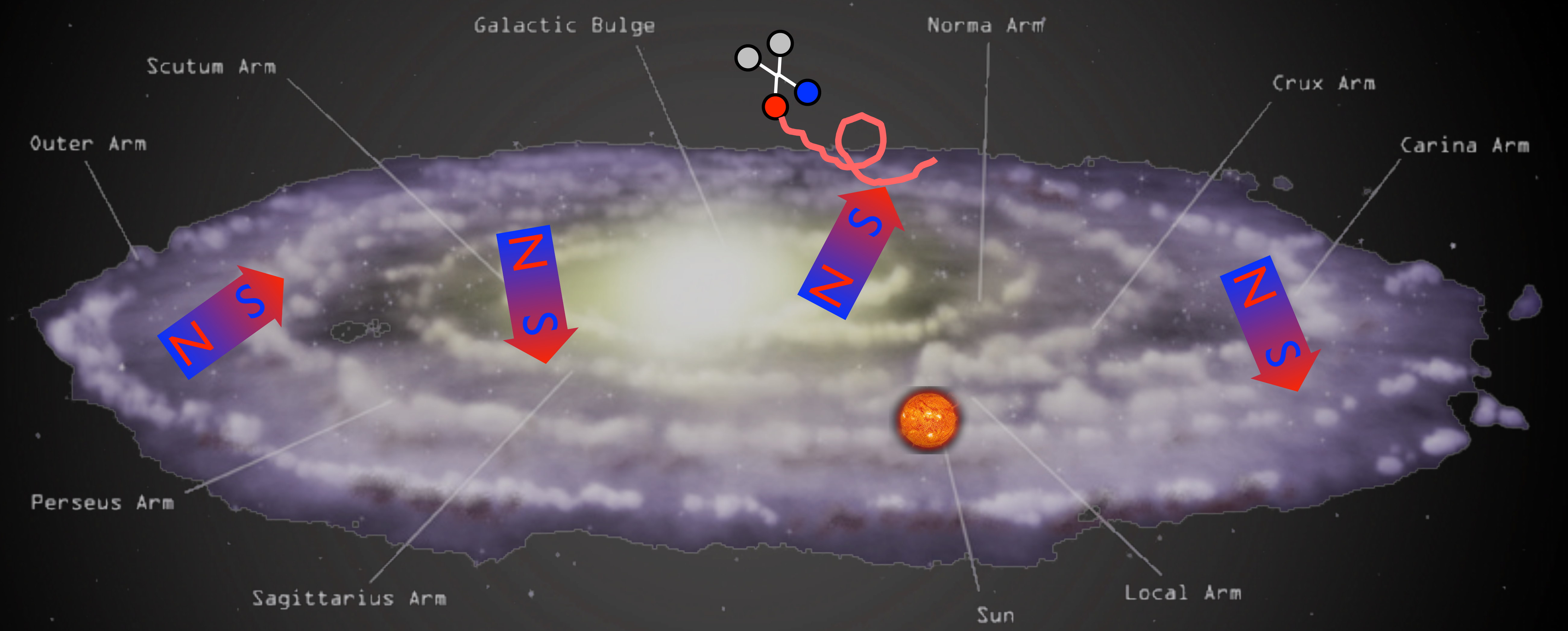
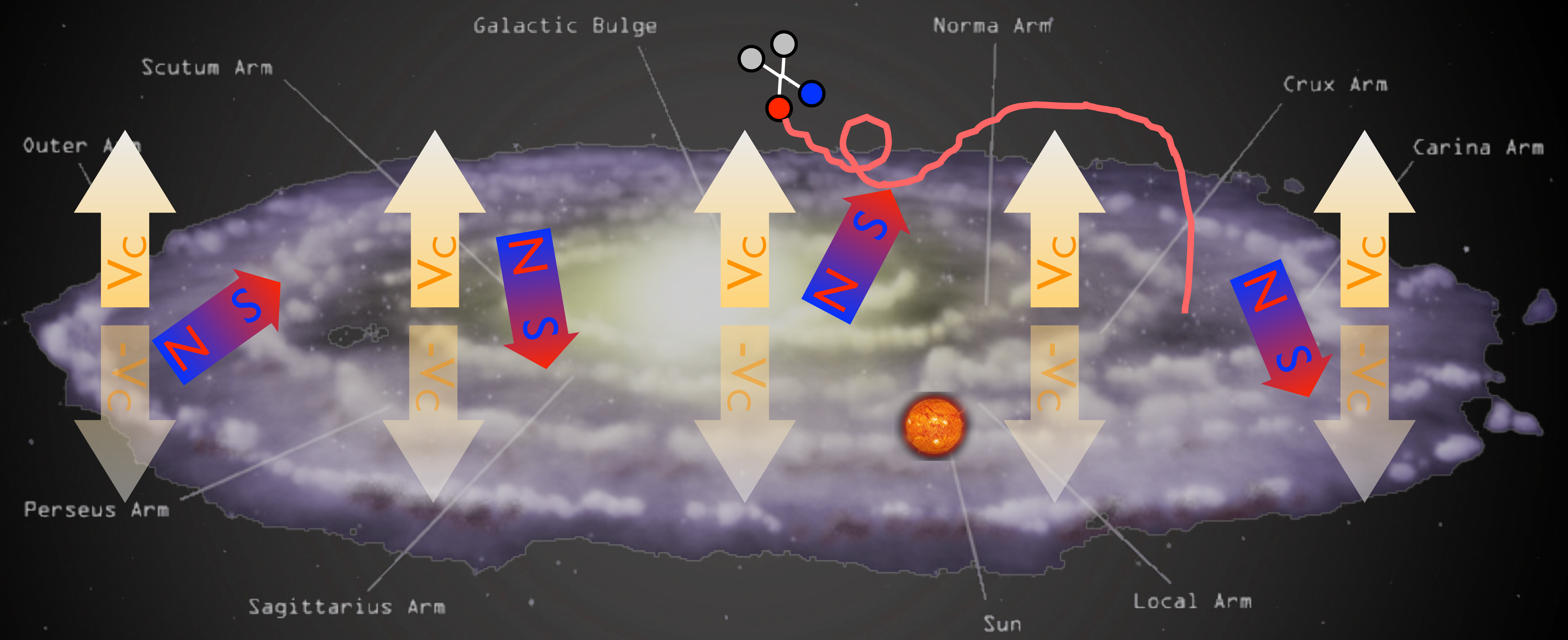
$\bar{p}$ and e^+ from DM annihilations in halo



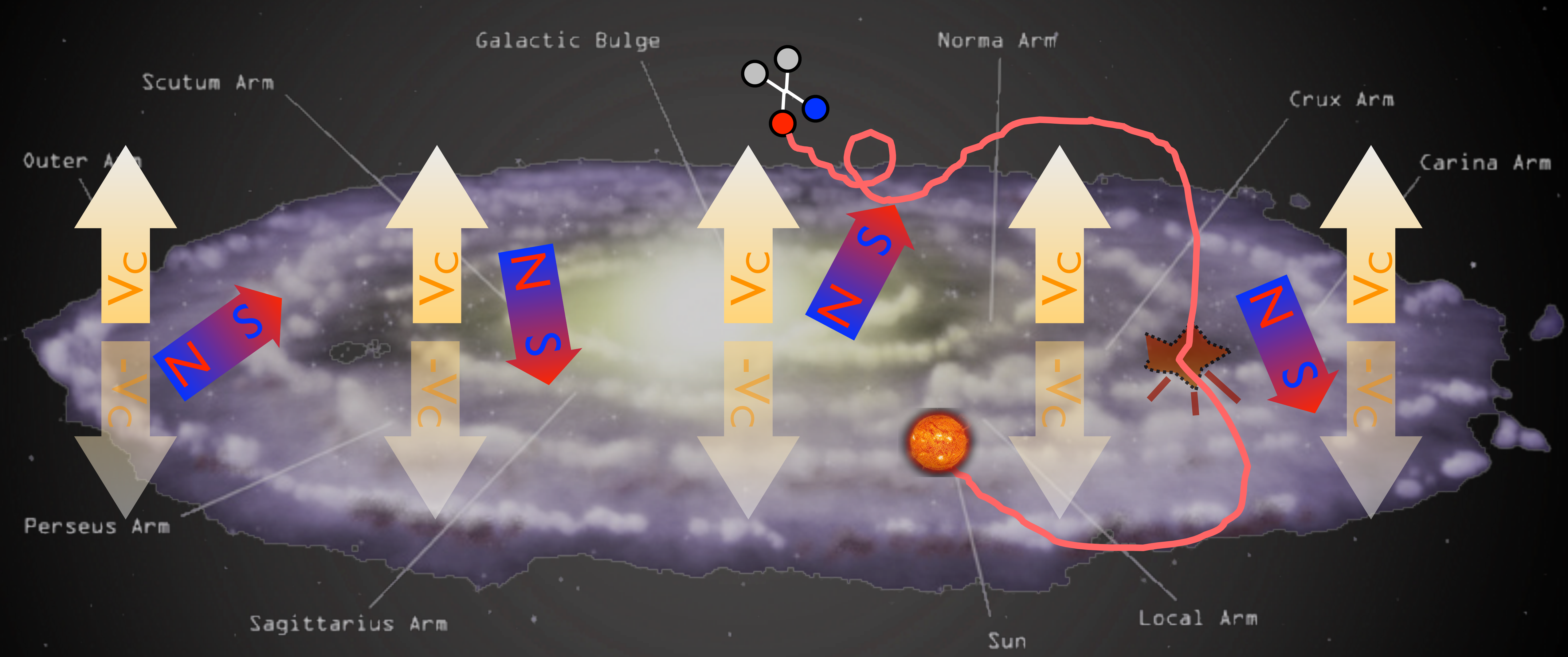
Indirect Detection: basics

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



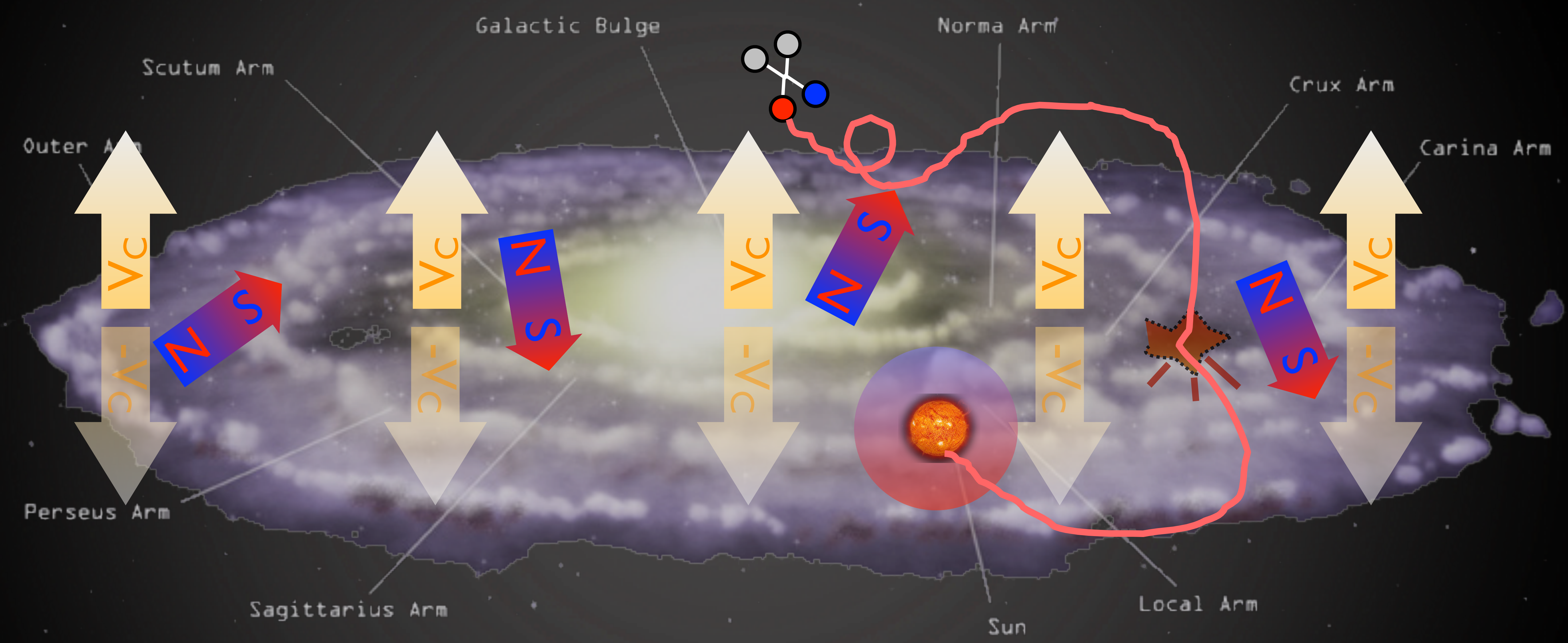
Indirect Detection: basics

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

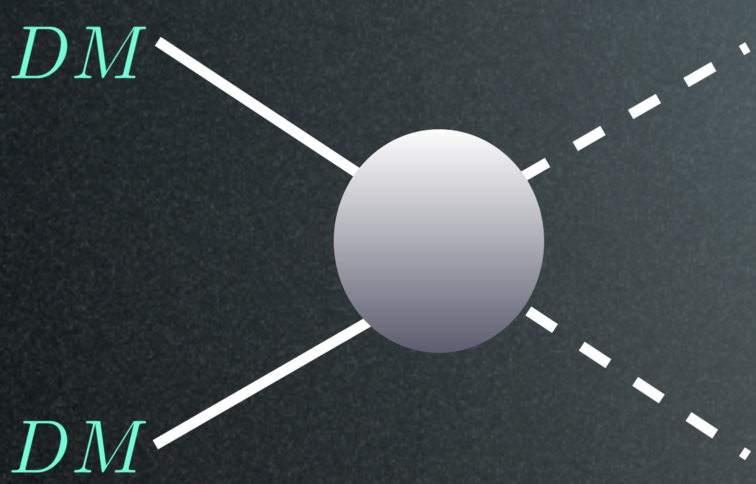


Indirect Detection: basics

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



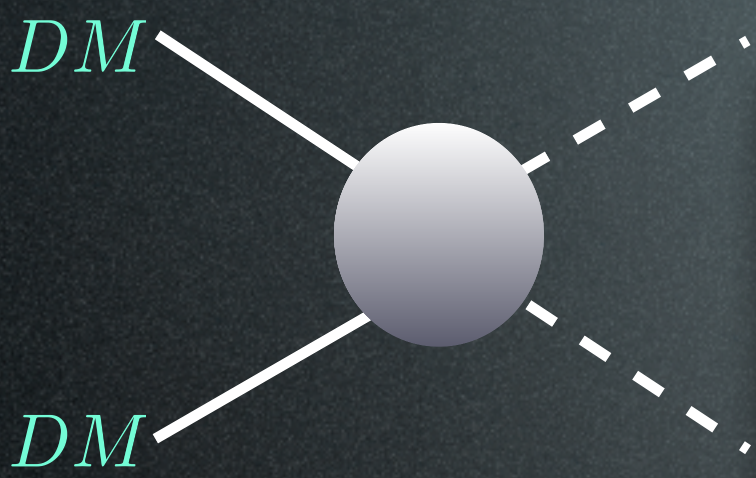
Indirect Detection: basics



$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

Indirect Detection: basics

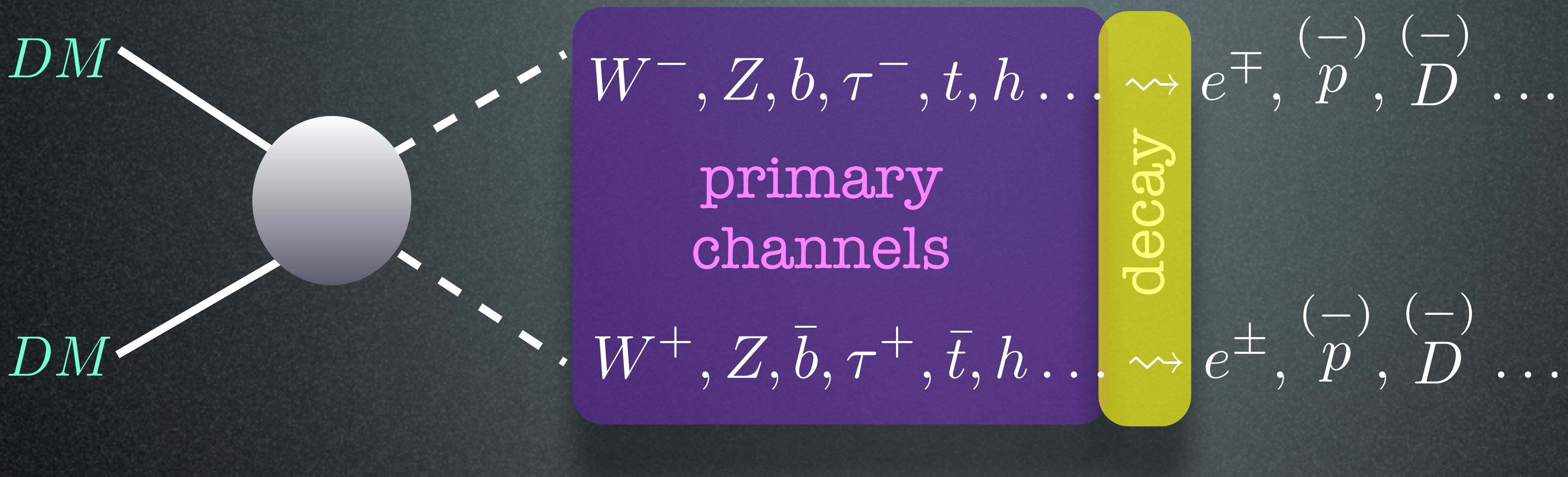


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

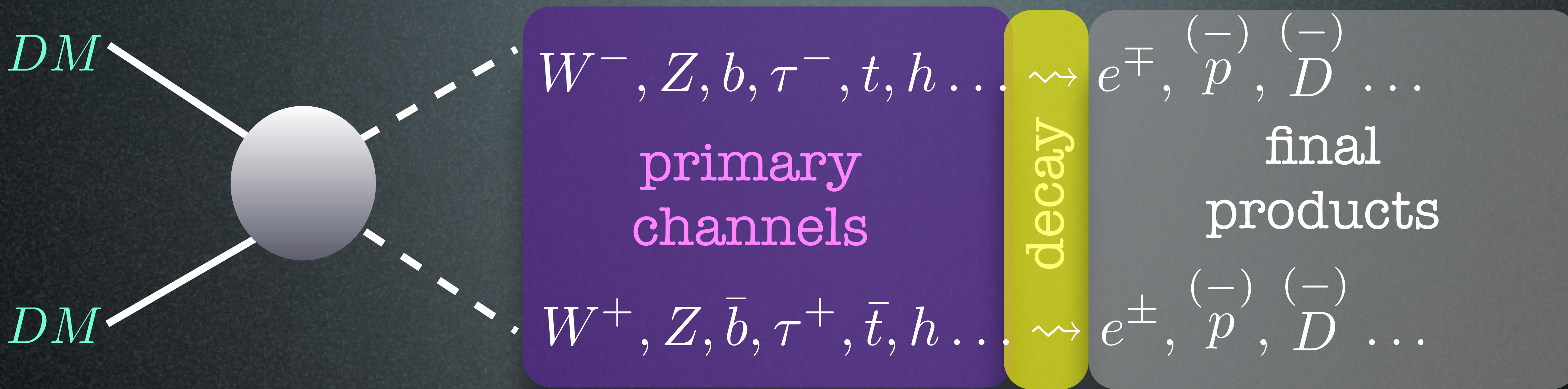
primary channels

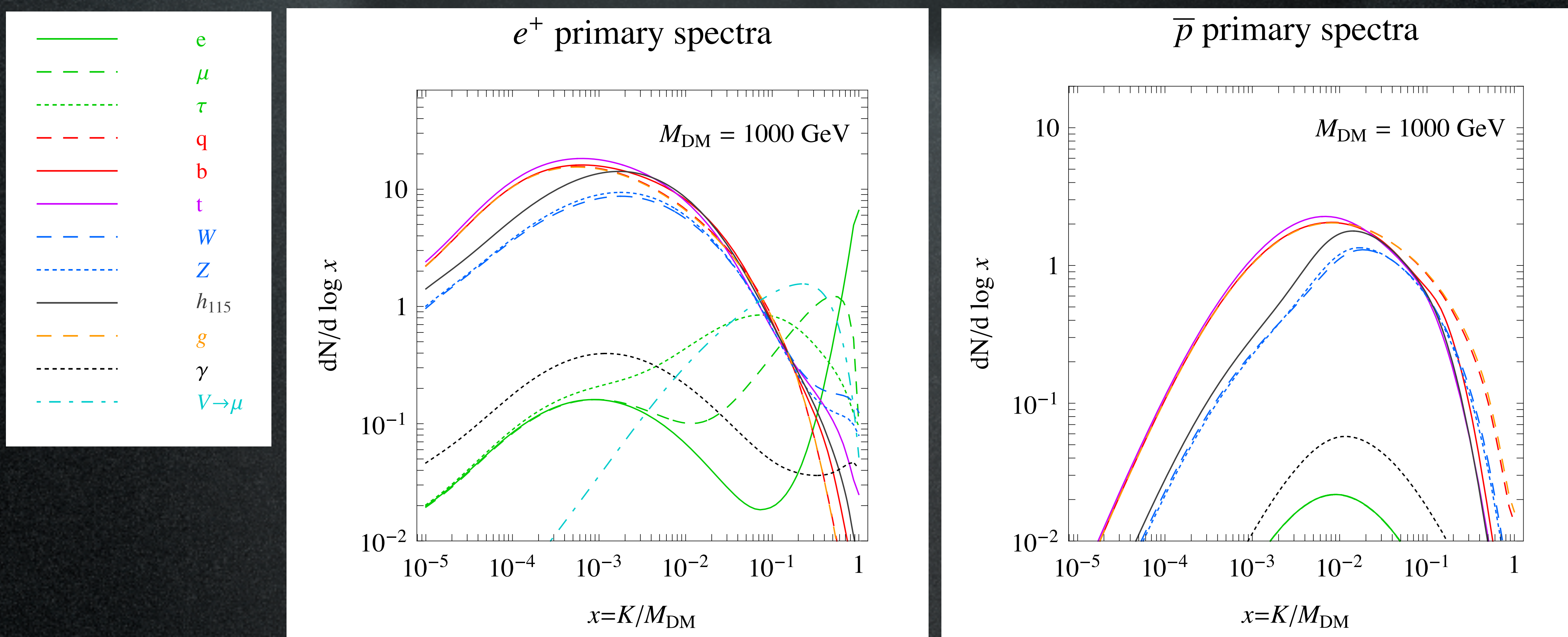
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

Indirect Detection: basics



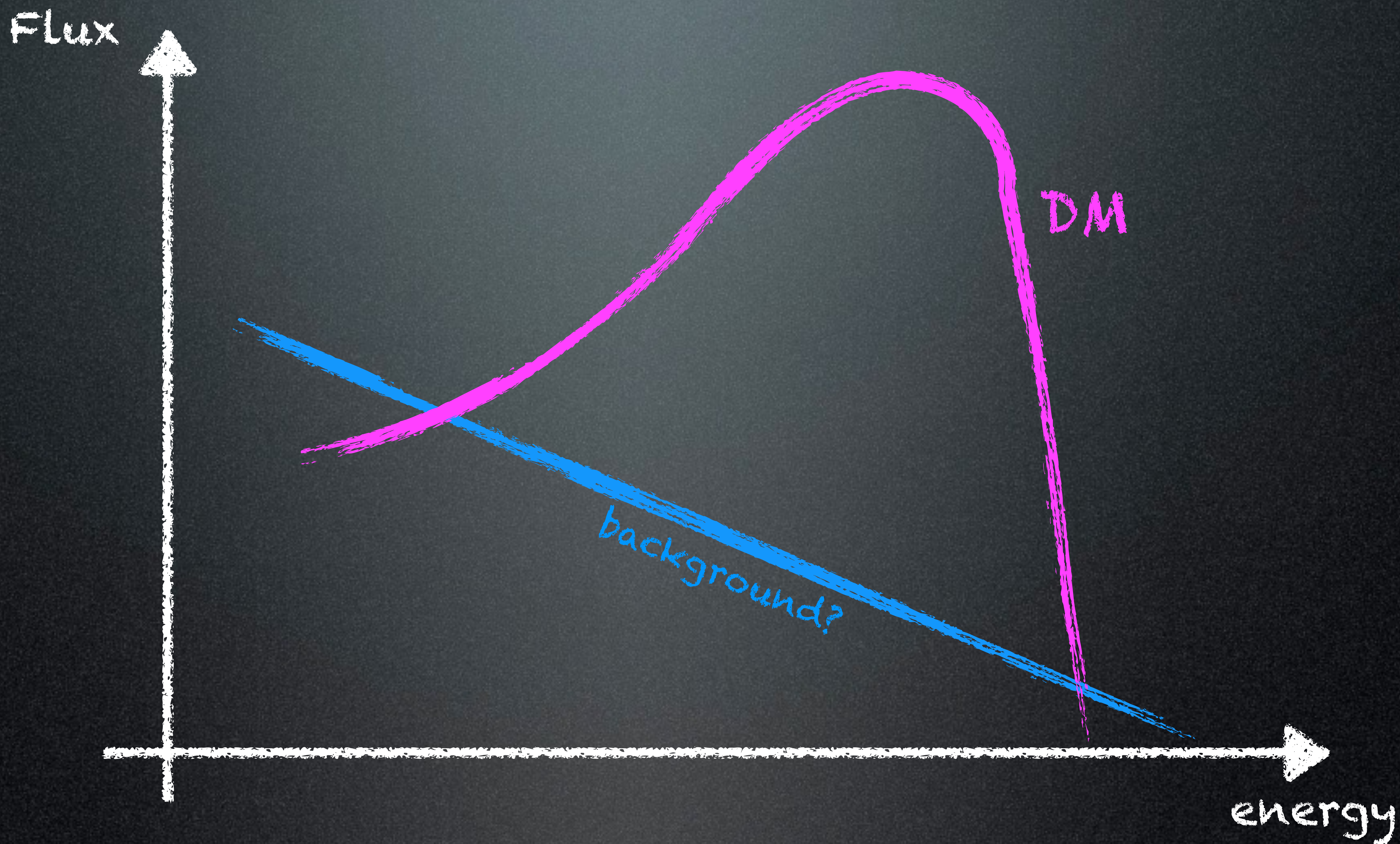
Indirect Detection: basics





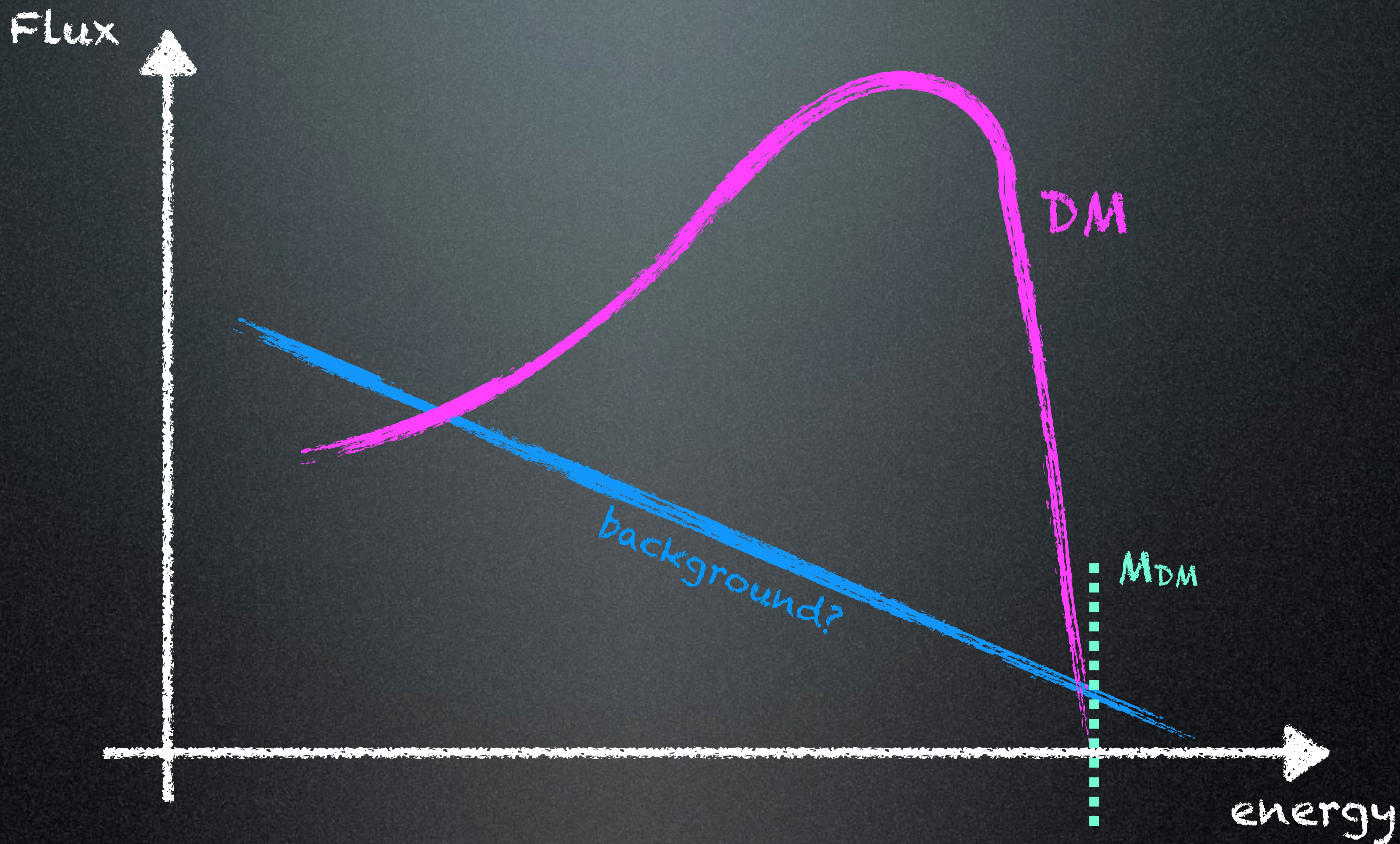
$$\frac{dN_{e^\pm}}{dE} \qquad \frac{dN_{\bar{p}}}{dE}$$

Fluxes at production



So what are the particle physics parameters?

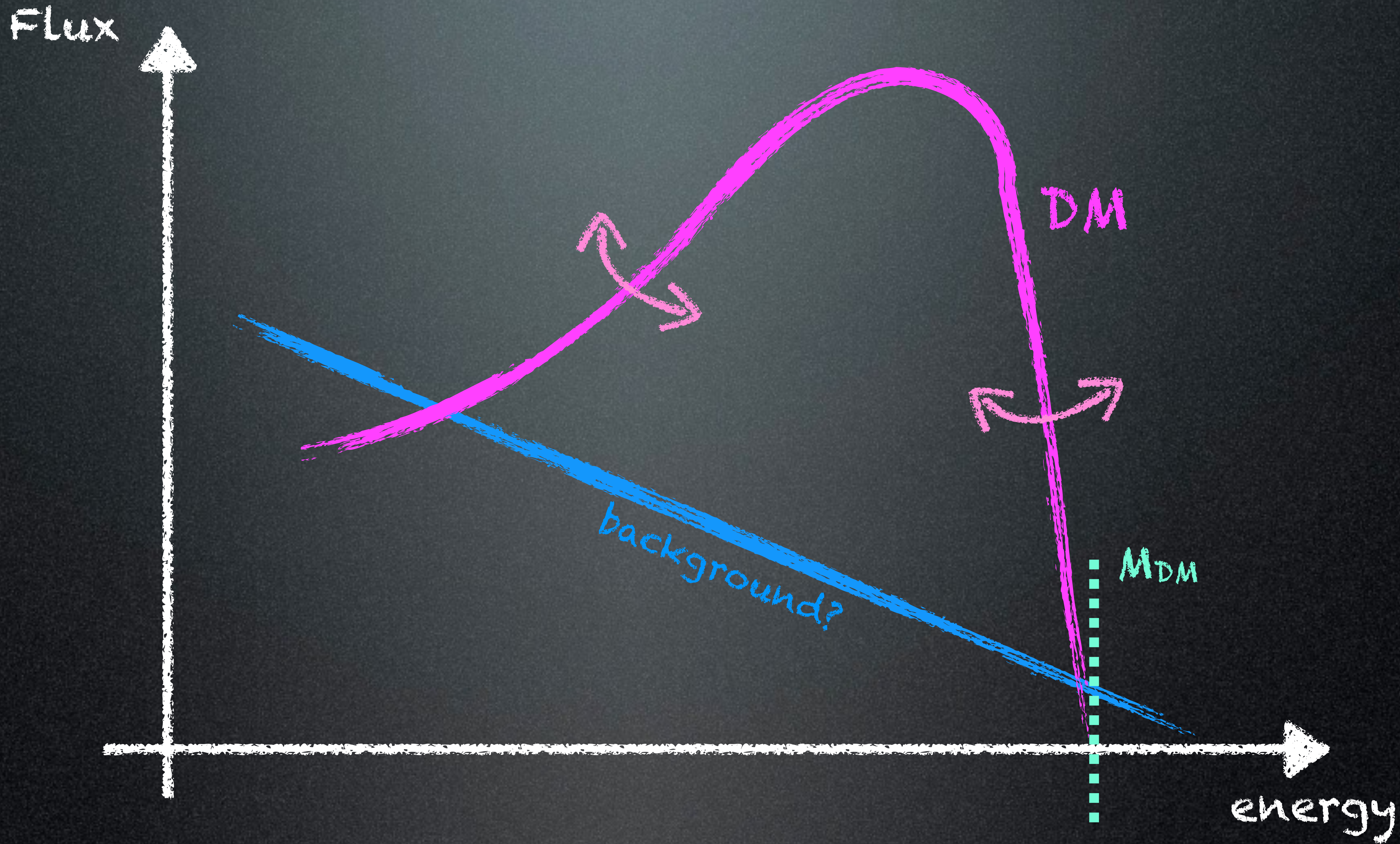
Fluxes at production



So what are the particle physics parameters?

1. Dark Matter mass

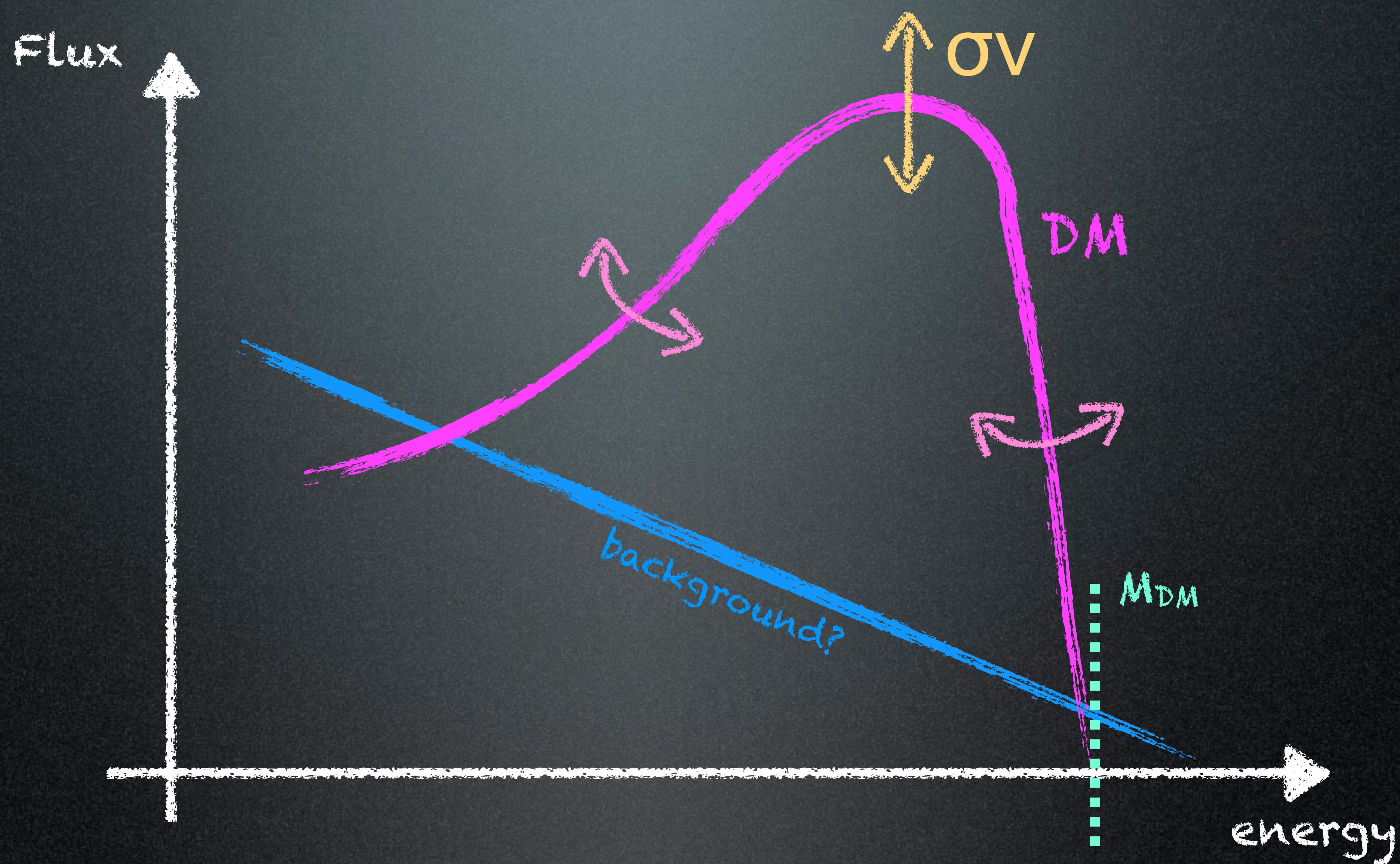
Fluxes at production



So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)

Fluxes at production

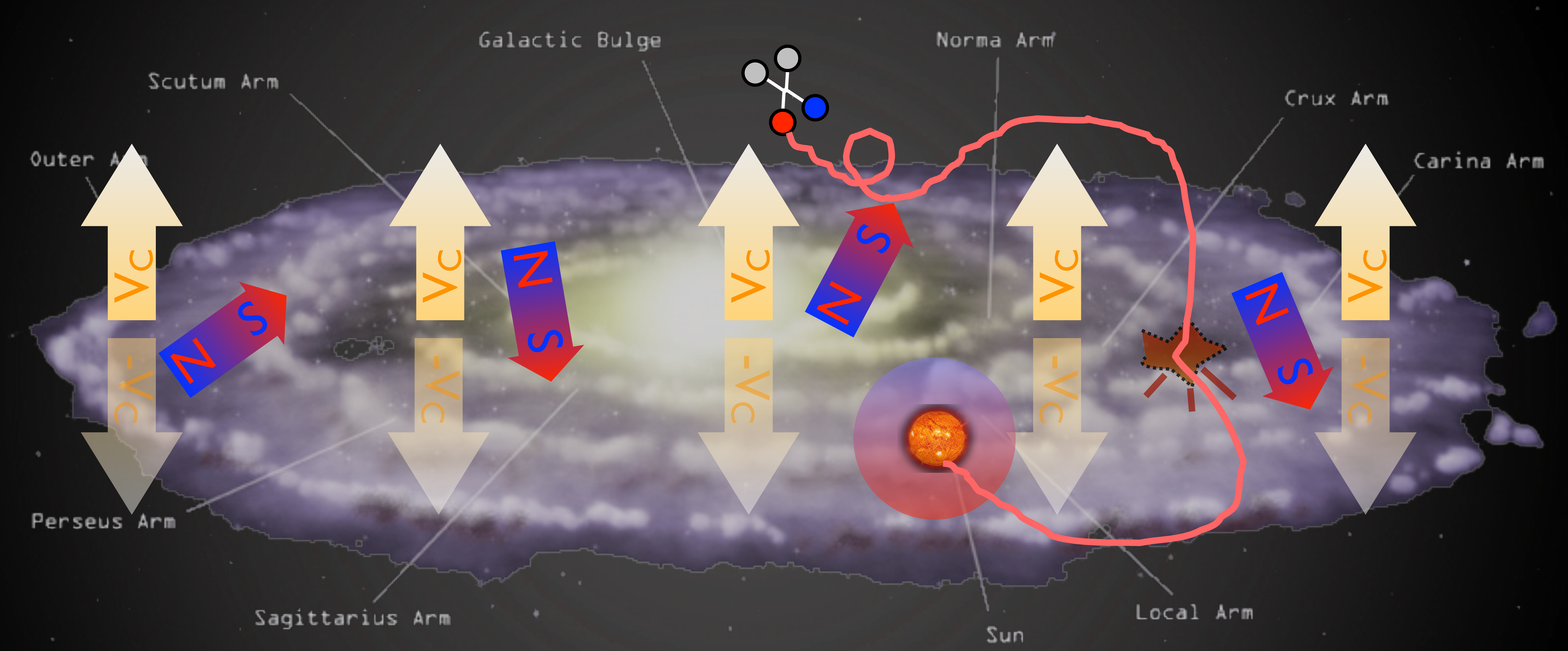


So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

Indirect Detection: basics

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

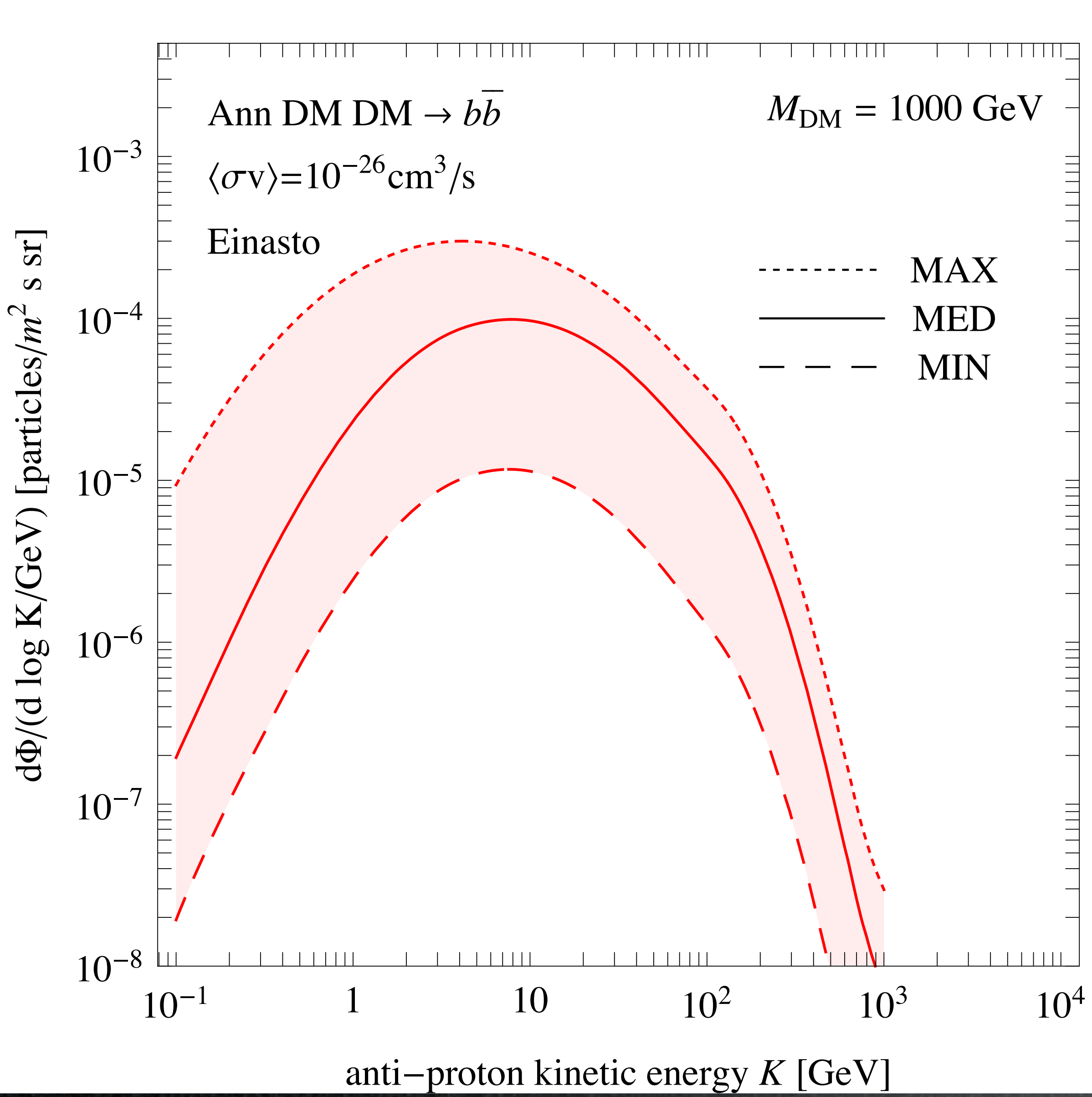


1. diffusion (on magnetic field granularities)
2. energy losses (ICS, bremsstrahlung, synchrotron)
3. convection
4. spallations
5. solar influence

Propagated fluxes

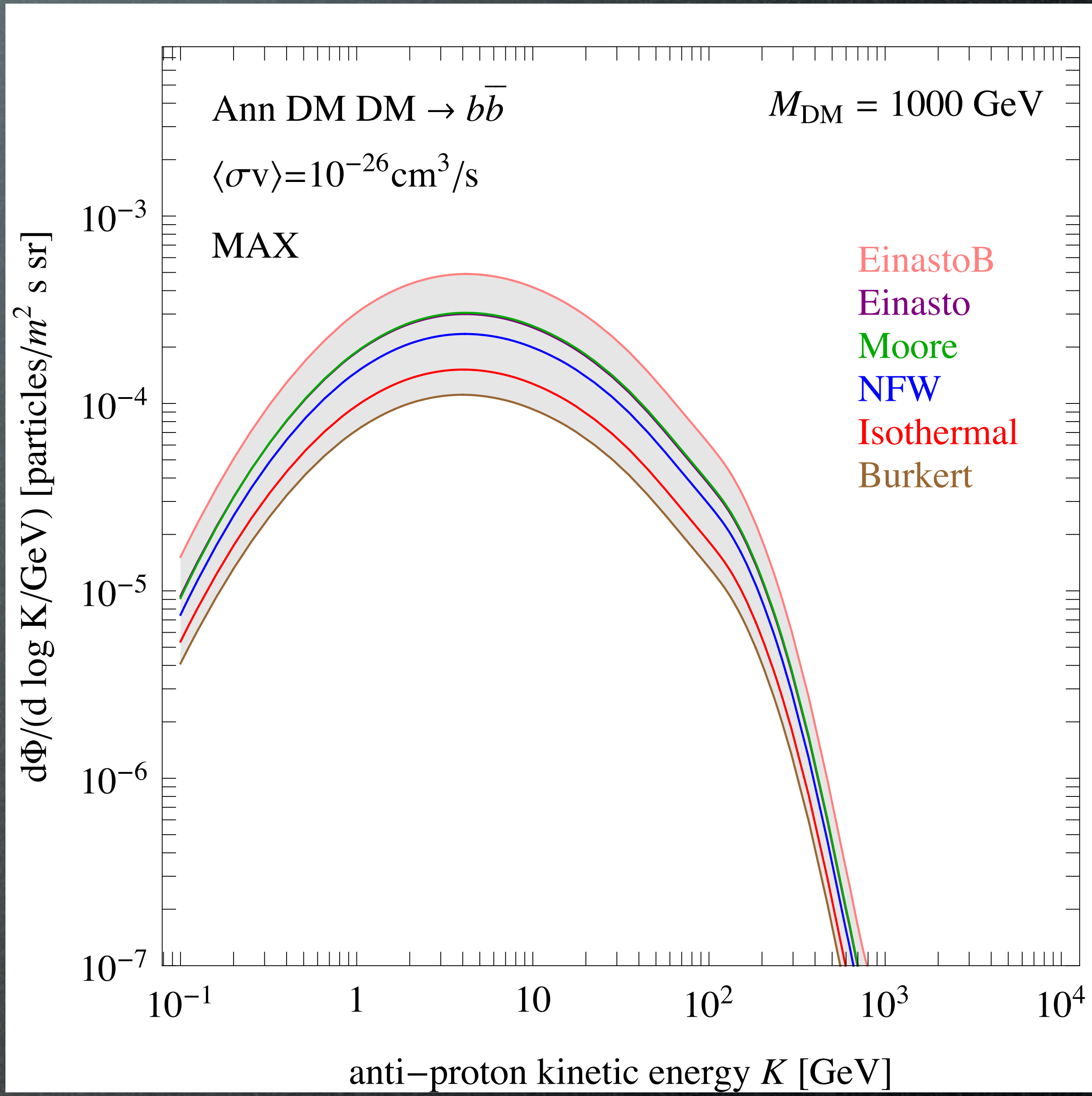
Antiprotons

Varying prop parameters



Almost 2 orders of magnitude

Varying halo profile



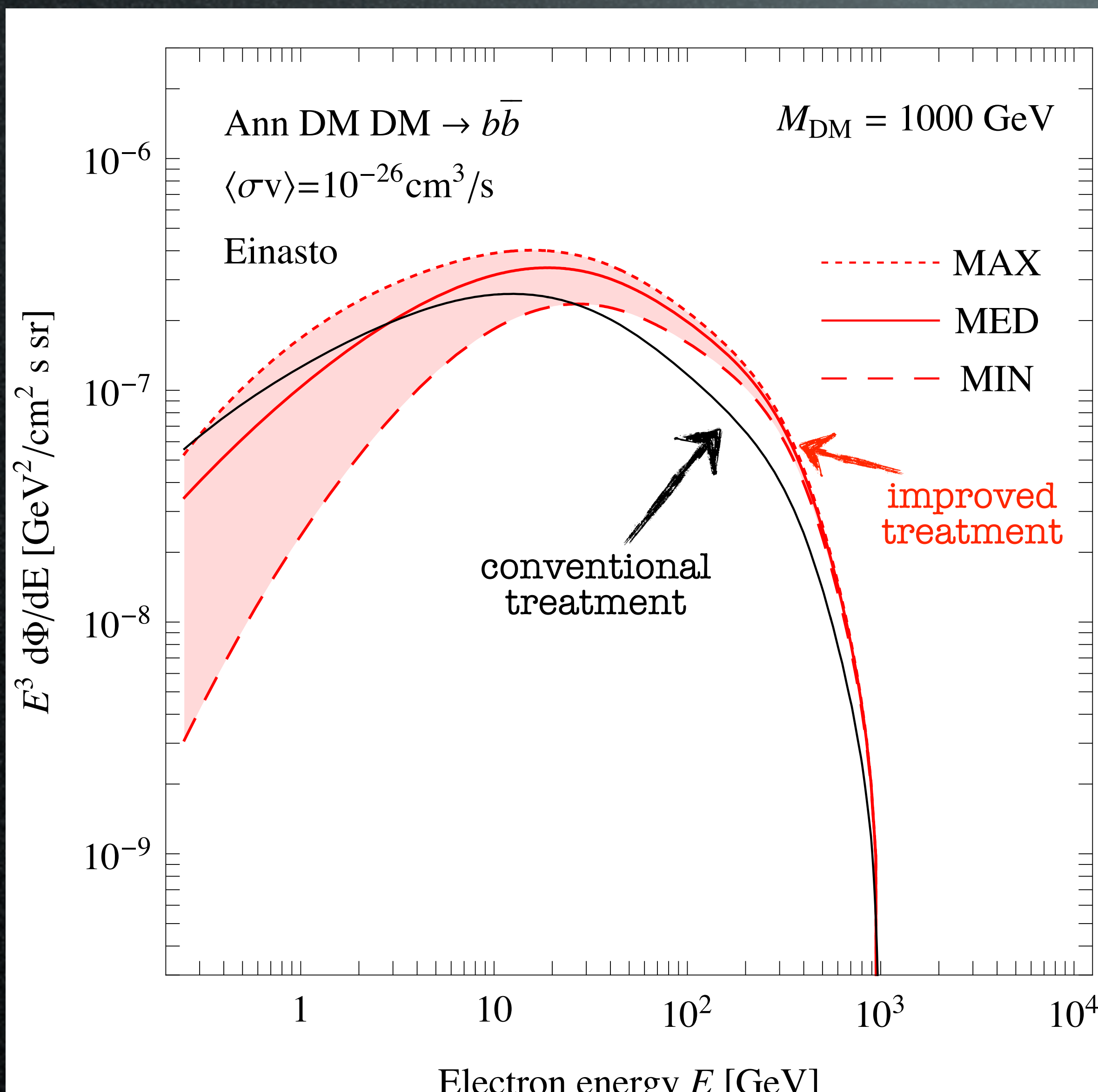
Almost 1 order of magnitude

Bottom line: Antiprotons are quite affected by propagation, but spectral shape somewhat preserved

Propagated fluxes

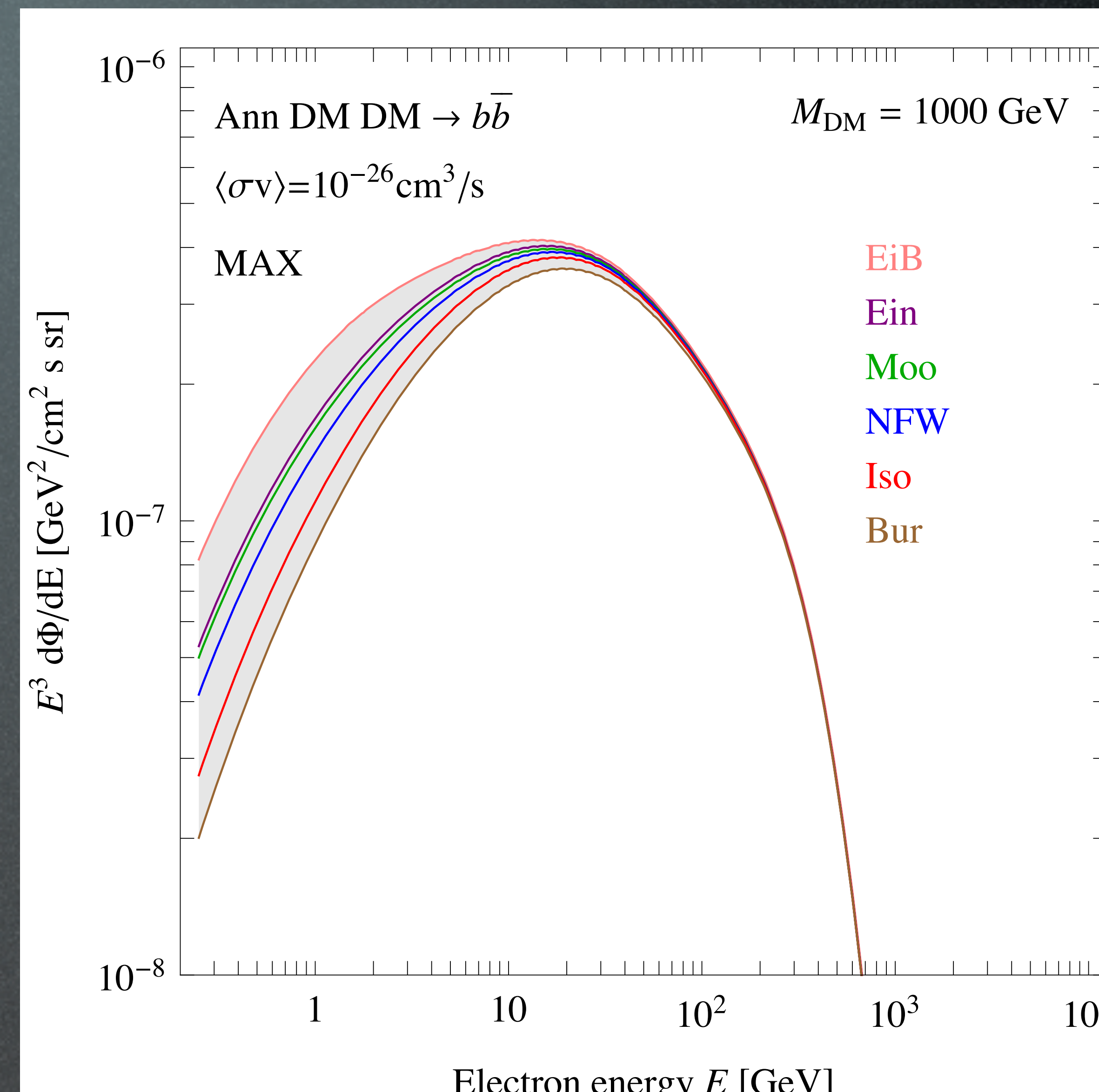
Positrons

Varying prop parameters



From factor 10 to no effect

Varying halo profile



From factor 10 to no effect

Bottom line: Positrons are affected by propagation, mainly at low energy

DM detection

direct detection

Xenon, LZ, DarkSide, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, X-ray satellites, radio telescopes

e^+ from annihil in galactic halo or center

AMS, Fermi

$\bar{p}$ from annihil in galactic halo or center

$\bar{d}$ from annihil in galactic halo or center

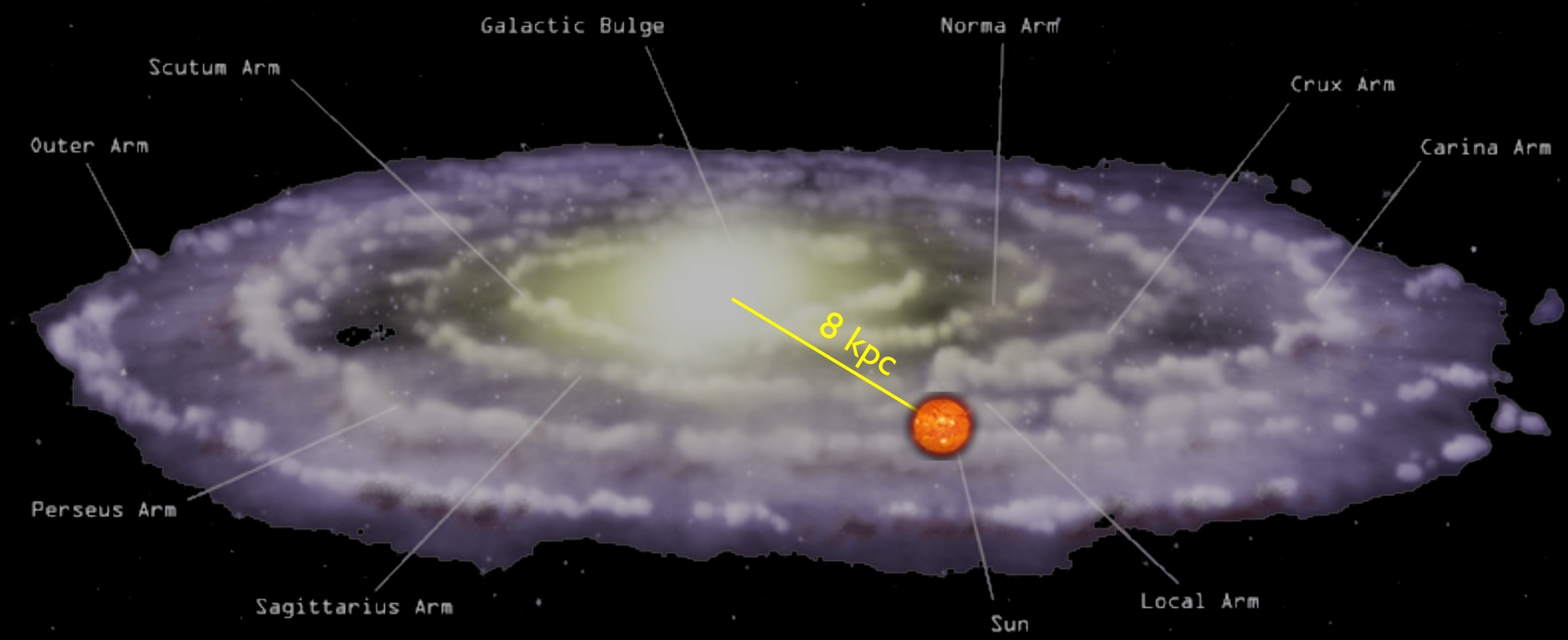
GAPS

$\nu, \bar{\nu}$ from annihil in massive bodies

Icecube, Km3Net

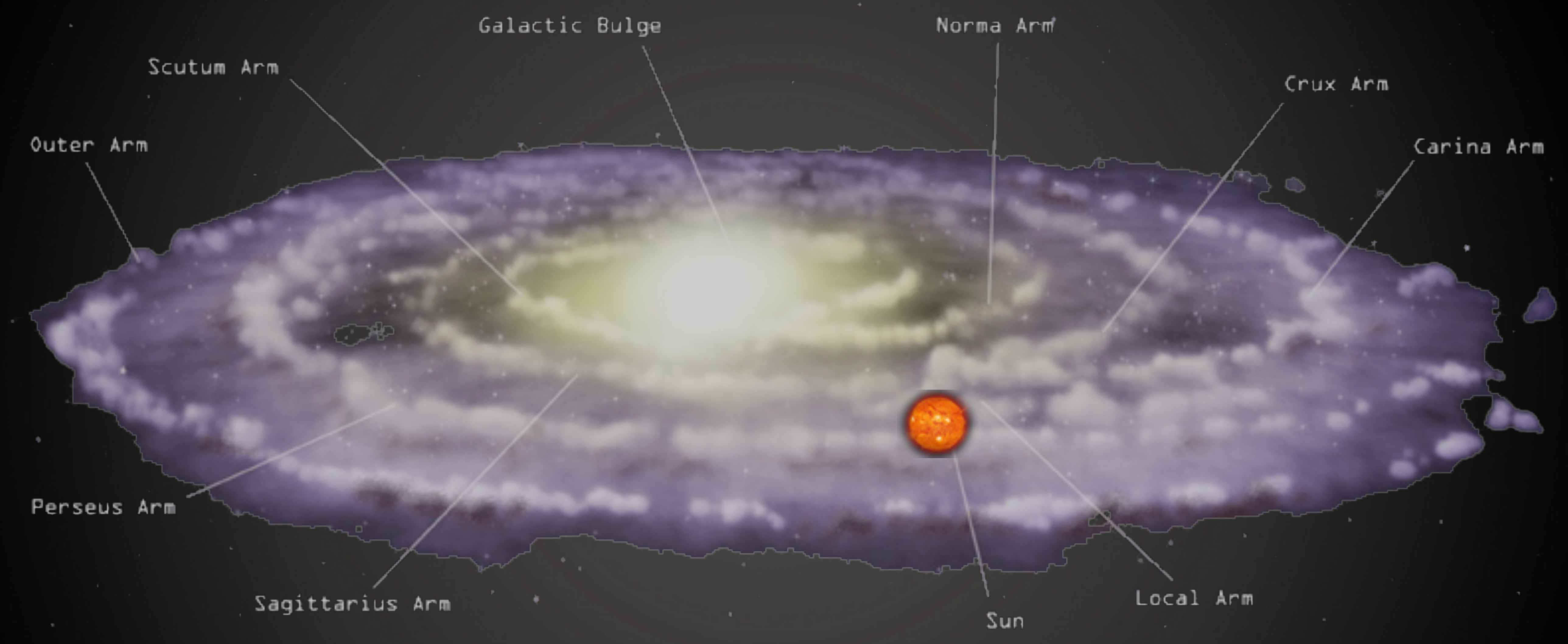
Basic picture

γ from DM annihilations in galactic center



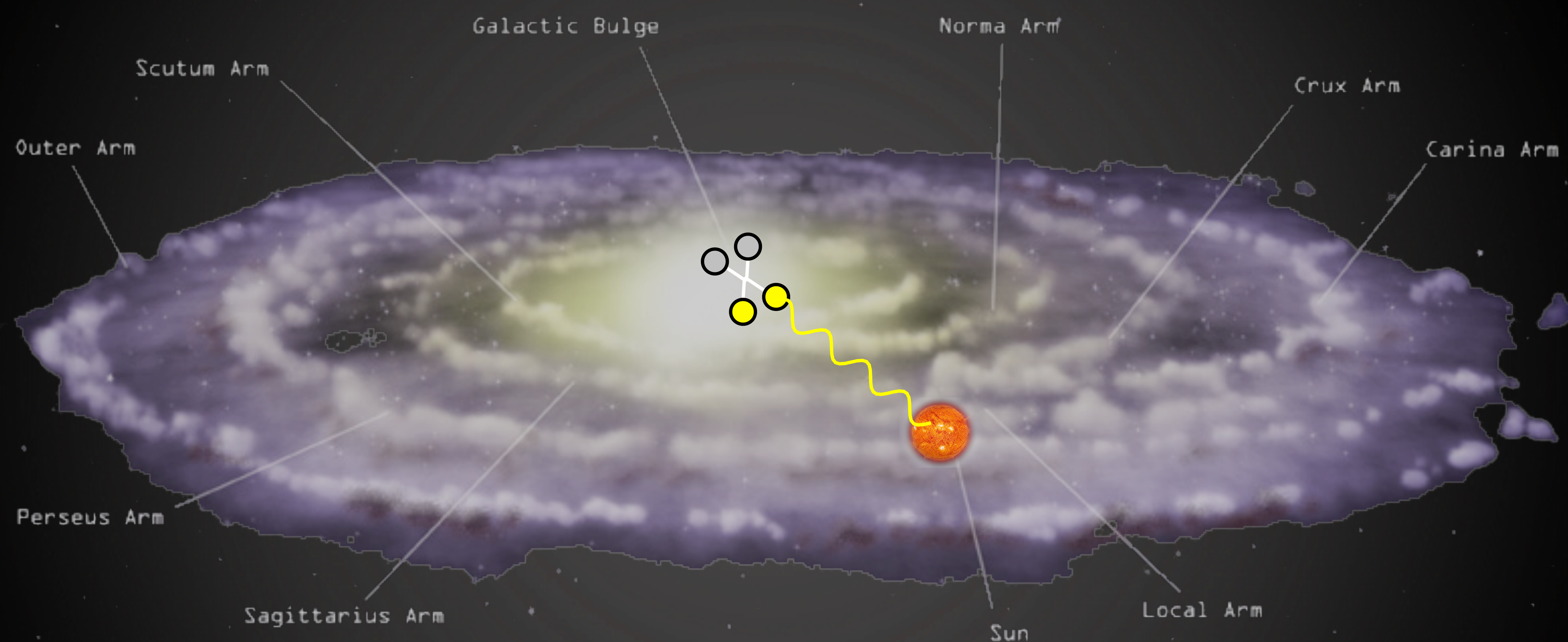
Basic picture

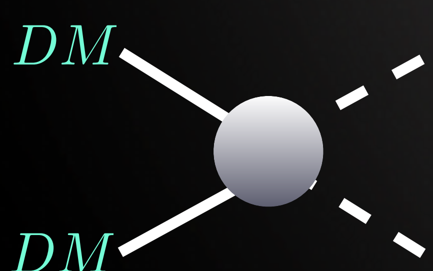
γ from DM annihilations in galactic center



Basic picture

γ from DM annihilations in galactic center



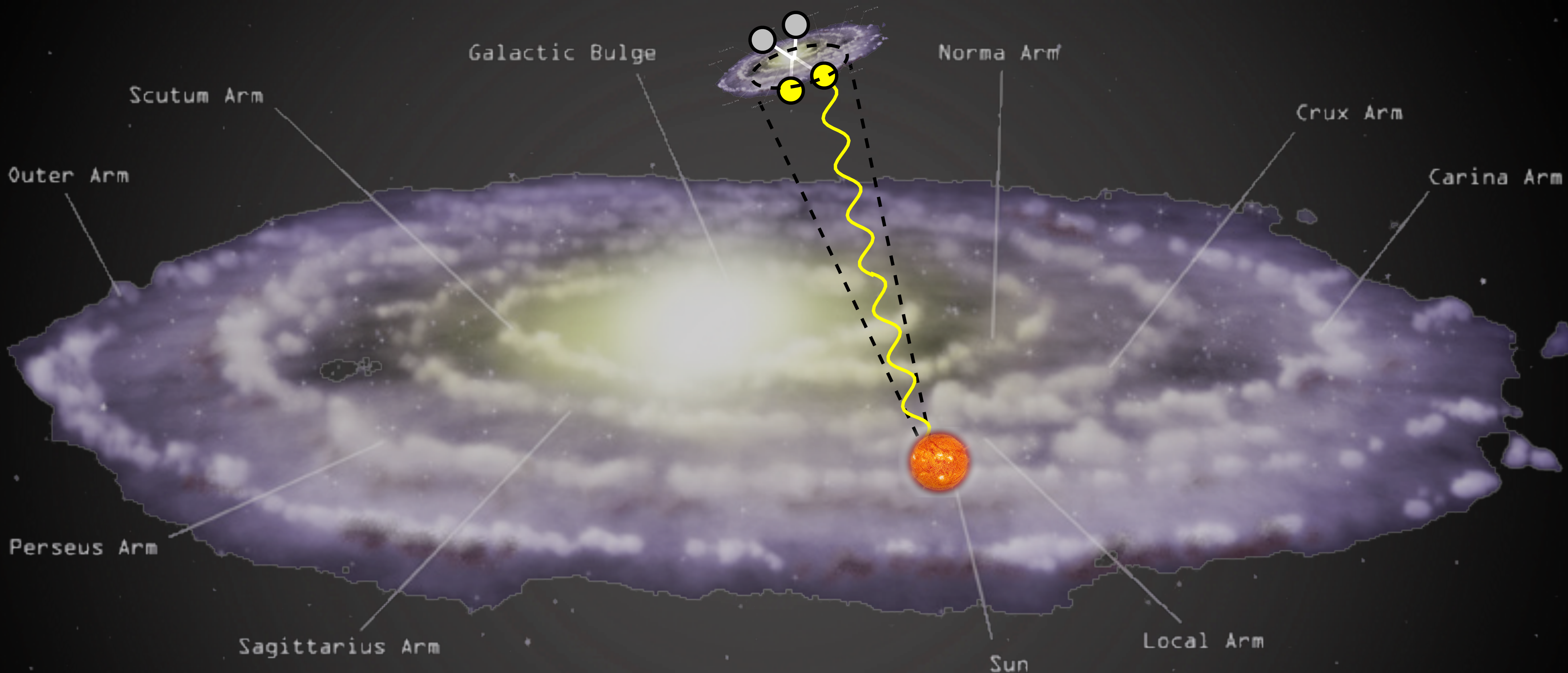


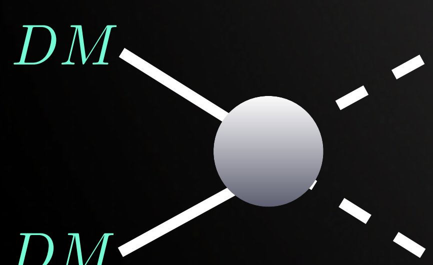
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

Basic picture: targets

γ from DM annihilations in dwarf galaxies



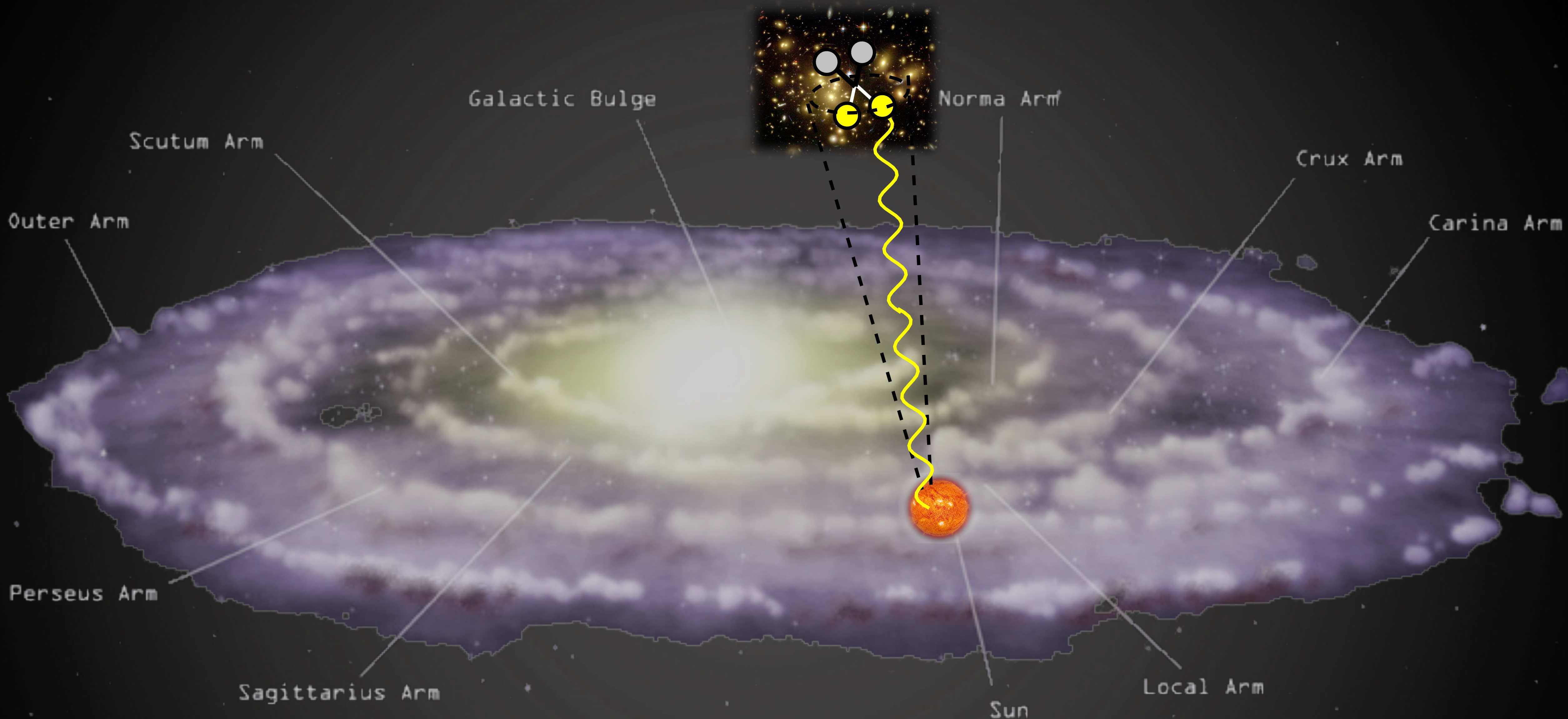


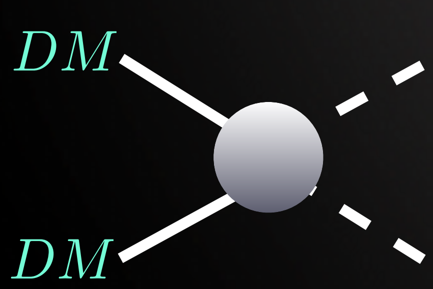
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

Basic picture: targets

γ from DM annihilations in galaxy clusters

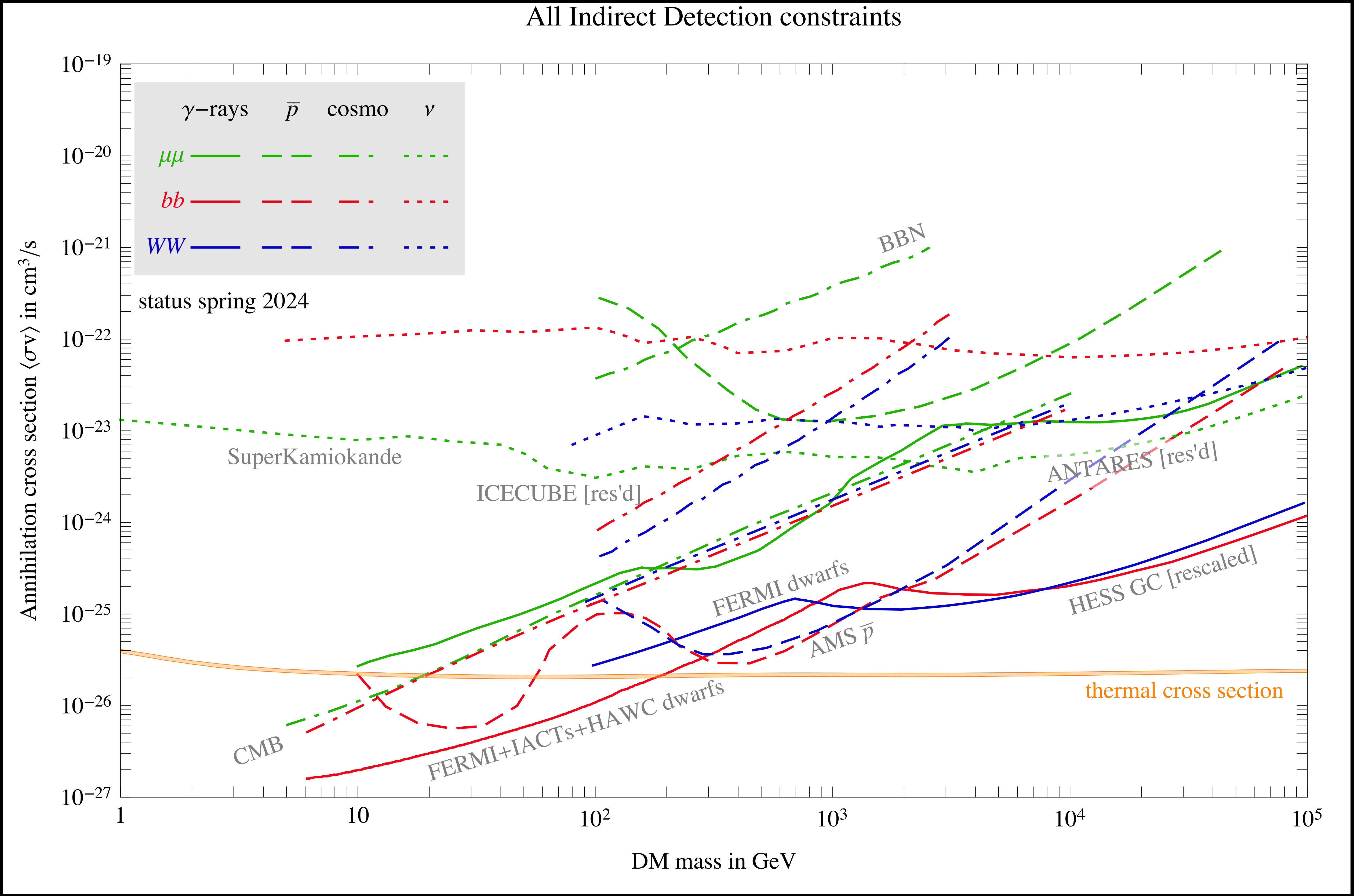




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

WIMP Indirect Detection



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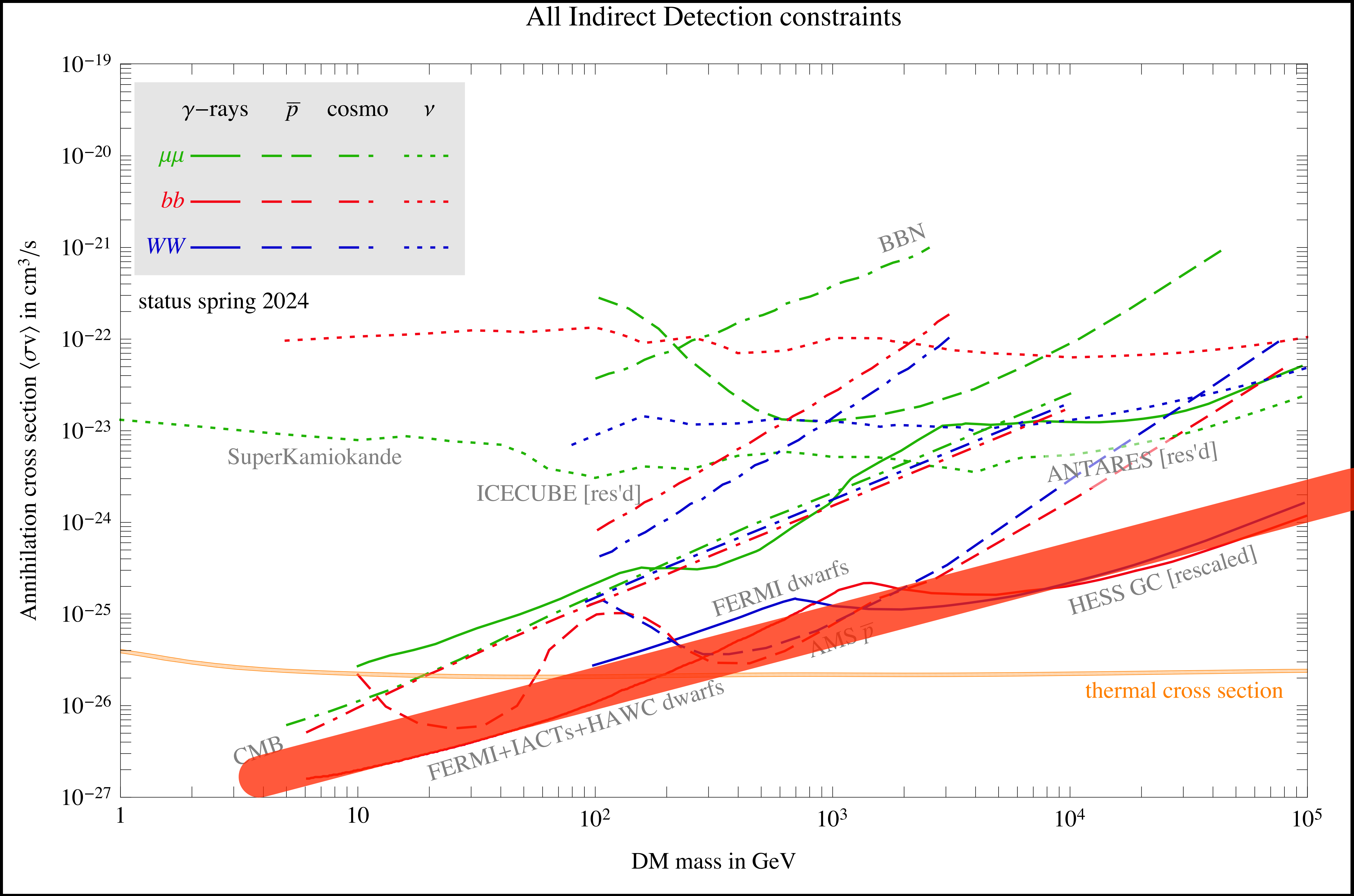
WIMP Indirect Detection



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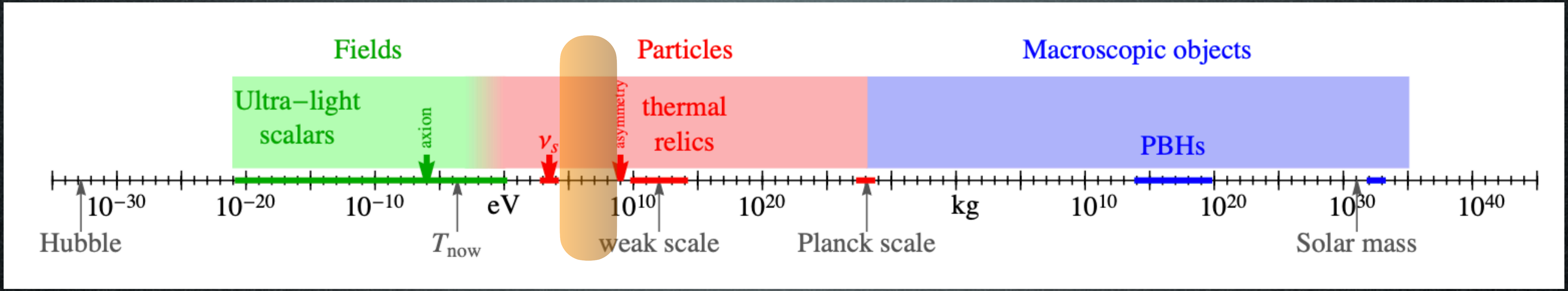
Candidates

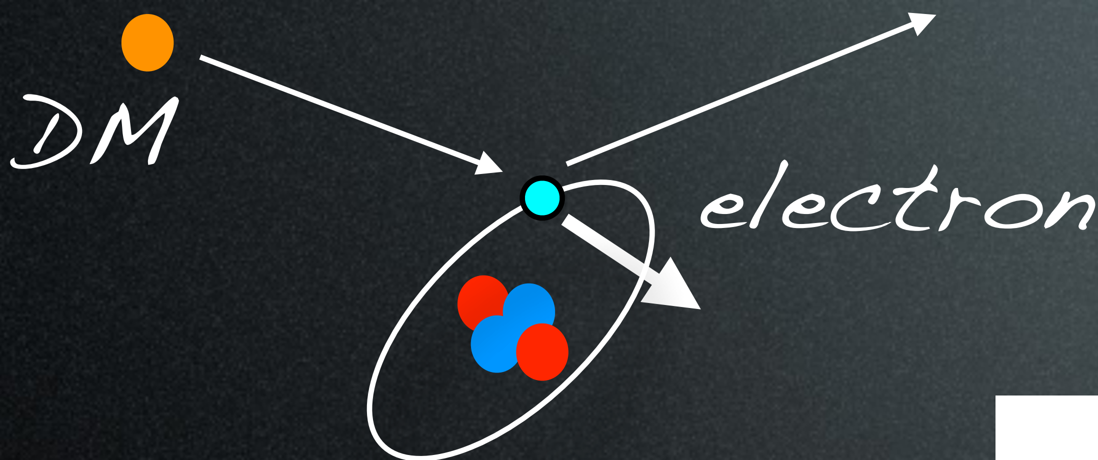
A matter of perspective: plausible mass ranges

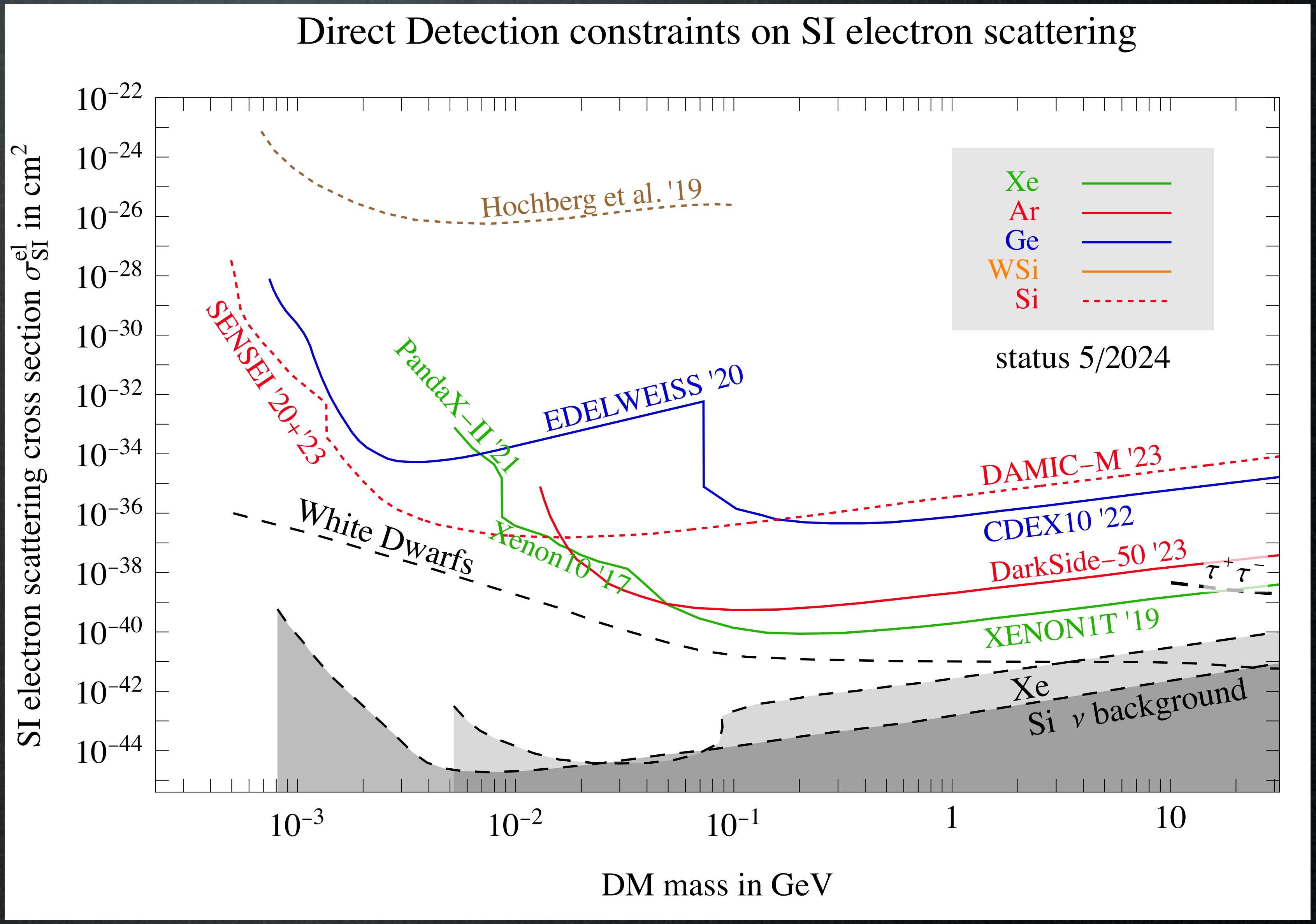


Sub-GeV DM

Light DM Direct Detection

electron recoil interactions





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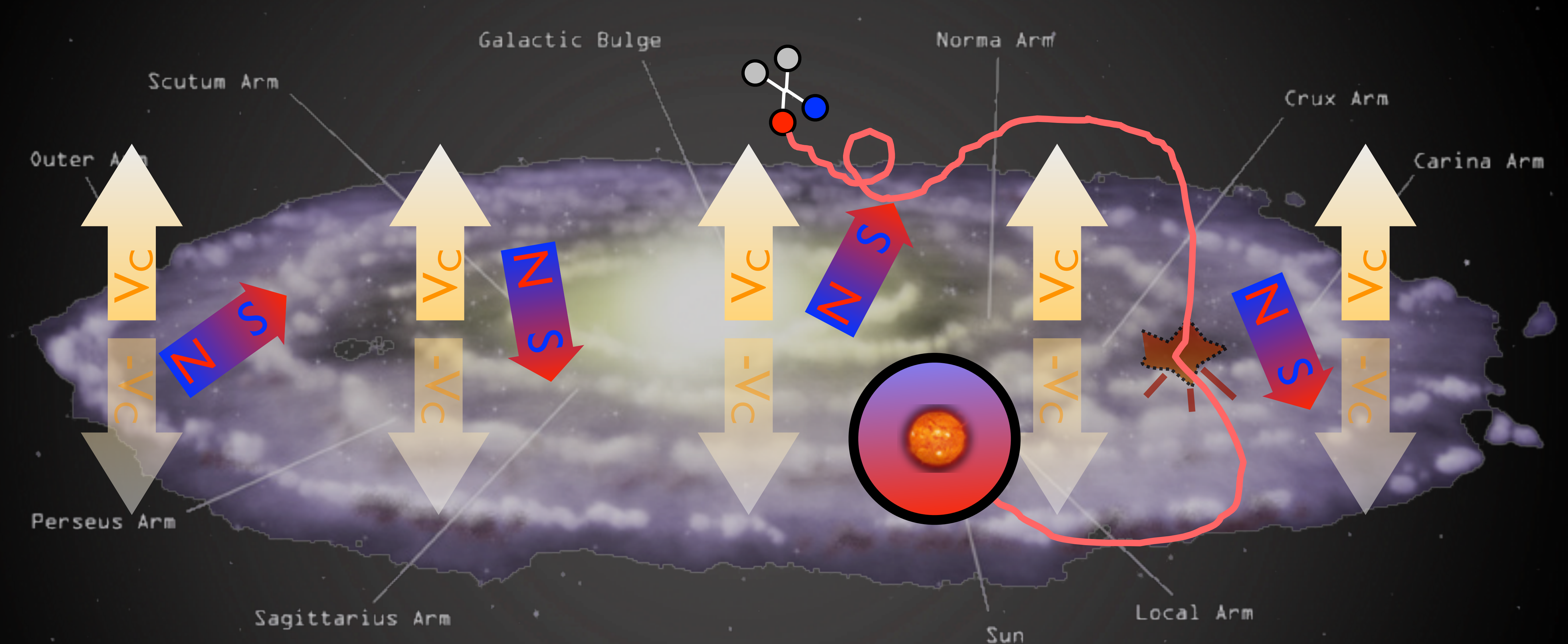
Indirect Detection: charged CRs

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



Indirect Detection: charged CRs

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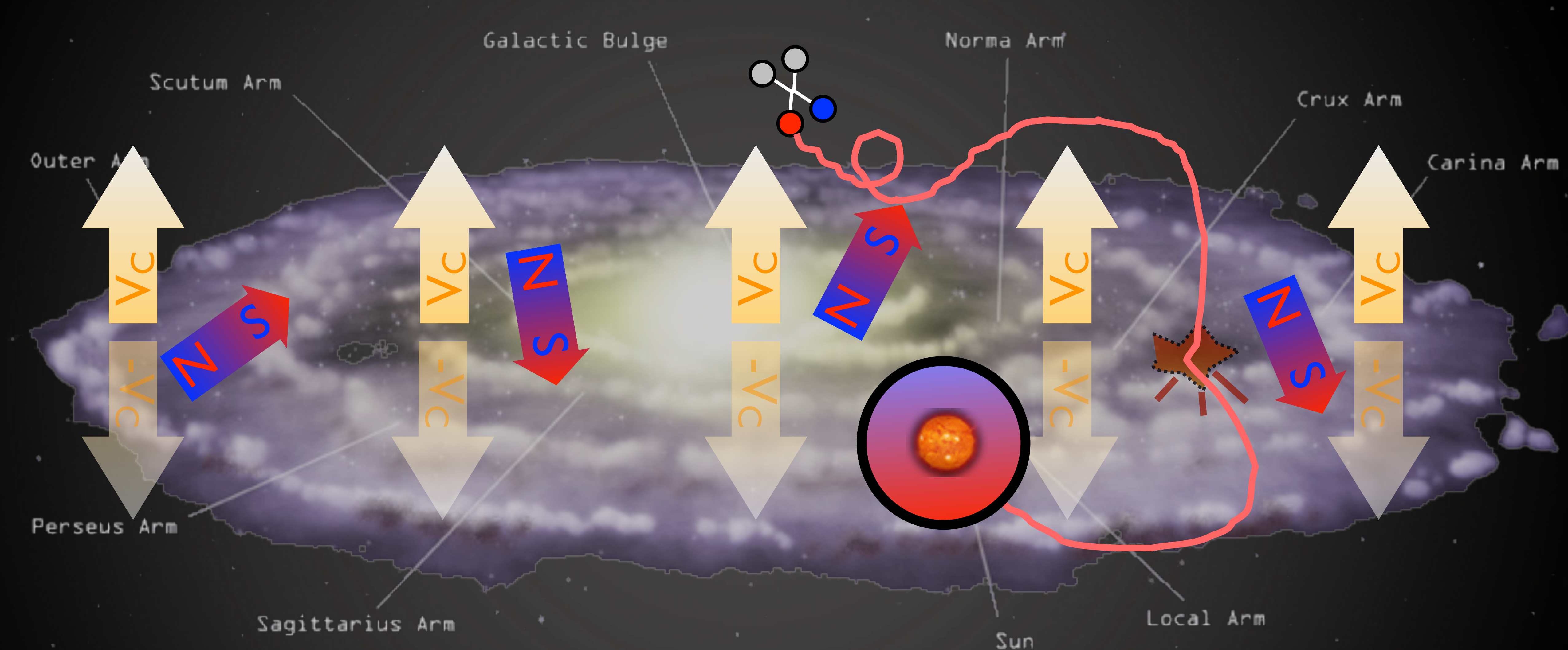
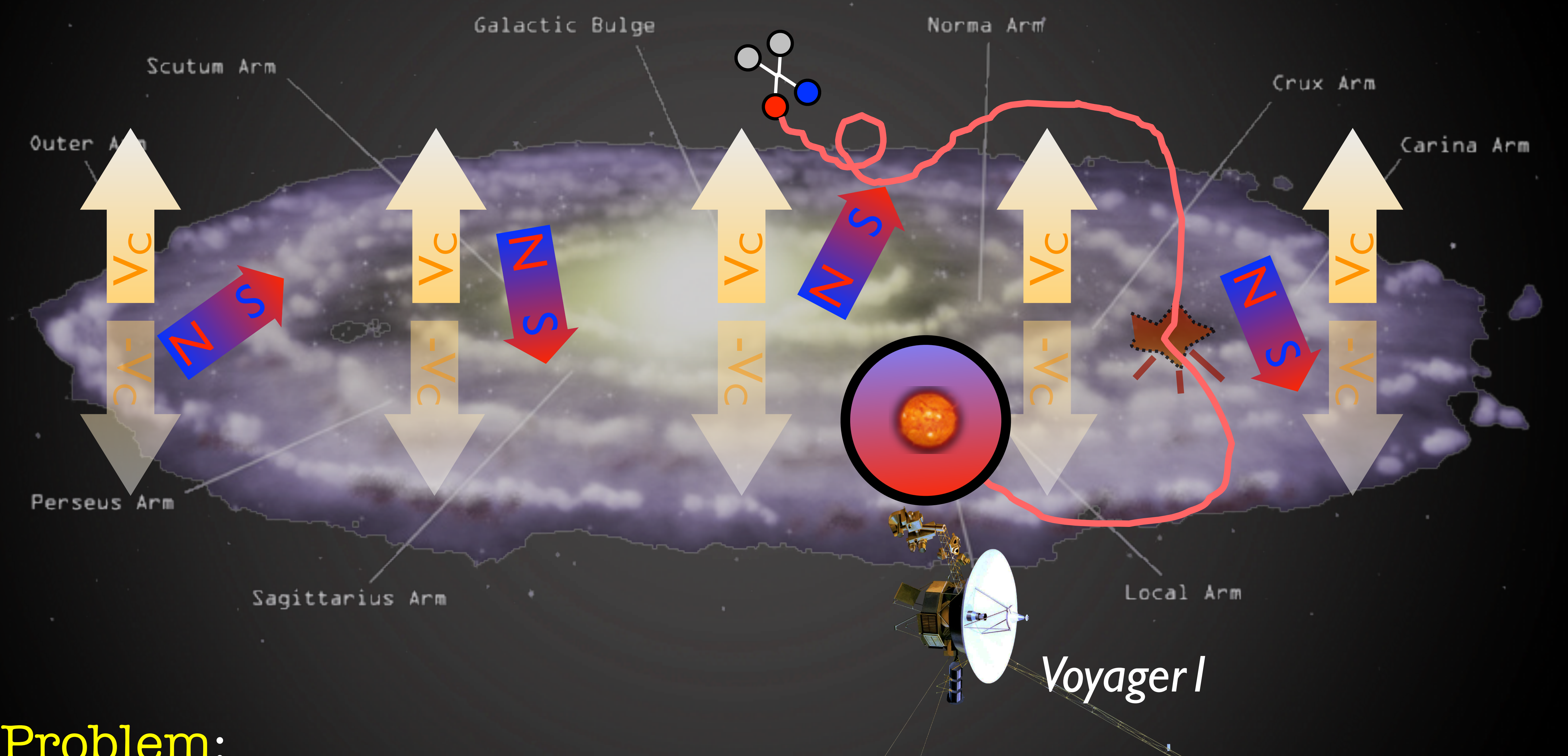


Problem:

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

Indirect Detection: charged CRs

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

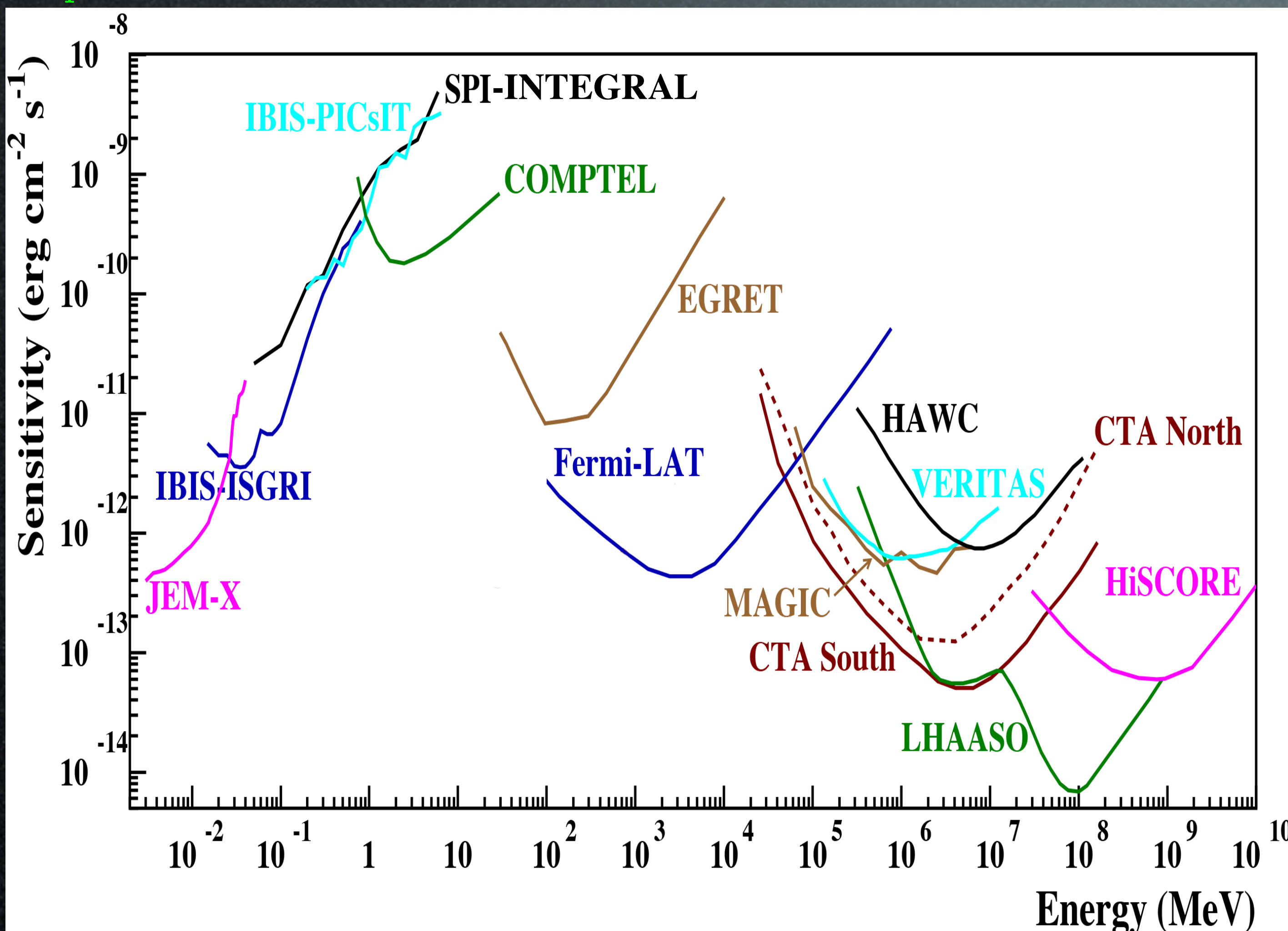


Problem:

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:

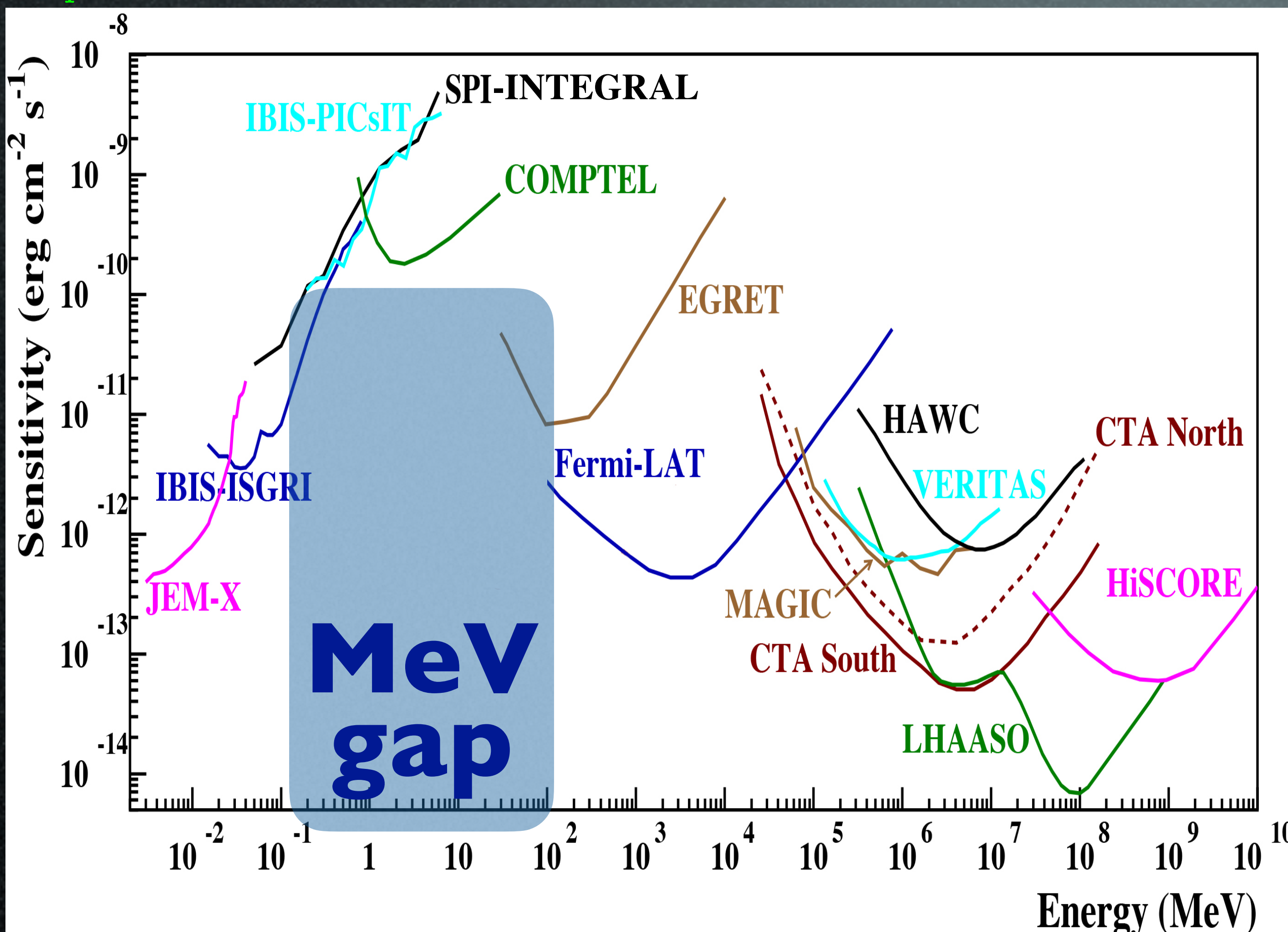
e-Astrogam?, Compair?, Amego?

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

Indirect detection: photons

adapted from 1611.02232



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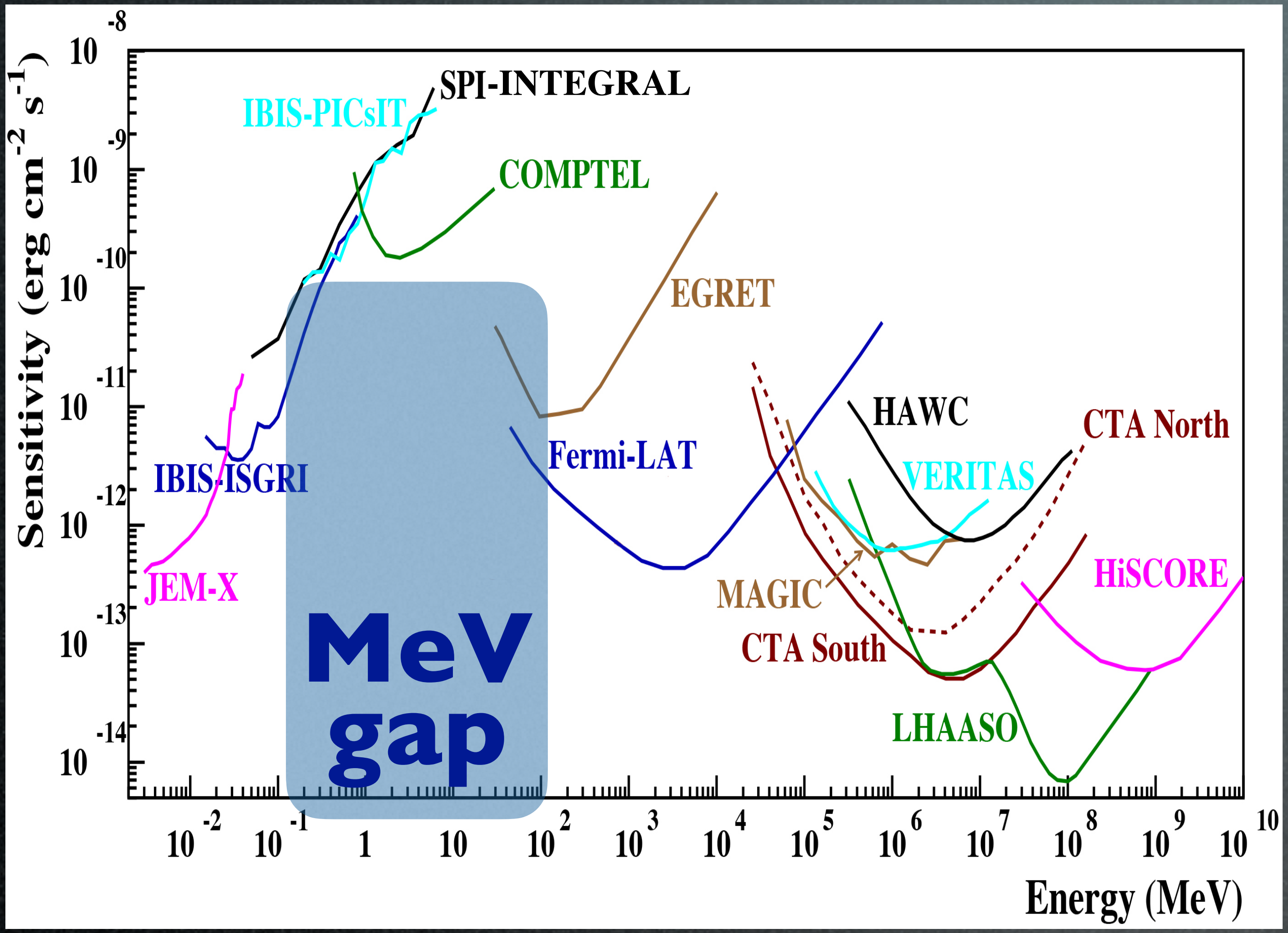


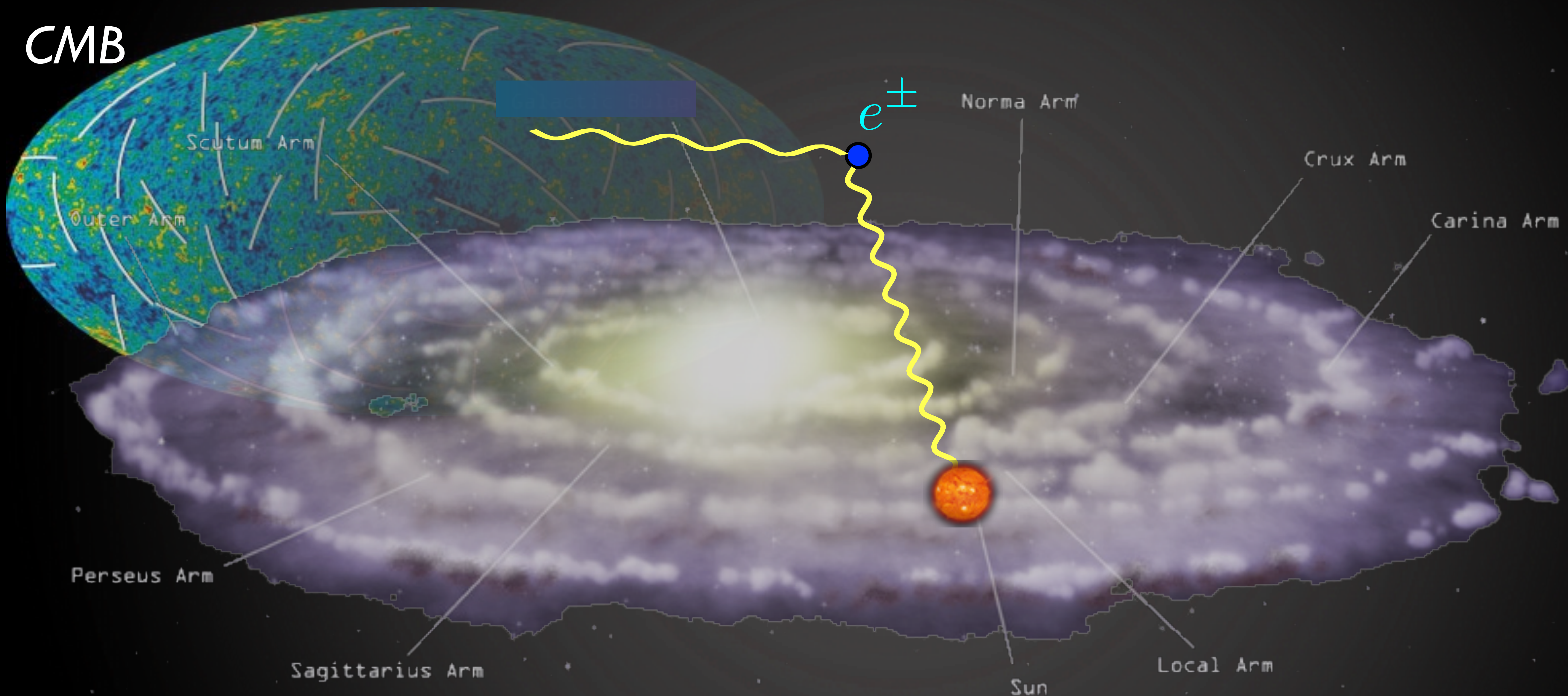
How to do better?

ICS & X-rays!

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493
Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

Secondary emission

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



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

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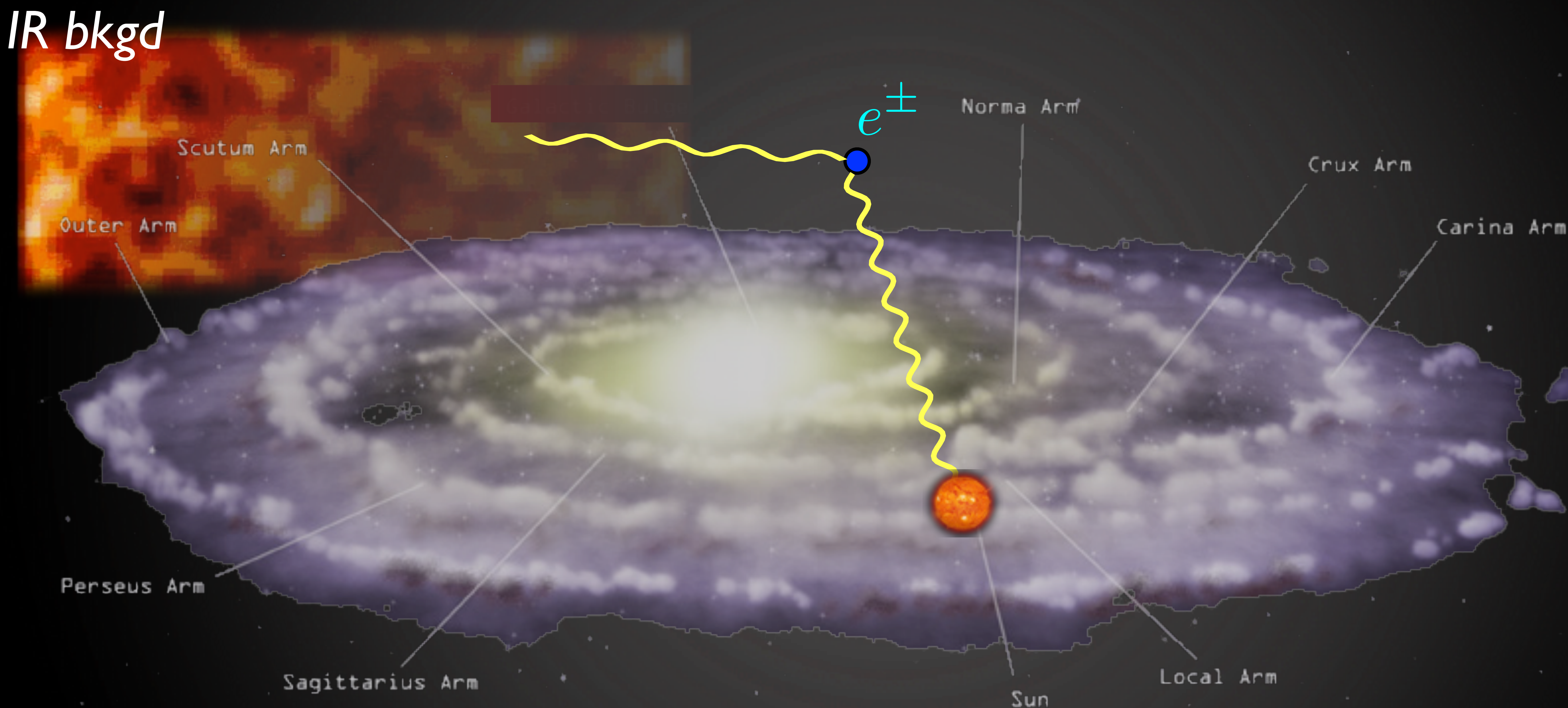

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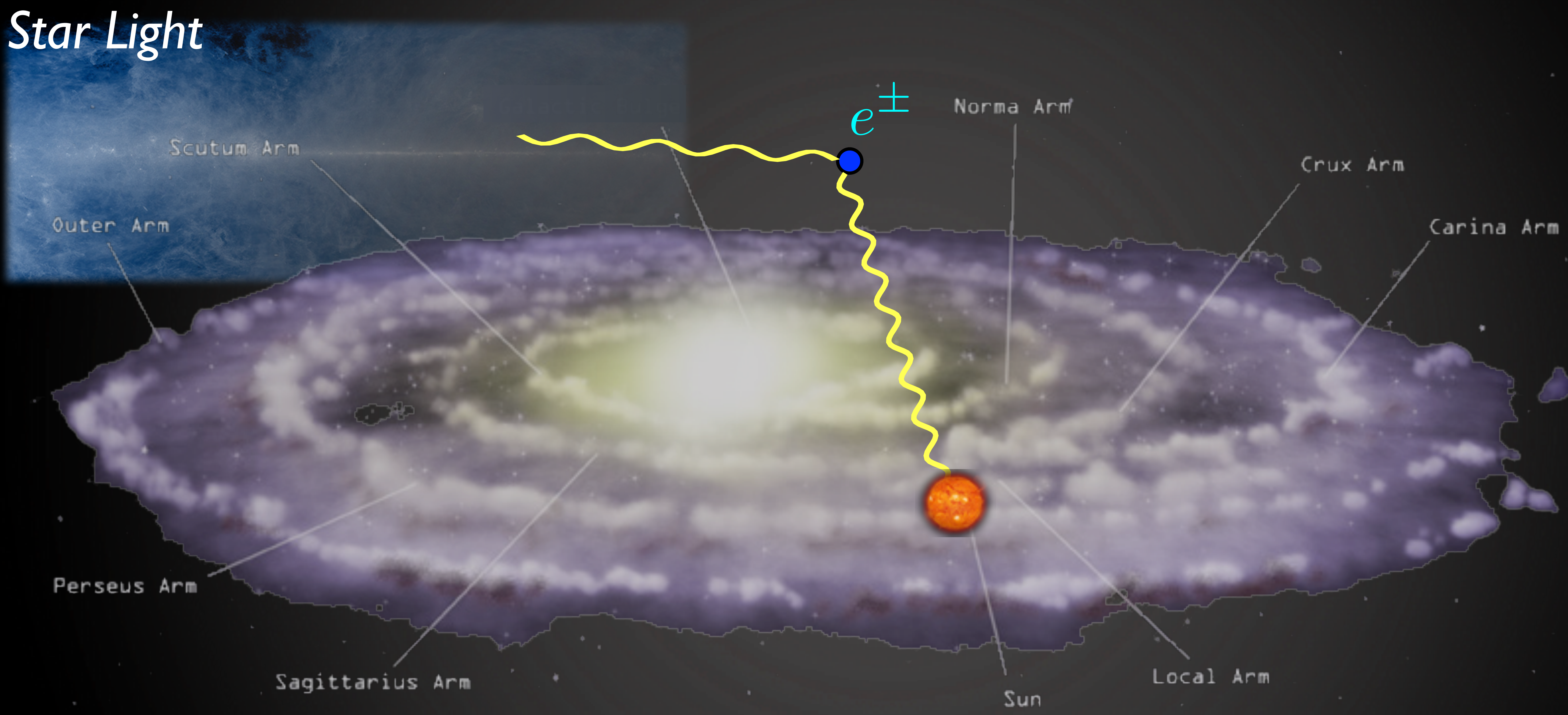

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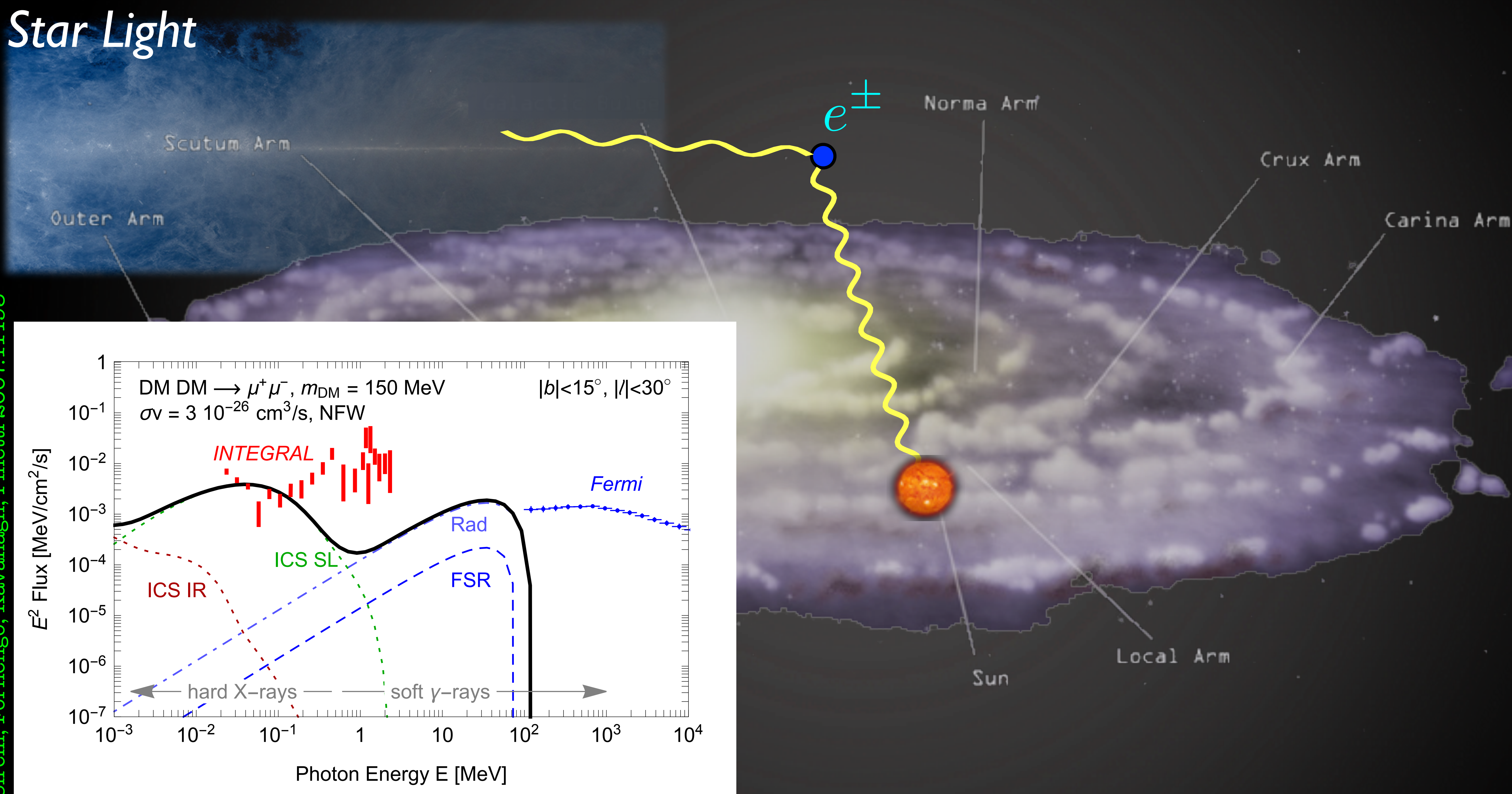

Cirelli, Fornengo, Kavanagh, Pinetti 2007.11493

- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
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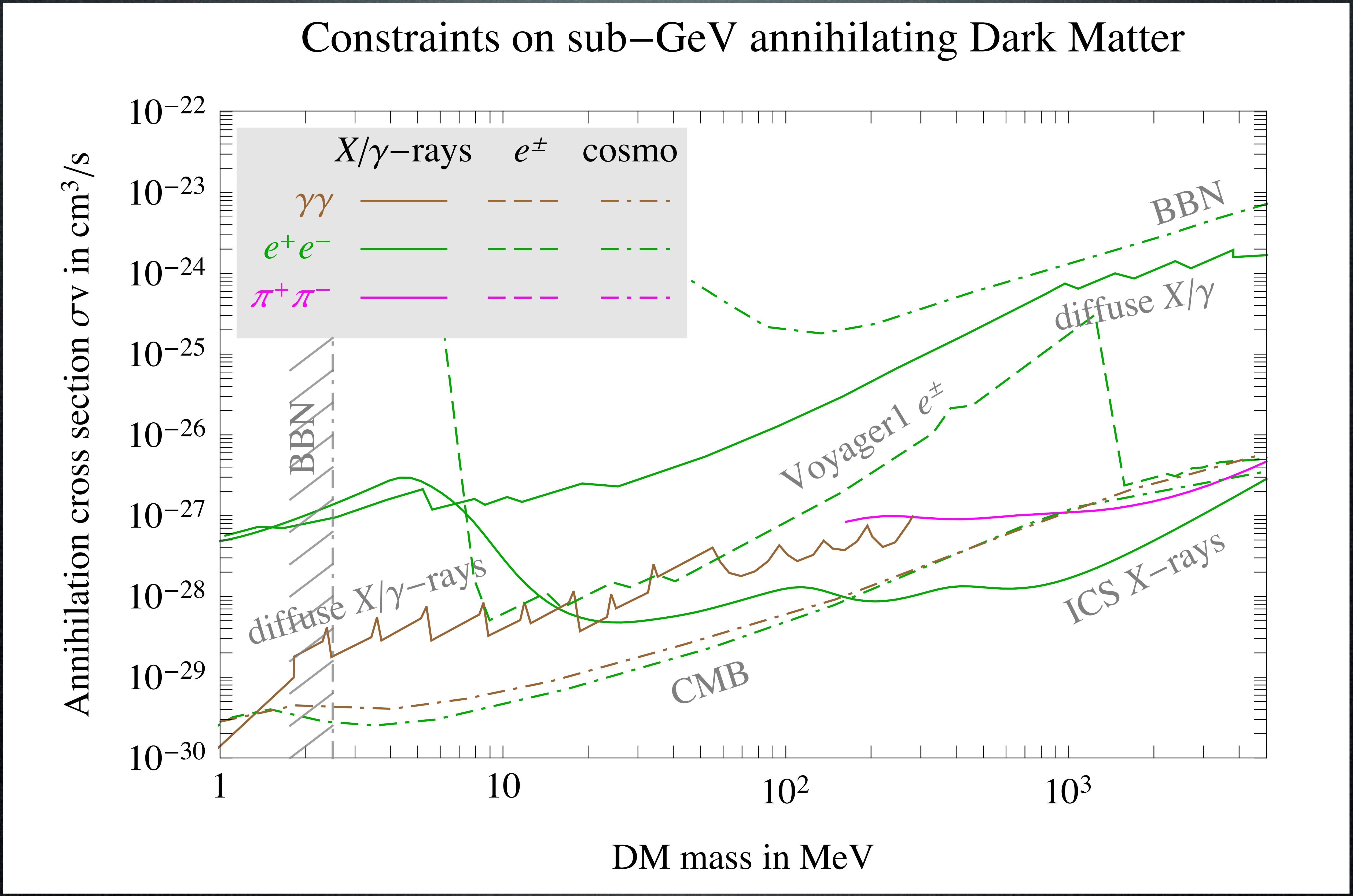
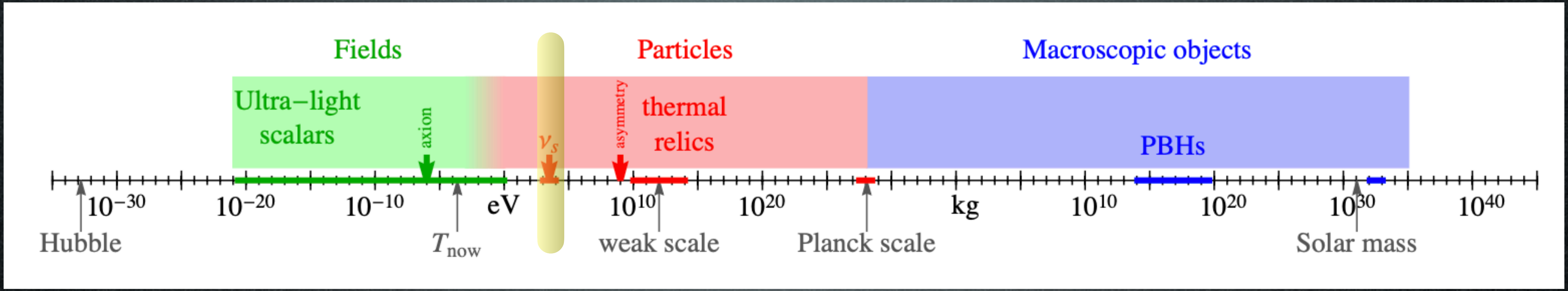
Comparing all bounds



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

Candidates

A matter of perspective: plausible mass ranges



KeV DM

X-ray line

Bulbul et al., 1402.2301

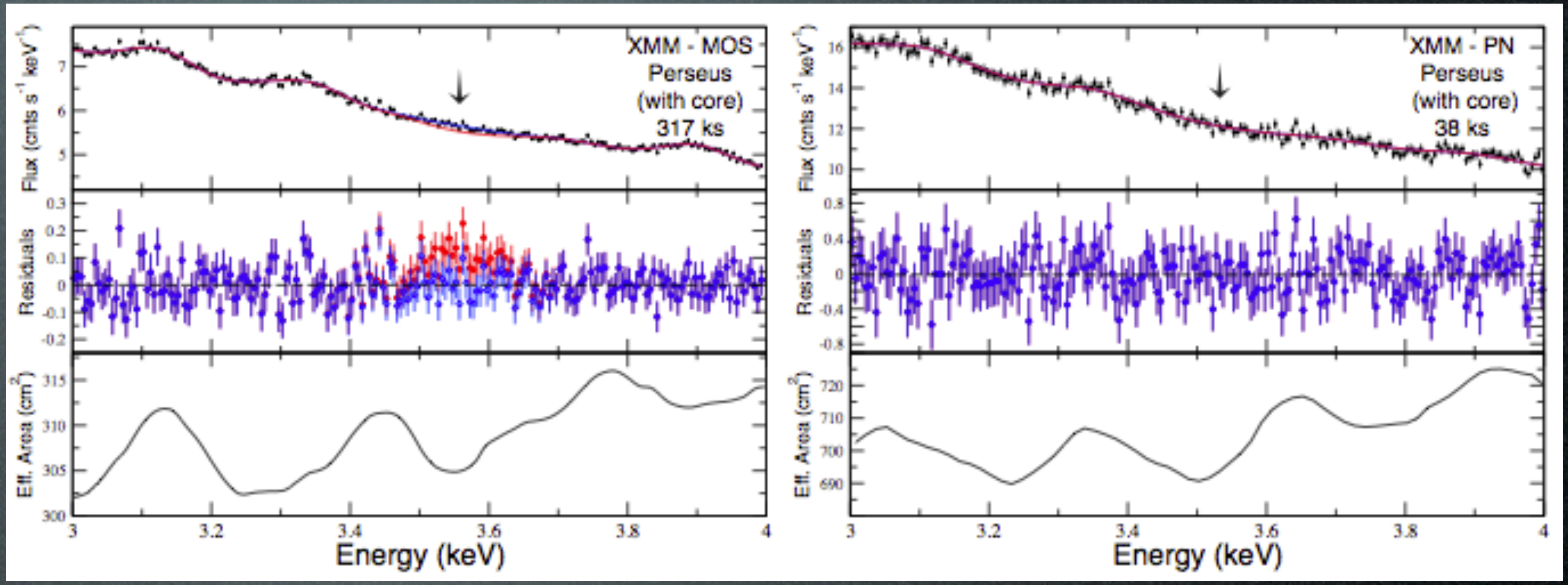
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

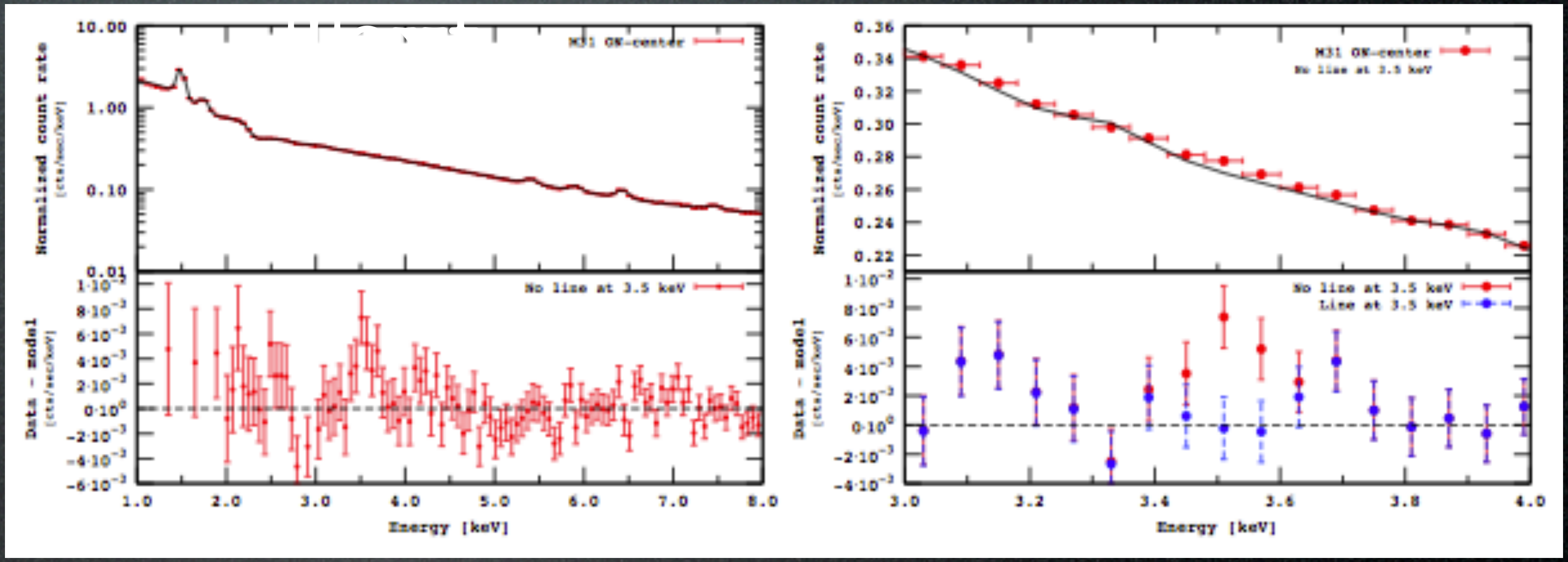
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

z = 0 and 0.0179

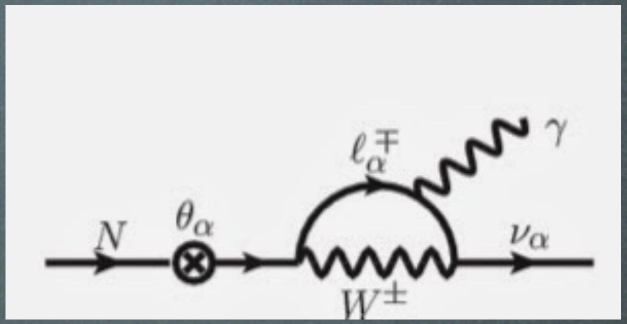
4.4σ

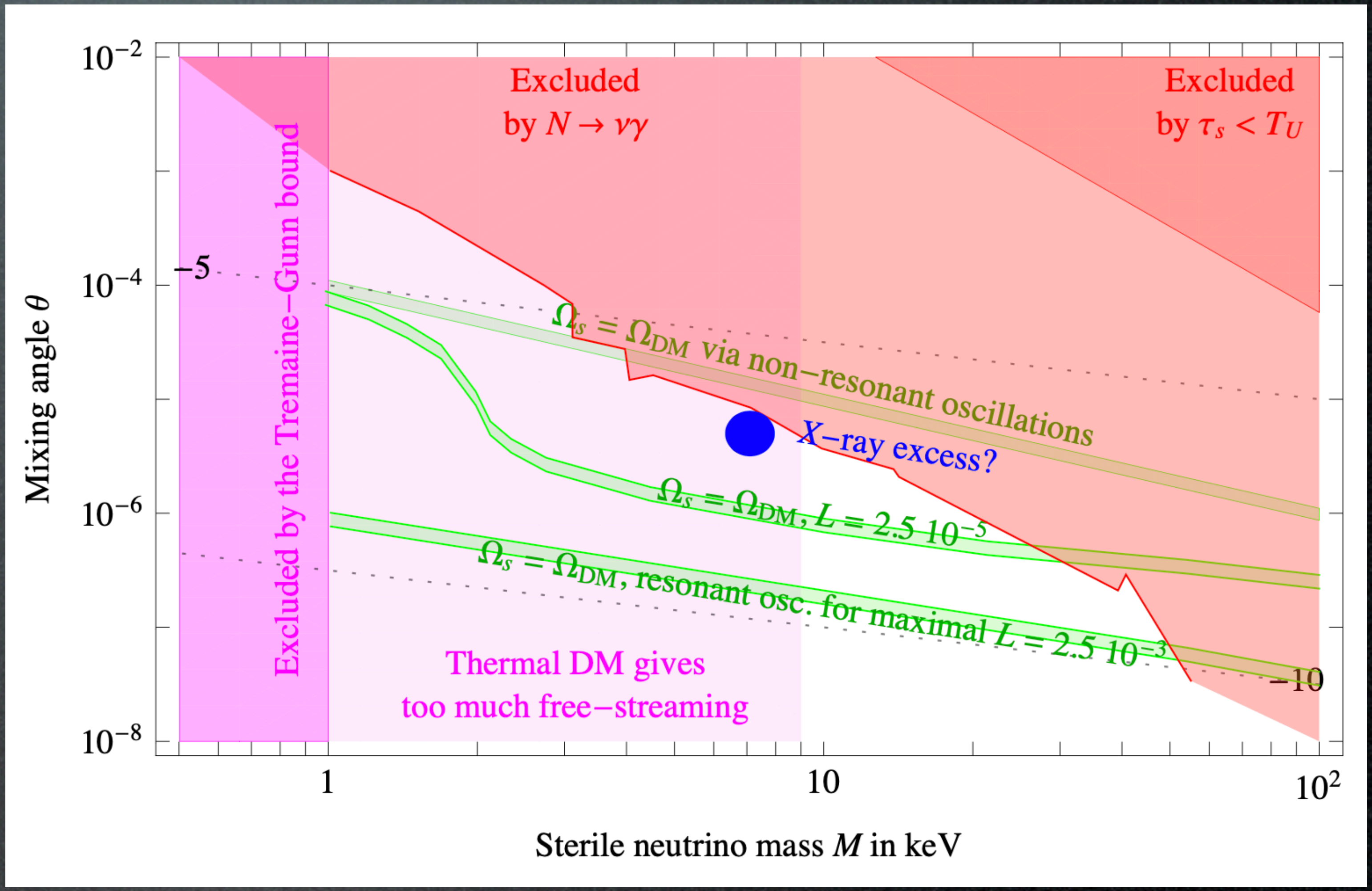


X-ray line

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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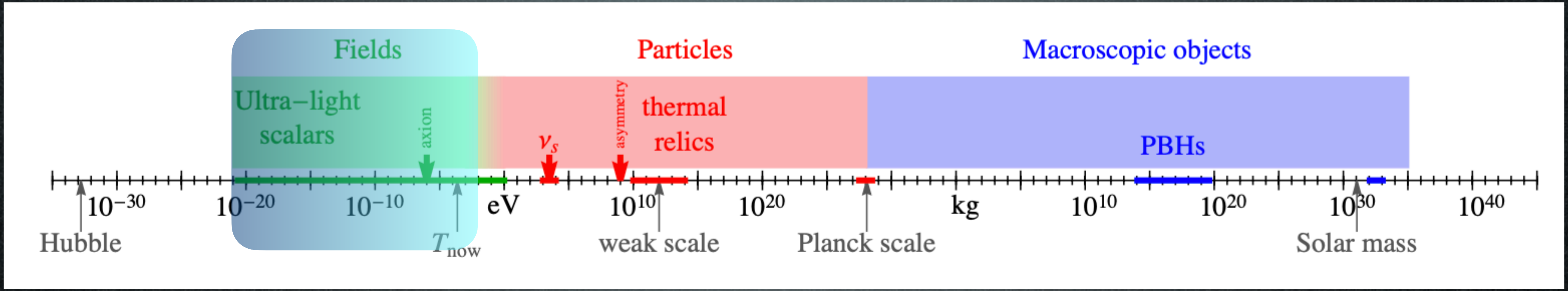
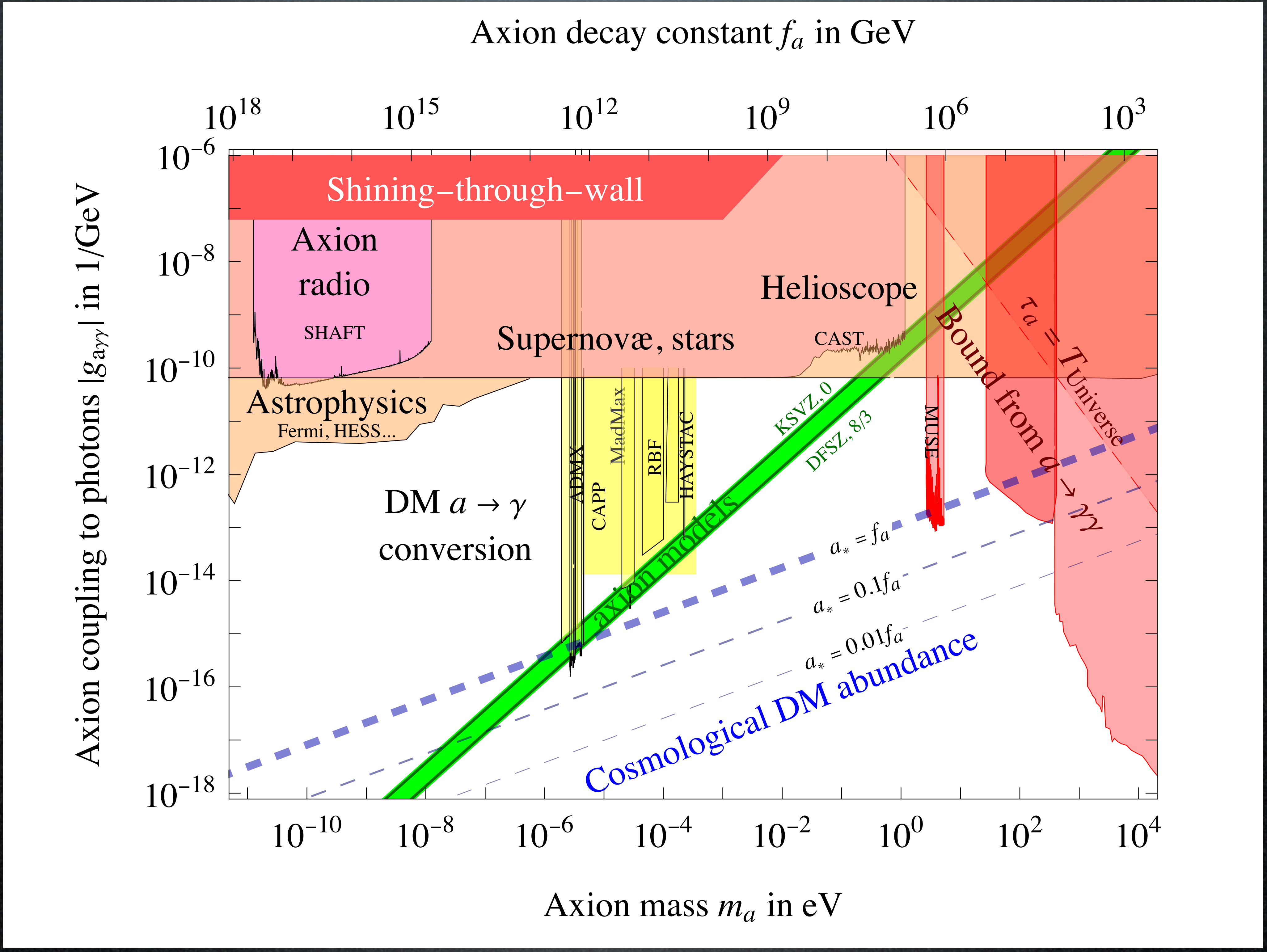
A matter of perspective: plausible mass ranges



Ultralight DM

Axions

Searches:



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

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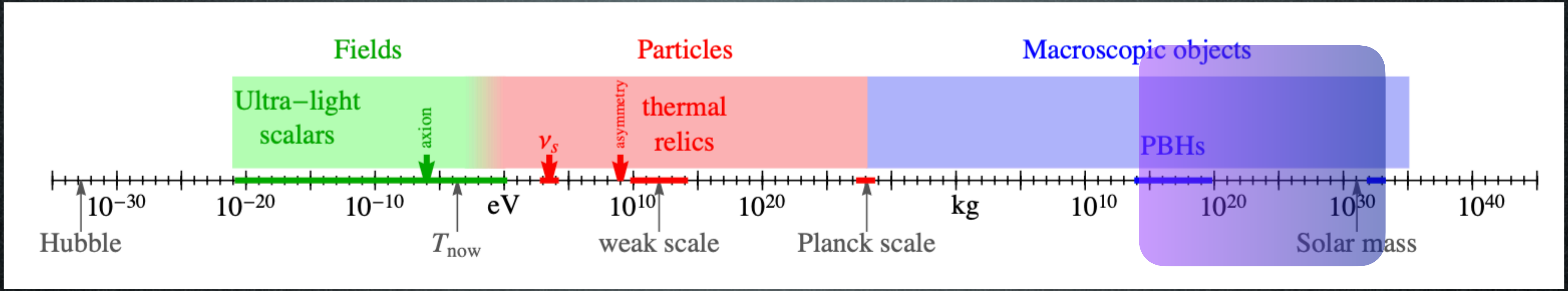


PBH DM?

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

'small' PBHs emit today by Hawking evaporation

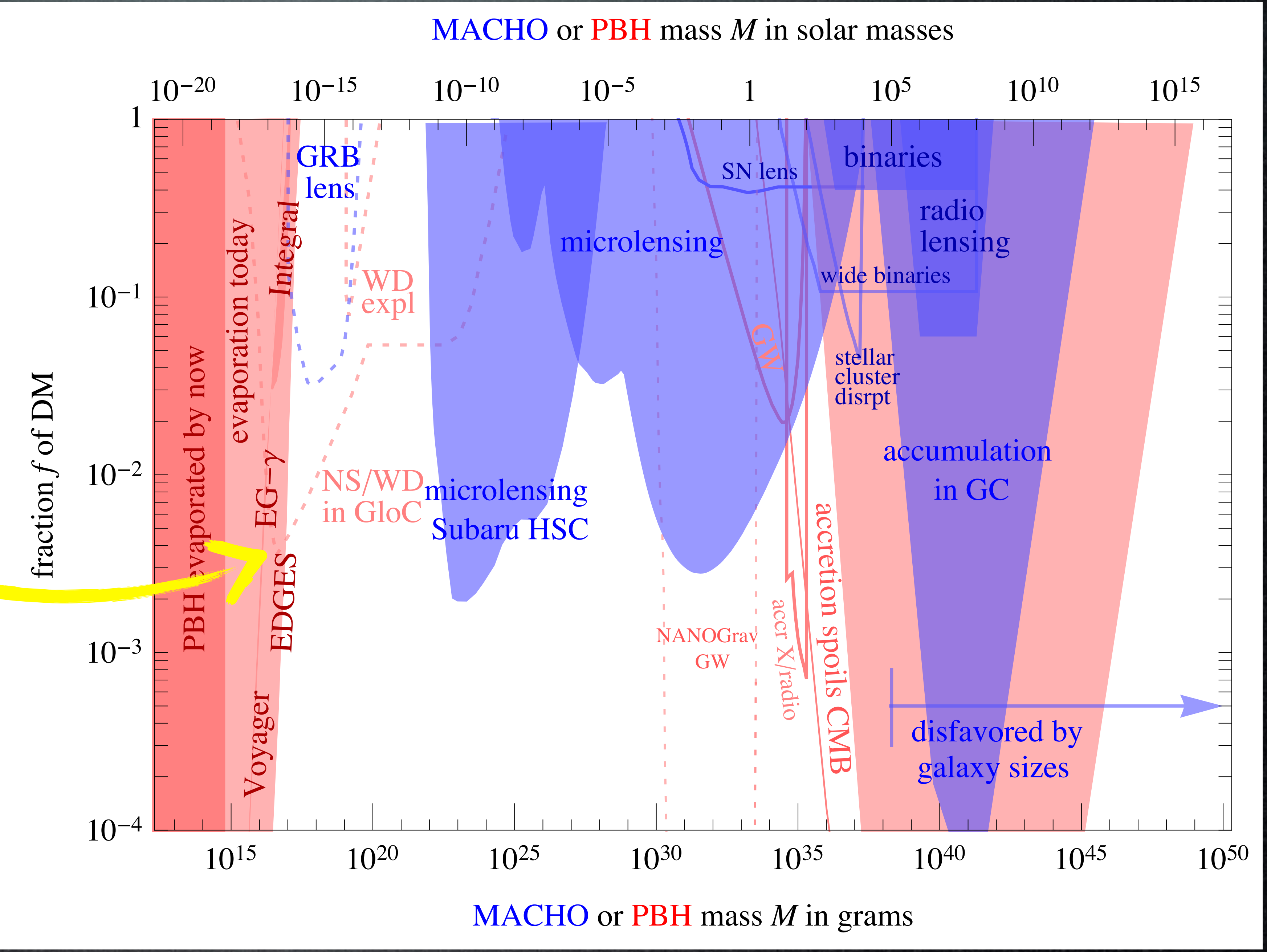
$$T = \frac{1}{8\pi G_N M}$$

rate

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

spectrum

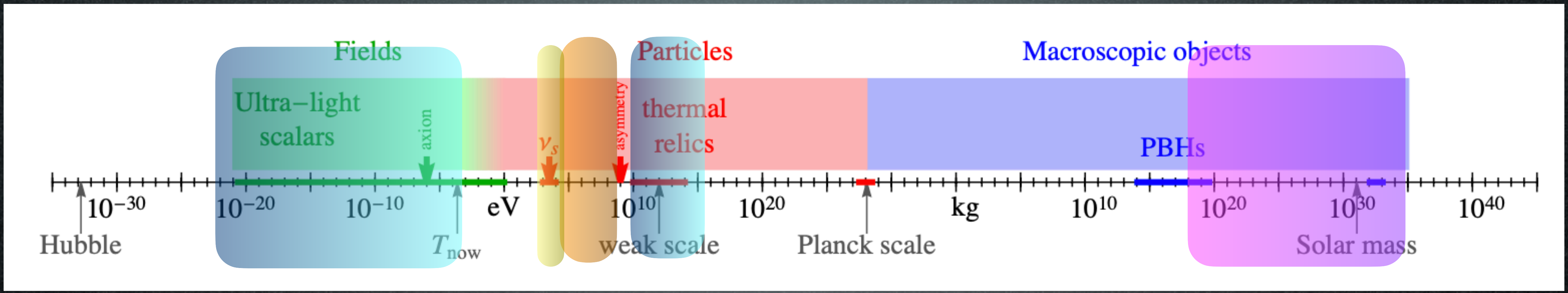
$$\frac{dN}{dt\,dE} = \frac{27}{2\pi}\frac{G^2M^2E^2}{e^{E/T}+1}$$



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

Conclusions

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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