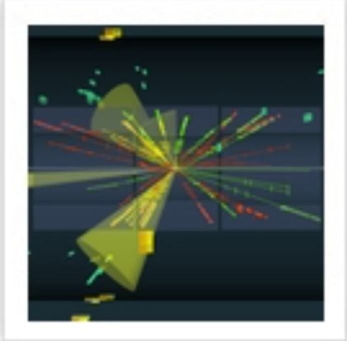

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

TAE 2023 - International Workshop on High Energy Physics

Sep 03 - 16, 2023

Dark Matter

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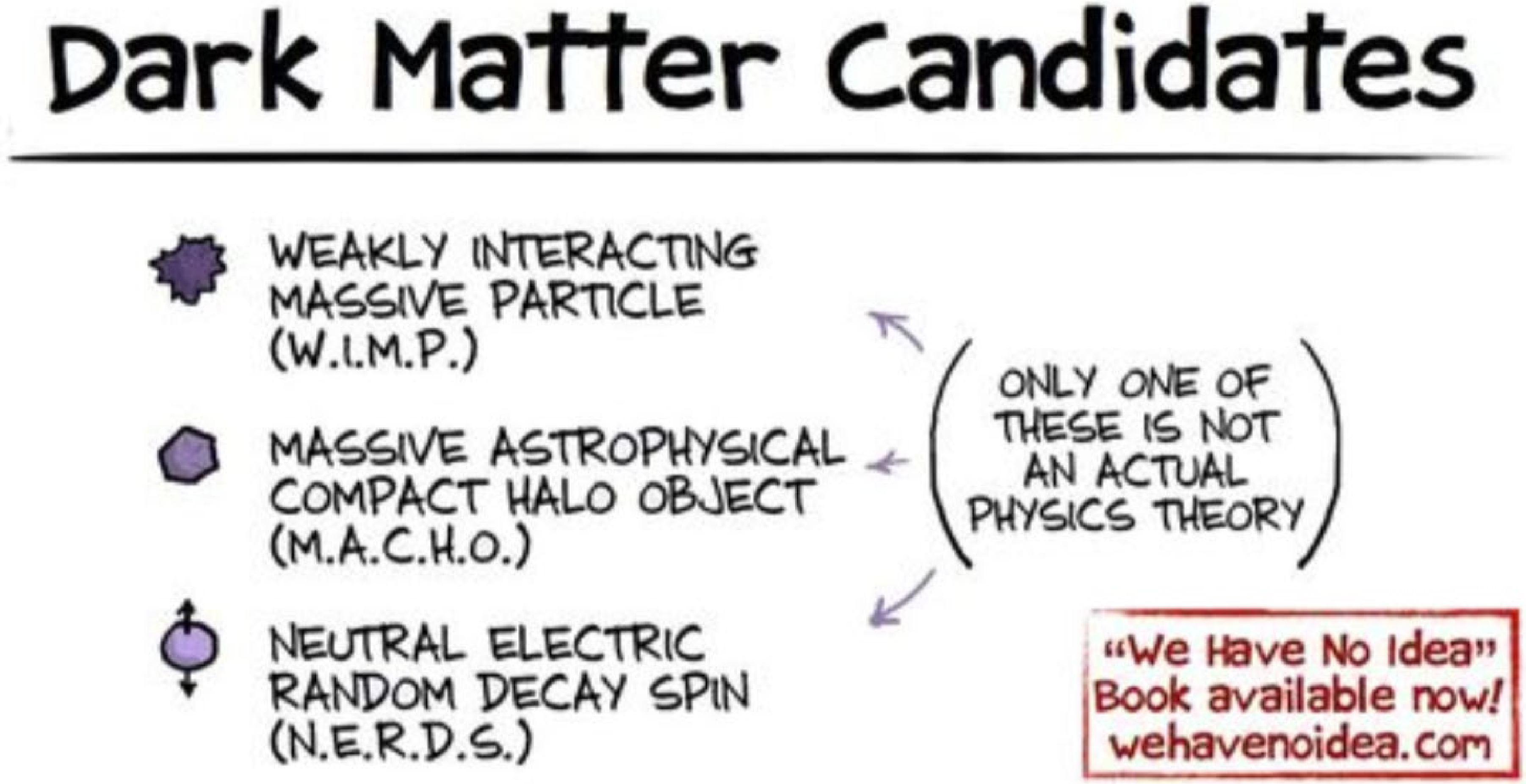
Universidad Zaragoza

Lecture II

Dark Matter Candidates



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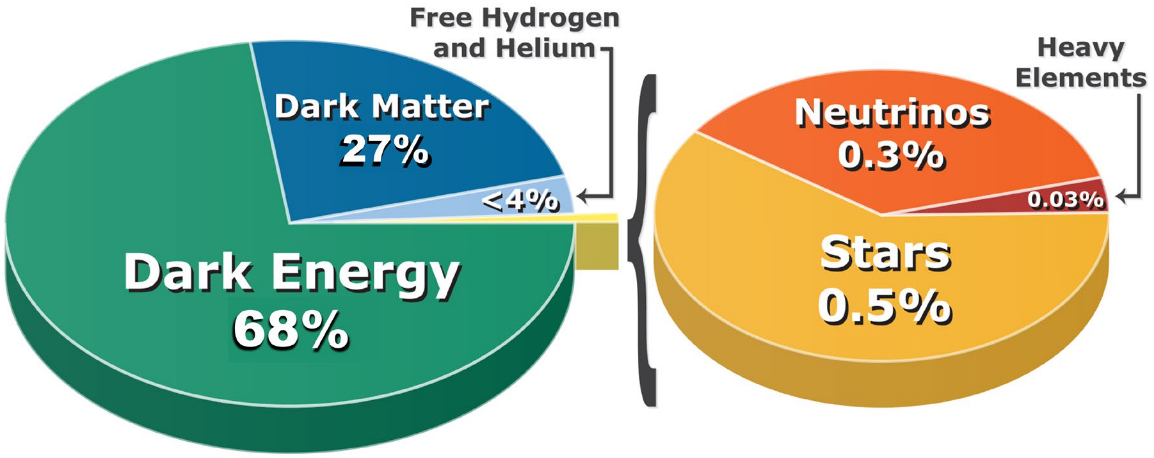
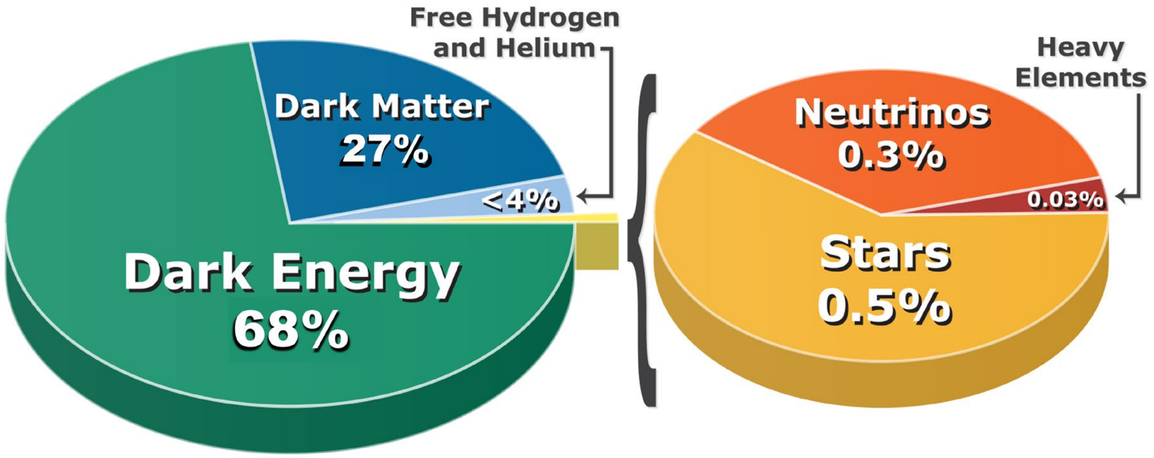
The standard model of cosmology (ΛCDM)



- **Most of the matter in the Universe is in the form of an unknown cold non-baryonic component which does not interact with photons (or does so very weakly).**

The standard model of cosmology (ΛCDM)



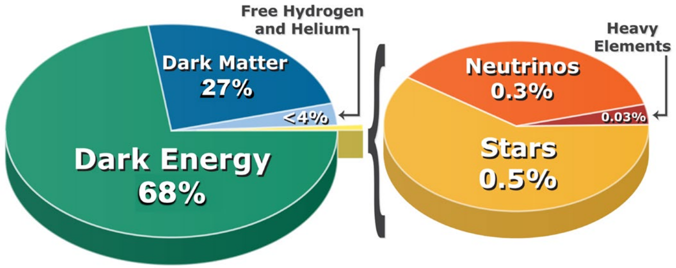
- Most of the matter in the Universe is in the form of an unknown cold non-baryonic component which does not interact with photons (or does so very weakly).
- We only know about the DM existence because of the gravitational effects it produce, but we do not have yet any clue about its nature(s) (it could be several species)

What do we know about DM?

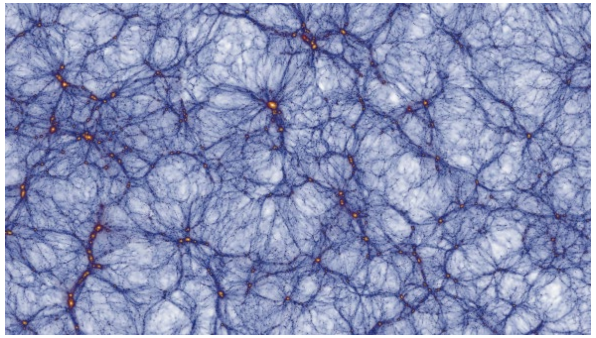
- Cold … or at least Warm (not moving very fast when structures formed)
- Non-baryonic
- Not interaction with photons (or extremely weak)
- Self-interaction $\sigma_{\mathrm{DM-DM}}/\mathrm{m}_{\mathrm{DM}} < 0.47\ \mathrm{cm}^2/\mathrm{g}$ (0.84 barn/GeV) at 95% CL
- Stable or very long-lived (lifetime must be long compared to cosmological timescales)
- Mass lower limits (from quantum effects)
  - fermions: Pauli exclusion (cannot be confined in galaxy-sized structures) → $\mathrm{m}_{\mathrm{F}} > 70\ \mathrm{eV}$
  - bosons: ultra-light species might erase small-scale structure, in conflict with CMB → $\mathrm{m}_{\mathrm{B}} > 10^{-22}\mathrm{eV}$
- Mass upper limits (from the stability against tidal disruption of structures): point-like DM mass < 5 $M_{\odot}$

What do we know about DM?

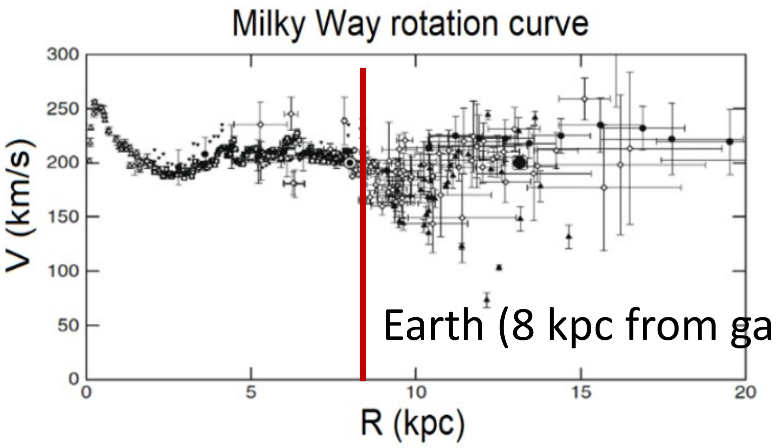
- From the CMB anisotropies we know very precisely how much DM we have



- From LSS & N-body simulations we know that its distribution is highly inhomogeneous



- From the Milky way rotation curve we also know how many DM are in the Earth's neighborhood



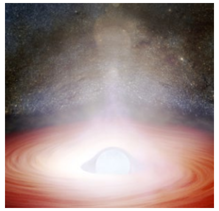
Local DM density:
$\rho \sim$ 0.3-0.5 GeV/cm^3

- Virialized halo → upper bound on the possible velocity of dark matter particles in the halo $v_{esc} \simeq \sqrt{\frac{2GM_{vir}}{R_{vir}}} \sim 550\ km/s$

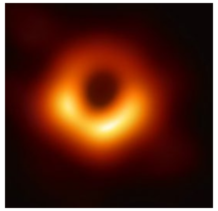
MACHOS (Massive astrophysical compact halo object)

Massive astrophysical compact halo objects with masses ranging from $\sim 10^{-6}$ to 10 solar masses

Jupiter-like planets



Neutron stars



Black holes

Brown dwarfs

They are strongly constrained by microlensing but, on top of that…

They are BARYONIC Dark Matter

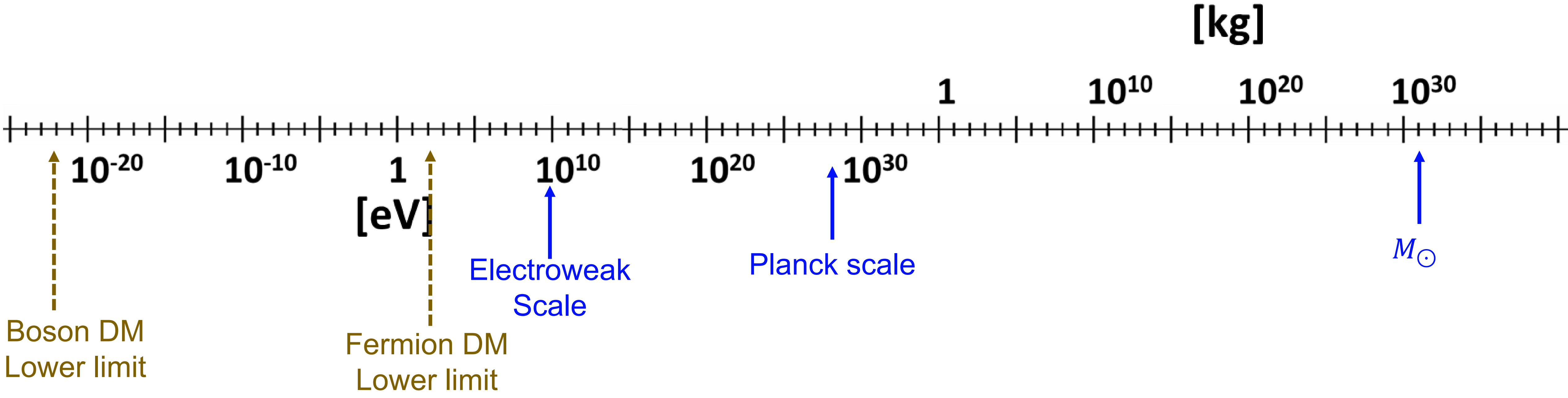
Not to be confused with (sometimes called)

dMACHOS (DARK massive astrophysical compact halo objects)

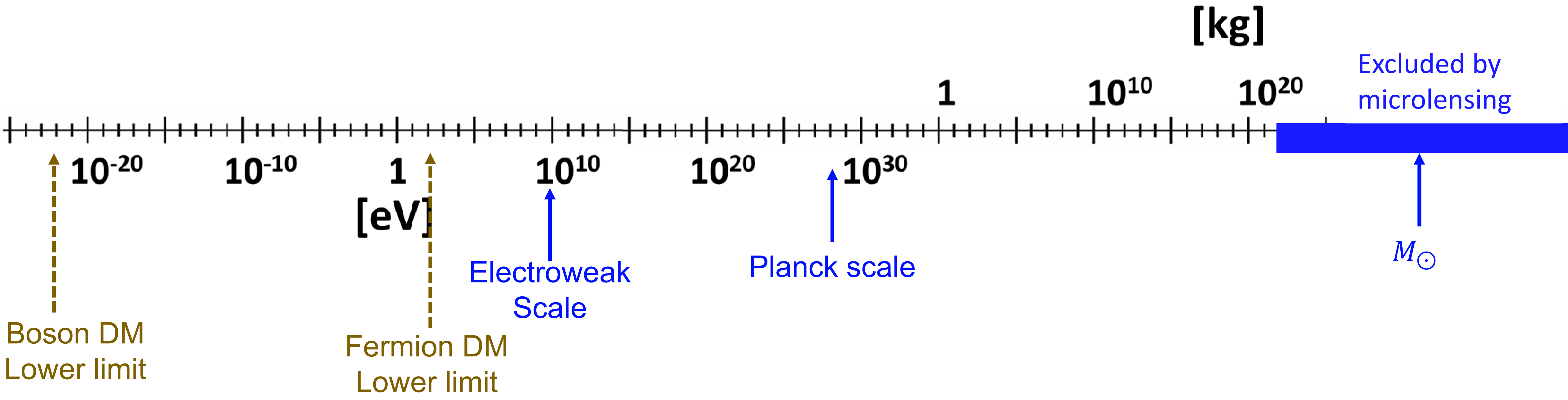
Any macroscopic dark matter candidate (non-baryonic) that interacts predominantly gravitationally with standard matter. (primordial black holes, Q-balls and other solitons, quark nuggets, mirror stars….)

…more on this later

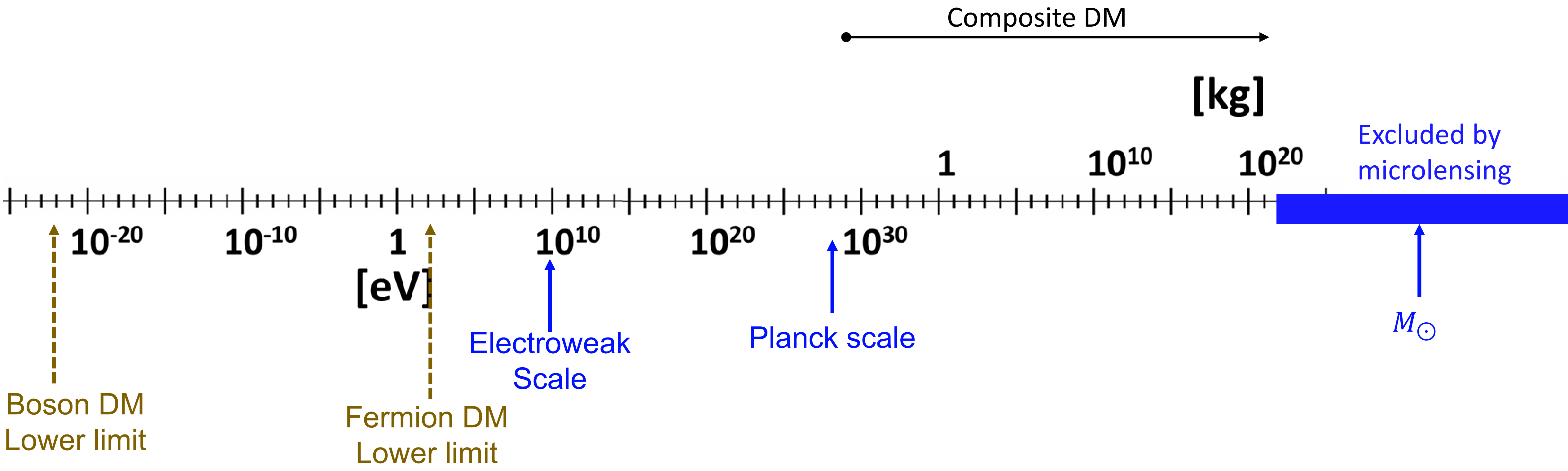
Dark Matter Candidates



Dark Matter Candidates



Dark Matter Candidates

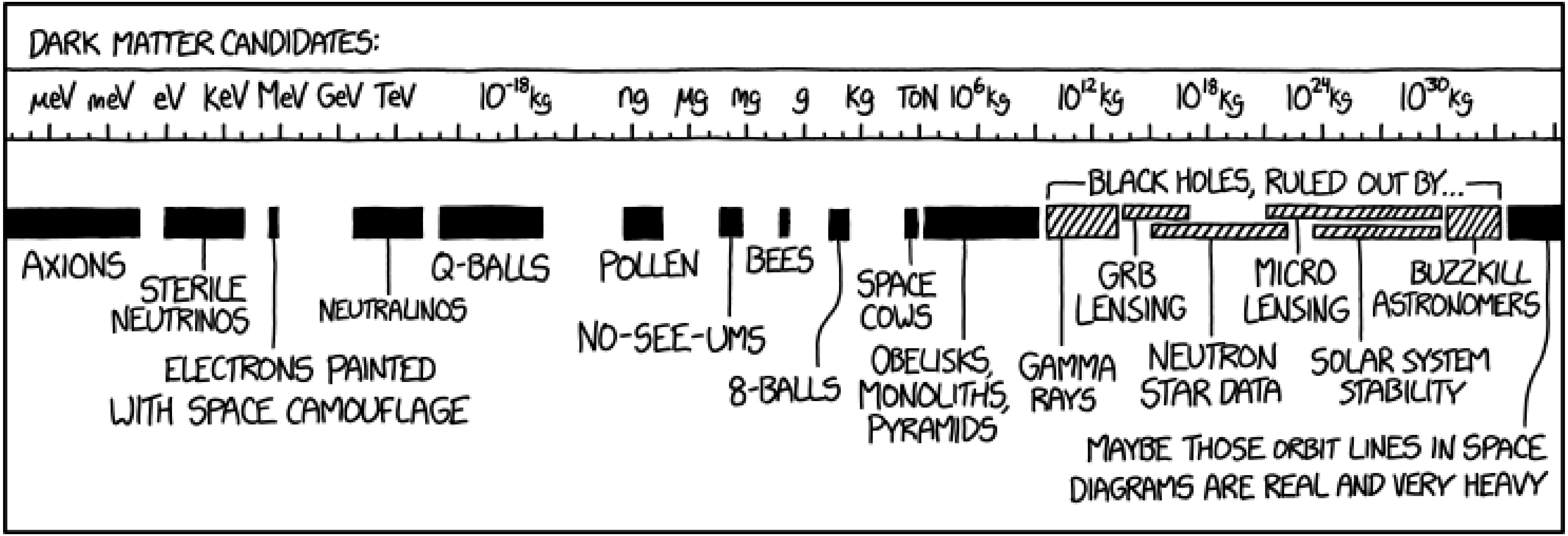


We know the DM mass density, so smaller mass → larger numerical density

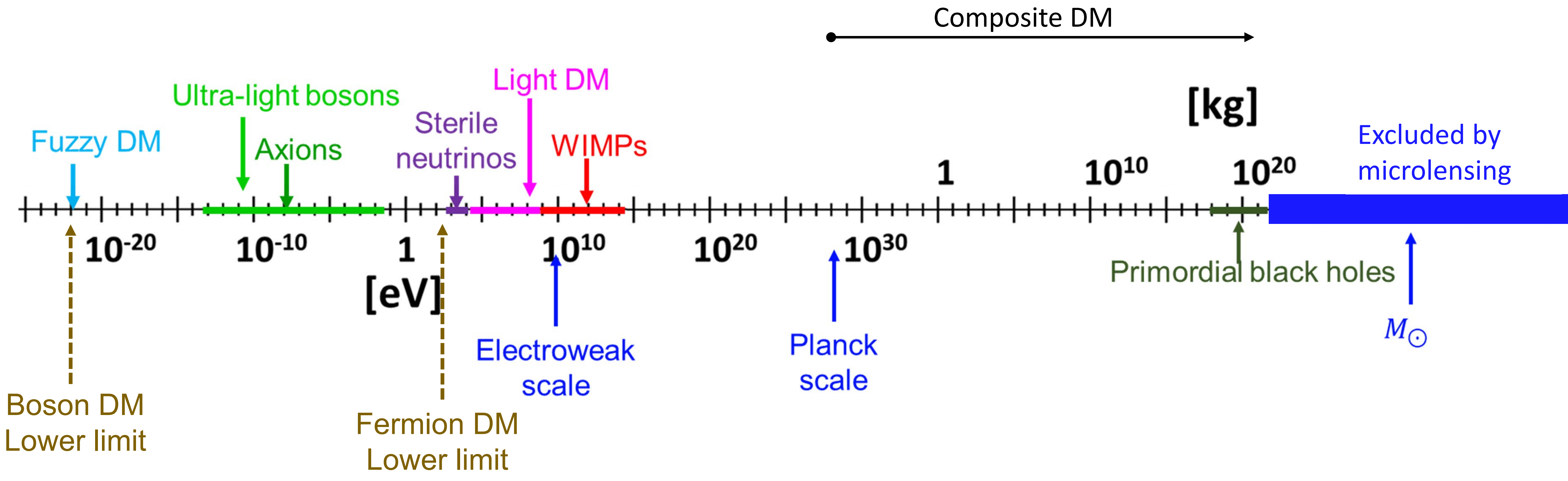
Dark Matter Candidates

- new particles (or compounds) based in solid BSM theories
- meet the requirements to be DM
- provide a production mechanism to generate CDM (or WDM) and explain the current density, or part of it (but not more)
- BONUS: solve other problems of the SM

Dark Matter Candidates

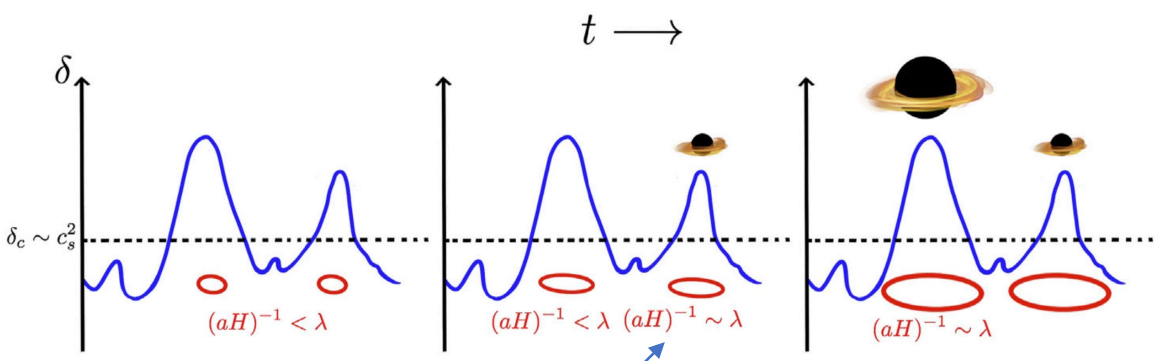


Dark Matter Candidates



Primordial black holes (PBH)

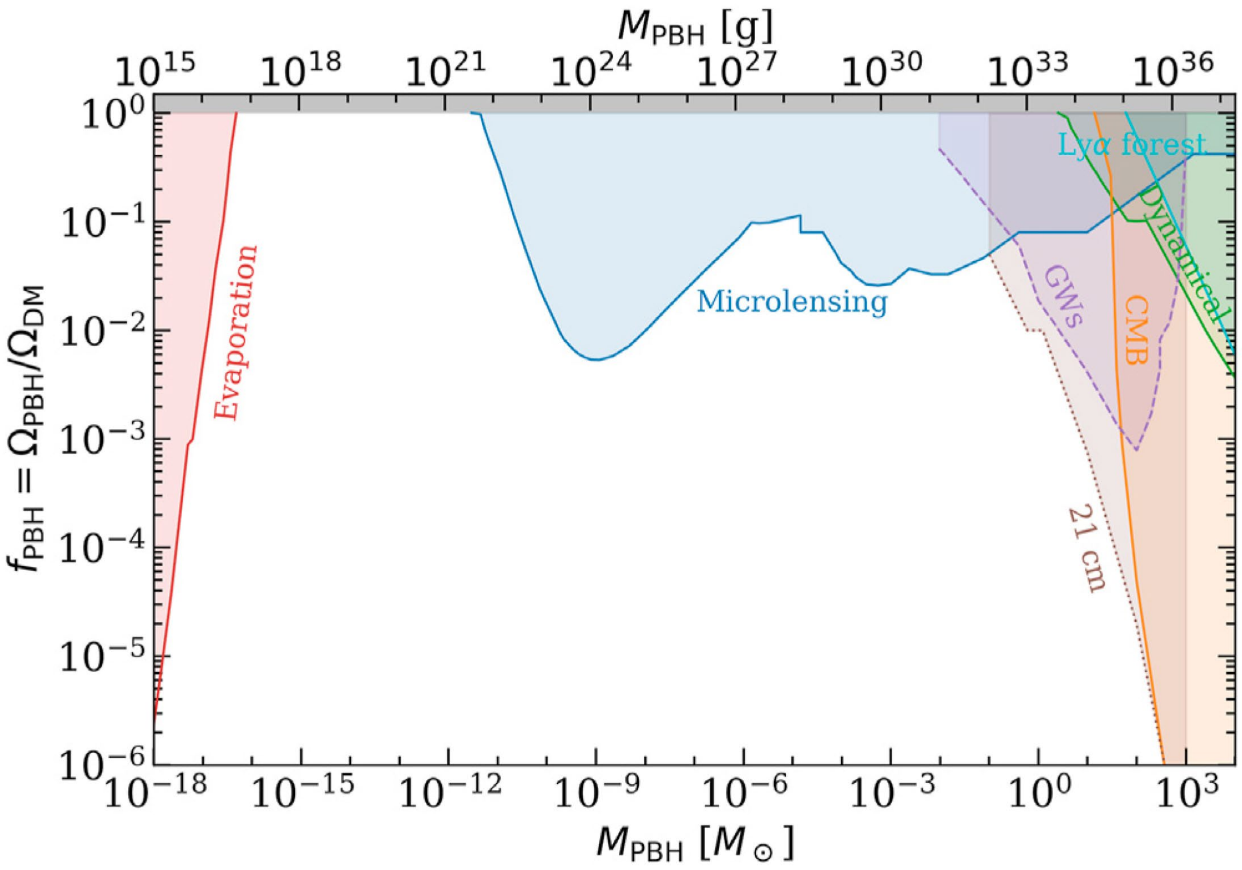
Black holes formed in the early Universe due to density fluctuations → non-baryonic DM



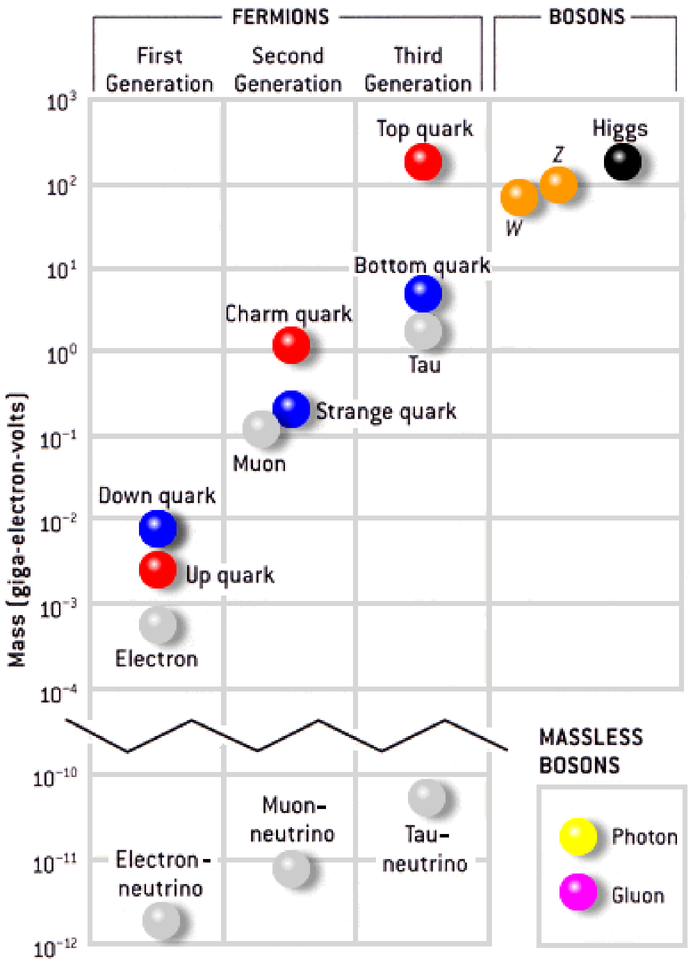
The region with overdensity collapses, giving rise to the formation of a PBH

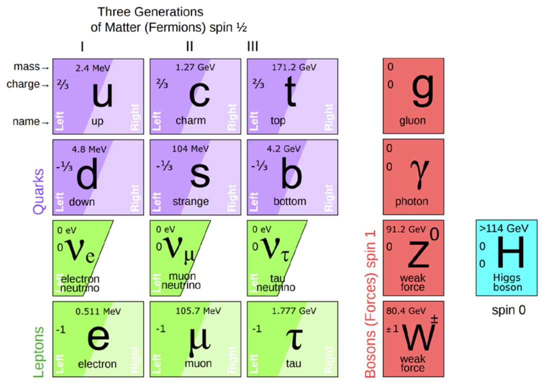
Its production typically requires exotic inflationary scenarios or physics beyond the standard model to fully account for all of the dark matter.

Experimental status:



Sterile neutrinos

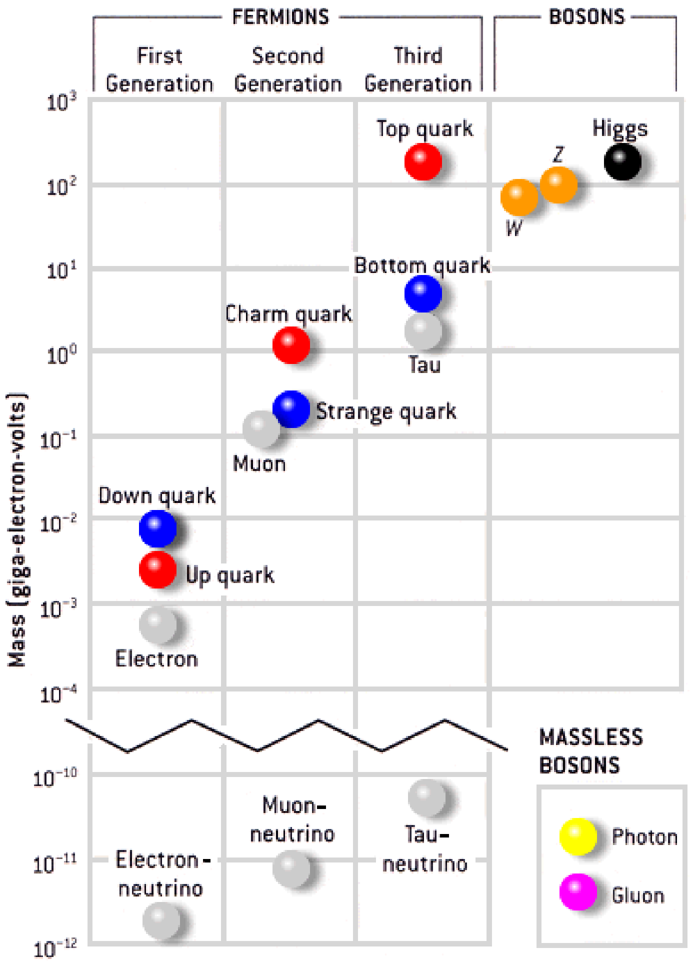


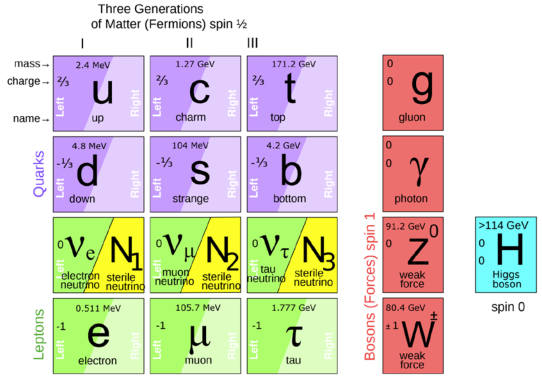


Many open questions in the neutrino sector

- Origin of neutrino masses
- Why are neutrinos so light?
- Dirac or Majorana?

Sterile neutrinos



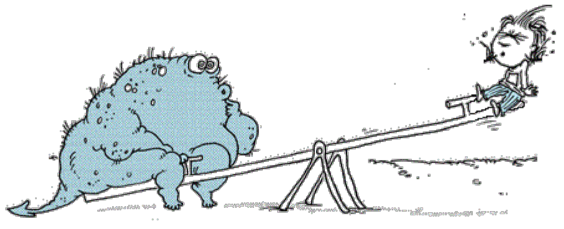


Many open questions in the neutrino sector

- Origin of neutrino masses
- Why are neutrinos so light?
- Dirac or Majorana?

Sterile neutrinos (N_i) are neutral right-handed leptons with no weak interactions except those induced by mixing with active neutrinos (…but could have interactions involving new physics)

Sterile neutrinos are a natural ingredient of the most popular mechanism to generate neutrino masses: the seesaw mechanism



Add singlet fermions to the $\mathcal{L}_{SM}$

$$\mathcal{L} = \mathcal{L}_{SM} - y^{\alpha i} L_\alpha N_i H - \frac{M_{ij}}{2} N_i N_j + h.c.$$

y^a couplings to leptons and Higgs field

Majorana mass term

M_{ij} can be whatever!!

keV-scale Sterile neutrinos as DM

Choosing masses of sterile neutrinos of the order of masses of other leptons (keV-GeV):

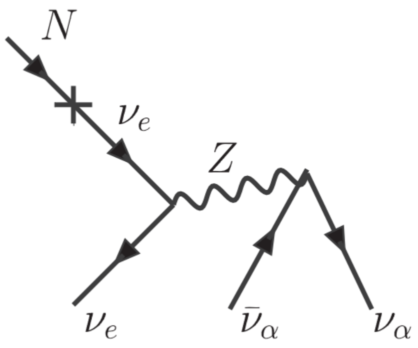
- Explain neutrino oscillations
- Generate correct matter-antimatter asymmetry
- Provides DM candidate

(Without introducing new physics above electro-weak scale)

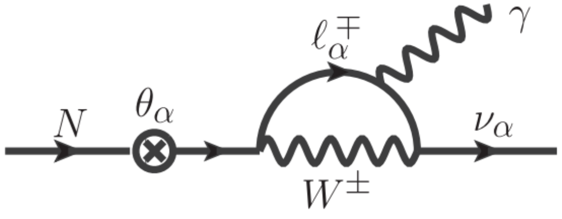
Sterile neutrino DM are produced out of equilibrium via mixing with active neutrinos and then redshifted to nonrelativistic velocities in the radiation-dominated epoch

→ **WARM DM** (but other production mechanism proposed for CDM)

Sterile neutrinos are decaying DM (but very long half life)



Decay to three active neutrinos (main mode)



Decay to one neutrino plus a quasi-monochromatic photon

Signature: γ-ray with $E_\gamma = \frac{M}{2}$

Detection Strategy: Look for gamma lines at X-ray quiet and DM dominated objects (like dwarf Spheroidals)

Axions

MORE ON THIS ON MAURIZIO's LECUTRES TOMORROW

Postulated to solve the Strong CP problem:

$$\mathcal{L}_{QCD} = \ \ldots + \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

The QCD lagrangian has a CP-violating term but the **neutron dipole is 10 orders of magnitude smaller than we expect if strong force violates CP**

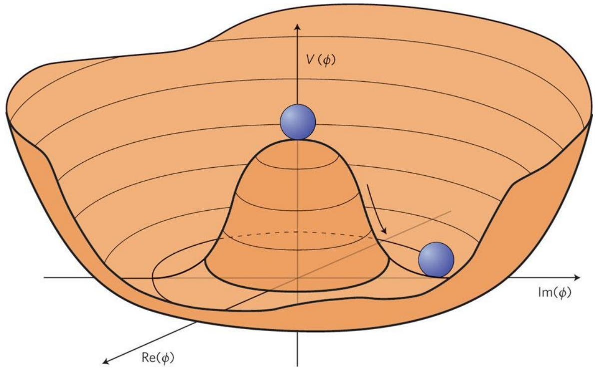
→ θ term of SM is bounded to very small values ($\theta < 10^{-10}$)

Peccei-Quinn Solution:

Add a new $U(1)_{PQ}$ global symmetry, spontaneously broken at a scale f_A. The associated Nambu-Goldstone boson (**the axion**) absorbs θ and dynamically takes a value that respects CP.

Axion field

$$\mathcal{L}_a \ni \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a \frac{A}{f_A}$$



A/f_A relaxes to zero, and therefore CP is conserved "dynamically"

Axion properties:

- Pseudoscalar
- Neutral
- Stable (or almost)
- Very light

$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a} \sim 0.6\ {\rm eV} \left(\frac{10^7\ {\rm GeV}}{f_a}\right)$$

- Coupling inversely proportional to f_A

Axions & ALPS as CDM

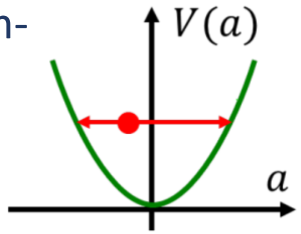
MORE ON THIS ON MAURIZIO's LECUTRES TOMORROW

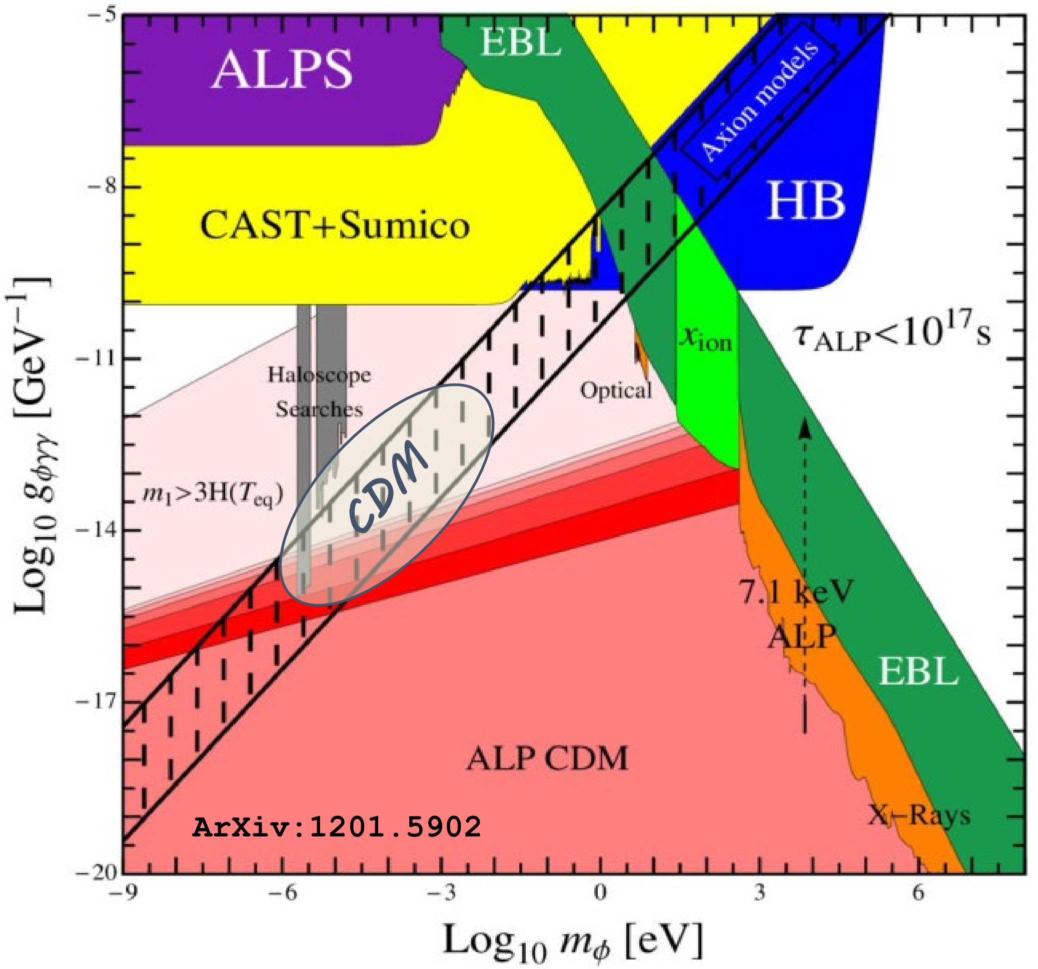
More axion-like particles (**ALPs**) may arise as Nambu-Goldstone Boson from the breaking of more than one anomalous $\boldsymbol{U(1)_{PQ}}$ **.** They have similar phenomenology as Axions, but **do not obey the relationship** $\boldsymbol{m_a \propto f_A}$

Can such ultra-lights particles be CDM?

Yes, they could be produced non-thermally (i.e., they were never in equilibrium with the primordial plasma) in enormous quantities and very low velocities in the early universe

Production mechanisms: vacuum-realignment (oscillating around minimum) and/or via decay of topological defects.





Fuzzy DM

DM as an extremely light (pseudo)scalar particle ($m \approx 10^{-22}$ eV!) e.g. (ultra-light) axion(-like) DM (ULA, ALP)…
Tiny mass ⇒ large numerical density, large de Broglie wavelength ($\lambda \sim 1/m$)

$$\rho_{local} \sim 0.4\ \text{GeV/cm}^3 \rightarrow 4 \times 10^{13} \left(\frac{10\mu eV}{m_a}\right) \text{axions/cm}^3 \quad \text{or} \quad 4 \times 10^{30}\ \text{fuzzy particles/cm}^3$$

$$\lambda_{dB} = \frac{h}{mv} = \frac{4.135 \times 10^{-15} eV/s}{\frac{m_a}{c^2} \times 250 \frac{\text{km}}{\text{s}}} = \frac{1.5\ km}{m_a\ (en\ \mu eV)}$$

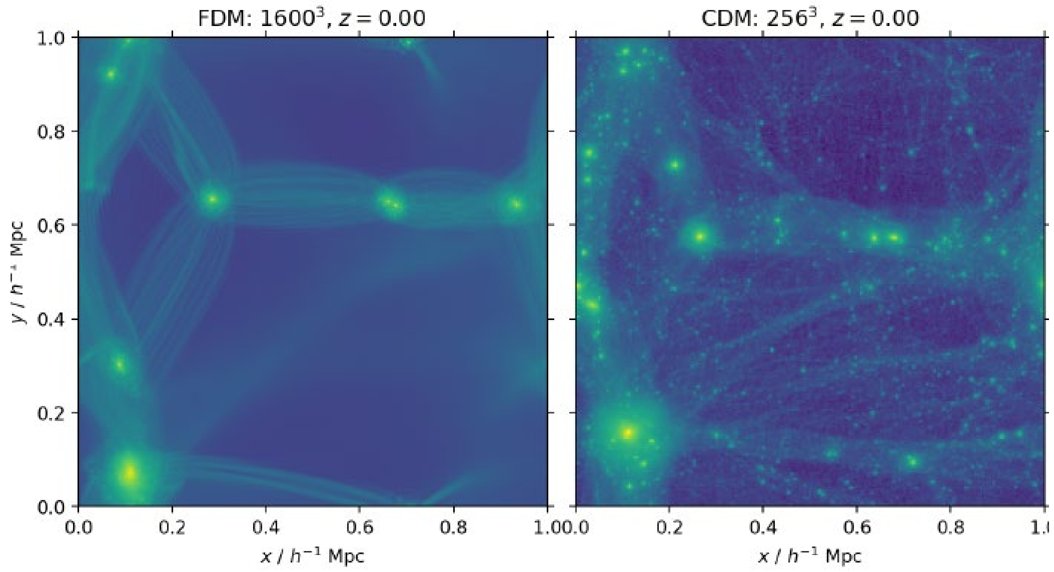
$$m_a = 1\mu eV \rightarrow \lambda_{dB} = 1.5\ km$$

$$m_a = 10^{-22} eV \rightarrow \lambda_{dB} = 0.48\ kpc$$ **"FUZZY"**

(MW radius: 30-40 kpc)

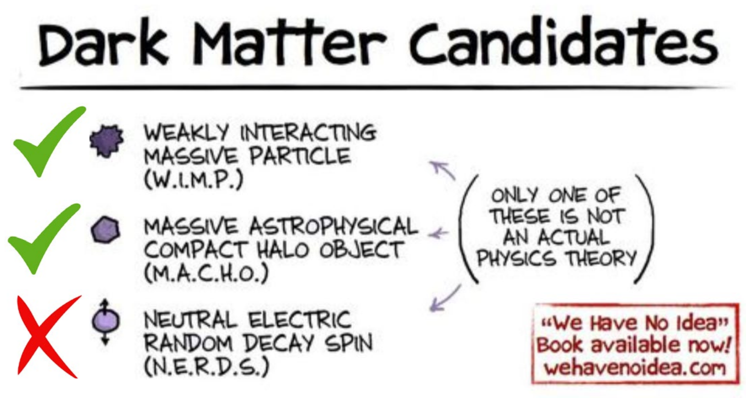
⇒ macroscopic quantum (wave) effects on kpc scales

Small-scale (sub-)structure suppressed compared to CDM

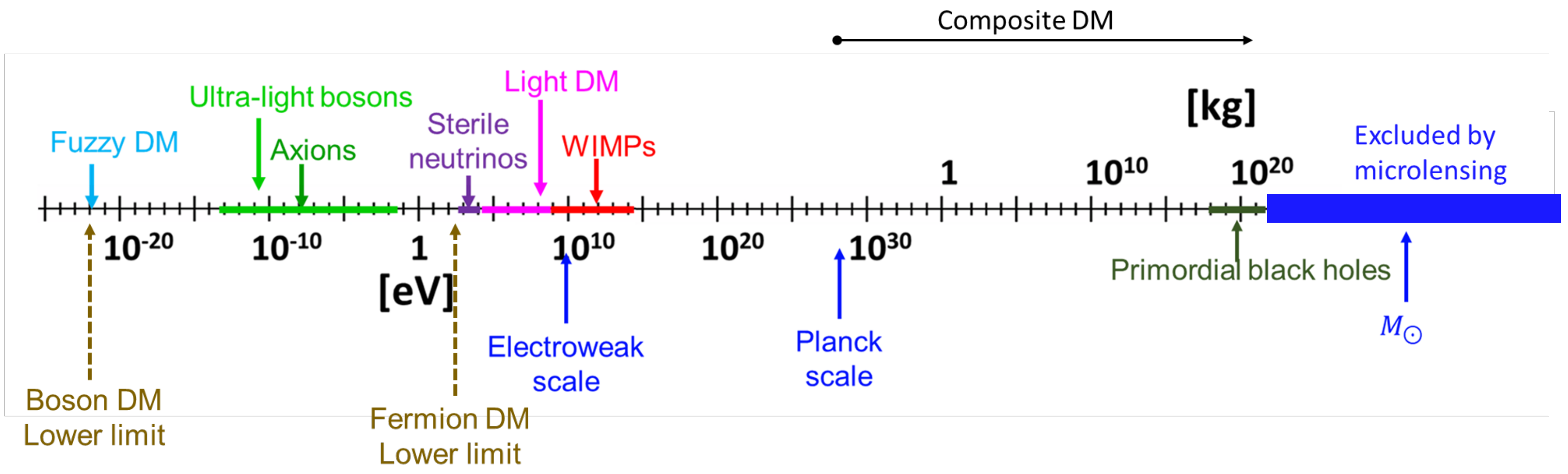


Simon May, Santander DM conference 2023

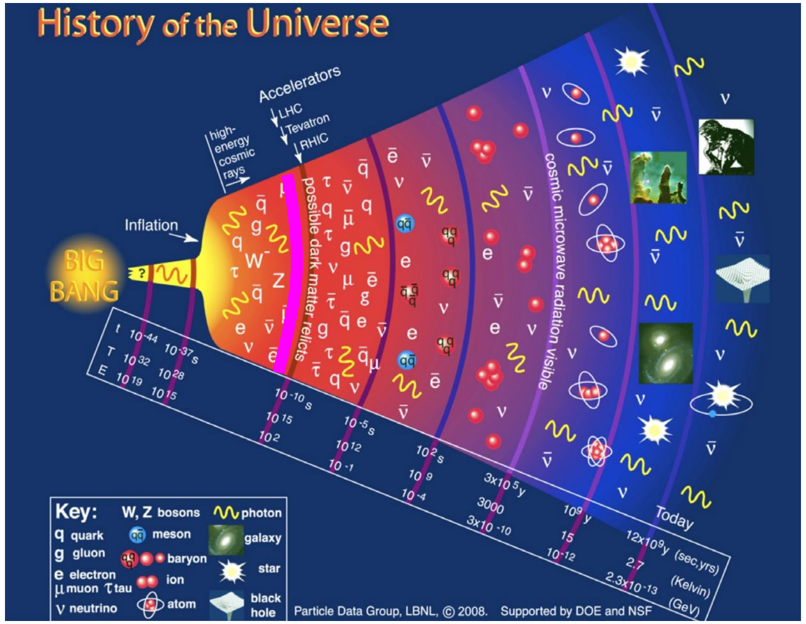
Weakly interacting massive particles (WIMPS)

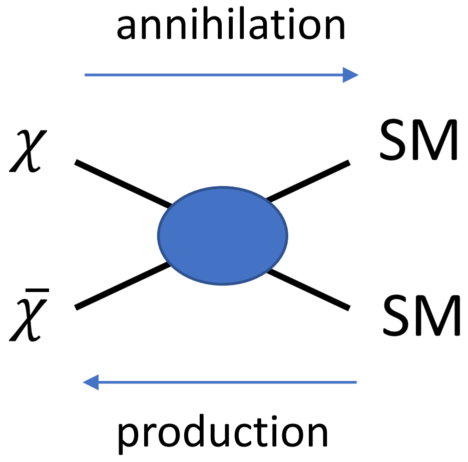


(yes, NERDs are (by now) not a DM candidate)



Thermal evolution





In the early Universe DM particles (χ) are assumed to be in thermal equilibrium with the plasma at temperature $T \ll m_\chi$

The DM number density is given by the Boltzmann equation:

n_χ: particle number density
n_{eq}: number density at equilibrium
σ: interaction cross section
v: relative velocity projectile/targets
H: Universe expansion rate =

[after simplifications]

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v \rangle (n_\chi^2 - n_{eq}^2)$$

Dilution due to expansion

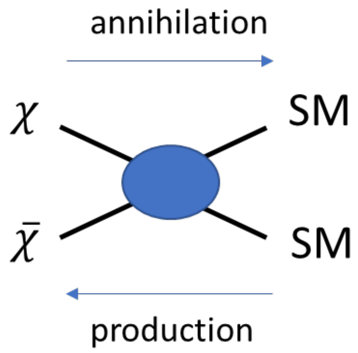
Dilution due to annhilation

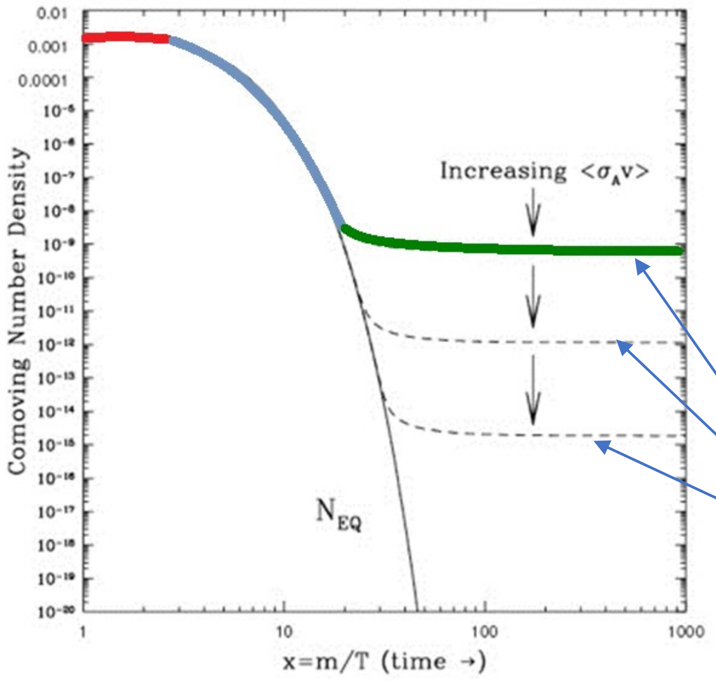
production

Thermal freeze-out (cold relic)

n_χ: number density
Γ: Rate for annihilation of χ

At the very beginning all the particles were in thermal equilibrium in a primordial plasma





Jungman *et al* hep-ph/9506380

- At $T > m_\chi/3$ $\quad \Gamma = n_\chi \langle \sigma v \rangle \ll H$

  mean-free-path much smaller than the Hubble radius

- At $T \approx m_\chi/3$

  $n_\chi \propto \exp(-\frac{m_\chi}{T})$ [non relativistic]

- When the condition $\Gamma \sim H$ is reached, it decouples from the primordial plasma → **it freezes-out**

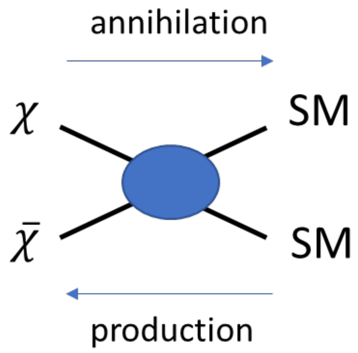
Γ depends on the particle, so the relation is broken at different times for the different species

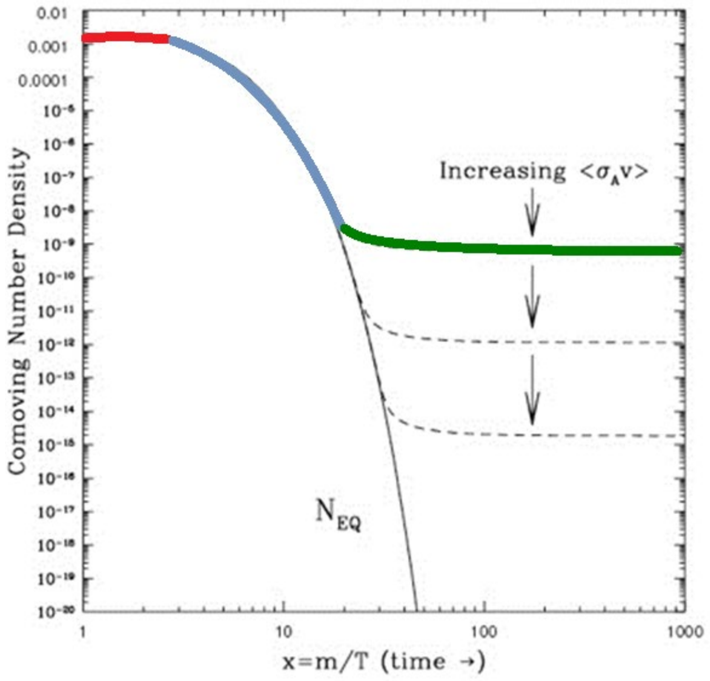
$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\text{pb}}{\langle \sigma v \rangle} \right)$$

$\Omega_\chi = \rho_\chi / \rho_{crit}$: present average densitiy of χ divided critical density
h: Hubble constant in units of 100 km/sec MPc

Thermal freeze-out and the WIMP miracle

At the very beginning all the particles were in thermal equilibrium in a primordial plasma





Jungman *et al* hep-ph/9506380

$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\text{pb}}{\langle\sigma v\rangle}\right)$$

The full DM relic abundance ($\Omega_\chi h^2 \sim 0.1$) is obtained for:

$$\langle\sigma v\rangle \simeq \frac{1}{10^9 GeV^2}$$

minimum annihilation cross section for a thermal candidate (a lower cross section will produce overabundance)

→ a O(weak scale) annihilation cross section and a weak-scale mass leads to a thermal relic DM candidate.

Such a candidate is called a **WIMP** (Weakly Interacting Massive Particle)

Thermal production mass bounds

- **Upper bound**: Unitarity of the scattering matrix [K. Griest and M. Kamionkowski, Phys. Rev. Lett. 64, 615 (1990)]

$$\sigma = \sum \sigma_J \qquad \sigma_J \leq \frac{4\pi(2J+1)}{m_\chi^2 v_{rel}}$$

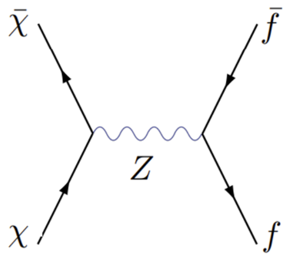
Partial-wave unitarity provides a maximum possible cross section and therefore a minimum possible $\Omega_\chi h^2$ for a given m_χ

$$\rightarrow m_\chi < 340\ TeV$$

(going to larger masses requires DM to be composite state)

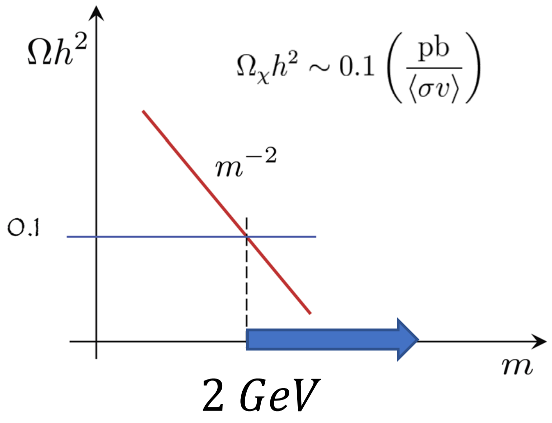
But non-thermal dark matter evades the unitarity argument and is often much heavier!

- **Lower bound**: Lee-Weinberg Bound for Weak interaction [B. Lee and S. Weinberg, Phys. Rev. Lett. 39, 165 (1977)]



$$\mathcal{L} \sim G_F[\bar{\chi}\Gamma\chi][\bar{f}\Gamma f] \quad \rightarrow \langle\sigma v\rangle \sim \frac{G_F^2 m_\chi^2}{\pi}$$

(Fermi limit)



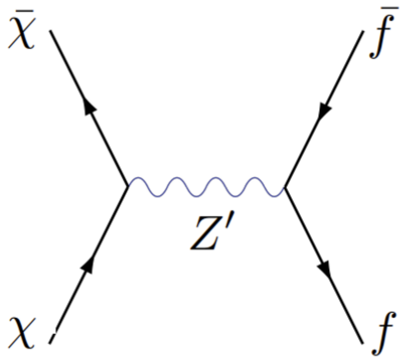
To avoid overdensity

$$m_\chi > 2\ GeV$$

Sub-GeV Thermal DM

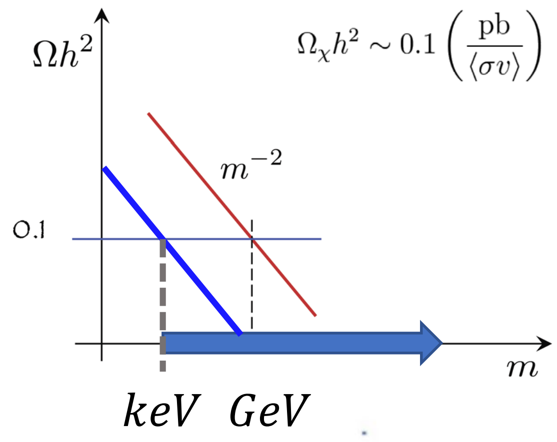
Weak interactions lead to overabundance for sub-GeV DM (strong force is even more constrained!)

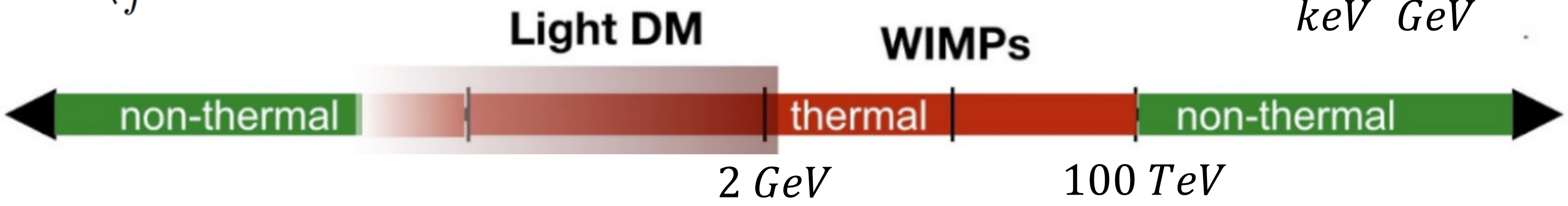
→ **We need new (light) mediators below the weak scale (Dark Sector)**



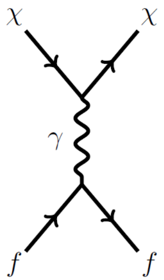
$$\langle \sigma v \rangle \sim \frac{g_\chi^2 g_f^2 m_\chi^2}{m_{Z'}^4}$$

For a light mediator $\langle \sigma v \rangle$ increases





NOTE: can be the photon this mediator?

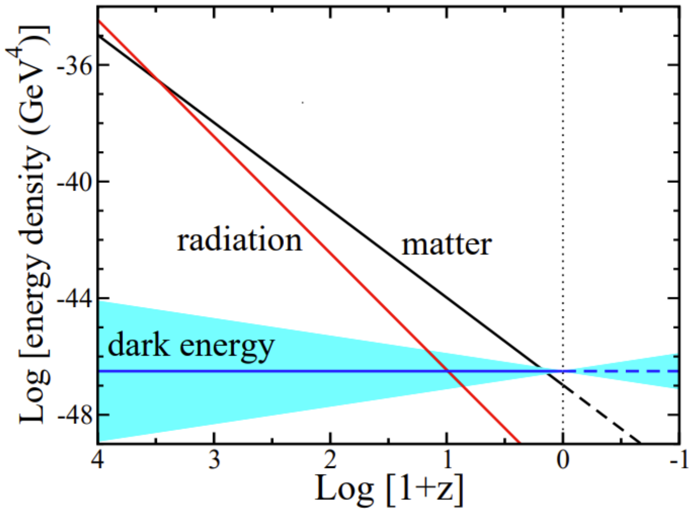


DM candidate with small, fractional electric charge $Q \ll 1$, (millicharged or minicharged DM)

But in general bounds in the charge impose by the expected imprint of their behavior in the early universe in the growth of DM structure and CMB anisotropies exclude the range acceptable to explain the relic density

Miracle assumptions

- **DM can only annihilate and be created in pairs into SM pairs**.
  Exceptions include co-annihilation (DM annihilates against other (heavier) states $\chi\chi' \to ff$) or SIMPs (models with $\chi\chi\chi \to \chi'\chi' \to ff$)
- **There is no DM particle-antiparticle asymmetry ($n_\chi = n_{\bar{\chi}}$)**.
  But there could be an asymmetry in the number density of χ and $\bar{\chi}$, similar to the baryons. Then, the relic density depends on both the annihilation rate and the asymmetry (Asymmetric DM)
- **The DM is in thermal equilibrium and then decouples while the Universe is radiation dominated**. If freeze-out occurs in a matter dominated era, $\langle\sigma v\rangle$ could be smaller. It could get around the need for new light mediators for sub-GeV thermal candidates.
- **The DM particles life time is O(the age of the Universe)**.
  DM WIMPs could be produced in the decay of other particles, thermal or not, or WIMPs could be unstable and decay into the DM after they decouple.



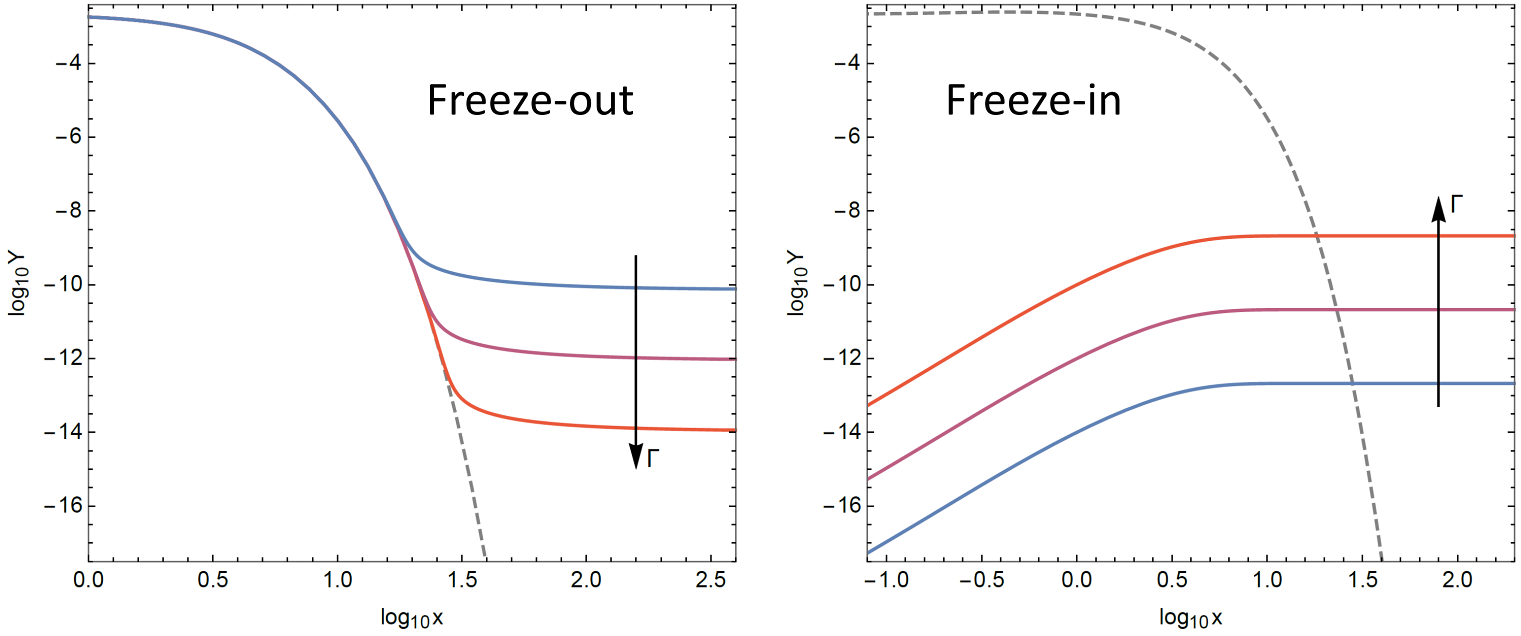
A change in any of these assumptions could lead to a very different relic abundance!

Alternative production mechanisms

- Freeze-in: *sterile neutrinos, gravitinos, FIMPs*
- Asymmetric freeze-out: *hidden sector models*
- Decay of meta-stable WIMPs: *SUPERWimps*
- Non thermal production:
  - Collapse of density perturbations: *PBH*
  - Boson condensates: *axions, ALPs*
- *…*

Freeze-in (FIMPs)

The DM particle couples to the visible SM sector very weakly, so that it never entered chemical equilibrium. The DM particles were produced by decay or annihilation processes from the visible sector, until the production ceased due to cooling below the relevant mass scale connecting the DM particle to the visible sector.



Feeble interacting Massive Particles (FIMPs)

The weakness of interactions between the DM and the SM particles in the freeze-in scenario implies that these models are inherently very difficult to search for in direct detection or collider experiments. But some signatures can be searched for.

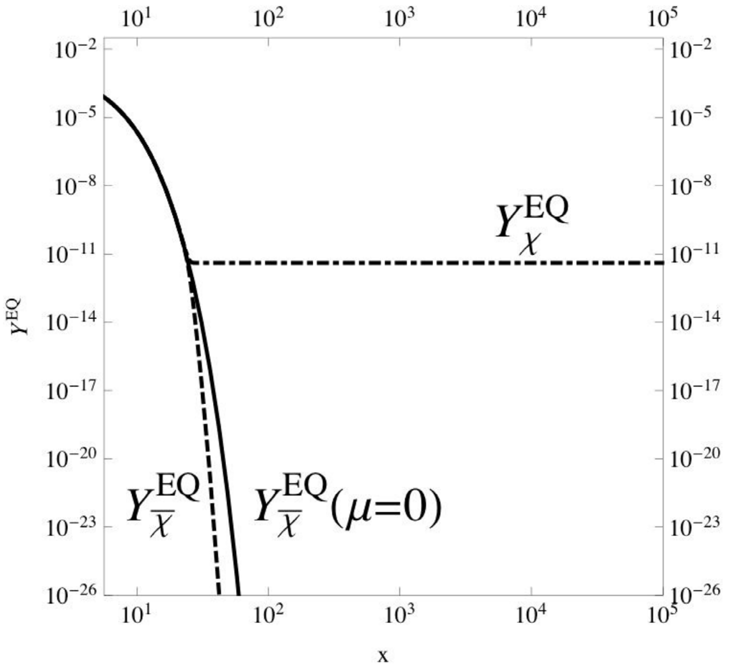
Models & signatures : "The Dawn of FIMP Dark Matter: A Review of Models and Constraints" arXiv:1706.07442v2

Asymmetric Dark Matter

Asymmetry in the number density of χ and $\bar{\chi}$

Appealing because could be a key to understand baryon asymmetry (even more when $\Omega_{DM} \sim \Omega_b$)

The simplest models assume a similar asymmetry of the DM and baryons, thus their relic number densities are similar. This implies $m_{DM} \sim 5\ GeV$



Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}}v\rangle\left(n_\chi n_{\bar{\chi}} - n_\chi^{EQ} n_{\bar{\chi}}^{EQ}\right).$$

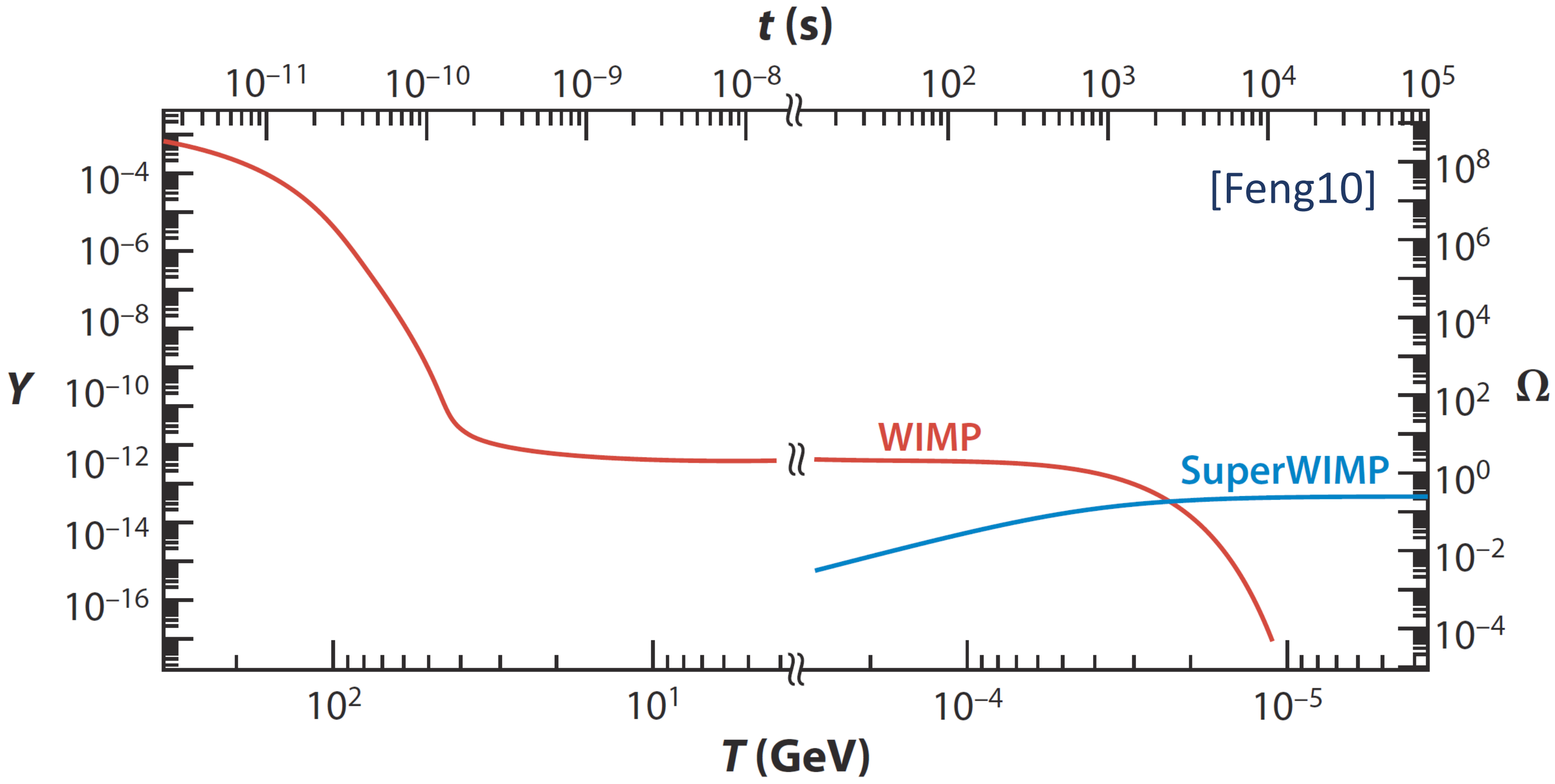
In the standard cosmology (i.e. assuming radiation domination at decoupling and entropy conservation) the relic density of the minority component is exponentially small with respect to the majority component density, which means that there is no DM annihilation after decoupling.

S. Nussinov, Phys. Lett. B 165 55 (1985).
G. Gelmini, L. Hall and M. Lin, Nucl. Phys. B 281 (1987) 726.

SUPERWimps (superweakly interacting massive particles)

WIMPs freeze out as usual in the early Universe, but are meta-stable and later decay to produce superWIMPs, which form the dark matter that exists today

$$\Omega_{\rm SWIMP} = \frac{m_{\rm SWIMP}}{m_{\rm WIMP}} \Omega_{\rm WIMP}.$$

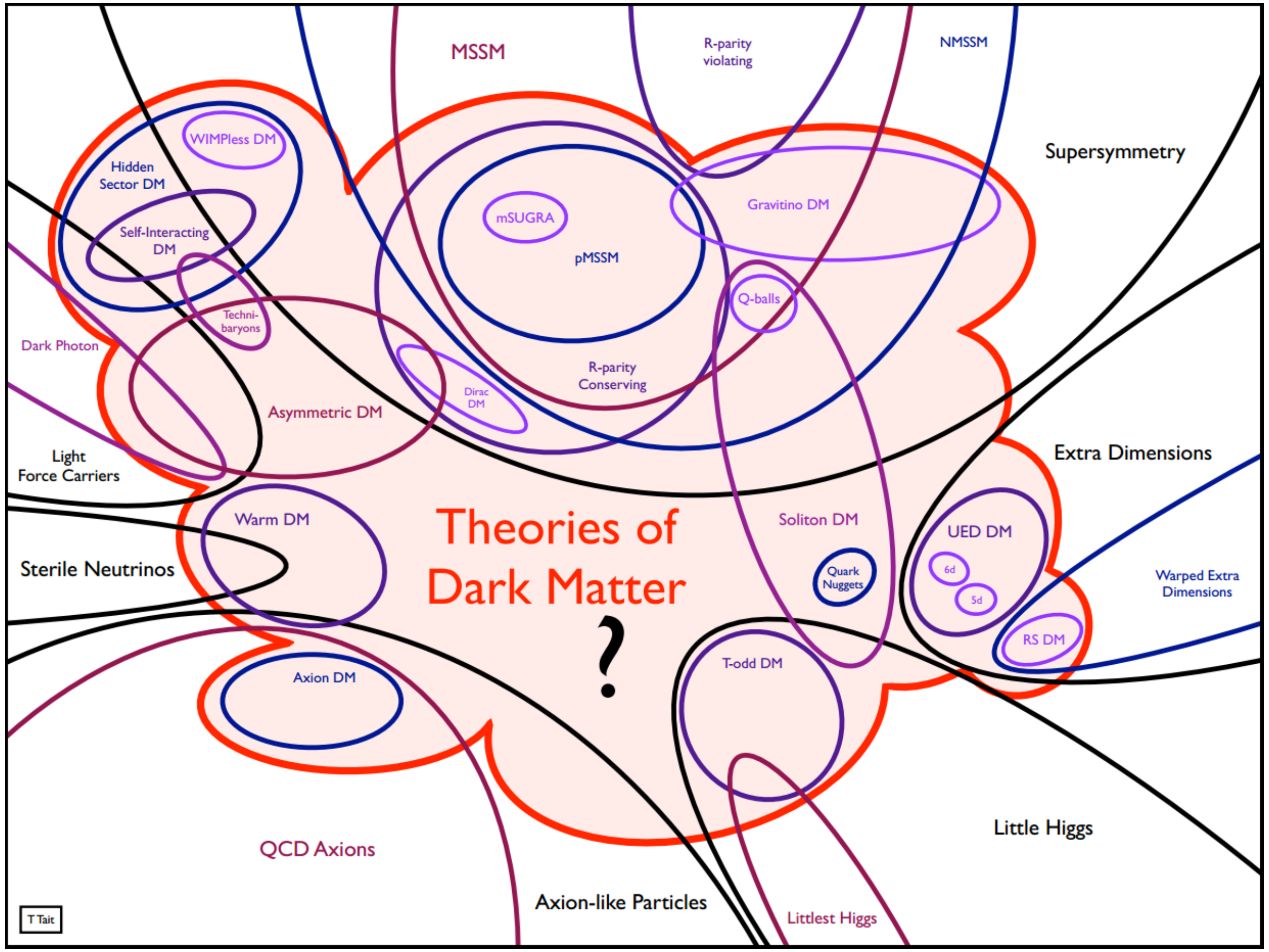


Candidates: Gravitino, axino …

DM models

There are many BSM theories trying to solve SM problems, that provides with DM candidates

Light DM



Axions and ALPS

WIMPs

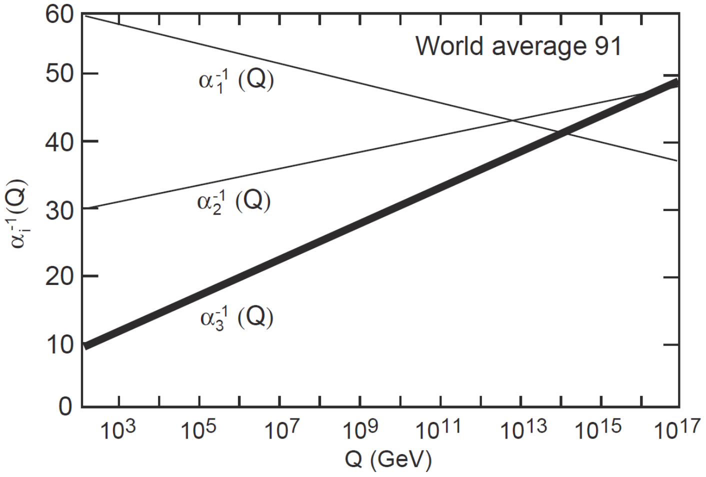
- **Supersymmetry**
- Additional dimensions
- Little Higgs
- …

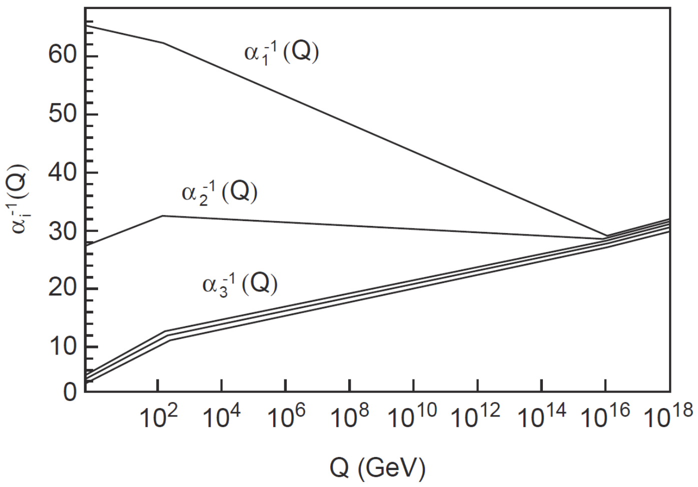
Supersymmetry: motivation

hierarchy problem: There is an enormous difference between the electroweak and Planck energy scales.
This problem arises in the **radiative corrections to the mass of the Higgs boson**. All particles get radiative corrections to their mass, but while fermion masses increase only logarithmically, **scalar masses increase quadratically** with energy. Supersymetry removes these divergences introducing a new symmetry:

$$Q|\text{fermion}\rangle = |\text{boson}\rangle; \quad Q|\text{boson}\rangle = |\text{fermion}\rangle$$

Another reason for interest in supersymmetric theories comes from the unification of gauge couplings. the three gauge couplings run in such a way that they are nearly all the same value at a high scale, $\sim 10^{16}\ GeV$ but the Standard Model alone fails to unify them to a common value. By introducing supersymmetry at the TeV scale, these forces naturally unify.





Supersymmetric extensions of the SM

There are many ways in which one can imagine embedding the SM within supersymmetry, the one which requires the introduction of the smallest number of superpartners is called the **Minimal Supersymmetric Standard Model (MSSM)**

In the MSSM, the exact discrete symmetry R-parity defined as $R \equiv (-1)^{3B+L+2s}$ is conserved → the lightest supersymmetric particle is stable (LSP), and is a DM candidate.

Despite being the simplest one, the MSSM has more than 100 free parameters (mass, mixing angles…), so it is common to work with simplified models. The most popular model for supersymmetric studies is minimal supergravity (mSUGRA/CMSSM), which is minimal in the sense that it includes the minimum number of particles and includes a large number of assumptions that drastically reduce the number of independent model parameters. Minimal supergravity is defined by five parameters:

$$M_0, M_{1/2}, A_0, tan\beta, sign(\mu)$$

The most important parameters are the universal scalar mass M_0 , the universal gaugino mass $M_{1/2}$ (both defined at the scale of grand unified theories $M_{GUT} \simeq 2 \times 10^{16} GeV$) and A_0(coupling between Higgses and scalar fermions)

Particles in the MSSM

- Introduce one additional Higgs field (for a total of **two Higgs doublets**, corresponding to five physical Higgs states) and associate spin 1/2 *Higgsinos* to the Higgs boson.
- Associate fermionic superpartners to all gauge fields. Gluons, $W^{\pm}$ and B bosons then get fermionic partners called *gluinos* ($\tilde{g}$), *winos* ($\widetilde{W}^{i}$) *and binos* ($\tilde{B}$), respectively.
- Associate scalar partners to the fermions, i.e. quarks and leptons get scalar partners called *squarks* and *sleptons*.

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	Quark	$\tilde{q}_L, \tilde{q}_R$	Squark	$\tilde{q}_1, \tilde{q}_2$	Squark
$l = e, \mu, \tau$	Lepton	$\tilde{l}_L, \tilde{l}_R$	Slepton	$\tilde{l}_1, \tilde{l}_2$	Slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	Neutrino	$\tilde{\nu}$	Sneutrino	$\tilde{\nu}$	Sneutrino
g	Gluon	$\tilde{g}$	Gluino	$\tilde{g}$	Gluino
$W^{\pm}$	W-boson	$\tilde{W}^{\pm}$	Wino		
H^{-}	Higgs boson	$\tilde{H}_1^{-}$	Higgsino	$\tilde{\chi}_{1,2}^{\pm}$	Chargino
H^{+}	Higgs boson	$\tilde{H}_2^{+}$	Higgsino		
B	B-field	$\tilde{B}$	Bino		
W^3	W^3-field	$\tilde{W}^3$	Wino		
H_1^0	Higgs boson			$\tilde{\chi}_{1,2,3,4}^{0}$	Neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	Higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	Higgsino		

SUSY DM Candidates

The requirement that DM be electrically neutral leads to three different DM candidates within SUSY:

1) sneutrinos: scalar superpartner of the SM neutrinos. They are not good dark matter candidates, as both their annihilation and scattering cross sections are large, and so they are underabundant or excluded by null results from direct detection experiments for all masses near m_{Weak} . Could be an inelastic DM candidate?

2) **Neutralino**: spin 1/2 fermions that are the mass eigenstates made from the higgsinos, winos and bino. They are the most common DM candidate in SUSY and their properties depend on how these states mix to form the mass eigenstates.

3) Gravitino: spin 3/2 fermionic partner of the spin-2 graviton: the spin-3/2 gravitino. Is not a WIMP (no thermal production) but could be a viable FIMP

For many years, the neutralino (χ) has been the standard DM candidate

A review:

G. Jungman, M. Kamionkowski, K. Griest, "Supersymmetric Dark Matter", Phys. Rep. 267 (1996) 105

Other theories for WIMPs

Kaluza-Klein and extra-dimensional theories

An alternative possibility for new weak-scale physics is extra dimensions: all particles propagate in flat, compact (size 10^{-18} m or smaller) extra dimensions. In the simplest model there is **one extra dimension compactified on a circle of size $\boldsymbol{R}$**. **Every SM particle has an infinite number of partner particles**, with one at every Kaluza-Klein (KK) level *n* with mass $\sim nR^{-1}$. In contrast to supersymmetry, these partner particles have the same spin.

Provide an alternative to SUSY, but do not solve the gauge hierarchy problem; These theories are a low-energy approximation to a more complete theory

The simplest models preserve a discrete parity (KK-parity) → the lightest KK particle (LKP) is stable and a possible dark matter candidate

The LKP is typically B^1 , the level 1 partner of the hypercharge gauge boson. The mass scales with the correct B^1 thermal relic density is $\boldsymbol{600\ GeV \leq m_{B^1} \leq 1.4\ TeV}$

Cheng HC, Feng JL, Matchev KT. 2002. *Phys. Rev. Lett.* 89:211301
Servant G, Tait TMP. 2003. *Nucl. Phys. B* 650:391–419

Other theories for WIMPs

Little Higgs

Another alternative mechanism to supersymmetry to stabilize the weak scale. Propose that **the Higgs boson is a pseudo-Goldstone boson arising from some global symmetry breaking at a TeV energy scale**. The divergences to the Higgs mass which remain are present only at the two-loop level and, therefore, the weak scale can be stabilized in an effective field theory which is valid up to ~ 10 TeV.
[NOTE: in Susy the divergences to the Higgs mass are exactly cancelled at all orders]

Many models. Two of them (at least) can contain dark matter candidates:

- "theory space" little Higgs models provide a possibly stable scalar particle which can provide the measured density of dark matter . Two mass regions are found providing WIMP candidates, the first region corresponding to **O(100 GeV),** the second region is for mass greater than **O(500 GeV).**

A. Birkedal-Hansen and J.G. Wacker, Phys. Rev. D **69**, 065022 [arXiv: hep-ph/0306161v2]

- Cheng and Low little Higgs model, solve the hierarchy problem between the electroweak scale and the masses of new particles constrained by electroweak precision measurements by introducing a new symmetry at the TeV scale which results in the existence of a stable WIMP candidate with a **~ TeV mass**.

H.C. Cheng, I. Low, JHEP 0309 (2003) 51 [arXiv:hep-ph/0308199].