Some dark matter candidates

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Some dark matter candidates

- To talk about particle dark matter, we need to have some "culprits" in mind

- Here are some popular candidates
  - WIMPs
  - Sterile Neutrinos
  - Axions
  - Primordial black holes

Neutrinos as dark matter

The earliest discussion of the role of neutrinos in cosmology appeared in a 1966 paper by S. S. Gershtein and Ya. B. Zeldovich [132]. To many scientists working in fields of cosmology and particle-astrophysics, it will be no surprise to see Zeldovich's name attributed to this pioneering work. Yakov Borisovich Zeldovich was an utterly prolific and versatile physicist, making major contributions to the fields of material science, nuclear physics (including the Soviet weapons program), particle physics, relativity, astrophysics, and cosmology. In terms of research at the interface between particle physics and cosmology, it can sometimes seem like Zeldovich did almost everything first.

Despite the very interesting and important results of these papers, it is notable that most of them did not attempt to address, or even acknowledge, the possibility that neutrinos could account for the missing mass observed by astronomers on galactic and cluster scales. Exceptions to this include the 1976 paper of Szalay and Marx, and the 1977 paper of Lee

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and Weinberg, whose final sentence reads as follows [194]:

> *Of course, if a stable heavy neutral lepton were discovered with a mass of order 1-15 GeV, the gravitational field of these heavy neutrinos would provide a plausible mechanism for closing the universe.*

gradually become more appreciated over the years to come. In 1978, for example, a paper by James Gunn, Ben Lee, Ian Lerche, David Schramm, and Gary Steigman included the following statement in their abstract [144]:

> *… such a lepton is an excellent candidate for the material in galactic halos and for the mass required to bind the great clusters of galaxies.*

- But as we discussed. Standard Model neutrinos, are HOT, and too light to account for the dark matter of the Universe

Weakly Interacting Massive Particles (WIMPs)

- In short, WIMPs behaves like a very heavy neutrino with only neutral current interactions

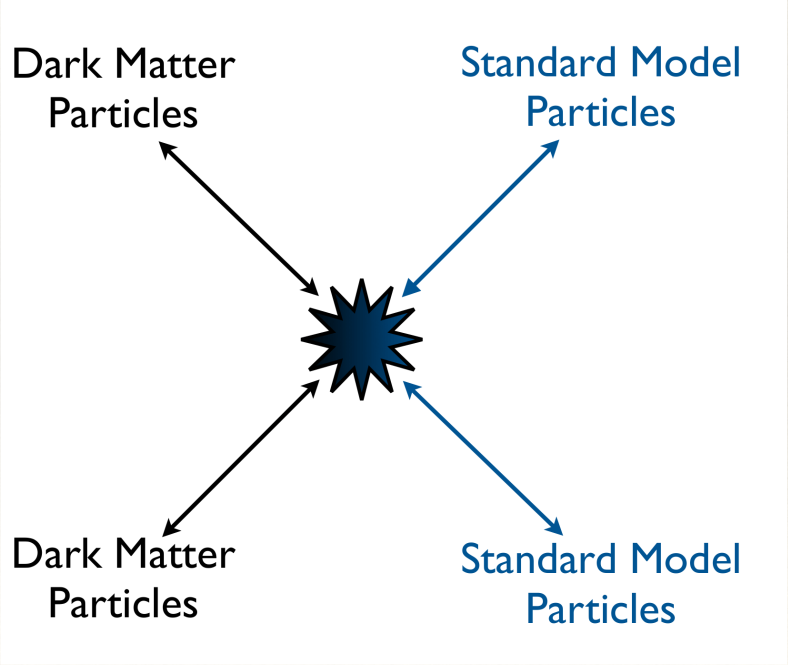
- Recall how we find the current day neutrino abundance
- Before decoupling
  - Neutrino are in thermal equilibrium with the Universe
  - Once the interaction rate falls below the Hubble rate (expansion rate of the universe)
  - Their abundances freezes, and evolve simply as radiation or matter (depending on its mass)
    - Their relative abundance to photons are only affected by electron positron annihilation.

Weakly Interacting Massive Particles (WIMPs)

- For WIMPs
- We assume they have these kind of 2-to-2 interactions
- Assuming they couple to standard model particles f

- That means at high temperatures in the early universe, in particular
- $T \gg m_\chi$
- This reaction is in equilibrium
- $\chi\chi \leftrightharpoons f\bar{f}$

- Note:
  - We dont know whether χ is a Majorana/Dirac Fermion or a boson, which introduces factor of two differences.



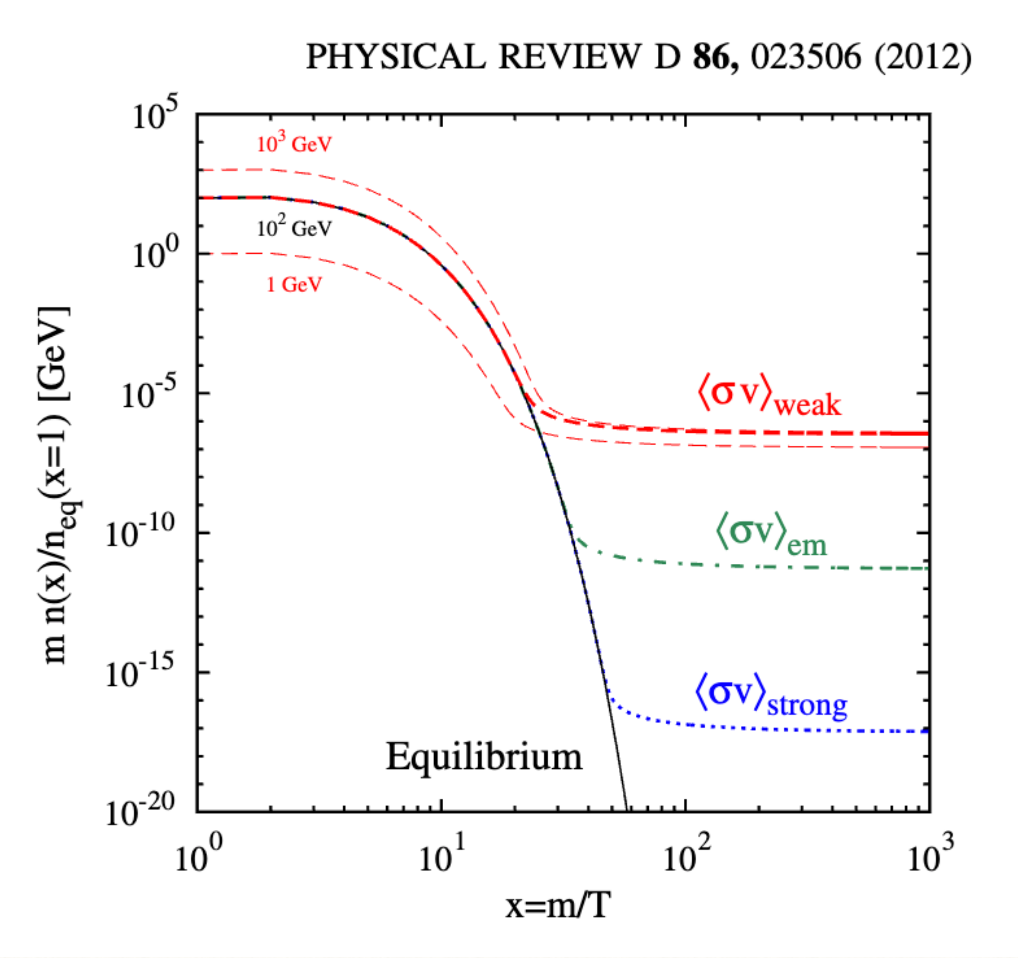
WIMP production

- At high temperature, wimps are in thermal equilibrium
- $\chi\chi \leftrightharpoons f\bar{f}$
- So we know its energy density at a given temperature
    - $\rho_{BE} = g_i \frac{\pi^2}{30} T^4; \rho_{FD} = \frac{7}{8} \rho_{BE}(g_i)$
- Once Temperature drops below m_χ, the reaction becomes one-sided. (This is similar to electron/positron annihilation)
- $\chi\chi \to f\bar{f}$, and this the number density of dark matter drops.

- The number density of dark matter will continue to decrease, until the forward reactions rate drops below the Hubble expansion rate

WIMP production

- The evolution equation
- $$\frac{dn}{dt} + 3Hn = \frac{d(na^3)}{a^3 dt} = \langle \sigma v \rangle (n_{\rm eq}^2 - n^2),$$
- Here n is the number density
- The interaction rate
  - $\Gamma \propto n^2 \sigma v$
  - n^2 because this is self-annihilation
- There are two cases when the RHS is taken as zero
- (1) When the interaction is strong: $n \to n_{eq}$
- (2) When the interaction rate $\Gamma/n \ll H$
  - When (2) happened, it is called a "freeze out"



WIMP miracle

- Turns out the final energy density $\rho_\chi = m_\chi n$, is only weakly dependent on the dark matter mass.

- It is mostly controlled by the cross section
- $< \sigma v >$
  - The bracket represents a thermal averaging, following the condition of the early Universe

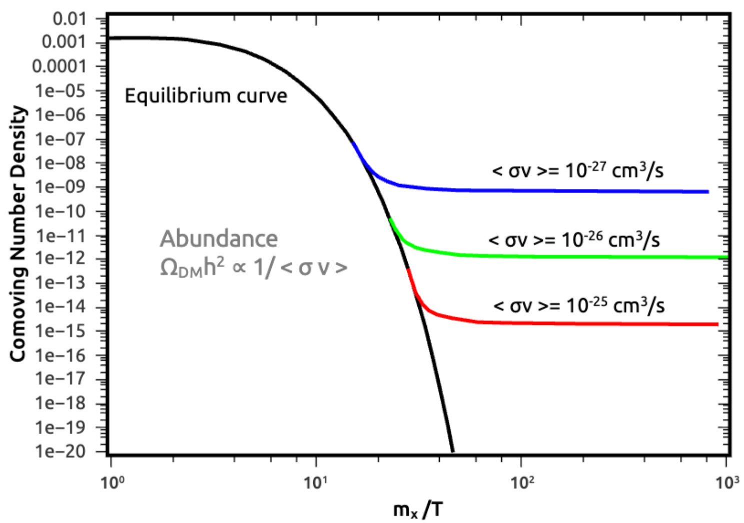
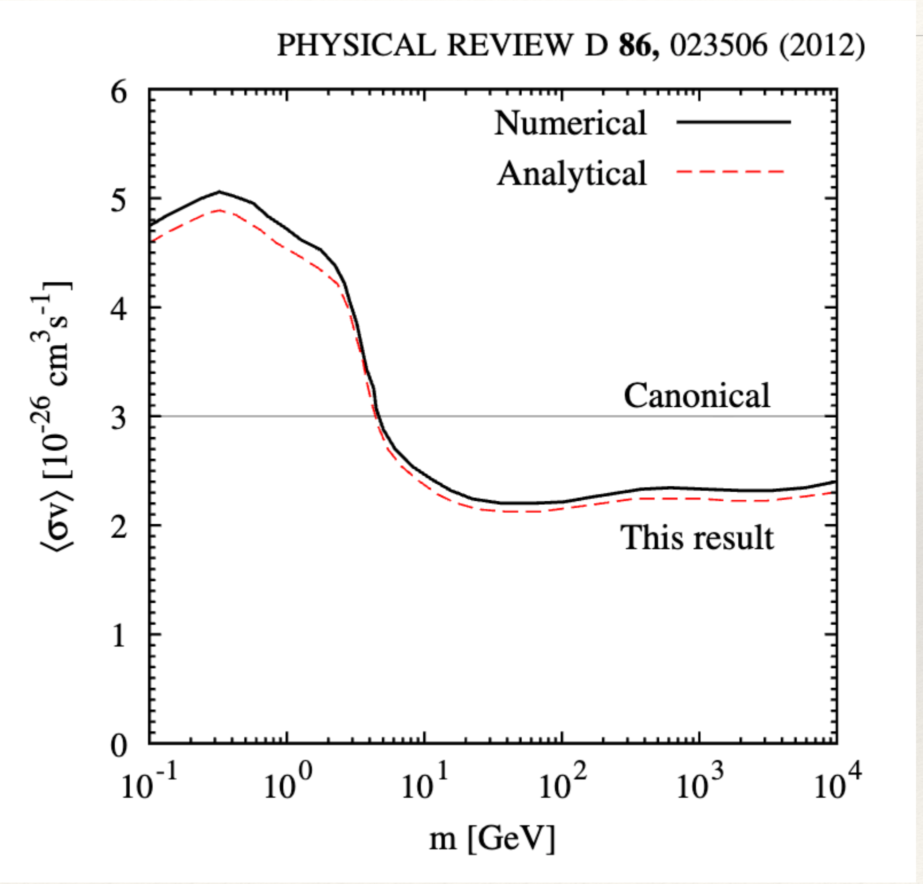


FIG. 1. Comoving number density evolution as a function of the ratio m_χ/T in the context of the thermal freeze-out. Notice that the size of the annihilation cross section determines the DM abundance since $\Omega_{DM} \propto 1/\langle\sigma v\rangle$.

WIMP miracle

- There is a magic number that
- $< \sigma v > \sim 3 \times 10^{-26} cm^3/s$, that corresponds to the current day observed dark matter abundance.
- $\sigma \sim 10^{-36} cm^2$
    - This is neutrino-like cross section!
- Weak-like interaction Physics, could produce the observed dark matter, with a new particle
- Perhaps This new physics, is simply the standard model "weak" interaction?
    - This is called WIMP miracle
    - Originally, the W in WIMP was referring to THE weak interaction

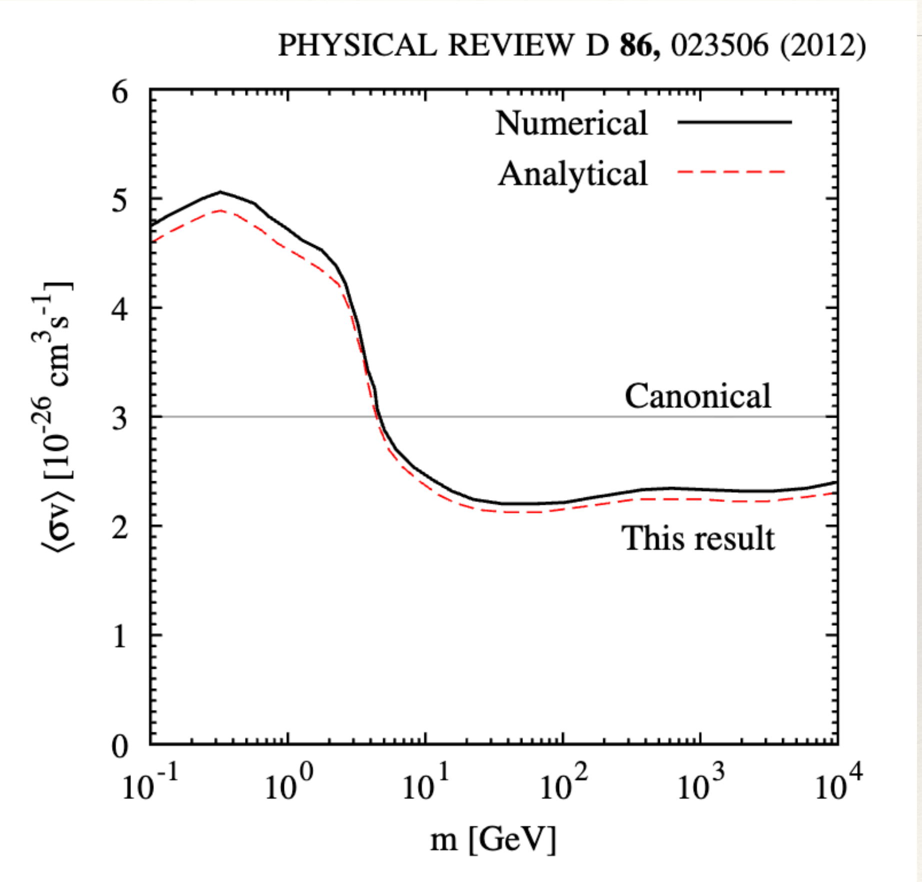


WIMP production

- A "generic WIMP" refers to dark matter that are produced using the freeze out mechanism.

- They must have this particular **total cross section**
- $< \sigma v > \sim 3 \times 10^{-26} cm^3/s$

- Larger than this
  - They freeze out later, not enough to explain the dark matter
- Smaller than this,
  - they "over close" the universe, i.e., too much dark matter, that is super not allowed.



WIMP Motivation

- Easy to cook up models for this
- Just need a interaction that look likes weak interaction, or simply use weak interaction
- For example.
- Supersymmetry

SUPERSYMMETRIC DARK MATTER

G. JUNGMAN[a], M. KAMIONKOWSKI[b,c], K. GRIEST[d]

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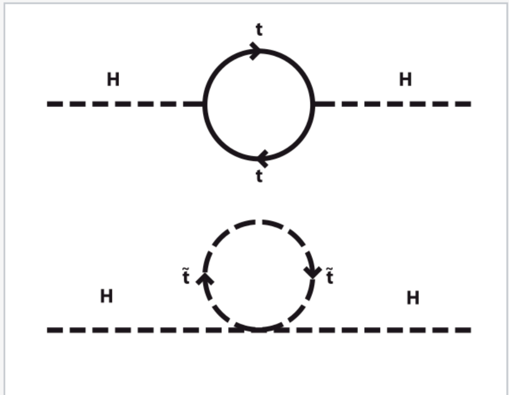
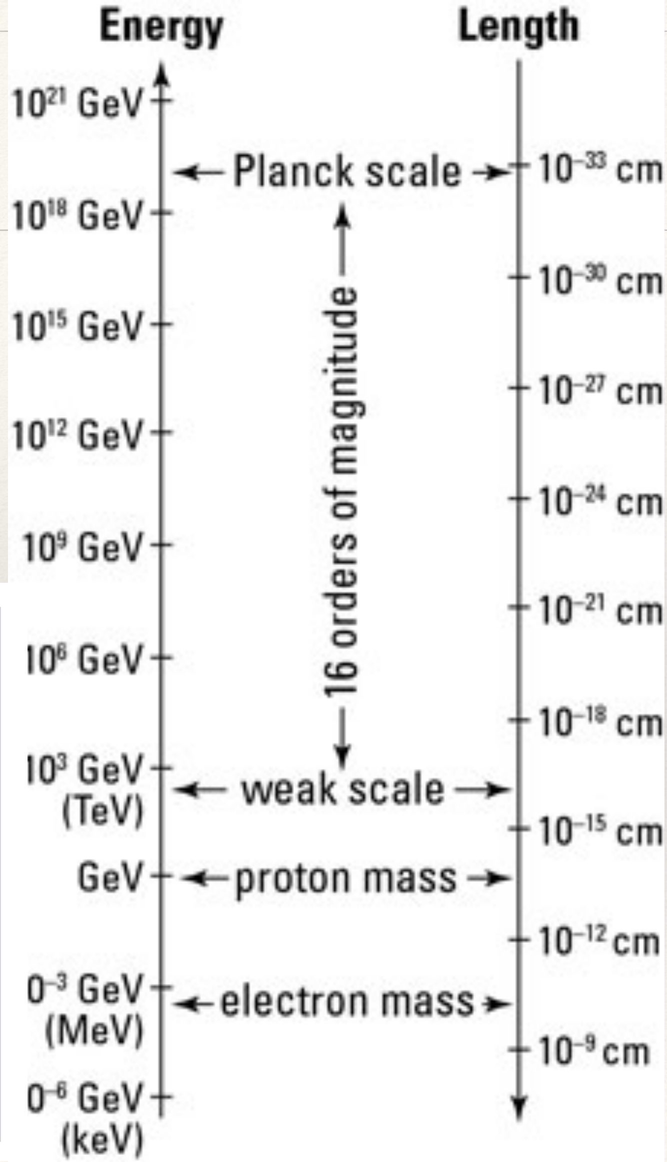
The Hierarchy Problem

- Together with Higgs, the standard model of particle physics have been figured out up to about TeV in energy.
- The theory is self consistent up to Planck scale.

- However, why the Higgs Boson has a mass of about 100 GeV?
- It gets quantum corrections term with the size of Planck mass in the standard Model
  - If there is supersymmetry, then these corrections are cancelled exactly by their super partners.

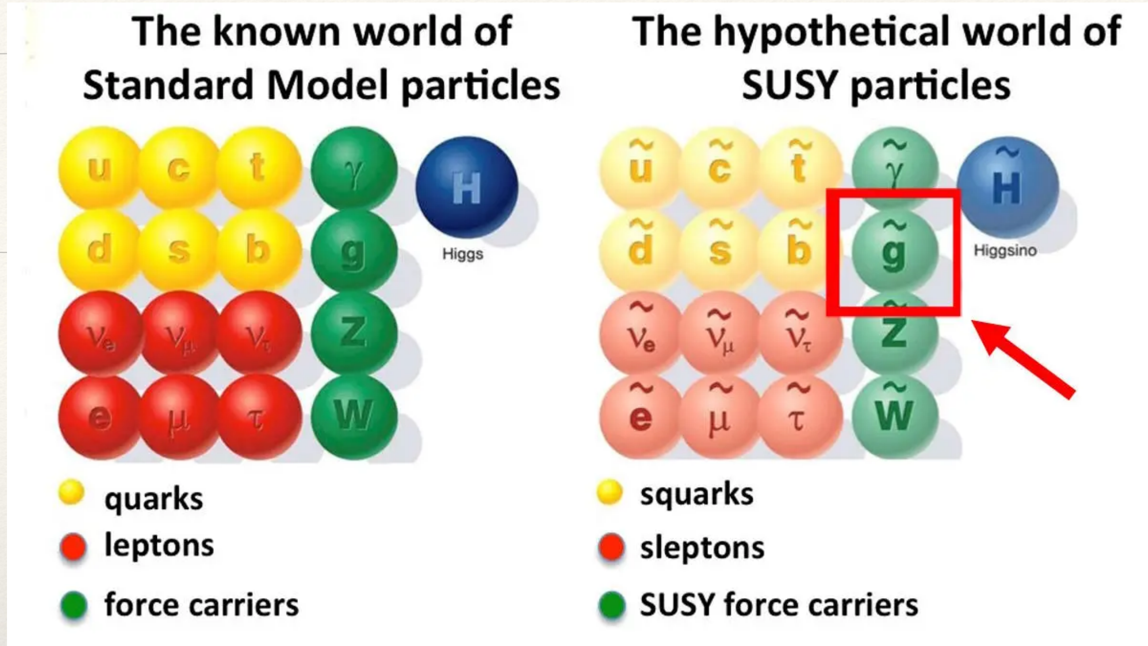


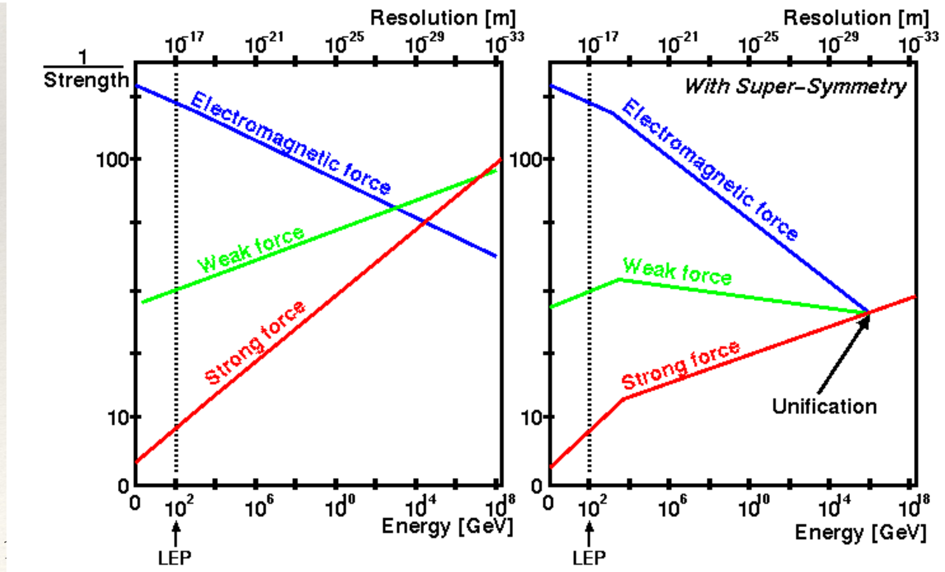
Cancellation of the Higgs boson quadratic mass renormalization between fermionic top quark loop and scalar stop squark tadpole Feynman diagrams in a supersymmetric extension of the Standard Model



Supersymmetry

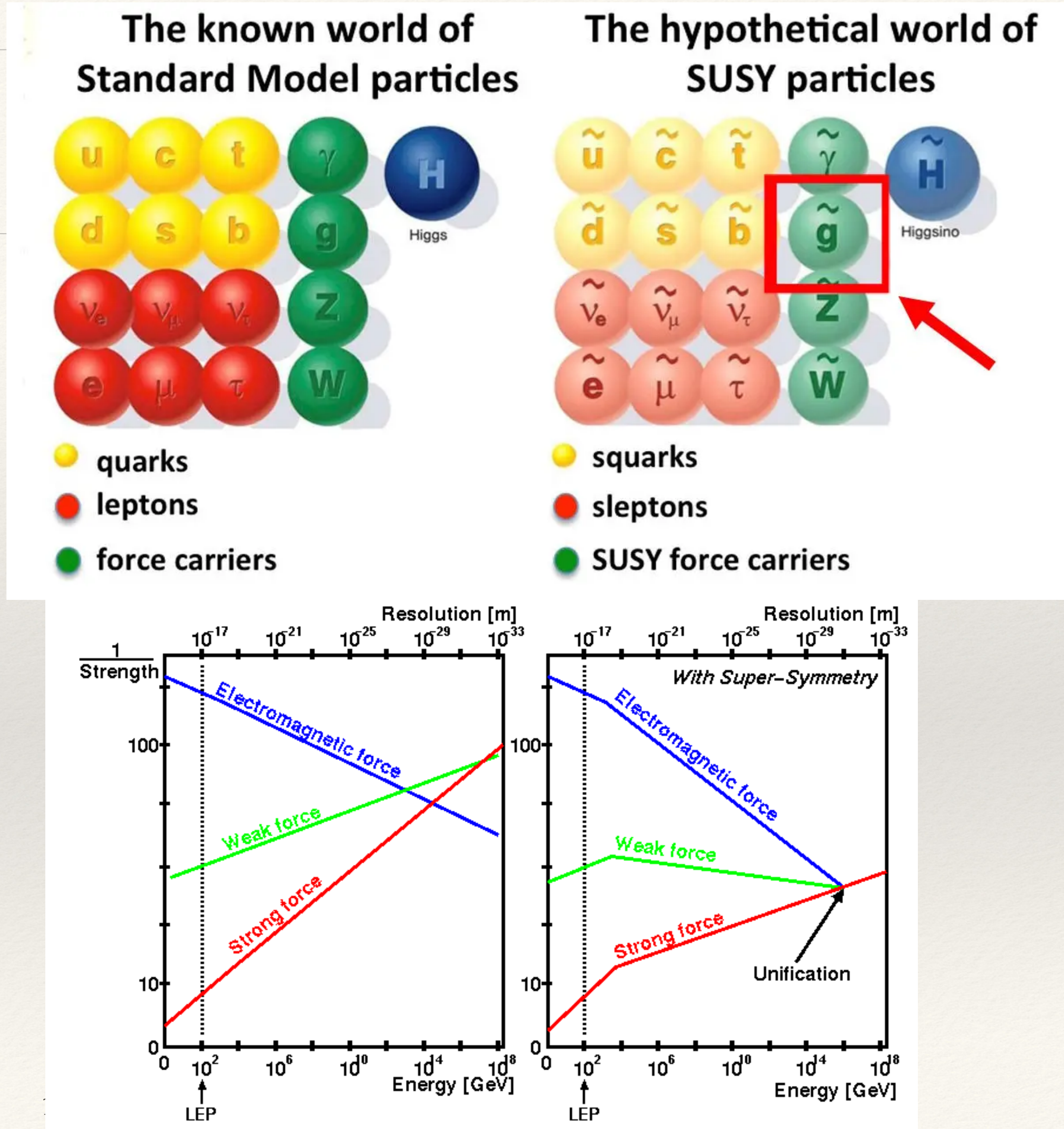
- For each know particle, they also have a super partner with different spins
  - Solves hierarchy problem
- Turns out, the coupling constants, are not constants!
- It cant be calculated how these couplings as a function of energy.
  - If there is supersymmetry, they all approach the same value at high energy (but before Planck)
  - Unification of forces may be possible!
- String theory likes supersymmetry





Supersymmetry

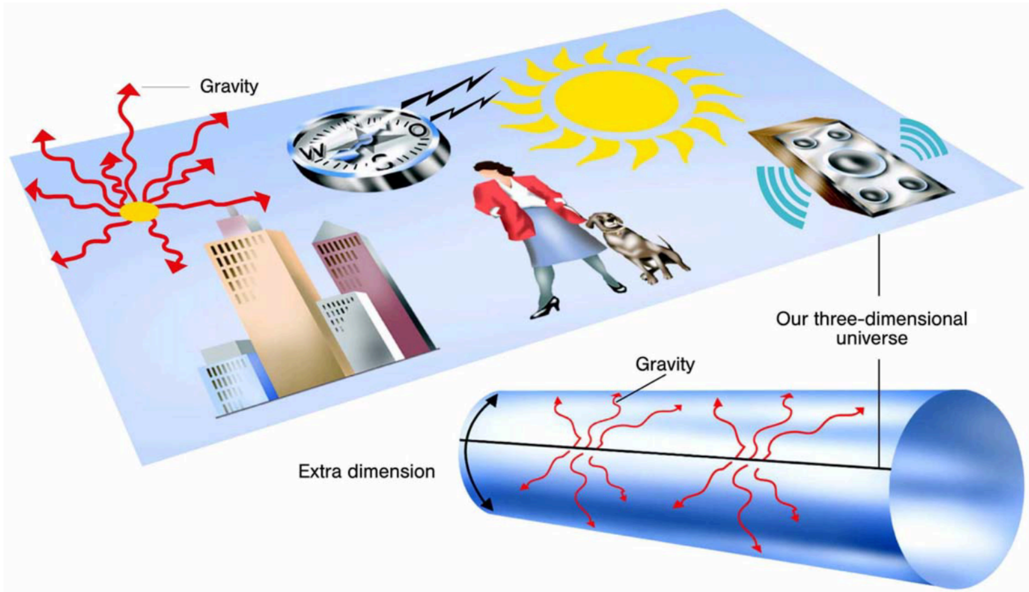
- Dark Matter just need to be a stable light super particle
  - Stablize by some symmetry properties



Large Extra dimensions

4. Extra Dimensions	“Large” Extra Dimensions

- Completely alternative approach to solve the hierarchy problem: ‘There is no hierarchy problem’
- Suppose, the SM fields live in ‘normal’ 3+1D space
- Gravity lives in 4 + δ Dimensions
- δ extra Dimensions are curled to a small volume (radius R):



Large Extra dimensions

- Bring down gravity to TeV
  - Solves hierarchy problem by lowering the Planck scale
- Can be tested in colliders
- Standard model particles could have non-zero modes in the folded dimensions.
  - New particles!
  - Could be a WIMP

4. Extra Dimensions	"Large" Extra Dimensions

For r < R, gravity follows Newtons law in 4+δ dimensions:

$$V(r) = \frac{G_S}{r^{\delta+1}}$$

For r > R, gravity follows effectively Newton's law in 4 dimensions, since the 'distance' in the extra dimensions does not rise anymore:

$$V(r) = \frac{G_S}{R^\delta r} = \frac{G_N}{r} \text{ with } G_N = \frac{G_S}{R^\delta}$$

The Planck-Mass $M^2_{Planck} = \hbar c / G_N$ only effectively appears so high at large distances. The true scale of gravity is

$$M_S^2 = \hbar c / G_S = \hbar c R^\delta / G_N$$

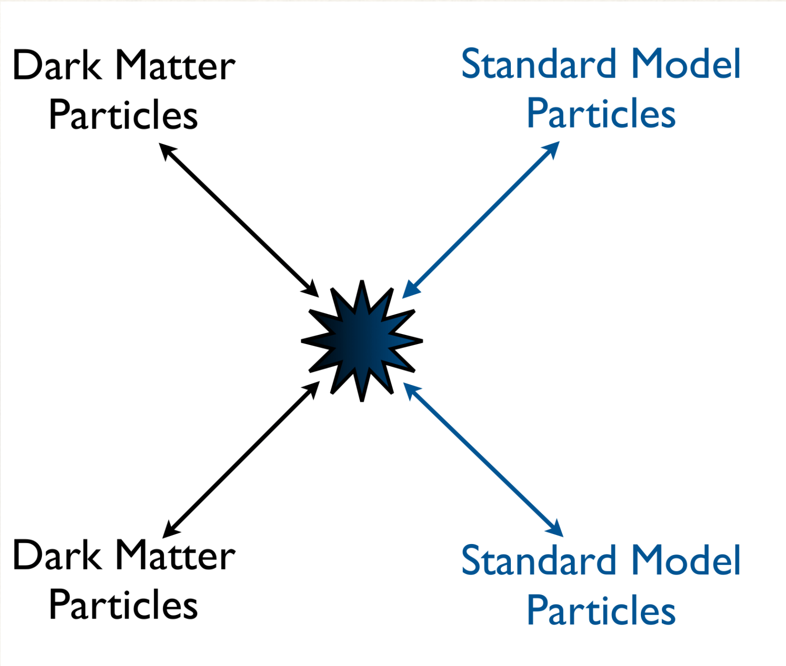
If e.g. R ~ o(100 μm) and δ=2 one obtains $M_S = o(1\,\text{TeV})$!

⇨ Gravity might become visible in TeV-scale colliders!

K. Desch - Physics at a Linear Collider - CERN - November 2004

Weakly Interacting Massive Particles (WIMPs)

- The key idea for testing WIMP
- Is to these the interactions in the right hand side



Axions

$$d_N = (5.2 \times 10^{-16} \mathrm{e} \cdot \mathrm{cm})\bar{\theta}.$$

Current experimental upper bounds on the dipole moment give an upper bound of $d_N < 10^{-26}$ e·cm,[6] which requires $\bar{\theta} < 10^{-10}$. The angle $\bar{\theta}$ can take any value between zero and 2π, so it taking on such a particularly small value is a fine-tuning problem called the strong CP problem.

- Axions does not need to be a dark matter
  - A scalar particle (boson)
- Original motivation for solving the
  - Strong CP problem

- Strong interaction theory permits a term that violates CP symmetry
- It contributes to the neutron electric dipole moment
- Experiment find that this number is extremely small
  - Not natural

- Axions are a by product of introducing a new symmetry to solves the strong CP problem
  - Remains the most believed solution to strong CP problem

- String theory likes axions and axion like-particles

[Submitted on 28 May 2009 (v1), last revised 23 Oct 2009 (this version, v2)]

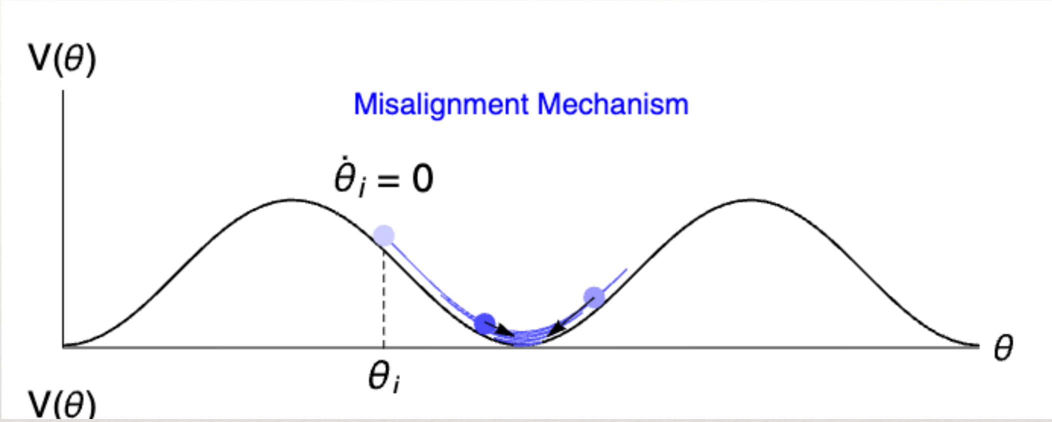
String Axiverse

Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Nemanja Kaloper, John March-Russell

String theory suggests the simultaneous presence of many ultralight axions possibly populating each decade of mass down to the Hubble scale 10^-33eV. Conversely the presence of such a plenitude of axions (an "axiverse") would be evidence for string theory, since it arises due to the

Axion dark matter

- If Axions are heavy, they can be produced thermally
  - (Meaning that they are produced early, and does not appear as hot dark matter)
- They can also be produced non-thermally
- A popular solution is the misalignment mechanism
- The "axions fields" are given some initial condition, but not in a ground state
- When Hubble rate, $H \gg m_a$, they are "frozen"
- When $H \sim m_a$, the fields start to roll to the minimum of the potential and start to oscillate
- $H \ll m_a$, these oscillations rapidly cooled to be the ground state, and become cold collision less dark matter.



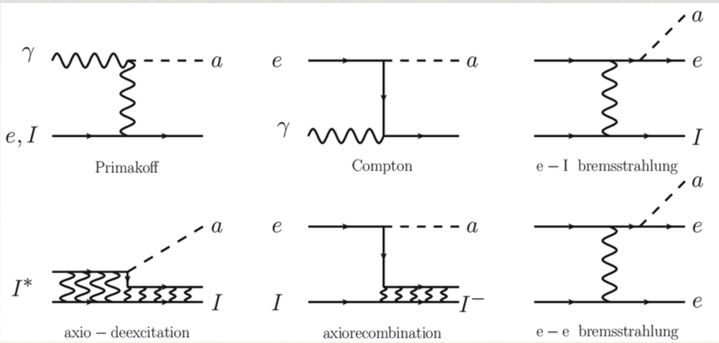
$$\Omega_a h^2 \sim 0.12 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \langle\theta_i^2\rangle ,$$

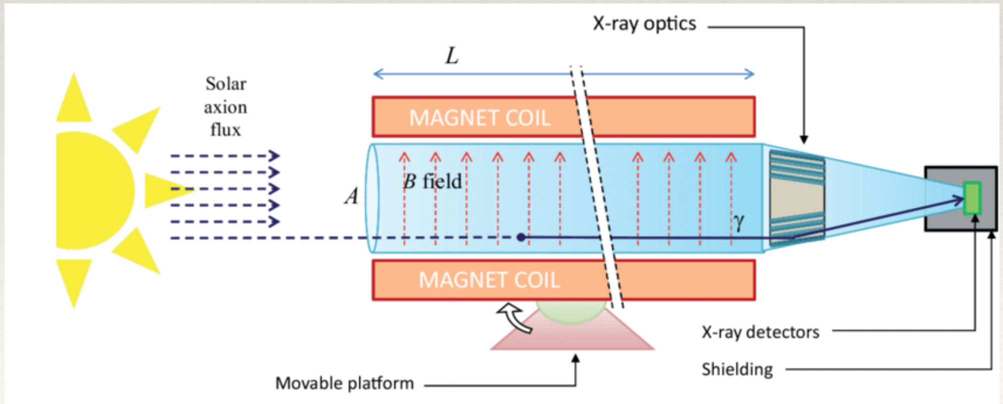
f_a is the axion theory energy scale

Non-dark matter axions

- Axions doesnt need to be dark matter
  - It can searched without the dark matter assumptions

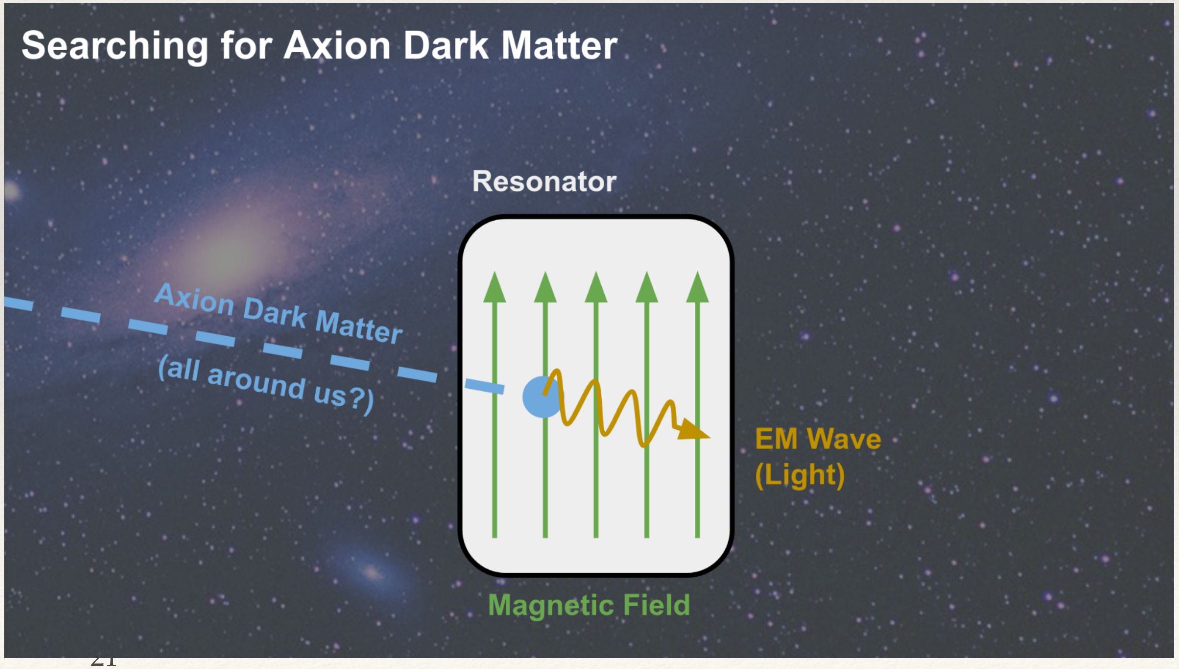
- E.g., CERN Axion Solar Telescope (CAST)
- Axions can be coupled to photons
- They will then produced by the Sun, and can be converted back in dark cavity using magnetic fields





Axion dark matter

- If axions are dark matter
- They can be searched using Halo scope
  - Axions from the halo will fly into the detector



Sterile Neutrinos

- The fact that neutrinos has mass, makes it more appealing to suggest there are right handed neutrinos (which has no interactions with anything)
- If there is mass eigenstate that are dominantly right handed, it can be a very appealing dark matter candidate.

- Having a heavy sterile neutrino also help solving the baryogengesis problem
- In principle, this could solves
  - Dark matter
  - Neutrino mass
  - Baryogengesis

Leptogenesis

https://arxiv.org/pdf/hep-ph/0502169.pdf

- Heavy right-handed neutrino decay (Condition 3)

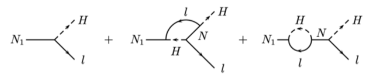


Figure 1: Tree level and one-loop diagrams contributing to heavy neutrino decays whose interference leads to Leptogenesis.

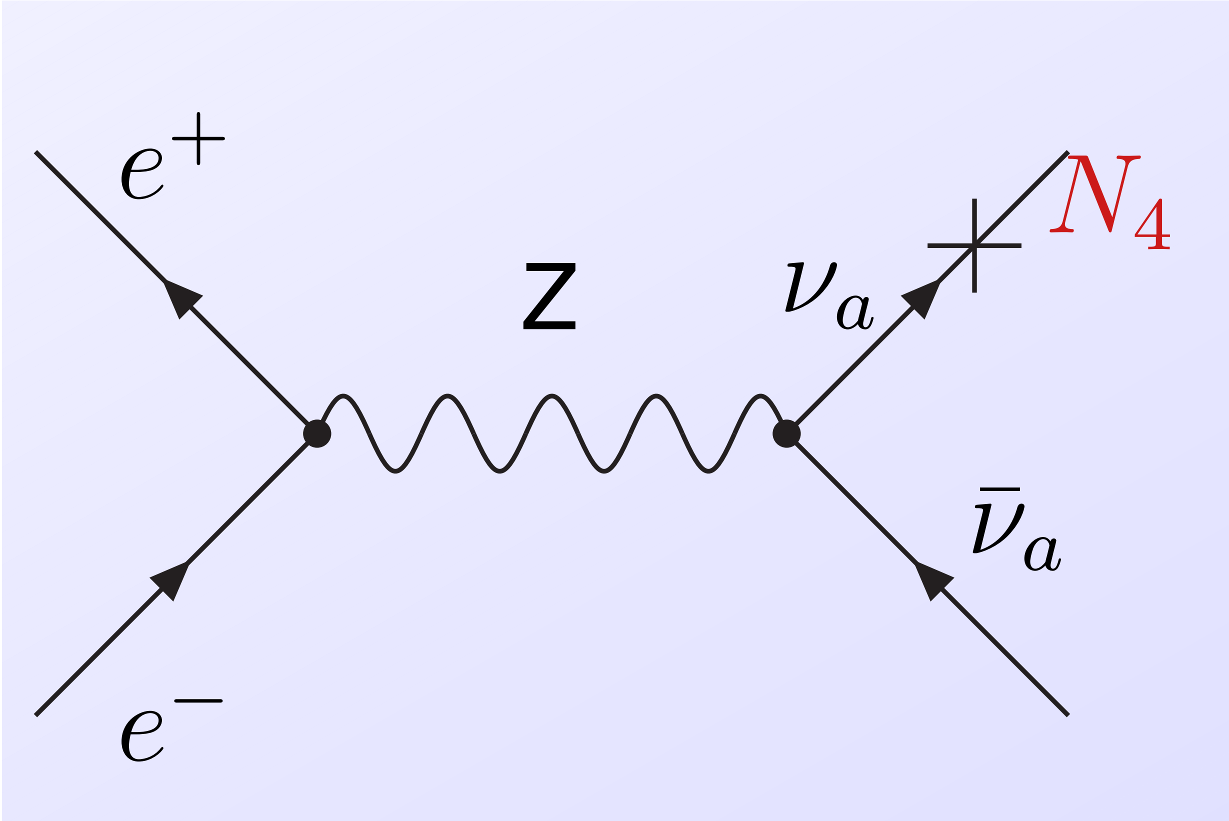
- The loop correction breaks lepton number L and CP (Condition 2)
- High temperature Standard model interactions, L -> B (Condition 1)
-
- If one of the right-handled neutrinos is keV, could be dark matter
- Neutrinos Mass via seesaw mechanism
- Baryon asymmetry

Sterile neutrino dark matter (Freeze-in)

- With some small mixing angle with active neutrinos, it is possible to produce the observed amount of dark matter via a very small mixing
- Before neutrino decoupling, active neutrinos are in thermal equilibrium
  - Constantly being produced and destroyed via interaction
  - Due to the small mixing, there is a small probability that each interaction produces a sterile neutrino

- $\frac{d}{dt}f_s = \frac{1}{2}\langle P\rangle\Gamma f_a$
- f_s, f_a are the distributions of the sterile and active neutrinos
- Γ is the interaction rate
- $< P >$ is the conversion probability

- A population of dark matter is built up slowly, until neutrino decoupling
- Dark matter was never in equilibrium with the Universe!
  - Freeze-in



The Dodelson-Widrow case

Sterile-neutrinos as dark matter

Scott Dodelson (Fermilab), Lawrence M. Widrow (Queen's U., Kingston and Canadian Inst. Theor. Astrophys.)

Mar, 1993

11 pages

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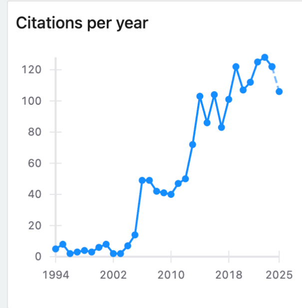
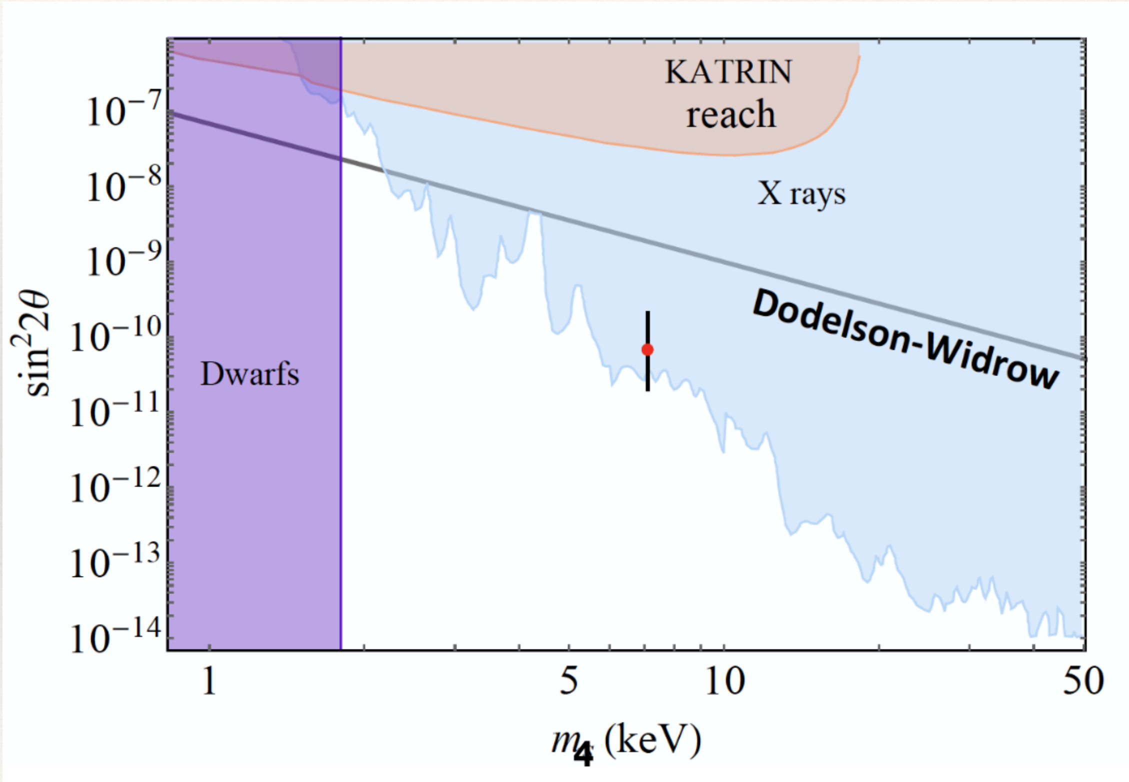


- The simplest freeze-in production of sterile neutrino dark matter with a mixing angle
- Sterile neutrino loving on this line can explain the observed dark matter abundance
- It is around keV energy range
  - Could be a warm dark matter too!



The Shi Fuller case

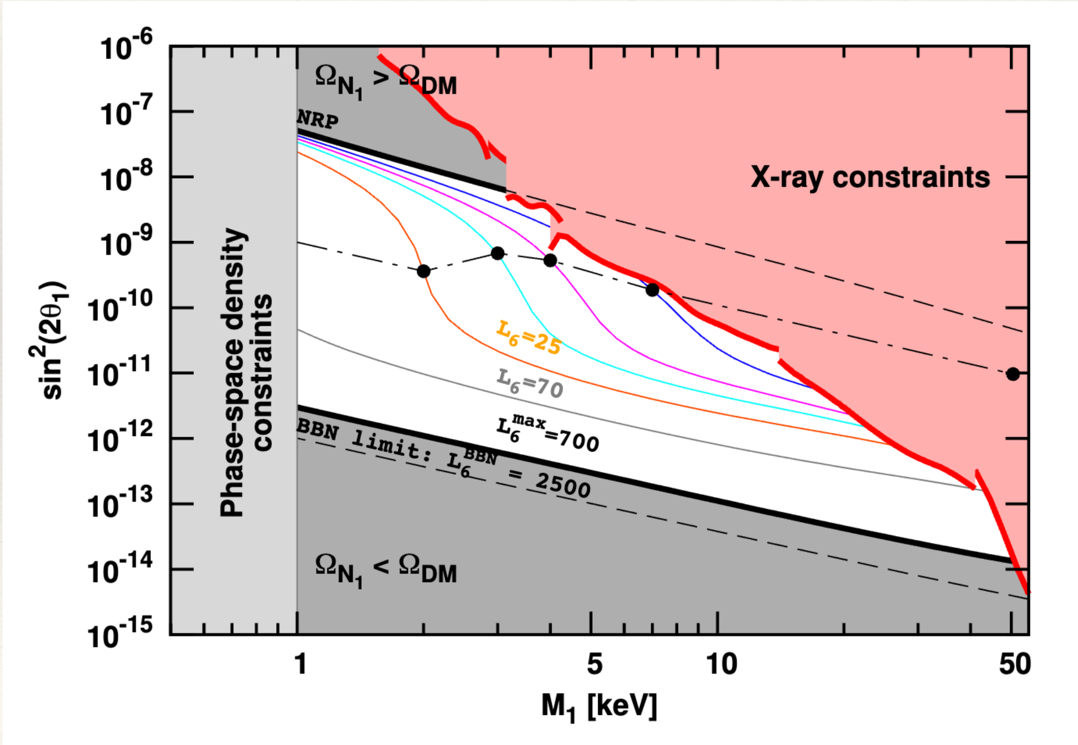
- Just like solar neutrino, the effective mixing between neutrinos and sterile neutrinos can be affected by matter potential.
- The universe is given by the
- In this case, it is possible a large amount of lepton asymmetry is hidden in the neutrino sector
- The lepton asymmetry acts like a matter potential to neutrinos (not sterile neutrinos)
- And could induce a resonance, and thus achieve maximum mixing with small mixing angle!
    - Allows dark matter production with small vacuum mixing angles

$$i\frac{d}{dx}\begin{pmatrix} a_\alpha \\ a_s \end{pmatrix} = \left\{\left(p + \frac{m_1^2+m_2^2}{4p} + \frac{V(x,p)}{2}\right) I + \frac{1}{2}\begin{pmatrix} V(x,p) - \Delta(p)\cos 2\theta & \Delta(p)\sin 2\theta \\ \Delta(p)\sin 2\theta & \Delta(p)\cos 2\theta - V(x,p) \end{pmatrix}\right\}\begin{pmatrix} a_\alpha \\ a_s \end{pmatrix}, \qquad (5.2)$$

where the first term is proportional to the identity and $\Delta(p) \equiv \delta m^2/2p$. In the context of the early universe it is most convenient to take $x = t$, the Friedman-Lemaitre-Robertson-Walker coordinate time (age of the universe), while in supernovae we take x to be position. The weak potential $V(x,p)$ represents the effects of neutrino neu-

The effective matter-mixing angle is

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + [\Delta(p)\cos 2\theta - V^D - V^T(p)]^2}. \qquad (5.4)$$



Primordial black holes PBH

- From BBN we know that dark matter cannot be Baryonic.
- If black holes have formed before BBN
  - Primordial
  - collisionless
  - Only gravity
- Perfect dark matter candidate!

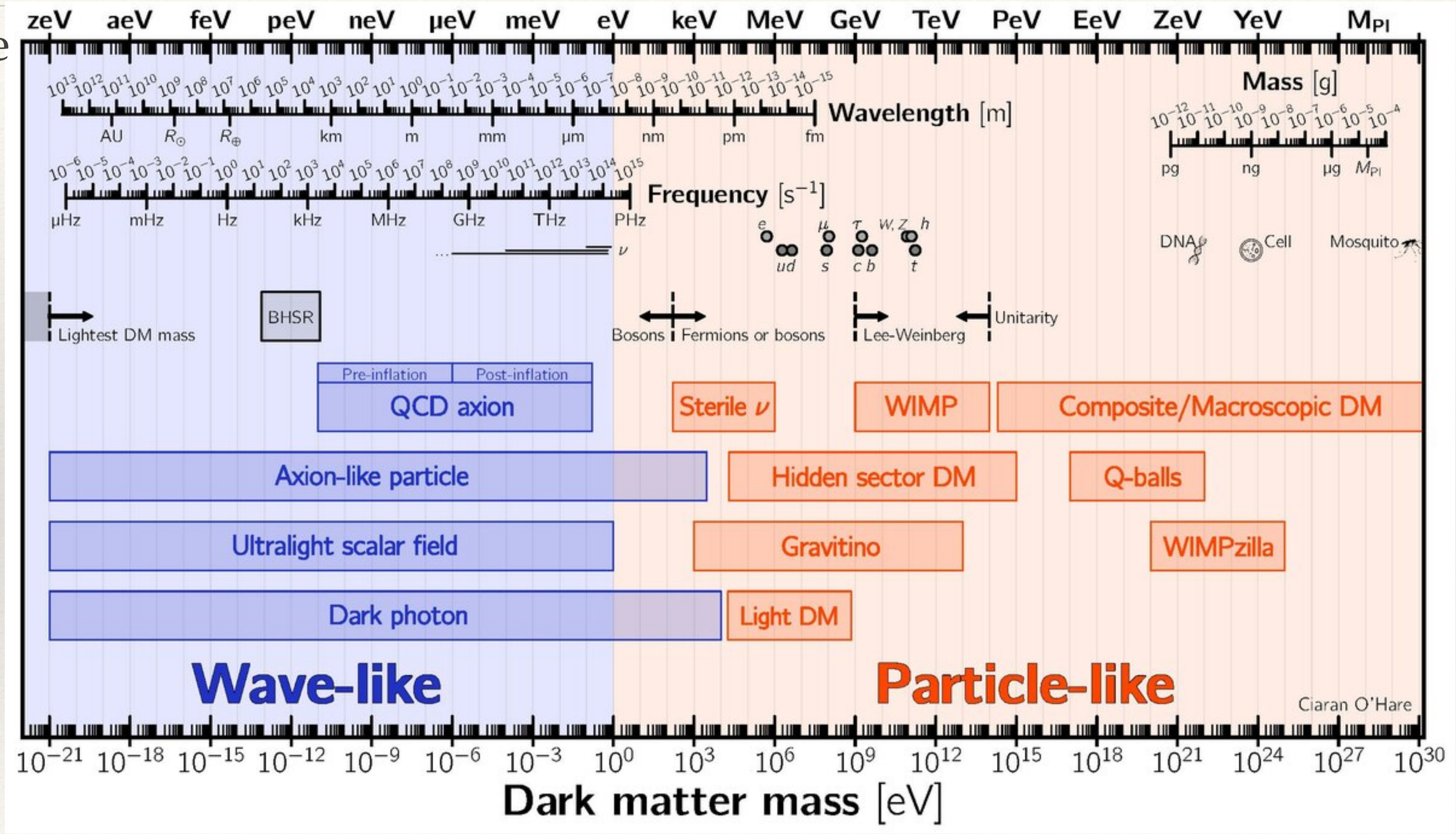
- How to make PBH dark matter?
- Normal black holes are formed from stellar collapse
- Supermassive black holes
  - Merger? Accretion? (Primordial?)
  -
- Before BBN, the universe has only density perturbations
- If, in a given volume, the density perturbation is larger than the Schwarzschild mass
- It collapses to PBHs

$$r_s = \frac{2GM}{c^2}$$

The origin of these perturbations are determined by the initial condition physics (inflation), or violent phase transitions

Dark Matter candidates overview

- From microscopic wave like
- To Particle like
- To Macroscopic objections



Dark Matter candidates overview

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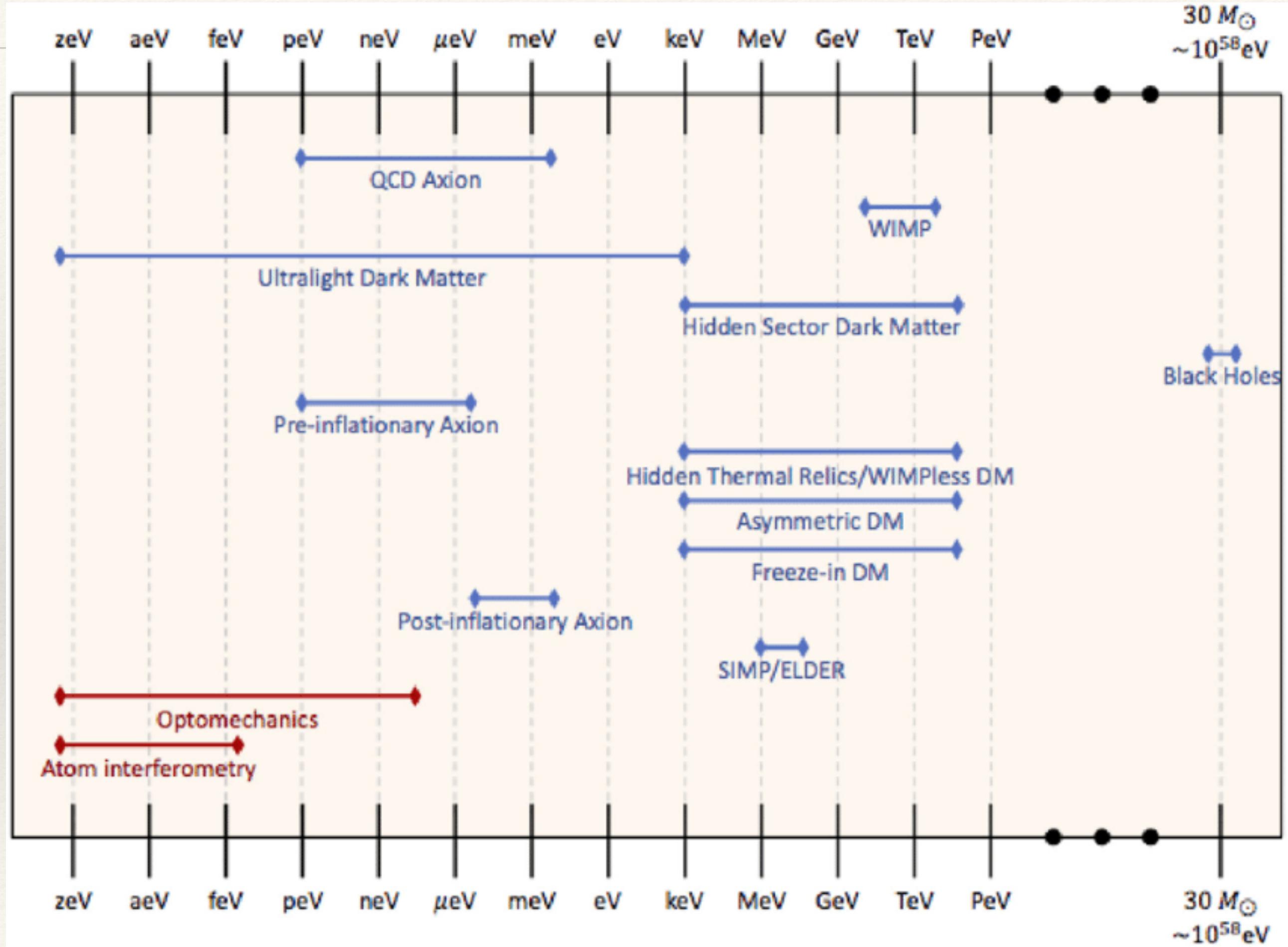
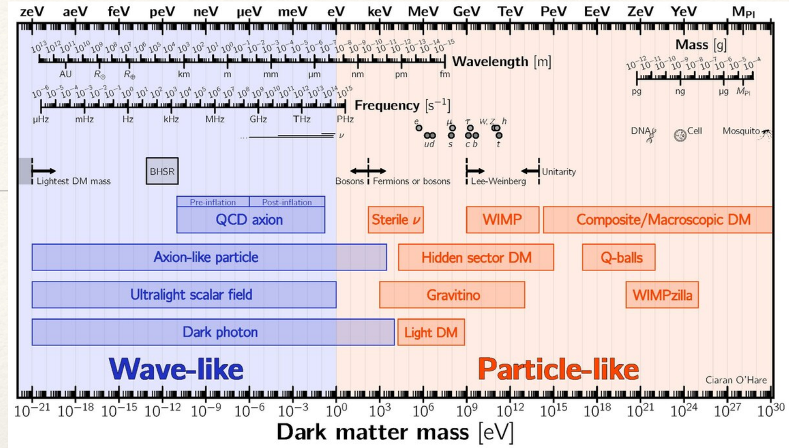


Some dark matter candidates



- To talk about particle dark matter, we need to have some “culprits” in mind
- WIMPs
  - Have 2 to 2 interactions at weak scales
- Axions
  - Have couplings to standard model particles
- Sterile neutrinos
  - Have mixing with active neutrinos
- Primordial black holes
  - Are black holes

Generally we need think about a specific, or a class of candidates to talk about detections