Dark Matter theories – An overview

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Introduction

- In the leading paradigm, dark matter (DM) is made of new, hypothetical particles

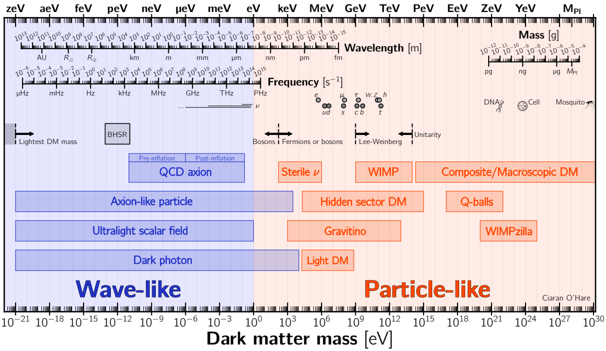
- Astrophysical and cosmological observations imply that the DM particle must be:
  - stable on cosmological time scales
  - non relativistic (from matter-radiation equivalence onwards)
  - with a null, or very small electric charge
  - abundant

- None of the known particles can simultaneously fulfil all these requirements

- ... and yet, there are several hypothetical particles that are compatible with them ...

DM particle candidates

- DM candidates can be classified by their De Broglie wavelength in the Milky Way
- For $n_\chi \lambda_{\rm DB}^3 > 1$, DM is described by classical waves
- For $n_\chi \lambda_{\rm DB}^3 < 1$, DM behaves like a particle
- Here, n_χ is the local DM number density, and $\lambda_{\rm DB}$ is the DM De Broglie wavelength



Particle-like DM

- For bosonic particle-like DM, the lower bound on mass is set by $n_\chi \lambda_{\rm DB}^3 < 1$, i.e. $m_\chi > 10$ eV

- For fermionic DM, the phase space density f is bound from above, i.e. $f \leq f_{\rm max}$.

- Requiring that the coarse-grained phase space density of a DM-dominated object is less than $f_{\rm max}$ implies

$$m_\chi \geq 0.1 \text{ keV} \left(\frac{4}{g_\chi}\right)^{1/4} \left(\frac{100 \text{ km/s}}{\sigma_v}\right)^{1/4} \left(\frac{\text{kpc}}{r_c}\right)^{1/2}$$

  Gunn and Tremaine (1979)

- As an upper bound on the DM particle mass, one typically assumes $M_{\rm Planck}$

DM particles with SM charges

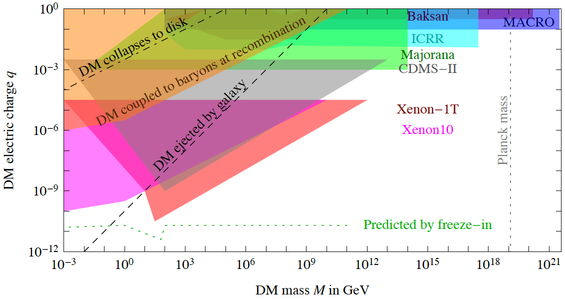
- Three main families of models where the DM particle is charged under the SM:
  - Milli-charged DM
  - WIMPs: Minimal DM / SUSY DM
  - Coloured DM

- **Coloured DM**: New coloured particles Q confined in "dark hadrons" could be the DM
  - Dark hadrons containing light quarks q, such as QQq or Qqq have $\sigma_n \sim \pi/\Lambda^2_{\rm QCD} \sim 10^{-26}$ cm^2
  - Ruled out for DM masses less than 10^{15} GeV
  - Neutral dark hadrons involving Q only, e.g. QQ, can be the DM
  - For TeV masses, they can be thermally produced

  De Luca *et al.* (2018)

- **Milli-charged DM** is characterised by the vector-like coupling to the photon $\mathscr{L} \supset qeA_\mu J^\mu_\chi$

- Constraints:



M. Cirelli, A. Strumia and J. Zupan (2024)

- **Minimal DM** consists of the lightest neutral component of *a given* SU(2) electroweak multiplet

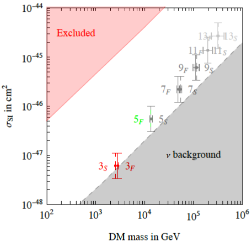
- This is in contrast with, e.g. SUSY neutralino DM, where DM consists of specific *linear combinations* of SU(2) multiplets

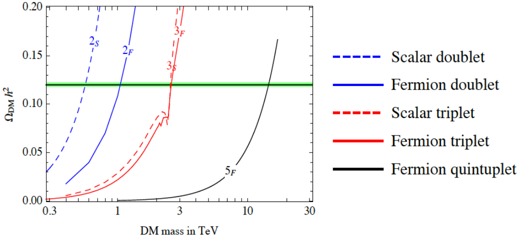
- An odd representation of dimension n (n-uplet) and zero hypercharge (Y=0) includes a neutral component: $Q = Y + T_3$, $T_3 = \mathrm{diag}\,[(n+1)/2 - i]$, $i = 1, \ldots, n$

- Only two free parameters, n and m_χ

  Cirelli, N. Fornengo and A. Strumia (2005)

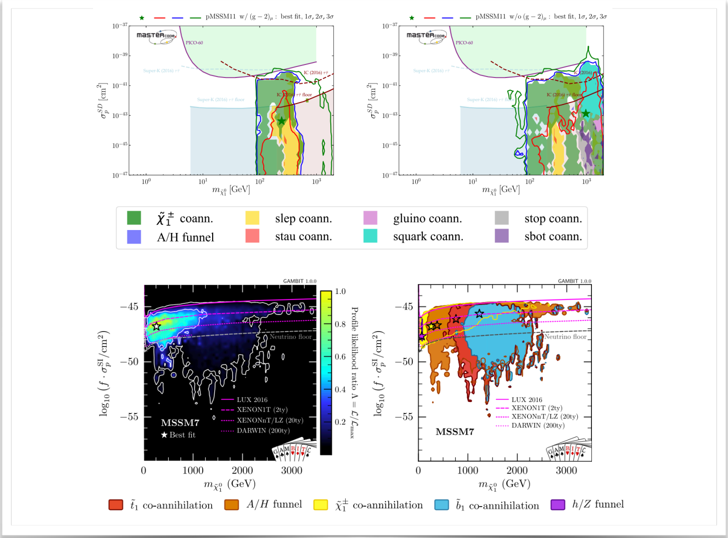
- Relic density and direct detection SI scattering cross sections for minimal DM





S. Bottaro *et al.* (2022)
M. Cirelli, A. Strumia and J. Zupan (2024)

DM particles with SM charges / SUSY DM

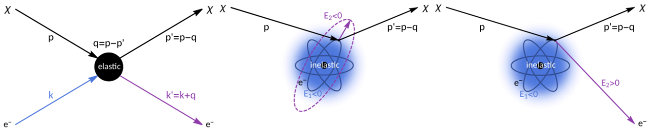


DM particles with BSM charges / sub-GeV DM

- A possible explanation for the lack of detection of GeV – TeV WIMPs is that DM is lighter than nucleons, and thus too light to induce an observable nuclear recoil

- Interestingly, this explanation would place DM in the same mass range as the known constituents of matter (i.e. 0.511 MeV – 0.938 GeV)

- The search for DM in this mass range motivates the study of DM-electron rather than -nucleon interactions (scattering by electrons is kinematically favoured)

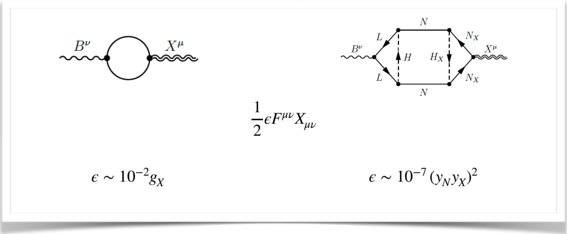


EFT for non-relativistic DM-electron interactions: R. Catena *et al.* (2019)
EFT combined with linear-response theory to model in-medium effects in DM-electron scattering: R. Catena and N. Spaldin (2024)

- In order to produce thermally DM candidates in this mass range, one has to circumvent the Lee-Weinberg bound by introducing new light mediator particles

- In explicit models, the new mediator(s) is (are) the gauge boson(s) of a beyond the SM gauge group, under which the DM particle is charged

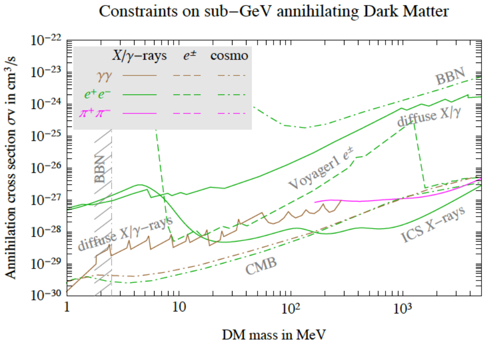
- If the new mediator is a massive U(1) gauge boson (i.e. "a dark photon"), a kinetic mixing with the ordinary photon is expected. For example:



T. Gherghetta, Jörn Kersten, K. Olive and M. Pospelov (2019)

- A sub-GeV DM particle inject significant amounts of energy in the universe by pair annihilation at and after recombination

- This indirect constraint plays an important role in sub-GeV DM model building

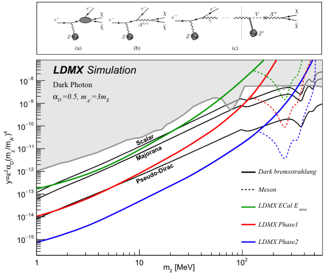


M. Cirelli, A. Strumia and J. Zupan (2019)

DM particles with BSM charges / sub-GeV DM

- Examples of light DM coupled to a dark photon via kinetic mixing include ($\mathscr{L} \supset -g_D A'_\mu J_D^\mu$):
  - Majorana DM, $J_D^\mu = (1/2)\bar{\chi}\gamma^\mu\gamma^5\chi$
  - Pseudo-Dirac DM, $J_D^\mu = i\bar{\chi}_1\gamma^\mu\chi_2$
  - Complex scalar DM, $J_D^\mu = i(\chi^*\partial^\mu\chi - \chi\partial^\mu\chi^*)$

- The thermally averaged annihilation cross section of these models is either p-wave or population-suppressed. They can thus evade energy injection constraints



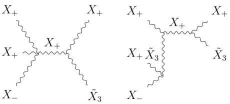
LDMX collaboration (2022)

DM particles with BSM charges / sub-GeV DM

- Additional examples of sub-GeV DM models include:
- Asymmetric Dirac DM
- Vector SIMPs
- Beyond kinetic mixing DM models

Vector SIMPs

If DM is a massive spin-1, X_μ, from a non-abelian gauge group with $\alpha_X \sim \mathcal{O}(1)$, it can be produced by the freeze-out of, e.g.



The predicted abundance is

$$\Omega \sim 0.33 \left(\frac{m_X / \alpha_X}{100\ \mathrm{MeV}} \right)^{3/2}$$

S. M. Choi *et al.* (2017); S. M. Choi *et al.* (2019)

Beyond kinetic mixing

Kinetic mixing implies a dark photon-electron vertex

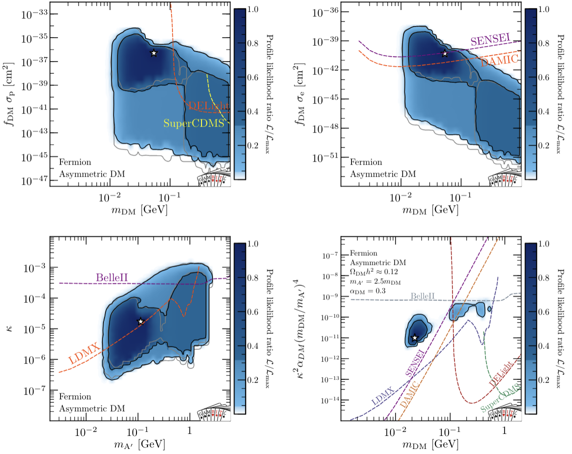
$$\Gamma_\mu = e\epsilon\gamma_\mu$$

This can be generalised by allowing for electron dark moments

$$\Gamma_\mu = e\epsilon\gamma_\mu + \frac{i\sigma_{\mu\nu}q^\nu}{\Lambda}\left[M(q^2) + iE(q^2)\gamma_5\right] + \ldots$$

T. Rizzo. (2021);

- Global fits of Asymmetric sub-GeV Dirac DM



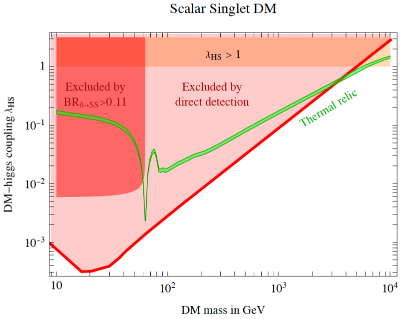
S. Balan, C. Balazs, T. Bringmann, C. Cappiello, R Catena, T. Emken, T. E. Gonzalo, T. R. Gray, W. Handley, Q. H., F. Kahlhoefer and A. C. Vincent (2024)

DM particles that are not charged / scalar singlet DM

- A minimal example is the real scalar singlet (S) model, with a $\mathbb{Z}_2$ symmetric $\mathscr{L}$:

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \lambda_{HS} S^2 |H|^2 - \frac{\lambda_S}{4} S^4$$

- S is thermally produced by the freeze-out of $SS \to h \to f\bar{f}$ and $SS \to hh$.
- It is not ruled out by observations only in a narrow range of masses around 5 TeV:



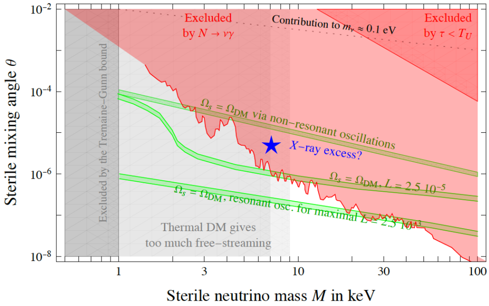
M. Cirelli, A. Strumia and J. Zupan (2024)

DM particles that are not charged / sterile neutrinos

- A second popular example is provided by the so-called sterile neutrino (N) defined by:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{i}{2}\bar{N}\gamma^\mu\partial_\mu N - \frac{1}{2}M_{ij}\bar{N}_i N_j^c - y_{ij}\bar{N}_i\widetilde{H}^\dagger L_j + \text{h.c.}$$

- N is unstable
- It is produced non-thermally via active to sterile neutrino conversion in the thermal bath



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- DM candidates can be classified by their mean occupation number in the Milky Way
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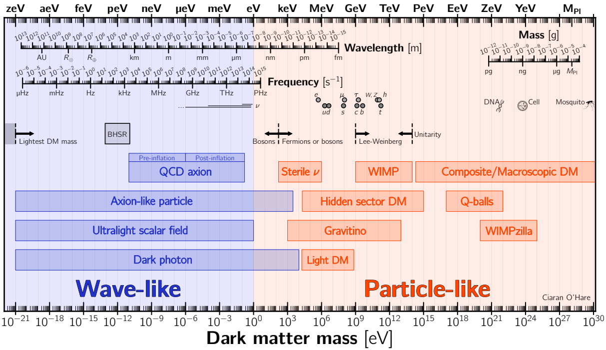
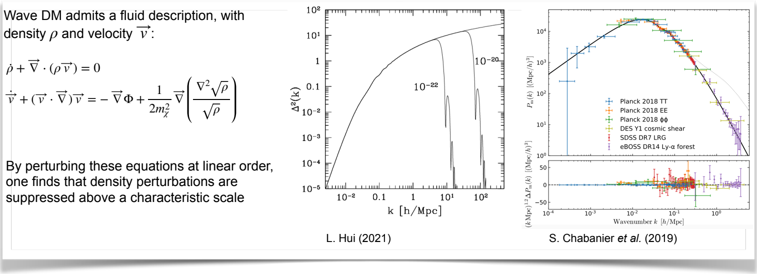


- The lower bound on the mass arises from cosmology, e.g. Lyman-alpha constraints:



- The upper bound, i.e. $m_\chi < 10$ eV, arises from $n_\chi \lambda_{\rm DB}^3 > 1$:

- Within this mass range, wave DM can only be bosonic (Pauli exclusion principle)

- Extensively investigated (non-thermal) production mechanisms include:
- Initial misalignment
- Decay of topological defects
- Inflaton decay

- Example: initial misalignment

1) Quantum fluctuations in De Sitter space

The DM field can be decomposed into the sum of a coarse-grained, long wavelength part, $\bar{\phi}(\vec{x},t)$, and a short wavelength part.

$\bar{\phi}(\vec{x},t)$ obeys the Langevin equation:

$$\dot{\bar{\phi}}(\vec{x},t) = -\frac{1}{3H}V'(\bar{\phi}) + f(\vec{x},t)$$

where

$$\langle f(\vec{x},t_1) f(\vec{x},t_2)\rangle = \frac{H^3}{4\pi^2}\,\delta(t_1 - t_2)$$

2) Induced vacuum expectation value

$\bar{\phi}(\vec{x},t)$ is thus a stochastic variable whose PDF is a solution to a Fokker Planck equation.

Its variance is:

$$\phi^* = \frac{H}{2\pi}\sqrt{N}$$

where N is the number of e-folds.

One identifies the axion VEV at the end of inflation with ϕ^*.

3) Implied abundance of cold DM

ϕ^* is the initial misalignment: the initial condition for the subsequent classical time evolution of the DM field

During this evaluation, the DM field oscillates around the minimum of its potential

These oscillations correspond to a pressure-less fluid with present abundance

$$\Omega \sim \sqrt{\frac{m_\chi}{\mathrm{eV}}}\left(\frac{\phi^*}{10^{11}\ \mathrm{GeV}}\right)^2$$

- The QCD Axion is the pseudo-Nambu Goldstone boson associated with a $U_{\mathrm{PQ}}(1)$ symmetry that is spontaneously broken at f_a, and explicitly broken at T_{QCD}

- Being a CP-odd scalar, the axion contributes to the QCD Lagrangian via the term

$$\mathscr{L}_{aGG} = -\frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} + \bar{\theta}\right) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

  where $\bar{\theta} = \theta_{\mathrm{QCD}} + N_f \theta_Y$

- While a evolves towards the minimum of its QCD-induced potential, $a/f_a + \bar{\theta}$ goes to zero, and CP is thus preserved in the strong sector of the Standard Model

- Axion Effective interaction Lagrangian (CP-preserving):

$$\mathscr{L}_{\text{int}} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu} - a\sum_{\psi} g_{a\psi}(i\bar{\psi}\gamma^5\psi) - aF_{\mu\nu}\sum_{\psi}\frac{g_{a\psi\gamma}}{2}(i\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi) + \dots$$

- The axion mass and coupling constants depend on f_a, and are thus not independent

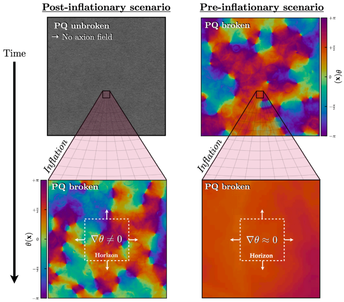
- Two scenarios for axion DM production:

The present cosmological abundance of axions is set by the misalignment mechanism in the pre-inflationary scenario, and by the decay of topological defects in the post-inflationary Scenario.

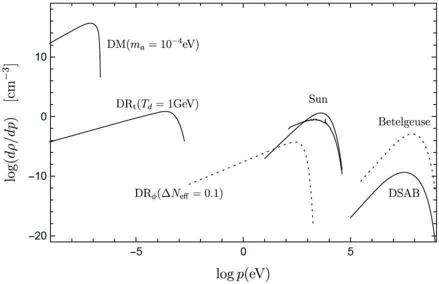
Here, θ denotes the axion field, i.e. a/f_a.

PQ stands for Peccei and Quinn symmetry.

Credit: C. O'Hare.



- Expected energy spectra (from natural sources), detection methods and signatures



Detection method	$g_{a\gamma}$	g_{ae}	g_{aN}	$g_{A\gamma n}$
Light shining through wall	×			
Polarization experiments	×			
Spin-dependent 5th force			×	
Helioscopes	×			
Primakoff-Bragg in crystals	×			
Underground ion. detectors	×	×	×	
Haloscopes	×			
Pick up coil & LC circuit	×			
Dish antenna & dielectric	×			
DM-induced EDM (NMR)			×	×
Spin precession in cavity		×		
Atomic transitions		×	×	

I. G. Irastorza, and J. Redondo (2018)

- One important constraint acting on the parameter space of axions is

$$m_a f_a \simeq m_\pi f_\pi$$

- Axion-like Particles, or ALPs, are characterised by their mass m_a being independent of f_a

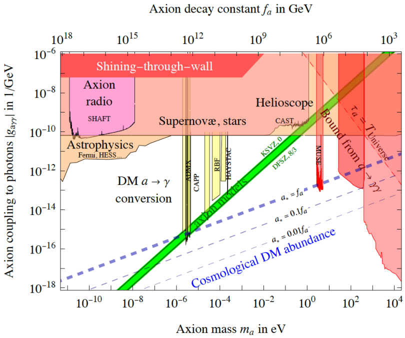
- They are predicted to arise generically, in addition to the axion, in low-energy effective field theories emerging from string theory

  E. Witten (1984)

- They are in general unrelated to QCD and do not provide a solution to the strong CP problem

- Multidimensional parameter space

- Summary of constraints on the axion-photon and ALP-photon coupling, $g_{a\gamma\gamma} = g_{a\gamma}$:



M. Cirelli, A. Strumia and J. Zupan (2024)

Summary

- The landscape of DM theories that is currently compatible with observations spans a wide range of masses (from wave-like to particle-like DM)

- It also spans a wide range of mechanisms to couple DM to ordinary matter (within and beyond the SM gauge group)

- Within this huge range of possibilities, I personally find of great interest:
  - The exploration of the TeV mass range within minimal DM
  - The synergy between particle and solid state physics in the study of sub-GeV DM
  - The increased focus on Axion DM searches