Maximum Mass for Particle Dark Matter

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Dark Matter Candidates

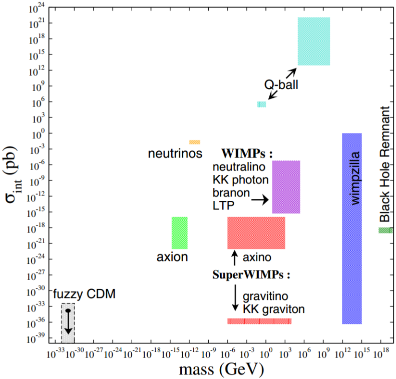


Figure 1 : Some dark matter candidates, taken from a July 2007 report from the Dark Matter Scientific Assessment Group

Typical Mass Scales

- Supersymmetry
  - Particle zoo: neutralinos, sneutrinos, axinos, etc ...
  - Dark matter: in phenomenological SUSY, $\sim 1 - 10\,\mathrm{TeV}$
- Little Higgs models
  - Motivation: stabilization of electroweak physics up to energies $\sim 1 - 10\,\mathrm{TeV}$
  - Dark matter: $\lesssim 1 - 10\,\mathrm{TeV}$
- Light scalar dark matter
  - Motivation: experimental hints, e.g., the 511 keV γ-ray signal; theoretical position somewhat *ad hoc*
  - Dark matter: mass scales $\sim 1 - 100\,\mathrm{MeV}$
- Kaluza-Klein and extra-dimensional theories
  - Motivation: unification, the heirarchy problem(s)
  - Dark Matter: mass scales $\sim 100\,\mathrm{GeV} - 10\,\mathrm{TeV}$

General Features - Expt.

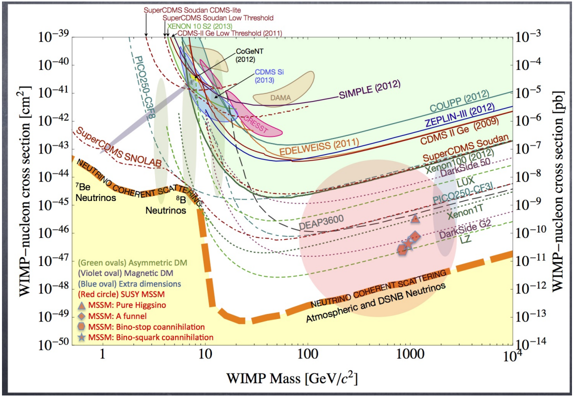


Figure 2 : Typical experimental mass ranges - CF1 Snowmass report

Unitarity (1/3)

- *Unitarity arguments* give the strongest model-independent theoretial bounds on thermal dark matter.
- Unitarity $\iff$ QM "probability ≤ 1"
  Unitarity $\iff$ Scattering probability bounded from above
- Recall from non-relativistic scattering theory the partial wave expansion of the scattering amplitude $f(\theta)$:

$$f(\theta) = \sum_{l}^{\infty} (2l+1)\left(\frac{e^{2i\delta_l}-1}{2ik}\right) P_l(\cos\theta)$$

- "Morally speaking" the Jacob-Wick partial wave expansion plays an analogous role for the helicity amplitude $\mathcal{M}$:

$$\mathcal{M}(\lambda_3\lambda_4;\lambda_1\lambda_2) = \frac{8\pi\sqrt{s}}{(p_i p_f)^{1/2}} e^{i(\lambda_i-\lambda_f)\phi} \sum_J (2J+1)\mathcal{M}^J_\lambda(s) d^J_{\lambda_i\lambda_f}(\theta)$$

- Partial wave unitarity $\Rightarrow |\mathcal{M}^J|^2 \leq |\mathrm{Im}\mathcal{M}^J| \leq 1$

Unitarity (2/3)

- Fact from cosmology:

$$\Omega_X h^2 \sim \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v_{\mathrm{rel}} \rangle_f}$$

- Parital wave unitarity $\Longrightarrow$ *Maximal* cross section $\langle \sigma v_{\mathrm{rel}} \rangle_f$
- Maximal cross section $\Longrightarrow \sigma_J \leq \pi(2J+1)/p_i^2$
- Observational data constrains Ωh^2
- Early universe kinematics: $p_i^2 = E^2 - m_X^2 \approx m_X^2 v_{\mathrm{rel}}^2/4$

Unitarity (3/3)

- $(\sigma_J)_{max} v_{rel} \approx \frac{3\times 10^{-22}(2J+1)\mathrm{cm}^3/\mathrm{sec}}{m_X/(1\mathrm{TeV})}$
- Detailed analysis: $J = 0$ term dominates $+\,\mathcal{O}(v_{\mathrm{rel}}^2/4)$ (Recall that $v_{rel} \approx 1/4 \ll 1$ at freezout)

Solve for m_X and insert numbers:

$$m_X \lesssim 30\,\mathrm{TeV}$$

- Details: K. Griest and M. Kamionkowski, Phys. Rev. Lett. 64 (1990) 615.
- Note that 30 TeV bound includes more recent PLANCK constraints on $\Omega_X h^2$

Evading Unitarity

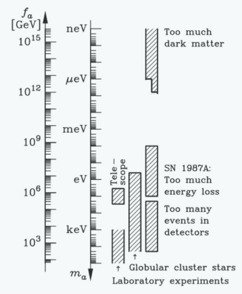
- Non-thermal relics - evade unitarity bounds most easily
  - Axions
  - Superheavy Dark matter - WIMPzillas etc.
  - Q-Balls
- The precise mass bound from unitarity depends a bit on particle nature ...
- Some subtlties about the applicability of partial wave expansion - issues of non-convergence - very unlikely.

Nota bene:

Unitarity itself still should hold in all cases; the previous argument simply does not always apply.

Axions

- Well motivated theoretically - QCD/Stringy origins
- Non-thermal relics - mass constrained to be very small



Very light axions forbidden: else too much dark matter

⇐Dark matter range:"axion window"

very hard to detect "invisible axions"

Heavy axions forbidden: else new pion-like particle

Figure 3 : Axion Constraints

Super Heavy Dark Matter

- Gravitationally produced at the end of inflation in cosmologically interesting amounts
- Stability guranteed by Global/Discreet/(Gauged)-R symmetry
- Observation of Ultra high energy cosmic rays above the GZK cutoff is another motivation to look at SHDMs.
- Above this $\sim 5 \times 10^{19}$ GeV cutoff, protons interact at resonance with CMB photons with large cross sections, making the universe opague to ultra high energy prtons over cosmological distances.
- Exotic SHDM candidates offer plausible explanation

WIMPzillas

- Non-thermal in nature - relic abundance set by production cross section
- Produced naturally at the end of inflation by the expansion of the background spacetime acting on vacuum quantum fluctuations of the dark matter field.
- Natural mass scale for these particles at inflaton-GUT scale $\sim 10^{10} - 10^{16}$ GeV
- Stability guranteed by discreet gauge symmetry - weakly broken
- D-matter (non-perturbative particle like states from conpactified D-branes) provides a somewhat larger mass
- Thermal production with $m_X \geq 10^{13}$ GeV requires a very high $T_{\rm reh}$

Experimental Constraints on SHDM

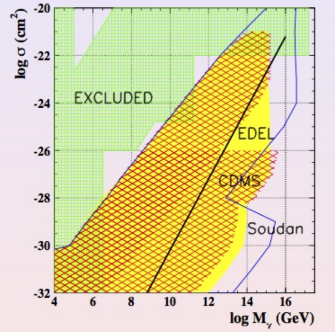


Figure 4 : Direct detection constraints

Experimental Constraints on SHDM

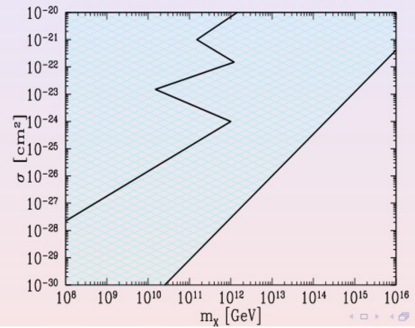


Figure 5 : Indirect detection constraints

Q-Balls

- Non-topological solitonic configurations - stability guranteed by a global $U(1)$ Noether charge.
- Distinct from a topological soliton which is stable because there is no continuous transformation that homotopically maps it to the vacuum.
- Arise generically in supersymmetric field theories.
- Can be produced in the early universe via phase transitions, fusion or pair production at high temperatures.
- Can decay via massless fermions that carry the same global charge.
- Mass $\sim 10^{10}$ GeV

Primordial Black Holes (PBHs)

- PBHs are predicted to form in the early Universe from large density fluctuations.
- There is a small window for PBHs as CDM.
- The upper window of PBH masses allowed can be probed with Kepler and WFIRST
- Ideally, the entire range for CDM can be probed with gravitational wave detectors. ($f_{GW} \sim 10^{-5} - 10^{-2}$Hz)

Expt. Constraints on Primordial Black Holes

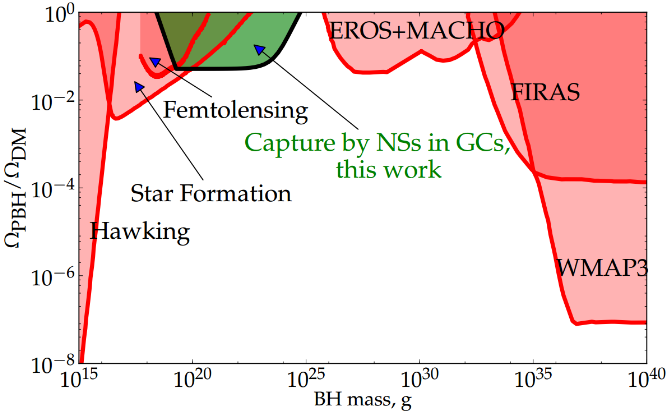


Figure 6 : Limits on Ω_{DM} from Capela et al., Phys. Rev. D 87, 123524 (2013)

Summary

- Unitarity restricts thermal dark matter - and thus a large class of explicit theories - to masses less than $\sim 30\,\text{TeV}$.
- Non-thermal dark matter evades the unitarity argument and is often much heavier.
- Some well-motivated models, like axions, often involve significanly lighter masses.

Question: Is there a maximum mass for a dark matter particle?
Answer: Yes, with caveats.

Thank You