Dark Matter from the Lattice

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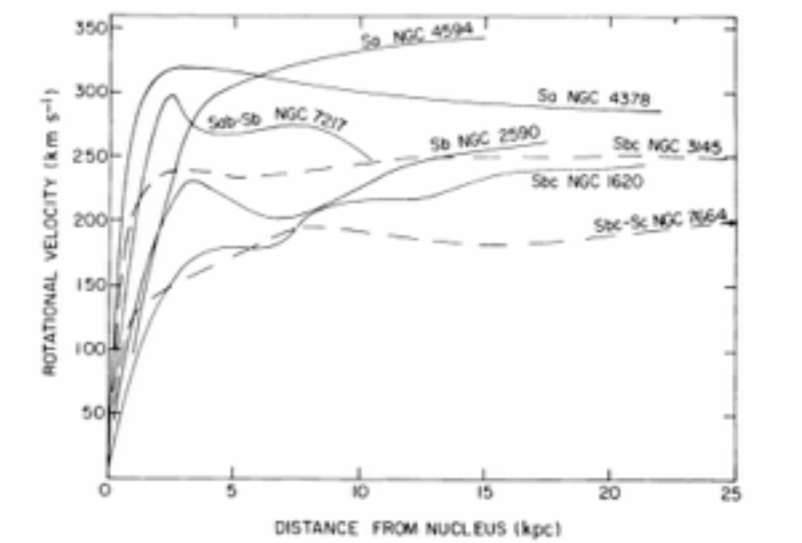
The 14th International workshop on QCD in extreme conditions
Plymouth University
August 3, 2016

Dark Matter Exists!

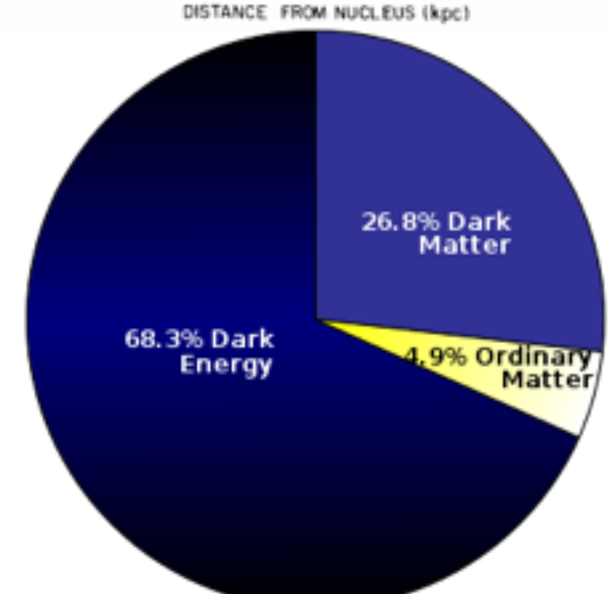
- In the 1970's, Vera Rubin found dark matter in galaxy rotation curves: $\Omega_D / \Omega_C \approx 0.2$.

- Many subsequent exp/obs confirmations:
    - CMB, Galaxy Surveys, Large Scale Structure, Strong/Weak Lensing, Bullet Cluster

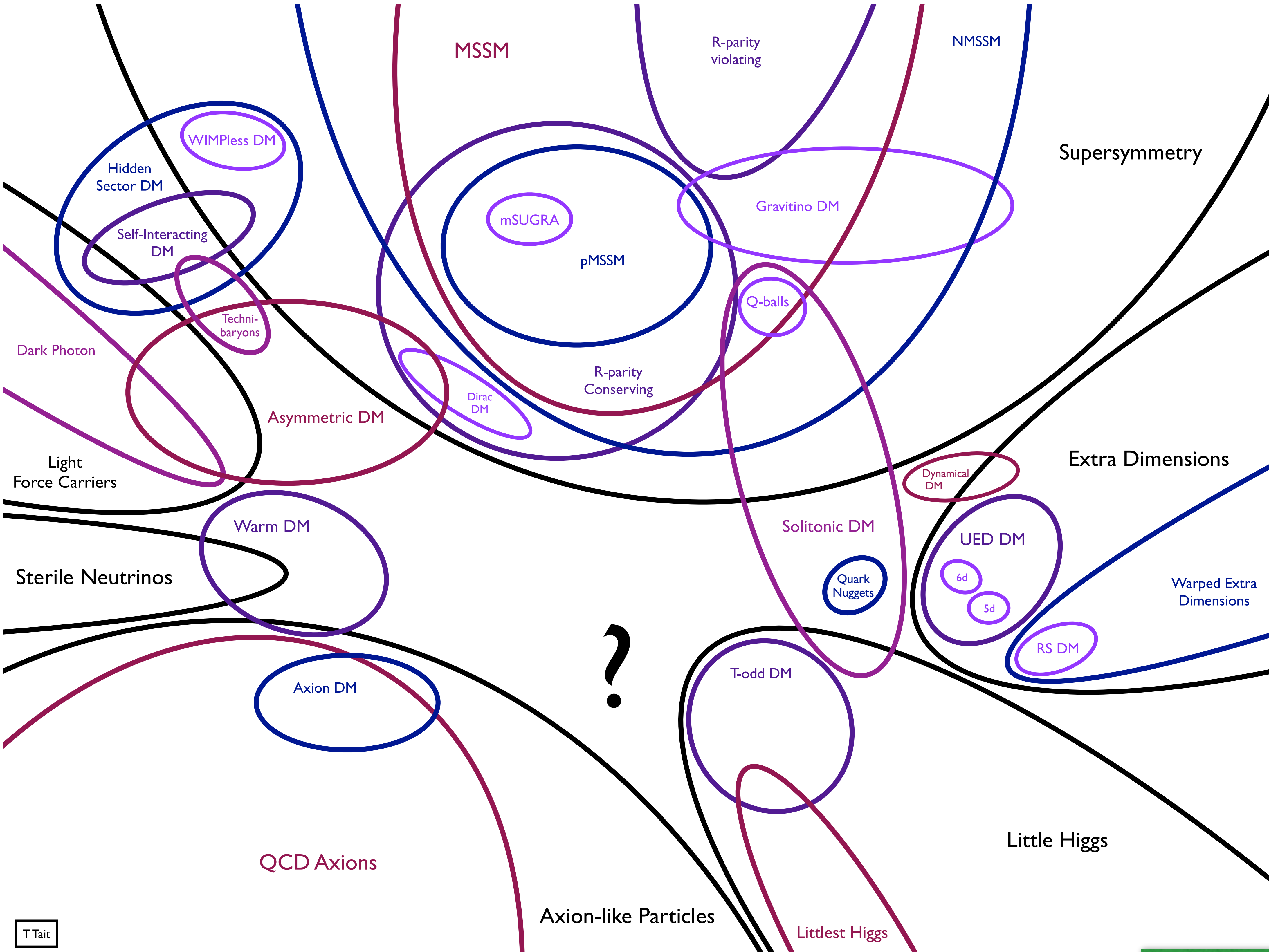


- All evidence is gravitational, so it's possible that's all there is.

- But, there are coincidences…

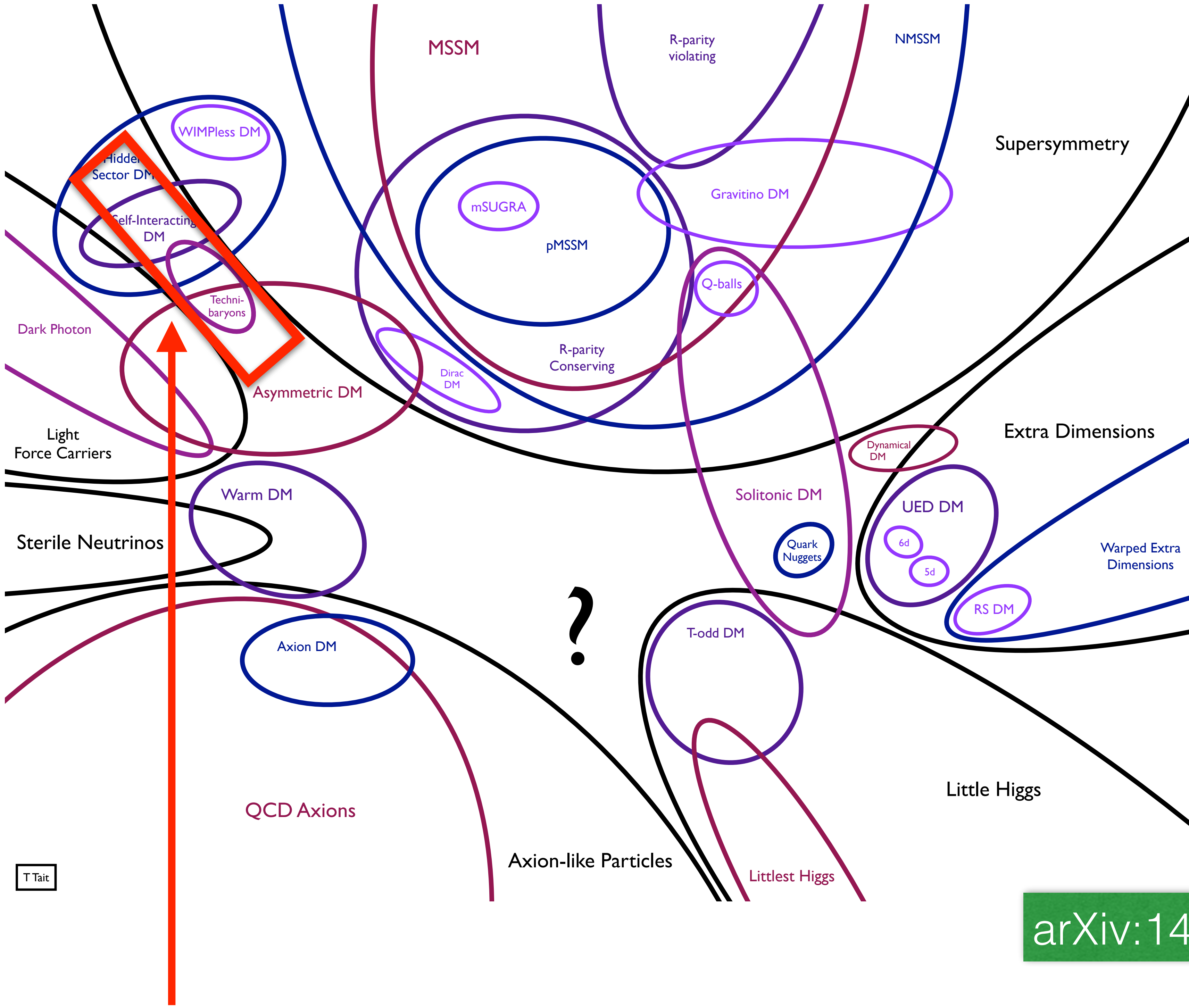


Theorists Love Dark Matter



arXiv:1401.6085

Theorists Love Dark Matter



arXiv:1401.6085

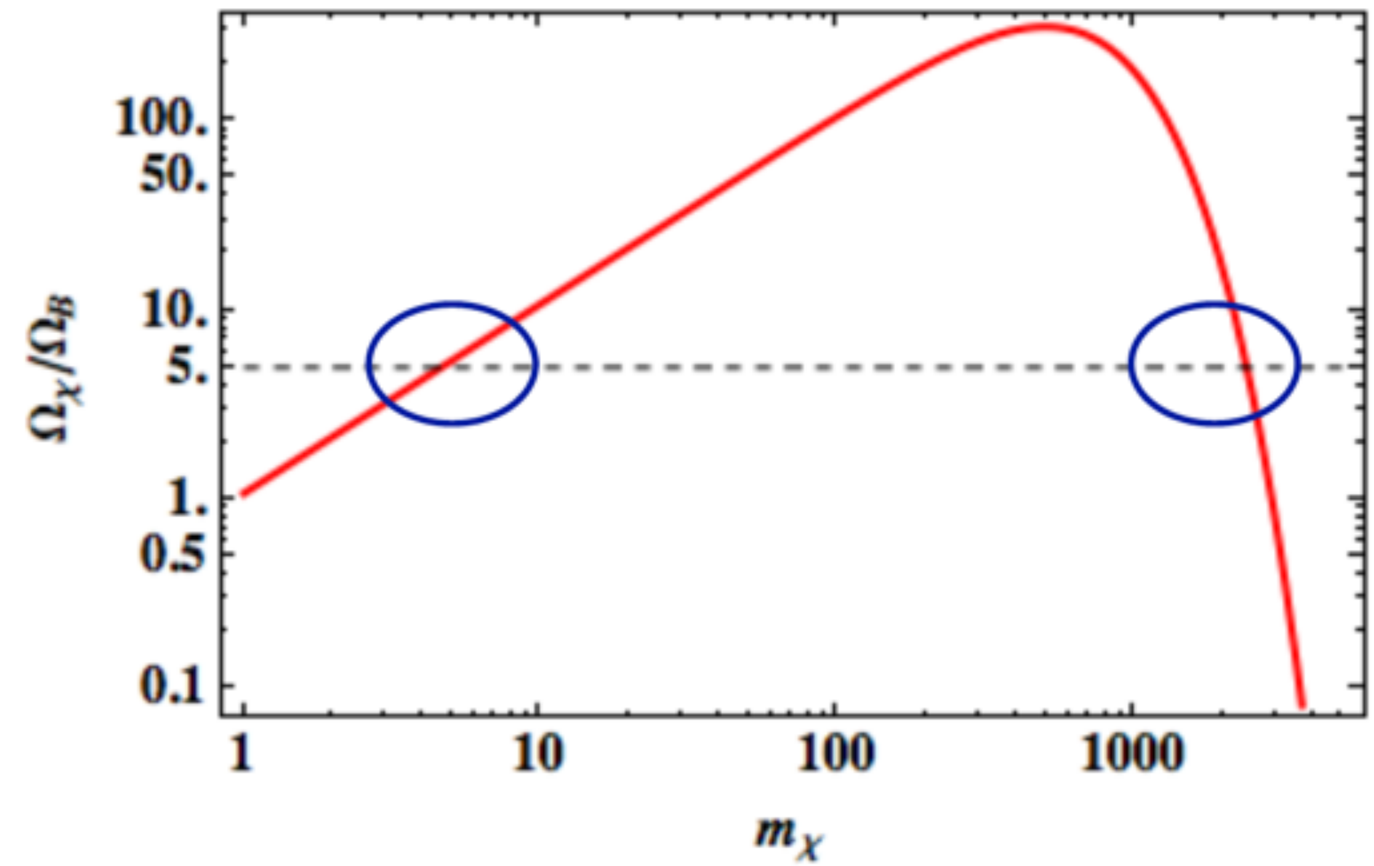
Where is composite dark matter?

Hint or Coincidence? (I)

- S. Nussinov, Phys. Lett. B 165 (1985) 55
- In 1985, $\Omega_D/\Omega_c \sim 0.2$ and $\Omega_B/\Omega_c \sim 0.01$.
- Baryon density: $\epsilon_B\, n_\gamma\, m_B$ where $\epsilon_B = (n_B - n_{\underline{B}}) / n_\gamma$. $\epsilon_B \sim 10^{-9}$, not $O(1)$, very sensitive to model details.
- If $n_D \sim n_\gamma$ then $\epsilon_B\, m_B / m_D \sim 0.01$. Could have been hugely different. Is this a hint?
- If DM participates in baryogenesis, $n_D = \epsilon_D\, n_\gamma$, so $\epsilon_B\, m_B / \epsilon_D\, m_D \sim 0.01$. Works great for technicolor (in 1985)!
- Today $\Omega_D/\Omega_B=5.5$, so really favors light **Asymmetric Dark Matter** $m_D \sim 5$ GeV. Not so great for technicolor today!
- ADM Review: K. M. Zurek, Phys.Rept. 537 (2014) 91.

Heavy Asymmetric Dark Matter

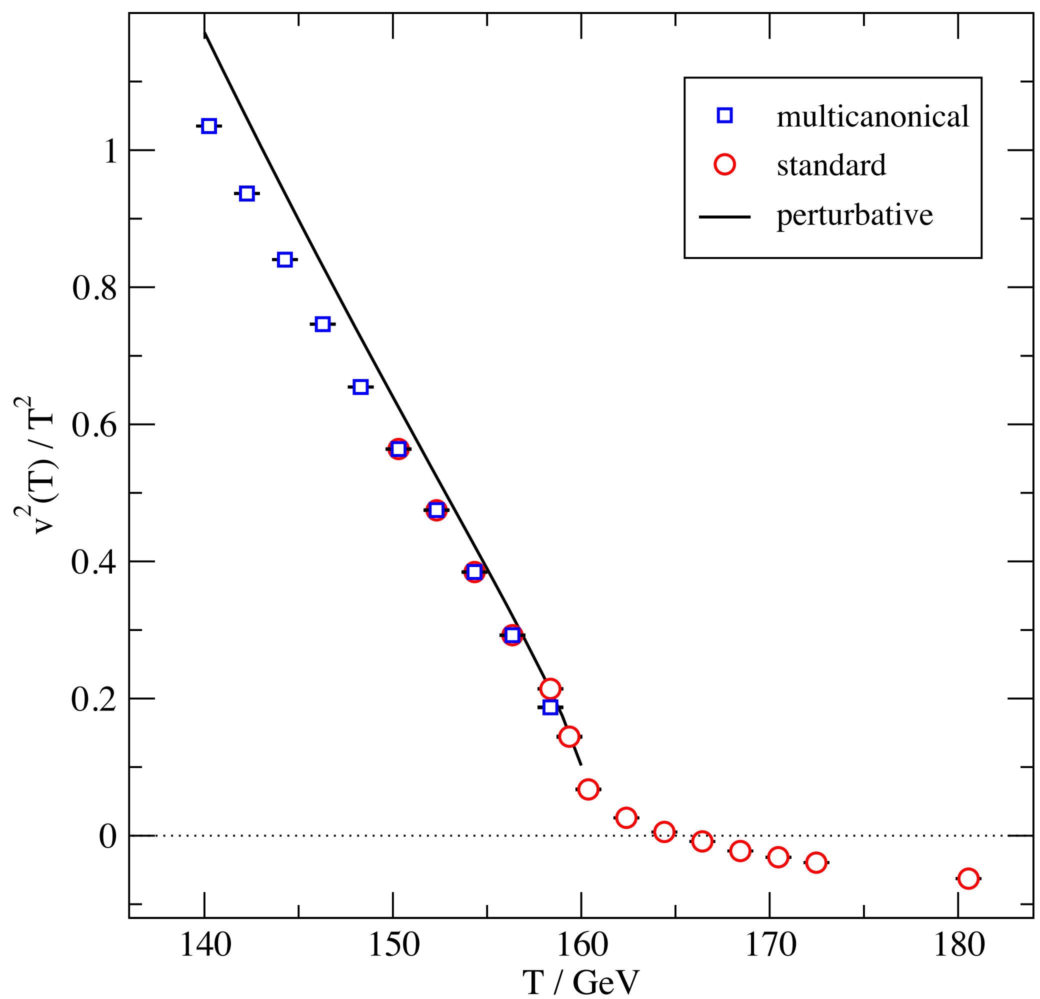
- Barr, Chivukula, Farhi, Phys. Lett. B 241 (1990) 387
- For $T<T_{sph}$, ϵ_B, ϵ_D frozen. $T_{sph} \sim 250$ GeV.
- Nussinov didn't notice if $T_{sph} < m_D$ then abundance is suppressed by $(m_D/T_{sph})^{3/2}\, e^{-m_D/T_{sph}}$.
- Two solutions: light 5 GeV, heavy 3 TeV.
- Heavy solution could be good news for technibaryon dark matter.
- But, specifics highly sensitive to model building details.

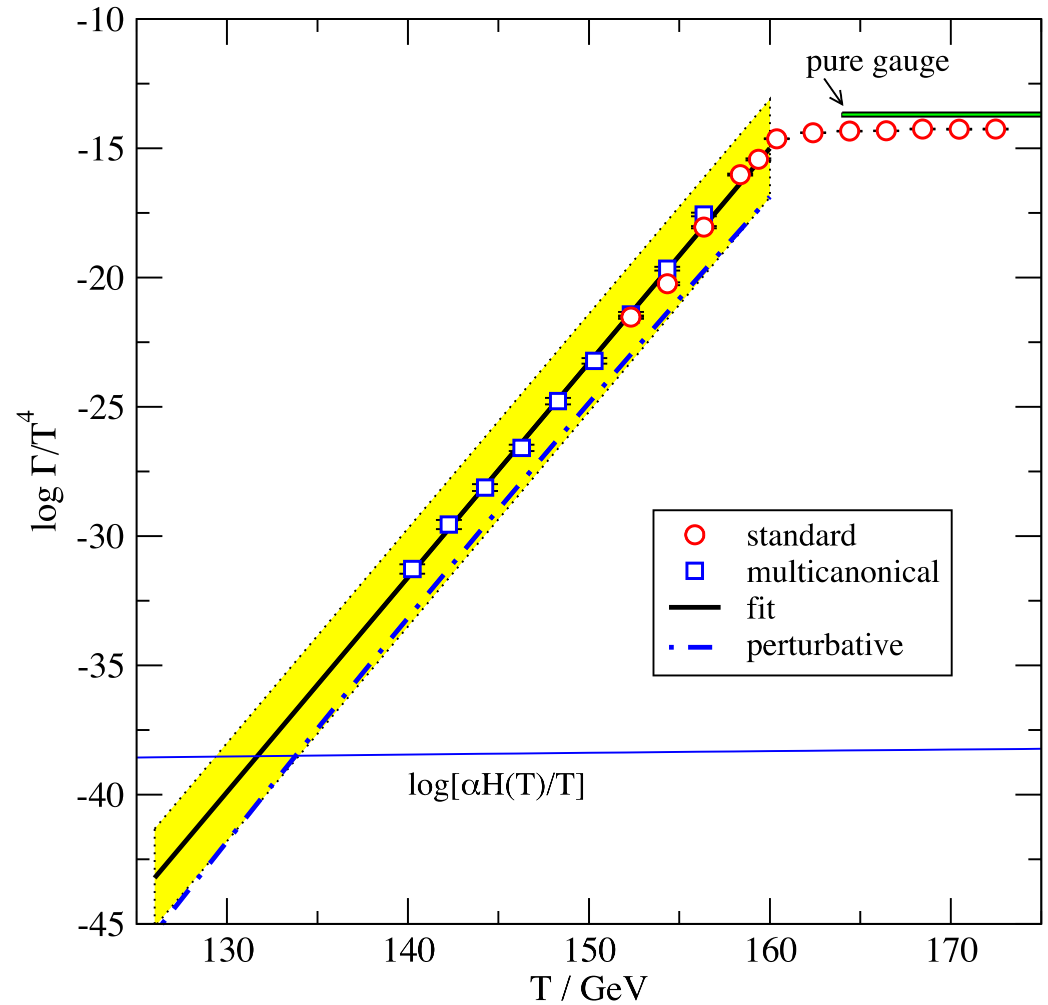


Lattice Estimate for T_{sph}

- D'Onofrio, Rummukainen, Tranberg, PRL 113 (2014) 141602
- Dimensionally reduced system matched to minimal SM
- Repeating for BSM theories would lead to a different dimensional reduction, matching, …

$$S = \int d^3x \left[\frac{1}{4} F^a_{ij} F^a_{ij} + |D_i \phi|^2 + m_3^2 |\phi|^2 + \lambda_3 |\phi|^4 \right]$$

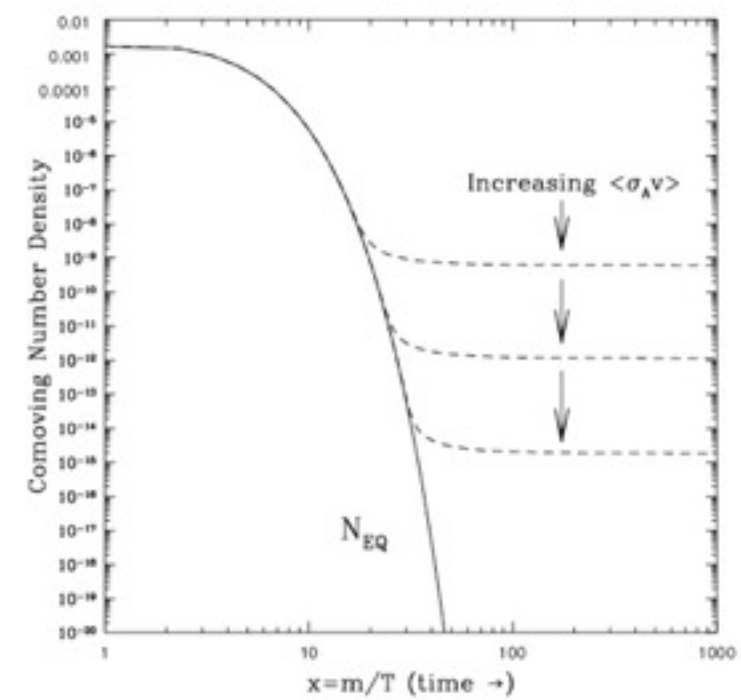




Hint or Coincidence? (II)

$$\Omega_{\rm dm}h^2 = 0.1199(27) \simeq 3\times10^{-27}{\rm cm^3s^{-1}}\langle\sigma_{\rm A}v\rangle^{-1}$$

$$\langle\sigma_{\rm A}v\rangle \sim \frac{\alpha^2}{M_{\rm dm}^2} \sim \alpha^2\left(\frac{100\ {\rm GeV}}{M_{\rm dm}}\right)^2 10^{-21}{\rm cm^3s^{-1}}$$



Jungman *et al* hep-ph/9506380

- Freeze-out occurs when the temperature falls below the mass and the abundance is determined by the annihilation cross section.

- If m_D ~ 100 GeV (EW scale) to get the right symmetric abundance, it should EW scale annihilation cross section (α~0.01).

- Used to be called the WIMP "miracle" but latest results from LUX have placed severe limits on such models.

- If you use α~16, analogous to **$N\bar{N}$** annihilation, m_D ~ 300 TeV. Not yet ruled out by LUX.

Astrophysical Hints?

- Dark matter plays a big role in galaxy formation and there are observations that don't agree with ΛCDM simulations:
  - Bulge-less disk galaxies, Cusp/Core problem, "Too Big to Fail", Missing Satellites.
- One proposed solution to some of these problems is to make self-interacting dark matter.

$$\sigma(v_{\rm rms})/M \sim 0.5 - 50\ {\rm cm}^2\ {\rm g}^{-1}, \quad v_{\rm rms} \simeq 10 - 100\ {\rm km\ s}^{-1}$$ arXiv:1412.1477

- Translate these numbers into natural units, it suggests dark matter masses as low as 10 MeV if weakly-coupled, up to 5 GeV if strongly coupled. Another coincidence?
- A more mundane possibility is baryon physics left out of simulations is responsible can explain anomalies. arXiv: 1501.00497 [astro-ph]

Coupling Dark Matter to SM

- If any of the hints are more than coincidences, then dark matter should have some interactions with the Standard Model.
- But, observed limits on potential DM-SM interactions are very constrained:
  - LEP-II constrains any new charged particles $M < 90$ GeV.
  - Z exchange ruled out: $\sigma(DM+N \rightarrow DM+N) \sim 10^{-38}\ cm^2$ but XENON/LUX $\sigma(DM+N \rightarrow DM+N) < 10^{-42}\ cm^2$.
- Composite DM can evade these constraints by having charged constituents confined in stable neutral hadrons.
- Composite Light ADM of 5 GeV is quite challenging because neutral composites usually have charged resonances (e.g. π^0, $\pi^{\pm}$).
- One possible approach: glueballs

Coupling Dark Baryons to SM

	$\psi\, \sigma^{\mu\nu}\, \psi\, F_{\mu\nu}$ Mag. Moment dim. 5	$(\psi\psi)\, v_\mu\, \partial_\nu\, F^{\mu\nu}$ Charge Radius dim. 6	$(\psi\psi)\, F_{\mu\nu}\, F^{\mu\nu}$ Polarizability dim. 7
Odd N_c No Flavor Sym.	✔	✔	✔
Odd N_c Flavor Sym			✔
Even N_c No Flavor Sym.		✔	✔
Even N_c Flavor Sym.			✔

Summary of Lattice Models

[references in Kribs & Neil, 1604.04627]

★ lattice
★ estimate
■ forbidden

Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) $N_f=1$	lattice	[Talk by Lewis, Wed.@11.50, new simulations are in progress]			
SU(2) $N_f=2$	lattice	estimate	forbidden (forbidden in pNGB DM)	estimate	lattice
SU(3) $N_f=2,6$	lattice		lattice	lattice	
SU(3) $N_f=8$	lattice	estimate			
SU(3) $N_f=2$ (S)	lattice	[Talk by Kuti, Mon.@15.15, small component of DM and tree-level interaction with Z boson]			
SU(4) $N_f=4$	lattice	lattice	forbidden	forbidden	lattice
			forbidden in Stealth DM		
SO(4) $N_f=2$ (V)	lattice				
SU(N) $N_f=0$	lattice	forbidden	forbidden	forbidden	forbidden
			forbidden in SUNonia		

E. Rinaldi, Lattice 2016

Lattice Strong Dynamics Collaboration

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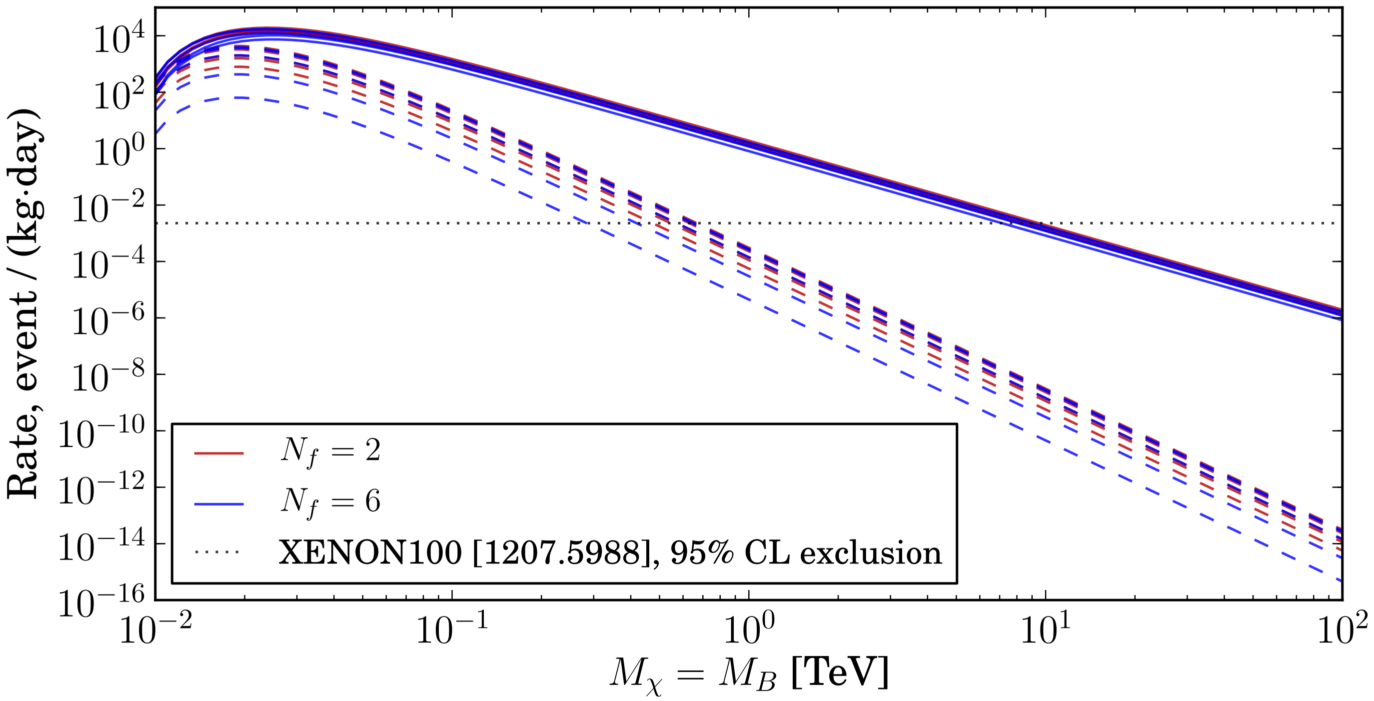
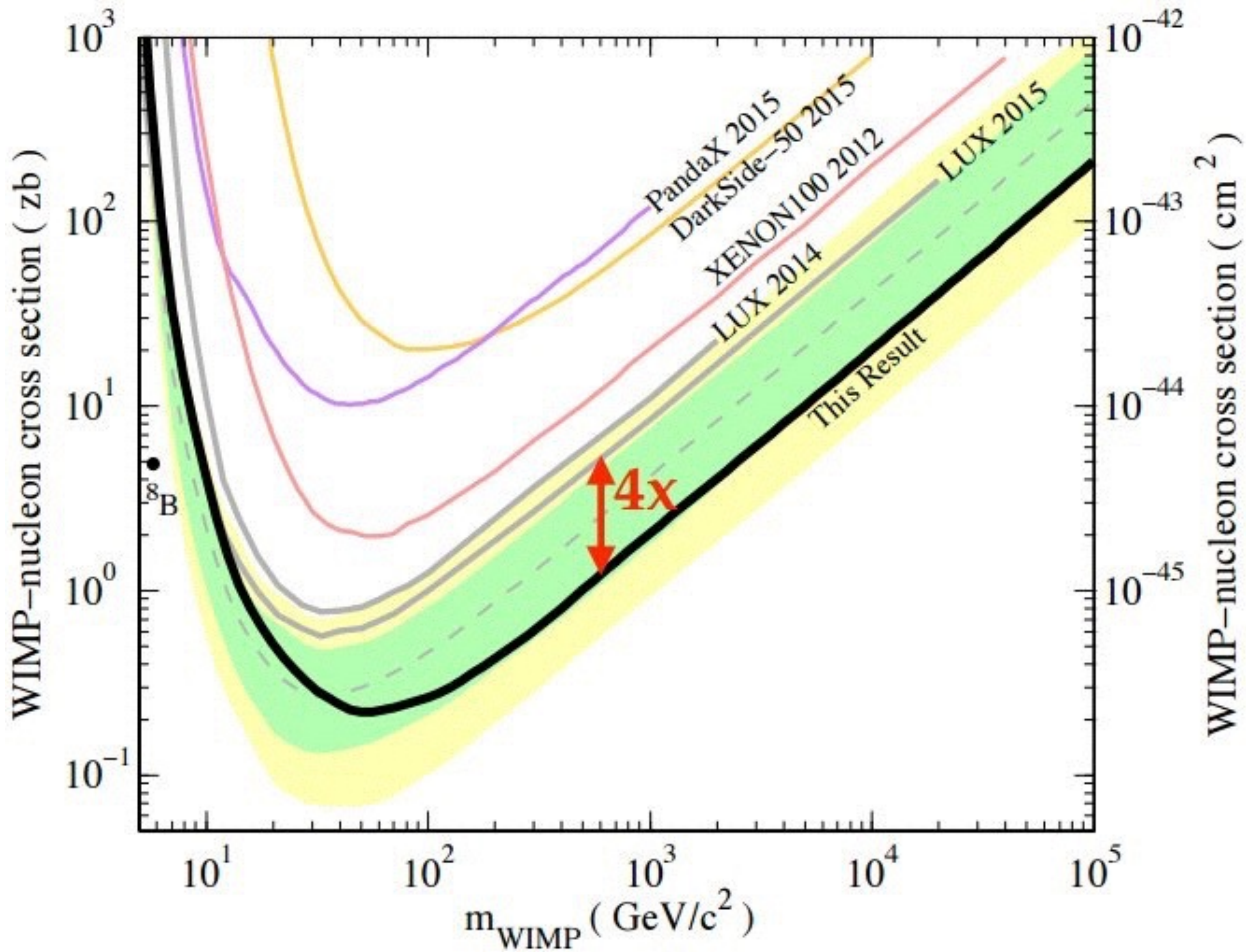
A Composite "Miracle"(II)



	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$SU(3)_D$
Q_1	1	1	2/3	3
Q_2	1	1	-1/3	3
Q_S	1	1	0	3

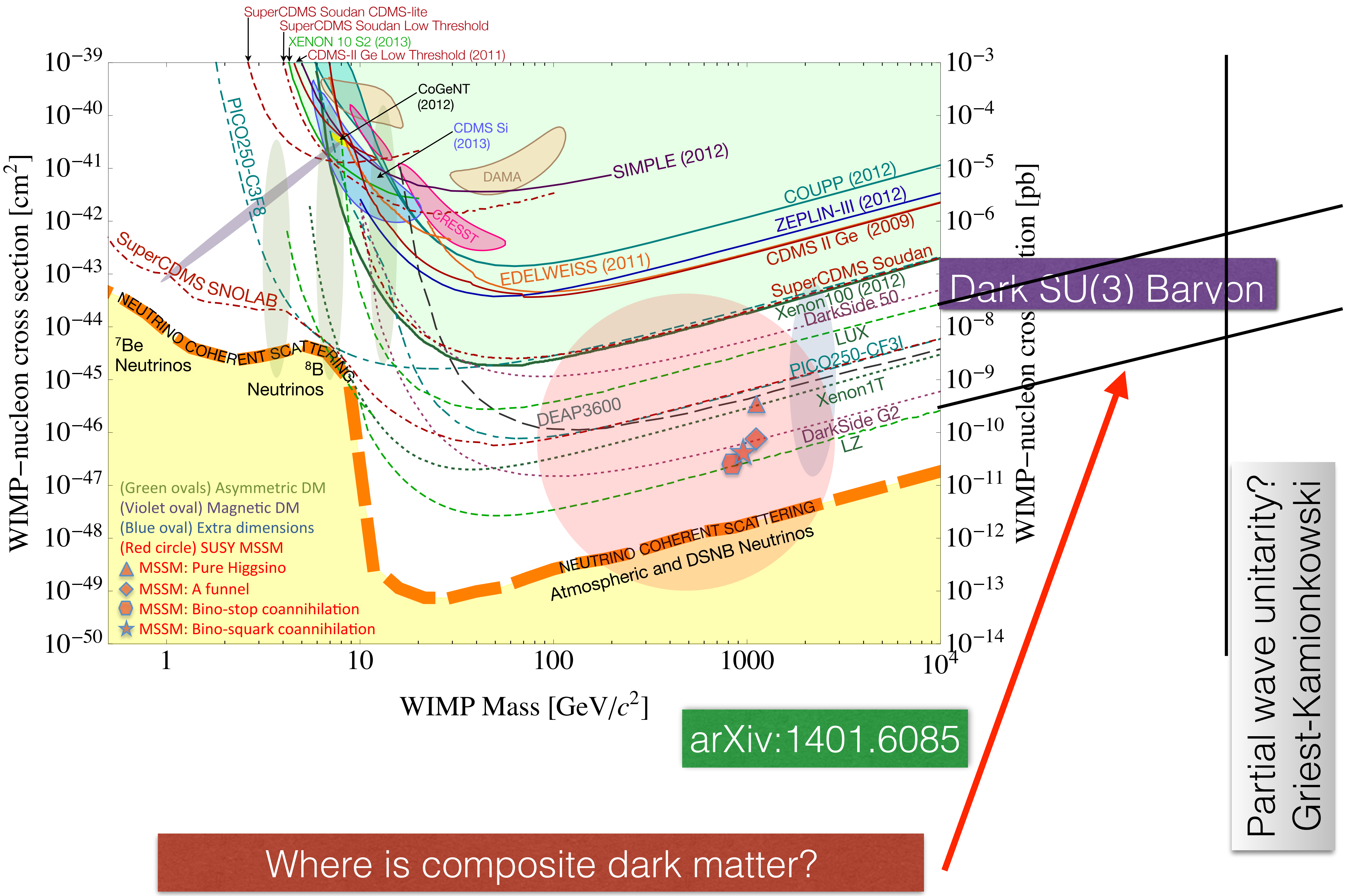
- [LSD Collab., Phys. Rev. D 88, 014502 (2013)]
- Composite fermion dark matter from new vector-like SU(3) gauge theory with Dirac mass terms. Can be a thermal relic.
- Solid lines: magnetic moment. Dashed lines: charge radius.
- **Full disclosure**: Not a complete model. Some dark sector breaking of G-parity needs to be added so dark pions decay but it shouldn't affect these results.

Latest Lux Result



http://luxdarkmatter.org

View from Snowmass



arXiv:1401.6085

Where is composite dark matter?

Partial Wave Unitarity

$$(\sigma_J)_{\max} v_{\rm rel} \approx \frac{4\pi(2J+1)}{m_\chi^2 v_{\rm rel}} \approx \frac{3\times 10^{-22}(2J+1)\,{\rm cm}^3/{\rm sec}}{[m_\chi/(1\ {\rm TeV})]^2}\,.$$

$$\Omega_{\rm dm}h^2 = 0.1199(27) \simeq 3\times 10^{-27}{\rm cm}^3{\rm s}^{-1}\langle\sigma_{\rm A}v\rangle^{-1}$$

$$\langle\sigma_{\rm A}v\rangle \sim \frac{\alpha^2}{M_{\rm dm}^2} \sim \alpha^2\left(\frac{100\ {\rm GeV}}{M_{\rm dm}}\right)^2 10^{-21}{\rm cm}^3{\rm s}^{-1}$$

- K. Griest and M. Kamionkowski, PRL 64 (1990) 615
- Assumes only 2→2 scattering.
- Partial wave unitarity sets a limit on the cross section in any partial wave.
- Combining this with the freeze out calculation puts a limit on thermal relics around 300 TeV.
- But, for $N\bar{N}$ annihilation, BR to 3π are order of magnitude larger than 2π. [C. Amsler, RMP 70 (1998) 1293]

Stealth Dark Matter (I)

- Composite dark matter can be lighter than 20 TeV if the leading low-energy interaction is dim. 7 polarizability.

- Requires even N_c so that baryons are scalars to eliminate magnetic moment interaction.

- Requires a global SU(2) custodial symmetry to eliminate charge radius interaction.

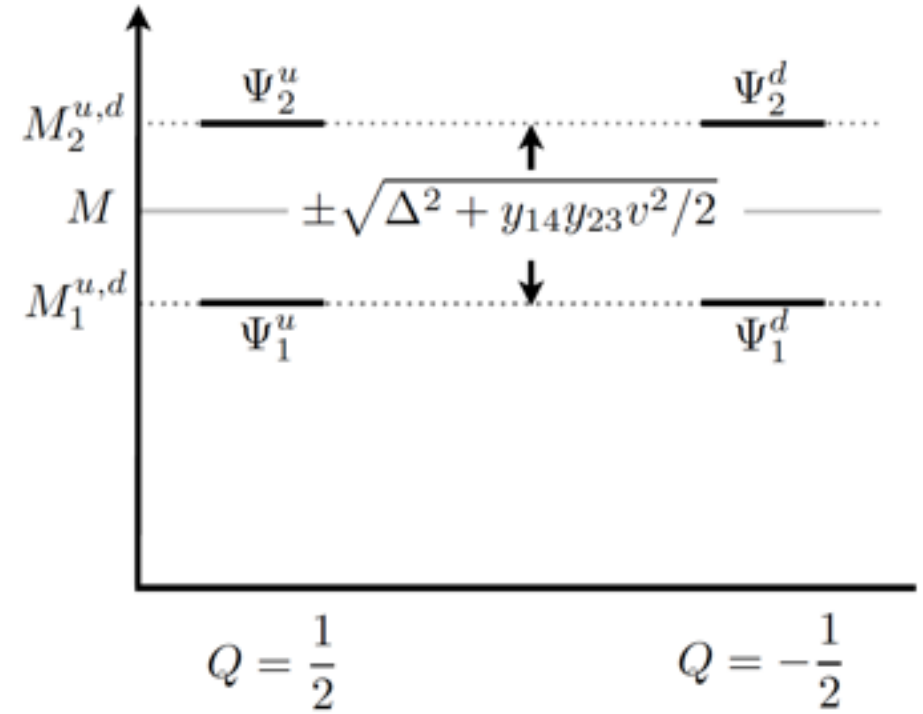
- Minimal coupling to weak SU(2) to enable dark pion decay. Now some coupling to Higgs boson.

- Also need vector-like masses so that dark sector doesn't impact Higgs vacuum alignment.

- Minimal model: Dark SU(4) color with $N_f = 4$ Dirac flavors.

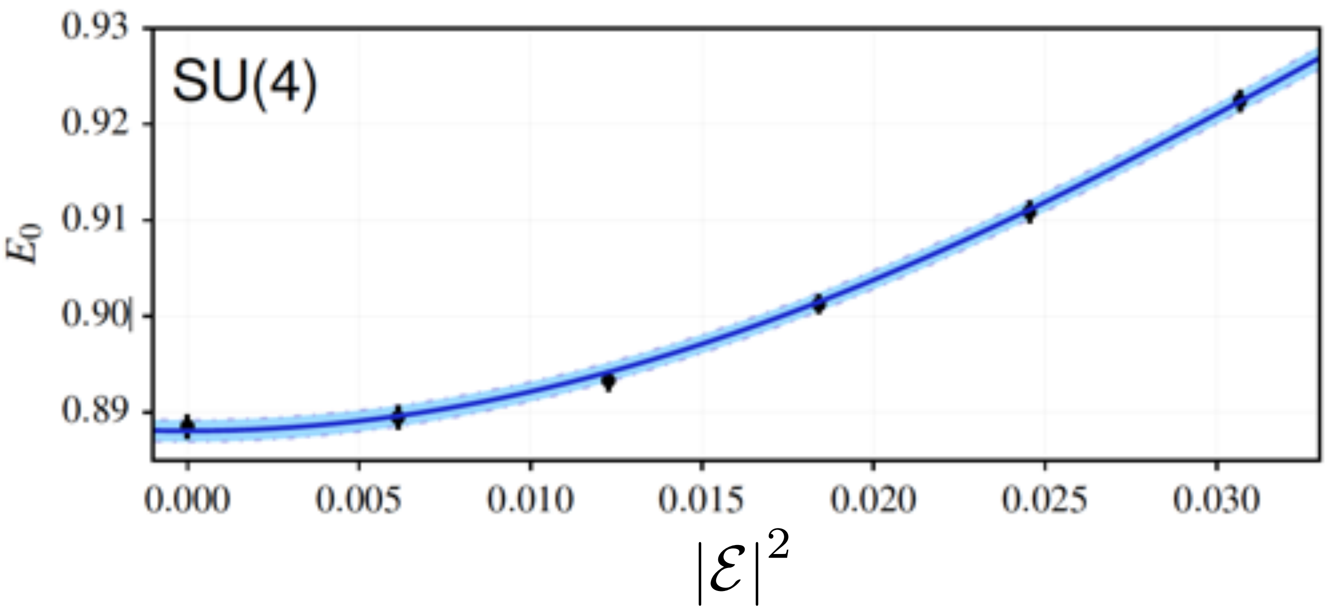
Stealth Dark Matter (II)

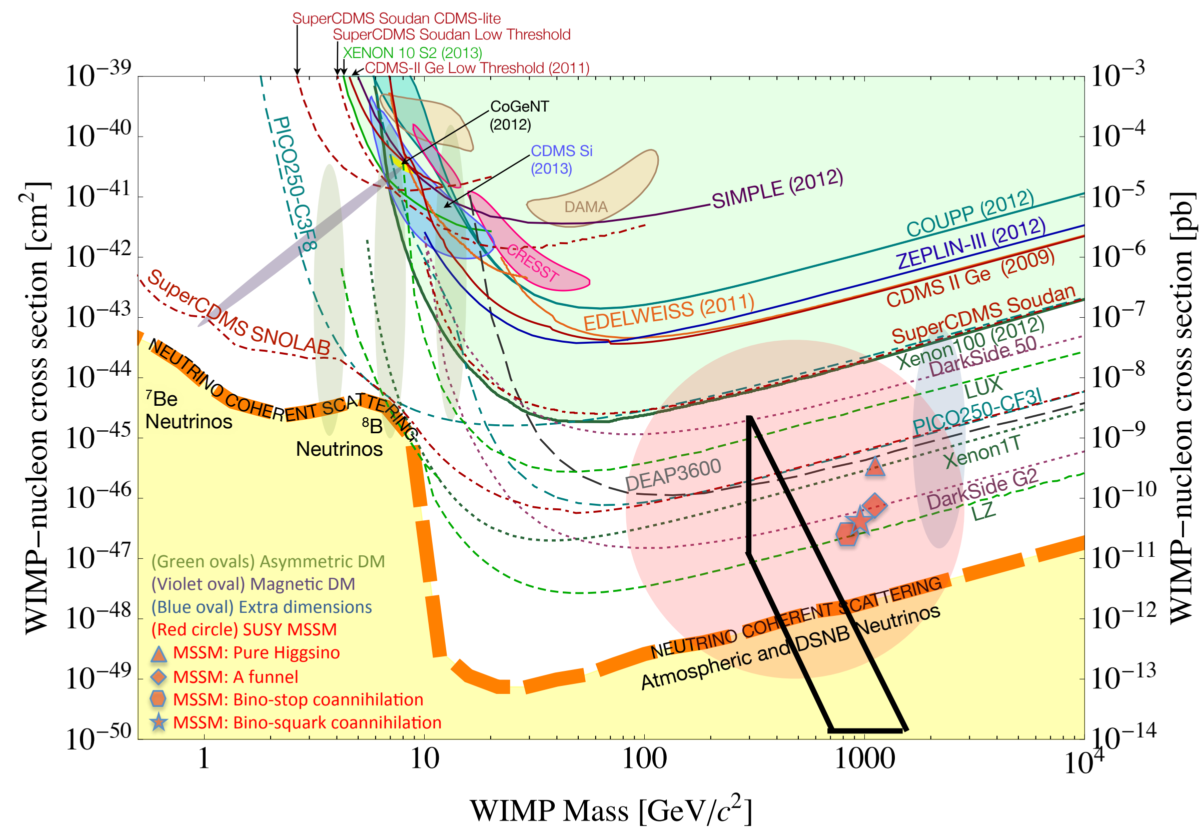
- Stable dark baryon is $(\psi_1^u \psi_1^u \psi_1^d \psi_1^d)$.
- Splitting between ψ_1 and ψ_2 Dirac doublets due either to vector mass splitting Δ or Yukawa couplings y.



- Coupling to Higgs can be made as small as needed (not a fine tuning) so that polarizability is dominant DM interaction, yet large enough to ensure no relic density of dark pions.
- Higgs VEV still dominates electroweak vacuum alignment and contributions to S and T parameters are small.
- arXiv:1402.6656, arXiv:1503.04203, arXiv:1503.04205.

SU(4) Polarizability





$$E_0(\mathcal{E}) = M_B + 2C_F\,|\mathcal{E}|^2$$

- Coherent DM-nucleus cross section:

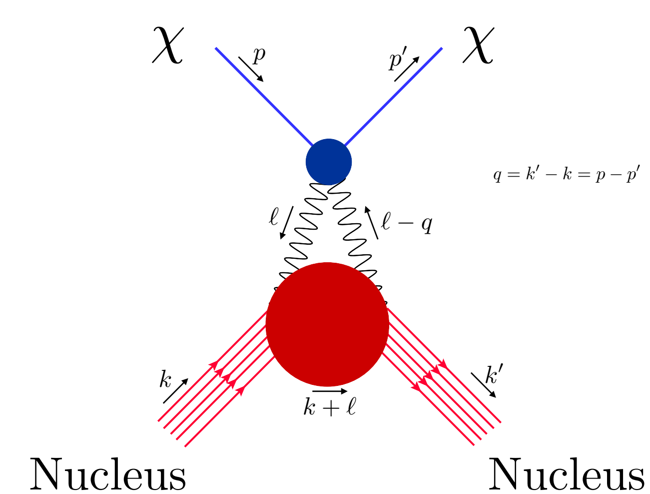
$$\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A}\left\langle \left|C_F f_F^A\right|^2 \right\rangle$$

- Nuclear matrix element [O(3) uncertainty]:

$$f_F^A = \langle A\,|F^{\mu\nu}F_{\mu\nu}|\,A\rangle$$

- Direct detection signal below neutrino background for M_B > 1 TeV. Stealth!

- Lower mass limit due to LEP-II bound on new charged particles



Concluding remarks

- Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. Stealth!
- No new forces required beyond SU(N) confining dark color force.
- Abundance can arise either by symmetric thermal freeze-out or by asymmetric dark baryogenesis.
- Future experiments could eventually rule out dark baryons with mag moments, even beyond the Griest-Kamionkowski bound.
- Composite dark matter around 1 GeV is still a challenge due to LEP bounds.
- We need to work harder to inform the broader DM community about our exciting results!