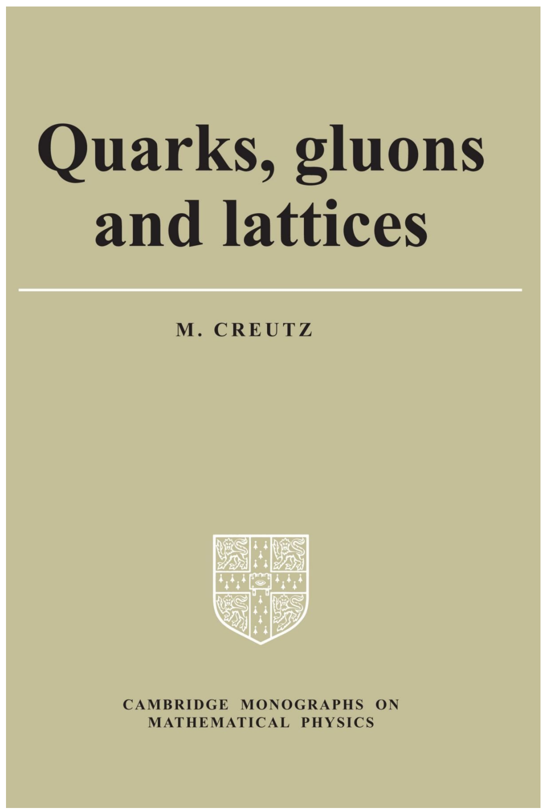
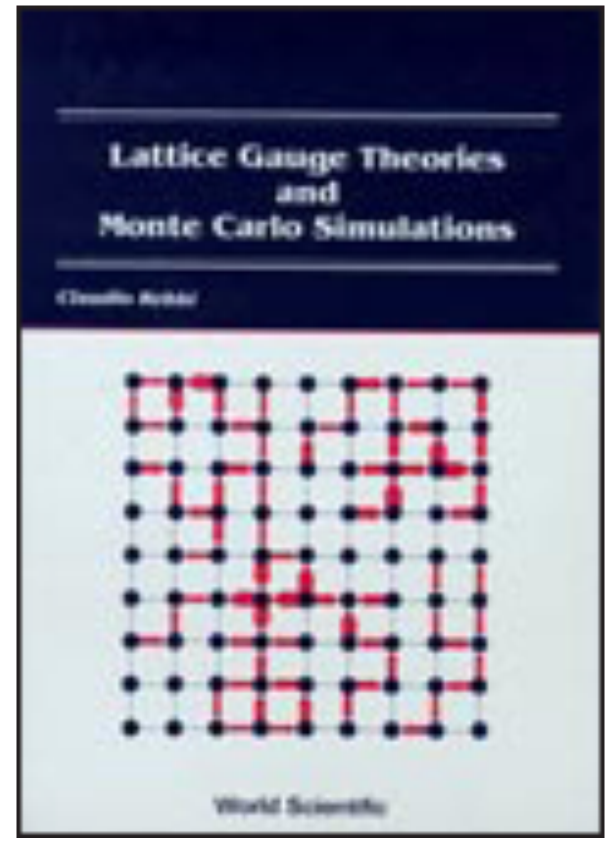
Composite Dark Matter

George T. Fleming
Yale University

My First Time…

- In 1994, Jeff Greensite told me to read these two books:





- For the next year or so, I poured over the research of the early 80’s. I was amazed at the breadth of the field: so many different models, different techniques. Mike’s name was everywhere.

- In 1996, I started research at Columbia and soon discovered the “wild west” days were over and the “industrial” QCD days had begun.

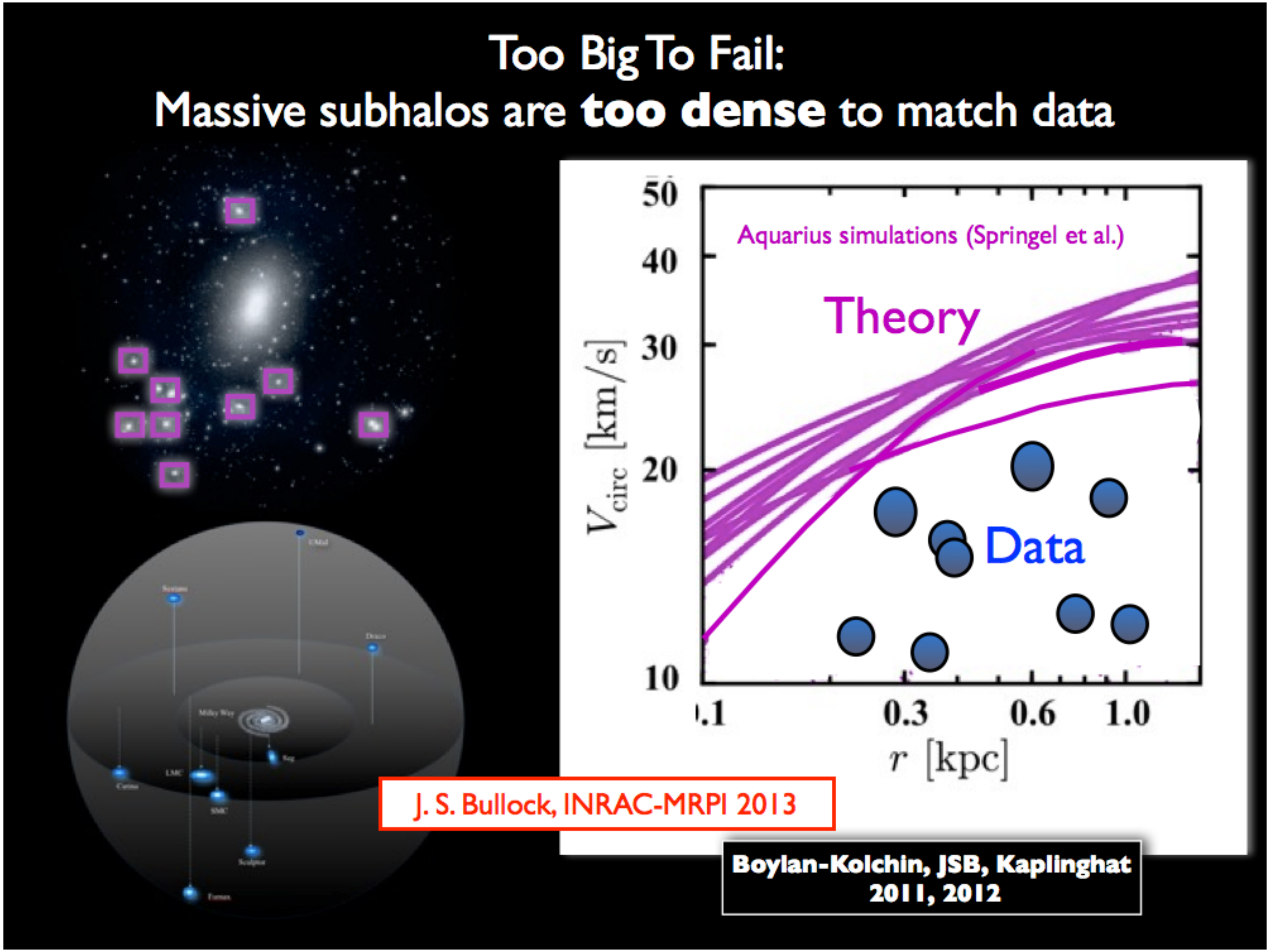
- I was so excited to meet Mike at Lattice ’96 and was very impressed at how easy it was to approach him and talk to him as a very young graduate student.

Beyond QCD

- In my career, I have always wanted to experience first hand the explosive growth of a new field like I read about in Mike and Claudio's books.
- But, looking for new strong interactions in physics beyond the standard model wouldn't have been my first choice.
- I was very skeptical of BSM because I had seen how hard it could be at Columbia in the late '90s (Chengzhong Sui).
- In retrospect, I am grateful that the USQCD executive committee asked me to help write the 2006 BSM white paper (with Mike!) because it forced me to reconsider BSM physics.
- Luckily, the BSM community has found a number of ways to make progress.
- Unfortunately, the Higgs mechanism appears to be very much like Weinberg envisioned in 1967.

BSM Is Out There

- Discovery of SM-like Higgs boson doesn’t mean BSM physics is dead:
  - What is the meaning of the hierarchy problem and naturalness?
- What solves the strong CP problem?
- What explains the matter-antimatter asymmetry?
- What is dark matter? Can it couple to the standard model? Is the mass scale related to the EW Higgs mechanism? Is it self-interacting?



Also the “Missing Satellite Problem”

A Composite "Miracle"(I)

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

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

- For **M_{dm} ~ 100 GeV** and α ~ 0.01 can be a thermal relic, but such WIMPs are being ruled out by XENON100/LUX.
- Current bounds on composite fermion dark matter are M_{dm}>20 TeV [LSD Collab., Phys. Rev. D 88, 014502 (2013)].
- Analogous to **$N\bar{N}$** annihilation, α ~ 16 which would mean M_{dm} ~ 320 TeV. Not ruled out but not likely to be observed soon.
- But, by dialing up the quark masses, we can bring down α to make a thermal relic M_{dm} ~ 20 TeV.
- Challenge: quark mass dependence of **$N\bar{N}$** annihilation, incl. heavy quarks.
- Strongly-interacting DM also helps with "too big to fail" problem.

Coupling to SM

	Dim-5 $\overline{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$ Magnetic Moment	Dim-6 $(\overline{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}$ Charge Radius	Dim-7 $(\overline{\psi}\psi)F_{\mu\nu}F^{\mu\nu}$ Polarizability
Odd Nc No baryon flavor sym.	✓	✓	✓
Odd Nc Baryon flavor sym.			✓
Even Nc No Baryon flavor sym.		✓	✓
Even Nc Baryon flavor sym.			✓

Buchoff Lat 2013

Lattice Strong Dynamics Collaboration

James Osborn

Rich Brower
Michael Cheng
Claudio Rebbi
Oliver Witzel
Evan Weinberg

Ethan Neil

Ethan Neil
Sergey Syritsyn

Meifeng Lin

Graham Kribs

Evan Berkowitz
Enrico Rinaldi
Chris Schroeder
Pavlos Vranas

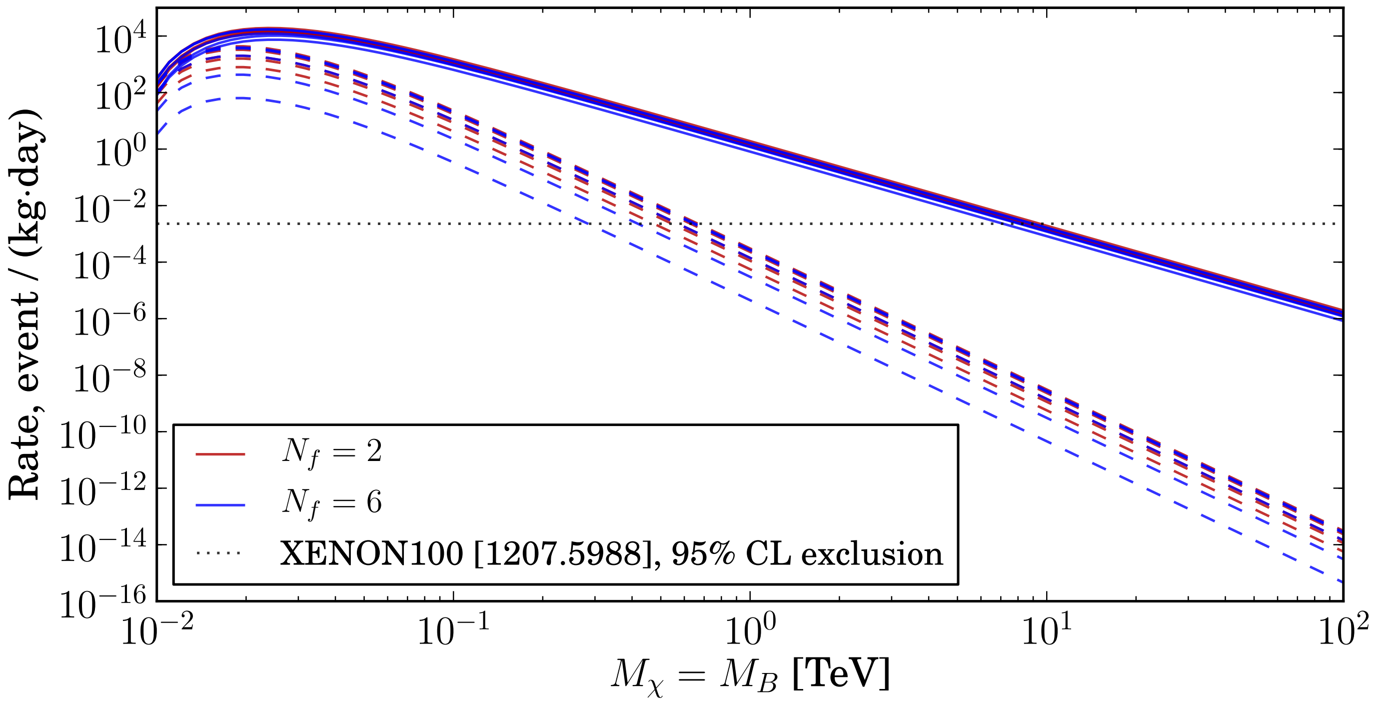
Joe Kiskis

David Schaich

Tom Appelquist
George Fleming

Mike Buchoff

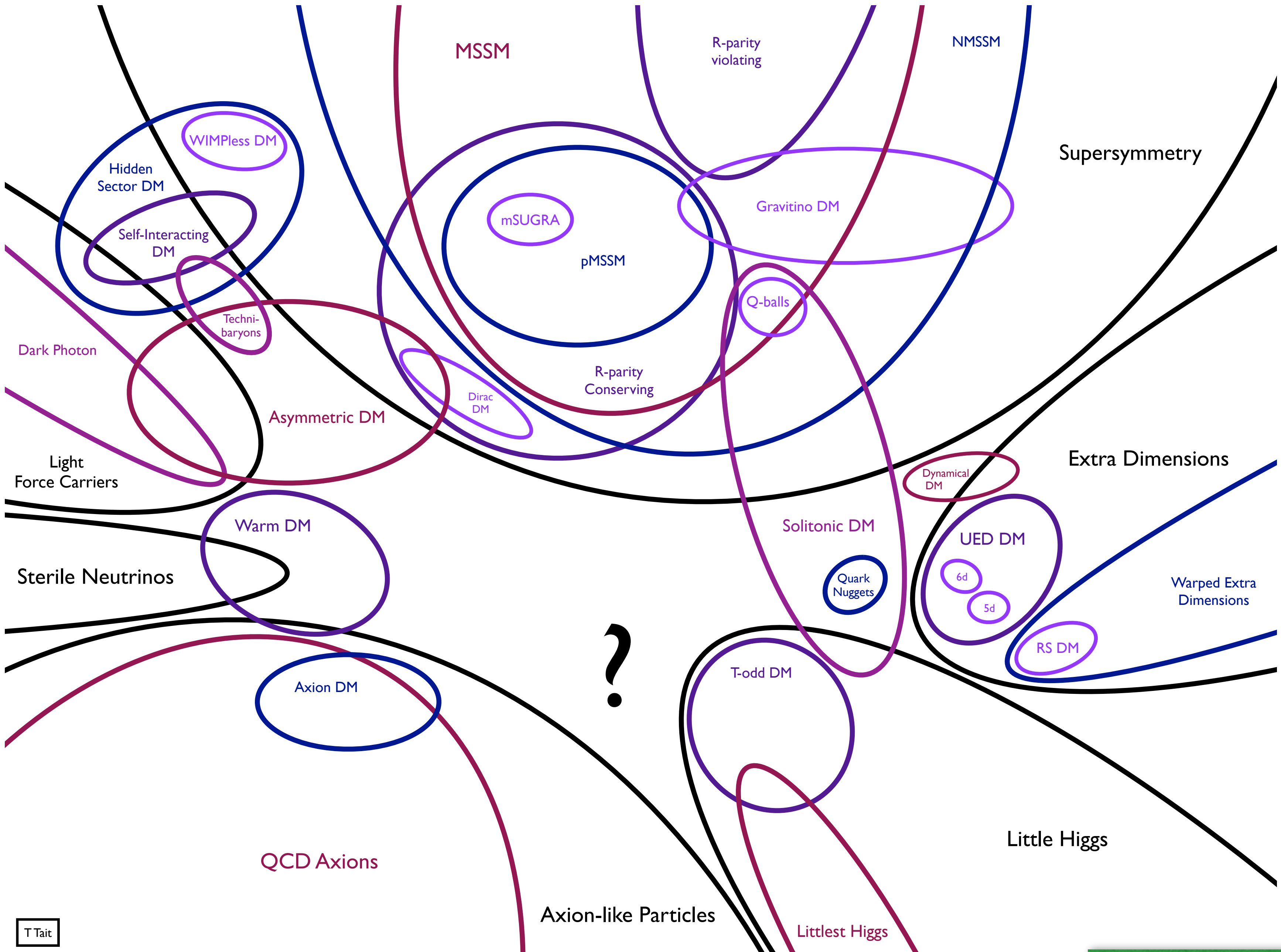
A Composite "Miracle"(II)



	SU(3)	SU(2)	U(1)	SU(3)
Q	1	1	2/3	3
Q	1	1	-1/3	3
Q	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.
- 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.

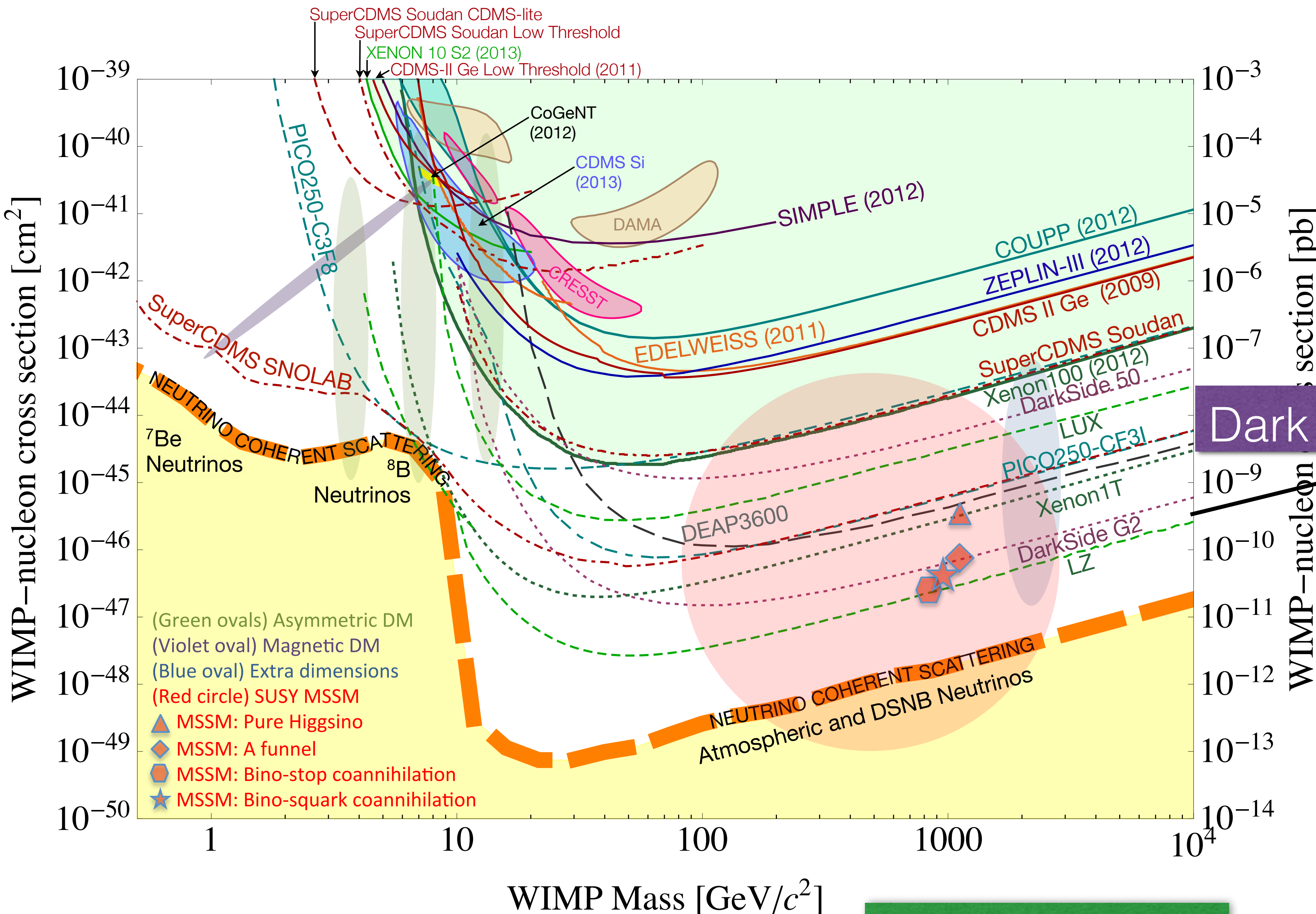
View from Snowmass (I)



arXiv:1401.6085

Where is composite dark matter?

View from Snowmass (II)



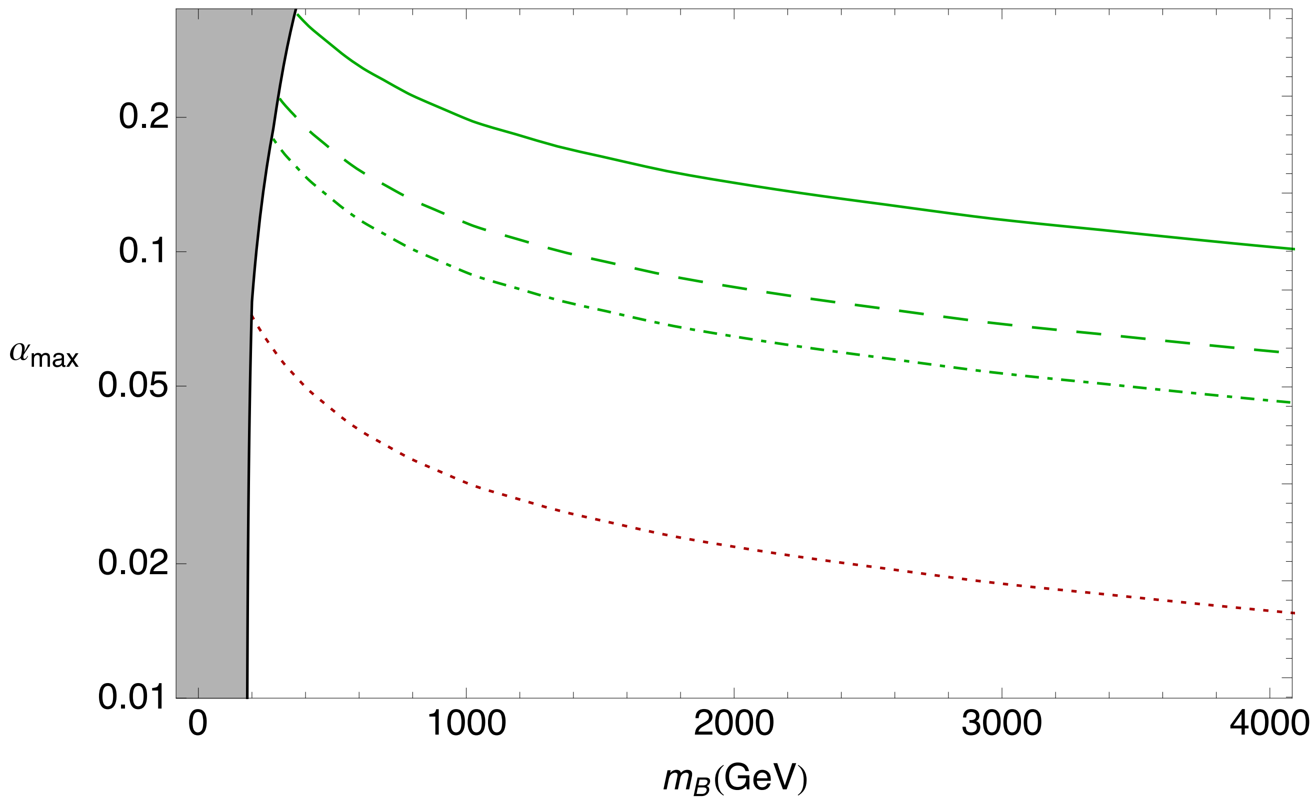
Dark SU(3) Baryon

Partial wave unitarity?

arXiv:1401.6085

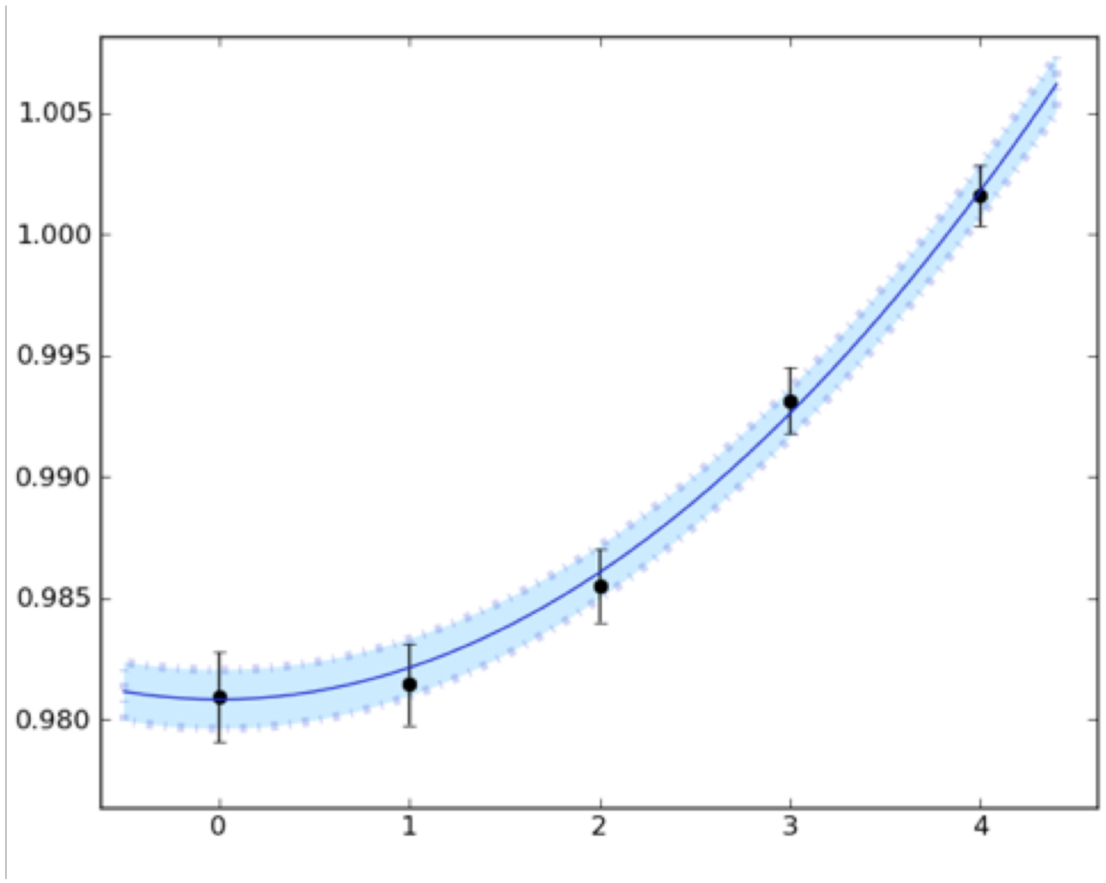
Where is composite dark matter?

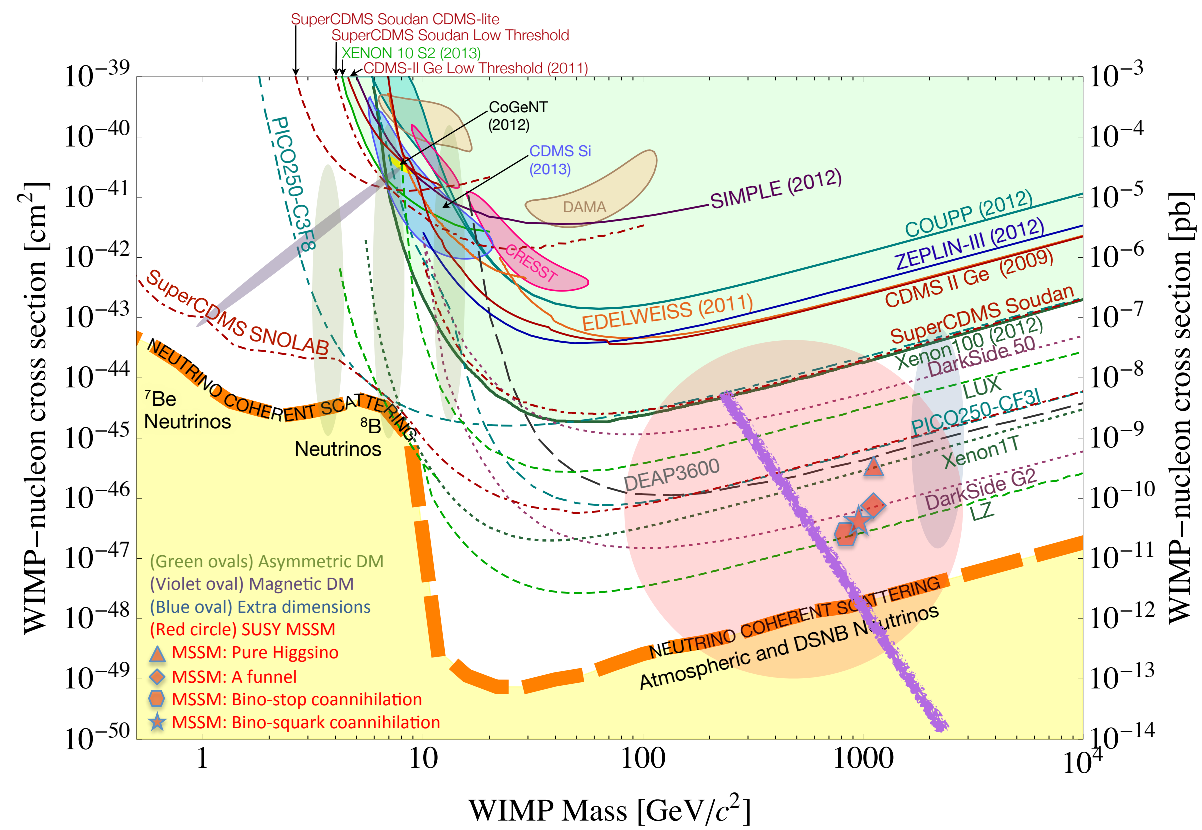
A Composite "Miracle"(III)



- [LSD Collab. + G. Kribs, arXiv:1402.6656]
- Composite bosonic dark matter from new SU(4) gauge theory.
- No magnetic moment or charge radius interactions. Polarizability interaction is likely too small to be seen, but LSD is computing it anyway.
- Enable coupling to Higgs by allowing some fraction α of quark mass to come from Yukawa interaction.
- Curves are M_P/M_V = 0.55, 0.7, 0.77, 1.

SU(4) Polarizibility





$$E_0(\mathbf{E}) = E_0(\mathbf{0}) + \alpha_E |\mathbf{E}|^2 + \ldots$$

- [LSD Collab. + G. Kribs, **VERY PRELIMINARY**]
- Stay tuned…

Concluding remarks

- BSM physics has many opportunities for new composite particles, *e.g.* dark matter.

- I didn't experience first hand the lattice revolution of the early '80s, but I like to think that lattice BSM research recaptures some of that early spirit.

- Unlike the early '80s, we have to work harder to make our non-lattice colleagues aware of our exciting results.

- Looking forward to continued discussion with Mike in the future.