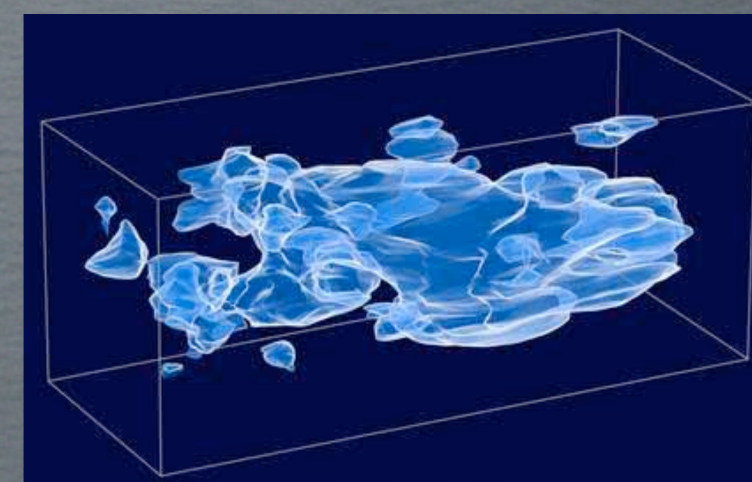
Composite Dark Matter Exclusions From the Lattice

An
LSD
Production



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Special Thanks:
Graham Kribs
Sergey Syritsyn

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL-PRES-595392

Lattice Strong Dynamics Collaboration

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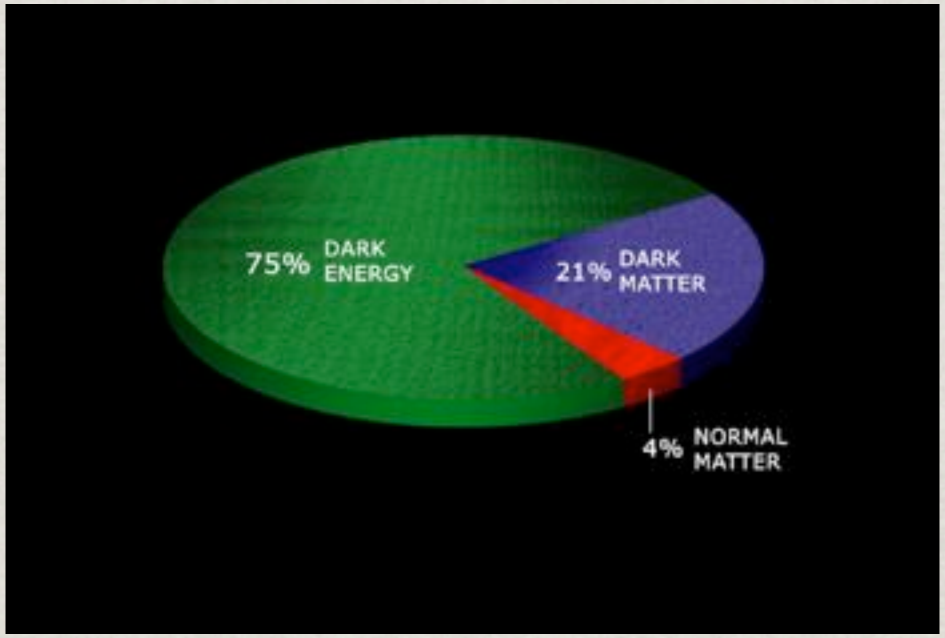
A slice of the Universe



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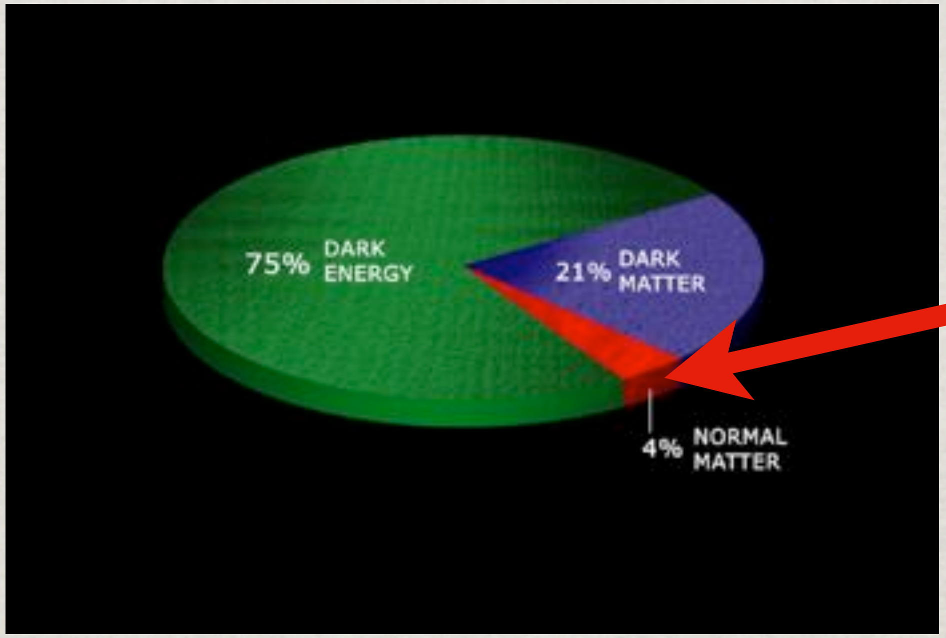
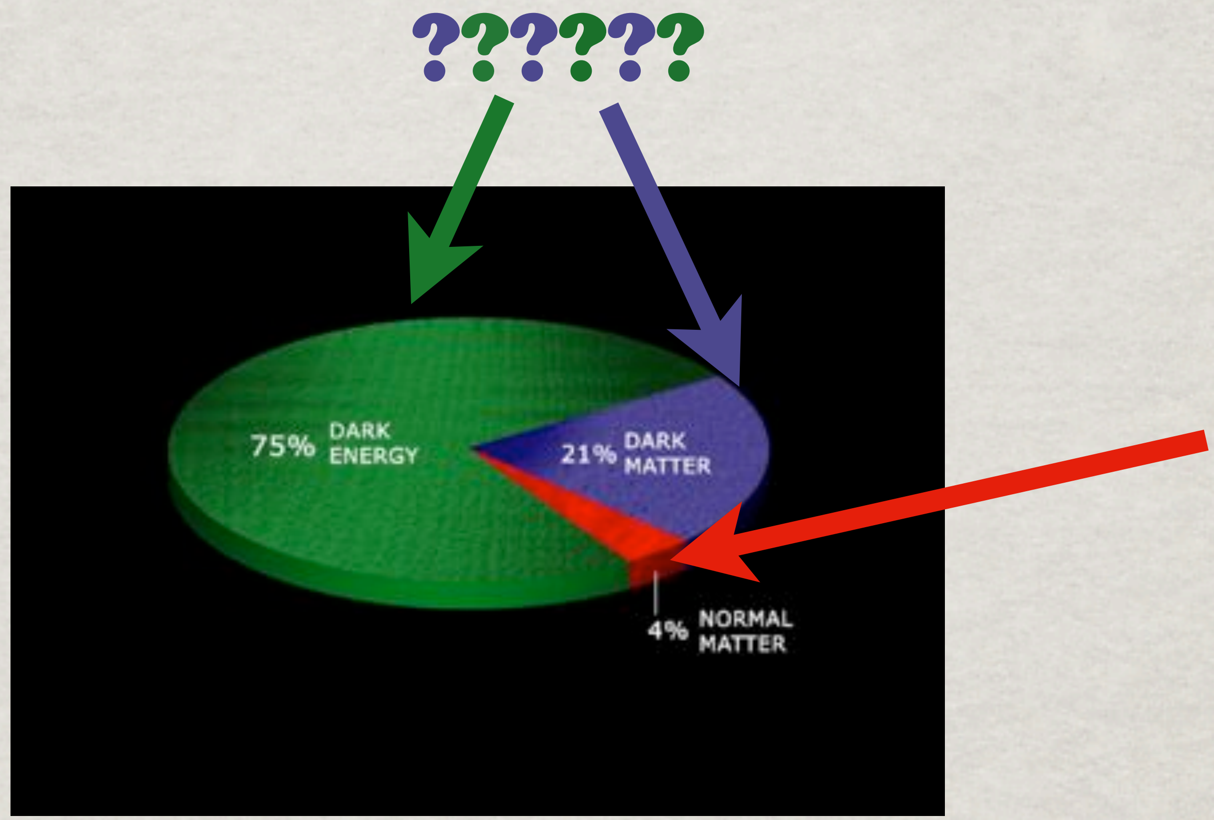


We Are Here

(QCD, EM, SM, etc.)

A slice of the Universe



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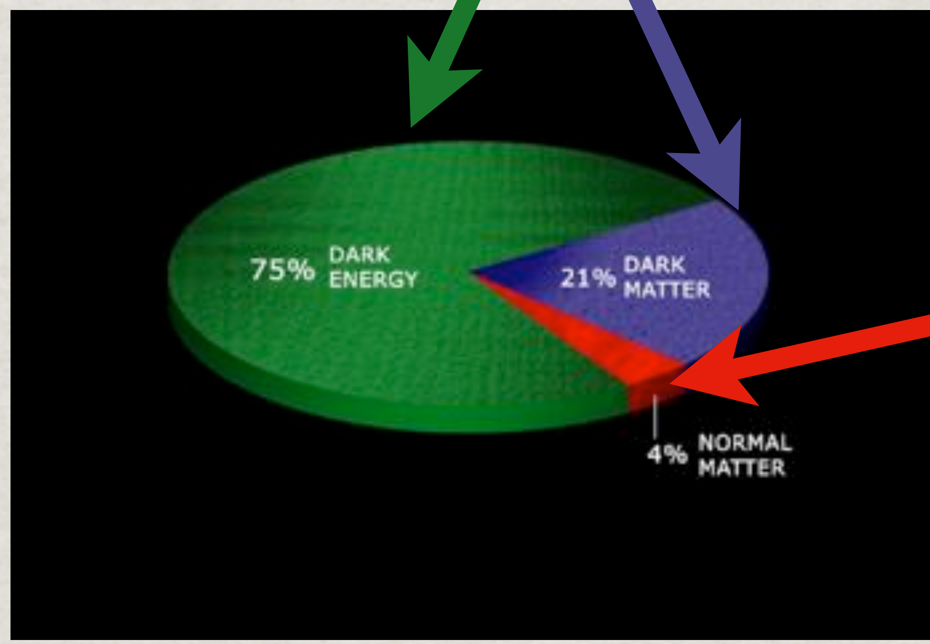
A slice of the Universe

??????

New Physics!!



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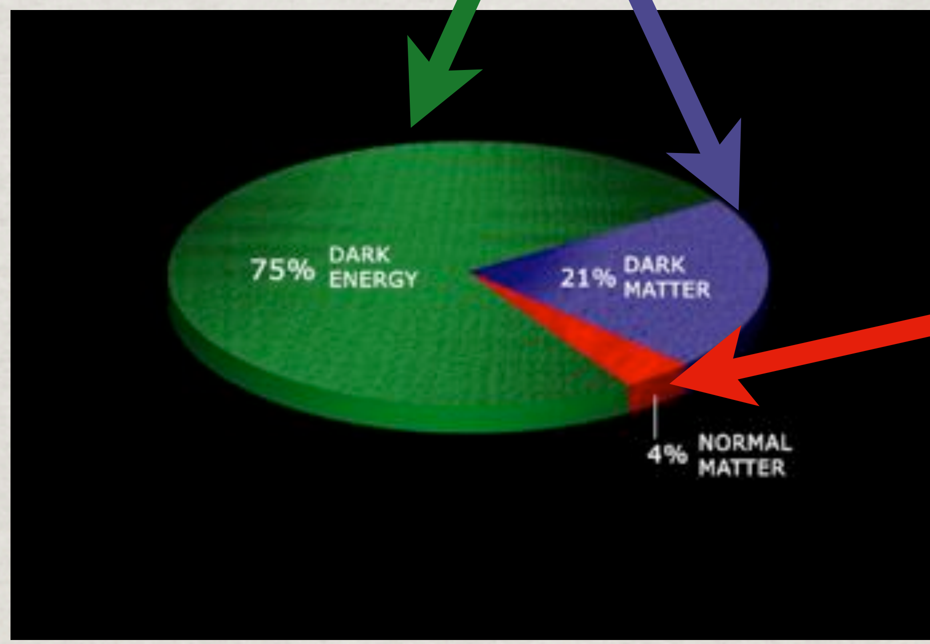
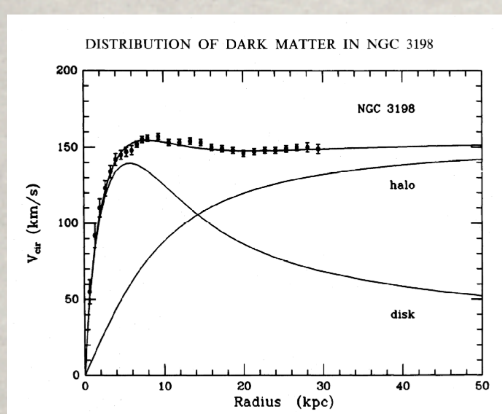


New Physics!!

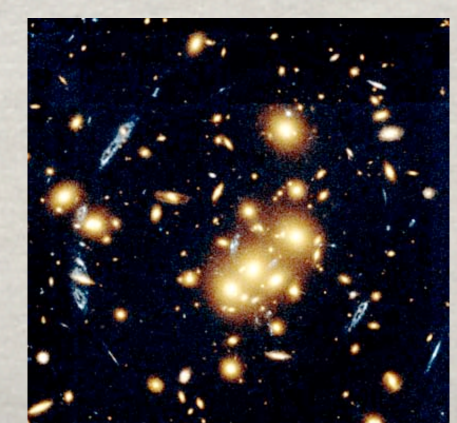
We Are Here

(QCD, EM, SM, etc.)

How do we know DM is there?



- Rotation Curves of Galaxies
- Gravitational Lensing



Gravity says it is there but...

...do we have any clue what it is?

- How does it interact with SM?
- How does it interact with itself?
- What is its spin or parity?
- Is it simultaneously matter and anti-matter?
- **What is its Mass?**

None of these questions have been answered to date...

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None of these questions have been answered to date...

...but there are several clues that can tell quite a bit

Three Primary Properties of dark matter

1. Candidate should be Stable

- Explain why dark matter has survived to today

➡ Implies a new symmetry and/or charge

2. Candidate should be EW Charge Neutral

- Explain why no visible evidence

➡ Implies lightest stable particle is chargeless

3. Candidate should explain observed relic density

$$\rho_D \sim 0.2\ \rho_c$$

How can this come about?

Thermal Relic

Dark Matter Annihilates → How much do we see today?

One approach to DM theories:

Choose DM Mass
Choose DM Interactions → $\rho_D \sim 0.2\ \rho_c$

"WIMP Miracle"

Assume Interactions at/near EW Scale → $M_D \sim \text{TeV}$

An Asymmetric alternative?

S.Nussinov (1985) R.S.Chivukula, T.P.Walker (1990) D.B.Kaplan (1992)

Observe a different relation:

$$\rho_D \sim 5\rho_B$$

$$M_D n_D \sim 5 M_B n_B$$

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If DM density is thermal: Unjustified Accident

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Observe a different relation:

Asymmetry

$$\rho_D \sim 5\rho_B$$

$$M_D n_D \sim 5 M_B n_B$$

If DM density is thermal: **Unjustified Accident**

Natural if DM density is also tied to asymmetry

$$n_D \sim n_B \Longrightarrow M_D \sim 5\ \text{GeV}$$

$$M_D \gg M_B \Longrightarrow n_B \gg n_D \sim e^{-M_D/T_{sph}}$$

Sphaleron connection → **Direct or Indirect coupling to EW**

Thermal vs. asymmetric

However:

Asymmetric relic density
suggests negligible thermal abundance

SMALL THERMAL ABUNDANCE → **LARGE ANNIHILATION RATE** → **STRONG COUPLINGS**

Tricky to achieve for perturbative, elementary DM

Strongly-coupled composite theories most interesting...

...this is where the lattice can play significant role!

Composite Dark Matter

1. Candidate should be Stable

➡ Implies a new symmetry and/or charge

Example: Baryons - Baryon Number

Mesons - G-parity Y.Bai, R.J.Hill (2010)

2. Candidate should be EW Charge Neutral

➡ Implies lightest stable particle is chargeless

Example: Can form neutral baryons

3. Candidate should explain observed relic density

➡ Asymmetry/sphalerons require charge couplings

Example: Charged Constituents

Our Focus: Direct Detection

- Before asking any other question, what models are excluded already by DD?

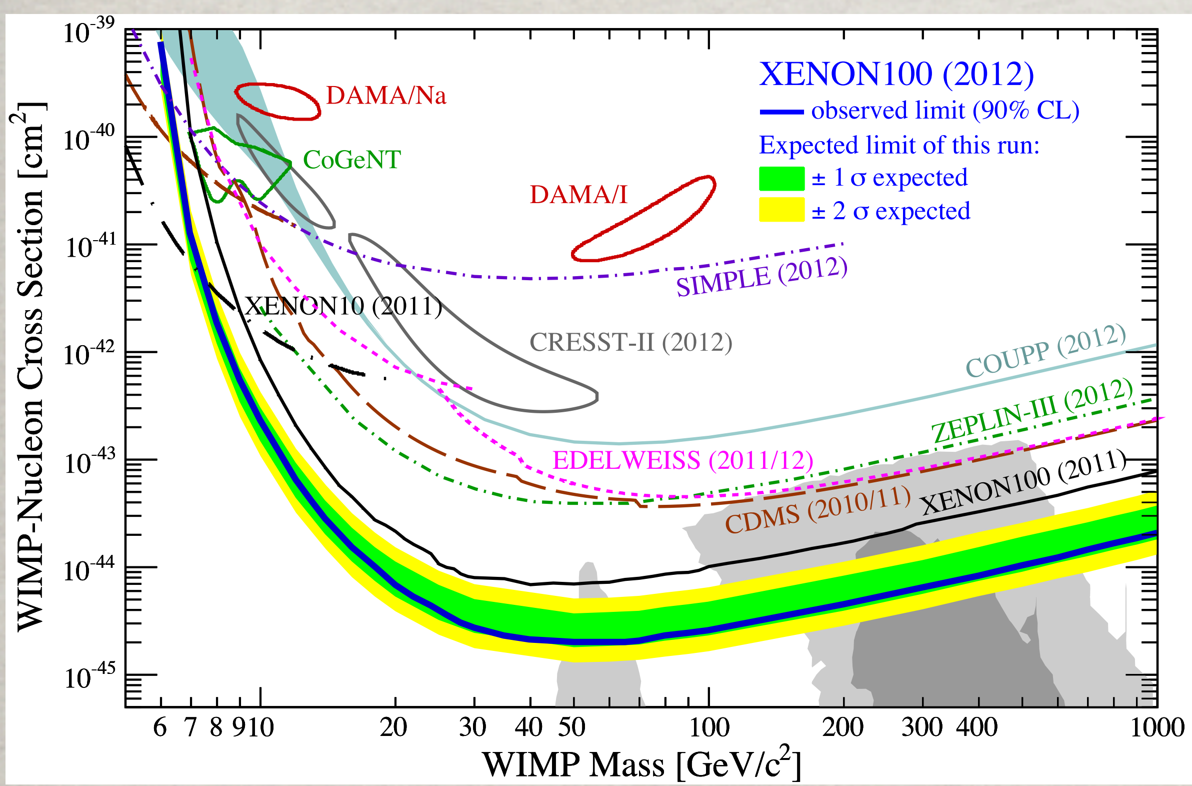
- Lattice simulates "vectorlike" theories
  - ➡ Directly addresses question in this case
- Lattice input can be built into theories with "chiral" couplings (Higgs, etc.)
  - ➡ DM phenomenologists can build theories using lattice results

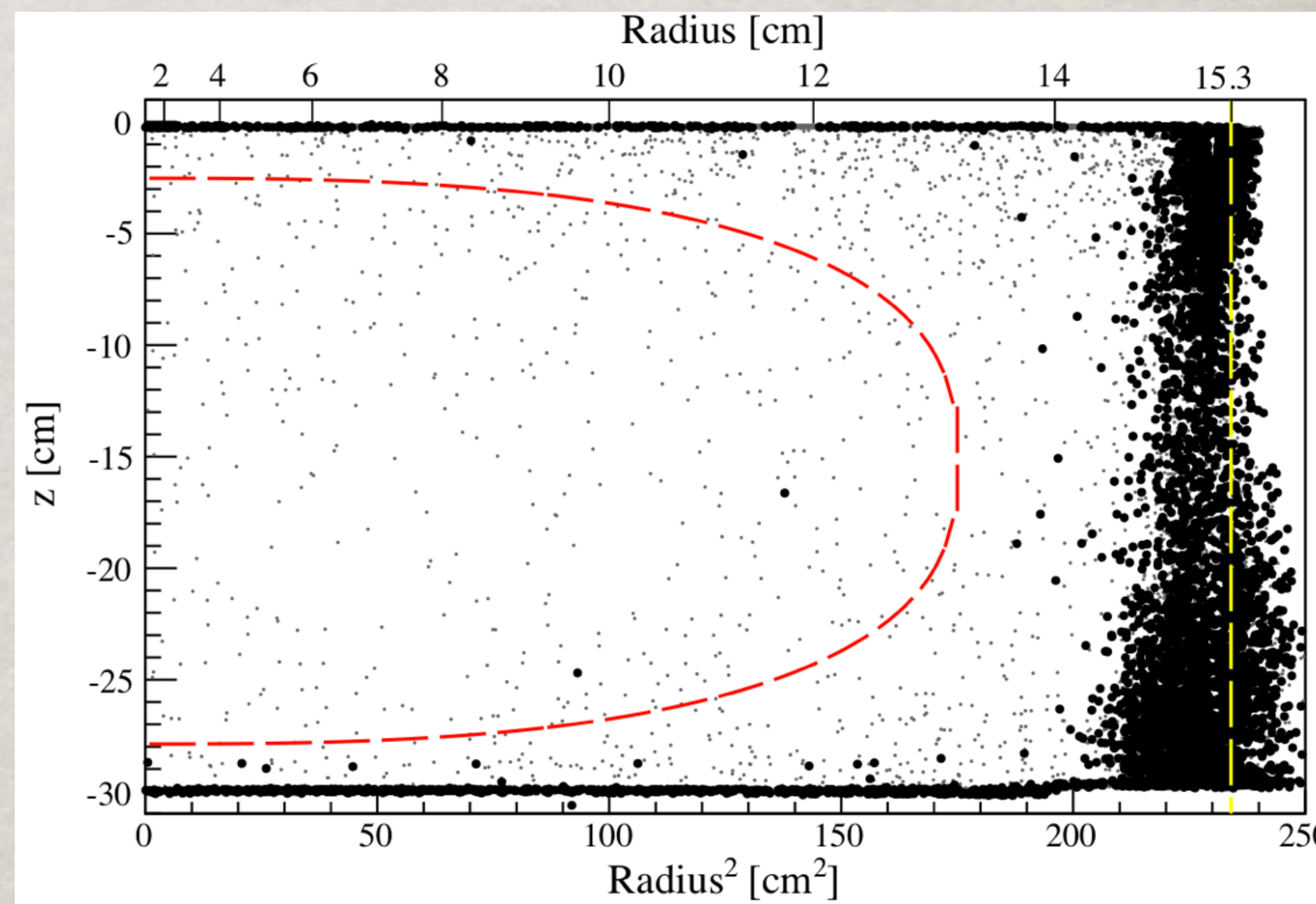
Direct Detection Limits

- Two observational channels:

1. Spin-independent (coherent) - Very tight constraints $\sigma \lesssim 10^{-45}\ \mathrm{cm}^2$
2. Spin-dependent - *Much* weaker constraints $\sigma \lesssim 10^{-37}\ \mathrm{cm}^2$

Xenon100 - arXiv:1207.5988





Tight Constraints?

- Assume a Dirac particle with net Z-boson charge

$$\sigma_{SI} \approx \frac{2}{\pi} G_F^2 m_N^2 \frac{\bar{N}^2}{A^2} \approx \frac{\bar{N}^2}{A^2}(3 \times 10^{-38} \text{ cm}^2) \qquad \frac{\bar{N}^2}{A^2} \sim \frac{1}{4}$$

Current spin-independent bounds: $\sigma \lesssim 10^{-45} \text{ cm}^2$

Excludes particles of this kind to masses greater than thousands of TeV

Neutralinos avoid this: Majorana → Spin-Dependent

This will plague composites with odd numbers of EW doublets!

Technicolor Implications?

Reminder: Want lightest stable particle to be chargeless

If even number of colors: **Not Difficult**

Example: Nc (massless) EW doublets
All charge assignments cancel

If odd number of colors: **Very Difficult**

Nc (massless) EW doublets → Net Charge

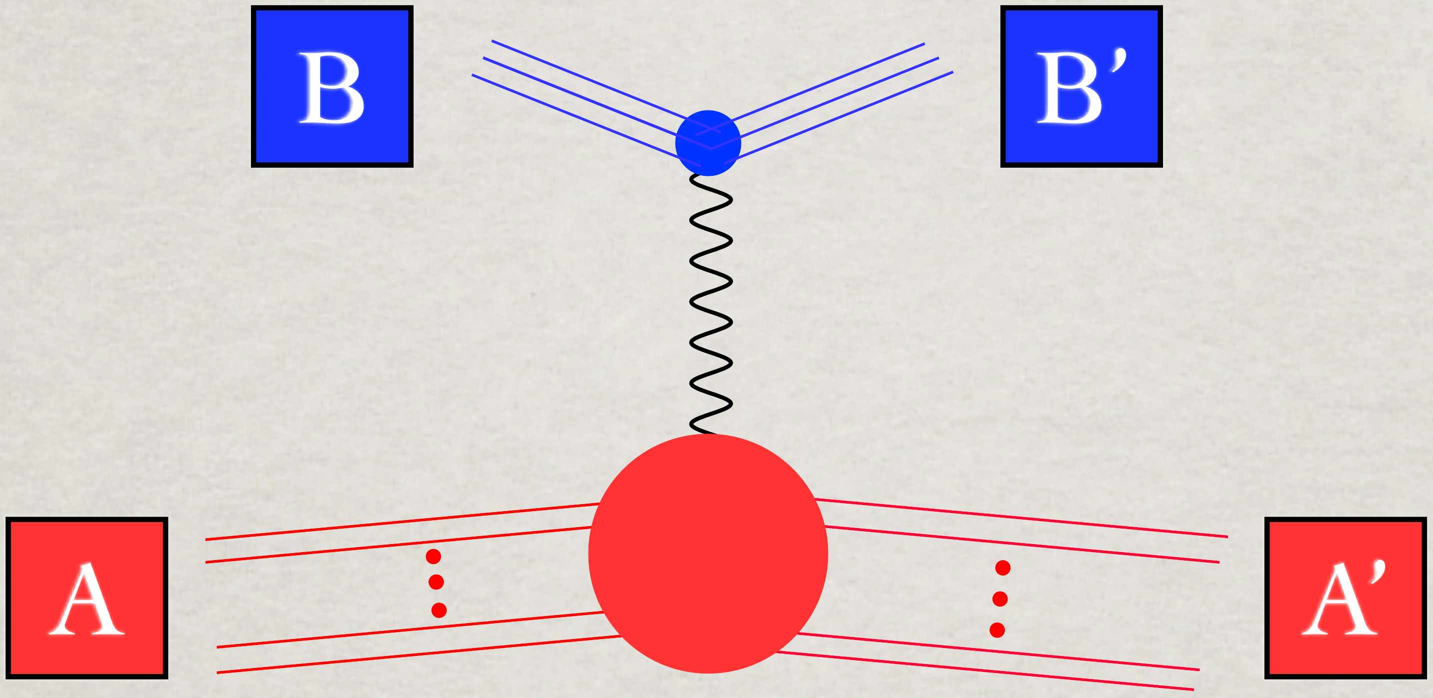
(Nc-1) (massless) EW doublets
1 massive EW singlet → No Charge

Our work will focus on odd Nc "vectorlike" theories that do not mediate EW breaking

How we might see it?

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

Cross-Section Calc.



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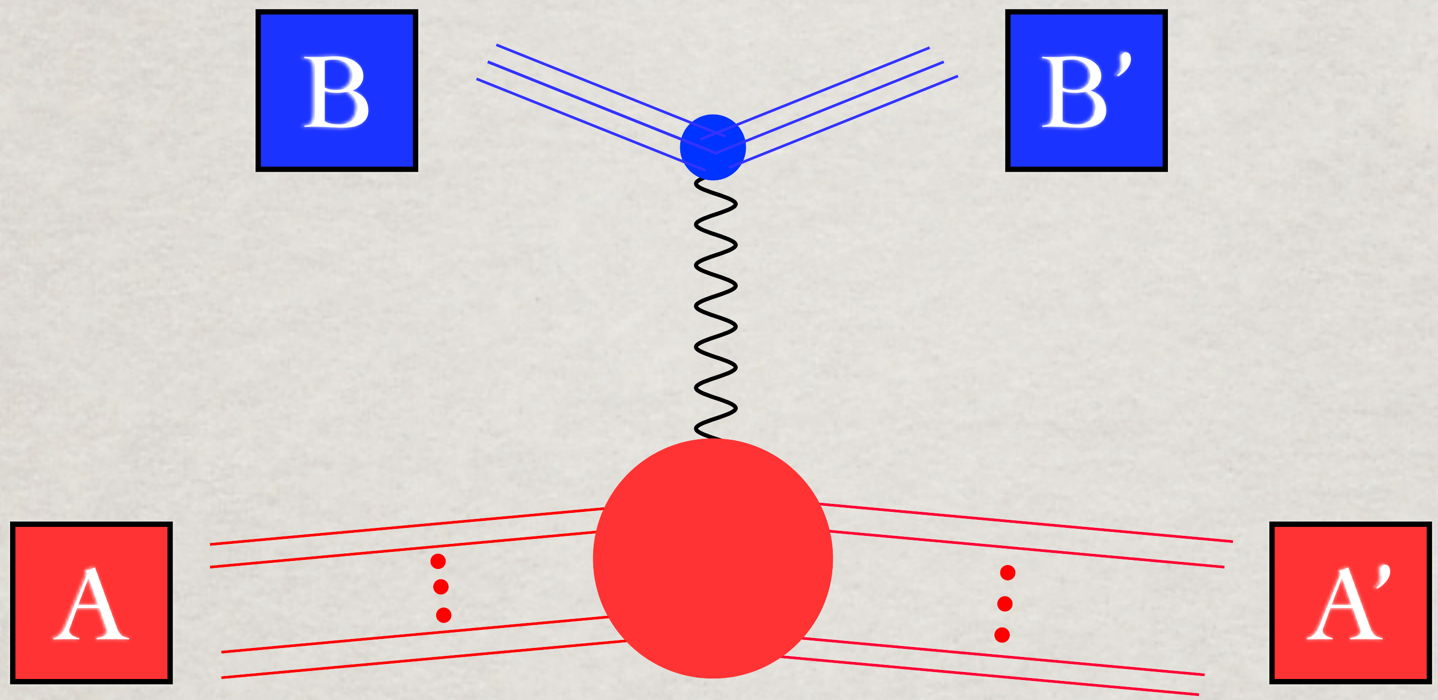
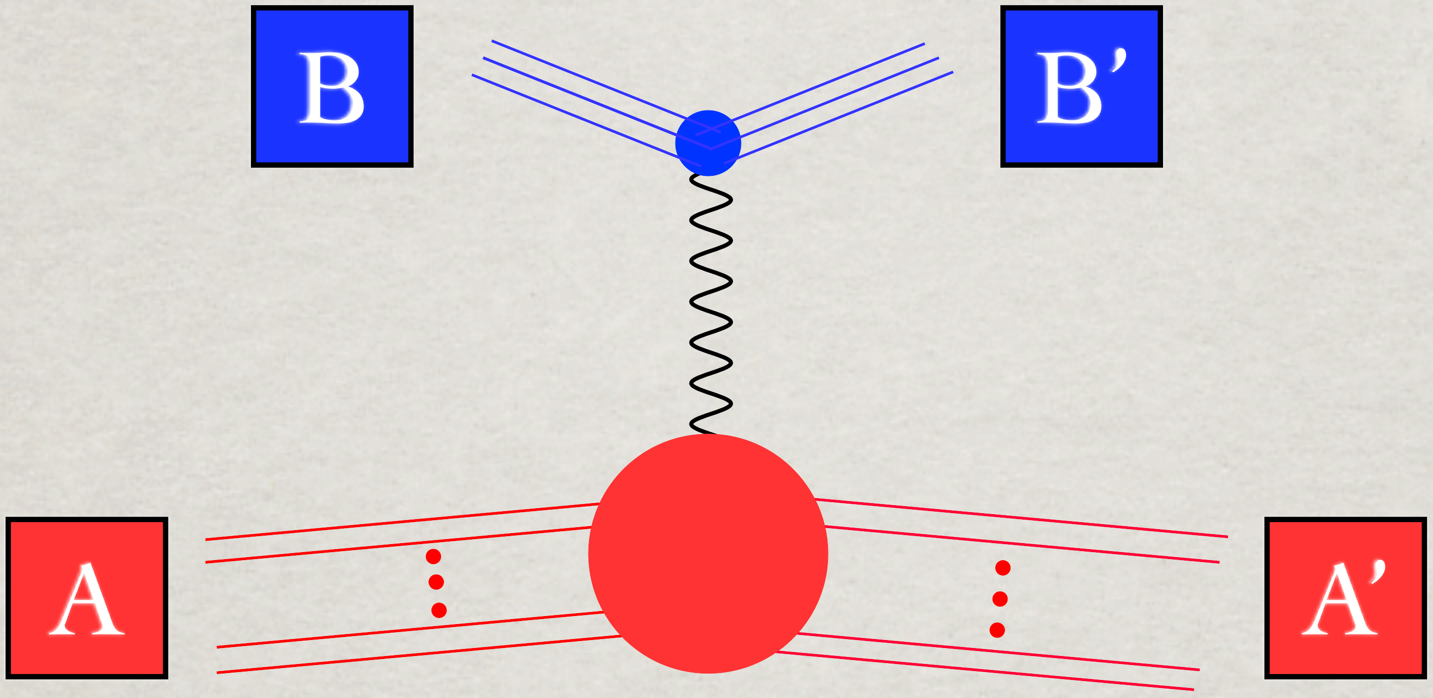


$$|\mathcal{M}|^2 = \frac{e^4}{Q^4}\mathcal{L}_A^{\mu\nu}\mathcal{L}_B^{\mu\nu}$$

$$\mathcal{L}_X^{\mu\nu} = \frac{1}{N_X}\sum_{X,X'}\langle X|J^\mu_{em}|X'\rangle\langle X'|J^\nu_{em}|X\rangle$$

Cross-Section Calc.



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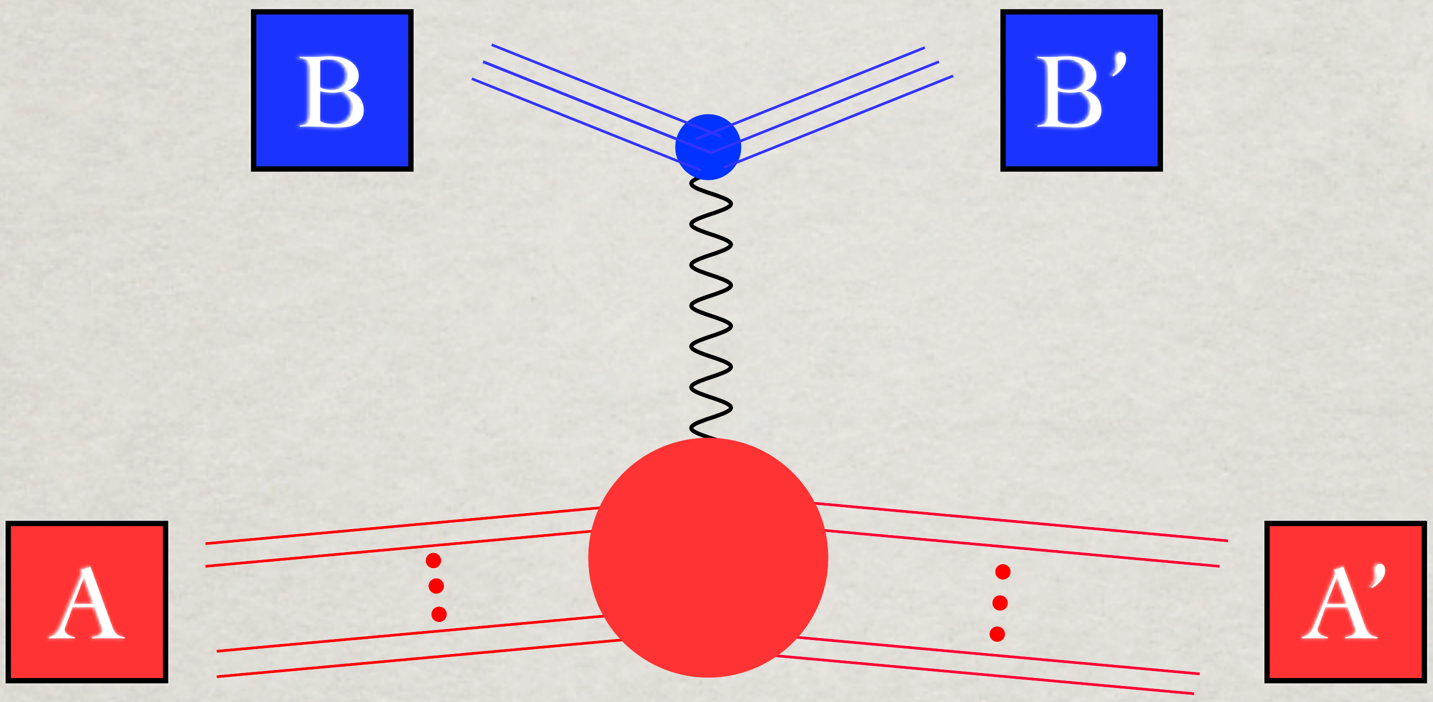
Spin-0: $\mathcal{L}_X^{\mu\nu} = 4F^2(Q^2)\bar{p}^{\mu}\bar{p}^{\nu}$

$$\bar{p}^{\mu} = \frac{1}{2}(p' + p)^{\mu}$$

Cross-Section Calc.



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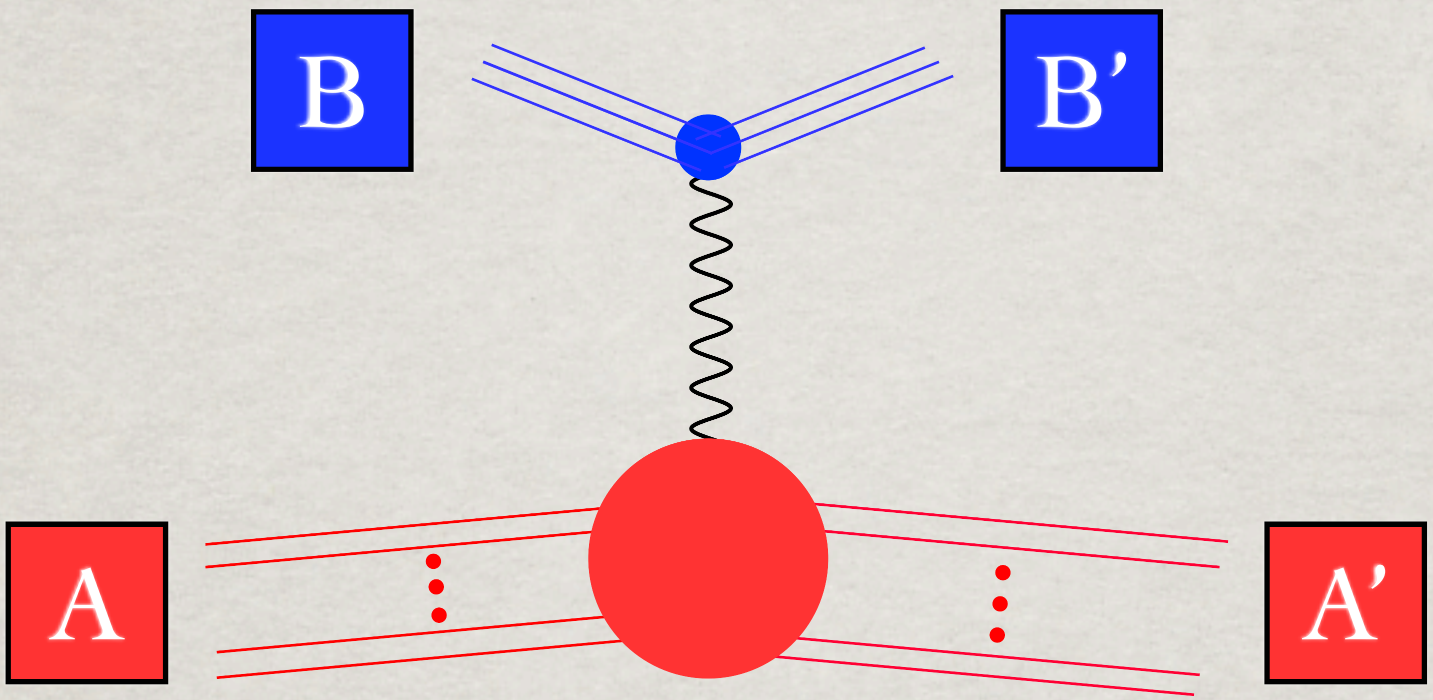
Spin-1/2: $\mathcal{L}_X^{\mu\nu} = 4\bar{p}^\mu\bar{p}^\nu(F_{1X}^2 + \frac{Q^2}{4M^2}F_{2X}^2) - (Q^2 g^{\mu\nu} + q^\mu q^\nu)(F_{1X}+F_{2X})^2$

Cross-Section Calc.



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Large disgusting nucleus: $\mathcal{L}_X^{\mu\nu} = 4W_{2X}(Q^2, q \cdot p)\bar{p}^{\mu}\bar{p}^{\nu} - W_{1X}(Q^2, q \cdot p)(Q^2 g^{\mu\nu} + q^{\mu}q^{\nu})$

Cross-Section Calc.

Bagnasco, Dine, Thomas (1993): hep-ph/9310290

Banks, Fortin, Thomas (2010): arXiv:1007.5515

$$\frac{d\sigma^{SI}_{MM}}{dE_R} = \frac{\pi(2\kappa\alpha)^2 Z^2}{4(m_D + m_N)^2 E_R^{max}} \left(\frac{(m_D + m_N)^2}{{m_D}^2} \frac{E_R^{max}}{E_R} - \frac{2m_N}{m_D} - 1 \right) |F_c(E_R)|^2$$

$$\frac{d\sigma^{SI}_{r}}{dE_R} = \frac{16\pi(Z\alpha)^2 Z^2 m_N^2 {m_D}^2 r^4}{(m_D + m_N)^2 E_R^{max}} |F_c(E_R)|^2$$

$$E_R^{max} = \frac{2m_N {m_D}^2 v^2}{(m_D + m_N)^2}$$

*Non-perturbative lattice input

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*Non-perturbative lattice input

$$\sigma^{SI} = \int dv f(v) \int_{E^N_{min}}^{E^N_{max}} dE_R \frac{d\sigma^{SI}}{dE_R}$$

Xenon100:

$$E^{Xe}_{min} = 6.6 \text{ keV}$$

$$E^{Xe}_{max} = 30.5 \text{ keV}$$

Three-Point Operators

$$\langle N(p')|\overline{q}(x)\gamma^\mu q(x)|N(p)\rangle = \overline{u}(p')\left[\gamma^\mu F_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M_B}F_2(q^2)\right]u(p)e^{iq\cdot x}$$

$$F_1(q^2) = 1 + \frac{1}{6}\langle r^2\rangle q^2 + \cdots$$

$$F_2(q^2) = \kappa + \frac{1}{6}\langle \tilde{r}^2\rangle q^2 + \cdots$$

Isovector: $\langle N|\overline{u}\gamma^\mu u - \overline{d}\gamma^\mu d|N\rangle$

Isoscalar: $\langle N|\overline{u}\gamma^\mu u + \overline{d}\gamma^\mu d|N\rangle$

"Neutron": $\langle N|\frac{2}{3}\overline{u}\gamma^\mu u - \frac{1}{3}\overline{d}\gamma^\mu d|N\rangle$

Three-Point Operators

Correlation Functions via path integral:

$$C_{\mathcal{O}} = \langle \mathcal{O} \rangle = \int d[U]\ \mathcal{O}\ \det(D_{lat}(U)) e^{-S_G(U)}$$

$$C_{NN}(\tau, \mathbf{p}) = \sum_{\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{x}} \langle \overline{N}(\mathbf{x}, \tau) N(0) \rangle$$

$$C_{N\mathcal{O}N}(\tau, \tau_0, \mathbf{p}, \mathbf{p}') = \sum_{\mathbf{x},\mathbf{y}} e^{-i\mathbf{p}'\cdot\mathbf{x} + i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{y}} \langle \overline{N}(\mathbf{x}, \tau_0) \mathcal{O}(\mathbf{y}, \tau) N(0) \rangle$$

Taking the appropriate ratio:

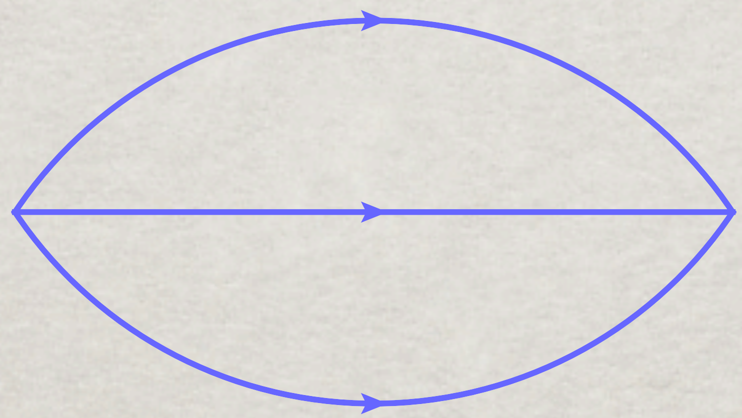
$$R_{\mathcal{O}}(\tau, \tau_0, \mathbf{p}, \mathbf{p}') \xrightarrow{\tau_0 \gg \tau \gg 1} \langle n(\mathbf{p}') | \mathcal{O} | n(\mathbf{p}') \rangle + \mathcal{O}(e^{-\Delta \tau}) + \mathcal{O}(e^{-\Delta(\tau_0 - \tau)})$$

Three-Point Calculation

Propagator Contractions:

$$\overline{q}_{i'}^{\alpha'}(y)\; q_i^{\alpha}(x) = S_{i'i}^{\alpha'\alpha}(y,x)$$

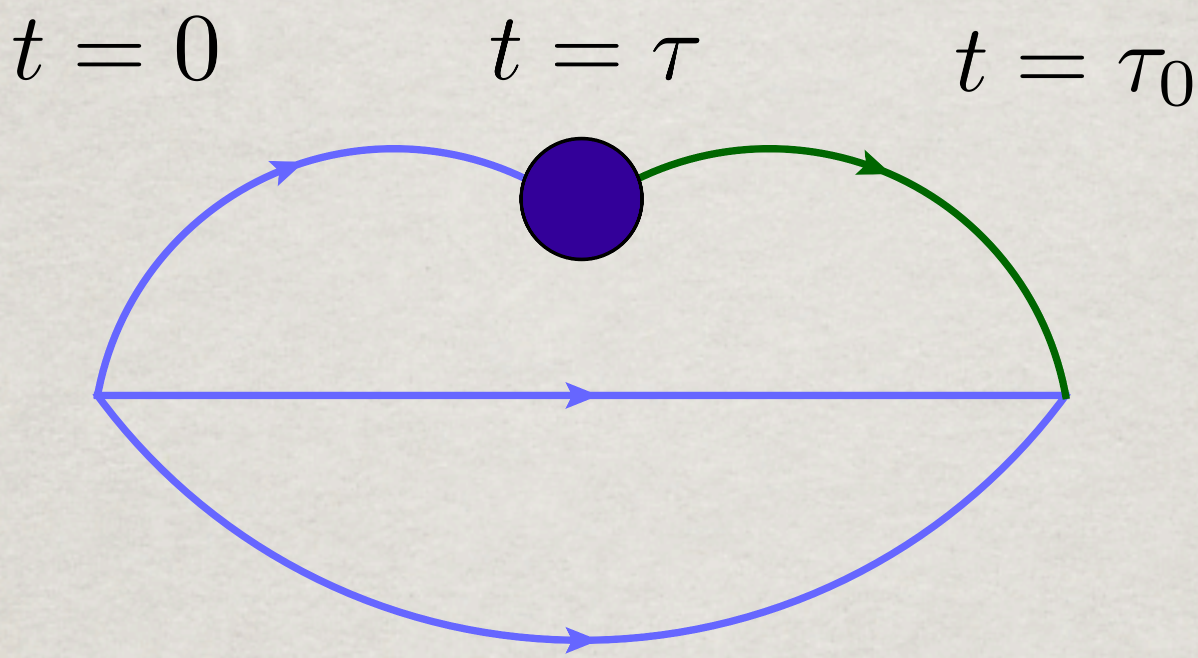
$C_{NN}(\tau, \mathbf{p})$



$t = 0$ $t = \tau$

1 Propagators → One measurements

Three-Point Calculation



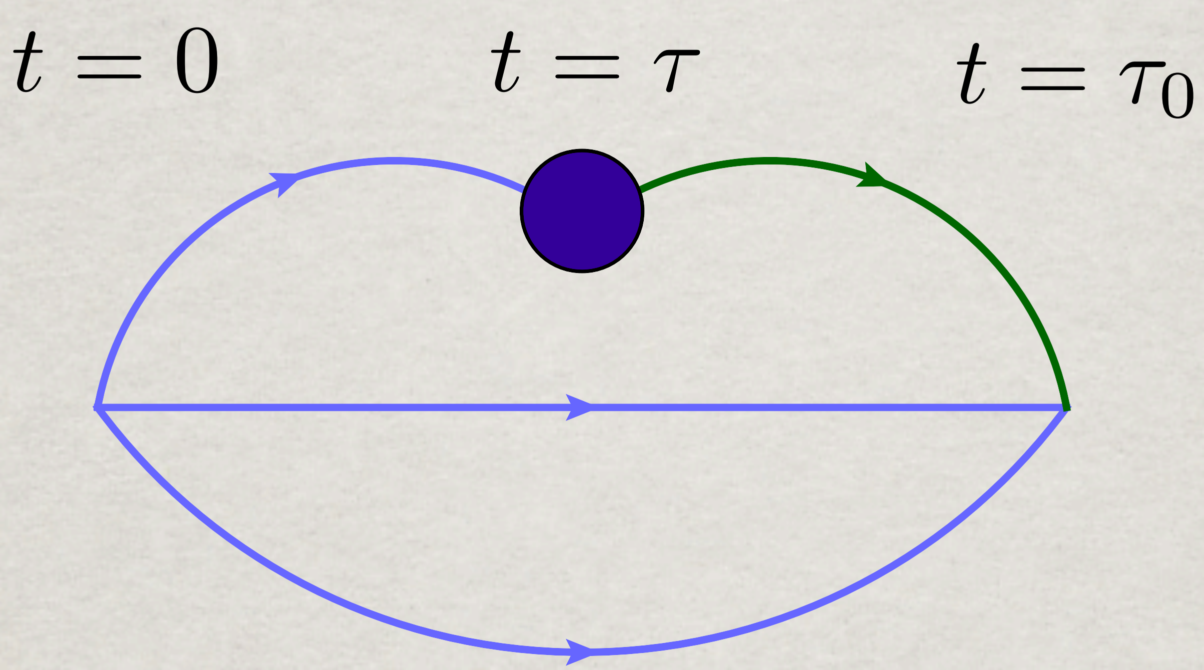
2 Propagators → One measurements
One time insertion

Need:

τ & τ_0 Large → Reduce
Excited Staes

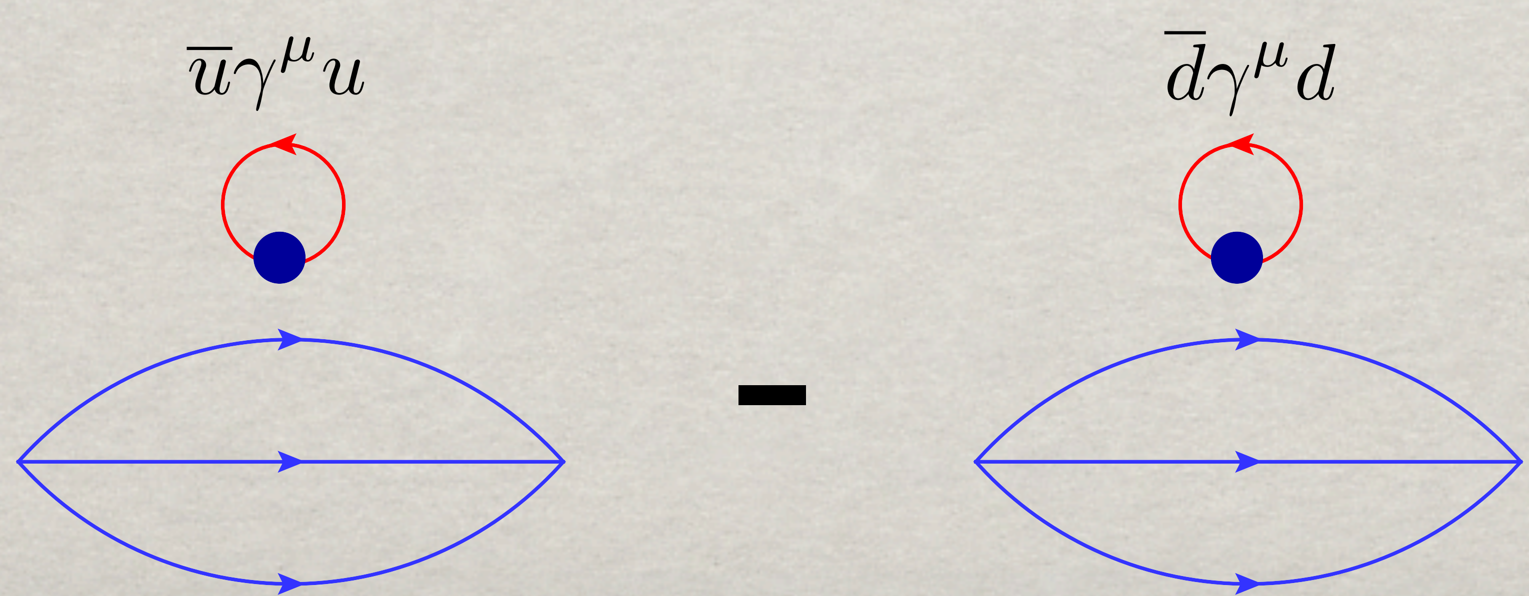
τ & τ_0 Not too large → Signal-to-noise
reduction

Three-Point Calculation



2 Propagators → One measurements
One time insertion

Isovector: (No disconnected diagrams)



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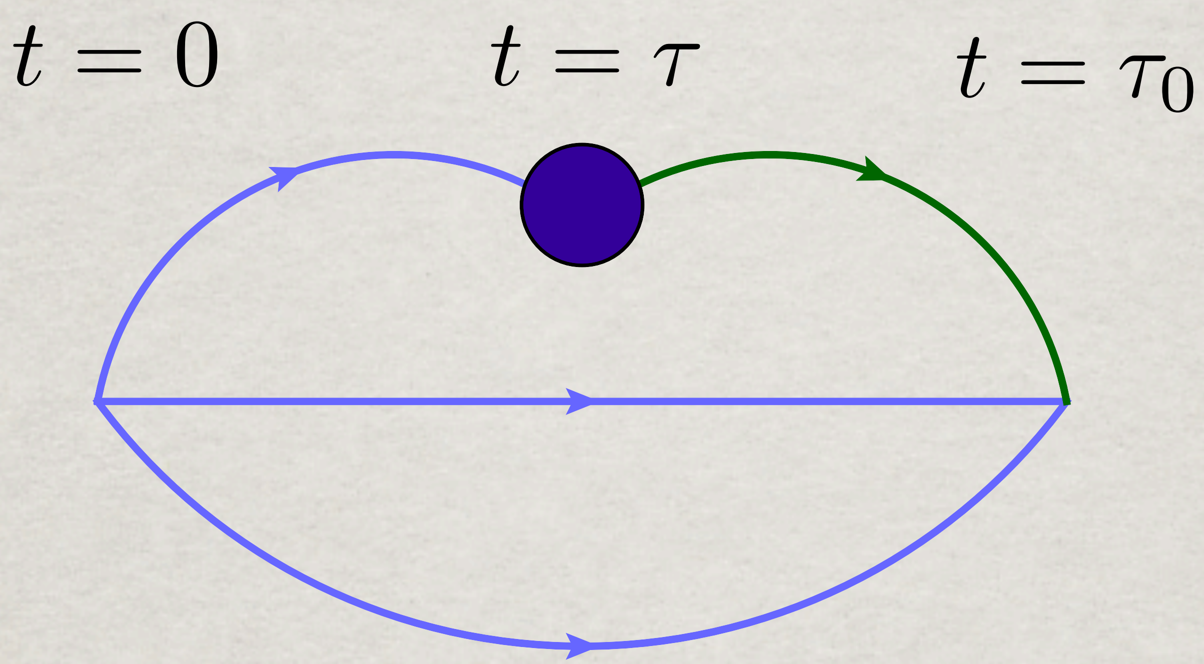
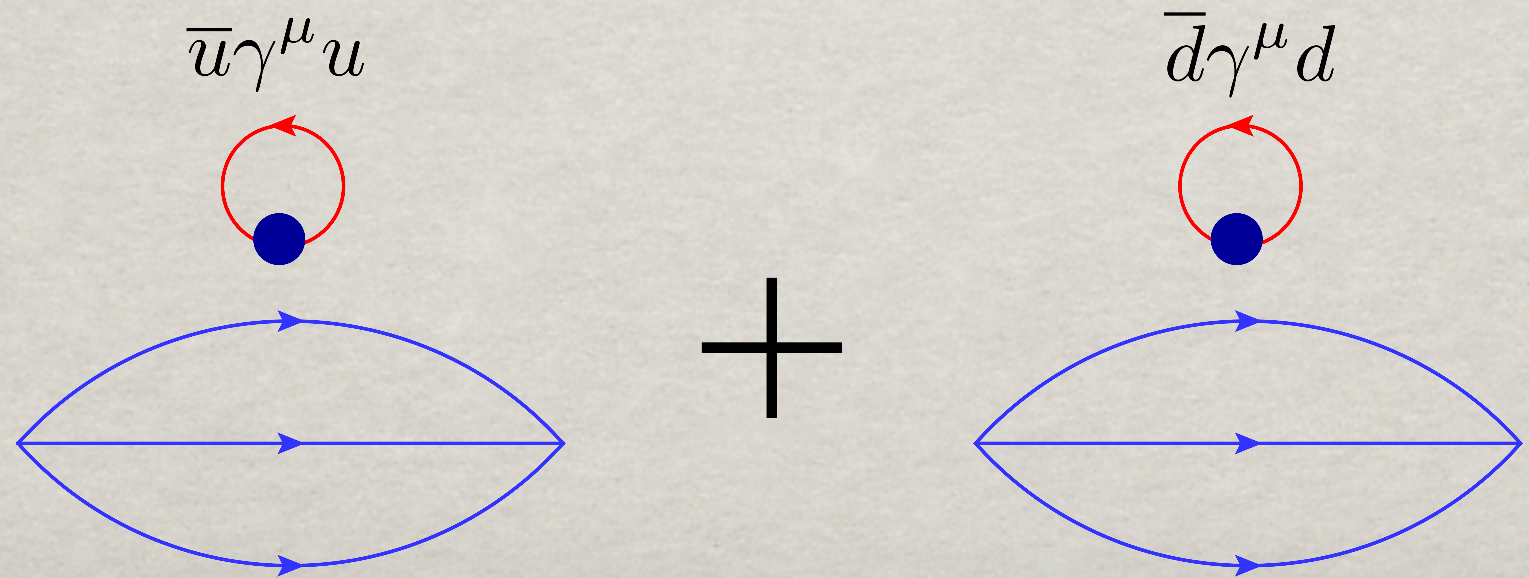


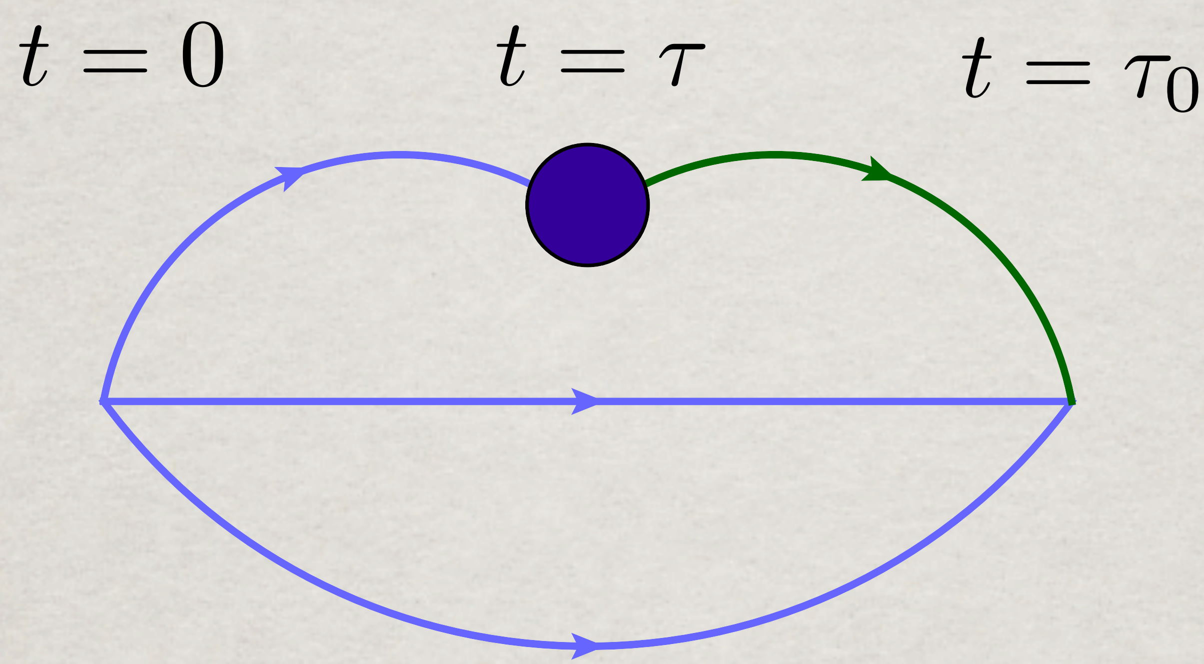
2 Propagators ⇒ One measurements
One time insertion

Isoscalar: (Need disconnected diagrams)



Omit in current calculation

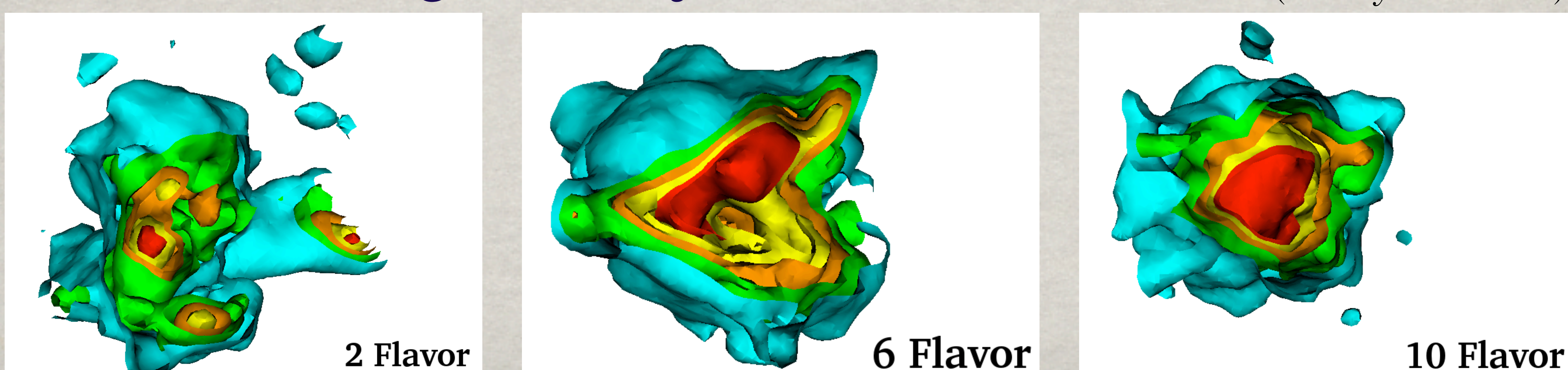
Three-Point Calculation



2 Propagators → One measurements
One time insertion

Transverse charge density:

(courtesy of J. Wasem)



Scale Setting

How do we define lattice spacing in physical units?

Lattice QCD:

Hadron Masses, HQ potentials, etc.

$$aM_\Omega = \# \quad \Rightarrow \quad a \approx \frac{\#}{1670\ \mathrm{MeV}}$$

Technicolor:

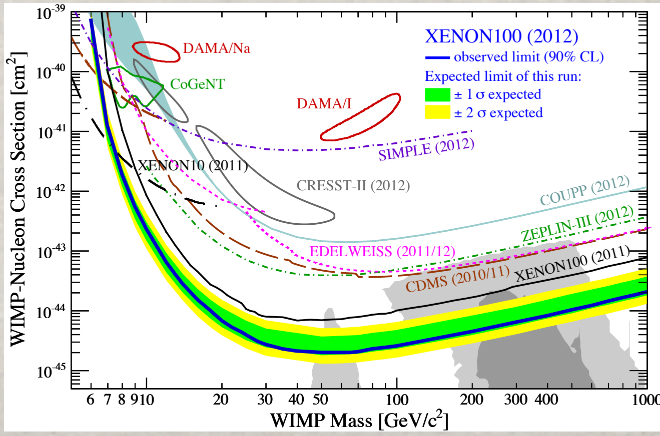
"Higgs" vev

$$af_\pi \xrightarrow{m_f \to 0} \# \quad \Rightarrow \quad a \approx \frac{\#}{246\ \mathrm{GeV}}$$

Dark Matter:

Dark Matter Mass

$$aM_B = \# \quad \Rightarrow \quad a \approx \frac{\#}{M_B}$$



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Dark Matter Mass

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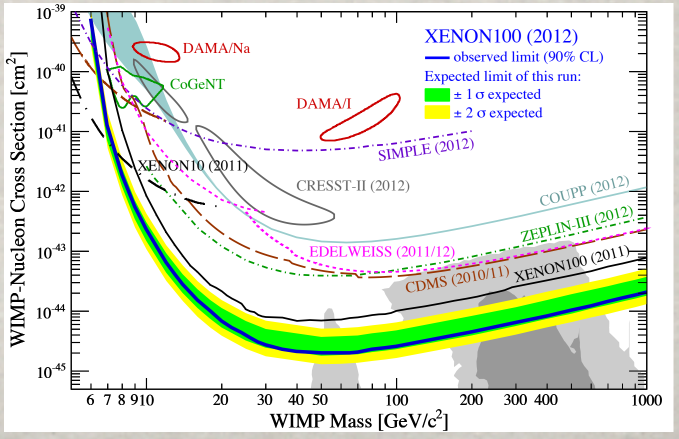
Vary this value



Calculation Details

10 DWF Ensembles:

- 32^3 x 64 x 16 lattices

$$am_\rho \sim \frac{1}{5}$$

2 flavor: m_f = 0.010 - 0.030

6 flavor: m_f = 0.010 - 0.030

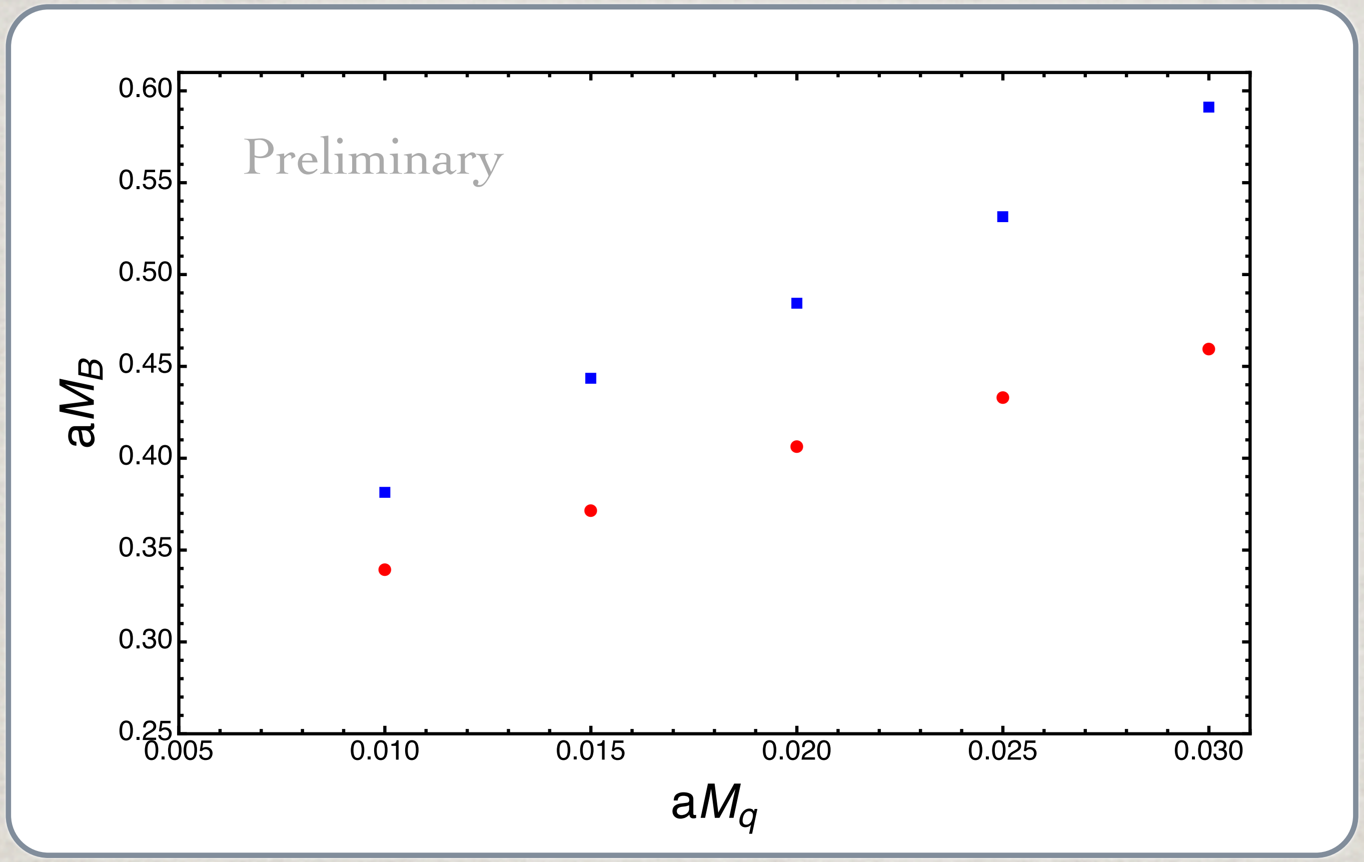
Table 1: 2 Flavor

m_q	# Configs	# Meas
0.010	564	1128
0.015	148	296
0.020	131	262
0.025	67	268
0.030	39	154

Table 1: 6 Flavor

m_q	# Configs	# Meas
0.010	221	442
0.015	112	224
0.020	81	162
0.025	89	267
0.030	72	259

Baryon Mass

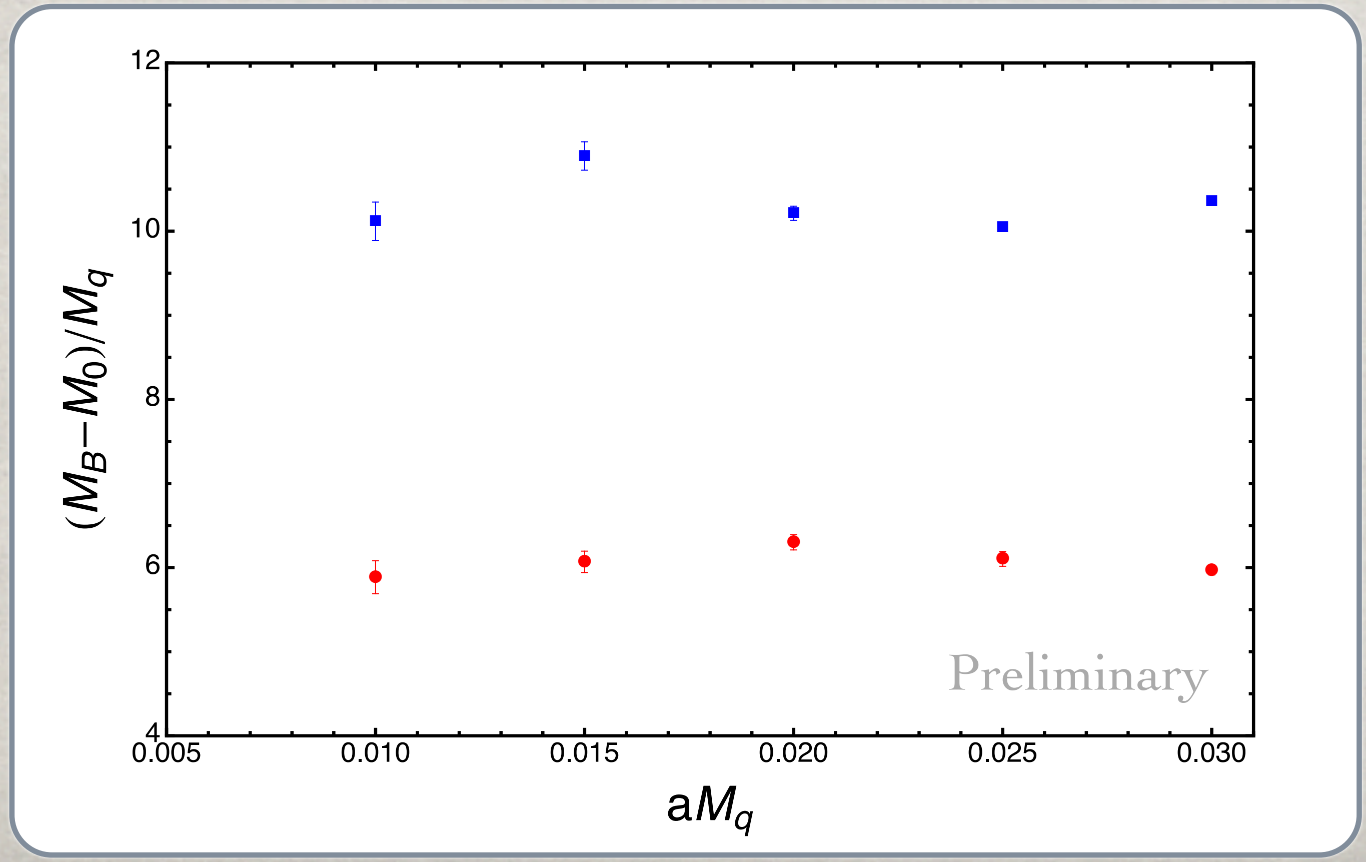


Red - 2 Flavor

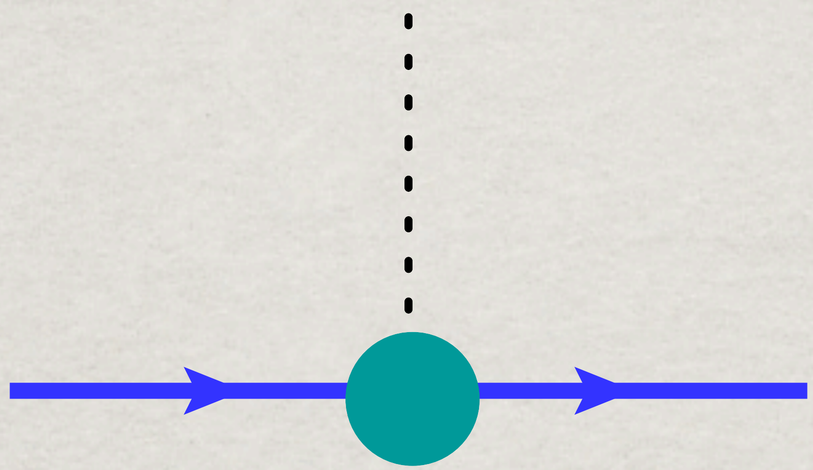
Blue - 6 Flavor

Feynman-Hellmann:

$$\sigma = M_q \frac{\partial M_B}{\partial M_q}$$



Axial Charge



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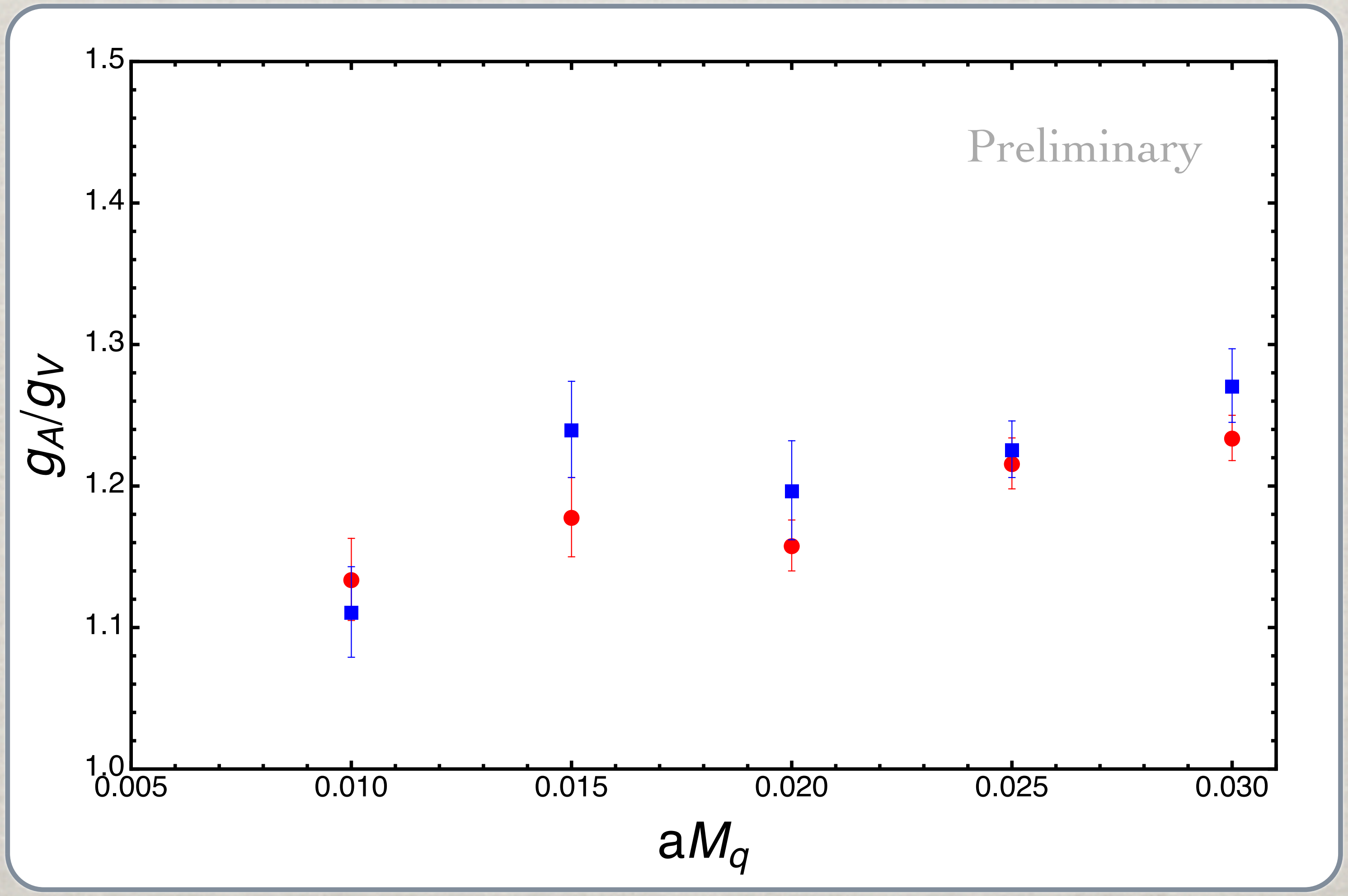
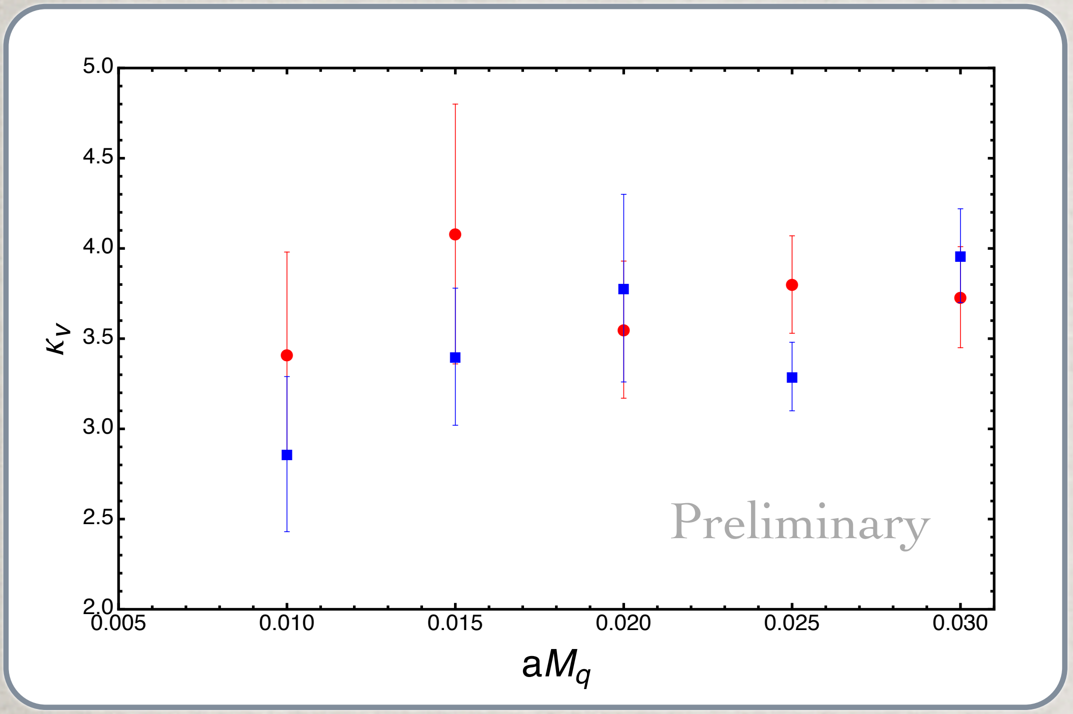


Magnetic Moment

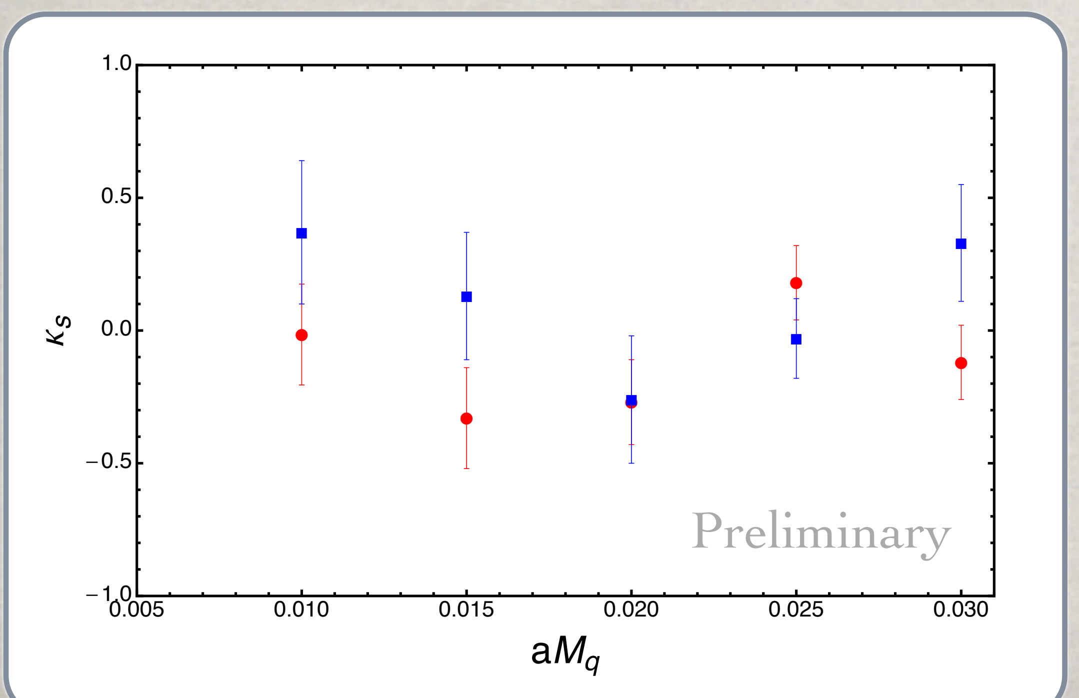
Red - 2 Flavor

Blue - 6 Flavor

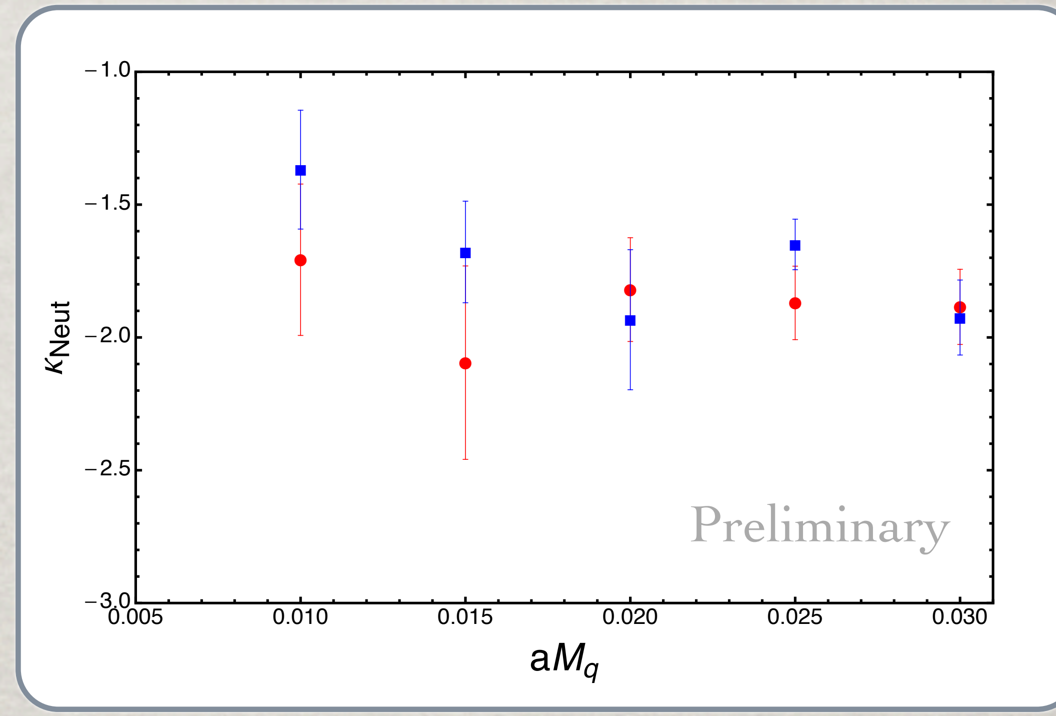
Isovector



Isoscalar



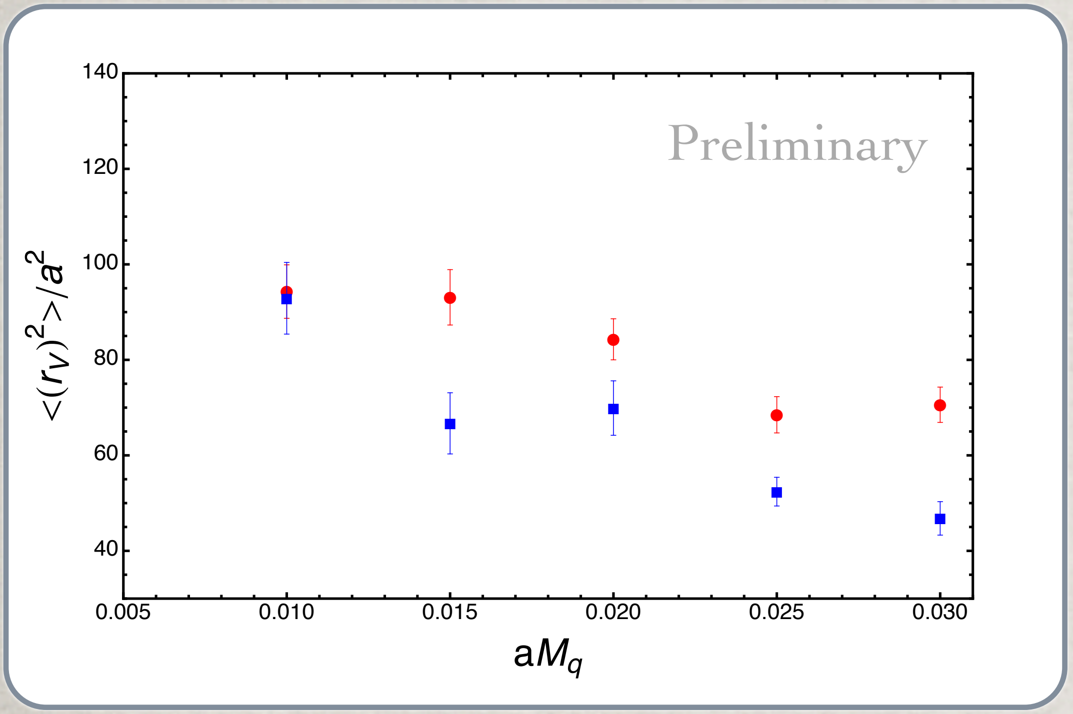
"Neutron"



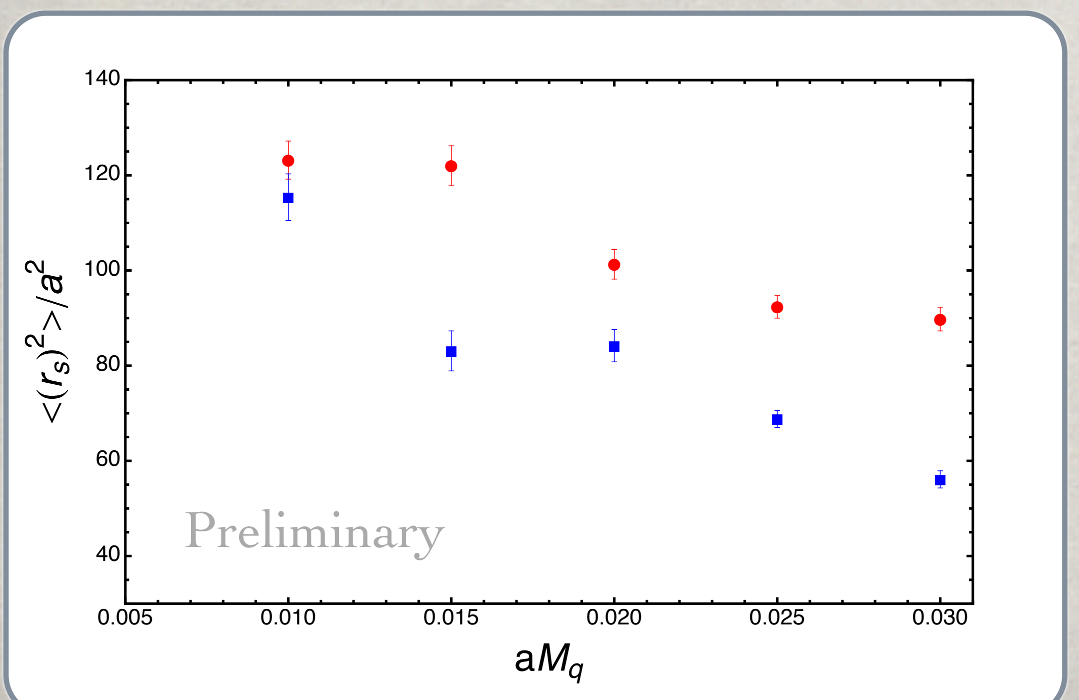
$$\mu = \frac{\kappa}{2M_B}$$

Charge Radius

Isovector



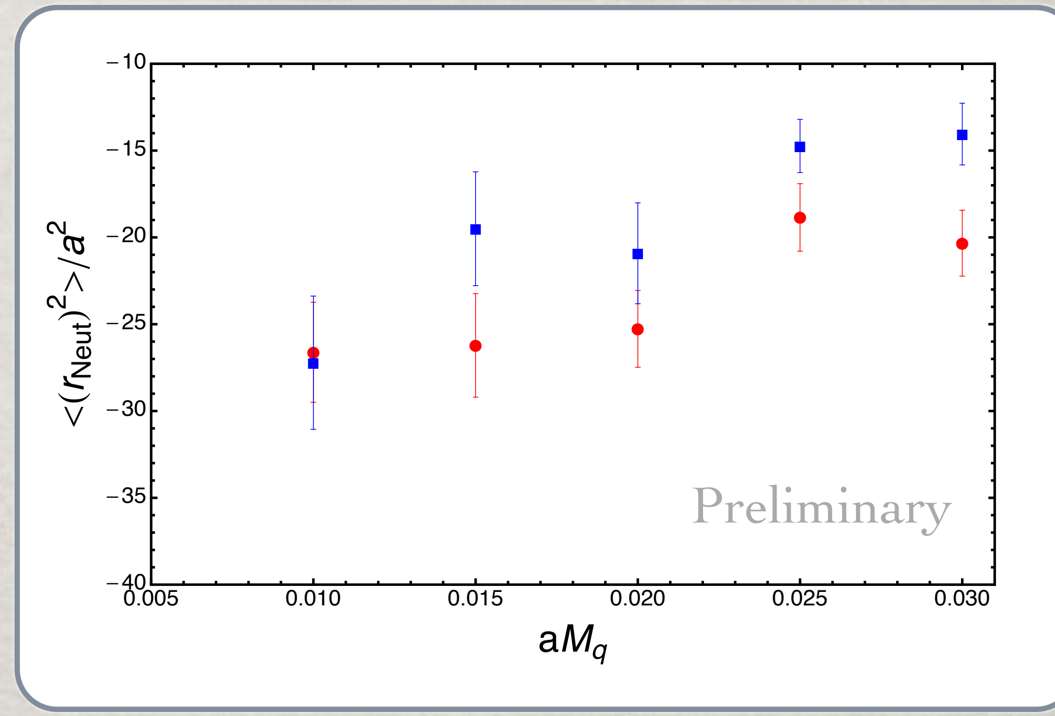
Isoscalar



Red - 2 Flavor

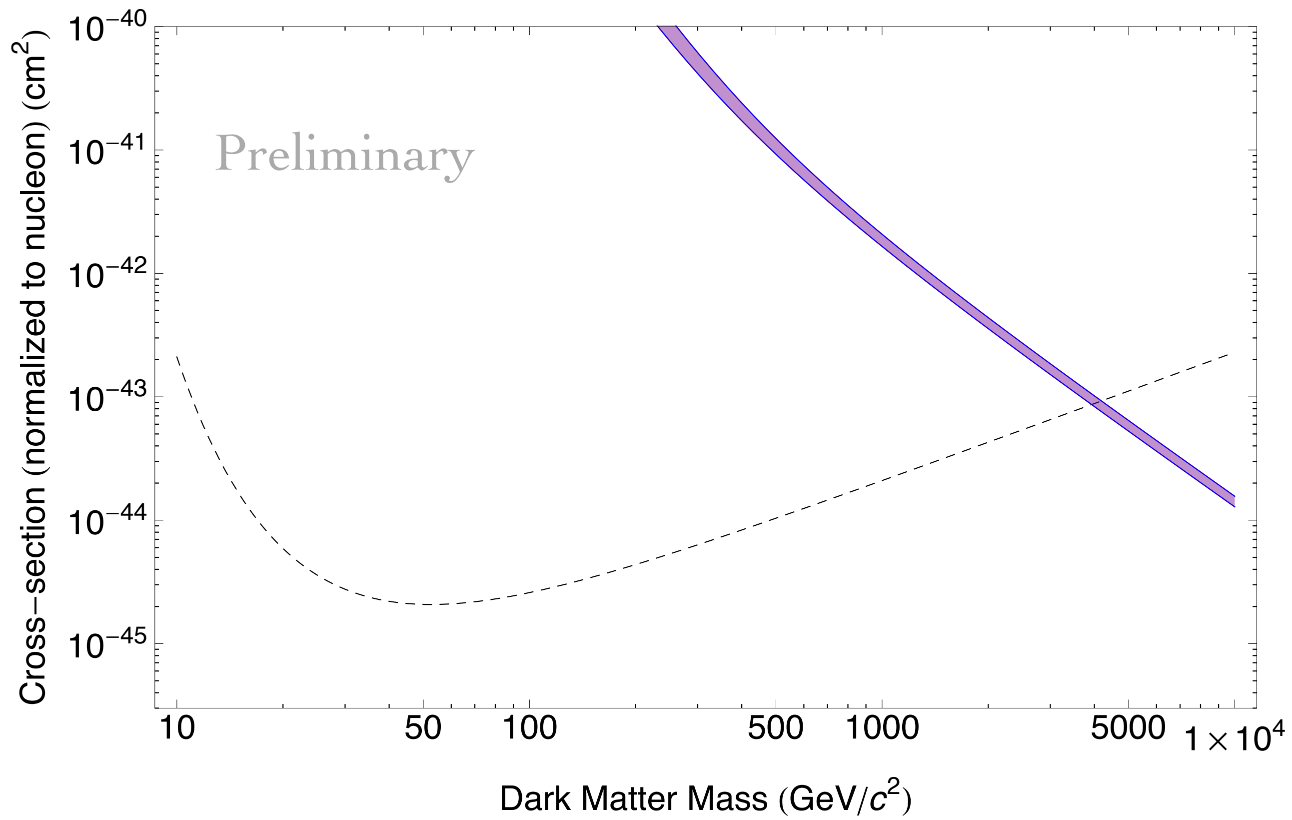
Blue - 6 Flavor

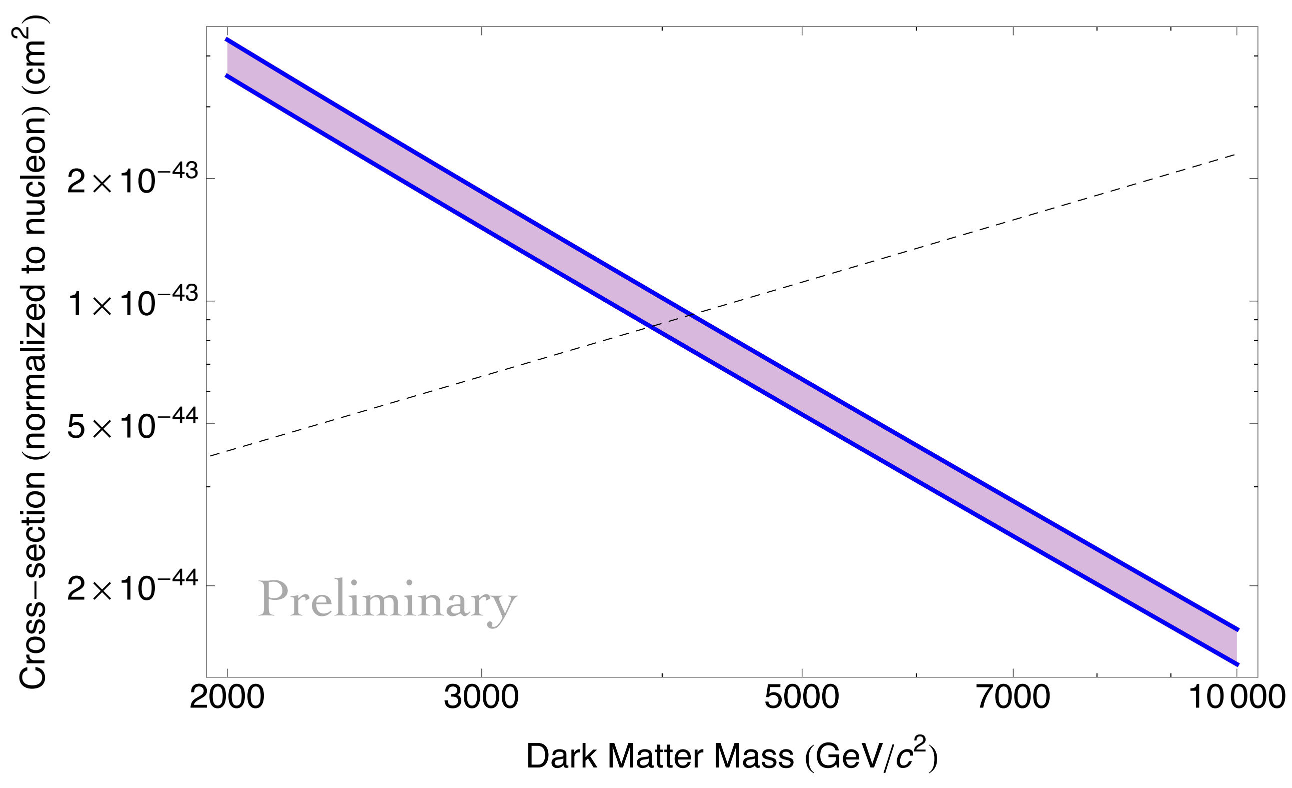
“Neutron”



$$\langle r^2 \rangle = \frac{1}{V} \int d^3r \; \rho(r) r^2$$

Exclusion Plots





Red - 2 Flavor

Blue - 6 Flavor

Dashed - Xenon100

arXiv: 1207.5988

Future Directions

1) Composites of different color

- Even colors most interesting

Naturally avoids current constraints

Phenomenology:

- Baryon group theory (possible FFs)
- Chargeless Combinations
- Flavor Symmetric baryons?

Lattice:

- Focus on 2 and 4 color (4 color more natural)
- Efficient codes, map parameter space, etc.

Future Directions

2) Extracting polarizabilities

- Dominant effect for flavor sym. baryons

Operator insertion methods not ideal

Background Field Method:

$$E \sim M + \frac{1}{2}\alpha\mathcal{E}^2 + \cdots$$

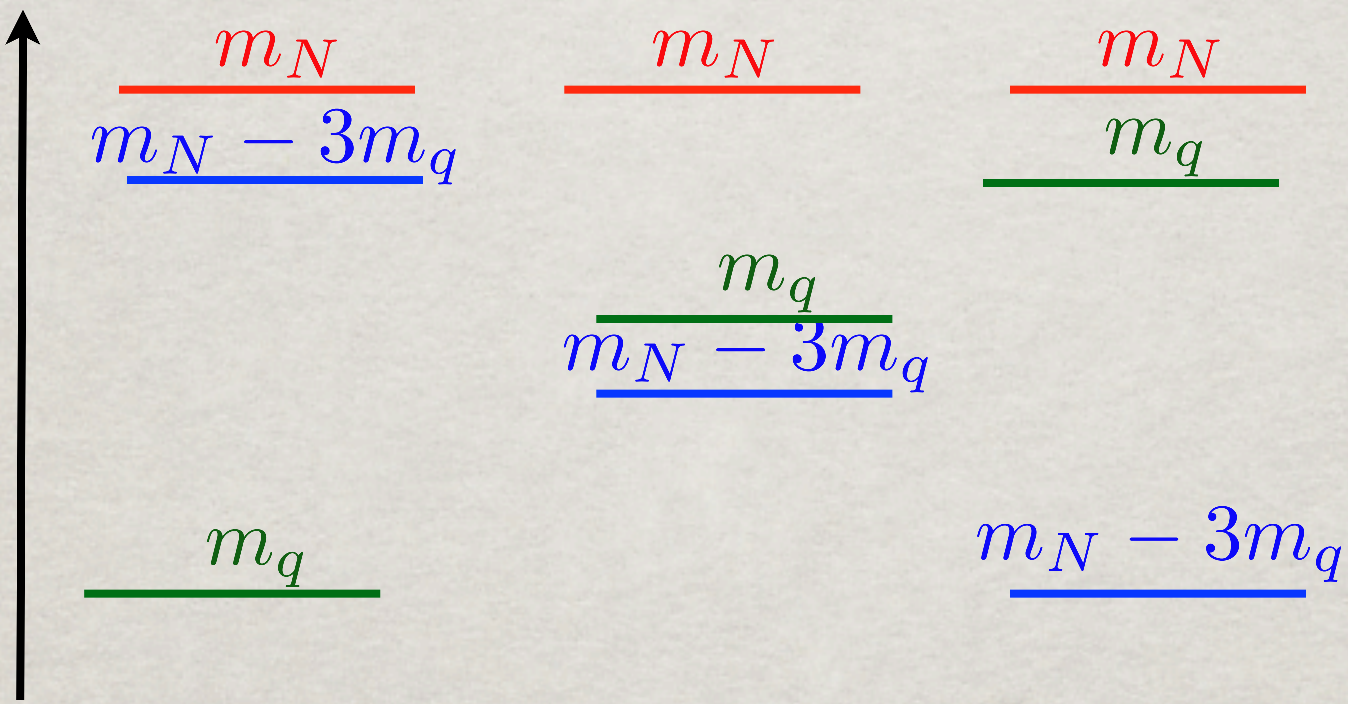
Small fields require large volumes

Lattice:

- Integrate background field into Dslash inversion
- Dynamical background fields

Future Directions

3) Examine new hierarchy of masses



$am_N \ll 1$	$am_N \ll 1$	$am_N \ll 1$
$Lm_q \gg 1$	$Lm_q \gg 1$	$L(m_N - 3m_q) \gg 1$

Larger fermion mass ⇒ Fewer light particles need to be explained

Future Directions

3) Composite DM with Scalar Constituents

Avoids bounds...
avoids simulating fermions...

Final Word

- Based purely on observational DM data:

Composite dark matter is the most "natural"

- Lattice can address place initial bounds on models
  - Tight constraints on odd Nc theories
  - Will explore charge radii and polarizabilities of even Nc theories
- Lattice and phenomenology go hand-in-hand
  - Build in perturbative "chiral" sector
  - Define viable theories and study possible cosmological observations

This research was supported by the LLNL LDRD "Illuminating the Dark Universe with PetaFlops Supercomputing" 13-ERD-023 and by the LLNL Multiprogrammatic and Institutional Computing program through the Tier 1 Grand Challenge award that has provided us with the large amounts of necessary computing power.