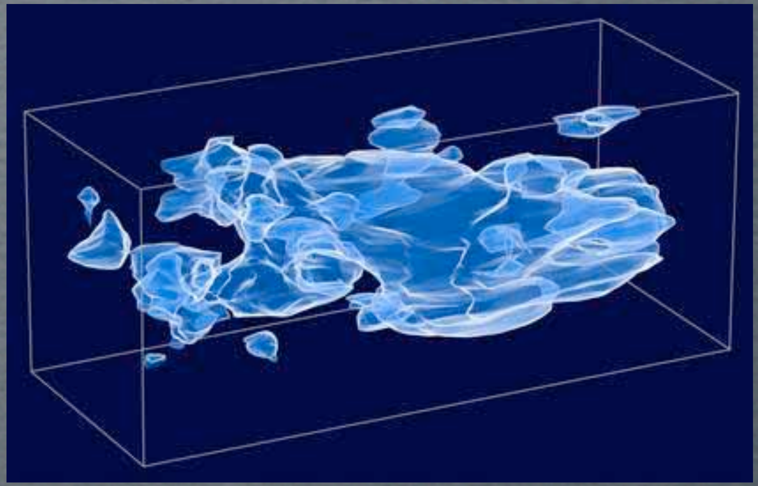
Composite Dark Matter Exclusions From the Lattice

An LSD Production



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Lattice Strong Dynamics Collaboration

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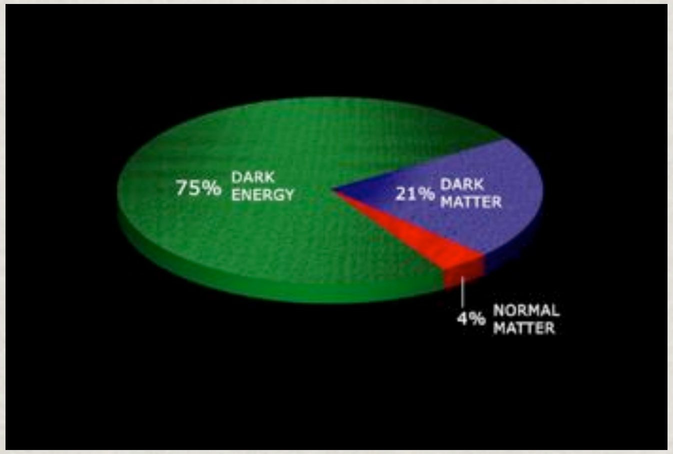
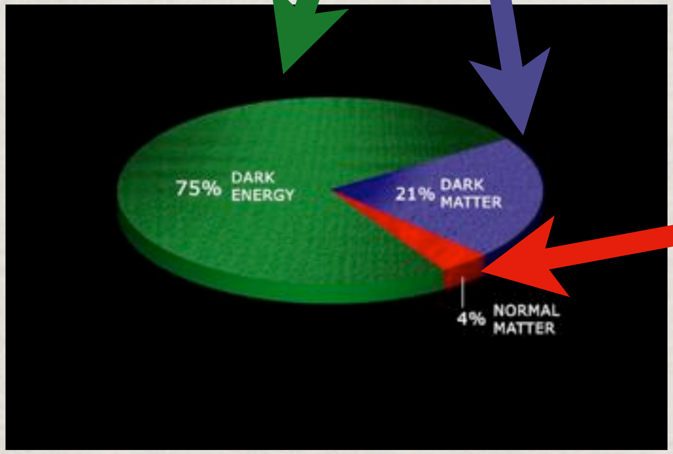
A slice of the Universe



A slice of the Universe

??????

New Physics!!



We Are Here

(QCD, EM, SM, etc.)

A slice of the Universe

??????

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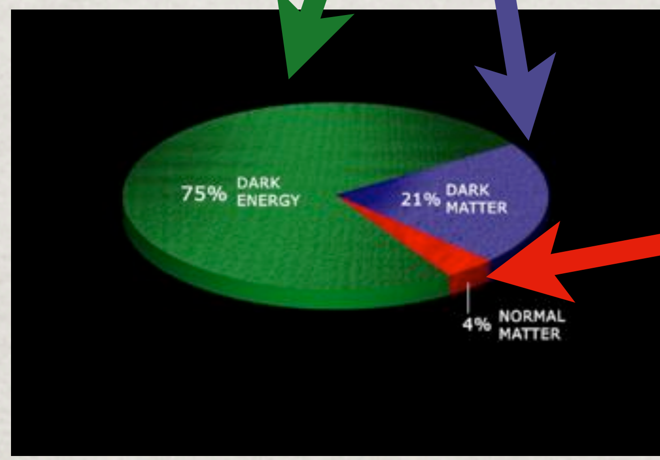
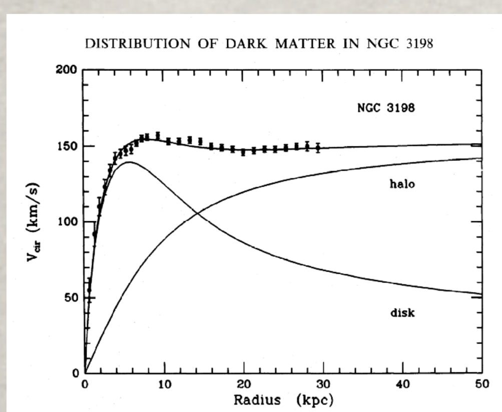


We Are Here

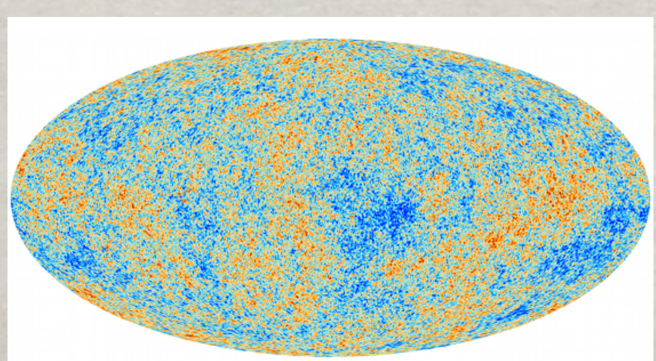
(QCD, EM, SM, etc.)

How do we know DM is there?



- Rotation Curves of Galaxies

- Gravitational Lensing



- Cosmological Backgrounds

Three Primary Properties of dark matter

1. Candidate should be Stable

- Explains why dark matter has survived to today

➡ Implies a new symmetry and/or charge

2. Candidate should be EW Charge Neutral

- Explains why there is 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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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!

Asymmetric Models

We Want:

★ Lightest stable composite chargeless (EM + weak)

★ Constituents that communicate with electroweak

Direct:

Subset of constituents that are non-singlet under $SU(2)_L$

Indirect:

Neutral, but couples to heavy, charged particles yet to be observed

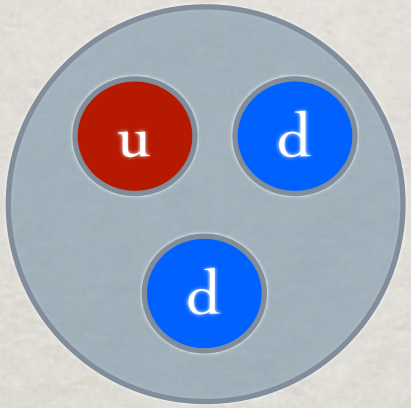
Bai, Schwaller 2013

Baryon Flavor Symmetry

Invariant under $SU(N_f)$ transformations

★ Flavor Non-symmetric

Example: (3-color neutron ala QCD)



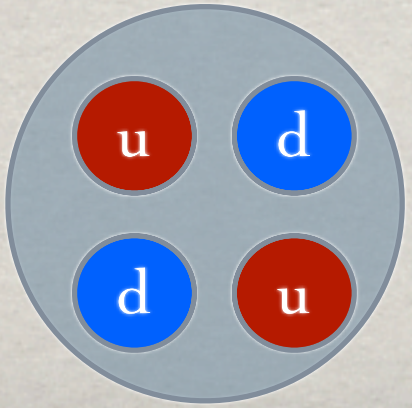
$$Q_u = Q_d$$

or

$$Q_u \neq Q_d$$

★ Flavor Symmetric

Example: (4-color neutron)



$$Q_u = -Q_d$$

only

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.			✓

Focus of current work

- Direct detection exclusions for odd number of colors

Explore:

- 3-colors
- Multiple degenerate masses
- 2 and 6 light flavors

Explores a range of confining theories for odd Nc theory

Focus of current work

- Direct detection exclusions for odd number of colors

Explore:

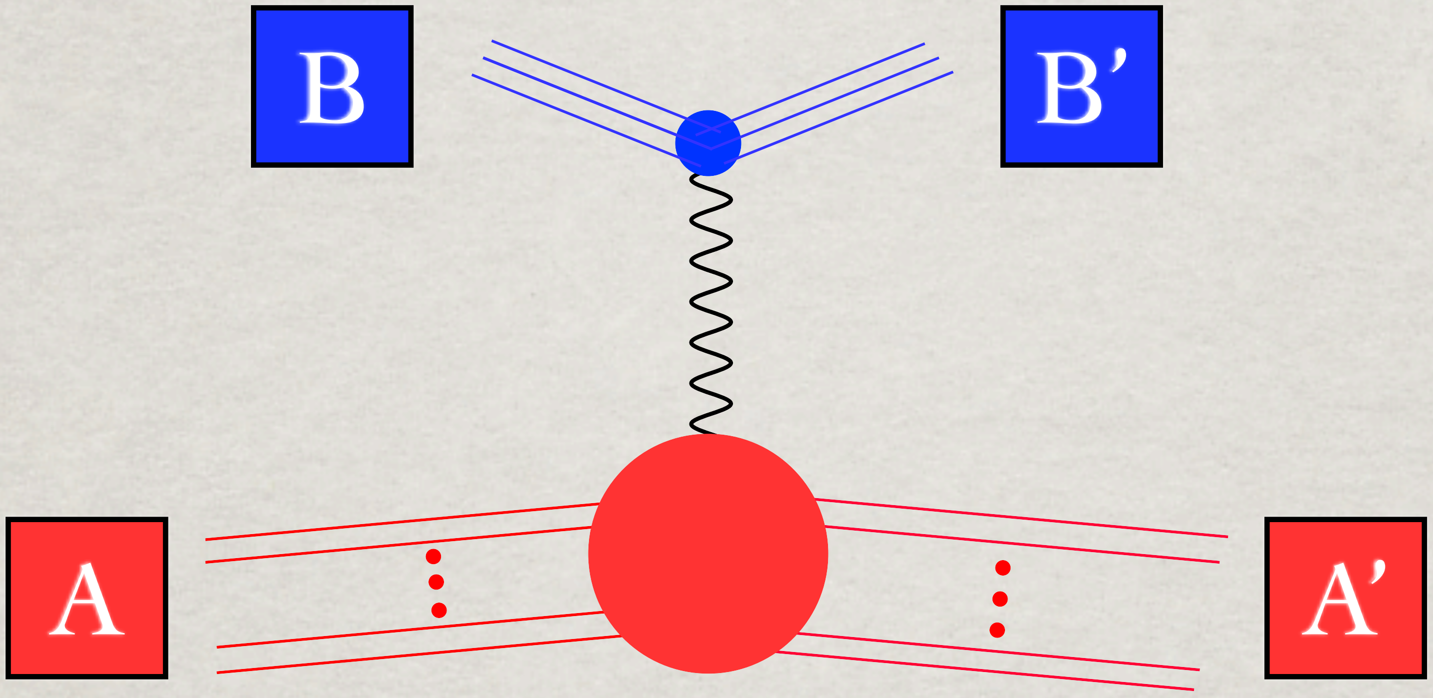
- 3-colors
- Multiple degenerate masses
- 2 and 6 light flavors

QCD sanity check

Something different...

Explores a range of confining theories for odd Nc theory

Cross-Section Calc.



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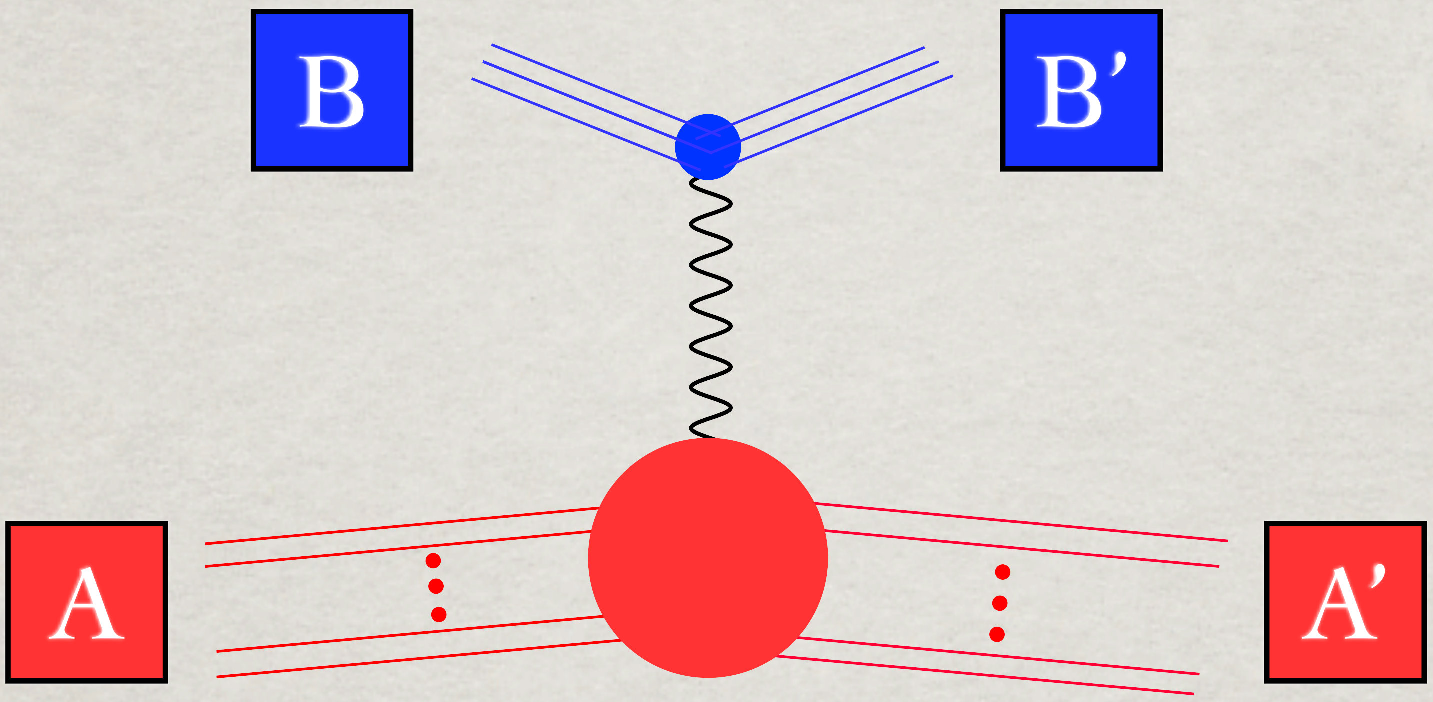

$$|\mathcal{M}|^2 = \frac{e^4}{Q^4} \mathcal{L}_A^{\mu\nu} \mathcal{L}_B^{\mu\nu}$$

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

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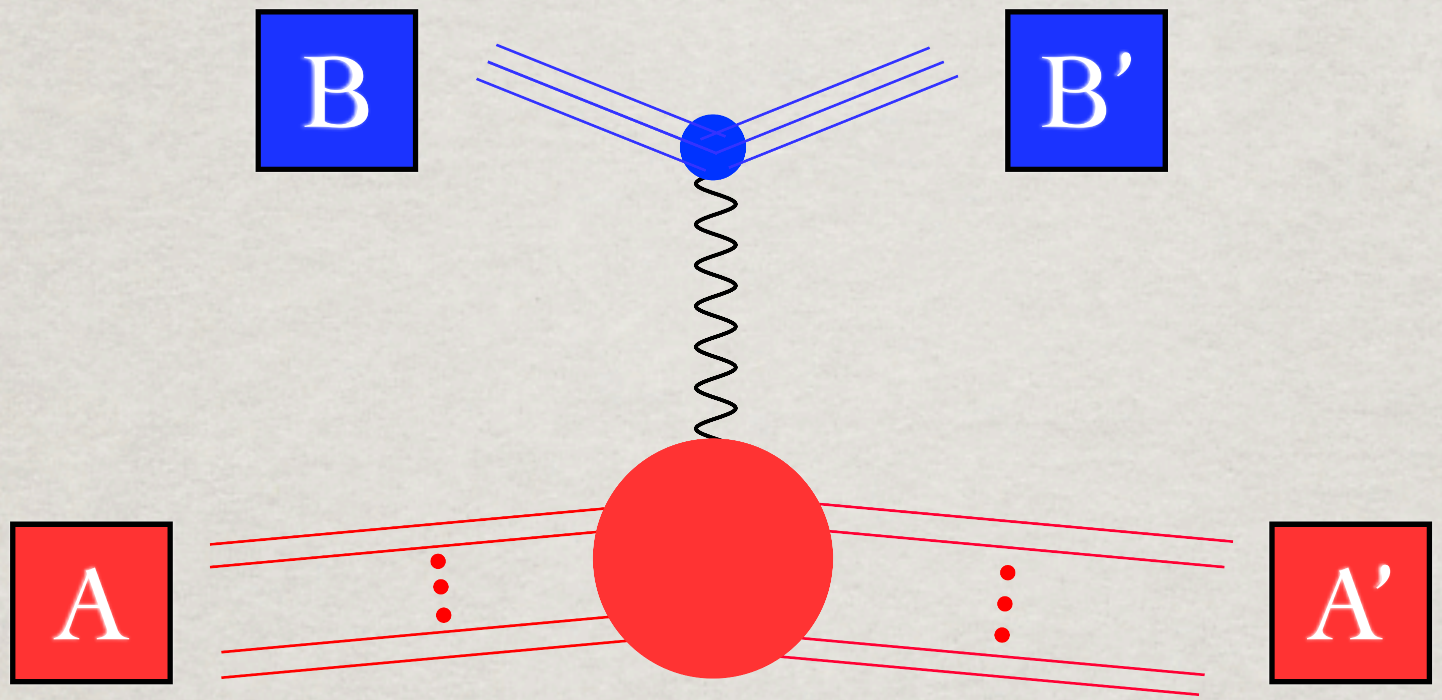

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$$\bar{p}^{\mu} = \frac{1}{2}(p' + p)^{\mu}$$

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

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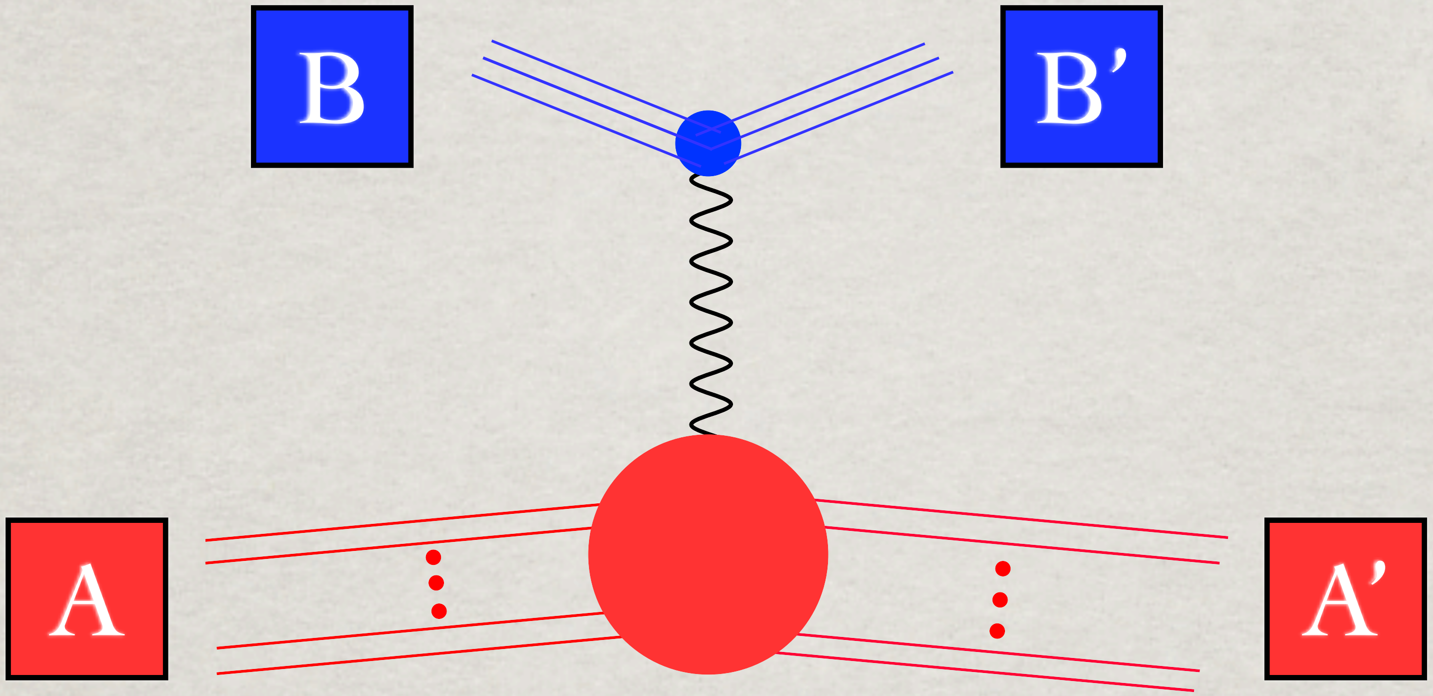

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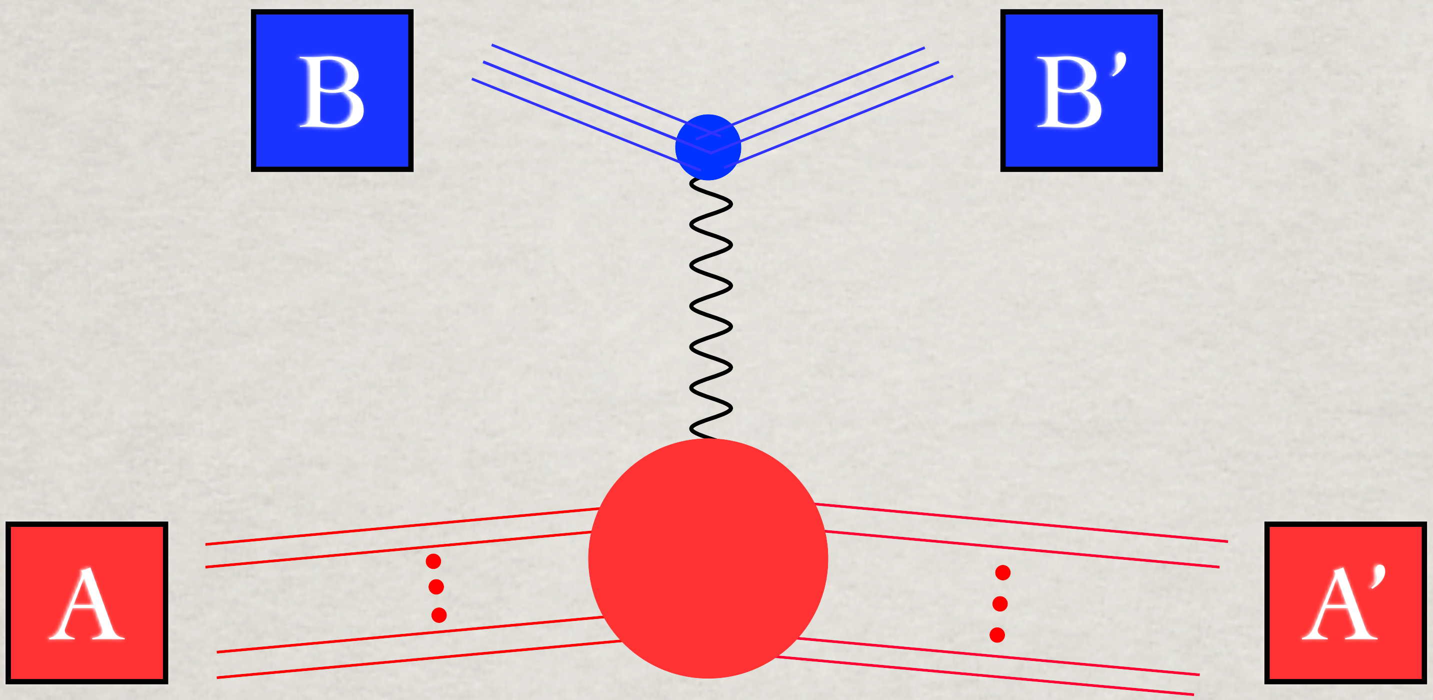
Cross-Section Calc.



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Large 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.

$$\frac{d\sigma}{dE_R} = \frac{\overline{|\mathcal{M}_{\rm SI}|^2} + \overline{|\mathcal{M}_{\rm SD}|^2}}{16\pi(M_\chi + M_T)^2 E_R^{\rm max}}$$

*Non-perturbative lattice input

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$$\overline{|\mathcal{M}_{\rm SD}|^2} = e^4\, \frac{2}{3}\left(\frac{J+1}{J}\right) \left[\left(A\frac{\mu_T}{\mu_n}\right) F_s(Q)\right]^2 \kappa_\chi^2$$

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$$R = \frac{M_{\rm detector}}{M_T} \frac{\rho_{\rm DM}}{M_\chi} \int_{E_{\rm min}}^{E_{\rm max}} dE_R \, \mathcal{A}cc(E_R) \left\langle v' \, \frac{d\sigma}{dE_R} \right\rangle_f$$

*Non-perturbative lattice input

Xenon100: $E_{min}^{Xe} = 6.6$ keV $E_{max}^{Xe} = 30.5$ keV

Three-Point Operators

$$\langle N(p')|\overline{\psi}\gamma^\mu\psi|N(p)\rangle = \overline{U}(p')\left[F_1^\psi(Q^2)\gamma^\mu + F_2^\psi(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_B}\right]U(p)$$

Isovector: $F^v_{1,2}(Q^2) = F^d_{1,2}(Q^2) - F^u_{1,2}(Q^2)$

Isoscalar: $F^s_{1,2}(Q^2) = F^d_{1,2}(Q^2) + F^u_{1,2}(Q^2)$

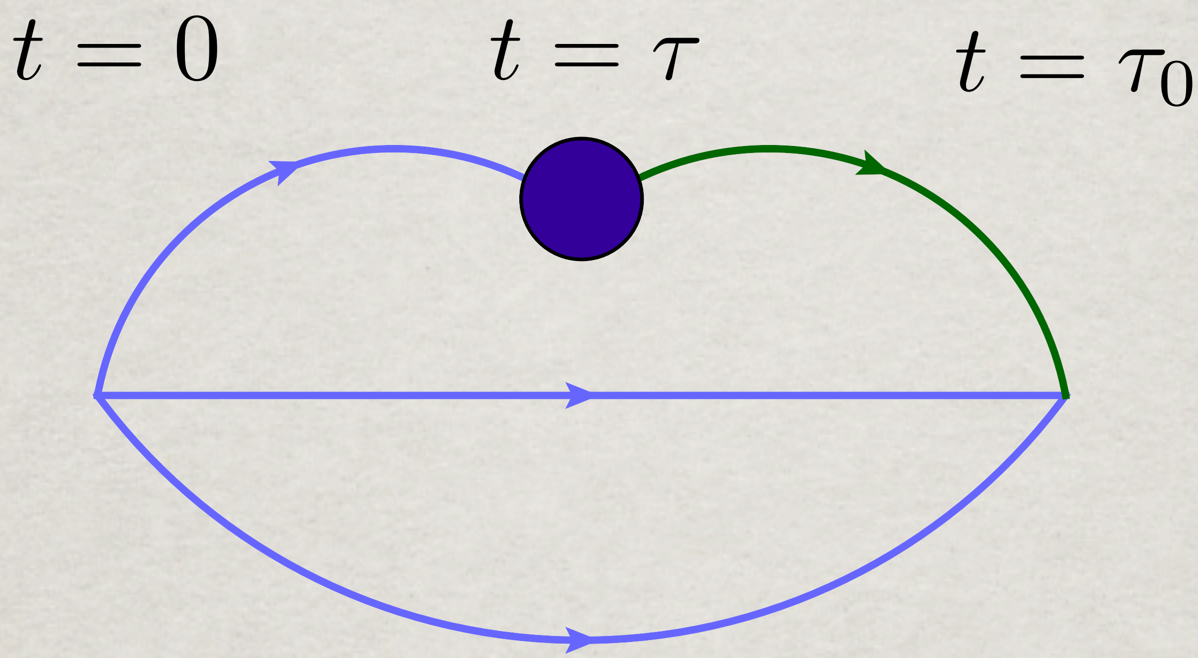
Neutral FF: $F_{1,2;\mathrm{neut}}(Q^2) = \frac{1}{6}F^s_{1,2}(Q^2) - \frac{1}{2}F^v_{1,2}(Q^2)$

$Q_u = 2/3 \quad Q_d = -1/3$

$$\kappa_{\mathrm{neut}} = F_{2;\mathrm{neut}}(0) \qquad \langle r^2_{1;\mathrm{neut}}\rangle = -6\frac{dF_{1;\mathrm{neut}}(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

$$\langle r^2_{E;\mathrm{neut}}\rangle = \langle r^2_{1;\mathrm{neut}}\rangle + \frac{3\kappa_{\mathrm{neut}}}{2M_B^2}$$

Three-Point Calculation

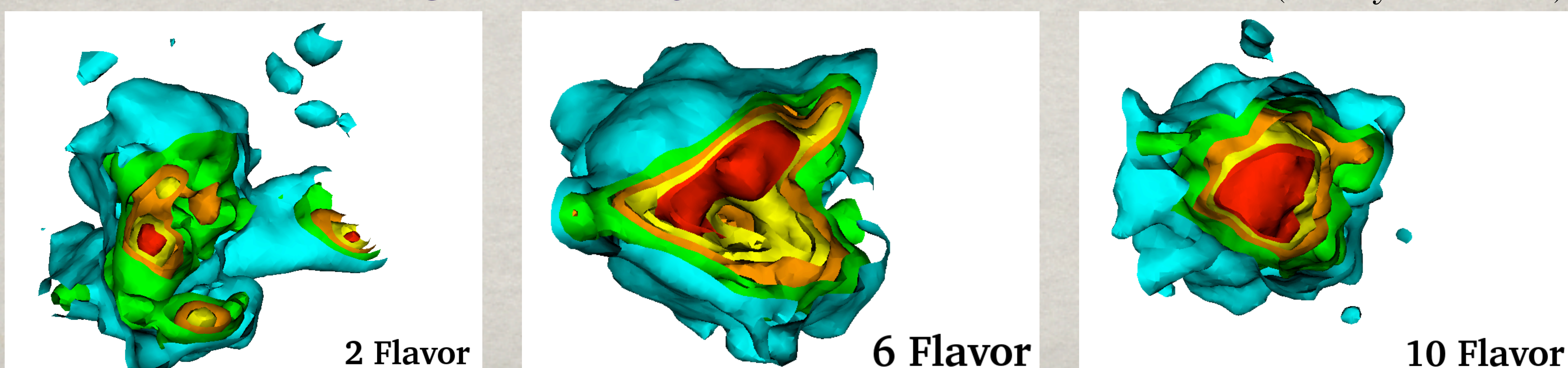


Disconected diagrams omitted in current calculation

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.

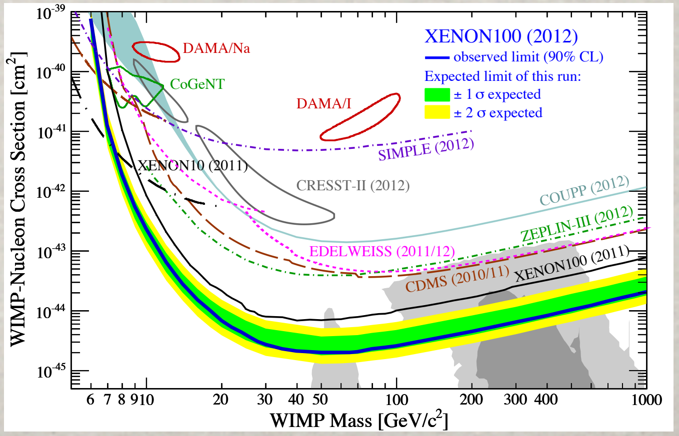
(Example) $$aM_\Omega = \# \quad \Rightarrow \quad a \approx \frac{\#}{1670\ \mathrm{MeV}}$$

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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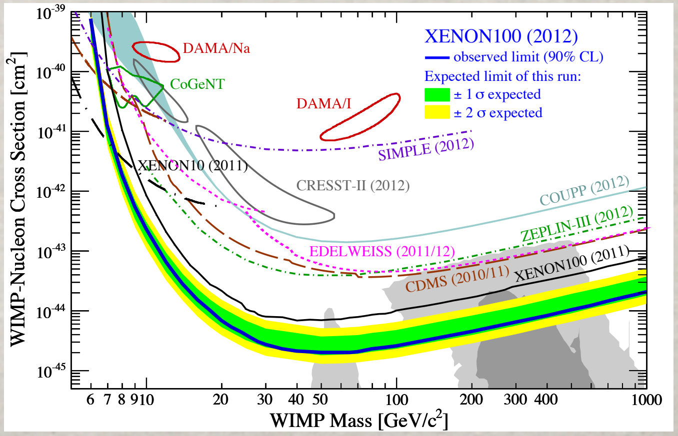
Dark Matter: Dark Matter Mass

$aM_B = \#$ ⇒ $a \approx \dfrac{\#}{M_B}$

Vary this value



Calculation Details

10 DWF Ensembles:

- $32^3 \times 64 \times 16$ 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

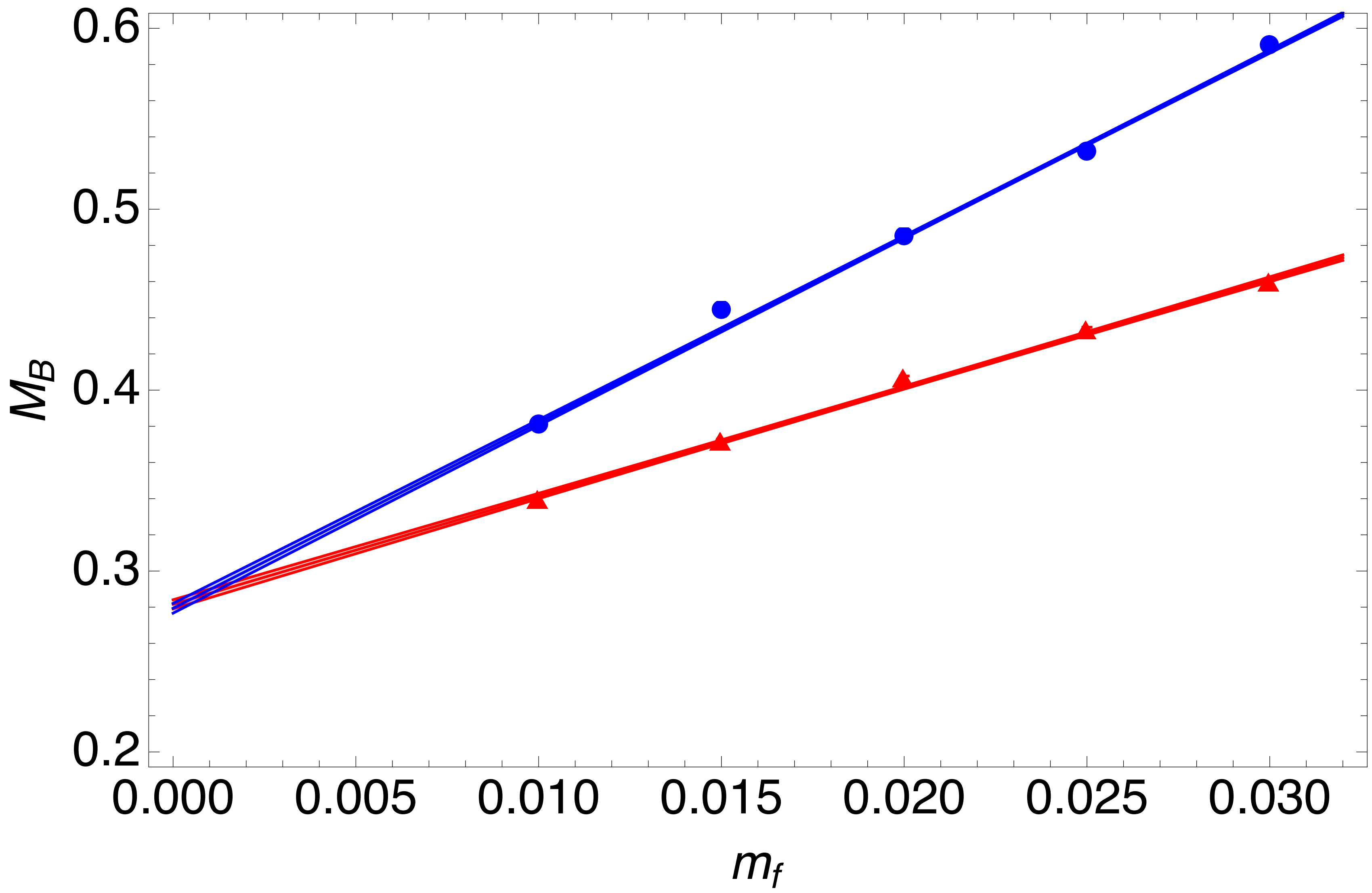
Table 1: 6 Flavor

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

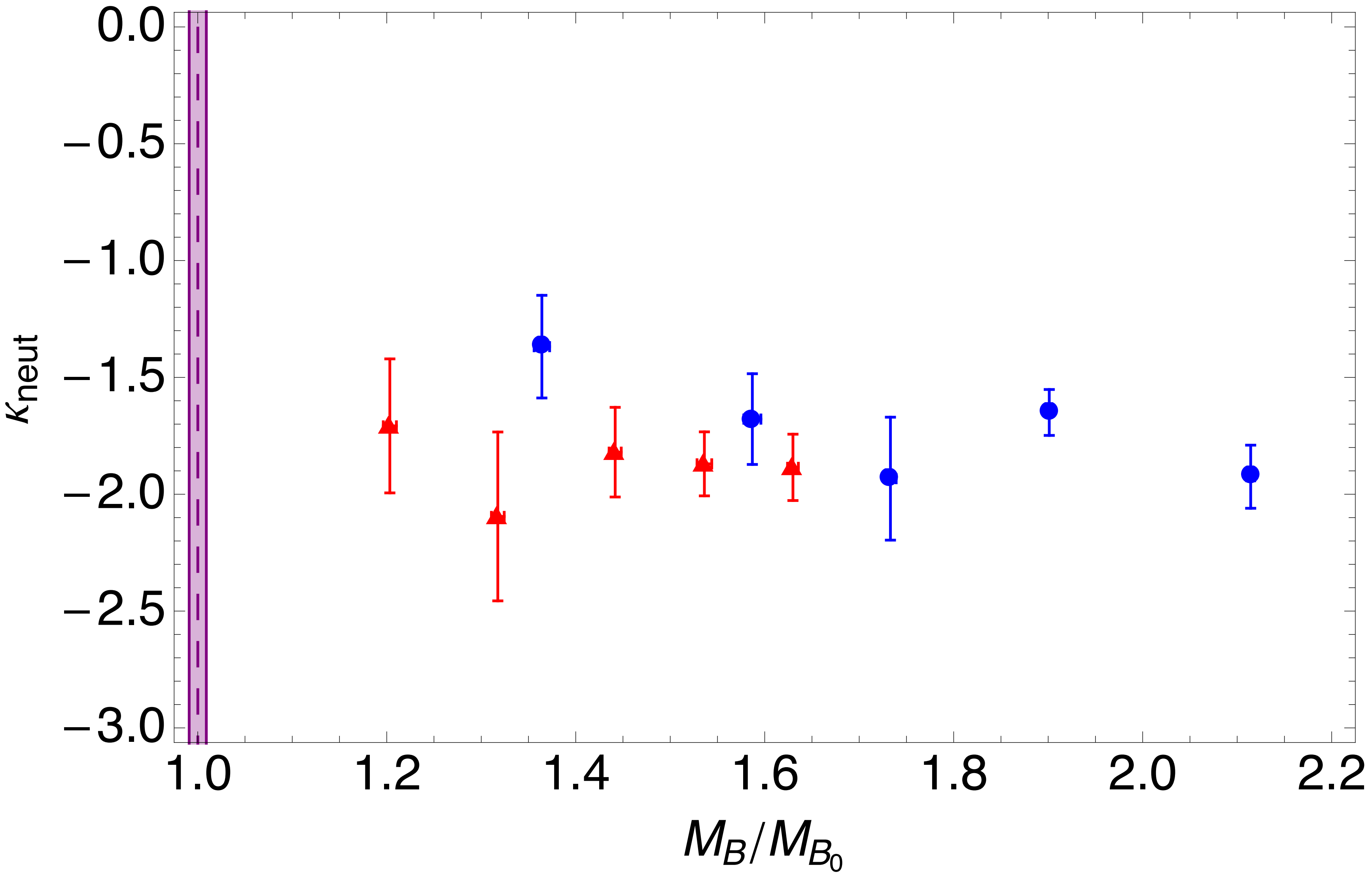
Blue - 6 Flavor



Magnetic Moment

Red - 2 Flavor

Blue - 6 Flavor



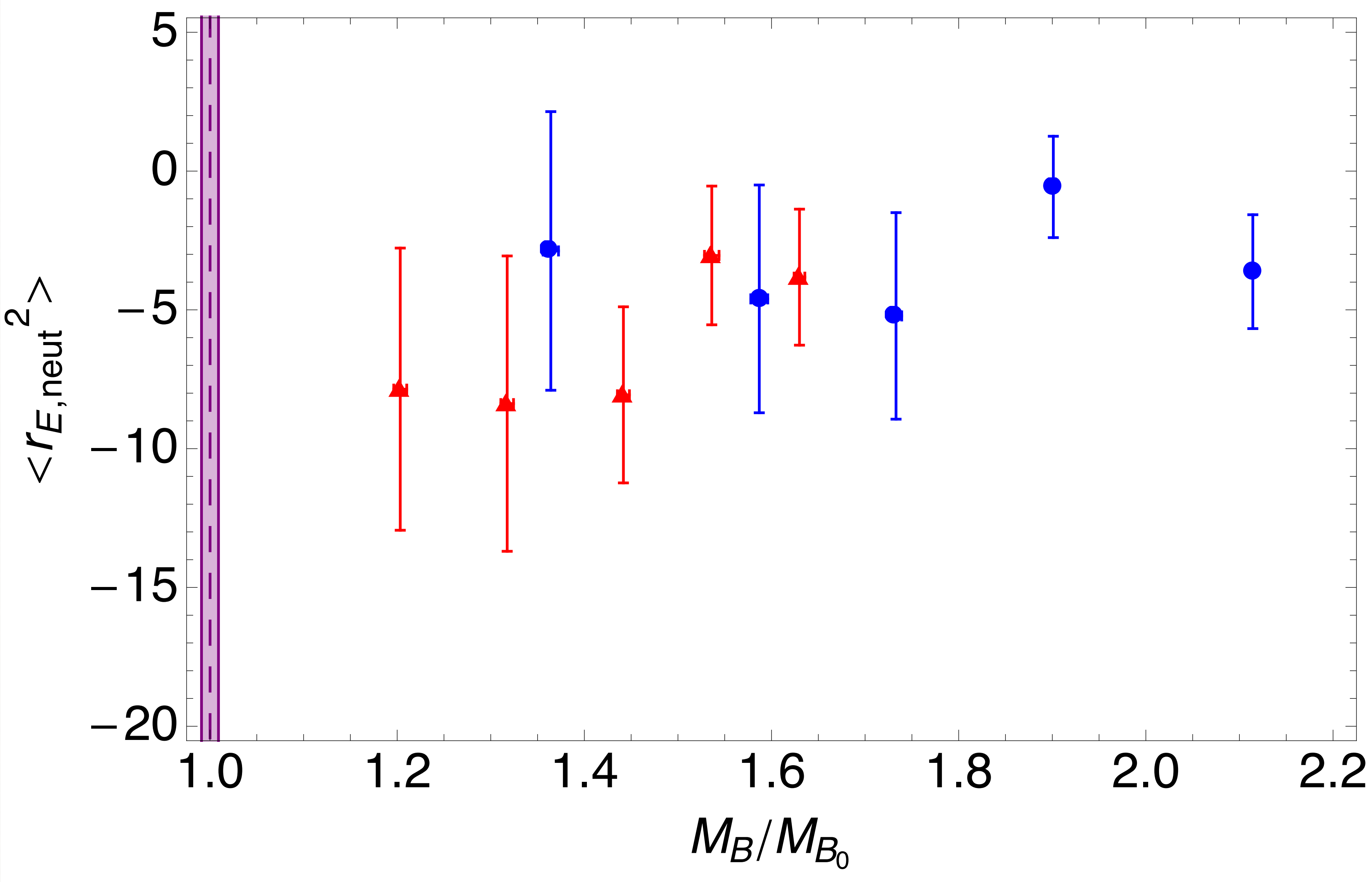
$$\mu = \frac{\kappa}{2M_B}$$

$$\kappa_{\rm neut} = \frac{1}{6}\kappa_s - \frac{1}{2}\kappa_v$$

Charge Radius

Red - 2 Flavor

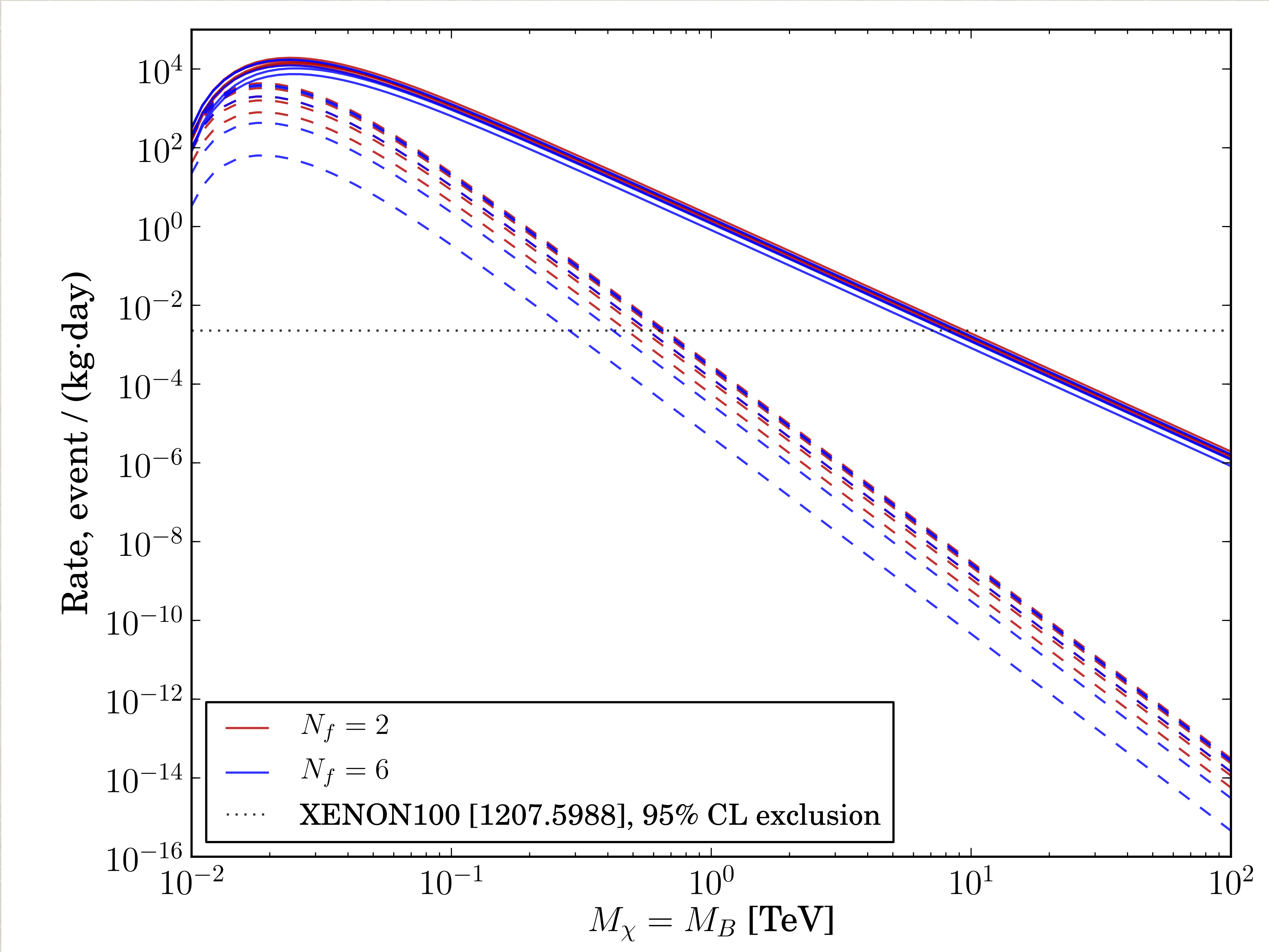
Blue - 6 Flavor



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

$$\langle r^2_{\mathrm{E,neut}} \rangle = \frac{1}{2}\langle r^2_{\mathrm{E},s} \rangle - \frac{1}{2}\langle r^2_{\mathrm{E},v} \rangle$$

Exclusion Plots



Dashed - Xenon100

PRD 88 014502 (2013)

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
    - ✷ Models with QCD charges excluded below 10 TeV
  - Currently exploring polarizabilities of even Nc theories
    - ✷ 4-color model building underway (Kribs, Neil, MIB)
    - ✷ 4-color baryon simulations in production (LSD)

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