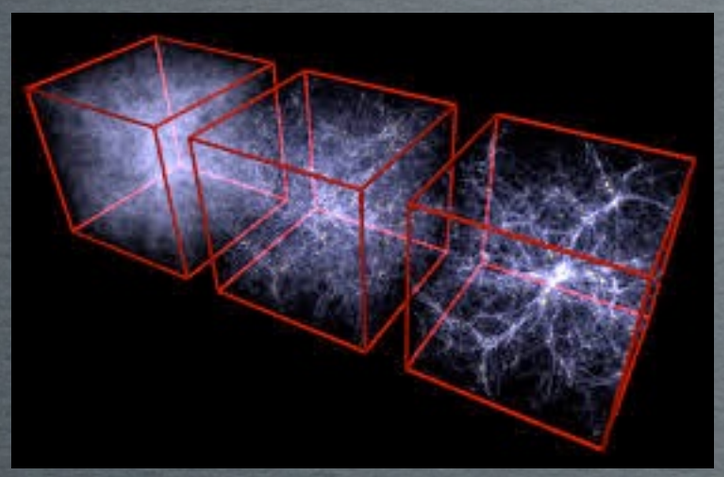
The Bosonic Side of Composite Dark Matter



Michael I. Buchoff
INT,
UW, Seattle

Primary collaborators:
Sergey Syritsyn
Ethan Neil
Graham Kribs
Chris Schroeder
Enrico Rinaldi

PRD 88 014502 (2013)

PRD 89 094508 (2013)
(Lattice)

arXiv: 1407.????
(Pheno)

Lattice **S**trong **D**ynamics 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

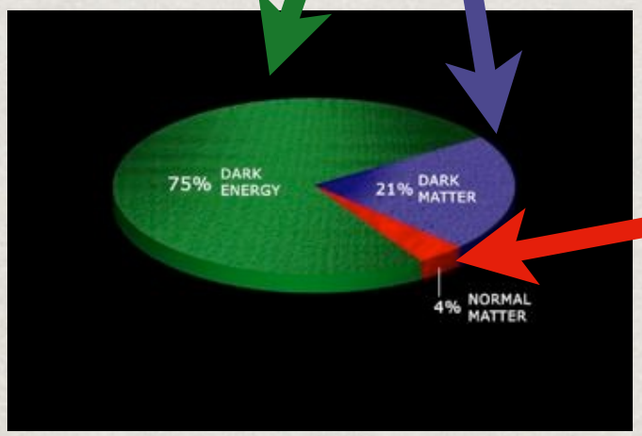
Tom Appelquist
George Fleming
Gennady Voronov

Mike Buchoff

A slice of the Universe

??????

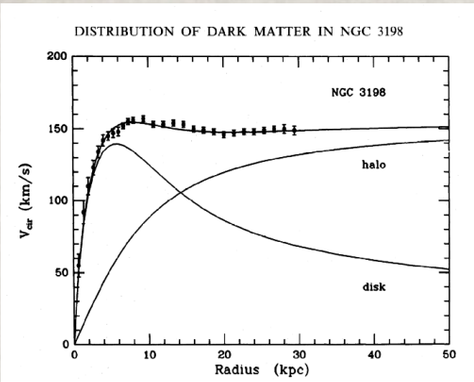
New Physics!!



We Are Here

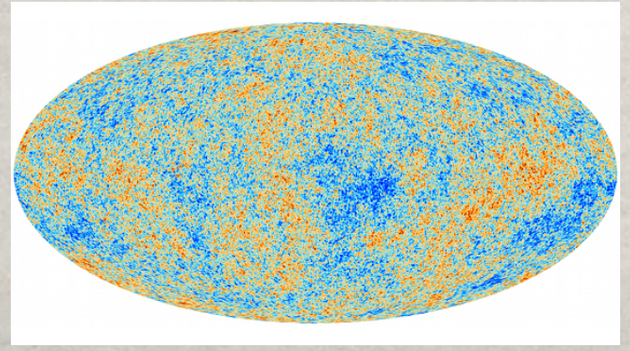
(QCD, EM, SM, etc.)

How do we know DM is there?



- Rotation Curves of Galaxies

- Gravitational Lensing



- Cosmic Microwave Background

Three Primary Properties of dark matter

Dark Matter Candidate should:

1. Be Long Lived

- Explains why dark matter has survived to today
  - ➡ Implies a new symmetry and/or charge

2. Be EW Charge Neutral

- Explains why there is no visible evidence
  - ➡ Implies lightest stable particle is chargeless

3. Explain Observed Relic Density

$$\rho_D \sim 0.25\ \rho_c$$

Thermal Relic

Dark Matter Annihilates → How much do we see today?

One approach to DM theories:

Choose DM Mass
Choose DM Interactions → $\rho_D \sim 0.25\ \rho_c$

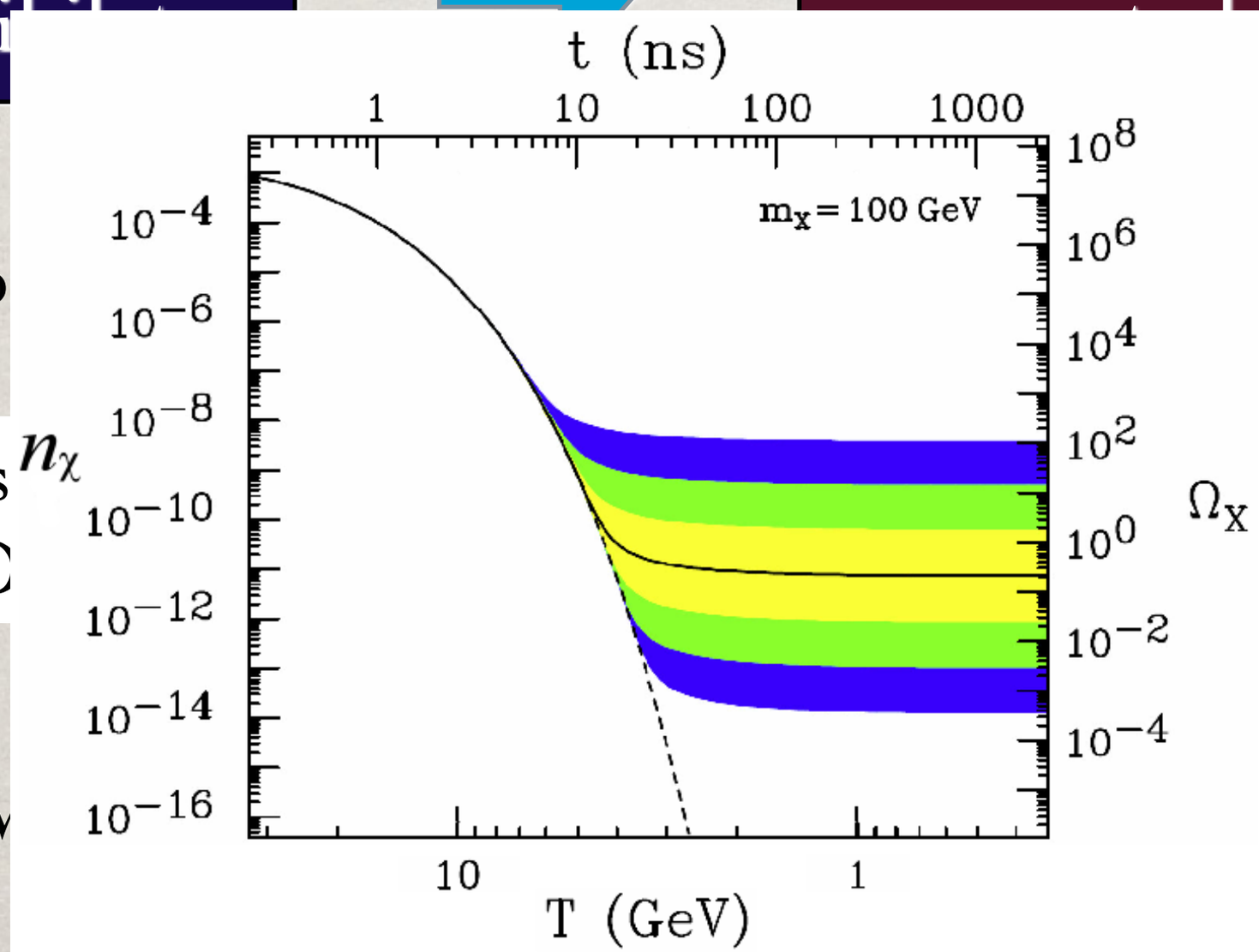
"WIMP Miracle"

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

Thermal Relic

Dark Matter
Anni

How much do we
y?



One appro

Choos
Choose D

"WIMP M

Ω_X 25 ρ_c

Assume Interactions
at/near EW Scale

$M_D \sim$ TeV

An Asymmetric alternative?

S.Nussinov (1985) S.M. Barr, R.S.Chivukula, E. Farhi (1990) 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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Asymmetry

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Observe a different relation:

Asymmetry

$$\rho_D \sim 5\boxed{\rho_B}$$

$$M_D n_D \sim 5 M_B n_B$$

If DM density is thermal: Unjustified Accident

Natural if DM density is also tied to asymmetry

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

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

Sphaleron connection $\Longrightarrow$ Direct or Indirect coupling to EW

Why Strong coupling?

Thermal

Large DM Mass → Strong Coupling

M. Buckley, E. Neil (2012)

Asymmetric

Small Thermal Abundance → Large Annihilation Rate → Strong Coupling

Studying strongly-coupled composite systems critical to fully understand landscape of DM theories

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

Three Primary Properties of dark matter

Dark Matter Candidate should:

1. Be Long Lived

➡ Implies a new symmetry and/or charge

Example: Baryons - Baryon Number
Mesons - G-parity Y.Bai, R.J.Hill (2010)

2. Be EW Charge Neutral

➡ Implies lightest stable particle is chargeless

Example: Can form neutral baryons

3. Explain observed relic density

➡Asymmetry require charge couplings

Example: Charged Constituents

LONG TERM OBJECTIVE

ULTIMATE GOAL:
To place a lower bound on nuclear cross-sections of composite DM with charged constituents

We Want:

- ★ Bound general classes of composite DM from first principles
- ★ Explore Higgs exchange and EM moments for direct detection
- ★ Study classes of models with minimal SM interaction strength

Final Goal:

LONG TERM OBJECTIVE

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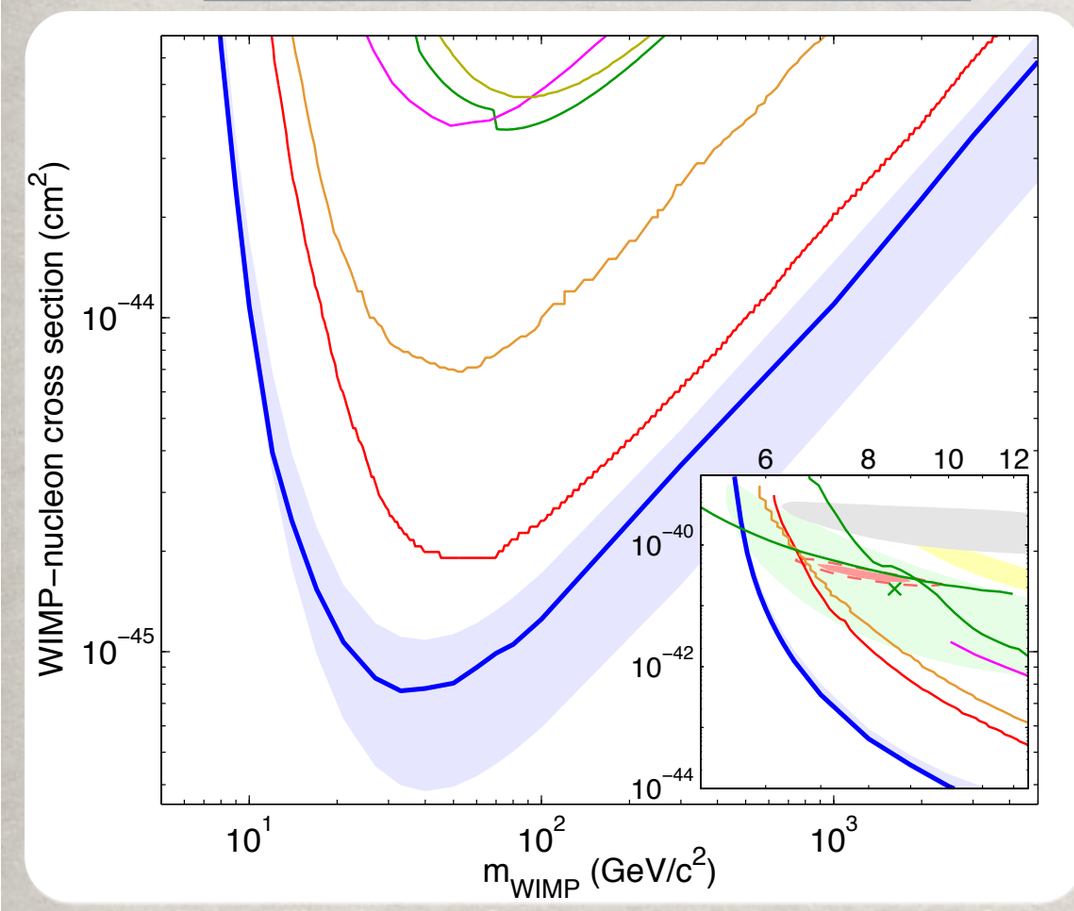
Final Goal:

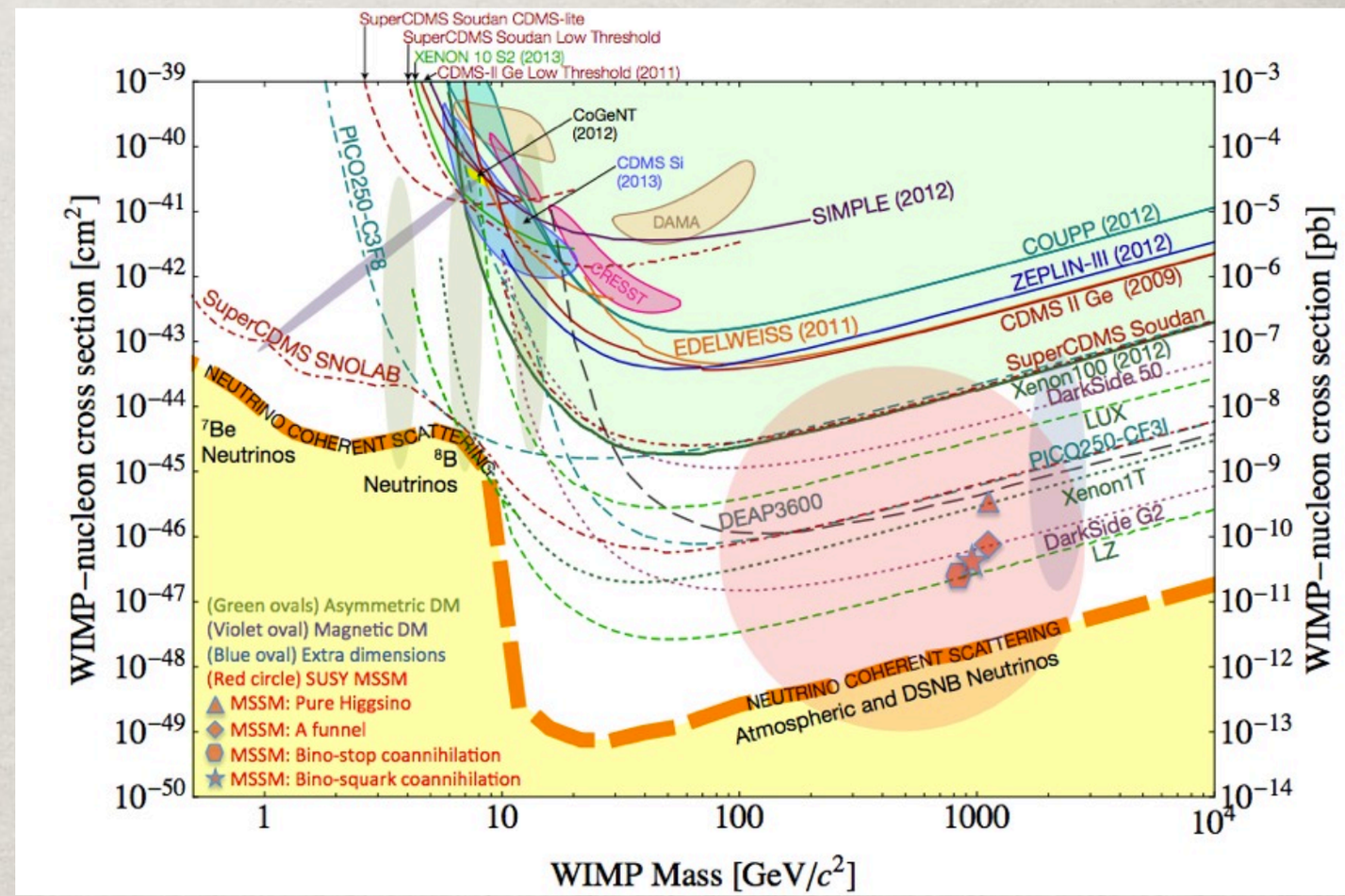
Our Focus: Direct Detection

- Before asking any other question, how strong are direct detection bounds?

LUX: PRL 112.091303



Experimental DM Frontier

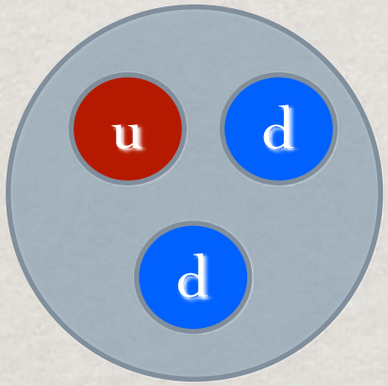


Spin-independent (coherent) - Very tight constraints $\sigma \lesssim 10^{-45}\ \mathrm{cm}^2$

Baryon Flavor Symmetry

★ Flavor Non-symmetric

Example: (3-color neutron ala QCD)



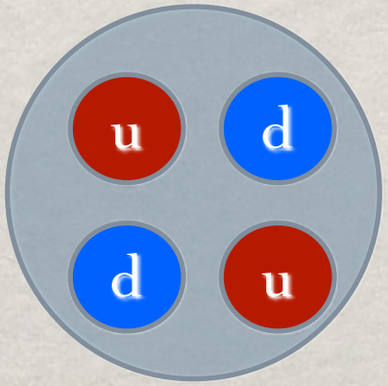
$$Q_u = Q_d$$

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 Previous work

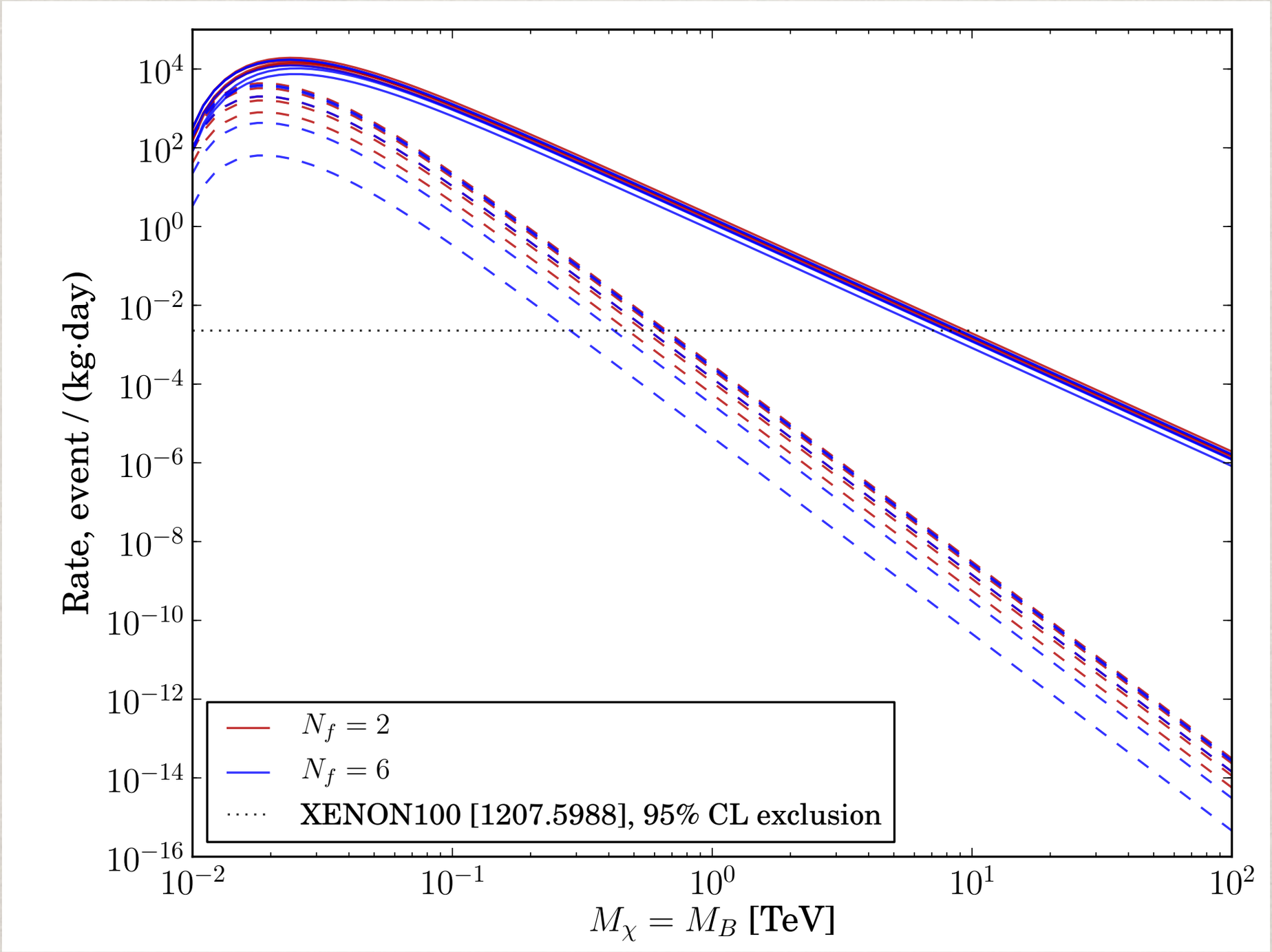
- Direct detection exclusions for odd number of colors

Explore:

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

Explores a range of confining theories for odd Nc theory

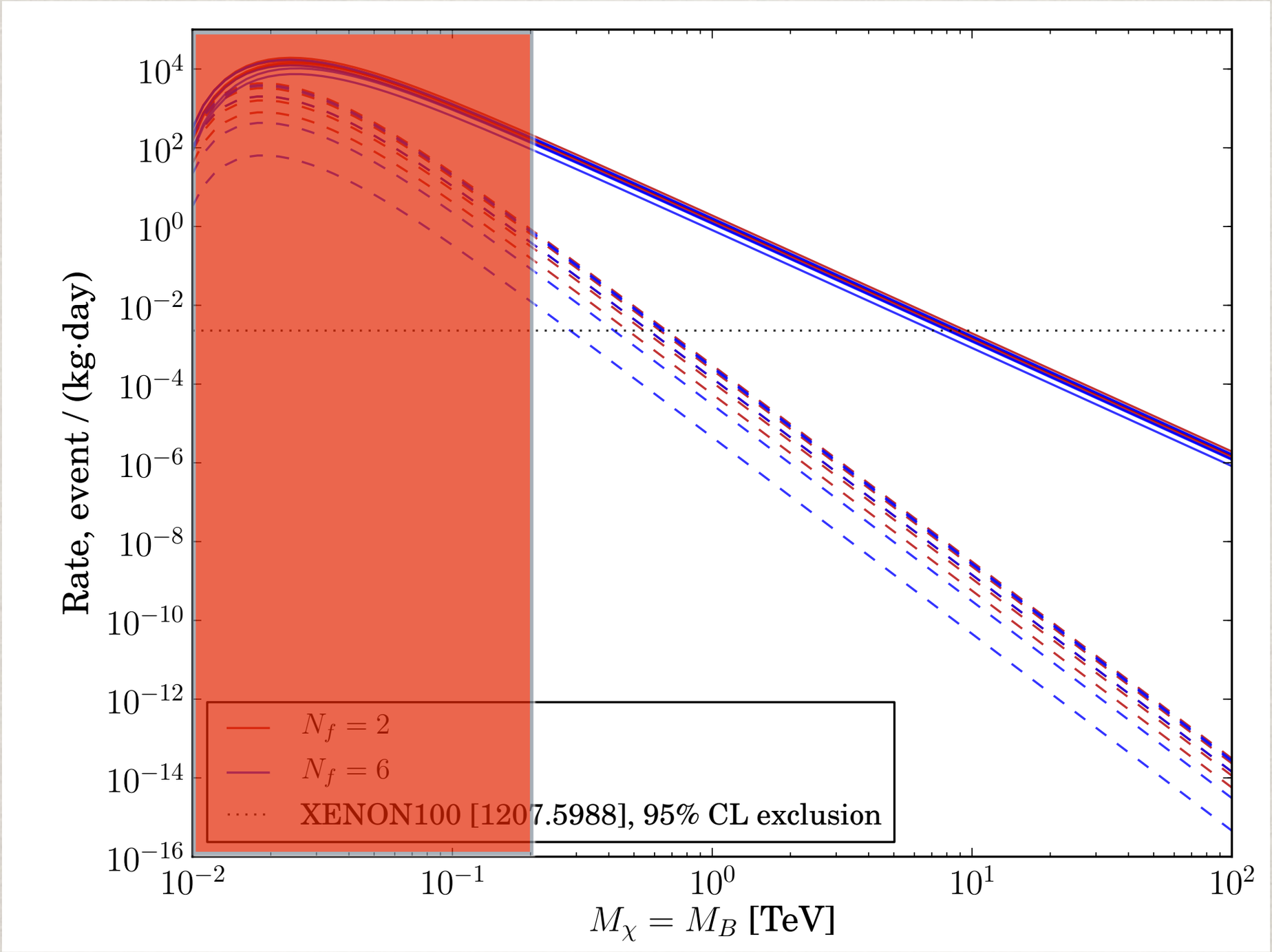
Exclusion Plots



Dashed horizontal line - Xenon100

PRD 88 014502 (2013)

Exclusion Plots



Dashed horizontal line - Xenon100

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LEP Bound on charged particles: M > 88 GeV

Focus of recent work

- Direct detection exclusions for even number of colors

Explore:

- 4-colors
- Multiple degenerate masses (quenched)
- Baryon spectra and sigma term

Allows for cross-section bounds from Higgs exchange

4-color baryons

- Bosonic baryons

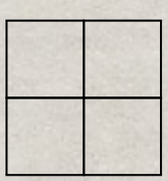
One Flavor: U

Spin-2: $\mathcal{O}_{B,S2}^{N_F=1} = (U^T C\gamma^i U)(U^T C\gamma^j U) \qquad i \neq j$

Two Flavors: $U \quad D$

Spin-2: $\mathcal{O}_{B,S2}^{N_F=2} = (U^T C\gamma^i U)(U^T C\gamma^j U) \qquad i \neq j$

Spin-1: $\mathcal{O}_{B,S1}^{N_F=2} = (U^T C\gamma^i U)(U^T C\gamma^5 D)$



Spin-0: $\mathcal{O}_{B,S1}^{N_F=2} = (U^T C\gamma^5 D)(U^T C\gamma^5 D)$

Higgs Exchange

- Higgs-nucleon cross-section:

$$\sigma_0(B,n) = \frac{\mu(m_B, m_n)^2}{\pi A^2}(Z\mathcal{M}_p + (A-Z)\mathcal{M}_n)^2$$

$$\mathcal{M}_a = \frac{y_f y_q}{2m_h^2}\sum_f \langle B|\bar{f}f|B\rangle \sum_q \langle a|\bar{q}q|a\rangle$$

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Per Nucleon

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$$\mathcal{M}_a = \frac{y_f y_q}{2m_h^2}\underbrace{\sum_f \langle B|\bar{f}f|B\rangle}_{\text{Dark}}\underbrace{\sum_q \langle a|\bar{q}q|a\rangle}_{\text{SM}}$$

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SM:

Light Quarks: $\langle n|m_q\bar{q}q|n\rangle = m_n f_q^{(n)}$

Heavy Quarks: $\langle n|m_q\bar{q}q|n\rangle = \frac{2}{27}m_n\left(1 - \sum_{q=u,d,s} f_q^{(n)}\right)$

Higgs Exchange

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Lattice QCD

Higgs Exchange

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Dark:

(Feynman-Hellmann)

$$\frac{1}{\sqrt{2}} y_f \equiv \left.\frac{\partial\, m_f(h)}{\partial\, h}\right|_{h=v} \qquad f_f^B = \frac{\langle B|m_f \bar{f} f|B\rangle}{m_B} = \frac{m_f}{m_B}\frac{\partial m_B}{\partial m_f}$$

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Per Nucleon

$$\mathcal{M}_{p,n} = \frac{g_{p,n} g_B}{m_h^2}$$

SM:

$$g_{p,n} = \frac{m_{p,n}}{v}\left[\sum_{q=u,d,s} f_q^{(p,n)} + \frac{6}{27}\left(1 - \sum_{q=u,d,s} f_q^{(p,n)}\right)\right]$$

Dark:

$$g_B = \frac{m_B}{v}\sum_f \frac{v}{m_f}\left.\frac{\partial\, m_f(h)}{\partial\, h}\right|_{h=v} f_f^{(B)}$$

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Lattice DM

Calculation Details

28 quenched Ensembles:

- Two # colors
- Four lattice volumes
- Three lattice spacings
- 3-6 fermion masses

N_c	β	κ	$N_s^3 \times N_t$	# Meas.
4	11.028	0.1554	$16^3 \times 32$	4878
			$32^3 \times 64$	1126
		0.15625	$16^3 \times 32$	4765
			$32^3 \times 64$	1146
			$48^3 \times 96$	1091
		0.1572	$32^3 \times 64$	1075
	11.5	0.1515	$16^3 \times 32$	2975
			$32^3 \times 64$	1057
		0.1520	$16^3 \times 32$	2872
			$32^3 \times 64$	1052
		0.1523	$16^3 \times 32$	2976
			$32^3 \times 64$	914
			$48^3 \times 96$	637
			$64^3 \times 128$	489
		0.1524	$16^3 \times 32$	2970
			$32^3 \times 64$	863
		0.1527	$32^3 \times 64$	1011
	12.0	0.1475	$32^3 \times 64$	1125
		0.1480	$32^3 \times 64$	1189
		0.1486	$32^3 \times 64$	1055
		0.1491	$16^3 \times 32$	411
		0.1491	$32^3 \times 64$	1050
		0.1491	$48^3 \times 96$	1150
		0.1491	$64^3 \times 128$	928
		0.1495	$32^3 \times 64$	1043
		0.1496	$32^3 \times 64$	1009
3	6.0175	0.1537	$32^3 \times 64$	1000
		0.1547	$32^3 \times 64$	1000

Table 1: Ensembles and number of measurements.

Calculation Details

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Summary of Lattice Details:

1. Volume systematic within statistical errors

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2. Discretization systematic within statistical errors

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Summary of Lattice Details:

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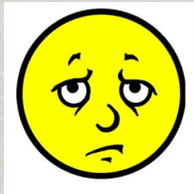
2. Discretization systematic within statistical errors

3. Three points to extract slope (more would be preferred)

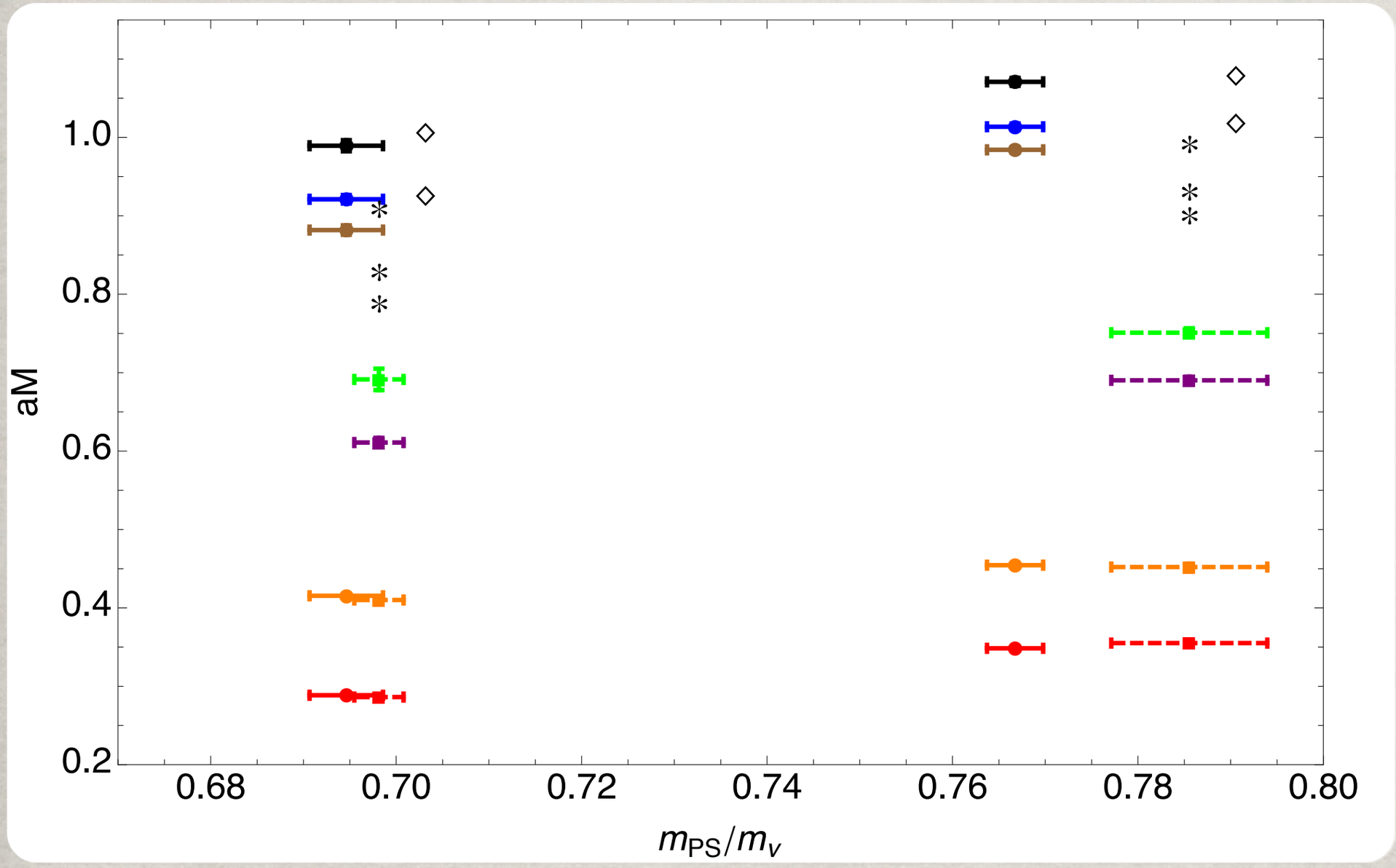


N_c	β	κ	$N_s^3 \times N_t$	# Meas.
4	11.028	0.1554	$16^3 \times 32$	4878
			$32^3 \times 64$	1126
		0.15625	$16^3 \times 32$	4765
			$32^3 \times 64$	1146
			$48^3 \times 96$	1091
		0.1572	$32^3 \times 64$	1075
	11.5	0.1515	$16^3 \times 32$	2975
			$32^3 \times 64$	1057
		0.1520	$16^3 \times 32$	2872
			$32^3 \times 64$	1052
		0.1523	$16^3 \times 32$	2976
			$32^3 \times 64$	914
			$48^3 \times 96$	637
			$64^3 \times 128$	489
		0.1524	$16^3 \times 32$	2970
			$32^3 \times 64$	863
		0.1527	$32^3 \times 64$	1011
	12.0	0.1475	$32^3 \times 64$	1125
		0.1480	$32^3 \times 64$	1189
		0.1486	$32^3 \times 64$	1055
		0.1491	$16^3 \times 32$	411
		0.1491	$32^3 \times 64$	1050
		0.1491	$48^3 \times 96$	1150
		0.1491	$64^3 \times 128$	928
		0.1495	$32^3 \times 64$	1043
		0.1496	$32^3 \times 64$	1009
3	6.0175	0.1537	$32^3 \times 64$	1000
		0.1547	$32^3 \times 64$	1000

Table 1: Ensembles and number of measurements.

PRD 89 094508

Large N Comparisons



Solid - 4 colors
Dashed - 3 colors

Black - Spin 2
Blue - Spin 1
Brown - Spin 0
Green - Spin 3/2
Purple - Spin 1/2
Orange - Vector
Red- Pseudoscalar

$$* : \; M(N_c, J) = N_c m_0 + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

$$\diamond : \; M(N_c, J) = N_c m_0^{(0)} + C + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

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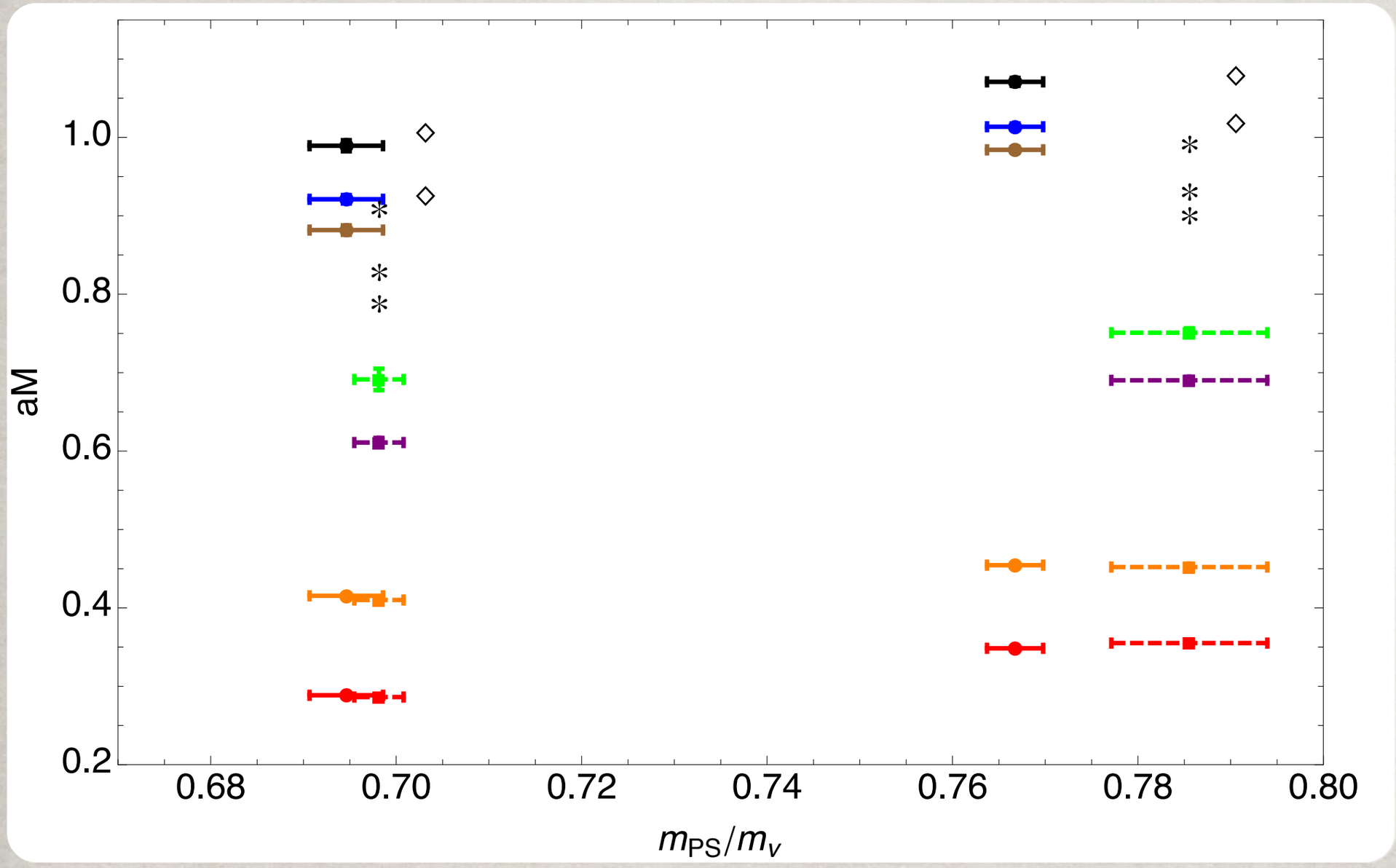

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Key Observation from DeGrand (2013)

Scale Setting

How do we define lattice spacing in physical units?

Lattice QCD:

Hadron Masses, HQ potentials, etc.

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

Technicolor:

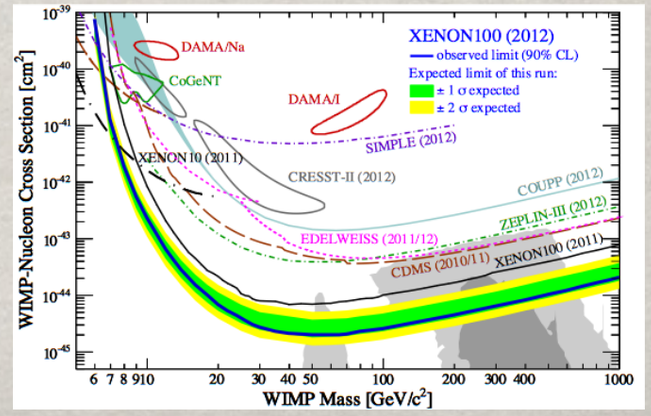
"Higgs" vev

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

Dark Matter:

Dark Matter Mass

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



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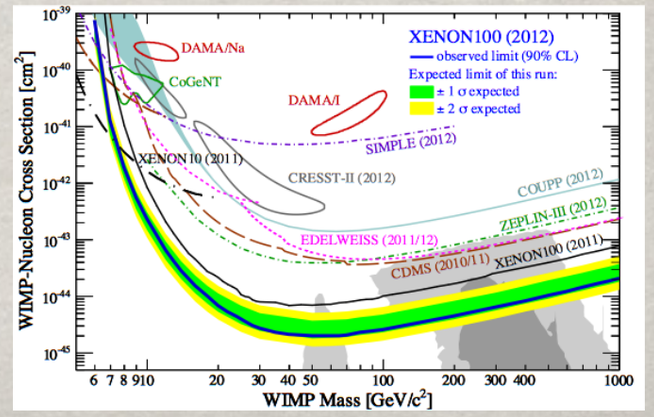
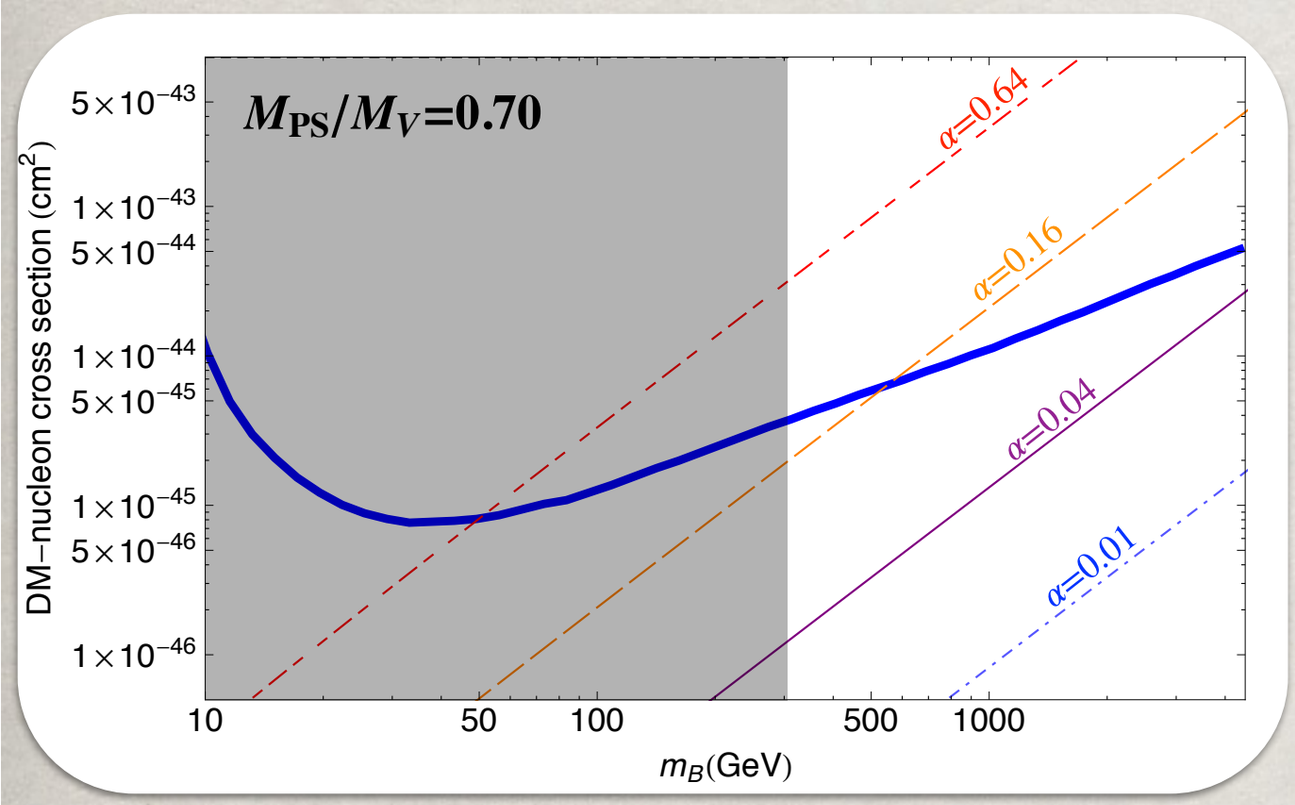
Vary this value



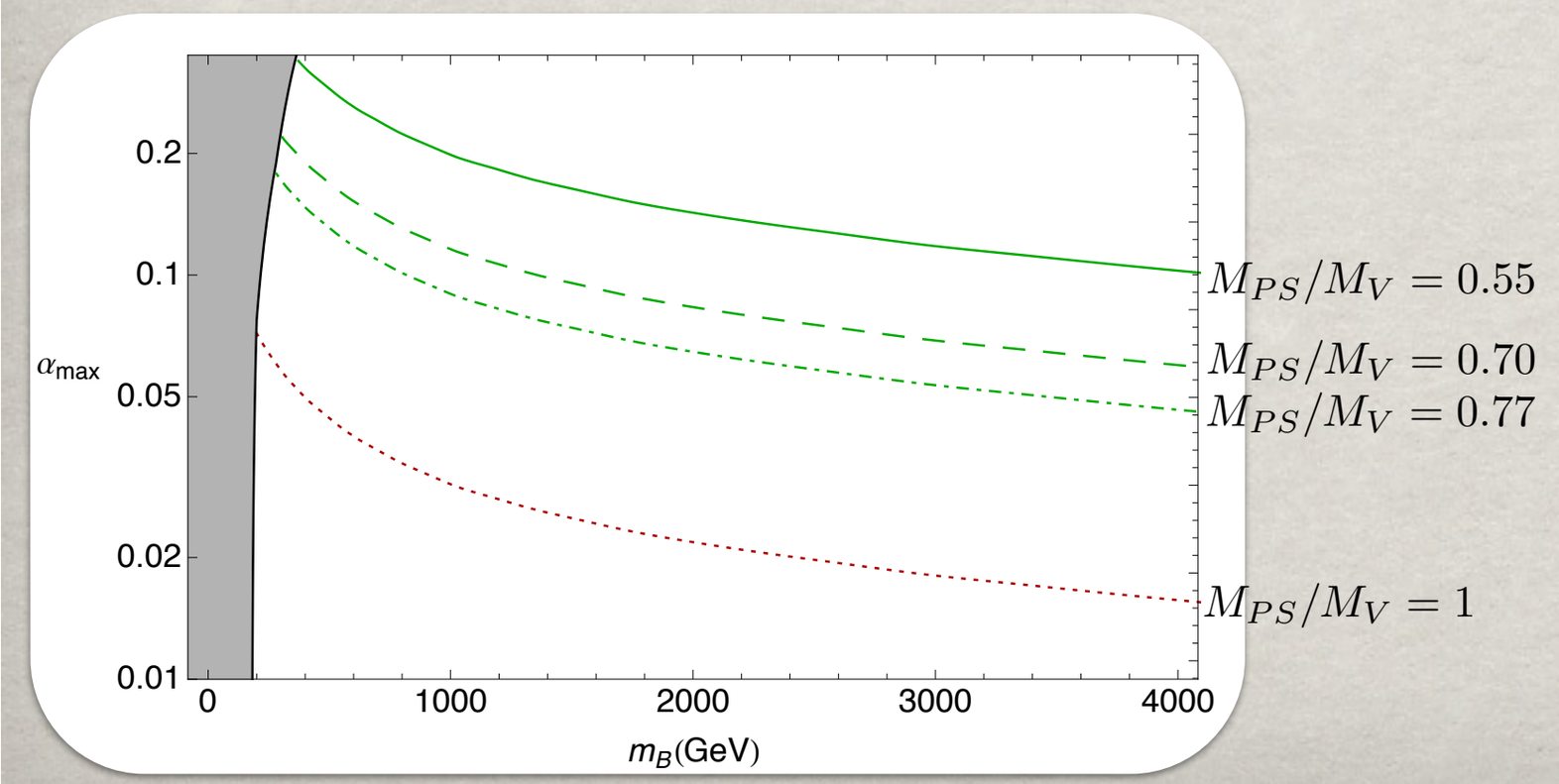
SIGMA TERM & HIGGS BOUND



$$\alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v}$$

$$0.153 \lesssim f^{(B)} \lesssim 0.338$$

$$2.82 \lesssim \frac{m_B}{m_{PS}} \lesssim 3.71$$



LEP Bound on charged particles: M > 88 GeV

PRD 89 094508

PARTICULAR MODEL

- Four Dirac Flavors with vector-like masses

Field	$\mathrm{SU}(N)_D$	$(\mathrm{SU}(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
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Mass Matrix (custodial symmetric):

$$\mathcal{L}_M = (\bar{\psi}_A^u \bar{\psi}_B^u) \begin{pmatrix} M - \Delta & yv/\sqrt{2} \\ yv/\sqrt{2} & M + \Delta \end{pmatrix} \begin{pmatrix} \psi_A^u \\ \psi_B^u \end{pmatrix} + (\bar{\psi}_A^d \bar{\psi}_B^d) \begin{pmatrix} M - \Delta & yv/\sqrt{2} \\ yv/\sqrt{2} & M + \Delta \end{pmatrix} \begin{pmatrix} \psi_A^d \\ \psi_B^d \end{pmatrix}$$

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$$m_\pm = M \pm \sqrt{2y^2v^2 + 4\Delta^2}$$

$$\sin^2\theta = \frac{1}{2}\left(1 - \frac{2\Delta}{\sqrt{2y^2v^2 + 4\Delta^2}}\right)$$

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$$\alpha = 2\cos\theta\sin\theta\frac{yv}{m_-}$$

$$\alpha \approx \frac{yv}{M} \quad M \gg 2yv \gg \Delta$$ Linear

$$\alpha \approx \frac{2(yv)^2}{M\Delta} \quad M \gg \Delta \gg 2yv$$ Quadratic

Cross section summary

- Back to cross section:

$$\sigma_0(B,n) = \frac{\mu(m_B, m_n)^2}{\pi A^2}(Z\mathcal{M}_p + (A-Z)\mathcal{M}_n)^2$$

$$\mathcal{M}_{p,n} = \frac{g_{p,n} g_B}{m_h^2}$$

$$g_B = \left(\frac{m_B}{v}\right)\alpha f^{(B)}$$

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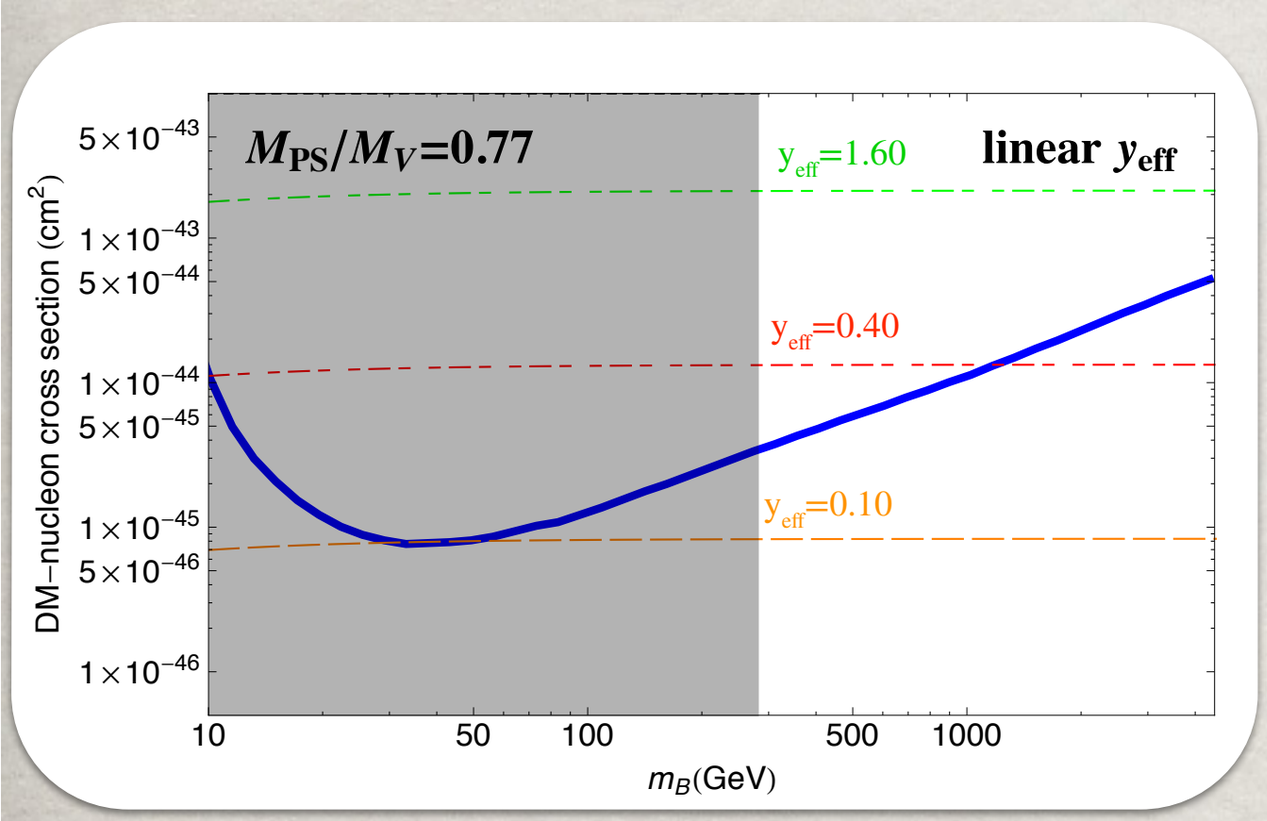
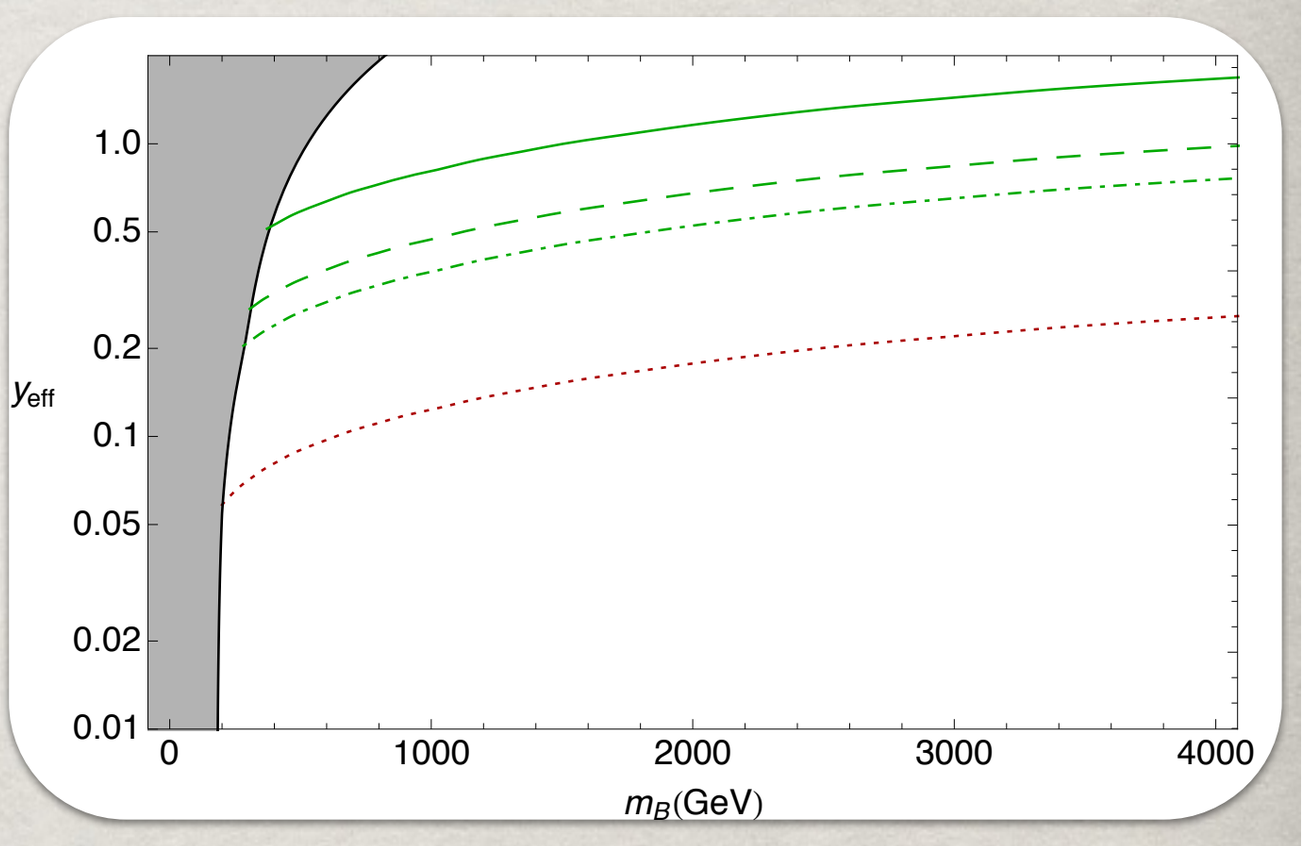
Varies with model parameters

$$f^{(B)} = \frac{m_-}{m_B}\frac{\partial m_B}{\partial m_-}$$

$$\alpha = 2\cos\theta\sin\theta\frac{yv}{m_-}$$

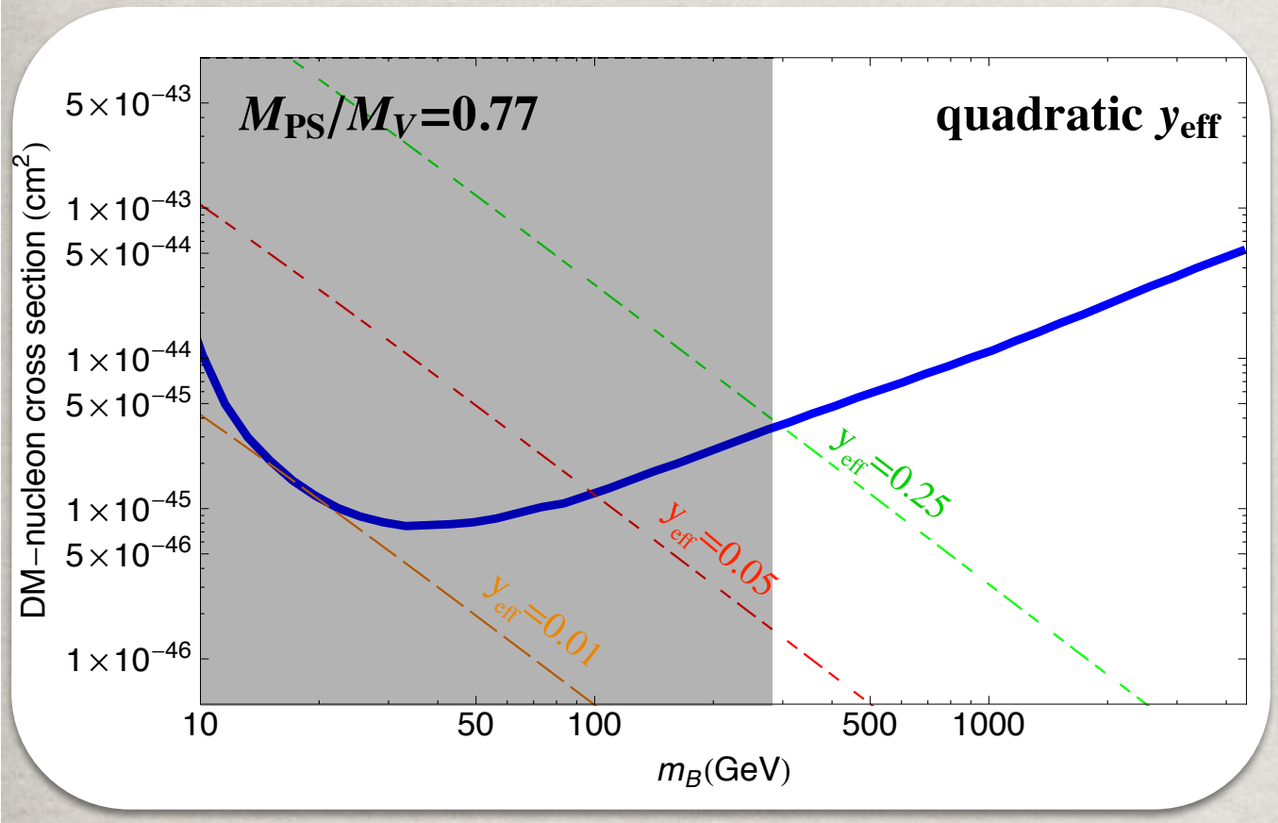
Linear Regime Bounds

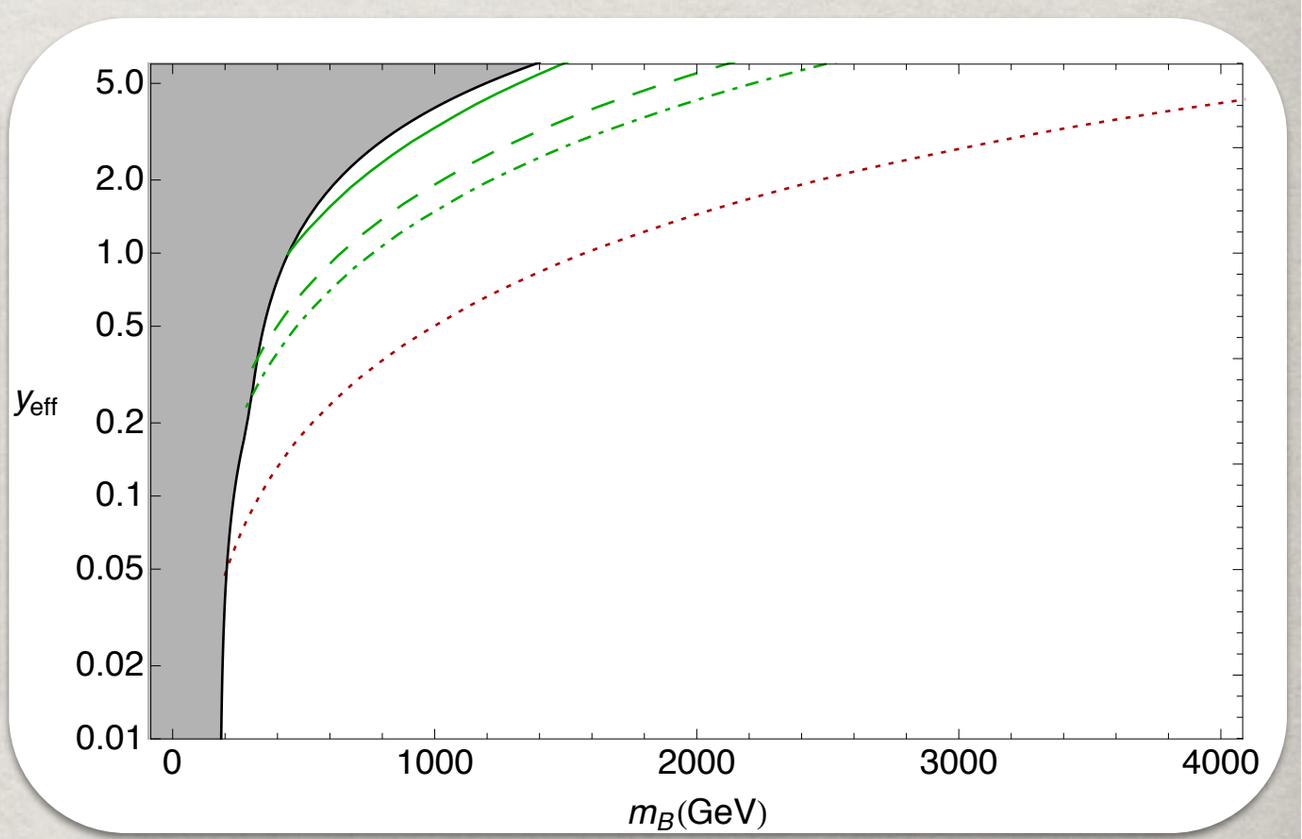




$$y_{\rm eff} \equiv y\left(\frac{M_B}{M}\right) \approx \alpha\frac{M_B}{v}$$

Quadratic Regime Bounds





$$y_{\rm eff}^2 \equiv y^2 \left(\frac{M_B^2}{M\Delta}\right) \approx \alpha \frac{M_B^2}{v^2}$$

Diagrammatic summary

Strongly coupled DM motivated from relic density

Composite DM addresses stability, neutrality, and density

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Fermion masses of chiral origin excluded

Solution

Vector-like masses

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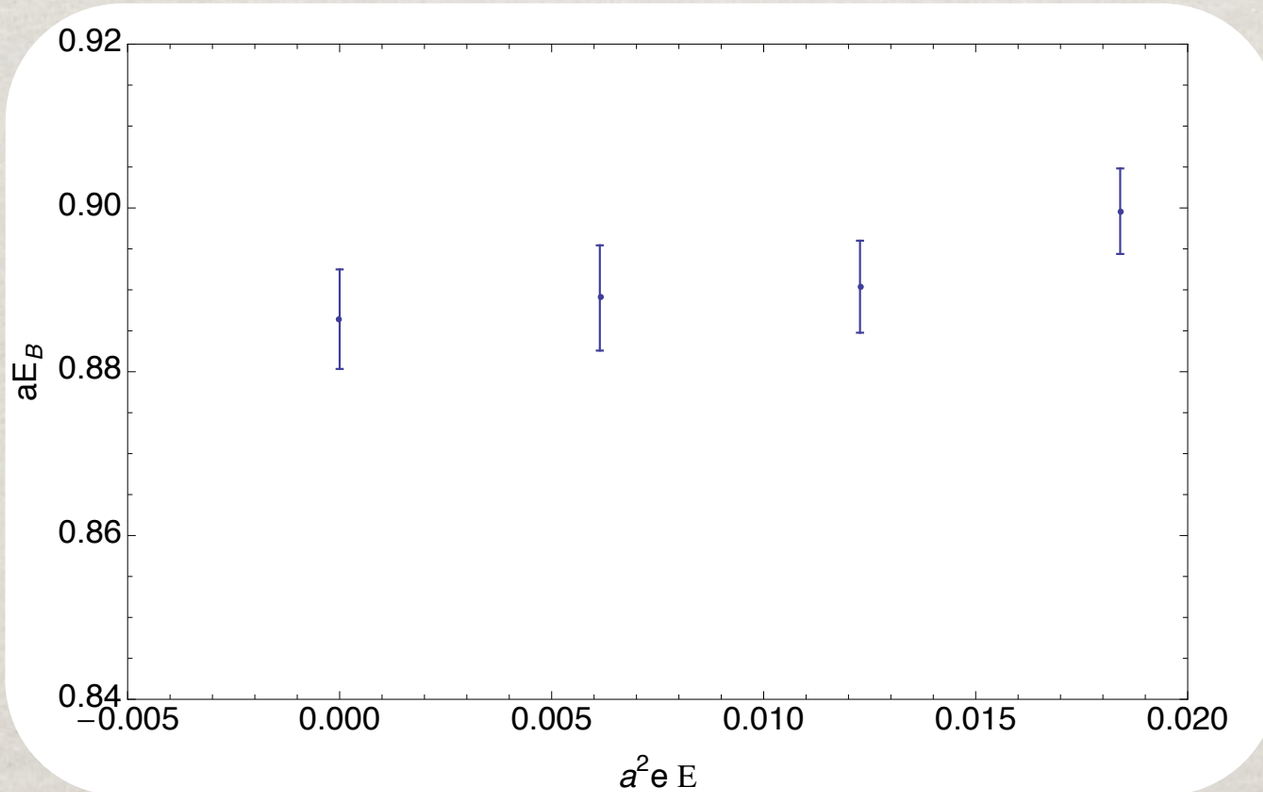
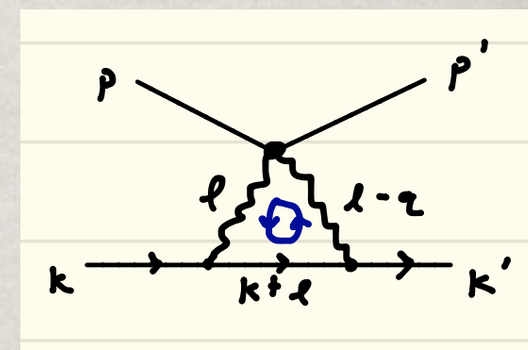
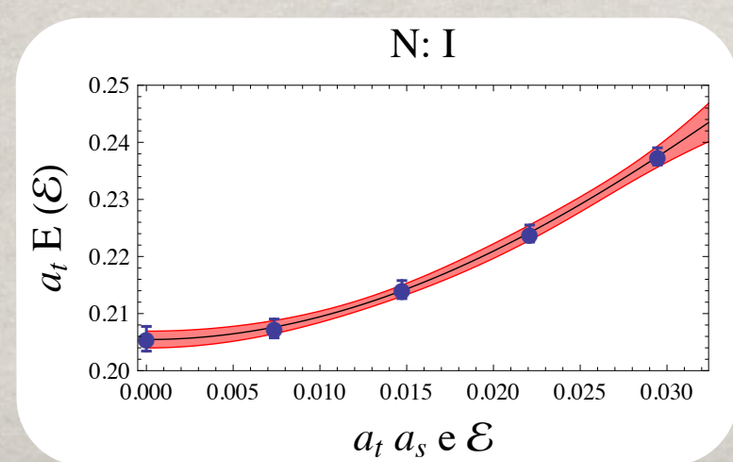
Very Preliminary
Polarizability Teaser

$$E = M_N + 4\pi\alpha_E \mathcal{E}^2 + \cdots$$

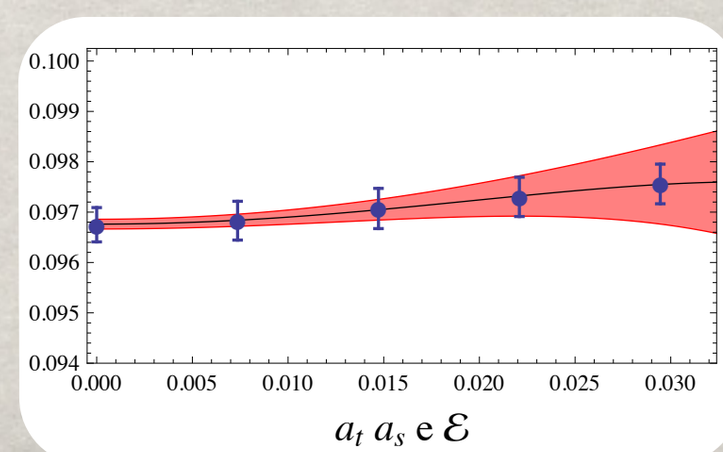




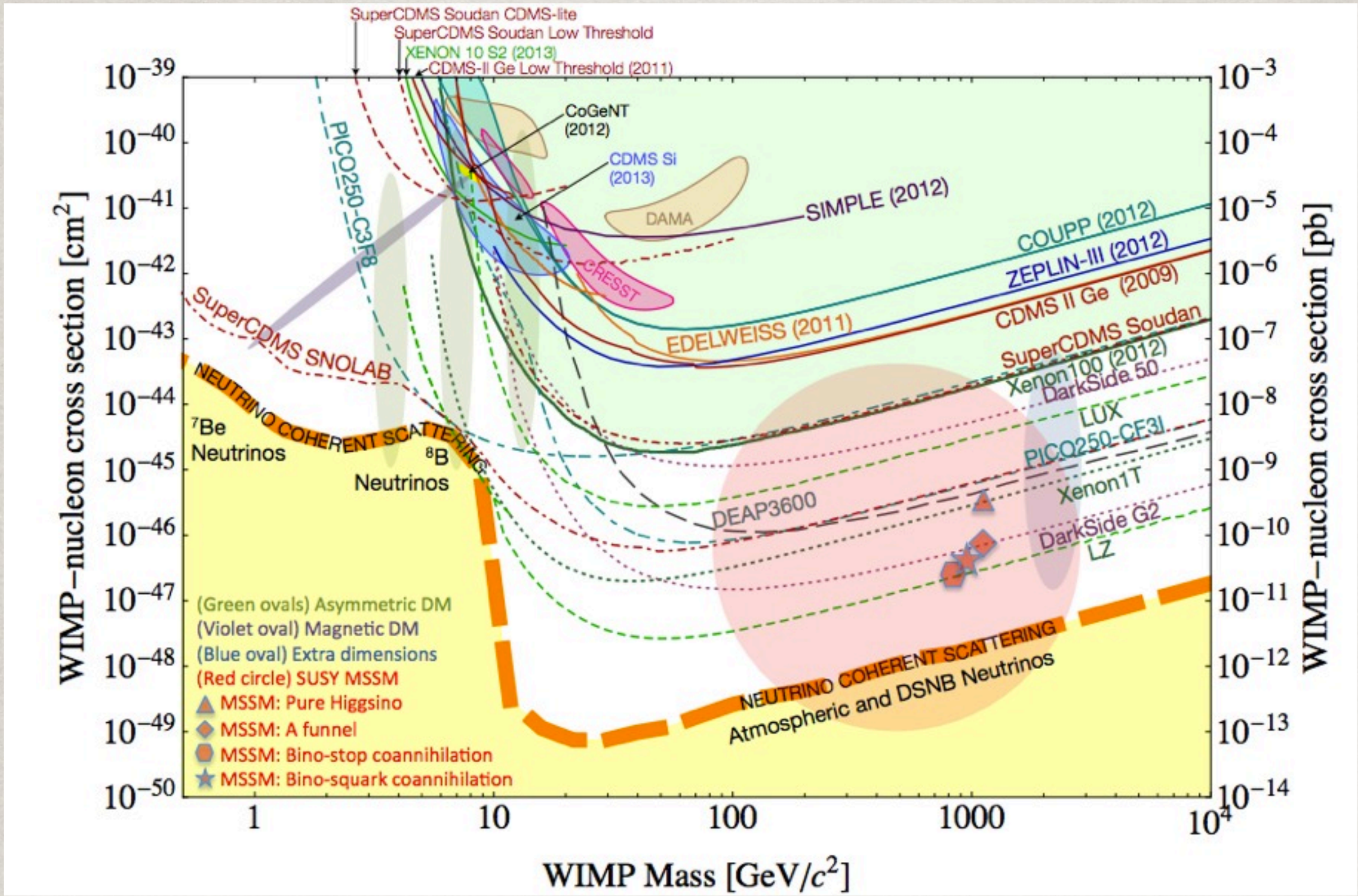
Neutron (Detmold, Tiburzi, Walker-Loud, 2010)



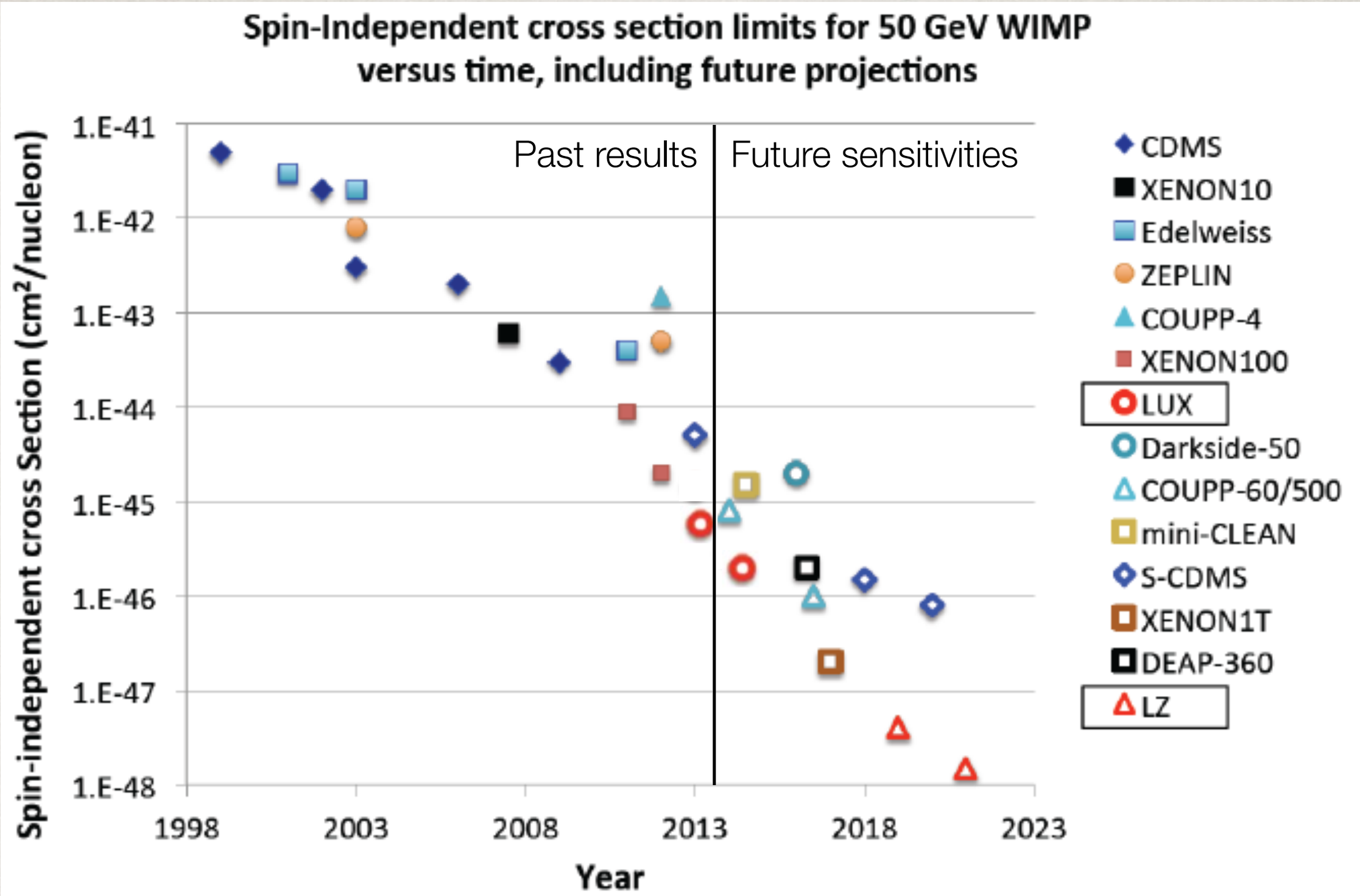
Neutral Kaon (Detmold, Tiburzi, Walker-Loud, 2009)



Backup



(Blair Edwards Presentation- Lattice Meets Experiment 2013)



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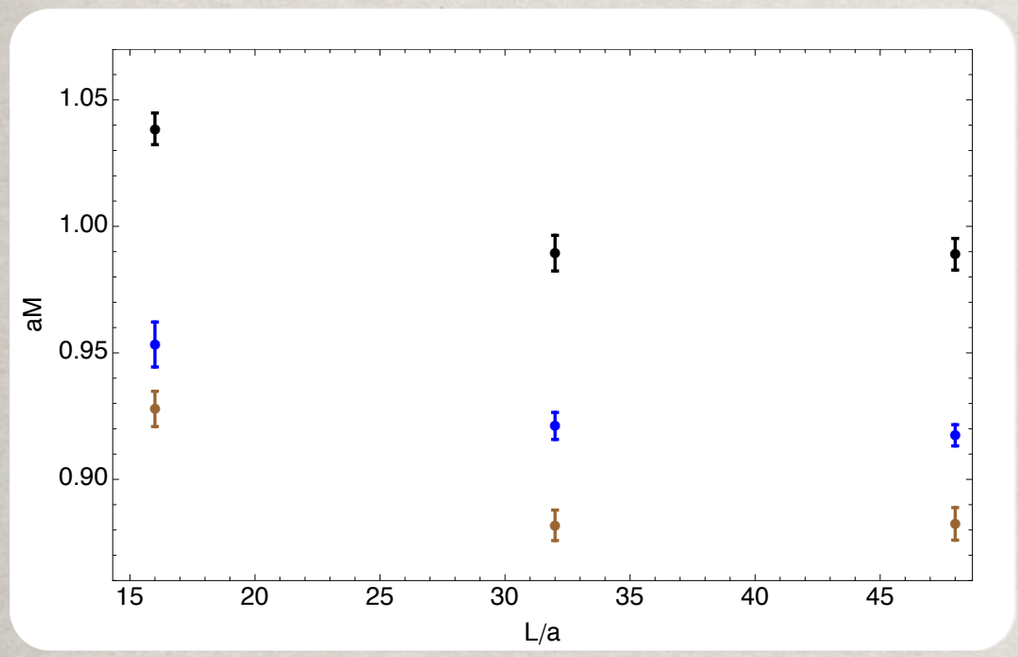
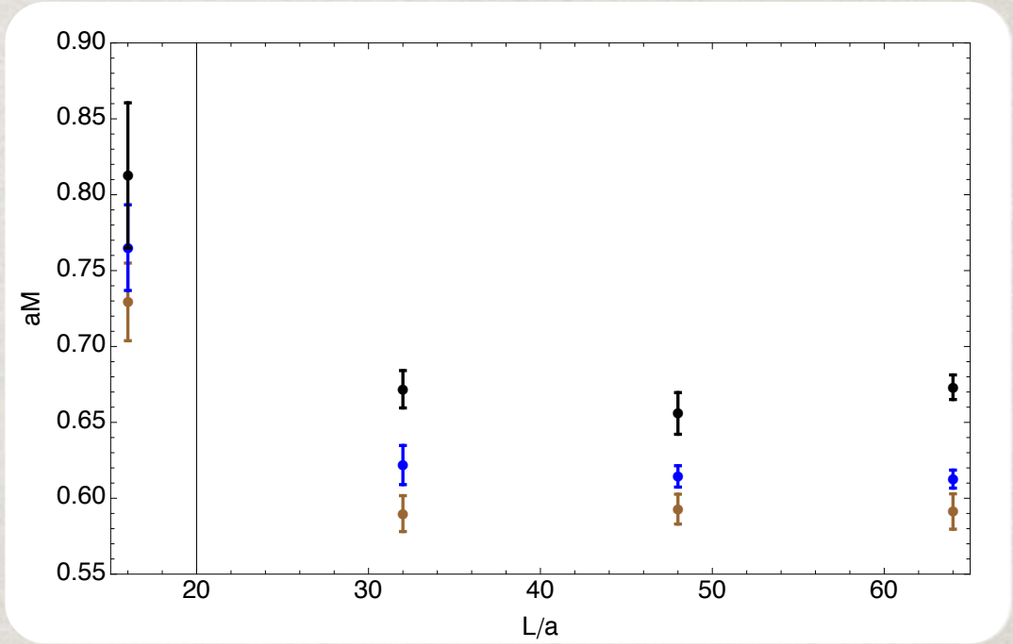
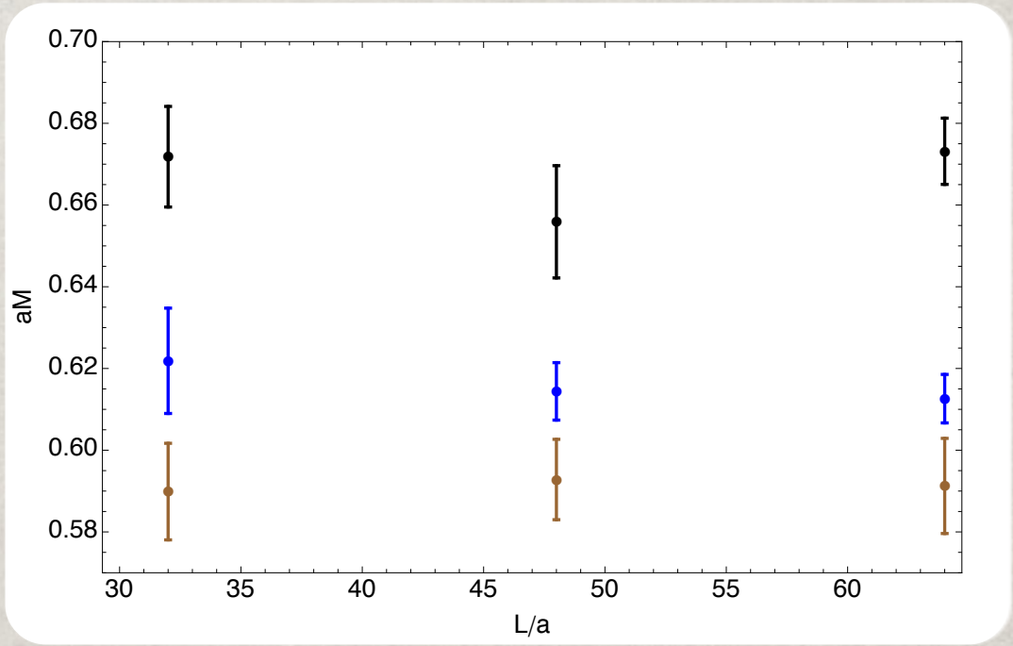
Volume effects



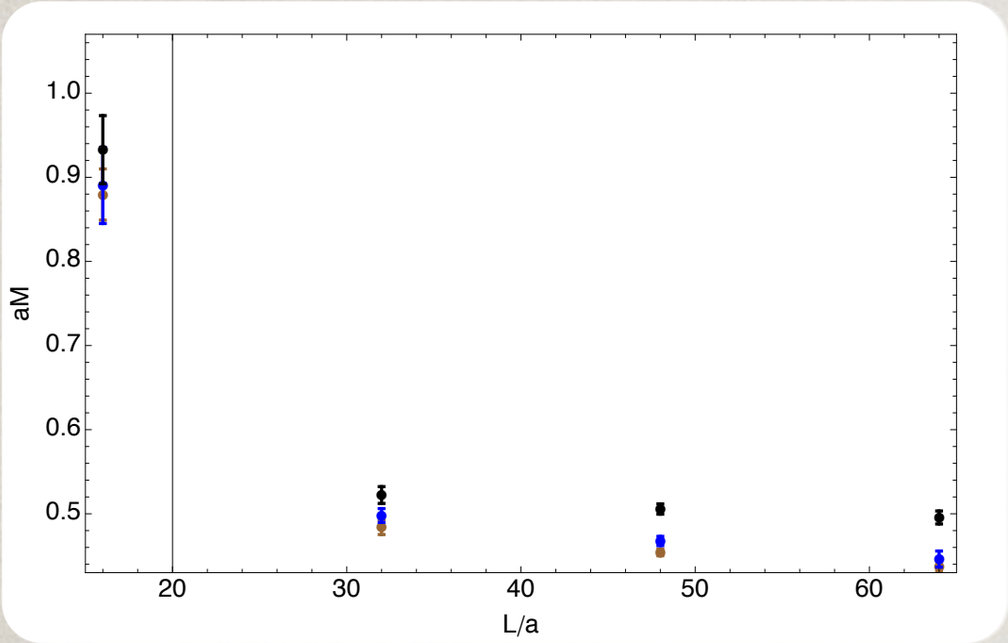
$\beta = 11.028$

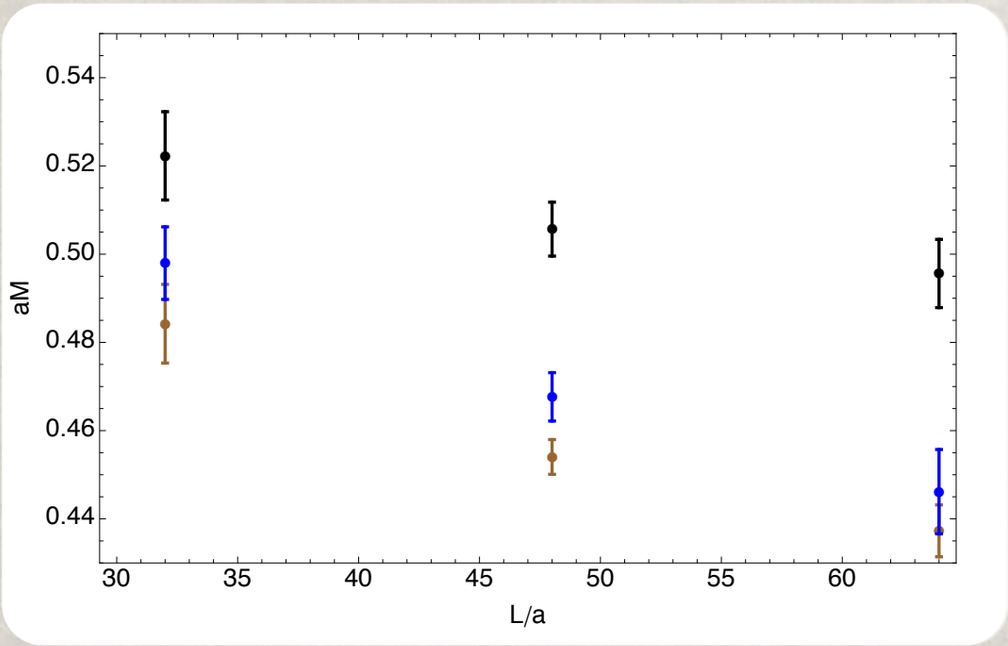


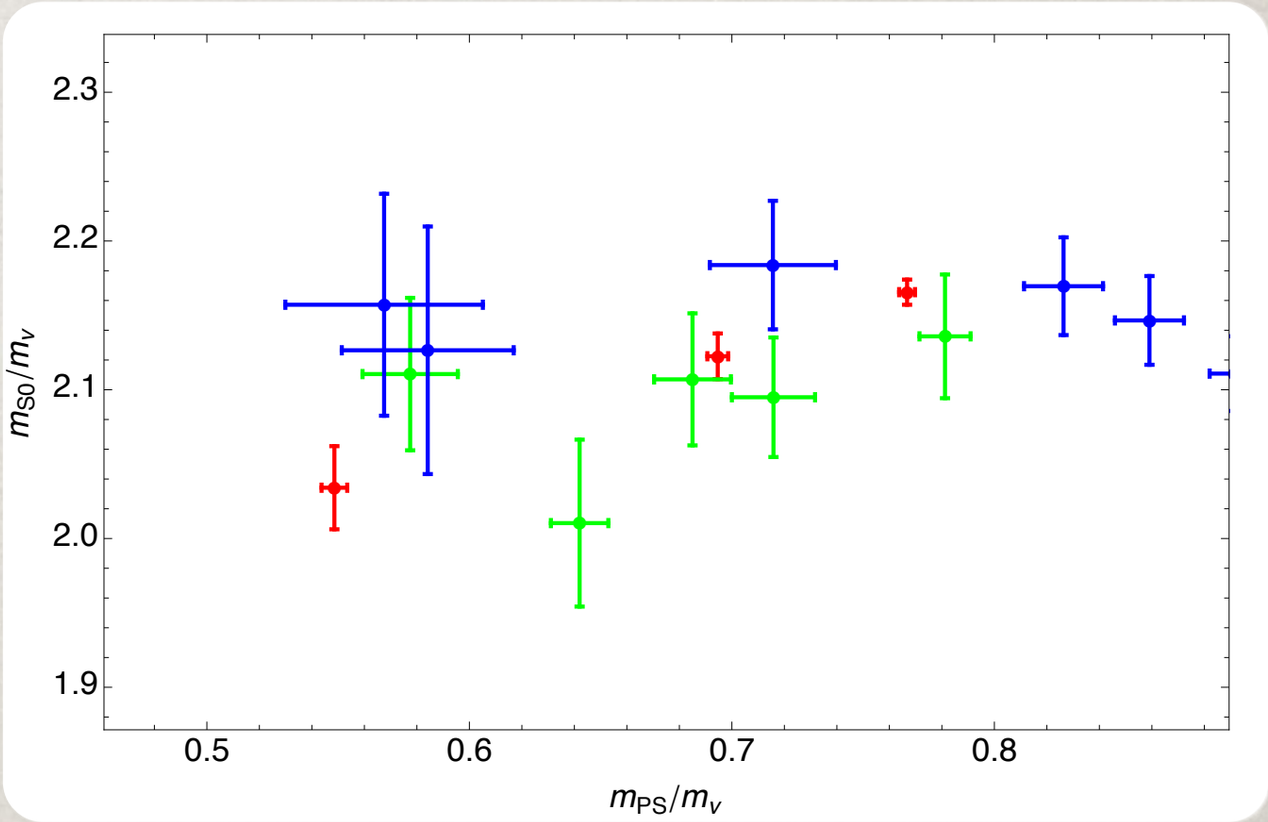


$\beta = 11.5$

Volume effects

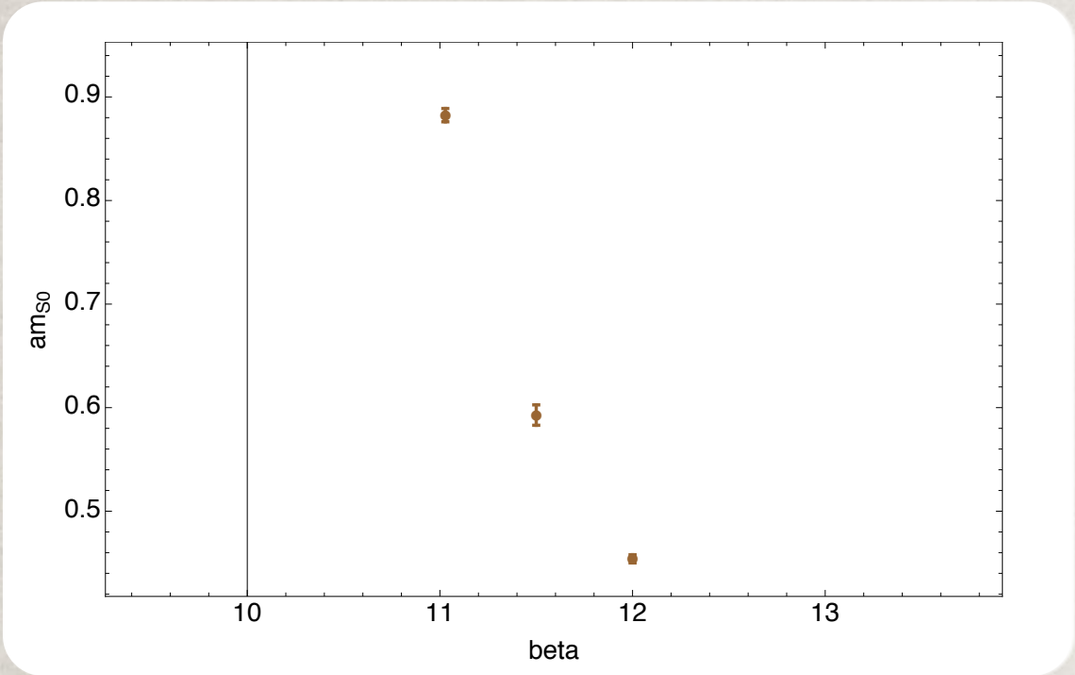


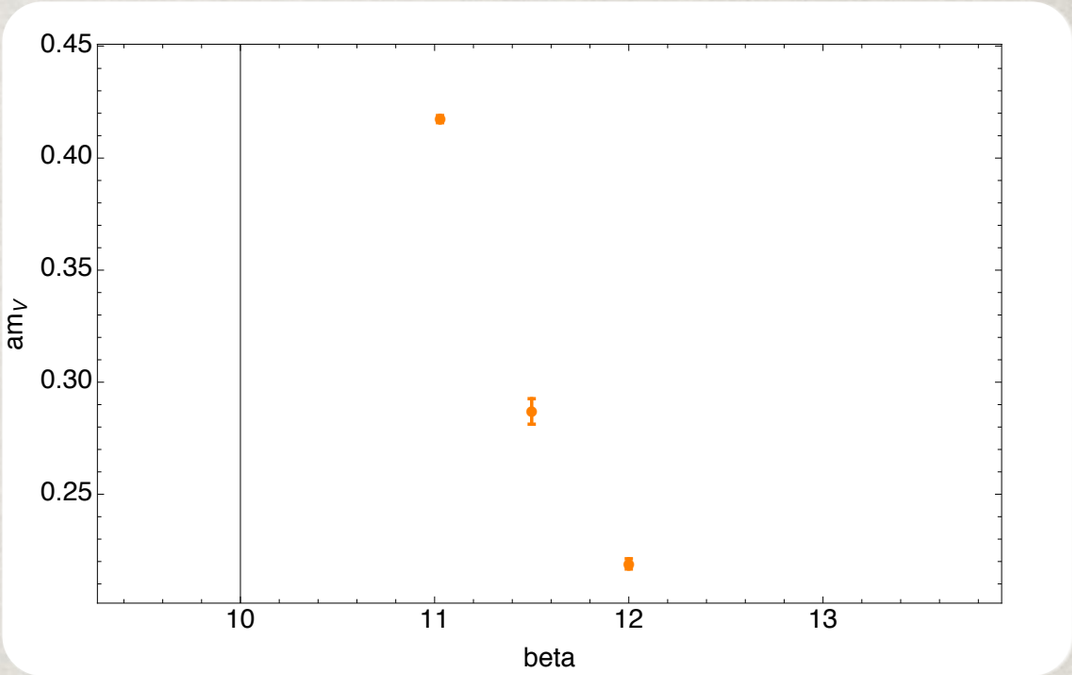


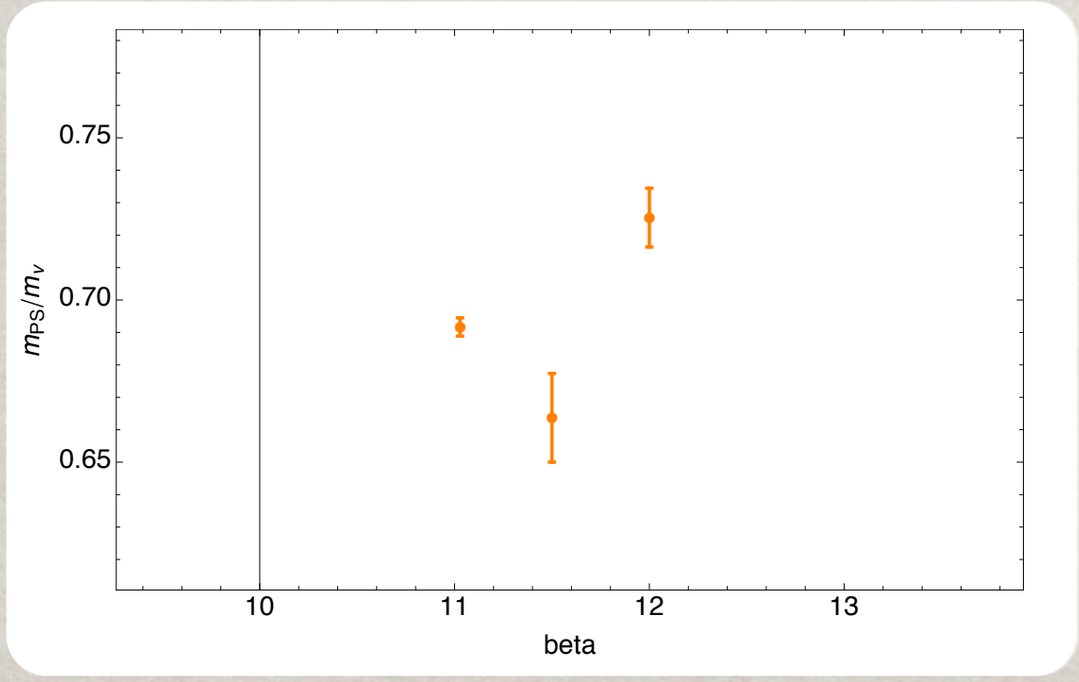


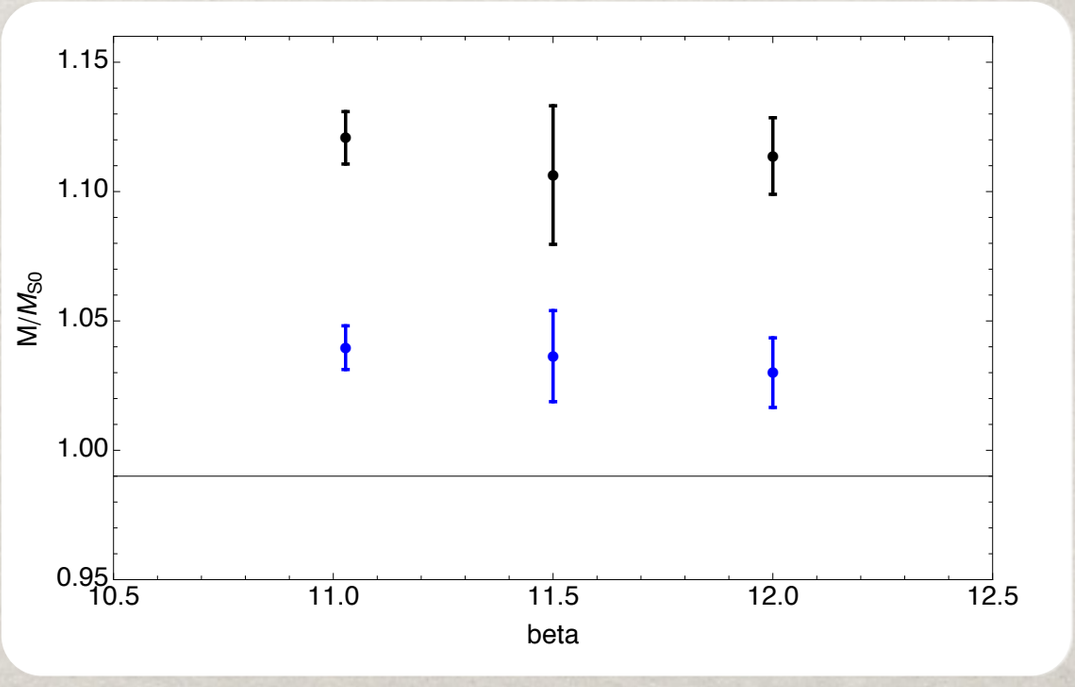
$\beta = 12.0$

Lattice spacing effects



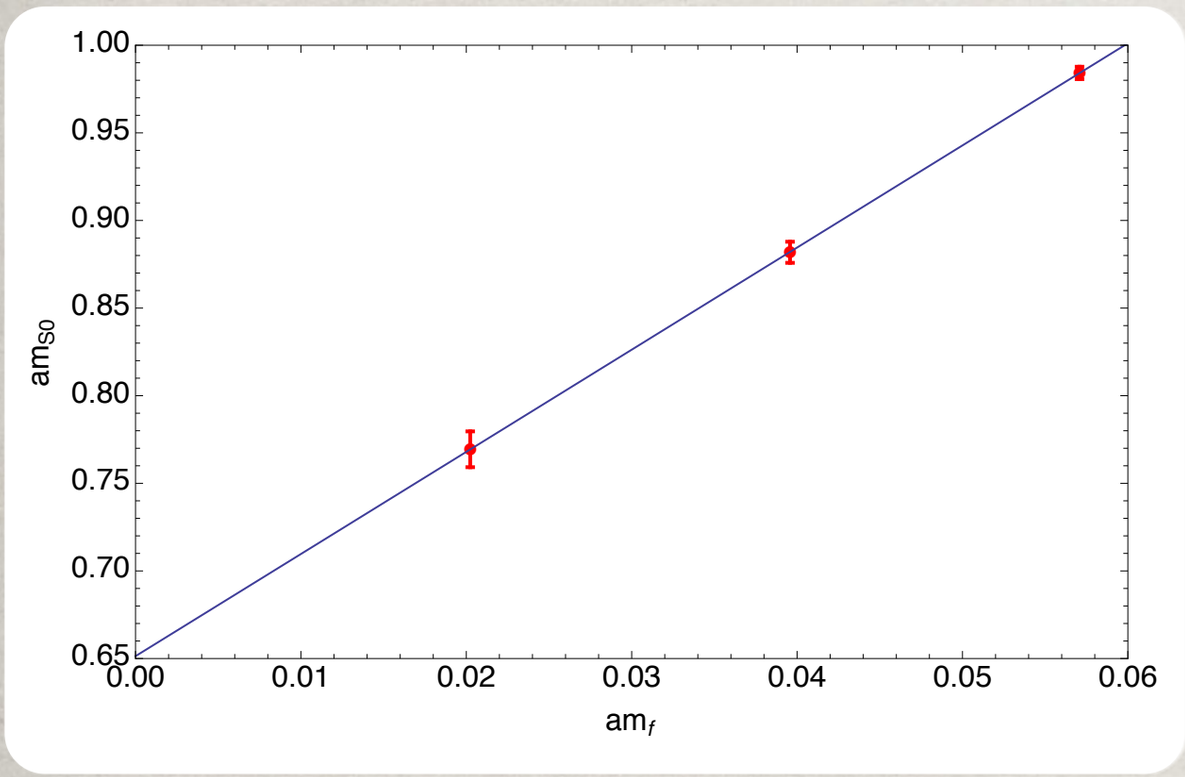




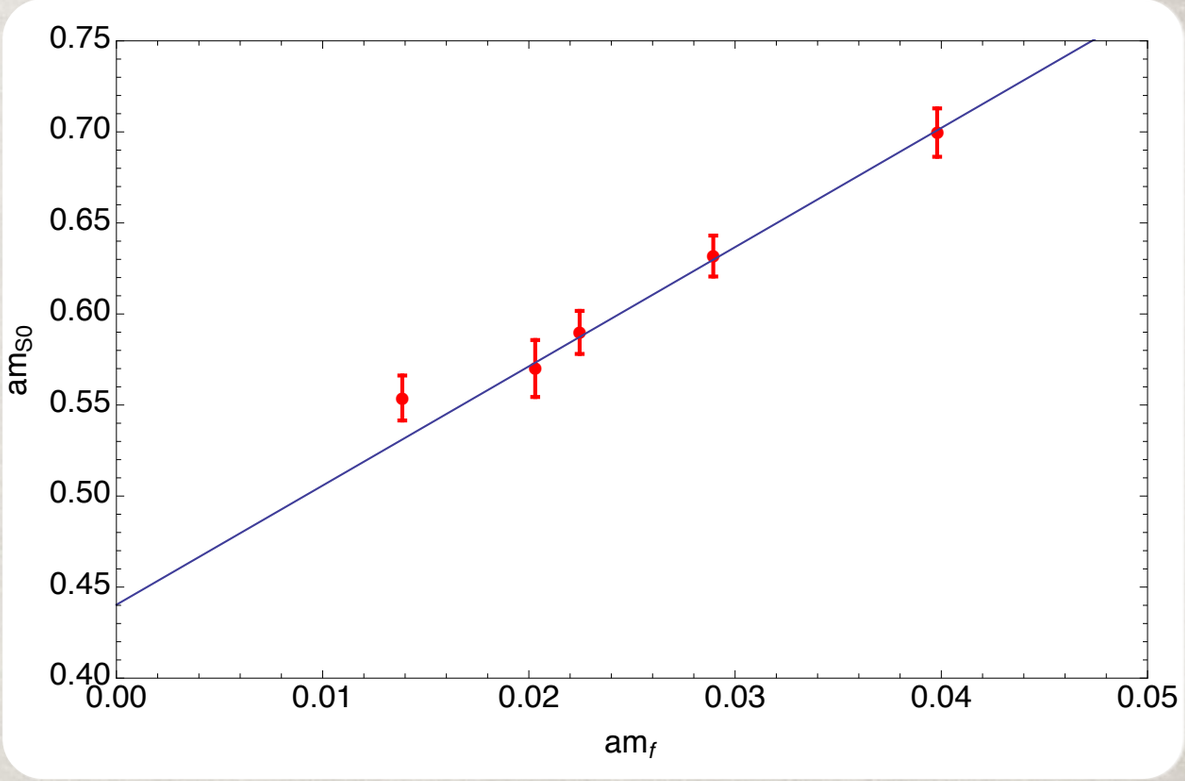


BARYON MASS DERIVATIVE

Coarse lattice spacing



Intermediate lattice spacing

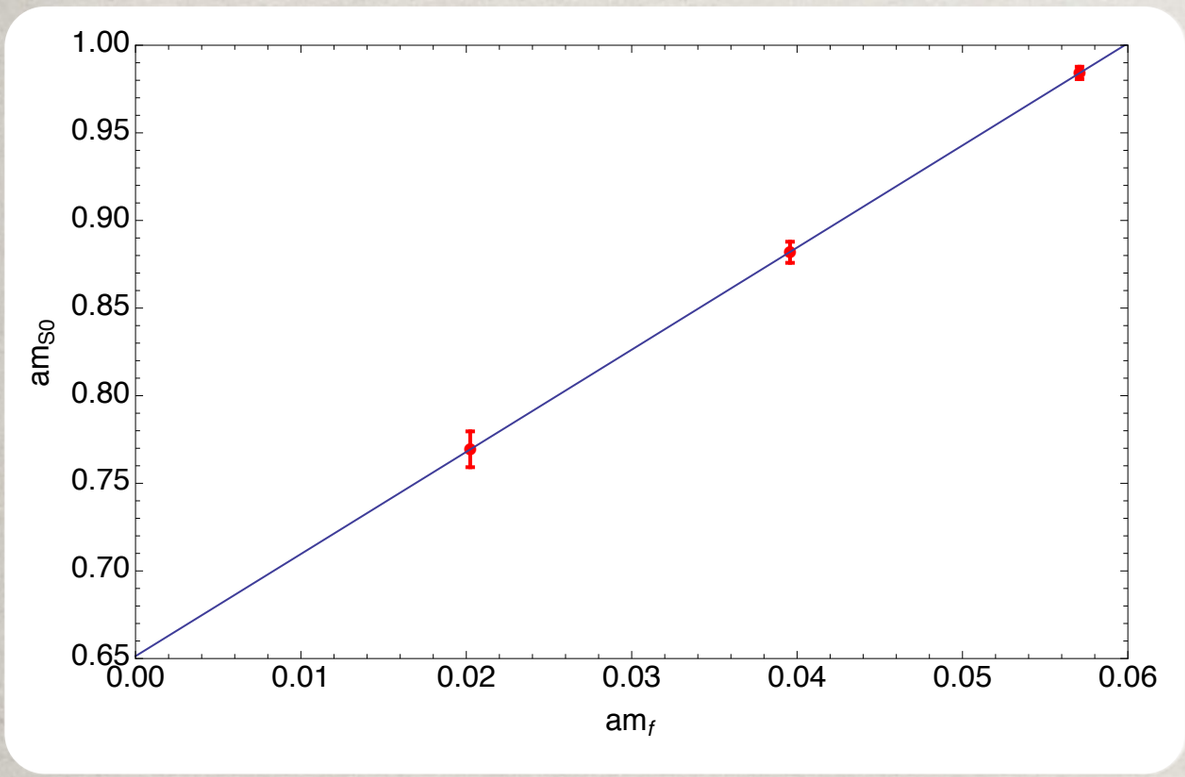


$$\frac{\partial m_B}{\partial m_f} = 5.83(30)$$

$$\frac{\partial m_B}{\partial m_f} = 6.55(91)$$

BARYON MASS DERIVATIVE

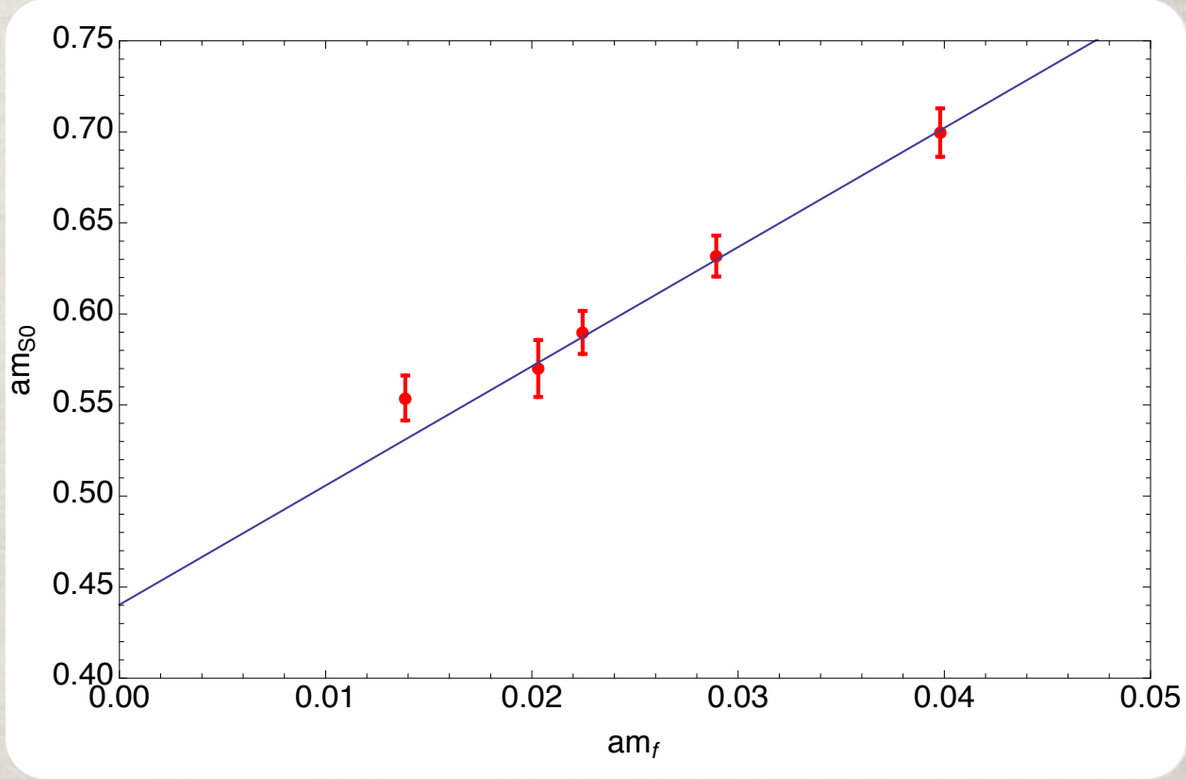
Coarse lattice spacing



$$\frac{m_{PS}}{m_V} = 0.695(4)$$

$$\frac{m_f}{m_B}\frac{\partial m_B}{\partial m_f} = 0.261(14)$$

Intermediate lattice spacing

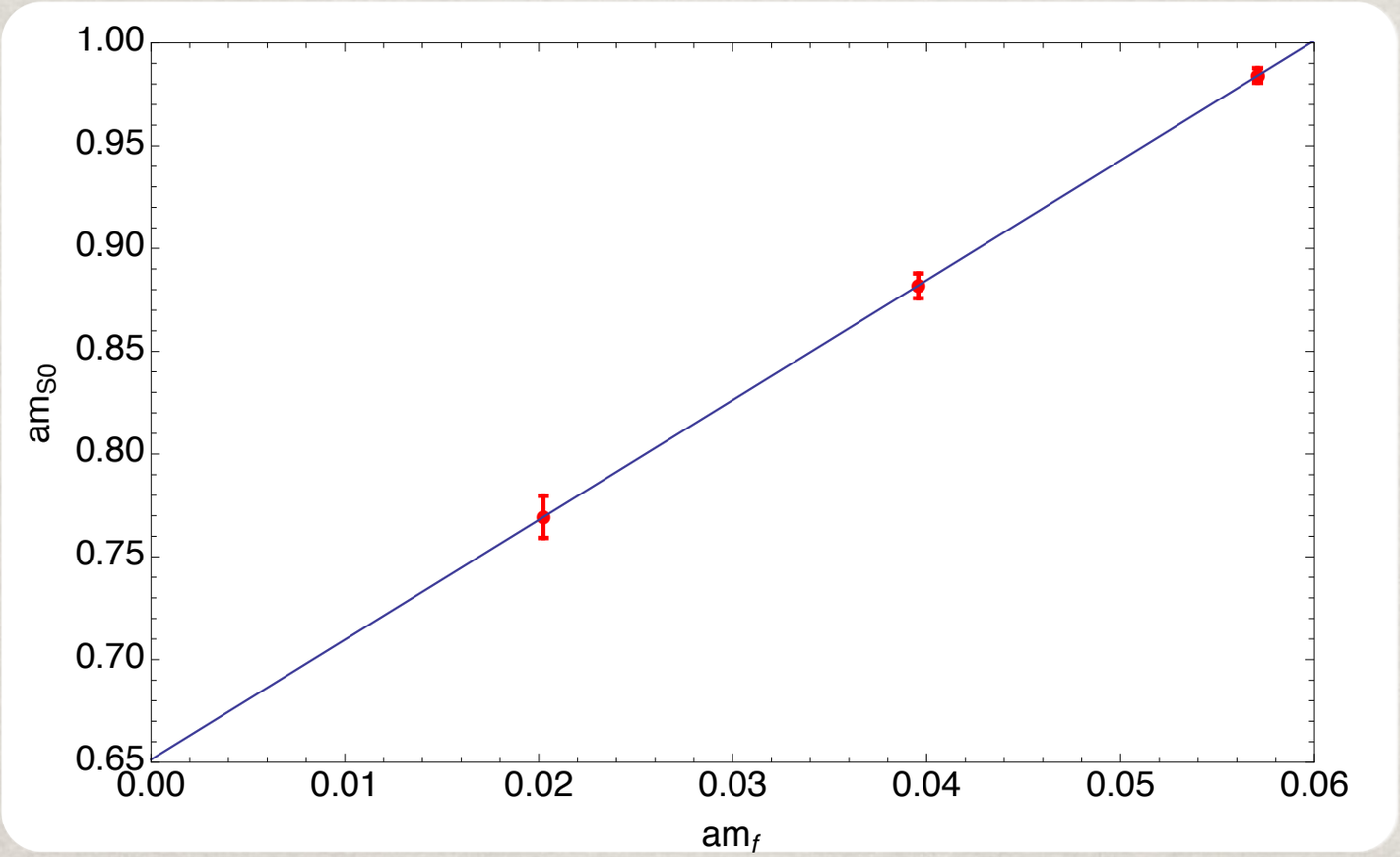


$$\frac{m_{PS}}{m_V} = 0.685(14)$$

$$\frac{m_f}{m_B}\frac{\partial m_B}{\partial m_f} = 0.249(35)$$

BARYON MASS DERIVATIVE

Coarse lattice spacing



$$0.153 \lesssim \frac{m_f}{m_B}\frac{\partial m_B}{\partial m_f} \lesssim 0.338$$

$$\frac{m_{PS}}{m_V} \approx 0.55$$

$$\frac{m_{PS}}{m_V} \approx 0.77$$

Vec. mass suppression?

- Mass Matrix: $\psi_L \equiv \begin{pmatrix} F_1 \\ F_2^\dagger \end{pmatrix}, \psi_R \equiv \begin{pmatrix} F_3 \\ F_4^\dagger \end{pmatrix}$

$$\langle H \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix} \quad \Rightarrow \quad \mathcal{L}_M = (\bar{\psi}_L \bar{\psi}_R) \begin{pmatrix} m_{12} & yv \\ yv & m_{34} \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

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$$m_\pm = \frac{1}{2}\left(m_{12} + m_{34} \pm \sqrt{4y^2v^2 + (m_{34} - m_{12})^2}\right)$$

Lattice Mass

$$\begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

Lattice Fermion

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Lattice Mass

Lattice Fermion

$$(\bar{\psi}_L \bar{\psi}_R) \begin{pmatrix} 0 & yh \\ yh & 0 \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \quad \Rightarrow \quad yh\ (\bar{\psi}_- \bar{\psi}_+) \begin{pmatrix} 2\cos\theta\sin\theta & \cos^2\theta - \sin^2\theta \\ \cos^2\theta - \sin^2\theta & -2\cos\theta\sin\theta \end{pmatrix} \begin{pmatrix} \psi_- \\ \psi_+ \end{pmatrix}$$

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$$y_f = 2y\cos\theta\sin\theta \qquad y_f \to \begin{cases} y & 2yv \gg (m_{34} - m_{12}) \\ \frac{2y^2v}{(m_{34} - m_{12})} & (m_{34} - m_{12}) \gg 2yv \end{cases}$$

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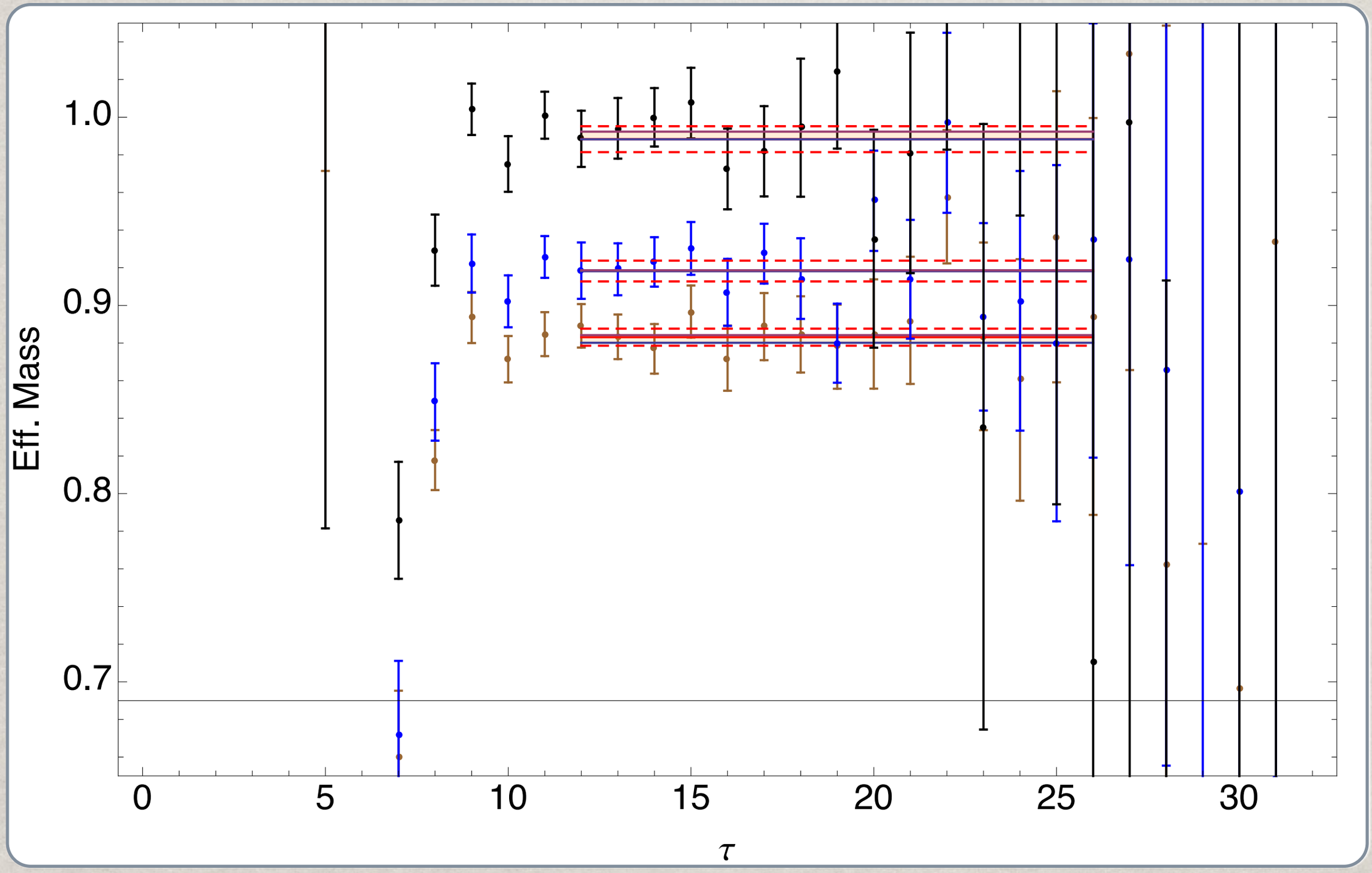
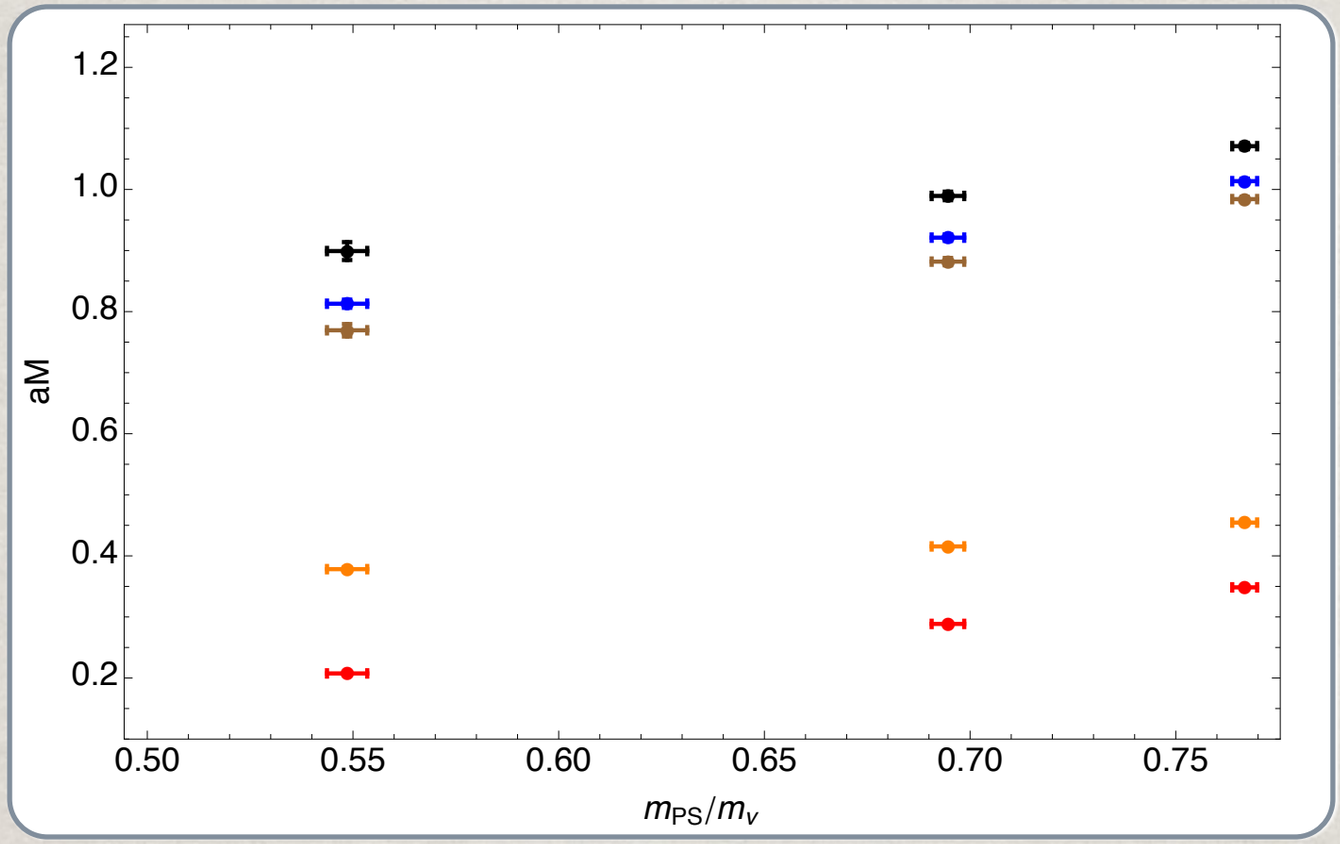
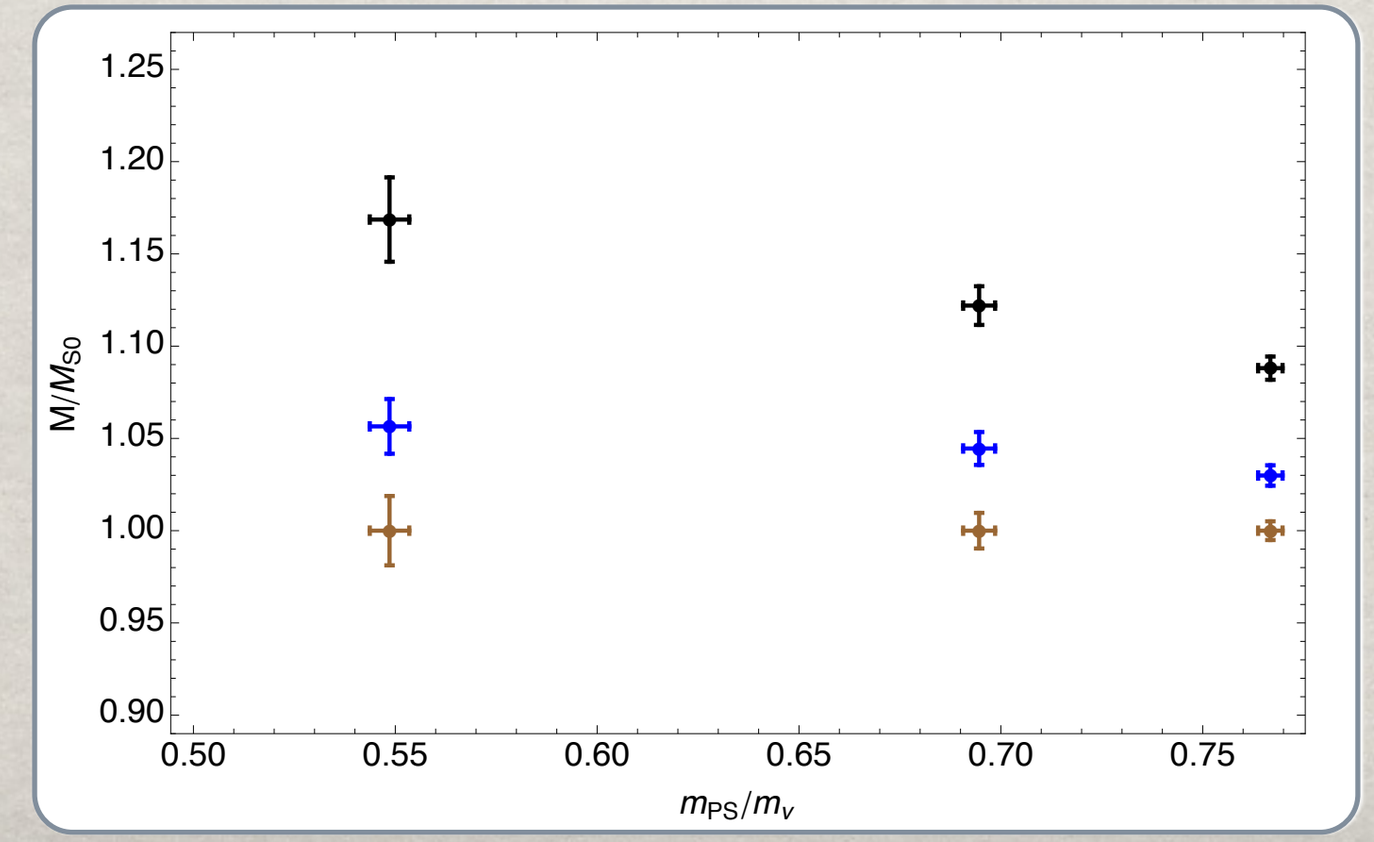
Suppression

Effective Mass Example

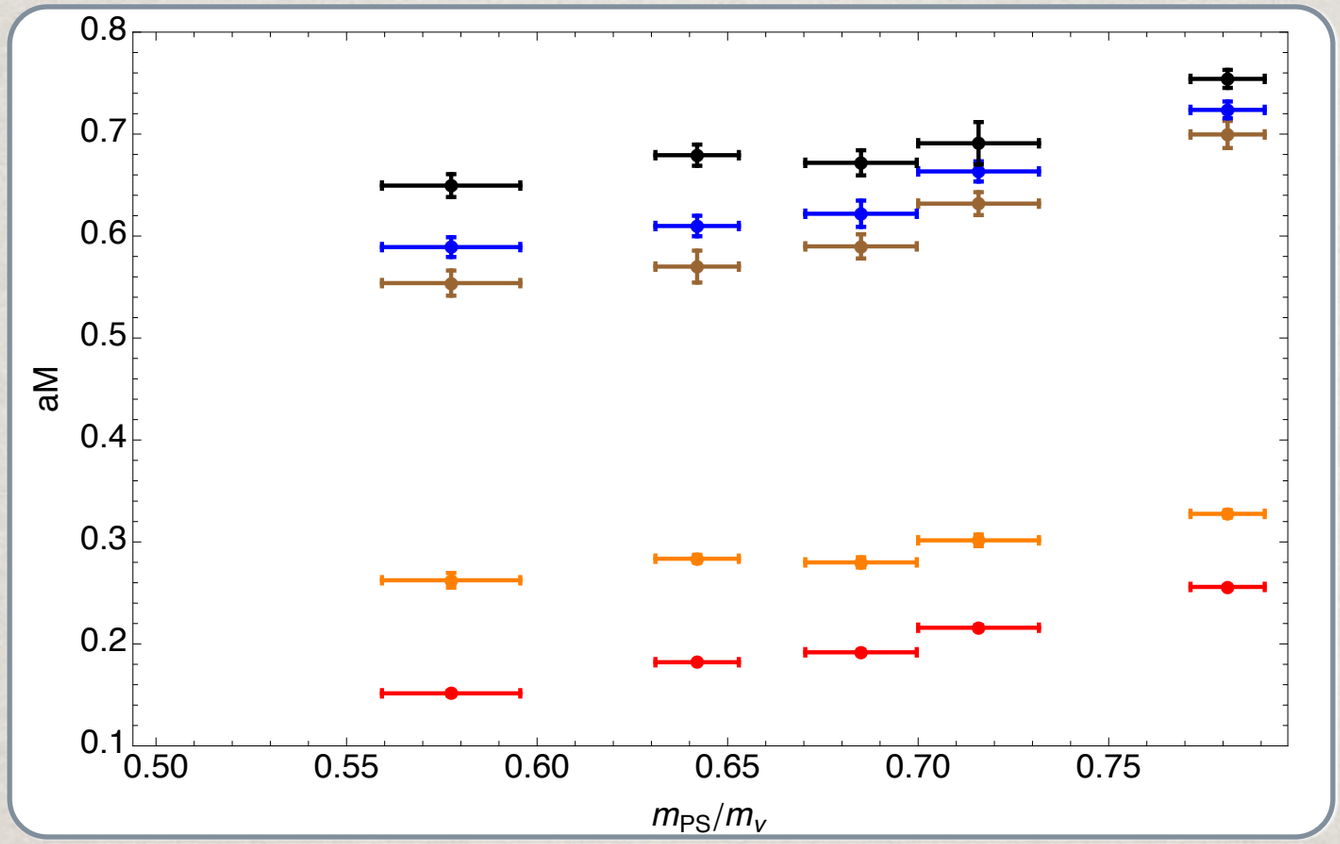


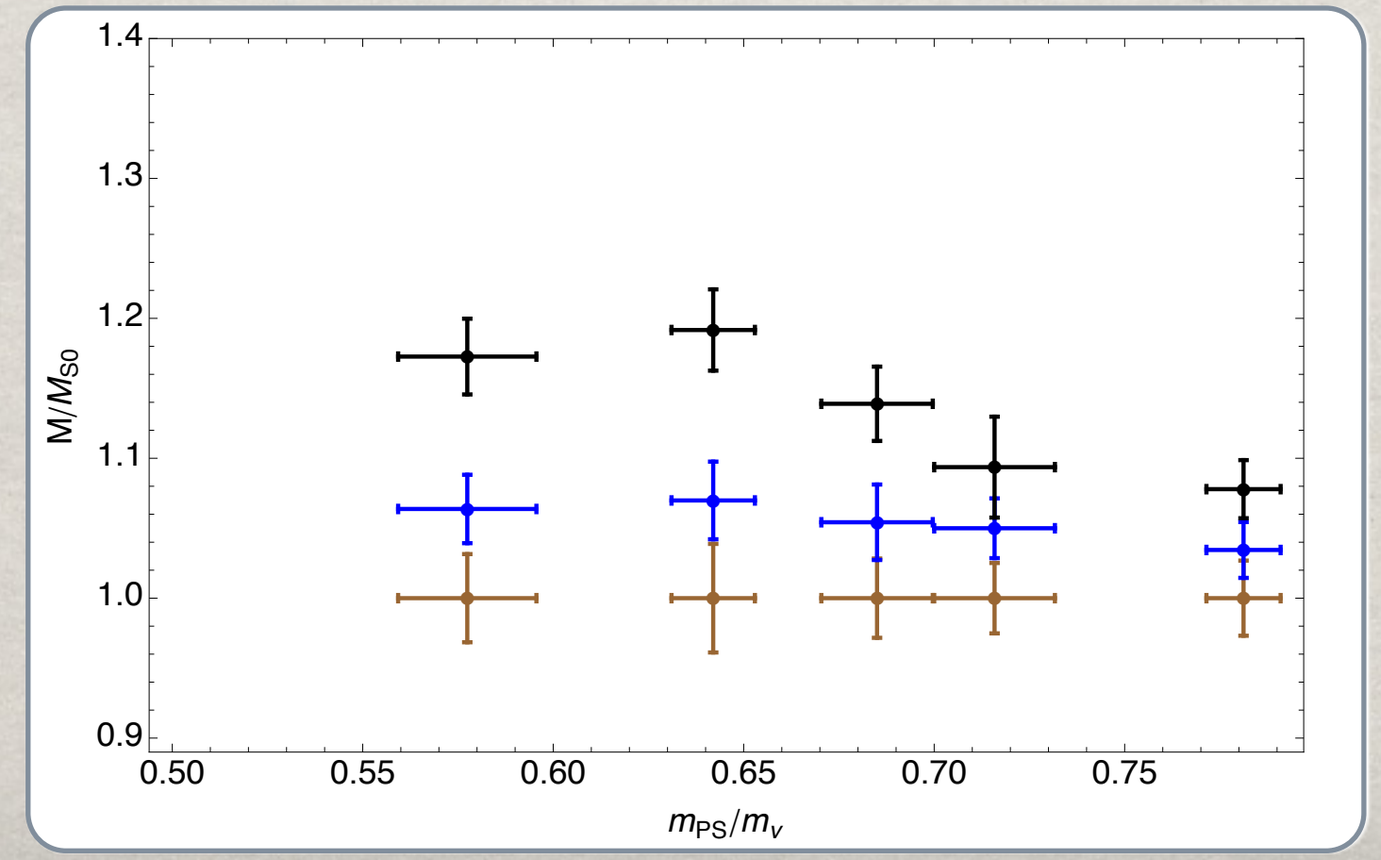
Coarse lattice spacing





Intermed. lattice spacing





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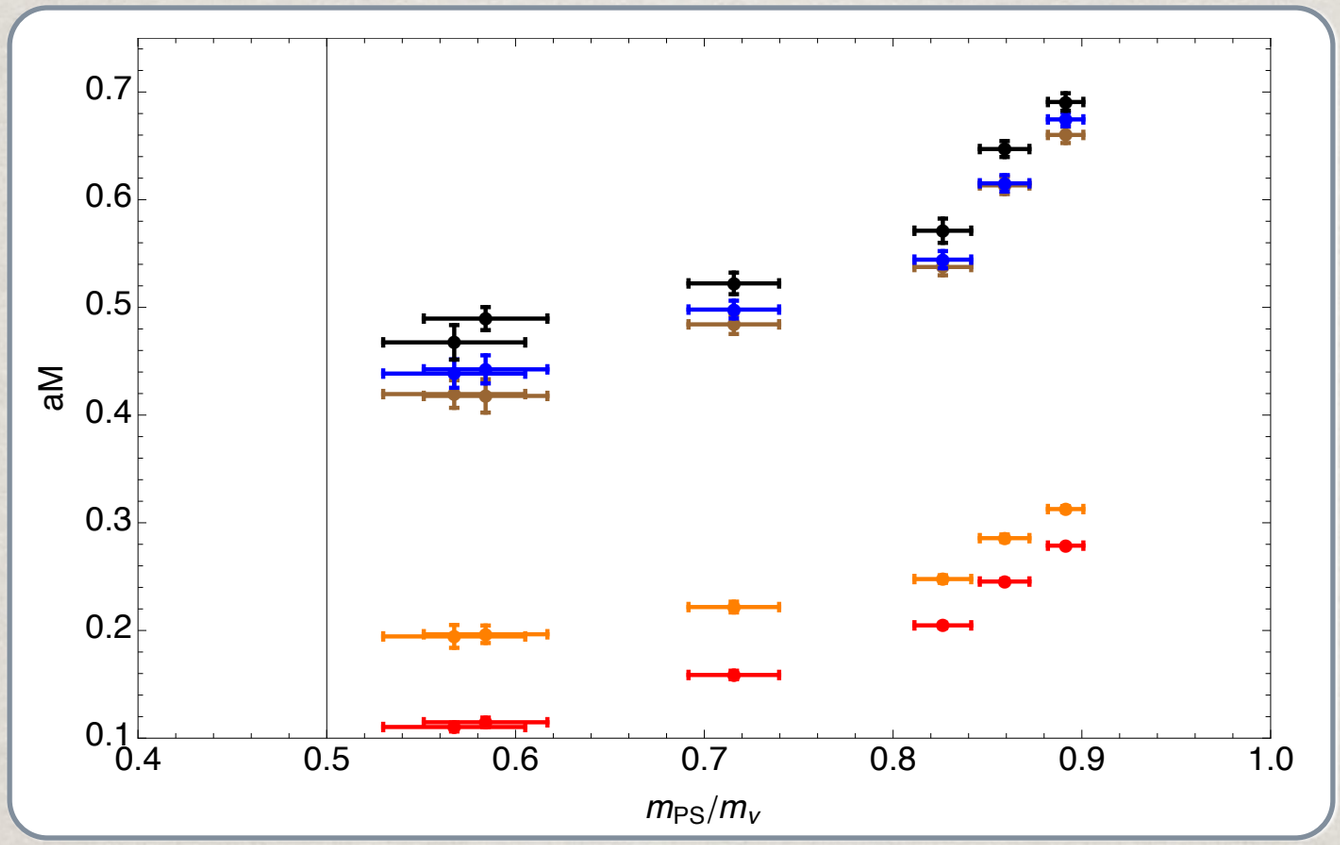

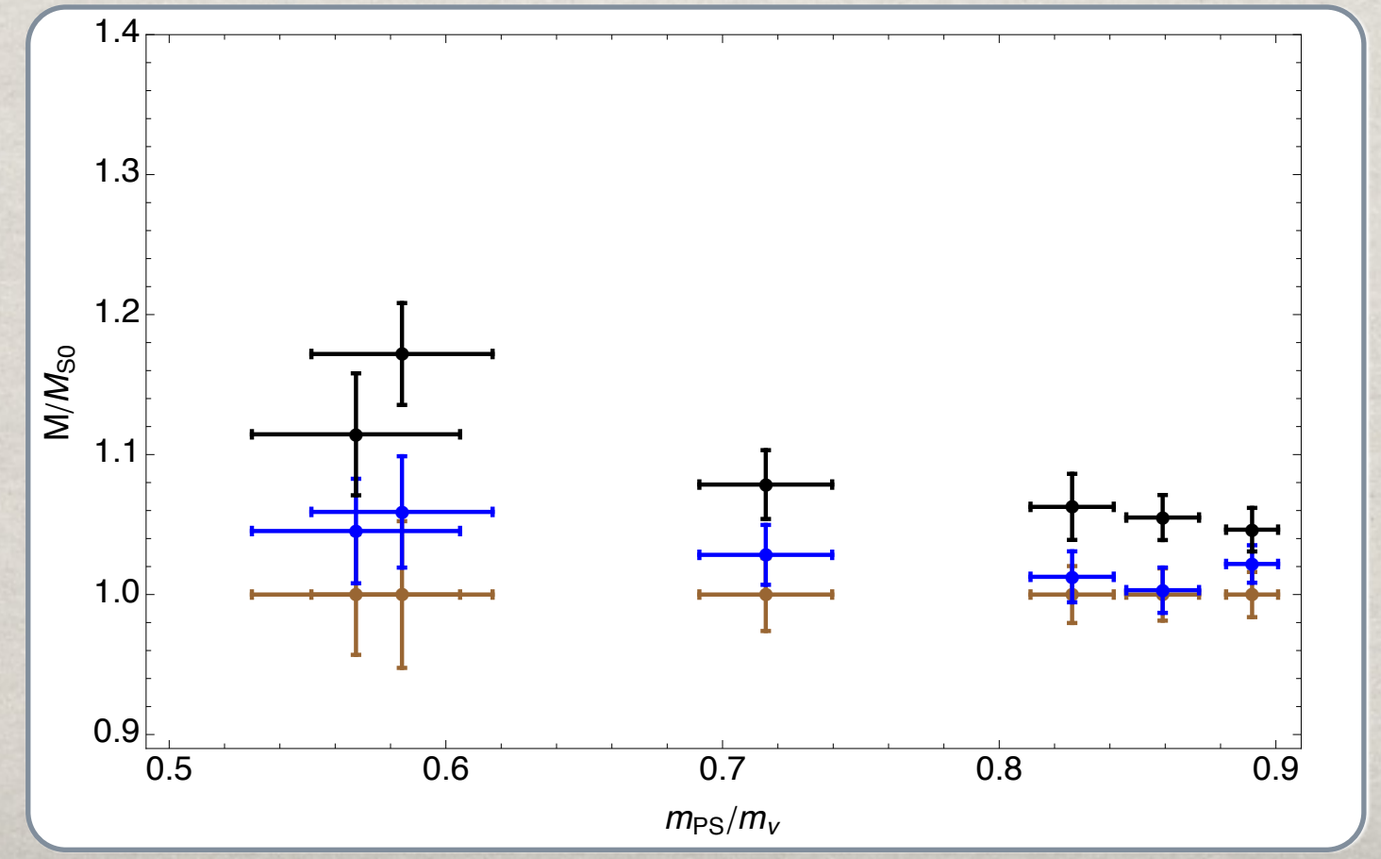

Tight Constraints?

- Assume a Dirac particle with net Z-boson charge

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

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

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!

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!

PARTICULAR MODEL

- Four Dirac Flavors with vector-like masses

Field	$\mathrm{SU}(N)_D$	$(\mathrm{SU}(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
F_3^u	$\mathbf{N}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_3^d	$\mathbf{N}$	$(\mathbf{1}, -1/2)$	$-1/2$
F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

Kinetic:

$$\mathcal{L}_{\mathcal{D}} = iF_1^\dagger \bar{\sigma}^\mu \nabla_{\mu,L} F_1 + iF_2^\dagger \bar{\sigma}^\mu \nabla^*_{\mu,L} F_2 + iF_3^{u\dagger} \bar{\sigma}^\mu \nabla_{\mu,R} F_3^{u\dagger} + iF_3^{d\dagger} \bar{\sigma}^\mu \nabla_{\mu,R} F_3^{d\dagger}$$
$$+ iF_4^{u\dagger} \bar{\sigma}^\mu \nabla^*_{\mu,R} F_4^{u\dagger} + iF_4^{d\dagger} \bar{\sigma}^\mu \nabla^*_{\mu,R} F_4^{d\dagger}$$

$$\nabla_L^\mu = \partial^\mu + igA^{a,\mu}(\tau_L^a/2)$$
$$(\nabla_L^\mu)^* = \partial^\mu - igA^{a,\mu}(\tau_L^a/2)$$
$$\nabla_R^\mu = \partial^\mu + ig' B^\mu(\tau_R^3/2)$$
$$(\nabla_R^\mu)^* = \partial^\mu - ig' B^\mu(\tau_R^3/2)$$

Left/Right Different

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F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

Masses:

Chiral

$$\mathcal{L}_{\mathcal{M}} = - y_{14}^u \epsilon_{ij} F_1^i H^j F_4^d - y_{14}^d \delta_{ij} F_1^i (H^\dagger)^j F_4^u + y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d + y_{23}^u \delta_{ij} F_2^i (H^\dagger)^j F_3^u$$
$$- M_{12} \epsilon_{ij} F_1^i F_2^j + M_{34}^u F_3^u F_4^d - M_{34}^d F_3^d F_4^u + \text{h.c.}$$

Vector-like