Composite nature of Dark Matter

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CP^3-Origins, Danish IAS, Univ. Southern Denmark

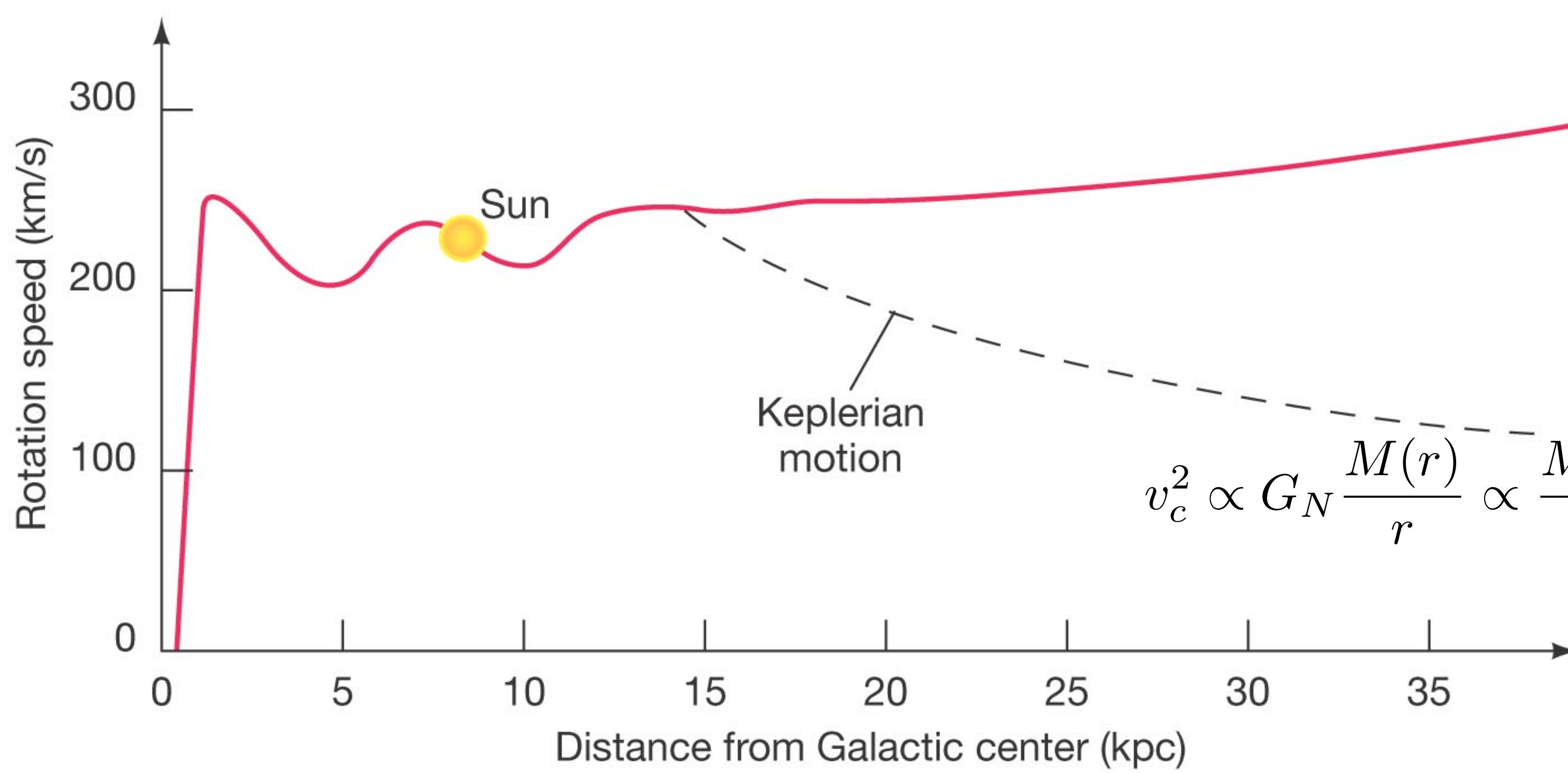
LME - BNL Decemer 2013

CP^3 Origins

Cosmology & Particle Physics

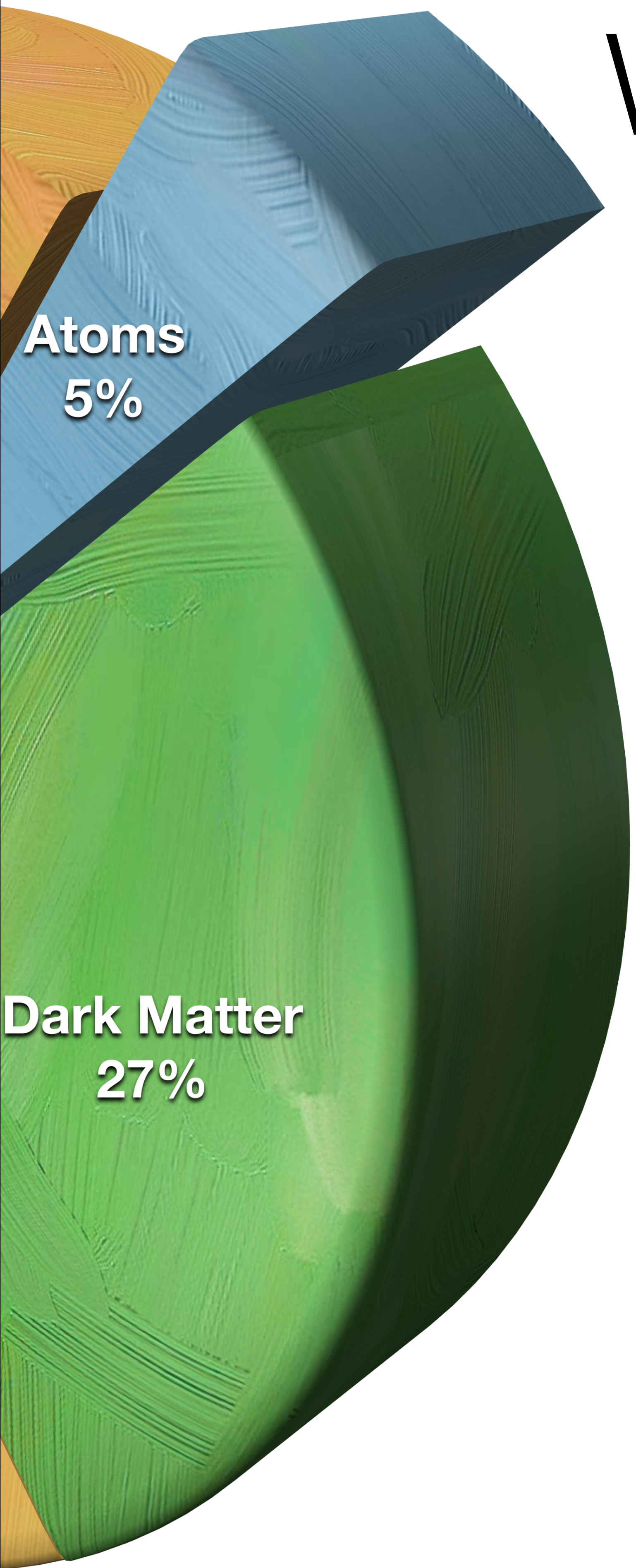
Dark matter

- Interacts at least gravitationally
- Electrically neutral & decoupled from primordial plasma
- Leads to density profile for galaxy rotation curves
- “if” cold: clusters & leads to structure formation
- Either stable or very long lived

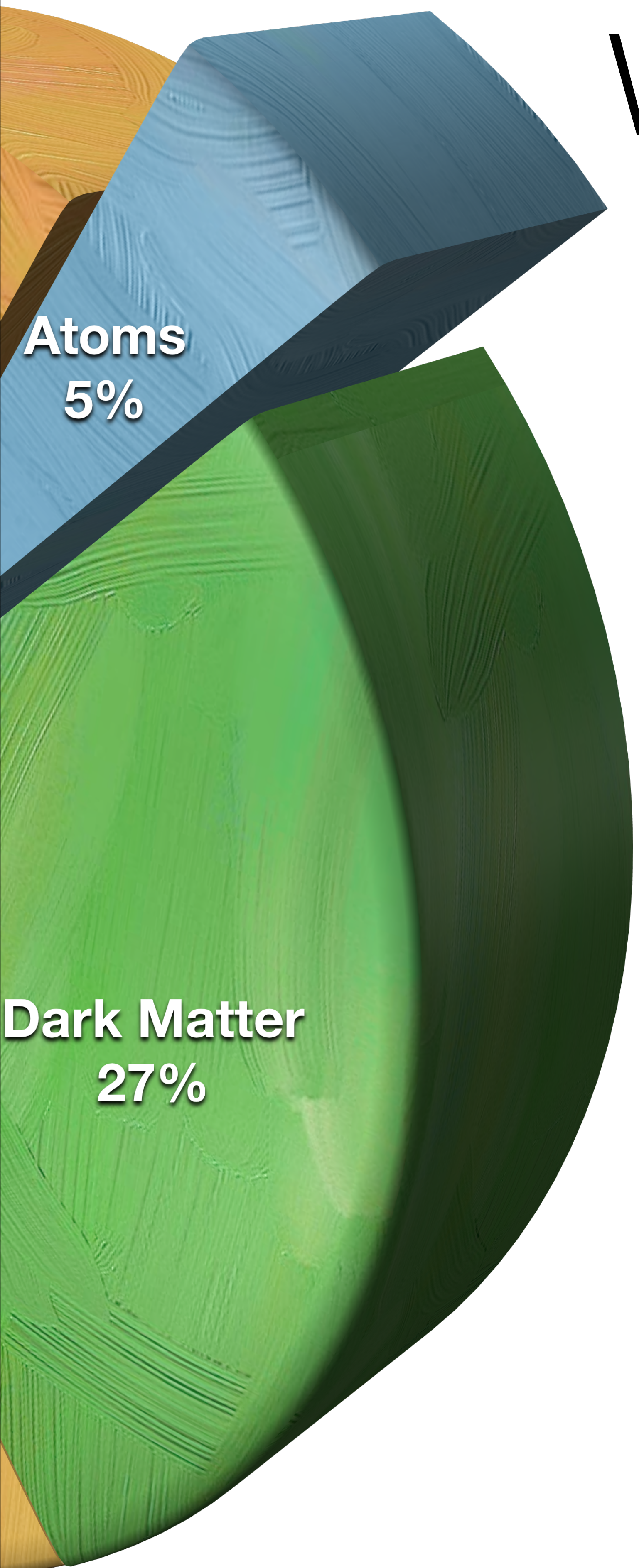


$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{\mathrm{tot}}}{r}$$

What makes dark matter ?



Atoms: 3 forces and many fund. particles



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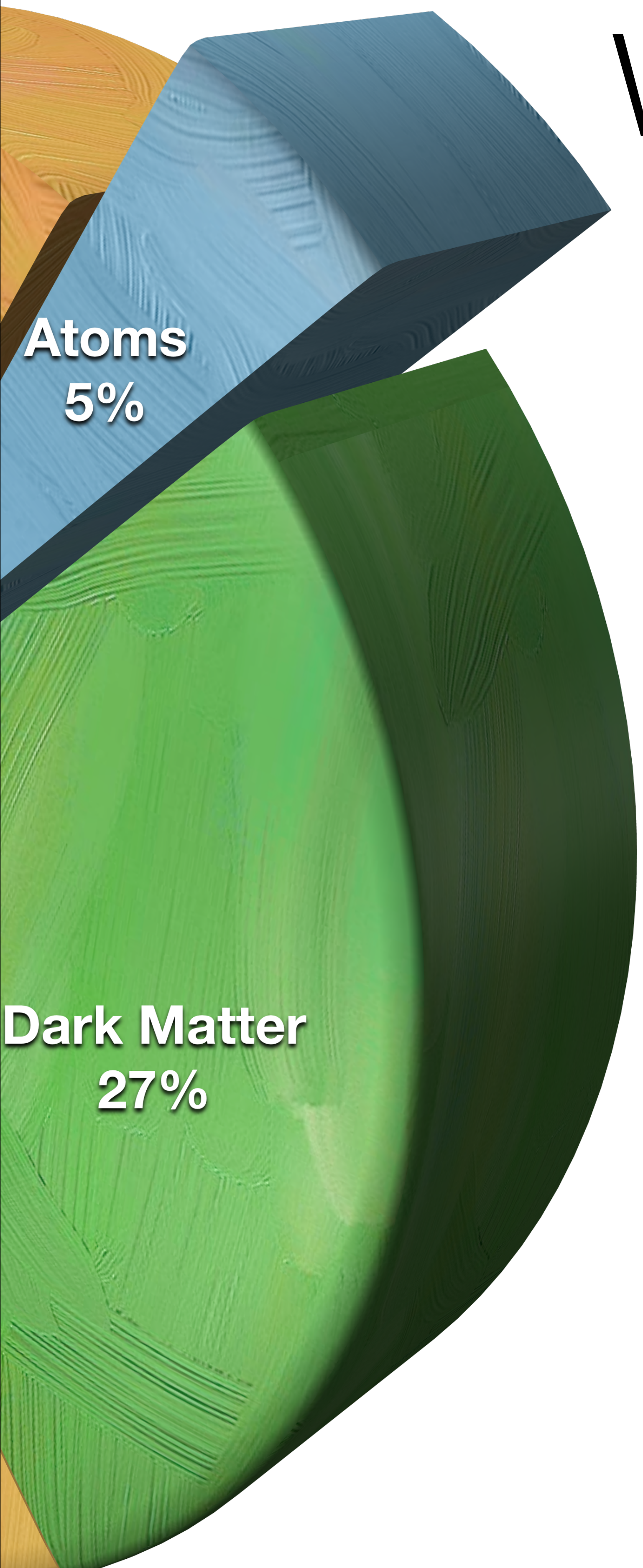
DM oversimplification

DM Particle



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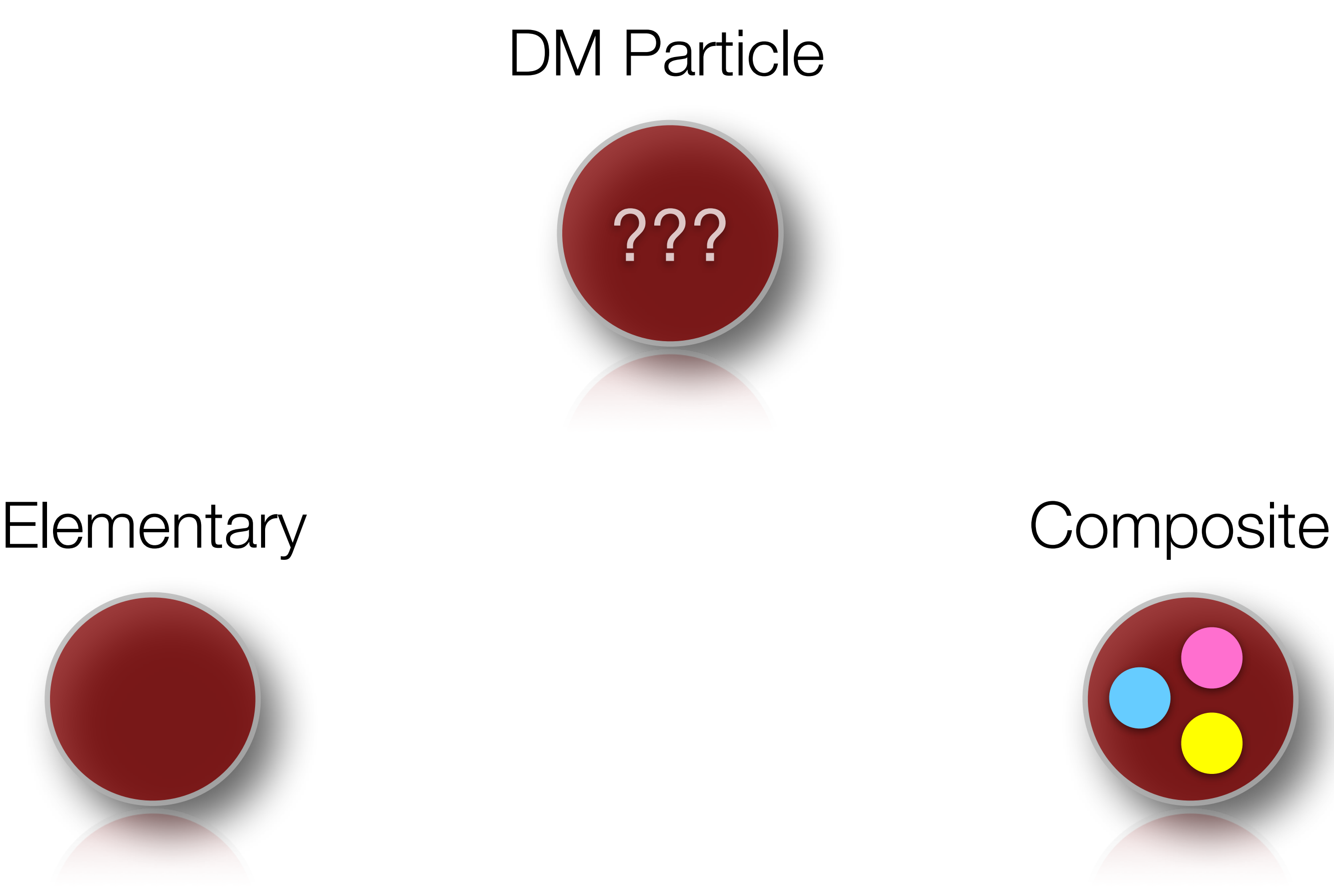

Incomplete DM list

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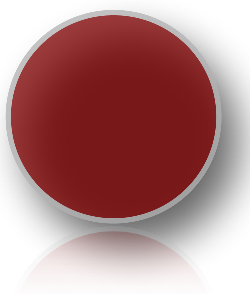
Elementary



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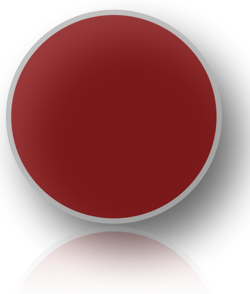

- Unnatural, classical conformality, delayed naturality
- Perturbative natural conformality Antipin, Mojaza, Sannino 13
- Natural extensions [Susy,..]
- Axions
- ...

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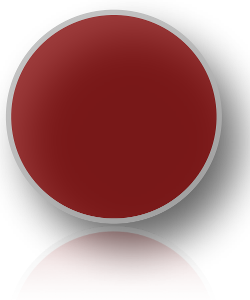

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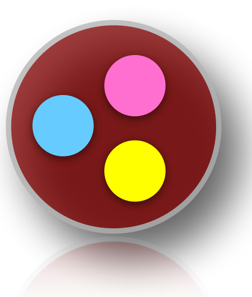

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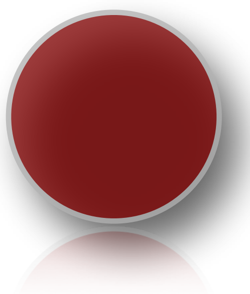

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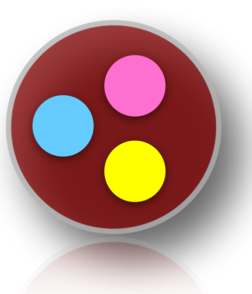

- New QCD-like sectors added by hand
- Composite DM from composite EW [Technicolor,..]
- Composite axions
- ...

In practice

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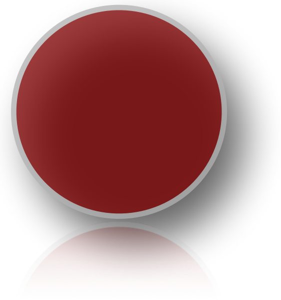
Elementary



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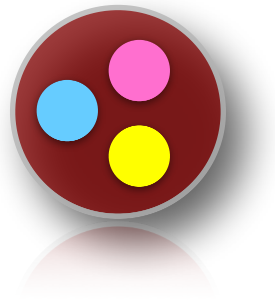

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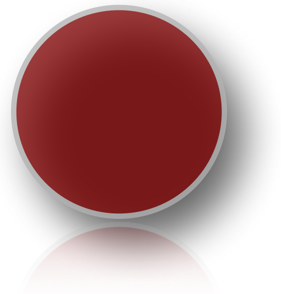

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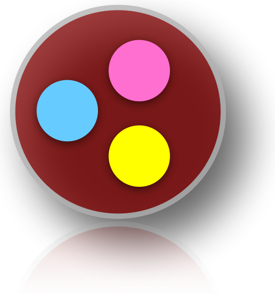

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In practice

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In practice

- Perturbative: We can compute
- Nonperturbative:
  - Effective lagrangians
  - First principle lattice simulations

Building composite DM

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- Gauge theories with fermionic matter

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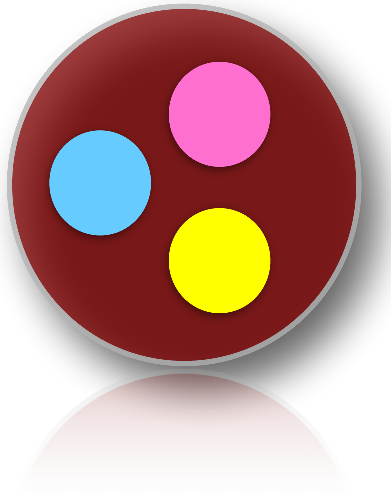
Building composite DM



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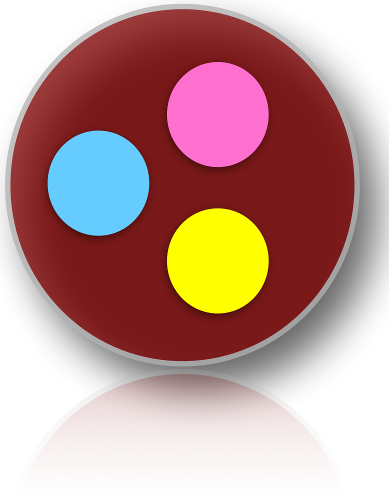

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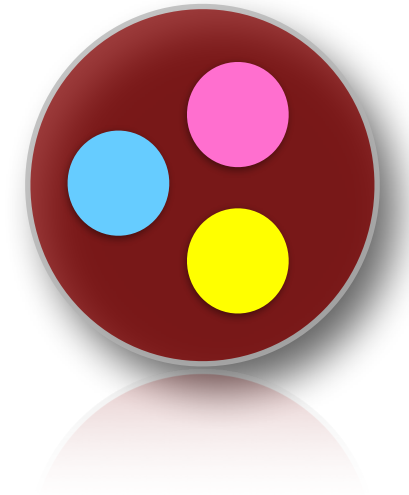

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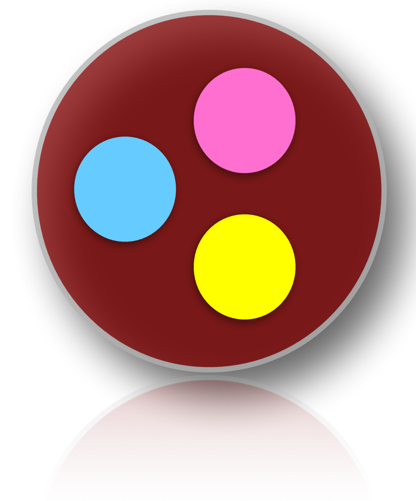

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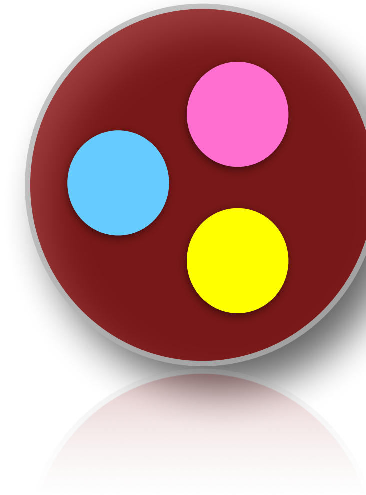

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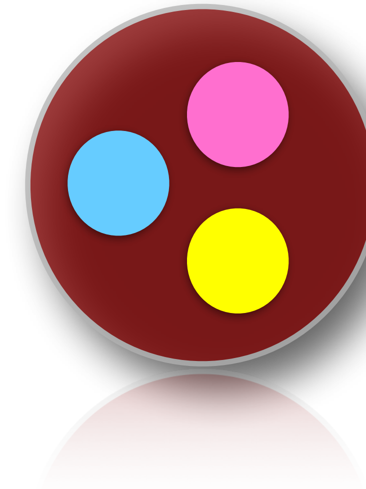

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Solve new strong dynamics!

(2-flavors) QCD - like

- Number of odd colors > 3
- Complex representations
- If below conformal window

$$SU(2) \times SU(2) \to SU(2)$$

- In Technicolor-like embedding the TC-neutron = DM (1- 3 TeV)
- Different flavors/SM embedding more possibilities

SU(2) = Sp(2) - Template

Appelquist, Sannino, 98, 99

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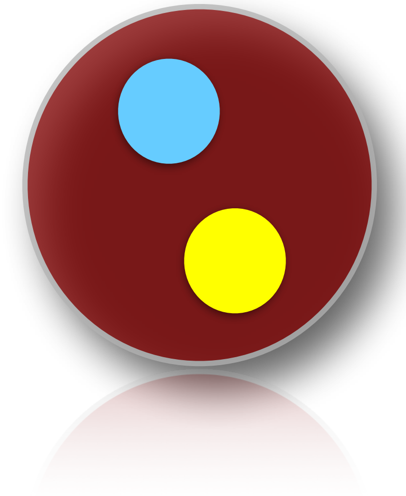
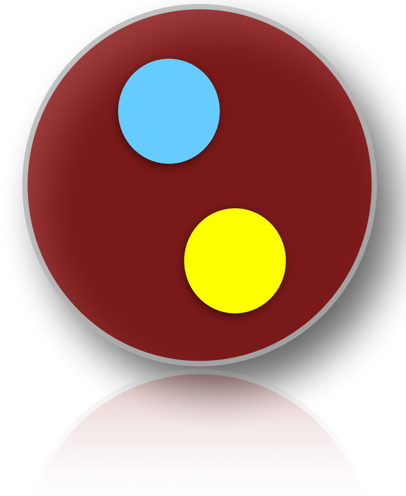
Sp(2)



$$\mathcal{L} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + \overline{Q}(i\gamma^{\mu}D_{\mu})Q$$

Sp(2)



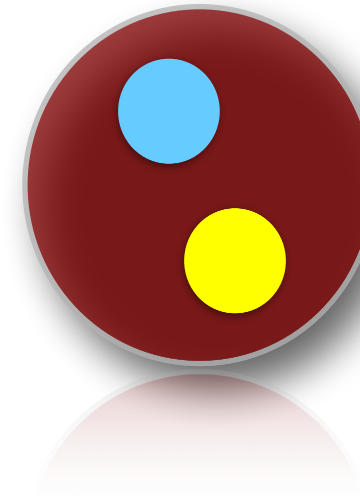
$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \overline{Q}(i\gamma^\mu D_\mu) Q$$

$$Q = \left(\begin{array}{c} U_L \\ D_L \\ -i\sigma^2 C \overline{U}_R^T \\ -i\sigma^2 C \overline{D}_R^T \end{array} \right)$$

- Act. invariant under SU(4) transf.

$$Q \to \left(1 + i \sum_{k=1}^{15} \alpha^k T^k \right) Q$$

Sp(2)



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$$Q \to \left(1 + i \sum_{k=1}^{15} \alpha^k T^k \right) Q$$

- Mass term respects Sp(4) with 10 generators

$$\delta\mathcal{L} = \frac{m}{2} Q^T (-i\sigma^2) C\, EQ + \mathrm{h.c.}$$

$$E = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

Theoretical expectations

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- @ m=0

$$\langle Q^T(-i\sigma^2)C\,EQ\rangle = \langle \bar{U}U + \bar{D}D\rangle = \Lambda^3 \neq 0$$

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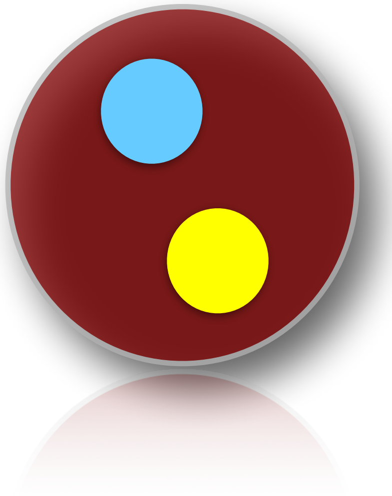
- SU(4) can break spontaneously to Sp(4)
- Composite spectrum are representations of Sp(4)
- 5 Goldstones

Hadronic operators



- Mesons

$$\mathcal{O}^{(\Gamma)}_{\overline{U}D} \equiv \overline{U}(x)\Gamma D(x) \ ,$$

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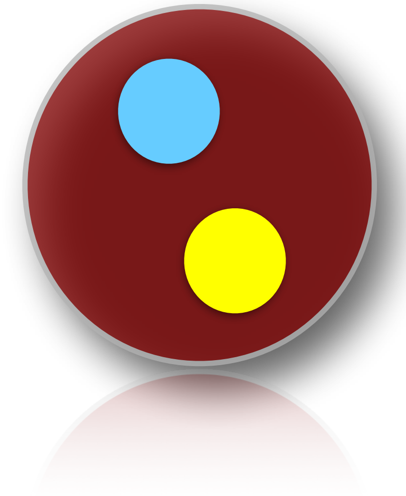
$$\Gamma = 1, \gamma^5, \gamma^\mu, ...$$

Hadronic operators



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- Baryons (diquarks)

$$\mathcal{O}^{(\Gamma)}_{UD} \equiv U^T(x)(-i\sigma^2)C\Gamma D(x) \; ,$$
$$\mathcal{O}^{(\Gamma)}_{DU} \equiv D^T(x)(-i\sigma^2)C\Gamma U(x) \; ,$$
$$\mathcal{O}^{(\Gamma)}_{UU\pm DD} \equiv \frac{1}{\sqrt{2}}\left(U^T(x)(-i\sigma^2 C)\Gamma U(x) \pm D^T(x)(-i\sigma^2 C)\Gamma D(x)\right)$$

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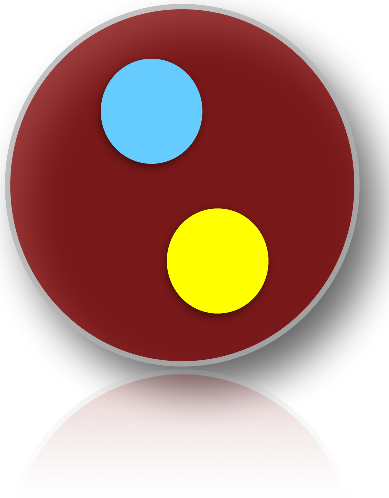
Facts



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J\left(\mathcal{O}^{(\Gamma)}_{UD}\right) &= J\left(\mathcal{O}^{(\Gamma)}_{\overline{U}D}\right), \\
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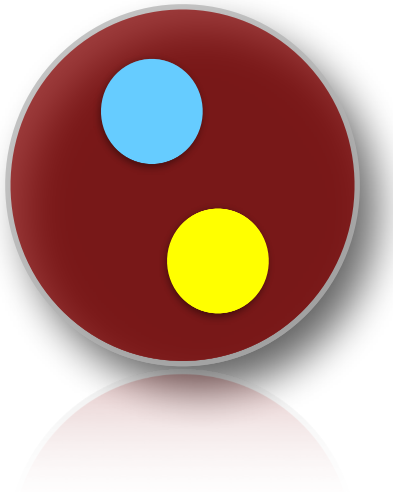

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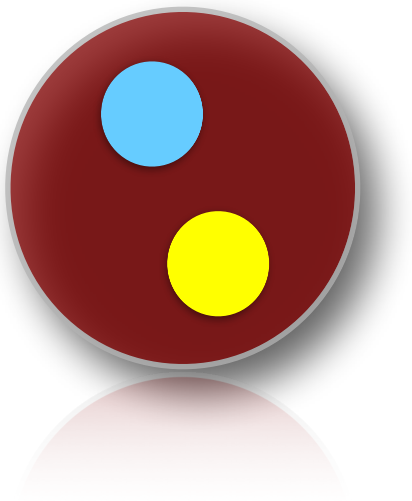
pseudoscalar $\quad \Pi^+ \quad \Pi^-$



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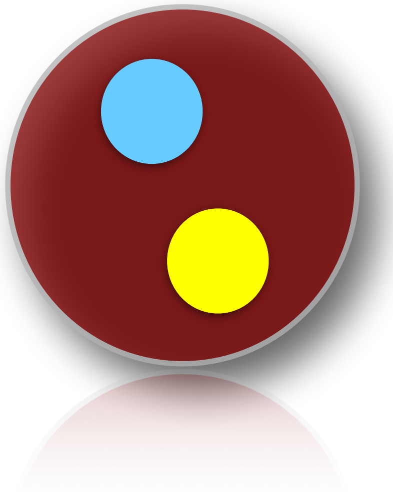
pseudoscalar	Π^+	Π^-
scalar baryon	Π_{UD}	$\Pi_{\overline{UD}}$



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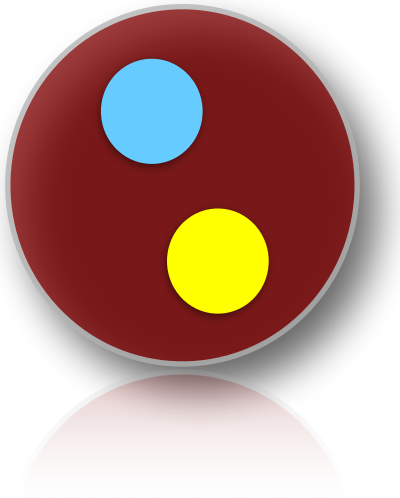
Minimal TC Model & DM



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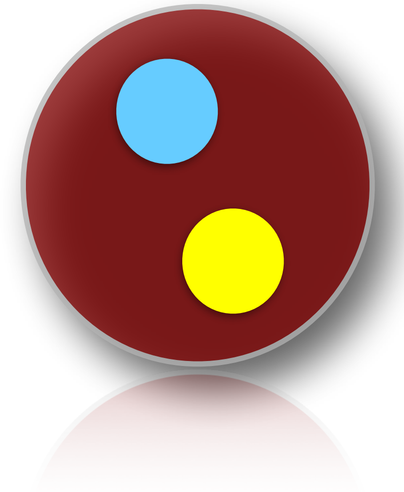

- Gauge $SU_L(2) x U_Y(1)$ in $SU(4)$

$$f_\Pi \simeq 246 \text{ GeV}$$

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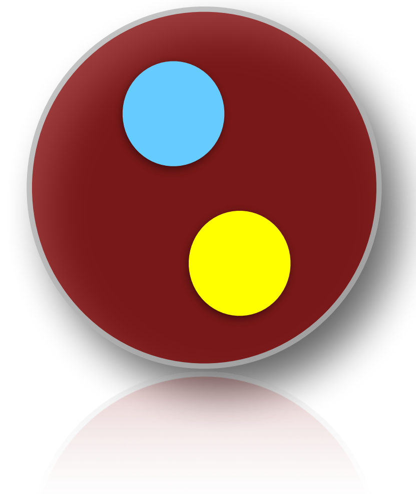

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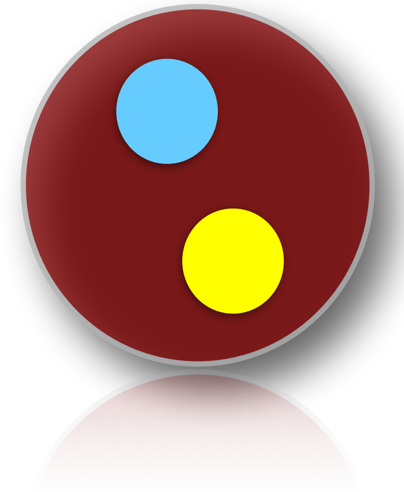

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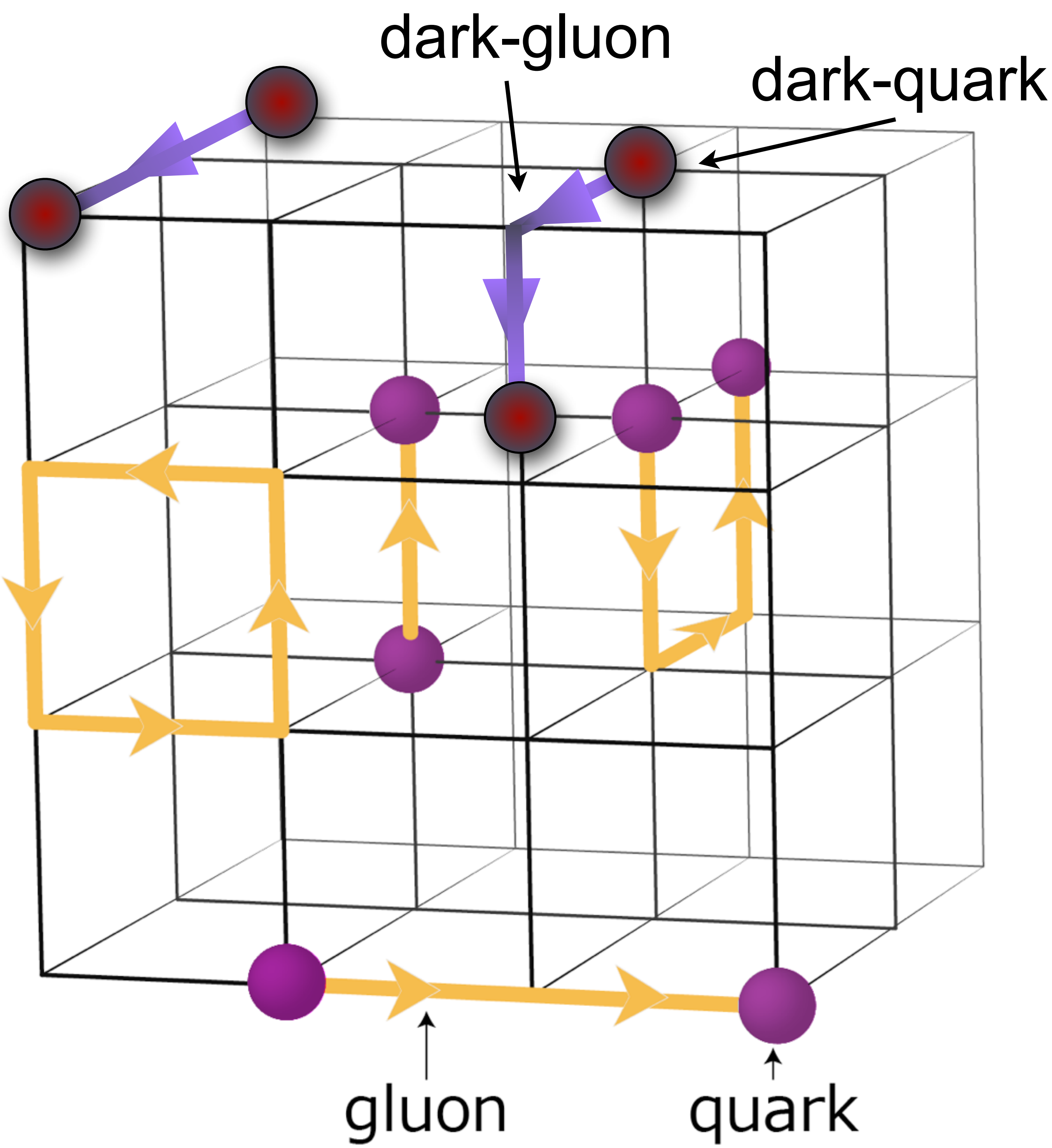
Dark matter on Lattice



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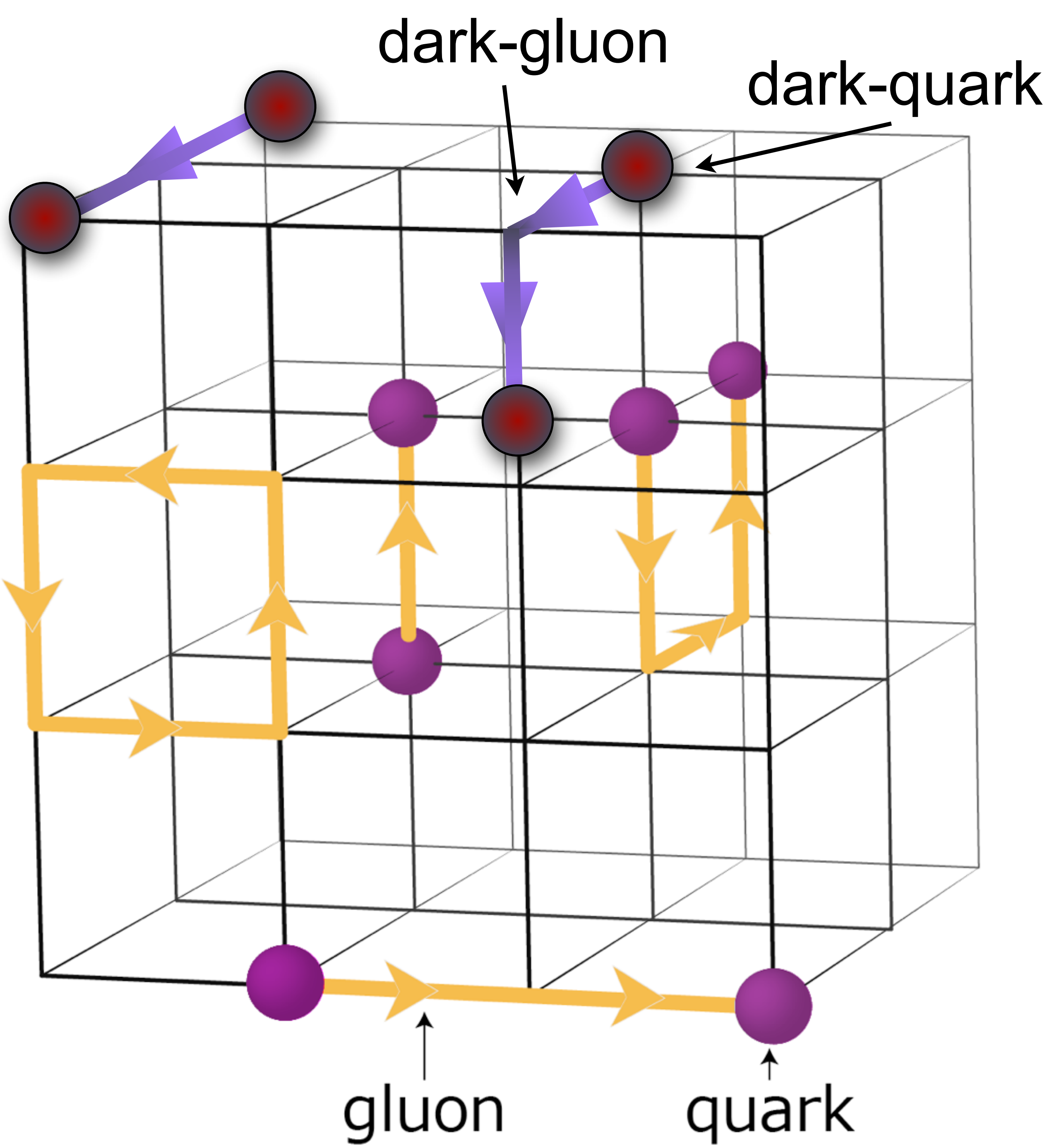

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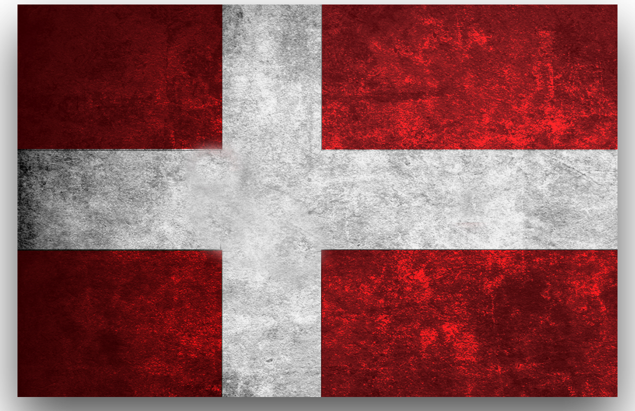
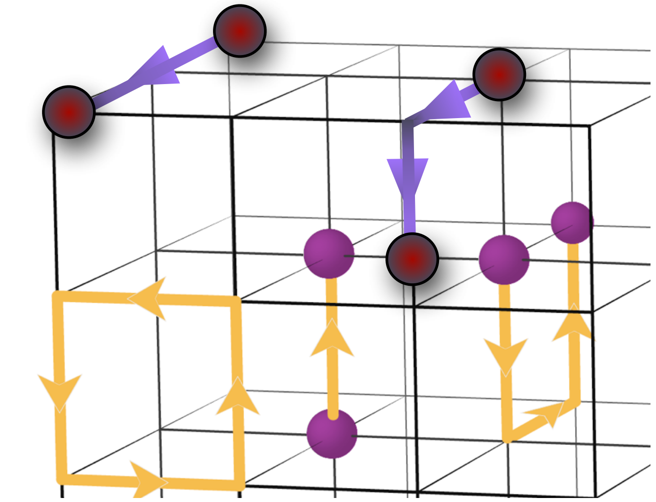
Canadian-Danish collaboration



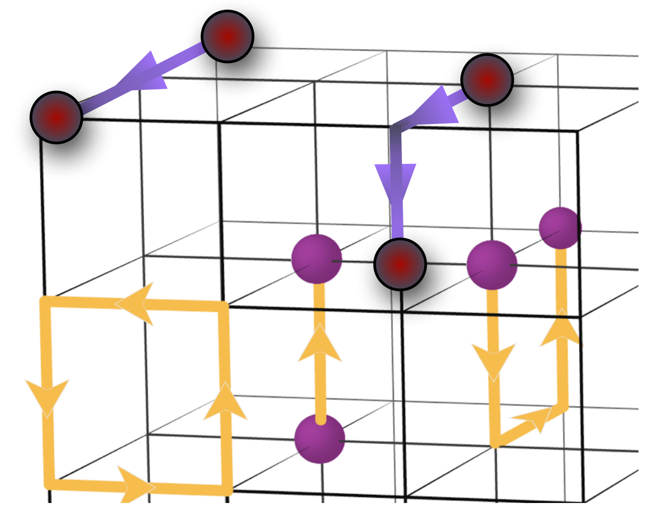
Dark Wilson action



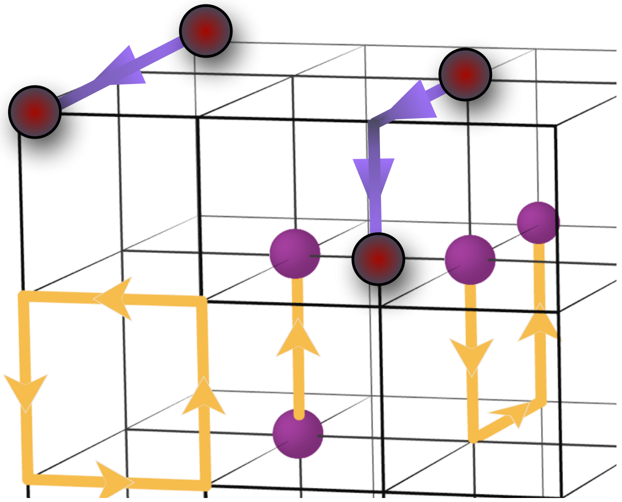
$$
\begin{aligned}
S_W &= \frac{\beta}{2}\sum_{x,\mu,\nu}\left(1-\frac{1}{2}\mathrm{ReTr}U_\mu(x)U_\nu(x+\hat{\mu})U_\mu^\dagger(x+\hat{\nu})U_\nu^\dagger(x)\right)\\
&+ (4+m_0)\sum_x \bar{\psi}(x)\psi(x)\\
&-\frac{1}{2}\sum_{x,\mu}\left(\bar{\psi}(x)(1-\gamma_\mu)U_\mu(x)\psi(x+\hat{\mu})+\bar{\psi}(x+\hat{\mu})(1+\gamma_\mu)U_\mu^\dagger(x)\psi(x)\right)
\end{aligned}
$$

β	Volume	m_0	Therm.	Conf.
2.0	$16^3 \times 32$	-0.85, -0.9, -0.94, -0.945, -0.947, -0.949	320	680
2.0	32^4	-0.947	500	680
2.2	$16^3 \times 32$	-0.60, -0.65, -0.68, -0.70, -0.72, -0.75	320	680
2.2	$24^3 \times 32$	-0.75	500	$\sim$2000
2.2	32^4	-0.72,-0.735, -0.75	500	$\sim$2000

Table 1: Parameters used in the simulations. The thermalization column refers to the number of discarded initial configurations and the configuration column refers to the number of independent configurations used in measurements.



- Fermion mass via PCAC



$$m_{\mathrm{q}} = \lim_{t\to\infty} \frac{1}{2} \frac{\partial_t V_{\Pi}}{V_{\mathrm{PP}}}$$

$$V_{\Pi}(t_i - t_f) = a^3 \sum_{x_1, x_2, x_3} \langle \overline{u}(t_i)\gamma_0\gamma_5 d(t_i)\overline{u}(t_f)\gamma_5 d(t_f)\rangle$$

$$V_{\mathrm{PP}}(t_i - t_f) = a^3 \sum_{x_1, x_2, x_3} \langle \overline{u}(t_i)\gamma_5 d(t_i)\overline{u}_1(t_f)\gamma_5 d(t_f)\rangle$$

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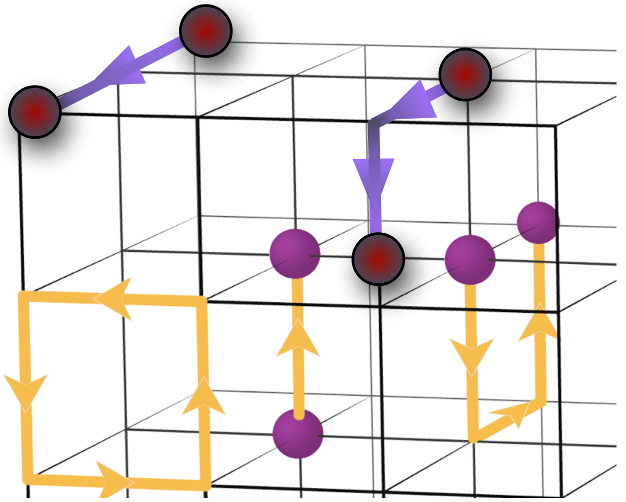

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$$V_{\rm PP}(t_i - t_f) = a^3 \sum_{x_1,x_2,x_3} \langle \overline{u}(t_i)\gamma_5 d(t_i)\overline{u}_1(t_f)\gamma_5 d(t_f)\rangle$$

- Decay constant

$$f_\Pi = \frac{m_{\rm q}}{m_\Pi^2} G_\Pi \qquad\qquad V_{\rm PP}(t_i - t_f) = -\frac{G_\Pi^2}{m_\Pi}\exp\left[-m_\Pi(t_i - t_f)\right]$$

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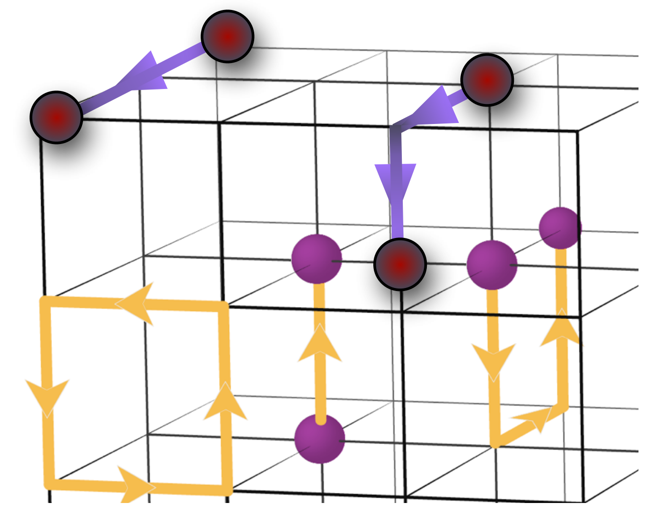

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$$V_{\mathrm{PP}}(t_i - t_f) = a^3 \sum_{x_1,x_2,x_3} \langle \overline{u}(t_i)\gamma_5 d(t_i)\overline{u}_1(t_f)\gamma_5 d(t_f)\rangle$$

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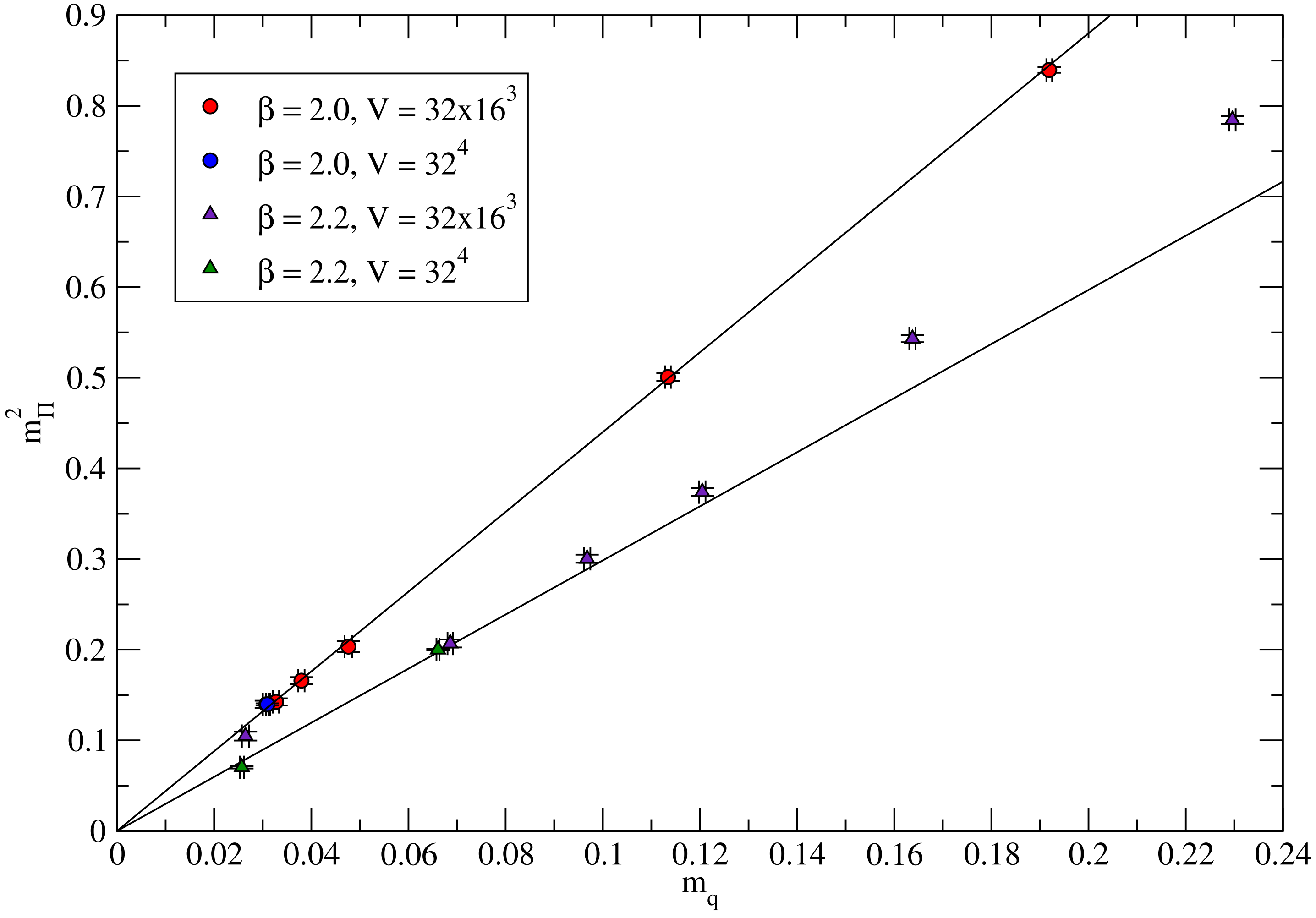
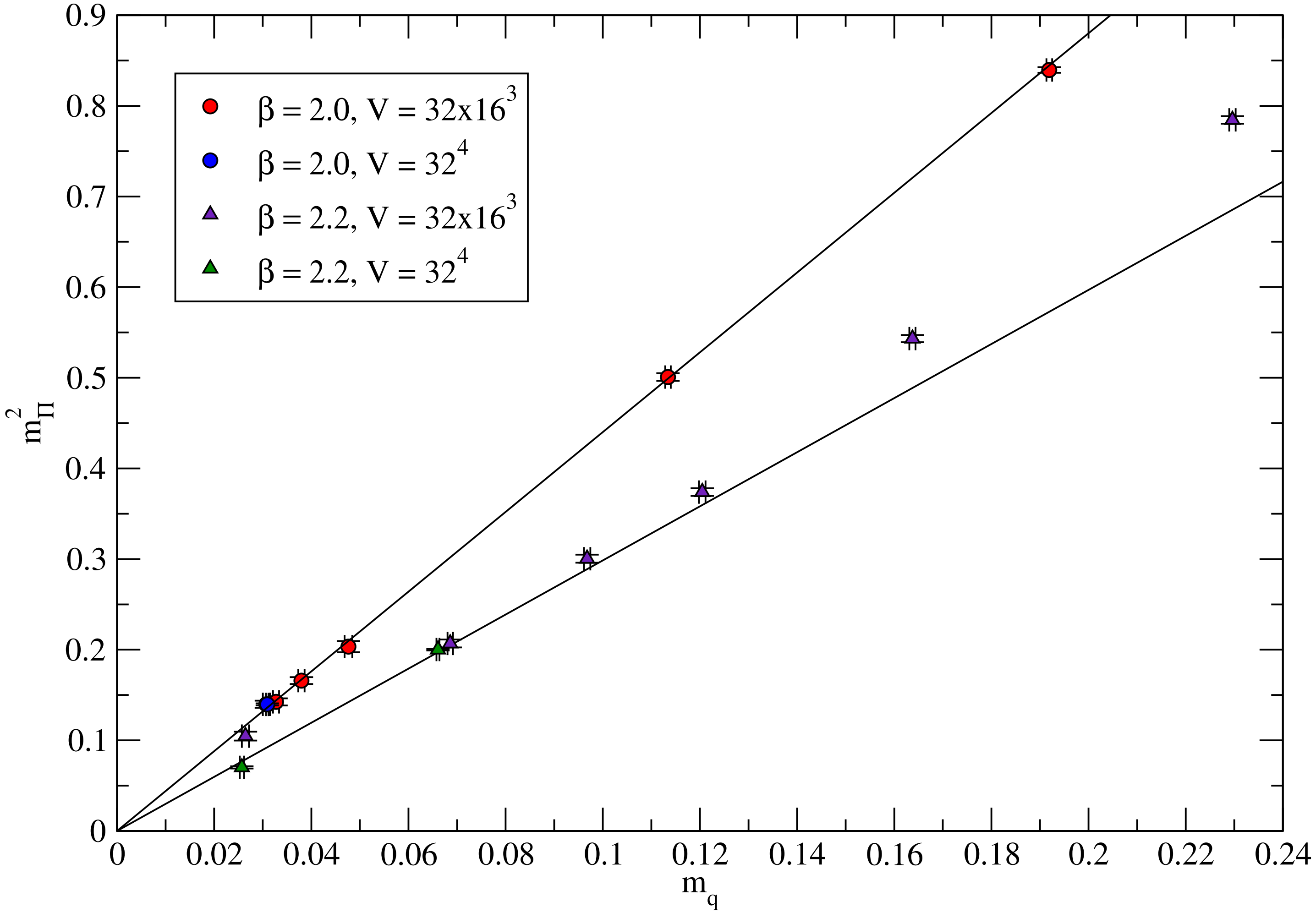
- 2 point functions

$$\begin{aligned} C^{(\Gamma)}_{\overline{u}d}(t_i - t_f) &= \sum_{\vec{x}_i,\vec{x}_f} \left\langle \mathcal{O}^{(\Gamma)}_{ud}(x_f)\mathcal{O}^{(\Gamma)\dagger}_{ud}(x_i)\right\rangle \\ &= \sum_{\vec{x}_i,\vec{x}_f} \mathrm{Tr}\Gamma S_{d\overline{d}}(x_f, x_i)\gamma^0\Gamma^\dagger\gamma^0 S_{u\overline{u}}(x_i, x_f) \end{aligned}$$

$$S_{u\overline{u}}(x, y) = \langle u(x)\overline{u}(y)\rangle$$

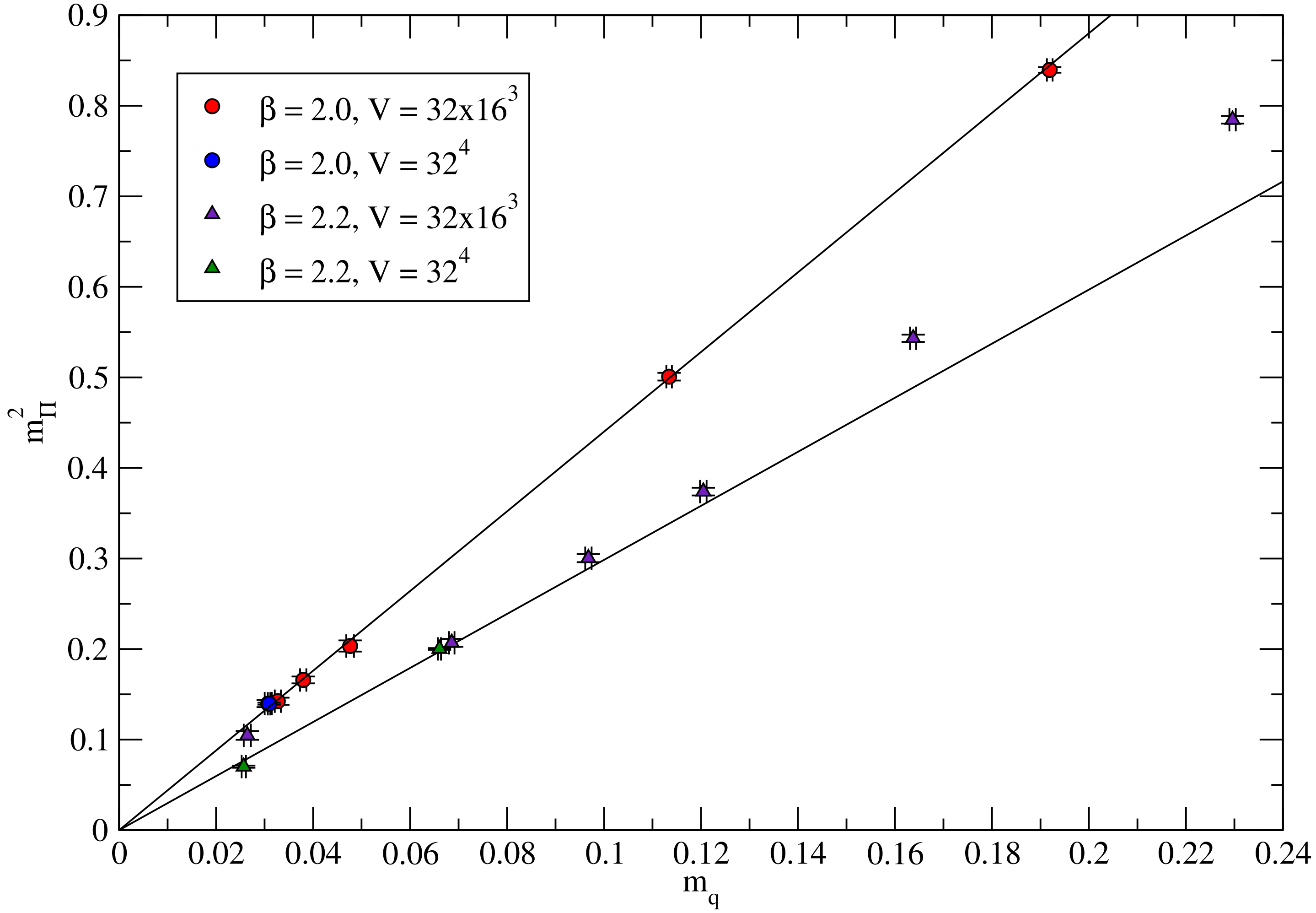


β = 2.0, V = 32x16^3
β = 2.0, V = 32^4
β = 2.2, V = 32x16^3
β = 2.2, V = 32^4
m_Π^2
m_q
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24



- Chiral symmetry breaks

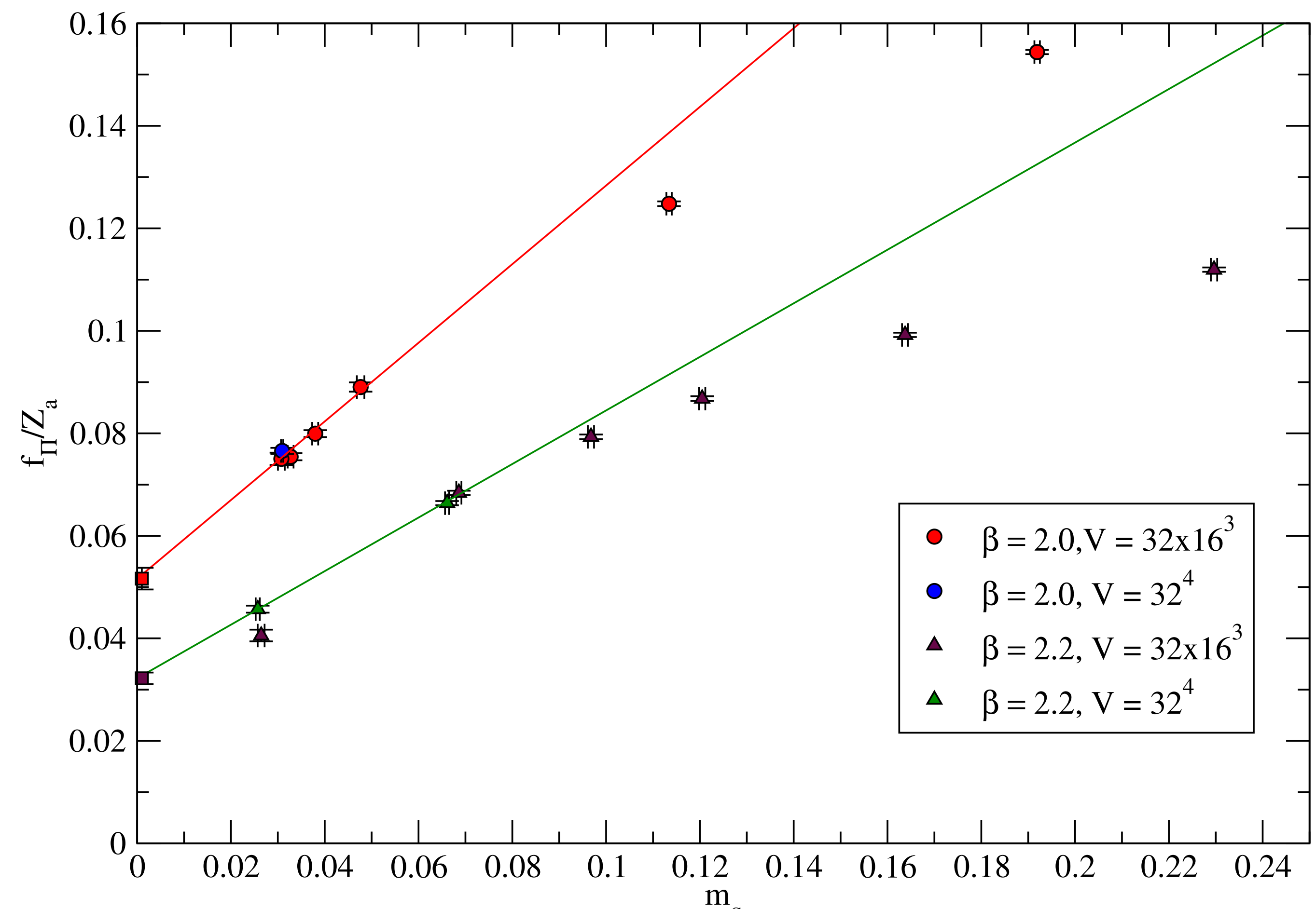
$$m_{\Pi}^2 \propto m_q$$

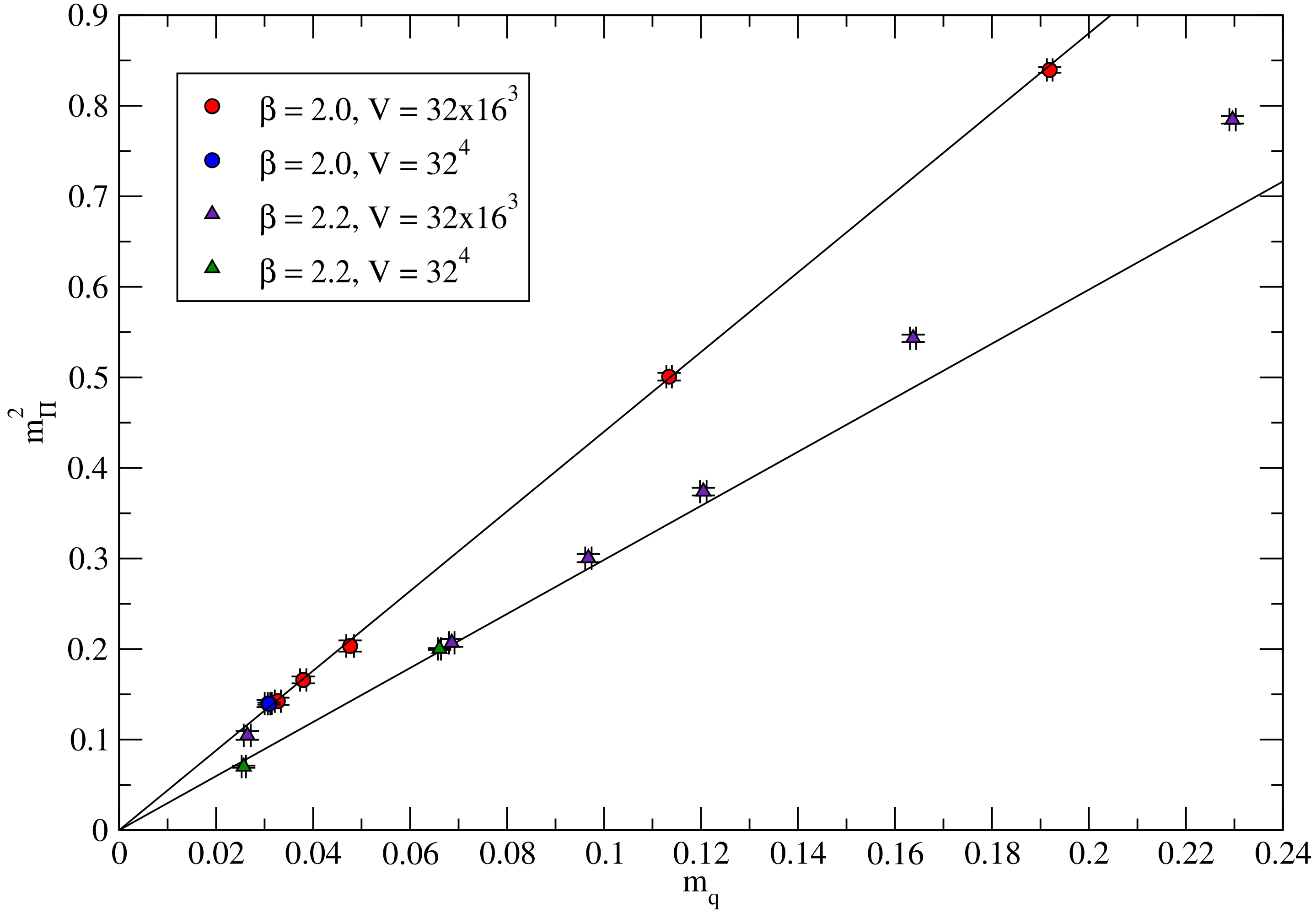


- Chiral symmetry breaks

$$m_\Pi^2 \propto m_q$$

- Nonzero decay constant





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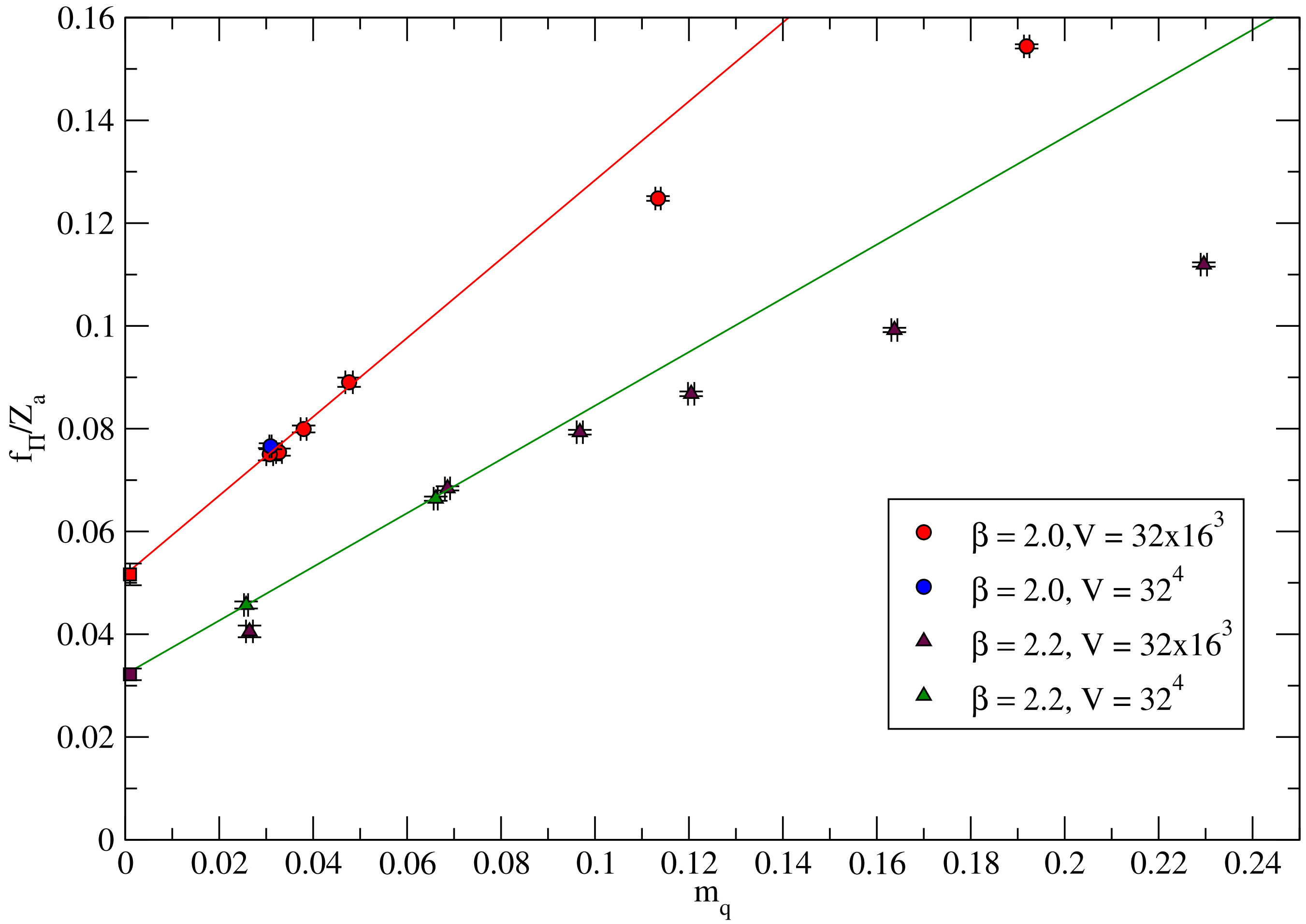
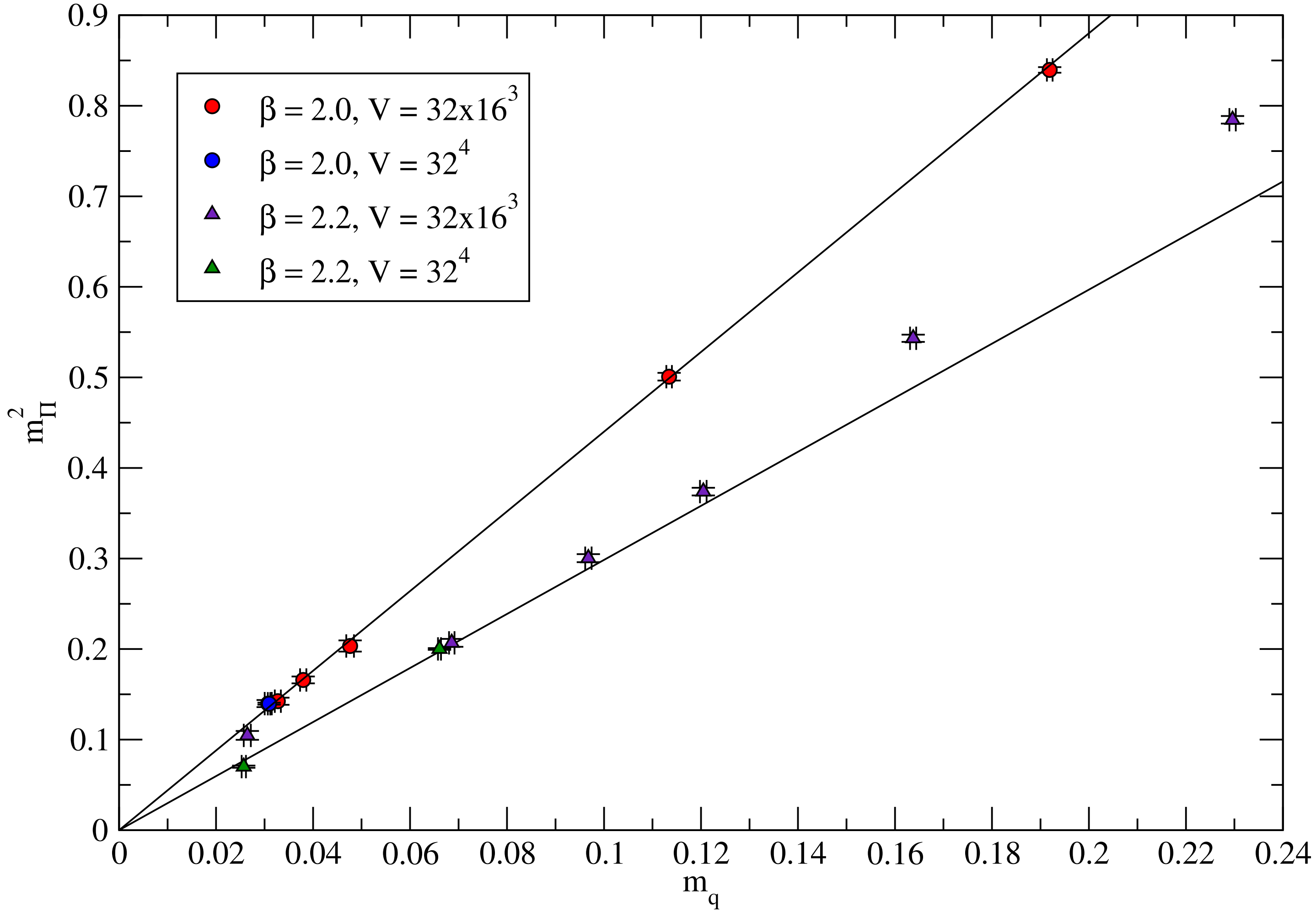


- Perturbative estimate of Z_a

$$Z_a = 1 - \frac{g_0^2}{16\pi^2}\frac{N^2-1}{2N}15.7 \stackrel{N=2}{=} 1 - 0.2983/\beta$$



- Chiral symmetry breaks

$$m_\Pi^2 \propto m_q$$

- Don't see yet the chiral logs

- Nonzero decay constant

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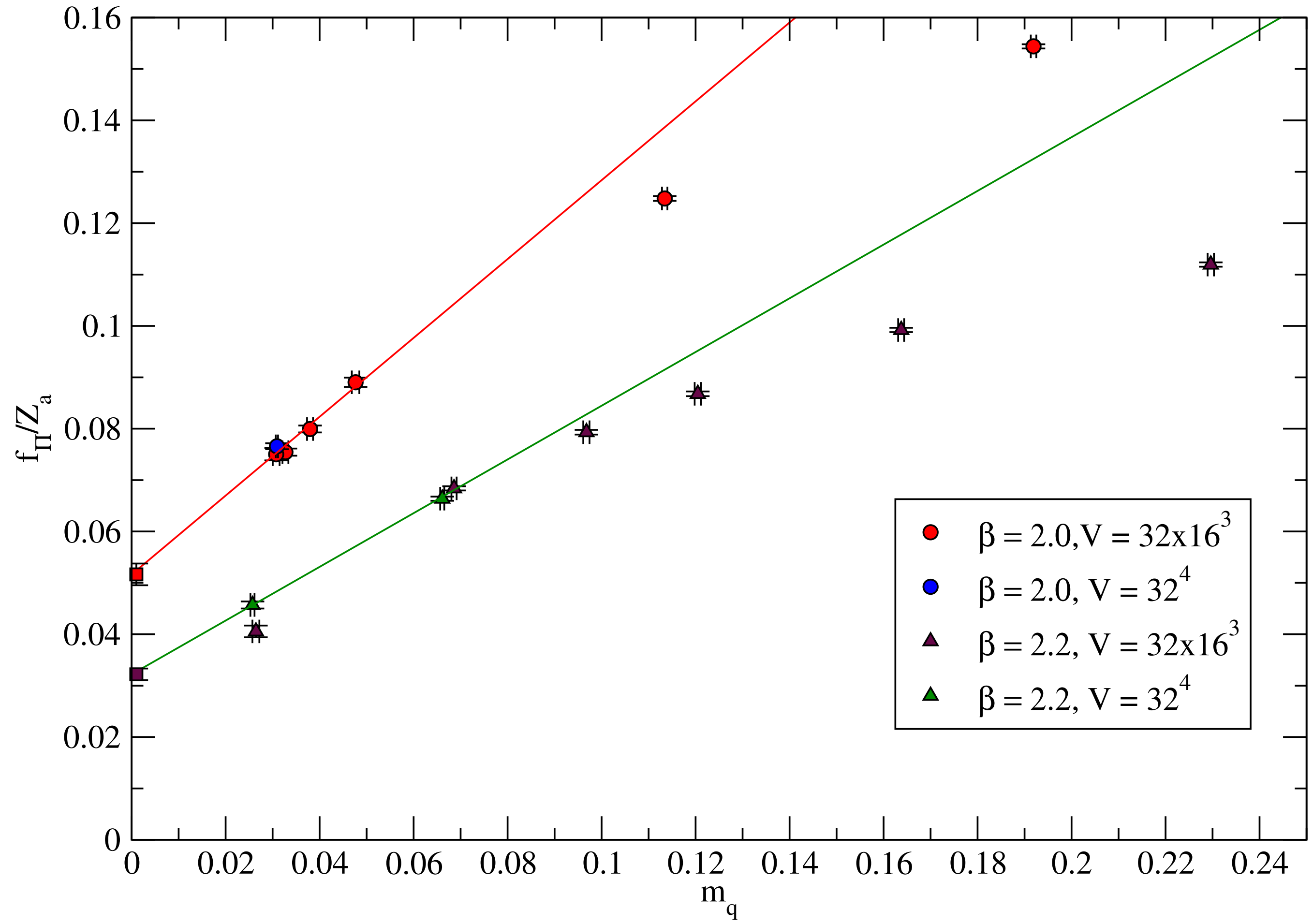
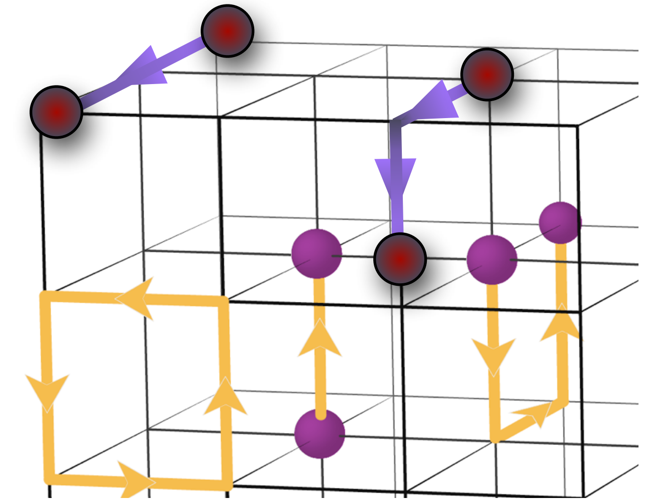
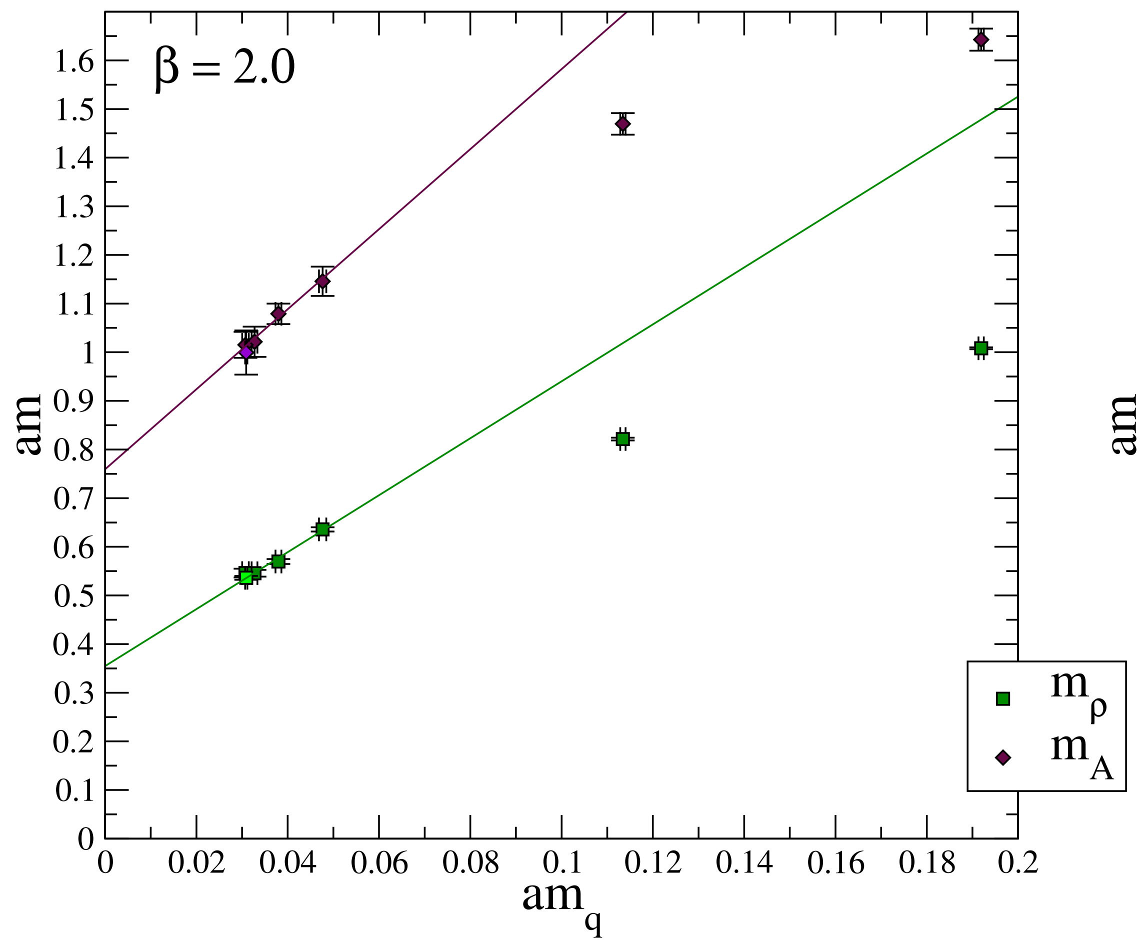
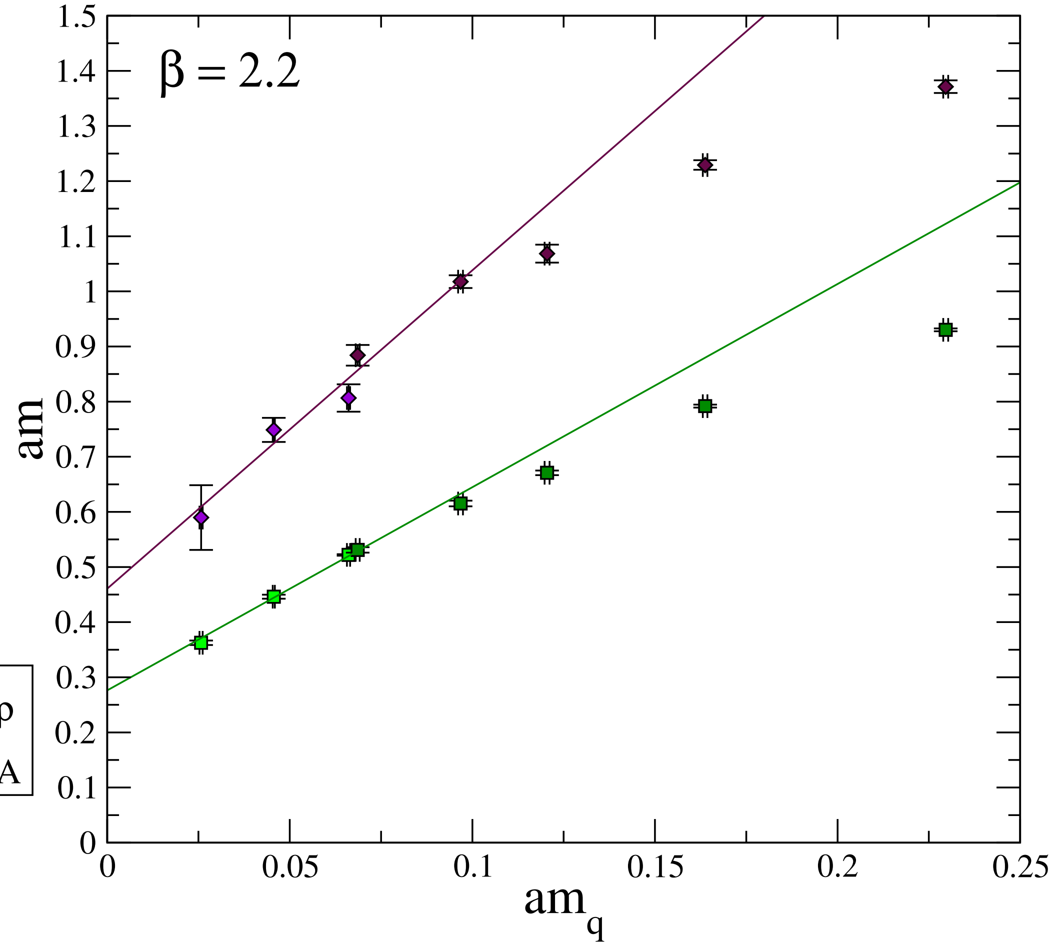


Spin one spectrum

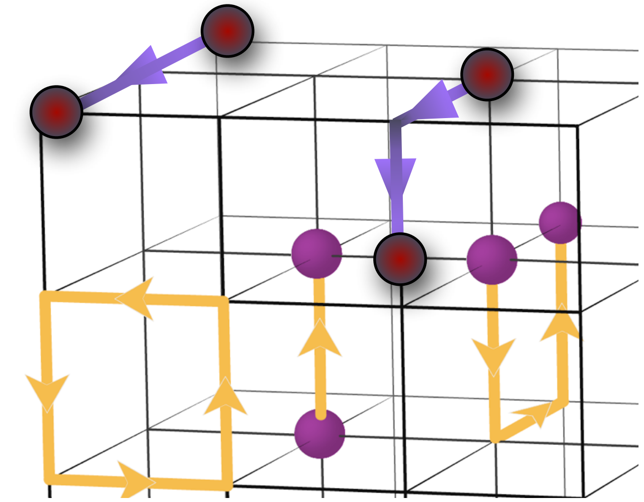


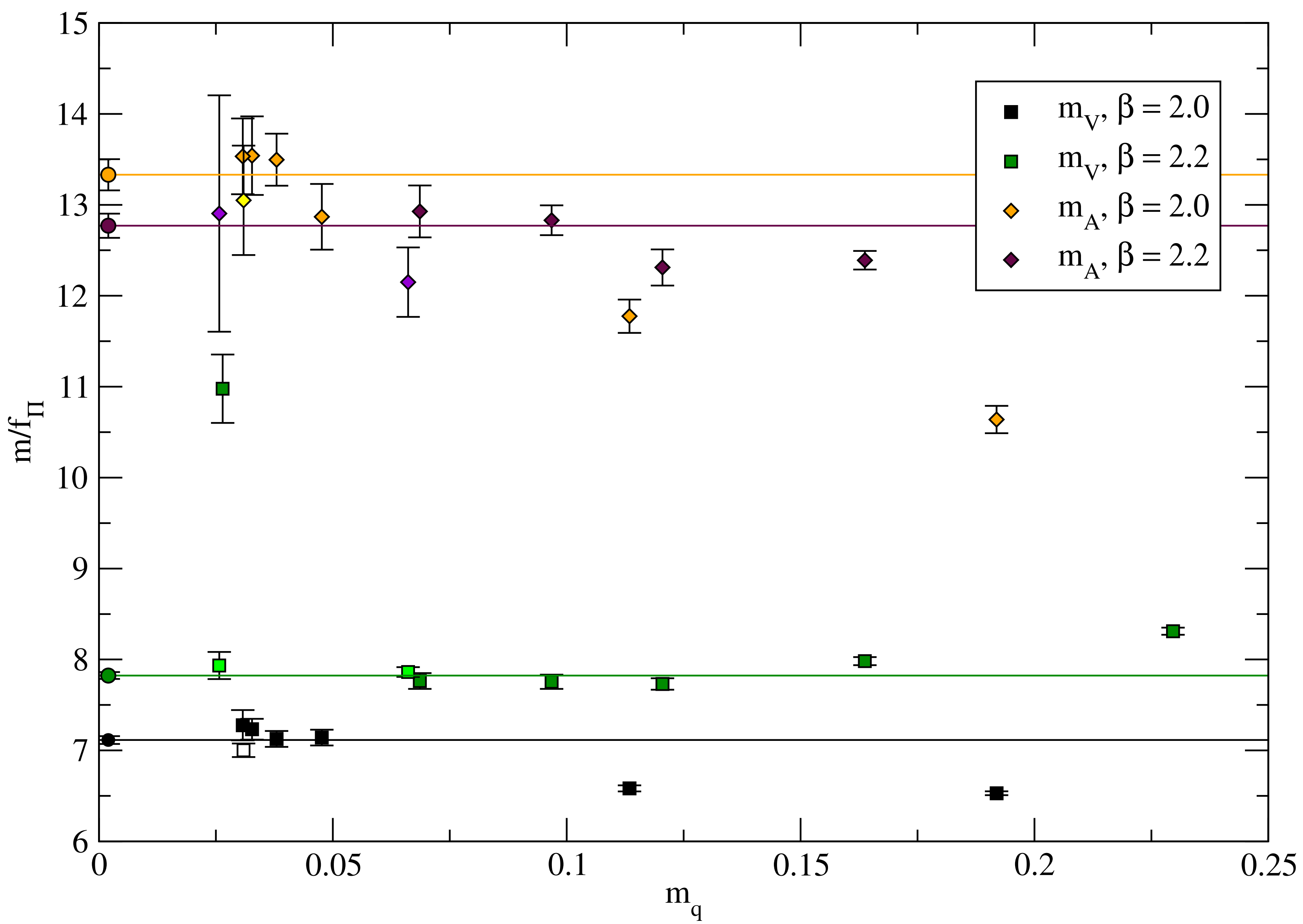
- 2 Volumes: $16^3 \times 32$ and 32^4 in lighter colors
- Smaller volume effects for beta = 2.0
- Larger volume effects for the most chiral points for beta = 2.2
- Volume corrections for lighter masses





Continuum estimates





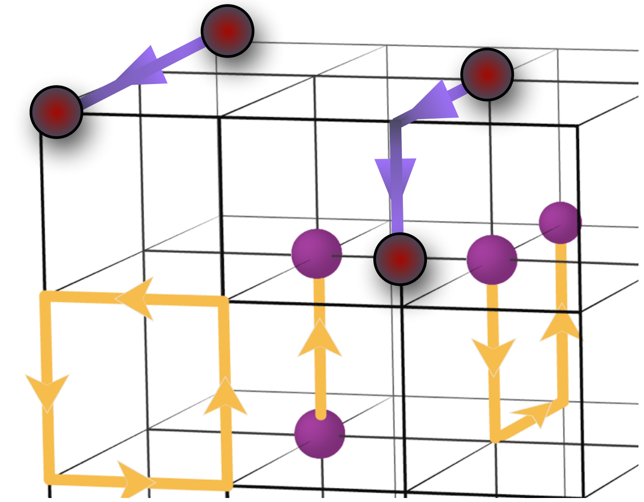
$$m_\rho \simeq 2510(40)(280)(300)\ \text{GeV}$$

$$f_\Pi \simeq 246\ \text{GeV}$$

$$m_A \simeq 3270(130)(370)(370)\ \text{GeV}$$

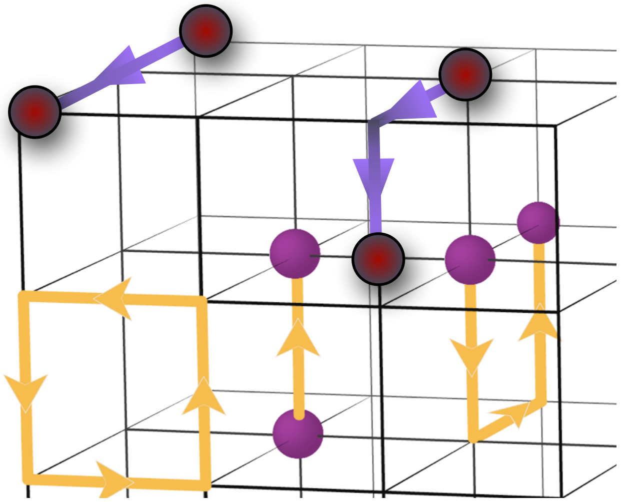
(stat.) (continuum) (Z_a)

DM-photon interaction



- U_L and D_L form a weak doublet
- U_R and D_R fields are weak singlets
- U (D) have 1/2 (-1/2) *electric charge*
- No gauge and Witten anomalies

DM-photon interaction



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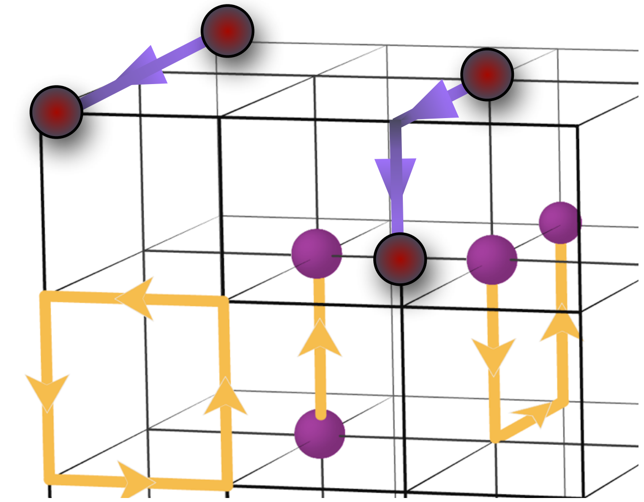
Dark coupling to photon via charge radius

$$\phi \equiv \Pi_{UD}$$

DM-photon interaction



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$$\mathcal{L}_\gamma = ie\frac{d_B}{\Lambda^2}\phi^* \overleftrightarrow{\partial_\mu}\phi\,\partial_\nu F^{\mu\nu}$$

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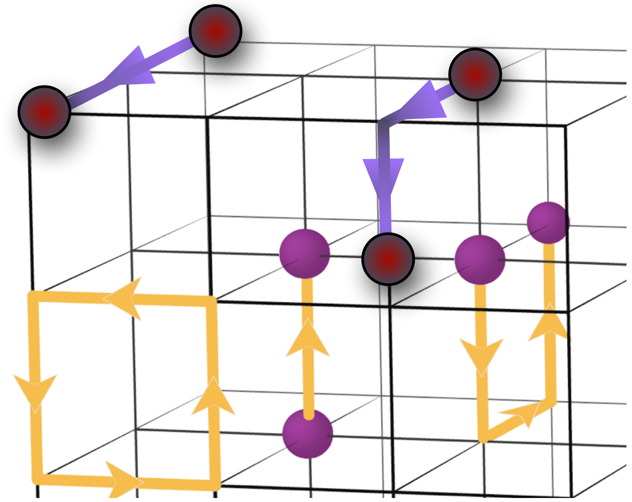

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$$\boxed{\frac{d_B}{\Lambda^2} = ?}$$

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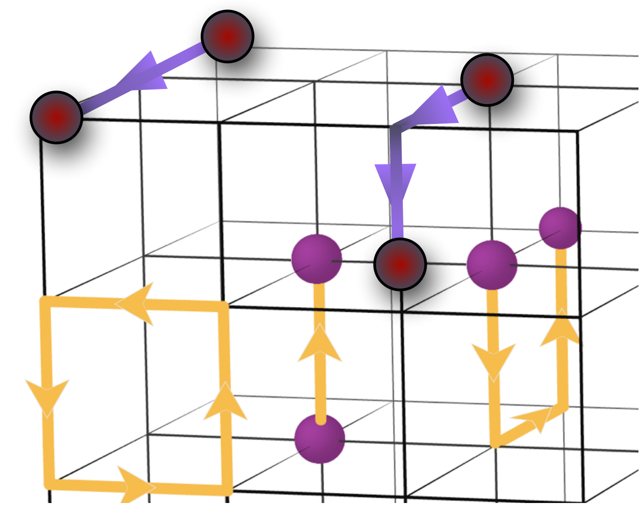

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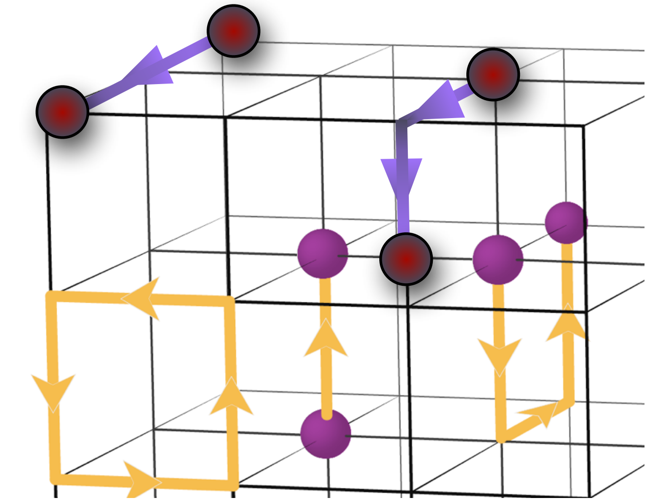
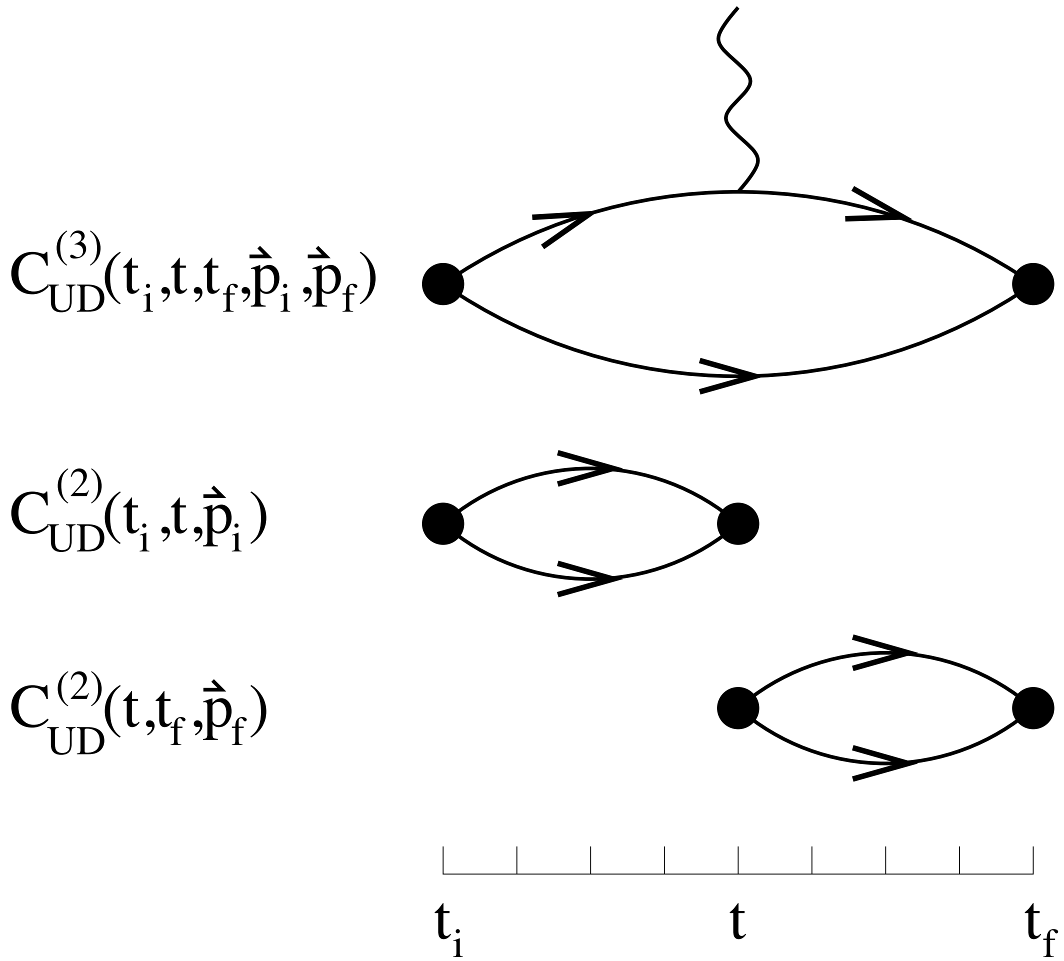
$$\boxed{\frac{d_B}{\Lambda^2} = ?}$$

- Need to determine 3-point functions (GBs form factors)

GBs vector form factors



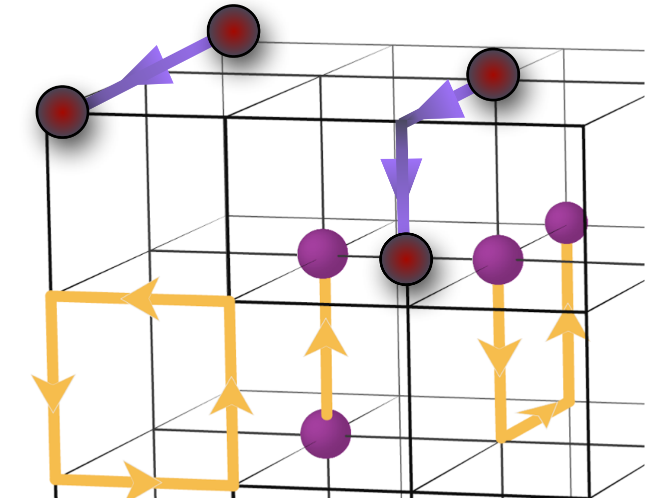


- Lattice electromagnetic current

$$
\begin{aligned}
V_\mu(x) &= \frac{1}{2}V^U_\mu(x) - \frac{1}{2}V^D_\mu(x) \\
V^X_\mu(x) &= \frac{1}{2}\overline{X}(x+\hat{\mu})(1+\gamma_\mu)U^\dagger_\mu(x)X(x) \\
&- \frac{1}{2}\overline{X}(x)(1-\gamma_\mu)U_\mu(x)X(x+\hat{\mu})
\end{aligned}
$$

$$
F_\Pi(Q^2) = \frac{C^{(3)}_{ud}(t_i, t, t_f, \vec{p}_i, \vec{p}_f)\, C^{(2)}_{ud}(t_i, t, \vec{p}_f)}{C^{(2)}_{ud}(t_i, t, \vec{p}_i)\, C^{(2)}_{ud}(t_i, t_f, \vec{p}_f)} \left(\frac{2E_\Pi(\vec{p}_f)}{E_\Pi(\vec{p}_i) + E_\Pi(\vec{p}_f)} \right)
$$

Avoiding disconnected diagrams



- Lattice simulation expensive for different fermion masses
- But for $m_U = m_D$ form factors vanish
- Up and Down are related in QCD at large N [works for N=3]

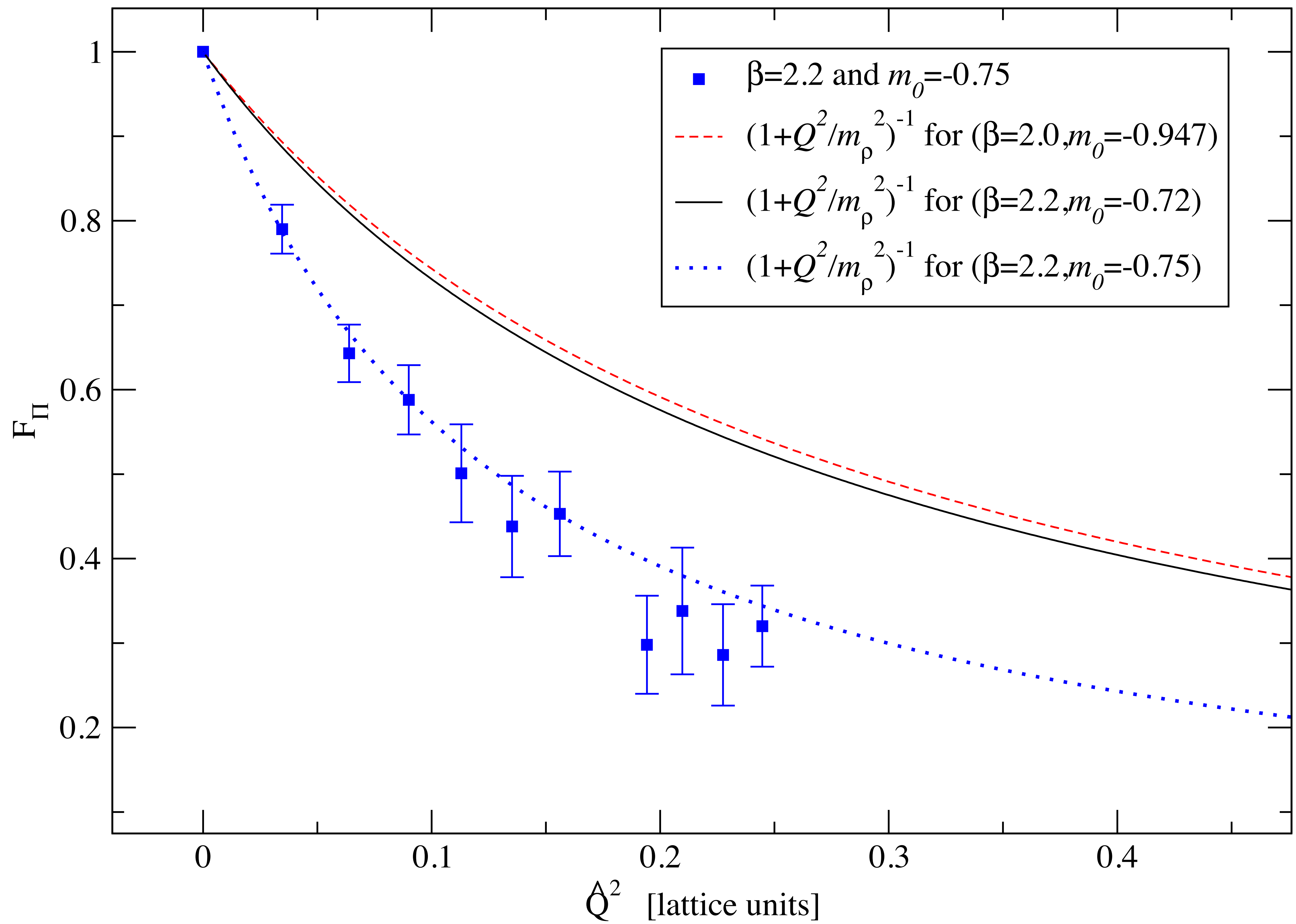
$$F_{\pi^+}(Q^2) \approx \frac{2}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)+\frac{1}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)$$

$$F_{K^+}(Q^2) \approx \frac{2}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)+\frac{1}{3}\left(\frac{m_\phi^2}{m_\phi^2+Q^2}\right)$$

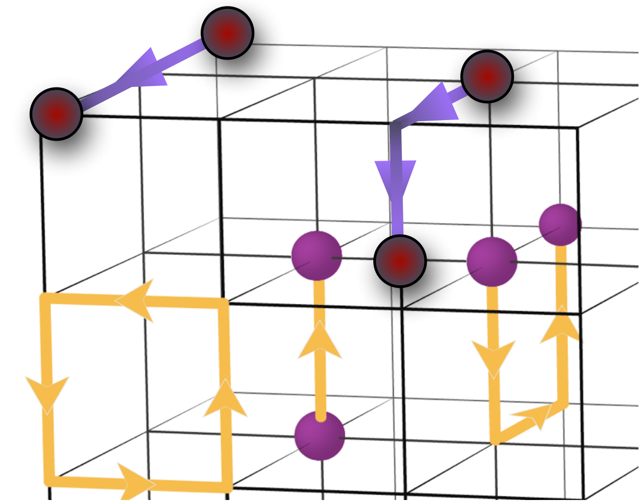
$$F_{K^0}(Q^2) \approx -\frac{1}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)+\frac{1}{3}\left(\frac{m_\phi^2}{m_\phi^2+Q^2}\right)$$

We will test VMD for SU(2)

GB form factor vs vector pole



Lattice prediction

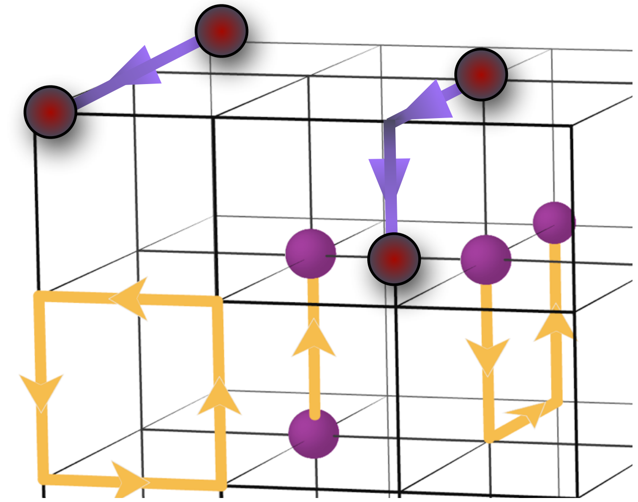


- Form factor requires isospin breaking from ETC

Lattice determines

$$\Lambda = m_\rho\,, \quad d_B = \frac{m_{\rho_U} - m_{\rho_D}}{m_\rho}$$

Lattice prediction



- Form factor requires isospin breaking from ETC

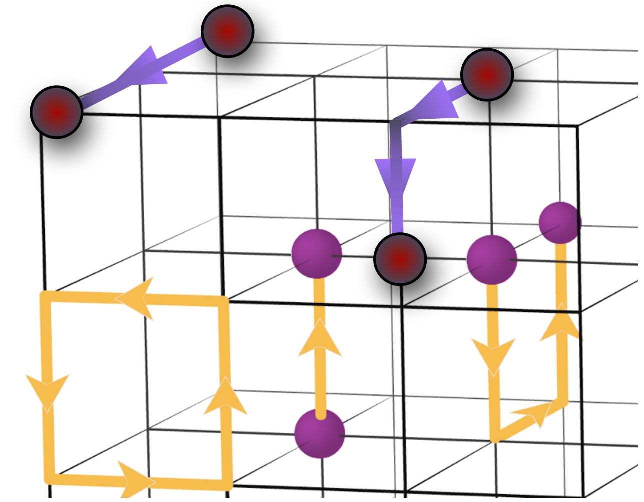
Lattice determines

$$\boxed{\Lambda = m_\rho\,, \quad d_B = \frac{m_{\rho_U} - m_{\rho_D}}{m_\rho}}$$

- EM cross section with proton

$$\sigma_p^\gamma = \frac{\mu^2}{4\pi}\left(\frac{8\pi\alpha d_B}{\Lambda^2}\right)^2 \quad \mu = \frac{m_\phi m_N}{m_\phi + m_N} \qquad |d_B| < 1 \quad m_\phi > m_p$$

Lattice prediction



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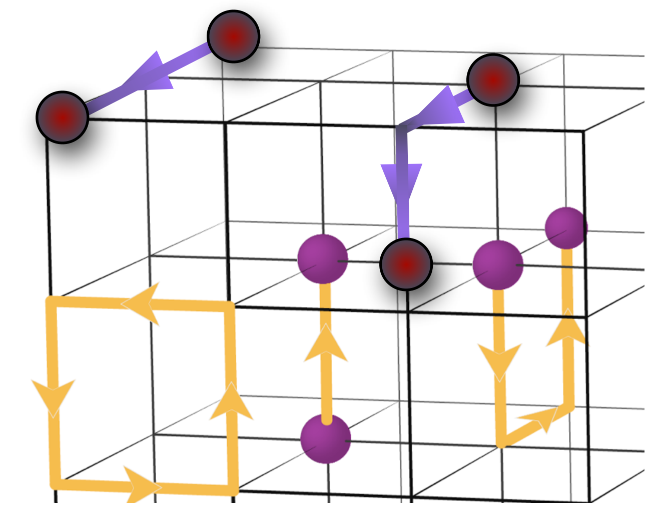
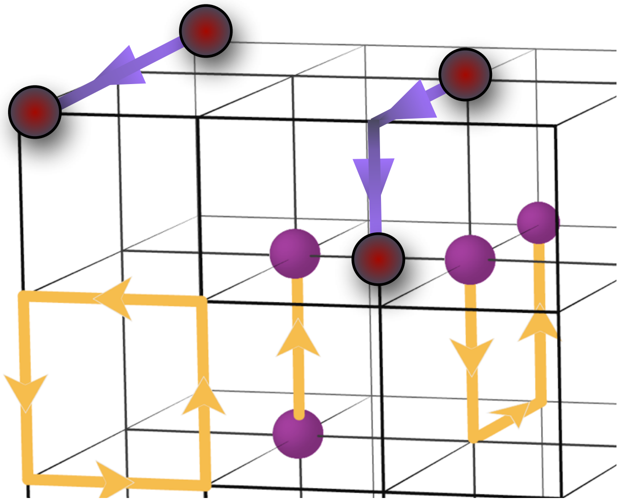
$$\boxed{\sigma_p^\gamma < 2.3 \times 10^{-44}\ \mathrm{cm}^2}$$

First principle !

Composite Higgs ?



Composite Higgs ?

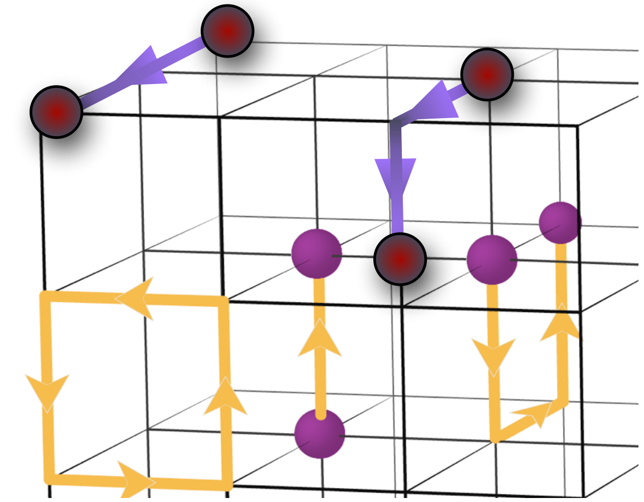


Basic interactions

$$\mathcal{L}_h = \frac{d_1}{\Lambda} h\, \partial_\mu \phi^* \partial^\mu \phi + \frac{d_2}{\Lambda} m_\phi^2\, h\, \phi^* \phi$$

$d_1 \approx d_2 \approx \mathcal{O}(1)$

Composite Higgs ?



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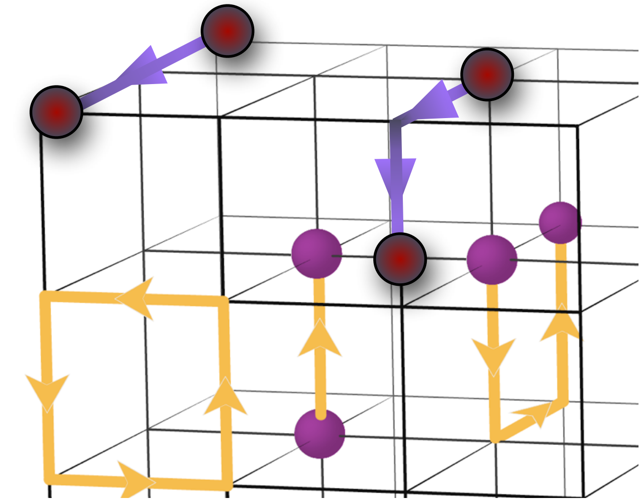

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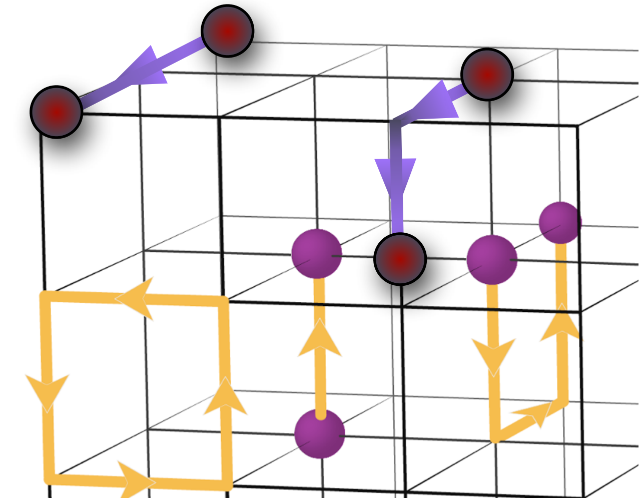
DM is a GB

Cross section with the proton

$$\sigma_p = \frac{\mu^2}{4\pi}\left[\frac{(d_1+d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} + 8\pi\alpha \frac{d_B}{\Lambda^2}\right]^2$$

$f \simeq 0.3$

Composite Higgs ?



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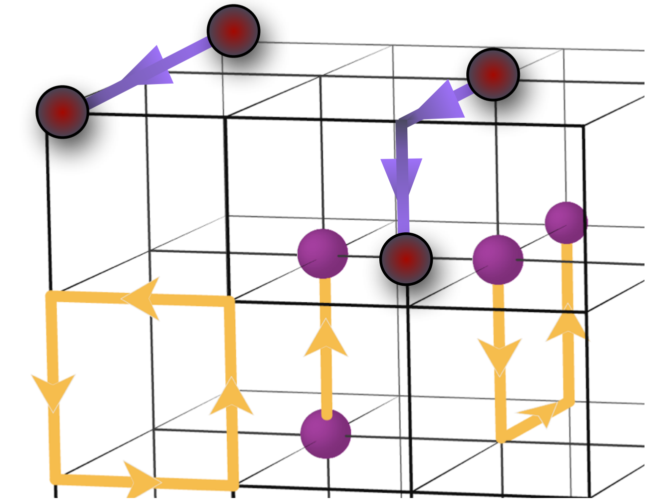
$f \simeq 0.3$

$$f_n = -\frac{(d_1 + d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} \qquad f_p = -\frac{(d_1 + d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} - 8\pi\alpha \frac{d_B}{\Lambda^2}$$

Composite Higgs ?



Talks by Foadi and Kuti

Basic interactions

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DM is a GB

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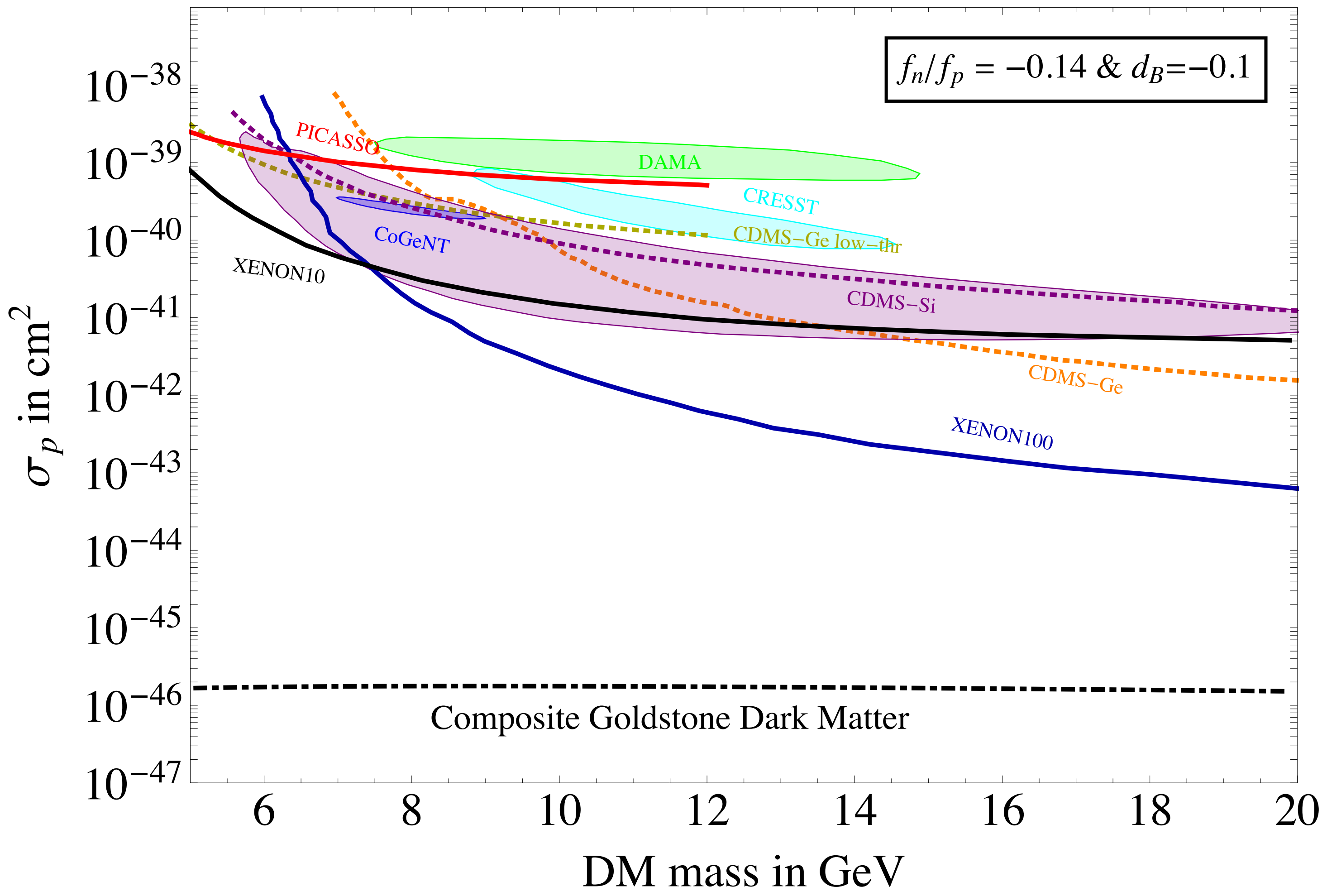
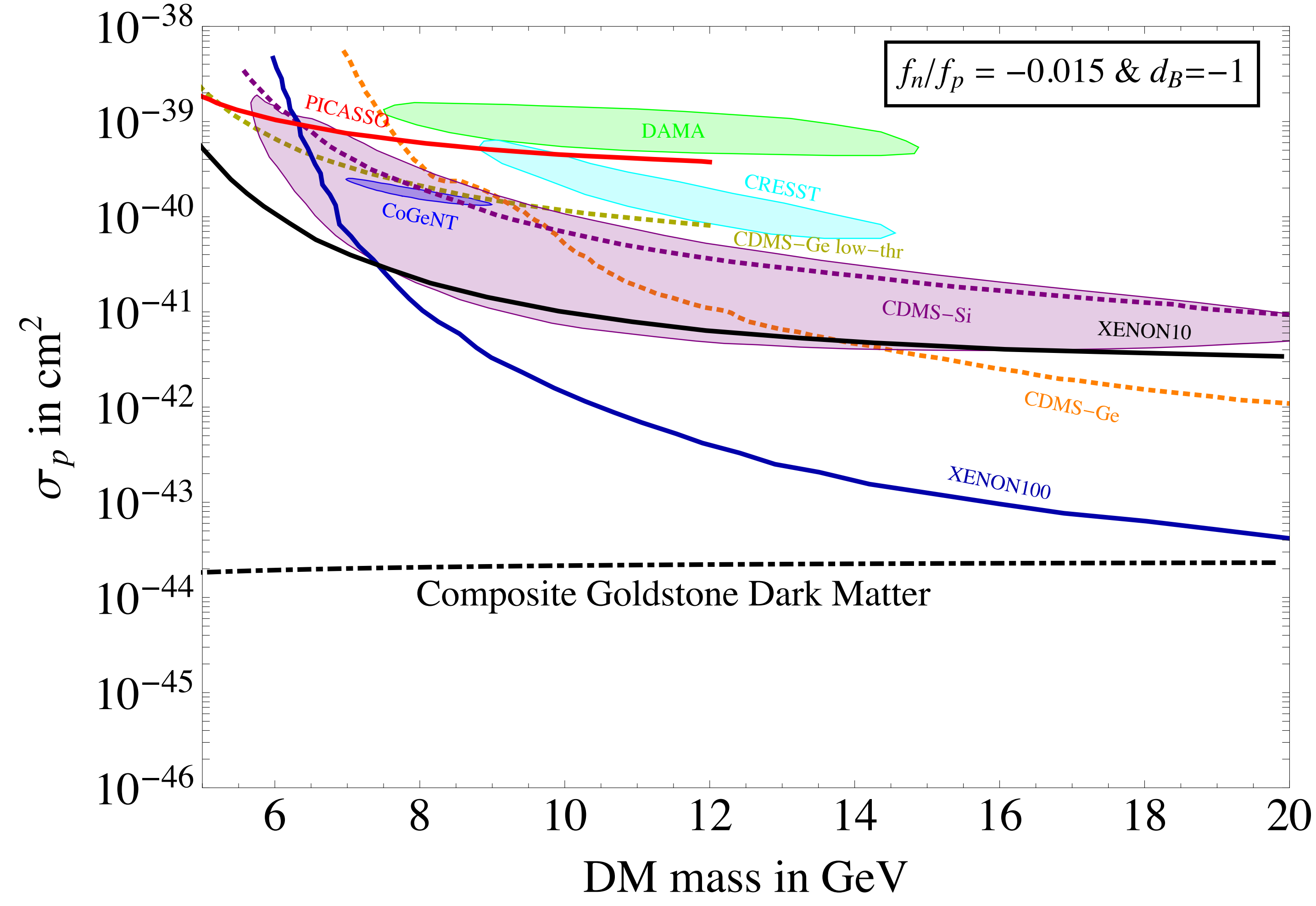
$f \simeq 0.3$

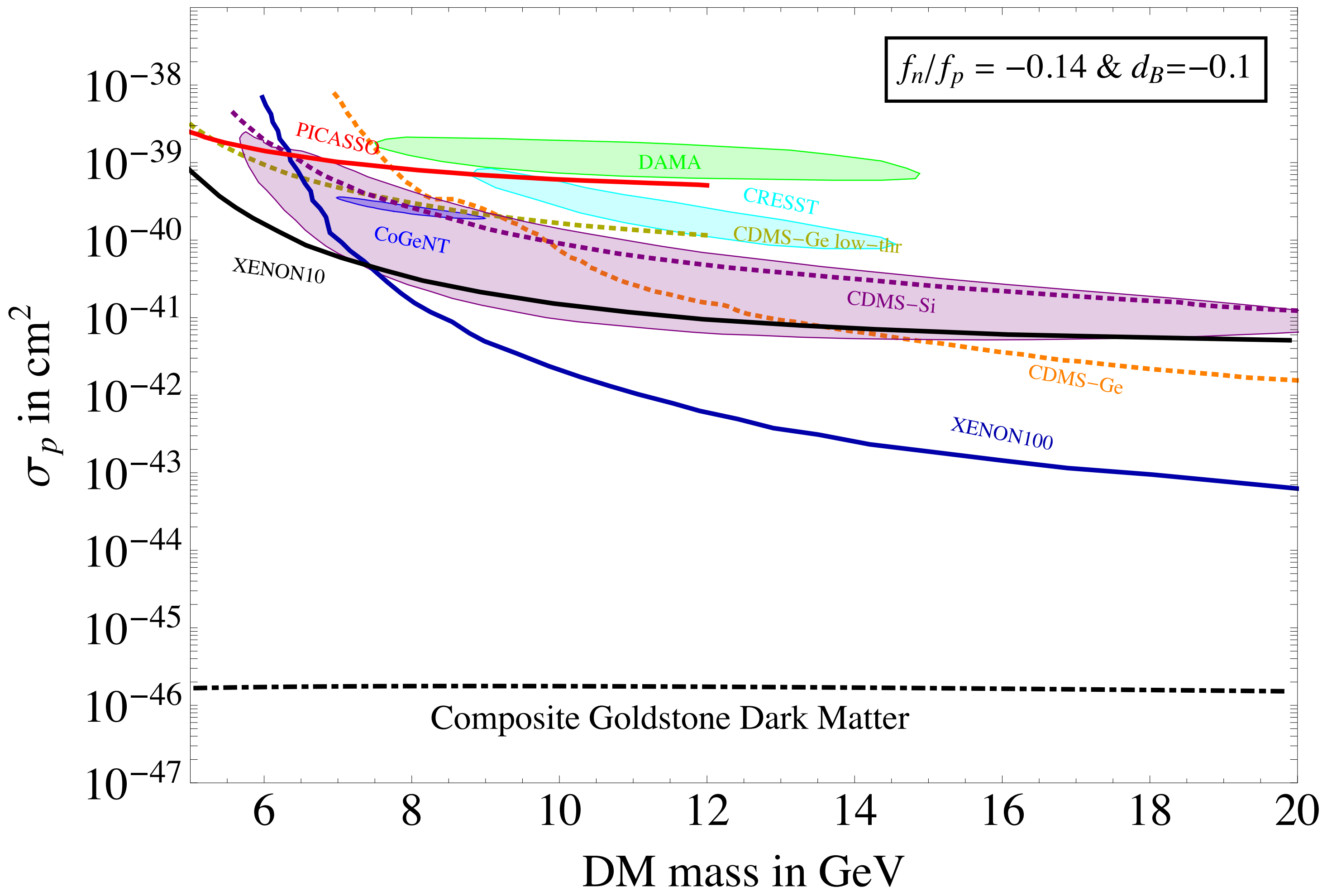
$$f_n = -\frac{(d_1+d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} \qquad f_p = -\frac{(d_1+d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} - 8\pi\alpha \frac{d_B}{\Lambda^2}$$



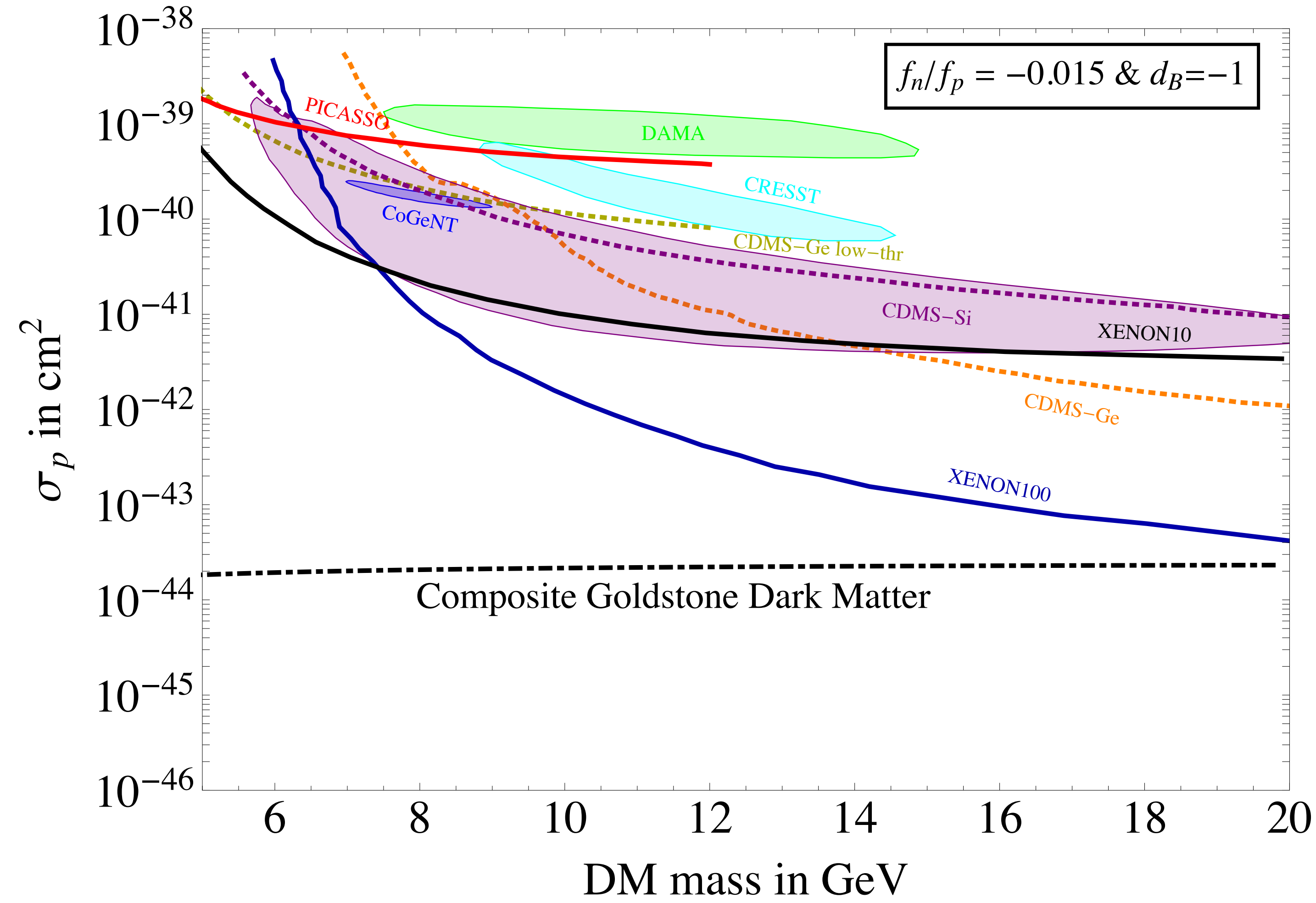
Experiments

Lattice





Experiments



Lattice

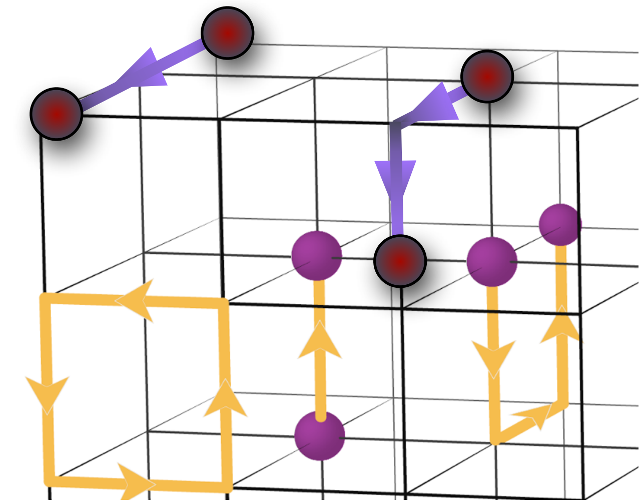
Summary

A natural avenue: Compositeness

Composite dark matter

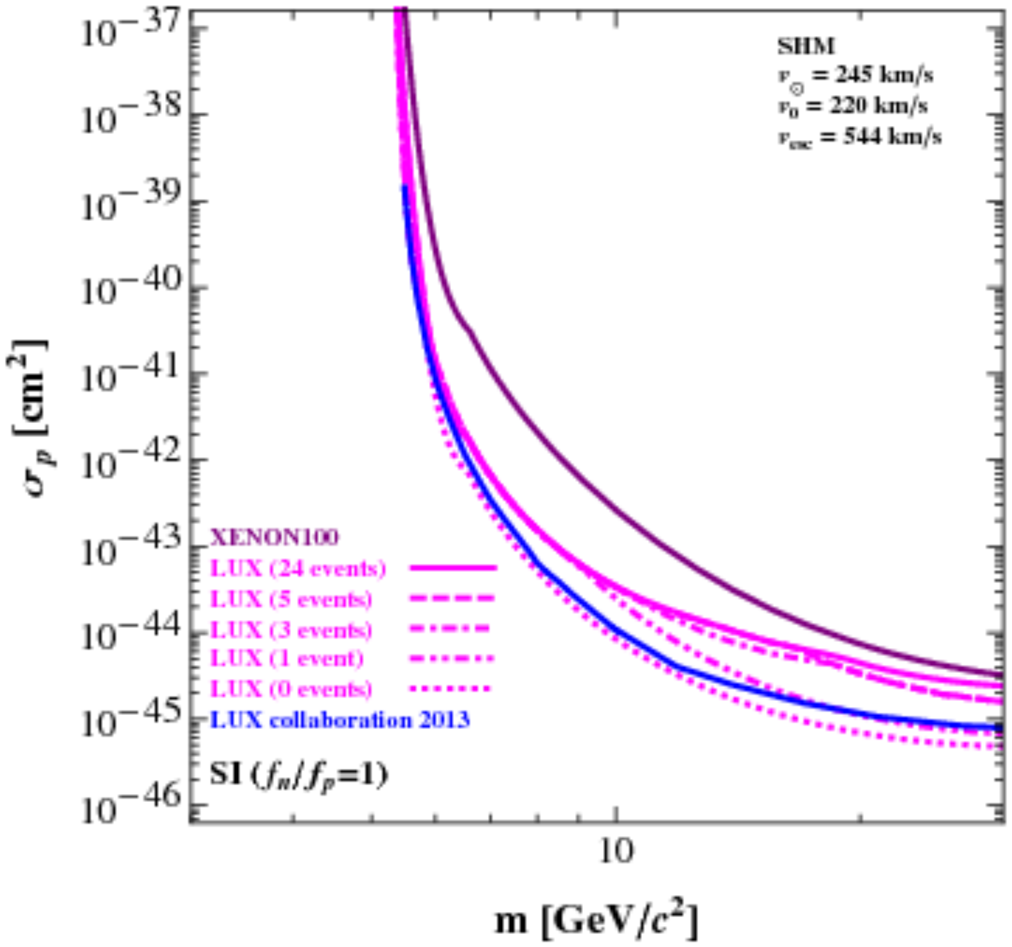
Template for a composite Goldstone DM

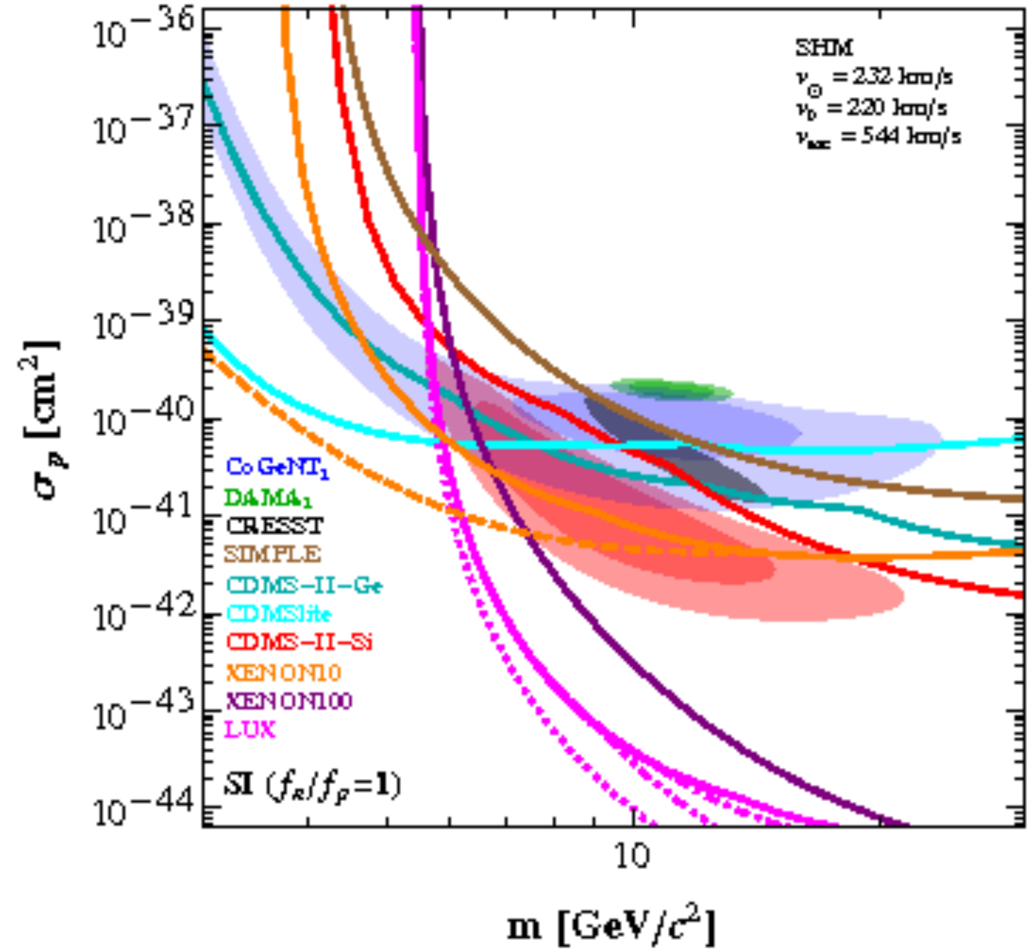
First principle dark lattice simulations

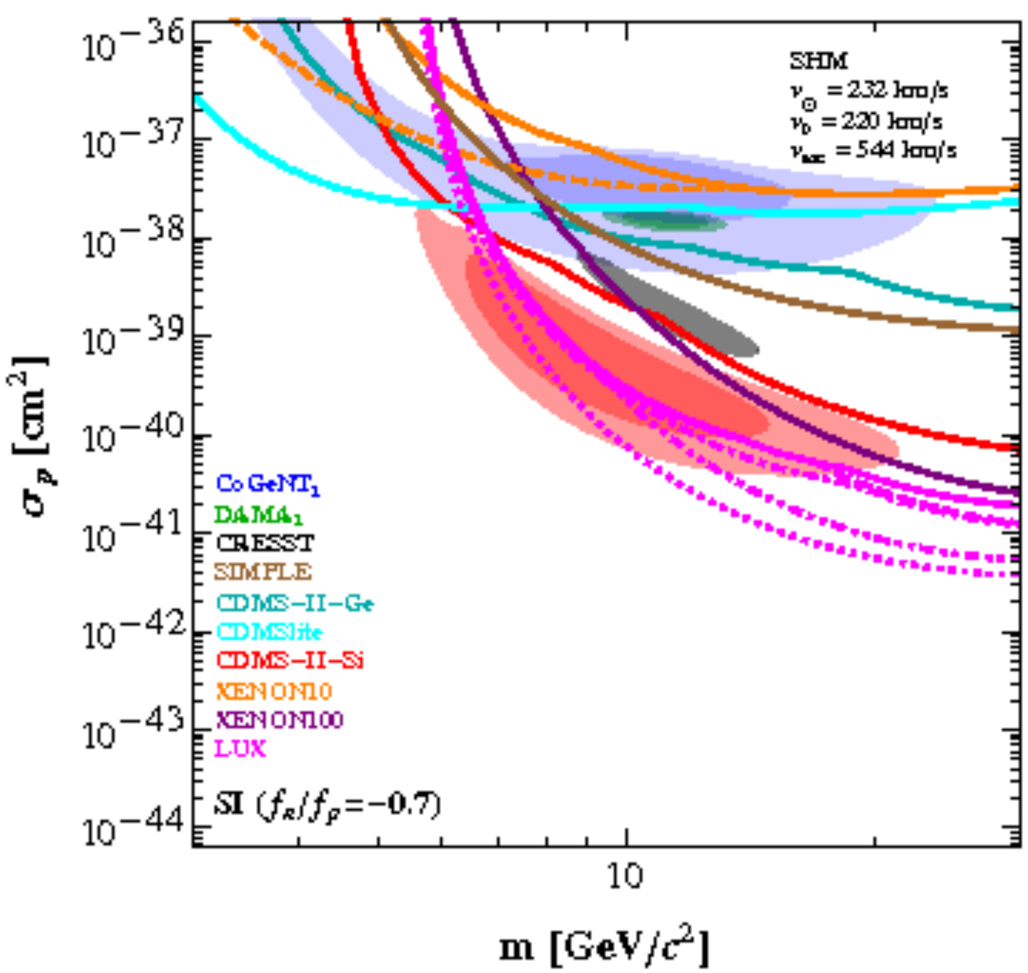


Backup slides

Lux

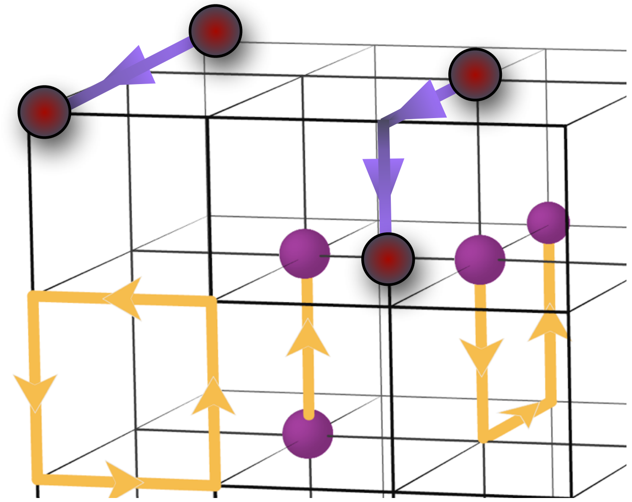




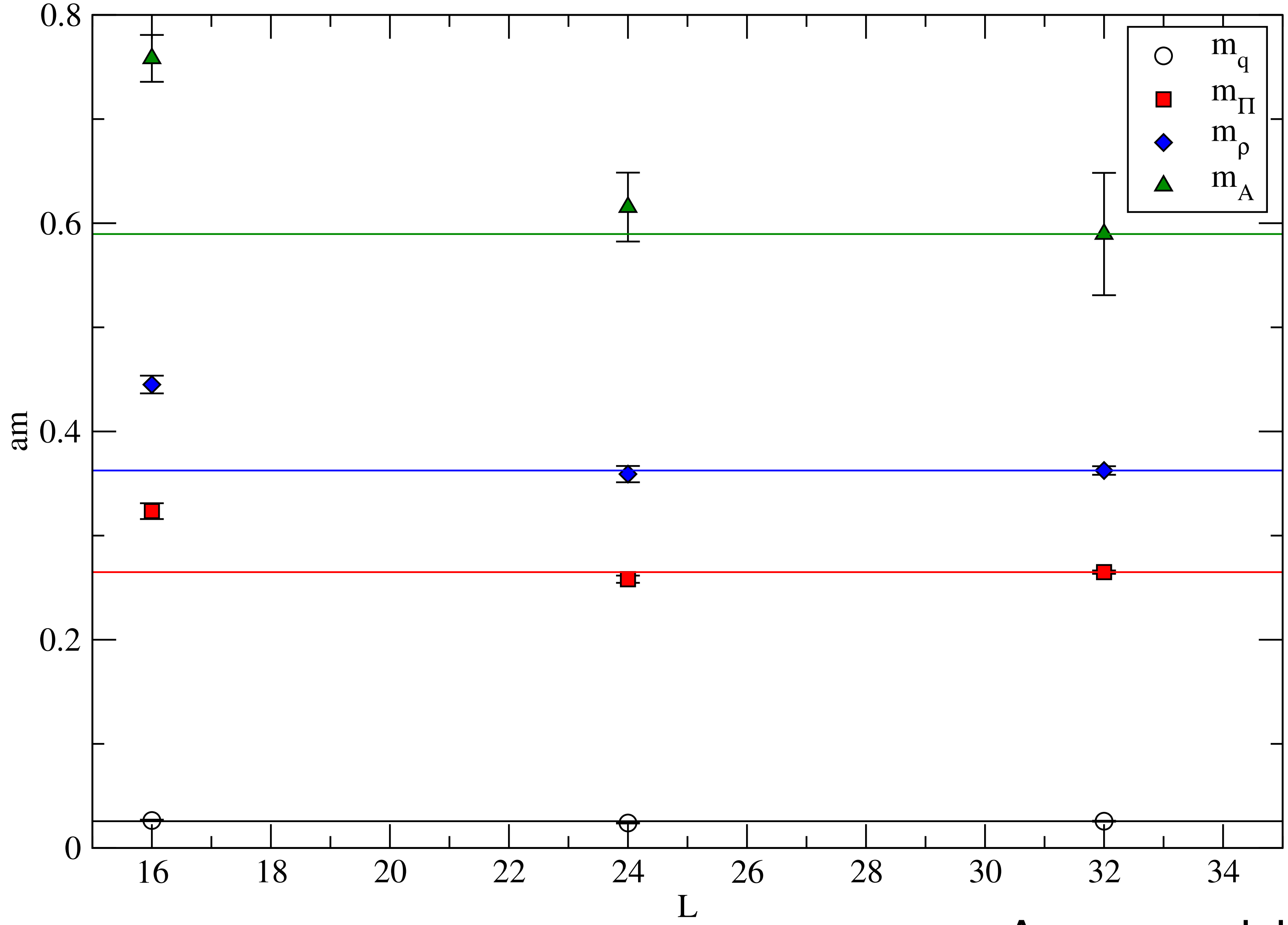


Analysis by
Del Nobile, Gelmini, Gondolo, Huh
1311.4247

Taming volume effects

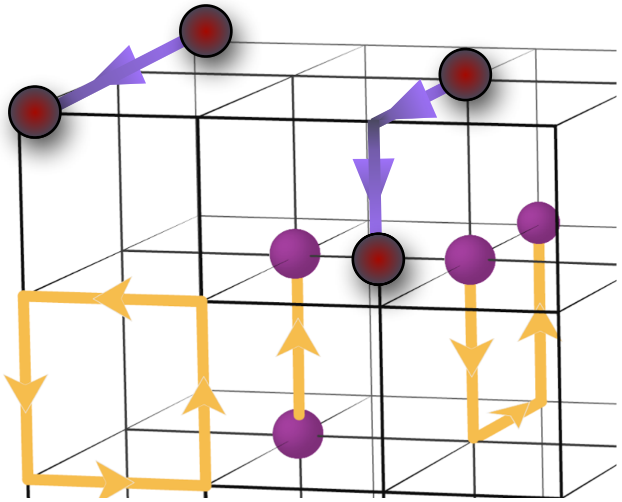


- 3 Volumes: L^3 x 32
- Most chiral point for beta = 2.2



Approaching infinite volume

Form factors relations

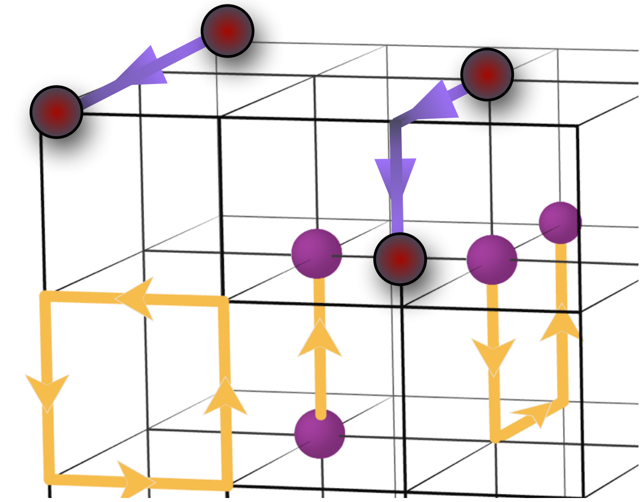


$$
\begin{aligned}
C^{(3)}_{UD}(t_i, t, t_f, \vec{p}_i, \vec{p}_f) &= T^U - T^D \\
C^{(3)}_{\overline{UD}}(t_i, t, t_f, \vec{p}_i, \vec{p}_f) &= -T^U + T^D \\
C^{(3)}_{U\overline{D}}(t_i, t, t_f, \vec{p}_i, \vec{p}_f) &= T^U + T^D \\
C^{(3)}_{\overline{U}D}(t_i, t, t_f, \vec{p}_i, \vec{p}_f) &= -T^U - T^D
\end{aligned}
$$

$$
C^{(3)}_{\overline{U}U+\overline{D}D}(t_i, t, t_f, \vec{p}_i, \vec{p}_f) = 0
$$

$$
T^X = \sum_{\vec{x}_i, \vec{x}, \vec{x}_f} e^{-i(\vec{x}_f - \vec{x})\cdot\vec{p}_f} e^{-i(\vec{x} - \vec{x}_i)\cdot\vec{p}_i} \left\langle 0 \left| \mathcal{O}^{(\gamma_5)}_{UD}(x_f) V^X_\mu(x) \mathcal{O}^{(\gamma_5)\dagger}_{UD}(x_i) \right| 0 \right\rangle
$$

Continuum estimates



meson	β	m GeV	m^i GeV
vector	2.0	1750(10)	2060(12)
vector	2.2	1920(10)	2230(11)
vector	∞	2210(40)(290)(300)	2510(40)(280)(300)
axial vector	2.0	3280(50)	3850(50)
axial vector	2.2	3140(40)	3630(40)
axial vector	∞	2900(120)(230)(370)	3270(130)(370)(370)

- The estimates with an "i" account for the Z_a factor
- The table above is obtained taking the ratio of m over Fpi first
- The table below are independent fits

meson	β	m GeV	m^i GeV
vector	2.0	1690(90)	1990(110)
vector	2.2	1860(60)	2120(70)
vector	∞	2160(270)(300)(270)	2430(300)(310)(300)
axial vector	2.0	3280(50)	3850(50)
axial vector	2.2	3140(40)	3630(40)
axial vector	∞	2900(120)(230)(370)	3270(130)(370)(370)