

Composite nature of Dark Matter

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CP³-Origins, Danish IAS, Univ. Southern Denmark

Lyon 2013

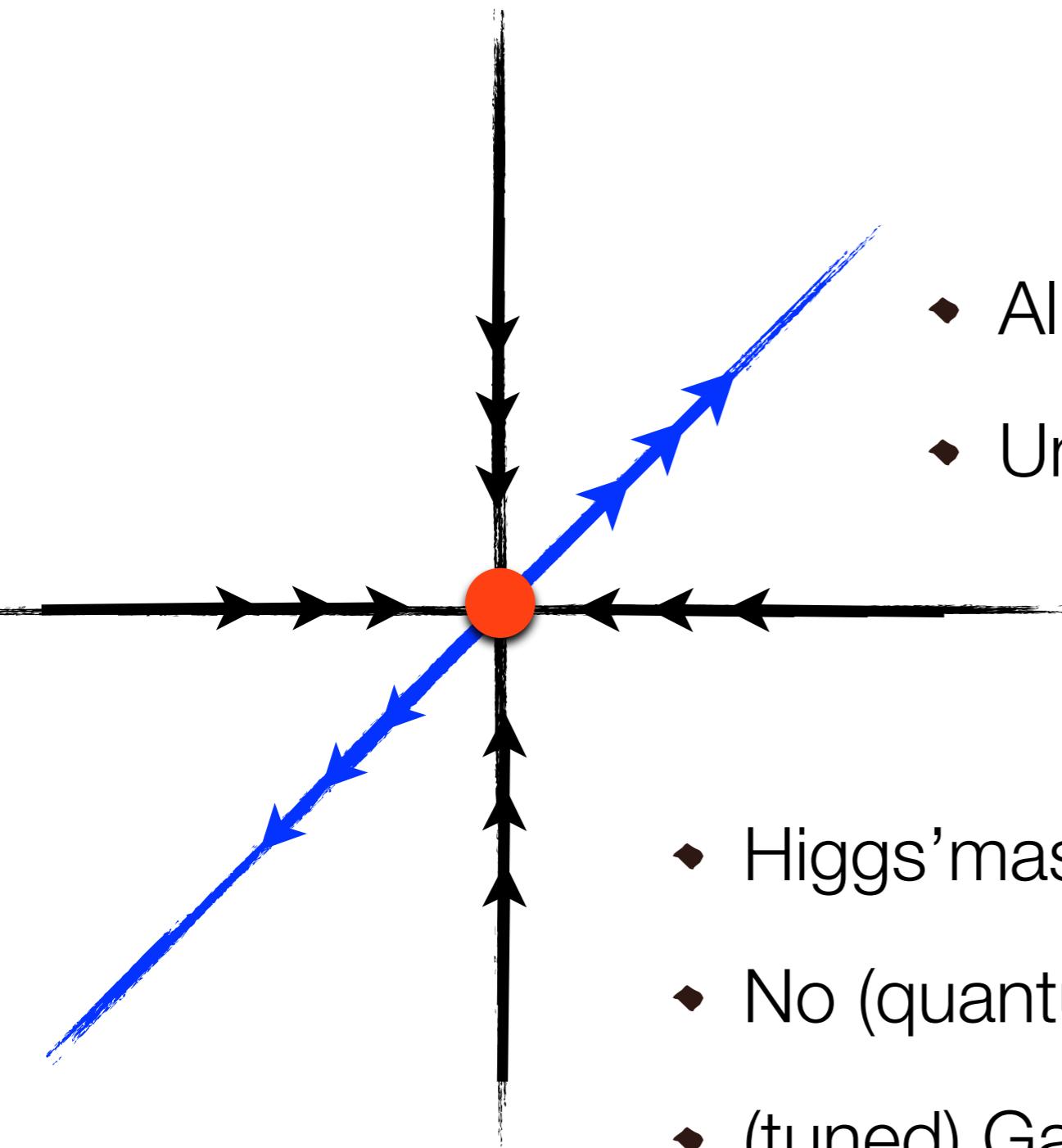
CP³ Origins
Cosmology & Particle Physics

Points

- ◆ Degrees of (un)naturality
- ◆ Composite Dark Matter
- ◆ Solving strong dark dynamics
- ◆ Confronting with experiments



RG (un)naturality



- ◆ All stable directions = Fixed point
- ◆ Unstable direction = Fine-tuned FP
- ◆ Higgs' mass = unstable direction
- ◆ No (quantum) symmetry = No protection
- ◆ (tuned) Gauge - Yukawa are interesting FTs

$$\ln \mathrm{formulæ}$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi_r)^2 - \frac{1}{2}m^2\phi_r^2 - \frac{\lambda}{4!}\phi_r^4 + \frac{\delta_Z}{2}(\partial_\mu\phi_r)^2 - \frac{\delta_m}{2}\phi_r^2 - \frac{\delta_\lambda}{4!}\phi_r^4$$

$$\phi_B \equiv \sqrt{Z}\phi_r \quad \delta_Z \equiv Z-1 \quad m^2 \equiv m_0^2Z-\delta_m \quad \delta_\lambda \equiv \lambda_0Z^2-\lambda$$

$$Z=1+f_1(\lambda,g_i)\log\frac{\Lambda^2}{m_0^2}+\ldots\qquad\qquad\qquad \delta_m=f_2(\lambda,g_i)\Lambda^2+\ldots$$

$$m^2=m_0^2(1+f_1(\lambda,g_i)\log\frac{\Lambda^2}{m_0^2})-f_2(\lambda,g_i)\Lambda^2$$

Degrees of (un)naturality

$$m^2 = m_0^2 \left(1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2} \right) - f_2(\lambda, g_i) \Lambda^2$$

- ◆ Tuning = No prediction for BSM physics*
- ◆ Tuning via “classical conformality” $\Lambda = 0, m_0 = 0$
- ◆ Delayed naturality $f_2 = 0$ Perturbatively
- ◆ Perturbative natural conformality (PNC) $f_2 = 0, m_0 = 0$

*Vacuum stability

Intriguing PNC model

- ◆ Conformal extension of the SM

Antipin, Mojaza, Sannino 2013

$$V_0 = V_0^{SM} + \lambda_{HS} H^\dagger H S^2 + \frac{\lambda_S}{4} S^4 + y_\chi S(\chi\chi + \bar{\chi}\bar{\chi})$$

$$V_0^{SM} = \lambda (H^\dagger H)^2 - \frac{1}{2} \left(g^2 W_\mu^+ W^{-\mu} + \frac{g^2 + {g'}^2}{2} Z_\mu Z^\mu \right) H^\dagger H + y_t(\bar{t}_L, 0) (i\sigma^2 H^*) t_R + \text{h.c.}$$

- ◆ 1-loop stability = Veltman conditions $f_2 = 0$

$$\begin{aligned} \lambda_{HS}(\mu_0) &= 6y_t^2(\mu_0) - \frac{9}{4}g^2(\mu_0) - \frac{3}{4}g'^2(\mu_0) \stackrel{\mu_0 \approx v}{\approx} 4.84 , & \lambda(\mu_0) &\approx 0 \quad \text{CW flatness} \\ \lambda_S(\mu_0) &= \frac{8}{3}y_\chi^2(\mu_0) - \frac{4}{3}\lambda_{HS}(\mu_0) \stackrel{\mu_0 \approx v}{\approx} \frac{8}{3}y_\chi^2(\mu_0) - 6.45 & \mu_0 &\simeq 246 \text{ GeV} \end{aligned}$$

- ◆ Higgs mass and its self-coupling vanish at tree-level

2 predictions

- ◆ Coleman E. Weinberg one-loop Higgs mass

$$m_h^2 = \frac{3}{8\pi^2} \left[\frac{1}{16} (3g^4 + 2g^2 g'^2 + g'^4) - y_t^4 + \frac{\lambda_{HS}^2}{3} \right] v^2 \quad \Rightarrow \quad m_h \approx 126 \text{ GeV ,}$$

- ◆ Tree - level induced S-mass

$$m_S^2 = \lambda_{HS} v^2 \quad \Rightarrow \quad m_S \approx 541 \text{ GeV}$$

- ◆ PNC models are very constrained

Natural theories

$$m^2 = m_0^2 \left(1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2} \right) - f_2(\lambda, g_i) \Lambda^2$$

- ◆ A symmetry exists protecting $f_2 = 0$
- ◆ Cutoff is physical as in composite models

Degrees of naturality



SM

Space of 4d theories

Delayed naturality

Veltman**

Natural

Susy/Technicolor

Classical CF (SSB via CW*)

Higgs = pseudo-dilaton,
With UV cutoff is unnatural

**Perturbative natural
conformality**

CW + Veltman

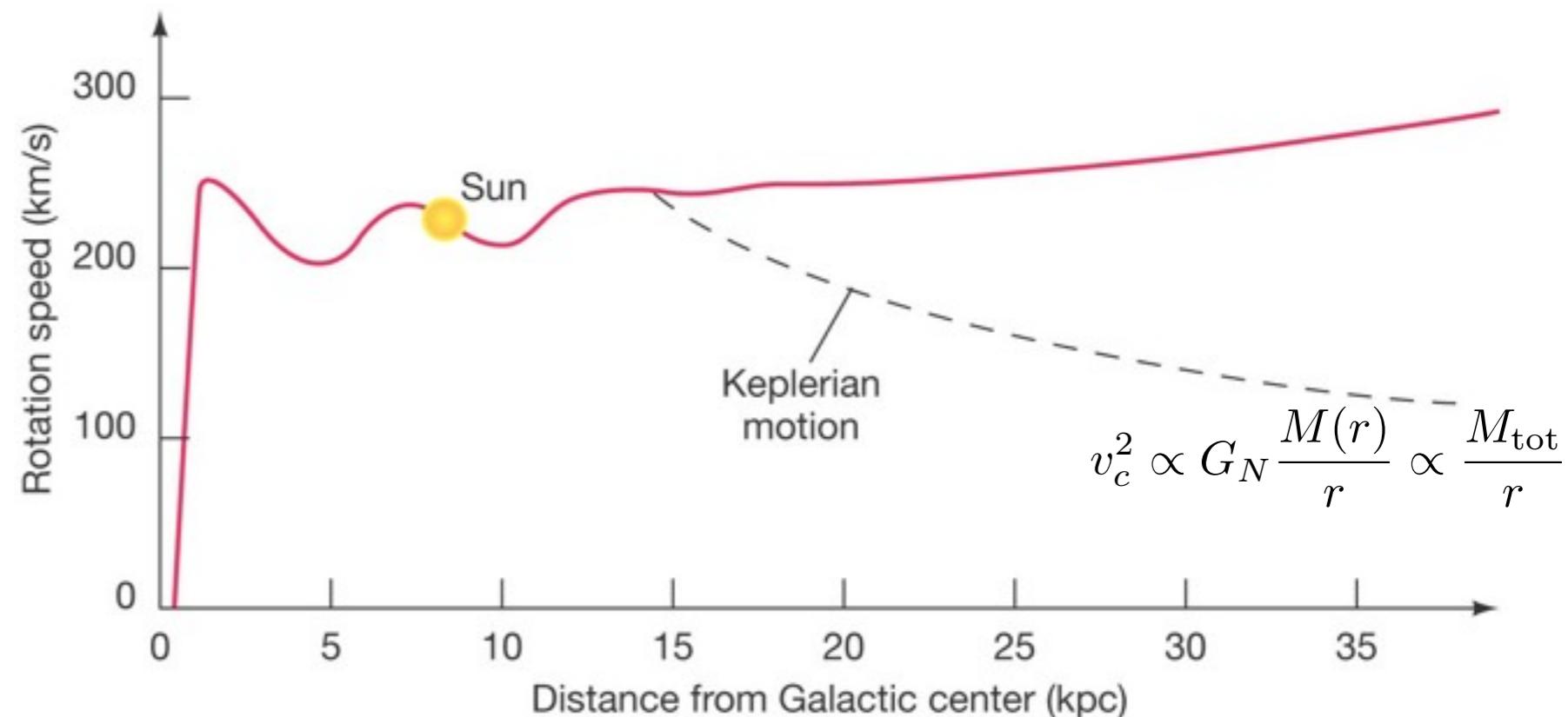
New physics needed!

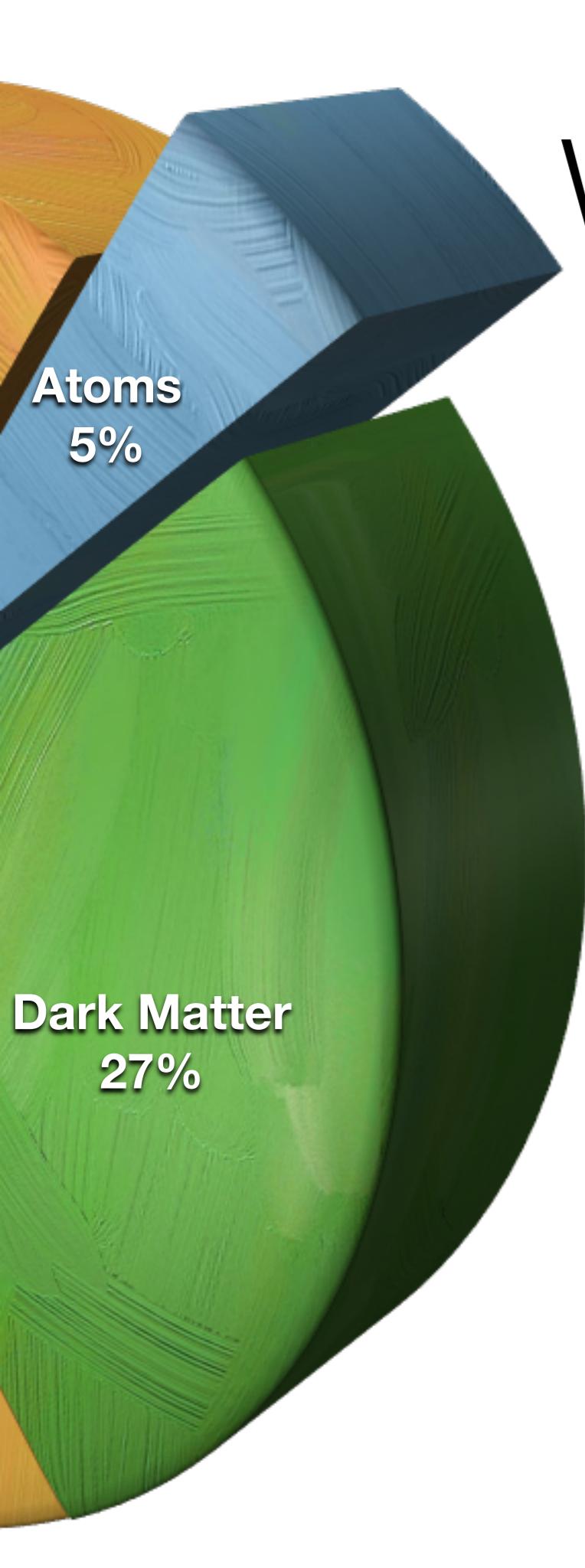
* CW = Coleman-Weinberg

**Perturbative cancellation of quadratic divergences

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





What makes dark matter ?

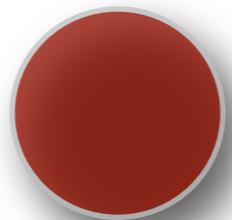
Atoms: 3 forces and many fund. particles

DM oversimplification

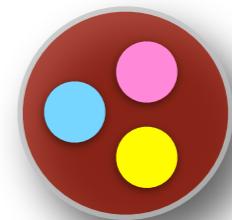
DM Particle

???

Elementary

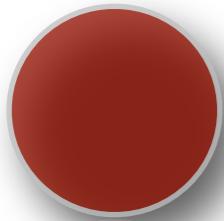


Composite



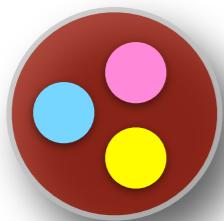
Incomplete DM list

Elementary



- ◆ Unnatural, classical conformality, delayed naturality
- ◆ Perturbative natural conformality
- ◆ Natural extensions [Susy,...]
- ◆ Axions
- ◆ ...

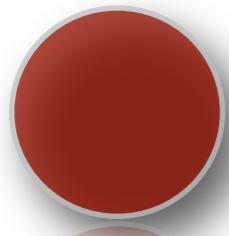
Composite



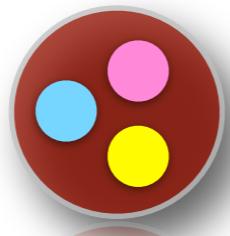
- ◆ New QCD-like sectors added by hand
- ◆ Composite DM from composite EW [Technicolor,...]
- ◆ Composite axions
- ◆ ...

In practice

Elementary

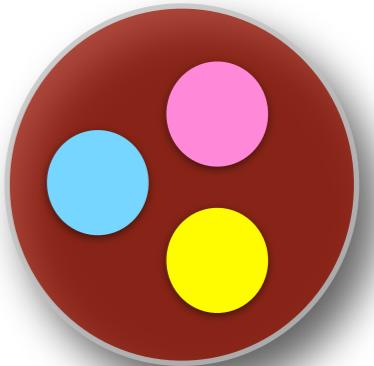


Composite



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

Building composite DM

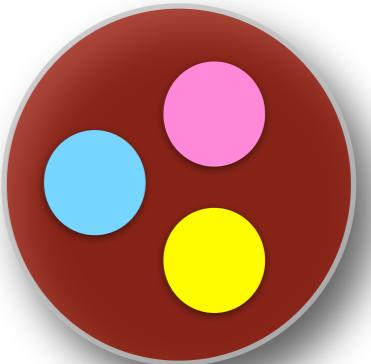


- ◆ Gauge theories with fermionic matter
- ◆ Gauge group: SU, SO, Sp, Exceptional
- ◆ Choose matter repr.
- ◆ Embed SM [e.g. Dynamical EWSB]

Resulting composite DM can be

- ◆ A fermion
- ◆ A (Goldstone) boson

Solve new strong dynamics!

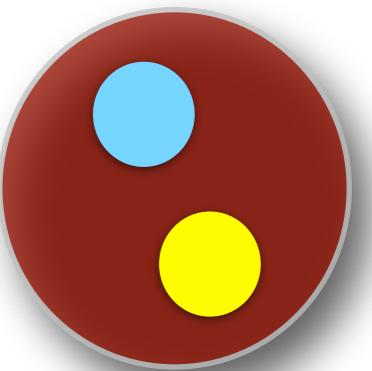


(2-flavors) QCD - like

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

$$SU(2) \times SU(2) \rightarrow SU(2)$$

- ◆ 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

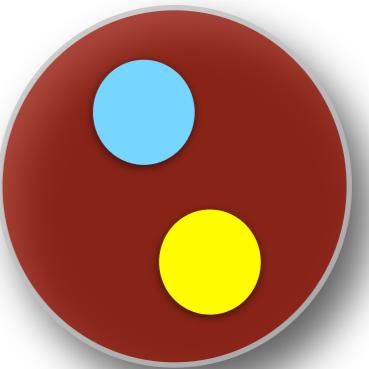
Ryttov, Sannino, 2008

Järvinen, Ryttov, Sannino, 2009

Lewis, Pica, Sannino 2012

Hietanen, Lewis, Pica, Sannino 2013

Sp(2)



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

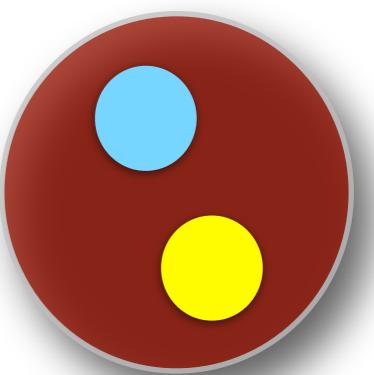
$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 C \bar{U}_R^T \\ -i\sigma^2 C \bar{D}_R^T \end{pmatrix}$$

- ◆ Act. invariant under SU(4) transf.

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

- ◆ Mass term respects Sp(4) with 10 generators

$$\delta \mathcal{L} = \frac{m}{2} Q^T (-i\sigma^2) C E Q + \text{h.c.} \quad E = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$



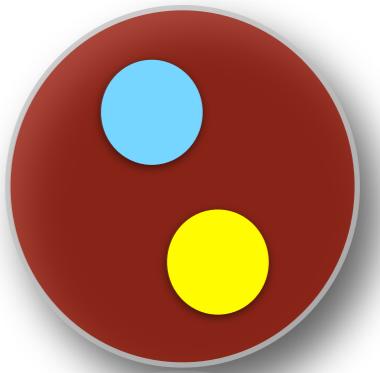
Theoretical expectations

- ◆ @ m=0

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

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

Hadronic operators



- ◆ Mesons

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

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

$$\mathcal{O}_{\bar{U}U \pm \bar{D}D}^{(\Gamma)} \equiv \frac{1}{\sqrt{2}} \left(\bar{U}(x)\Gamma U(x) \pm \bar{D}(x)\Gamma D(x) \right)$$

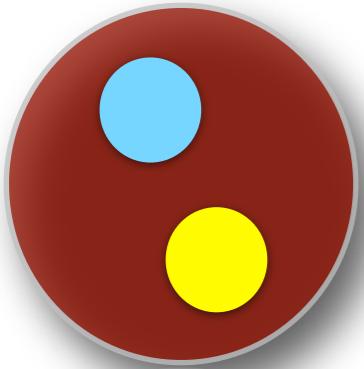
$$\mathcal{O}_{UD}^{(\Gamma)} \equiv U^T(x)(-i\sigma^2)C\Gamma D(x) ,$$

- ◆ Baryons (diquarks)

$$\mathcal{O}_{DU}^{(\Gamma)} \equiv D^T(x)(-i\sigma^2)C\Gamma U(x) ,$$

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

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



Facts

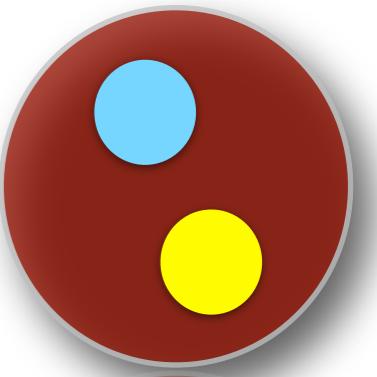
- ◆ Mesons and baryons are mass-degenerate
- ◆ Equal angular momentum & opposite parity

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

$$P\left(\mathcal{O}_{UD}^{(\Gamma)}\right) = -P\left(\mathcal{O}_{\overline{U}\overline{D}}^{(\Gamma)}\right)$$

- ◆ 5 Goldstones

pseudoscalar	Π^+	Π^-	Π^0
scalar baryon	Π_{UD}	$\Pi_{\overline{U}\overline{D}}$	



Minimal TC Model & DM

- ◆ Gauge $SU_L(2) \times U_Y(1)$ in $SU(4)$

Appelquist, Sannino, 98, 99

Ryttov, Sannino, 2008

Järvinen, Ryttov, Sannino, 2009

$$F_\Pi \simeq 256 \text{ GeV}$$

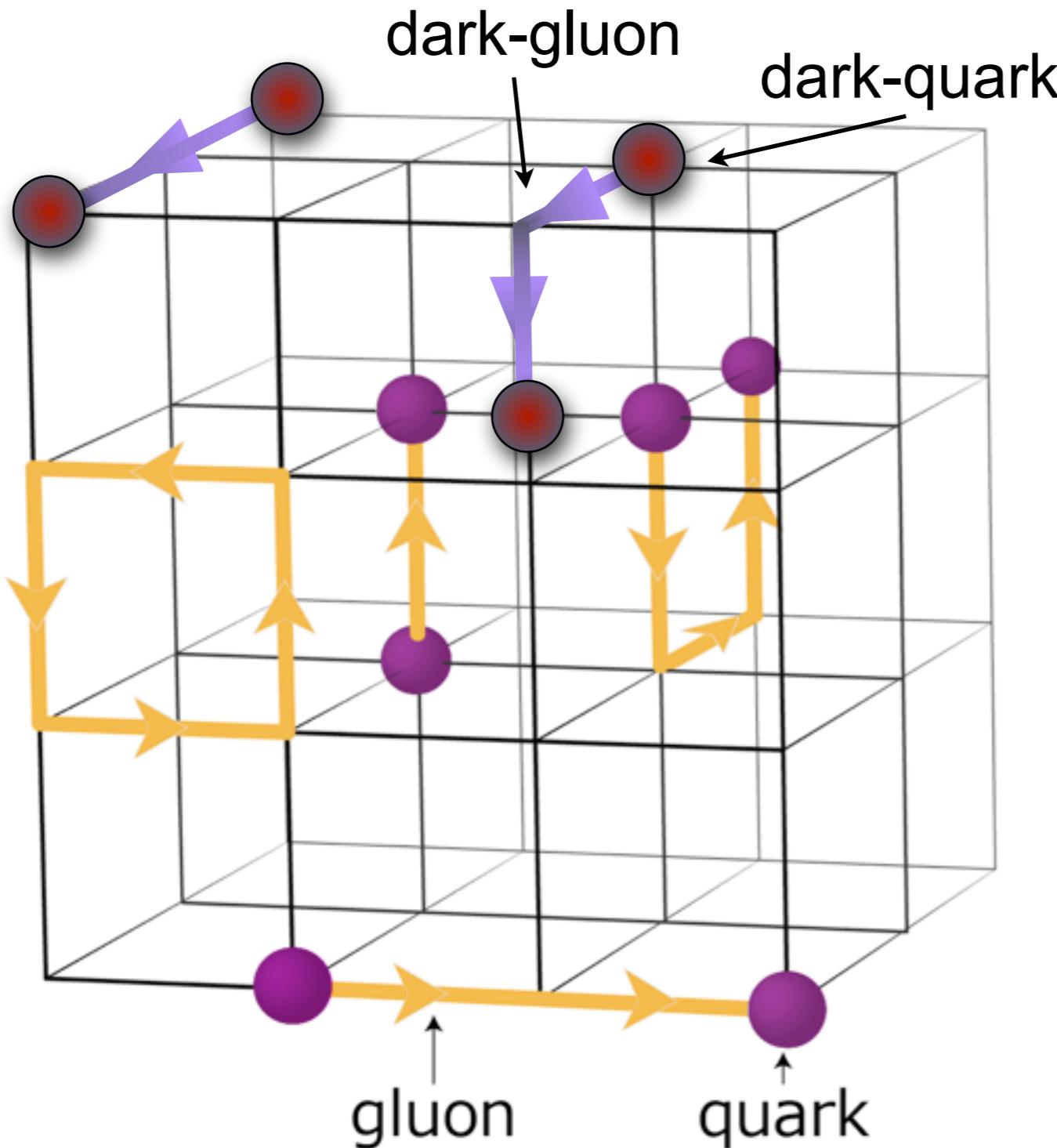
- ◆ Such that

$$\begin{array}{ccc} \Pi^+ & \Pi^- & \Pi^0 \end{array} \quad \text{Longitudinal W and Z}$$

$$\begin{array}{cc} \Pi_{UD} & \Pi_{\overline{UD}} \end{array} \quad \text{Goldstone DM \& anti-DM, SM singlet}$$

- ◆ Fermion mass generation sectors can yield mass to DM

Dark matter on Lattice



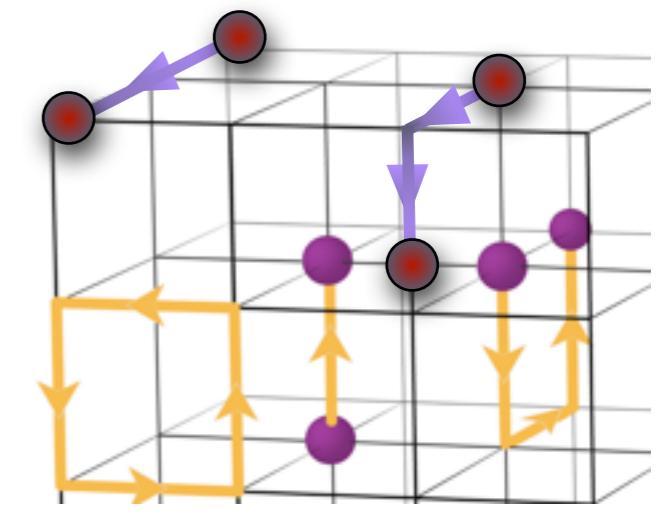
Lewis, Pica, Sannino 2012

Hietanen, Pica, Sannino, Søndergaard 2013

Hietanen, Lewis, Pica, Sannino 2013

Dark Wilson action

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



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	32^4	-0.72, -0.75	500	~ 2000

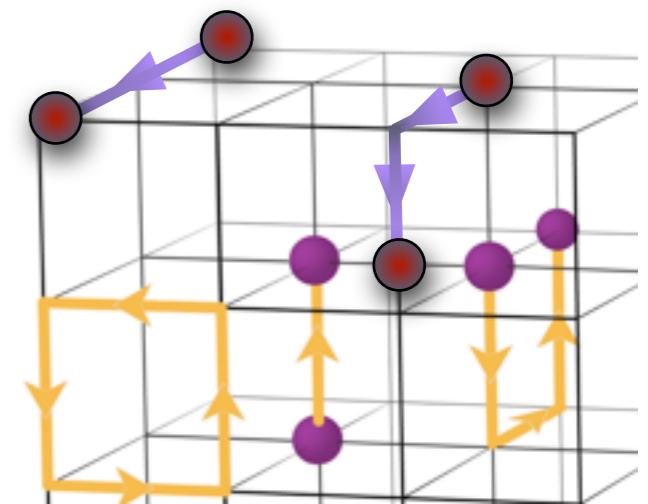
Table 1: Parameters used in the simulations. The thermalization column refers to the number of discarded initial configurations and the configuration column refers to the number of independent configurations used in measurements.

- ◆ Fermion mass via PCAC

$$m_q = \lim_{t \rightarrow \infty} \frac{1}{2} \frac{\partial_t V_\Pi}{V_{PP}}$$

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

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



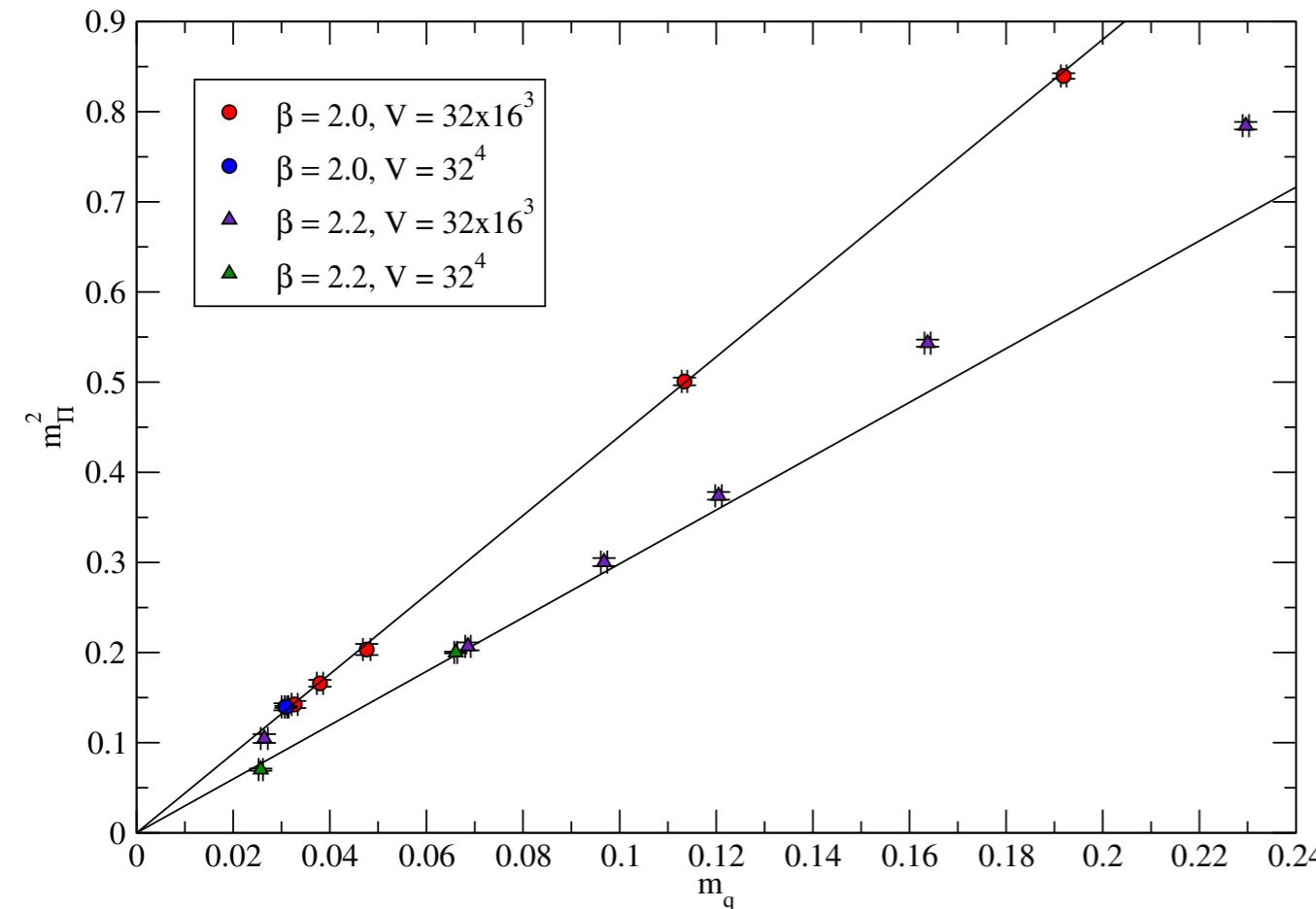
- ◆ Decay constant

$$f_\Pi = \frac{m_q}{m_\Pi^2} G_\Pi$$

$$V_{PP}(t_i - t_f) = -\frac{G_\Pi^2}{m_\Pi} \exp [-m_\Pi(t_i - t_f)]$$

- ◆ 2 point functions

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



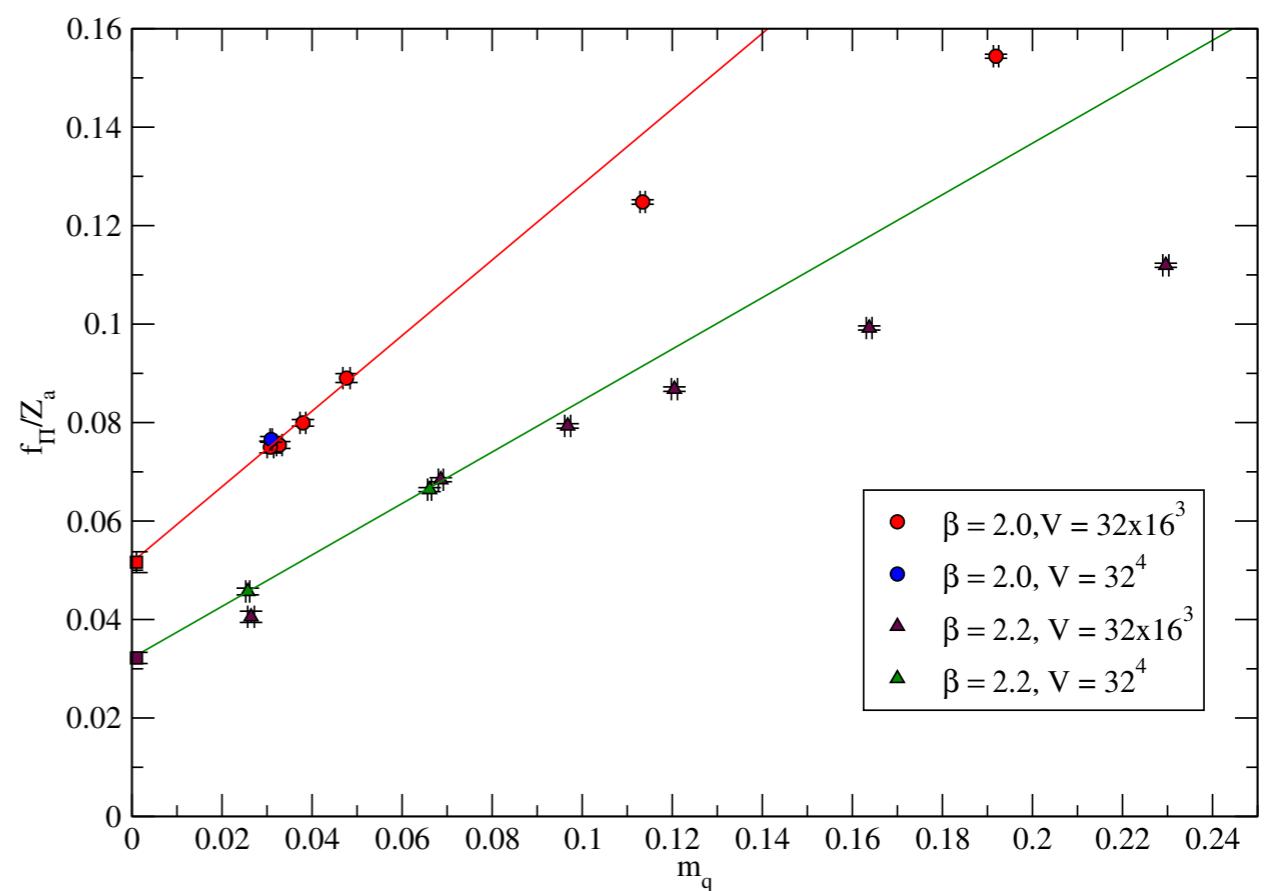
◆ Chiral symmetry breaks

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

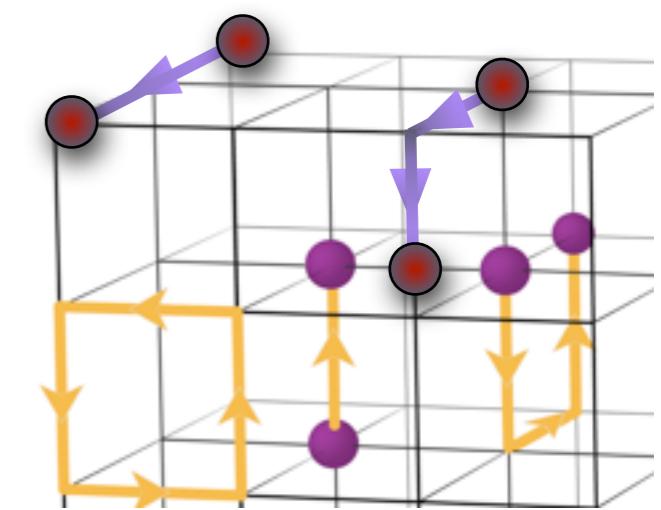
◆ Nonzero decay constant

◆ Perturbative estimate of Z_a

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

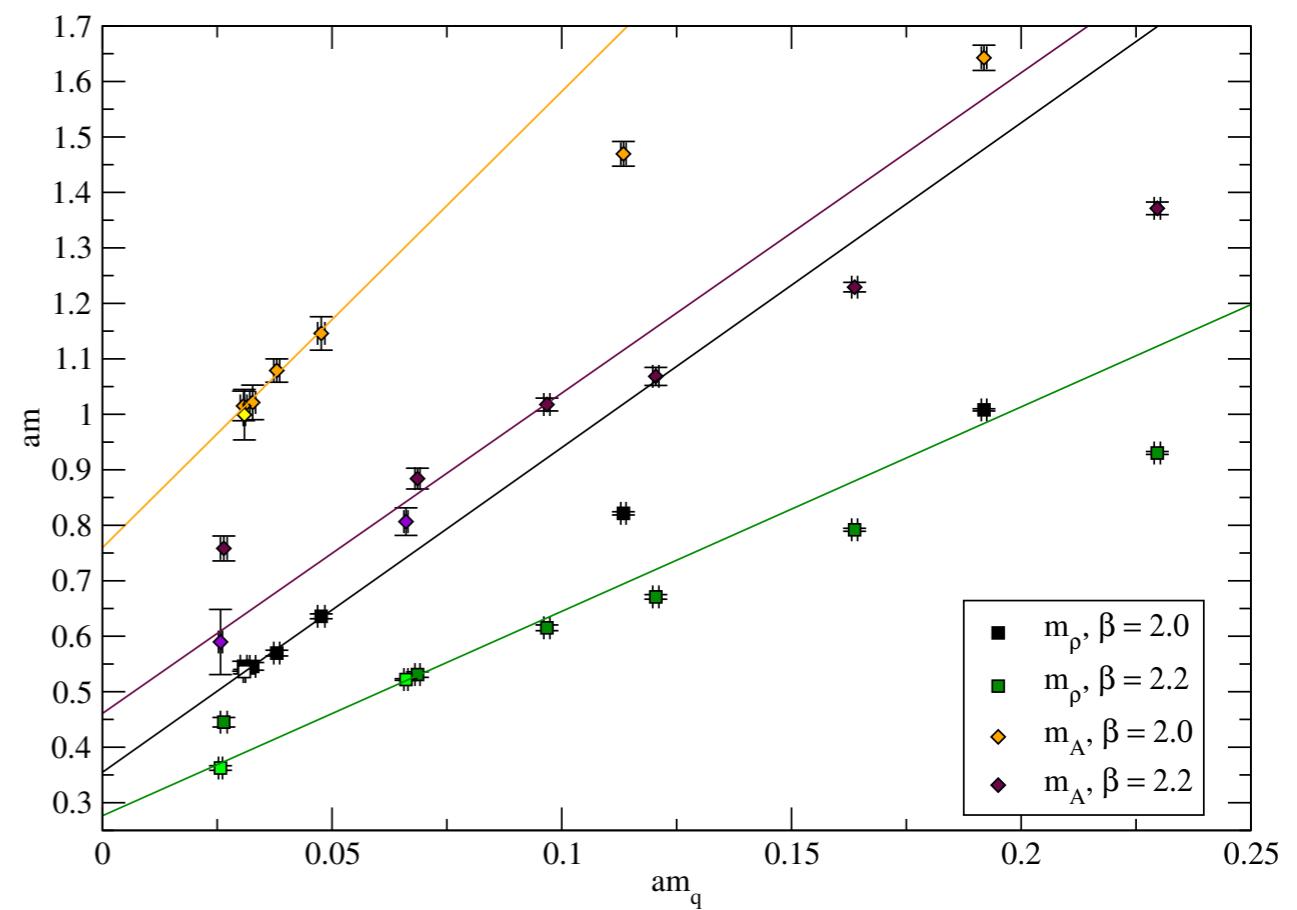


Spin one spectrum



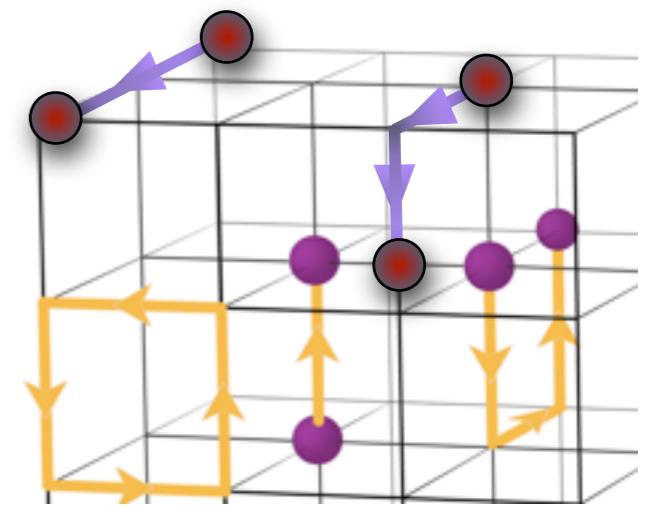
$m_\rho \approx 2500$ GeV

$m_A \approx 3200$ GeV



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



Dark coupling to photon via charge radius

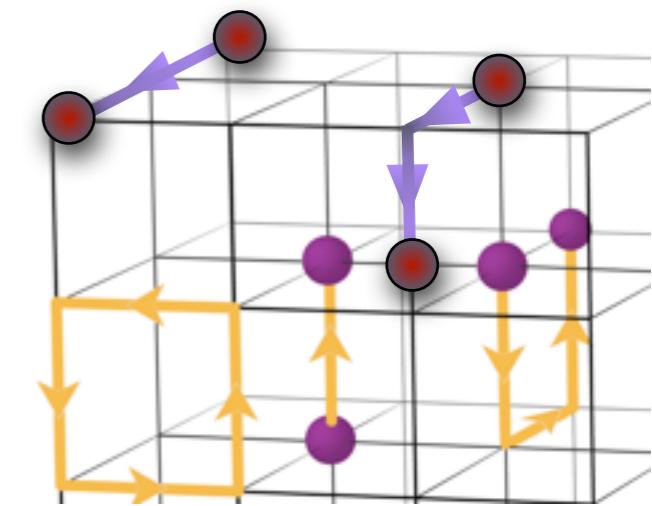
$$\phi \equiv \Pi_{UD}$$

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

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

Lattice prediction

- Form factor requires isospin breaking from ETC



Lattice compute

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

- EM cross section with proton

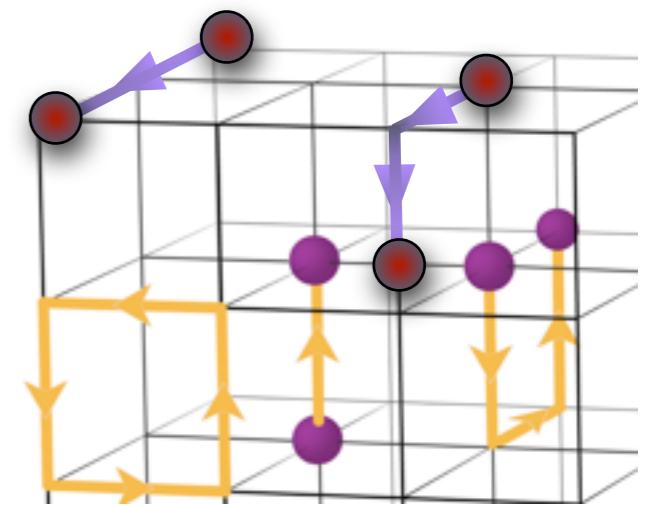
$$\sigma_p^\gamma = \frac{\mu^2}{4\pi} \left(\frac{8\pi\alpha d_B}{\Lambda^2} \right)^2 \quad \mu = \frac{m_\phi m_N}{m_\phi + m_N} \quad |d_B| < 1 \quad m_\phi > m_p$$

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

First principle !

Composite Higgs ?

Basic interactions



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

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

DM is a GB

Cross section with the proton

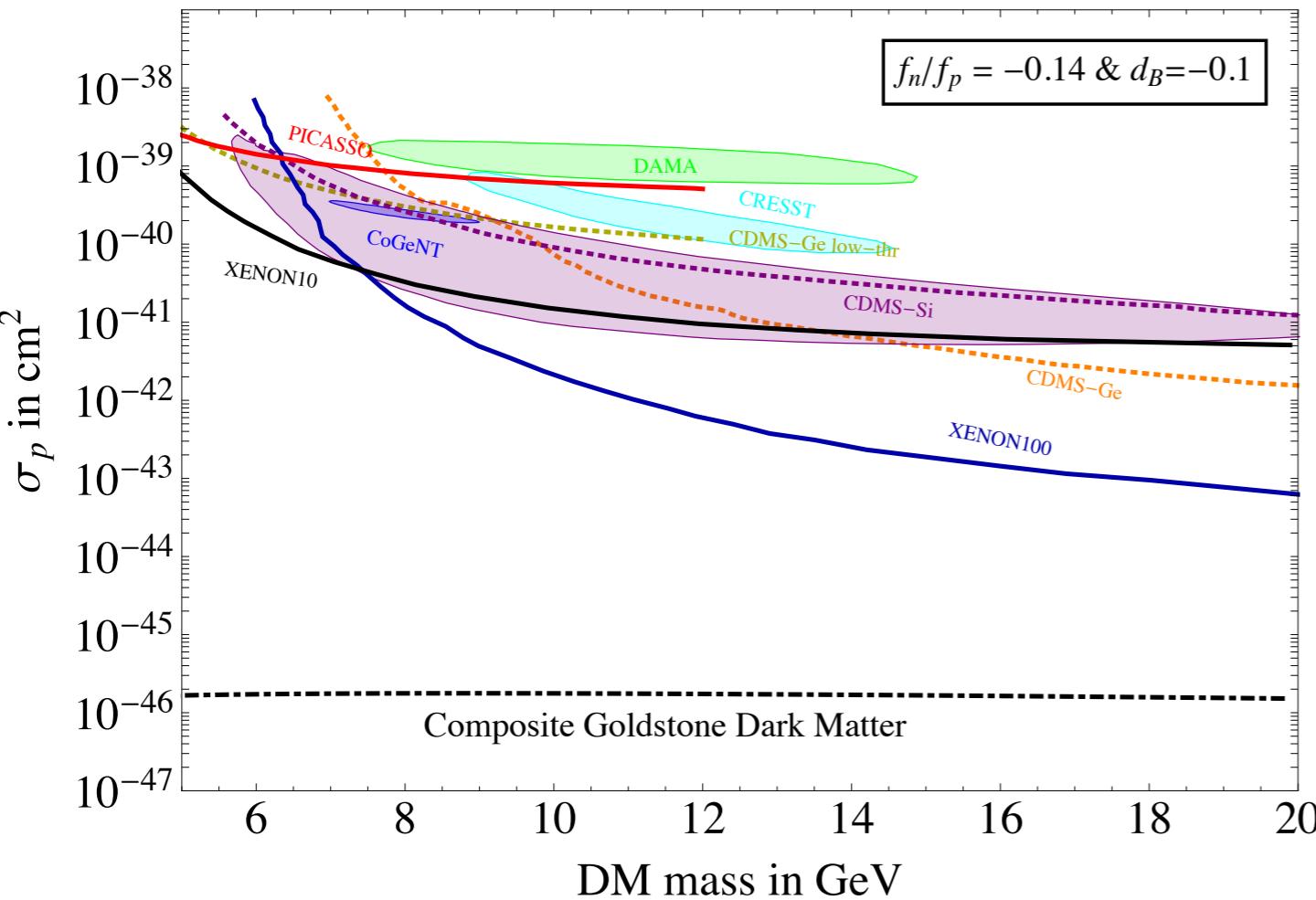
$$\sigma_p = \frac{\mu^2}{4\pi} \left[\frac{(d_1 + d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} + 8\pi\alpha \frac{d_B}{\Lambda^2} \right]^2$$

$$f \simeq 0.3$$

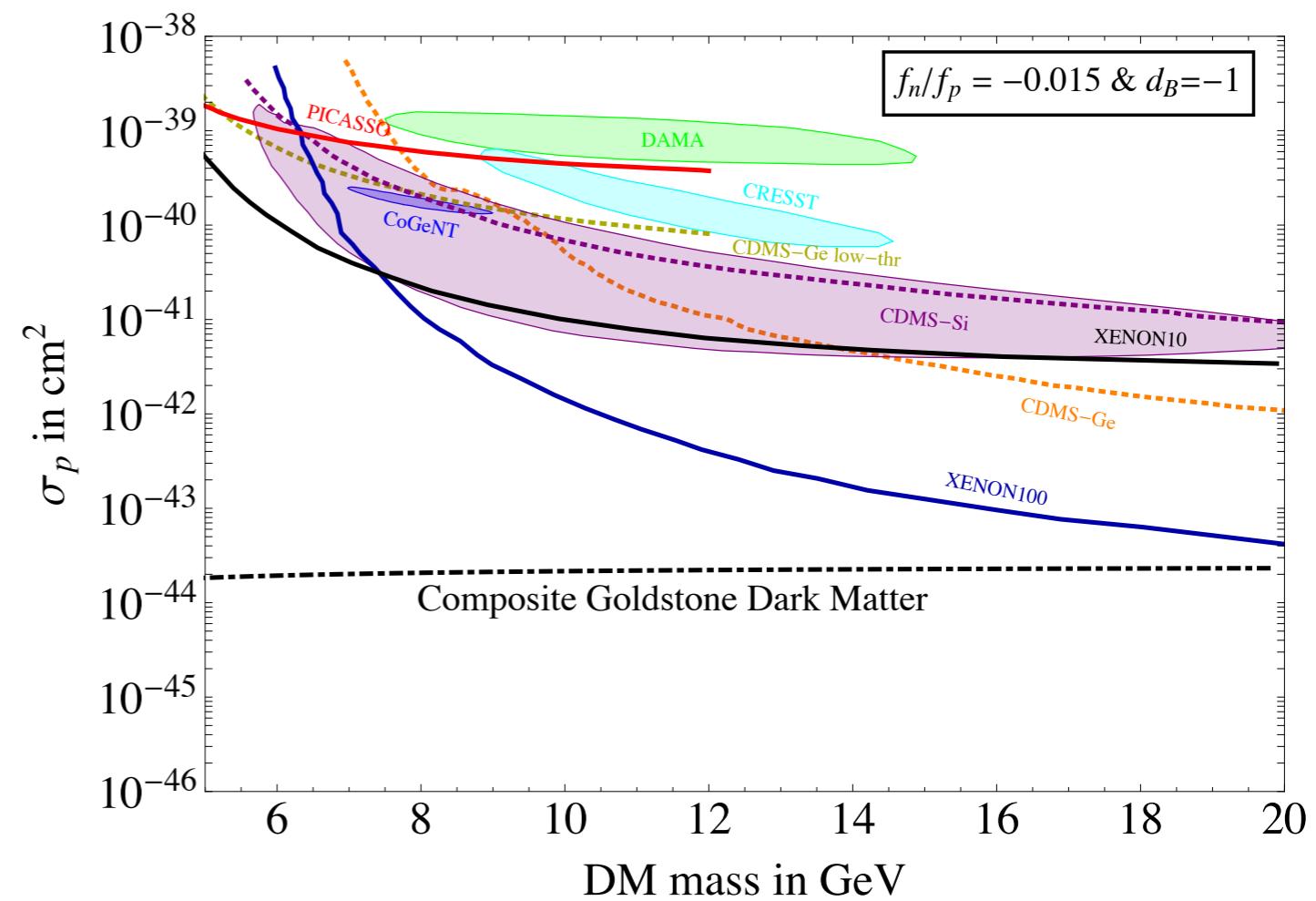
$$f_n = -\frac{(d_1 + d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda}$$

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

Experiments



Lattice



Summary

RG (un)naturality

PNC model

A natural avenue: Compositeness

Composite dark matter

Template for a composite Goldstone DM

First principle dark lattice simulations