Strong Dynamics

A treasure trove for Standard Model & Beyond

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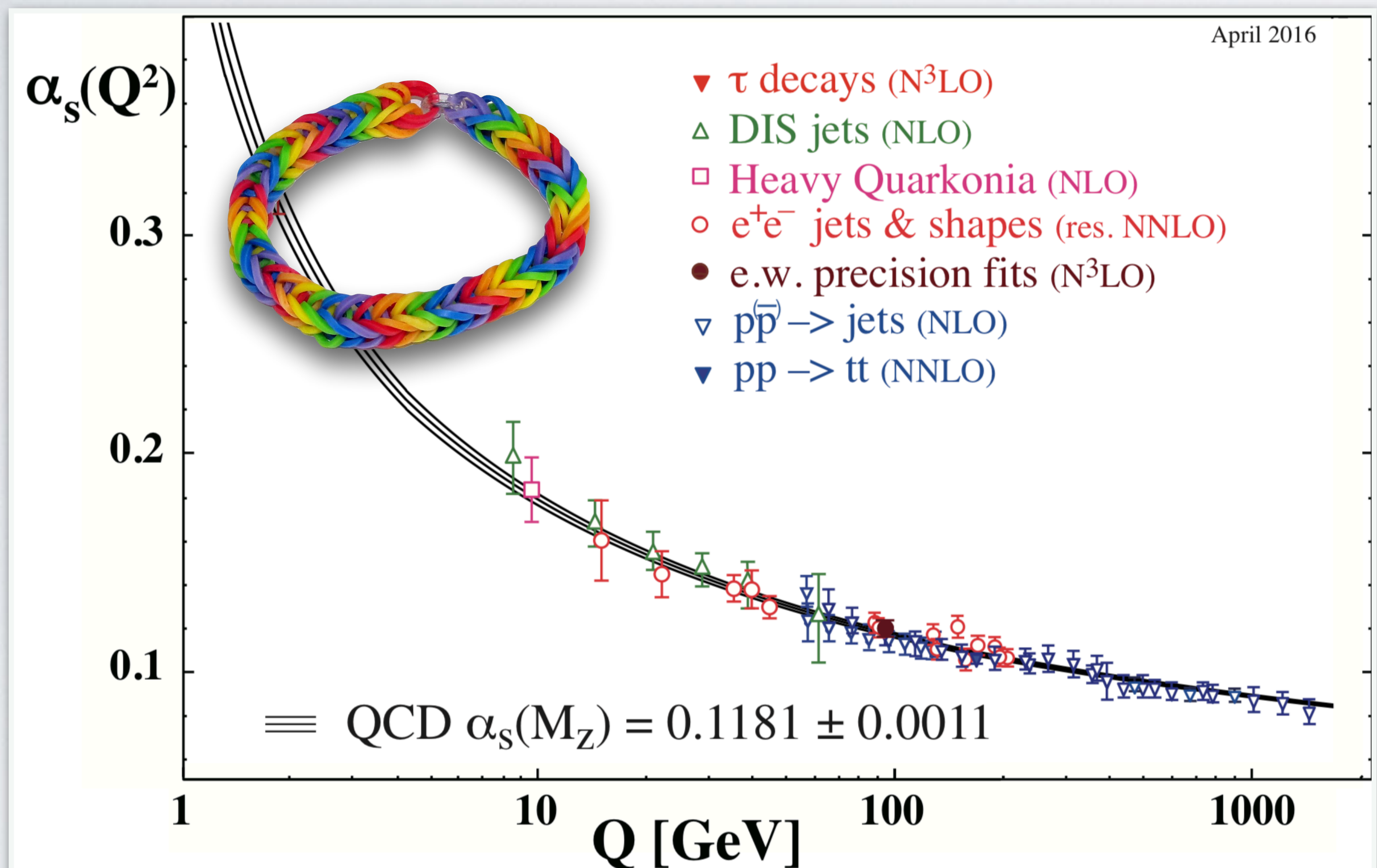
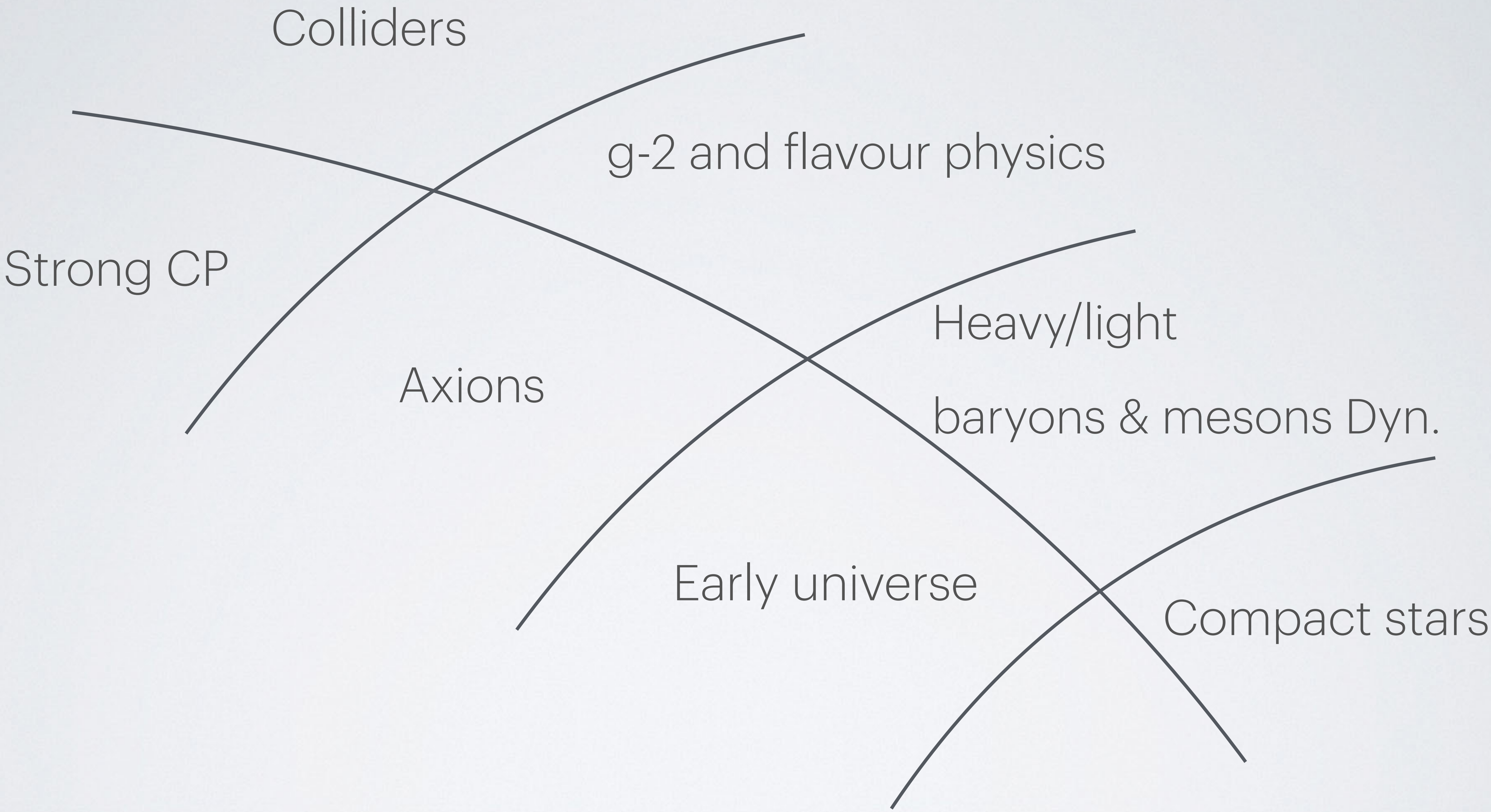
Quantum Chromodynamics

1973



51 years of QCD

QCD


Colliders
g-2 and flavour physics
Strong CP
Heavy/light
Axions
baryons & mesons Dyn.
Early universe
Compact stars

Matter Phase Diagram

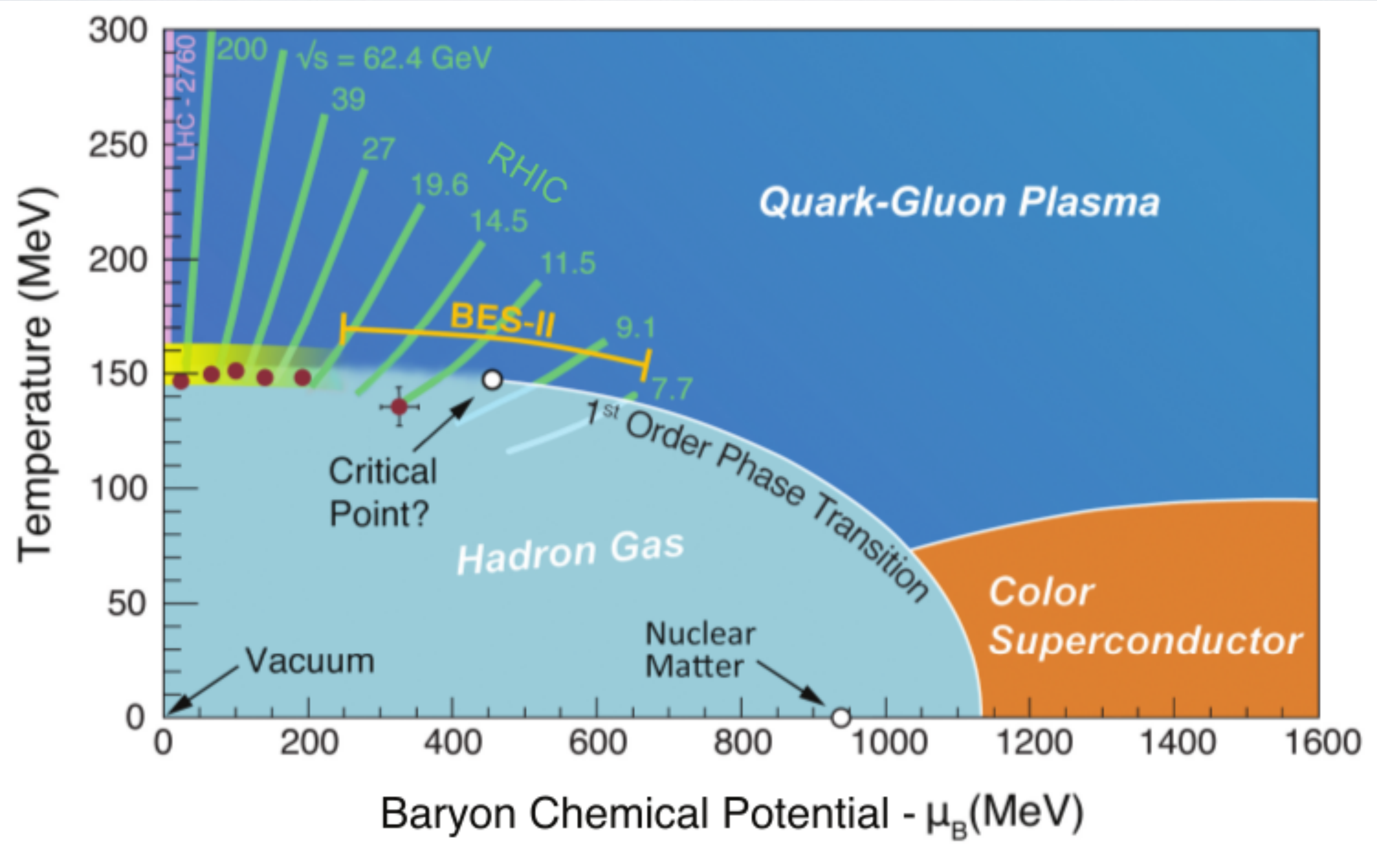
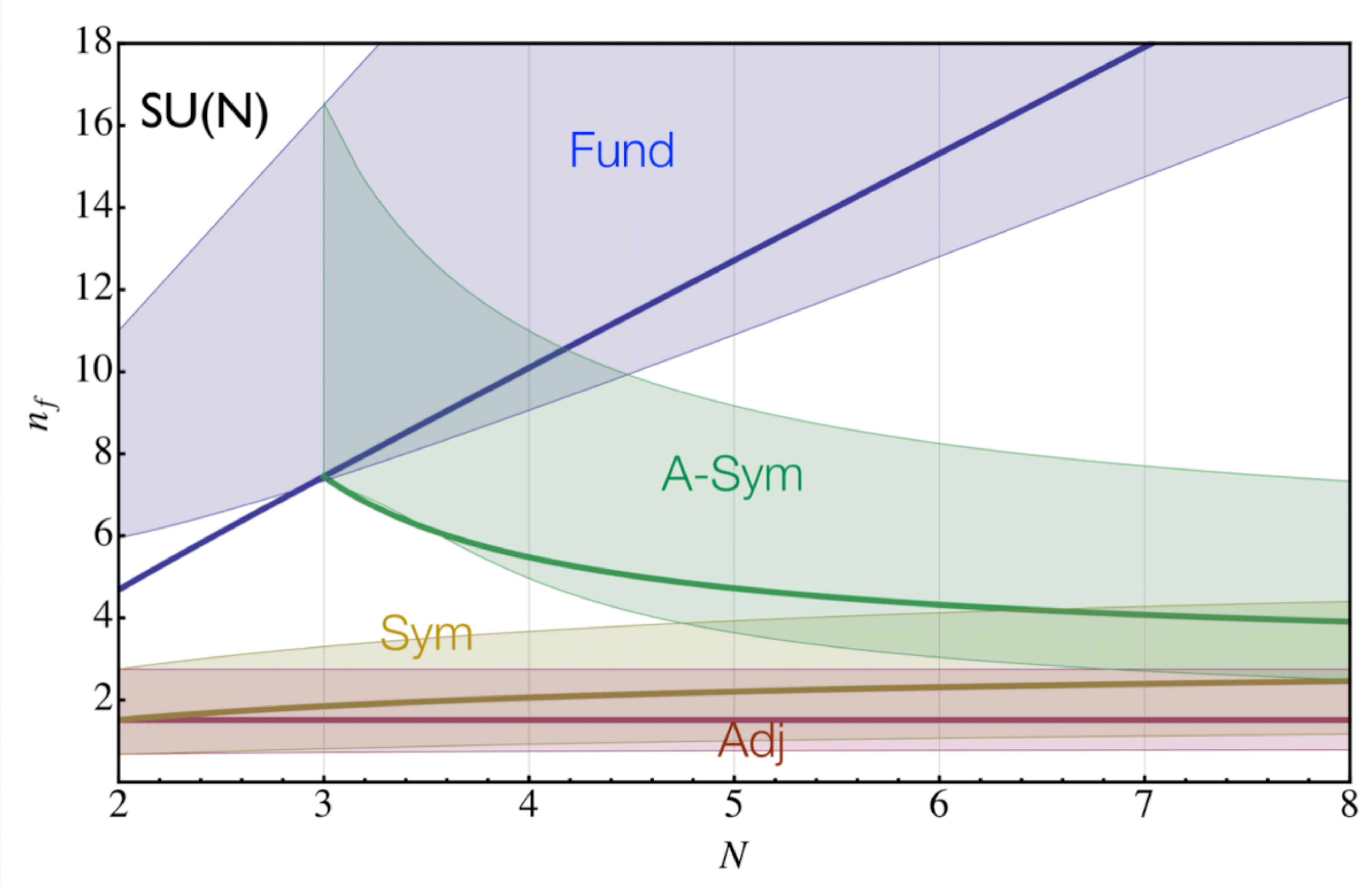


Diagram from [NSAC 2015 Long Range Plan for Nuclear Physics](#).

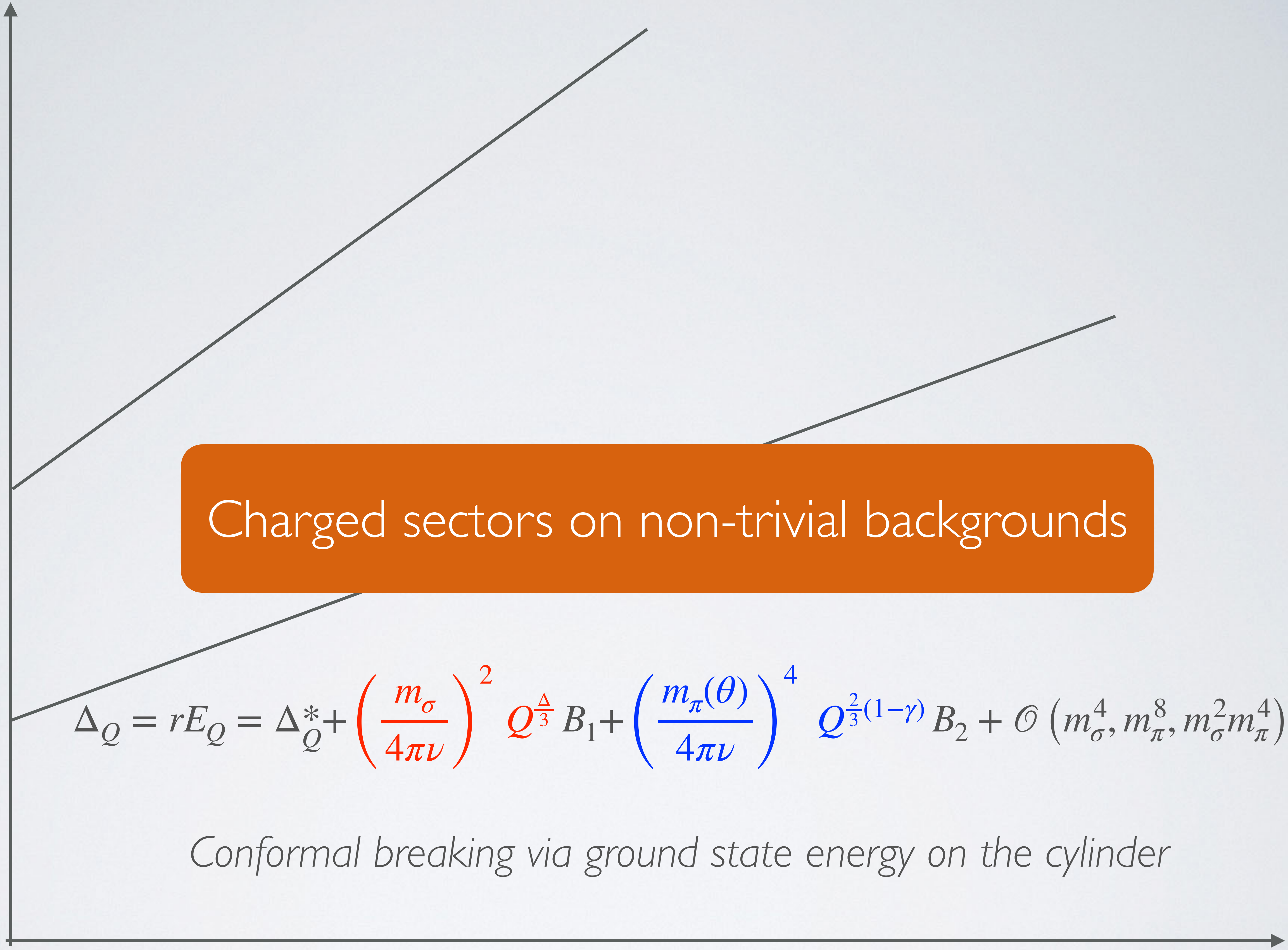
Quantum Phase Diagram



Appelquist, Karabali, Wijewardhana 86

Sannino, Tuominen, PRD 71 (2005) 051901

Dietrich, Sannino, PRD 75 (2007) 085018



Charged sectors on non-trivial backgrounds

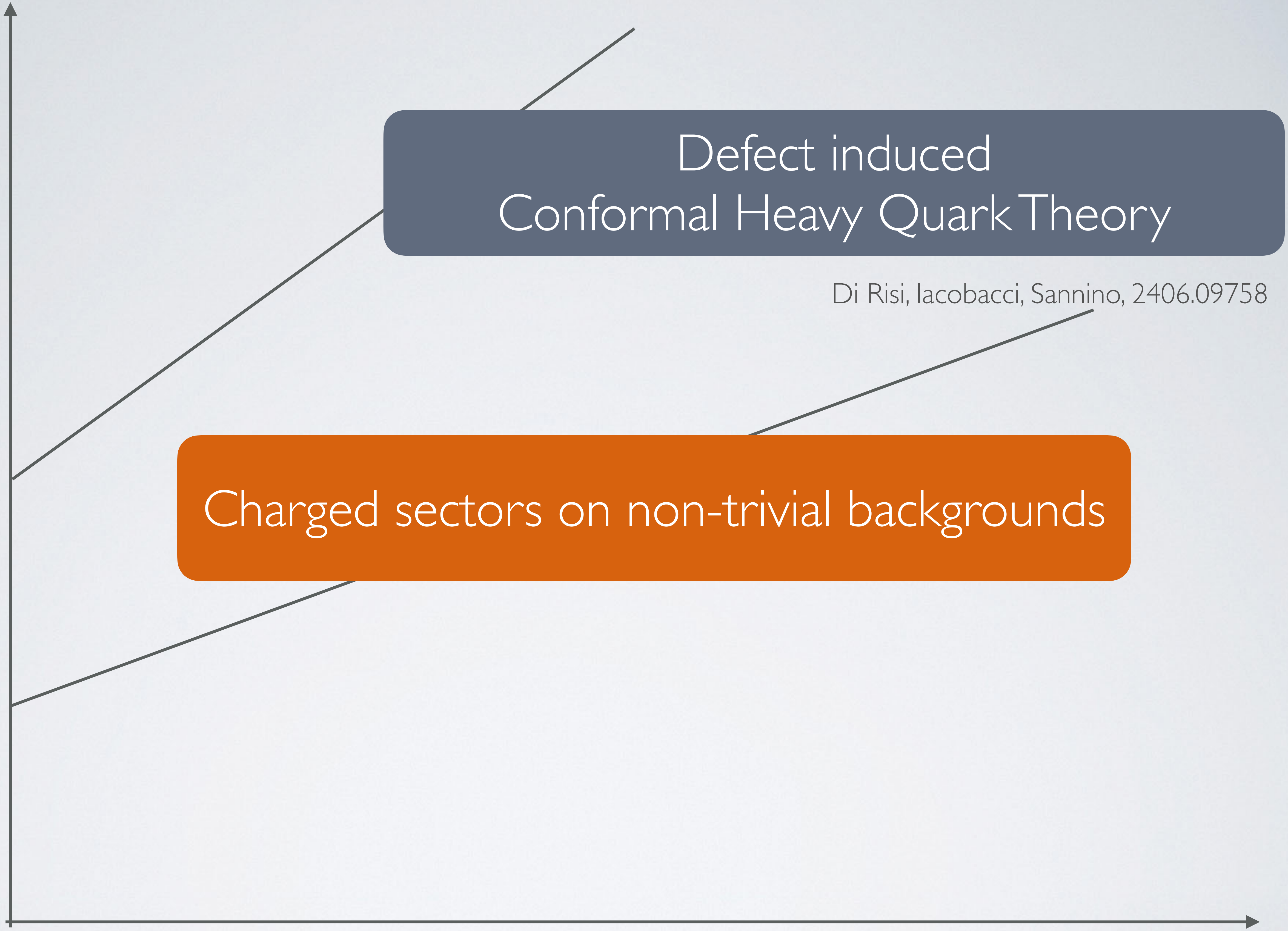
$$\Delta_Q = rE_Q = \Delta_Q^* + \left(\frac{m_\sigma}{4\pi\nu}\right)^2 Q^{\frac{\Delta}{3}} B_1 + \left(\frac{m_\pi(\theta)}{4\pi\nu}\right)^4 Q^{\frac{2}{3}(1-\gamma)} B_2 + \mathcal{O}\left(m_\sigma^4, m_\pi^8, m_\sigma^2 m_\pi^4\right)$$

Conformal breaking via ground state energy on the cylinder

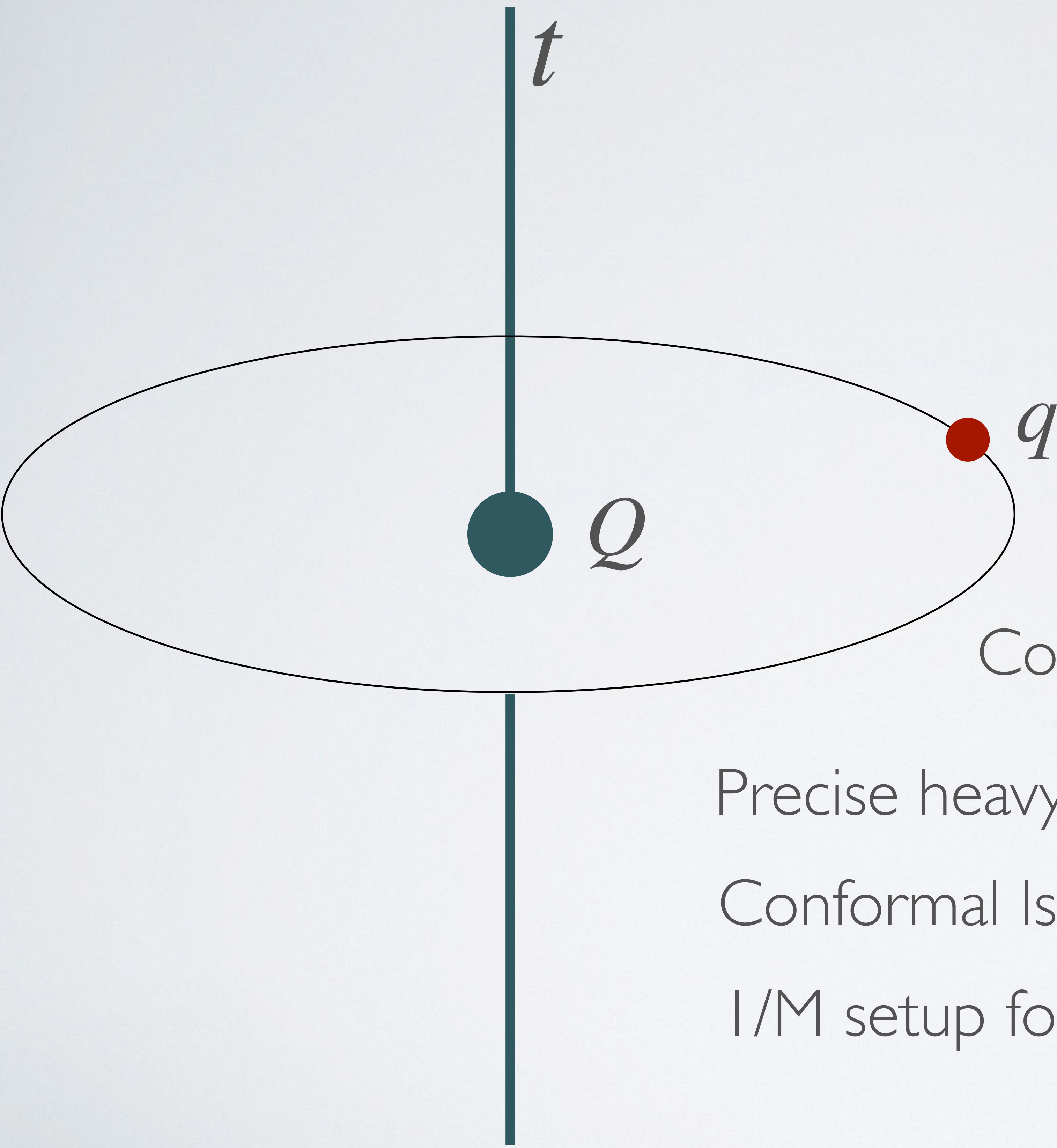
Orlando, Reffert, Sannino, PRD101(2020) 6, 065018: *PRD*103(2021)10, 105026

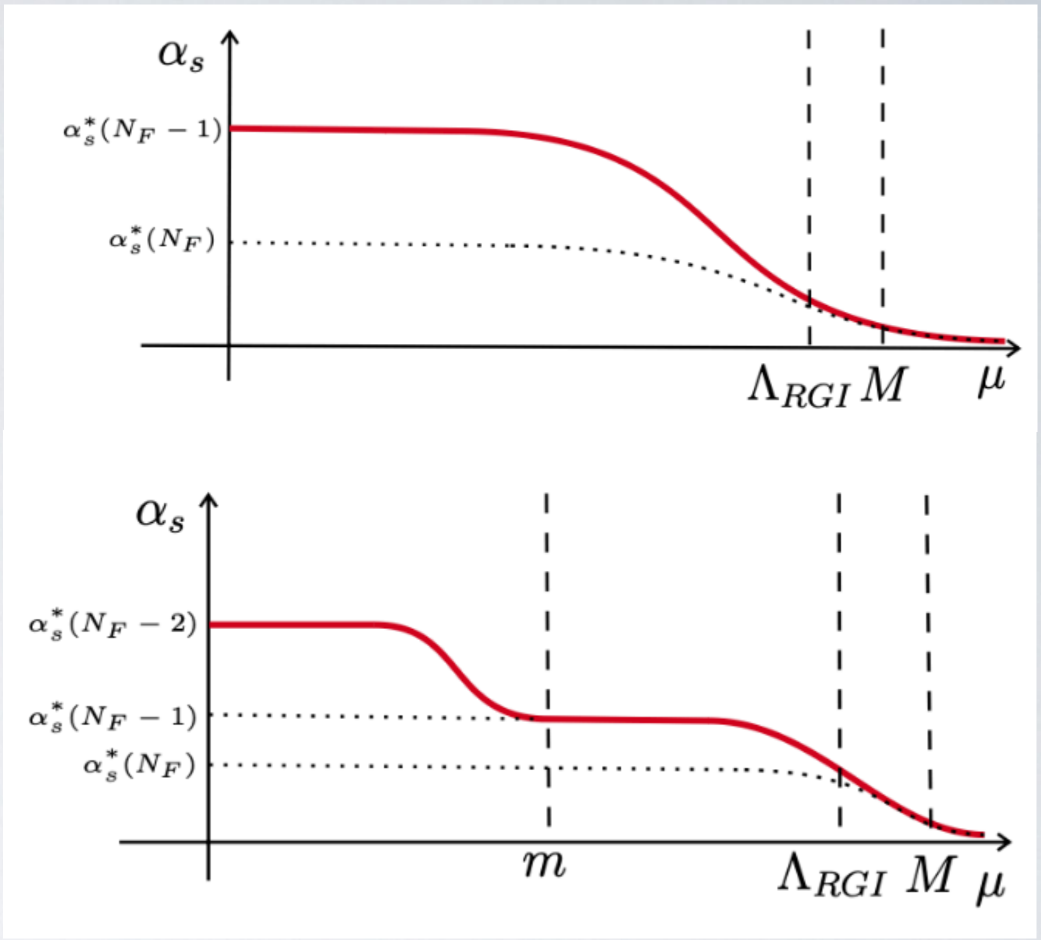
Bersini, D'Alise, Sannino, Torres, JHEP 11(2022)080; PR107(2023)12,12;

Bersini, D'Alise, Gambardella, Sannino,, in PRD


Defect induced
Conformal Heavy Quark Theory
Di Risi, Iacobacci, Sannino, 2406.09758
Charged sectors on non-trivial backgrounds

Wilson line defect / Massive heavy quark





Conformal brown muck

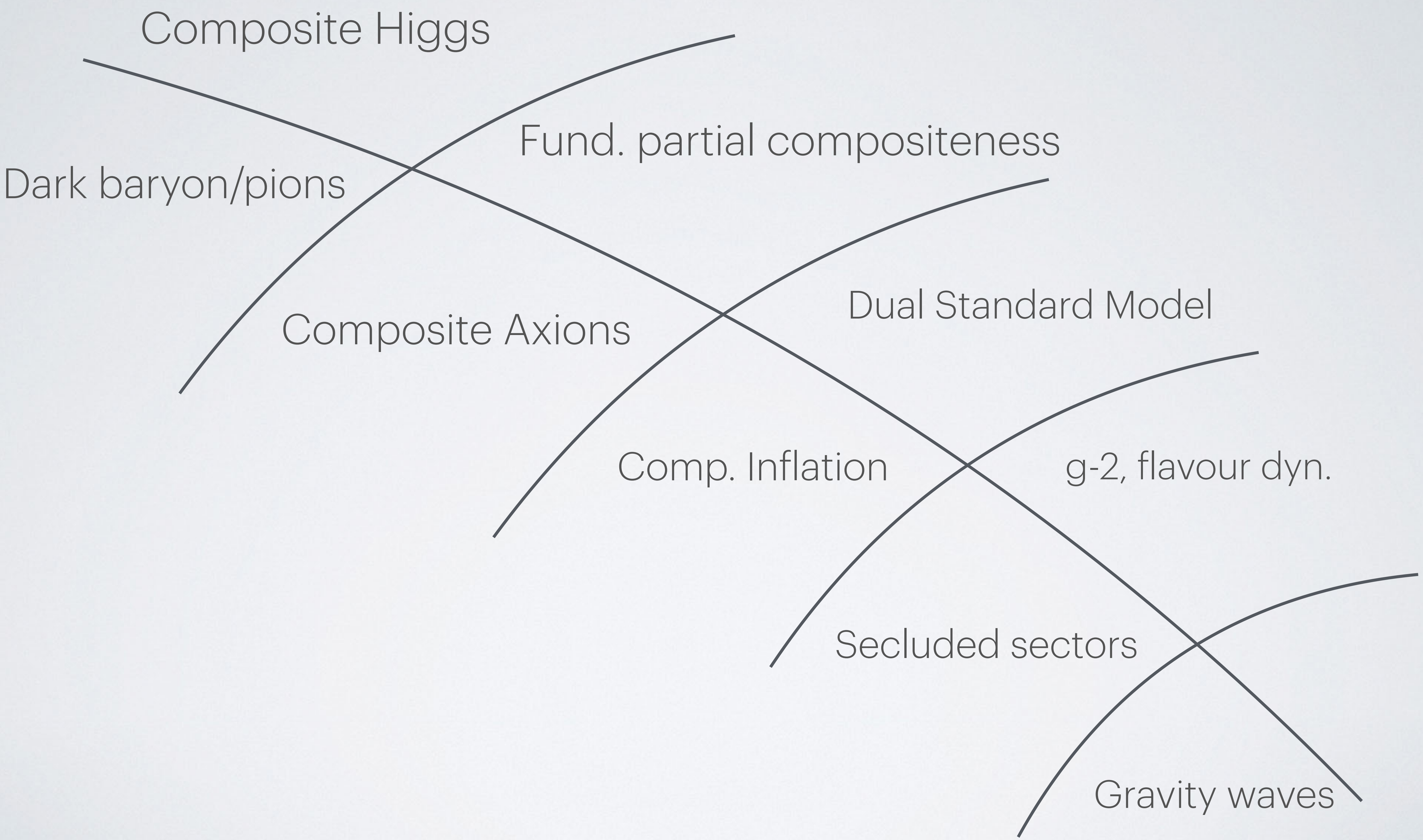
Precise heavy meson spectrum

Conformal Isgur-Wise function

1/M setup for Dynamical Defects

Di Risi, Iacobacci, Sannino, 2406.09758

New composite dynamics



Dual Standard Model

Standard Model Higgs

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

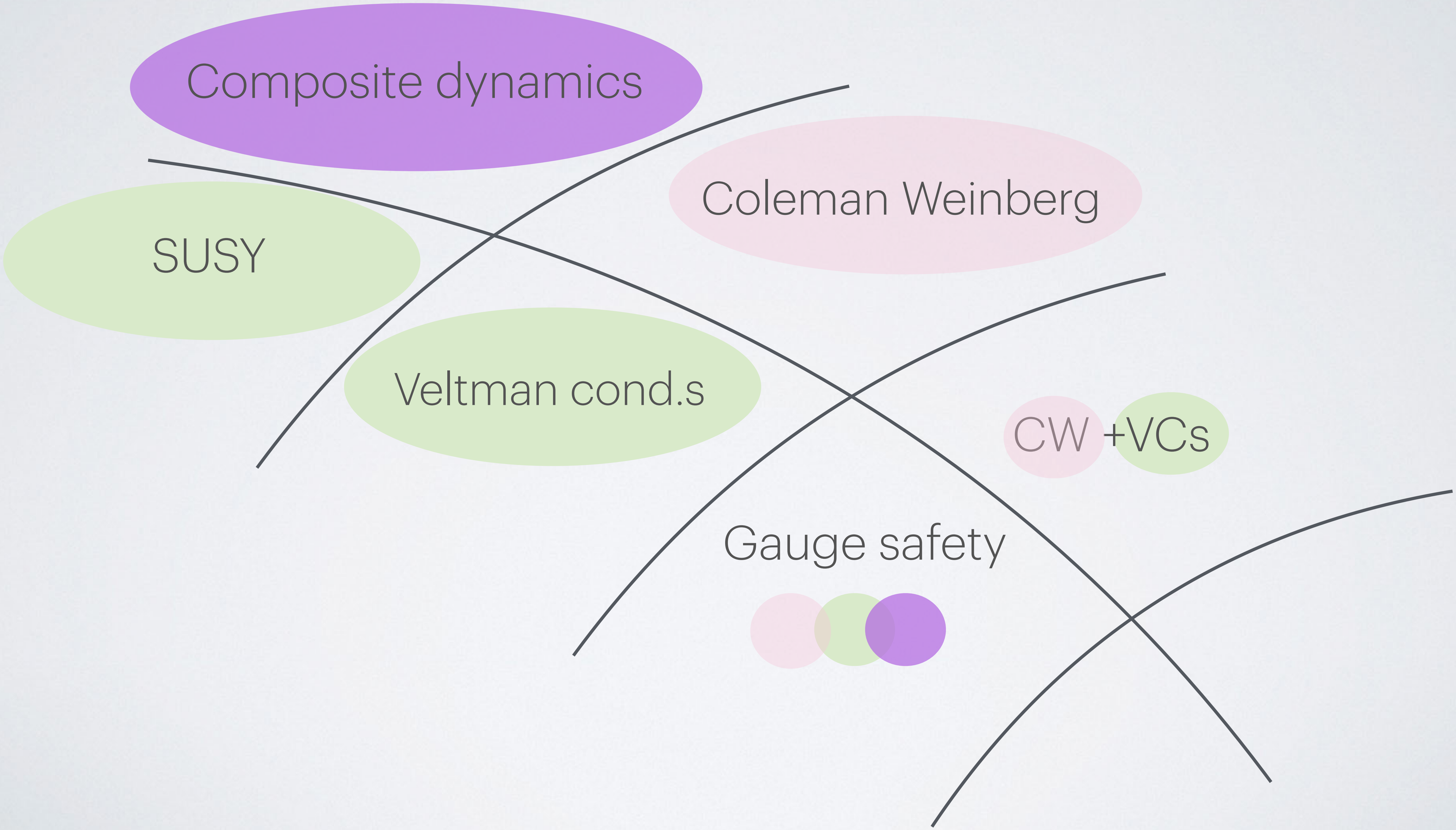
Standard model: cancel m_0 against cutoff Λ

Natural theories

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

- (Super) symmetry protecting $f_2 = 0$
- Cutoff is physical as in composite models

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

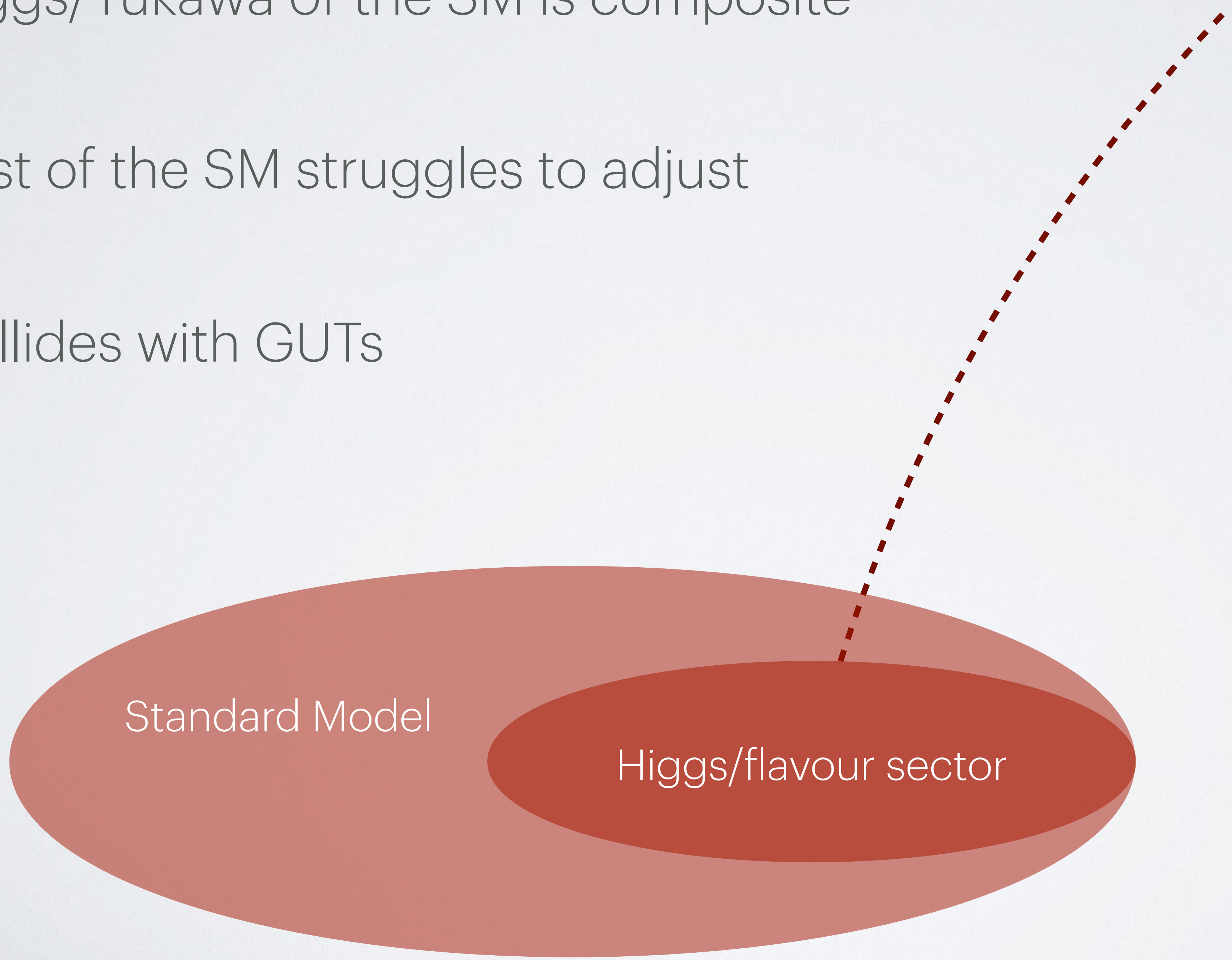


Composite Higgs Dynamics

Higgs/Yukawa of the SM is composite

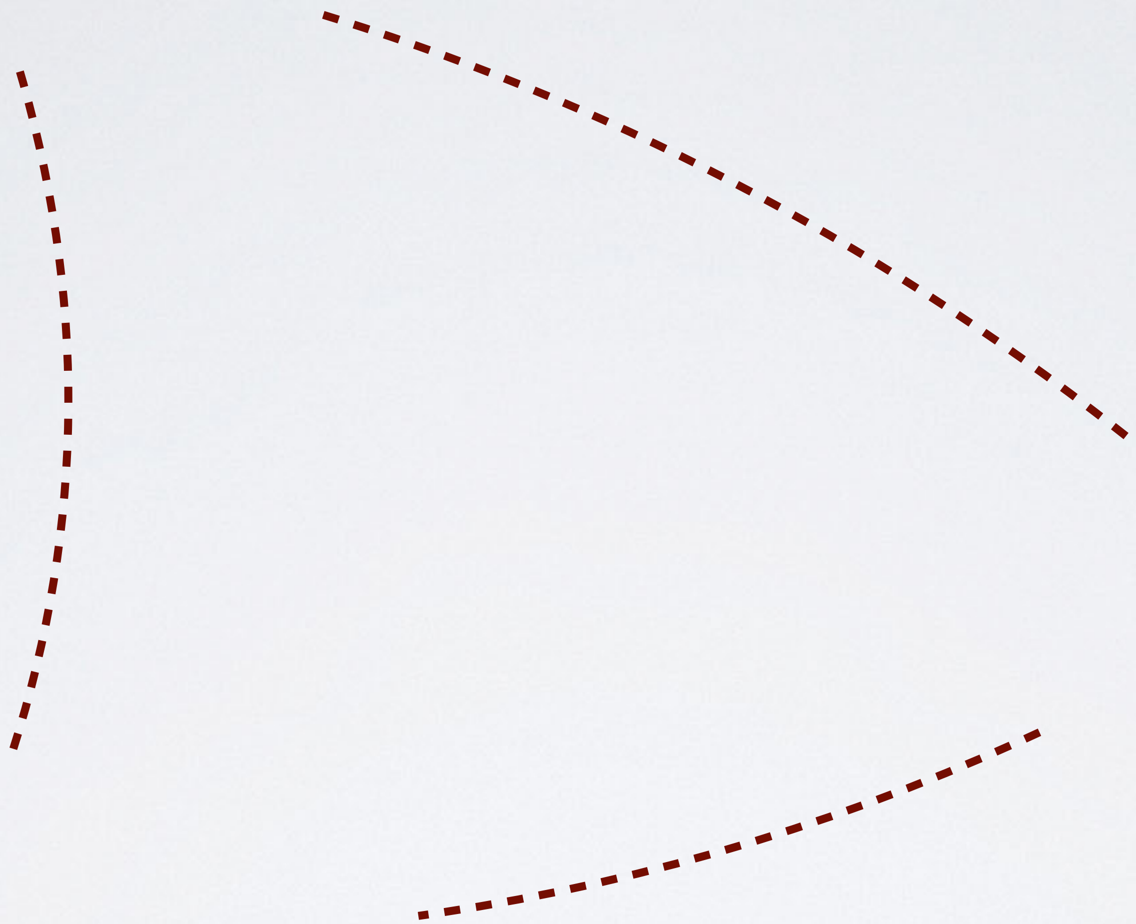
Rest of the SM struggles to adjust

Collides with GUTs



What if the SM were deeply composite?

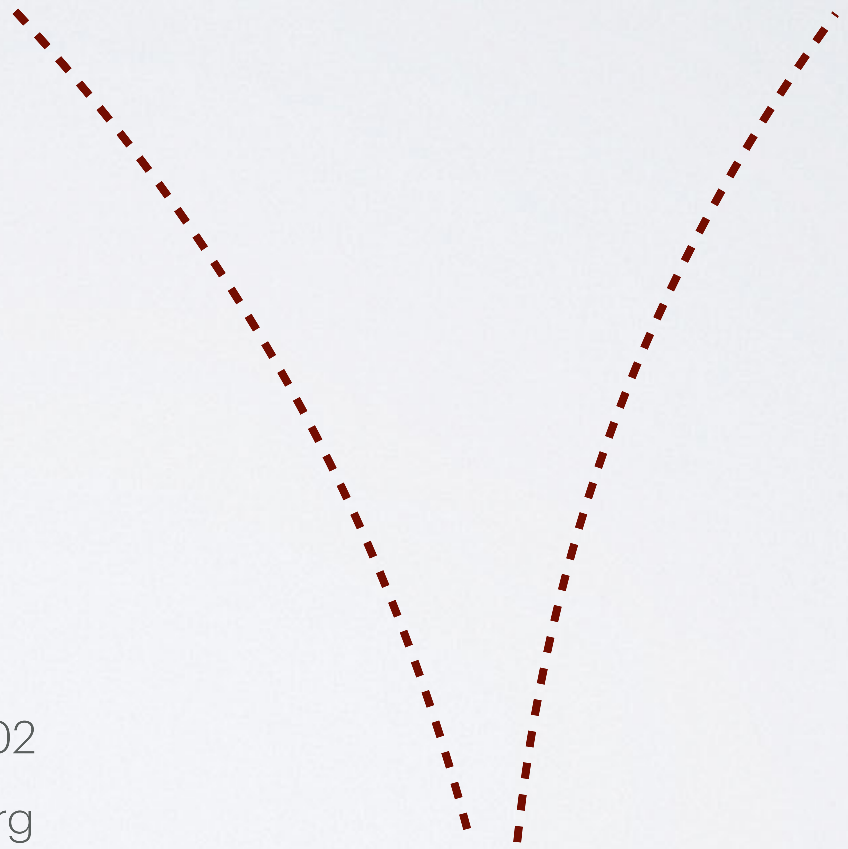
Examples



Gauge symmetries are redundant descriptions of nature

Electro-Magnetic Duality

Seiberg's gauge-gauge susy duality



Non susy attempts:

- F. Sannino, QCD Dual, PRD 80 (2009) 065011
- F. Sannino, Magnetic S-parameter, PRL 105 (2010) 232002
- Z. Komargodski, Vector Mesons interpretations of Seiberg Duality, JHEP 1102.019(2011)

SM as magnetic theory

SU(3) x SU(2) x U(1)

Perturbative at the EW scale

Elementary quarks, leptons, Higgs,...

$n_g = 3$ generations, why?

F. Sannino MPLA 26 (2011) 1763-1769, e-print 1102.5100

Pioneering work by Abbott and Farhi,
“Are the Weak Interactions Strong?”, PLB, B101 (1981), 69

SUSY/Extra Dim attempts

Maekawa and Takahashi, hep-ph/9510426

Csáki, Shirman, Terning, 1106.3074

Cui, Gherghetta, Wells, 0907.0906

Abel, Gherghetta, 1010.5655

Craig, Stolarski, Thaler, 1106.2164

Standard Model

Fields	SU(3)	$SU(2n_g)_L$	$SU(2n_g)_R$
q	$\square$	$\overline{\square}$	1
$\tilde{q}$	$\overline{\square}$	1	$\square$
l	1	$\overline{\square}$	1
$\tilde{l}$	1	1	$\square$
Φ_H	1	$\square$	$\overline{\square}$

SU(3) is QCD

n_g generations

$q, \tilde{q}$ L & R-conjugated quarks

$\ell, \tilde{\ell}$ L & R-conjugated quarks

Weak interactions embedded in $SU(2n_g)_L$

Higgs extended to a $2n_g \times 2n_g$ complex matrix

Weak and hypercharge interactions in $SU(2n_g)_L \times SU(2n_g)_R$

SM has a group theoretical appeal

Way forward

Fields	SU(3)	$SU(2n_g)_L$	$SU(2n_g)_R$
q	$\square$	$\overline{\square}$	1
$\tilde{q}$	$\overline{\square}$	1	$\square$
l	1	$\overline{\square}$	1
$\tilde{l}$	1	1	$\square$
Φ_H	1	$\square$	$\overline{\square}$

Pati-Salam

Fields	SU(4)	$SU(2n_g)_L$	$SU(2n_g)_R$
p	$\square$	$\overline{\square}$	1
$\tilde{p}$	$\overline{\square}$	1	$\square$
Φ_H	1	$\square$	$\overline{\square}$

$p = (q^1, q^2, q^3, \ell)$

Keep the same structure

Fields	SU(3)	$SU(2n_g)_L$	$SU(2n_g)_R$
q	$\square$	$\overline{\square}$	1
$\tilde{q}$	$\overline{\square}$	1	$\square$
l	1	$\overline{\square}$	1
$\tilde{l}$	1	1	$\square$
Φ_H	1	$\square$	$\overline{\square}$

Investigated both

F. Sannino MPLA 26 (2011) 1763-1769, e-print 1102.5100

G.Cacciapaglia, F. Sannino e-print 2407.17281

IR Magnetic upgrade

Fields	$SU(X)$	$SU(2n_g)_L$	$SU(2n_g)_R$	$U(1)_V$	$U(1)_{AF}$
λ_m	Adj	1	1	0	1
q	$\square$	$\overline{\square}$	1	$\frac{2n_g-X}{X}$	$-X/2n_g$
$\tilde{q}$	$\overline{\square}$	1	$\square$	$-\frac{2n_g-X}{X}$	$-X/2n_g$
M	1	$\square$	$\overline{\square}$	0	$-1+X/n_g$
ϕ	$\square$	$\overline{\square}$	1	$\frac{2n_g-X}{X}$	$1-X/2n_g$
$\tilde{\phi}$	$\overline{\square}$	1	$\square$	$-\frac{2n_g-X}{X}$	$1-X/2n_g$
Φ_H	1	$\square$	$\overline{\square}$	0	X/n_g

Fermion fields, 't Hooft AC more restrictive

Squark-like states, ensures matter decoupling

$X = 4$ Pati-Salam

$X = 3$ Leptons are singlets

F.S. MPLA 26 (2011) 1763-1769, e-print 1102.5100
Mojaza, Nardecchia, Pica, F.S. PRD 83 (2011), 065022
Antipin, Mojaza, Pica, F.S. JHEP 06 (2013) 037

Possible Electric Dual

Fields	$SU(2n_g - X)$	$SU(2n_g)_L$	$SU(2n_g)_R$	$U(1)_V$	$U(1)_{AF}$
λ	Adj	1	1	0	1
Q	$\square$	$\square$	1	1	$-\frac{2n_g - X}{2n_g}$
$\tilde{Q}$	$\overline{\square}$	1	$\overline{\square}$	-1	$-\frac{2n_g - X}{2n_g}$

All 't Hooft ACs are satisfied

Consistent flavour decoupling

Magnetic states are deep electric composites

Electric SM theory is gauge-fermionic

$$\Phi_H \sim Q\lambda\lambda\tilde{Q}$$

$$M \sim Q\lambda\tilde{Q}$$

$$\phi \sim \tilde{Q}\lambda$$

$$\tilde{\phi} \sim Q\lambda$$

Sannino, MPLA 26 (2011) 1763-1769, e-print 1102.5100
Mojaza, Nardecchia, Pica, F.S. PRD 83 (2011), 065022
Antipin, Mojaza, Pica, F.S. JHEP 06 (2013) 037

This duality can be tested

Fields	$SU(2n_g - X)$	$SU(2n_g)_L$	$SU(2n_g)_R$	$U(1)_V$	$U(1)_{AF}$
λ	Adj	1	1	0	1
Q	$\square$	$\square$	1	1	$-\frac{2n_g - X}{2n_g}$
$\tilde{Q}$	$\overline{\square}$	1	$\overline{\square}$	-1	$-\frac{2n_g - X}{2n_g}$

Magnetic fixed points investigated in perturbation theory

Electric theory to simulate on the lattice

- IR conformality/compare to Magnetic results
- Spectrum,
- Chiral symmetry breaking patterns

Sannino MPLA 26 (2011) 1763-1769, e-print 1102.5100

Antipin, Mojaza, Pica, F.S. Magnetic Fixed Points and Emergent Supersymmetry, JHEP 06 (2013) 037

On why 3 generations

No explanation from SM, MSSM, CH ....

Insight on the # of generations

The ED has *non-abelian* gauge group $SU(2n_g - X)$

Electric non-abelian requirement for either X=4 or 3

$$2n_g - X \geq 2 \quad \Rightarrow \quad n_g \geq 3$$

Upper bound via Magnetic freedom

Pati-Salam, X=4

$$3 \leq n_g \leq 6$$

For X=3

$$3 \leq n_g \leq 4$$

Electric-Magnetic understanding of why at least 3 generations

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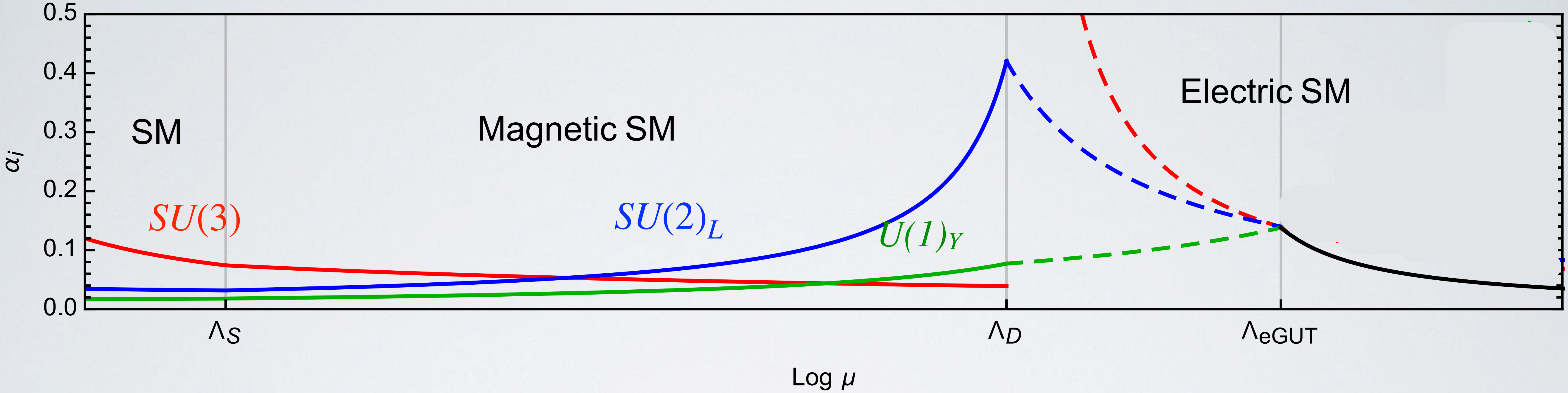
Duality at work



At Λ_S SUSY-like states emerge, completing the Magnetic SM

At Λ_D the Electric Dual takes over

$$\frac{1}{\alpha_e} \sim \alpha_m = \frac{g_m^2}{4\pi}$$

At Λ_{eGUT} we can envision Electric GUTs

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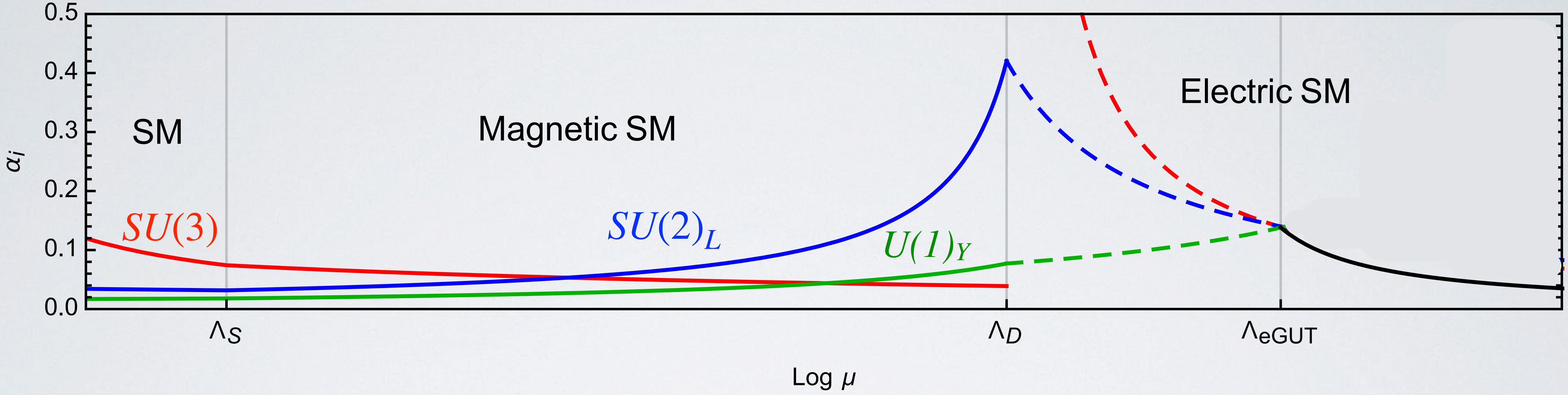
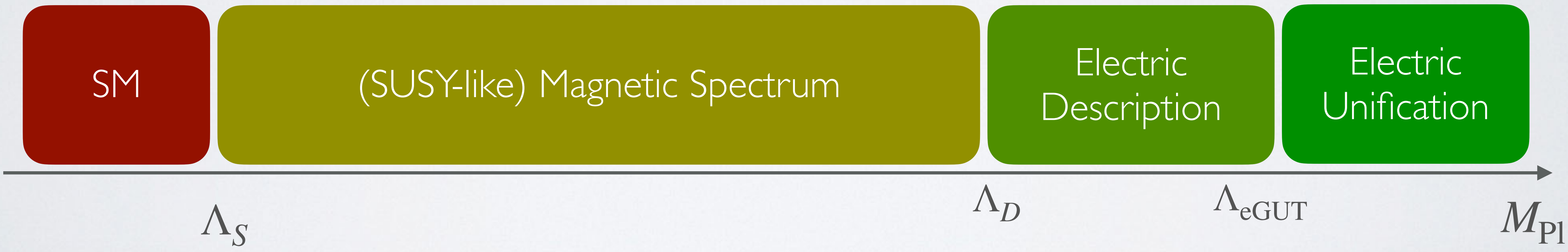
From example to paradigm





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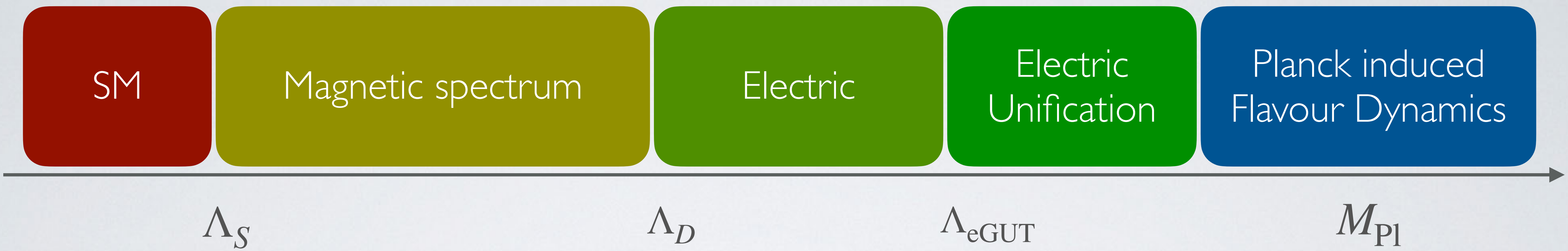
Gravity induced flavour dynamics



Flavour: Planck suppressed in ED Operators $\quad \mathscr{L}_{\rm Planck} \supset \frac{c^{abcd}}{M_{\rm Pl}^2}(Q^a\tilde{Q}^b)(Q^c\tilde{Q}^d)^\dagger$

TeV Scalar masses μ generated at Λ_D via $\quad \frac{(Q^a\tilde{Q}^b)(Q^c\tilde{Q}^d)^\dagger}{M_{\rm Pl}^2} \to \mu^2\,\Phi_H^\dagger\Phi_H$

$$\mu^2 \sim \frac{\Lambda_D^4}{M_{\rm Pl}^2} \qquad \Rightarrow \qquad \Lambda_D \sim \sqrt{\mu\, M_{\rm Pl}}\;\; 10^{11}\ {\rm GeV}$$

Scalar democracy to generate Yukawa structure

Novel avenues for flavour dynamics

Cacciapaglia, Sannino e-print 2407.17281

Hill, Machado, Thomsen, Turner, PRD, 1902.07214

What does the paradigm tell us?

Electric nature appears at high energies

Quarks and Higgs are composite

Generation # is part of the gauge structure

New eGUTs avenues

SM is a natural theory in plain sight

At colliders

New composites appear at Λ_S (few TeVs)

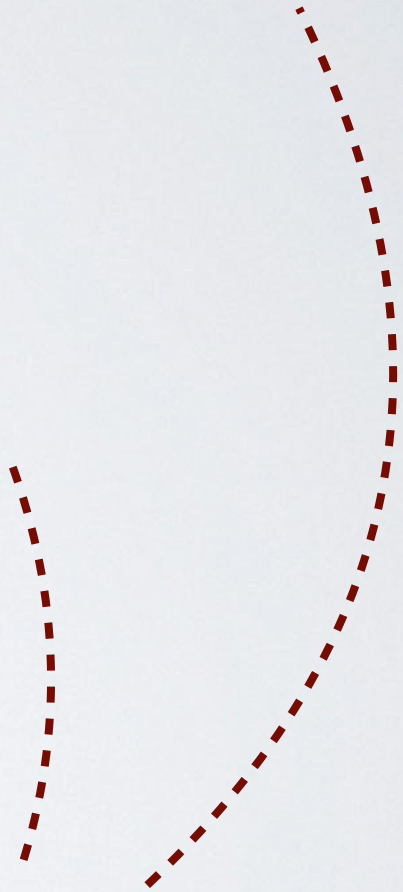
Emerging SUSY-like QCD states

Higgsino-like states from mesino

Several heavy Higgs doublets (Future Colliders)

What about dark matter?

Can be part of the Magnetic/Electric paradigm



Lightest Mesino, for an example.

DM required via ′t Hooft ACs (see Mesino)

Much left to be investigated

Conclusions

New ways to understand near-conformal dynamics

Electro Magnetic duality/modelling is unexplored

Investigate duality for UV finite/safe theories

Experimentally testable

Lattice can test non-SUSY duality

Solving strong dynamics is paramount for a deeper understanding of nature

Thank you

"Others have seen what is and asked: Why is it?

I have seen what could be and asked: Why not?"

Pablo Picasso

Back-up slides

“Others have seen what is and asked: Why is it?

I have seen what could be and asked: Why not?”

Pablo Picasso

Magnetic dual flavour structure

Allowed operators

$$\mathscr{L}_m \supset y\ q\tilde{q}\Phi_H + y'\ q\tilde{\phi}M + \tilde{y}'\ \tilde{q}\phi M + \xi_L\ \lambda_m q\phi^\dagger + \xi_R\ \lambda_m \tilde{q}\tilde{\phi}^\dagger + \mathrm{h.c.}$$

SUSY for $y = y' = \tilde{y}'$ and $\xi_L = \xi_R = g_m$

$$Y = T_3 + \frac{Q_v}{6}$$

The generalised Higgs field decomposes as

$$\phi_H = \{H^u_{ij}, H^d_{ij}\} \qquad i, j = 1,2,3$$

18 Higgs doublets

Massive states & Scalar democracy

States with mass higher than Λ_S

$\lambda_m \quad \phi \quad \tilde{\phi} \quad M$

All but one Higgs doublet of $\phi_H = \{H^u_{ij}, H^d_{ij}\}$

Democratic magnetic Yukawa

$$y\ q\tilde{q}\Phi_H = y \sum_{i,j} \left(q^i_L u^j_R H^u_{ij} + q^i_L d^j_R H^d_{ij} \right)$$

SM hierarchies via Higgs VEV hierarchies

$$Y^u_{ij} = y \frac{\langle H^u_{ij} \rangle}{v} \quad \text{and} \quad Y^d_{ij} = y \frac{\langle H^d_{ij} \rangle}{v}$$

$$v^2 = \sum_{ij} \left(\langle H^u_{ij} \rangle^2 + \langle H^d_{ij} \rangle^2 \right) = \frac{1}{2} (246\ \text{GeV})^2$$

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Hill, Machado, Thomsen, Turner, PRD, 1902.07214