Present & Future

of

Composite Dynamics

Francesco Sannino

D·IAS

QUANTUM THEORY CENTER

QCD

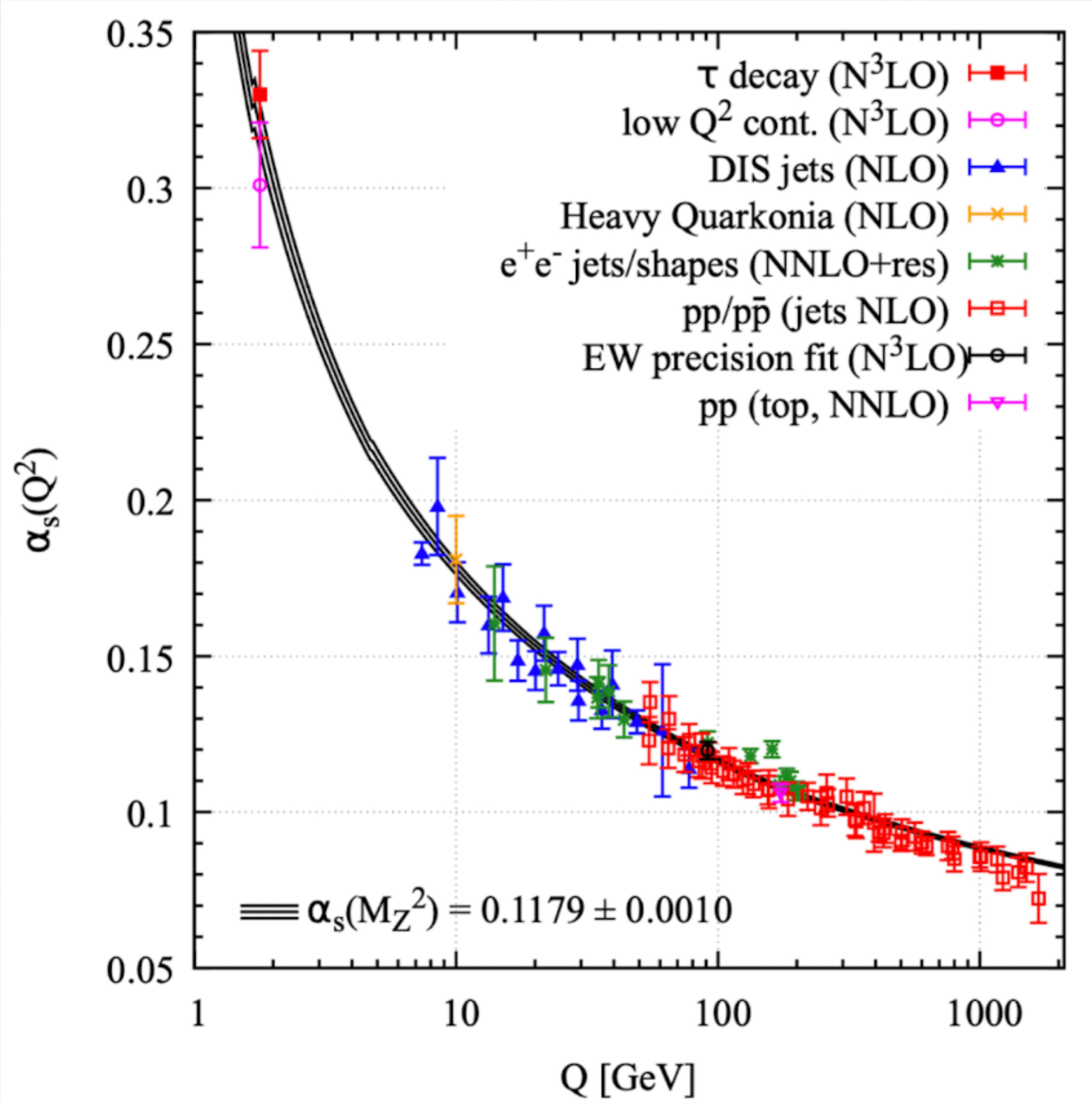
3 colors + 6 flavours

Weakly coupled in UV

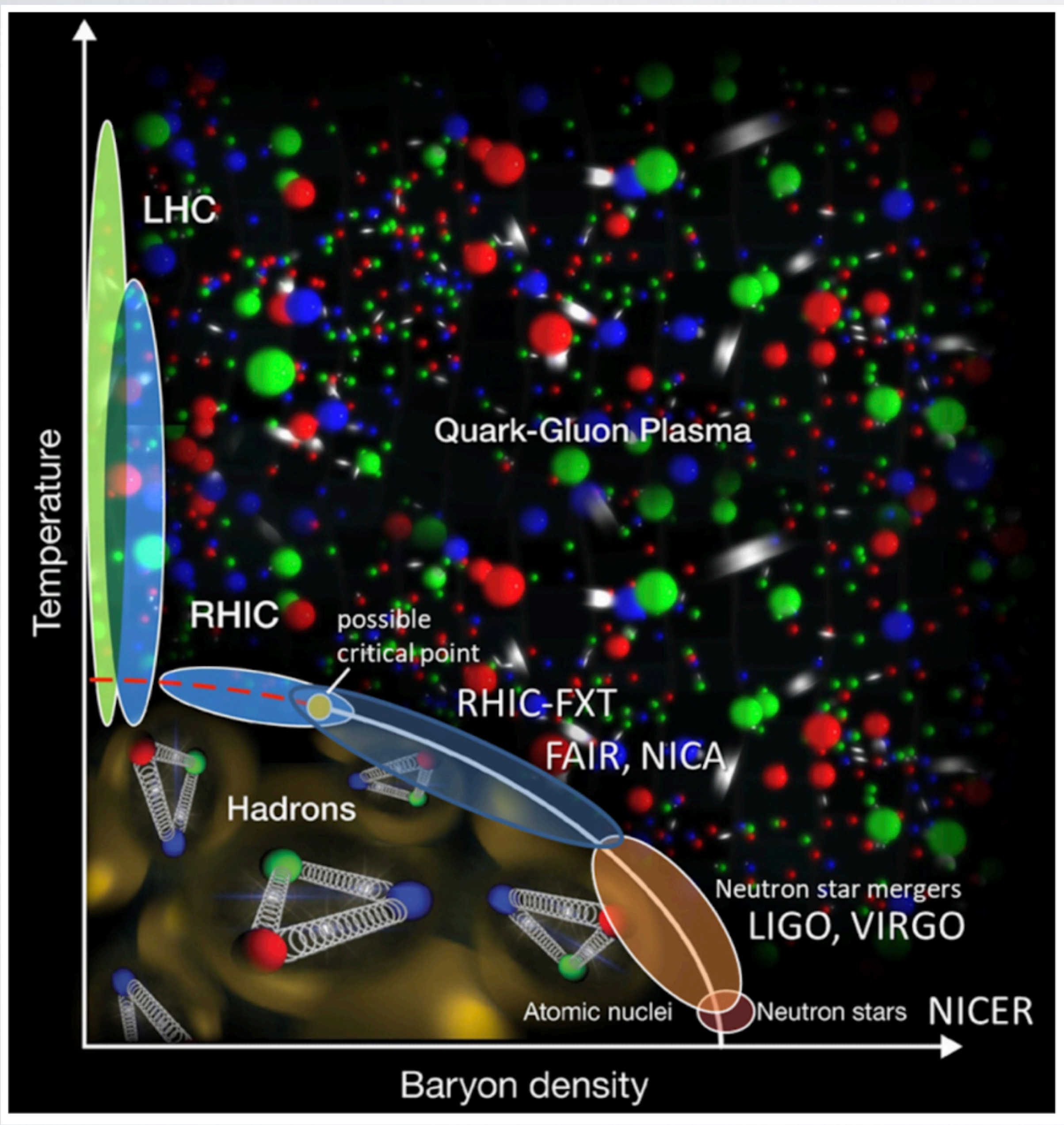
Strongly coupled in IR

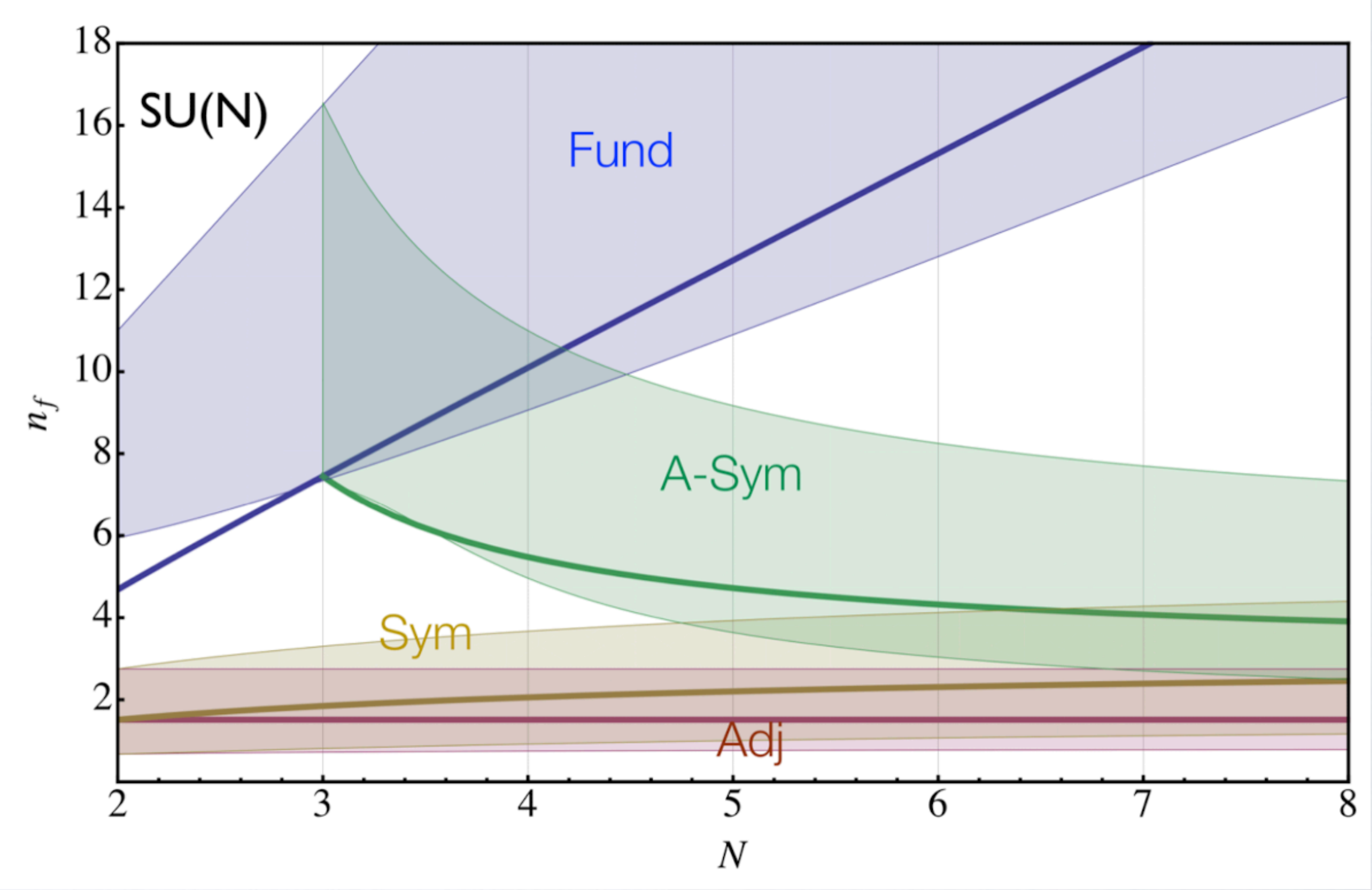
Spontaneous chiral breaking

Confines



Some open questions





Methodologies

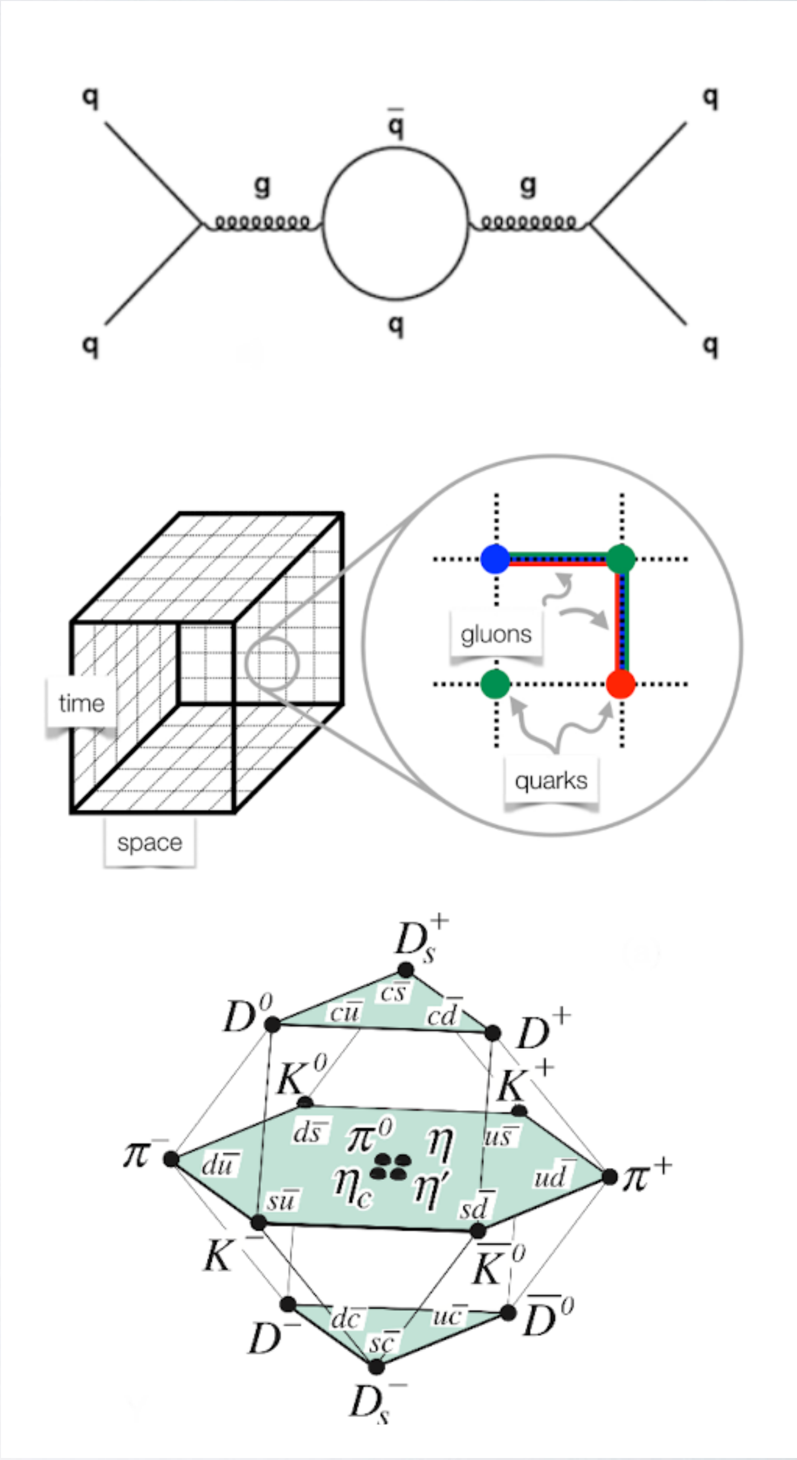
Perturbation theory

Effective theories

Lattice

Large N, Quantum numbers

Models: Quark model,
Polyakov loop,
Nambu Jona-Lasinio,
Holography
….



Composite landscape

Fields	Interactions	IRRP	UV behaviour
G_μ	$-\frac{1}{4g^2}\,G^{\mu\nu}G_{\mu\nu}$	Adj	Free
$G_\mu + \psi$	$+i\bar{\psi}\gamma_\mu D^\mu\psi$	Adj, Fund., ...	Free, Safe/Effective
$G_\mu + \phi$	$+D\phi^* D\phi - \lambda\,(\phi^*\phi)^2$	Adj, Fund., ...	Effective
$G_\mu + \phi + \psi$	$\cdots + y\,\bar{\psi}\phi\psi$	Adj, Fund., ...	Free, Safe, Effective

Supersymmetric versions are highly interesting

Applications

Bright

Colliders

Compact stars

g-2, flavour physics

Heavy baryon and mesons

QCD

Dark

Strong CP

Axions

Early universe

New composite dynamics

Technicolor

Composite Goldstone Higgs

Fund. Partial compositeness

g-2, flavour physics, Mw

Dark baryons & pions

SIMPs

Composite inflation

Secluded sectors/

Gravitational Waves

Sannino, 0911.0931, Acta Phys. Polon. B 40 (2009) 3533-3743

Cacciapaglia, Pica, Sannino, 2002.04914, *Phys. Rept. 877 (2020) 1-70*

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Physics Letters B 605 (2005) 369–375

PHYSICS LETTERS B

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New solutions to the strong CP problem

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Received 9 October 2004; received in revised form 11 November 2004; accepted 12 November 2004

Available online 18 November 2004

Editor: H. Georgi

Abstract

We exhibit a solution to the strong CP problem in which ultraviolet physics renders the QCD θ angle physically unobservable. Our models involve new strong interactions beyond QCD and particles charged under both the new interactions and ordinary color.

The Physics of the θ-angle

for

Composite Extensions of the Standard Model

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We analyse the θ-angle physics associated to extensions of the standard model of particle interactions featuring new strongly coupled sectors. We start by providing a pedagogical review of the θ-angle physics for Quantum Chromodynamics (QCD) including also the axion properties. We then move to analyse composite extensions of the standard model elucidating the interplay between the new θ-angle with the QCD one. We consider first QCD-like dynamics and then generalise it to consider several kinds of new strongly coupled gauge theories with fermions transforming according to different matter representations. Our analysis is of immediate use for different models of composite Higgs dynamics, composite dark matter and inflation.

Preprint: CP³-Origins-2013-34 & DIAS-2013-34

Published for SISSA by Springer
Received: September 1, 2022
Revised: November 1, 2022
Accepted: November 2, 2022
Published: November 15, 2022

The θ-angle and axion physics of two-color QCD at fixed baryon charge

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Abstract: We analyze the impact of the θ-angle and axion dynamics for two-color (in fact any Sp($2N$)) QCD at nonzero baryon charge and as a function of the number of matter fields on the vacuum properties, the pattern of chiral symmetry breaking as well as the spectrum of the theory. We show that the vacuum acquires a rich structure when the

JHEP11(2022)080

Scaling results for Charged sectors of near conformal QCD

2401.08457

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Abstract: We provide the leading near conformal corrections on a cylinder to the scaling dimension Δ_Q^* of fixed isospin charge Q operators defined at the lower boundary of the Quantum Chromodynamics conformal window:

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

Pure (super) glue

Facts:

Mass gap

Confines

Glueballs

Methodologies:

Lattice

Large N ('t Hooft and Corrigan Ramond)

Power of supersymmetry

Applications:

Composite Higgs theories

Composite non-minimal glueball inflation

Composite gluonic dark matter

Gravity waves via deconfinment/confinement phase transitions

One flavour QCD

Facts:

$U_A(1)$ axial anomaly

Chiral and gluon condensate

Gueball and massive mesons

	$SU(N)$	$U_V(1)$	$U_A(1)$
g_μ	Adj	0	0
q	$\square$	+1	+1
$\tilde{q}$	$\bar{\square}$	-1	+1

Applications:

Dark matter for 2 colors

Like glue theory for other N except no strict confinement

Analog computer for super Yang Mills

Two index SU(N) Theories

QCD, Supersymmetry, Orientifold

&

Weinberg's $\pi\pi$ scattering

Two-index SU(N) theories

QCD, Orientifolds, Super Yang-Mills, Lattice
and
Steven Weinberg's $\pi\pi$ scattering legacy

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Abstract: I review and improve on how two-index SU(N) gauge-fermion theories help access salient information about the large N vacuum and spectrum of QCD, super Yang Mills and meson-meson scattering. The interplay with recent lattice simulations will be employed to deduce the size of $1/N^2$ corrections. Through the meson-meson scattering analysis I will honor Steven Weinberg's memory by showing how two-index extrapolations naturally accommodate the appearance of tetraquarks states crucial to unitarize meson-meson scattering at low energies.

'T Hooft large N

Facts:

Planar diagrams

Gluons dominate

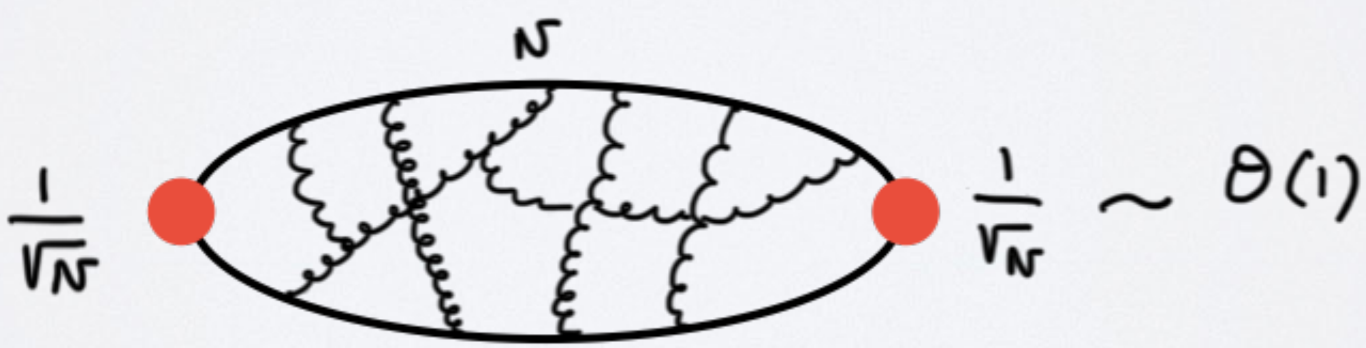
Baryons decoupling

Quark-antiquark mesons are leading in N

Eta prime mass is 1/N suppressed

$G_\mu \longrightarrow N^2$

$q, \tilde{q} \longrightarrow N$



Corrigan and Ramond large N

Facts:

Planar diagrams

Gluons count as quarks

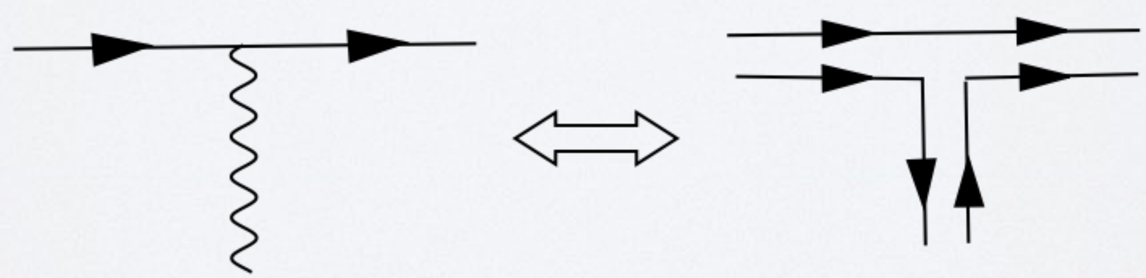
Multiquark states are leading in N

Better scattering unitarity

Resolve Weinberg puzzles

Eta prime mass is order one

	$SU(N)$	$U_V(1)$	$U_A(1)$
G_μ	Adj	0	0
ψ	$\boxminus$	+1	+1
$\tilde{\psi}$	$\overline{\boxminus}$	−1	+1



Super YM - orientifold connection

O^{+}	$SU(N)$	$U_V(1)$	$U_A(1)$
g_μ	Adj	0	0
ψ	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	+1	+1
$\tilde{\psi}$	$\overline{\begin{smallmatrix}\square\\ \square\end{smallmatrix}}$	−1	+1

O^{-}	$SU(N)$	$U_V(1)$	$U_A(1)$
g_μ	Adj	0	0
ψ	$\square\square$	+1	+1
$\tilde{\psi}$	$\overline{\square\square}$	−1	+1

$\longrightarrow$

SYM	$SU(N)$	$U_R(1)$
g_μ	Adj	0
λ	Adj	+1

Armoni, Shifman, Veneziano, th/0302163

Sannino, Shifman, th/0309252

Sannino, th/0507251

Effective Orientifold Lagrangian

Scalar condensate

$$\varphi = -\frac{3}{32\pi^2 N}\,\tilde{\psi}^{[i,j]}\,\psi_{[i,j]} \xRightarrow{N\to\infty} \lambda\lambda$$

$N \to \infty$ Renormalization Group Invariant Scale

$$\Lambda^3 = \frac{9}{32\pi^2}\,\Lambda^3_{sym} \qquad \Lambda^3_{sym} = \mu^3\left(\frac{16\pi^2}{3N\,g^2(\mu)}\right)\exp\left(\frac{-8\pi^2}{N\,g^2(\mu)}\right)$$

Effective Orientifold Lagrangian

$$\mathcal{L}_{eff} = f(N)\left\{\frac{1}{\alpha}(\varphi\bar{\varphi})^{-2/3}\partial_\mu\bar{\varphi}\,\partial^\mu\varphi - \frac{4}{9}\alpha(\varphi\bar{\varphi})^{2/3}\underbrace{\left(\log\Phi\,\log\bar{\Phi} - b\right)}\right\}$$

$$\Phi = \varphi^{1+\varepsilon_1}\,\bar{\varphi}^{-\varepsilon_2} \qquad \bar{\Phi} = \bar{\varphi}^{1+\varepsilon_1}\,\varphi^{-\varepsilon_2}$$

VY theory

$\Lambda = 1$

ε_1 and $\varepsilon_2 \sim 1/N$

$\underline{N \to \infty}$

$f(N) \to N^2$

$b \sim 1/N$

Effective anomalies

$\varphi \to (1+3\gamma)\varphi$ Scale

$\varphi \to (1+2i\gamma)\varphi$ axial

$$\delta S_{eff}^{Scale} = \int d^4x \left\{ -\frac{4}{3}\alpha f \, (\varphi\bar{\varphi})^{2/3} (1+\epsilon_1-\epsilon_2)(\ln\bar{\Phi}+\ln\Phi) \right\}$$

$$\delta S_{eff}^{Axial} = \int d^4x \left\{ -8i\,\frac{\alpha f}{9} \, (\varphi\bar{\varphi})^{2/3} (1+\epsilon_1+\epsilon_2)(\ln\bar{\Phi}-\ln\Phi) \right\}$$

Underlying anomalies matching

$$\theta^{\mu}_{\mu} = \frac{\beta_{\theta\pm}(a)}{a^2} \frac{1}{32\pi^2} G^{a}_{\mu\nu} G^{a\,\mu\nu} \qquad \partial^{\mu} J_{\mu} = [N \pm 2] \frac{1}{16\pi^2} G^{a}_{\mu\nu} \tilde{G}^{a\,\mu\nu}.$$

$$\beta_{\theta\pm}(a) := \frac{da}{d\ln\mu^2} \qquad a = g^2/(4\pi)^2$$

$$\chi := 1 + \epsilon_1 + \epsilon_2 = \frac{N \pm 2}{N}$$

$$\Upsilon := 1 + \epsilon_1 - \epsilon_2 = \frac{\beta_{\theta\pm}}{\beta_{SYM}} = -\frac{1}{3N} \frac{\beta_{\theta\pm}}{a^2}$$

$$\Rightarrow \begin{cases} 2\epsilon_2 = \chi - \Upsilon \\ \epsilon_1 = 1 - \dfrac{\chi + \Upsilon}{2} \end{cases}$$

Spectrum & Vacuum Energy

$$V_{min} = E_{VAC} = -\frac{4\alpha f}{g} b + \mathcal{O}(N^0) \longrightarrow b \geq 0$$

K.T. normalization

$$\varphi = \langle\varphi\rangle(1 + c h) \qquad h = \frac{1}{\sqrt{2}}(\sigma + i\eta') \qquad c^2 = \frac{\alpha}{f}|\langle\varphi\rangle|^{-2/3}$$

$$M_\sigma = \frac{2}{3}\alpha\Lambda\left(1 + \frac{2}{9}b\right)\left[\underline{\tau} + \frac{4}{9}b\right] \qquad M_{\eta'} = \frac{2}{3}\alpha\Lambda\left(1 + \frac{2}{9}b\right)\underline{x}$$

$$\boxed{\frac{M_{\eta'}}{M_\sigma} = \frac{x}{\tau + \frac{4}{9}b} = \frac{1 \pm 2/N}{\frac{\beta_{0\pm}}{\beta_{SYM}} + \frac{4}{9}b} \leq \frac{1 \pm 2/N}{\beta_{0\pm}/\beta_{SYM}}}$$

Predictions 1.0

$$\boxed{\frac{M_{\eta'}}{M_{\sigma}} = \frac{x}{\tau + \frac{4}{9}b} = \frac{1 \pm 2/N}{\frac{\beta_{\theta\pm}}{\beta_{sym}} + \frac{4}{9}b} \leq \frac{1 \pm 2/N}{\beta_{\theta\pm}/\beta_{sym}}}$$

$x := 1 \pm \frac{2}{N}$ one loop exact

$\tau := \frac{\beta_{\theta\pm}}{\beta_{sym}} = 1 \mp \frac{4}{9N}$ @ one loop

Leading order

$$\left.\frac{M_{\eta'}}{M_{\sigma}}\right|_{\theta\pm} = 1 + x - \tau - \frac{4}{9}b + O(N^{-2}) = 1 \pm \frac{22}{9N} - \frac{4}{9}b + O(N^{-2})$$

Predictions 2.0

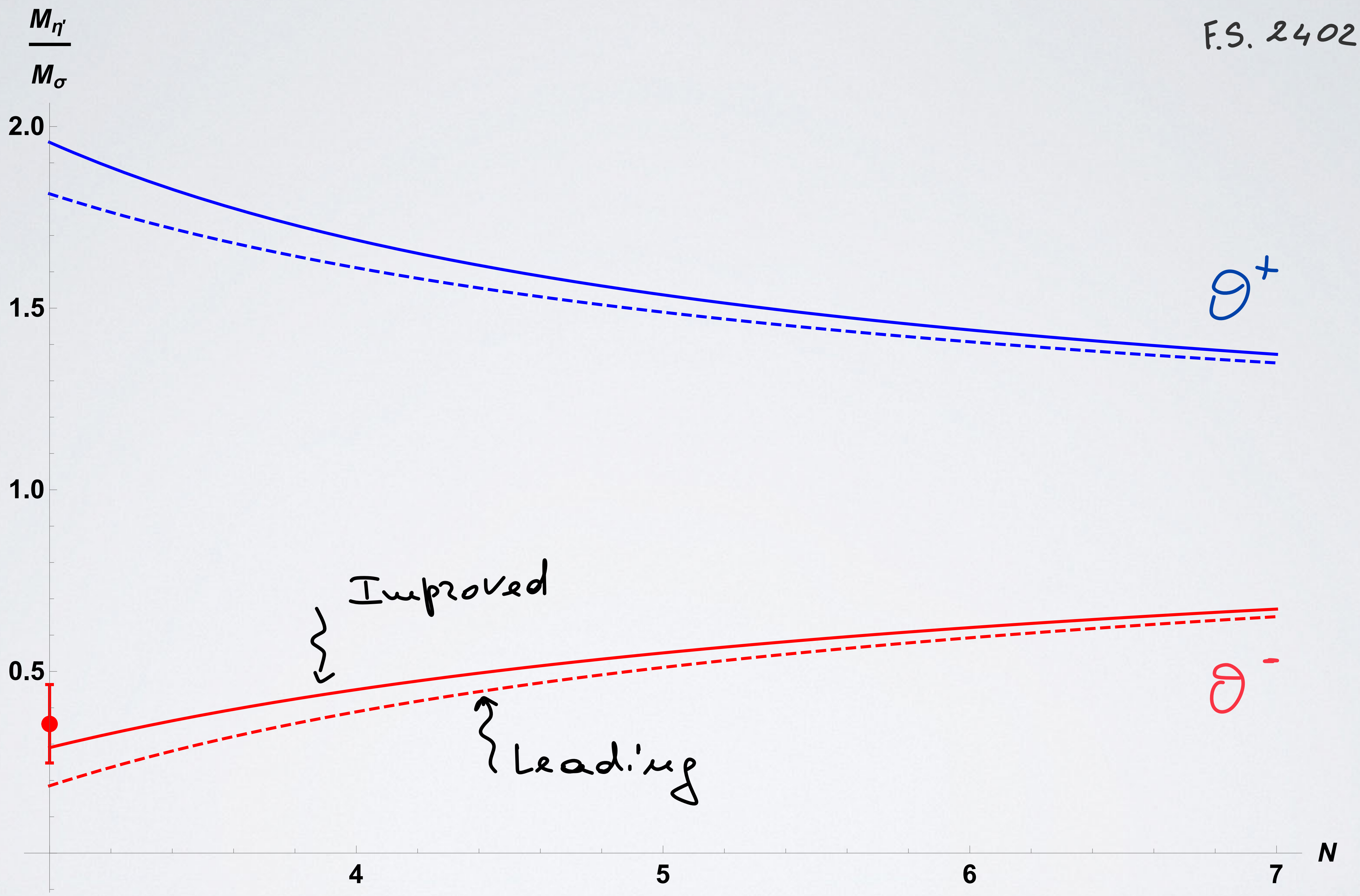
$$\boxed{\frac{\Gamma_{\eta'}}{\Gamma_\rho} = \frac{x}{\tau + \frac{4}{9}b} = \frac{1 \pm 2/N}{\frac{\beta_{\theta\pm}}{\beta_{sym}} + \frac{4}{9}b} \leq \frac{1 \pm 2/N}{\beta_{\theta\pm}/\beta_{sym}}}$$

Improved

$$\left.\frac{\Gamma_{\eta'}}{\Gamma_\rho}\right|_{\theta\pm} = \frac{x}{\tau + \frac{4}{9}b} \leq \frac{1 \pm 2/N}{1 \mp \frac{4}{9N}}$$

Predictions vs Lattice

F.S. 2402.05850



Lattice

Della Morte et al. PRD 107 (2023) 114506
2302.10514

Size of higher order corrections

$$\left.\frac{M_{\eta'}}{M_{\tilde{\eta}}}\right|_{\Theta^-} = 1 - \frac{22}{9N} - \frac{4}{9}b + \frac{k}{N^2} + \mathcal{O}(N^{-3})$$

Comparing with lattice data

$$b = 0 \quad \Rightarrow \quad k \geq 1.54$$

$$b \simeq \frac{1}{N} \quad \Rightarrow \quad k \simeq 2.87$$

Natural size

The quark mass weighs in

$$\begin{cases} \Delta \mathcal{L}_m = 4\dfrac{m}{3\lambda} N^2 (\varphi + \bar{\varphi}) \sim m \lambda \lambda \\ \lambda = N g^2 / 8\pi^2 \end{cases}$$

$\lambda \longrightarrow$ gluino field

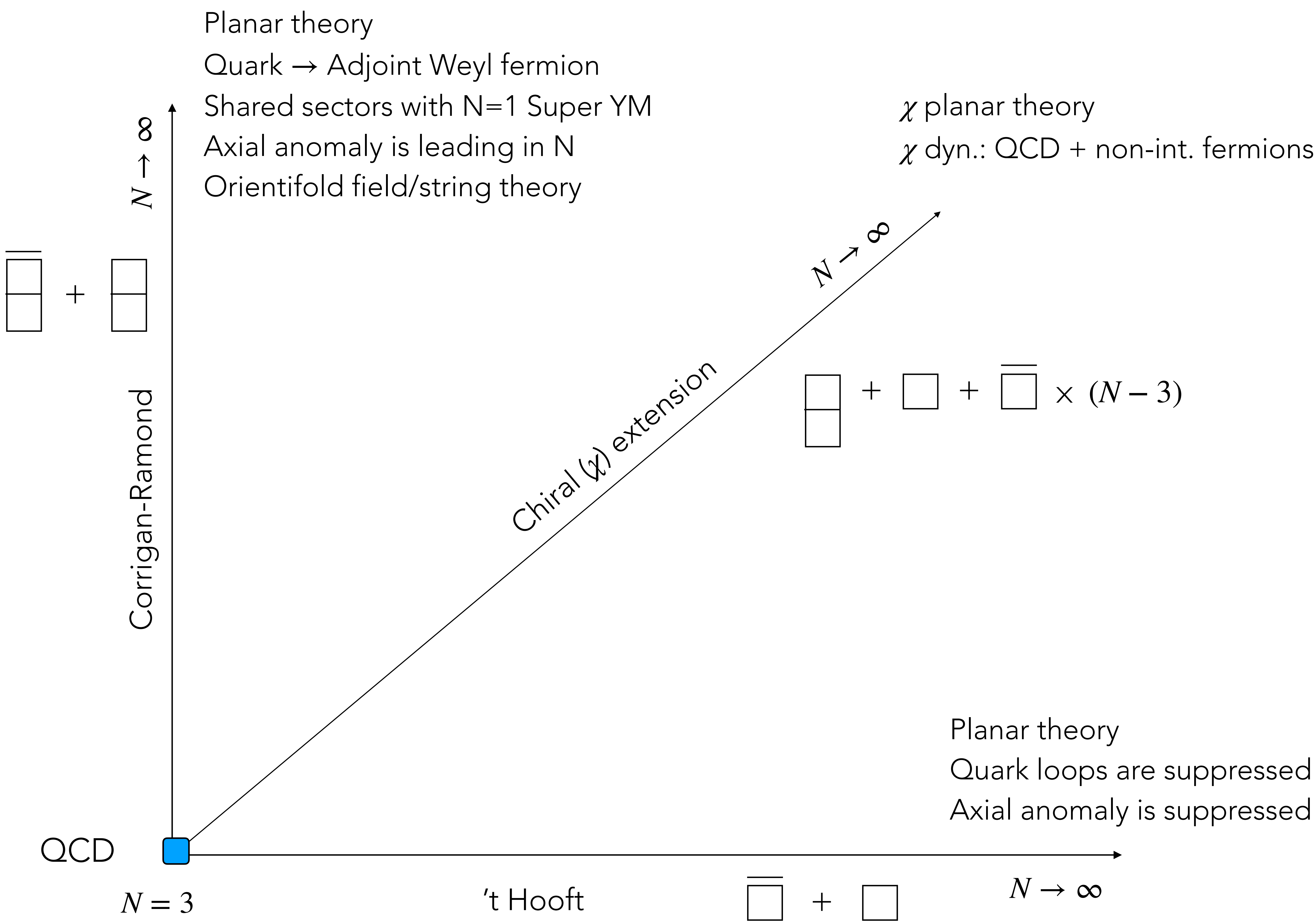
Veneziano, Masiero

$$\mathcal{E}_{vac}(\theta) = -\frac{4\alpha f}{9} b \Lambda^4 + \frac{8N^2}{3\lambda} m \Lambda^3 \min_k \left\{ -\cos\left[\frac{\theta + 2\pi k}{N-2}\right] \right\}$$

The quark mass weighs in

$$\frac{M_{\eta'}}{M_{\sigma}} = \frac{1-\frac{2}{N}}{\frac{\beta_0}{\beta_{SYM}}+\frac{4}{9}b} - \frac{m}{\alpha\lambda\Lambda} = 1-\frac{22}{9N} - \frac{4}{9}b - \frac{m}{\alpha\lambda\Lambda} + O(m^2, N^0, m N^{-1})$$

$$\frac{\langle G_{\mu\nu} G^{\mu\nu}\rangle}{64\pi^2 N} = \frac{4}{3\lambda} m\Lambda^3 + \frac{8}{27}\alpha b \Lambda^4 + O(m^2, N^0, m N^{-1})$$



Planar theory
Quark → Adjoint Weyl fermion
Shared sectors with N=1 Super YM
Axial anomaly is leading in N
Orientifold field/string theory
$N \to \infty$
Corrigan-Ramond
χ planar theory
χ dyn.: QCD + non-int. fermions
$N \to \infty$
Chiral (χ) extension
$\times\ (N-3)$
Planar theory
Quark loops are suppressed
Axial anomaly is suppressed
QCD
$N = 3$
't Hooft
$N \to \infty$

Partial summary

Pseudo and scalar spectrum

Vacuum properties

Size of subleading N corrections

Predictions for other SU(N) theories

Ask me more about chiral gauge theories

More than one flavor

Pion scattering, tetraquarks and large N

Coleman : In the large N limit, quadrilinear make meson pairs and nothing else.

Weinberg : But is this justified?

PRL 110 (2013) 261601

Weinberg's reasoning

W: Coleman could be right if $\Gamma(T \to \pi\pi)$ grows with N

$\Rightarrow$ exotic states do not exist as distinct states.

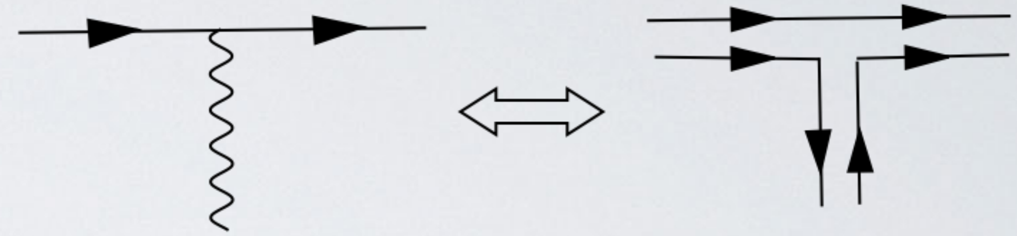
but then argues that their width decreases instead

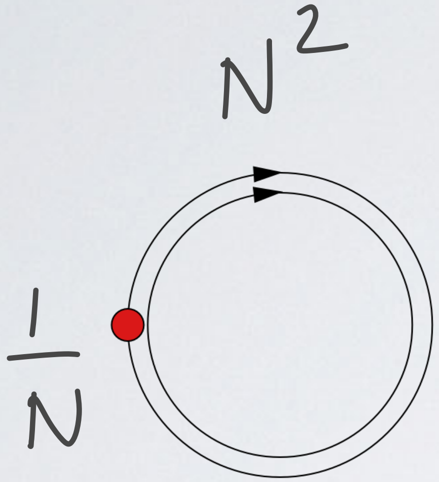
$\Rightarrow$ Justified in 't Hooft large N.

F: The above is incorrect since m_T can grow with N

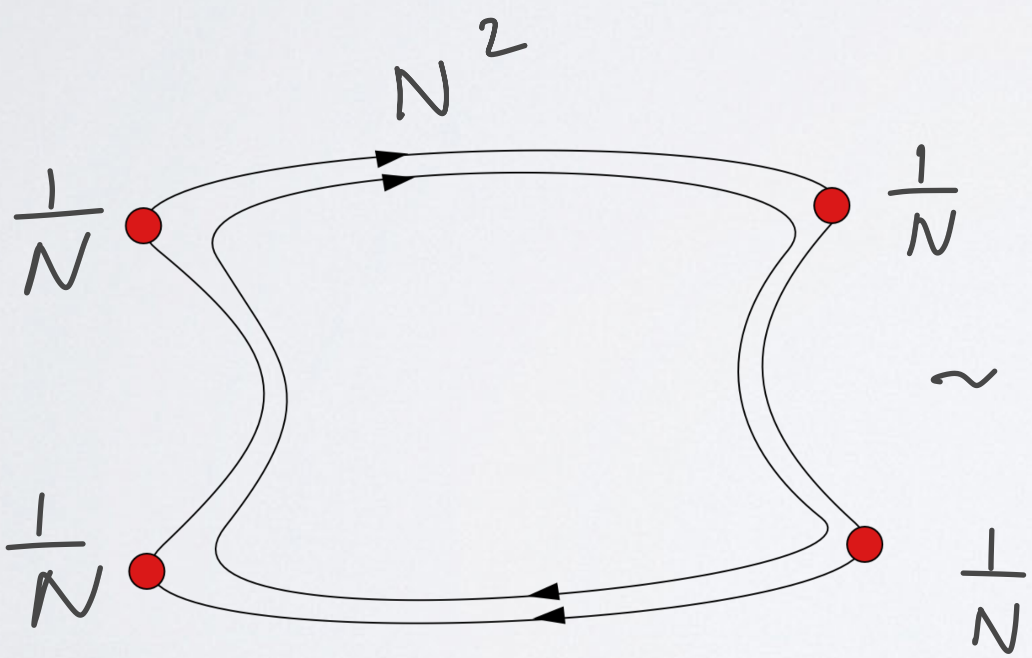
and also their decay width (see $f_0(500)$).

CR limit resolution





$\sim \quad F_\pi \simeq N$



$\sim \quad \frac{1}{N^2}$

't Hooft

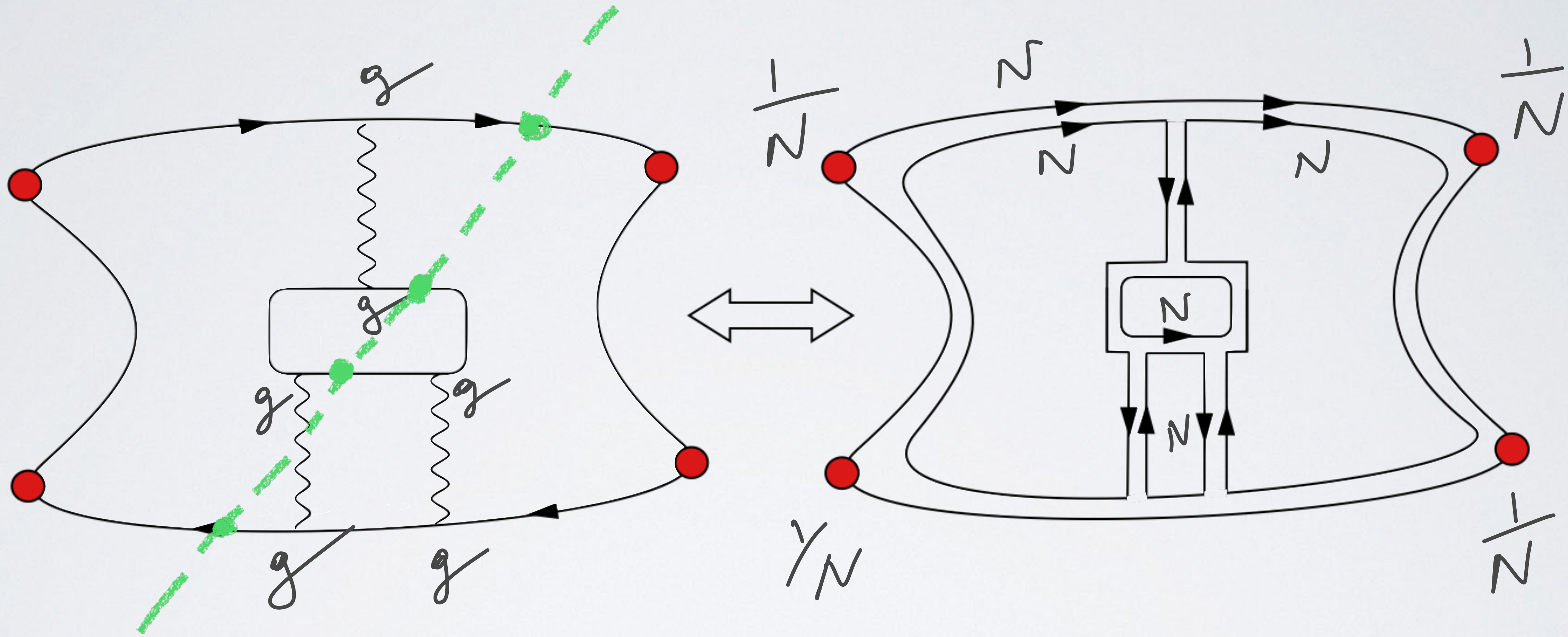
$F_\pi \sim \sqrt{N}$

$A(\pi\pi \to \pi\pi) \sim \frac{1}{N}$

$$A(\pi\pi \to \pi\pi) = \frac{6}{N(N-1)} A(\pi\pi \to \pi\pi)_{N=3}$$

Exotic leading in N

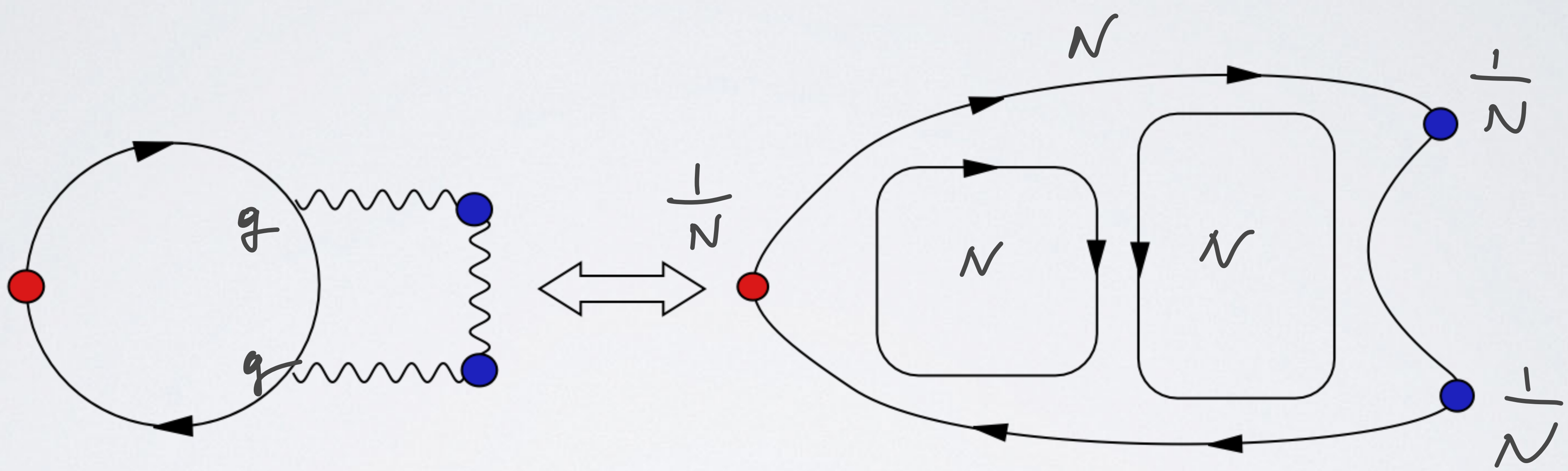
$$\sim g^6 \frac{1}{N^4} \cdot N^5 \sim \frac{(g^2 N)^3}{N^2} \sim \frac{1}{N^2}$$



Four quark state leading in CR limit

Meson decay into glueballs

Mesons and glueballs in the CR limit have same rules



$$A(M \to G\,G) \sim g^2 \frac{N^3}{N^3} = \frac{(g^2N)}{N} \sim \frac{1}{N}$$

$$\Gamma(M \to G\,G) \sim \frac{1}{N^2}$$

Summary

CR large N is a better description of meson meson scattering

Scattering amplitudes unitarize faster in N

Exotic states are leading in N and help unitarize meson scattering

Axial anomaly well captured and QCD spectrum better captured

Many things to do from holographic descriptions to phase transitions

Future

20+ years to check/understand QCD dynamics/SYM, properly

New directions for fixed charged sectors/near conformal dynamics

Finite density, theta angle vs flavor phase diagram for 2 and 3 colors

Novel ways to disentangle dilaton spectrum via fixed charged sectors

Huge # of applications form cosmology, astro and particle physics thank you