Searching for Walking Technicolor theory on the Lattice

Based on arXiv:1011.2577 [hep-lat/ph]

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in collaboration with

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Seminar@IPMU, Feb. 17, 2011

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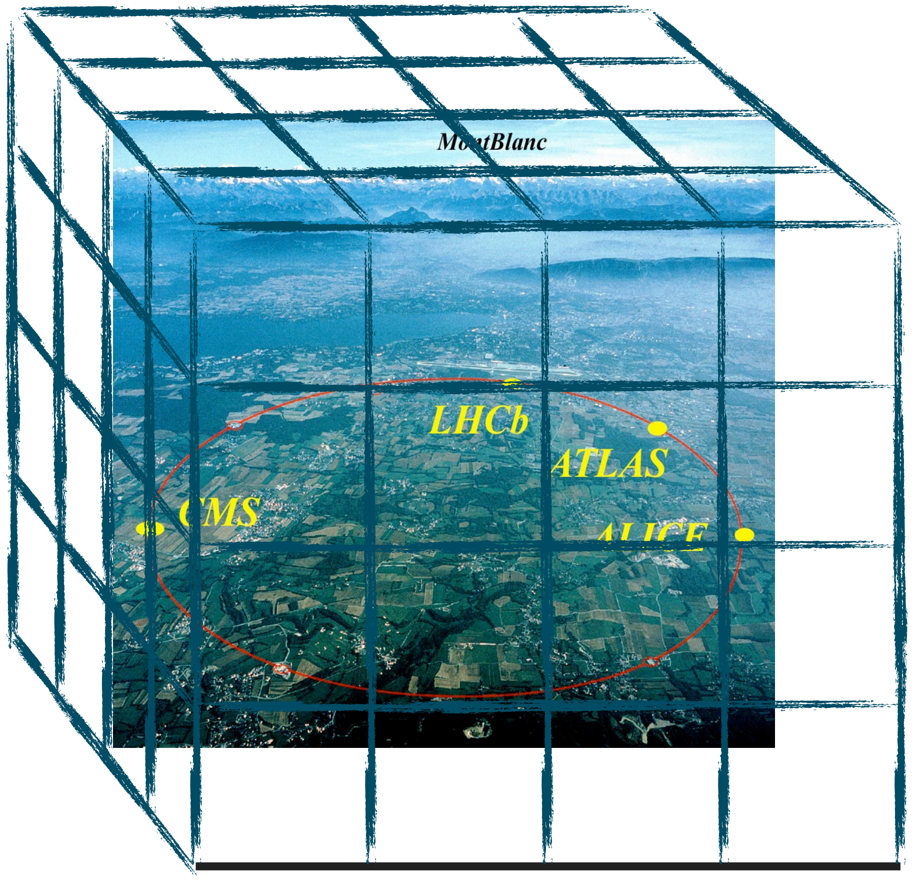

I. Introduction

Successes of Lattice **QCD**

- Hadron masses and their interactions
- Physics@$T \neq 0$
- The SM parameters
- Weak matrix elements
- ...

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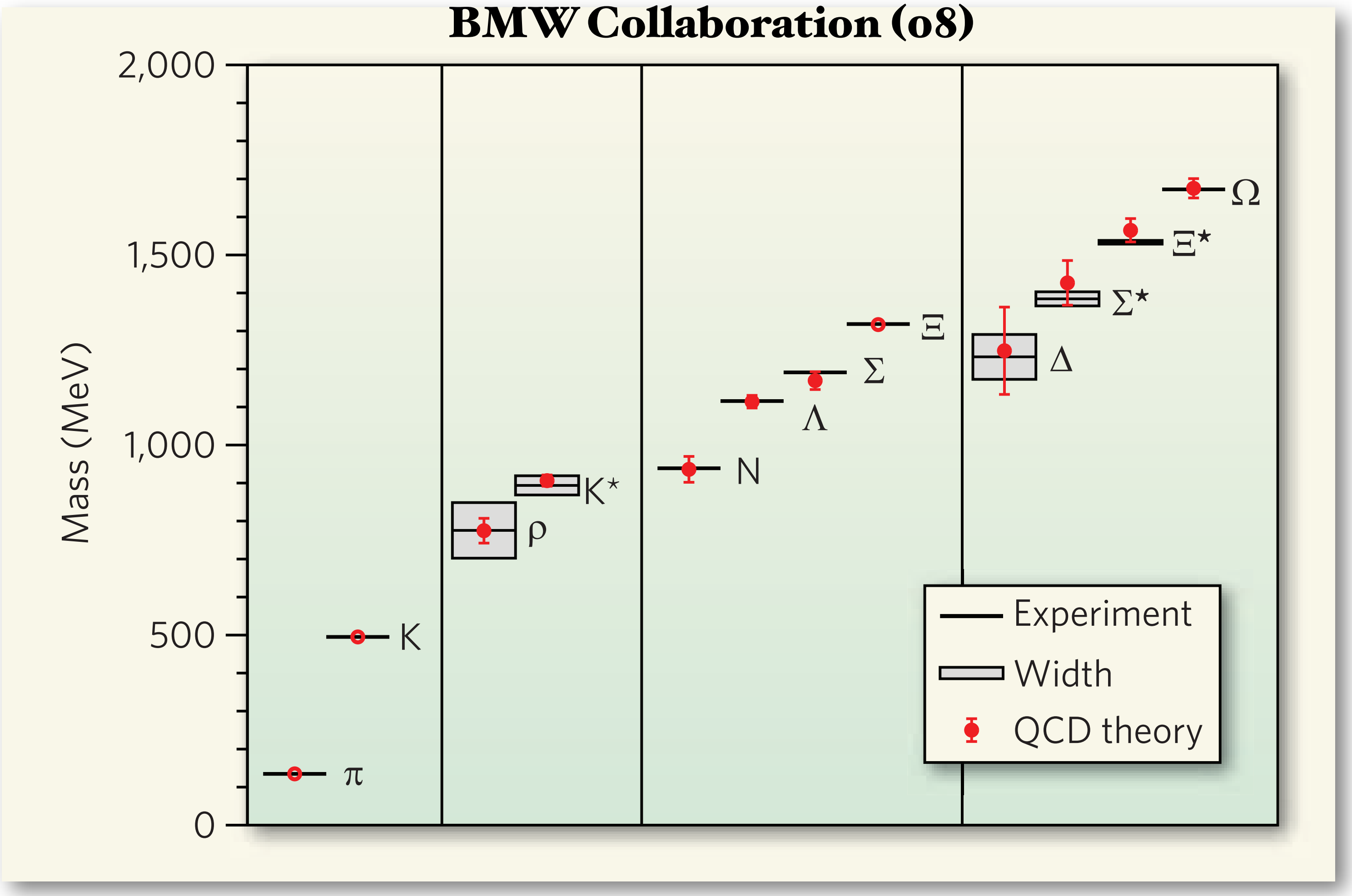

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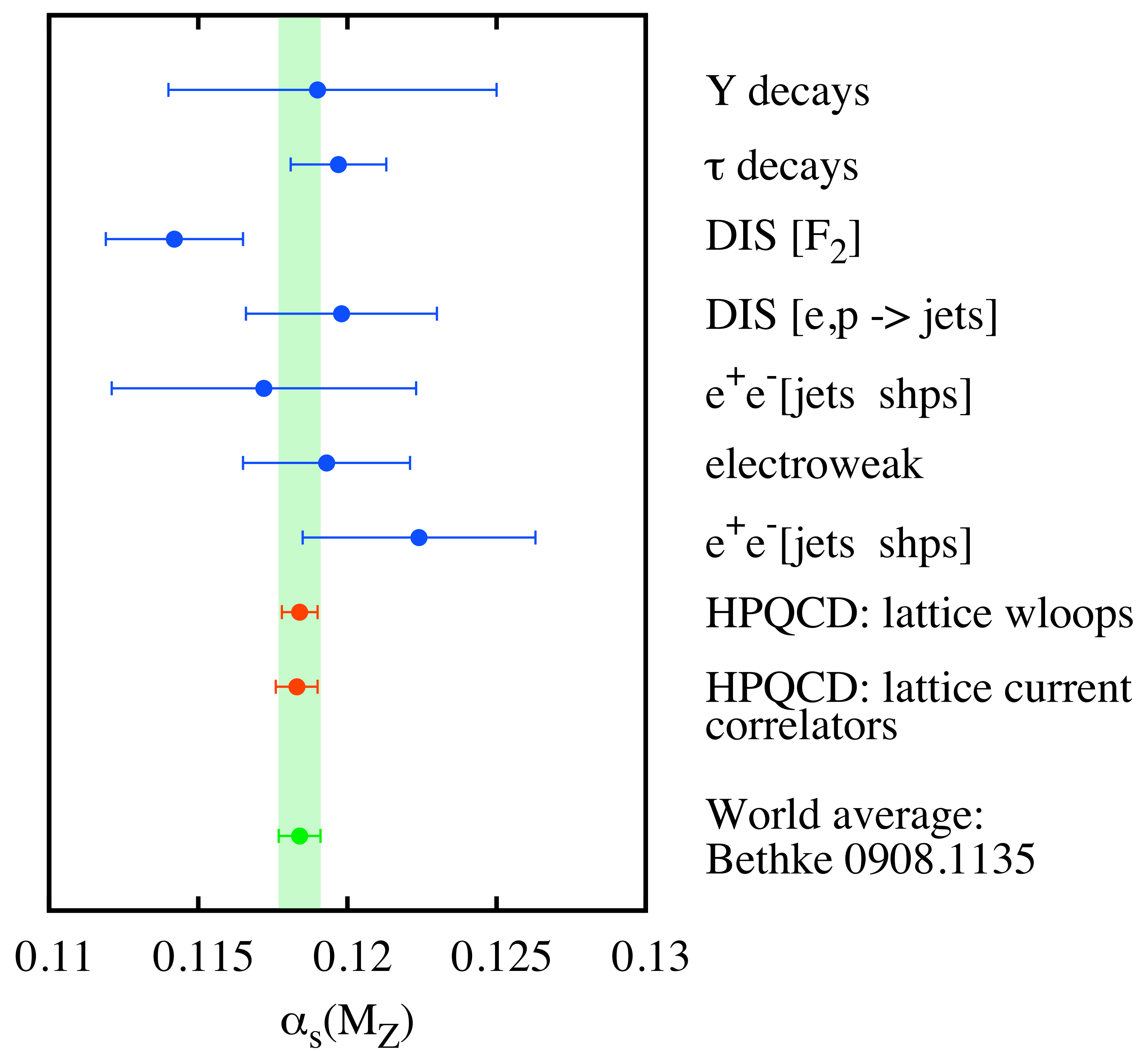

Successes of Lattice **QCD**

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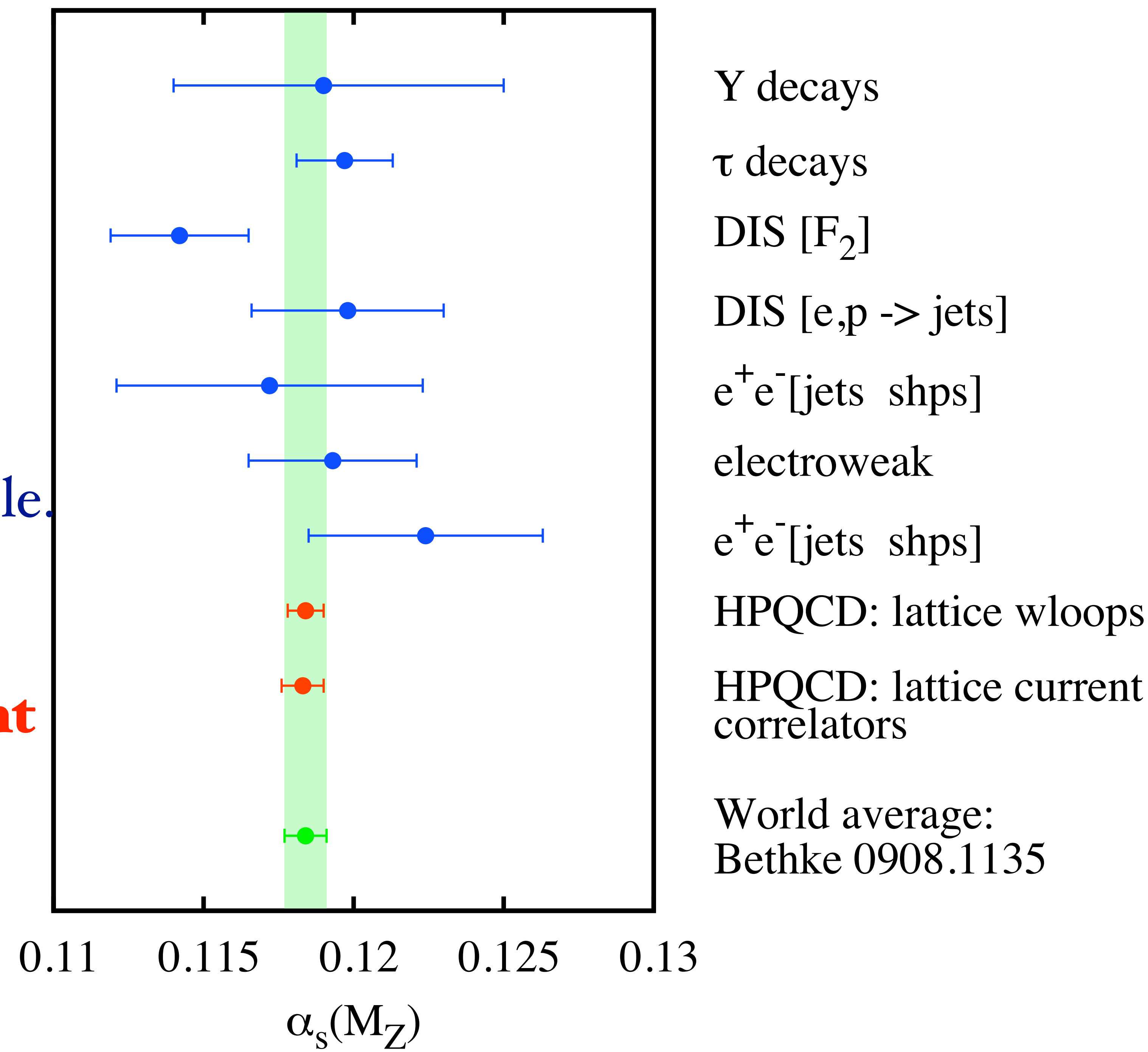
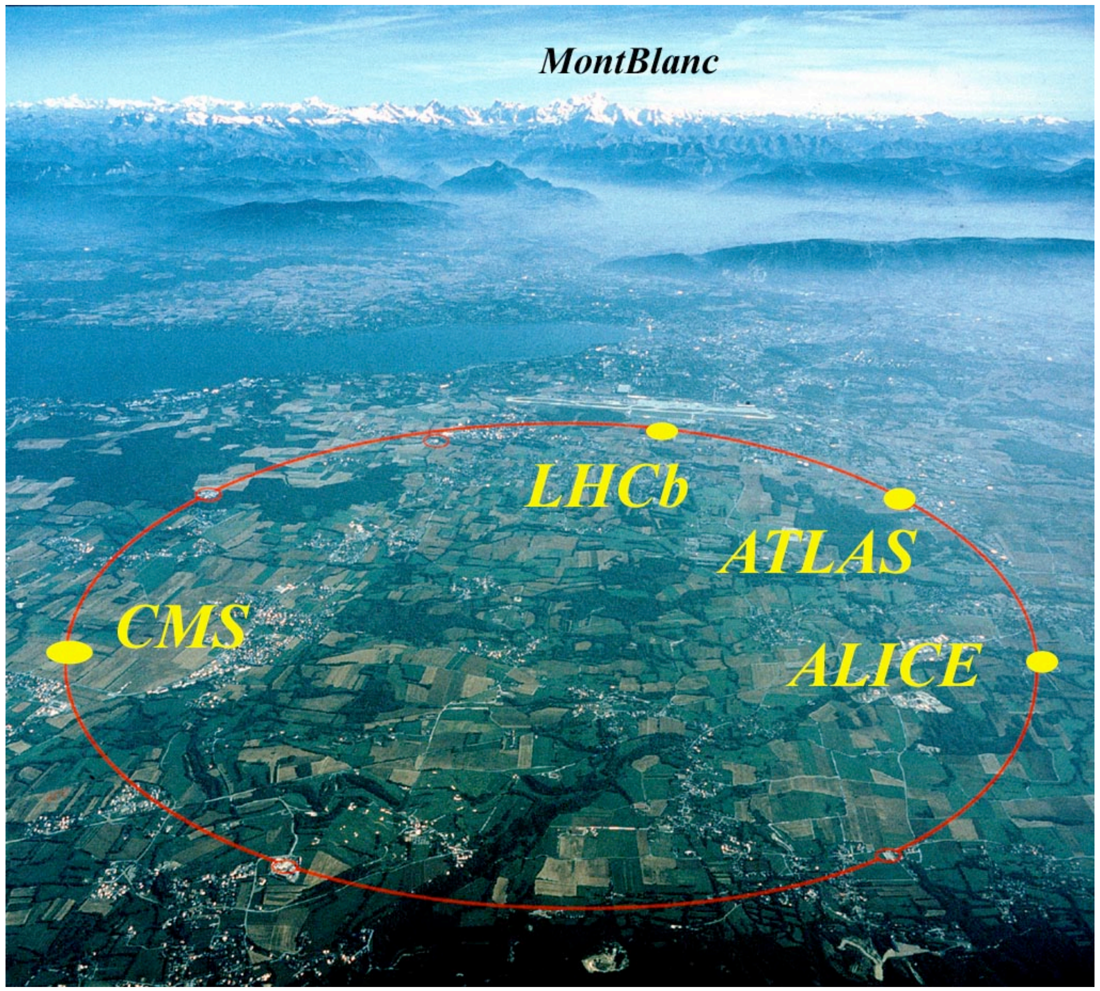
Lattice calculations truly reliable.

Apply to **Something different**



LHC era



- Higgs mechanism
- Physics above the EW scale
- Among many NP candidates, Technicolor is attractive and best suited for Lattice Simulation.

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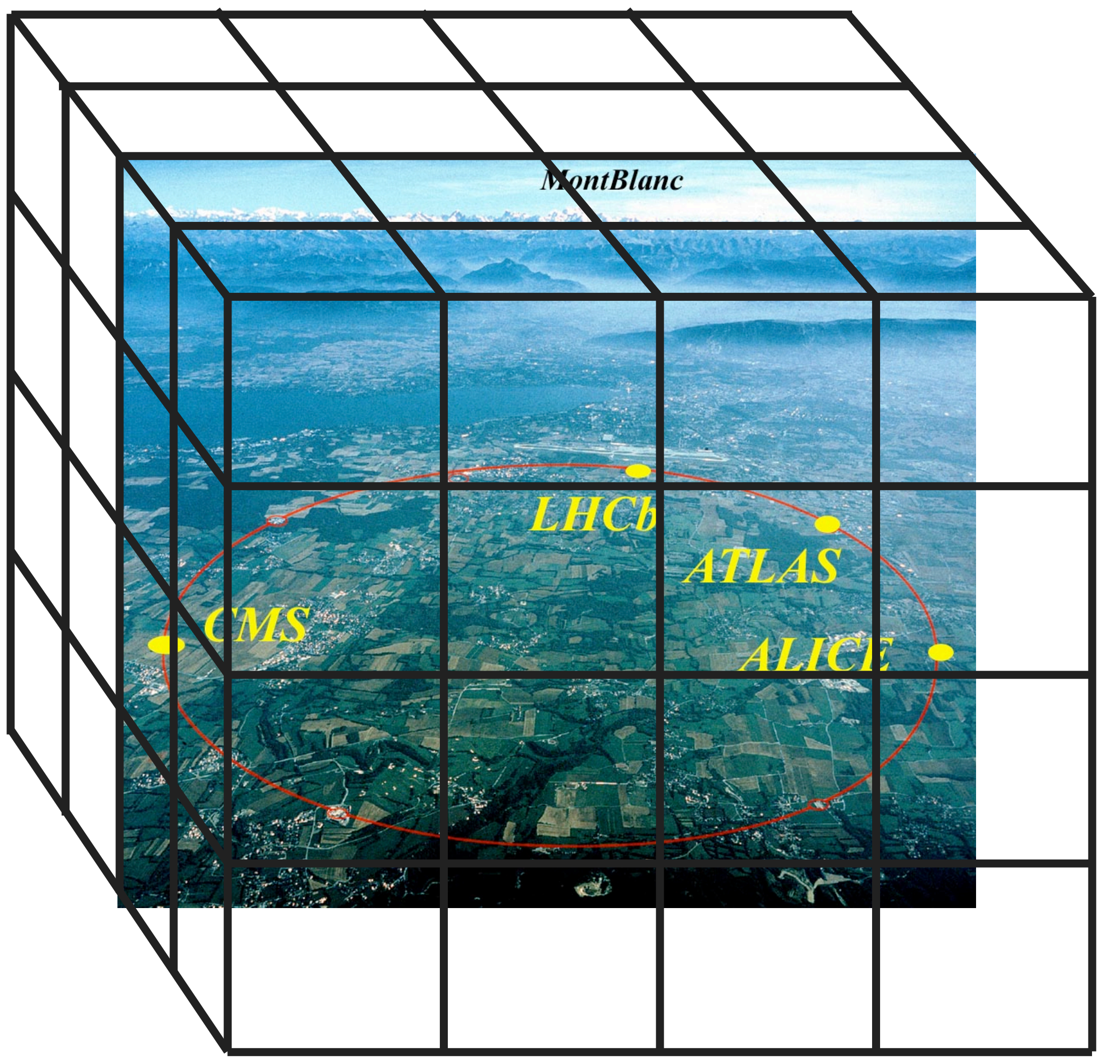

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Use Lattice to explore LHC physics

Technicolor (TC) [Weinberg(1979), Susskind(1979)]

Alternative to the Higgs sector in the SM

- QCD-like strong coupling vector-like Gauge theory inducing SχSB
  $\langle\bar{\psi}_L\psi_R\rangle \neq 0$ @ $\Lambda_{\rm TC}$ ⇒ EWSB (NG boson = techni-pion)

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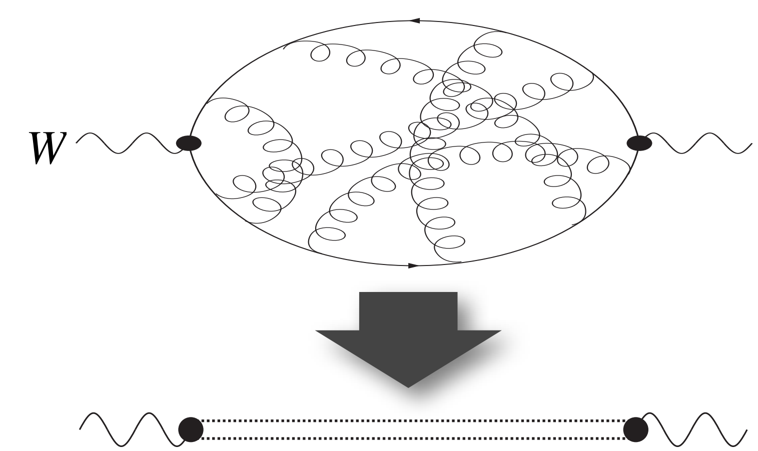
  $\Lambda_{TC} \sim (F_{TC} / f_\pi)\times\Lambda_{QCD} \sim 2600\times\Lambda_{QCD} \sim O(1)$ TeV

$$\frac{g^{\mu\nu} - q^\mu q^\nu/q^2}{q^2\left[1 - g_2^2\,\Pi(q^2)\right]} \overset{S\chi SB}{\Longrightarrow} \frac{g^{\mu\nu} - q^\mu q^\nu/q^2}{q^2\left[1 - g_2^2\left(\frac{F_{TC}^2}{4q^2}\right)\right]} = \frac{g^{\mu\nu} - q^\mu q^\nu/q^2}{q^2 - \left(\frac{g_2 F_{TC}}{2}\right)^2}$$



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- No elementary scalar particle ⇒ No fine tuning

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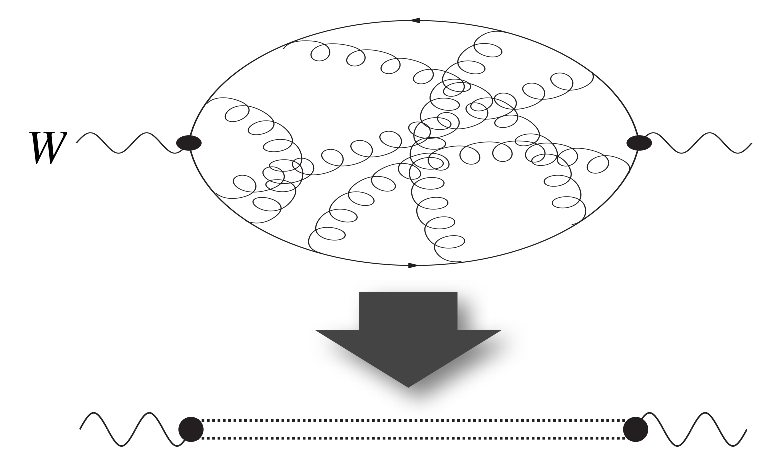

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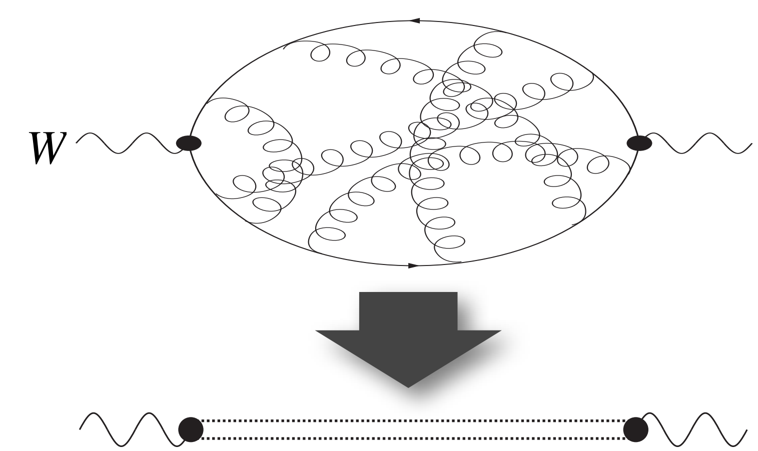

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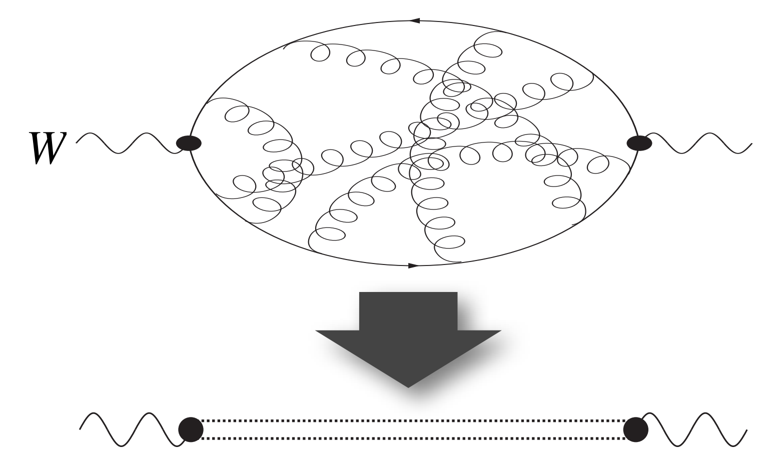


However, uncalculable …
Non-Perturbative Dynamics ⇒ quantitative treatment difficult

Extended TC and its Breaking

TC must be extended to give mass to the SM fermions.
⇒ New gauge interaction **ETC (unspecified)**
Lane and Eichten ('80), Dimopoulos and Susskind ('79)

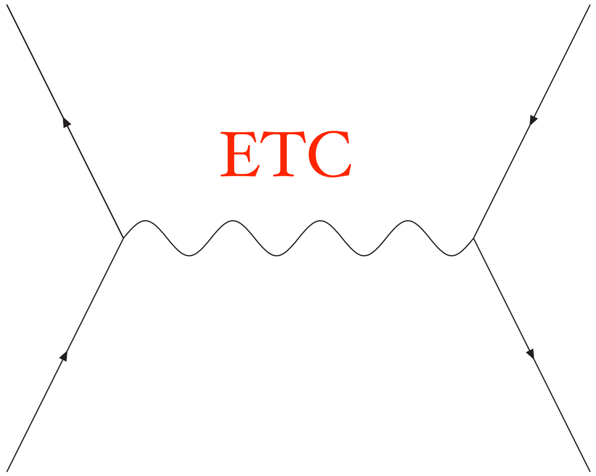
ETC breaking@$M_{\rm ETC}$ ⇒ various four-ferm ops. induced

ETC fermion multiplet: $F^{\rm ETC}=(F_1, \ldots, F_{N_{TC}}, f_{SM3}, f_{SM2}, f_{SM1})$

At $\mu < M_{\rm ETC}$, $\frac{g_{ETC}^2}{M_{ETC}^2} C(\mu) (\bar{F} F)(\bar{f} f)$ & $\frac{g_{\rm ETC}^2}{M_{\rm ETC}^2} (\bar{f}' \Gamma_\mu f)(\bar{f}' \Gamma_\mu f)$

quark/lepton mass — FCNC

$$C(\mu) = \exp\left(\int_\mu^{M_{ETC}} d\mu' \frac{\gamma(\mu')}{\mu'}\right) = \exp\left(\int_{g^2(\mu)}^{g^2(M_{ETC})} dg'^2 \frac{\gamma(g'^2)}{\beta(g'^2)}\right)$$



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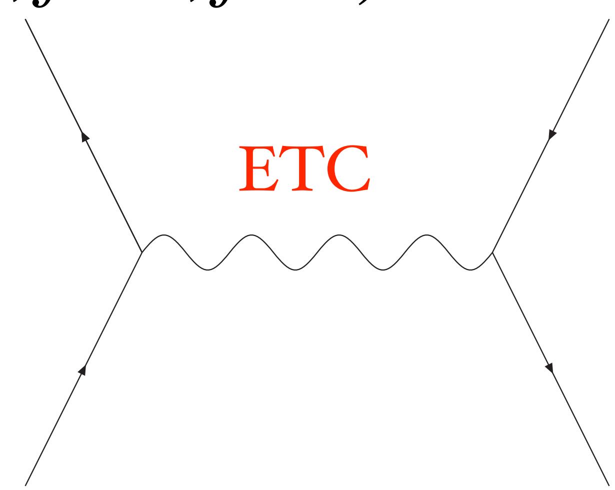

$M_{\rm ETC}$ constrained by

$$m_q \sim g_{\rm ETC}^2 \frac{\langle\, 0|\bar{F}F|0\,\rangle}{2\, M_{\rm ETC}^2} \sim g_{\rm ETC}^2 \frac{M_{\rm TC}^3}{2\, M_{\rm ETC}^2}$$

and

Δm in K^0-$\bar{K}^0$, D^0-$\bar{D}^0$, ...

Problem 1: FCNC & m_q

At $\mu < M_{\rm ETC}$, $\frac{g^2_{ETC}}{M^2_{ETC}} C(\mu) (\bar{F} F)(\bar{f} f)$ & $\frac{g^2_{\rm ETC}}{M^2_{\rm ETC}} (\bar{f}' \Gamma_\mu f)(\bar{f}' \Gamma_\mu f)$

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conflicts with

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$C(M_{\rm TC}) \sim \left(\dfrac{M_{\rm ETC}}{M_{\rm TC}}\right)^\gamma \gg 1$ & $M_{\rm ETC} \gg M_{\rm TC}$ must be satisfied.

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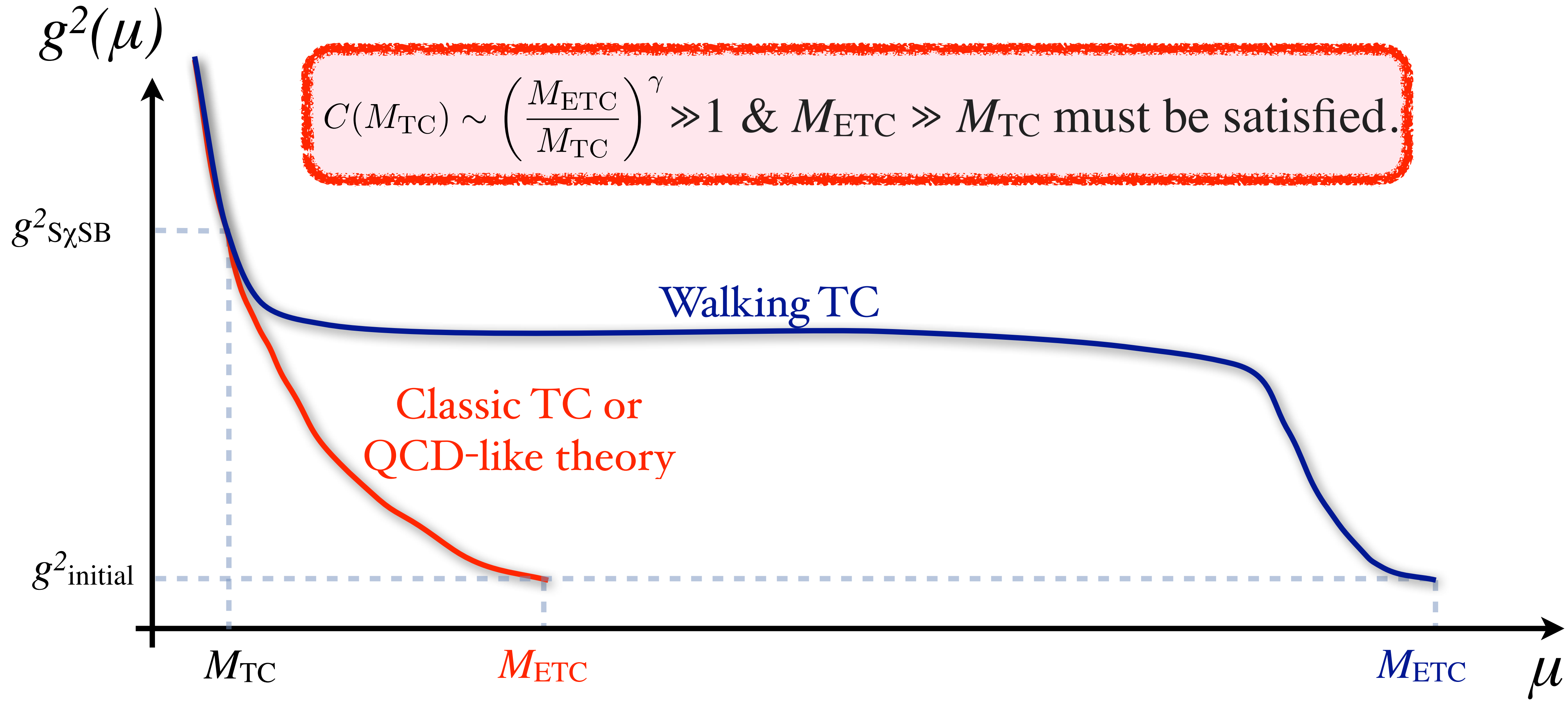


Walking Technicolor (WTC)

Holdom(1981); Yamawaki, Bando, Matsumoto(1986); Appelquist, Karabali, Wijewardhana(1986);
Akiba, Yanagida(1986); Bando, Morozumi, So, Yamawaki(1987)

$C(M_{\rm TC}) \sim \left(\frac{M_{\rm ETC}}{M_{\rm TC}}\right)^{\gamma} \gg 1$ & $M_{\rm ETC} \gg M_{\rm TC}$ must be satisfied.

Inputs

Theory

$M_{\rm ETC}$

$g_{\rm TC}^2(M_{\rm ETC})$

⇒

Dynamics determines everything

$C(M_{\rm TC}),\ M_{\rm TC}/M_{\rm ETC},\ \Sigma_{\rm TC}(m_{q,l}),\ f_{\rm TC},$
$S,\ m_{\sigma},\ m_{\rho},$ ....

No tunable parameter!

e.g.) SU(3) gauge theory with 2 or 3-flavors of techni-quarks
(*i.e.* scaled-up QCD) does not respect the condition.

➡ **Such a self-serving GT really exists?**

Problem 2: S-parameter

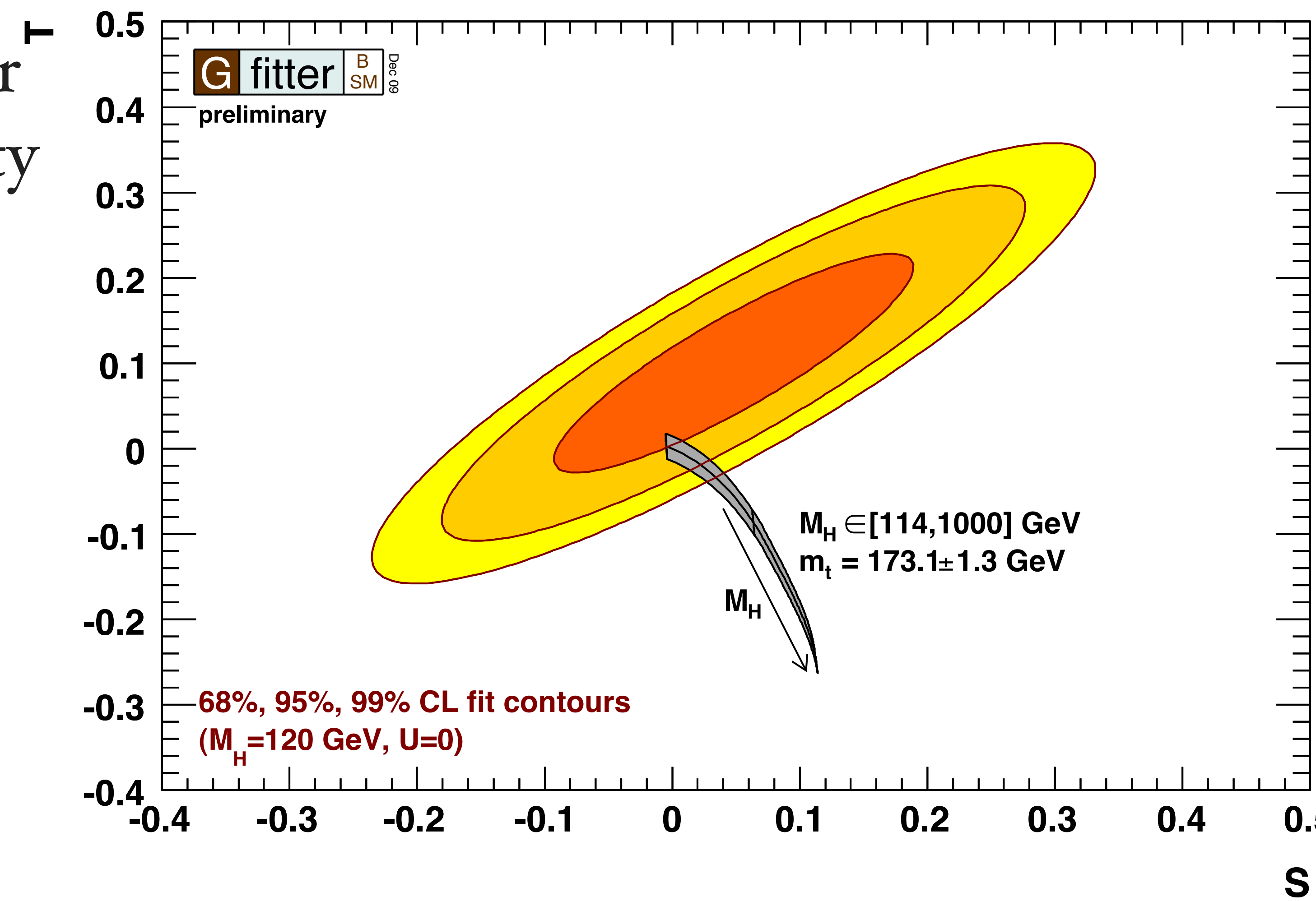
Peskin & Takeuchi (90,92)

- Rescaled QCD (S≥0.45) excluded
- Walking dynamics ⇒ S-parameter different from QCD (due to parity doubling?)
- Non-perturbative mathod is necessary.
- We know how to calculate S on the Lattice!

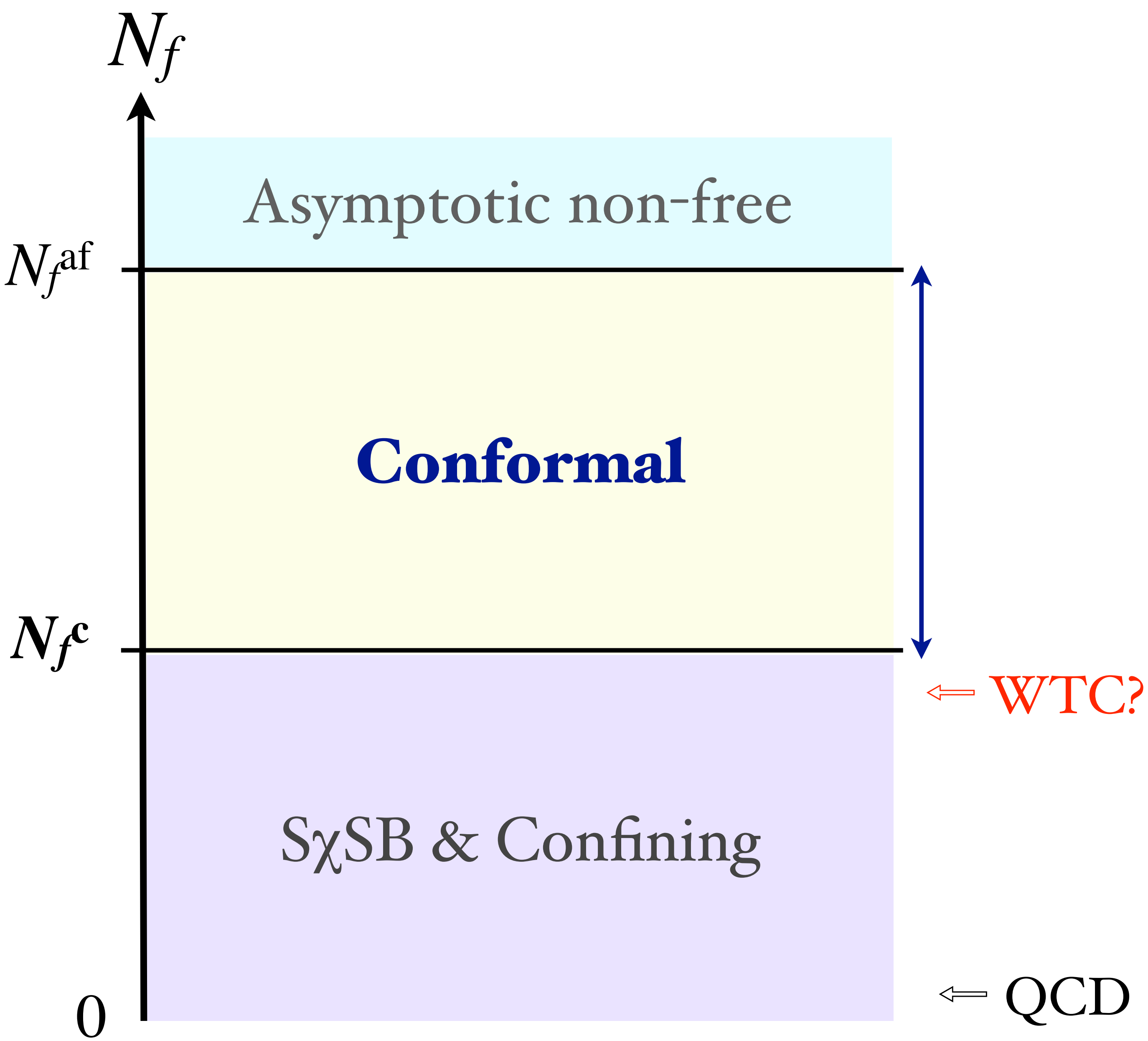
JLQCD (08):two-flavor QCD

c.f. RBC & UKQCD(10):three-flavor QCD
LSD(10): six-flavor QCD
T. DeGrand (10):sextet QCD

J. Haller [the Gfitter group} (www.cern.ch/gfitter), hep-ph/1006.0003



Conformal Window



Speculation on “Phase diagram” of GT

Find the location of N_f^{c} in various GT.

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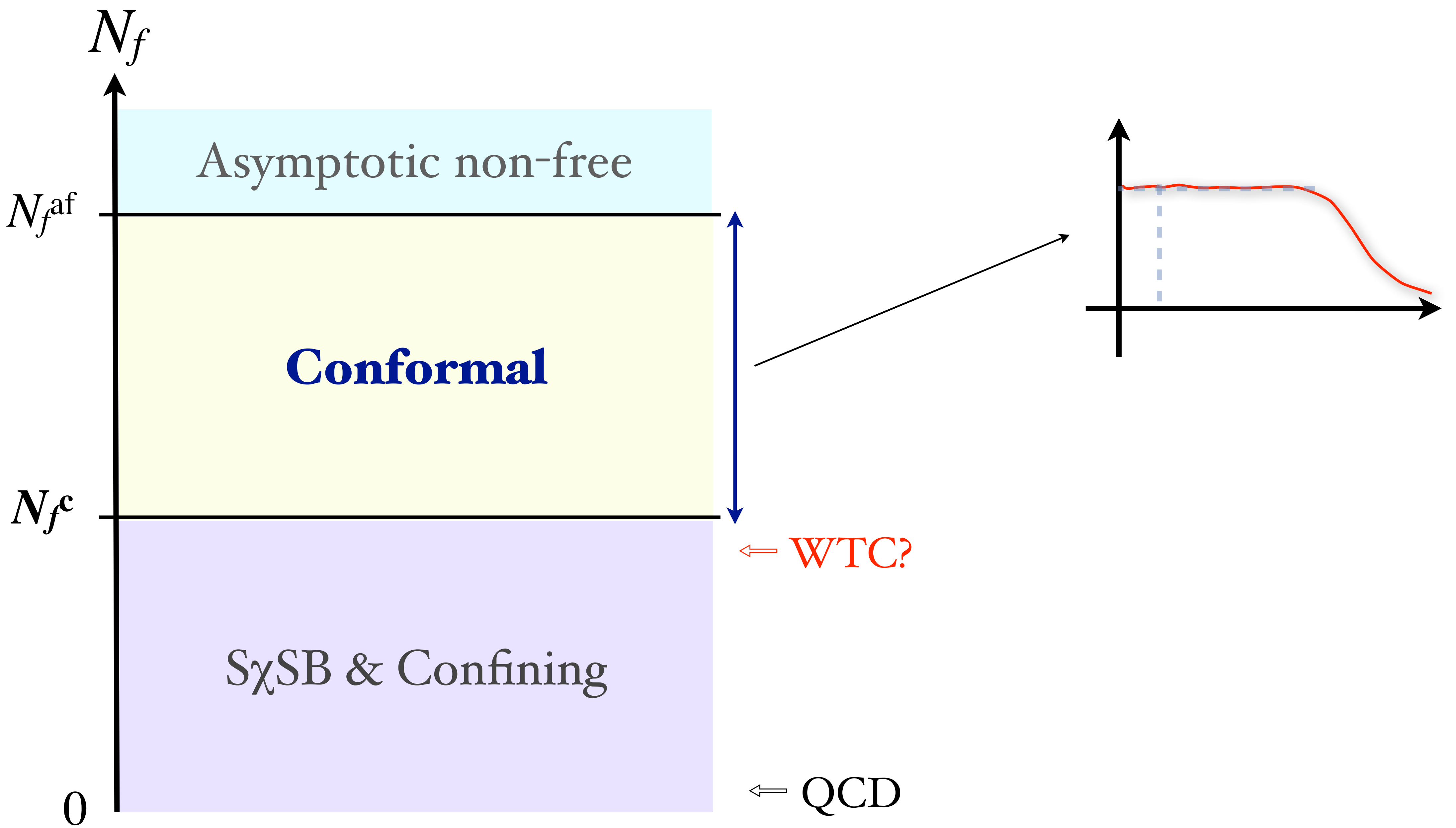

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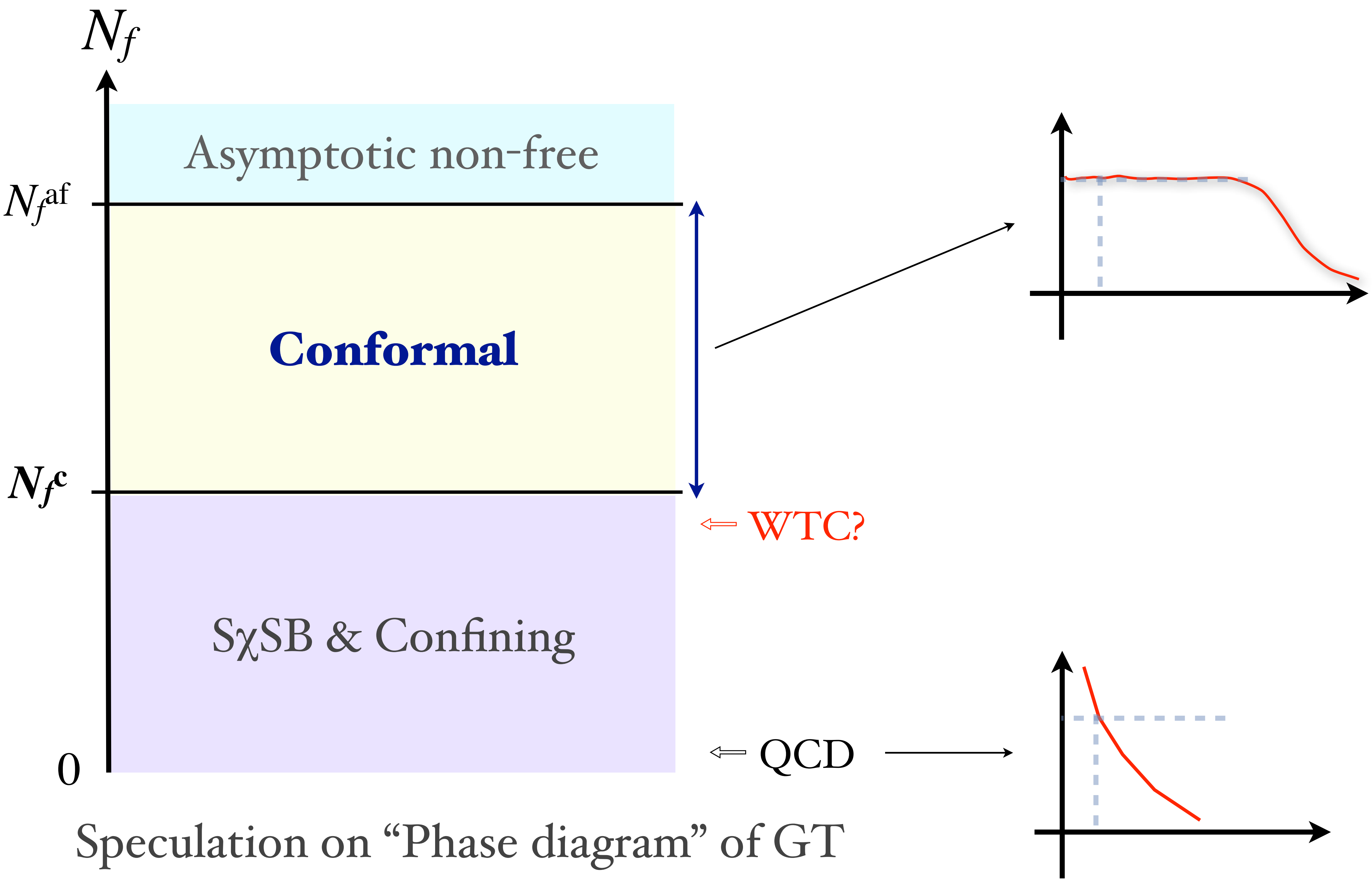

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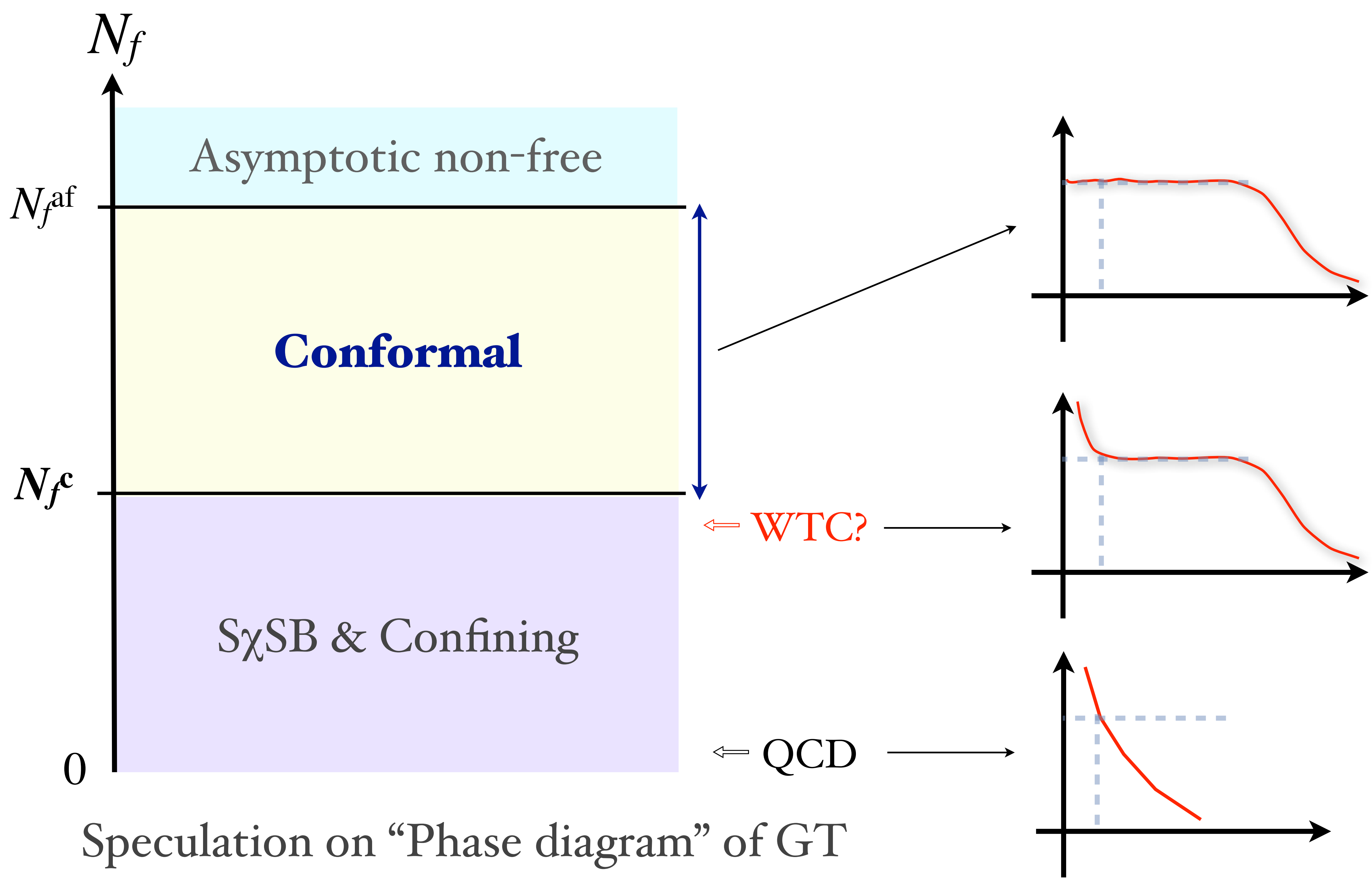


Speculation on “Phase diagram” of GT

Find the location of N_f^c in various GT.

Strategy on the lattice

Searching phase (-2012?)

Calculate **running coupling** and **anomalous dimension** directly on the lattice.

Calculate **hadron spectrum** to see whether SχSB takes place or not.

Prediction phase (2013?-)

Perform large-scale lattice simulation of candidate theories to find the precise values for f_π, m_ϱ, (m_σ), Σ, S-parameter, ...

Now is in Searching phase.

Prediction phase on the Next-Generation supercomputer?

Candidates for WTC

So far, the following SU(Nc) gauge theories have been intensively studied.

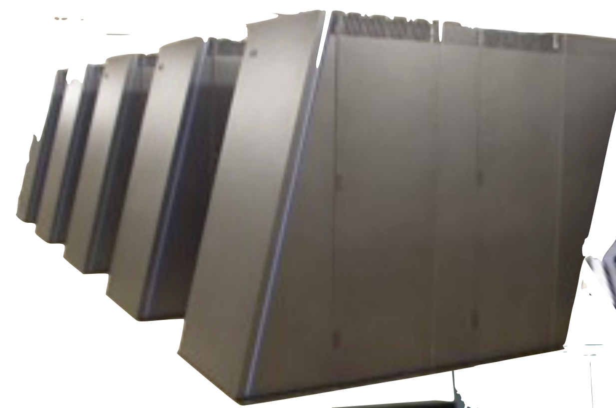
	N_c	N_f	Rep.	Running g²	spectroscopy
Large N_f QCD	3	6~16	fund.	$8 < N^c_f < 12$	$N^c_f > 12$ $N^c_f < 12$
Large N_f two-color QCD	2	6, 8	fund.	$N^c_f < 6$	-
Sextet QCD	3	2	sextet	conformal	conformal confinment
Two-color adjoint QCD	2	2	adjoint	conformal	conformal

Currently, many contradictions and little consensus

II. Lattice calculation of running coupling

Machines used

- Supercomputer@KEK (SR11K, BG/L)
- GPGPU & CPU servers@KEK
- INSAM GPU cluster@Hiroshima
- GPGPU, GCOE cluster system@Nagoya
- B-factory computer system







Perturbation

SU(3) gauge theory with N_f fundamental Dirac fermions:

$$\beta(g^2(L)) = L\frac{\partial g^2(L)}{\partial L} = b_1 g^4(L) + b_2 g^6(L) + b_3 g^8(L) + b_4 g^{10}(L) + \cdots ,$$

$$b_1 = \frac{2}{(4\pi)^2}\left[11 - \frac{2}{3}N_f\right],$$ ← universal and positive for $N_f \leq 16$

$$b_2 = \frac{2}{(4\pi)^4}\left[102 - \frac{38}{3}N_f\right].$$ ← universal

$$b_3^{\overline{\mathrm{MS}}} = \frac{2}{(4\pi)^6}\left[\frac{2857}{2} - \frac{5033}{18}N_f + \frac{325}{54}N_f^2\right],$$

$$b_4^{\overline{\mathrm{MS}}} = \frac{2}{(4\pi)^8}\left[29243.0 - 6946.30\,N_f + 405.089\,N_f^2 + 1.49931\,N_f^3\right],$$

$$b_3^{\mathrm{SF}} = b_3^{\overline{\mathrm{MS}}} + \frac{b_2\,c_2^\theta}{2\pi} - \frac{b_1\,(c_3^\theta - {c_2^\theta}^2)}{8\pi^2}.$$ (c_2^θ, c_3^θ : coefficients depending on SF setup)

Perturbation

SU(3) gauge theory with N_f fundamental Dirac fermions:

Perturbation

SU(3) gauge theory with N_f fundamental Dirac fermions:

Perturbative IRFP for SU(3) gauge theory with fermions in fund. rep.

N_f	4	6	8	10	12	14	16
2-loop universal				27.74	9.47	3.49	0.52
3-loop SF	43.36	23.75	15.52	9.45	5.18	2.43	0.47
3-loop $\overline{\text{MS}}$		159.92	18.40	9.60	5.46	2.70	0.50
4-loop $\overline{\text{MS}}$			19.47	10.24	5.91	2.81	0.50

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- $N_f^{\mathbf{c}}$ depends on scheme in perturbation theory
- Schwinger–Dyson analysis suggests that SχSB occurs at $g^2 \sim \pi^2$.
- PT analysis suggests that N_f =8~12 are interesting!

Perturbation

SU(3) gauge theory with N_f fundamental Dirac fermions:

Ex) anomalous dimension in SF scheme:

$$\gamma^{\mathrm{SF}} = \frac{8}{(4\,\pi)^2}\, g^2\ \{1 + (0.1251 + 0.0046\, N_f)\ g^2\}$$

With $g_{\mathrm{FP}}{}^2$ for 3-loop β-function in SF scheme,

$$\gamma^{\mathrm{SF}}_{\mathrm{FP}} = \begin{cases} 2.76183 & \text{for } N_f = 8 \\ 1.25265 & \text{for } N_f = 10 \\ 0.50772 & \text{for } N_f = 12 \end{cases} \sim O(1)$$

Perturbation is not reliable.

Use Lattice method!

Schrödinger functional scheme

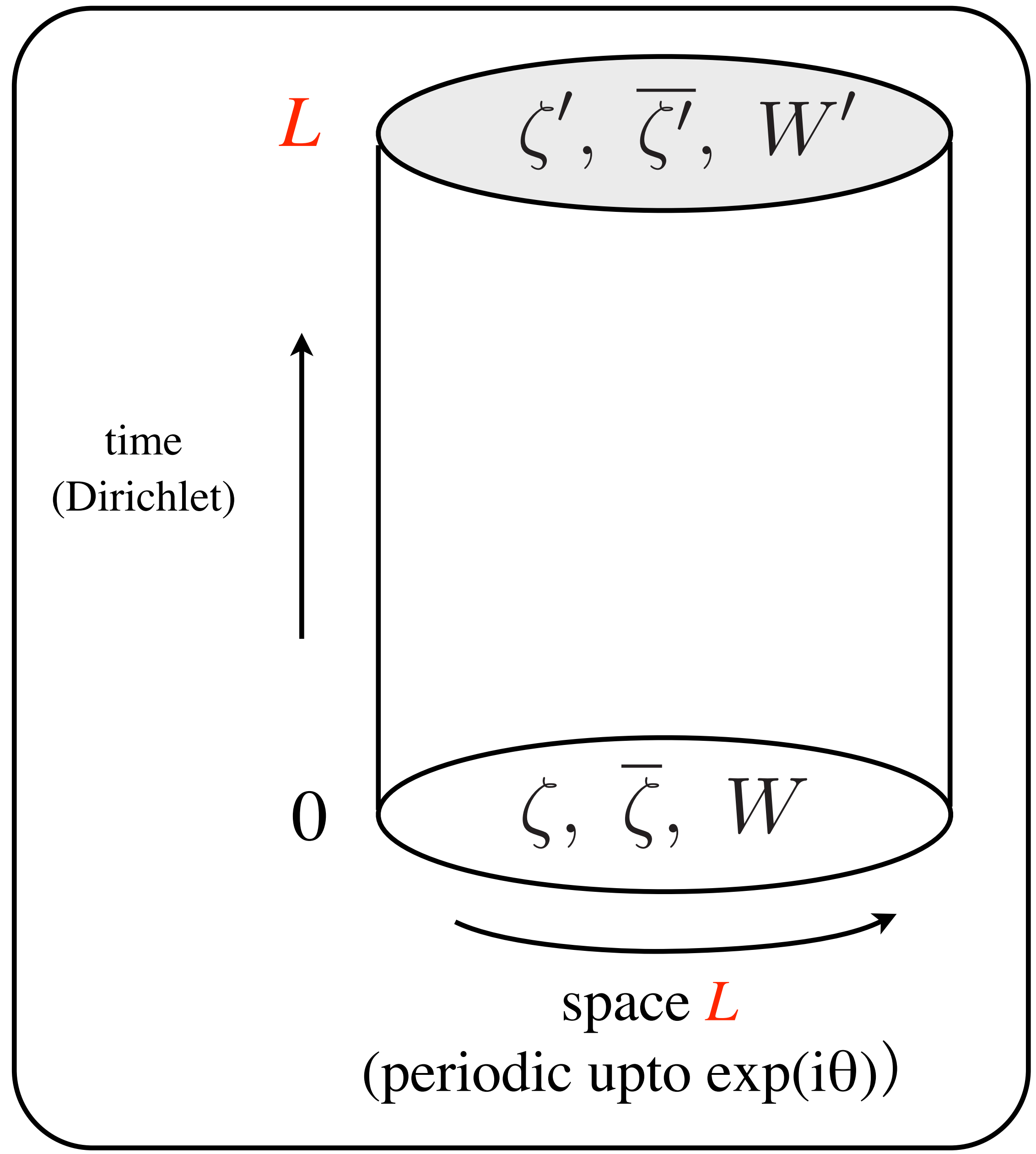
Luscher, Weisz, Wolff, NPB(1991), and subsequent many papers

- Consider SU(N_c) GT in a cylinder with L^4
- Boundary conditions in time are fixed such that bulk fields have a non-vanishing color-electric background.
- Then effective action:

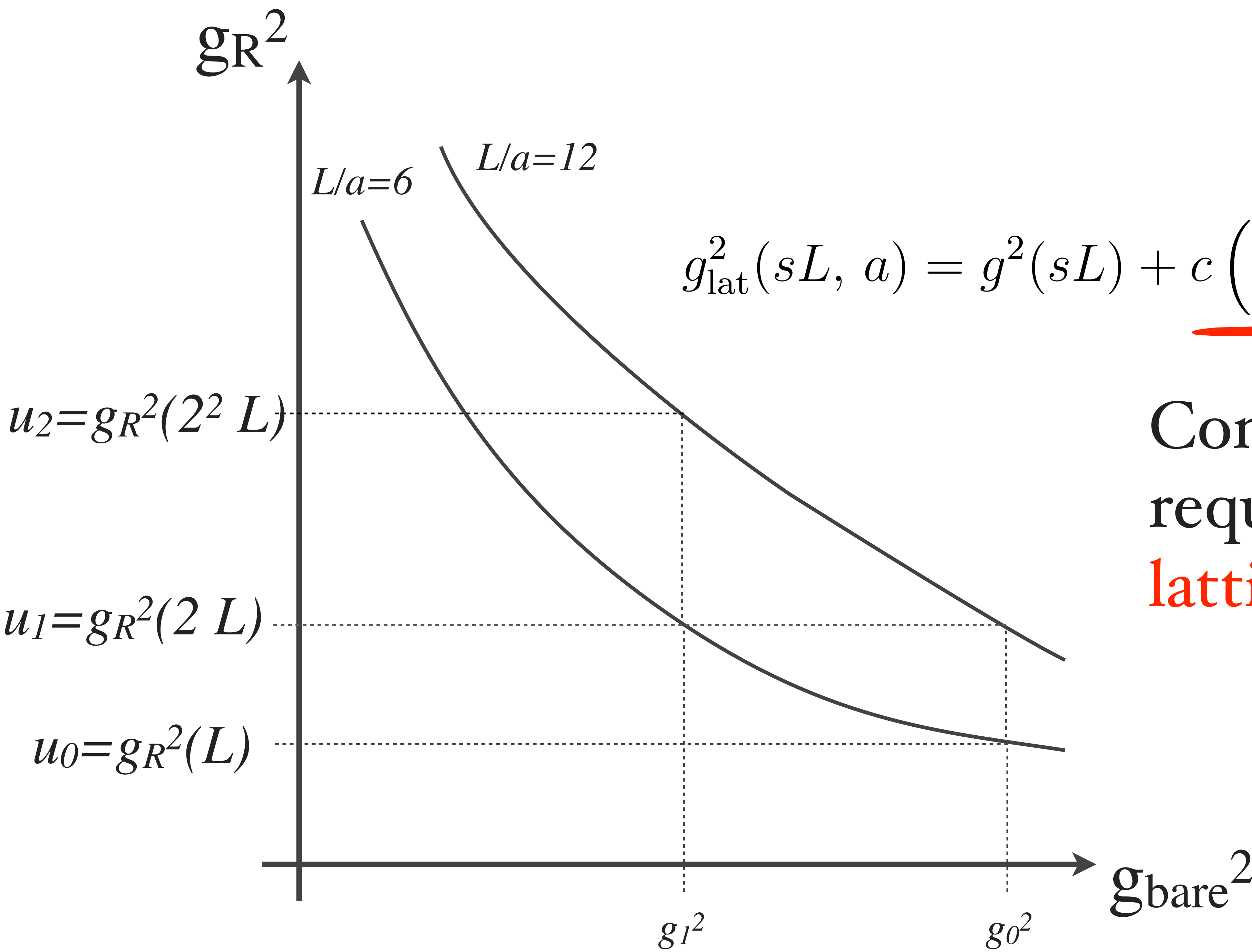
$$\Gamma = g(L)^{-2} S_{YM}^{cl}$$

where $S_{YM}^{cl} = \int d^4x\, F_{\mu\nu}^2$

- $g(L)^2$: non-perturbative & gauge-invariant
- Scale of g^2 is given by L. Various $L \Rightarrow$ Running of $g^2(L)$



How to calculate "running"?

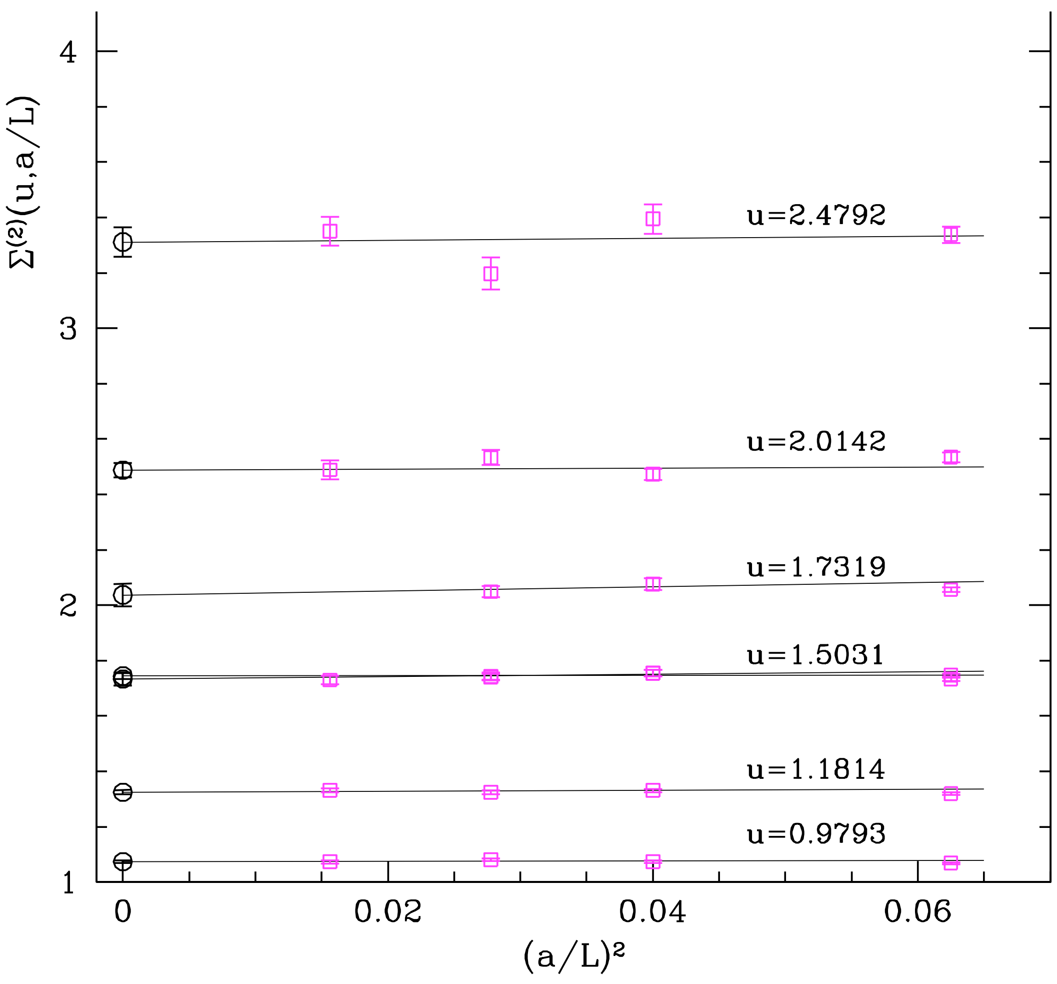


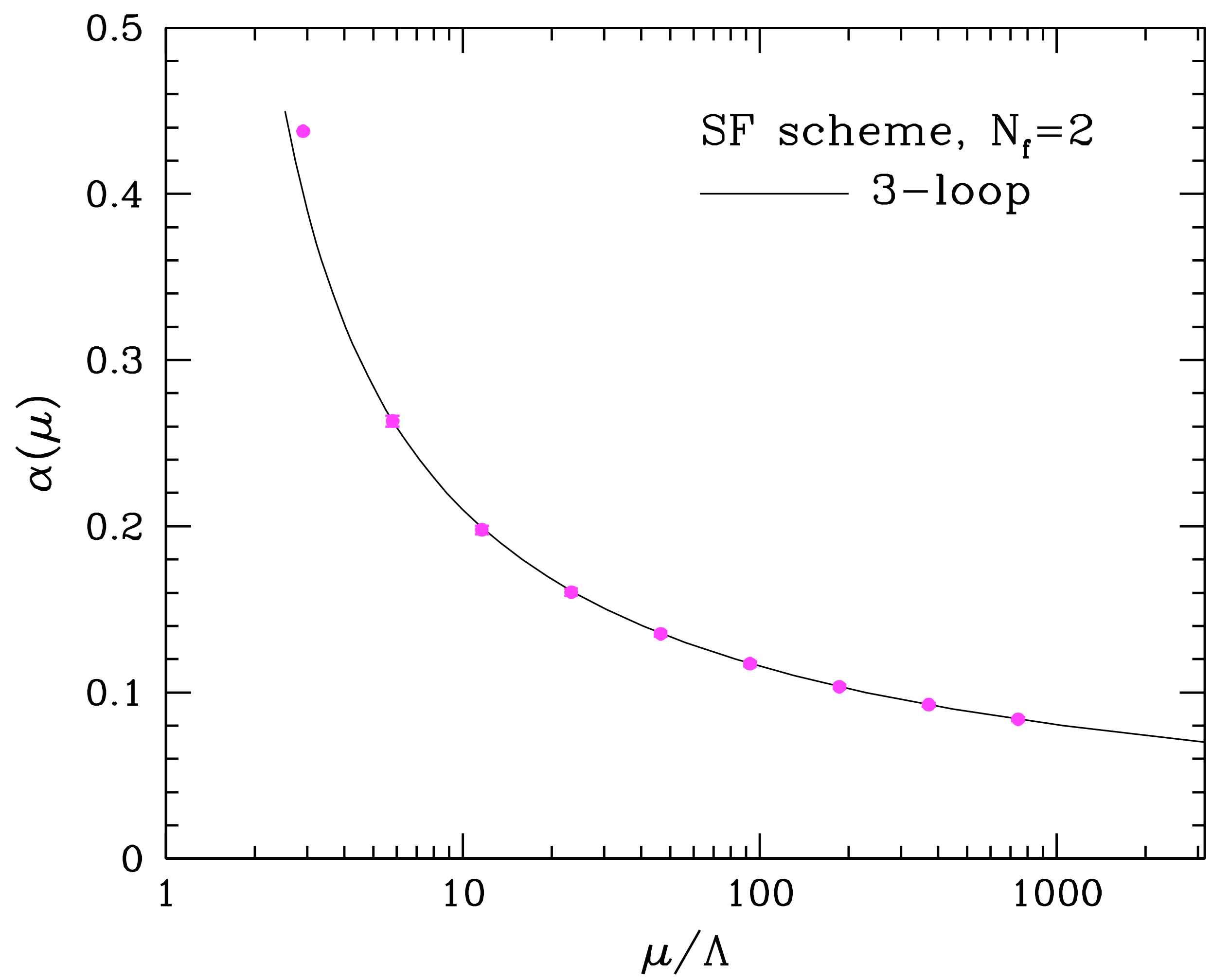
$$g^2_{\rm lat}(sL,\, a) = g^2(sL) + c\left(\frac{a}{sL} - \frac{a}{L}\right) + O(a^2/L^2)$$

Continuum limit required to remove lattice artifacts.

Example: 2-flavor QCD

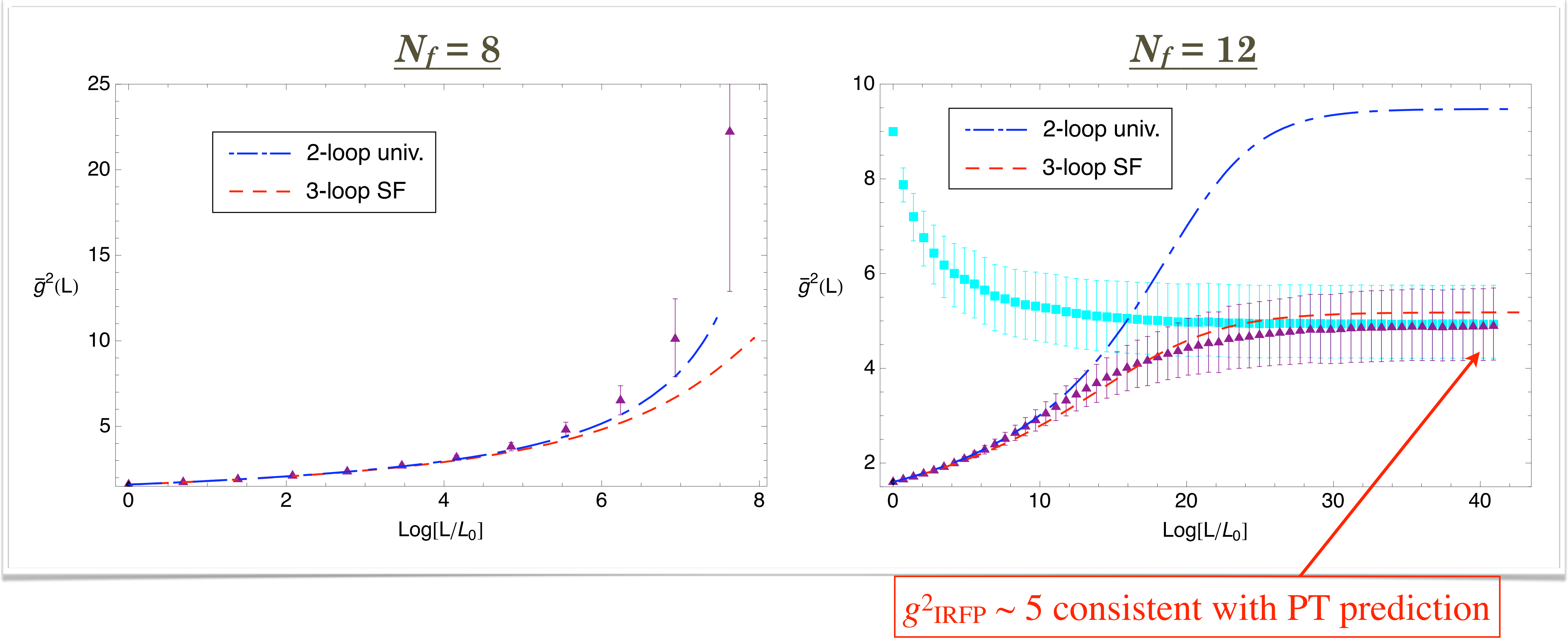
ALPHA Collaboration(2005)





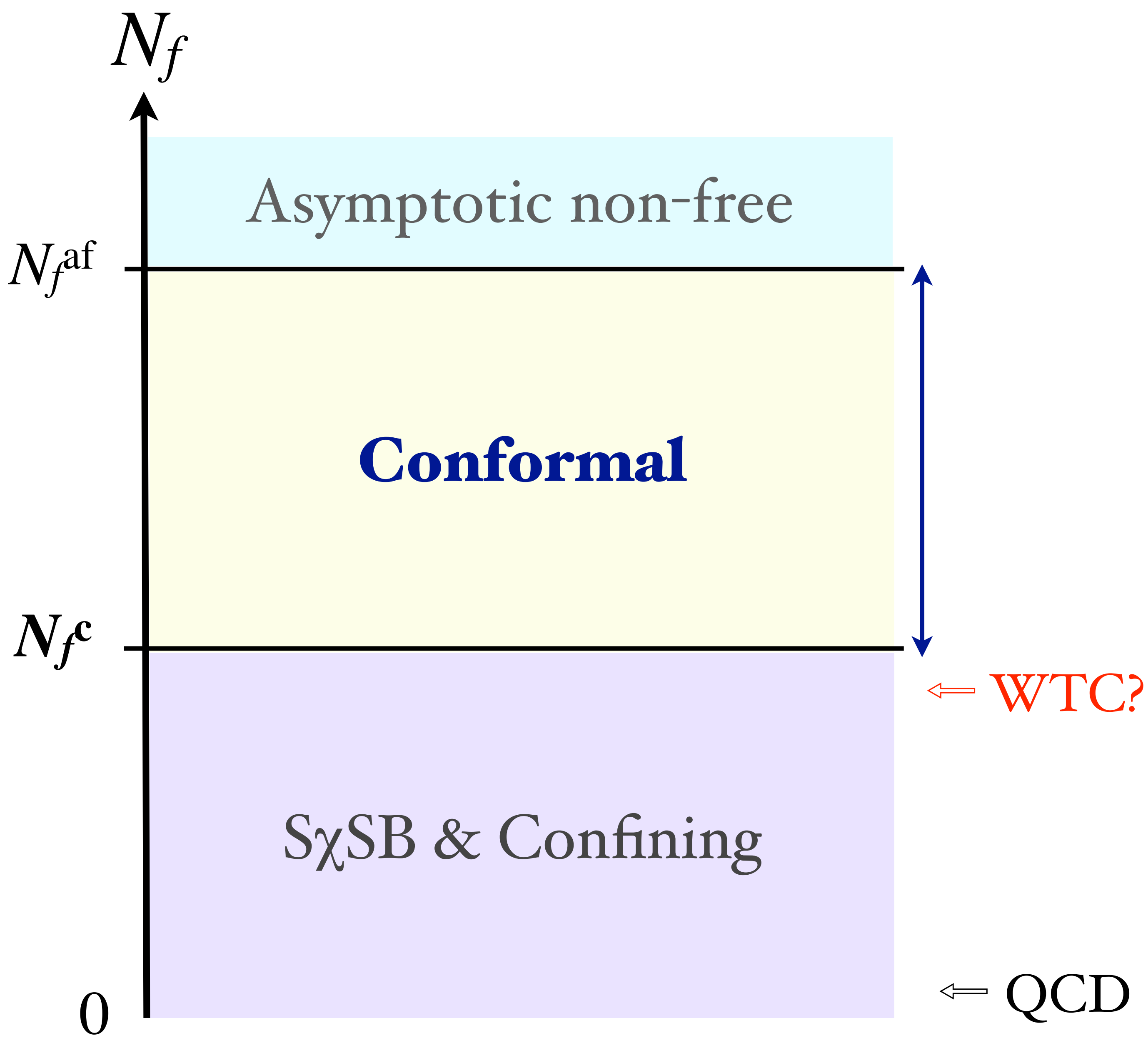
8 & 12 flavor QCD

Appelquist, Fleming, Neil, PRL100:171607, 2008; PRD79:076010, 2009



Conclusion: N_f=12 is too large while N_f=8 is too small.
(12-flavor QCD is still under debate.)

Conformal Window



Speculation on "Phase diagram" of GT

For SU(3) GT,

$$8 < N_f^c < 12$$

⇓

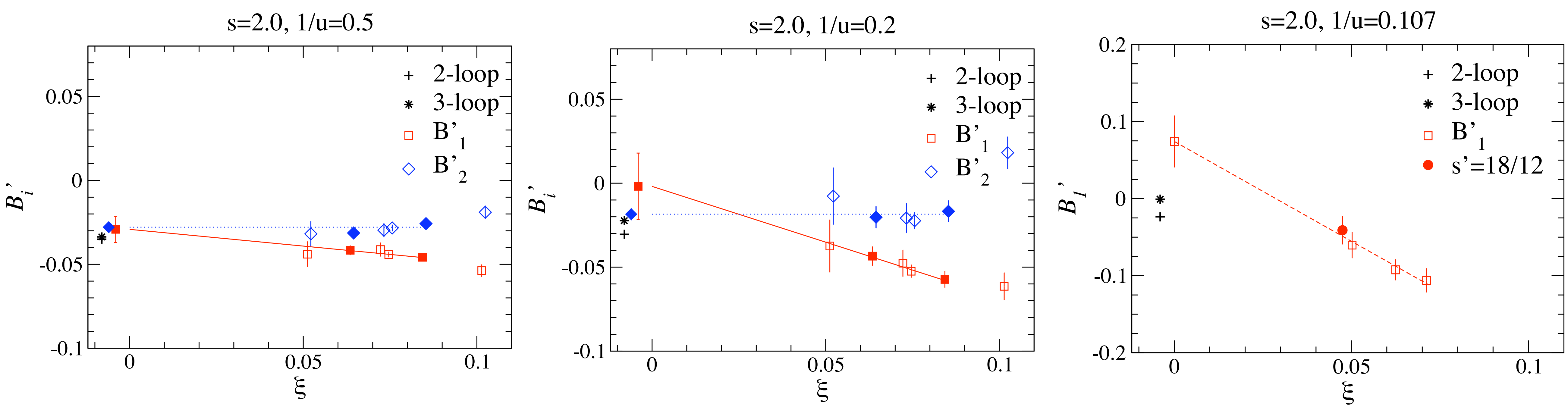
$$N_f = 10$$

Find the location of N_f^c in various GT.

10 flavor QCD (This work)

Discrete beta function: $B(u_i,\ s) = \dfrac{1}{u_{i+1}} - \dfrac{1}{u_i}$ where $u_i = g_R^2(s^i L)$

Y. Shamir, B. Svetitsky and T. DeGrand, PRD78(2008)031502



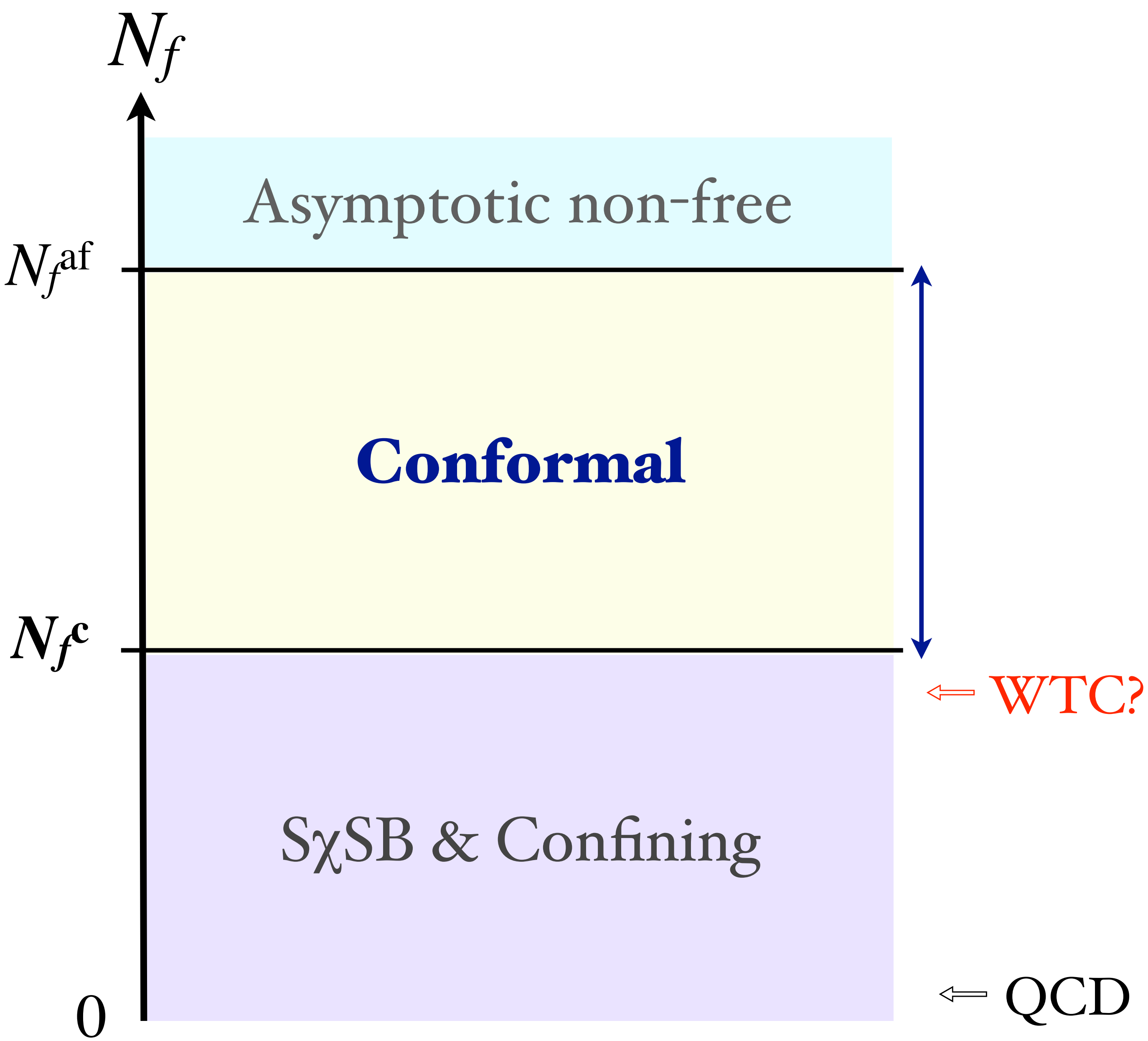
negative

consistent with zero

positive

Extrapolation to the continuum limit shows sign-flip before g_{SF}^2 reaches about 10. $g_{FP}^2 = 3.3 \sim 9.35$

Conformal Window



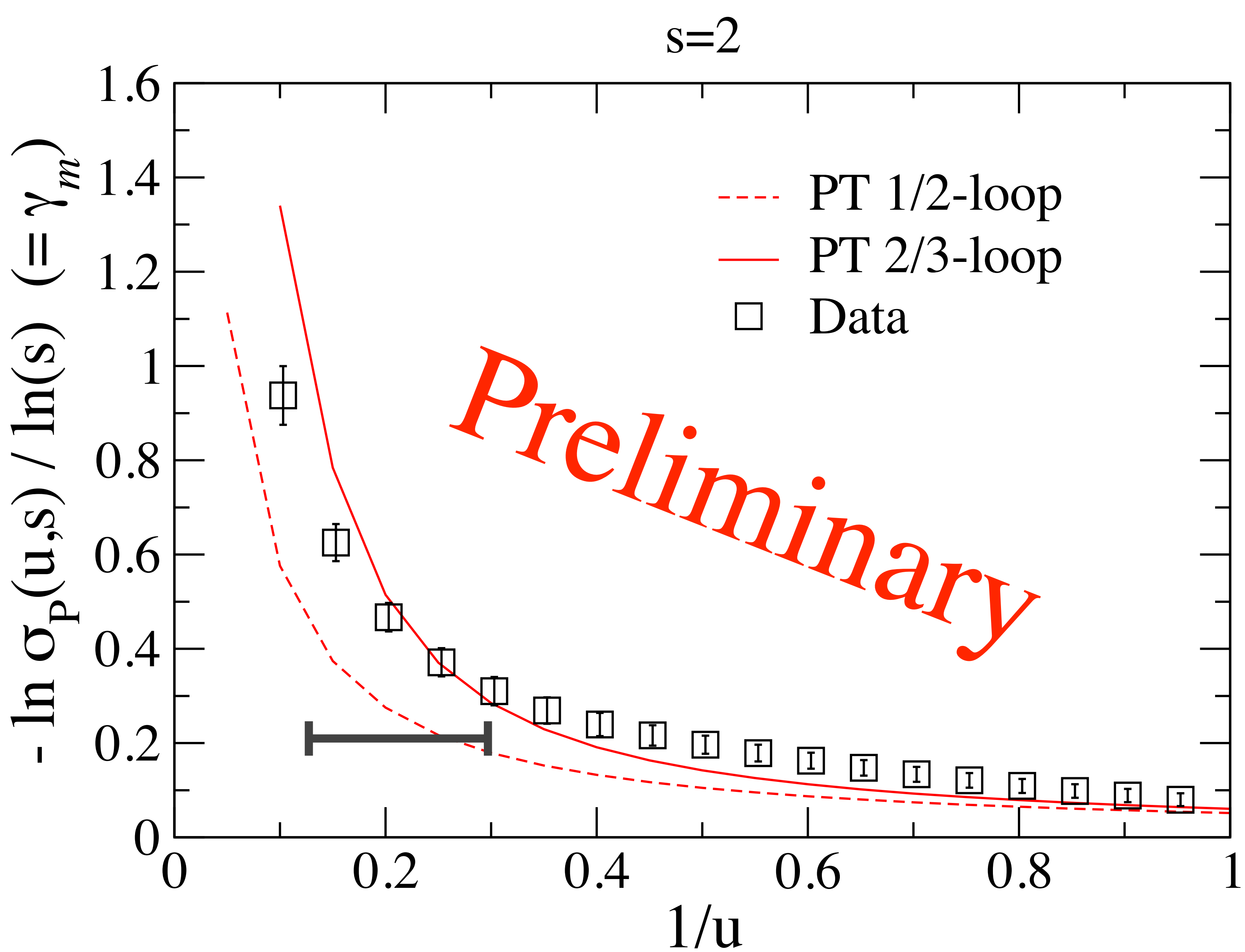
Speculation on “Phase diagram” of GT

For SU(3) GT,

$$8 < N_f^c < 10$$

Anomalous dimension

Calculation of γ_m is possible and in progress!



- $\sigma_P = Z_P(s\,L)\ /\ Z_P(L)$
- With $3.3 < g^2{}_{FP} < 9.35$, $0.28 < \gamma_m < 1.0$!
- Precise value of $g^2{}_{FP}$ is necessary.

Comments

- Lattice can also calculate γ. In progress!

$\gamma^{\rm SF} < 0.6$	Sextet QCD with 2-f	[DeGrand et al., arXiv:1006.0707v1]
$0.05 < \gamma^{\rm SF} < 0.56$	2-color adj. QCD with 2-f	[Bursa et al., arXiv:0910.4535v1]
$0.135 < \gamma^{\rm SF} < 1.03$	2-color QCD with 6-f	[Bursa et al., arXiv:1007.3067v1]

  Not precise yet.

- If theory is in conformal window, the existence of IRFP is scheme-independent. Calculations from different schemes may give independent check.

  Itoh et al. and Holland et al. : 12-flavor QCD

III. Summary and outlook

Summary and outlook

- ✓ Lattice technique can be used to search for realistic WTC models and to see whether the long-standing (~30 yrs) problems in TC are really resolved by WTC.
- ✓ As a first step, we started with the study of running coupling of 10-flavor QCD to identify *conformal window* in SU(3) GT.
- ✓ The result shows evidence of IRFP in $3.3 < g^2_{FP} < 9.4$.

  $\Rightarrow 8 < N_f^c < 10$
- ✓ $0.28 < \gamma_m < 1.0$ is obtained from preliminary analysis. Pinning down γ_m requires precise value of the IRFP.
- ✓ Next important task is to calculate S-parameter.