FRANCESCO SANNINO

THE FUTURE OF COMPOSITE DYNAMICS

The landscape

QCD

- 3 colors + 6 flavors
- Weakly coupled in UV
- Strongly coupled in IR
- Spontaneous χ-Sym

$\Downarrow$

π

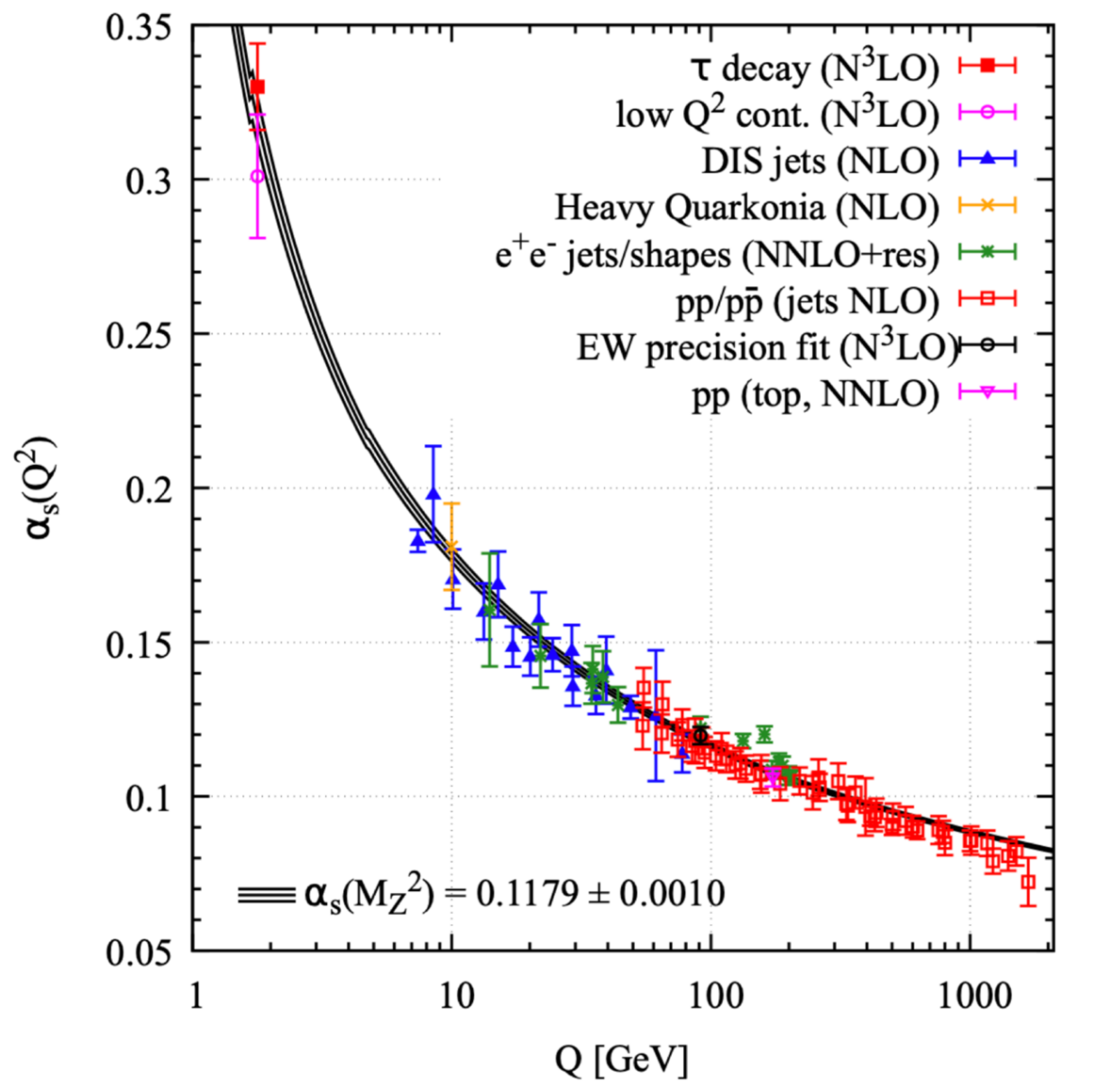
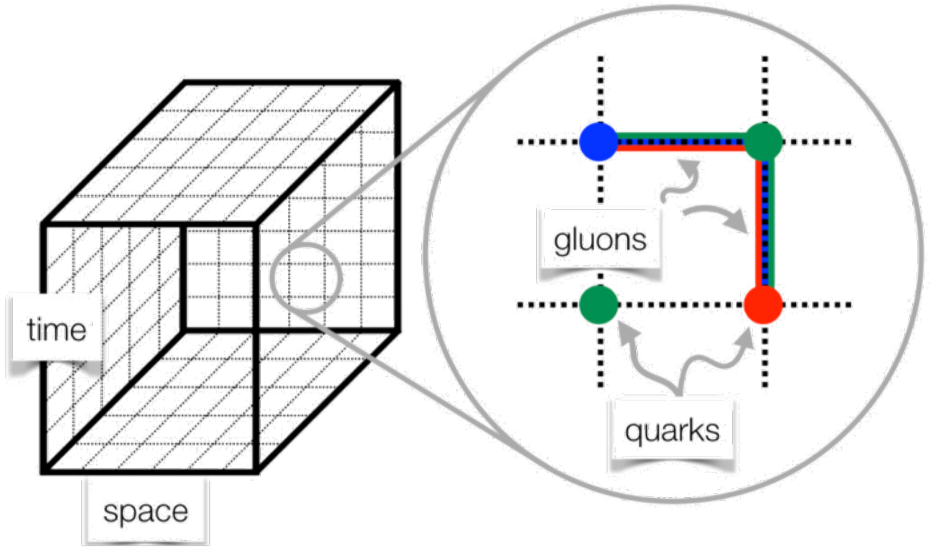
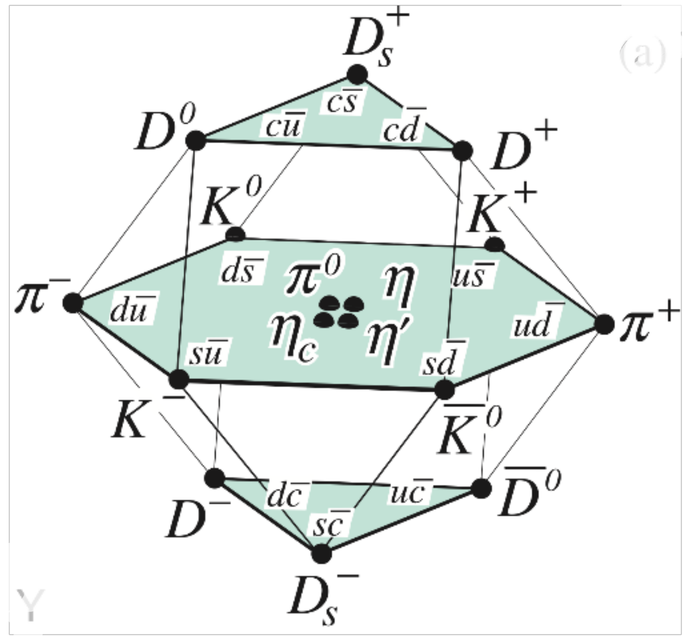
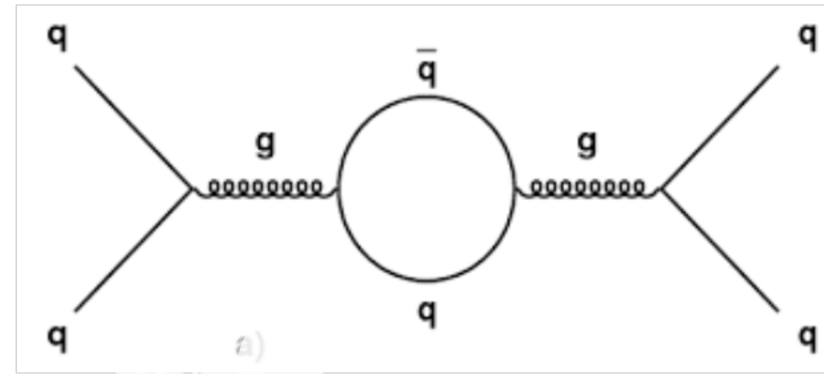


Figure 9.3: Summary of measurements of α_s as a function of the energy scale Q. The respective degree of QCD perturbation theory used in the extraction of α_s is indicated in brackets (NLO: next-to-leading order; NNLO: next-to-next-to-leading order; NNLO+res.: NNLO matched to a resummed calculation; N^3LO: next-to-NNLO).

Methodologies



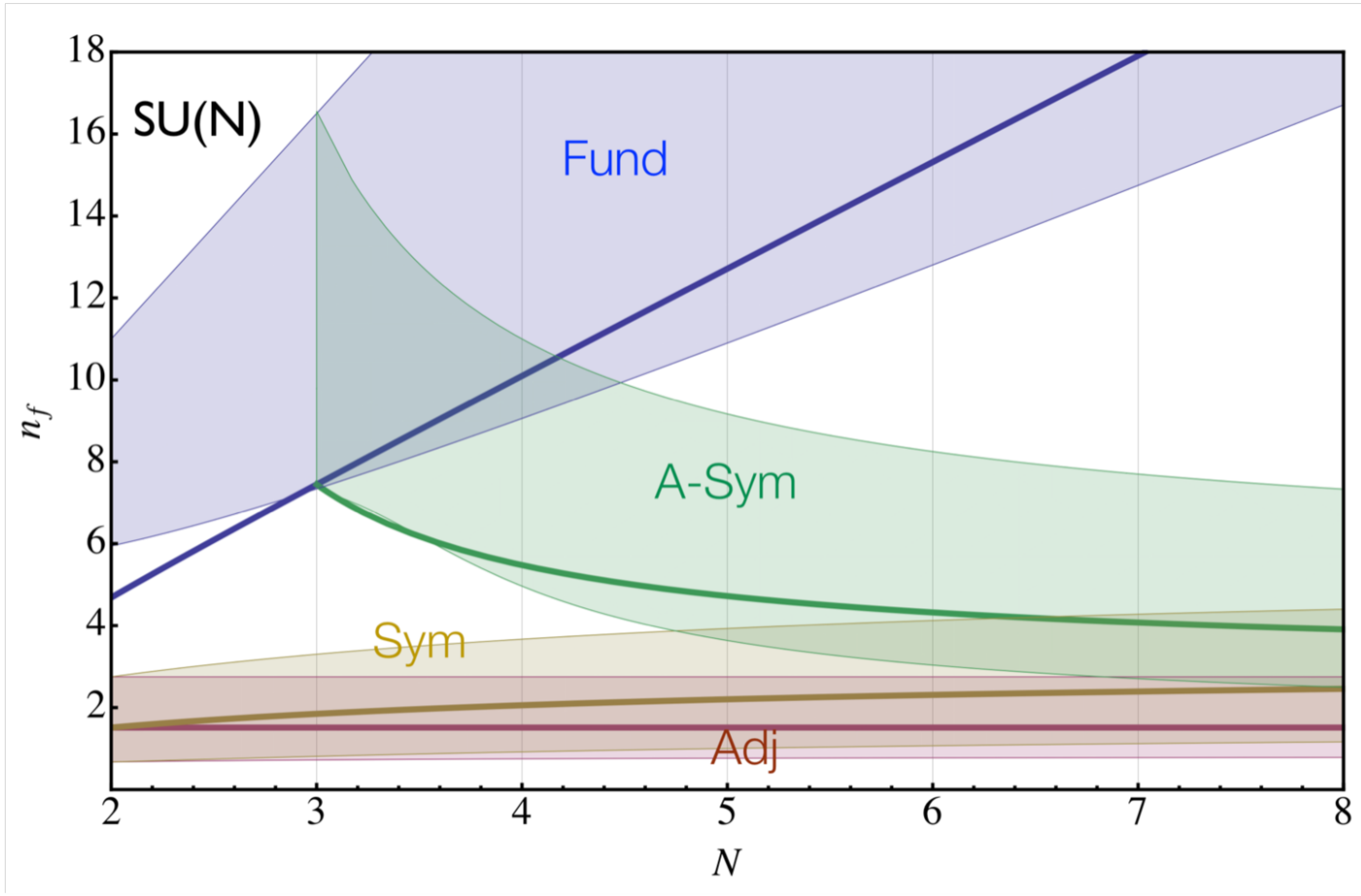


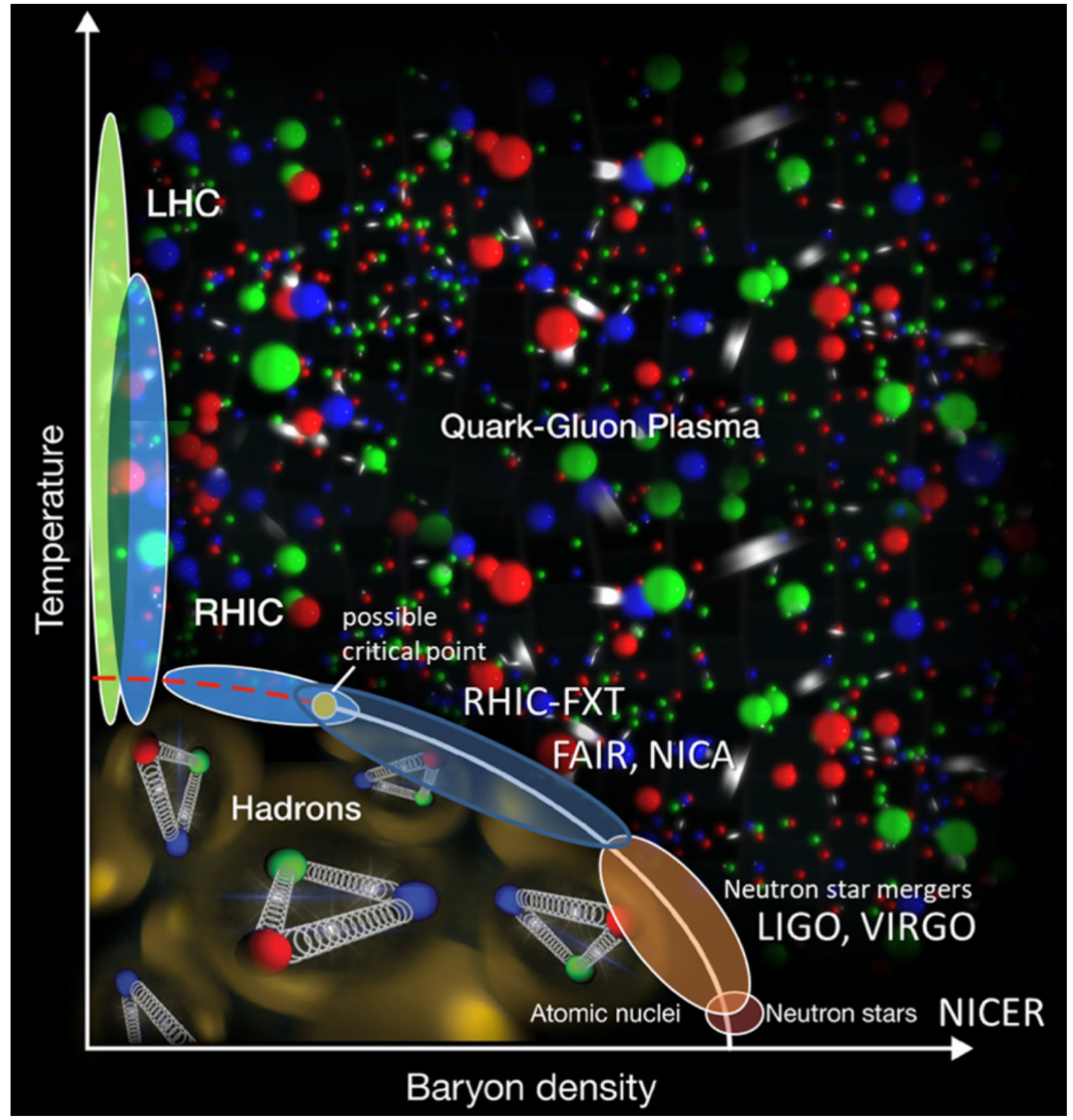


Strong — Weak → E

- Effective field theories — Perturbation theory
- Lattice, large # of colors/flavors/quantum numbers
- Models: { Quark model
  Polyakov loop model
  Nambu Jona-Lasinio's
  holography

Open issues


SU(N)
Fund
A-Sym
Sym
Adj
n_f
N
18
16
14
12
10
8
6
4
2
2
3
4
5
6
7
8


LHC
Quark-Gluon Plasma
Temperature
RHIC
possible
critical point
RHIC-FXT
FAIR, NICA
Hadrons
Neutron star mergers
LIGO, VIRGO
Atomic nuclei
Neutron stars
NICER
Baryon density

Composite landscape

	Interactions	Rep	UV
G_μ	$-\frac{1}{4g^2} G_{\mu\nu} G^{\mu\nu}$	Adj	Free
$G_\mu + \psi$	$+ i \bar{\psi} \gamma^\mu D_\mu \psi$	Fund, Adj + ..	Free Safe ?
$G_\mu + \phi$	$D_\mu \phi^* D^\mu \phi$ $- \lambda (\phi^* \phi)^2$	Fund, Adj, ...	Landau Pole
$G_\mu + \psi + \phi$	$+ \cdots + y \bar{\psi} \phi \psi$	Depends on Rep.	Free Safe Free/Safe

Susy Compositeness is interesting

Applications

Bright | **Dark**

Colliders
Early universe
Compact stars

} **QCD** {

Strong CP problem
axions

Technicolor
Composite Goldstone Higgs
Fund. Partial Compositeness

- R_K and R_{K^*}
- g-2 of μ

} **New Composite Dynamics** {

Dark Baryons
Dark Pions
SIMPs
Composite Inflaton

Cacciapaglia, Pica, Sannino Phys. Rept. 877 (2020) 2002.04914

Cacciapaglia, Cot, Sannino Phys. Lett. B (2022) 136864, 2104.0818

2002.04914 // Phys. Rept. 877 (2020)

Fundamental Composite Dynamics: A Review

Giacomo Cacciapaglia[♠], Claudio Pica[♦] and Francesco Sannino[♥]

[♠] *Université de Lyon, F-69622 Lyon, France: Université Lyon 1, Villeurbanne CNRS/IN2P3, UMR5822, Institut de Physique des deux Infinis (IP2I) de Lyon.*

[♦] *CP³-Origins, Institute of Mathematics and Computer Science, University of Southern Denmark, Odense, Denmark*

[♥] *CP³-Origins and Danish-IAS, University of Southern Denmark, Odense, Denmark*
&
Dept. of Physics "Ettore Pancini", Univ. di Napoli "Federico II", Napoli, Italy

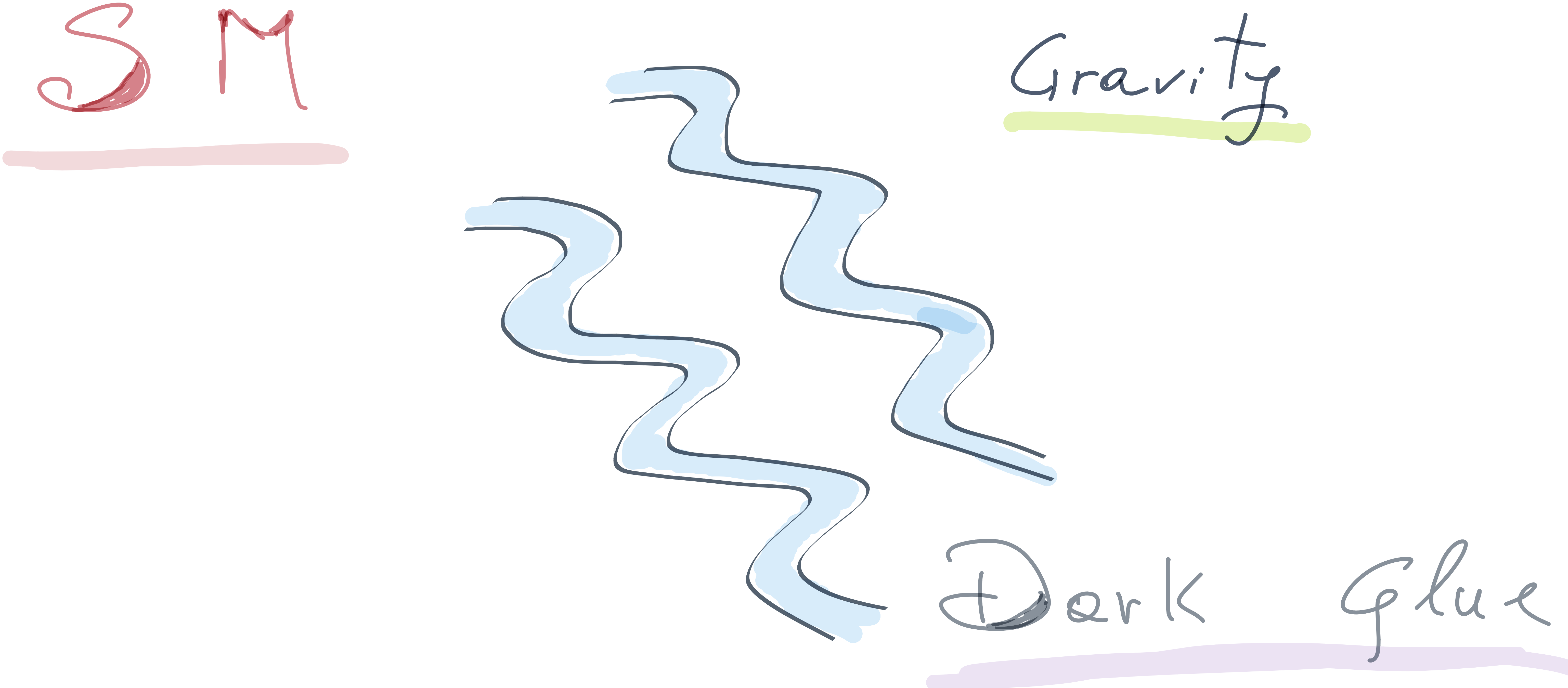
Includes conformal window/dynamics on the lattice

Let's start very simple

Huang, Reichert, Sammis, Wang 2012.11614

Halverson, Long, Maiti, Nelson 2012.04071

Reichert, Sammino, Wang, Zhang 2109.11552


SM
Gravity
Dark Glue

Dark glue sector

$$\mathcal{L} = \mathcal{L}_{SM} - \underbrace{\frac{1}{4g^2}\,\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]}_{SU(N)\text{ glue theory}} + \text{residual int.}$$

Add a novel "dark" glue sector to SM

Minimal interaction with gravity

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{pl}^2}{2} R + \mathcal{L}_{SM} - \frac{1}{4g^2} G^2 + \text{residual int.} \right]$$

Pure glue facts

SU(N) glue theory

Z_N center group symmetry

Z_N is broken

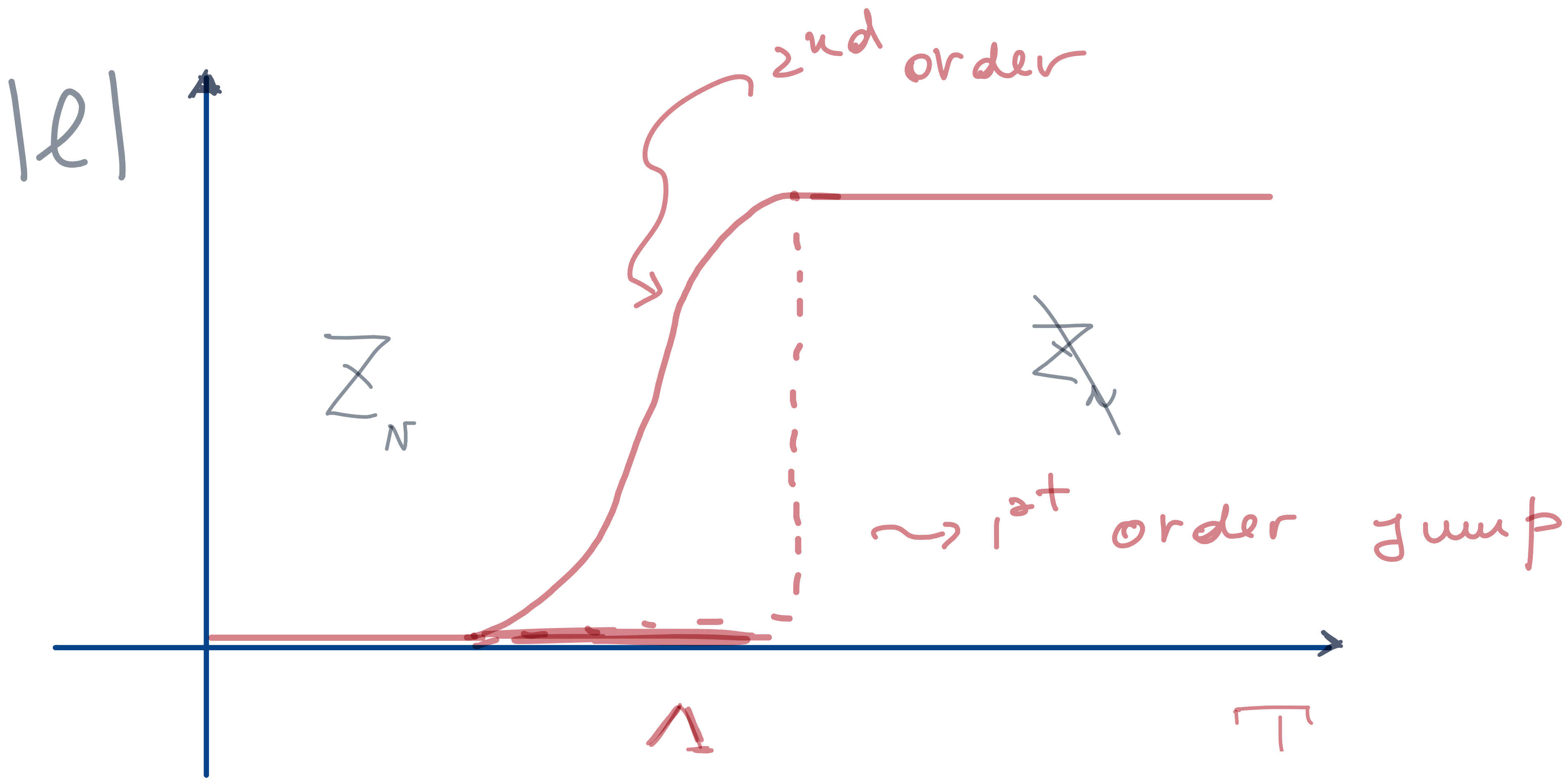
Z_N is restored

Confinement phase transition

Order parameter

Polyakov loop

$$\ell(\vec{x}) = \frac{1}{N} \operatorname{Tr}[L] \qquad L = \mathcal{P}\exp\left[ig\int_0^{1/T} A_0(x,\tau)\,d\tau\right]$$



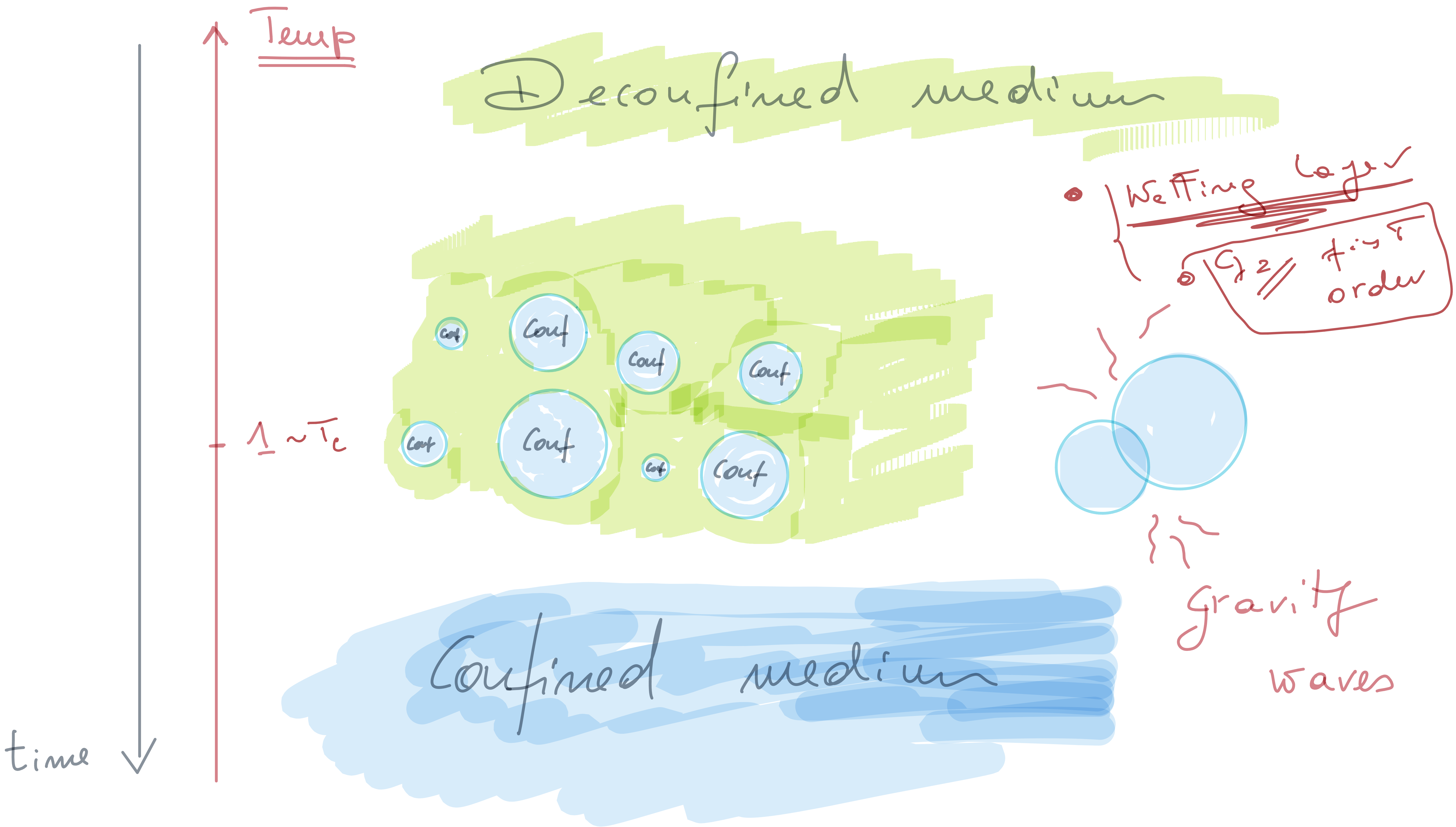
SU(2) 2nd order

SU(N>2) 1st order

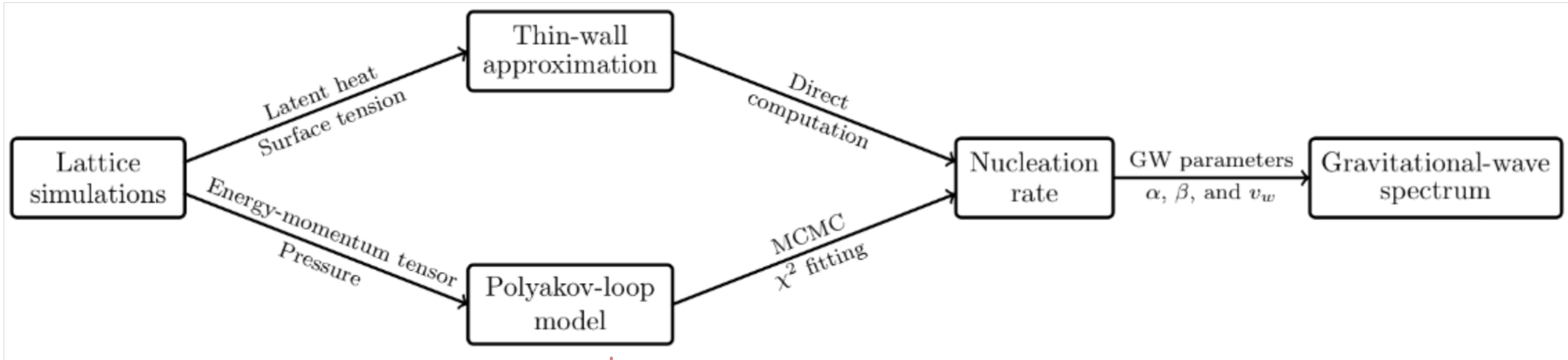
Pisarski: hep-ph/0006205, 0112037

Sannino: hep-ph/0204174

Dark glue evolution [1st order transition]



Strategies



↳ Beyond State of the art N = 4, 5, 6 and 8

MCMC = Markov Chain Monte Carlo

Lattice

Lucini, Teper, Wenger hep-lat/0502003

Panero 0907.3719

GW:

Bodeker and Moore 1703.08215
0903.4099

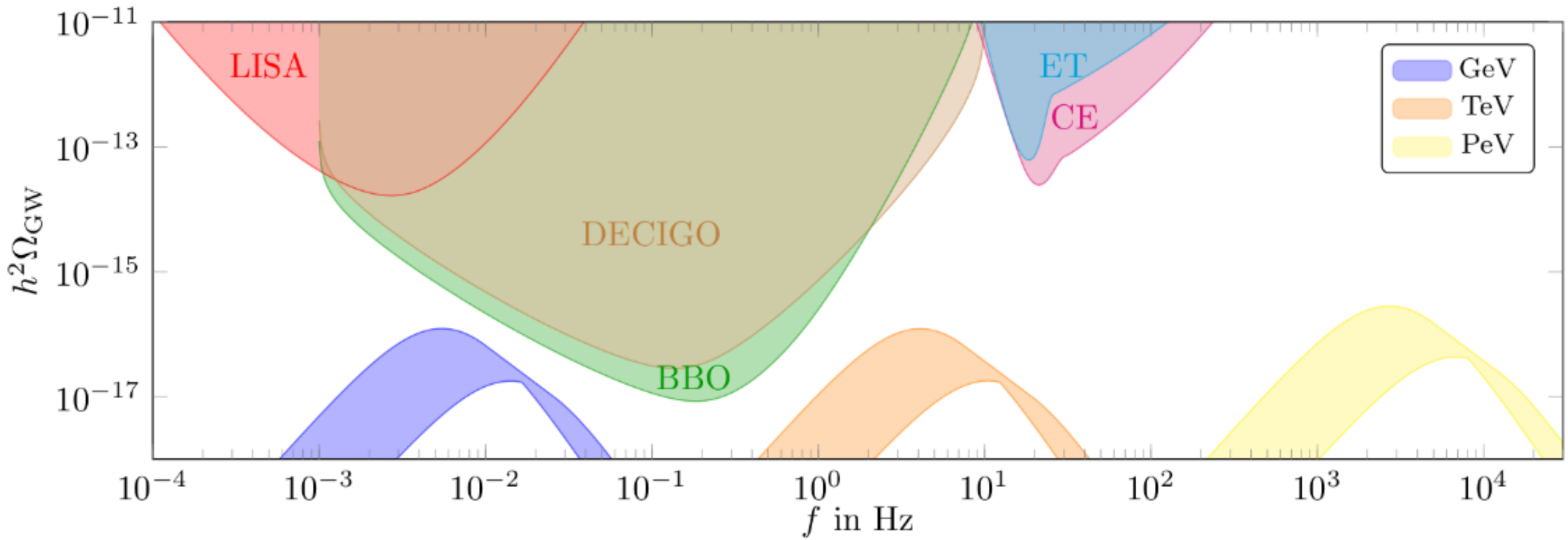


Figure 11. We display the GW spectrum of the $SU(6)$ phase transition for different confinement scales including $T_c = 1\,\mathrm{GeV}$, $1\,\mathrm{TeV}$, and $1\,\mathrm{PeV}$. We compare it to the power-law integrated sensitivity curves of LISA, BBO, DECIGO, CE, and ET.

$\alpha = \frac{1}{3} \frac{\Delta\theta}{\omega_+}$ $\omega_+ :=$ enthalpy density $= \partial p / \partial \ln T \,|_+$

$+ :=$ outside (metastable)

$- :=$ inside bubble (stable)

- $\alpha \approx 1/3 \sim$ PT-strength
- $\beta \approx 10^4 - 10^5$ Hubble time $\sim$ inverse duration of the PT
- GW from sound waves not bubble collision / turbulence
- N ~ independence for $N \geq 6$

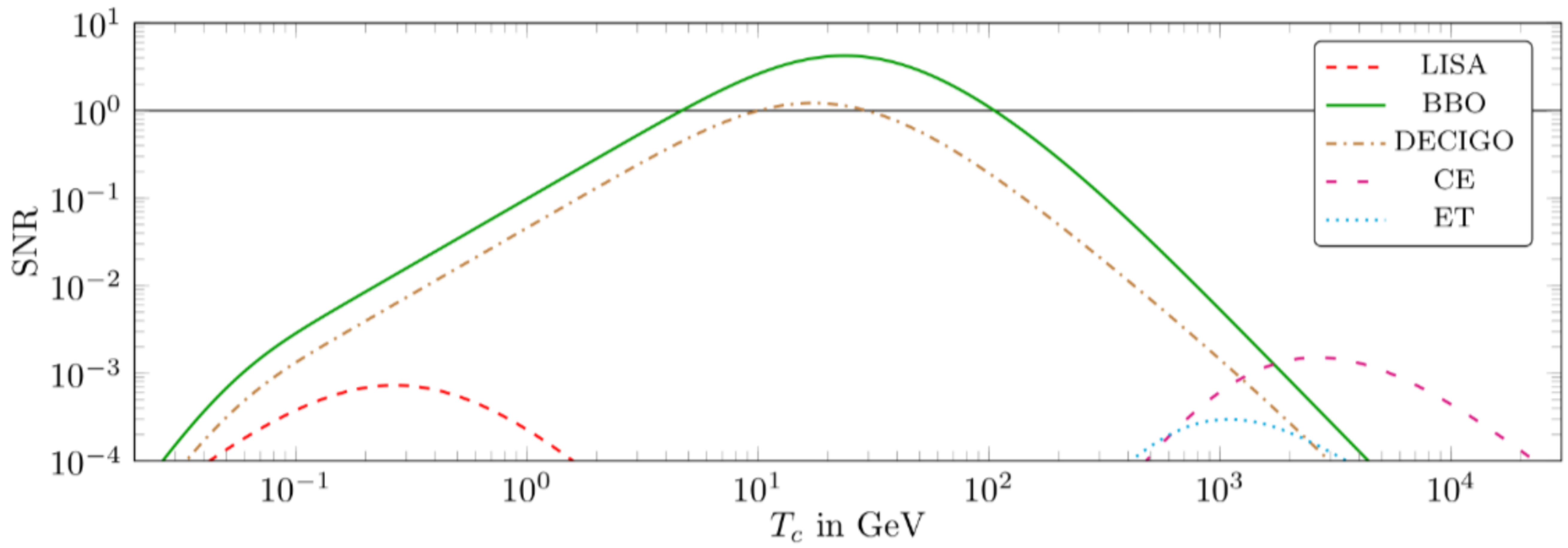


Figure 12. We display the SNR for the phase transition in a dark $SU(6)$ sector as a function of the confinement temperature T_c from experiments of LISA, BBO, DECIGO, CE, and ET. We assume an observation time of three years.

Constraining "n" copies ⟹

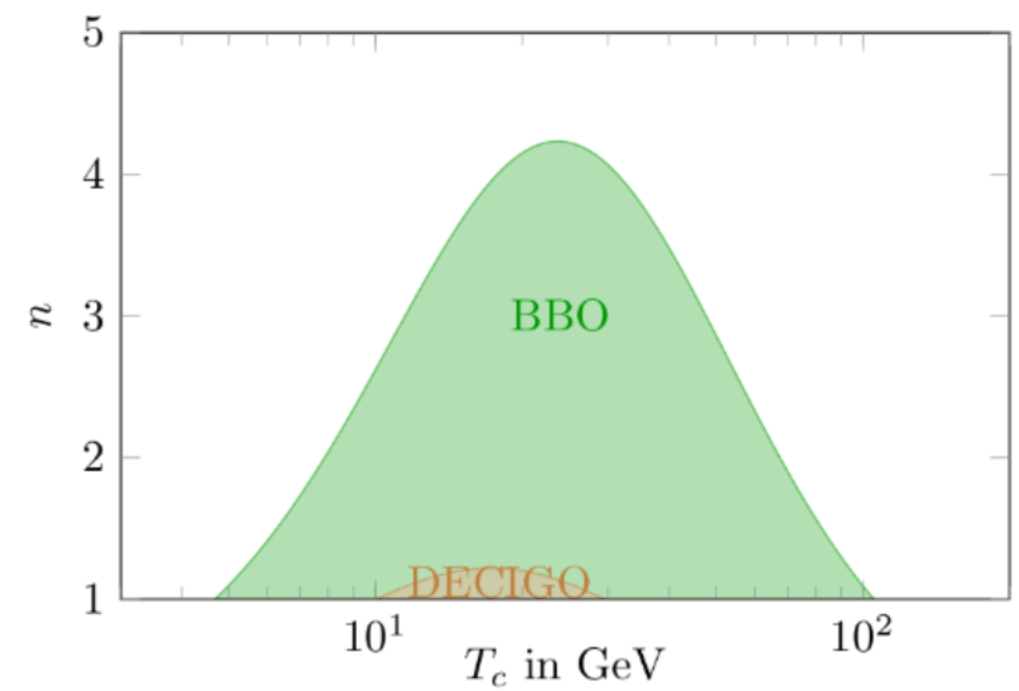


Figure 13. We display the exclusion curves of n dark $SU(N)$ phase transitions from the experiments BBO, DECIGO as a function of the confinement temperature T_c. We assume an observation time of three years and that the signal is detectable for a signal-to-noise ratio SNR > 1.

Dark gauge-fermion theory

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4g^2}\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \sum_f \bar{\psi}^f \not{D} \psi^f + m \bar{\psi}^f \psi^f$$

Minimally coupled to gravity.

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{pl}^2}{2} R + \mathcal{L}_{SM} - \frac{1}{4g^2}\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \sum_f \bar{\psi}^f \not{D} \psi^f + m \bar{\psi}^f \psi^f\right]$$

Reichert, Sannino, Wang, Zhang 2109.11552

How many phase transitions?

Temperature

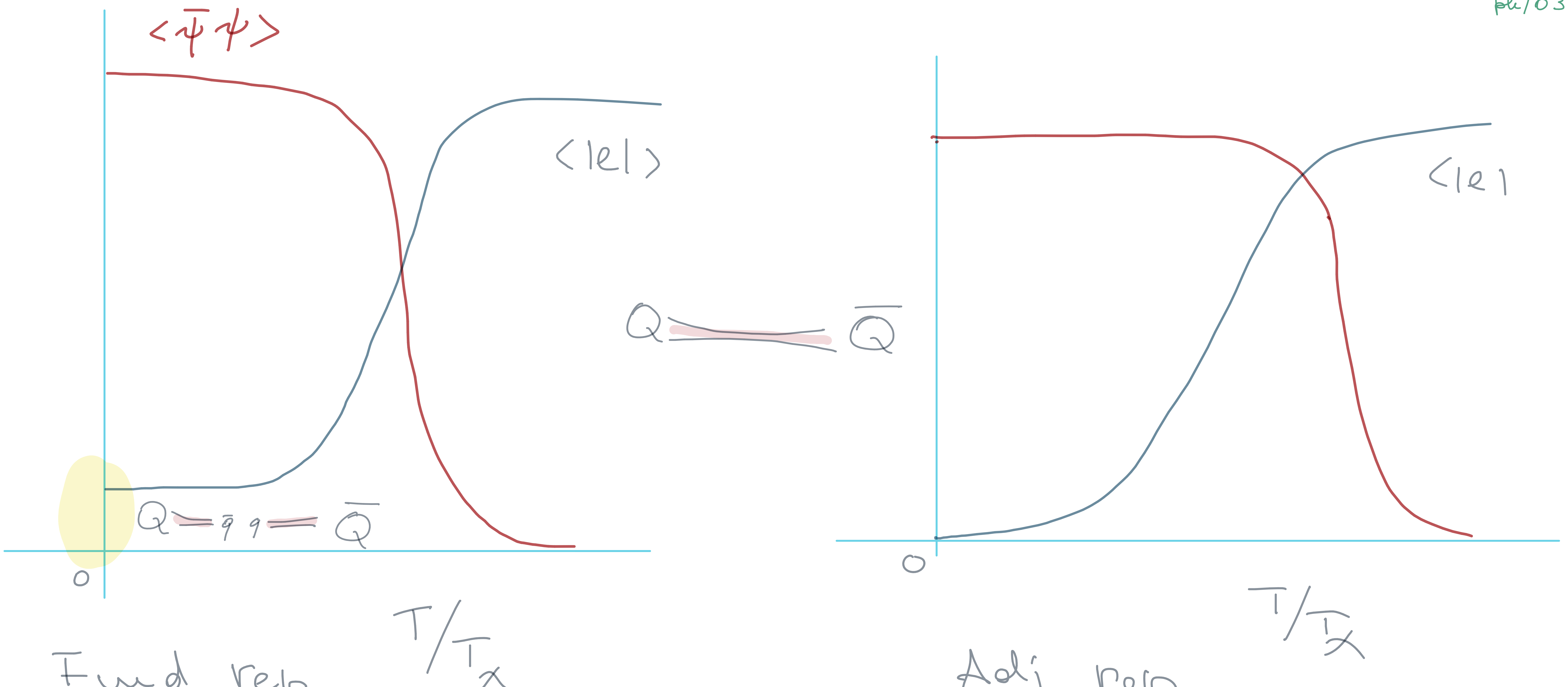
T_χ — χ = chiral — $\langle \bar{\psi} \psi \rangle \neq 0$ — $m = 0$

T_c — c := confinement — $\langle |\ell| \rangle = 0$ ⇝ Confinement PT existence depends on whether fermion rep respect centre symmetry.

Mocsy, Sannino, Tuominen, PRL 92 (2004)
ph/0308135

Phase Transition Order Parameters

Mocsy, Sannino, Tuominen, PRL 92 (2004) hep-ph/0308135



Fund rep

$\left\{ \begin{array}{l} \mathbb{Z}_N \text{ broken} \\ \Downarrow \\ \text{No confinement} \end{array} \right.$

Adj rep

$\left\{ \begin{array}{l} \mathbb{Z}_N \text{ unbroken} \\ \Downarrow \\ \text{Confinement} \end{array} \right.$

Polyakov Nambu Jona Lasinio (PNJL)

3 Dirac flavors in fund. of SU(3)

1 Dirac flavor in Adj of SU(3)

1 Dirac flavor in 2-index Symmetric of SU(3)

Results

- 2-index → stronger confinement PT
- Adj and 2-index → weak/continuous PT
- Confinement PT ~ BBO with SNR ~ O(10)

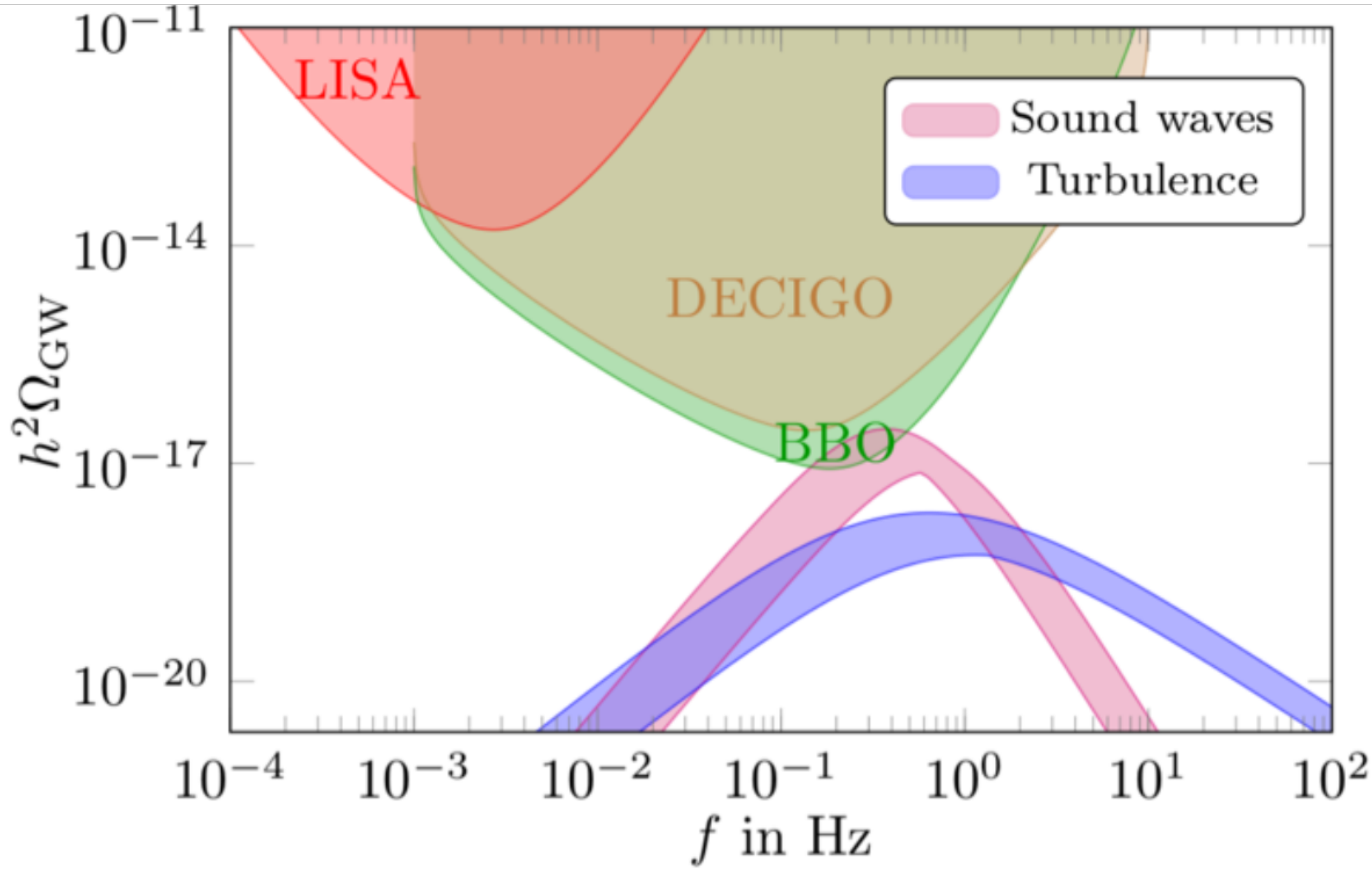


Figure 11. Gravitational-wave spectrum from sound waves in comparison with the contribution from turbulence at the example of the two-index symmetric representation for $T_c = 100\,\mathrm{GeV}$.

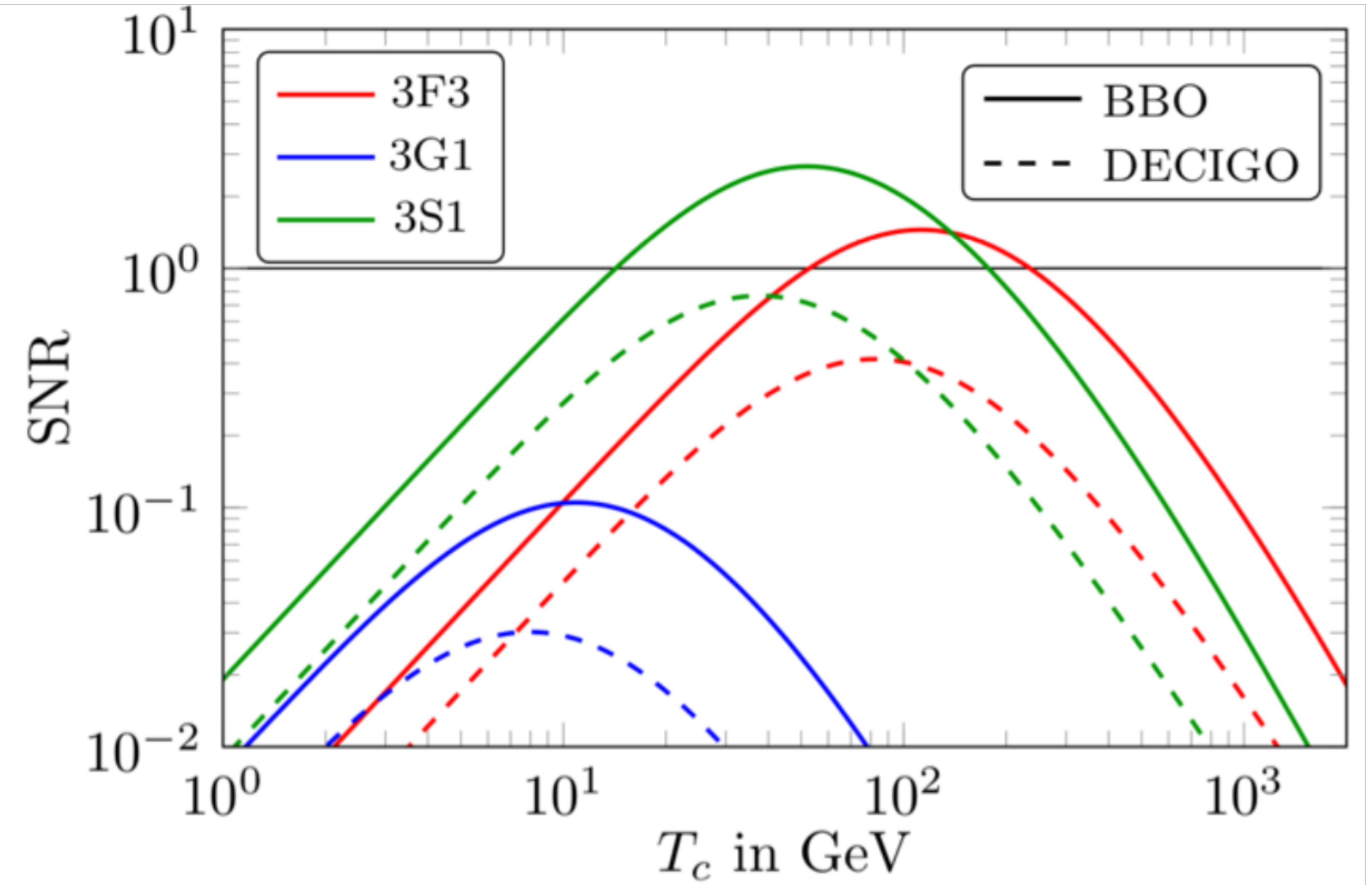


Figure 12. Signal-to-noise ratio as a function of the critical temperature for the best-case scenarios of each model at BBO and DECIGO. We assumed an observation time of three years.

WANTED

DEAD or ALIVE

- Pure glue thermodynamics for different SU(N)
- Gauge-fermion thermodynamics SU(N)
- Order PT for χ and confinement
- String Tension
- Bag constant
- Near conformal dynamics

Future wish list

Conformal Window

Temperature/density Phase Diagram

Beyond Perturbation theory

Discover composite bright/dark dyn.

A glimpse in LHCb data?

FRANCESCO SANNINO

NATURALNESS DEUS EX MACHINA OF g-2 & LEPTON NON-UNIVERSALITY

SDU

SSM
Scuola Superiore Meridionale

D·IAS

Fundamental partial compositeness

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[b] *Dipartimento di Fisica dell'Università di Pisa and INFN, Italy*
[c] *CERN, Theory Division, Geneva, Switzerland*
[d] *Department of Physics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*

Naturalness of lepton non-universality and muon g-2

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[2] *University of Lyon, Université Claude Bernard Lyon 1, F-69001 Lyon, France*
[3] *Scuola Superiore Meridionale, Largo S. Marcellino, 10, 80138 Napoli NA, Italy*
Danish Institute for Advanced Study, Univ. of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark
[5] *Dipartimento di Fisica, E. Pancini, Universitá di Napoli Federico II, INFN sezione di Napoli, Complesso Universitario di Monte S. Angelo Edificio 6, via Cintia, 80126 Napoli, Italy*
[6] *CP^3-Origins, Univ. of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark*

We show that the observed anomalies in the lepton sector can be explained in extensions of the Standard Model that are natural and, therefore, resolve the Higgs sector hierarchy problem. The scale of new physics is around the TeV and Technicolor-like theories are ideal candidate models.

Flavour anomalies after the R_{K^*} measurement

(updated including the Moriond 2019 data from LHCb and Belle[1])

Guido D'Amico[a], Marco Nardecchia[a], Paolo Panci[a], Francesco Sannino[a,b], Alessandro Strumia[a,c], Riccardo Torre[d], Alfredo Urbano[a]

[a] *Theoretical Physics Department, CERN, Geneva, Switzerland*
[b] *CP^3-Origins and Danish IAS, University of Southern Denmark, Denmark*
[c] *Dipartimento di Fisica dell'Università di Pisa and INFN, Italy*
[d] *Theoretical Particle Physics Laboratory, Institute of Physics, EPFL, Lausanne, Switzerland*

Flavor Physics and Flavor Anomalies in Minimal Fundamental Partial Compositeness

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[2] *Danish IAS, University of Southern Denmark, Odense, Denmark*
[3] *Excellence Cluster Universe, TUM, Boltzmannstr. 2, 85748 Garching, Germany*

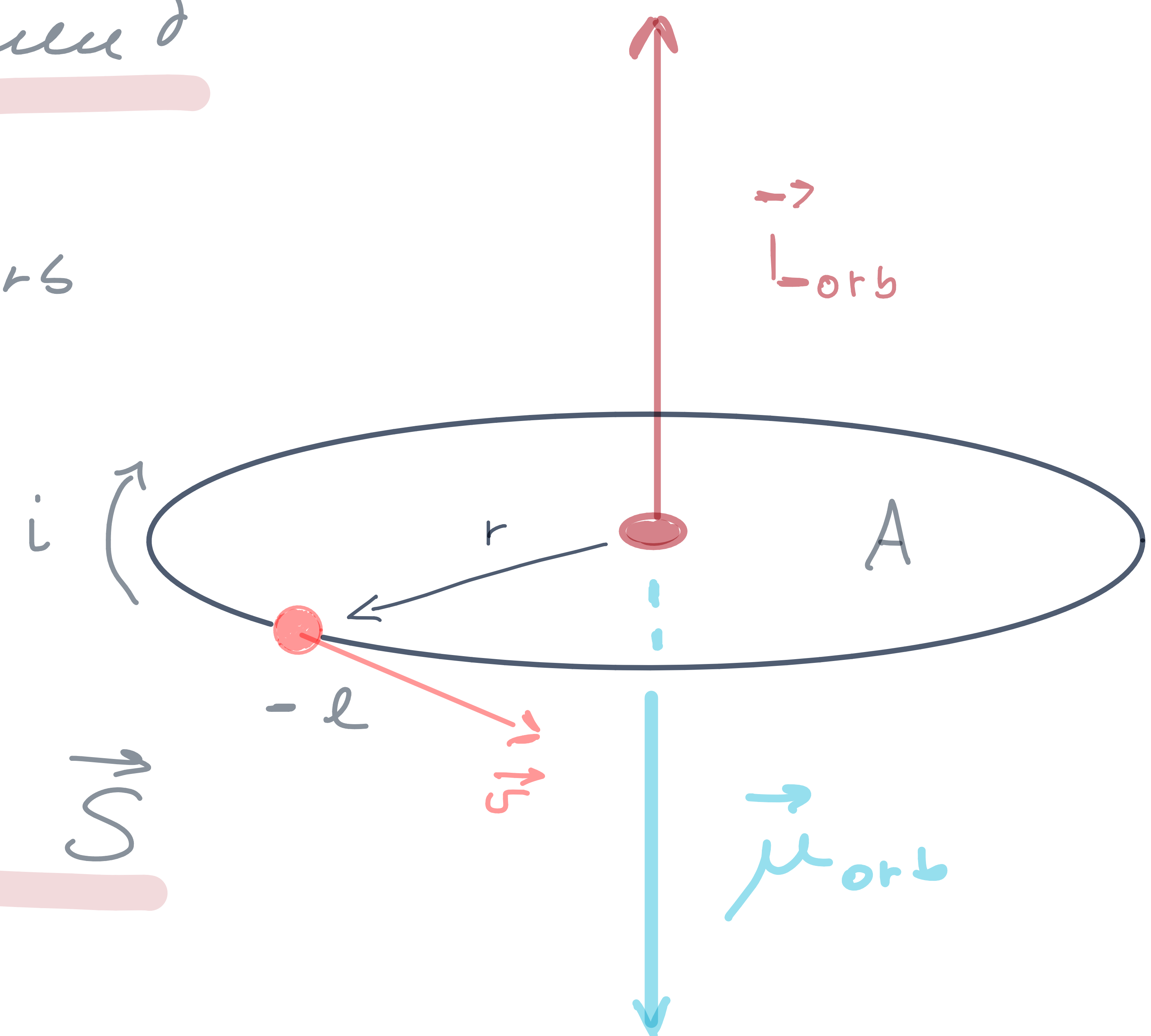
Partial compositeness is a key ingredient of models where the electroweak symmetry is broken by a composite Higgs state. Recently, a UV completion of partial compositeness was proposed, featuring a new strongly coupled gauge interaction as well as new fundamental fermions and scalars. We work out the full flavor structure of the minimal realization of this idea and investigate in detail the consequences for flavor physics. While CP violation in kaon mixing represents a significant constraint on the model, we find many viable parameter points passing all precision tests. We also demonstrate that the recently observed hints for a violation of lepton flavor universality in $B \to K^{(*)}\ell\ell$ decays can be accommodated by the model, while the anomalies in $B \to D^{(*)}\tau\nu$ cannot be explained while satisfying LEP constraints on Z couplings.

g and minus 2 genesis

Orbital magnetic moment

$$\vec{\mu}_{orb} = i\vec{A} = \frac{-e}{2\pi r}v \cdot \pi r^2 \hat{A} = -\frac{e}{2m}\vec{L}_{orb}$$

$$\vec{L}_{orb} = \vec{r} \wedge m\vec{v}$$



Intrinsic angular momentum $\vec{S}$

$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

g-genesis

↳ proportionality factor

g from Dirac equation

QM

Field	SL(2, ℂ)	Charge	Mass
ψ	$(\frac{1}{2},0)+(0,\frac{1}{2})$	q	m

$$i\frac{\partial\psi}{\partial t} = \left(\vec{\alpha}\cdot\left(-i\vec{\nabla} - q\vec{A}\right) + \beta m + qA_0\right)\psi$$

ψ 4-component spinor

Pauli's non relativistic 2-component ϕ spinor

$$i\frac{\partial\phi}{\partial t} = \left[\frac{\left(-i\vec{\nabla}-q\vec{A}\right)^2}{2m} - 2\frac{q}{2m}\vec{S}\cdot\vec{B} + qA_0\right]\phi$$

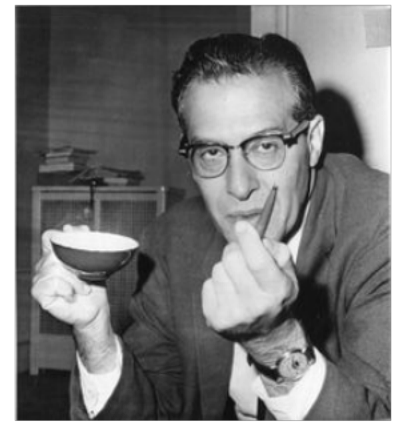
Comparing with the potential energy $V = -\vec{\mu}\cdot\vec{B}$

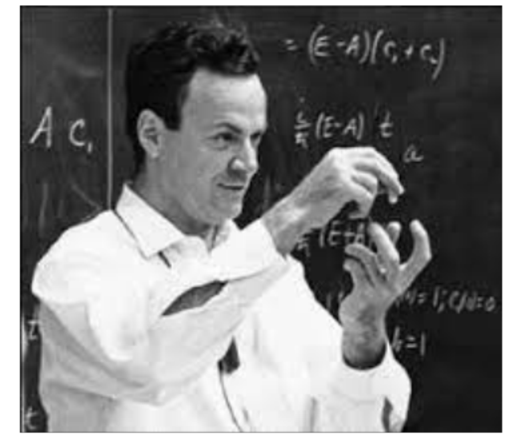
$$\vec{\mu} = 2\frac{q}{2m}\vec{S}$$

Dirac predicts $g=2$ or $\boxed{g-2=0}$

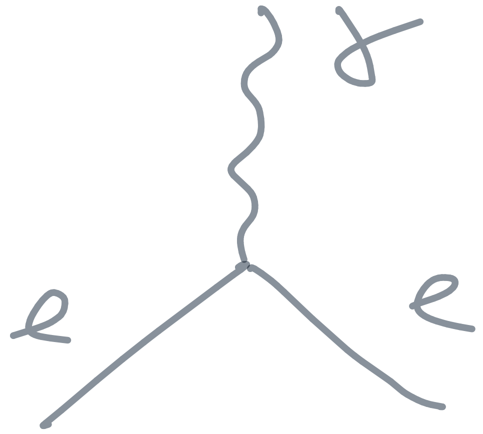
QED

Schwinger, Tomonaga, Feynman

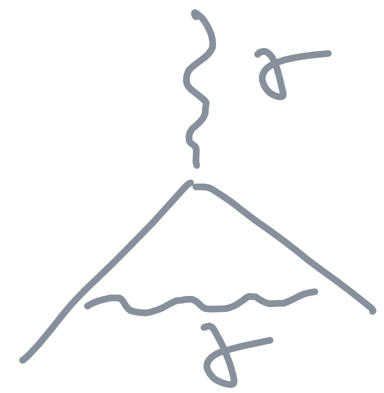




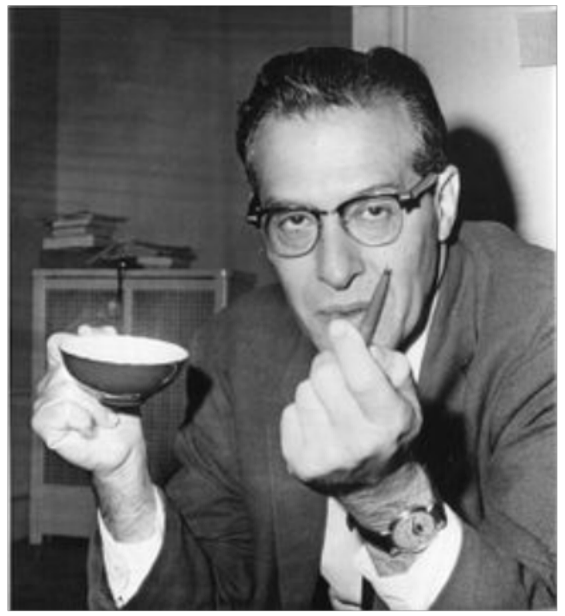
Elementary process

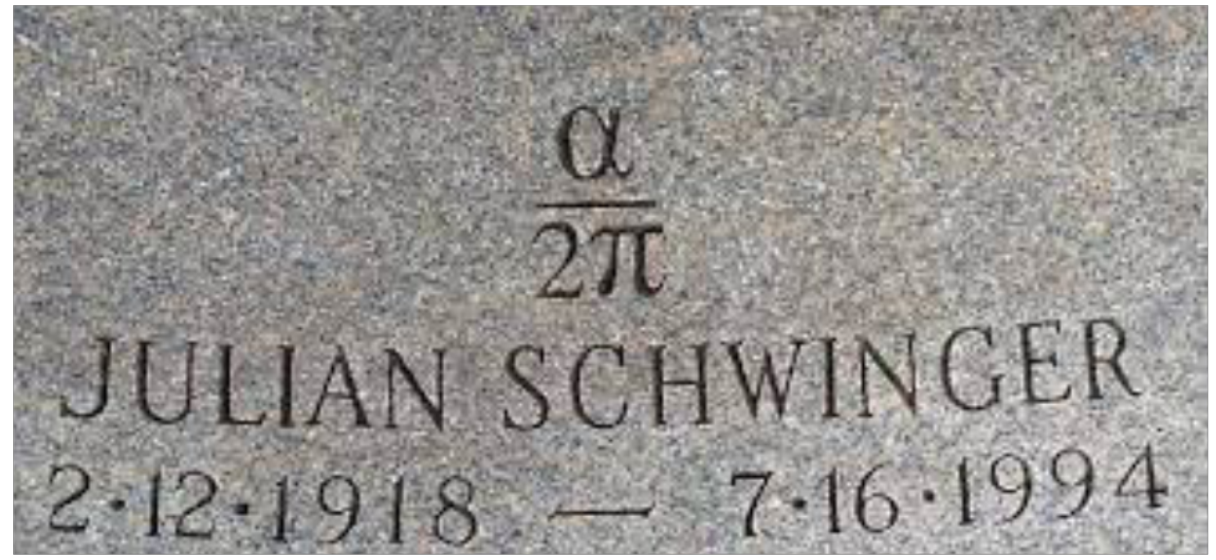


Schwinger's one loop computation



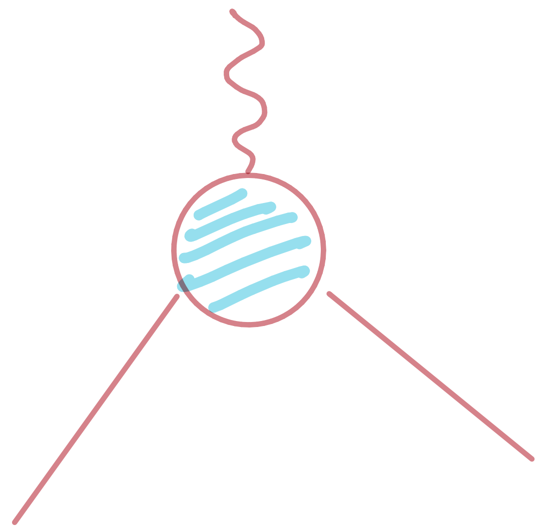
↳ Dirac's limit





$$\frac{g_e - 2}{2} = a_e = \frac{\alpha}{2\pi} + \mathcal{O}(\alpha^2)$$

1948



g-2 anomaly

$$a_{\text{lepton}} = \frac{g_\ell - 2}{2} = \underbrace{a_e^{\text{QED}} + a_e^{\text{weak}} + a_e^{\text{hadronic}}}_{\text{SM}} + \underbrace{a_e^{\text{NP}}}_{\text{BSM}}$$

Standard Model Corrections

Representative contributions

QED Weak QCD/hadronic

QED

α^5 — 5th-order

$116\,584\,718.9(1) \times 10^{-11}$ — 0.001 ppm

Weak

α^3

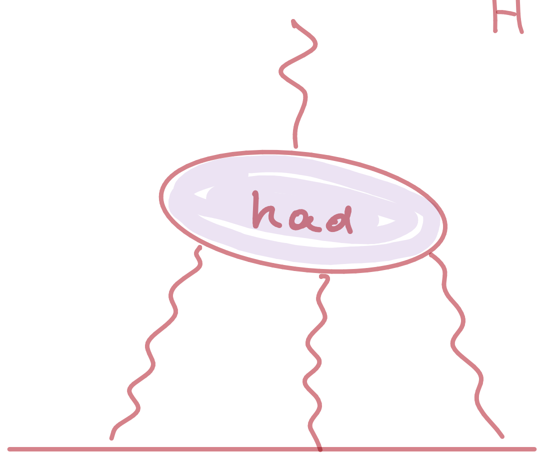
$153.6\,(1.0) \times 10^{-11}$ — 0.01 ppm

HVP

α^2

$6845\,(40) \times 10^{-11}$ — 0.37 ppm

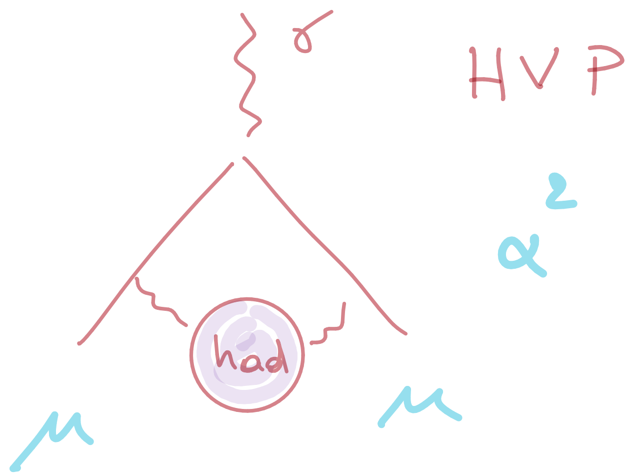
HLbL

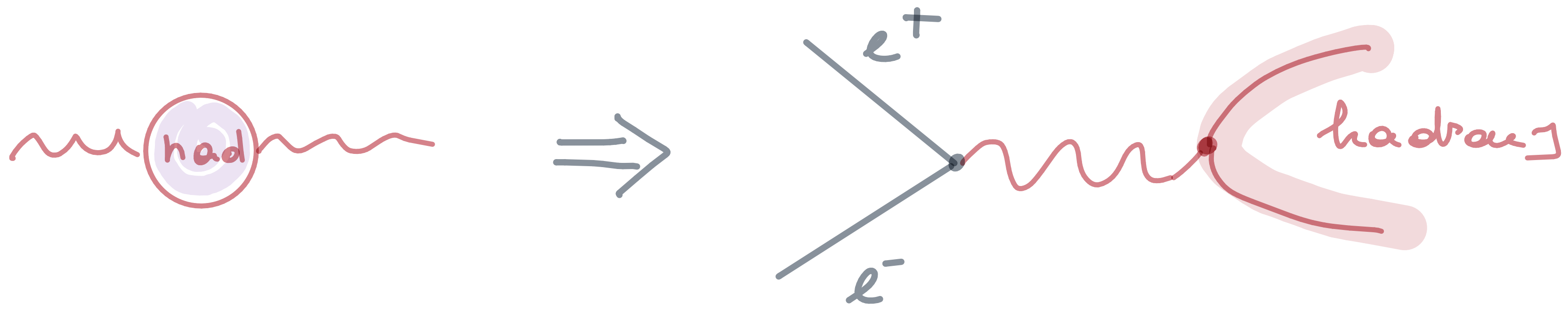


α^3

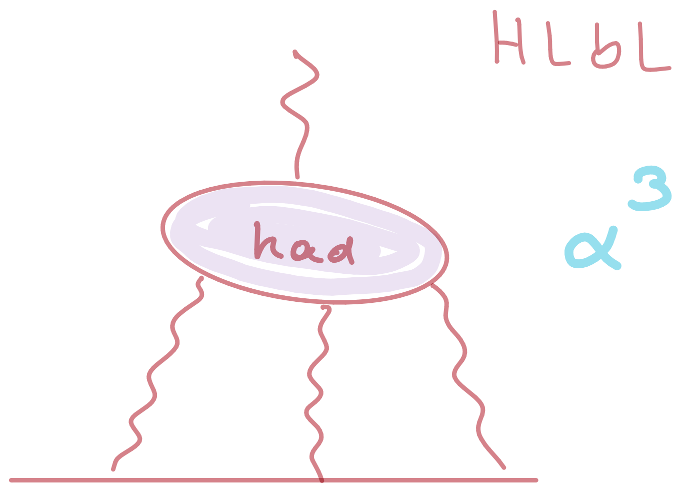
$92(18) \times 10^{-11}$ — 0.15 ppm

Dispersive approach





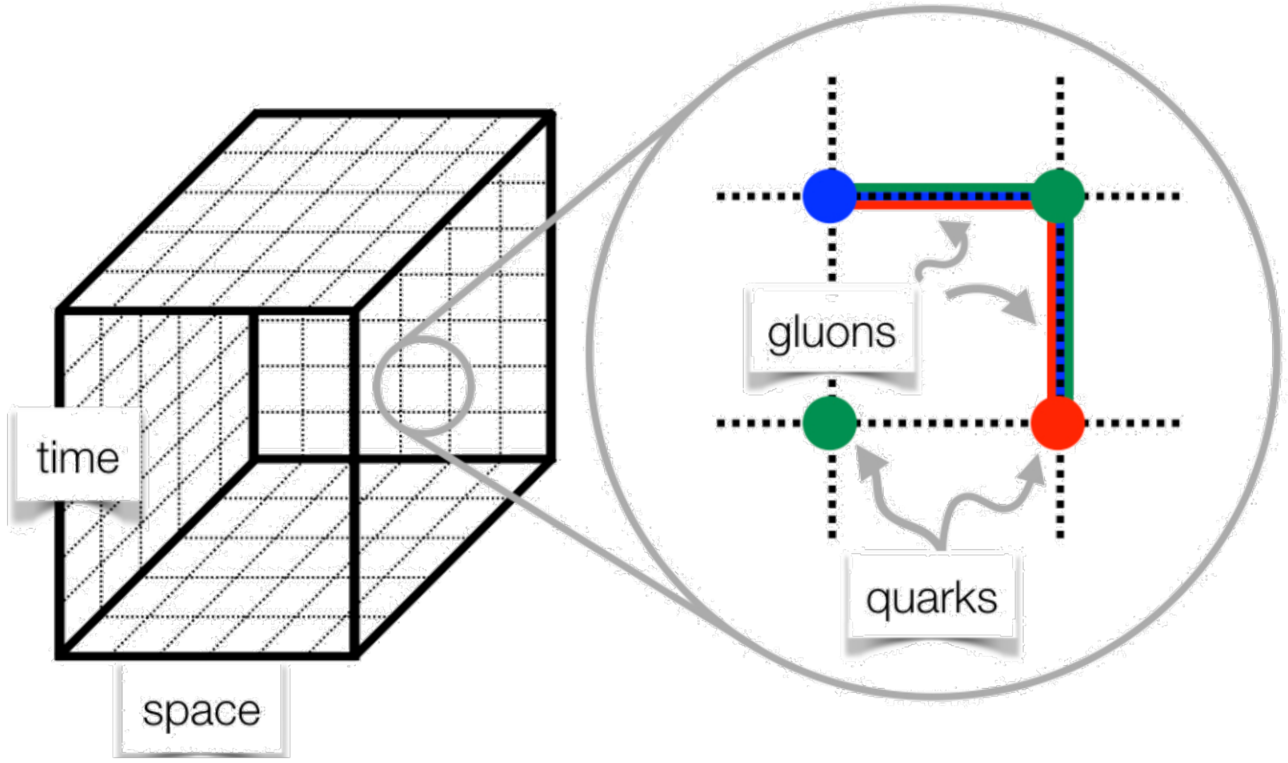
Experimental data + dispersion theory
⇒ HVP with ~ 0.6% error



Allows data-driven evaluation
with 20% error.
(HLbL subleading)

Data driven

Lattice QCD



Discrete space-time

Finite spatial volume

Finite time extent

Expensive

Ab-initio QCD

SM-based evaluations

HVP : ~ 2% error vs 0.2% dispersive*

HLbL : ~ 45% error vs 20% dispersive

BMW20*

2021

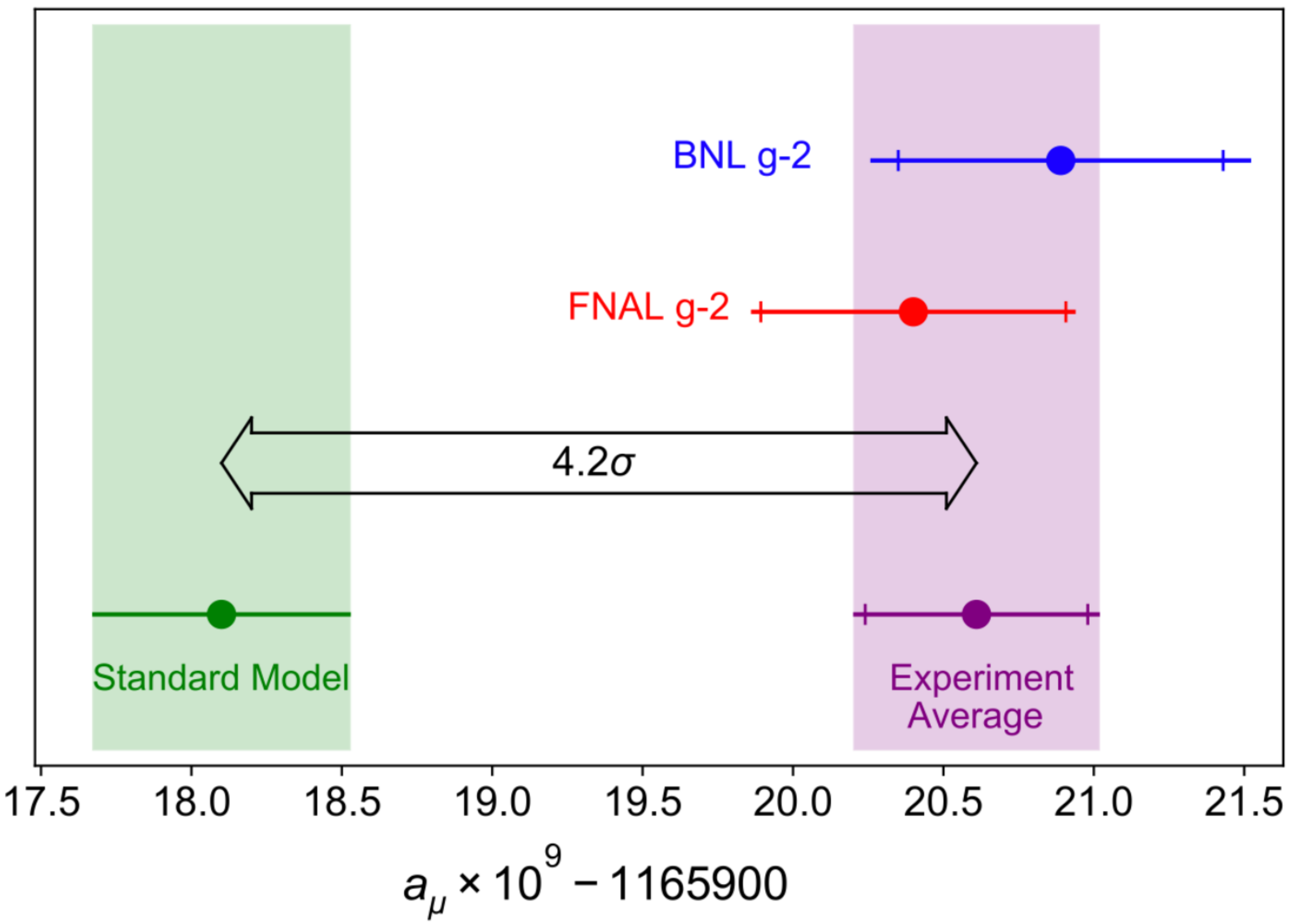


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g - 2$ Theory Initiative recommended value [13] for the standard model is also shown.

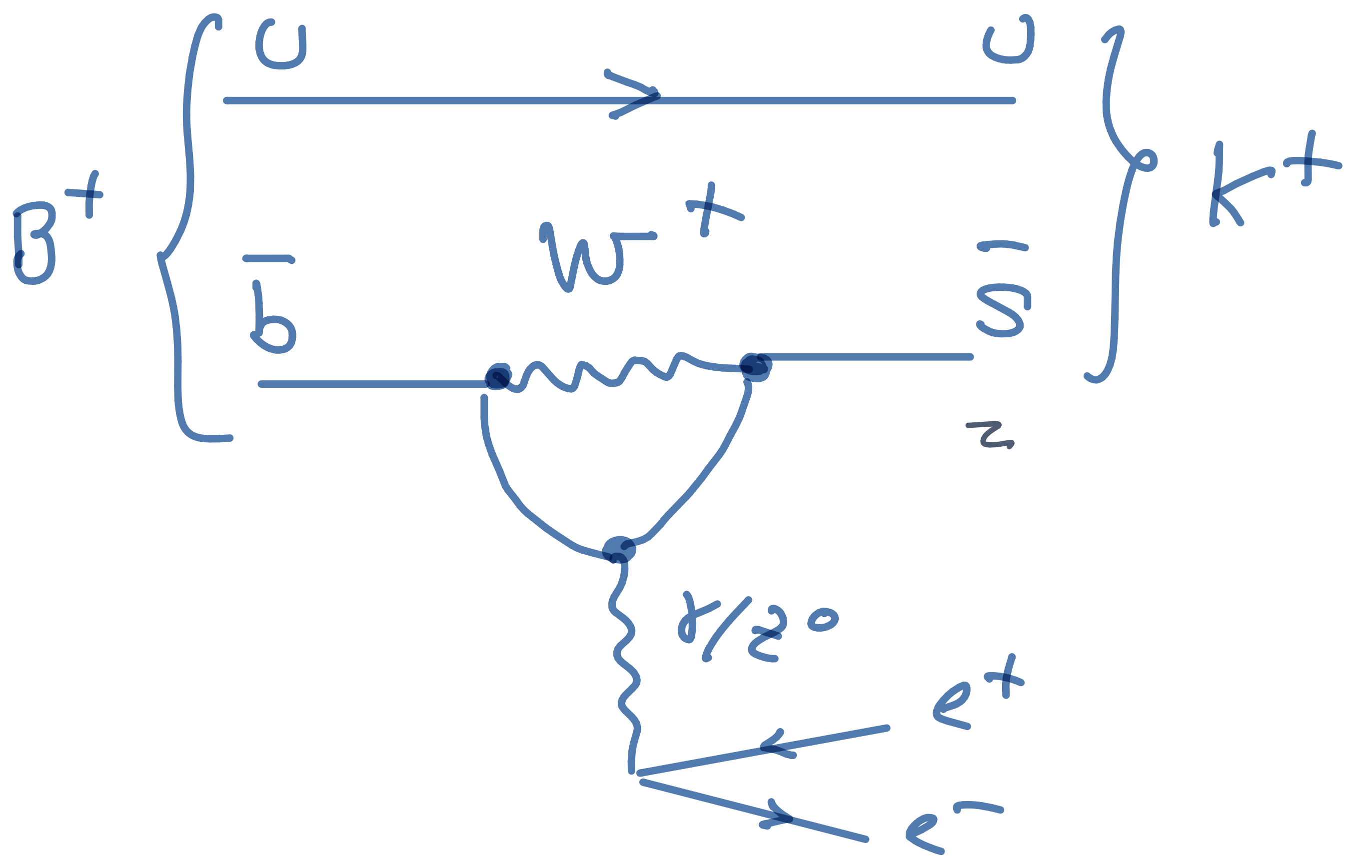
(True ?)

Anomalies don't appear alone!

Lepto flavor (non) universality

LHCb 2021

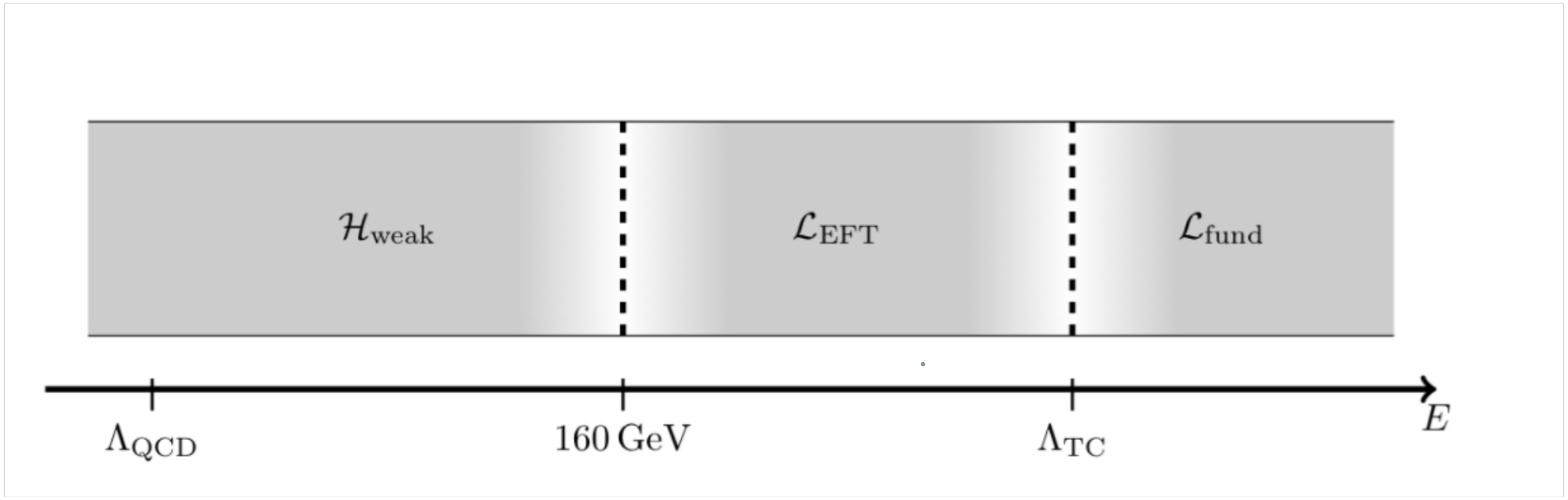
$$R_K = \frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to K^+ e^+ e^-)} = 0.846 \begin{smallmatrix} +0.044 \\ -0.041 \end{smallmatrix}$$



$\Rightarrow$ 3.1σ from SM

See A. Crivellini's talk

Effective analysis



$$R_K \simeq 1 + 2\,\frac{\mathrm{Re}\, C^{BSM}_{b_{L+R}(\mu-e)_L}}{C^{SM}_{b_L \mu_L}}$$

$$C_{bx(\mu-e)_y} = C_{bx\mu_y} - C_{bxe_y}$$

$$C_{b_{L+R}e_y} = C_{b_L e_y} + C_{b_R e_y}$$

$$2\, C_9^{(\prime)} = C_{b_{L(R)}\mu_{L+R}}$$

$$2\, C_{10}^{(\prime)} = -\, C_{b_{L(R)}\mu_{L-R}}$$

D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre 1704.05438

General Observations

* ☆ theory uncertainty for $g-2$
* ☆ No theory uncertainty for R_K
* ☆ New physics in $R_K \rightarrow g-2$
* ☆ Hints of a modified Yukawa sector

Natural to explain them together

Deus ex machina

Naturalness

Technical naturality

Physical parameters remain small under radiative corrections.

$$m_e = m_e^0 \, R\left(\mu / m_e^0\right) \qquad \text{protected}$$

$$m_H^2 = m_H^{0\,2} \, R\left(\mu / m_H^0\right) + \circ \, \Lambda^2 \qquad \text{unprotected}$$

depends on the physics.

Honored Solutions

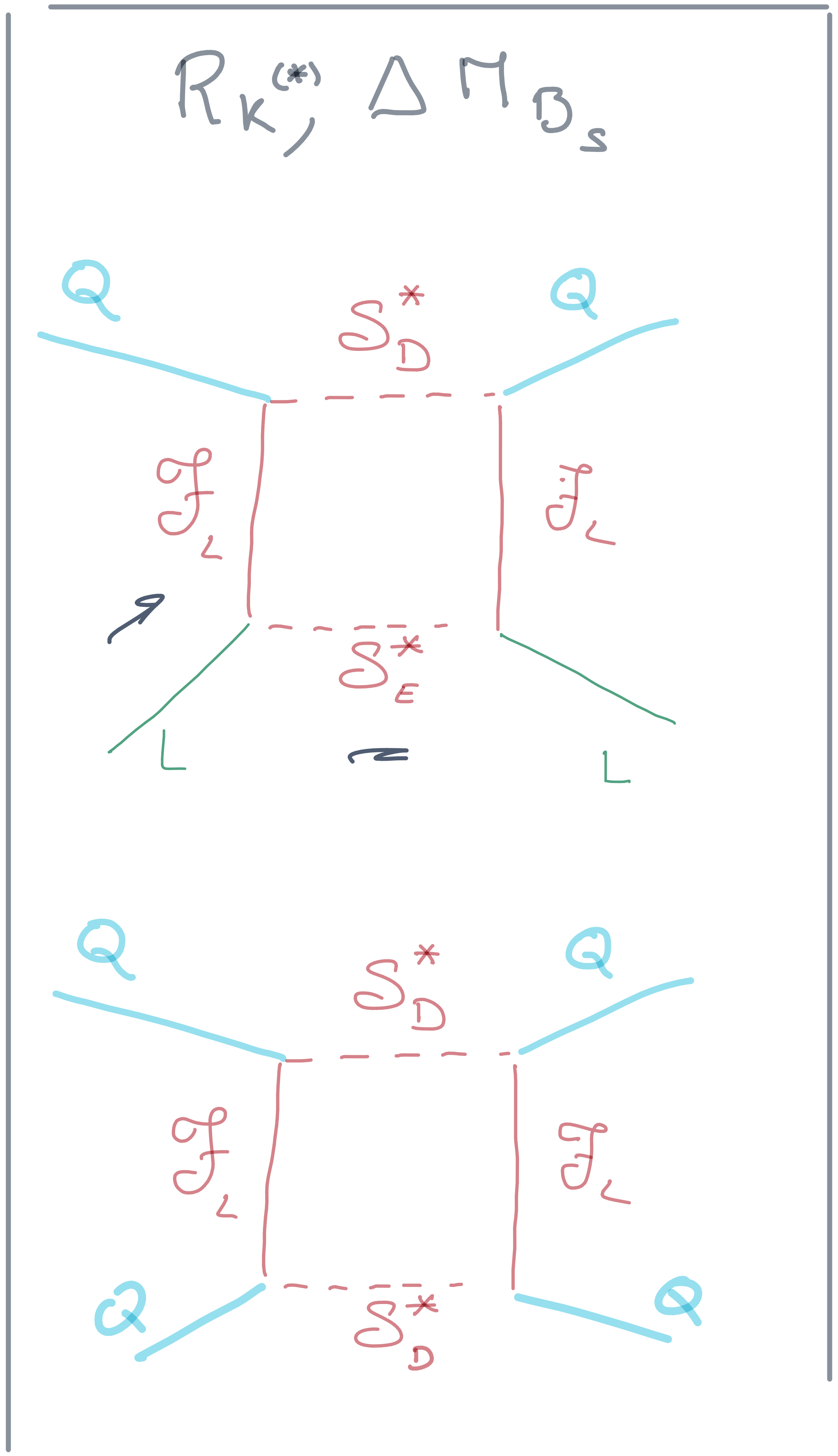
SUSY — Fermion $\Longleftrightarrow$ Boson protects Bosons

Technicolor — Bosons are fermion composite.

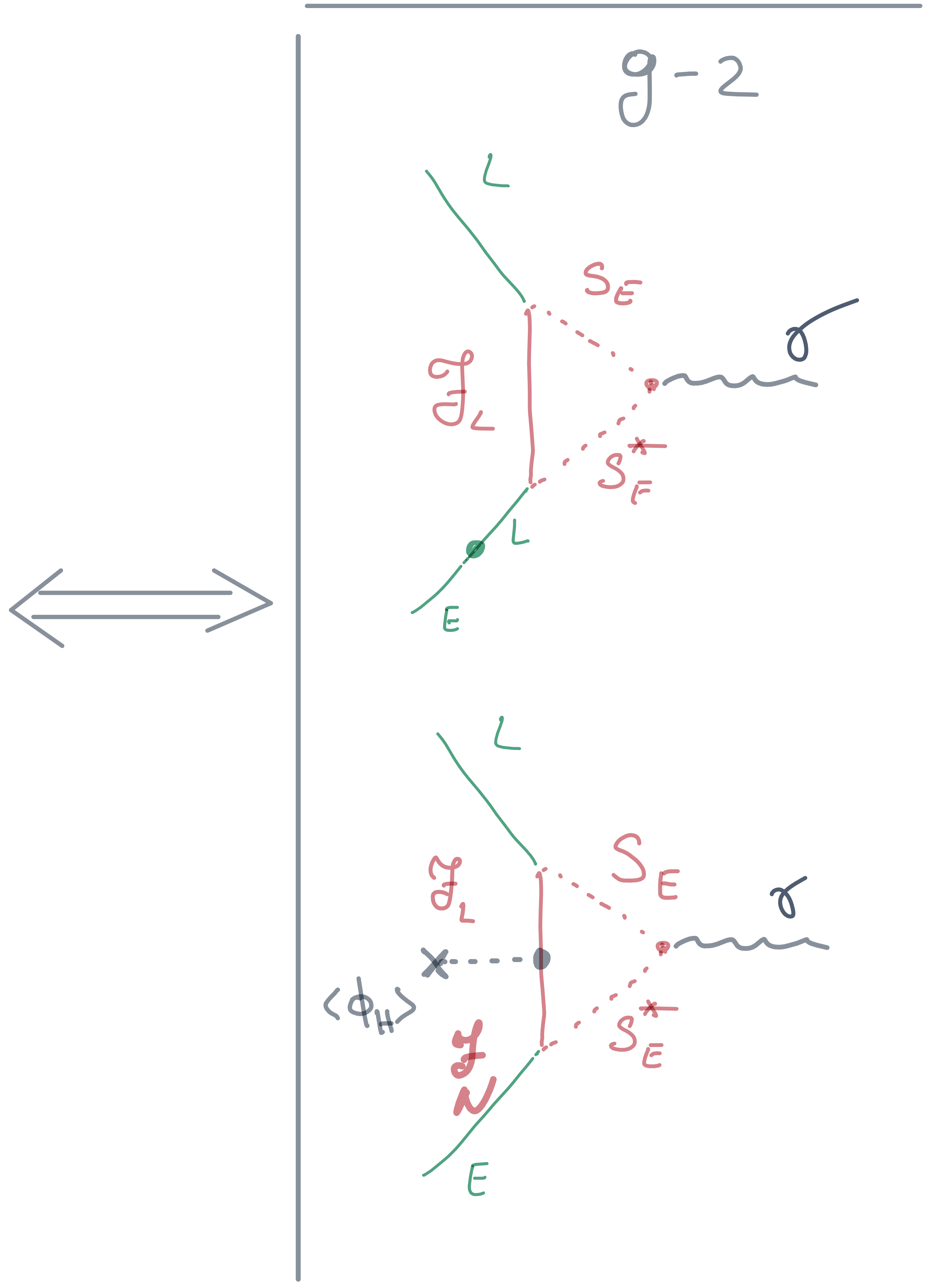
Strategy

- Skeleton model
- Varying degree of naturality // compositions
- Compare with anomalies

Skeleton



$R_{K^{(*)}}$, ΔM_{B_s}
Q
S_D^*
Q
$\mathcal{F}_L$
$\mathcal{F}_L$
S_E^*
L
L
Q
S_D^*
Q
$\mathcal{F}_L$
$\mathcal{F}_L$
Q
S_D^*
Q



g - 2
L
S_E
γ
$\mathcal{F}_L$
S_F^*
L
E
L
S_E
γ
$\mathcal{F}_L$
$\langle \phi_H \rangle$
$\mathcal{F}_N$
S_E^*
E

Skeleton Lagrangian

$$-\mathcal{L}_{NP} = y_1^{ij} L^i \mathcal{F}_L S_E^{j*} + y_E E^c \mathcal{F}_N^c S_E + y_Q Q \mathcal{F}_L S_D^* + y_U U^c \mathcal{F}_E^c S_D + y_D D^c \mathcal{F}_N^c S_D$$

$$+ \sqrt{2}\, \kappa \left(\mathcal{F}_L \mathcal{F}_N^c + \mathcal{F}_E \mathcal{F}_L^c \right) \phi_H + h.c.$$

	G_{TC}	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$\mathcal{F}_L$	$\square$	1	$\square$	Y
$\mathcal{F}_N^c$	$\overline{\square}$	1	1	$-Y - 1/2$
$\mathcal{F}_E^c$	$\overline{\square}$	1	1	$-Y + 1/2$
S_E^j	$\square$	1	1	$Y - 1/2$
S_D^j	$\square$	$\square$	1	$Y + 1/6$

What does it embrace?

Weak dynamics

Model

1] $\mathcal{G}_{TC} \approx$ (quasi) global symmetry $\Rightarrow$ Perturbative

$\mathcal{F}$, $\mathcal{S}$ are weakly coupled

L. Calibbi, R. Ziegler, J. Zupan, 1804.00009

P. Arnan, L. Hofer, F. Mescia, A. Crivellin, 1608.07832

with DM Arcadi, Calibbi, Fedele, Mescia, 2104.03228

⋮

Strong dynamics

Fund. Partial Composition

2] G_{TC} strongly coupled
S fundamental Scalar

$\mathcal{F} S \sim$ Composite Baryons
$\psi B \sim$ Partial Compositeness

$\Longrightarrow$

- Composite Goldstone Higgs ✓
- Traditional Technicolor ✗
- Near conformal TC ✓
  [Higgs ~ pseudo-dilaton]

Cacciapaglia, Sannino 1402.0233
Sannino, Strumia, Tesi, Vigiani 1607.01659

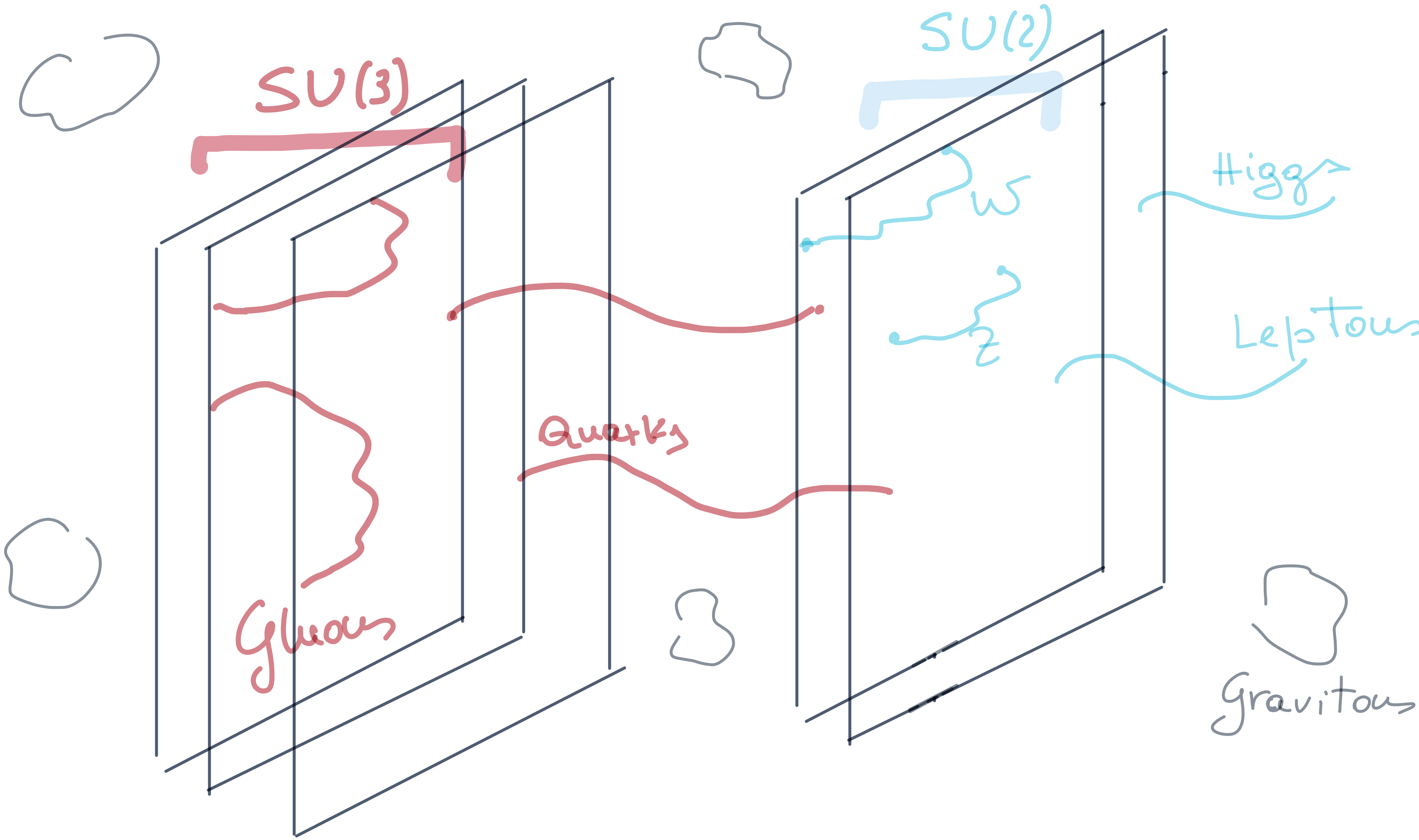
Partial Compositeness

3] As in 2] but with $S \sim \mathcal{F}\mathcal{F} \sim \chi\mathcal{F}, \chi\chi, \chi Z$

$\mathcal{F}, \chi, Z$ all fermions

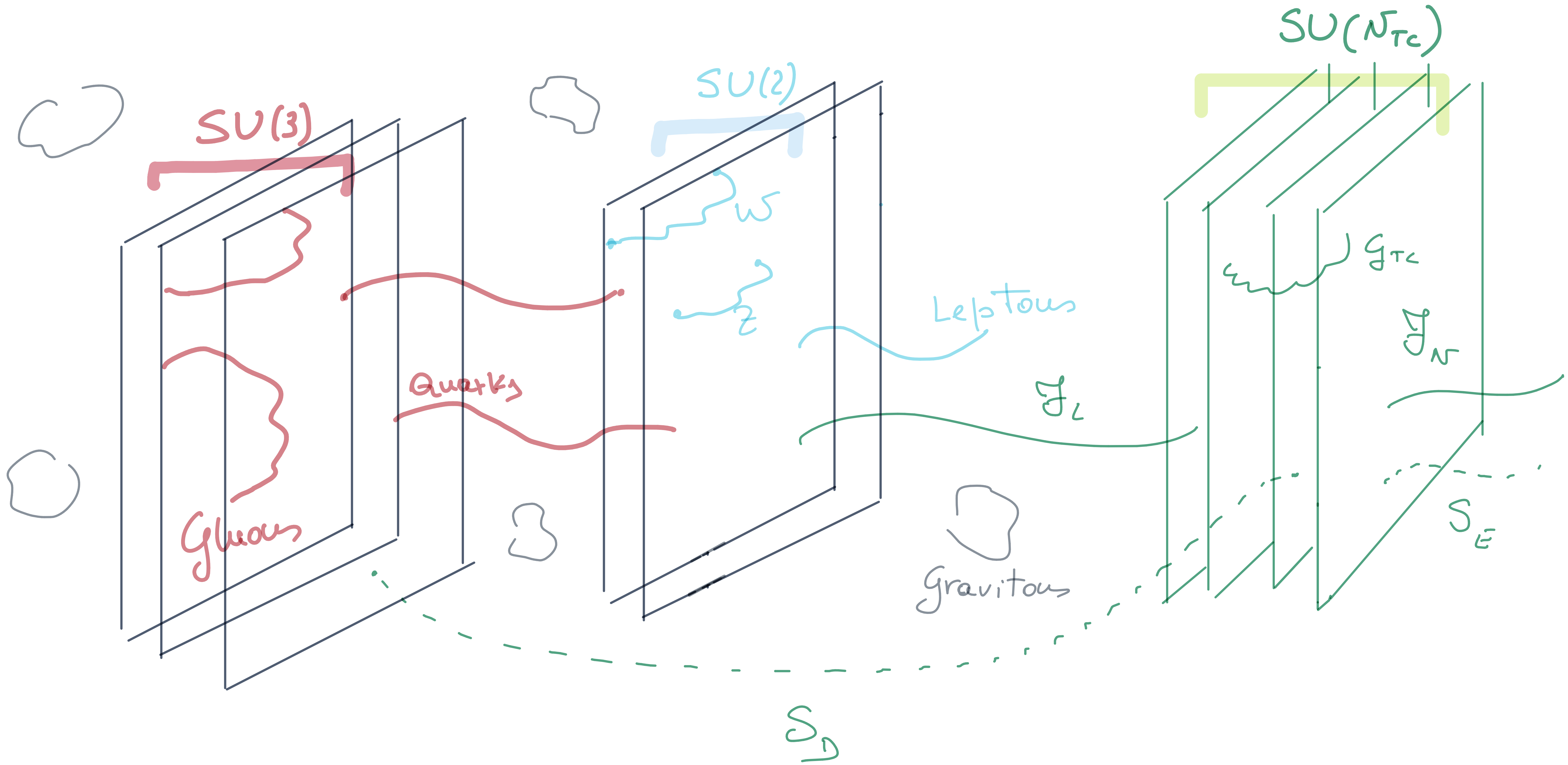
Ferretti and Karateev, 1312.5330

Stringy Standard Model



Aldazabal, Ibanez, Quevedo, Uranga hep-th/0005067

Stringy // holographic version



Comparison with R_K and g-2

	Coefficient	Perturbative one-loop result	Non-perturbative NDA
R_K	$c_{b_L\mu_L}$	$N_{\rm TC}\frac{(y_Ly_L^\dagger)_{\mu\mu}(y_Qy_Q^\dagger)_{bs}}{(4\pi)^2M_{\mathcal{F}}^2}\frac{1}{4}F(x,y)$	$\frac{(y_Ly_L^\dagger)_{\mu\mu}(y_Qy_Q^\dagger)_{bs}}{g_{\rm TC}^2\Lambda_{\rm TC}^2}$
B_s mix	$C_{B\bar{B}}$	$N_{\rm TC}\frac{(y_Qy_Q^\dagger)_{bs}^2}{(4\pi)^2M_{\mathcal{F}}^2}\frac{1}{8}F(x,x)$	$\frac{(y_Qy_Q^\dagger)_{bs}^2}{g_{\rm TC}^2\Lambda_{\rm TC}^2}$
	Δa_μ	$N_{\rm TC}\frac{m_\mu(y_Ly_E^\dagger)_{\mu\mu}\kappa v_{\rm SM}}{(4\pi)^2M_{\mathcal{F}}^2}\left[2q_{S_E}F_{LR}(y)+2q_{\mathcal{F}}G_{LR}(y)\right]+$ $N_{\rm TC}\frac{m_\mu^2(y_Ly_L^\dagger)_{\mu\mu}}{(4\pi)^2M_{\mathcal{F}}^2}\left[2q_{S_E}F_7(y)+2q_{\mathcal{F}}\tilde{F}_7(y)\right]$	$\frac{m_\mu^2}{\Lambda_{\rm TC}^2}\left(1+\frac{(y_Ly_L^\dagger)_{\mu\mu}}{g_{\rm TC}^2}\right)$

$q_{S_E}=y-\frac{1}{2}$ $\quad q_{\mathcal{F}}=y+\frac{1}{2}$

$x=M_{SD}^2/M_F^2$ $\quad y=M_{SE}^2/M_{\mathcal{F}}^2$

$C_9=C_{10}$

Cacciapaglia, Cot, Sannino 2104.08818

L. Calibbi, R. Ziegler, J. Zupan, 1804.00009

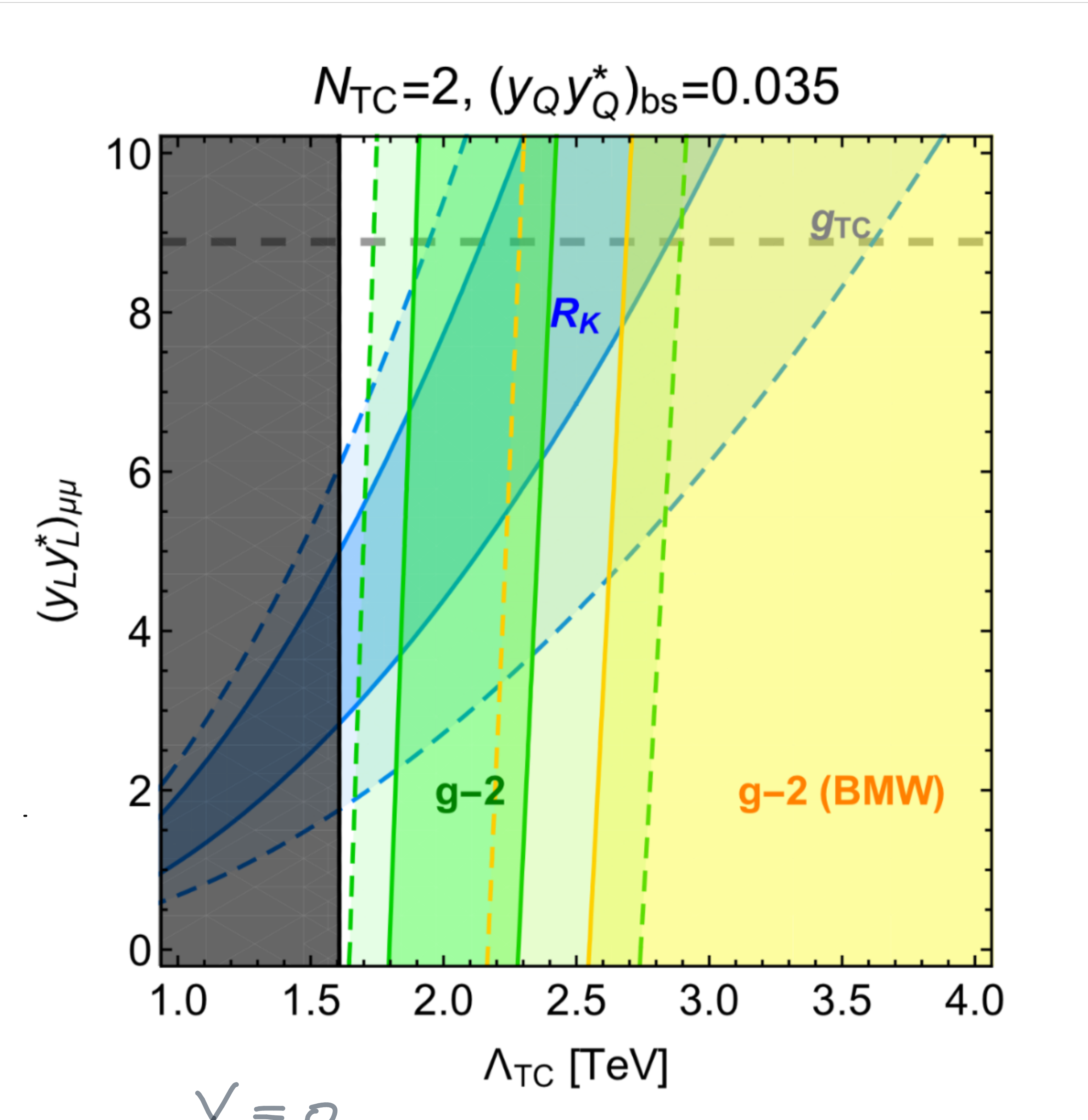
P. Arnan, L. Hofer, F. Mescia, A. Crivellin, 1608.07832

with DM Arcadi, Calibbi, Fedele, Mescia, 2104.03228

Composite

$m_\mu \sim N_{TC}\frac{(y_Ly_E^\dagger)_{\mu\mu}}{(4\pi)^2}\kappa v_{SM}$

Composite avenue



$y = 0$

$$\Delta a_\mu \sim \frac{m_\mu^2}{\Lambda_{TC}^2}$$

- Δa_μ → new physics scale
- $\Lambda_{TC} \approx 2$ TeV
- Large left-handed μ-Yukawa coupling

What does not work?

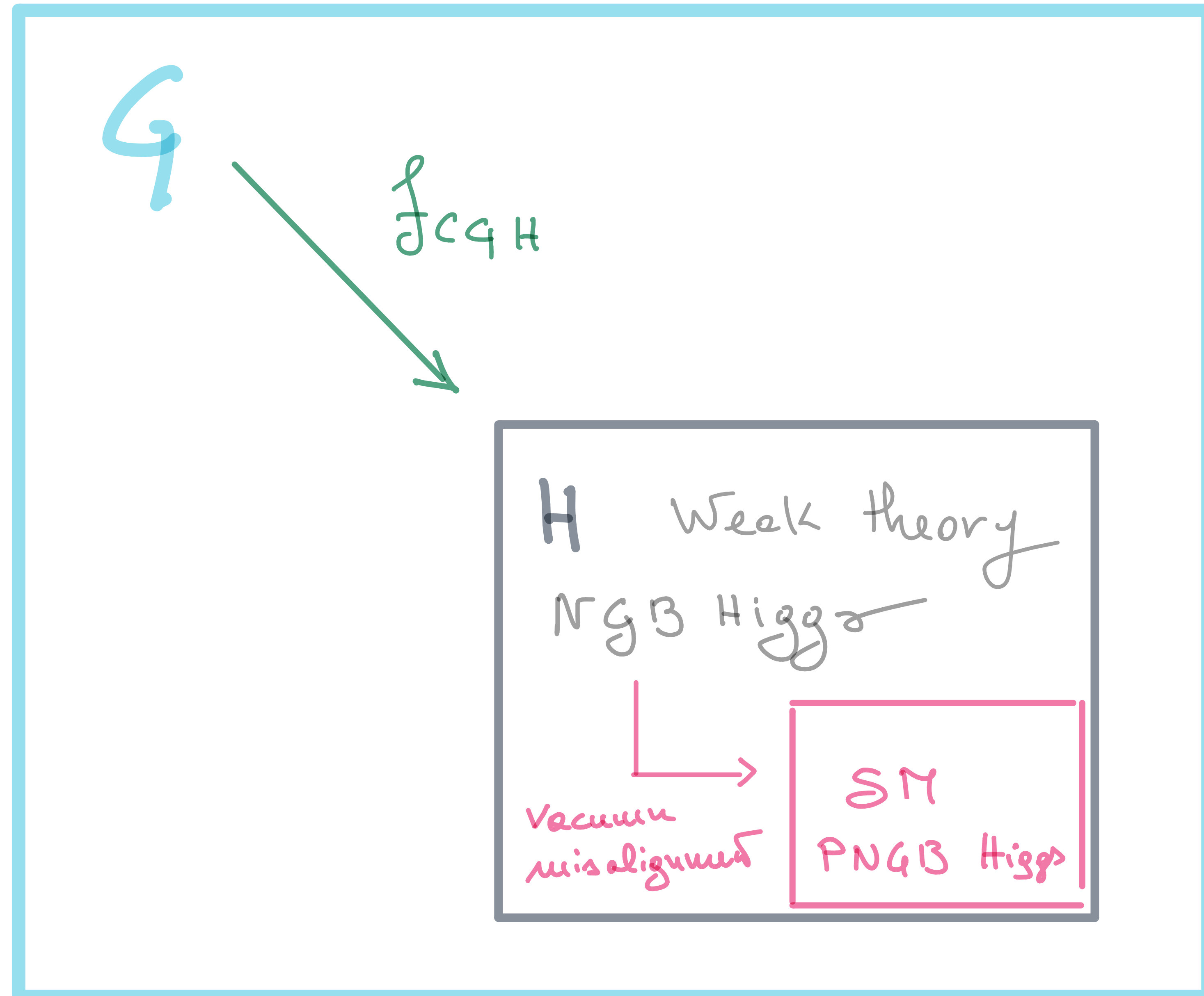
$$\Delta a_\mu(CGH) \approx \frac{v_{SM}^2}{f_{CGH}^2}\,\frac{m_\mu^2}{\Lambda_{TC}^2}$$

$$\Lambda_{TC} \approx 4\pi v_{SM} \approx 2\,\text{TeV}$$

$$f_{CGH} \sim (4-5)\,\Lambda_{TC} \Rightarrow \text{small } \Delta a_\mu$$

Frigerio, Nardecchia, Serra, Vecchi 1807.04279

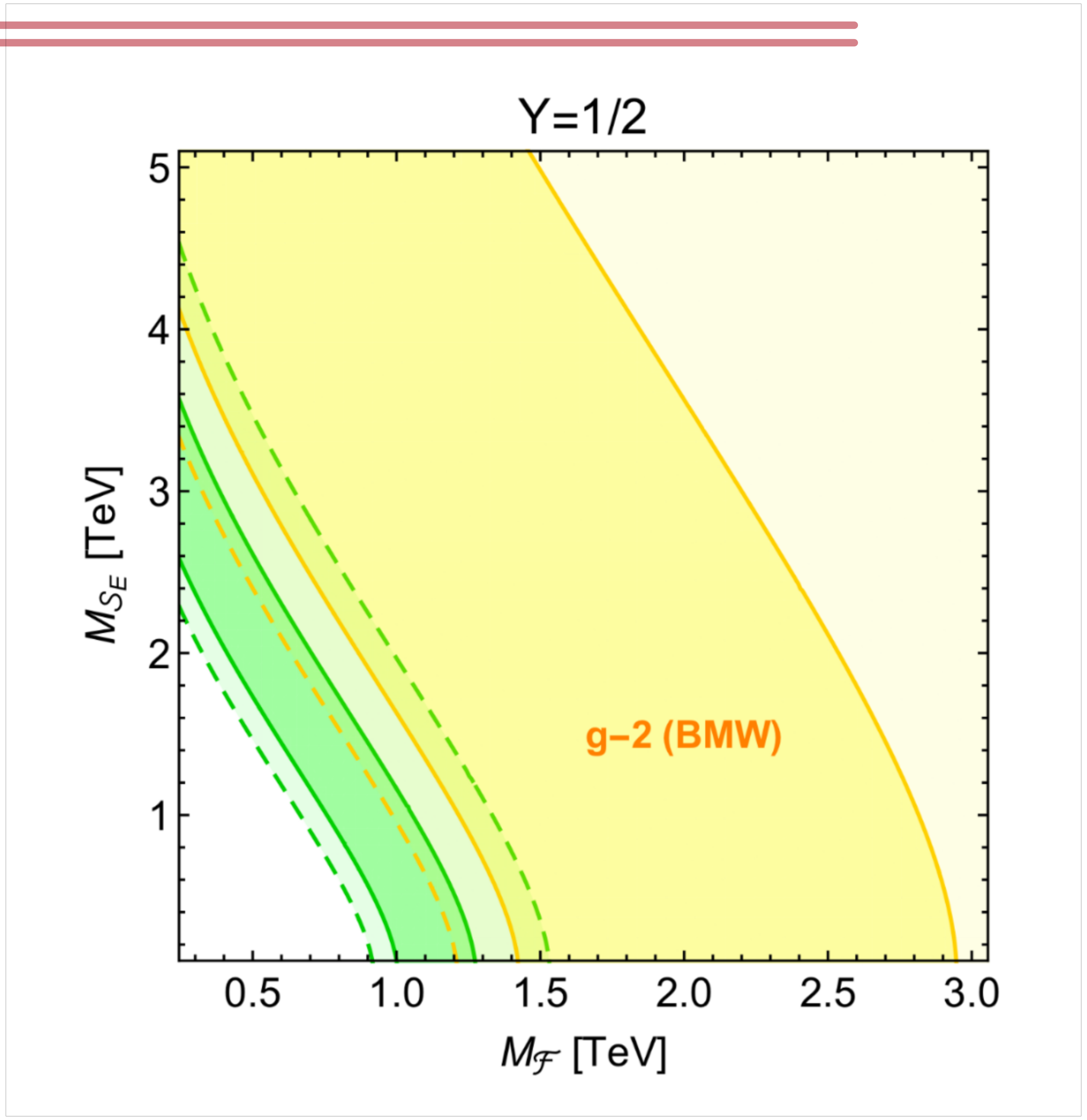
Composite Goldstone Higgs (CGH)

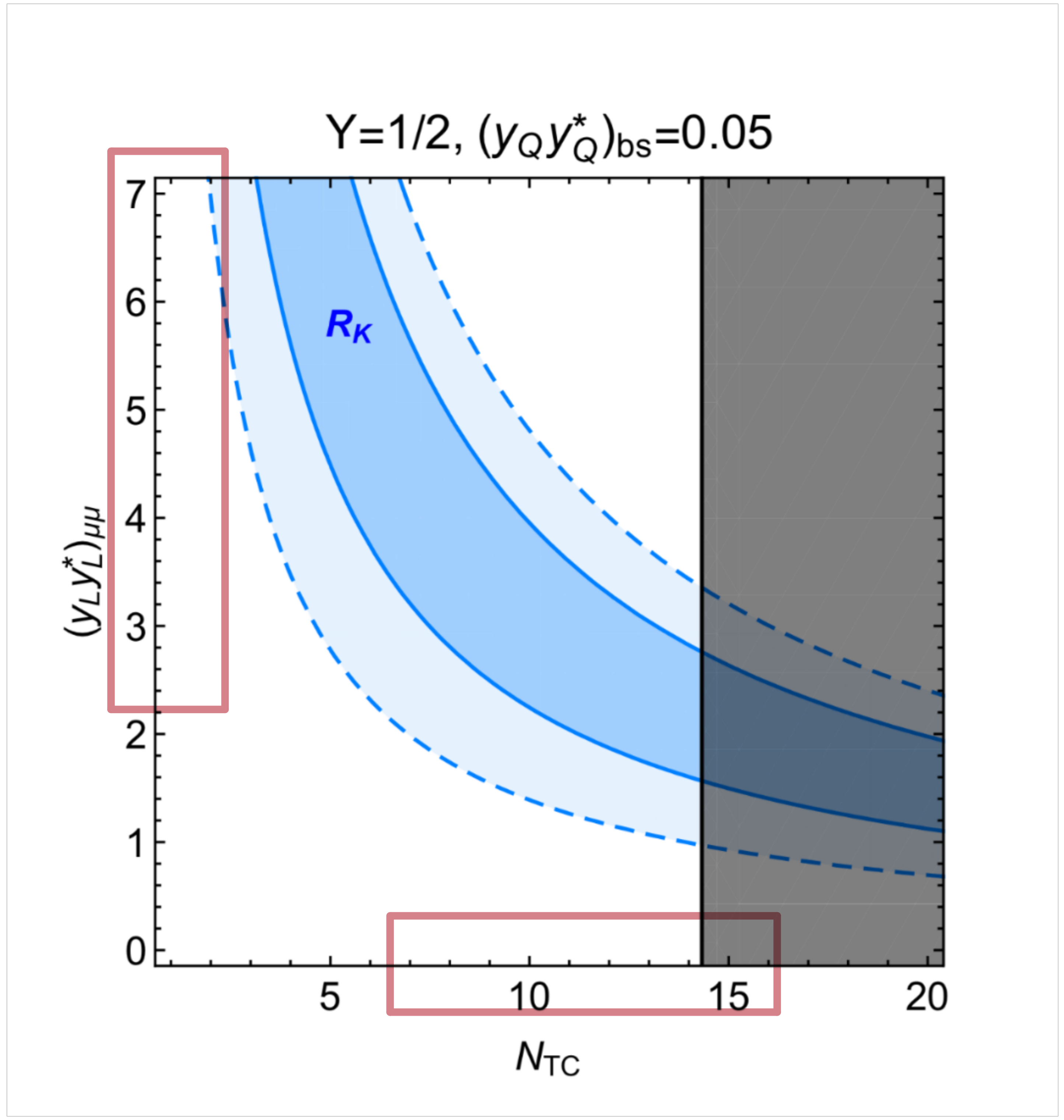


Kaplan, Georgi PLB 136, 183 (1984)

What works less?

Radiative models





S_D mass LHC constrained (1.5 TeV benchmark)

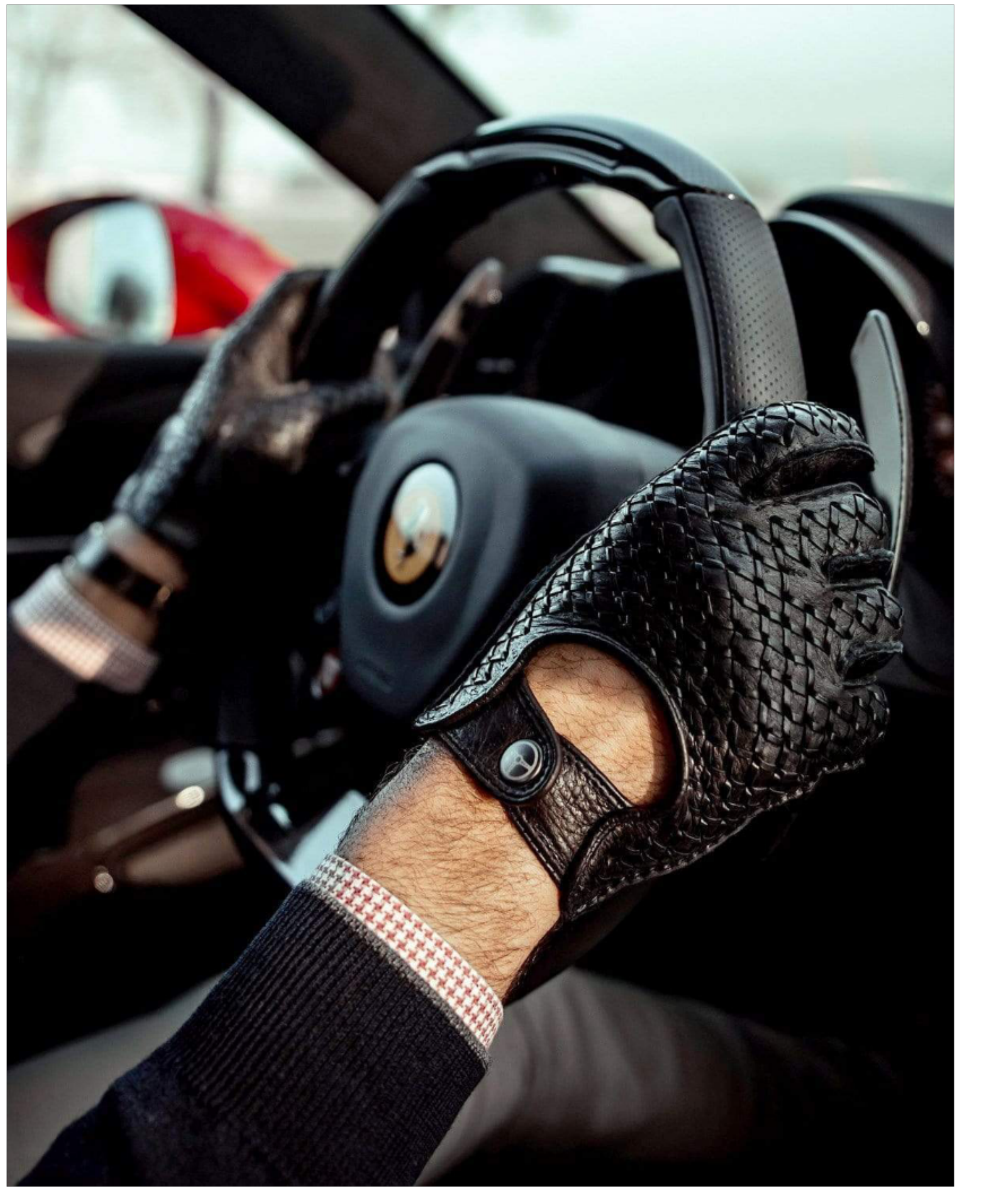
$$m_\mu = \frac{N_{TC} (y_L y_E^+)_{\mu\mu}}{(4\pi)^2} \kappa v_{SM} \ln \frac{\Lambda^2}{M_{\mathcal{F}}^2}$$

Yukawa: Low energy Landau poles

See L. Calibbi

What works

- EW scale composite dynamics
- Near conformal dynamics // TC dilaton
- (Fund.) partial compositeness



The gloves naturally fitting Δa_μ and R_K

Scale and dynamics of new physics in tune with natural extensions of SM

Conclusions

- Near discovery ?
- Ex. 2-4 TeV TCρ
- New CP-phases for baryogenesis
- Study Strong dynamics
- Conformal Window

Exciting times

Backup slides

Polyakov loop model

$$\ell\,(x) = \frac{1}{N}\mathrm{Tr}[\mathbf{L}]$$

$$\mathbf{L} = \mathcal{P}\exp\left[i\,g\int_0^{1/T} A_0(x,\tau)\,\mathrm{d}\tau\right]$$

$$V^{(3)}_{\mathrm{PLM}} = T^4\left(-\frac{a(T)}{2}|\ell|^2 + b(T)\ln\left[1-6|\ell|^2+4(\ell^{*3}+\ell^3)-3|\ell|^4\right]\right)$$

$$a(T) = a_0 + a_1\left(\frac{T_c}{T}\right) + a_2\left(\frac{T_c}{T}\right)^2 + a_3\left(\frac{T_c}{T}\right)^3$$

$$b(T) = b_3\left(\frac{T_c}{T}\right)^3$$

Thermodynamics

Free energy density

$$f = -\frac{T}{V} \log Z \qquad Z = \text{partition function} \qquad \log Z = -\frac{V}{T} f$$

Pressure

$$p = T \frac{\partial \log Z}{\partial V}\Big|_T \xrightarrow[f \text{ is } V \text{ independent}]{\text{Thermodynamic limit}} p = -f$$

Energy density

$$e = \frac{T^2}{V}\frac{\partial \log Z}{\partial T}\Big|_V = \frac{T^2}{V}\left[-V \frac{\partial}{\partial T}\left(\frac{f}{T}\right)\right] = T^2\left[-\frac{1}{T}\frac{\partial f}{\partial T} + \frac{f}{T^2}\right] = -p + \frac{\partial p}{\partial \log T}$$

Trace of energy-momentum tensor

$$\Theta/T^4 := \frac{\partial}{\partial \log T}\left(p/T^4\right) = T\left[\frac{\partial p}{\partial T}\frac{1}{T^4} - \frac{4}{T^5}p\right] \Rightarrow \Theta = \frac{\partial p}{\partial \log T} - 4p \Rightarrow \Theta - e = -4p + p = -3p \rightarrow$$

$$\rightarrow \Theta = e - 3p \rightarrow e = \Theta + 3p$$

Entropy density

$$s = \frac{1}{V}\log Z + \frac{e}{T} = \frac{1}{V}\left(-\frac{V}{T}f\right) + \frac{e}{T} = \frac{p+e}{T} = \frac{4p+\Theta}{T} \rightarrow \frac{s}{T^3} = \frac{\Theta + 4p}{T^4}$$

Panero · 0907.3719

Thermodynamics
PLM

Impose for $T \to \infty$ $\left[\begin{array}{l}\text{Stefan-Bolzmann limit} \\ |\ell| \to 1\end{array}\right.$

$\downarrow$

$$f_{PLM} = V_{PLM}$$

$$\left.\frac{p}{T^4}\right|_{T\to\infty} \to 1.21\,(N^2-1)\frac{\pi^2}{45}$$

$$T\to\infty \qquad \frac{V^{(3)}_{PLM}}{T^4} = -\frac{a_0}{2}|\ell|^2 + b_4|\ell|^4 - b_3(\ell^3 + \ell^{*3})$$

Setting $b_3 \approx 0 \Rightarrow$ ground state for $-a_0 + 4b_4|\ell|^2 = 0 \qquad |\ell|^2 = \frac{a_0}{4b_4} = 1$

$$\left.\frac{V^{(3)}_{PLM}}{T^4}\right|_{T\to\infty} \simeq -|\ell|^2\left[\frac{a_0}{2} - b_4|\ell|^2\right] = -\frac{a_0}{4b_4}\left[\frac{a_0}{2} - b_4\frac{a_0}{4b_4}\right] = -\frac{a_0}{4b_4}\left[\frac{a_0}{4}\right]$$

$\{b_3 = 0$ for simplicity

$$\Rightarrow \quad \left.f_{PLM}\right|_{T=\infty} = -\left.p_{PLM}\right|_{T=\infty} = -\frac{a_0}{4}T^4 \Rightarrow \frac{p_{PLM}}{T^4} = \frac{a_0}{4} = 1.21\,(N^2-1)\frac{\pi^2}{45}$$

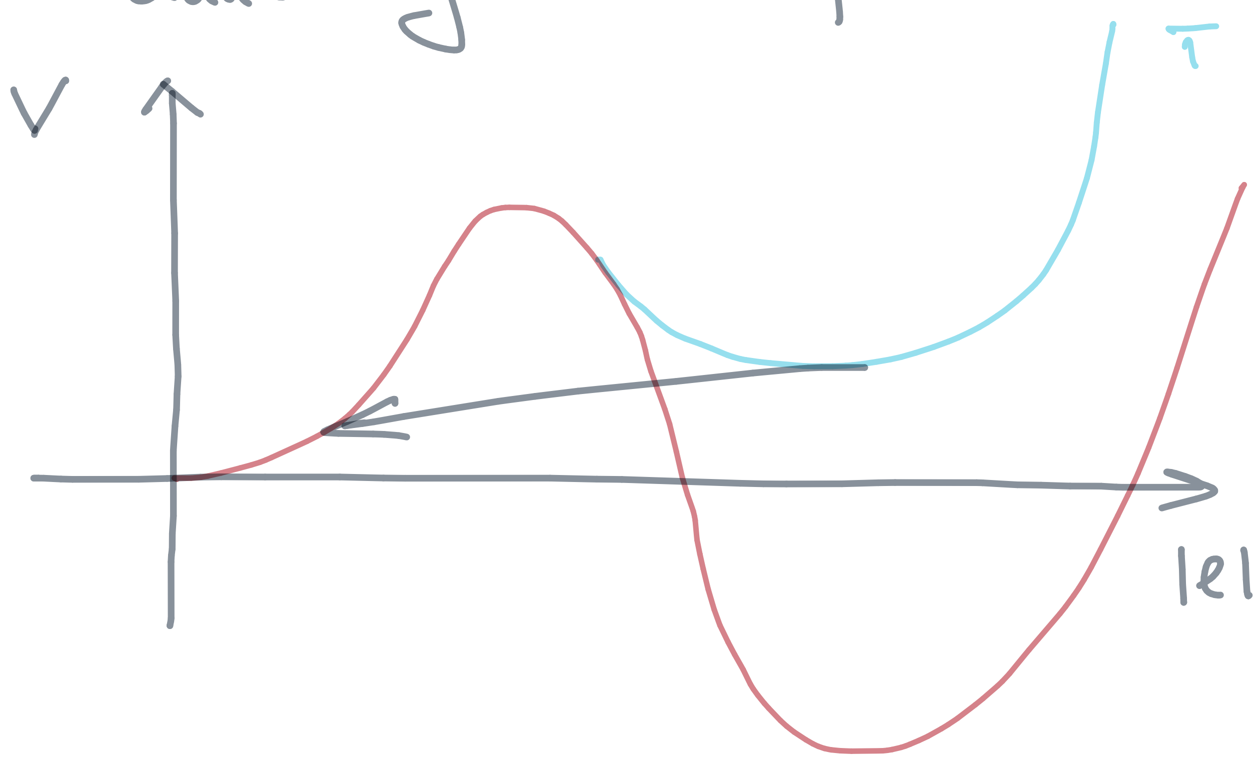
Bubble nucleation

~~Z_N~~

$|e| = 0$ → $|e| = 1$

Z_N → T

Tunnelling rate from broken phase to unbroken phase



T_H

$T_H > T$

$$\Gamma[T] = T^4 \left(\frac{S_3(T)}{2\pi T} \right)^{3/2} e^{-S_3(T)/T}$$

$$S_3(T) = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2} \left(\frac{d\rho}{dr} \right)^2 + V_{eff}(\rho, T) \right]$$

→ 3d Euclidean action

$\rho :=$ scalar field with effective potential V_{eff}

$[\rho] = 1$ $\quad [e] = 0$ $\quad [V_{eff}[\rho, T]] = 4$

$$\rho = \ell T \quad r' = rT \Rightarrow S_3(T) = 4\pi T \int_0^\infty dr'\, r'^2 \left[\frac{1}{2}\left(\frac{d|\ell|}{dr'}\right)^2 + V'_{eff}(|\ell|, T) \right]$$

$$\frac{d\rho}{dr} = \left(\frac{d\ell}{dr}\right) T = \frac{d\ell}{d\, r/T}$$

$$dr = \frac{dr'}{T} \Rightarrow r^2 dr = \frac{r'^2}{T^3} dr'$$

$$T^2 r^2 dr \left(\frac{d\ell}{dr}\right)^2 = \frac{r'^2 dr'}{T^3} \cdot T^2 \frac{(d\ell)^2}{\frac{(dr')^2}{T^2}} = \frac{r'^2 dr'}{T} \frac{\left(\frac{d\ell}{dr'}\right)^2}{T^2} = T r'^2 dr' \left(\frac{d\ell}{dr'}\right)^2$$

$$r^2 dr\, V(|\ell|, T) = \frac{r'^2 dr'}{T^3} \cdot T^4\, V'_{eff}(|\ell|, T) = T\, r'^2 dr'\, V'_{eff}(|\ell|, T)$$

$$V'_{eff}(|\ell|, T) = \frac{V_{PLT}(|\ell|, T)}{T^4}$$

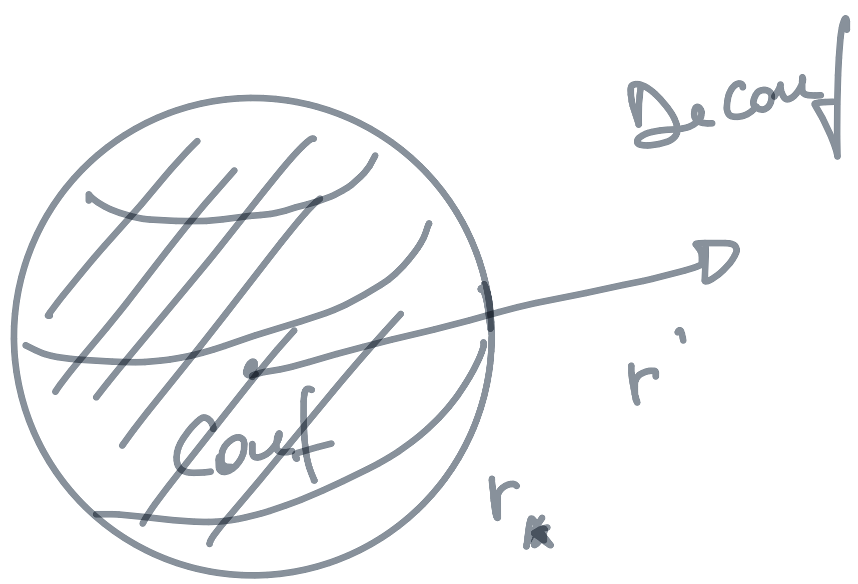
$r :=$ physical bubble radious

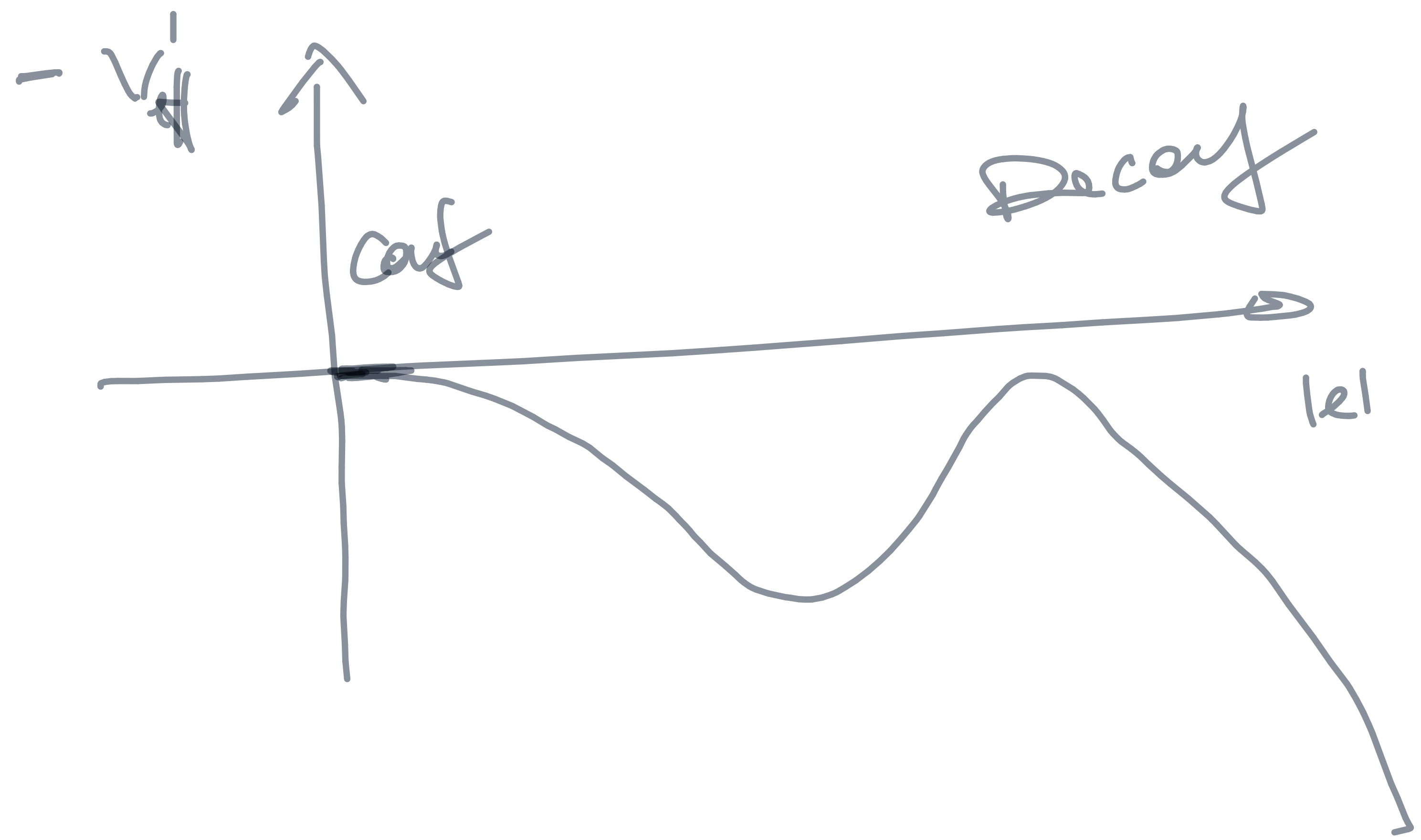
$r' = rT$ bubble radious × Temperature

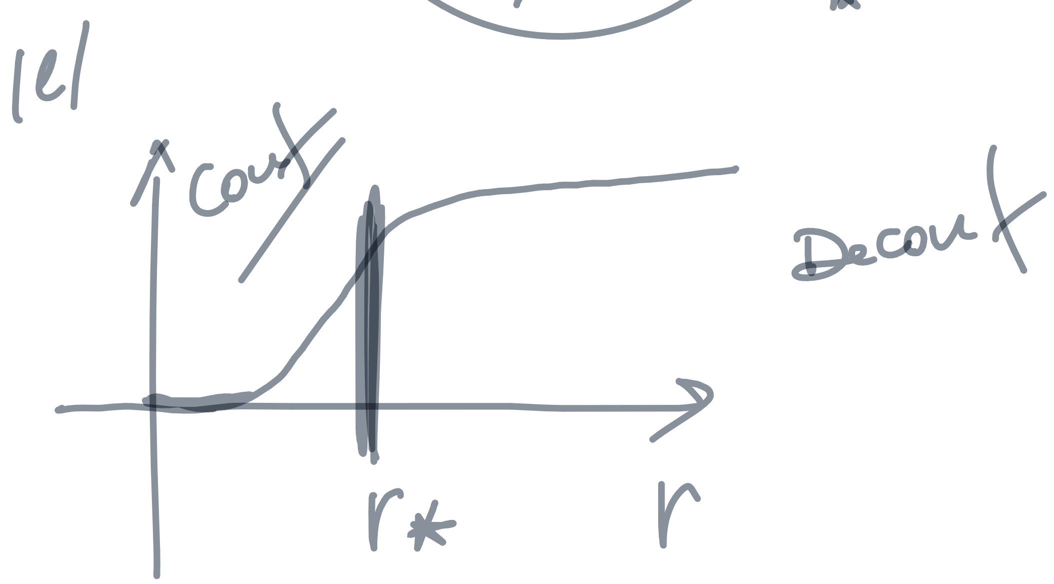
Bubble profile (instanton solution)

$$\frac{d^2\phi(r')}{dr'^2} + \frac{2}{r'}\frac{d\phi(r')}{dr'} - \frac{\partial V'_{eff}(\phi,T)}{\partial \phi} = 0$$

boundey conditions $\frac{d\phi}{dr'}(r'=0, T) = 0$ $\lim_{r'\to 0} \phi(r', T) = 0$







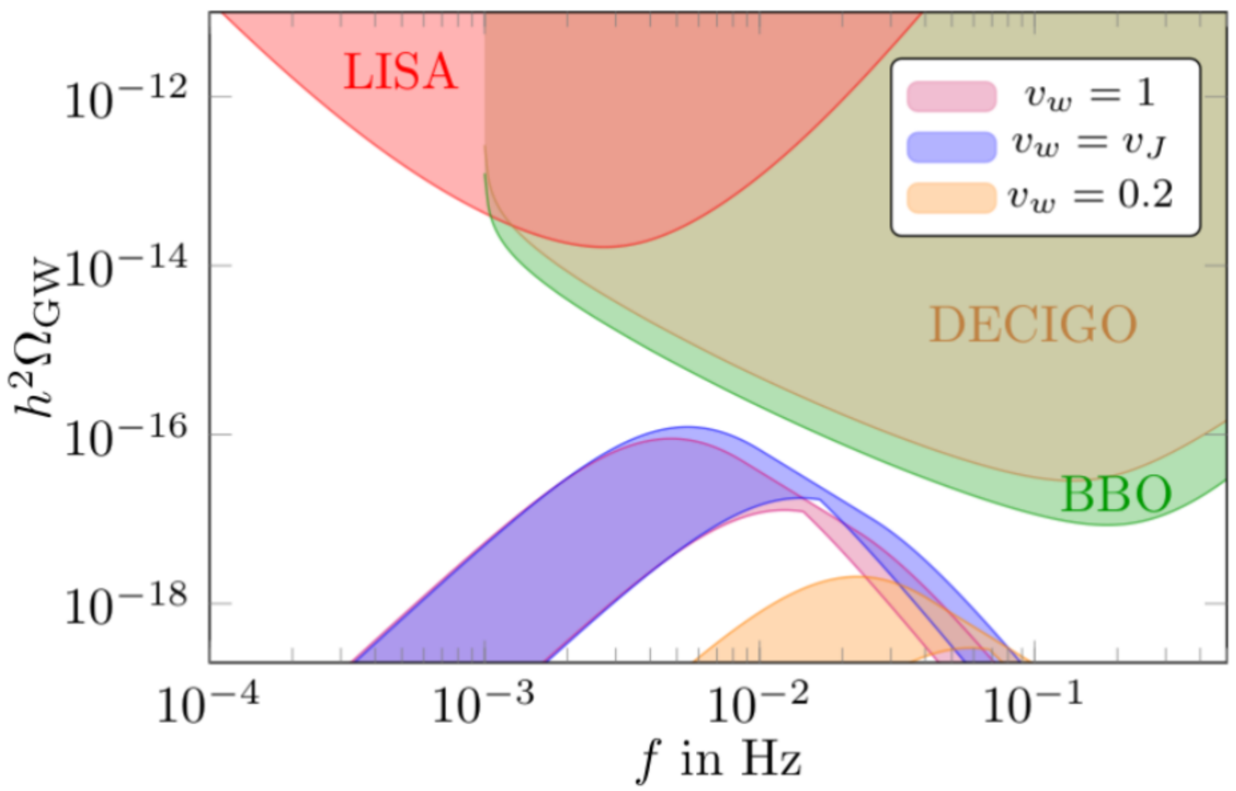


Figure 8. GW spectrum for the $SU(6)$ phase transition for different bubble-wall velocities, i.e., $v_w = 1$, $v_w = 0.2$, and $v_w = v_J$ the Chapman-Jouguet detonation velocity, see (48). The bands on the GW signal represent the small statistical lattice errors affecting the derivation of the α and $\tilde{\beta}$ parameters and include a further generous extra factor of five to account for hidden systematic errors.

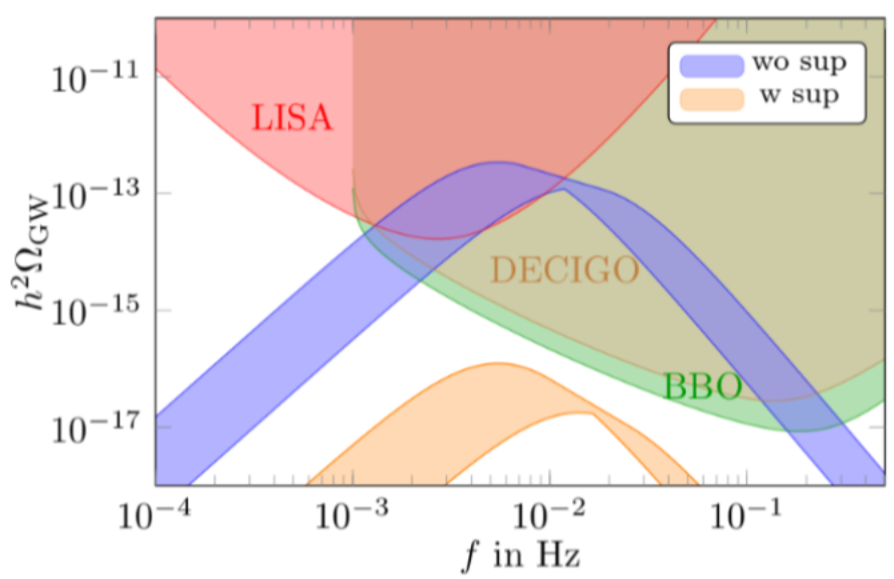


Figure 9. Comparison of the $SU(6)$ GW spectrum with and without the suppression factor of (53).

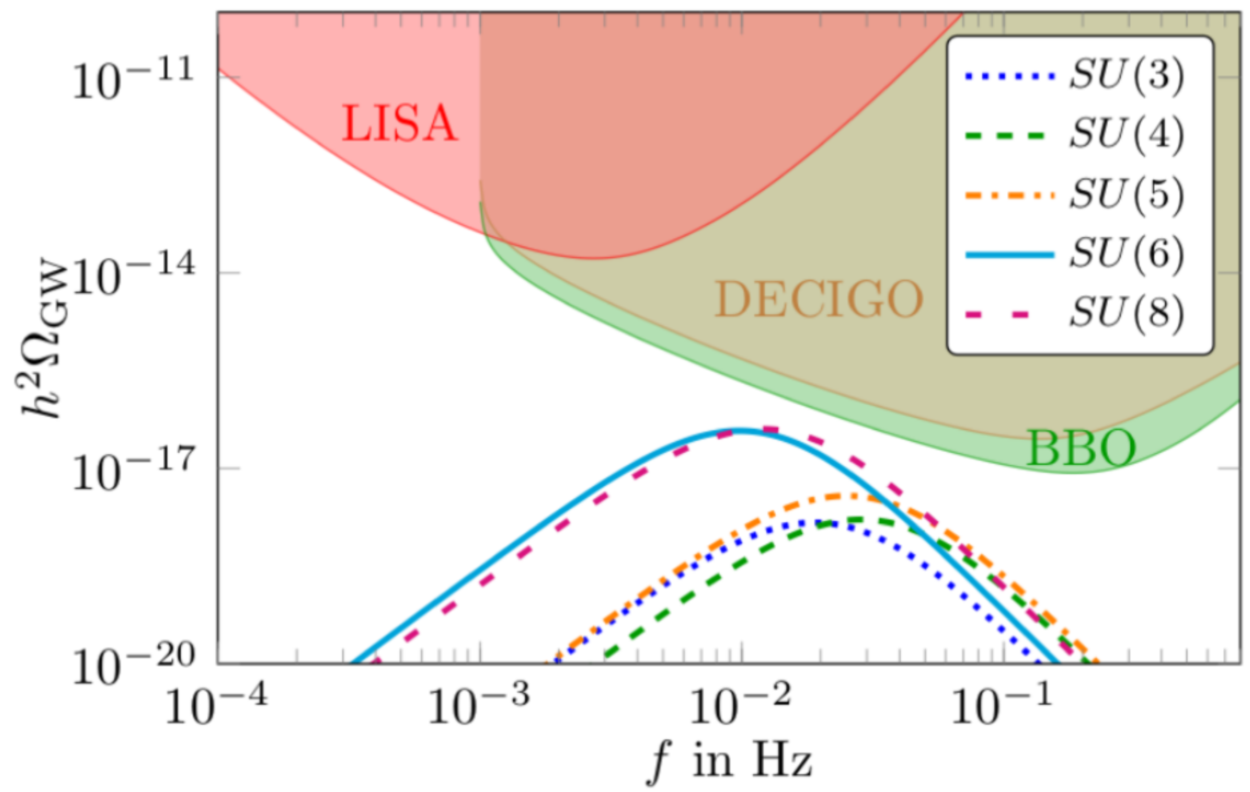


Figure 10. GW spectra from the $SU(N)$ deconfinement phase transition for different values of N. All spectra are plotted with the bubble-wall velocity set to the Chapman-Jouguet detonation velocity.