Conformal Dynamics and EWSB

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Kyoto 2009

UNIVERSITY OF SOUTHERN DENMARK

Thank you Koichi

Dynamical Electroweak Symmetry Breaking

Unparticle Physics

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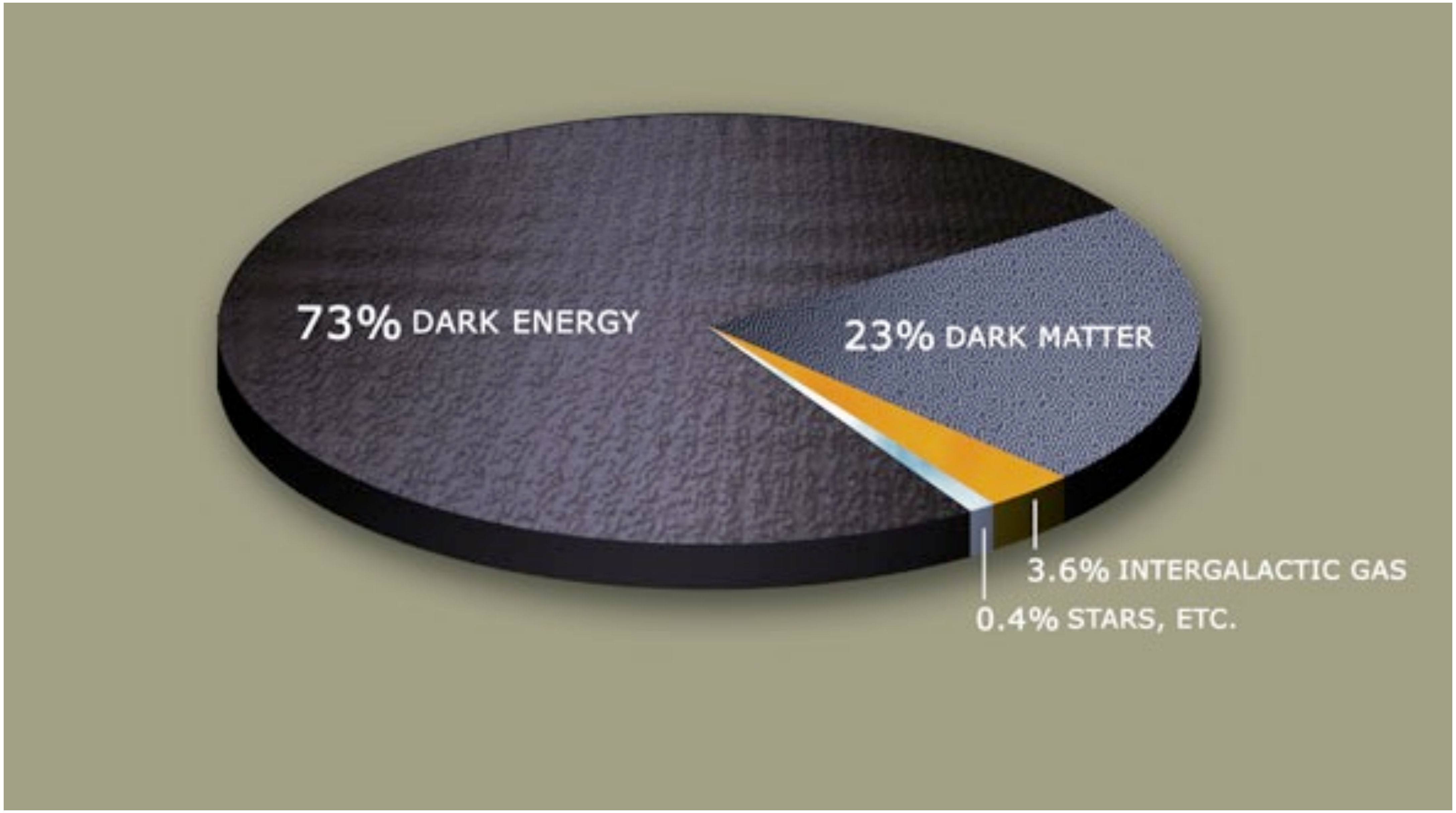
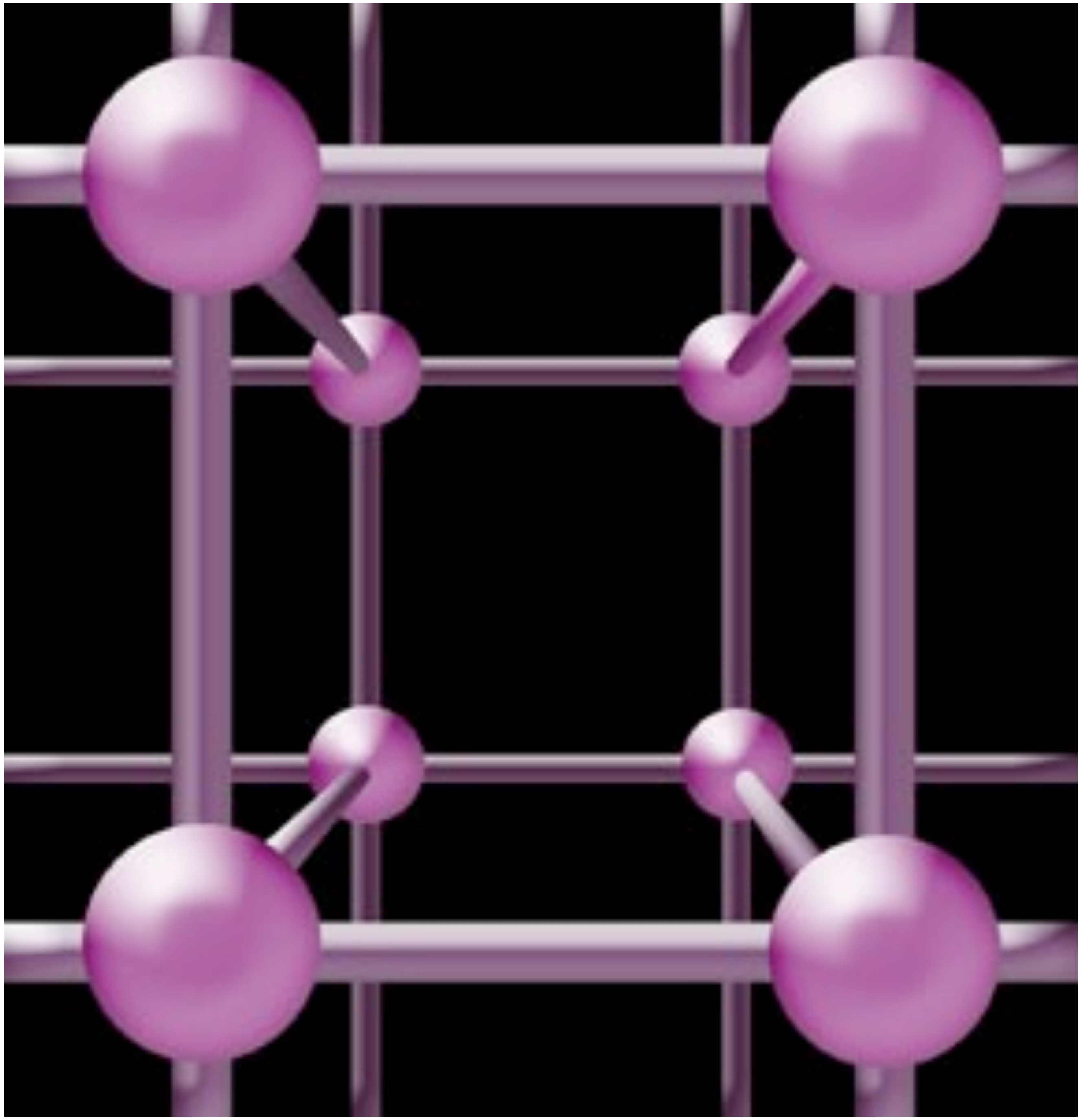

73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Natural Asymmetric Dark Matter

Electroweak Baryogenesis



We can probe the dynamics of our extensions

Plan

DEWSB

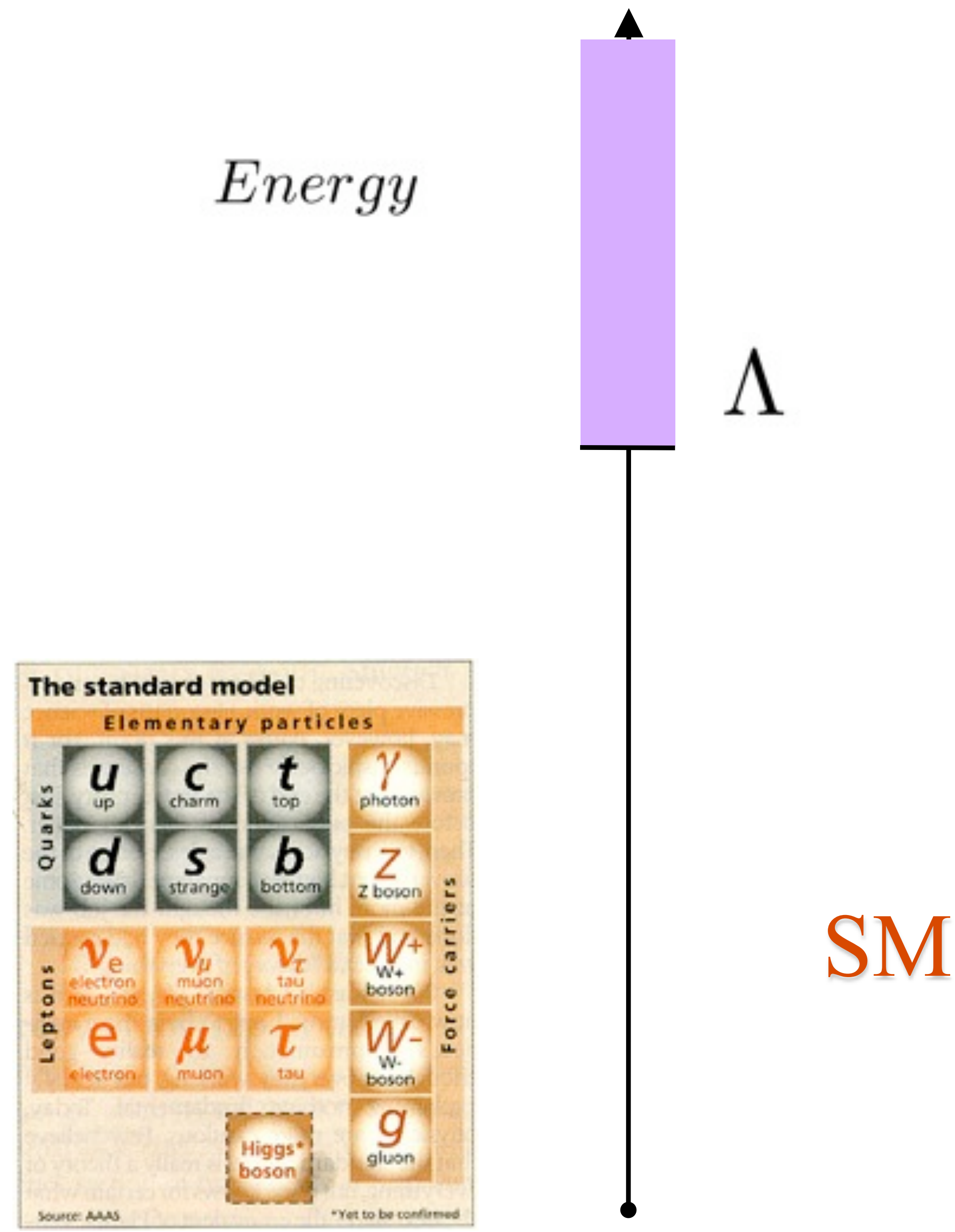
Need for CFT

Status-of-the-art 4D Non-SUSY CFT

Asymmetric Dark Matter

(Ultra) Minimal Walking Models

Low Energy Effective Theory



Dynamical EW Breaking

$$L(H) \to -\frac{1}{4}F^{a\mu\nu}F^{a}_{\mu\nu} + i\,\bar{Q}\gamma^{\mu}D_{\mu}Q + \cdots$$

Dots are partially fixed by Anomalies as well as other principles

$$\cdots \qquad \to \qquad L(\text{New SM Fermions})$$

Technicolor

New Strong Interactions at ~ 250 GeV
[Weinberg, Susskind]

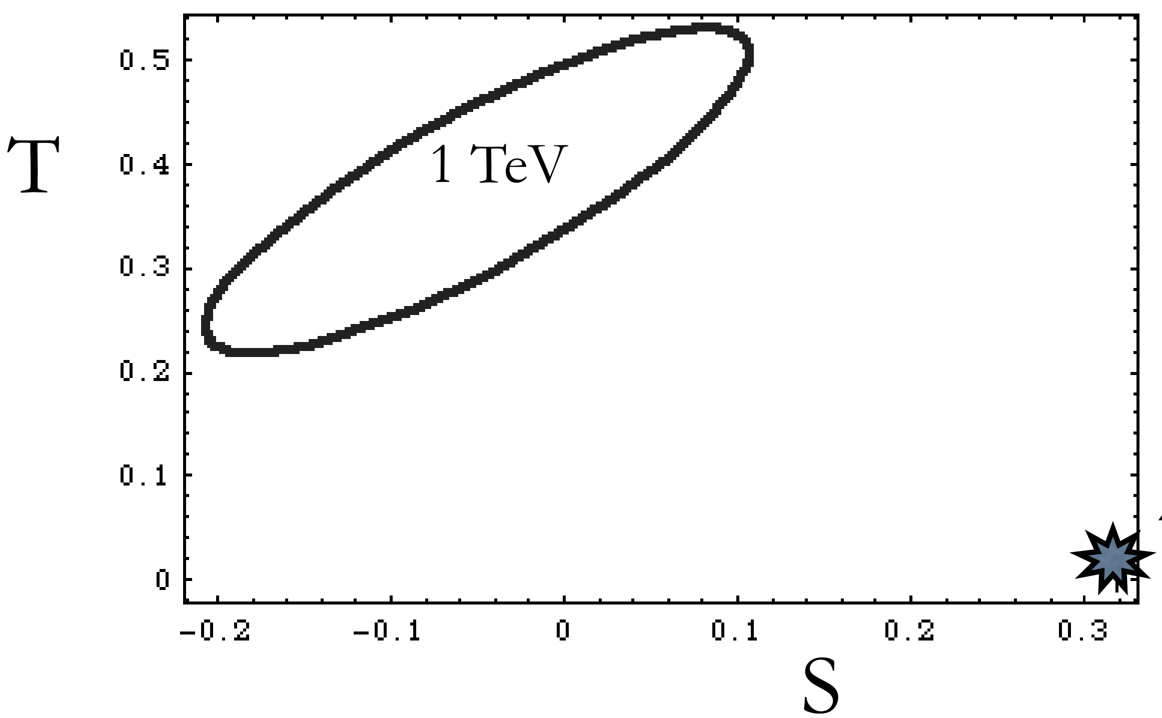
Natural to use QCD-like dynamics.

$$SU(N)_{TC} \times SU(3)_C \times SU_L(2) \times U_Y(1)$$

$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad\qquad \Lambda_{TC} \simeq 250\ GeV$$

Large & Positive S from QCD-like Technicolor

Peskin and Takeuchi, 90



SU(3) + 1 Fund. Doublet

Weinberg, Susskind

Kennedy-Lynn, Peskin-Takeuchi, Altarelli-Barbieri, Bertolini- Sirlin, Marciano-Rosner

Masses to SM Fermions

The need to Extend Technicolor

$$\bar{L} \cdot H e_R \qquad \rightarrow \qquad \bar{L} \frac{\bar{Q}Q}{\Lambda_{ETC}^2} e_R$$

Different Approaches

Scalar-less New Gauge Interactions (Extended TC)

Marry SUSY and Technicolor

Add New Scalars in the Flavor Sector

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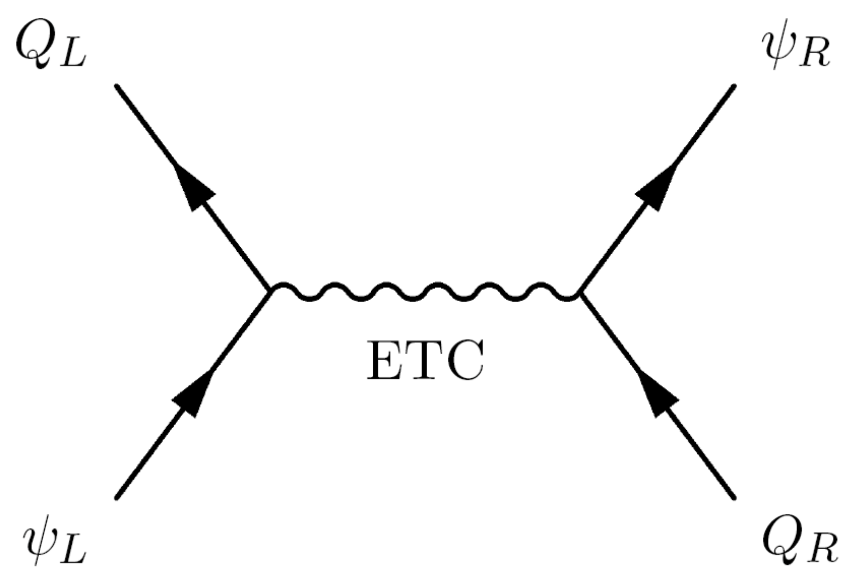
Extended Technicolor



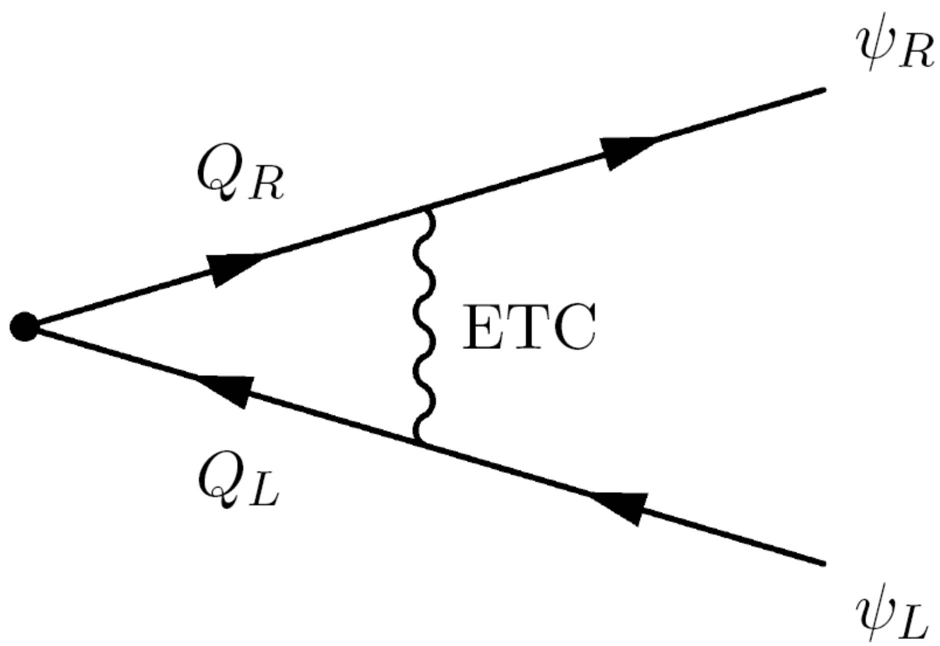
$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda_{ETC}^2} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda_{ETC}^2} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda_{ETC}^2} + \dots$$

PNG Masses

SM-Fermion Masses

FCNC Operators

Beta - Terms



$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC}$$

Gamma - Terms

$$\frac{1}{\Lambda^2_{ETC}}(\bar{s}\gamma^5 d)(\bar{s}\gamma^5 d) + \frac{1}{\Lambda^2_{ETC}}(\bar{\mu}\gamma^5 e)(\bar{e}\gamma^5 e) + \dots$$

$$\downarrow$$

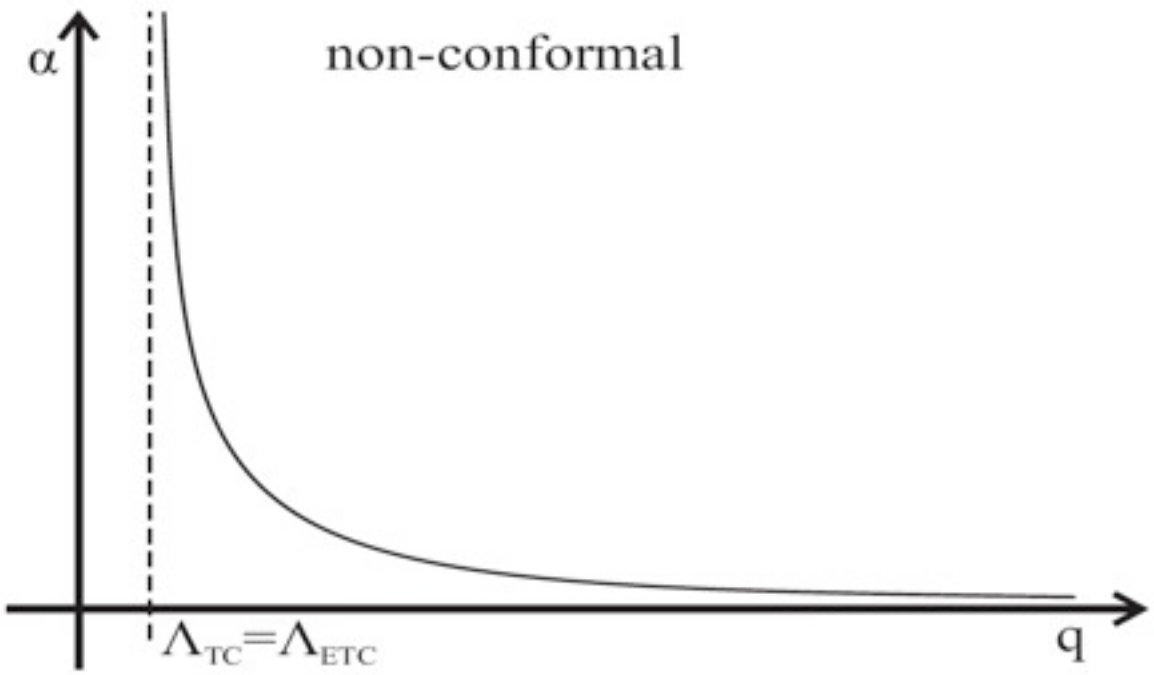
$$\Lambda_{ETC} \geq 10^3 \Lambda_{TC}$$

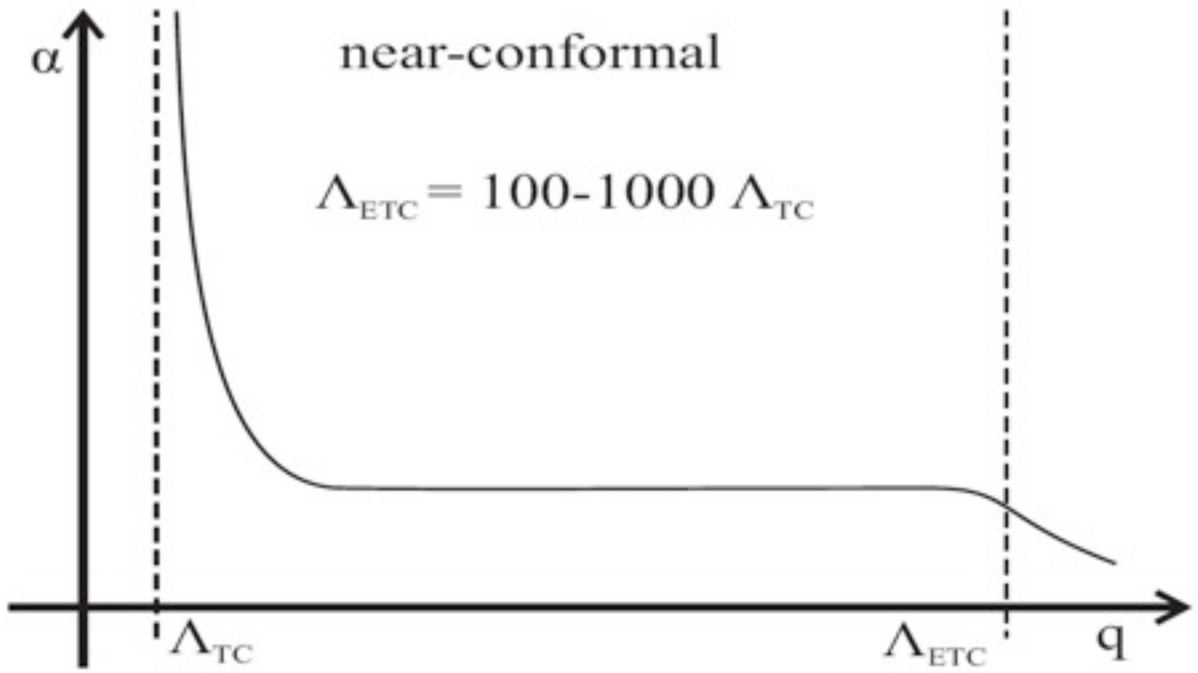
$$< \bar{Q}Q >_{ETC} \approx < \bar{Q}Q >_{TC} \sim \Lambda^3_{TC}$$

$$m_{\mathrm{f}} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC} \quad \ll \quad m_{\mathrm{Top}}$$

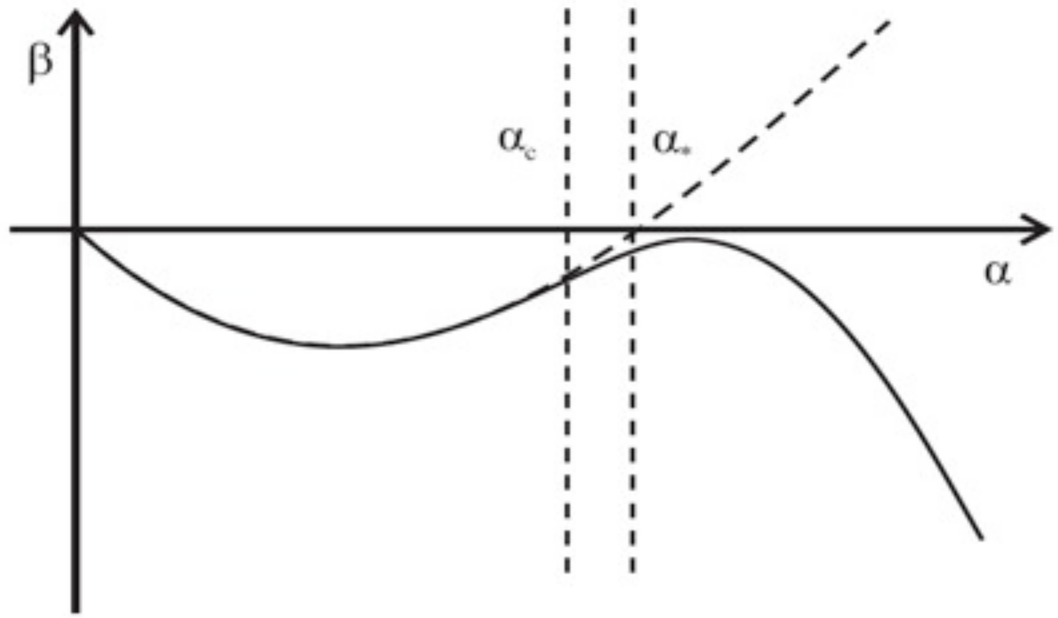
Walking versus Running

Near Conformal Properties





Appelquist, Bowick, Chivukula, Cohen, Eichten, Georgi, Hill, Holdom, Karabali, Lane, Mahanta, Miransky, Shrock, Simmons, Terning, Wijewardhana, Yamawaki



Why the walking can help ?

$$\langle \bar{Q}Q_{ETC} \rangle = \exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\, \gamma_m(\alpha(\mu)) \right) \langle \bar{Q}Q_{TC} \rangle$$

<u>QCD-Like</u>

$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\, \gamma_m(\alpha(\mu)) \right) \sim (\ln(\Lambda_{ETC}/\Lambda_{TC}))^{\gamma_m}$$

<u>Near the conformal window</u>

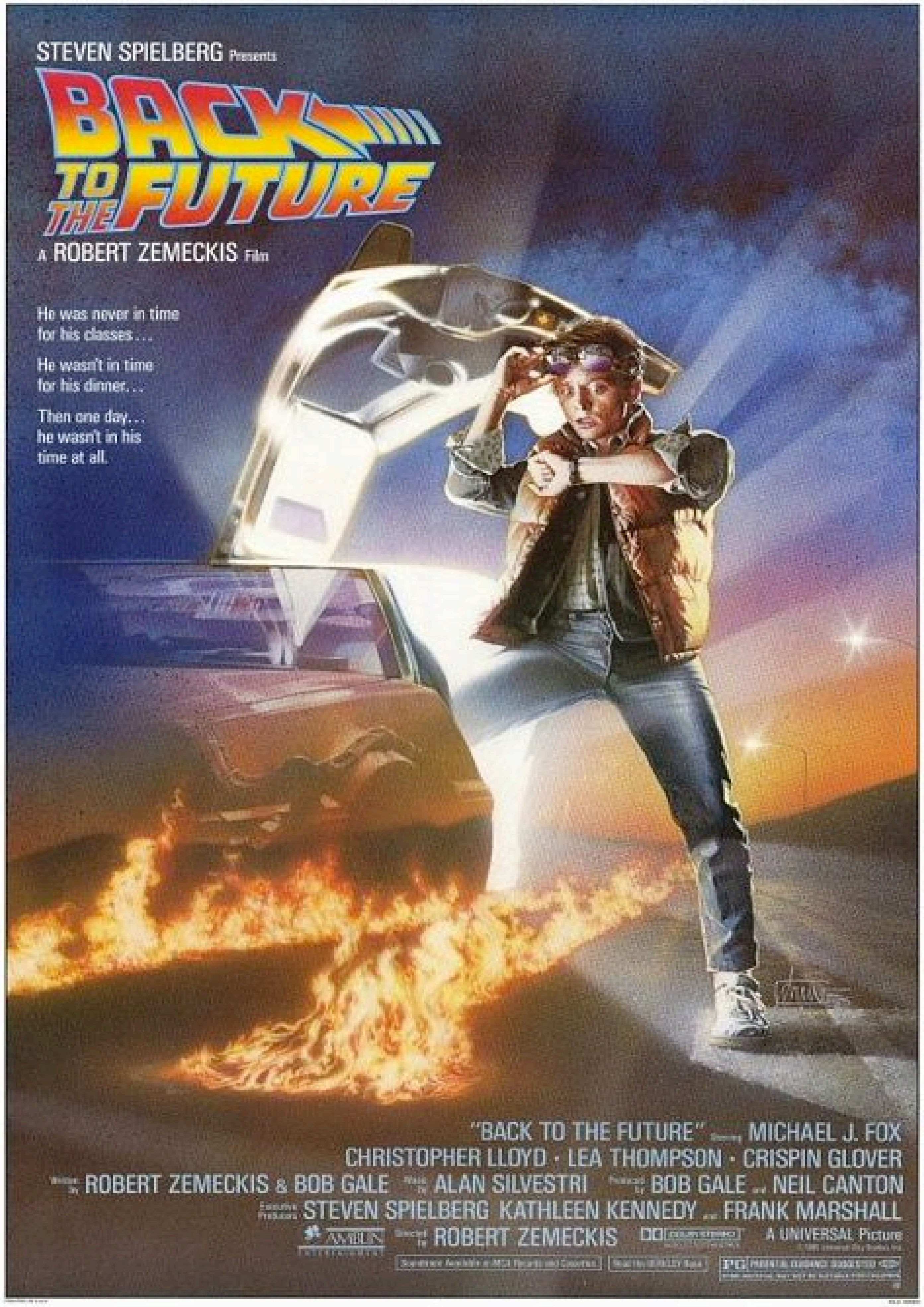
$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\, \gamma_m(\alpha(\mu)) \right) \sim (\Lambda_{ETC}/\Lambda_{TC})^{\gamma_m(\alpha^\star)}$$

Fermion Mass Enhancement

$$m_{\mathrm{f}} \approx \frac{g_{ETC}^2}{\Lambda_{ETC}^2} < \bar{Q}Q >_{ETC} = \frac{g_{ETC}^2}{\Lambda_{ETC}^2} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^{\gamma_m(\alpha^*)} < \bar{Q}Q >_{TC}$$

Recent ETC models

Appelquist, Christiansen, Shrock, Piai


STEVEN SPIELBERG Presents
BACK TO THE FUTURE
A ROBERT ZEMECKIS Film
He was never in time for his classes . . .
He wasn't in time for his dinner. . .
Then one day. . . he wasn't in his time at all.
"BACK TO THE FUTURE" MICHAEL J. FOX
CHRISTOPHER LLOYD · LEA THOMPSON · CRISPIN GLOVER
ROBERT ZEMECKIS & BOB GALE ALAN SILVESTRI BOB GALE NEIL CANTON
STEVEN SPIELBERG KATHLEEN KENNEDY FRANK MARSHALL
AMBLIN
ROBERT ZEMECKIS
A UNIVERSAL Picture
PG

S in Walking Technicolor

$$S_{WTC} < S_{TC}$$

Appelquist, F.S.
Kurachi Shrock

We will take as an estimate:

$$S_{WTC} \approx S_{\rm naive} = \frac{1}{6\pi}\frac{N_f}{2}d(R)$$

Besides

$$S = S_{(W)TC} + S_{NS}$$

Offset the first term

Rule:

Find Walking Theories with EW embedding minimizing S

Progress in Strong Dynamics I:

Analytically discovered a universal picture

Phase Diagrams for SO(N) and Sp(2N)	F.S. 09
Phase Diagrams for SU(N)	Ryttov, F.S. 07 F.S. and Tuominen 04 Dietrich, F.S. 06

Useful methods to understand Near-Conformal Dynamics

Newly Conjectured all-orders beta function	Ryttov, F.S. 07
Conformal Chiral Dynamics	F.S. 08 F.S. and R. Zwicky 08 Stephanov 07

Progress in Strong Dynamics II:

Lattice

Any Rep.

Catterall, F.S. 07

Catterall, Giedt, F.S., Schneible 08

Del Debbio, Frandsen, Panagopoulos, F.S. 08

Del Debbio, Patella, Pica. 08

Hietanen, Rantaharju, Rummukainen, Tuominen 08

DeGrand, Shamir, Svetitsky, 08

Del Debbio, Patella, Pica, 08

Fund. Rep

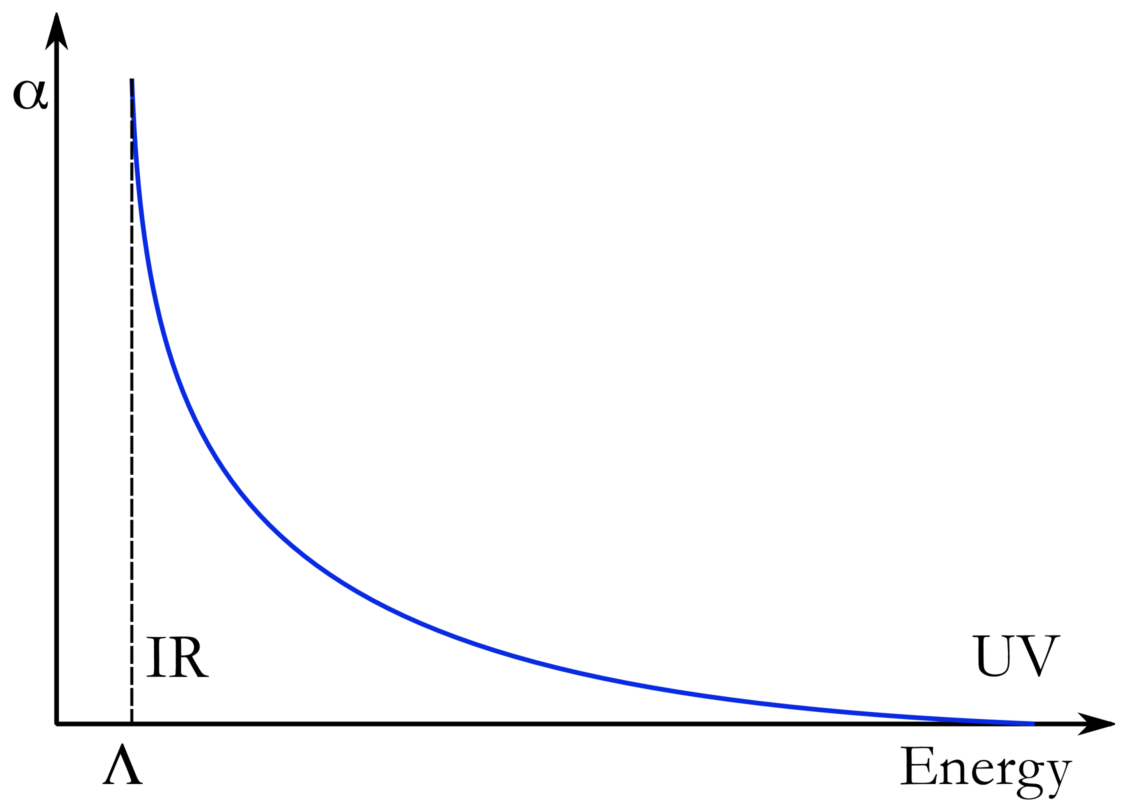
Appelquist, Fleming, Neil 07

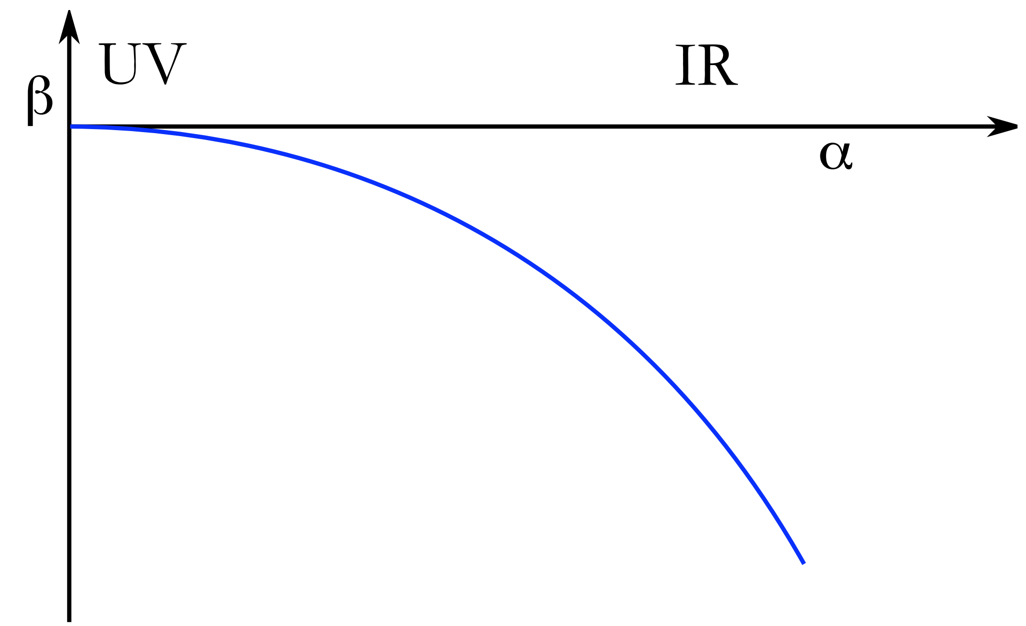
Deuzman, Lombardo, Pallante 08

Fodor, Holland, Kuti, Nogradi, Schroeder, 08

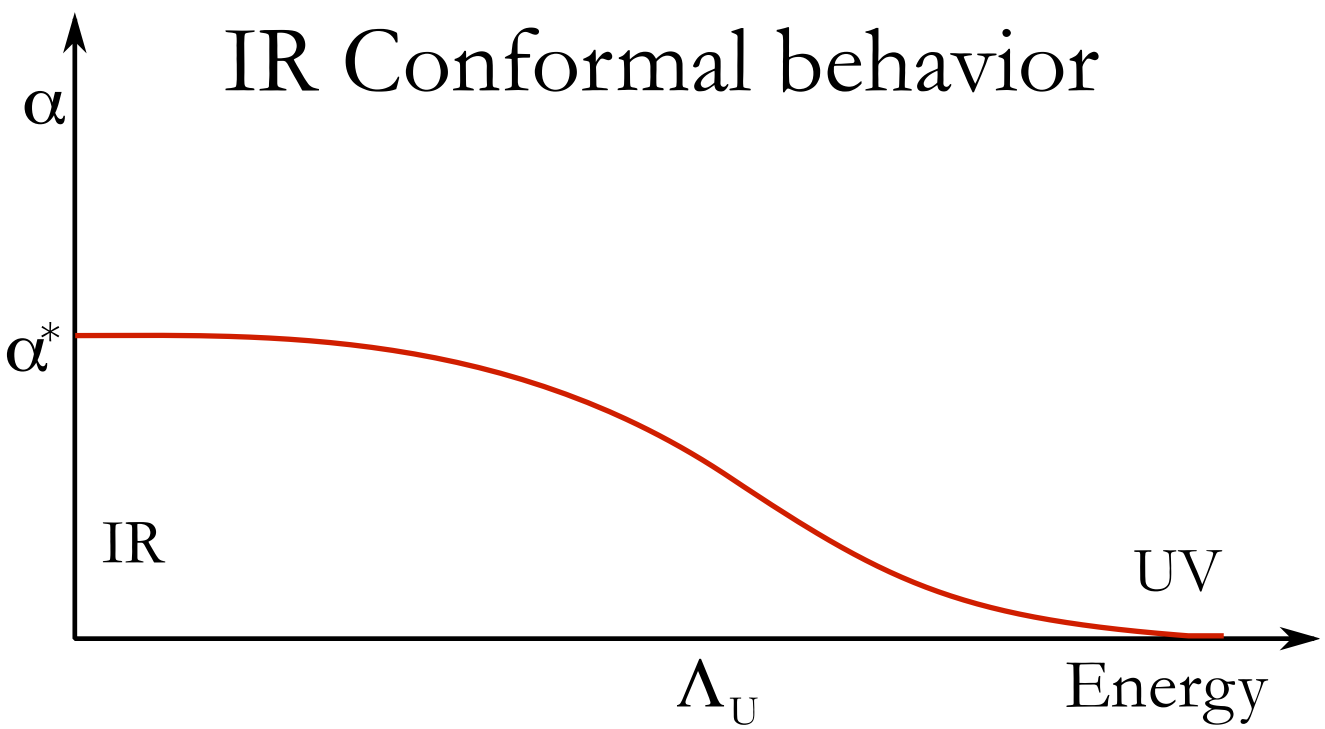
Phases of Gauge Theories

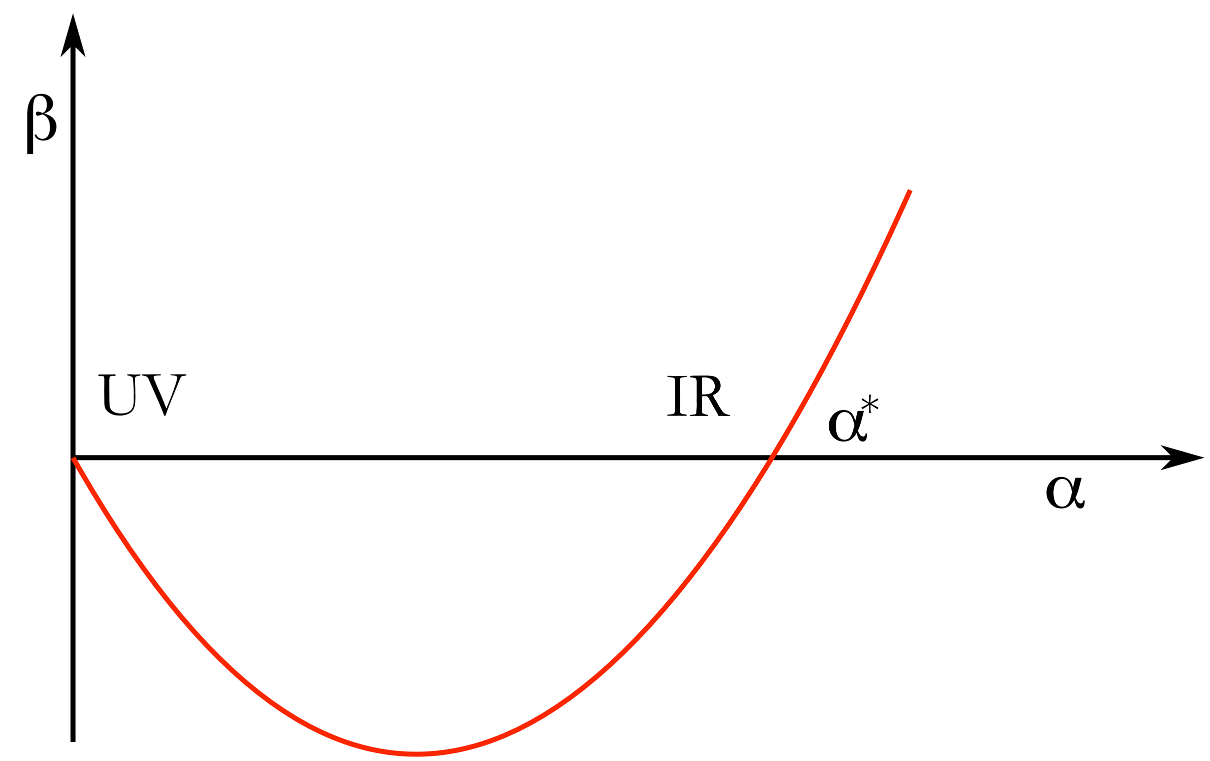
QCD-like Theory





Coulomb





IR Conformal Phase

Gauge Theory Knobs

Gauge Group, i.e. SU, SO, SP

Matter Representation

# of Flavors per Representation

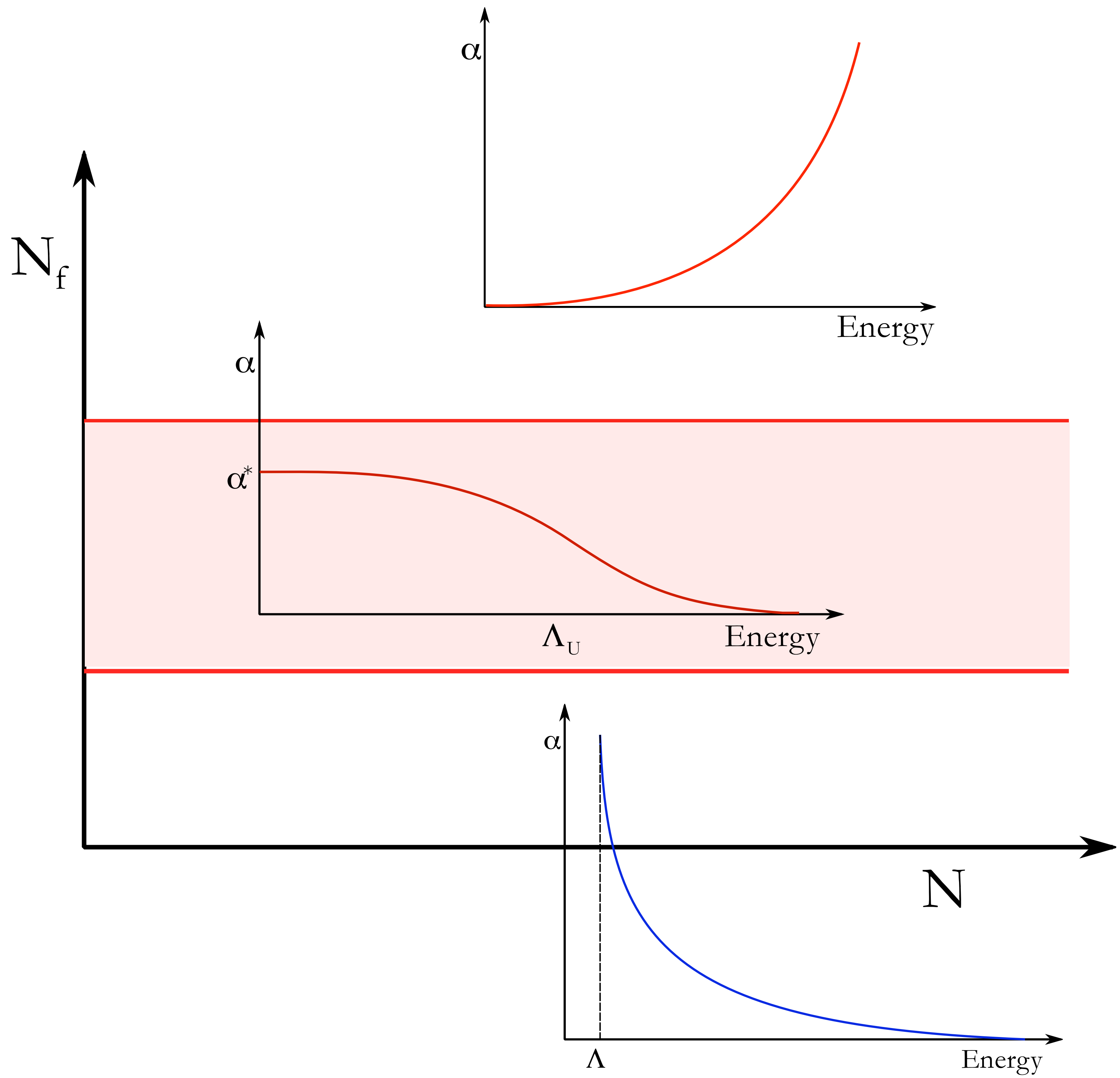
Temperature

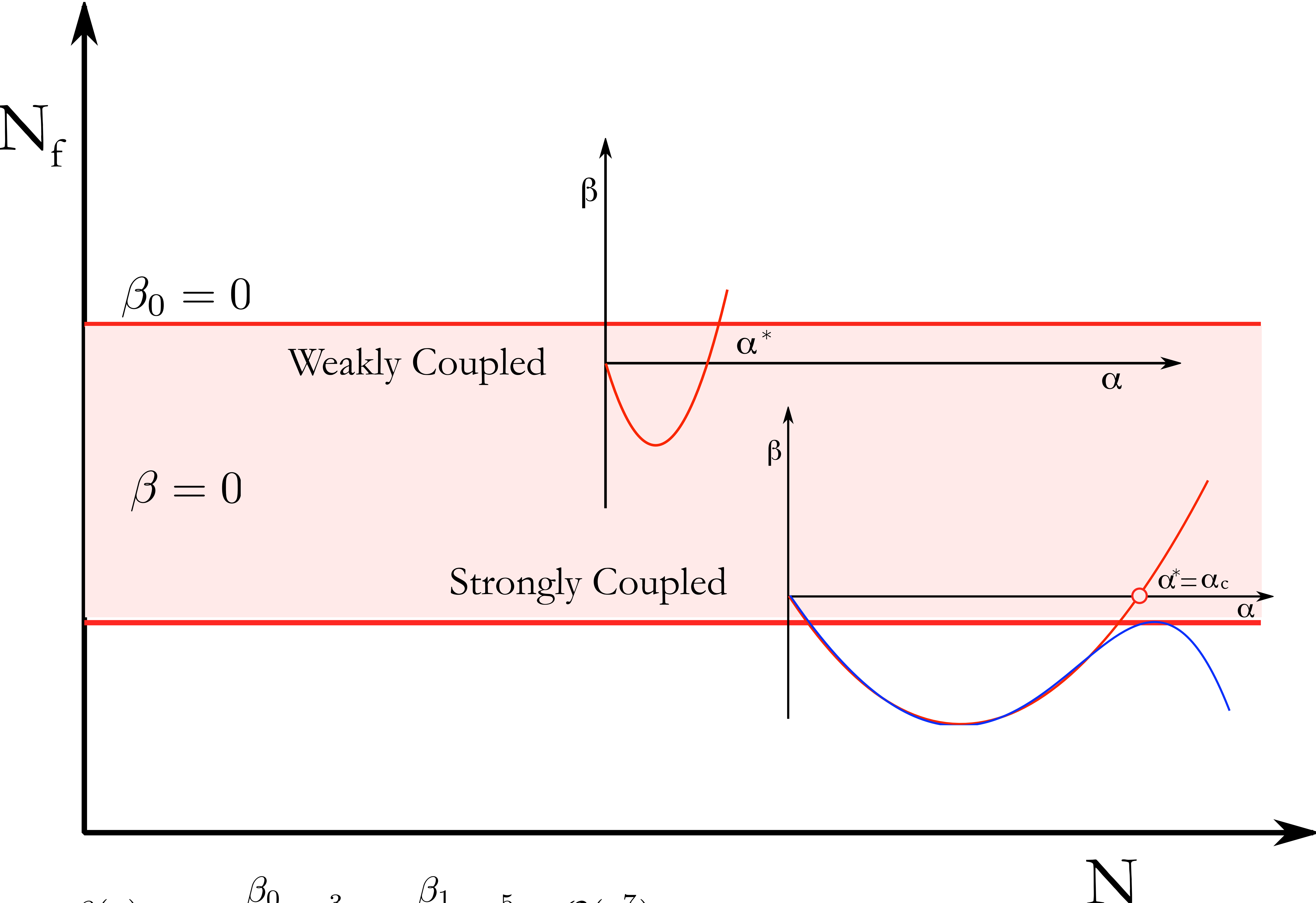
Matter Density (i.e. Chemical Potential)

Example

SU(N)

Adjoint Dirac Matter





$$\beta(g) = -\frac{\beta_0}{(4\pi)^2} g^3 - \frac{\beta_1}{(4\pi)^4} g^5 + \mathcal{O}(g^7)$$

Beta Function

Ryttov and F.S. 07

All orders beta function conjecture

$$\beta(g) = -\frac{g^3}{(4\pi)^2}\frac{\beta_0 - \frac{2}{3}T(r)N_f\gamma(g^2)}{1 - \frac{g^2}{8\pi^2}C_2(G)(1 + \frac{2\beta_0'}{\beta_0})}$$

$$\gamma = -d\ln m/d\ln\mu$$

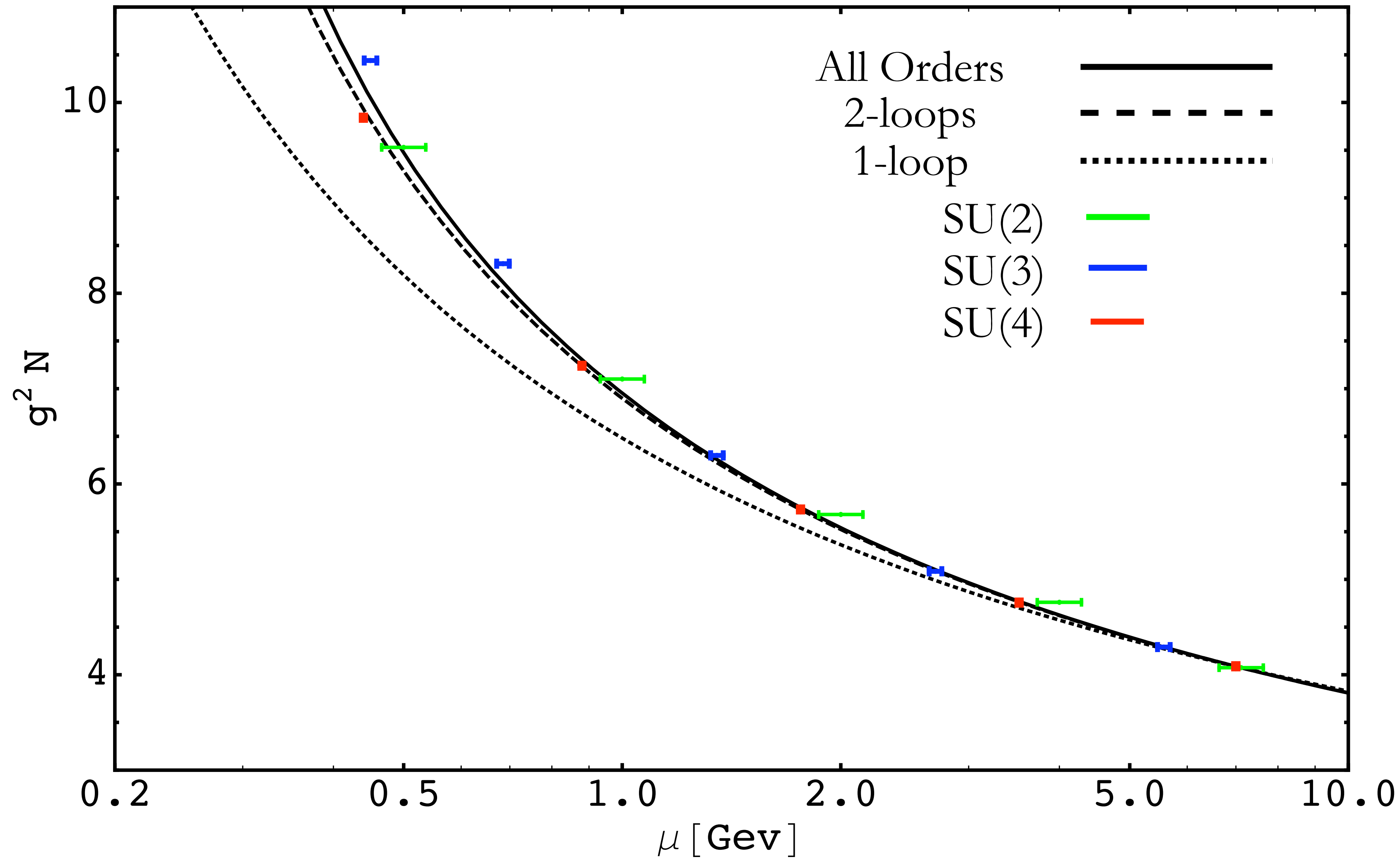
$$\gamma(g^2) = \frac{3}{2}C_2(r)\frac{g^2}{4\pi^2} + O(g^4)$$

$$\beta_0 = \frac{11}{3}C_2(G) - \frac{4}{3}T(r)N_f$$

$$\beta_0' = C_2(G) - T(r)N_f$$

Ryttov and F.S. 07

Running in Yang - Mills for different N



Luscher, Sommer, Wolff, Weisz, 92 SU(2)

Luscher, Sommer, Weisz, Wolff 94 SU(3)

Lucini and Moraitis 07 SU(4)

Bounds on the Conformal Window

$$\beta = 0 \quad \longrightarrow \quad \gamma = \frac{11C_2(G) - 4T(r)N_f}{2T(r)N_f}$$

Unitarity of the Conformal Operators demands:

$$\gamma \leq 2$$

Ryttov and F.S. 07

Back to the Example

SU(N) Adjoint Dirac Matter

$$\gamma \leq 2\,, \quad \Longrightarrow \quad N_f^c \geq \frac{11}{8}$$

$$\gamma = 1\,, \quad \Longrightarrow \quad N_f^c = \frac{11}{6} = 1.8\bar{3}$$

$$N_{f\,\mathrm{Ladder}}^c = 2.075$$

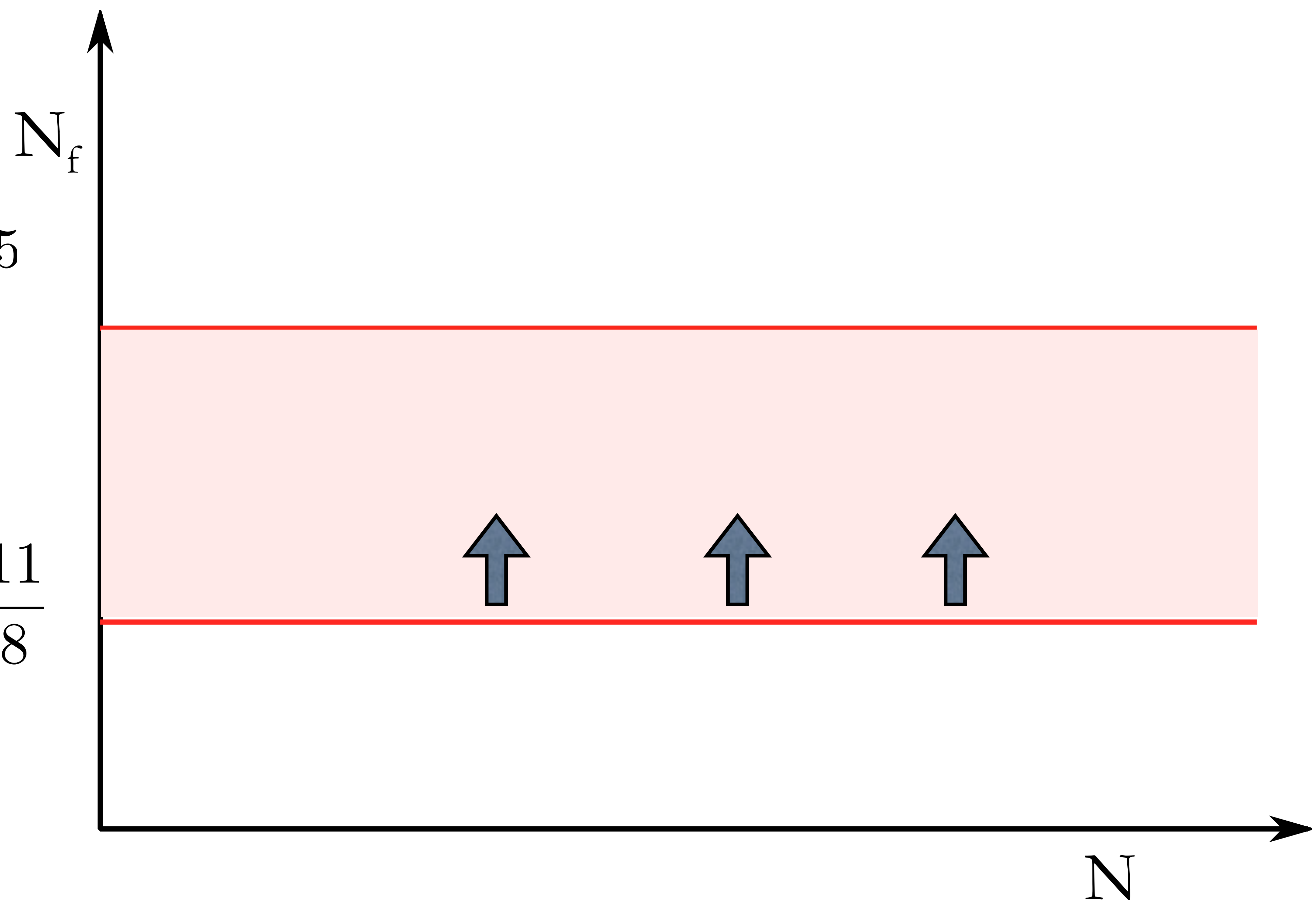
Pelasing Discovery!

Back to the Example

SU(N) Adjoint Dirac Matter

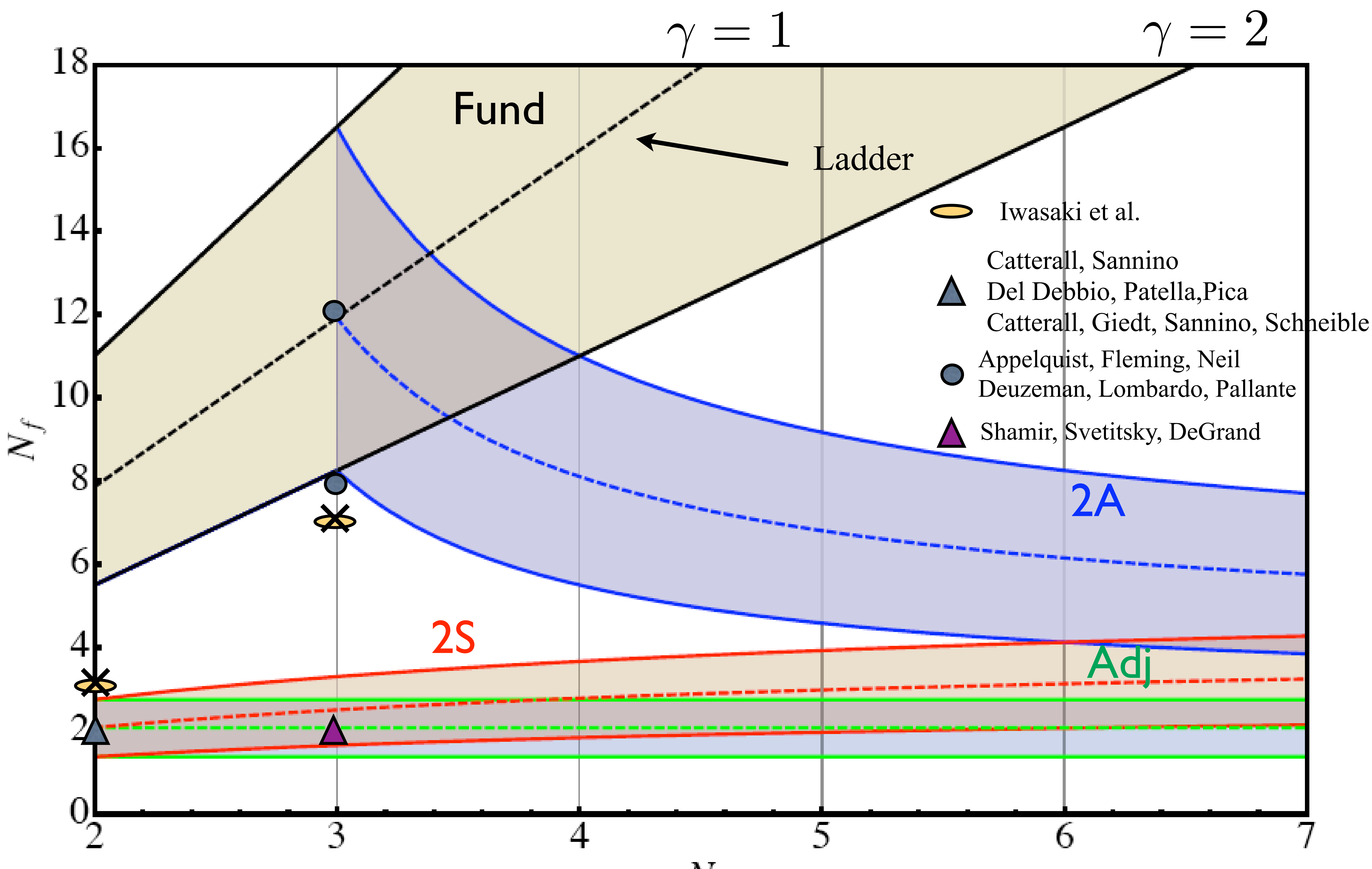
$$N_f^{\text{Asymp}} = 2.75$$

$$\gamma \leq 2 \rightarrow N_f^c \geq \frac{11}{8}$$



A Universal Picture

SU(N) Phase Diagram

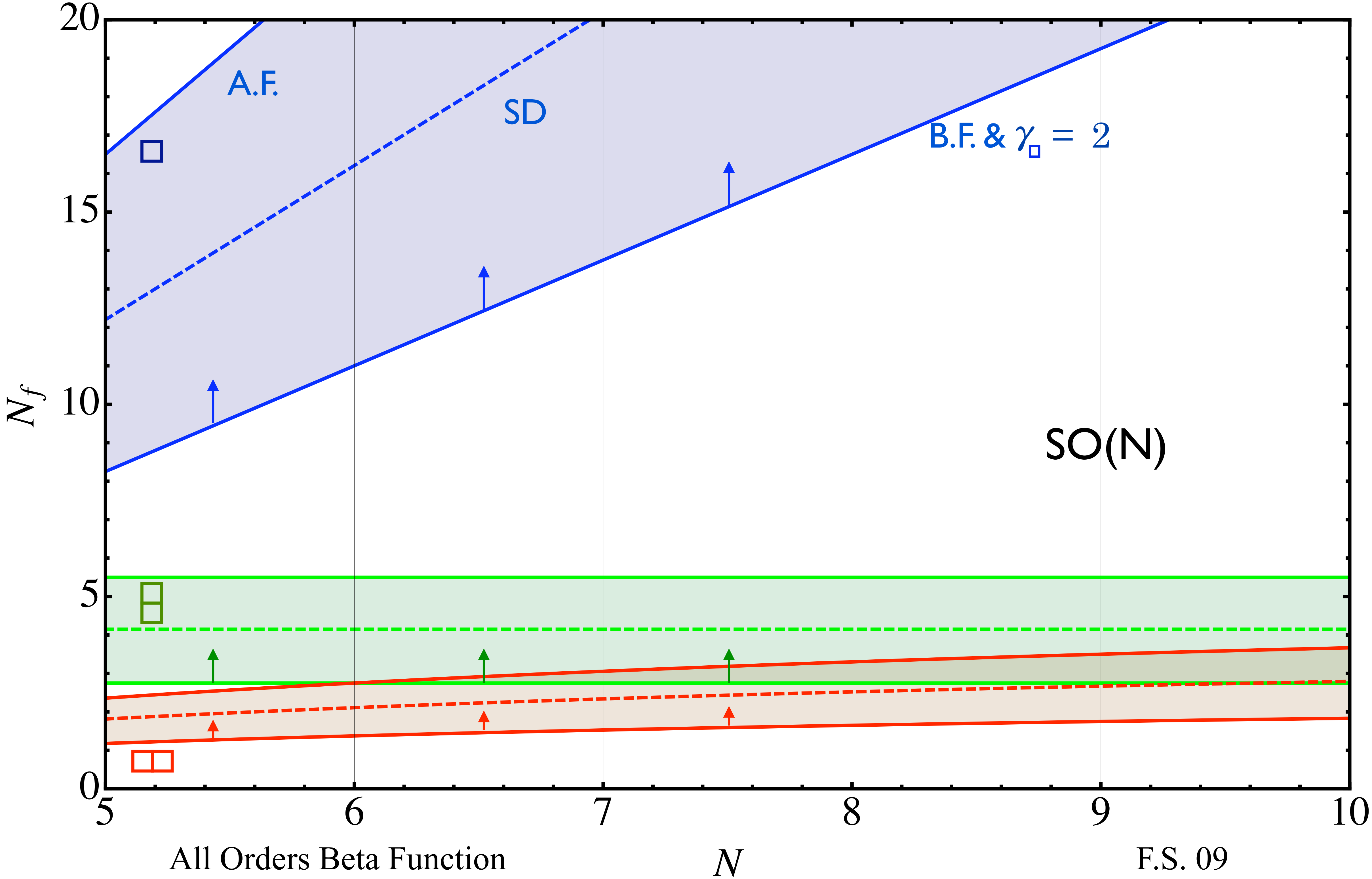


All Orders Beta Function

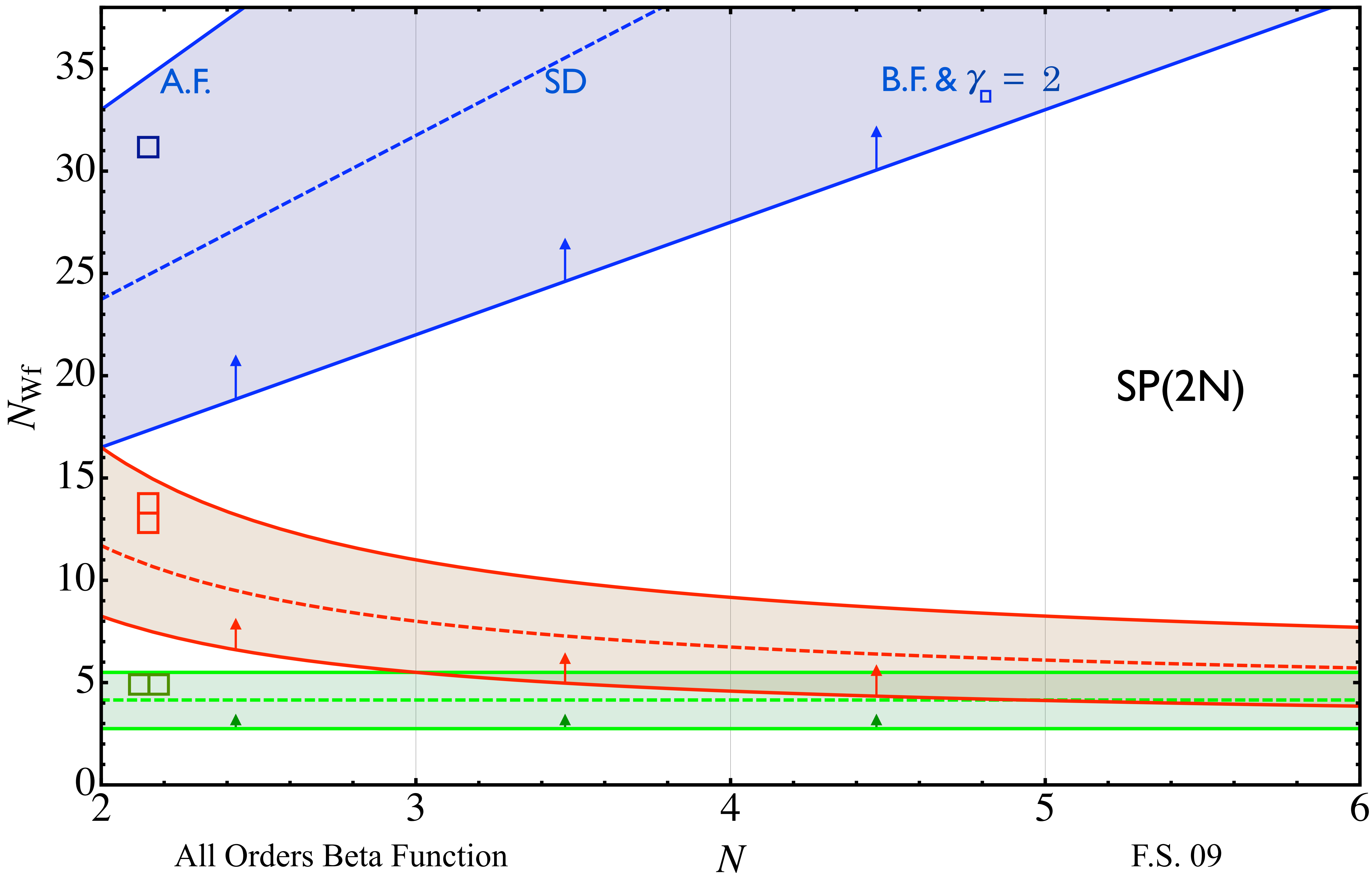
Ryttov and F.S. 07

Be Imaginative!

SO(N) Phase Diagram



Sp(2N) Phase Diagram



Sensible Models of DEWSB

Identified Many EW Viable Walking and Custodial TC Models

Minimal Walking Technicolor (MWT)

F.S. - Tuominen 04
Dietrich - F.S. - Tuominen 05
Dietrich - F.S. 06

Higher Dimensional Representations

Ultra Minimal Walking Technicolor (UMT)

Ryttov, F.S. 08

Beyond Minimal Walking Technicolor

Partially EW Gauged Technicolor

F.S. - Tuominen 04
Dietrich - F.S. - Tuominen 05
Dietrich - F.S. 06

Split Technicolor

Additional Fermions in SM

Ryttov, F.S. 06

Custodial TC

Appelquist, F.S. 98
Foadi, Frandsen, F.S. 07

Similar to BESS models of Casalbuoni et al.

Dark Matter

$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$

Ω_B

To the presence of a U(1) baryon number approx. conserved.

We observe a B - Anti B asymmetry.

If the asymmetry is generated above the EW scale the conservation of B - L by the EW interaction allows B to survive the EW phase transition.

The point above does not imply B - L conserved at energies higher than the EW scale.

What if DM is due to an asymmetry?

A particle similar to the nucleon

But electrically neutral

At most EW-type cross sections

Great if connected to the Electroweak Symmetry Breaking sector of the SM

Technicolor is a natural example (**TIMP**)

Technibarion is similar to the nucleon

TB number like the B number

At most EW-type cross sections

EW scale and interactions built in

Ultra Minimal Technicolor is the first physical realization
Ryttov - F.S. 08

PAMELA/ATIC Decaying Dark Matter + Unification,
Nardi, F.S., Strumia, 08.

Nussinov, 86
Barr - Chivukula - Farhi 90
Sarkar 96
Gudnason - Kouvaris - F.S. 06

Within Technicolor

TIMP can be a Boson or a Fermion

Can be (or not) neutral w.r.t. Weak Interactions

Ultra Minimal Technicolor

TIMP is a pseudo Goldstone-boson

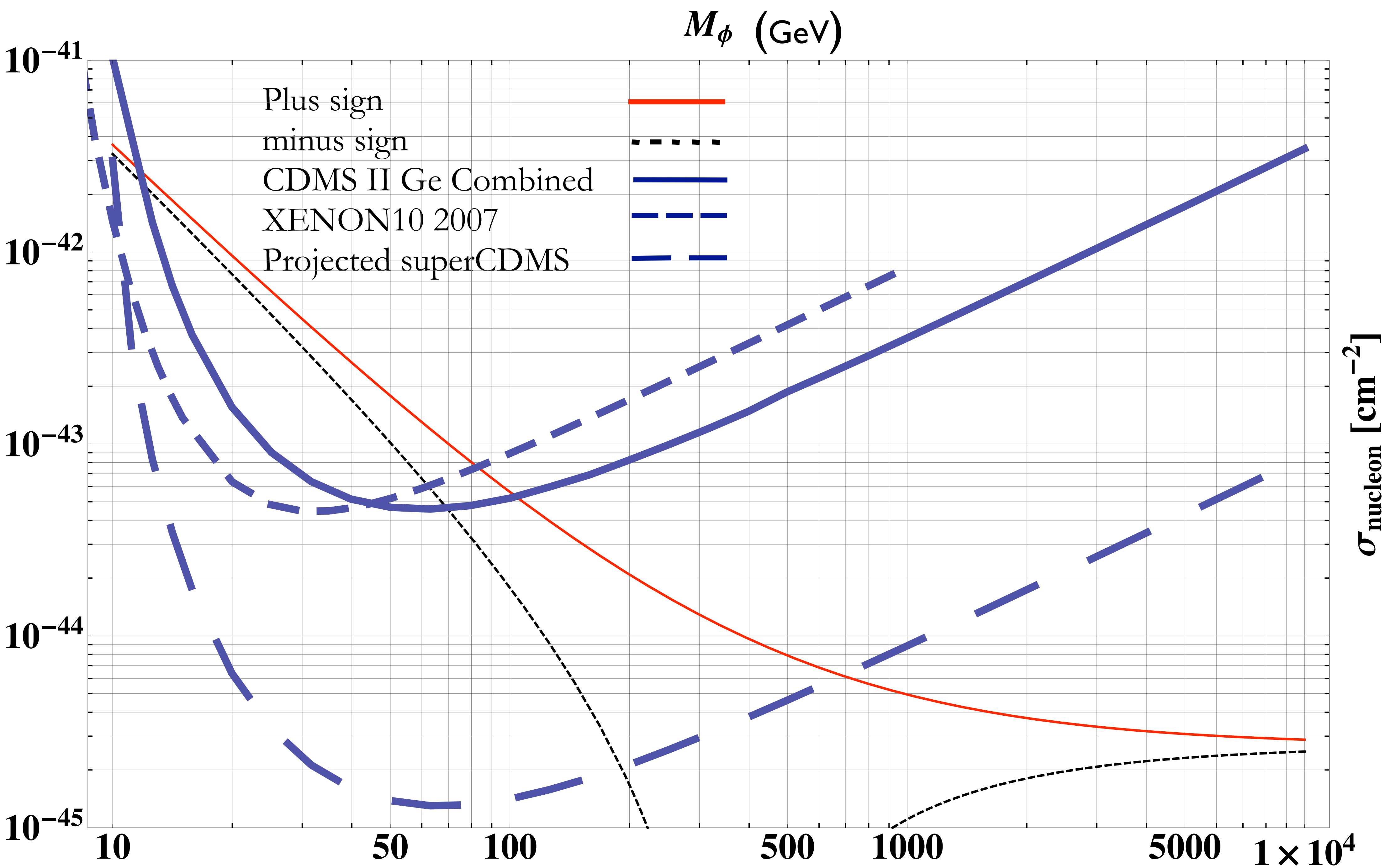
Ryttov - F.S. 08

Composite Unparticle + TC

F.S. - Zwicky 08

Unbaryon (To investigate)

Earth Based Constraints



$d_M = 1$

$d_B = \pm 1$

$\Lambda = 3\ TeV$

$M_H = 300$ GeV

Foadi, Frandsen, F.S. 08

$$\sigma_{\mathrm{nucleon}} = \frac{\mu^2}{4\pi}\left[\frac{Z}{A}\frac{8\pi\,\alpha\,d_B}{\Lambda^2} + \frac{d_M\, f m_N}{M_H^2 M_\phi}\right]^2$$

$$\mu = M_\phi m_N/(M_\phi + m_N)$$

Asymmetric DM Relic Density

$$\frac{m_{TB}}{m_p} \approx \frac{1 \text{ TeV}}{1 \text{ GeV}} = 10^3$$

$$\frac{TB}{B} \propto \exp\left[-\frac{m_{TB}(T^*)}{T^*}\right] \sim 10^{-3} \qquad T^* \sim 200 \text{ GeV}$$

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{TB}{B}\frac{m_{TB}}{m_p} \sim \mathcal{O}(1)$$

Conditions

Universe Electric Neutrality

Chemical Equilibrium

EW Sphaleron Processes, Kuzmin-Rubakov-Shaposhnikov

TB - B violated at High Energies & approx. conserved at EW

(Extra) EW Phase Transitions

Baryogenesis

Cline, Jarvinen, F.S. 08

Jarvinen, Ryttov, F.S. 09

Minimal Walking Technicolor

F.S. and Tuominen 04

Dietrich, F.S. Tuominen 06

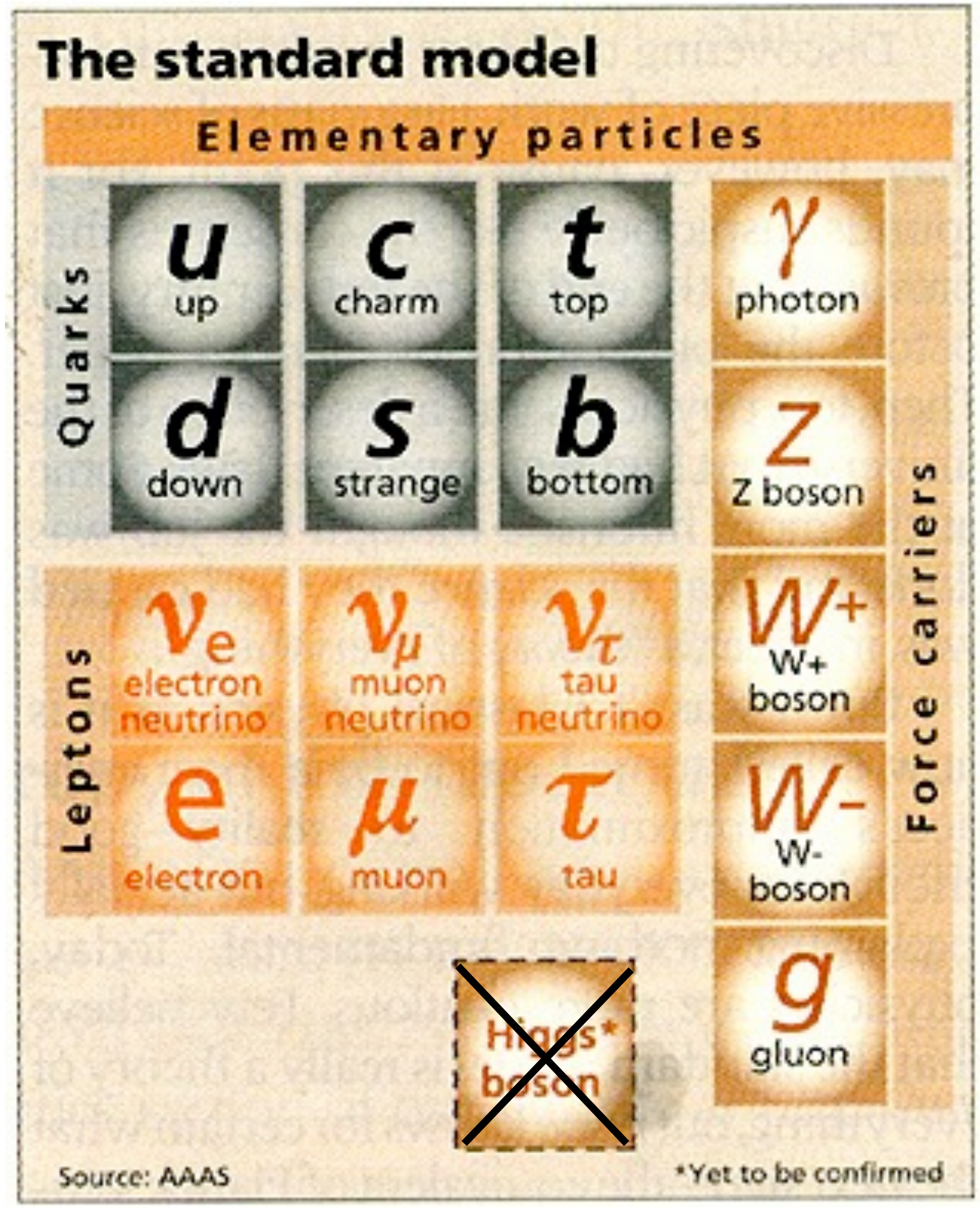
Gudnason, Kouvaris, F.S. 06

Gudnason, Ryttov, F.S. 06

Foadi, Frandsen, Ryttov, F.S. 07

Cline, Jarvinen, F.S. 08

Belyaev, Foadi, Frandsen, Jarvinen, Pukhov, F.S. 08



U(1)

SU(2)

SU(3)

N
Extra Neutrino

E
Extra Electron

U
t-up

G
t-glue

D
t-down

SU(2)

U and D: Adj of SU(2)

MWT Features

The most economical WT theory

Compatible with precision measurements

Possible DM candidates and nice Unification

Can support 1st order Electroweak Phase Transition

Can support exotic electric charges

Lattice studies have begun

MWT effective lagrangian

$$\mathcal{L}(\text{Composites}) + \mathcal{L}(\text{Mixing with SM}) + \mathcal{L}(\text{New Leptons}) + \mathcal{L}(\text{SM} - \text{Higgs})$$

Appelquist, F.S. 99

R. Foadi, M. T. Frandsen, Ryttov, F.S. 07

LHC - Signals

Drell-Yan production of heavy vectors

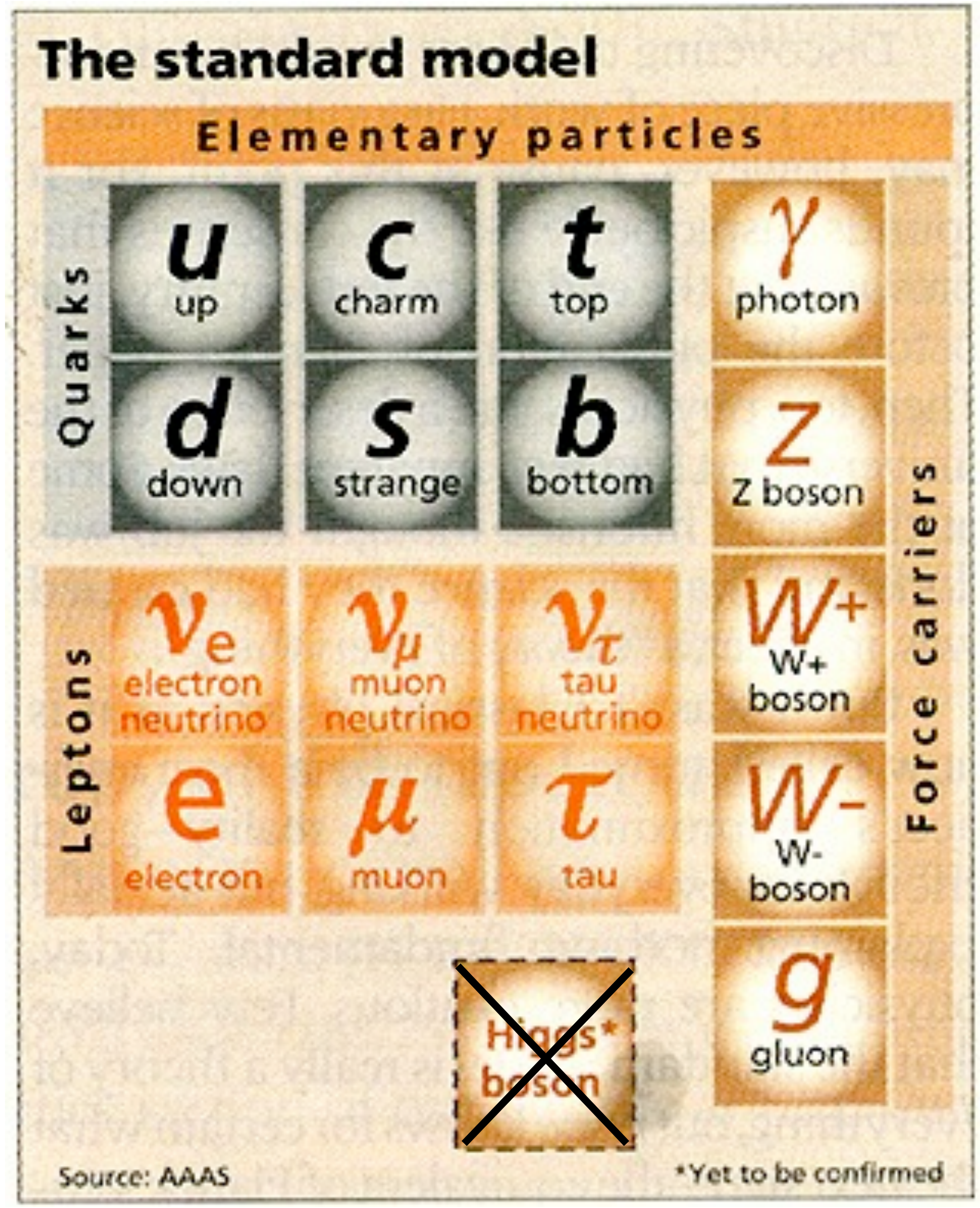
Vector Boson Fusion production of heavy vectors

Can be seen via HW and HZ production

A. Belyaev, R. Foadi, M. T. Frandsen,
M. O. Jarvinen, A. Pukhov, F.S. 08

Ultra Minimal Walking Technicolor

Ryttov and F.S. 08



U(1)

SU(2)

SU(3)

U
t-up

G
t-glue

D
t-down

$\lambda^1 \quad \lambda^2$
t-lambda

SU(2)

U and D: Fund of SU(2)

t-lambdas: Adj of SU(2)
Singlet of SM
Weyl Fermions

UMT Features

The most economical “2 rep” WT theory

Smallest naive S-parameter & # of fermions

Asymmetric DM candidate visible at the LHC

Extra Electroweak PT (very exciting)

Rich unexplored Collider Phenomenology

Summary

- DEWSB is very much alive
- DEWSB Cosmology is exciting
- 4D Non-SUSY CFT