Phases of Gauge Theories

Francesco Sannino

CP^3 - Origins

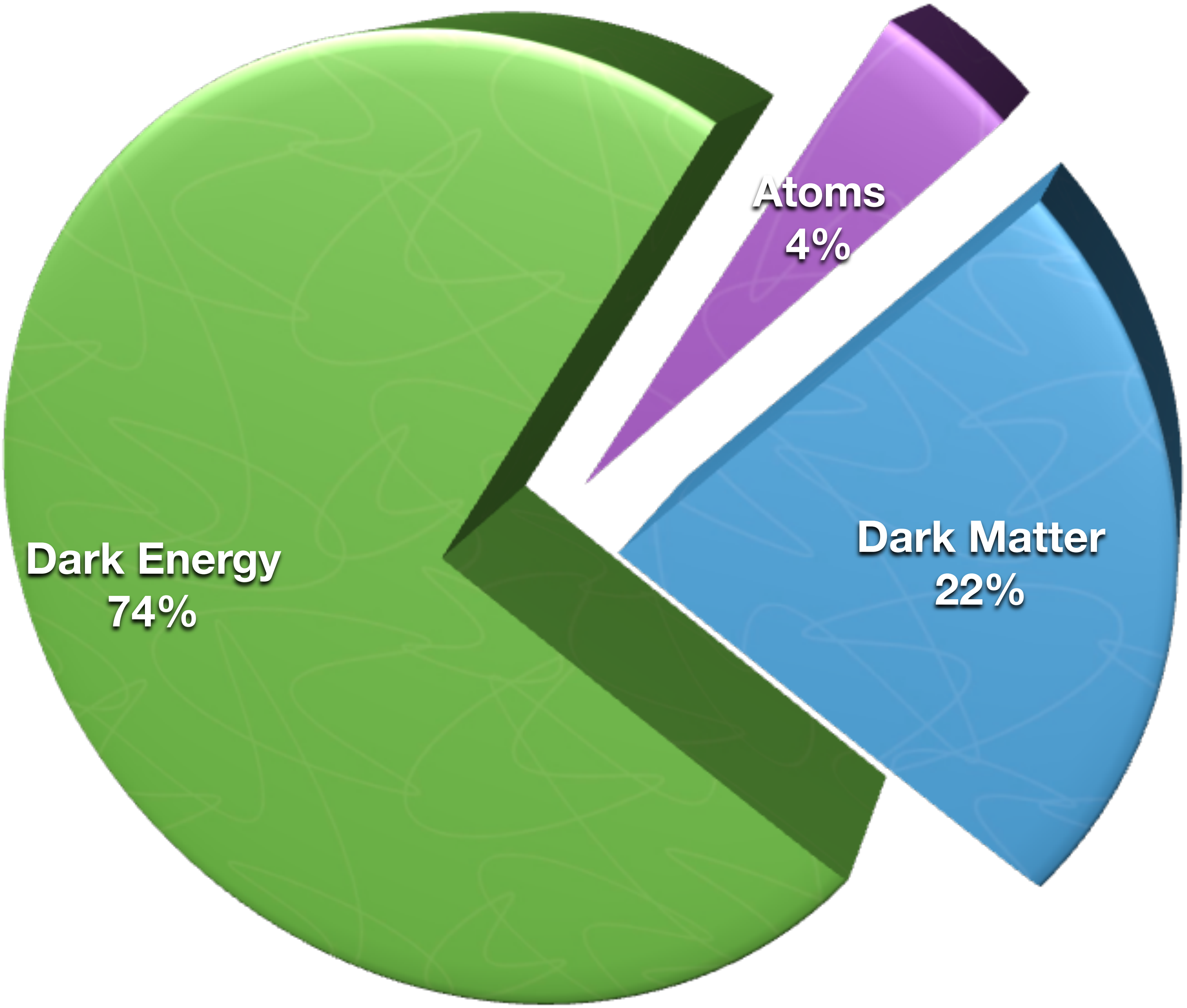
Particle Physics & Origin of Mass

July 2010 @ Quark Matter - Roma


U

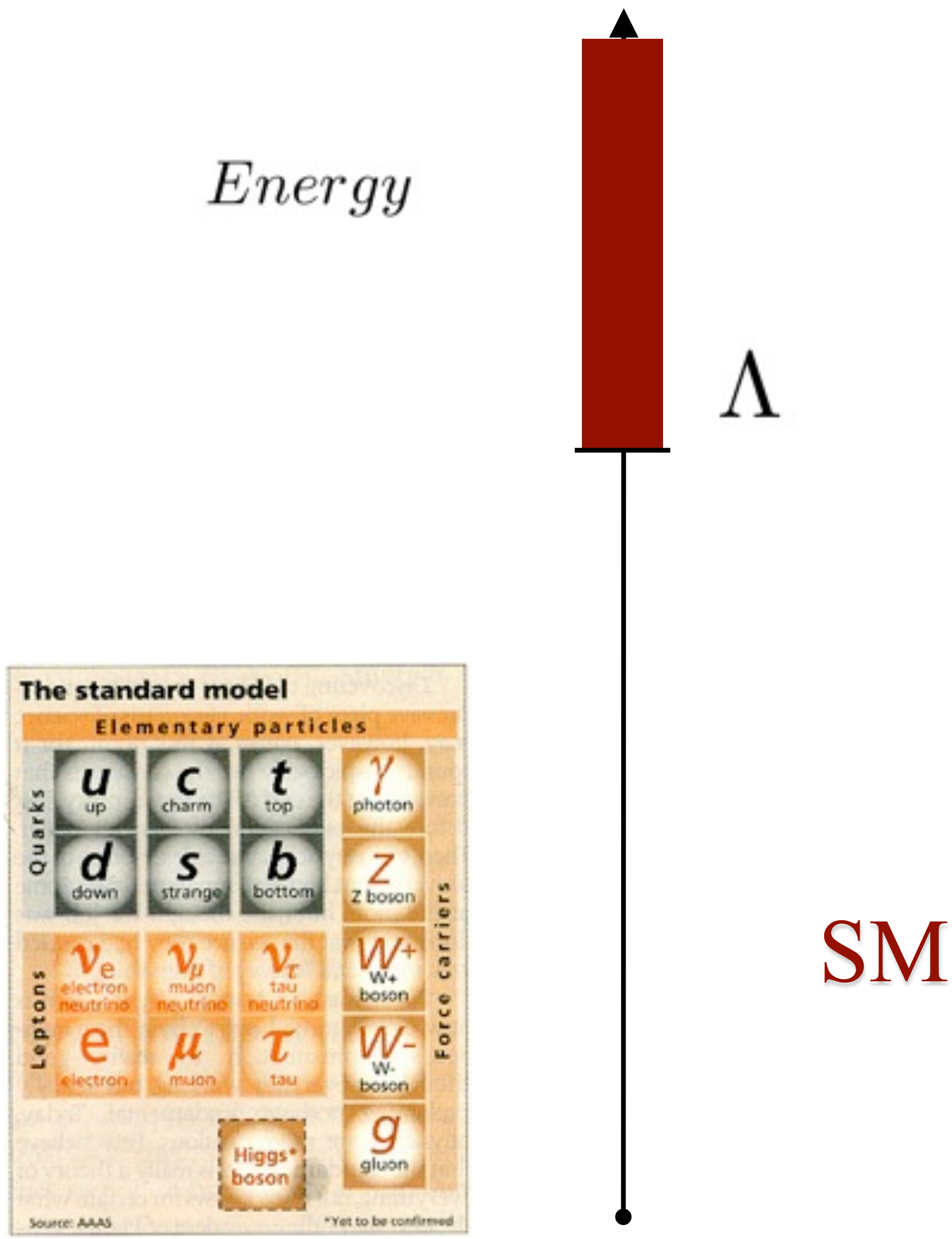
Cosmology

Cosmology



Standard Model

Standard Model



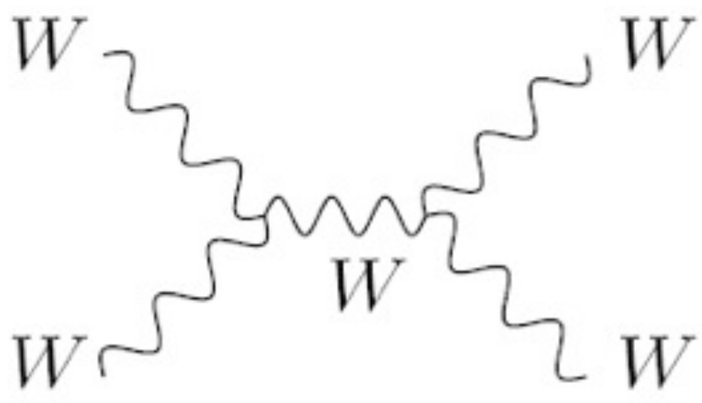
CP3 - Origins

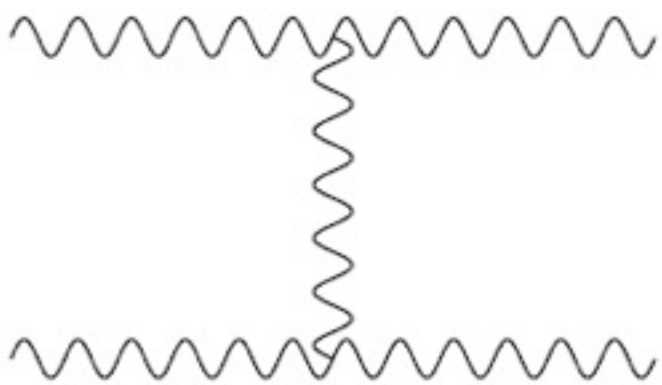
Particle Physics & Origin of Mass

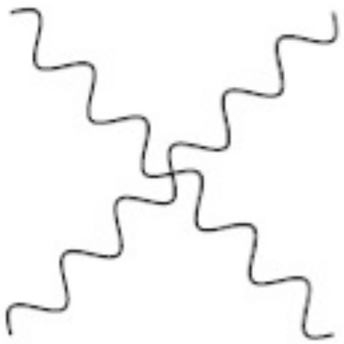
WW Scattering

CP3 - Origins
Particle Physics & Origin of Mass

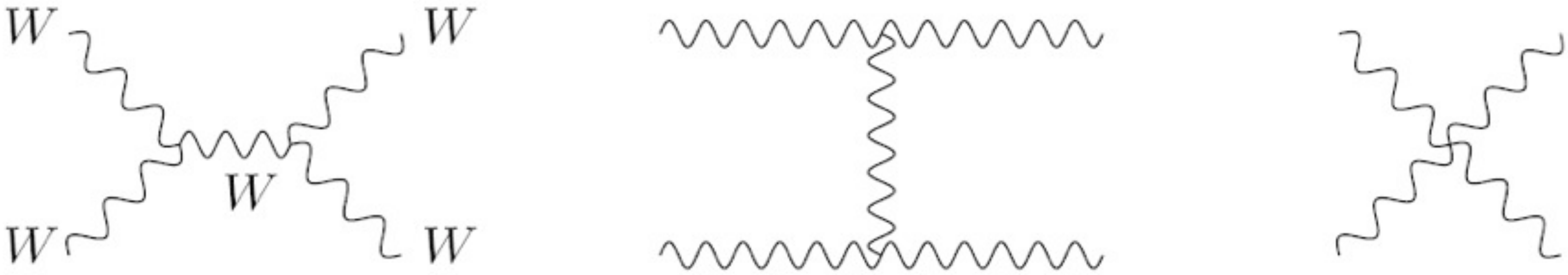
WW Scattering







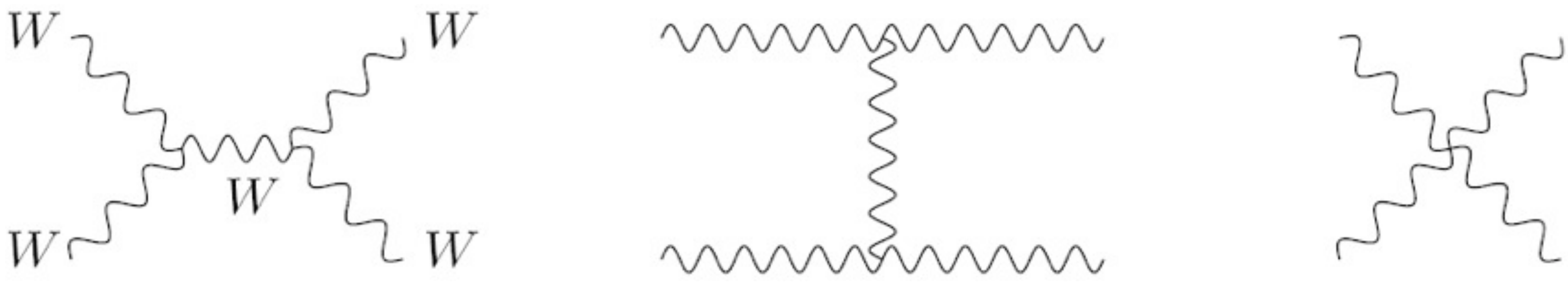
WW Scattering



S-wave amplitude:

$$A_0 = \frac{G_F}{8\pi\sqrt{2}}\ s$$

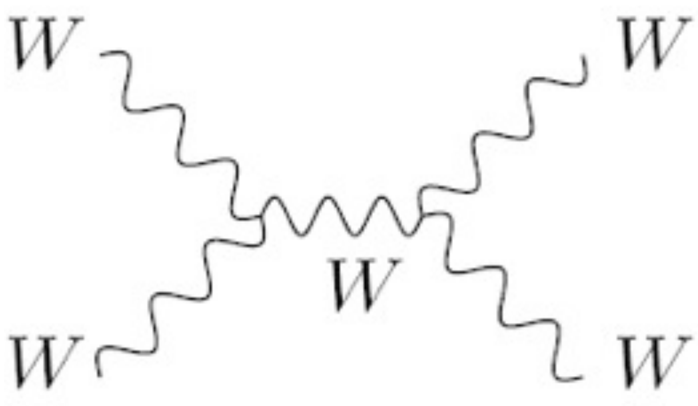
WW Scattering

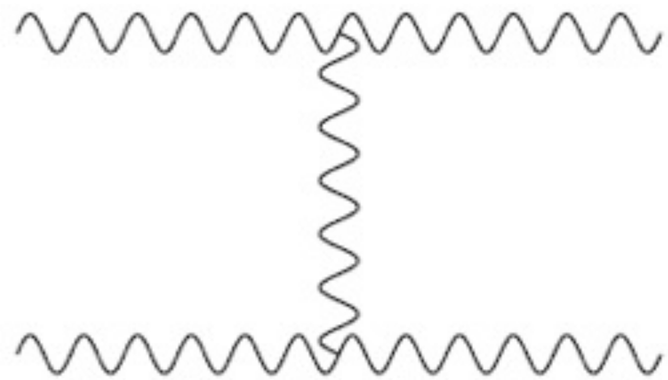


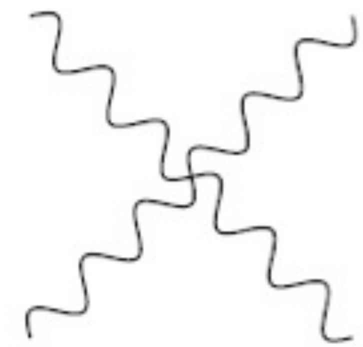
S-wave amplitude:

$$A_0 = \frac{G_F}{8\pi\sqrt{2}} s$$

WW Scattering





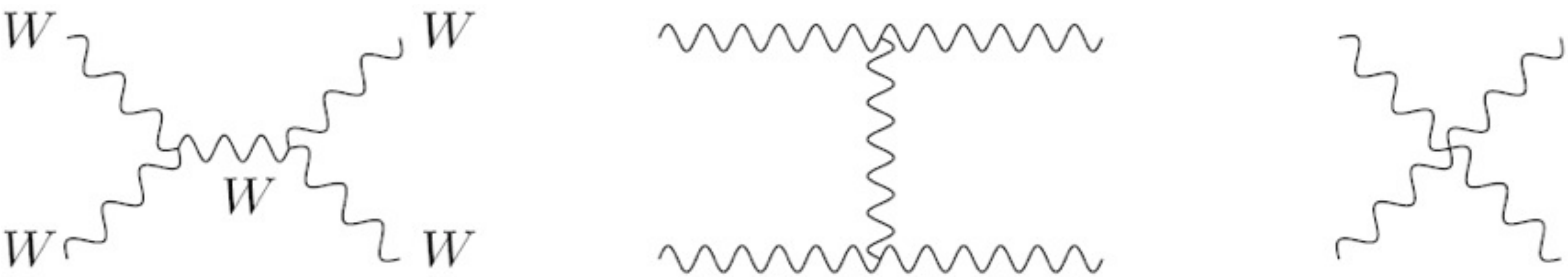


S-wave amplitude:

$$A_0 = \frac{G_F}{8\pi\sqrt{2}} s \qquad G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

$$\simeq 1.14 \times 10^{-5} \mathrm{GeV}^{-2}$$

WW Scattering



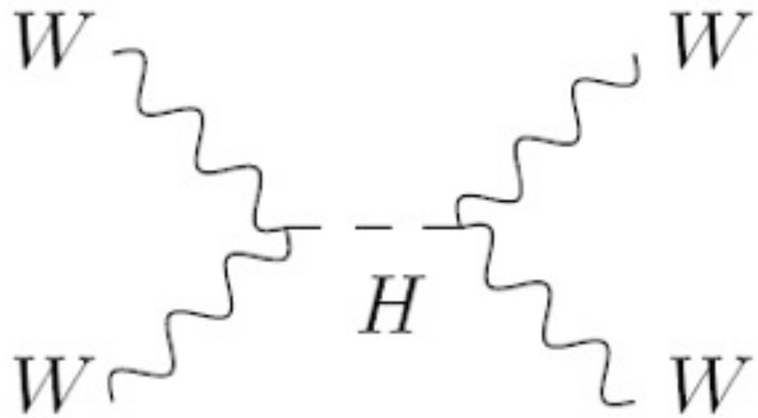
S-wave amplitude:

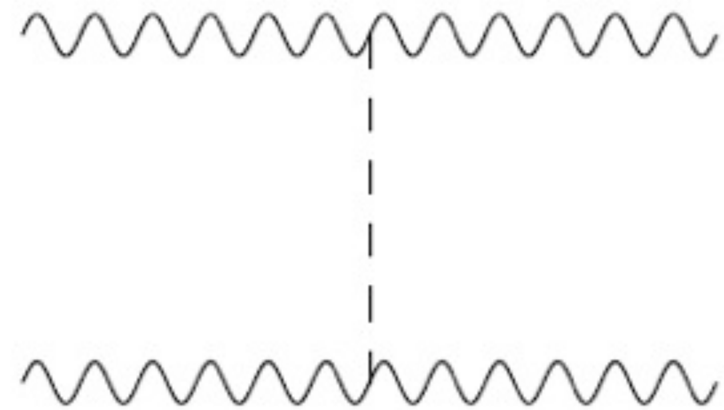
$$A_0 = \frac{G_F}{8\pi\sqrt{2}} s \qquad G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

$$\simeq 1.14 \times 10^{-5}\mathrm{GeV}^{-2}$$

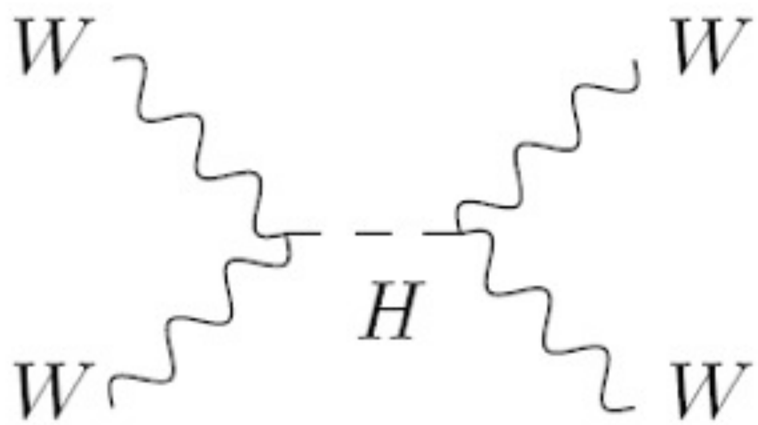
Unitarity:

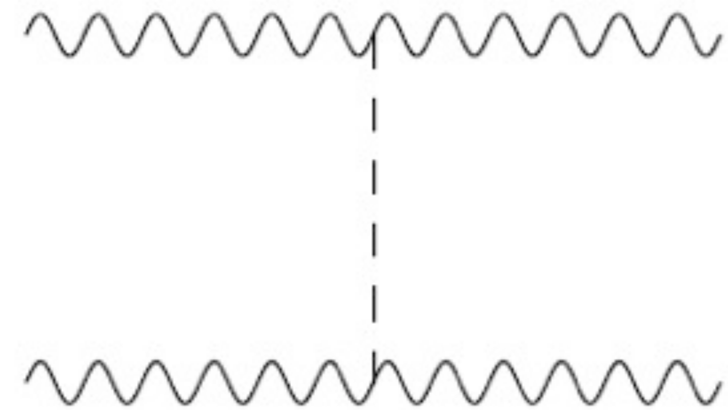
$$\Re\left[A_0\right] \leq \frac{1}{2} \longrightarrow s \leq 4\pi\sqrt{2}/G_F \sim (1.2\ \mathrm{TeV})^2$$





$$A_0' = -\frac{G_F}{8\pi\sqrt{2}}\ s$$





$$A_0' = -\frac{G_F}{8\pi\sqrt{2}}\ s$$

Theorem:

Unitarity requires the existence of a weakly coupled Higgs particle or New Physics around the Terascale!

Origin of mass

The Higgs

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi_2 + i\,\pi_1 \\ \sigma - i\,\pi_3 \end{pmatrix}$$

CP3 - Origins

Particle Physics & Origin of Mass

Custodial symmetries

Custodial symmetries

$$[i\,\tau_2 H^*\ ,\ H] = \frac{1}{\sqrt{2}}\,(\sigma + i\,\vec{\tau}\cdot\vec{\pi}) \equiv M$$

Custodial symmetries

$$\left[i\,\tau_2 H^* \ , \ H \right] = \frac{1}{\sqrt{2}} \left(\sigma + i\, \vec{\tau} \cdot \vec{\pi} \right) \equiv M$$

$$SU_L(2) \times SU_R(2)$$

CP3 - Origins
Particle Physics & Origin of Mass

Custodial symmetries

$$[i\,\tau_2 H^*\ ,\ H] = \frac{1}{\sqrt{2}}\,(\sigma + i\,\vec{\tau}\cdot\vec{\pi}) \equiv M$$

$$SU_L(2) \times SU_R(2)$$

$$g_{L/R} \in SU_{L/R}(2) \qquad\qquad M \to g_L M g_R^\dagger$$

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] - \frac{m^2}{2}\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda}{4}\,\mathrm{Tr}\left[M^\dagger M\right]^2$$

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] - \boxed{\frac{m^2}{2}\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda}{4}\mathrm{Tr}\left[M^\dagger M\right]^2}$$

↕

$$SU_L(2) \times SU_R(2)$$

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] - \frac{m^2}{2}\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda}{4}\mathrm{Tr}\left[M^\dagger M\right]^2$$

$$SU_L(2) \times U_Y(1)$$

$$SU_L(2) \times SU_R(2)$$

$$\mathcal{L} \;=\; \frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] - \frac{m^2}{2}\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda}{4}\mathrm{Tr}\left[M^\dagger M\right]^2$$

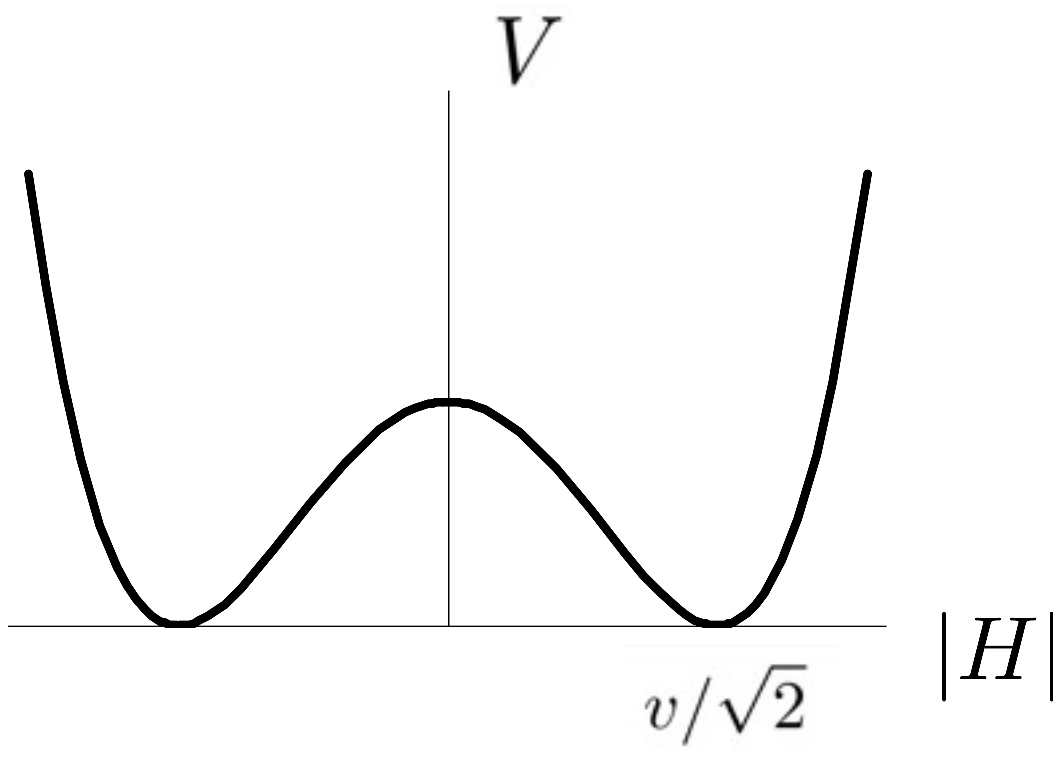
$$SU_L(2)\times U_Y(1) \qquad\qquad SU_L(2)\times SU_R(2)$$

$$D_\mu M = \partial_\mu M - i\,g\,W_\mu M + i\,g' M\,B_\mu$$

$$W_\mu = W_\mu^a \frac{\tau^a}{2}\,, \qquad B_\mu = B_\mu \frac{\tau^3}{2}$$

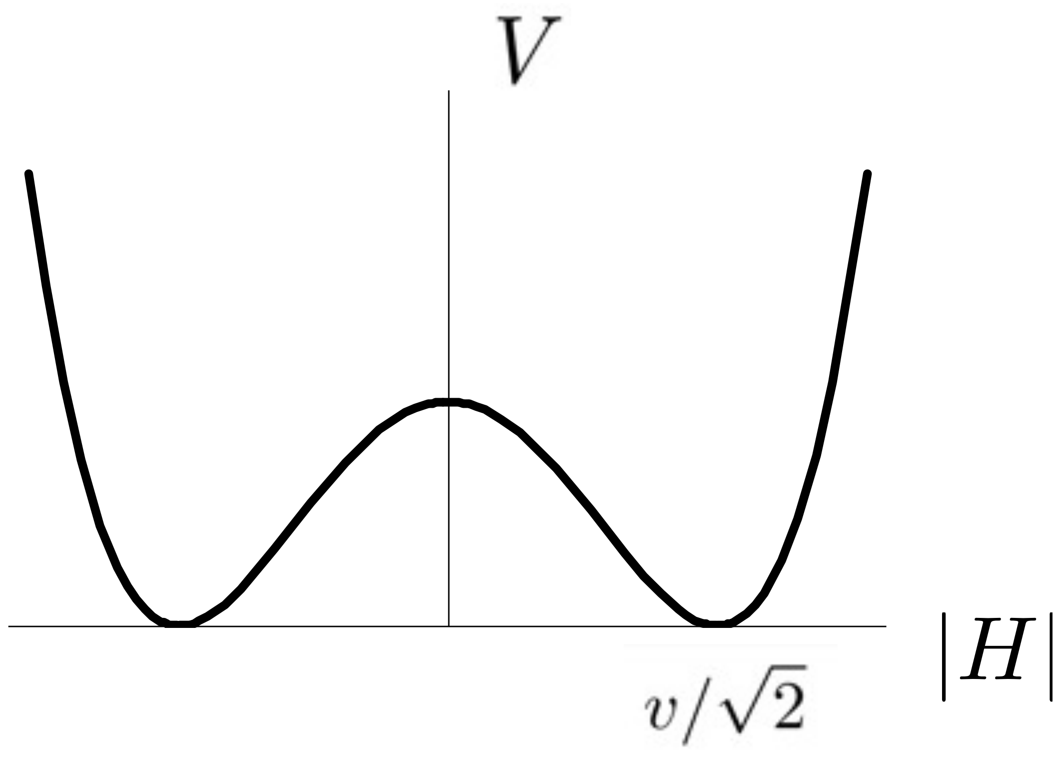
$$m^2 < 0$$

$$m^2 < 0$$



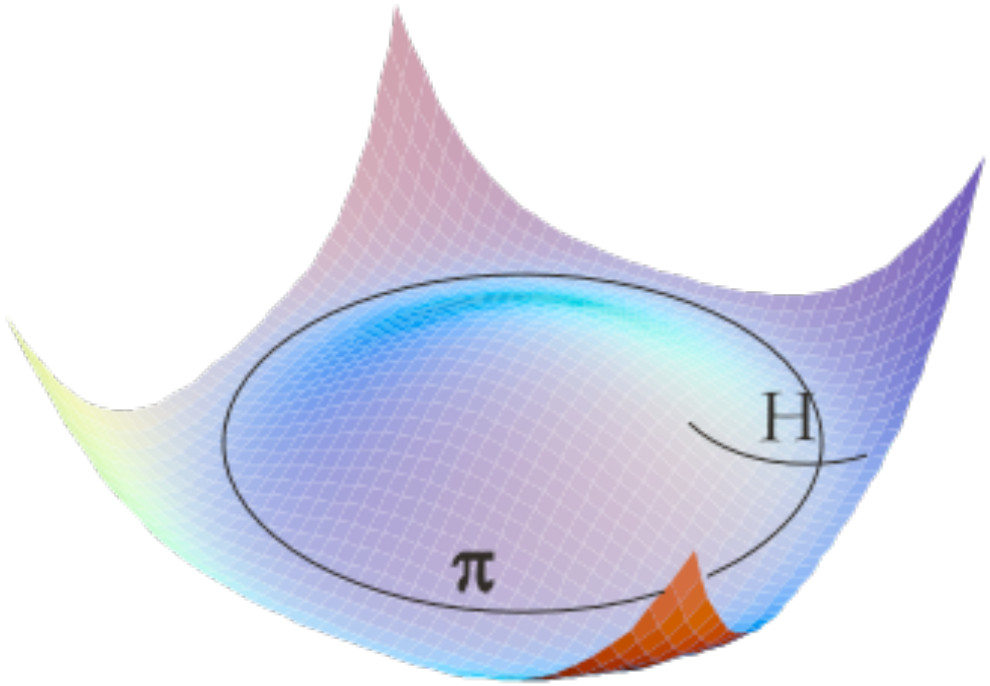
$$\langle \sigma^2 \rangle \equiv v^2 = \frac{|m^2|}{\lambda}$$

$$m^2 < 0$$



$$\langle \sigma^2 \rangle \equiv v^2 = \frac{|m^2|}{\lambda}$$

$$\sigma = v + h$$



Gauge Boson-Masses

$$\frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right]$$

Gauge Boson-Masses

$$\frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] \longrightarrow M_W = gv/2 = M_z \cos\theta_w$$

Gauge Boson-Masses

$$\frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] \longrightarrow M_W = gv/2 = M_z \cos\theta_w$$

$\updownarrow$

$$SU_L(2) \times SU_R(2) \rightarrow SU_V(2)$$

Gauge Boson-Masses

$$\frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] \longrightarrow M_W = gv/2 = M_z \cos\theta_w$$

$\updownarrow$

$$SU_L(2) \times SU_R(2) \to SU_V(2)$$

$$e = g\, sin\theta_w \qquad \cos\theta_w = g/\sqrt{g^2 + g'^2}$$

Gauge Boson-Masses

$$\frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] \longrightarrow M_W = gv/2 = M_z \cos\theta_w$$

$$\updownarrow$$

$$SU_L(2) \times SU_R(2) \rightarrow SU_V(2)$$

$$e = g\, sin\theta_w \qquad \cos\theta_w = g/\sqrt{g^2 + g'^2}$$

Quark-Masses

$$-\lambda_d\, \bar{Q}_L \cdot H d_R$$

Gauge Boson-Masses

$$\frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] \longrightarrow M_W = gv/2 = M_z\,\cos\theta_w$$

$$\updownarrow$$

$$SU_L(2) \times SU_R(2) \to SU_V(2)$$

$$e = g\,sin\theta_w \qquad \cos\theta_w = g/\sqrt{g^2 + g'^2}$$

Quark-Masses

$$-\lambda_d\,\bar{Q}_L \cdot H d_R \longrightarrow m_d = \lambda_d\,v/\sqrt{2}$$

Gauge Boson-Masses

$$\frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] \longrightarrow M_W = gv/2 = M_z \cos\theta_w$$

$$\updownarrow$$

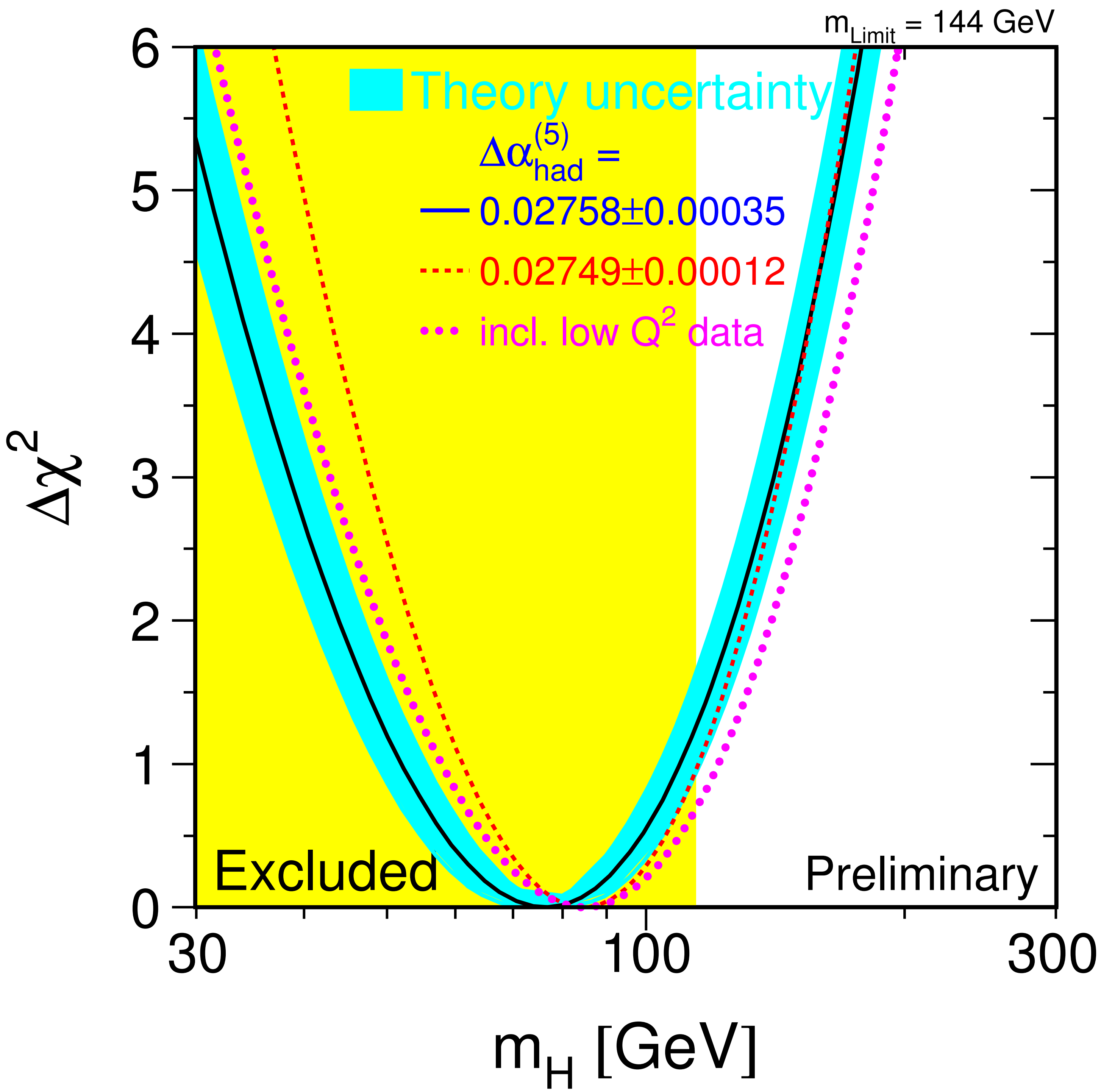
$$SU_L(2) \times SU_R(2) \rightarrow SU_V(2)$$

$$e = g\, sin\theta_w \qquad \cos\theta_w = g/\sqrt{g^2 + g'^2}$$

Quark-Masses

$$-\lambda_d\, \bar{Q}_L \cdot H d_R \longrightarrow m_d = \lambda_d\, v/\sqrt{2}$$

SM Higgs: Current Status:

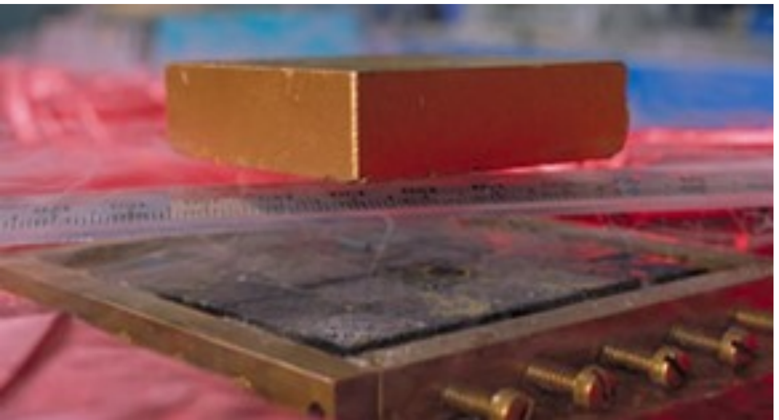


Search for the Higgs Particle

Status as of March 2009

Higgs mechanism in Nature

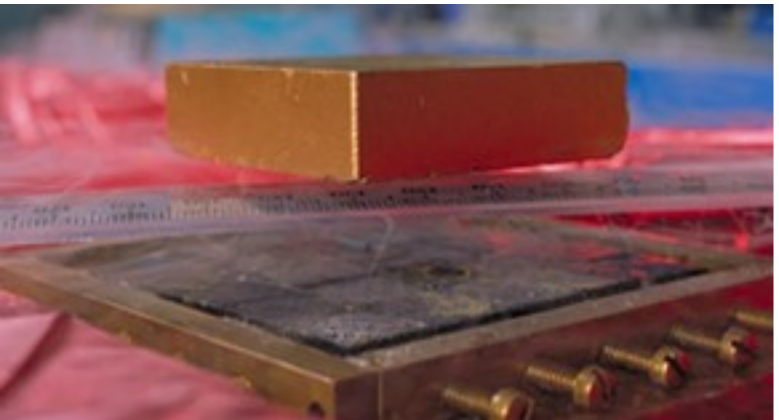
Superconductivity



Superconductivity

Macroscopic-Screening
Non-Relativistic

SM-Screening
Relativistic

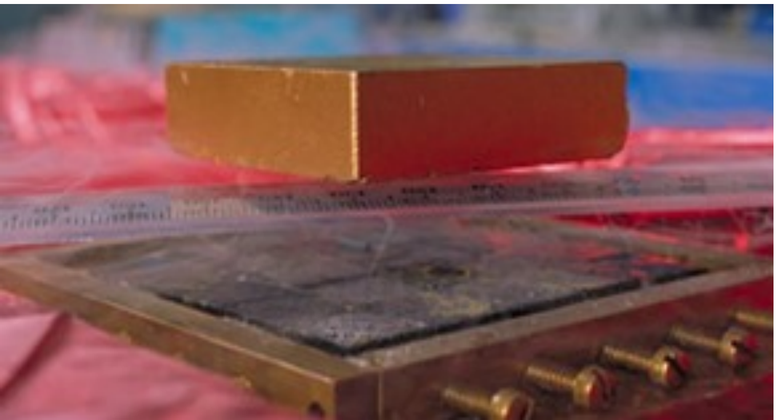


Superconductivity

Macroscopic-Screening
Non-Relativistic

SM-Screening
Relativistic

$$T < T_c$$



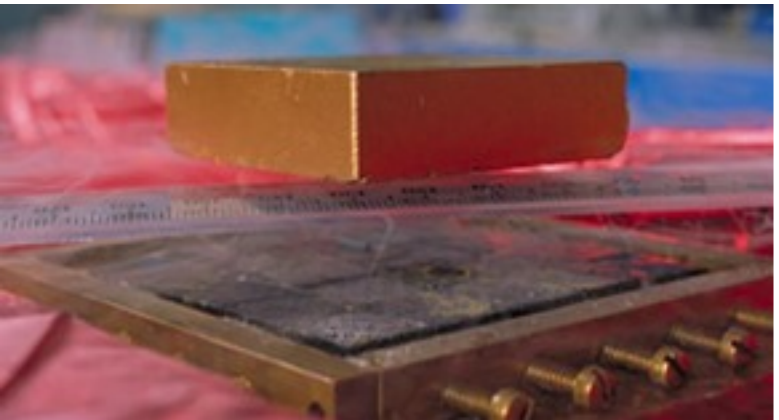
Superconductivity

Macroscopic-Screening
Non-Relativistic

SM-Screening
Relativistic

$$T < T_c$$

$n_s = \text{Density SC electrons}$



Superconductivity

Macroscopic-Screening
Non-Relativistic

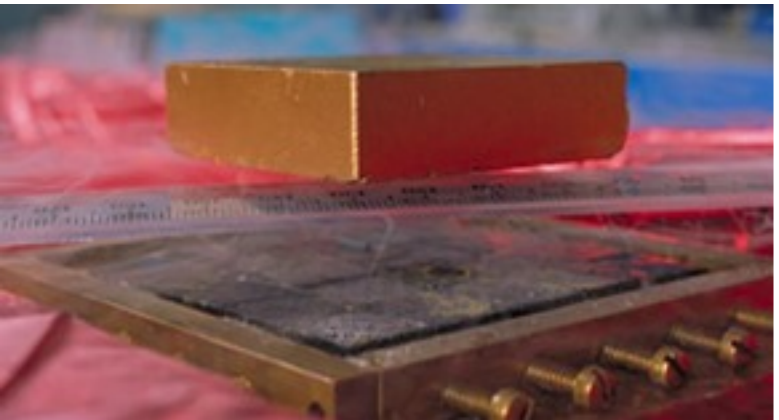
SM-Screening
Relativistic

$$T < T_c$$

$n_s = \text{Density SC electrons}$

$$|\psi|^2 = n_C = \frac{n_s}{2}$$

$$|H|^2 = \frac{v^2}{2}$$



Meissner-Mass
Static Vector Potential

Weak-GB-Mass

Meissner-Mass

Static Vector Potential

$$M^2 = q^2 n_s / 2m$$

Weak-GB-Mass

$$M_W^2 = g^2 v^2 / 4$$

Meissner-Mass

Static Vector Potential

Weak-GB-Mass

$$M^2 = q^2 n_s/2m$$

$$M_W^2 = g^2 v^2/4$$

$m = 2m_e \quad q = -2e$

Meissner-Mass
Static Vector Potential

$$M^2 = q^2 n_s/2m$$

$$m = 2m_e \quad q = -2e$$

$$n_s \sim 4 \times 10^{28} m^{-3}$$

Weak-GB-Mass

$$M_W^2 = g^2 v^2/4$$

$$M_W \sim 80\ GeV$$

Meissner-Mass
Static Vector Potential

Weak-GB-Mass

$$M^2 = q^2 n_s/2m$$

$$M_W^2 = g^2 v^2/4$$

$$m = 2m_e \quad q = -2e$$

$$n_s \sim 4 \times 10^{28} m^{-3}$$

$$M_W \sim 80\ GeV$$

$$\xi = 1/M \sim 10^{-6} cm$$

$$\xi_W = 1/M_W \sim 10^{-15} cm$$

Meissner-Mass
Static Vector Potential

Weak-GB-Mass

$$M^2 = q^2 n_s/2m$$

$$M_W^2 = g^2 v^2/4$$

$$m = 2m_e \quad q = -2e$$

$$n_s \sim 4 \times 10^{28} m^{-3}$$

$$M_W \sim 80\ GeV$$

$$\xi = 1/M \sim 10^{-6} cm$$

$$\xi_W = 1/M_W \sim 10^{-15} cm$$

Hidden structure

Meissner-Mass

Static Vector Potential

Weak-GB-Mass

$$M^2 = q^2 n_s/2m$$

$$M_W^2 = g^2 v^2/4$$

$$m = 2m_e \quad q = -2e$$

$$n_s \sim 4 \times 10^{28} m^{-3}$$

$$M_W \sim 80\ GeV$$

$$\xi = 1/M \sim 10^{-6} cm$$

$$\xi_W = 1/M_W \sim 10^{-15} cm$$

Hidden structure

????

Instability of the Fermi Scale

$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246\ \text{GeV}$$

$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246 \text{ GeV}$$

$$M_H^2 = 2\lambda\, v^2$$

CP3 - Origins
Particle Physics & Origin of Mass

Quantum corrections

Quantum corrections

$$M_{H_R}^2 = R \times M_{H_B}^2 + \Lambda^2$$

CP3 - Origins
Particle Physics & Origin of Mass

Quantum corrections

$$M_{H_R}^2 = R \times M_{H_B}^2 + \Lambda^2$$

A mass appears even if ab initio is set to zero!

Quantum corrections

$$M_{H_R}^2 = R \times M_{H_B}^2 + \Lambda^2$$

A mass appears even if ab initio is set to zero!

No custodial symmetry protecting a scalar mass.

CP3 - Origins
Particle Physics & Origin of Mass

Quantum corrections

$$M_{H_R}^{2} = R \times M_{H_B}^{2} + \Lambda^2$$

A mass appears even if ab initio is set to zero!

No custodial symmetry protecting a scalar mass.

Hierarchy between the EW scale and the Planck Scale.

Definition of Natural

Definition of Natural

Small parameters stay small under radiative corrections.

CP3 - Origins
Particle Physics & Origin of Mass

Electron mass

Electron mass

If set to zero the $U(1)_L \times U(1)_R$ forbids its regeneration

$$m_{eR} = R \times m_{eB}$$

Electron mass

If set to zero the $U(1)_L \times U(1)_R$ forbids its regeneration

$$m_{eR} = R \times m_{eB}$$

Naturalness begs an explanation of the origin of mass.

CP3 - Origins
Particle Physics & Origin of Mass

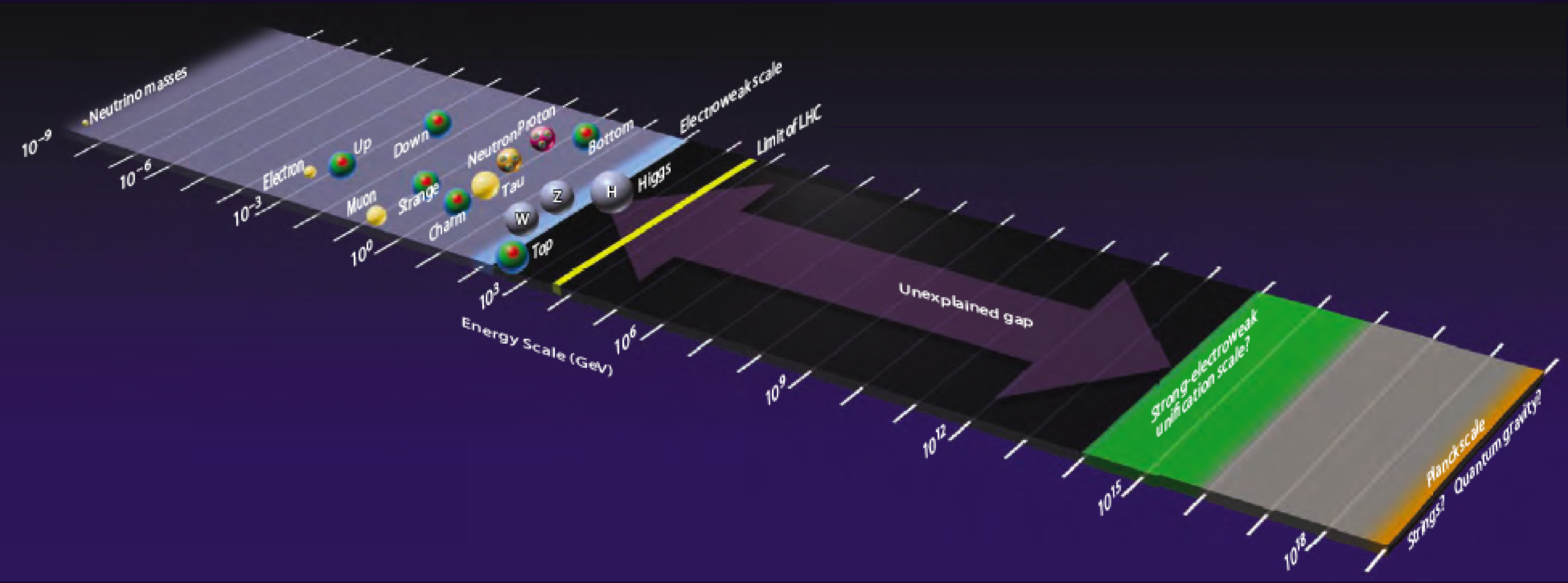
Electron mass

If set to zero the $U(1)_L \times U(1)_R$ forbids its regeneration

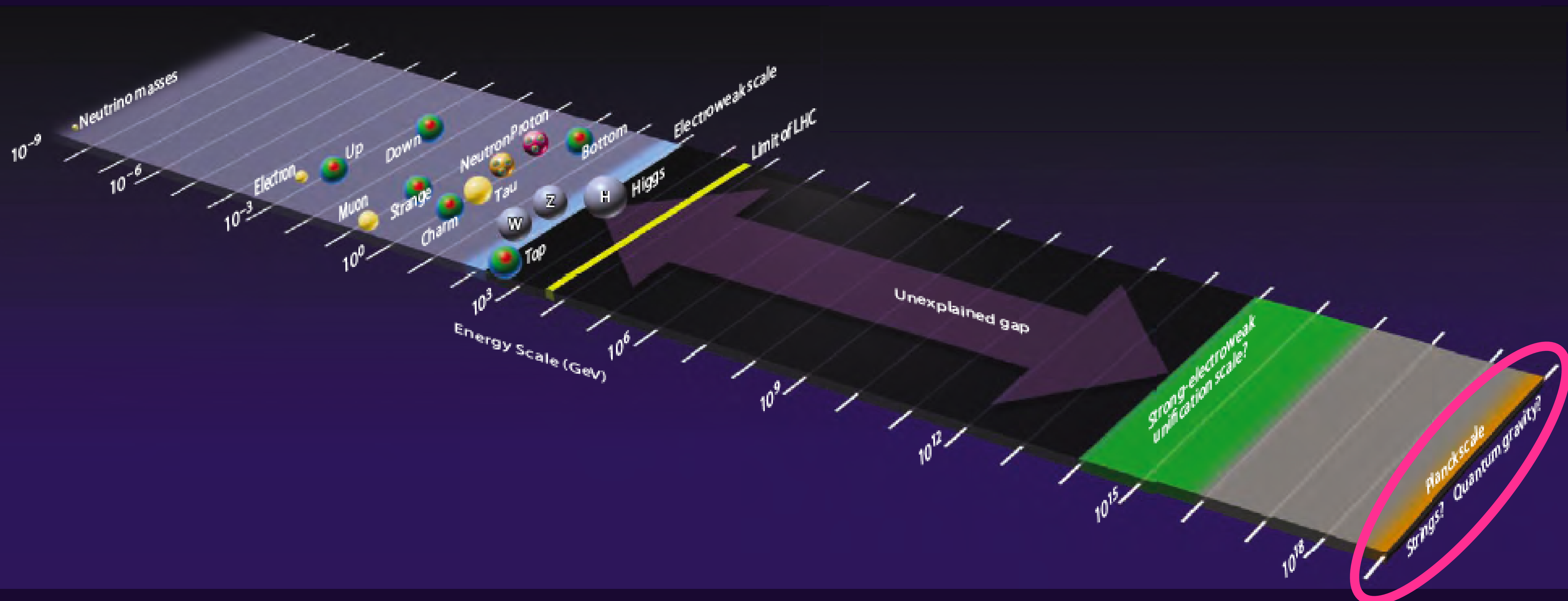
$$m_{e\,R} = R \times m_{e\,B}$$

Naturalness begs an explanation of the origin of mass.

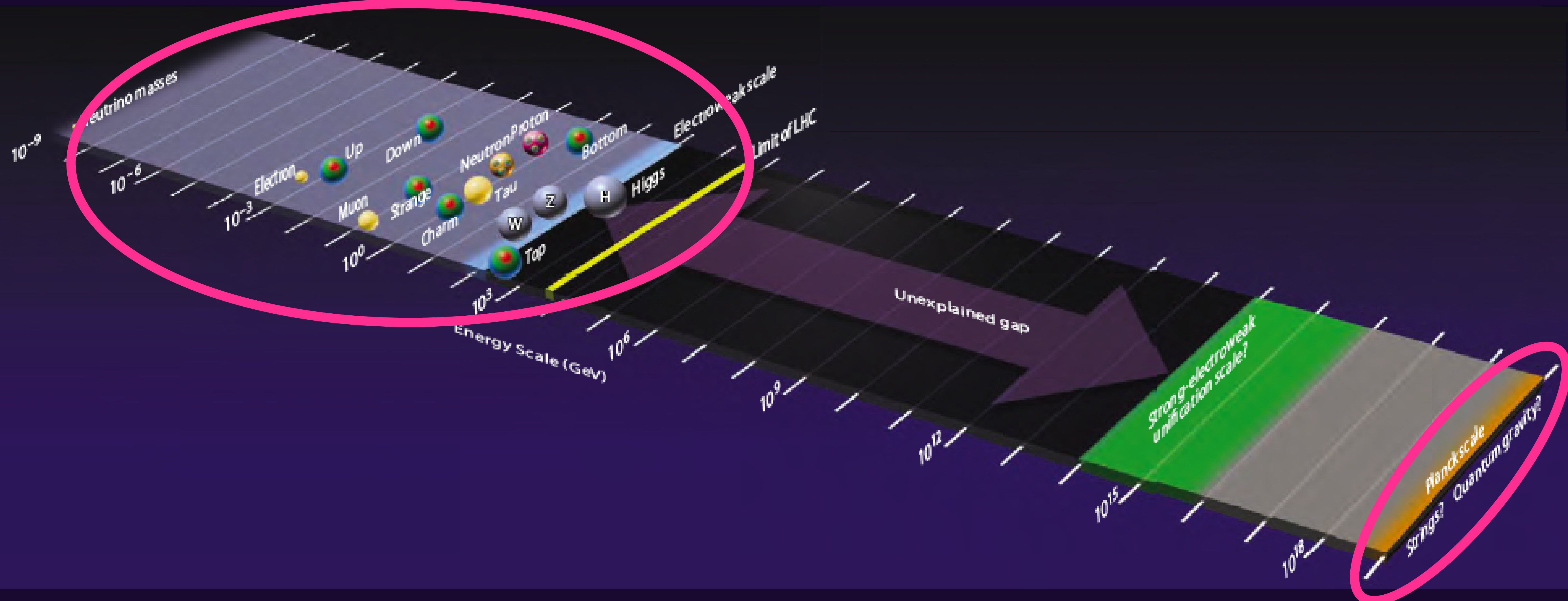
No conflict with any small value of the electron mass



Neutrino masses
10^-9
10^-6
10^-3
10^0
10^3
10^6
10^9
10^12
10^15
10^18
Electron
Up
Down
Muon
Strange
Charm
Neutron
Proton
Tau
Bottom
W
Z
H
Higgs
Top
Electroweak scale
Limit of LHC
Unexplained gap
Energy Scale (GeV)
Strong-electroweak unification scale?
Planck scale
Strings?
Quantum gravity?



Neutrino masses
10⁻⁹
10⁻⁶
10⁻³
10⁰
10³
10⁶
10⁹
10¹²
10¹⁵
10¹⁸
Electron
Up
Down
Neutron
Proton
Bottom
Muon
Strange
Tau
Charm
W
Z
H
Higgs
Top
Electroweak scale
Limit of LHC
Energy Scale (GeV)
Unexplained gap
Strong-electroweak unification scale?
Planck scale
Strings?
Quantum gravity?



10^{-9}
Neutrino masses
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Electron
Up
Down
Muon
Strange
Charm
Neutron Proton
Tau
Bottom
W
Z
H
Higgs
Top
Electroweak scale
Limit of LHC
Energy Scale (GeV)
Unexplained gap
Strong-electroweak unification scale?
Planck scale
Strings?
Quantum gravity?

Many Models

(?)MSSM

XLMS D

......

Technicolor

Branes

Unparticle

AdS/?

Many Models

- (?)MSSM
- XLMS D
- $
- Technicolor
- Branes
- ......
- Unparticle
- AdS/?

Theory landscape

Theory landscape

Gauge Group

Theory landscape

Gauge Group

Matter

Theory landscape

Gauge Group

Matter

SUSY

CP³ - Origins
Particle Physics & Origin of Mass

Theory landscape

Gauge Group

Matter

SUSY

N=1

N=2

N=4

Theory landscape

Gauge Group

Matter

SUSY

Non SUSY

N=1

N=2

N=4

Theory landscape

Gauge Group

Matter

SUSY	Non SUSY
N=1	Fermions
N=2	Fermions + Bosons
N=4	Bosons

Theory landscape

Gauge Group

Matter

SUSY	Non SUSY
N=1	Fermions
N=2	Fermions + Bosons
N=4	Bosons

Vector

Theory landscape

Gauge Group

Matter

SUSY	Non SUSY
N=1	Fermions
N=2	Fermions + Bosons
N=4	Bosons

Vector Chiral

Theory landscape

Gauge Group

Matter

SUSY	Non SUSY
N=1	Fermions
N=2	Fermions + Bosons
N=4	Bosons

Vector Chiral

Theory landscape

Gauge Group

Matter

SUSY	Non SUSY
N=1	Fermions
N=2	Fermions + Bosons
N=4	Bosons

Vector Chiral

Theory landscape

Gauge Group

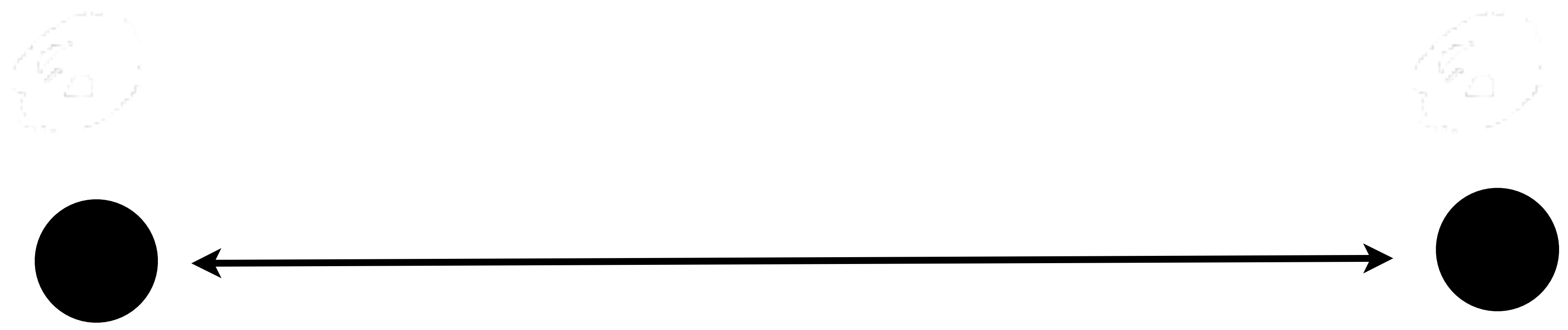
Matter

SUSY	Non SUSY
N=1	Fermions
N=2	Fermions + Bosons
N=4	Bosons

Vector Chiral

Phases

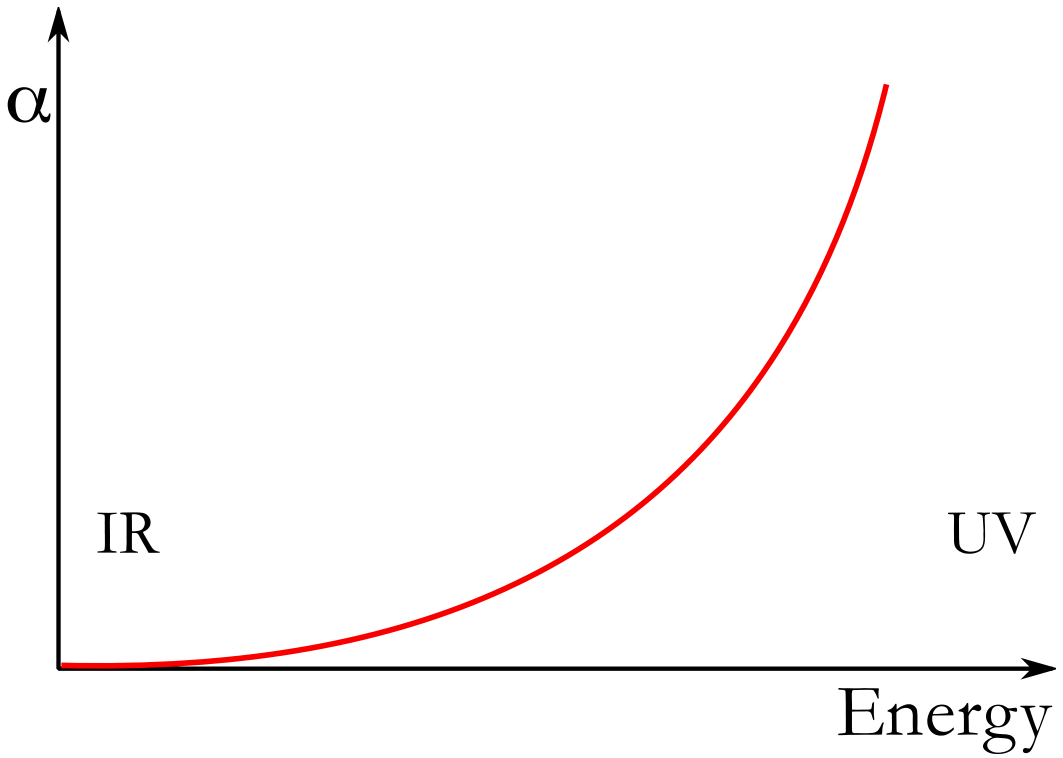
$$V(r)$$



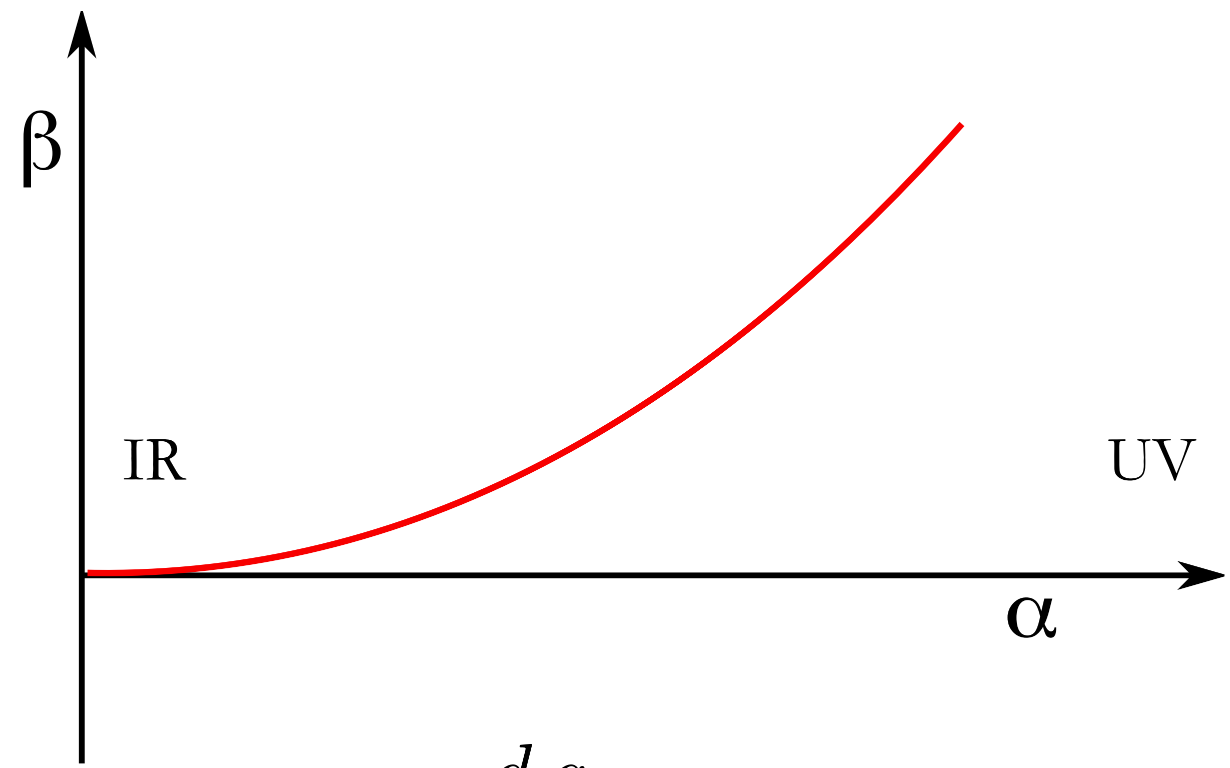
Free Electric

$$V(r) \propto \frac{1}{r \log(r)}$$

$$\alpha(r) \to \frac{1}{\log(r)}$$



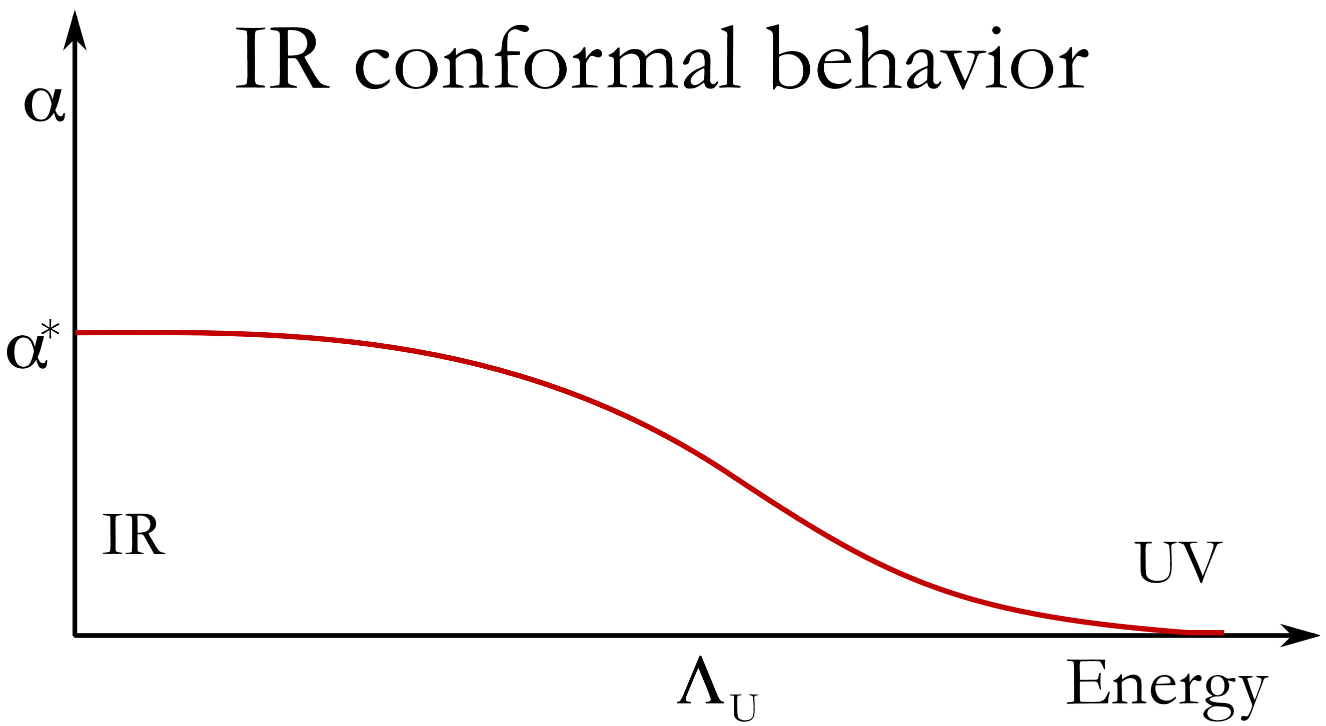
$$\alpha = \frac{g^2}{4\pi}$$

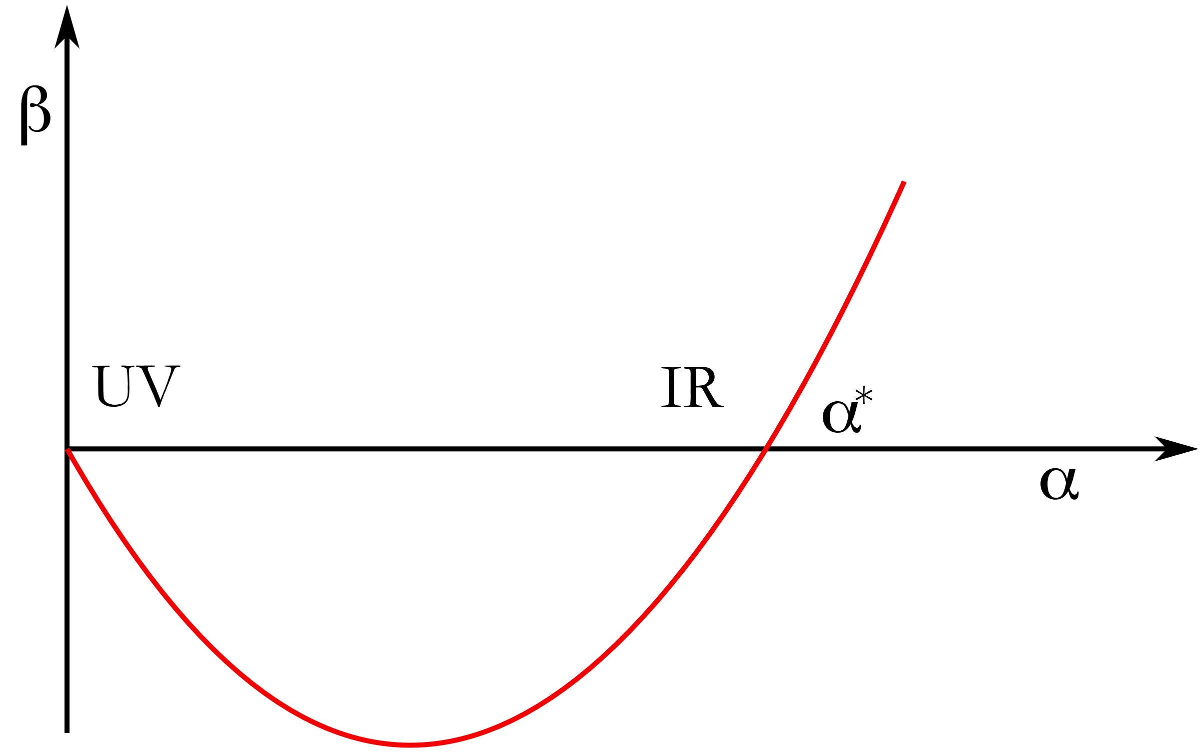


$$\beta = \frac{d\, g}{d \ln \mu}$$

Coulomb

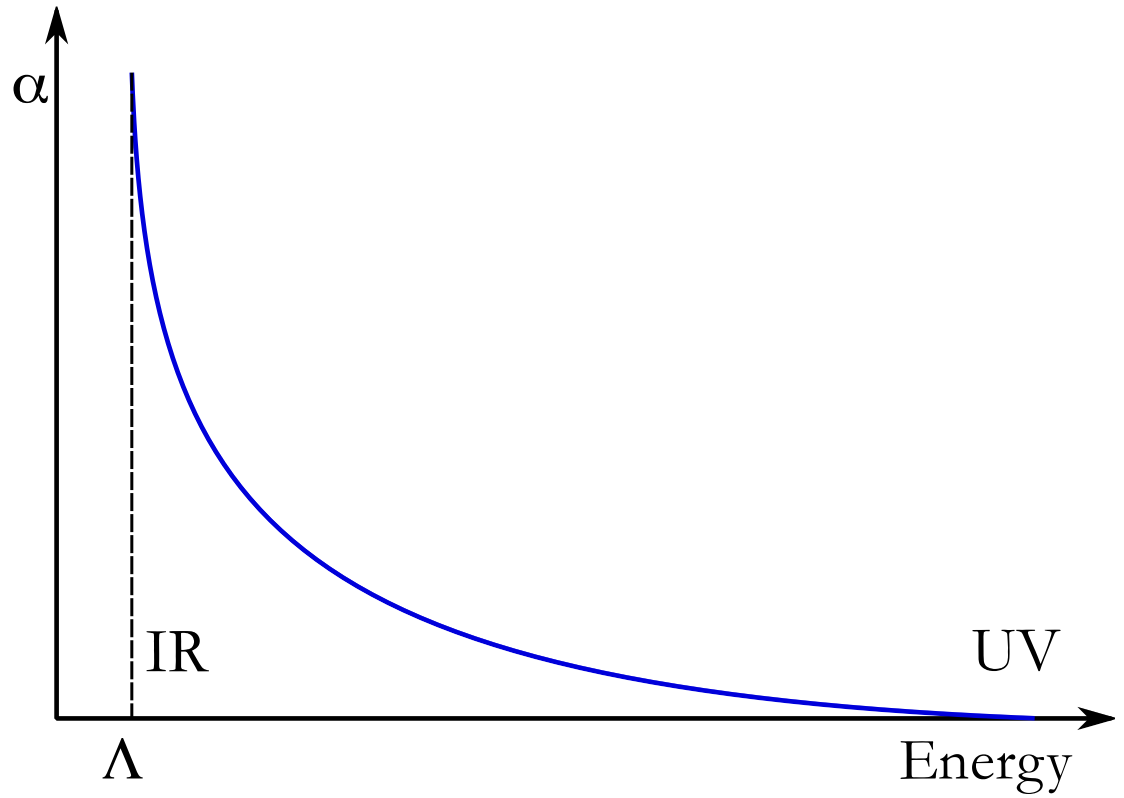
$$V(r) \propto \frac{1}{r}$$

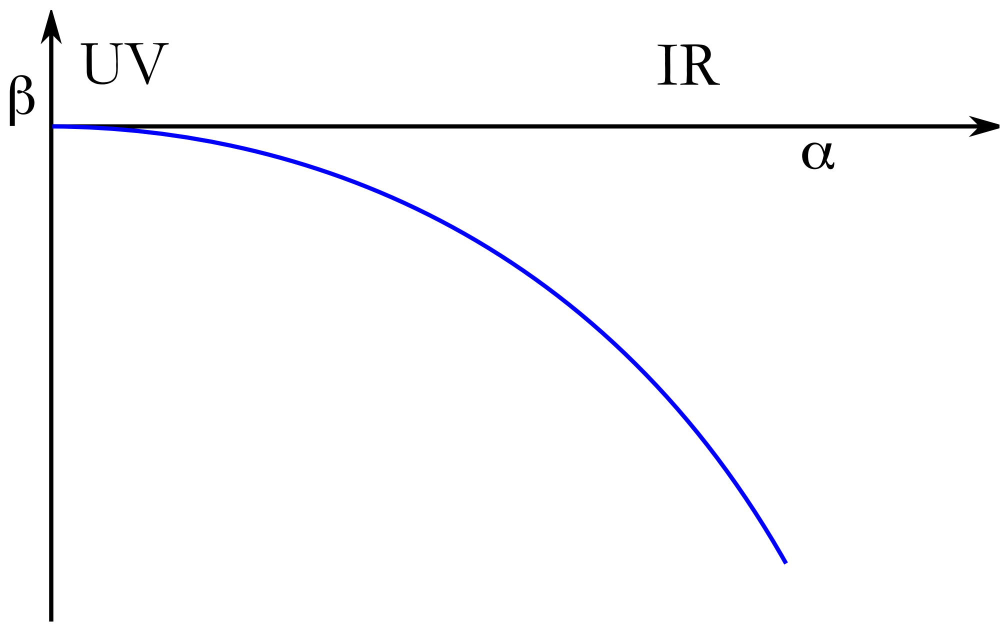




IR Conformal Phase

QCD - Like





$$V \propto \sigma\, r$$

Knobs

Knobs

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

Knobs

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

Matter Representation

Knobs

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

Matter Representation

# of Flavors per Representation

Knobs

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

Matter Representation

# of Flavors per Representation

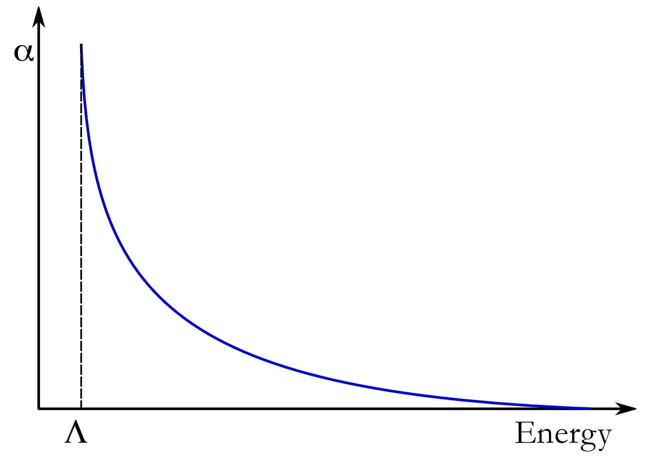
N_f

Knobs

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

Matter Representation

# of Flavors per Representation

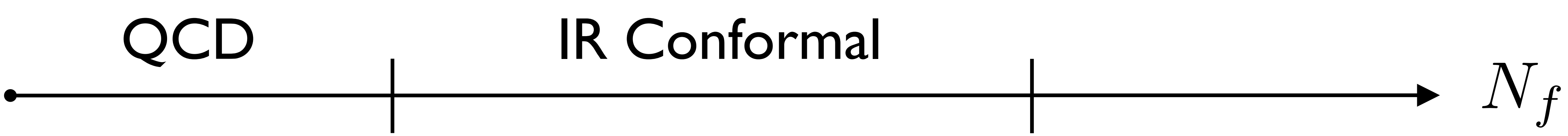


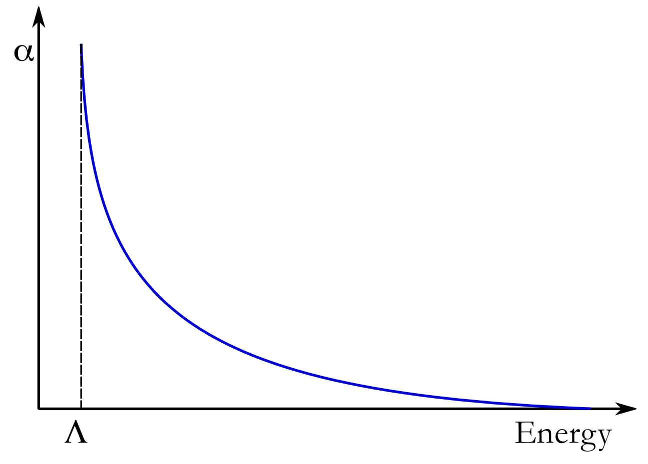
Knobs

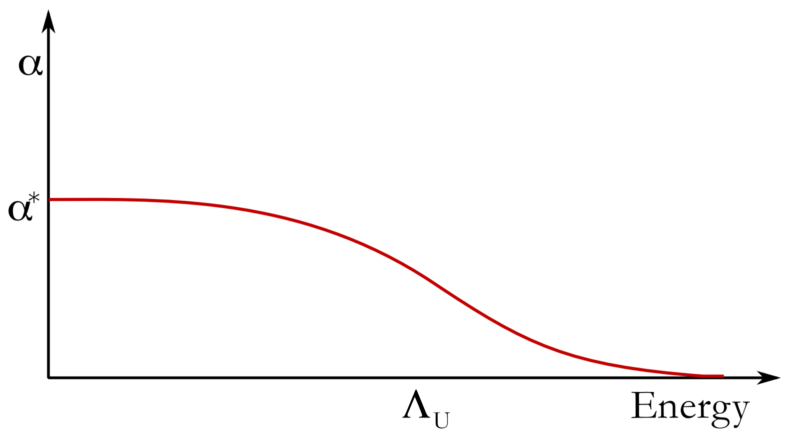
Gauge Group, i.e. SU, SO, SP

Matter Representation

# of Flavors per Representation





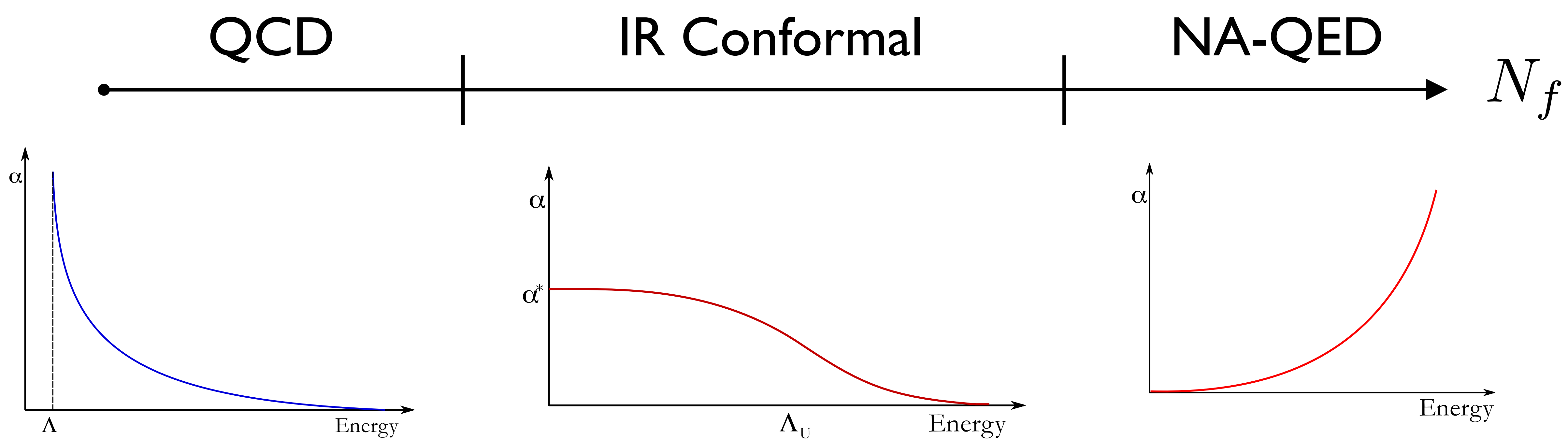


Knobs

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

Matter Representation

# of Flavors per Representation



CP^3 - Origins

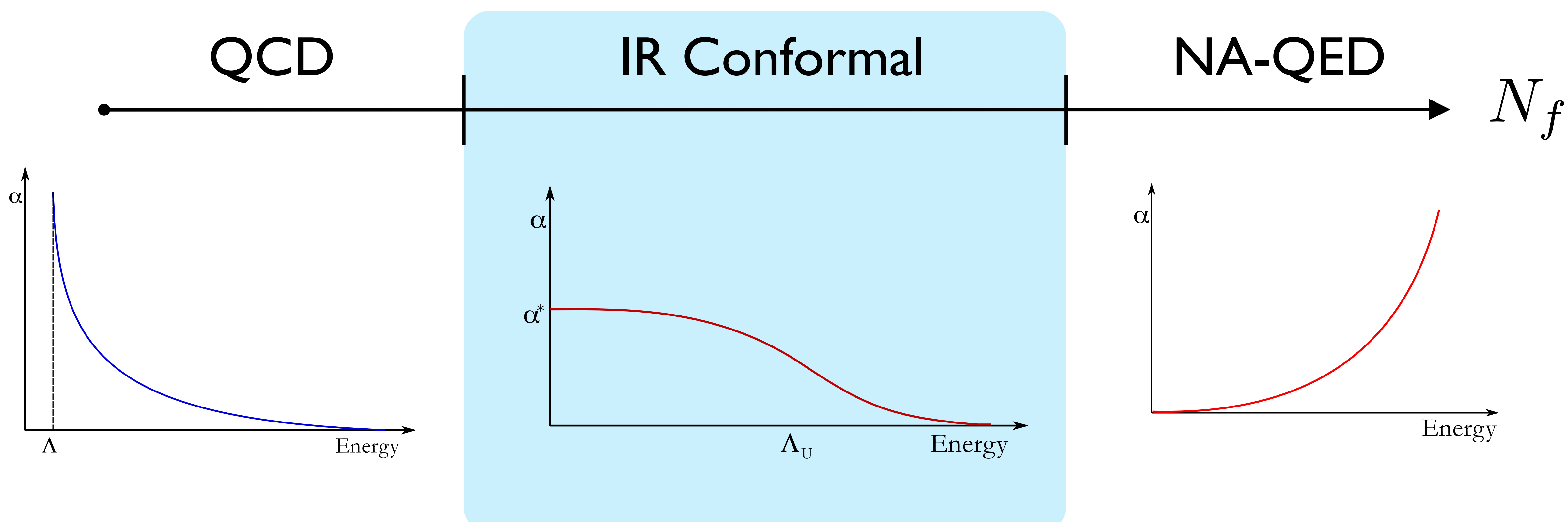
Particle Physics & Origin of Mass

Knobs

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

Matter Representation

# of Flavors per Representation



Example

SU(N)

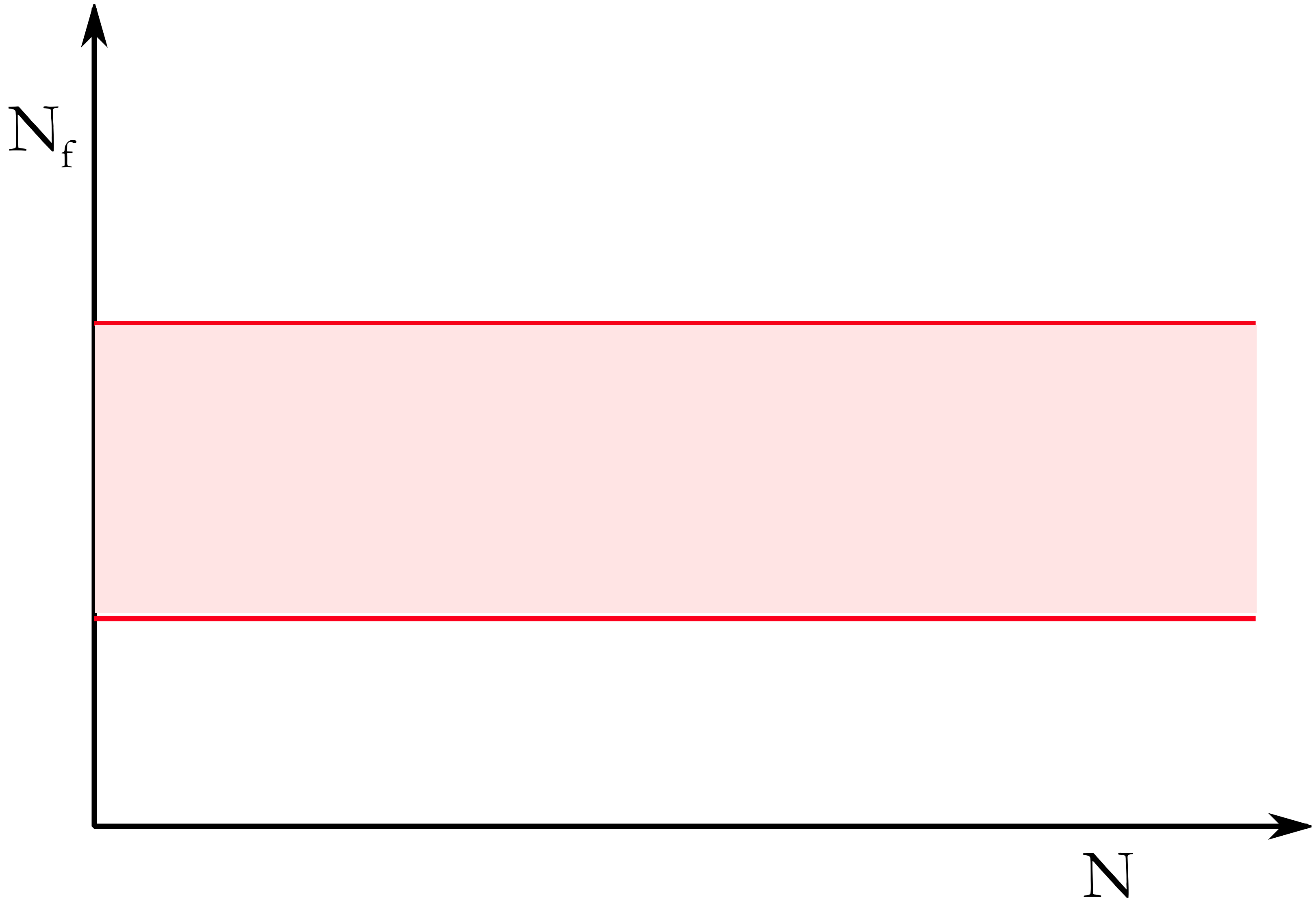
Adjoint Dirac Matter

Nf

Temperature = 0

Matter Density (i.e. Chemical Potential(s)) =0

Example



SU(N)

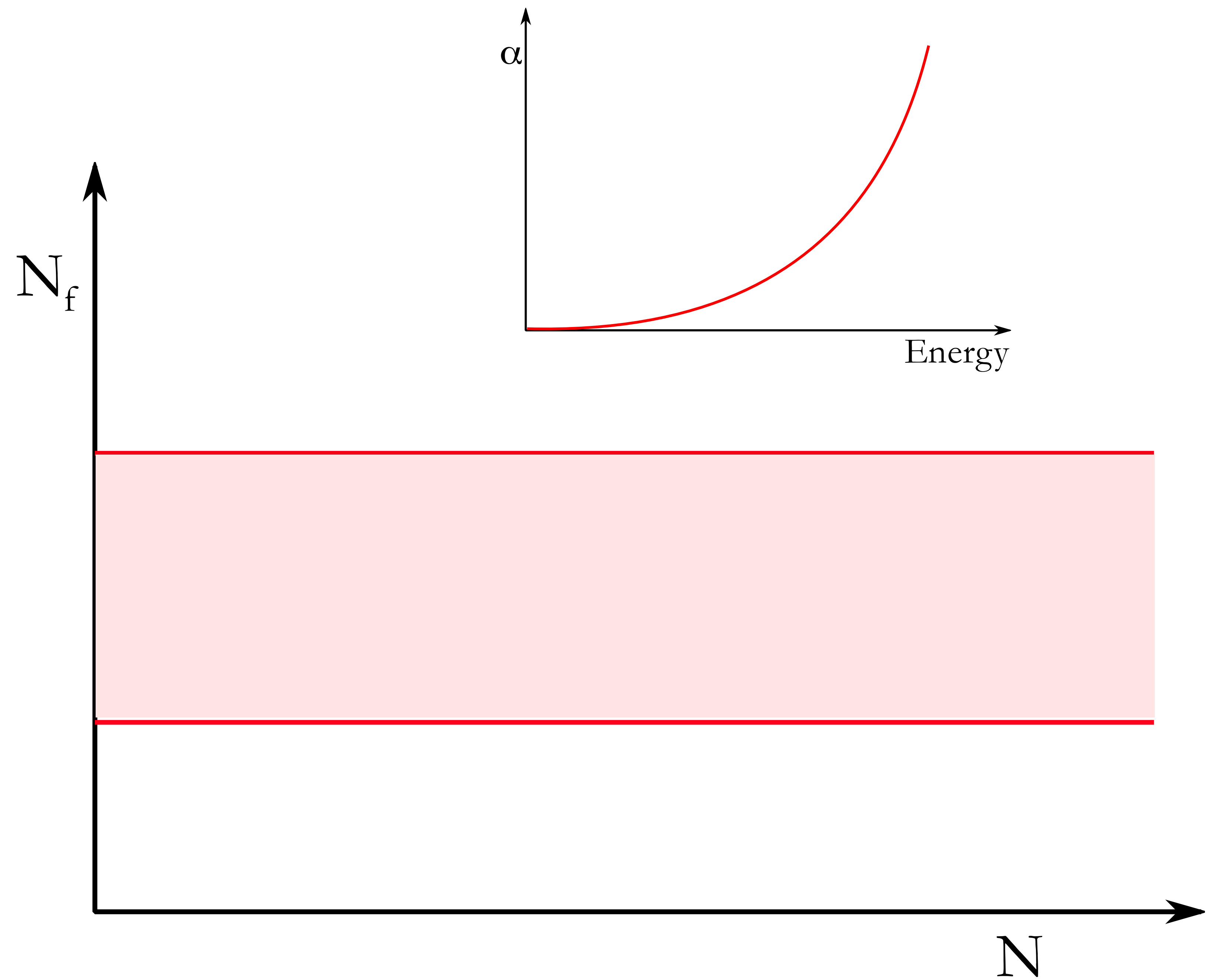
Adjoint Dirac Matter

Nf

Temperature = 0

Matter Density (i.e. Chemical Potential(s)) =0

Example



SU(N)

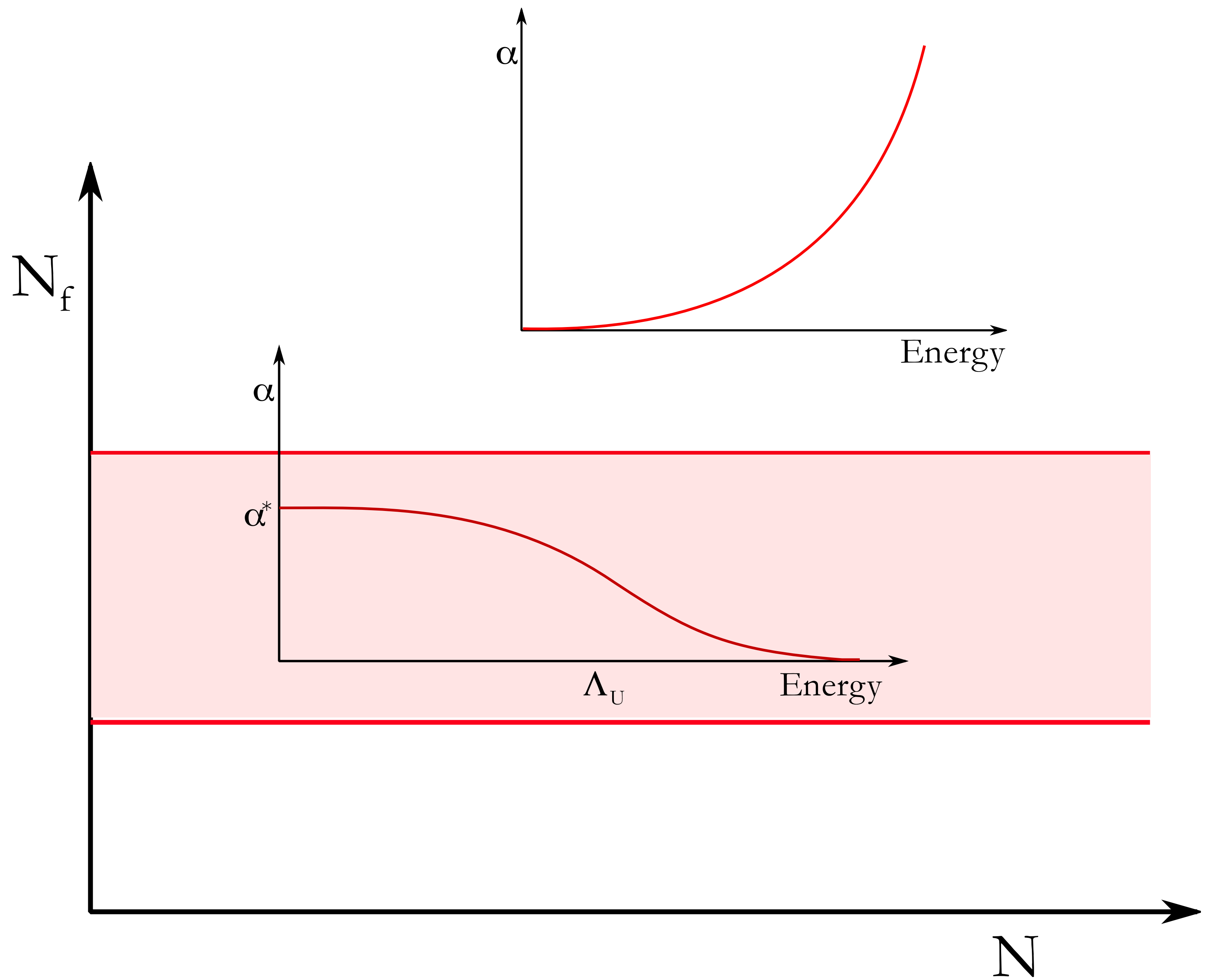
Adjoint Dirac Matter

Nf

Temperature = 0

Matter Density (i.e. Chemical Potential(s)) =0

Example



SU(N)

Adjoint Dirac Matter

Nf

Temperature = 0

Matter Density (i.e. Chemical Potential(s)) =0

Example

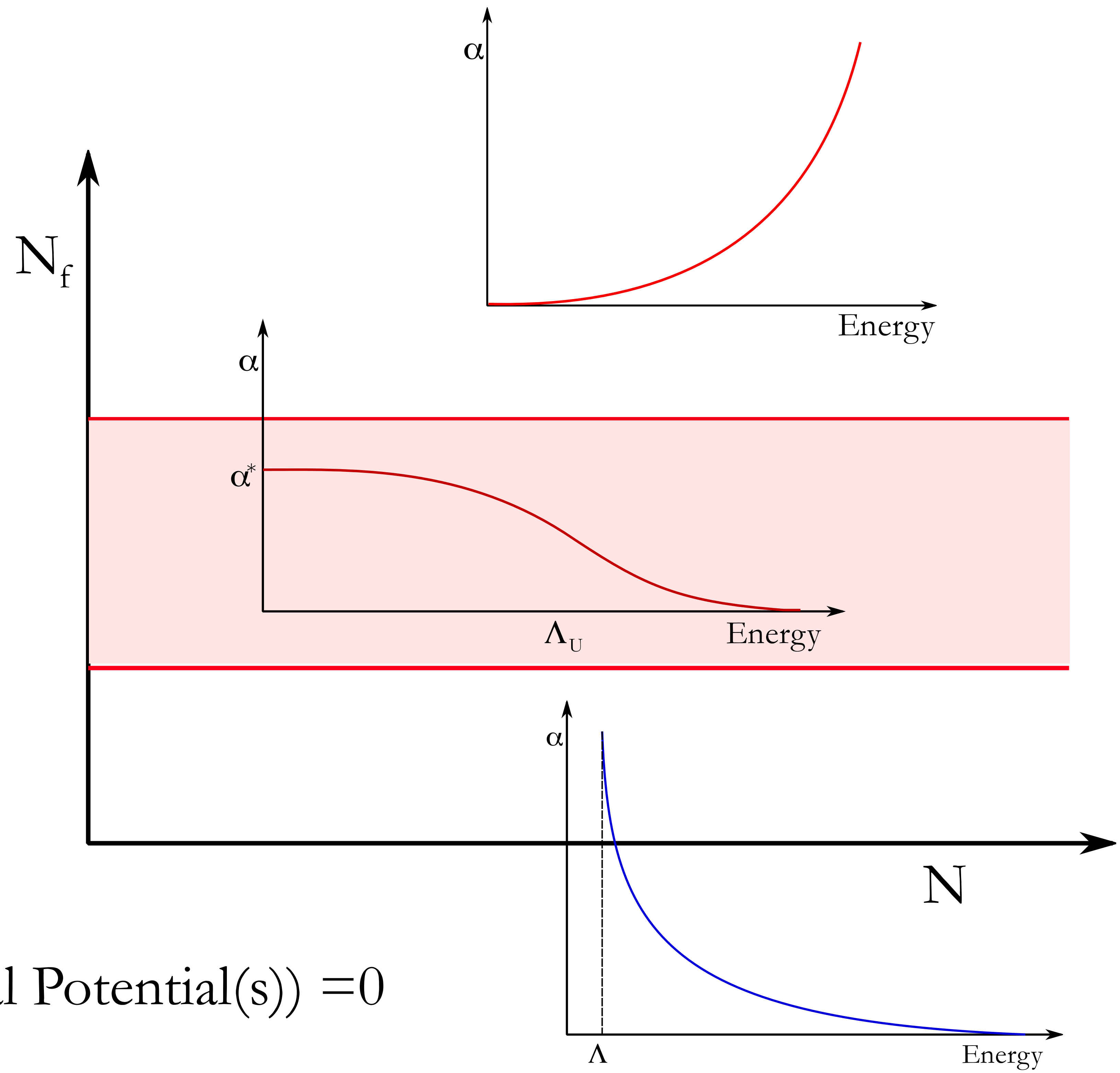
SU(N)

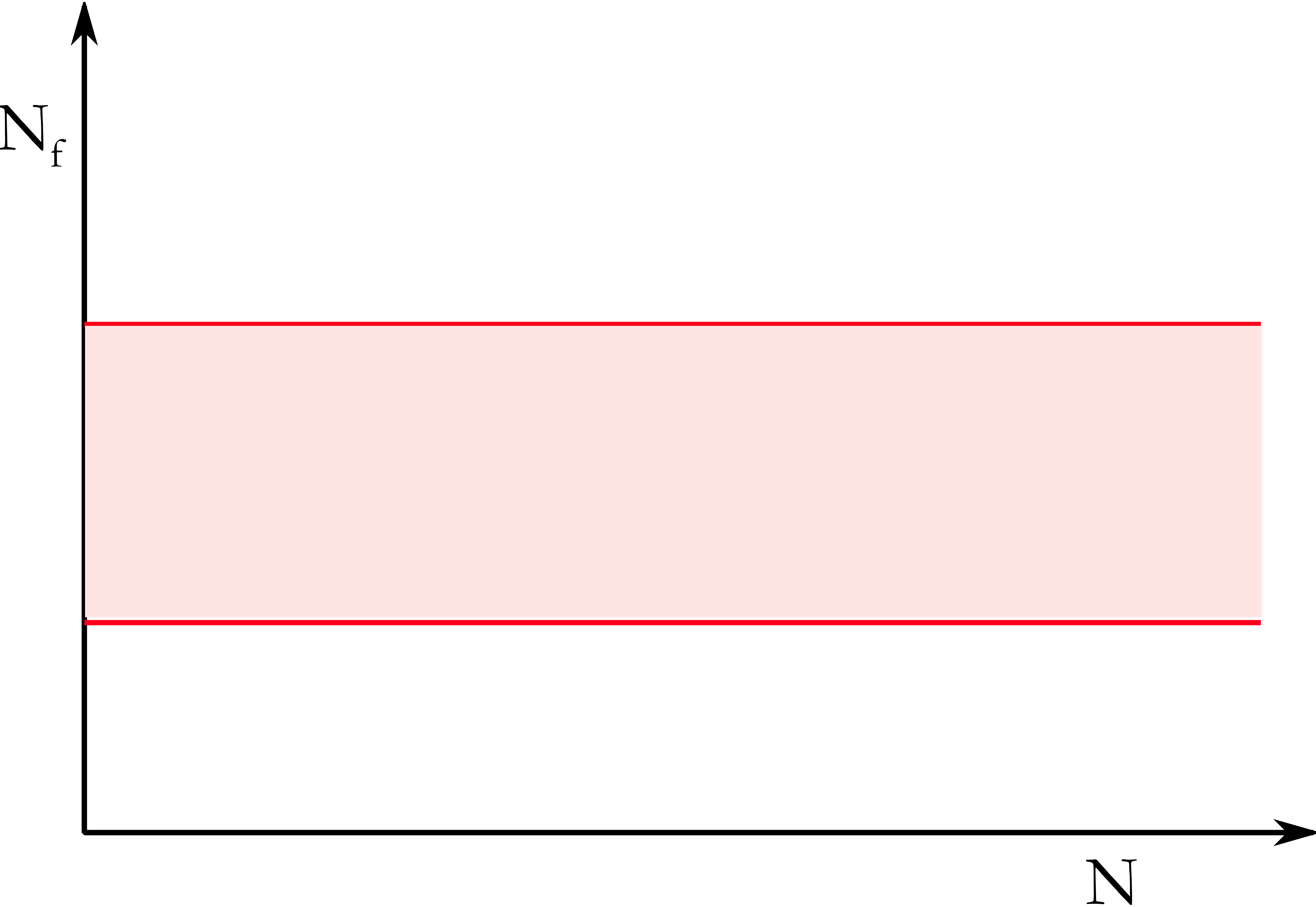
Adjoint Dirac Matter

Nf

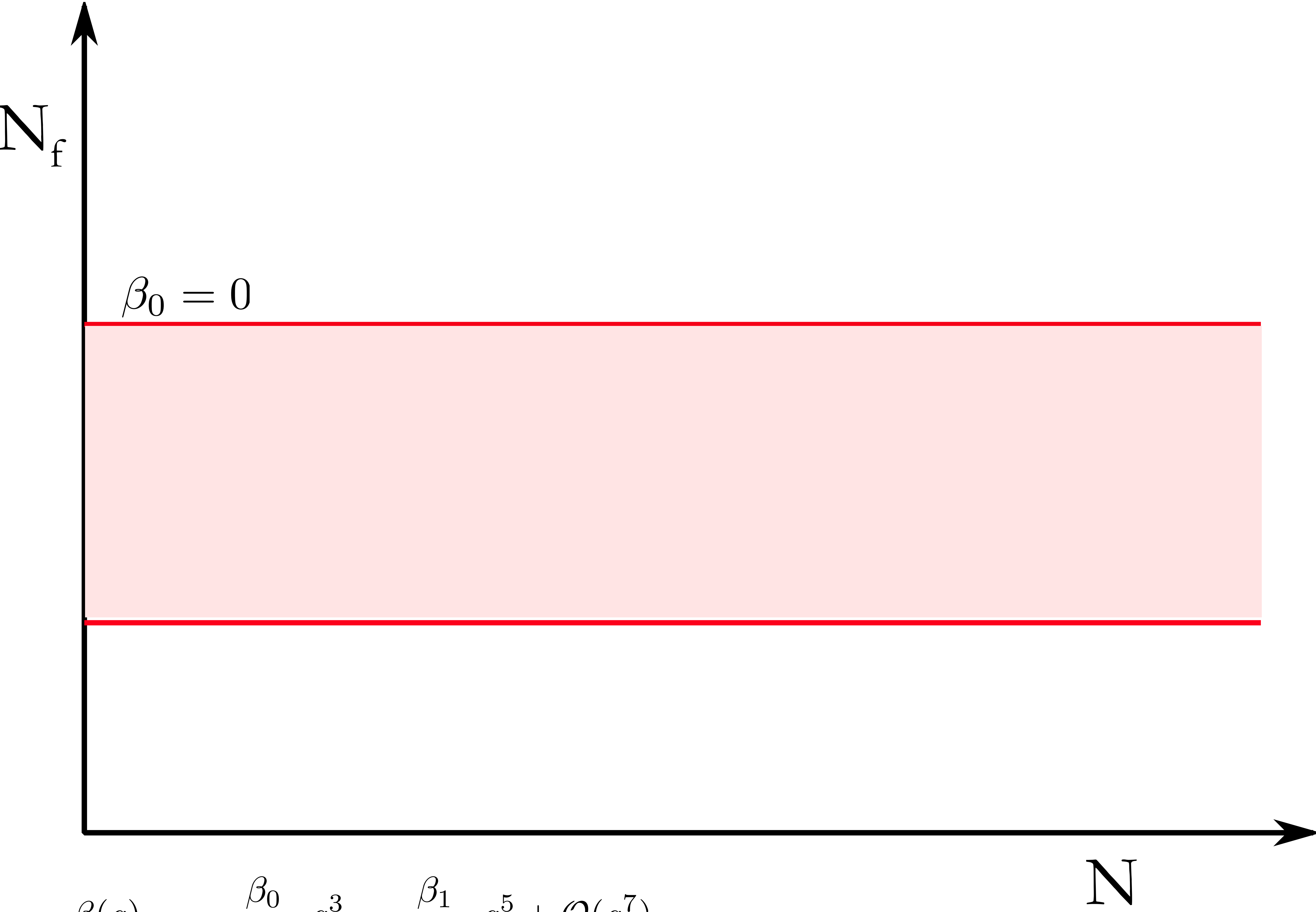
Temperature = 0

Matter Density (i.e. Chemical Potential(s)) =0

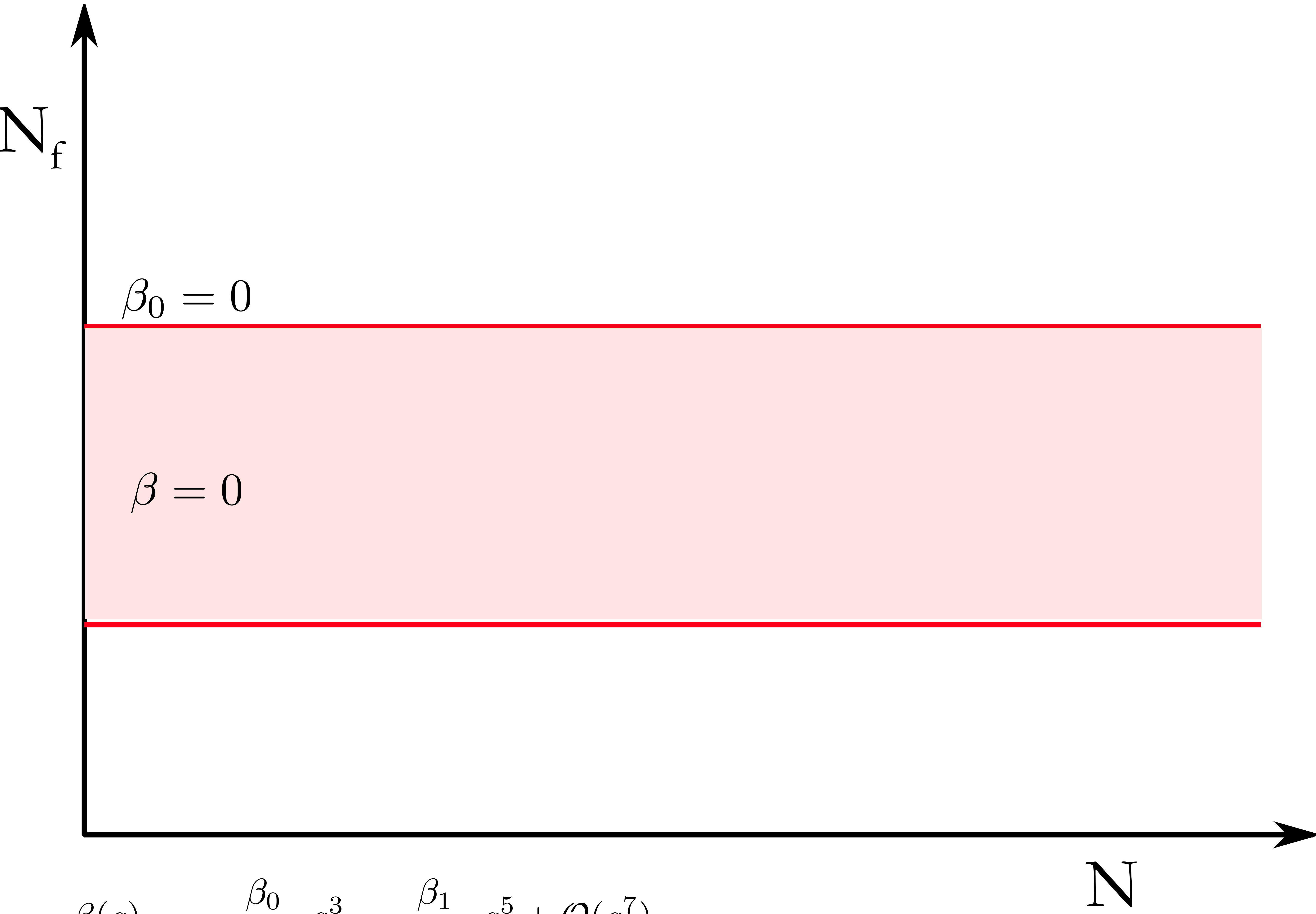




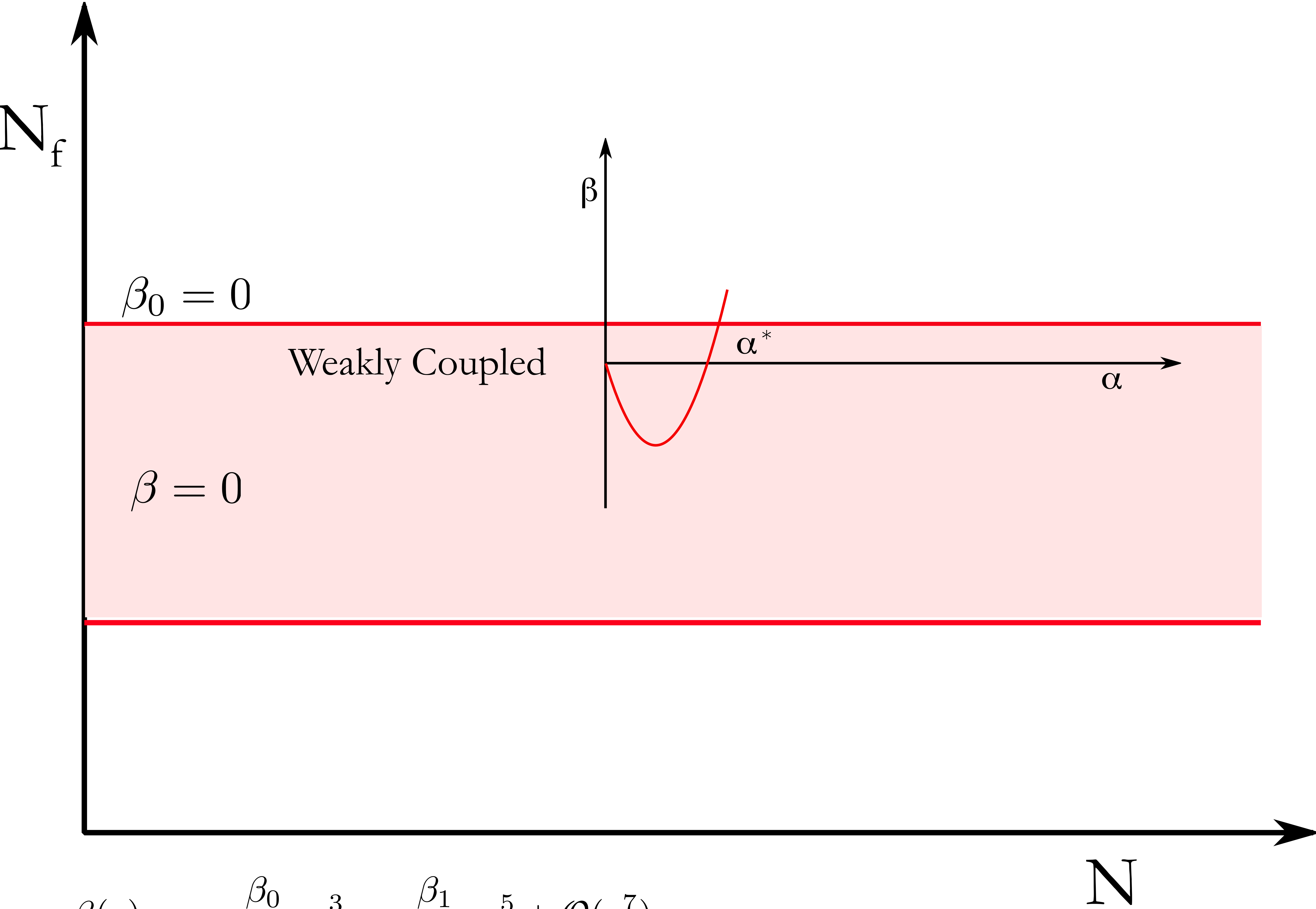
N_f
N



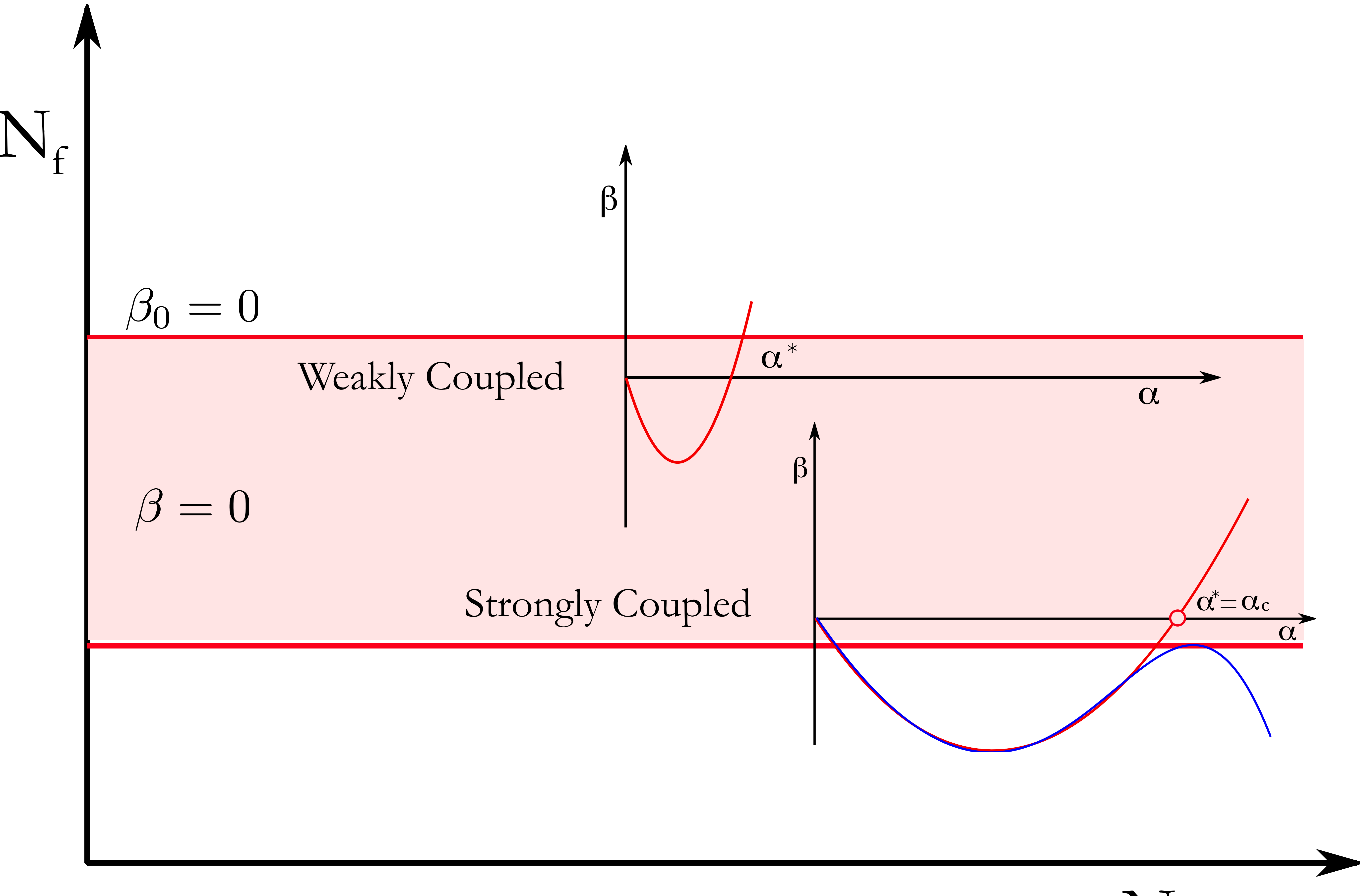
$$\beta(g) = -\frac{\beta_0}{(4\pi)^2} g^3 - \frac{\beta_1}{(4\pi)^4} g^5 + \mathcal{O}(g^7)$$



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



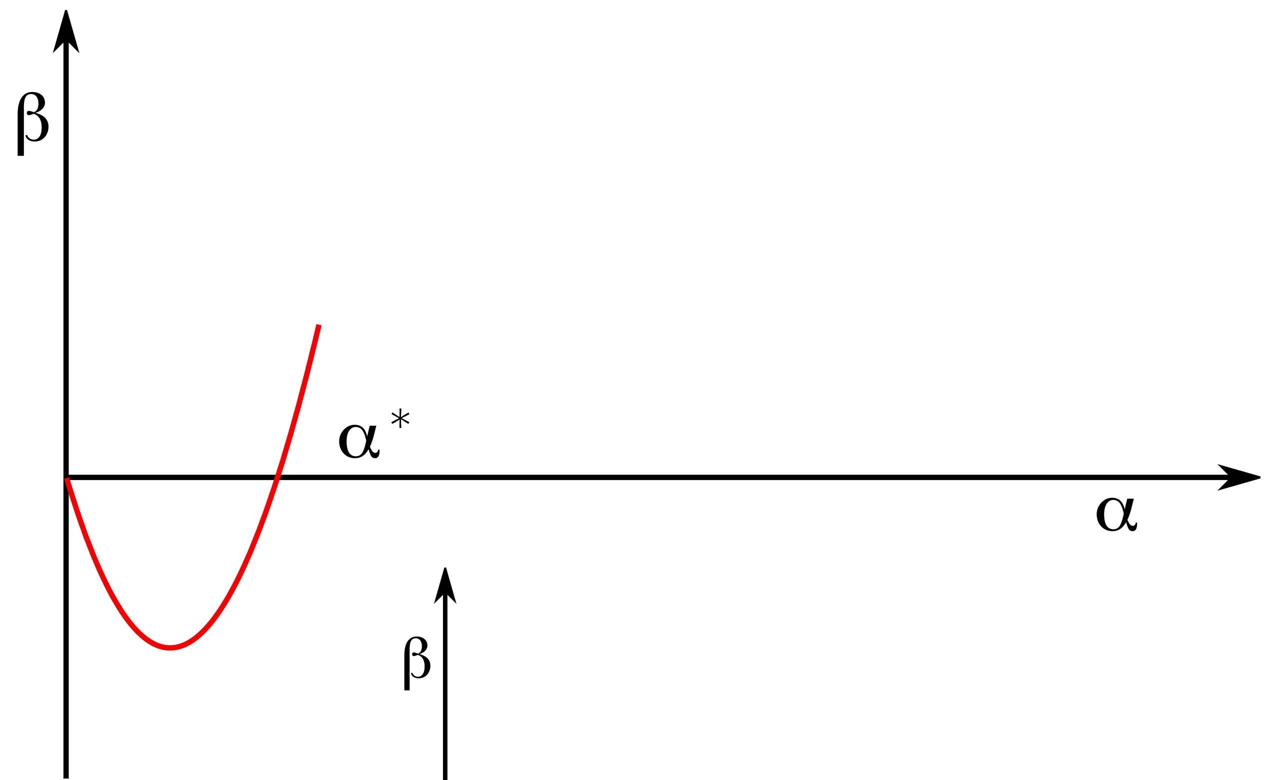
$$\beta(g) = -\frac{\beta_0}{(4\pi)^2} g^3 - \frac{\beta_1}{(4\pi)^4} g^5 + \mathcal{O}(g^7)$$



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

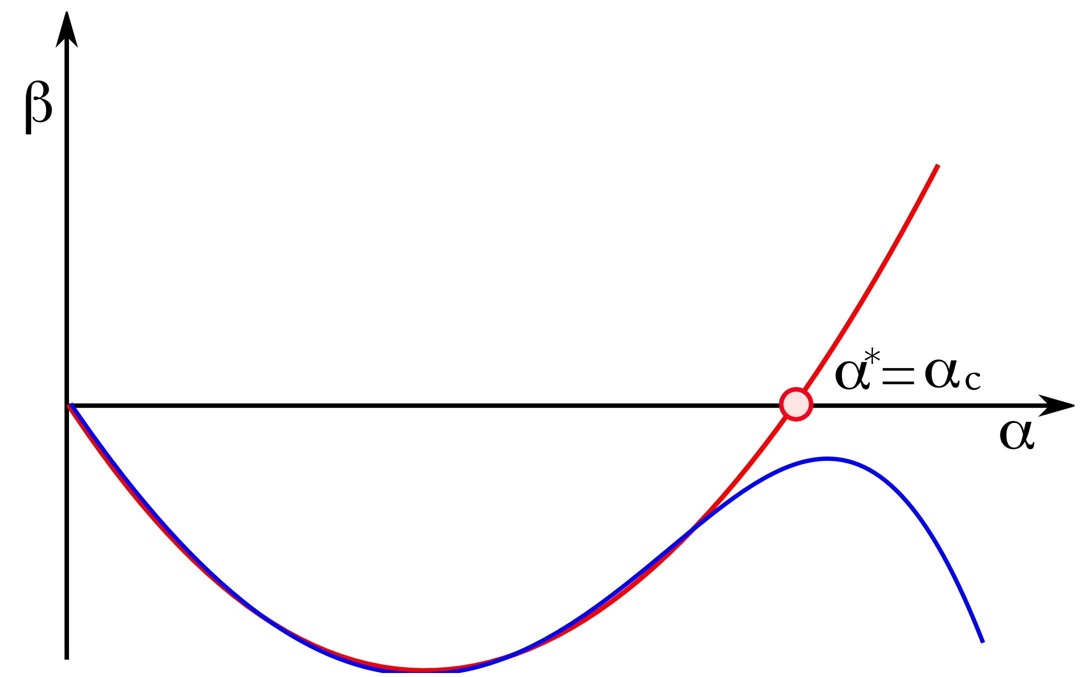
$$\beta_0 = 0$$

Weakly Coupled



$$\beta = 0$$

Strongly Coupled



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

CP3 - Origins

Particle Physics & Origin of Mass

Analytic Tools

CP3 - Origins
Particle Physics & Origin of Mass

SUSY

The all orders beta function of NSVZ

Unitarity Bounds for Conformal Theories

Non-Renormalization of Superpotentials

‘t Hoofts Anomaly Matching Conditions

a-Maximization

Instanton Calculus

....

Seiberg, Intriligator, Novikov, Shifman, Vainshtein, Zakharov.

CP3 - Origins
Particle Physics & Origin of Mass

Non SUSY

Different approaches

Schwinger - Dyson

Instanton Inspired Calculus

Thermal degrees of freedom count

Exact Renormalization Methods

Certain Topological excitations

Appelquist, Bowick, Chivukula, Cohen, Eichten, Gies, Hill, Holdom, Karabali, Jaeckel, Fisher, Lane, Litim, Mahanta, Miransky, Pawlowski, Percacci, Poppitz, Shrock, Simmons, Terning, Unsal, Wijewardhana, Yamawaki

..continued

Also:

The all orders beta function conjecture* (RS)

Chiral Gauge Theories beta function (F.S.)

Unitarity of the Operators for Conformal Theories

Gauge Dualities (F.S.)

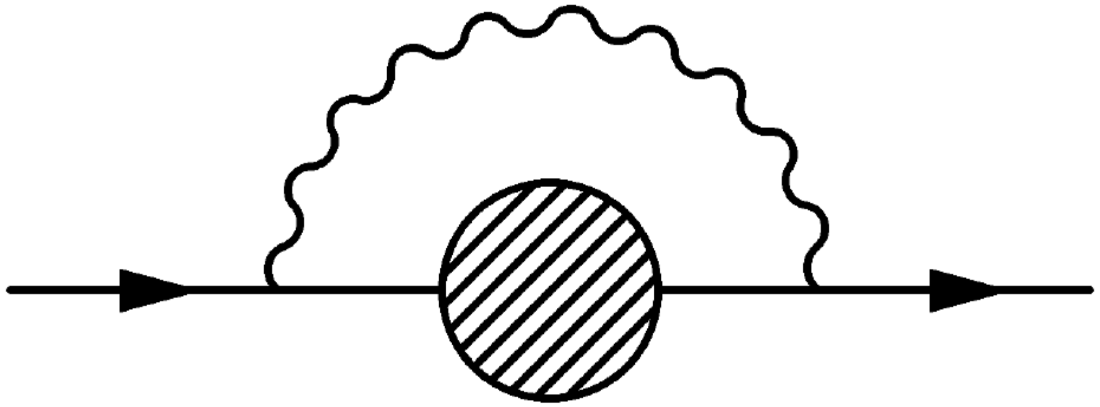
First Principle Lattice Computations

*Variations on the beta function (AT)

RS - Ryttov, F.S. 07
F.S. 09
AT - Antipin, Tuominen 09

CP3 - Origins
Particle Physics & Origin of Mass

Schwinger - Dyson



The full nonperturbative fermion propagator reads:

$$iS^{-1}(p) = Z(p)\left(\not{p} - \Sigma(p)\right)$$

The Euclidianized gap equation in Landau gauge is:

$$\Sigma(p) = 3C_2(R)\int \frac{d^4k}{(2\pi)^4}\,\frac{\alpha\left((k-p)^2\right)}{(k-p)^2}\,\frac{\Sigma(k^2)}{Z(k^2)k^2 + \cancel{\Sigma^2}(k^2)}$$

$$Z(k^2) = 1$$

$$\beta(\alpha) \simeq 0 \qquad \alpha(\mu) \approx \alpha_c \qquad \alpha_c = \frac{\pi}{3C_2(r)}$$

CP^3 - Origins

Particle Physics & Origin of Mass

In practice

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

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

$$\beta = 0$$

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

$$\beta = 0 \qquad \longrightarrow$$

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

$$\beta = 0 \longrightarrow \frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$$

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

$$\beta = 0 \quad \longrightarrow \quad \frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$$

$$\alpha_c = \frac{\pi}{3C_2(r)}$$

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

$$\beta = 0 \quad \longrightarrow \quad \frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$$

$$\alpha_c = \frac{\pi}{3C_2(r)} \quad \longleftrightarrow$$

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

$$\beta = 0 \quad \longrightarrow \quad \frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$$

$$\alpha_c = \frac{\pi}{3C_2(r)} \quad \longleftrightarrow \quad \gamma(2-\gamma) = 1$$

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

$$\beta = 0 \longrightarrow \frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$$

$$\alpha_c = \frac{\pi}{3C_2(r)} \longleftrightarrow \gamma(2-\gamma) = 1$$

$$\alpha^* \leq \alpha_c$$

SU(N) Dirac Fermions in representation "r"

$$N^c_{f\,\text{Ladder}} = \frac{17C_2(G) + 66C_2(r)}{10C_2(G) + 30C_2(r)}\frac{C_2(G)}{T(r)}$$

$$C_2(G) = C_2(Adj) = N$$

CP3 - Origins
Particle Physics & Origin of Mass

Back to the example

SU(N)   Adjoint Dirac Matter

Back to the example

SU(N) Adjoint Dirac Matter

$$C_2(r) = C_2(G) = T(G) = N$$

Back to the example

SU(N)   Adjoint Dirac Matter

$$C_2(r) = C_2(G) = T(G) = N$$

$$\beta_0 = \frac{11}{3}N - \frac{4}{3}NN_f = 0 \ , \quad \rightarrow \quad N_f^{\rm Asymp} = \frac{11}{4} = 2.75$$

Back to the example

SU(N) Adjoint Dirac Matter

$$C_2(r) = C_2(G) = T(G) = N$$

$$\beta_0 = \frac{11}{3}N - \frac{4}{3}N N_f = 0 \ , \quad \rightarrow \quad N_f^{\text{Asymp}} = \frac{11}{4} = 2.75$$

$$N^c_{f\,\text{Ladder}} = \frac{17+66}{10+30} = 2.075$$

Back to the example

SU(N) Adjoint Dirac Matter

$$C_2(r) = C_2(G) = T(G) = N$$

$$\beta_0 = \frac{11}{3}N - \frac{4}{3}NN_f = 0 \ , \quad \rightarrow \quad N_f^{\mathrm{Asymp}} = \frac{11}{4} = 2.75$$

$$N^c_{f\,\mathrm{Ladder}} = \frac{17+66}{10+30} = 2.075$$

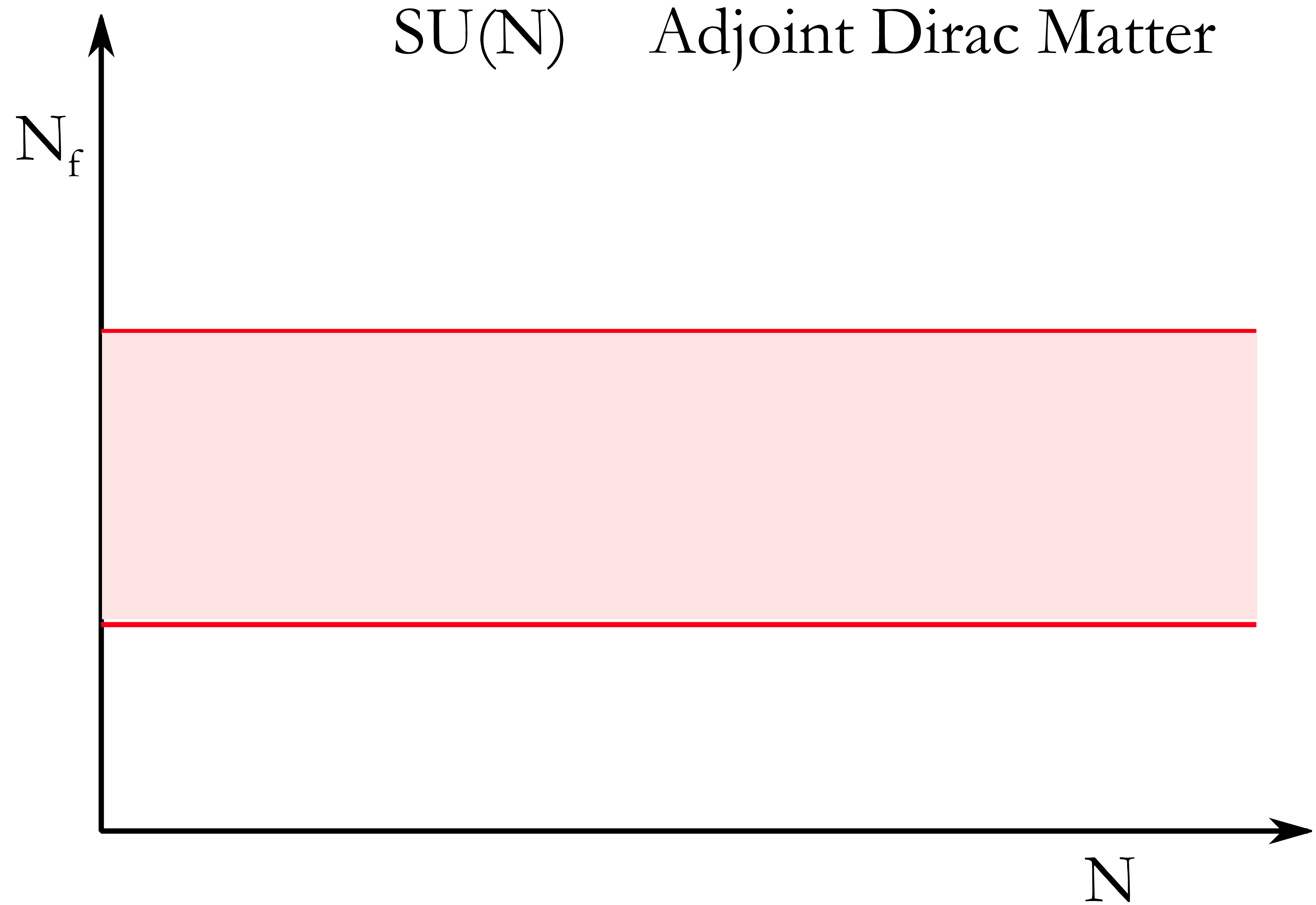
F.S. - Tuominen 04

Back to the example

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

$$N^c_{f\,\text{Ladder}} = 2.075$$

F.S. - Tuominen 04



Another Example

SU(N)   2-index Symmetric Rep

	$SU(N)$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	$U_A(1)$
$Q_{\{ij\}}$	$\square\square$	$\square$	1	1	1
$\widetilde{Q}^{\{ij\}}$	$\overline{\square\square}$	1	$\overline{\square}$	-1	1
G_μ	Adj	0	0	0	0

Here Q and $\widetilde{Q}$ are Weyl fermions.

The A-type is obtained by substituting $\square\square$ with $\begin{smallmatrix}\square\\\square\end{smallmatrix}$.

CP3 - Origins
Particle Physics & Origin of Mass

Diagram for Symm. Rep.

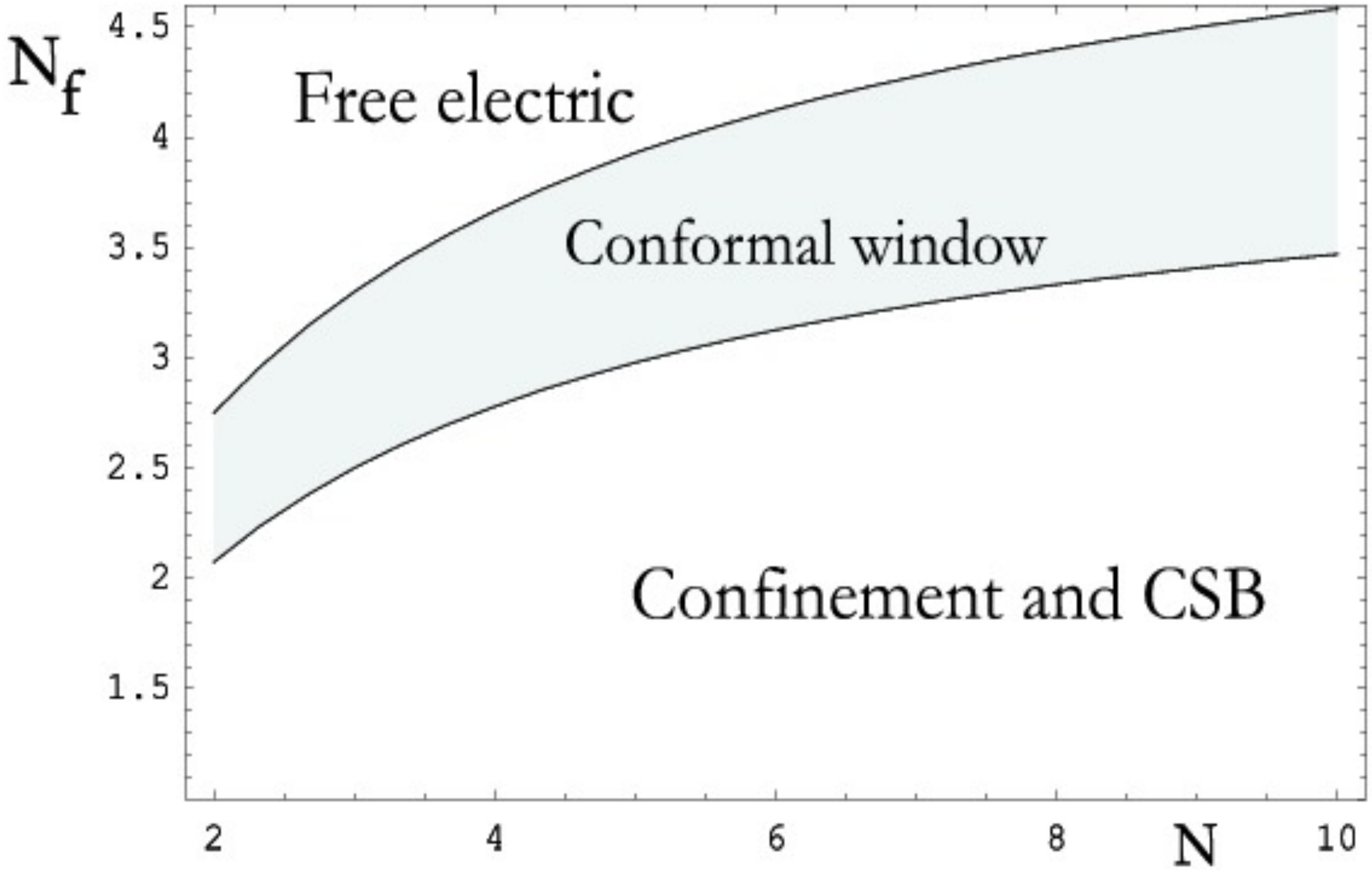
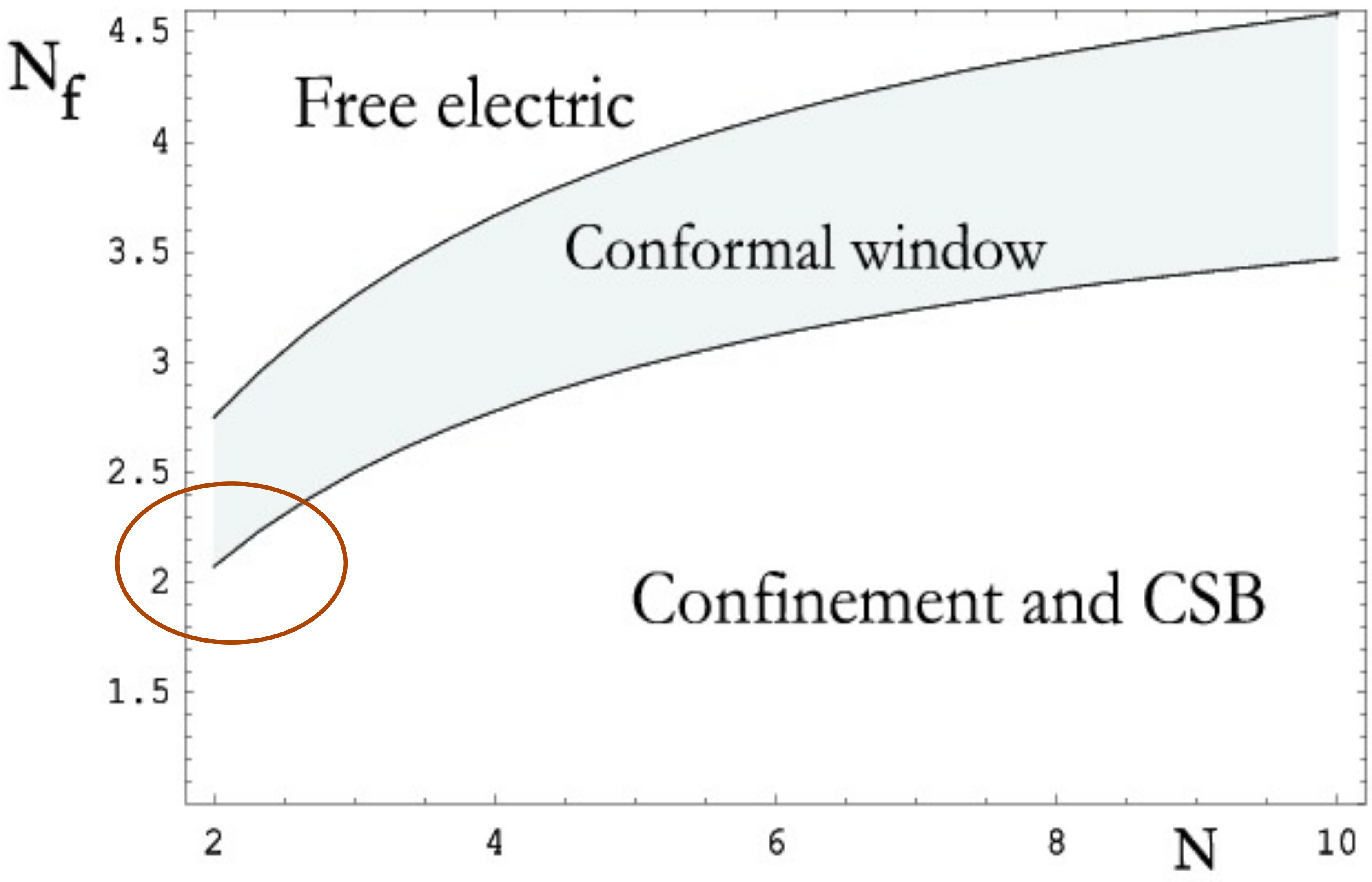
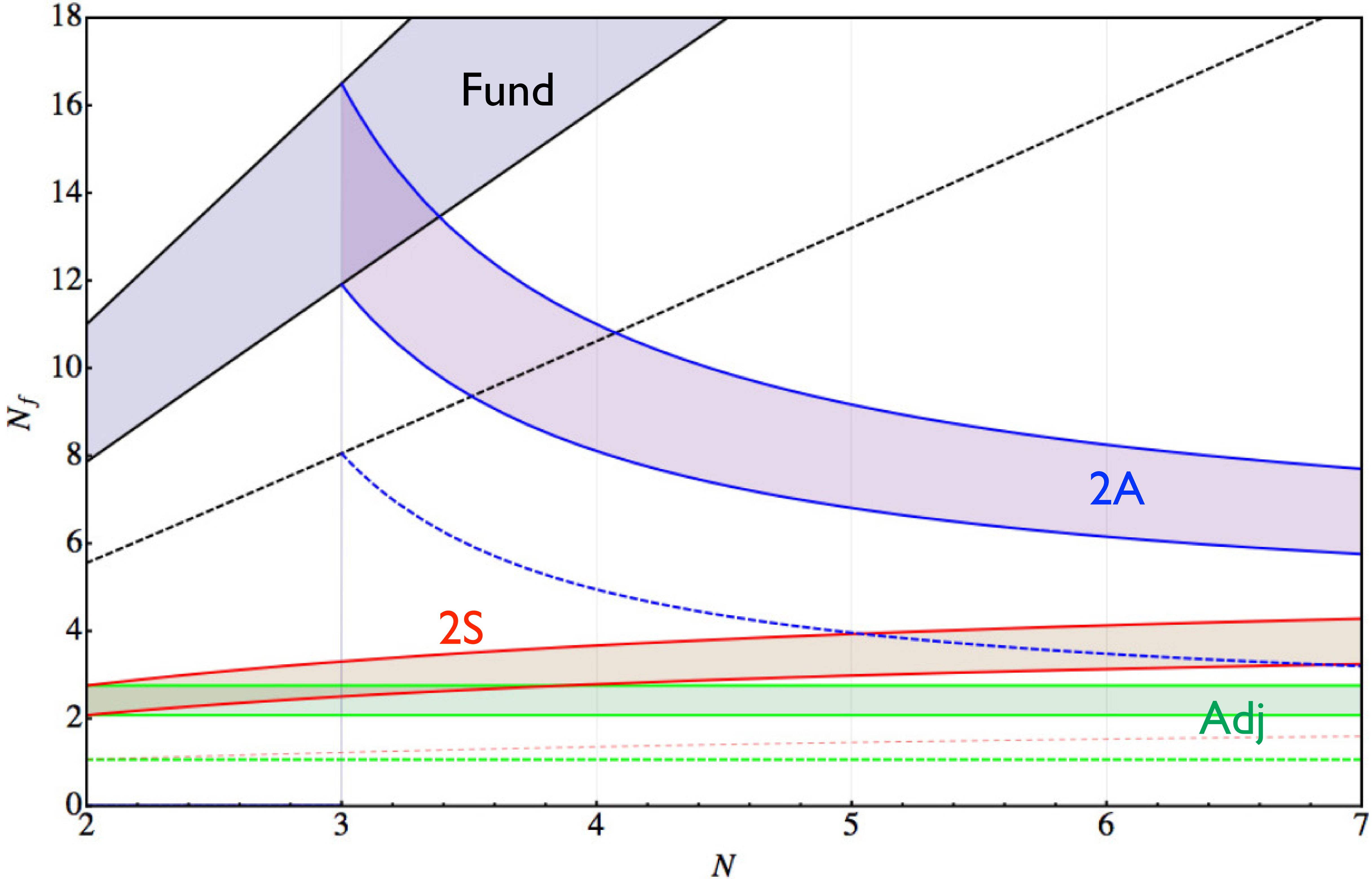


Diagram for Symm. Rep.



SD - Phase Diagram

CP3 - Origins
Particle Physics & Origin of Mass



Ladder approximation

Dietrich and F.S. 06

CP3 - Origins

Particle Physics & Origin of Mass

SUSY

CP3 - Origins
Particle Physics & Origin of Mass

SUSY β function

SUSY β function

NSVZ

SUSY β function

$$\beta(g) = -\frac{g^3}{16\pi^2}\frac{\beta_0 + 2T(r)N_f\gamma(g^2)}{1 - \frac{g^2}{8\pi^2}C_2(G)}$$

NSVZ

SUSY β function

$$\beta(g) = -\frac{g^3}{16\pi^2}\frac{\beta_0 + 2T(r)N_f\gamma(g^2)}{1 - \frac{g^2}{8\pi^2}C_2(G)}$$

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

NSVZ

SUSY β function

$$\beta(g) \;=\; -\frac{g^3}{16\pi^2}\frac{\beta_0 + 2T(r)N_f\gamma(g^2)}{1-\frac{g^2}{8\pi^2}C_2(G)}$$

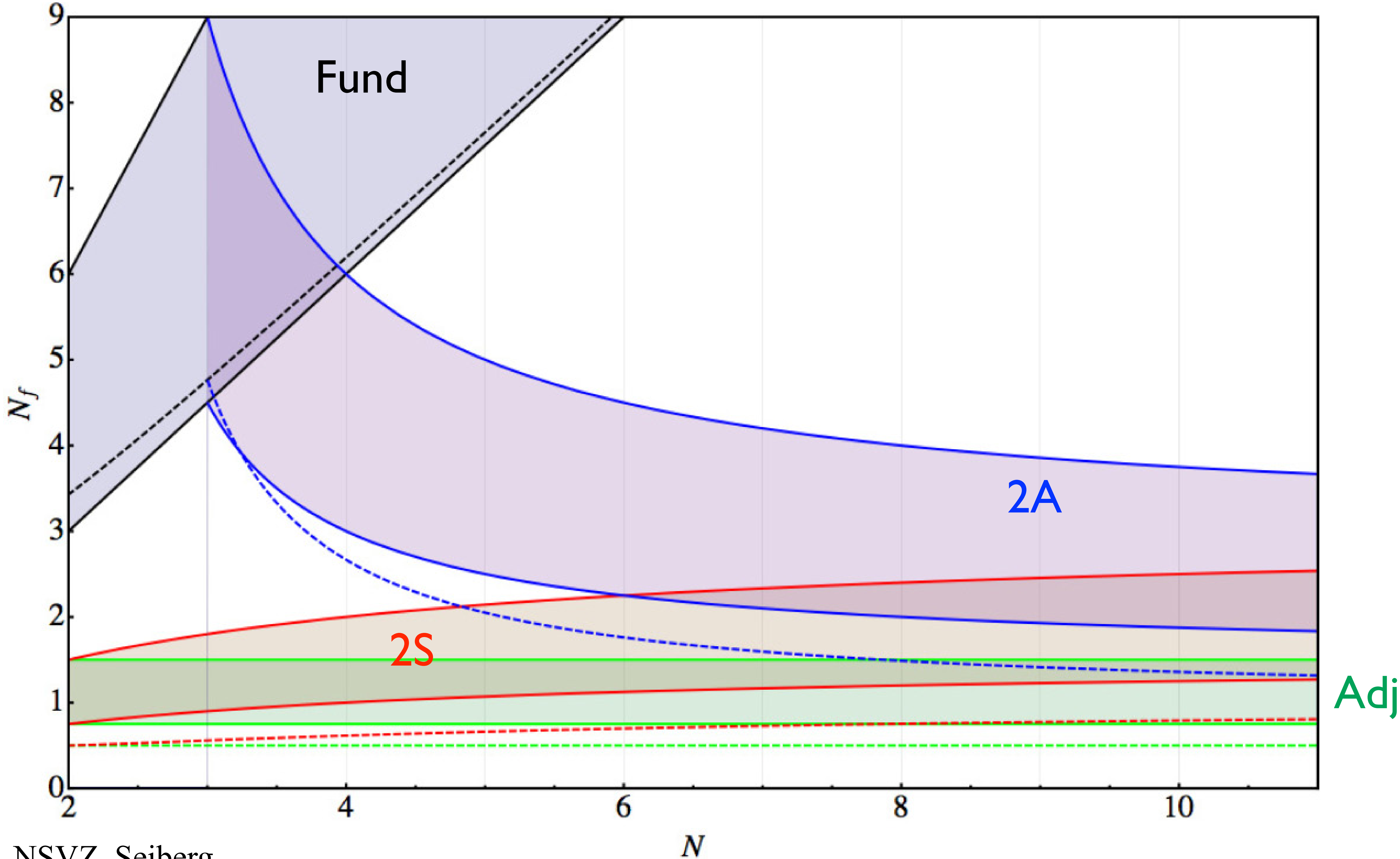
$$\gamma(g^2) \;=\; -\frac{g^2}{4\pi^2}C_2(r) + O(g^4)$$

$$\gamma(g^2) = -d\ln Z(\mu)/d\ln\mu$$

$$\beta_0 = 3C_2(G) - 2T(r)N_f$$

NSVZ

SUSY Phase Diagram



NSVZ, Seiberg
Intriligator-Seiberg

Ryttov and F.S. 07

CP3 - Origins

Particle Physics & Origin of Mass

β - function

Ryttov and F.S. 07

β function conjecture

CP³ - Origins
Particle Physics & Origin of Mass

β function conjecture

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

Ryttov and F.S. 07

β function conjecture

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

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

Ryttov and F.S. 07

CP3 - Origins
Particle Physics & Origin of Mass

β function conjecture

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

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

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

Ryttov and F.S. 07

CP[3] - Origins
Particle Physics & Origin of Mass

β 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

Recovering SYM

$SU(N)$ $\qquad N_f = \frac{1}{2}$ $\qquad$ Adjoint Matter

CP3 - Origins
Particle Physics & Origin of Mass

Recovering SYM

$SU(N) \qquad N_f = \frac{1}{2} \qquad$ Adjoint Matter

Ryttov and F.S. 07

Recovering SYM

$SU(N)$ $\qquad N_f = \frac{1}{2}$ $\qquad$ Adjoint Matter

$$\beta(g) = -\frac{g^3}{(4\pi)^2} 3N \frac{1 - \frac{\gamma_{\rm Adj}}{9}}{1 - \frac{g^2}{8\pi^2}\frac{4N}{3}}$$

Ryttov and F.S. 07

CP3 - Origins
Particle Physics & Origin of Mass

Recovering SYM

$SU(N)$ $N_f = \frac{1}{2}$ Adjoint Matter

$$\beta(g) = -\frac{g^3}{(4\pi)^2} 3N \frac{1 - \frac{\gamma_{\rm Adj}}{9}}{1 - \frac{g^2}{8\pi^2}\frac{4N}{3}}$$

$$\beta_{SYM}(g) = -\frac{g^3}{(4\pi)^2} \frac{3N}{1 - \frac{g^2}{8\pi^2} N}$$

Ryttov and F.S. 07

CP3 - Origins
Particle Physics & Origin of Mass

Recovering SYM

$SU(N)$ $\quad N_f = \frac{1}{2}$ $\quad$ Adjoint Matter

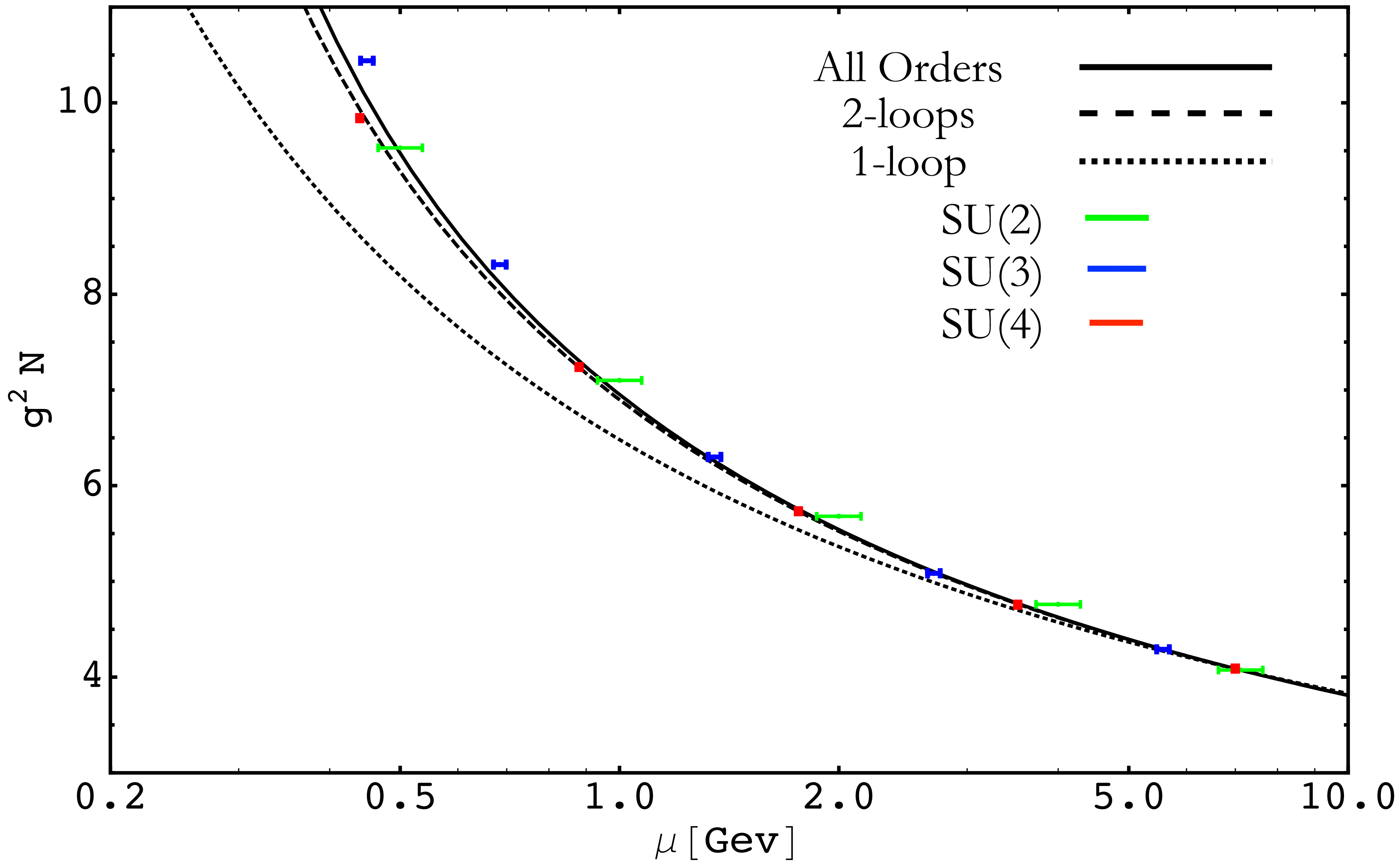
$$\beta(g) = -\frac{g^3}{(4\pi)^2} 3N \frac{1 - \frac{\gamma_{\rm Adj}}{9}}{1 - \frac{g^2}{8\pi^2}\frac{4N}{3}}$$

$$\beta_{SYM}(g) = -\frac{g^3}{(4\pi)^2}\frac{3N}{1 - \frac{g^2}{8\pi^2}N}$$

$$\gamma_{\rm Adj} = \frac{g^2}{8\pi^2}\frac{3N}{1 - \frac{g^2}{8\pi^2}N}$$

Ryttov and F.S. 07

Confronting with YM



Luscher, Sommer, Wolff, Weisz, 92	SU(2)
Luscher, Sommer, Weisz, Wolff 94	SU(3)
Lucini and Moraitis 07	SU(4)

CP³ - Origins
Particle Physics & Origin of Mass

Bounding the window

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

Unitarity of the Conformal Operators demands:

$$\gamma \leq 2$$

Ryttov and F.S. 07

Confronting with YM

SU(N) Adjoint Dirac Matter

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

Confronting with YM

SU(N) Adjoint Dirac Matter

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

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

Confronting with YM

SU(N) Adjoint Dirac Matter

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

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

$$N^c_{f\,\mathrm{Ladder}} = 2.075$$

Confronting with YM

SU(N) Adjoint Dirac Matter

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

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

Conformal in the IR

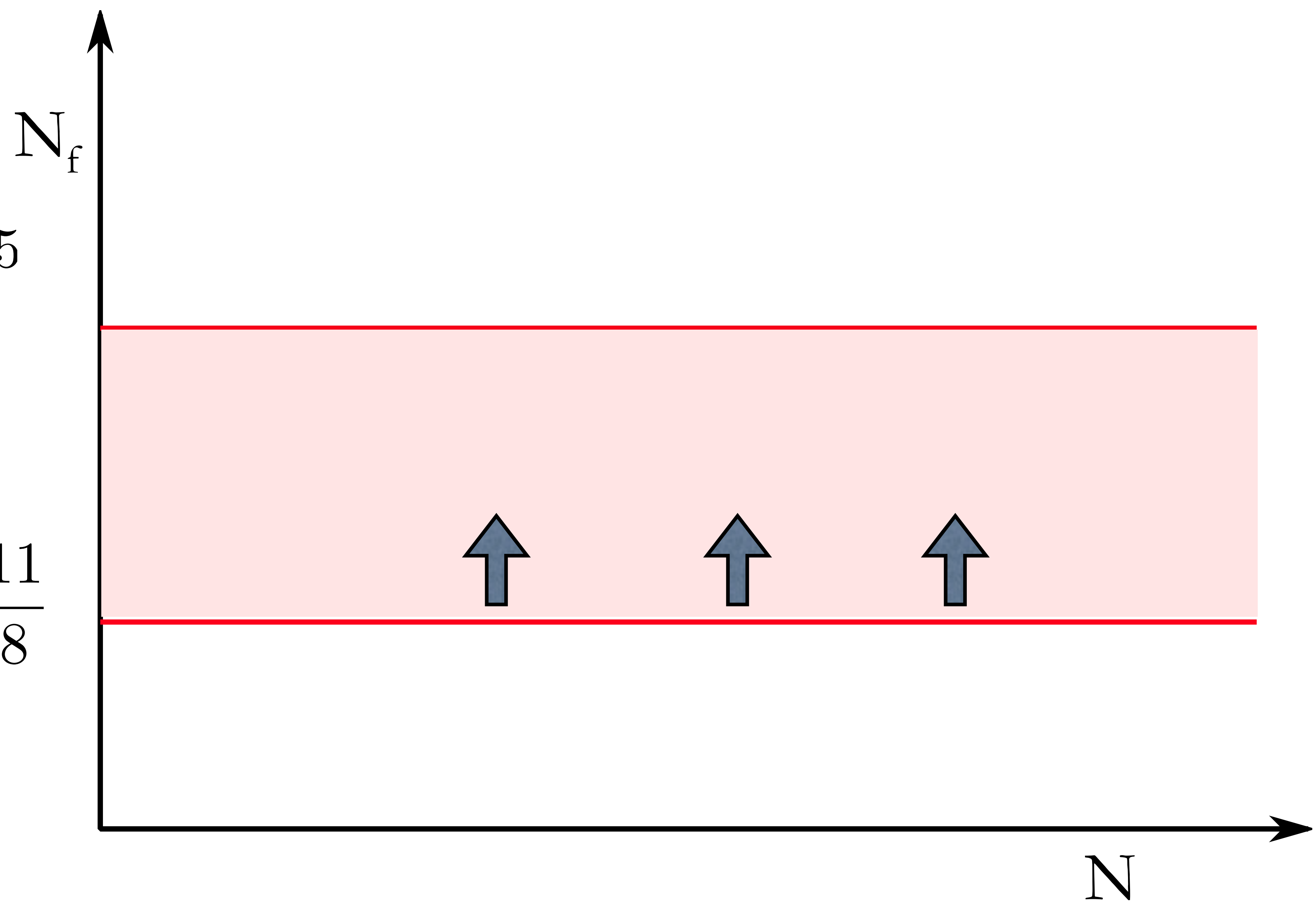
$$N^c_{f\,\text{Ladder}} = 2.075$$

Back to the example

SU(N) Adjoint Dirac Matter

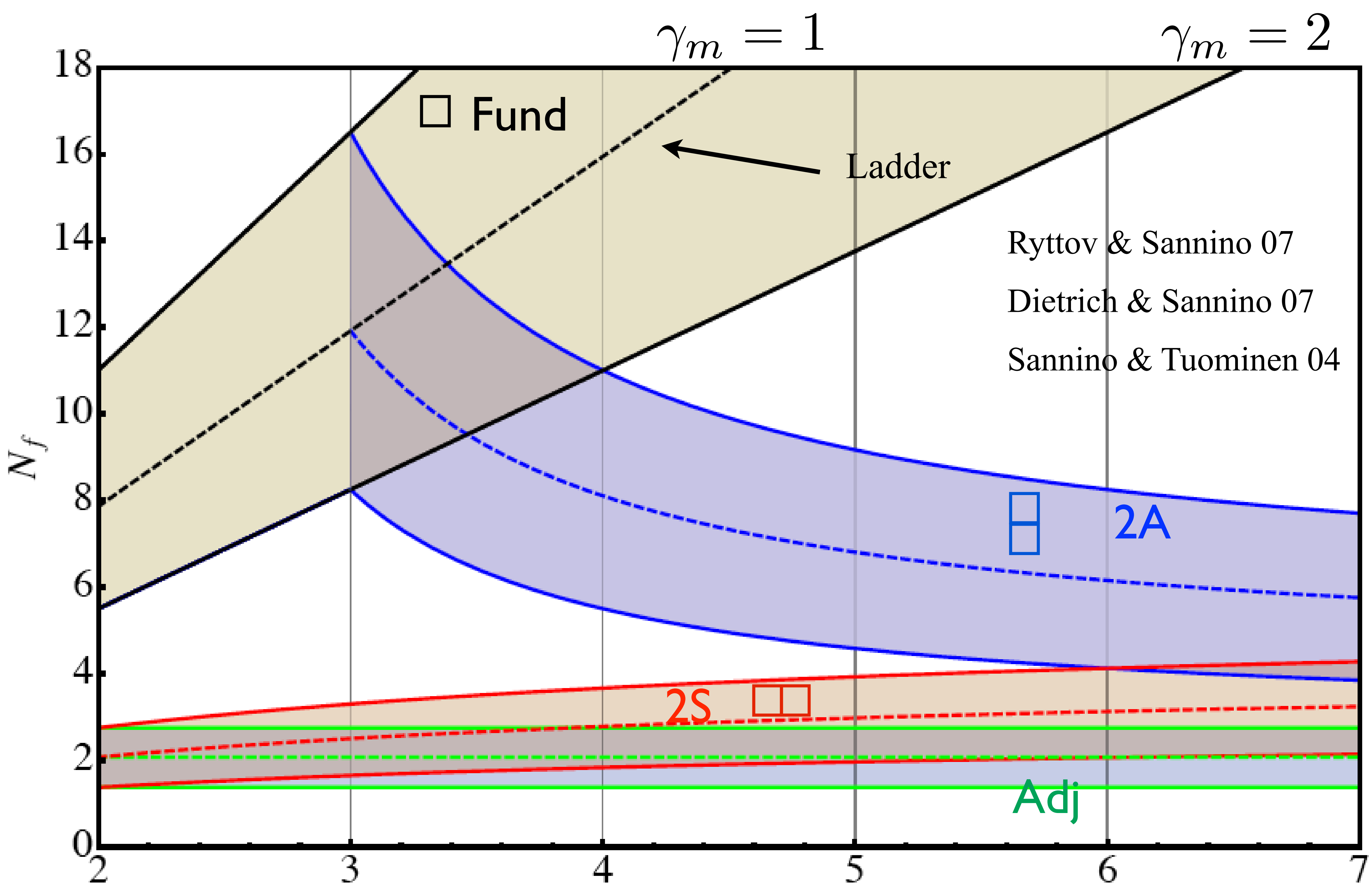
$$N_f^{\rm Asymp} = 2.75$$

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



Universal Picture

SU(N) Phase Diagram

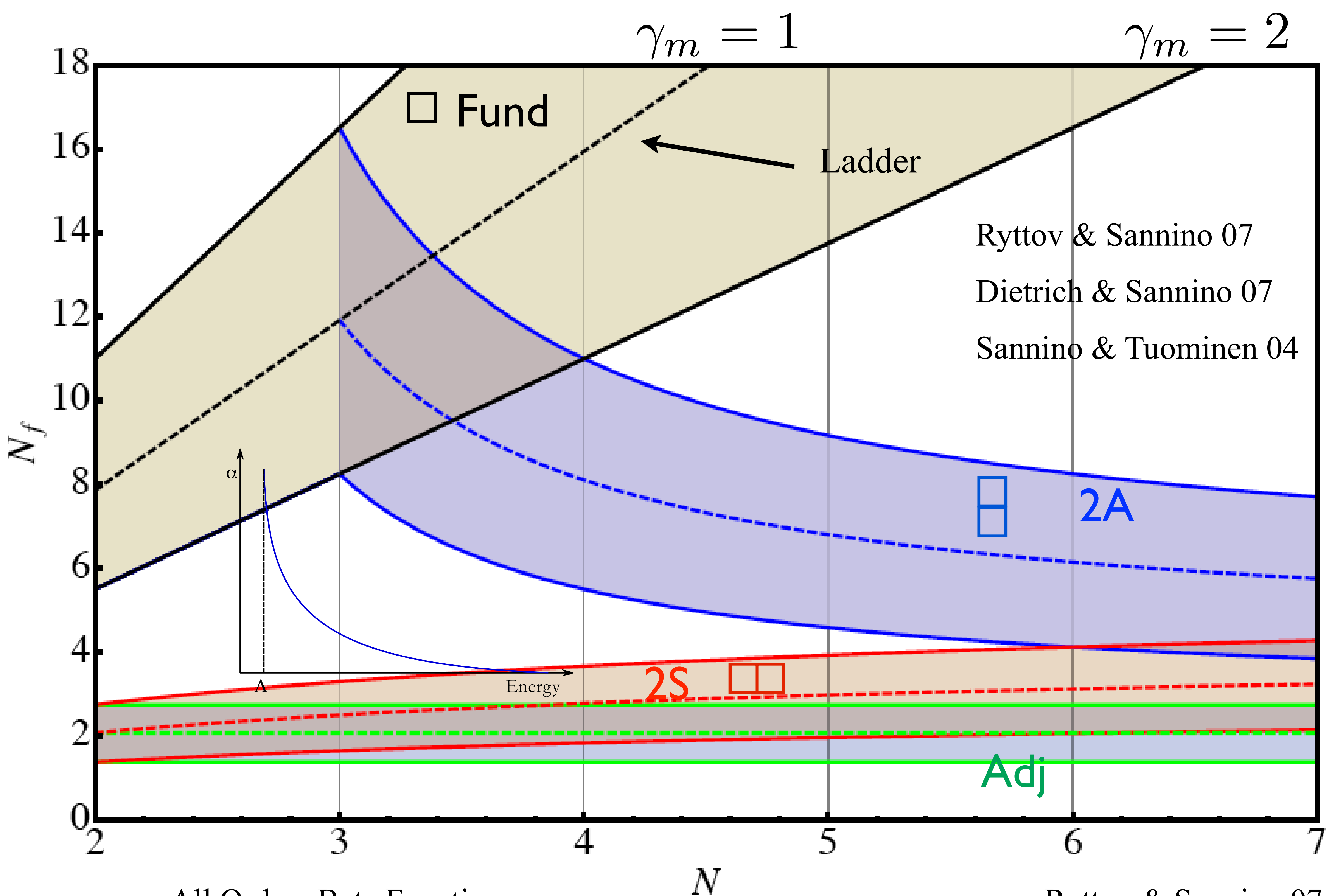


All Orders Beta Function

Ryttov & Sannino 07

CP3 - Origins
Particle Physics & Origin of Mass

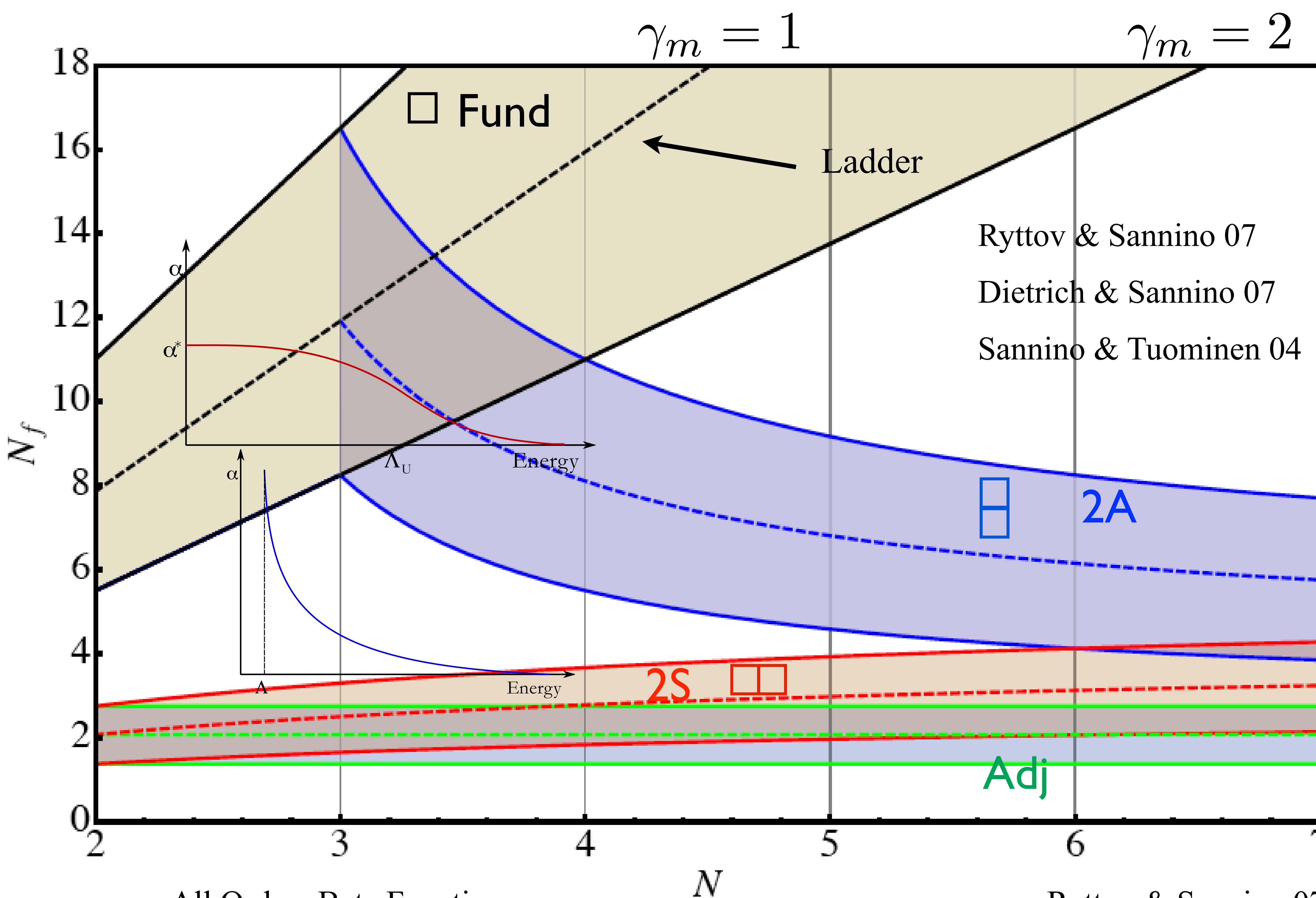
SU(N) Phase Diagram



All Orders Beta Function

Ryttov & Sannino 07

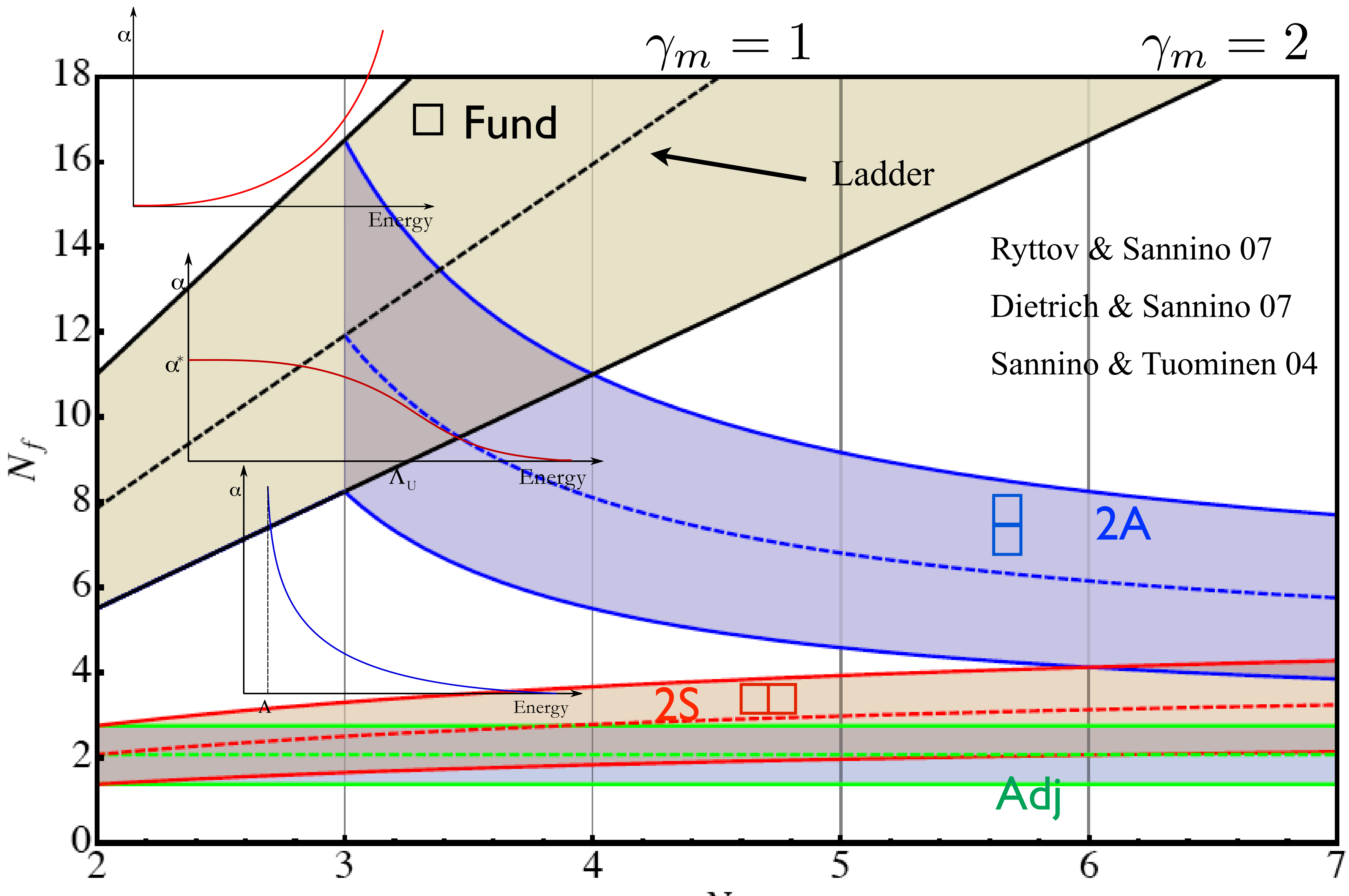
SU(N) Phase Diagram



All Orders Beta Function

Ryttov & Sannino 07

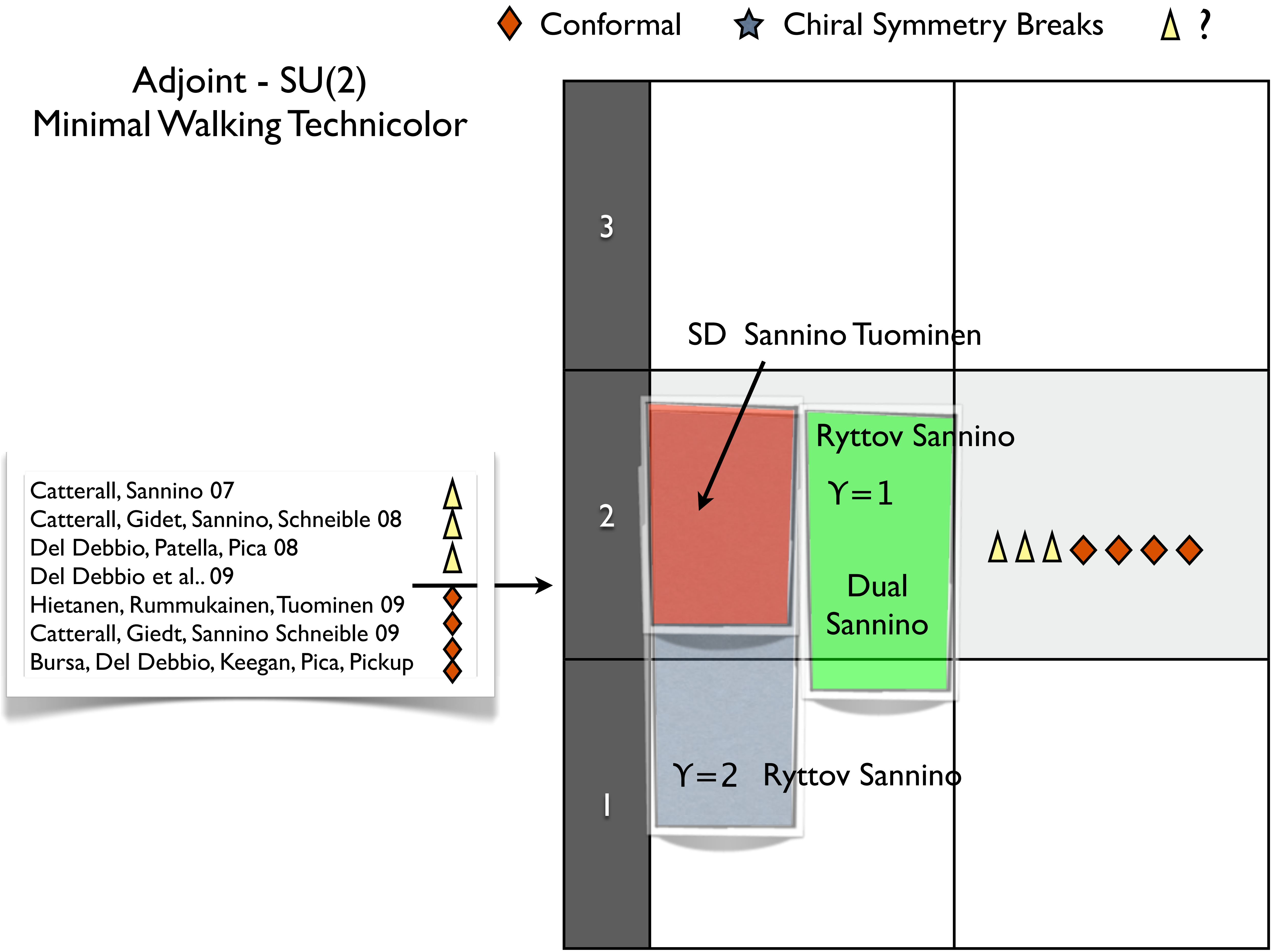
SU(N) Phase Diagram



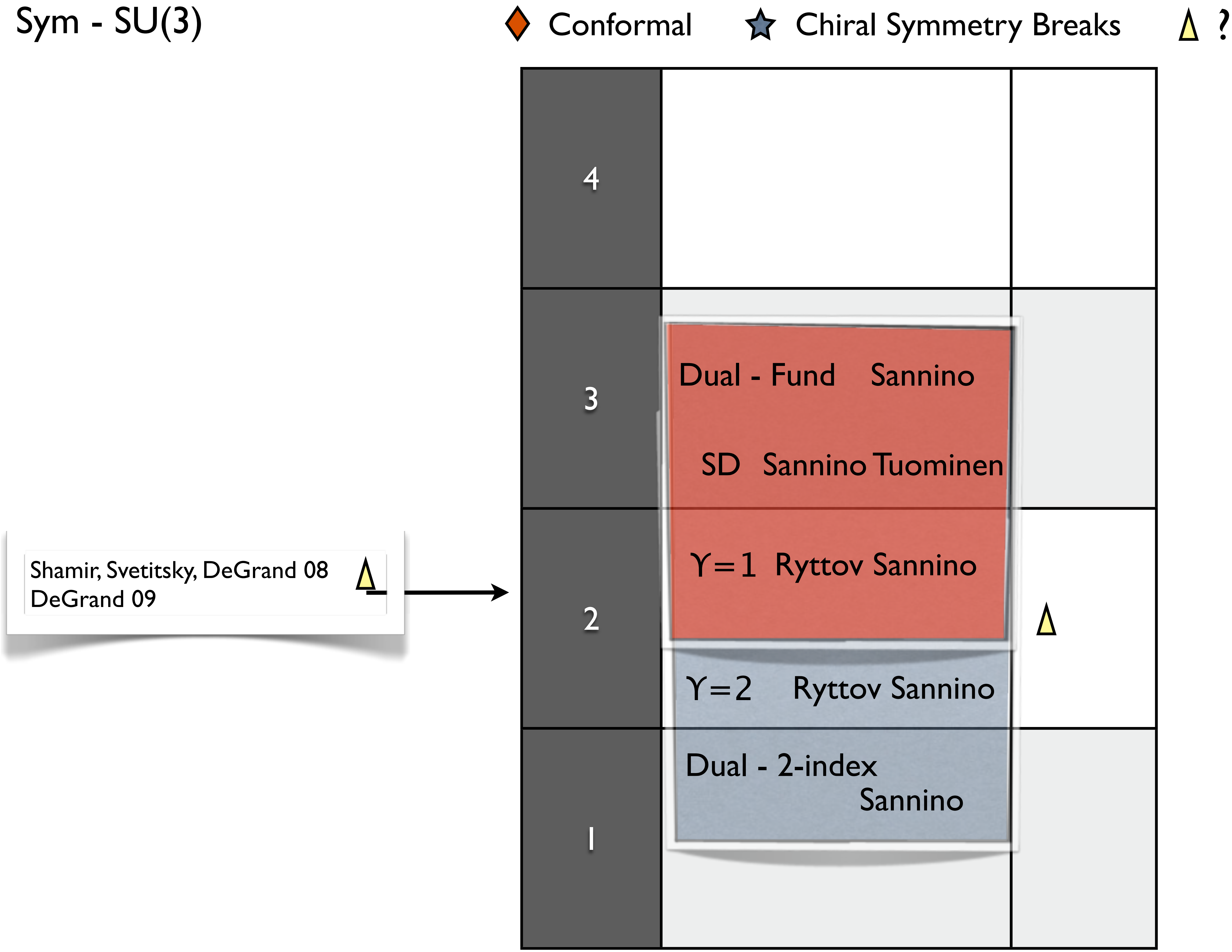
All Orders Beta Function

Ryttov & Sannino 07

Adjoint - SU(2)
Minimal Walking Technicolor

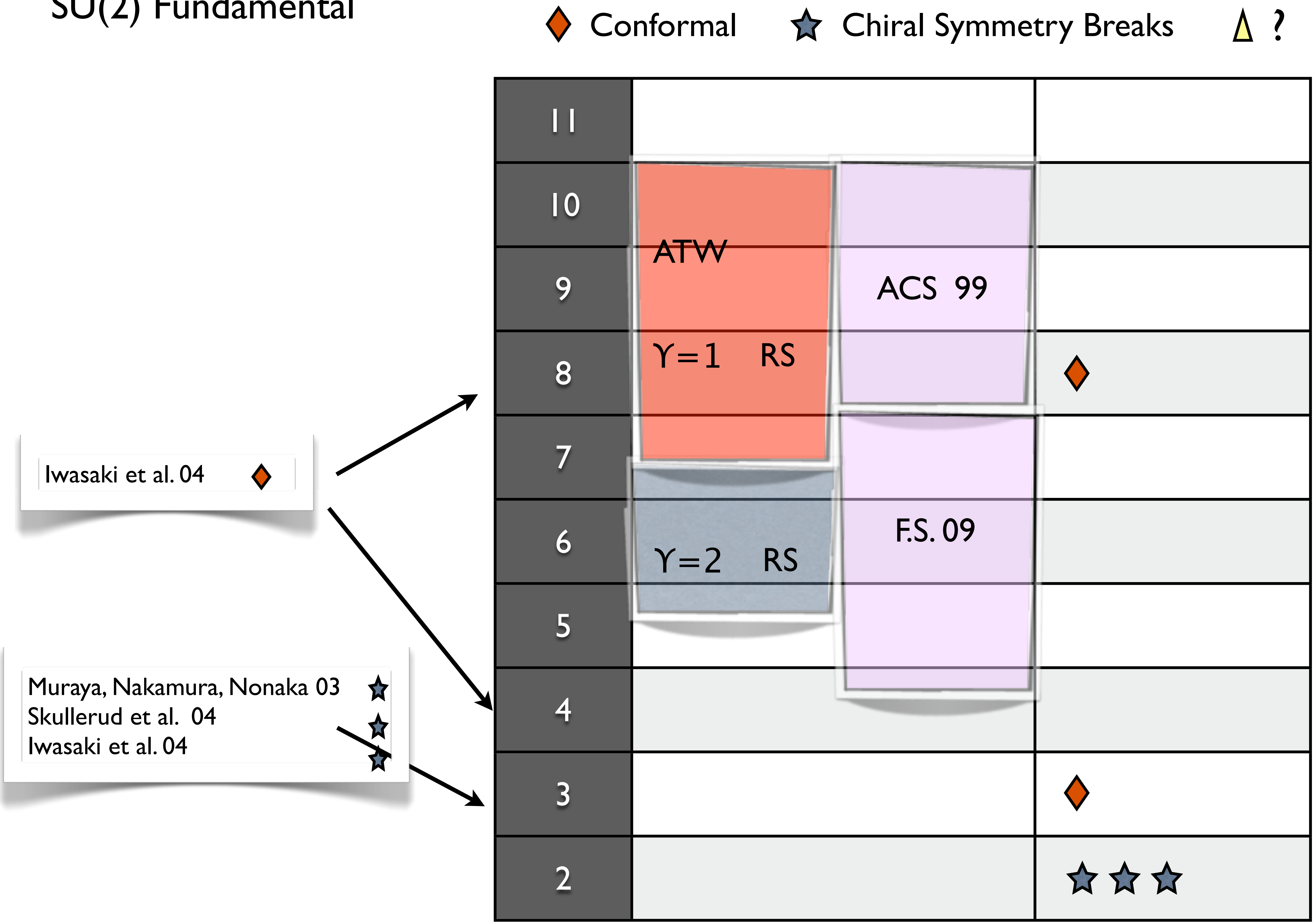


Sym - SU(3)



Conformal
Chiral Symmetry Breaks
?
Shamir, Svetitsky, DeGrand 08
DeGrand 09
4
3
2
1
Dual - Fund Sannino
SD Sannino Tuominen
ϒ=1 Ryttov Sannino
ϒ=2 Ryttov Sannino
Dual - 2-index
Sannino

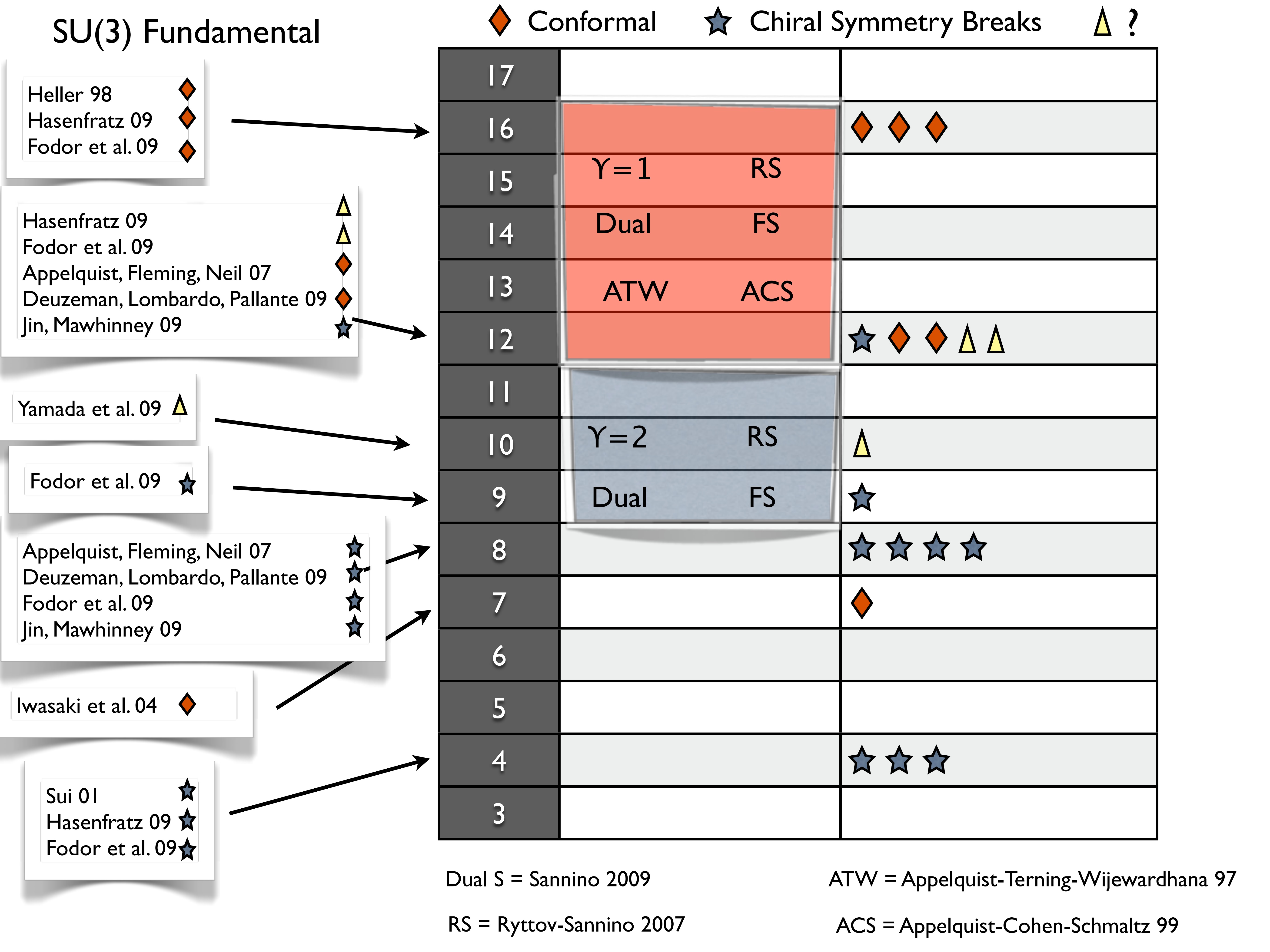
SU(2) Fundamental



RS = Ryttov-Sannino 2007

ATW = Appelquist-Terning-Wijewardhana 97

ACS = Appelquist-Cohen-Schmaltz 99



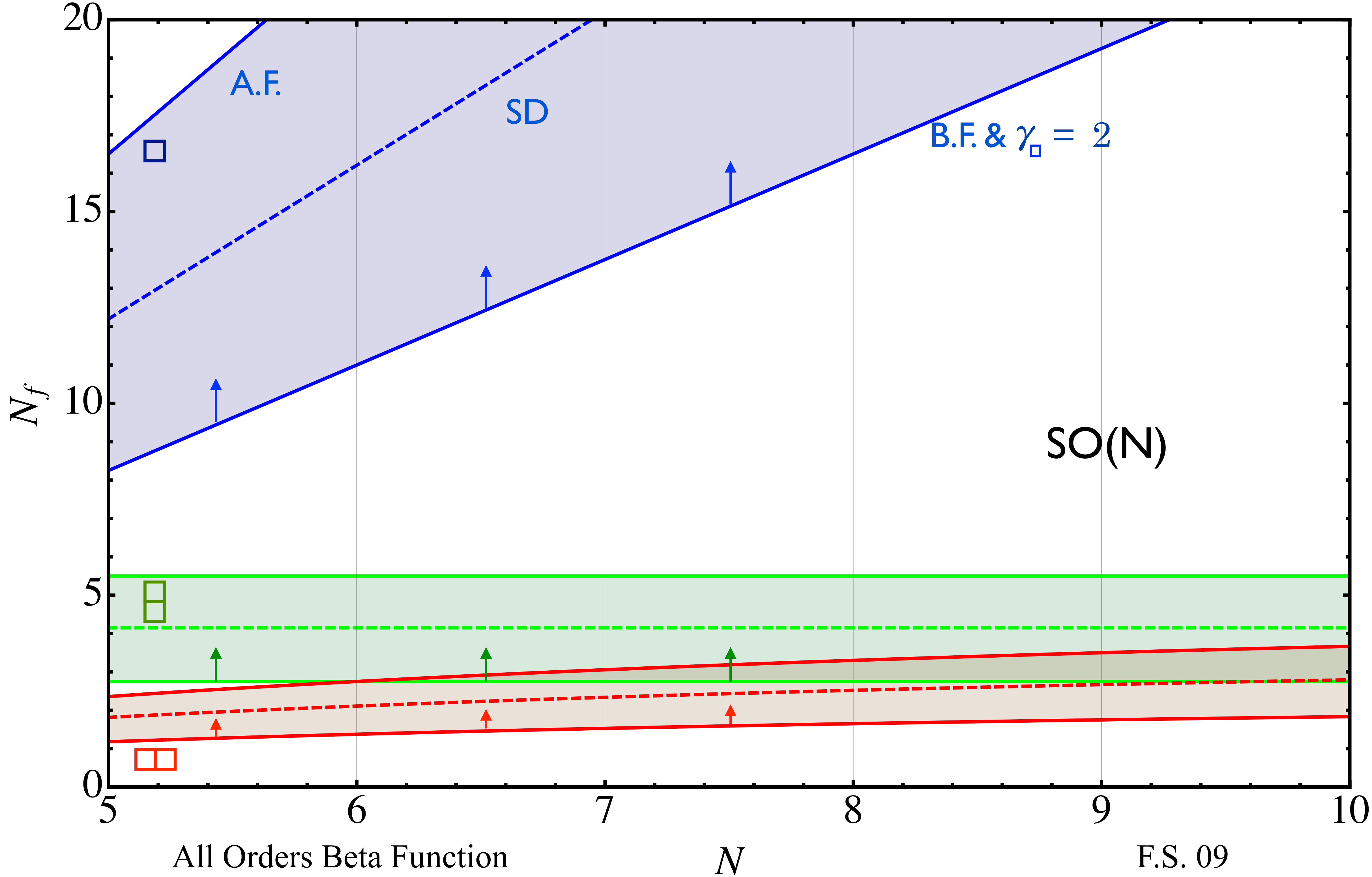
SU(3) Fundamental
Conformal
Chiral Symmetry Breaks
?
Heller 98
Hasenfratz 09
Fodor et al. 09
Hasenfratz 09
Fodor et al. 09
Appelquist, Fleming, Neil 07
Deuzeman, Lombardo, Pallante 09
Jin, Mawhinney 09
Yamada et al. 09
Fodor et al. 09
Appelquist, Fleming, Neil 07
Deuzeman, Lombardo, Pallante 09
Fodor et al. 09
Jin, Mawhinney 09
Iwasaki et al. 04
Sui 01
Hasenfratz 09
Fodor et al. 09
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
ϒ=1
RS
Dual
FS
ATW
ACS
ϒ=2
RS
Dual
FS
Dual S = Sannino 2009
RS = Ryttov-Sannino 2007
ATW = Appelquist-Terning-Wijewardhana 97
ACS = Appelquist-Cohen-Schmaltz 99

CP3 - Origins

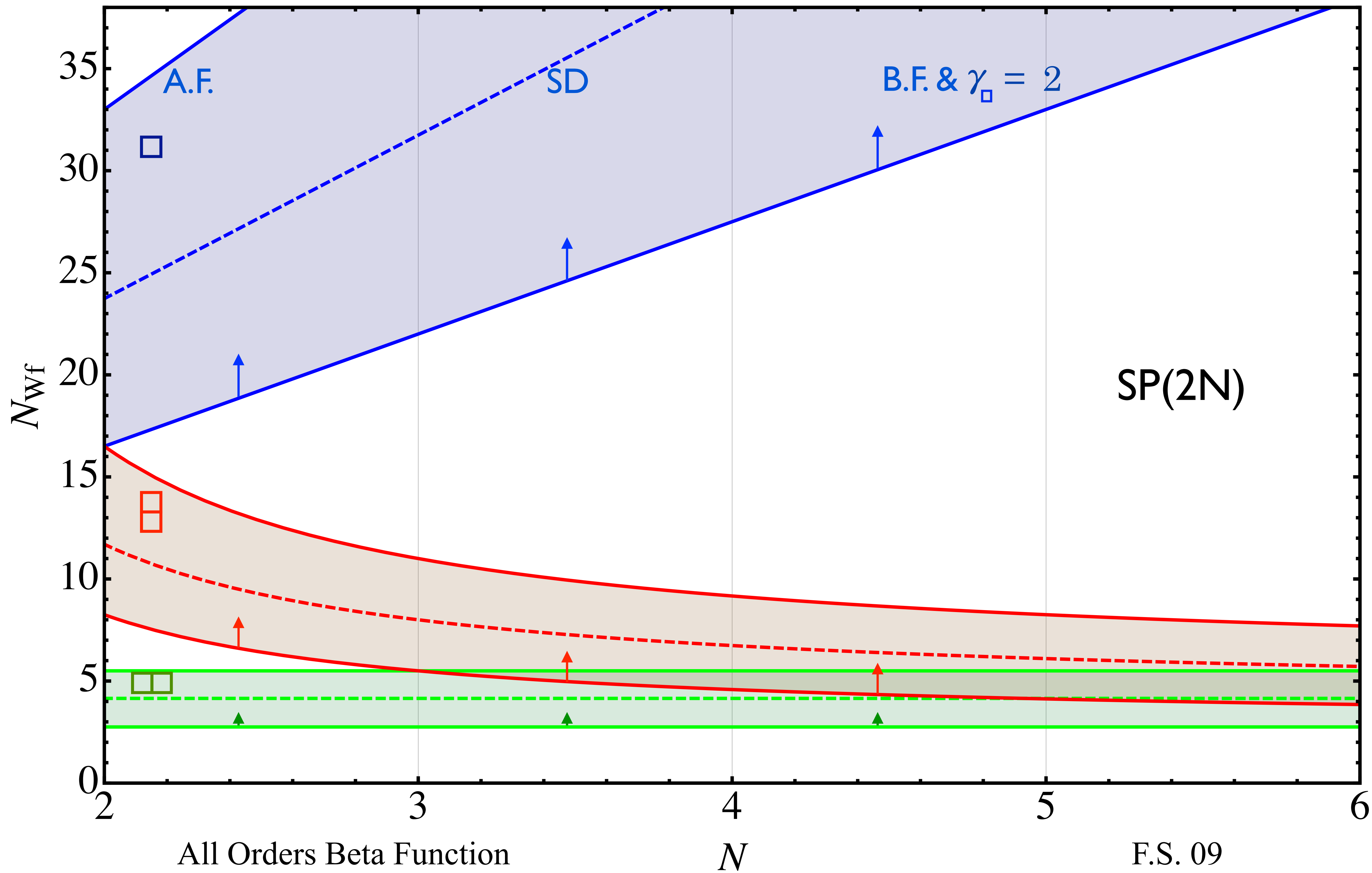
Particle Physics & Origin of Mass

Be imaginative!

SO(N) Phase Diagram



Sp(N) Phase Diagram



Chiral Gauge Theories

What does chiral mean?

Cannot give a mass term in the Lagrangian

What does chiral mean?

Cannot give a mass term in the Lagrangian

Why study them?

What does chiral mean?

Cannot give a mass term in the Lagrangian

Why study them?

The Standard Model is chiral

What does chiral mean?

Cannot give a mass term in the Lagrangian

Why study them?

The Standard Model is chiral

Grand Unifications

What does chiral mean?

Cannot give a mass term in the Lagrangian

Why study them?

The Standard Model is chiral

Grand Unifications

Extended technicolor models

What does chiral mean?

Cannot give a mass term in the Lagrangian

Why study them?

The Standard Model is chiral

Grand Unifications

Extended technicolor models

First principle lattice computations are impossible

Bars - Yankielowicz (BY)

Fields	$[SU(N)]$	$SU(N+4+p)$	$SU(p)$	$U_1(1)$	$U_2(1)$
S	$\square\square$	1	1	$N+4$	$2p$
$\bar{F}$	$\bar{\square}$	$\bar{\square}$	1	$-(N+2)$	$-p$
F	$\square$	1	$\square$	$N+2$	$-(N-p)$

Bars - Yankielowicz (BY)

Fields	$[SU(N)]$	$SU(N+4+p)$	$SU(p)$	$U_1(1)$	$U_2(1)$
S	$\square\square$	1	1	$N+4$	$2p$
$\bar{F}$	$\bar{\square}$	$\bar{\square}$	1	$-(N+2)$	$-p$
F	$\square$	1	$\square$	$N+2$	$-(N-p)$

Generalized Georgi-Glashow (GGG)

Fields	$[SU(N)]$	$SU(N-4+p)$	$SU(p)$	$U_1(1)$	$U_2(1)$
A	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	1	$N-4$	$2p$
$\bar{F}$	$\bar{\square}$	$\bar{\square}$	1	$-(N-2)$	$-p$
F	$\square$	1	$\square$	$N-2$	$-(N-p)$

Chiral beta function conjecture

$$\beta_\chi(g) = -\frac{g^3}{(4\pi)^2}\frac{\beta_0 - \frac{2}{3}\sum_{i=1}^{k} T(r_i)p(r_i)\gamma_i(g^2)}{1 - \frac{g^2}{8\pi^2}C_2(G)\left(1 + \frac{2\beta'_\chi}{\beta_0}\right)}$$

$p(r_i)$ vector-like pairs

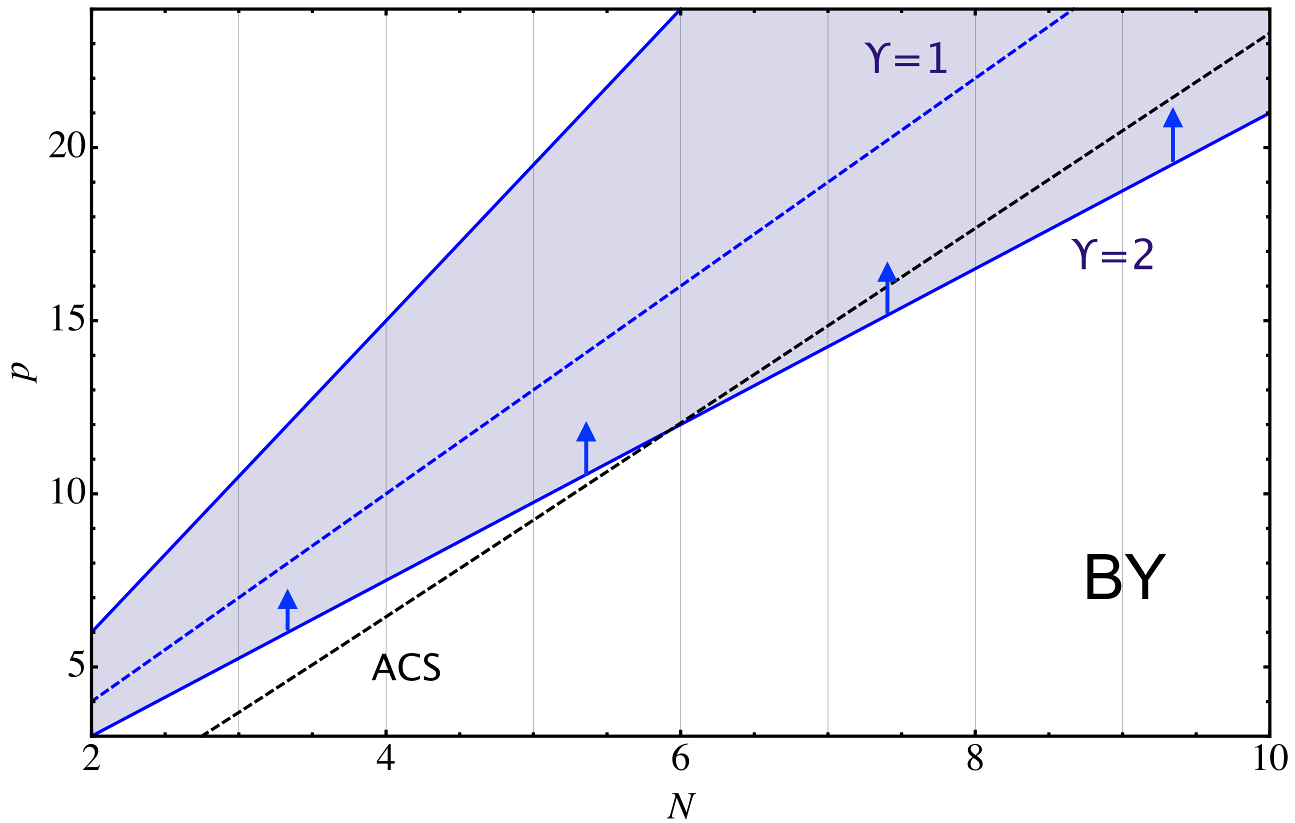
γ_i mass anomalous dimension

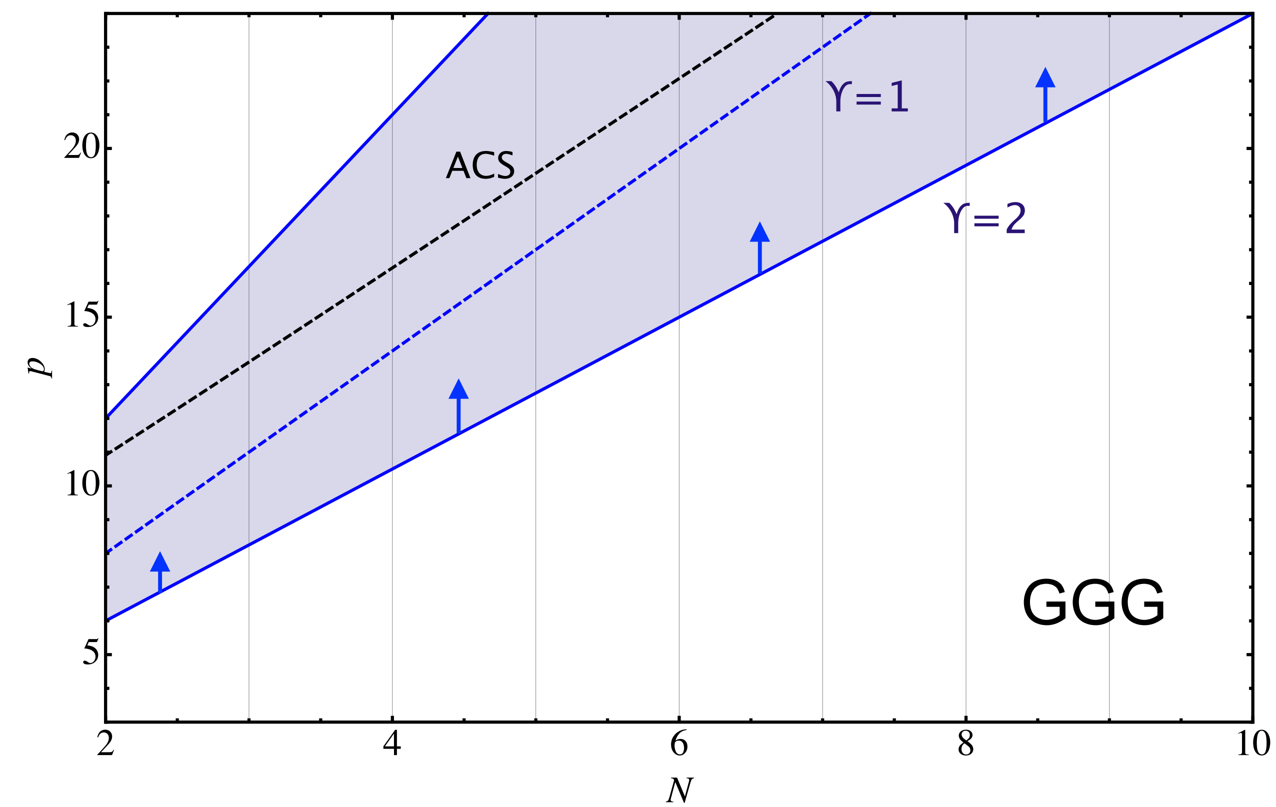
β_0 one-loop coefficient

β'_χ Fixed to agree with the 2-loop coefficient

F.S. 09

Chiral Gauge Theories Phase Diagram





Chiral Beta Function F.S. 09

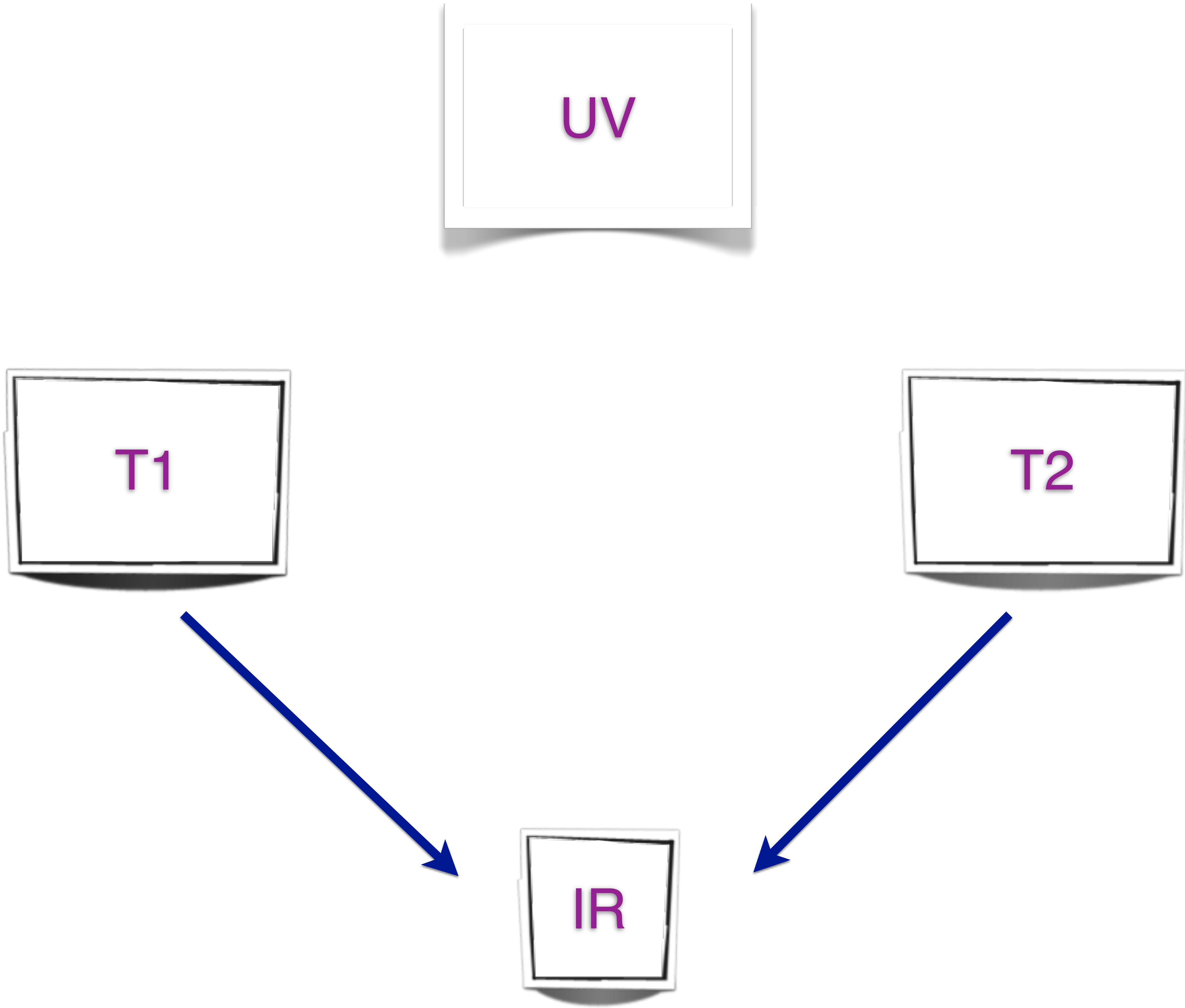
Thermal: Appelquist, Cohen, Schmaltz, Shrock 99

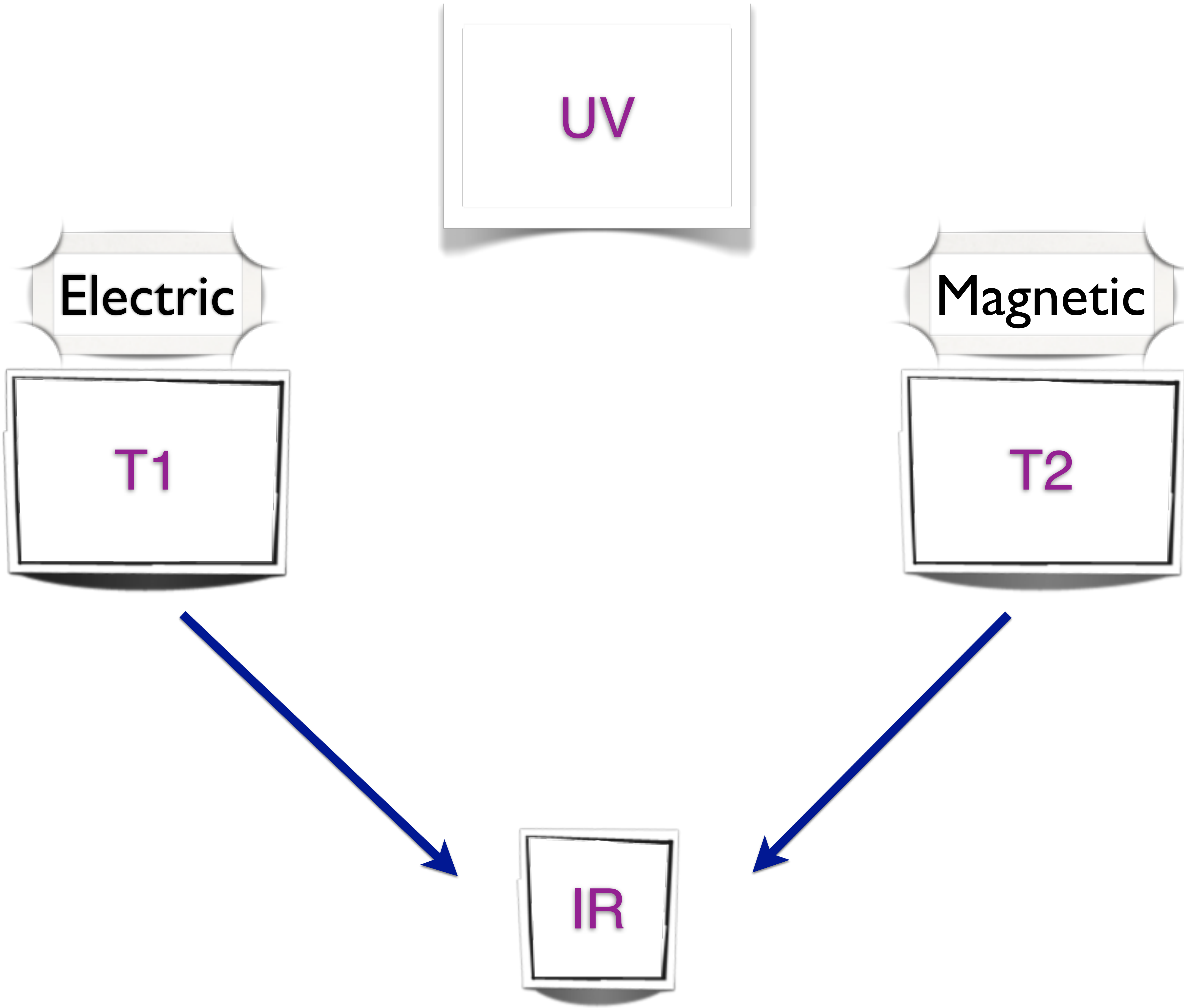
Appelquist, Duan, F.S., 2000

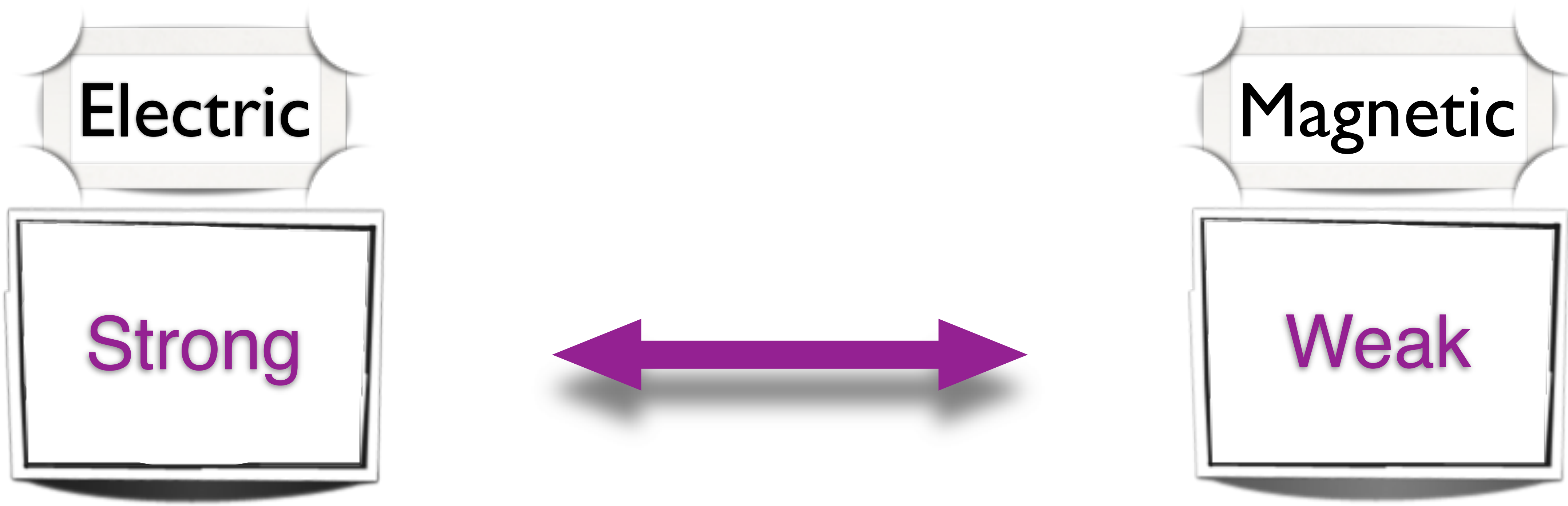
Poppitz & Unsal have similar results with a different method

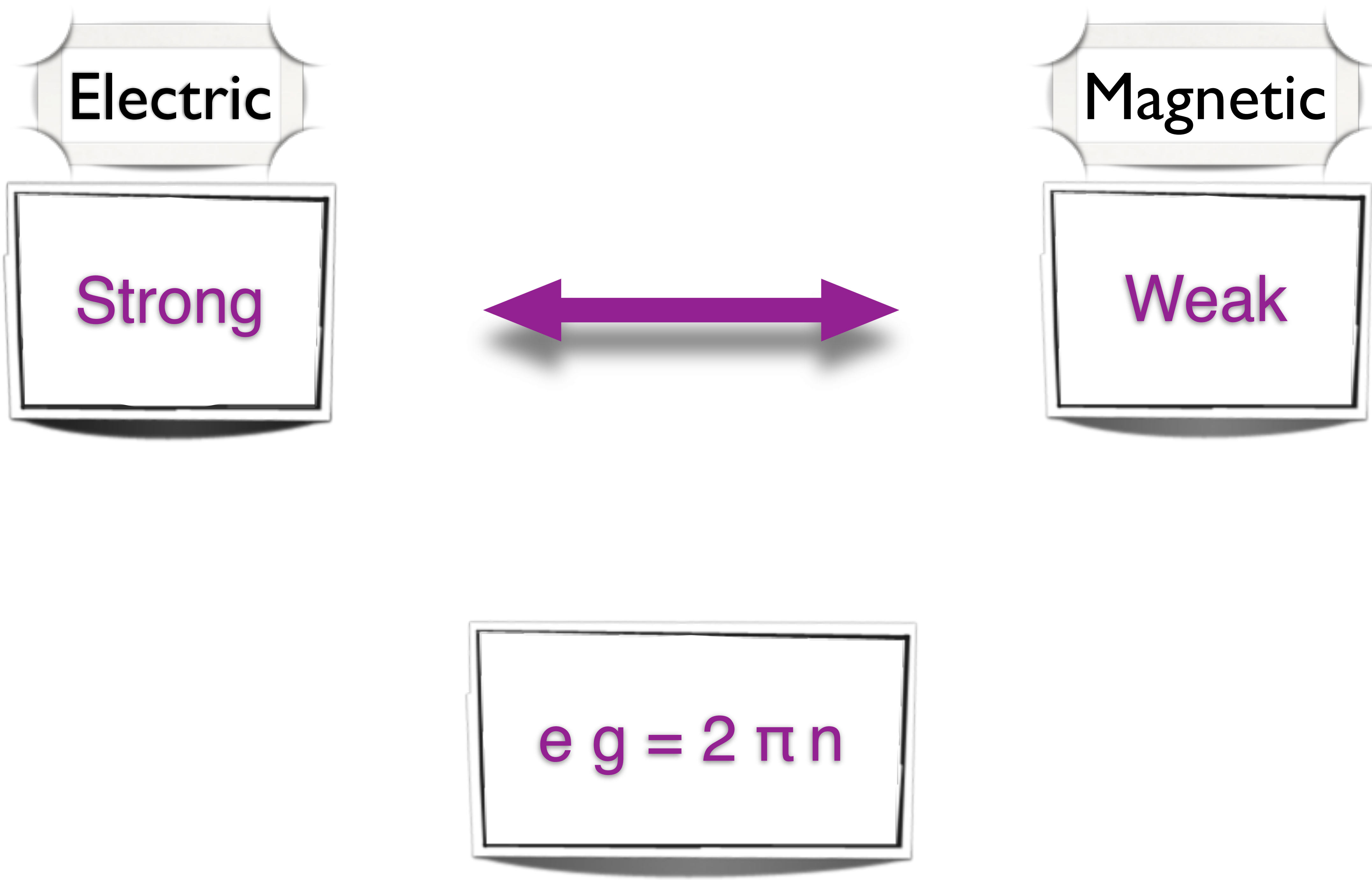
Duals


UV
T1
T2


UV
T1
T2
IR


UV
Electric
Magnetic
T1
T2
IR


Electric
Strong
Magnetic
Weak


Electric
Magnetic
Strong
Weak
e g = 2 π n

QCD Dual

F.S. 09

QCD Dual

Within the Conformal Window

QCD Dual

Within the Conformal Window

‘t Hooft Anomaly Conditions Respected

QCD Dual

Within the Conformal Window

‘t Hooft Anomaly Conditions Respected

Operator Matching

QCD Dual

Within the Conformal Window

‘t Hooft Anomaly Conditions Respected

Operator Matching

Flavor Decoupling

QCD Dual

Within the Conformal Window

‘t Hooft Anomaly Conditions Respected

Operator Matching

Flavor Decoupling

RS beta function

QCD Dual

F.S. 09

Within the Conformal Window

‘t Hooft Anomaly Conditions Respected

Operator Matching

Flavor Decoupling

RS beta function

Super QCD   Seiberg 96

QCD Dual

F.S. 09

Within the Conformal Window

‘t Hooft Anomaly Conditions Respected

Operator Matching

Flavor Decoupling

RS beta function

Super QCD   Seiberg 96

Previous attempt Terning 98

Fields	$[SU(3)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$
Q	$\square$	$\square$	1	1
$\widetilde{Q}$	$\overline{\square}$	1	$\overline{\square}$	-1
G_μ	Adj	1	1	1

T1

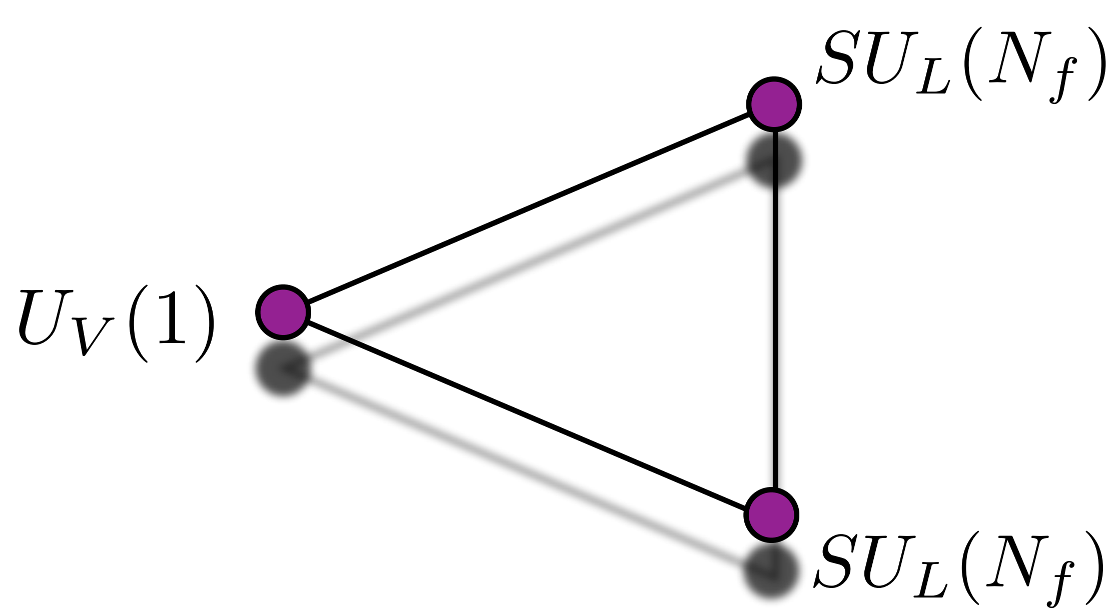
Fields	$[SU(3)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$
Q	$\square$	$\square$	1	1
$\widetilde{Q}$	$\overline{\square}$	1	$\overline{\square}$	-1
G_μ	Adj	1	1	1

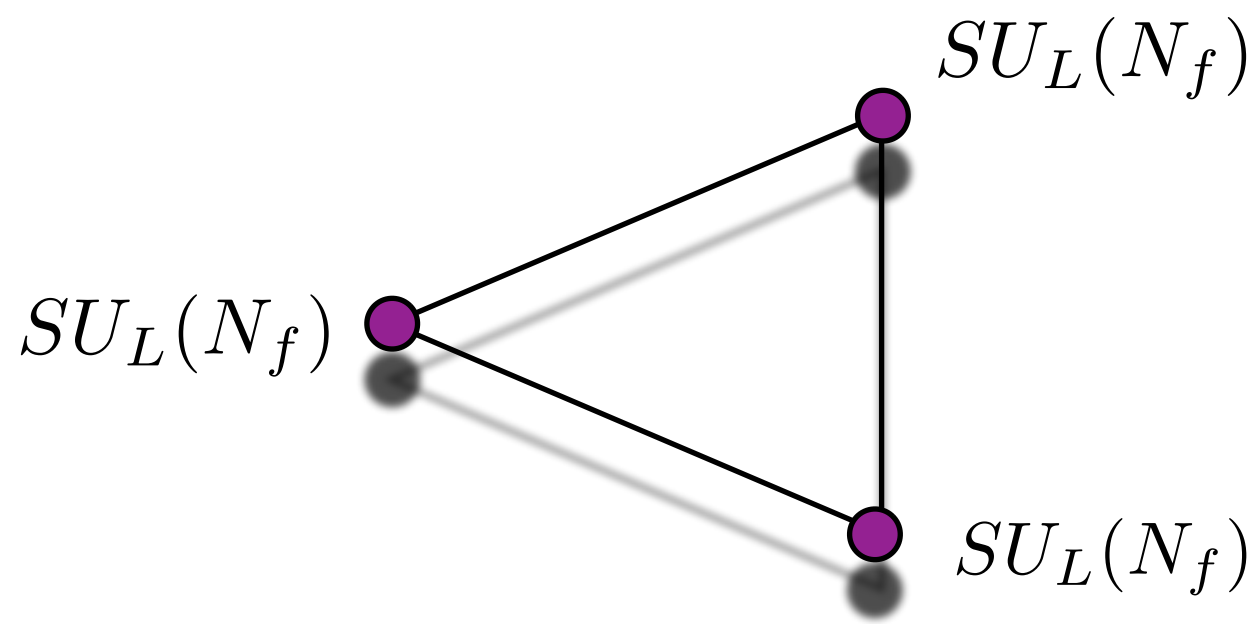
T1

T2

Fields	$[SU(X)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	# of copies
q	$\square$	$\square$	1	y	1
$\widetilde{q}$	$\overline{\square}$	1	$\overline{\square}$	$-y$	1
A	1	$\yng(1,1,1)$	1	3	ℓ_A
S	1	$\yng(3)$	1	3	ℓ_S
C	1	$\yng(2,1)$	1	3	ℓ_C
B_A	1	$\yng(1,1)$	$\square$	3	ℓ_{B_A}
B_S	1	$\yng(2)$	$\square$	3	ℓ_{B_S}
D_A	1	$\square$	$\yng(1,1)$	3	ℓ_{D_A}
D_S	1	$\square$	$\yng(2)$	3	ℓ_{D_S}
$\widetilde{A}$	1	1	$\overline{\yng(1,1,1)}$	-3	$\ell_{\widetilde{A}}$
$\widetilde{S}$	1	1	$\overline{\yng(3)}$	-3	$\ell_{\widetilde{S}}$
$\widetilde{C}$	1	1	$\overline{\yng(2,1)}$	-3	$\ell_{\widetilde{C}}$

‘t Hooft Anomaly Matching





Operator Matching

Magnetic	Electric
$A, \ S, \ \ldots.$	Baryons
M	$M \sim \overline{Q}Q$
$\epsilon_{c_1 \ldots . c_X} q^{c_1} \cdots q^{c_X}$	Baryonic bound states

A QCD Dual

F.S. 09

Fields	$[SU(2N_f - 5N)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	# of copies
q	$\square$	$\square$	1	$\frac{N(2N_f-5)}{2N_f-5N}$	1
$\widetilde{q}$	$\overline{\square}$	1	$\overline{\square}$	$-\frac{N(2N_f-5)}{2N_f-5N}$	1
A	1	$\begin{array}{c}\square\\\square\\\square\end{array}$	1	3	2
B_A	1	$\begin{array}{c}\square\\\square\end{array}$	$\square$	3	-2
D_A	1	$\square$	$\begin{array}{c}\square\\\square\end{array}$	3	2
$\widetilde{A}$	1	1	$\overline{\begin{array}{c}\square\\\square\\\square\end{array}}$	-3	2

Dual Theory

$$L_{\text{Dual}} = L_{\text{Kin}}\left[q, \tilde{q}, A, B_A, D_A, \tilde{A}\right] + L_M$$

Dual Theory

$$L_{\rm Dual} = L_{\rm Kin}\left[q, \tilde{q}, A, B_A, D_A, \tilde{A}\right] + L_M$$

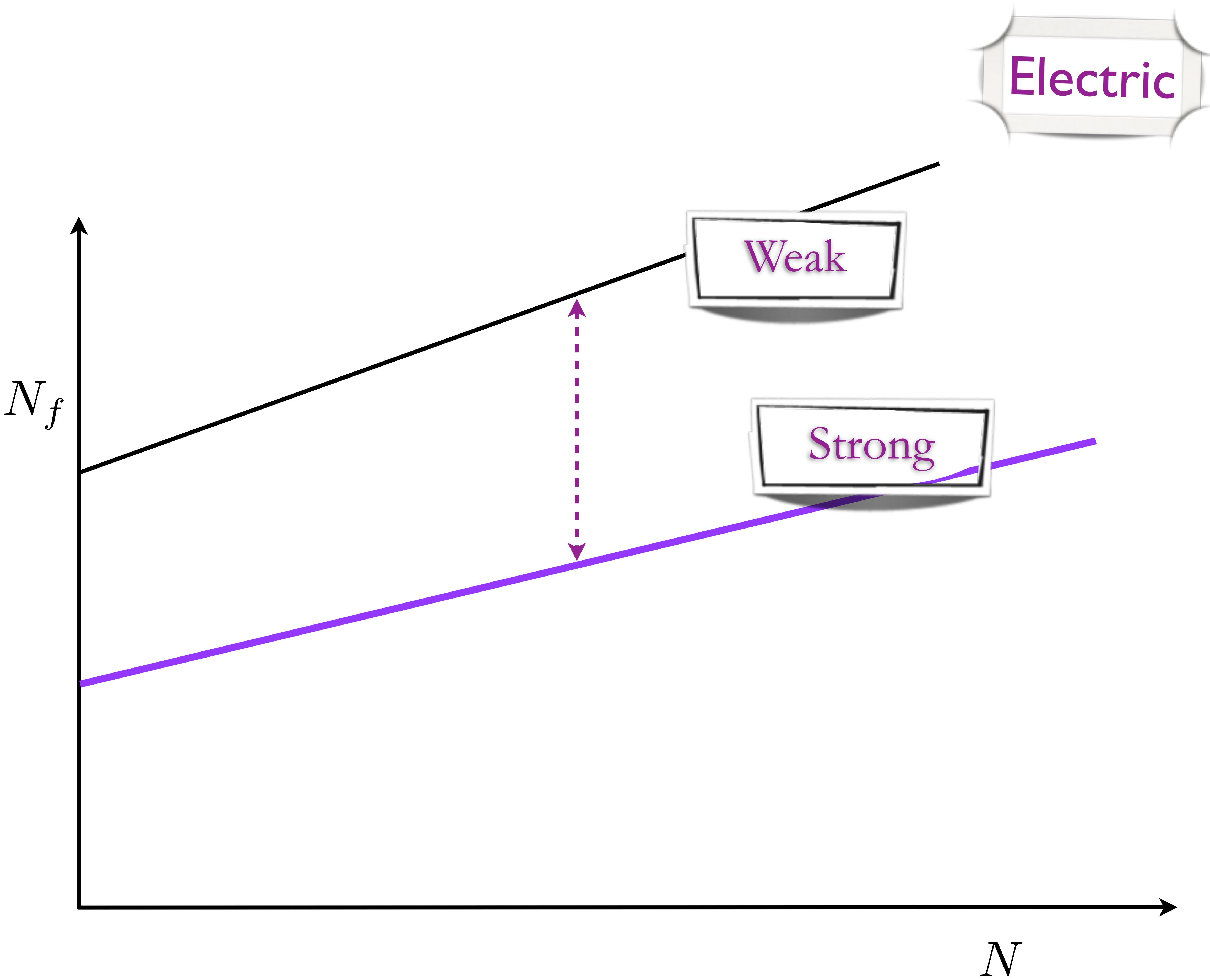
$$\begin{aligned} L_{\rm M} &= Y_{q\widetilde{q}}\; q\; M\; \widetilde{q} + Y_{AB_A}\; A\, M \overline{B}_A + Y_{CB_A}\; C\, M \overline{B}_A + Y_{CB_S}\; C\, M \overline{B}_S + Y_{SB_S}\; S\, M \overline{B}_S + \\ &+ \; Y_{B_A D_A}\; B_A\, M\, \overline{D}_A + Y_{B_A D_S}\; B_A\, M\, \overline{D}_S + Y_{B_S D_A}\; B_S\, M\, \overline{D}_A + Y_{B_S D_S}\; B_S\, M\, \overline{D}_S + \text{h.c.} \end{aligned}$$

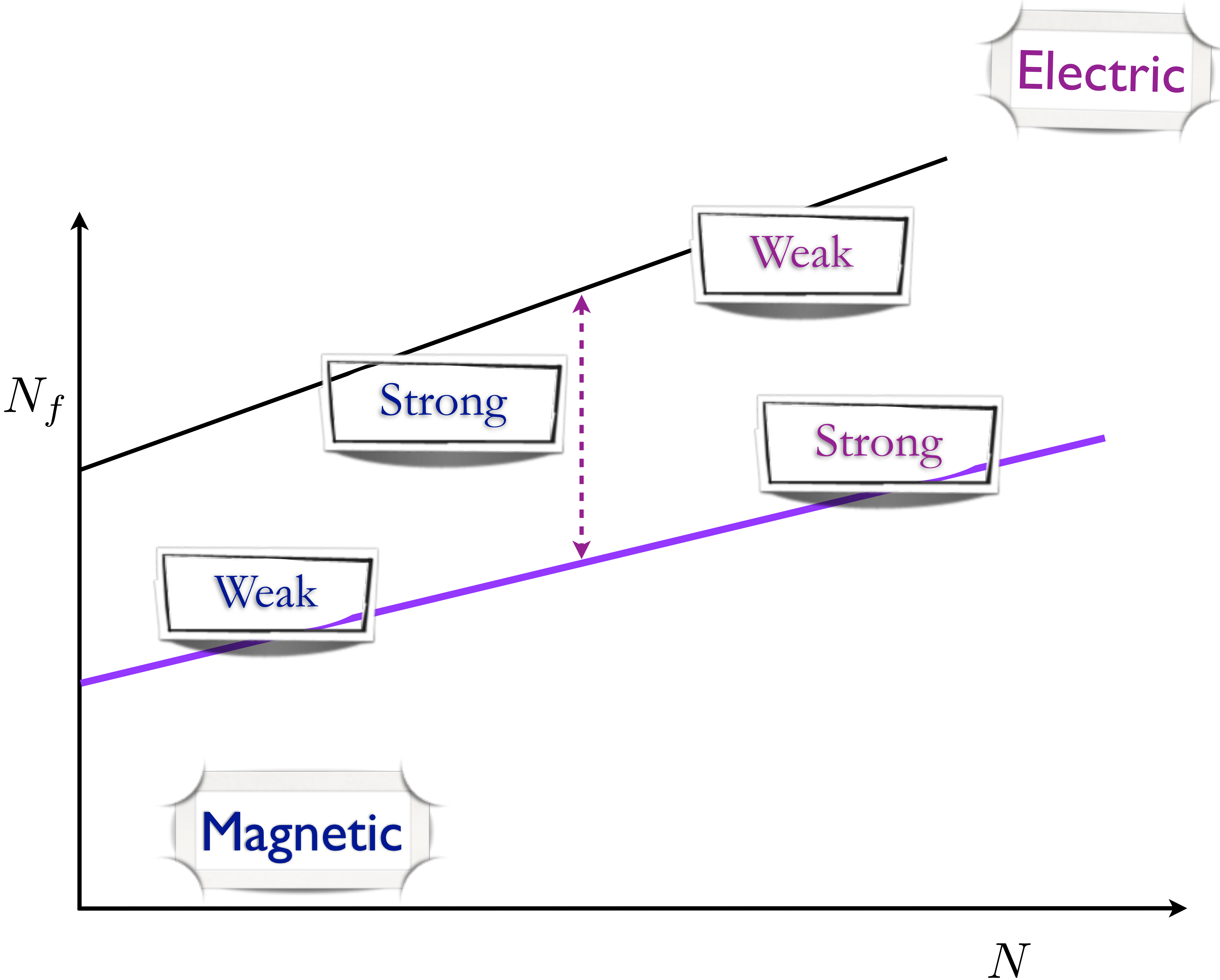
Dual Theory

$$L_{\text{Dual}} = L_{\text{Kin}}\left[q, \tilde{q}, A, B_A, D_A, \tilde{A}\right] + L_M$$

$$\begin{aligned} L_{\text{M}} &= Y_{q\tilde{q}}\, q\, M\, \tilde{q} + Y_{AB_A}\, A\, M\, \overline{B}_A + Y_{CB_A}\, C\, M\, \overline{B}_A + Y_{CB_S}\, C\, M\, \overline{B}_S + Y_{SB_S}\, S\, M\, \overline{B}_S + \\ &+ Y_{B_A D_A}\, B_A\, M\, \overline{D}_A + Y_{B_A D_S}\, B_A\, M\, \overline{D}_S + Y_{B_S D_A}\, B_S\, M\, \overline{D}_A + Y_{B_S D_S}\, B_S\, M\, \overline{D}_S + \text{h.c.} \end{aligned}$$

$$B[\epsilon_{c_1 \dots . c_X} q^{c_1} \cdots q^{c_X}] = 3\ (2N_f - 5) = \# \times B[\epsilon_{c_1 \dots . c_3} Q^{c_1} \cdots Q^{c_3}]$$


Electric
Weak
Strong
N_f
N


Electric
Weak
Strong
Strong
Weak
Magnetic
N_f
N

Magnetic Asymp. Freedom

Magnetic Asymp. Freedom

$$\beta_0 = \frac{11}{3}(2N_f - 5N) - \frac{2}{3}N_f \geq 0$$

Magnetic
Asymp. Freedom

$$\beta_0 = \frac{11}{3}(2N_f - 5N) - \frac{2}{3}N_f \geq 0$$

$\Updownarrow$

$$N_f \geq \frac{11}{4}N$$

Magnetic
Asymp. Freedom

Electric
Chiral Sym. Restored

$$\beta_0 = \frac{11}{3}(2N_f - 5N) - \frac{2}{3}N_f \geq 0$$

$$N_f \geq \frac{11}{4}N$$

$$N_f^{BF}|_{\gamma=2} \geq \frac{11}{4}N$$

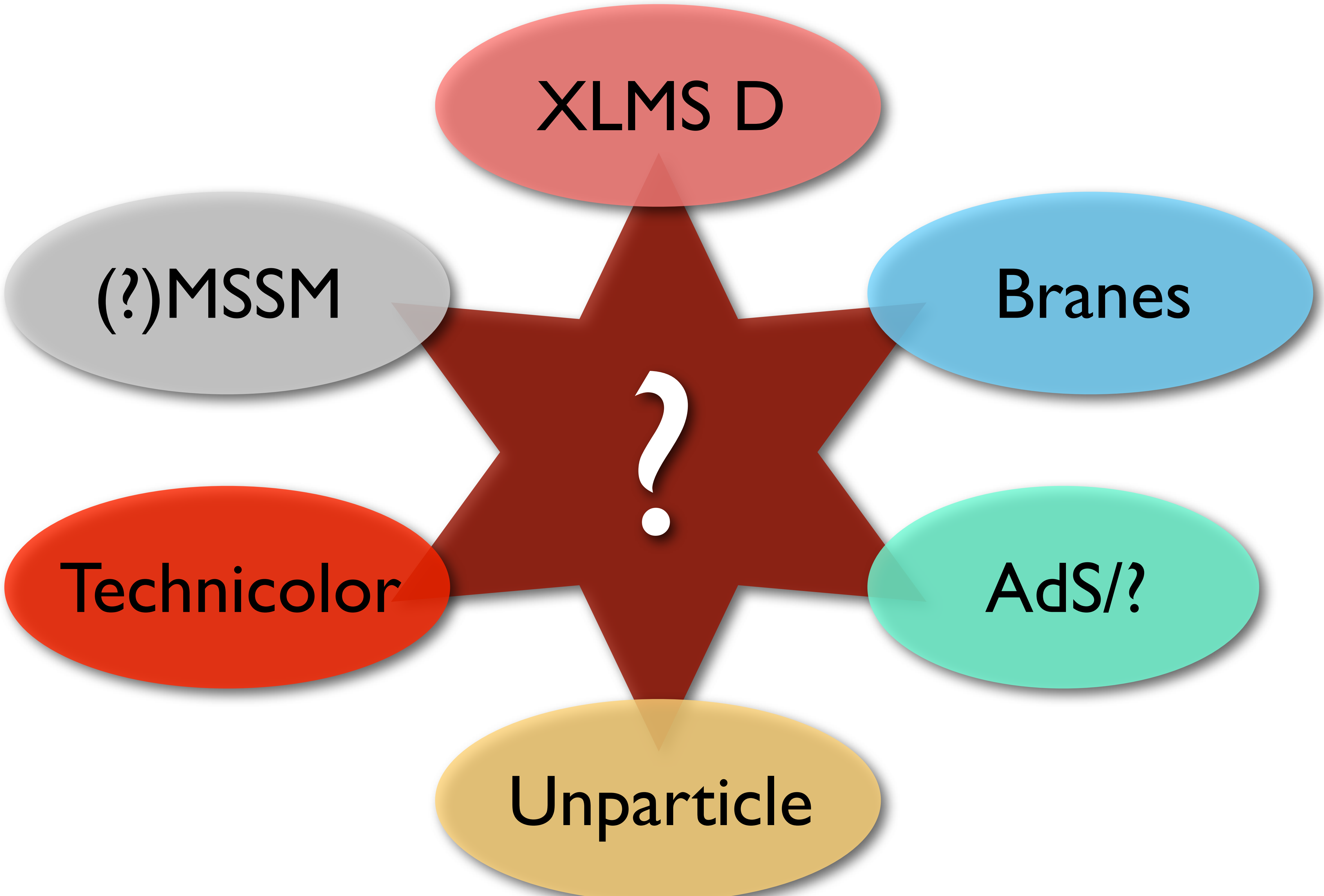
Duality summary

- Duality can be tested on the Lattice
- Reduces the number of theories
- Use to compute nonperturbative quantities like the VV-AA correlator.

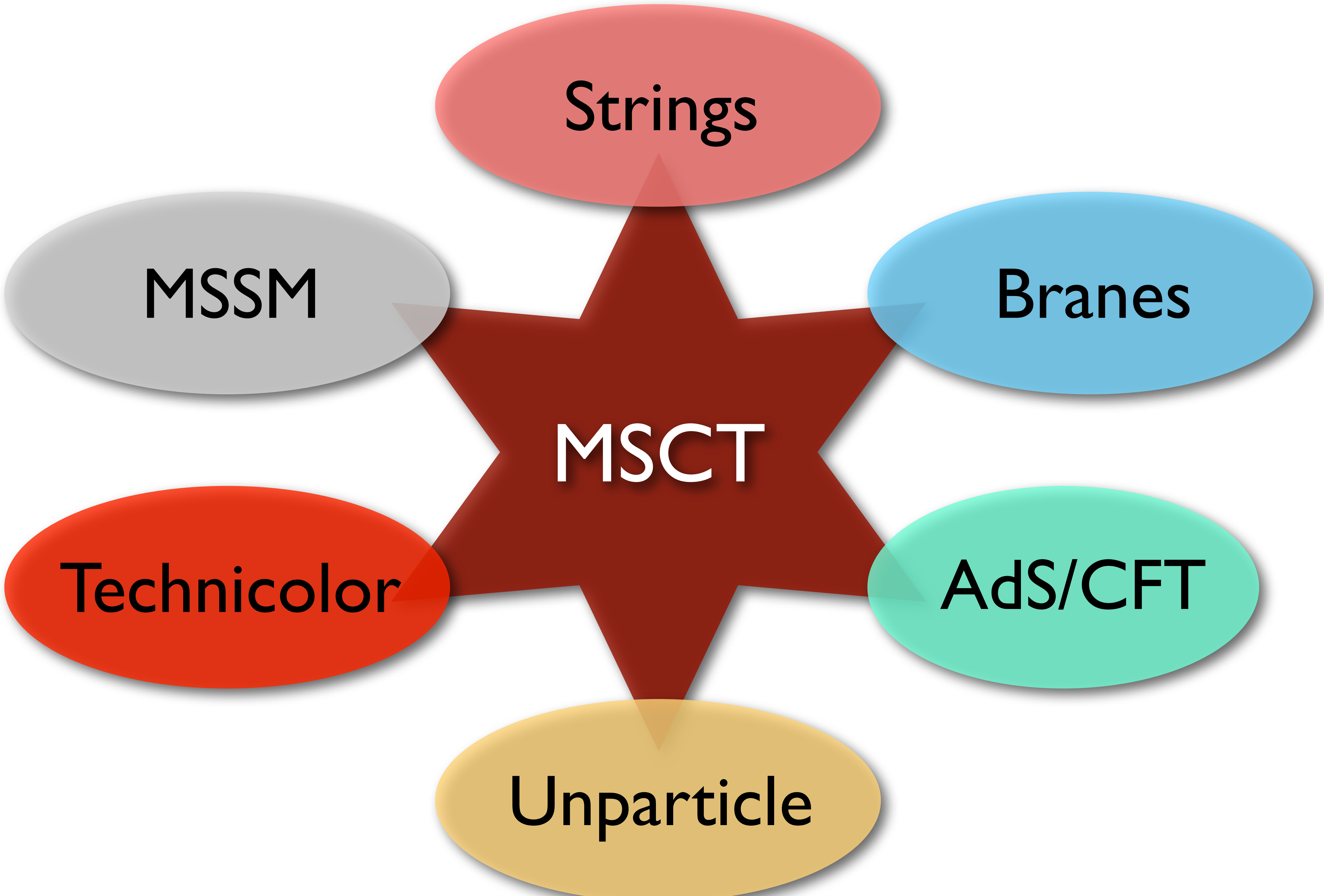
Many Models

- (?)MSSM
- XLMS D
- ......
- Technicolor
- Branes
- Unparticle
- AdS/?

Unifying in Model Space



Minimal Superconformal TC



Conclusions

CP3 - Origins
Particle Physics & Origin of Mass

Conclusions

- DEWSB can naturally occur at the LHC

CP3 - Origins
Particle Physics & Origin of Mass

Conclusions

- DEWSB can naturally occur at the LHC
- Phase Diagram of strongly interacting theories

CP3 - Origins
Particle Physics & Origin of Mass

Conclusions

- DEWSB can naturally occur at the LHC
- Phase Diagram of strongly interacting theories
- Unification in theory space

CP3 - Origins
Particle Physics & Origin of Mass

Conclusions

- DEWSB can naturally occur at the LHC
- Phase Diagram of strongly interacting theories
- Unification in theory space
- DEWSB cosmology is exciting.. another time