Composite Conformal Dynamics

Francesco Sannino

CP^3 - Origins

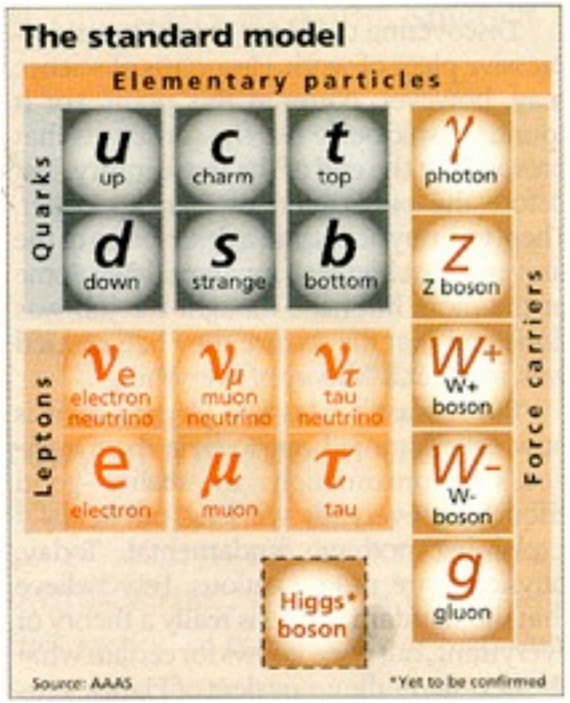
Particle Physics & Origin of Mass

Nagoya March 2012

Riddles


Atoms
4%
Electro
Magnetic
Strong
Weak
Gravity
Dark Energy
74%
Dark Matter
22%
?
?

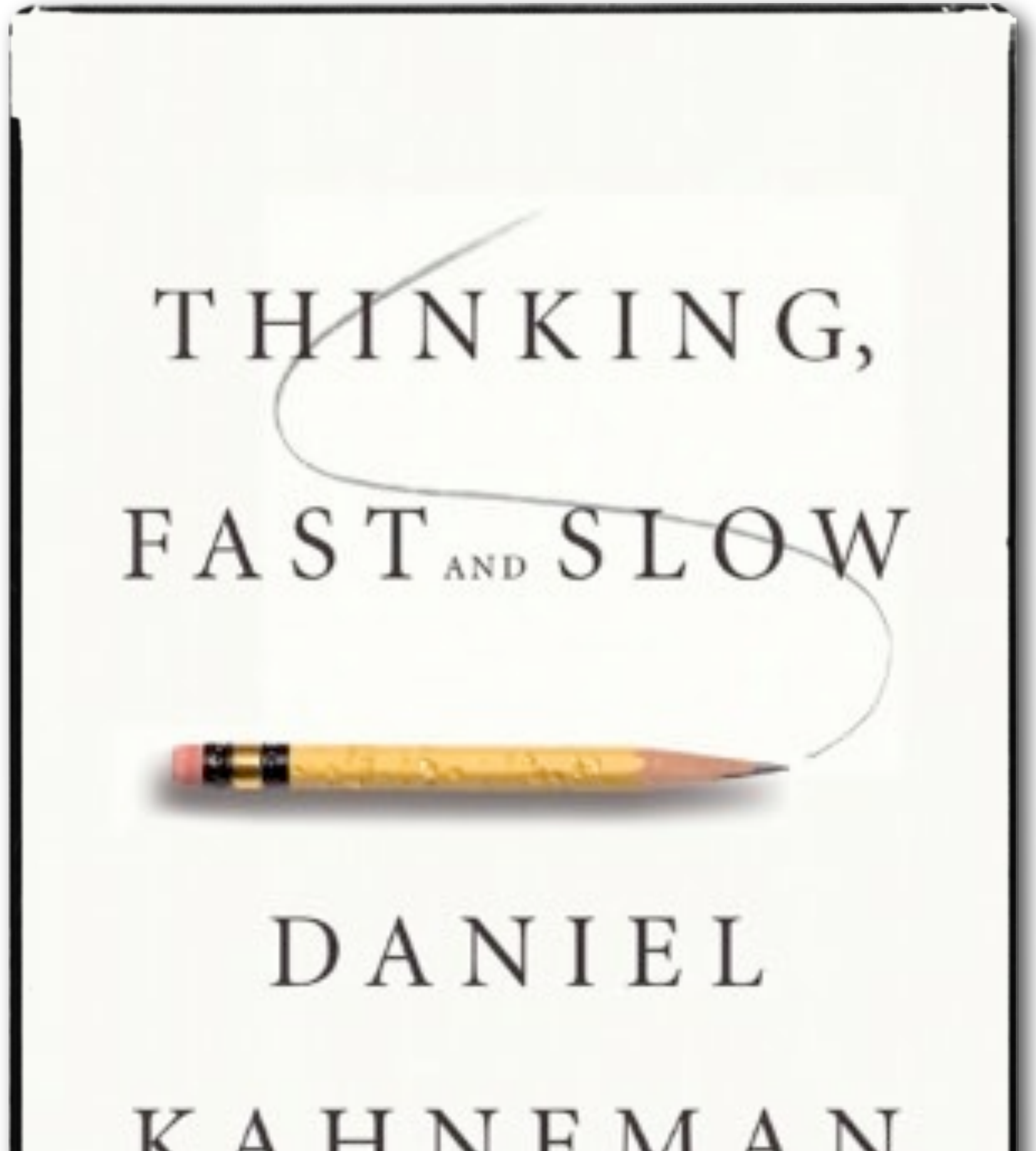
Beyond?



Theoretical blah blah blah...

Carlo Rubbia

Planck Scale


THINKING,
FAST AND SLOW
DANIEL
KAHNEMAN
WINNER OF THE NOBEL PRIZE IN ECONOMICS

Thinking Slow

- Gauge bosons

  Spin 1

- Fermions

  Spin 1/2

- Graviton   Spin 2

- Dark matter sector ?

- Inflationary sector ?

Lorentz Group basics

- Lorentz group is SL(2, C)

- Spin 1/2 is the fund. representation

- All other spins are derived

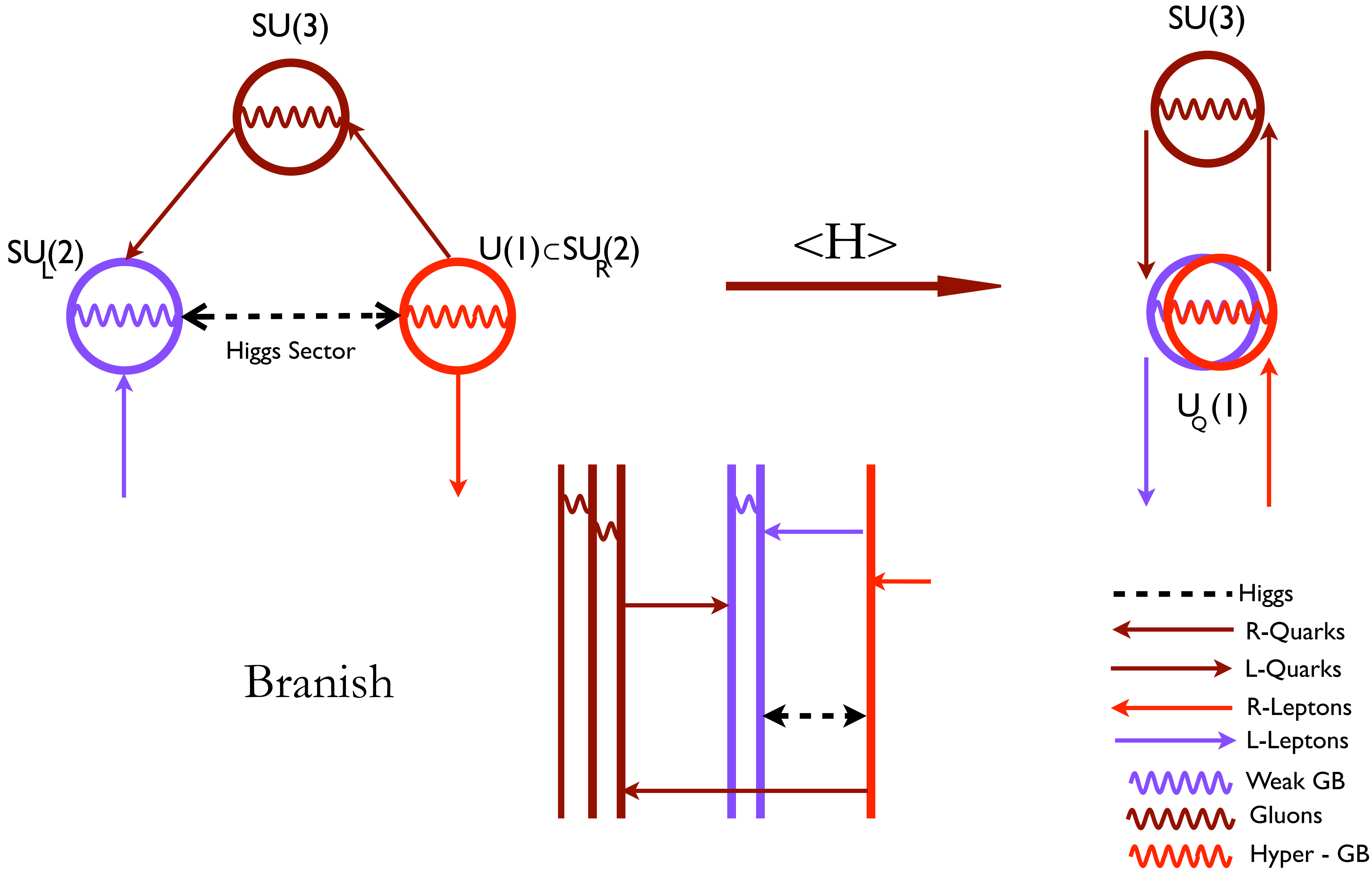
- No need for fund. scalars

What about Supersymmetry?

Supersymmetry is an emergent theory

See for example Antipin, Mojaza, Pica and Sannino arXiv:1105.1510

SM - Geometry



SU(3)
$SU_L(2)$
$U(1) \subset SU_R(2)$
Higgs Sector
<H>
SU(3)
$U_Q(1)$
Branish
Higgs
R-Quarks
L-Quarks
R-Leptons
L-Leptons
Weak GB
Gluons
Hyper - GB

Fermi Scale

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

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

Natural SM mass spectrum

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

$$M_W = g\,\frac{v}{2} \approx g \text{ 123 GeV}$$

$$M_H = \lambda\,\sqrt{2}\,v \approx \lambda \text{ 345 GeV}$$

$$m_f = \lambda_f \frac{v}{\sqrt{2}} \approx \lambda_f \text{ 174 GeV}$$

Top has the right energy scale!

Light quarks and leptons are odd!

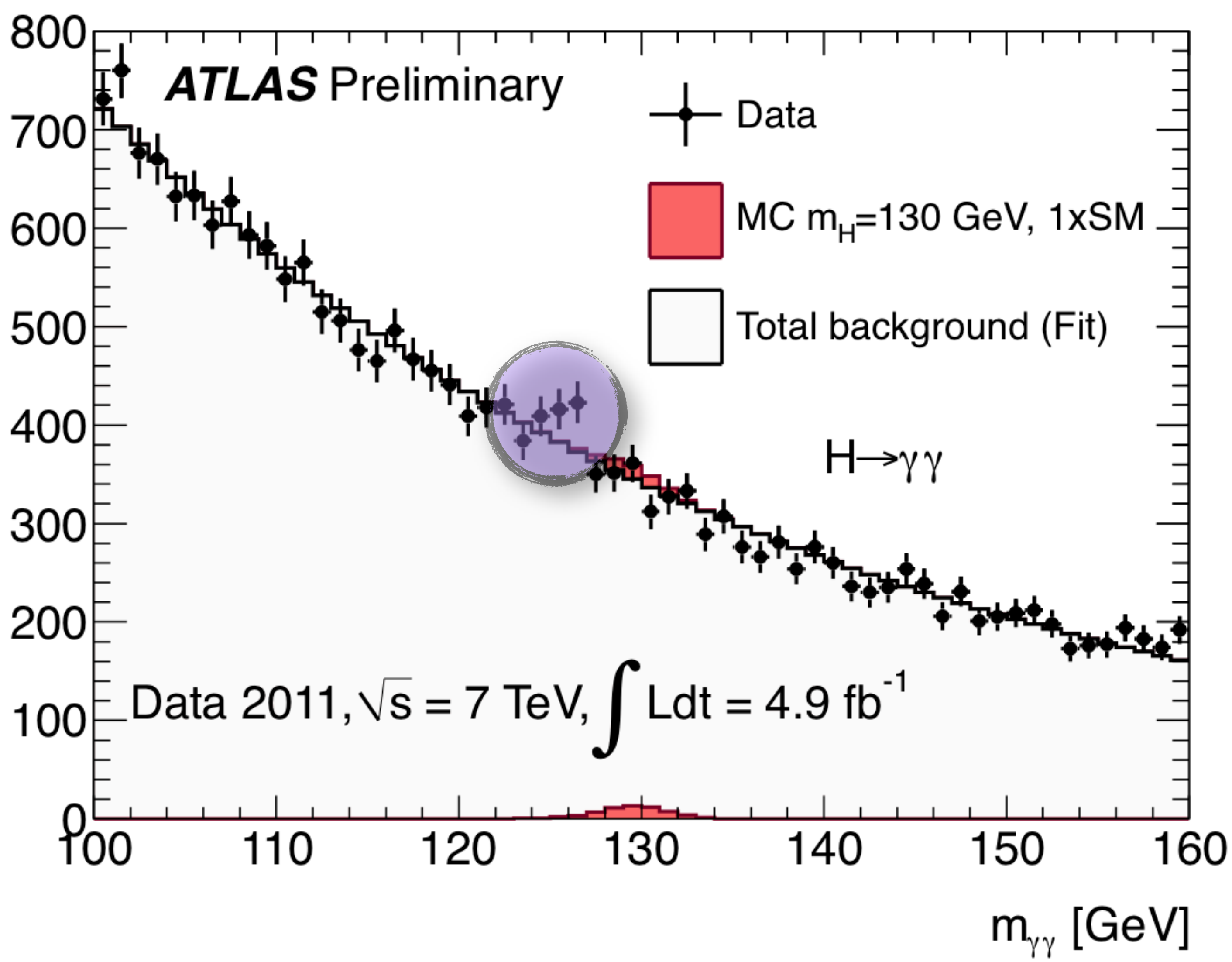
O’ Higgs, where art thou!

Light Higgs Anatomy

$$pp \to \gamma\gamma \quad 4.9\mathrm{fb}^{-1} \quad m_H = 126.5 \ \pm 0.7 \text{ GeV} \ \ R = 2^{+0.9}_{-0.7}$$

$$pp \to WW^* \to \ell^+\nu\ell'^-\bar{\nu}' \quad 4.7\mathrm{fb}^{-1} \quad \text{no} \quad \text{excess} \quad R = 0.16^{+0.6}_{-0.6}@126\text{GeV}$$

$$pp \to ZZ^* \to \ell^+\ell^-\ell'^-\ell'^+ \quad 4.8\mathrm{fb}^{-1} \quad \mathrm{m_H} = 126 \pm 2 \text{ GeV} \quad R = 1.2^{+1.2}_{-0.8}$$



Light Higgs Anatomy cont.

$$pp \to \gamma\gamma \quad 4.8\mathrm{fb}^{-1} \quad m_H = 125 \ \ \mathrm{GeV} \ \ R = 1.65^{+0.67}_{-0.6}$$

$$pp \to WW^* \to \ell^+\nu\ell'^-\bar{\nu}' \quad 4.6\mathrm{fb}^{-1} \quad \mathrm{no \ \ excess} \quad R = 0.4^{+0.6}_{-0.55}@126\mathrm{GeV}$$

$$pp \to ZZ^* \to \ell^+\ell^-\ell'^-\ell'^+ \quad 4.7\mathrm{fb}^{-1} \quad \mathrm{m_H} = 125 \pm 2 \ \mathrm{GeV} \quad R = 0.58^{+1.0}_{-0.58}$$

$$H \to b\bar{b} \quad 10/9.7 \ \mathrm{fb}^{-1} \quad m_H = 115 - 135 \ \mathrm{GeV} \quad R = 1.6^{+0.6}_{-0.6}@120 \ \mathrm{GeV}$$

What if Higgs-like state is there?

“Higgs” @ 125 GeV vs unitarity scale:

$$\frac{M_H}{1.2\ \mathrm{TeV}} \simeq 0.1$$

- Mass of the “Higgs” versus EW ChPT convergence radius scale:

$$\frac{M_H}{4\pi v} \simeq 0.04 \longleftrightarrow \text{Conformal Goldstone}$$

- Compare with mass of the pion versus ChPT convergence radius:

$$\frac{M_\pi}{4\pi F_\pi} \simeq 0.1 \longleftrightarrow \text{Goldstone}$$

Conformal Goldstone

- Spontaneous breaking of scale (conformal) symmetry

$$\partial_\mu D^\mu = \Theta^\mu_\mu = \sum_i \beta(g_i) \frac{\partial \mathcal{L}}{\partial g_i}$$

- Dilaton mass and decay constant

$$\langle D | \partial_\mu D^\mu | 0 \rangle = -f_D m_D^2$$

- In near-conformal technicolor like models

$$f_D = v \qquad\qquad m_D = M_H$$

LHC Higgs "potential" discovery

$$f_D = v \quad m_D = M_H$$

- Would imply

$$m_D \ll 4\pi f_D \ , \qquad m_D < f_D$$

- For comparison in QCD

$$M_\pi \ll 4\pi F_\pi \ , \qquad M_\pi \simeq F_\pi$$

- What kind of models can do this?

Near Conformal Models

- Conformal technicolor models (Light Composite Higgs)

$$\frac{M_H}{v} \simeq (N_f^c - N_f)^\nu$$

Dietrich, Sannino, Tuominen hep-ph/0510217

Dietrich, Sannino hep-ph/0611341

ν critical exponent

N_f^c critical number of techniflavors for conformality

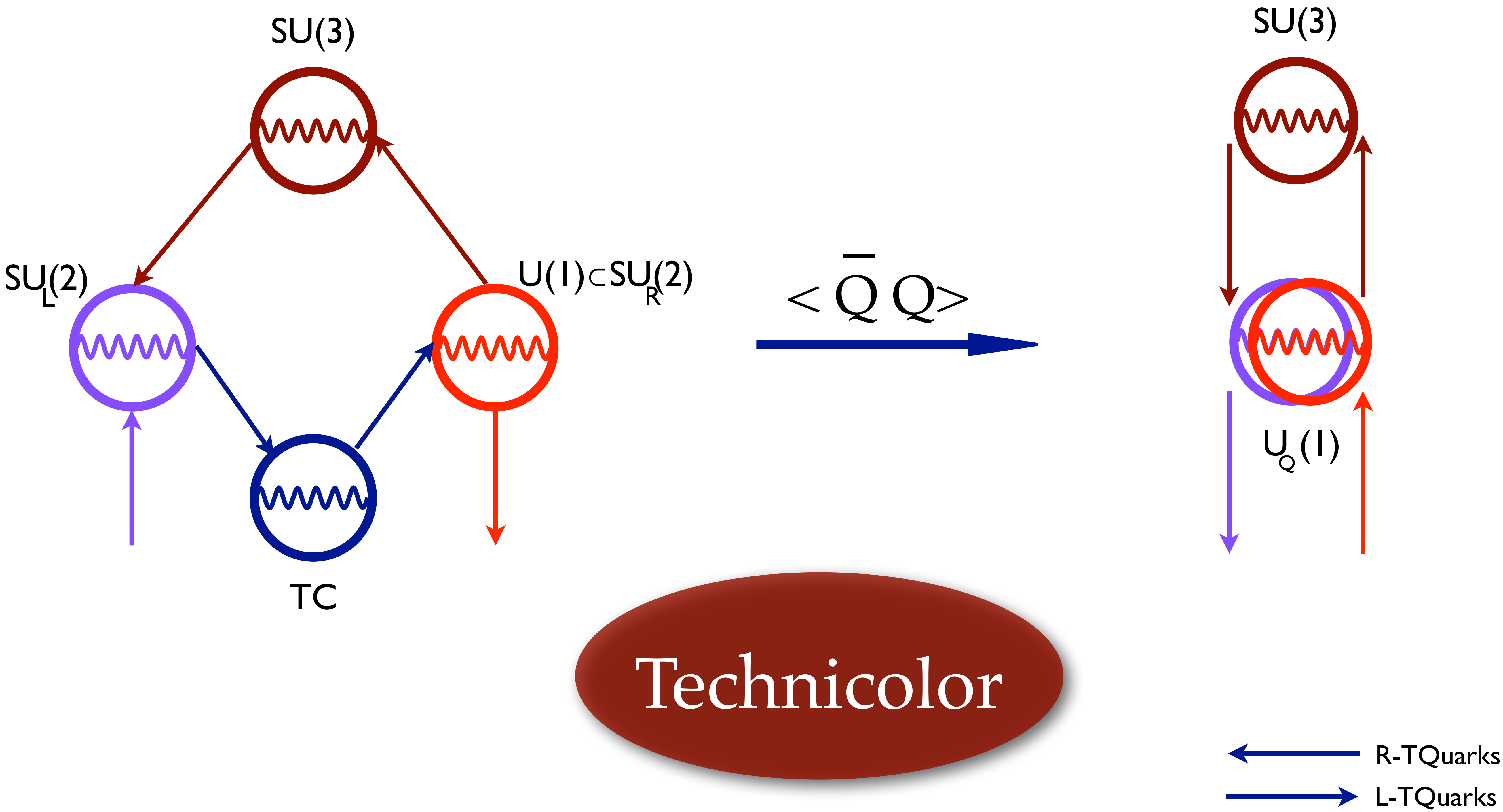
- Other examples?

Calculable perturbative examples

Grinstein, Uttayarat 1105.2370

Antipin, Mojaza, Sannino 1107.2932

Technicolor - Geometry



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

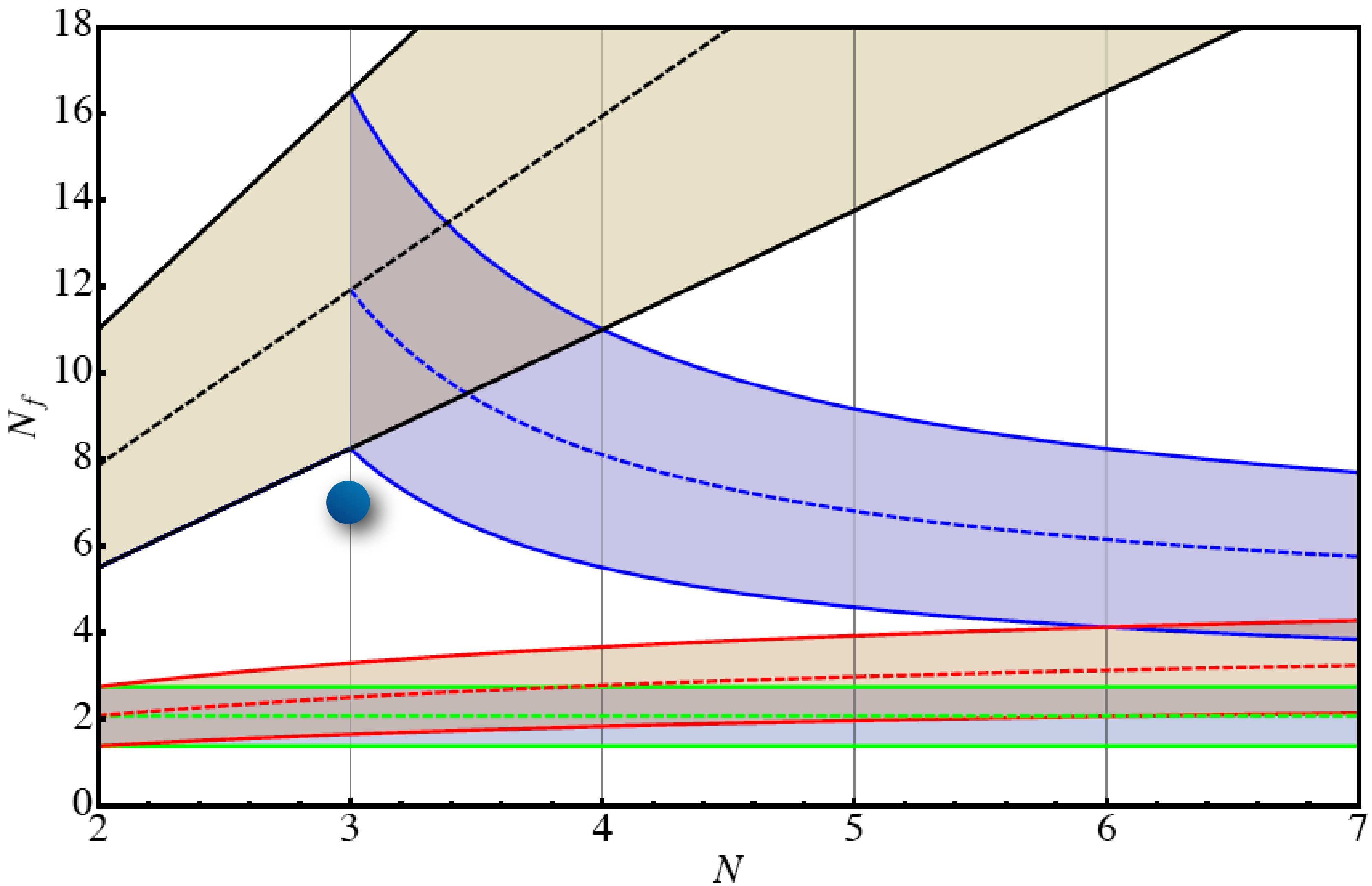
$$\cdots \qquad \to \qquad L(\text{New SM Fermions})$$

Wanted!

- Minimal Technicolor passing precision tests
- ETC for Fermion masses generation
- Non QCD dynamics / Walking
- Large mass anomalous dimensions ?
- Dark matter candidates

iWalk

No seriously, Walking?



Dietrich Sannino 06

Fukano & Sannino 10

How can one tune an integer number?

Anomalous dimensions may be small

ideal Walking = iWalk

Fukano & Sannino 10

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

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

Appelquist, Soldate, Takeuchi and Wijewardhana, 88

Miranky and Yamawaki 88

Kondo, Mino, Yamawaki 89

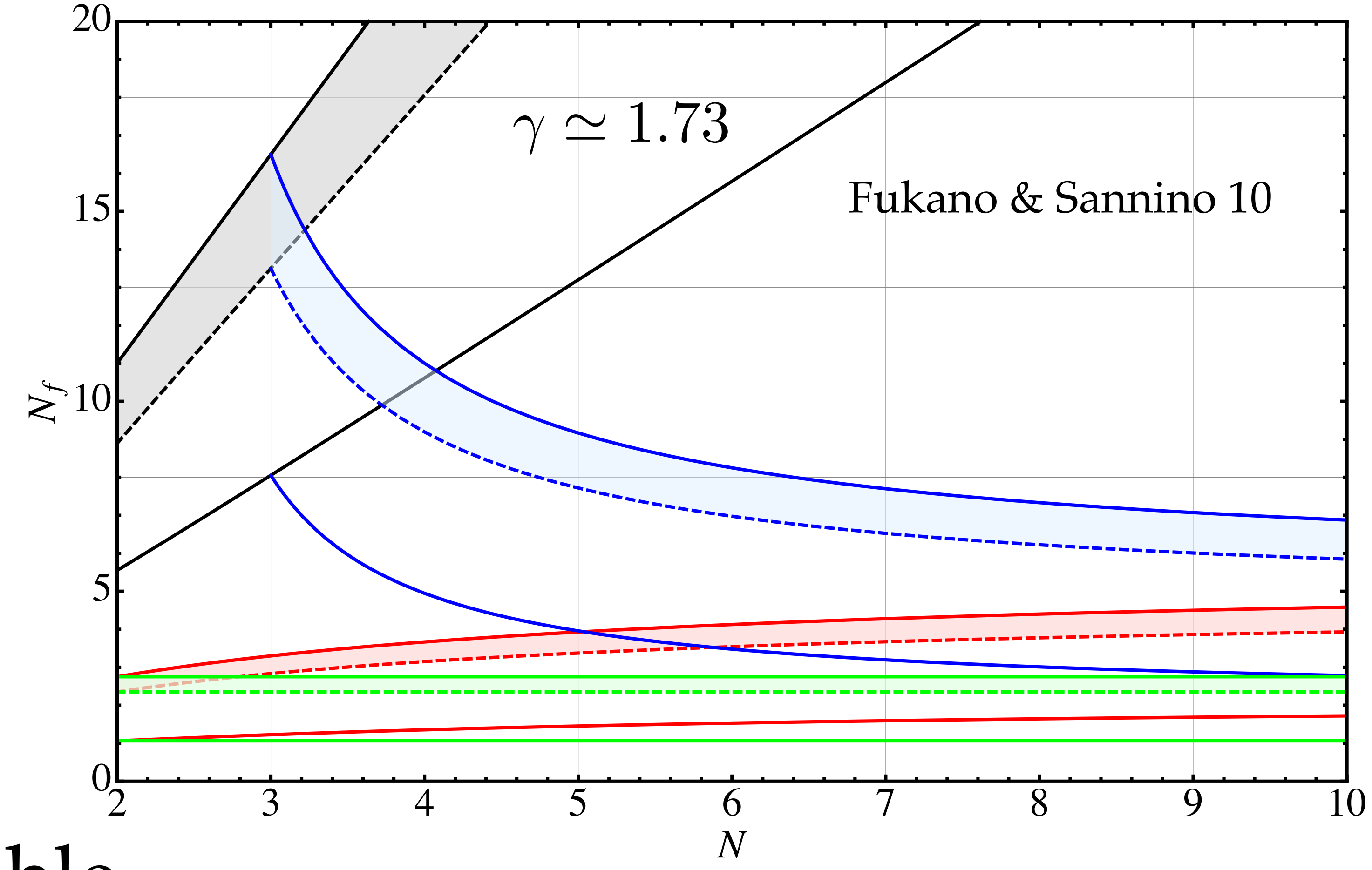
Takeuchi 96

Yamawaki, Kurachi and Shrock 08

Gauged Nambu Jona-Lasinio

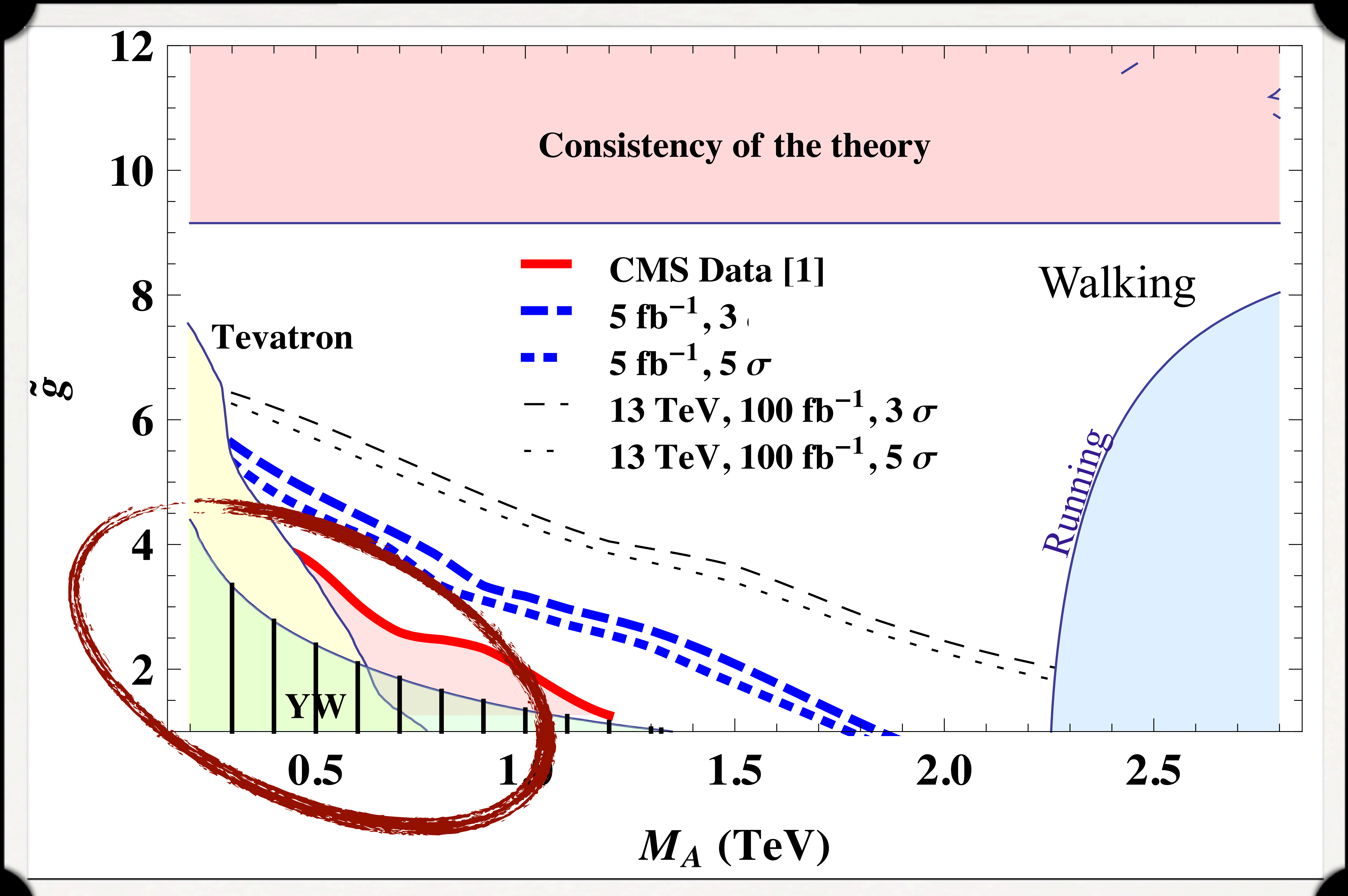
Fukano & Sannino 10

- As if the number of flavors is continuous
- Anomalous dimensions increase



- Phenomenologically viable
- Being tested!

Discovering Working Technicolor



Much unexplored !

Andersen, Hapola, Sannino 11

Belyaev, Foad, Frandsen, Jarvinen, Pukhov, Sannino 08

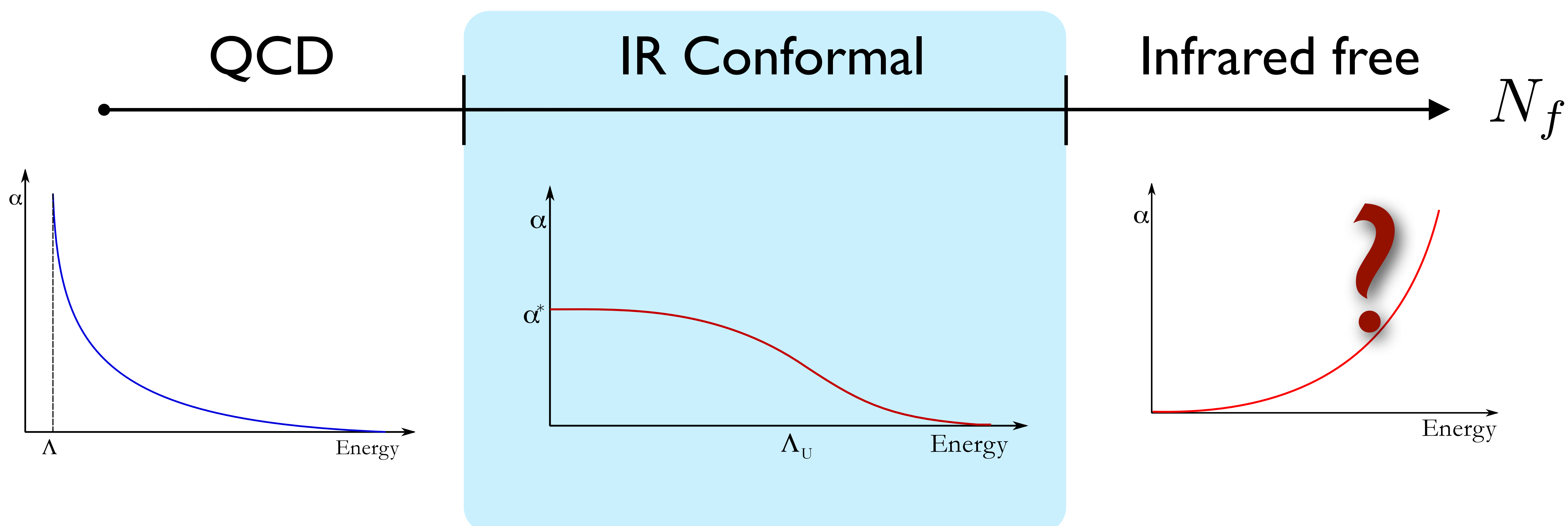
Need to go beyond QCD

Knobs

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

Matter Representation

# of Flavors per Representation



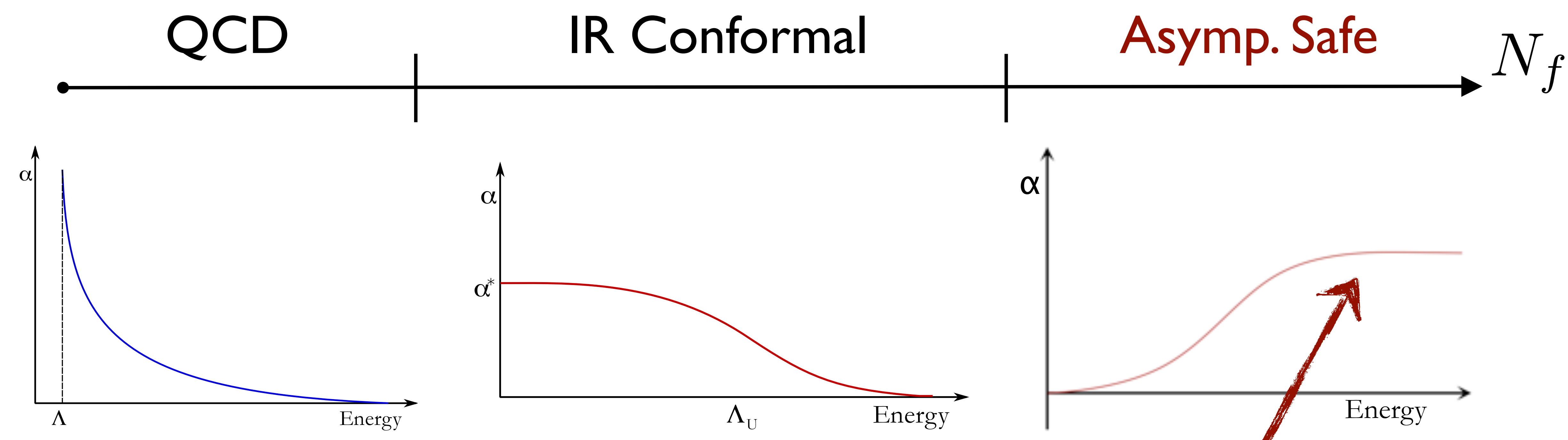
A novel phase @ large Nf

Interesting structure at large Nf

Pica & Sannino 10

First coefficients at large Nf are known

Ciuchini, Derkachov, Gracey, Manashov '99



$$\alpha_{UV} = \frac{3\pi}{T_F N_f}$$

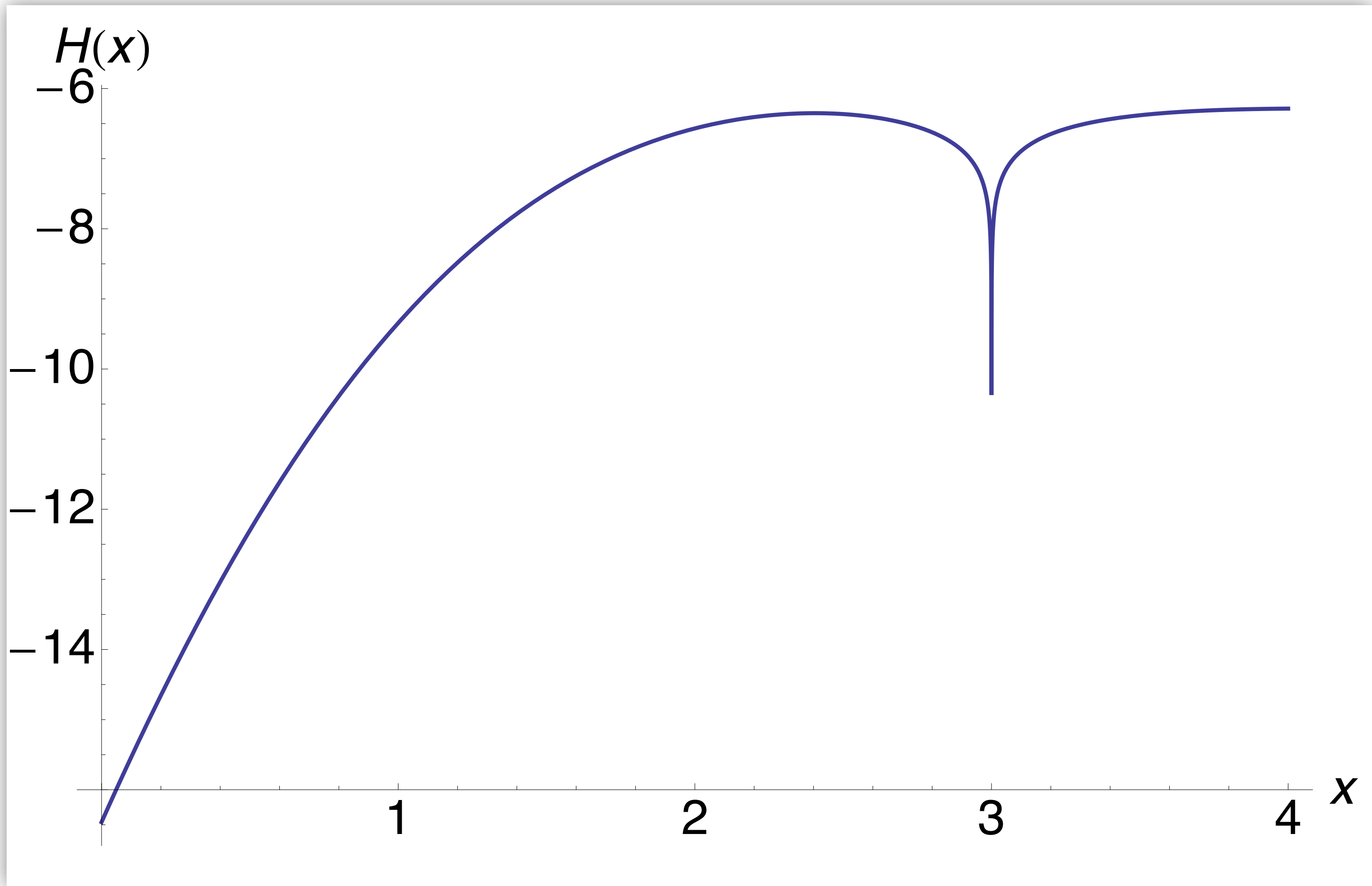
A novel phase @ large Nf

$$\frac{3}{4N_fT_f}\frac{\beta(a)}{a^2} = 1 + \frac{H\left(4aN_fT_f\right)}{N_f} + \ldots$$

$$a = \frac{\alpha}{4\pi}$$

$$\alpha_{UV} = \frac{3\pi}{T_F N_f}$$

Pica & Sannino 10

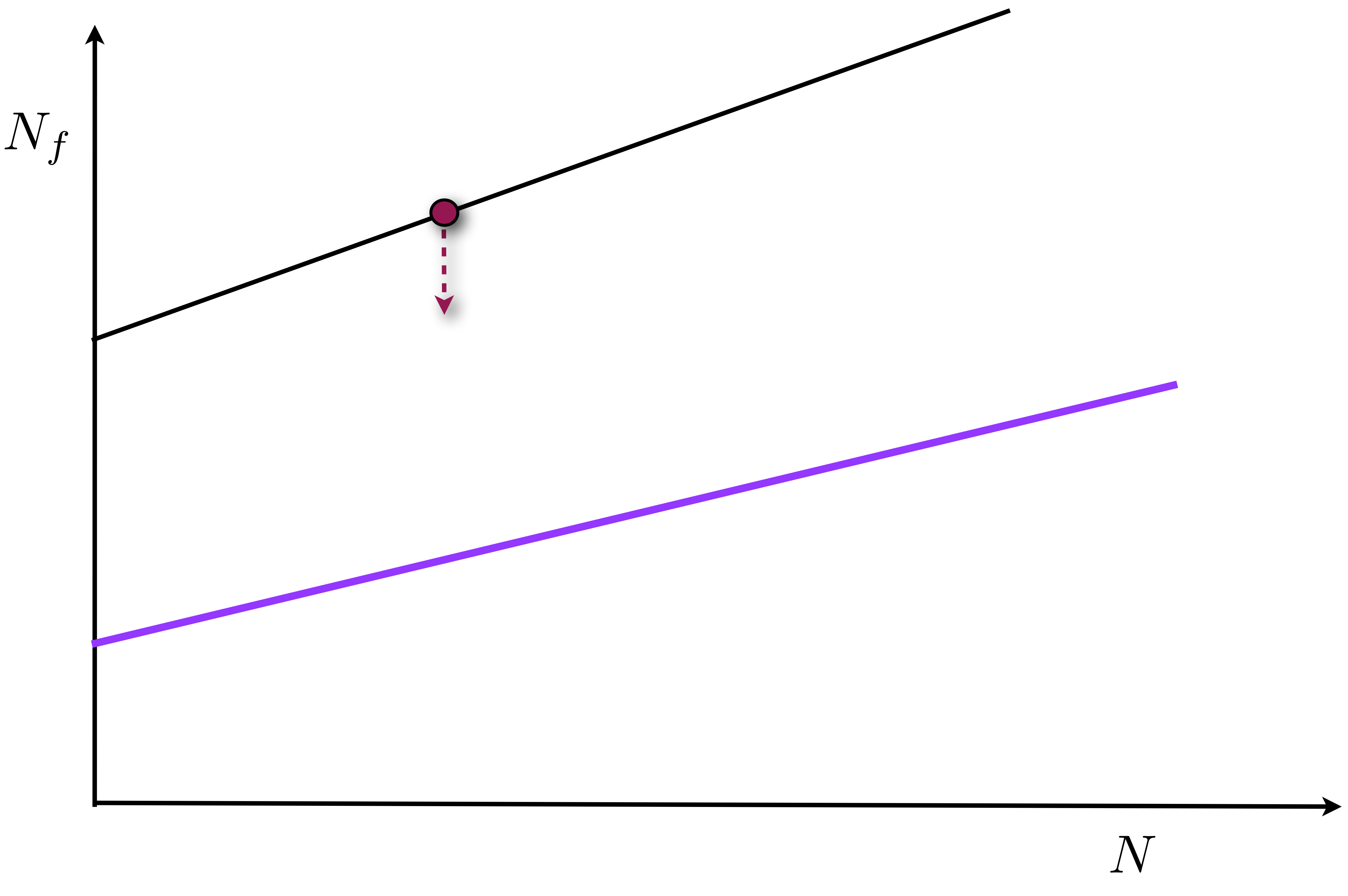


Ciuchini, Derkachov, Gracey, Manashov ‘99

B. Holdom, 2010

Perturbation theory

Perturbative region



Four loops

$$a = \frac{\alpha}{4\pi} = \frac{g^2}{16\pi^2}$$

Van Ritbergen, Vermaseren, Larin 97

Vermaseren, Larin, Van Ritbergen, 97

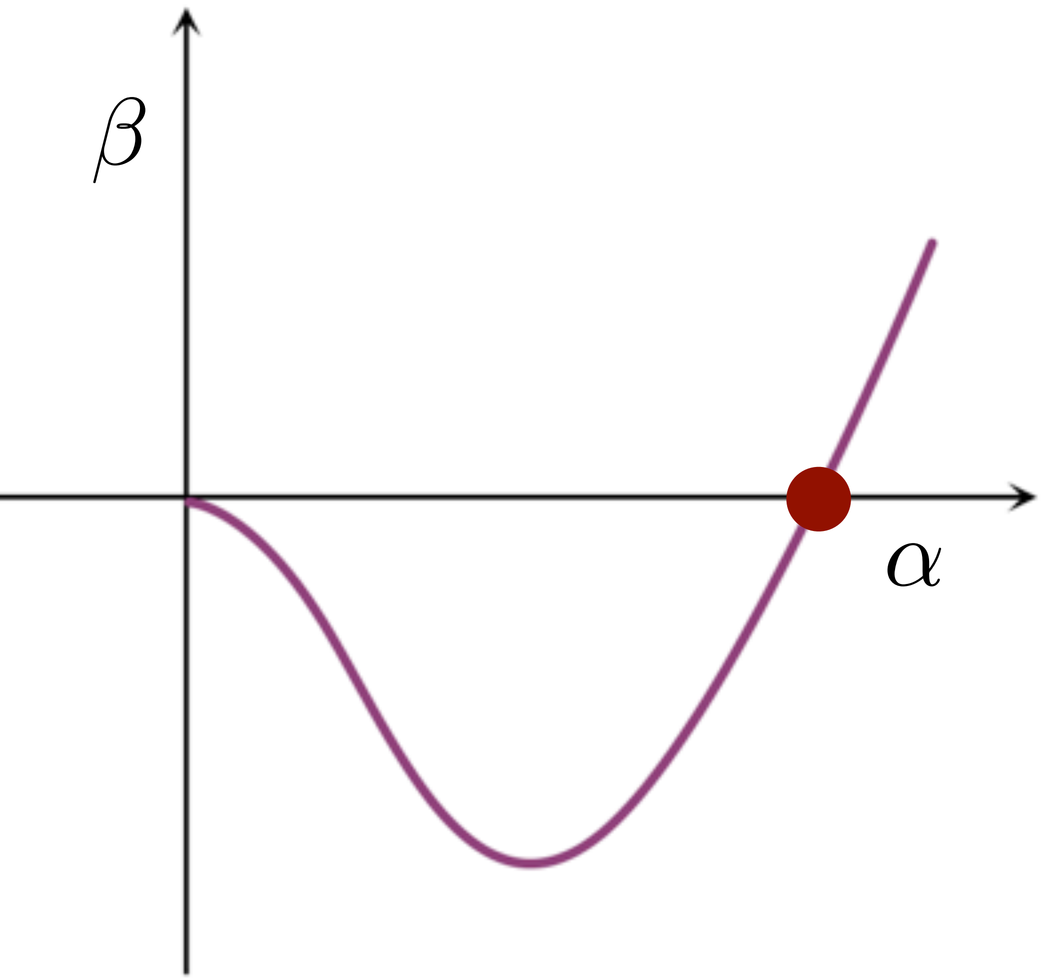
$$\frac{da}{d\ln\mu^2} \quad = \quad \beta(a) = -\beta_0 a^2 - \beta_1 a^3 - \beta_2 a^4 - \beta_3 a^5 + O(a^6) \ ,$$

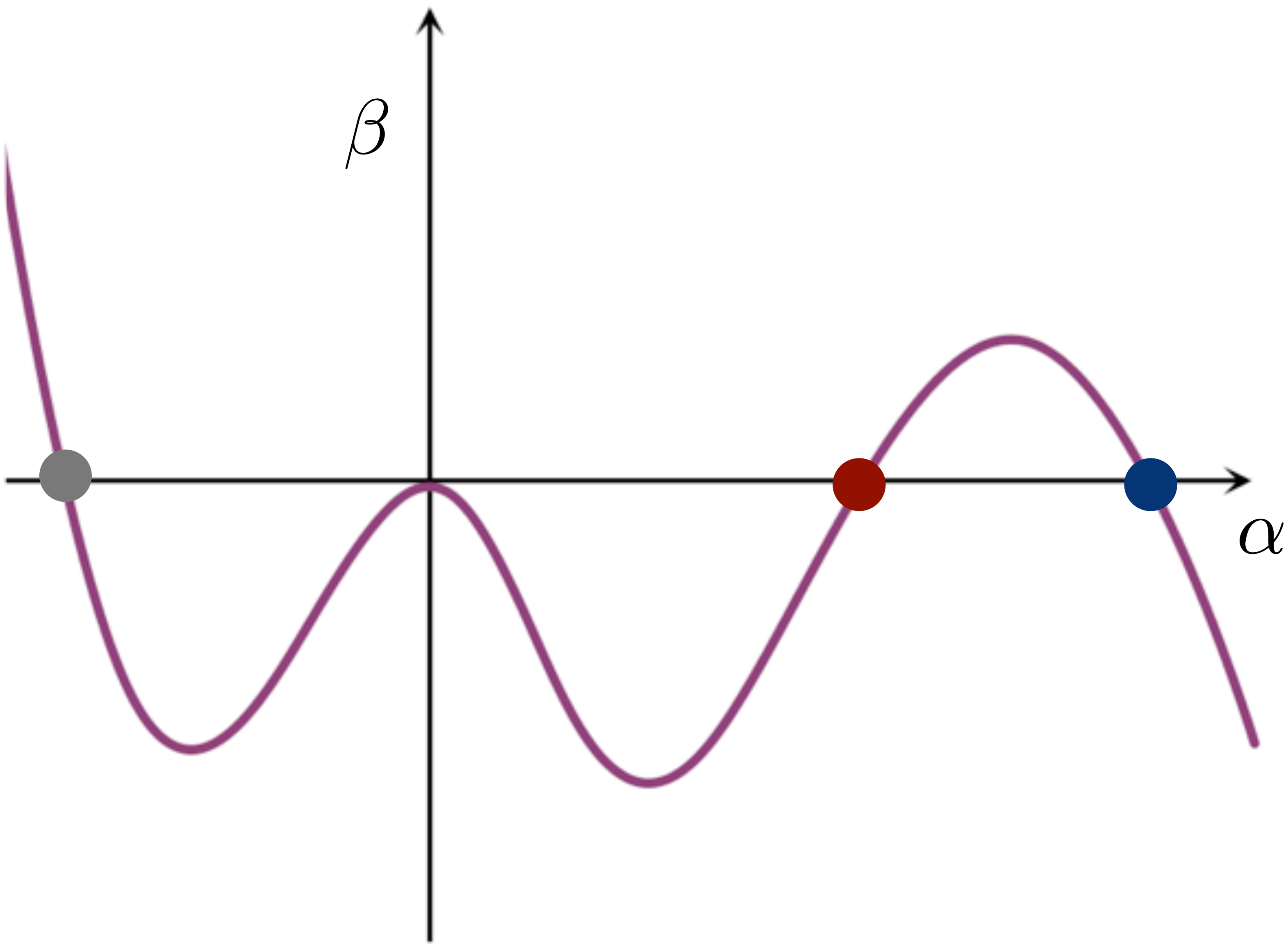
$$-\frac{d\ln m}{d\ln\mu^2} \quad = \quad \frac{\gamma(a)}{2} = \gamma_0 a + \gamma_1 a^2 + \gamma_2 a^3 + \gamma_3 a^4 + O(a^5) \ ,$$

Generalized 4th order Casimirs for SU(N), SO(N) and SP(N)

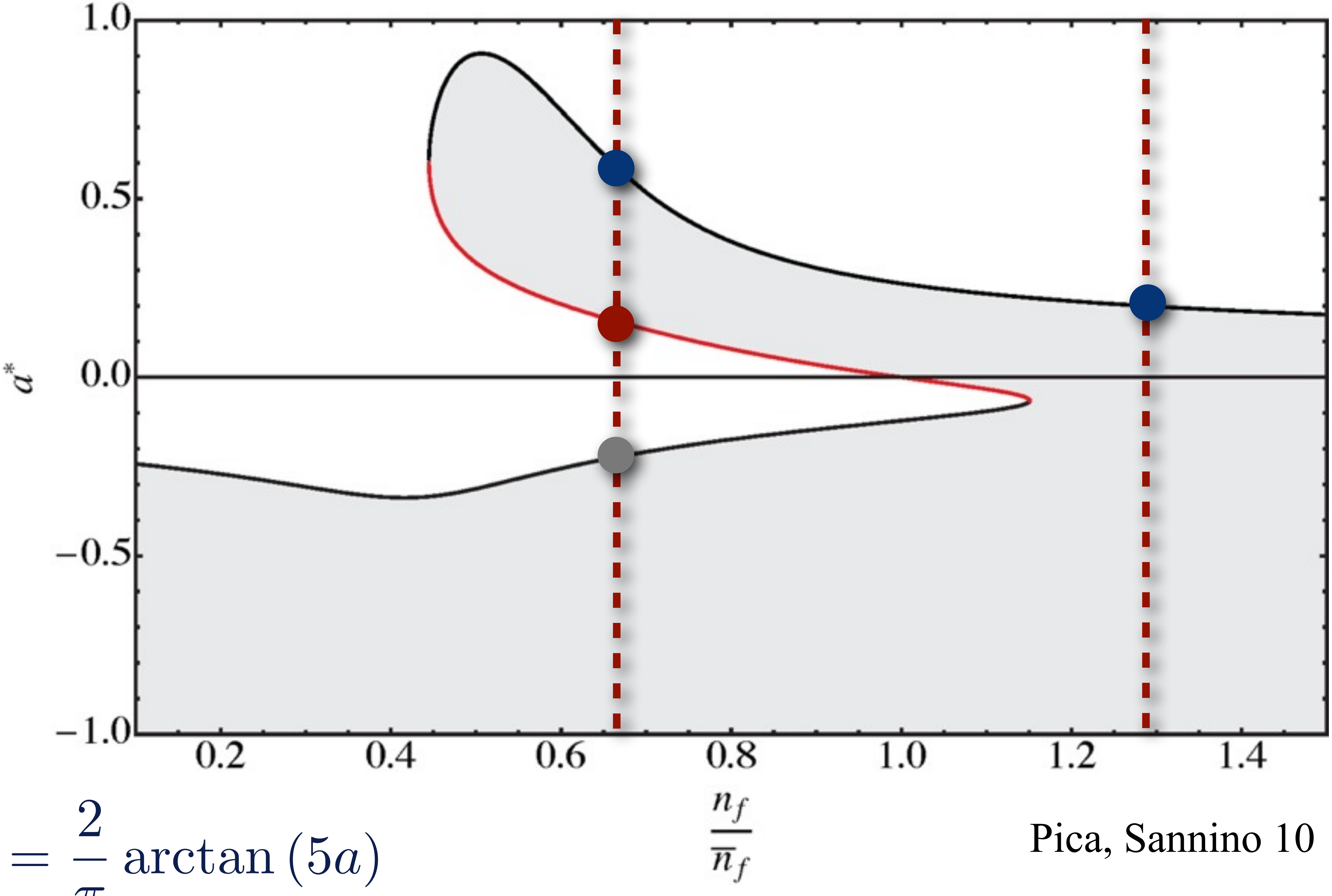
Mojaza, Pica, Sannino 10

Zero's - Dynamics





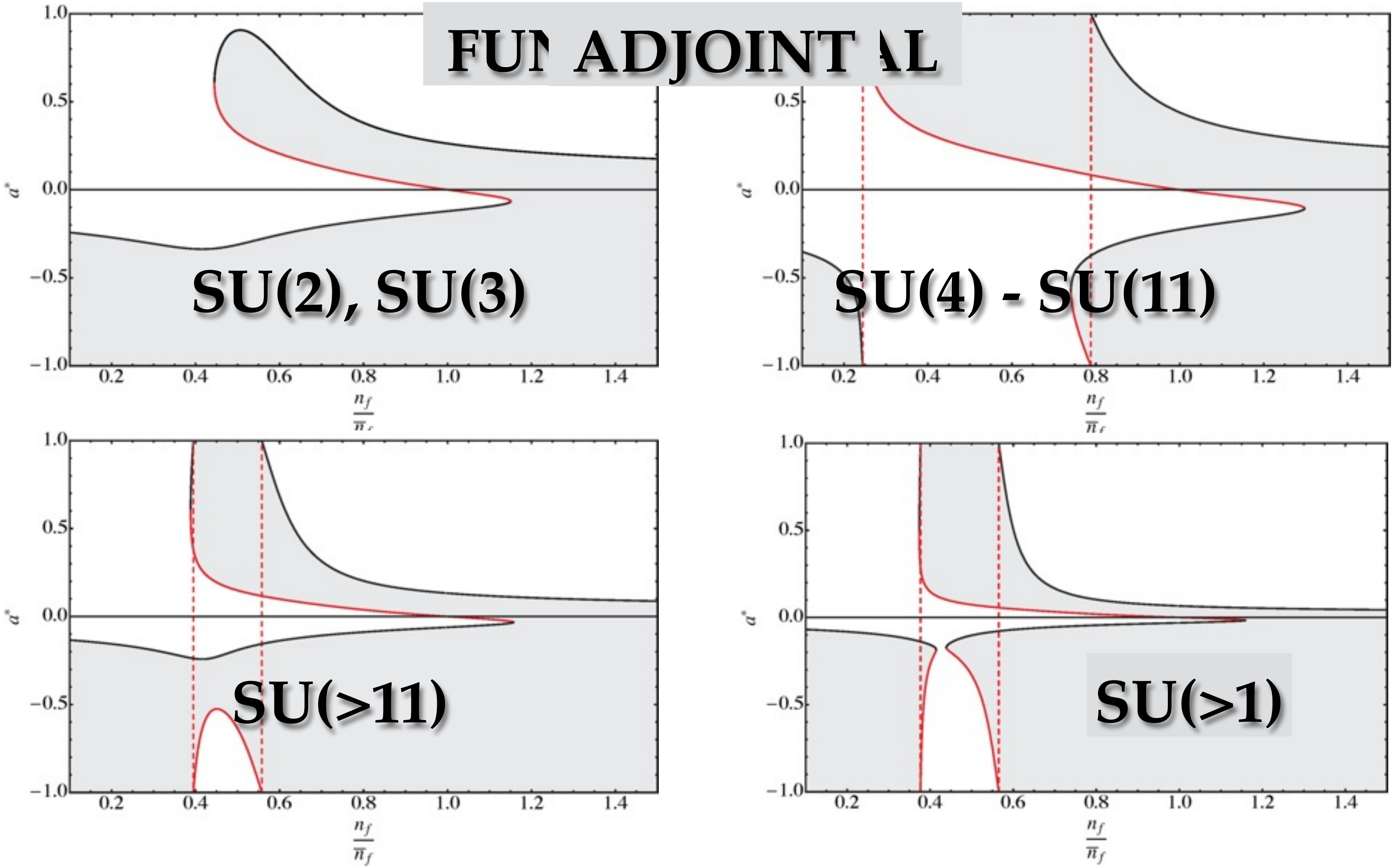
4 - loop Zerology



$$a^* = \frac{2}{\pi} \arctan(5a)$$

Pica, Sannino 10

4 - Zerology



FP γ is physical

$$\tilde{\alpha} = \sum_{n=1}^{\infty} h_n \alpha^n \,, \quad \text{with} \quad h_1 = 1 \,,$$

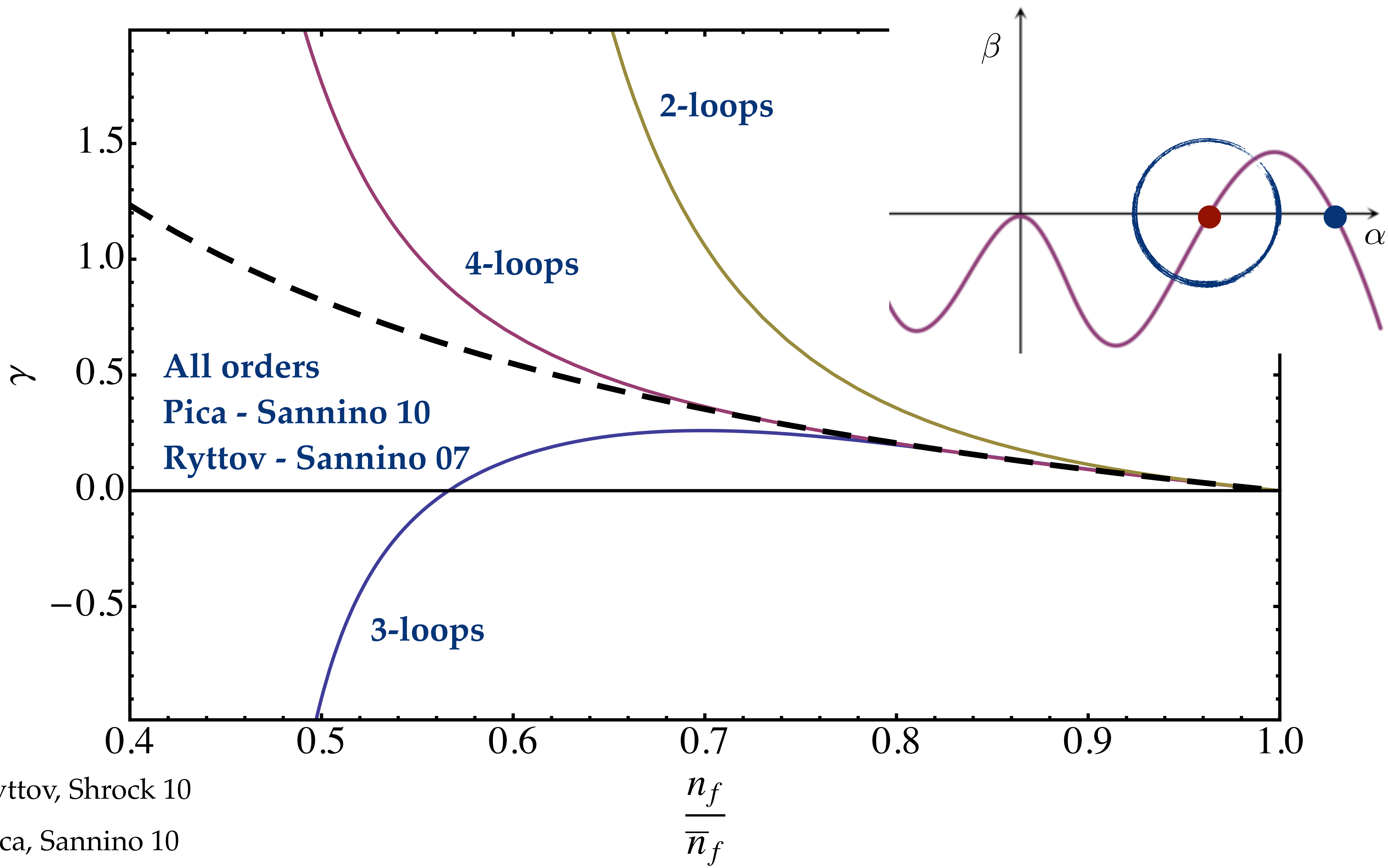
$$\tilde{m} = m\, z_m\, (\alpha) = m \sum_{n=0}^{\infty} \ell_n \alpha^n \,, \text{ with } \ell_0 = 1$$

$$\beta(\alpha) = \frac{\partial \alpha}{\partial \tilde{\alpha}} \tilde{\beta}(\tilde{\alpha}) \,,$$

$$\gamma(\alpha) = \tilde{\gamma}(\tilde{\alpha}) - \tilde{\beta}(\tilde{\alpha}) \frac{\partial \ln z_m}{\partial \tilde{\alpha}}$$

γ_0 , β_0 and β_1 are universal

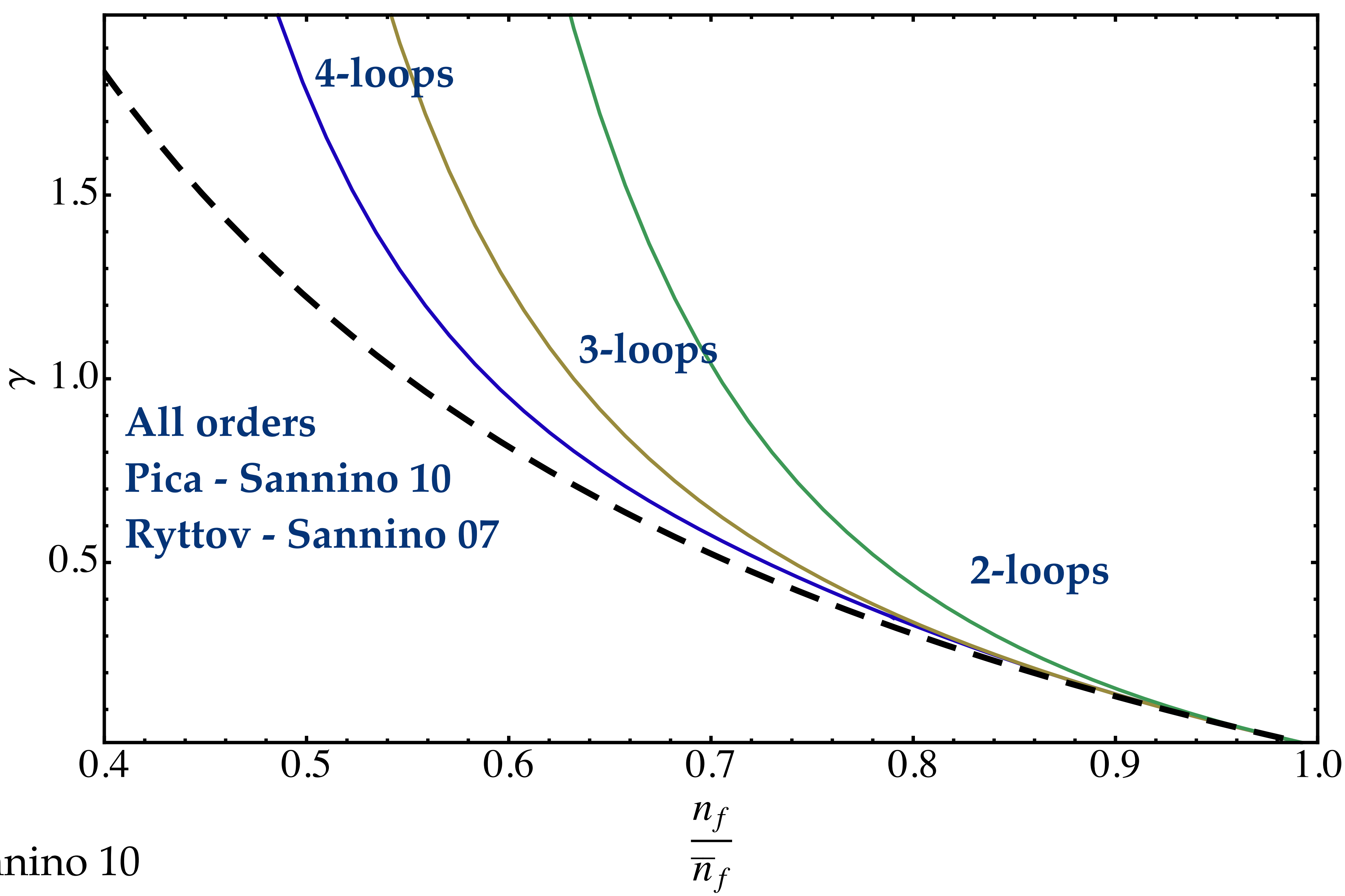
γ – Fundamental



Ryttov, Shrock 10

Pica, Sannino 10

γ – Minimal Walking

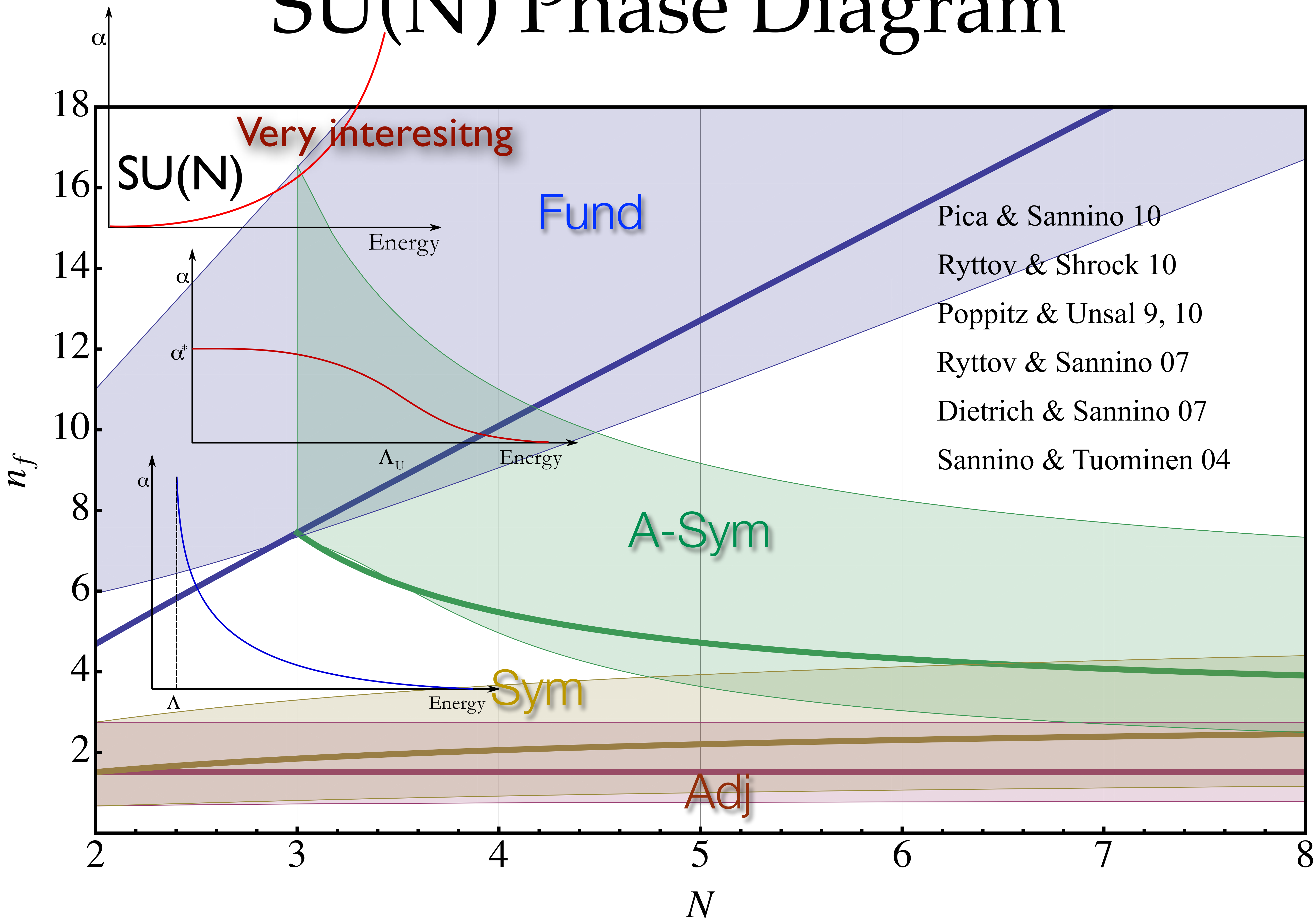


Pica, Sannino 10

Ryttov, Shrock 10

Universal Picture

SU(N) Phase Diagram



A Perturbative Dilaton Model

O. Antipin, M. Mojaza, F. Sannino - hep-ph/1107.2932

QCD-like

Adjoint fermion

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}F^2 + \sum_j^{N_f} i\bar{\psi}_j \not{D}\psi_j + i\lambda^a \sigma^\mu D_\mu^{ab}\bar{\lambda}^b$$

$$+y_H \bar{\psi}_i H_{ij}\psi_j + \mathrm{Tr}\,|\partial_\mu H|^2 - u_1 \left(\mathrm{Tr}H^\dagger H\right)^2 - u_2 \mathrm{Tr}\left(H^\dagger H\right)^2$$

Higgs-sector

~ Mesons

Spectrum extremely close to the wanted one!

$$H \sim \psi\bar{\psi}$$

Infrared physics

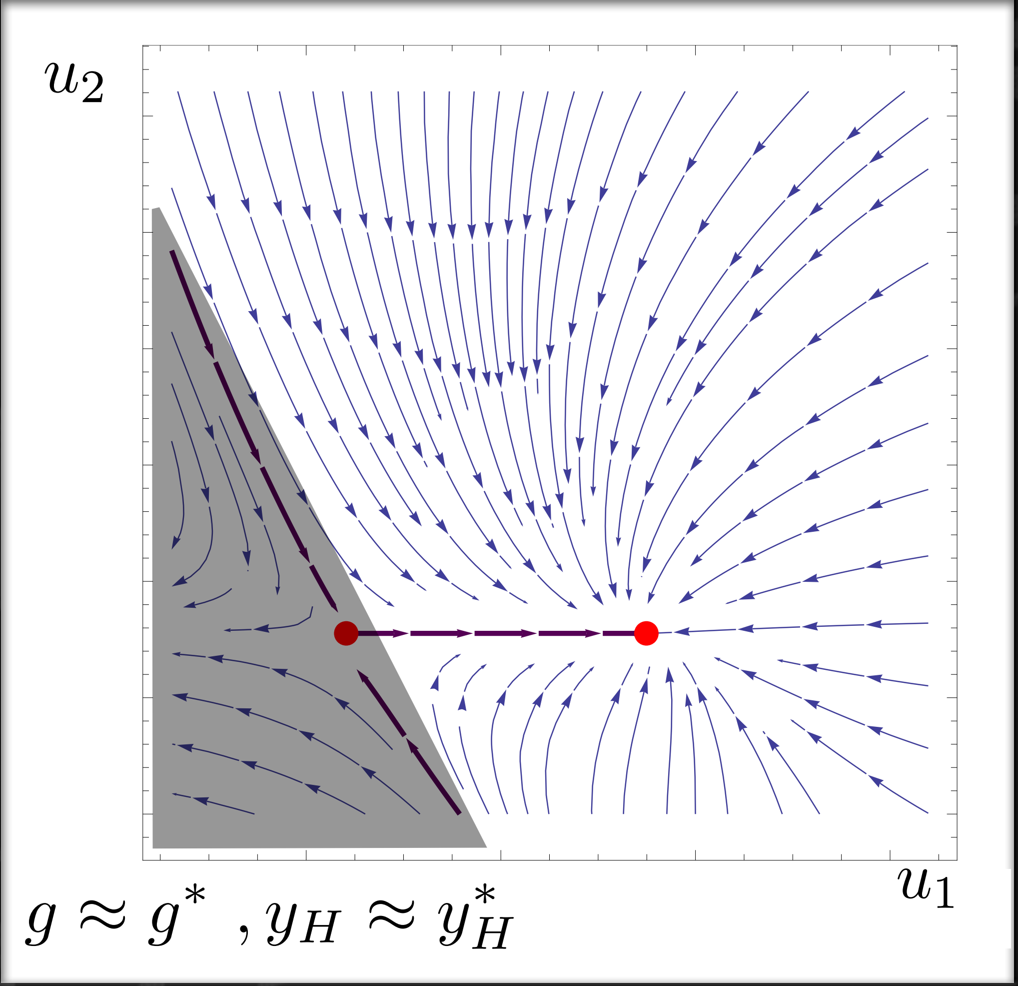
$$\mathcal{L} = \mathcal{L}_K(F_{\mu\nu}, \lambda, \psi, H; g) + y_H \bar{\psi} H \psi - u_1 \left(\mathrm{Tr} H^\dagger H\right)^2 - u_2 \mathrm{Tr}\left(H^\dagger H\right)^2$$

Perturbative IR stable fixed point (a la Banks-Zaks)

$$N_f/N_c \equiv x = x_{\mathrm{AF}}(1-\epsilon) < x_{\mathrm{AF}}$$

$$\{g^{*2}, y_H^{*\,2}, u_1^*, u_2^*\} \sim \epsilon$$

IR conformal or?



Spontaneous symmetry breaking

$$\mathcal{L} = \mathcal{L}_K(F_{\mu\nu}, \lambda, \psi, H; g) + \sqrt{\frac{a_H}{N_f}}\bar{\psi}H\psi - \frac{z_1}{N_f^2}\left(\mathrm{Tr}H^\dagger H\right)^2 - \frac{z_2}{N_f}\mathrm{Tr}\left(H^\dagger H\right)^2$$

Coleman-Weinberg mechanism

H. Yamagishi, 1980

$$\frac{dV_{\mathrm{eff}}^{\mathrm{RG}}}{d\mu} = \left(\mu\frac{\partial}{\partial\mu} + \sum_i \beta(g_i)\frac{\partial}{\partial g_i} + \gamma_\phi \phi_c \frac{\partial}{\partial \phi_c}\right) V_{\mathrm{eff}}^{\mathrm{RG}} = 0$$

$$H_{ij}^c = \phi_c \delta_{ij}$$

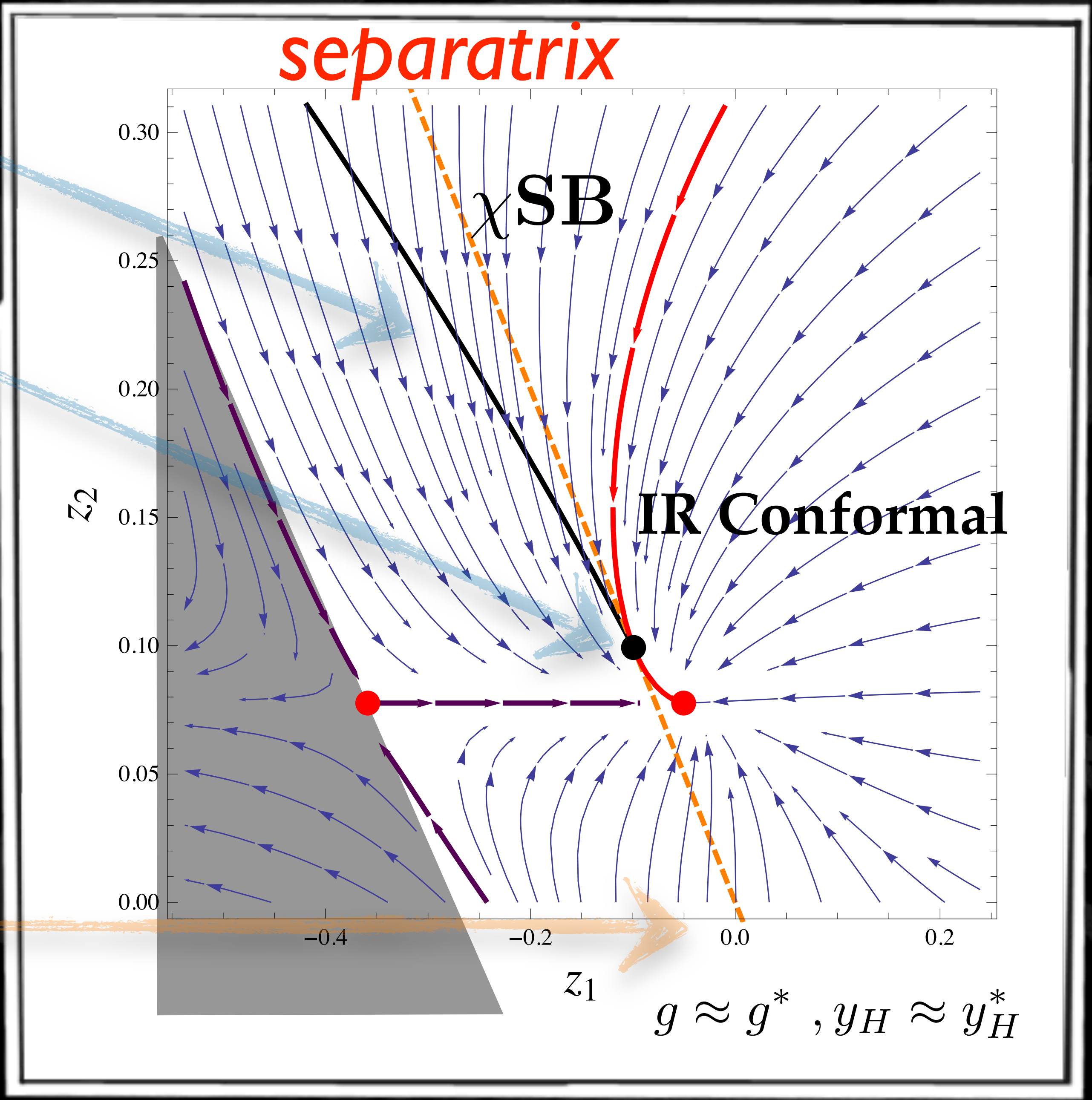
The Light Dilaton

$$V_{\text{eff}}^{\text{RG}\,\prime}(\phi_c) = 0$$

$$V_{\text{eff}}^{\text{RG}\,\prime\prime}(\phi_c) = 0 \Rightarrow$$

$$m_\phi^{(1)\,2} \propto 4z_2^2 - x a_H = 0$$

$$V_{\text{eff}}^{\text{RG}}(\phi_c) = 0$$



ϕ arbitrarily light by tuning: $4z_2^2 - x a_H = \delta$ small

Is it the Dilaton?

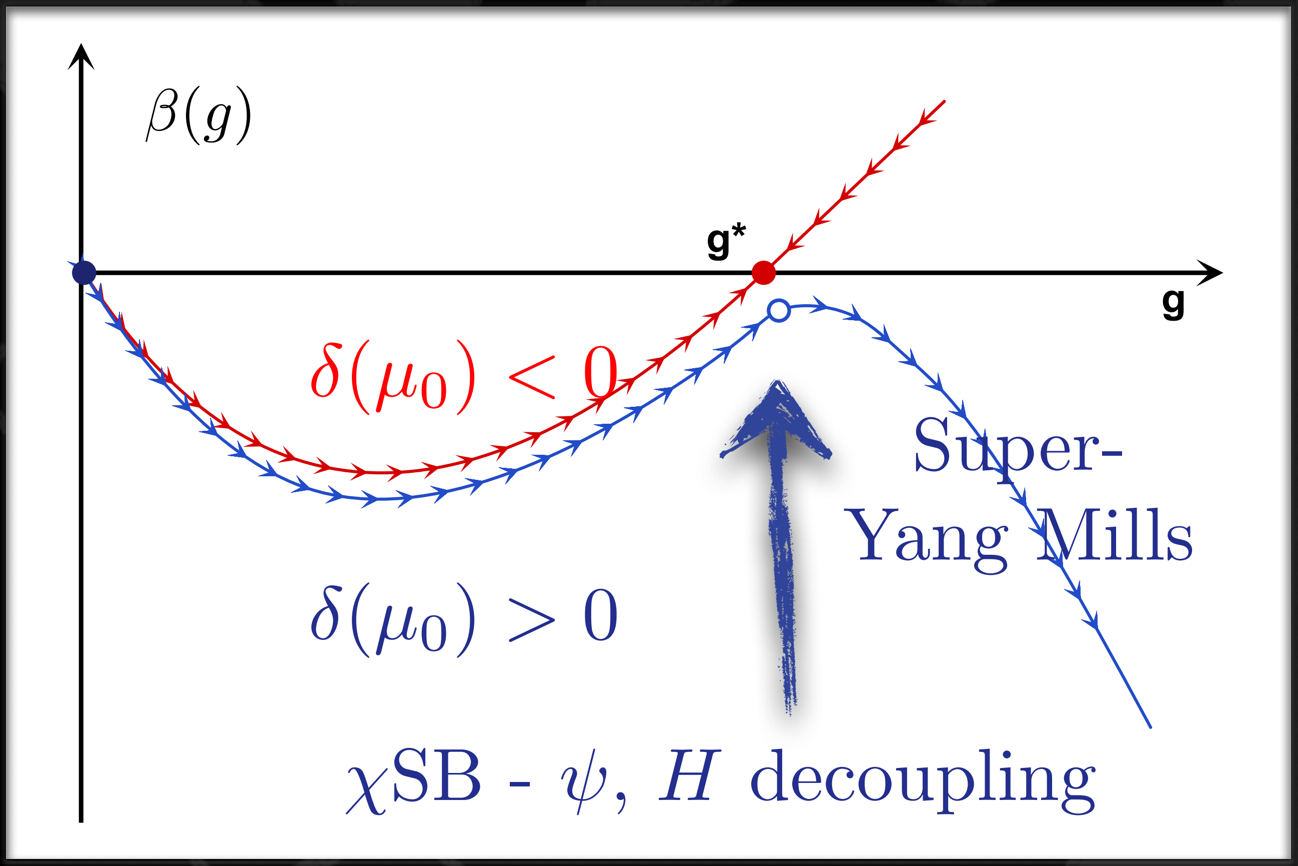
$$\partial_\mu D^\mu = \Theta^\mu_\mu = \sum_i \beta(g_i) \frac{\partial \mathcal{L}}{\partial g_i}$$

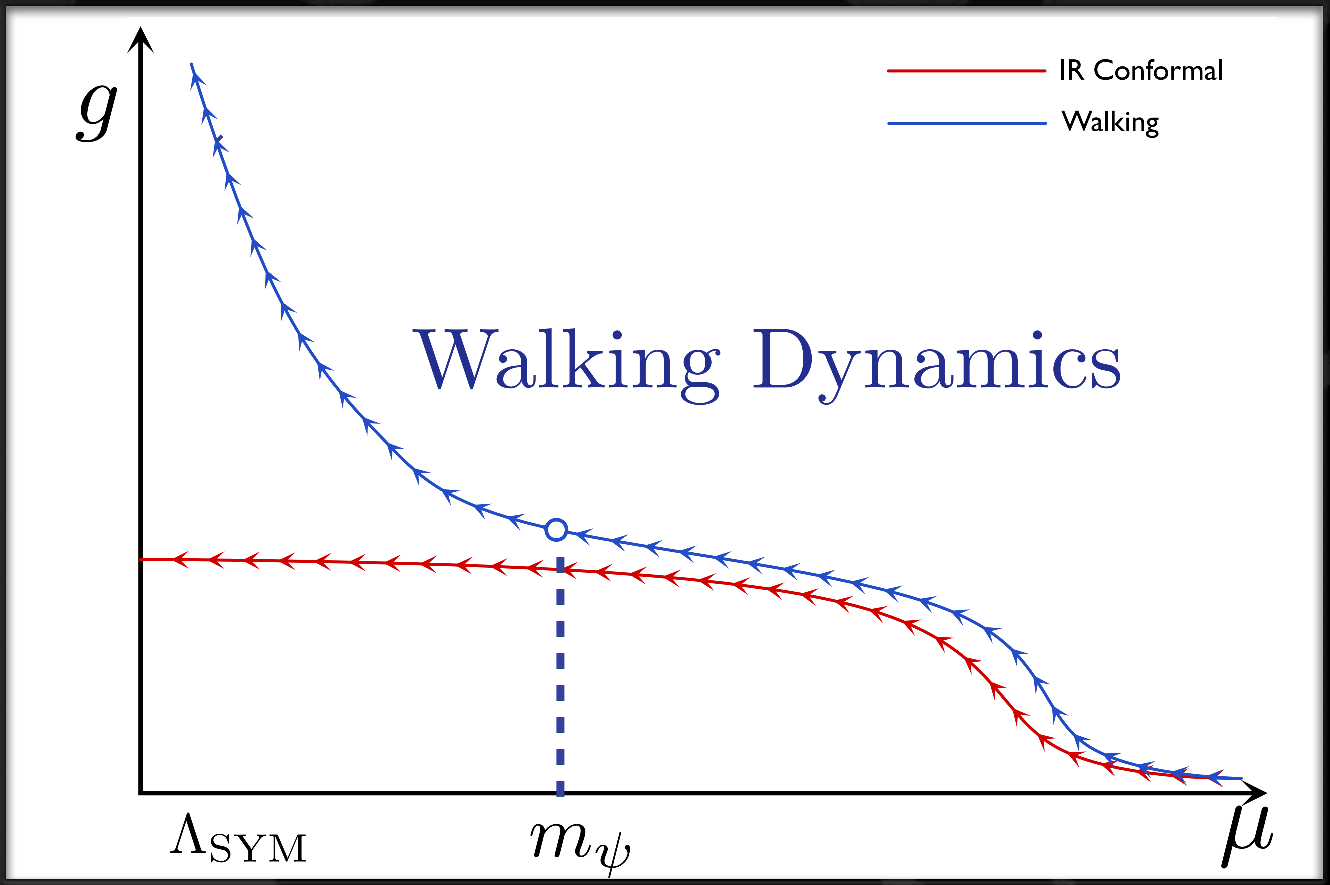
$$\langle D | \partial_\mu D^\mu | 0 \rangle = -f_D m_D^2$$

$$\Theta^\mu_\mu \propto (\beta_1 + \beta_2)\phi + \cdots \quad \text{since } \beta(g), \beta(y_H) \approx 0 \text{ at } \mu_0$$

$$\delta(\mu_0) \lesssim \epsilon$$

The Complete Picture





$$\langle \lambda\lambda \rangle = -\frac{9}{32\pi^2}\Lambda^3_{SYM}$$

$$\Lambda^2_{\rm SYM} = v^2\left(\frac{3}{11\epsilon}\right)^{2/3}\exp\left(-\frac{6}{22\epsilon}\right) .$$

Full Spectrum of Broken Phase

Mass eigenstates of quarks and mesons

$$H_{ij} \approx (\phi_c + \phi + i\pi^0)\delta_{ij} + h^a T^a_{ij} + i\pi^a T^a_{ij}, \qquad a = 1, \dots N_{\rm f}^2 - 1$$

DM Higgs EW

μ

$m^2_{\rm NGB} = 0$ $m^2_{\rm SYM} \sim e^{-1/\epsilon}$ $m^2_d \sim \delta\epsilon$ $m^2_\psi \sim m^2_h \sim \epsilon$

N_f^2 $4(N_c^2 - 1)$ 1 $4N_f N_c + (N_f^2 - 1)$

Minimal Working TC

- Minimal WT

$SU(2)_{TC}$ $\square\!\square$ **U** **D** **N** **E**

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

- Next to MWT

$SU(3)_{TC}$ $\square\!\square$ **U** **D**

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

- Orthogonal

Vanilla TC

$SO(4)_{TC}$ $\square$ **U** **D**

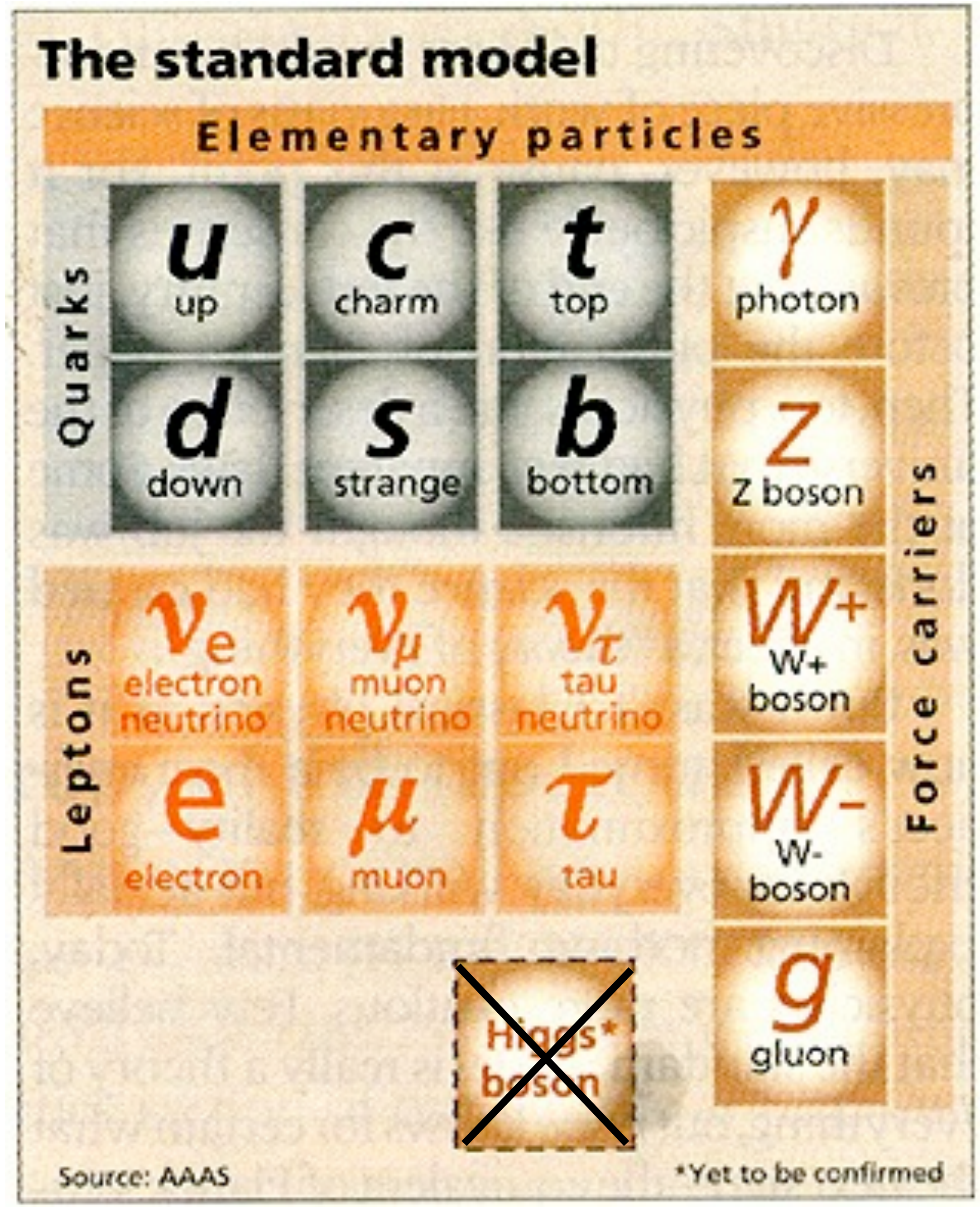
Frandsen, Sannino 09

- Ultra MT

$SU(2)_{TC}$ $\square$ **U** **D**

Ryttov & Sannino 08

Minimal Walking Technicolor



U(1)

SU(2)

SU(3)

N Extra Neutrino

ζ Extra Electron

U t-up

G t-glue

D t-down

SU(2)

F.S. + Tuominen 04

Dietrich, F.S., Tuominen 05

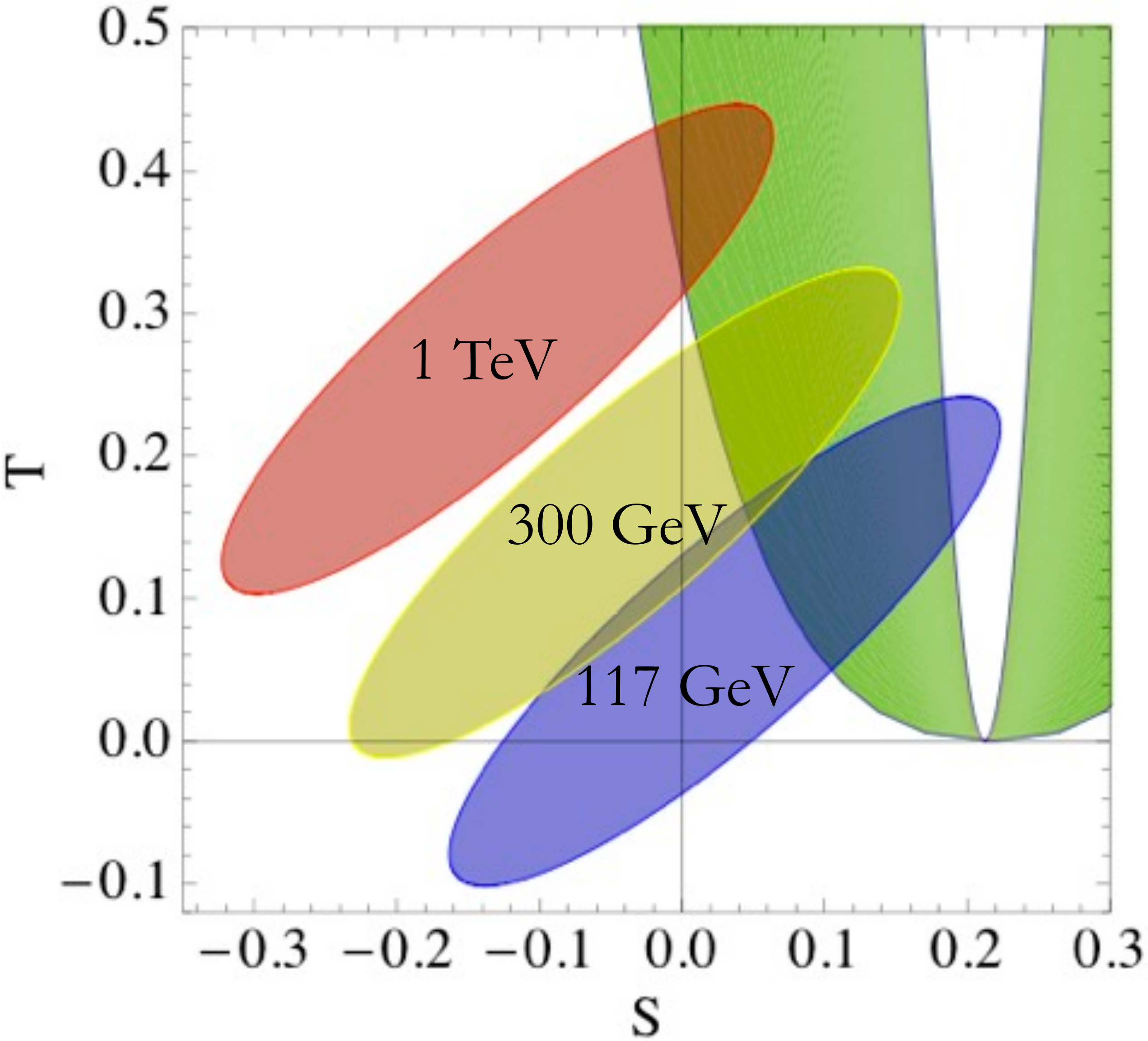
U and D: Adj of SU(2)

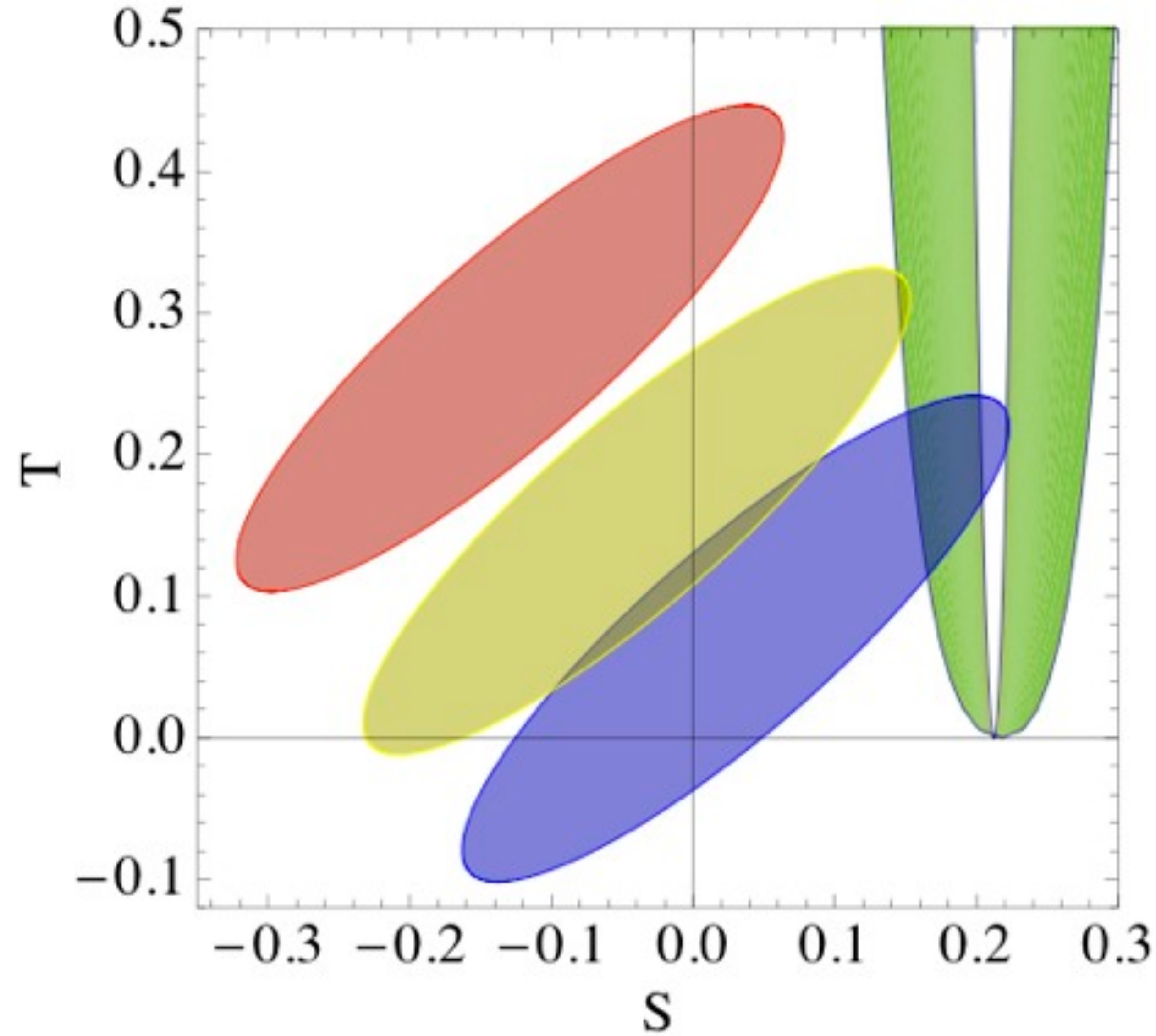
S beyond TC...

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

Offset the first term

New Leptons & Precision Data





Exotic Leptonic hypercharge Y=-3/2

Standard Model Leptonic hypercharge

Conclusions

- DEWSB can naturally occur at the LHC
- Phase Diagram of strongly interacting theories
- Minimal models of technicolor
- Composite Dark Matter and Inflation (... another time)

MWT Features

- The most economical WT theory
- Compatible with precision measurements
- Possible DM candidates
- Light Composite Higgs
- Under investigation on the Lattice

MWT Effective Lagrangian

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

Composite Higgs H

Composite Axial - Vector States $R_{1,2}$

Heavy Electron ζ

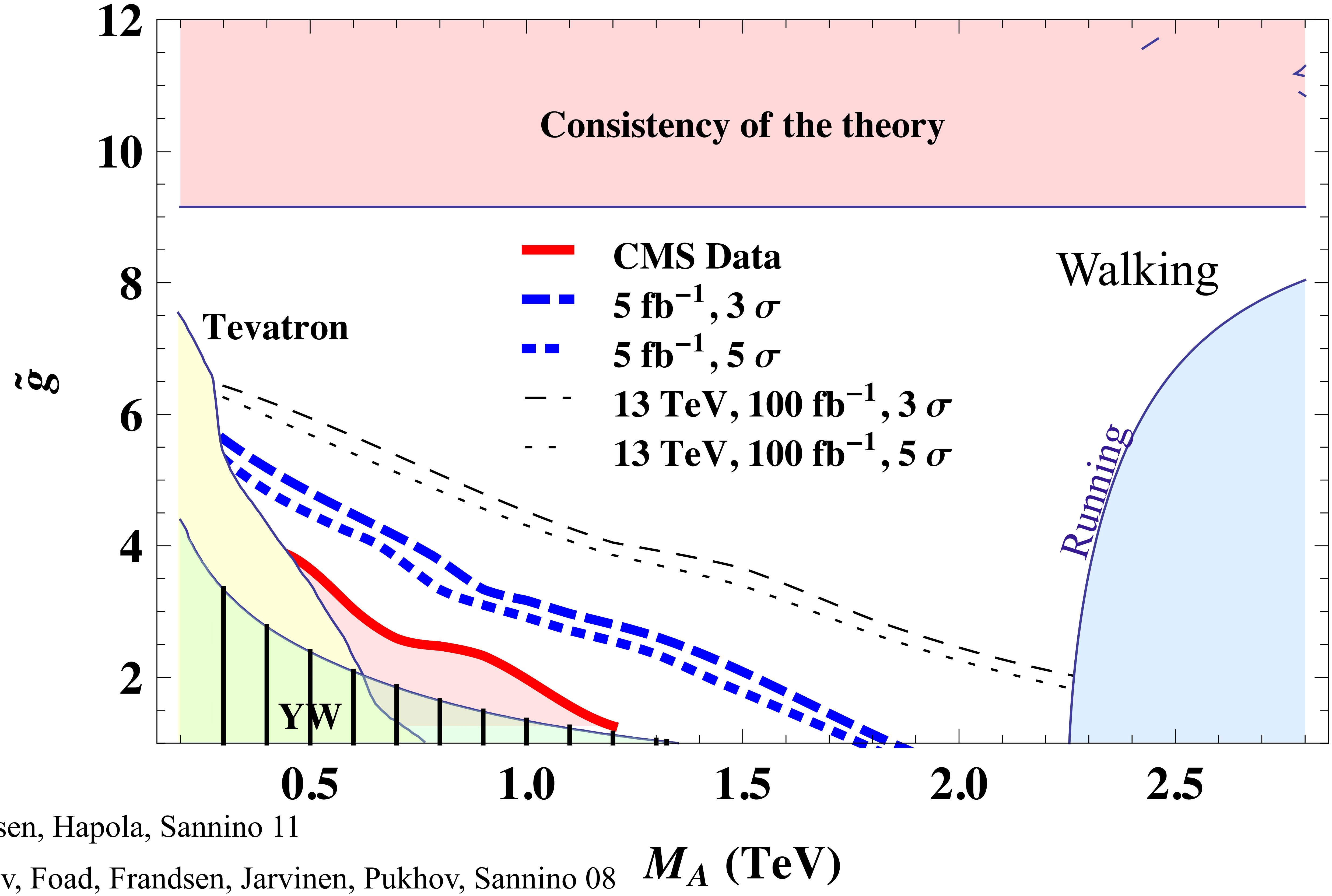
2 Heavy Majoranas N_1 N_2

Frandsen, Masina, Sannino 09

Hapola, Masina, Sannino 11

Foadi, Frandsen, Ryttov & F.S. 07

Constraining MWT



Andersen, Hapola, Sannino 11

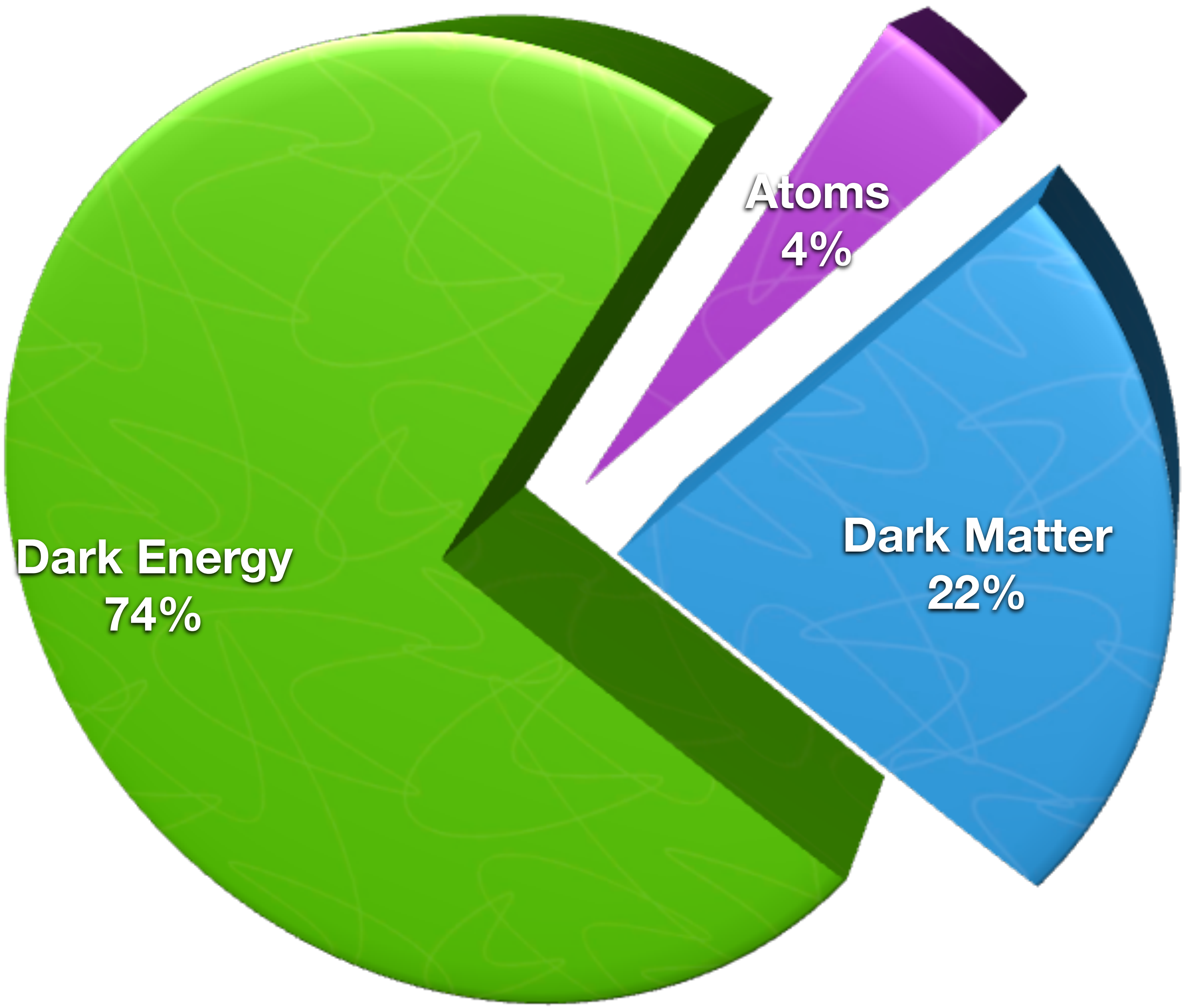
Belyaev, Foad, Frandsen, Jarvinen, Pukhov, Sannino 08

Conclusions

- DEWSB can naturally occur at the LHC
- Phase Diagram of strongly interacting theories
- Minimal models of technicolor
- Composite Dark Matter
- Composite inflation.

Back - up

Dark Matter

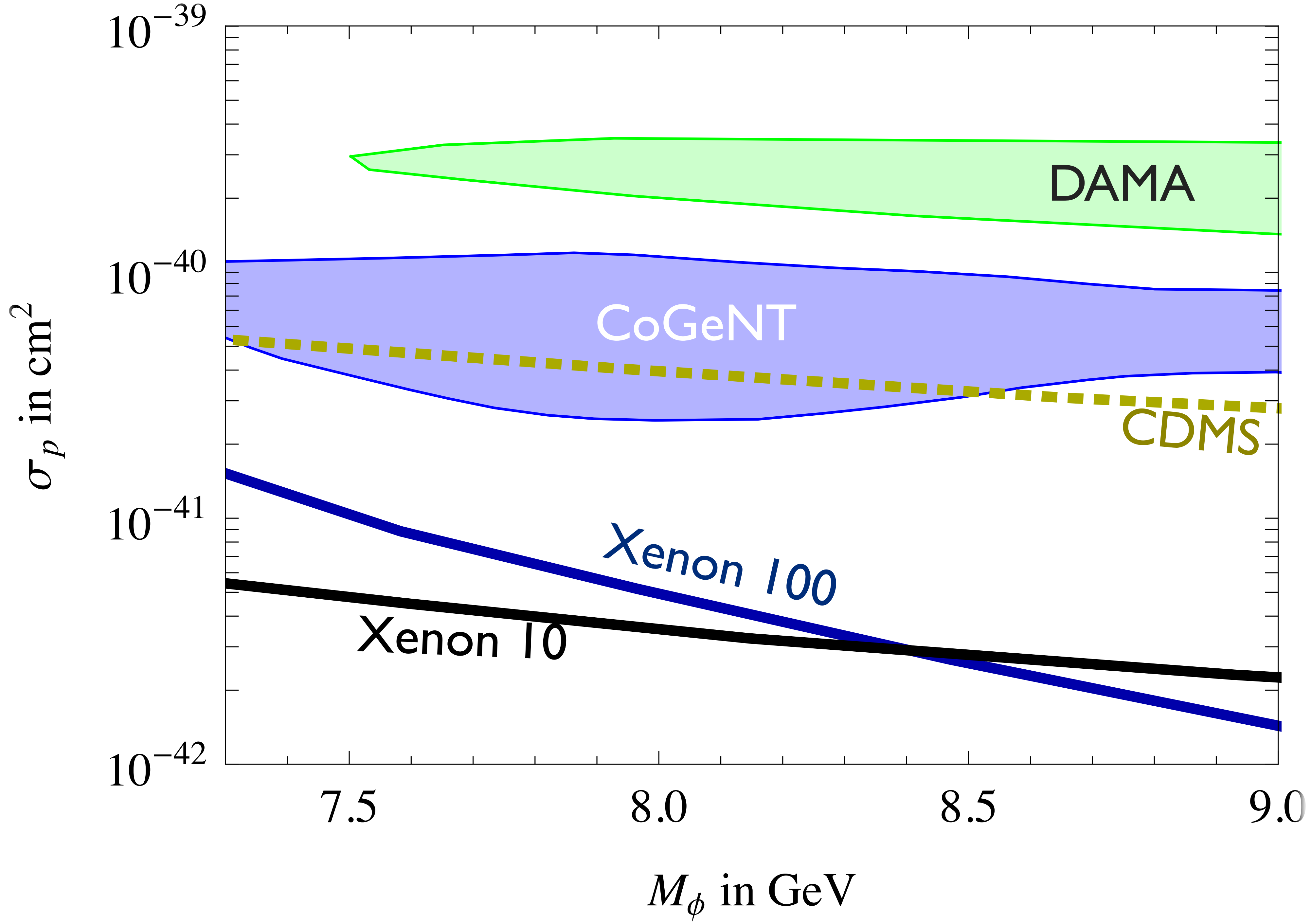


$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$

DM asymmetry

- A particle similar to the nucleon
- Electrically neutral
- At most EW-type cross sections
- Great if connected to EW (Observable at LHC)

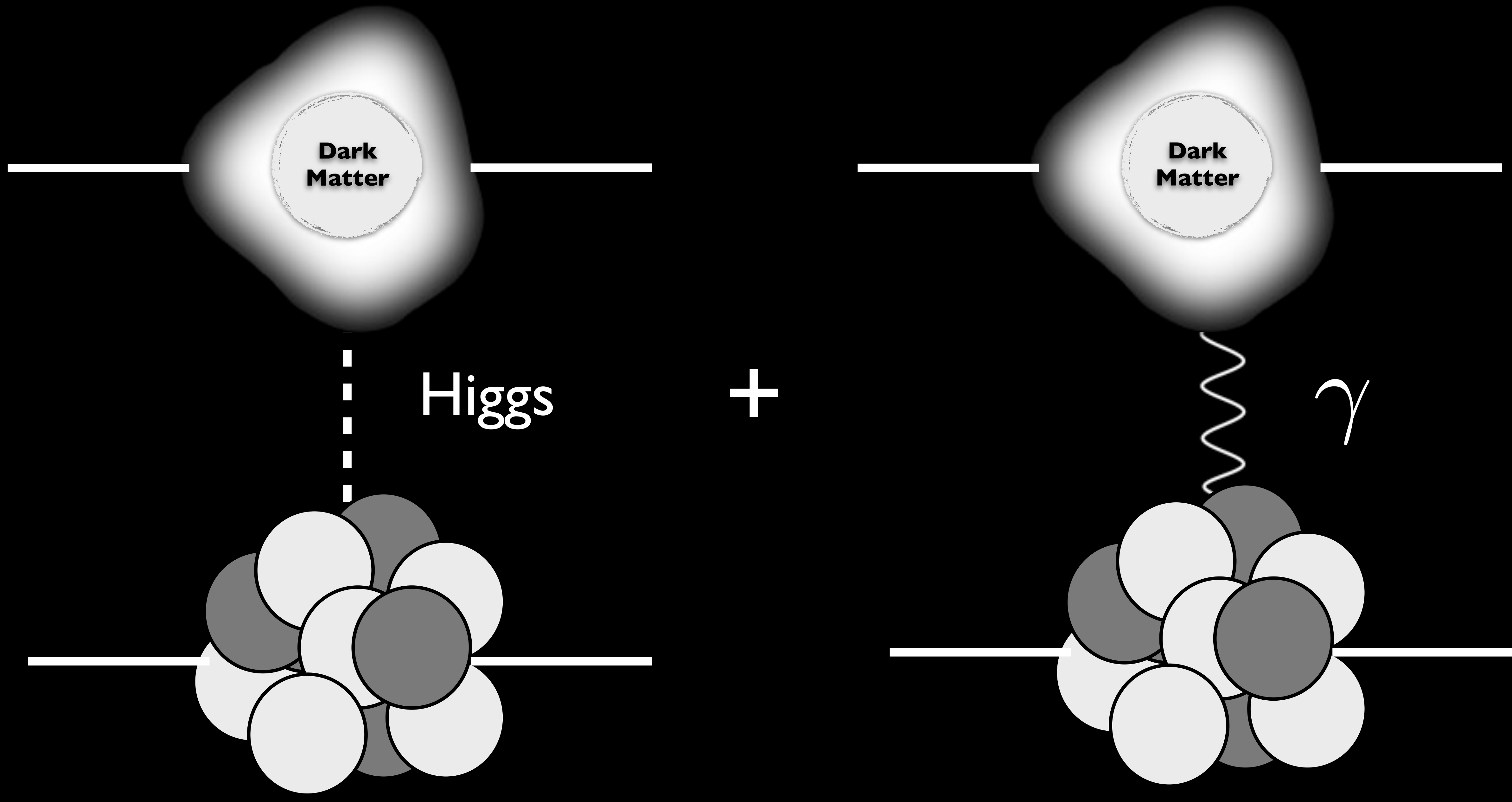
Puzzle



10^{-39}
10^{-40}
10^{-41}
10^{-42}
σ_p in cm^2
DAMA
CoGeNT
CDMS
Xenon 100
Xenon 10
7.5
8.0
8.5
9.0
M_ϕ in GeV

Quantum Mechanics

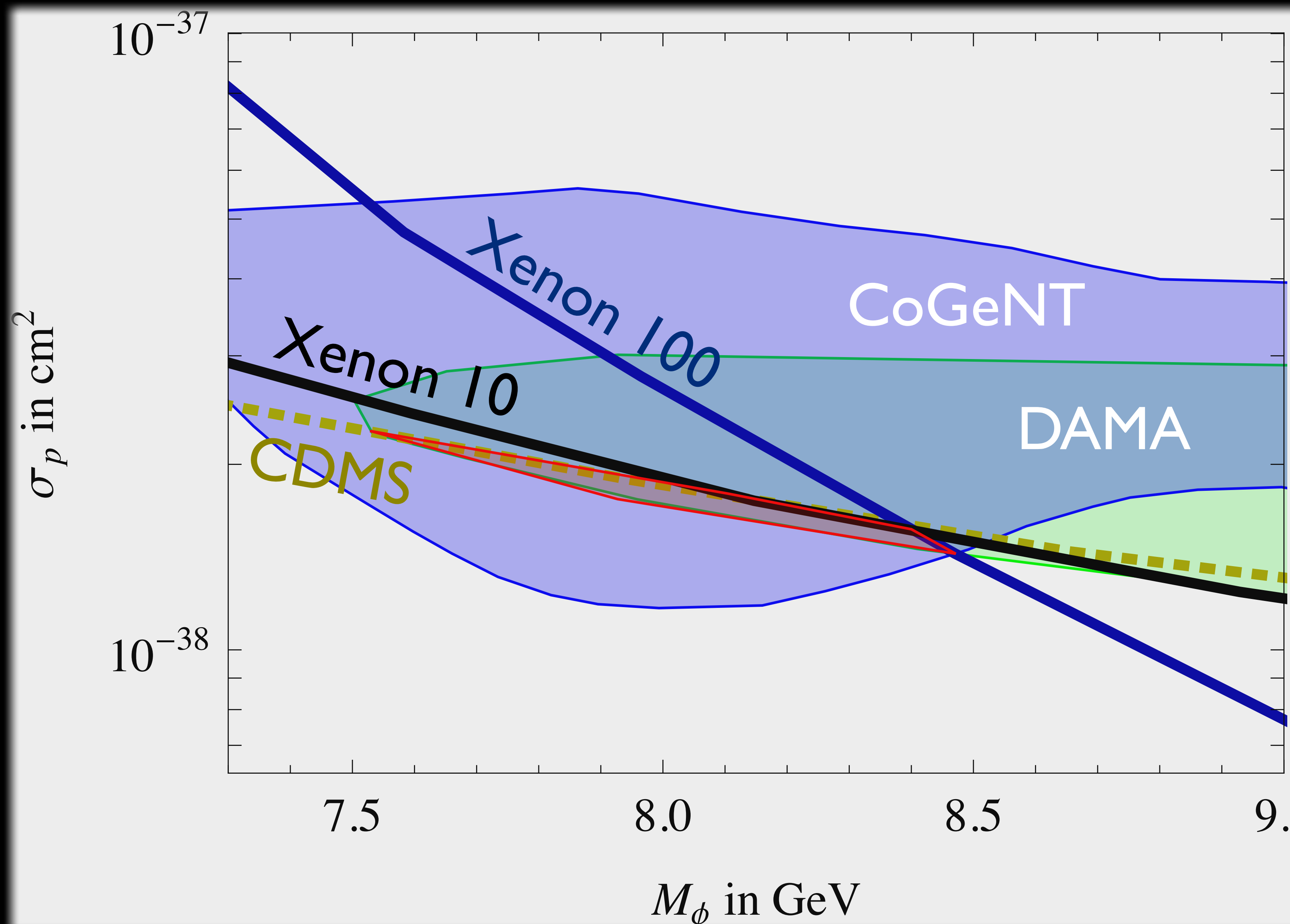
Del Nobile, Kouvaris, Sannino 11



Interfering Composite ADM

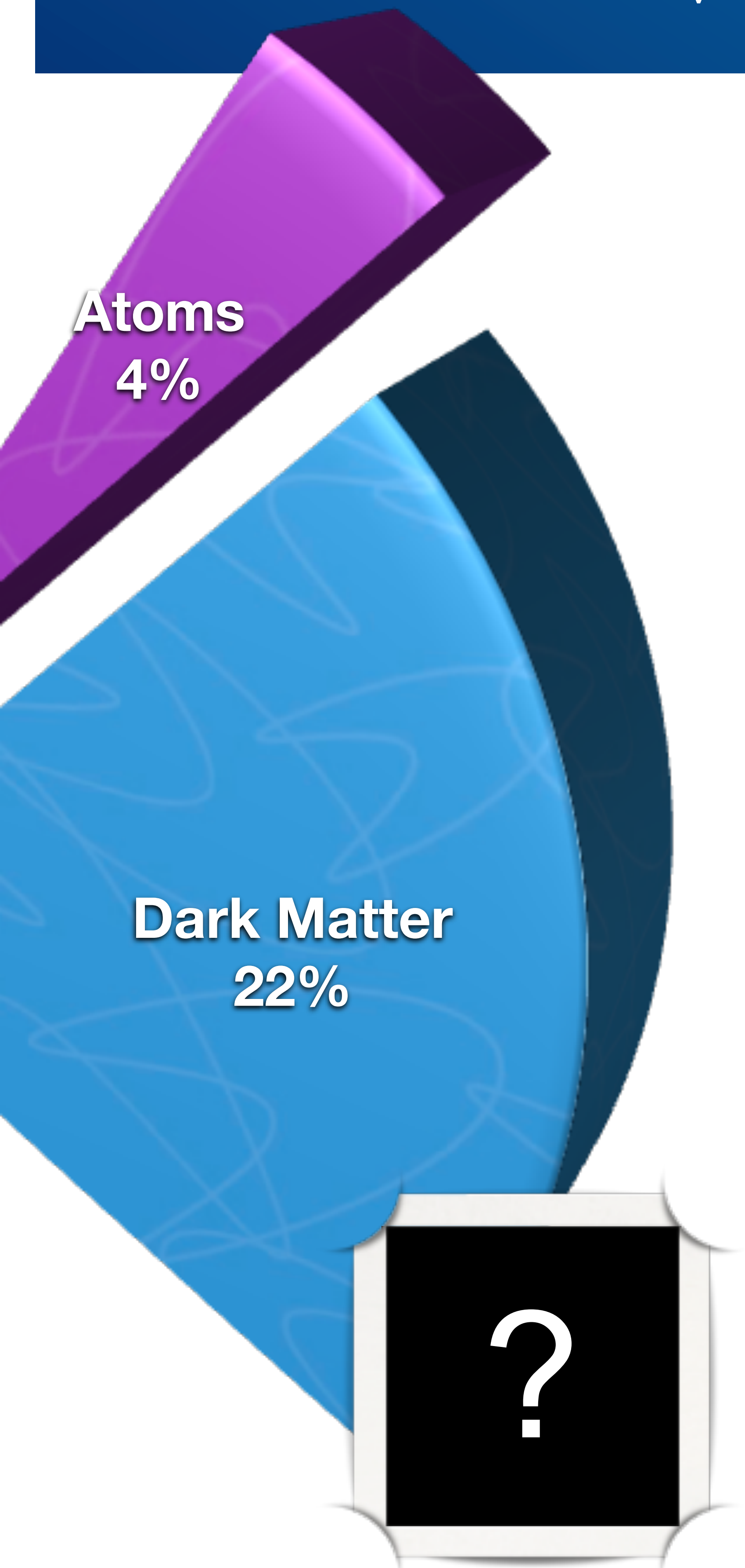
CoGeNT and DAMA

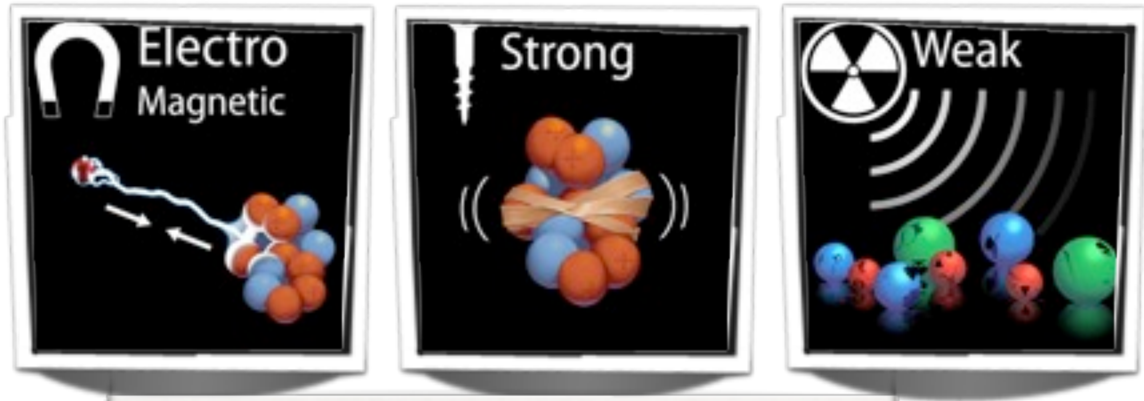
Del Nobile, Kouvaris, Sannino 11



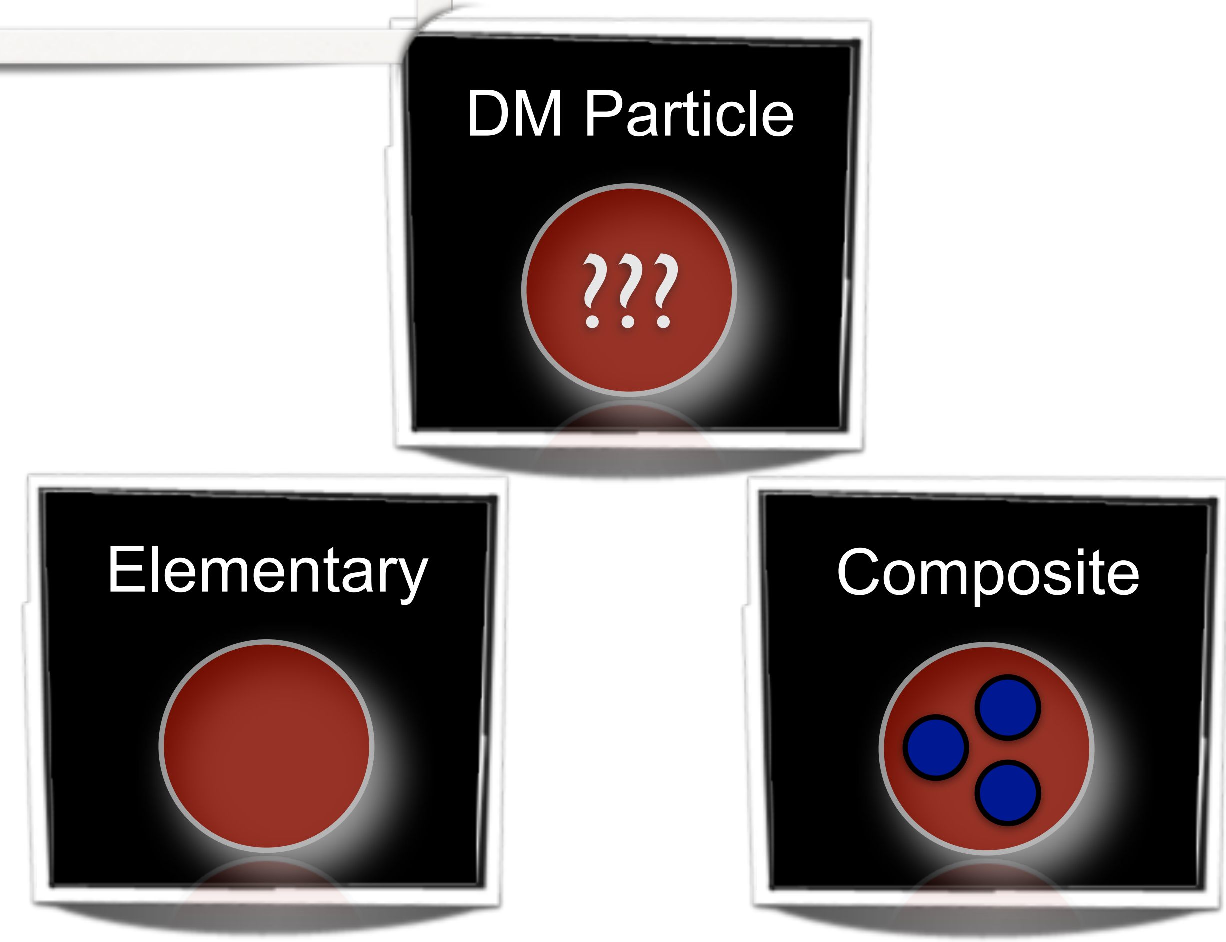
Chang et al. 2010, Feng et al, 2011, Frandsen et al. 2011

What makes DM?





Oversimplification



(Un)TC Interact. Massive Particle (u)TIMP

TIMPs	Masses	Annih.	Asymm	Symm	Models
TC-Baryon	(1 - 3) TeV	-	X	-	Complex-Rep Traditional TC
TC-PGB	5 GeV - .5 TeV	X	X	X	(Pseudo)-Real (UMT, MWT, OT)
Unbaryon	(1 - 10) GeV	X	X	X	Techni-unparticle

TC-Baryon

Nussinov, 86
Barr - Chivukula - Farhi 90
Sarkar 96
Gudnason - Kouvaris - F.S. 06
Foadi, Frandsen, Sannino 09
Nardi, Sannino., Strumia, 08.
Sannino, 10

TC-PGB

Gudnason - Kouvaris - Sannino. 06
Ryttov - Sannino 08
Frandsen & Sannino. 09

Unbaryon

D.B. Kaplan 92
Sannino, Zwicky 09
Frandsen, Sarkar, 10

Related

Kouvaris 06,07,10
Kainulainen, Virkajarvi, Tuominen 06,09,10

Mixed TIMP DM

Belyaev, Frandsen, Sannino, Sarkar 10

DM and GUTs

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

Light

Heavy

$$m_{TB} \sim 5 \text{ GeV}$$

$$m_{TB} \approx (1-3) \text{ TeV}$$

$$\frac{TB}{B} \approx \mathcal{O}(1)$$

$$\frac{TB}{B} \approx \exp\left[-\frac{m_{TB}}{T^*}\right]$$

GUTs

$$\tau \sim \frac{M_{GUT}^4}{m_{TB}^5} \sim 3 \times 10^{37} \text{sec}$$

$$\tau \sim \frac{M_{GUT}^4}{m_{TB}^5} \sim 10^{26} \text{sec}$$

Gudnason, Ryttov, FS 06

Nardi, FS, Strumia, 08.

New life in Technicolor

Not the Coldplay album

The model

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}F^2 \qquad + \sum_j^{N_f} i\overline{\psi}_j \not{D} \psi_j$$

$$+ y_H \bar{\psi}_i H_{ij} \psi_j + \mathrm{h.c.}$$