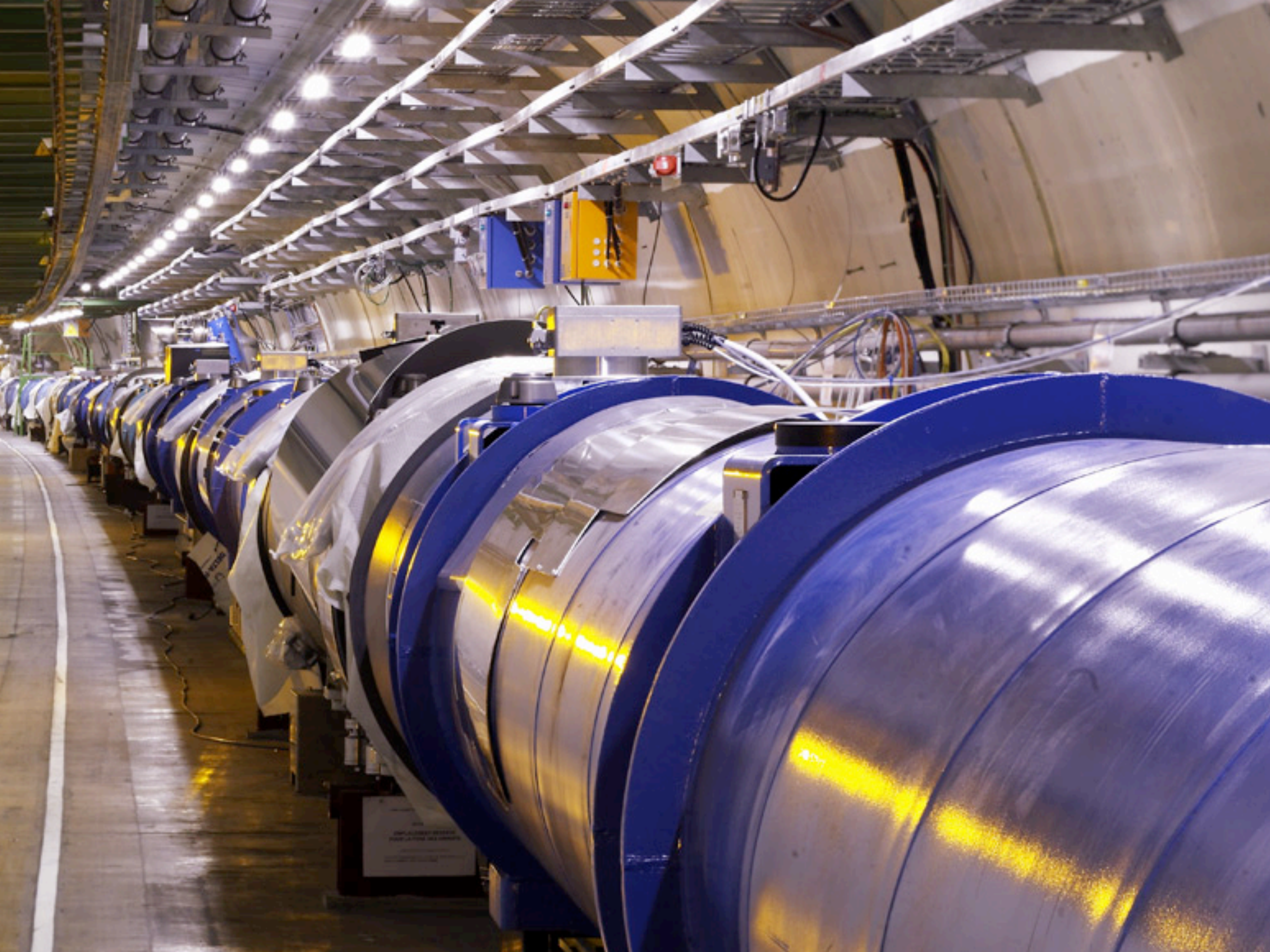
Technicolor & Beyond

Francesco Sannino

CP^3 - Origins

Particle Physics & Origin of Mass

August 2010 @ SUSY10 - Bonn



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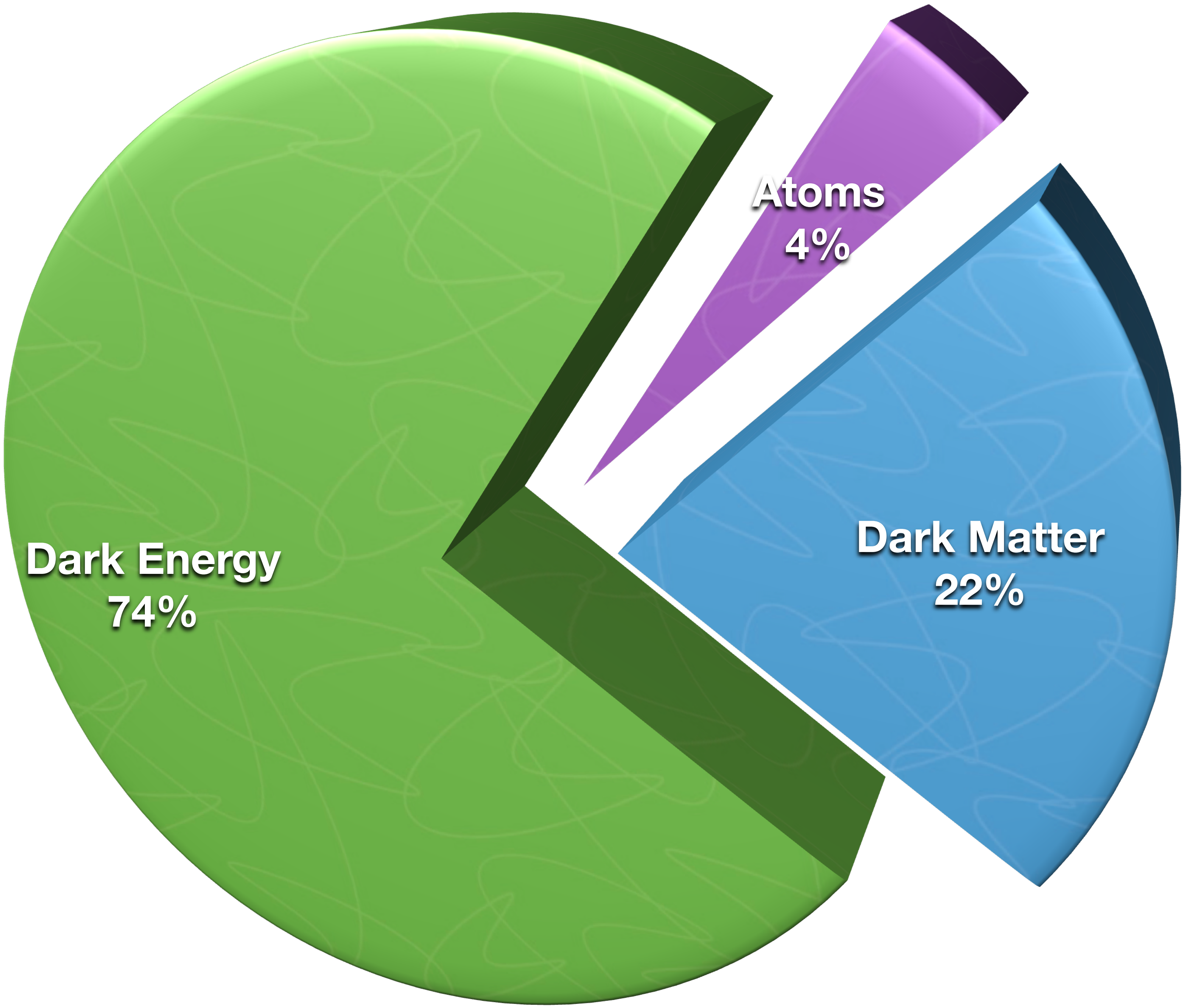
Cosmology



Many Models

(?)MSSM

XLMS D

Technicolor

......

Branes

Unparticle

AdS/?

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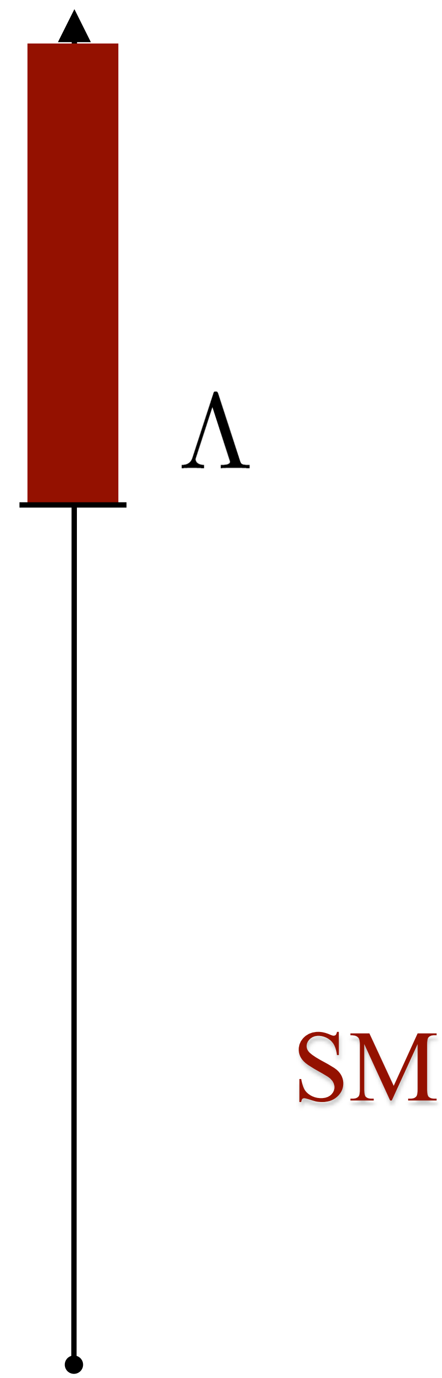
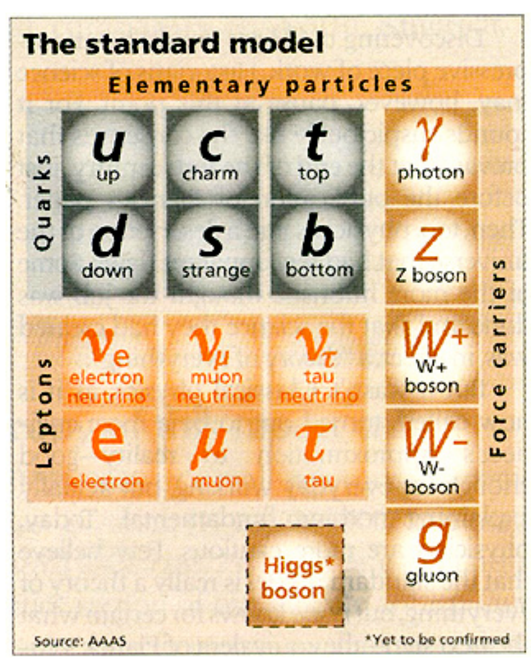
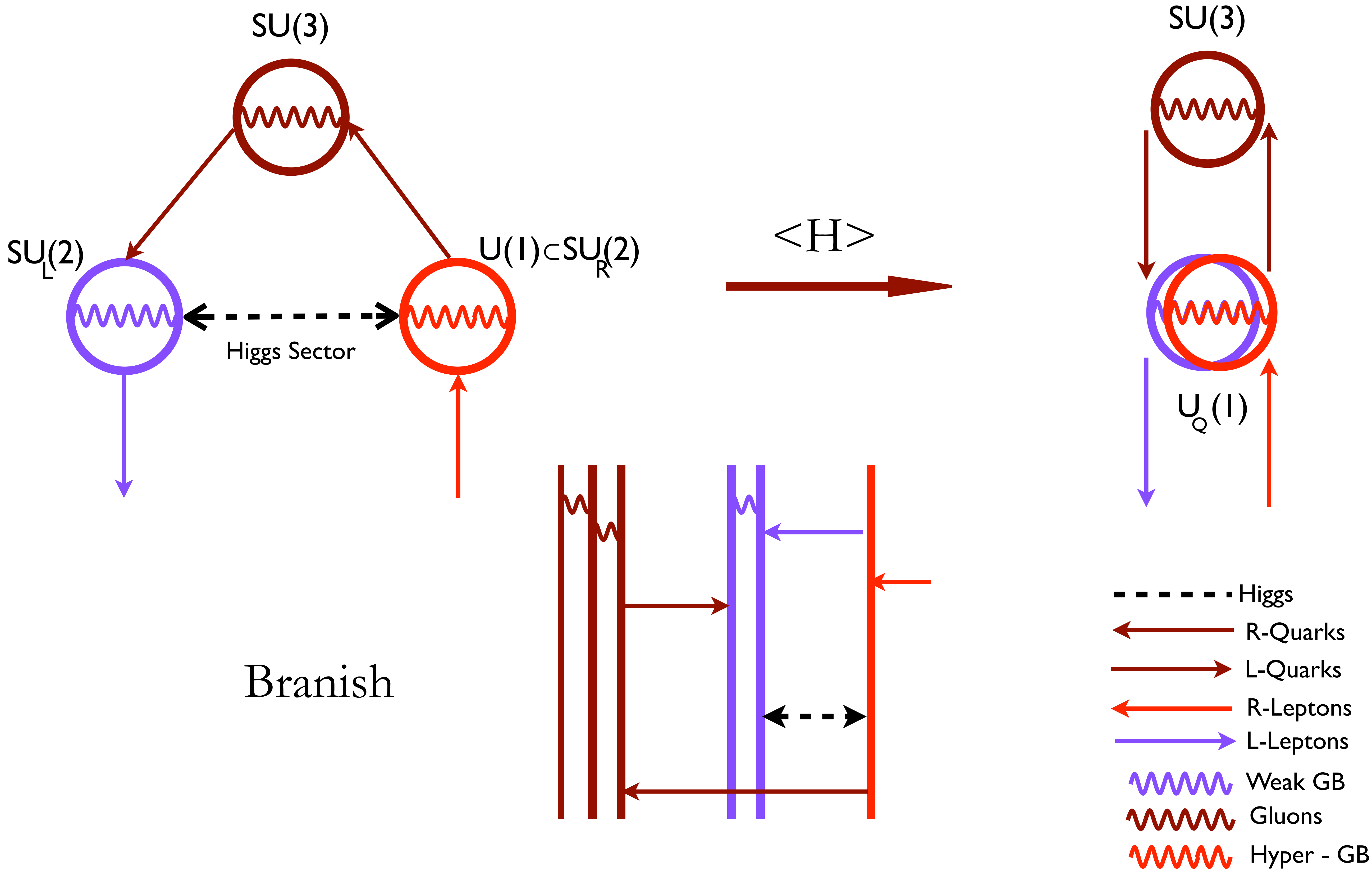
Standard Model

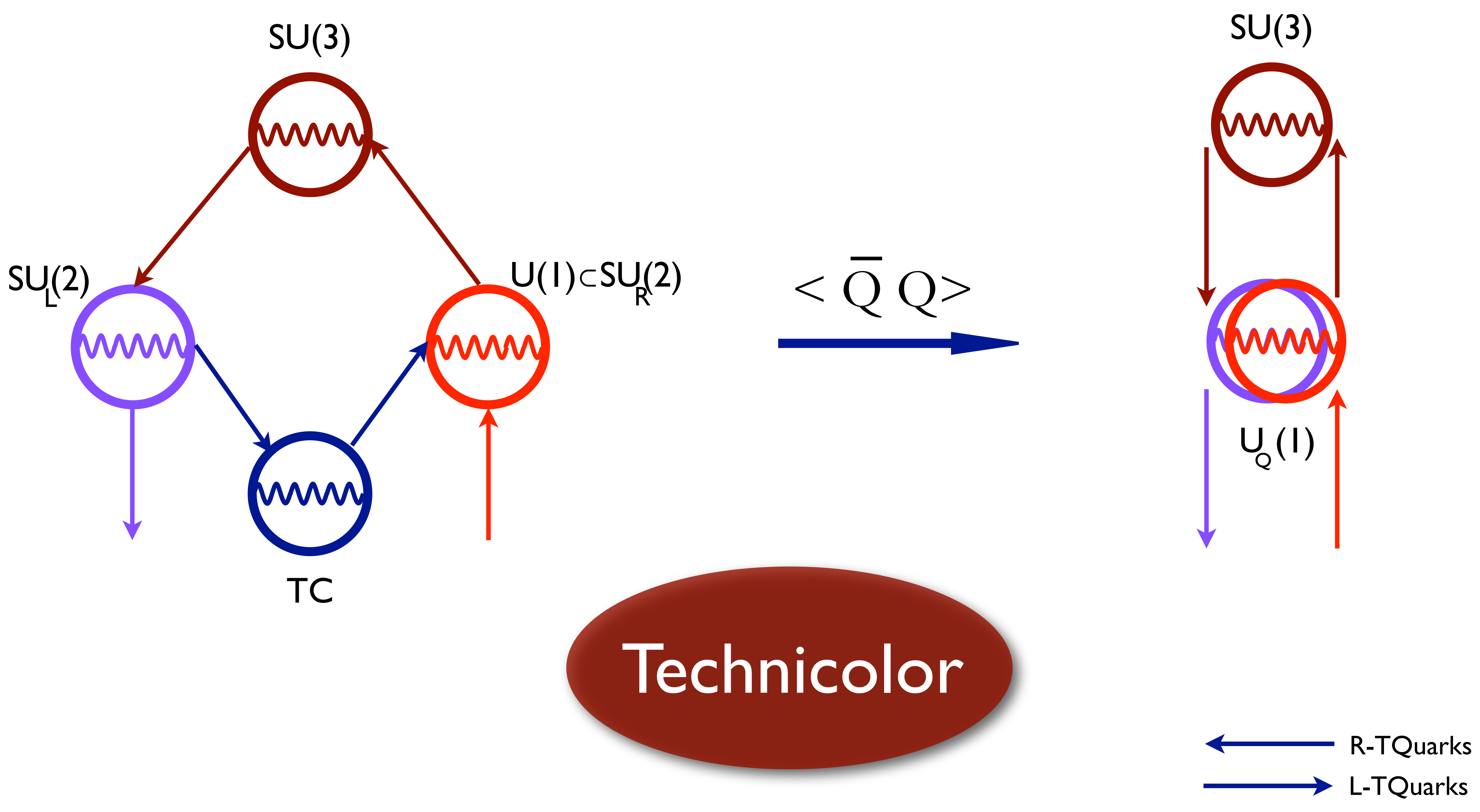




SM - cartoon


SU(3)
SU_L(2)
U(1)⊂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

Technicolor - cartoon



QCD-like TC

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

Natural to use QCD-like dynamics.

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

$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda^3_{TC} \qquad\qquad \Lambda_{TC} \simeq 1 \text{ TeV}$$

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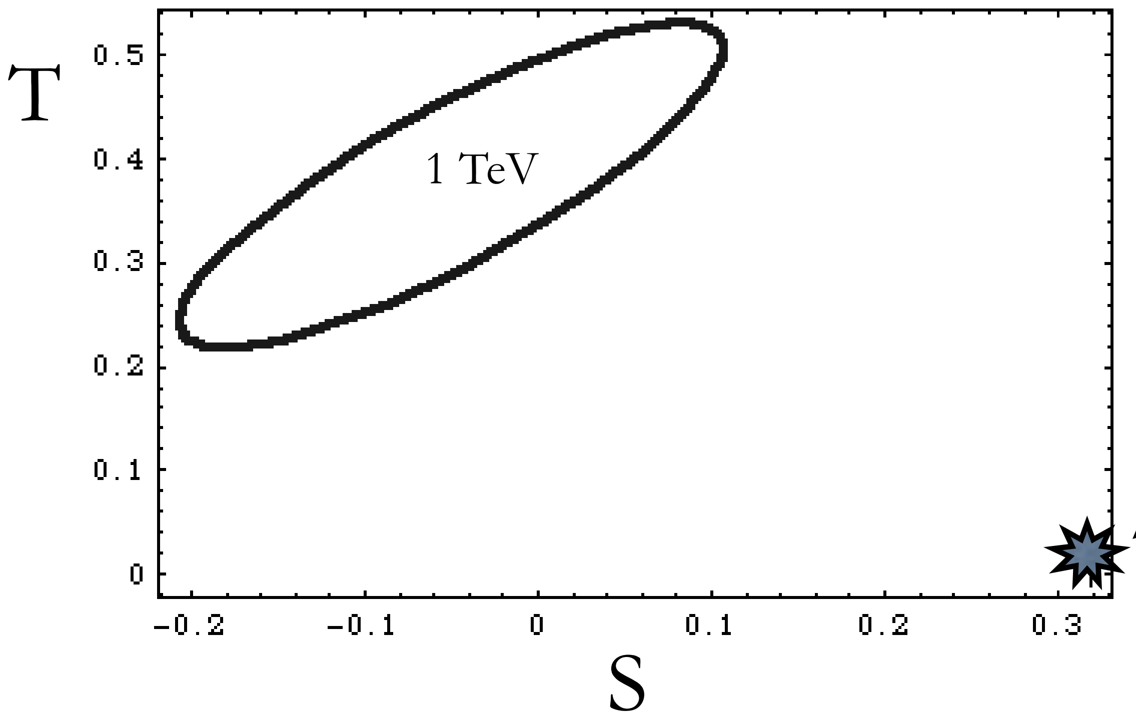
Need novel dynamics

Large & Positive S from QCD-like Technicolor



SU(3) + 1 Fund. Doublet

Weinberg, Susskind

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

$$S = -16\pi \frac{\Pi_{3Y}(m_Z^2) - \Pi_{3Y}(0)}{m_Z^2},$$

$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 m_Z^2},$$

SM Fermion Masses

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Extending Technicolor

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

Different Approaches

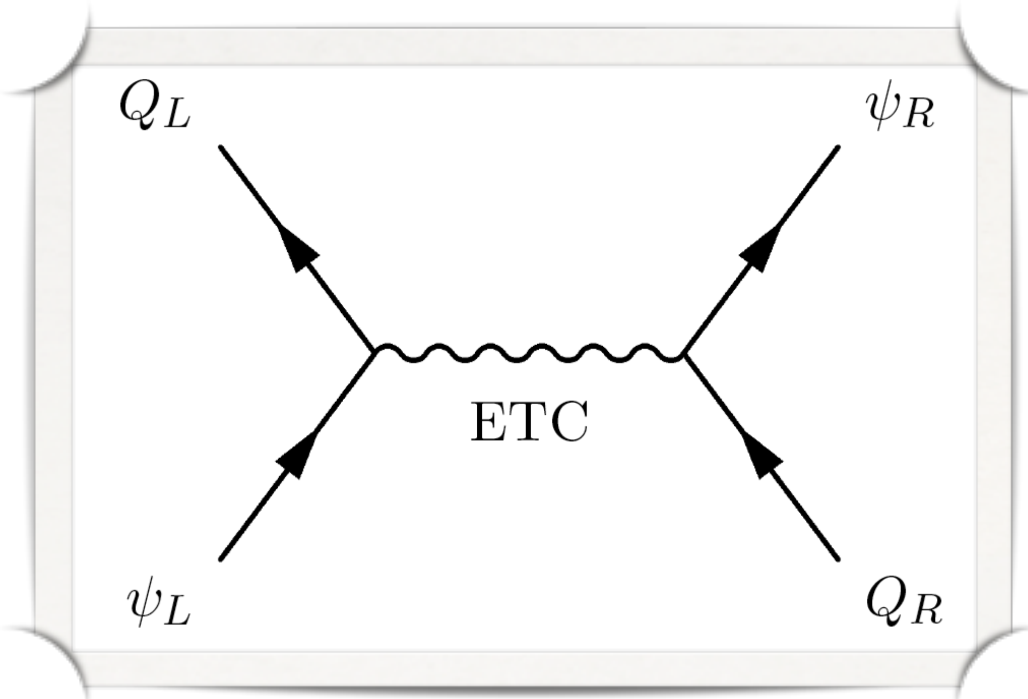
Scalar-less New Gauge Interactions (Extended TC)

Marry SUSY and Technicolor

Add New Scalars in the Flavor Sector

.....

Extended Technicolor



Eichten & Lane 80

Recent investigations

Ryttov & Shrock 10

Modifies TC dynamics

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

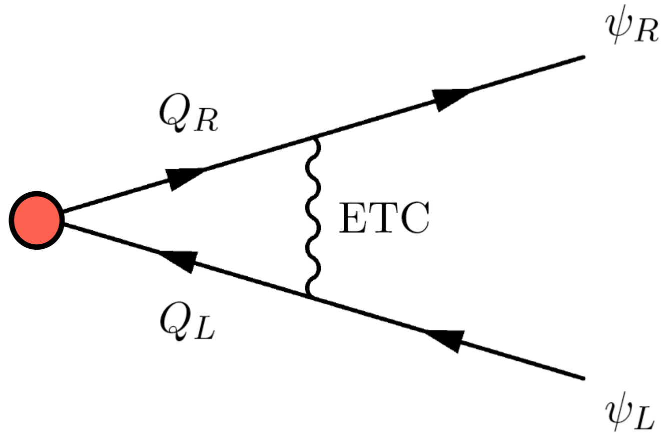
PNG Masses

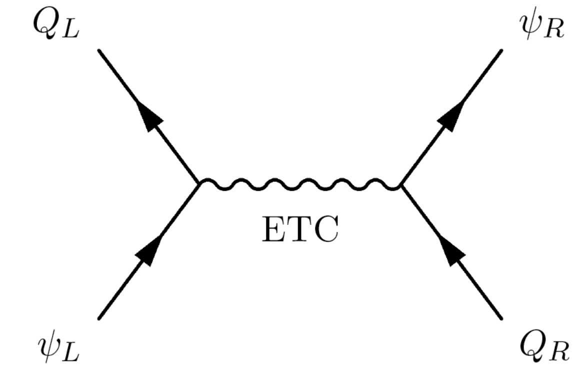
SM-Fermion Masses

FCNC Operators

Energy

Λ_{ETC}





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

Λ_{TC}

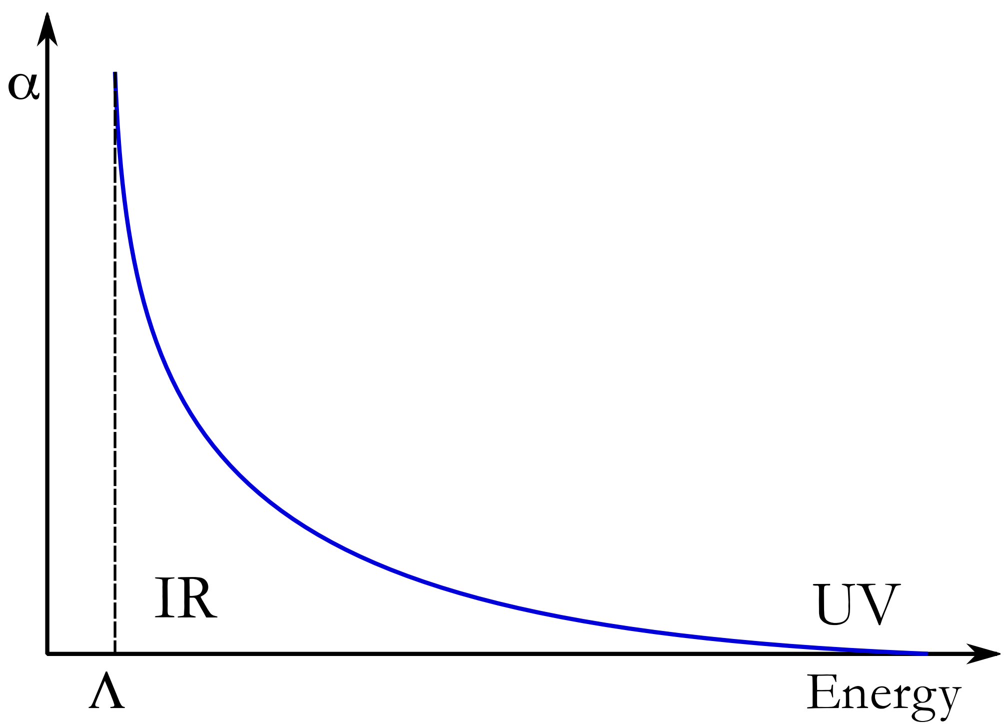
Electroweak breaks

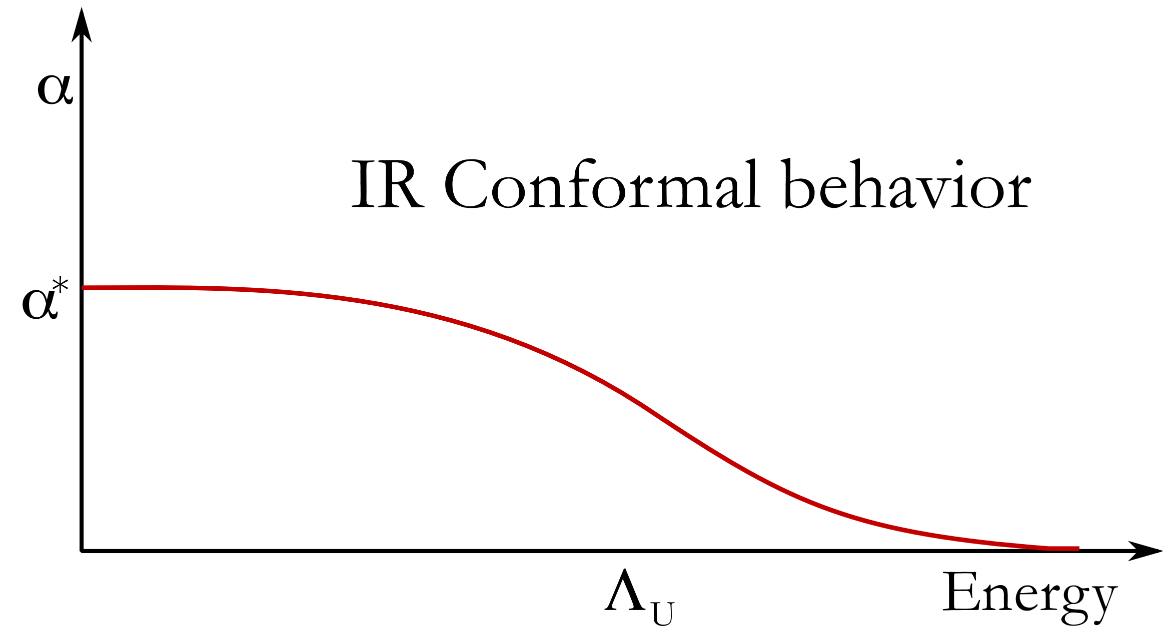
$$< \bar{Q}Q >_{ETC} \approx < \bar{Q}Q >_{TC} \sim \Lambda^3_{TC}$$

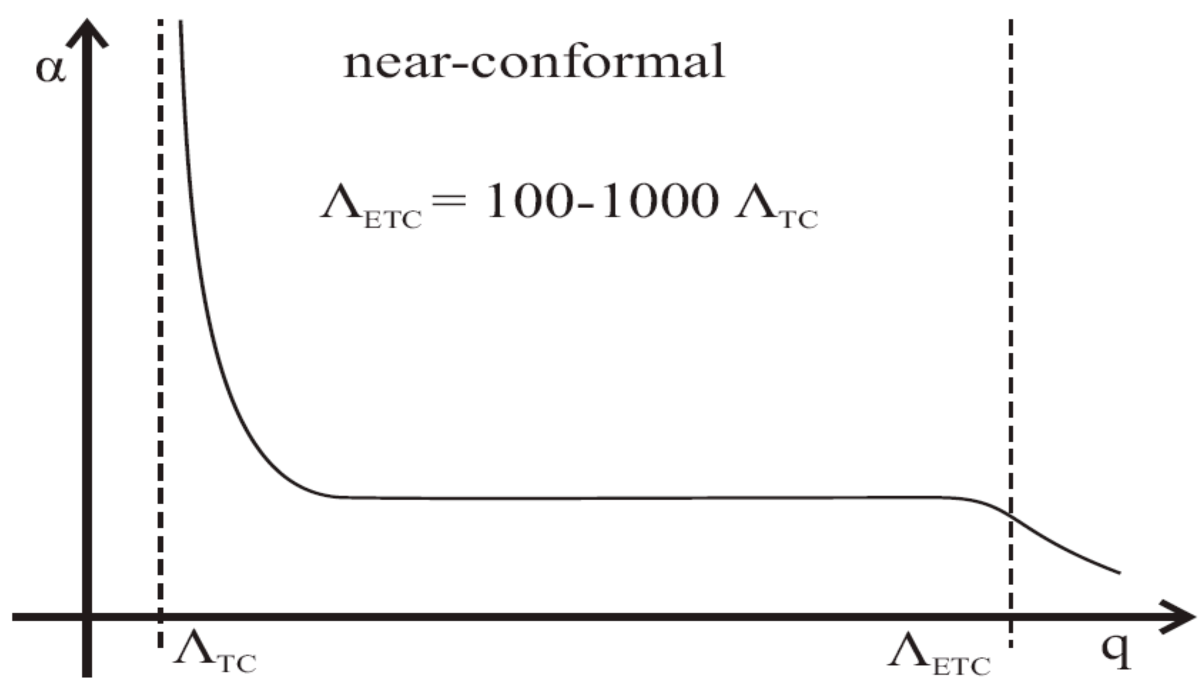
$$\boxed{m_{\mathrm{f}} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC} \quad \ll \quad m_{\mathrm{Top}}}$$

Beyond QCD

Near Conformal







Why walking helps?

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

QCD-Like

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

Near the conformal window

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

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

If large anomalous dimension, around $\gamma_m(\alpha^*) \sim 1.7$

$$\downarrow$$

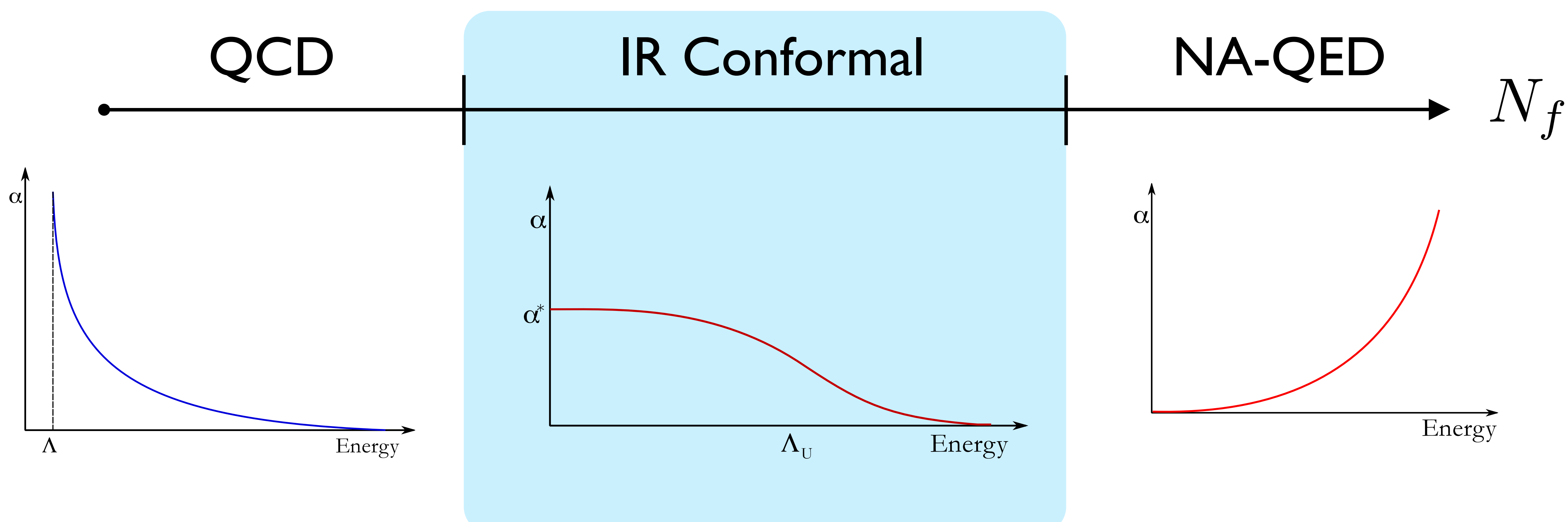
Fermion Mass Enhancement & FCNC decoupling

Gauge Theory Knobs

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

Matter Representation

# of Flavors per Representation



Universal Picture

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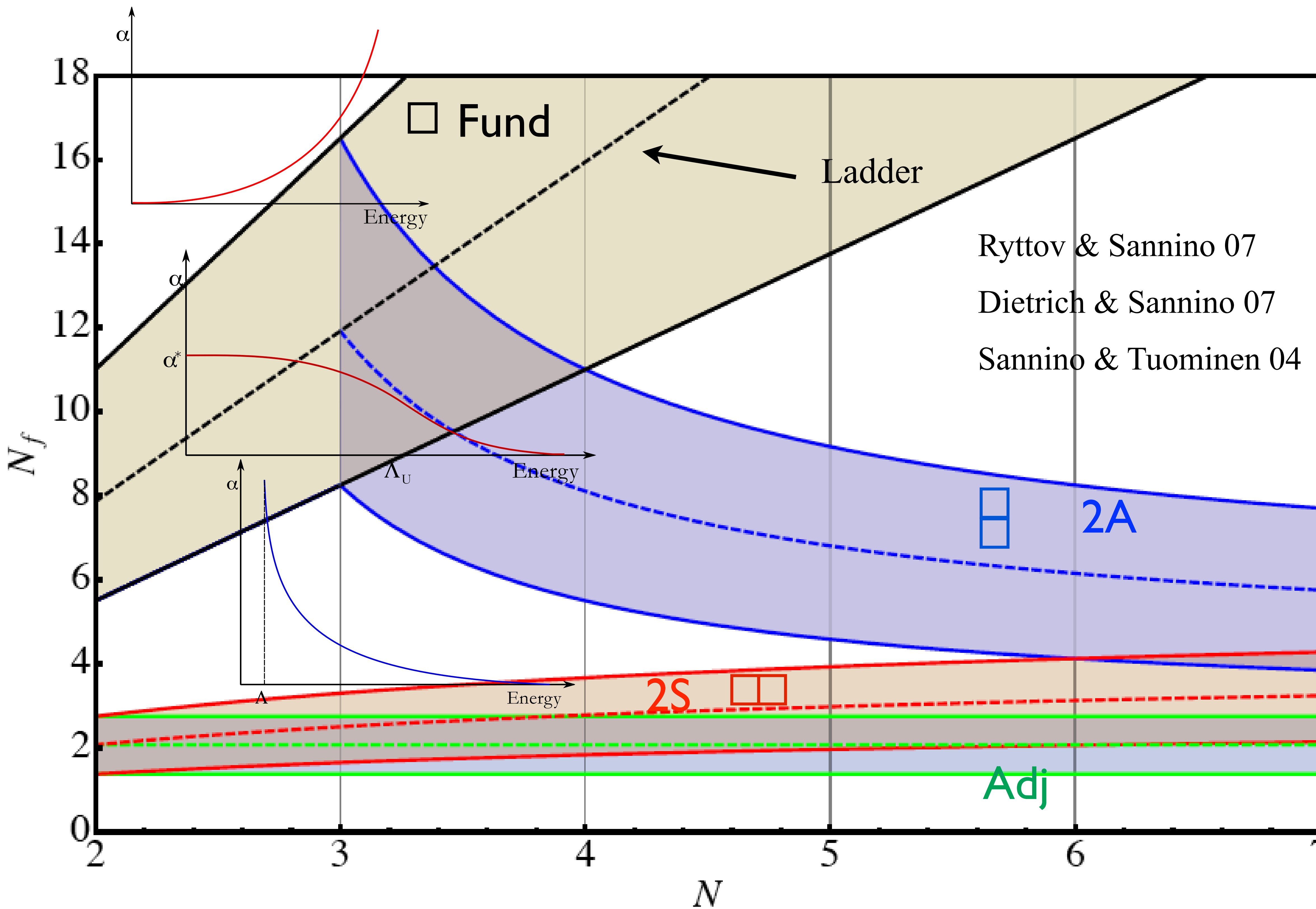
SU(N) Phase Diagram



Minimal Working TC

- Minimal WT

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

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

Frandsen, Sannino 09

- Ultra MT

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

Ryttov & Sannino 08

- Other models/ETC

Farhi and Susskind 79;
Eichten and Lane 89;
Appelquist and Terning 94;
Appelquist, Christensen, Pia and Shrock 04
Evans and Sannino 08
Ryttov and Shrock 09,10

- Effective Theories

Appelquist, Da Silva, Sannino 99;
Da Silva, Duan, Sannino. 99
Foadi, Frandsen, Ryttov, Sannino. 07
Lane and Martin 09

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New life in Technicolor

Not the Coldplay album

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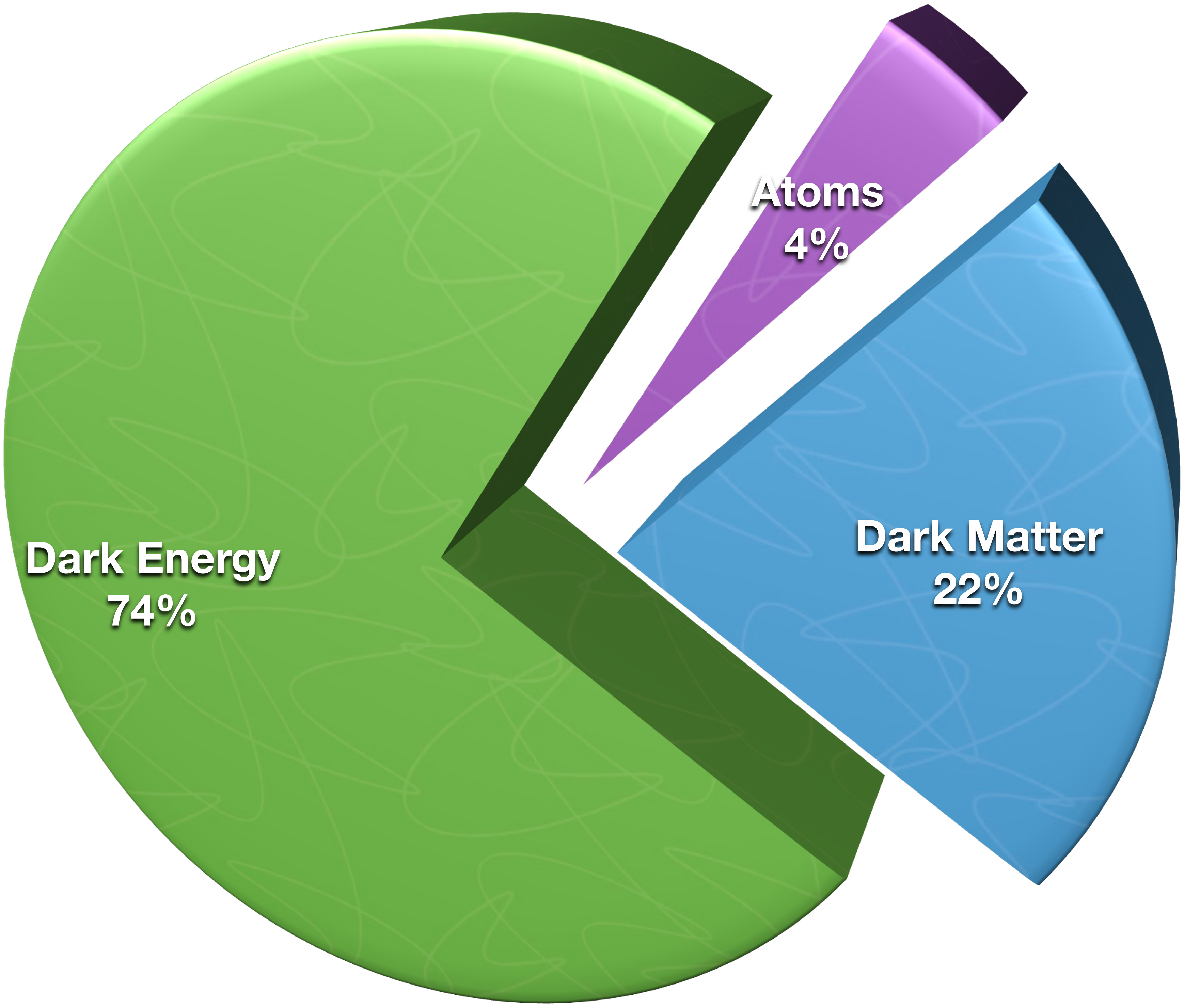
Dark Matter



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

Asymmetric DM

A particle similar to the nucleon

At most EW-type cross sections

Technibaryon is similar to the nucleon

EW scale and interactions built in

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

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

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

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(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	50 GeV - 1 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

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DM and GUTs

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

Light

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

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

Heavy

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

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

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.

Beyond Technicolor

(?)MSSM

XLMS D

Technicolor

Branes

......

Unparticle

AdS/?

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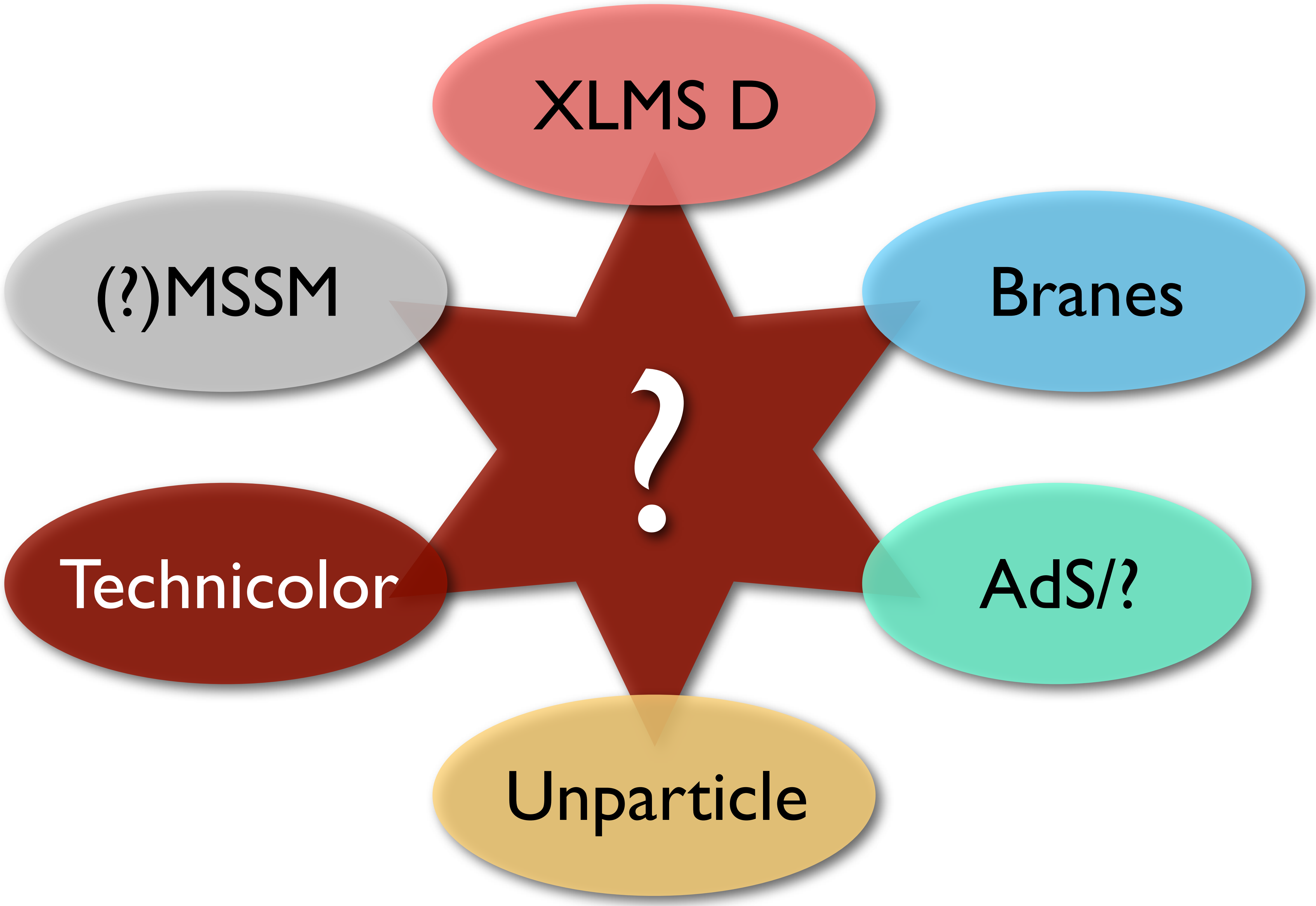
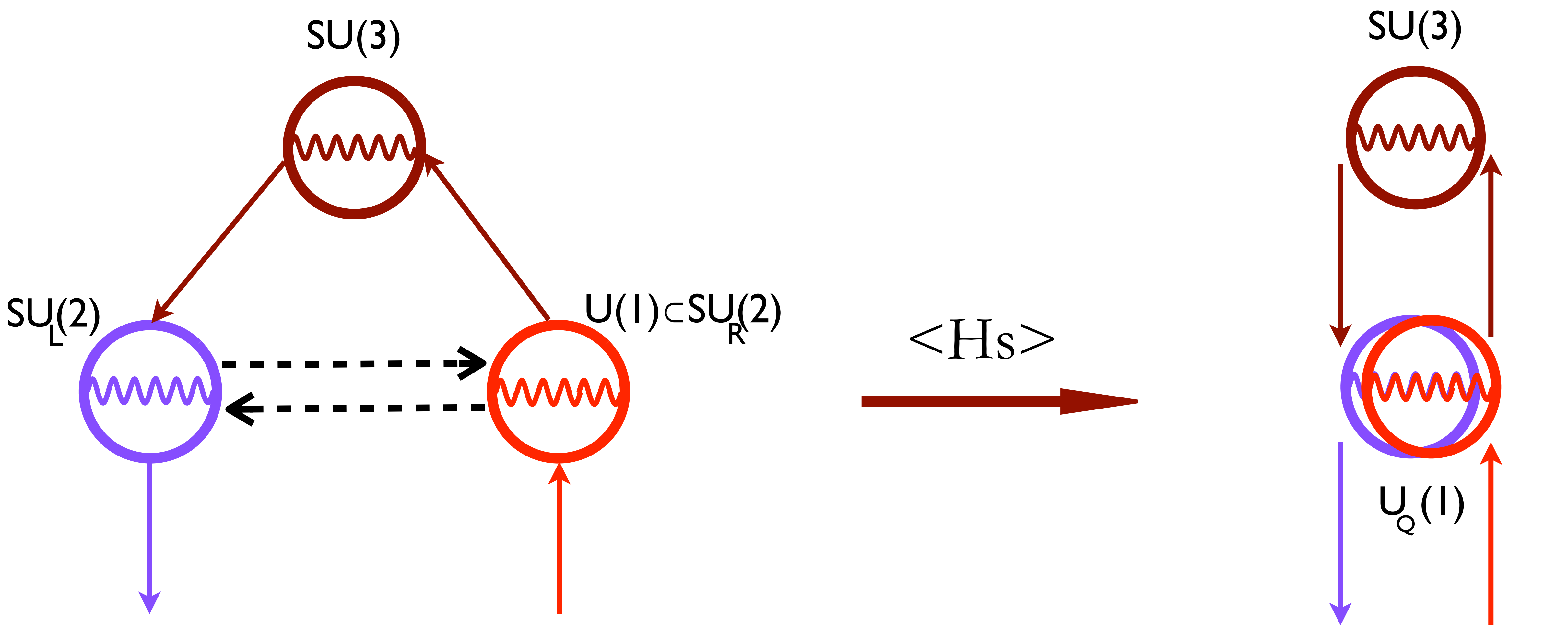
Unifying in Model Space

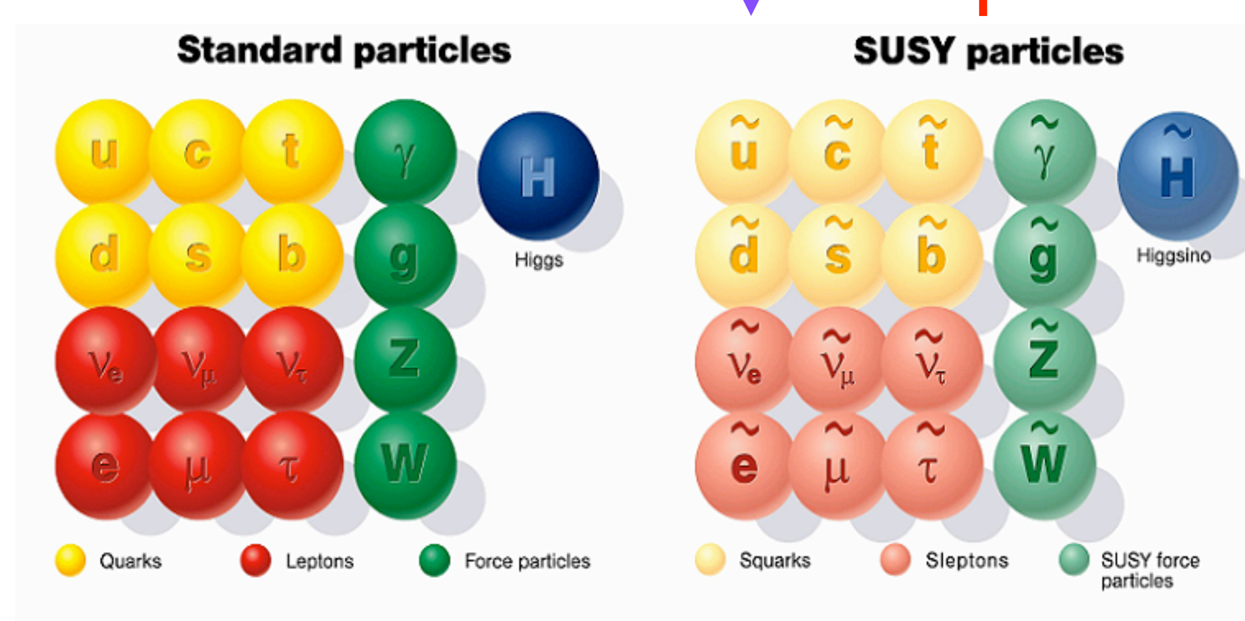


Theoretical Criterions

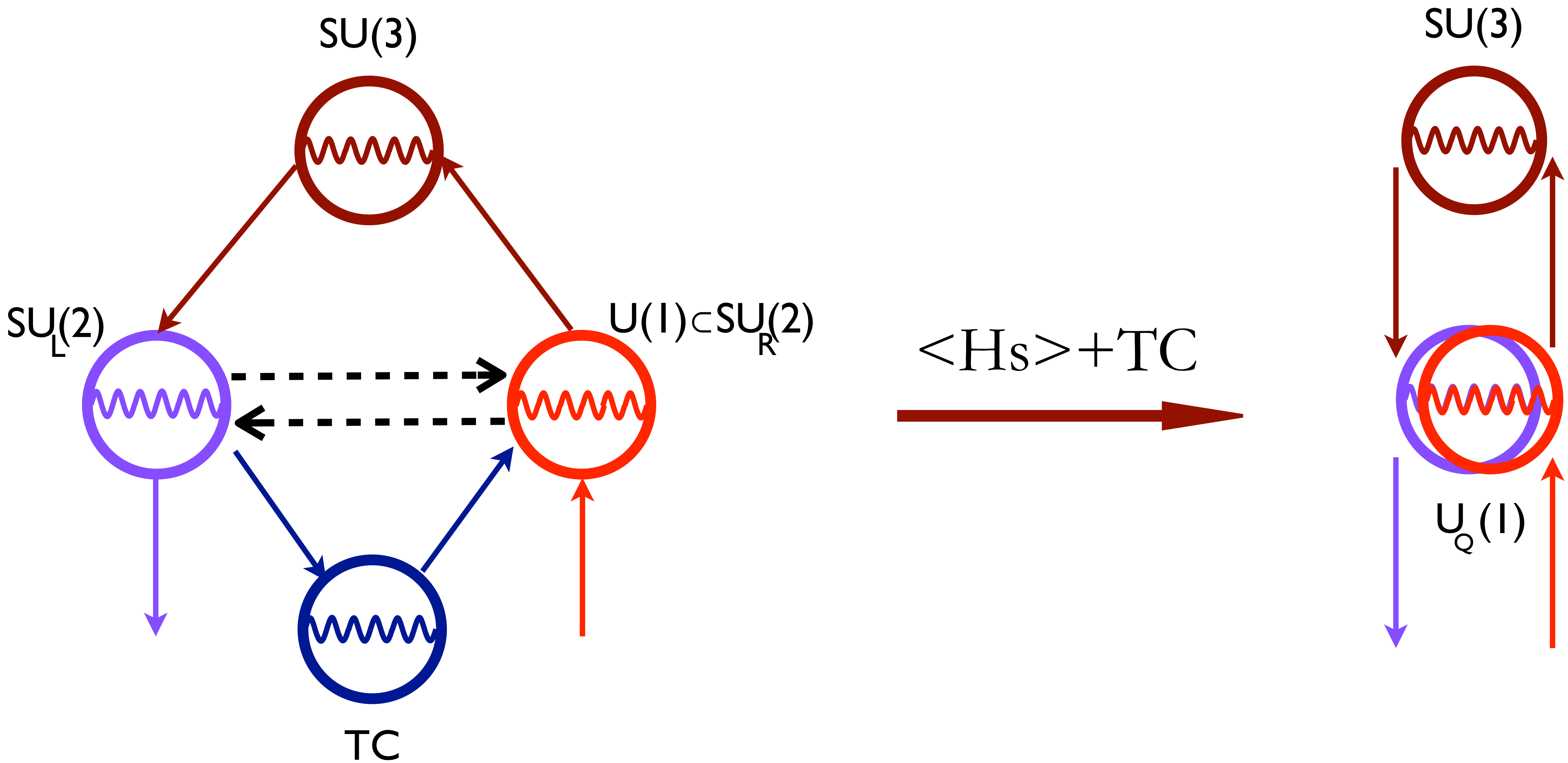
- Naturalizes the SM
- New strong dynamics
- Supersymmetric
- Near conformal
- Link to extra dim. and strings
- Possibly calculable

MSSM - cartoon





Super Technicolor



Bonus: A working model of ETC

Dine, Fischler and Srednicki, 81

Antola, Di Chiara, Sannino, Tuominen 10

From MWT to N=4

Matter in Adjoint of SU(2)

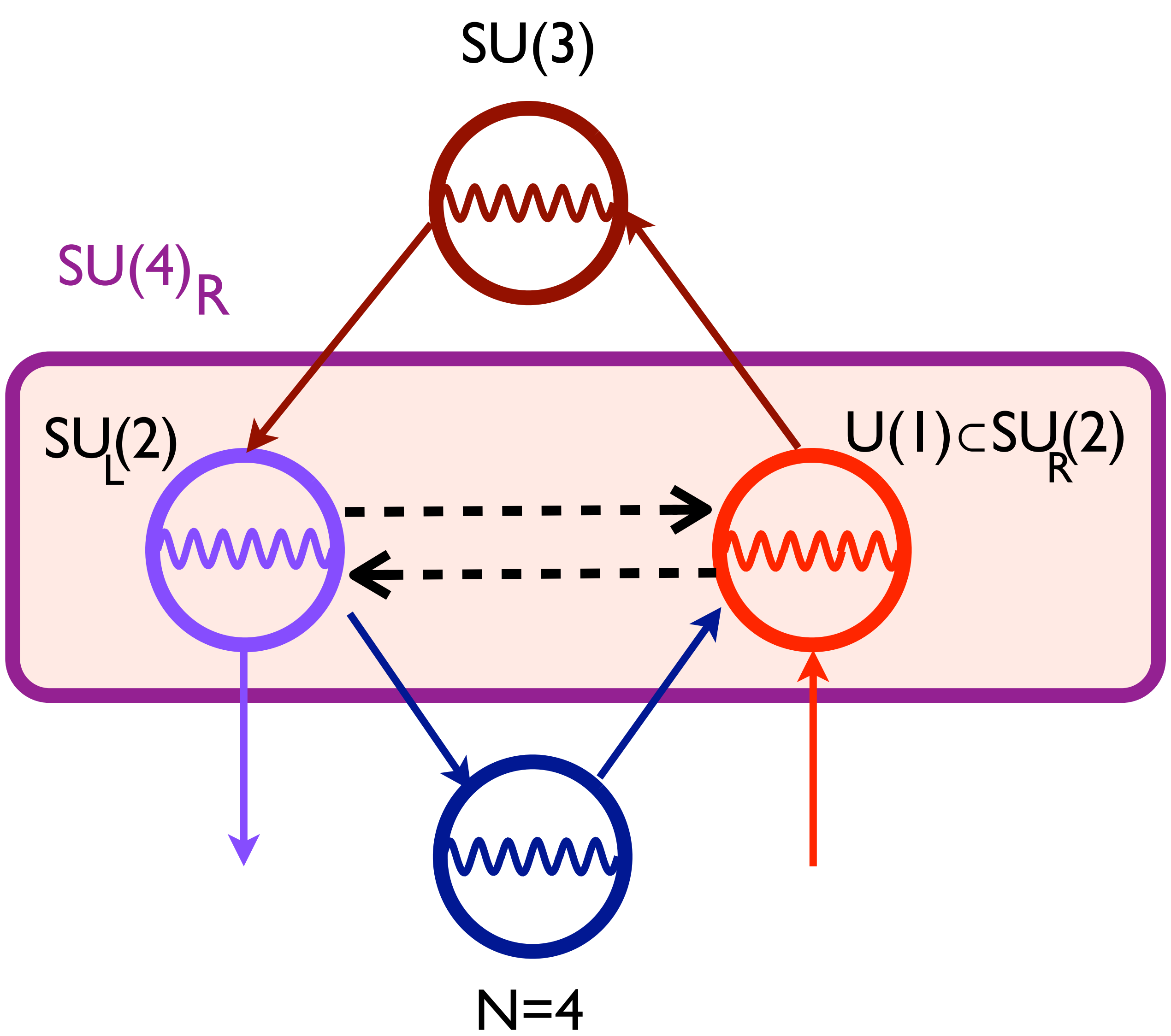
MWT	Minimal S-partners	N=1 Multiplets	N=4
G_μ	G_μ	V	
	$\bar{D}_R$		V
$\bar{D}_R$			Φ_3
$\bar{U}_R$	$\bar{U}_R \quad \tilde{\bar{U}}_R$	Φ_3	Φ_1
U_L	$U_L \quad \tilde{U}_L$	Φ_1	Φ_2
D_L	$D_L \quad \tilde{D}_L$	Φ_2	

N=4 - SU(N) requires

$$P = -\frac{g}{3\sqrt{2}}\epsilon_{ijk} f^{abc}\Phi_i^a\Phi_j^b\Phi_k^c, \; i = 1,2,3; a = 1,\cdots, N^2-1$$

Antola, Di Chiara, Sannino, Tuominen 10

Minimal Superconformal TC



- MSCT as minimal susy extension of MWT
- Highest degree of space-time symmetry
- Natural connection to string theory
- Unifies different extensions of the SM
- Very rich and falsifiable phenomenology

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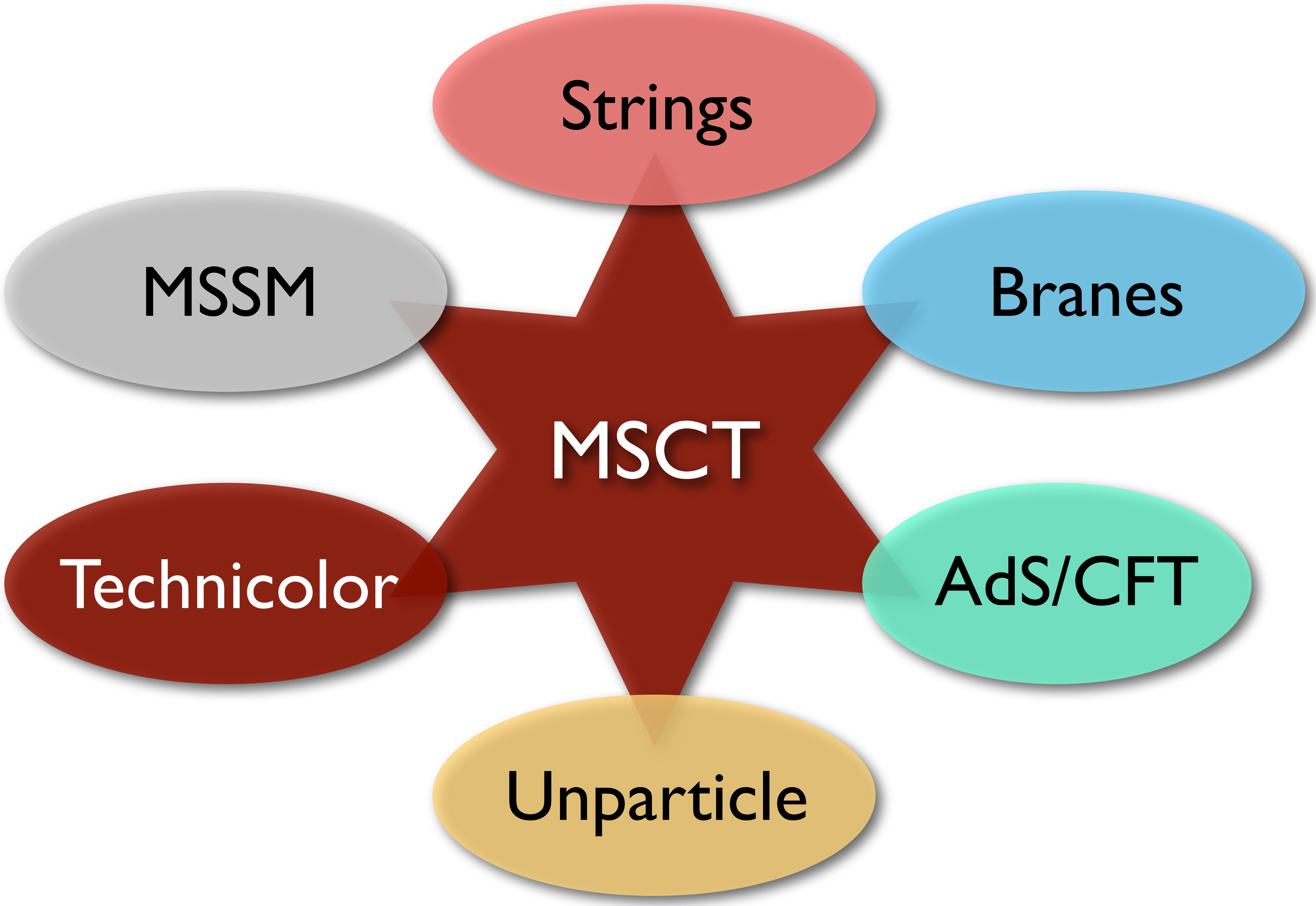
Minimal Superconformal TC



Conclusions

- DEWSB can naturally occur at the LHC
- Phase Diagram of strongly interacting theories
- Minimal models of technicolor
- Unification in theory space/Technicolor meets string theory
- DEWSB cosmology is exciting

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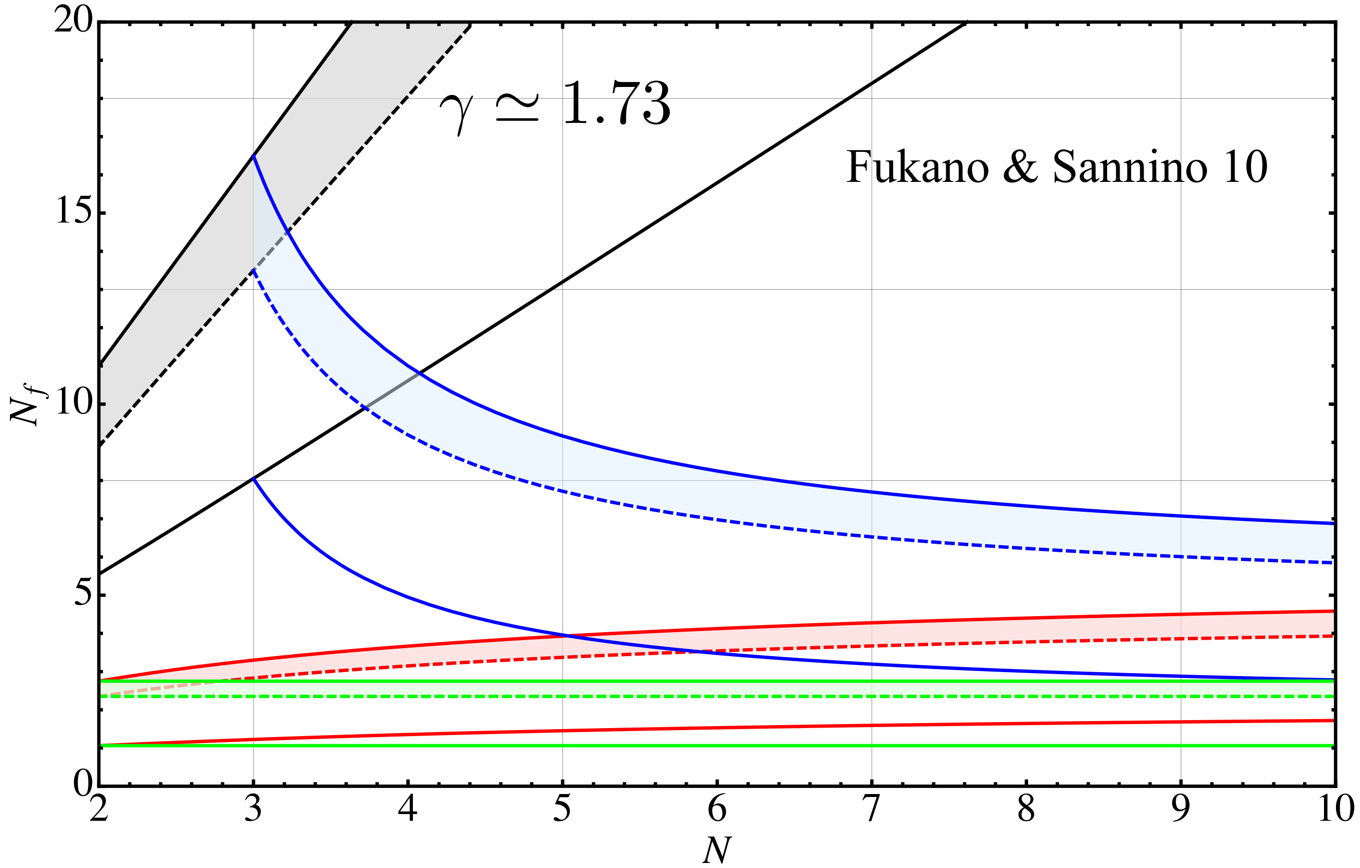
Particle Physics & Origin of Mass

Backup slides

SU(N) Phase Diagram + 4 Fermions



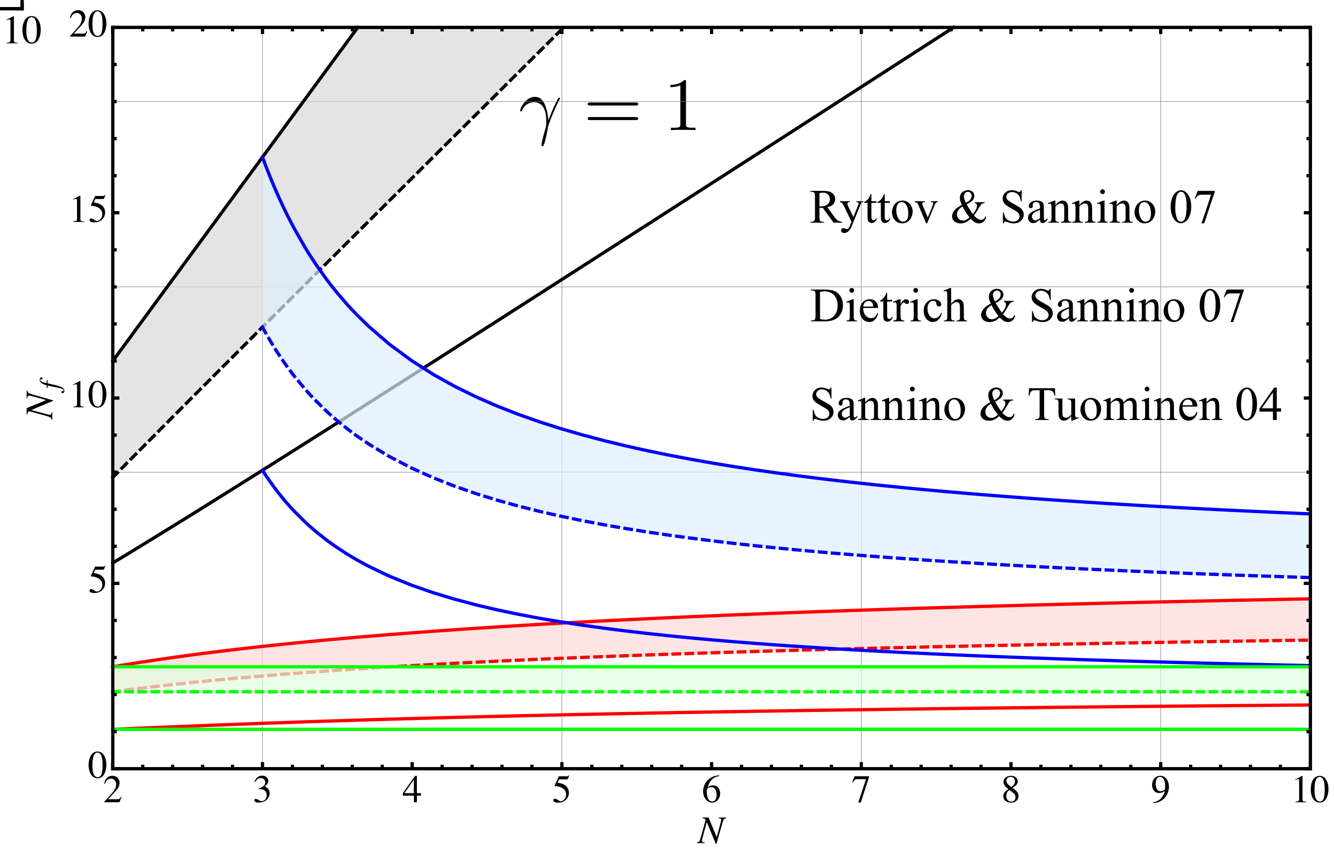
Fukano & Sannino 10

Ideal Walking:

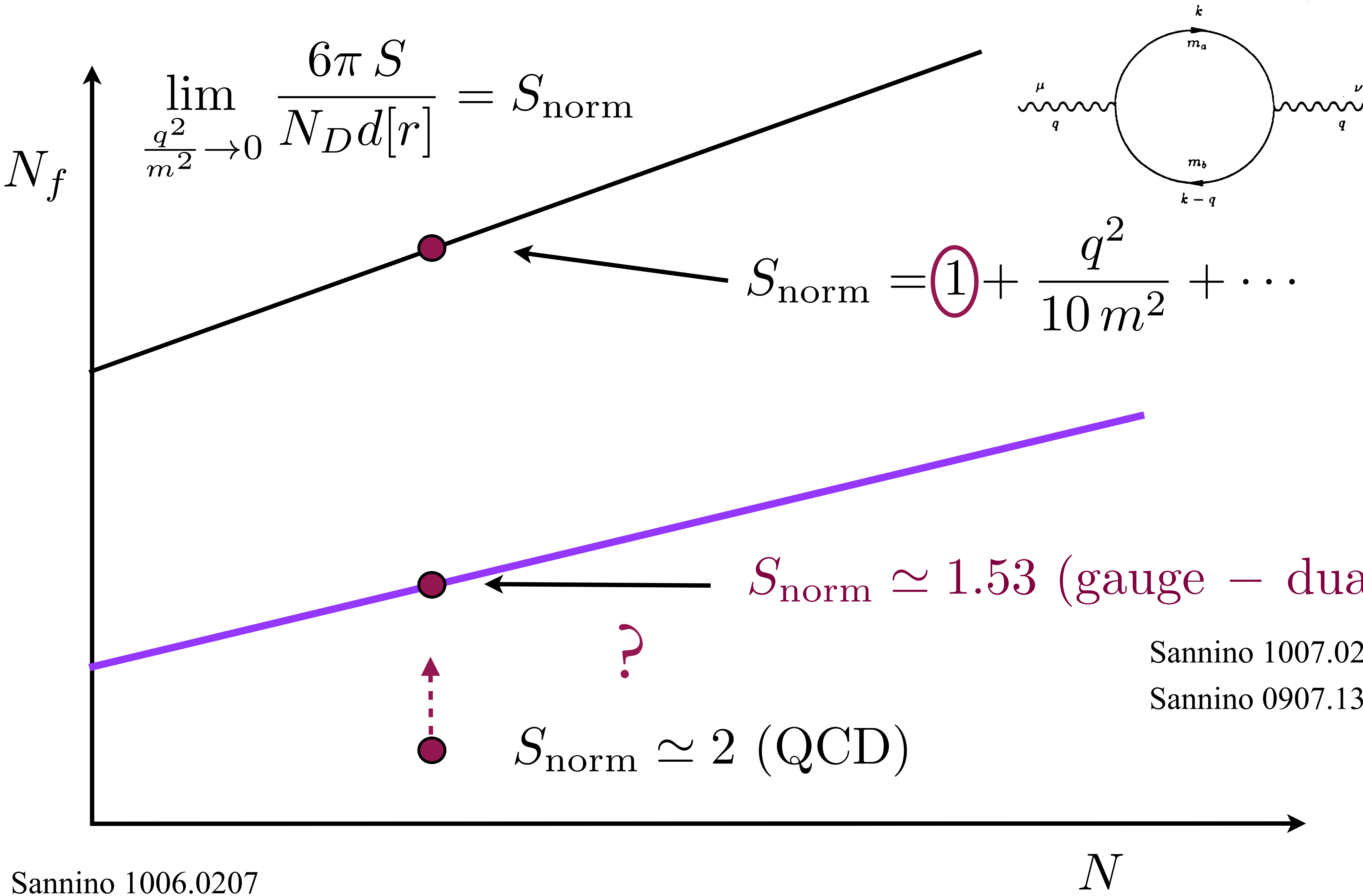
Use 4 Fermion interactions to exit conformal window and provide correct Top mass.

Ordinary Walking:

Requires huge fine-tuning to be near the lower end of the conformal window and unlikely to provide the correct Top mass.



Exact conformal S

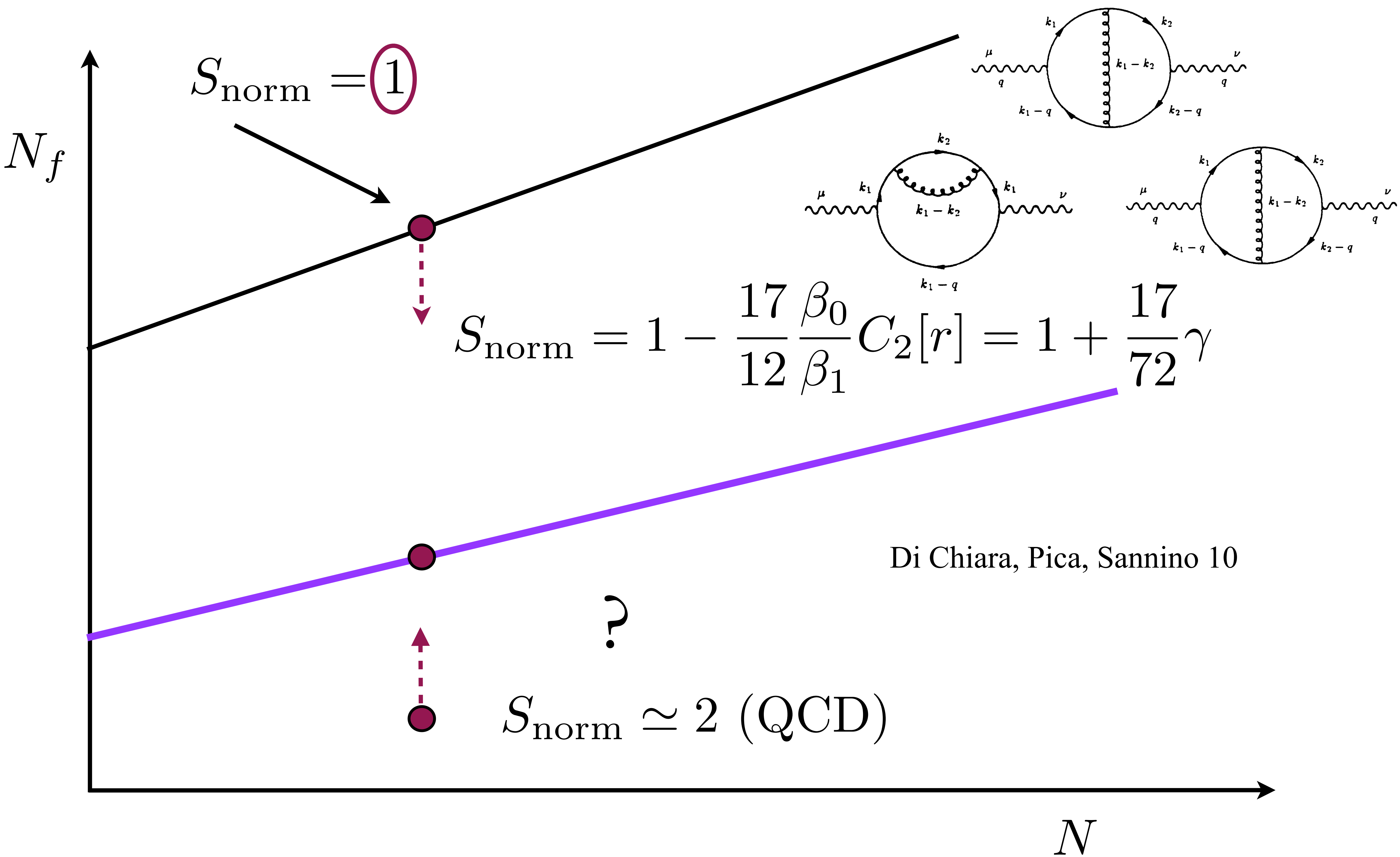


Sannino 1007.0254

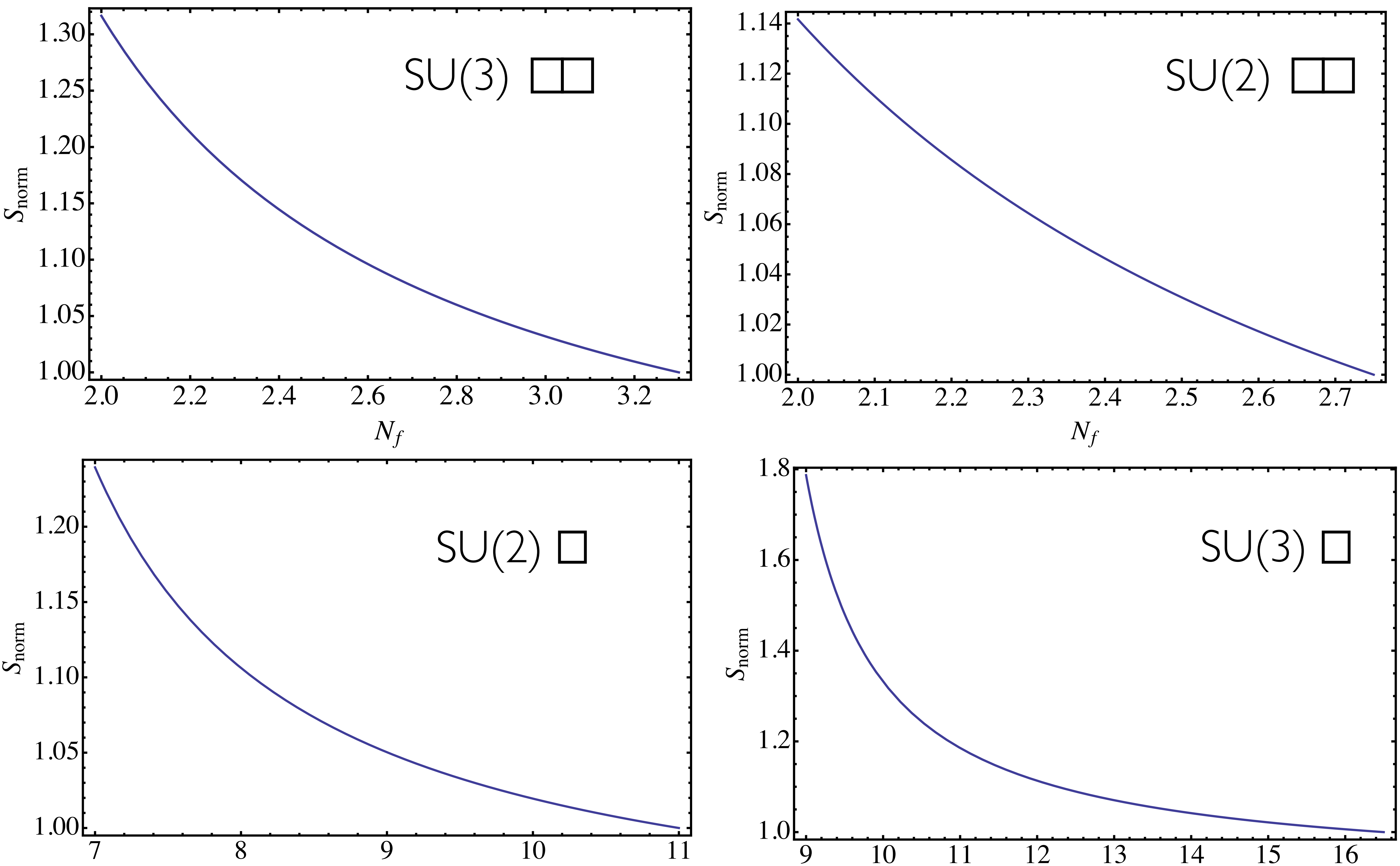
Sannino 0907.1364

Sannino 1006.0207

Conformal S @ 2 loops



Conformal S @ 2 loops



Di Chiara, Pica, Sannino -- To appear

S - conjecture

Sannino 1006.0207

$$\lim_{\frac{q^2}{m^2}\to 0} \frac{6\pi\, S}{N_D d[r]} = S_{\rm norm} \geq 1$$

S increases as Nf decreases

S counts relevant degrees of freedom

Sannino 1007.0254

S tests weak-strong gauge duality

Strong constraints for old models!

Unification

Farhi-Susskind, 79

Gudnason-Ryttov-F.S. 06

1 - loop running for SU(n)

$$\alpha_n^{-1}(\mu) = \alpha_n^{-1}(M_Z) - \frac{b_n}{2\pi} \ln\left(\frac{\mu}{M_Z}\right)$$

Degree of SU(3)xSU(2)xU(1) Unification

$$B_{Th} \leftarrow \frac{b_3 - b_2}{b_2 - b_1} \quad = \quad \frac{\alpha_3^{-1} - \alpha^{-1}\sin^2\theta_w}{(1+c^2)\alpha^{-1}\sin^2\theta_w - c^2\alpha^{-1}} \rightarrow B_{Exp}$$

Unification Scale

$$M_{GUT} = M_Z \exp\left[2\pi \frac{\alpha_2^{-1}(M_Z) - \alpha_1^{-1}(M_Z)}{b_2 - b_1}\right]$$

Standard Model

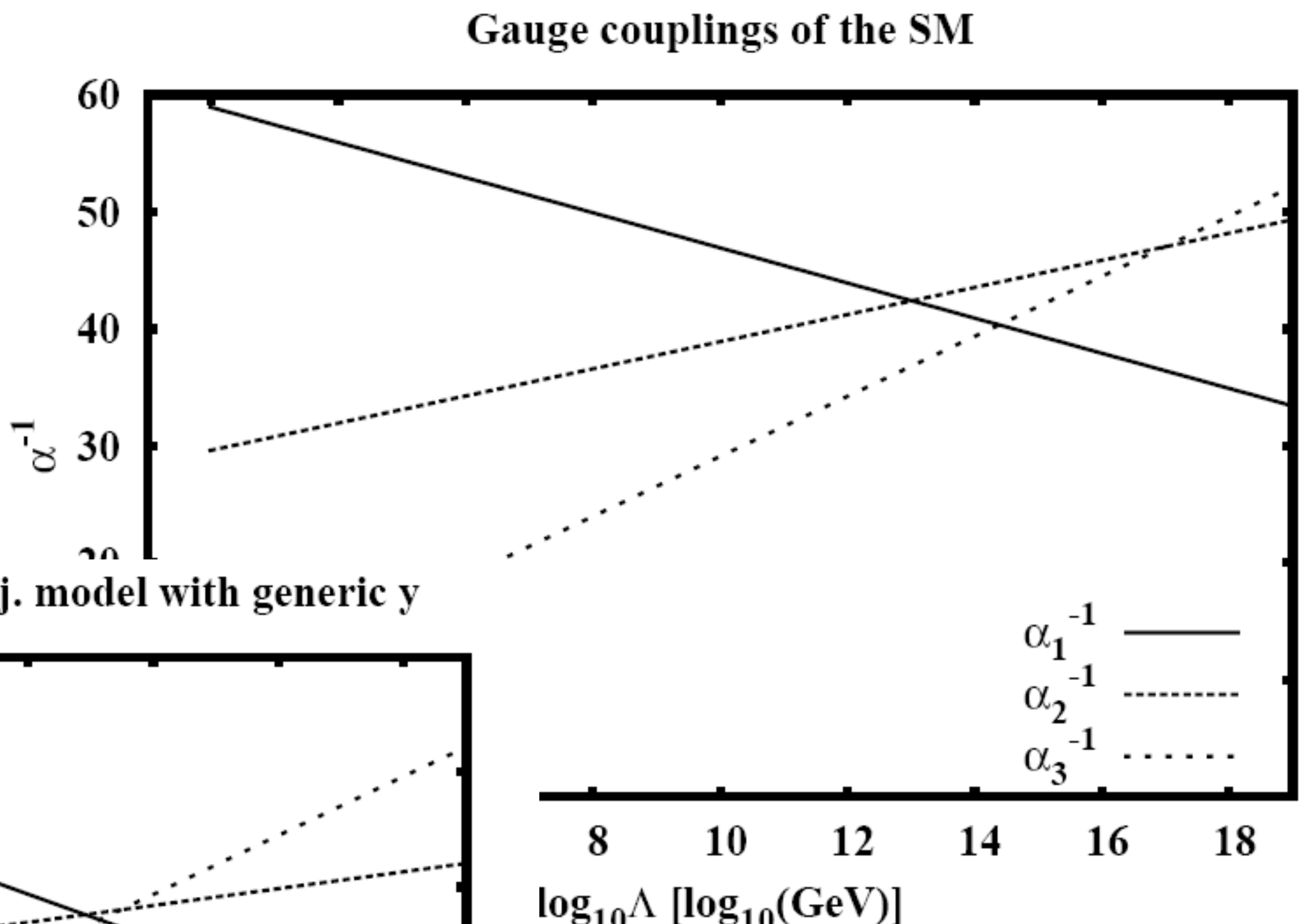
$$
\begin{aligned}
b_3 &= \frac{4}{3}N_g - 11 \\
b_2 &= \frac{4}{3}N_g - \frac{22}{3} + \underbrace{\frac{1}{6}}_{\text{Higgs}} \\
b_1 &= \frac{3}{5}\left(\frac{20}{9}N_g + \frac{1}{6}\right) = \frac{4}{3}N_g + \underbrace{\frac{1}{10}}_{\text{Higgs}}
\end{aligned}
$$

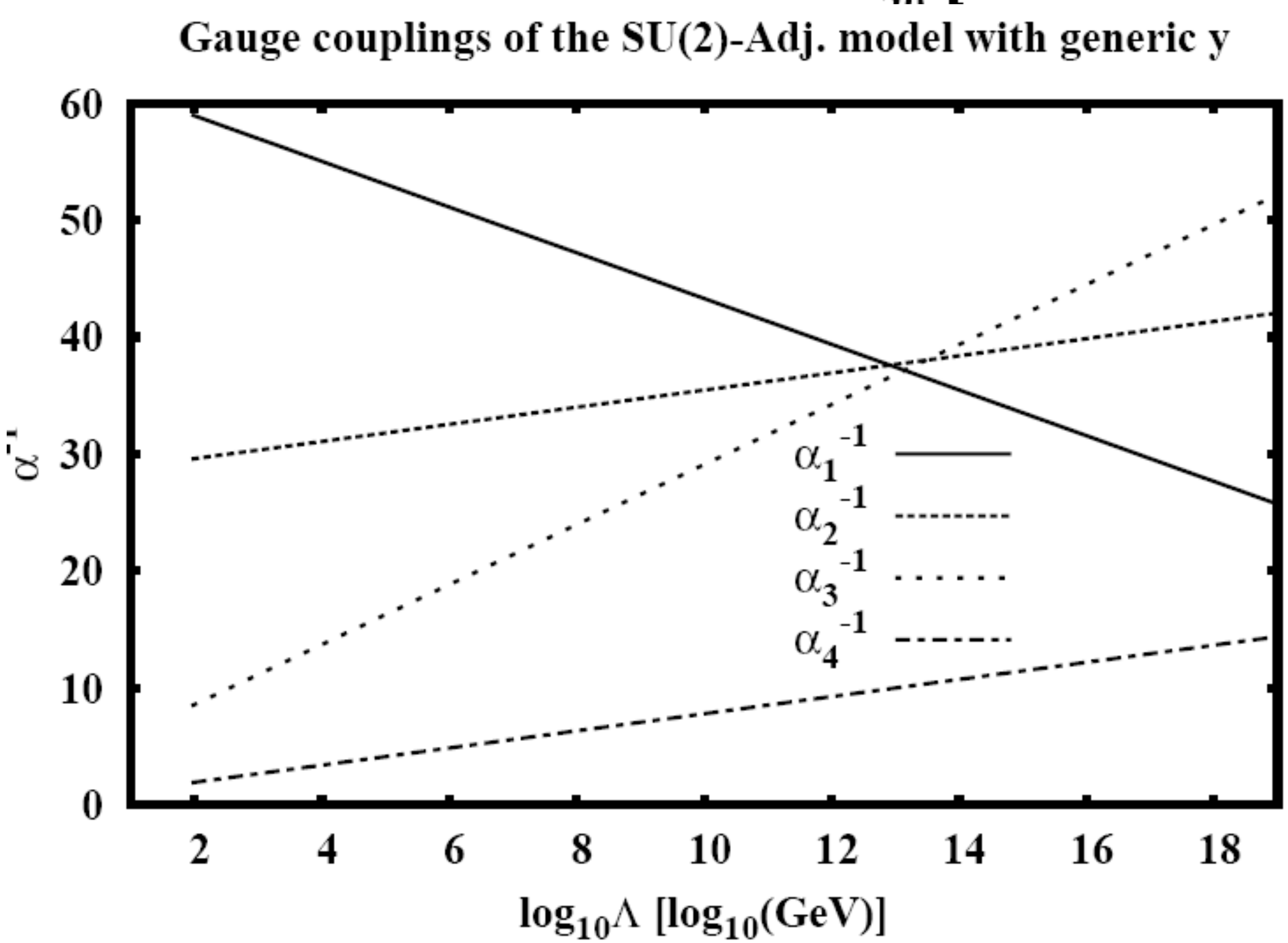
$B_{\mathrm{Th}} \sim 0.53 \qquad B_{\mathrm{Exp}} \sim 0.72$

Minimal Walking Technicolor

$$
\begin{aligned}
b_3 &= \frac{4}{3}N_g - 11 \\
b_2 &= \frac{4}{3}N_g - \frac{22}{3} + \frac{2}{3}\frac{1}{2}\left(\frac{2(2+1)}{2} + 1\right) = \frac{4}{3}\left(N_g + 1\right) - \frac{22}{3} \\
b_1 &= \frac{3}{5}\left(\frac{20}{9}N_g + \frac{20}{9}\right) = \frac{4}{3}\left(N_g + 1\right)
\end{aligned}
$$

$B_{\mathrm{Th}} \sim 0.68 \qquad B_{\mathrm{Exp}} \sim 0.72$


Gauge couplings of the SM
α^{-1}
60
50
40
30
20
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(GeV)]
α_1^{-1}
α_2^{-1}
α_3^{-1}


Gauge couplings of the SU(2)-Adj. model with generic y
α^{-1}
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
$\log_{10}\Lambda$ [$\log_{10}$(GeV)]
α_1^{-1}
α_2^{-1}
α_3^{-1}
α_4^{-1}

Adding Adjoint SM Matter

Minimal Walking Technicolor + SM Adjoint Matter

Colored Octet of Majorana Particles

Weak Triplet of Majorana Fermions

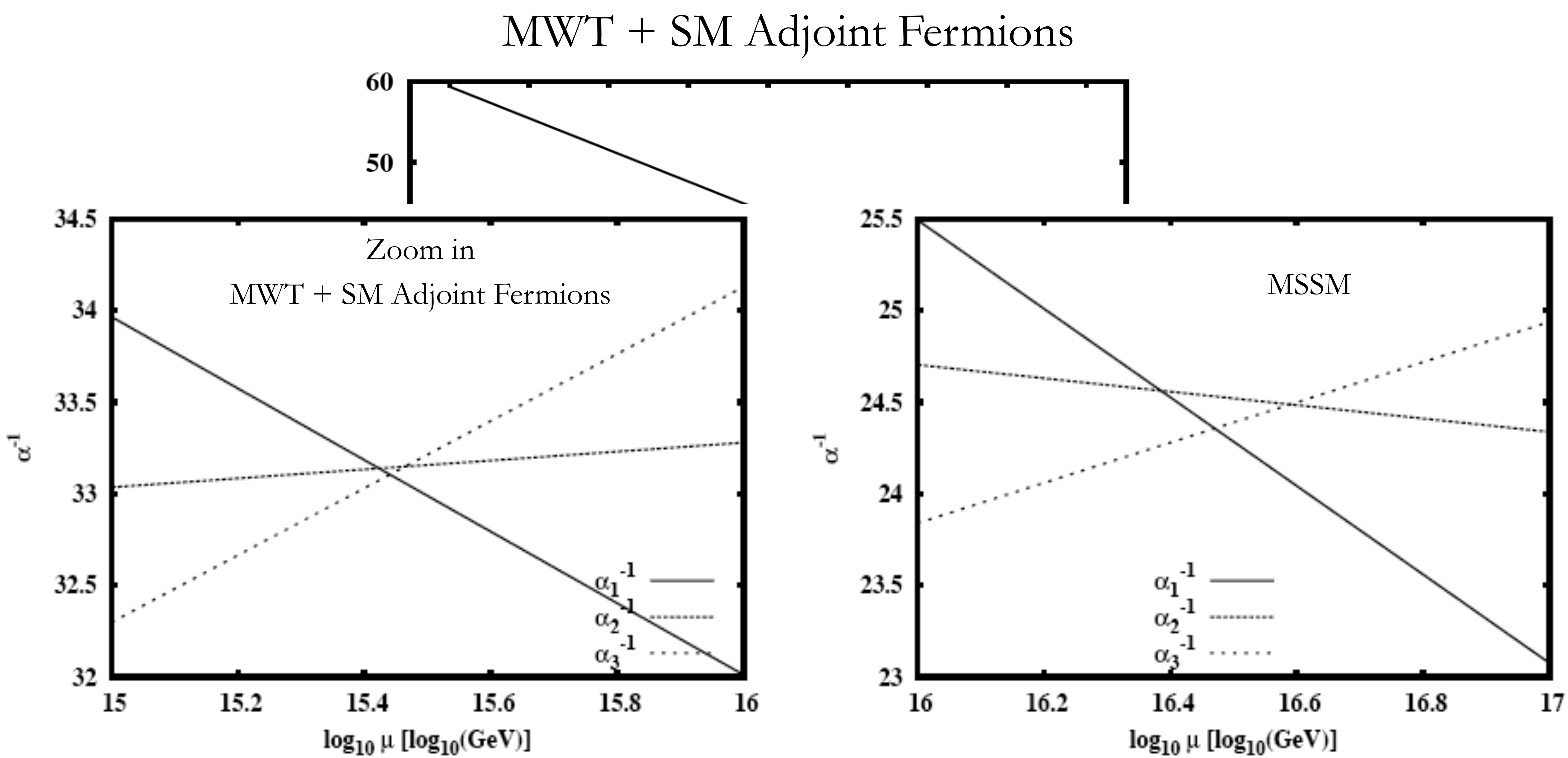
Extra SM Weyl Singlet

$$
\begin{aligned}
b_3 &= \frac{4}{3}N_g - 11 + 2 \\
b_2 &= \frac{4}{3}\left(N_g + 1\right) - \frac{22}{3} + \frac{4}{3} \\
b_1 &= \frac{4}{3}\left(N_g + 1\right)
\end{aligned}
$$

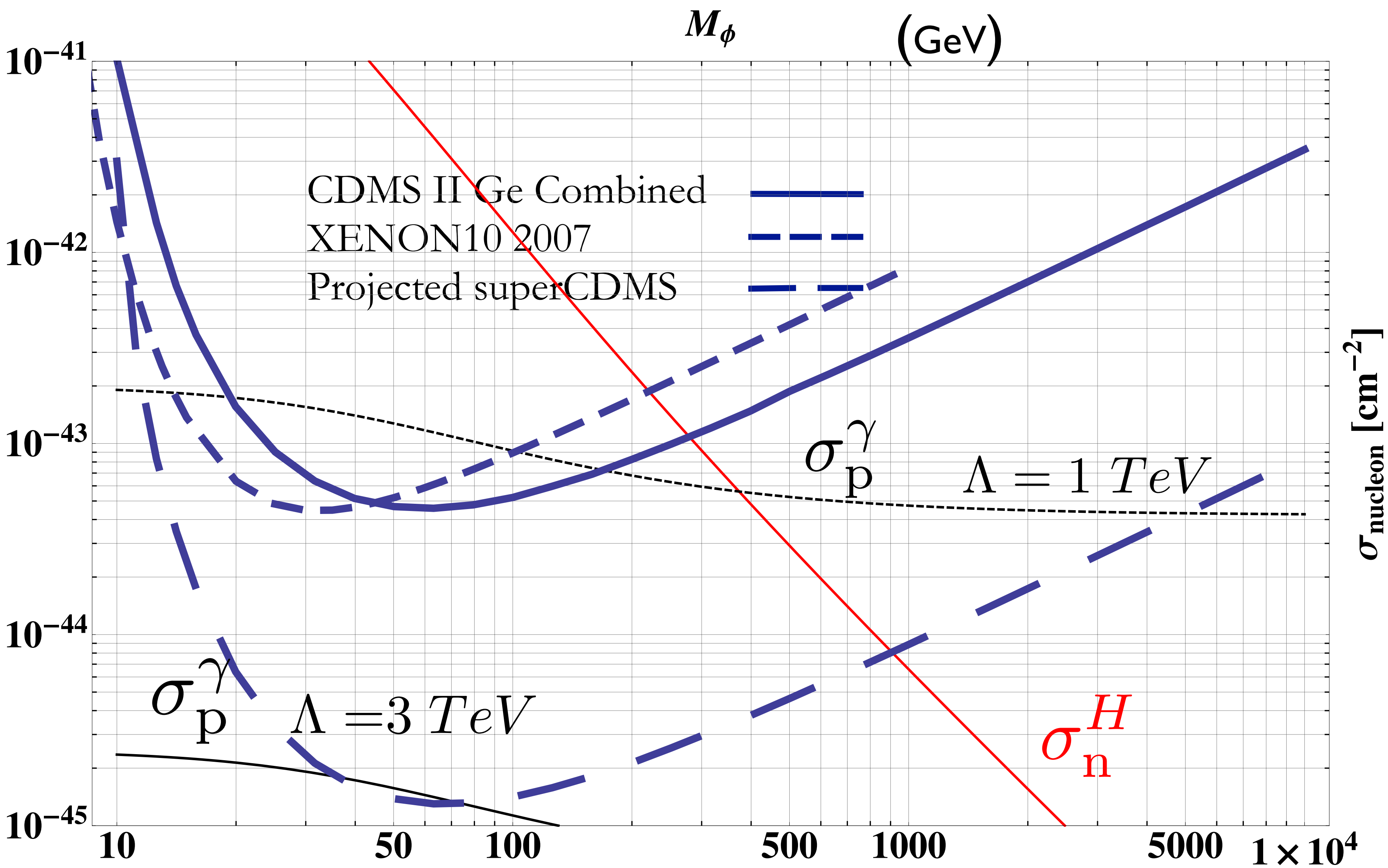
Gudnason-Ryttov-F.S. ph/0612230

Bajc-Senjanovic ph/0612029

$$B_{\rm Th} = 13/18 = 0.72(2) \quad \text{versus} \quad B_{\rm Exp} \simeq 0.72$$


MWT + SM Adjoint Fermions
60
50
Zoom in
MWT + SM Adjoint Fermions
34.5
34
33.5
33
32.5
32
15
15.2
15.4
15.6
15.8
16
log10 μ [log10(GeV)]
α-1
α1-1
α2-1
α3-1
MSSM
25.5
25
24.5
24
23.5
23
16
16.2
16.4
16.6
16.8
17
log10 μ [log10(GeV)]
α-1
α1-1
α2-1
α3-1

Direct Constraints



$$f = 0.3$$
$$d_M = 1$$
$$d_B = 1$$
$$M_H = 300 \text{ GeV}$$

$$\sigma_n^H = \frac{\mu^2}{4\pi}\left[\frac{d_M\, f m_N}{M_H^2 M_\phi}\right]^2 \qquad \sigma_p^\gamma = \frac{\mu^2}{4\pi}\left[\frac{8\pi\,\alpha\, d_B}{\Lambda^2}\right]^2$$

Foadi, Frandsen, F.S. 08

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