Dynamical EW Breaking & Cosmology

Francesco Sannino

CP^3 - Origins

Particle Physics & Origin of Mass

July 2010 @ CERN - Lattice


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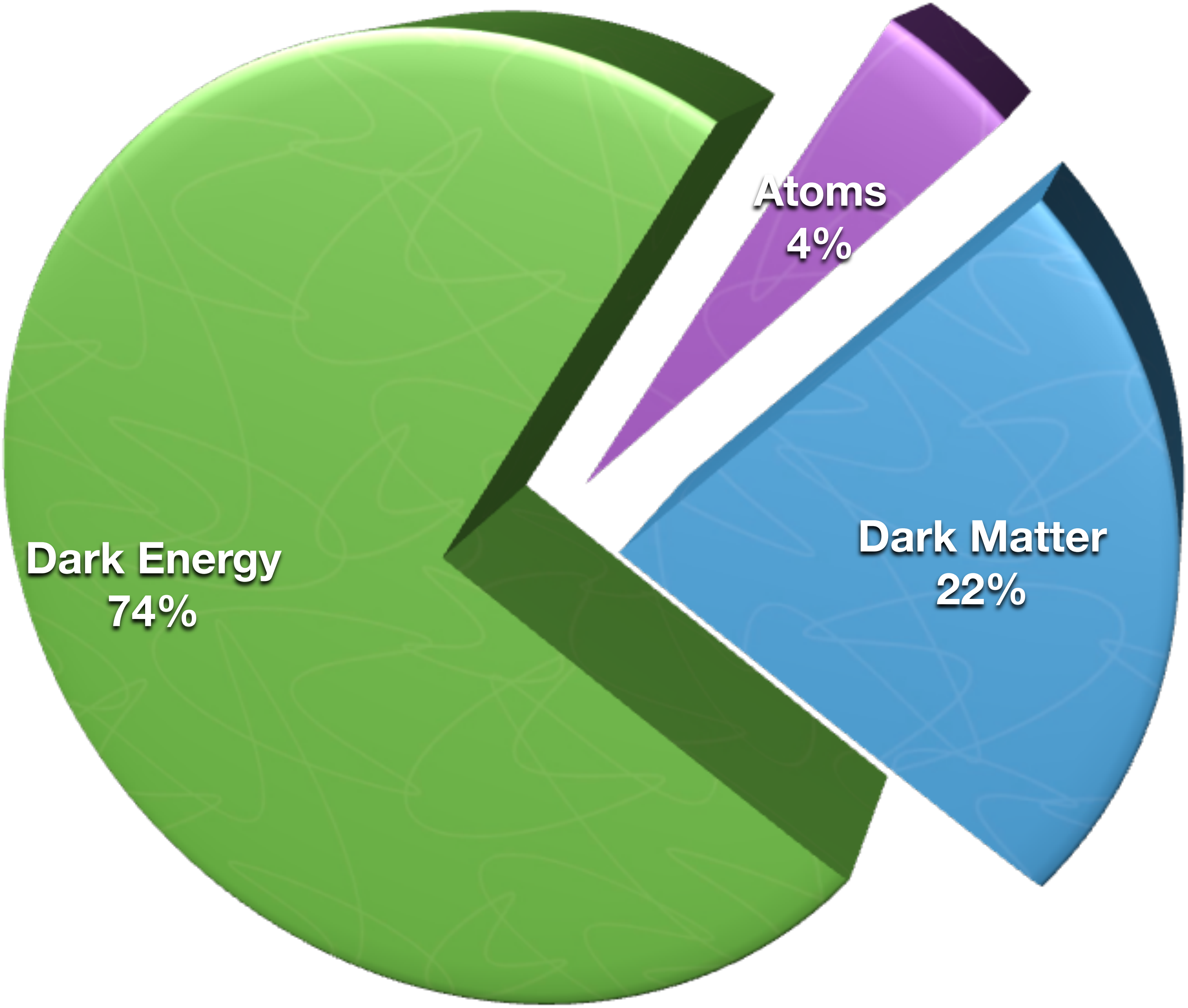
CP3 - Origins
Particle Physics & Origin of Mass

Cosmology



Many Models

(?)MSSM

$$$

XLMS D

......

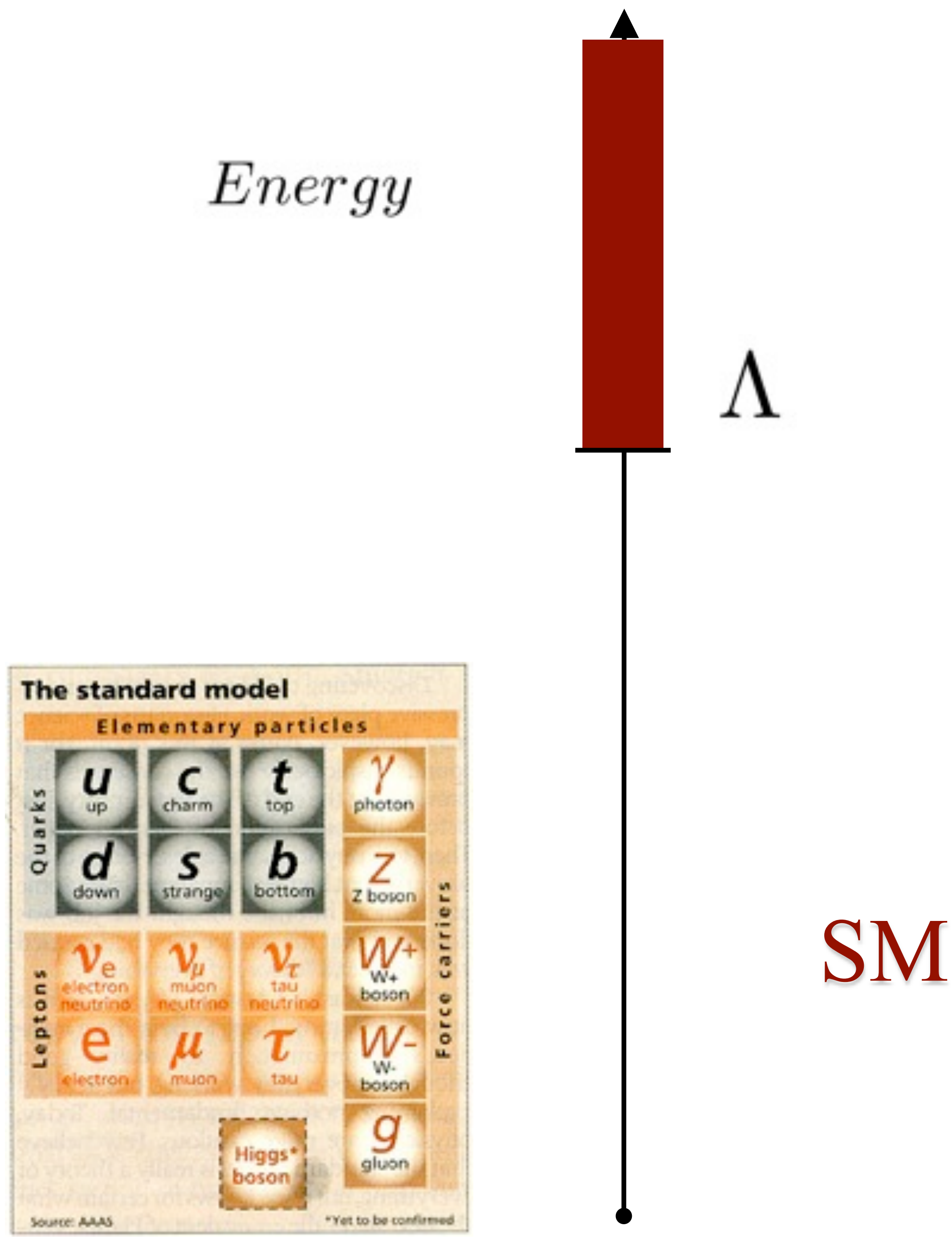
Technicolor

Branes

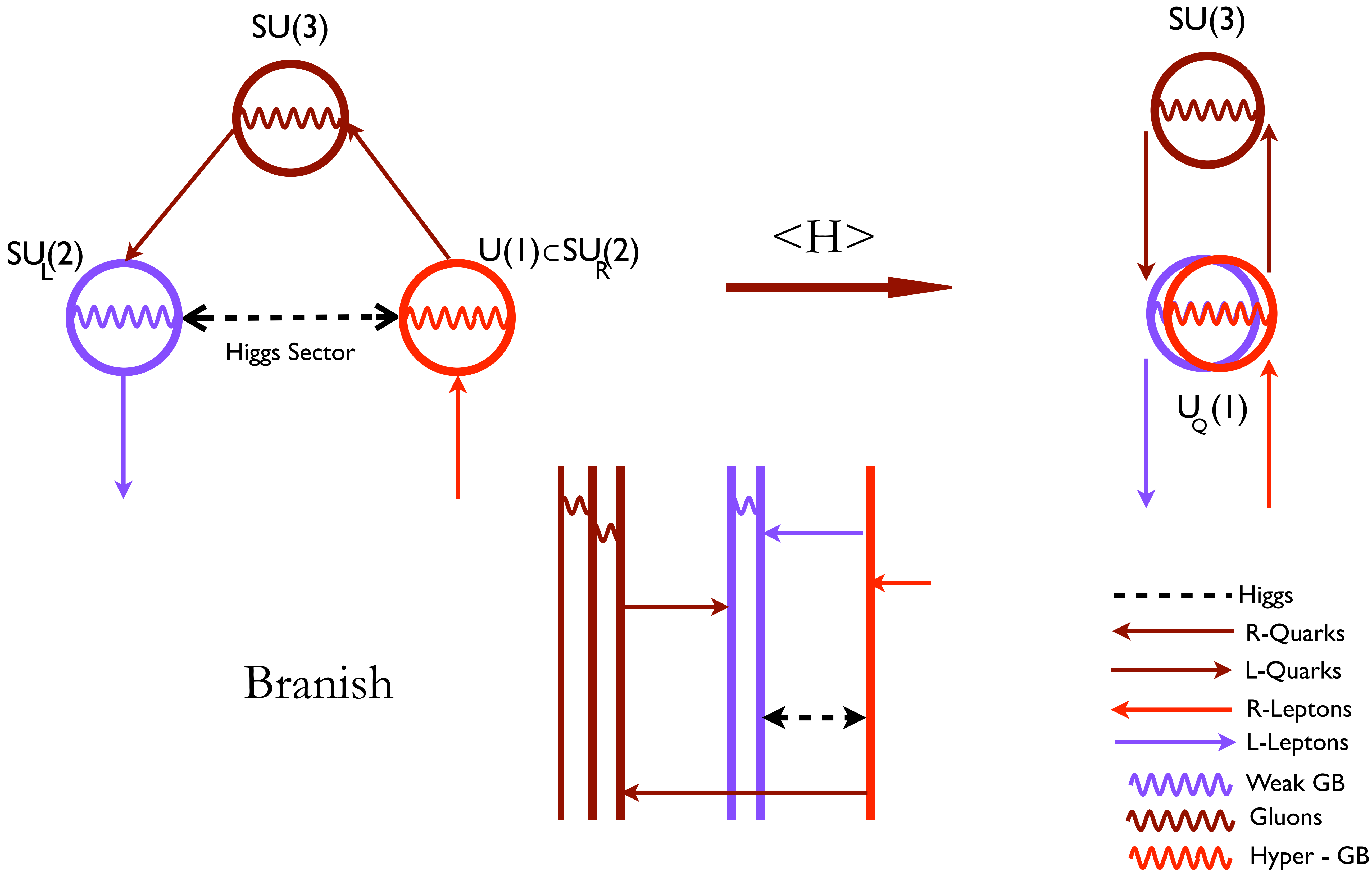
Unparticle

AdS/?

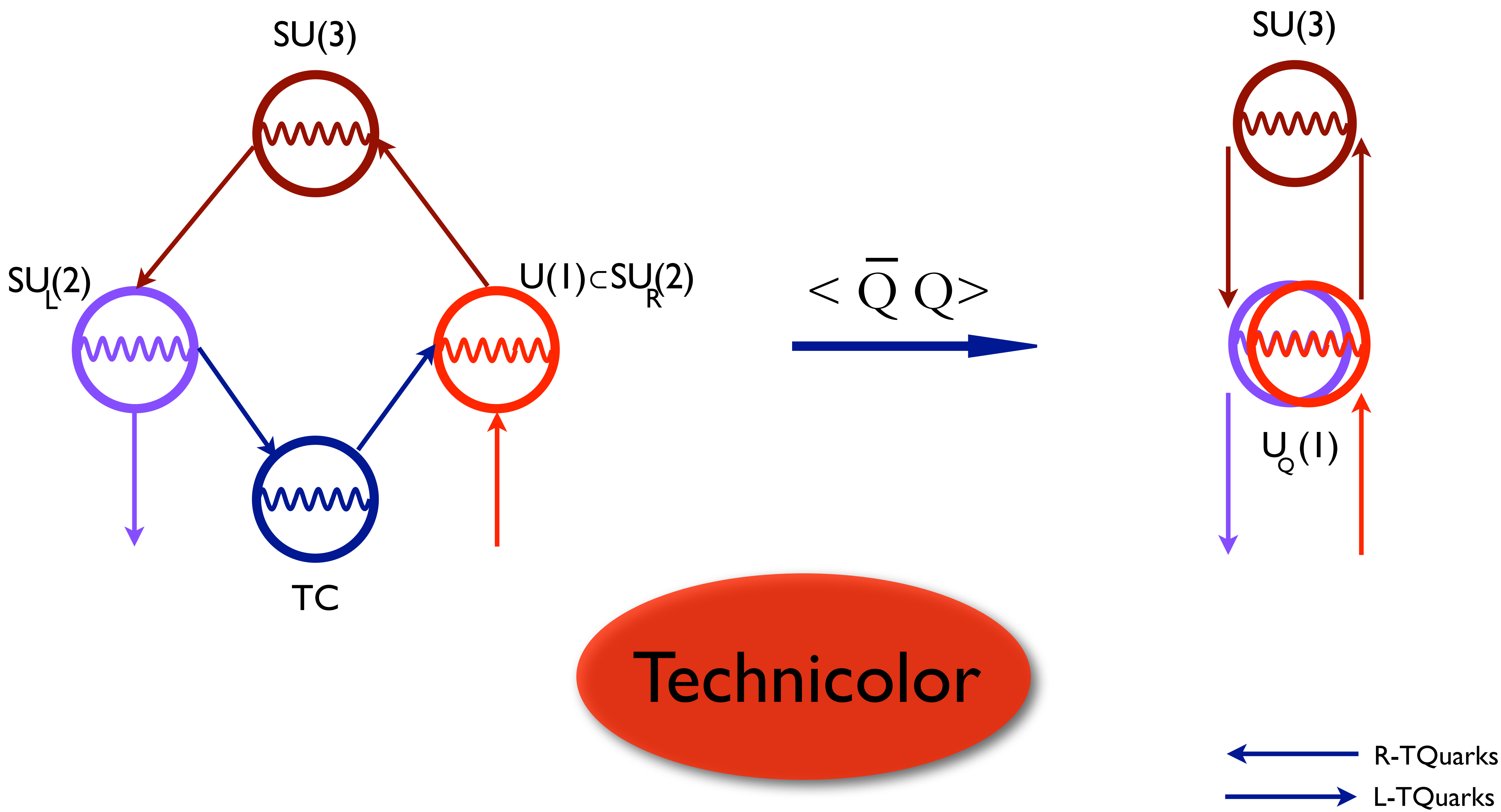
Standard Model



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]

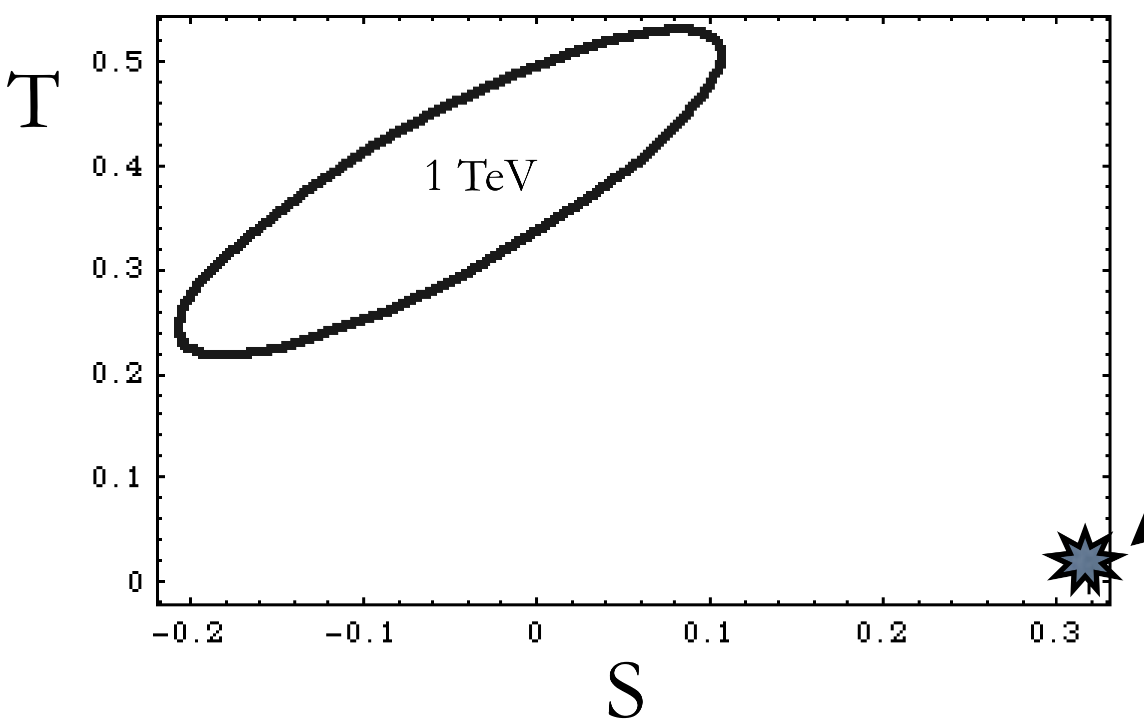
Natural to use QCD-like dynamics.

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

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

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

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

Different approaches

Scalar-less New Gauge Interactions (Extended TC)

Marry SUSY and Technicolor

Add New Scalars in the Flavor Sector

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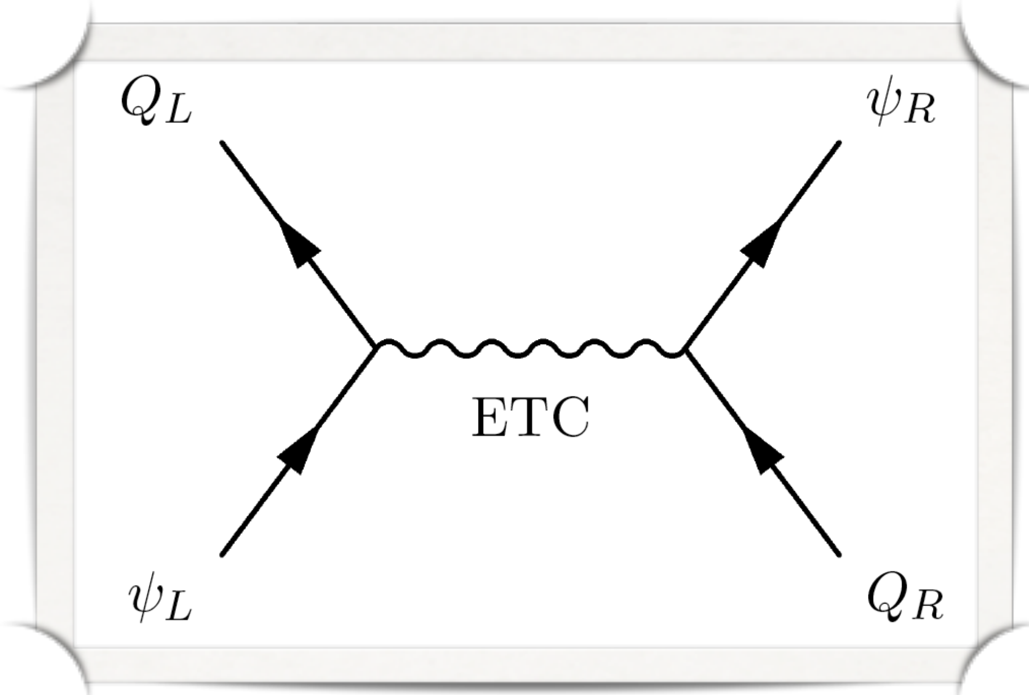
Extended Technicolor



Eichten & Lane 80

Recent investigations
Ryttov & Shrock 10

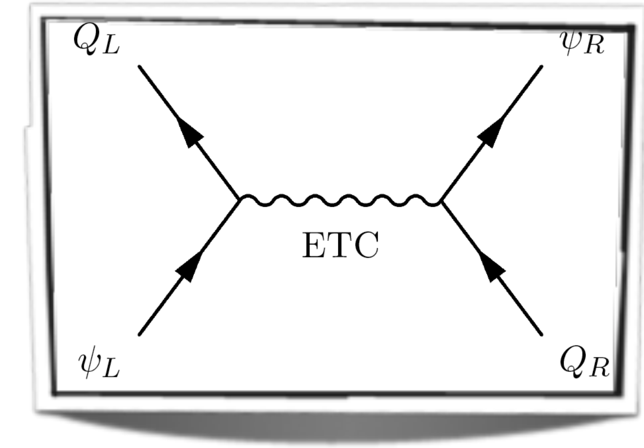
Modifies TC dynamics

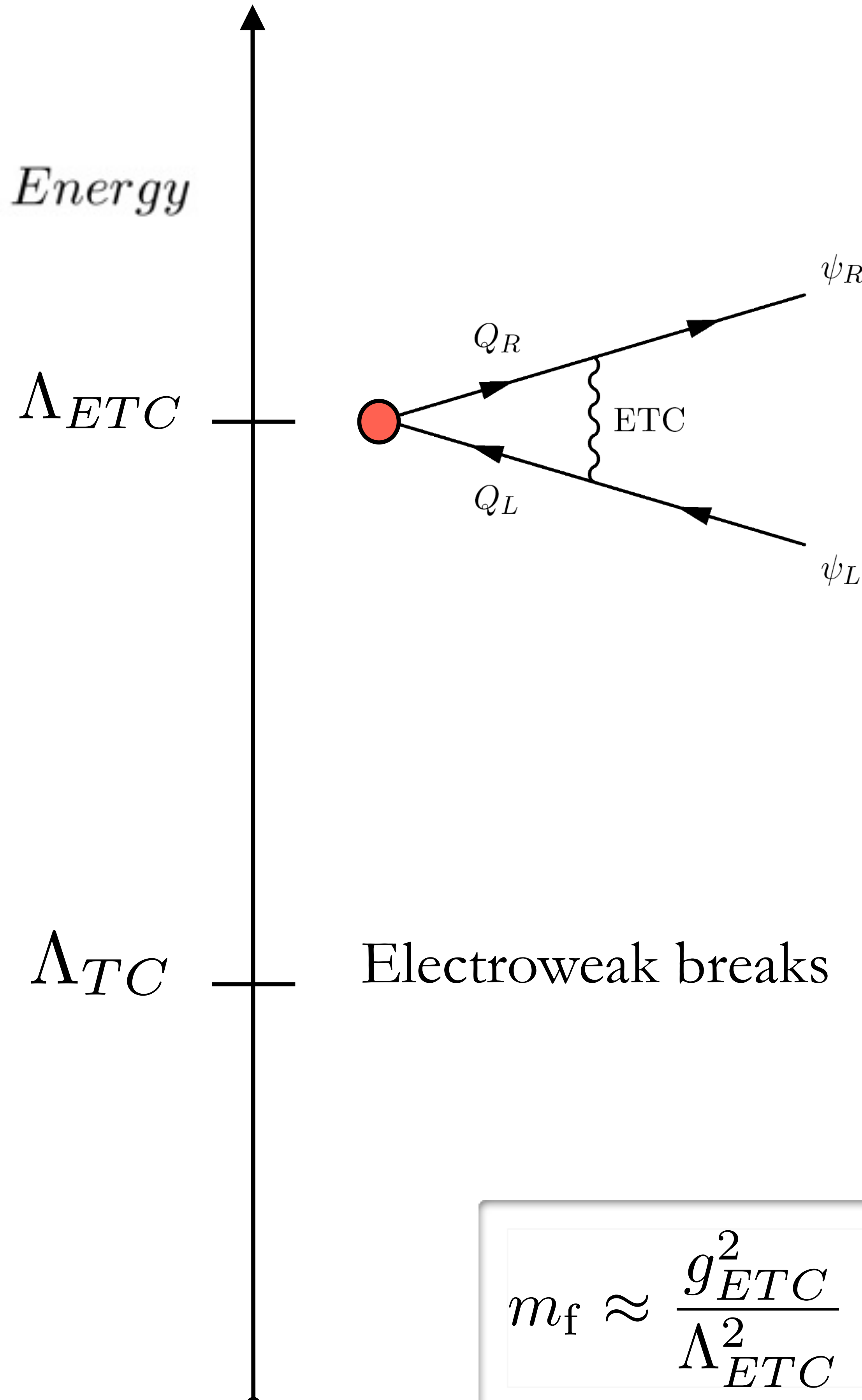
$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \dots$$

PNG Masses

SM-Fermion Masses

FCNC Operators





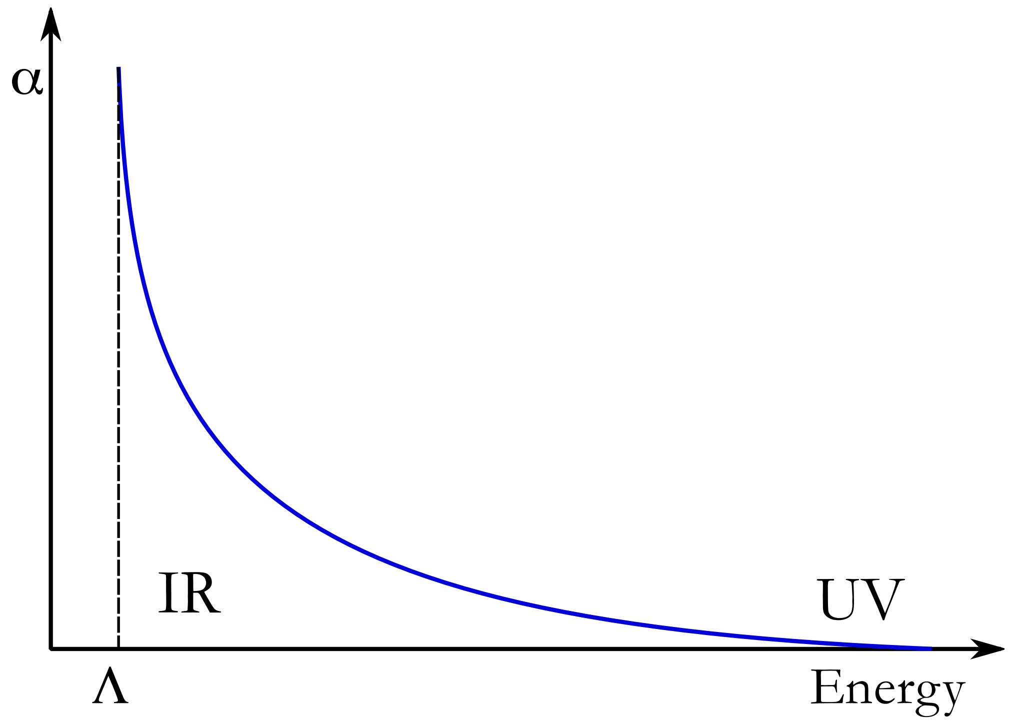
$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC}$$

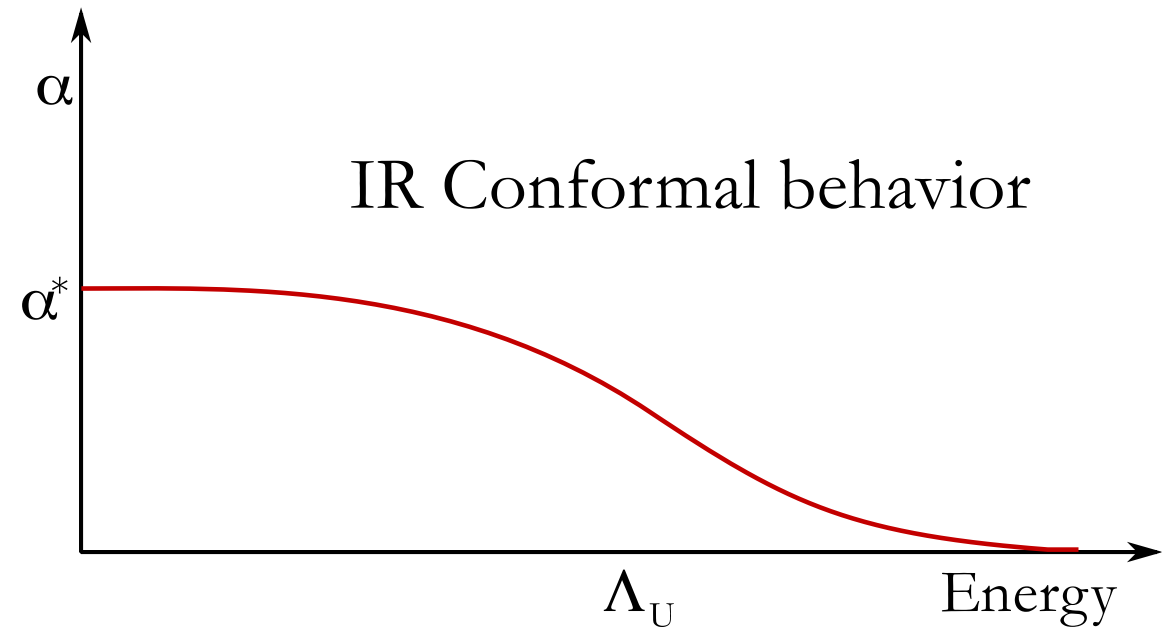
$$< \bar{Q}Q >_{ETC} \approx < \bar{Q}Q >_{TC} \sim \Lambda^3_{TC}$$

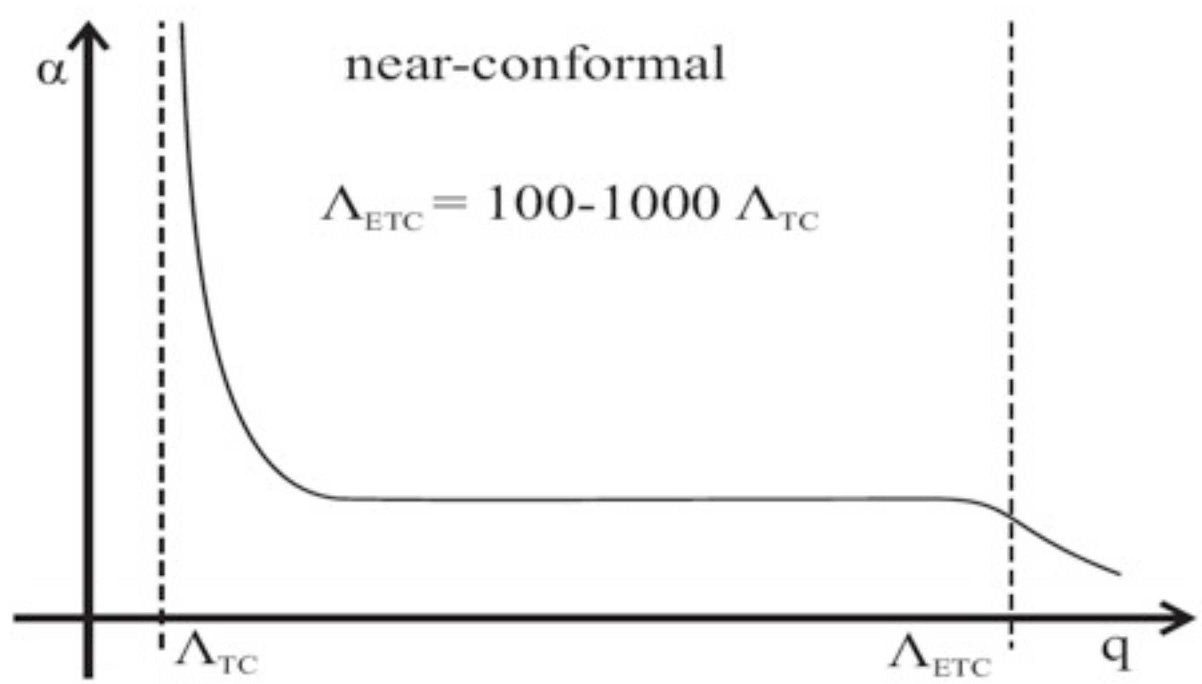
$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC} \quad \ll \quad m_{\rm Top}$$

Beyond QCD

Near Conformal







Why walking helps?

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

<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>

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

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

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

$$\downarrow$$

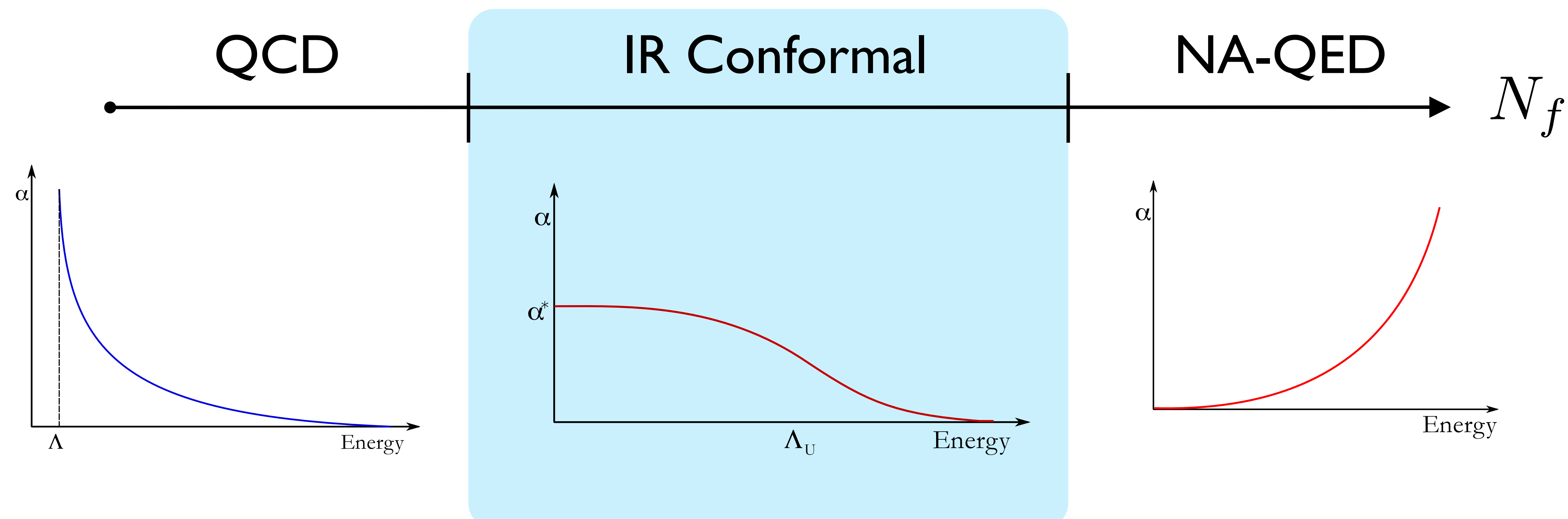
Fermion Mass Enhancement & FCNC decoupling

Gauge Theory Knobs

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

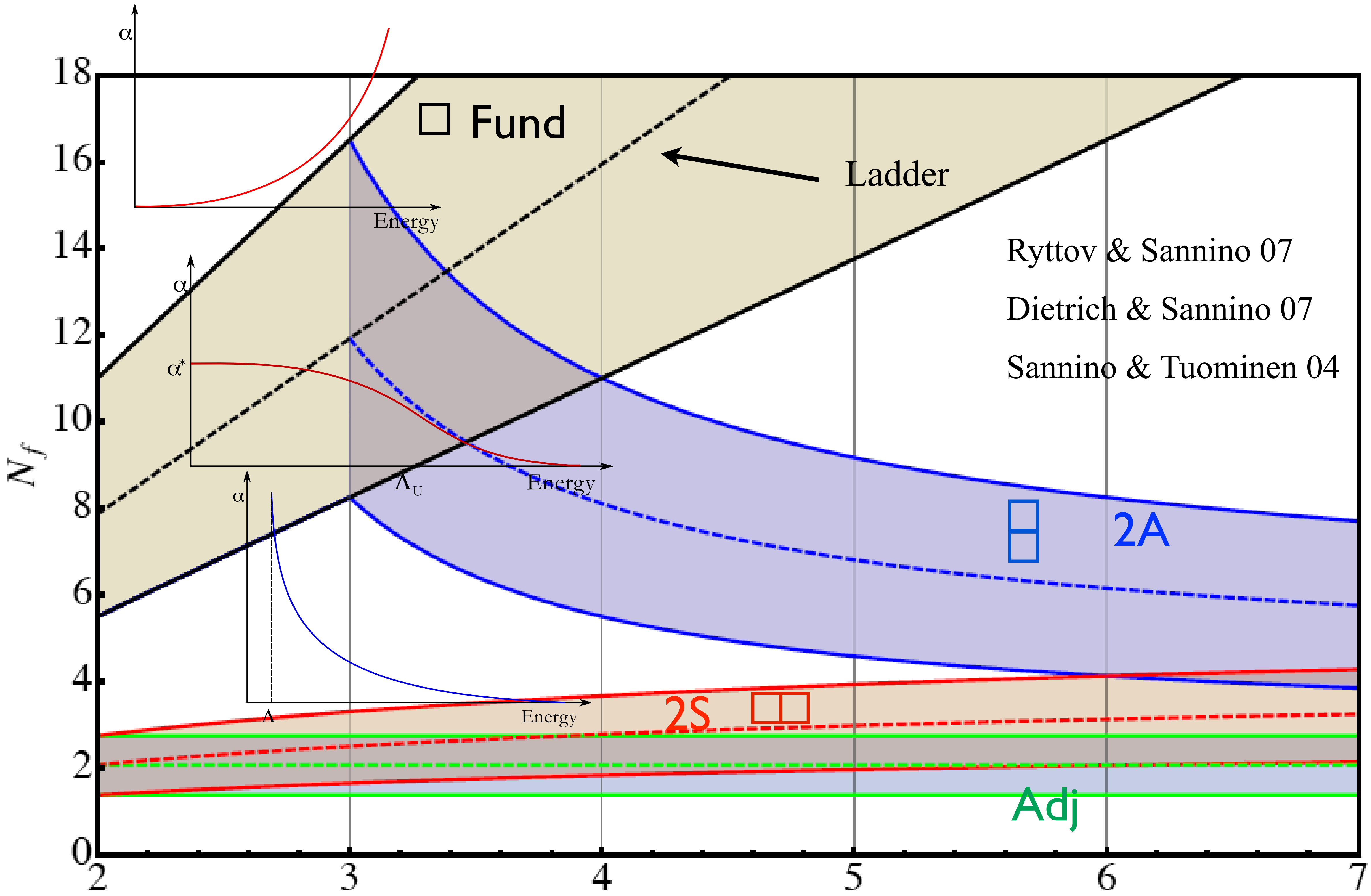
Matter Representation

# of Flavors per Representation



Universal Picture

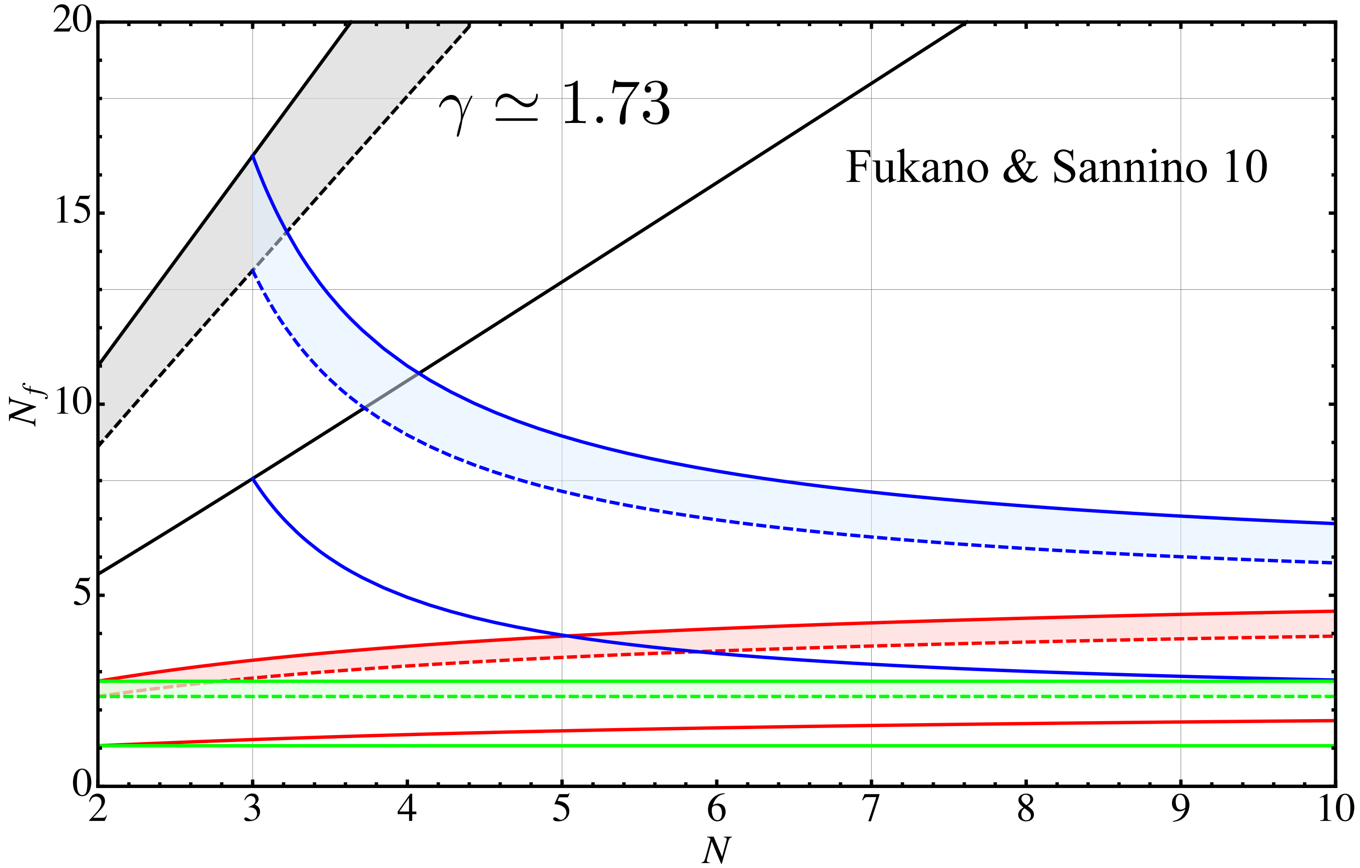
SU(N) Phase Diagram



All Orders Beta Function

Ryttov & Sannino 07

SU(N) Phase Diagram + 4 Fermions



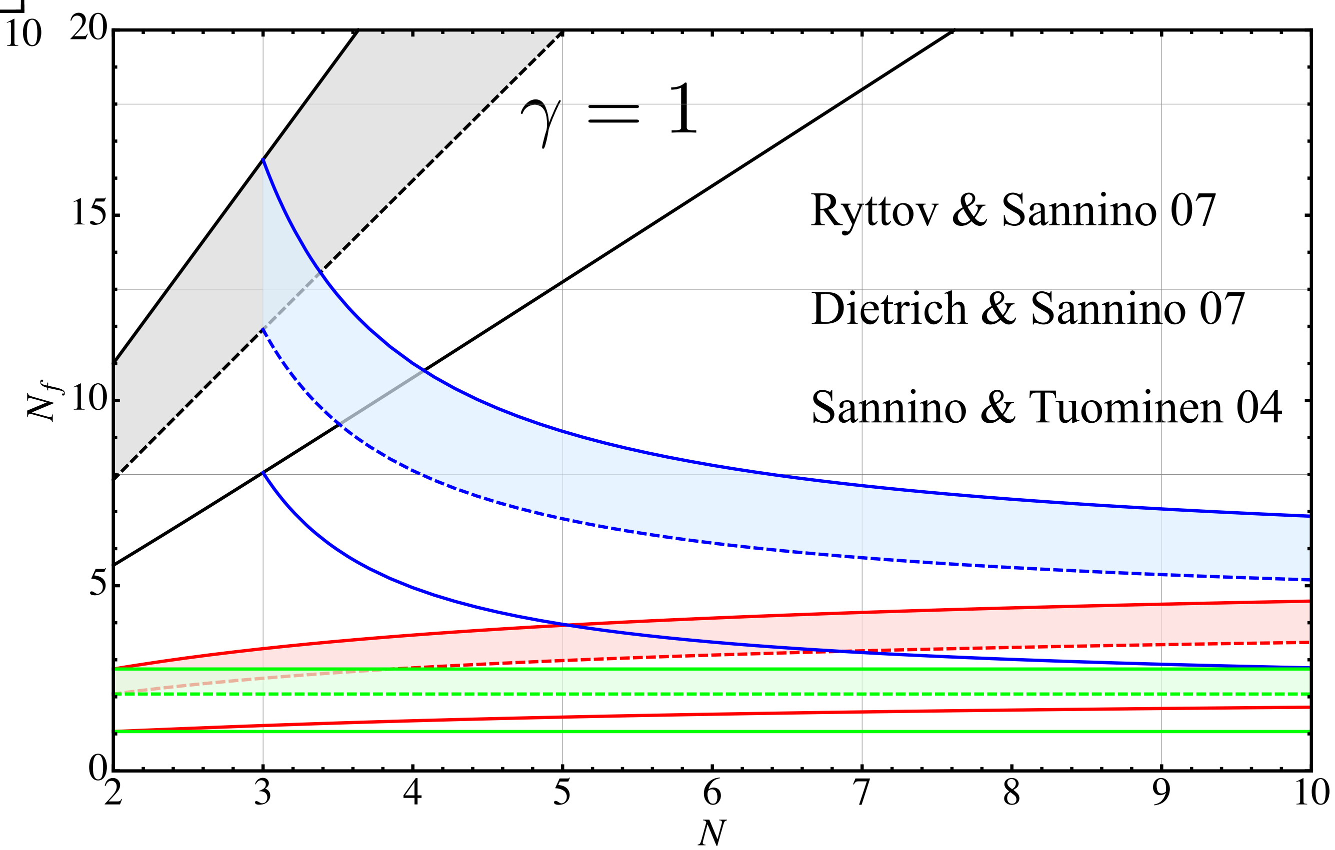
Fukano & Sannino 10

Ideal Walking:

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

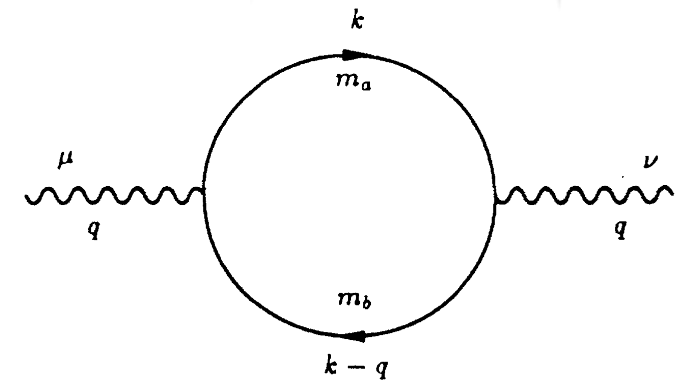
Ordinary Walking:

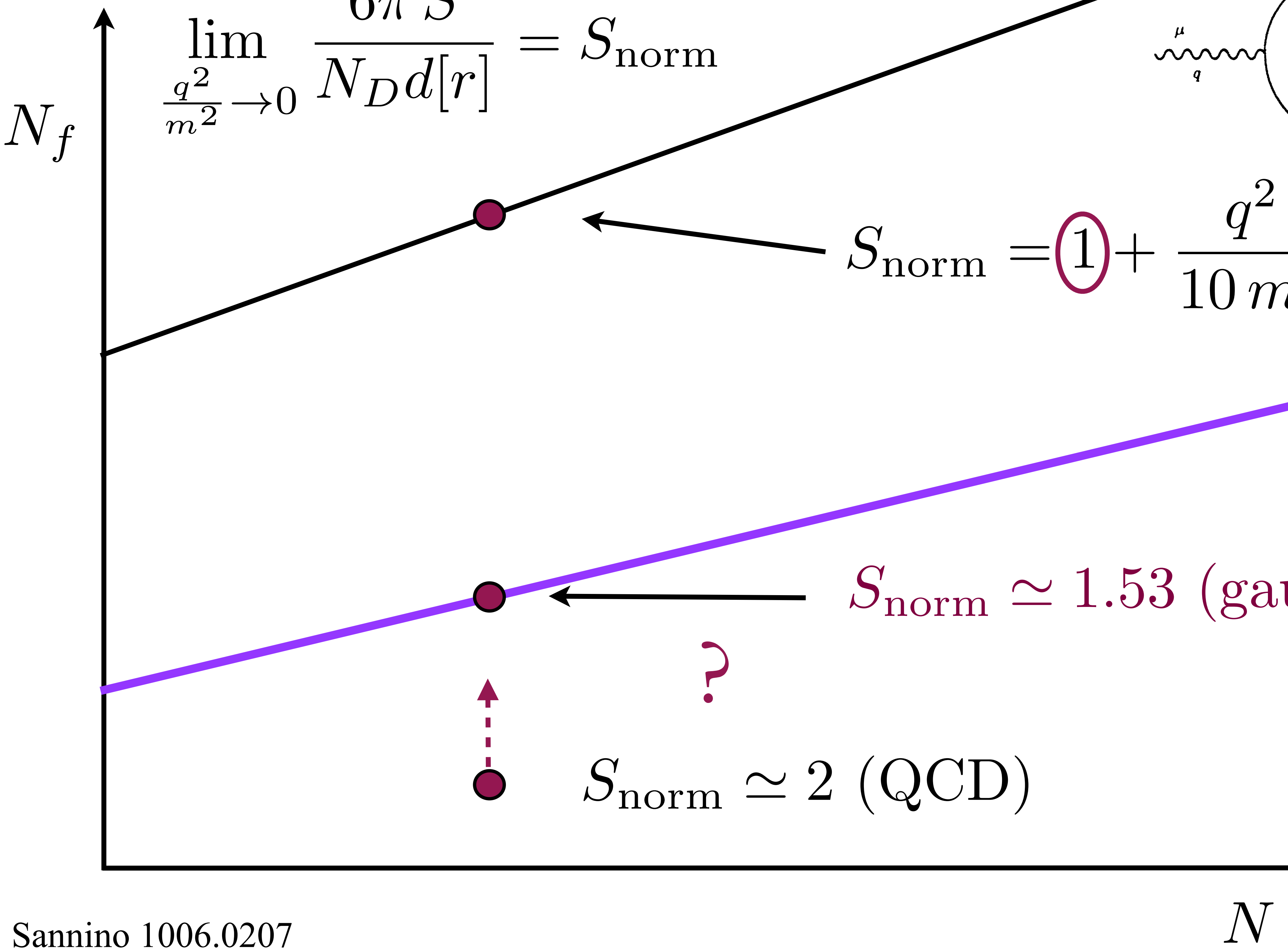
Requires huge fine-tuning to be near the lower end of the conformal window and unlikely to provide the correct Top mass.



Exact conformal S

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



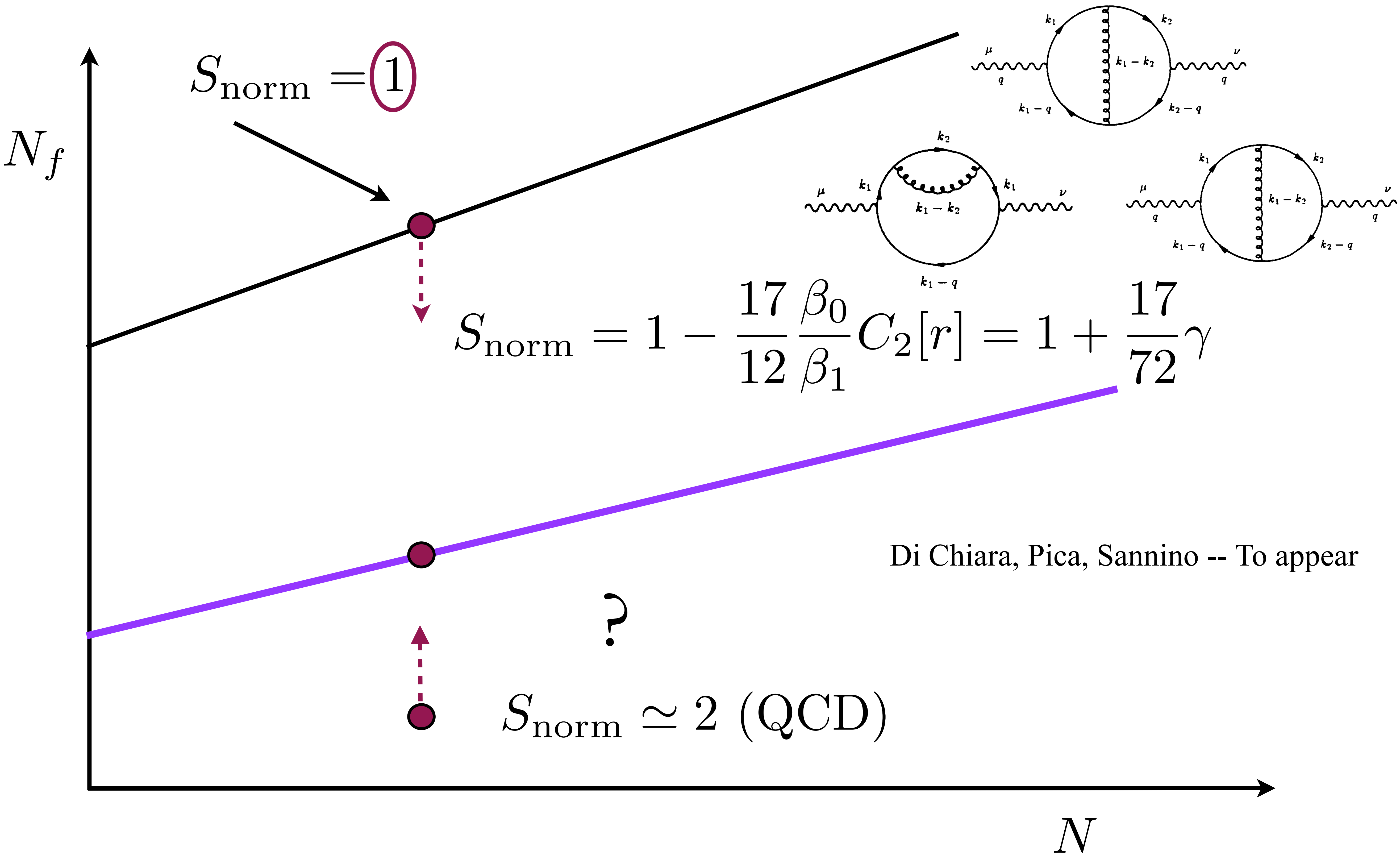


Sannino 1007.0254

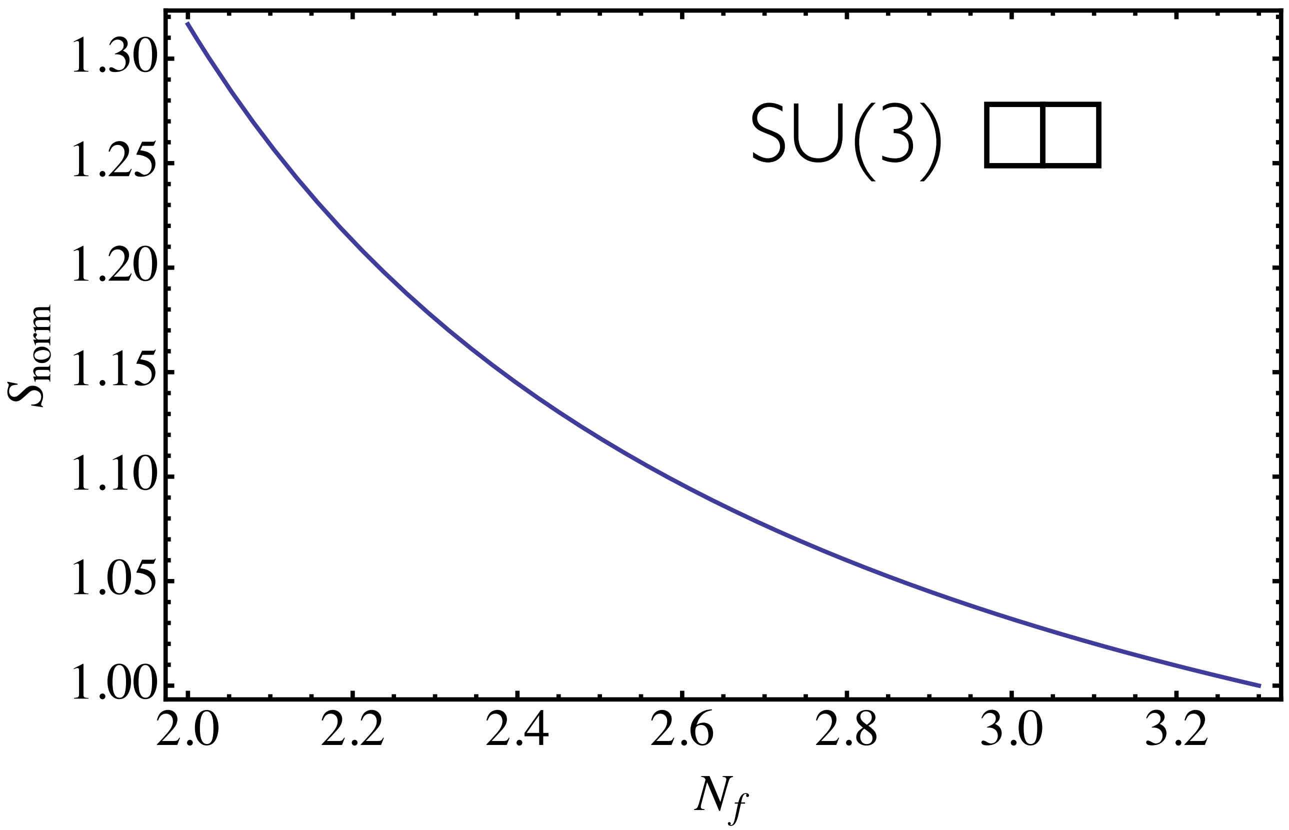
Sannino 0907.1364

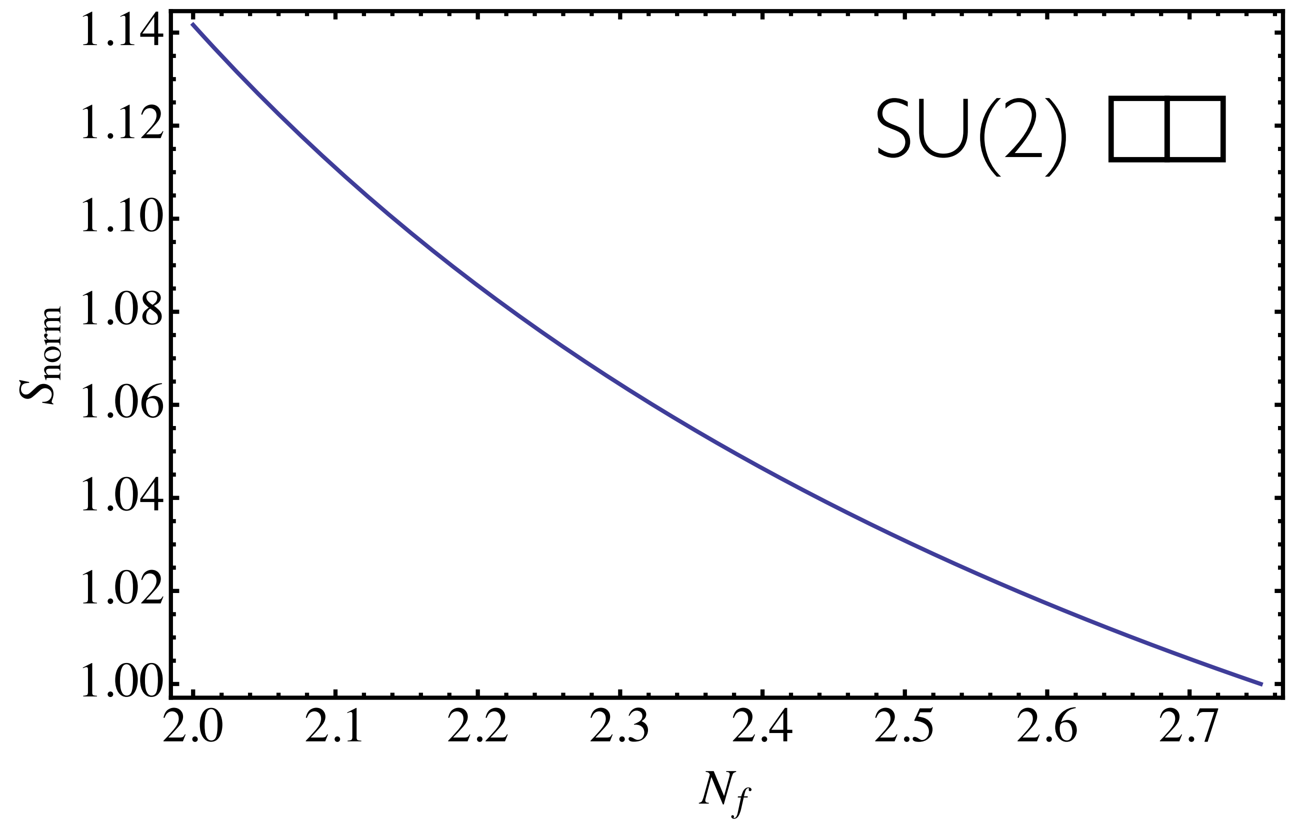
Sannino 1006.0207

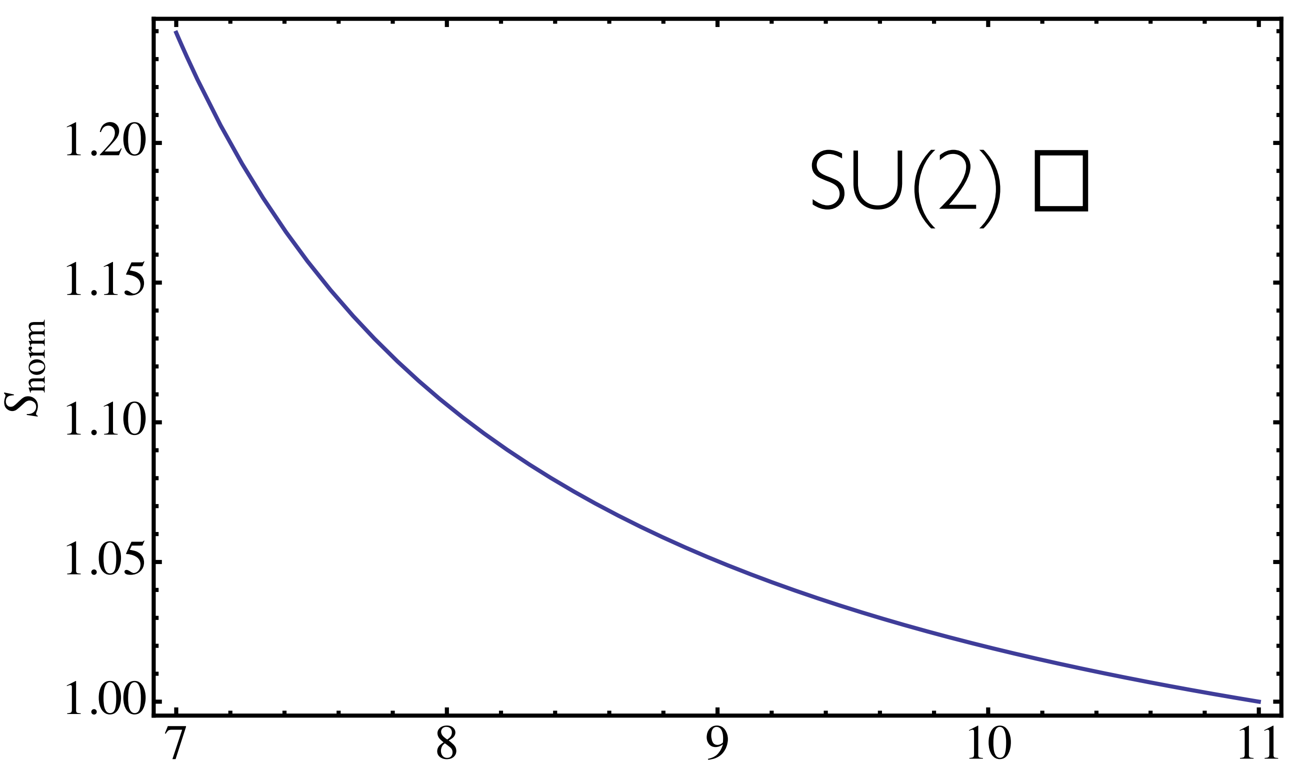
Conformal S @ 2 loops

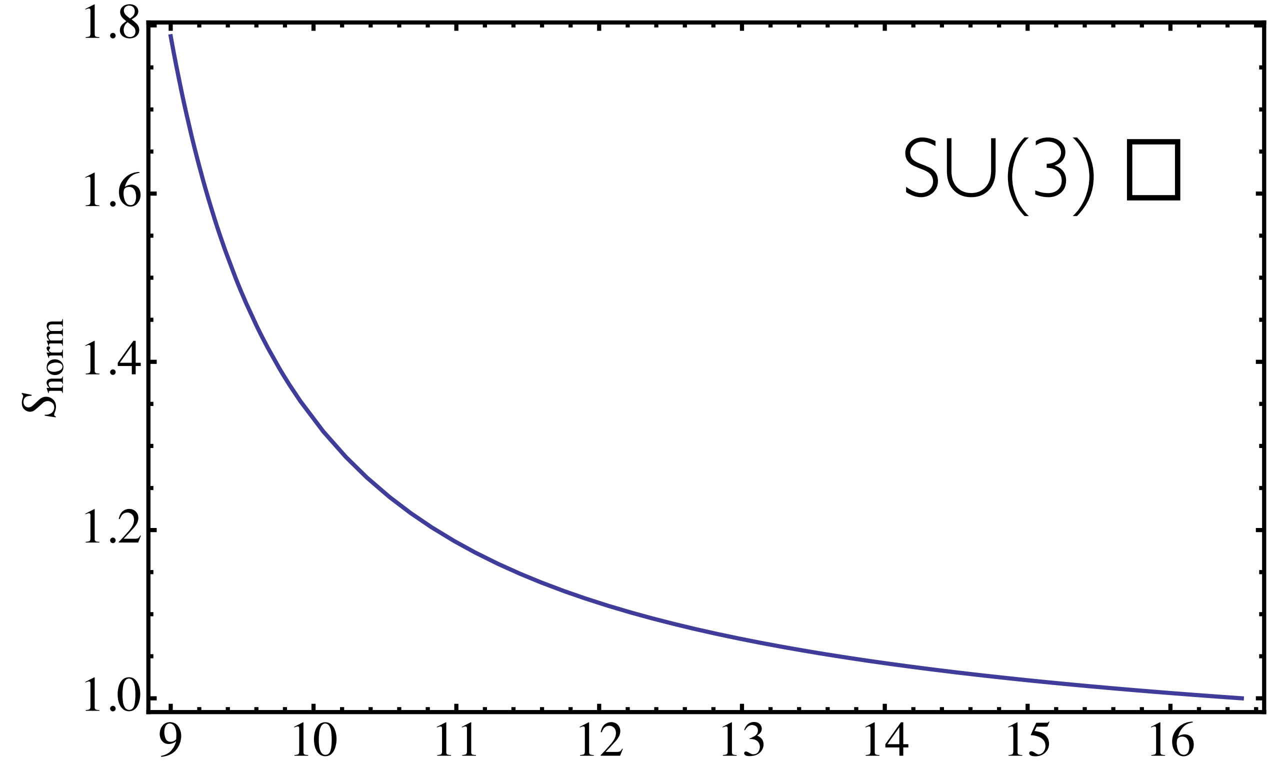


Conformal S @ 2 loops









N_f Di Chiara, Pica, Sannino -- To appear N_f

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!

Minimal Working TC

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- 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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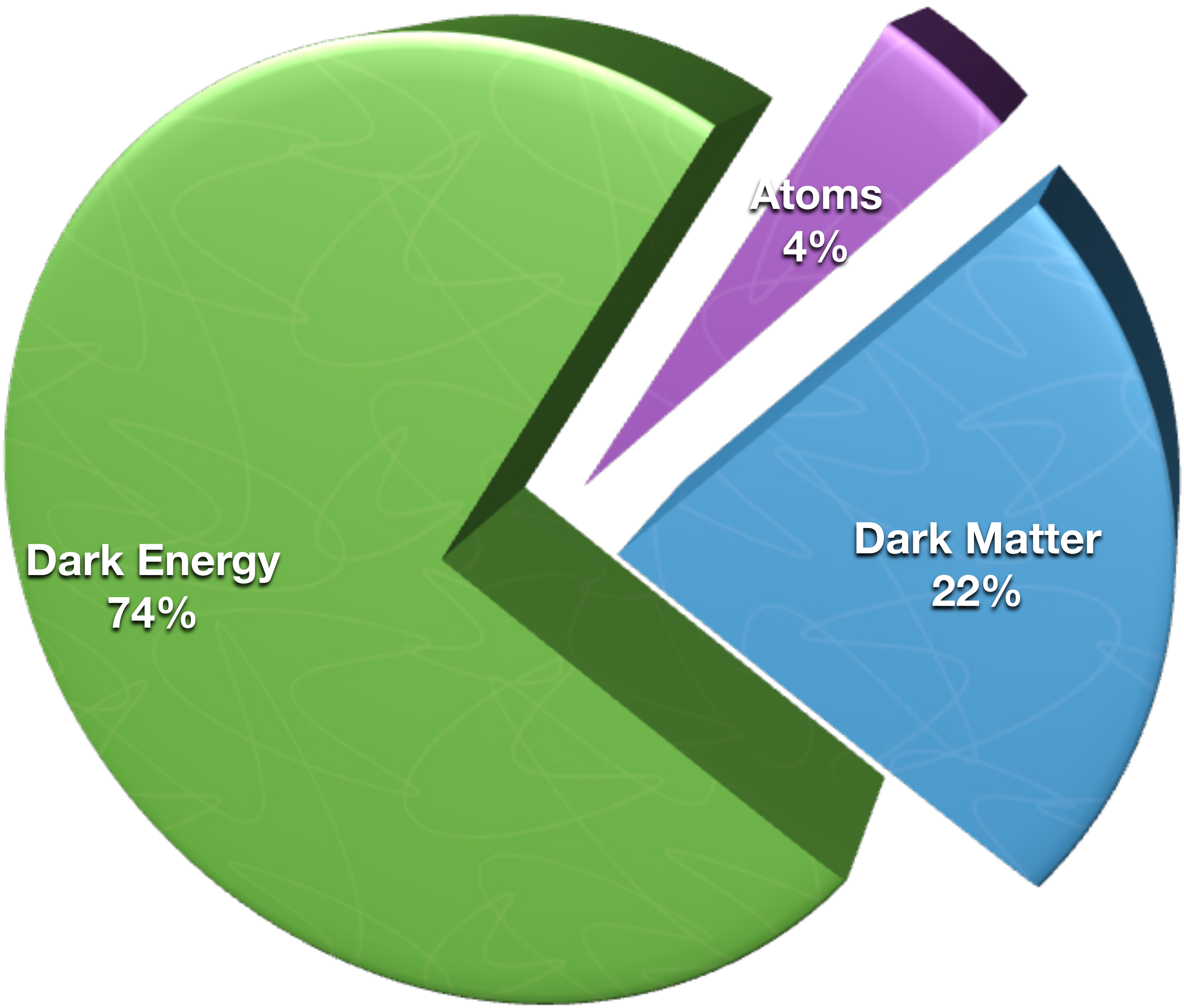
New life in Technicolor

Not the Coldplay album

Dark Matter



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

Asymmetric DM

A particle similar to the nucleon

But electrically neutral

At most EW-type cross sections

Great if connected to the ESWB

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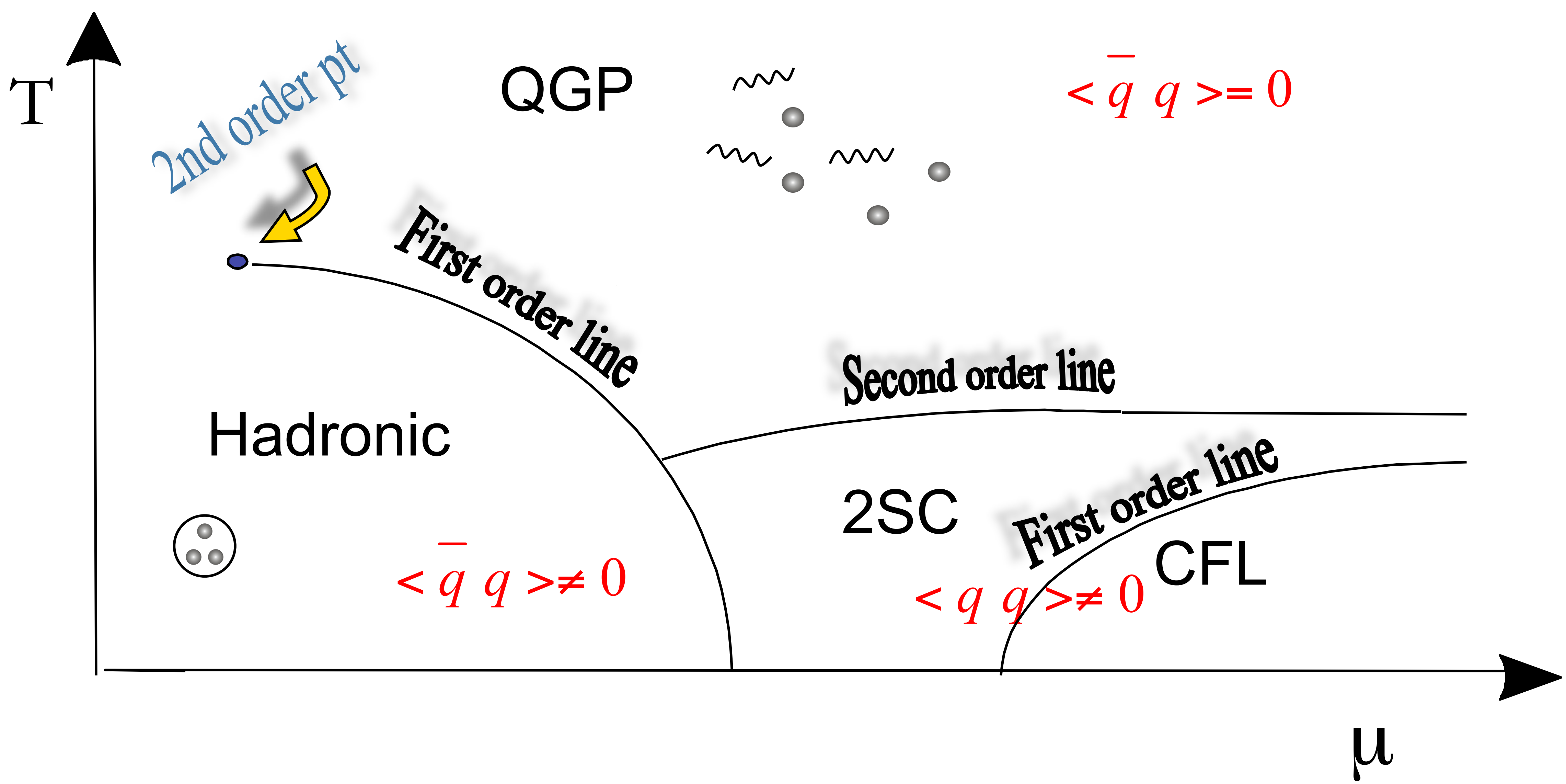
XXXX - Technicolor

QCD Phase Diagram



DM vs TC

Technibaryon 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 & Sannino 08

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

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

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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

Sannino and 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

$$m_{TB} \ll T^* \sim 5 \text{ GeV}$$

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

$$T^* \sim 200 \text{ GeV}$$

Heavy

$$m_{TB} \approx 8T^* \approx (1-3) \text{ TeV}$$

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

GUTs

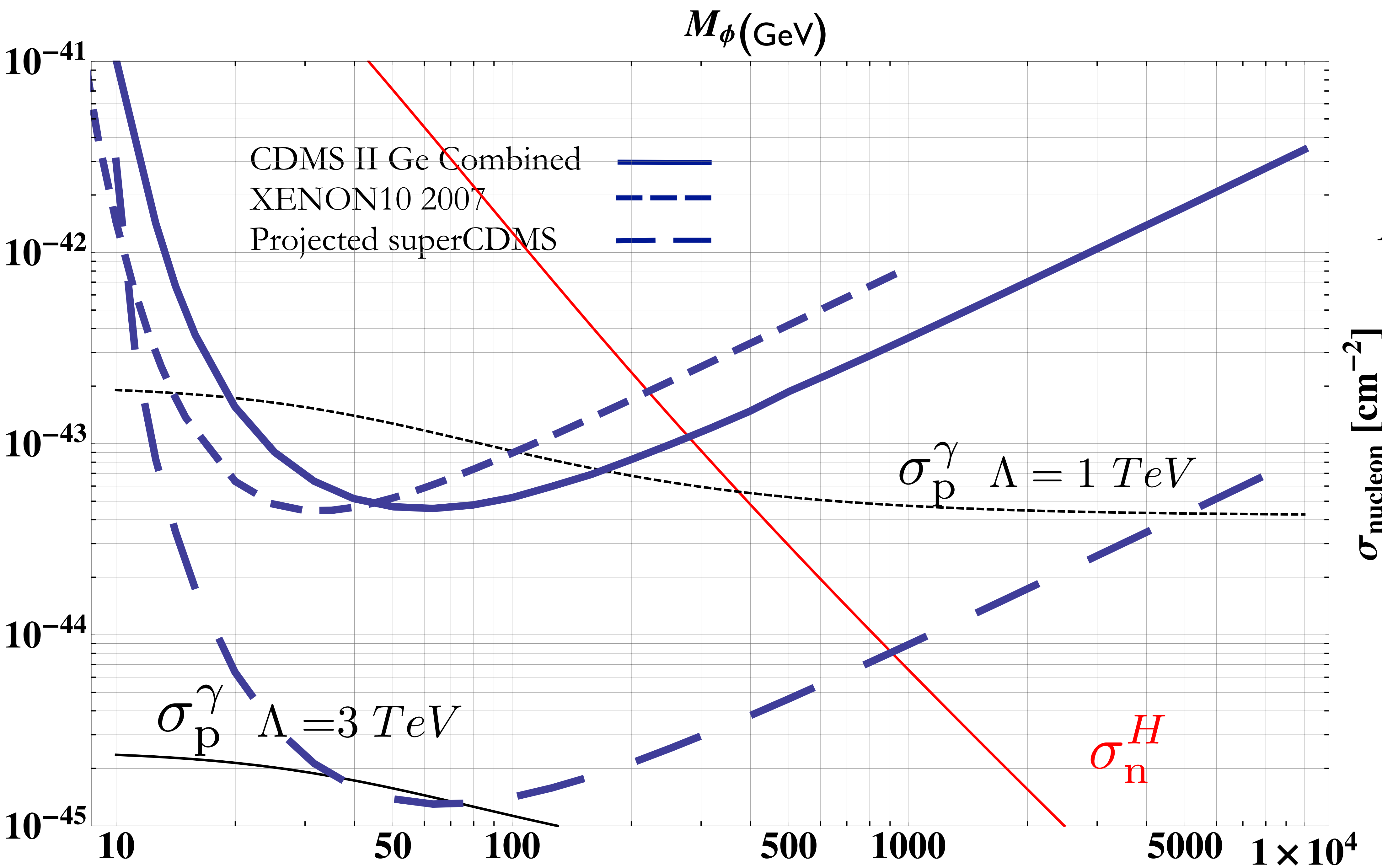
$$\tau \sim \frac{M_{GUT}^4}{m_{TB}^5} \sim 3 \times 10^{37}\text{sec}$$

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

Gudnason, Ryttov, Sannino 06

Nardi, Sannino, Strumia, 08.

Direct Constraints



$f = 0.3$

$d_M = 1$

$d_B = 1$

$M_H = 300$ GeV

Foadi, Frandsen, Sannino. 08

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

Many Models

(?)MSSM

XLMS D

......

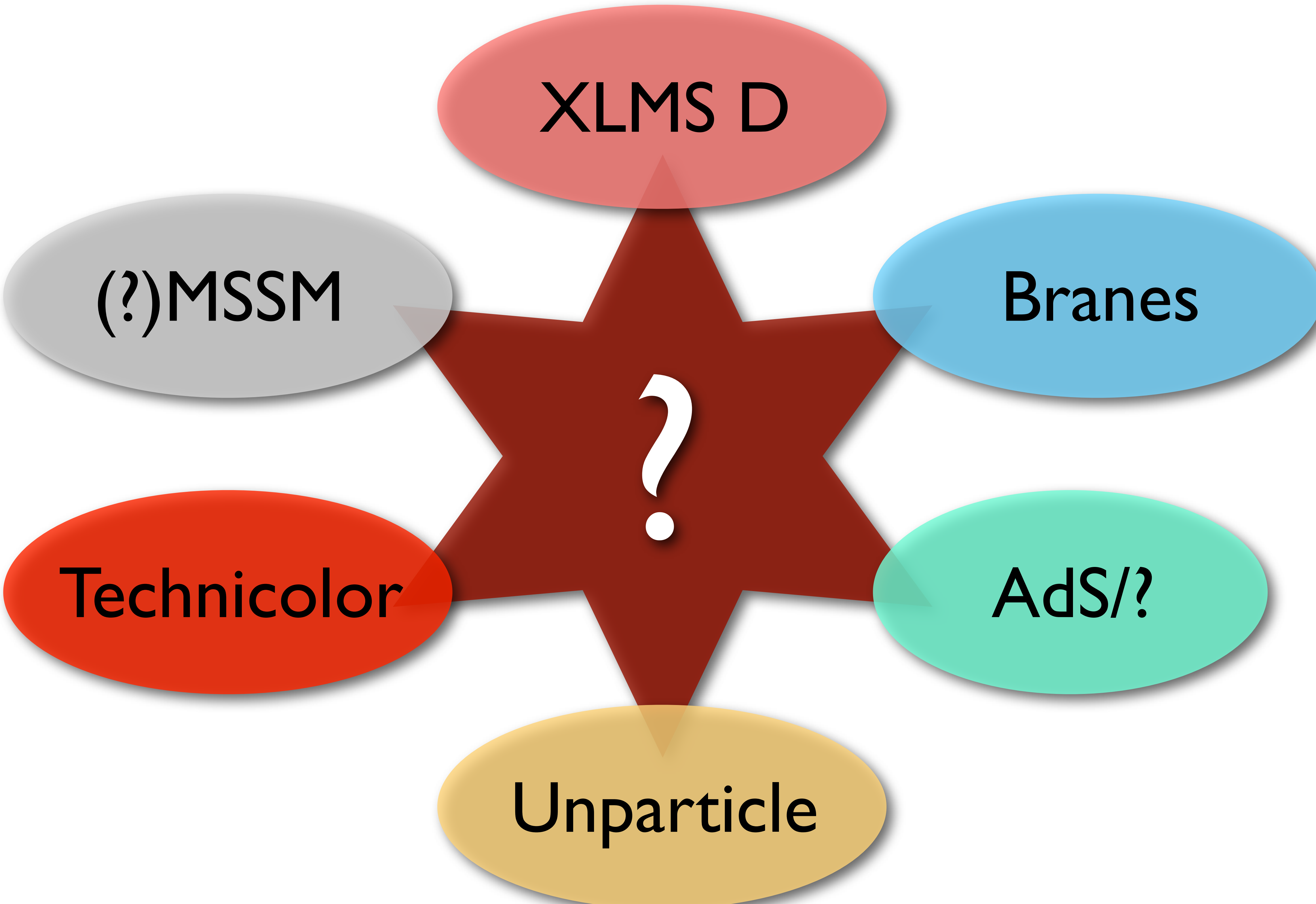
Technicolor

Branes

Unparticle

AdS/?

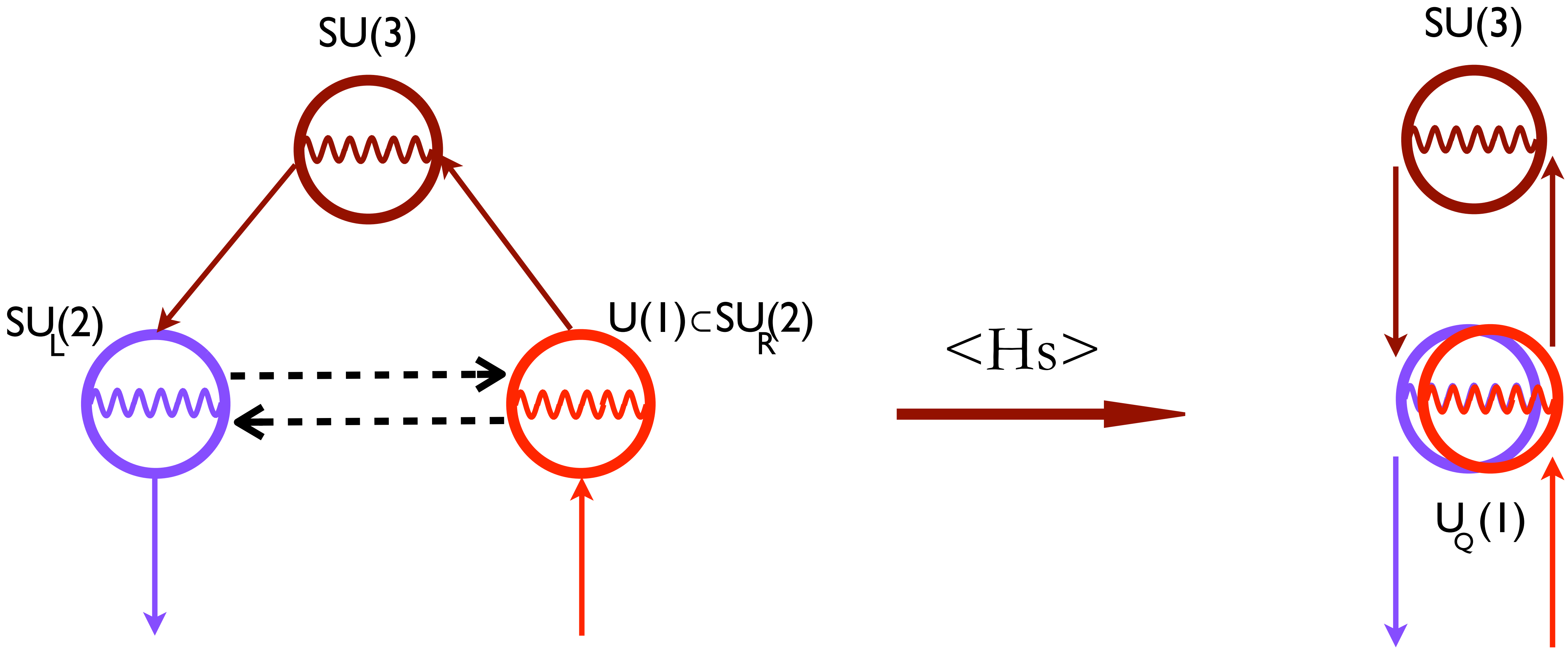
Unifying in Model Space

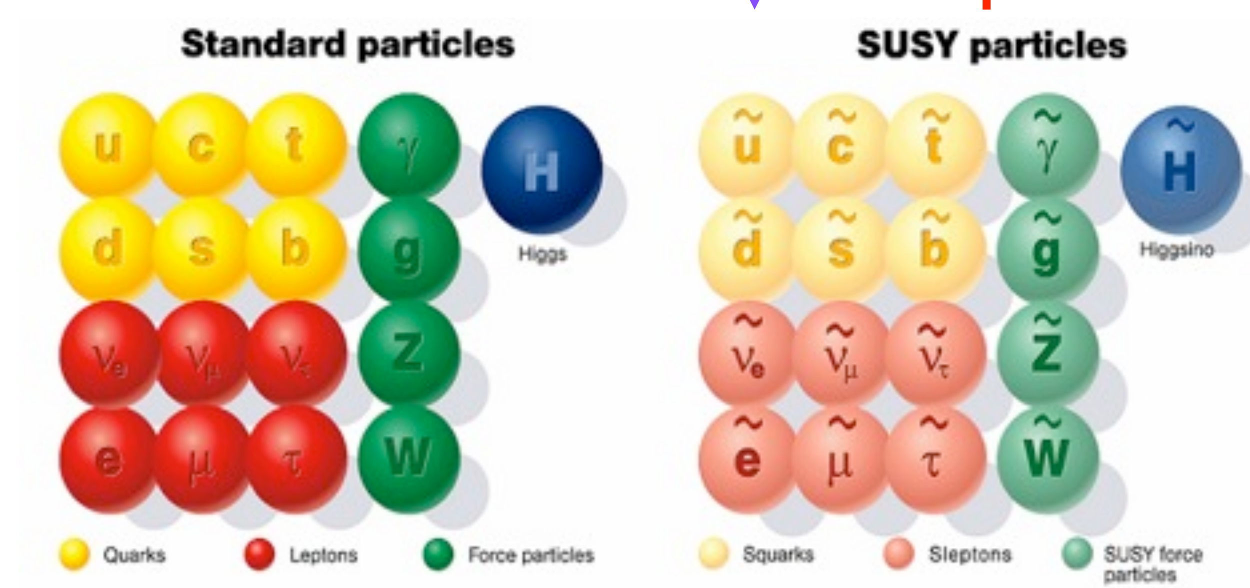


Criterions

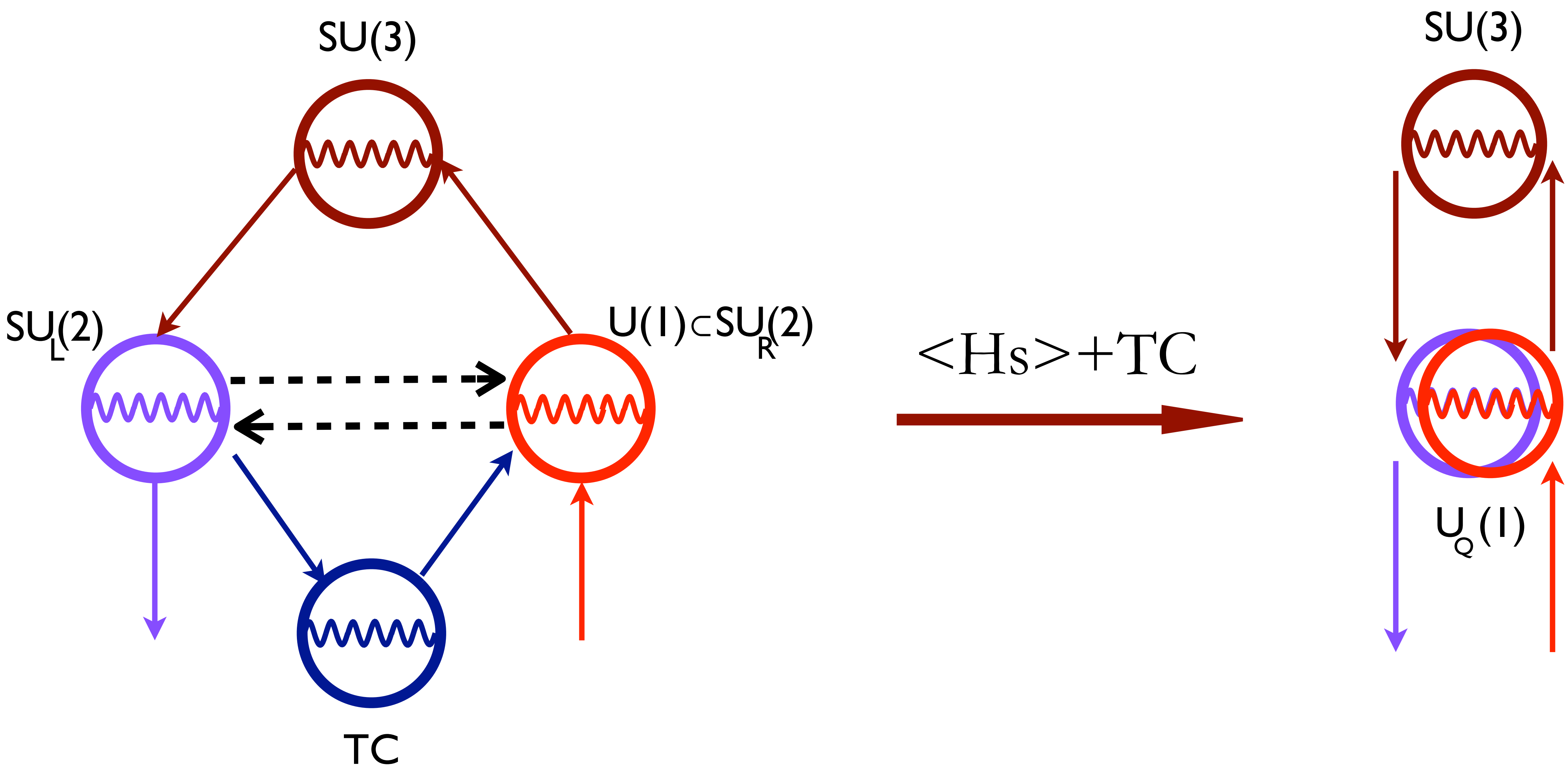
- Naturalizes the SM
- New strong dynamics
- Supersymmetric
- Near conformal
- Link to extra dim. and strings
- Possibly calculable

MSSM - cartoon





Super Technicolor



Bonus: A working model of ETC

From MWT to N=4

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

... and now

- N=4 breaks to N=1 via electroweak interactions
- Add MSSM superpotential and SUSY breaking

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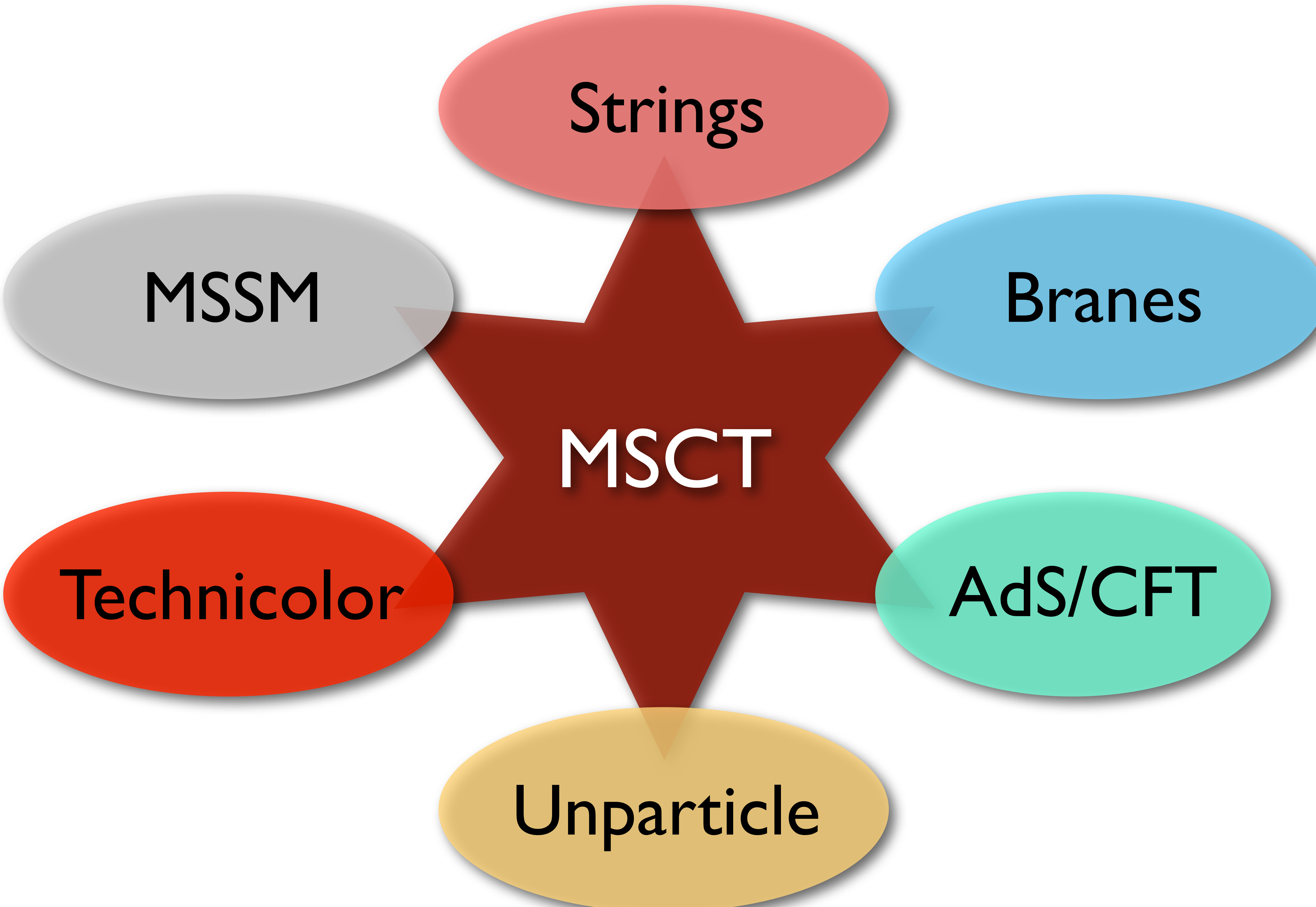
Minimal Superconformal TC



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MSCT - facts

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

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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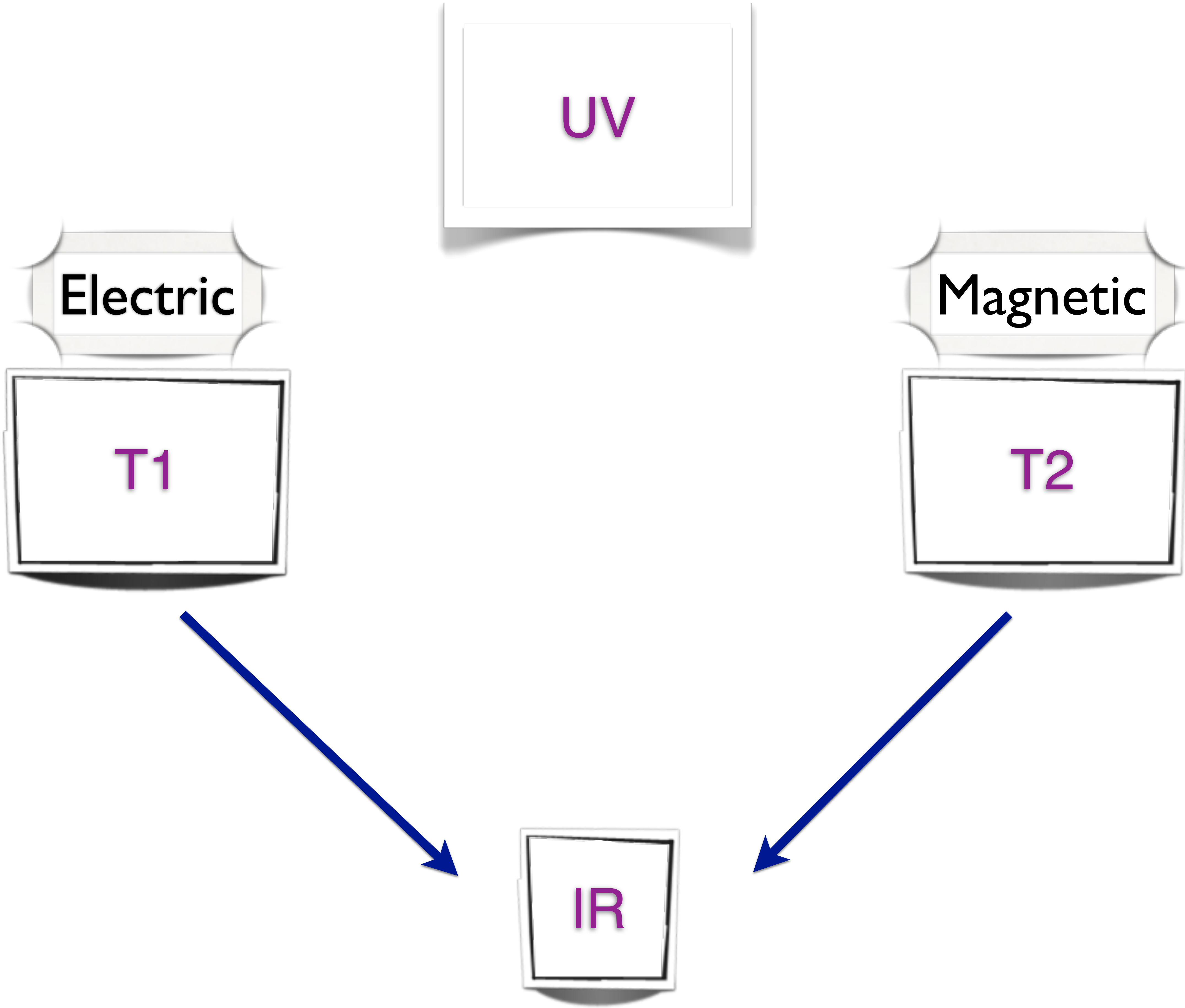
Backup slides

Duals


UV
Electric
Magnetic
T1
T2
IR

Electric

Strong

↔

Magnetic

Weak

$$e\, g = 2 \pi n$$

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

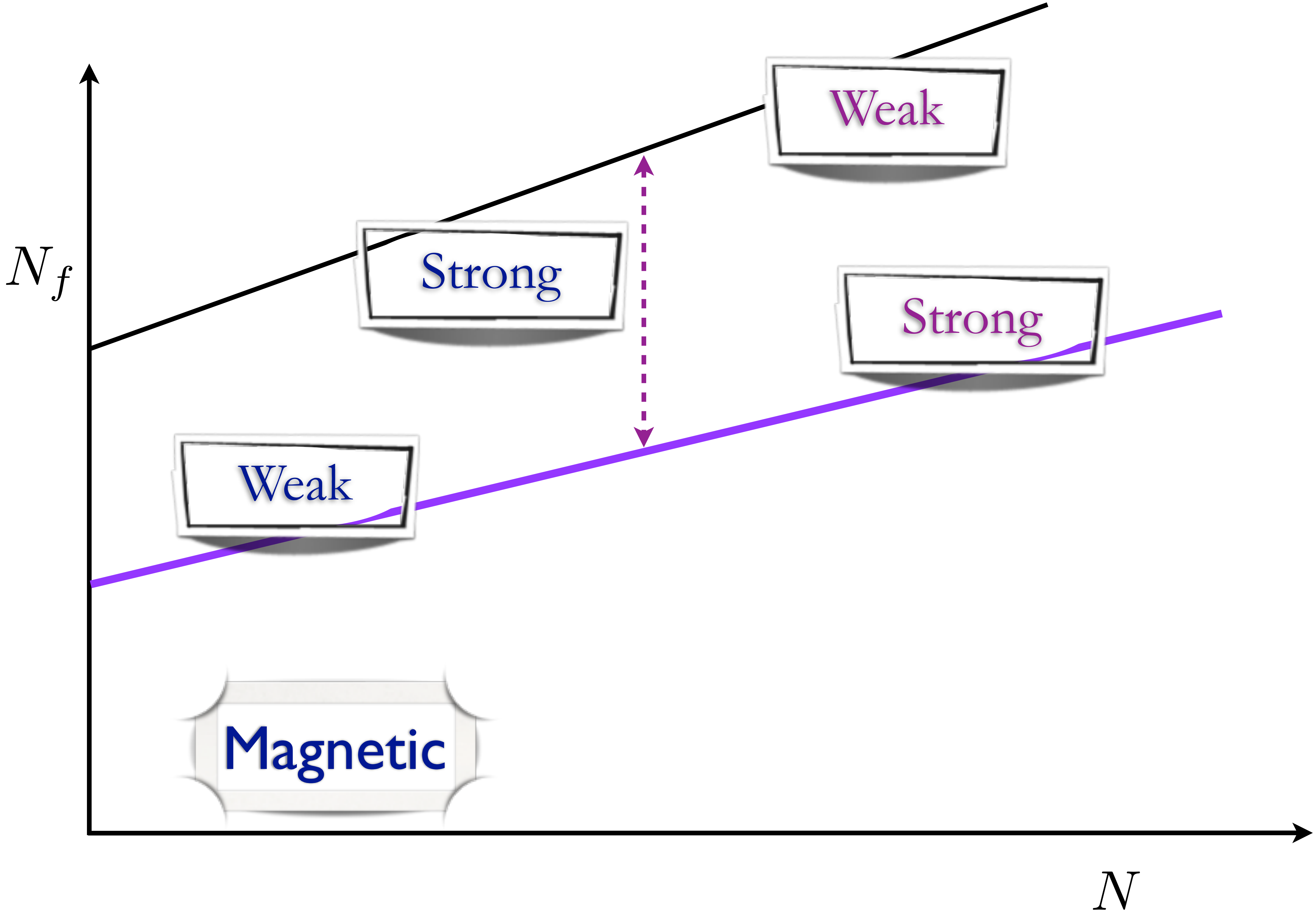
Fields	$[SU(3)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$
Q	$\yng(1)$	$\yng(1)$	1	1
$\widetilde{Q}$	$\overline{\yng(1)}$	1	$\overline{\yng(1)}$	-1
G_μ	Adj	1	1	1

T1

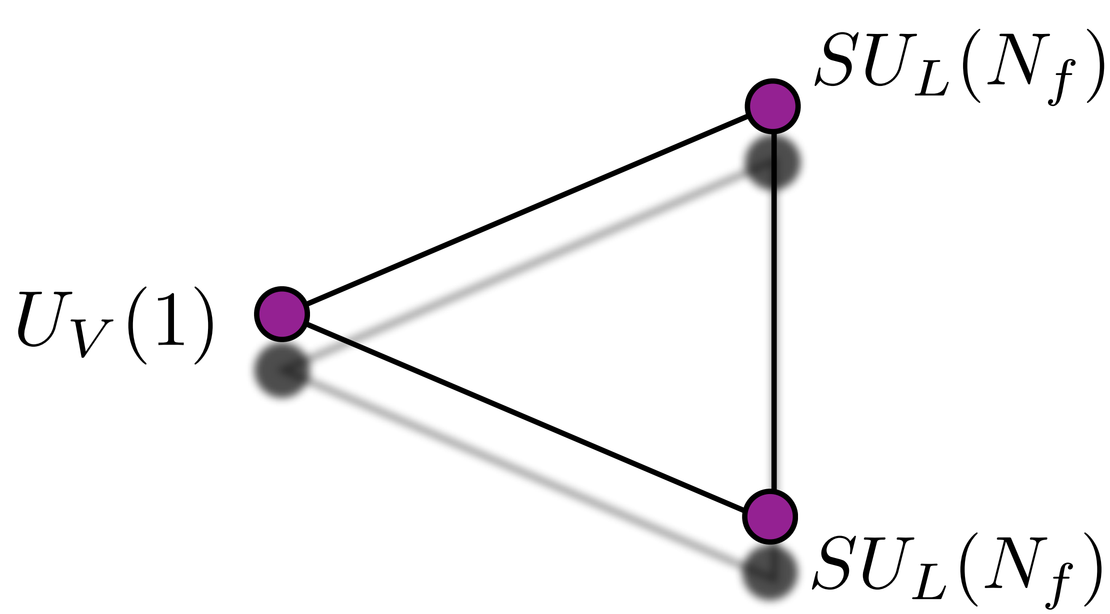
T2

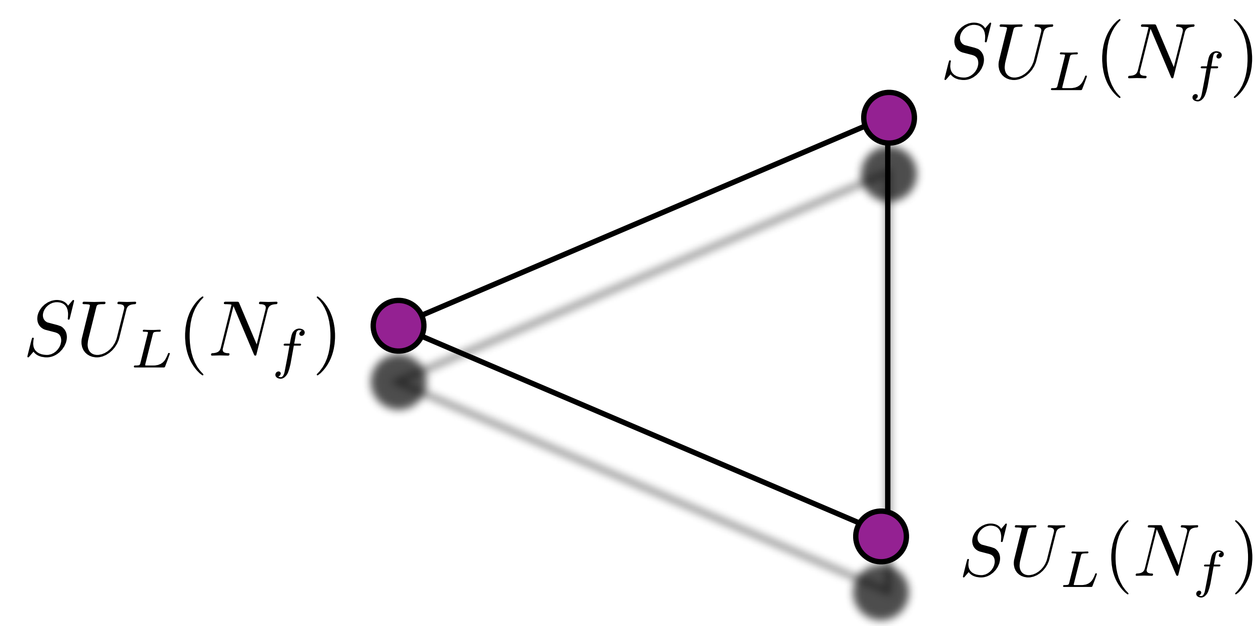
Fields	$[SU(X)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	# of copies
q	$\yng(1)$	$\yng(1)$	1	y	1
$\widetilde{q}$	$\overline{\yng(1)}$	1	$\overline{\yng(1)}$	$-y$	1
A	1	$\yng(1,1,1)$	1	3	ℓ_A
S	1	$\yng(3)$	1	3	ℓ_S
C	1	$\yng(2,1)$	1	3	ℓ_C
B_A	1	$\yng(1,1)$	$\yng(1)$	3	ℓ_{B_A}
B_S	1	$\yng(2)$	$\yng(1)$	3	ℓ_{B_S}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

Weak-Strong Duality



‘t Hooft Anomaly Matching





Operator Matching

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

A QCD Dual

F.S. 09

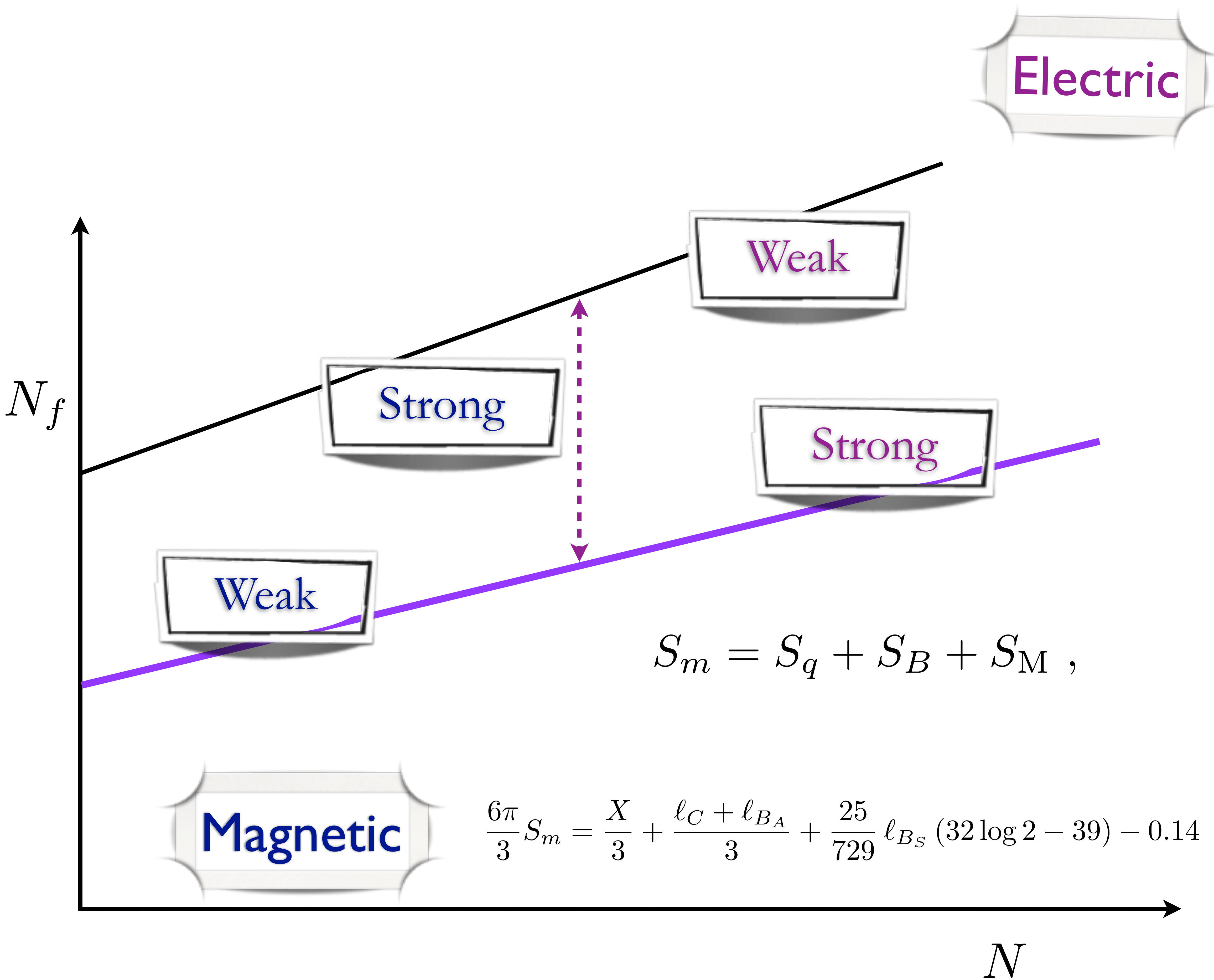
Fields	$[SU(2N_f-5N)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	# of copies
q	$\square$	$\square$	1	$\frac{N(2N_f-5)}{2N_f-5N}$	1
$\widetilde{q}$	$\overline{\square}$	1	$\overline{\square}$	$-\frac{N(2N_f-5)}{2N_f-5N}$	1
A	1	$\begin{smallmatrix}\square\\\square\\\square\end{smallmatrix}$	1	3	2
B_A	1	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$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

Dual Theory

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

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

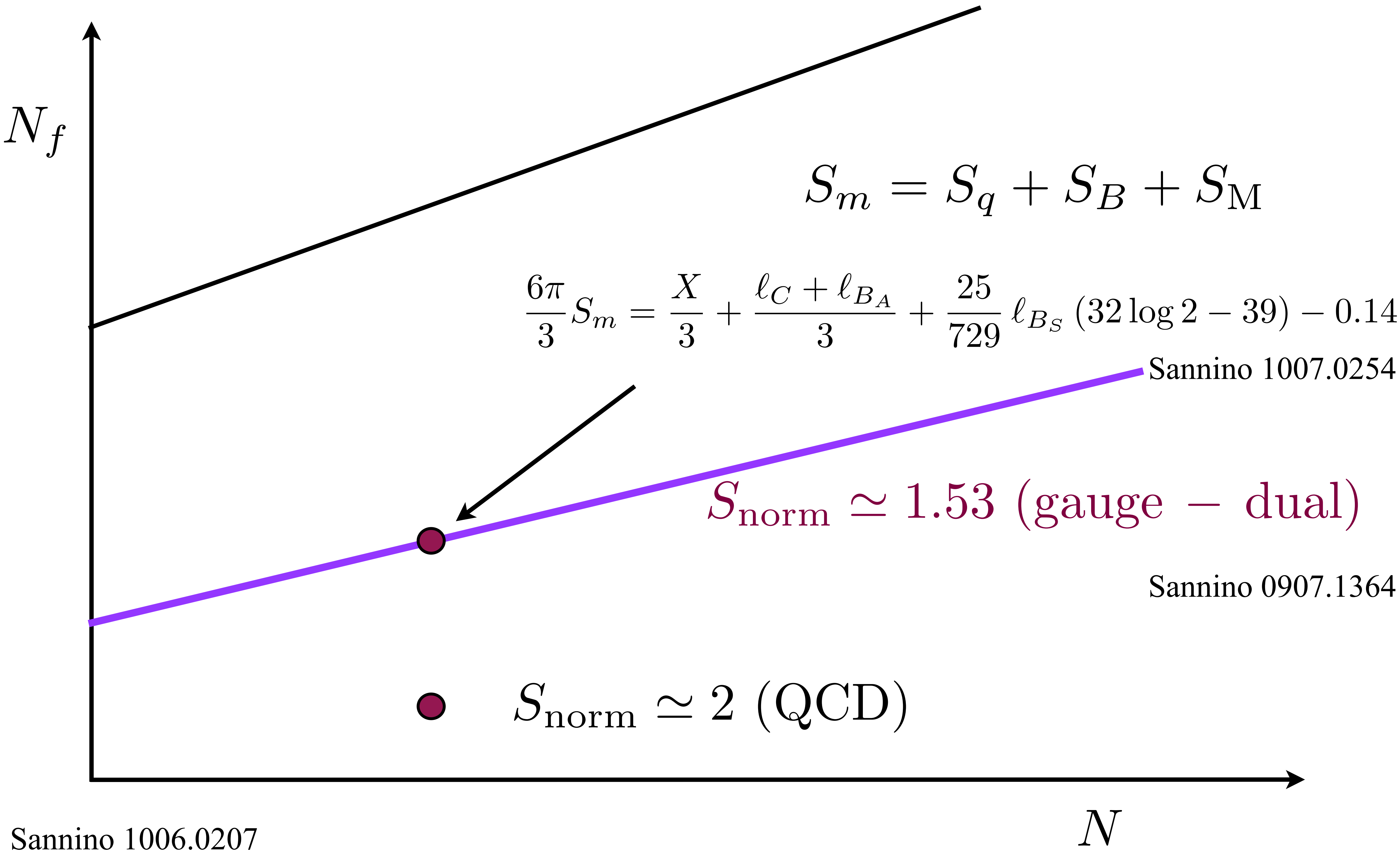
$$B[\epsilon_{c_1 \ldots . c_X} q^{c_1} \cdots q^{c_X}] = 3\;(2N_f - 5) = \# \times B[\epsilon_{c_1 \ldots . c_3} Q^{c_1} \cdots Q^{c_3}]$$



$$S_m = S_q + S_B + S_{\rm M} \ ,$$

$$\frac{6\pi}{3} S_m = \frac{X}{3} + \frac{\ell_C + \ell_{B_A}}{3} + \frac{25}{729}\ell_{B_S}\left(32\log 2 - 39\right) - 0.14$$

Dual conformal S



Sannino 1006.0207

Magnetic
Asymp. Freedom

Electric
Chiral Sym. Restored

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

↕

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

↔

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