Composite Dynamics

Francesco Sannino

CP^3 - Origins

Particle Physics & Origin of Mass

NEXT Graduate School 18 July 2011

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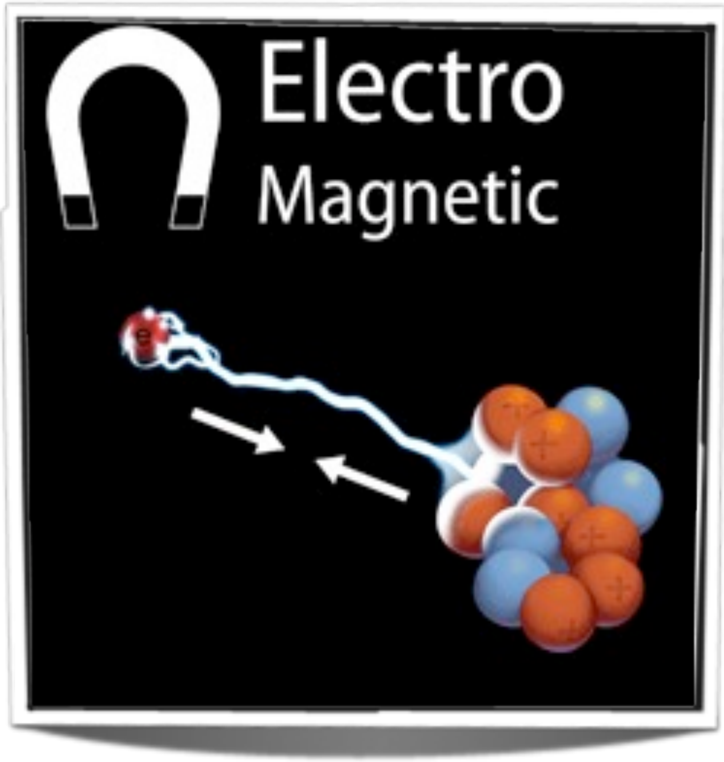
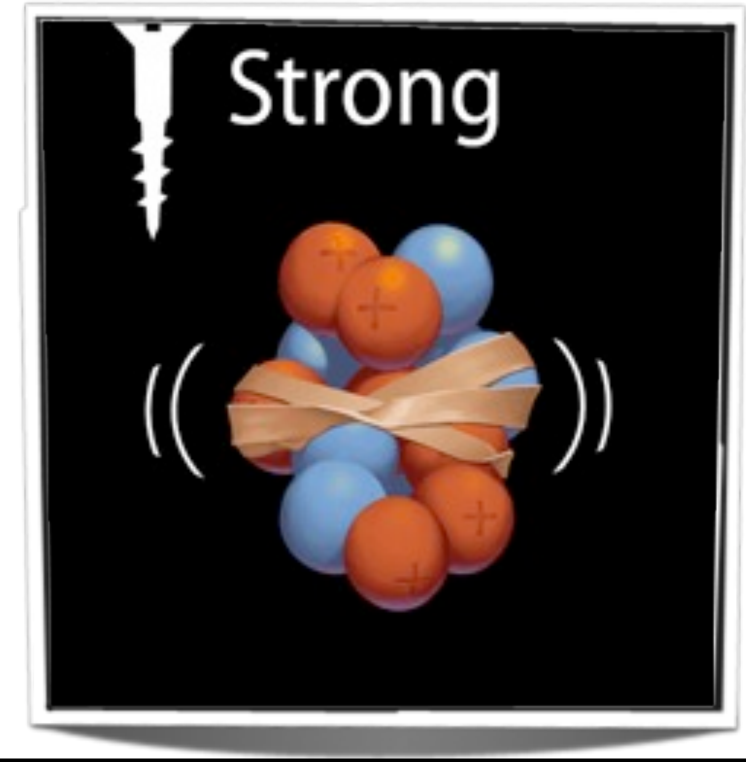
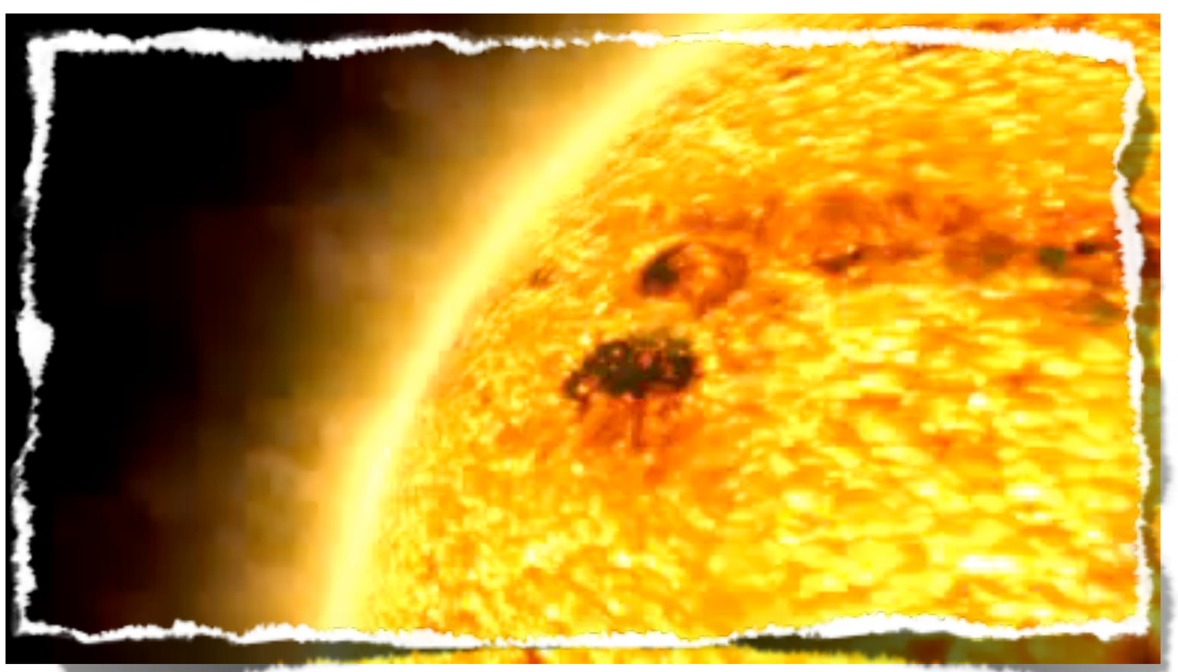
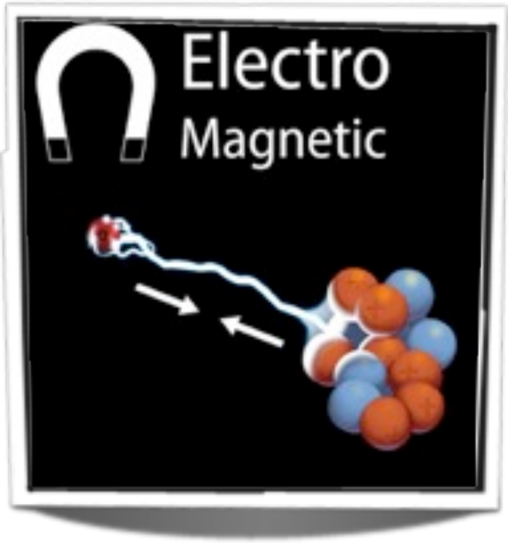
Standard Model

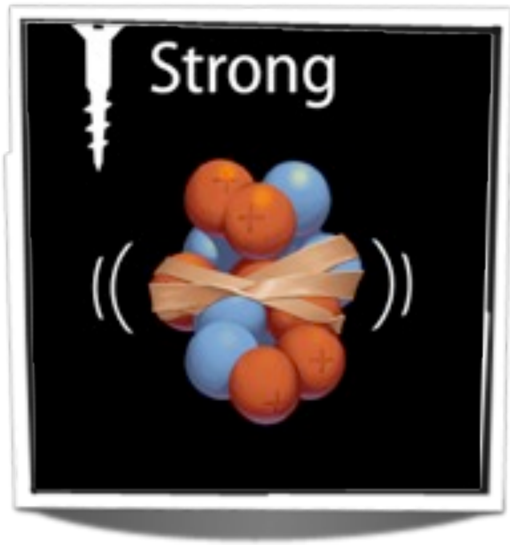




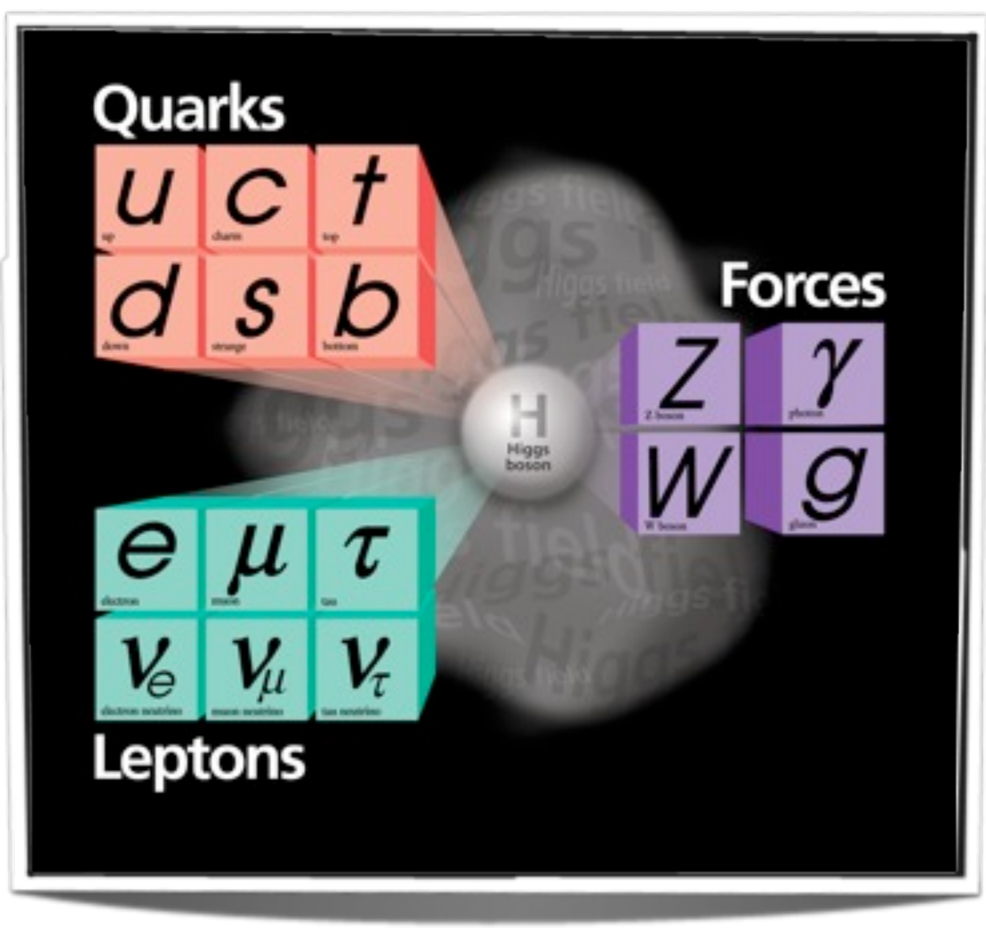


Mystery of Mass





Standard Model is incomplete!



Top

Riddles

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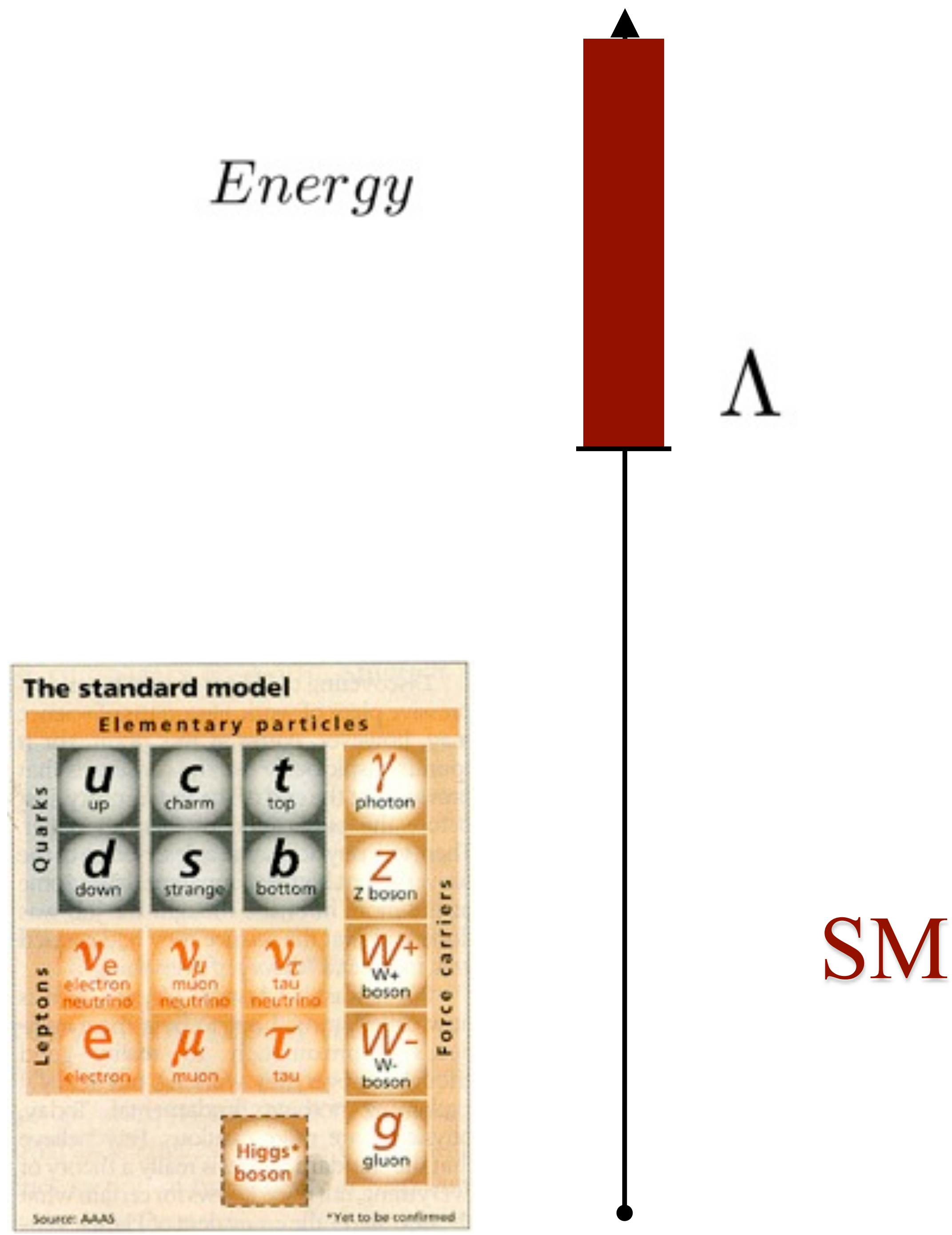
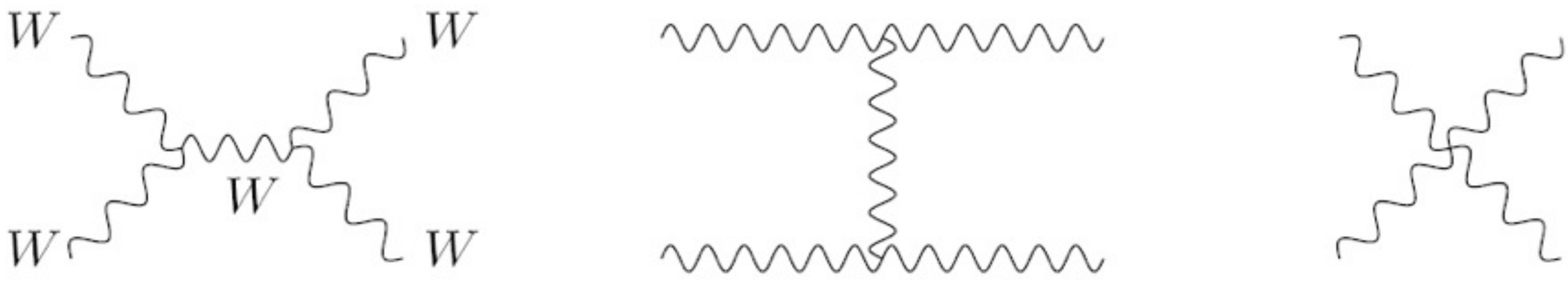
Standard Model



TeV Scale

CP^3 - Origins
Particle Physics & Origin of Mass

WW Scattering



S-wave amplitude:

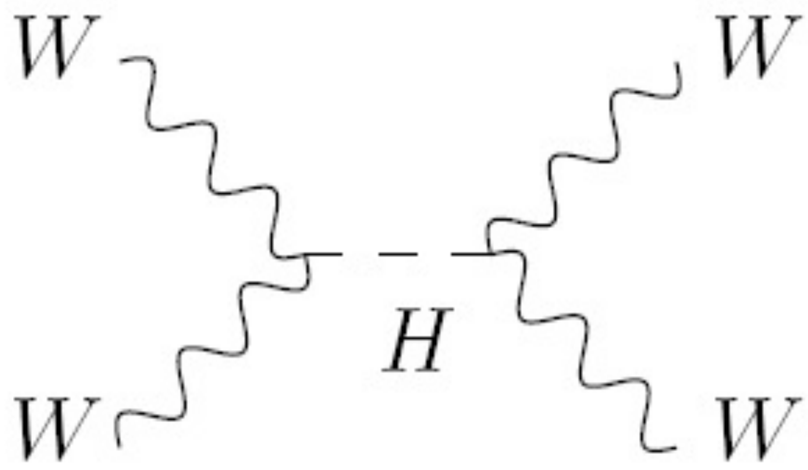
$$A_0 = \frac{G_F}{8\pi\sqrt{2}}\, s \qquad G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

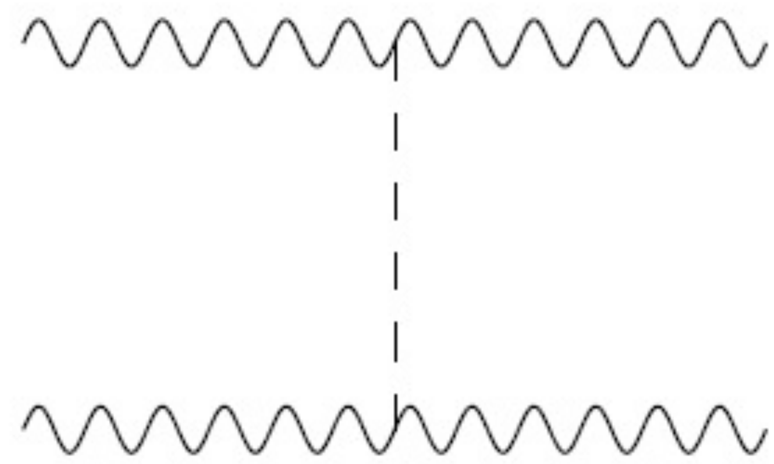
$$\simeq 1.14 \times 10^{-5}\mathrm{GeV}^{-2}$$

Unitarity:

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

WW Scattering





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

Theorem:

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

Origin of mass

The Higgs

$$H = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \pi_2 + i\,\pi_1 \\ \sigma - i\,\pi_3 \end{array} \right)$$

Custodial symmetries

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

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

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

Custodial symmetries

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

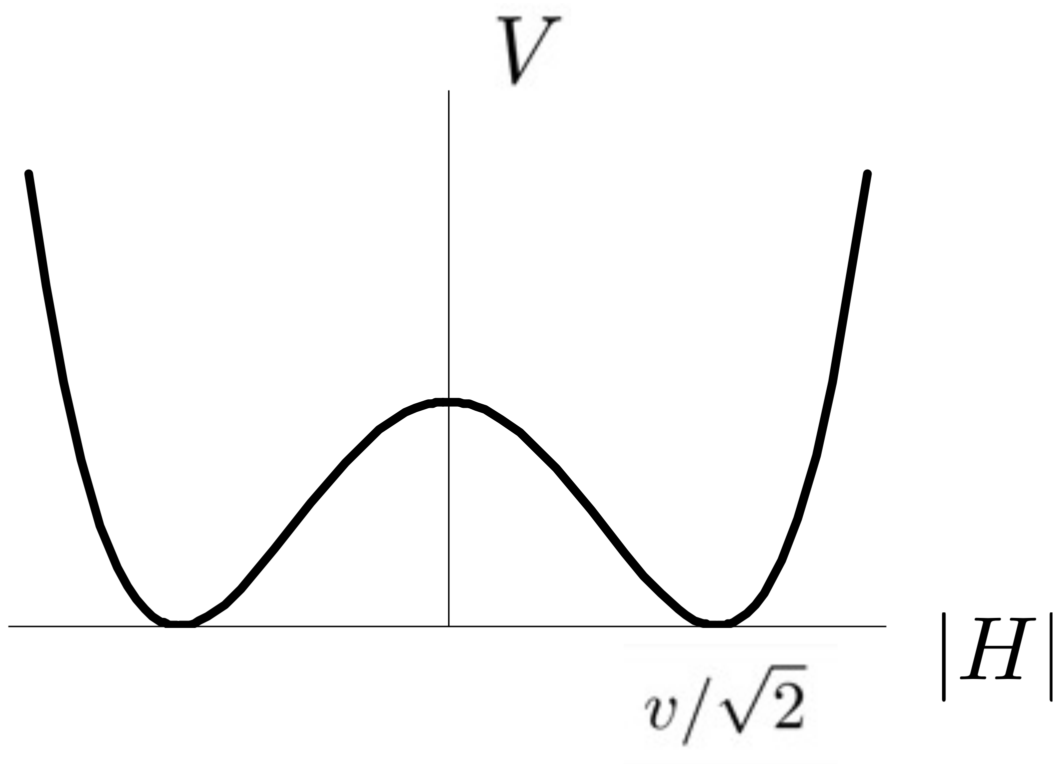
$$SU_L(2) \times U_Y(1) \qquad\qquad SU_L(2) \times SU_R(2)$$

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

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

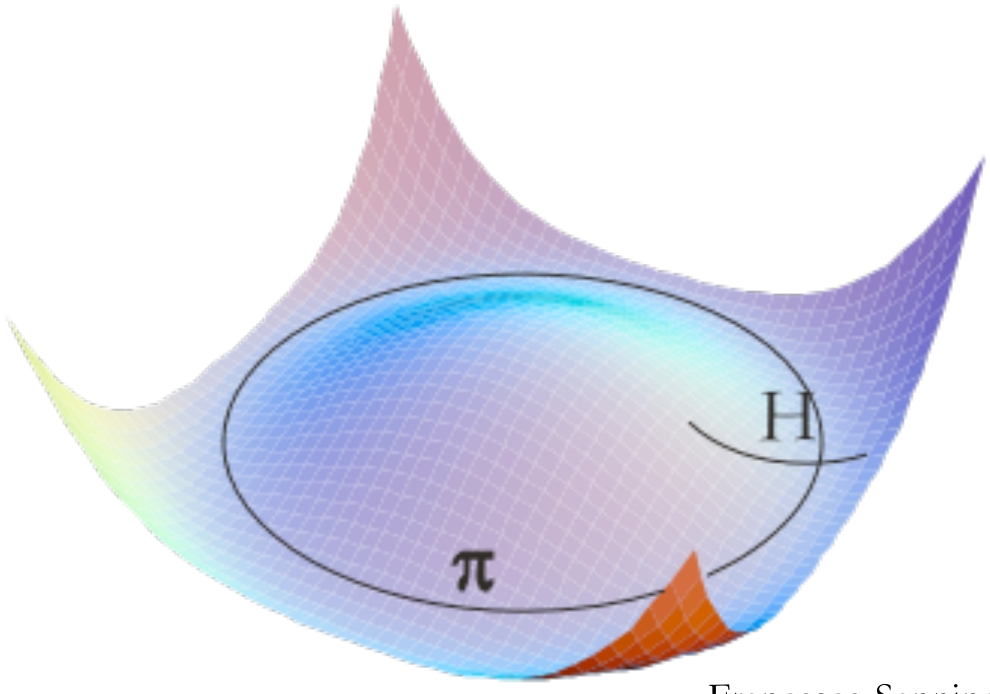
Custodial symmetries

$$m^2 < 0$$



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

$$\sigma = v + h$$



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Custodial symmetries

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

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

Higgs mechanism in Nature

Superconductivity

Macroscopic-Screening
Non-Relativistic

SM-Screening
Relativistic

$$T < T_c$$

$n_s =$ Density SC electrons

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

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

Superconductivity

Meissner-Mass
Static Vector Potential

Weak-GB-Mass

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

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

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

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

$$M_W \sim 80\ GeV$$

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

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

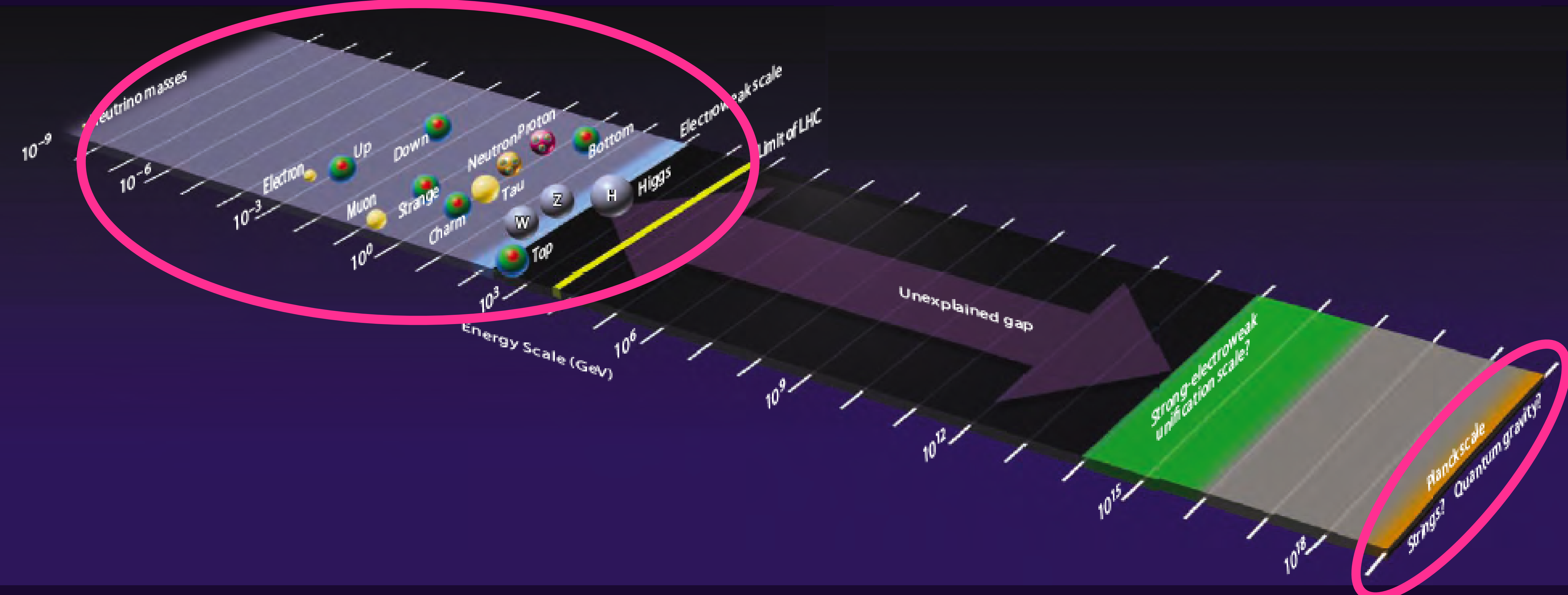
Hidden structure

????

Fermi Scale

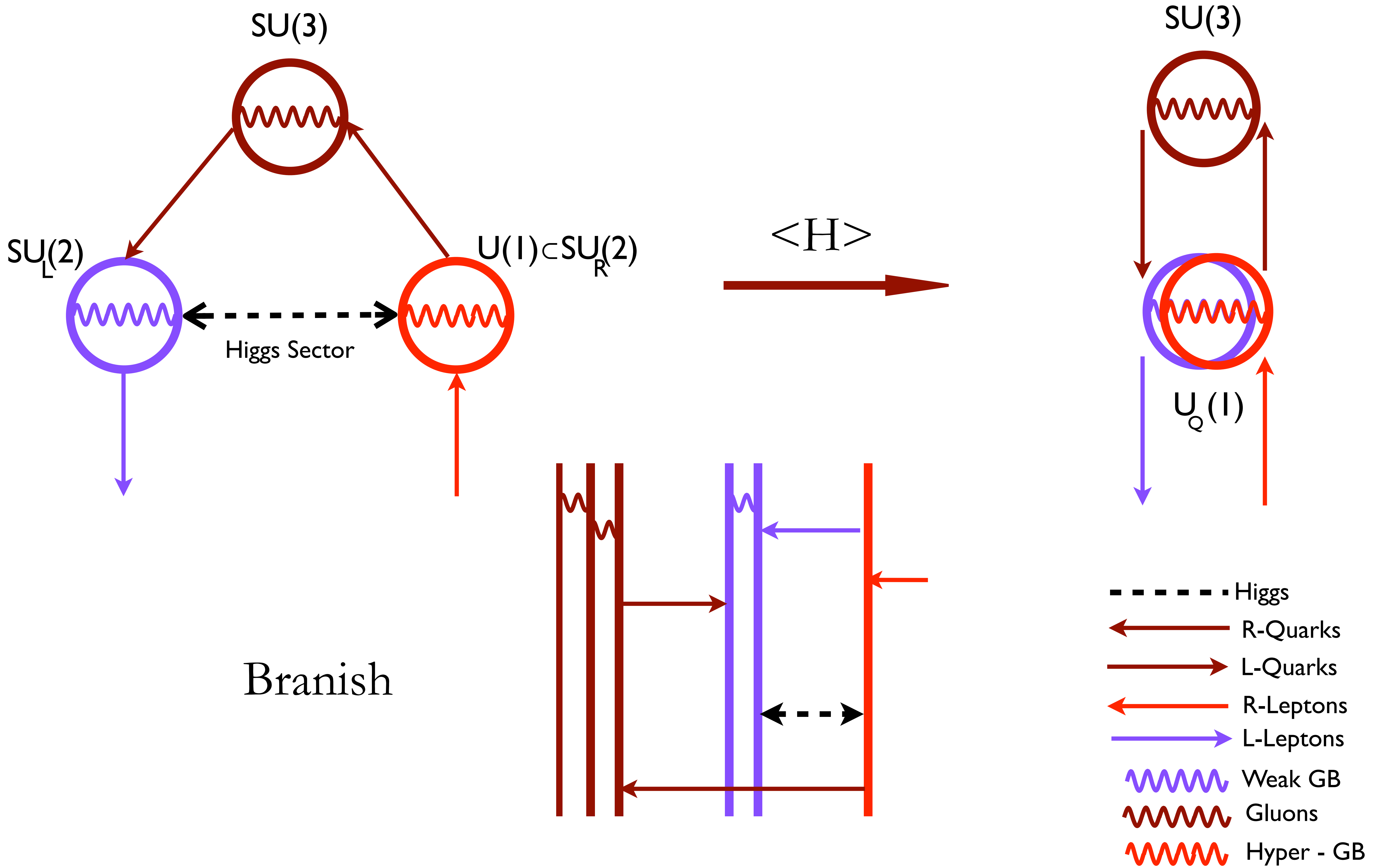
$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246\ \text{GeV}$$

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



eutrino 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
Energy Scale (GeV)
Unexplained gap
Strong-electroweak unification scale?
Planck scale
Strings?
Quantum gravity?

SM - Geometry



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

Many Models

(?)MSSM

XLMS D

Technicolor

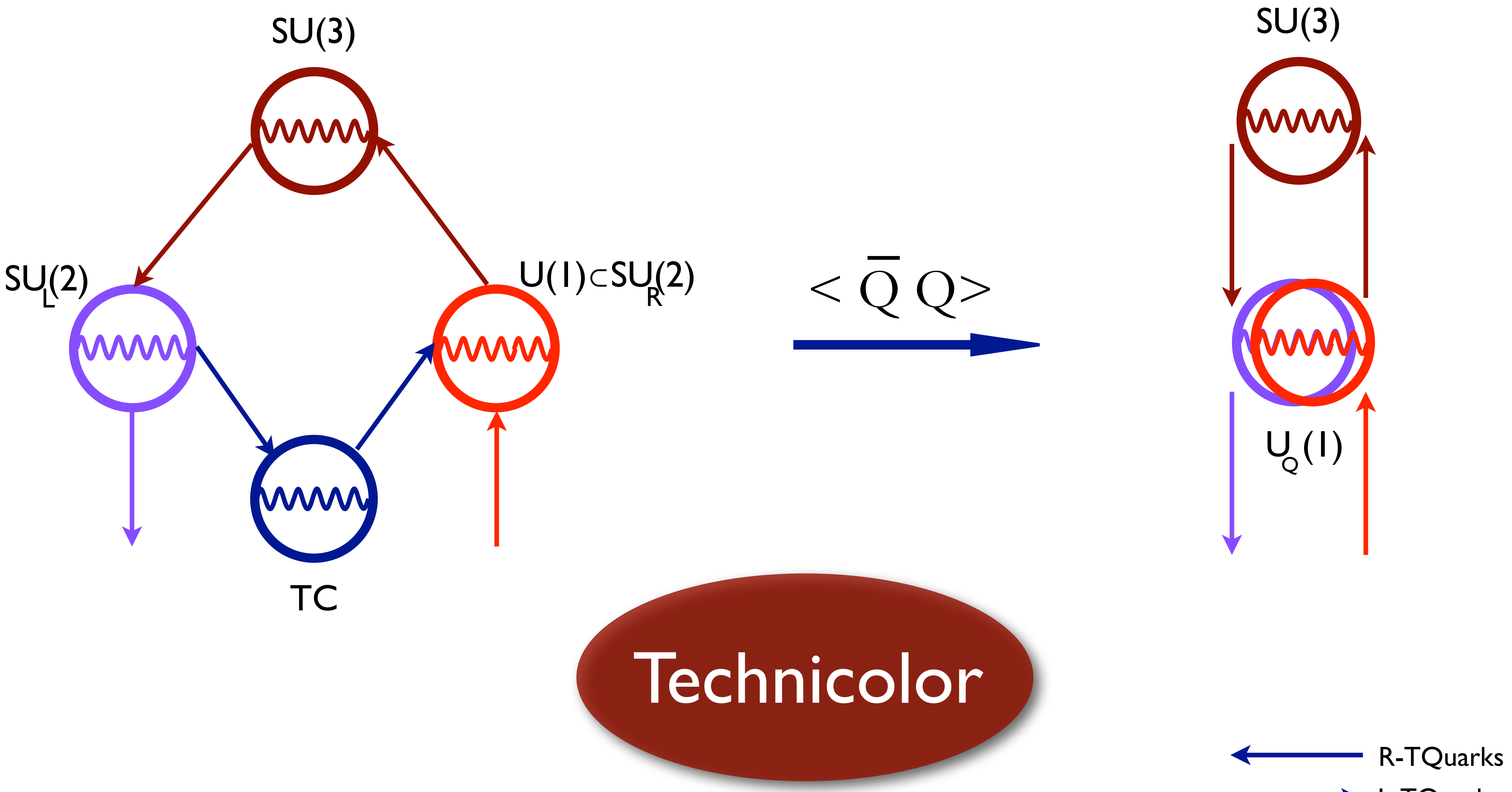
......

Branes

Unparticle

AdS/?

Technicolor - Geometry



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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

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

QCD-like TC

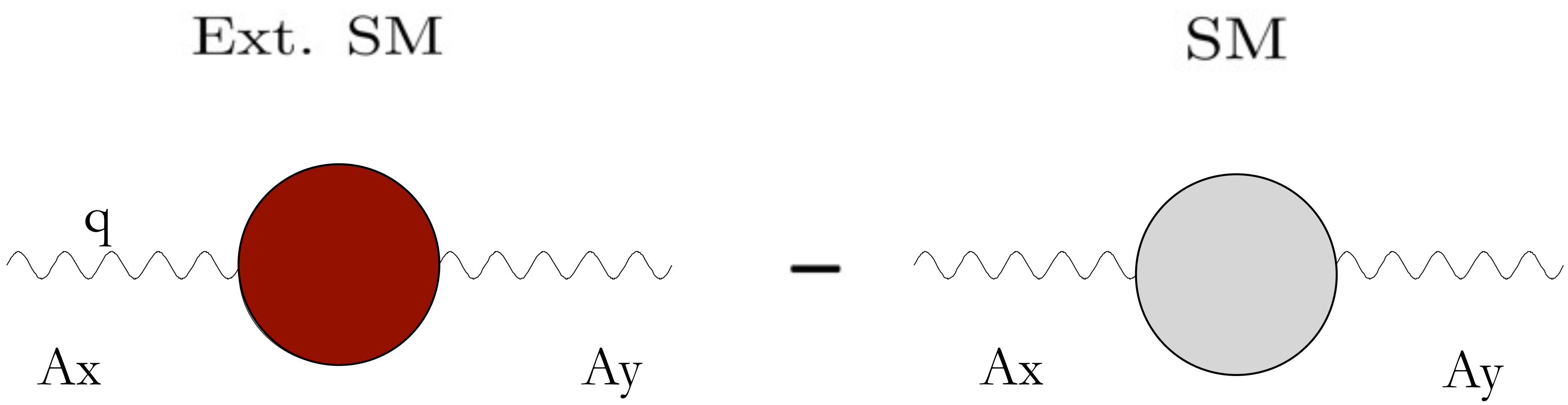
New Strong Interactions at ~ 250 GeV
[Weinberg, Susskind]

Natural to use QCD-like dynamics.

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

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

S & T



$$\Pi^{\mu\nu}_{XY}(q^2) = \Pi_{XY}(q^2) g^{\mu\nu} + \cdots$$

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

S & T

S-measures the left - right type current correlator

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

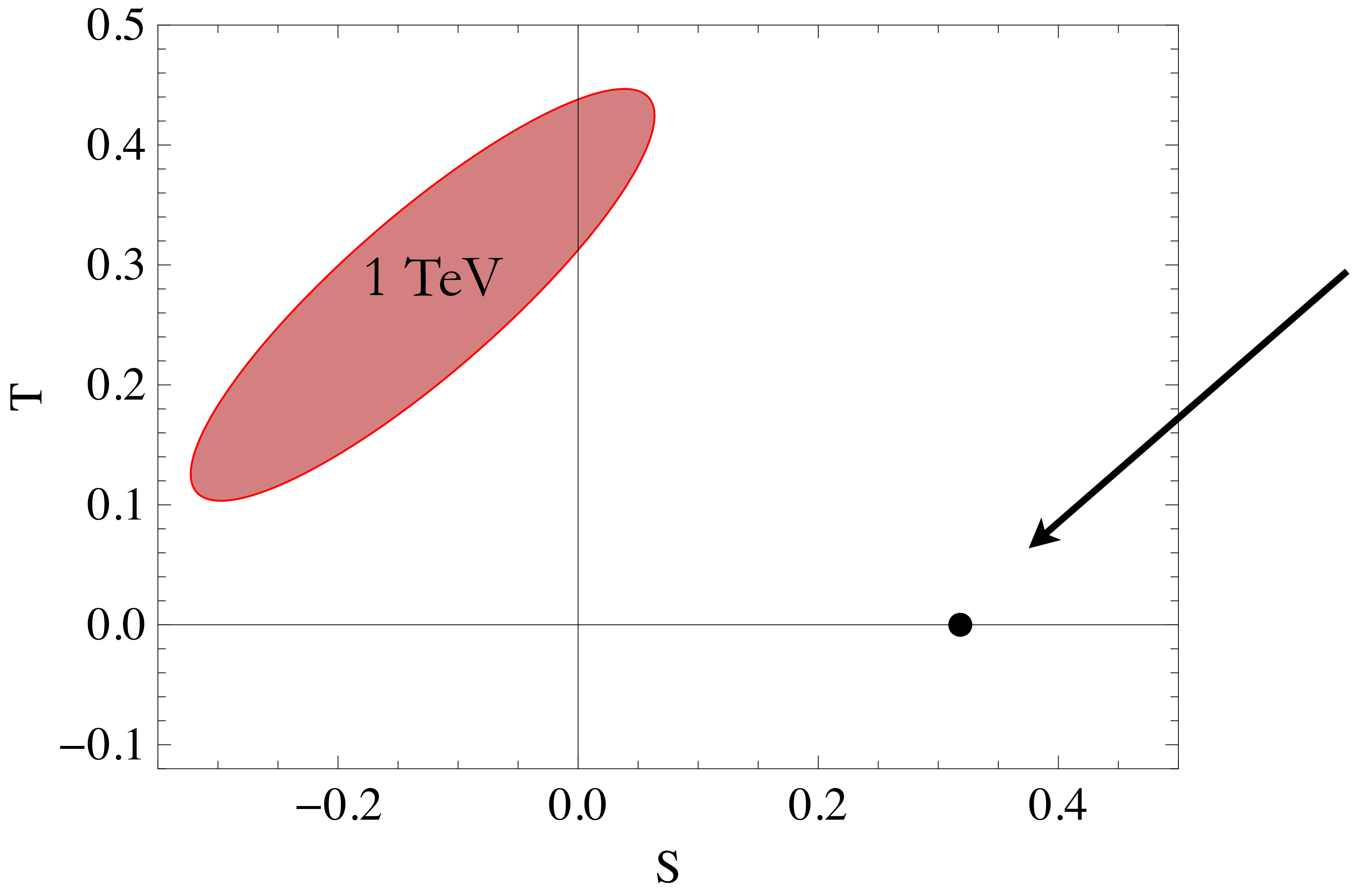
T-measures deviations from

$$m_{\mathrm{W}}^2 = \cos^2\theta_{\mathrm{W}}\, m_{\mathrm{Z}}^2$$

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

Need novel dynamics

Large & Positive S from QCD-like Technicolor



SU(3) + 1 Fund. Doublet

Weinberg, Susskind

SM Fermion Masses

Extending Technicolor

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

Different Approaches

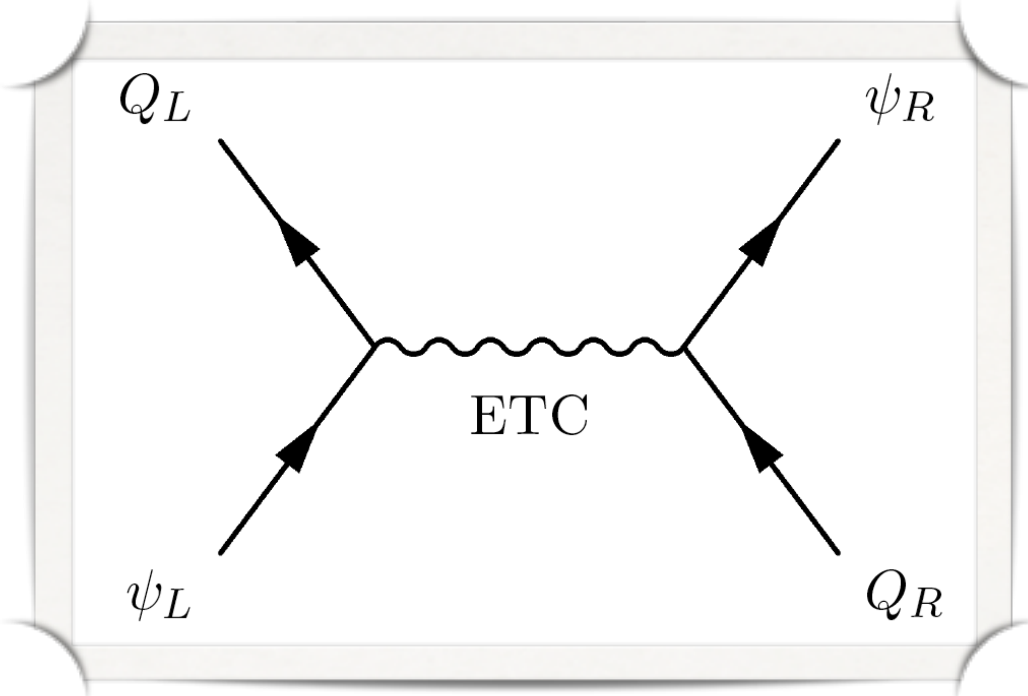
Scalar-less New Gauge Interactions (Extended TC)

Marry SUSY and Technicolor

Add New Scalars in the Flavor Sector

.....

Extended Technicolor



Eichten & Lane 80

Recent investigations

Ryttov & Shrock 10

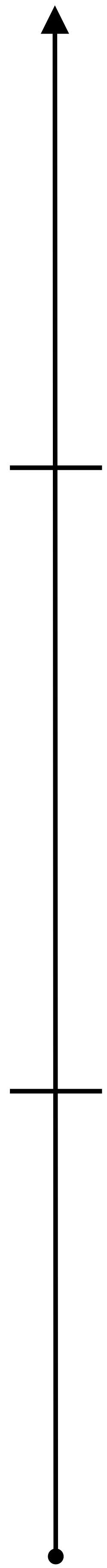
Modifies TC dynamics

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

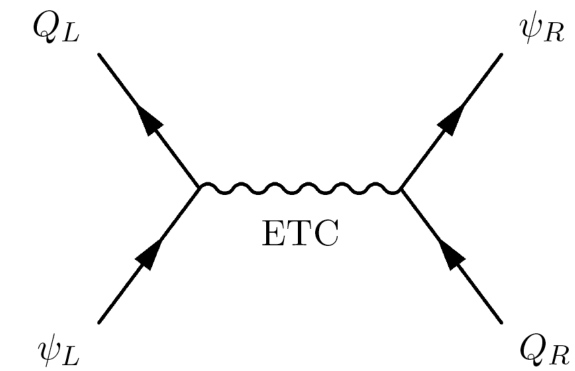
PNG Masses

SM-Fermion Masses

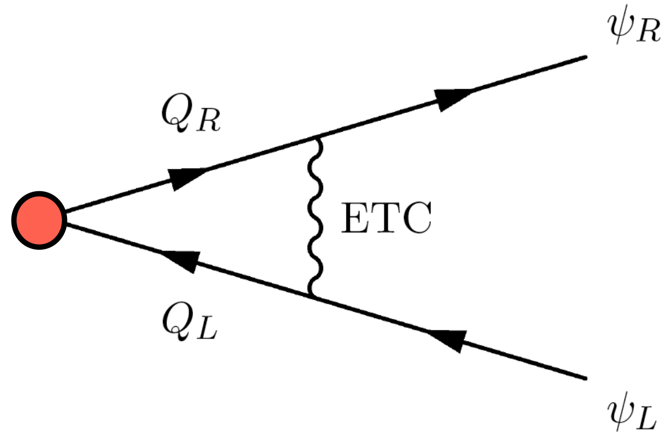
FCNC Operators



Energy



Λ_{ETC}



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

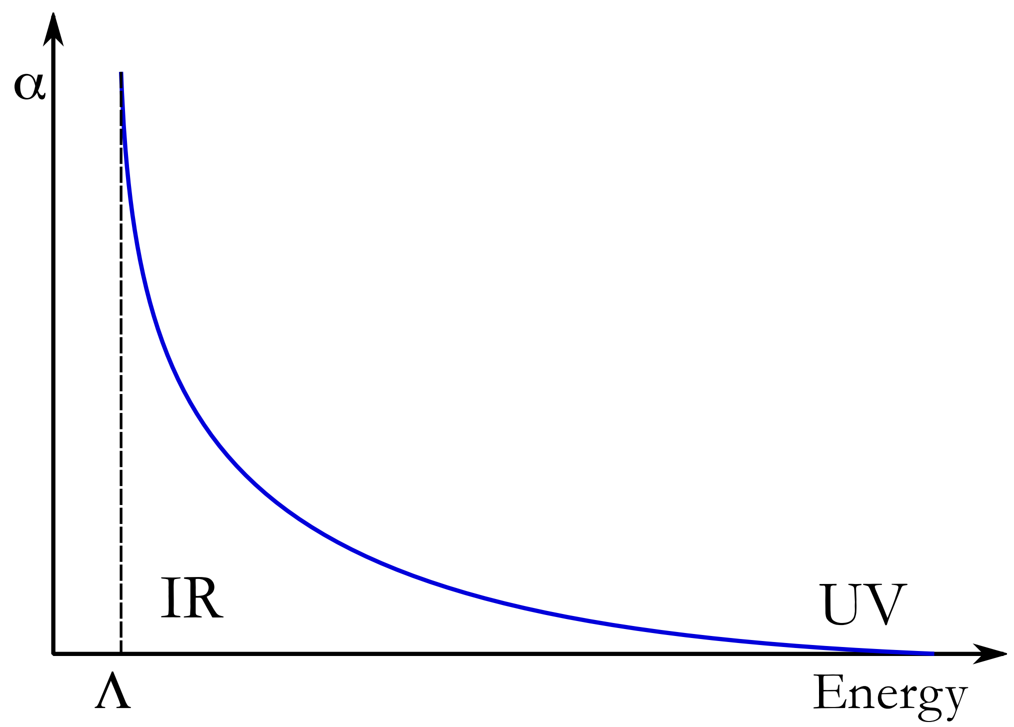
Λ_{TC} Electroweak breaks

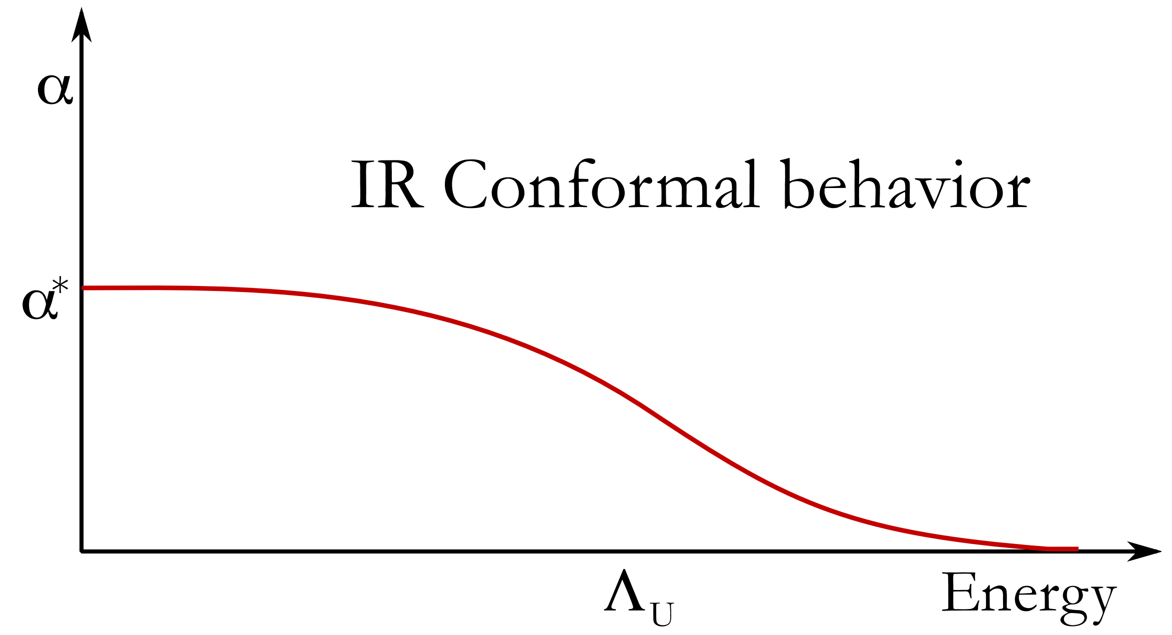
$$< \bar{Q}Q >_{ETC} \approx < \bar{Q}Q >_{TC} \sim \Lambda_{TC}^3$$

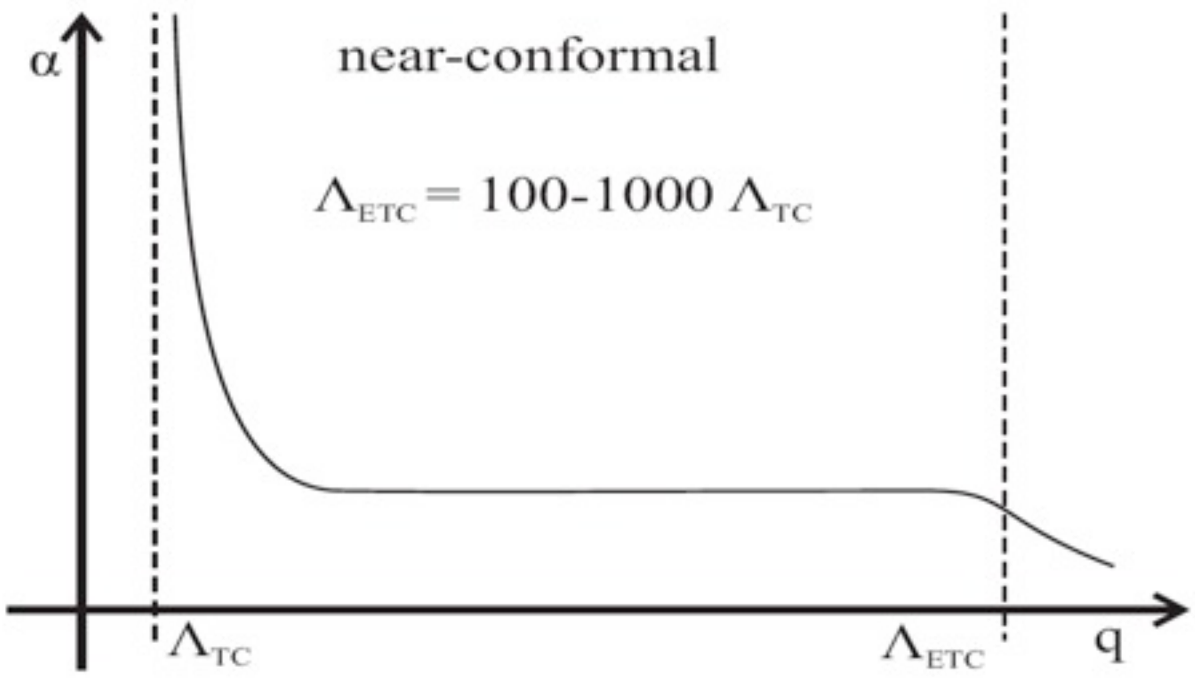
$$m_{\rm f} \approx \frac{g_{ETC}^2}{\Lambda_{ETC}^2} < \bar{Q}Q >_{ETC} \quad \ll \quad m_{\rm Top}$$

Need to go 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>

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

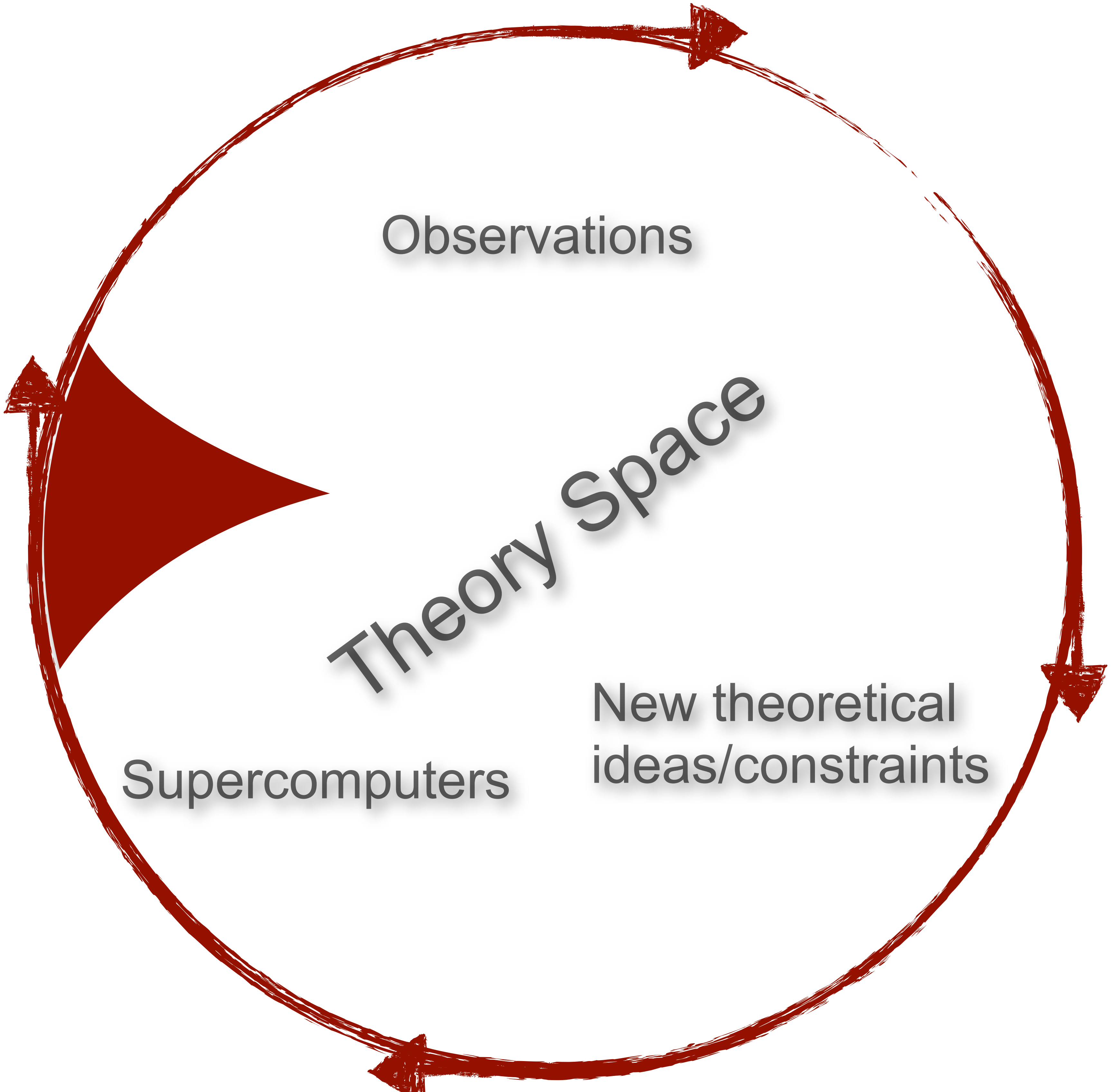
$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC} = \frac{g^2_{ETC}}{\Lambda^2_{ETC}} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma_m(\alpha^*)} < \bar{Q}Q >_{TC}$$

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

$$\downarrow$$

Fermion Mass Enhancement & FCNC decoupling

Selecting Nature's Next Force



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Theory space

Gauge Theories

Gauge Group

Matter

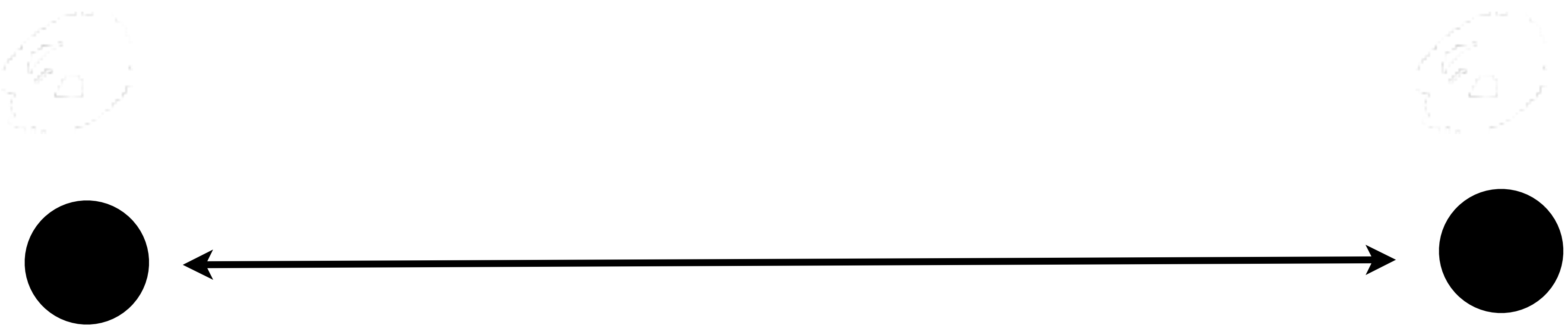
SUSY	Non SUSY
N=1	Fermions
N=2	Fermions + Bosons
N=4	Bosons

Vector Chiral

Xtreme-conditions

Phases

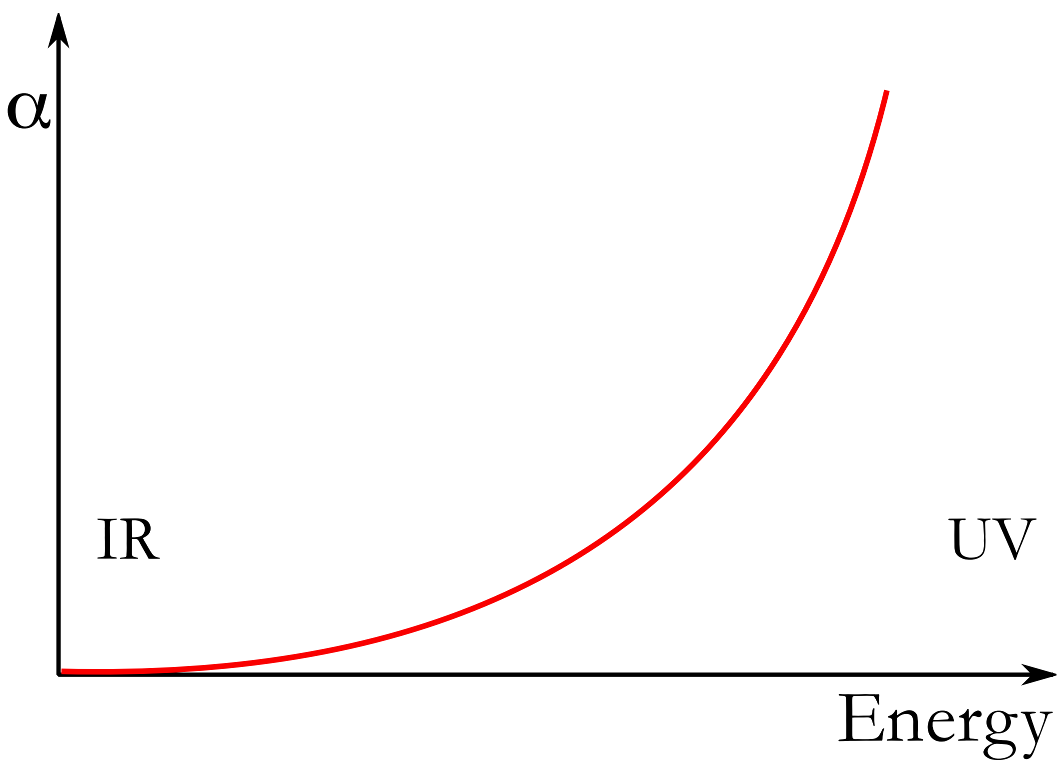
$$V(r)$$

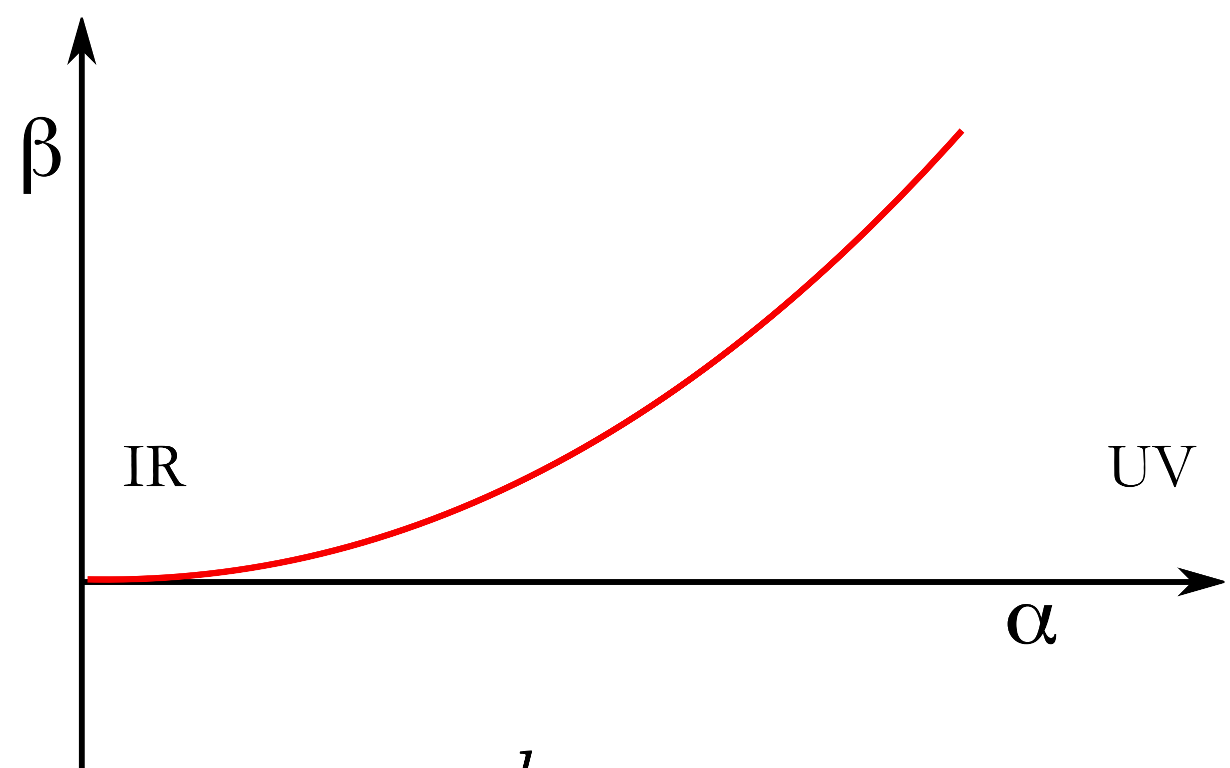


Free Electric

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

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





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

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

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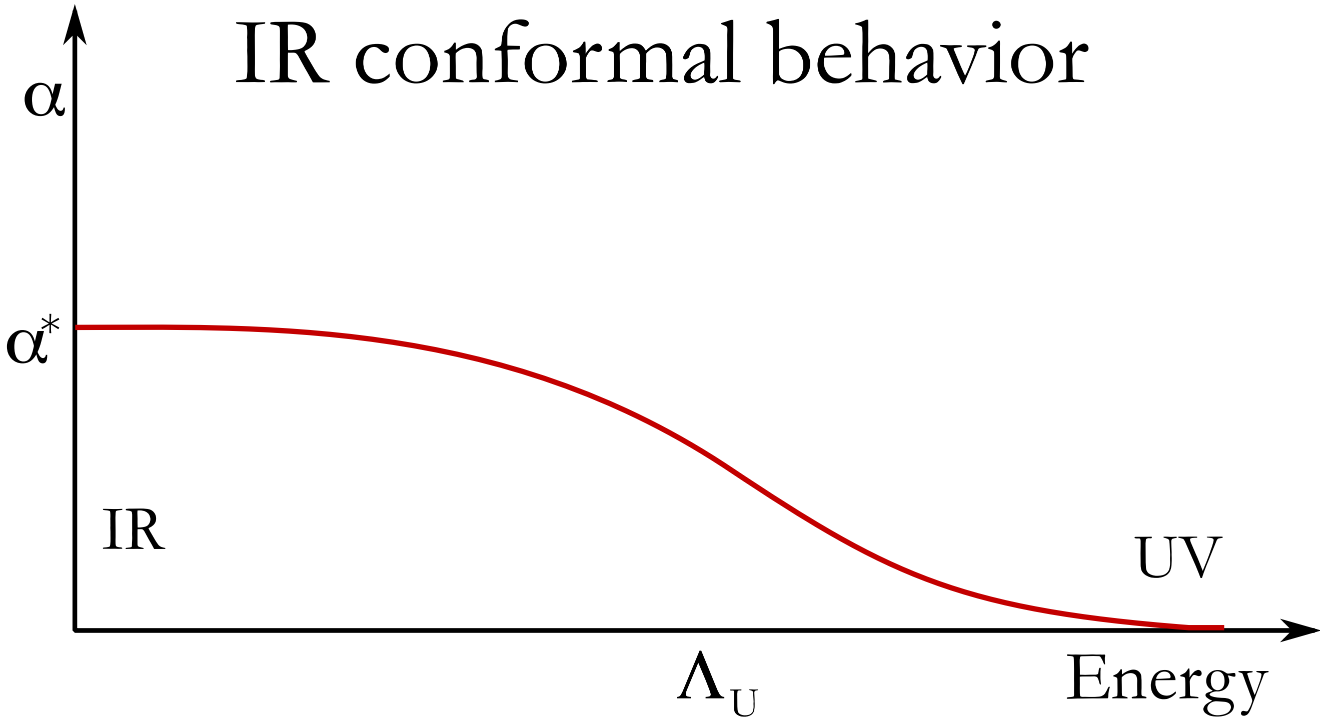
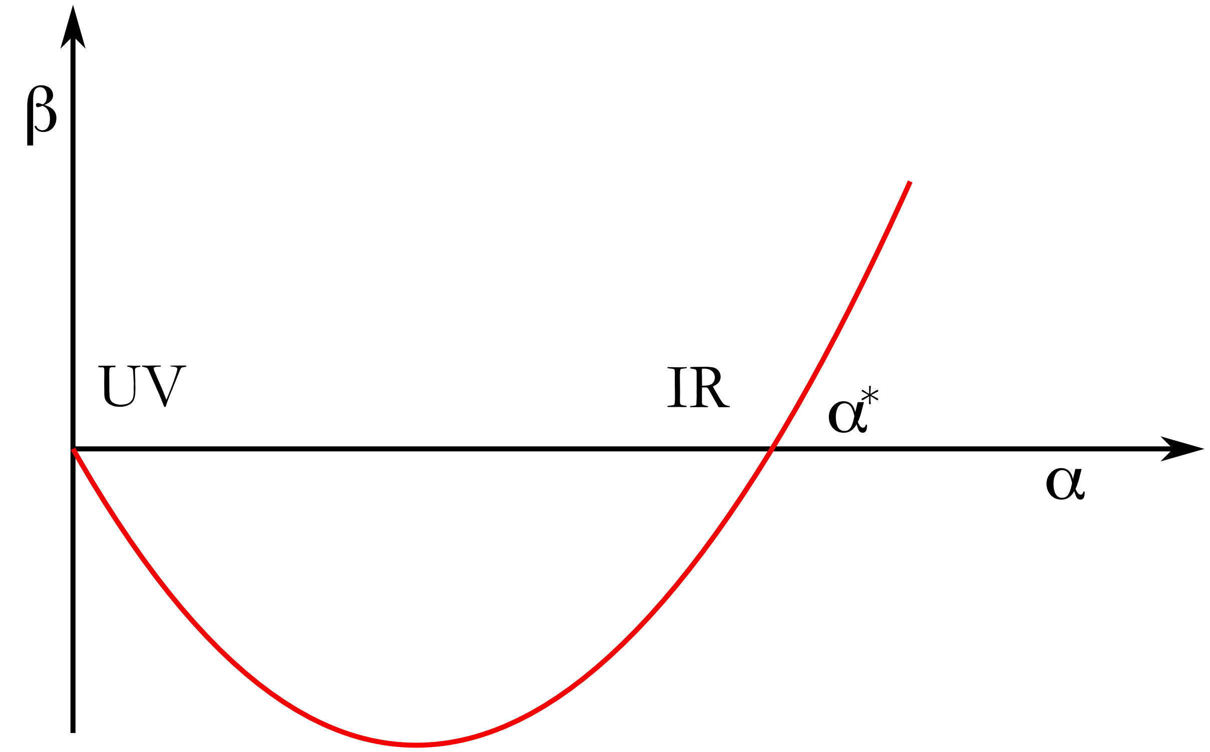
Coulomb

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

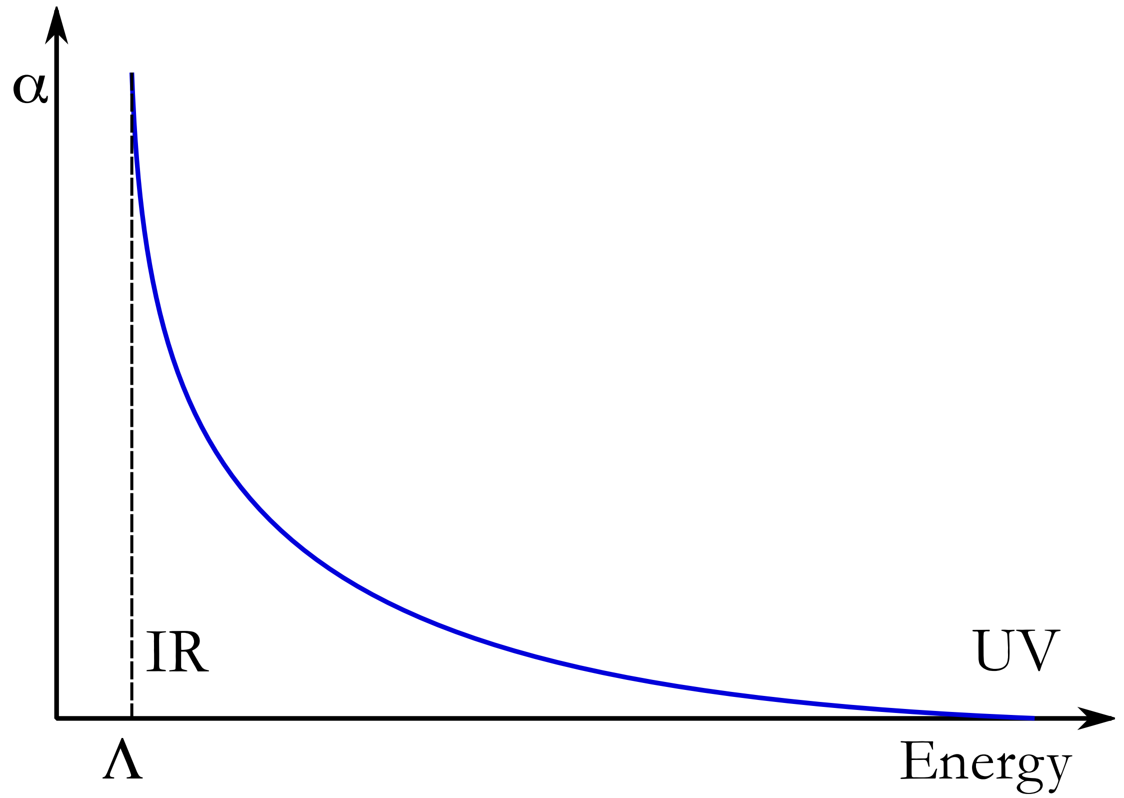
IR conformal behavior

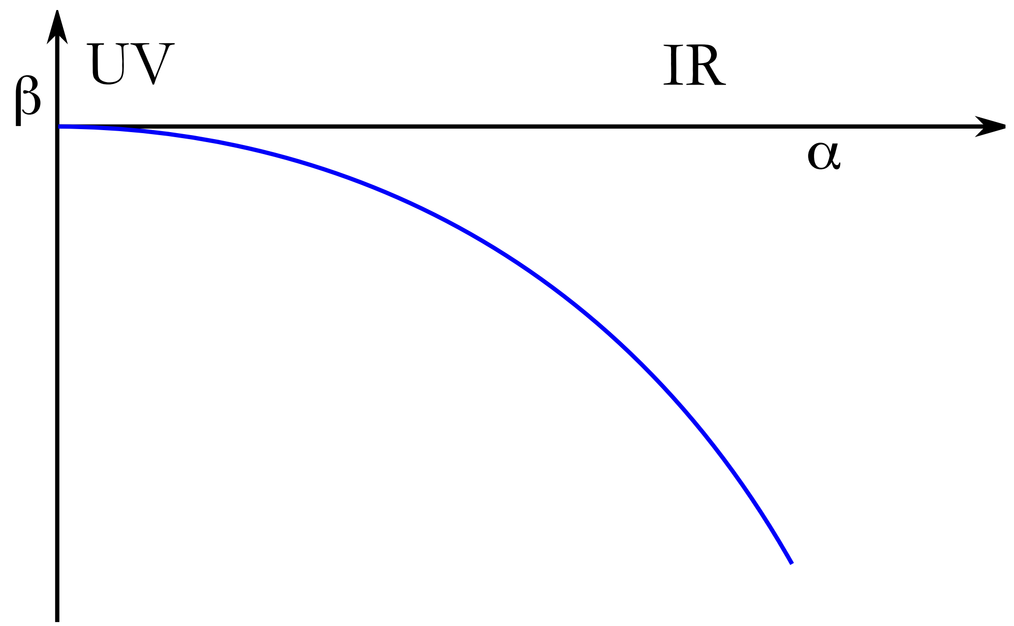




IR Conformal Phase

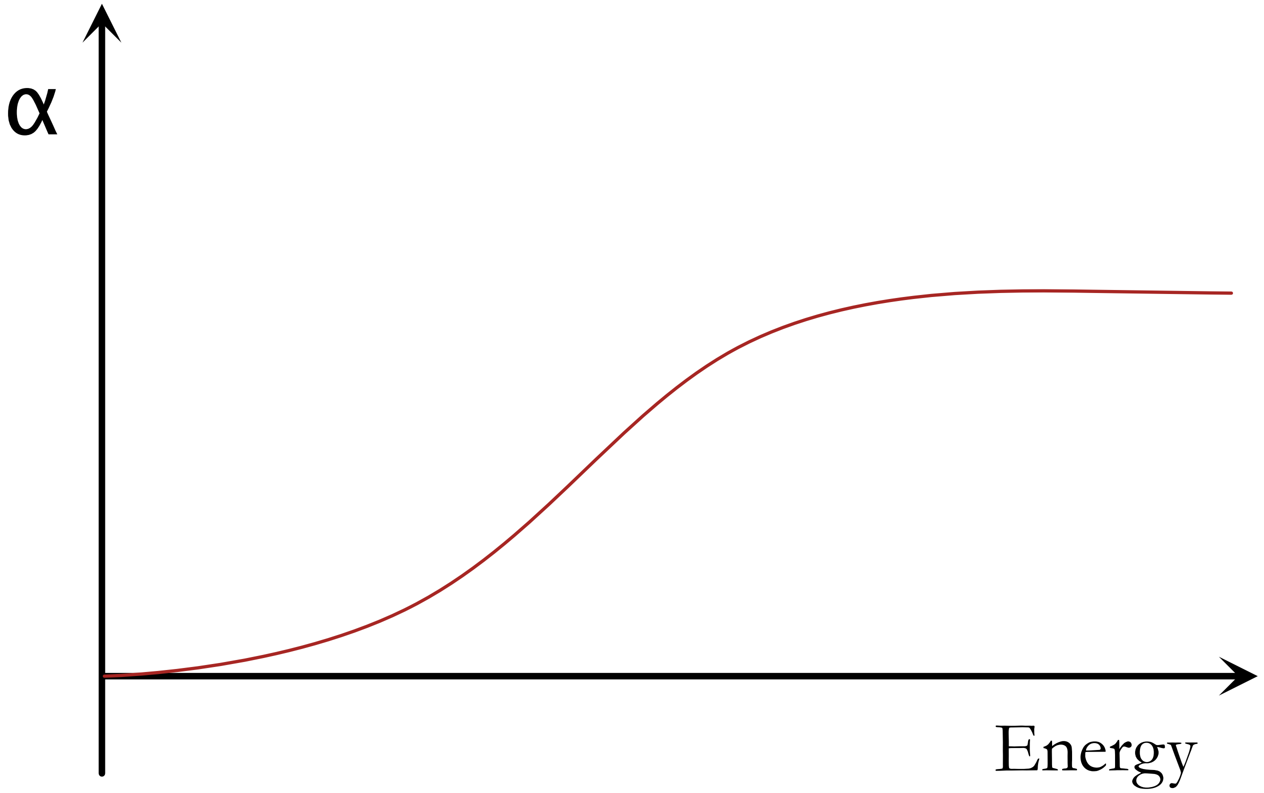
QCD - Like

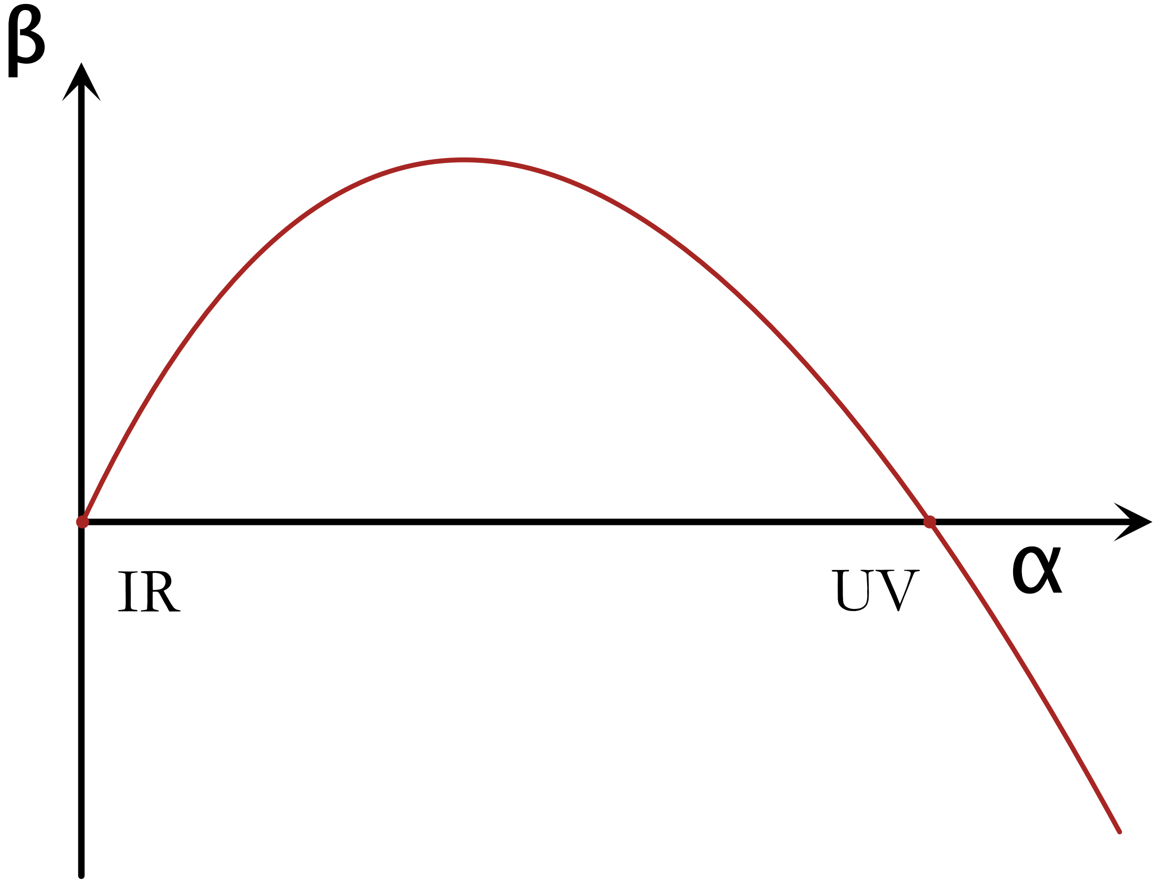




$$V \propto \sigma\, r$$

Asymptotic safety



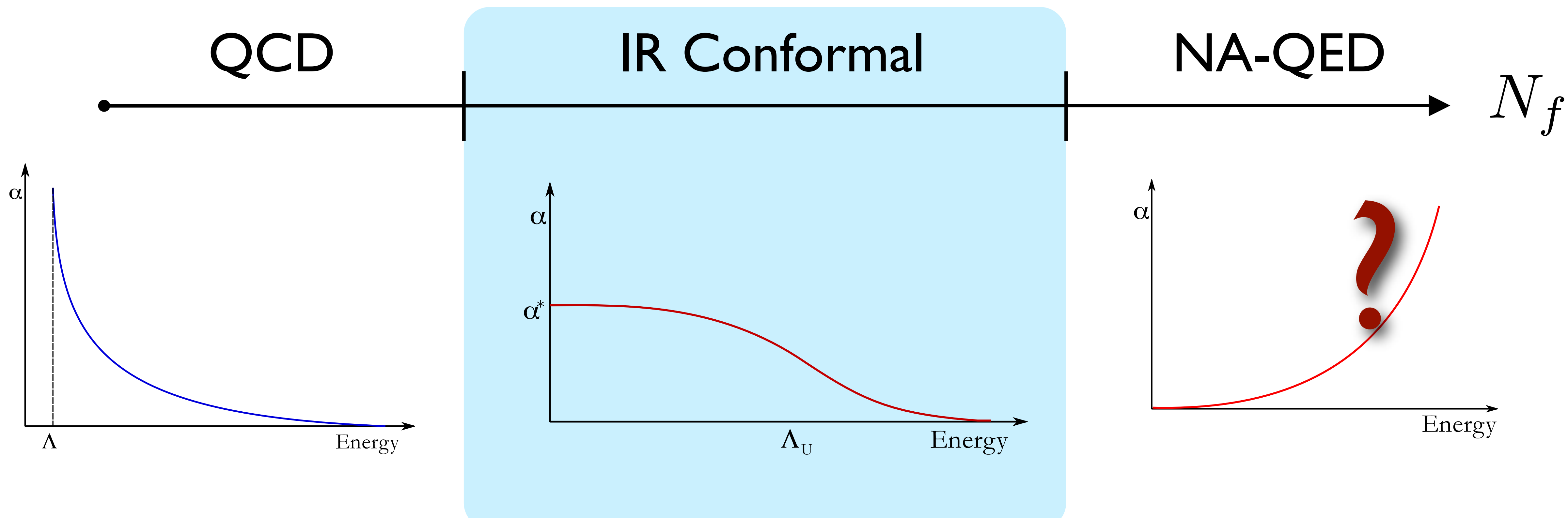


Knobs

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

Matter Representation

# of Flavors per Representation

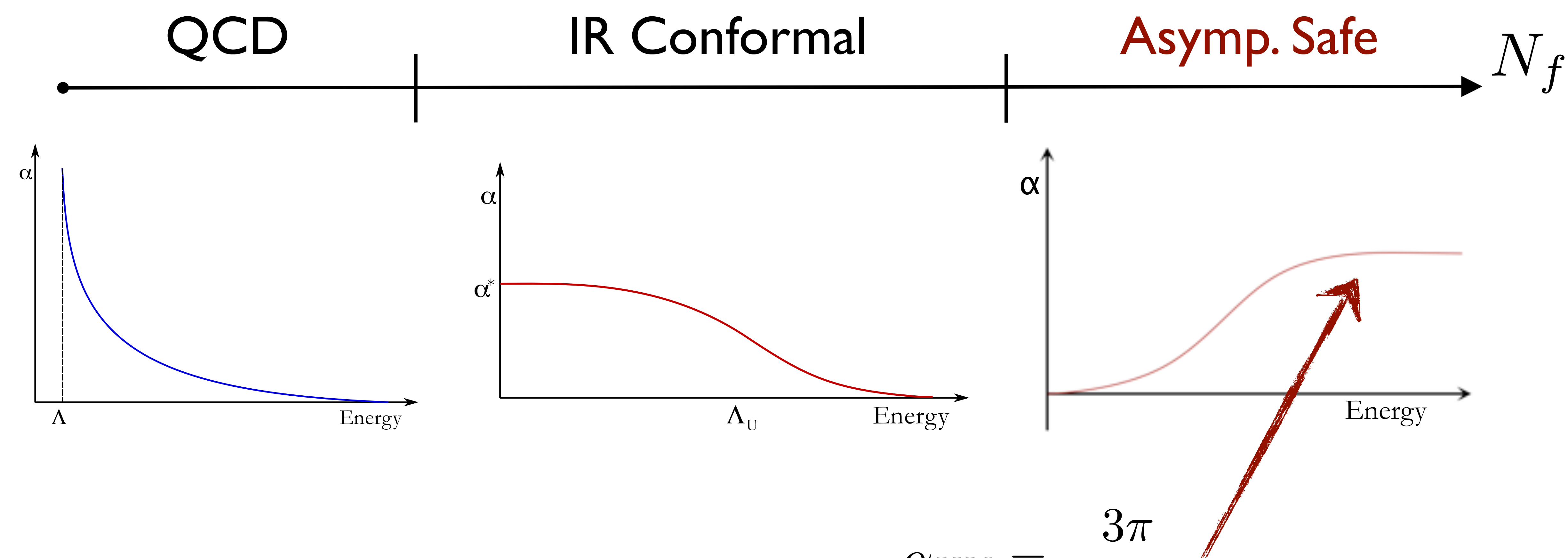


A novel phase @ large Nf

Interesting structure at large Nf

Pica & Sannino 10

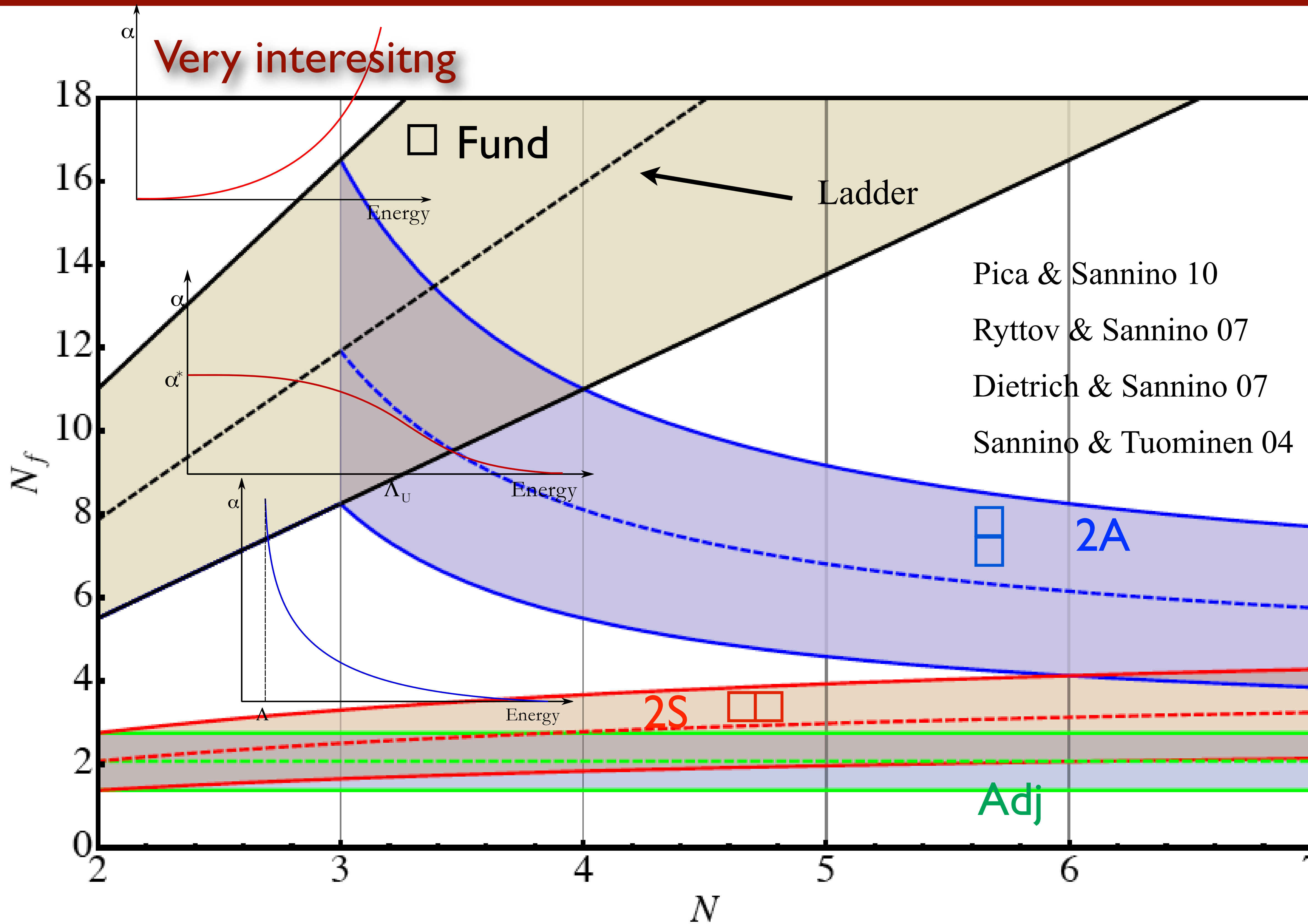
Entire series at large Nf is known



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

Universal Picture

SU(N) Phase Diagram



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What is the use?

(?)MSSM

- Dynamical SUSY breaking

Composite DM

- Dark matter candidates

Unparticle

- Natural models of unparticle

Technicolor

- Viable models of TC

Strong Int.

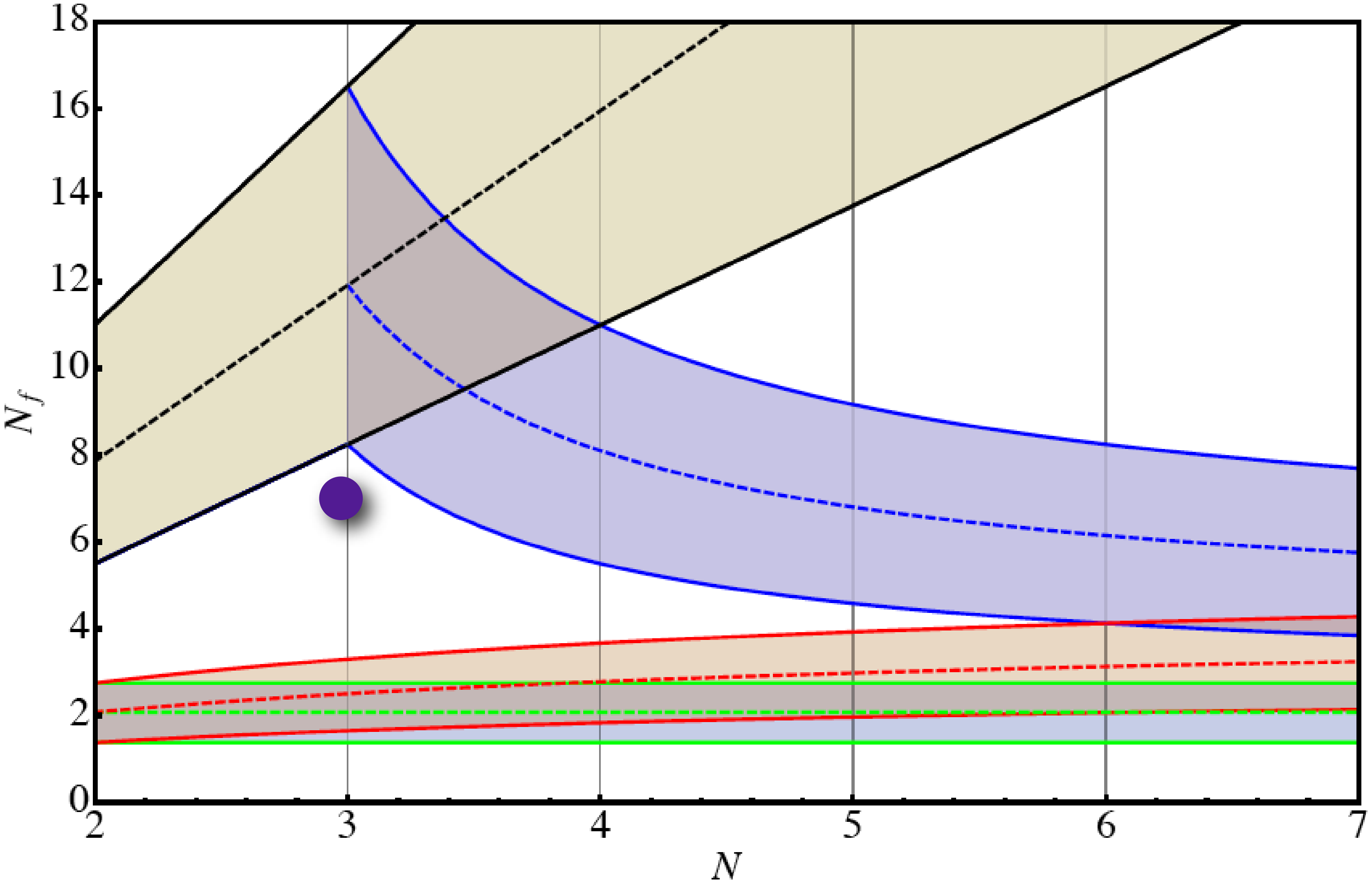
- Better understanding

Lattice BSM

- Testable

Ideal Walking

Ideal?



Walking is highly fine tuned

Anomalous dimensions are small

Ideal walking

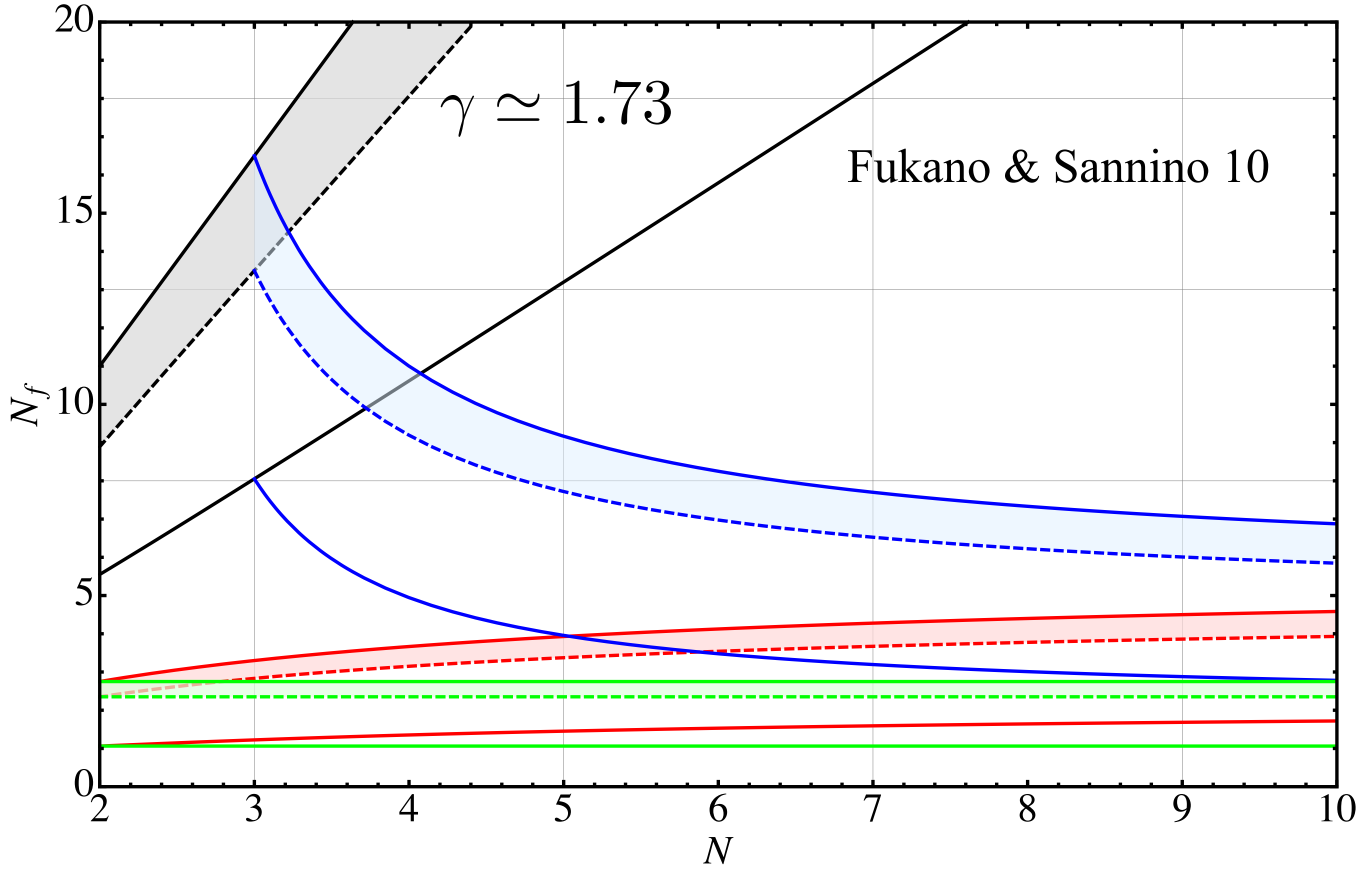
Fukano & Sannino 10

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

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

Gauged Nambu Jona-Lasinio

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



- Phenomenologically viable
- Being tested!

CP³ - Origins
Particle Physics & Origin of Mass

S in Gauge Theories

$$i\Pi^{a,b}_{\mu\nu}(q) \equiv \int d^4x\, e^{-iqx}\left[< J^a_{\mu,V}(x) J^b_{\nu,V}(0) > - < J^a_{\mu,A}(x) J^b_{\nu,A}(0) >\right]$$

$$\Pi^{a,b}_{\mu\nu}(q) = \left(q_\mu q_\nu - g_{\mu\nu} q^2\right)\ \delta^{ab}\Pi(q^2)$$

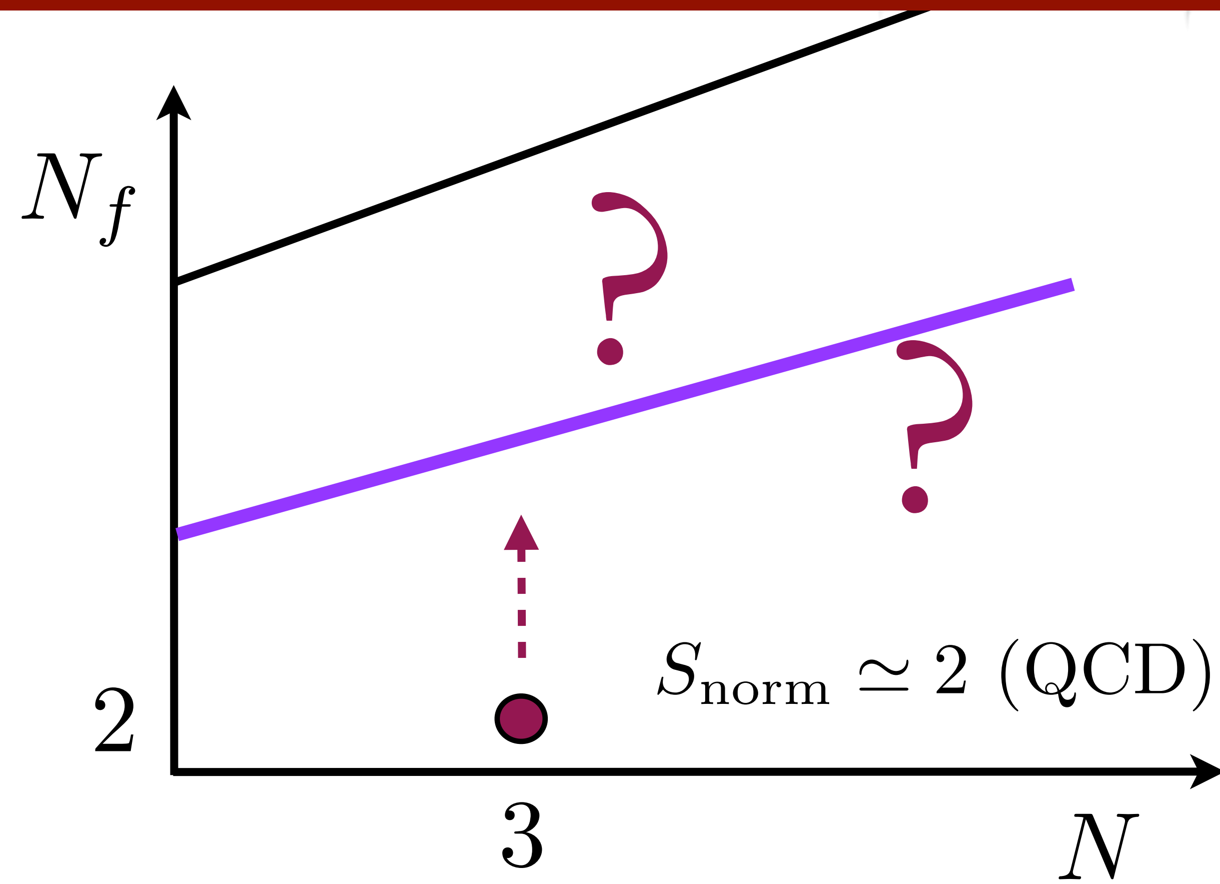
$$S[q^2] = -16\pi \frac{\Pi(q^2) - \Pi(0)}{q^2}$$

- This is not automatically the phenomenological S-parameter
- Unambiguous
- It is the definition to use in lattice simulations

Open Questions

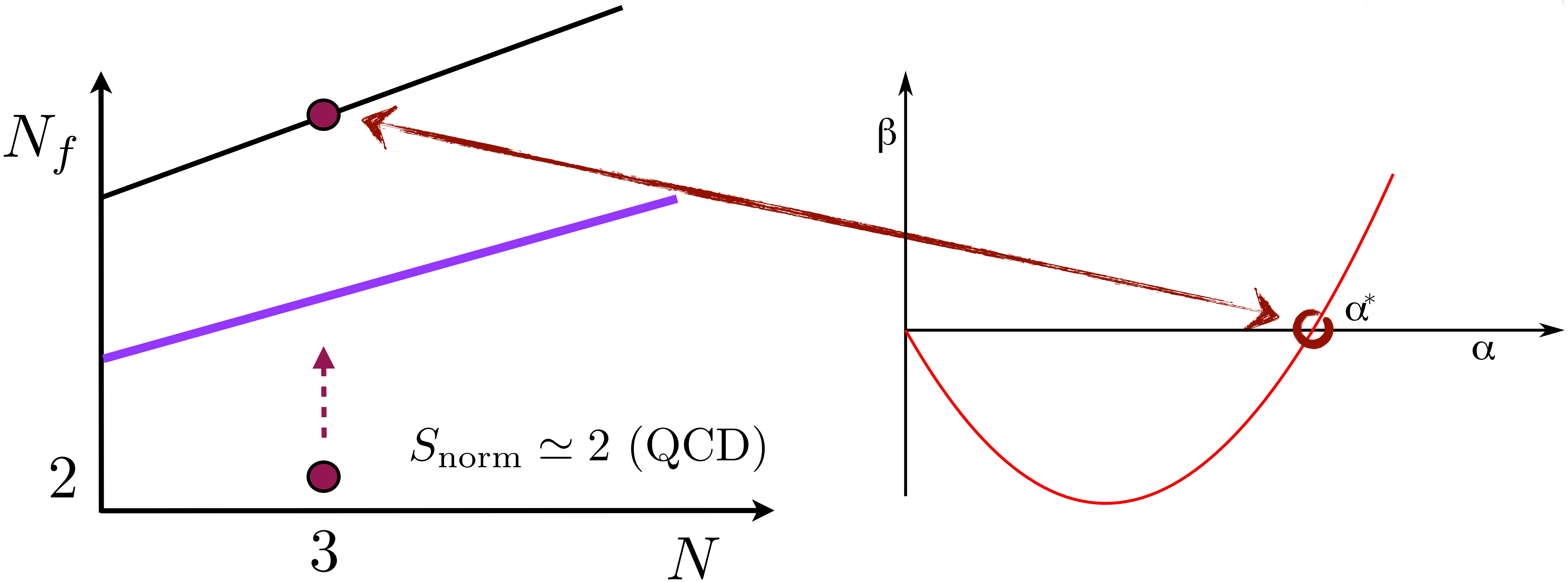
$$\lim_{\frac{q^2}{m^2}\to 0} \frac{6\pi\, S}{N_D d[r]} = S_{\text{norm}}$$

$$N_D = \frac{N_f}{2}$$

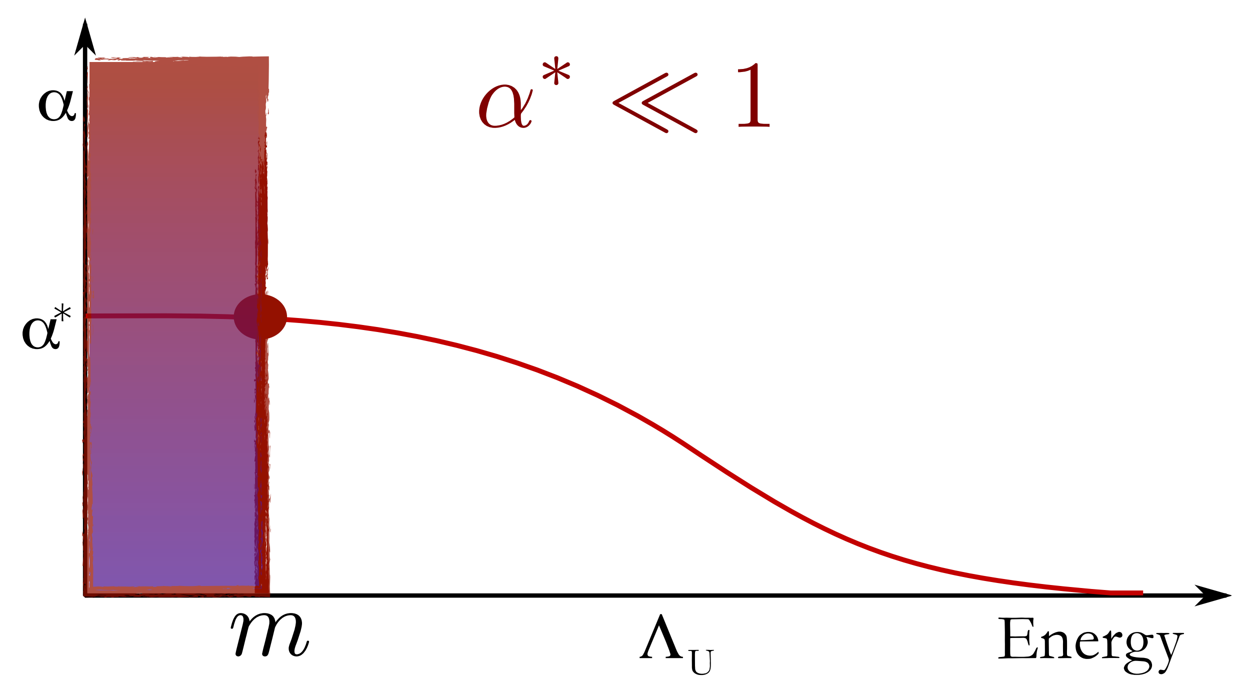


- Does S vanish as we approach the conformal window ?
- What happens at the lower boundary ?
- What is its value inside the conformal window ?

Perturbative Conformal S



- Calculable nontrivial conformal theory

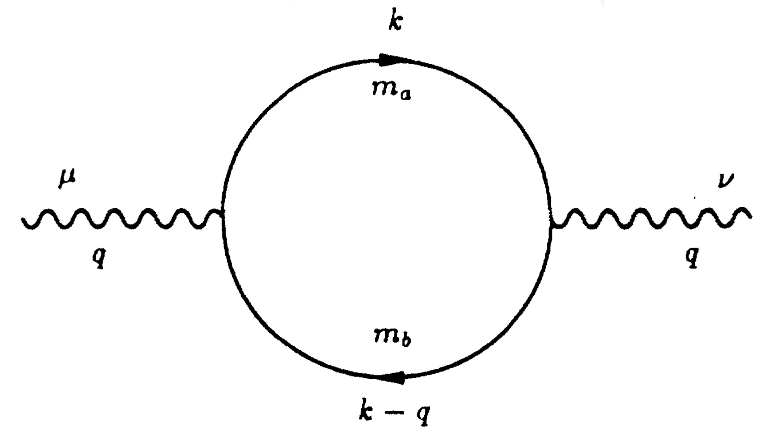


- Mass term to probe conformality.

Sannino 1006.0207

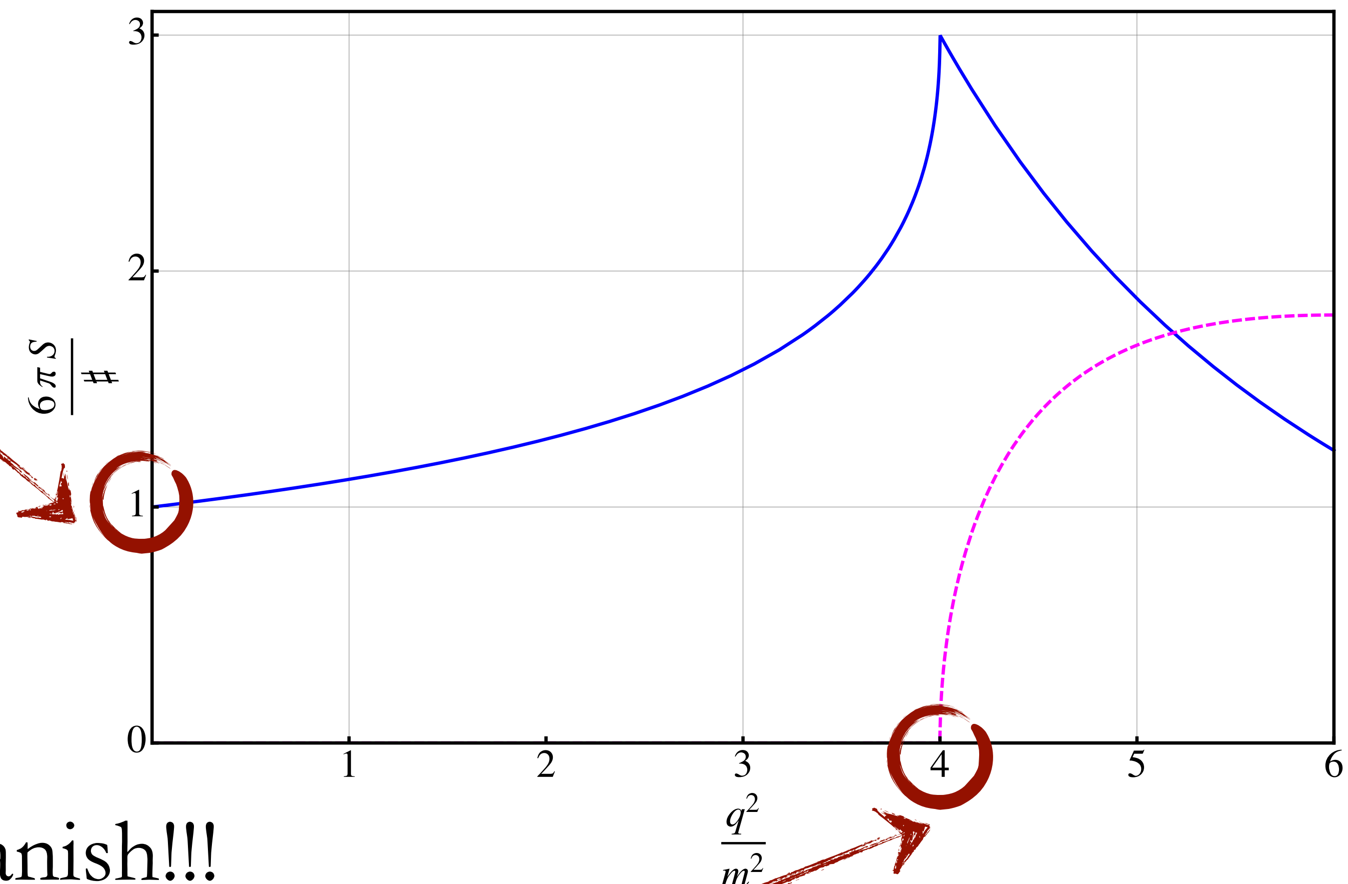
One - loop

$$\lim_{\frac{q^2}{m^2}\to 0} S = \frac{\sharp}{6\pi}\left[1 + \frac{1}{10x} + \frac{1}{70x^2} + \mathcal{O}(x^{-3})\right]$$



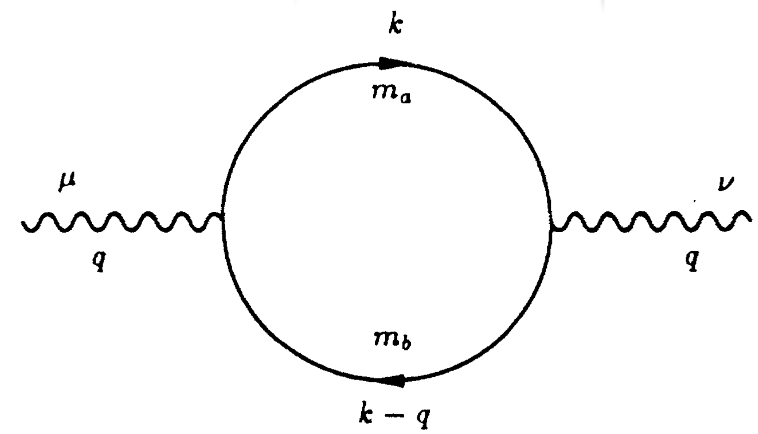
$$x = \frac{m^2}{q^2}$$

$$\sharp = N_D\, d[r]$$



- S at zero momentum does not vanish!!!
- A nonzero imaginary part develops

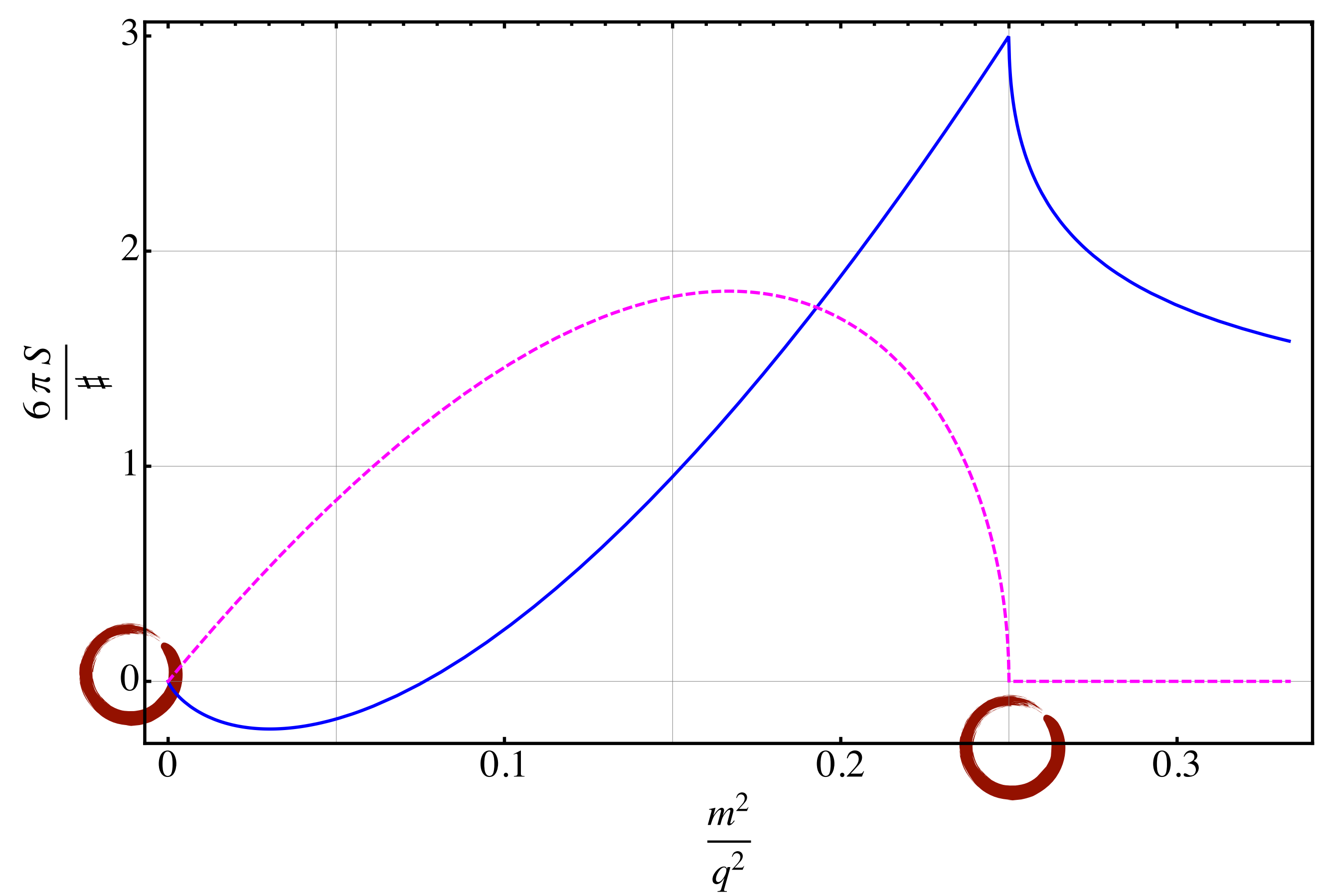
Conformal limit



$$\lim_{\frac{m^2}{q^2}\to 0} \Re[S] = x\,\frac{\sharp}{\pi}\,[2+\log(x)] + \mathcal{O}(x^2)$$

$$\lim_{\frac{m^2}{q^2}\to 0} \Im[S] = x\,\sharp + \mathcal{O}(x^2)$$

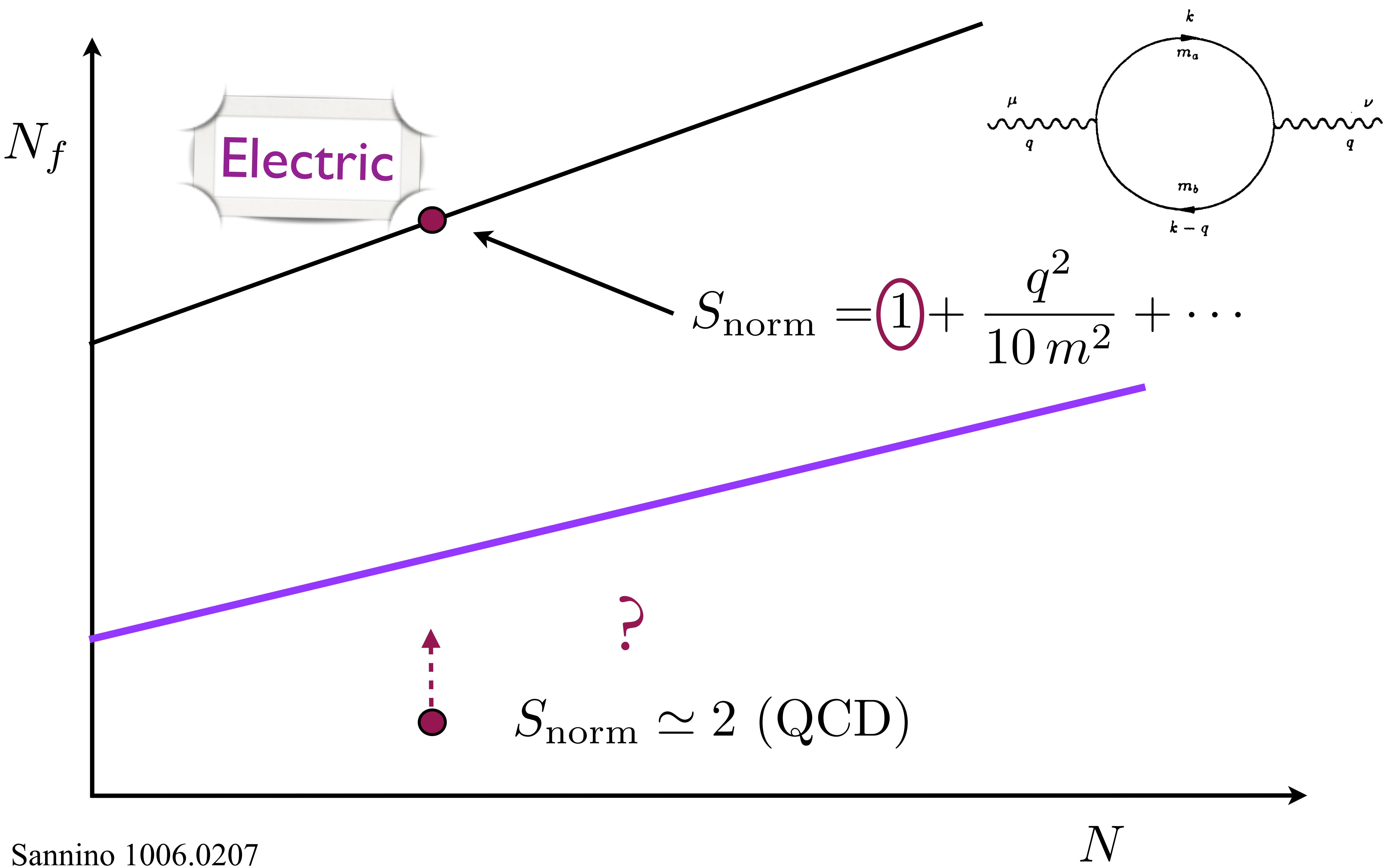
$$\sharp = N_D\, d[r] \qquad x = \frac{m^2}{q^2}$$



- Real and Imaginary part vanish

Sannino 1006.0207

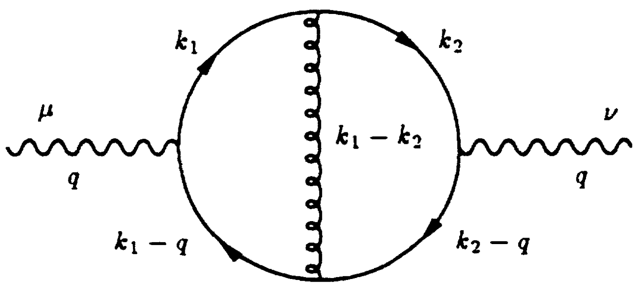
One - loop S-ummary

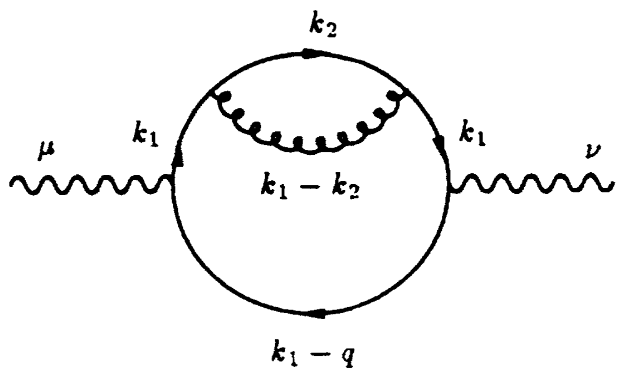


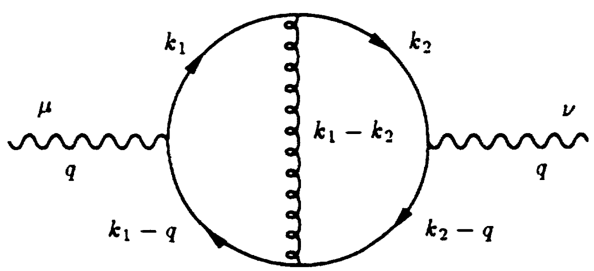
Sannino 1006.0207

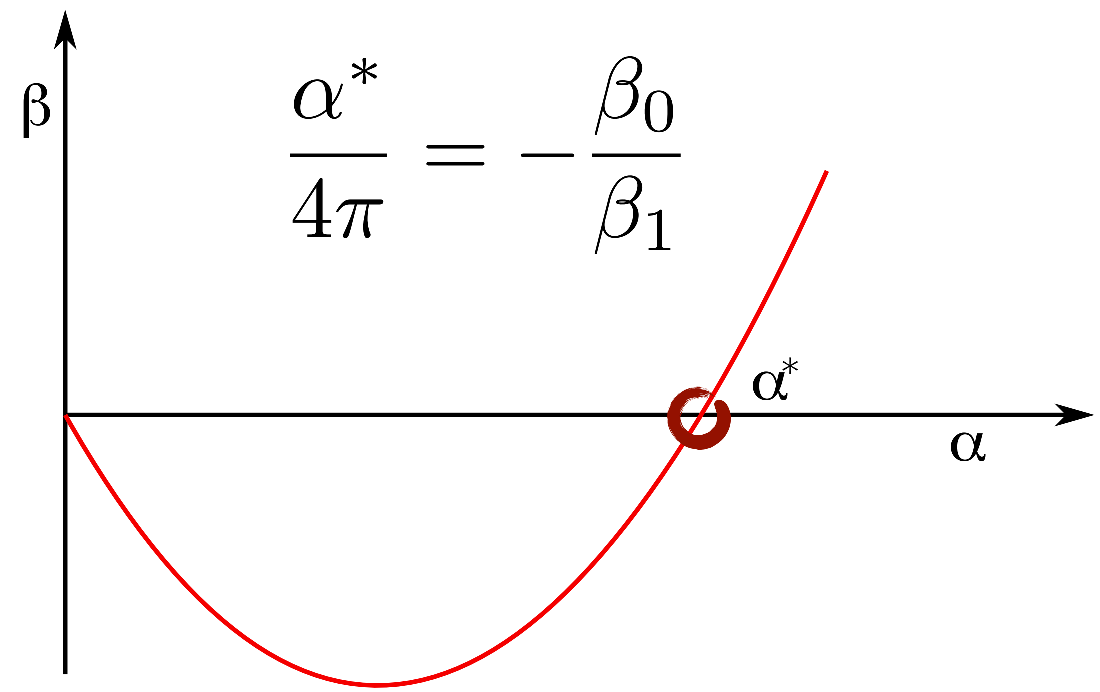
CP3 - Origins
Particle Physics & Origin of Mass

Flavor Structure







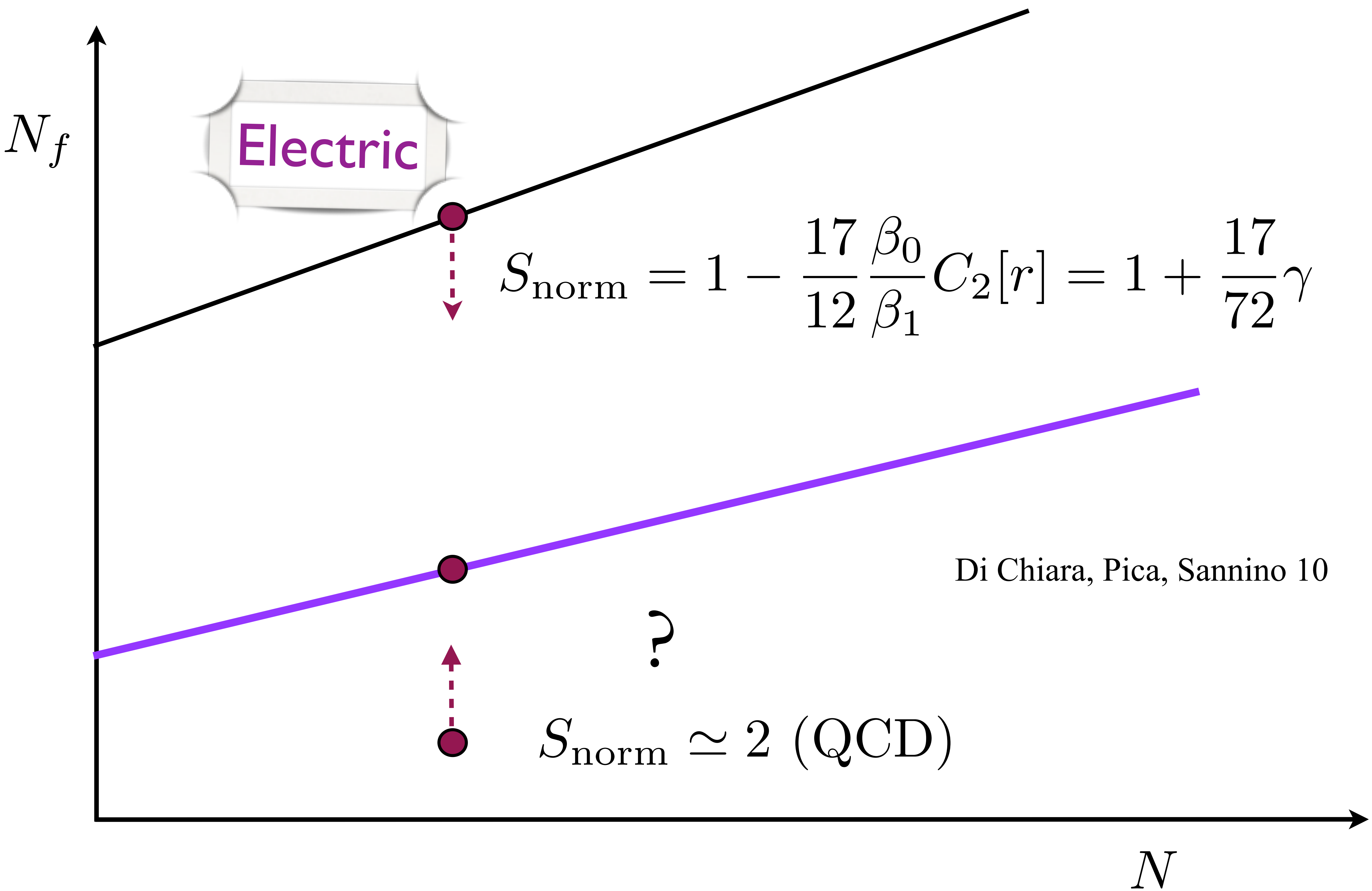


$$S_{\text{norm}} = 1 + \frac{17}{72}\gamma\left(\alpha^*\right) \qquad \gamma(\alpha) = \frac{3}{2}C_2\left[r\right]\frac{\alpha}{\pi}$$

Di Chiara, Pica, Sannino 10

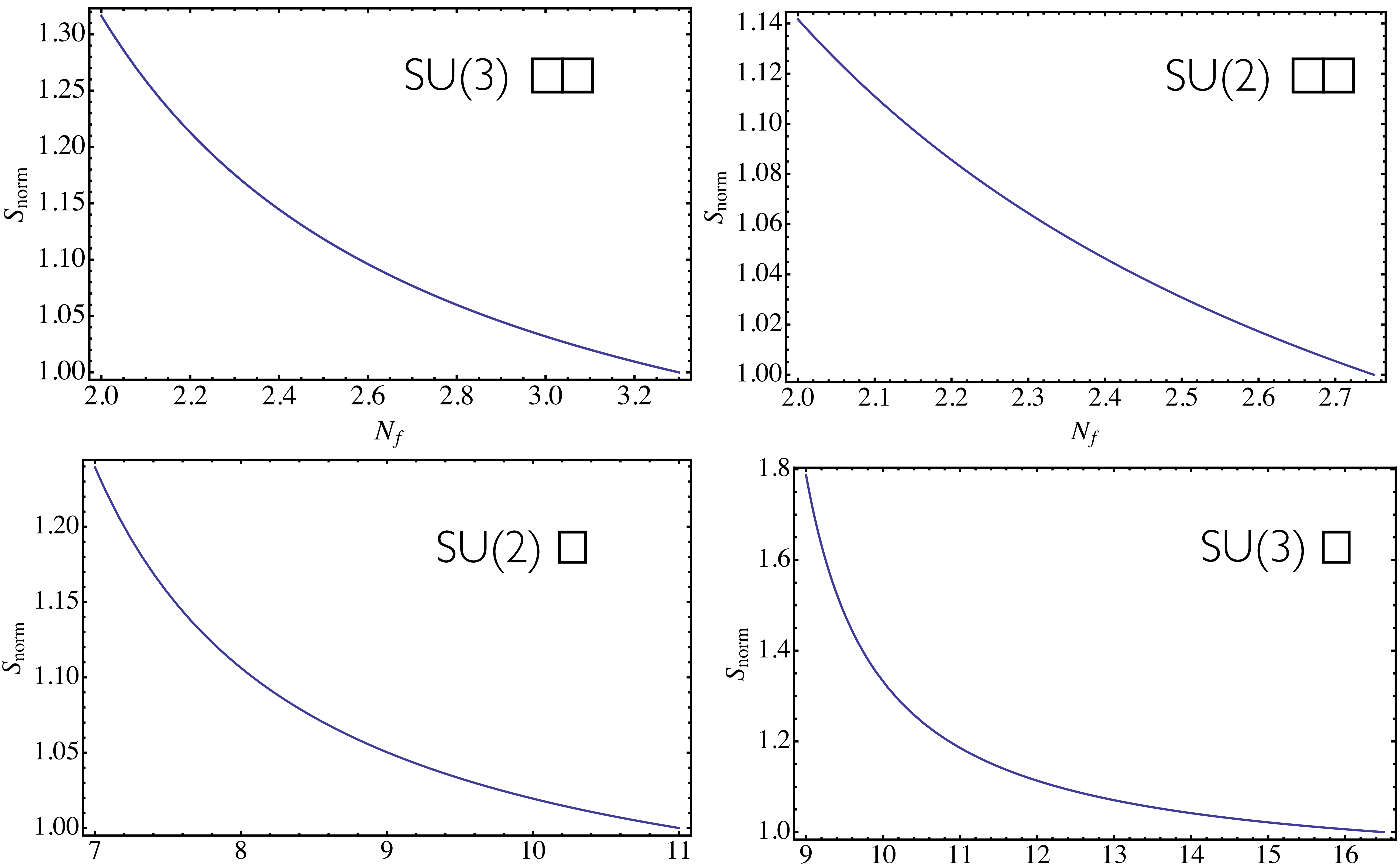
CP3 - Origins
Particle Physics & Origin of Mass

Conformal S @ 2 loops



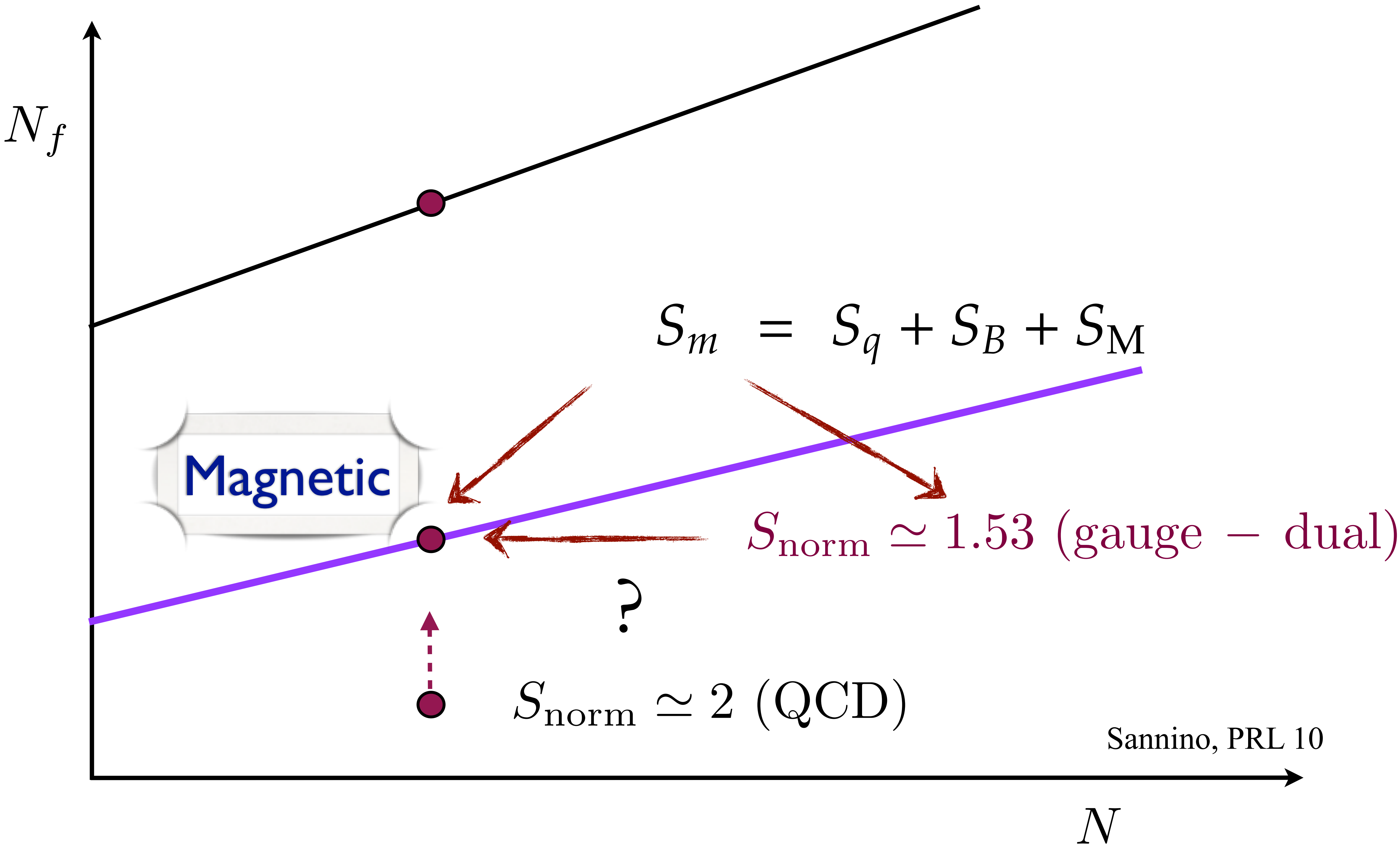
CP^3 - Origins
Particle Physics & Origin of Mass

Conformal S @ 2 loops



Di Chiara, Pica, Sannino - 2010

Magnetic S



N_f
$S_m = S_q + S_B + S_M$
Magnetic
$S_{\rm norm} \simeq 1.53$ (gauge − dual)
?
$S_{\rm norm} \simeq 2$ (QCD)
Sannino, PRL 10
N

Magnetic S

Magnetic

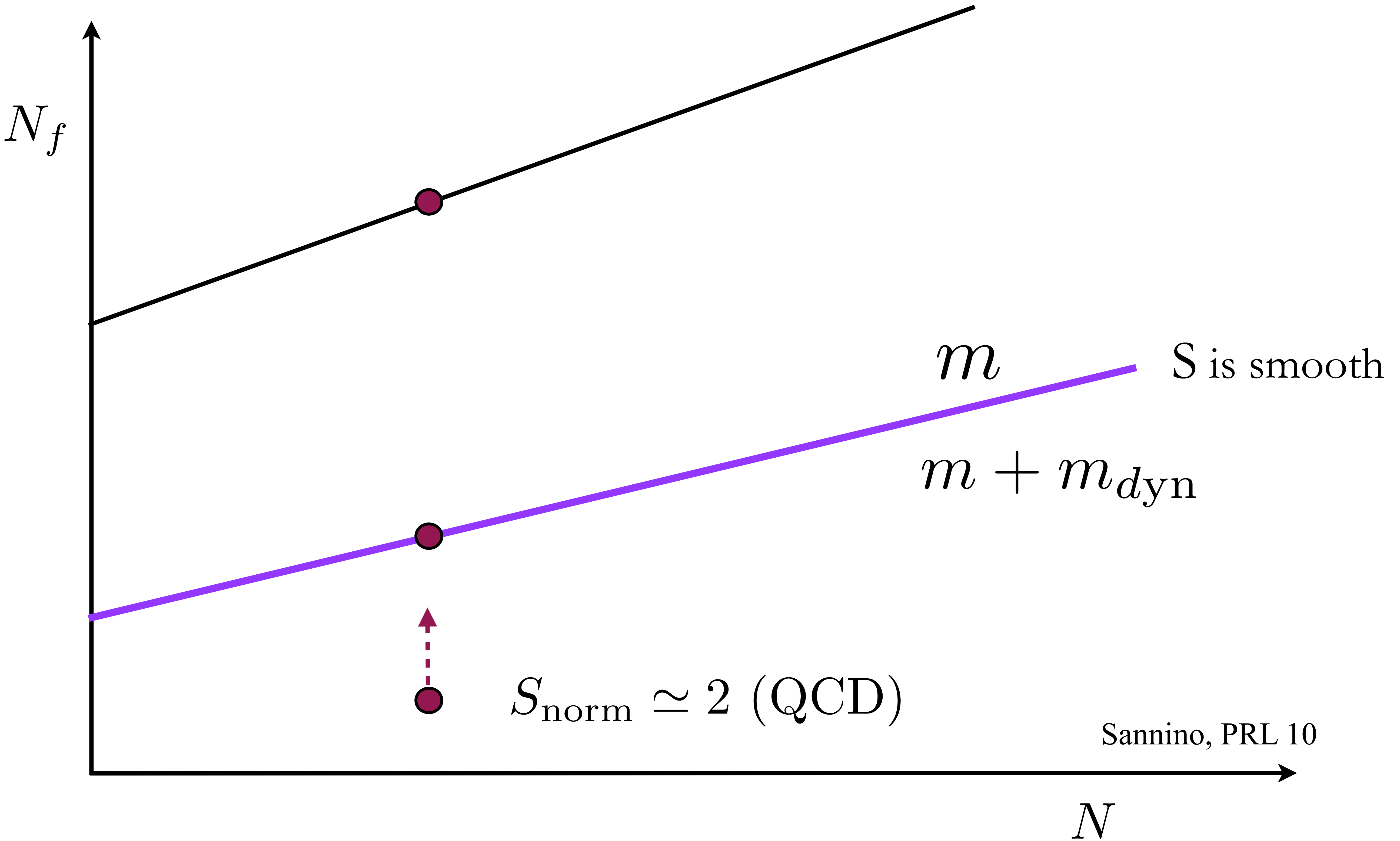
Fields	$[SU(X)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	# of copies
q	$\square$	$\square$	1	y	1
$\widetilde{q}$	$\overline{\square}$	1	$\overline{\square}$	$-y$	1
A	1	(three boxes, vertical)	1	3	ℓ_A
S	1	(three boxes, horizontal)	1	3	ℓ_S
C	1	(two boxes over one)	1	3	ℓ_C
B_A	1	(two boxes, vertical)	$\square$	3	ℓ_{B_A}
B_S	1	(two boxes, horizontal)	$\square$	3	ℓ_{B_S}
D_A	1	$\square$	(two boxes, vertical)	3	ℓ_{D_A}
D_S	1	$\square$	(two boxes, horizontal)	3	ℓ_{D_S}
$\widetilde{A}$	1	1	(three boxes, vertical, conjugate)	-3	$\ell_{\widetilde{A}}$
$\widetilde{S}$	1	1	(three boxes, horizontal, conjugate)	-3	$\ell_{\widetilde{S}}$
$\widetilde{C}$	1	1	(two boxes over one, conjugate)	-3	$\ell_{\widetilde{C}}$
M^i_j	1	$\square$	$\overline{\square}$	0	1

$$S_m = S_q + S_B + S_M$$

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

Sannino PRL, 10

Below the window



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

Tested to higher loops: Di Chiara, Pica, Sannino 10

Strong constraints for old models!

In fact ...

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

Offset the first term

Rule:

Find WT minimizing the lower bound for S

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

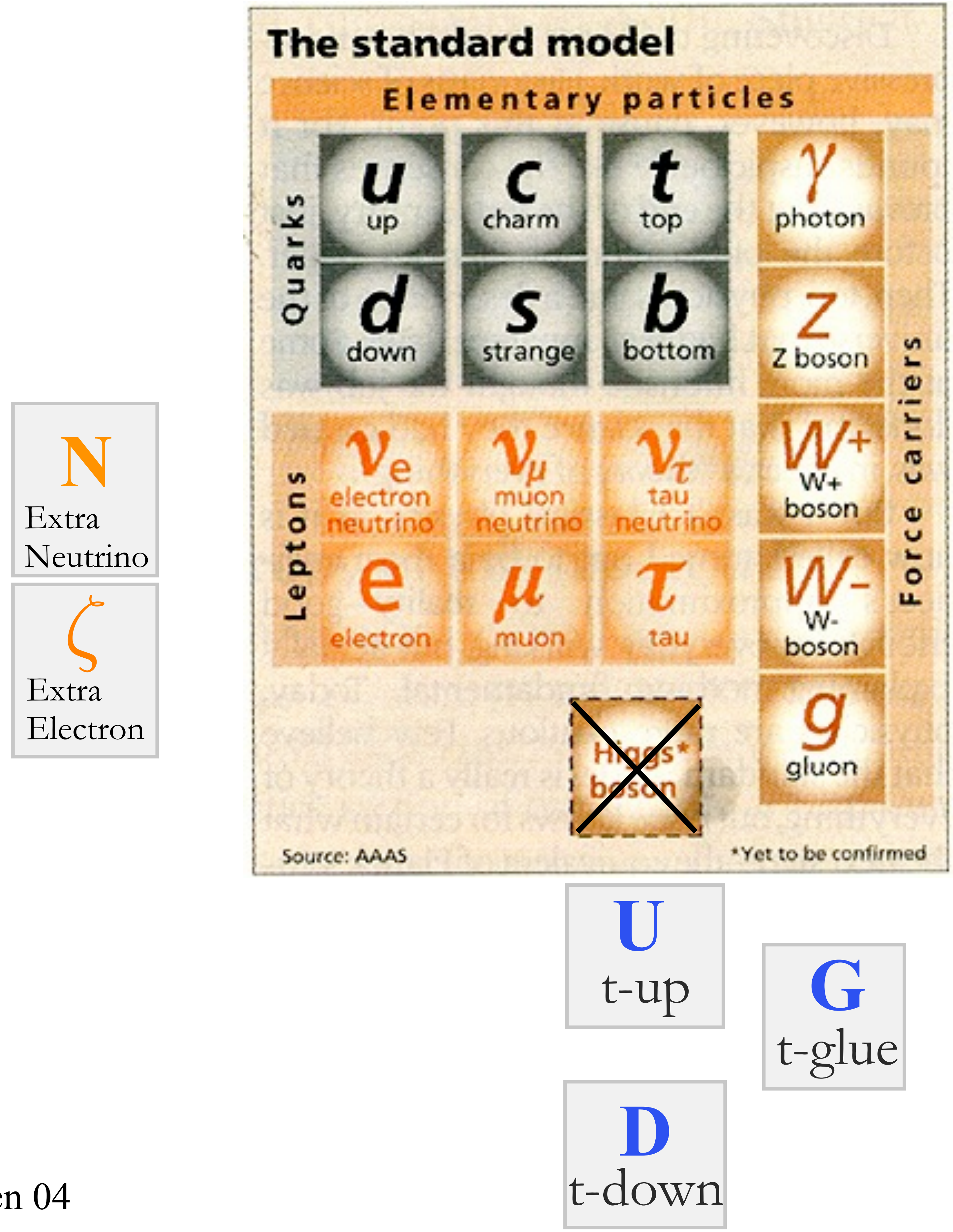
- Ultra MT

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

Ryttov & Sannino 08

Vanilla TC
&
Scooby -Doo

Minimal Walking Technicolor



U(1)

SU(2)

SU(3)

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

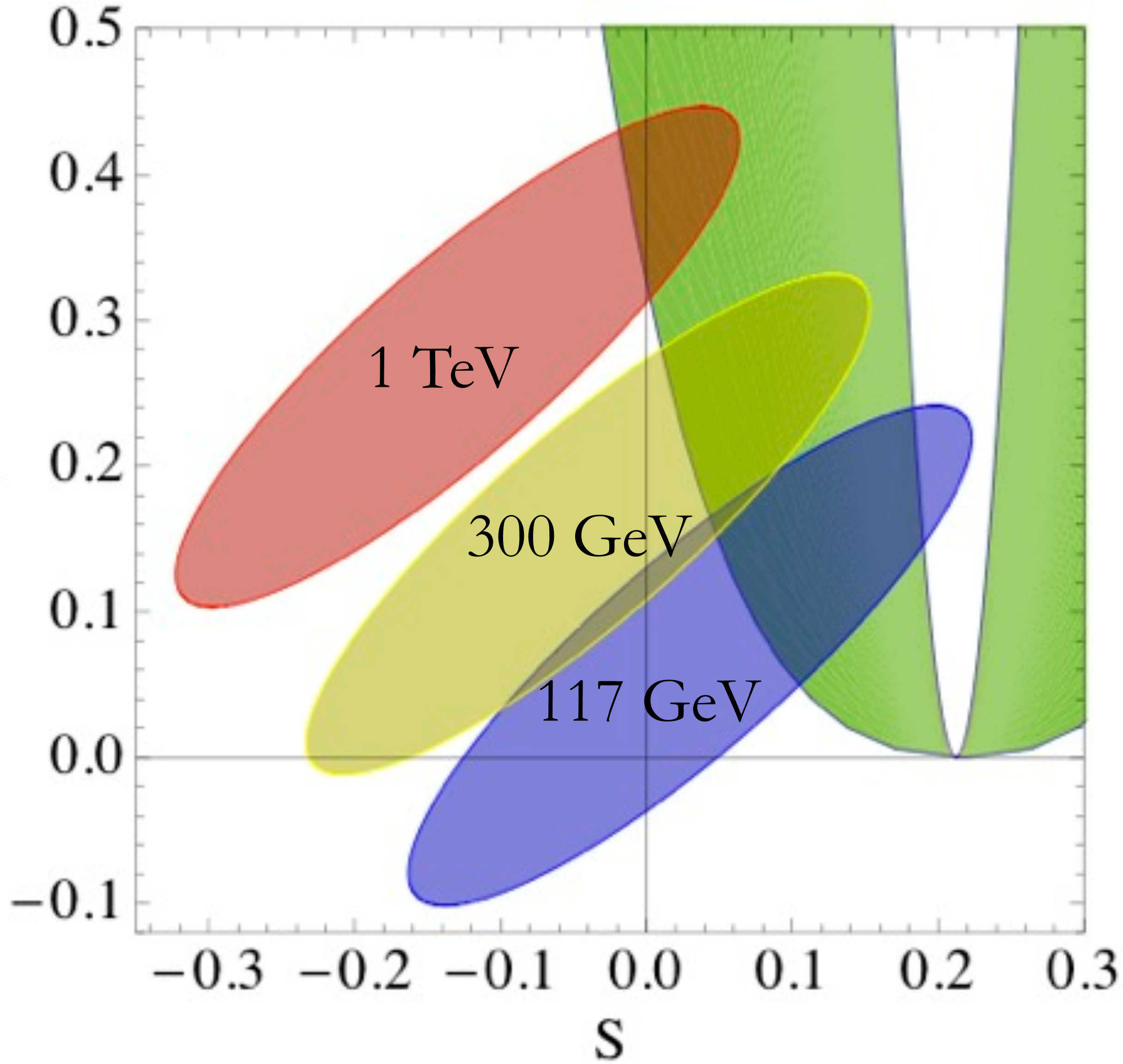
$$\text{Fermions :} \qquad \psi_L = \begin{pmatrix} \psi_{1L} \\ \psi_{2L} \end{pmatrix}, \qquad \psi_{1R}, \qquad \psi_{2R}$$

$$\text{Hypercharge :} \qquad Y, \qquad Y + \frac{1}{2}, \qquad Y - \frac{1}{2}$$

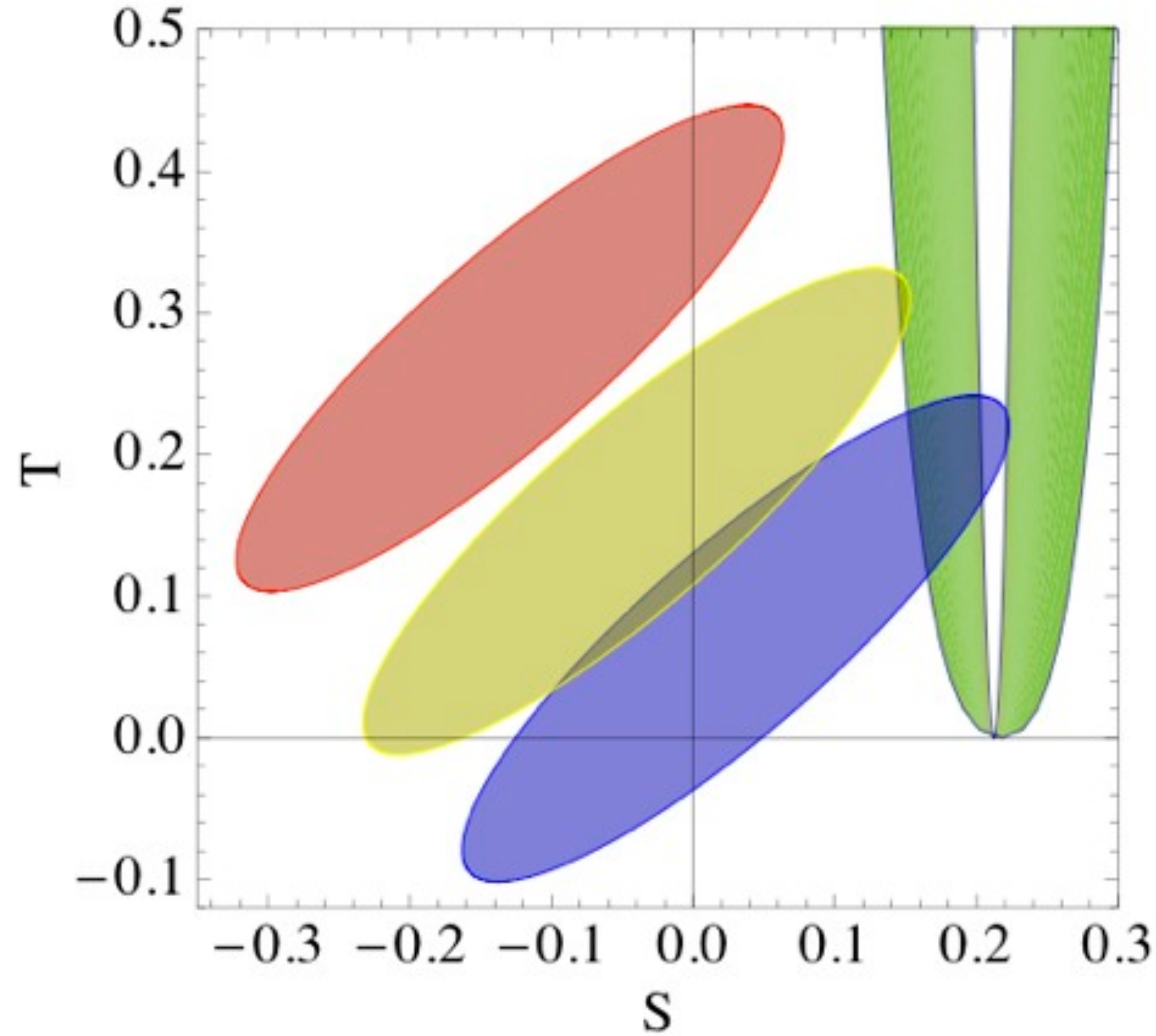
$$S_{\text{Leptons}} = \frac{1}{6\pi}\left[1 - 2Y \ln\left(\frac{M_1}{M_2}\right)^2 + \frac{1+8Y}{20}\left(\frac{m_Z}{M_1}\right)^2 + \frac{1-8Y}{20}\left(\frac{m_Z}{M_2}\right)^2 + O\left(\frac{m_Z^4}{M_i^4}\right)\right]$$

$$M_{1,2}^2 \gg m_Z^2$$

New Leptons & Precision Data



Exotic Leptonic hypercharge Y=-3/2



Standard Model Leptonic hypercharge

MWT Features

- The most economical WT theory
- Compatible with precision measurements
- Possible DM candidates and Unification
- Can support 1st order Electroweak Phase Transition
- Features a light composite Higgs
  Dietrich, F.S., Tuominen 05.
  Da Silva, Doff, Natale 08, 09.
- Lattice studies have begun

MWT Effective Lagrangian

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

Composite Higgs — H

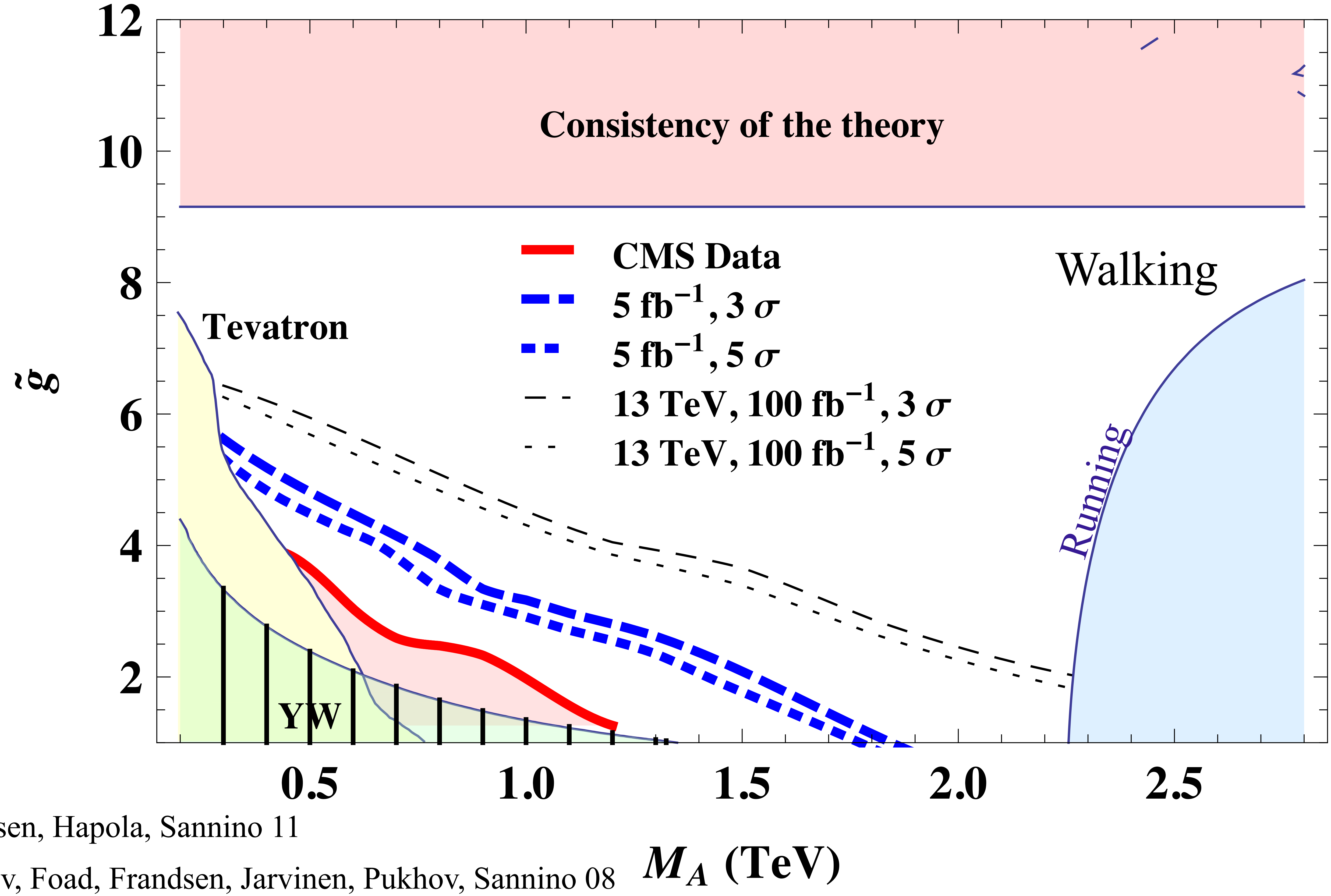
Composite Axial - Vector States — $R_{1,2}$

Heavy Electron — ζ

2 Heavy Majoranas — N_1 N_2

Hapola, Masina, Sannino 11 Frandsen, Masina, Sannino 09

Constraining MWT



Andersen, Hapola, Sannino 11

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

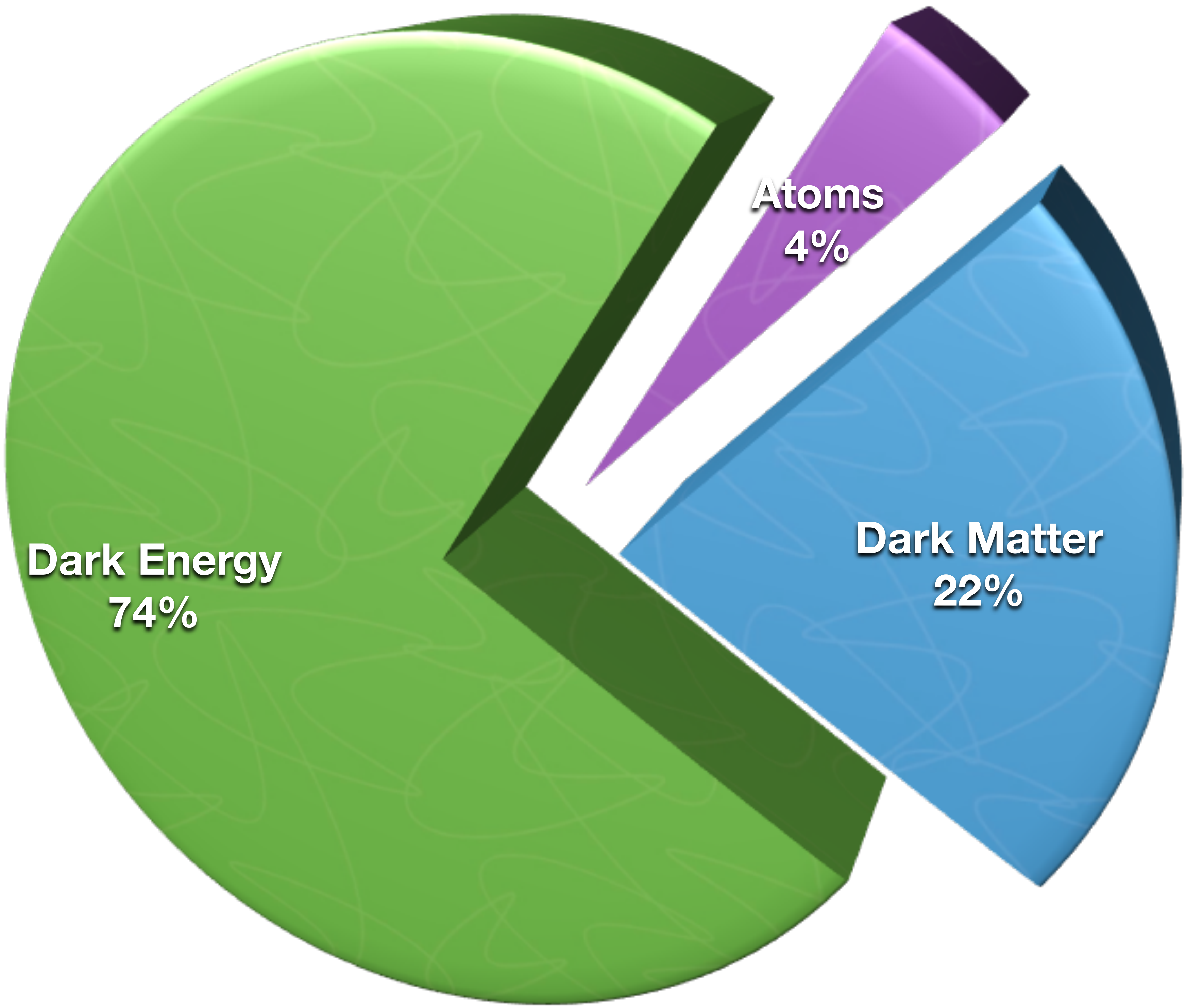
NEXT

- Implement technibaryon sector of MWT in CalCHEP - MadGraph
- Composite fermions in MWT
- Topological terms (in progress)
- Orthogonal technicolor
- Implement Ultra Minimal Walking Technicolor
- Supersymmetric extension of Minimal Walking Technicolor

New life in Technicolor

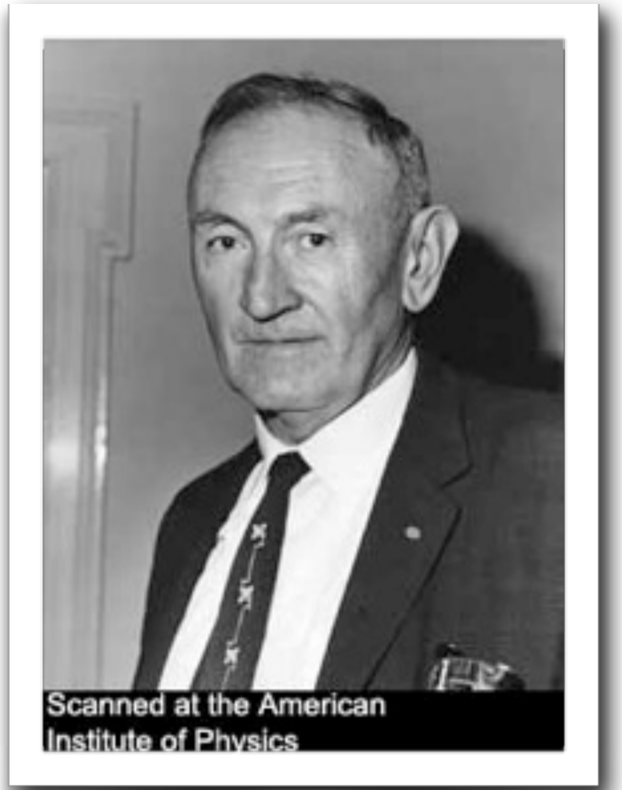
Not the Coldplay album

Dark Matter



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

First evidence for DM



- 1953 F. Zwicky found the first evidence for DM
- Velocity dispersion of the galaxies in the COMA cluster
- **Dark Matter** was dubbed then!

Cluster Evidence Today

- From X-ray emission: Stronger evidences
- Temperature of the cluster gas too high!
- Factor 5 higher than the one from baryonic matter

Bullet Cluster

Self interactions

- From bullet cluster one deduces:

Markevitch et al. 03

$$\sigma \leq 1.7 \times 10^{-24}\mathrm{cm}^2 \sim 10^9\mathrm{pb}$$

- Stronger constraints requiring large cores of clusters.

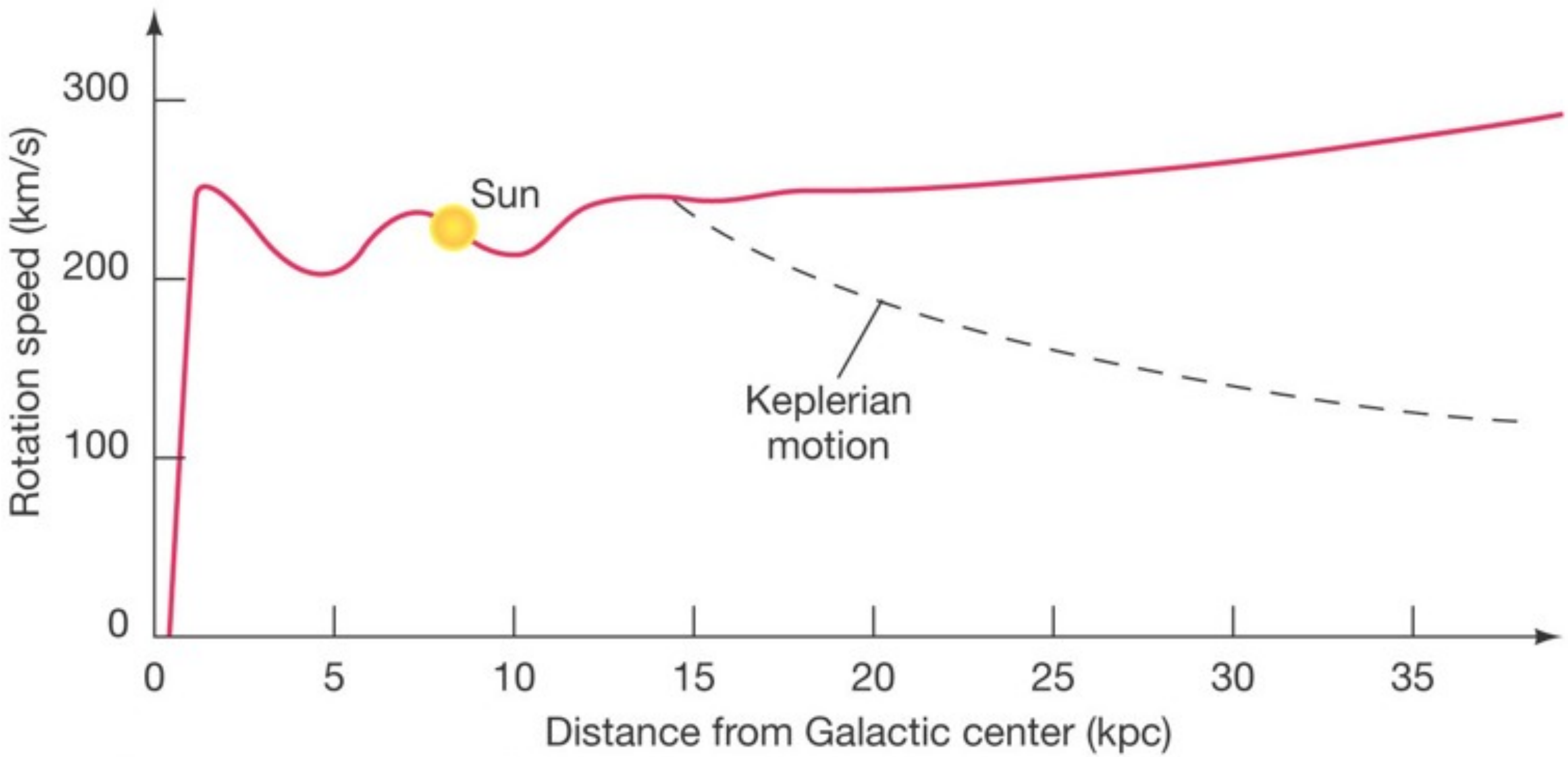
Yoshida, Springer & White 00

- Sphericity of halos.

Galactic Scales

- Stars in the outer part of galaxies rotate faster than expected!

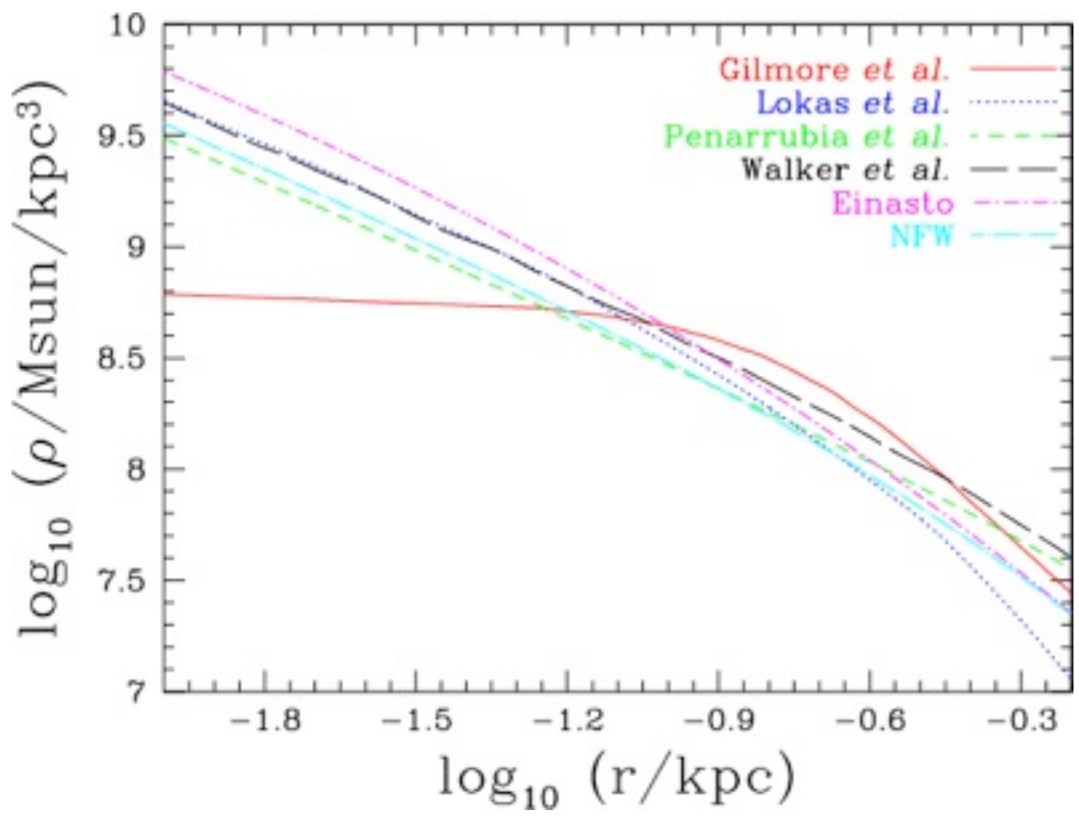
$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{\rm tot}}{r}$$



Galactic Scales

- We need something like:

$$M(r) \propto r \quad \Longrightarrow \quad \rho_{DM} \propto r^{-2}$$



- Density is uncertain in the internal regions of galaxies

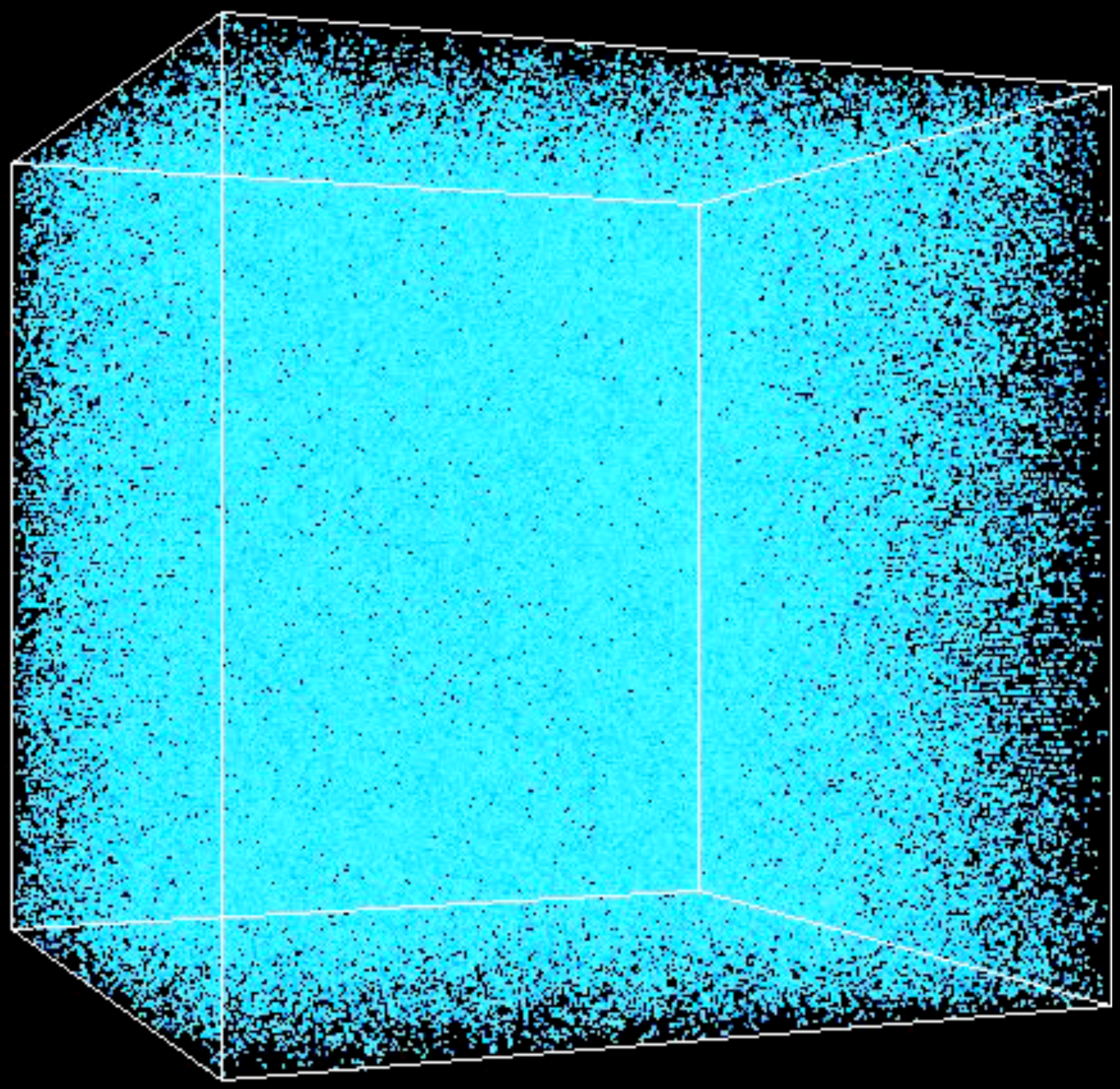
- Data & numerical simulations: Isothermal, NFW, Moore, Kratsov, Einasto, etc...

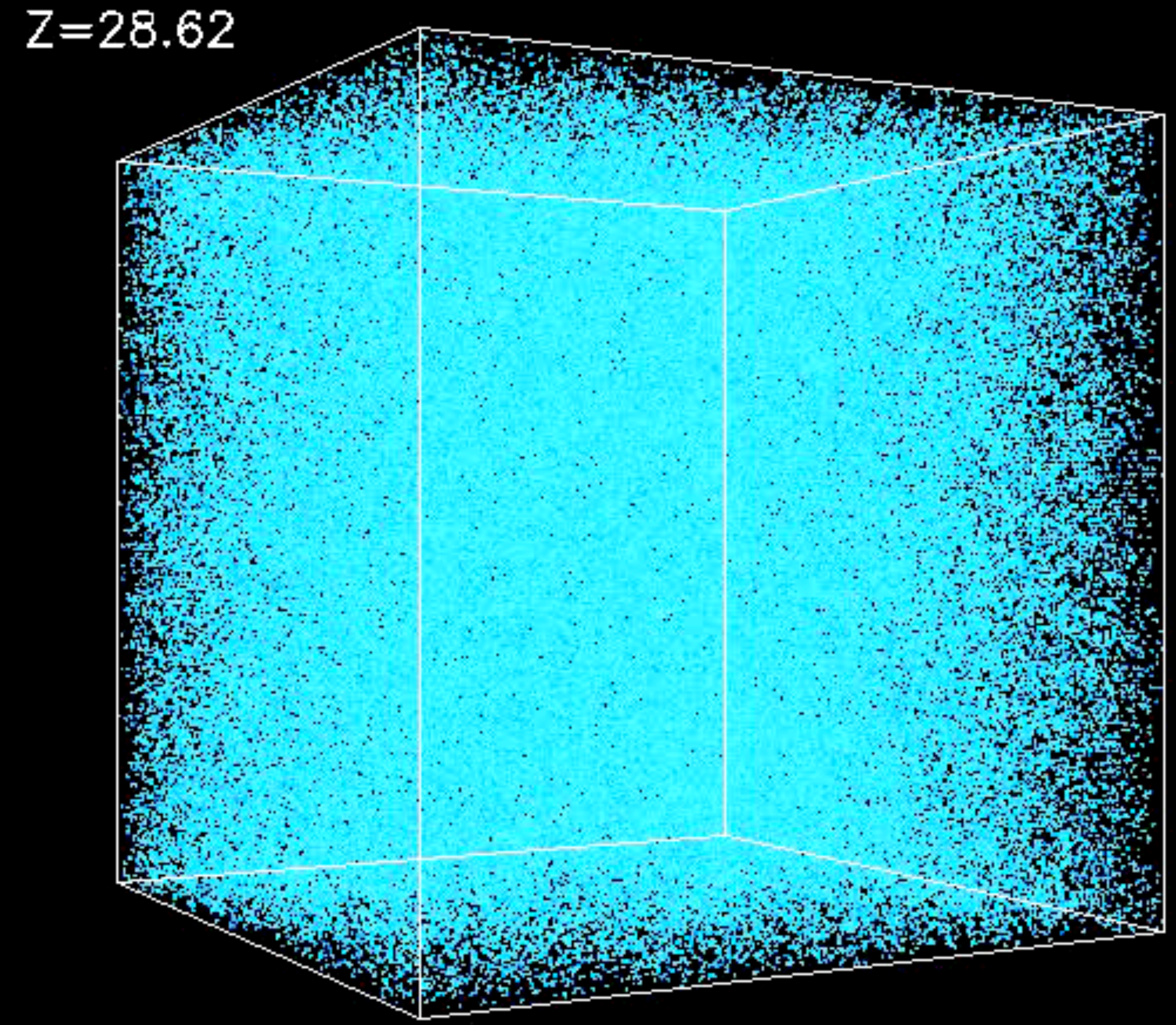
$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{R}\right)^{\gamma}\left[1+\left(\frac{r}{R}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$

Large structure formation

V. Springel, MPA Munich

Yoshida et al. 03

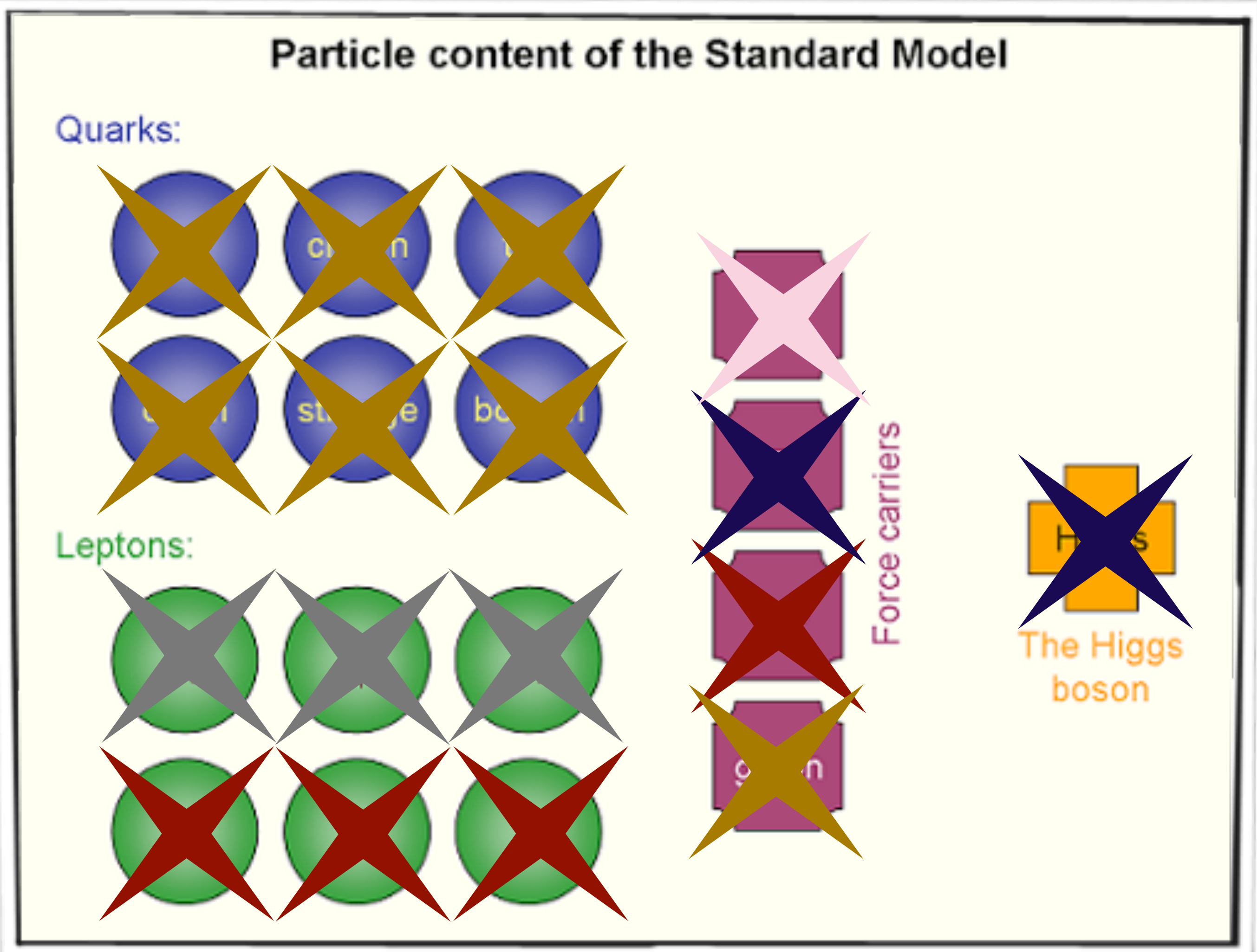




DM Properties

- Interacts gravitationally
- Electrically neutral and decoupled from primordial plasma
- Lead to correct density profile for galaxy rotation curves
- Cold DM: Must cluster & lead to structure formation
- Either stable or very long lived

DM candidates in SM?



- Charged
- Decaying too soon/ Charged
- Baryonic / Charged
- Massless like graviton
- For thermal neutrinos

$$\Omega_\nu h^2 \sim \frac{\sum_i m_{\nu i}}{93\text{eV}} \leq 0.07$$

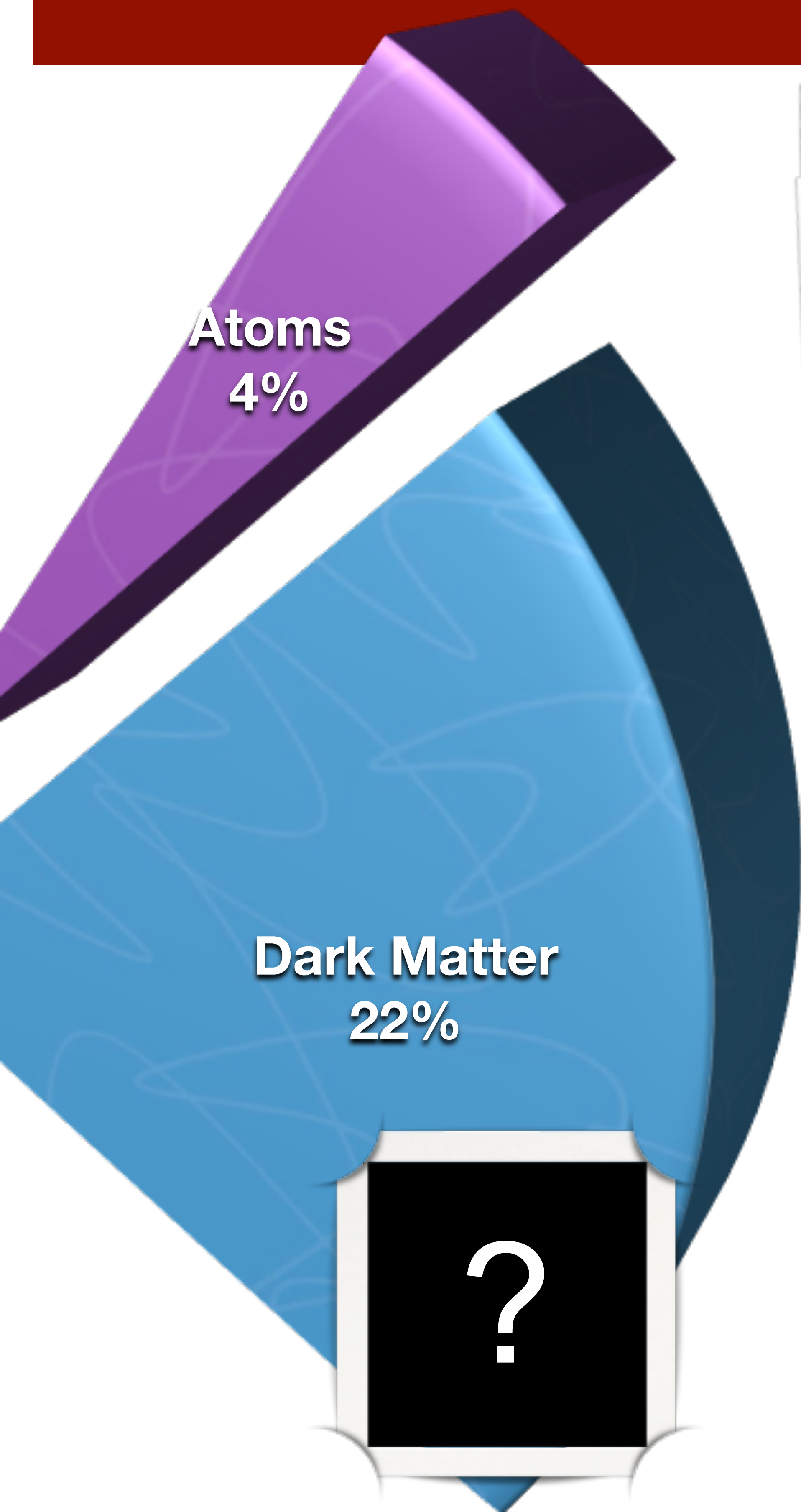
$$m_\nu \leq 2\text{eV (Tritium } \beta \text{ decay)}$$

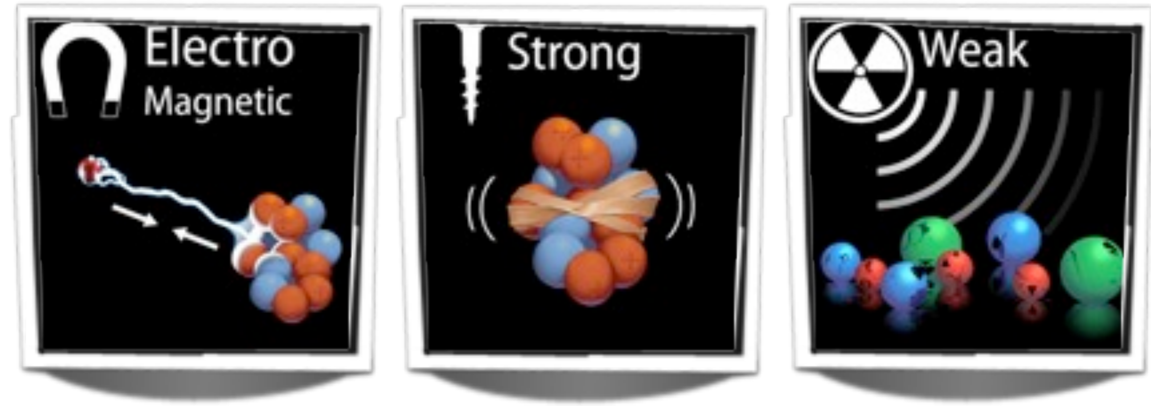
- LSS constrain also

$$m_\nu \leq 0.27 - 1\text{eV} \quad \Longrightarrow \quad \Omega_\nu \ll \Omega_{DM}$$

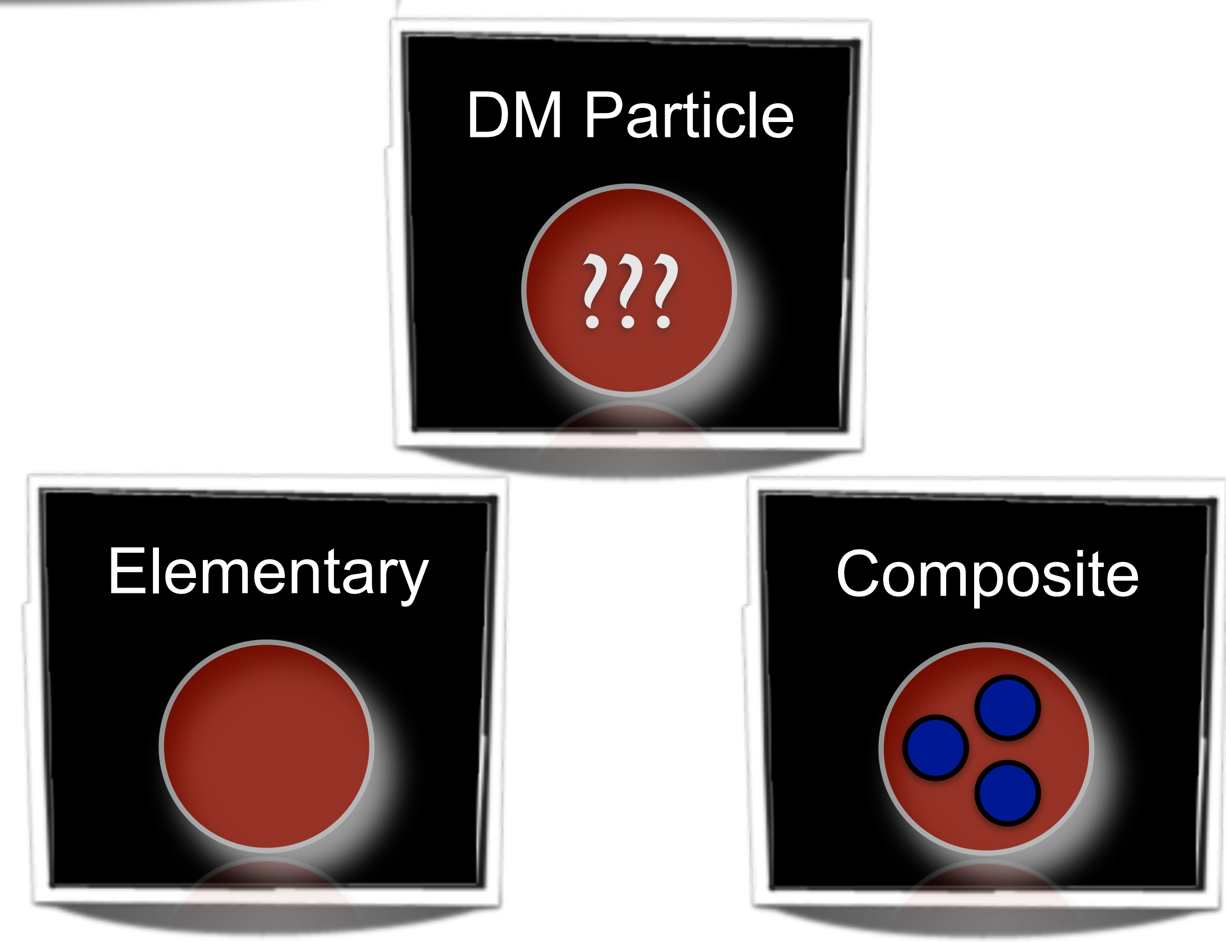
Need beyond SM!!

What makes DM?

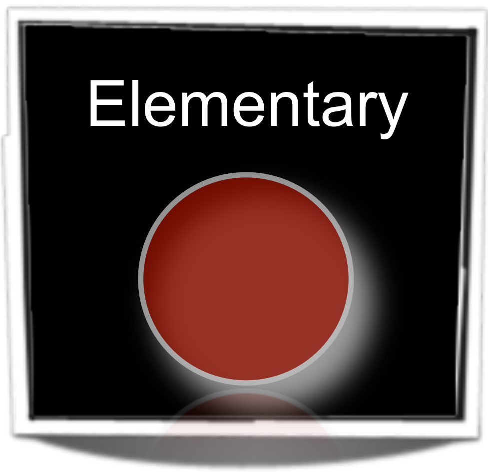




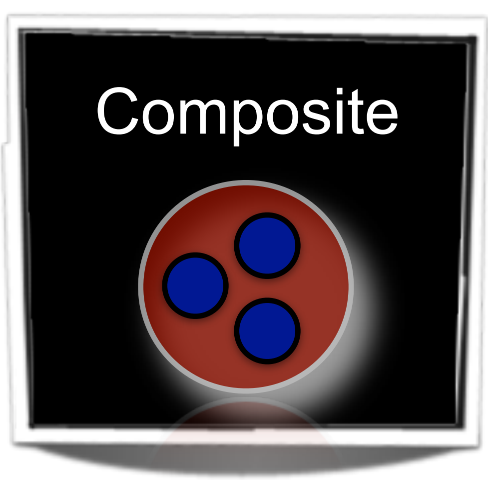
Oversimplification



DM candidates



- Minimal Supersymmetric Standard Model
- Axion
- Just another particle with no links to SM



- New strong force with new quarks (techni-baryon, meson, ...)
- Un-baryons

Incomplete list

DM asymmetry

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

(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

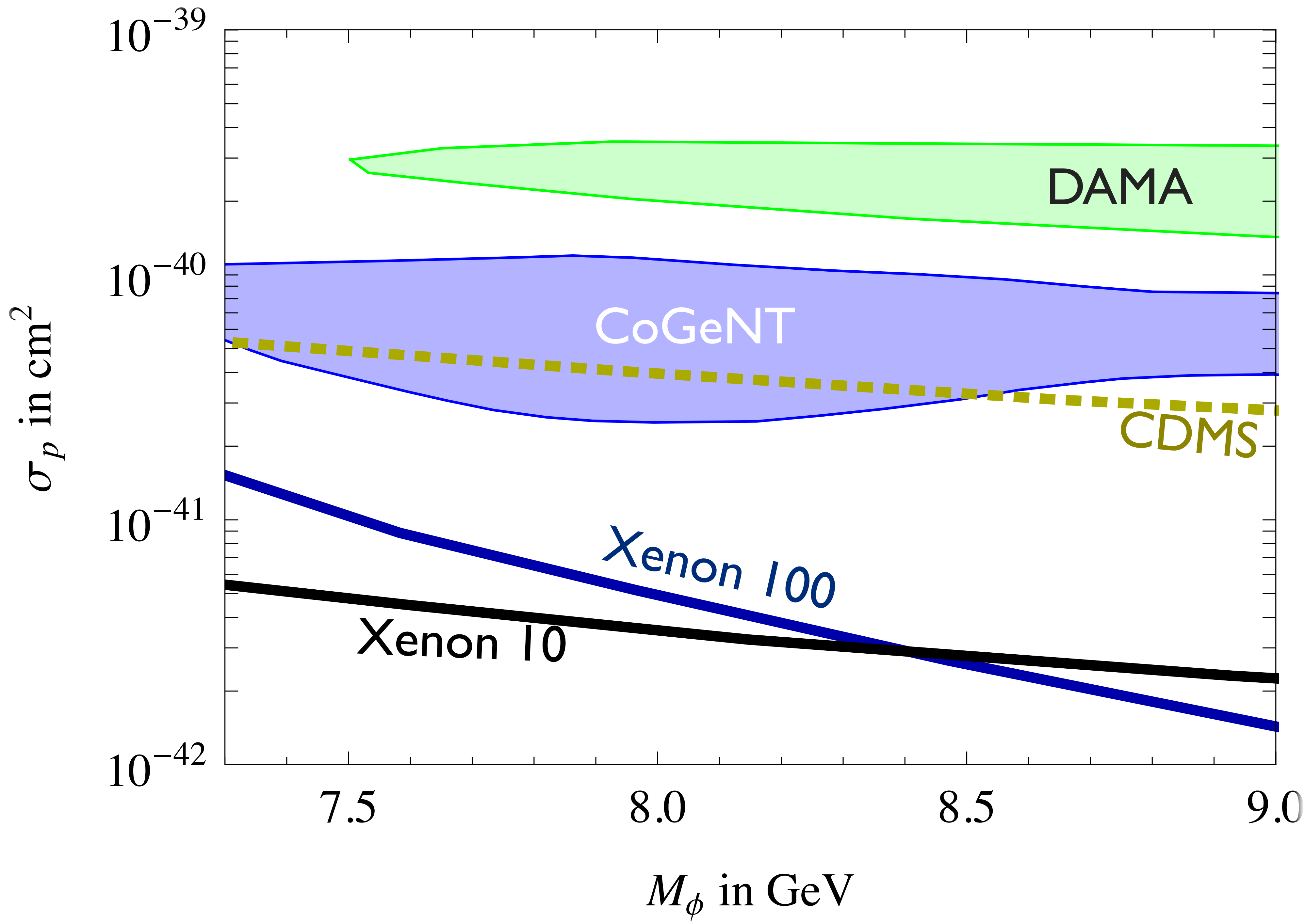
$$\tau \sim \frac{M_{GUT}^4}{m_{TB}^5} \sim 3 \times 10^{37}\text{sec}$$

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

Gudnason, Ryttov, FS 06

Nardi, FS, Strumia, 08.

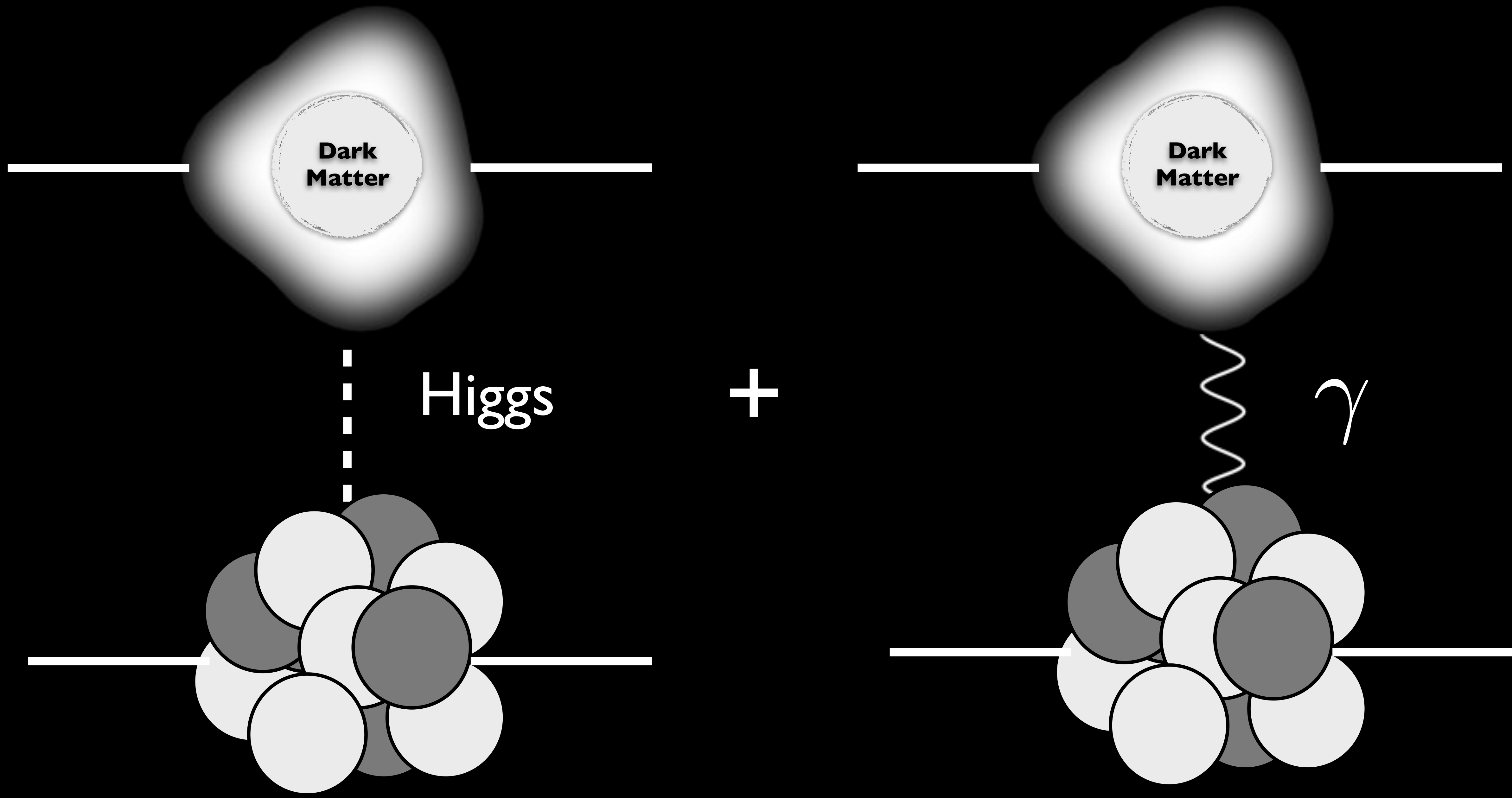
Puzzle



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

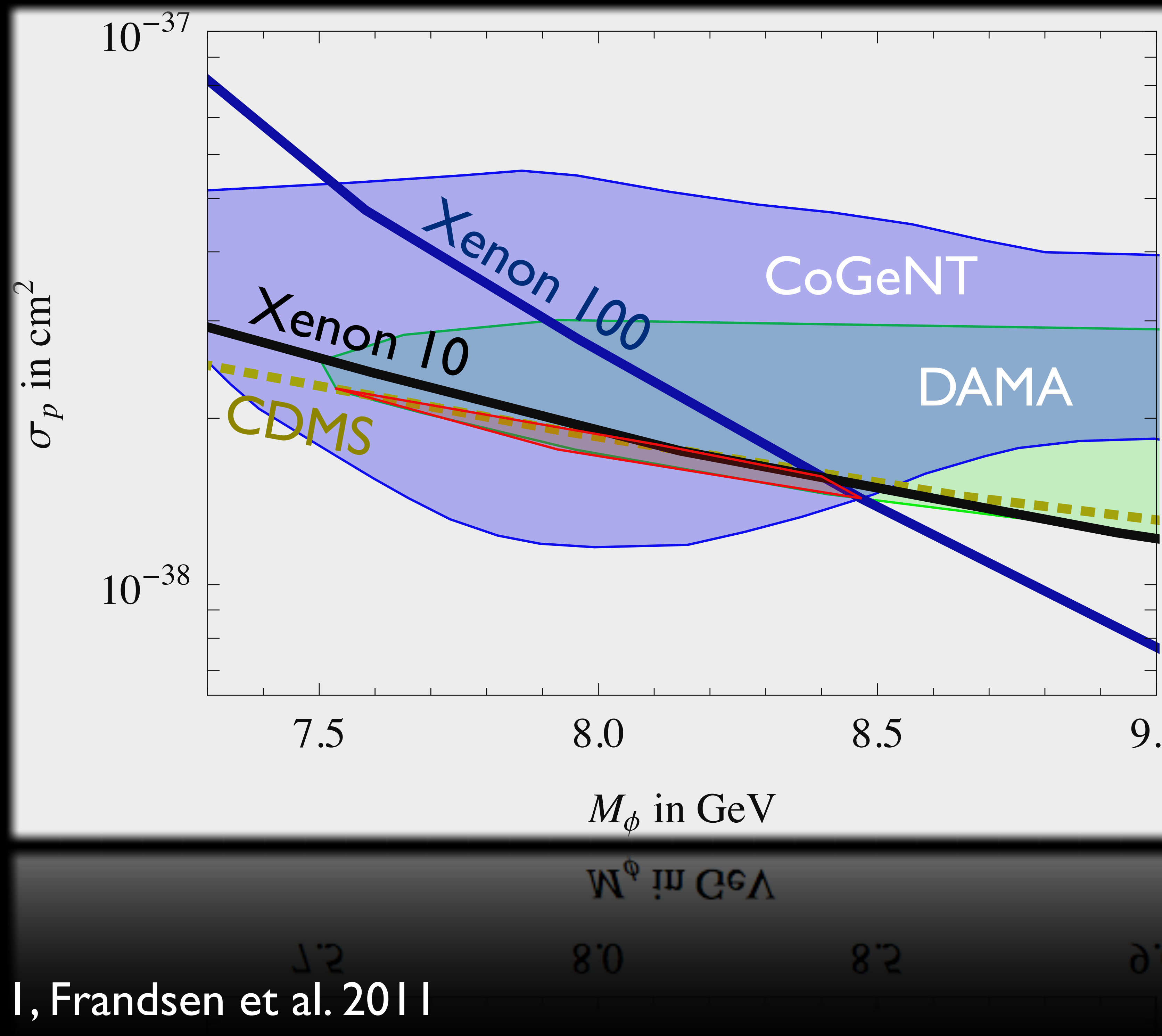
Del Nobile, Kouvaris, Sannino 11



Interfering Composite ADM

CoGeNT and DAMA

Del Nobile, Kouvaris, Sannino 11



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

Conclusions

- DEWSB can naturally occur at the LHC
- Phase Diagram of strongly interacting theories
- Minimal models of technicolor are near conformal
- Composite Dark Matter
- Composite inflation... to discuss another time.