DIAS
Danish Institute for Advanced Study

UNIVERSITY OF SOUTHERN DENMARK

Composite Dynamics

Francesco Sannino

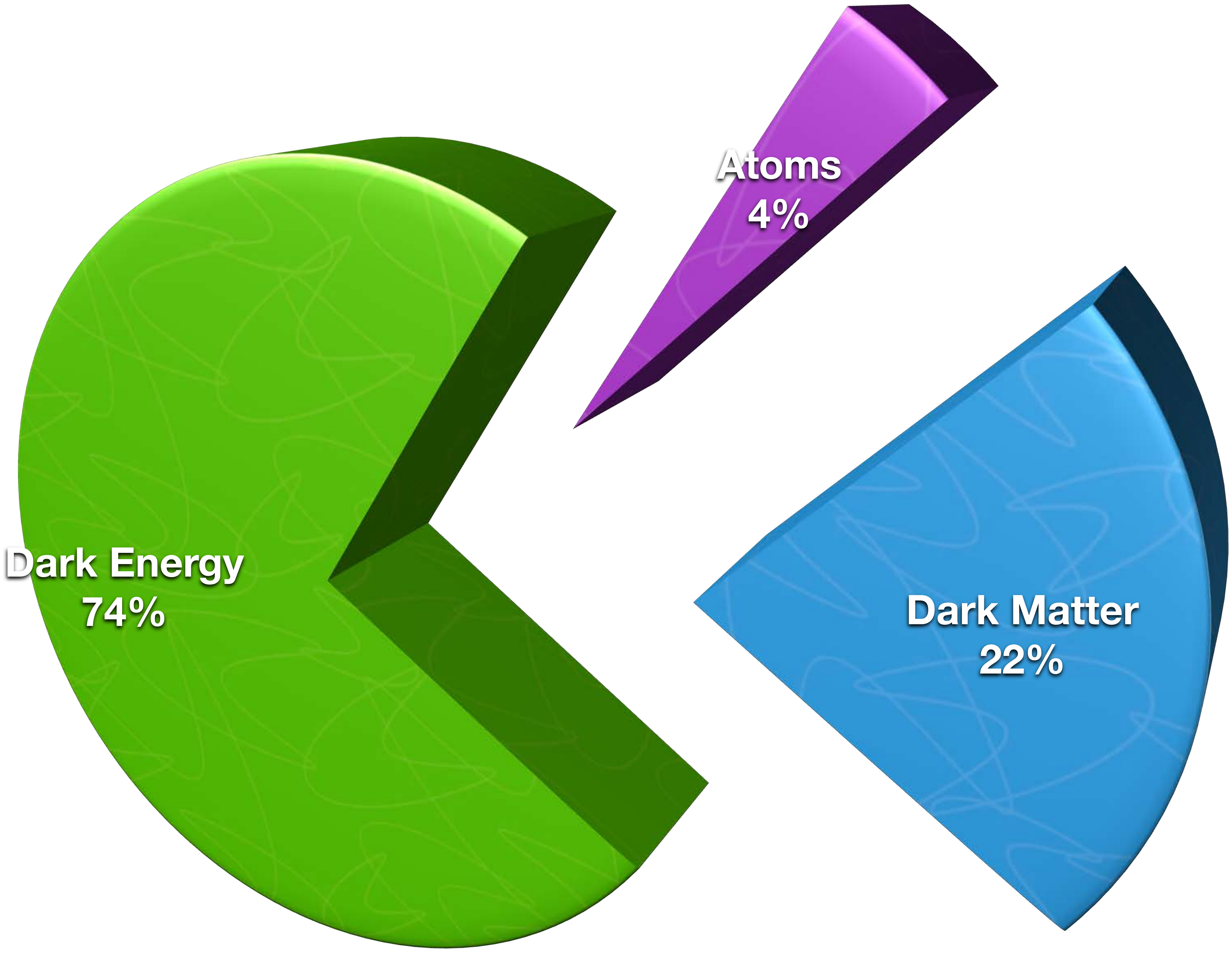
CP3 - Origins

Particle Physics & Origin of Mass

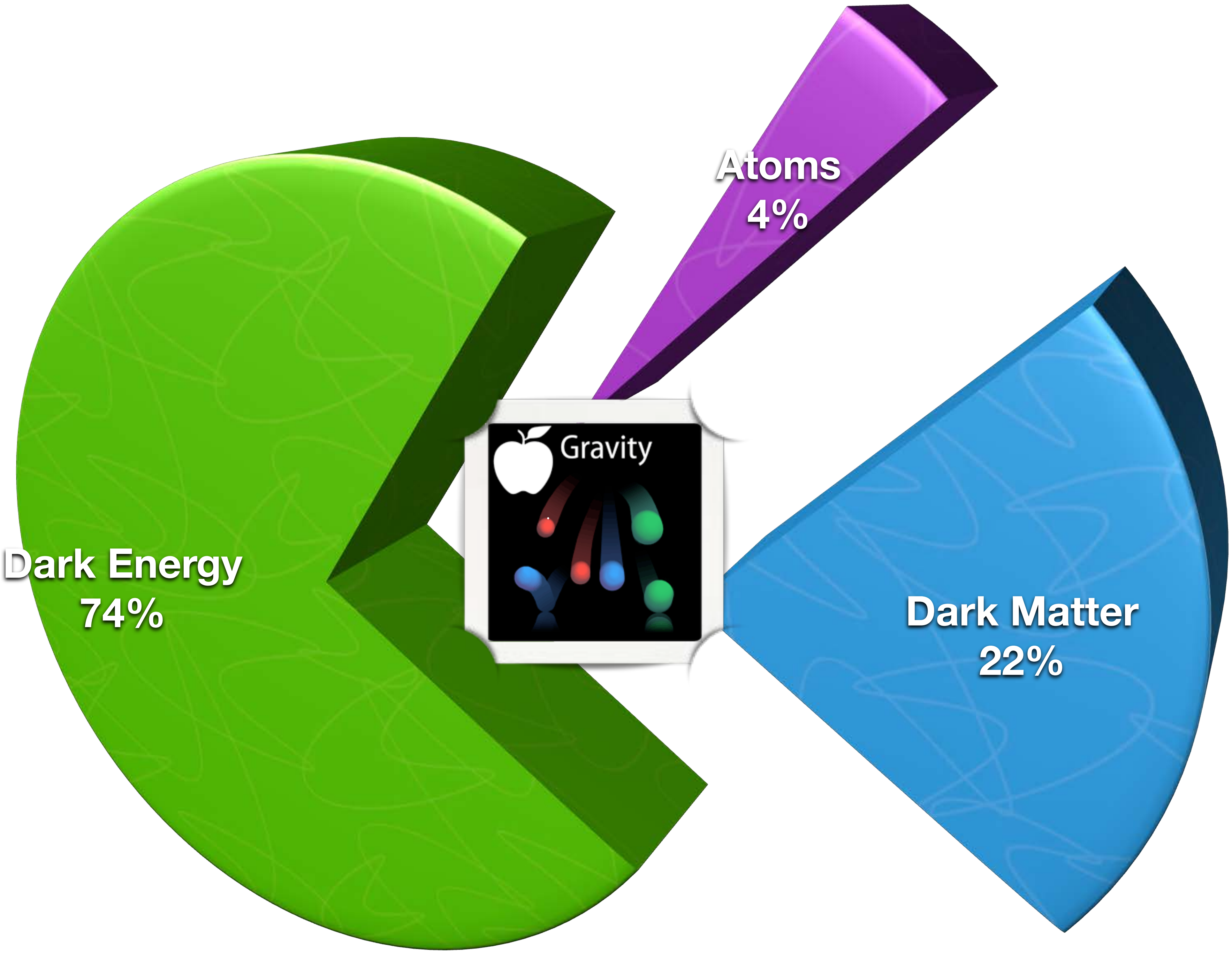
Vienna - November 25 - 2011

Riddles

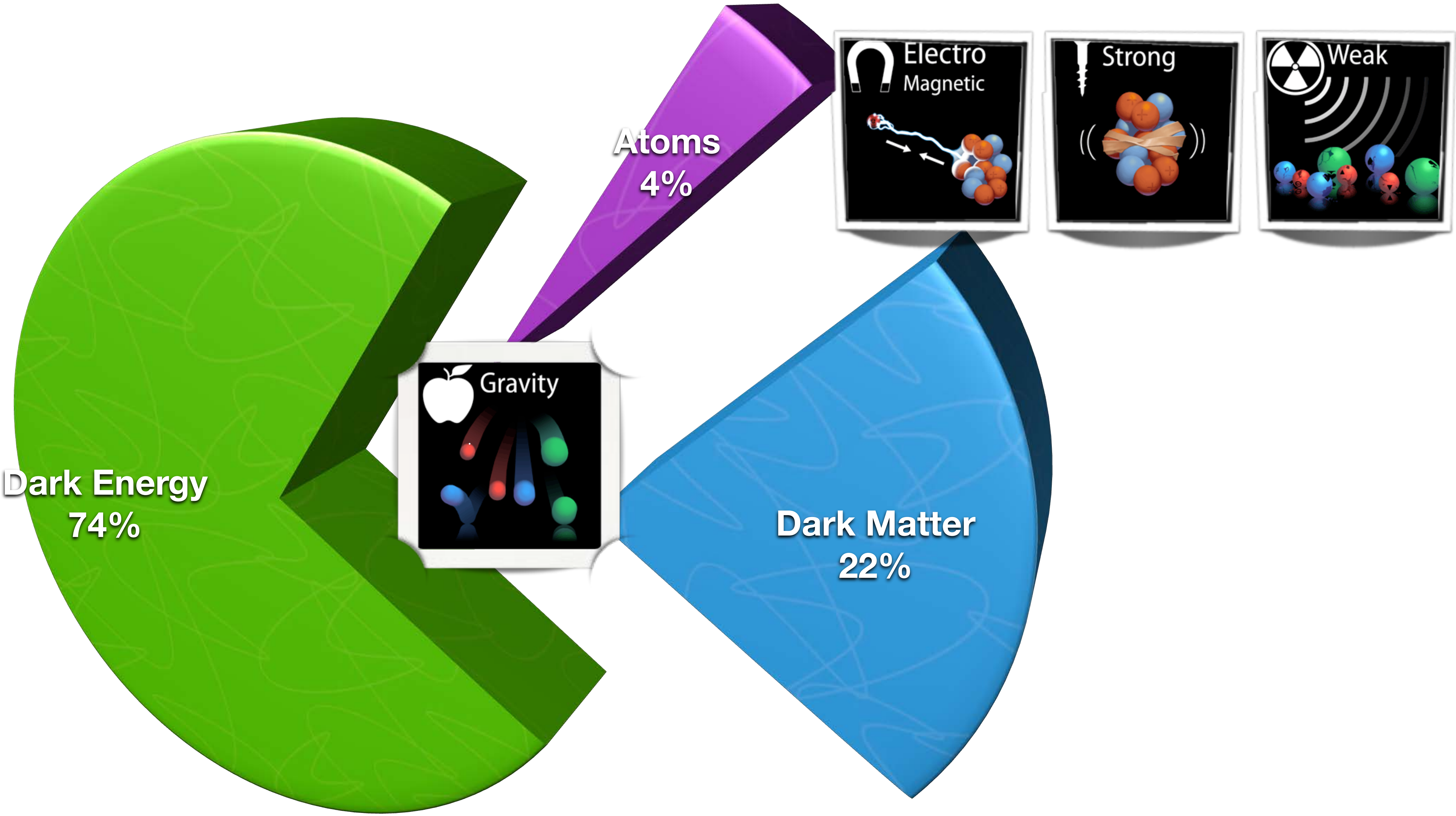
Riddles



Riddles



Riddles



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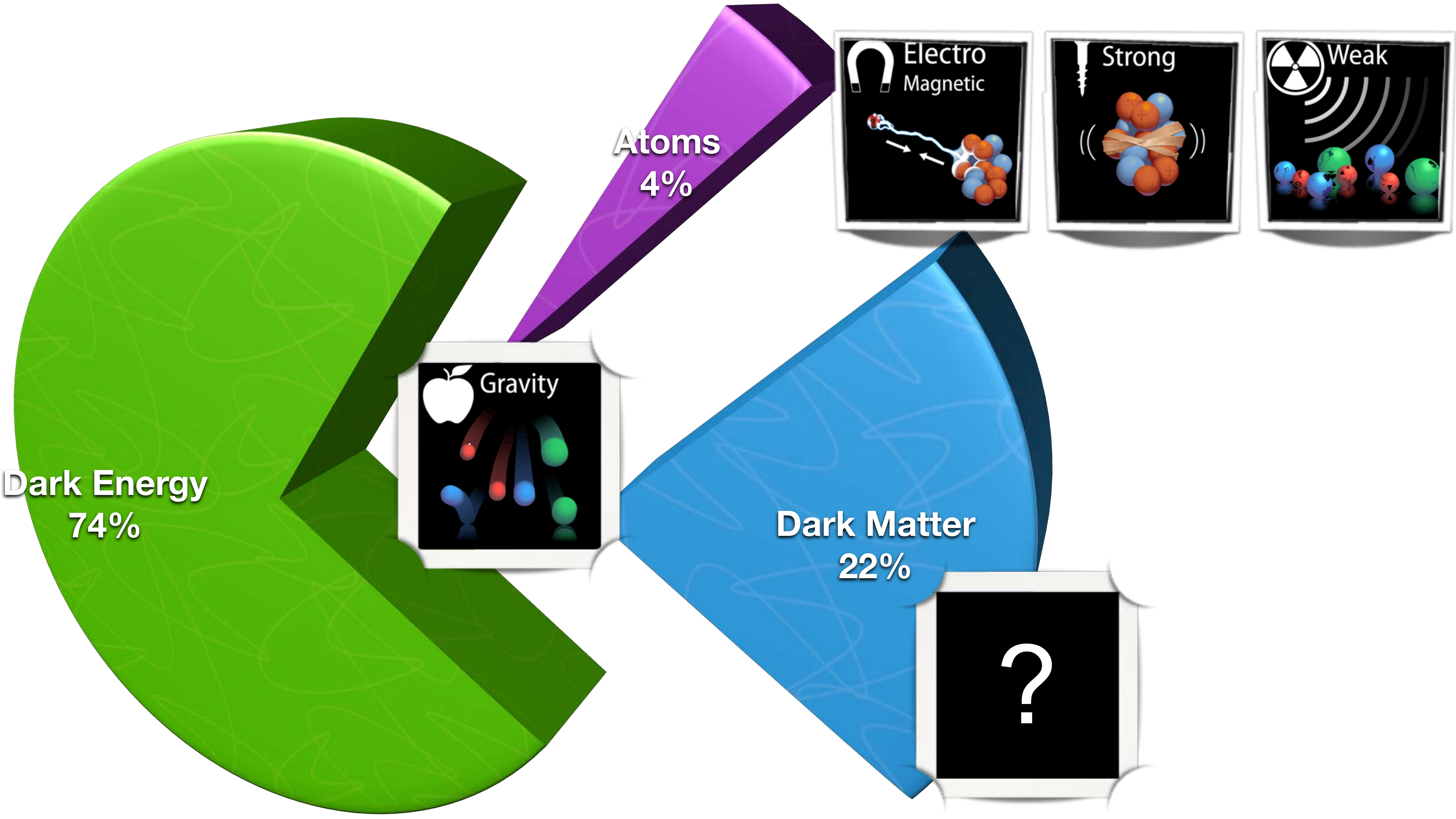
Riddles



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Riddles

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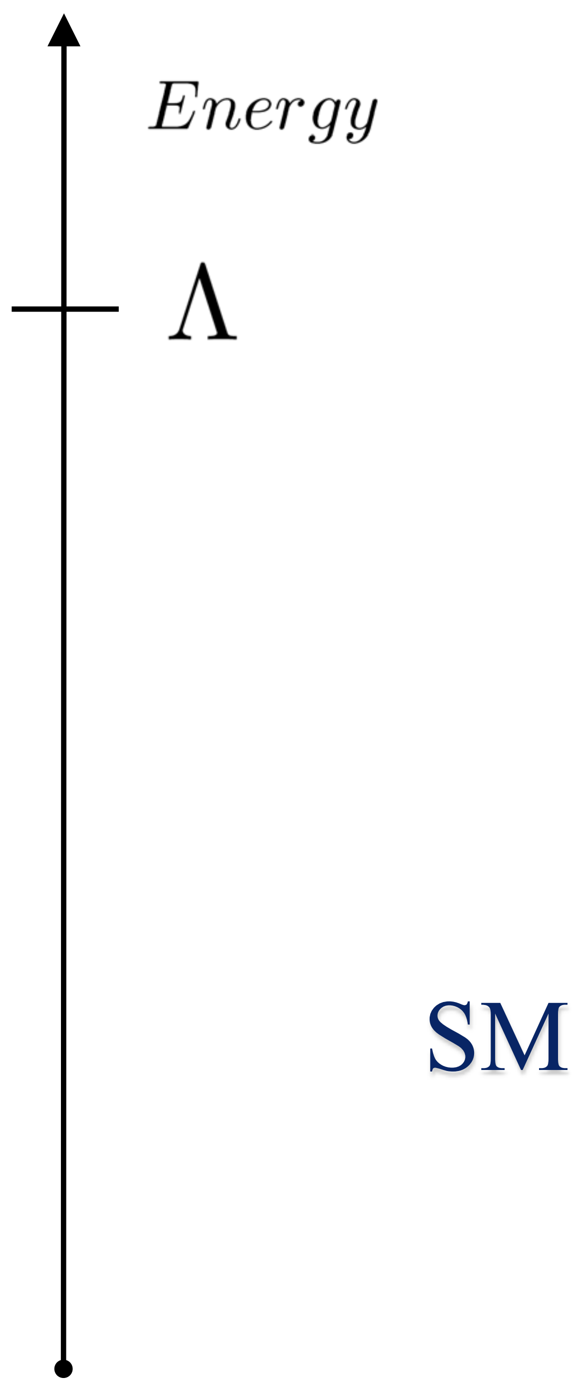
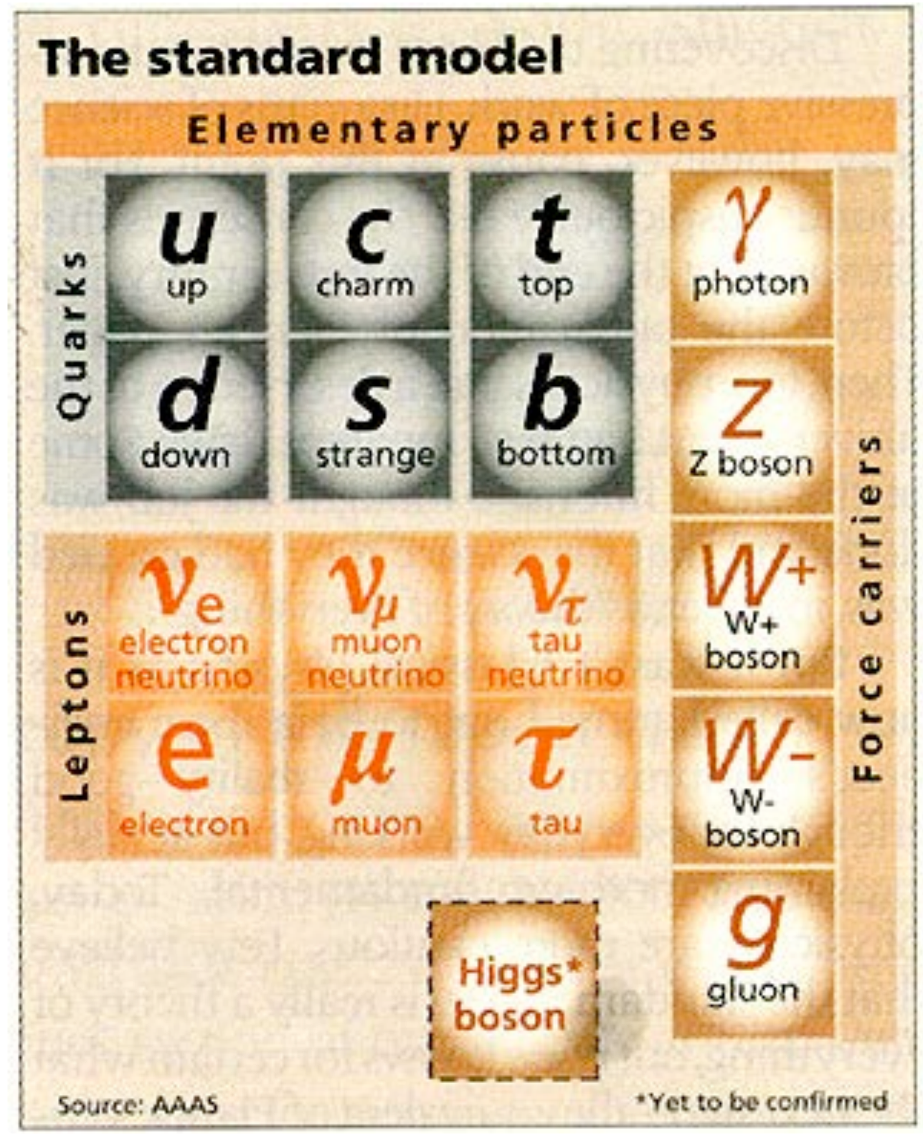
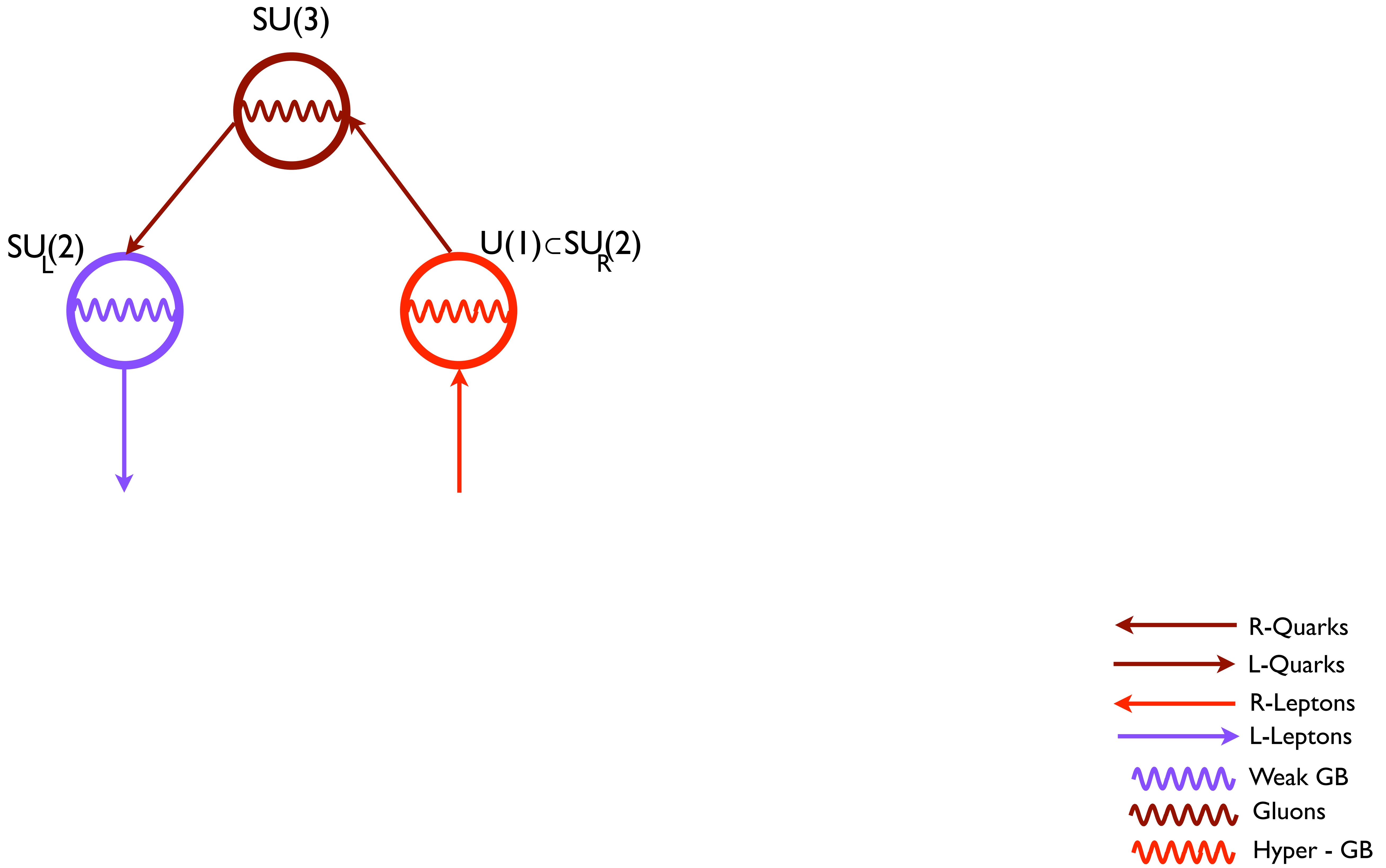
Standard Model

Standard Model





SM - Geometry



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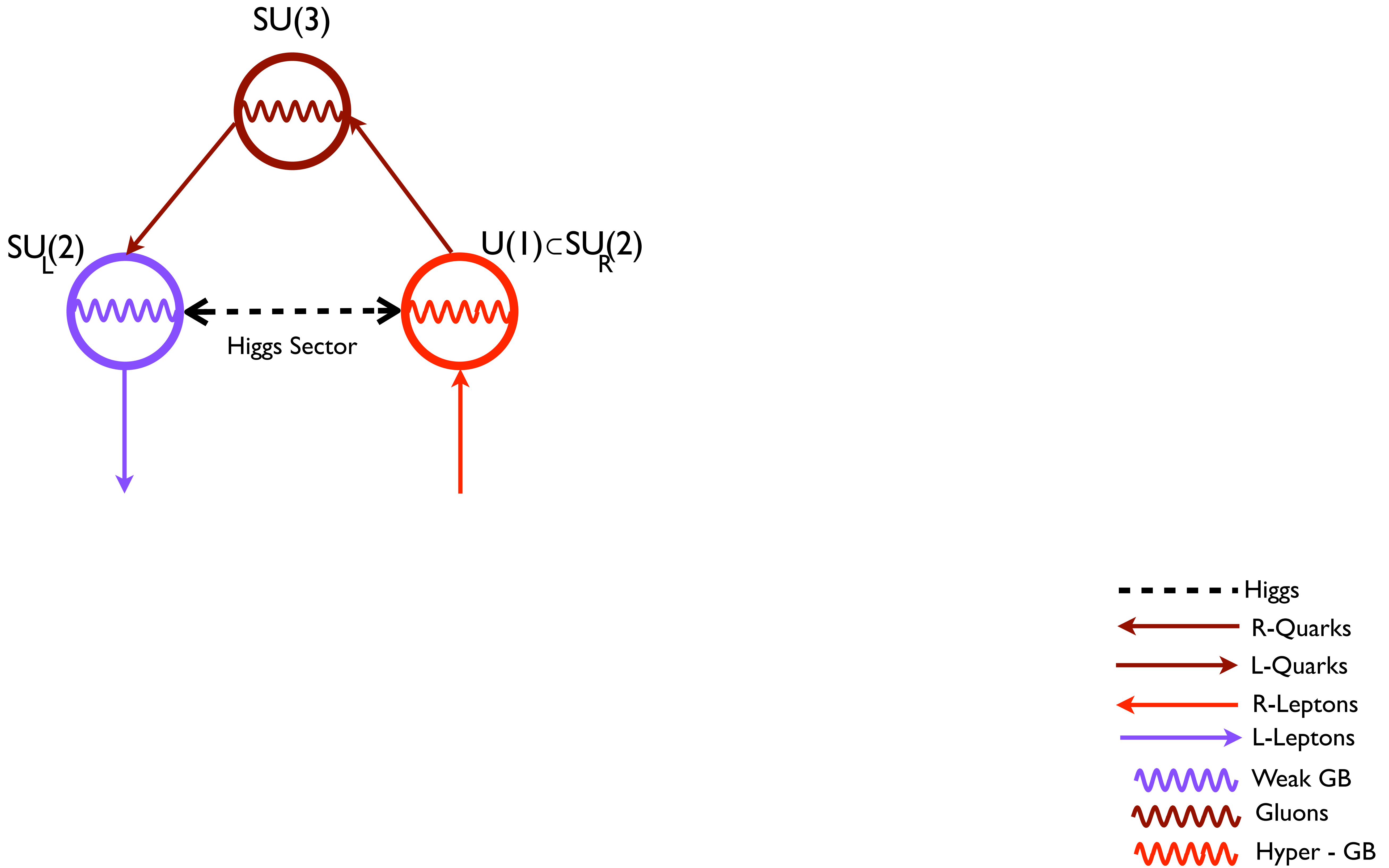

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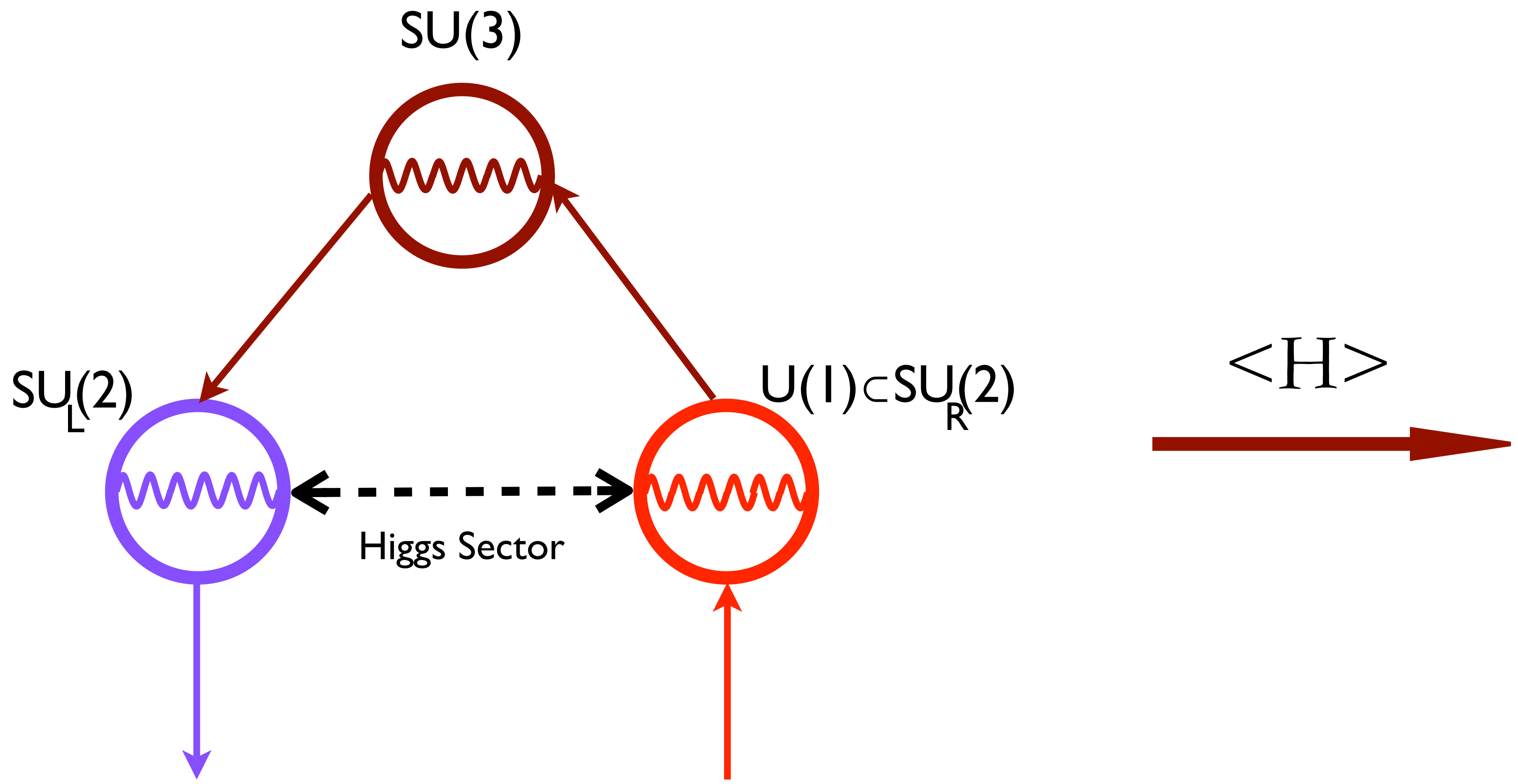

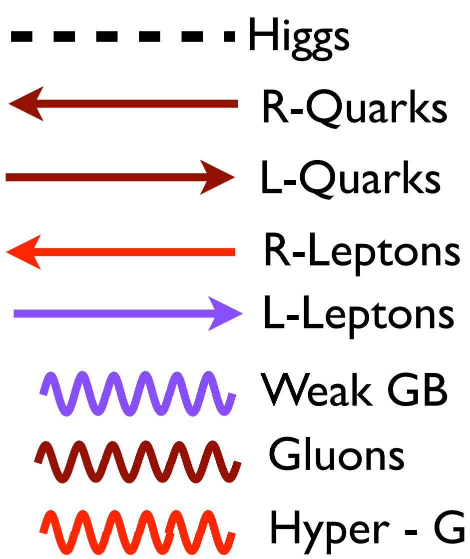

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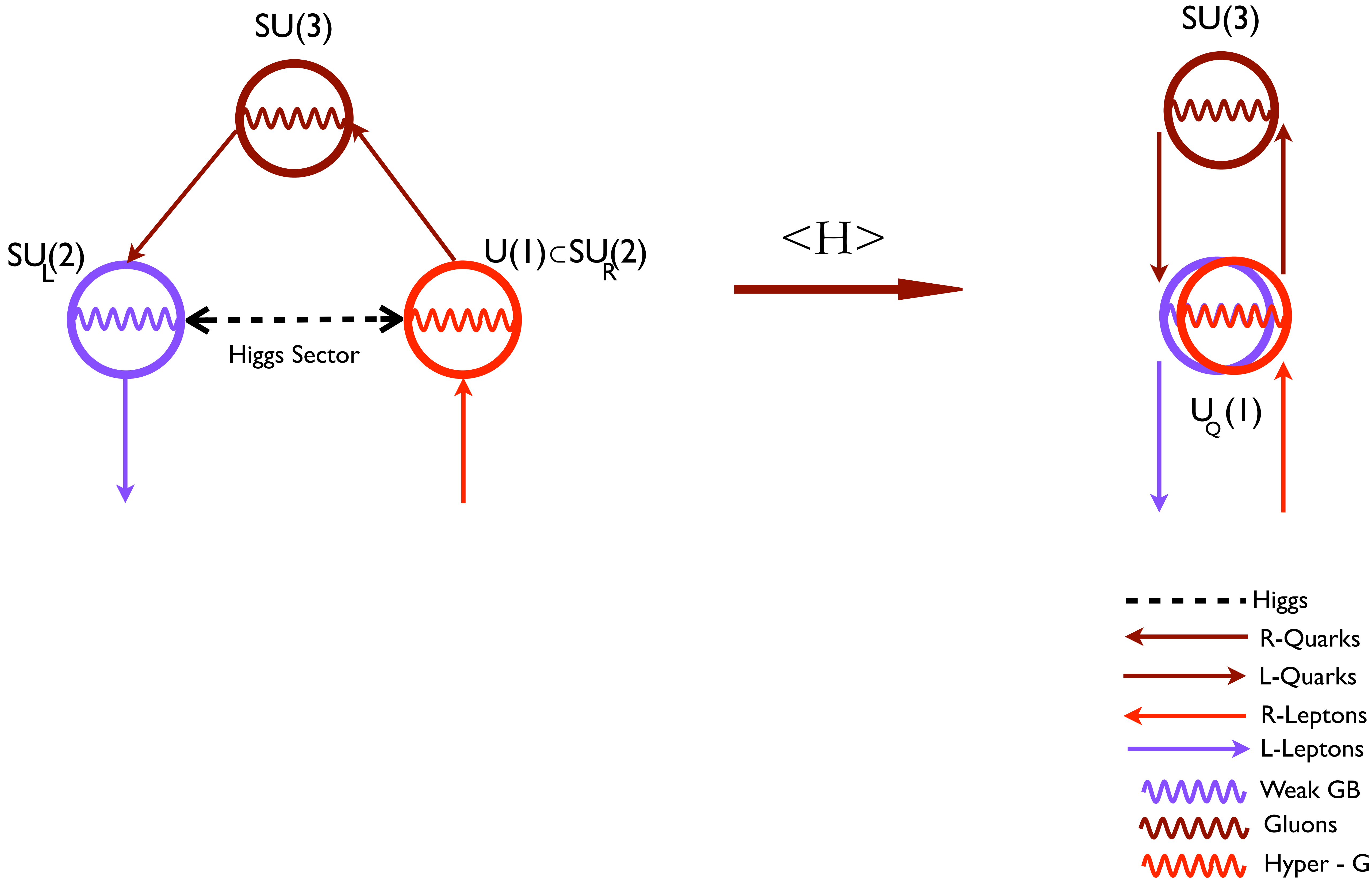

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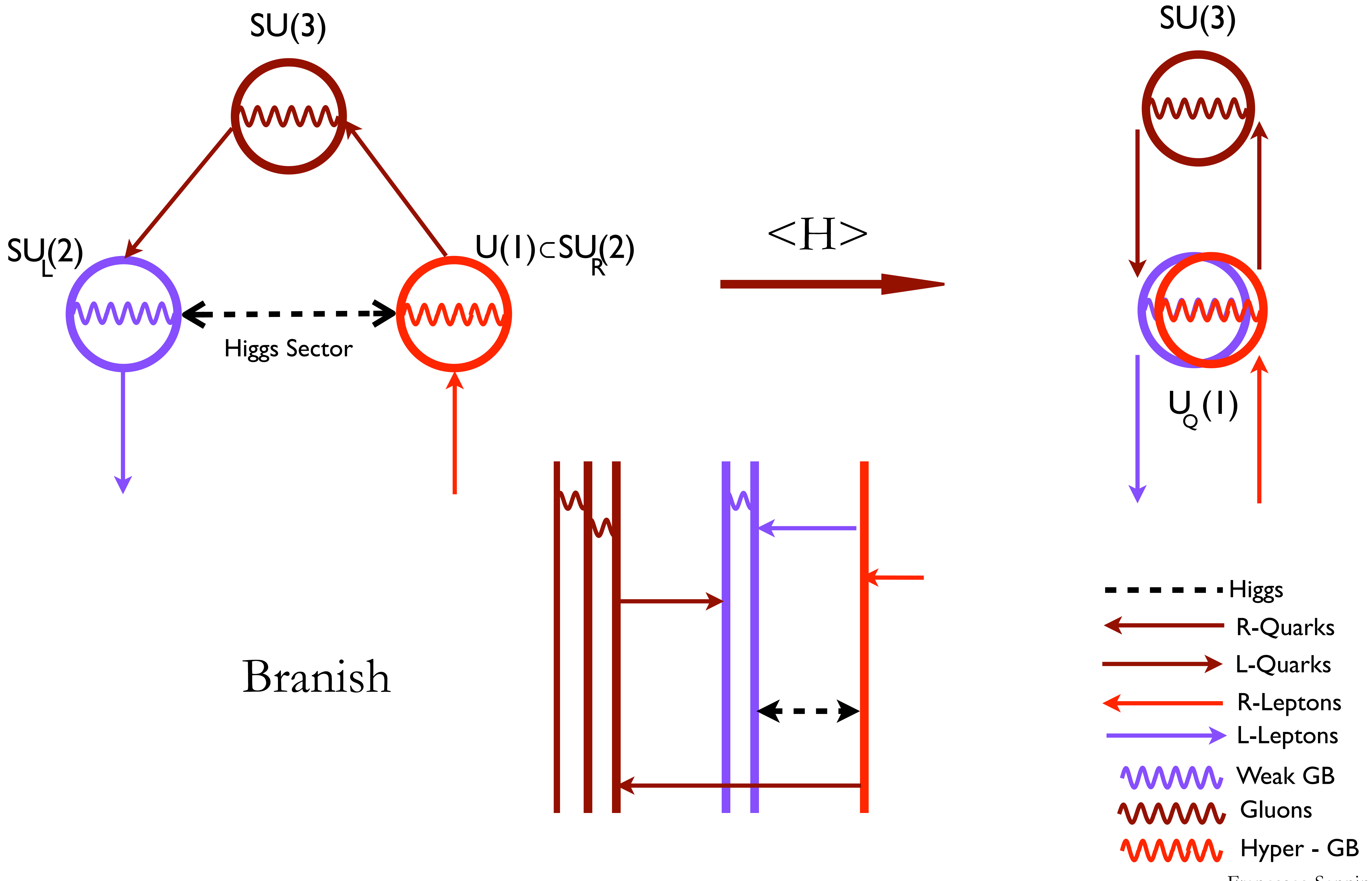

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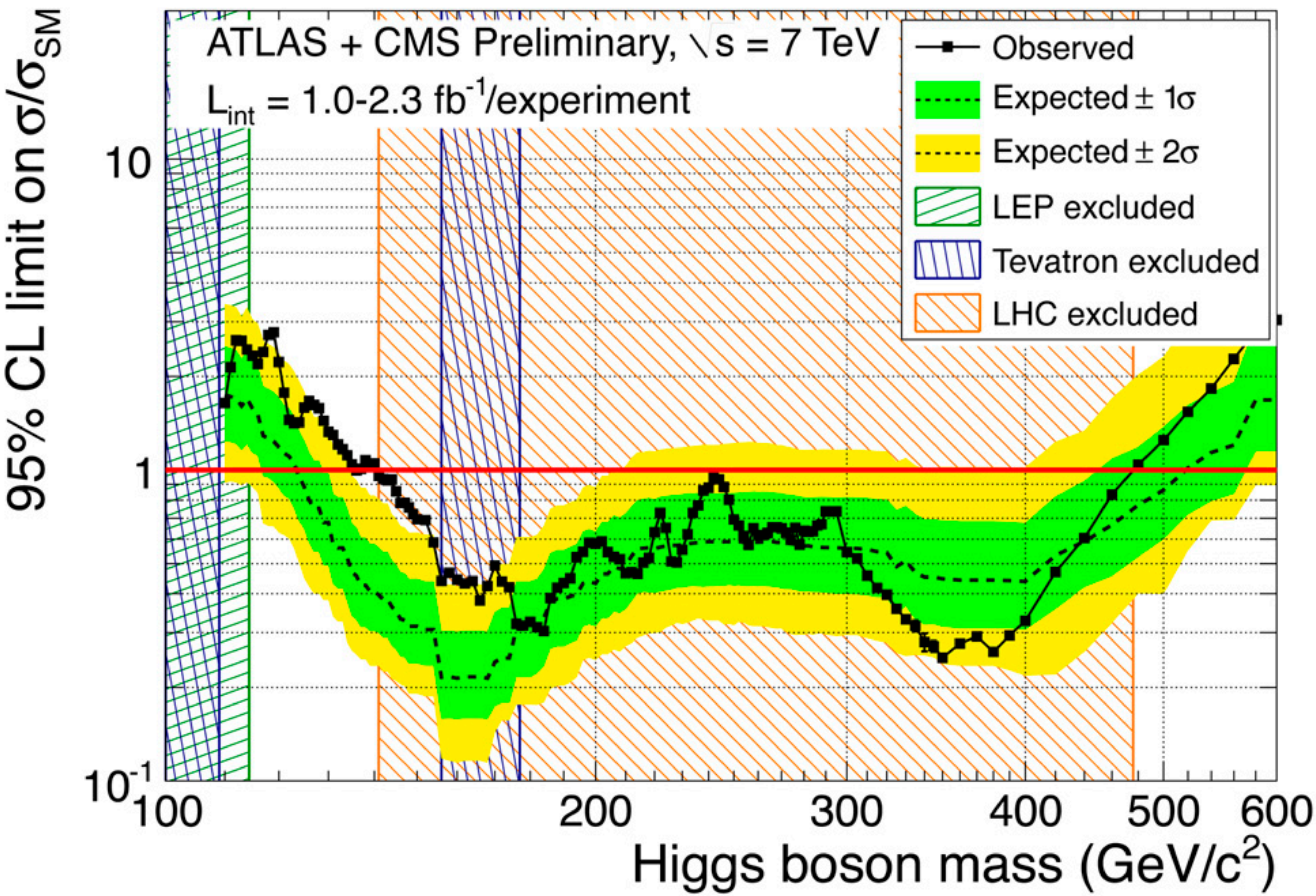
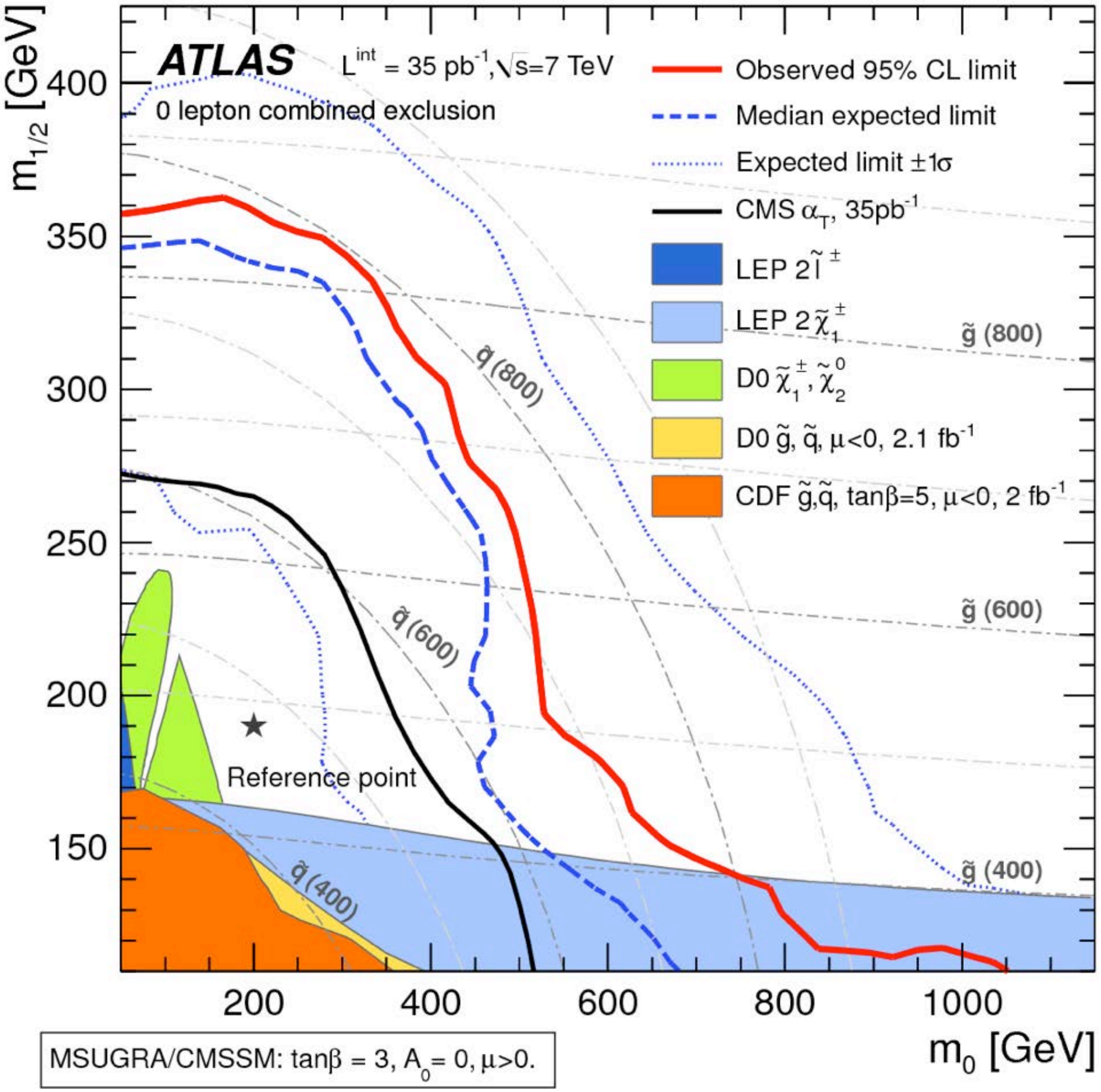
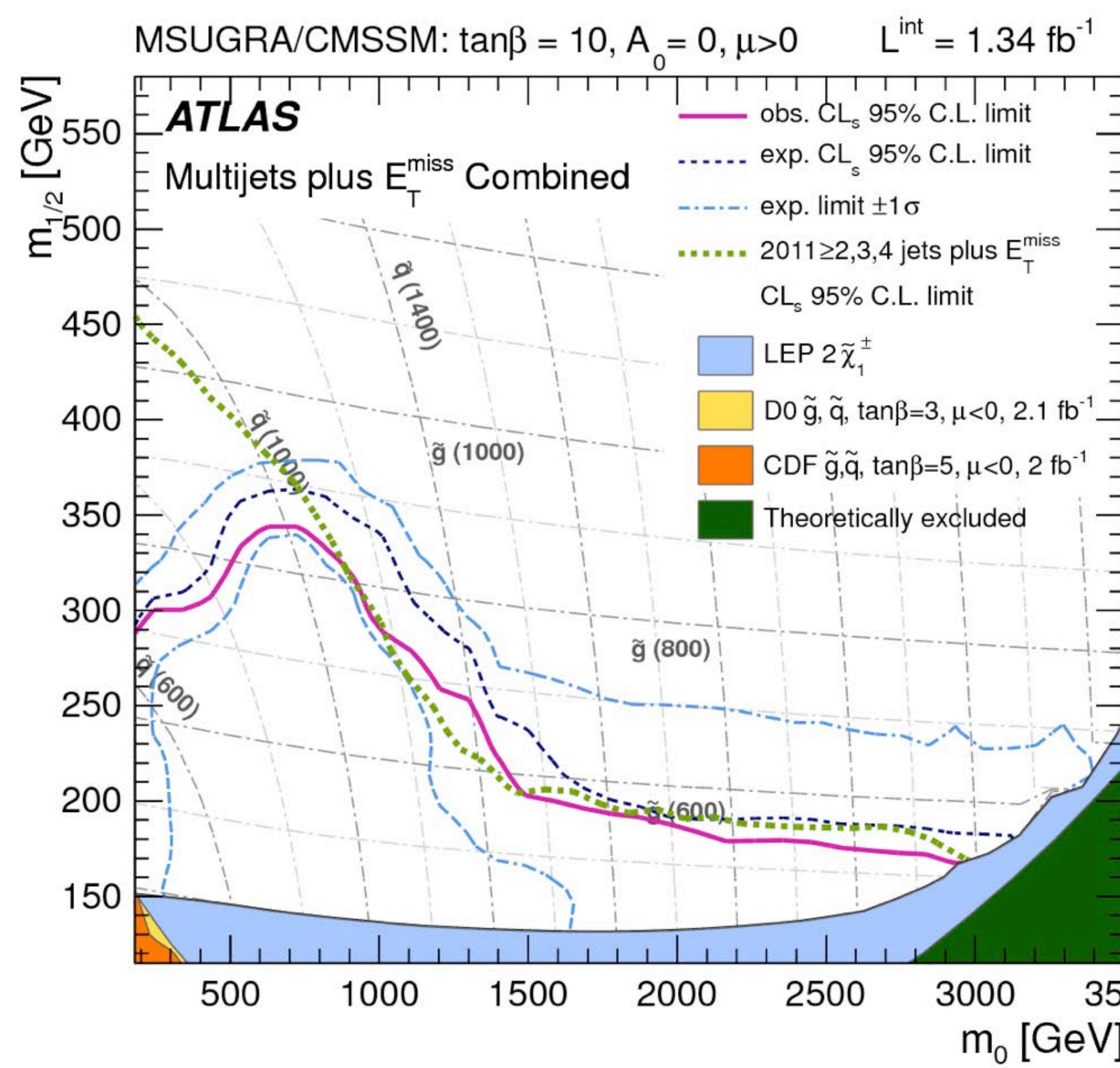
O' Higgs, where art thou!



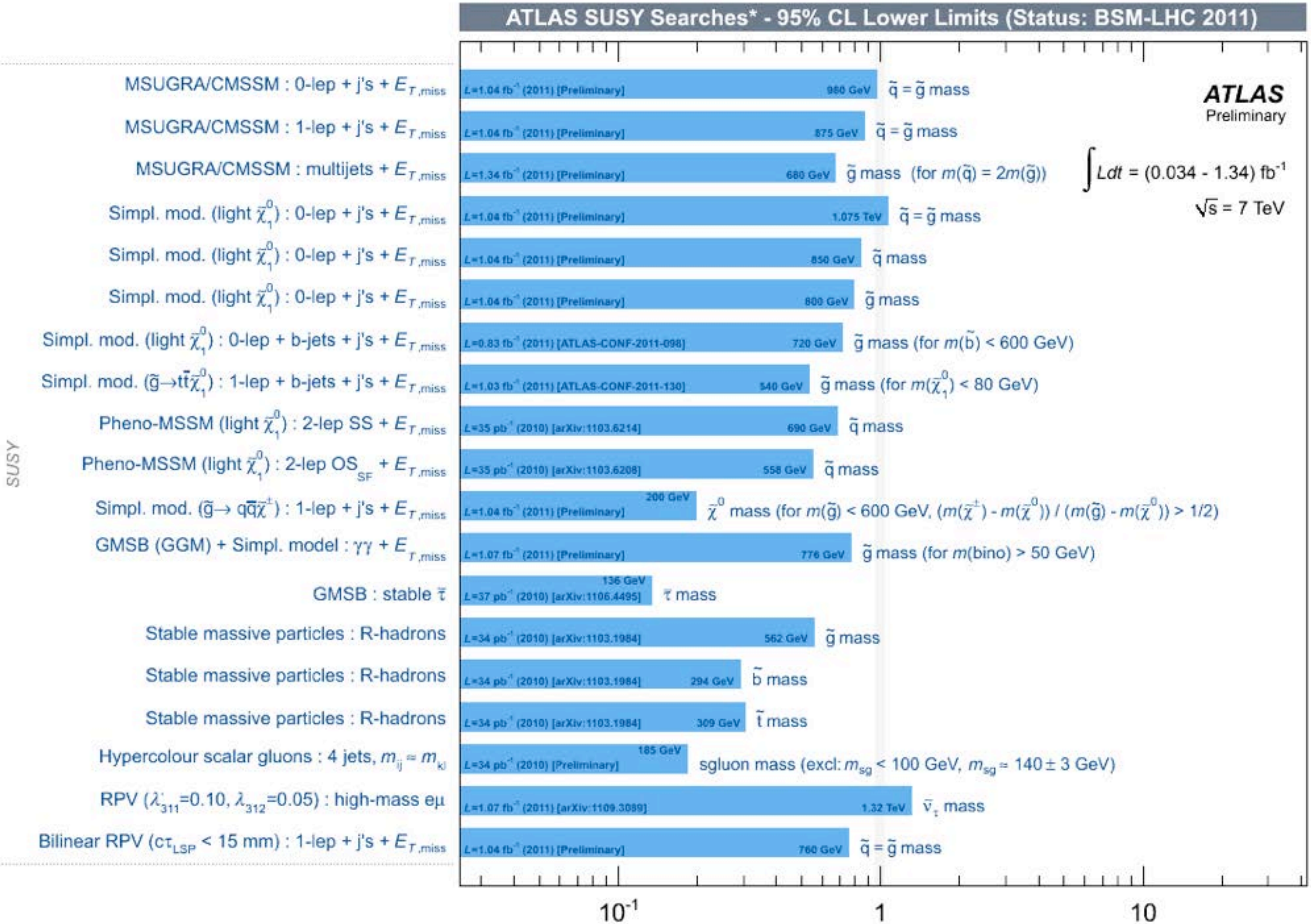
ATLAS + CMS Preliminary, √s = 7 TeV
L_{int} = 1.0-2.3 fb^{-1}/experiment
Observed
Expected ± 1σ
Expected ± 2σ
LEP excluded
Tevatron excluded
LHC excluded
95% CL limit on σ/σ$_{SM}$
10
1
10^{-1}
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

MSSM Status





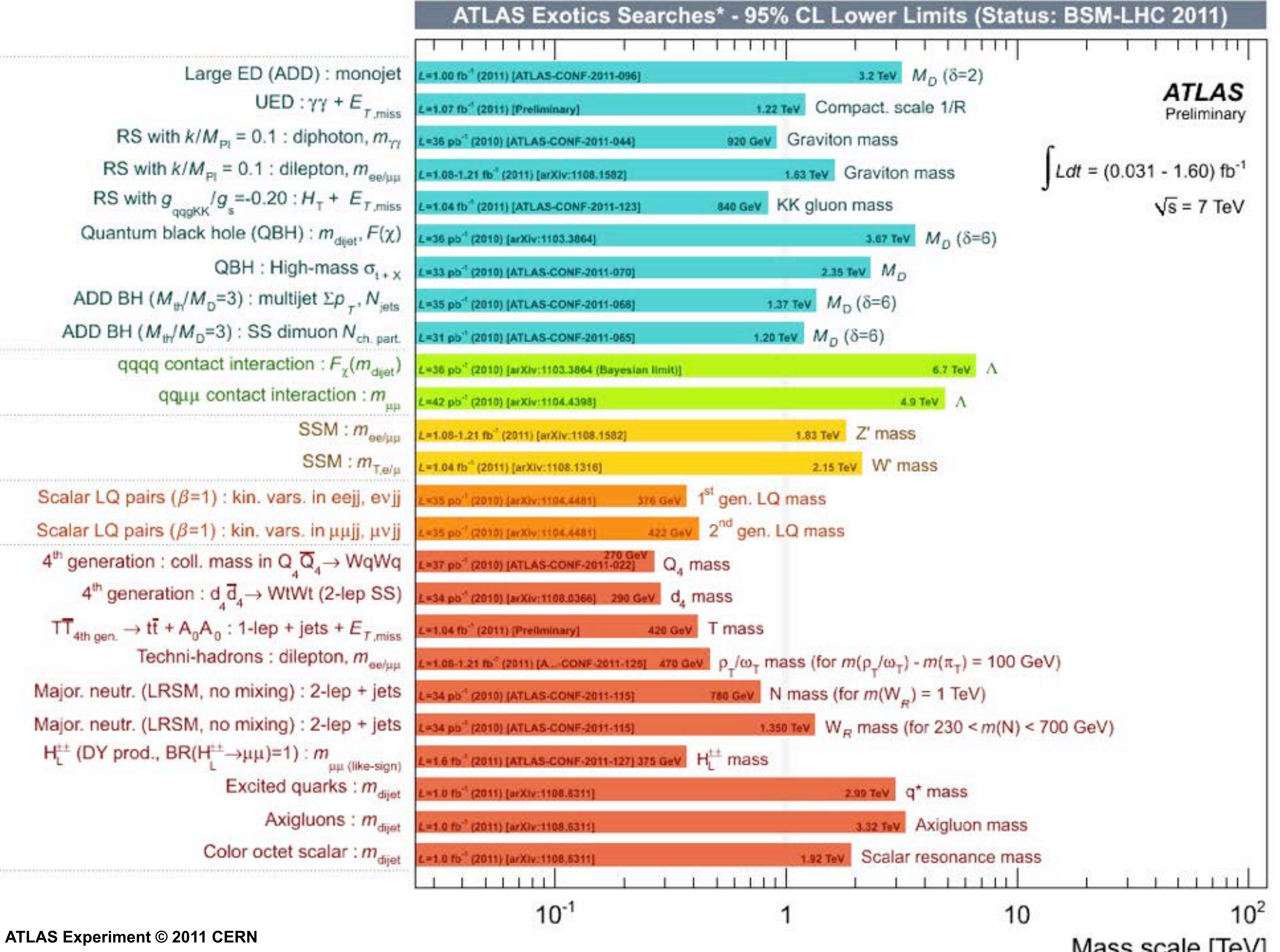
MSUGRA/CMSSM = five parameters:
the universal scalar mass m_0, gaugino mass $m_{1/2}$,
the trilinear scalar coupling A_0,
tan β: the ratio of the VEV of the two Higgses
the sign of the higgsino mass parameter μ.



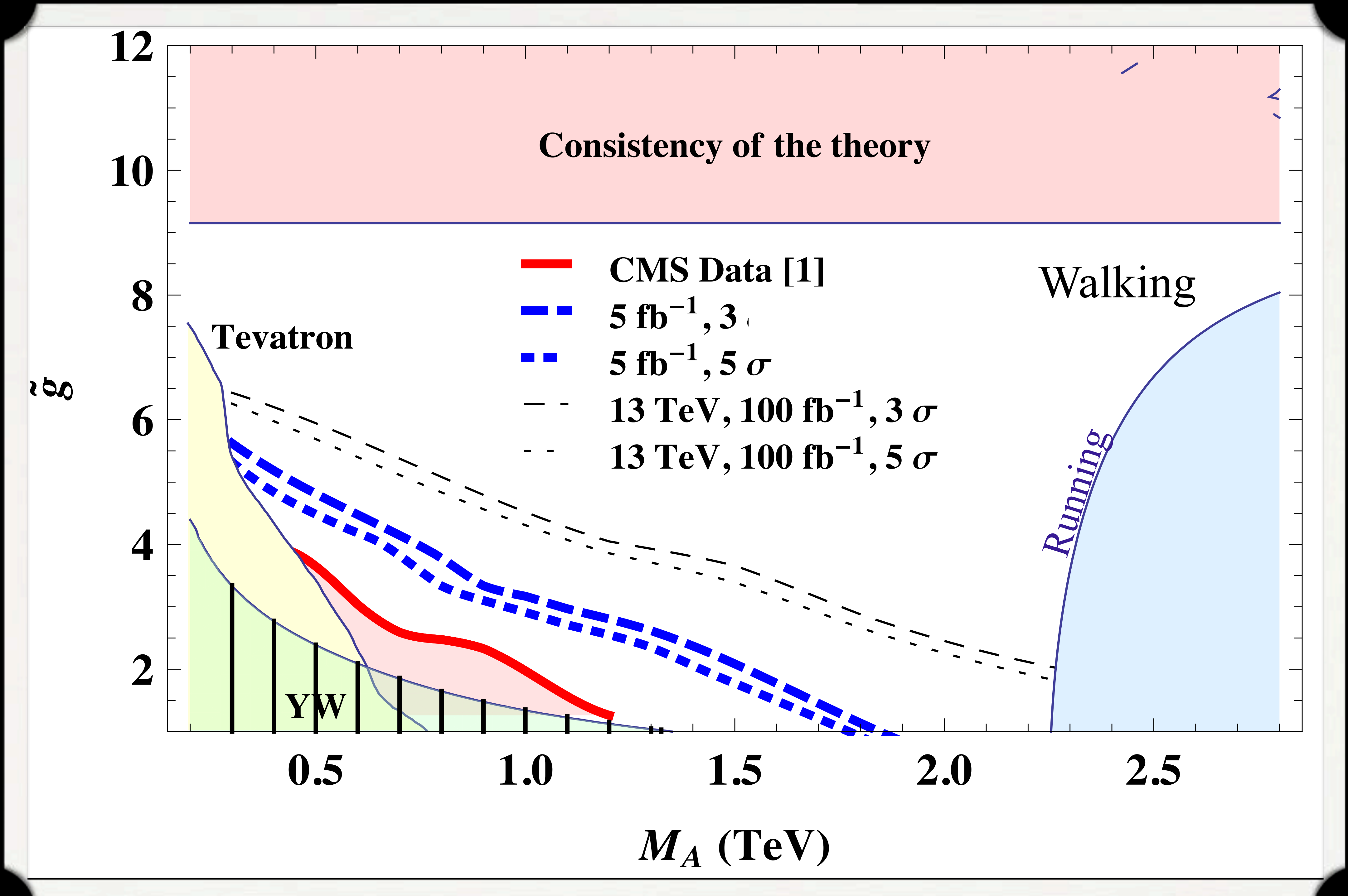
ATLAS Experiment © 2011 CERN

*Only a selection of the available results leading to mass limits shown

What else has LHC not seen ?

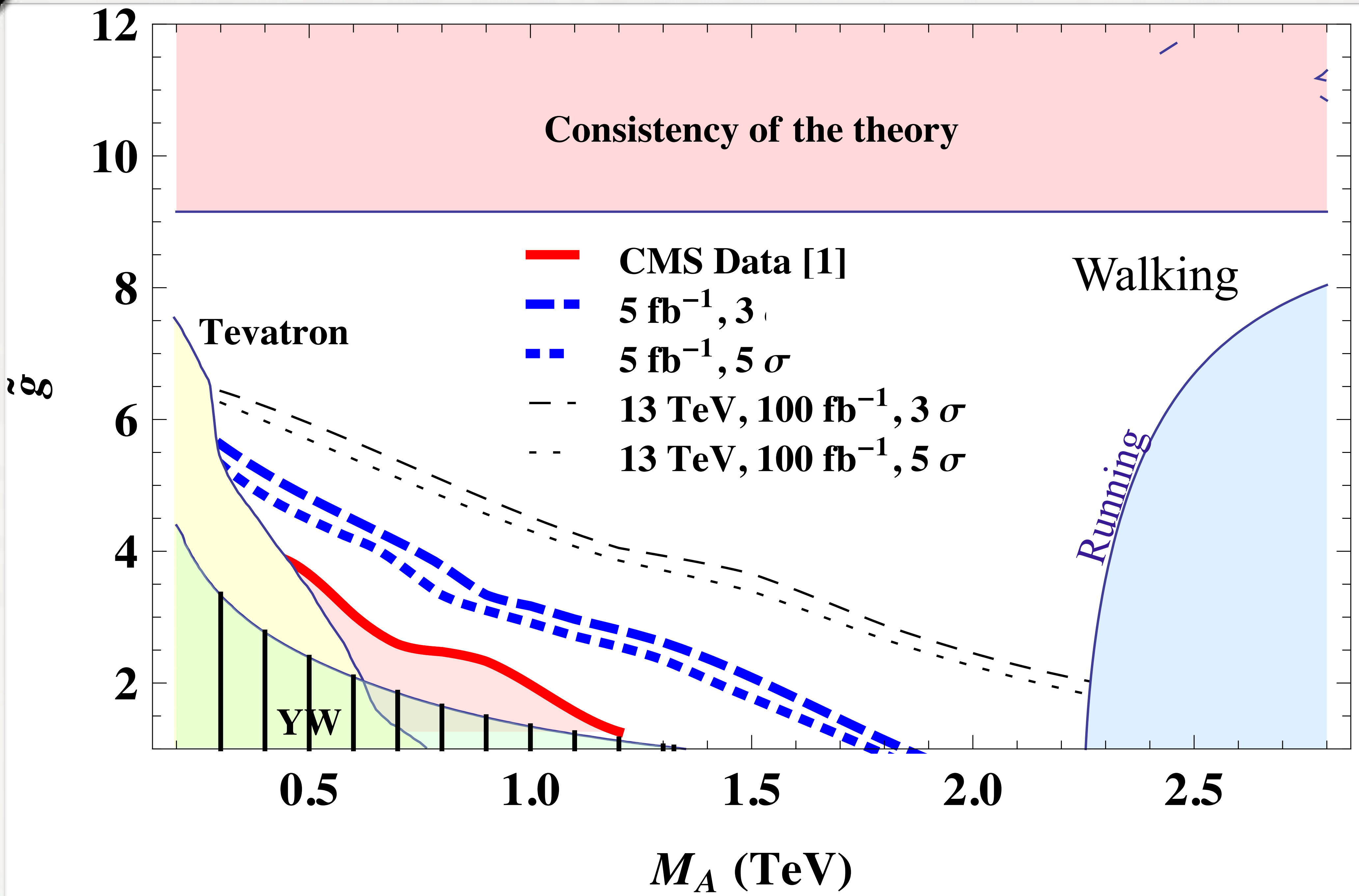

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: BSM-LHC 2011)
ATLAS Preliminary
∫Ldt = (0.031 - 1.60) fb⁻¹
√s = 7 TeV
Large ED (ADD) : monojet
L=1.00 fb⁻¹ (2011) [ATLAS-CONF-2011-096] 3.2 TeV M_D (δ=2)
UED : γγ + E_T,miss
L=1.07 fb⁻¹ (2011) [Preliminary] 1.22 TeV Compact. scale 1/R
RS with k/M_Pl = 0.1 : diphoton, m_γγ
L=36 pb⁻¹ (2010) [ATLAS-CONF-2011-044] 920 GeV Graviton mass
RS with k/M_Pl = 0.1 : dilepton, m_ee/μμ
L=1.08-1.21 fb⁻¹ (2011) [arXiv:1108.1582] 1.63 TeV Graviton mass
RS with g_qqgKK/g_s=-0.20 : H_T + E_T,miss
L=1.04 fb⁻¹ (2011) [ATLAS-CONF-2011-123] 840 GeV KK gluon mass
Quantum black hole (QBH) : m_dijet, F(χ)
L=36 pb⁻¹ (2010) [arXiv:1103.3864] 3.67 TeV M_D (δ=6)
QBH : High-mass σ_t+X
L=33 pb⁻¹ (2010) [ATLAS-CONF-2011-070] 2.35 TeV M_D
ADD BH (M_th/M_D=3) : multijet Σp_T, N_jets
L=35 pb⁻¹ (2010) [ATLAS-CONF-2011-068] 1.37 TeV M_D (δ=6)
ADD BH (M_th/M_D=3) : SS dimuon N_ch. part.
L=31 pb⁻¹ (2010) [ATLAS-CONF-2011-065] 1.20 TeV M_D (δ=6)
qqqq contact interaction : F_χ(m_dijet)
L=36 pb⁻¹ (2010) [arXiv:1103.3864 (Bayesian limit)] 6.7 TeV Λ
qqμμ contact interaction : m_μμ
L=42 pb⁻¹ (2010) [arXiv:1104.4398] 4.9 TeV Λ
SSM : m_ee/μμ
L=1.08-1.21 fb⁻¹ (2011) [arXiv:1108.1582] 1.83 TeV Z' mass
SSM : m_T,e/μ
L=1.04 fb⁻¹ (2011) [arXiv:1108.1316] 2.15 TeV W' mass
Scalar LQ pairs (β=1) : kin. vars. in eejj, eνjj
L=35 pb⁻¹ (2010) [arXiv:1104.4481] 376 GeV 1st gen. LQ mass
Scalar LQ pairs (β=1) : kin. vars. in μμjj, μνjj
L=35 pb⁻¹ (2010) [arXiv:1104.4481] 422 GeV 2nd gen. LQ mass
4th generation : coll. mass in Q4 Q̄4 → WqWq
L=37 pb⁻¹ (2010) [ATLAS-CONF-2011-022] 270 GeV Q4 mass
4th generation : d4 d̄4 → WtWt (2-lep SS)
L=34 pb⁻¹ (2010) [arXiv:1108.0366] 290 GeV d4 mass
TT̄4th gen. → tt̄ + A0A0 : 1-lep + jets + E_T,miss
L=1.04 fb⁻¹ (2011) [Preliminary] 420 GeV T mass
Techni-hadrons : dilepton, m_ee/μμ
L=1.08-1.21 fb⁻¹ (2011) [A...-CONF-2011-125] 470 GeV ρT/ωT mass (for m(ρT/ωT) - m(πT) = 100 GeV)
Major. neutr. (LRSM, no mixing) : 2-lep + jets
L=34 pb⁻¹ (2010) [ATLAS-CONF-2011-115] 780 GeV N mass (for m(W_R) = 1 TeV)
Major. neutr. (LRSM, no mixing) : 2-lep + jets
L=34 pb⁻¹ (2010) [ATLAS-CONF-2011-115] 1.350 TeV W_R mass (for 230 < m(N) < 700 GeV)
H_L^±± (DY prod., BR(H_L^±±→μμ)=1) : m_μμ (like-sign)
L=1.6 fb⁻¹ (2011) [ATLAS-CONF-2011-127] 375 GeV H_L^±± mass
Excited quarks : m_dijet
L=1.0 fb⁻¹ (2011) [arXiv:1108.6311] 2.99 TeV q* mass
Axigluons : m_dijet
L=1.0 fb⁻¹ (2011) [arXiv:1108.6311] 3.32 TeV Axigluon mass
Color octet scalar : m_dijet
L=1.0 fb⁻¹ (2011) [arXiv:1108.6311] 1.92 TeV Scalar resonance mass
10⁻¹
1
10
10²
Mass scale [TeV]

What about Technicolor ?



Andersen, Hapola, Sannino 11

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



Much unexplored !

Andersen, Hapola, Sannino 11

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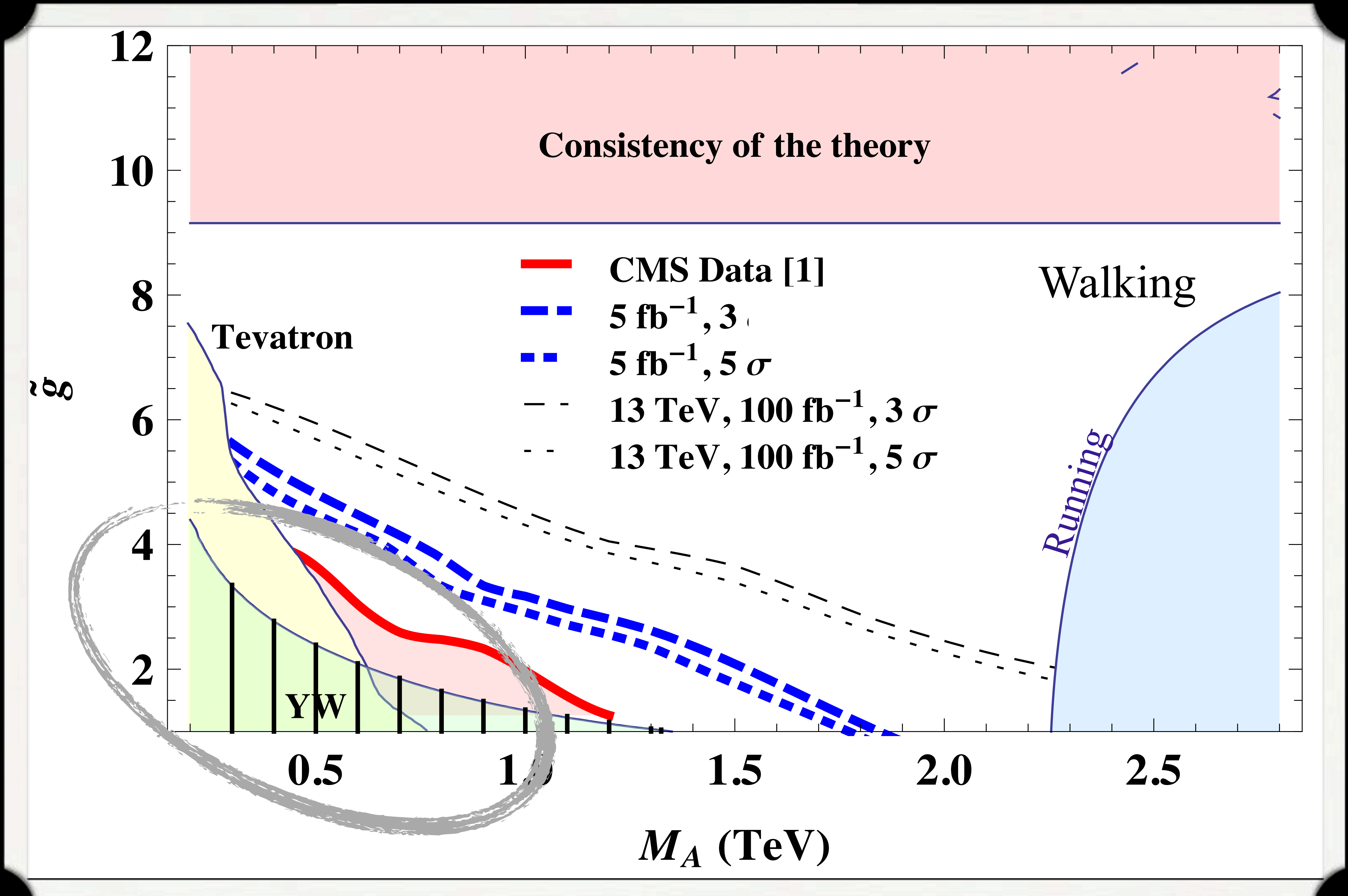

Much unexplored !

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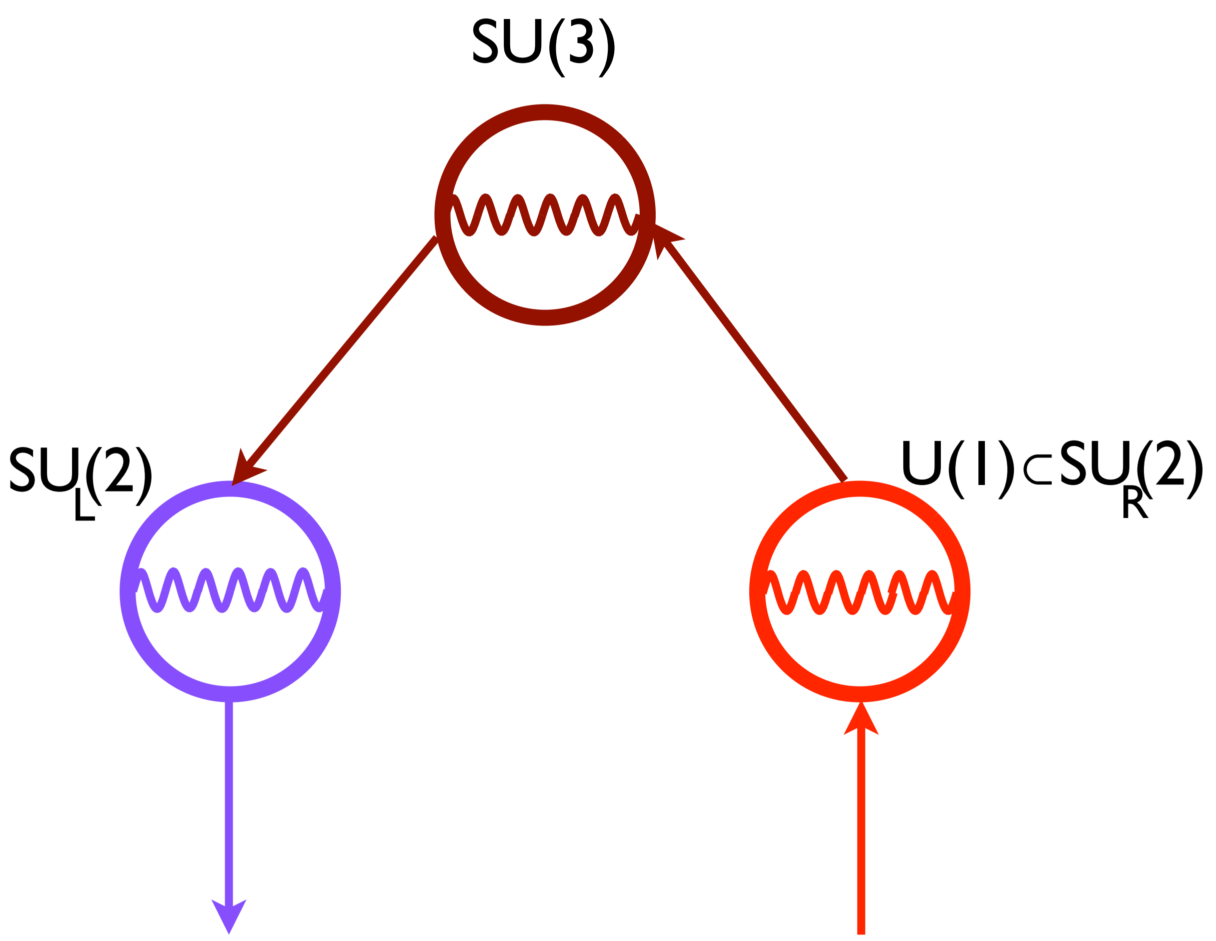
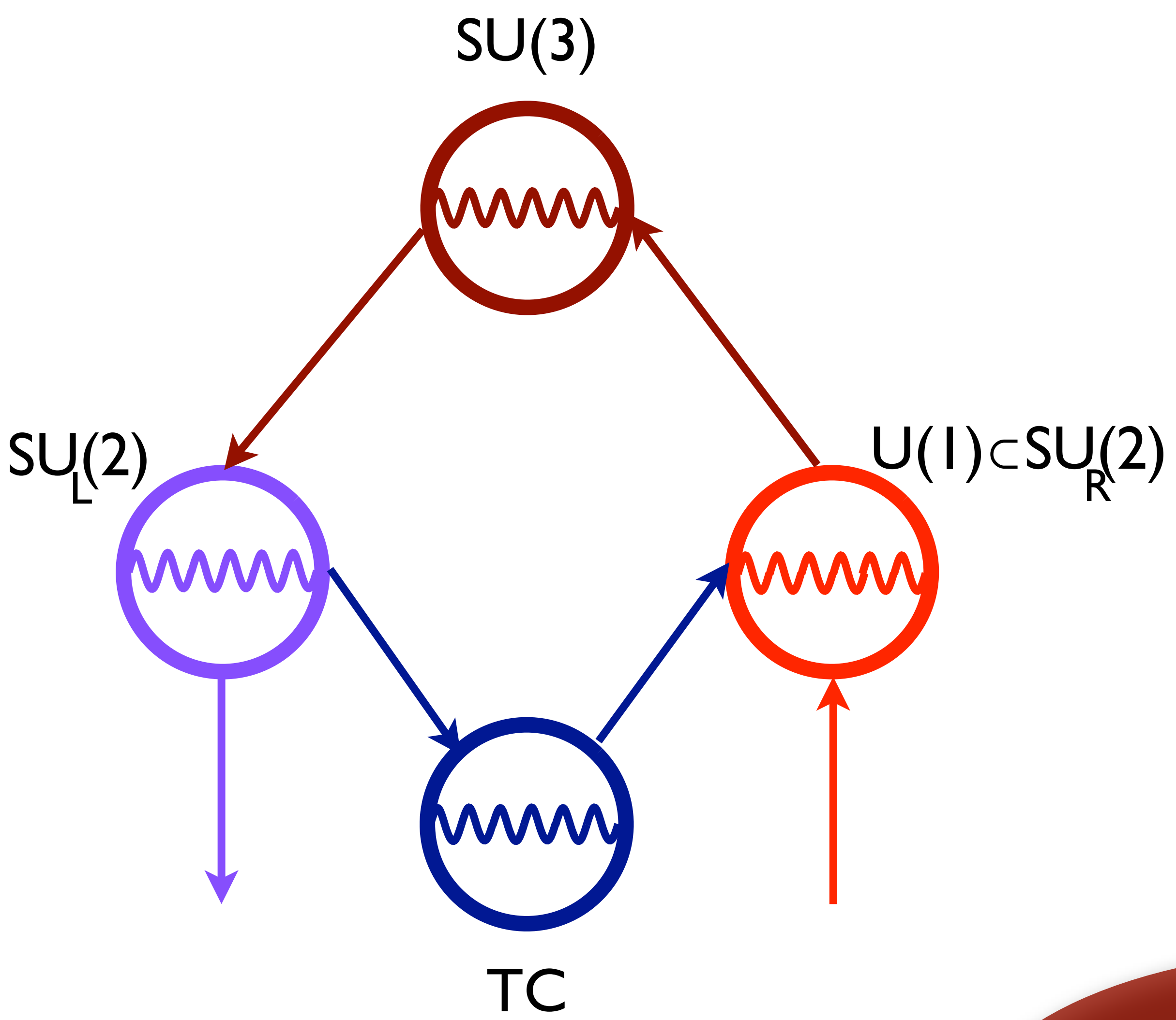
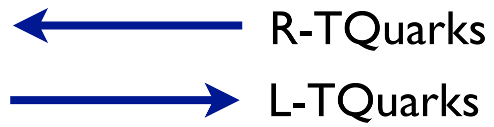
Technicolor - Geometry



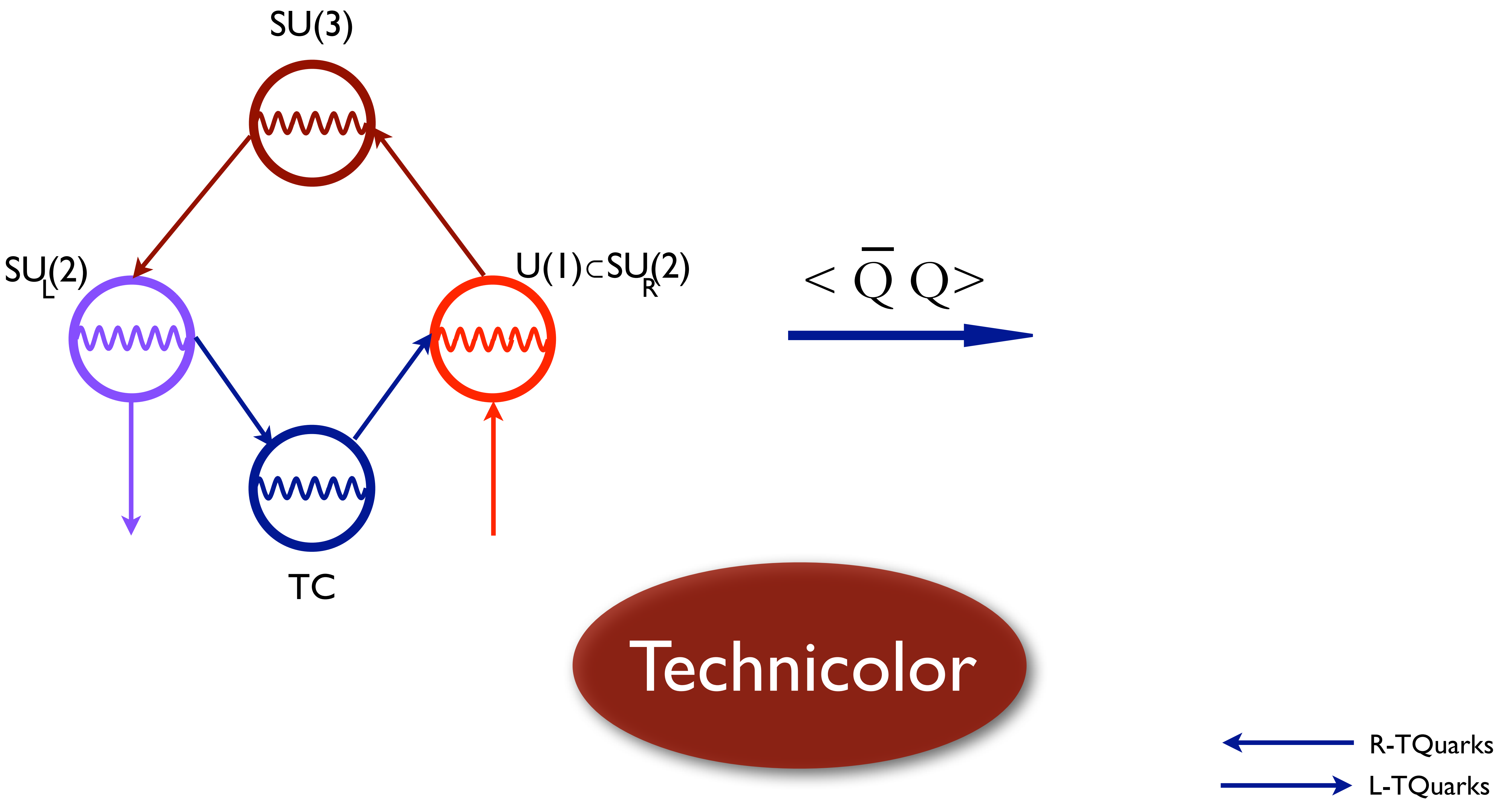
Technicolor - Geometry



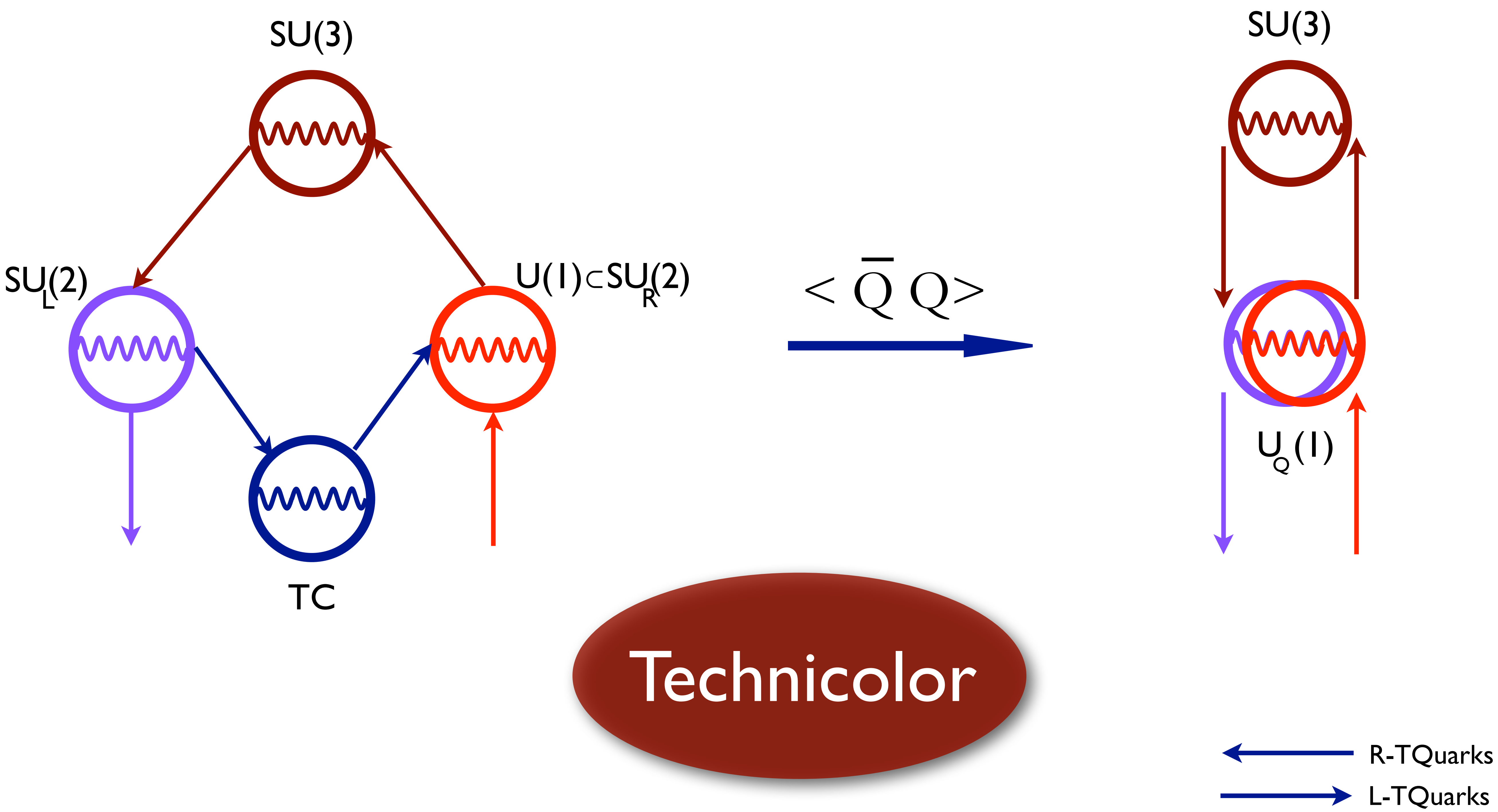
Technicolor



Technicolor - Geometry



Technicolor - Geometry



Dynamical EW Breaking

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

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

Dots are partially fixed by Anomalies as well as other principles

Dynamical EW Breaking

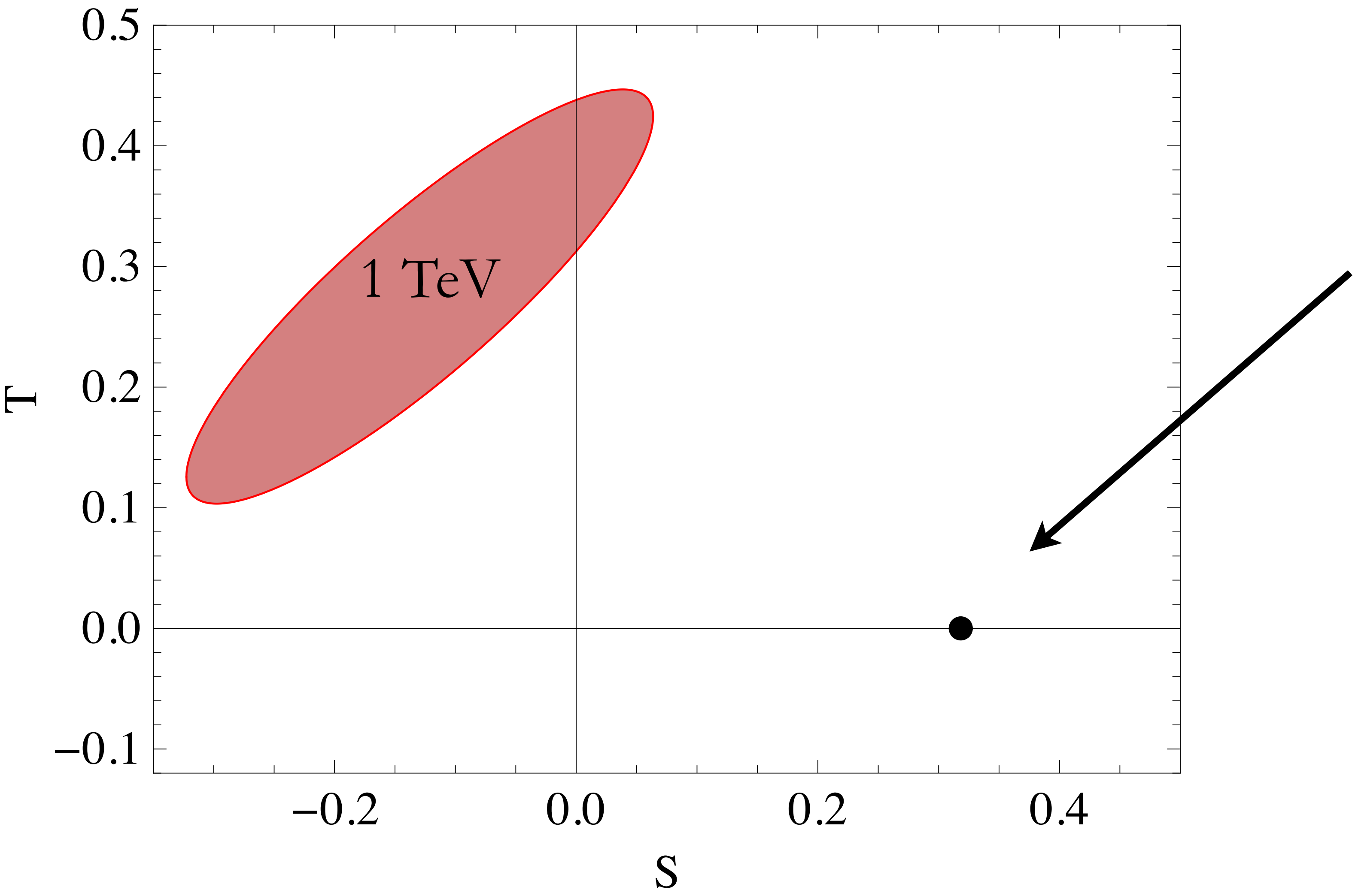
$$L(H) \to -\frac{1}{4}F^{a\mu\nu}F^{a}_{\mu\nu} + i\,\bar{Q}\gamma^{\mu}D_{\mu}Q + \cdots$$

Dots are partially fixed by Anomalies as well as other principles

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

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

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Scalar-less New Gauge Interactions (Extended TC)

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Marry SUSY and Technicolor

Different Approaches

Scalar-less New Gauge Interactions (Extended TC)

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Add New Scalars in the Flavor Sector

Different Approaches

Scalar-less New Gauge Interactions (Extended TC)

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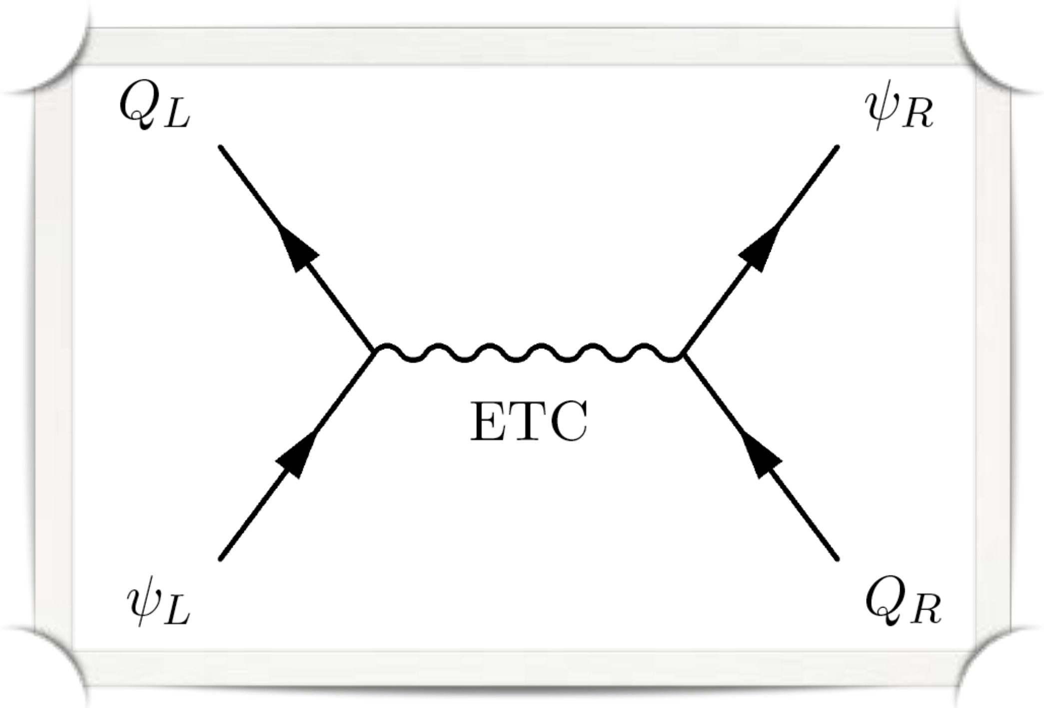
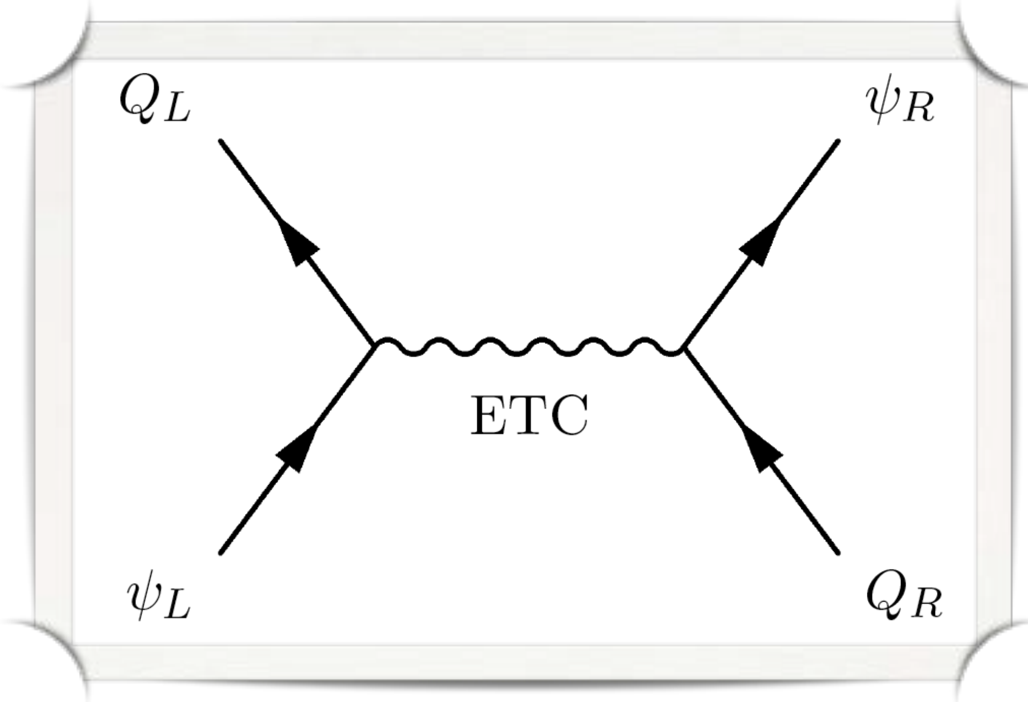
.....

Naive Extended Technicolor



Eichten & Lane 80

Naive Extended Technicolor

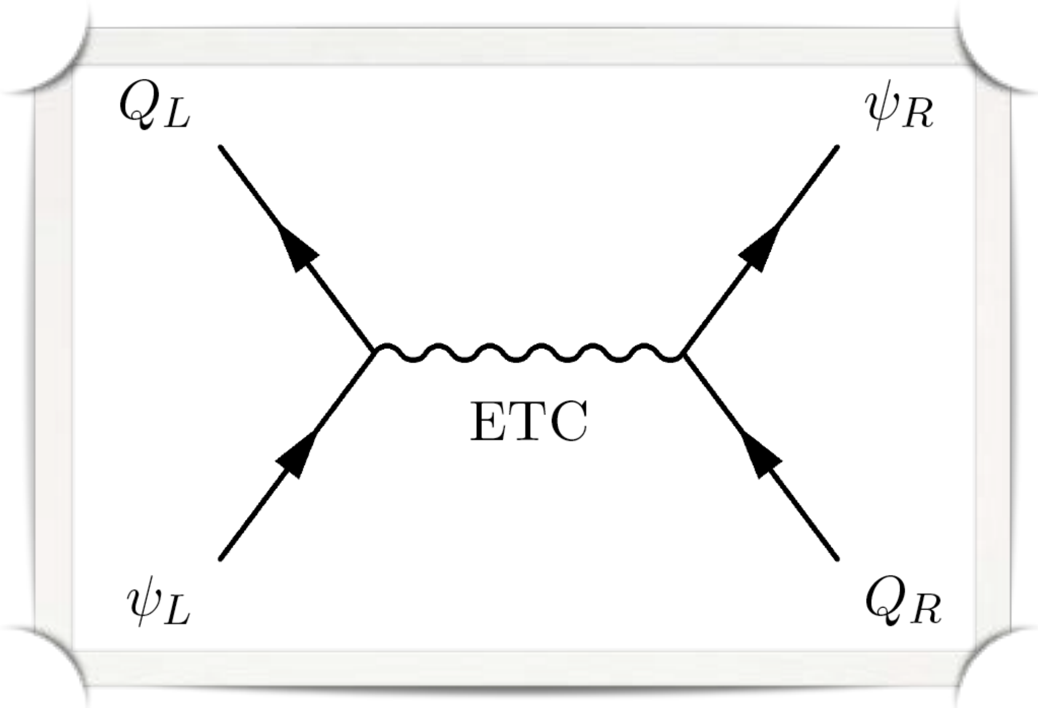


Eichten & Lane 80

Recent investigations

Ryttov & Shrock 10

Naive Extended Technicolor



Eichten & Lane 80

Recent investigations

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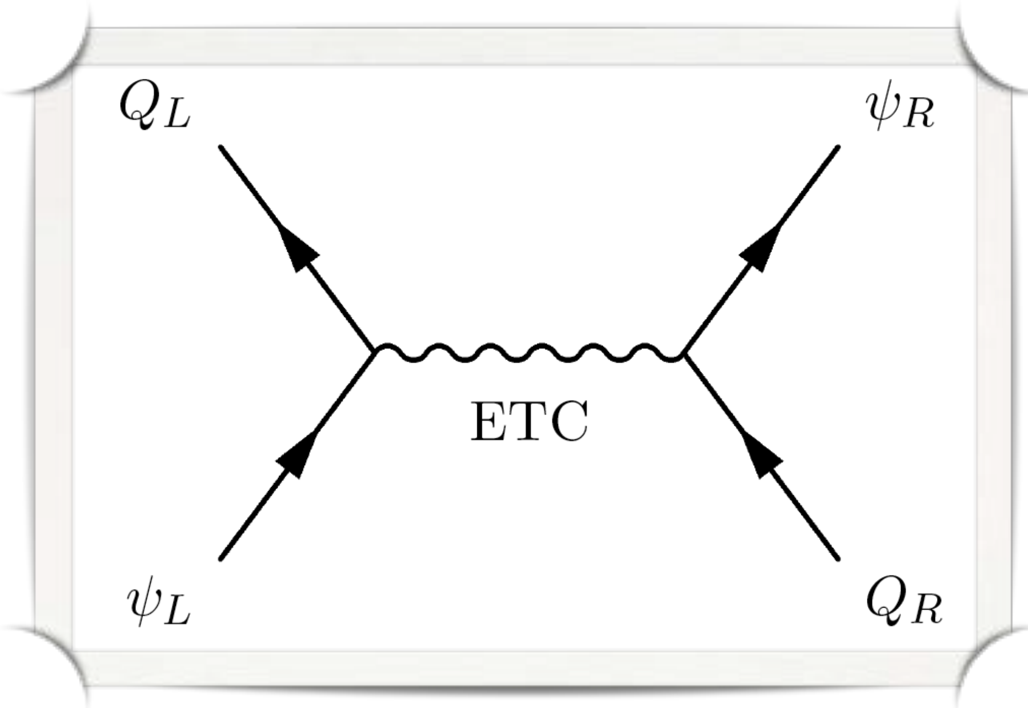
$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \dots$$

Naive Extended Technicolor



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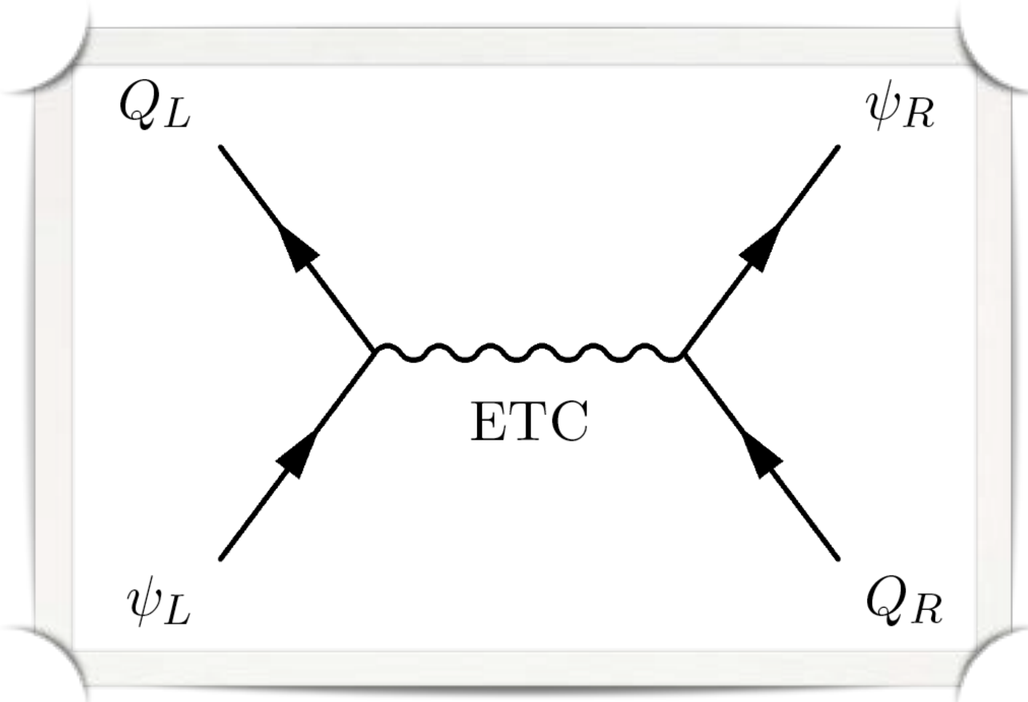
$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda_{ETC}^2} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda_{ETC}^2} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda_{ETC}^2} + \dots$$

PNG
Masses

Naive Extended Technicolor



Eichten & Lane 80

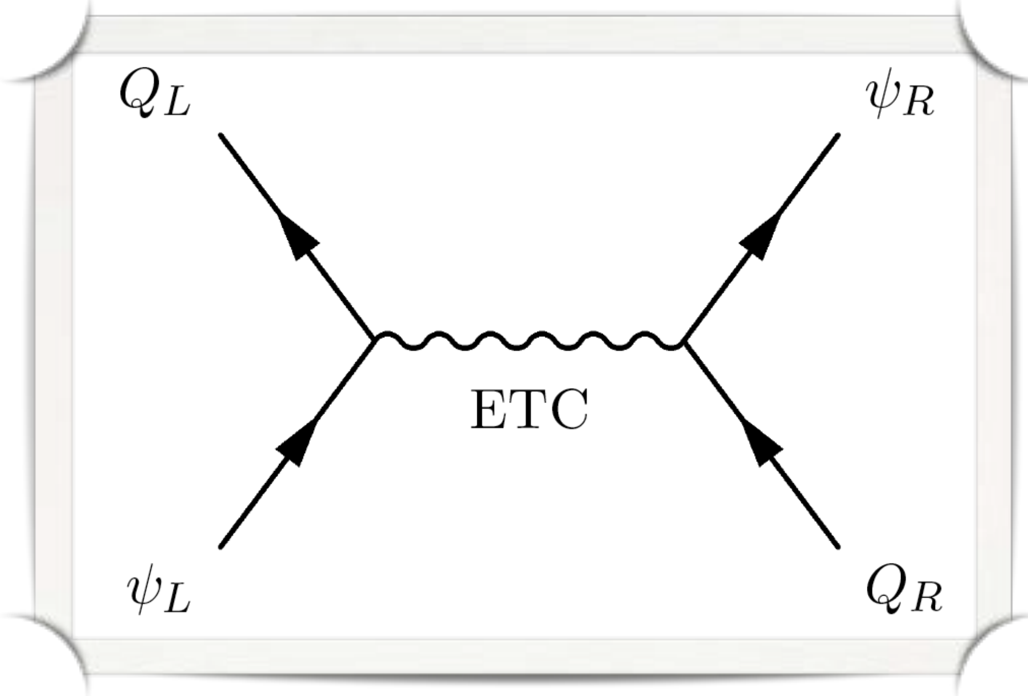
Recent investigations
Ryttov & Shrock 10

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

PNG
Masses

SM-Fermion
Masses

Naive Extended Technicolor



Eichten & Lane 80

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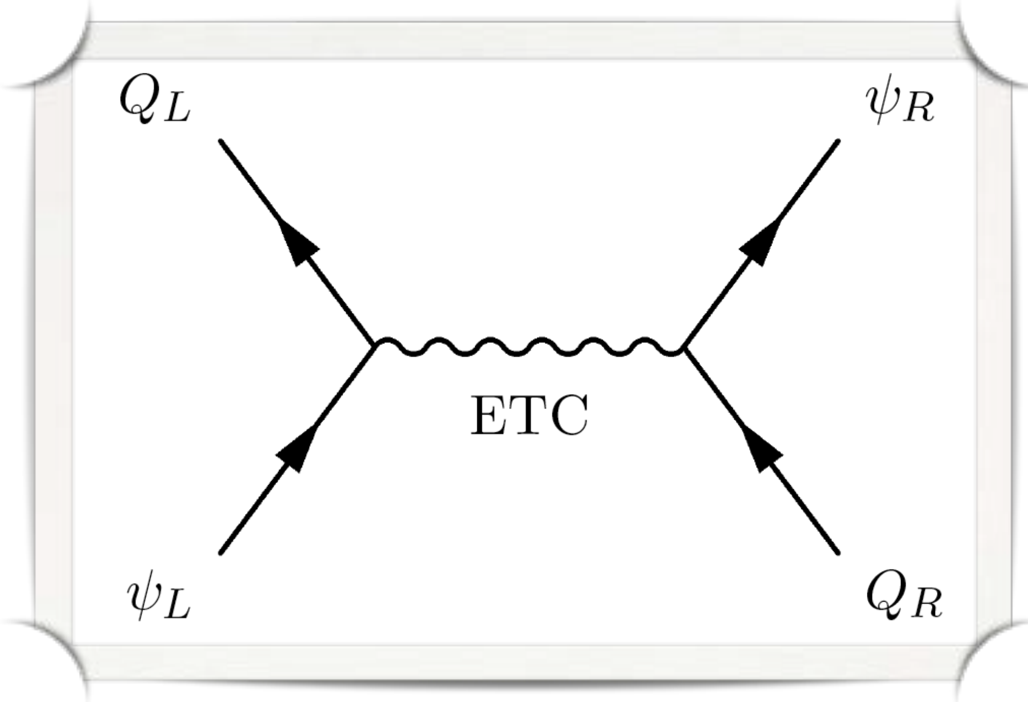
PNG Masses

SM-Fermion Masses

FCNC Operators

Naive Extended Technicolor



Eichten & Lane 80

Recent investigations

Ryttov & Shrock 10

Modifies TC dynamics

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

PNG Masses

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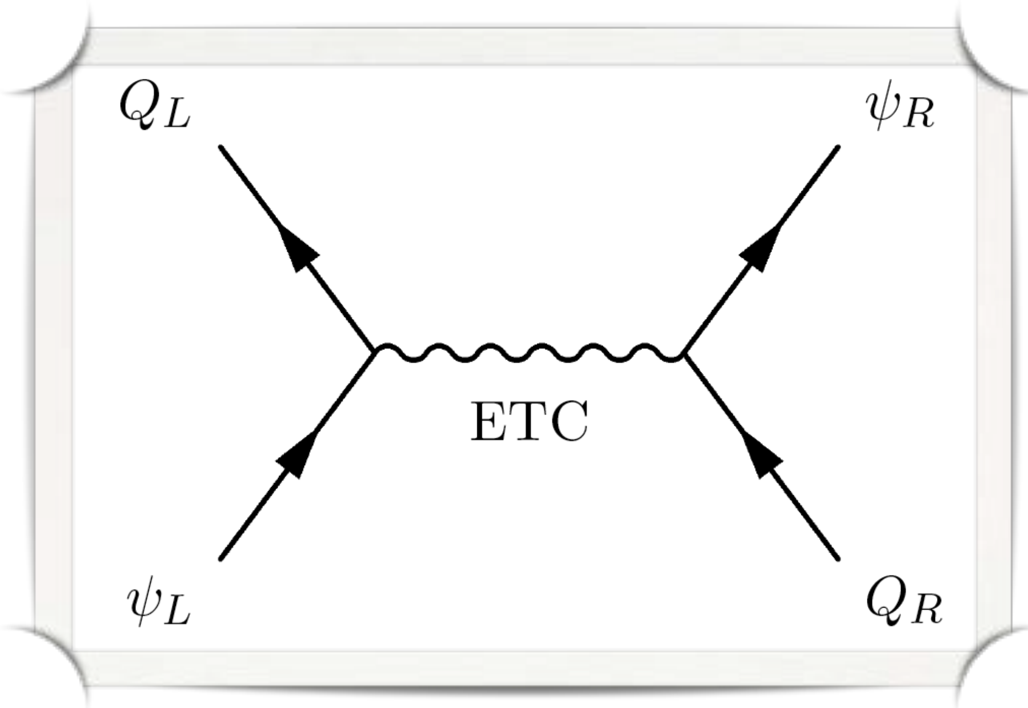

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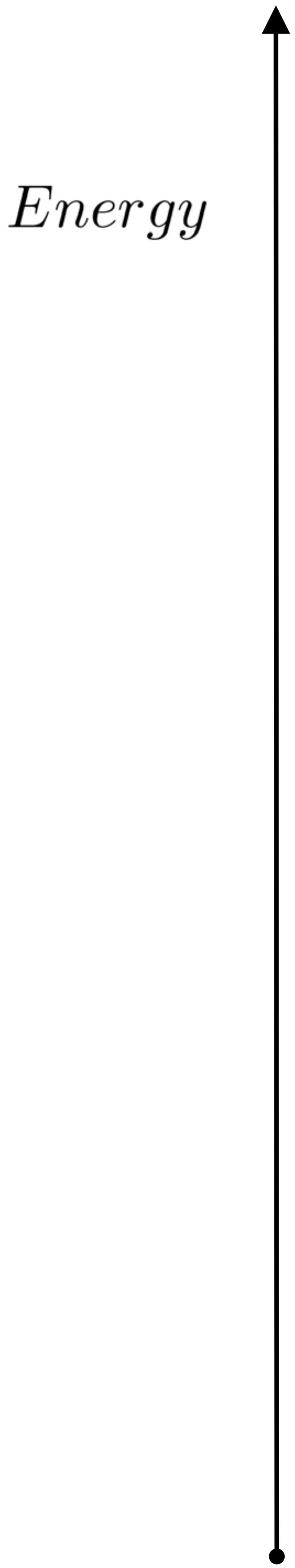
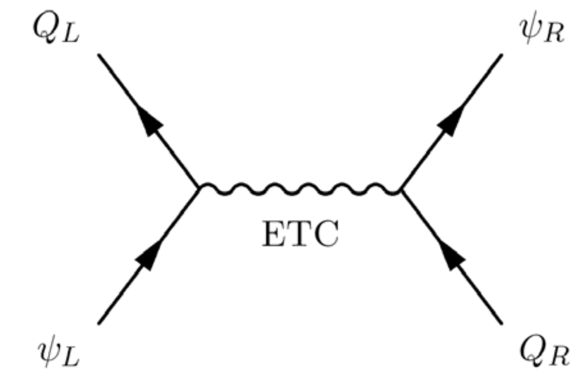
PNG Masses

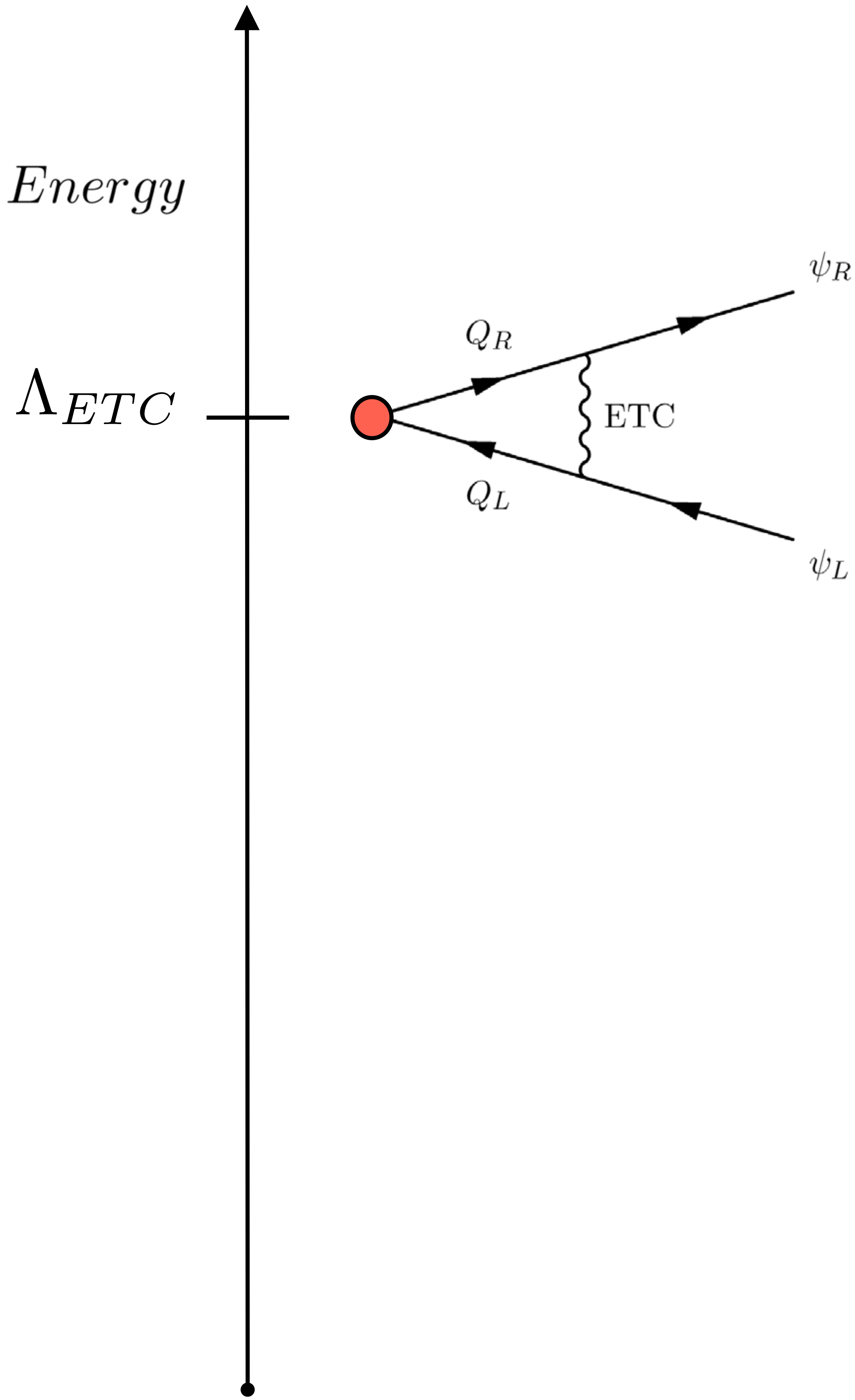
SM-Fermion Masses

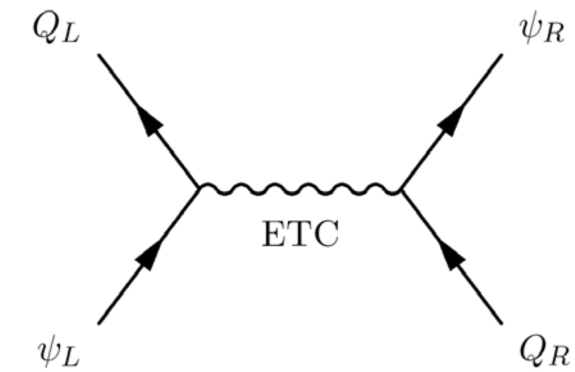
FCNC Operators

Antola, Di Chira, Sannino, Tuominen 10,11

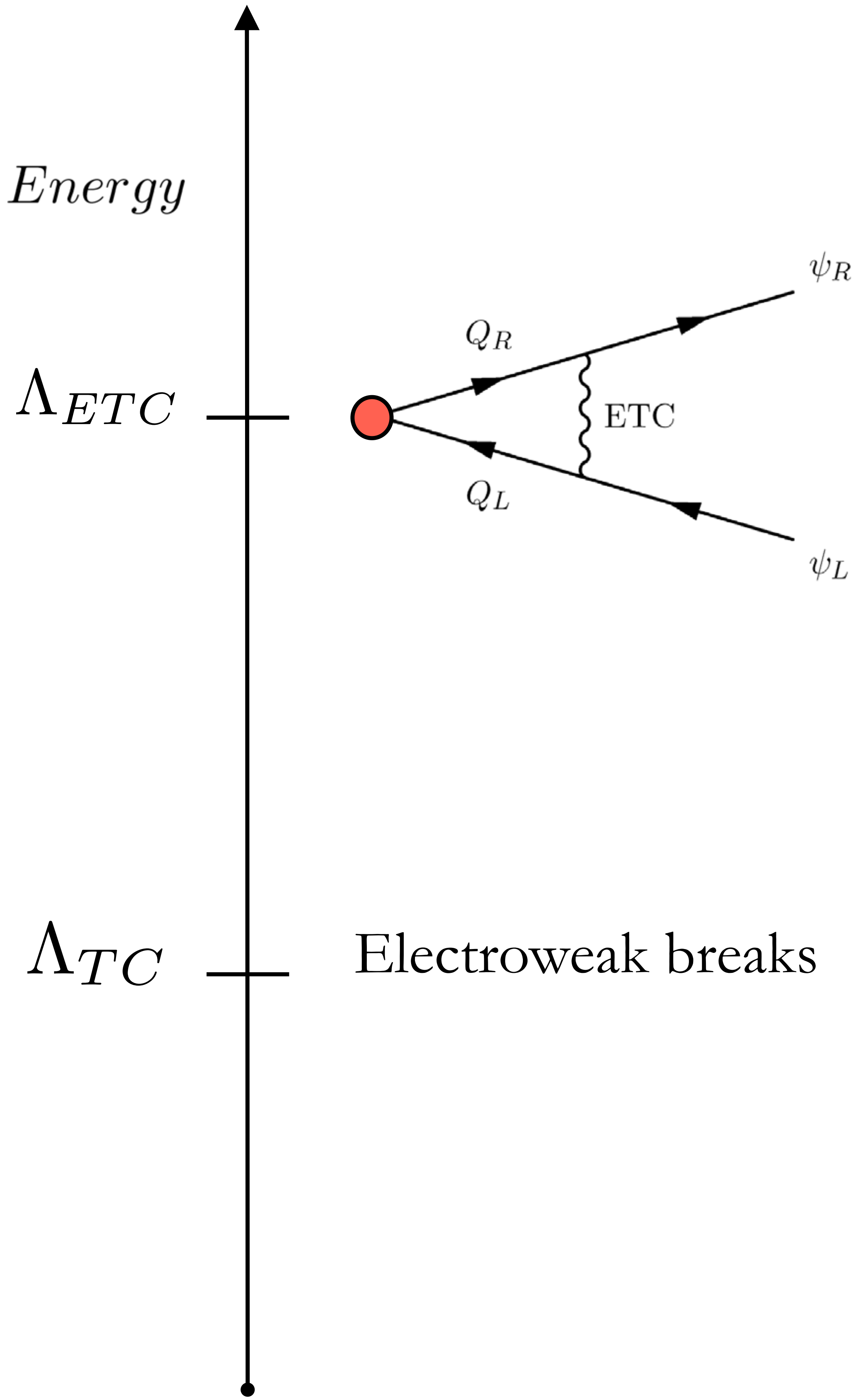

$Energy$

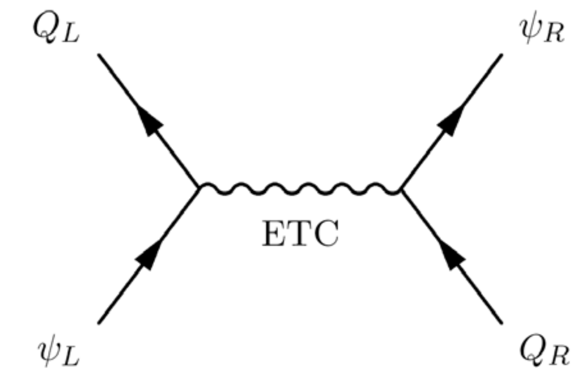

Q_L
ψ_R
ETC
ψ_L
Q_R



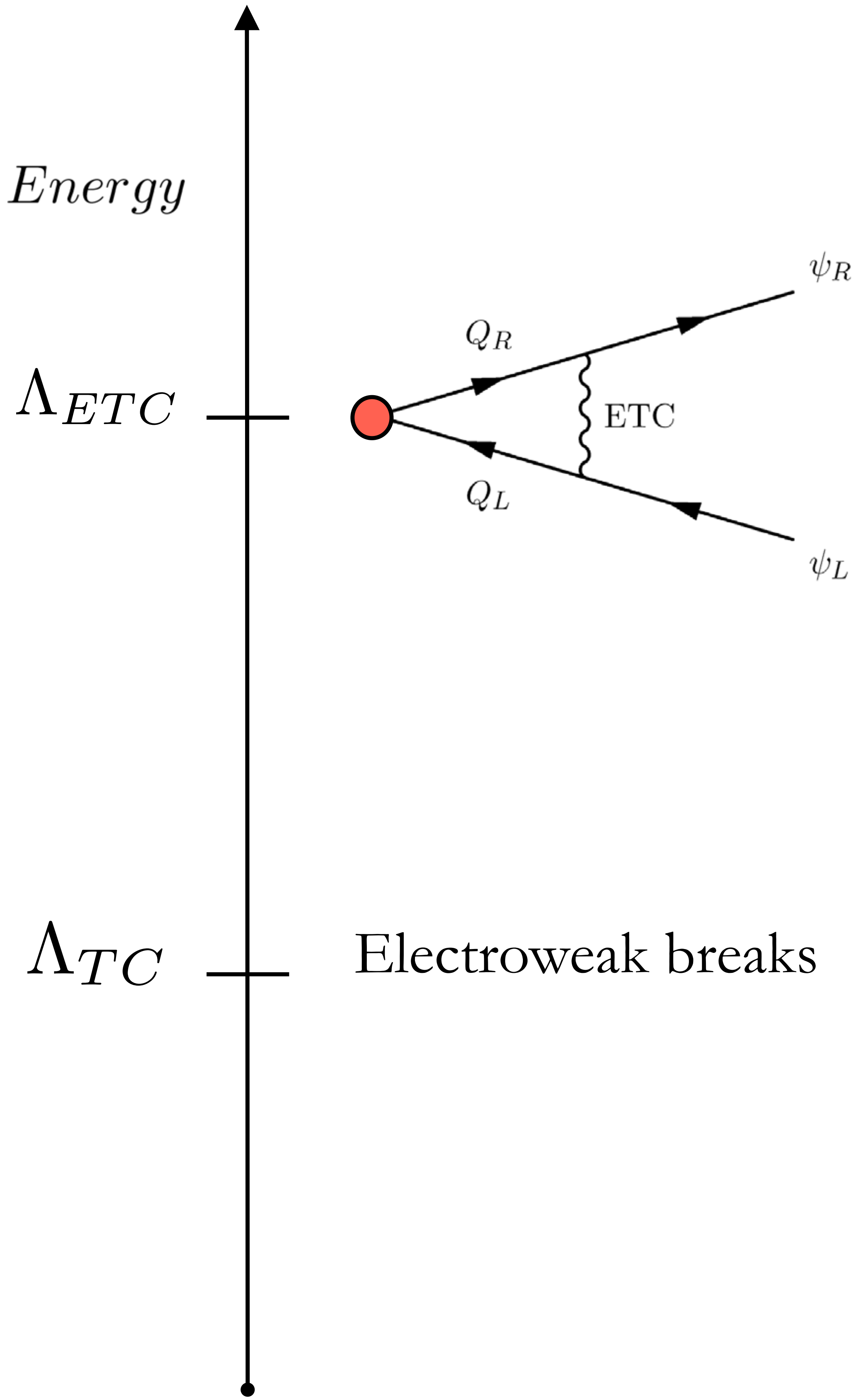


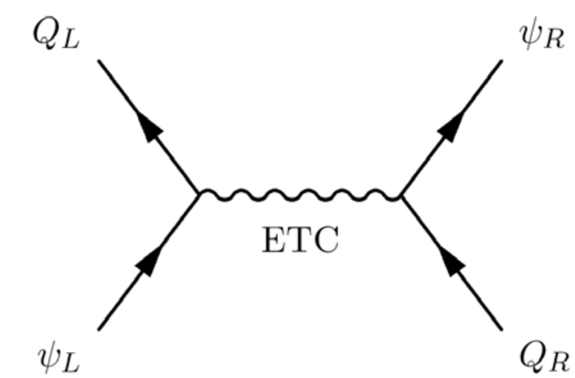
$$m_{\rm f} \approx \frac{g_{ETC}^2}{\Lambda_{ETC}^2} < \bar{Q}Q >_{ETC}$$





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

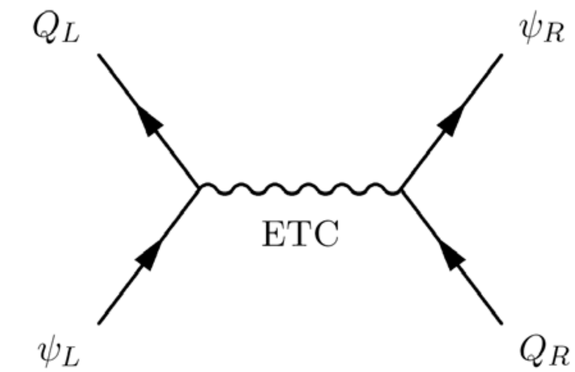




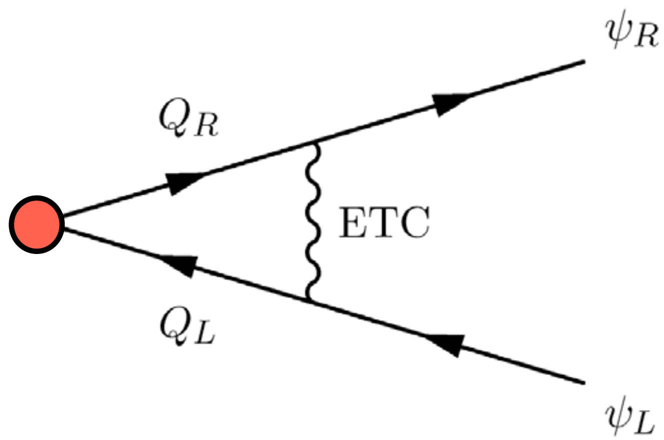
$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC}$$

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

Energy



Λ_{ETC}



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

Λ_{TC} Electroweak breaks

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

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

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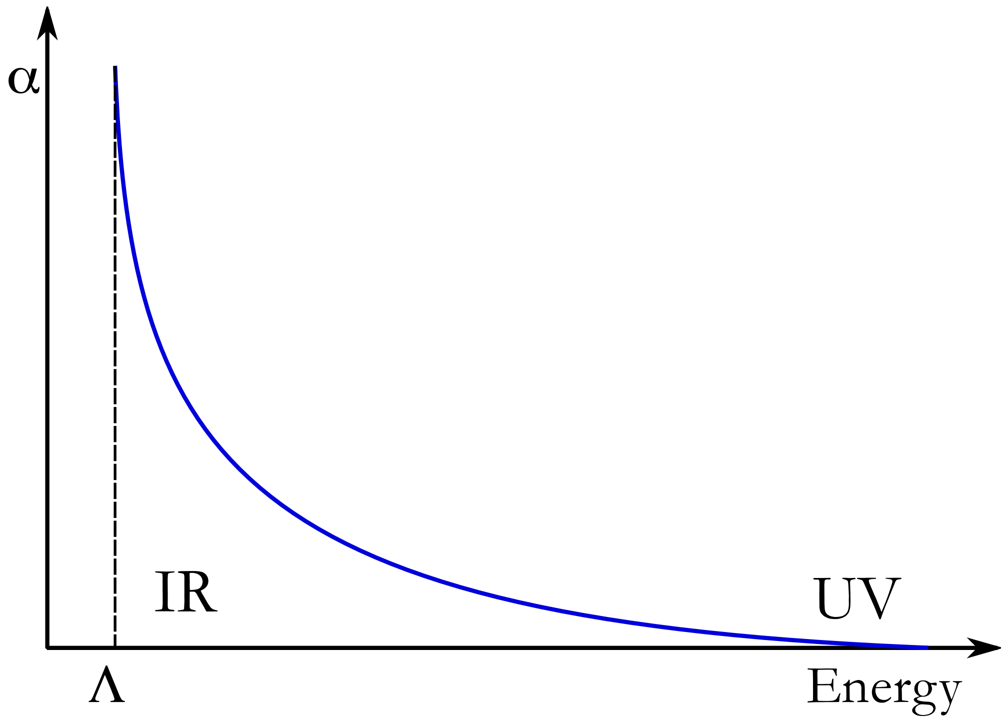
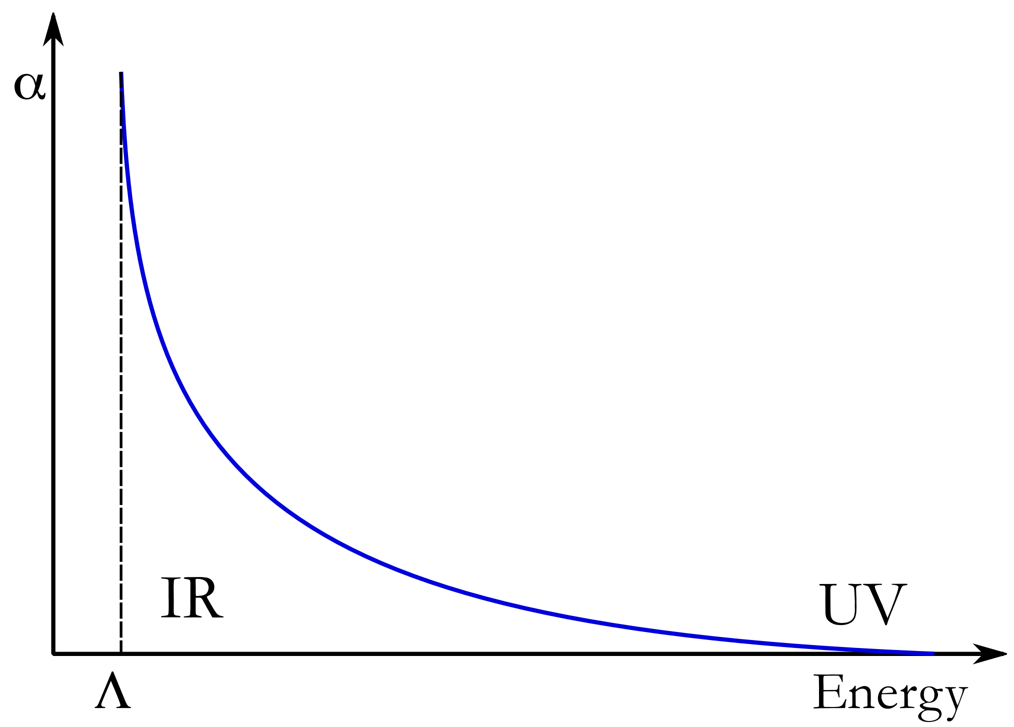
Need to go beyond QCD

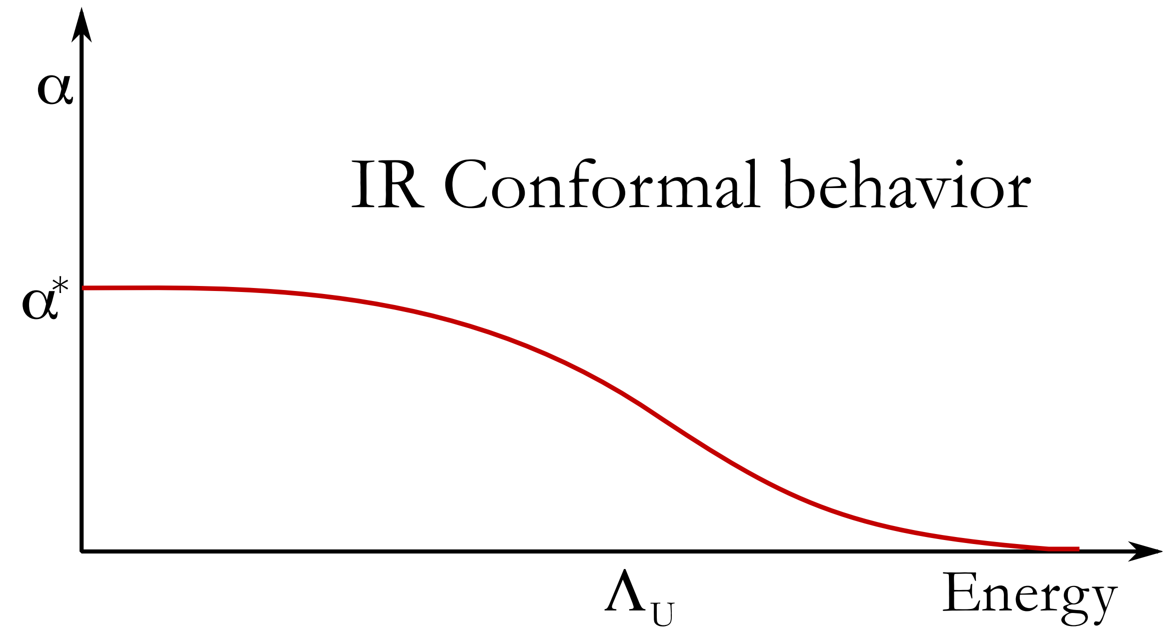
Near Conformal

Near Conformal

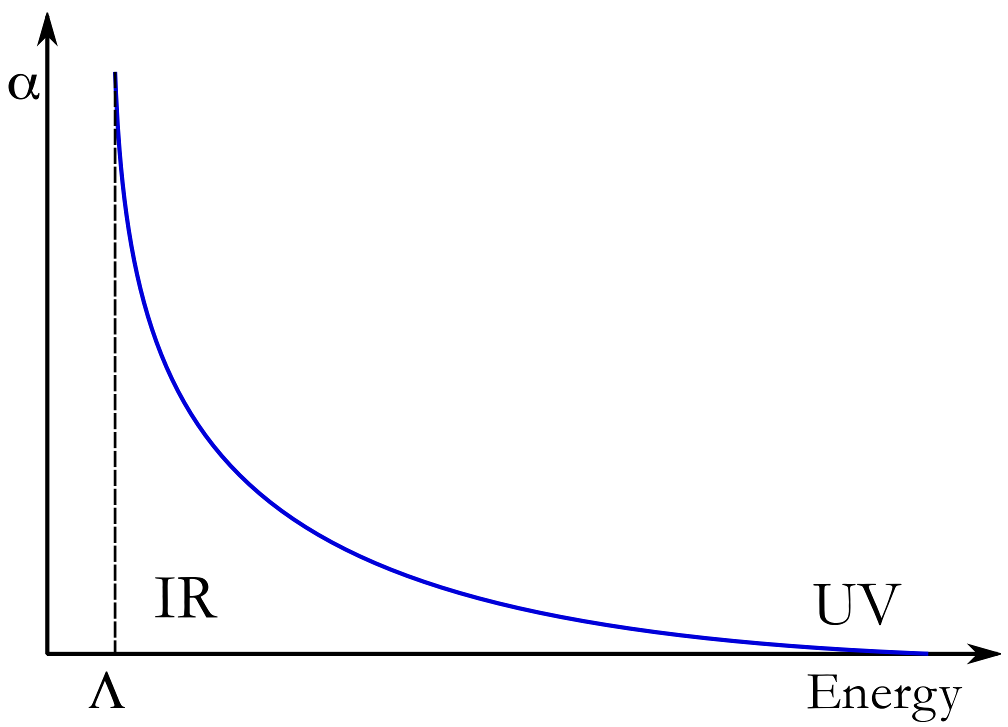


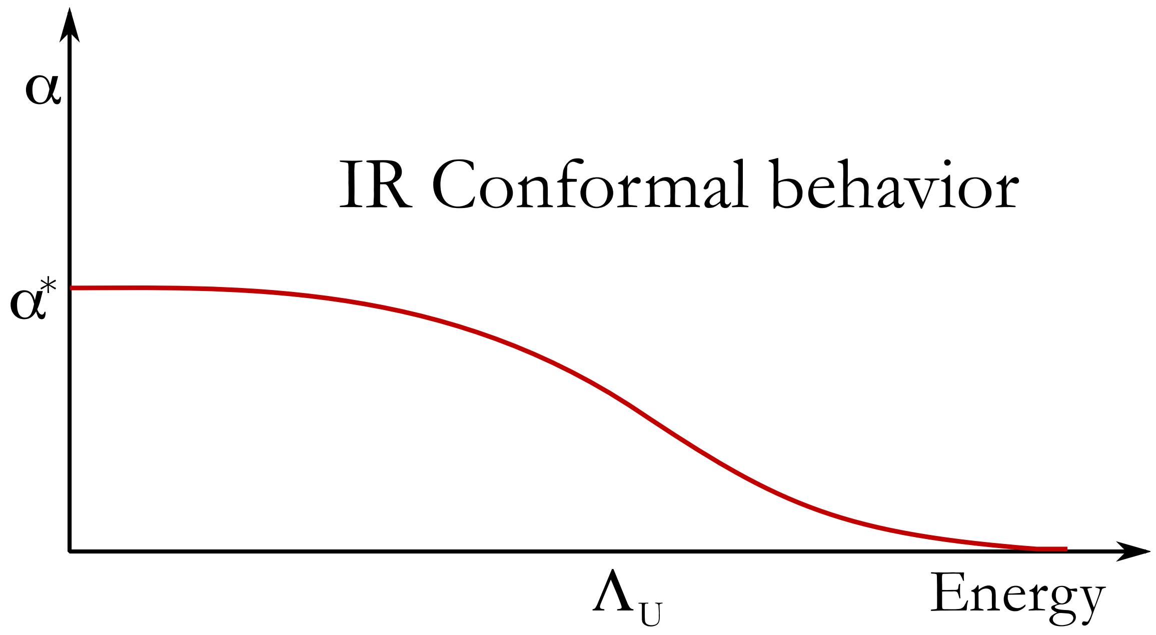
Near Conformal

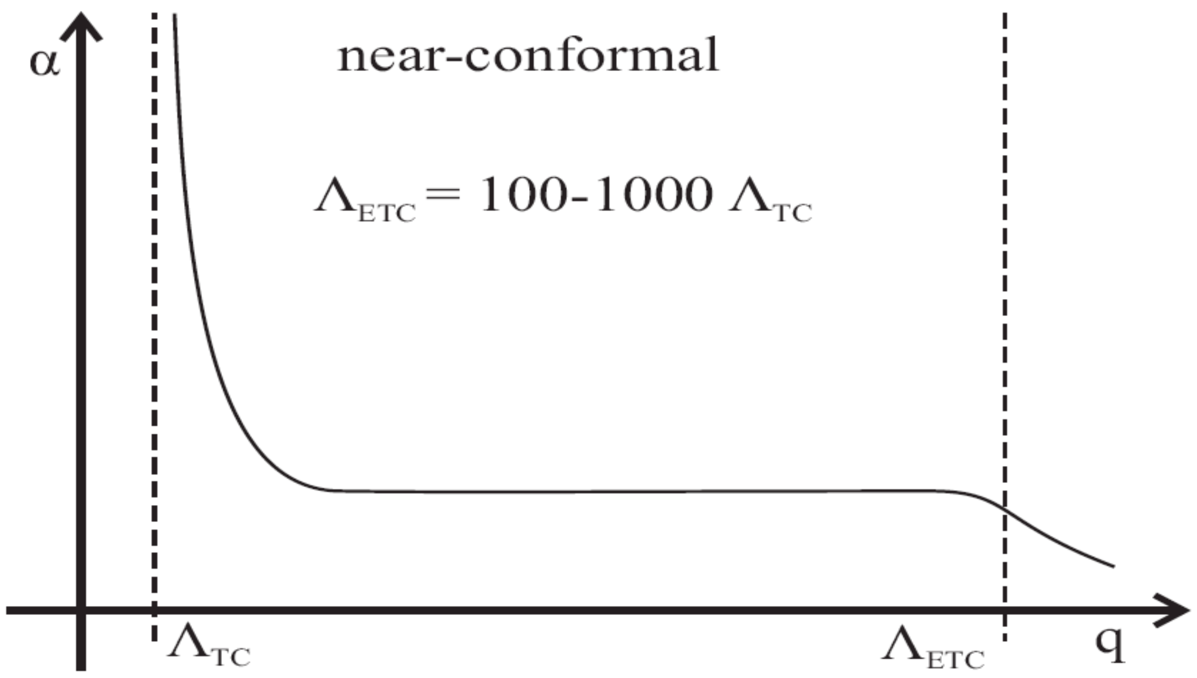




Near Conformal







Why walking helps?

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

Why walking helps?

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<u>QCD-Like</u>

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

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<u>Near the conformal window</u>

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

Why walking helps?

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

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<u>Near the conformal window</u>

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

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

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

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

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

↓

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

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

$$\downarrow$$

Fermion Mass Enhancement & FCNC decoupling

Ingredients

- Understand Phase Diagram of gauge theories

- Understand Phase Diagram of gauge theories
- Walking: Is it really phenomenologically viable?

- Understand Phase Diagram of gauge theories
- Walking: Is it really phenomenologically viable?
- Need a working example of ETC

Phase diagram

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

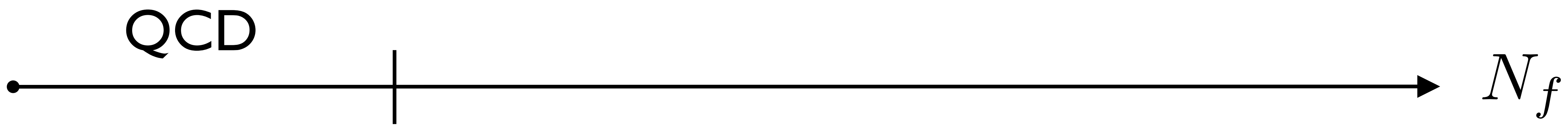
N_f

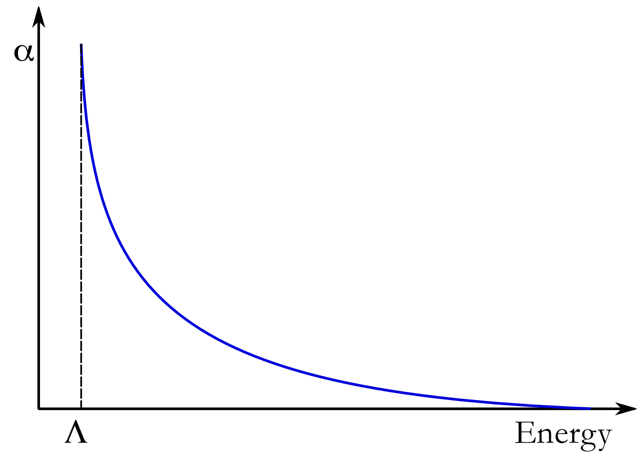
Knobs

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

Matter Representation

# of Flavors per Representation



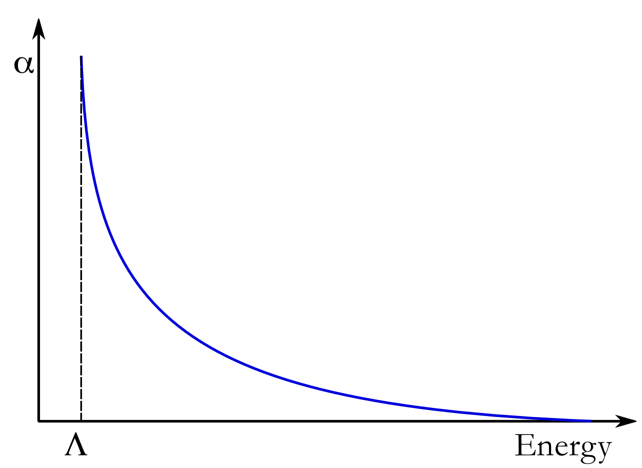


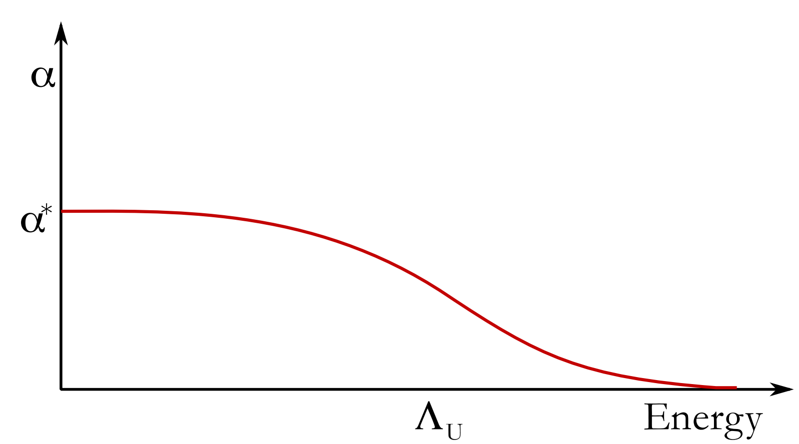
Knobs

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

Matter Representation

# of Flavors per Representation





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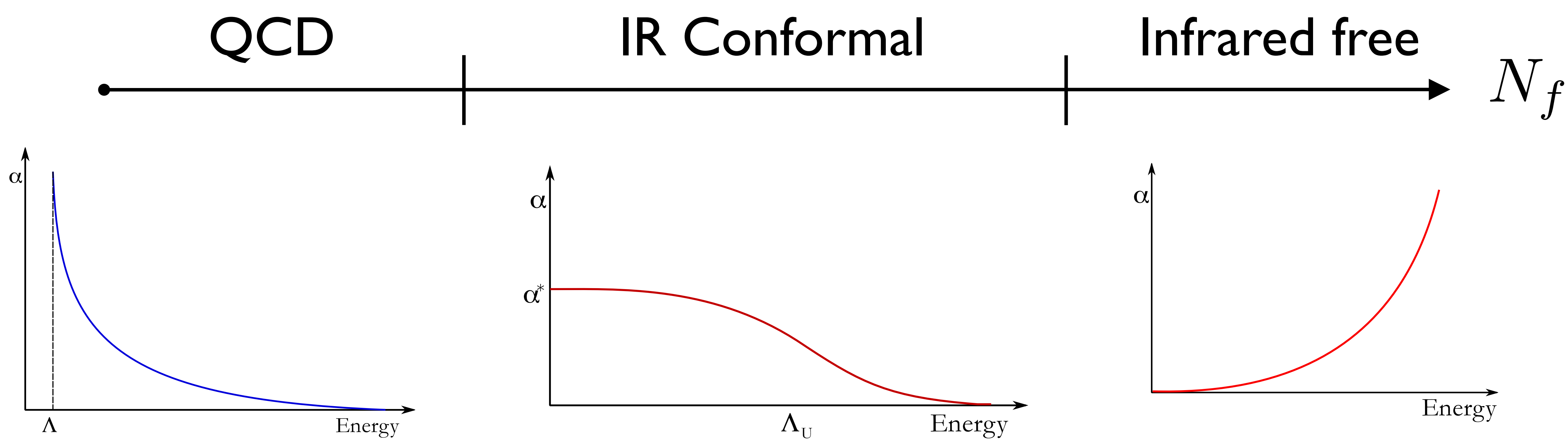
Gauge Group, i.e. SU, SO, SP

Matter Representation

# of Flavors per Representation

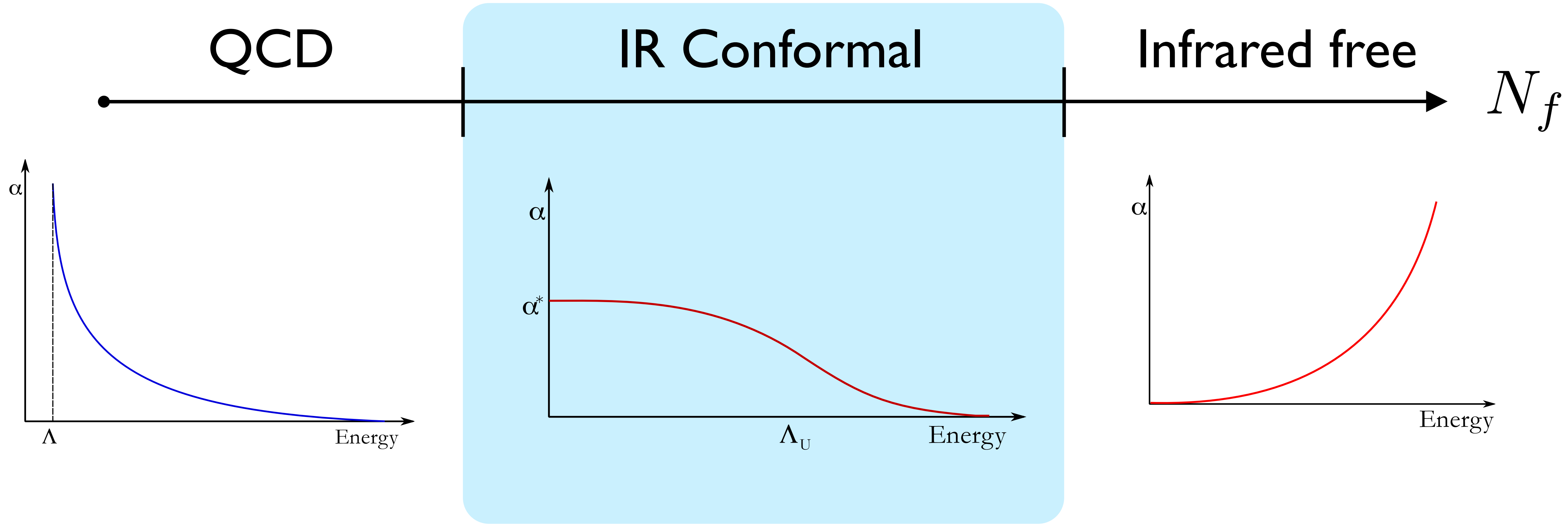


Knobs

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

Matter Representation

# of Flavors per Representation



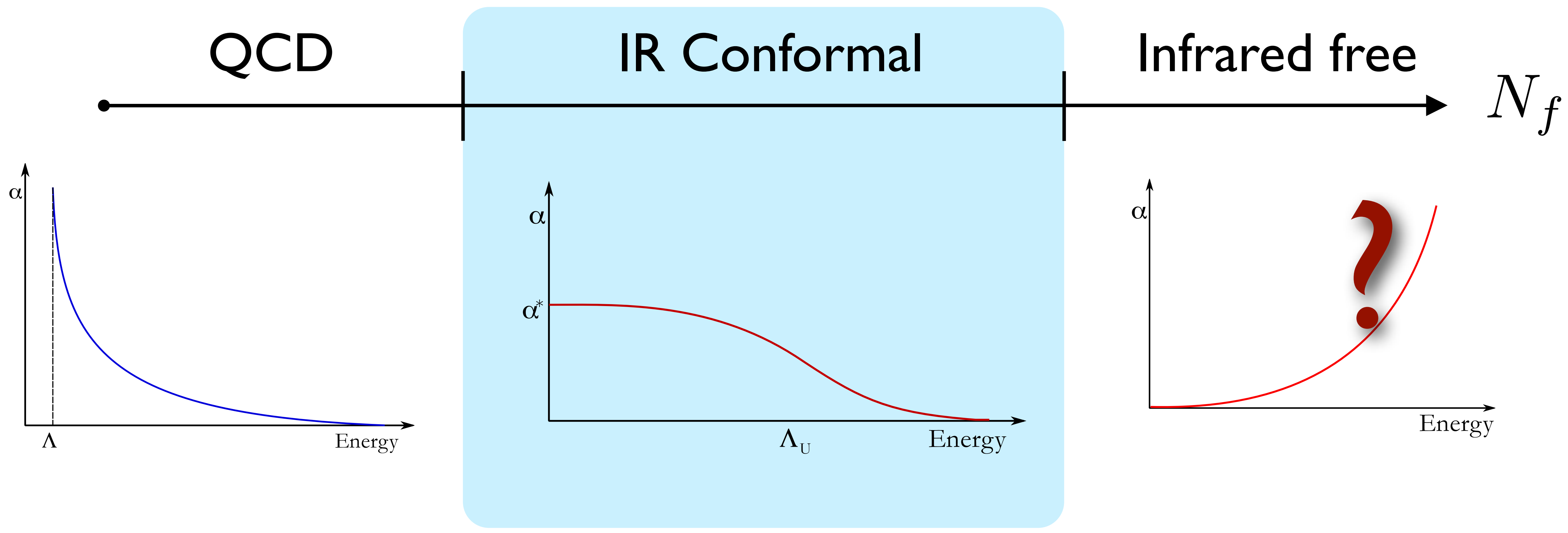
Francesco Sannino

Knobs

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

Matter Representation

# of Flavors per Representation



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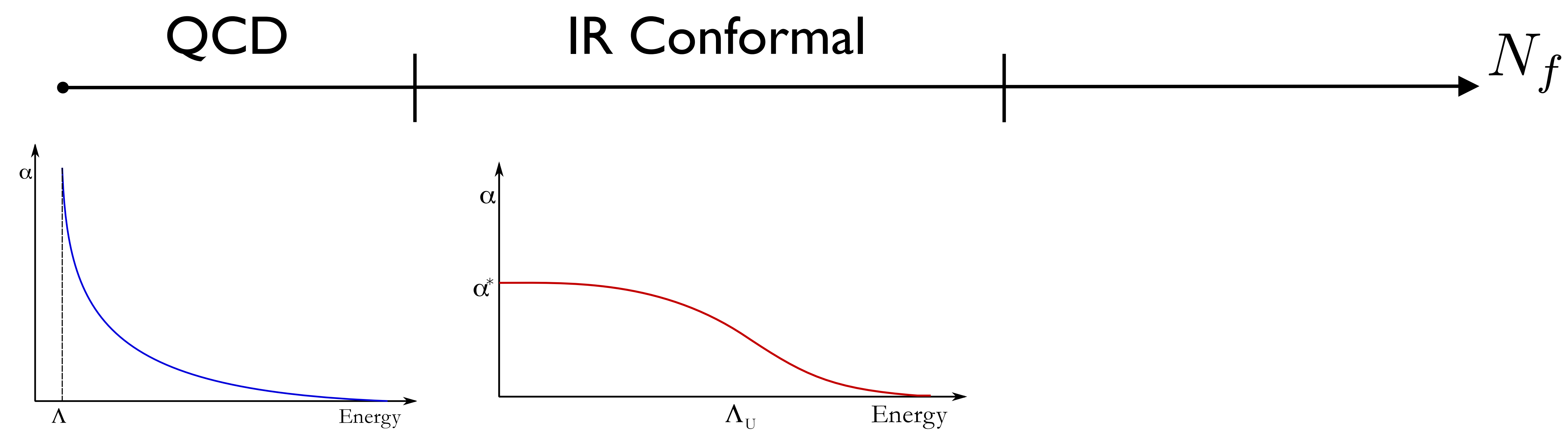
A novel phase @ large Nf

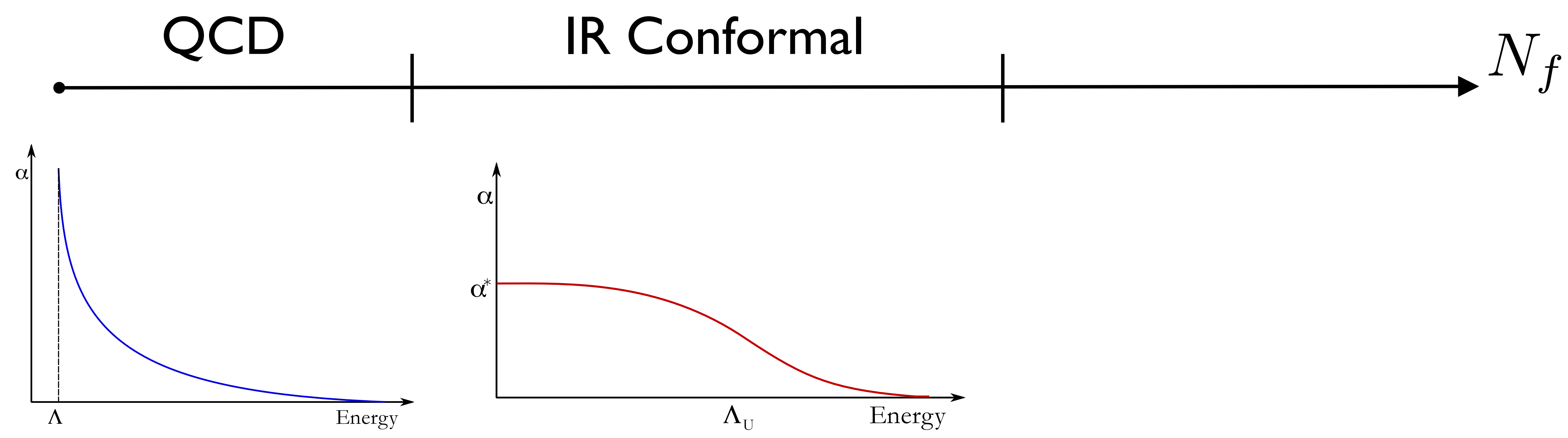
Pica & Sannino 10



A novel phase @ large Nf

Interesting structure at large Nf

Pica & Sannino 10

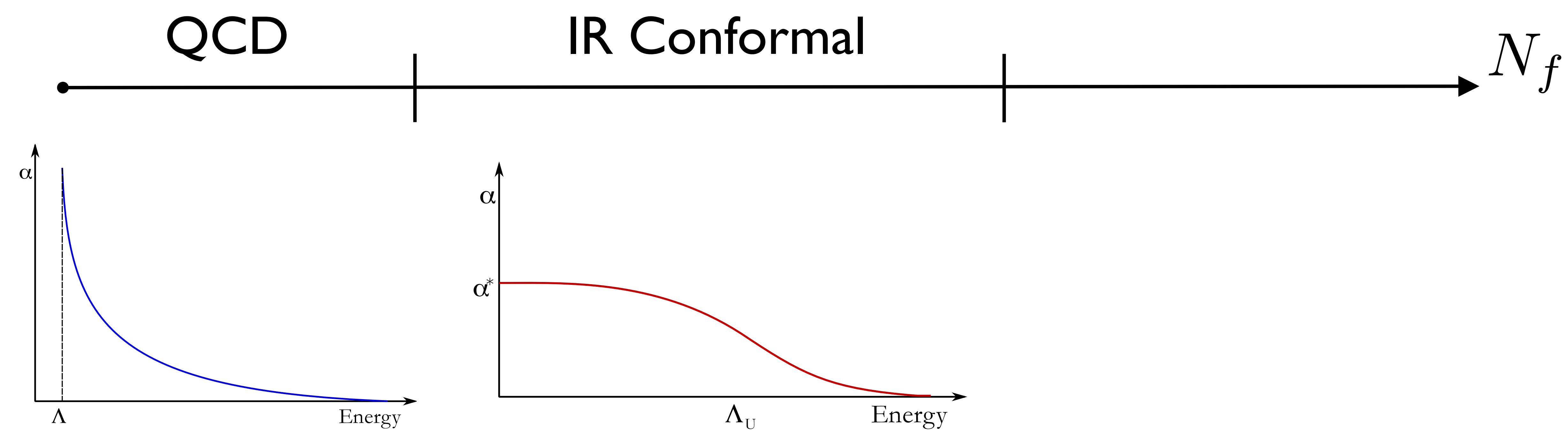


A novel phase @ large Nf

Interesting structure at large Nf

Pica & Sannino 10

Entire series at large Nf is known



A novel phase @ large Nf

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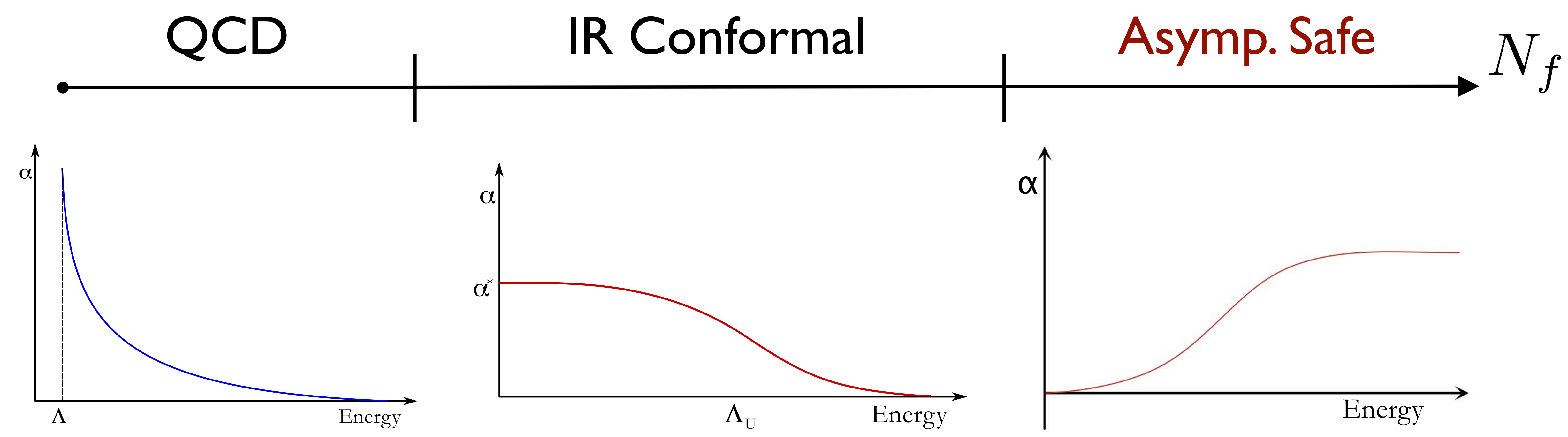

A novel phase @ large Nf

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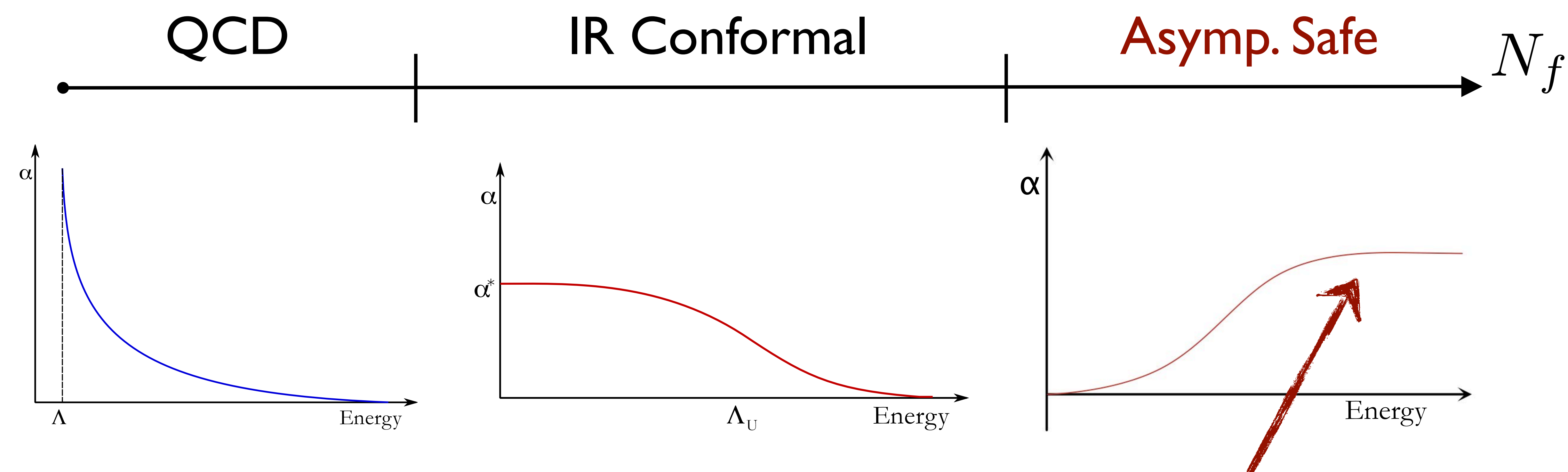
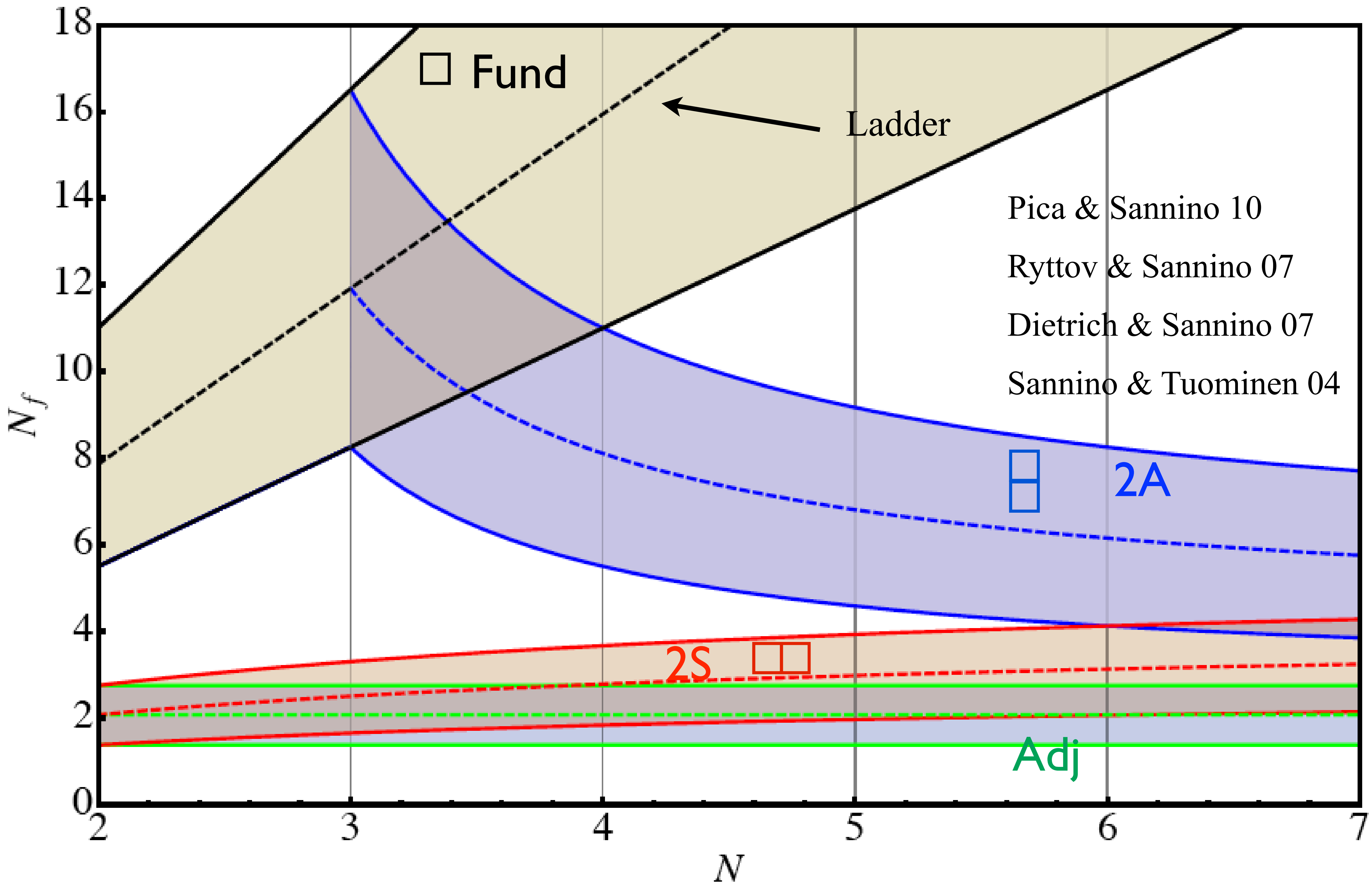


$$\alpha_{UV} = \frac{3\pi}{T_F N_f}$$

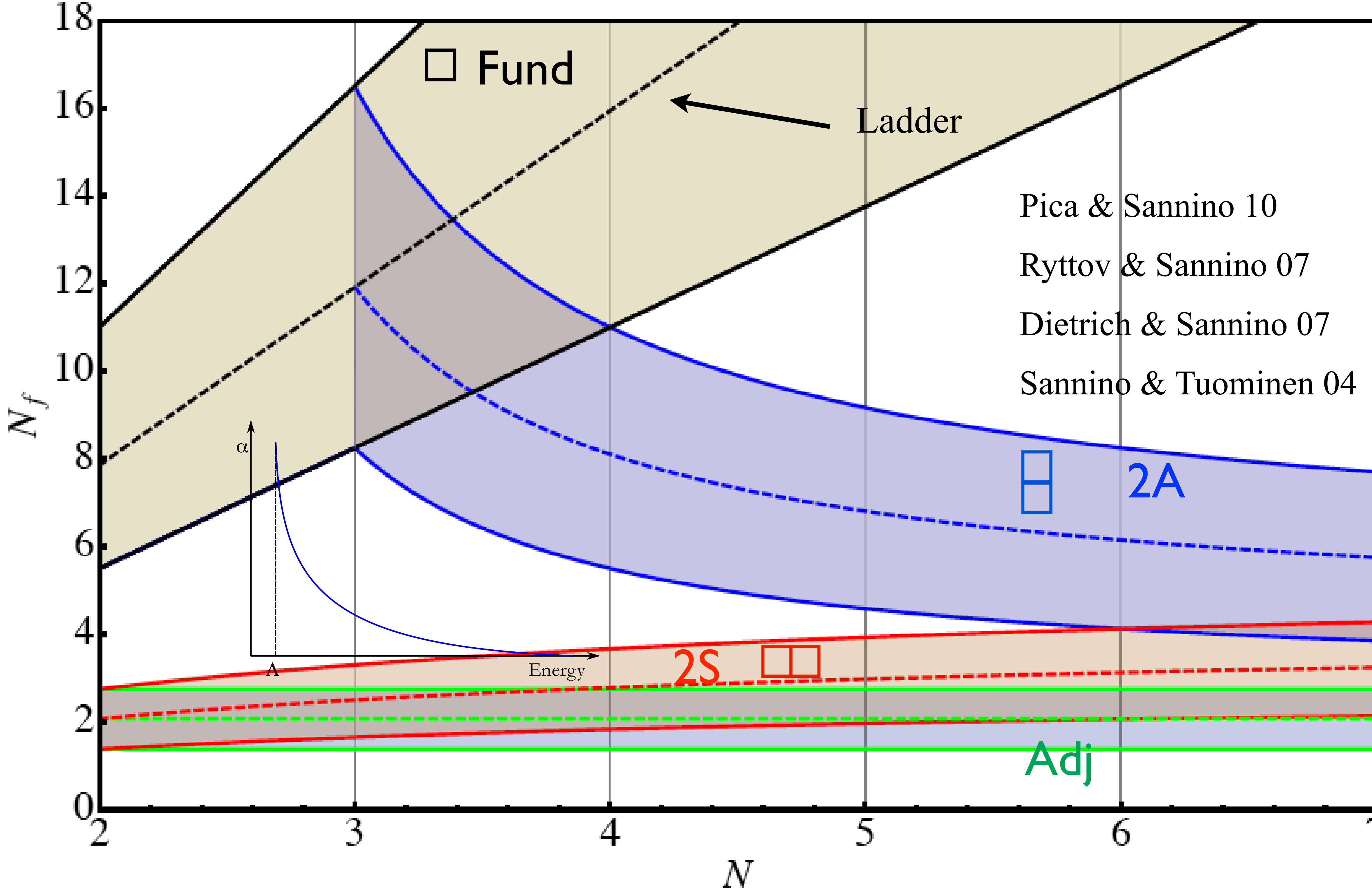
Universal Picture

SU(N) Phase Diagram



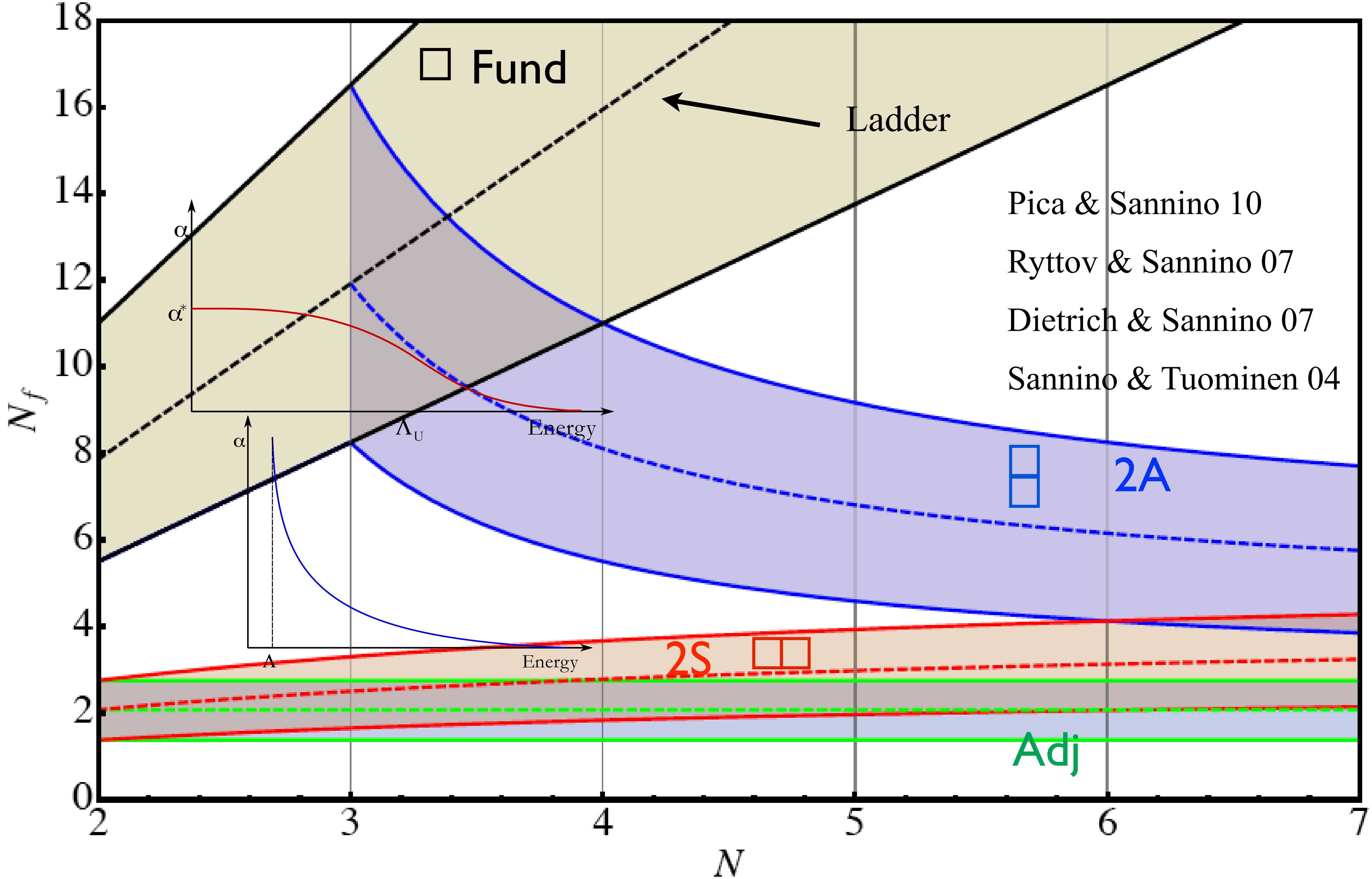
Francesco Sannino

SU(N) Phase Diagram



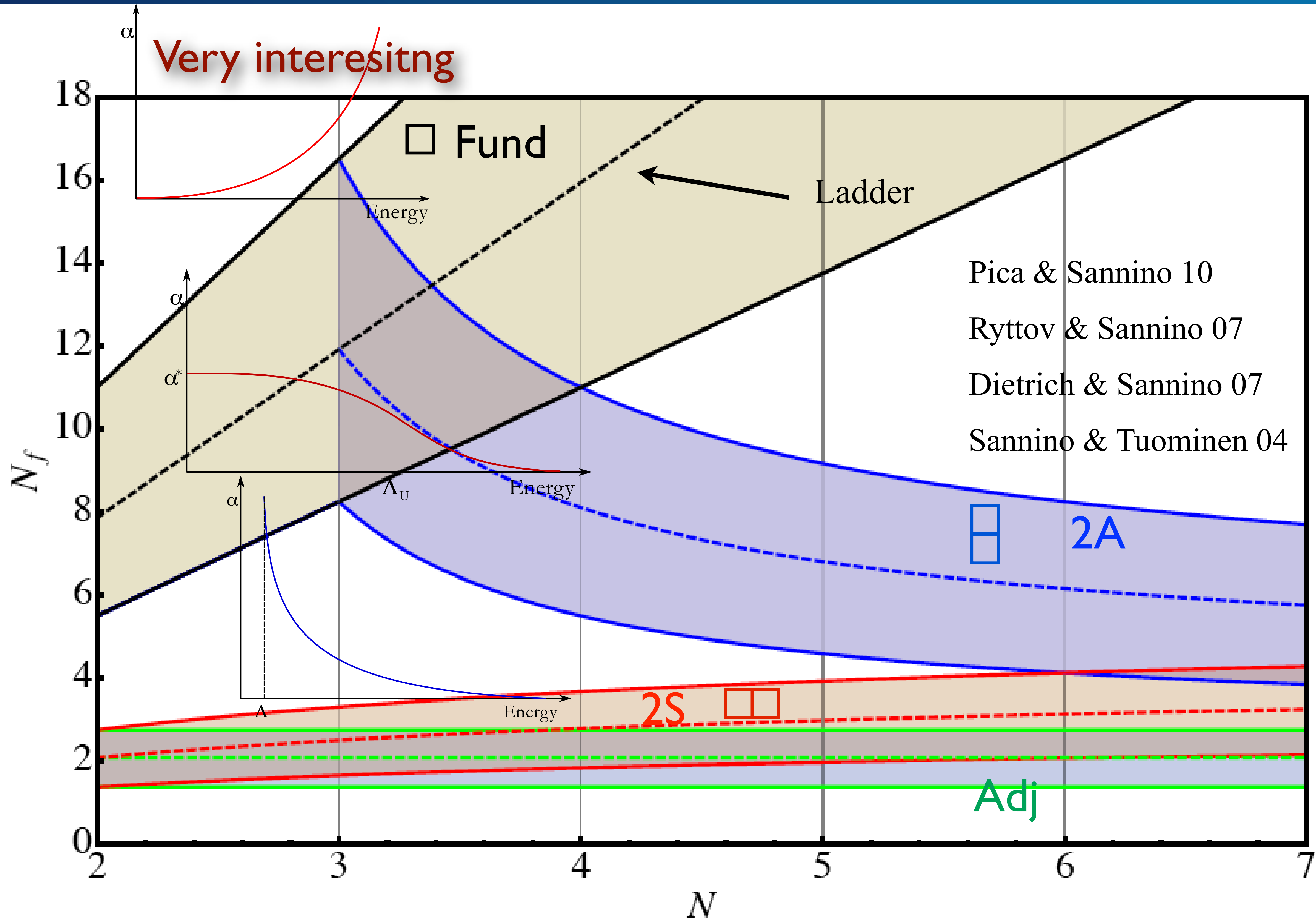
Francesco Sannino

SU(N) Phase Diagram



Francesco Sannino

SU(N) Phase Diagram



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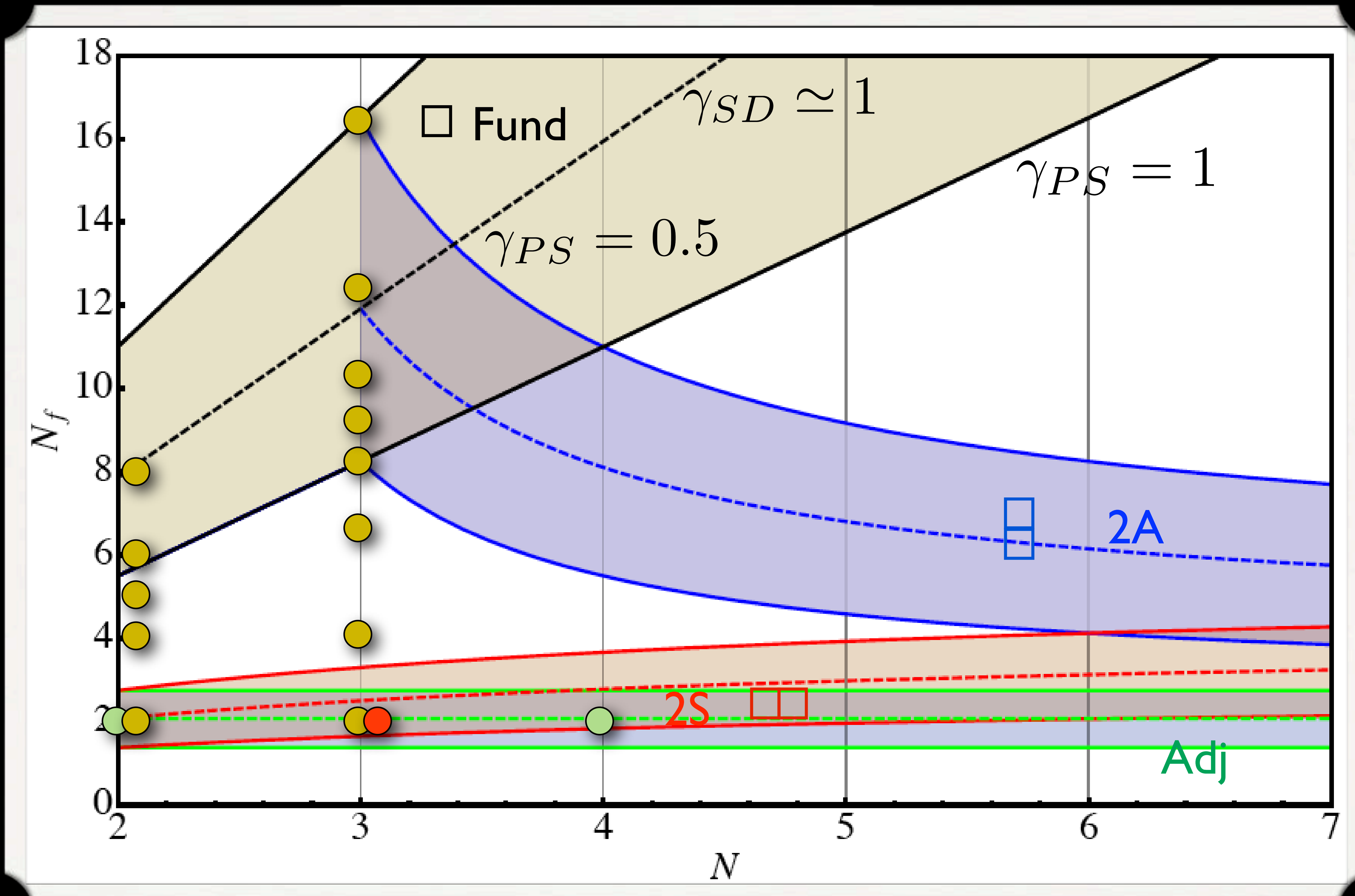
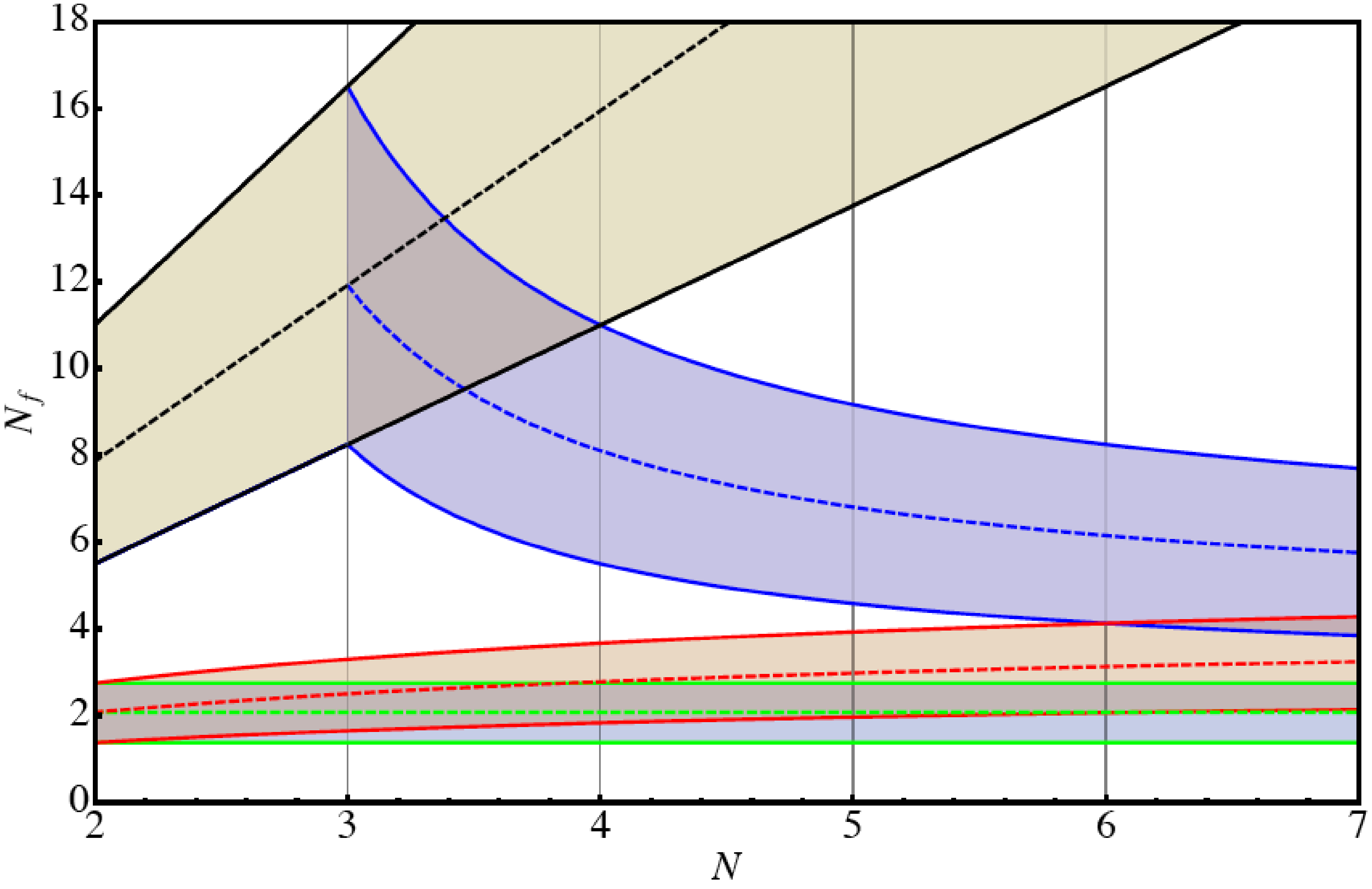
Lattice SU(N) Phase Diagram



iWalk

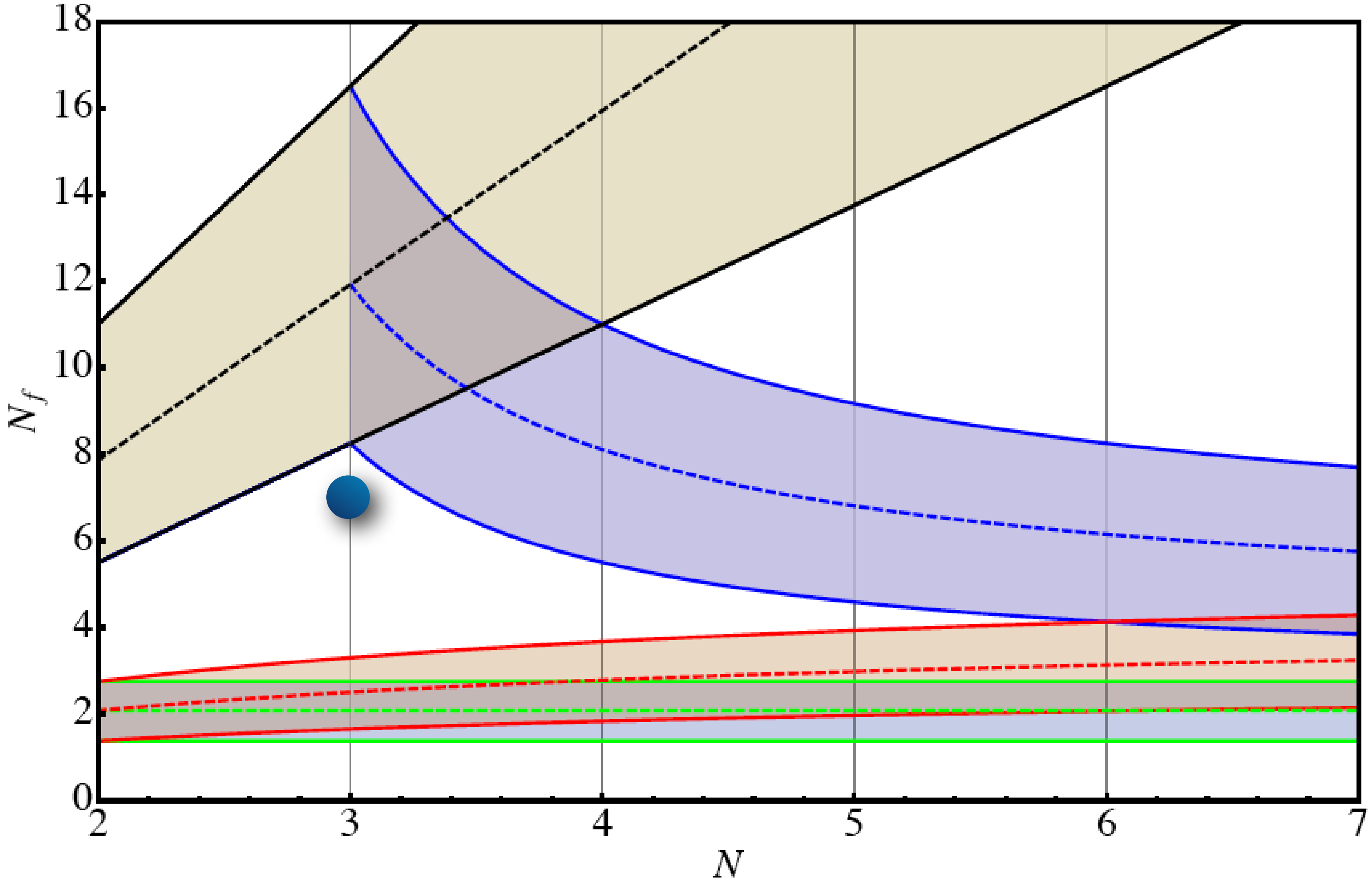
iWalk = ideal Walking



Dietrich Sannino 06

Fukano & Sannino 10

iWalk = ideal Walking

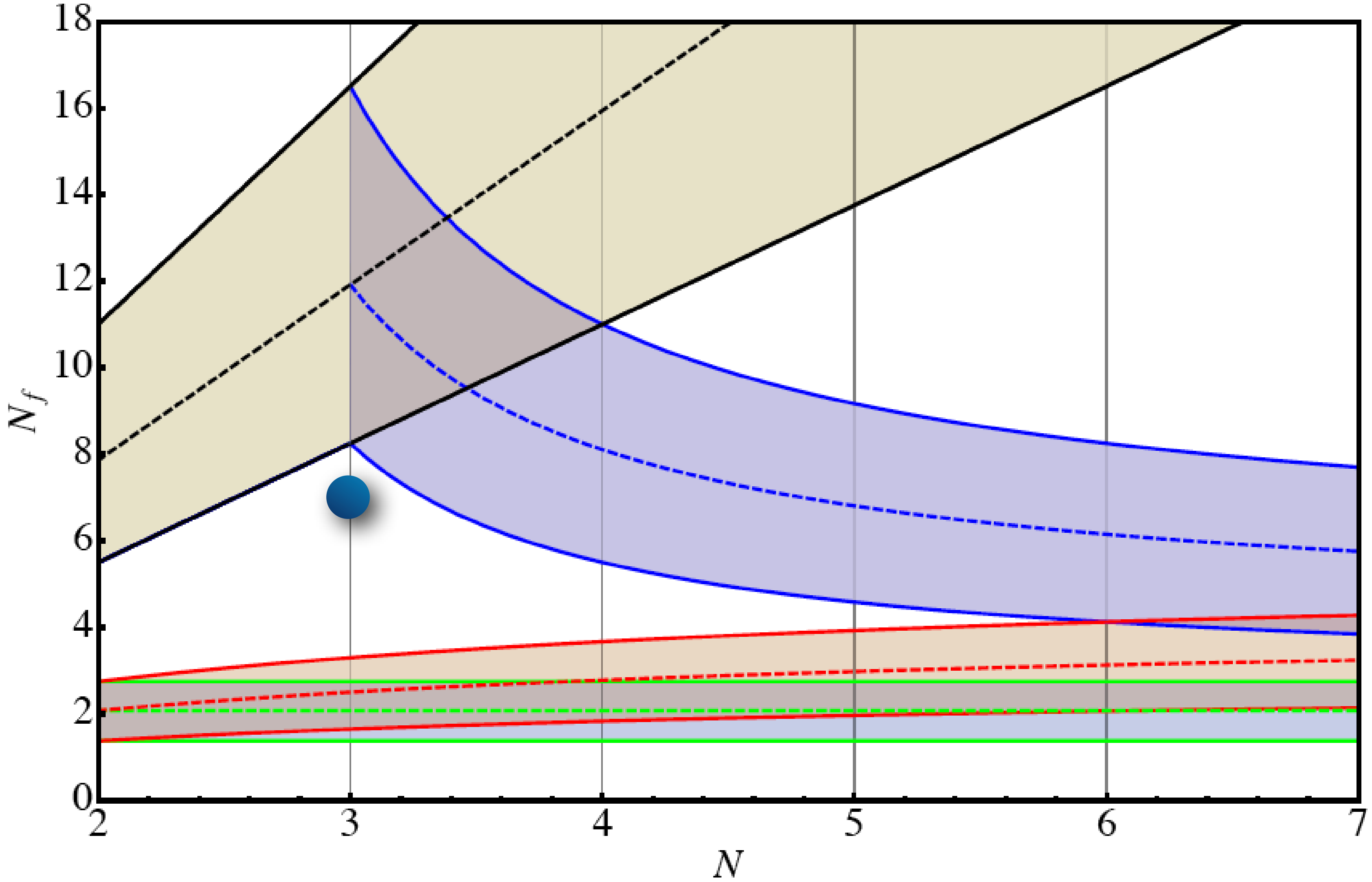


Dietrich Sannino 06

Fukano & Sannino 10

Walking is fine tuned

iWalk = ideal Walking



Dietrich Sannino 06

Fukano & Sannino 10

Walking is fine tuned

Anomalous dimensions may be small

iWalk

Fukano & Sannino 10

Appelquist, Soldate, Takeuchi and Wijewardhana, 88
Kondo, Mino, Yamawaki 89
Takeuchi 96
Yamawaki, Kurachi and Shrock 08

iWalk

Fukano & Sannino 10

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

Appelquist, Soldate, Takeuchi and Wijewardhana, 88

Kondo, Mino, Yamawaki 89

Takeuchi 96

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iWalk

Fukano & Sannino 10

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

$$\alpha_{ab}\frac{\bar{Q}T^{a}Q\bar{Q}T^{b}Q}{\Lambda^{2}_{ETC}} + \beta_{ab}\frac{\bar{Q}_{L}T^{a}Q_{R}\bar{\psi}_{R}T^{b}\psi_{L}}{\Lambda^{2}_{ETC}} + \gamma_{ab}\frac{\bar{\psi}_{L}T^{a}\psi_{R}\bar{\psi}_{R}T^{b}\psi_{L}}{\Lambda^{2}_{ETC}} + \ldots$$

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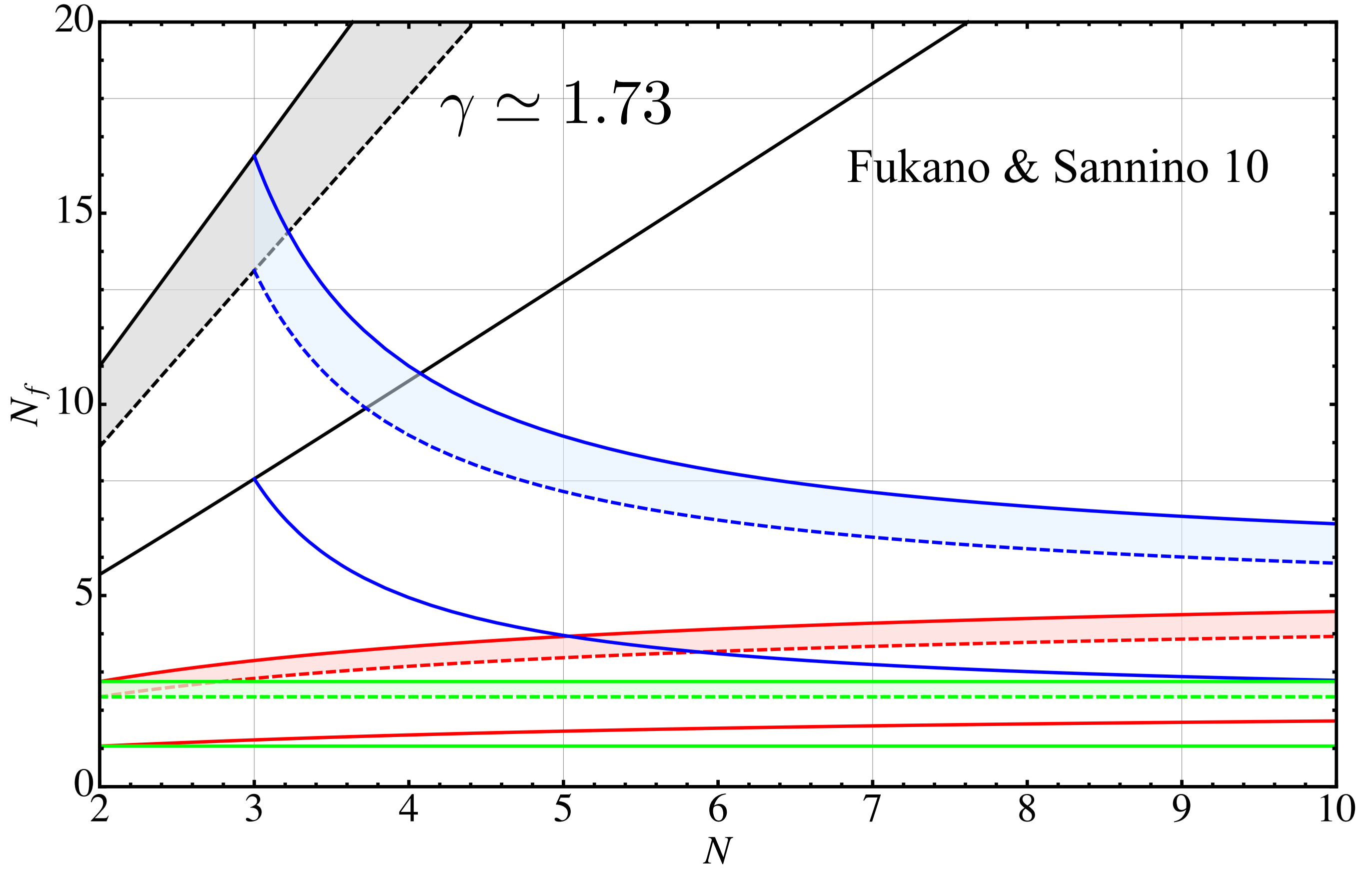
Gauged Nambu Jona-Lasinio

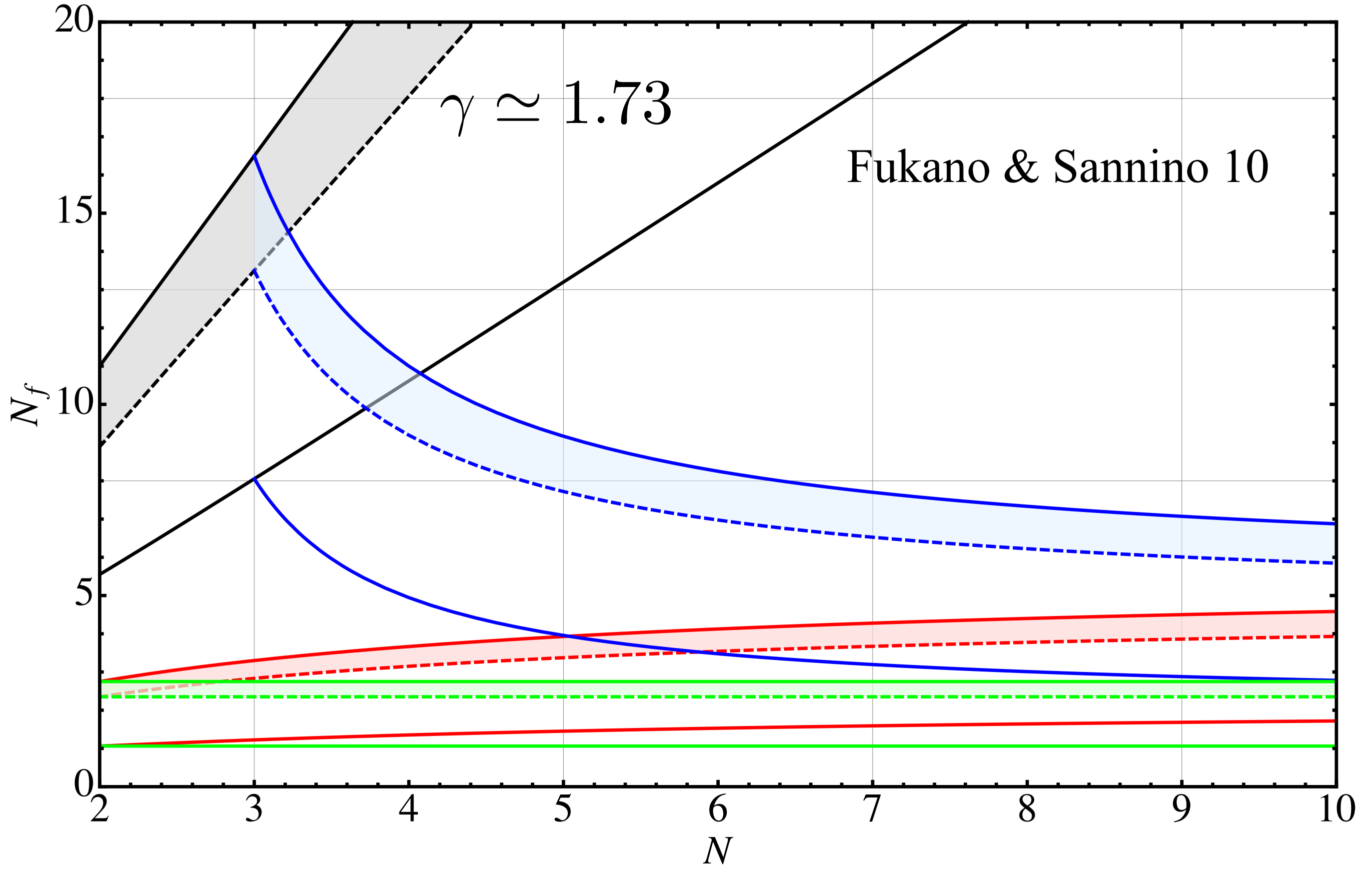
Fukano & Sannino 10



Gauged Nambu Jona-Lasinio

Fukano & Sannino 10

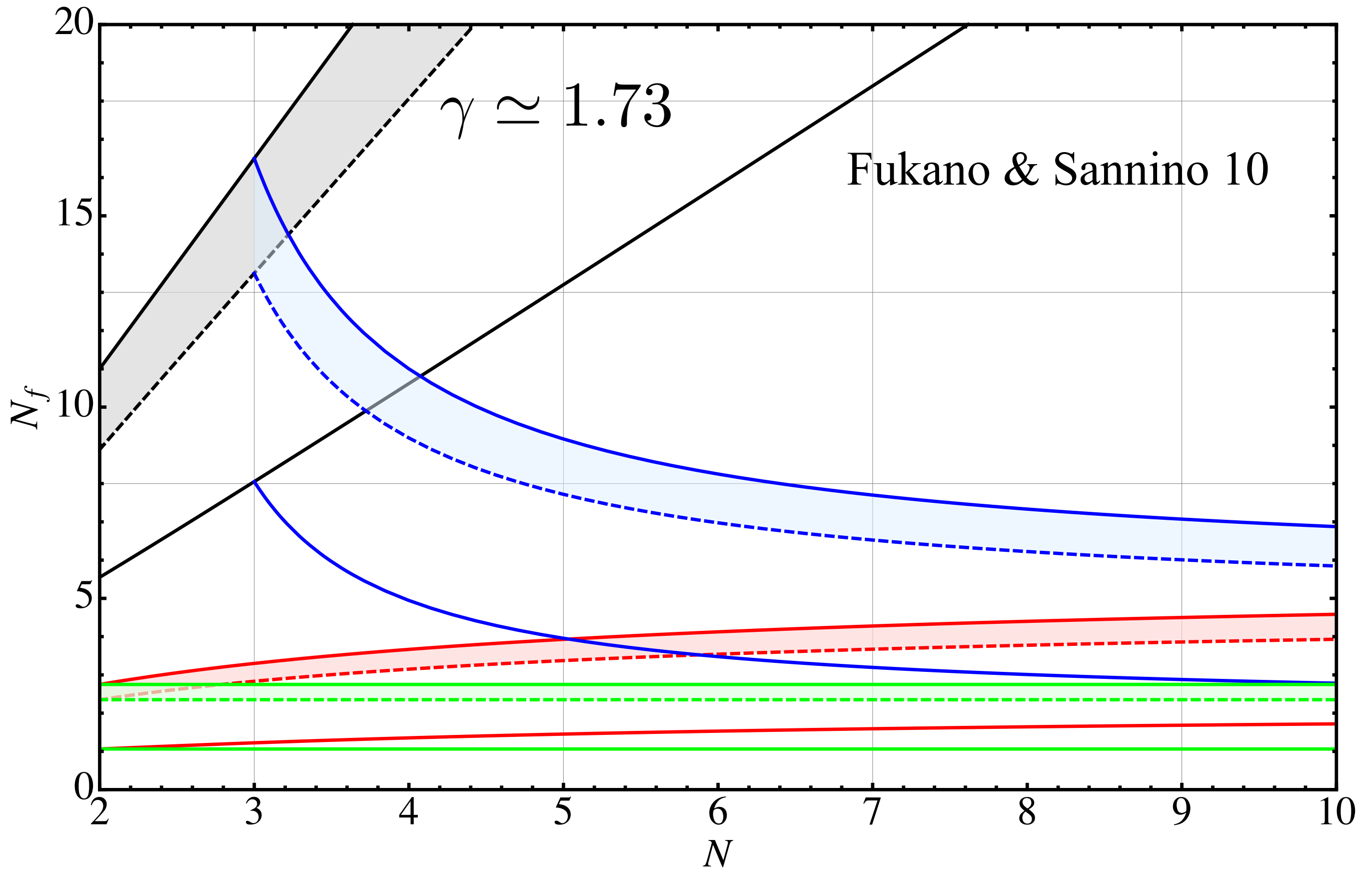
- As if the number of flavors is continuous



Gauged Nambu Jona-Lasinio

Fukano & Sannino 10

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



Gauged Nambu Jona-Lasinio

Fukano & Sannino 10

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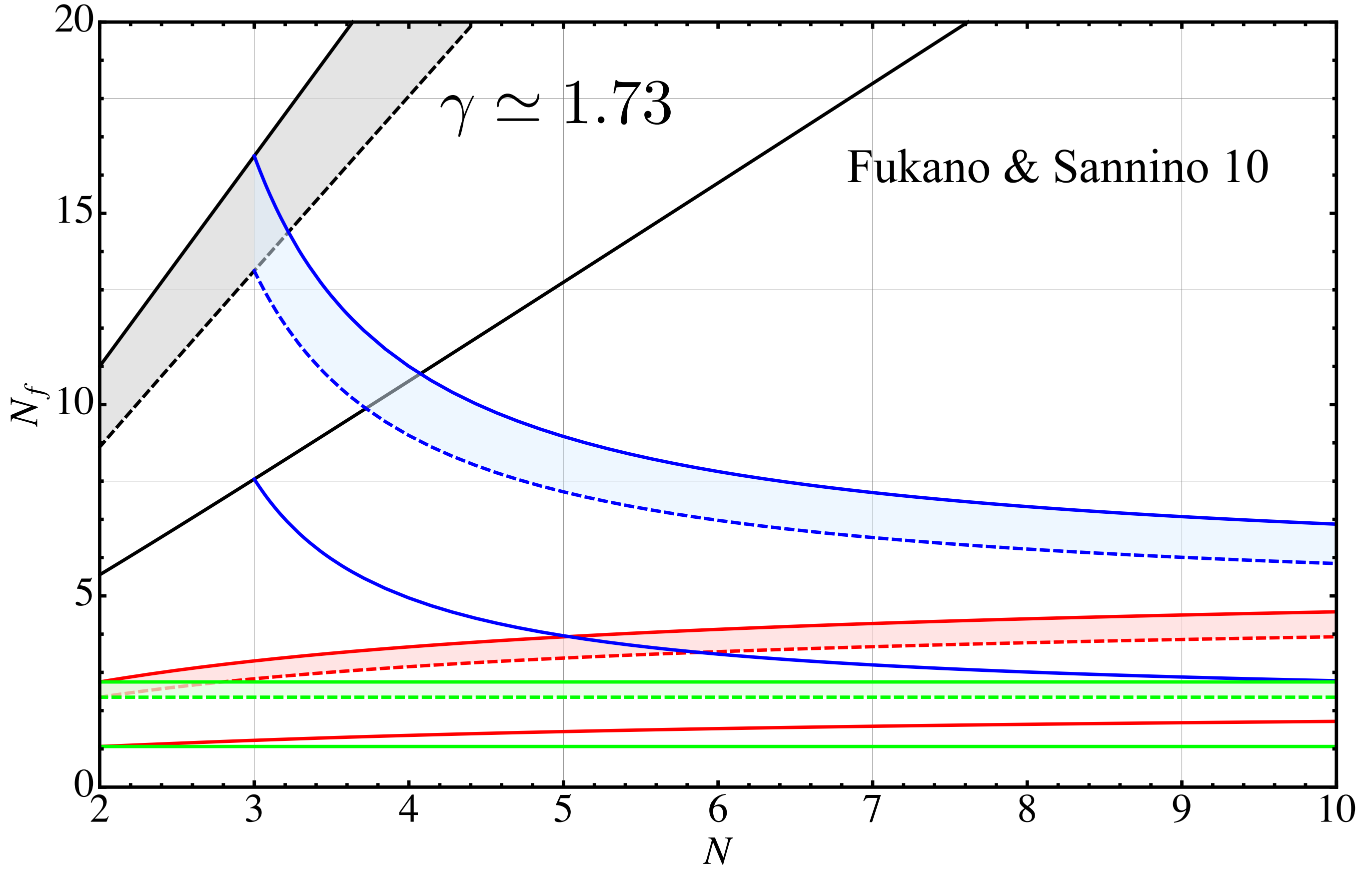
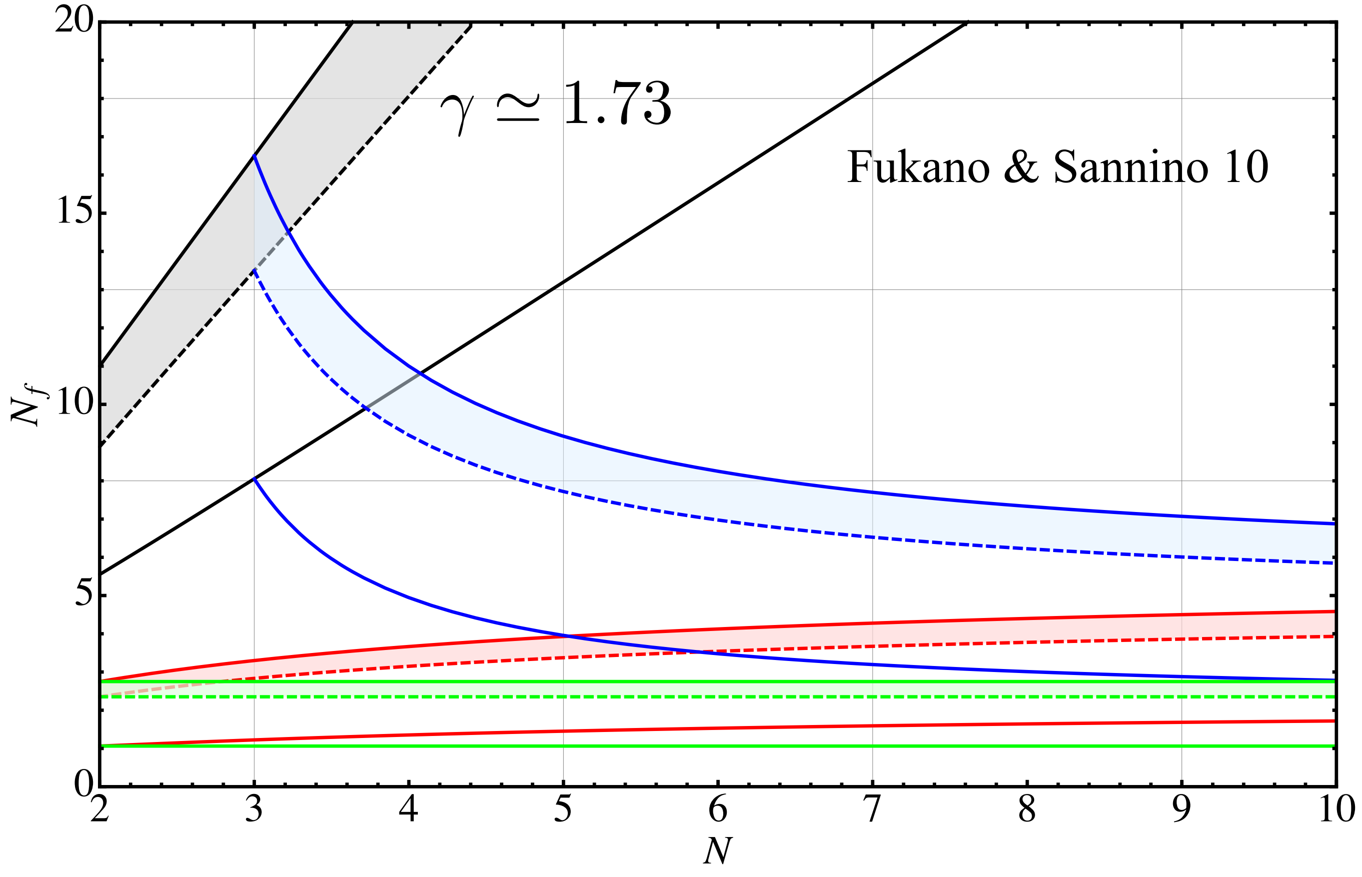


- Phenomenologically viable

Gauged Nambu Jona-Lasinio

Fukano & Sannino 10

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



- Phenomenologically viable
- Being tested!

Minimal Working TC

U
D

Minimal Working TC

- Minimal WT

$SU(2)_{TC}$ $\square\!\square$ $\begin{matrix} \mathbf{U} & \mathbf{N} \\ \mathbf{D} & \mathbf{E} \end{matrix}$

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

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

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

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

Frandsen, Sannino 09

Minimal Working TC

- Minimal WT

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

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

- Next to MWT

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

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

- Orthogonal

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

Frandsen, Sannino 09

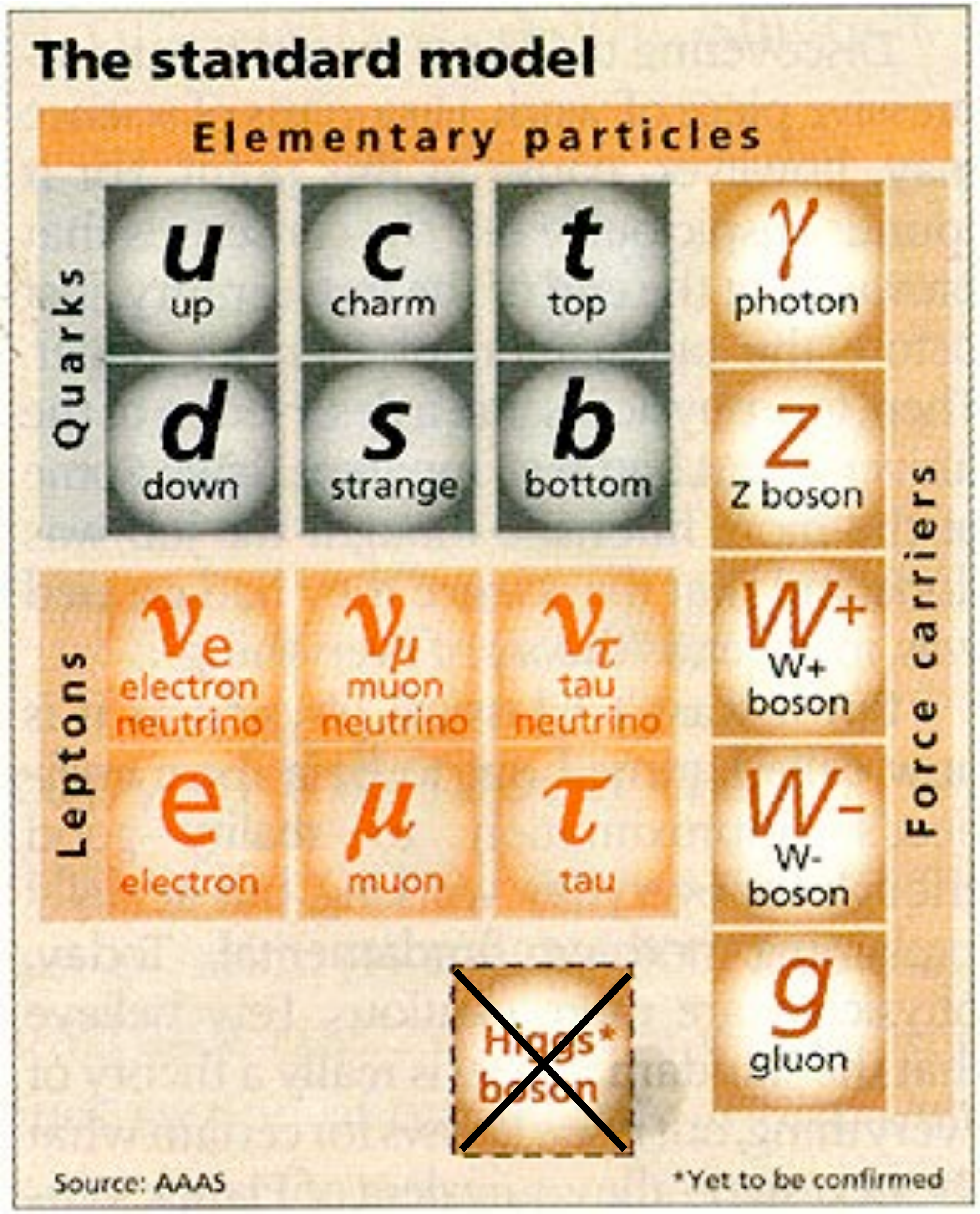
Vanilla TC

- Ultra MT

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

Ryttov & Sannino 08

Minimal Walking Technicolor



U(1)

SU(2)

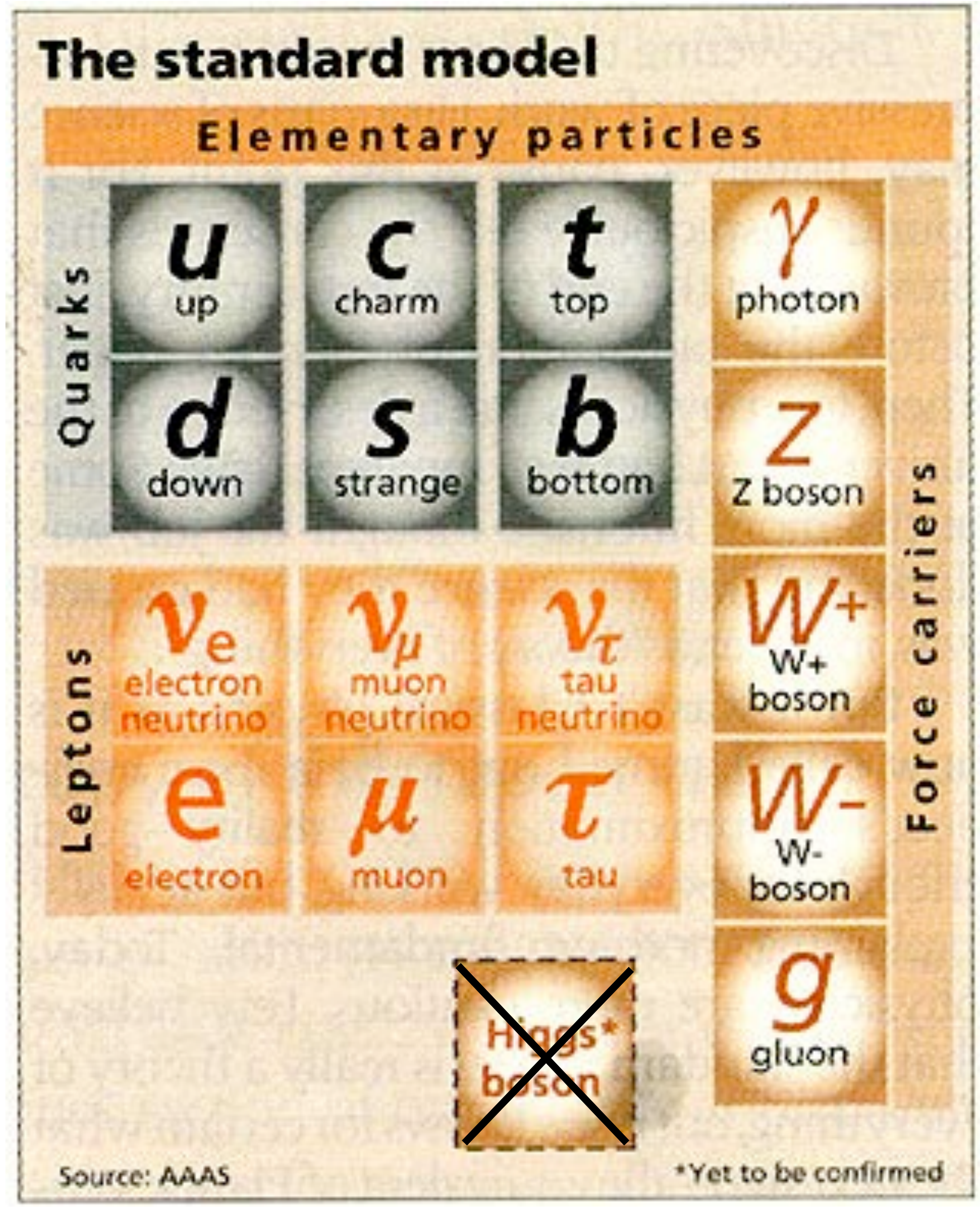
SU(3)

F.S. + Tuominen 04

Dietrich, F.S., Tuominen 05

Extra Neutrino: N

Extra Electron: ζ



U(1)

SU(2)

SU(3)

U t-up

D t-down

G t-glue

SU(2)

F.S. + Tuominen 04

Dietrich, F.S., Tuominen 05

U and D: Adj of SU(2)

S beyond TC…

S beyond TC...

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

S beyond TC...

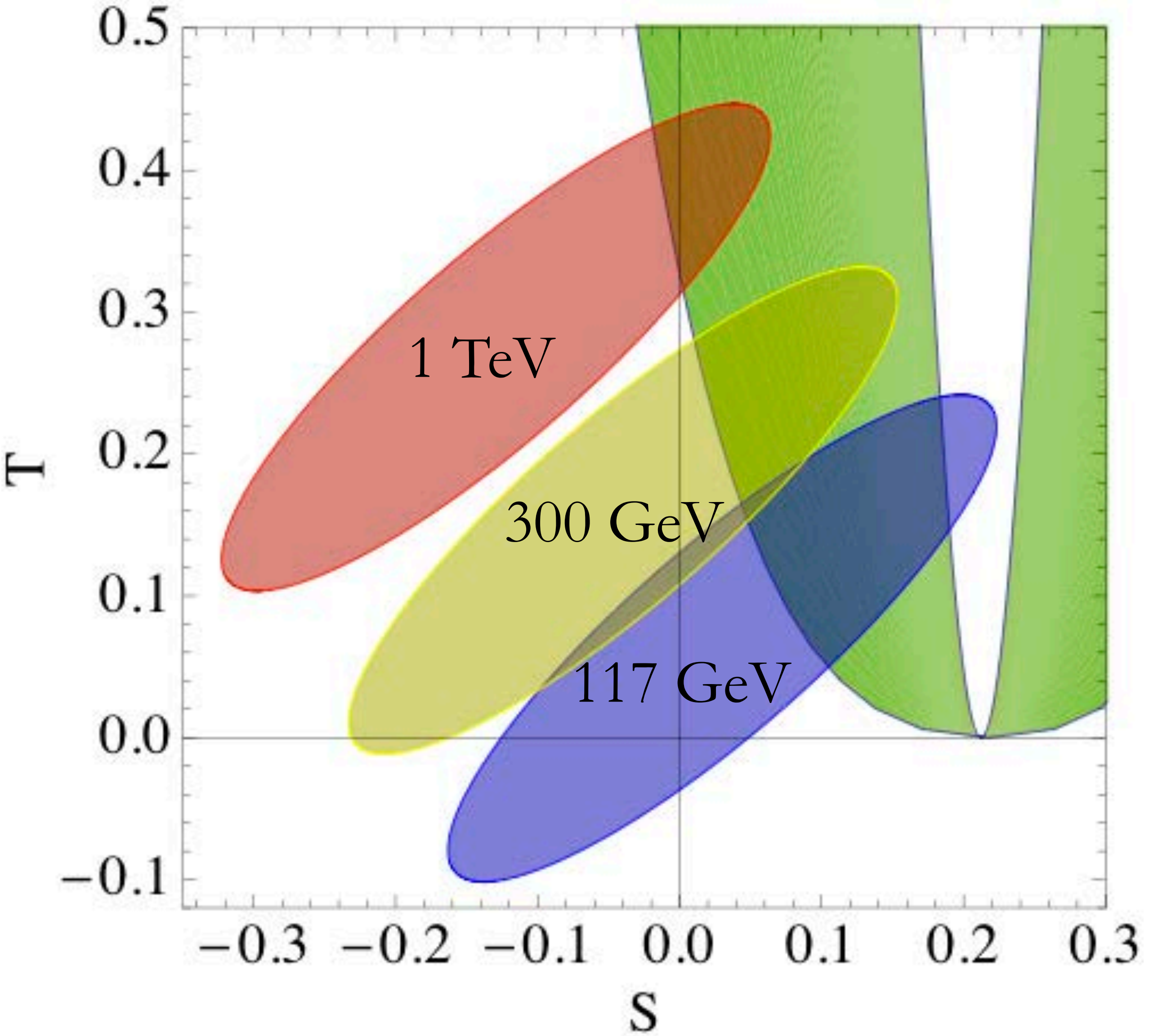
$$S = S_{(W)TC} + S_{NS}$$

S beyond TC...

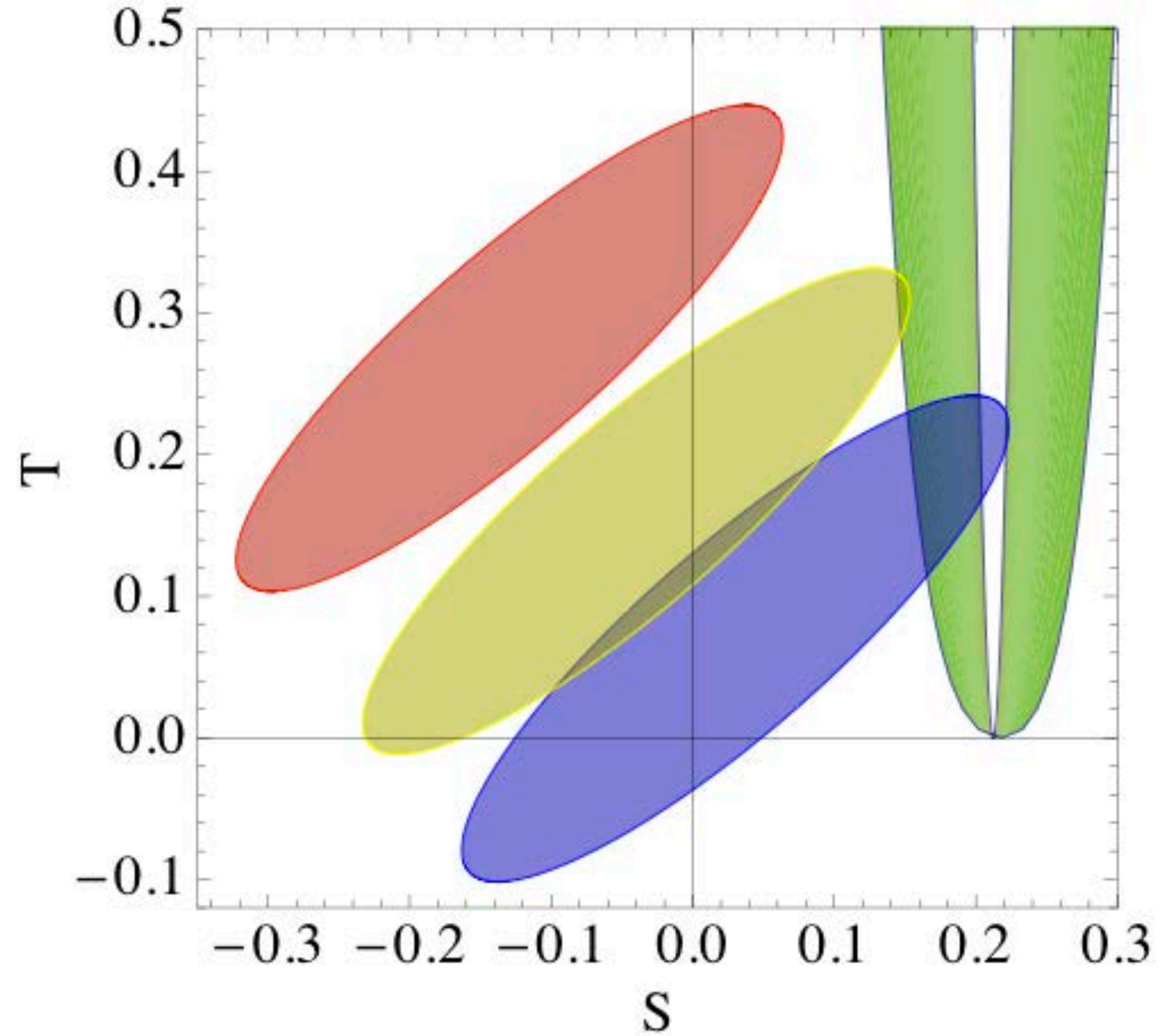
$$S = S_{(W)TC} + S_{NS}$$

Offset the first term

New Leptons & Precision Data



Exotic Leptonic hypercharge Y=-3/2



Standard Model Leptonic hypercharge

MWT Features

MWT Features

- The most economical WT theory

MWT Features

- The most economical WT theory
- Compatible with precision measurements

MWT Features

- The most economical WT theory
- Compatible with precision measurements
- Possible DM candidates

MWT Features

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

MWT Effective Lagrangian

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

Foadi, Frandsen, Ryttov & F.S. 07

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	$R_{1,2}$

Foadi, Frandsen, Ryttov & F.S. 07

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

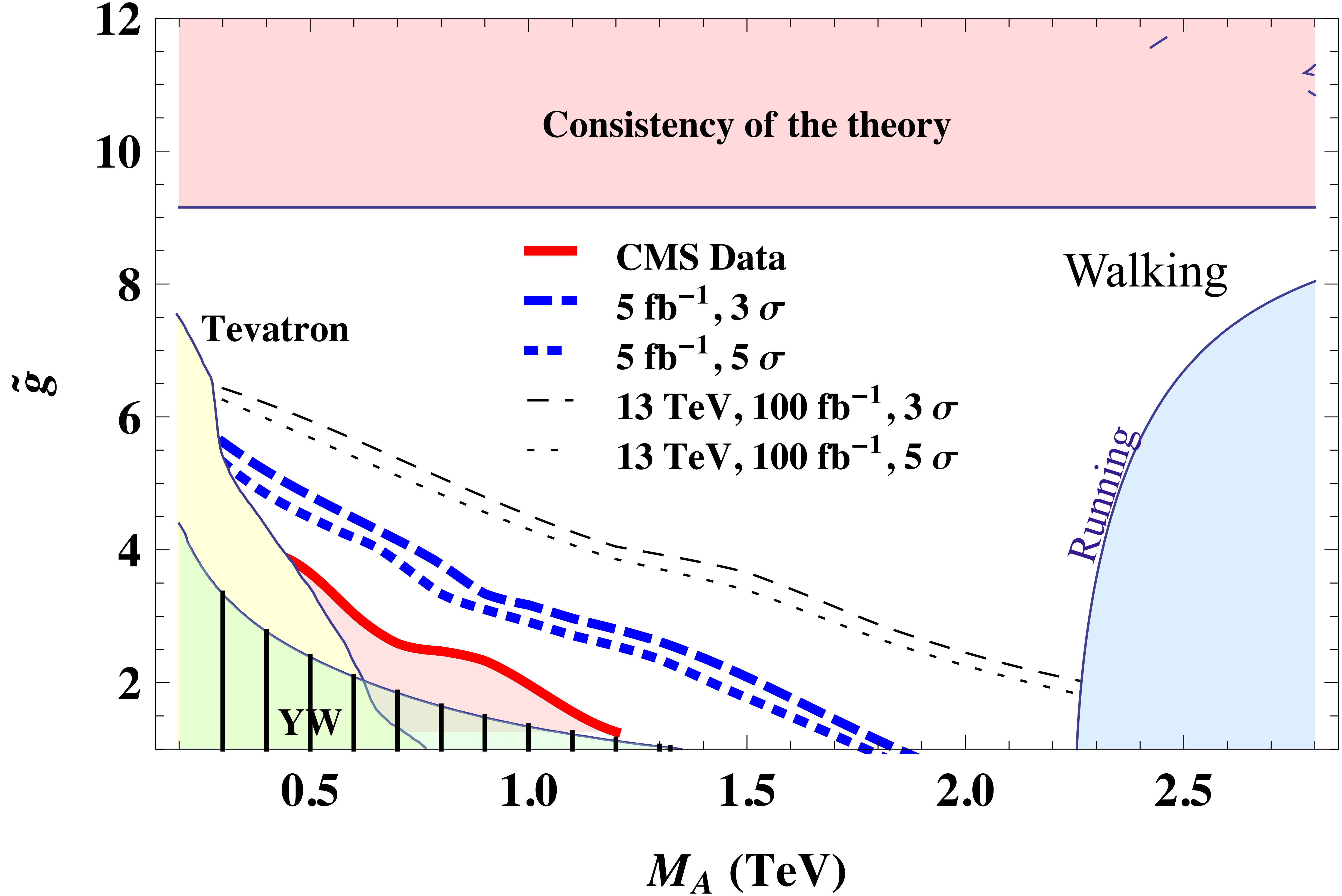
2 Heavy Majoranas — $N_1 \quad N_2$

Frandsen, Masina, Sannino 09

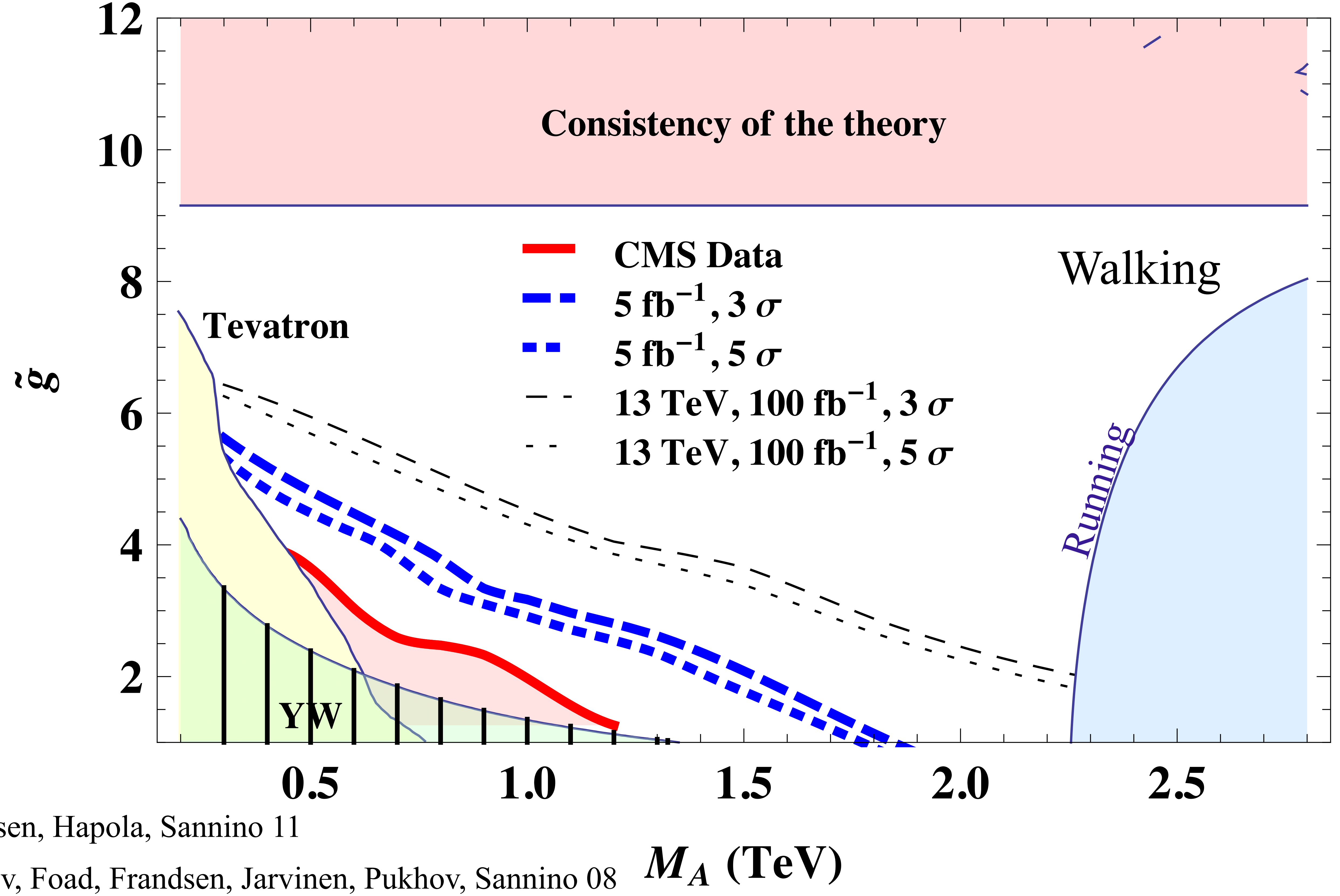
Hapola, Masina, Sannino 11

Foadi, Frandsen, Ryttov & F.S. 07

Constraining MWT



Constraining MWT

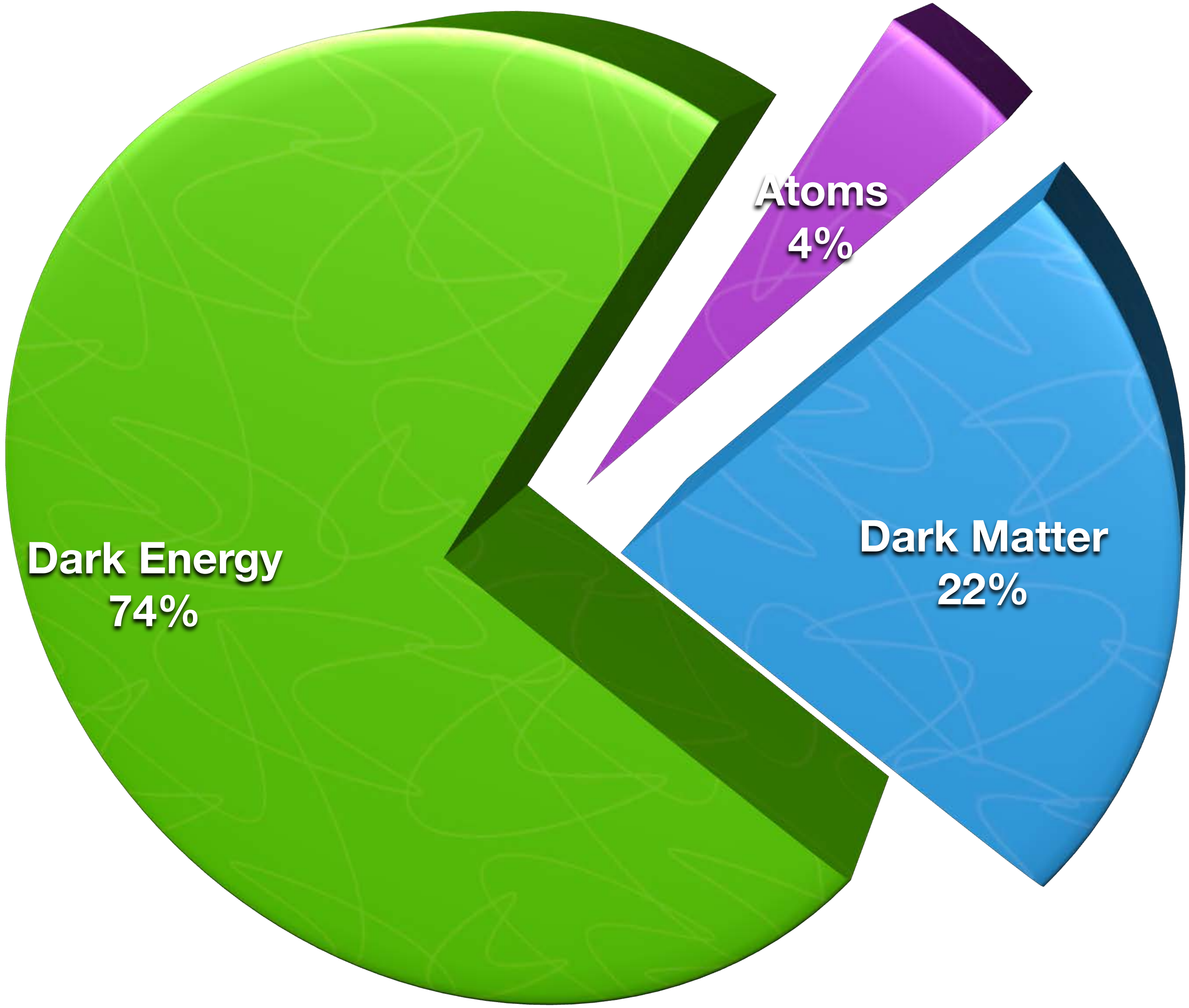


Andersen, Hapola, Sannino 11

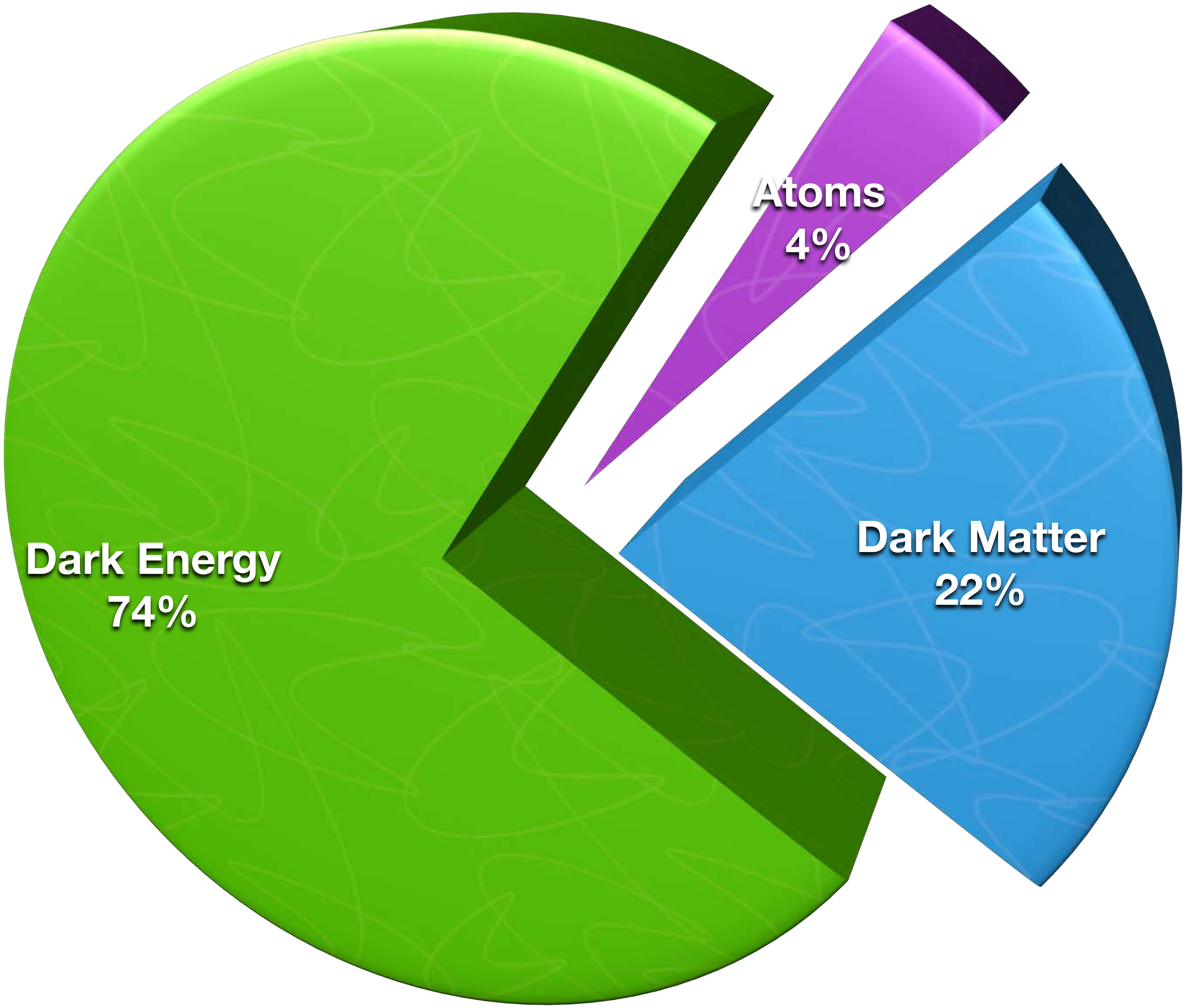
Belyaev, Foad, Frandsen, Jarvinen, Pukhov, Sannino 08

Dark Matter

Dark Matter

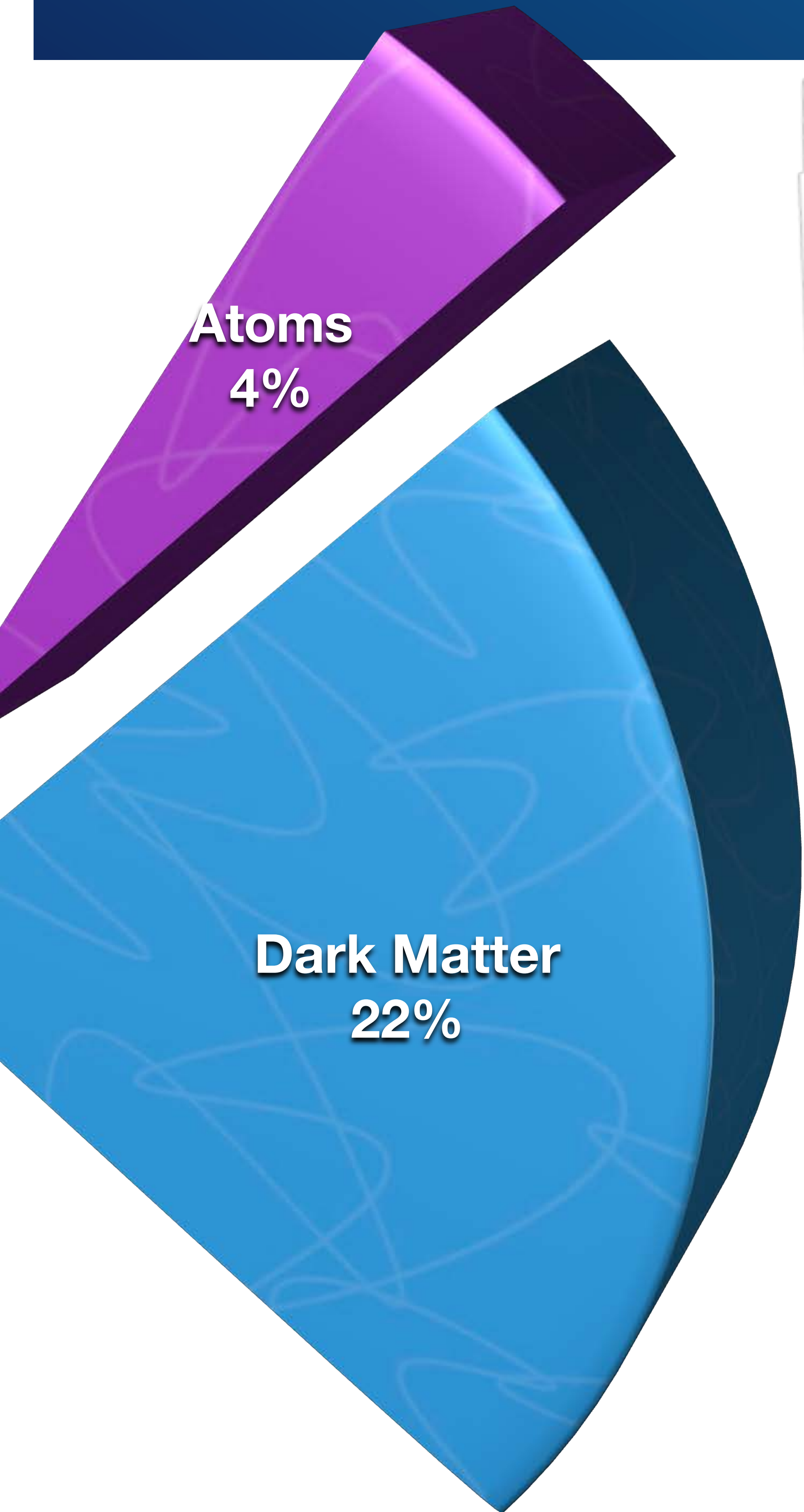


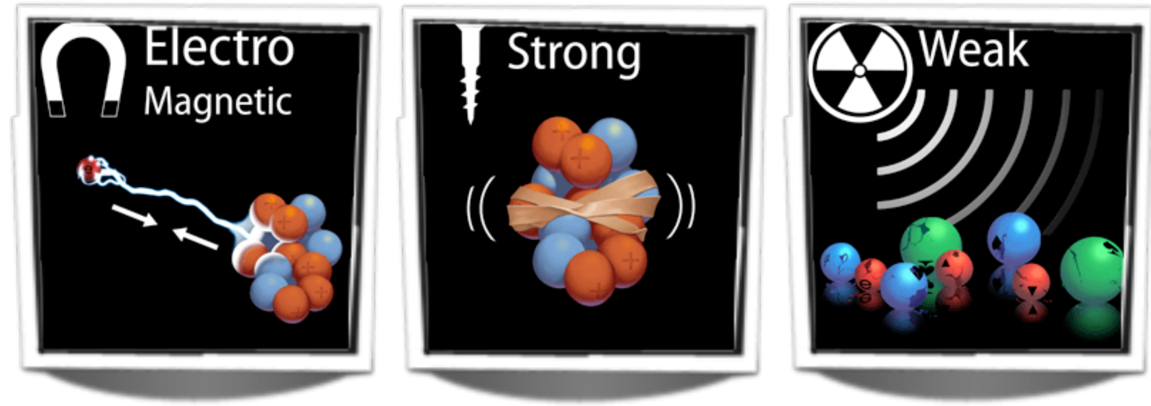
Dark Matter



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

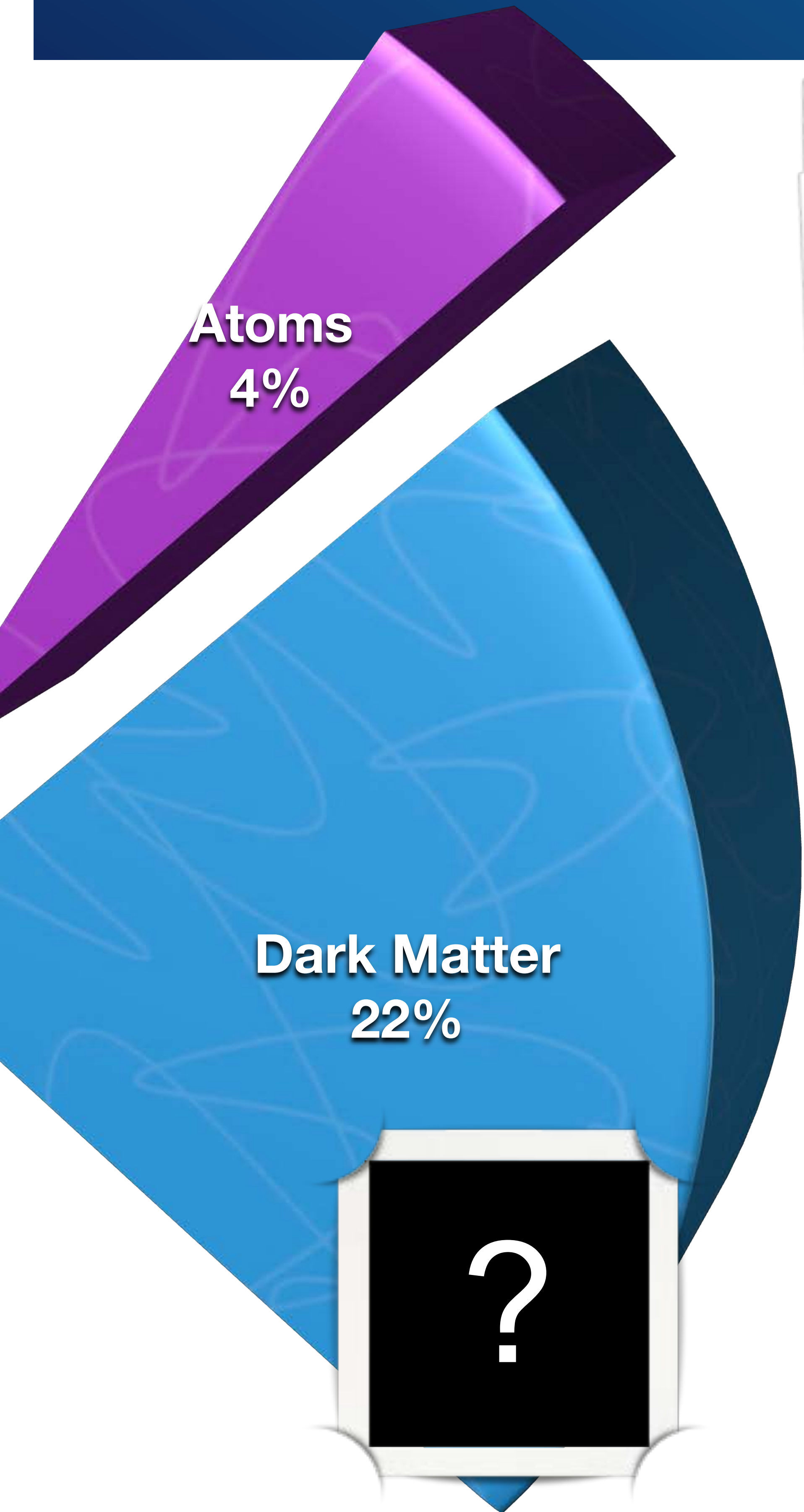
What makes DM?

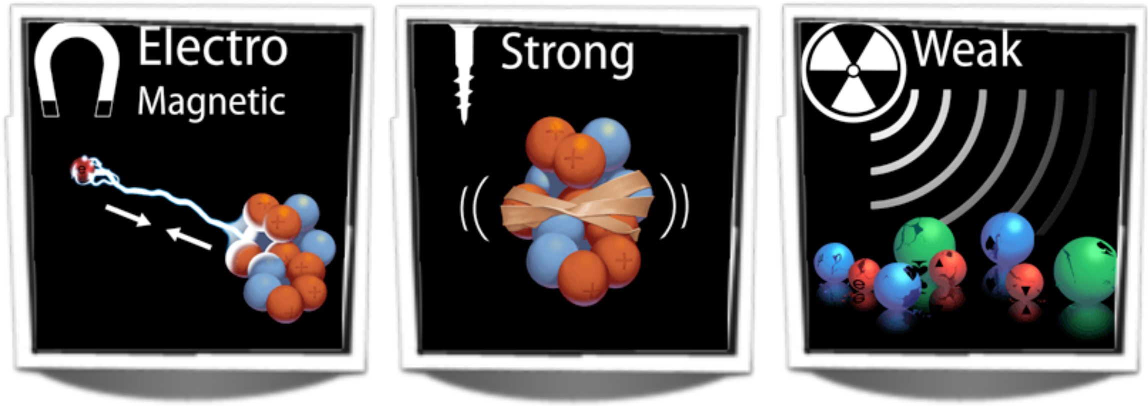




Francesco Sannino

What makes DM?





Francesco Sannino

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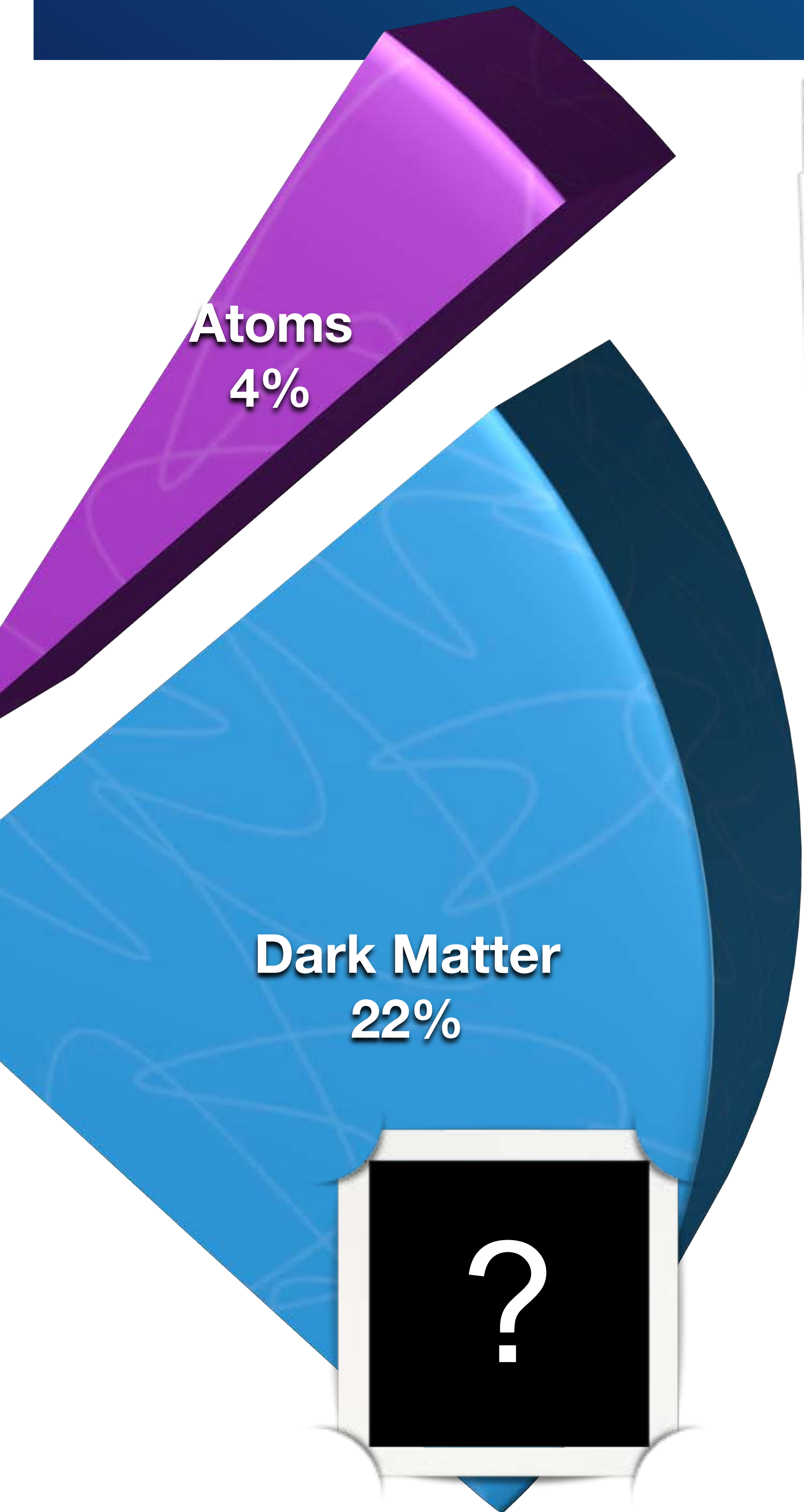
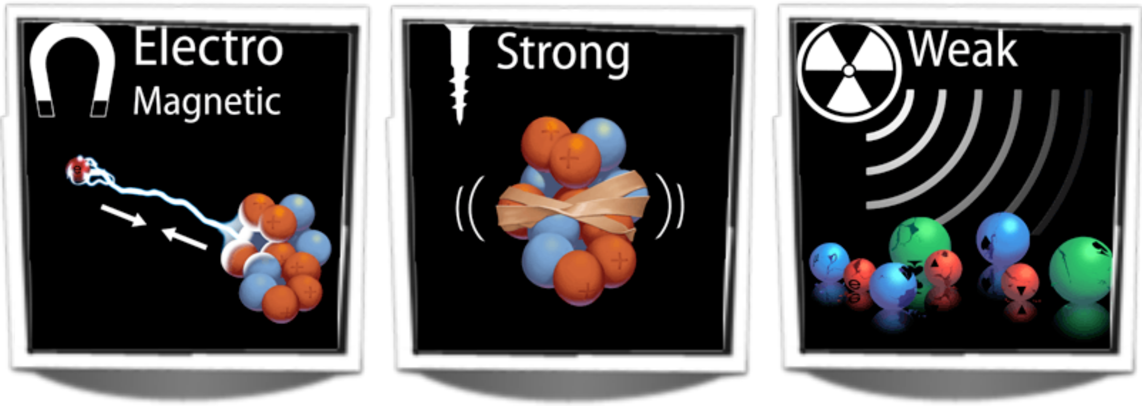
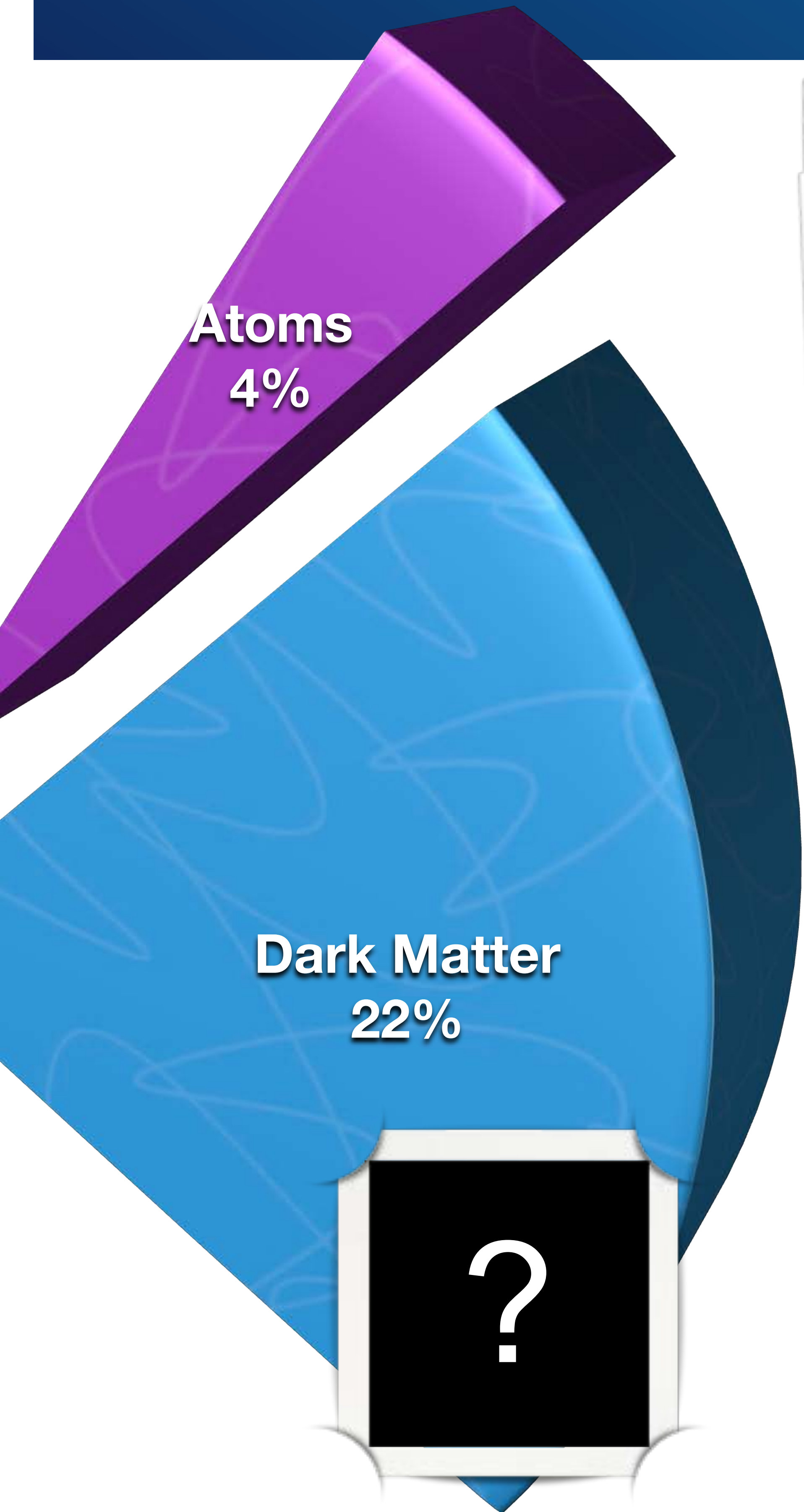
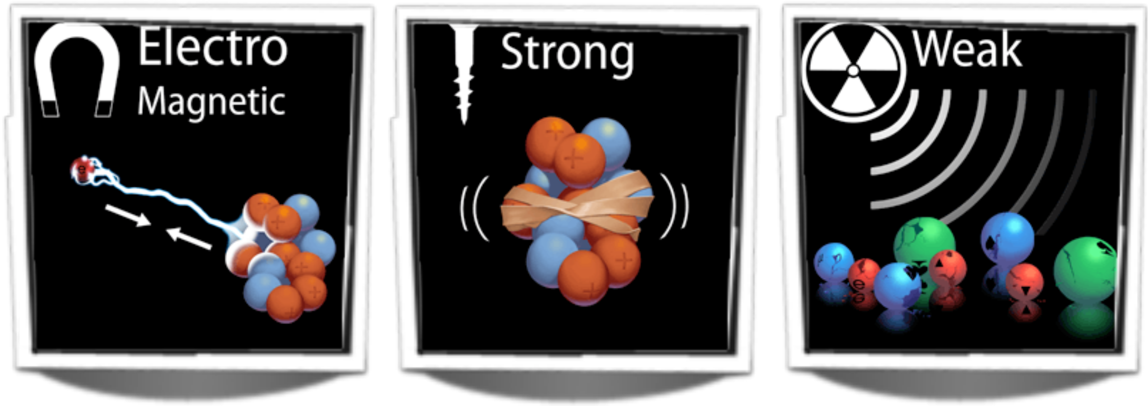
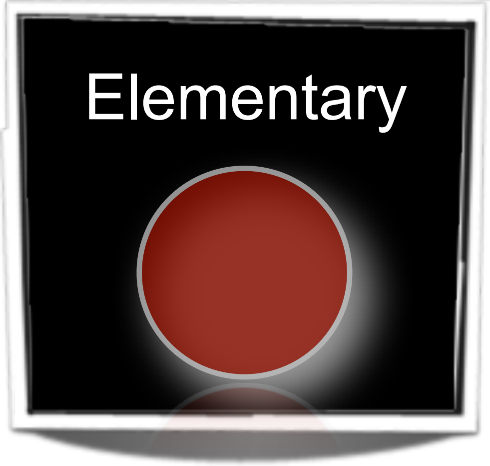




What makes DM?







Francesco Sannino

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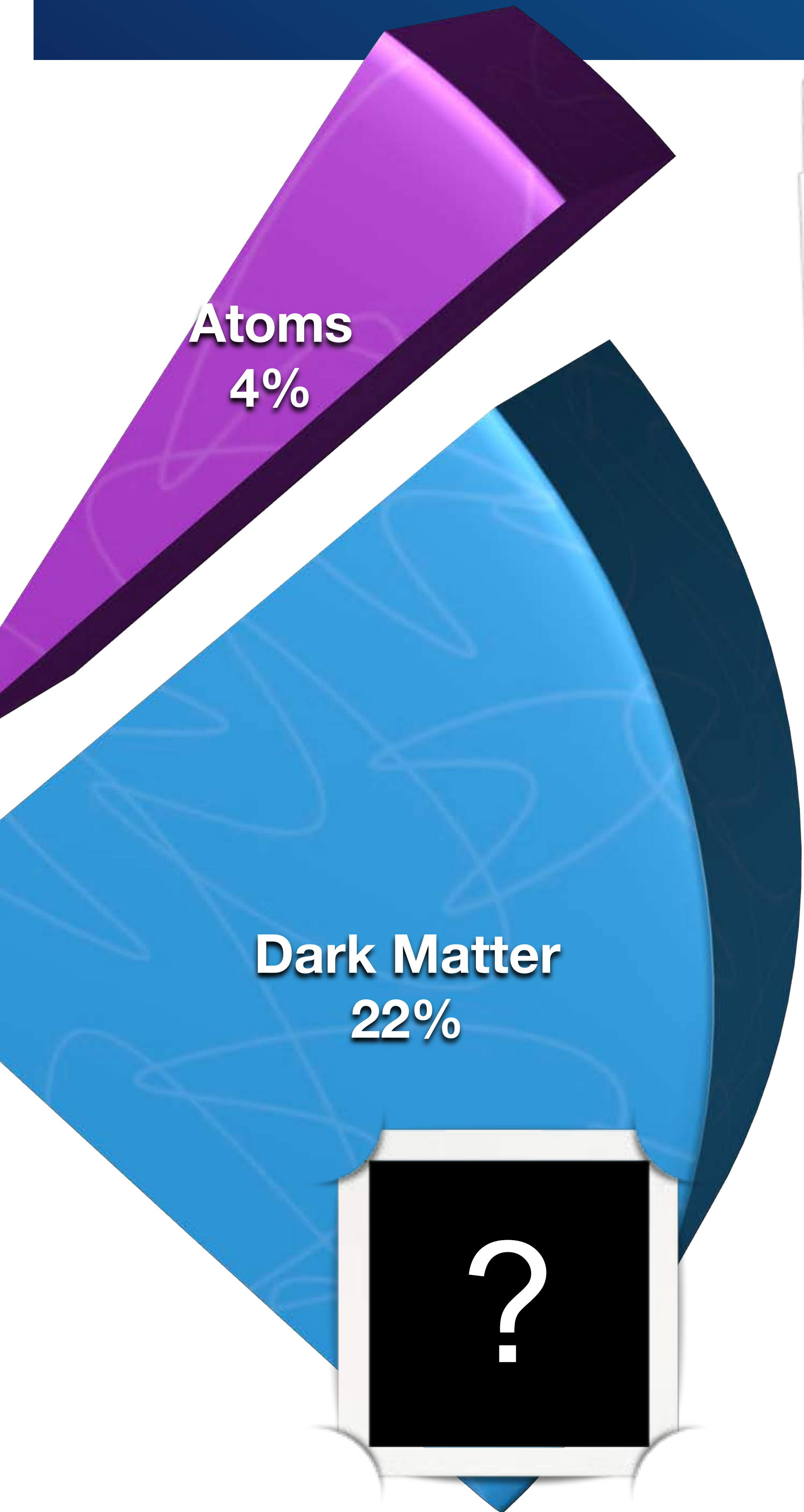
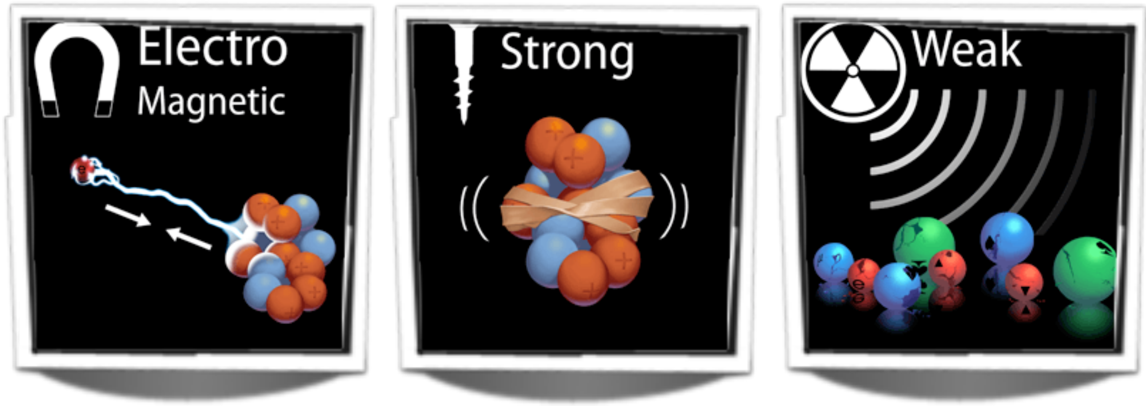
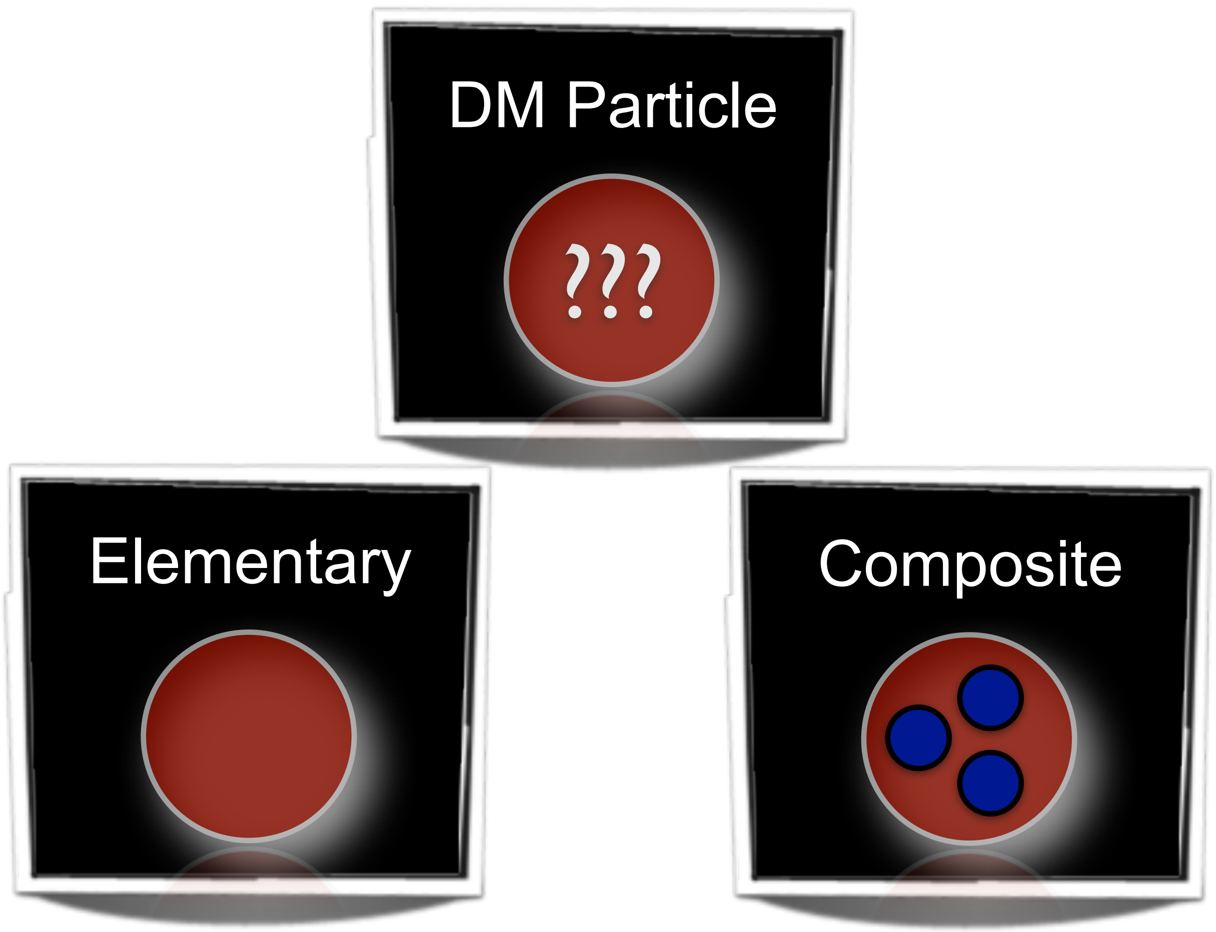
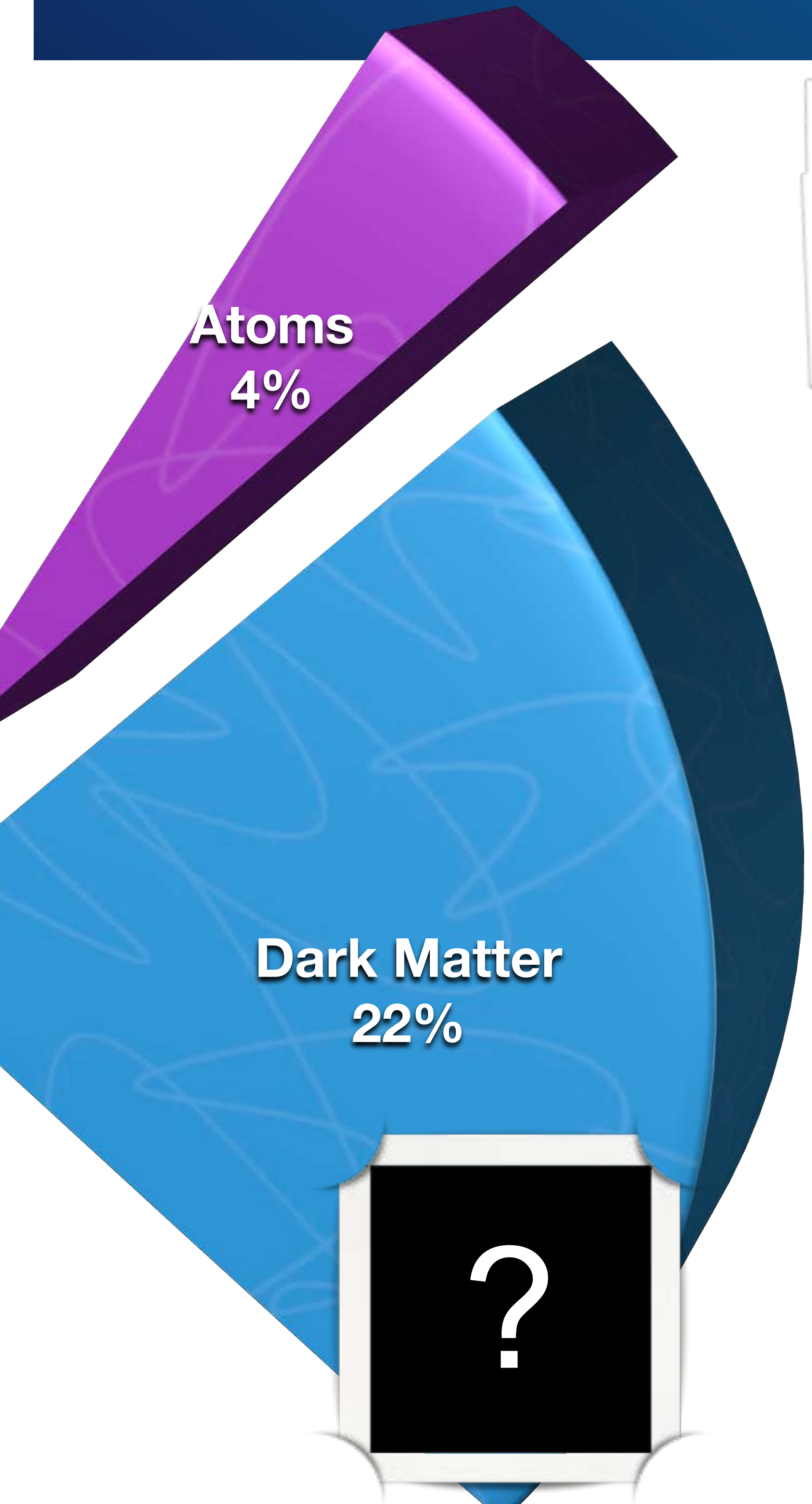
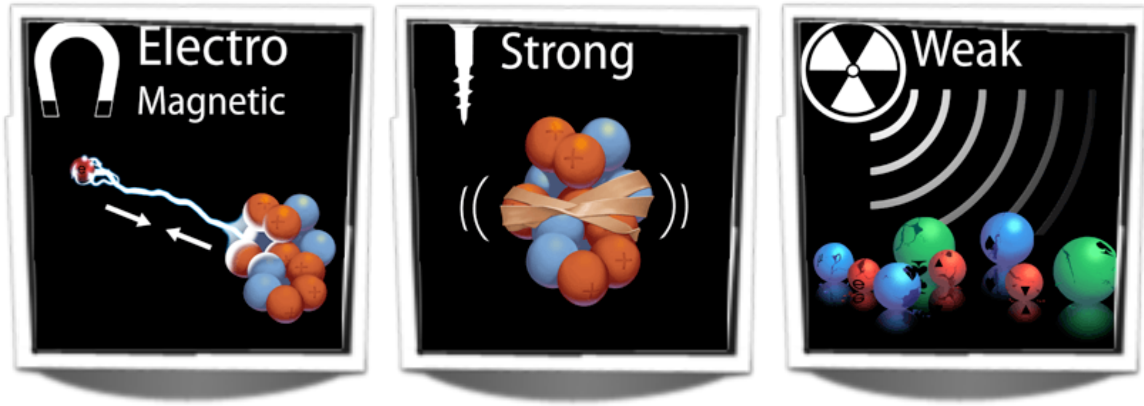




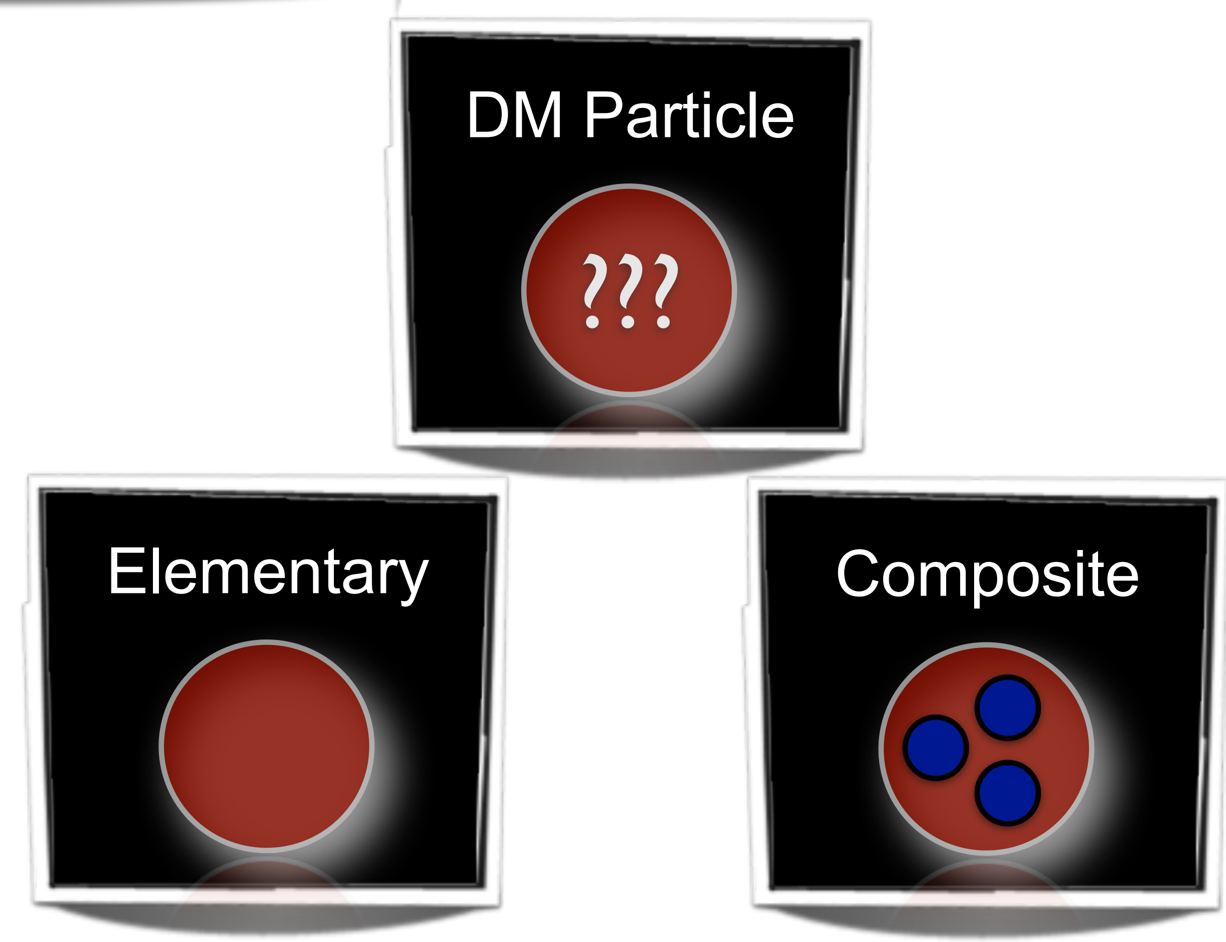


What makes DM?





Oversimplification



DM asymmetry

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- A particle similar to the nucleon

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- Electrically neutral

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- At most EW-type cross sections

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

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

TIMPs	Masses	Annih.	Asymm	Symm	Models

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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

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

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GUTs

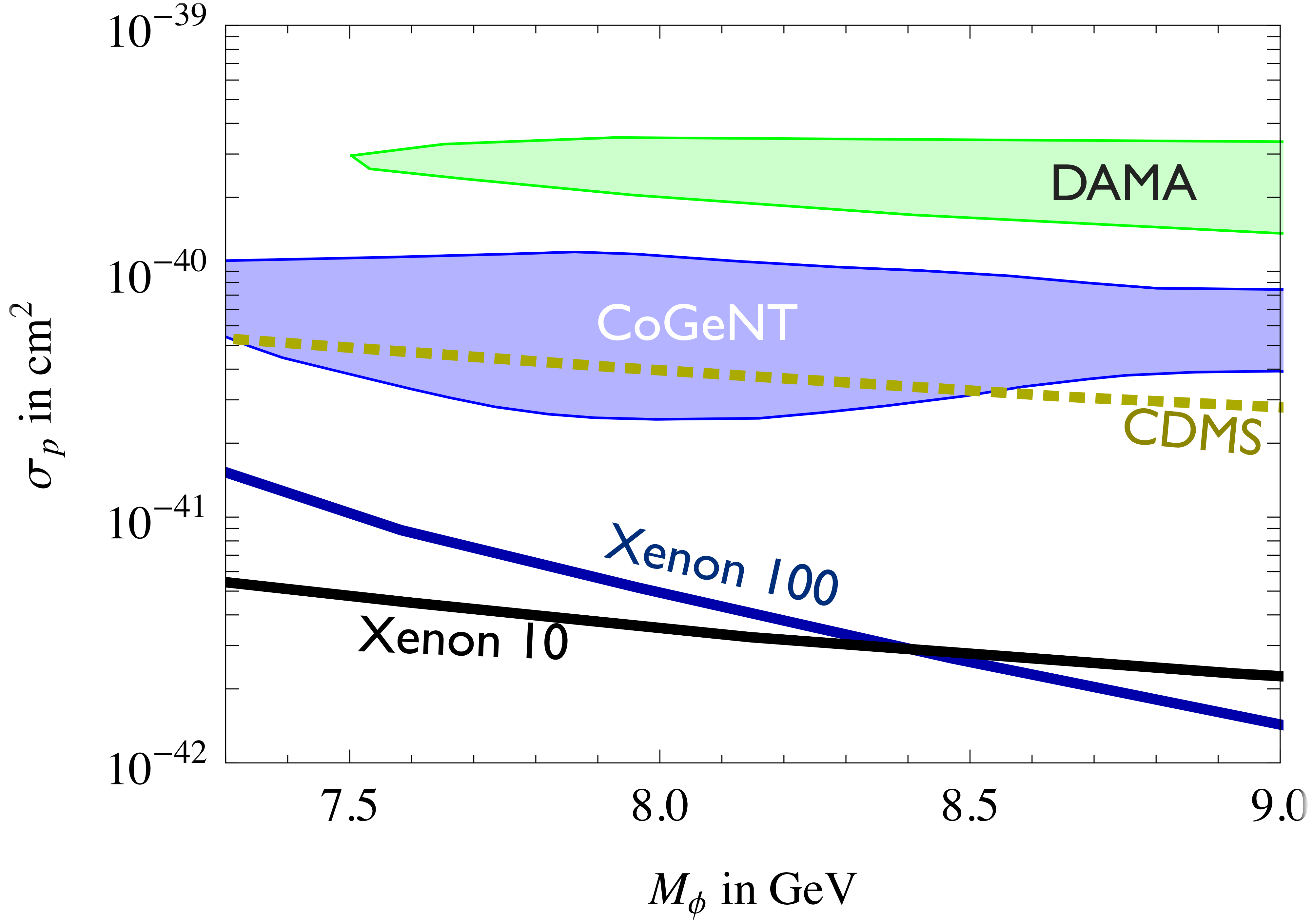
$$\tau \sim \frac{M_{GUT}^4}{m_{TB}^5} \sim 3\times 10^{37}\text{sec}$$

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

Gudnason, Ryttov, FS 06

Nardi, FS, Strumia, 08.

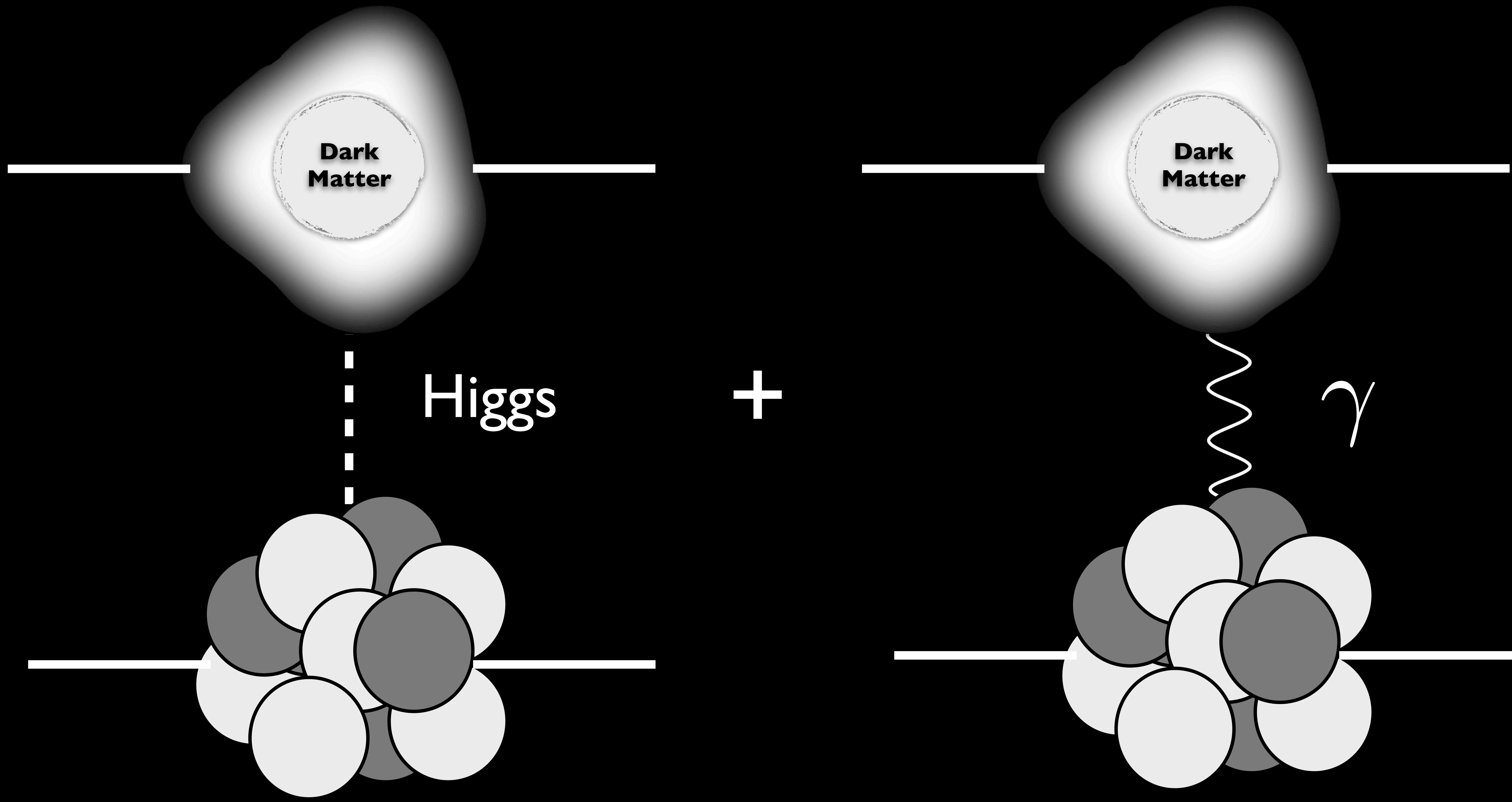
Puzzle



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

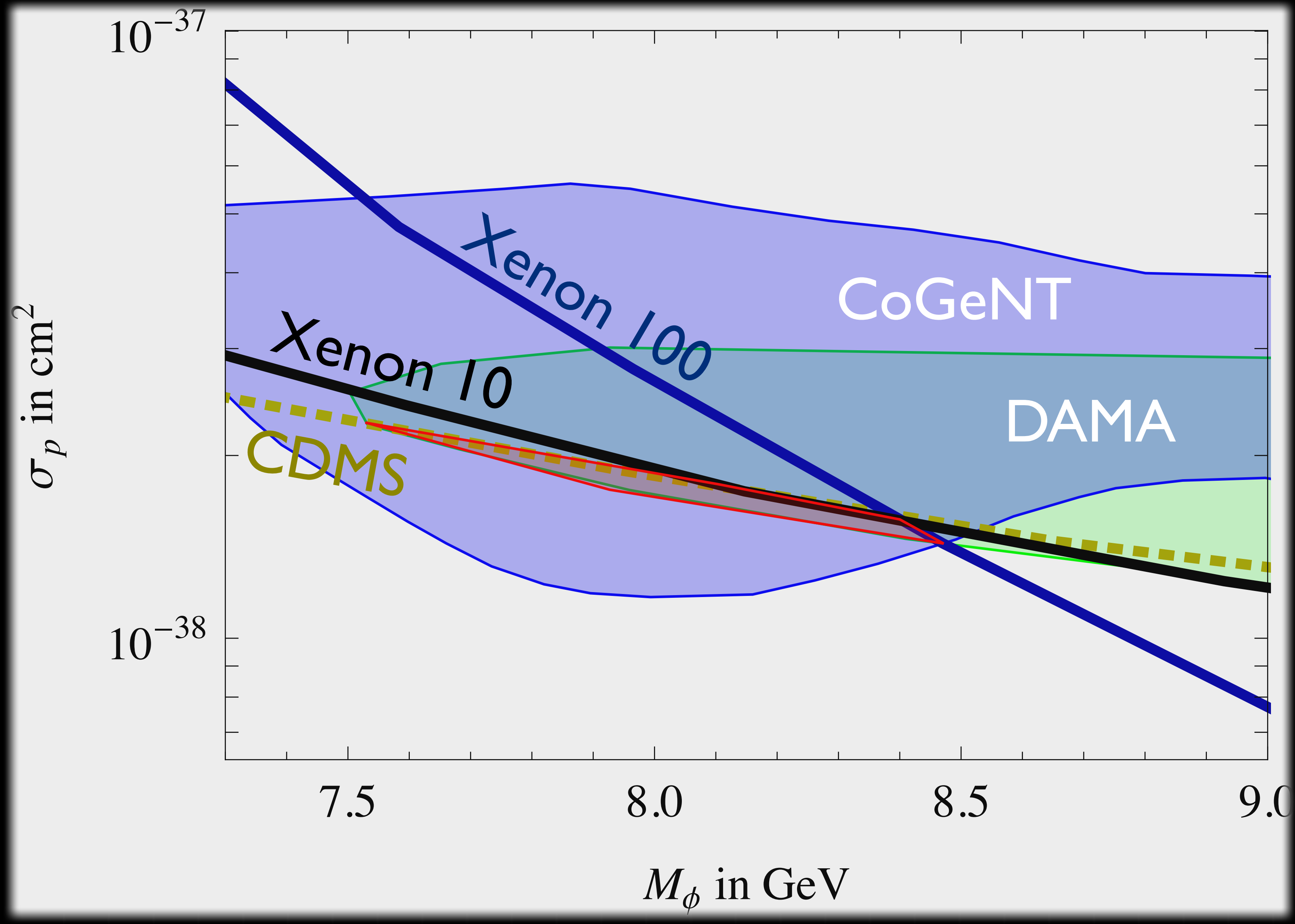
Del Nobile, Kouvaris, Sannino 11



Interfering Composite ADM

CoGeNT and DAMA

Del Nobile, Kouvaris, Sannino 11



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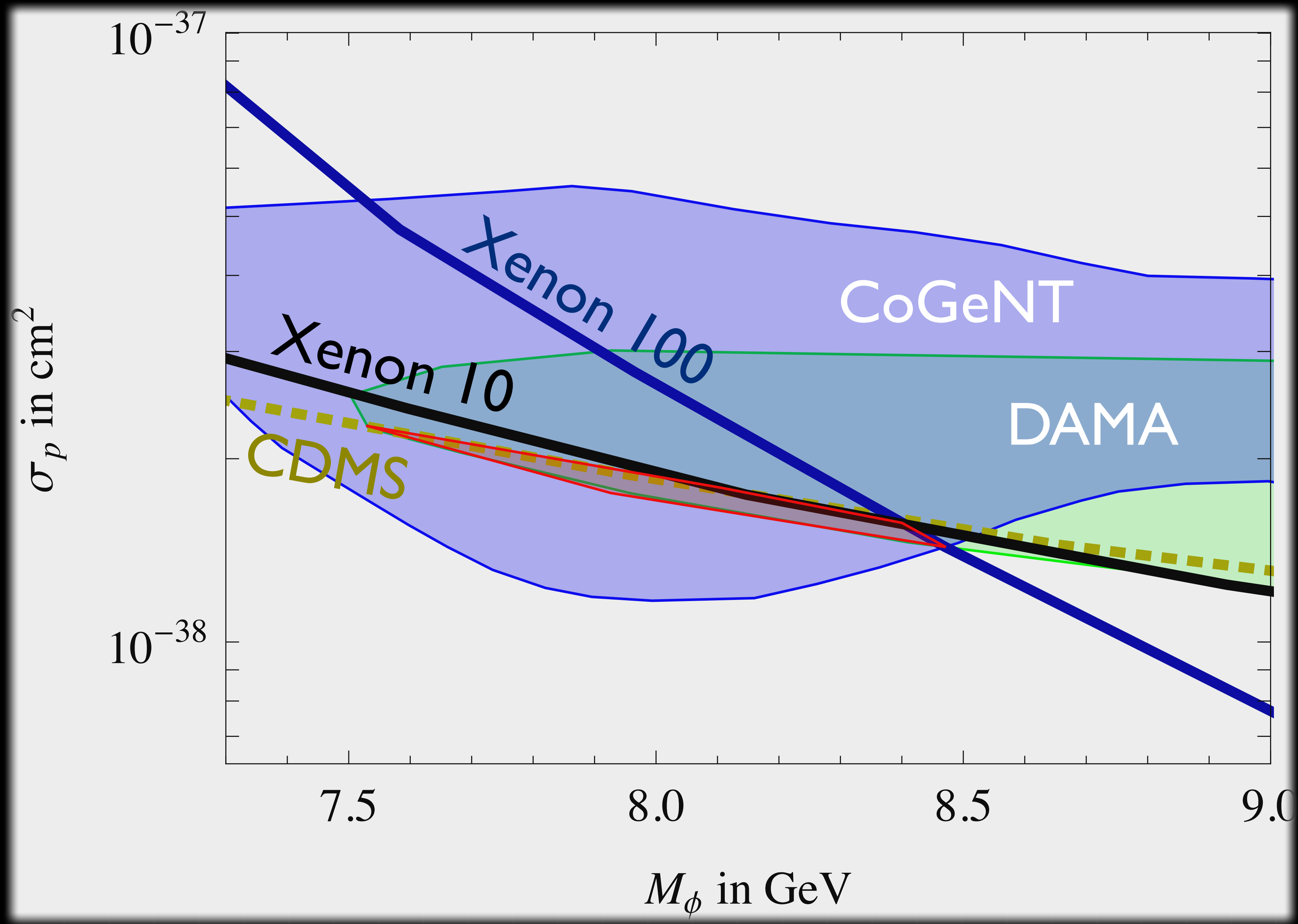
CoGeNT and DAMA

Del Nobile, Kouvaris, Sannino 11



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

Conclusions

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- Phase Diagram of strongly interacting theories

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- Phase Diagram of strongly interacting theories
- Minimal models of technicolor
- Composite Dark Matter
- Composite inflation... another time