Rethinking Fundamental Interactions

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CP3 Origins
Cosmology & Particle Physics

Asymptotic Safety in QFT

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CP3 Origins
Cosmology & Particle Physics

The Standard Model ado

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Fields:

Gauge fields + fermions + scalars

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Gauge fields + fermions + scalars

Interactions:

Gauge: SU(3) x SU(2) x U(1) at EW scale

The Standard Model ado

Fields:

Gauge fields + fermions + scalars

Interactions:

Gauge: SU(3) x SU(2) x U(1) at EW scale

Yukawa: Fermion masses/Flavour

Culprit: Higgs

Scalar self-interaction

Gauge - Yukawa theories

$$L = -\frac{1}{2}F^2 + i\overline{Q}\gamma_\mu D^\mu Q + y(\overline{Q}_L H Q_R + \mathrm{h.c.})$$

$$\mathrm{Tr}\left[\mathrm{D}\mathrm{H}^\dagger \mathrm{D}\mathrm{H}\right] - \lambda_\mathrm{u}\mathrm{Tr}\left[(\mathrm{H}^\dagger\mathrm{H})^2\right] - \lambda_\mathrm{v}\mathrm{Tr}\left[(\mathrm{H}^\dagger\mathrm{H})\right]^2$$

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Gauge $$\boxed{\mathrm{Tr}\left[\mathrm{DH^\dagger DH}\right]} - \lambda_{\mathrm{u}}\mathrm{Tr}\left[(\mathrm{H^\dagger H})^2\right] - \lambda_{\mathrm{v}}\mathrm{Tr}\left[(\mathrm{H^\dagger H})\right]^2$$

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Yukawa

Gauge

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Scalar selfinteractions

4D: standard model, dark matter, …

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Scalar selfinteractions

4D: standard model, dark matter, …

3D: condensed matter, phase transitions

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Scalar selfinteractions

4D: standard model, dark matter, …

3D: condensed matter, phase transitions

2D: graphene, …

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Scalar selfinteractions

4D: standard model, dark matter, …

3D: condensed matter, phase transitions

2D: graphene, …

4plusD: extra dimensions, string theory, …

Gauge - Yukawa theories

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Gauge $$\boxed{\mathrm{Tr}\left[\mathrm{DH}^\dagger\mathrm{DH}\right]} - \boxed{\lambda_\mathrm{u}\mathrm{Tr}\left[(\mathrm{H}^\dagger\mathrm{H})^2\right] - \lambda_\mathrm{v}\mathrm{Tr}\left[(\mathrm{H}^\dagger\mathrm{H})\right]^2}$$

Scalar selfinteractions

4D: standard model, dark matter, …

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Universal description of physical phenomena

Two main issues

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- EW scale stability
- UV triviality (Landau Pole)

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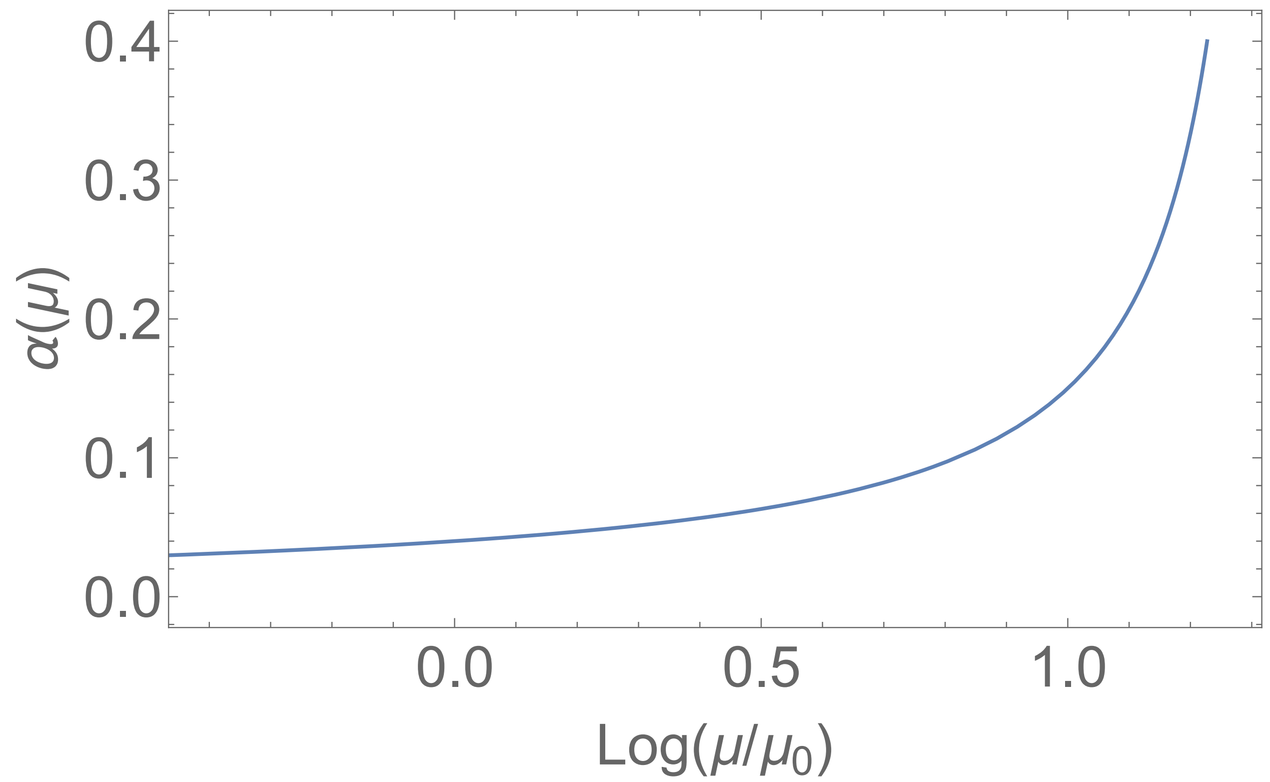
- UV triviality (Landau Pole)



Two main issues

- EW scale stability
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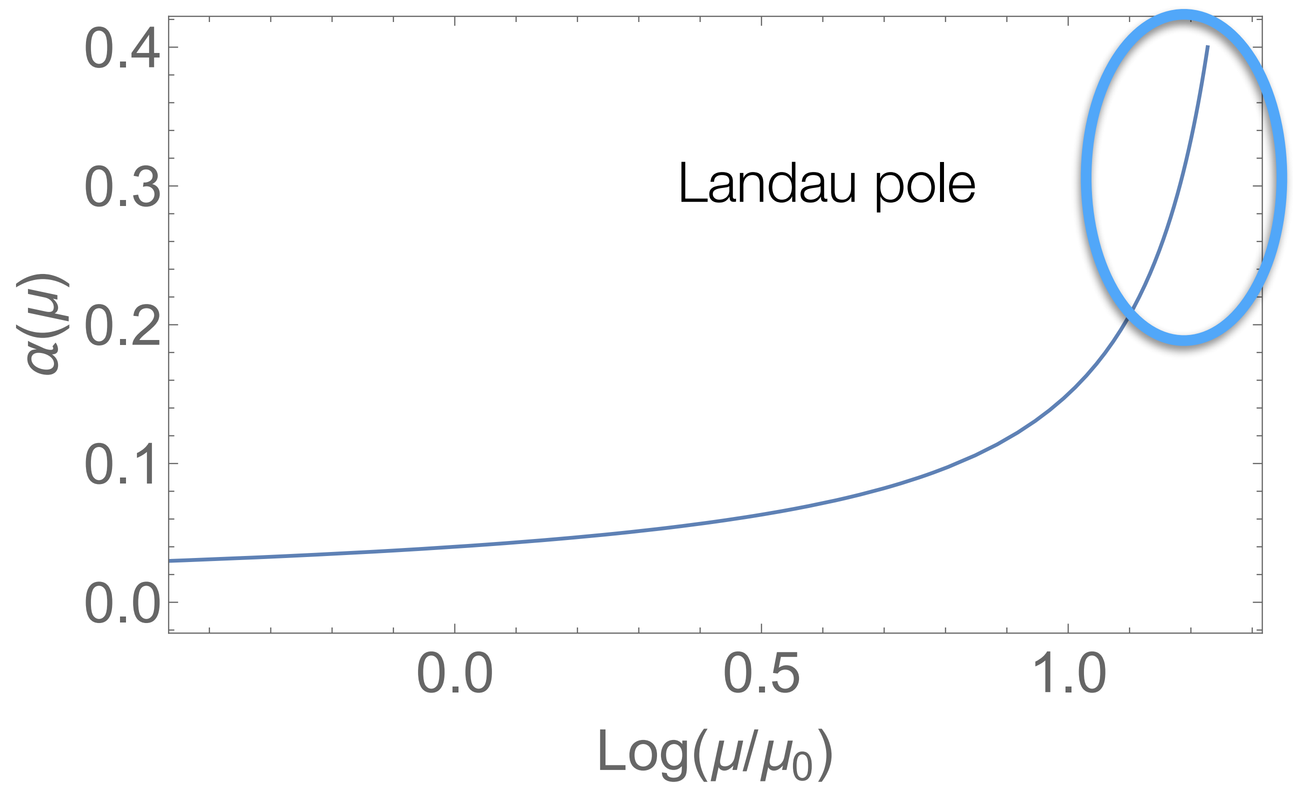

Fundamental theory

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Wilson: A fundamental theory has an UV fixed point

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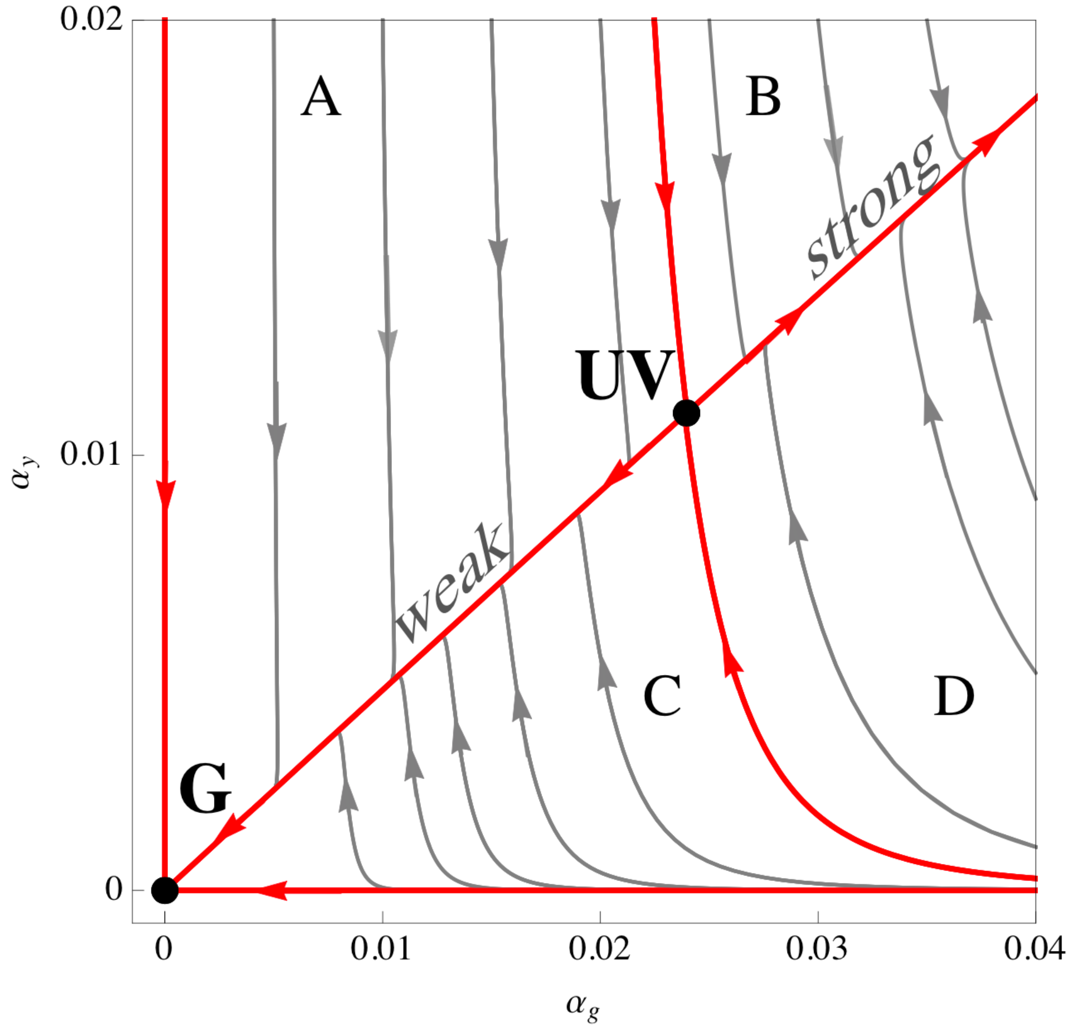

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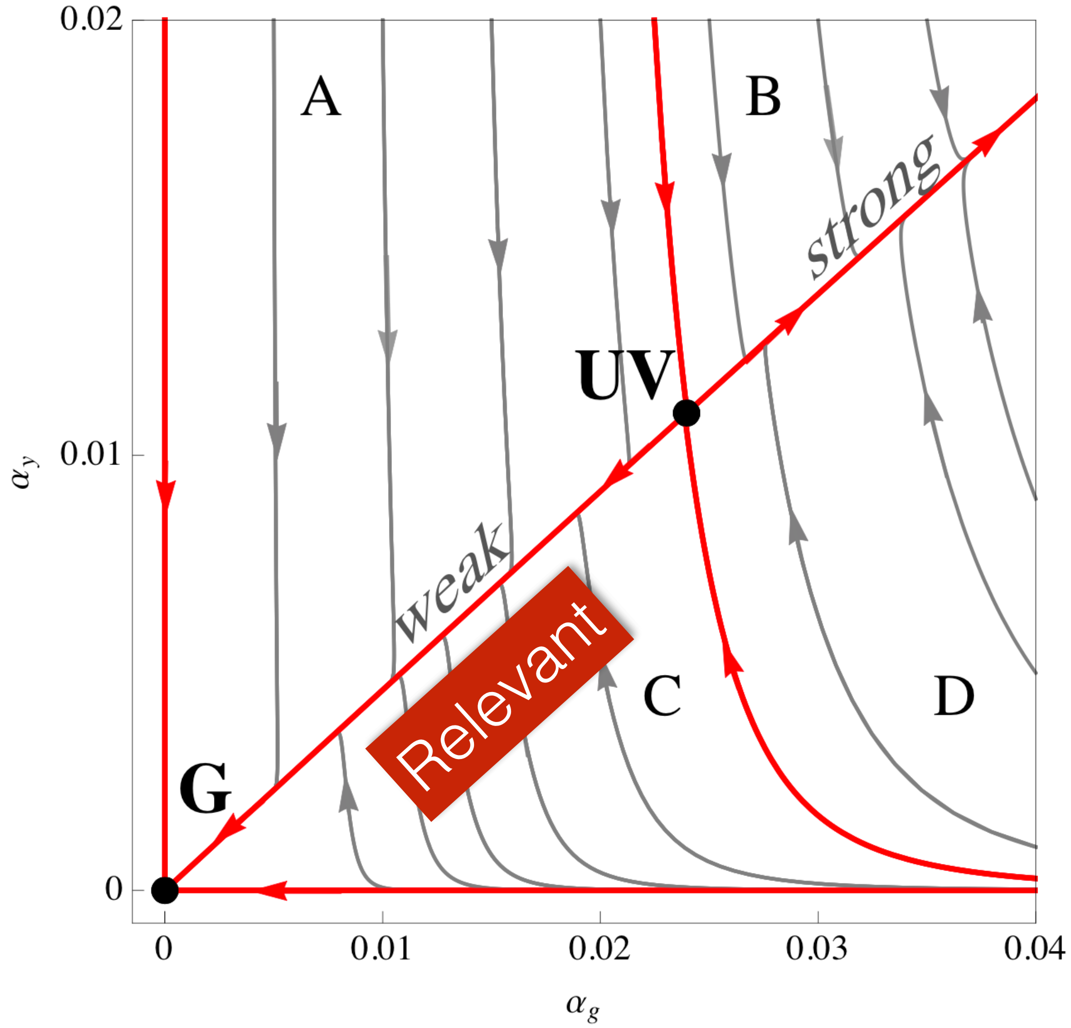

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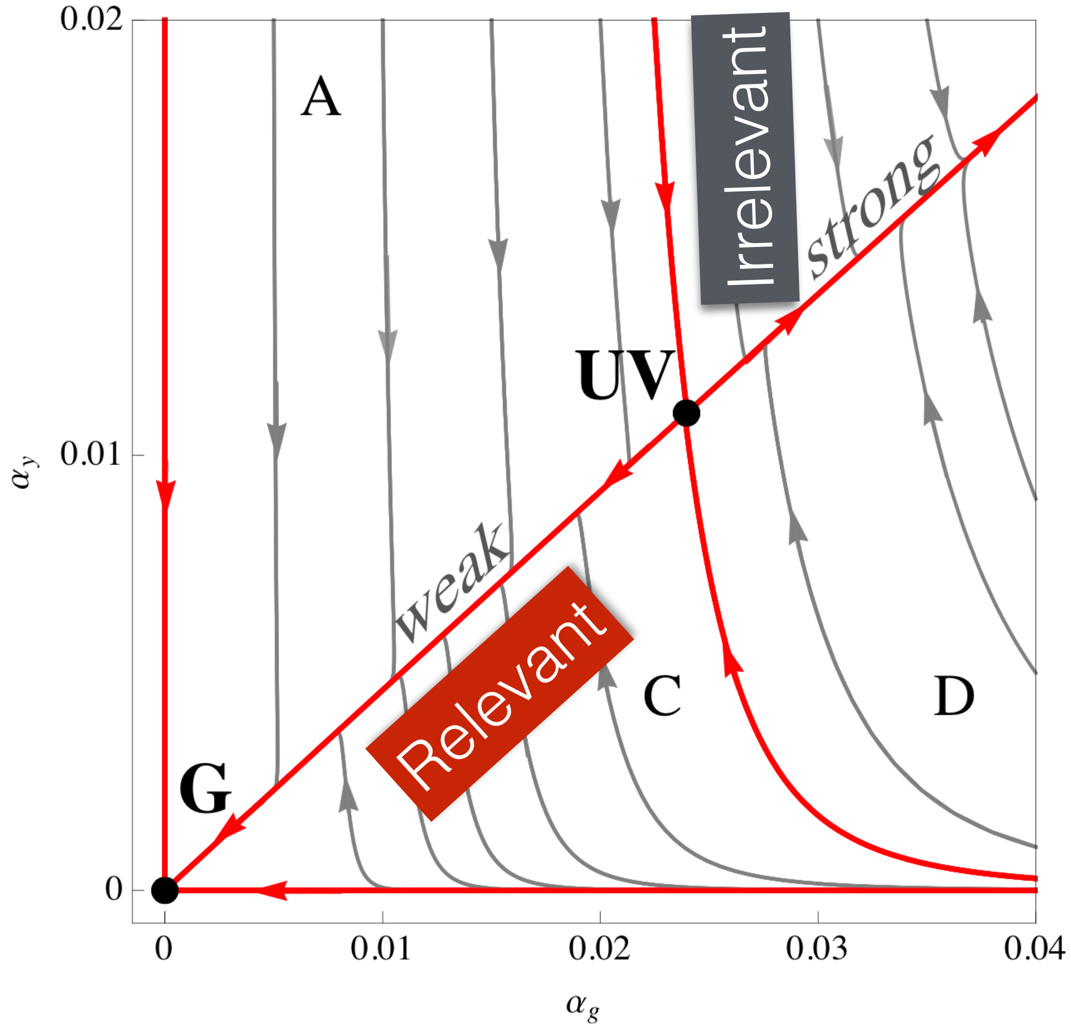
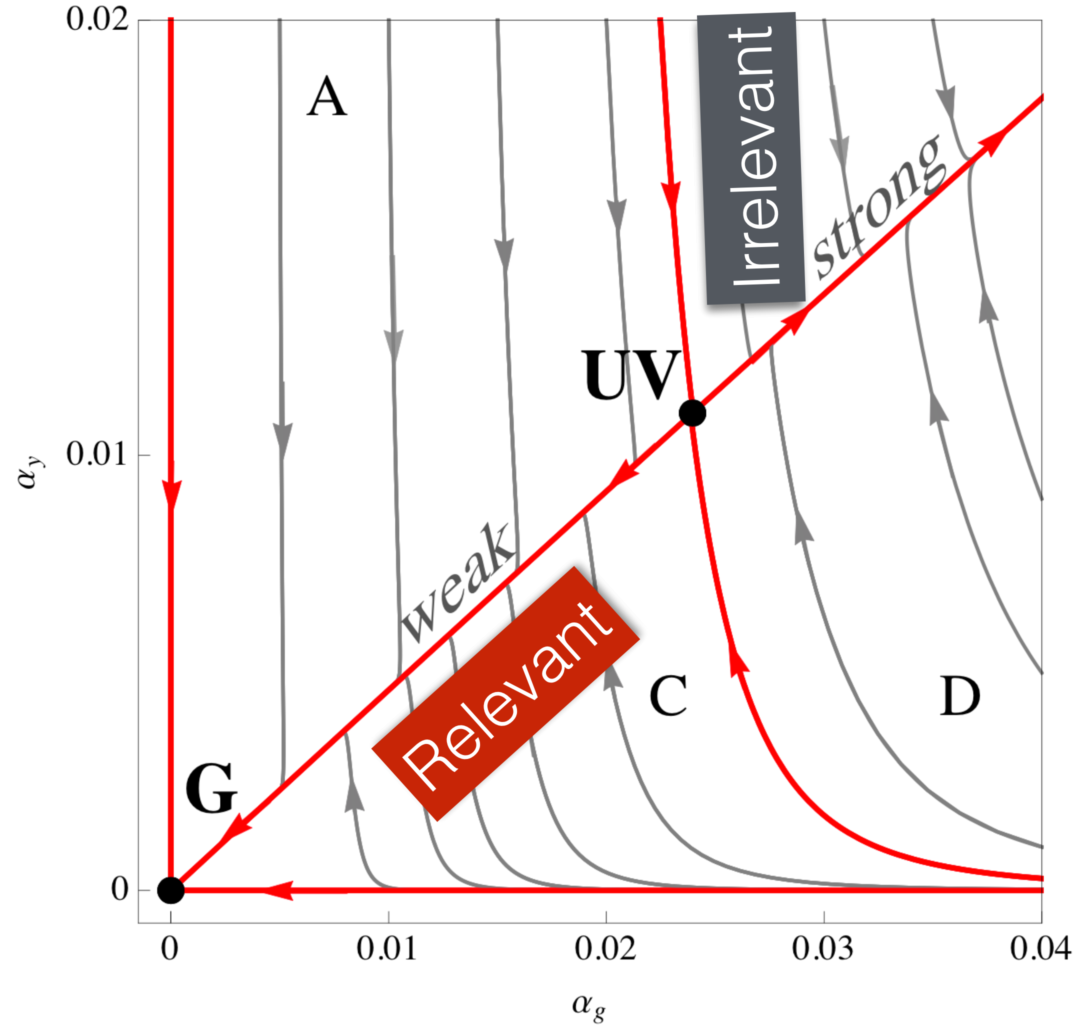


Fundamental theory

Wilson: A fundamental theory has an UV fixed point

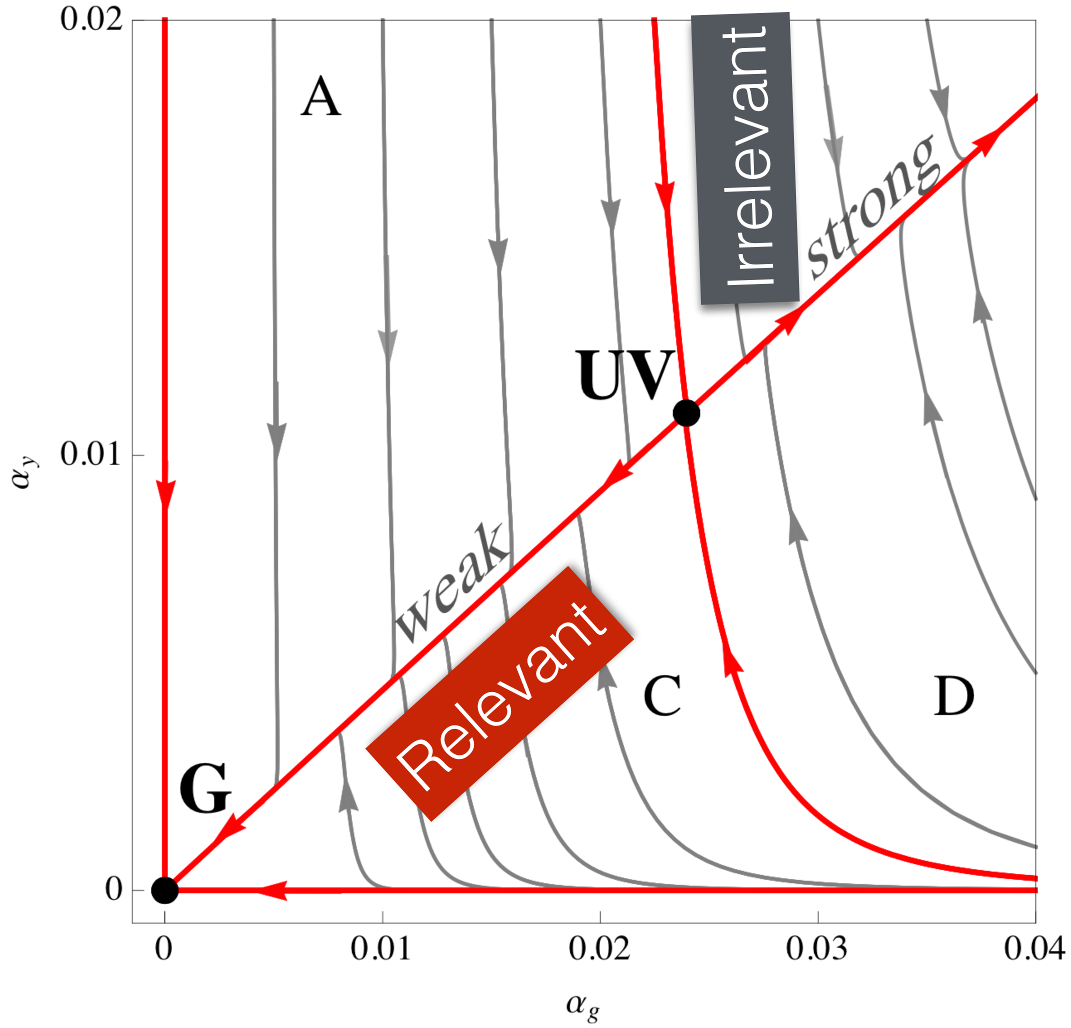
- Short distance conformality



Fundamental theory

Wilson: A fundamental theory has an UV fixed point

- Short distance conformality
- Continuum limit well defined



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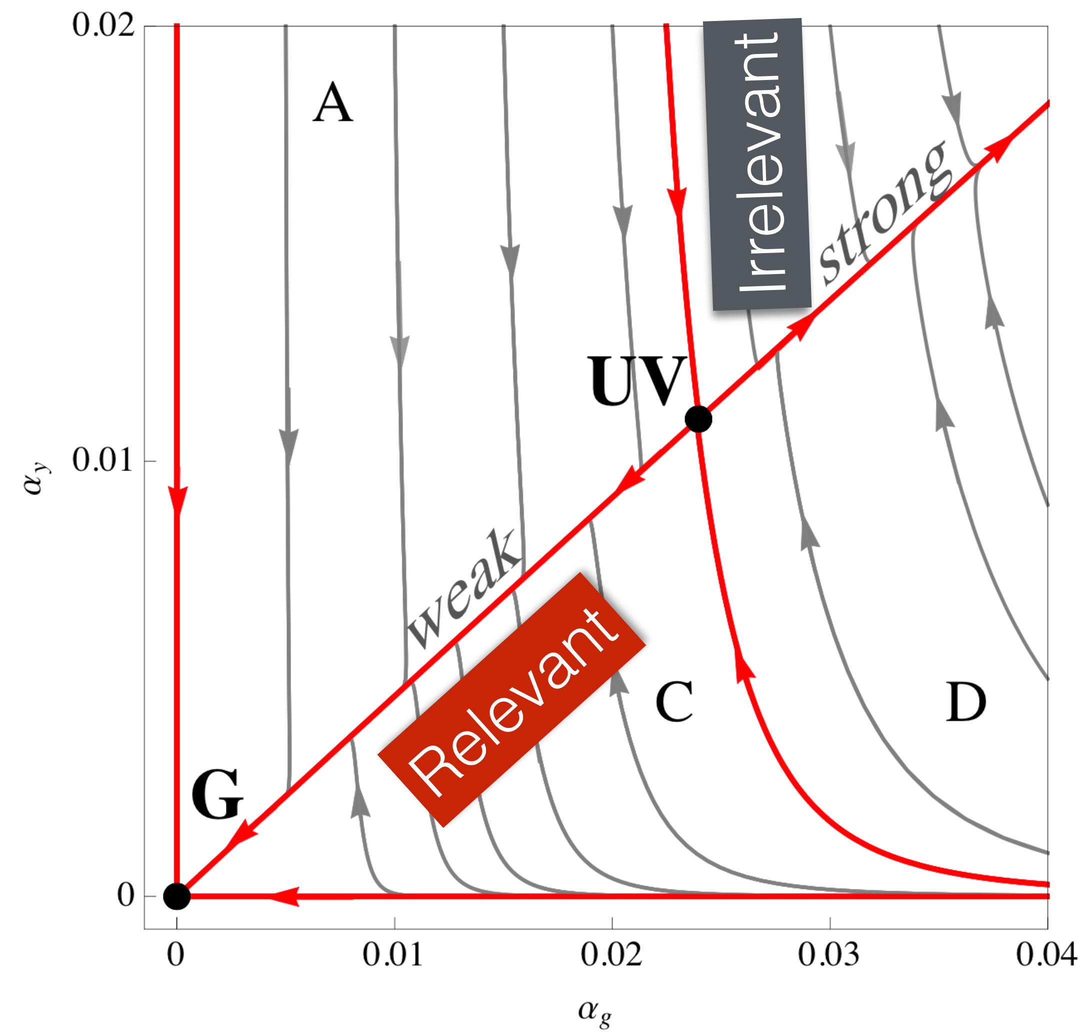

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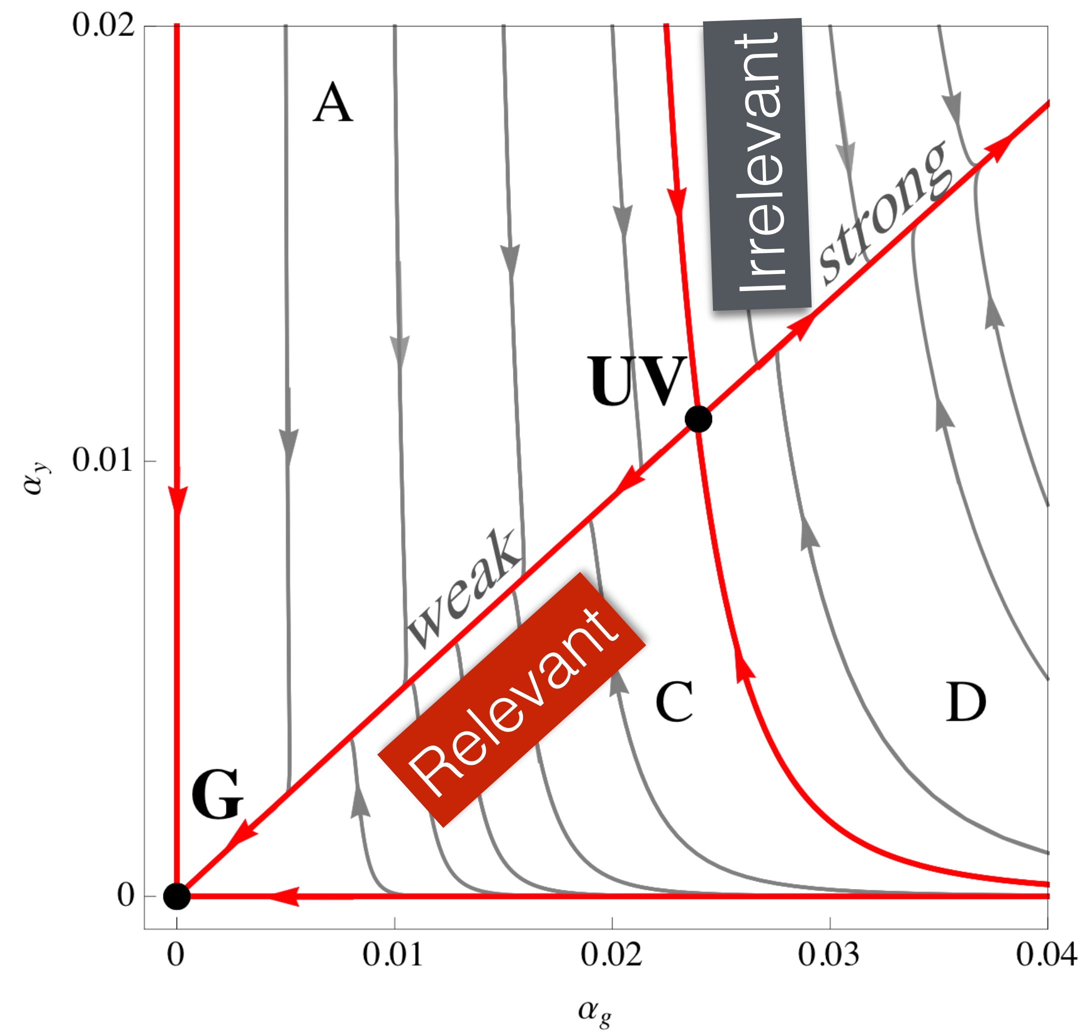
- Short distance conformality
- Continuum limit well defined
- Complete UV fixed point
- Smaller critical surface dim. = more IR predictiveness



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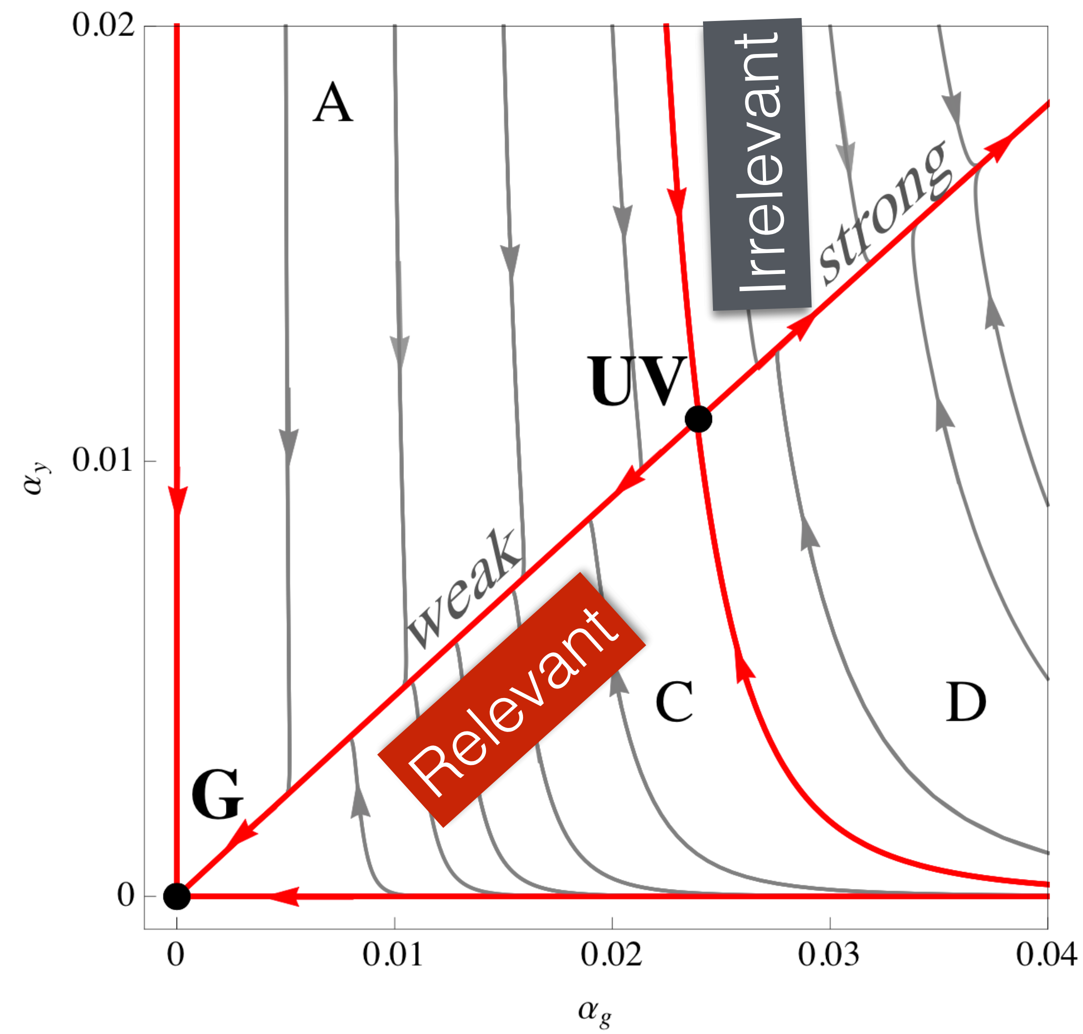

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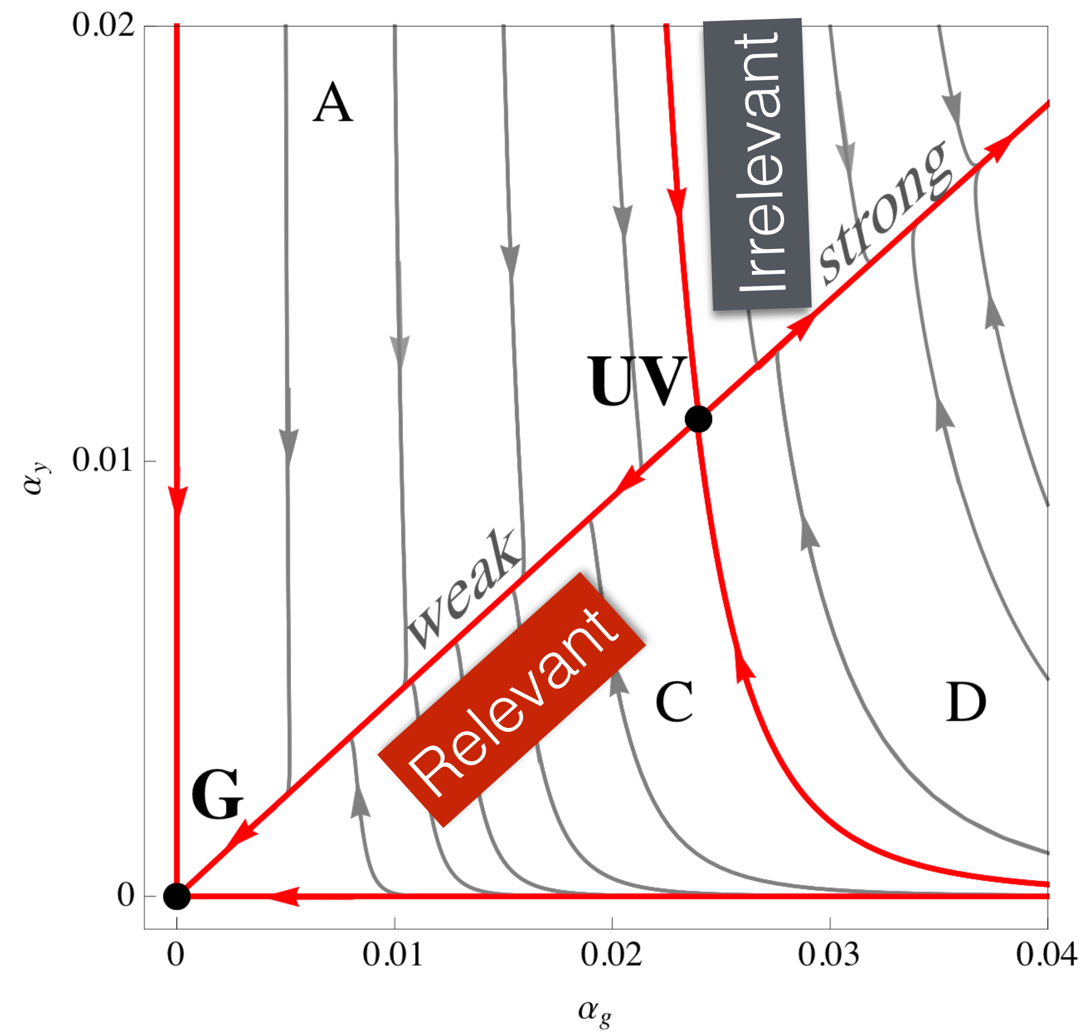


The Standard Model is not a fundamental theory

Asymptotic Freedom

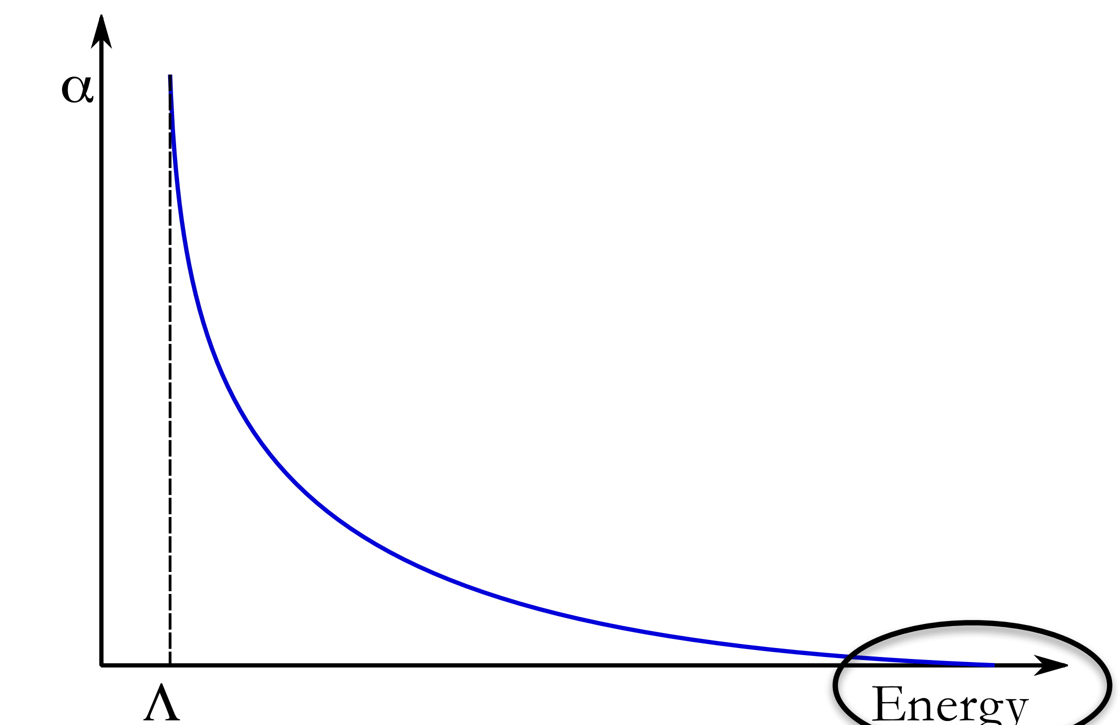
Asymptotic Freedom

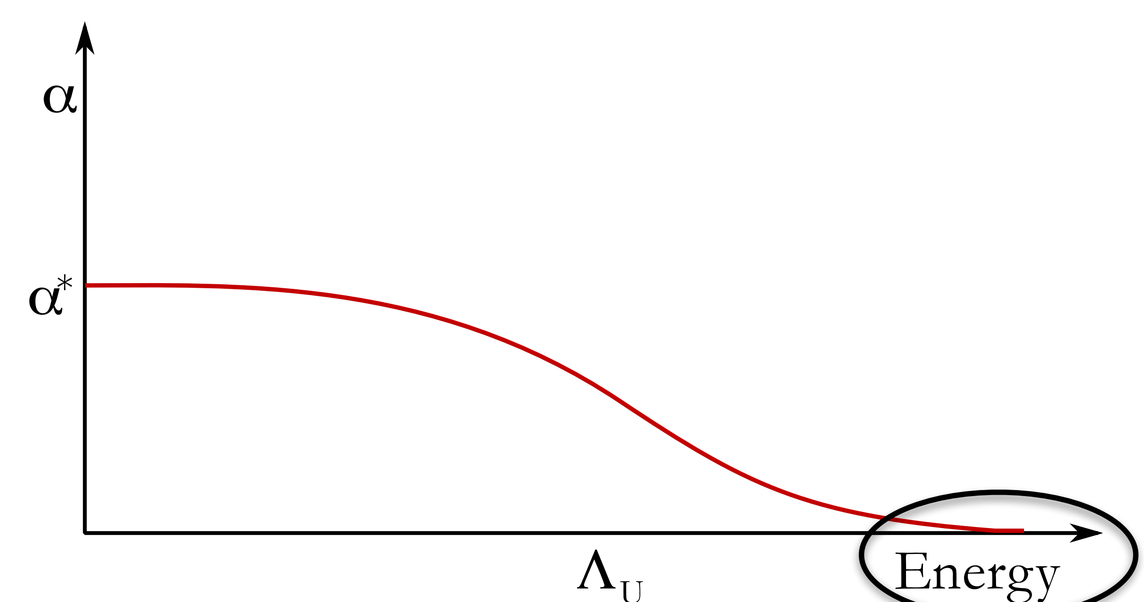
Trivial UV fixed point

Asymptotic Freedom

Trivial UV fixed point

- Non-interacting in the UV

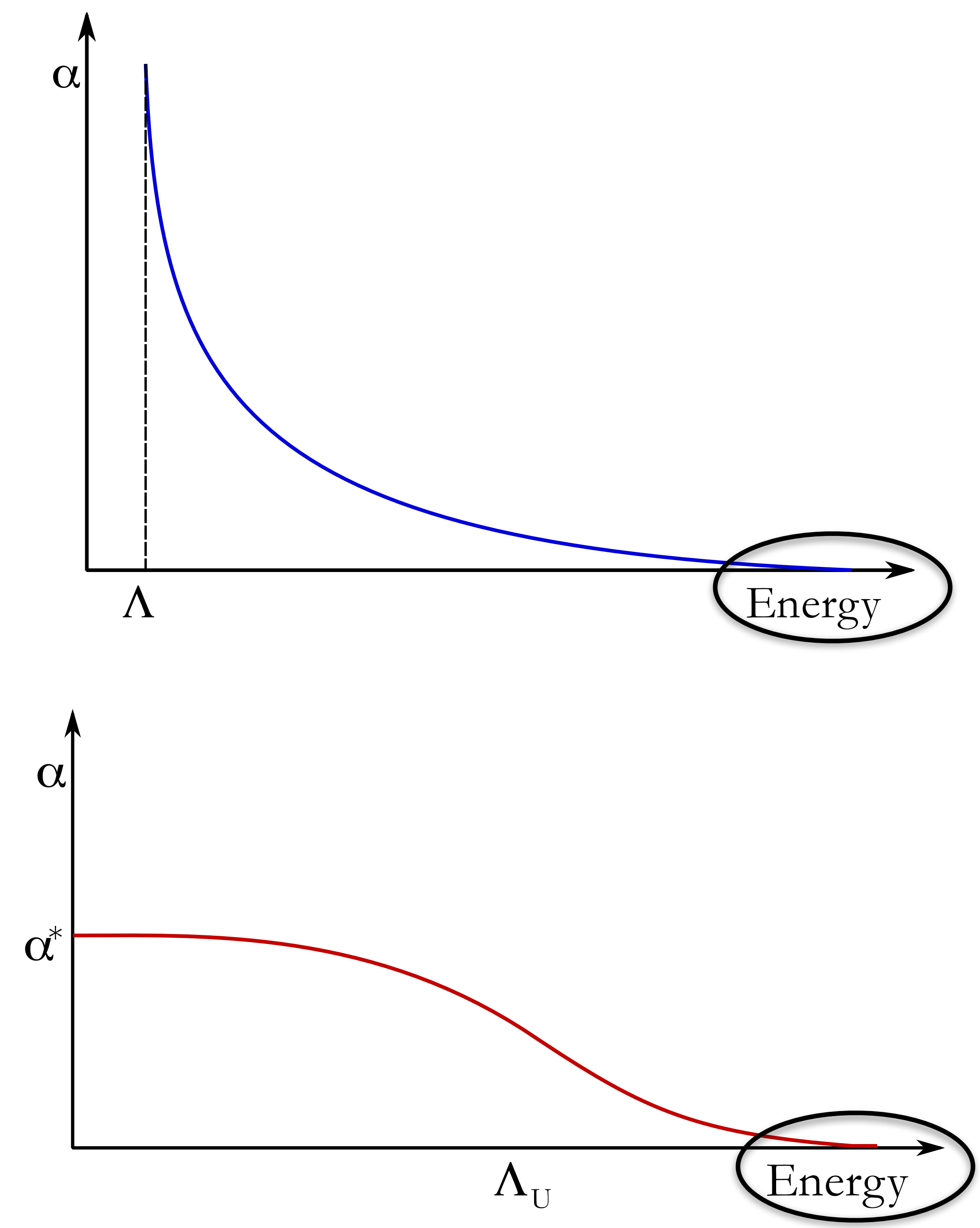




Asymptotic Freedom

Trivial UV fixed point

- Non-interacting in the UV
- UV logarithmic approach



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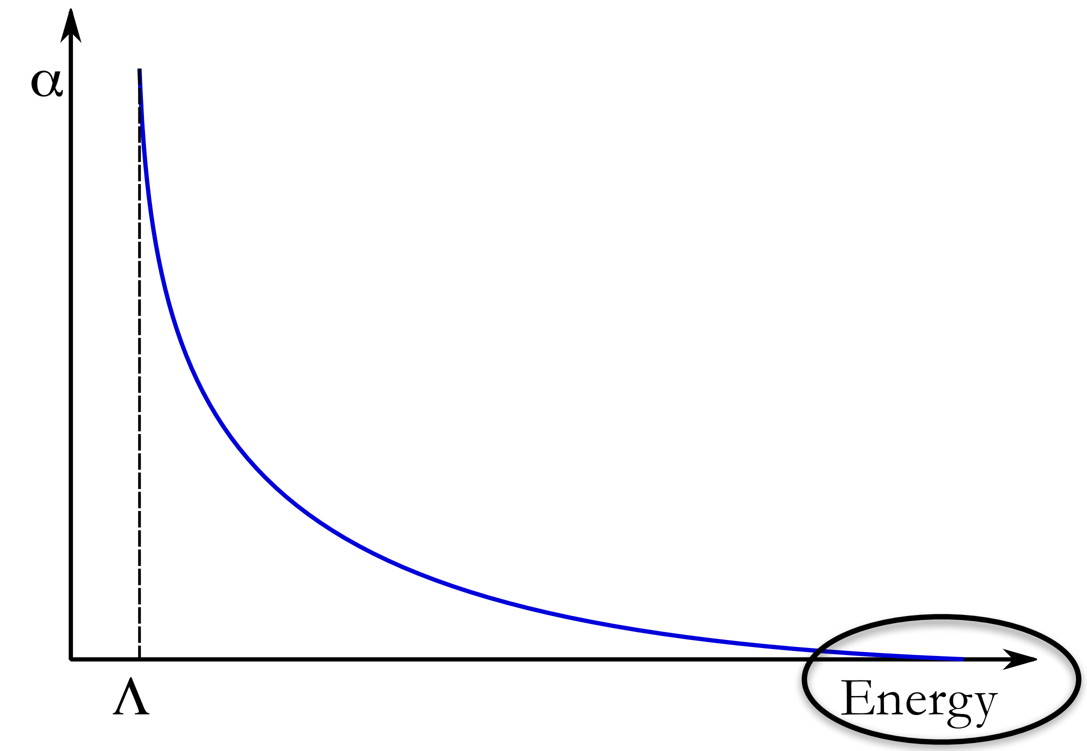
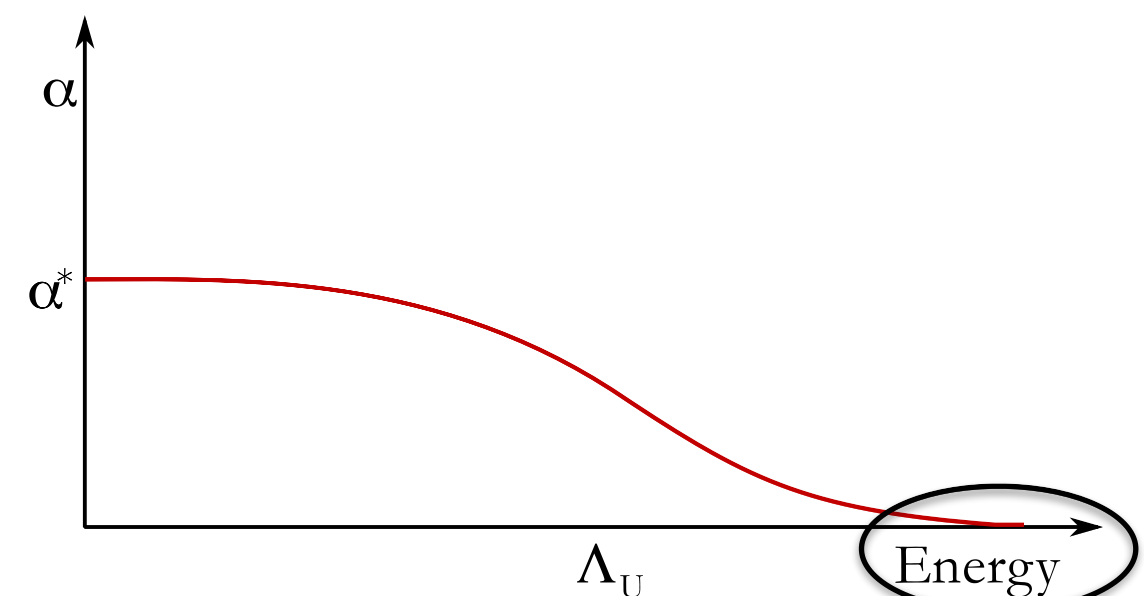
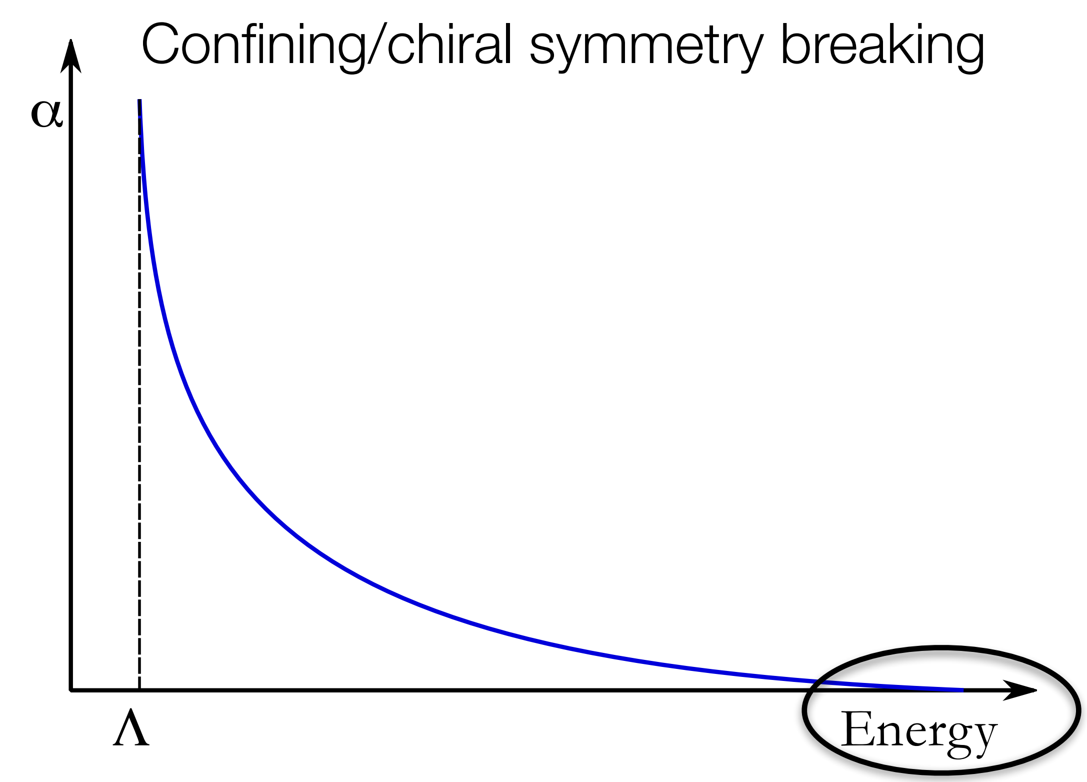


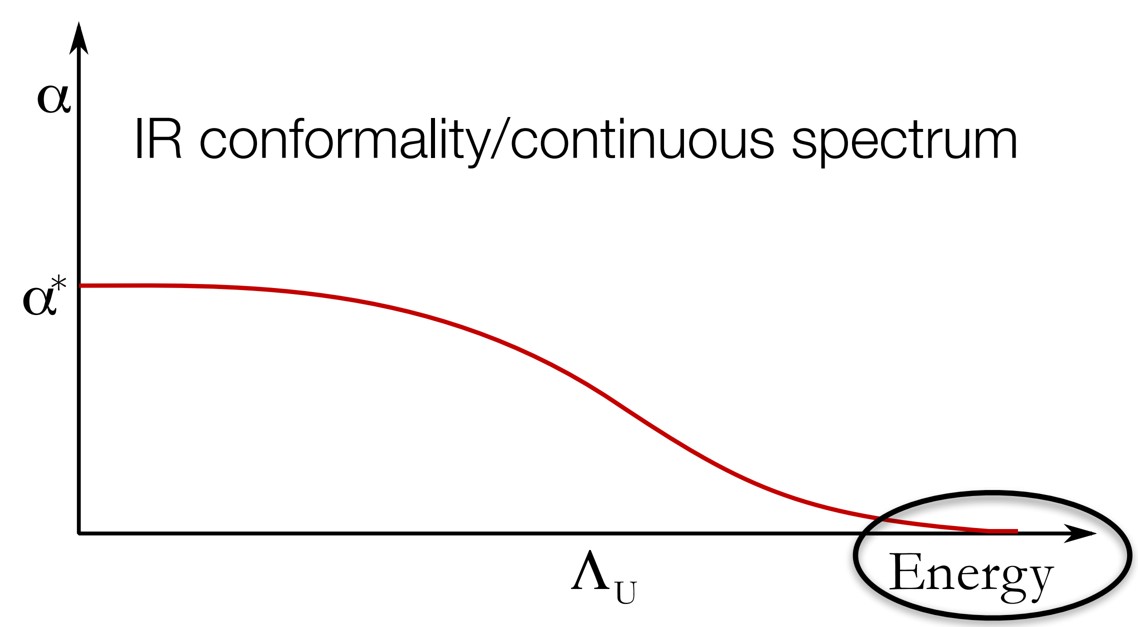


Asymptotic Freedom

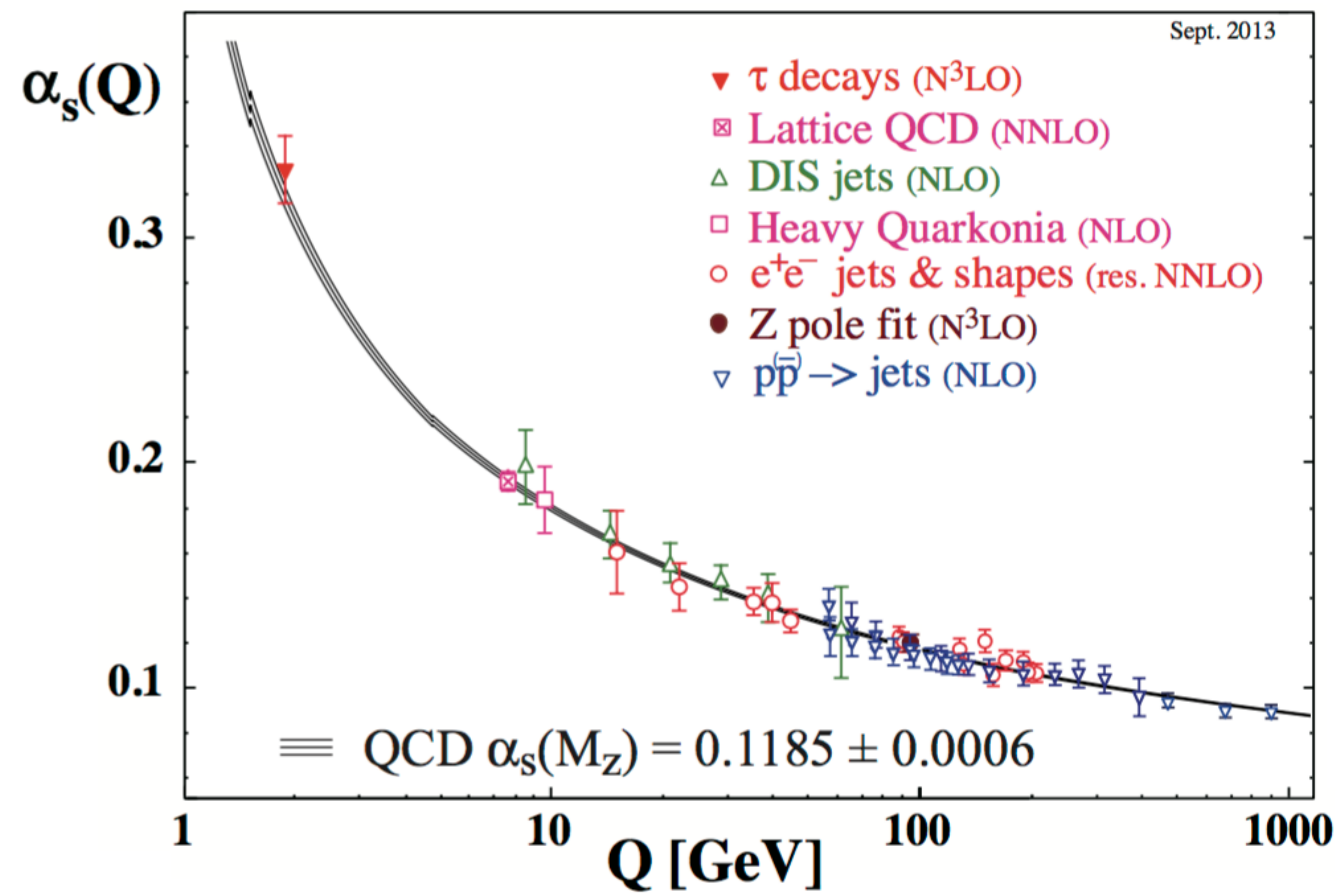
Trivial UV fixed point

- Non-interacting in the UV
- UV logarithmic approach
- Perturbation theory in UV
- IR conformal or dyn. scale





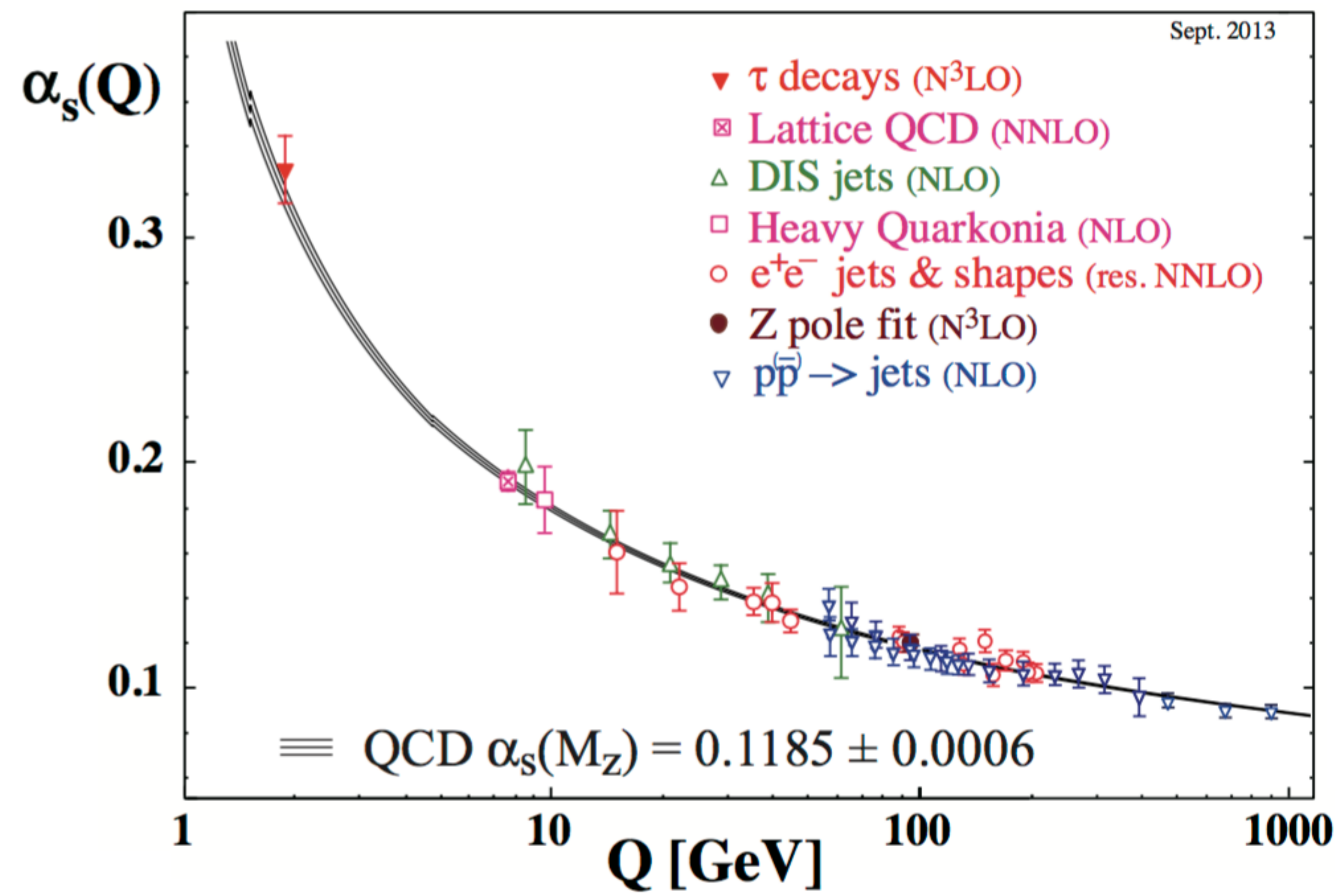
QCD



Sept. 2013
$\alpha_s(Q)$
τ decays (N3LO)
Lattice QCD (NNLO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e+e− jets & shapes (res. NNLO)
Z pole fit (N3LO)
pp(−) –> jets (NLO)
0.3
0.2
0.1
QCD $\alpha_s(M_Z)$ = 0.1185 ± 0.0006
1
10
100
1000
Q [GeV]

QCD

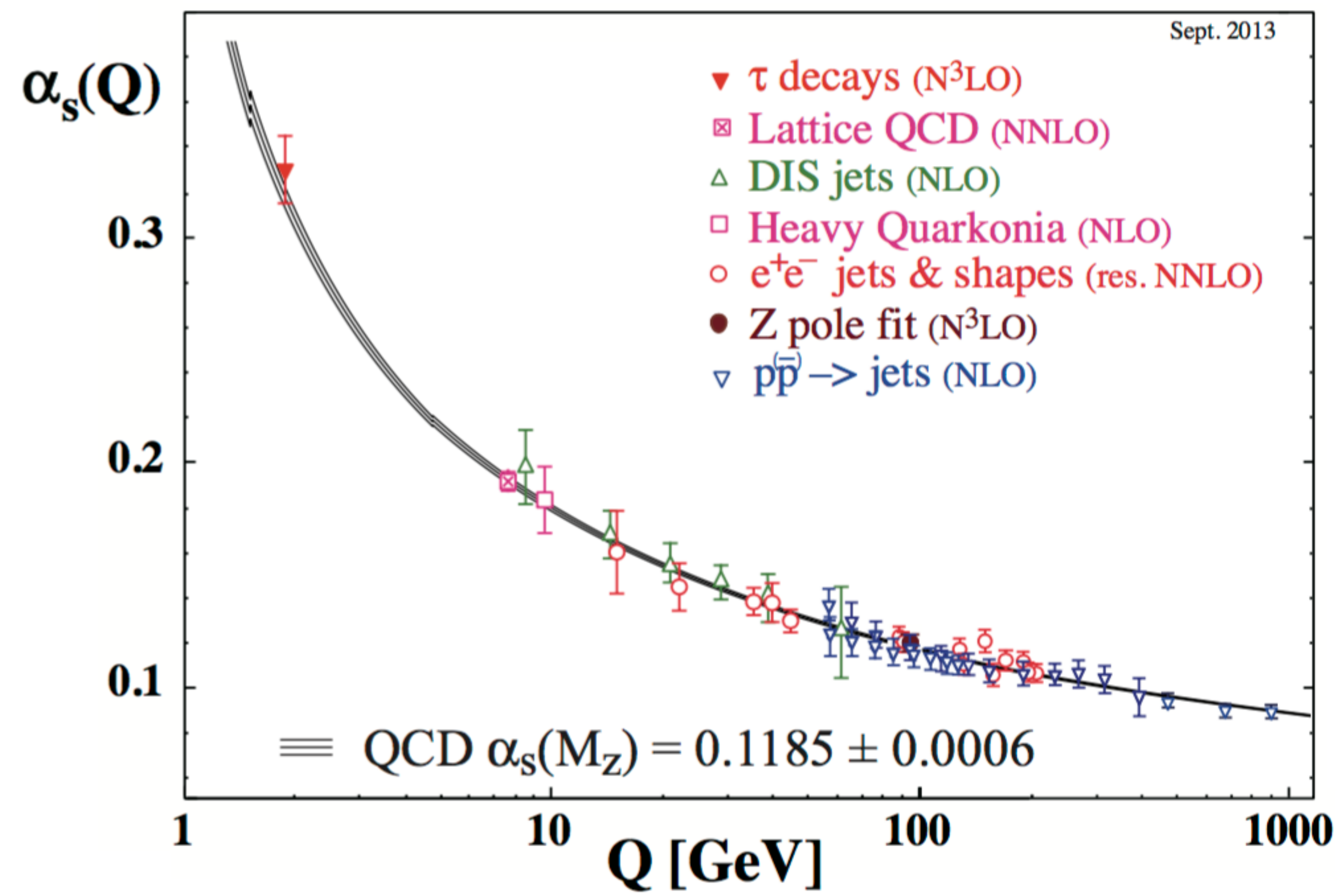
QCD is not IR conformal because



QCD

QCD is not IR conformal because

- Hadronic spectrum/dyn. mass



QCD

QCD is not IR conformal because

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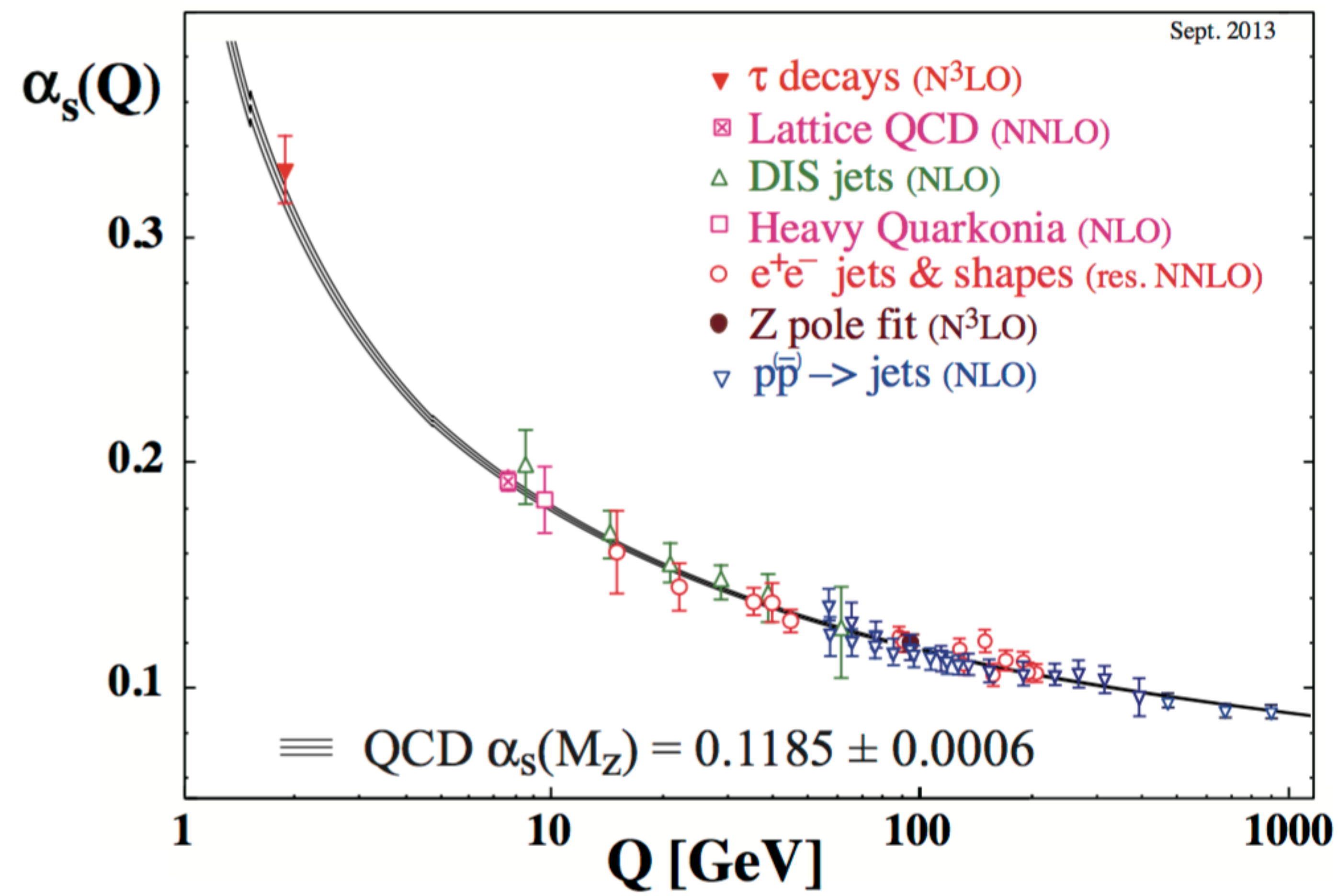

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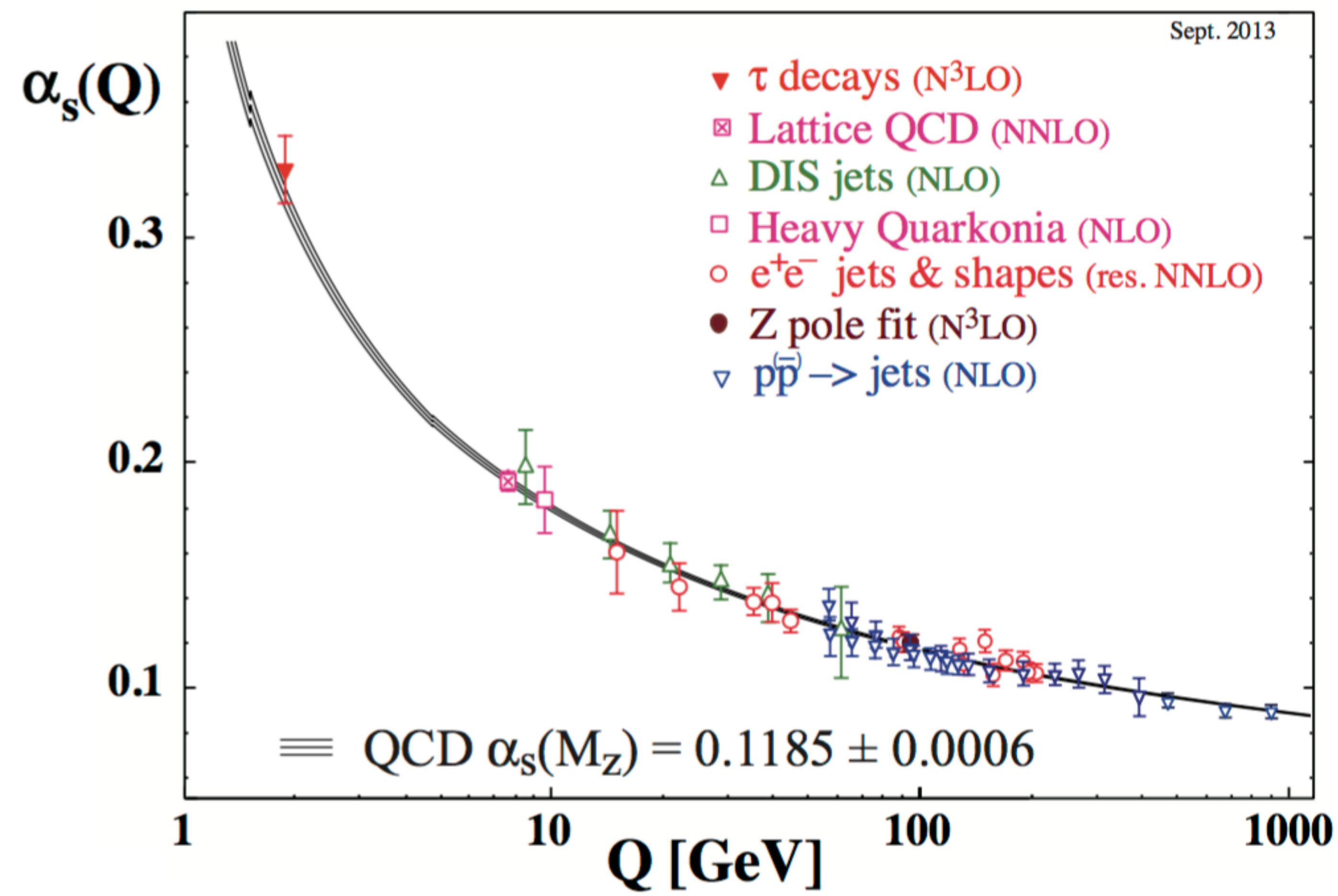

Asymptotic freedom verified < TeV

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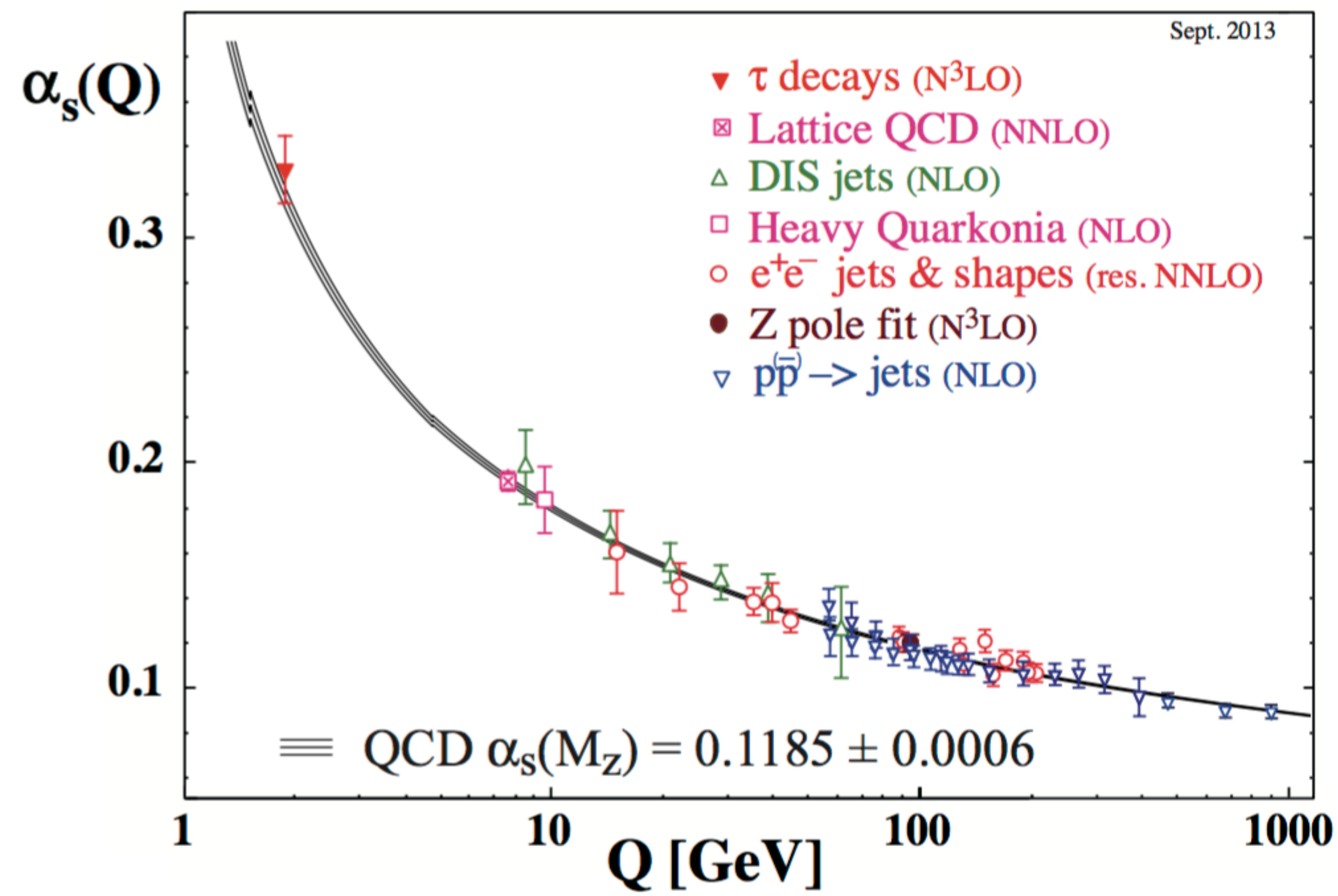


Asymptotic freedom verified < TeV

If above TeV asymptotic freedom is lost, then what?

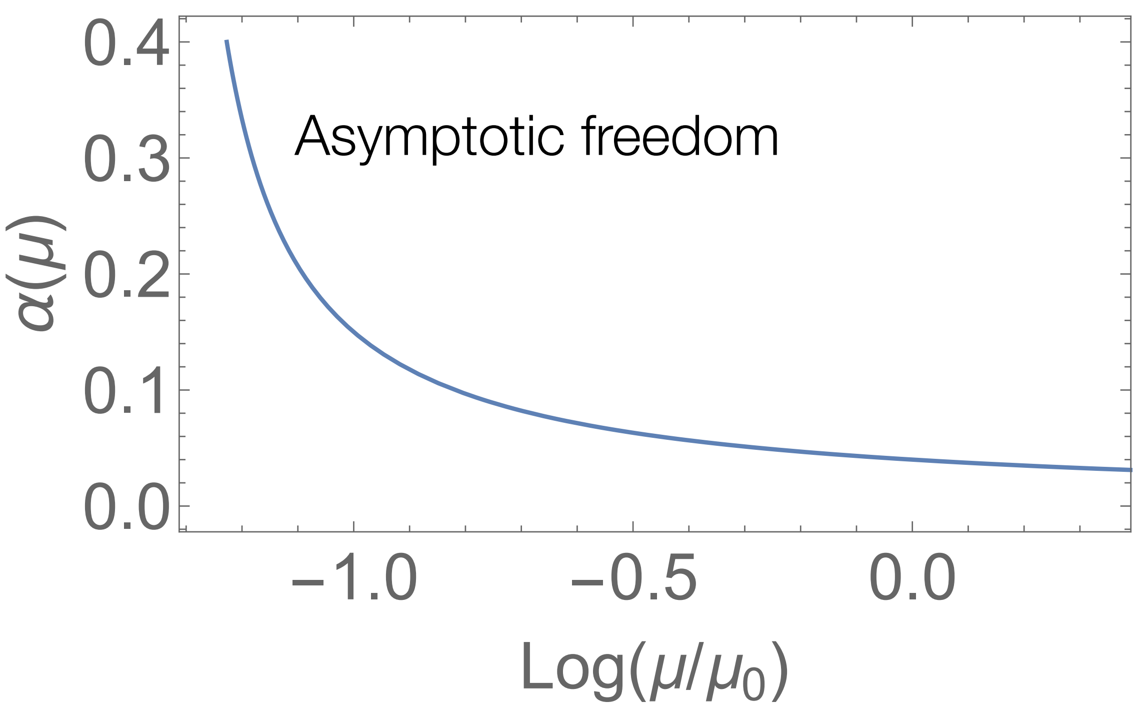
Beyond asymptotic freedom

Asymptotic Safety

Wilson: A fundamental theory has an UV fixed point

Trivial fixed point

- Non-interacting in the UV
- Logarithmic scale depend.



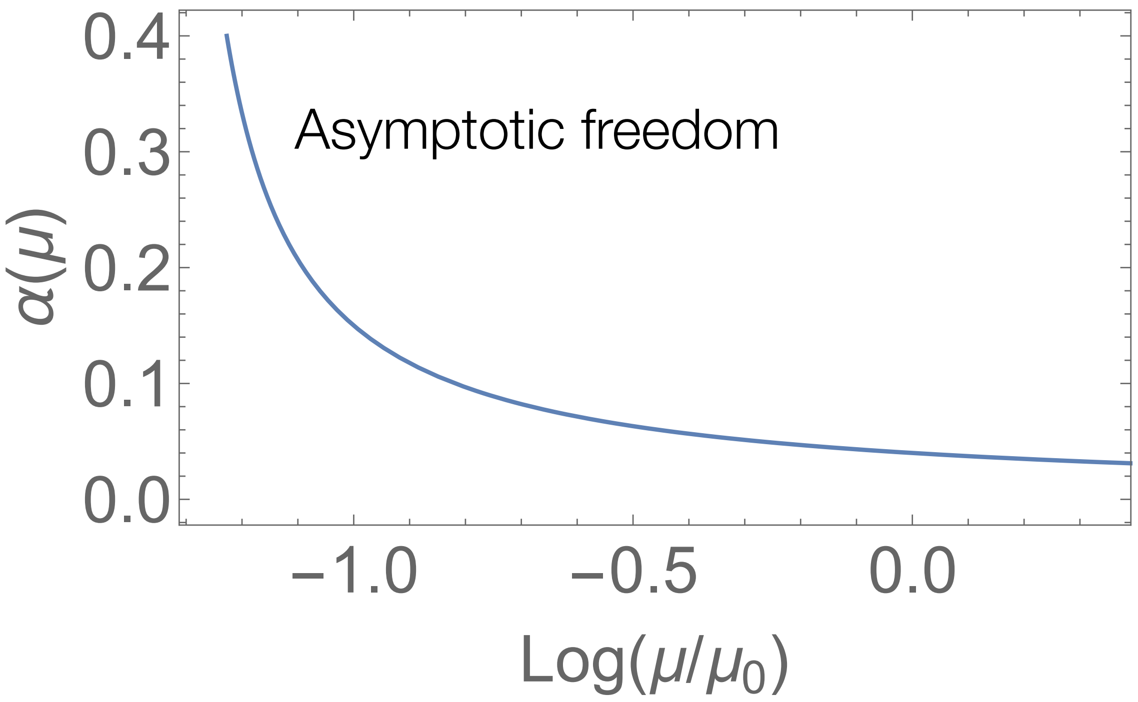
Asymptotic Safety

Wilson: A fundamental theory has an UV fixed point

Trivial fixed point

Interacting fixed point

- Non-interacting in the UV
- Logarithmic scale depend.



Asymptotic Safety

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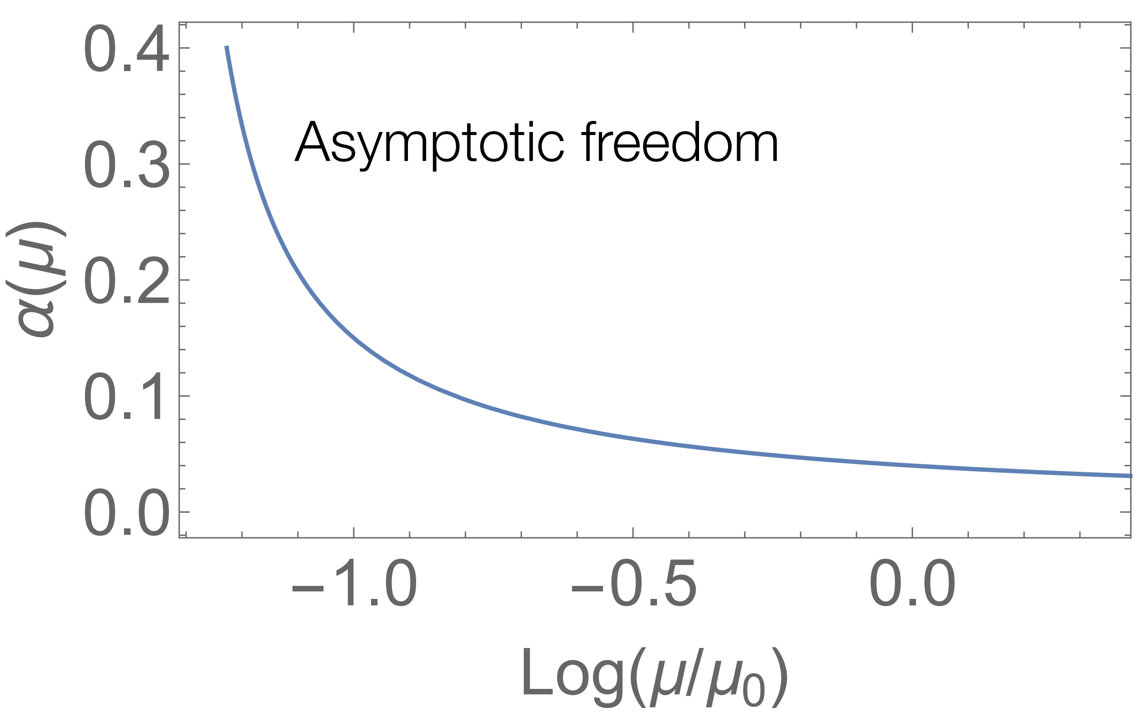
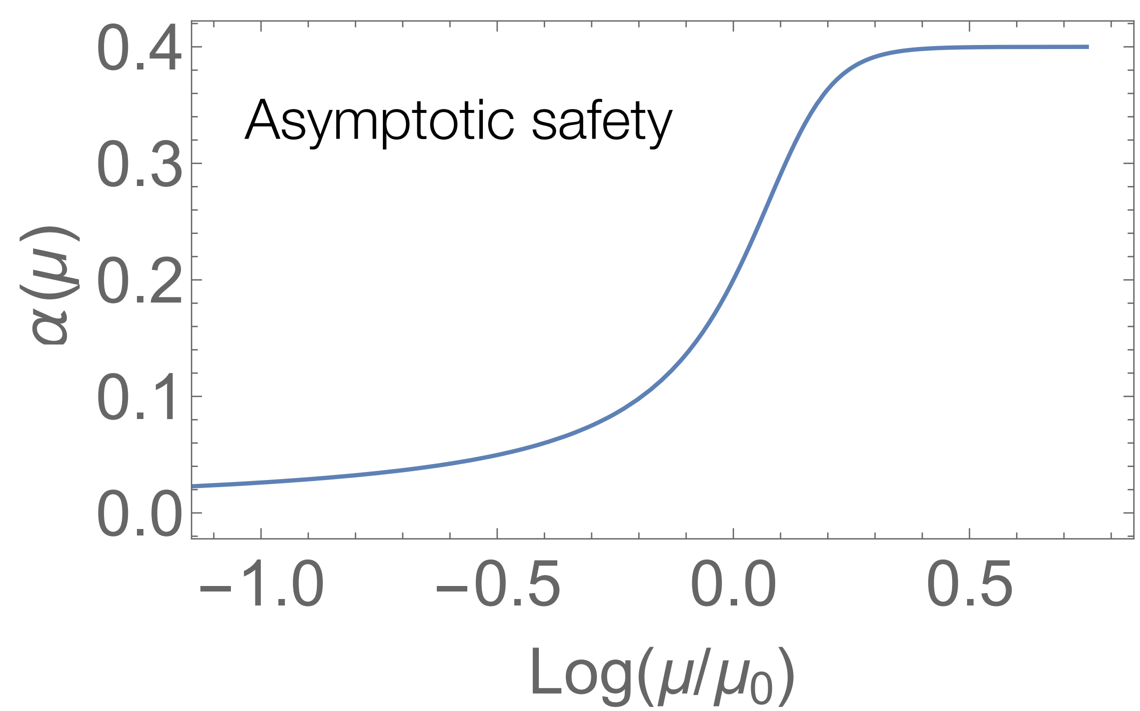
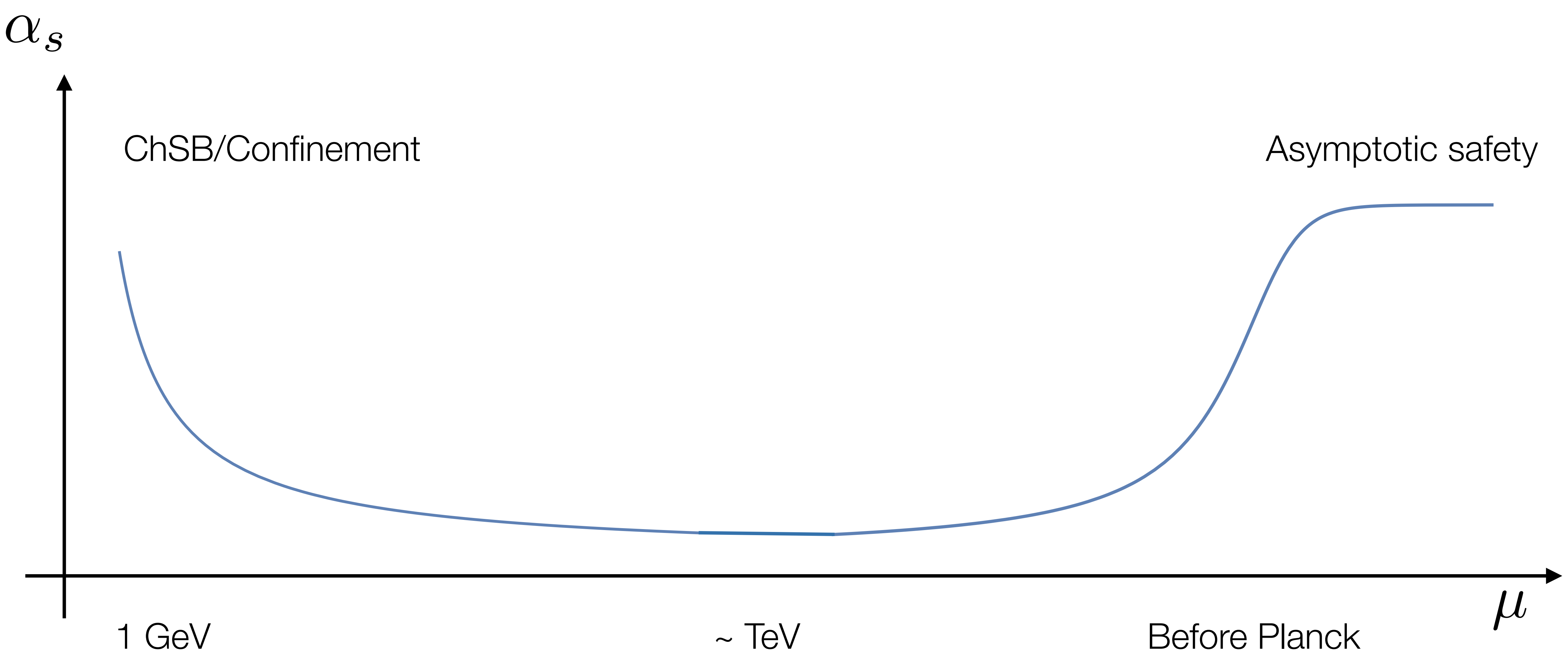


Interacting fixed point

- Integrating in the UV
- Power law

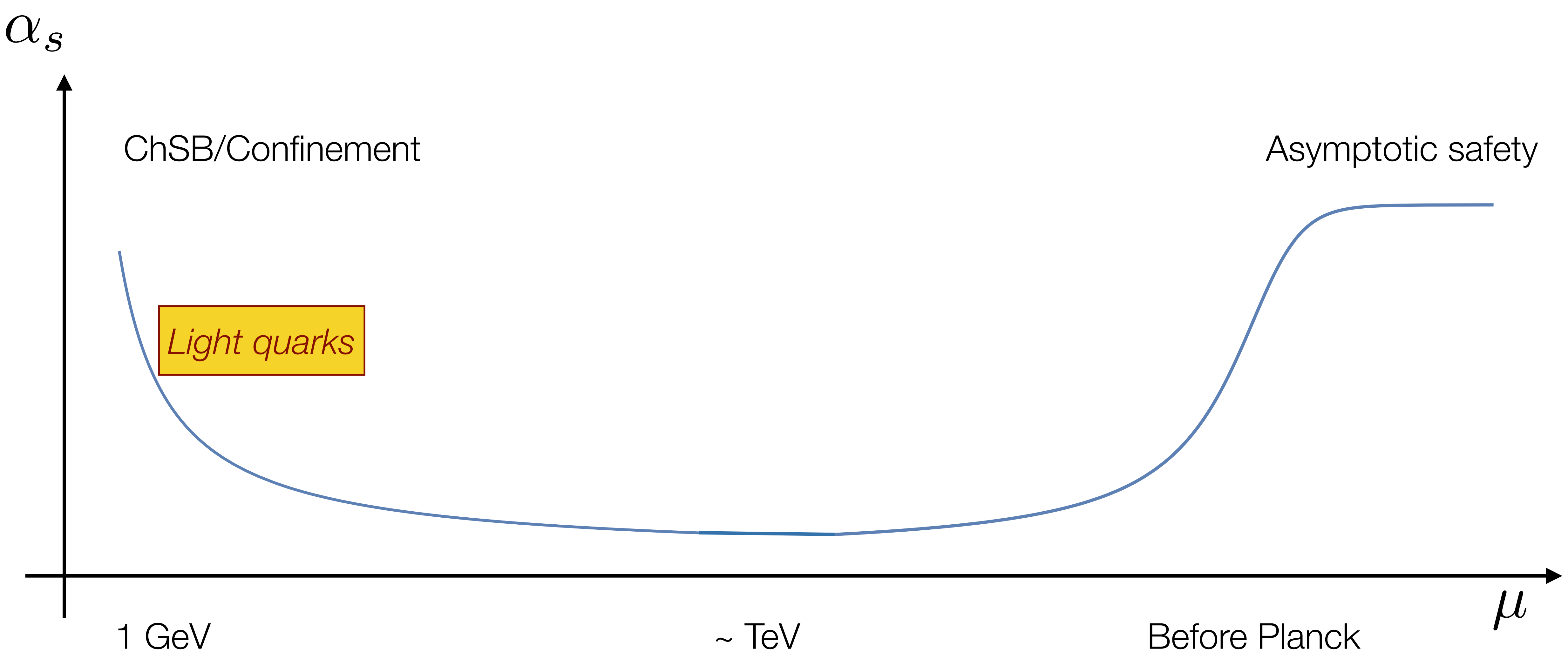


Safe QCD scenario



Sannino, 1511.09022

Safe QCD scenario



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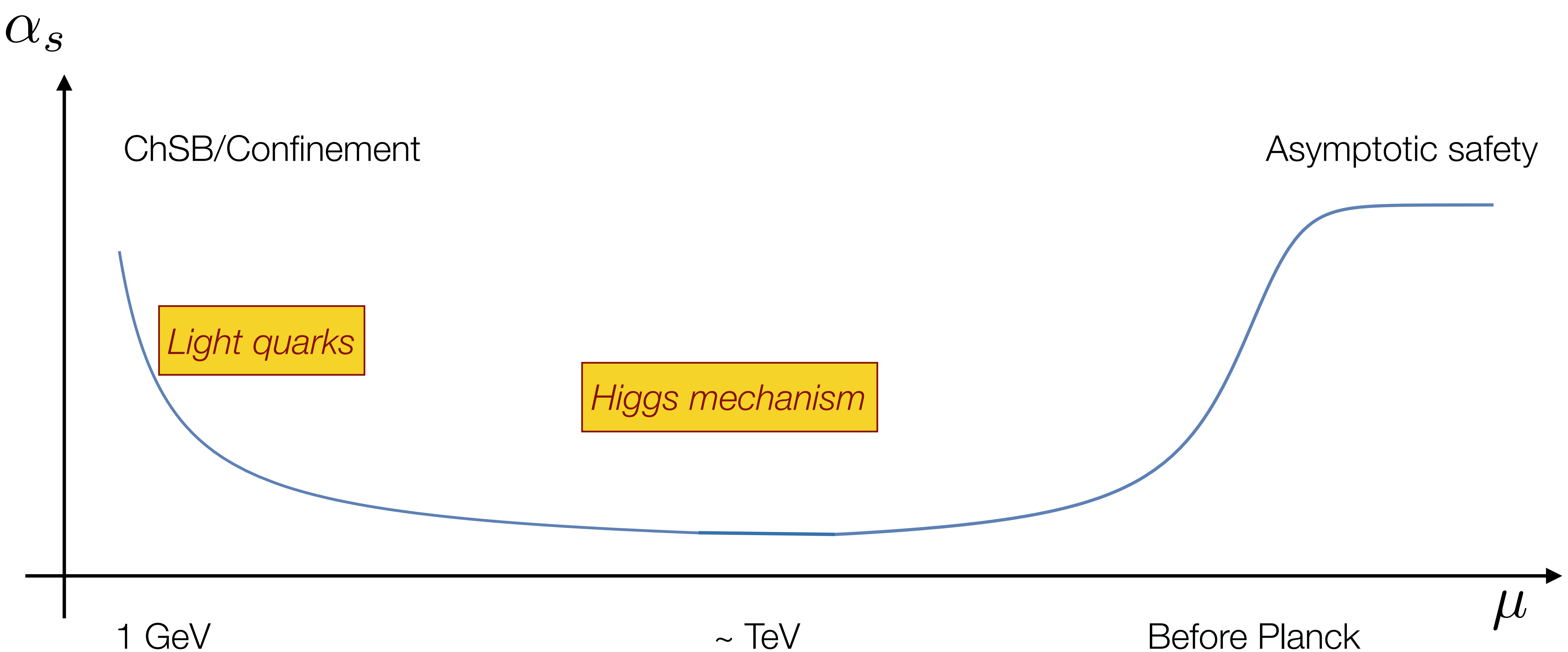

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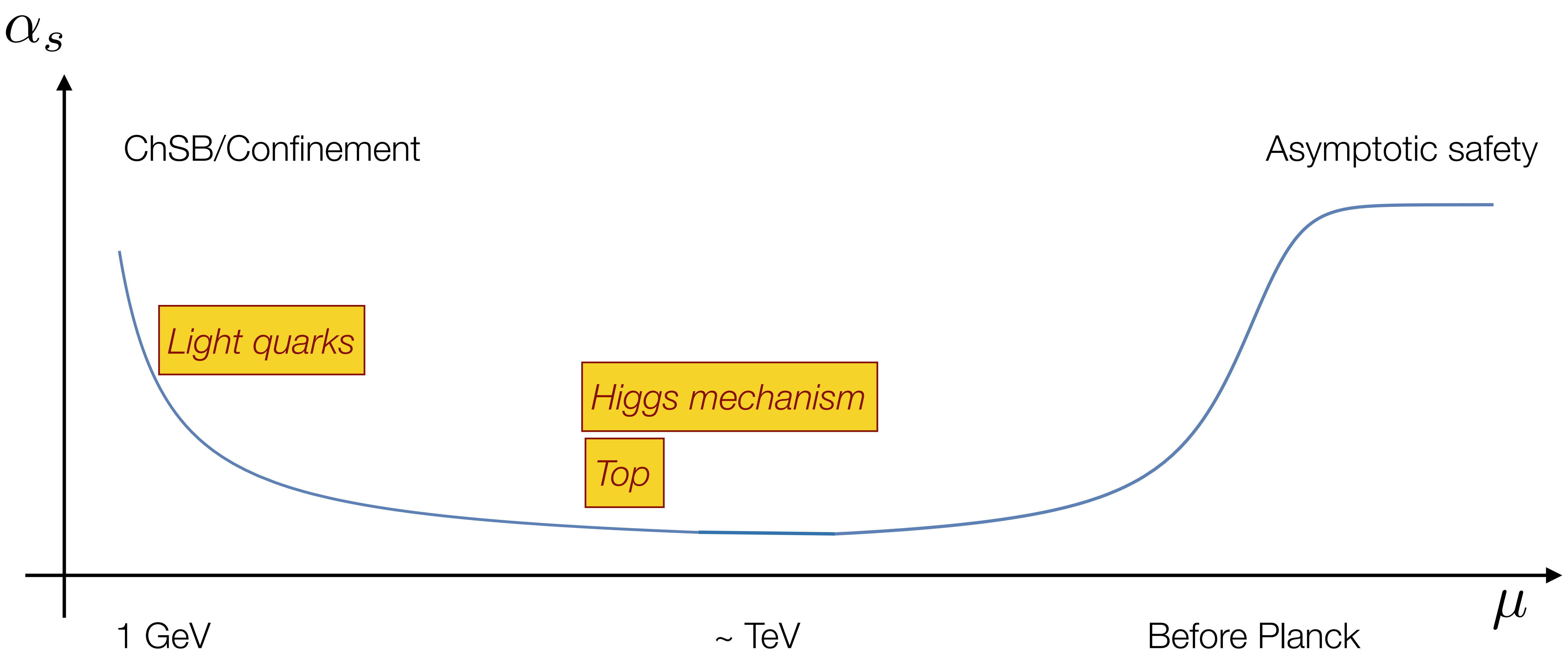

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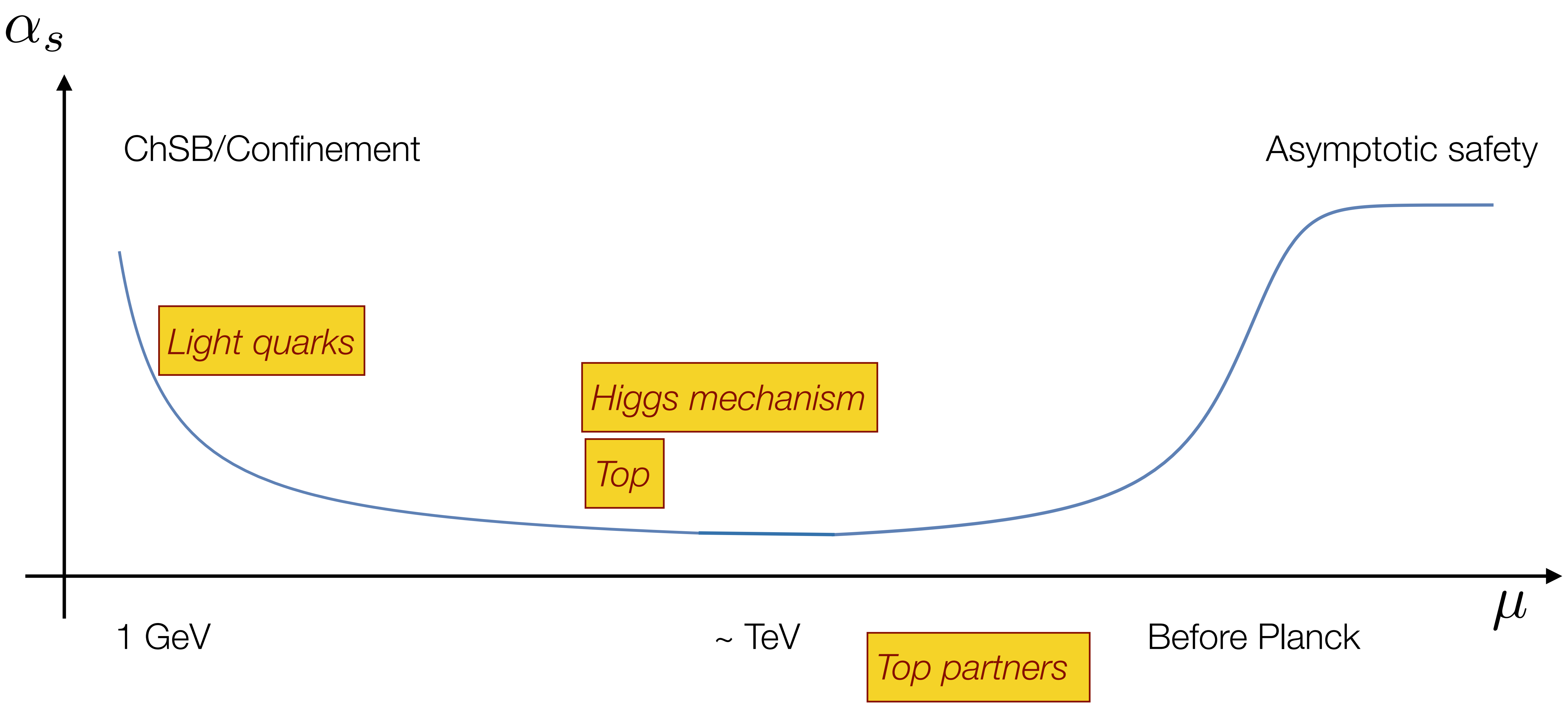

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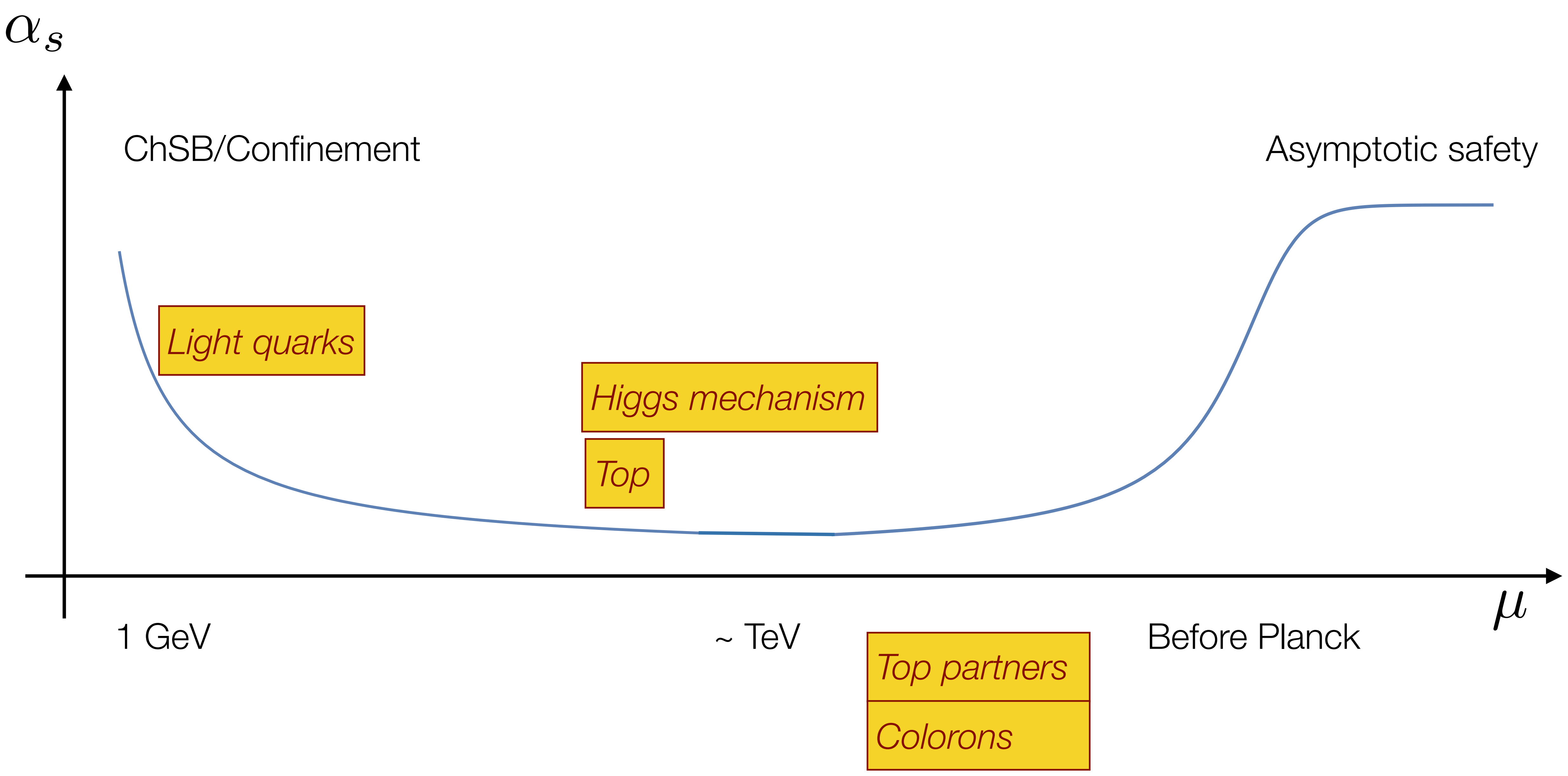

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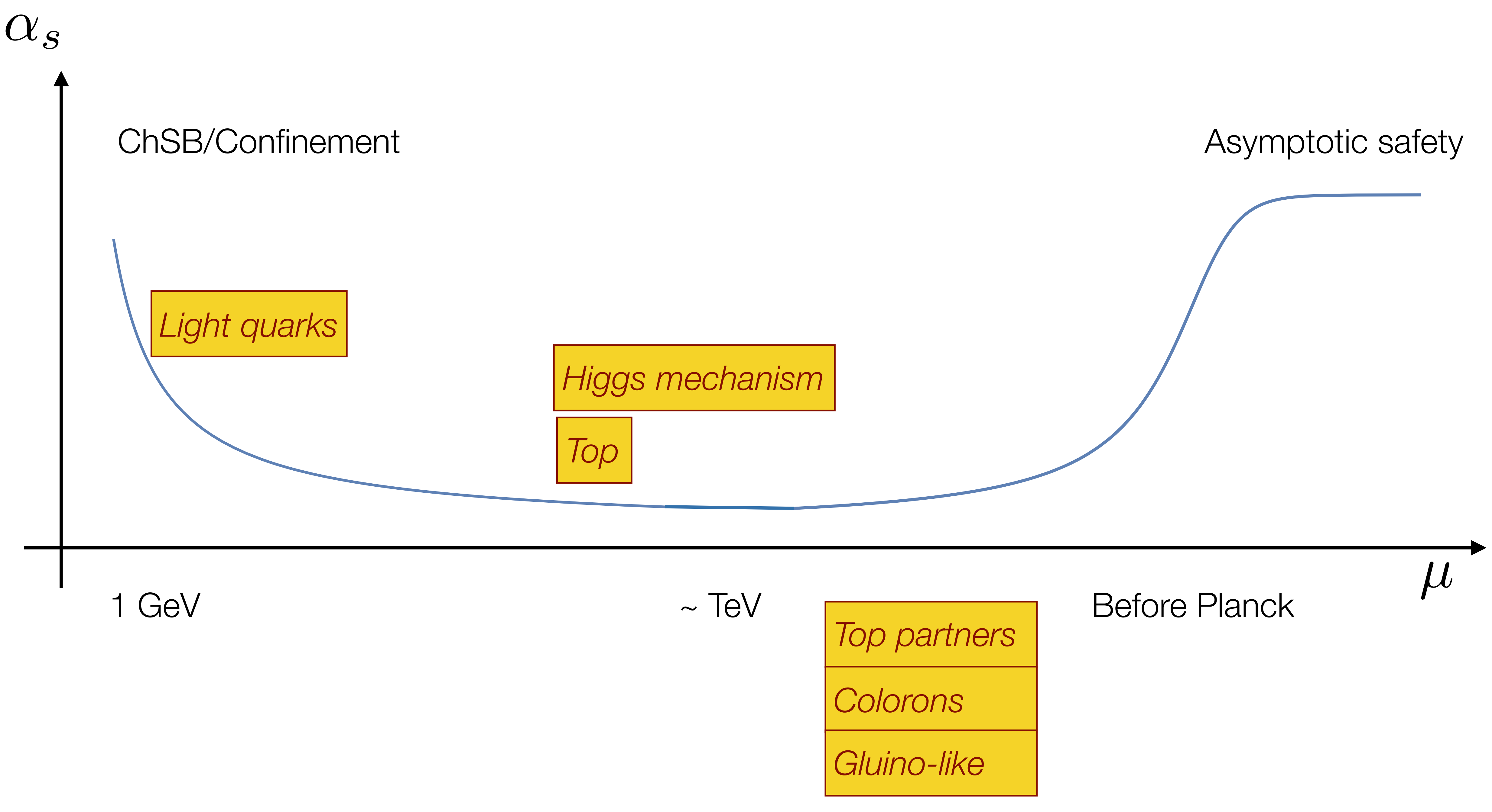

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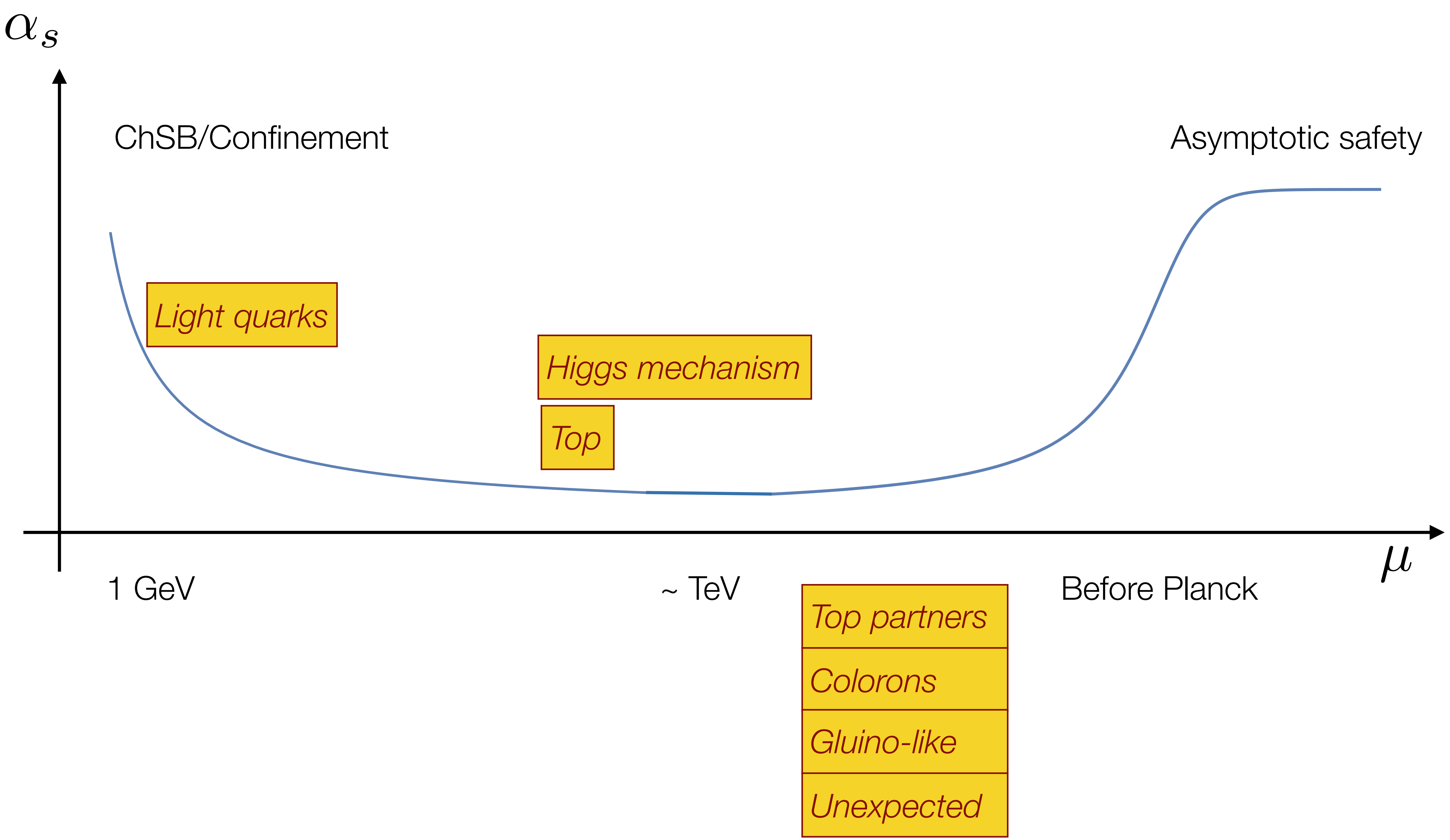

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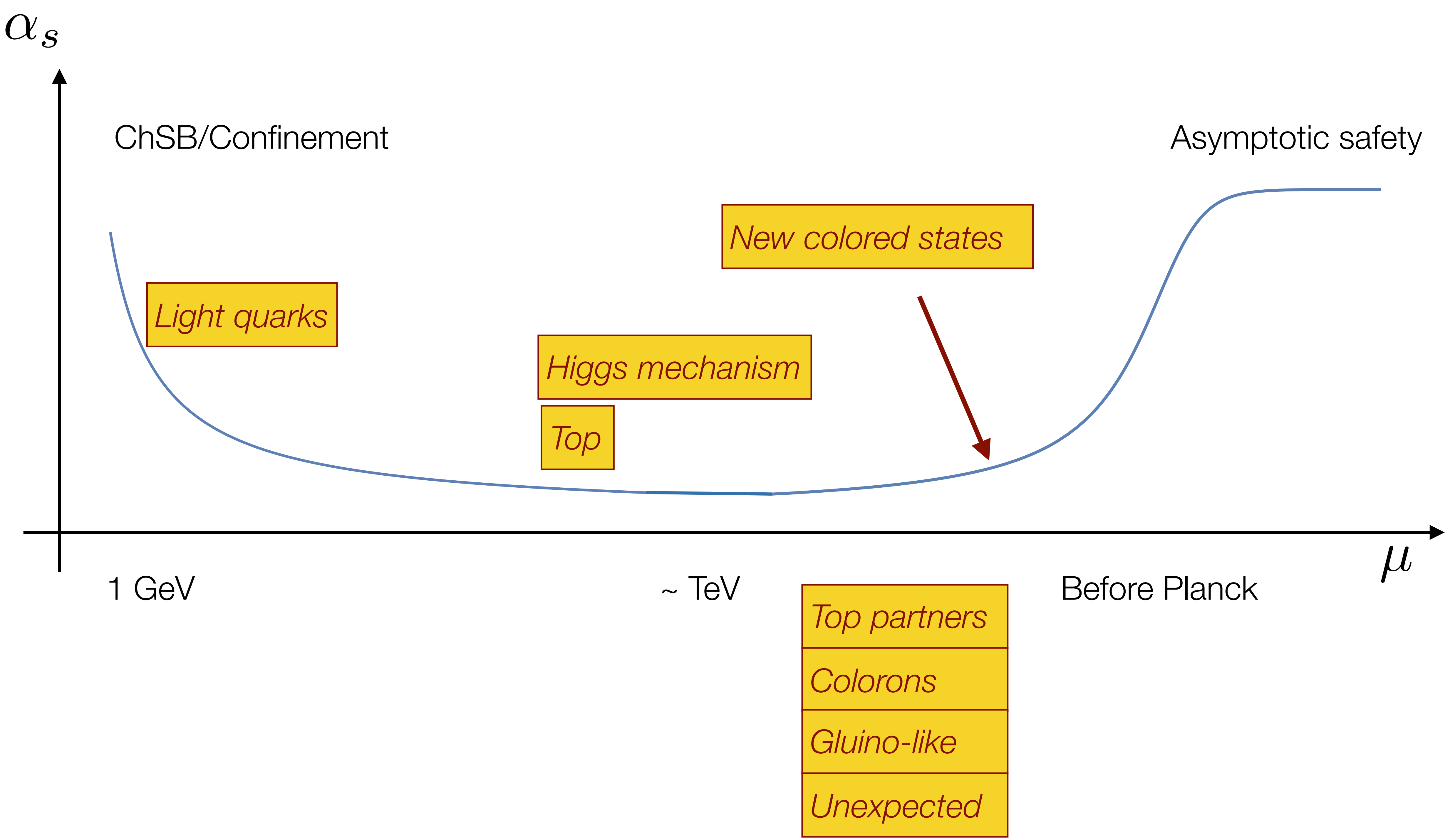

Sannino, 1511.09022

Does a theory like this exists?

Exact 4D Interacting UV Fixed Point

Litim and Sannino, 1406.2337, JHEP

Exact 4D Interacting UV Fixed Point

Litim and Sannino, 1406.2337, JHEP

$$L = -F^2 + i\overline{Q}\gamma \cdot DQ + y(\overline{Q}_L H Q_R + \mathrm{h.c.}) +$$

$$\mathrm{Tr}\left[\partial \mathrm{H}^\dagger \partial \mathrm{H}\right] - \mathrm{uTr}\left[(\mathrm{H}^\dagger \mathrm{H})^2\right] - \mathrm{vTr}\left[(\mathrm{H}^\dagger \mathrm{H})\right]^2$$

Fields	$[SU(N_c)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$
G_μ	Adj	1	1	0
Q_L	$\square$	$\overline{\square}$	1	1
Q_R^c	$\overline{\square}$	1	$\square$	-1
H	1	$\square$	$\overline{\square}$	0

Veneziano Limit

- Normalised couplings

$$\alpha_g = \frac{g^2\, N_C}{(4\pi)^2}\,, \quad \alpha_y = \frac{y^2\, N_C}{(4\pi)^2}\,, \quad \alpha_h = \frac{u\, N_F}{(4\pi)^2}\,, \quad \alpha_v = \frac{v\, N_F^2}{(4\pi)^2}$$

$$\frac{v}{u} = \frac{\alpha_v}{\alpha_h N_F}$$

At large N $\quad \dfrac{N_F}{N_C} \in \Re^+$

Non-Asymptotically Free

$$\beta_g = \partial_t \alpha_g = -B\alpha_g^2 \qquad t = \ln \frac{\mu}{\mu_0}$$

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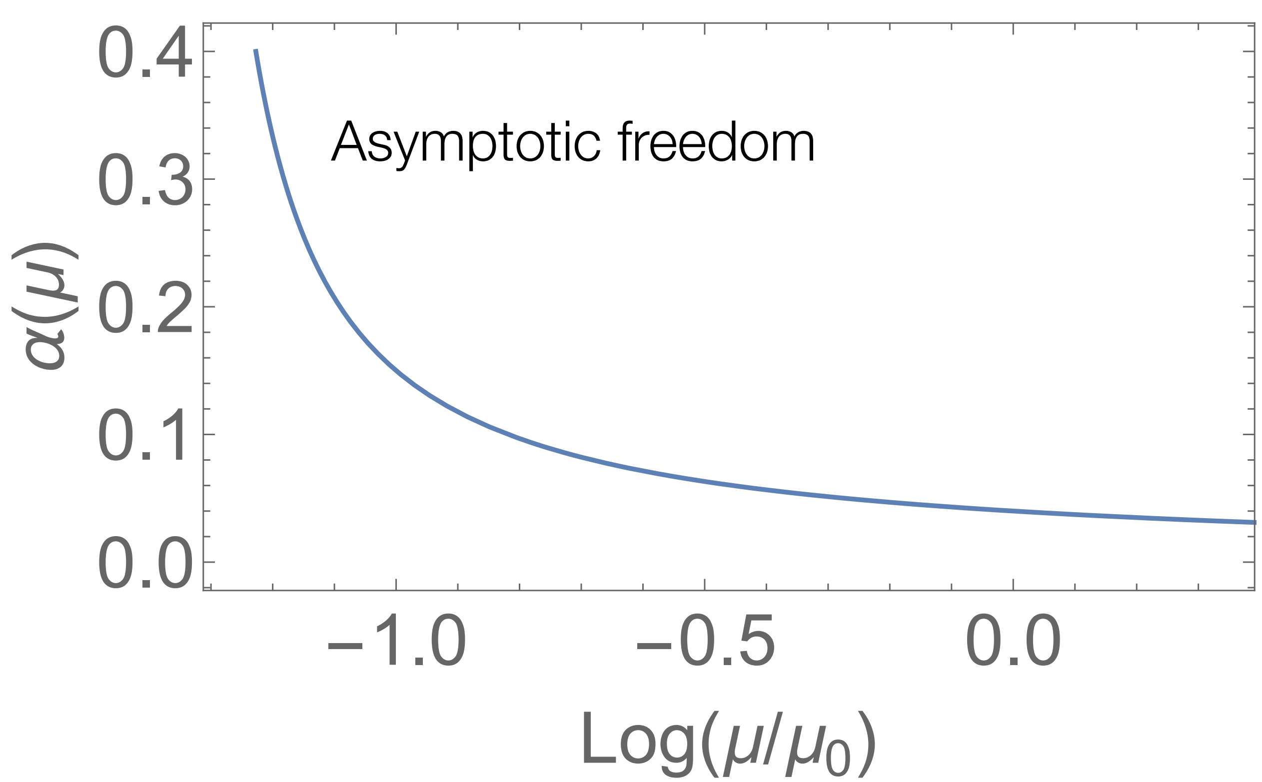
$$t = \ln \frac{\mu}{\mu_0}$$

$B > 0$



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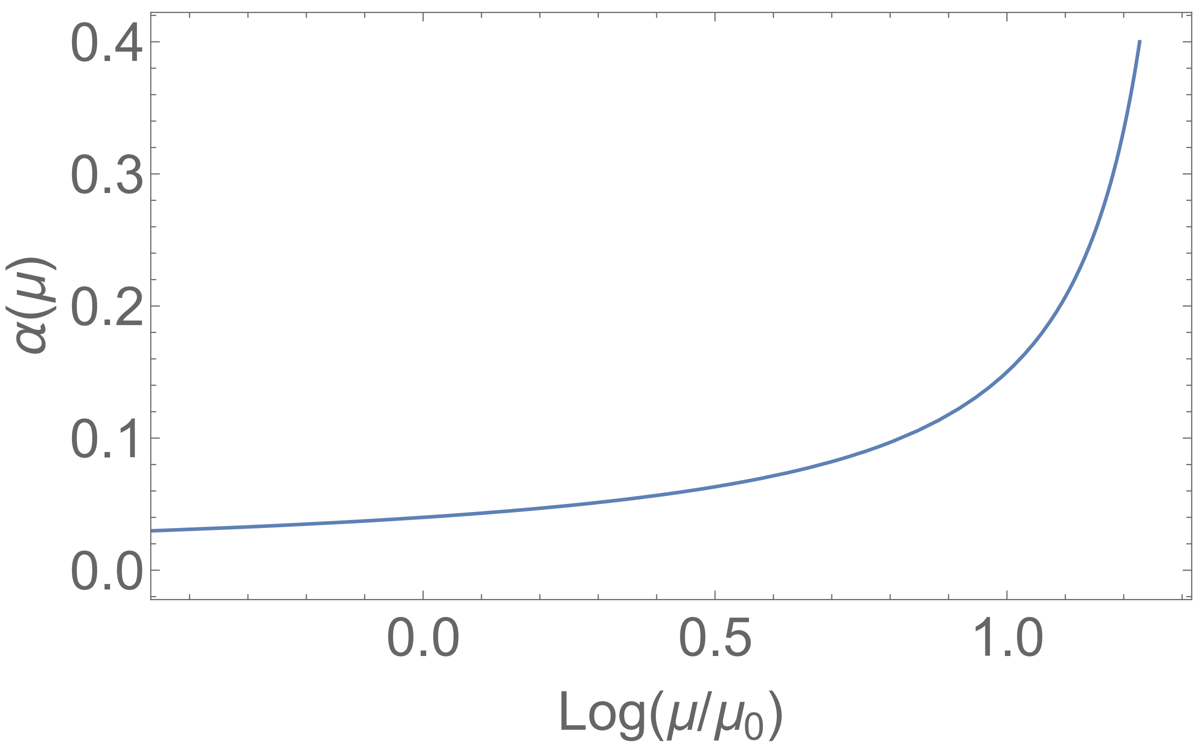

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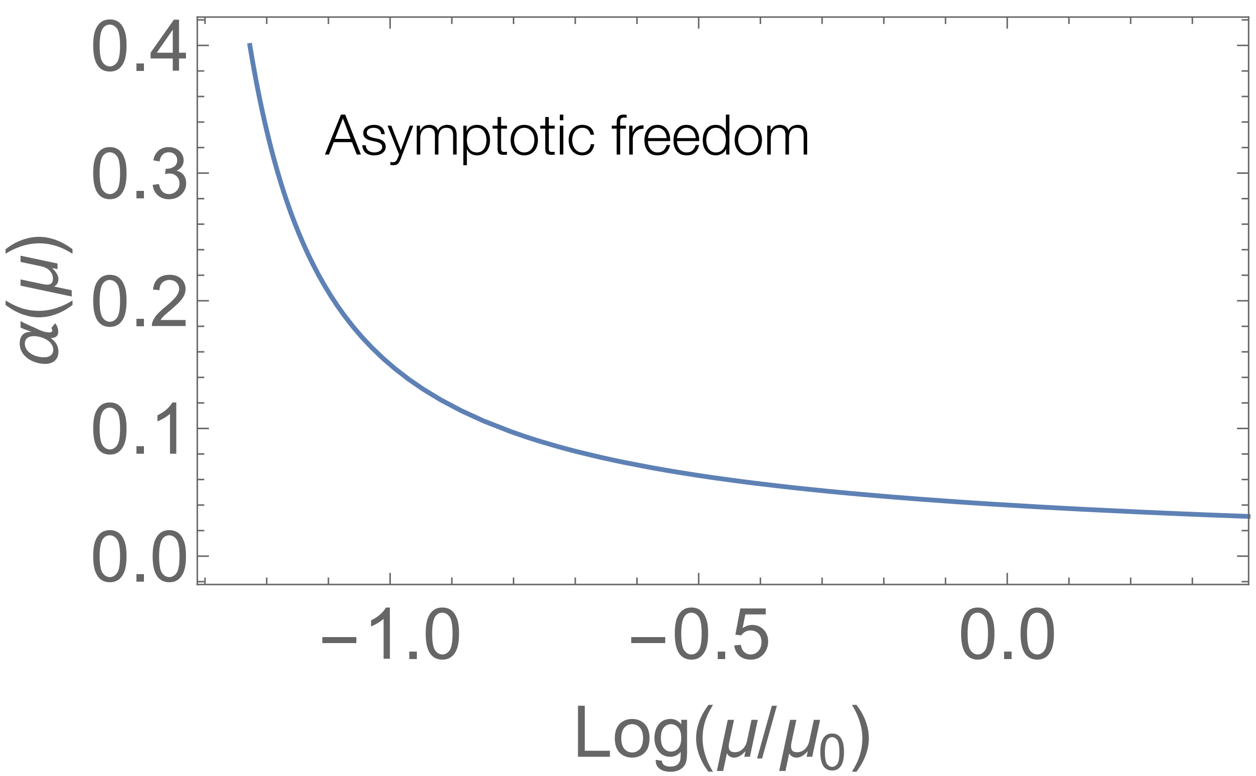

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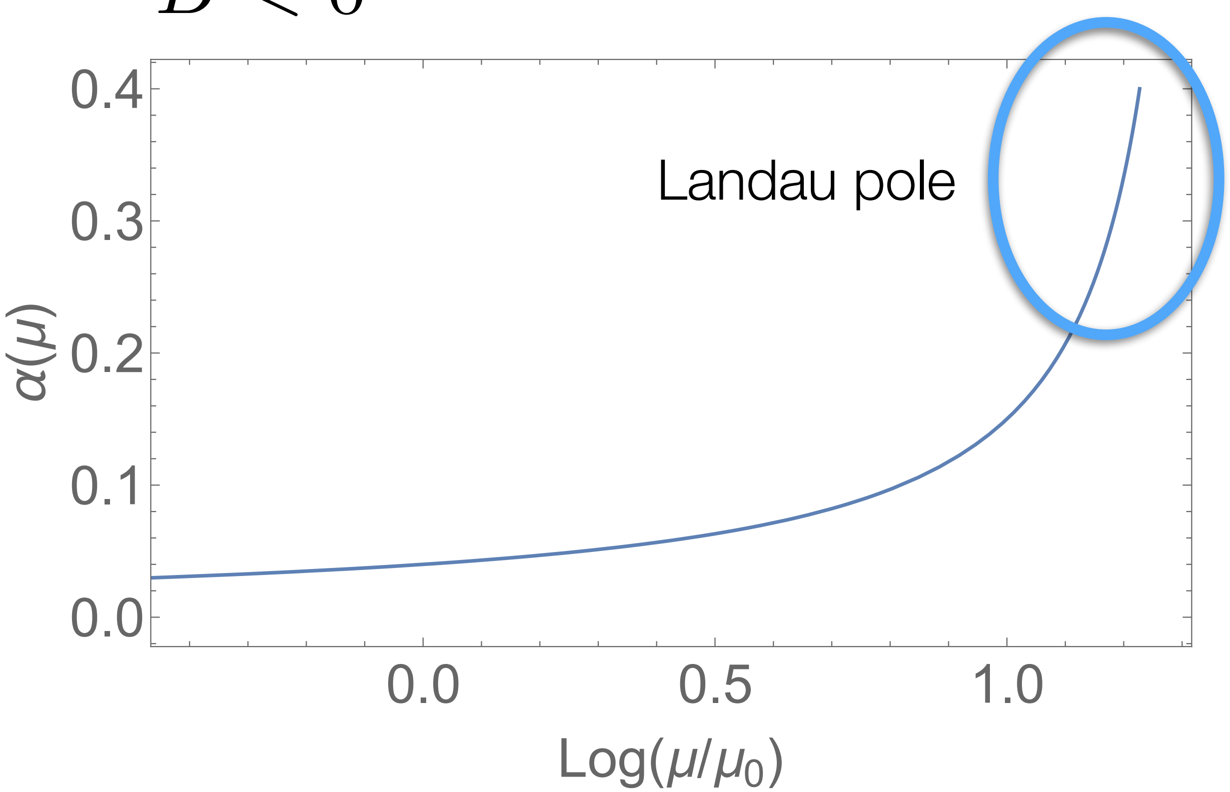

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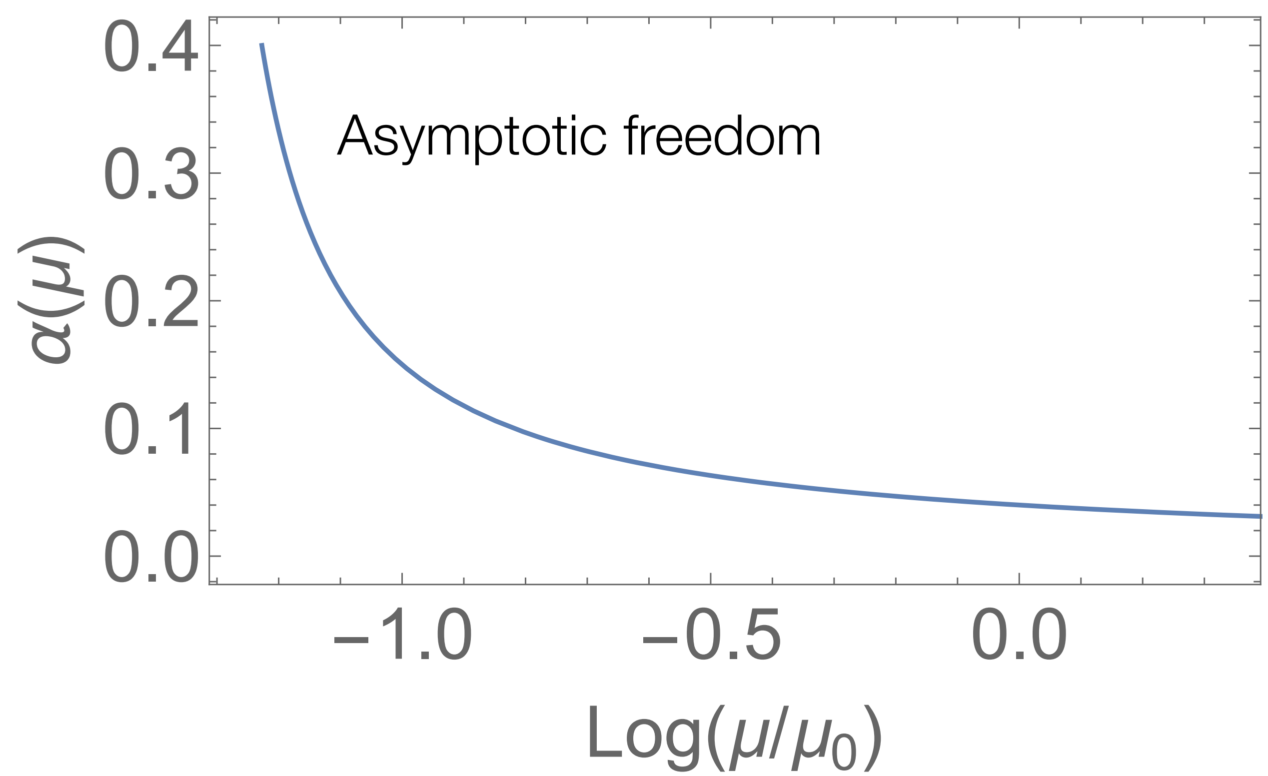

Small parameters

$$B = -\frac{4}{3}\epsilon$$

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$$\epsilon = \frac{N_F}{N_C} - \frac{11}{2}$$

$$0 \leq \epsilon \ll 1$$

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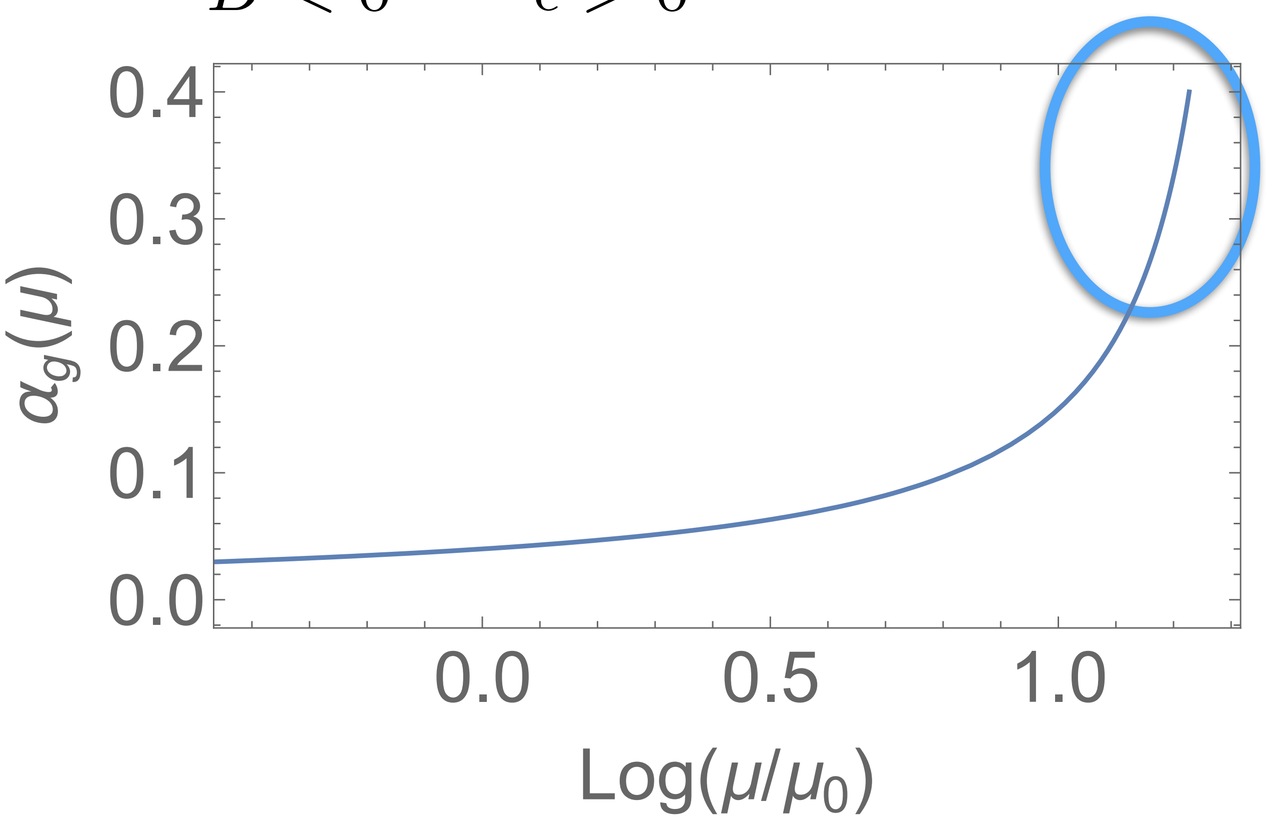
$$B = -\frac{4}{3}\epsilon$$

$$\epsilon = \frac{N_F}{N_C} - \frac{11}{2}$$

$B < 0 \qquad \epsilon > 0$



$$0 \leq \epsilon \ll 1$$

Landau Pole ?

Can NL help?

$$\beta_g = -B\alpha_g^2 + C\alpha_g^3$$

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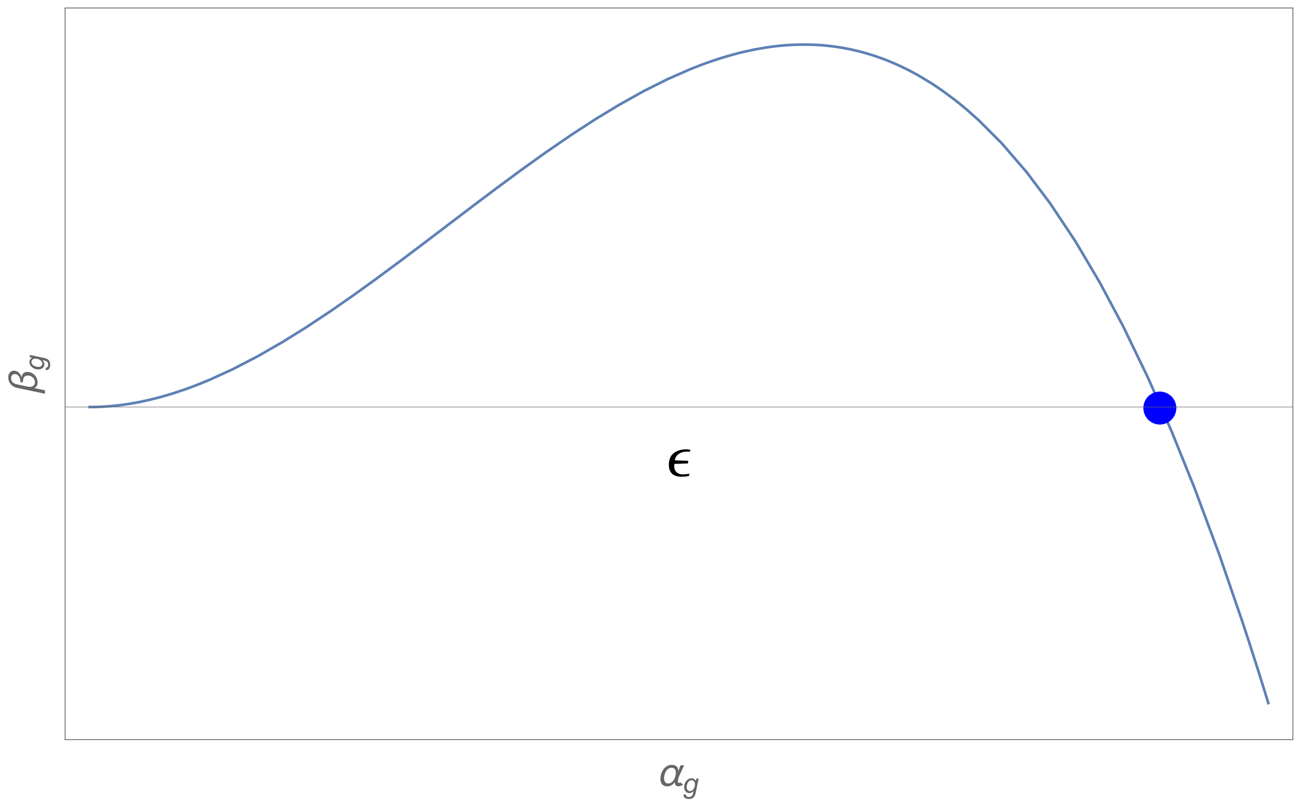

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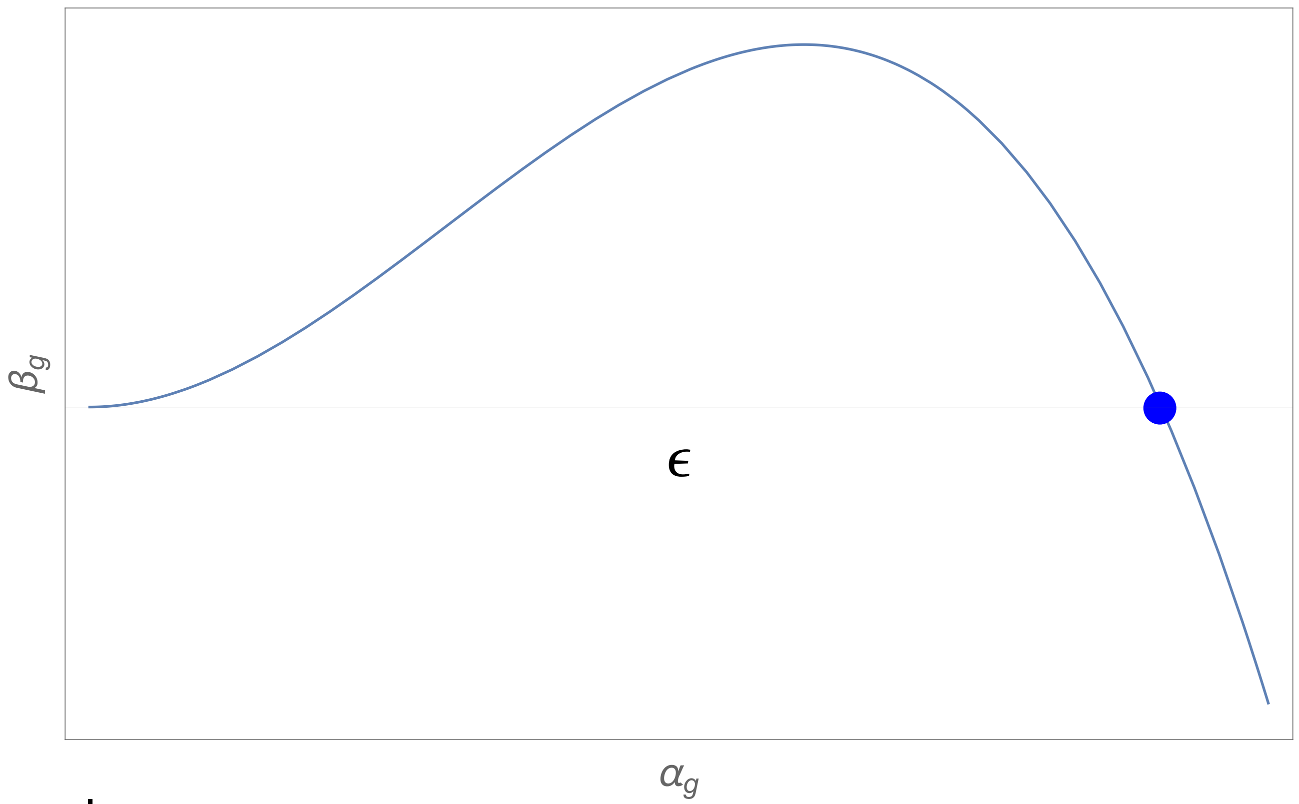

Impossible in Gauge Theories with Fermions alone

Caswell, PRL 1974

Add Yukawa

$$\beta_g = \alpha_g^2 \left[\frac{4}{3}\epsilon + \left(25 + \frac{26}{3}\epsilon \right) \alpha_g - 2 \left(\frac{11}{2} + \epsilon \right)^2 \alpha_y \right]$$

$$\beta_y = \alpha_y \ \left[\left(13 + 2\epsilon \right) \alpha_y - 6\, \alpha_g \right]$$

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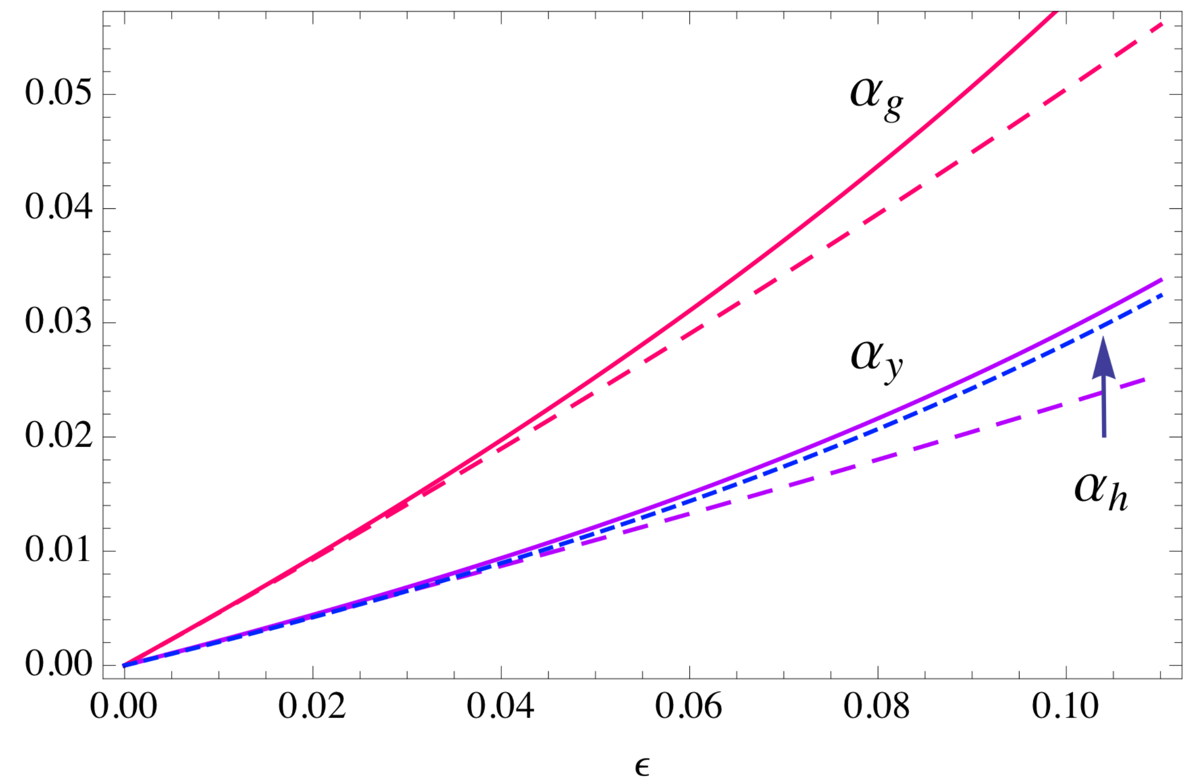

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Litim and Sannino, 1406.2337, JHEP

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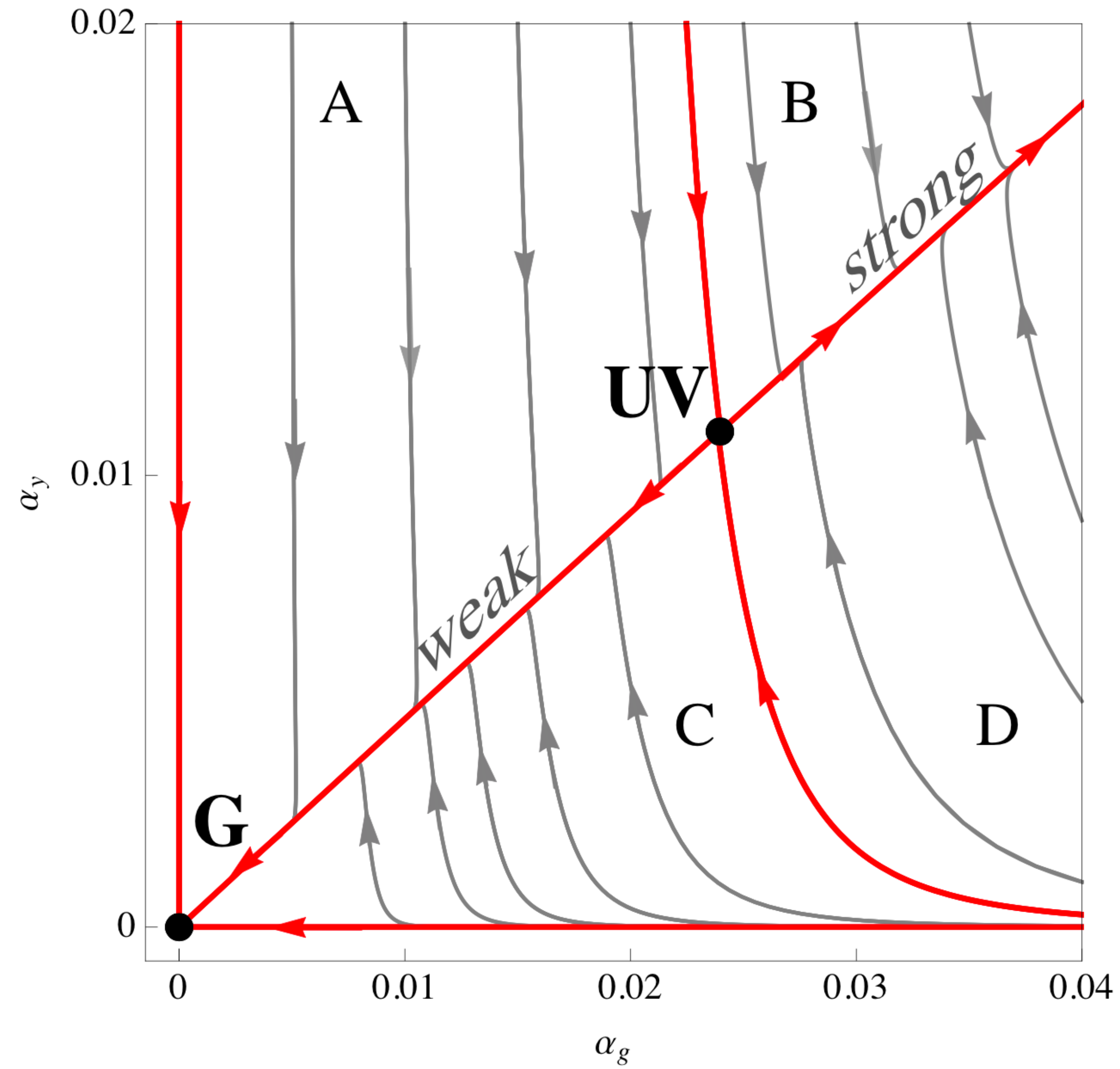

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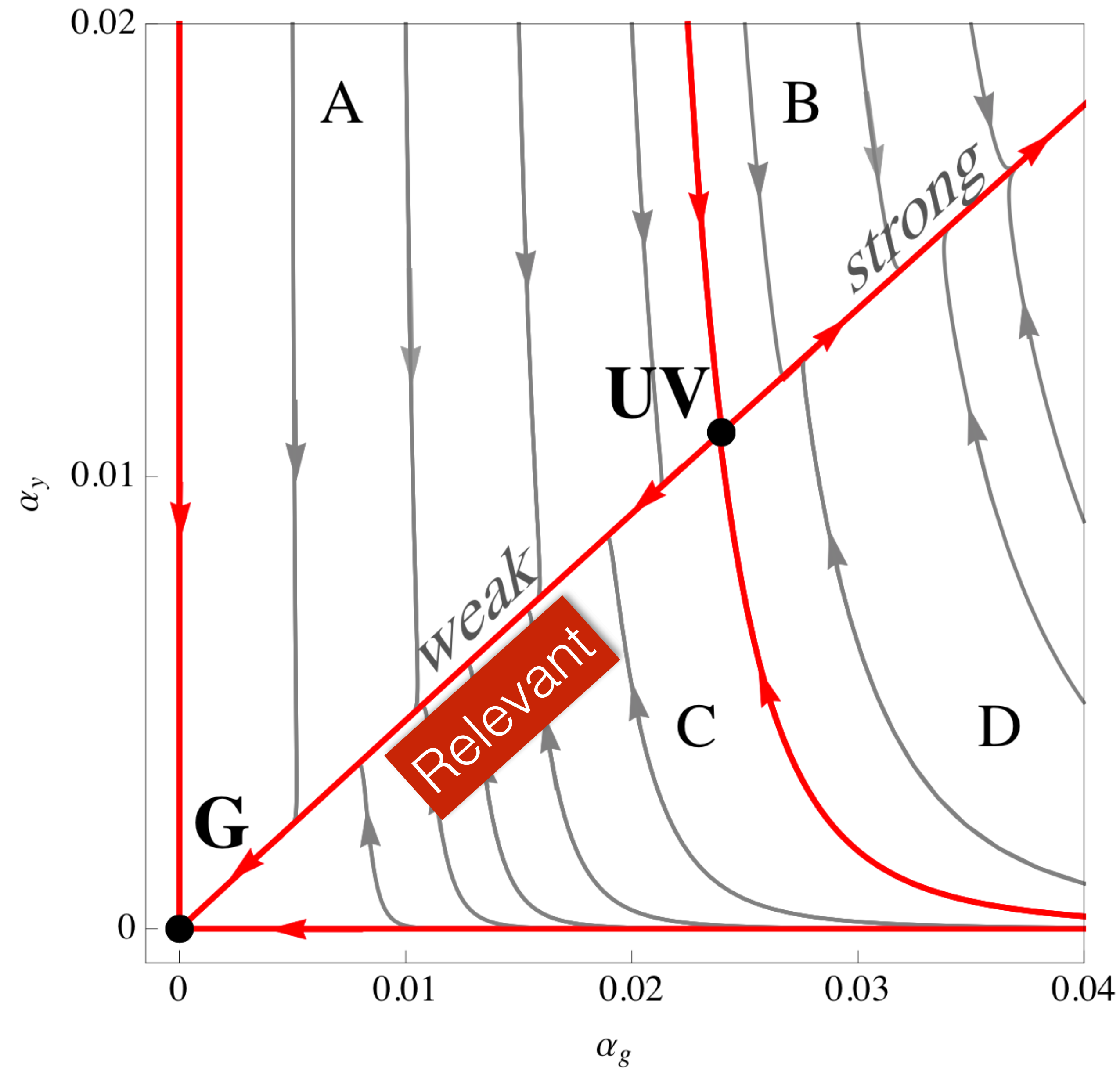

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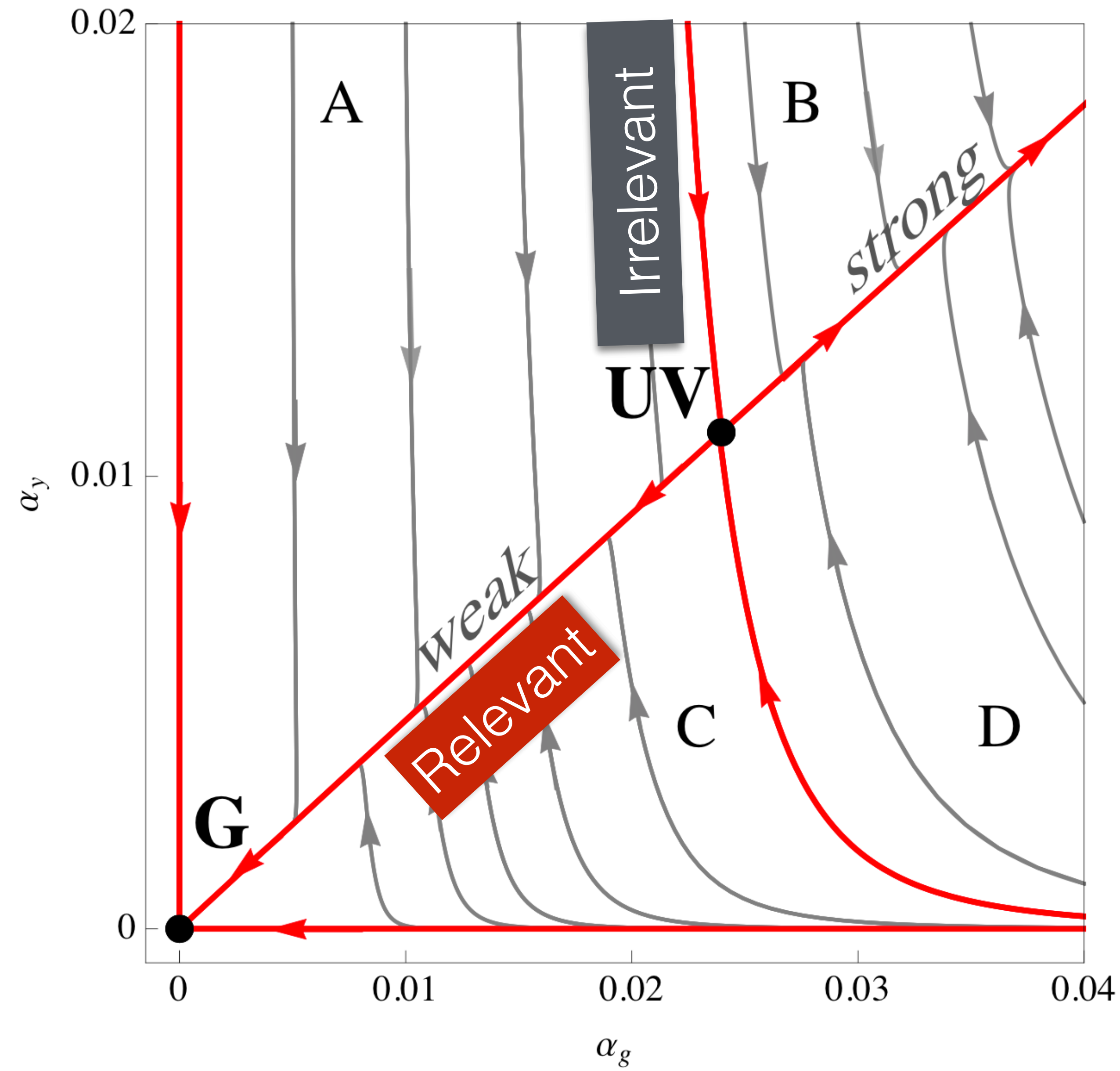

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Phase Diagram

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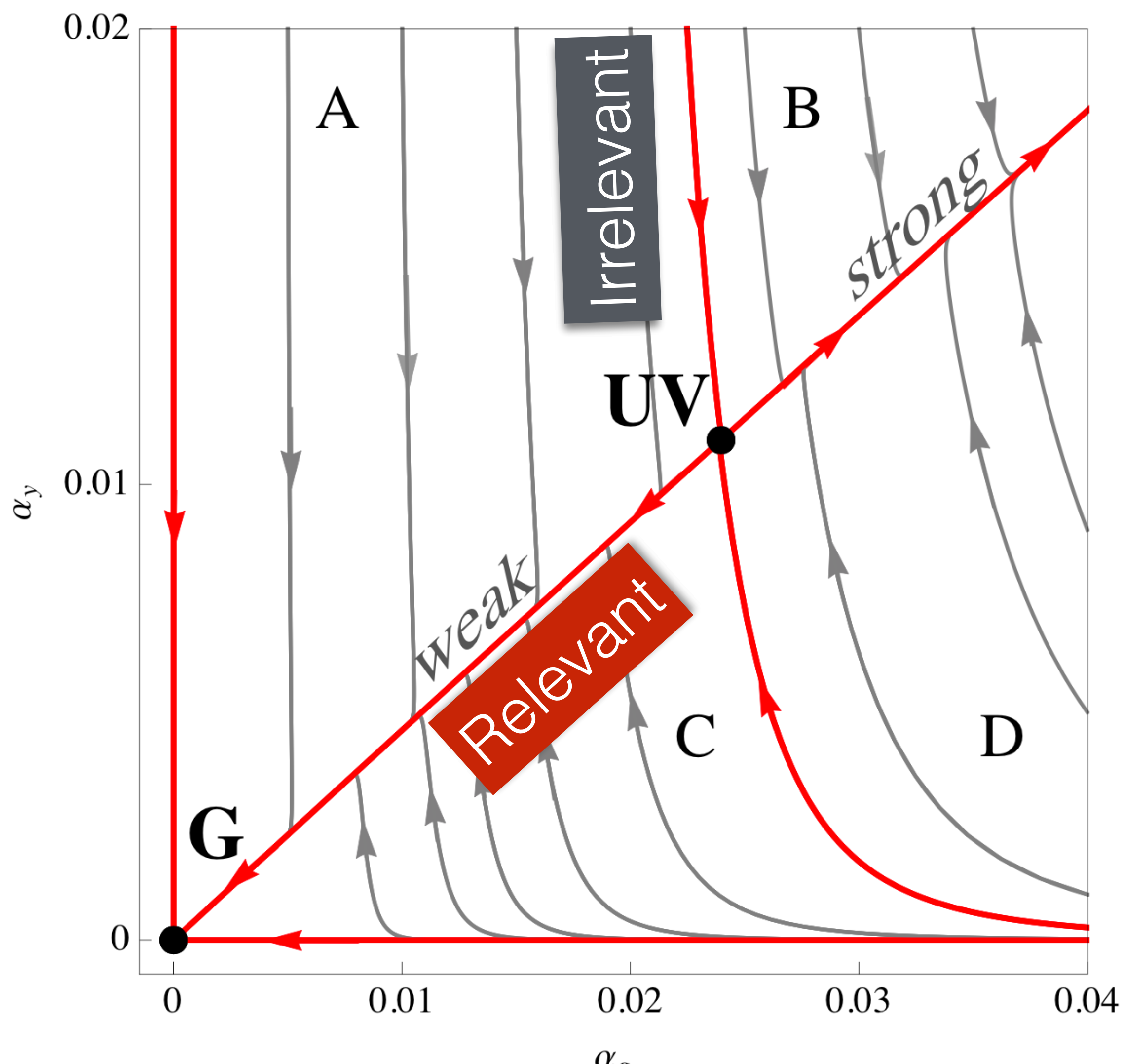

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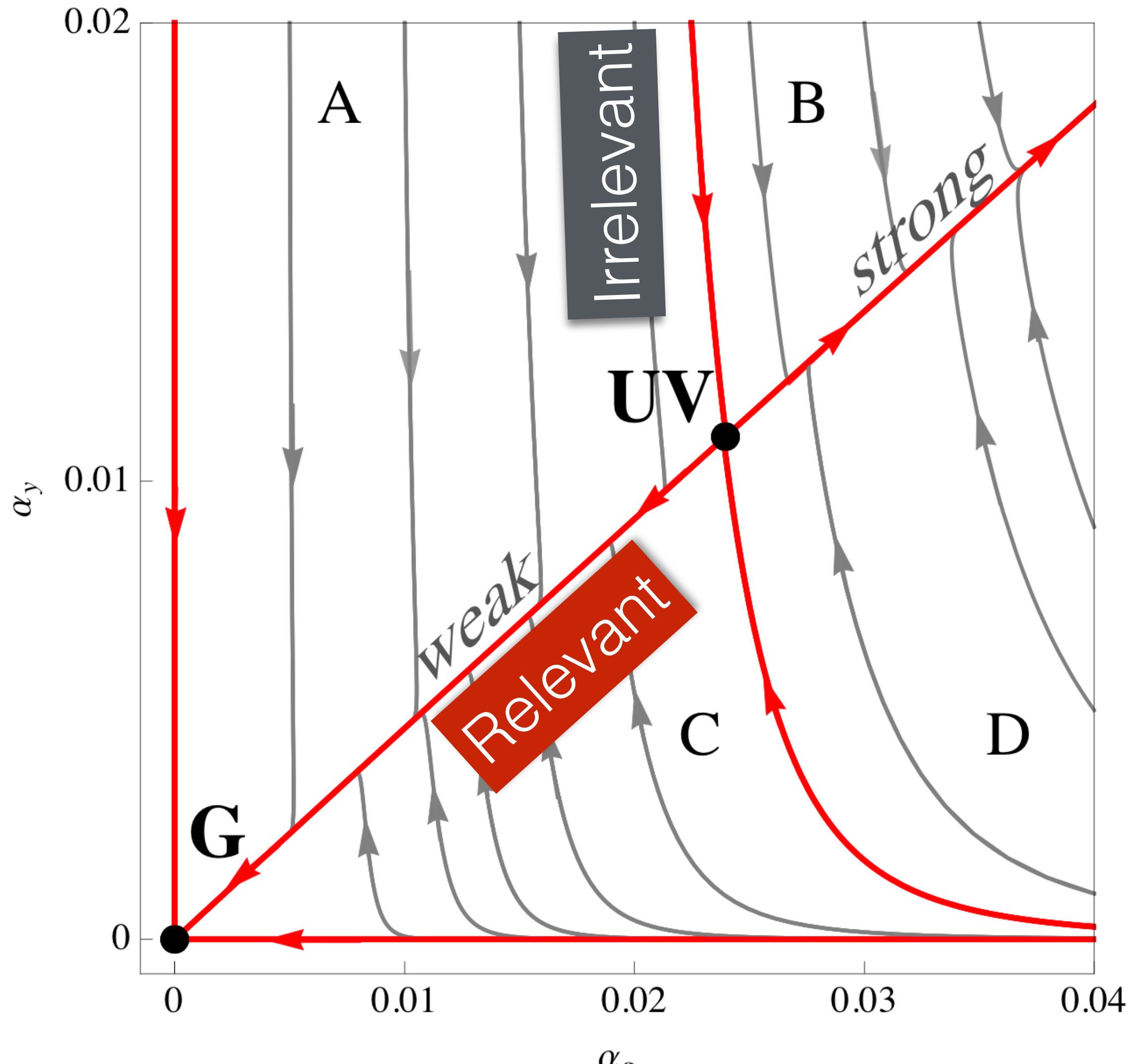

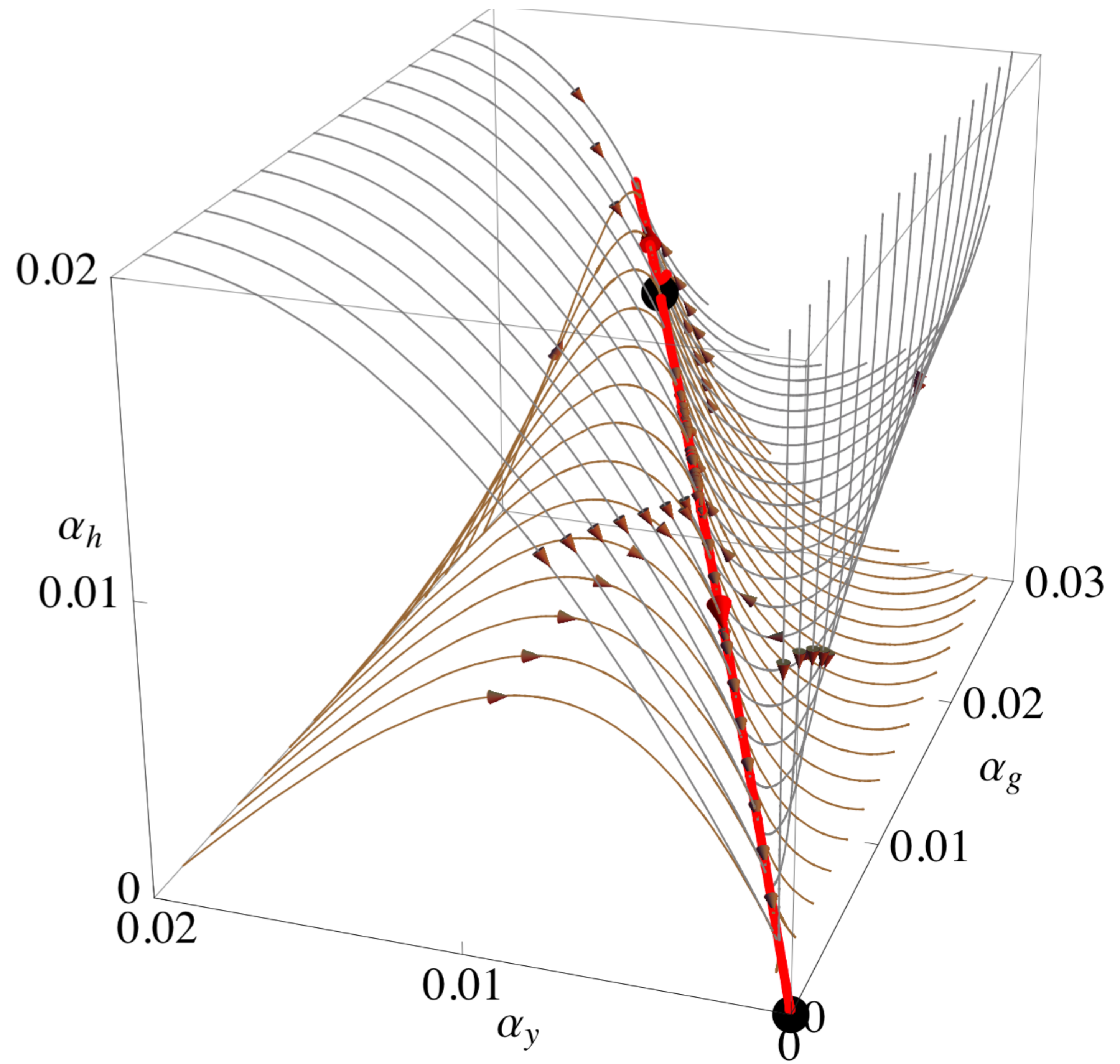

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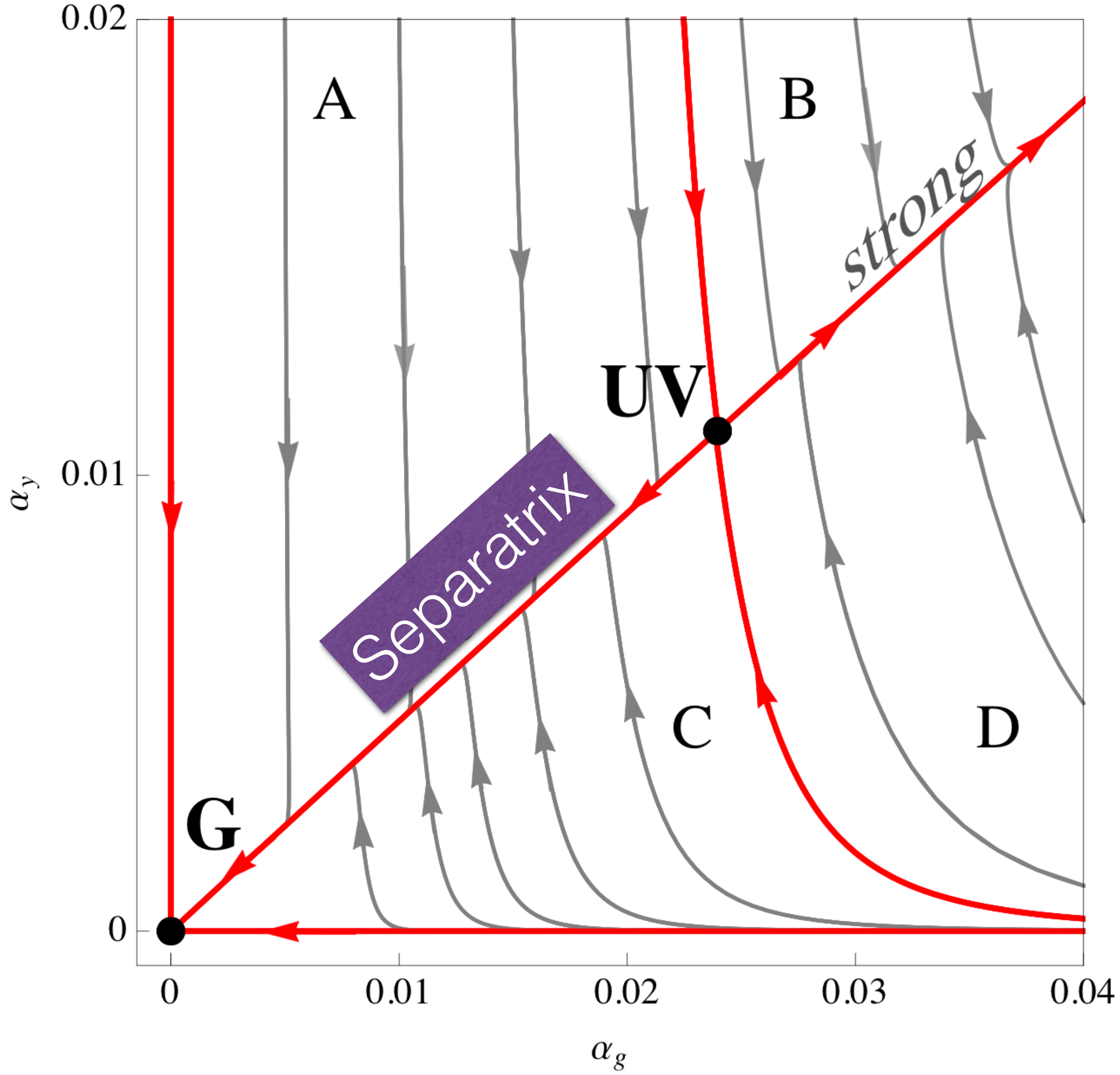
Separatrix = Line of Physics

Globally defined line connecting two FPs



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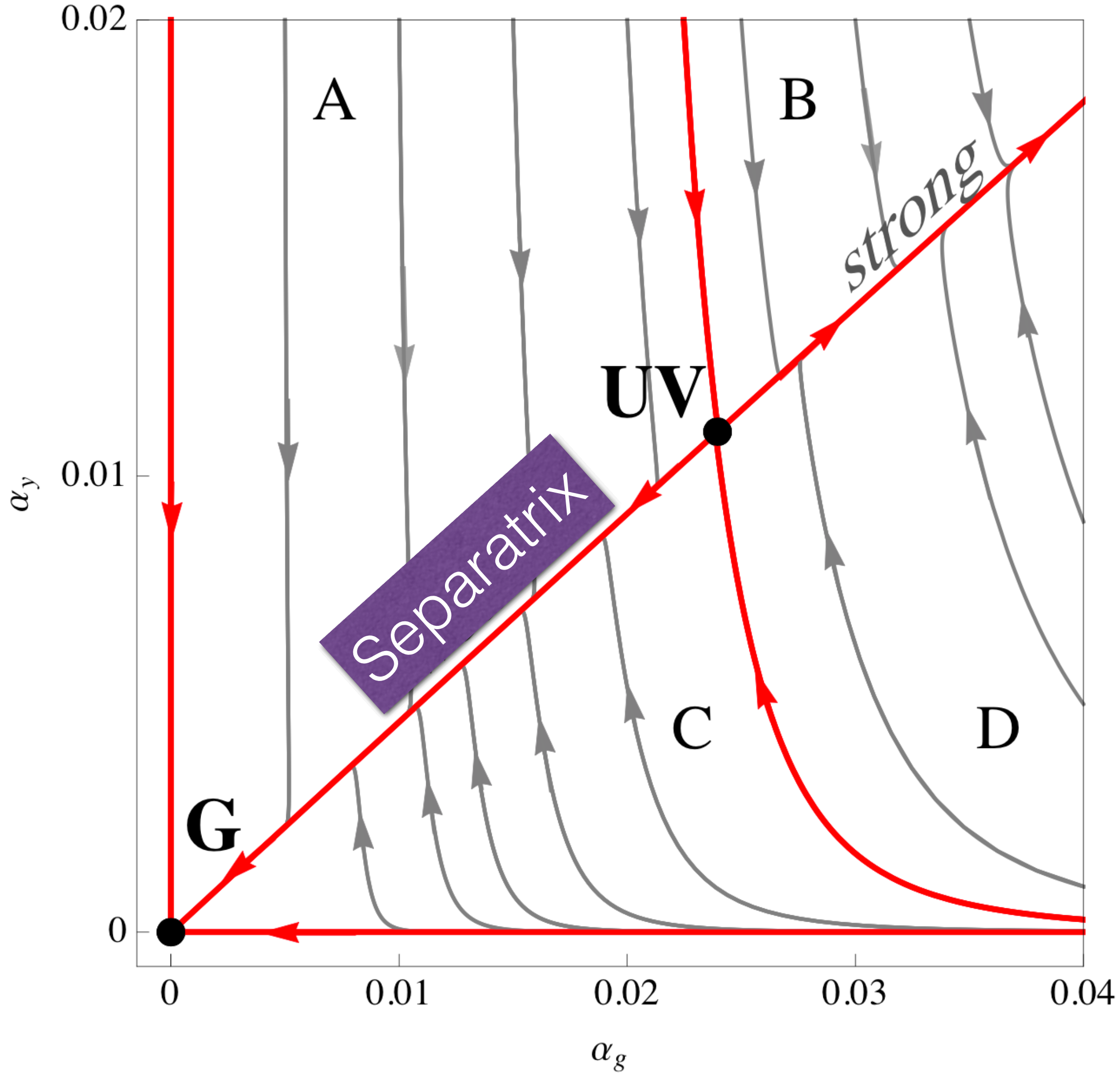

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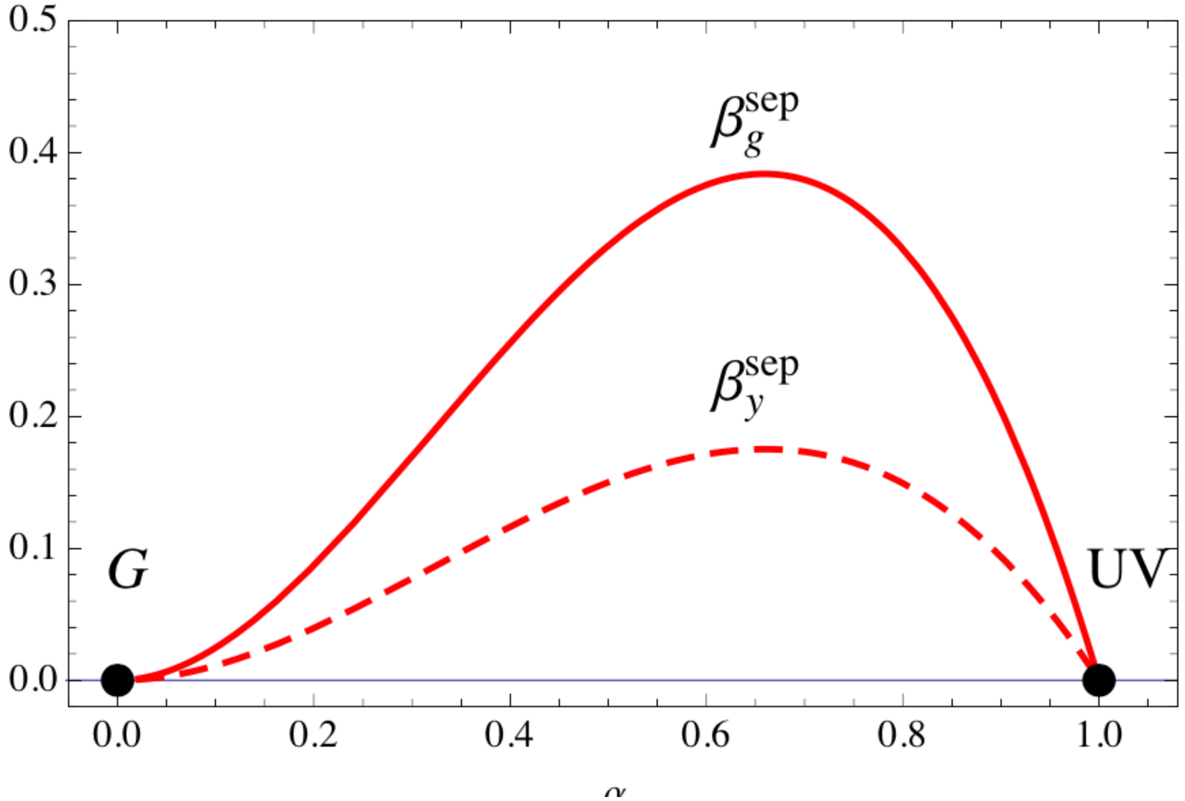
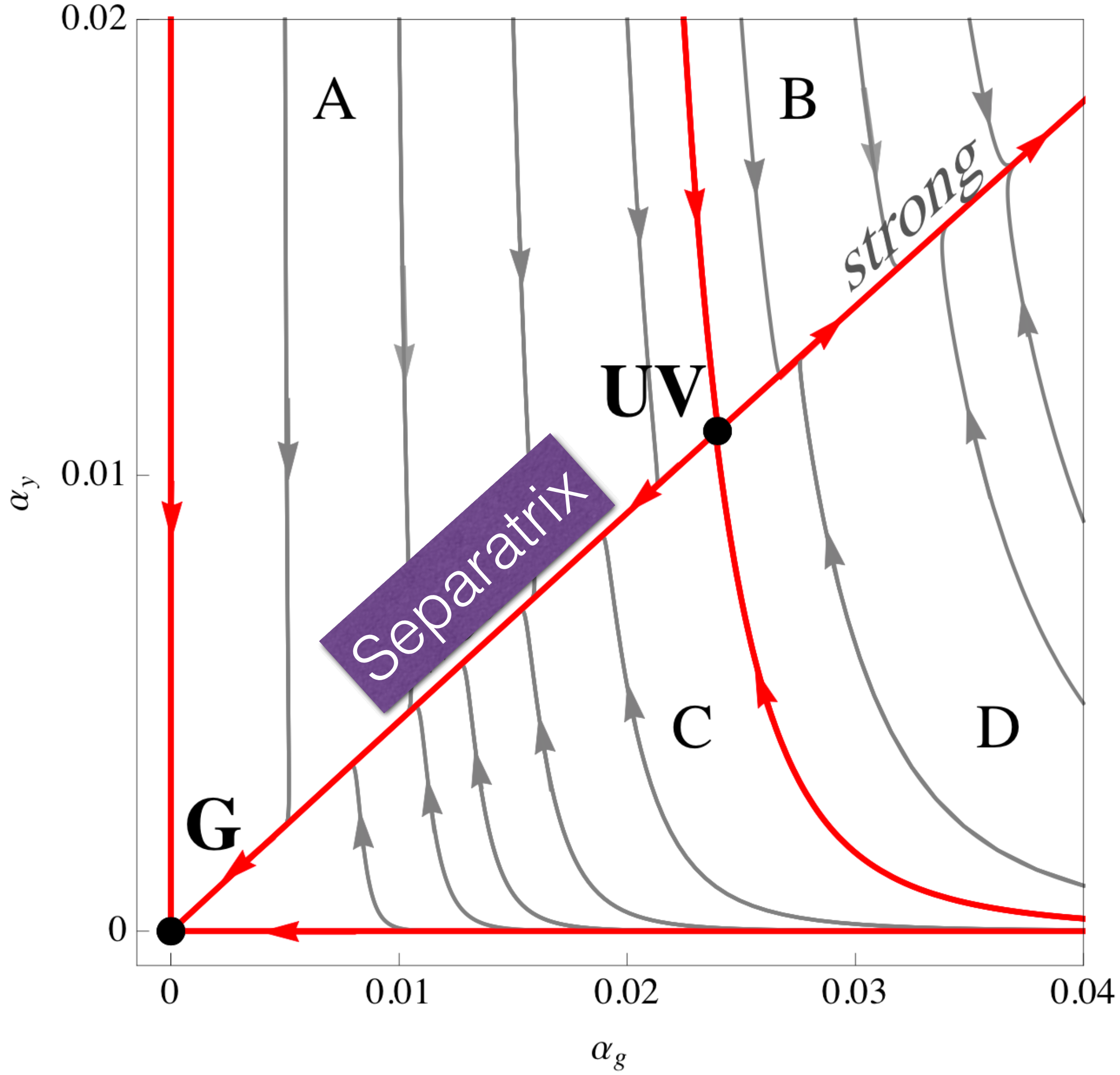
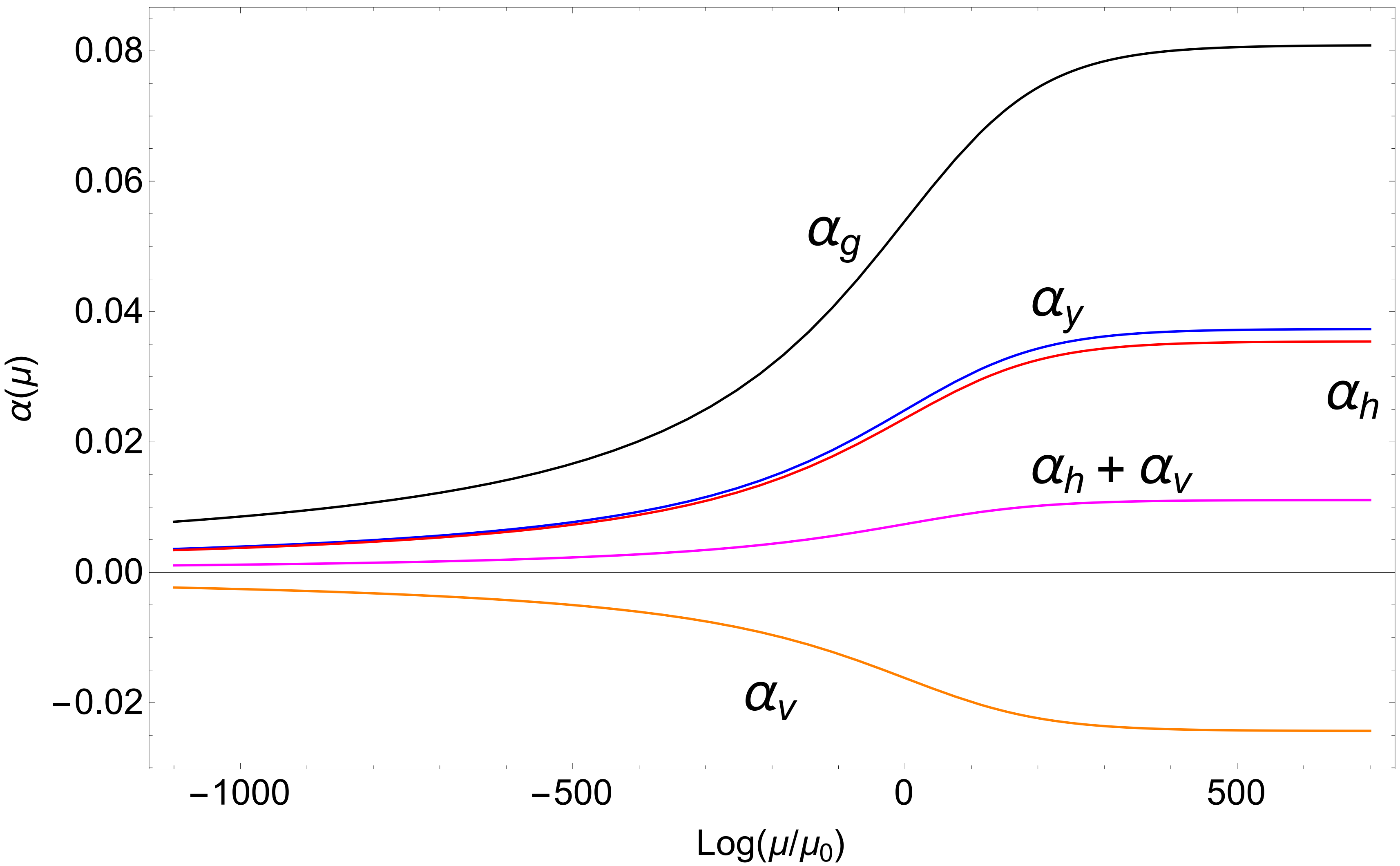




Complete asymptotic safety

Litim and Sannino, 1406.2337, JHEP

Gauge + fermion + scalars theories can be fund. at any energy scale



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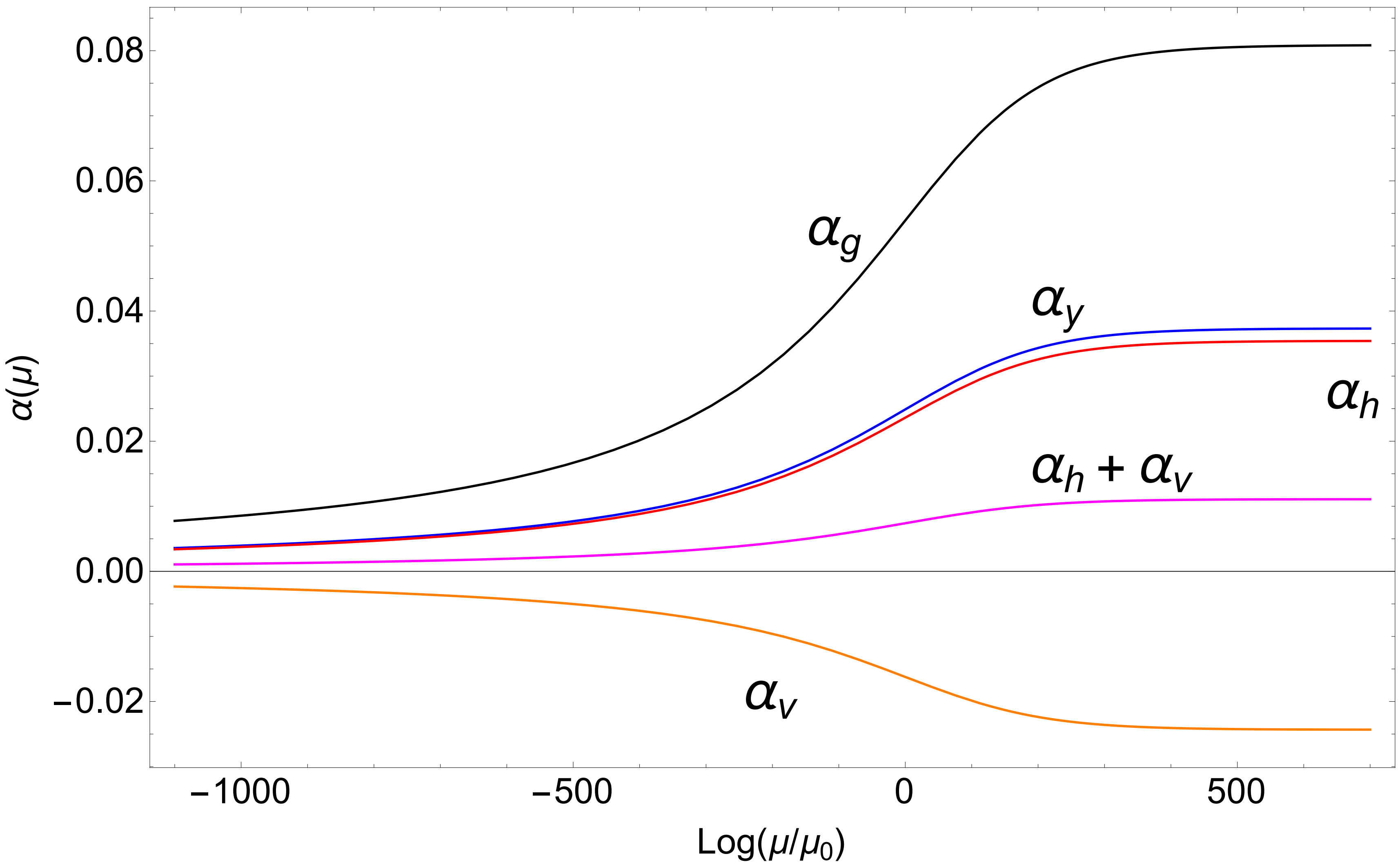


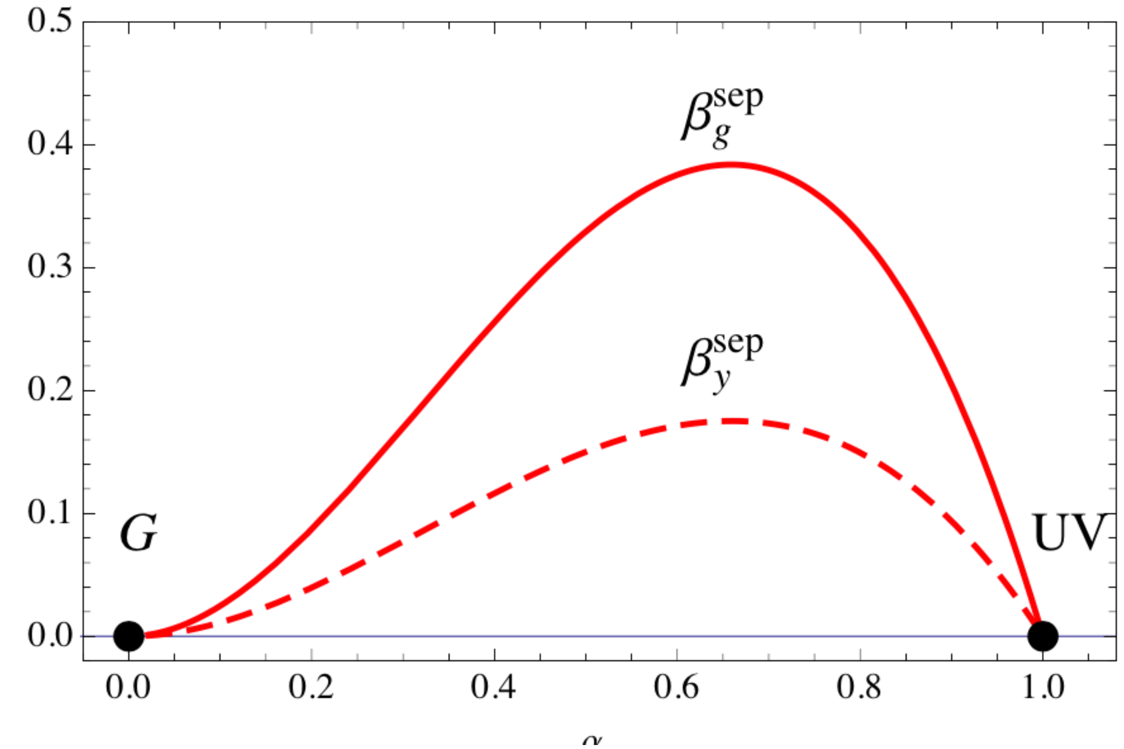
Scalars are needed to make the theory fundamental

Safe variation for the a-theorem function

Antipin, Gillioz, Mølgaard, Sannino 13

Safe variation for the a-theorem function

To leading order



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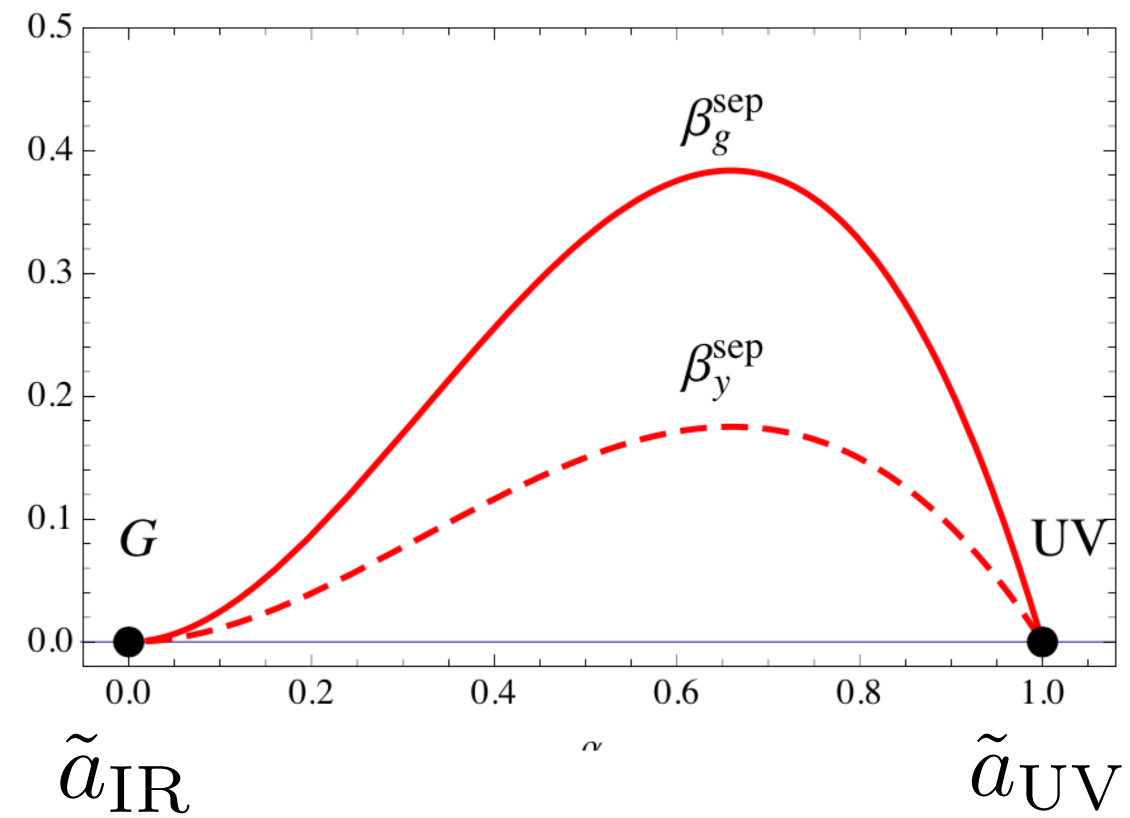

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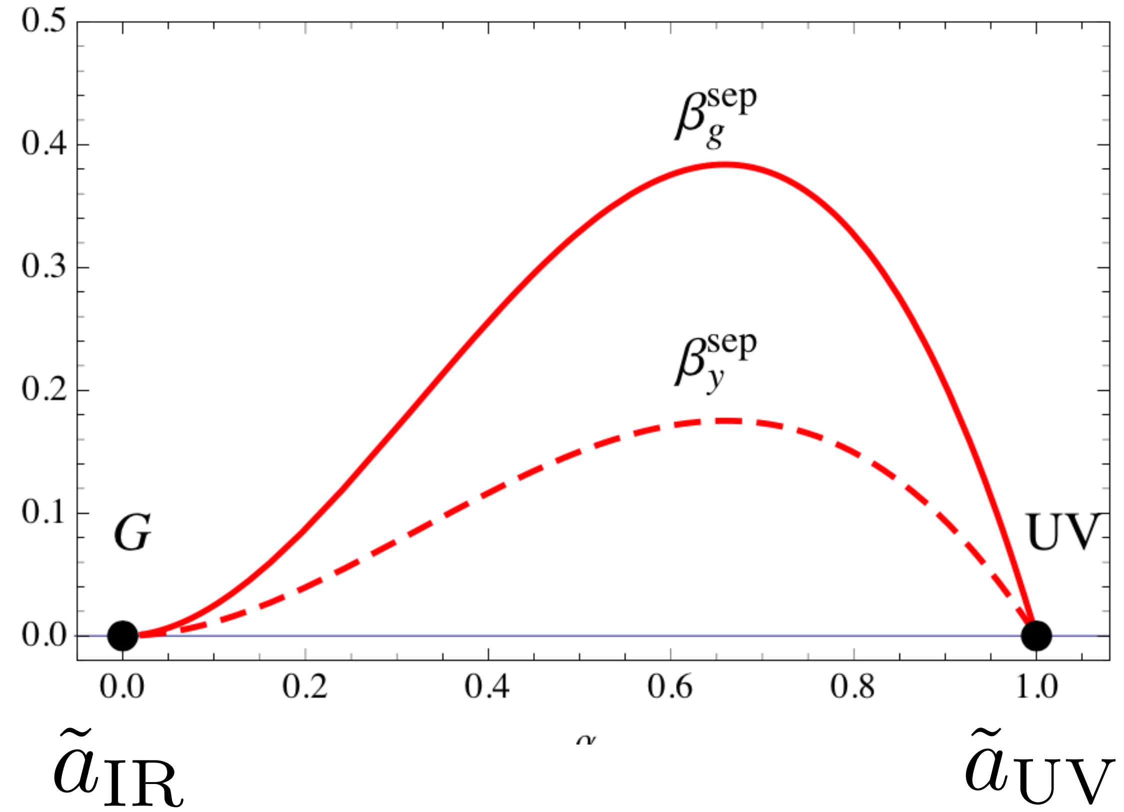

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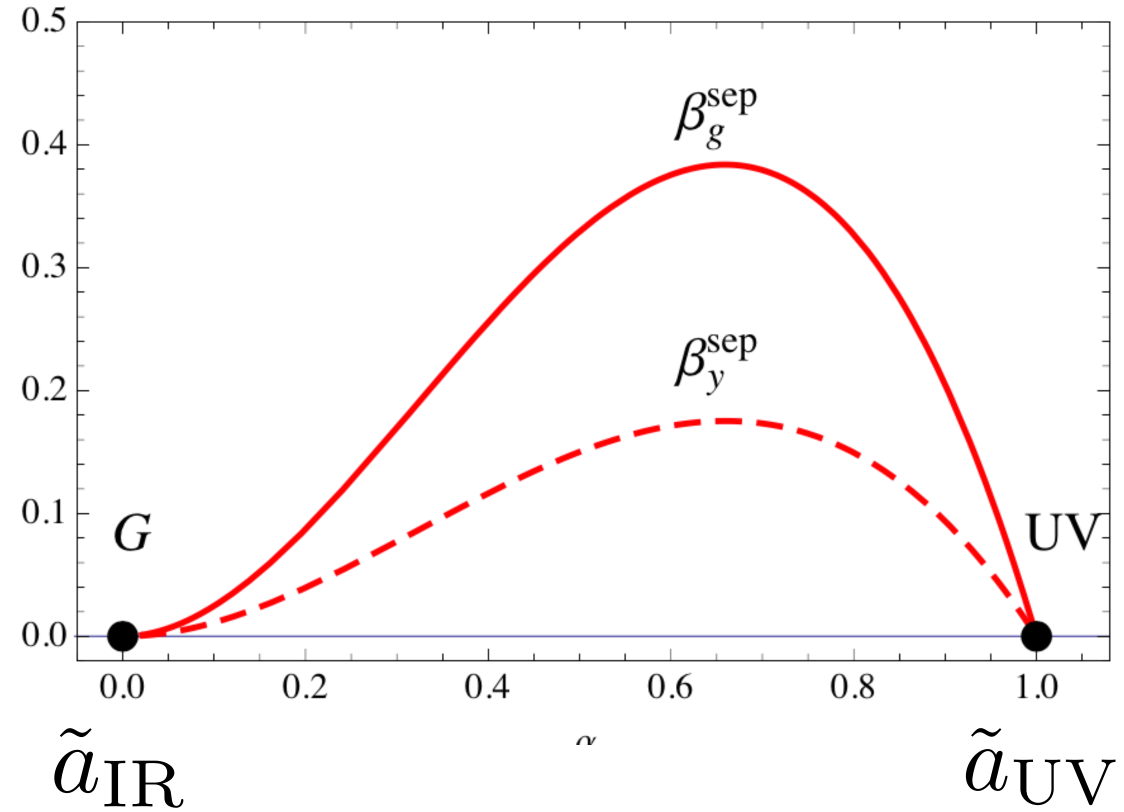

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Antipin, Gillioz, Mølgaard, Sannino 13

Bootstrap and composite operators

Antipin, Mølgaard, Sannino 14

Supersymmetry is unsafe

Intriligator and Sannino, 1508.07413, JHEP

Martin and Wells, hep-ph/0011382, PRD

SQCD with H

Fields	$[SU(N_c)]$	$SU_L(N_f)$	$SU_R(N_f)$	$U_V(1)$	$U(1)_R$
W_α	Adj	1	1	0	1
Q	$\square$	$\overline{\square}$	1	1	$1-\frac{N_c}{N_f}$
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No perturbative UV fixed point

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SQCD with H

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Assume a nonperturbative fixed point, however

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Check if SQCD without H has an UV fixed point

SQCD

SQCD

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SQCD

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SQCD

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SQCD with(out) H cannot be asymptotically safe

SQCD

Unitarity bound is not sufficient

$$\mathcal{M} = Q\tilde{Q} \qquad D_{SCFT}(\mathcal{M}) = \frac{3}{2}R_{SCFT}(\mathcal{M}) = 3\frac{N_f - N_c}{N_f}$$

$$\mathcal{B} = Q^{N_c} \qquad D_{SCFT}(\mathcal{B}) = D_{SCFT}(\widetilde{\mathcal{B}}) = \frac{3}{2}R_{SCFT}(\mathcal{B}) = \frac{3}{2}N_c\frac{N_f - N_c}{N_f}$$

Can be ruled out via a-theorem $\quad a(R) = 3\mathrm{Tr}U(1)_R^3 - \mathrm{Tr}U(1)_R.$

$$a_{\mathrm{UV-safe}} - a_{\mathrm{IR-safe}} < 0$$

SQCD with(out) H cannot be asymptotically safe

*Generalisation to different susy theories using a-maximisation**

What did we achieve?

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Gauge + fermion + scalars theories can be fund. at any energy scale

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Precise results: independent on scheme choice

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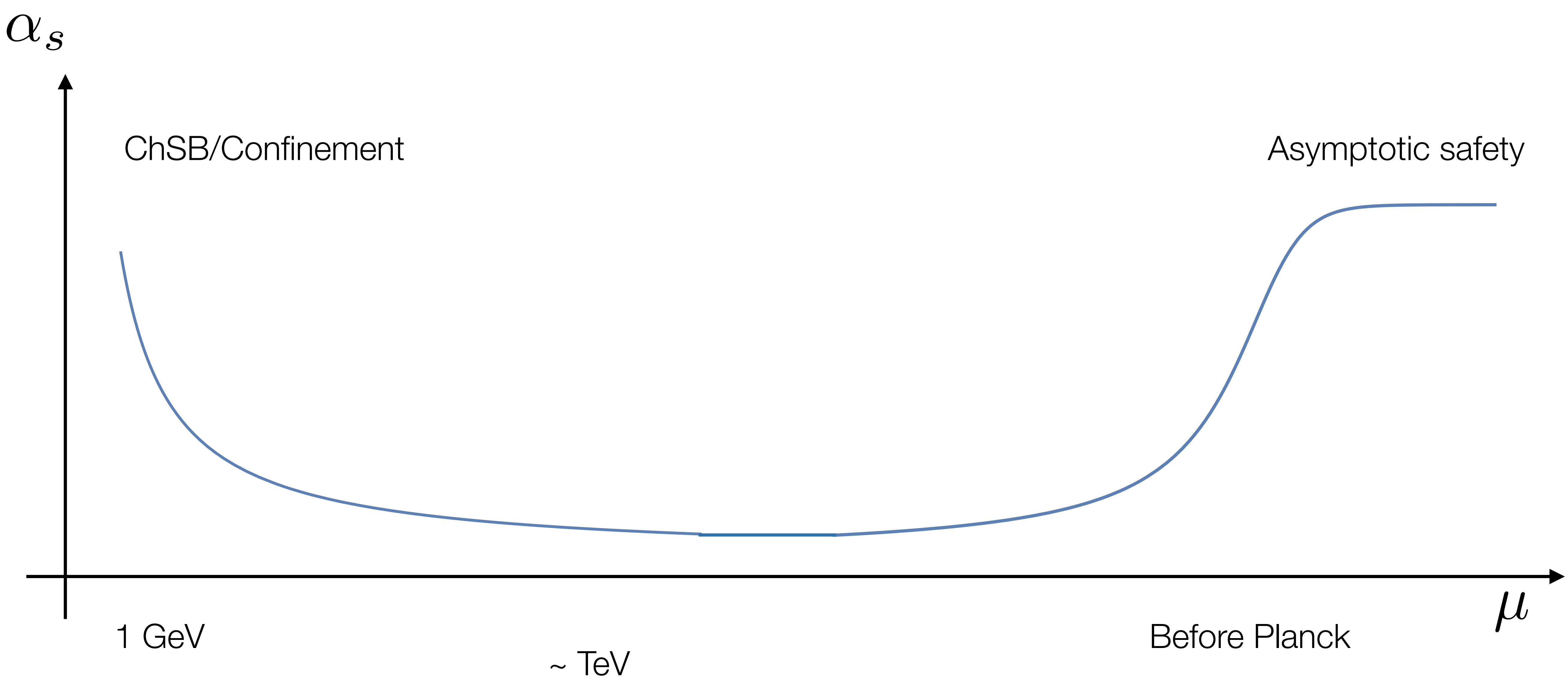
Existence of UV nontrivial Gauge-Yukawa theories

Discovered UV complete Non-Abelian QED-like theories

Scalars are needed to render the UV theory dynamically finite

Safe QCD scenario is testable



Sannino, 1511.09022

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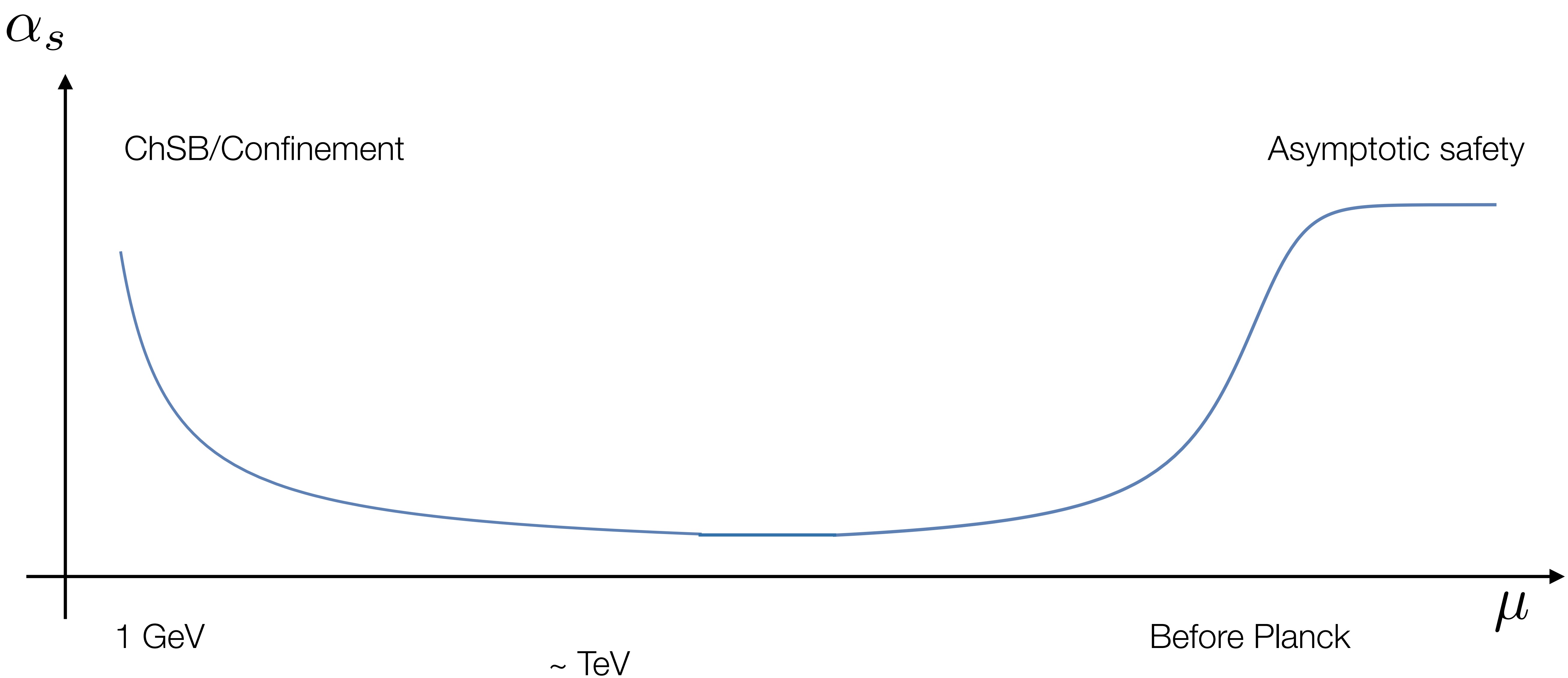

Asymptotic freedom is not a must for UV complete theories

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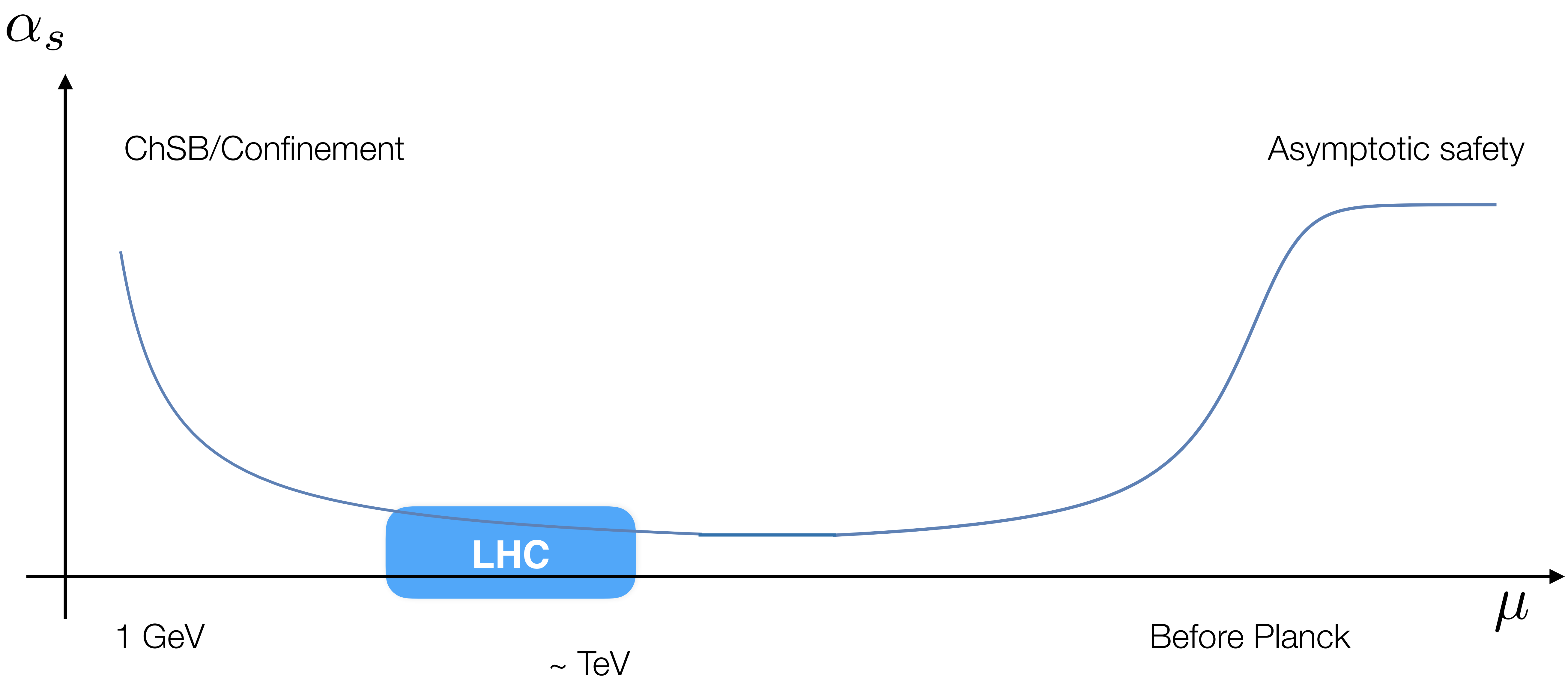

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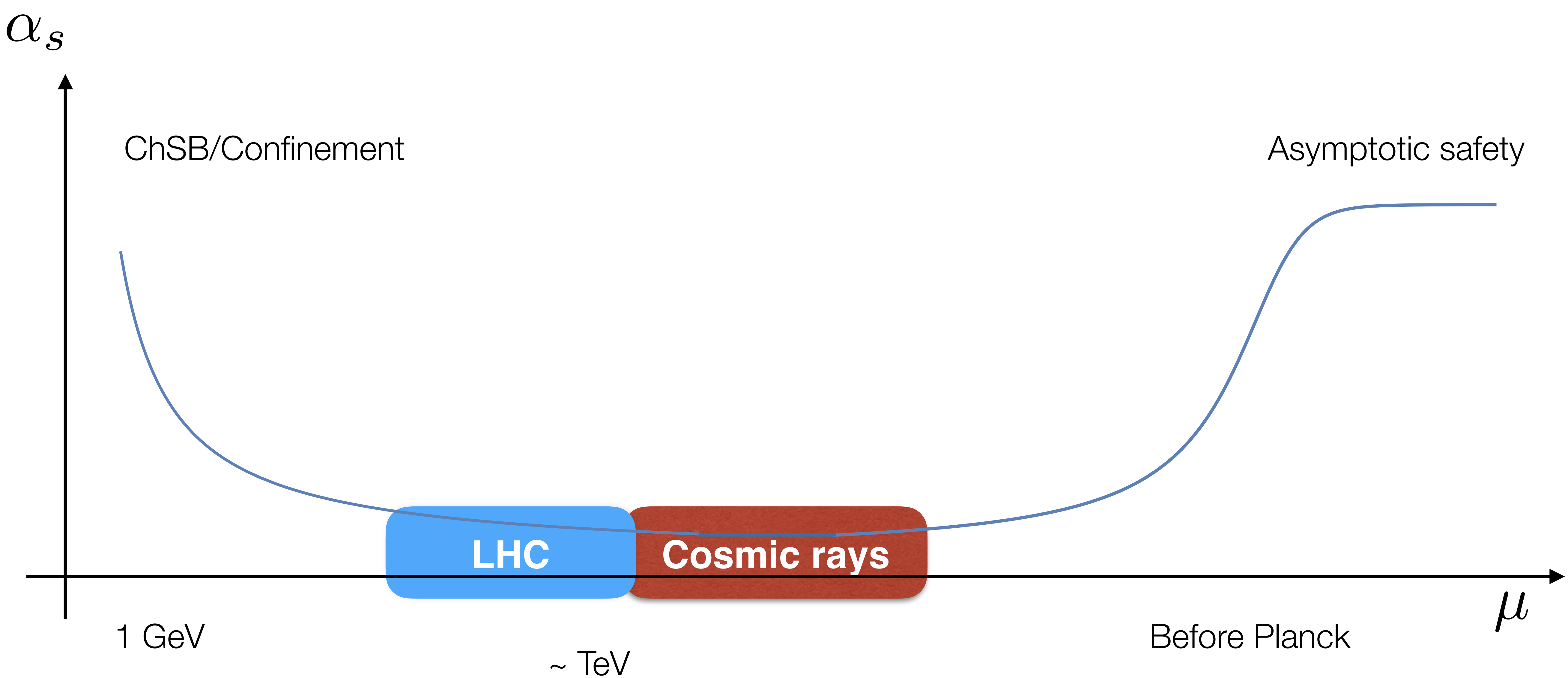

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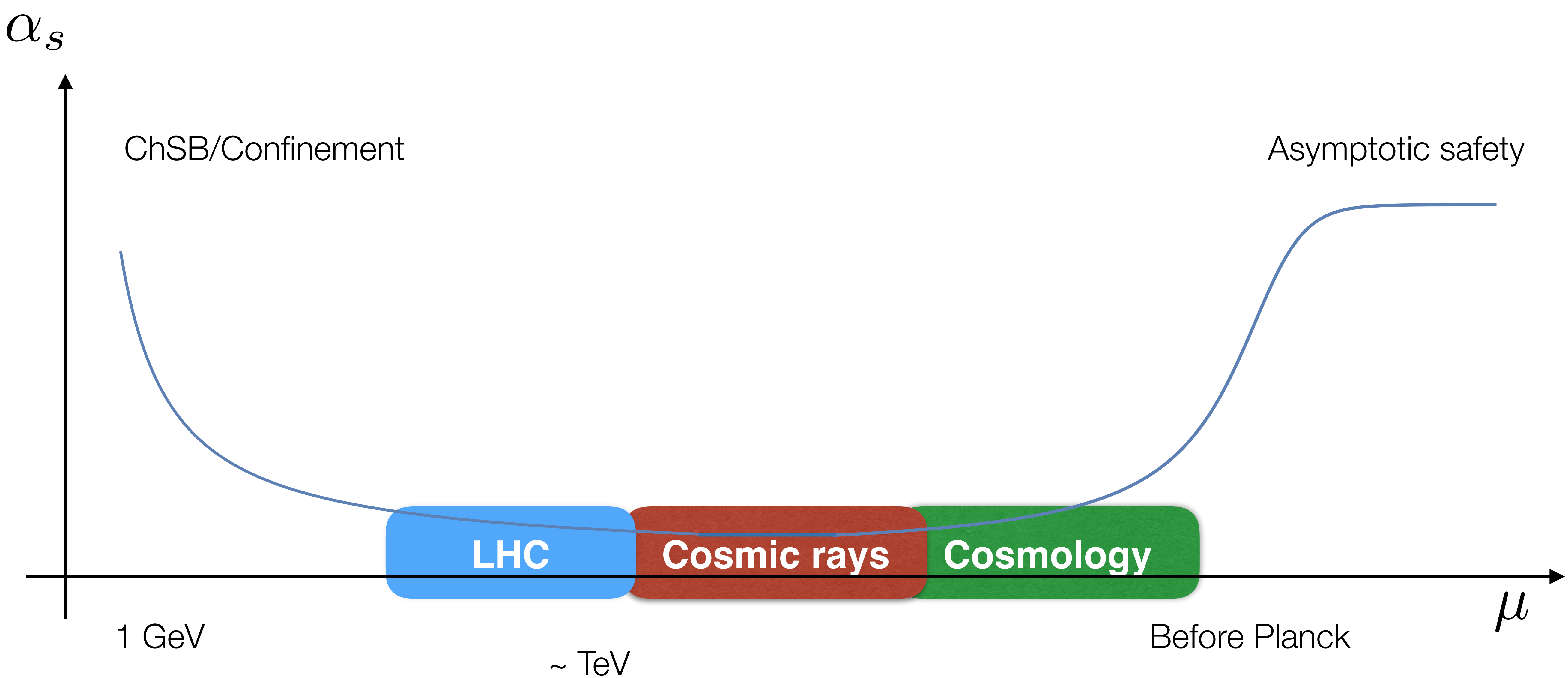
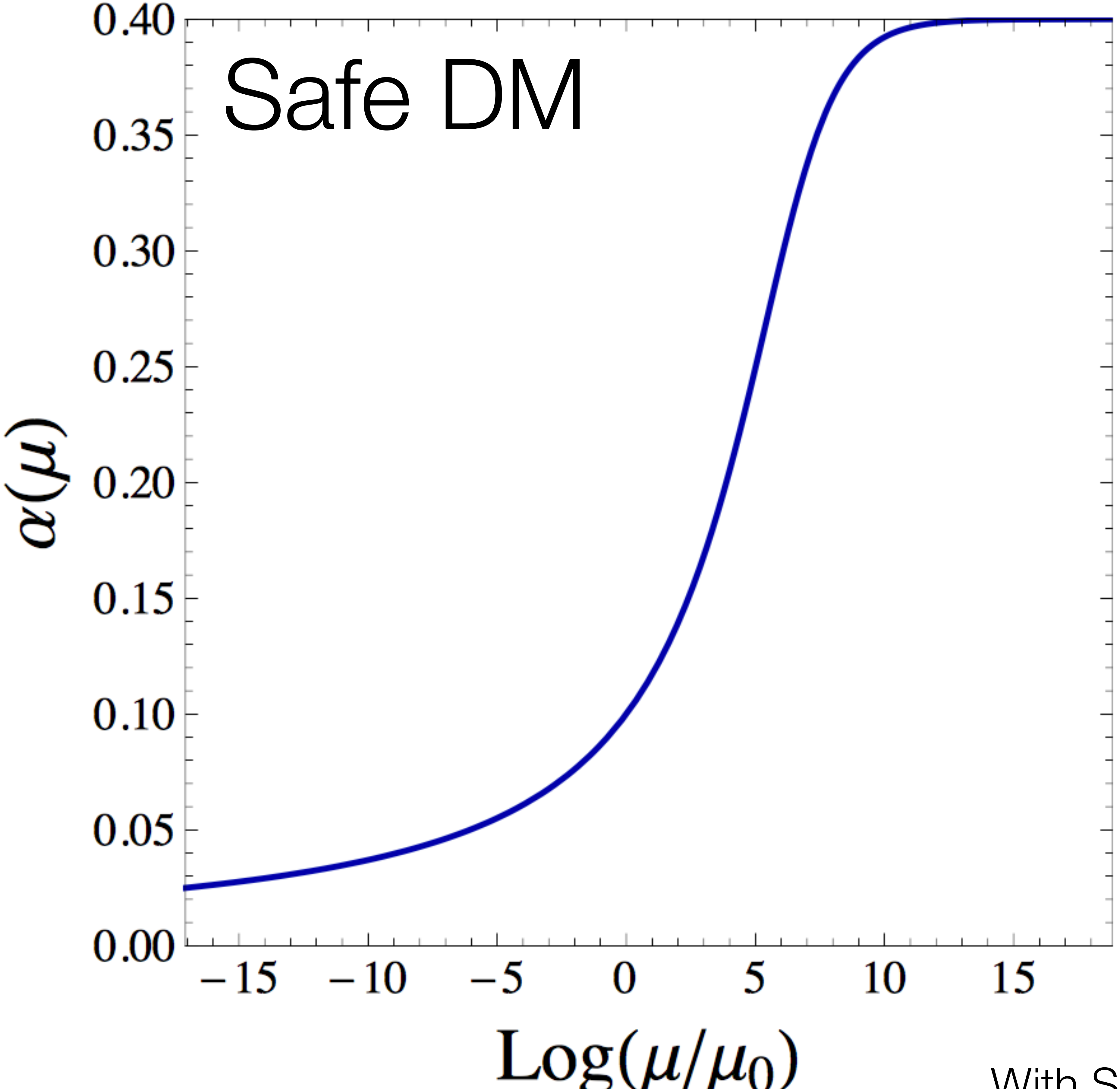


Asymptotic freedom is not a must for UV complete theories

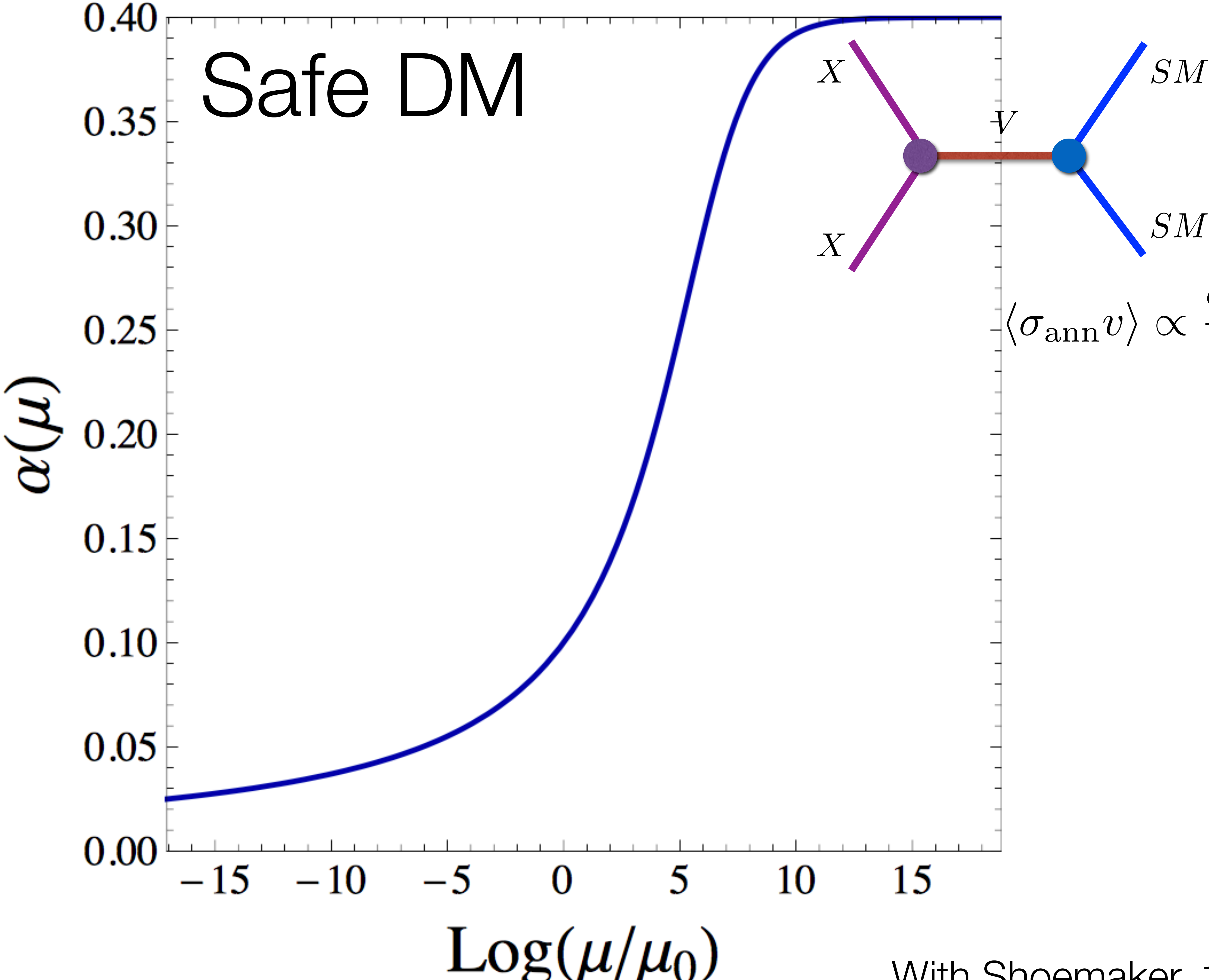
Sannino, 1511.09022

Safe DM

With Shoemaker, 1412.8034

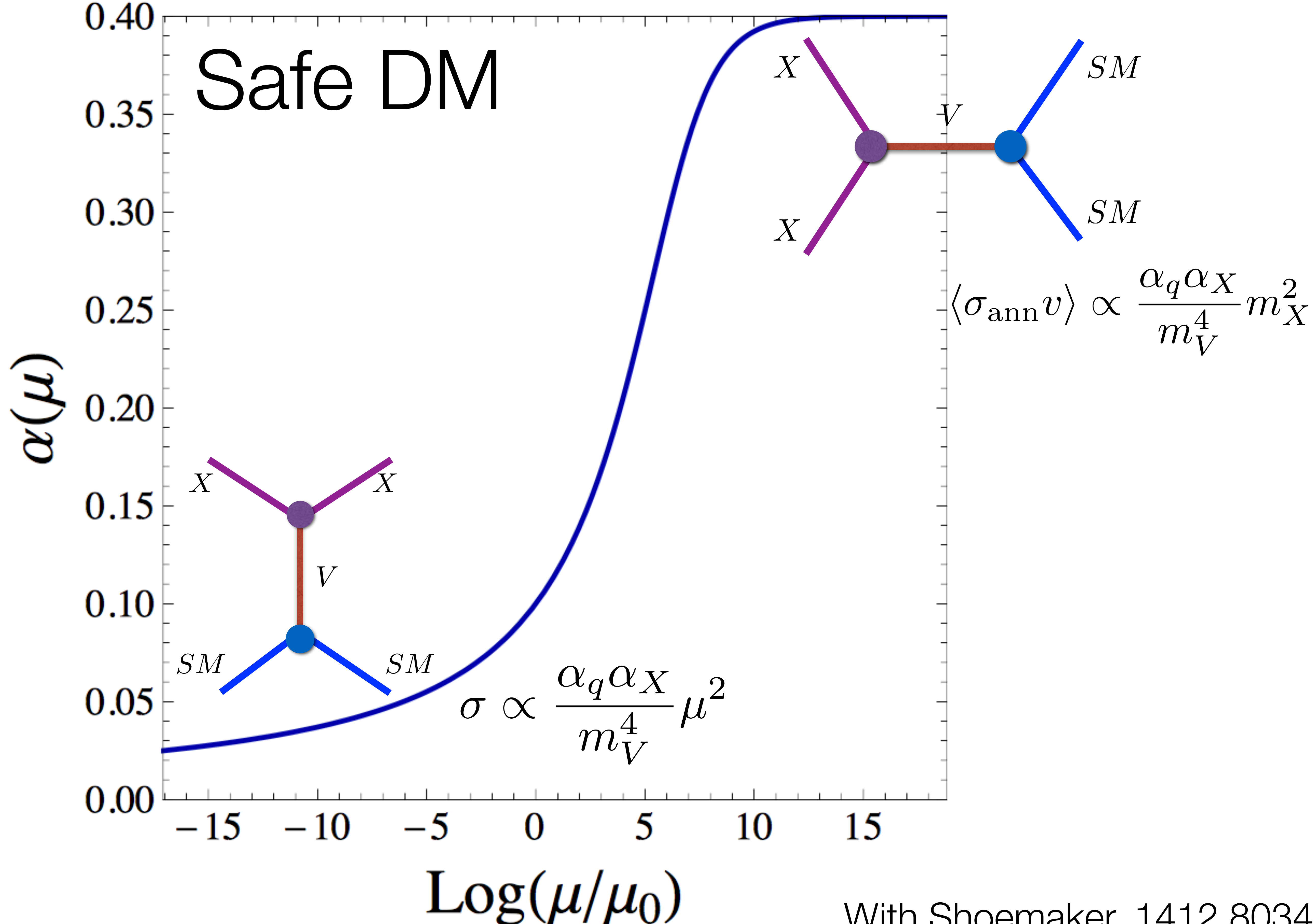


With Shoemaker, 1412.8034



$$\langle \sigma_{\mathrm{ann}} v \rangle \propto \frac{\alpha_q \alpha_X}{m_V^4} m_X^2$$

With Shoemaker, 1412.8034



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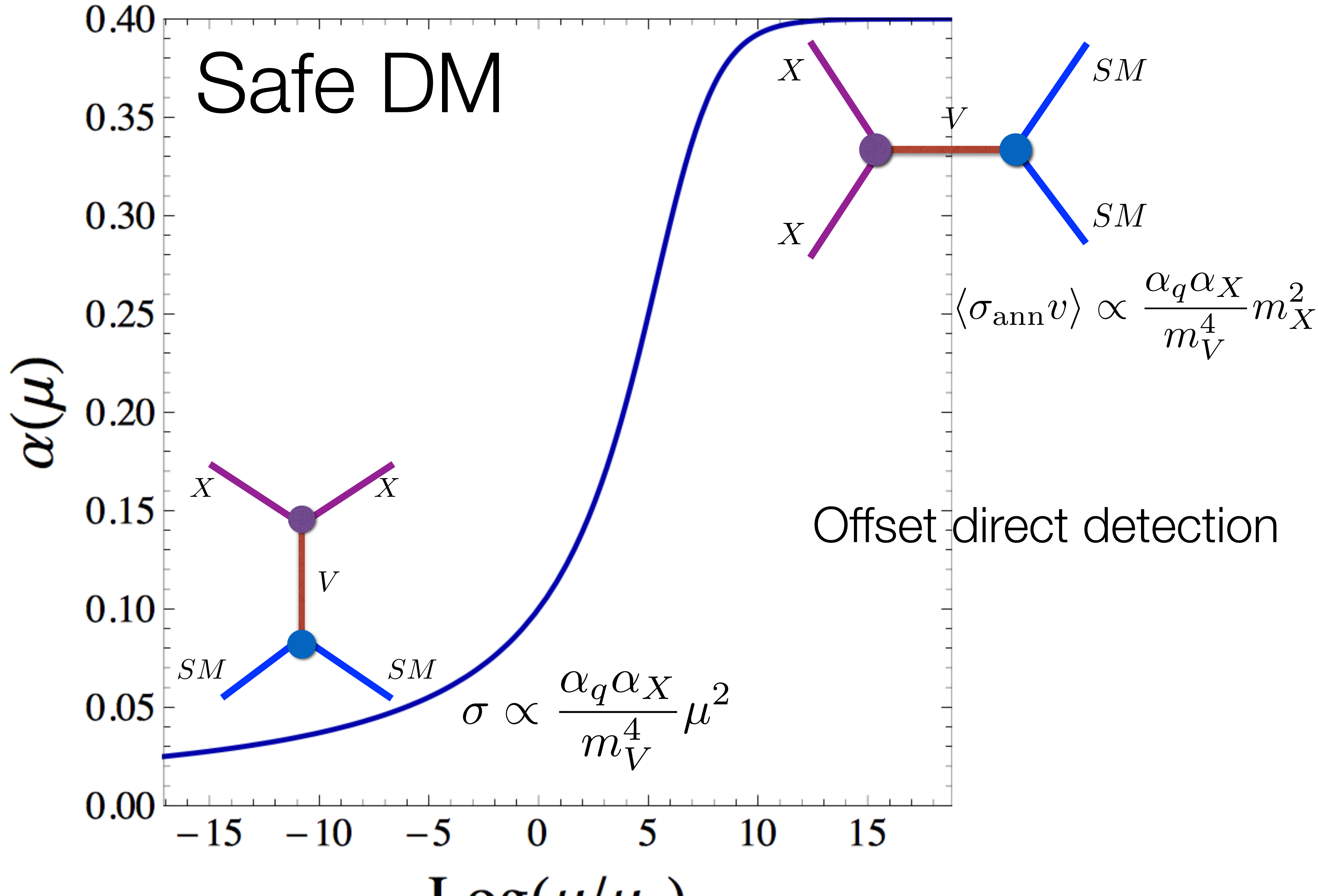

With Shoemaker, 1412.8034

Outlook

Outlook

- Novel models of DM/Inflation 1412.8034 & 1503.00702
- Asymptotically safe extensions of the SM (e.g. QCD)
- New ways to unify flavour, scalar and gauge interactions
- Super asymptotic safety is not guaranteed*
- Beyond P.T. (Lattice, dualities, holography, …)
- Similarities and differences w.r.t. to N=4 (Wilson loops, MHV)
- Asymptotic safe quantum gravity **?

* Intriligator and Sannino, 1508.07411

** Weinberg

Future

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- Fundamental theories

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- Beyond perturbation theory

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- (Out of) equilibrium thermodynamics

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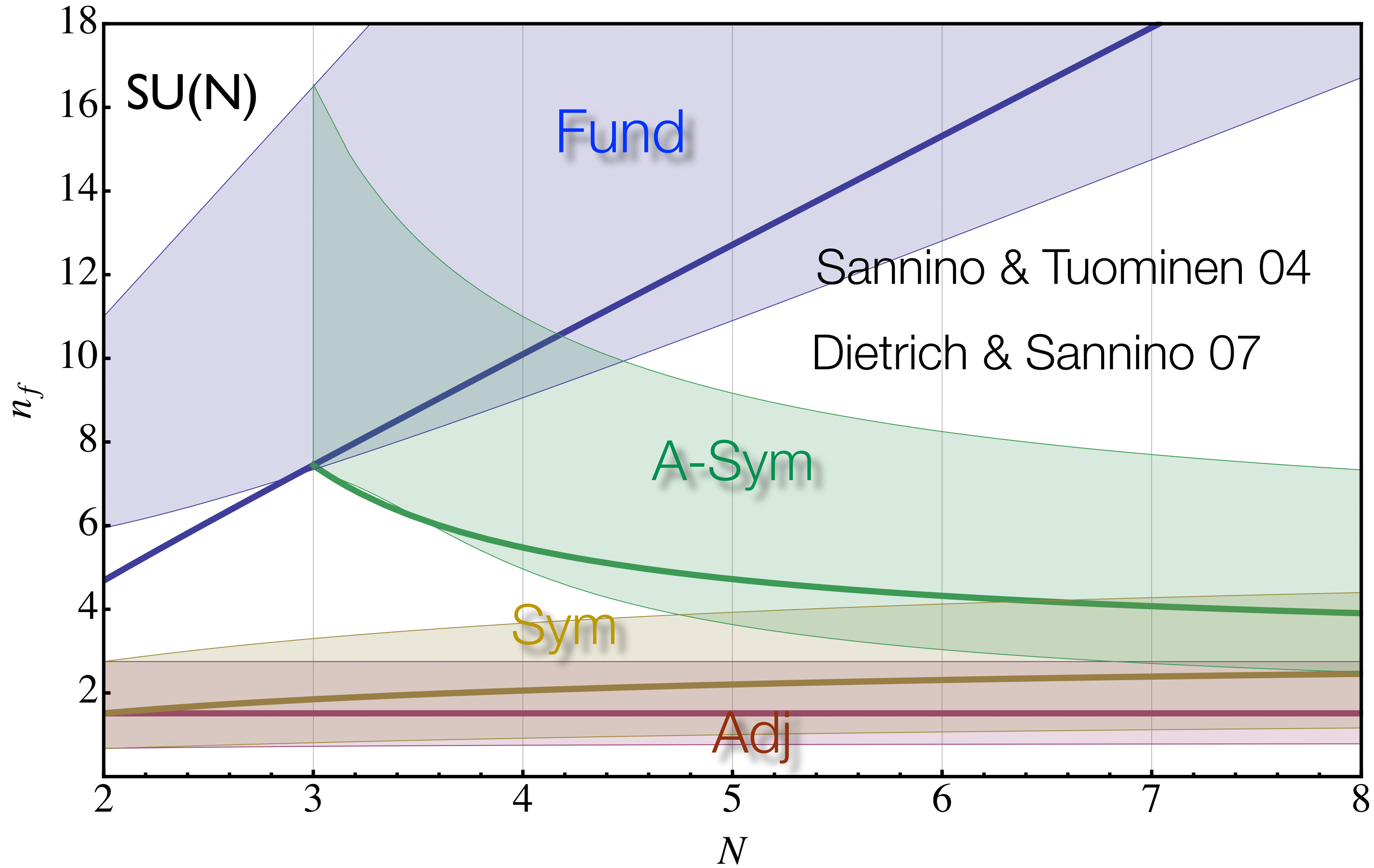
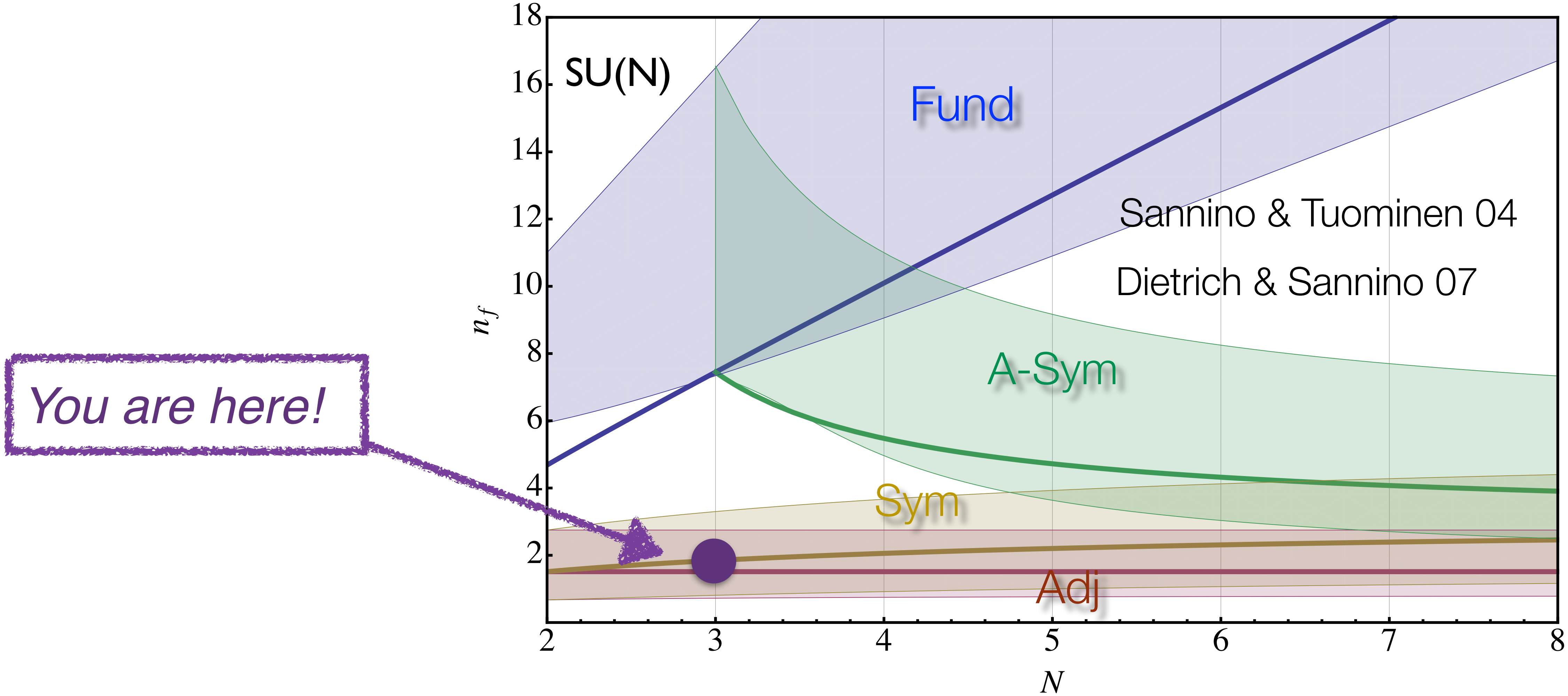


Future

- Fundamental theories
- Beyond perturbation theory
- (Out of) equilibrium thermodynamics
- Phase diagram of fundamental interactions



We pursue fundamental theories of Nature

Backup slides

a-theorem

$$\mathcal{L} = \mathcal{L}_{CFT} + g_i \mathcal{O}^i$$

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$$g_i = g_i(x)$$

Tool: Curved backgrounds

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Tool: Curved backgrounds

$$\gamma_{\mu\nu} \to e^{2\sigma(x)}\gamma_{\mu\nu}$$

Conformal transformation

$$g_i(\mu) \to g_i(e^{-\sigma(x)}\mu)$$

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Conformal transformation

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$$W = \log\left[\int \mathcal{D}\Phi e^{i\int d^4x\mathcal{L}}\right]$$

Variation of the generating functional

Weyl (anomaly) relations

$$\Delta_\sigma W \equiv \int d^4x\, \sigma(x) \left(2\gamma_{\mu\nu} \frac{\delta W}{\delta \gamma_{\mu\nu}} - \beta_i \frac{\delta W}{\delta g_i} \right) = \sigma \left(aE(\gamma) + \chi^{ij} \partial_\mu g_i \partial_\nu g_j G^{\mu\nu} \right) + \partial_\mu \sigma w^i \, \partial_\nu g_i G^{\mu\nu} + \ldots$$

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$$E(\gamma) = R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2$$ Euler density

$$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2}\gamma^{\mu\nu}R$$ Einstein tensor

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β_i Beta functions

$a, \quad \chi^{ij}, \quad \omega^i$ Functions of couplings

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Einstein tensor

$$\beta_i$$

Beta functions

$$a, \quad \chi^{ij}, \quad \omega^i$$

Functions of couplings

Weyl relations from abelian nature of Weyl anomaly

$$\Delta_\sigma\Delta_\tau W = \Delta_\tau\Delta_\sigma W$$

Perturbative a-theorem

$$\tilde{a} \equiv a - w^i \beta_i \qquad\qquad \frac{\partial \tilde{a}}{\partial g_i} = \left(-\chi^{ij} + \frac{\partial w^i}{\partial g_j} - \frac{\partial w^j}{\partial g_i}\right)\beta_j$$

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Osborn 89 & 91, Jack & Osborn 90

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Analyticity: a-tilde bigger in UV

Komargodski & Schwimmer 11, Komargodski 12

Gauge - Yukawa theories/Gradient Flow

Antipin, Gillioz, Mølgaard, Sannino 13

Jack and Poole 15

Gauge - Yukawa theories/Gradient Flow

omega is an exact form

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Relations among the modified β of different couplings

Precise prescription for expanding beta functions in perturb. theory

Antipin, Gillioz, Mølgaard, Sannino 13

Jack and Poole 15

The Compositeness Solution

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- EW scale = Composite scale

- UV non-interacting

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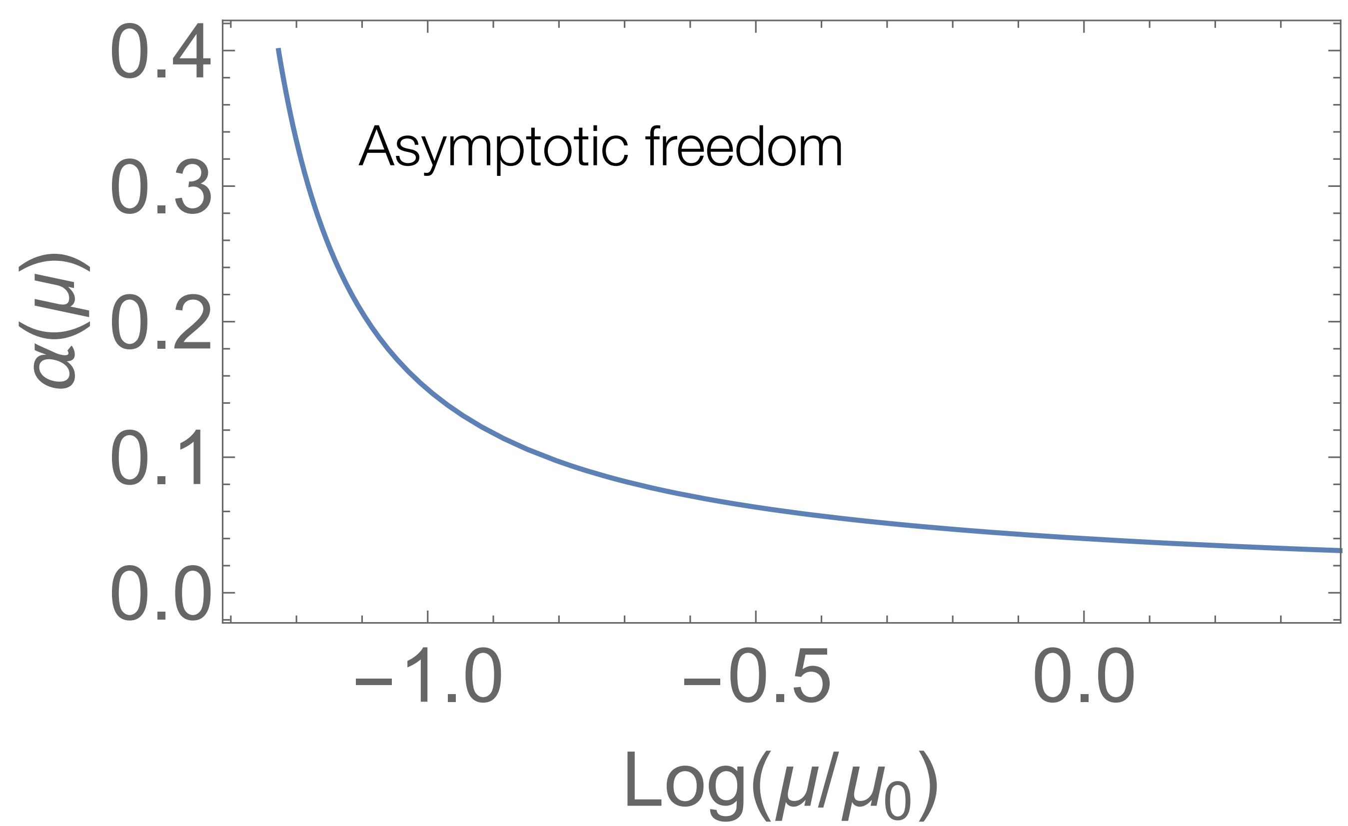
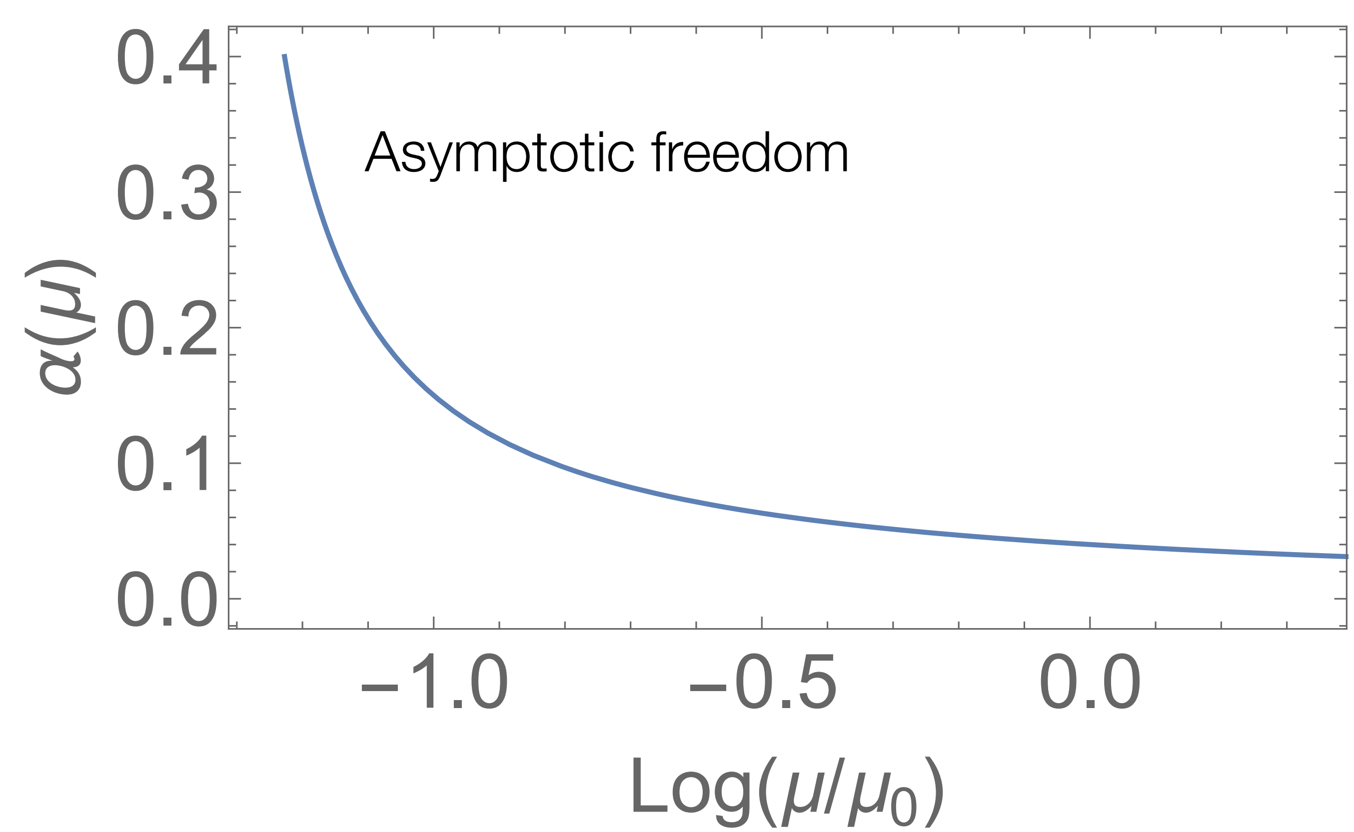


The Compositeness Solution

- EW scale = Composite scale
- UV non-interacting
- Not ruled out

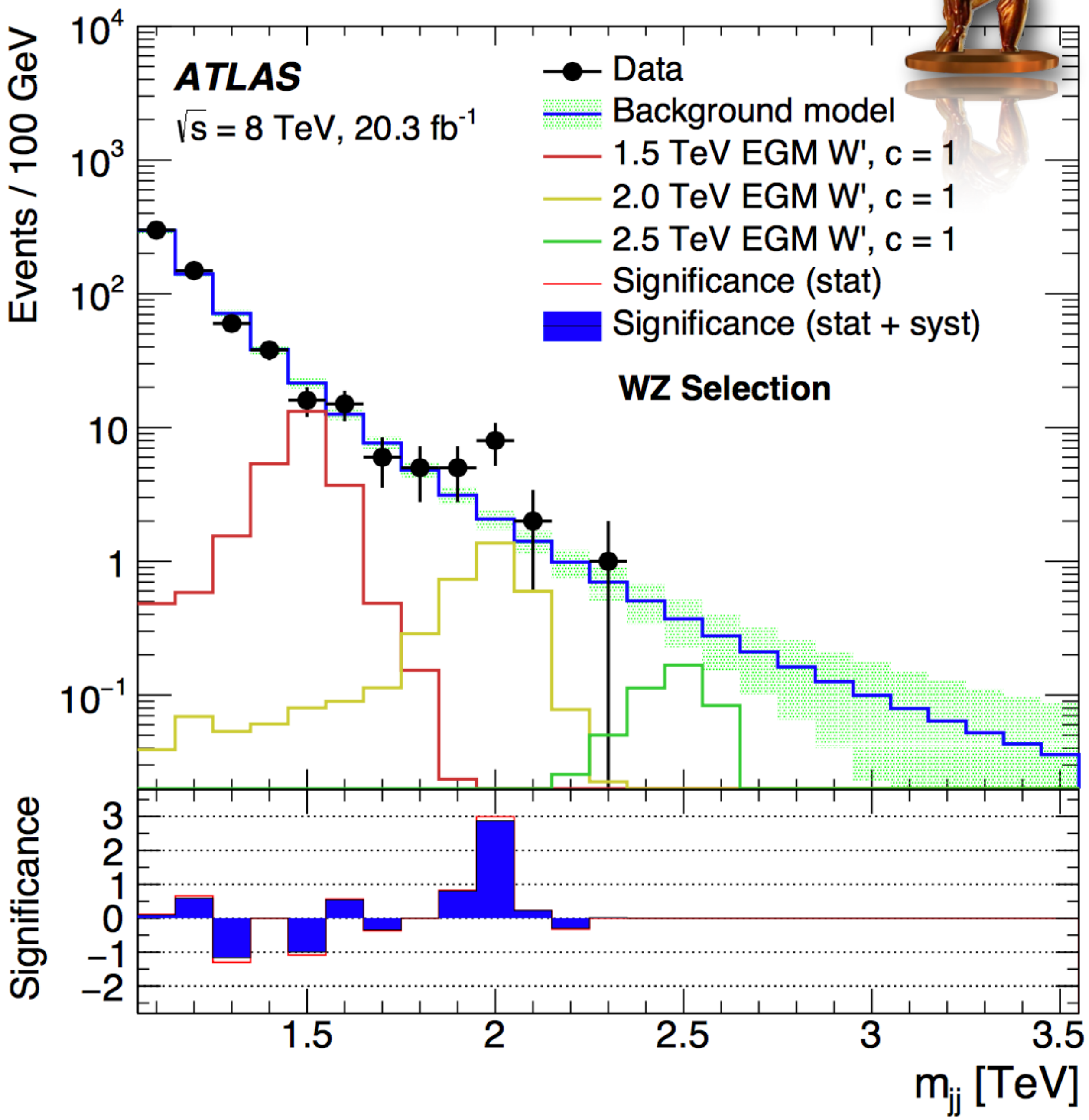
Arbey et al. 1502.04718



Diboson excesses

CERN-PH-EP-2015-115

3rd June/revised 15th June*



- WZ, WW and ZZ excesses

$$3.4,\ 2.6,\ 2.9\ \sigma$$

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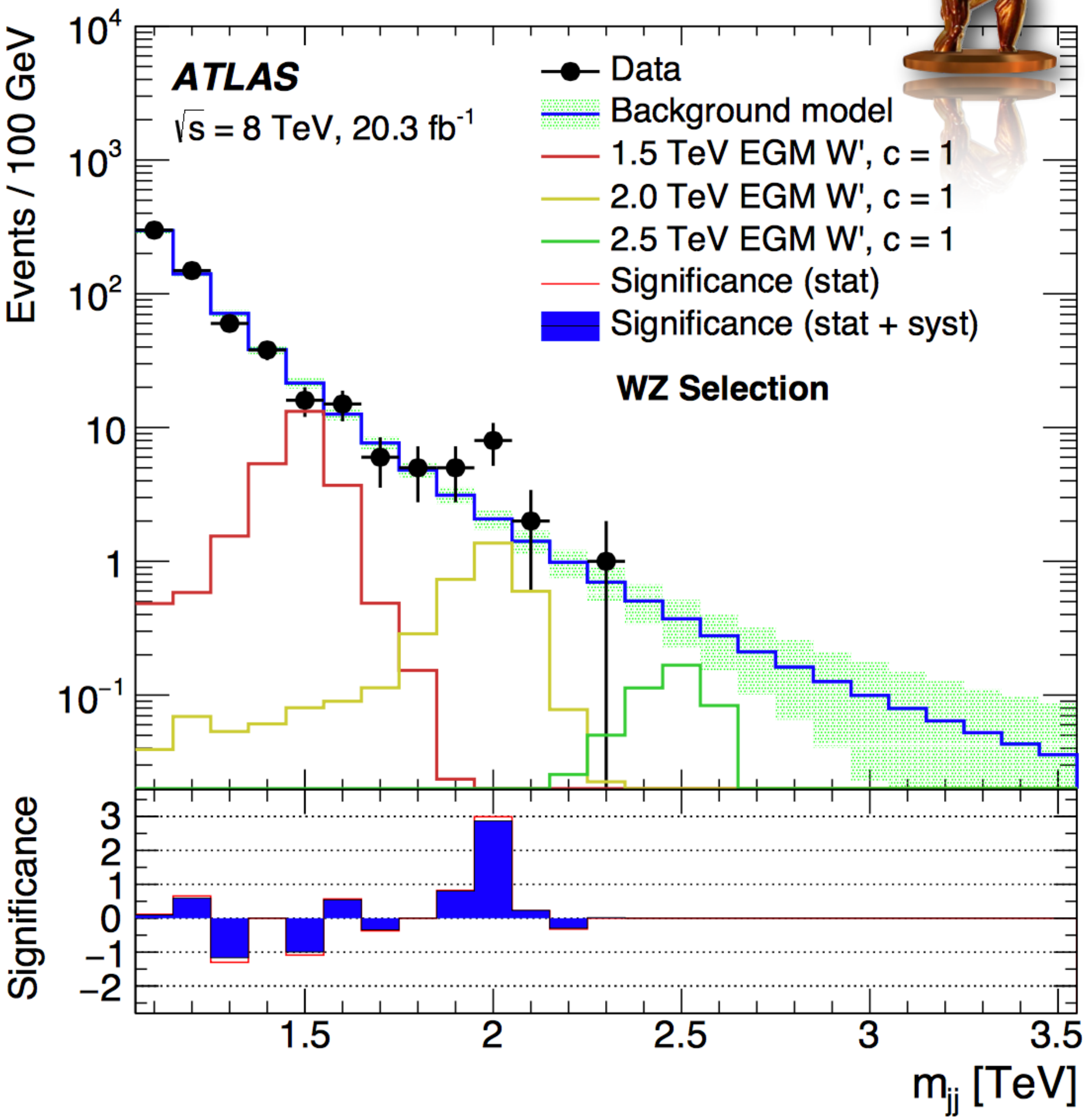
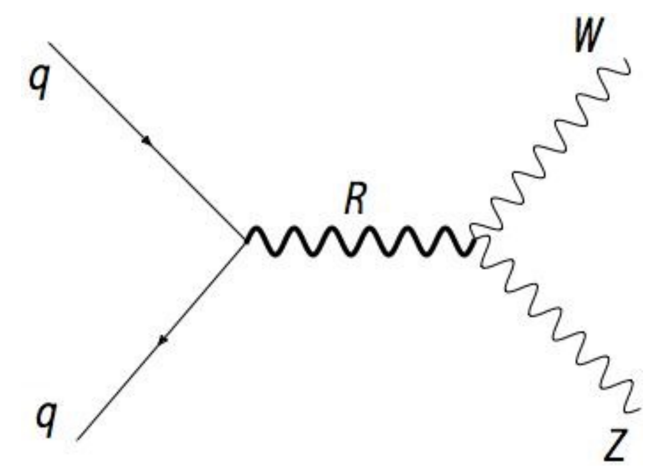


Frandsen, Franzosi, Sannino hep-ph/1506.04392



General effective Lagrangian analysis

$$\sigma(pp \to R \to WZ) \sim (10 - 30)\ fb$$

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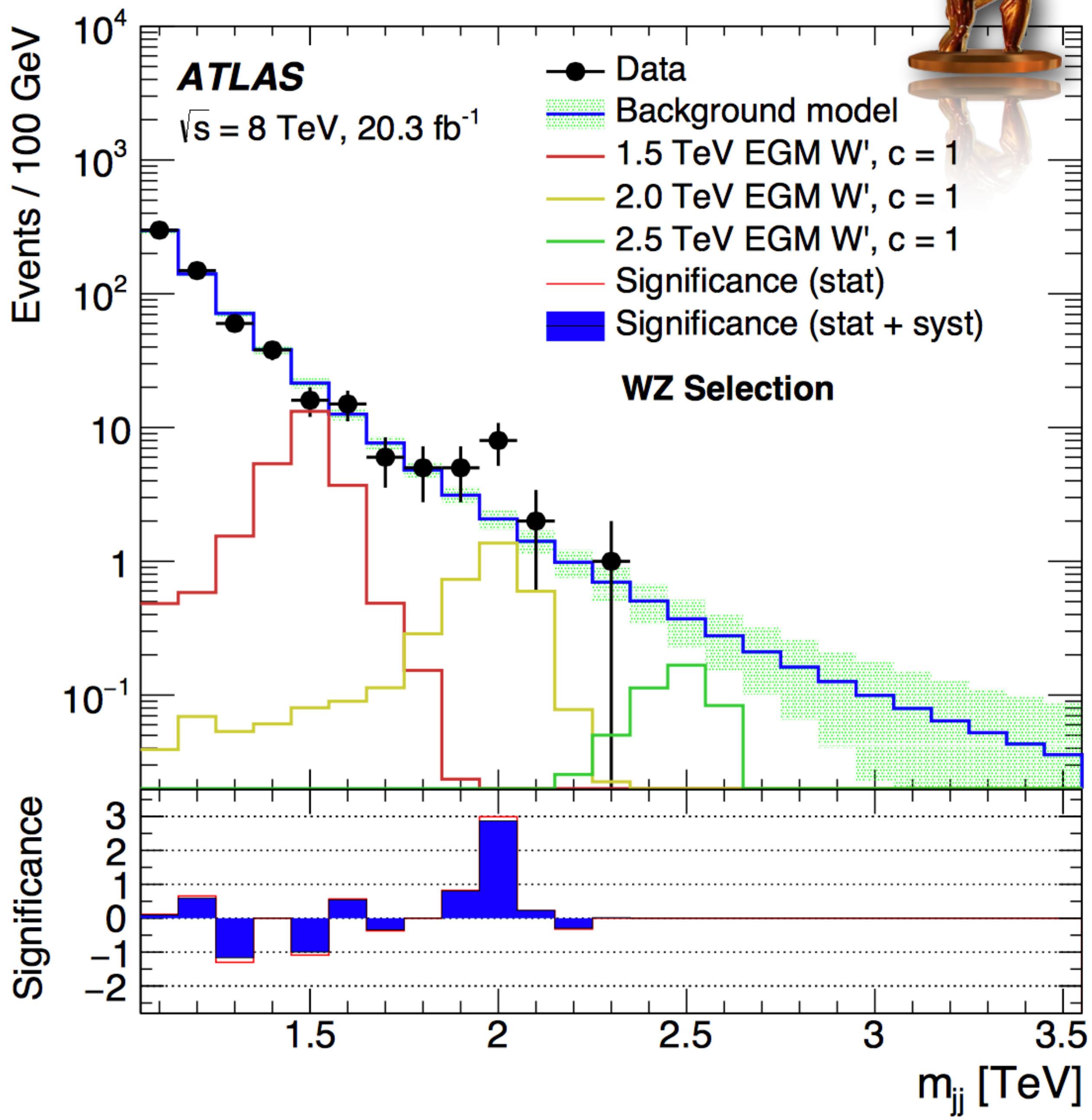

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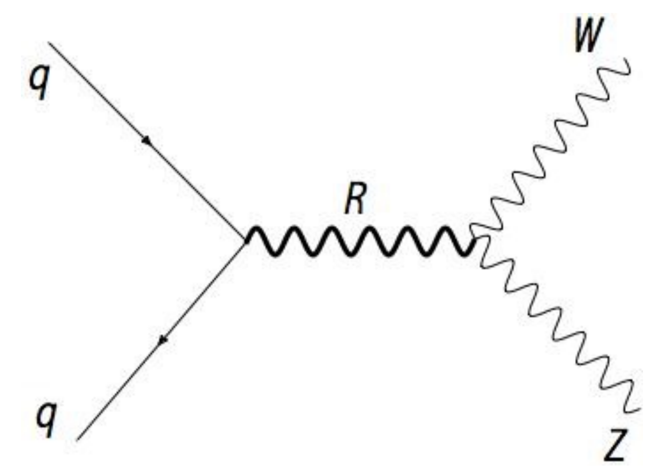

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✓ Spin-one mass range

✓ Vector decay constant

✓ Dileptons constraints

✓ Dijets contraints

Lattice predictions

Lattice predictions

Minimal (Walking) Technicolor

SU(3) symmetric $f_\pi \simeq 246\ \mathrm{GeV}$

Sannino, Tuominen 0405209

Dietrich, Sannino, Tuominen 0405209

$$m_{R_V} \simeq 1.75 \pm 0.1\ \mathrm{TeV}$$

Fodor, Holland, Kuti, Nogradi, Schroeder, Wong, 1209.0391

$$m_{R_A} \simeq 2.3 \pm 0.1\ \mathrm{TeV}$$

Lattice predictions

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(Ultra) Minimal Technicolor & Composite (Goldstone) Higgs

SU(2) fundamental

Ryttov, Sannino, 0809.0713

Cacciapaglia, Sannino, 1402.0233

$$m_{R_V} \simeq (2.5 \pm 0.5) \ \frac{\text{TeV}}{\sin\theta}$$

$$m_{R_A} \simeq (3.3 \pm 0.7) \ \frac{\text{TeV}}{\sin\theta}$$

Lewis, Pica, Sannino, 1109.3513

Knobs

Knobs

Gauge Group: SU, SO, SP, Exceptional

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Matter Representation

Knobs

Gauge Group: SU, SO, SP, Exceptional

Matter Representation

# of Flavors per Representation

Knobs

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Matter Representation

# of Flavors per Representation

4 Fermi interactions

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$$\bullet\!\longrightarrow \quad N_f$$

Knobs

Gauge Group: SU, SO, SP, Exceptional

Matter Representation

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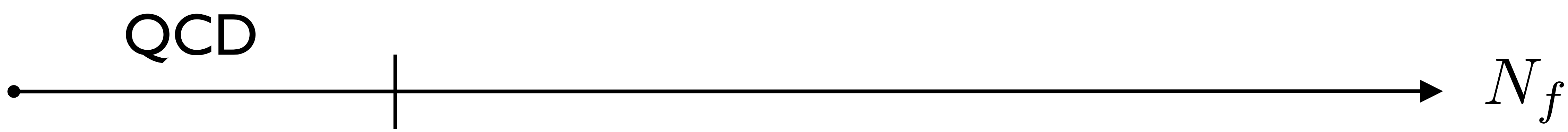
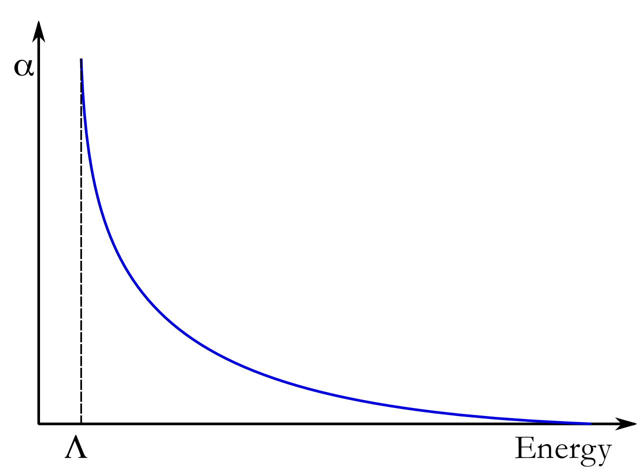
4 Fermi interactions





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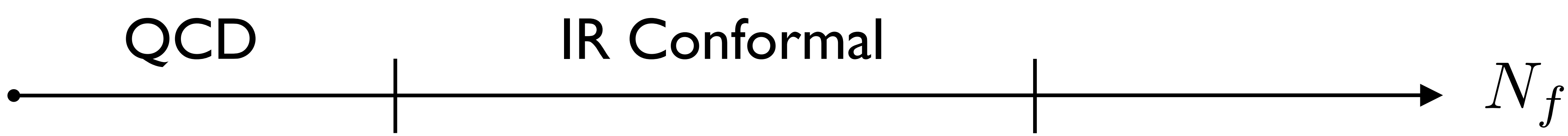

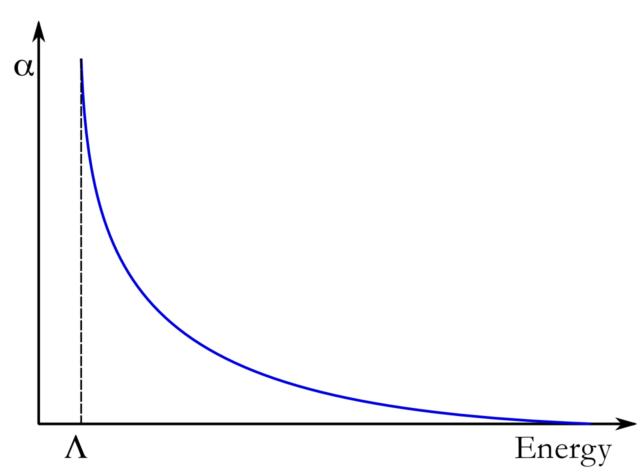

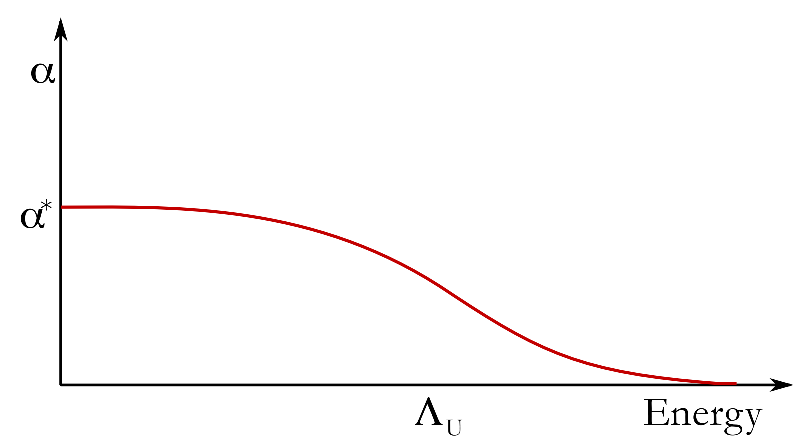

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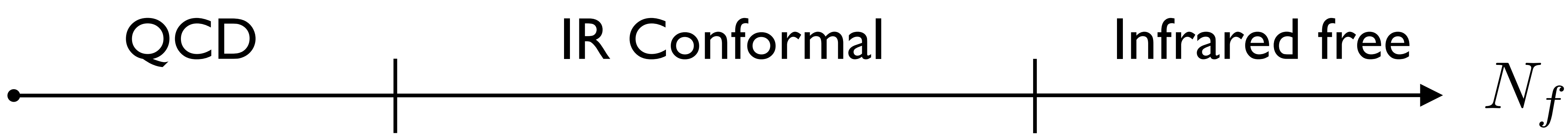

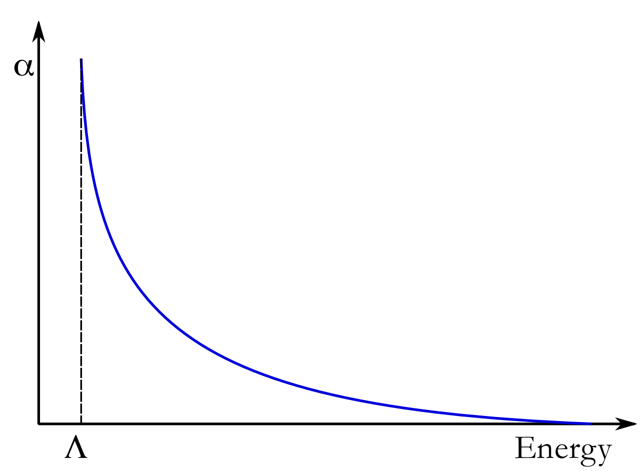

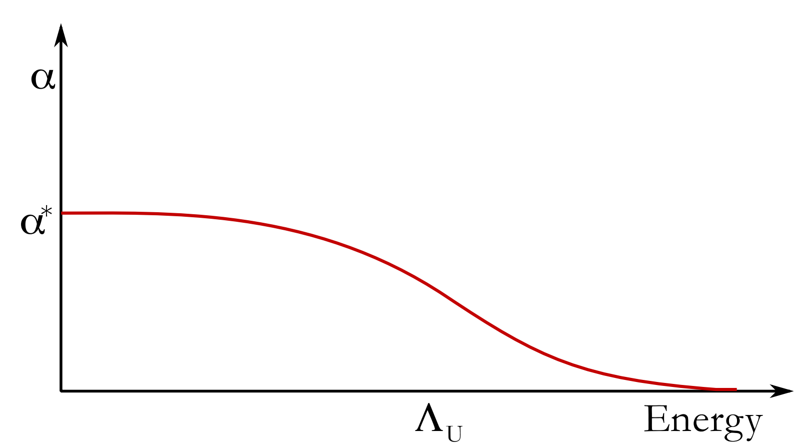

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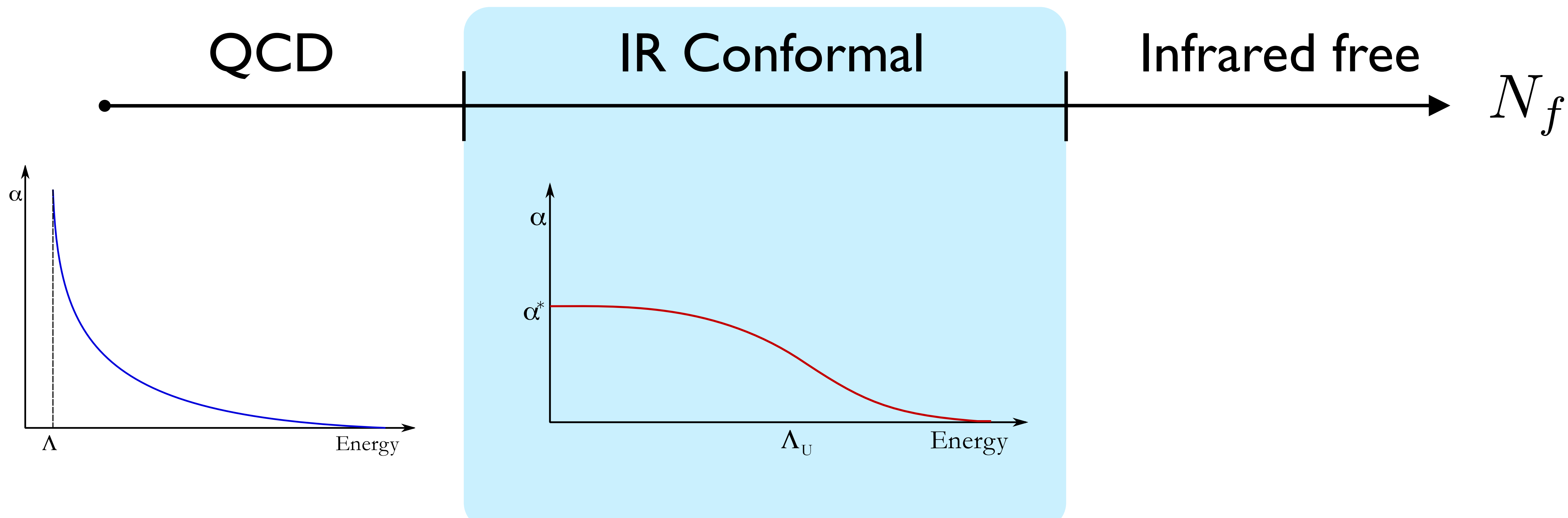

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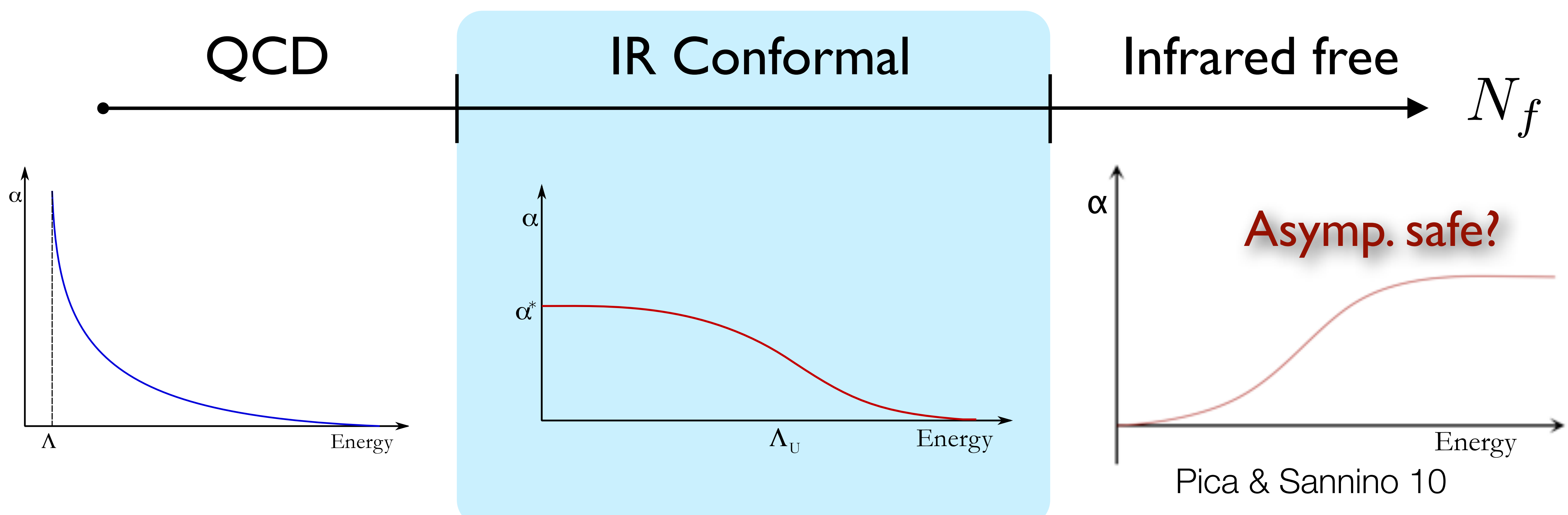
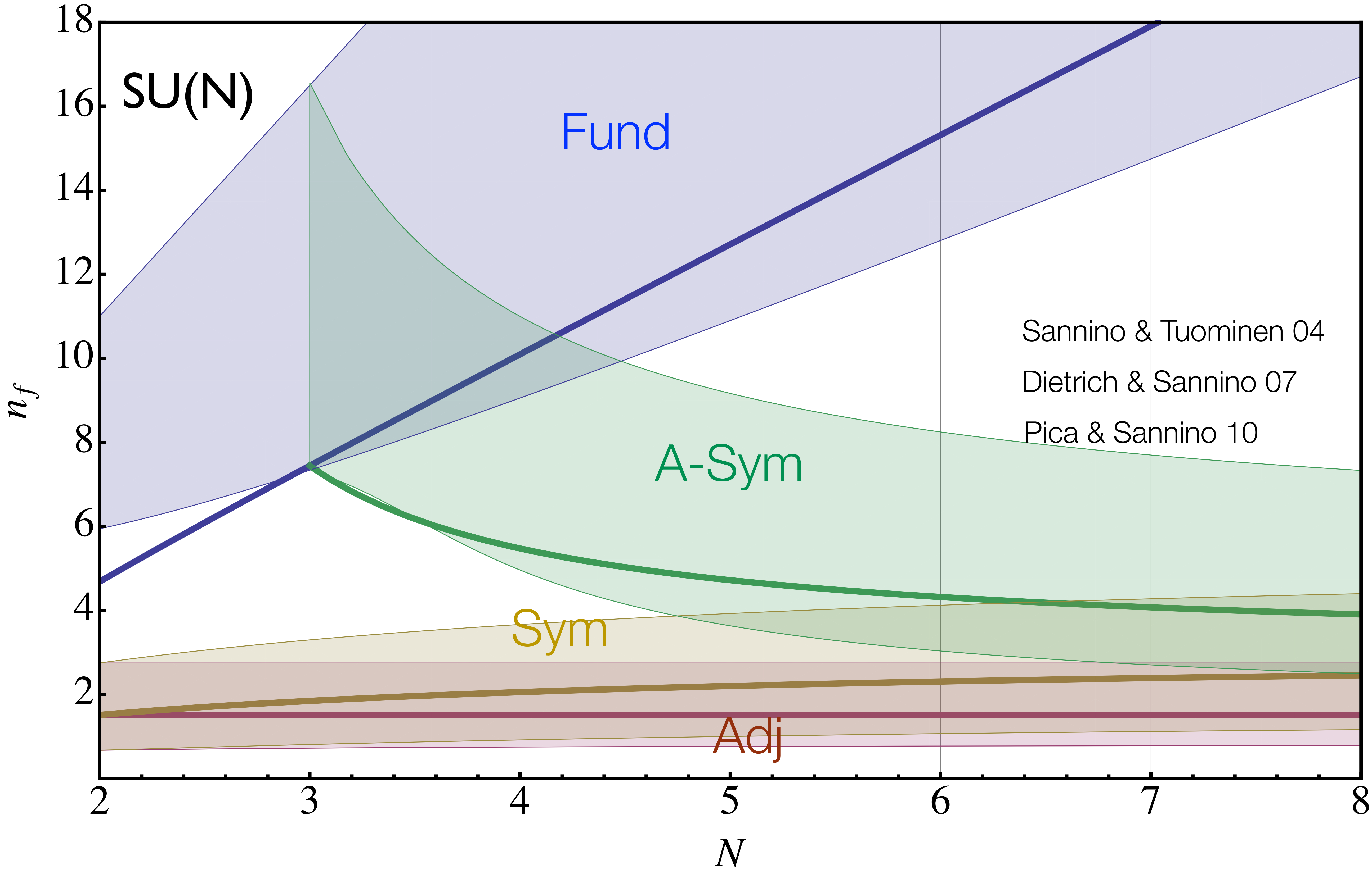
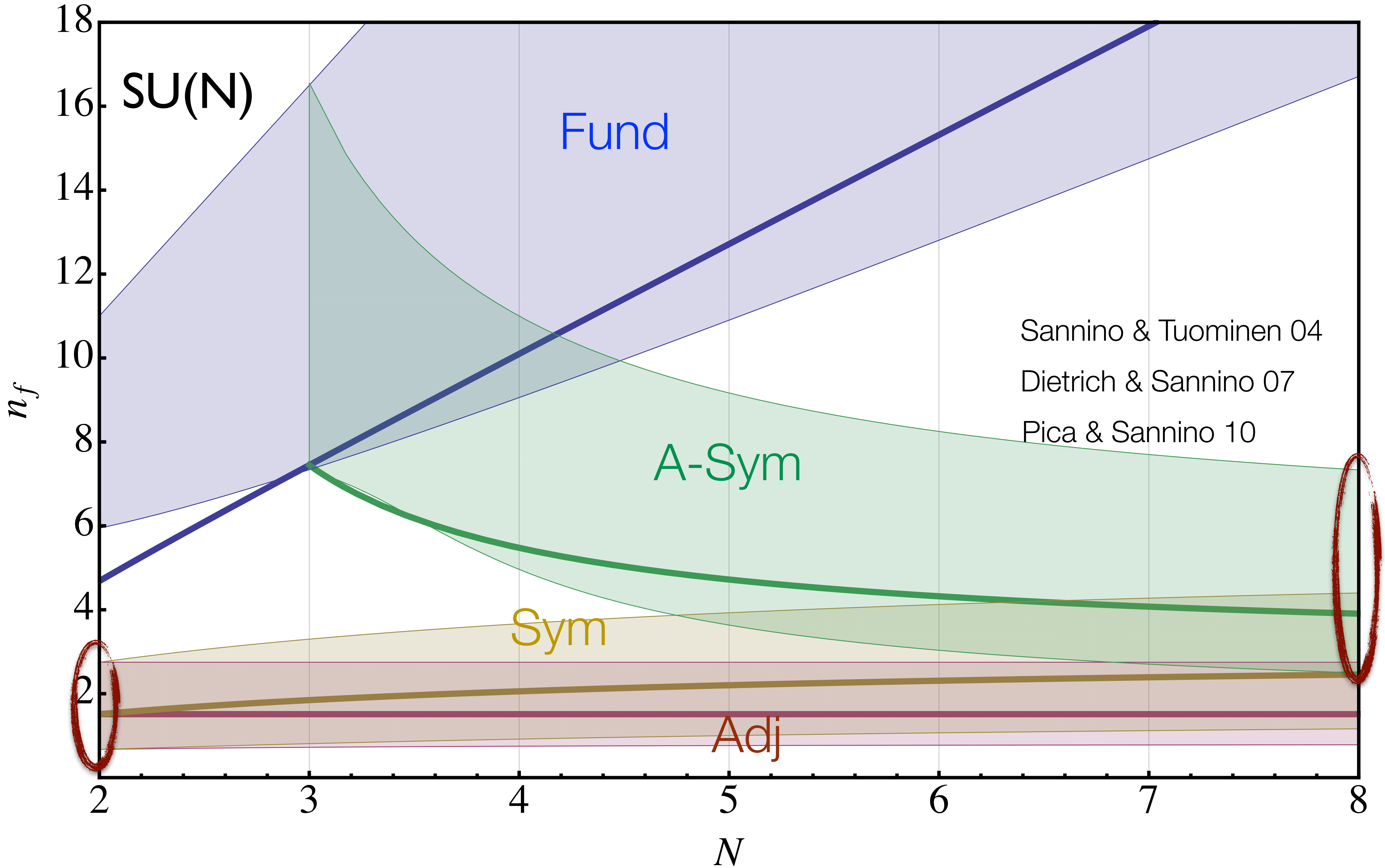


Pica & Sannino 10

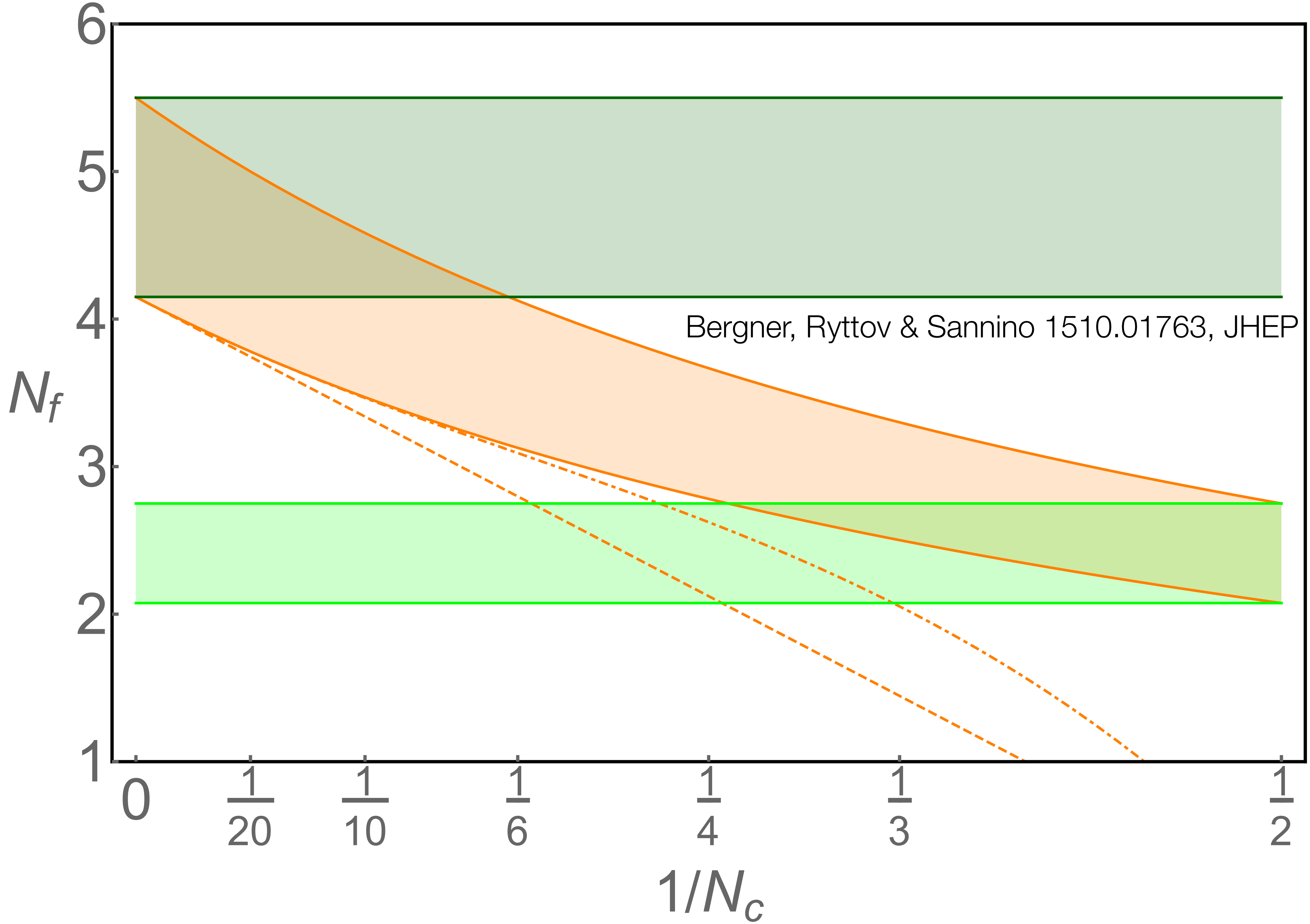
SU(N) Phase Diagram



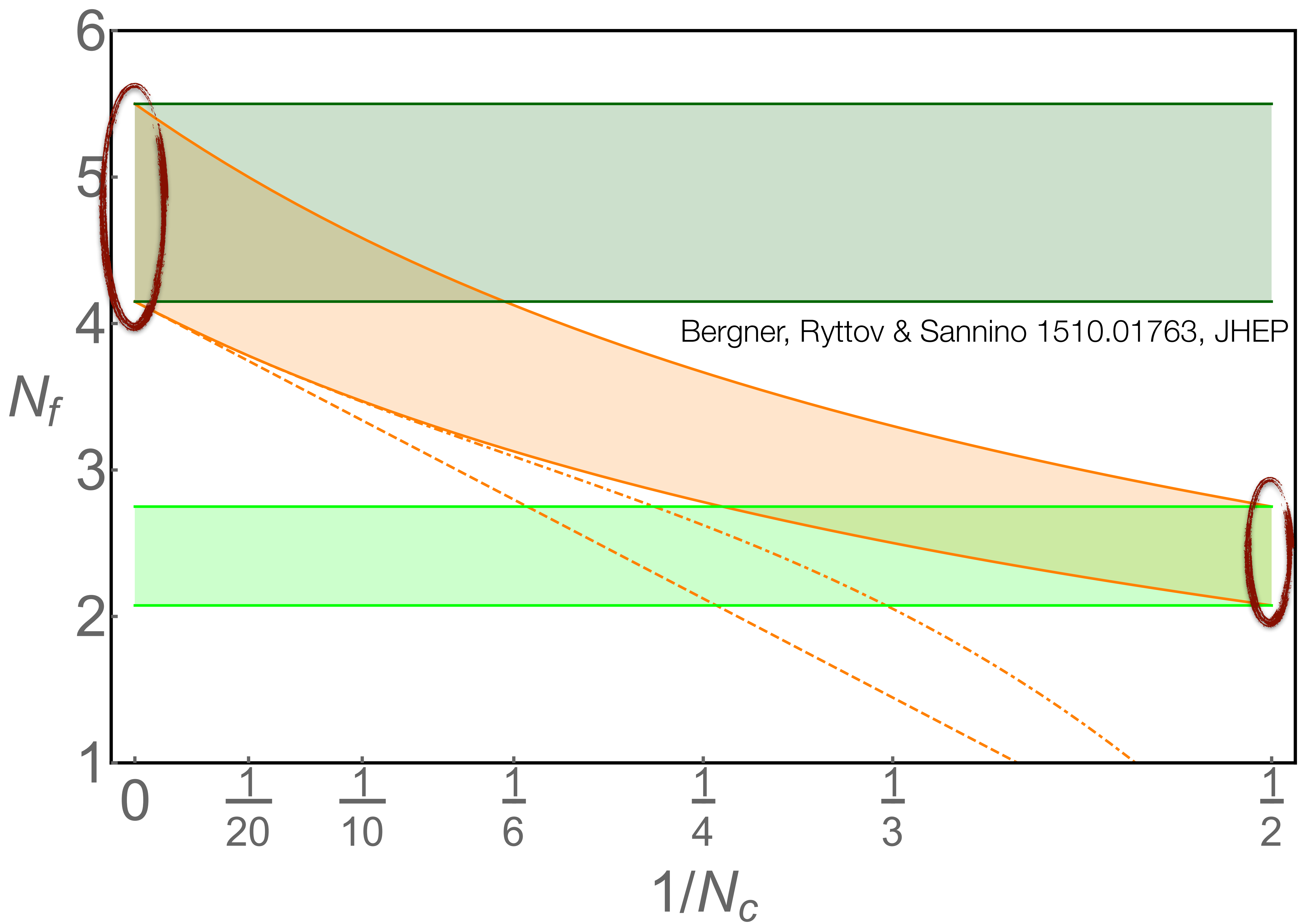
SU(N) Phase Diagram



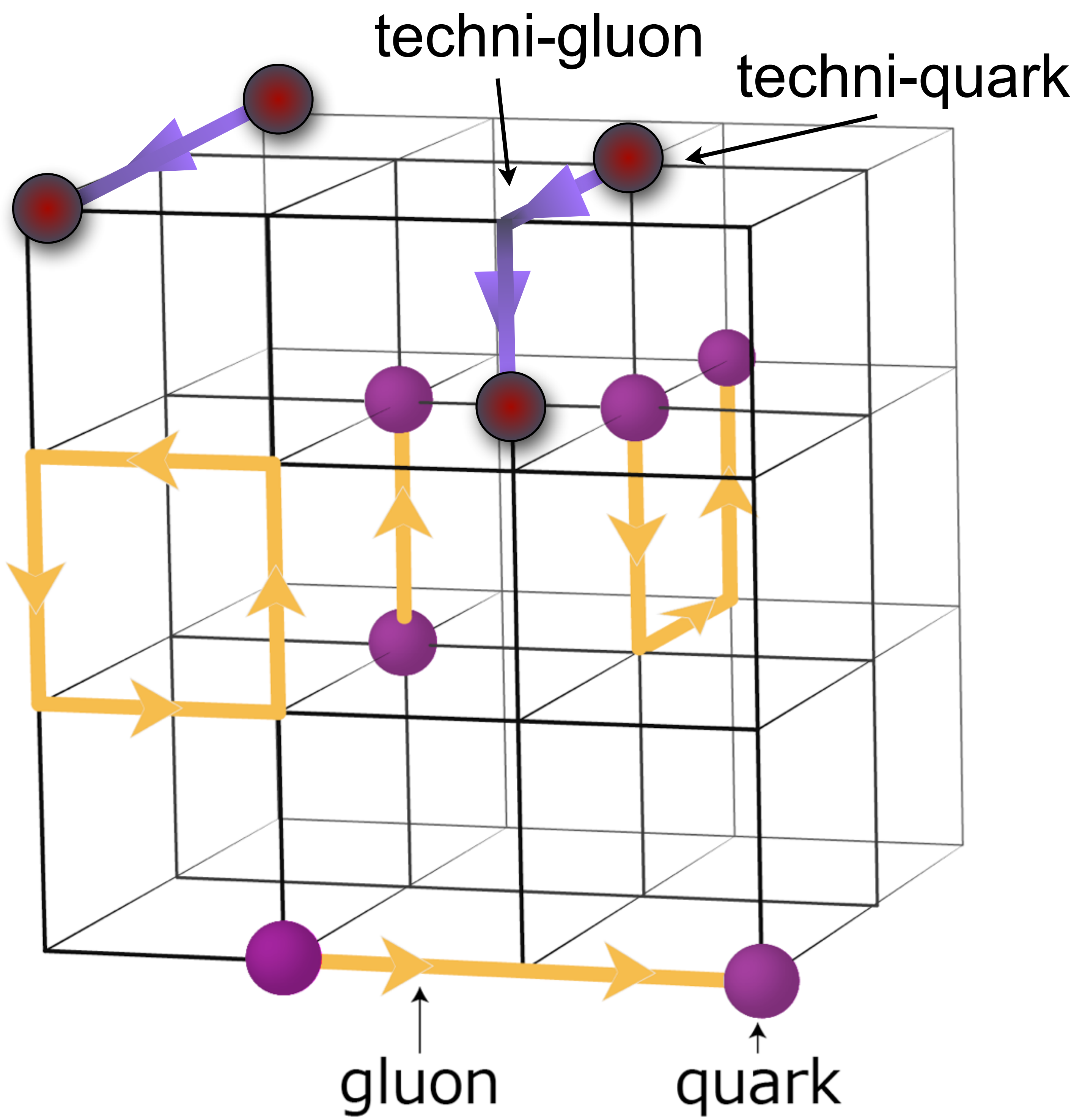
From 2 to infinite N & exact results



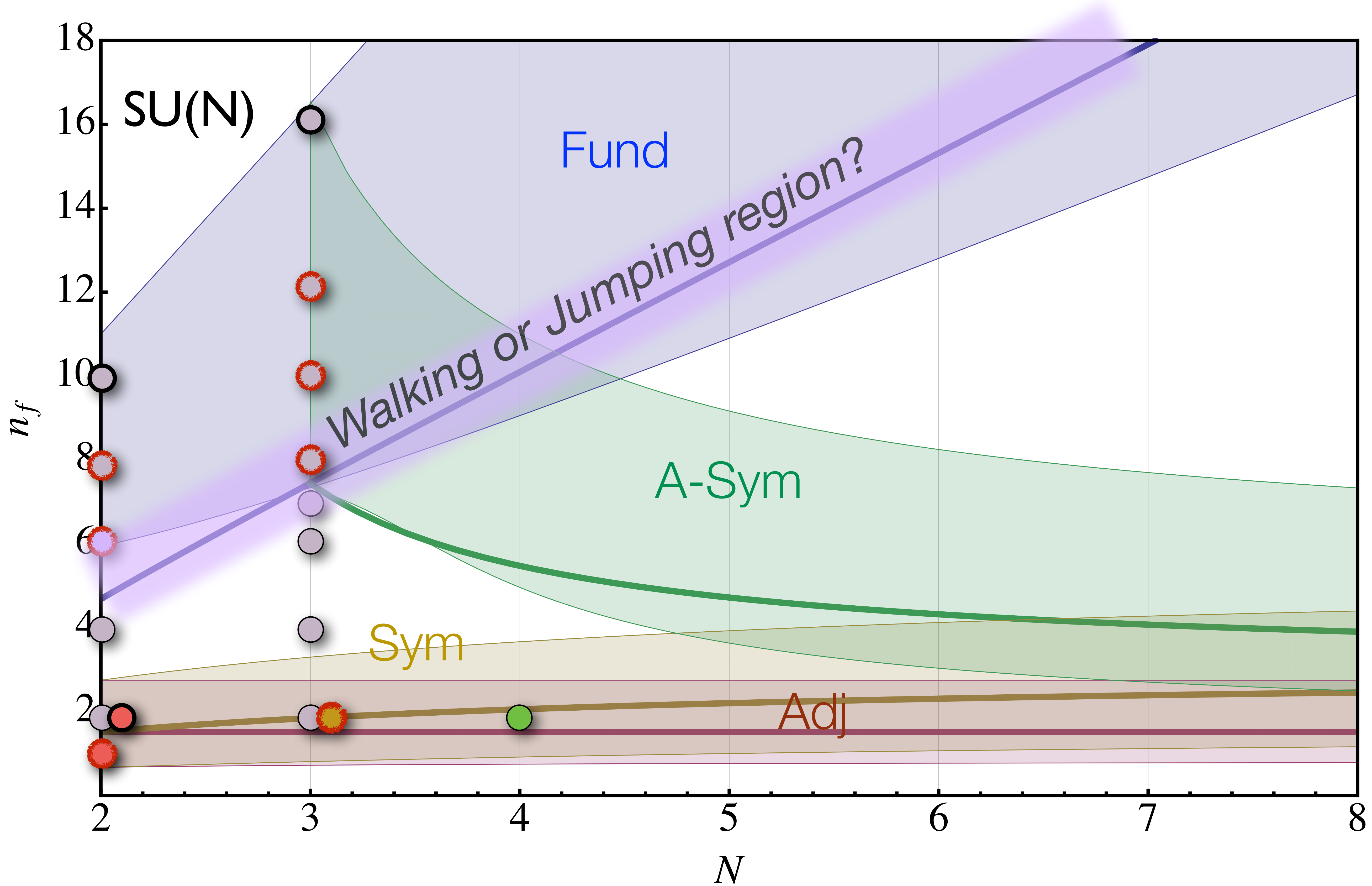
From 2 to infinite N & exact results



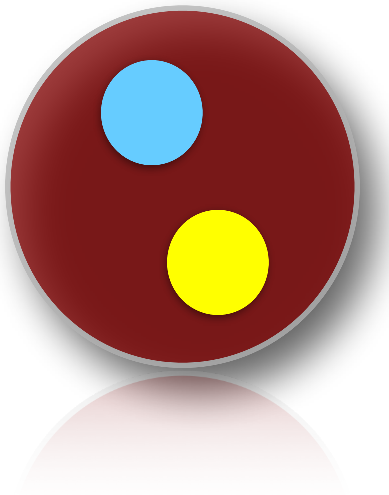
Composite Dynamics on the Lattice



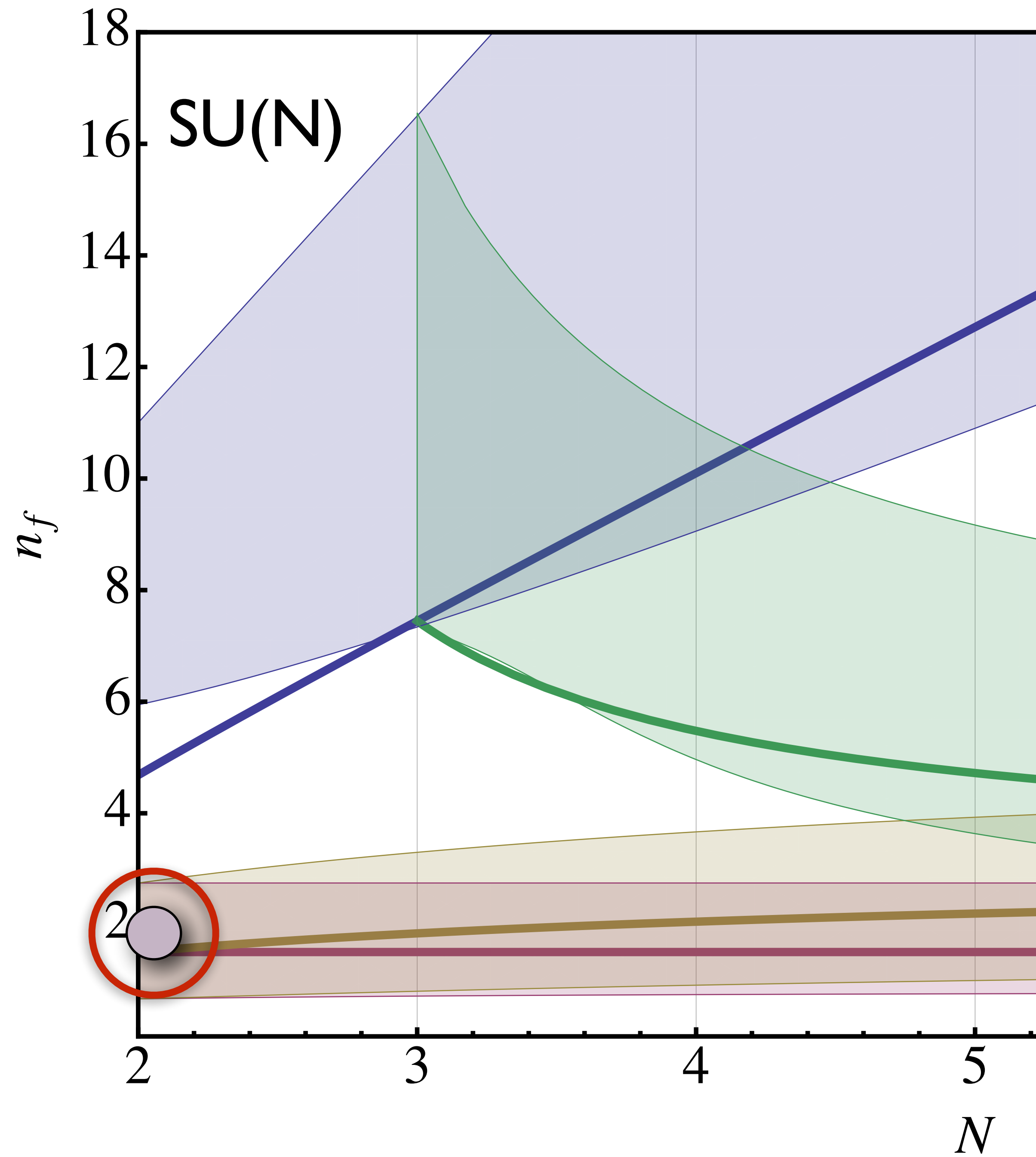
Lattice SU(N) Phase Diagram



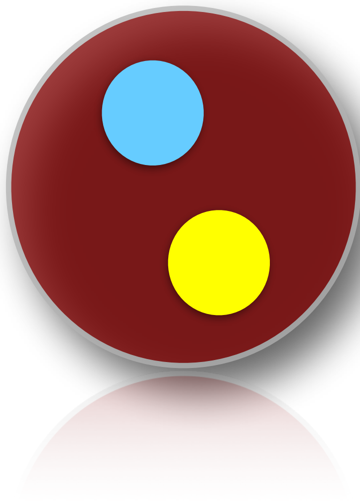
SU(2) = Sp(2) with 2 Flavors



Minimal Fund. Gauge Theory



SU(2) = Sp(2) with 2 Flavors



Minimal Fund. Gauge Theory

- Unified TC & Comp. Goldstone Higgs
- TC Meson DM
- Stealth DM
- Dark Nuclei
- SIMPlest Miracle
- …