Asymptotically Safe Standard Model

Francesco Sannino

Plan

- Meaning of fundamental
- Asymp. safe theories in 4D
- Large Nf asymptotic safety
- Asymptotically safe standard model
- Exact nonperturbative results for N=1 supersymmetric safety
- Super GUTs with R-parity are trivial = unphysical
- SUSY-like radiative symmetry breaking in UV safe theories*
- New paths in (astro)particle physics

Standard Model

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Fields:

Gauge fields + fermions + scalars

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Interactions:

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

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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

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

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

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Scalar selfinteractions

4D: standard model, dark matter, …

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4D: standard model, dark matter, …

Lower D: condensed matter, phase transitions, graphene

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4D plus: extra dimensions, string theory, …

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Scalar selfinteractions

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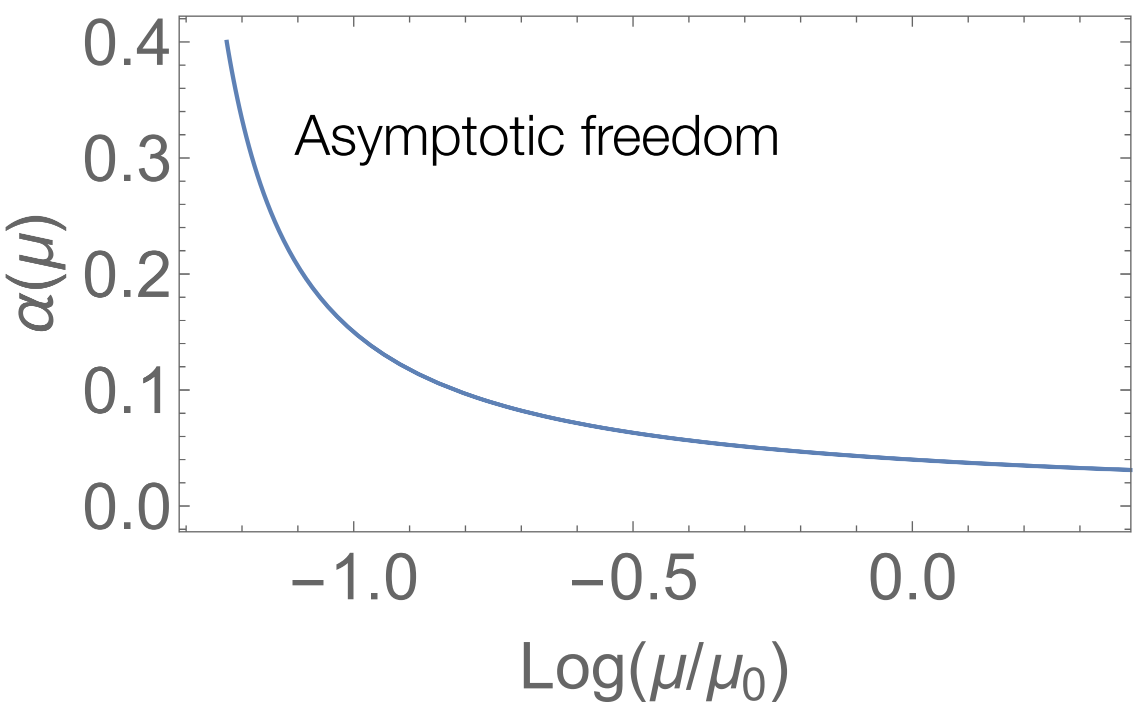
Universal description of physical phenomena

Fundamental theory

Wilson: A fundamental theory has an UV fixed point

Trivial fixed point

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



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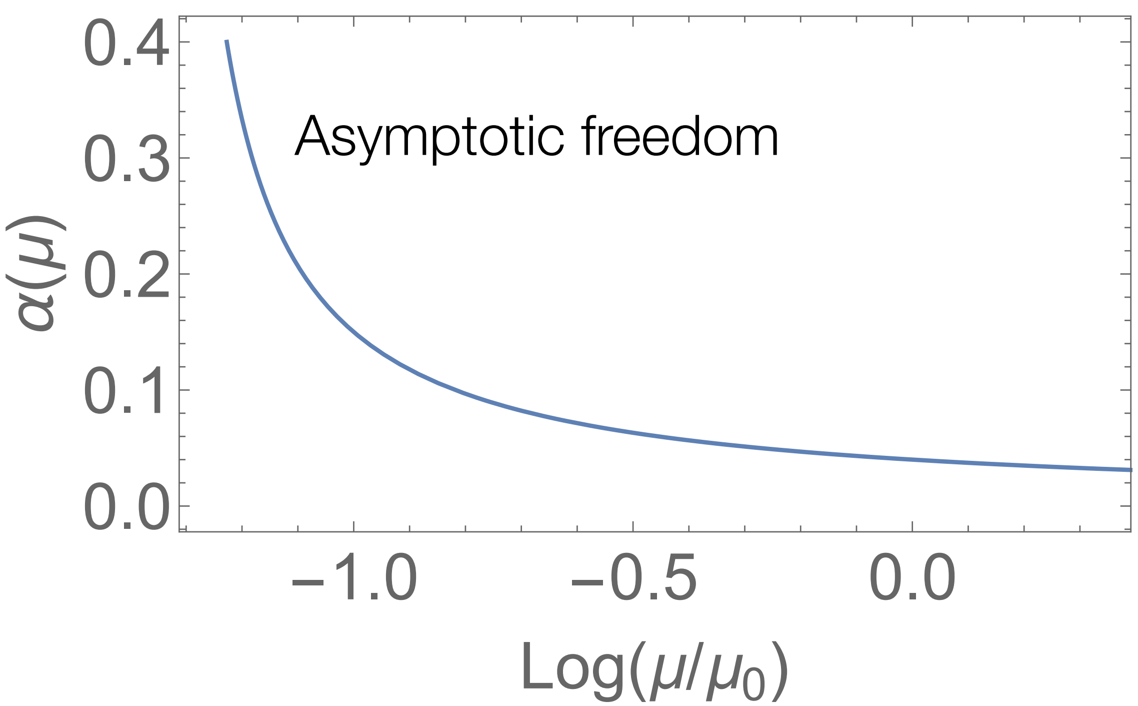

Interacting fixed point

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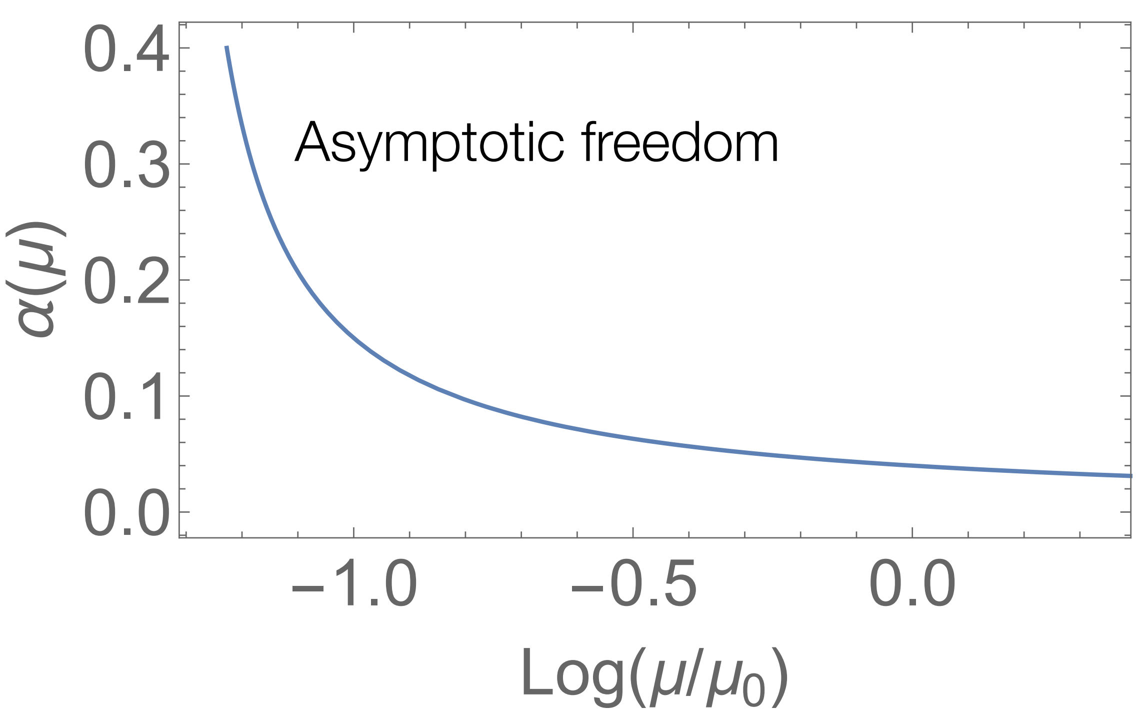

Interacting fixed point

- Integrating in the UV
- Power law

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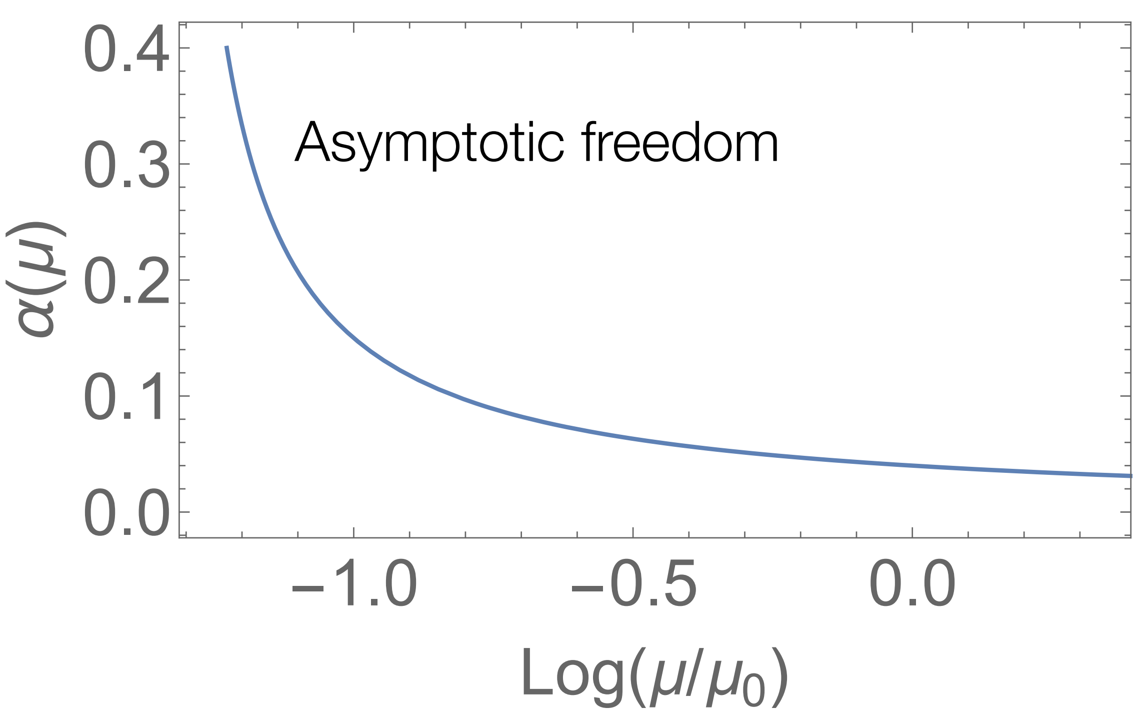

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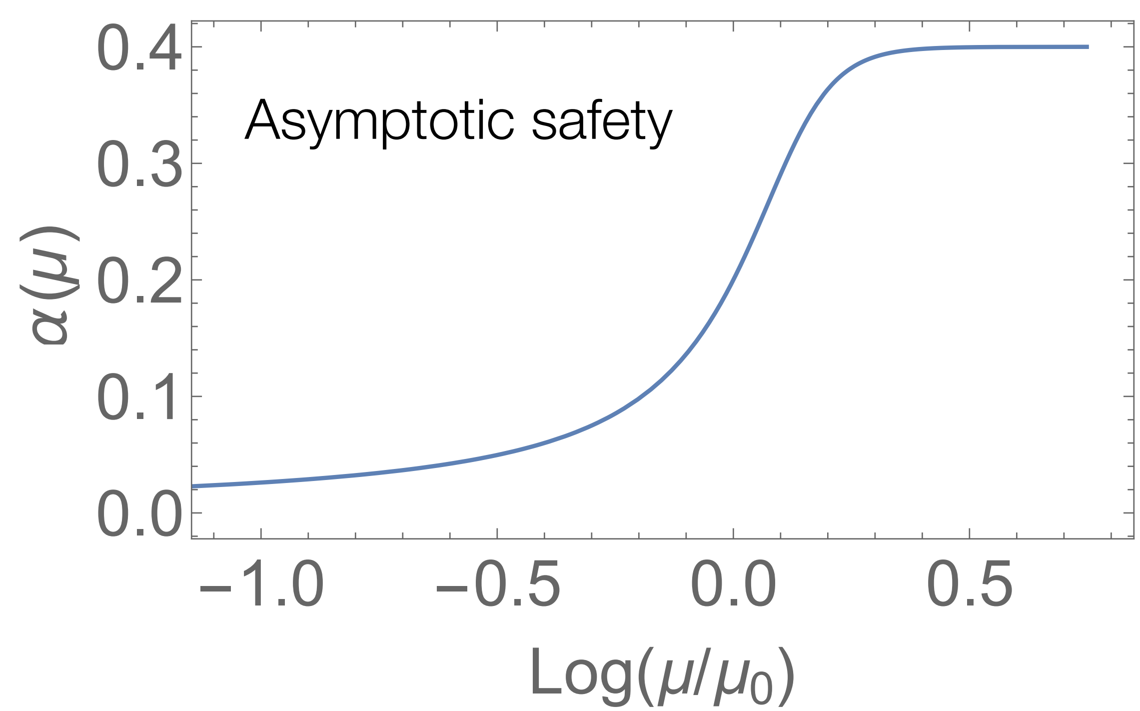
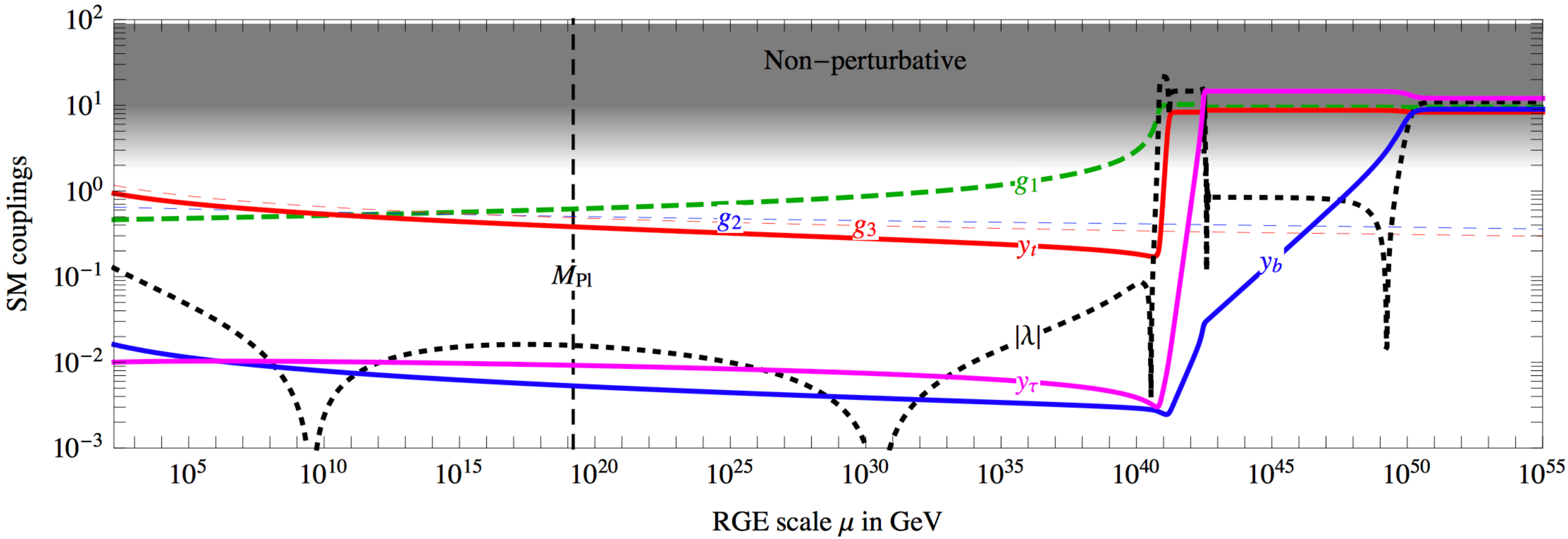


Is the Standard Model safe?



SM RGE at 3 loops in $g_{1,2,3}$, y_t, λ and at 2 loops in $y_{b,\tau}$

Pelaggi, Sannino, Strumia, Vigiani 1701.01453

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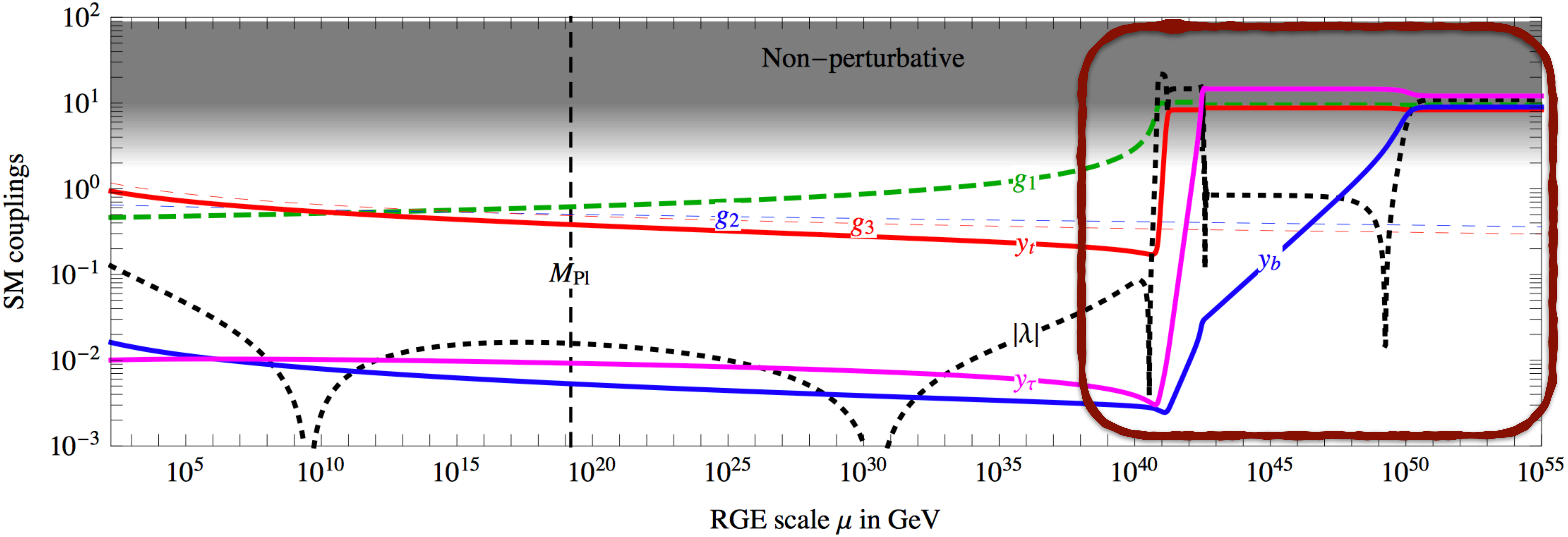

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Do theory like these exist?

Precise and/or nonperturbative exact results for UV interacting fixed points

Exact 4D Interacting UV Fixed Point

Antipin, Gillioz, Mølgaard, Sannino 1303.1525 PRD

Litim and Sannino, 1406.2337, JHEP

Litim, Mojaza, Sannino, 1501.03061, JHEP

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

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

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

Litim and Sannino, 1406.2337, JHEP

Litim, Mojaza, Sannino, 1501.03061, JHEP

- 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

$$\frac{N_F}{N_C} \in \Re^+$$

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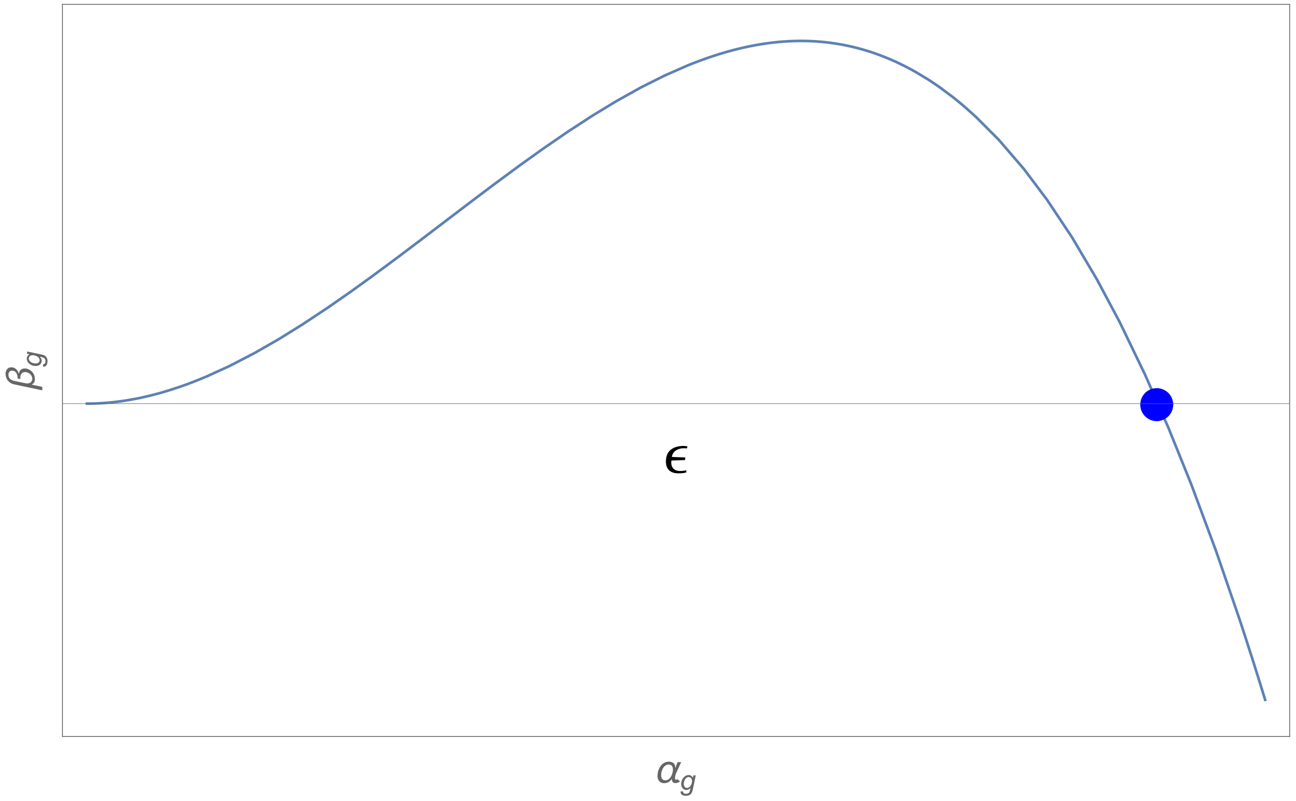

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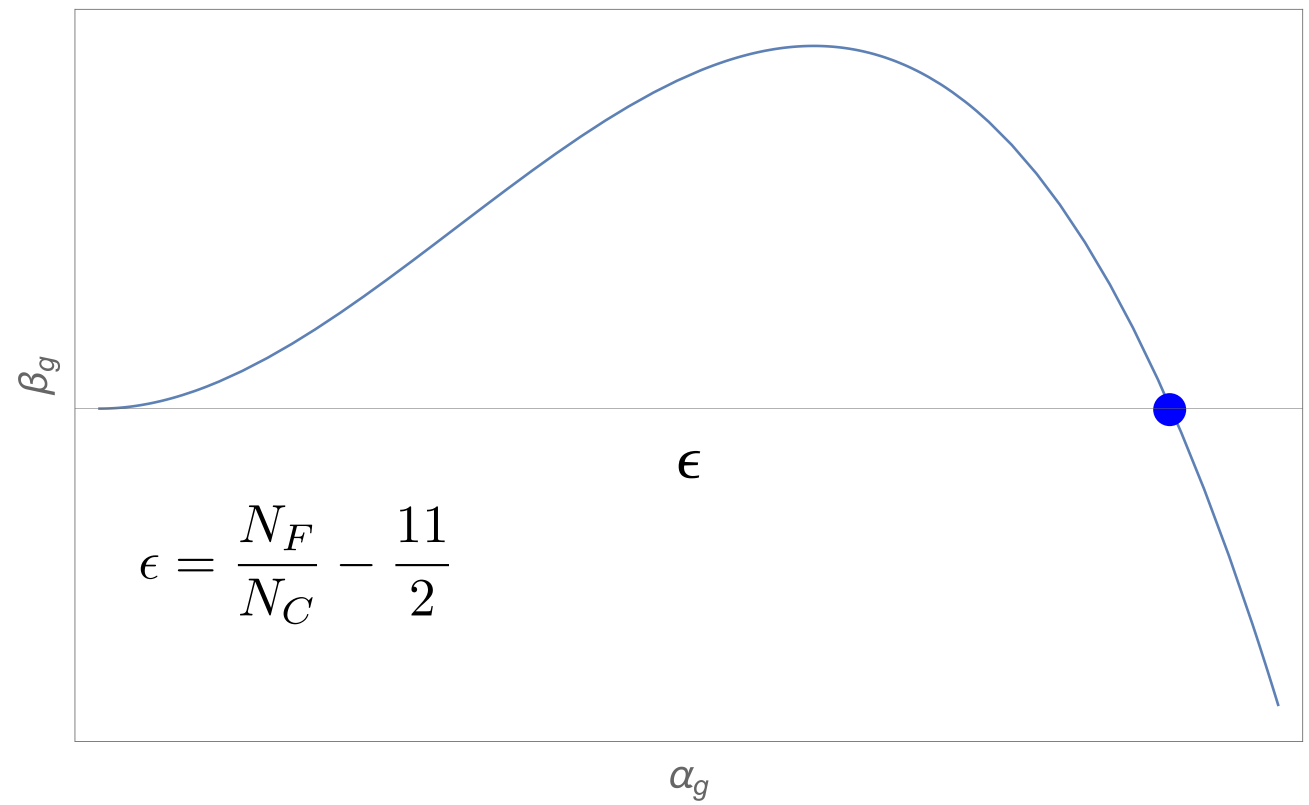

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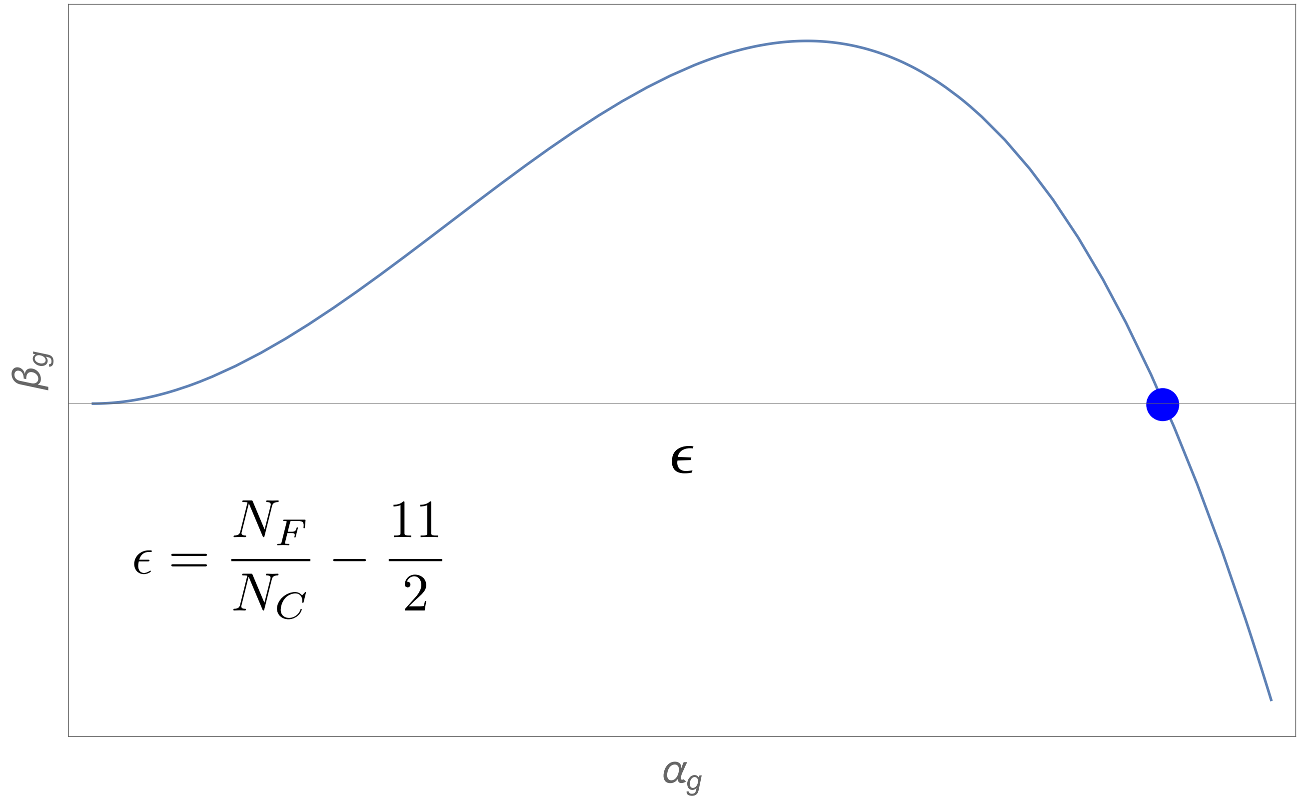


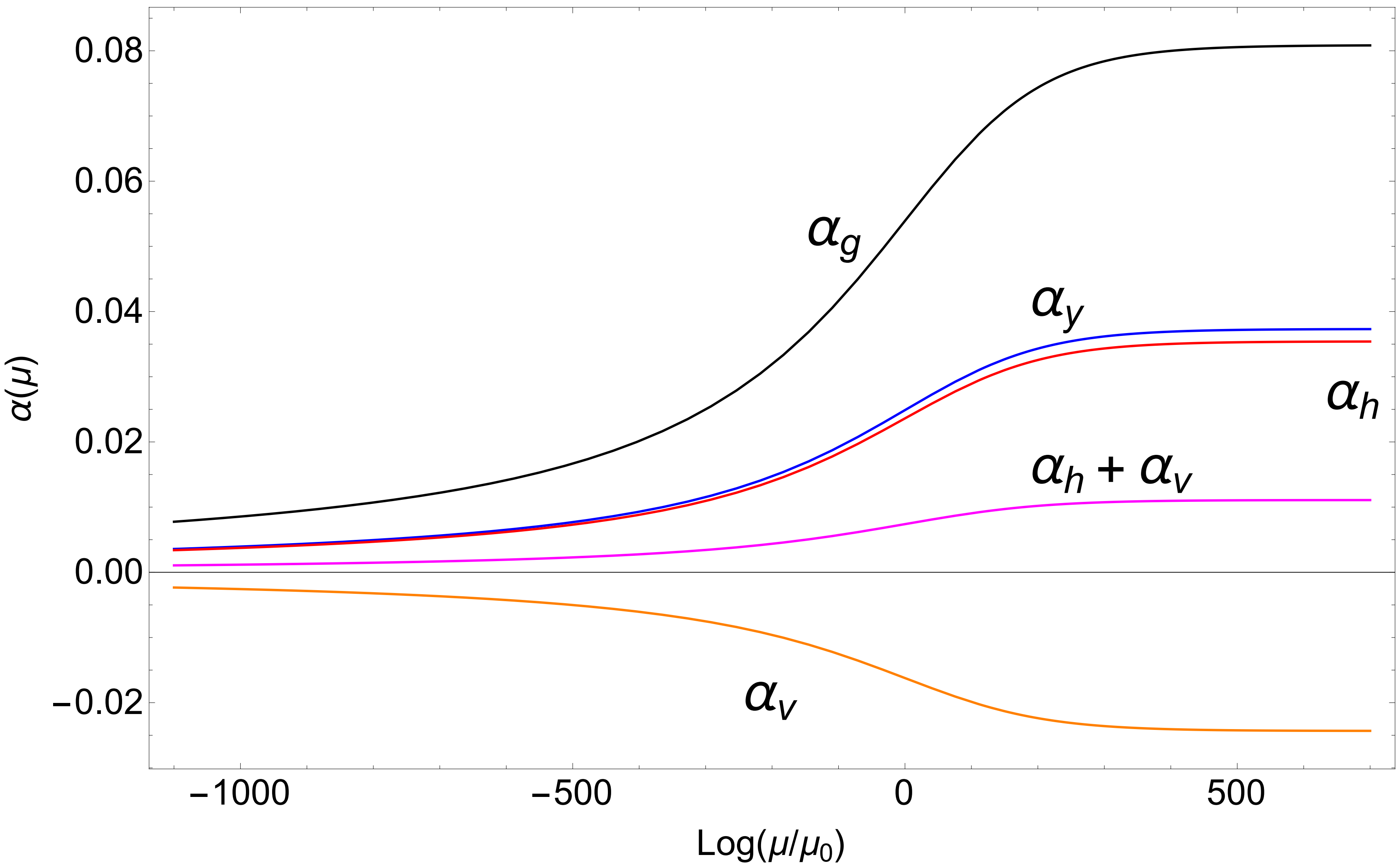
Impossible in Gauge Theories with Fermions alone

Caswell, PRL 1974

Complete asymptotic safety

Litim and Sannino, 1406.2337, JHEP

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



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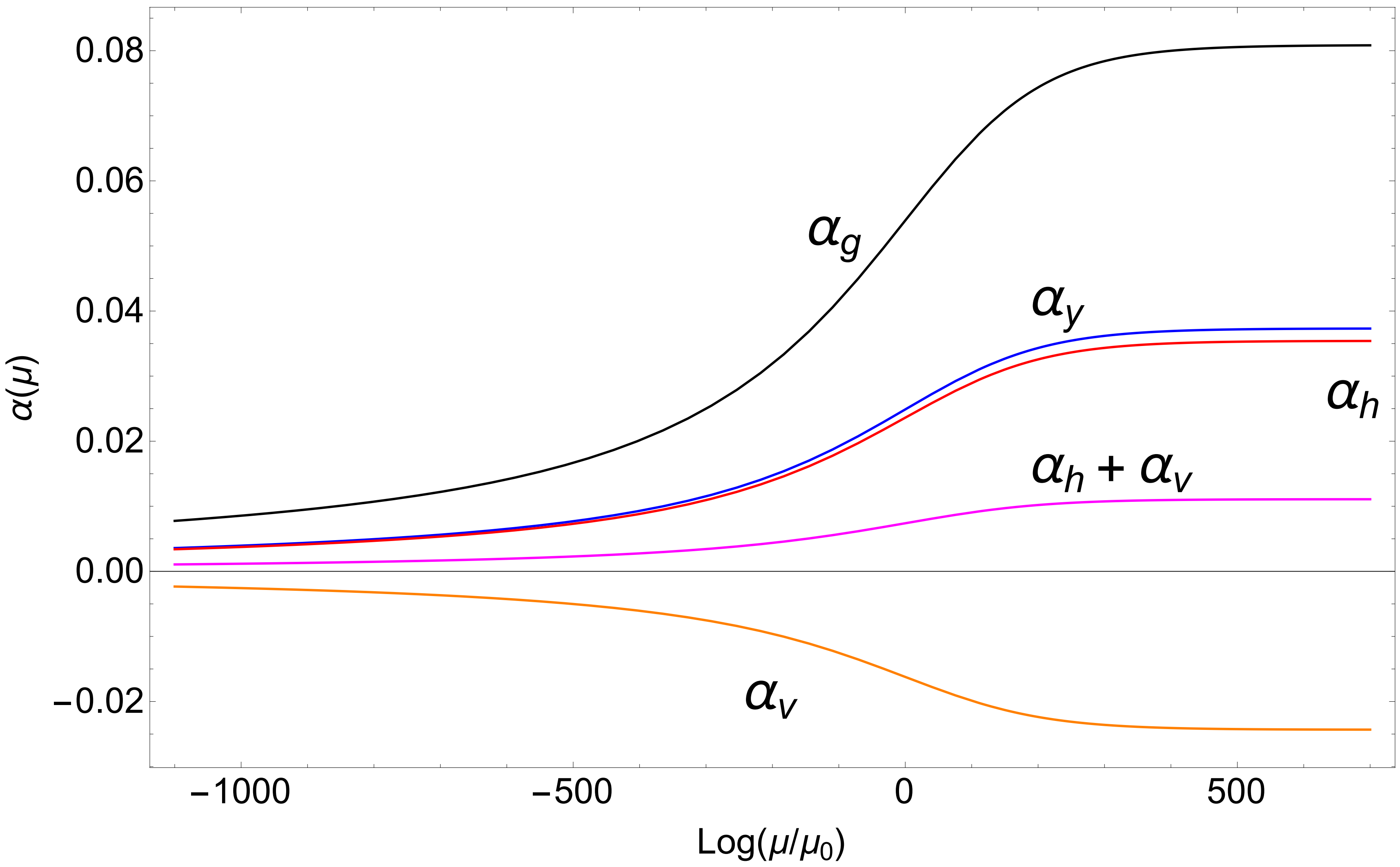

Scalars are needed perturbatively to make the theory fundamental

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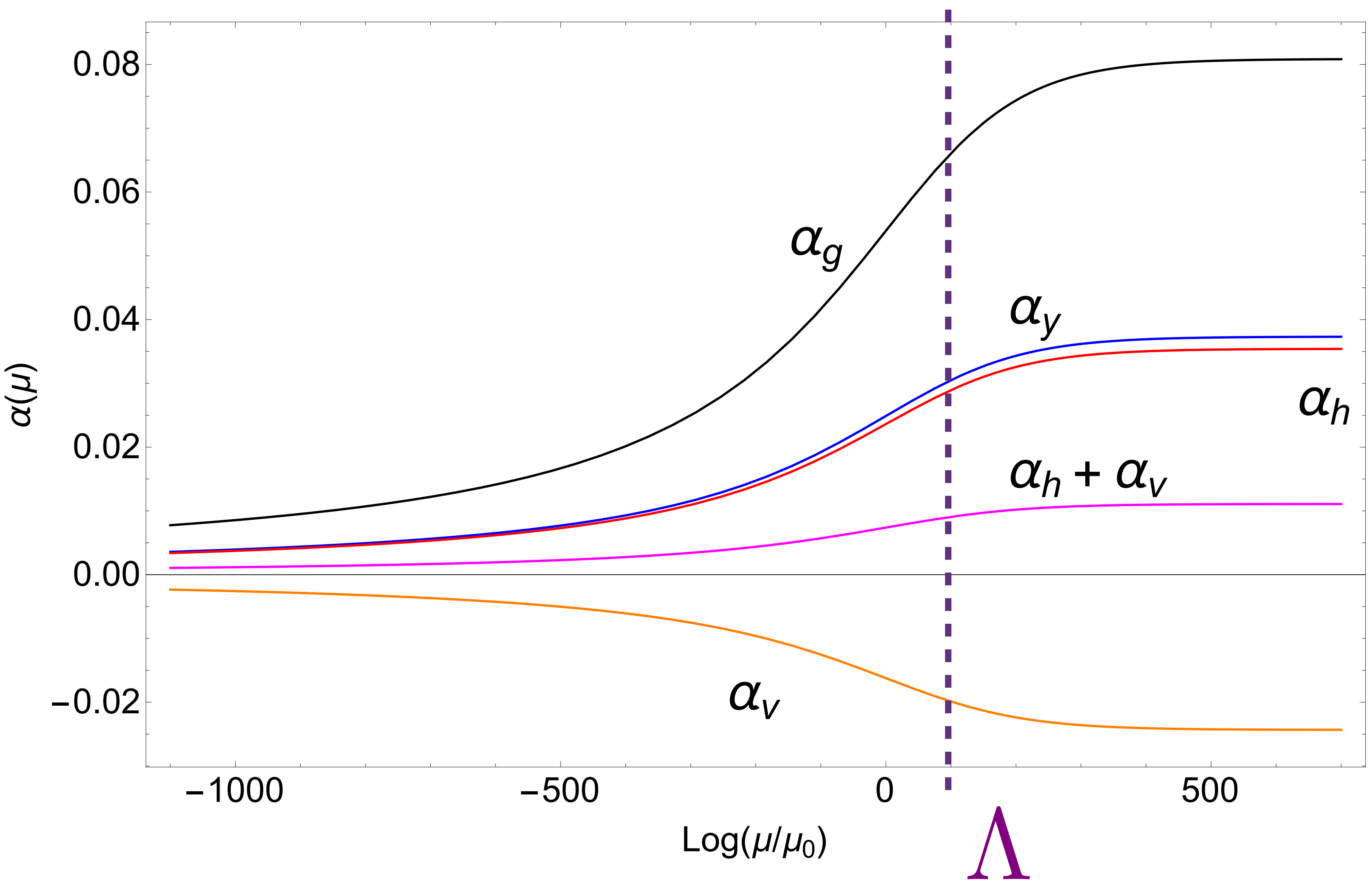

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Gauged Higgs UV Fixed Point

Pelaggi, Sannino, Strumia, Vigiani, 1701.01453

Fields	Gauge symmetries		Global symmetries	
	Spin	$\mathrm{SU}(N_c)$	$\mathrm{U}(N_F)_L$	$\mathrm{U}(N_F)_R$
ψ	$1/2$	$\square$	$\overline{\square}$	1
$\bar{\psi}$	$1/2$	$\overline{\square}$	1	$\square$
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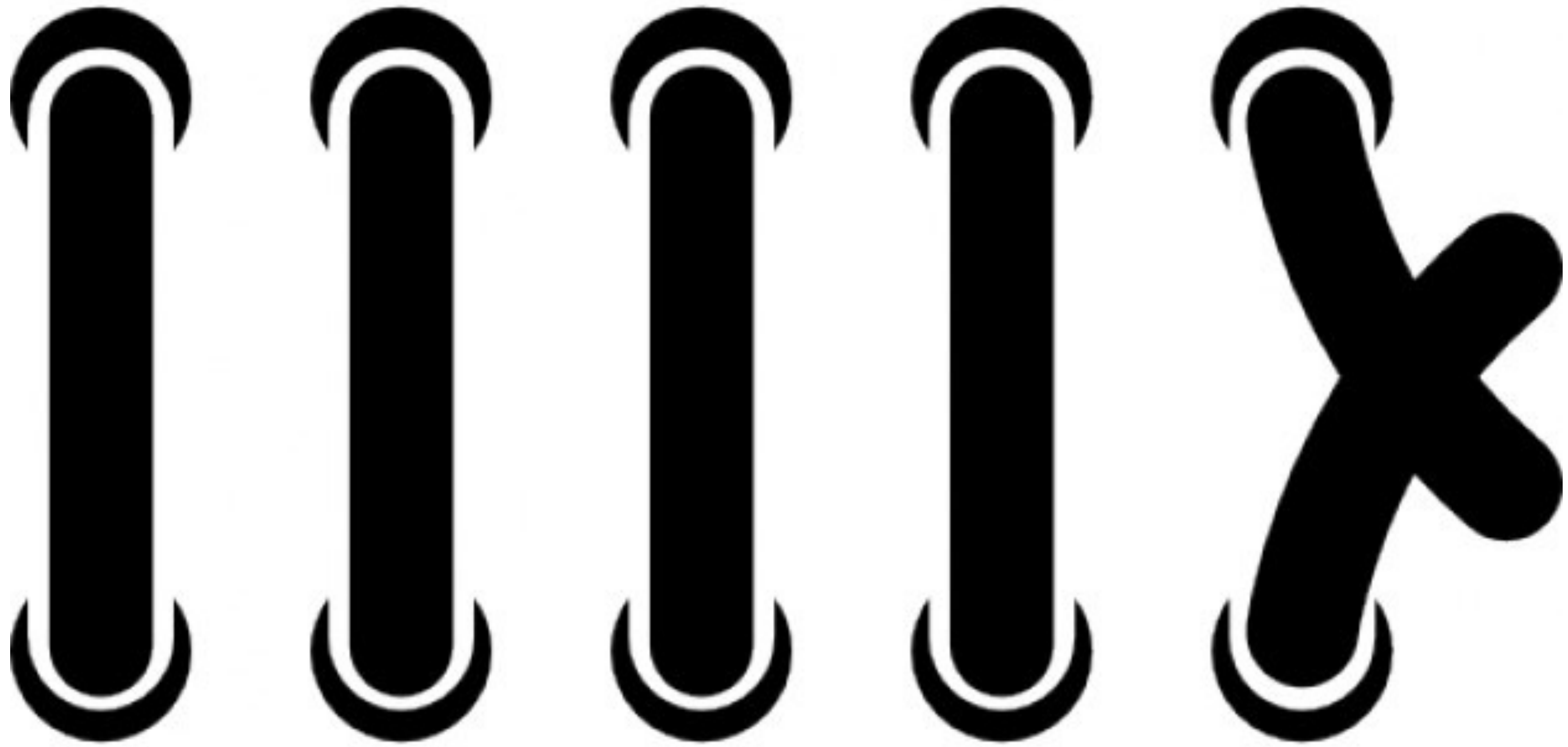
Controllably safe in all couplings



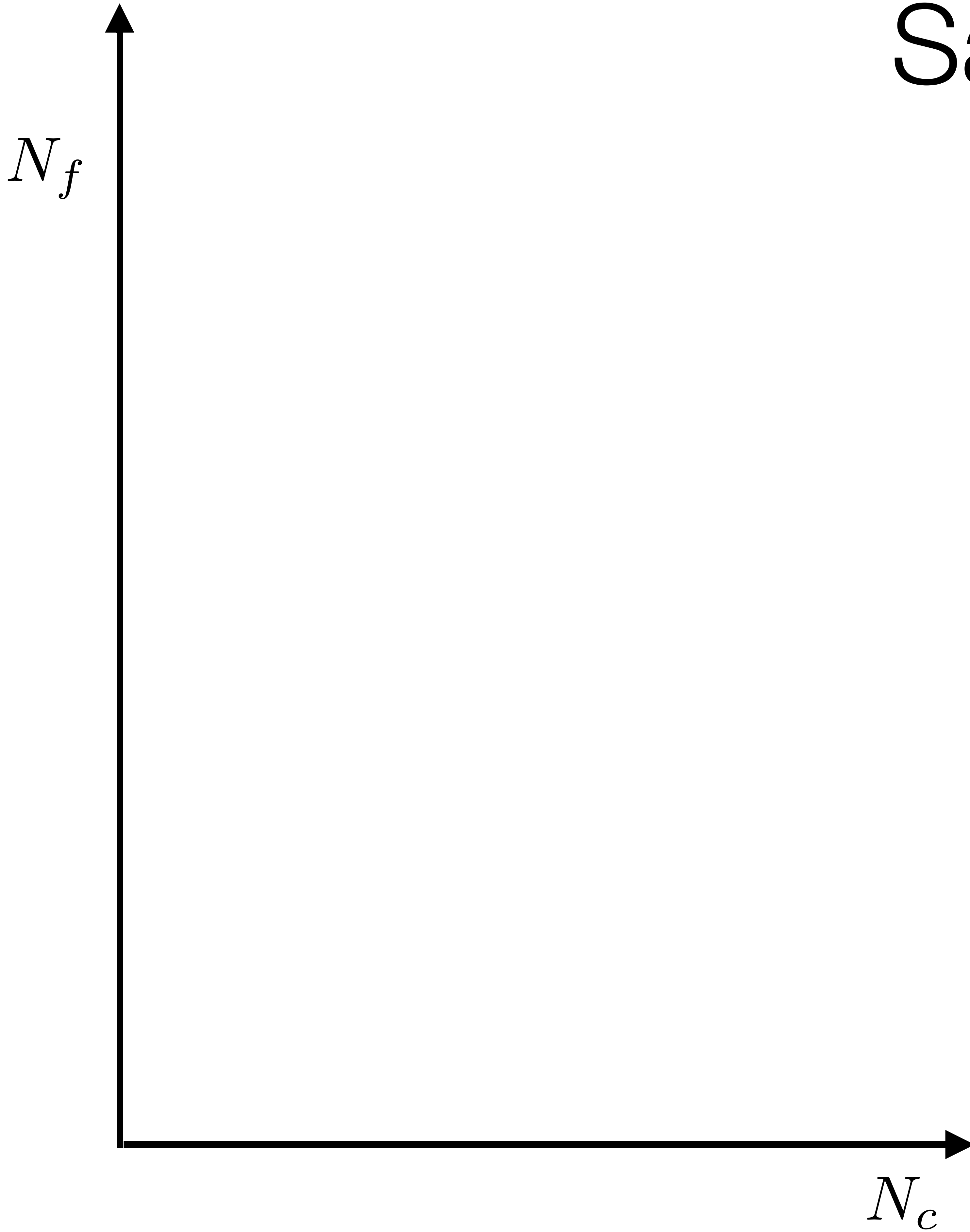
Higgs as shoelace

Conformal Window 2.0: Large Nf Story

Sannino, ERG 2016, Heidelberg

Antipin and Sannino to appear

Safe QCD



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Pica and Sannino 1011.5917, PRD

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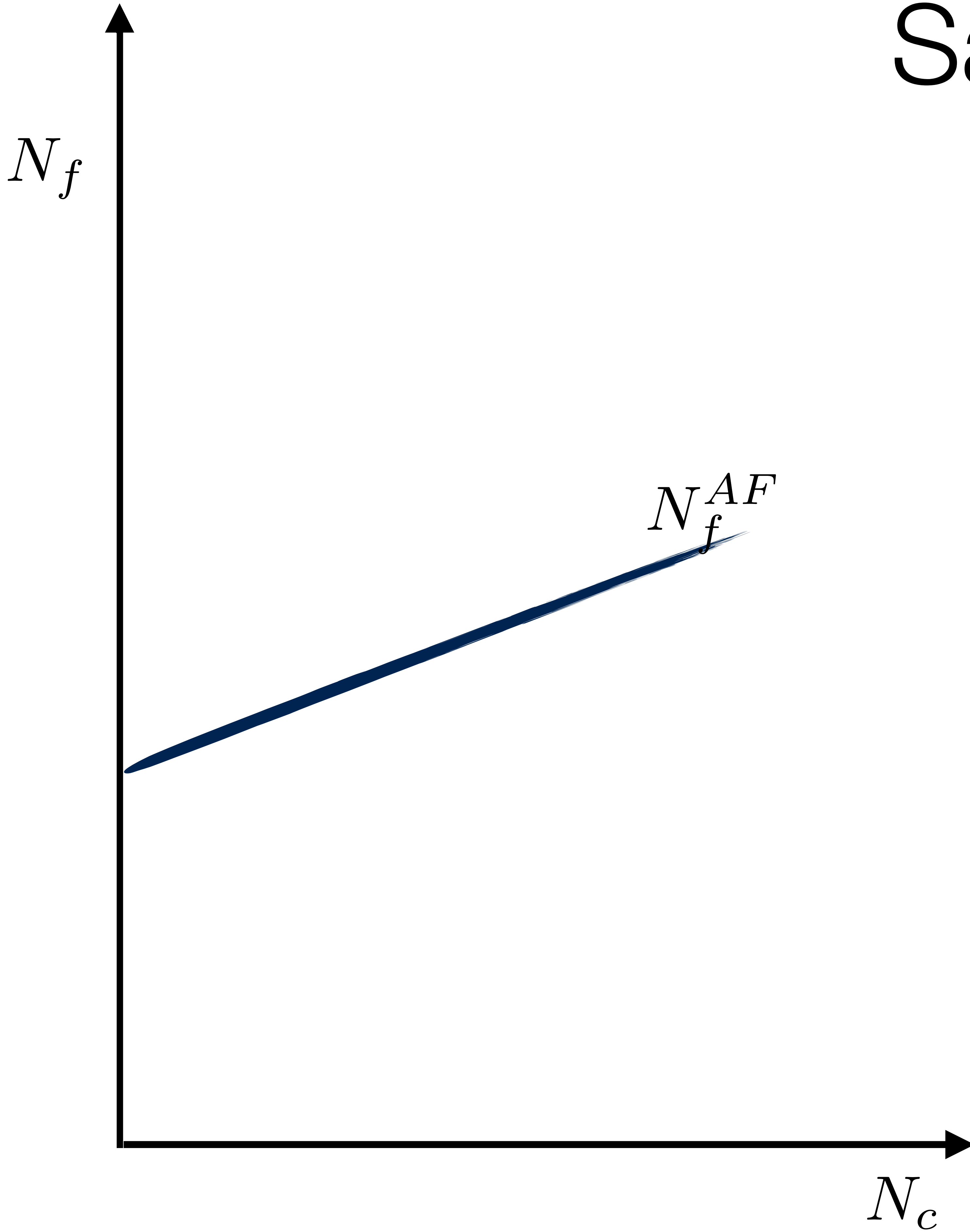

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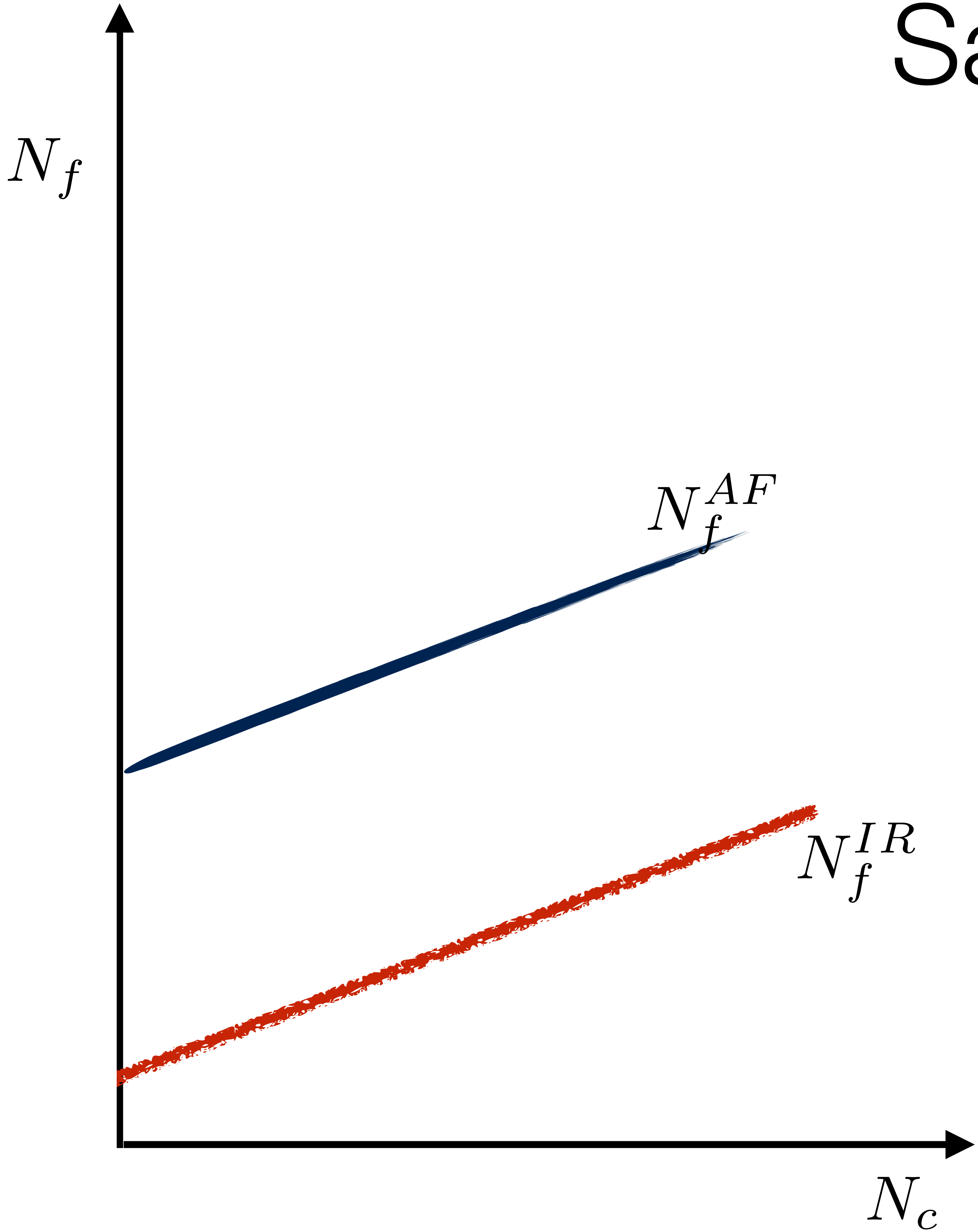

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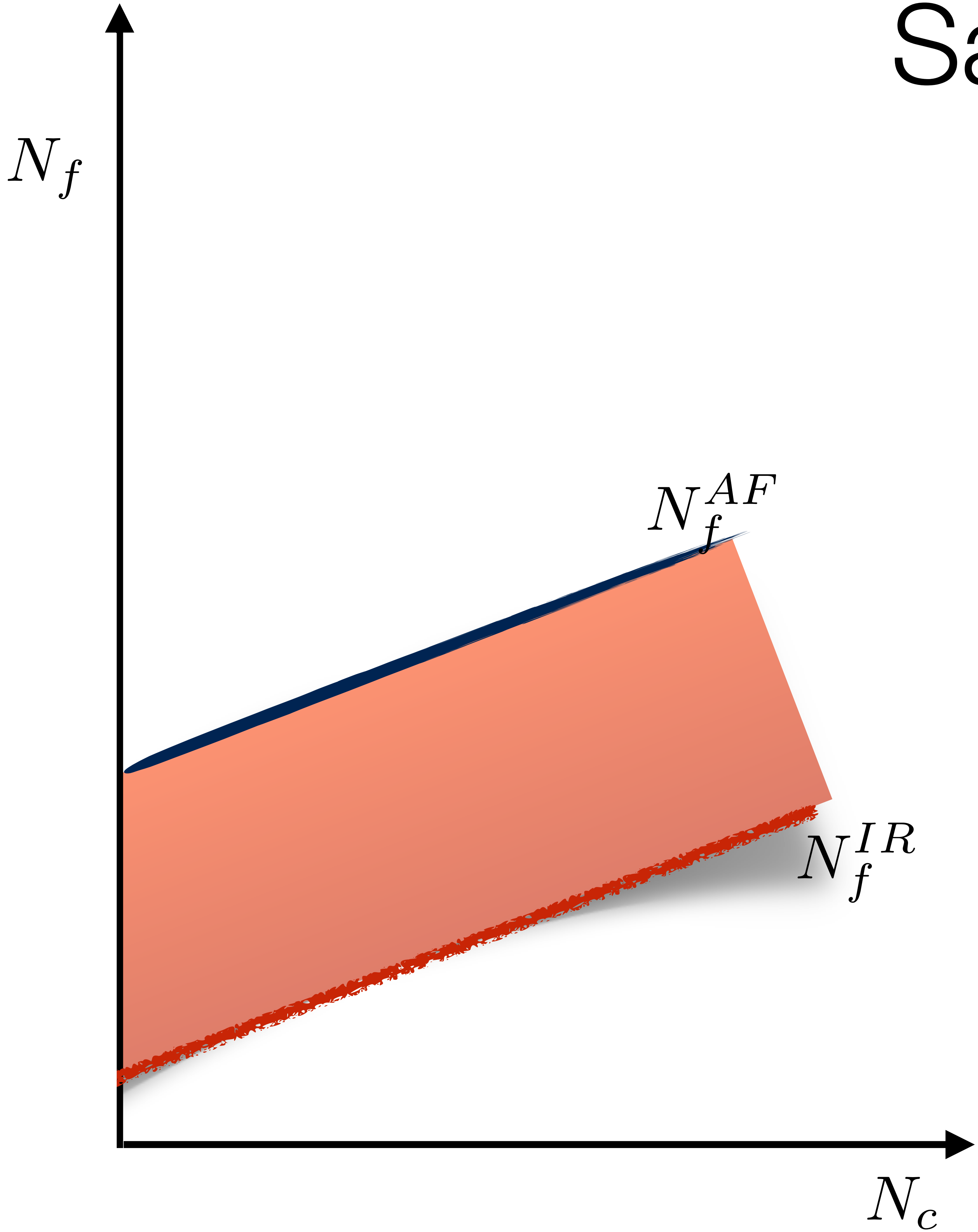

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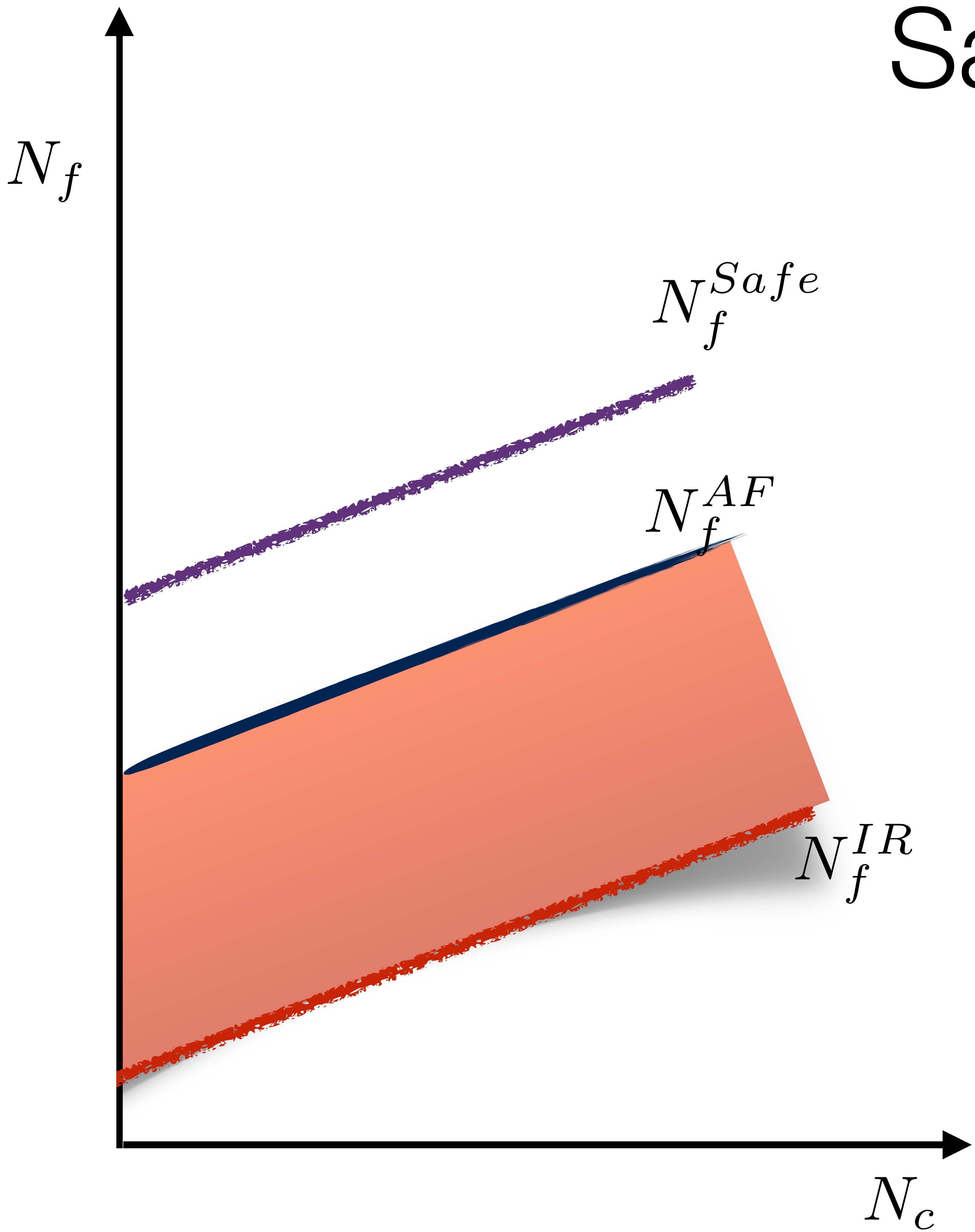

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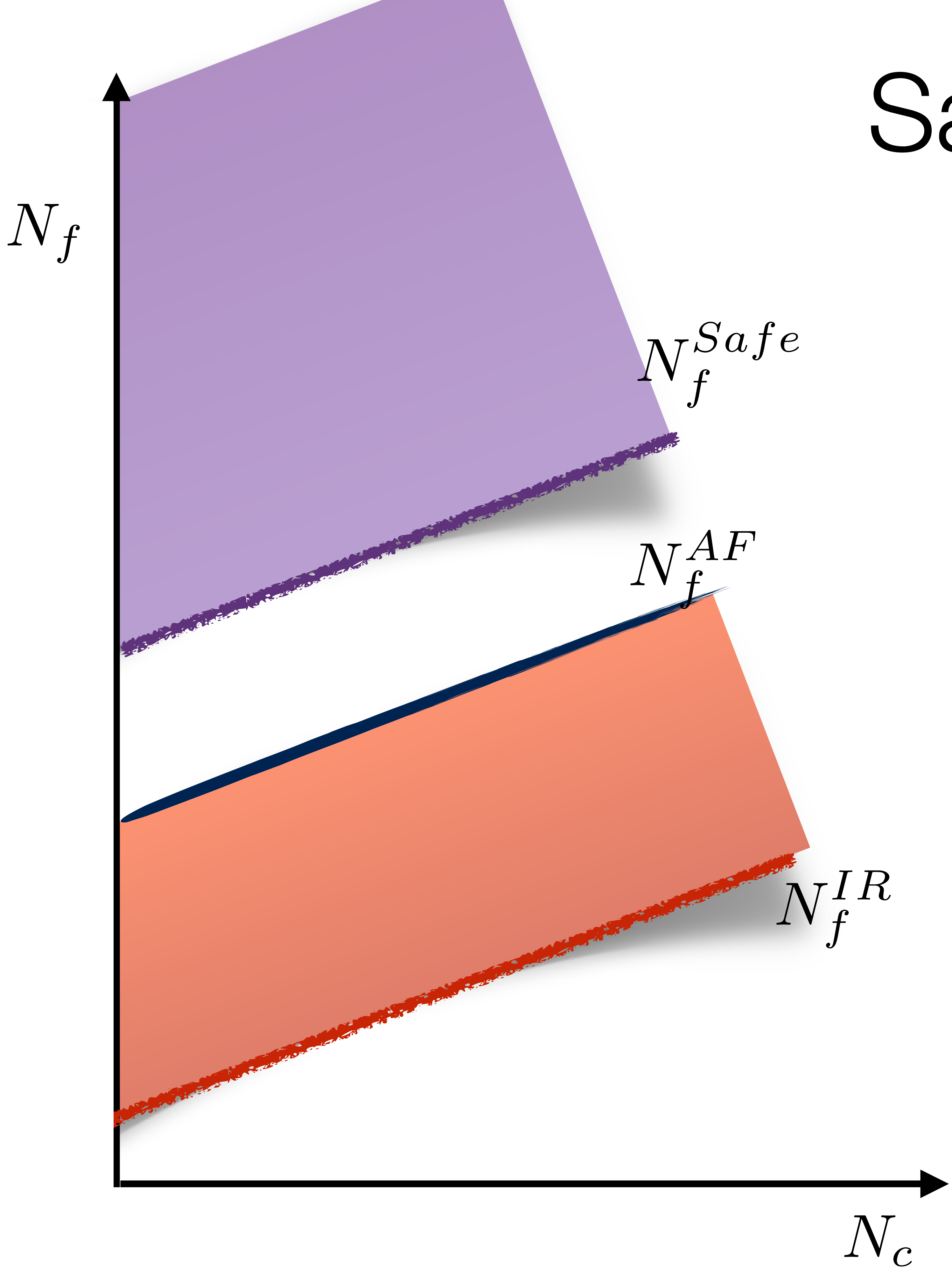

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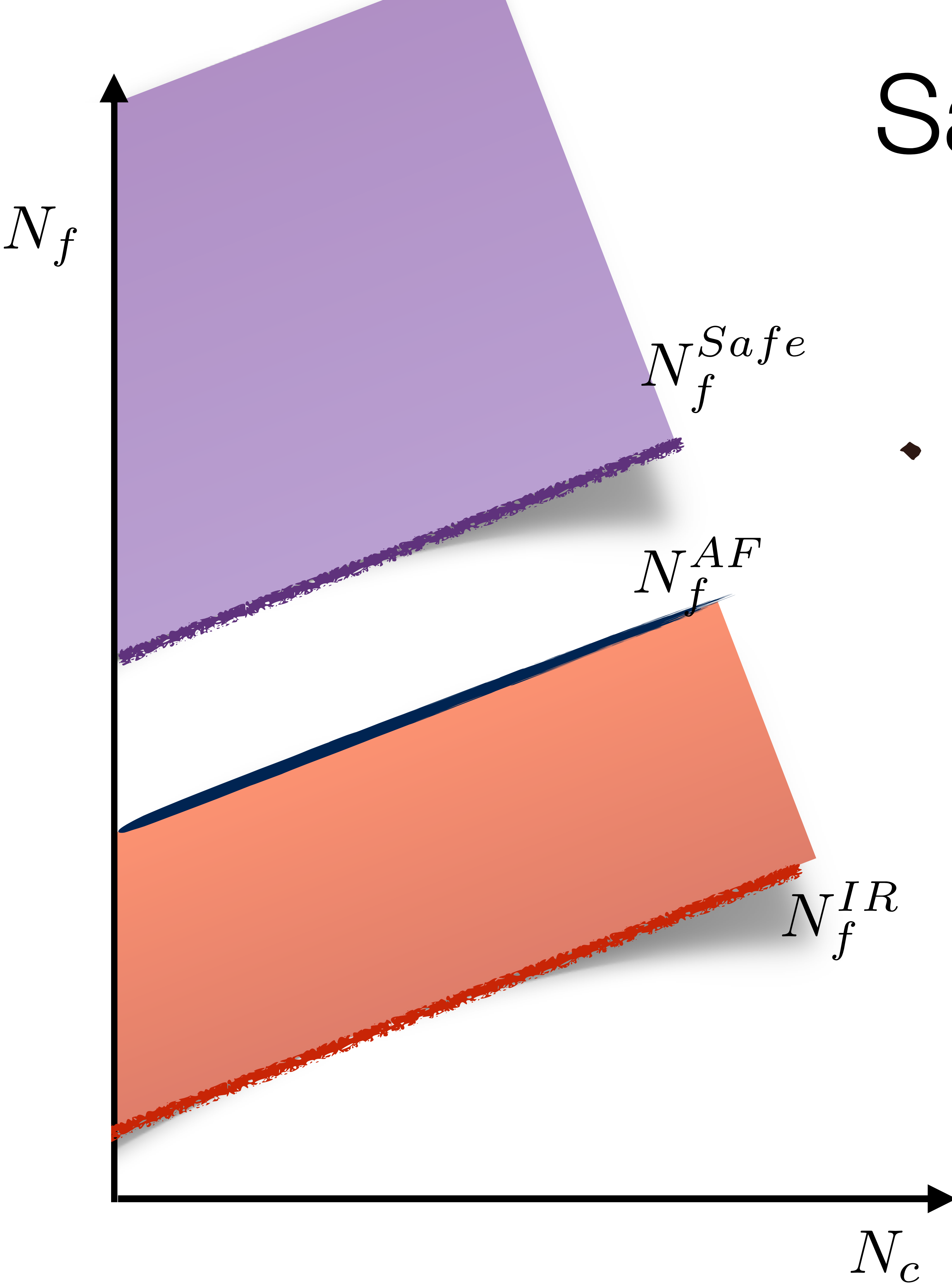

- Must exist a critical Safe Nf

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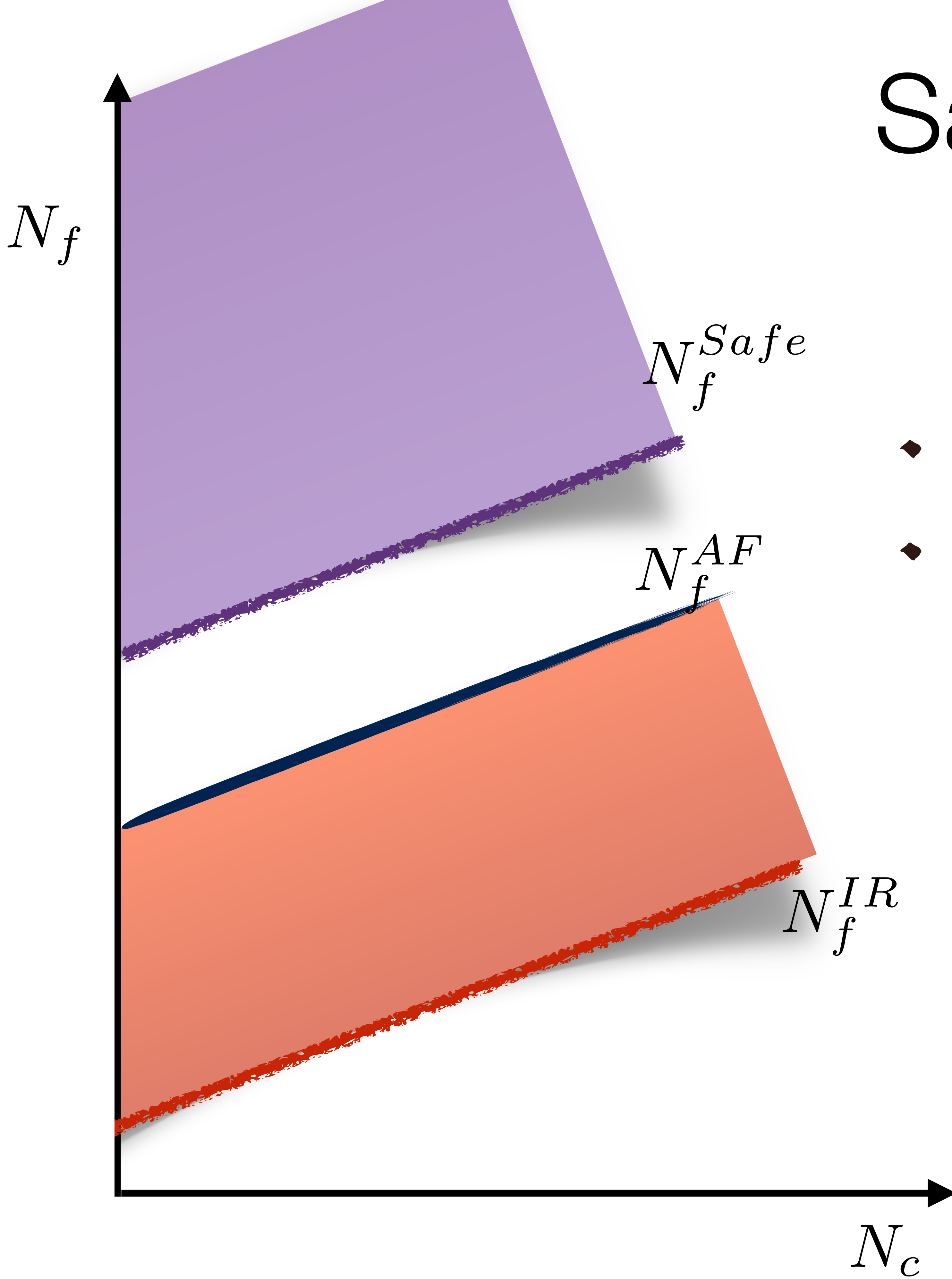

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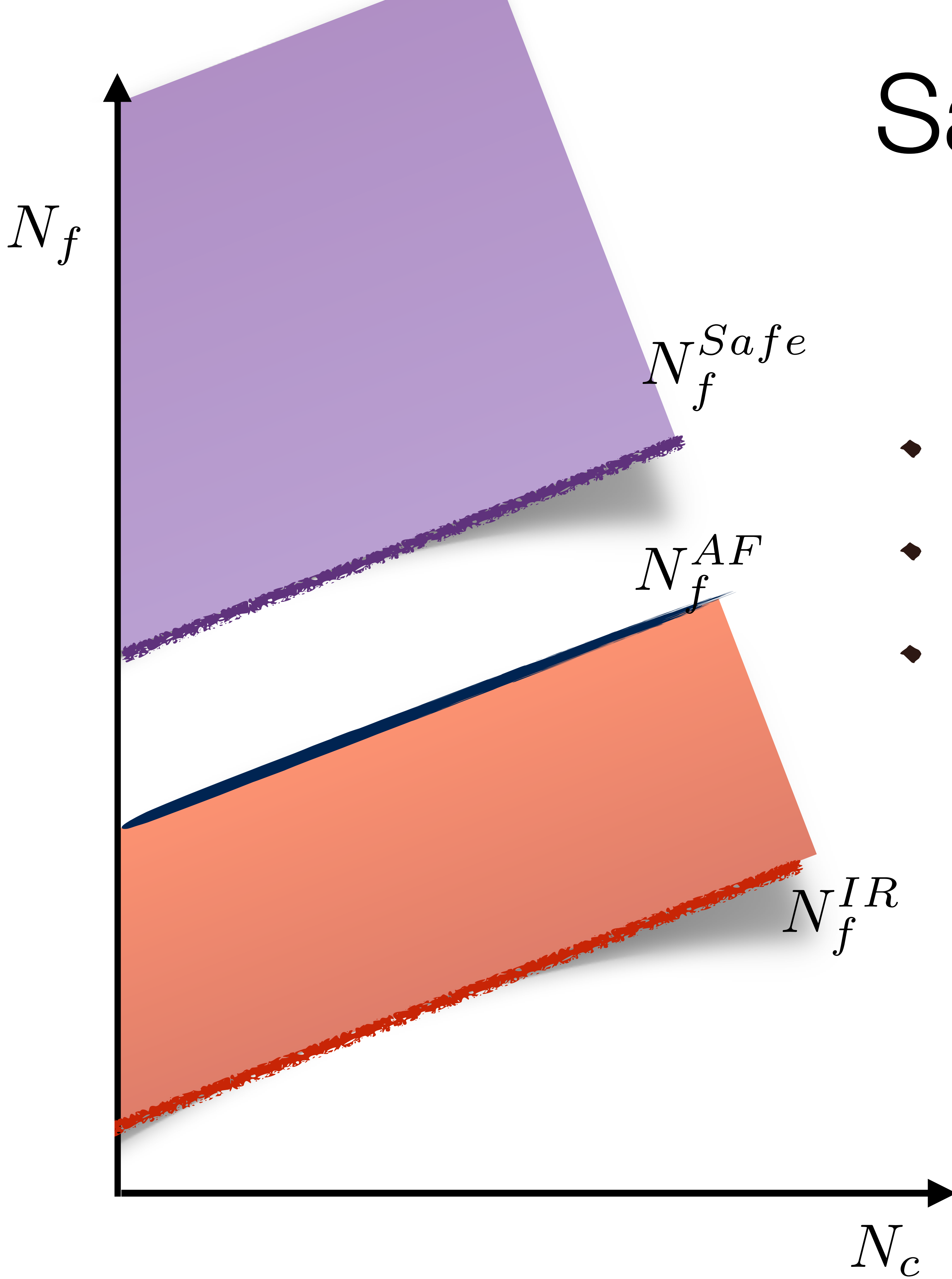

- Must exist a critical Safe Nf
- Unsafe region in Nf-Nc
- Continuous (Walking) transition?

Sannino, ERG 2016, Heidelberg

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Large Nf (Standard Model)

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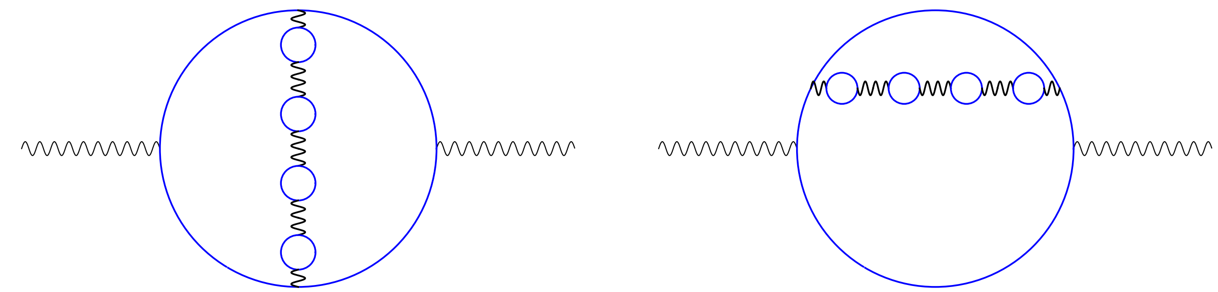
$$\frac{\partial \alpha_i}{\partial \ln \mu} = \beta_{\alpha_i} = \beta_{\alpha_i}^{\rm SM} + \beta_{\alpha_i}^{\rm extra}$$



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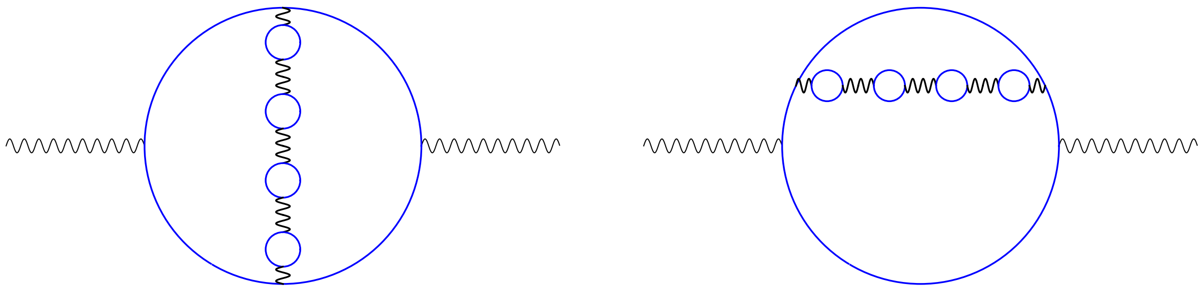
Palanques-Mestre, Pascual, Commun. Math. Phys. 84
Gracey, PLB, 96, Holdom PLB 2011
Pica and Sannino 1011.5917, PRD

Large Nf (Standard Model)

$$\frac{\partial \alpha_i}{\partial \ln \mu} = \beta_{\alpha_i} = \beta^{\mathrm{SM}}_{\alpha_i} + \beta^{\mathrm{extra}}_{\alpha_i}$$

$$\beta^{\mathrm{extra}}_{\alpha_i} = \frac{\alpha_i^2}{2\pi}\Delta b_i + \frac{\alpha_i^2}{3\pi} F_i(\Delta b_i \frac{\alpha_i}{4\pi})$$



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$$\frac{\partial \alpha_i}{\partial \ln \mu} = \beta_{\alpha_i} = \beta_{\alpha_i}^{\text{SM}} + \beta_{\alpha_i}^{\text{extra}}$$

$$\beta_{\alpha_i}^{\text{extra}} = \frac{\alpha_i^2}{2\pi}\Delta b_i + \frac{\alpha_i^2}{3\pi}F_i(\Delta b_i \frac{\alpha_i}{4\pi})$$

$$\Delta b_Y = \frac{4}{3}Y^2 N_F D_{R_2} D_{R_3} \qquad \Delta b_2 = \frac{2}{3}N_F D_{R_3}$$

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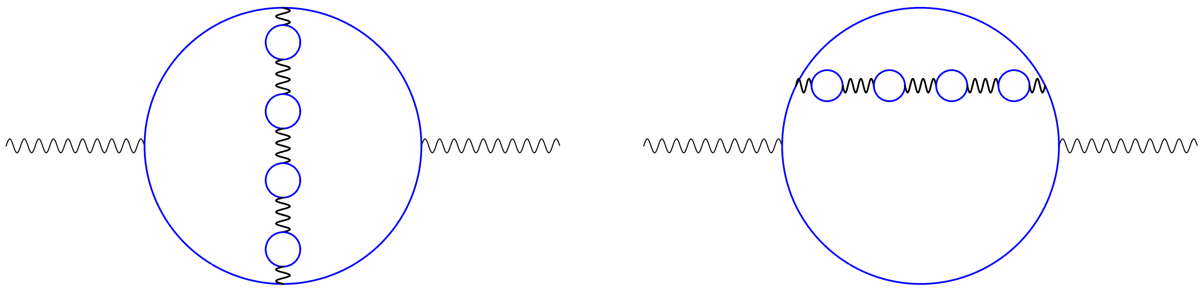

Antipin and Sannino, to appear
Palanques-Mestre, Pascual, Commun. Math. Phys. 84
Gracey, PLB, 96, Holdom PLB 2011
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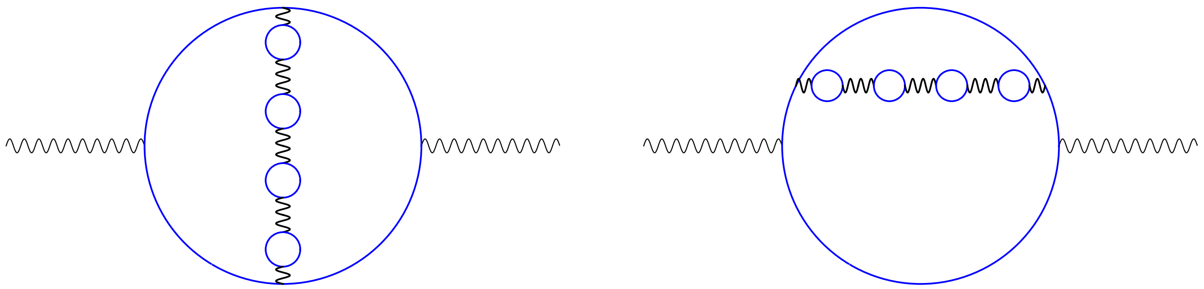

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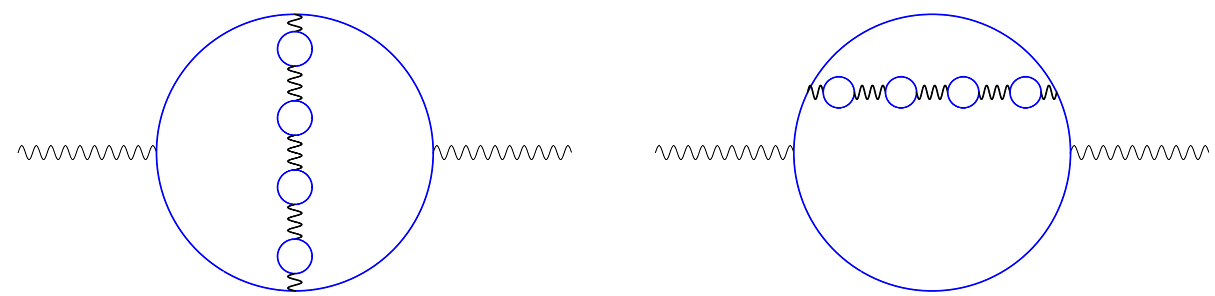

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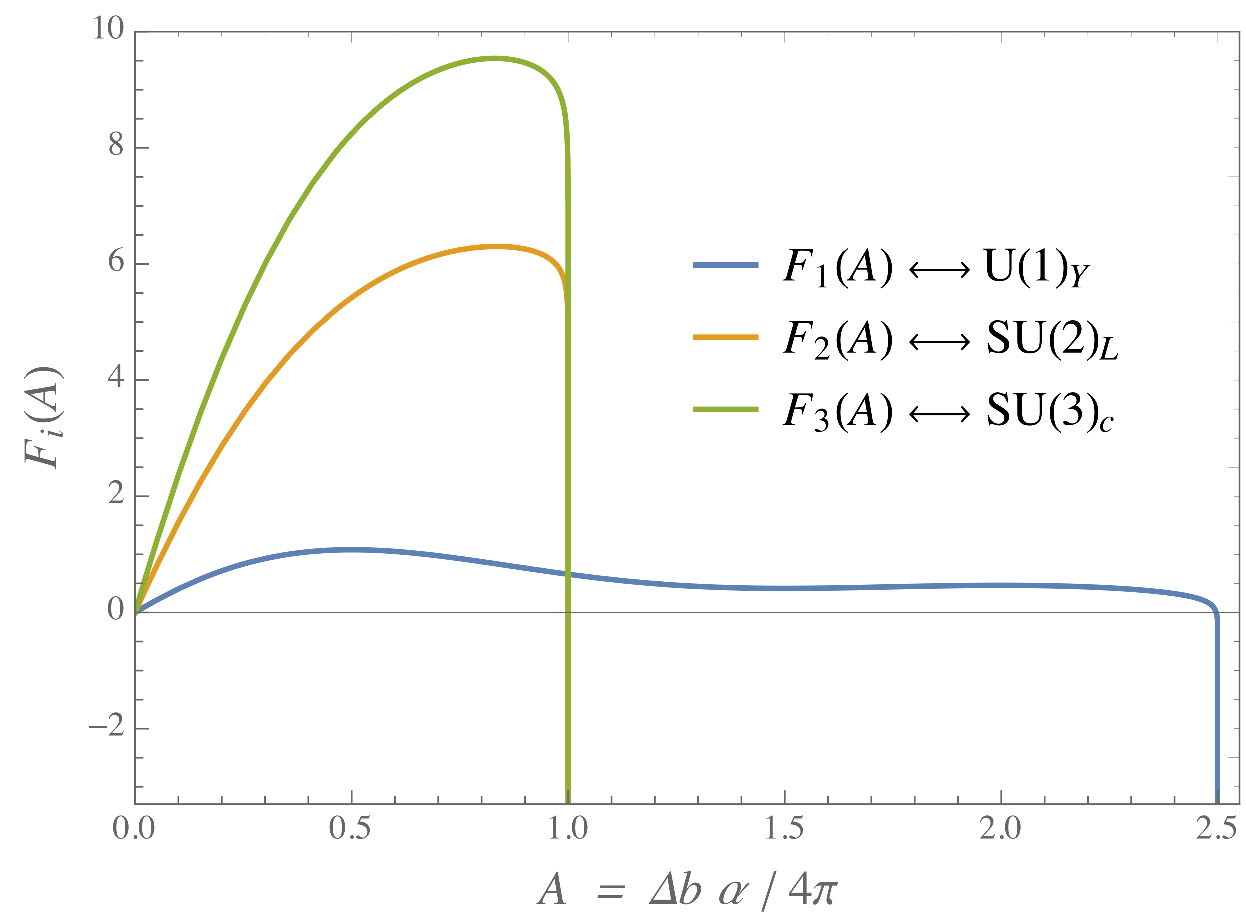

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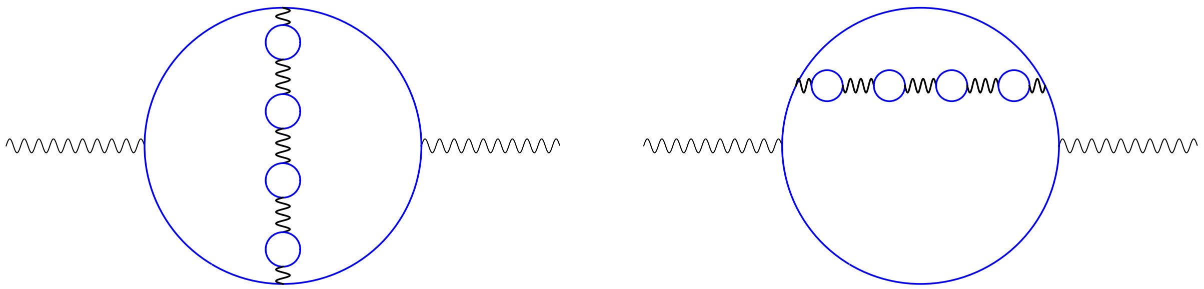
Abel, Sannino 1707.06638
Pelaggi, Plascencia, Salvio, Sannino, Smirnov, Strumia 1708.00437
Mann, Meffe, Wang, Sannino, Steele, Zhang 1707.02942



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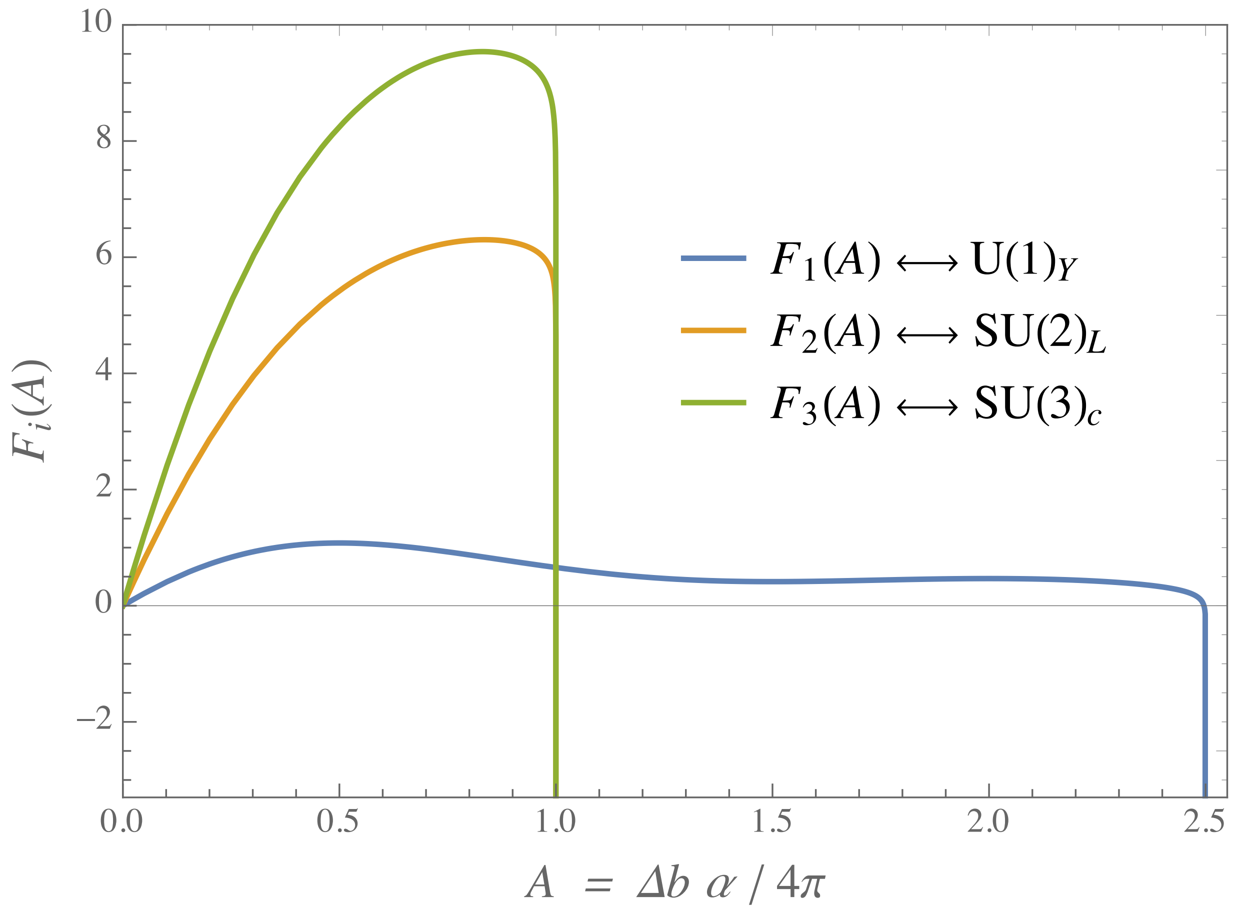

Paths to a Safe Standard Model

Large Nf resummation via vector-like fermions
[Mann et al. 1707.02942, Pelaggi et al. 1708.00437]

(Perturbative) safety via dynamical breaking,
[Abel, Sannino 1707.06638, Bond et al.1702.01727]

New paths not yet explored

Large Nf Safe Standard Model

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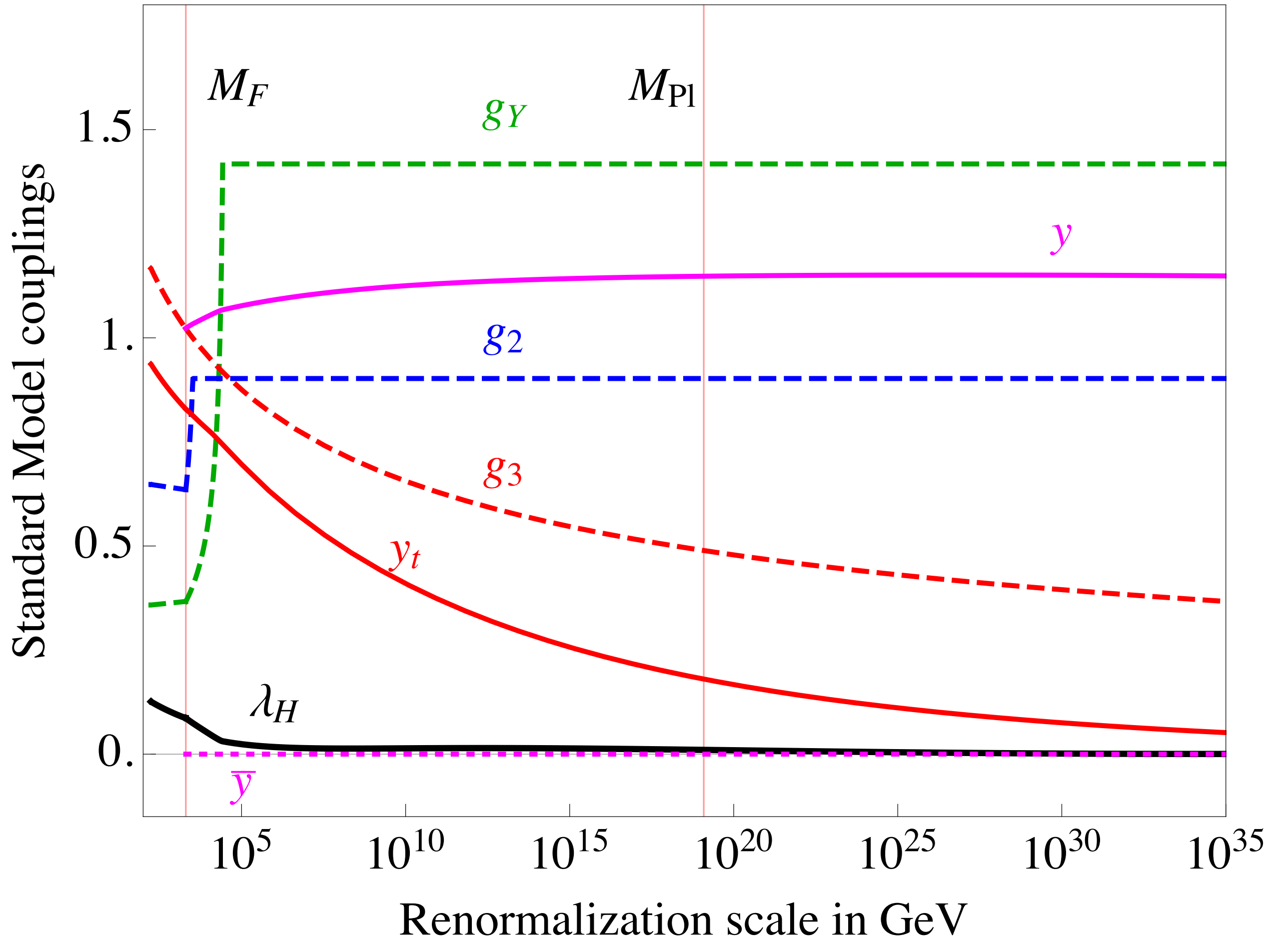

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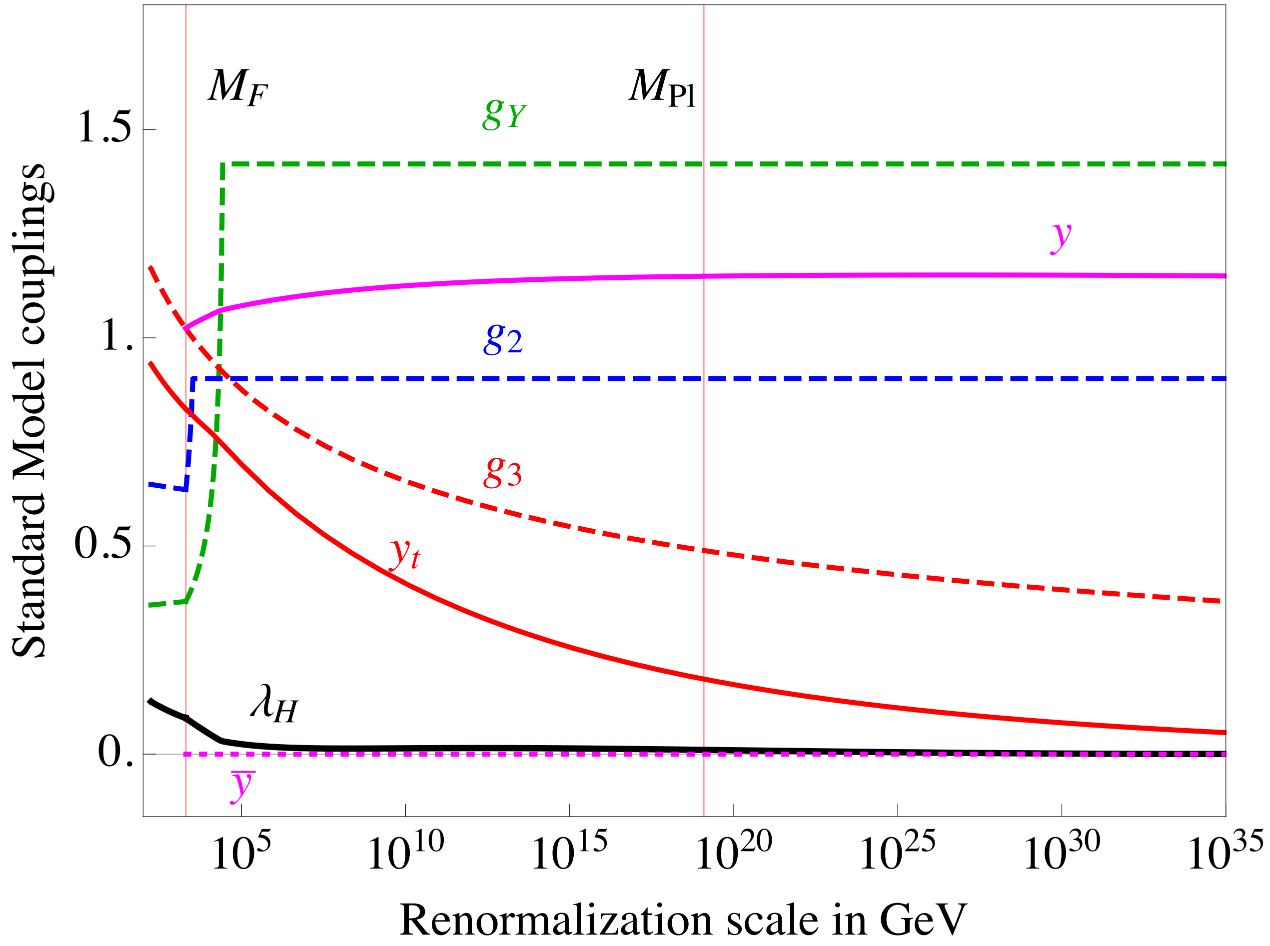

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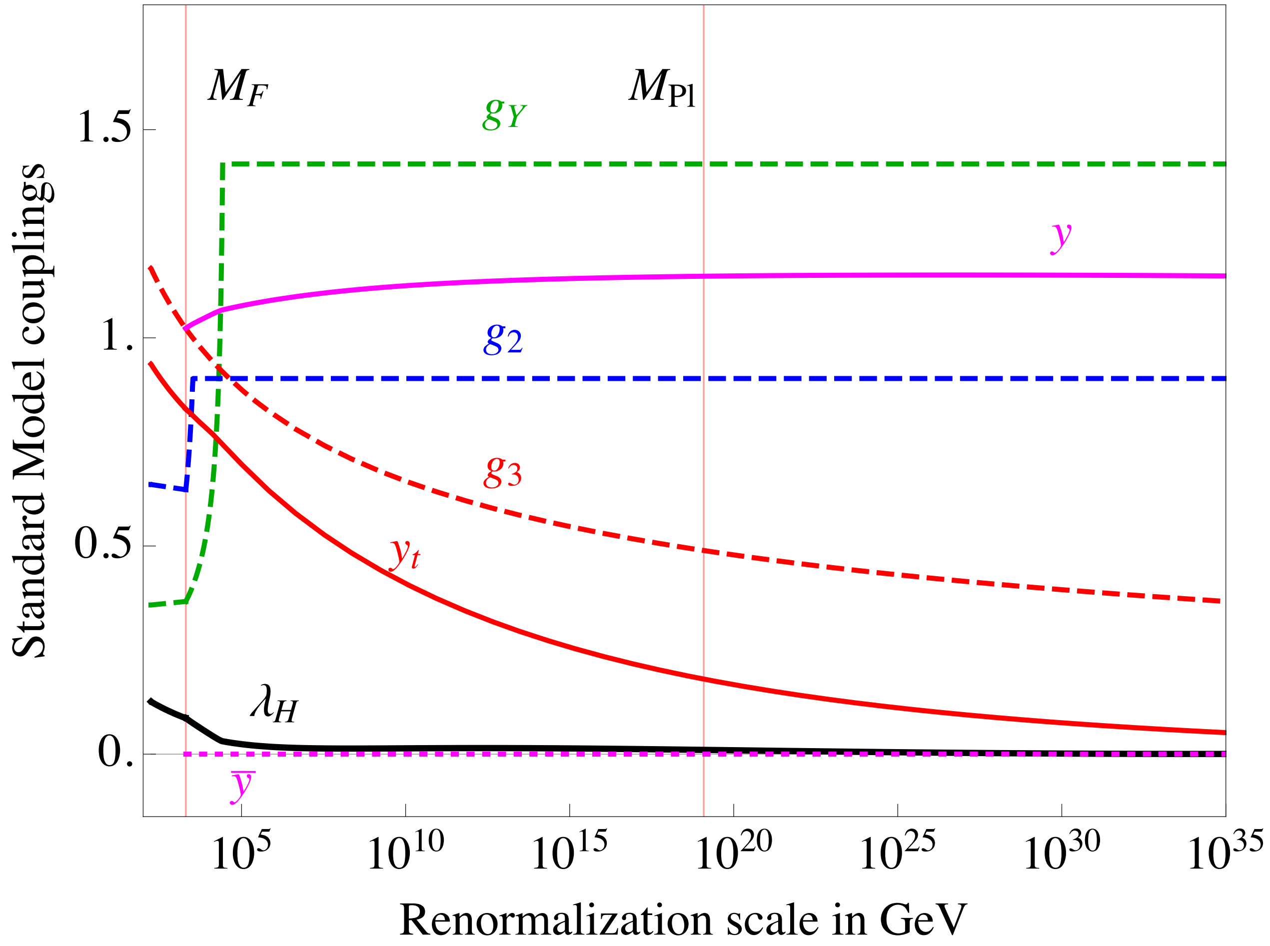
Large theory space at our disposal



Supersymmetric (un)safety

Intriligator and Sannino, 1508.07413, JHEP

Bajc and Sannino, 1610.09681, JHEP

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Exact results beyond perturbation theory

a-theorem

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Stronger constraint for asymp. safety, since at least one large R > 5/3

SQCD with H

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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

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SQCD

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Non-abelian SQED with(out) H cannot be asymptotically safe

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

Unsafe SUSY GUTs

Bajc and Sannino, 1610.09681, JHEP

Unsafe SUSY GUTs

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Exact results

Gaining R parity… but

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R-symmetry from SO(10) Cartan subalgebra generator B-L

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Introduce 126 + 126* Higgs in SO(10)

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$$R = (-1)^{3(B-L)+2S} = M(-1)^{2S} \quad \text{with} \quad M = (-1)^{3(B-L)}$$

M = matter parity

Elegant breaking of SO(10) preserving R-parity:

Introduce 126 + 126* Higgs in SO(10)

126(126*) SM and SU(5) singlet has B-L=-2(2) preserving R-parity

asymp. freedom is lost

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$$W_{Yukawa} = 16_a \left(Y_{10}^{ab} 10 + Y_{126}^{ab} \overline{126} + Y_{120}^{ab} 120 \right) 16_b$$

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To fully break SO(10) to SM add 210 of SO(10)

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In summary: 3 x 16 + 126 + 126* + 10 + 210 contributes

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In summary: 3 x 16 + 126 + 126* + 10 + 210 contributes

$$\beta_{1-loop} = +109$$

Asymptotic freedom is badly lost!

Exact results

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Minimal SO(10) without super potential

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3 x 16 + 126 + 126 + 10 + 210* ***is unsafe****.*

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Minimal SO(10) with general 3-linear super potential

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Exotic examples exist requiring thousands of generations!

Minimal SO(10) with general 3-linear super potential

$$W = y_1\, 210^3 + y_2\, 210\, 126\, \overline{126} + y_3\, 210\, 126\, 10 + y_4\, 210\, \overline{126}\, 10 + \sum_{a,b=1,2,3} 16_a\, 16_b\, \left(y_{5,ab}\, 10 + y_{6,ab}\, \overline{126}\right)$$

Exact results

Minimal SO(10) without super potential

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- *All trilinear present then: R=2/3 for all fields and no NSVZ UV fixed point*
- *Eliminate one 16 from super potential passes the constraints*

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Minimal SO(10) without super potential

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Exotic examples exist requiring thousands of generations!

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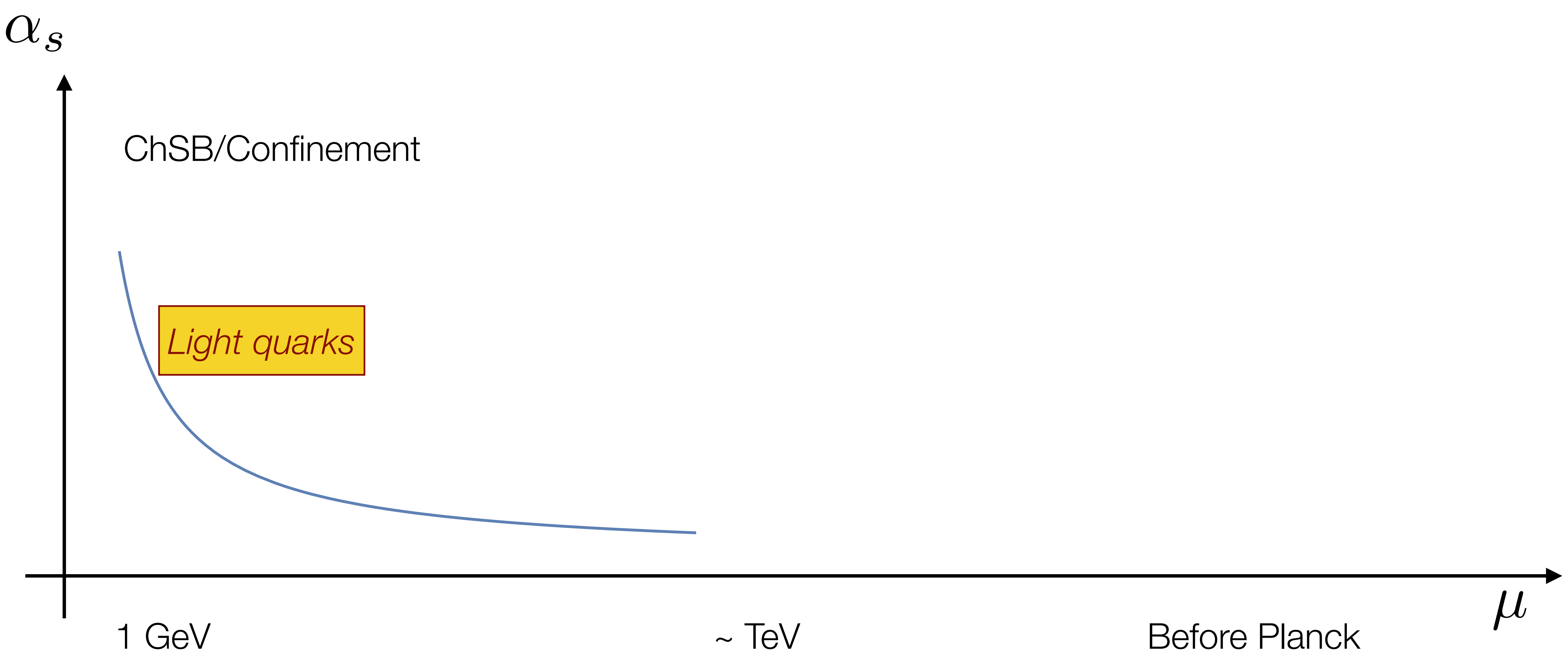
Super GUTs with R-charge are challenging!

Safe QCD

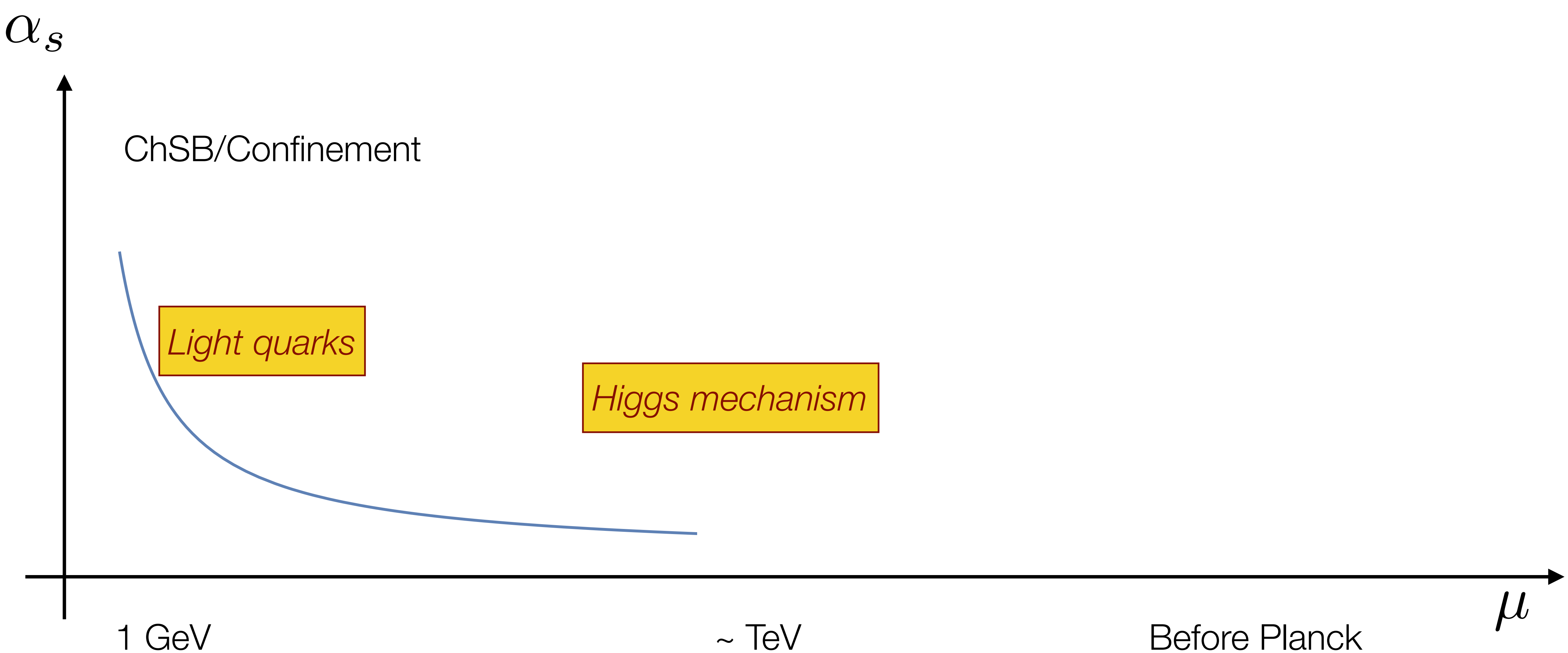
Sannino, 1511.09022



Pica & Sannino,1011.5917 PRD

Safe QCD

Sannino, 1511.09022



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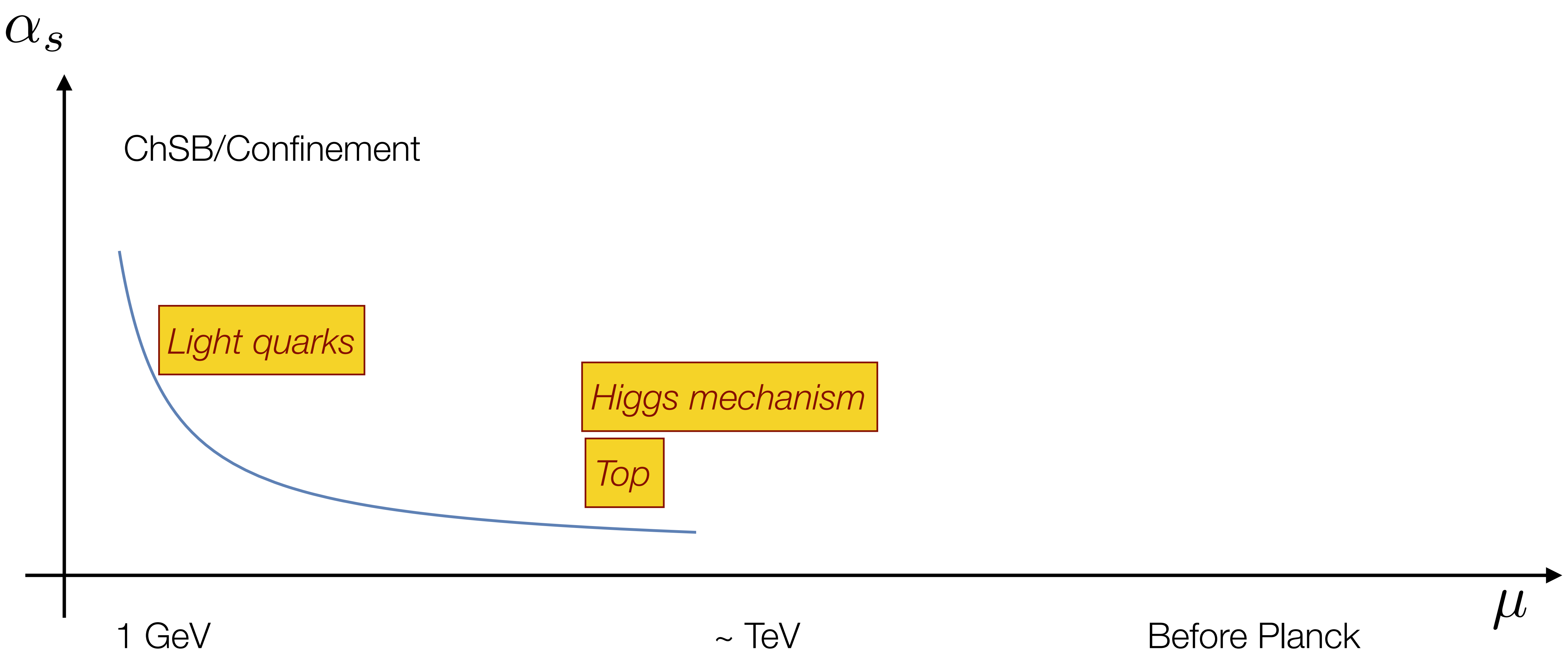

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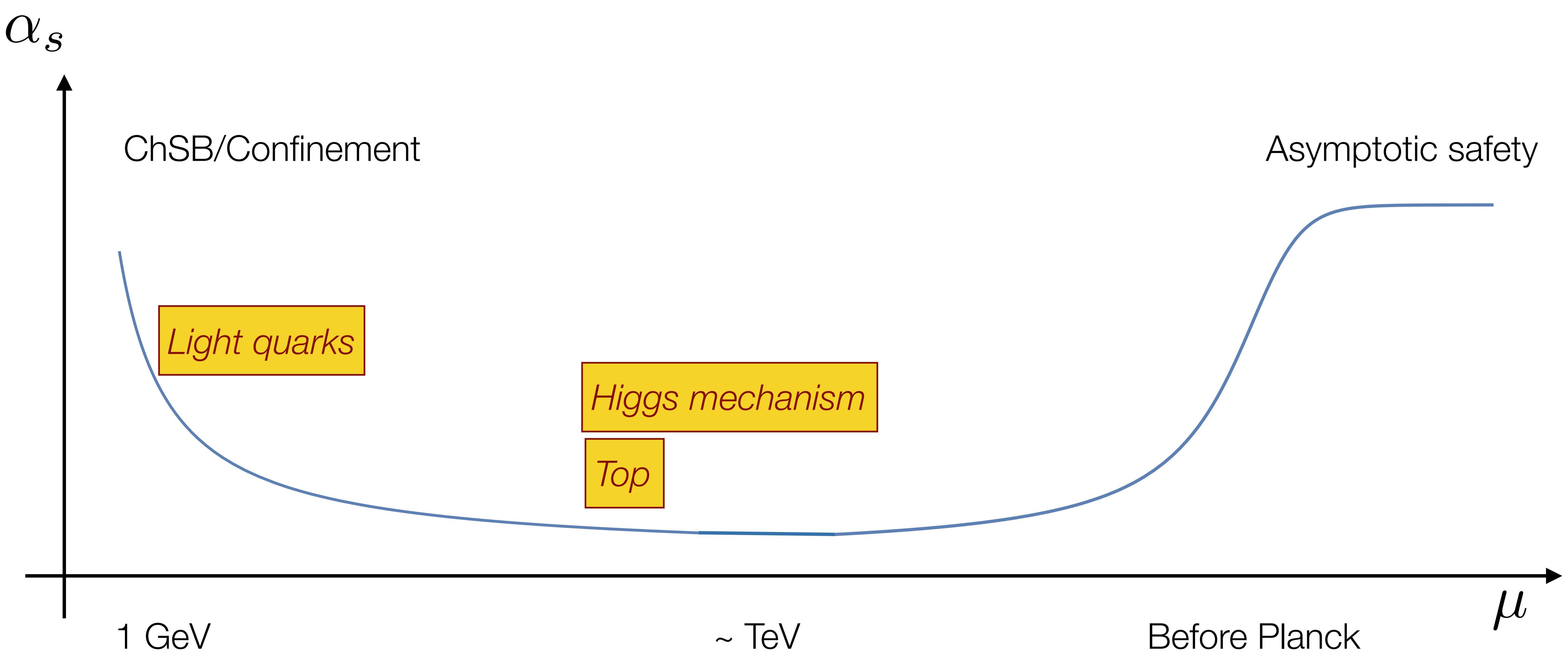

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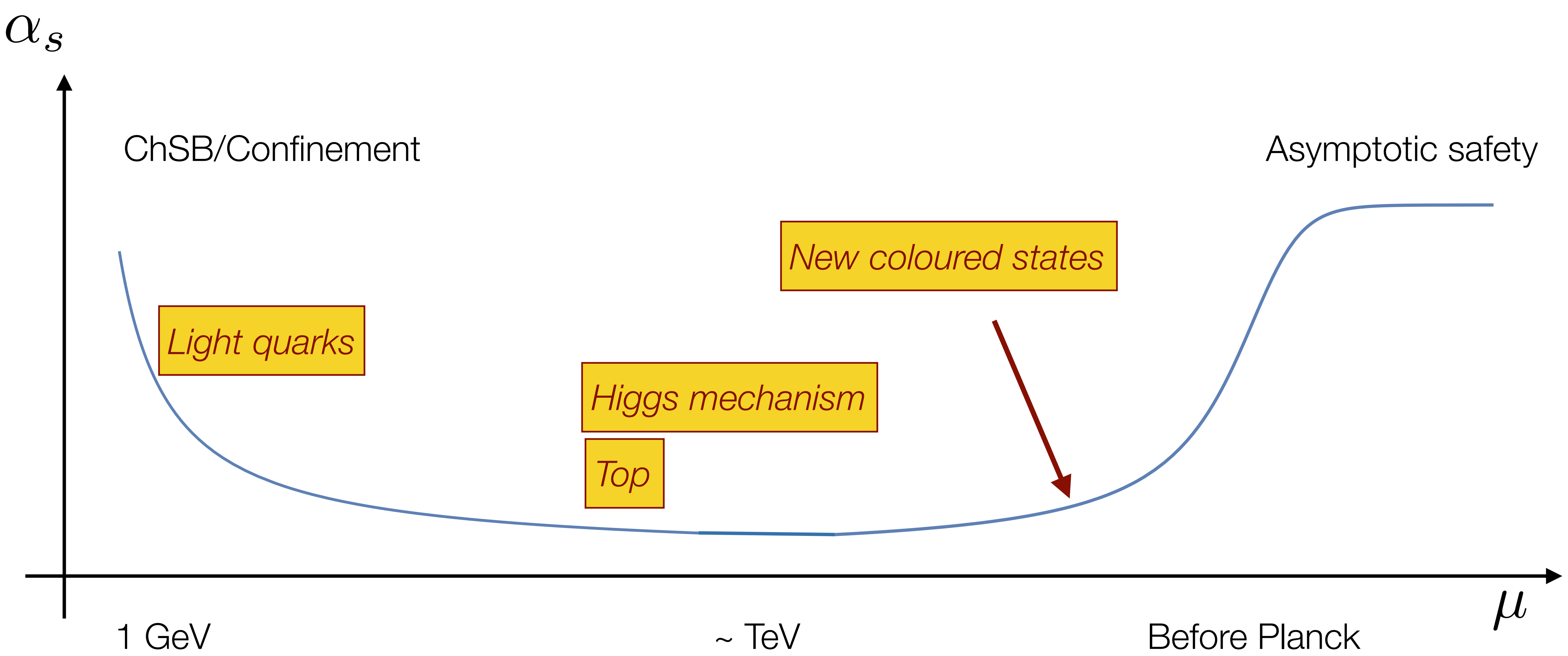

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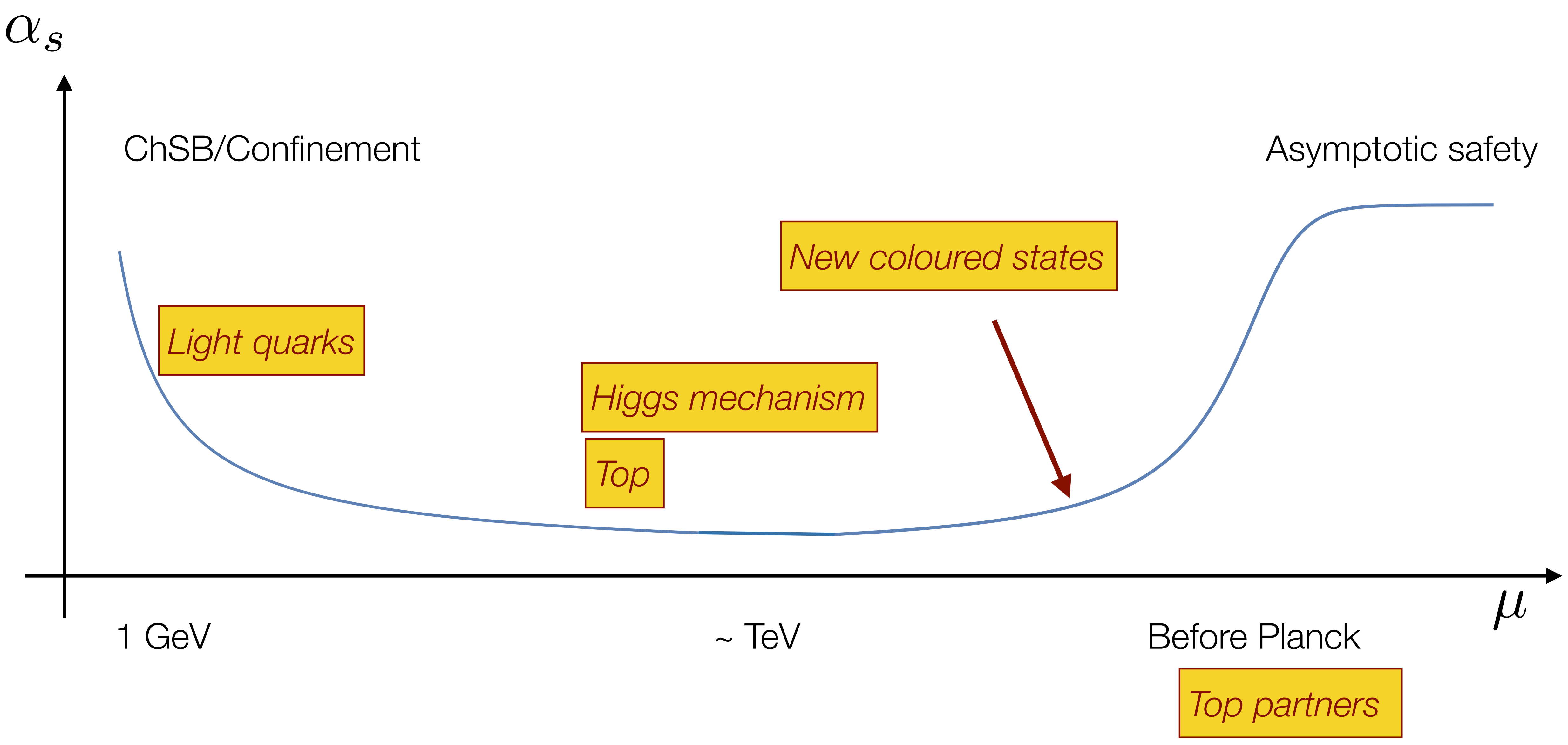

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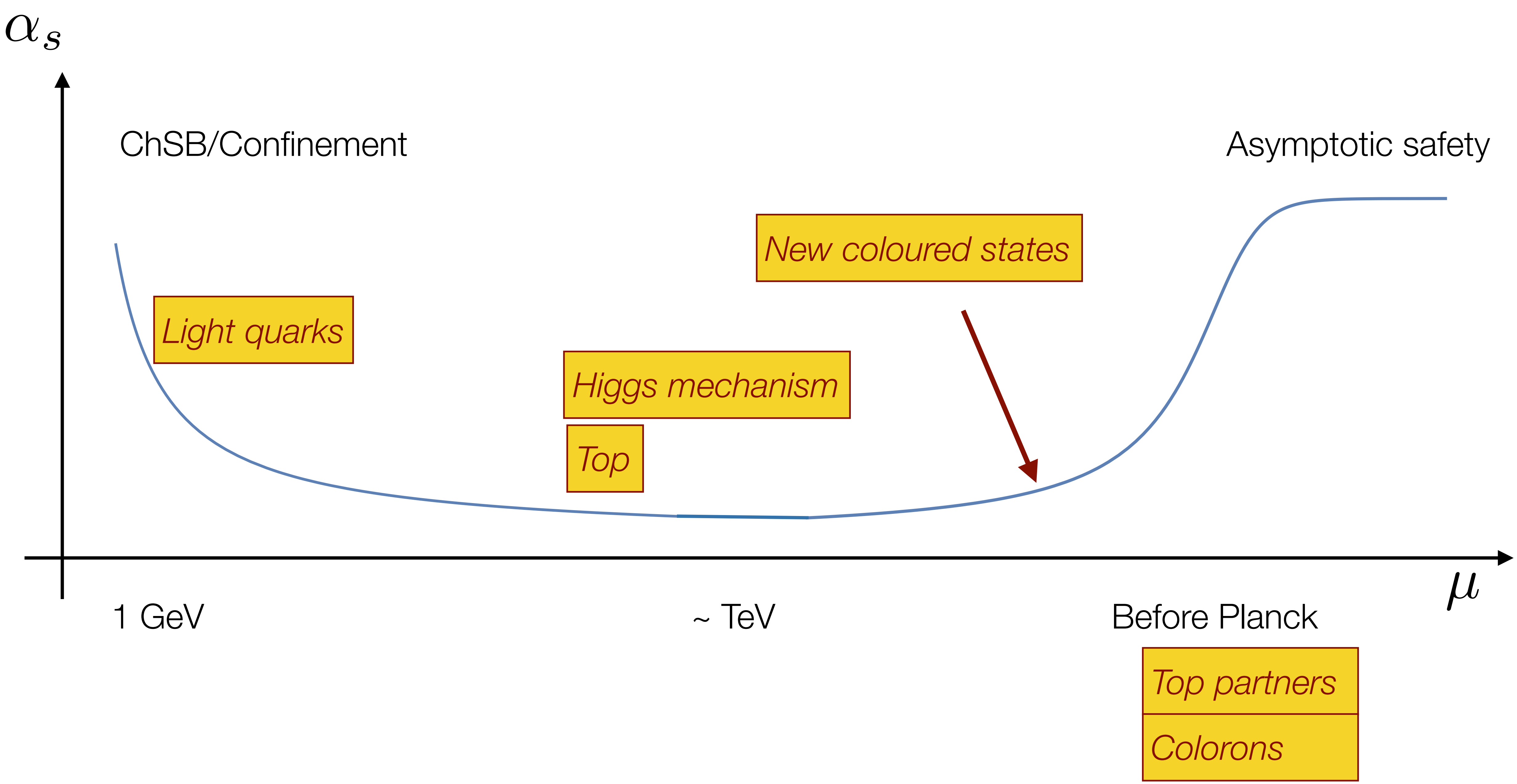

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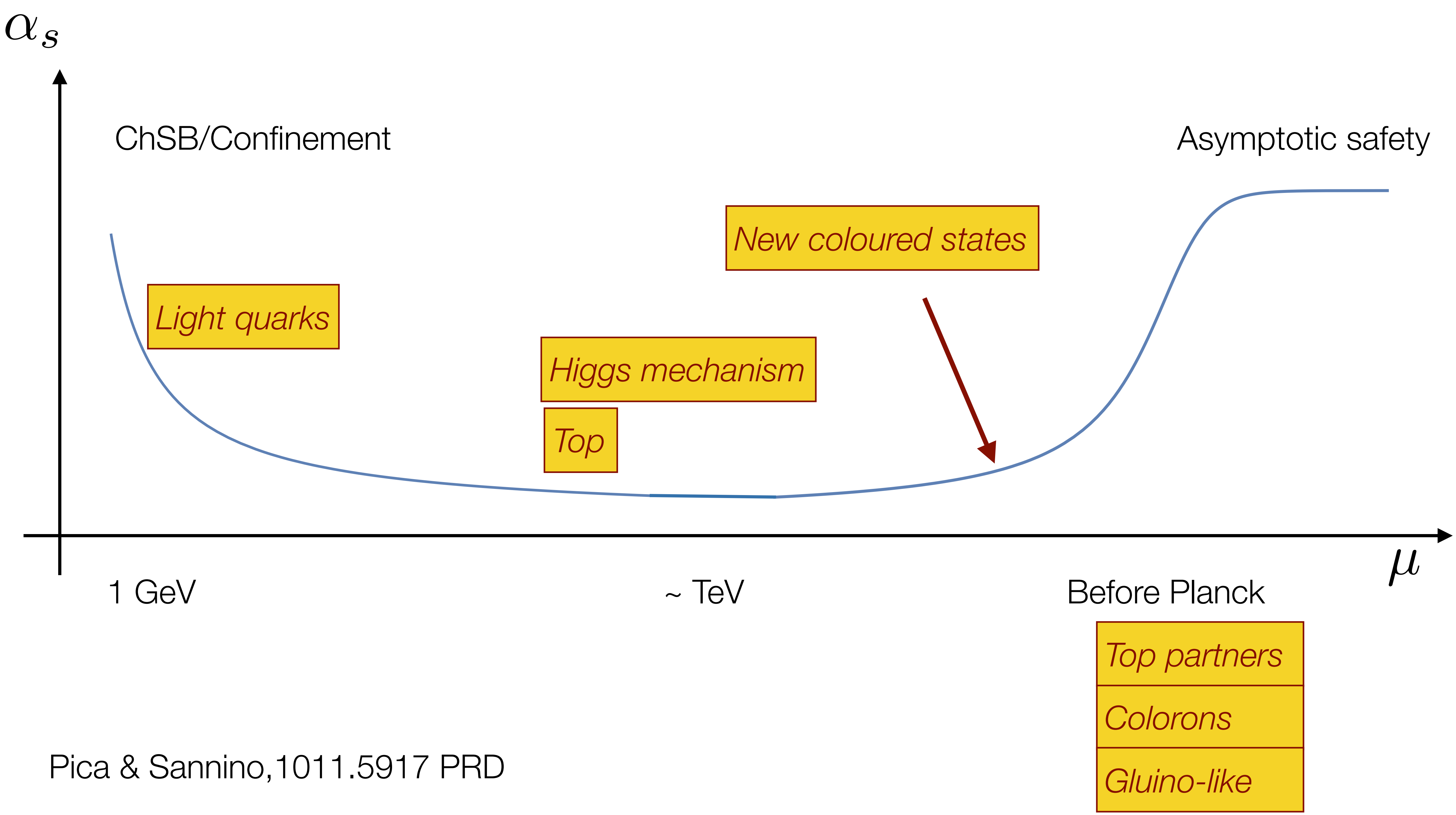

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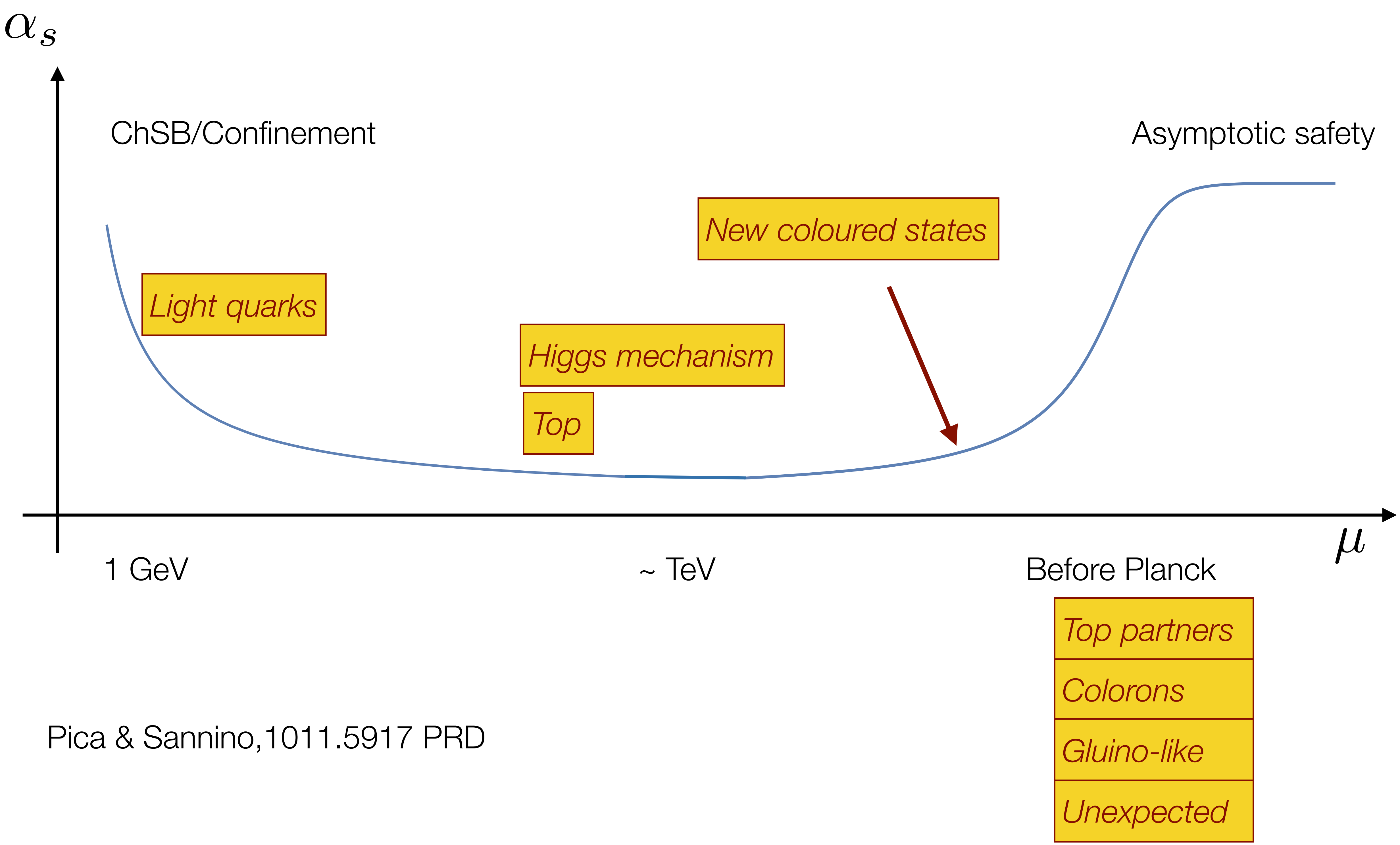
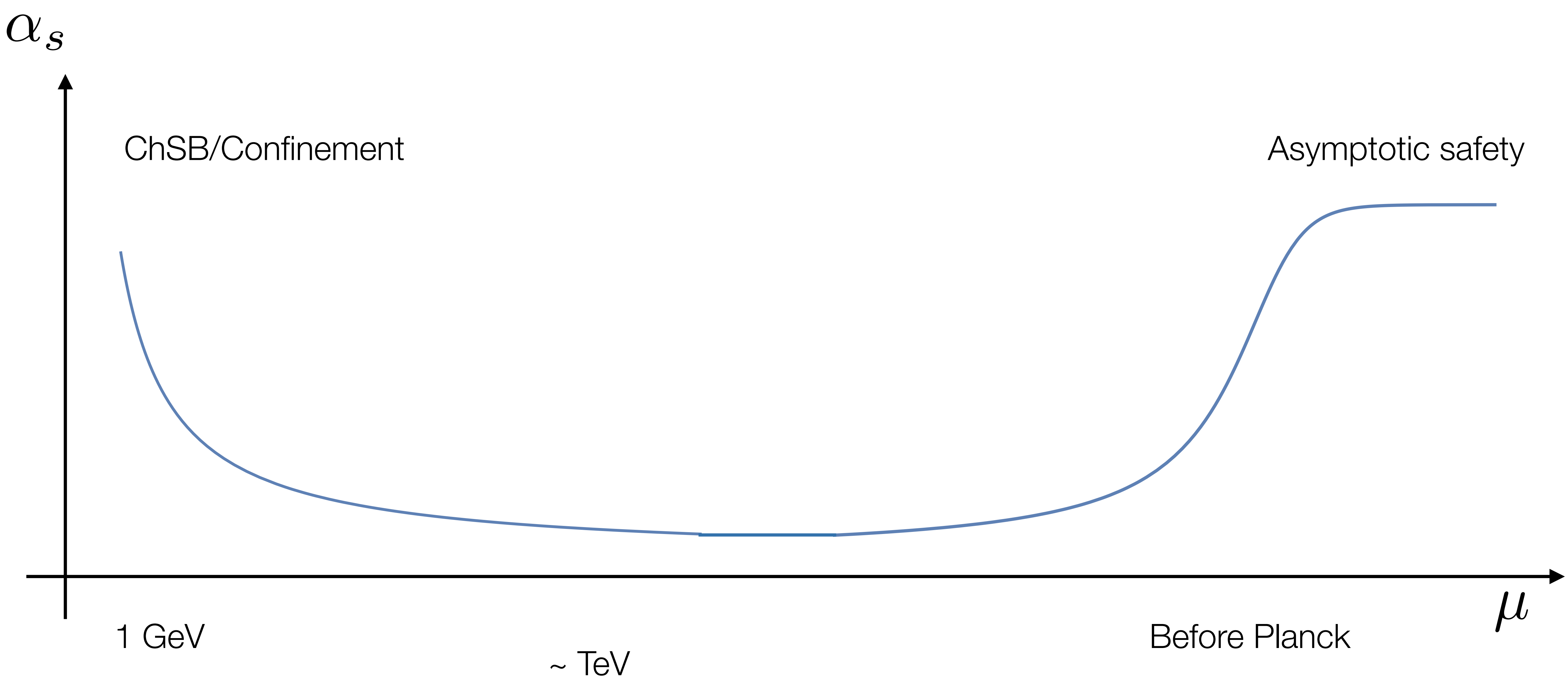


Pica & Sannino,1011.5917 PRD

Testing safe QCD scenarios

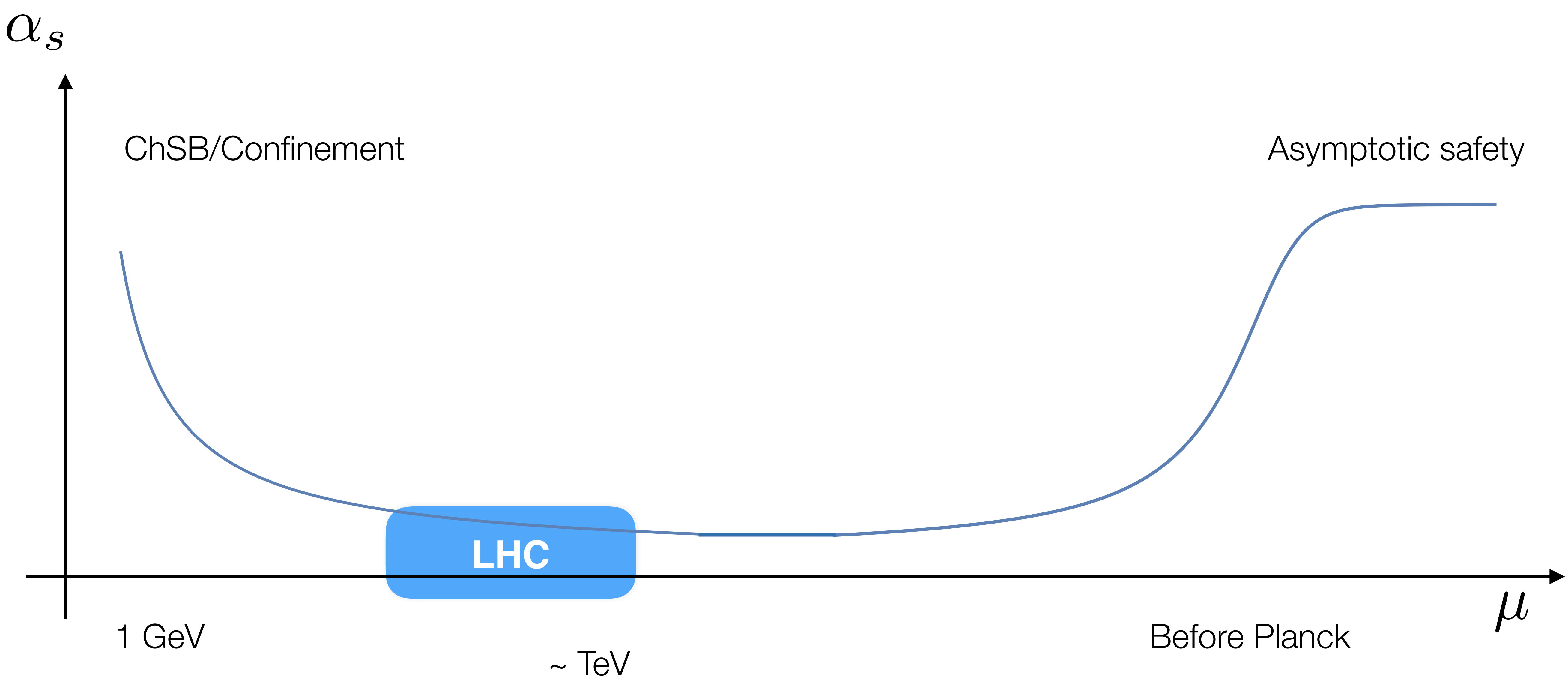
Sannino, 1511.09022



Asymptotic freedom is not a must for UV complete theories

Testing safe QCD scenarios

Sannino, 1511.09022

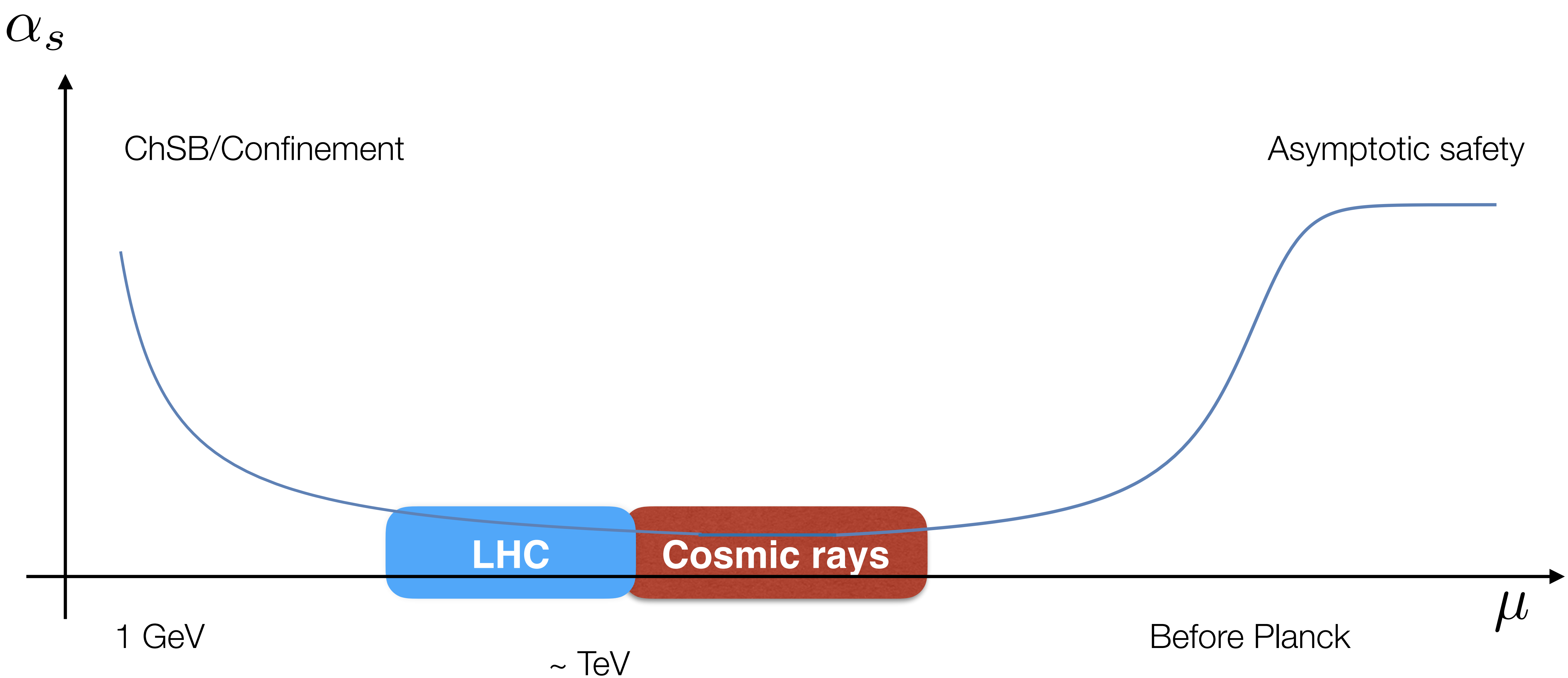


Asymptotic freedom is not a must for UV complete theories

Model independent tests of new coloured states at the LHC
Becciolini, Gillioz, Nardecchia, Sannino, Spannowsky 1403.7411, PRD

Testing safe QCD scenarios

Sannino, 1511.09022



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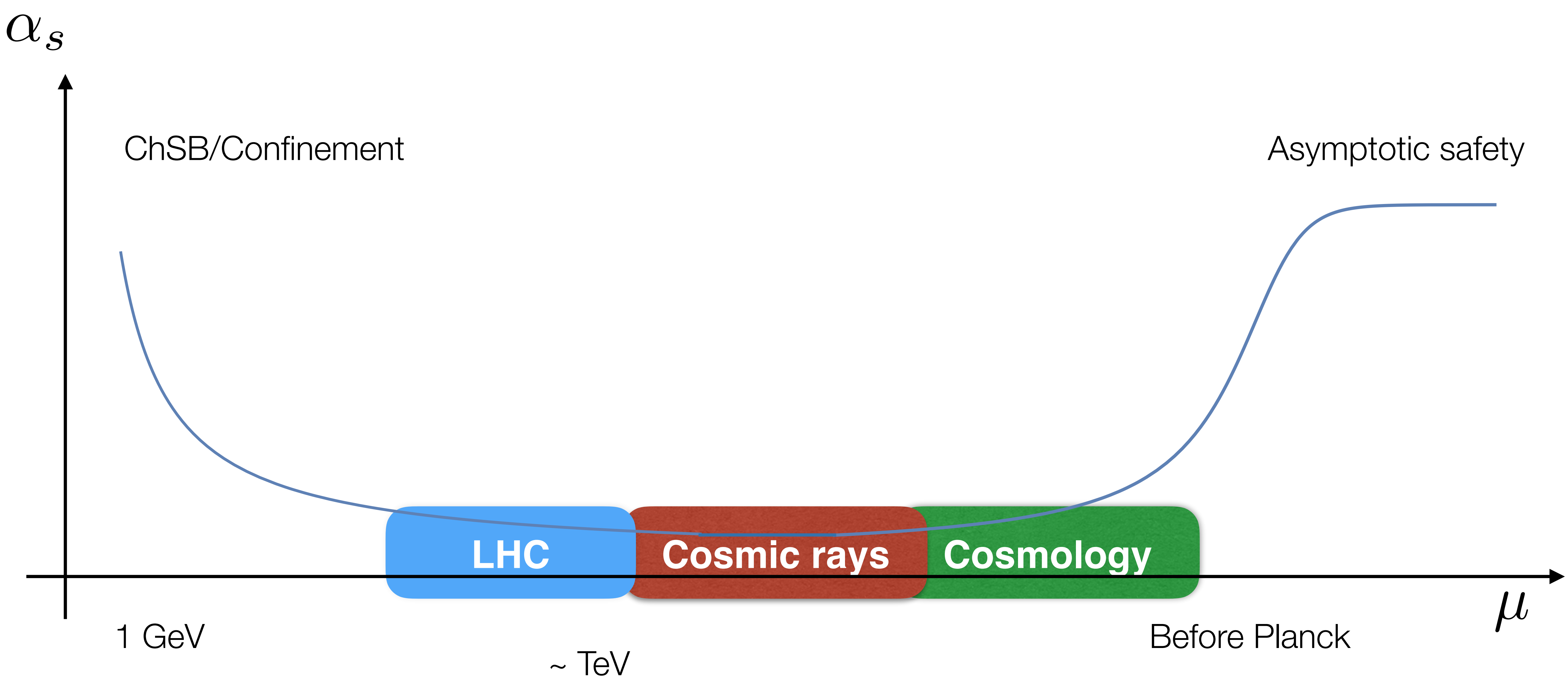

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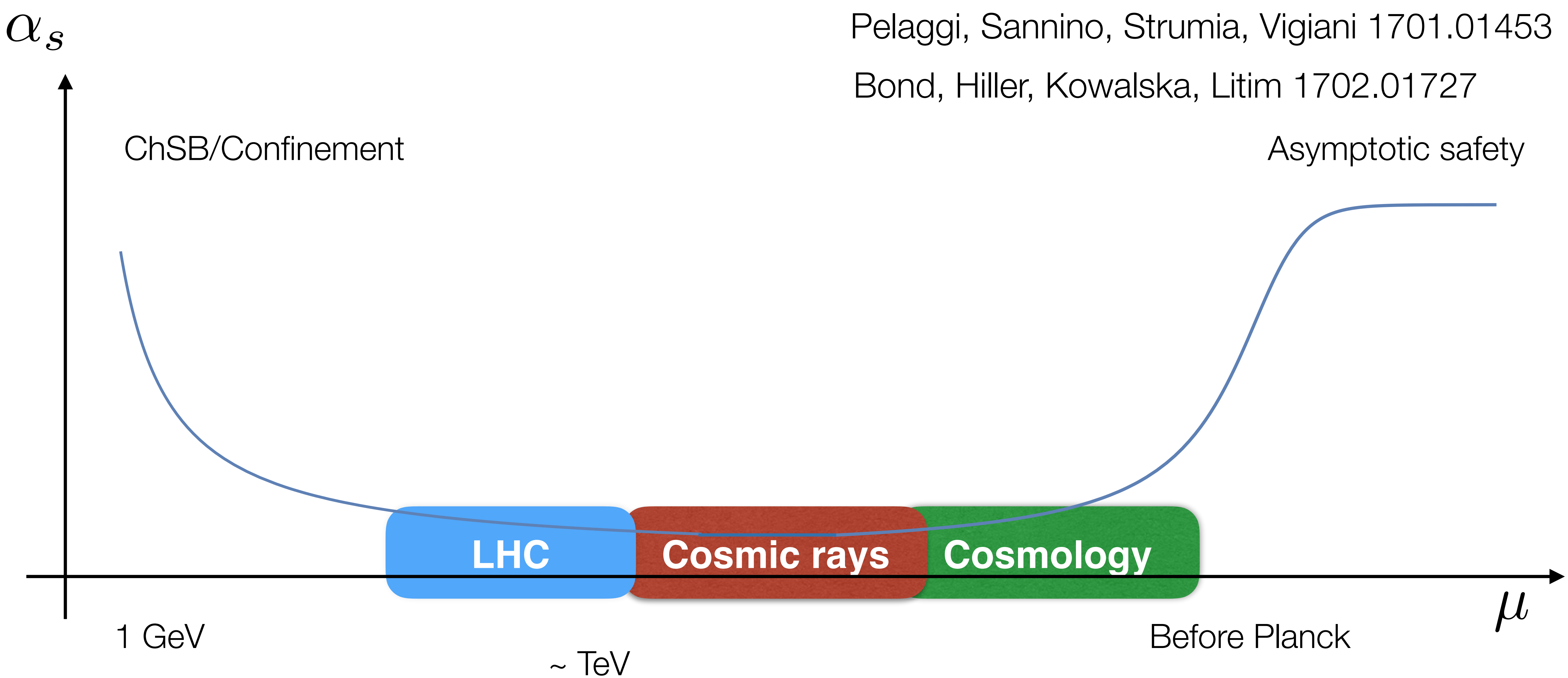
Pelaggi, Sannino, Strumia, Vigiani 1701.01453

Bond, Hiller, Kowalska, Litim 1702.01727



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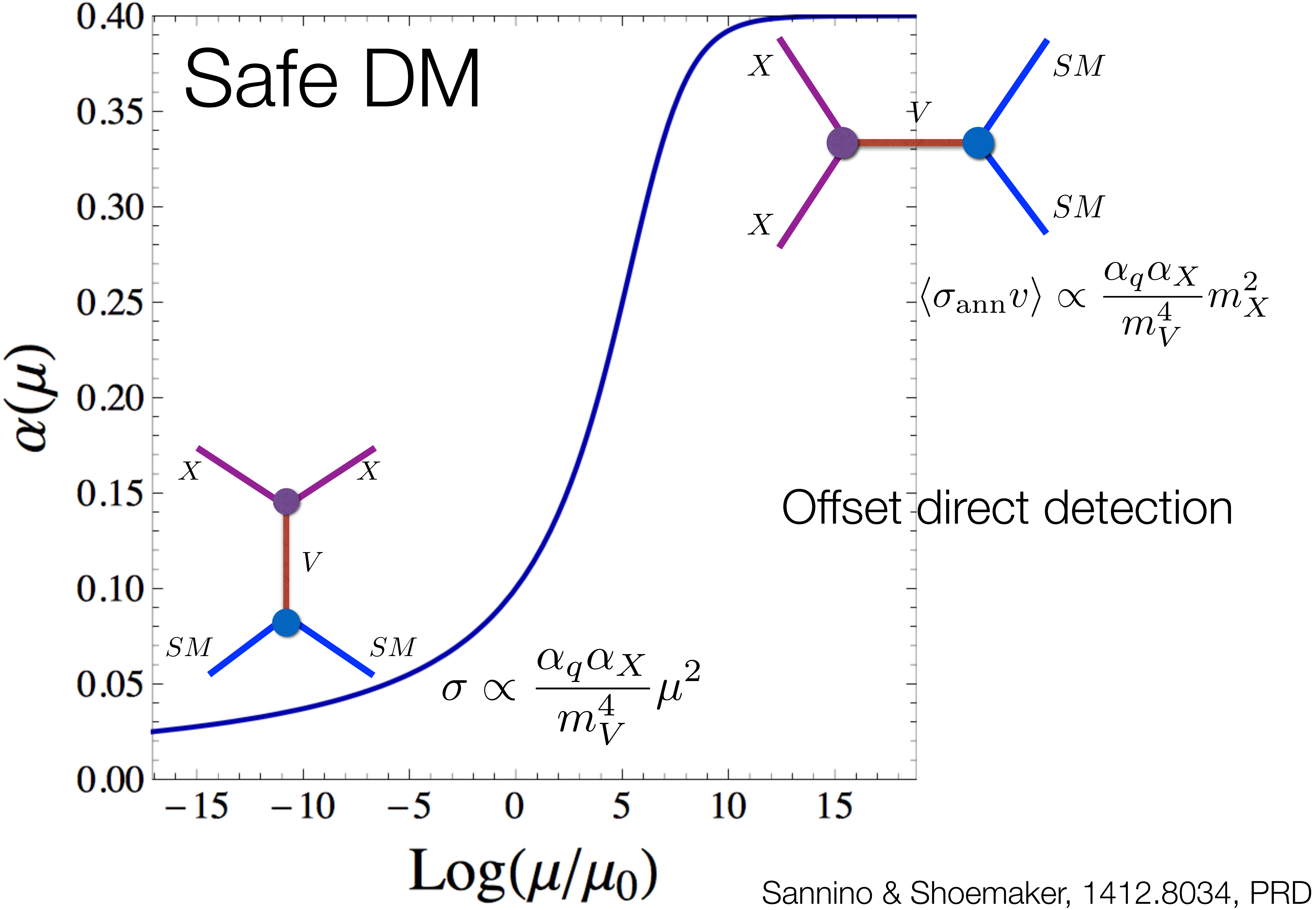
What next?

What next?

- Explore different paths for a safe extension of the SM
- Extend the number of (super) safe theories
- Cosmological and particle physics consequences
- Radiative symmetry breaking [Abel and Sannino 1704.00700]
- Interplay with gravity

Safe Dark Matter



Sannino & Shoemaker, 1412.8034, PRD