

# Hard talk on compositeness

Francesco Sannino

with Cacciapaglia | 402.0233

Pica | 604.02572

Strumia, Tesi e Vigiani, | 607.01659

Cacciapaglia, Gertov, Thomsen | 704.07845

Stangl, Straub, Thomsen. | 712.07646

DIAS

CP<sup>3</sup> Origins  
Cosmology & Particle Physics

# Why composite dynamics in 2018?

- ◆ Dynamical SM has occurred before (QCD)
- ◆ Rich spectrum and phenomenology
- ◆ Composite Flavour Dynamics including Flavour Anomalies
- ◆ Intriguing DM paradigms (see SIMP, TIMP, hidden worlds, ...)
- ◆ Can be natural, but it is not a must
- ◆ Microscopic theory can be fundamental a la Wilson (Safe or Free)

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*Tremendous progress in charting strong dynamics*

*Conformal Window 1.0 and 2.0*

# Types of compositeness

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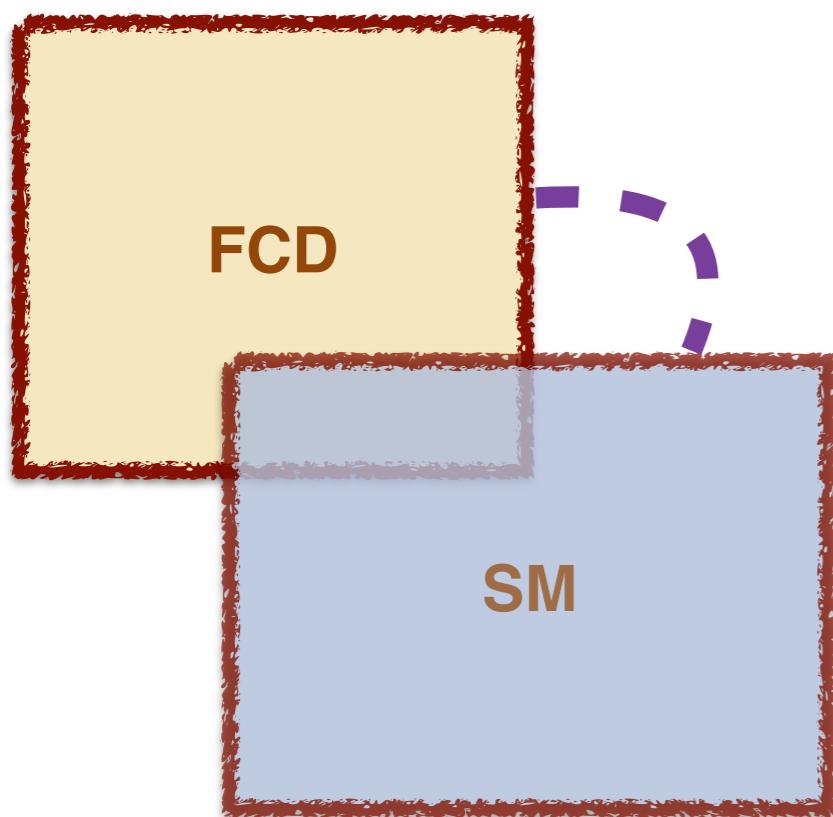
Building Blocks

# Types of compositeness

Building Blocks

SM charged

Type I



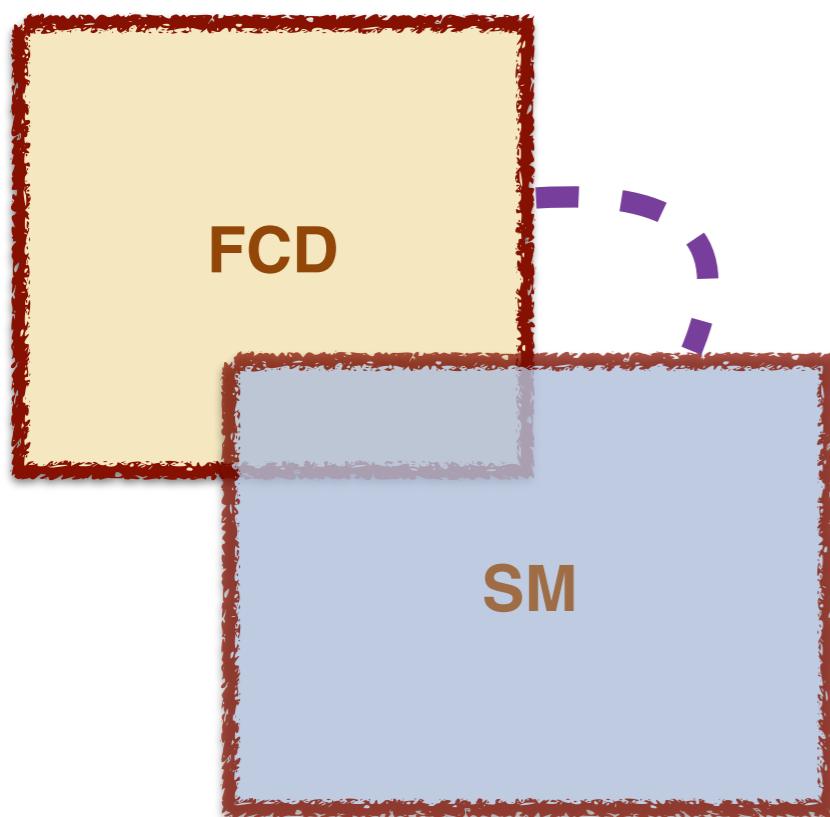
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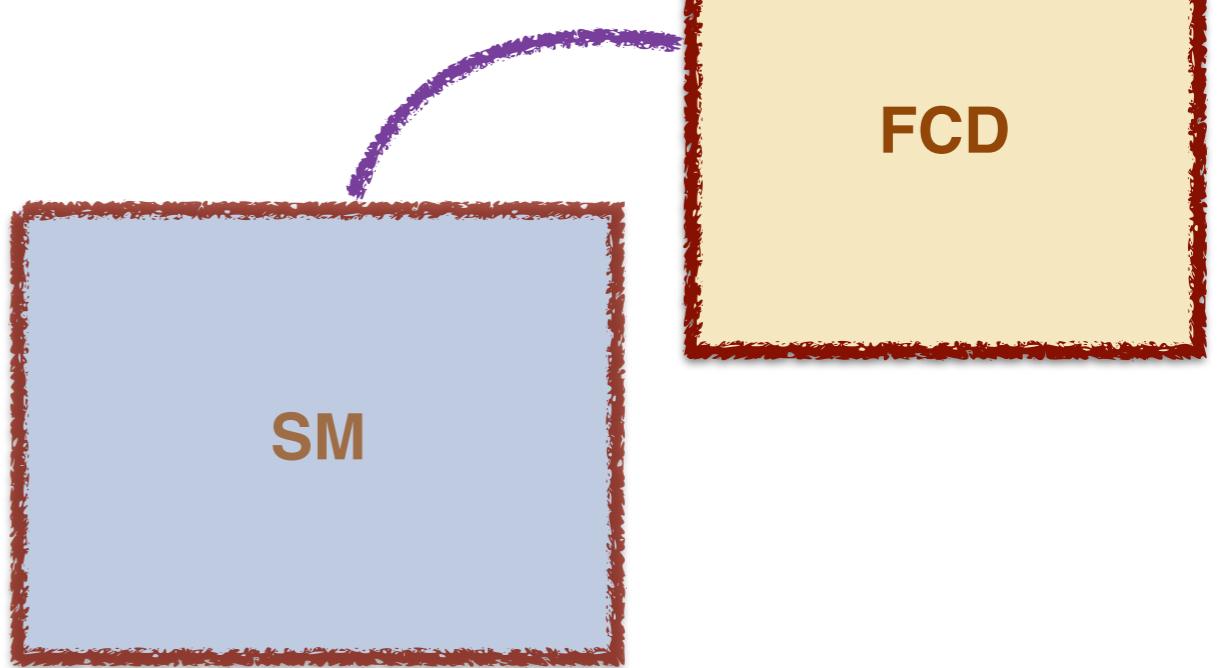
SM charged

SM singlets

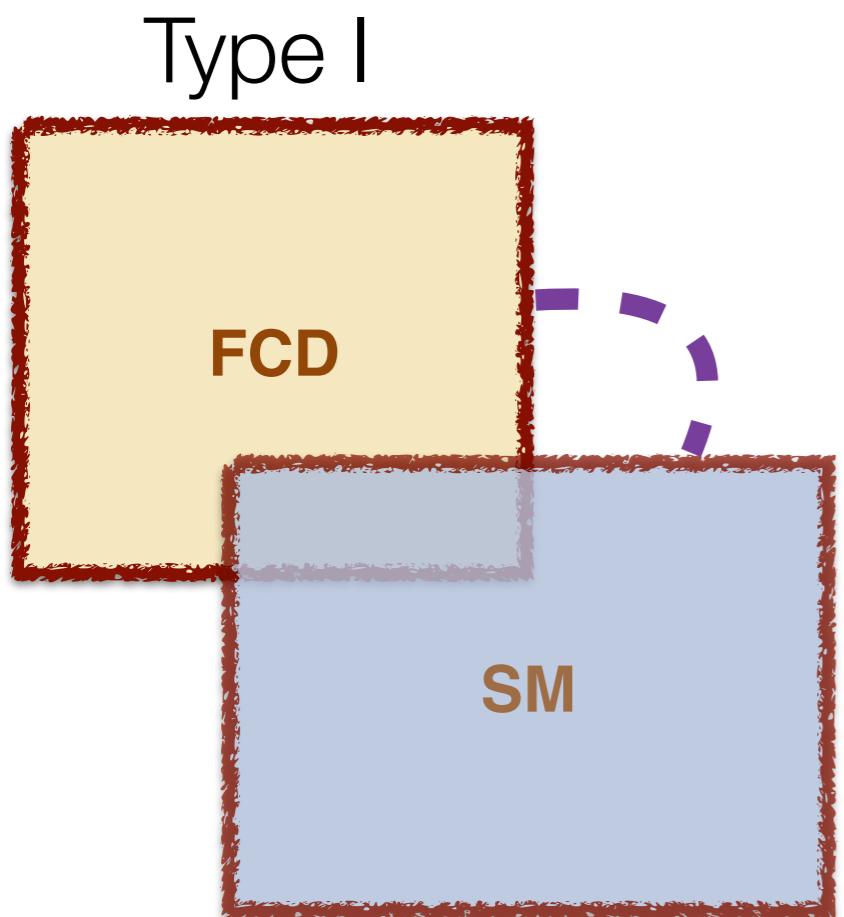
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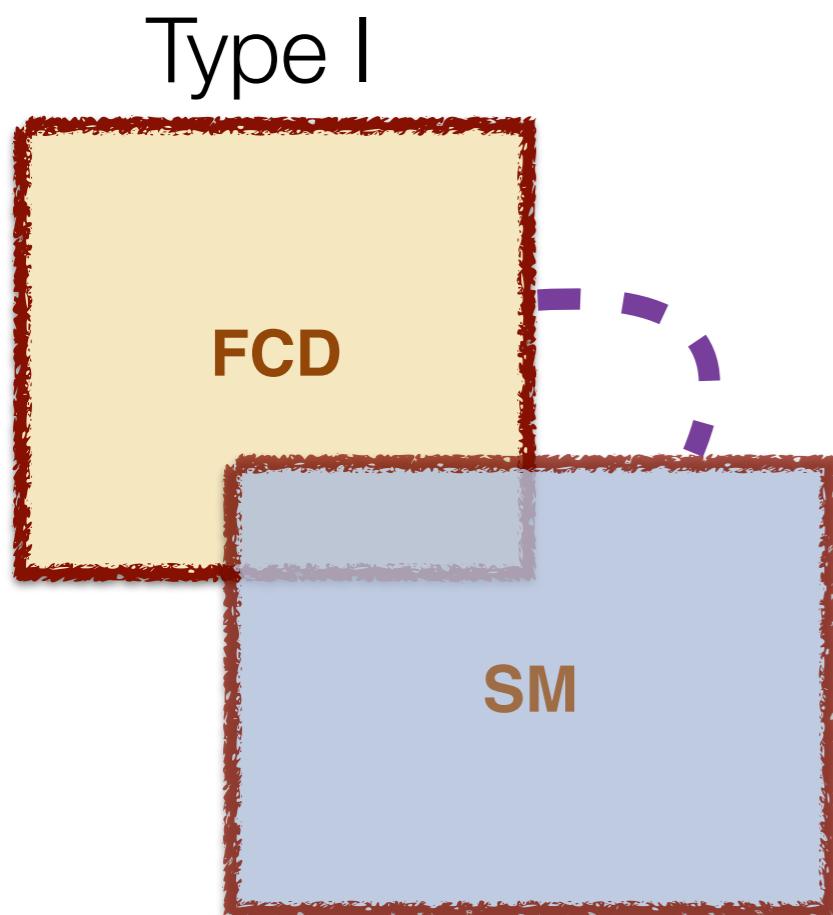
Type II



# FCD Type I



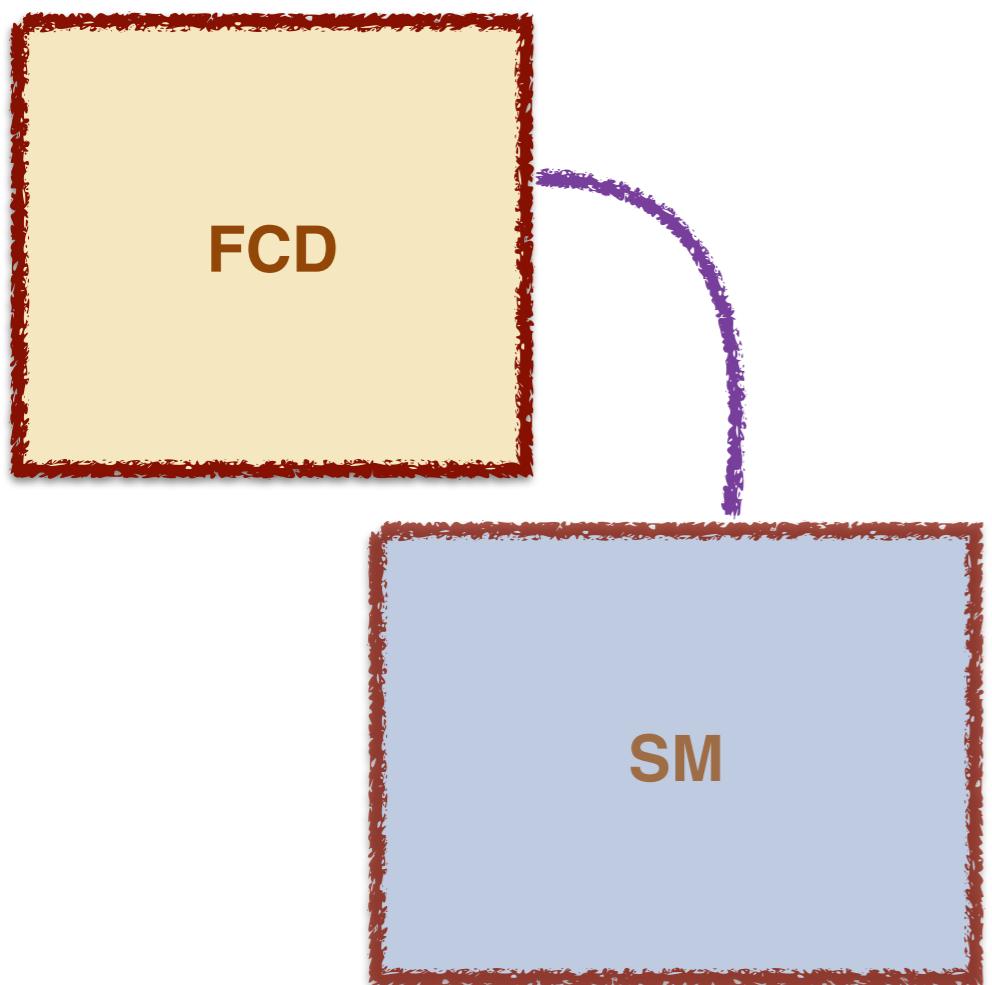
# FCD Type I



- Fundamental Composite Higgs
- TC Baryon DM
- TC Meson DM
- Stealth DM
- Solitons/Little Higgs
- ....

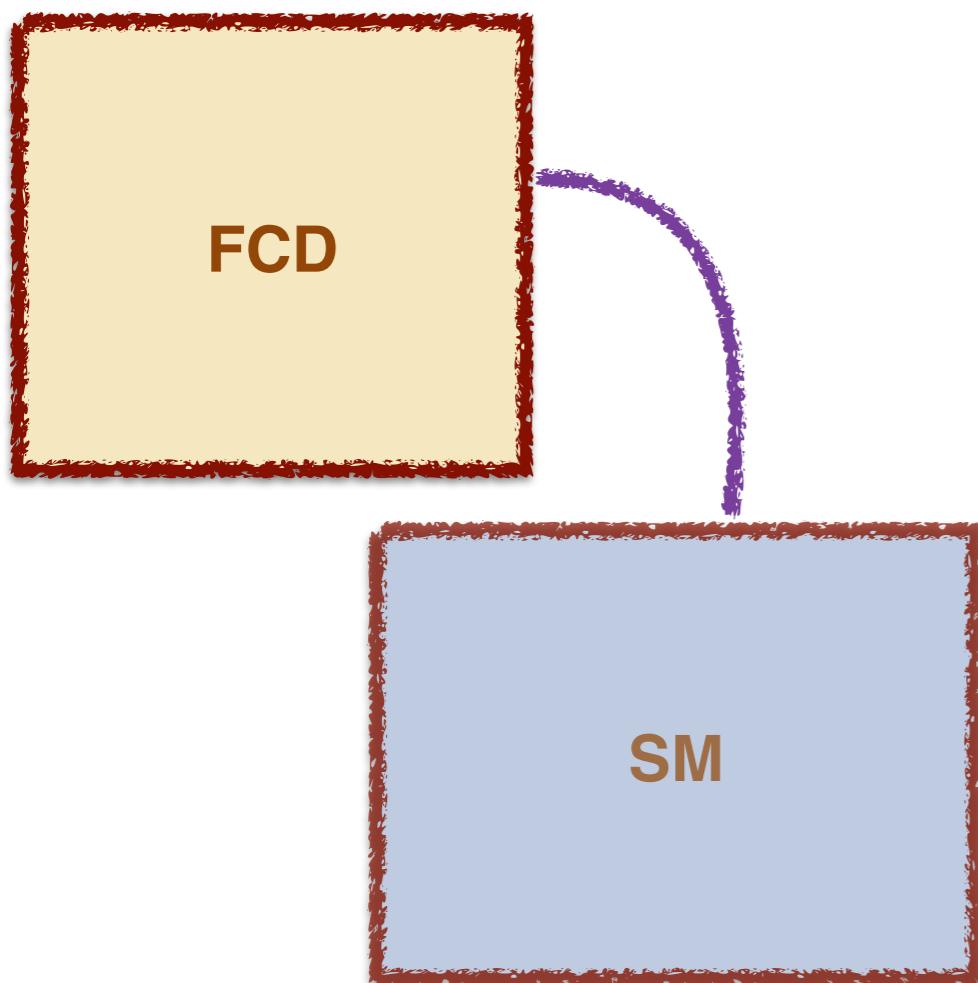
# FCD Type II

Type II



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Type II



- Dark Nuclei
- SIMPlest Miracle
- Solitonic
- ....

# Partial Composite Goldstone Higgs

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Higgs is a composite pseudo goldstone SM doublet

D.B. Kaplan & H. Georgi, 84

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SM fermions masses via (effective) Lagrangian operators

$$f\mathcal{B}$$

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Extra-dim, no-lagrangian approaches, (in)effective theories

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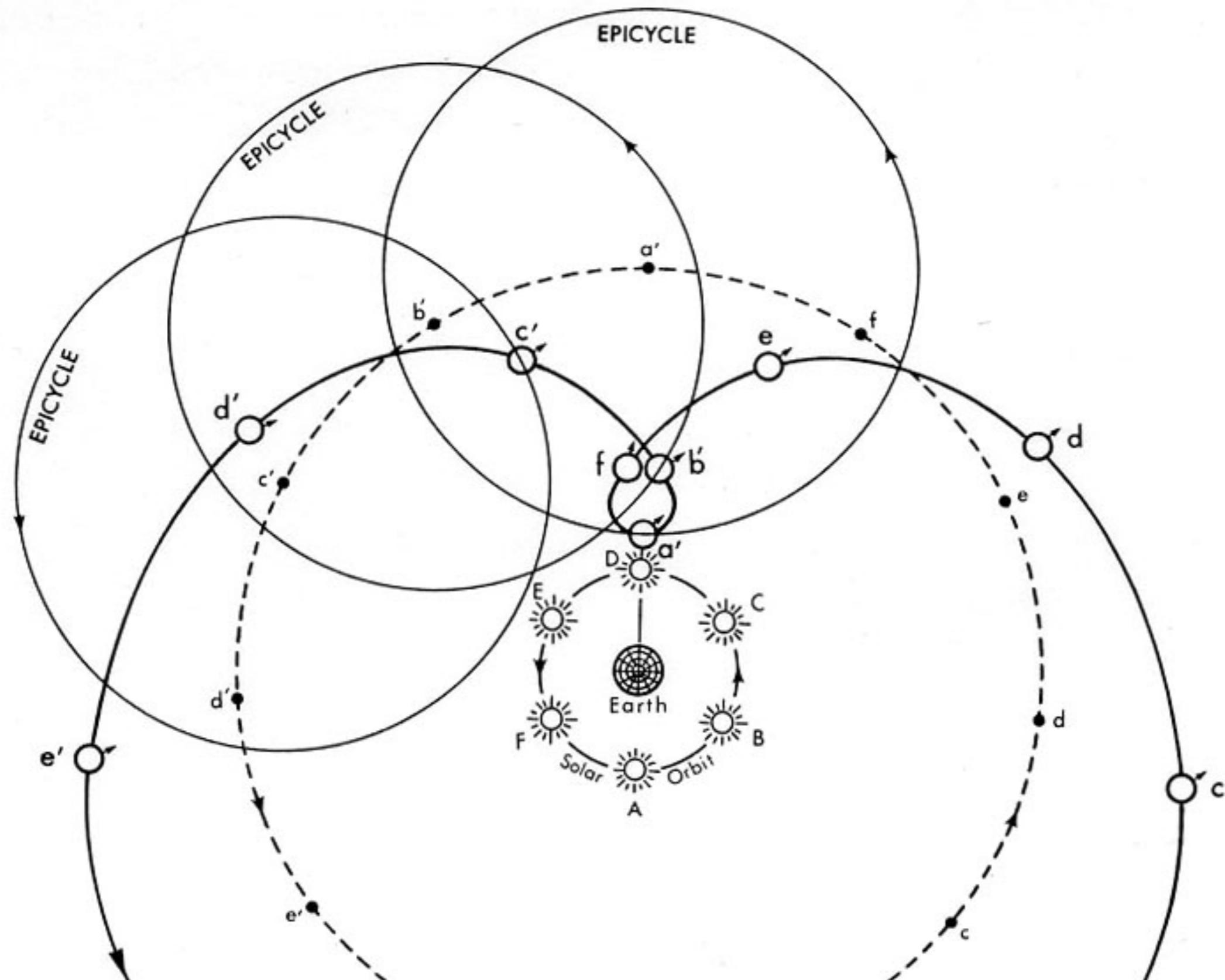
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Extra-dim, no-lagrangian approaches, (in)effective theories

*It talks like a Higgs, it walks like a Higgs, but it is not the Higgs*

Price of naturalness

# Ptolemaic Fermion Mass-Generation



so far..

- ◆ QQX, QQQ UV attempts by Cacciapaglia, Gerghetta, Ferretti, Vecchi, FS
- ◆ Phenomenology by Buttazzo, Cacciapaglia, De Andrea, De Curtis, Isidori, Moretti, Nardecchia, Pomarol, Redi, Tesi ...
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*No microscopic fermion theory exists able to give masses to SM fermions*

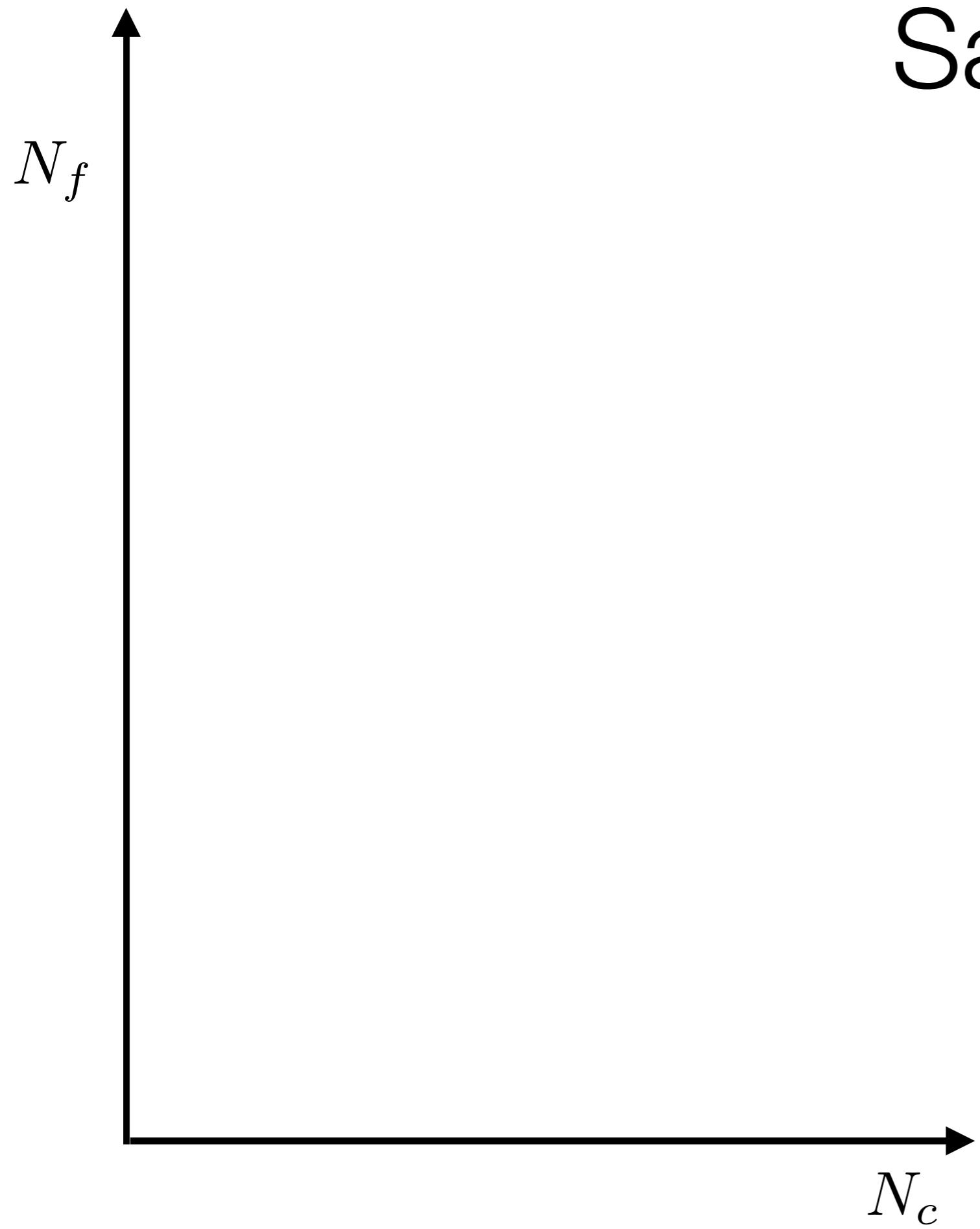
*A small revolution*

# Conformal Window 2.0: Large Nf Story

Sannino, ERG 2016, Heidelberg

Antipin and Sannino, 1709.02354

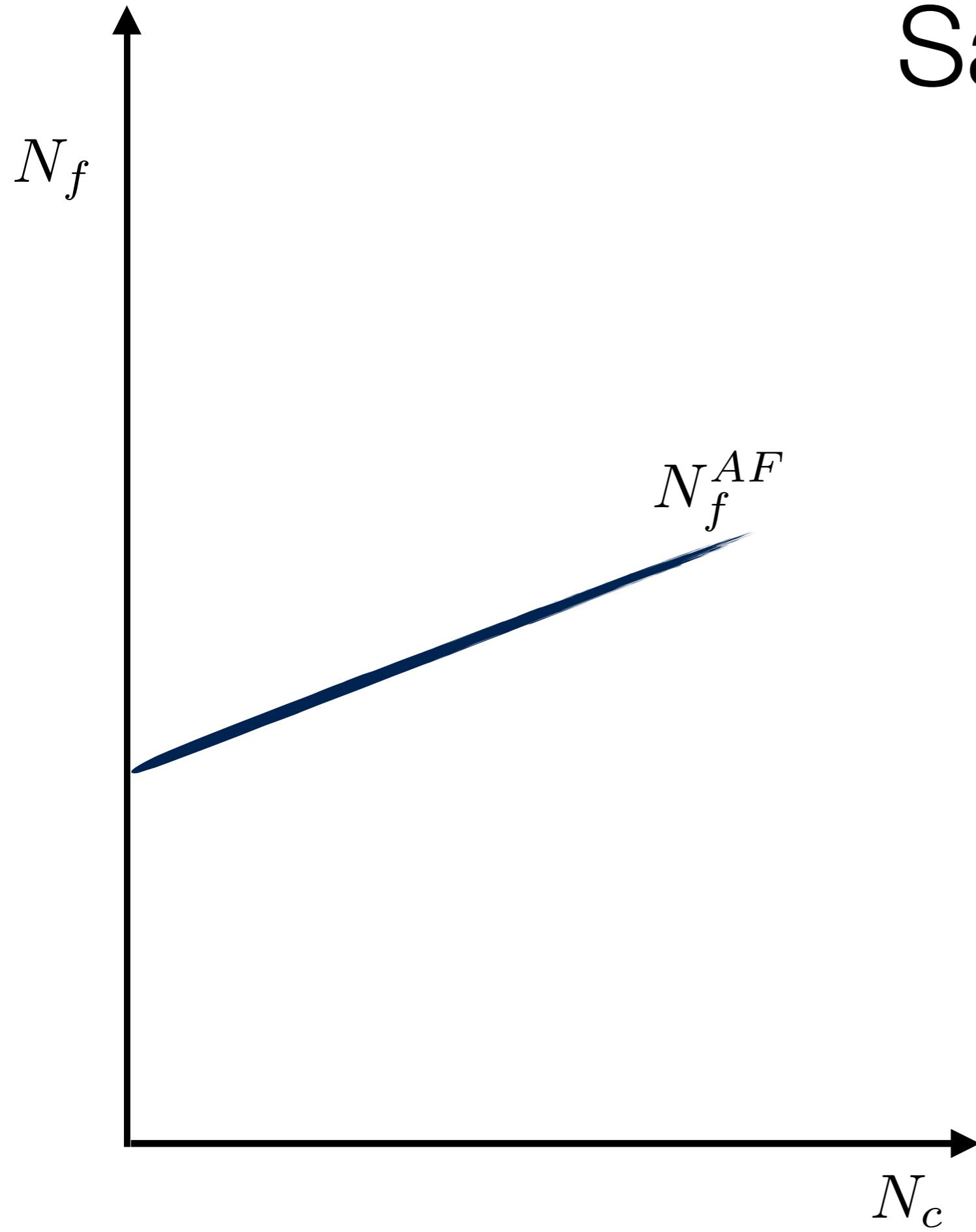
# Safe QCD



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Pica and Sannino 1011.5917, PRD

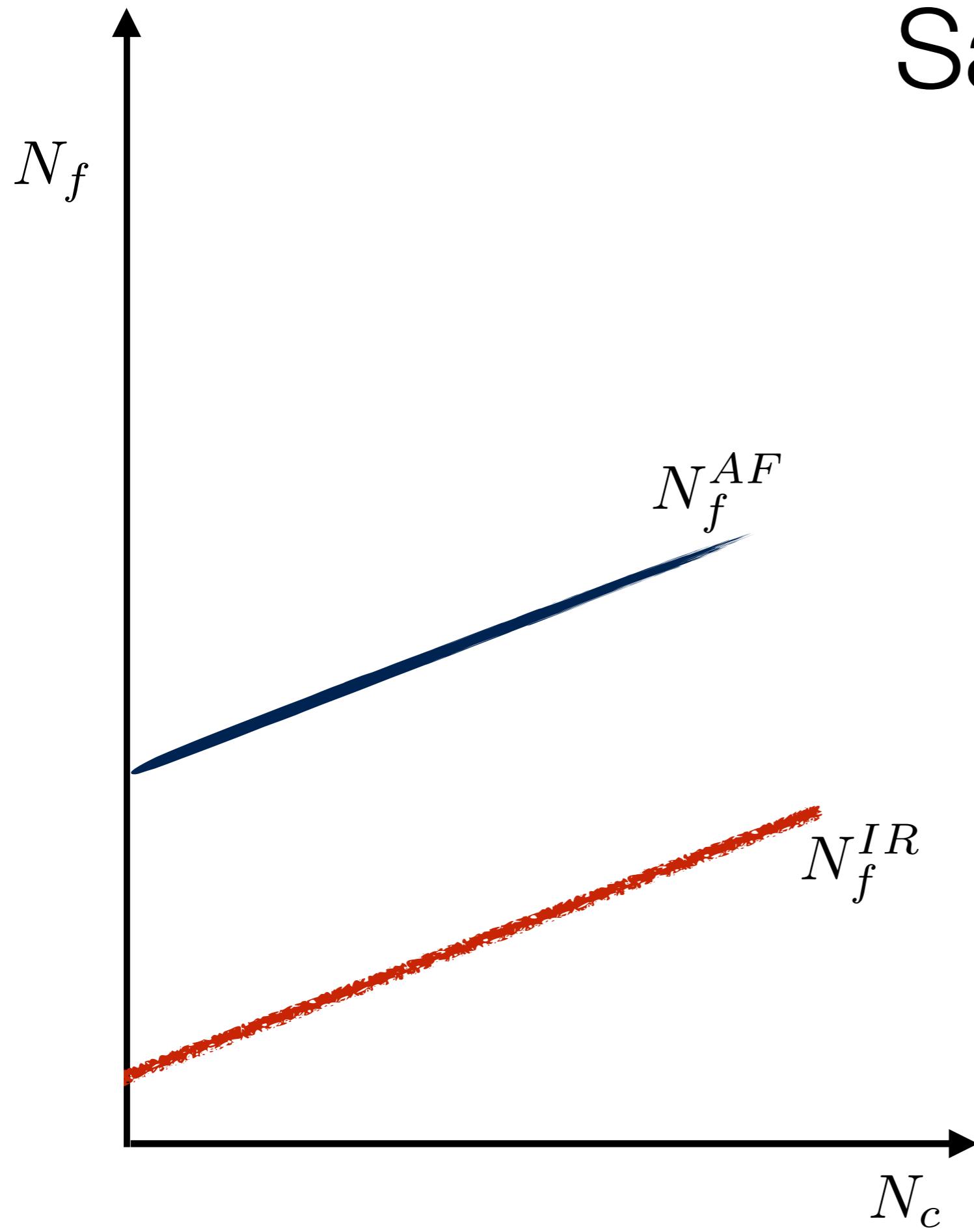
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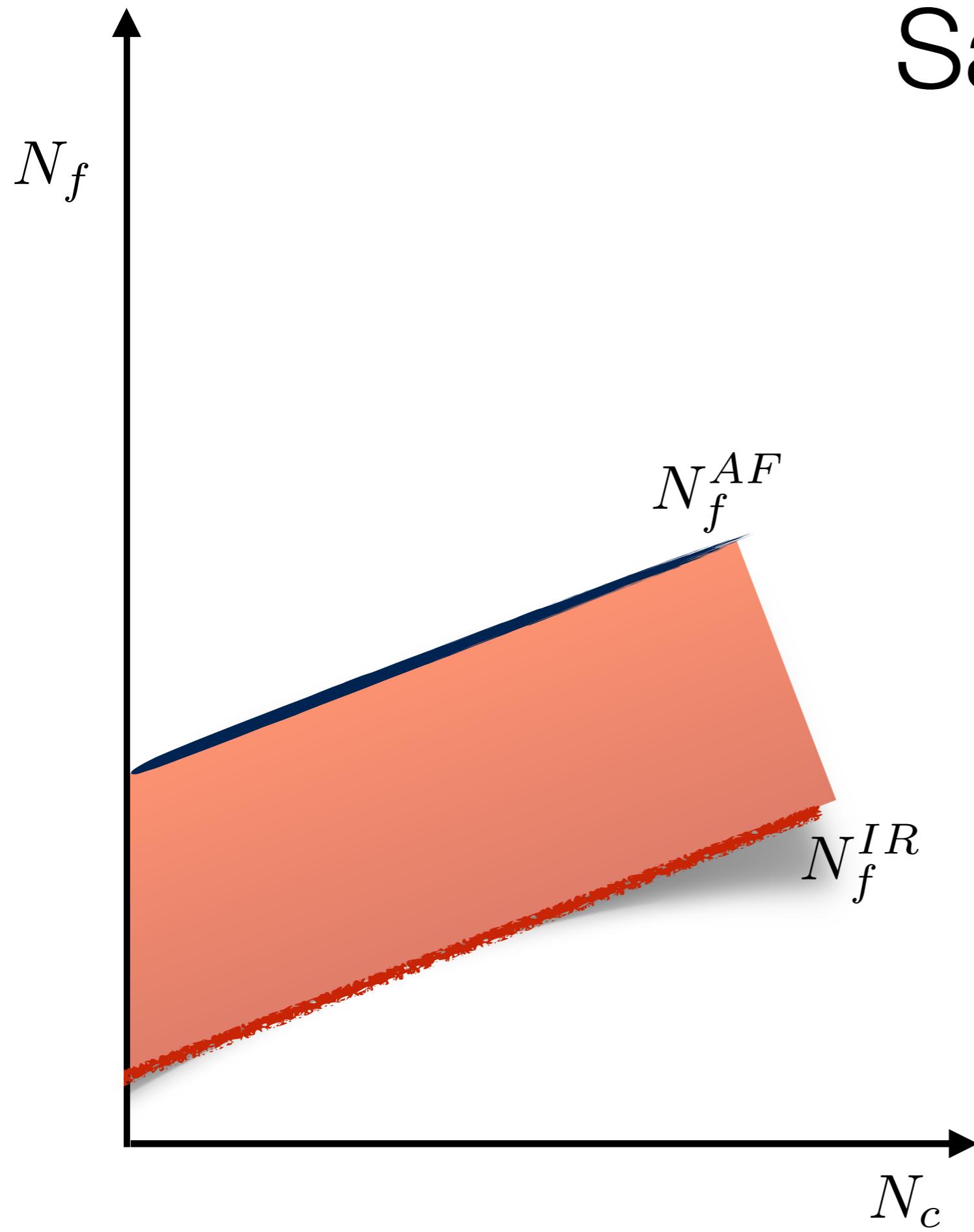
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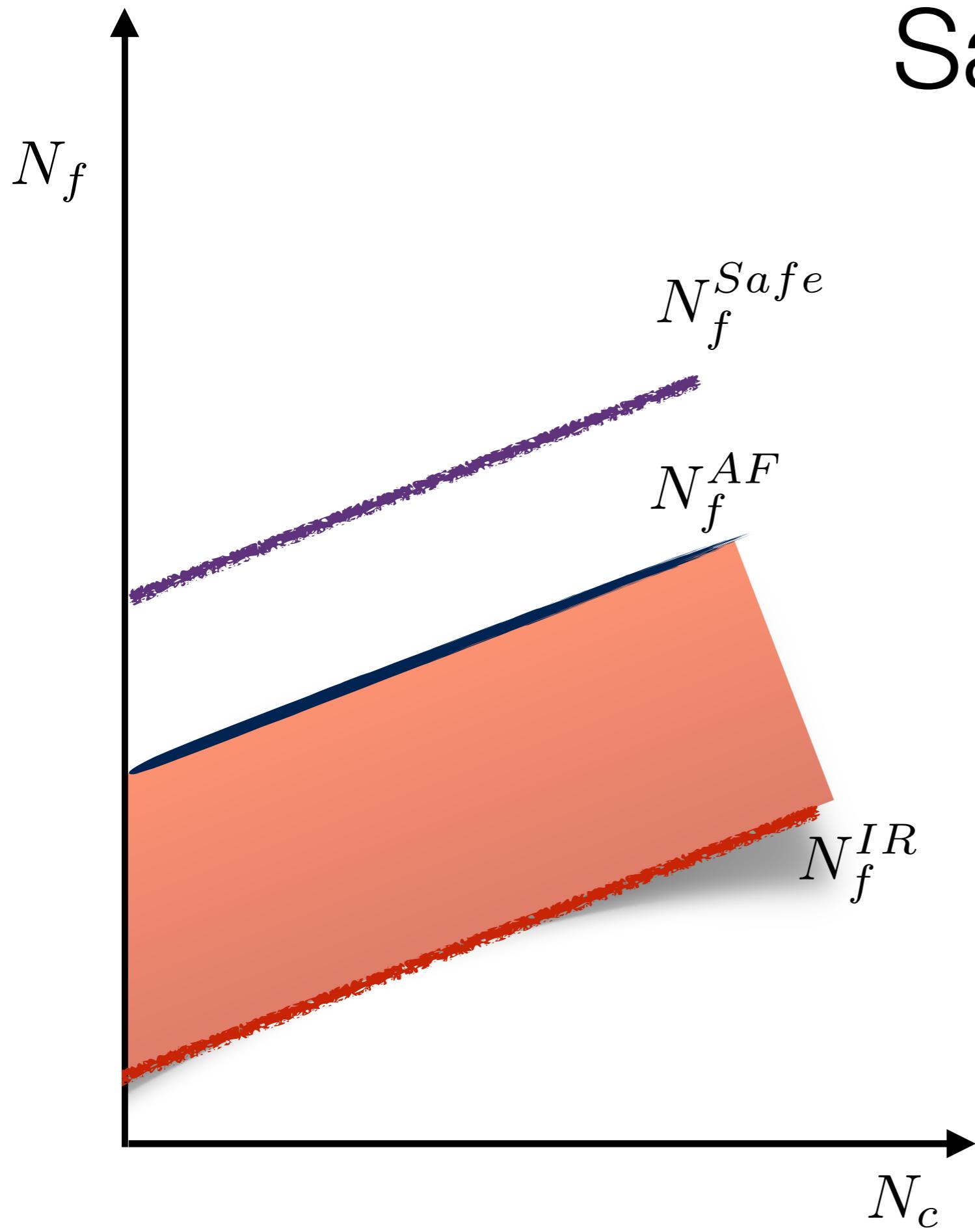
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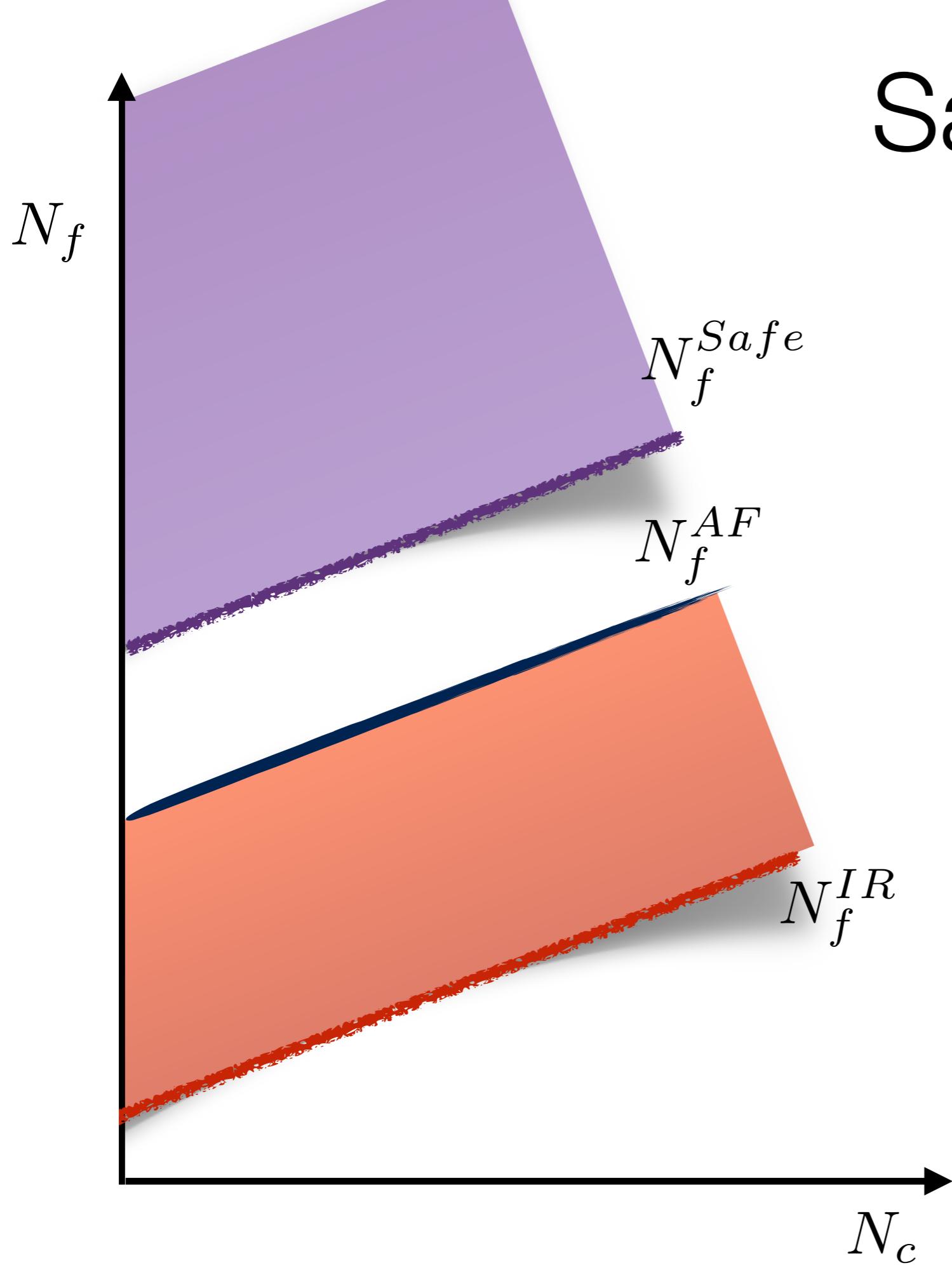
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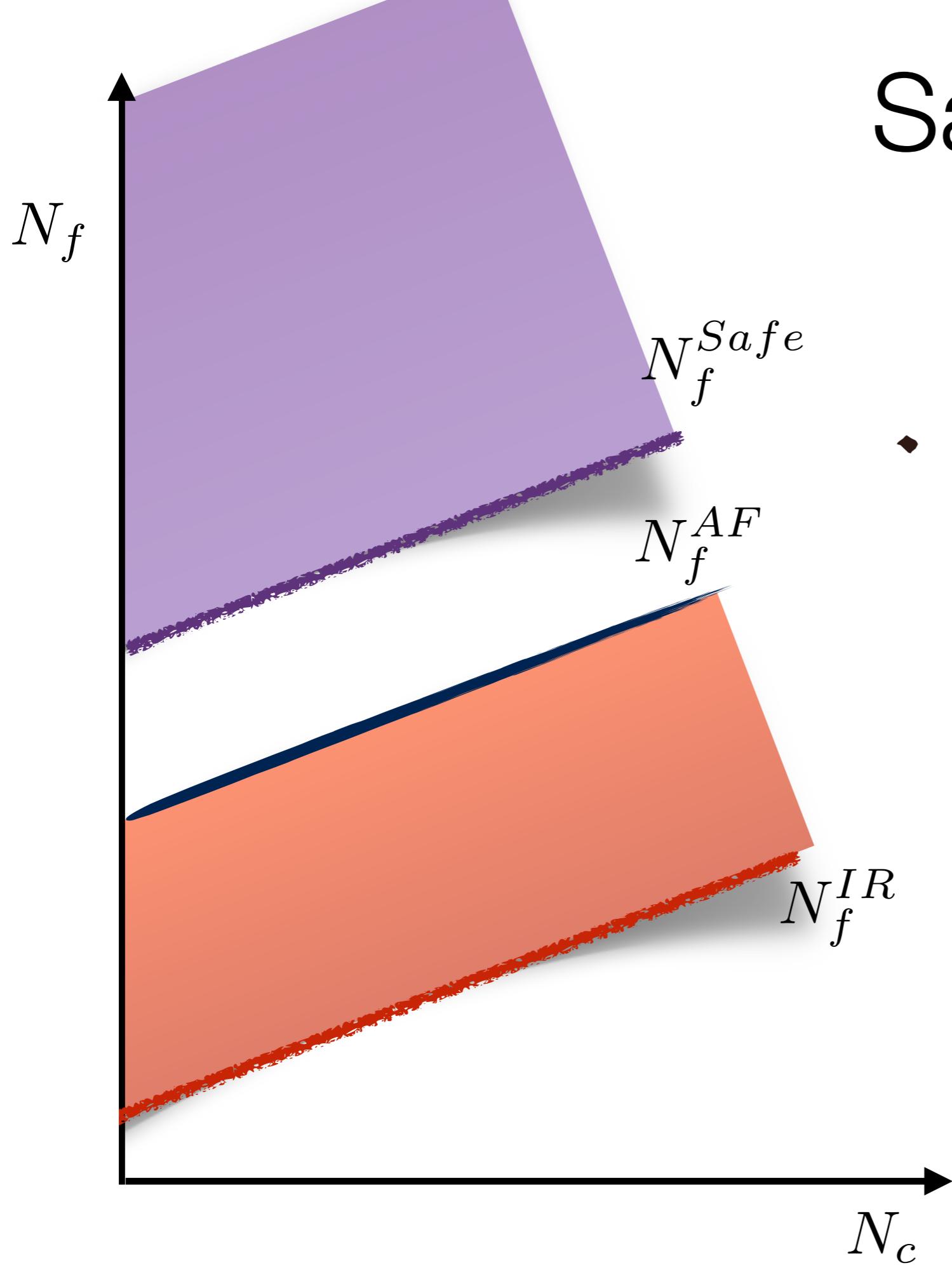
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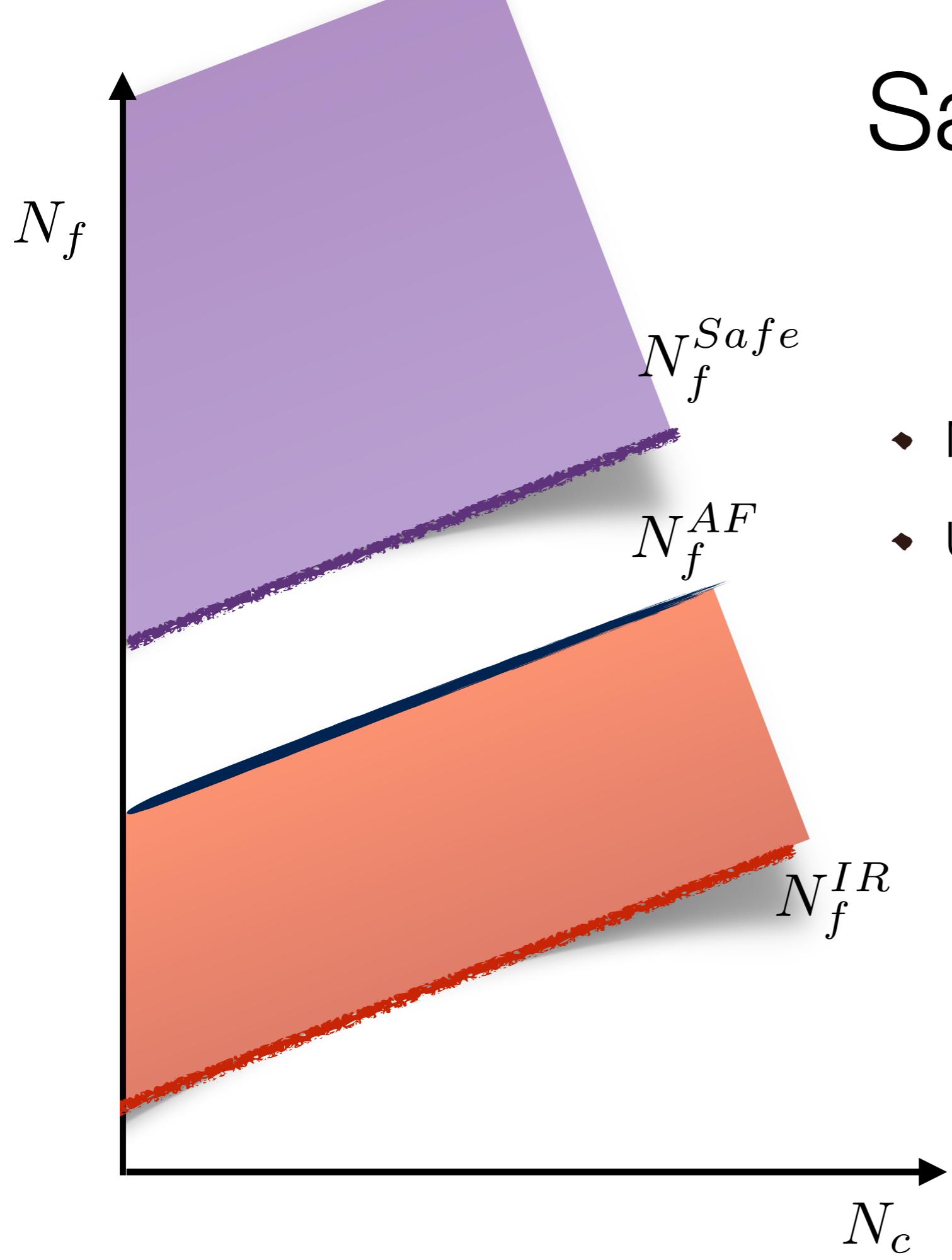


- ◆ Must exist a critical Safe  $N_f$

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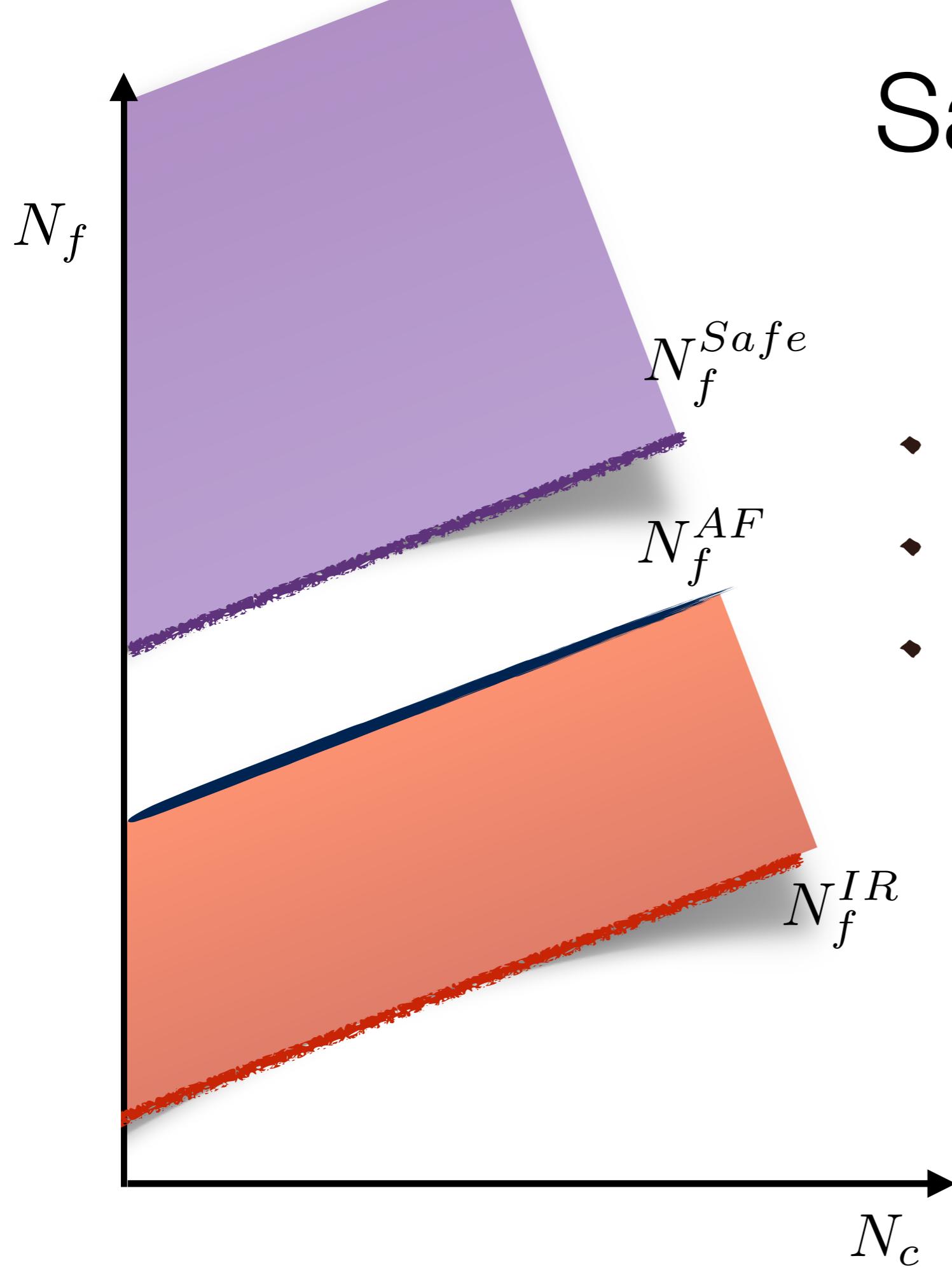


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- ◆ Unsafe region in  $N_f$ - $N_c$

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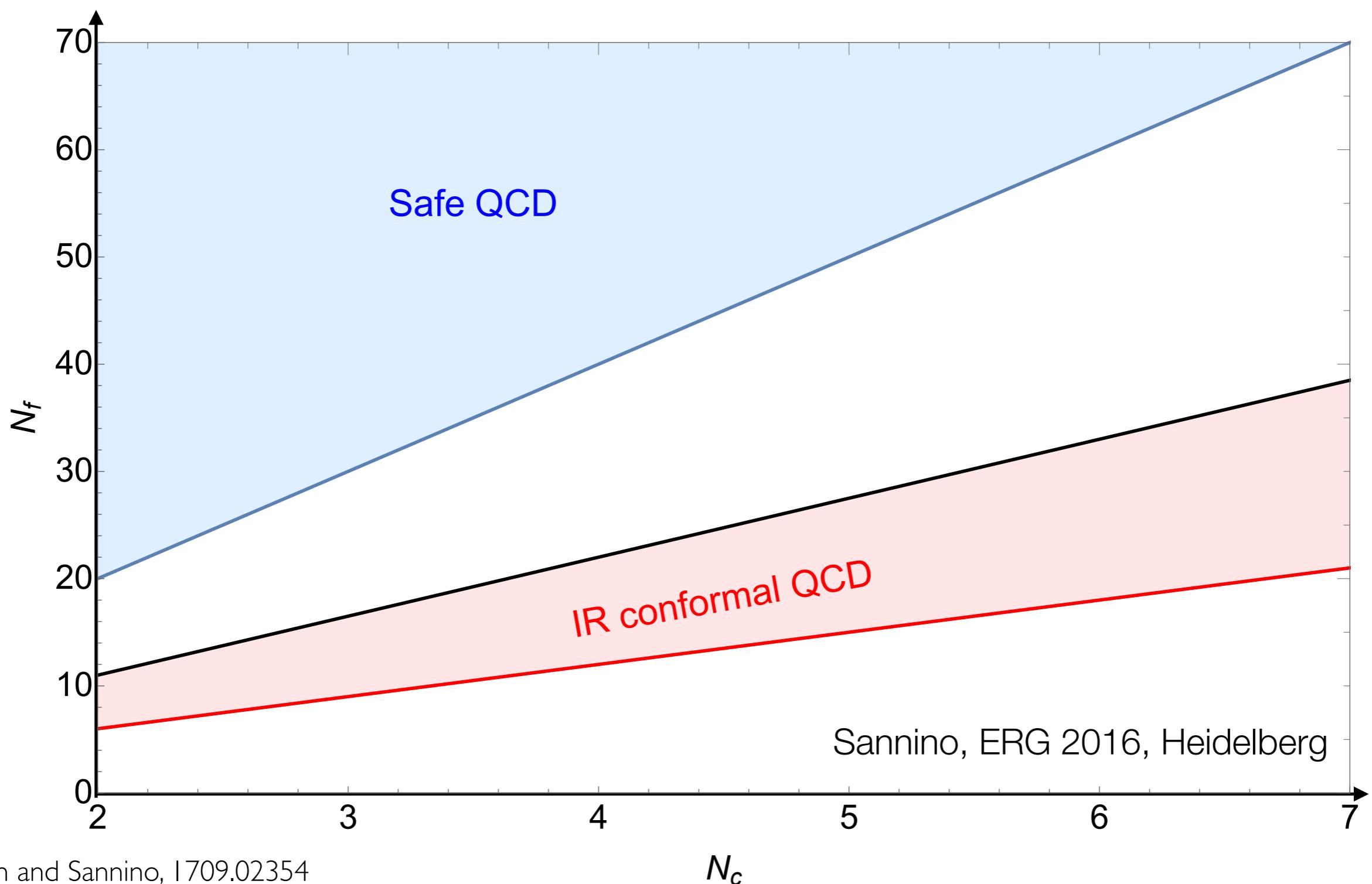


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- ◆ Unsafe region in  $N_f$ - $N_c$
- ◆ Continuous (Walking) transition?

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# Safe QCD: Conformal Window 2.0



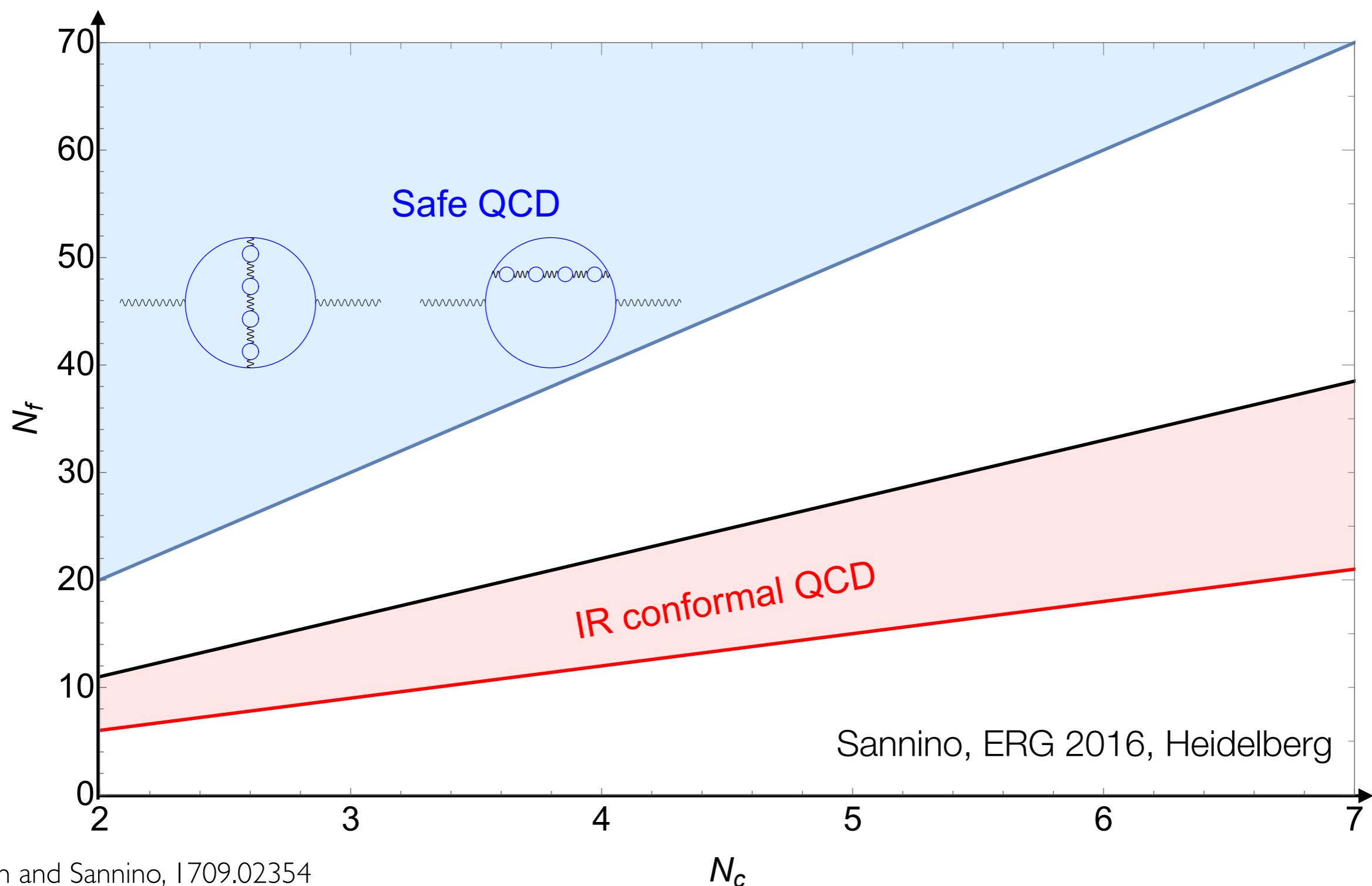
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Palanques-Mestre, Pascual, Commun. Math. Phys. 84

Gracey, PLB, 96, Holdom PLB 2011

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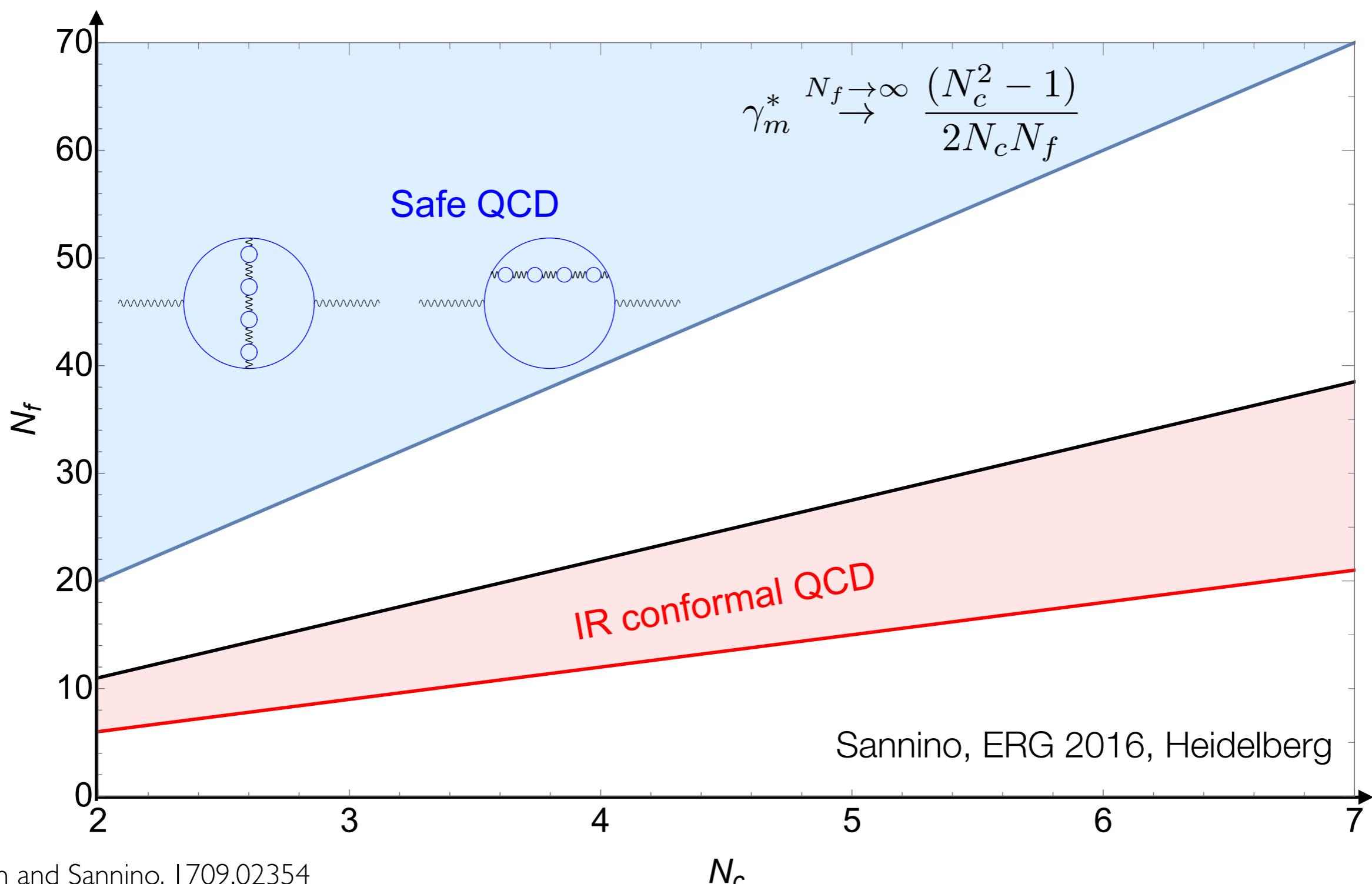
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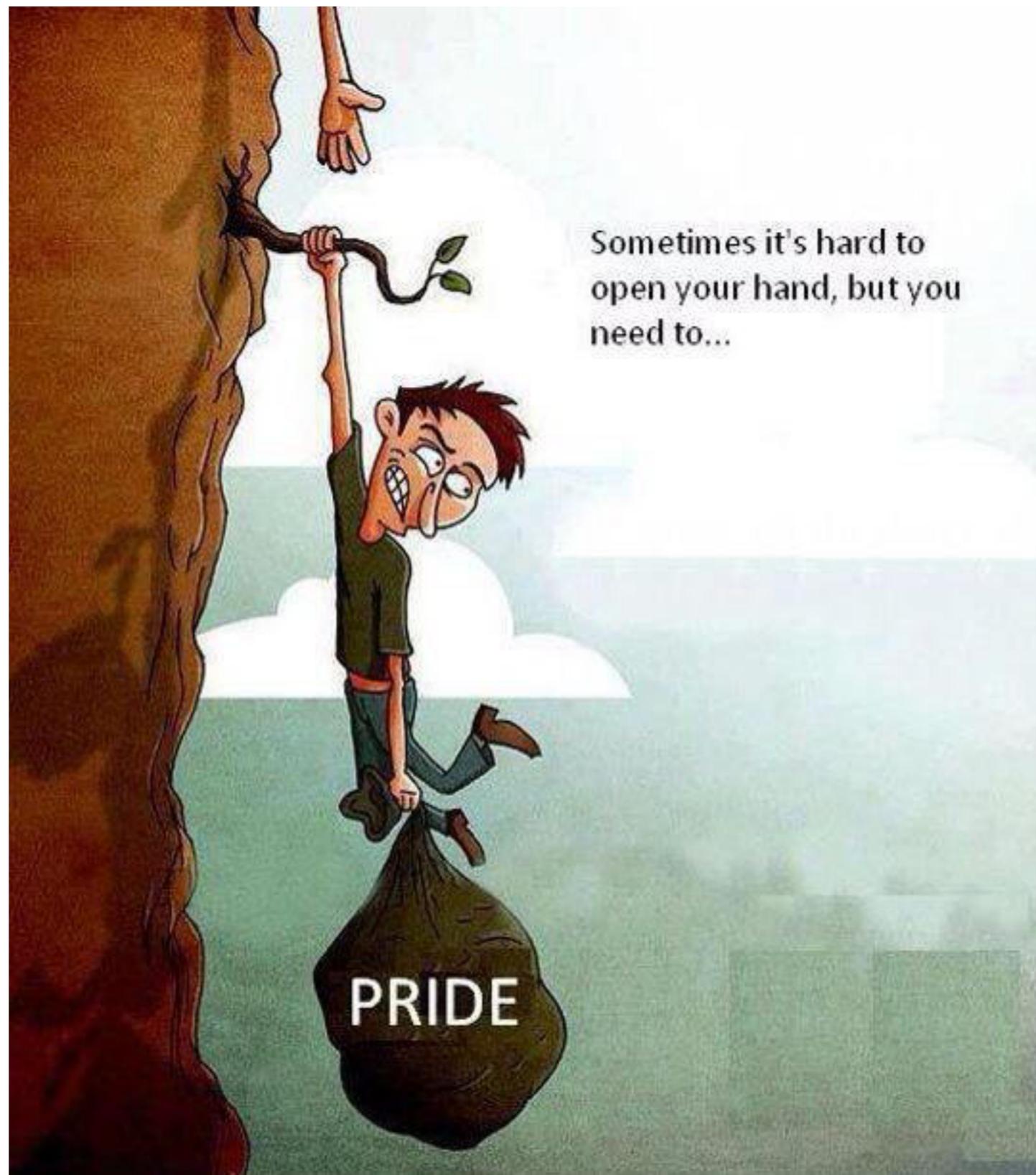
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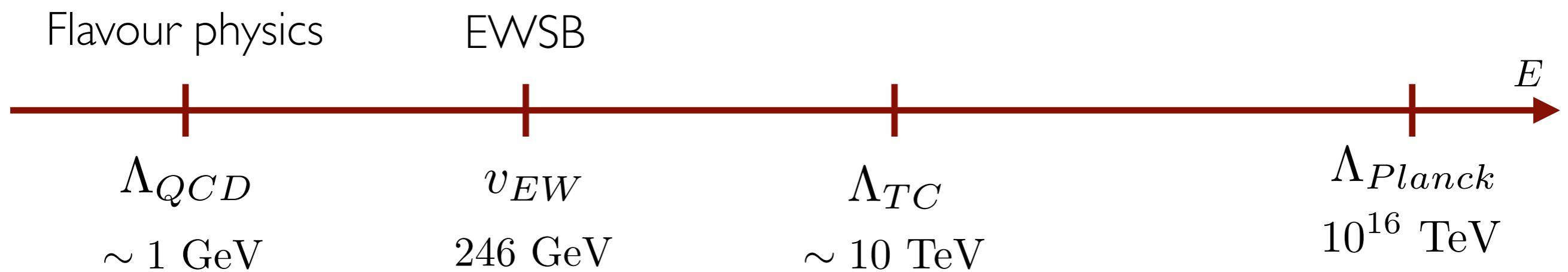
# Fermion mass generation with only TC fermions



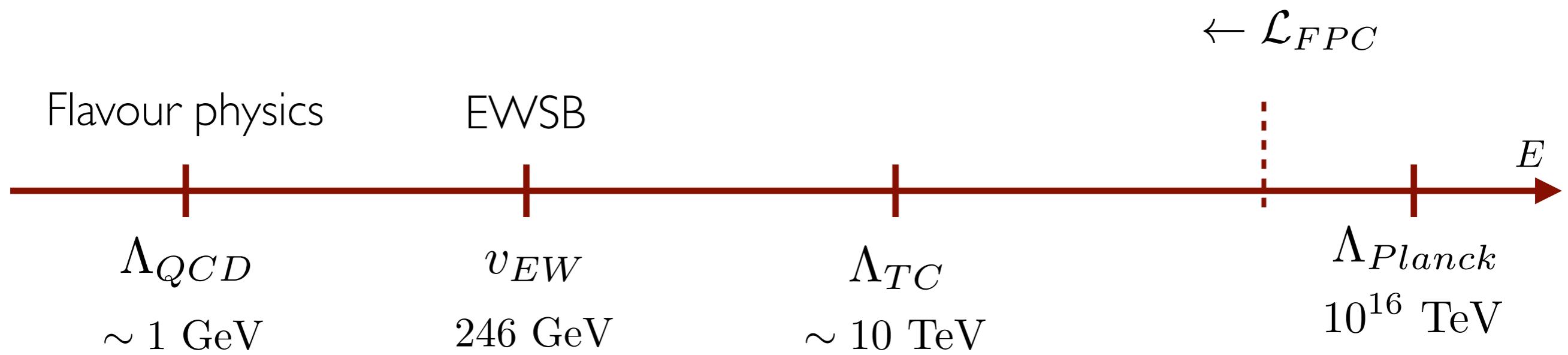


Sometimes it's hard to  
open your hand, but you  
need to...

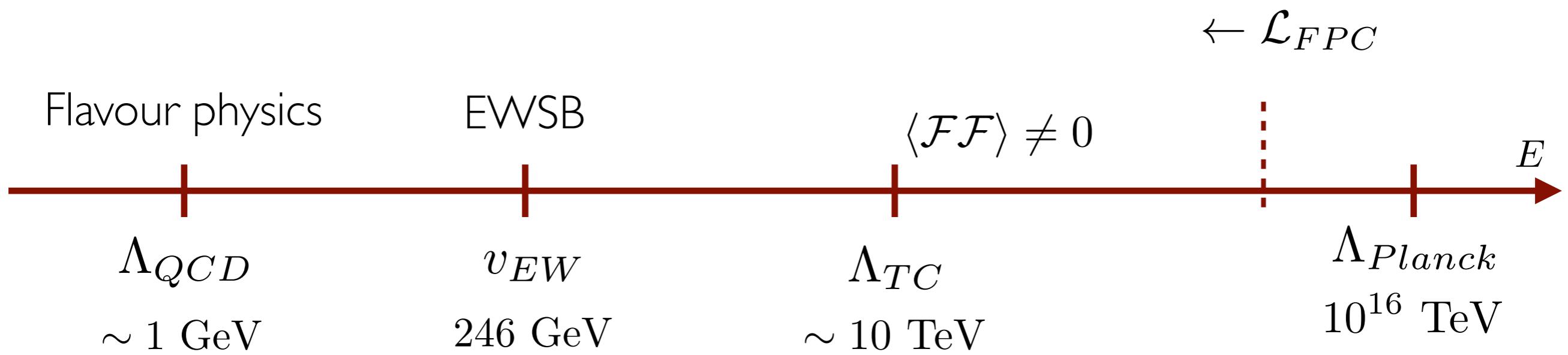
# Fundamental (Partial) Compositeness



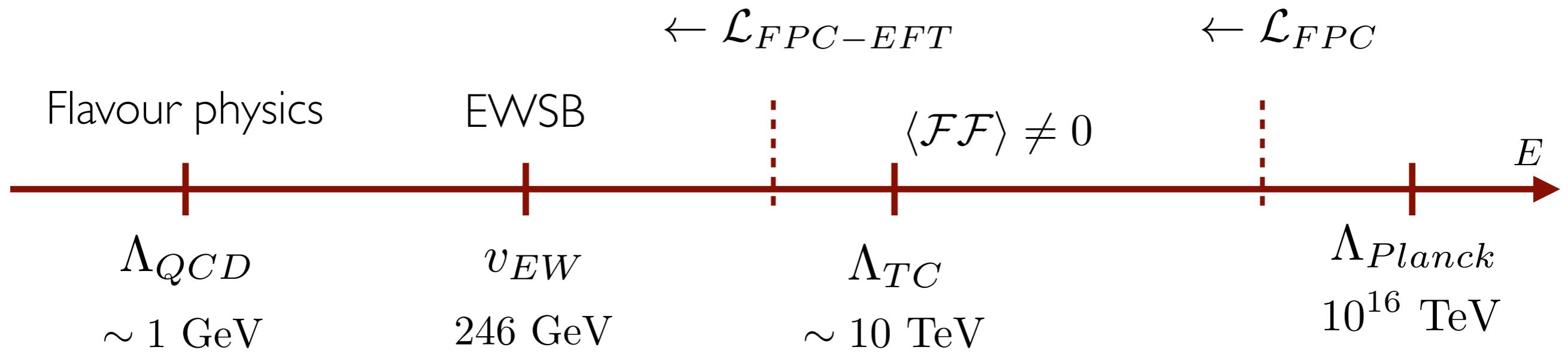
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$\mathcal{F}$



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- ◆ Large anomalous dim. not needed
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Fundamental composite dynamics generating ‘all’ SM fermion masses

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Quarks and leptons acquire mass via mixing with TC-Baryon



*If you do not like the new scalars:*

*Think at them as composite*

*Play with an extra-dimensional setup*

....

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$S$        $N_{TC} \times N_s$  matrix

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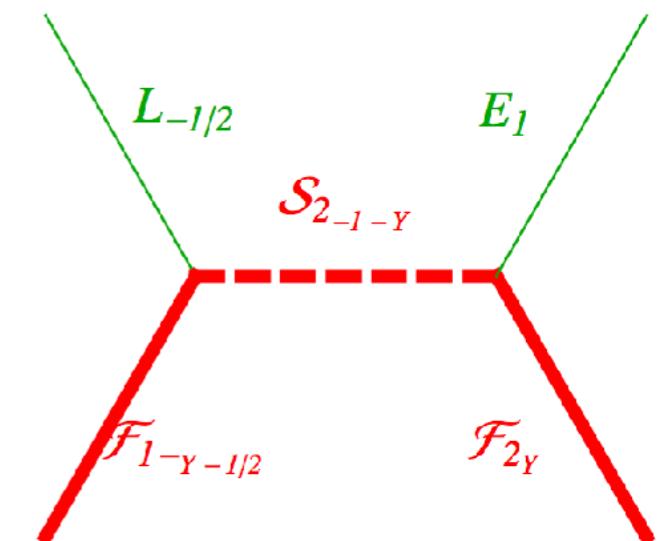
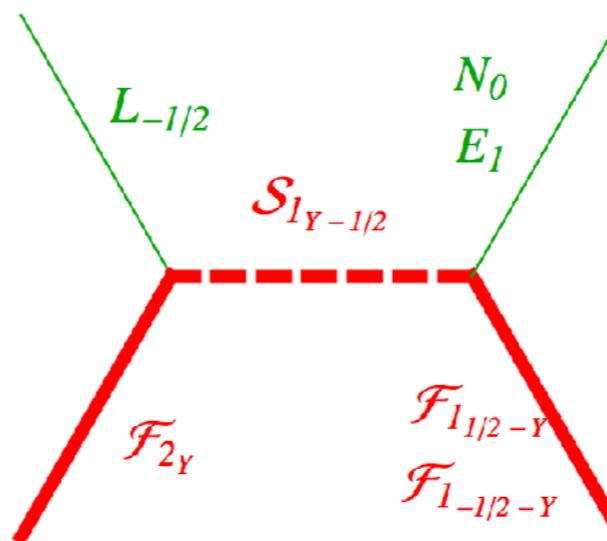
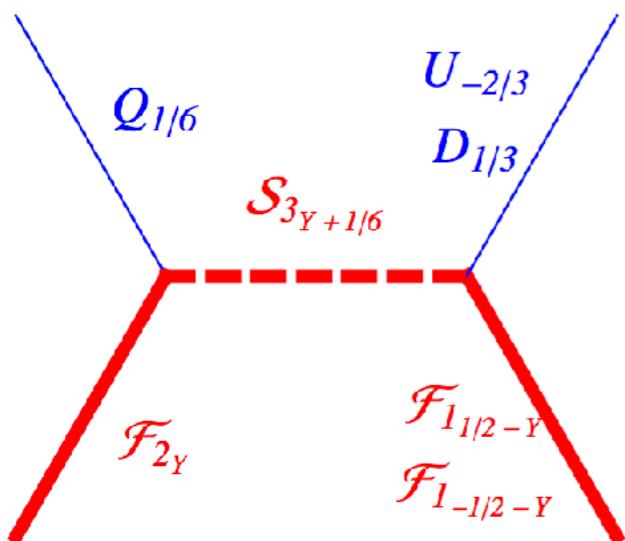
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# Underlying theories

Fields	Gauge	Global symmetry of fermions			Global, scalars	
	$SU(N)_{TC}$	$SU(N_F)_L$	$SU(N_F)_R$	$U(1)_V$	$SU(N_S)$	$U(1)_S$
$\mathcal{F}$	$N$	$N_F$	1	+1	1	0
$\mathcal{F}^c$	$\bar{N}$	1	$\bar{N}_F$	-1	1	0
$\mathcal{S}$	$N$	1	1	0	$N_S$	1

	$SO(N)_{TC}$	$SU(N_F)$	$O(N_S)$
$\mathcal{F}$	$N$	$N_F$	1
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	$Sp(N)_{TC}$	$SU(N_F)$	$Sp(2N_S)$
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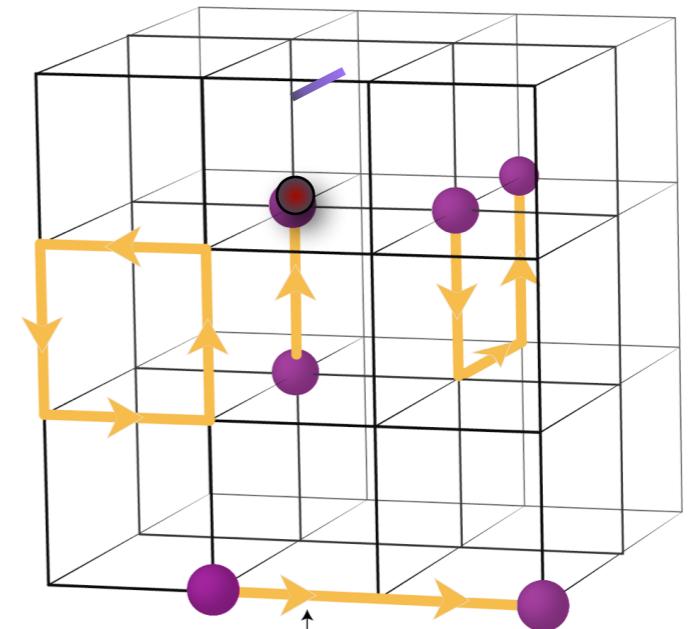
  

	$Sp(N)_{TC}$	$SU(N_F)$	$Sp(2N_S)$
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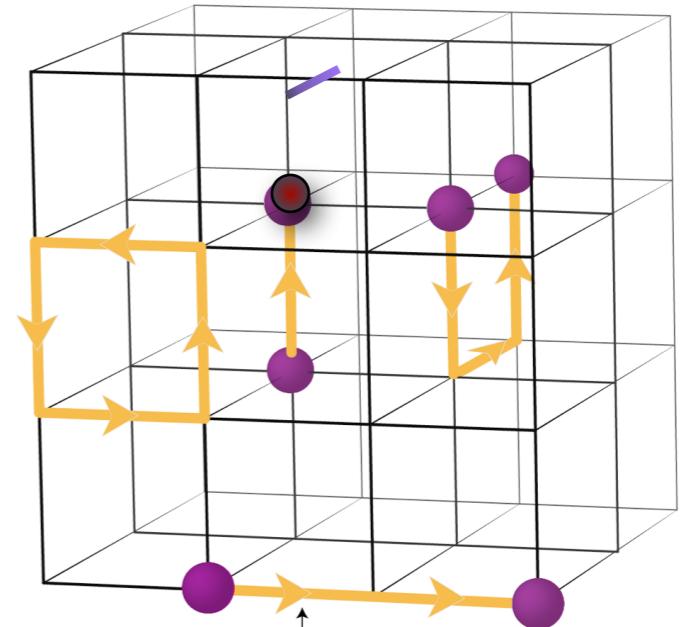
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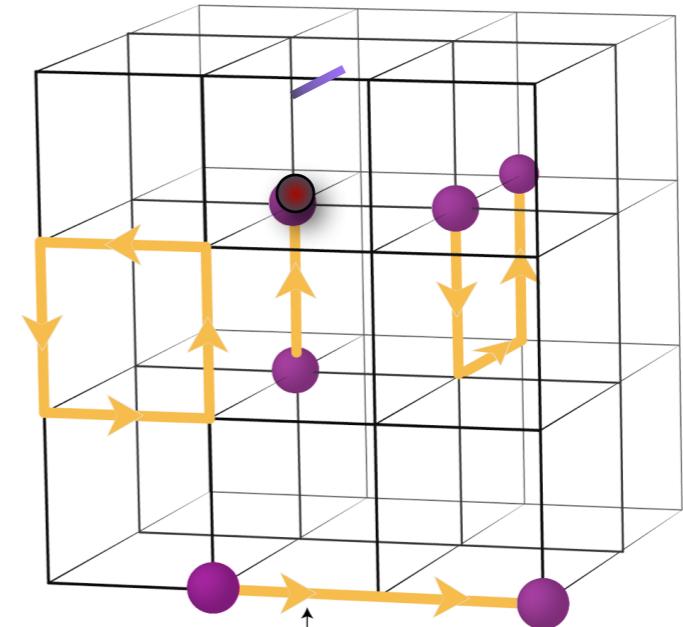
- ◆  $SP(2)=SU(2)$  TC Gauge Group
- ◆ 2 TC Dirac Flavours
- ◆ 12 TC complex scalars



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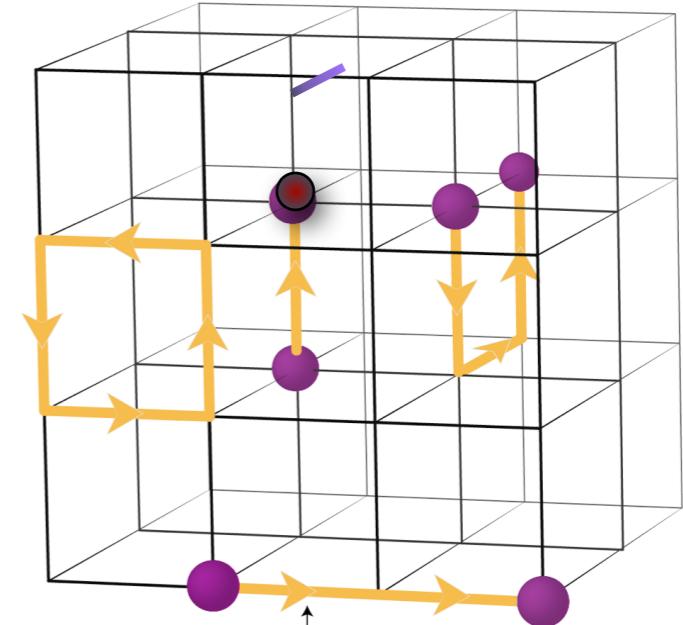


$$\begin{aligned}\mathcal{L}_{\text{kin}} = & -\frac{1}{4} \mathcal{G}_{\mu\nu}^a \mathcal{G}^{a\mu\nu} + i \mathcal{F}^\dagger \bar{\sigma}^\mu D_\mu \mathcal{F} - \left( \frac{1}{2} \mathcal{F}^T m_{\mathcal{F}} \epsilon_{\text{TC}} \mathcal{F} + \text{h.c.} \right) + \\ & (D_\mu \mathcal{S})^\dagger (D^\mu \mathcal{S}) - \mathcal{S}^\dagger m_{\mathcal{S}}^2 \mathcal{S}\end{aligned}$$

# Minimal (Partial) Compositeness

*First complete microscopic composite theory of flavour dynamics*

- ◆  $\text{SP}(2)=\text{SU}(2)$  TC Gauge Group
- ◆ 2 TC Dirac Flavours
- ◆ 12 TC complex scalars



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$$\begin{aligned} \mathcal{L}_{\text{yuk}} = & y_Q Q_\alpha \mathcal{S}_q \epsilon_{\text{TC}} \mathcal{F}_{\uparrow\downarrow}^\alpha - y_{\bar{u}} \bar{u} \mathcal{S}_q^* \bar{\mathcal{F}}_{\downarrow} + y_{\bar{d}} \bar{d} \mathcal{S}_q^* \bar{\mathcal{F}}_{\uparrow} \\ & + y_L L_\alpha \mathcal{S}_l \epsilon_{\text{TC}} \mathcal{F}_{\uparrow\downarrow}^\alpha - y_{\bar{\nu}} \bar{\nu} \mathcal{S}_l^* \bar{\mathcal{F}}_{\downarrow} + y_{\bar{e}} \bar{e} \mathcal{S}_l^* \bar{\mathcal{F}}_{\uparrow} - \tilde{y}_{\bar{\nu}} \bar{\nu} \mathcal{S}_l \bar{\mathcal{F}}_{\uparrow} + \text{h.c.} \end{aligned}$$

# “Complete” matter content

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	$\mathcal{F}_{\downarrow}$	$\bar{\mathcal{F}}_{\uparrow}$	$\bar{\mathcal{F}}_{\downarrow}$	$\mathcal{S}_q$	$\mathcal{S}_l$
$G_{\text{SM}}$	$(1, 2, 0)$	$(1, 1, -\frac{1}{2})$	$(1, 1, \frac{1}{2})$	$3 \times (\bar{3}, 1, -\frac{1}{6})$	$3 \times (1, 1, \frac{1}{2})$
TC symmetries		$4_{\mathcal{F}} \otimes N_{\text{TC}}$			$24_{\mathcal{S}} \otimes N_{\text{TC}}$

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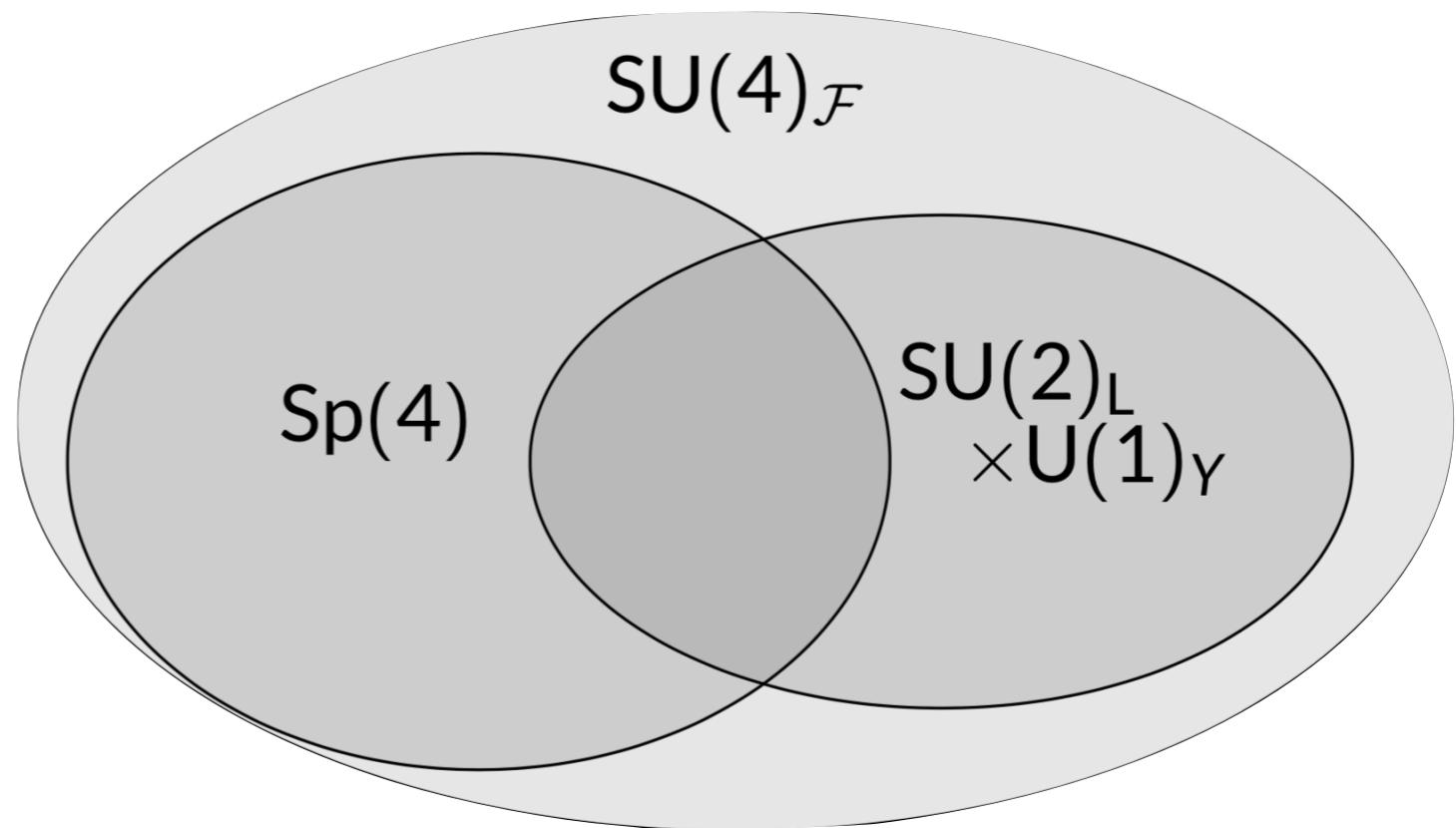
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# Dynamical symmetry breaking

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$$\mathrm{SU}(4)_{\mathcal{F}} \times \mathrm{Sp}(24)_S \supseteq G_{\mathrm{SM}}$$

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Appelquist, Sannino, 98, 99

Ryttov, Sannino, 2008

Katz, Nelson Walker, 2005

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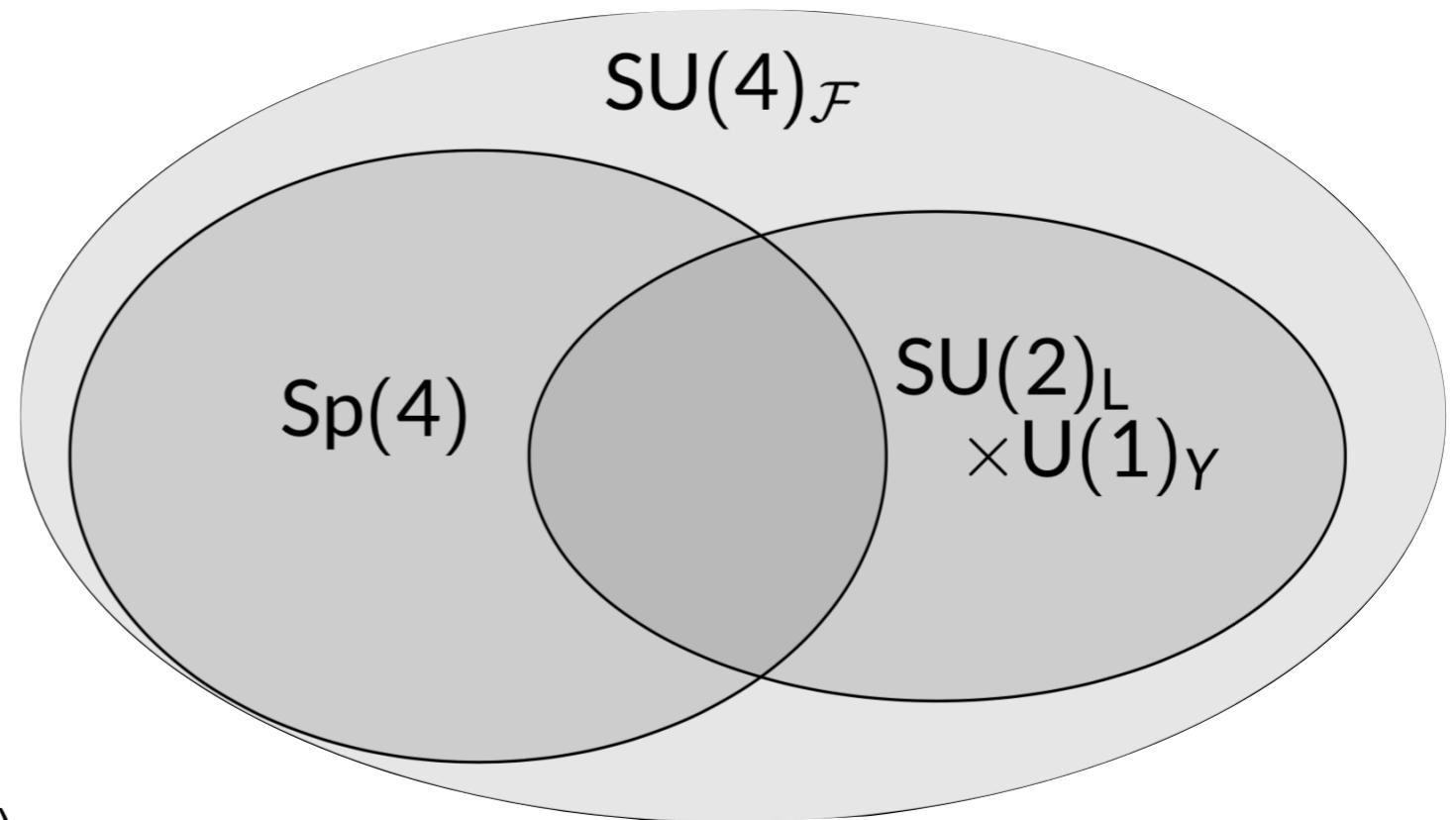
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Lattice proof of ChSB  $\mathrm{SU}(4)/\mathrm{Sp}(4)$

Lewis, Pica, Sannino, 1109.3513

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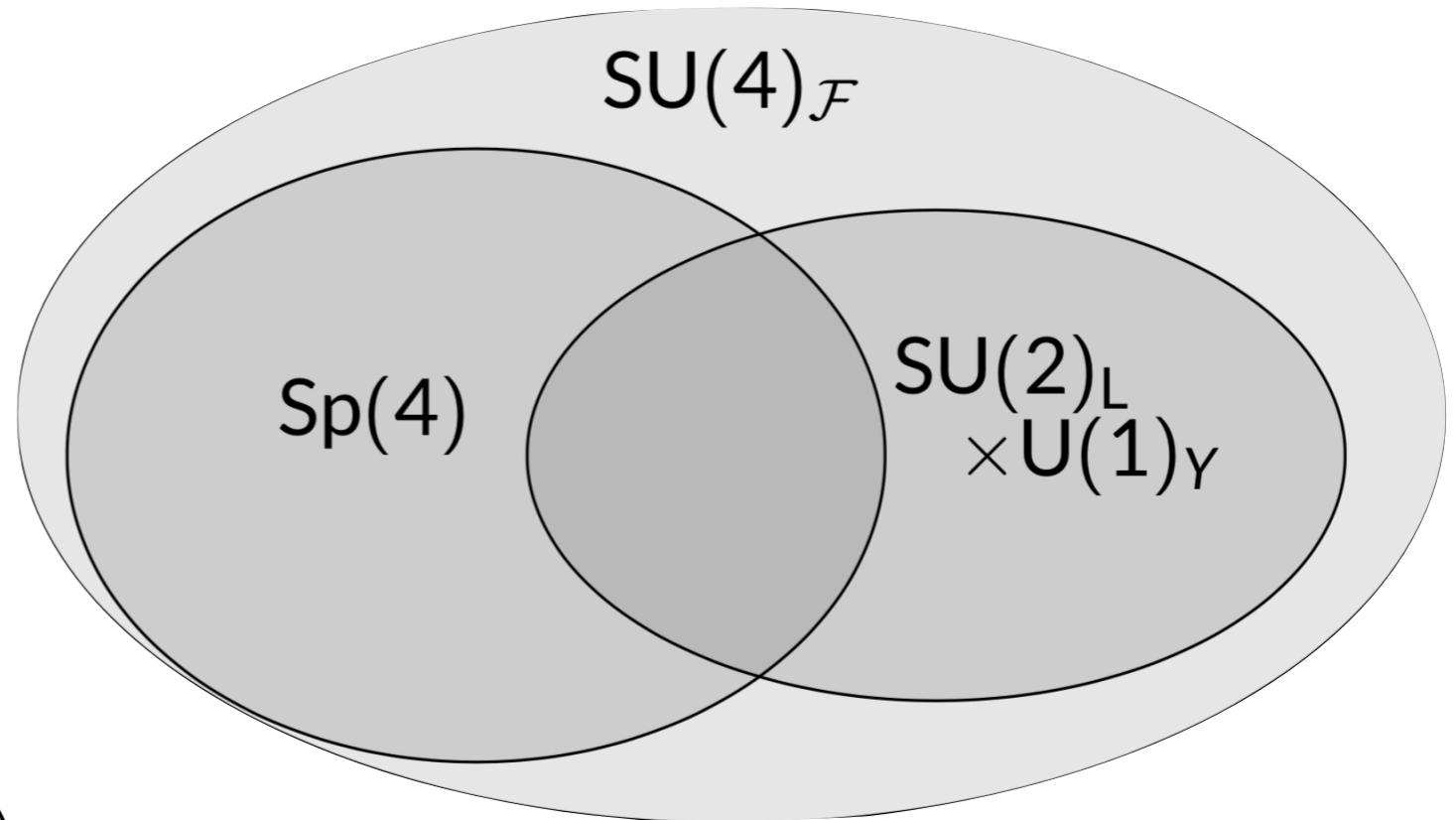
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And lattice vector spectrum

$$m_V = \frac{3.2(5)}{\sin \theta} \text{ TeV} \quad m_A = \frac{3.6(9)}{\sin \theta} \text{ TeV}$$

Appelquist, Sannino, 98, 99

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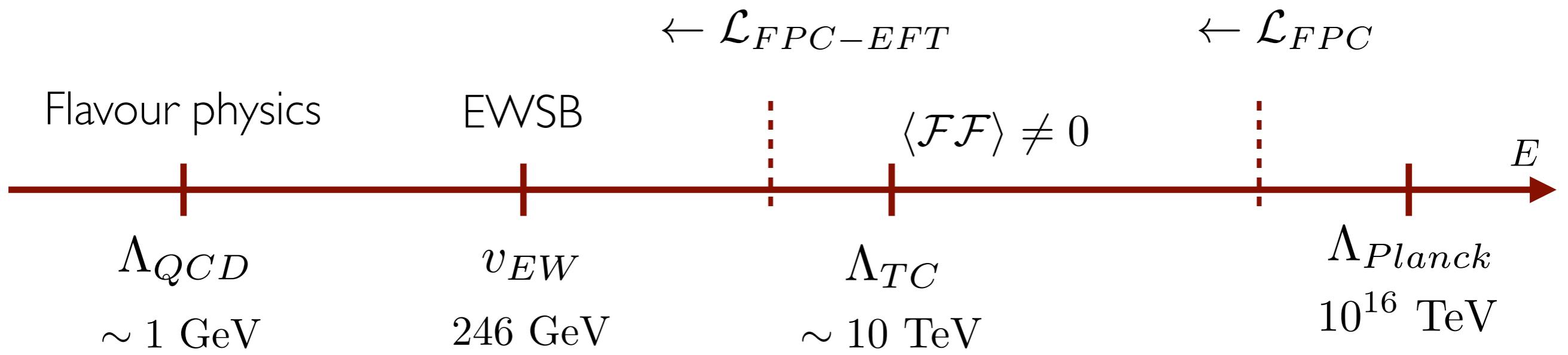
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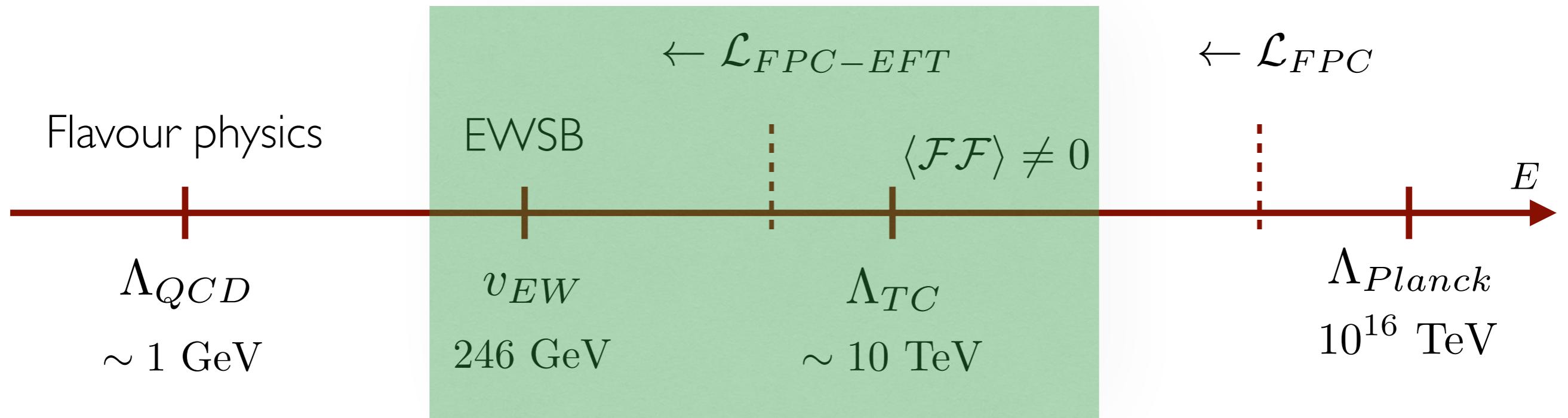
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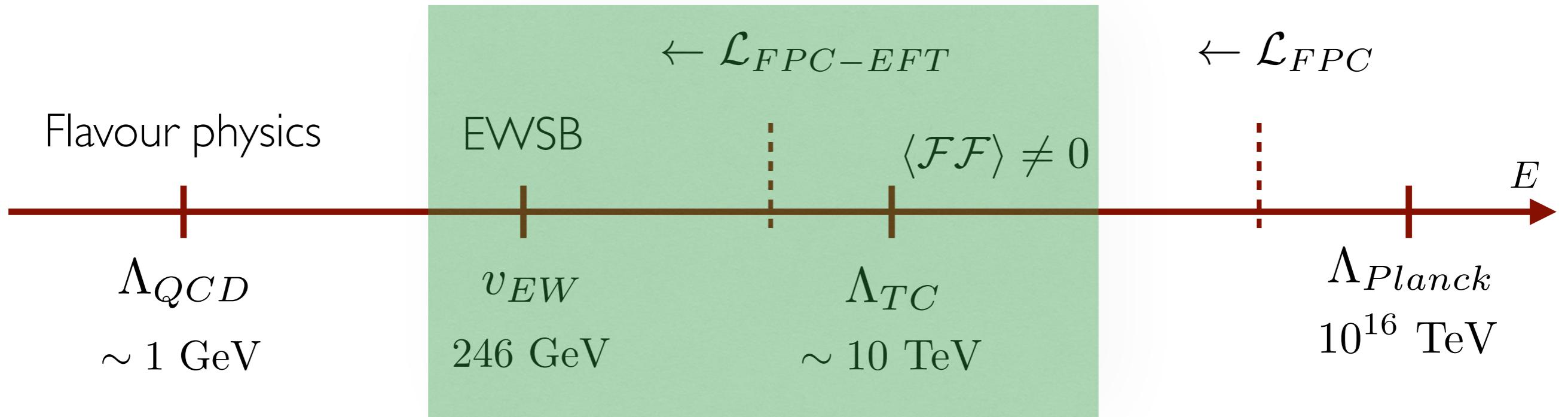
# EW effective theory



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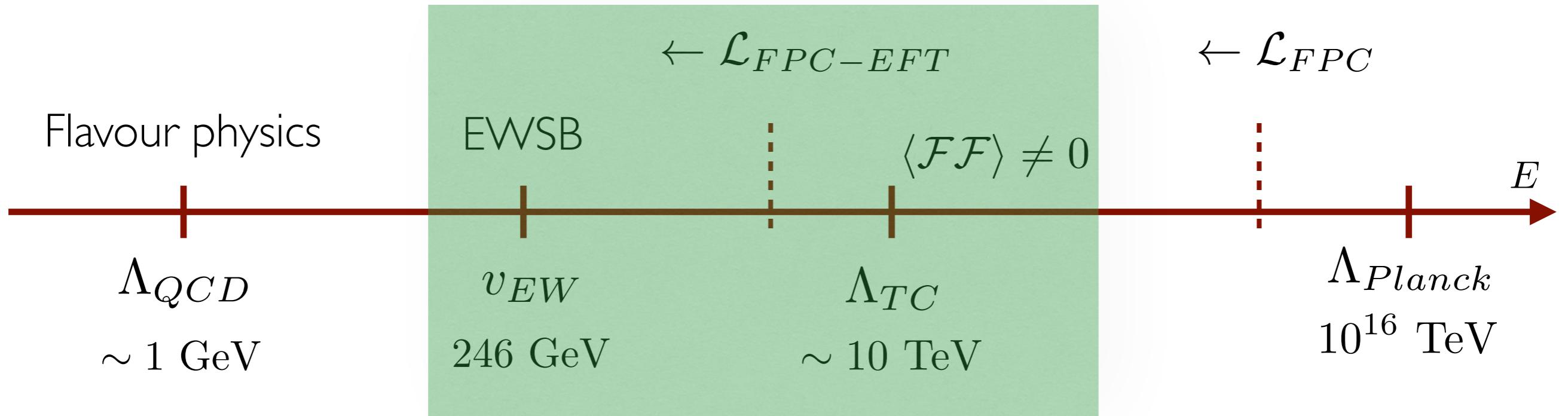


# EW effective theory



$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM-Higgs}} + \mathcal{L}_2 + \sum_A C_A \mathcal{O}_A + \left( \sum_A C'_A \mathcal{O}'_A + \text{h.c.} \right)$$

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NP in “A” operators. They can be reliably classified and computed

# Fermion masses

# Fermion masses

Effective mass term operator

# Fermion masses

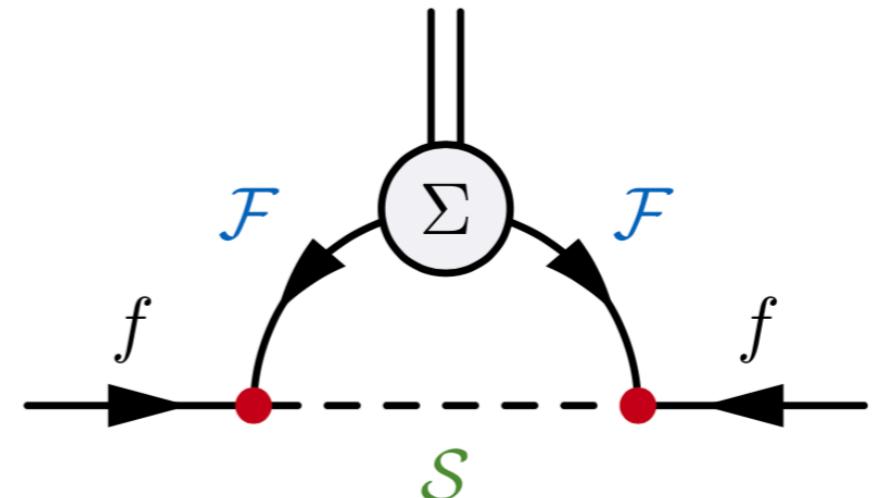
Effective mass term operator

$$C_{\text{yuk}} \mathcal{O}_{\text{yuk}} = C_{\text{yuk}} \frac{f_{\text{TC}}}{8\pi} (\psi^{i_1 a_1} \psi^{i_2 a_2}) \epsilon_{i_1 i_2} \Sigma^{a_1 a_2}$$

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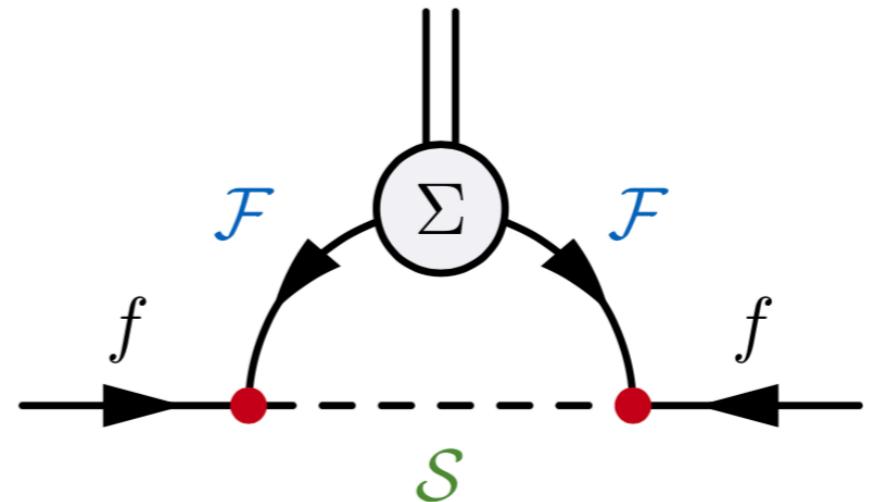


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$$v_{\text{ew}} = \sqrt{2} f_{\text{TC}} s_\theta$$

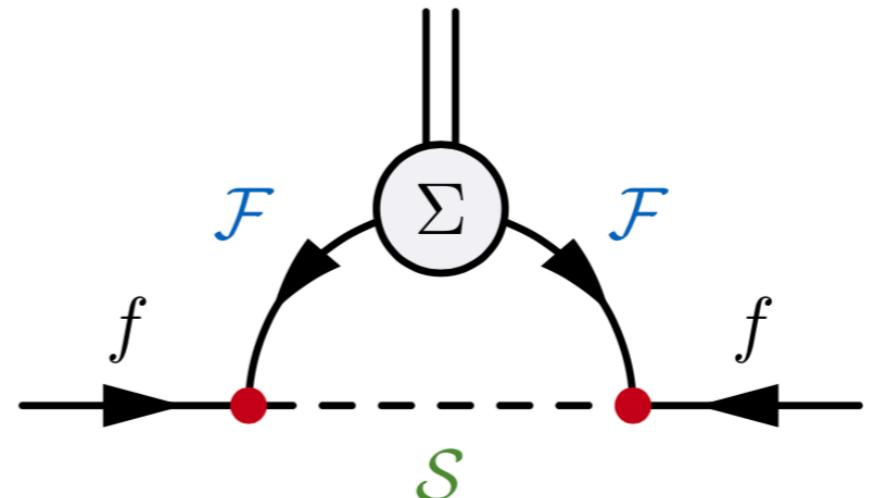


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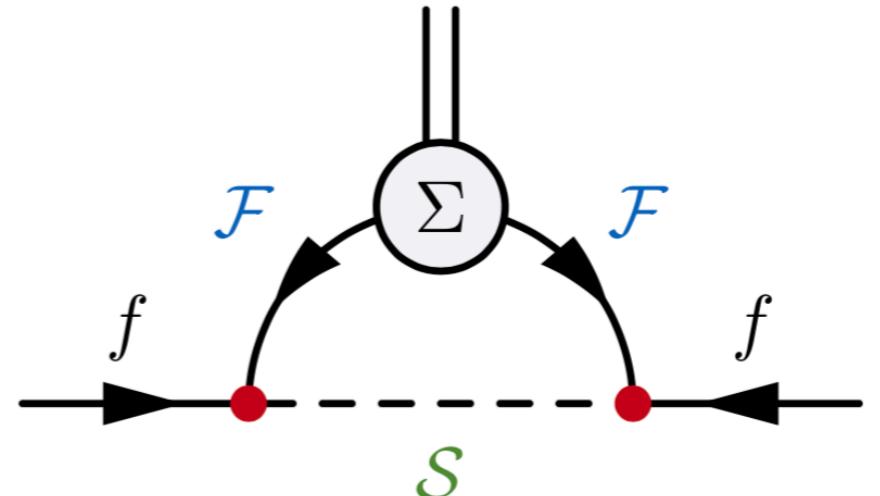
Coupling to the Higgs

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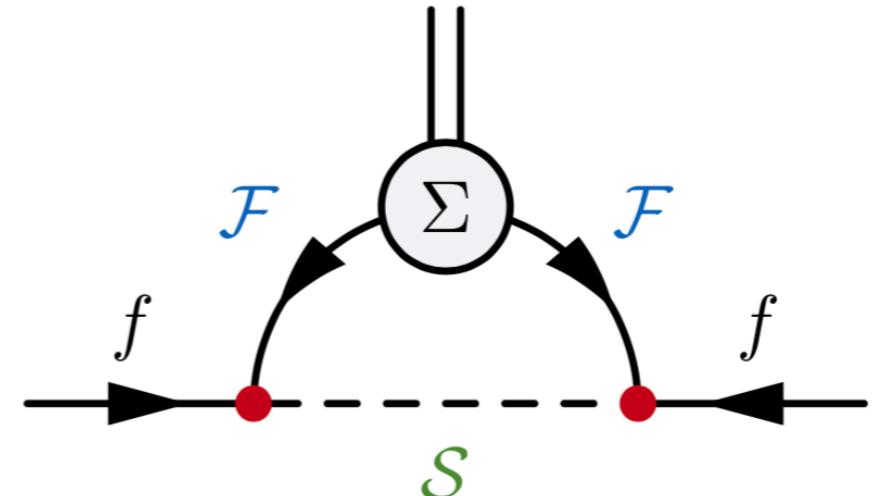
$$C_{\text{yuk}} \mathcal{O}_{\text{yuk}} \supset - \sum_{f \in \{u,d\}} \underbrace{\frac{C_{\text{yuk}} v_{\text{ew}}}{4\pi \sqrt{2}} (y_q y_f^T)_{ij}}_{(m_f)_{ij}} q_f^i f^j \left( 1 + \frac{c_\theta h}{v_{\text{ew}}} + \dots \right)$$

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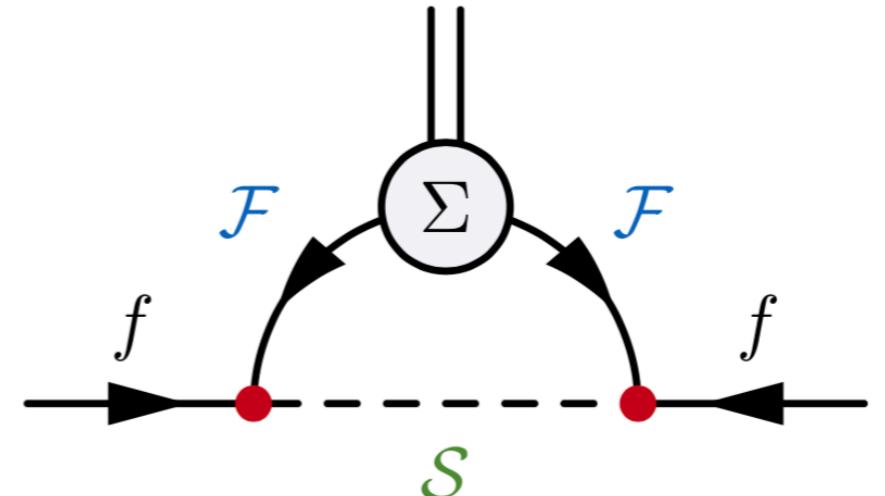
Top quark mass

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Top quark mass

$$Y_{\text{SM}}^u = \frac{C_{\text{Yuk}}}{4\pi} (y_q y_u^\top)_{ij} \Rightarrow (y_q y_u^\top)_{tt} \sim 4\pi$$

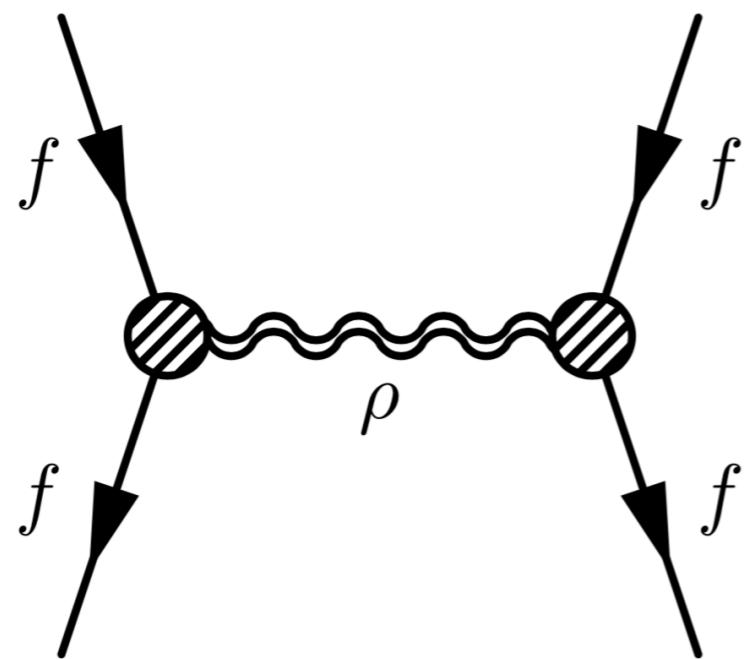
# Unified Composite Flavour Physics

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Naive tree-level NP contributions

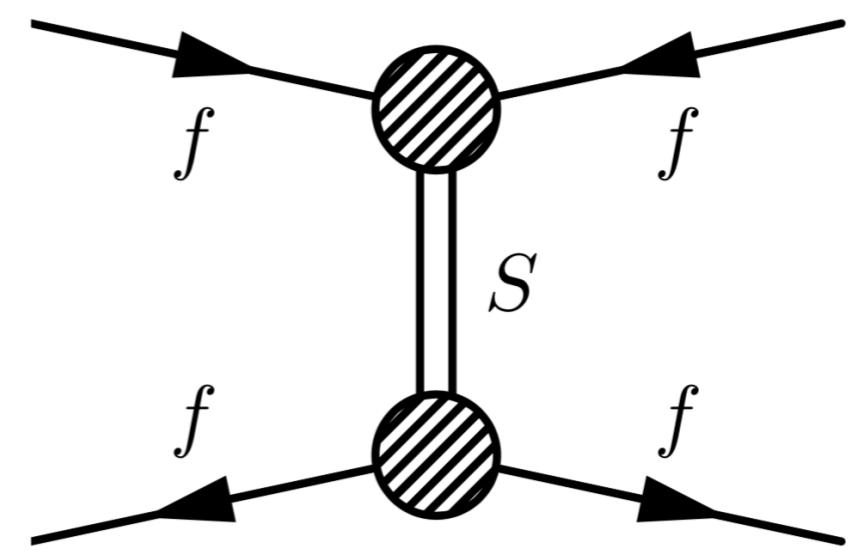
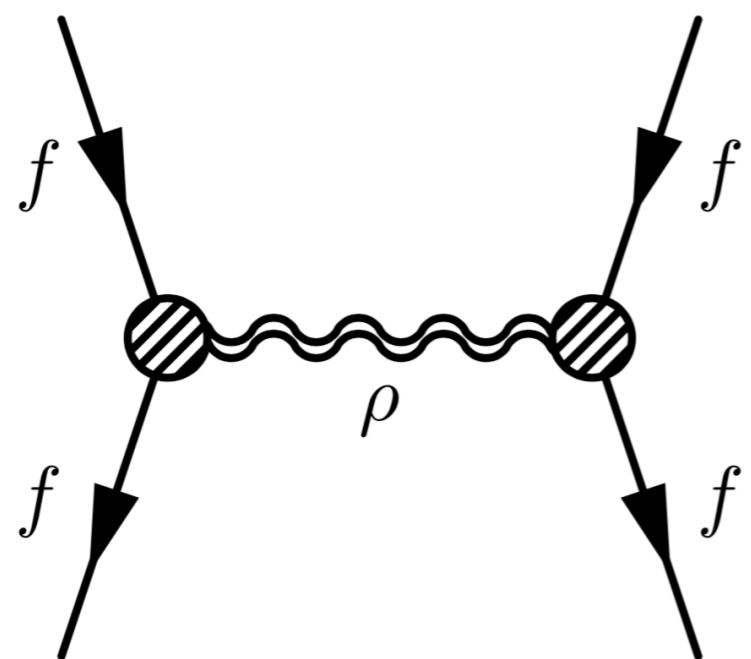
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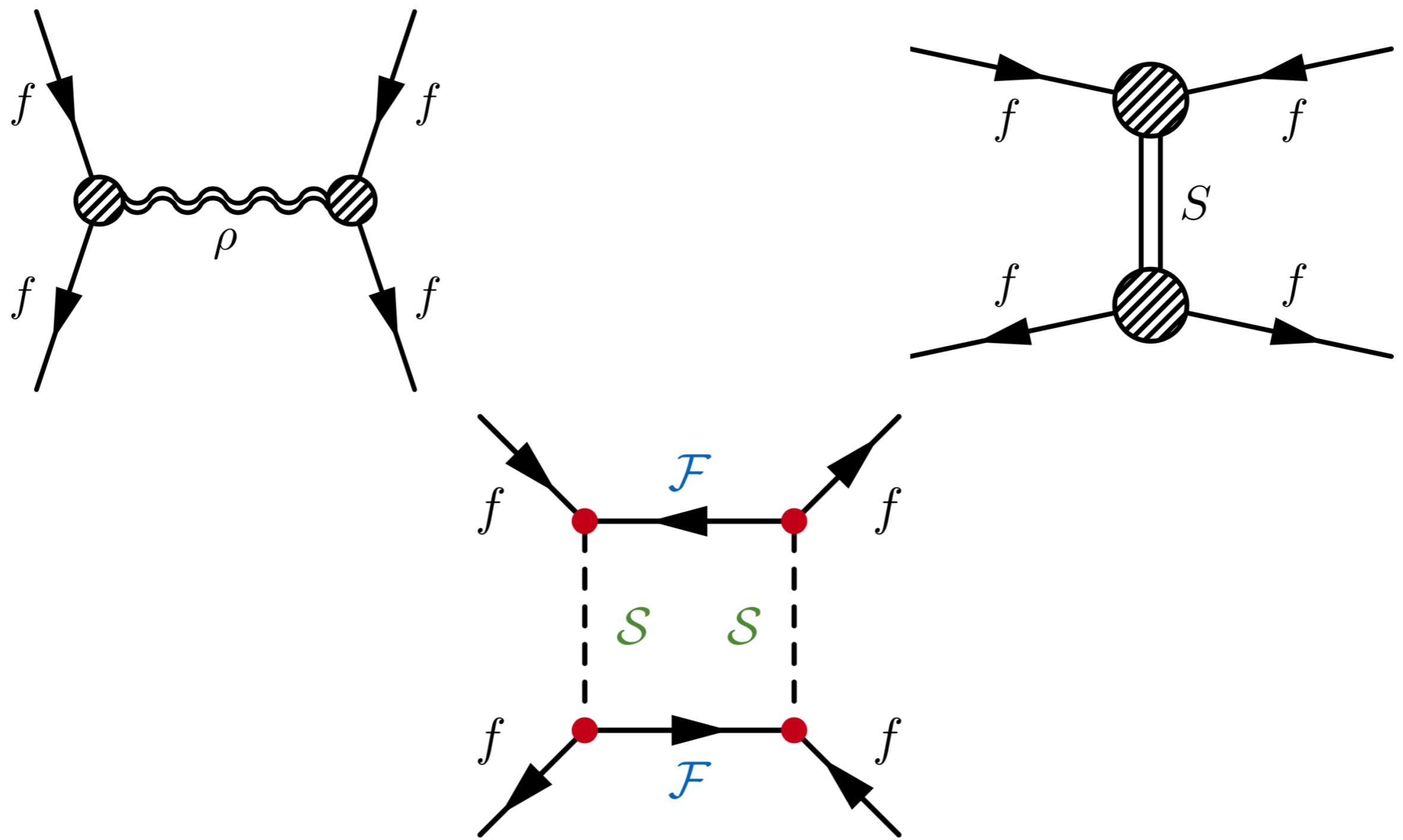
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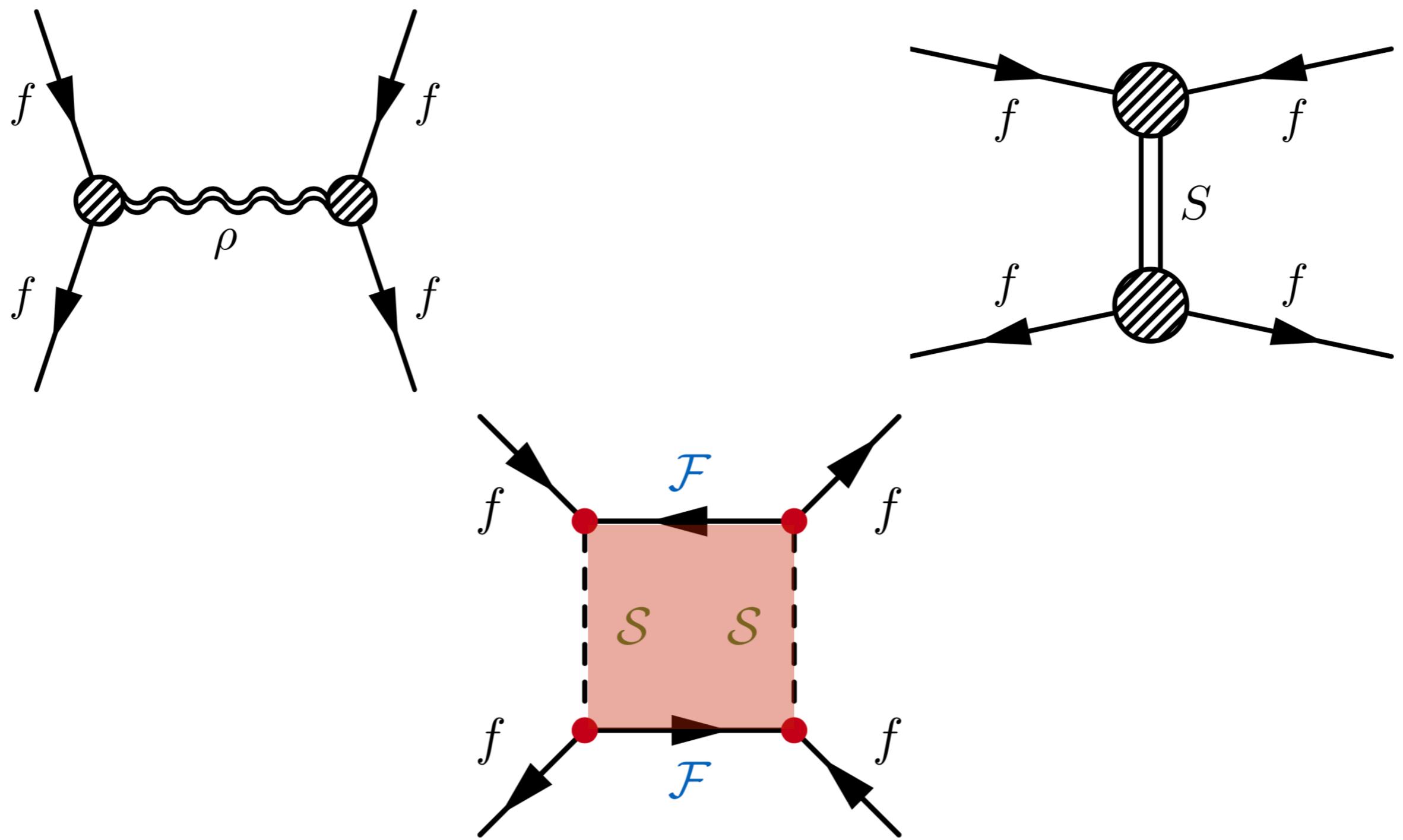
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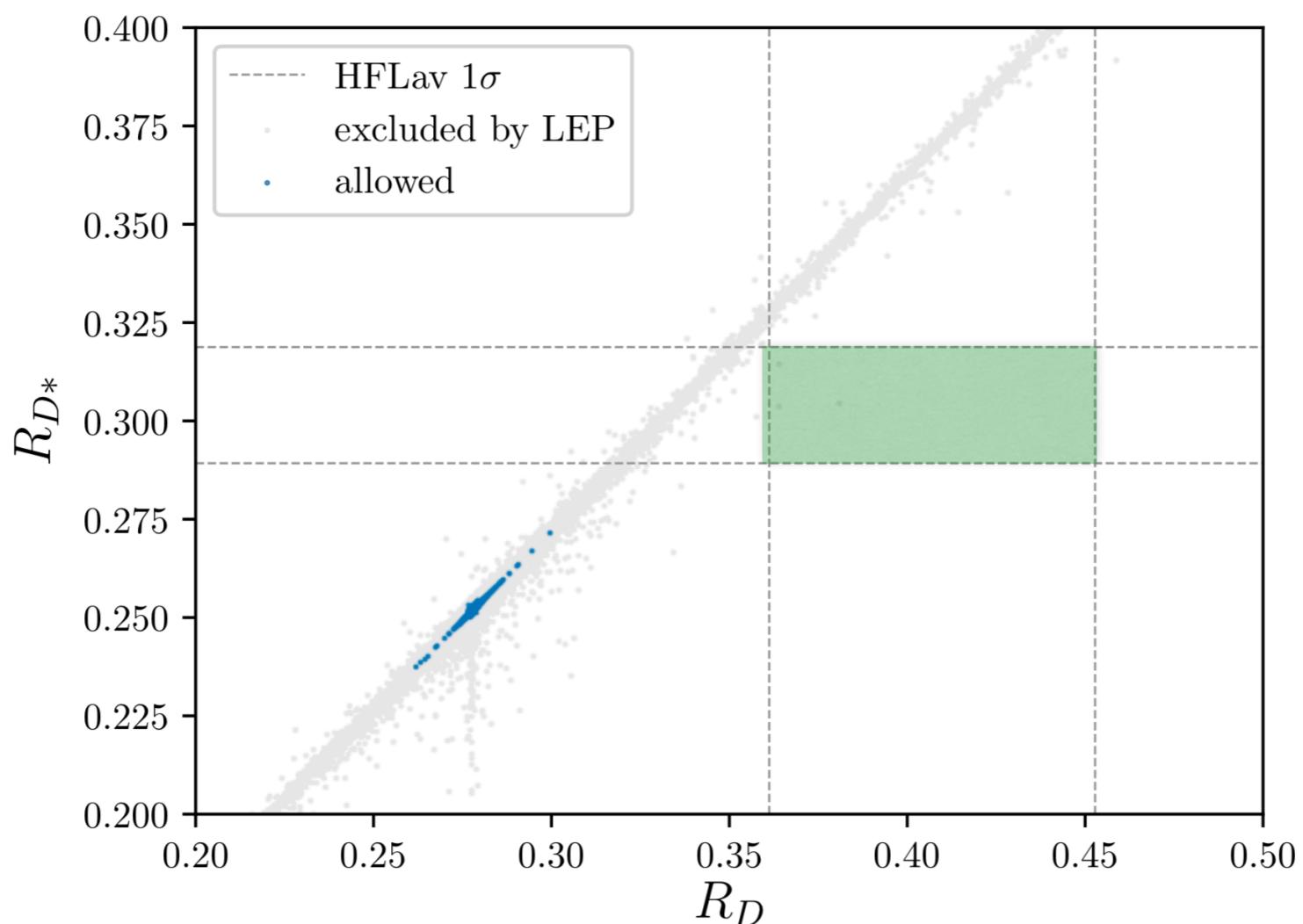
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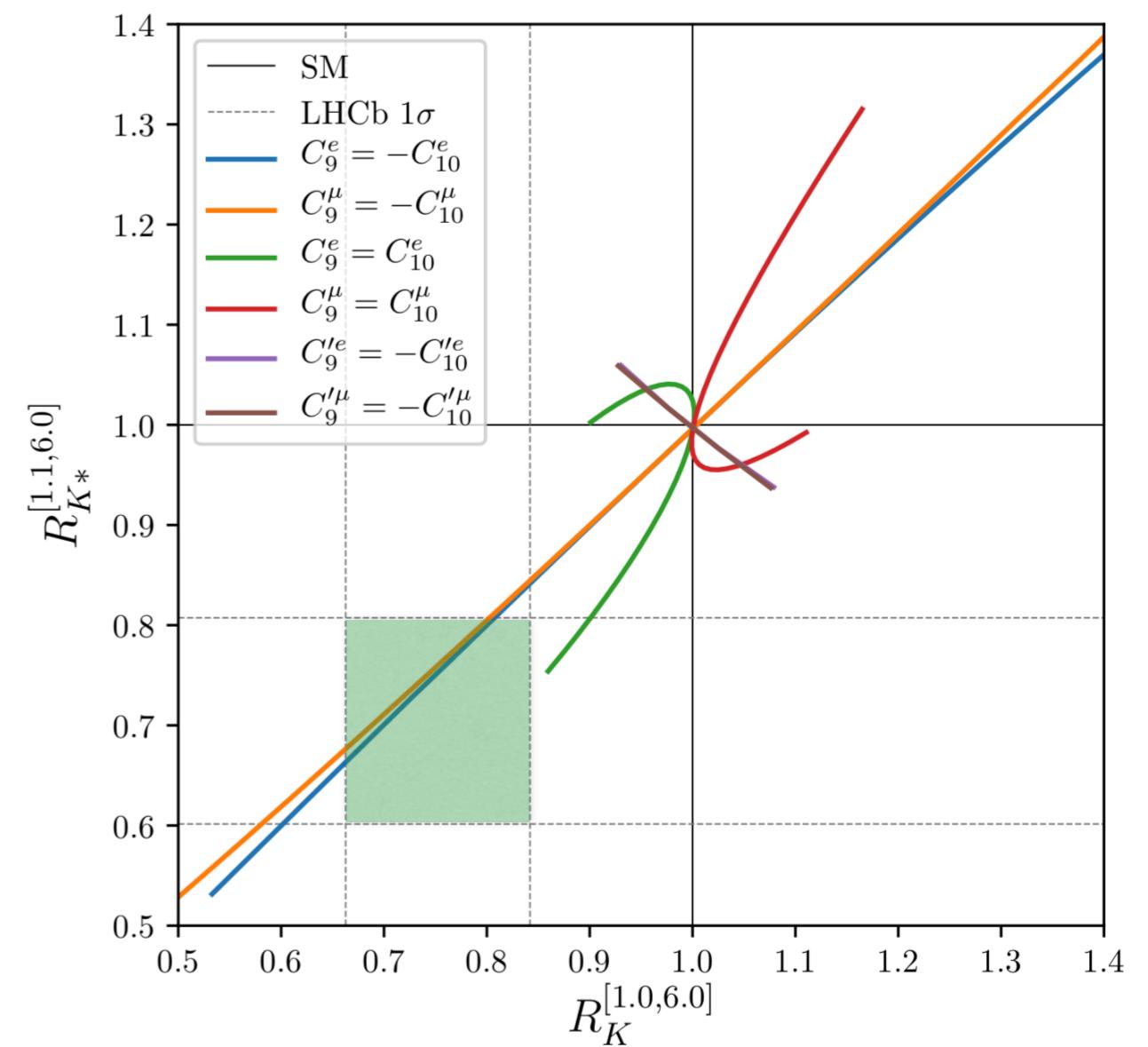
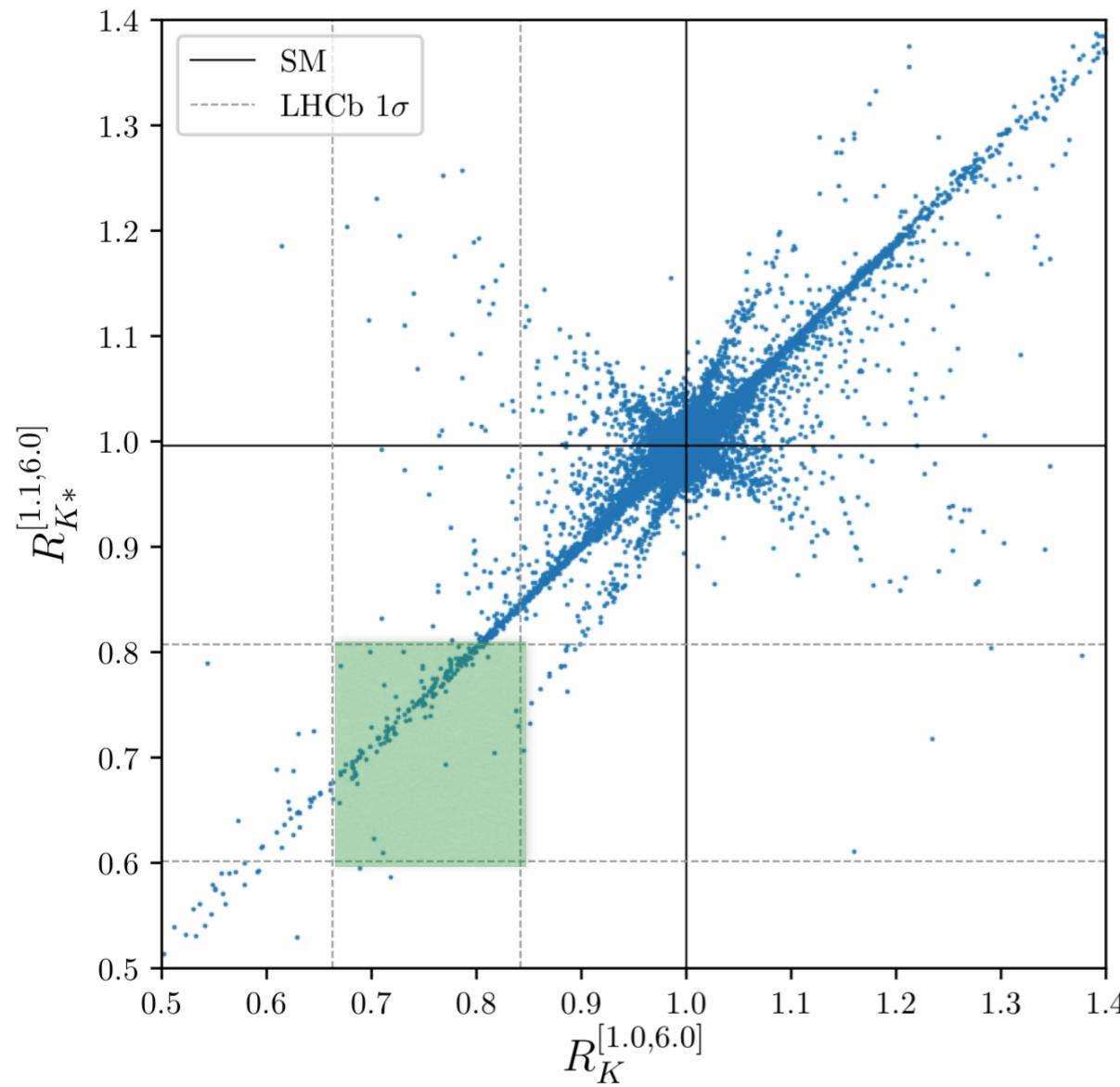


# $R_{D(*)}$

- ◆ Strong constraints via  $\epsilon_k$ , but enough parameter space
- ◆ Strong constraints from tests of e- $\mu$  universality in charged current decays
- ◆ Large deviations from SM disfavoured by Z partial widths (modified  $Z\tau\tau$  coupling)

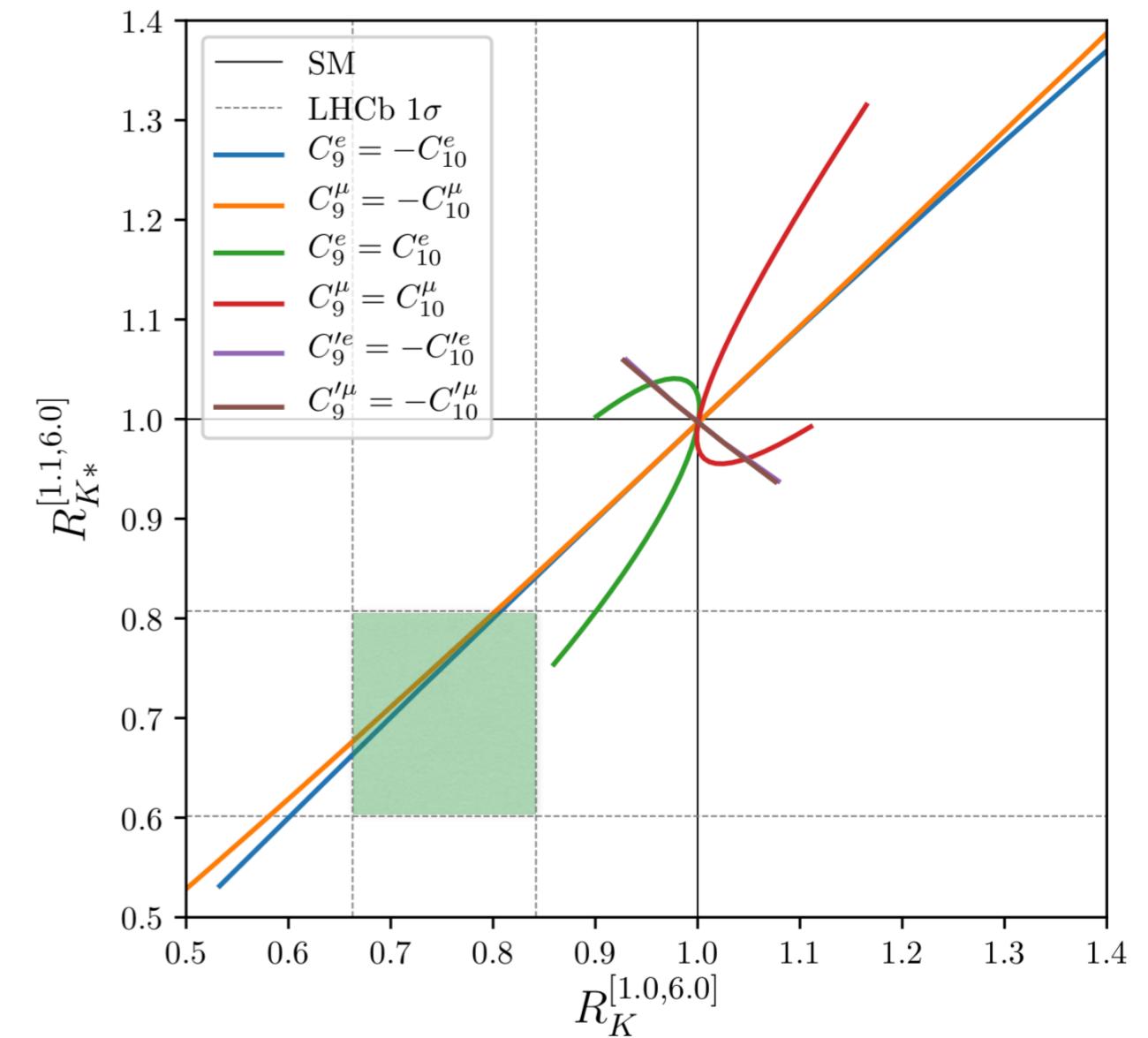
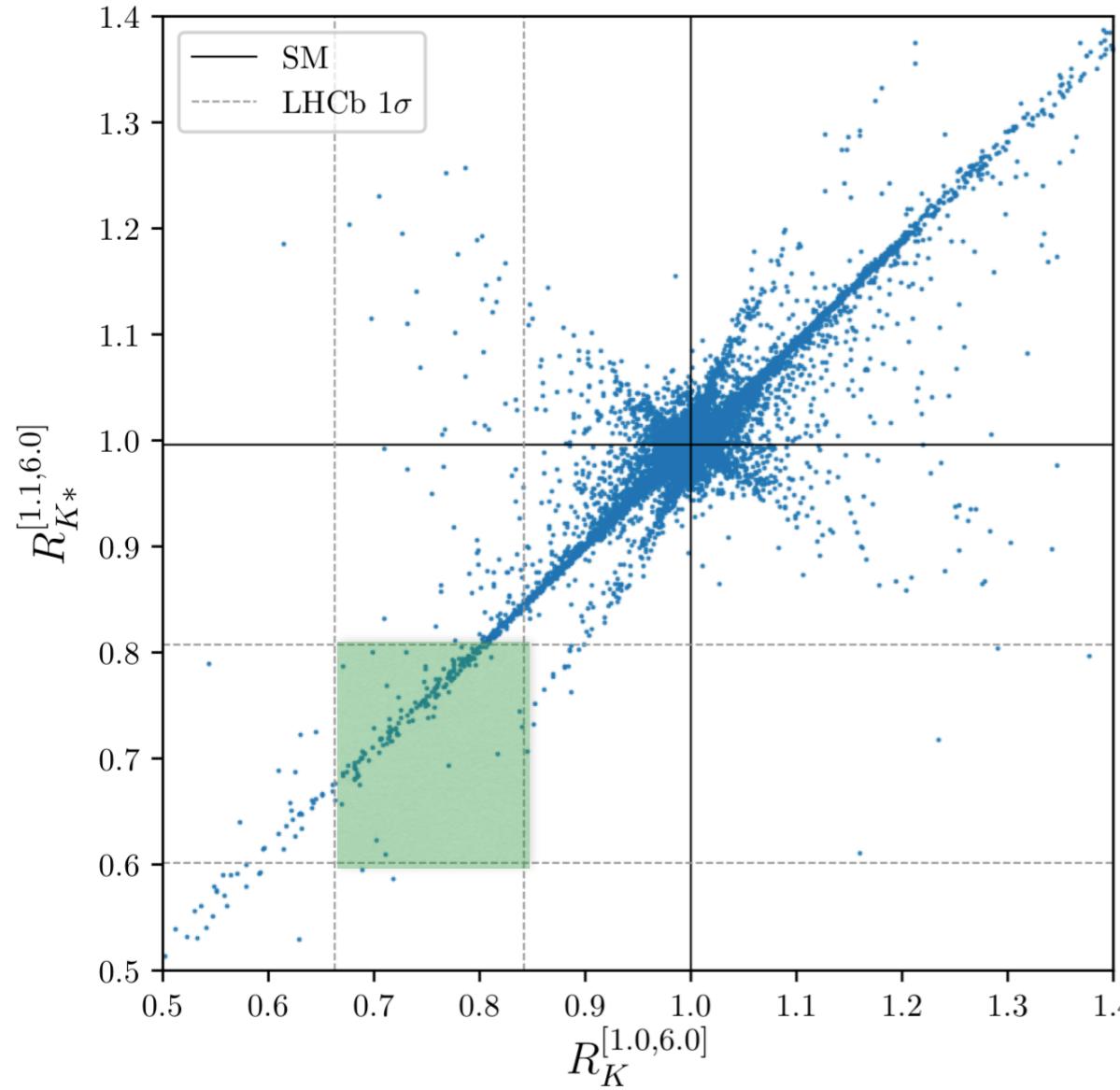


$R_K(*)$



# $R_K(*)$

Anomalies in rare B decays can be explained



# What next?

# What next?

- ◆ Composite neutrino physics
- ◆ Fundamental Composite Minimal Falvour Violation and/or Froggatt Nielsen,...
- ◆ Fundamental partial composite dynamics on the lattice
- ◆ Baryogenesis
- ◆ Electroweak phase transition
- ◆ Dark matter
- ◆ Safe embedding and its dynamics on and off the lattice

thank you

*“Nothing is invented, for it’s written in nature first. Originality consists of returning to the origin.”*

Antoni Gaudí

# Backup slides

# Dynamical EW breaking

# Dynamical EW breaking

$$\left\langle \mathcal{F}^{\textcolor{blue}{a}} \epsilon_{\text{TC}} \mathcal{F}^{\textcolor{blue}{b}} \right\rangle \propto \Sigma_\theta^{ab} = c_\theta \begin{pmatrix} i\sigma^2 & 0 \\ 0 & -i\sigma^2 \end{pmatrix} + s_\theta \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

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$$\Sigma=\exp\left[\frac{2i}{f_{\text{TC}}}\boldsymbol{\Pi}_{\textcolor{blue}{A}} X^{\text{A}}_\theta\right]\Sigma_\theta,\qquad f_{\text{TC}}\simeq\frac{\Lambda_{\text{TC}}}{4\pi}$$

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$$\begin{aligned}\mathcal{L}_2&=\frac{f_{\text{TC}}^2}{4}\text{Tr}\left[D_\mu\Sigma^\dagger D^\mu\Sigma\right]\\&=\frac{s_\theta^2f_{\text{TC}}^2}{4}\left(g'^2\,B_\mu B^\mu-2g'g\,W_\mu^3B^\mu+g^2\,W_\mu^aW^{a\mu}\right)+\ldots\end{aligned}$$

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$$\left\langle \mathcal{F}^{\textcolor{blue}{a}} \epsilon_{\text{TC}} \mathcal{F}^{\textcolor{blue}{b}} \right\rangle \propto \Sigma_\theta^{ab} = c_\theta \begin{pmatrix} i\sigma^2 & 0 \\ 0 & -i\sigma^2 \end{pmatrix} + s_\theta \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\Sigma = \exp \left[ \frac{2i}{f_{\text{TC}}} \textcolor{blue}{\Pi_A} X_\theta^A \right] \Sigma_\theta, \qquad f_{\text{TC}} \simeq \frac{\Lambda_{\text{TC}}}{4\pi}$$

$$\begin{aligned} \mathcal{L}_2 &= \frac{f_{\text{TC}}^2}{4} \text{Tr} \left[ D_\mu \Sigma^\dagger D^\mu \Sigma \right] \\ &= \frac{s_\theta^2 f_{\text{TC}}^2}{4} \left( g'^2 B_\mu B^\mu - 2g' g W_\mu^3 B^\mu + g^2 W_\mu^a W^{a\mu} \right) + \dots \end{aligned}$$

$$v_{\text{ew}} = \sqrt{2} f_{\text{TC}} s_\theta$$

# Basis of four-fermion operators

MFPC allows for 5 self-hermitian (and 3 complex) four-fermion ope.

$$\mathcal{O}_{4f}^{(1)} = \frac{1}{64\pi^2\Lambda_{TC}^2} (\psi'^{i_1}{}_{a_1} \psi'^{i_2}{}_{a_2}) (\bar{\psi}'{}^{i_3}{}_{a_3} \bar{\psi}'{}^{i_4}{}_{a_4}) \sum^{a_1 a_2} \sum^{\dagger}_{a_3 a_4} \epsilon_{i_1 i_2} \epsilon_{i_3 i_4}$$

$$\mathcal{O}_{4f}^{(2)} = \frac{1}{64\pi^2\Lambda_{TC}^2} (\psi'^{i_1}{}_{a_1} \psi'^{i_2}{}_{a_2}) (\bar{\psi}'{}^{i_3}{}_{a_3} \bar{\psi}'{}^{i_4}{}_{a_4}) (\delta^{a_1}_{a_3} \delta^{a_2}_{a_4} - \delta^{a_1}_{a_4} \delta^{a_2}_{a_3}) \epsilon_{i_1 i_2} \epsilon_{i_3 i_4}$$

$$\mathcal{O}_{4f}^{(3)} = \frac{1}{64\pi^2\Lambda_{TC}^2} (\psi'^{i_1}{}_{a_1} \psi'^{i_2}{}_{a_2}) (\bar{\psi}'{}^{i_3}{}_{a_3} \bar{\psi}'{}^{i_4}{}_{a_4}) \sum^{a_1 a_2} \sum^{\dagger}_{a_3 a_4} (\epsilon_{i_1 i_4} \epsilon_{i_2 i_3} - \epsilon_{i_1 i_3} \epsilon_{i_2 i_4})$$

$$\mathcal{O}_{4f}^{(4)} = \frac{1}{64\pi^2\Lambda_{TC}^2} (\psi'^{i_1}{}_{a_1} \psi'^{i_2}{}_{a_2}) (\bar{\psi}'{}^{i_3}{}_{a_3} \bar{\psi}'{}^{i_4}{}_{a_4}) (\delta^{a_1}_{a_3} \delta^{a_2}_{a_4} \epsilon_{i_1 i_3} \epsilon_{i_2 i_4} + [3 \leftrightarrow 4])$$

$$\mathcal{O}_{4f}^{(5)} = \frac{1}{64\pi^2\Lambda_{TC}^2} (\psi'^{i_1}{}_{a_1} \psi'^{i_2}{}_{a_2}) (\bar{\psi}'{}^{i_3}{}_{a_3} \bar{\psi}'{}^{i_4}{}_{a_4}) (\delta^{a_1}_{a_3} \delta^{a_2}_{a_4} \epsilon_{i_1 i_4} \epsilon_{i_2 i_3} + [3 \leftrightarrow 4])$$

# Basis of four-fermion operators

3 complex four-fermion ope.

$$\mathcal{O}_{4f}^6 = \frac{1}{128\pi^2\Lambda_{\text{TC}}^2} (\psi^{i_1}{}_{a_1} \psi^{i_2}{}_{a_2}) (\psi^{i_3}{}_{a_3} \psi^{i_4}{}_{a_4}) \Sigma^{a_1 a_2} \Sigma^{a_3 a_4} \epsilon_{i_1 i_2} \epsilon_{i_3 i_4},$$

$$\mathcal{O}_{4f}^7 = \frac{1}{128\pi^2\Lambda_{\text{TC}}^2} (\psi^{i_1}{}_{a_1} \psi^{i_2}{}_{a_2}) (\psi^{i_3}{}_{a_3} \psi^{i_4}{}_{a_4}) (\Sigma^{a_1 a_4} \Sigma^{a_2 a_3} - \Sigma^{a_1 a_3} \Sigma^{a_2 a_4}) \epsilon_{i_1 i_2} \epsilon_{i_3 i_4}$$

$$\mathcal{O}_{4f}^8 = \frac{1}{128\pi^2\Lambda_{\text{TC}}^2} (\psi^{i_1}{}_{a_1} \psi^{i_2}{}_{a_2}) (\psi^{i_3}{}_{a_3} \psi^{i_4}{}_{a_4}) \Sigma^{a_1 a_2} \Sigma^{a_3 a_4} (\epsilon_{i_1 i_4} \epsilon_{i_2 i_3} - \epsilon_{i_1 i_3} \epsilon_{i_2 i_4}).$$

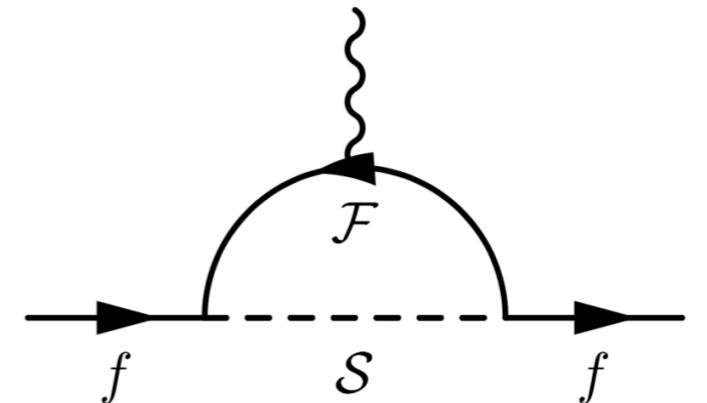
Modified coupling between SM fermions and Gauge bosons

$$\mathcal{O}_{\Pi f} = \frac{i}{32\pi^2} (\psi^\dagger{}^{i_1 a_1} \bar{\sigma}_\mu \psi^{i_2}{}_{a_2}) \Sigma_{a_1 a_3}^\dagger \overleftrightarrow{D}^\mu \Sigma^{a_3 a_2} \epsilon_{i_1 i_2}$$

# EW precision data: $Z \rightarrow b\bar{b}$

Fundamental partial compositeness

$$\mathcal{O}_{\Pi f} = \frac{if_{\text{TC}}}{\Lambda_{\text{TC}}} (\bar{\psi}'^{i_1 a_1} \bar{\sigma}^\mu \psi'^{i_2 a_2}) \epsilon_{i_1 i_2} (\Sigma^\dagger D_\mu \Sigma)_{a_1}{}^{a_2}$$



Down type quarks

$$C_{\Pi f} \mathcal{O}_{\Pi f} \supset -\frac{g s_\theta^2 C_{\Pi f}}{2 c_w} \frac{f_{\text{TC}}}{\Lambda_{\text{TC}}} Z^\mu \left[ (\tilde{y}_q \tilde{y}_q^\dagger)_{ij} (\bar{q}_d^j \bar{\sigma}_\mu q_d^i) - (y_d y_d^\dagger)_{ij} (d^i \sigma_\mu \bar{d}^j) \right]$$

$$c_w \delta g_{b,L}/g = (3.0 \pm 1.5) \cdot 10^{-3}$$

$$\left| C_{\Pi f} (\tilde{y}_q \tilde{y}_q^\dagger)_{bb} \right| \lesssim 3.2 \left( \frac{\Lambda_{\text{TC}}}{10 \text{ TeV}} \right)^2$$

$$R_K(*)$$

NP contribution to  $(\bar{s}_L \gamma_\nu b_L)(\bar{\mu}_L \gamma^\nu \mu_L)$

$$-\frac{C_{4f}^{(4)} + C_{4f}^{(5)}}{2} (\tilde{y}_q \tilde{y}_q^\dagger)_{bs} (\tilde{y}_\ell \tilde{y}_\ell^\dagger)_{\mu\mu} \simeq 0.10 \left( \frac{\Lambda_{TC}}{10 \text{ TeV}} \right)^2 \quad (\text{best fit})$$

Constraints @95% CL

$$Z \rightarrow \mu^+ \mu^-: \quad |C_{\Pi f} (\tilde{y}_\ell \tilde{y}_\ell^\dagger)_{\mu\mu}| \lesssim 1.1 \left( \frac{\Lambda_{TC}}{10 \text{ TeV}} \right)^2$$

$$B_s - \bar{B}_s \text{ mixing: } \left| (C_{4f}^{(4)} + C_{4f}^{(5)}) (\tilde{y}_q \tilde{y}_q^\dagger)_{bs}^2 \right| \lesssim 4.4 \cdot 10^{-3} \left( \frac{\Lambda_{TC}}{10 \text{ TeV}} \right)^2$$

$$-\frac{C_{4f}^{(4)} + C_{4f}^{(5)}}{2} (\tilde{y}_q \tilde{y}_q^\dagger)_{bs} (\tilde{y}_\ell \tilde{y}_\ell^\dagger)_{\mu\mu} \lesssim 0.05 \left| \frac{C_{4f}^{(4)} + C_{4f}^{(5)}}{2C_{\Pi f}} \right|^{1/2} \left( \frac{\Lambda_{TC}}{10 \text{ TeV}} \right)^2$$

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SM spurion structure

Coupling	Flavor symmetry of SM fermions					Flavor of TC-scalars	
	$U(3)_L$	$U(3)_E$	$U(3)_Q$	$U(3)_U$	$U(3)_D$	$U(3)_{S_N}$	$U(3)_{S_{Uc}}$
$y_L$	3	1	1	1	1	3	1
$y_E$	1	3	1	1	1	$\bar{3}$	1
$y_Q$	1	1	3	1	1	1	3
$y_U$	1	1	1	3	1	1	$\bar{3}$
$y_D$	1	1	1	1	3	1	$\bar{3}$
$m_{S_N}^2$	1	1	1	1	1	$3 \otimes \bar{3}$	1
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3 mix matrices in  $y_f$  + 2 in  $m_S^2$

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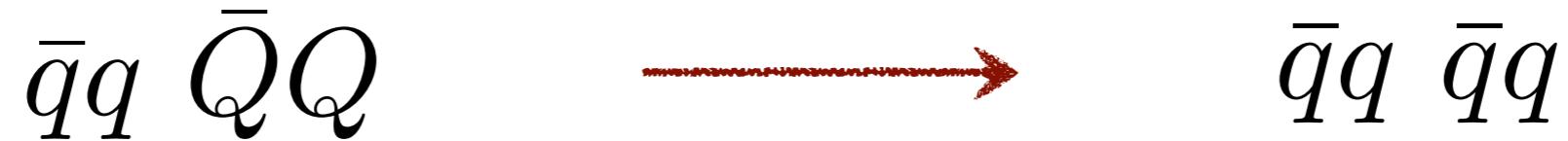
- ◆ Very rich structure
- ◆ Hundreds of composite states to discover
- ◆ Effective theories used so far are ineffective

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$$\bar{q}Hq \longrightarrow \frac{\bar{q}q}{\Lambda^2} \bar{Q}Q$$

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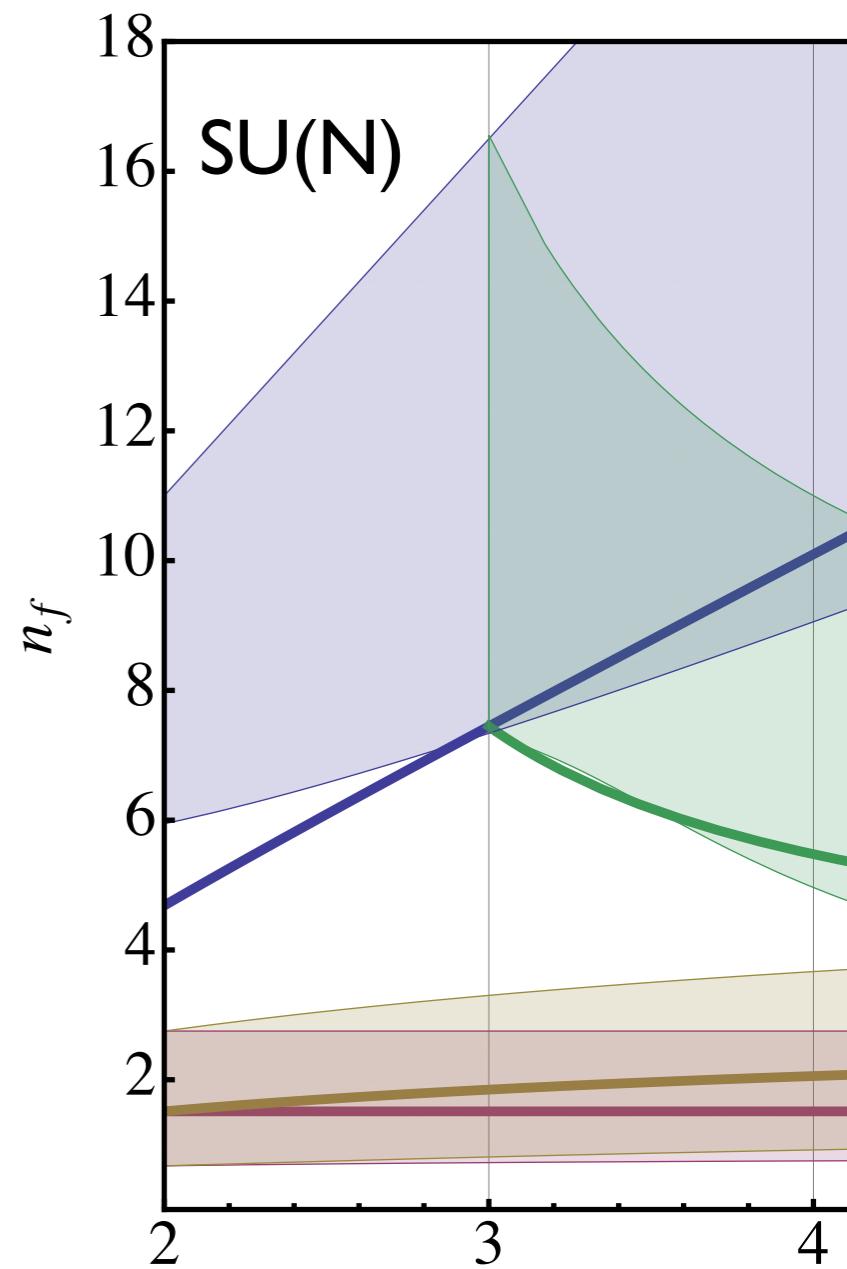
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$$D(\bar{Q}Q) = 3 - \gamma_m , \quad \gamma_m \rightarrow 2$$

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*Conformal Window 1.0*

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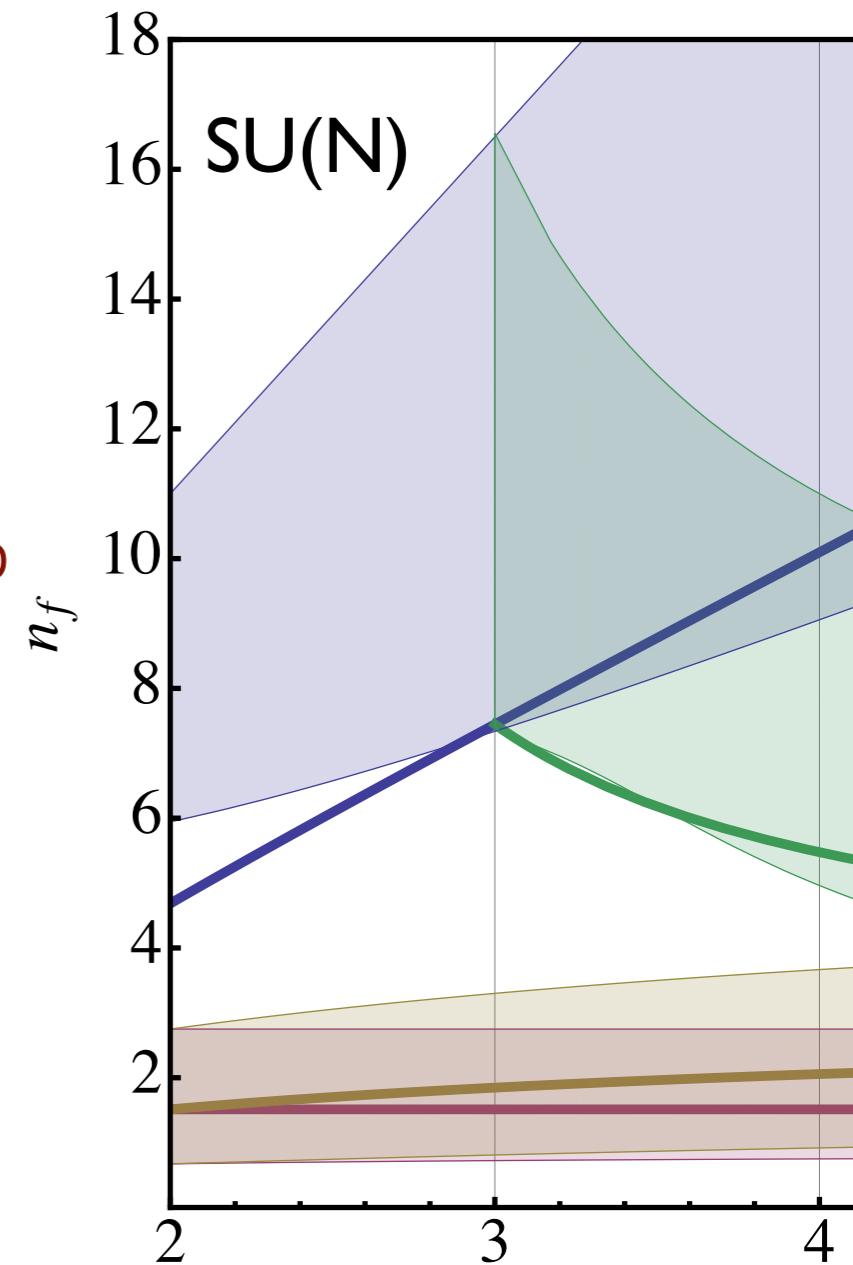
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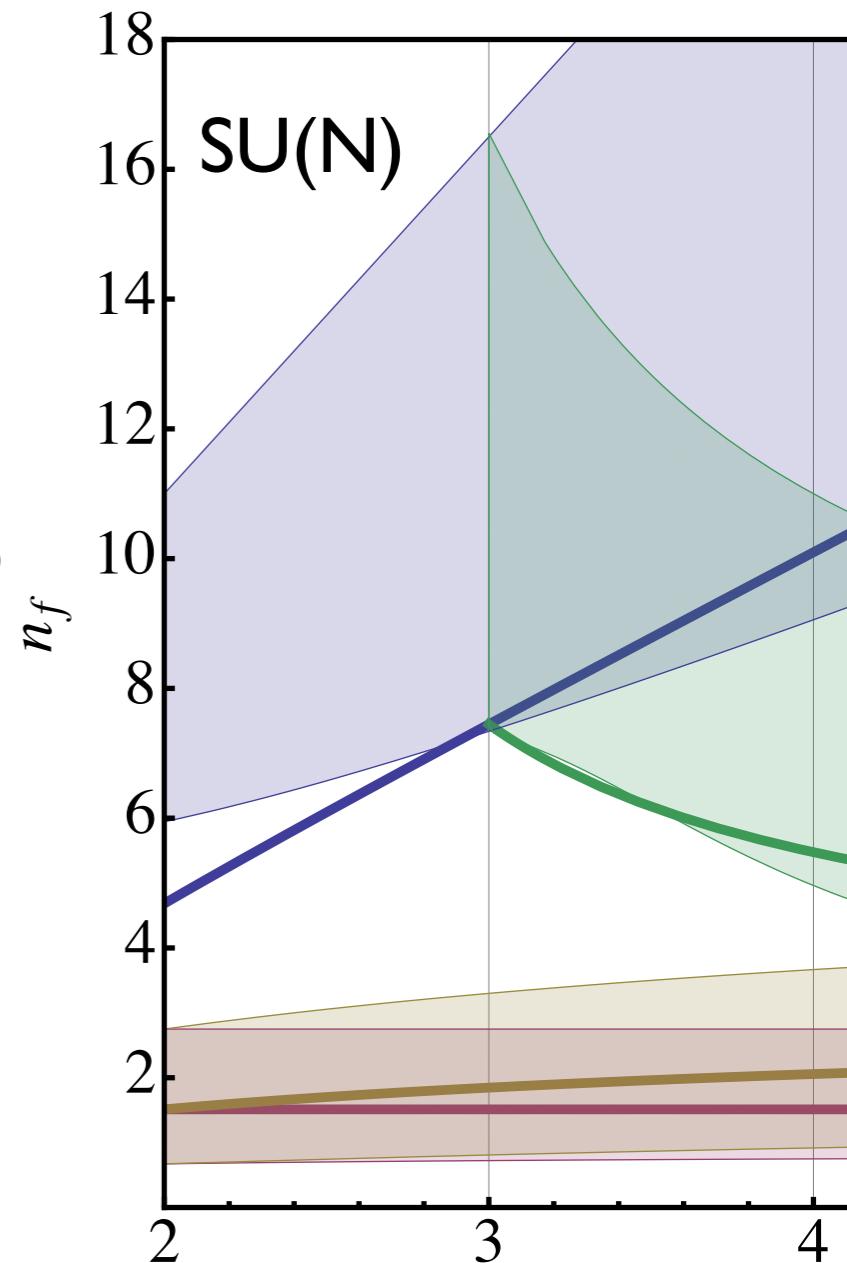
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**Epicycle of the epicycle:** Requires also suppression of

$$\bar{q}q \; \bar{Q}Q \quad \bar{Q}Q \; \bar{Q}Q \quad \xrightarrow{\text{---}} \quad \gamma^B > \gamma_m$$

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Tiny PC Baryons anomalous dim (solid estimate beyond PT)

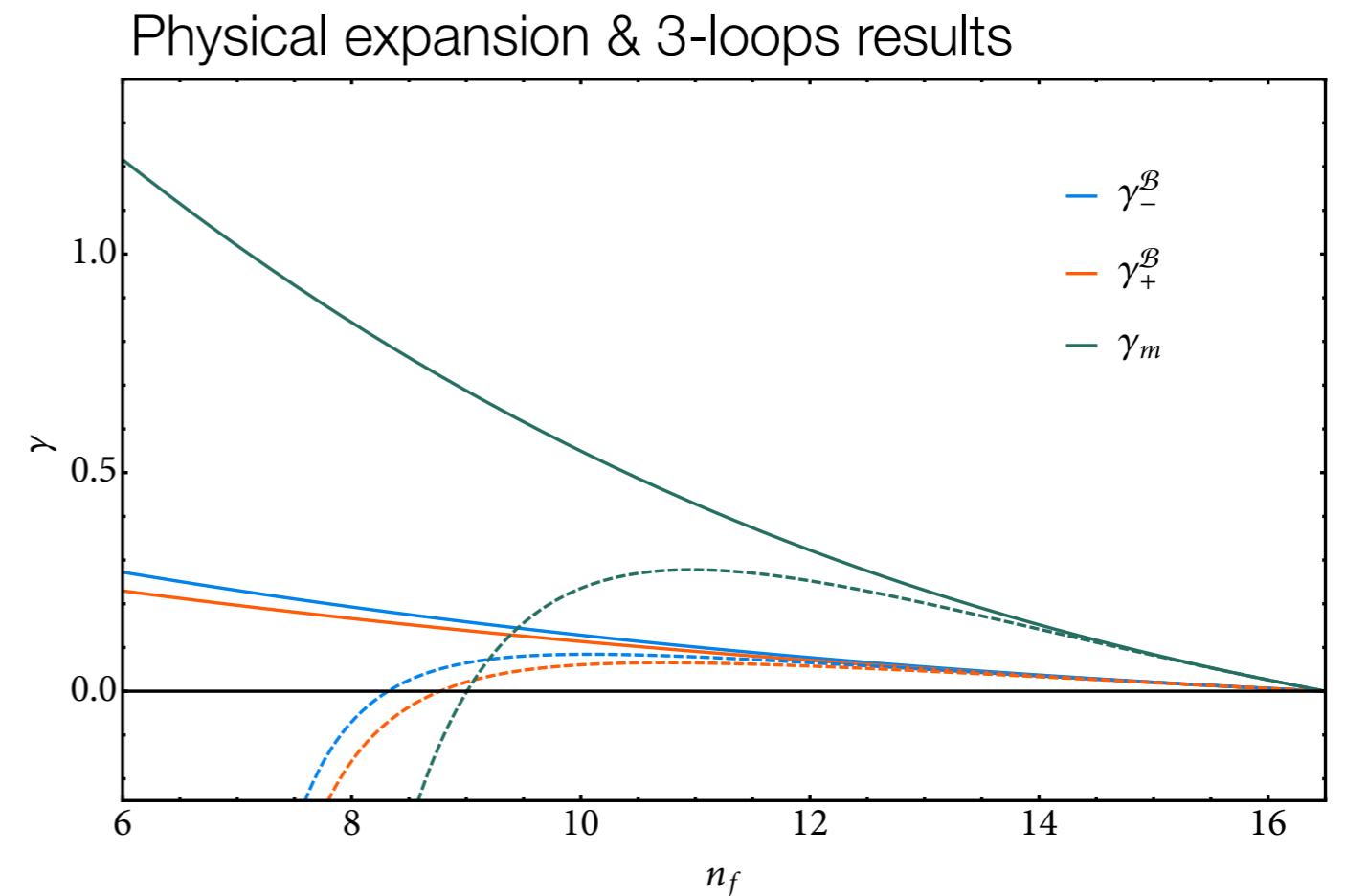
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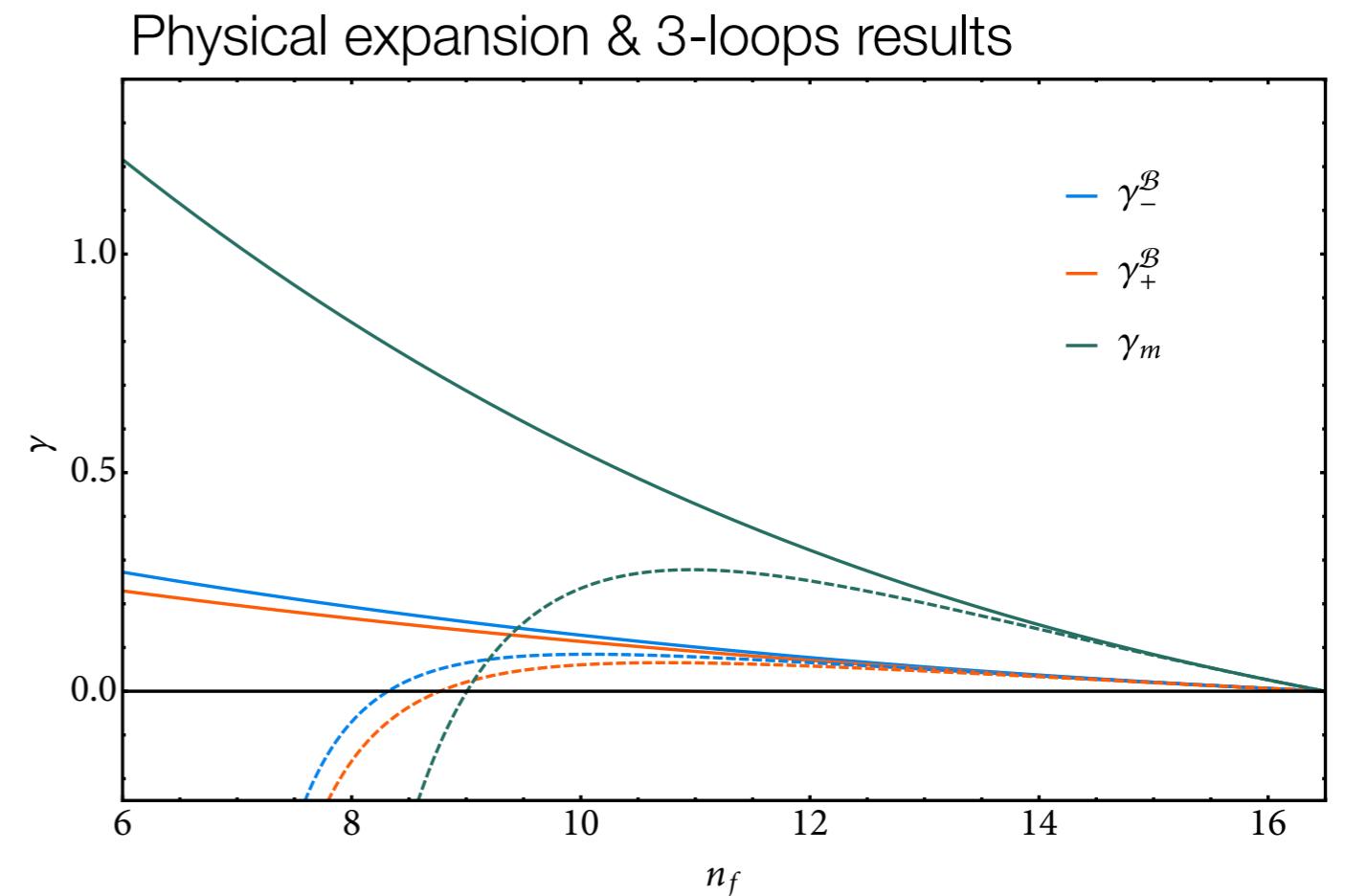
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*Partial compositeness epicycle is very challenging*

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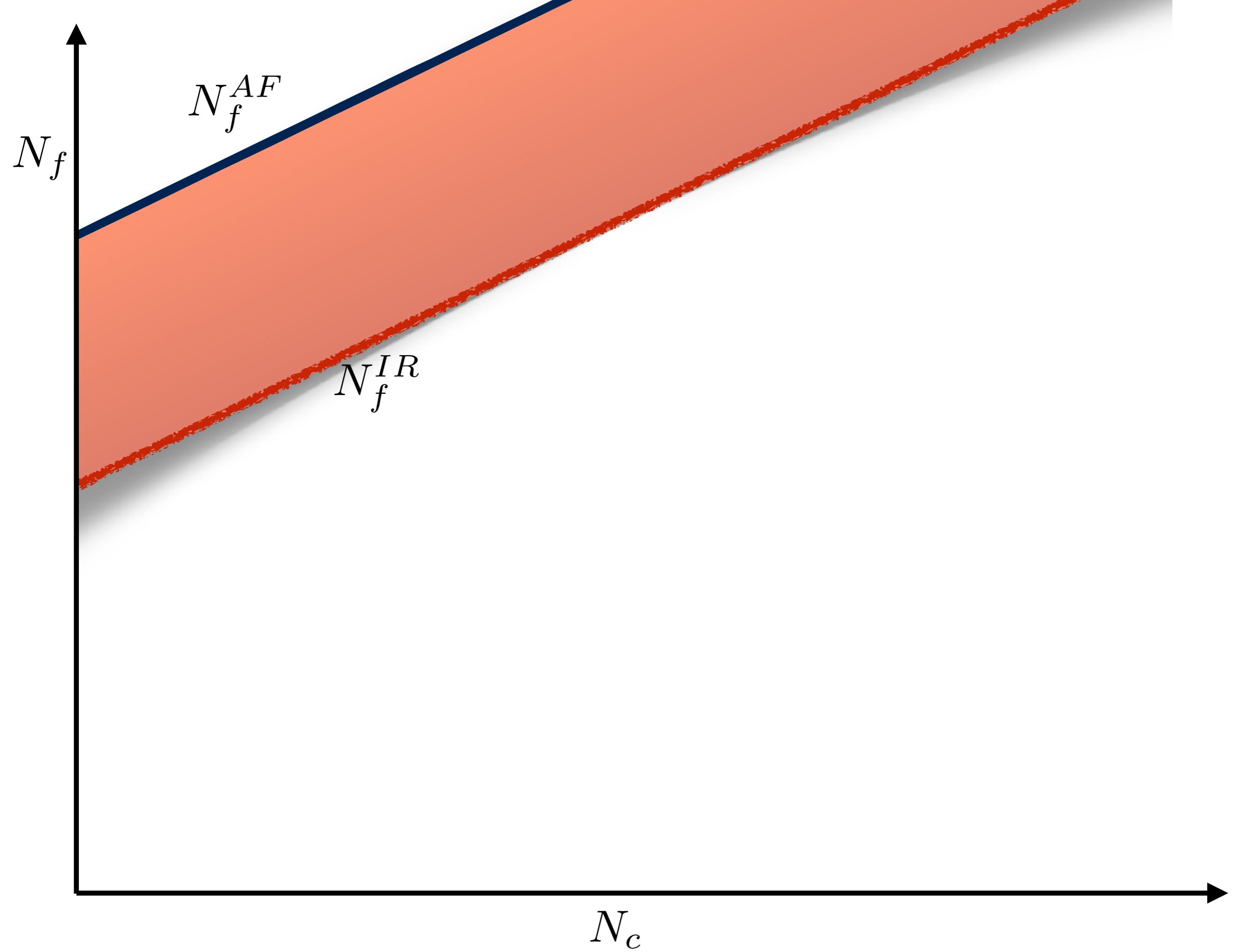
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New states at the TeV Scale!



$N_f$  $N_f^{AF}$  $N_f^{IR}$  $\langle \mathcal{F} \mathcal{F} \rangle \neq 0$  $N_c$

