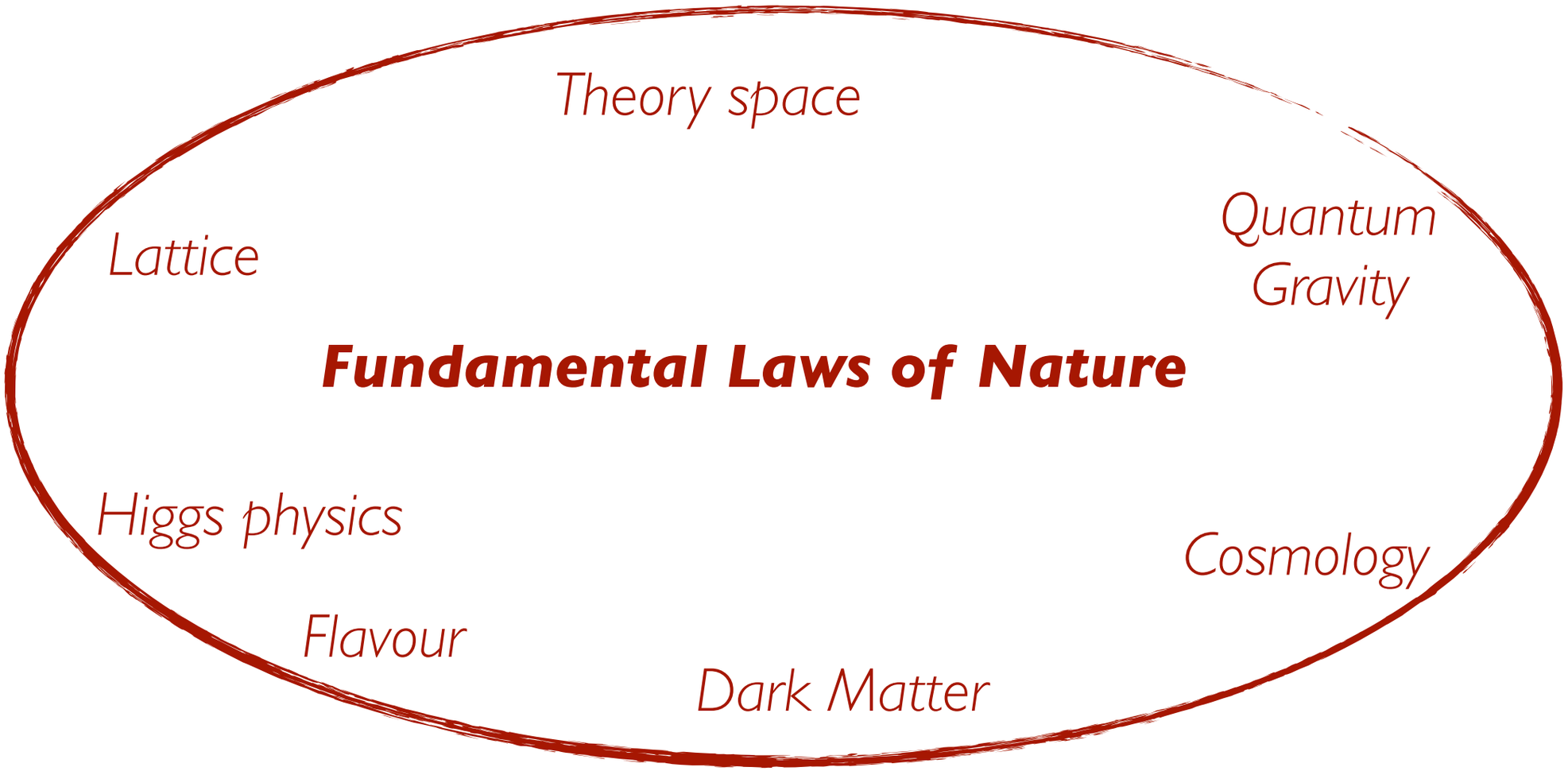
Fundamental Interactions

Francesco Sannino

Fundamental Laws of Nature


Theory space
Lattice
Quantum Gravity
Fundamental Laws of Nature
Higgs physics
Cosmology
Flavour
Dark Matter

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What is the Higgs?

Flavour

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Fermion masses

SM is quantum unstable/
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What is DM?

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Where does it come from?

How do we discover it?

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What drives inflation?

Initial singularity

Galaxy formation

Strong gravity/
Gravity waves

Fundamental theory of gravity

Black hole horizon and
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Map fundamental theories a la Wilson

Phases of Quantum Field Theory

Conformal dynamics

Example: a-theorem

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Example: a-theorem

Numerically solve QFTs and Gravity

Strong dynamics

New algorithms

Strong gravity/ Gravity waves

Fundamental theory of gravity

Black hole horizon and interior

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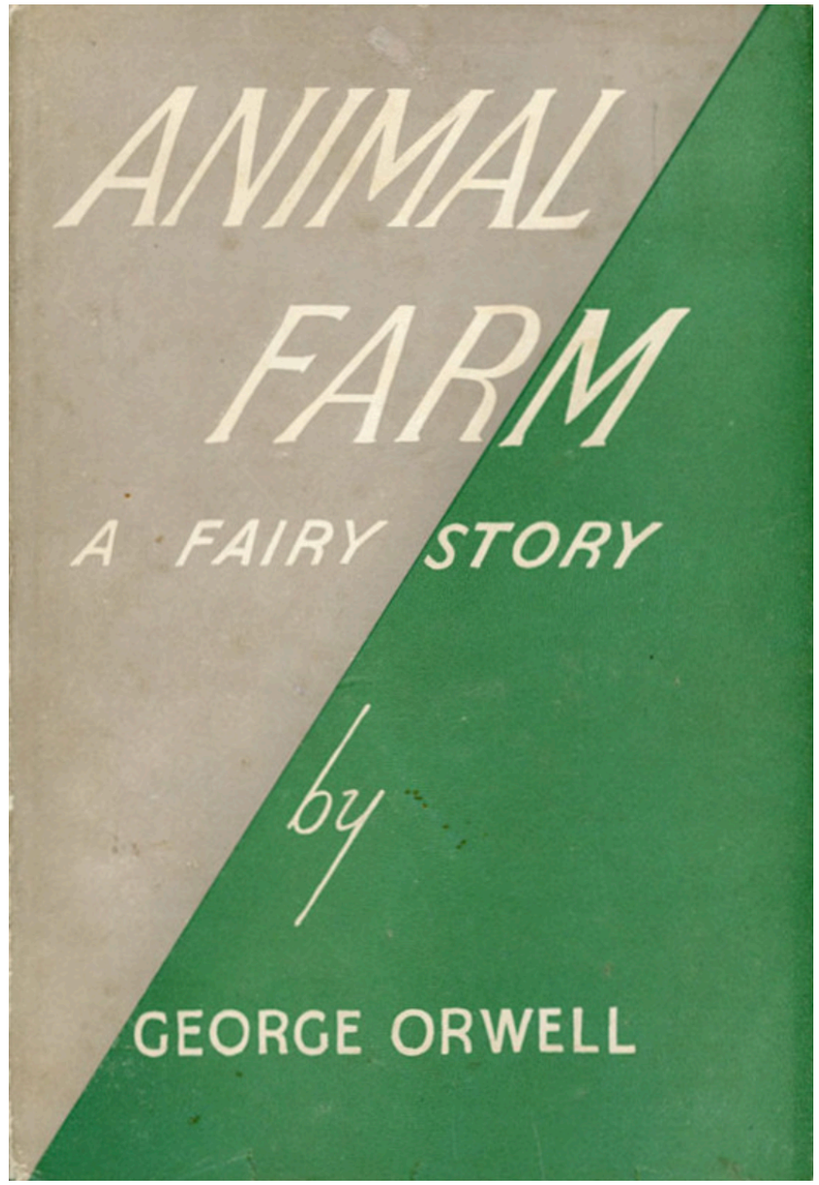
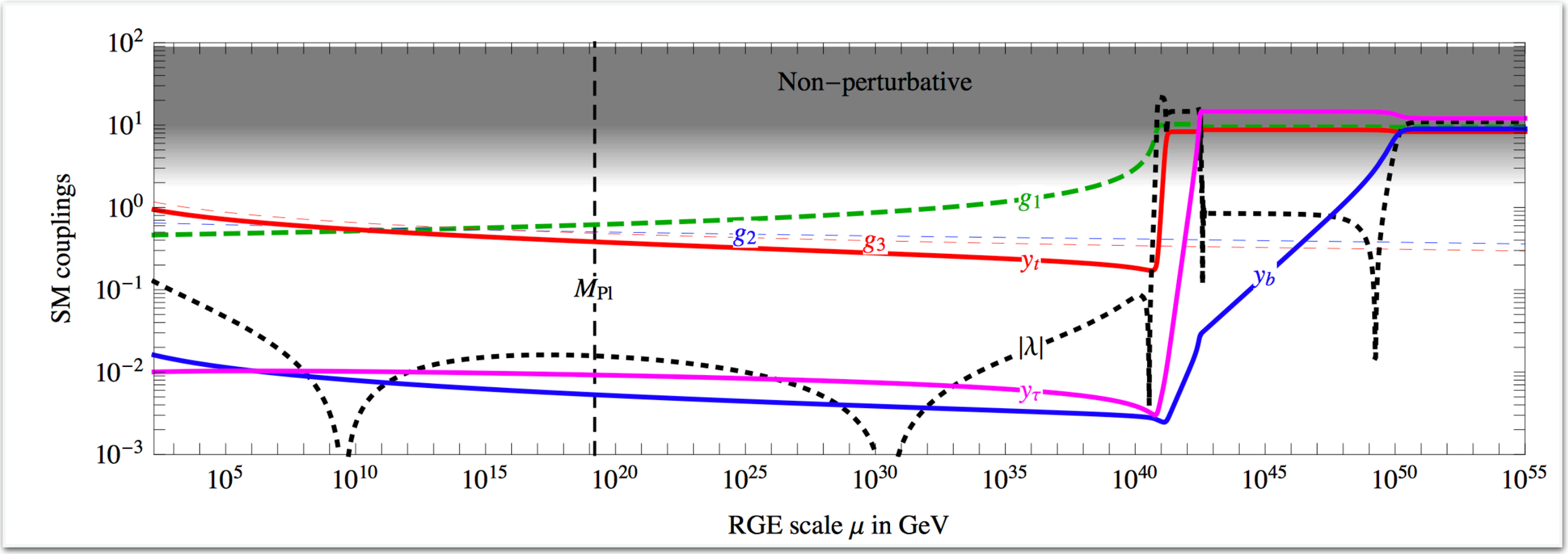
The Standard Model is not a fundamental theory

Fundamental theories

All theories are equals but some theories are more equal than others



Is the Standard Model safe?



Pelaggi, Sannino, Strumia, Vigiani 1701.01453

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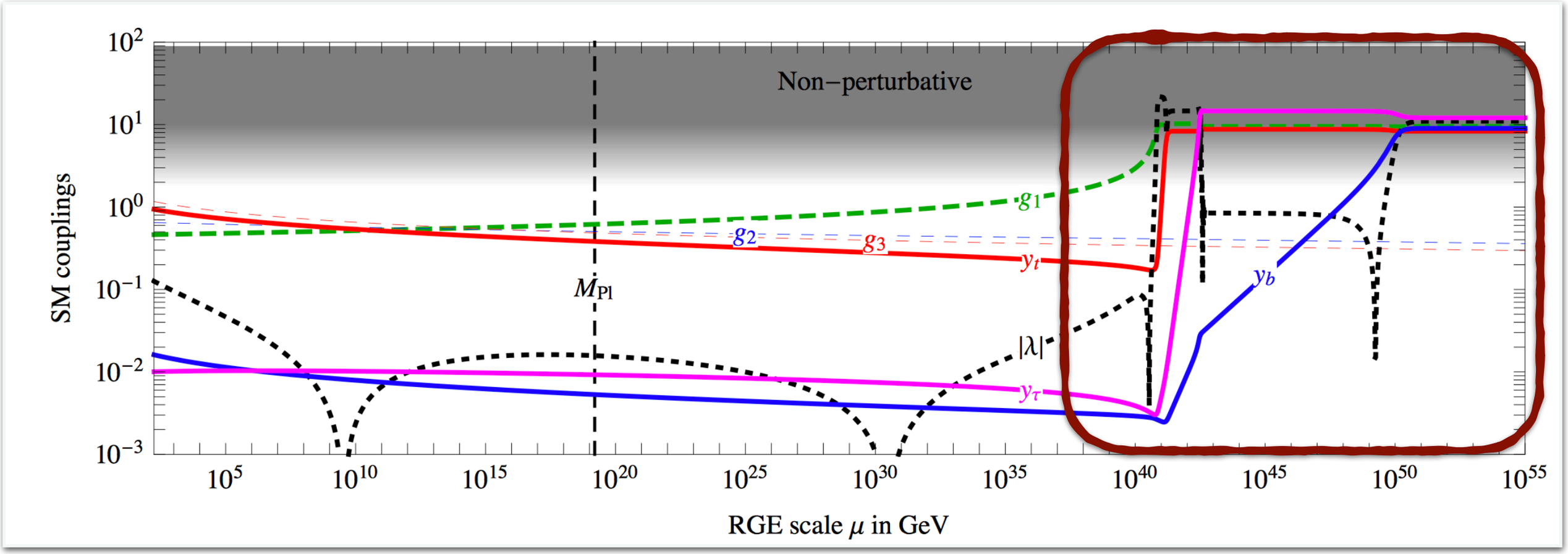


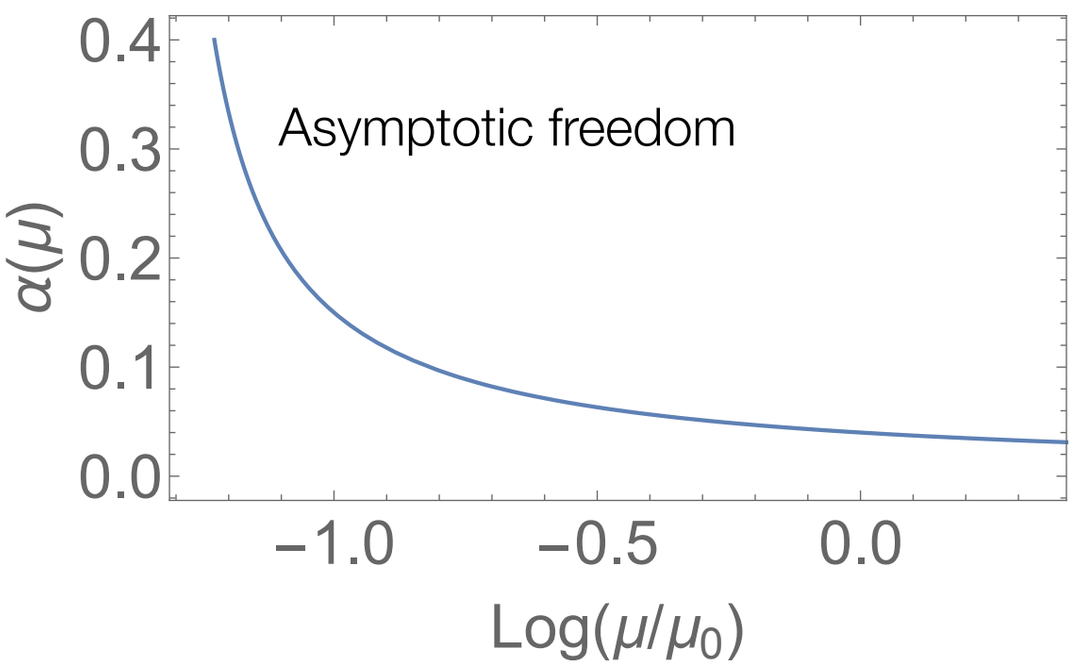
Pelaggi, Sannino, Strumia, Vigiani 1701.01453

Free versus Safe

Wilson: A fundamental theory has an UV fixed point

Trivial fixed point

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



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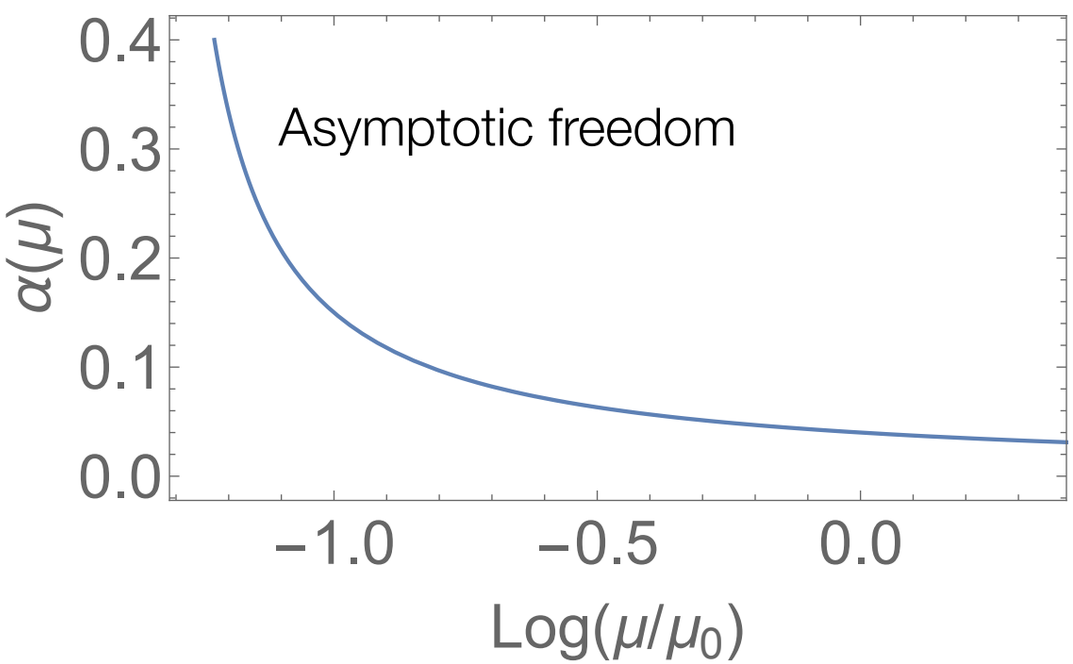

Interacting fixed point

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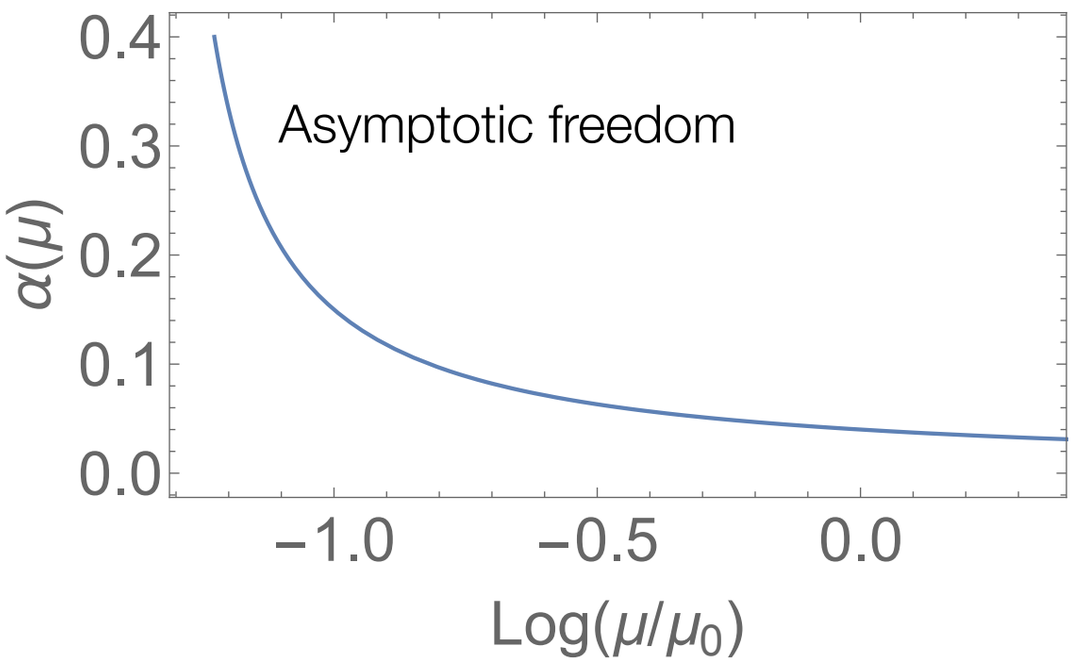
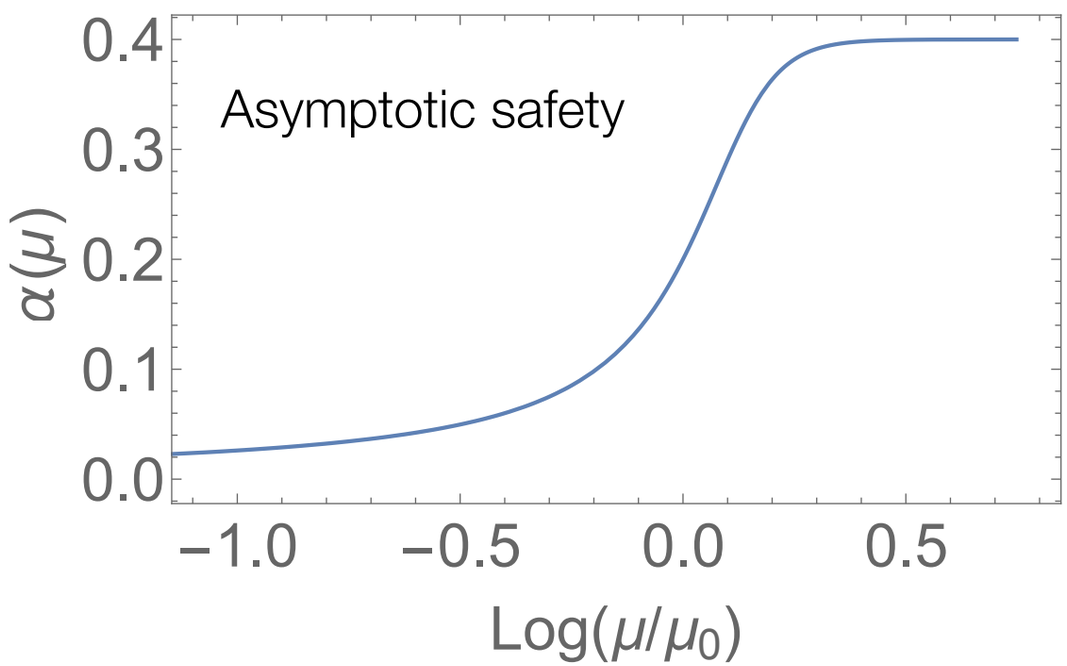


Interacting fixed point

- Integrating in the UV
- Power law



Do theory like these exist?

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

Visual help

Visualising Gauge-Yukawa theories

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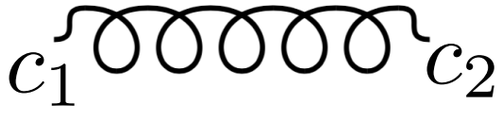
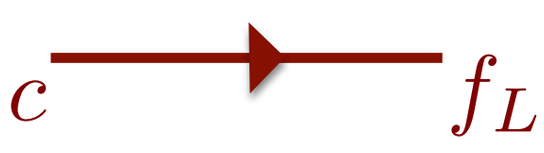
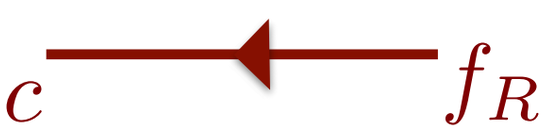
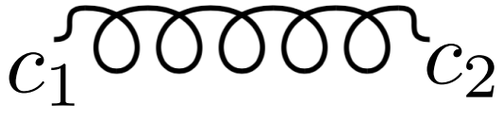
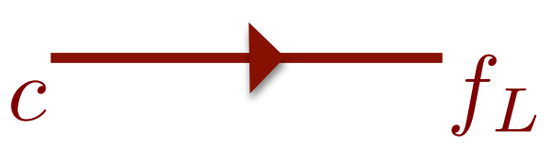
$G_{\mu\ c_2}^{\ c_1}$ 

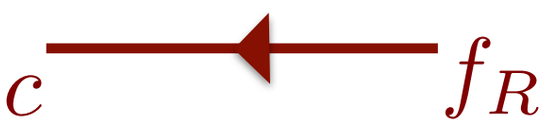
$\psi_{f_L}^{c}$ 

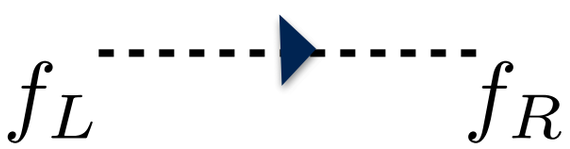
$\widetilde{\psi}_{c}^{f_R}$ 

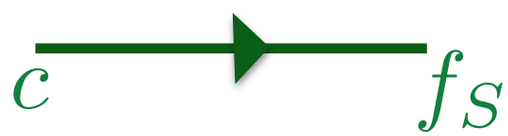
Visualising Gauge-Yukawa theories

$G_{\mu\ c_2}^{\ c_1}$ 

$\psi_{f_L}^{c}$ 

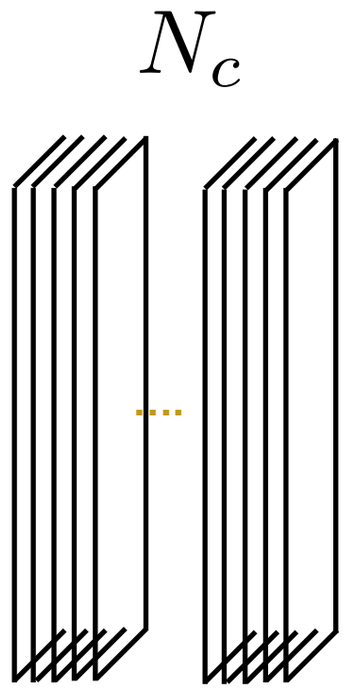
$\widetilde{\psi}_{c}^{f_R}$ 

$\mathcal{H}_{f_R}^{f_L}$ 

$H_{f_S}^{c}$ 

Free

Large N_c



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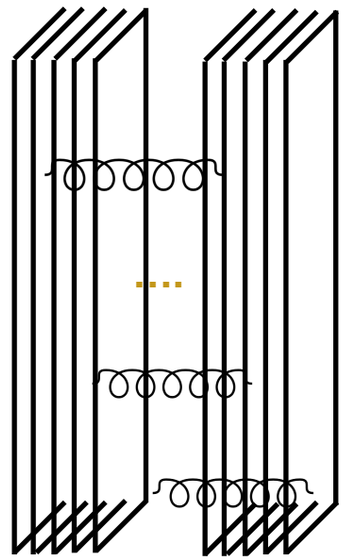
N_c



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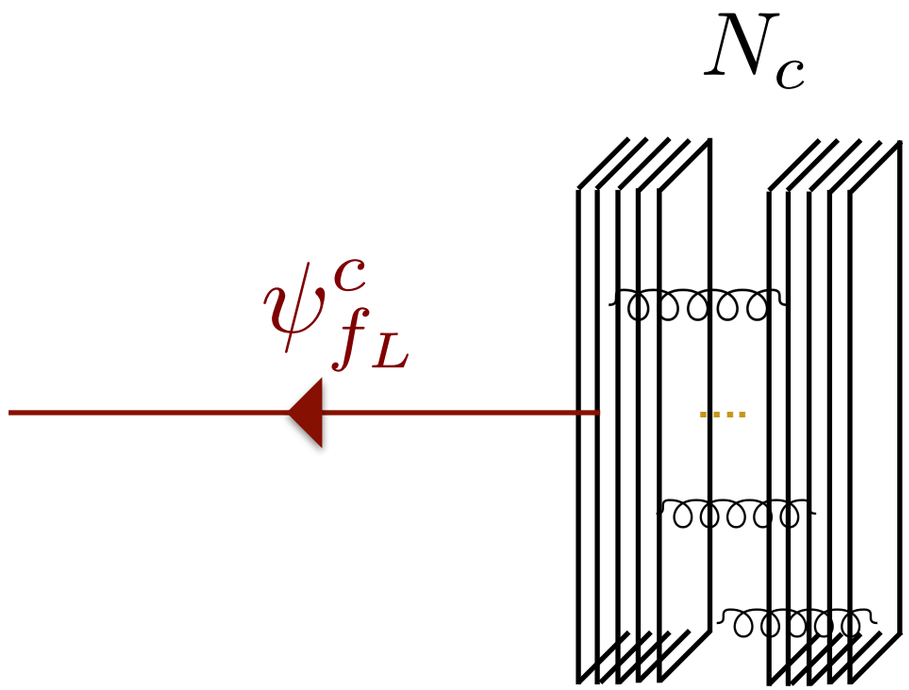

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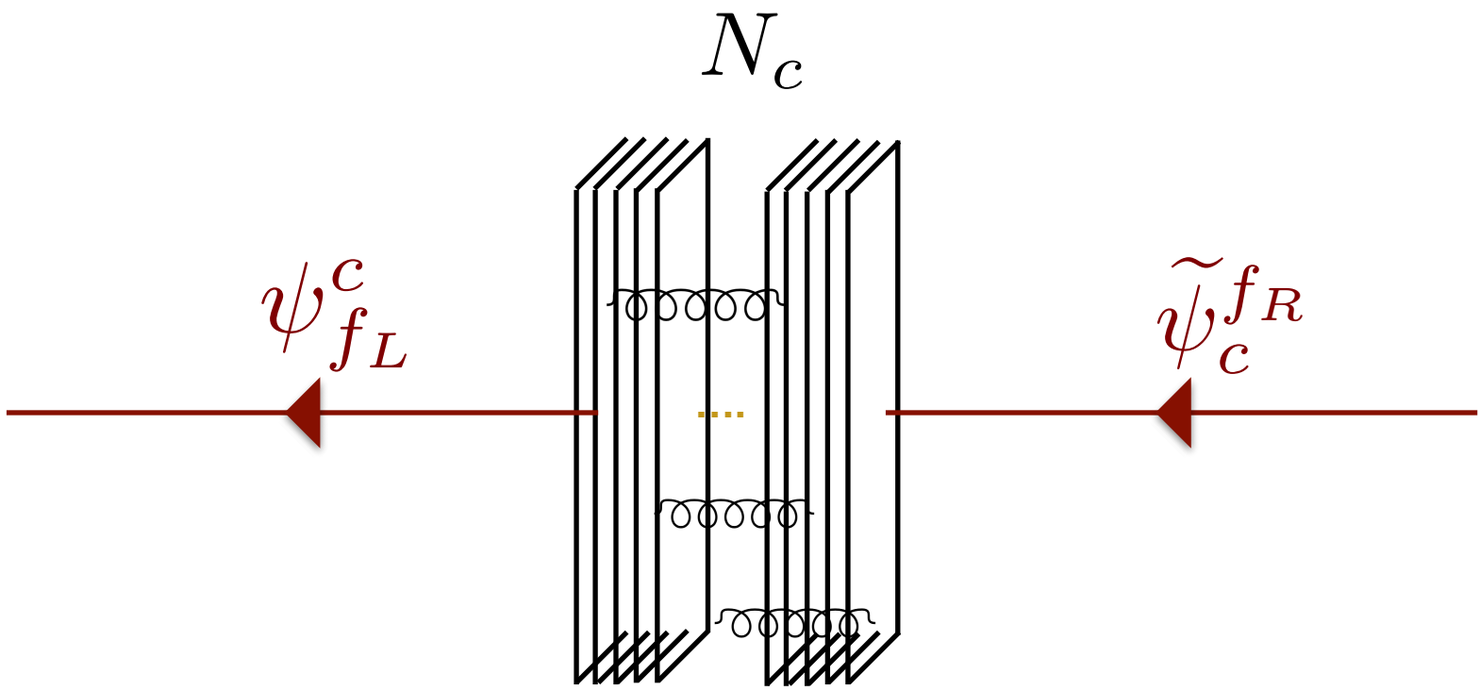

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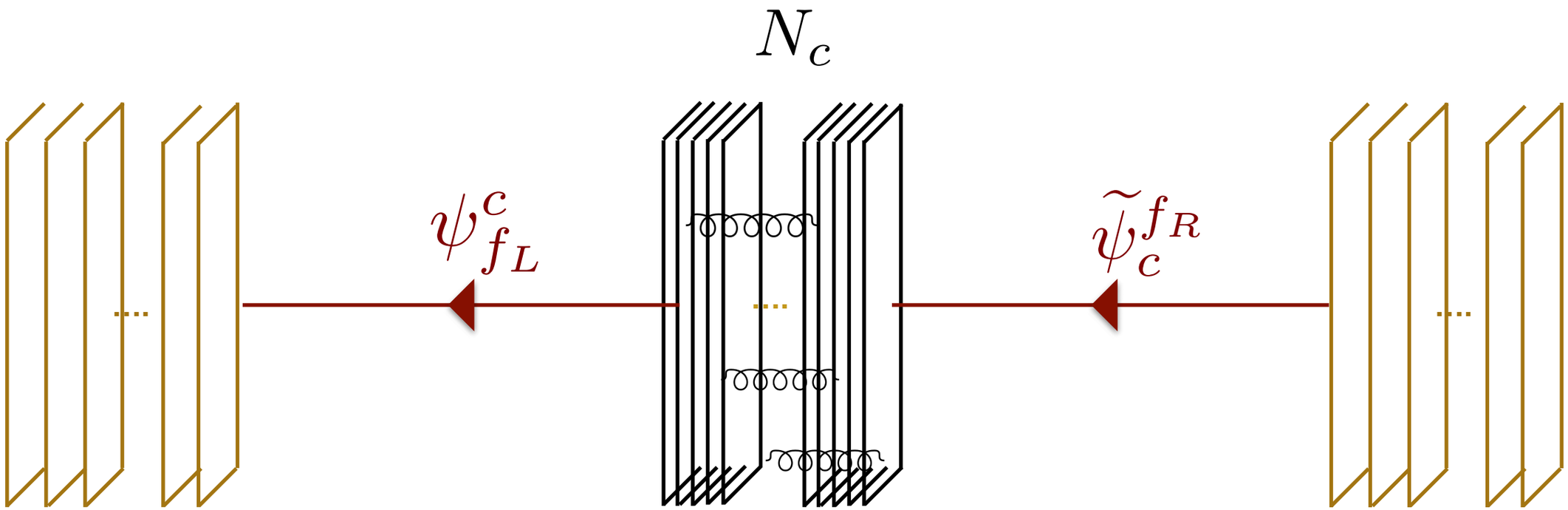

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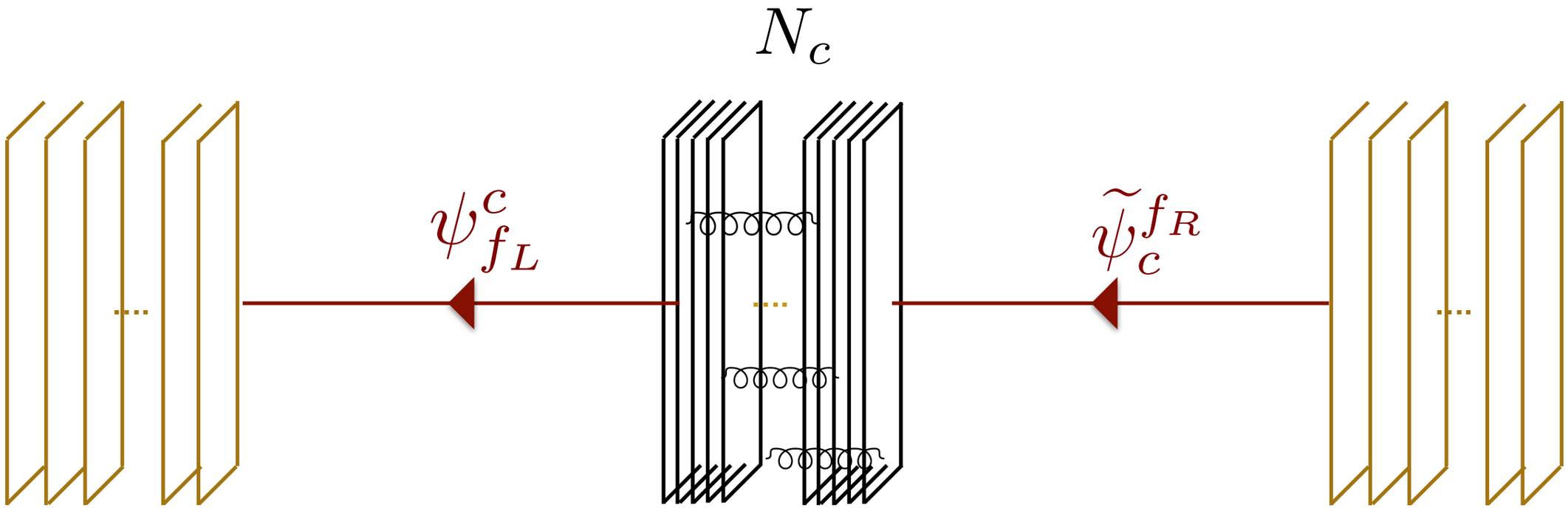

- IR dynamics of QCD-like theories

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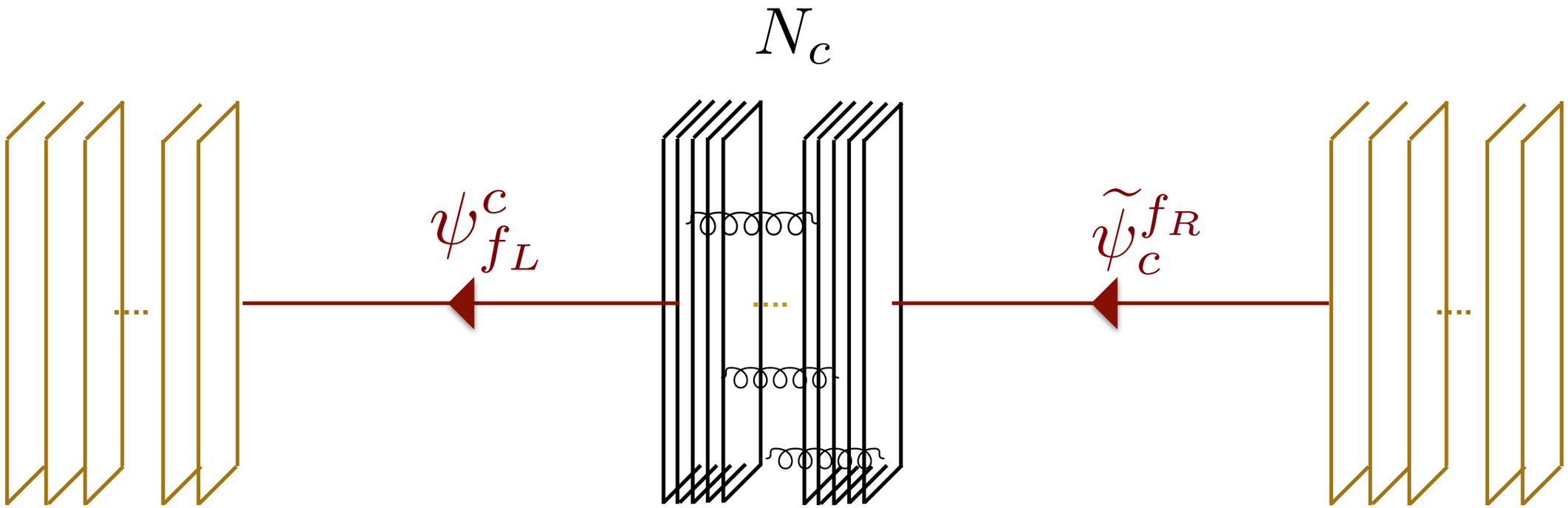

- IR dynamics of QCD-like theories
- Planar diagrams dominate

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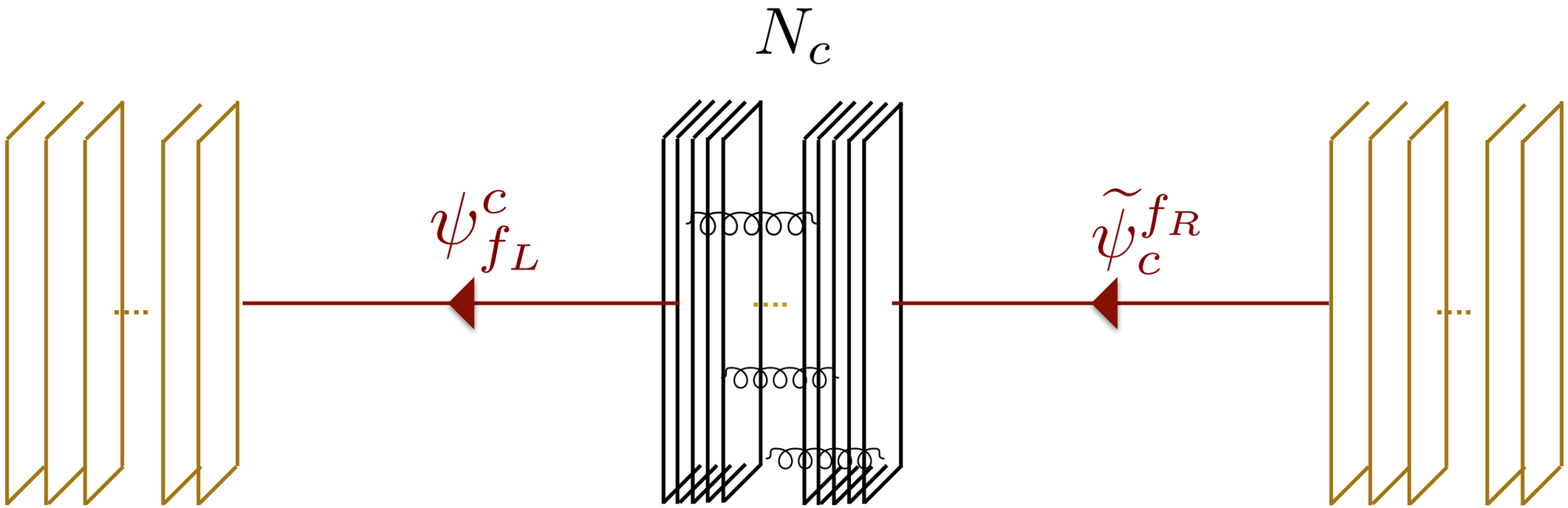

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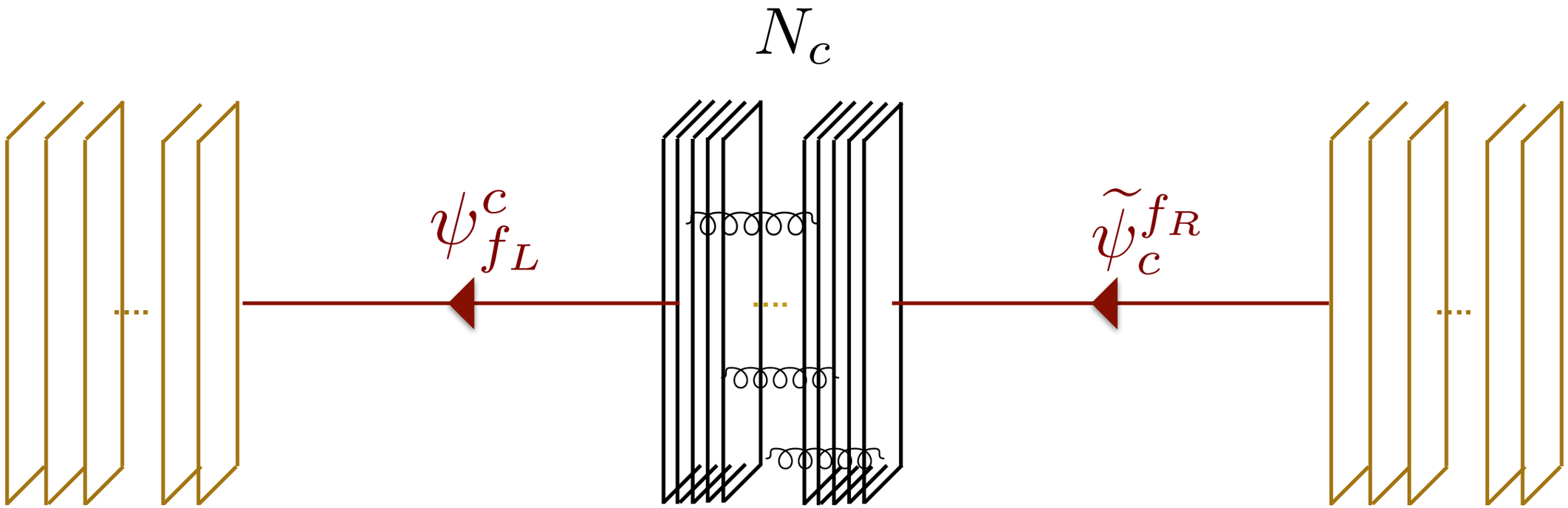

- IR dynamics of QCD-like theories
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- Fermion loops are suppressed

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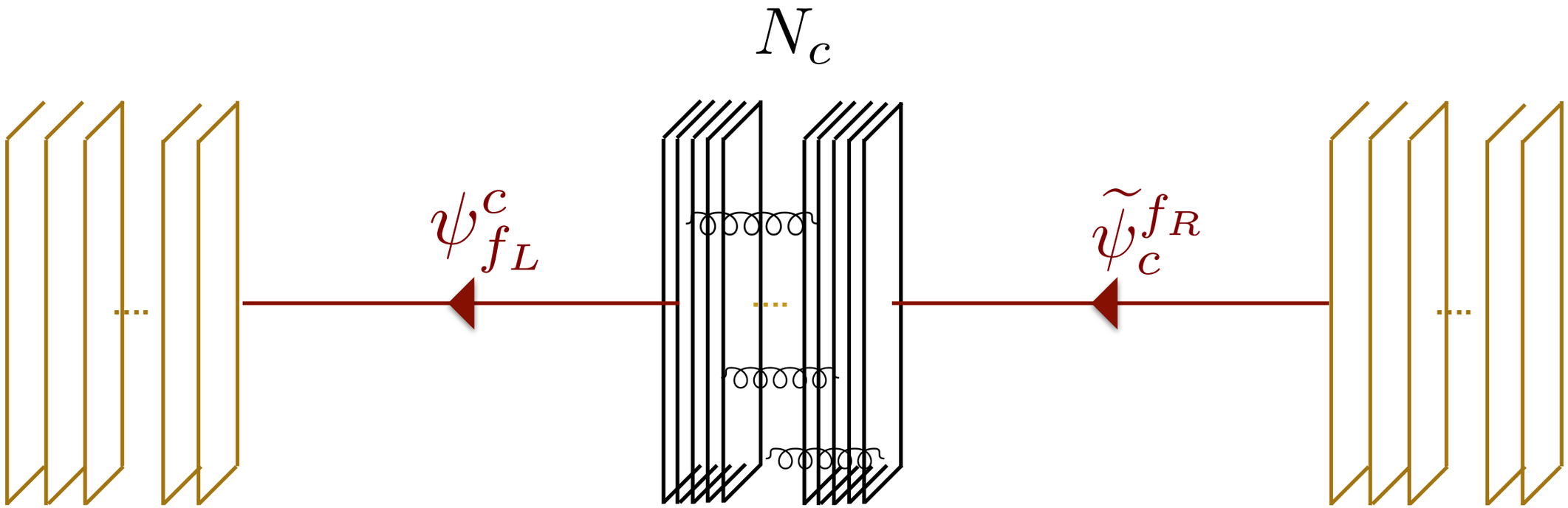

- IR dynamics of QCD-like theories
- Planar diagrams dominate
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- Fermion loops are suppressed
- Axial anomaly is suppressed

Large N_f

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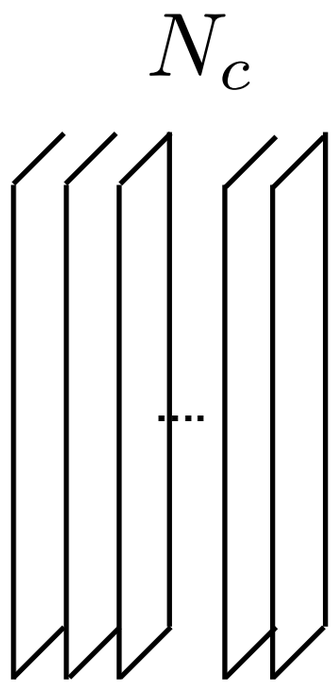

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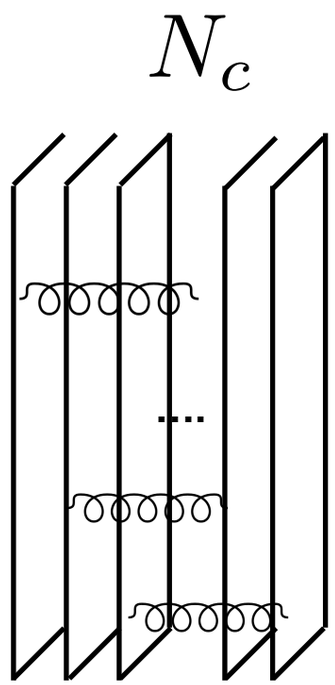

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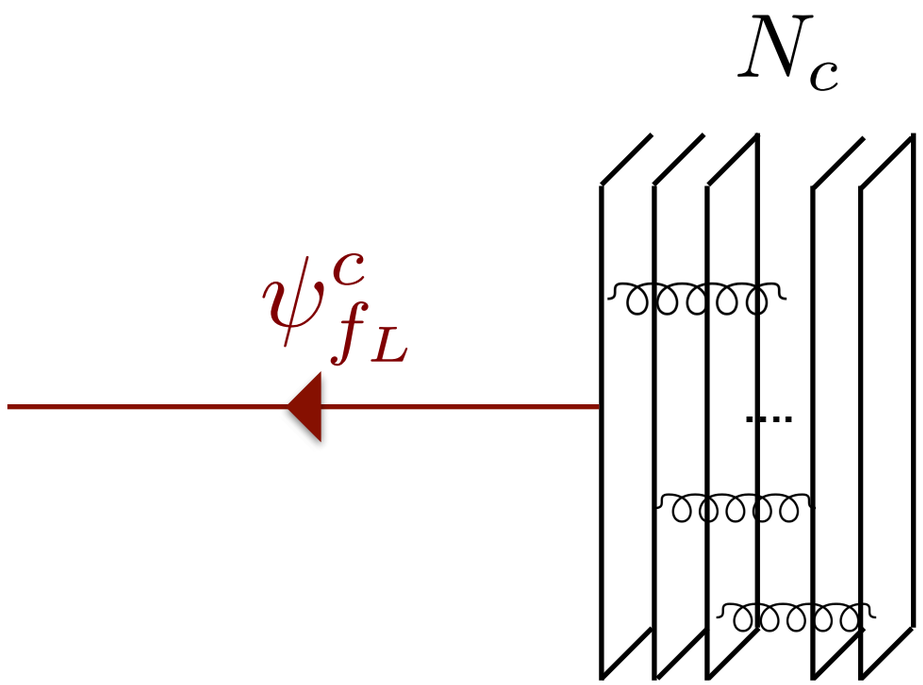

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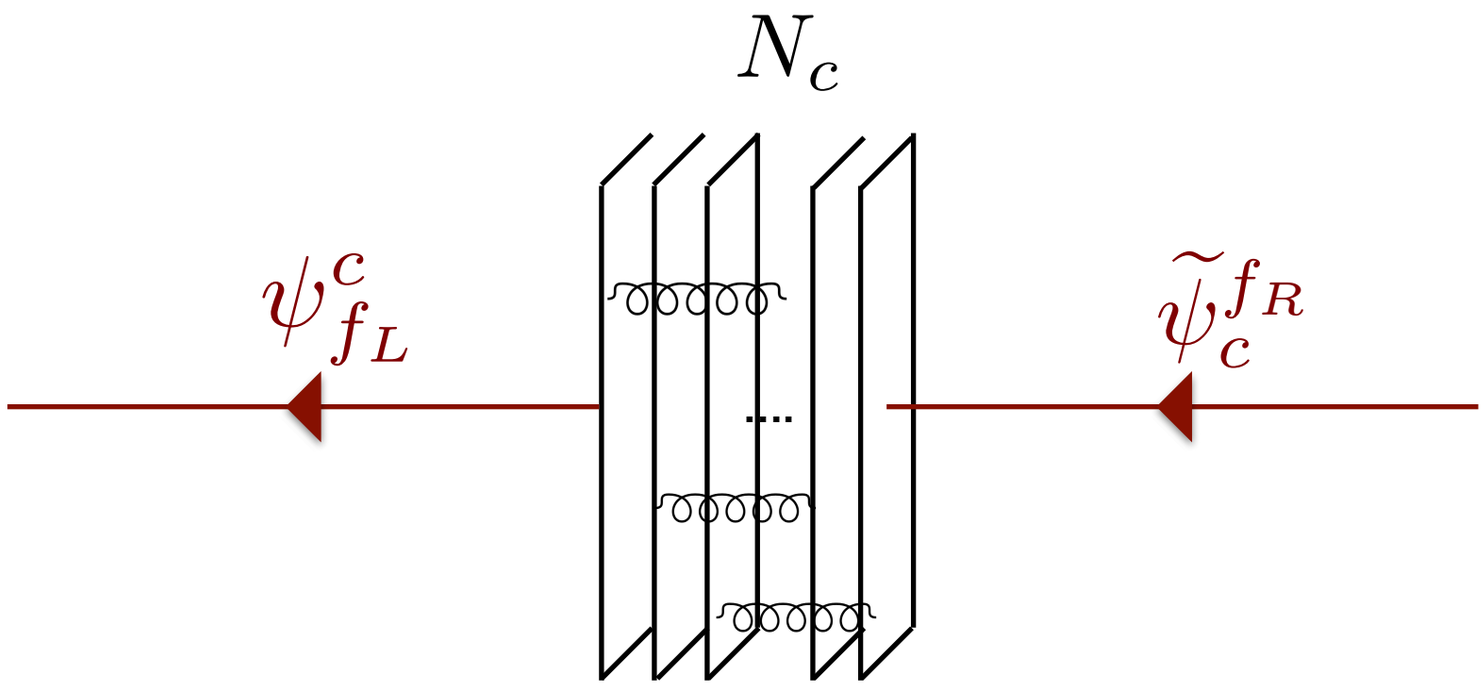

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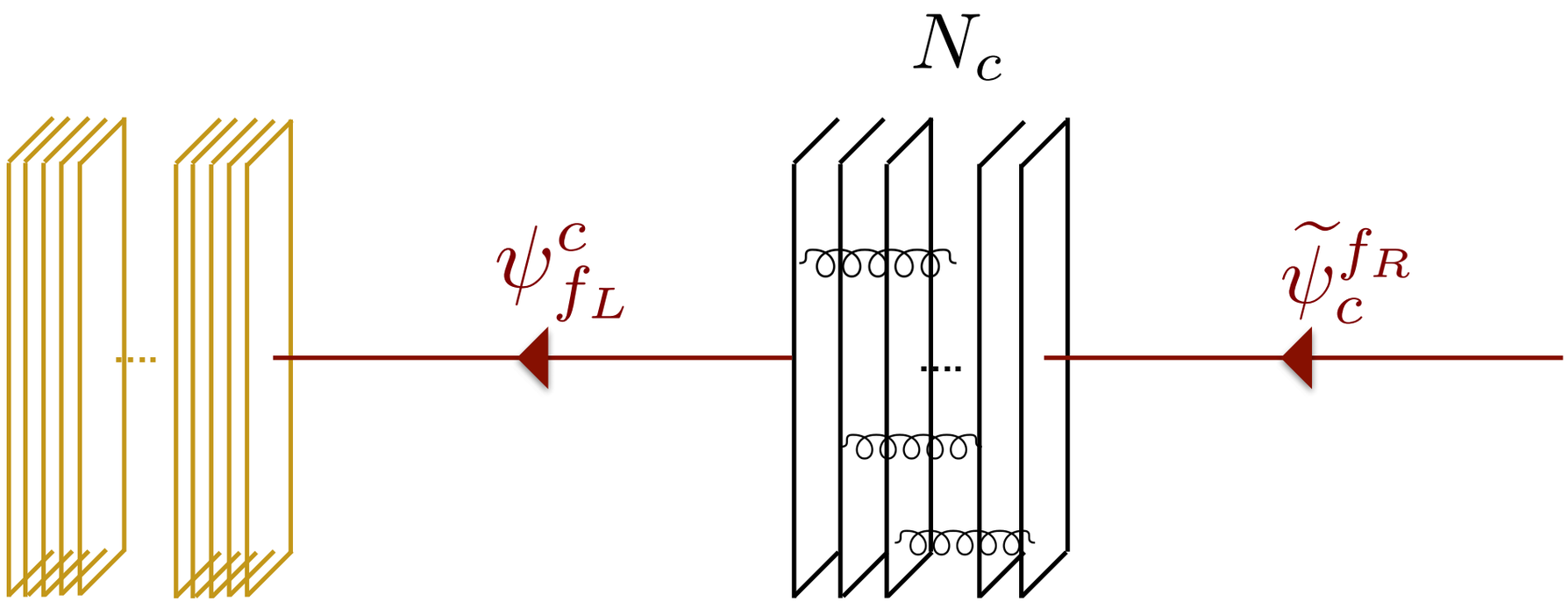

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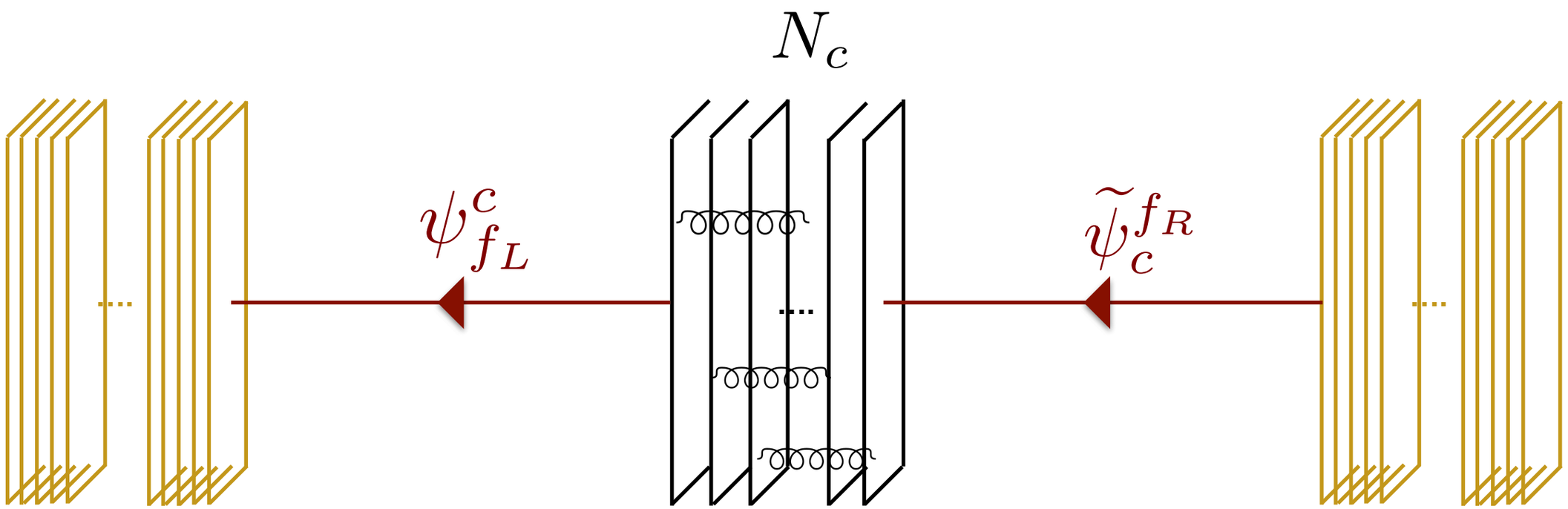

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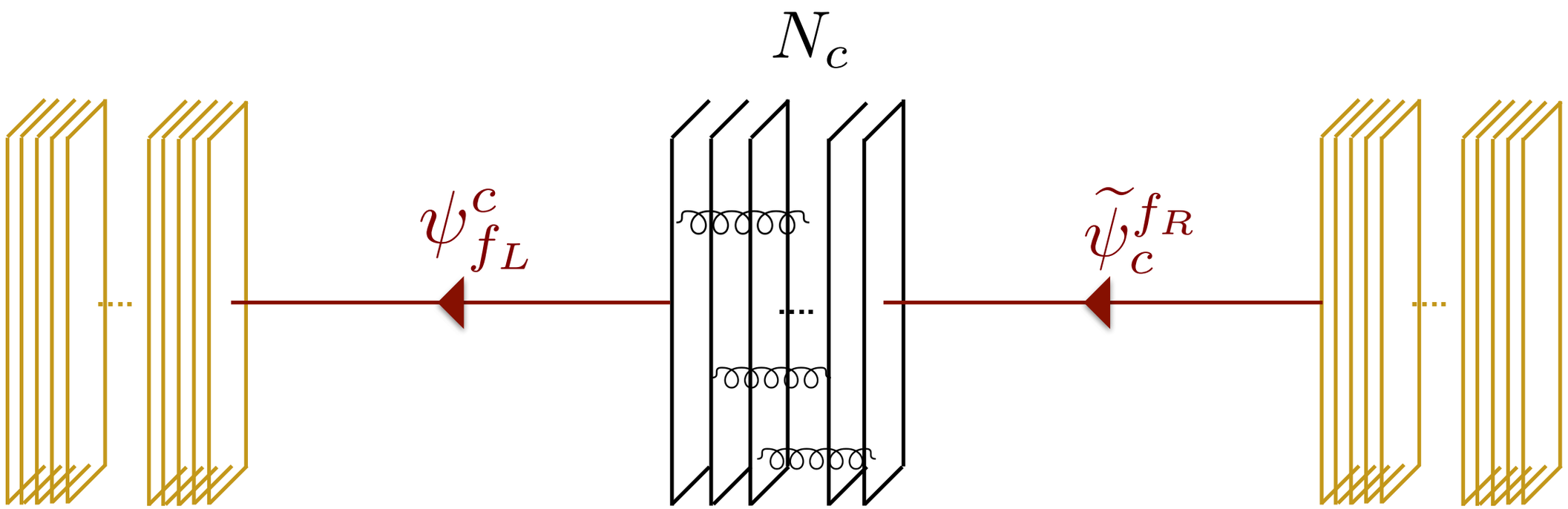
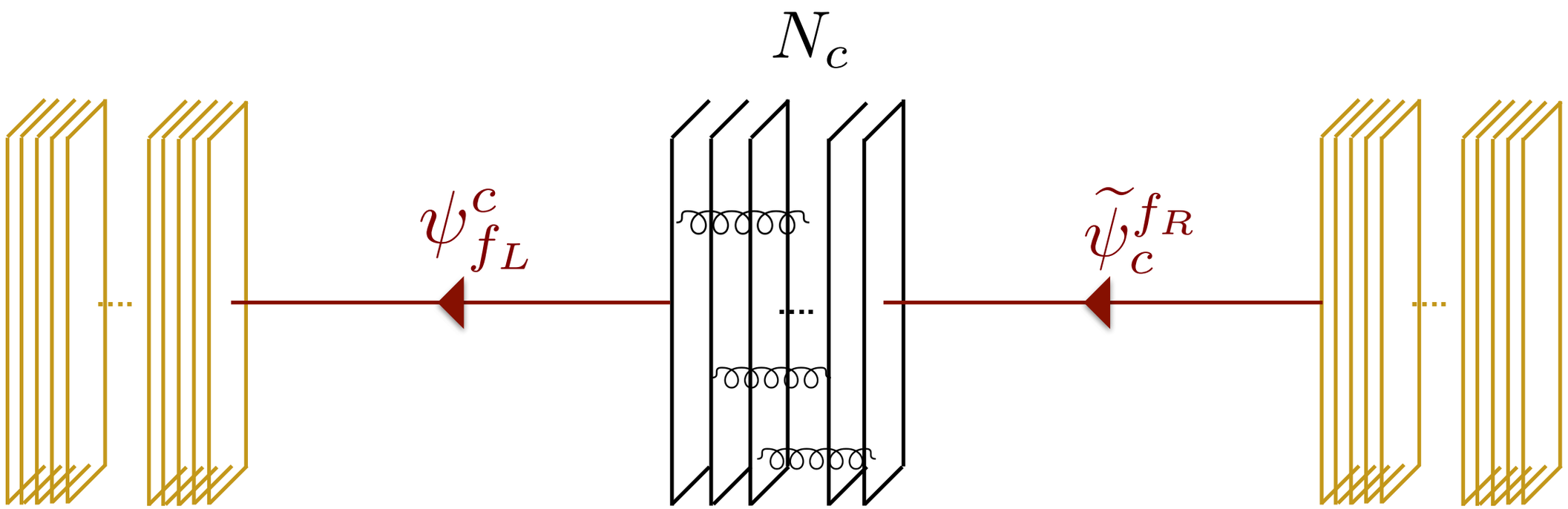


- UV dynamics of non asymptotically free theories

Large N_f



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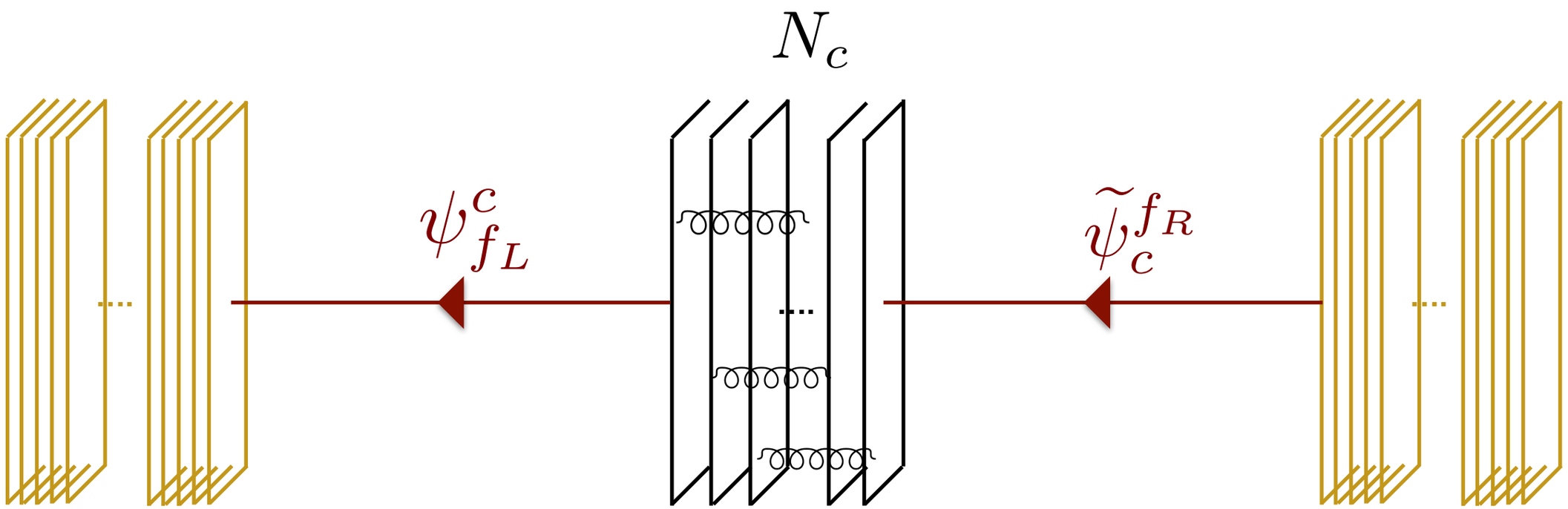

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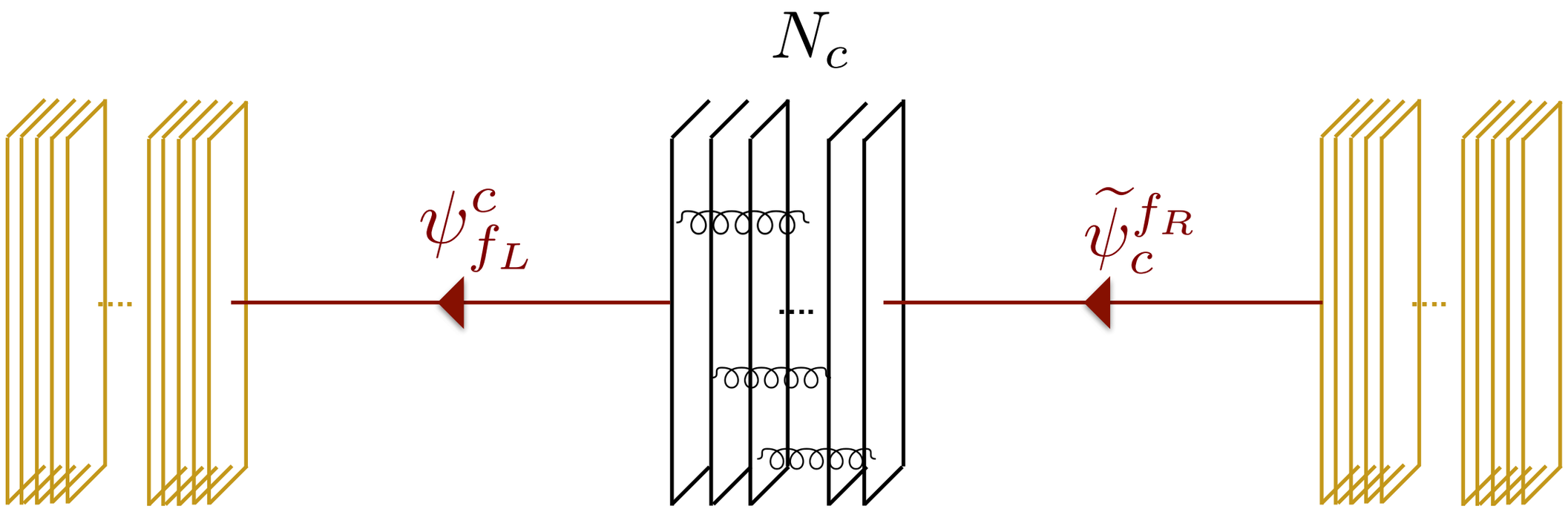

N_{f_L} N_{f_R}

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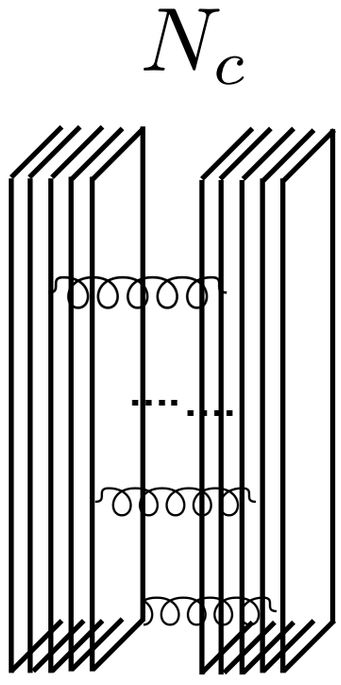
- a-theorem (non)monotonicity

Large N_c



Pay attention

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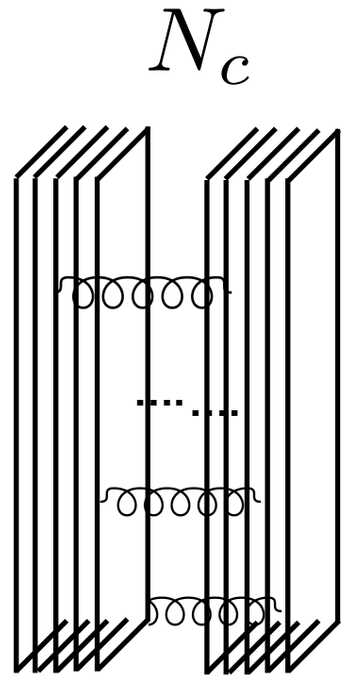

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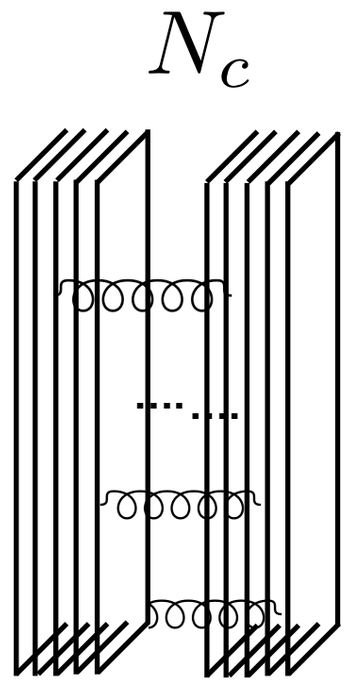

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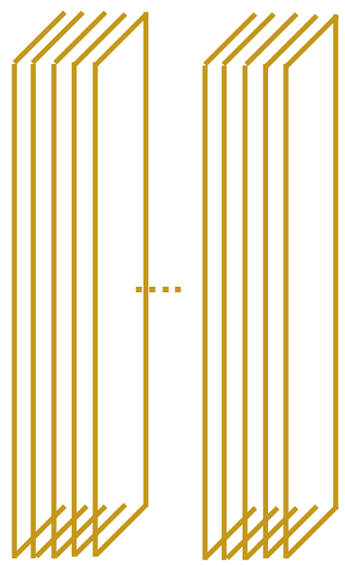

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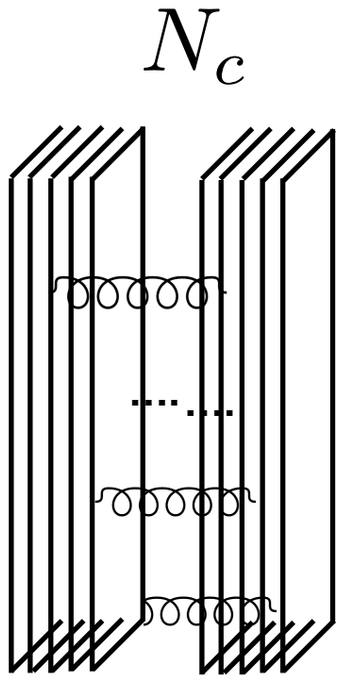

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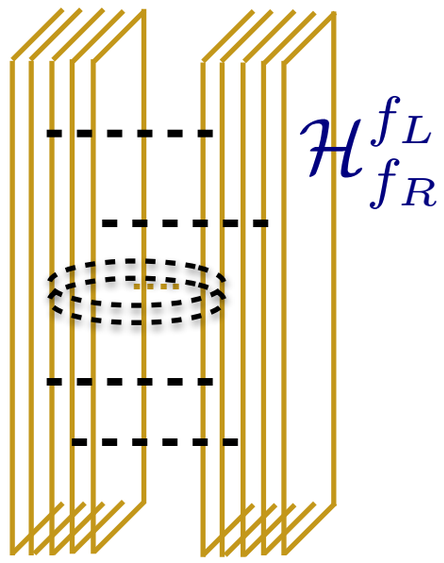

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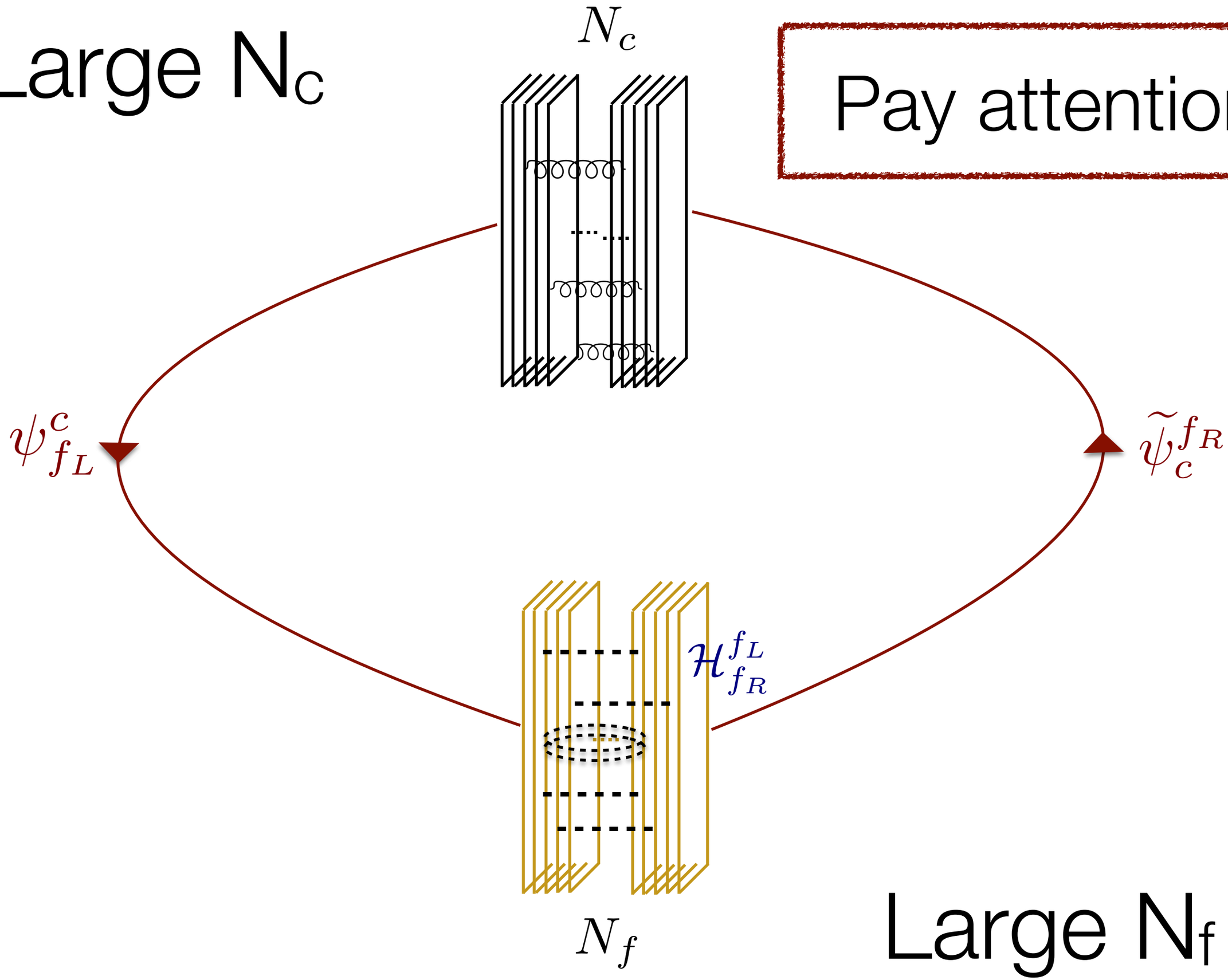

Pay attention

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Exact 4D Interacting UV Fixed Point

Litim and Sannino, 1406.2337, JHEP

Litim, Mojaza, Sannino, 1501.03061, JHEP

Exact 4D Interacting UV Fixed Point

Litim and Sannino, 1406.2337, JHEP

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

$$\text{Tr}\left[\partial \text{H}^\dagger \partial \text{H}\right] - \text{u}\text{Tr}\left[(\text{H}^\dagger \text{H})^2\right] - \text{v}\text{Tr}\left[(\text{H}^\dagger \text{H})\right]^2$$

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

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

Veneziano Limit

Litim and Sannino, 1406.2337, JHEP

Litim, Mojaza, Sannino, 1501.03061, JHEP

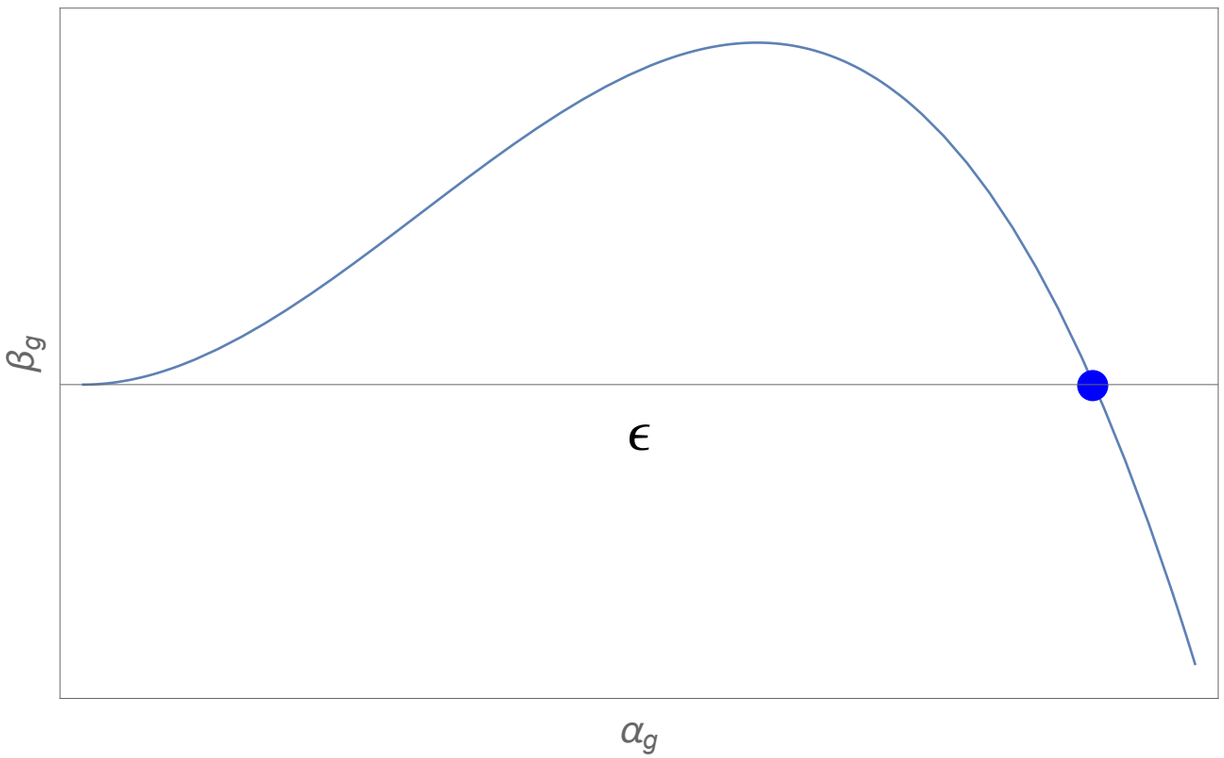
- Normalised couplings

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

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

At large N

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



Veneziano Limit

Litim and Sannino, 1406.2337, JHEP

Litim, Mojaza, Sannino, 1501.03061, JHEP

- Normalised couplings

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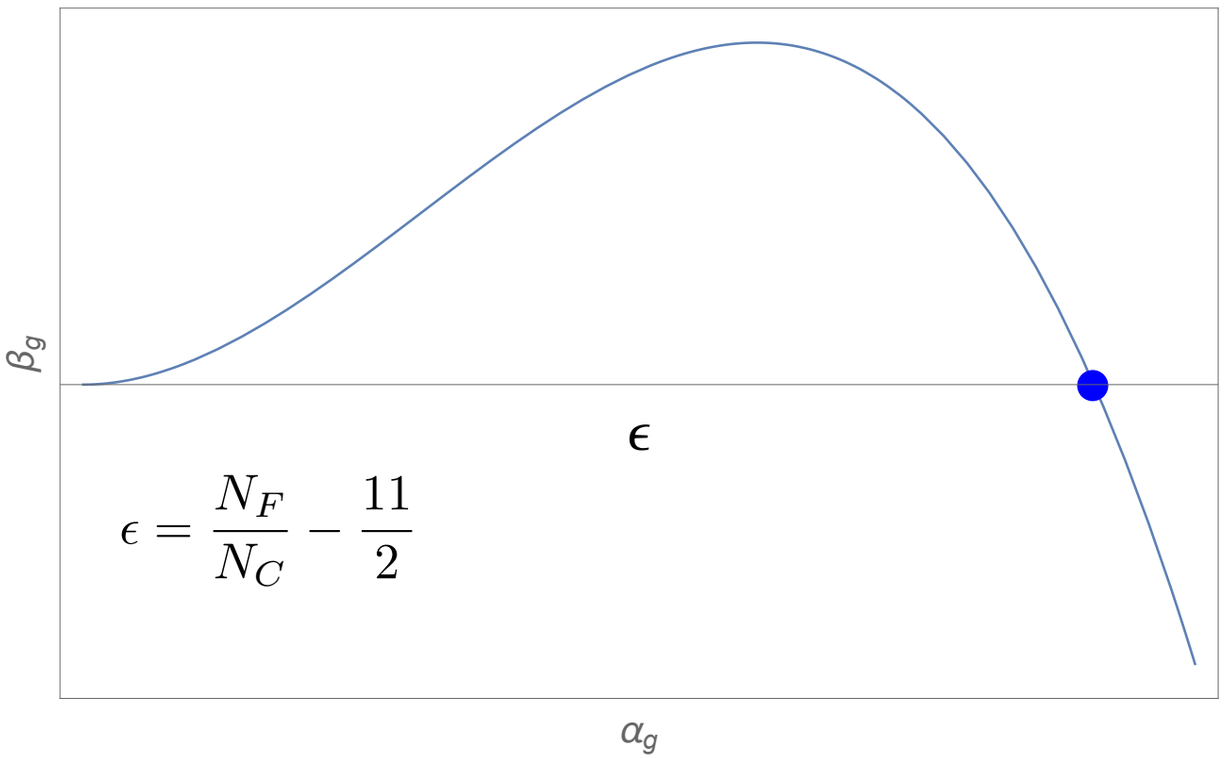

Veneziano Limit

Litim and Sannino, 1406.2337, JHEP

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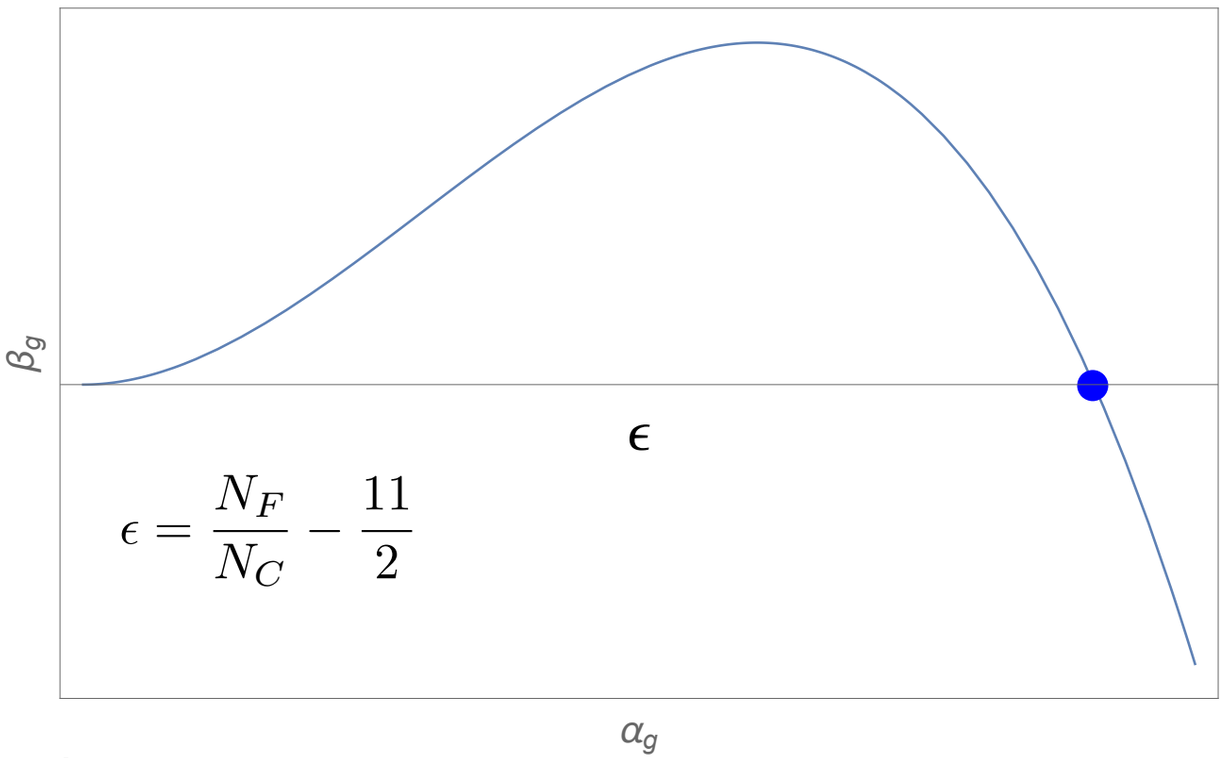


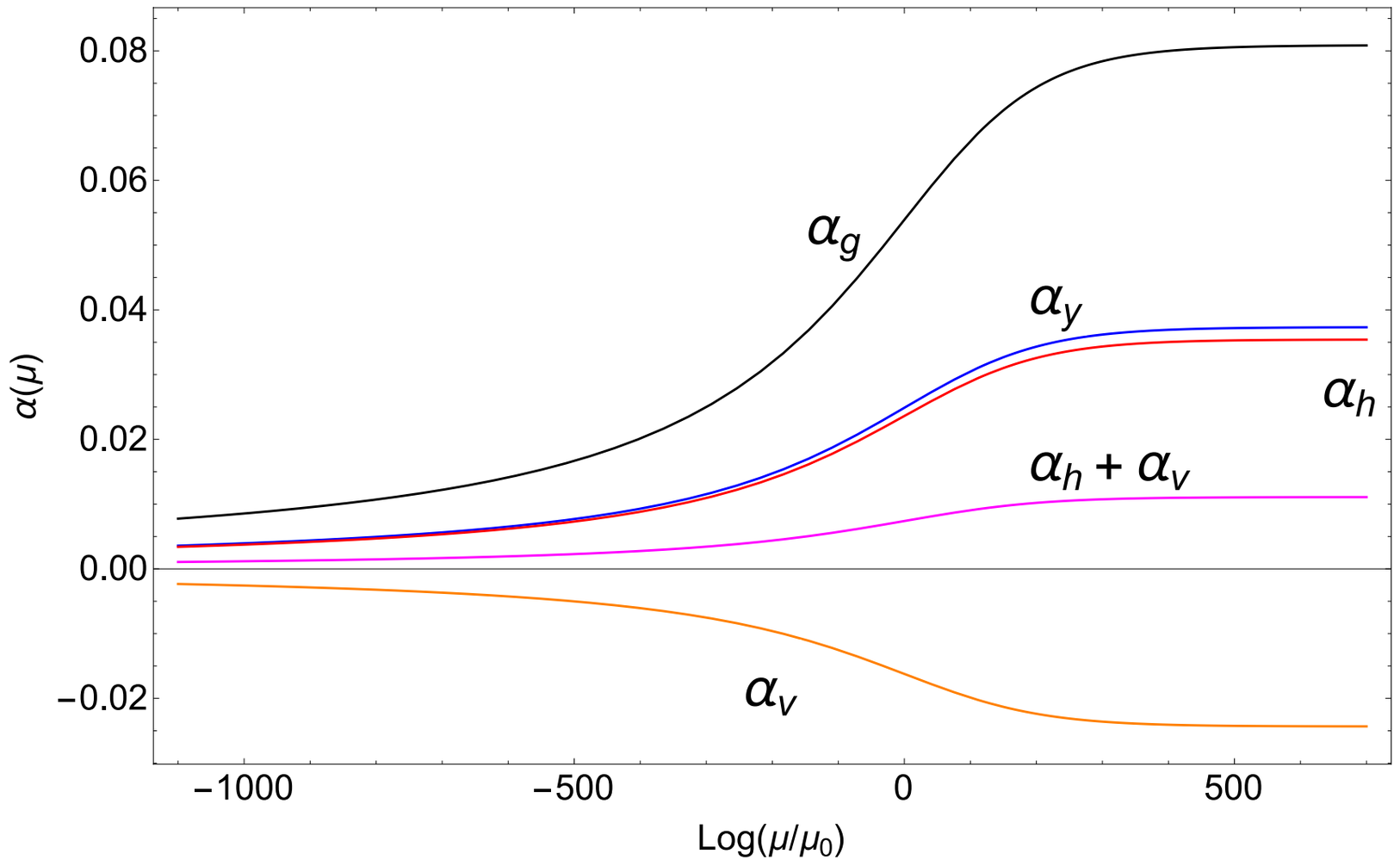
Impossible in Gauge Theories with Fermions alone

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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Litim and Sannino, 1406.2337, JHEP

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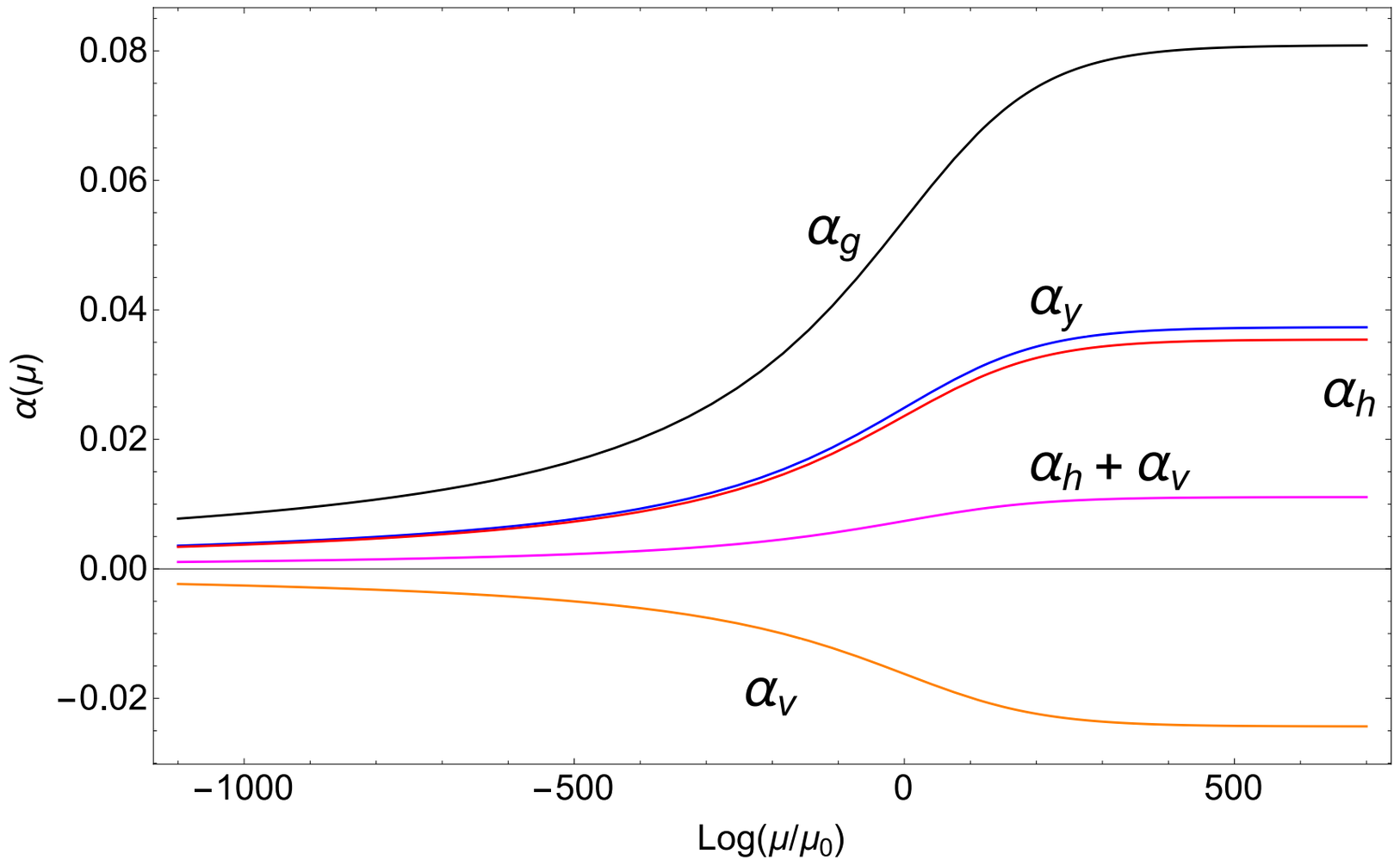

Scalars are needed perturbatively to make the theory fundamental

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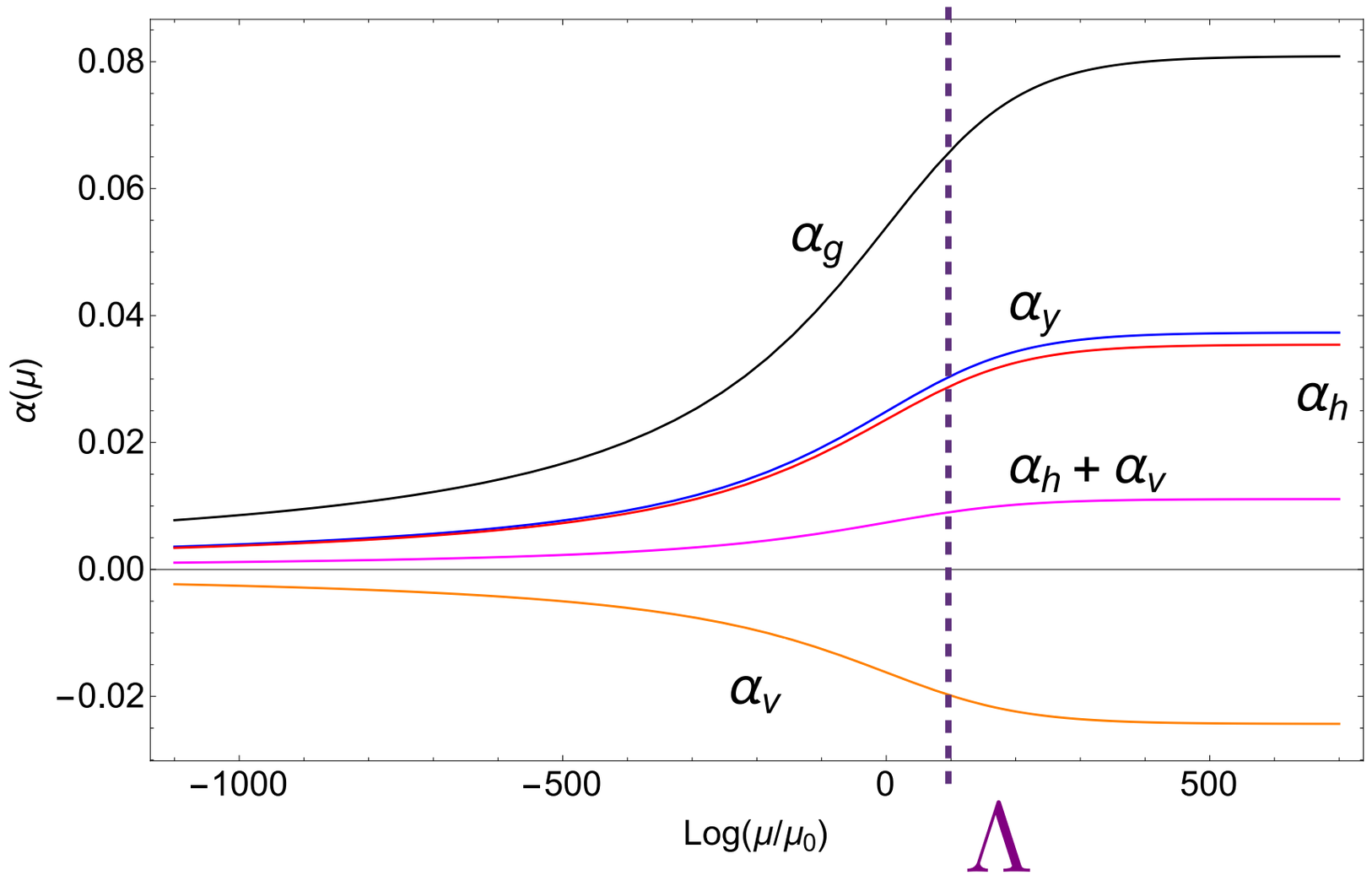
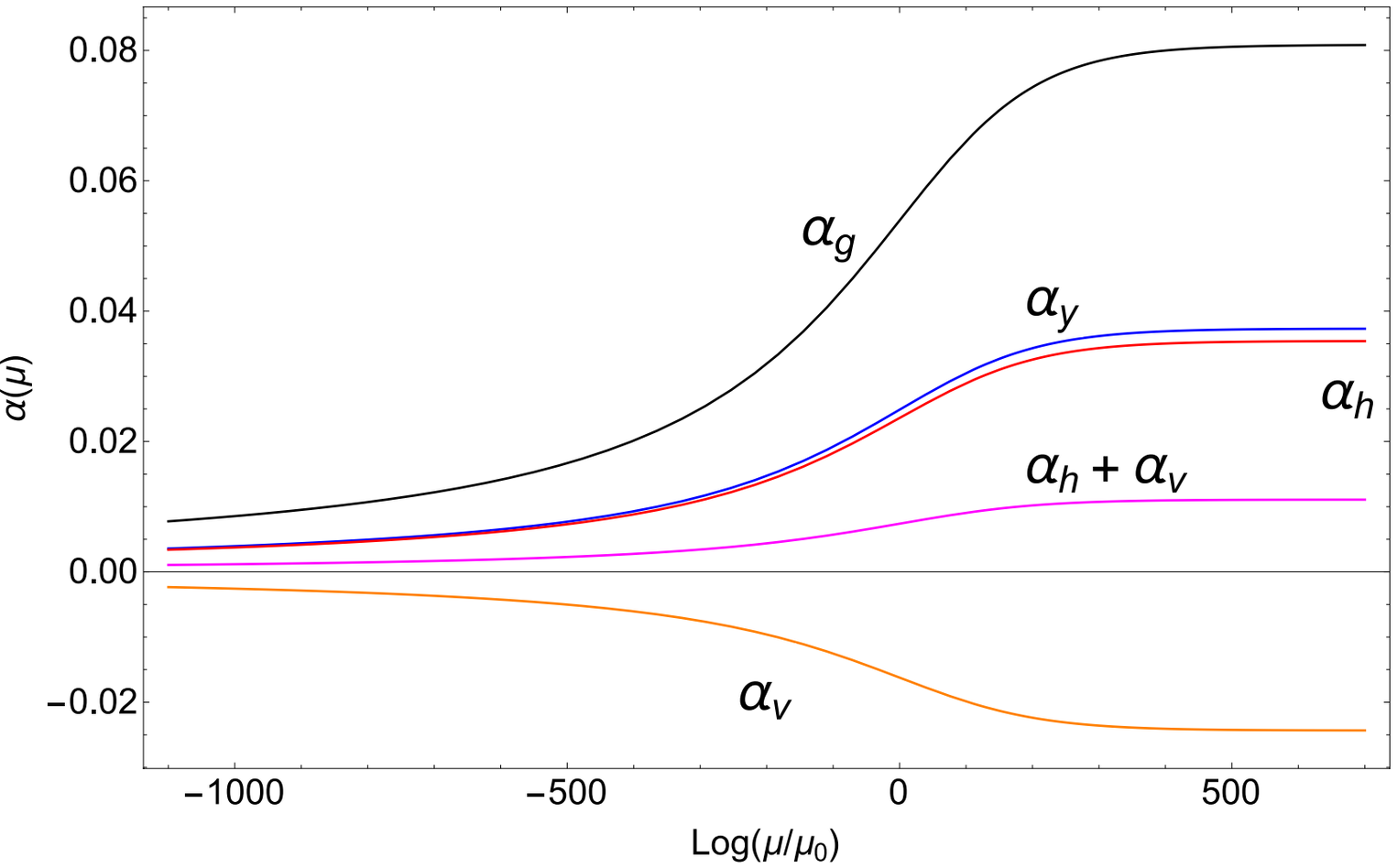
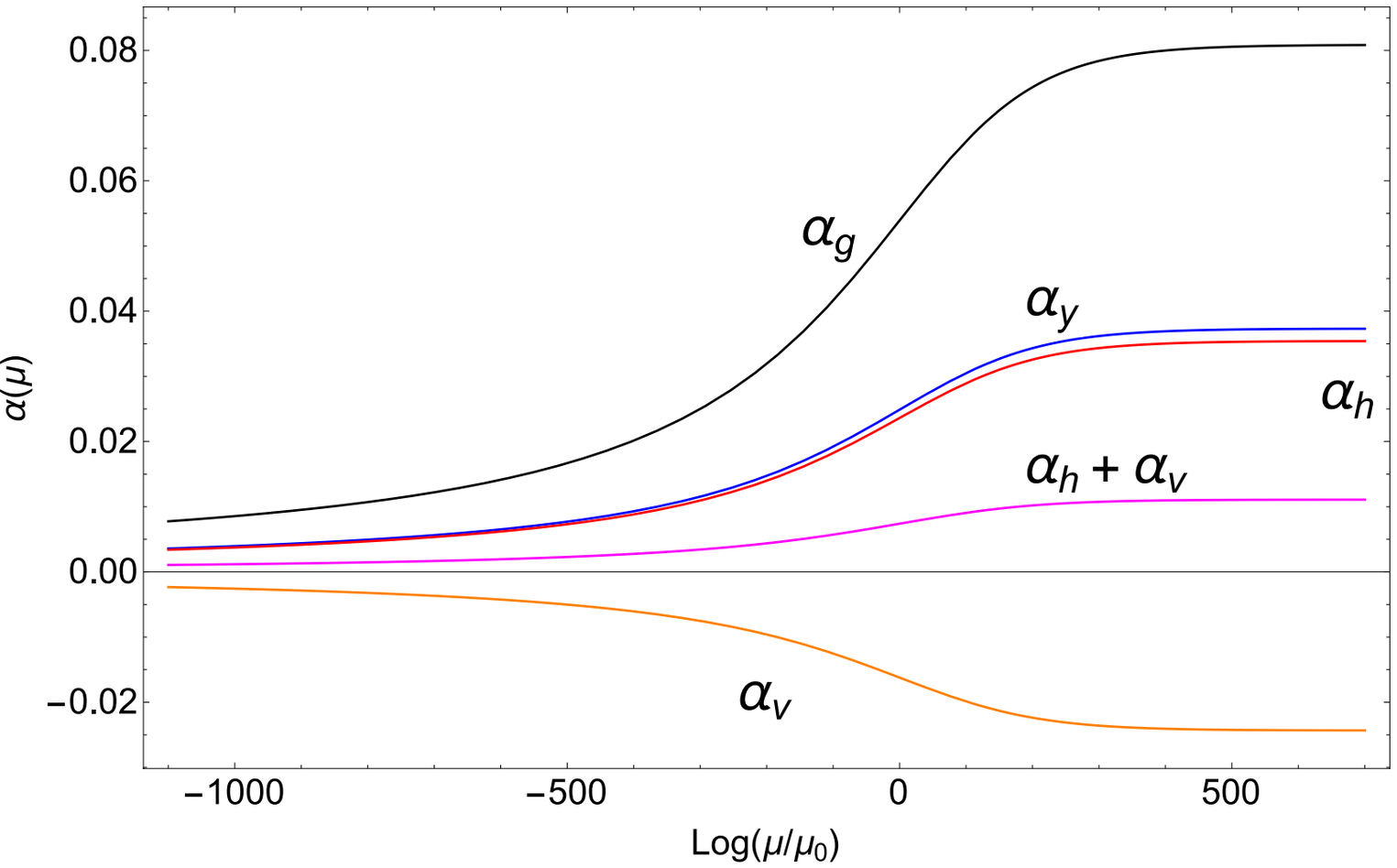
Litim and Sannino, 1406.2337, JHEP

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

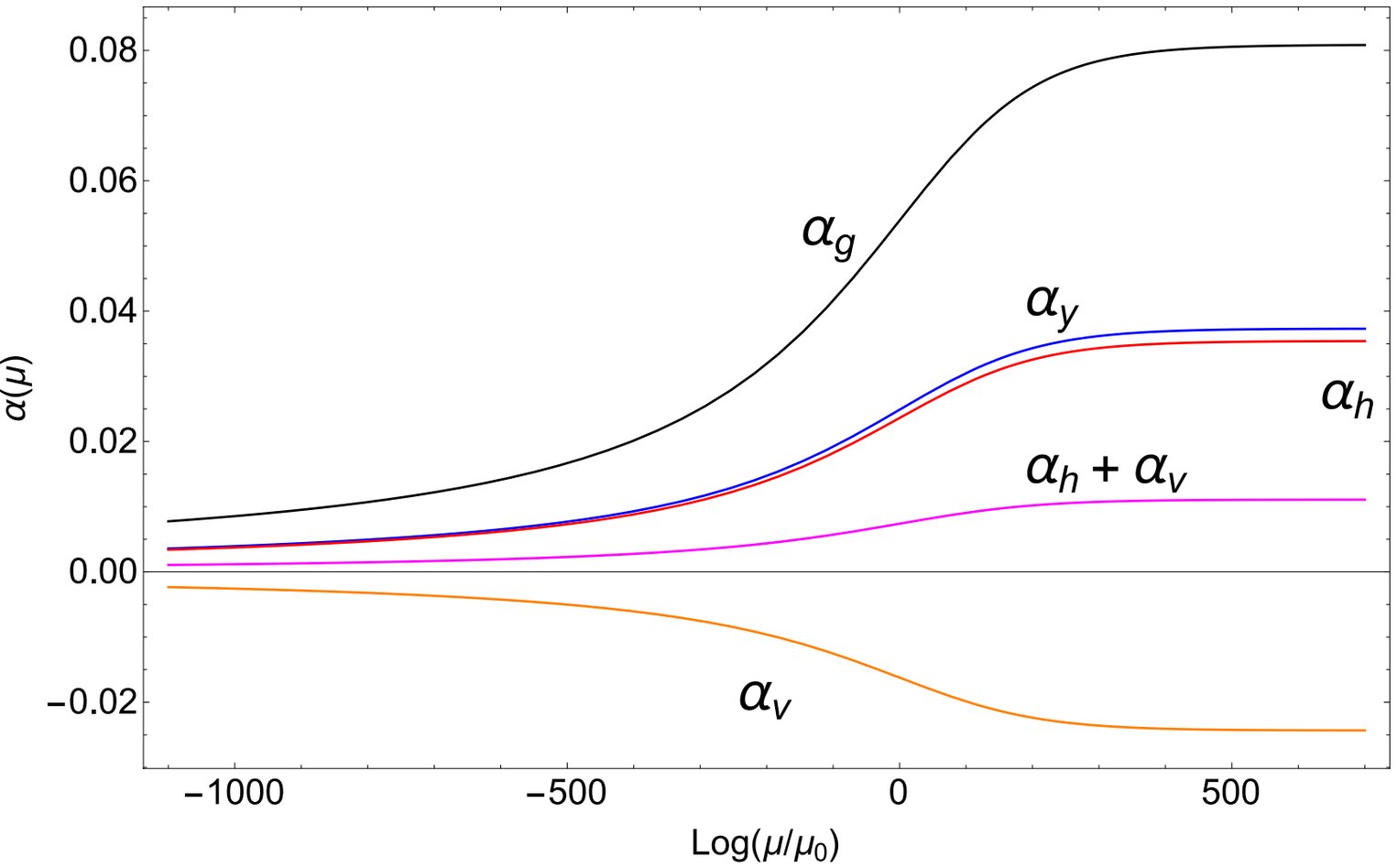


Scalars are needed perturbatively to make the theory fundamental


0.08
0.06
0.04
0.02
0.00
−0.02
α(μ)
α_g
α_y
α_h
α_h + α_v
α_v
−1000
−500
0
500
Log(μ/μ_0)

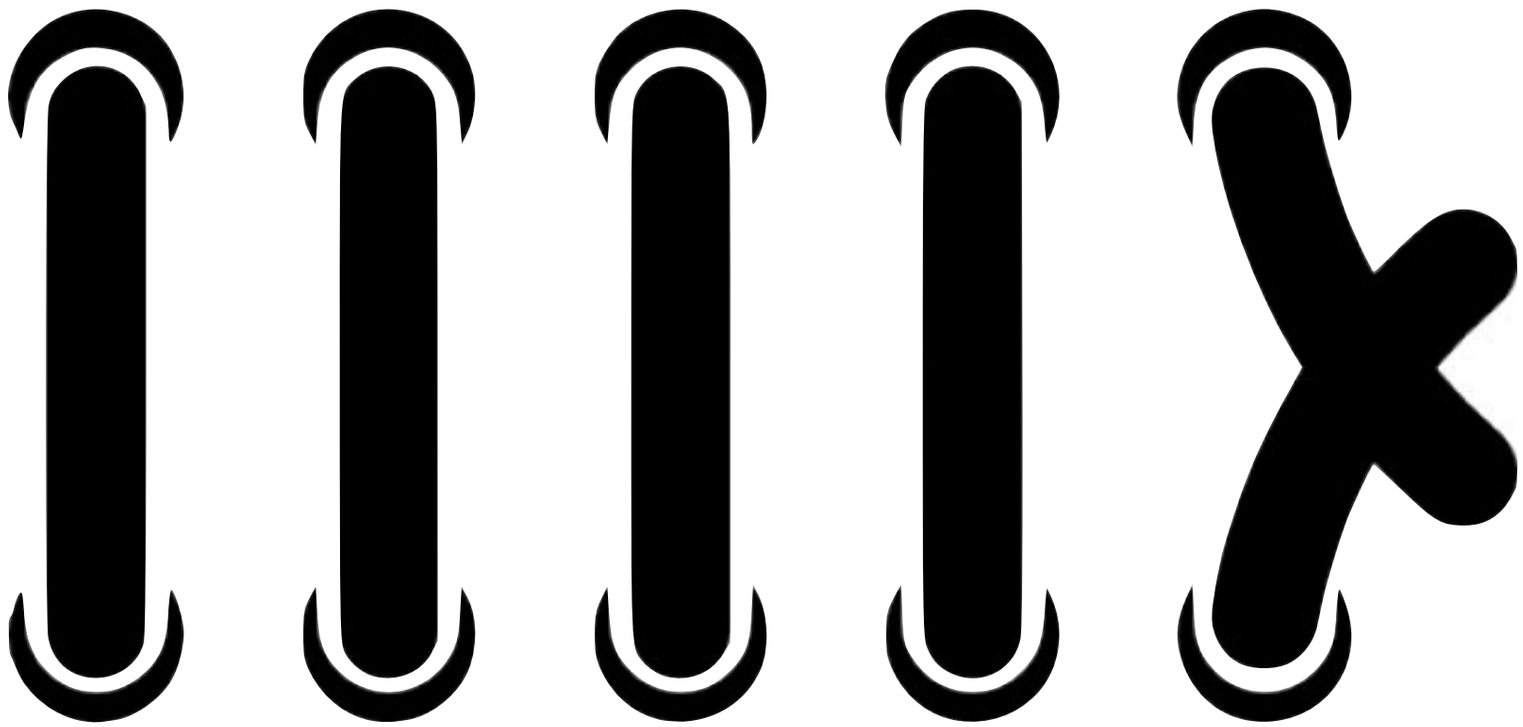


Condensed matter type unification across interactions



Condensed matter type unification across interactions

First 4D realisation of Wilson and Weinberg's safe paradigm



Higgs as shoelace

Safe, naturally

Abel, Sannino 1704.00700

Safe, naturally

- A theory without a UV cutoff is technically natural with(out) scalars

Abel, Sannino 1704.00700

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- A theory without a UV cutoff is technically natural with(out) scalars
- No quadratic divergences can emerge because of IR/UV conformality

Abel, Sannino 1704.00700

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- Masses still sensitive to new physical thresholds

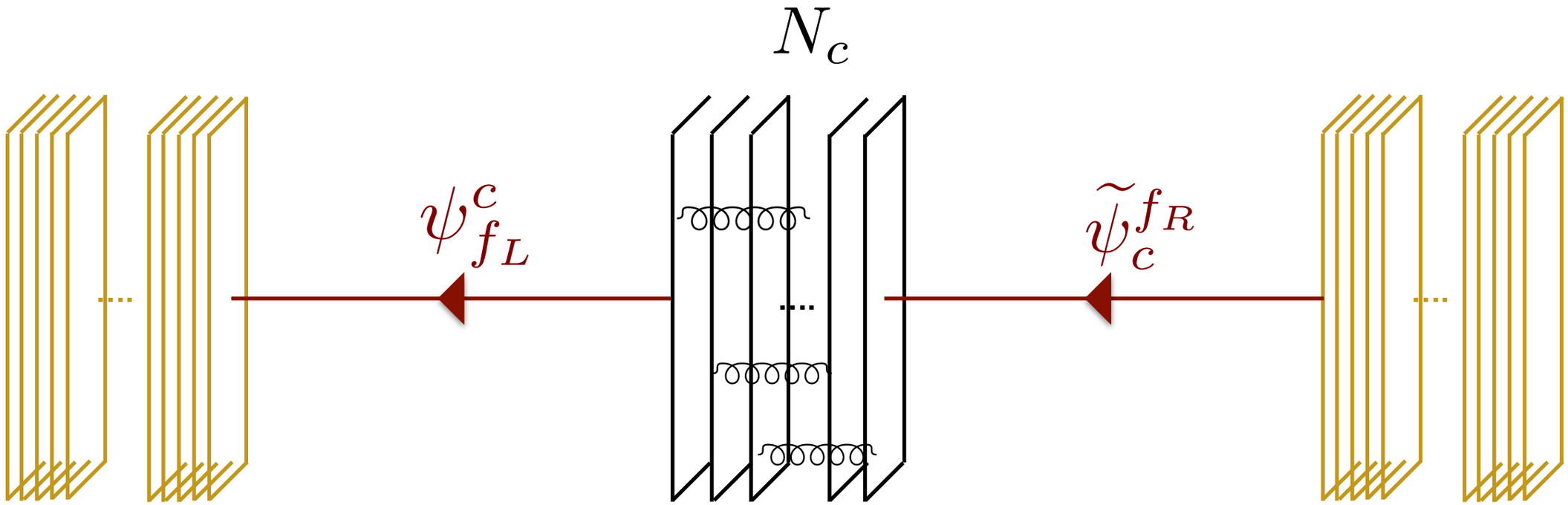
Abel, Sannino 1704.00700

Safe, naturally

- A theory without a UV cutoff is technically natural with(out) scalars
- No quadratic divergences can emerge because of IR/UV conformality
- Masses still sensitive to new physical thresholds
- New states needed to make the SM safe must be around the TeV corner

Abel, Sannino 1704.00700

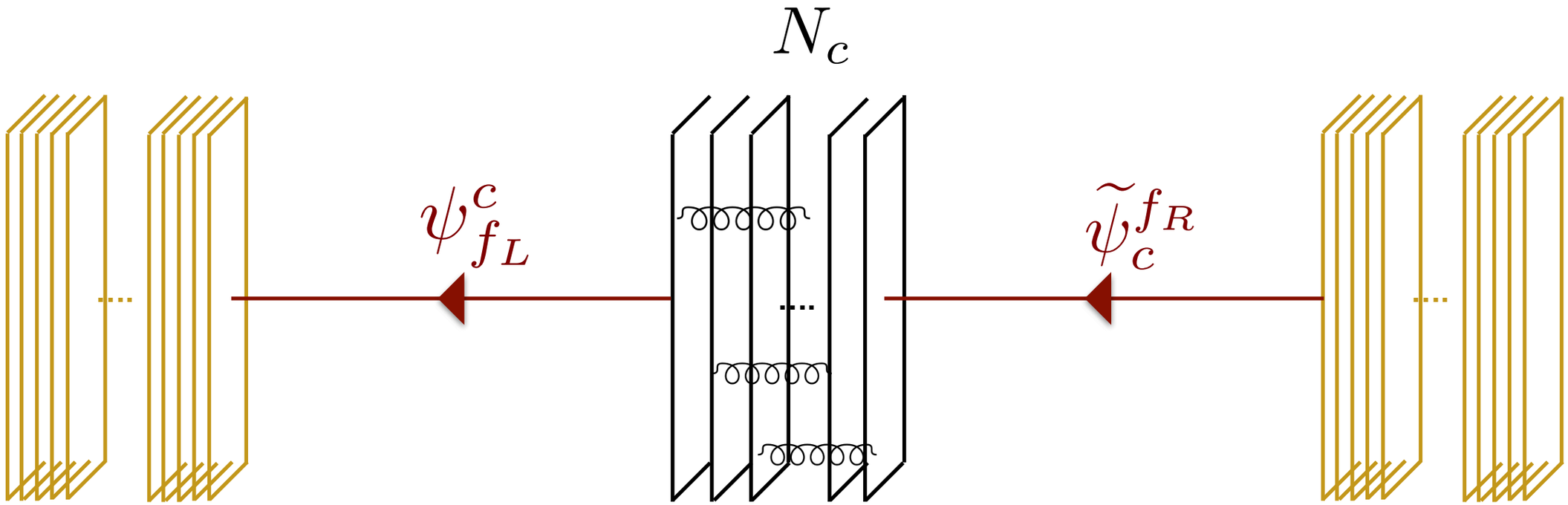
Conformal Window 2.0: Large Nf story



Sannino, ERG 2016, Trieste

Antipin and Sannino, 1709.02354

Conformal Window 2.0: Large Nf story



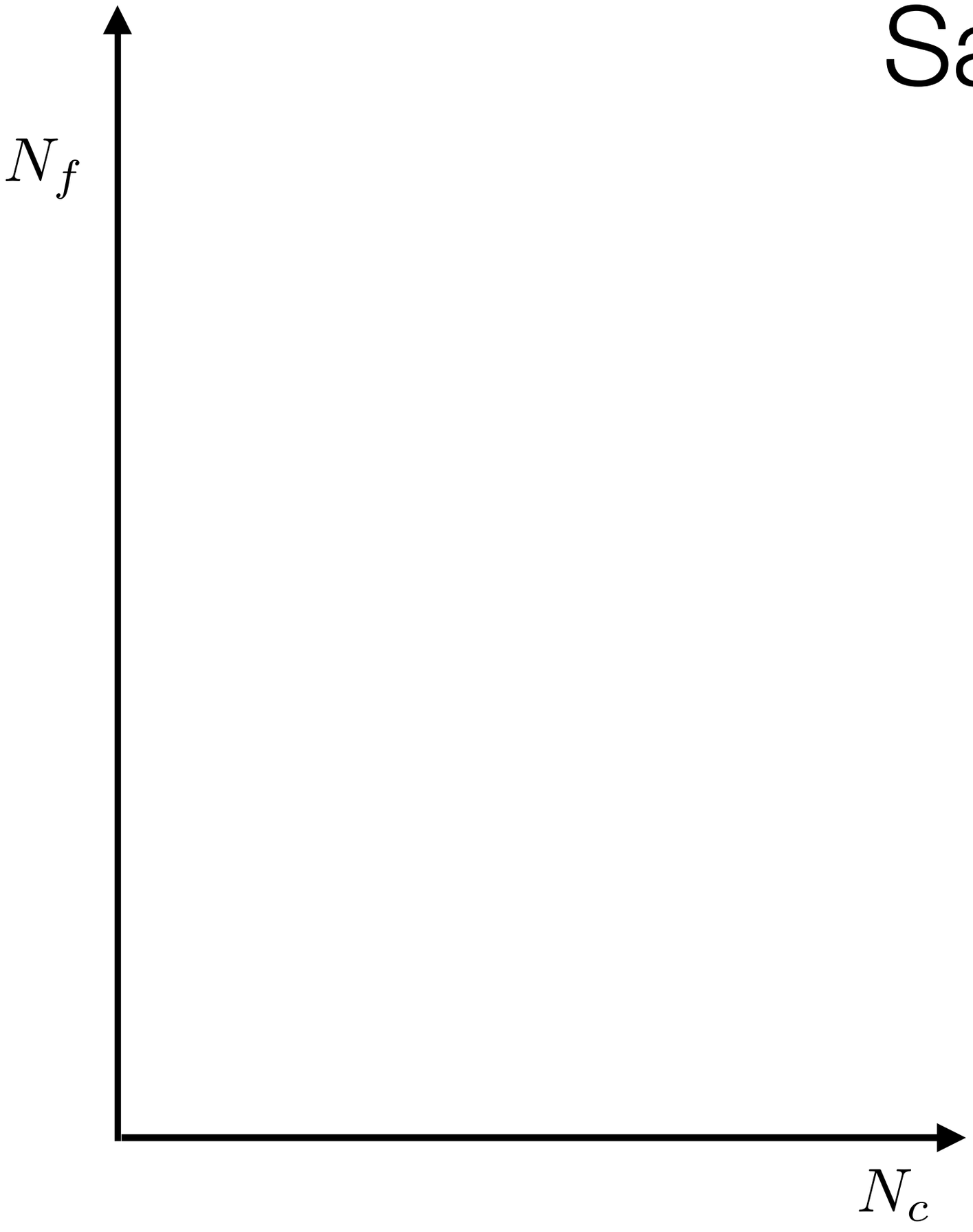
Sannino, ERG 2016, Trieste

Antipin and Sannino, 1709.02354

- *Test strong version of the Jack and Osborn a-theorem function*

Antipin, Dondi, Sannino, Thomsen,1808.00482

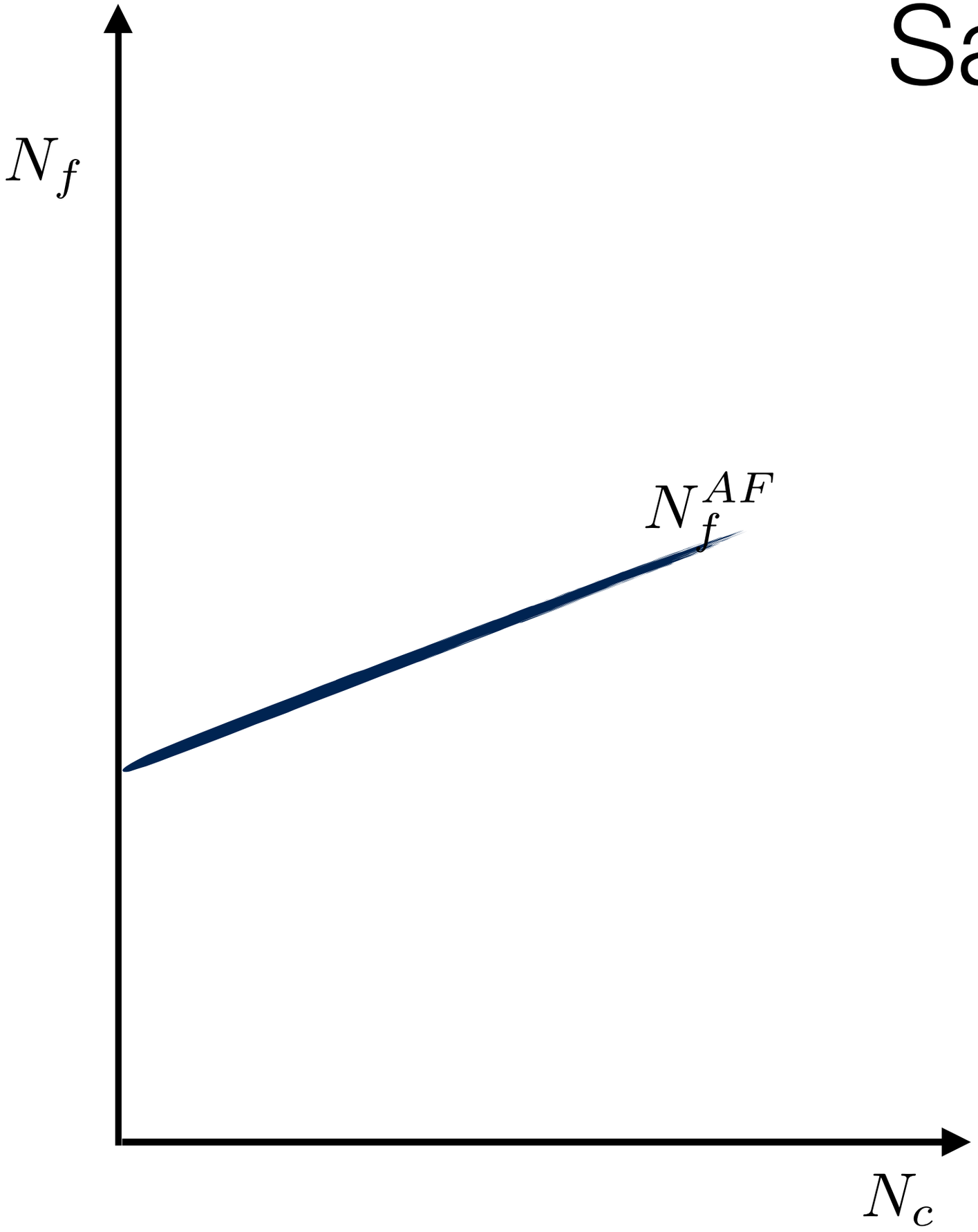
Safe QCD



Sannino, ERG 2016, Trieste

Antipin and Sannino, 1709.02354
Pica and Sannino 1011.5917, PRD

Safe QCD



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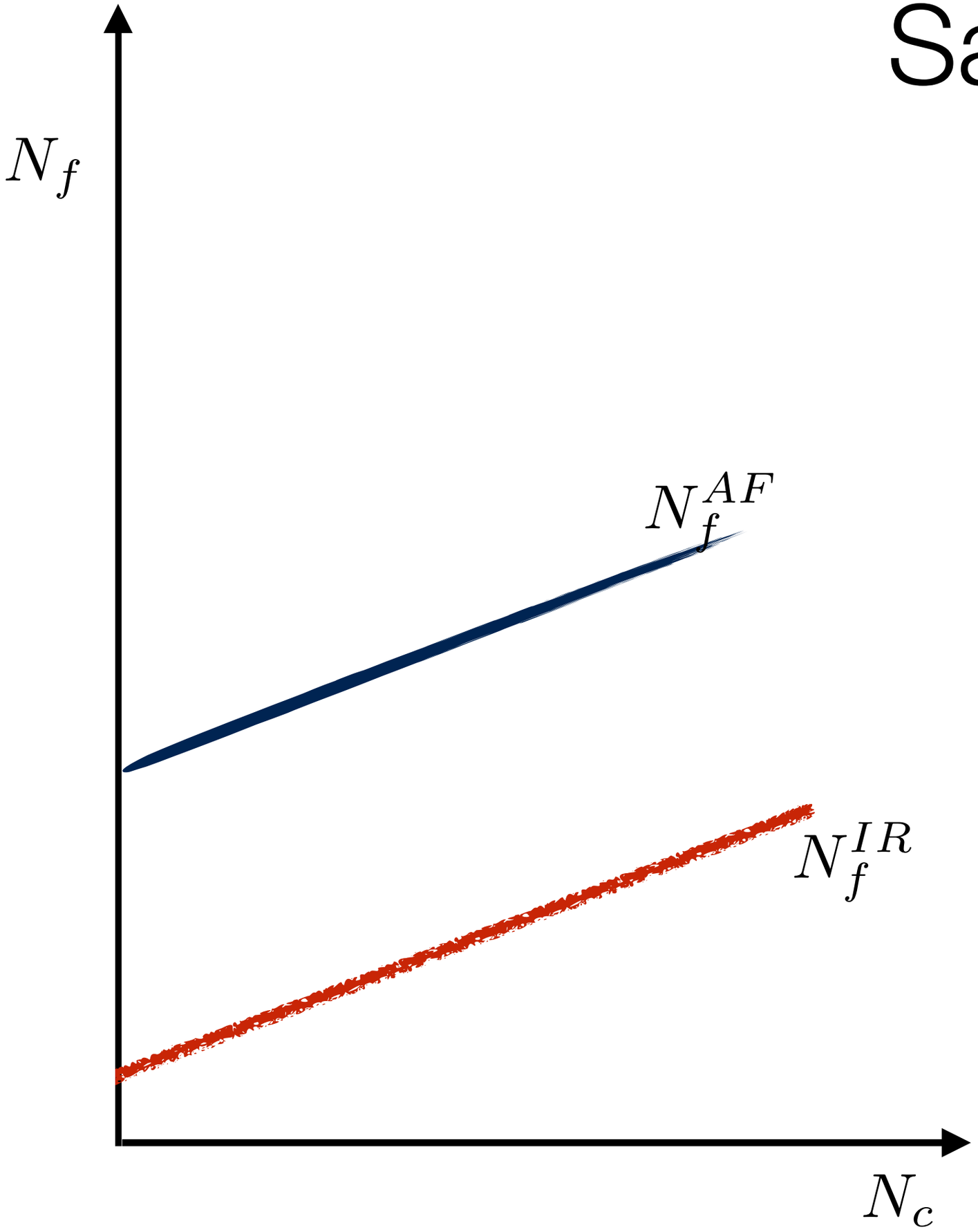

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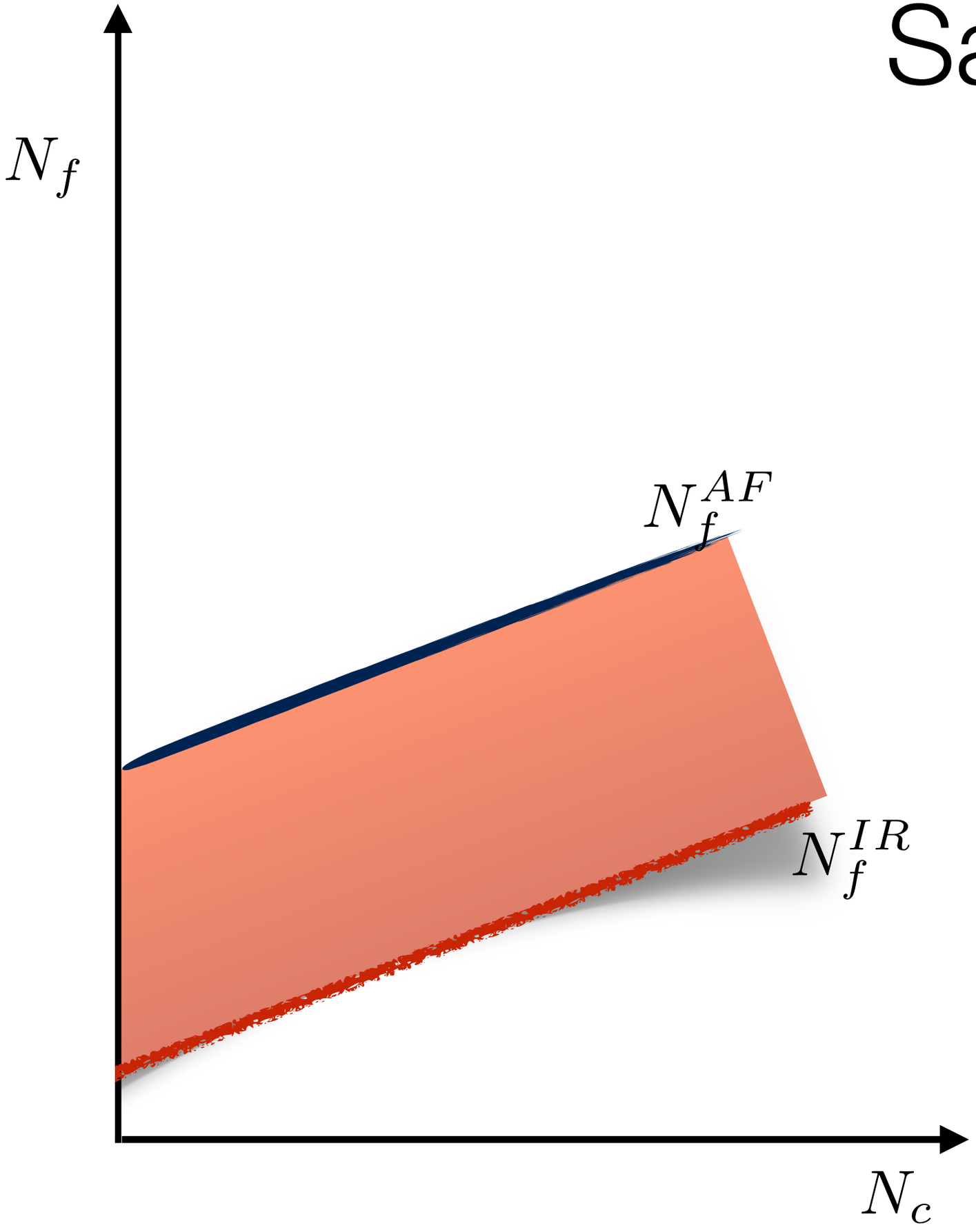

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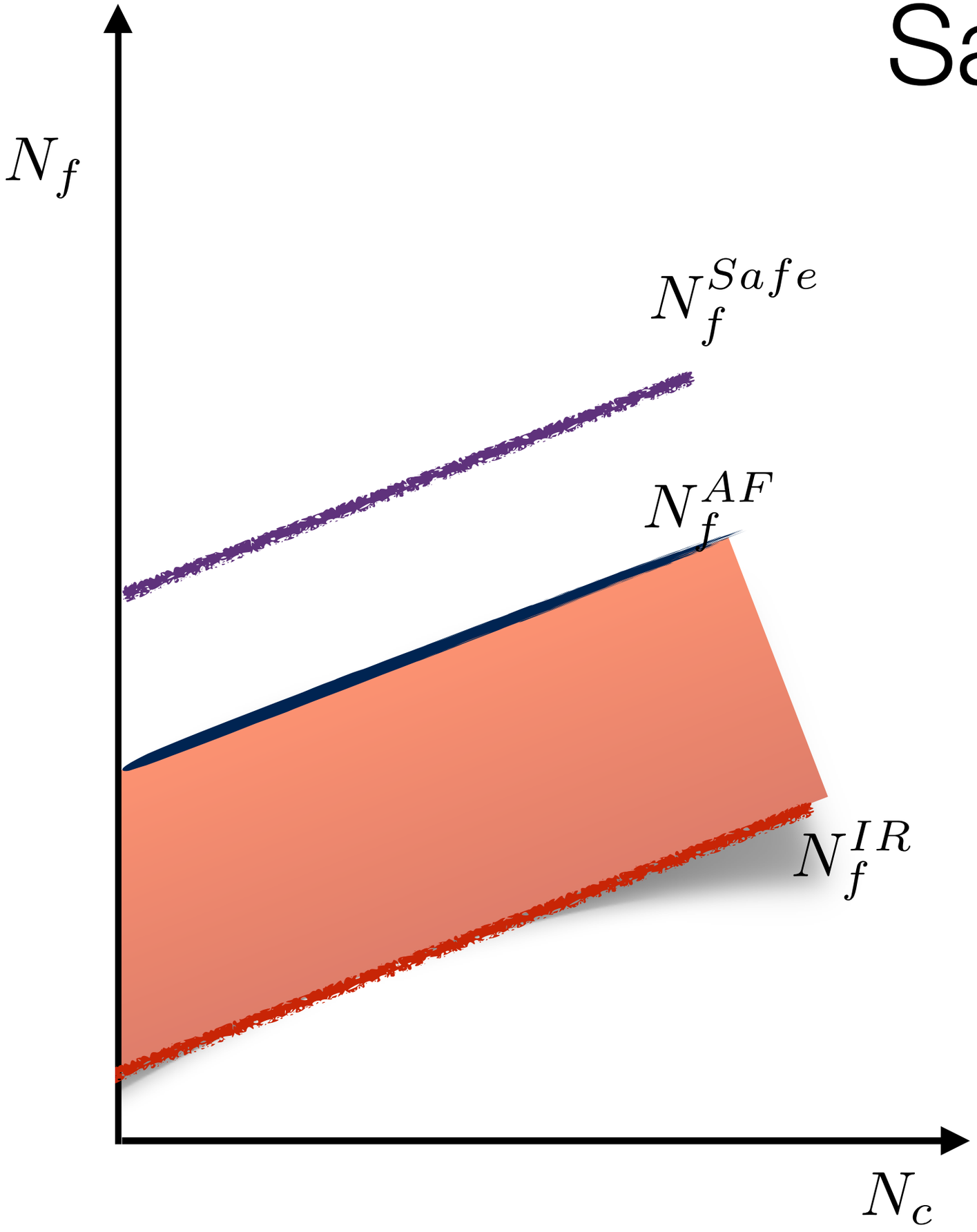

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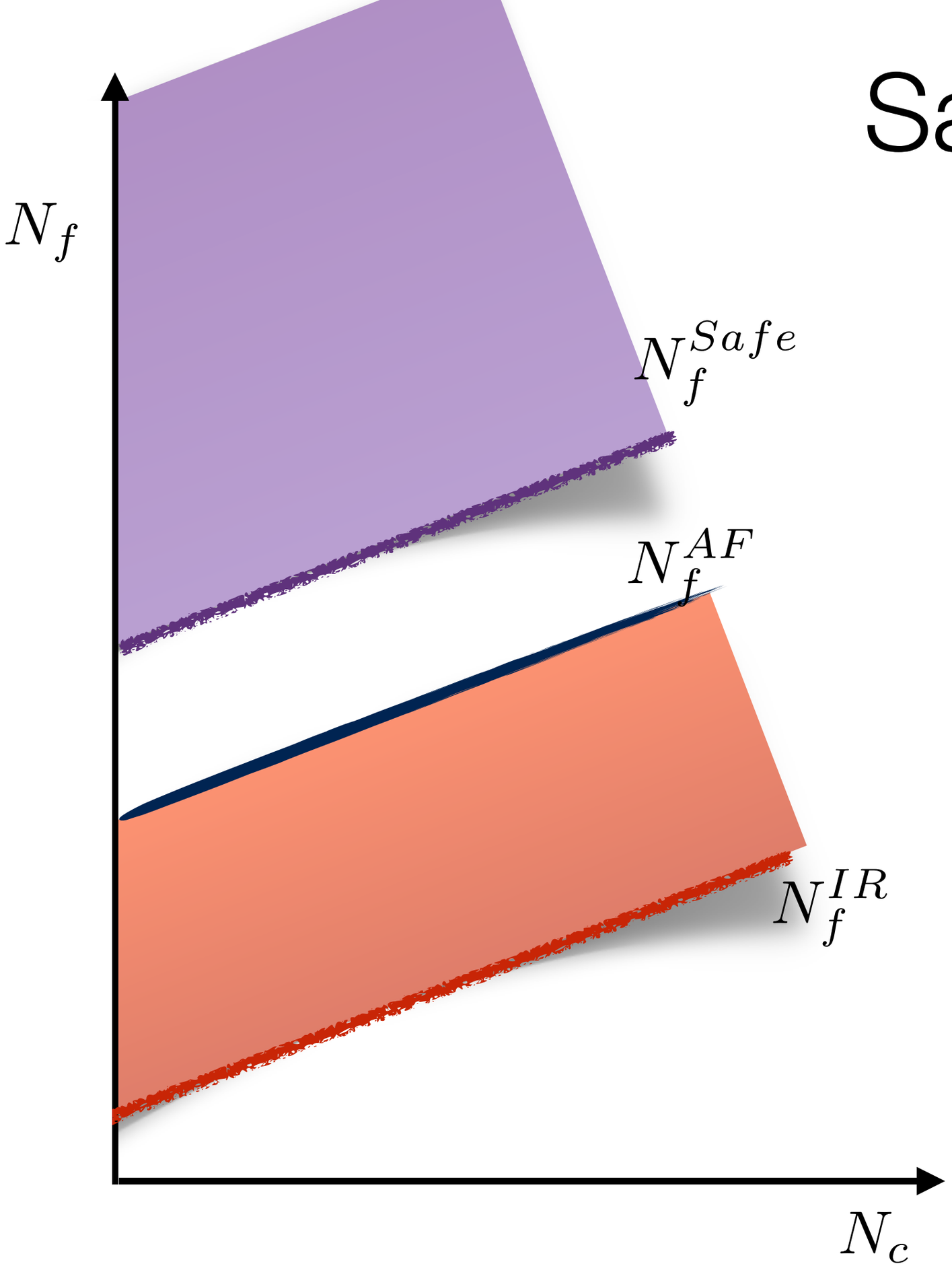

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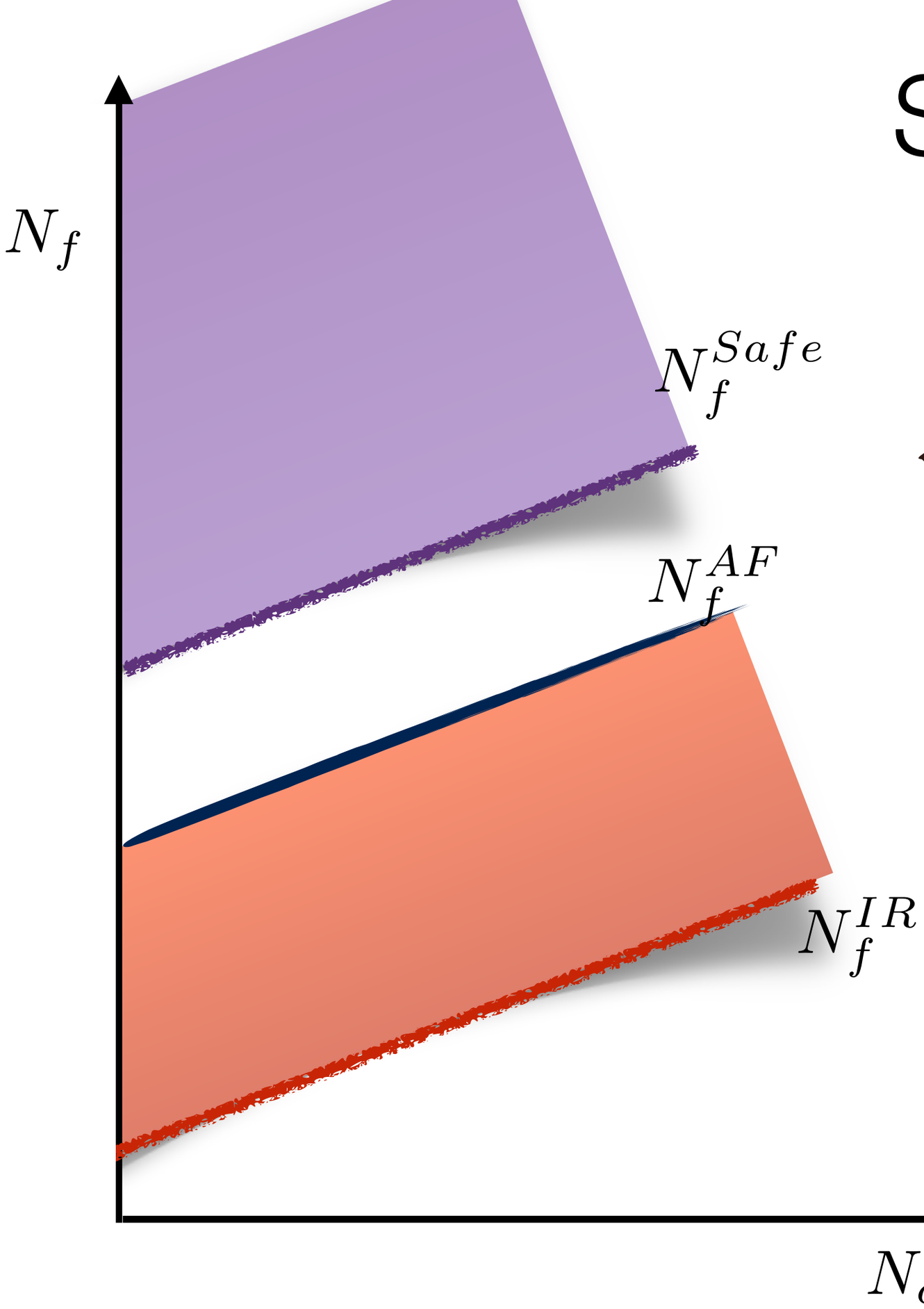

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Sannino, ERG 2016, Trieste

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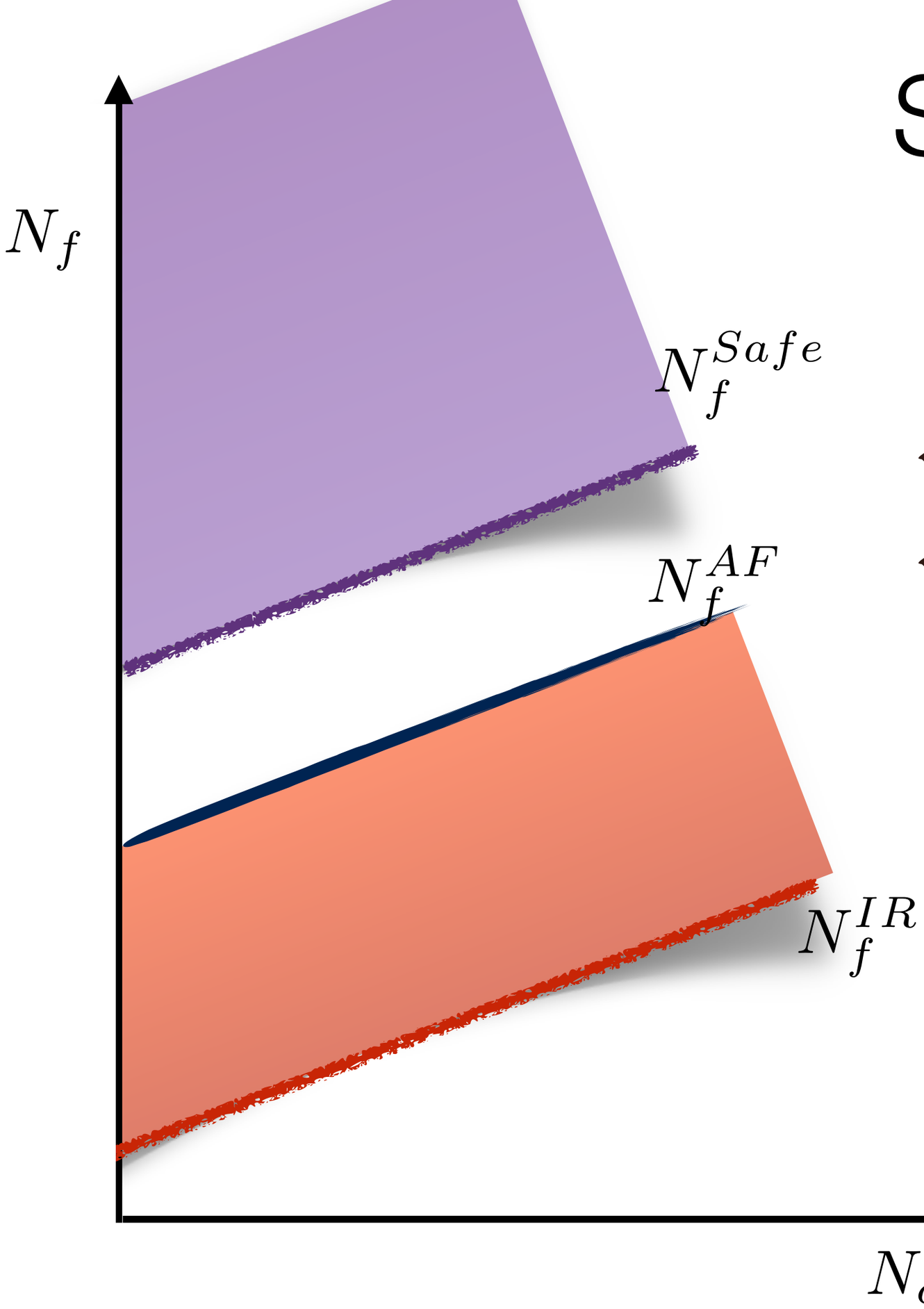
Safe QCD



- Must exist a critical Safe Nf
- Unsafe region in Nf-Nc

Sannino, ERG 2016, Trieste

Antipin and Sannino, 1709.02354
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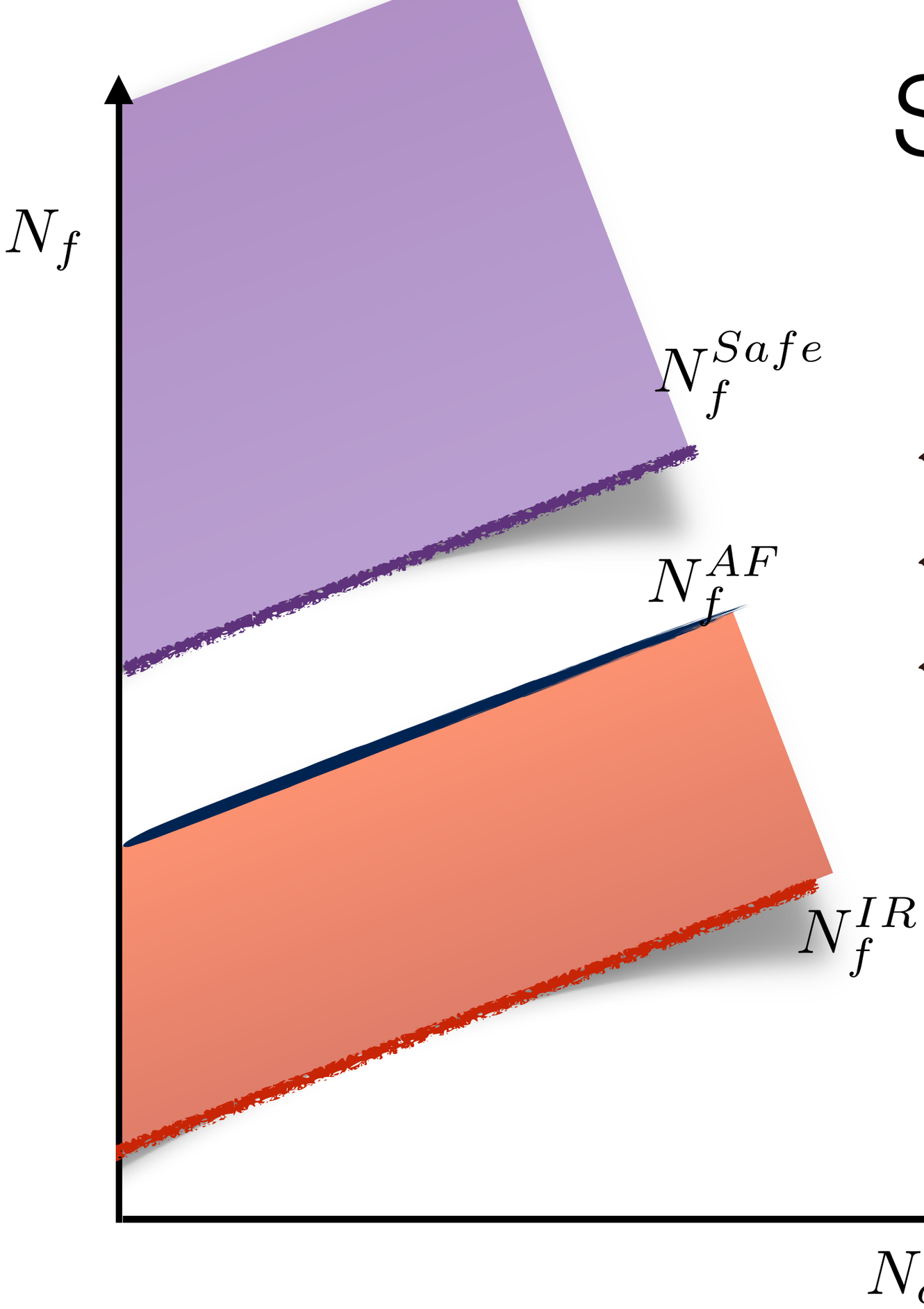

- Must exist a critical Safe Nf
- Unsafe region in Nf-Nc
- Continuous (Walking) transition?

Sannino, ERG 2016, Trieste

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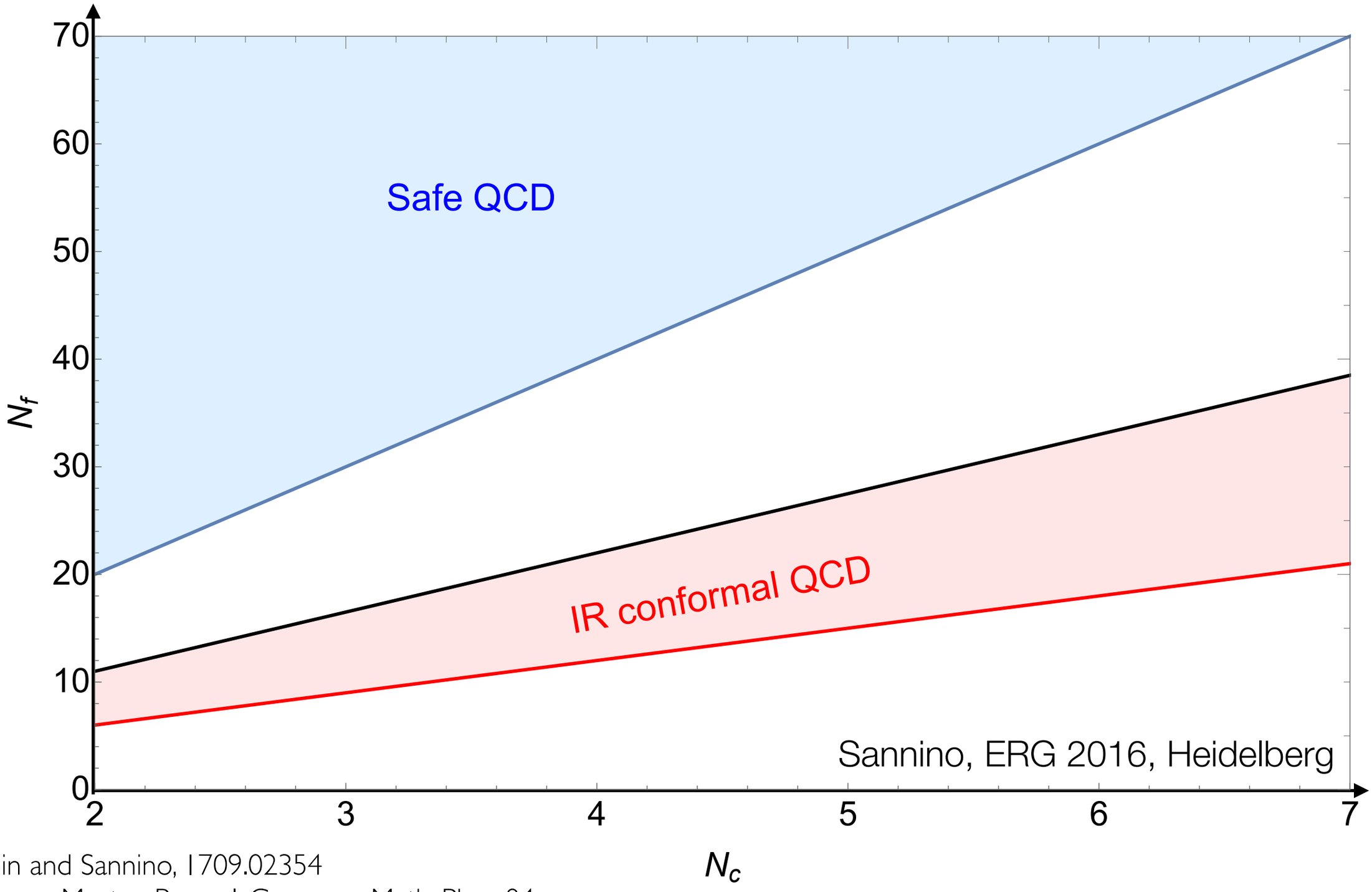
Pica and Sannino 1011.5917, PRD

Safe QCD: Conformal Window 2.0



Antipin and Sannino, 1709.02354
Palanques-Mestre, Pascual, Commun. Math. Phys. 84
Gracey, PLB, 96, Holdom PLB 2011
Pica and Sannino 1011.5917, PRD

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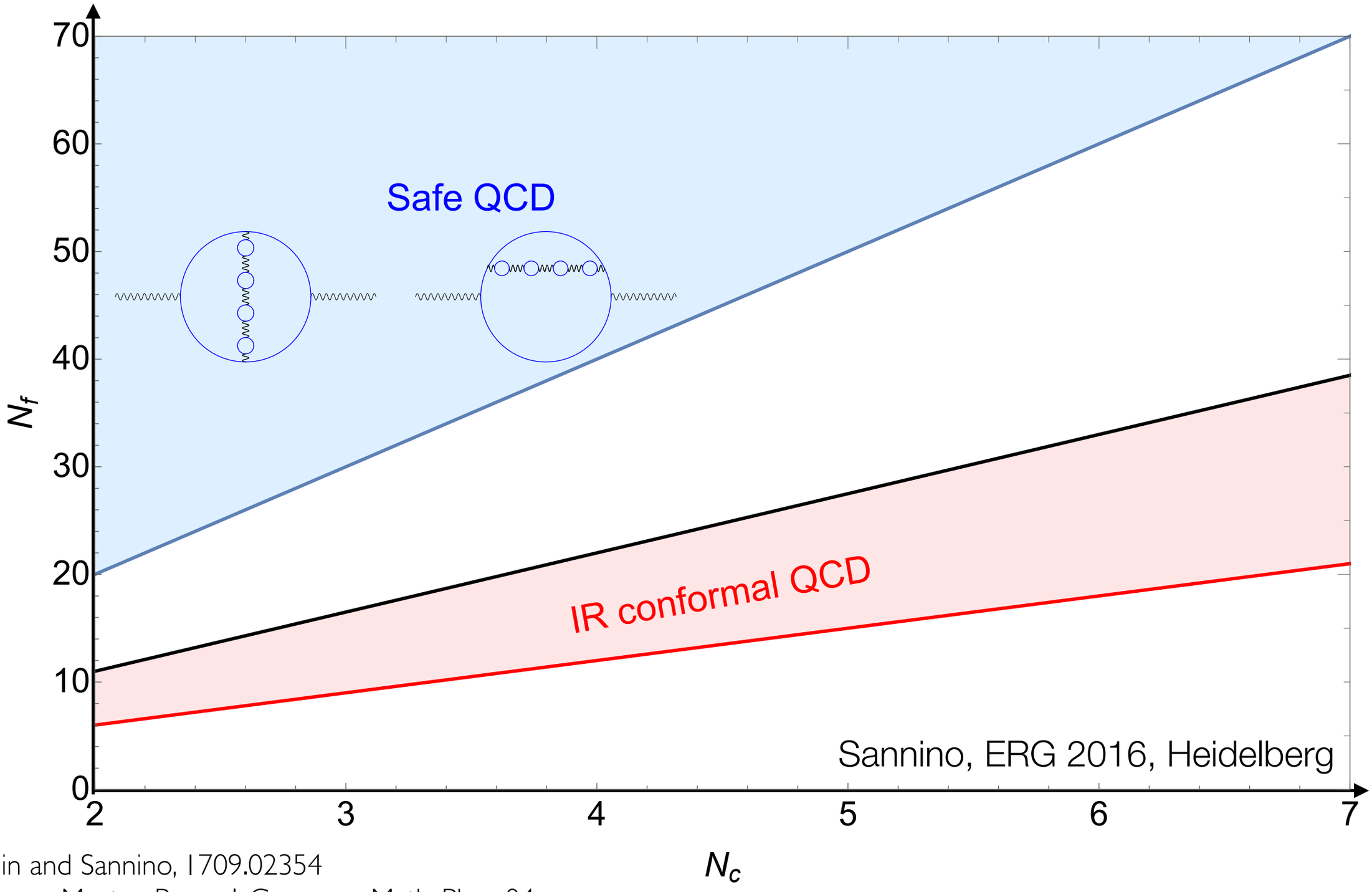

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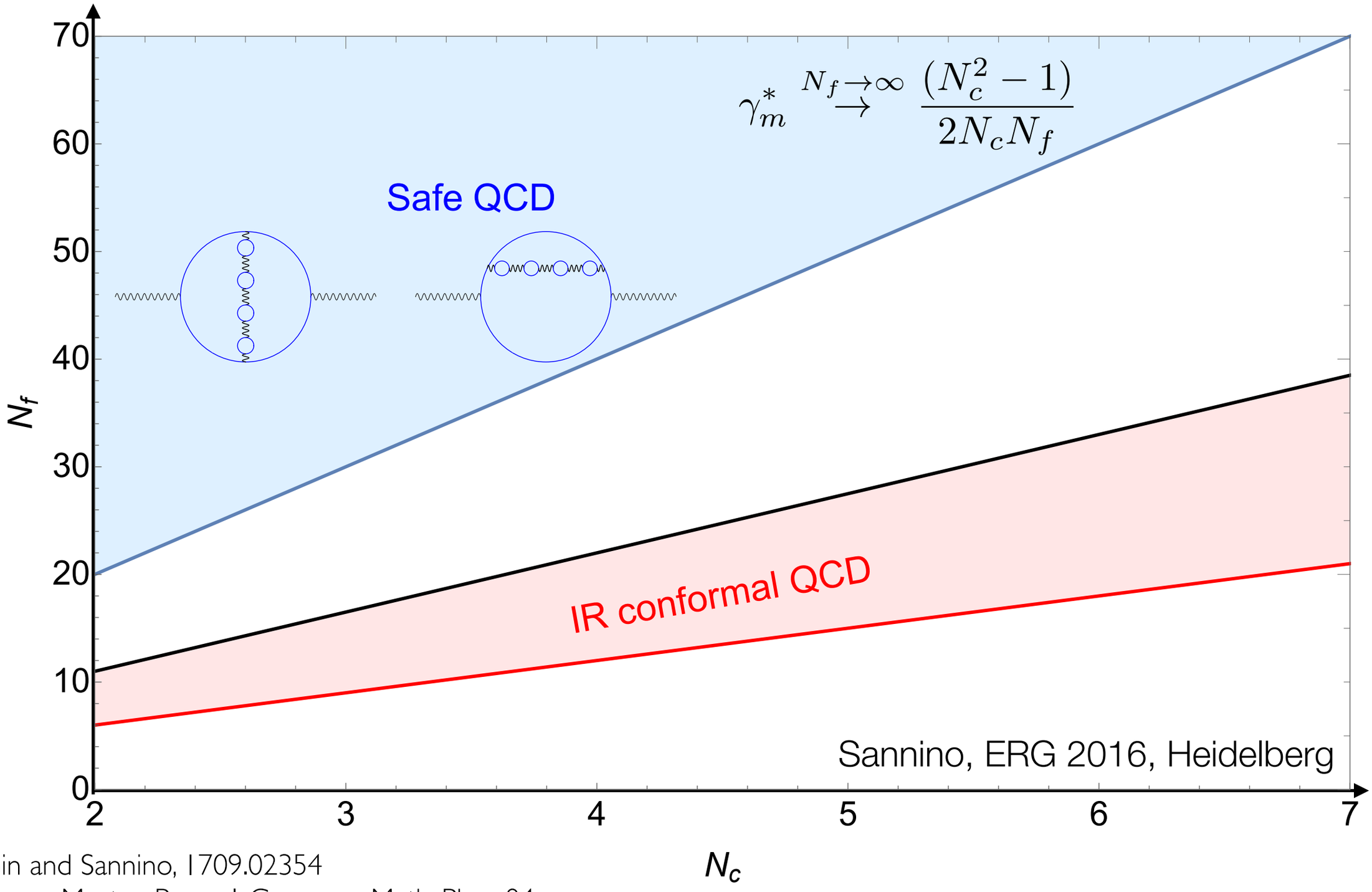

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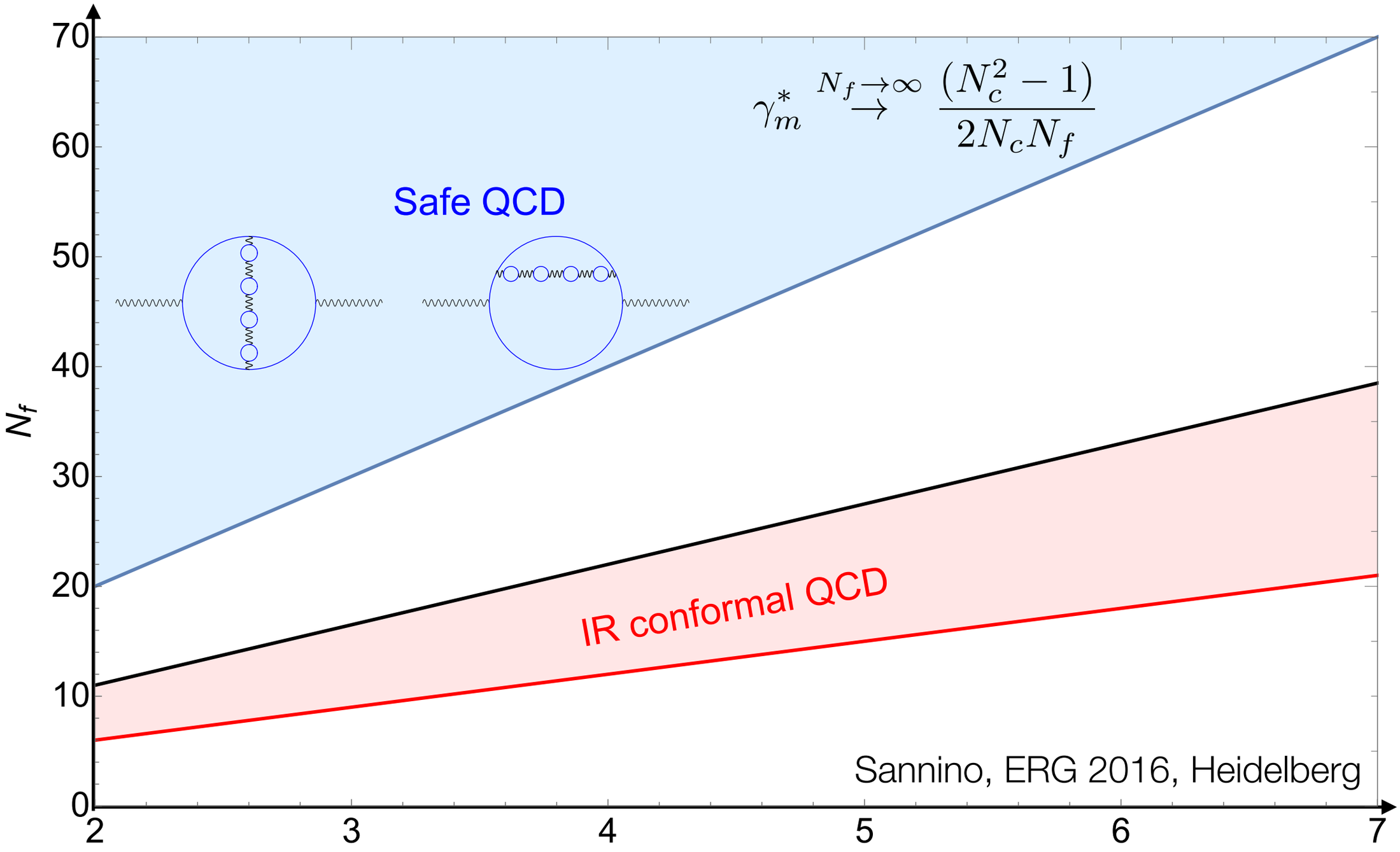

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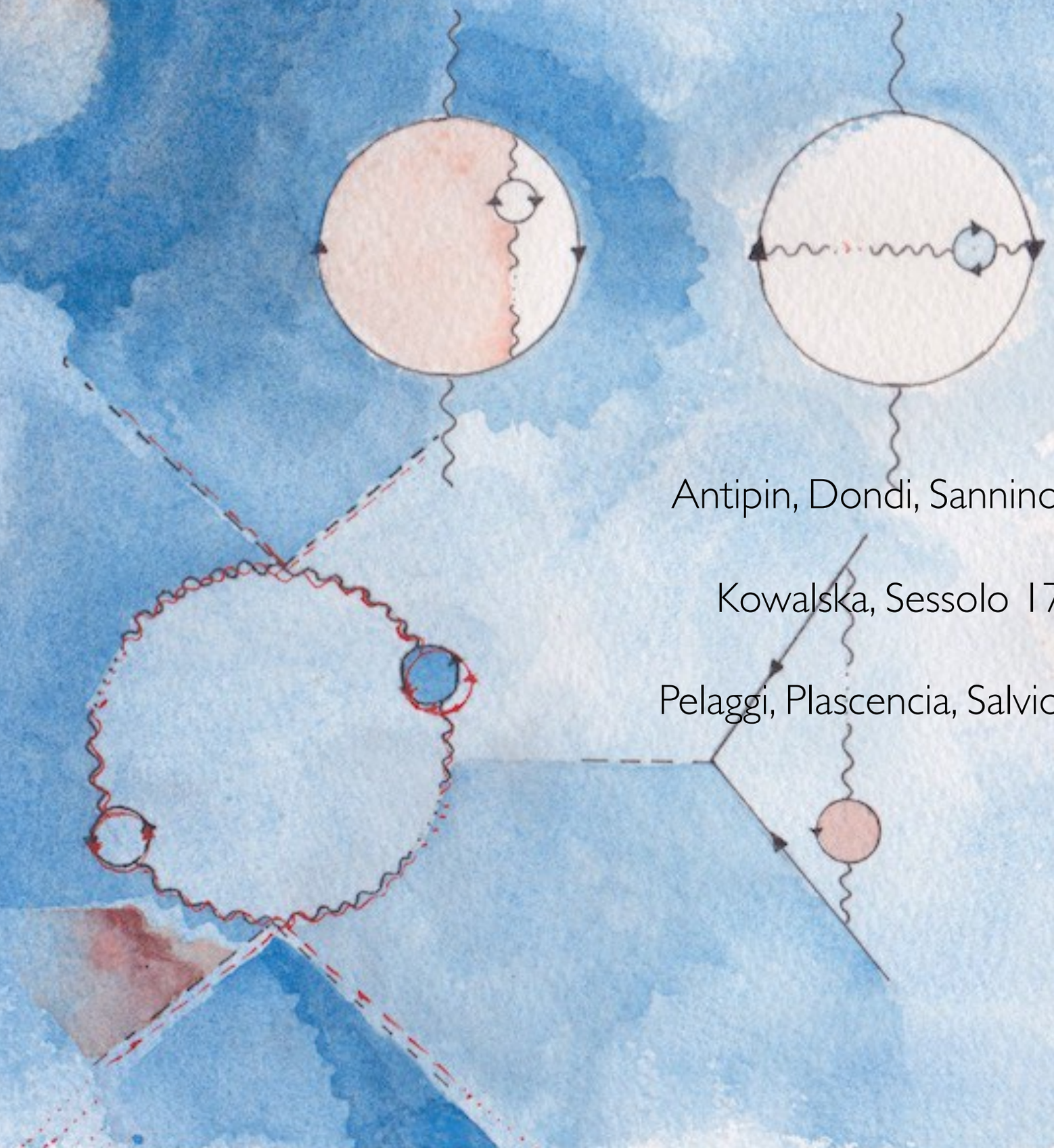
Palanques-Mestre, Pascual, Commun. Math. Phys. 84
Gracey, PLB, 96, Holdom PLB 2011
Pica and Sannino 1011.5917, PRD

Scalars are not needed at large Nf

Gauge-Yukawa beta functions at large Nf



Antipin, Dondi, Sannino, Thomsen, Zhi-Wei Wang 1803.09770

Kowalska, Sessolo 1712.06859 Alanne, Blasi 1806.06954

Pelaggi, Plascencia, Salvio, Sannino, Smirnov, Strumia 1708.00437

Artist: Kaća Bradonjić

Mapping fundamental interactions, the history

Maps not only allow us to go from point A to point B but add an extra dimension to discovery, exploration and insights.

F.S.

Mapping fundamental interactions, the history

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Claudius Ptolemy, 13th Century world map

Ptolemy's world didn't recognise the Pacific and American Landmass

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F.S.

Claudius Ptolemy, 13th Century world map
Ptolemy's world didn't recognise the Pacific and American Landmass

Thanks to GPS, satellites, computers, smart phones we travel with ease

Mapping fundamental interactions

Pre 2005 | 2005 | Beyond QCD

N_f

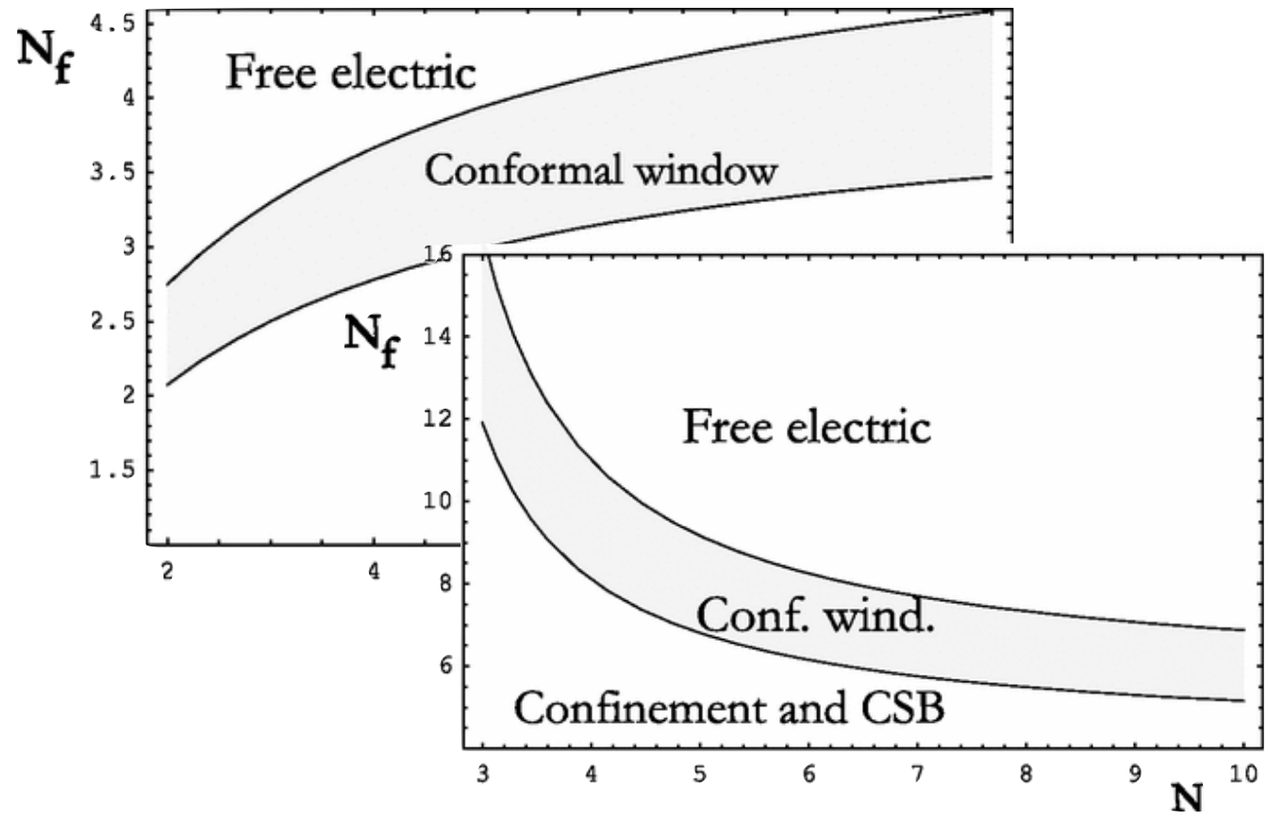
Freedom is lost
but no clue on what else

16.5

Freedom without mass

~ 12

Freedom with mass



Orientifold theory dynamics and symmetry breaking
Francesco Sannino, Kimmo Tuominen
Published in Phys.Rev. D71 (2005) 051901

Mapping fundamental interactions

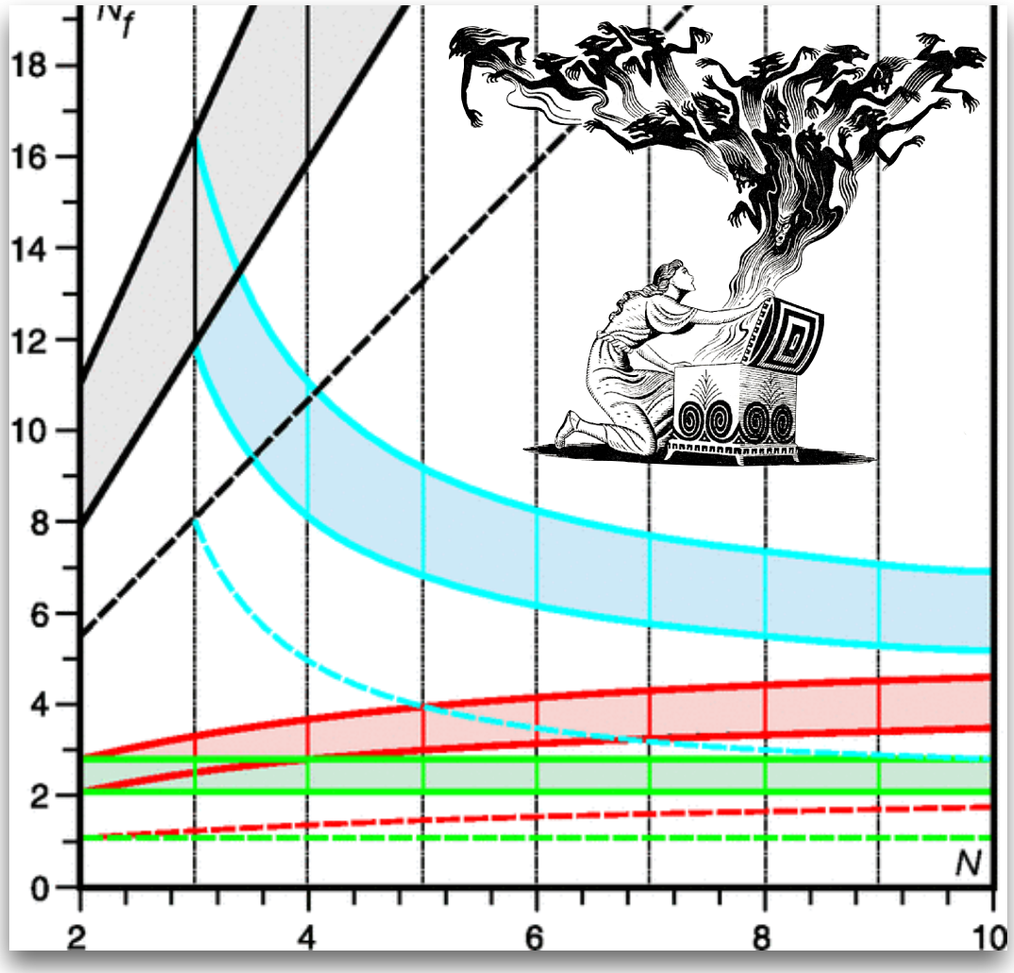
2006

Much known and used diagram for fundamental interactions

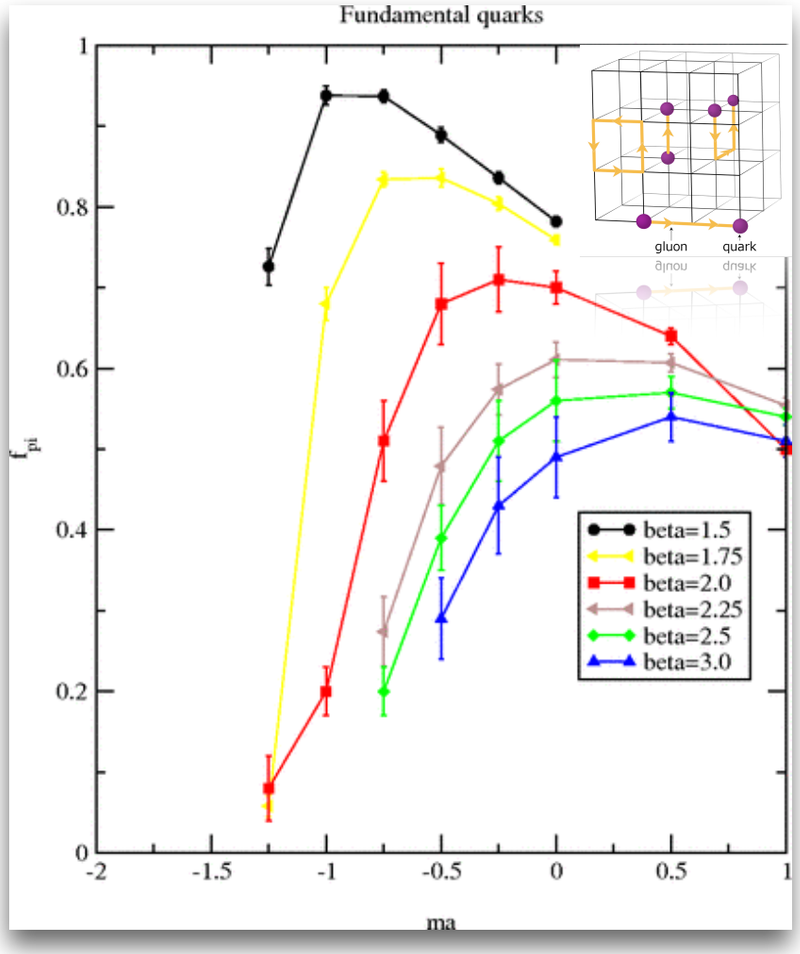
Julius Kuti. San Diego

2007

Pioneering BSM lattice studies



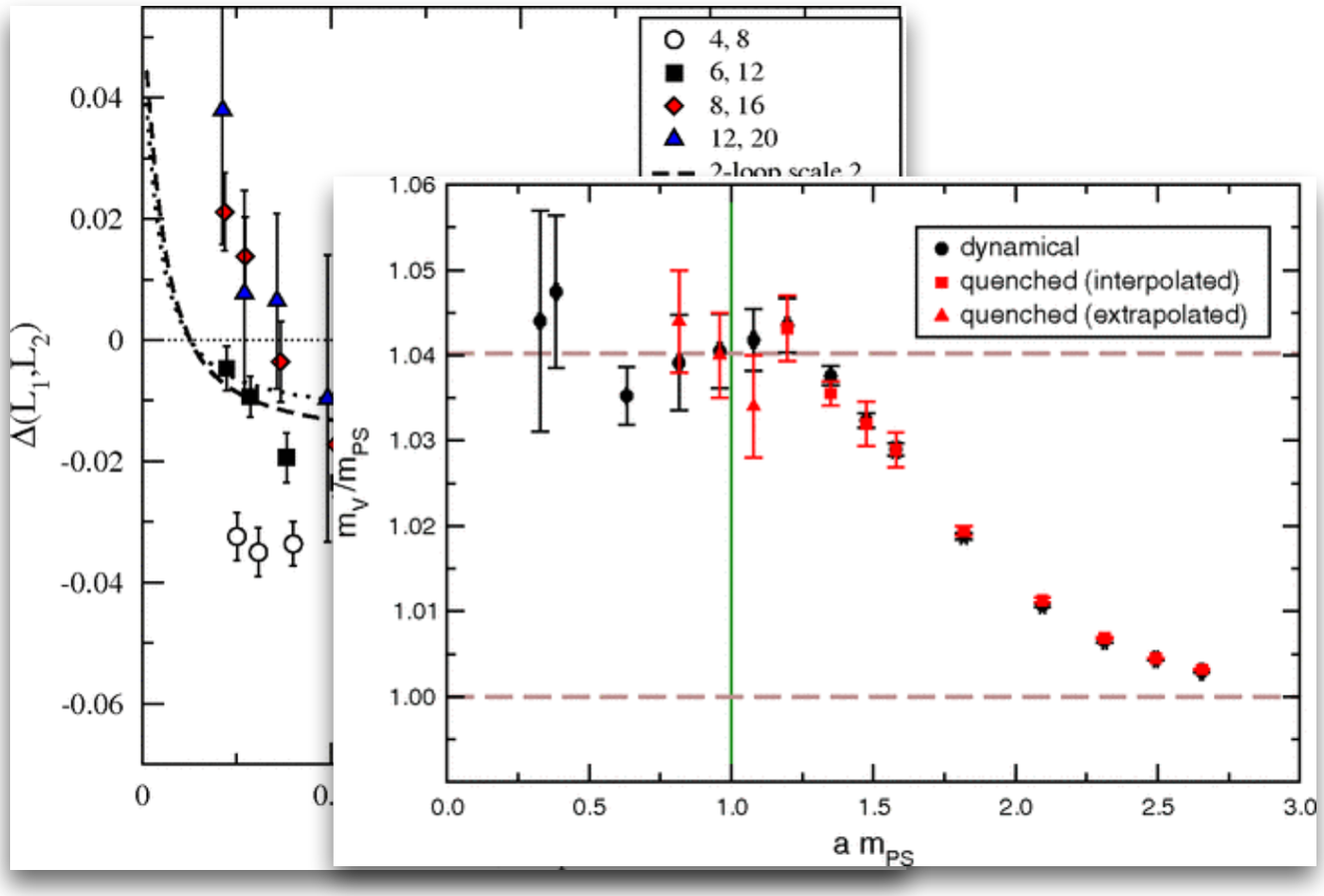
Conformal window of SU(N) gauge theories...
Dennis Dietrich, Francesco Sannino
Phys.Rev. D75 (2007) 085018



Minimal walking on the lattice
Simon Catterall, Francesco Sannino
Phys. Rev. D76 (2007) 034504

Mapping fundamental interactions

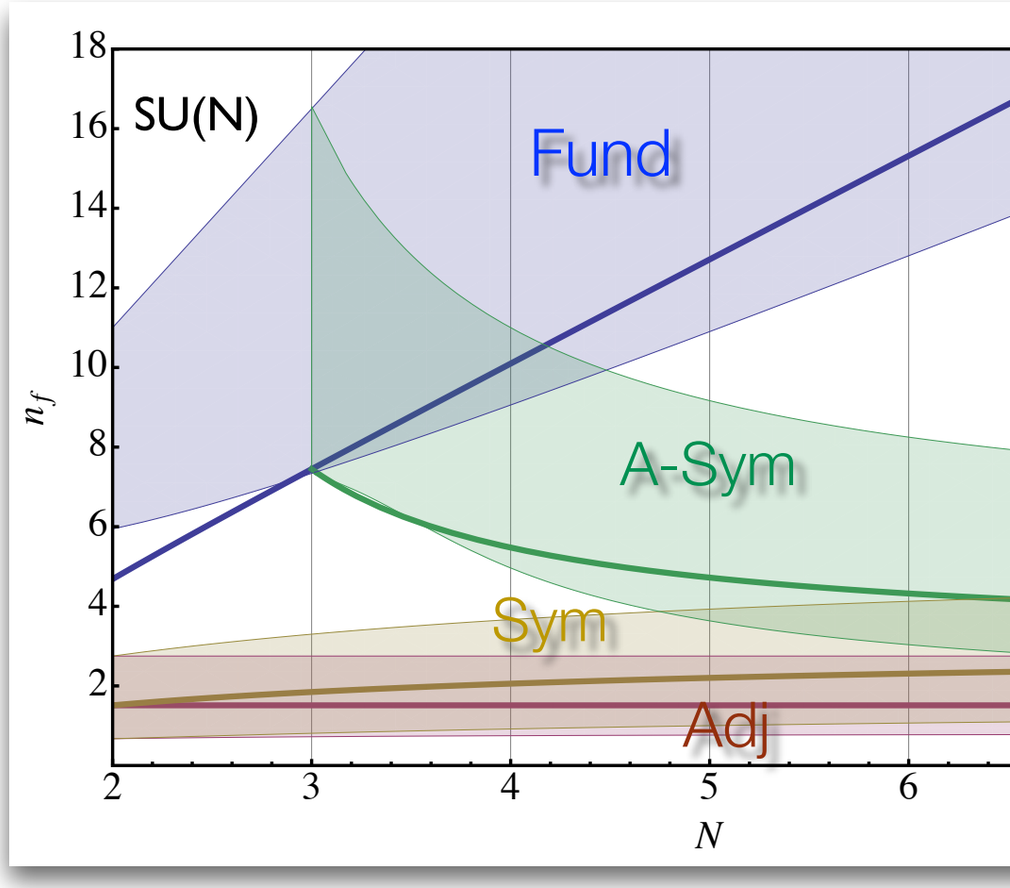
009 Lattice BSM golden era



Evolution of the coupling constant in SU(2) with adjoint fermions
Ari J. Hietanen, Kari Rummukainen, Kimmo Tuominen.
Phys.Rev. D80 (2009) 094504

Conformal versus confining scenario in SU(2) with adjoint fermions
L. Del Debbio, B. Lucini, A. Patella, C. Pica, and A. Rago
Phys. Rev. D (2009) 80, 074507

2010 Higher loop computation



UV and IR Zeros of Gauge Theories at The Four L
Claudio Pica, Francesco Sannino
Phys.Rev. D83 (2011) 035013. First hints of Asymp

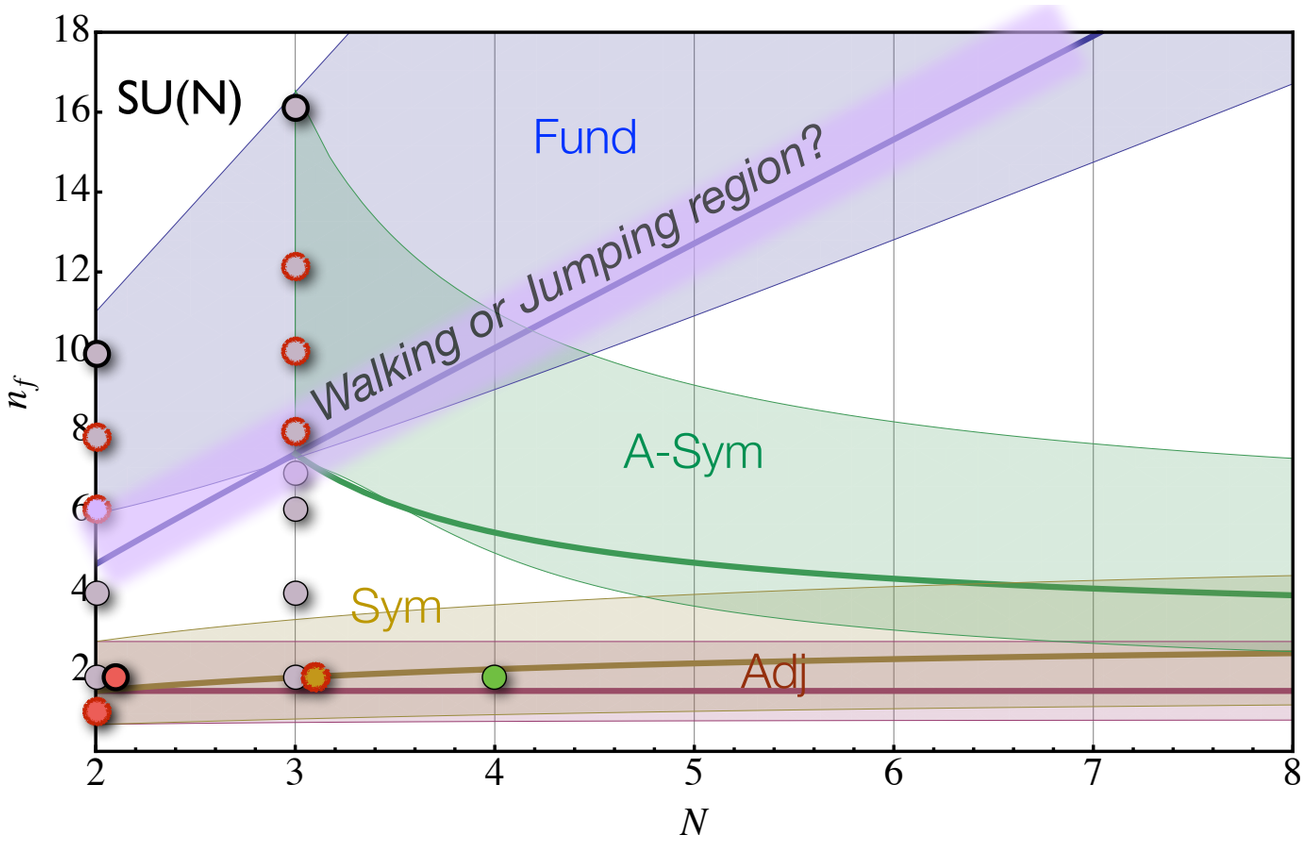
Higher-Loop Corrections to the Infrared Evolution
Thomas A. Ryttov, Robert Shrock
Phys.Rev. D83 (2011) 056011

Mapping fundamental interactions

Millions of core super hours later…

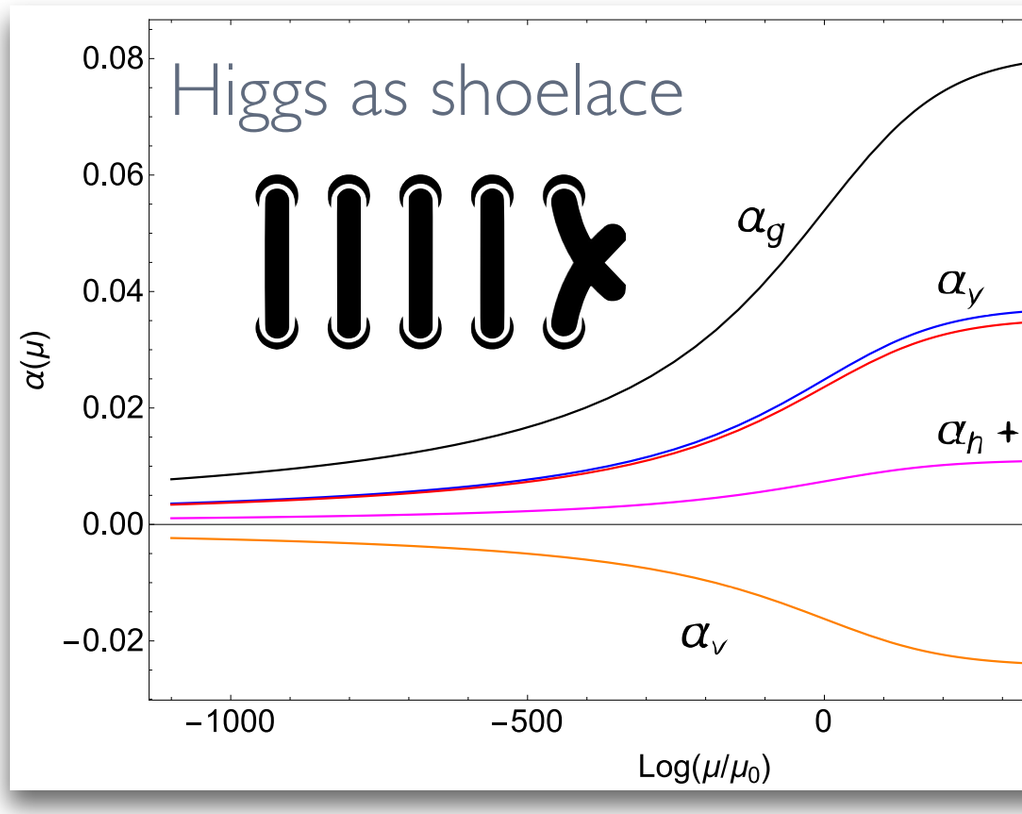
2014

Safety guaranteed



Explosion of lattice (HPC) work

LSD in US, LatKMI in Japan,
San Diego - Wuppertal - Pacific
Dutch-Italian, Finnish, UK
US - UK - CP3-Canada



Asymptotic safety guaranteed

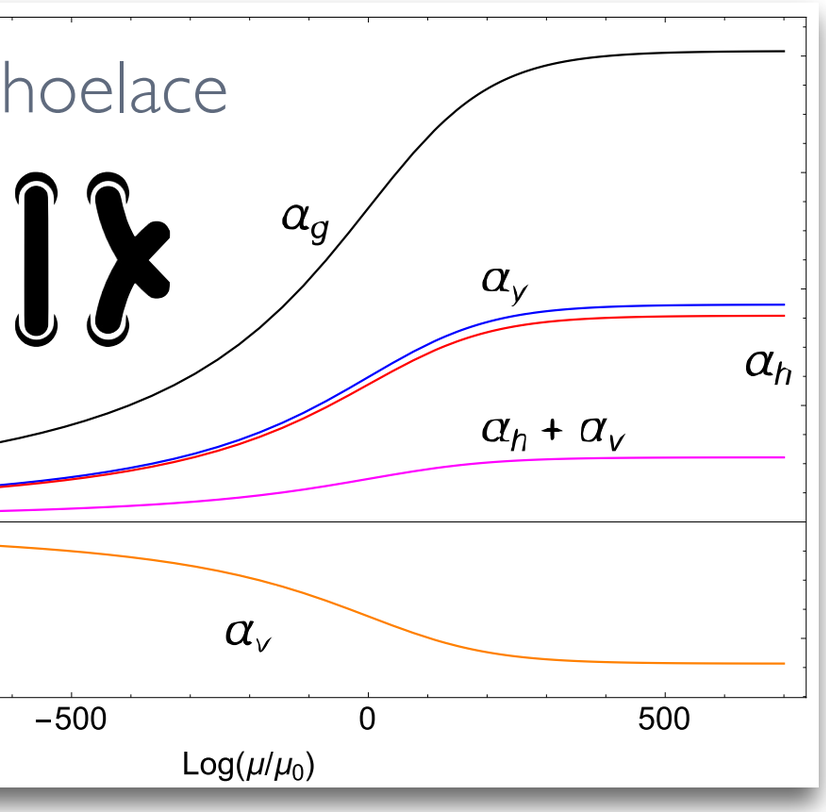
Daniel F. Litim, Francesco Sannino
JHEP 1412 (2014) 178

Mapping fundamental interactions

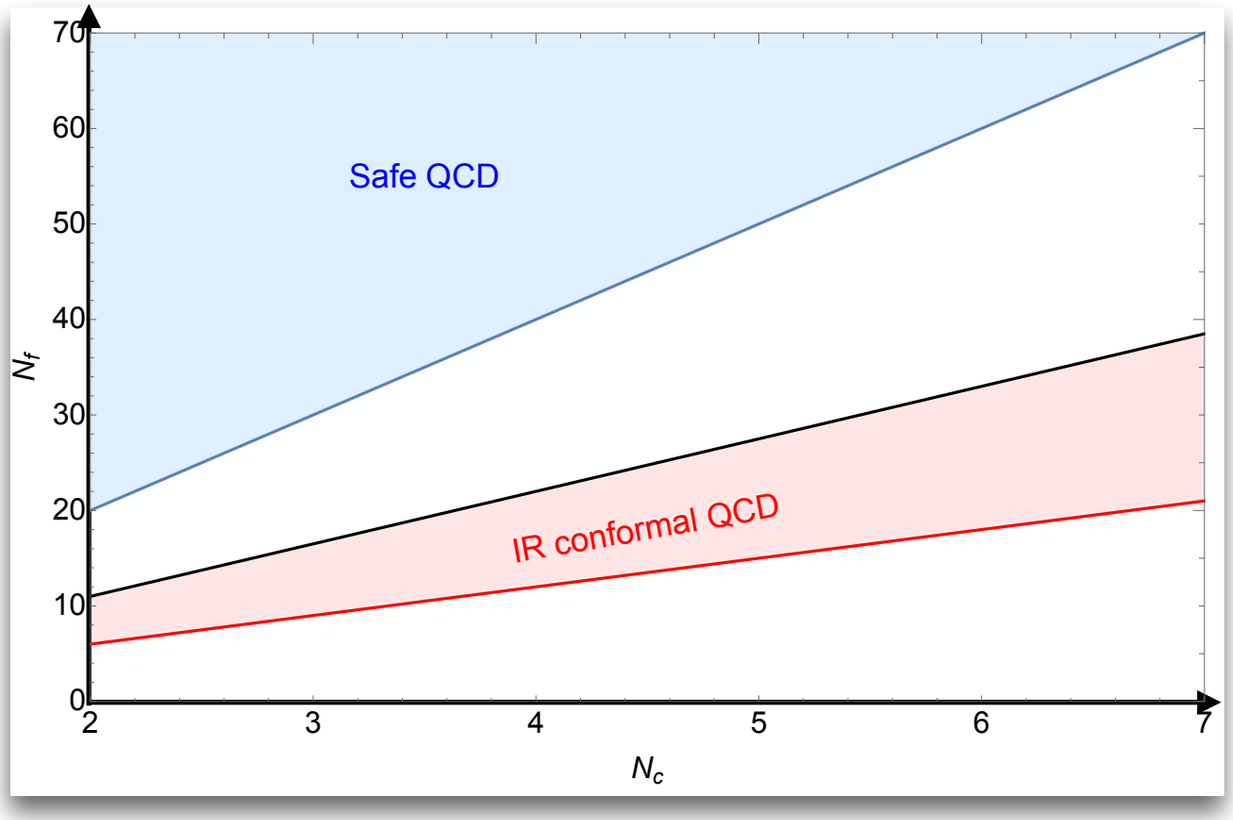
y guaranteed

2018

Safe QCD: World of opportunities



ranteed
sco Sannino
8



Conformal Window 2.0: The Large Nf story
Oleg Antipin, Francesco Sannino
arXiv:1709.02354. To appear in Physical Review D.

Mapping fundamental interactions

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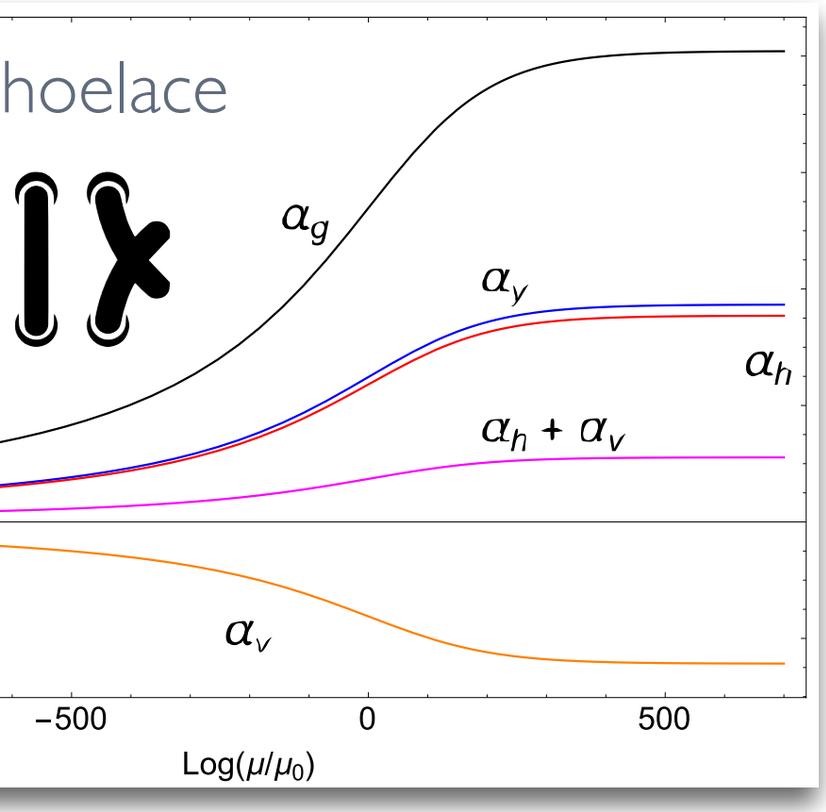

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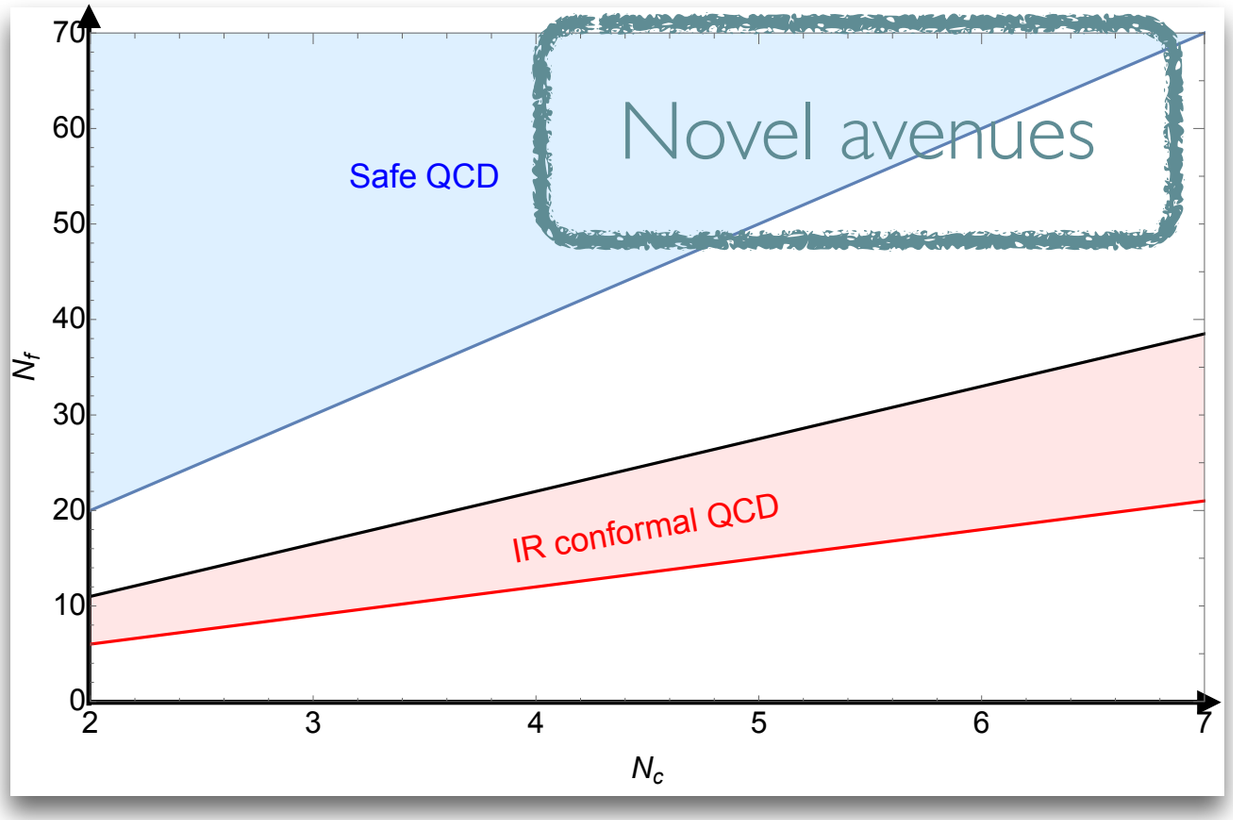


Conformal Window 2.0: The Large Nf story

Oleg Antipin, Francesco Sannino

arXiv:1709.02354. To appear in Physical Review D.

Safe Standard Model

Paths to a Safe Standard Model

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

Safety via dynamical breaking at large Nf and Nc,
[Abel and Sannino 1707.06638]

U(1) is safe within Safe Pati-Salam
[Molinaro, Sannino, Wang, 1807.03669]

Perturbative safety of the SM
[Barducci et al. 1807.05584, Bond et al. 1702.01727]

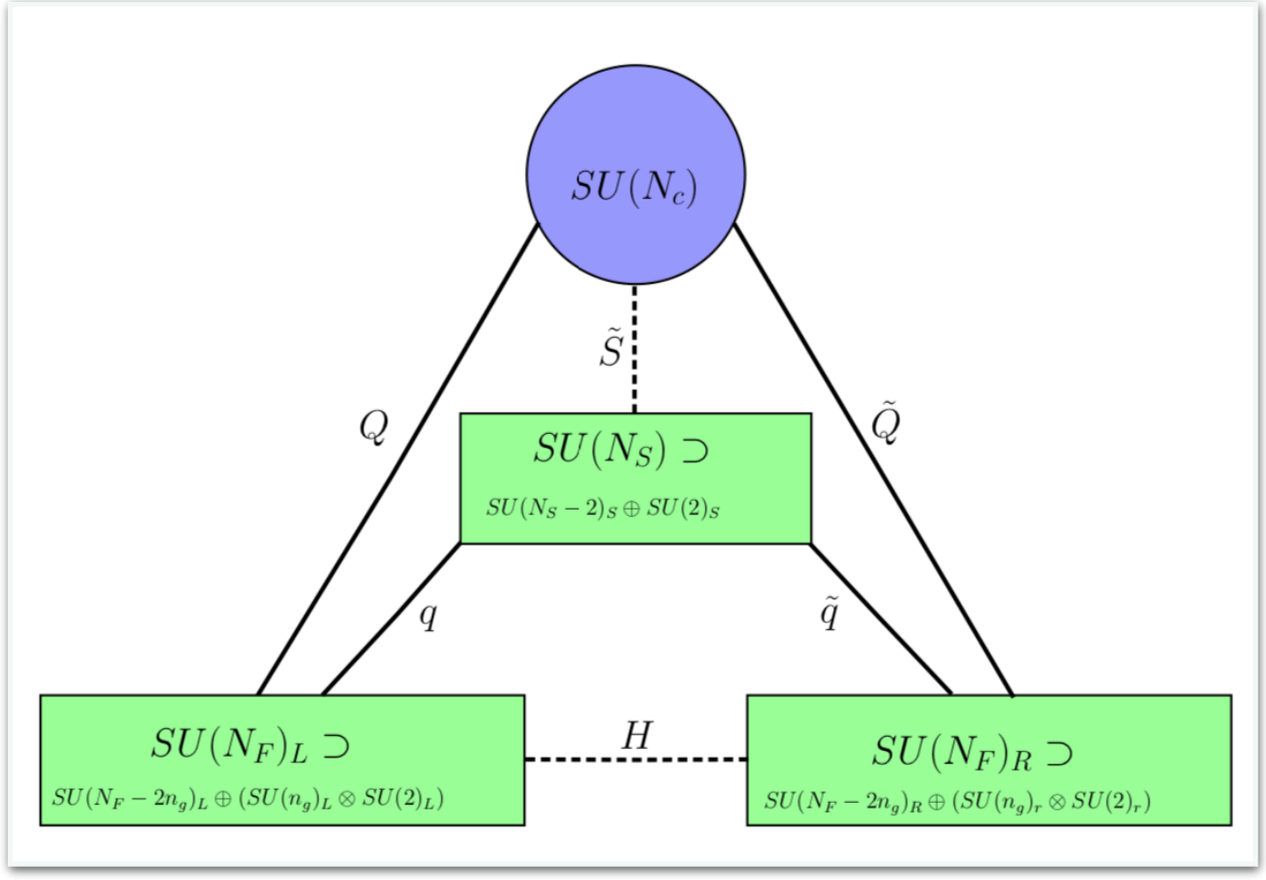
Towards a fundamental safe theory of composite Higgs and Dark Matter
[Cacciapaglia, Vatani, Ma, Wu, 1812.04005]

Proof of principle
for
Safe Standard Model

A complete asymptotically safe embedding of the Standard Model
[Abel, Mølgaard, Sannino, 1812.04856]

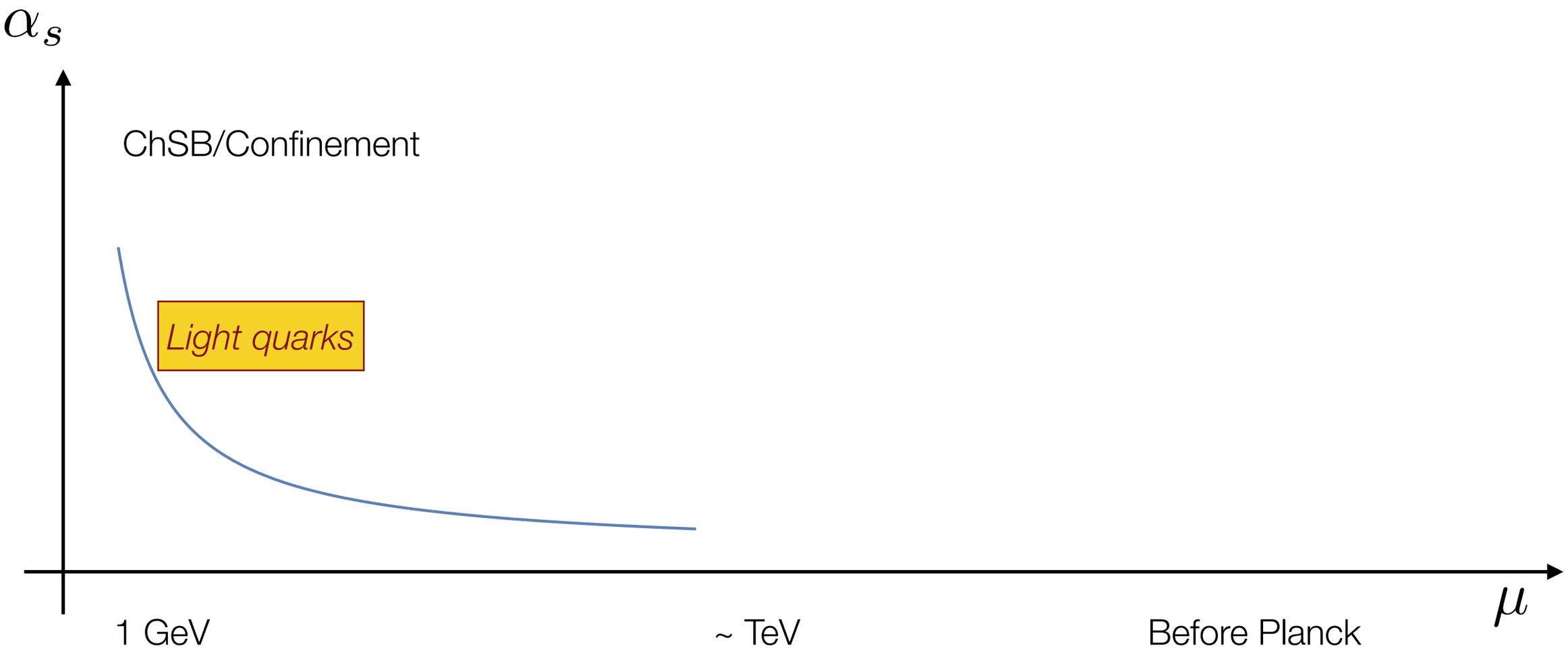
See Steve's (Abel) talk

Tetrad Model



Safe QCD

Sannino, 1511.09022



Pica & Sannino,1011.5917 PRD

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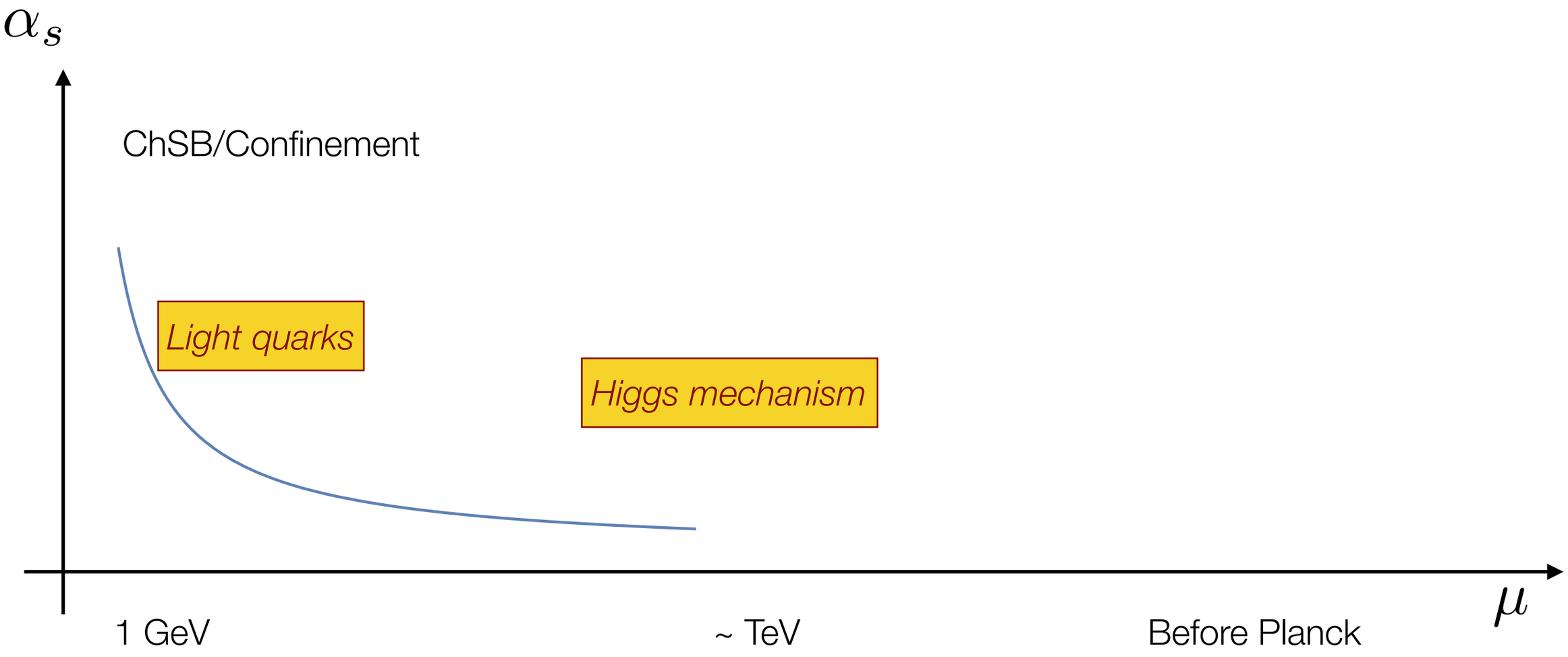

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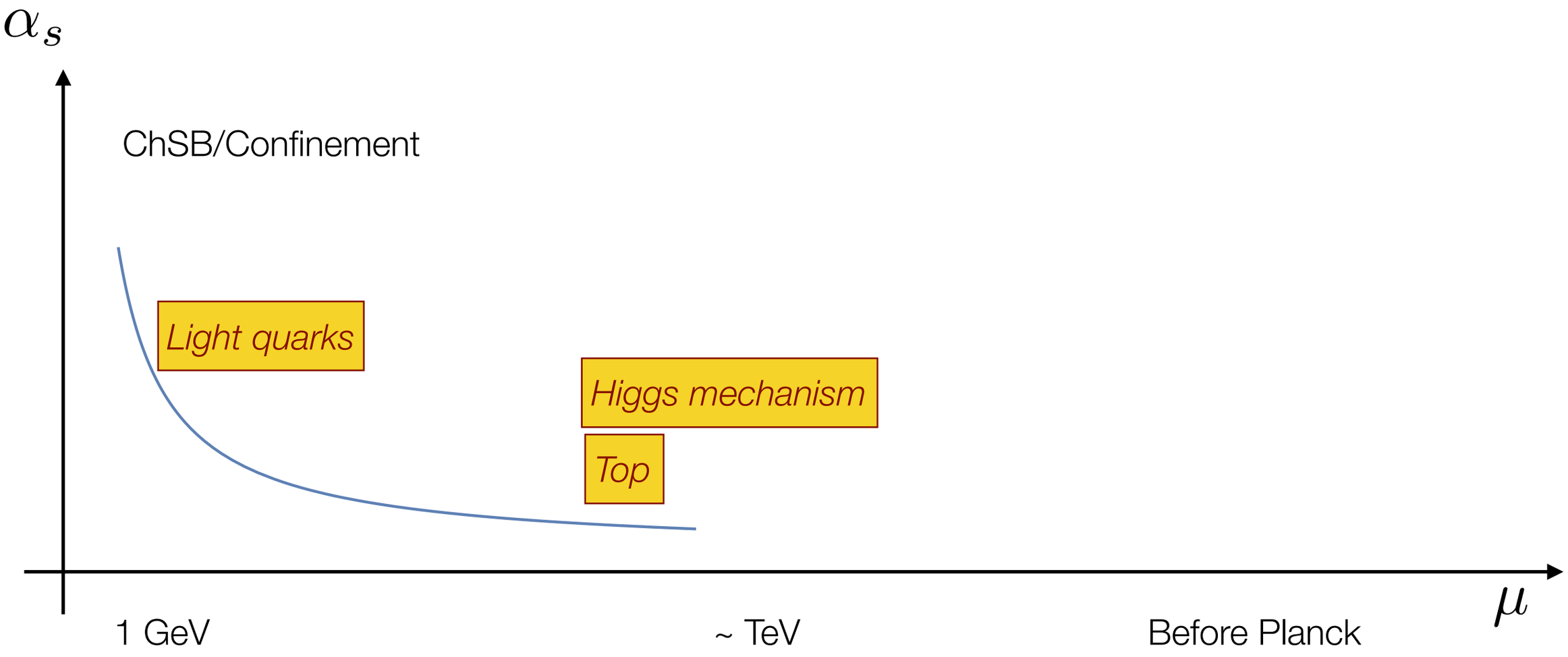

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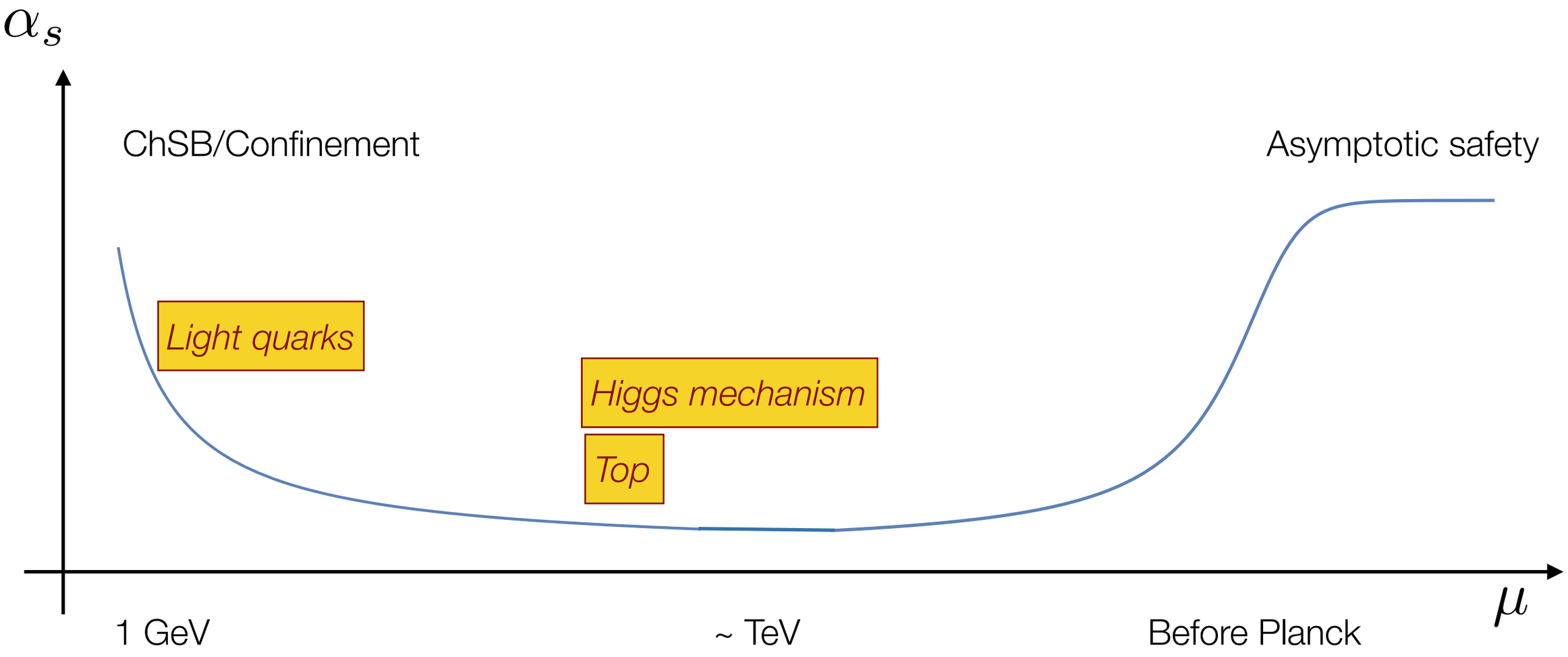

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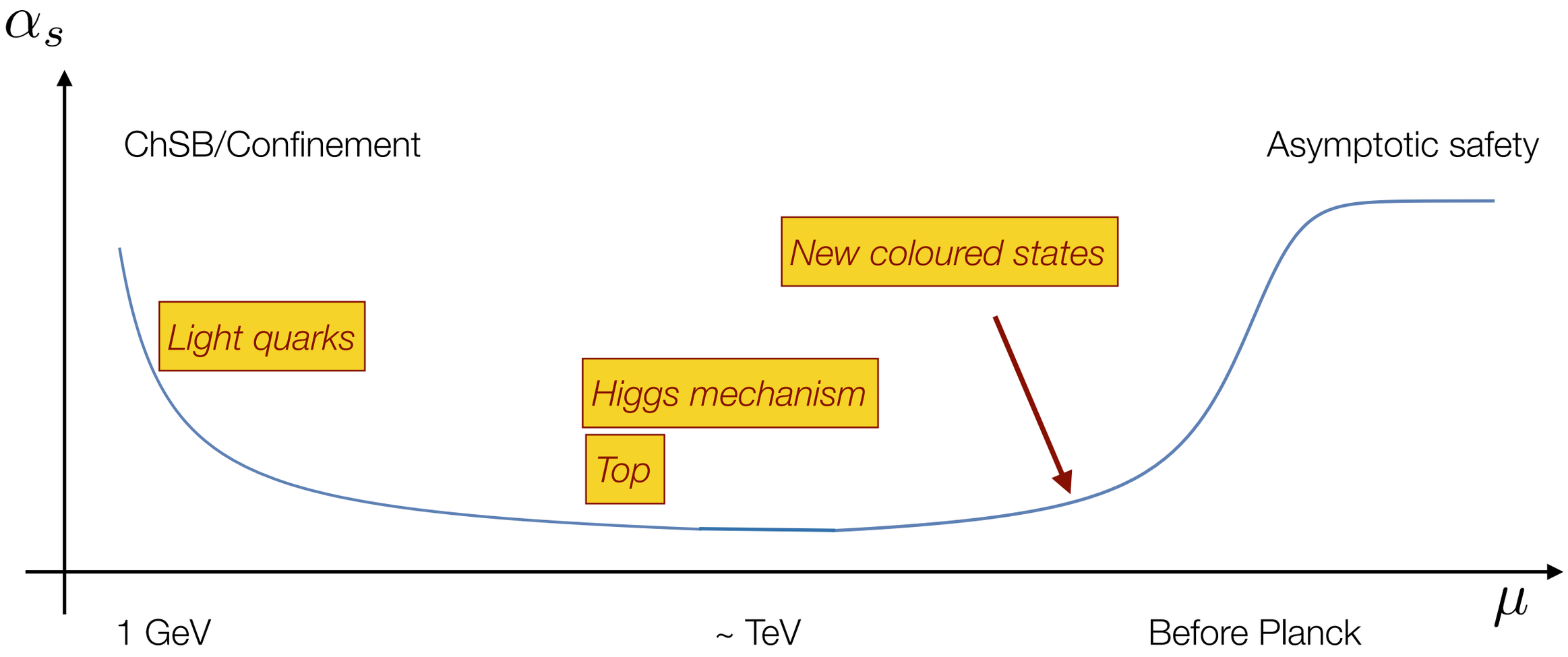

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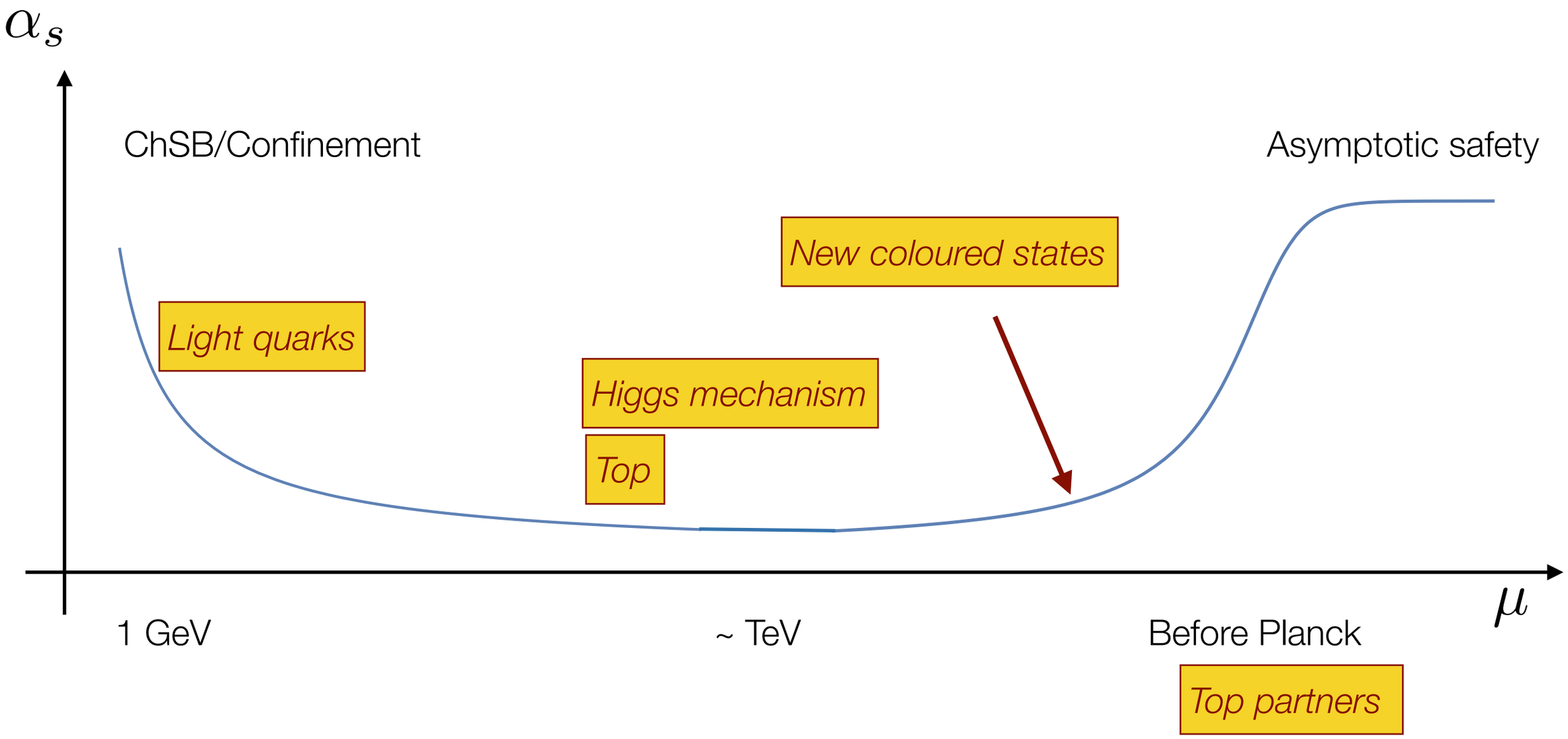

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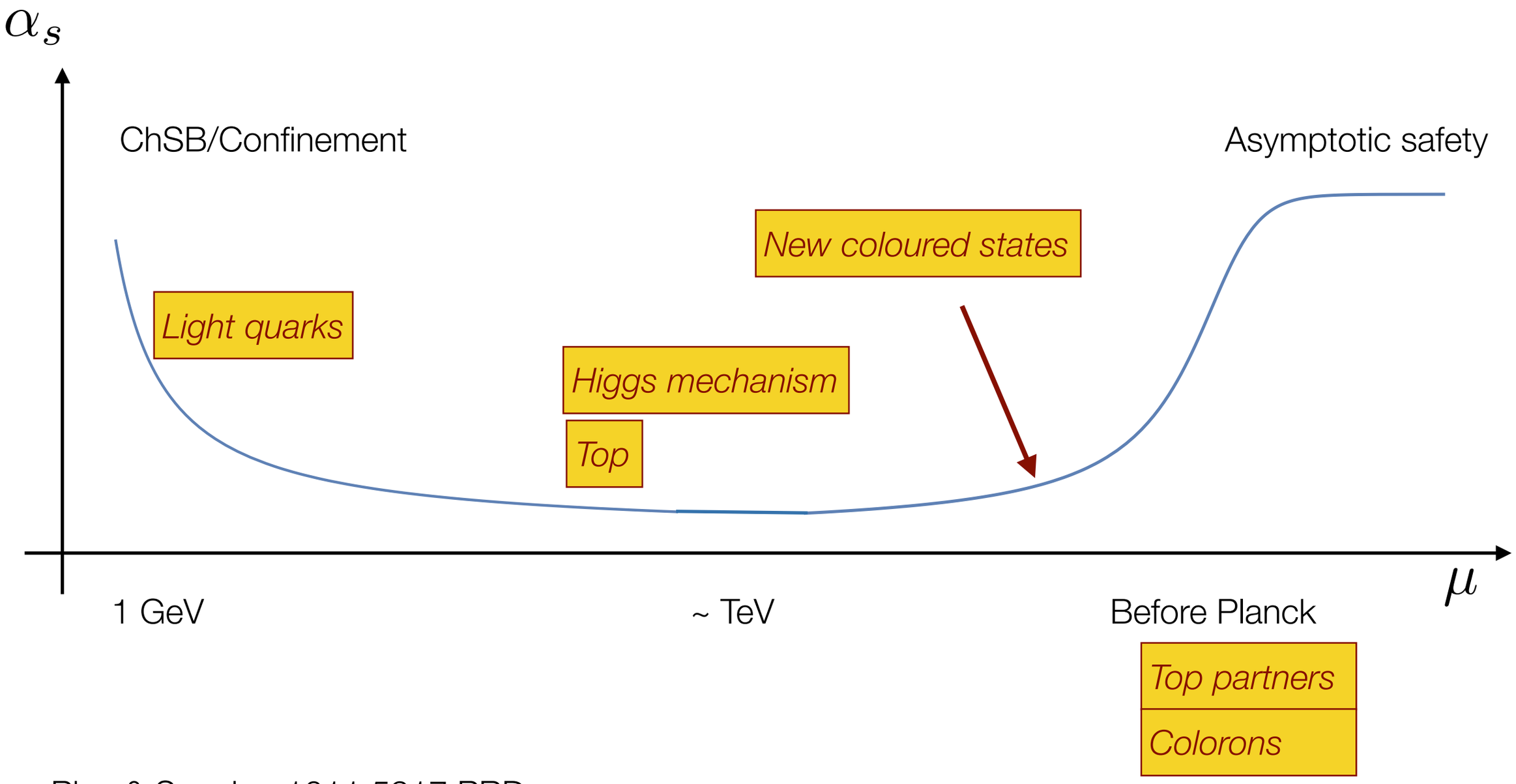

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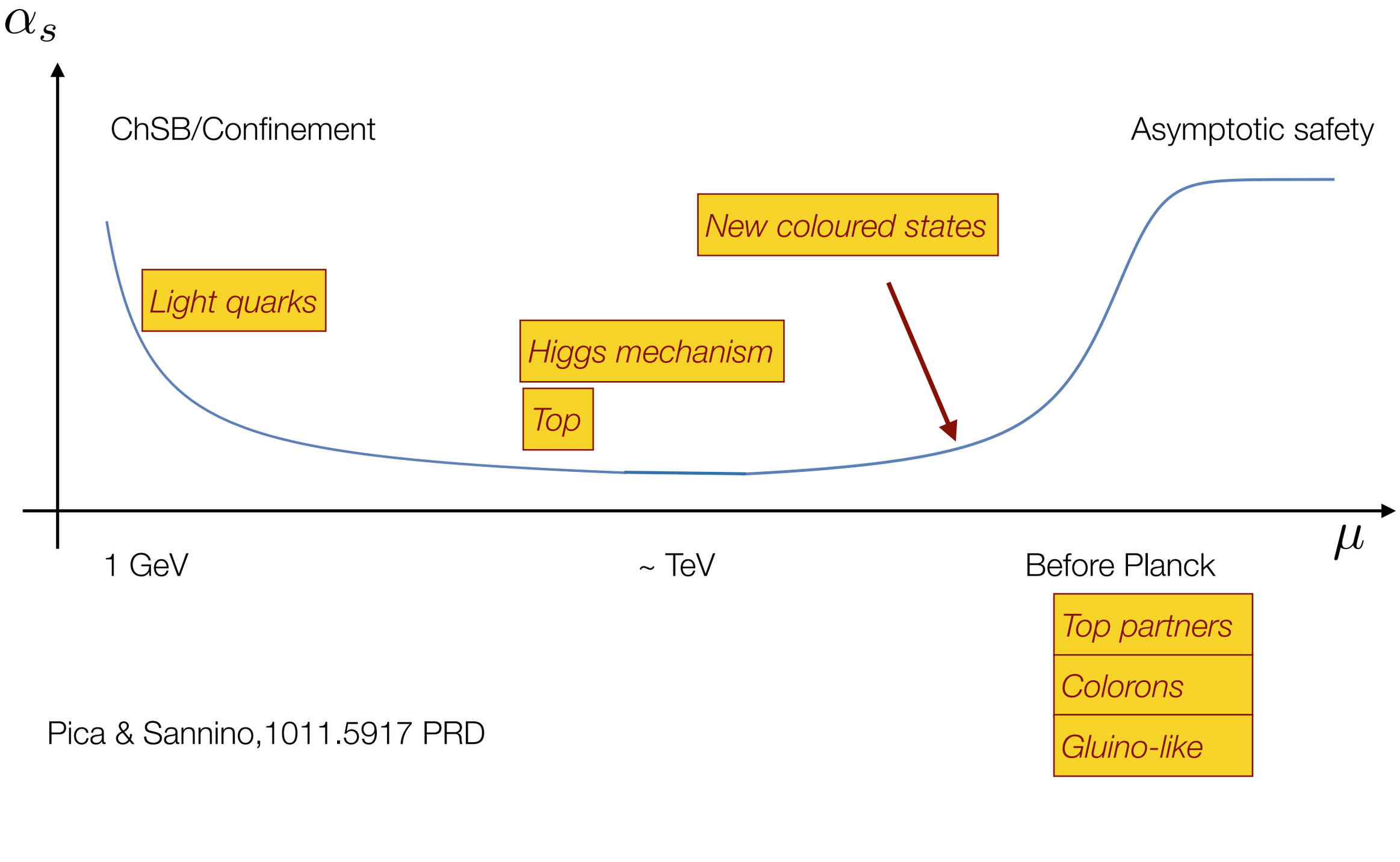

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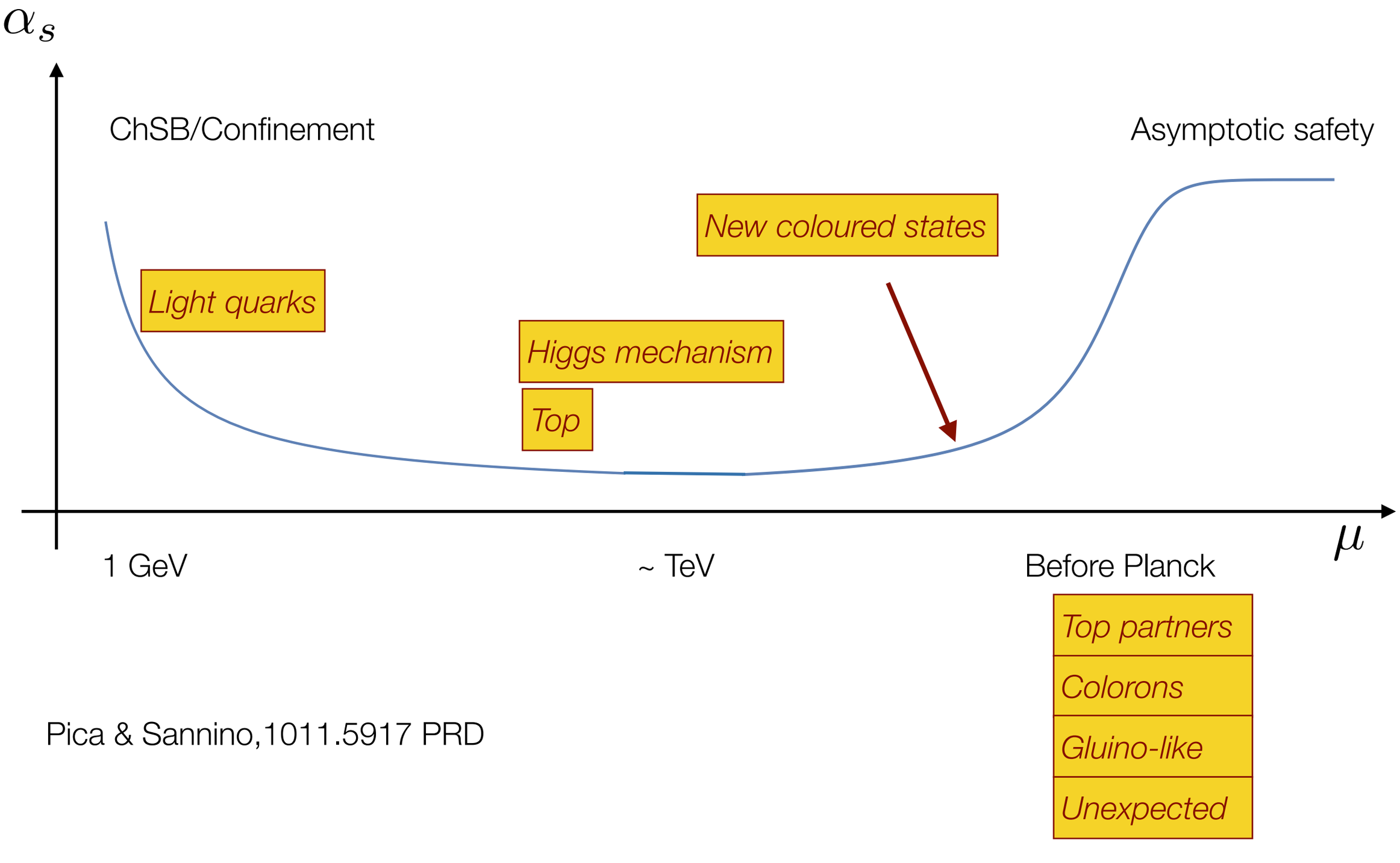

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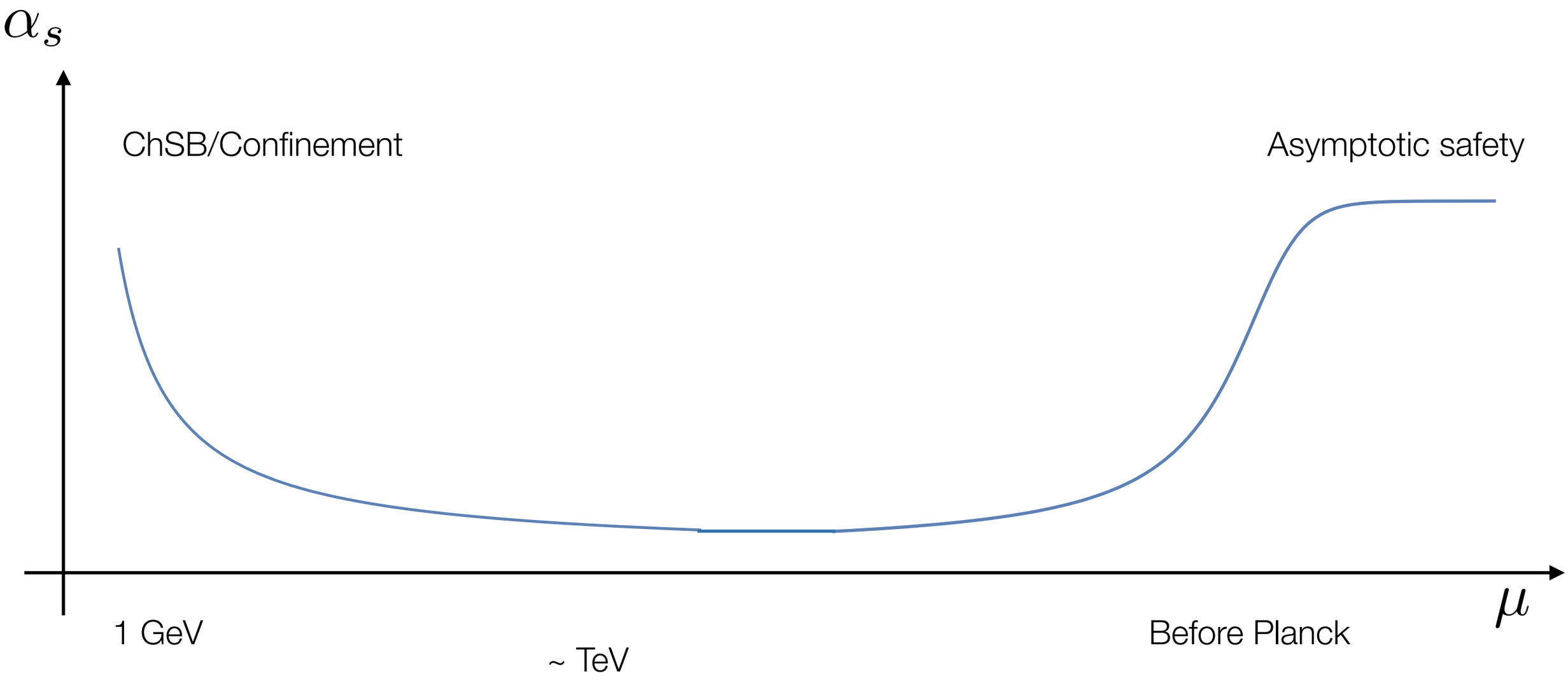
Testing safe QCD scenarios

Sannino, 1511.09022



Beyond asymptotic freedom for UV complete theories

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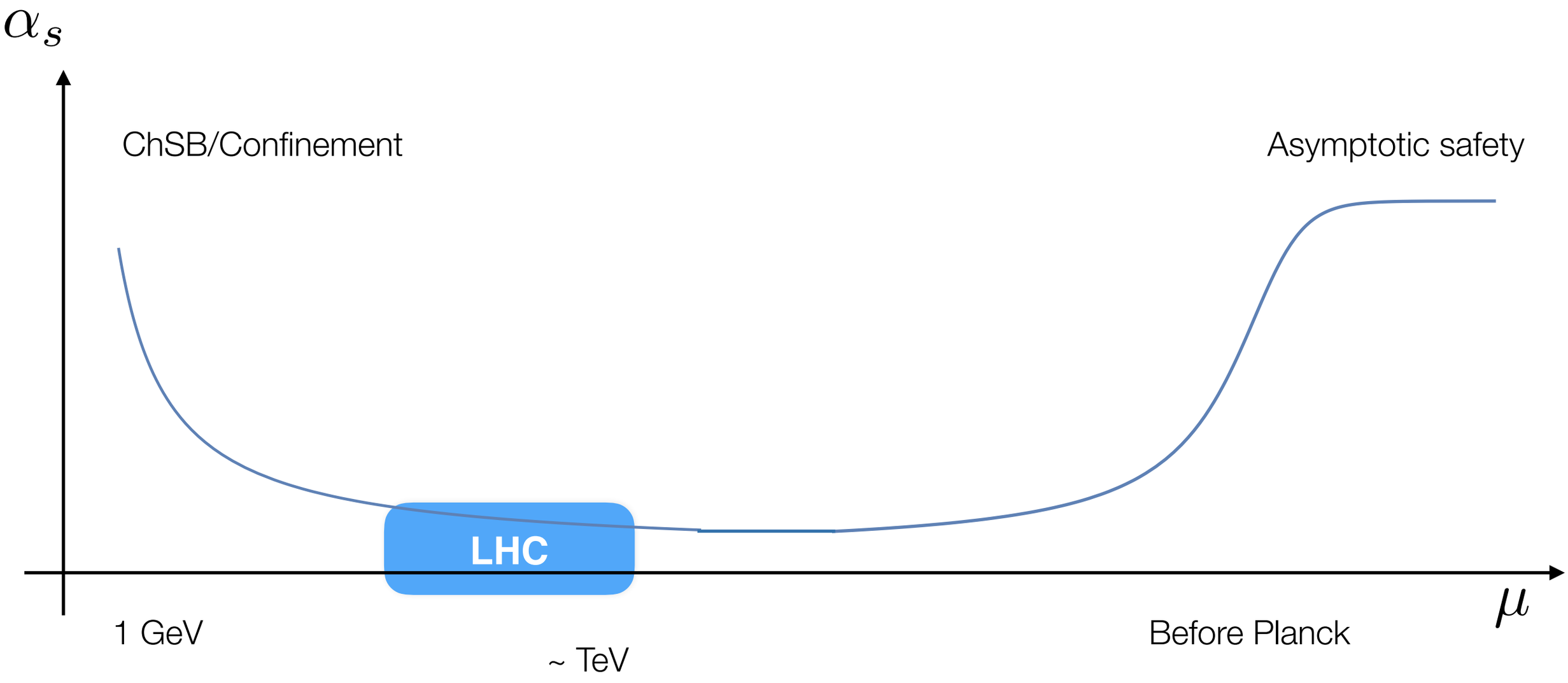

Beyond asymptotic freedom for UV complete theories

Model independent tests of new coloured states at the LHC

Becciolini, Gillioz, Nardecchia, Sannino, Spannowsky 1403.7411, PRD

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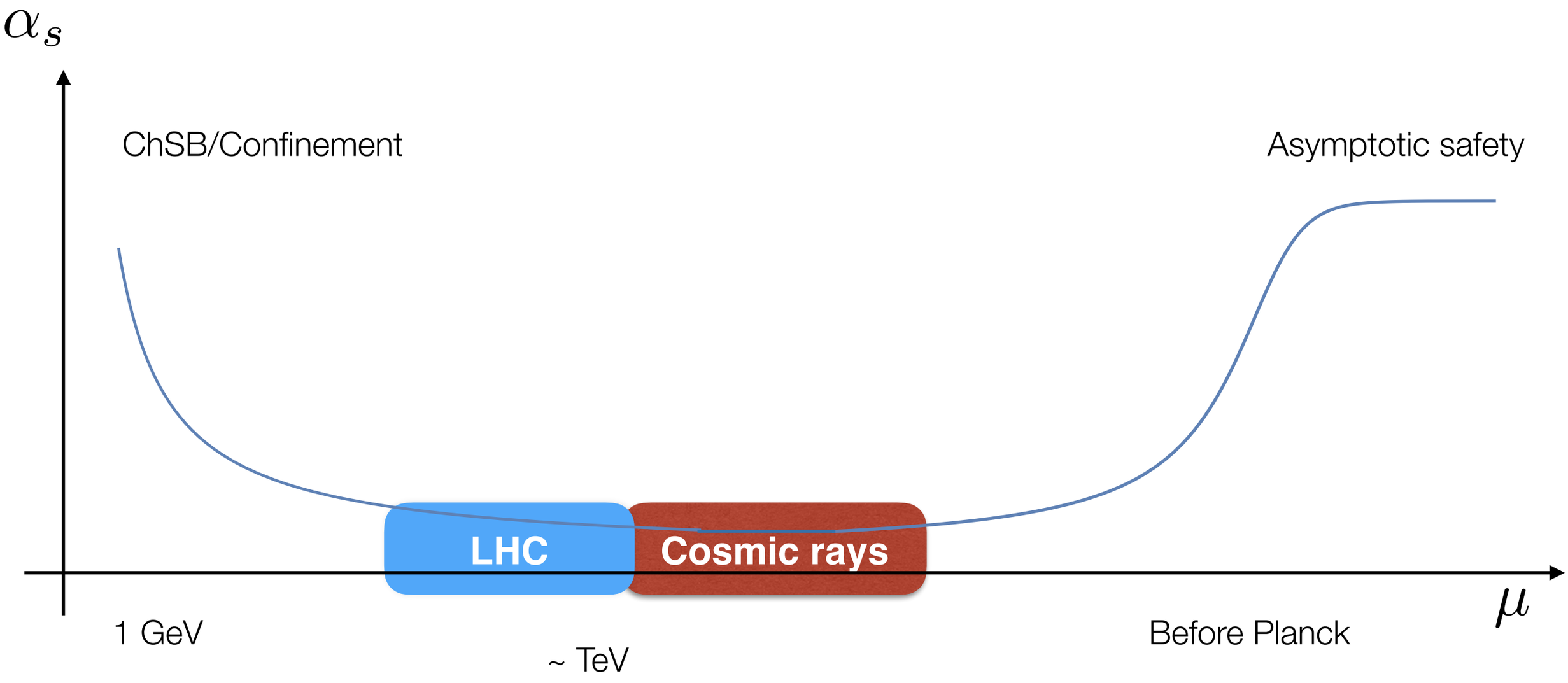

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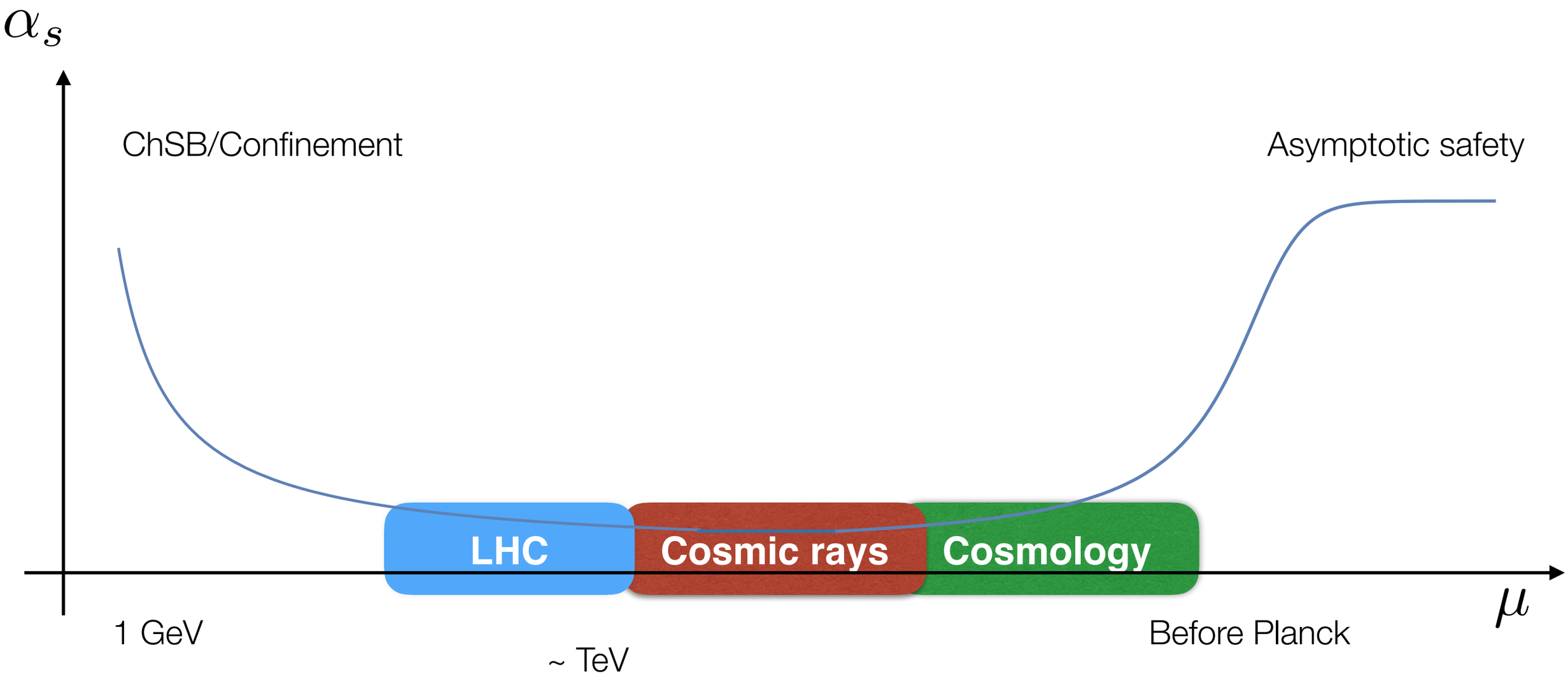

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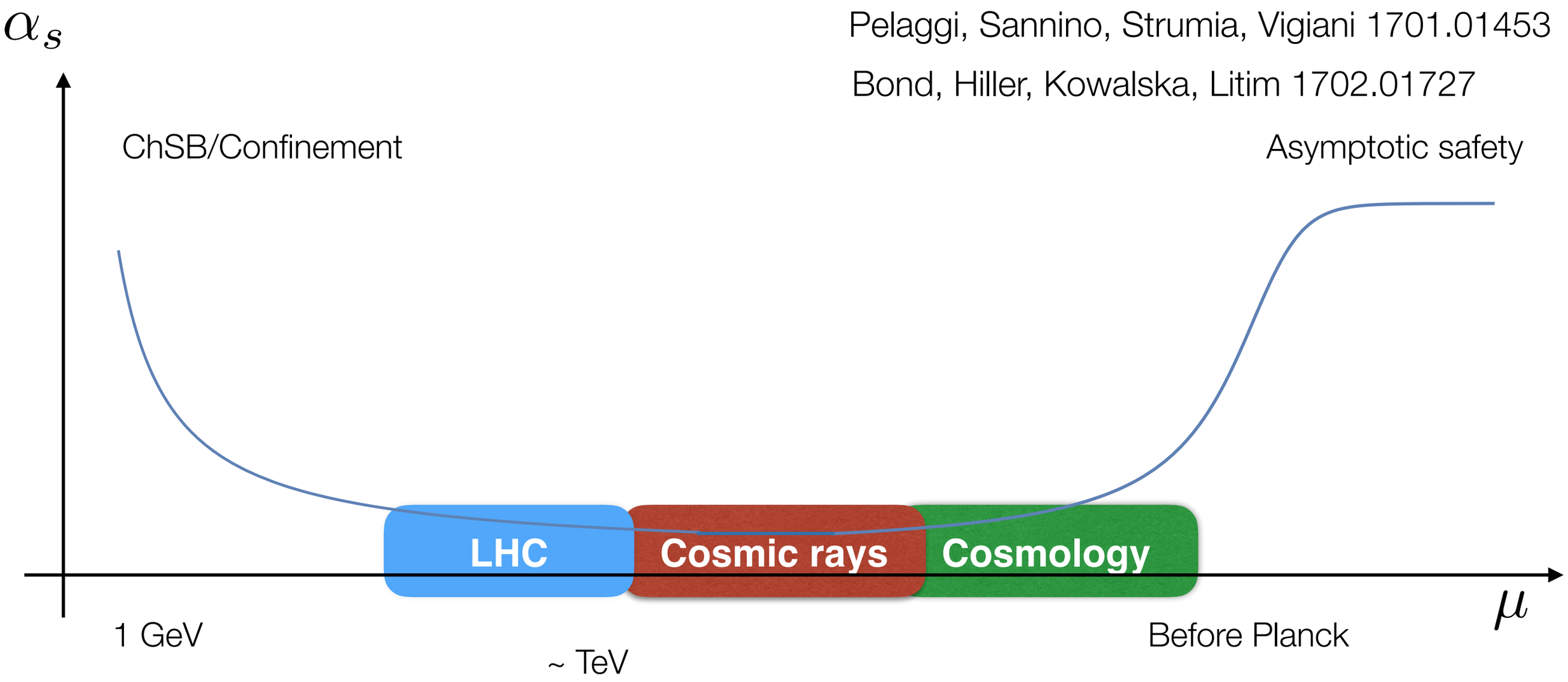
Pelaggi, Sannino, Strumia, Vigiani 1701.01453

Bond, Hiller, Kowalska, Litim 1702.01727



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Applications

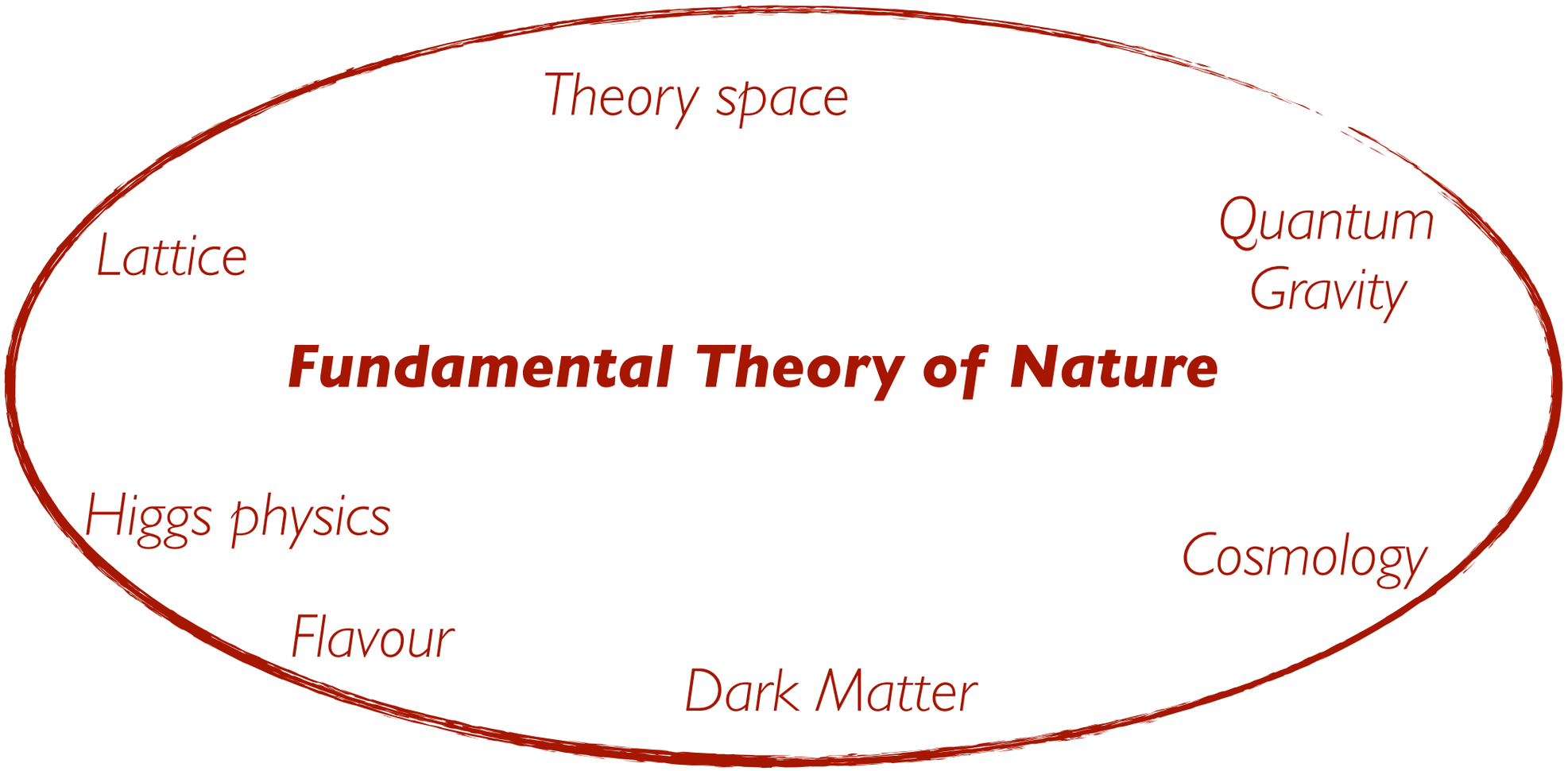
Applications

- Novel fundamental extensions of the SM
- Calculable radiative symmetry breaking mechanisms
- Cosmological models of inflation
- Novel (astro) particle physics phenomena and models
- Beyond asymptotic freedom
- Below and above 4 space-time dimensions

Frontier

Frontier

- Conformal window 2.0 on and off the lattice
- Novel (super) fundamental theories
- Gauge-gravity and gauge-gauge duality
- Resurgence studies of large Nf theories
- Safe amplitudes
- Safe axions
- ....


Theory space
Lattice
Quantum Gravity
Fundamental Theory of Nature
Higgs physics
Cosmology
Flavour
Dark Matter

Map fundamental theories a la Wilson

Phases of Quantum Field Theory

Conformal dynamics

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Black hole horizon and interior

Strong gravity/ Gravity waves

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thank you

"Nothing is invented, for it's written in nature first. Originality consists of returning to the origin."

Antoni Gaudí

Supersymmetric (un)safety

Intriligator and Sannino, 1508.07413

Bajc and Sannino, 1610.09681

Bajc, Dondi, Sannino, 1709.07436

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Exact results beyond perturbation theory

Central charges

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

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Generalisation to several susy theories using a-maximisation*

Intriligator and Sannino, 1508.07413, JHEP

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SUSY GUTs + R charge are challenging

Bajc and Sannino, 1610.09681, JHEP

Safe SUSY mechanics

Bajc and Sannino, 1610.09681

Bajc, Dondi, Sannino, 1709.07436

Bond, Litim, 1709.06953

Safe SUSY mechanics

To avoid the Intriligator-Sannino constraints

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- At least one large R-charge for some of the fields

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- At least one large R-charge for some of the fields
- UV-Interacting to IR-Interacting can be achieved with moderate R-charges [First non-SUSY example Esbensen-Ryttov-Sannino 1512.04402]
- Adding IR/UV relevant operators to modify the flow

Bajc and Sannino, 1610.09681

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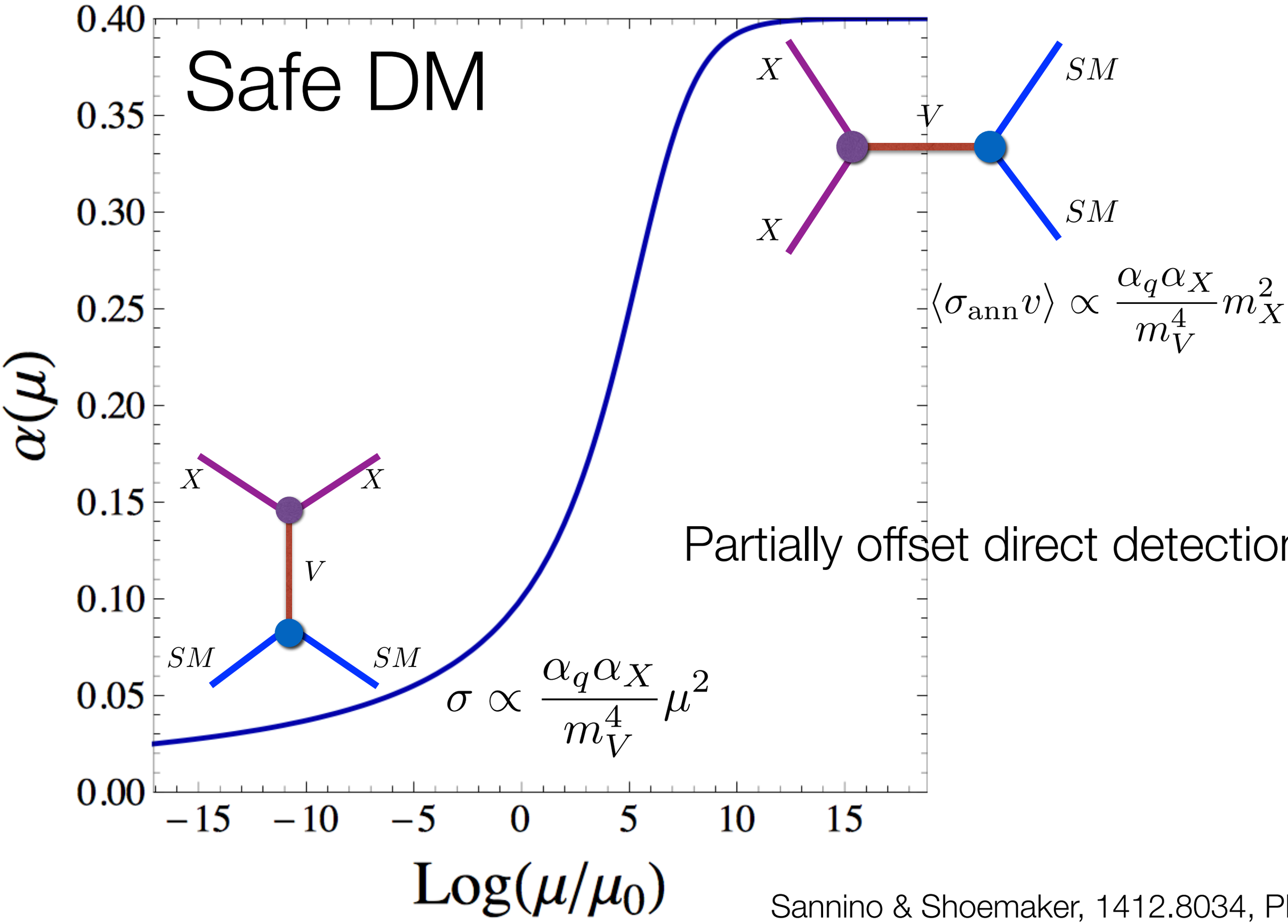
Safe DM

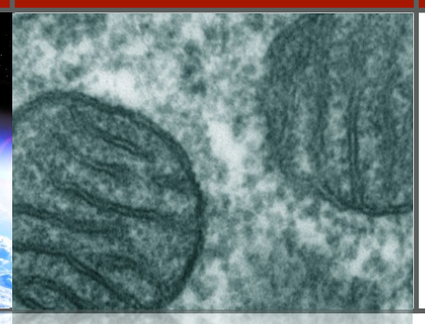


Partially offset direct detection

Sannino & Shoemaker, 1412.8034, PRD

Cosmic Calendar

January	February	March	April	May	June
					
Big Bang **13.8 billion years ago**		**Galaxy form** **11 billion years ago**			

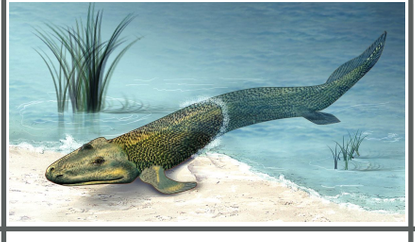
July	August	September	October	November	December
					to be cont.
	Sun and planets **4.5 billion years ago**	**First known life** **3.5 billion years ago**	**Oxygenation** **2.3 billion years ago**	**Complex cells** **1 billion years ago**	

1 month = 1.1 billion years

1 day = 37.8 millions years

1 minute = 26.238 years

December *

1	2	3	4	5	6
7	8	9	10	11	12
13	14 **First animals 670 mil yrs ago** 	15	16	17 **First fish 530 mil yrs ago** 	18
19	20 **Land plants 450 mil yrs ago** 	21 **Insects 400 mil yrs ago** 	22 **Amphibians 350 mil yrs ago** 	23 **Reptiles 300 mil yrs ago** 	24
25 **Dinosaurs 230 mil yrs ago** 	26 **Mammals 200 mil yrs ago** 	27 **Birds 150 mil yrs ago** 	28 **Flowers 130 mil yrs ago** 	29	30 **Dino extinction 65 mil yrs ago** 

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One second before midnight

Dark energy accelerated expansion

Structure formation

Cosmic Microwave Background radiation is visible

Accelerators

RHIC & LHC heavy ions

LHC protons

High-energy cosmic rays

Size of visible universe

Inflation

TODAY

Big Bang

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

$t = 10^{-36}$ s
$E = 10^{16}$ GeV

$t = 10^{-10}$ s
$E = 10^{2}$ GeV

$t = 10^{-4}$ s
$E = 10^{-1}$ GeV

$t = 10^{2}$ s
$E = 10^{-4}$ GeV

$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

Key

- quark
- gluon
- electron
- muon
- tau
- neutrino
- W Z bosons
- meson
- baryon
- ion
- atom
- photon
- star
- galaxy
- black hole