Title: Charting Fundamental Interactions

Date: Jun 05, 2018 09:15 AM

URL: http://pirsa.org/18060009

Abstract: I summarise the state-of-the-art in our understanding of fundamental interactions and will set the stage for present and future studies and phenomenological applications.

Plan of the week

- Meaning of fundamental
- Safe theories in 4D [Litim, Thomsen]
- Large Nf safety [Thomsen]
- Safe standard model [Abel, Mann, Salvio, Wang]
- SUSY-like radiative symmetry breaking [Abel]
- SUSY (un)safety [Dondi, Litim]
- New paths in (astro)particle physics
- Interplay with gravity and cosmology [Afshordi, Eichhorn, Reichert, Salvio, Yamanda]
- Theoretical challenges and opportunities

Challenging the Standard Model

- What is the SM?
- What does it describe?
- What does it fail to account for?
- What is the meaning of fundamental?
- How can we extend the SM and why should we?

Wait! Gauge & Yukawa interactions?

- Gauge interactions: Demand symmetries to be local

$$\phi(x) \to e^{i\theta}\phi(x) \qquad \theta = \theta(x)$$

$$\partial_\mu \to D_\mu = \partial_\mu - igA_\mu \qquad gA_\mu \to gA_\mu + \partial_\mu\theta(x)$$

- Yukawa interactions come from “accidental” interactions

$$y\ \bar{q}_L H q_R$$

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- Yukawa interactions come from "accidental" interactions

$$y\, \bar{q}_L H q_R$$

- Further accidental operators, scalar self-couplings

$$\lambda \mathrm{Tr}\left[H^\dagger H H^\dagger H\right]$$

Gauge - Yukawa theories

$$L = -\frac{1}{2}F^2 + i\overline{Q}\gamma_\mu D^\mu Q + y(\overline{Q}_L H Q_R + \text{h.c.}) - \text{Tr}\left[\text{DH}^\dagger \text{DH}\right] - \lambda_u \text{Tr}\left[(\text{H}^\dagger \text{H})^2\right] - \lambda_v \text{Tr}\left[(\text{H}^\dagger \text{H})\right]^2$$

Yukawa

Gauge

Scalar selfinteractions

4D: standard model, dark matter, …

3D: condensed matter, phase transitions

2D: graphene, …

4plusD: extra dimensions, string theory, …

Universal description of physical phenomena

Standard Model (blind spots)

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

Gauge $\quad \text{Tr}\left[\text{DH}^\dagger \text{DH}\right] - \lambda_u \text{Tr}\left[(\text{H}^\dagger \text{H})^2\right] - \lambda_v \text{Tr}\left[(\text{H}^\dagger \text{H})\right]^2$

Scalar selfinteractions

- Gauge structure is established
- Yukawa structure partially constrained (flavour physics)
- Higgs self-coupling is not directly constrained
- Unsafe field theory

But it does work well, so far!

Naive spectrum

$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246 \text{ GeV}$$

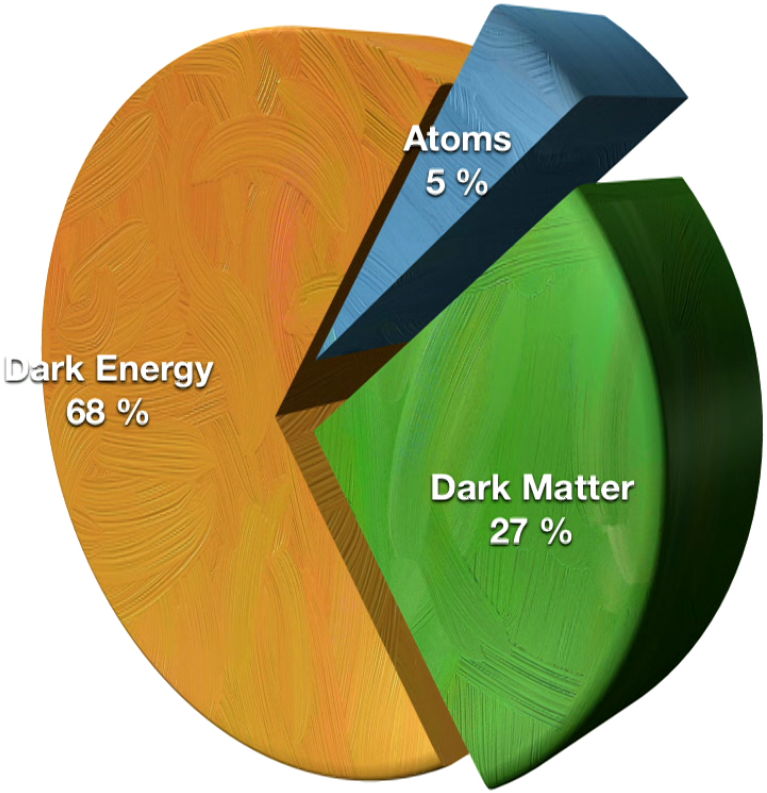
$$M_W = g\,\frac{v}{2} \approx g\ 123 \text{ GeV}$$

$$M_H = \sqrt{\lambda\,2}\,v \approx \sqrt{\lambda}\ 345 \text{ GeV}$$

$$m_f = \lambda_f \frac{v}{\sqrt{2}} \approx \lambda_f\ 174 \text{ GeV}$$

Top has the right energy scale!

SM fails to account for

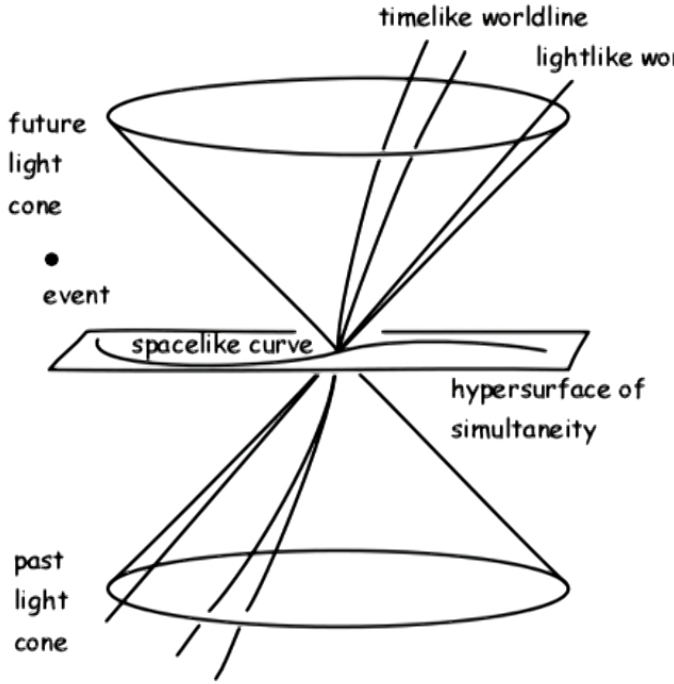


- Dark matter
- Dark energy
- Matter over antimatter
- Neutrino masses*

Meaning of fundamental 1:

Fields

3 + 1 space time



- SL(2,C) ~ SO(3,1) Lorentz group
- Spinors fund. rep.
- Lagrangian: SL(2,C) scalar

Fundamental Fields

Irreducible representations of SL(2,C)

- Spin 0 scalar (0,0) (Fundamental ?)
- Spin 1/2 Weyl (1/2, 0) , (0,1/2)
- Spin 1/2 Dirac (1/2, 0) + (0,1/2)
- Spin 1/2 Majorana (1/2, 0) + (1/2,0)* ?
- Spin 1 Gauge bosons (1/2, 1/2)
- Spin 3/2 Gravitino …. ?
- Spin 2 Graviton …. ?
- …

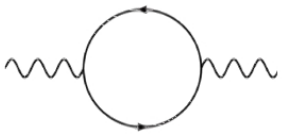
Beyond massless spin 1, theories are not renormalisable

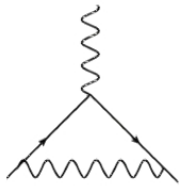
Meaning of fundamental 2:

Interactions

QED is not fundamental (unsafe)

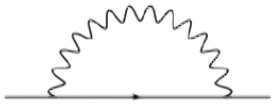
$$\beta \equiv \frac{\partial \alpha}{\partial \ln \mu/\mu_0} = \frac{2}{3}\alpha^2$$

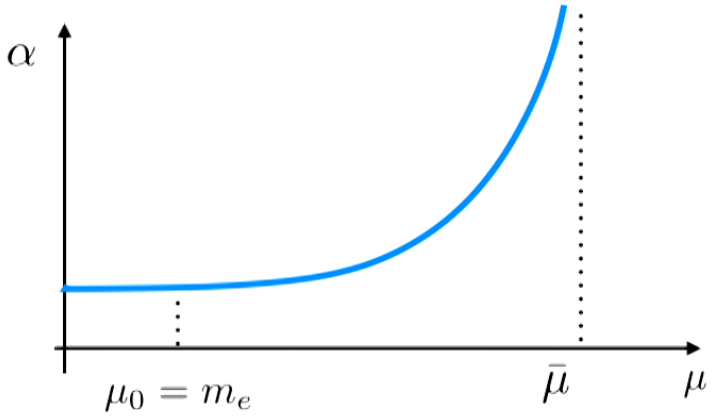




$$\alpha(\mu) = \frac{\alpha_0}{1 - \frac{2}{3}\alpha_0 \log \mu/\mu_0}$$

$$\bar{\mu} = \mu_0 \exp\left[\frac{3}{2\,\alpha_0}\right]$$





Trivial = UV unsafe

Cutoff independent iff non-interacting!

Fundamental interactions

Wilson: A fundamental theory has an UV fixed point

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

Complete Asymptotic Freedom

All marginal couplings vanish in the UV

- CAF conditions obtained at 1-loop
- Gauge coupling drives CAF
- IR conformal or dyn. scale generated

$$\mu \frac{d\alpha_H}{d\mu} = \alpha_H \left[c_2 \alpha_H + c_1 \alpha_g \right]$$

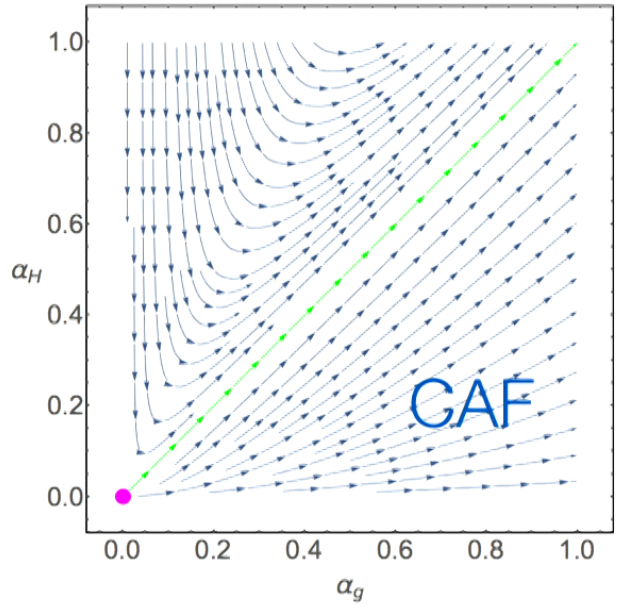
$$c_1 < 0 \qquad c_2 > 0$$

Cheng, Eichten, Li, PRD 9, 2259 (1974)

Callaway, Phys. Rept. 167, 241

Holdom, Ren, Zhang, 1412.5540

Giudice, Isidori, Salvio, Strumia, 1412.2769



Pica, Ryttov, Sannino, 1605.04712 + higher orders for IR conformality

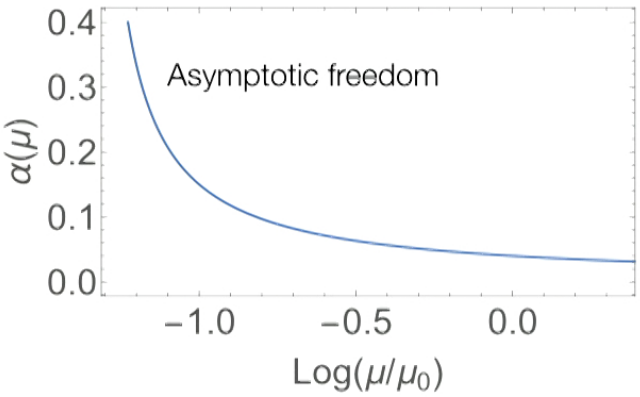
Asymptotic Safety

Wilson: A fundamental theory has an UV fixed point

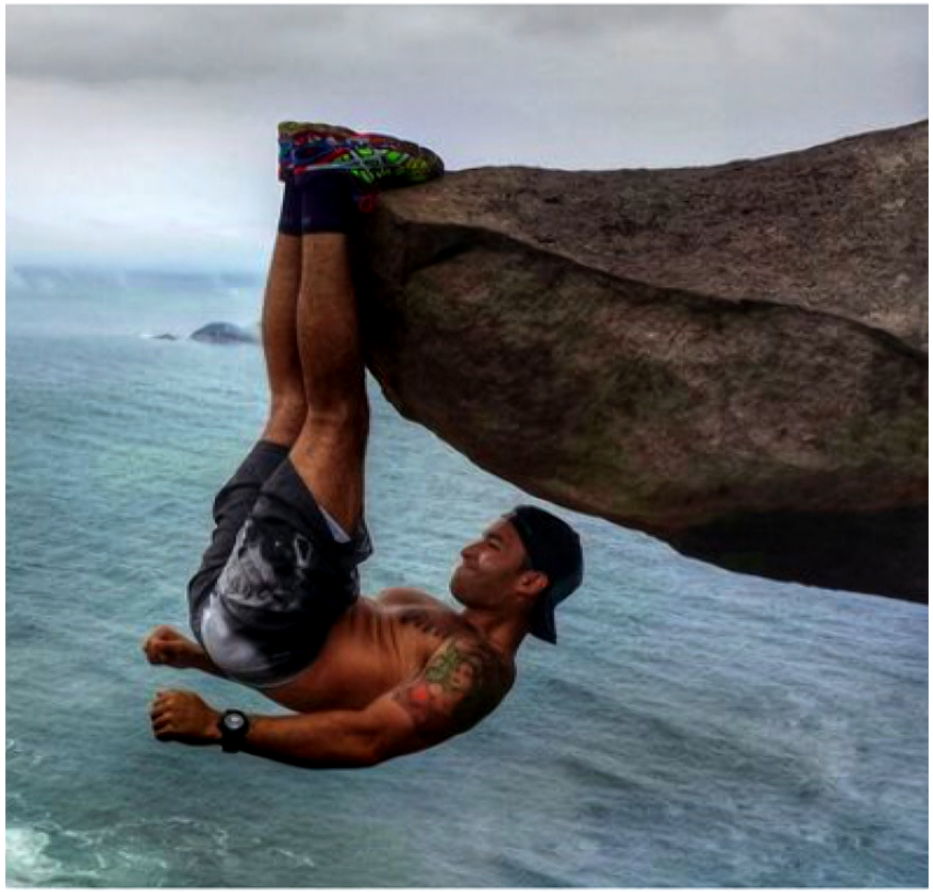
Trivial fixed point

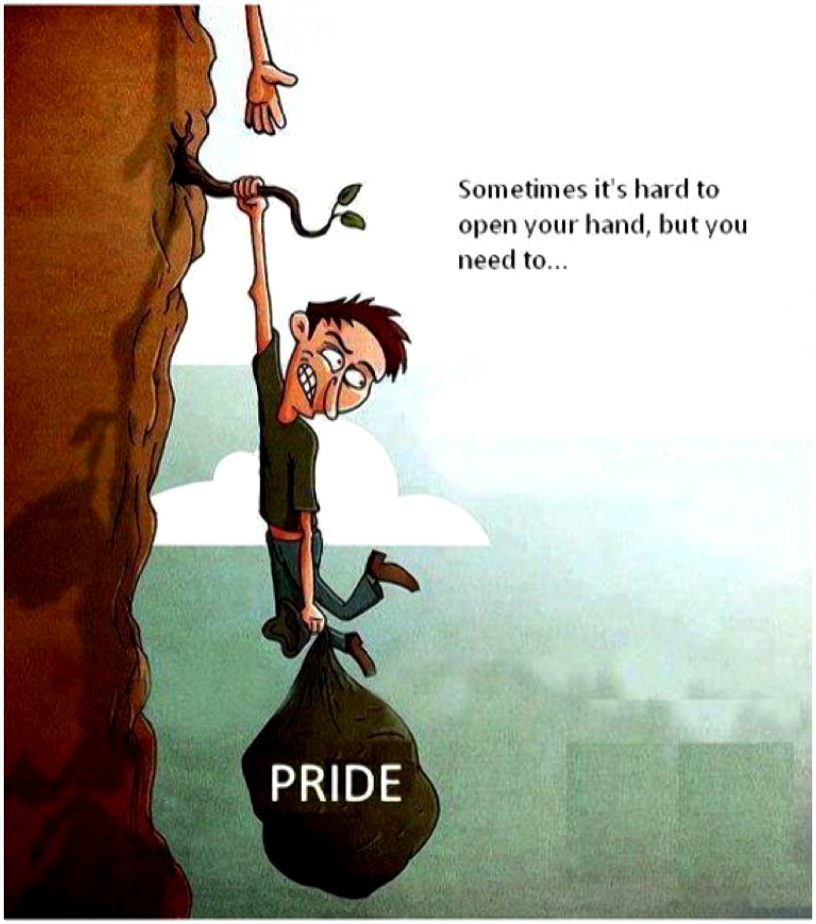
Interacting fixed point

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



Beyond standard model physics




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

The Standard Model ado

Fields:

Gauge fields + fermions + scalars

Interactions:

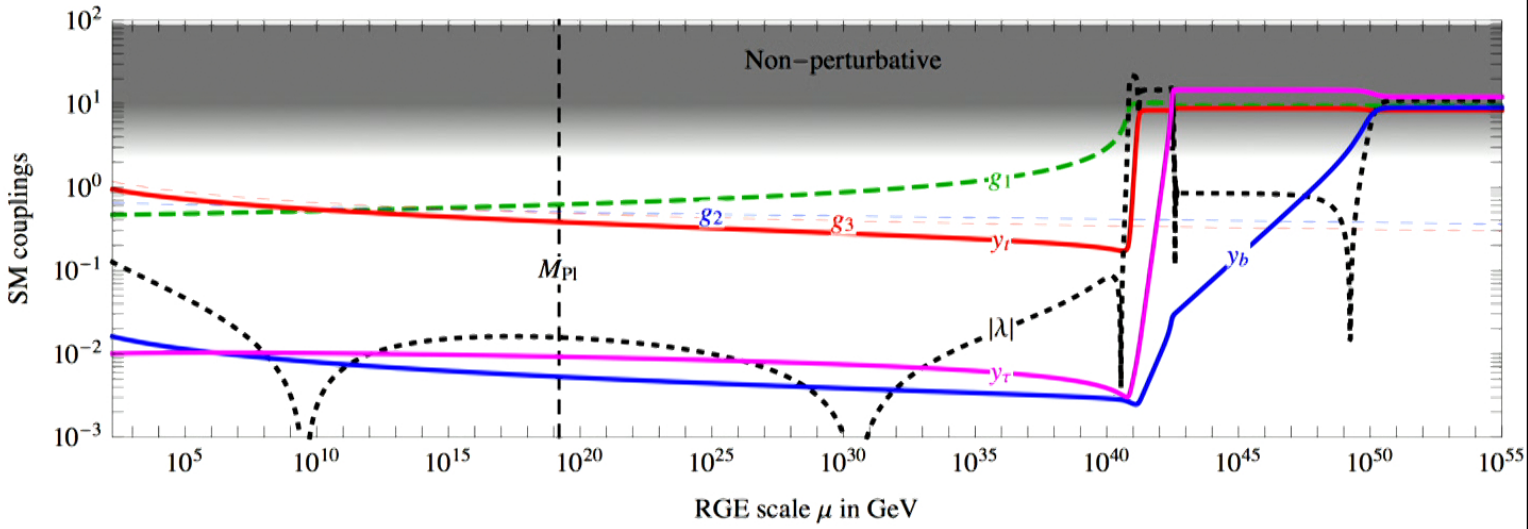
Gauge: SU(3) x SU(2) x U(1) at EW scale

Yukawa: Fermion masses/Flavour

Culprit: Higgs

Scalar self-interaction

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

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

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

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

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

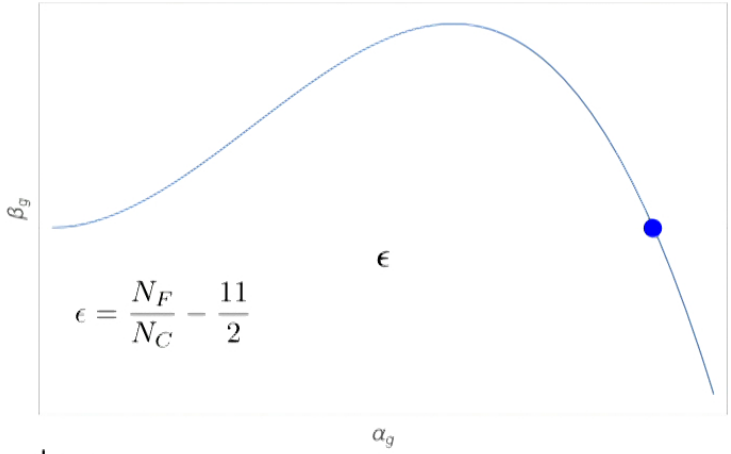
- Normalised couplings

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

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

At large N

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



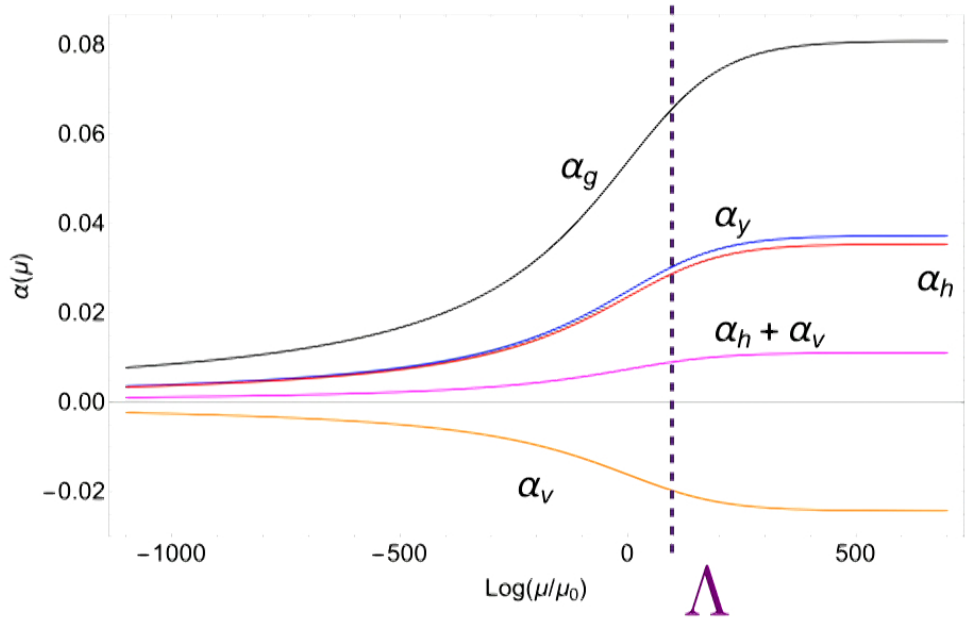
Impossible in Gauge Theories with Fermions alone

Caswell, PRL 1974

Complete asymptotic safety

Litim and Sannino, 1406.2337, JHEP

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



Scalars are needed perturbatively to make the theory fundamental

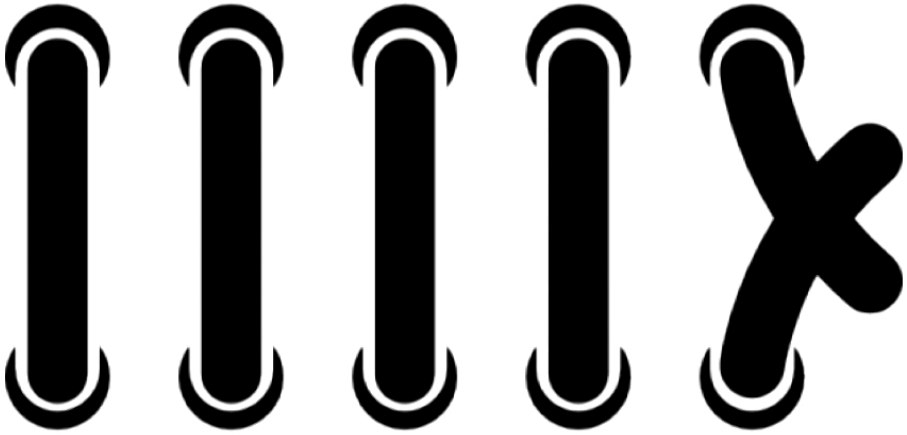
Gauged Higgs UV Fixed Point

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	$\square$
S	0	1	$\square$	$\overline{\square}$
H	0	$\square$	1	1
N	$1/2$	1	1	$\overline{\square}$
N'	$1/2$	1	$\square$	1

$$V = \lambda_{S1}(\mathrm{Tr}S^\dagger S)^2 + \lambda_{S2}\,\mathrm{Tr}(S^\dagger S S^\dagger S) + \lambda_H(H^\dagger H)^2 + \lambda_{HS}(H^\dagger H)\,\mathrm{Tr}(SS^\dagger)$$

$$\mathscr{L}_Y = y\,S_{ij}\psi_i\bar{\psi}_j + y'\,S^*_{ij}N_iN'_j + \tilde{y}\,H\bar{\psi}_iN_i + \tilde{y}'\,H^*\psi_iN'_i + \mathrm{h.c.}$$



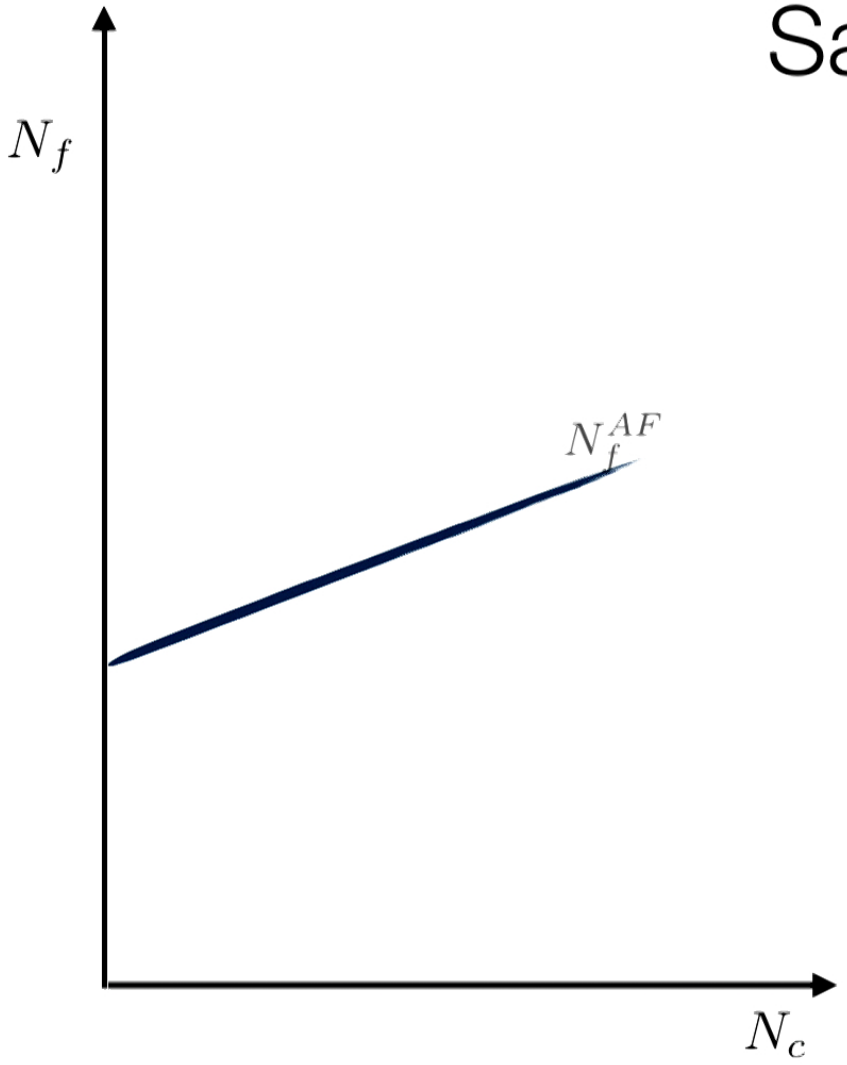
Higgs as shoelace

Safe, naturally

- A theory without a UV cutoff is technically natural with(out) scalars
- No quadratic divergences can emerge because of IR/UV conformality
- Higgs mass is independent on the intrinsic UV from IR
- All masses only sensitive to new physical thresholds
- IR Conformal symmetry works as chiral symmetry for fermion masses
- New states needed to make the SM safe must be around the TeV corner

Pelaggi, Sannino, Strumia, Vigiani, 1701.01453

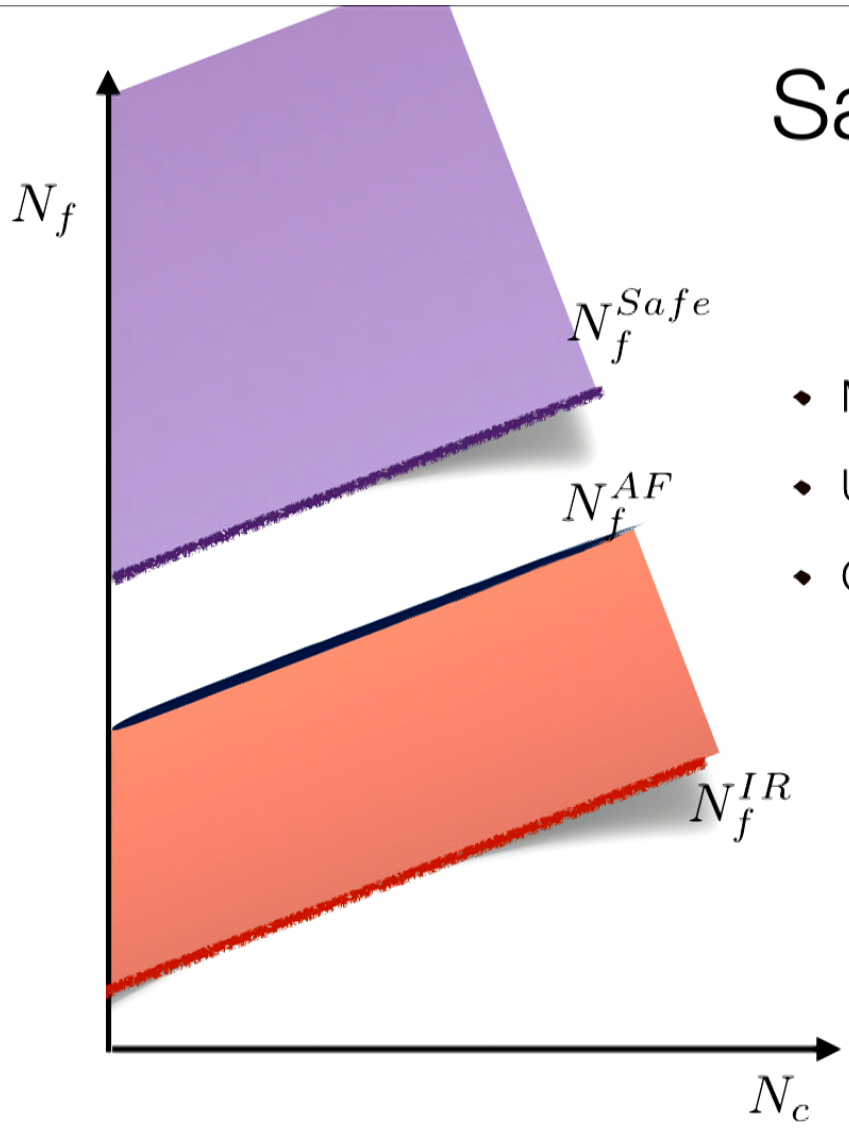
Safe QCD



Sannino, ERG 2016, Heidelberg

Antipin and Sannino, 1709.02354
Pica and Sannino 1011.5917, PRD

Safe QCD

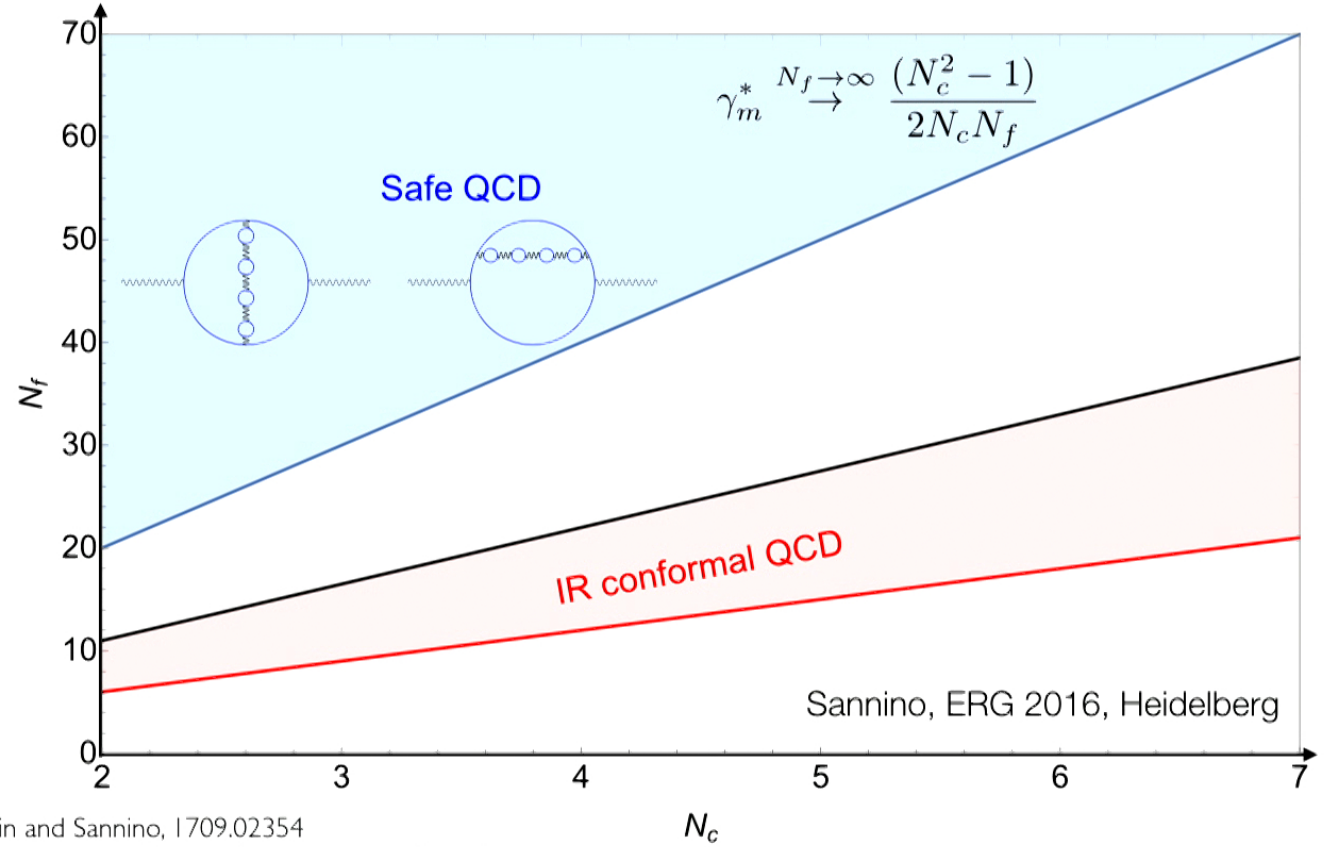


- Must exist a critical Safe Nf
- Unsafe region in Nf-Nc
- Continuous (Walking) transition?

Sannino, ERG 2016, Heidelberg

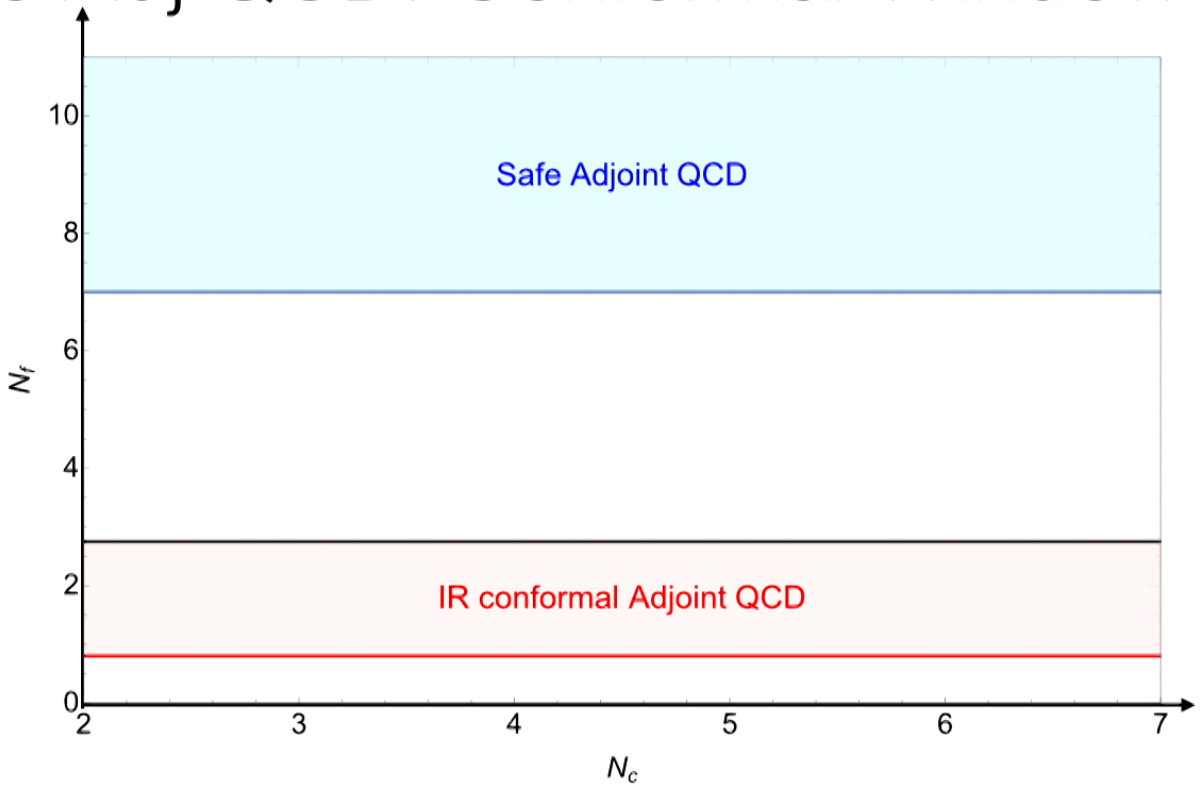
Antipin and Sannino, 1709.02354
Pica and Sannino 1011.5917, PRD

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

Safe Adj QCD: Conformal Window 2.0



Sannino, ERG 2016, Heidelberg
Antipin and Sannino, 1709.02354

Maps are great aren't they?

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.

Maps are great aren't they?

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.

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

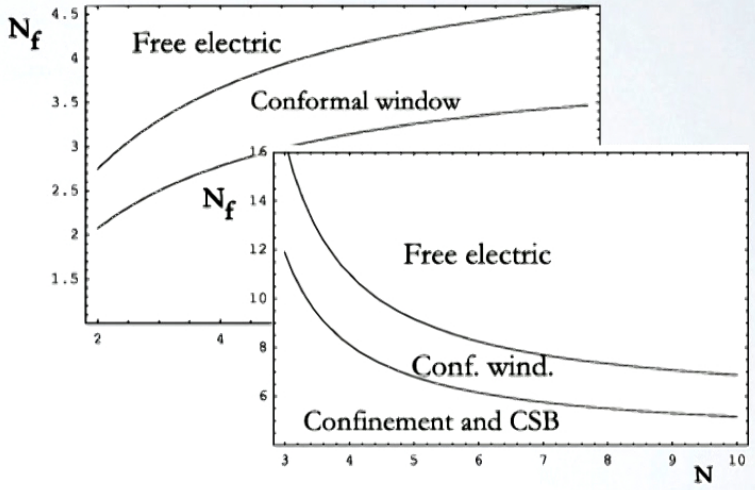
Freedom is lost
but no clue on what else

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

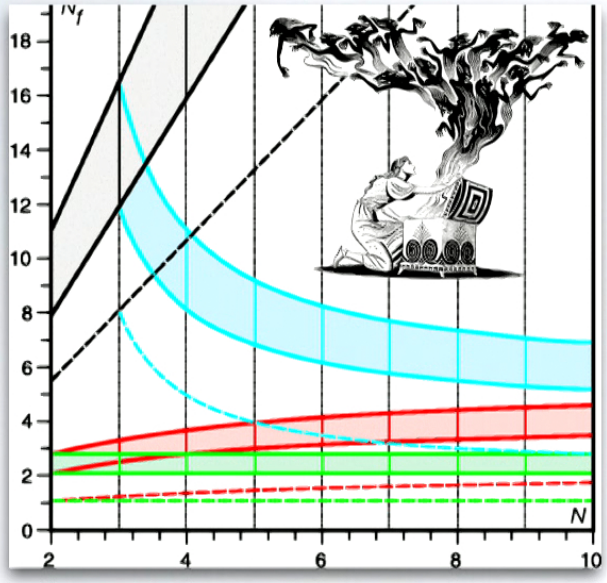
2006

Much known and used diagram for fundamental interactions

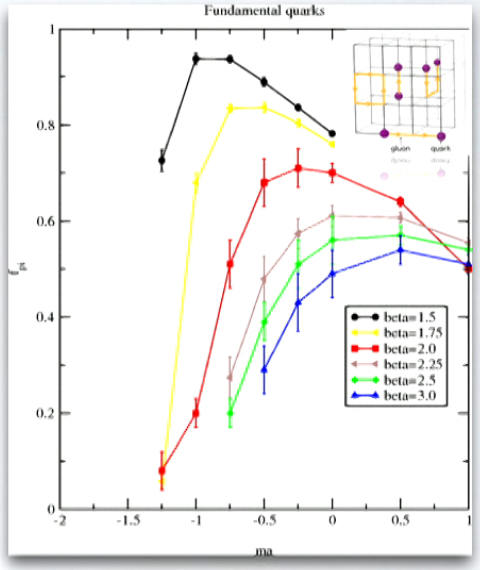
Julius Kuti. San Diego

2007

Pioneering BSM lattice studies



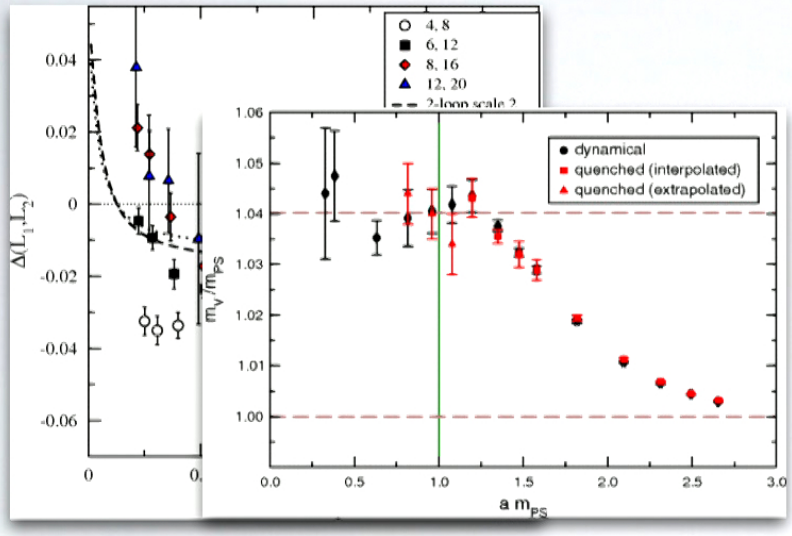
Conformal window of SU(N) gauge theories...
Dennis Dietrich, Francesco Sannino
Phys.Rev. D75 (2007) 085018



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

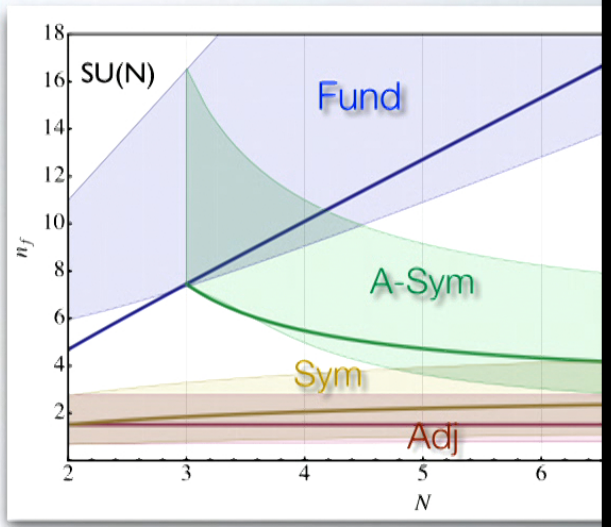
Mapping fundamental interactions

009 Lattice BSM golden era 2010 Higher loop computatio



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

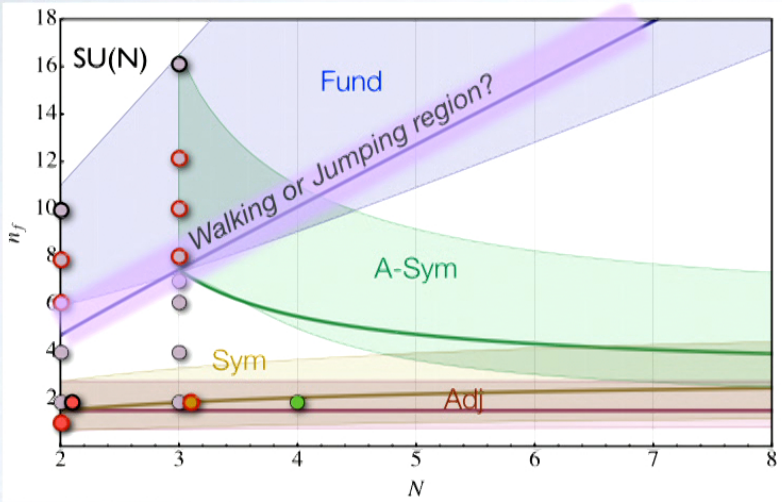


UV and IR Zeros of Gauge Theories at The Four L
Claudio Pica, Francesco Sannino
Phys.Rev. D83 (2011) 035013. First hints of Asymp

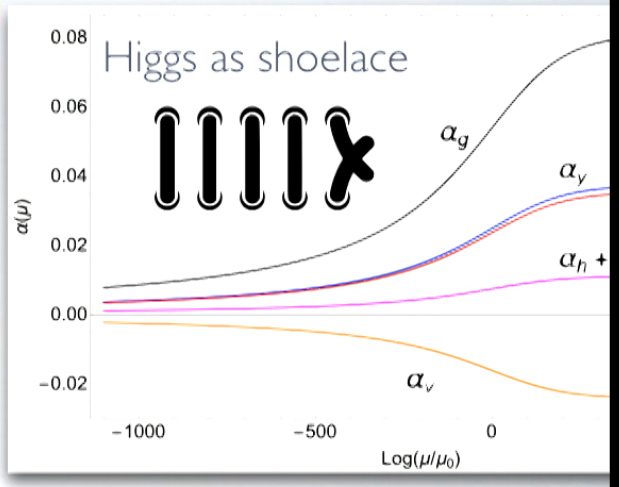
Higher-Loop Corrections to the Infrared Evolution
Thomas A. Ryttov, Robert Shrock
Phys.Rev. D83 (2011) 056011

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



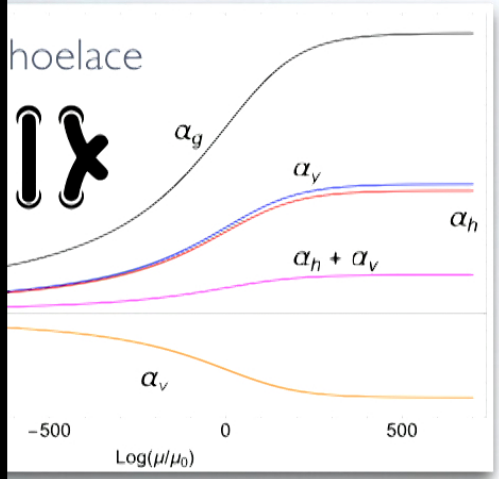
Asymptotic safety guaranteed
Daniel F. Litim, Francesco Sannino
JHEP 1412 (2014) 178

Mapping fundamental interactions

guaranteed

2018

Safe QCD: World of opportunities



ranteed
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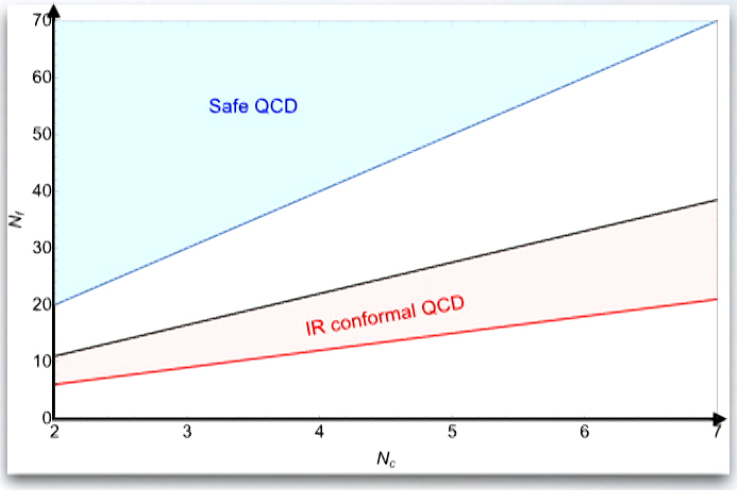


Conformal Window 2.0: The Large Nf story
Oleg Antipin, Francesco Sannino
arXiv:1709.02354. To appear in Physical Review D.

Paths to a Safe Standard Model

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

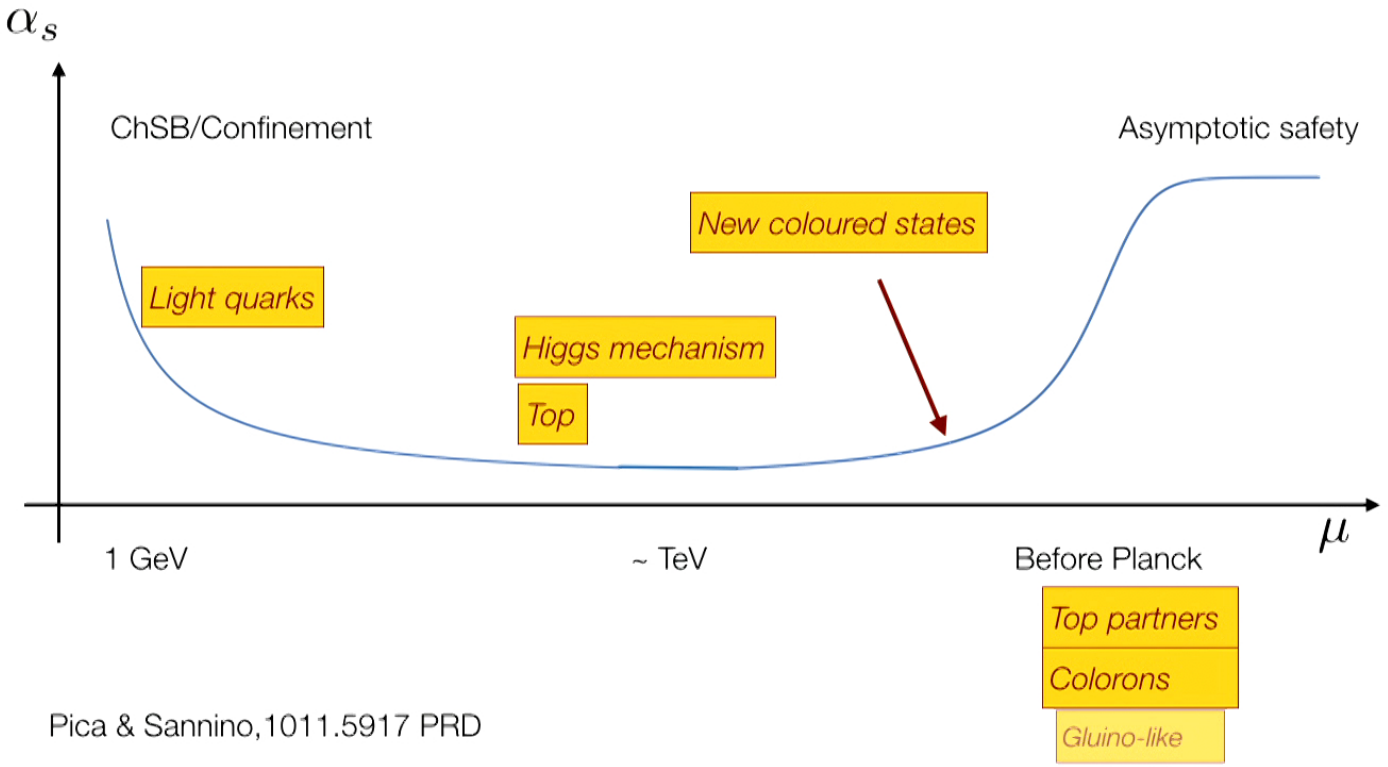
(Perturbative) safety via dynamical breaking,
[Abel, Sannino 1707.06638, Bond et al.1702.01727]

New paths not yet explored

See contributions from [Abel, Mann, Salvio, Wang]

Safe QCD

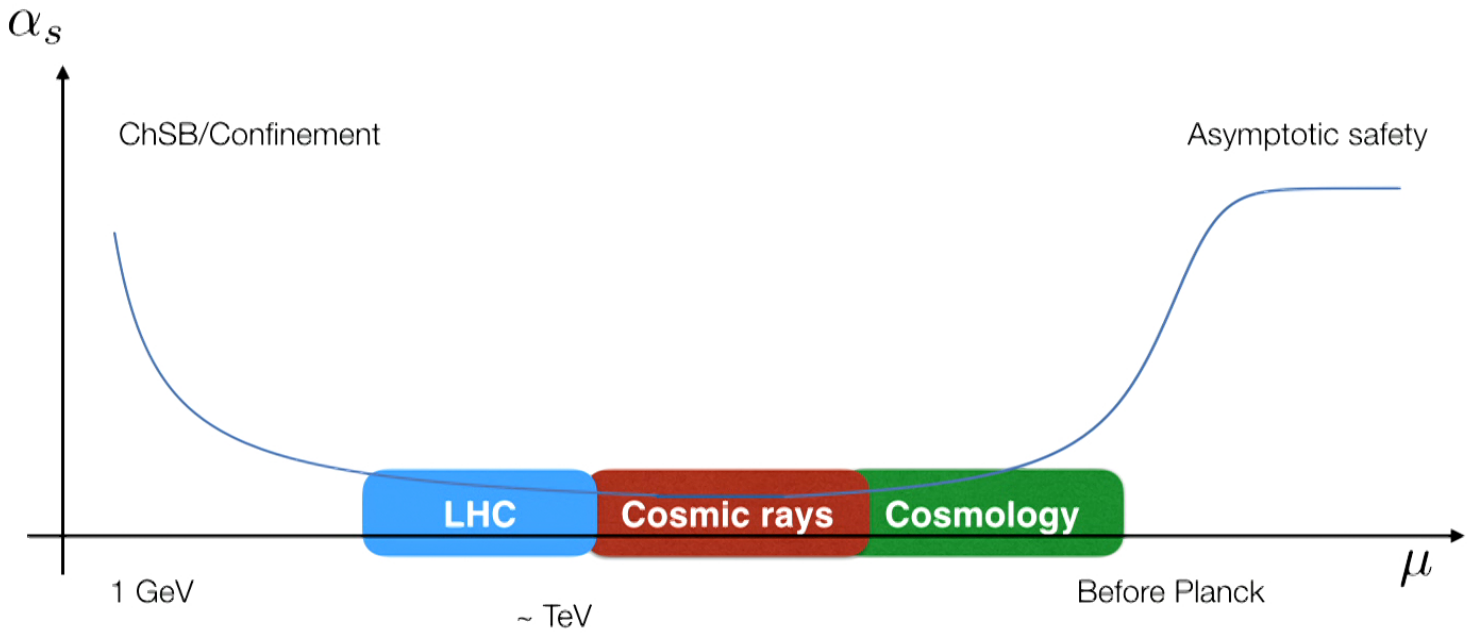
Sannino, 1511.09022



Pica & Sannino,1011.5917 PRD

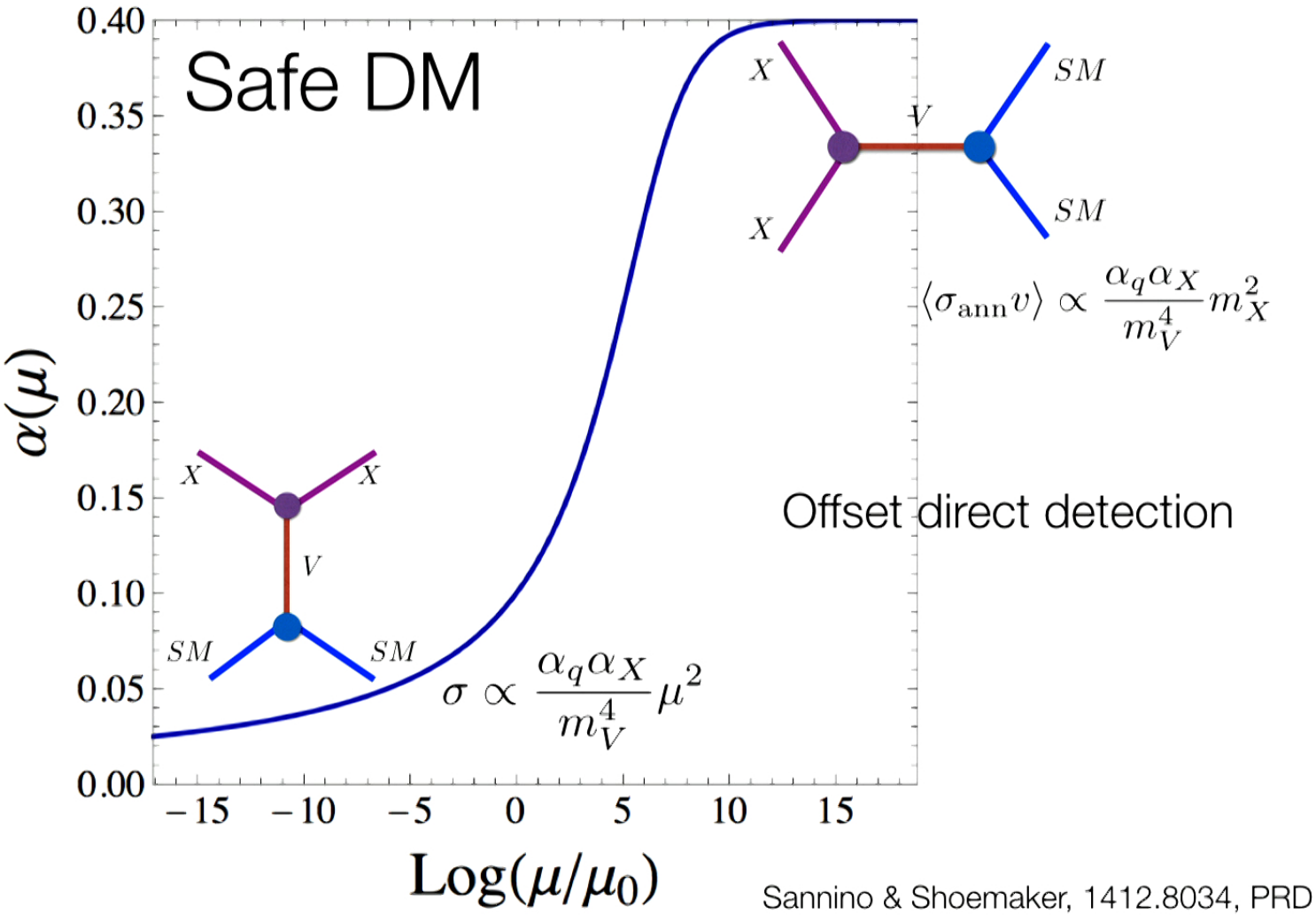
Testing safe QCD scenarios

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



Sannino & Shoemaker, 1412.8034, PRD

Worlds of possibilities

- Explore different paths for a safe extension of the SM
- Extend the number of (super) safe theories
- Cosmological and (astro) particle physics consequences
- Different implementations of radiative symmetry breaking
- Gravity gauge-gravity duality
- Gauge-gauge duality
- Safe QCD on the lattice
- Interplay with gravity

thank you

"The first principle is that you must not fool yourself - and you are the easiest person to fool"

Richard Feynman