FRANCESCO SANNINO

SOLVING (Q)FT:
FROM WEAK GRAVITY CONJECTURE TO PANDEMICS

SDU

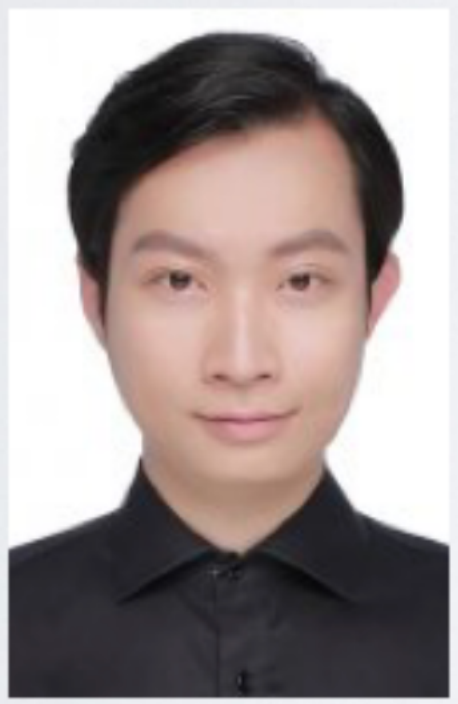
SSM
Scuola Superiore Meridionale

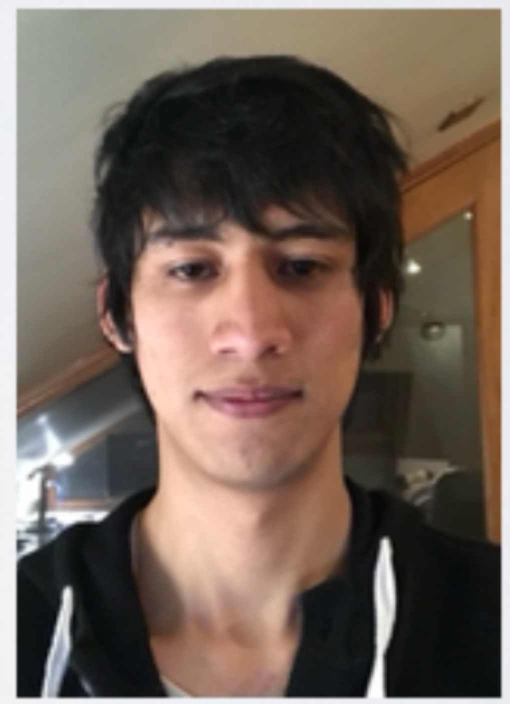
D-IAS

Solving QFT Collaborators





… the privilege to work with amazing people

Papers

Journal of High Energy Physics
A refereed journal, written, run and distributed by electronic means

Asymptotic safety guaranteed

D. Litim and F. Sannino, JHEP 12 (2014) 178

Journal of High Energy Physics
A refereed journal, written, run and distributed by electronic means

A safe CFT at large charge

D. Orlando, S. Reffert and F. Sannino, JHEP08 (2019)

PHYSICAL REVIEW D

Near-Conformal Dynamics at Large Charge

D. Orlando, S. Reffert and F. Sannino, *Phys.Rev.D* 101 (2020) 6, 065018

PHYSICAL REVIEW D

Charting the O(N) model

Antipin, Bersini, Sannino, Wang, Zhang Phys.Rev.D 102 (2020) 4, 045011

PHYSICAL REVIEW D

Charging the Conformal Window

D. Orlando, S. Reffert and F. Sannino, *Phys.Rev.D* 103 (2021) 10, 105026

Papers

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Charging the non-Abelian Higgs theories

Antipin, Bersini, Sannino, Wang, Zhang Phys.Rev.D 102 (2020) 12, 125033

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Charting the O(N) model

Antipin, Bersini, Sannino, Wang, Zhang Phys.Rev.D 102 (2020) 4, 045011

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Untangling scaling dimensions of fixed charge operators in Higgs theories

Antipin, Bersini, Sannino, Wang, Zhang Phys.Rev.D 103 (2021) 12, 125024

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

More on the cubic versus quartic interaction equivalence in the O(N) model

Antipin, Bersini, Sannino, Wang, Zhang submitted to Phys.Rev.D

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Asymptotically free and safe fate of symmetry nonrestoration

Bajc, Lugo, Sannino, Phys.Rev.D 103 (2021) 096014

Standard model

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + i\bar{\psi} \not{D} \psi + D_\mu H D^\mu H^* + y \bar{\psi} H \psi + \lambda (H^+ H)^2 + m_H^2 H^+ H + \Lambda^4$$

Standard model

Well tested

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + i\bar{\psi} \not{D} \psi + D_\mu H D^\mu H^* + i\theta G \wedge G$$

$$+ y \cdot \bar{\psi} H \psi + \lambda (H^+ H)^2 + m_H^2 H^+ H + \Lambda^4$$

y = flavor physics LHC(b), Bell, g-2, ...

λ = future colliders

Accidental Symmetries

Standard model

Well tested

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + i\bar{\psi} \not{D} \psi + D_\mu H D^\mu H^* + i\theta G \wedge G$$

$$+ y \bar{\psi} H \psi + \lambda (H^+ H)^2 + m_H^2 H^+ H + \Lambda^4$$

$m_H^2 H^+ H$

Λ^4

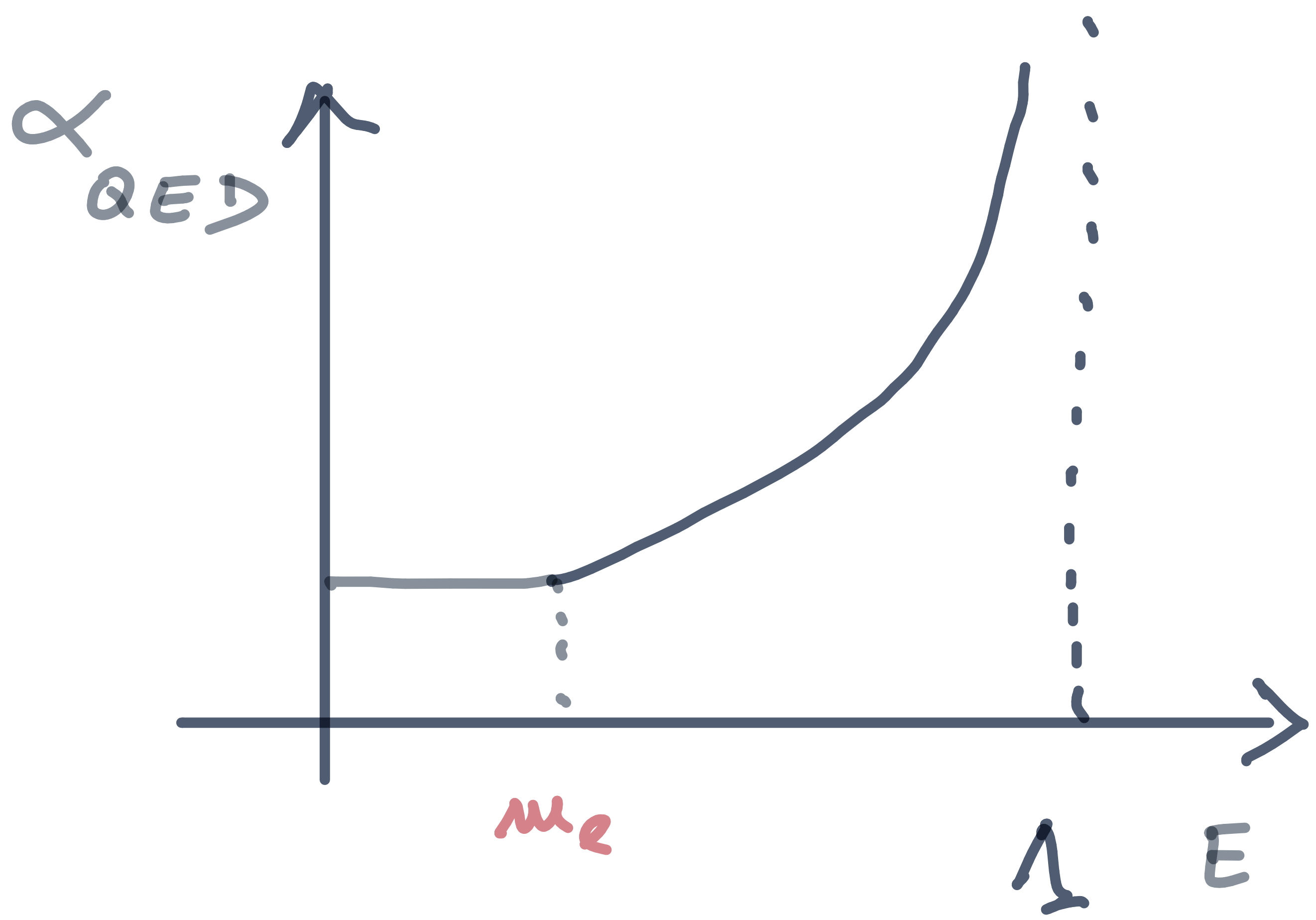
Super rinormalizable operators

Technical naturality problem

Cosmological constant

Example of Effective theory

* QED



$\Lambda \to \infty \Rightarrow \alpha_{QED} \Rightarrow 0$

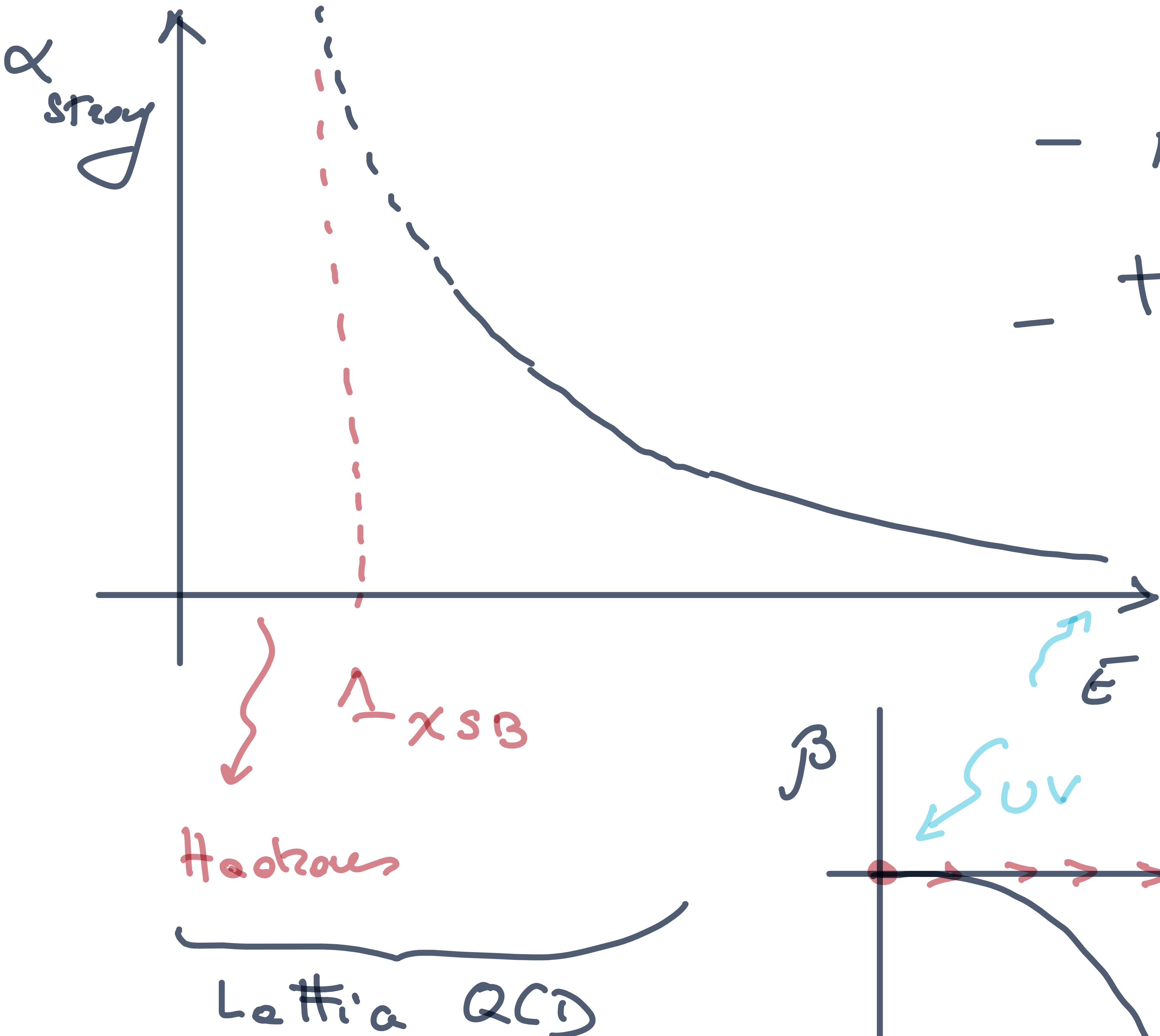
Proven at all orders in PT at leading order in $1/N_f$

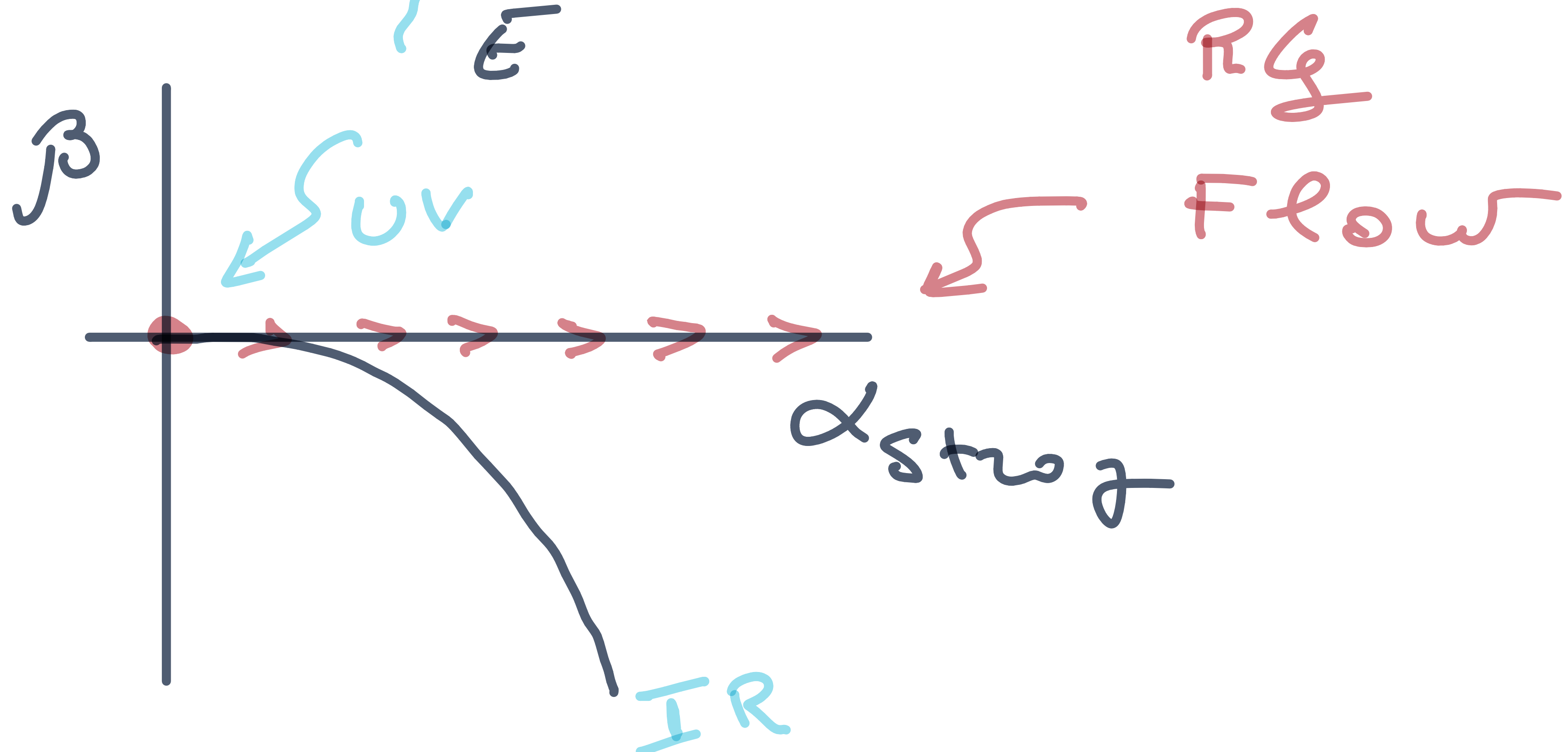
1709.02354

Example of fundamental theory

QCD

- No UV cutoff
- trivial UV conformality





Complete Asymptotic Freedom

All marginal couplings vanish in the UV

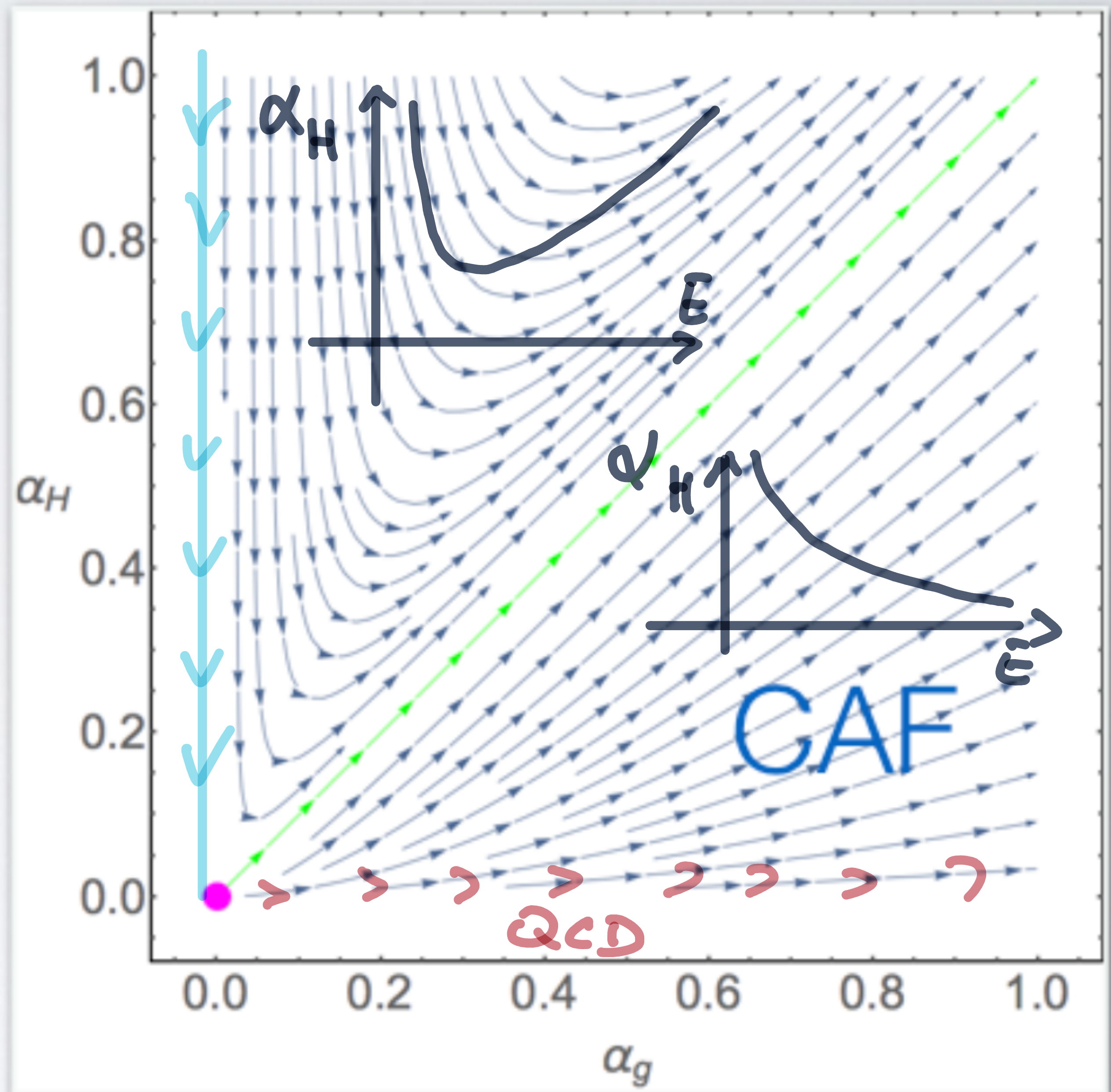
CAF conditions obtained at 1-loop

Gauge coupling drives CAF

IR conformal or dyn. scale generated

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

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



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

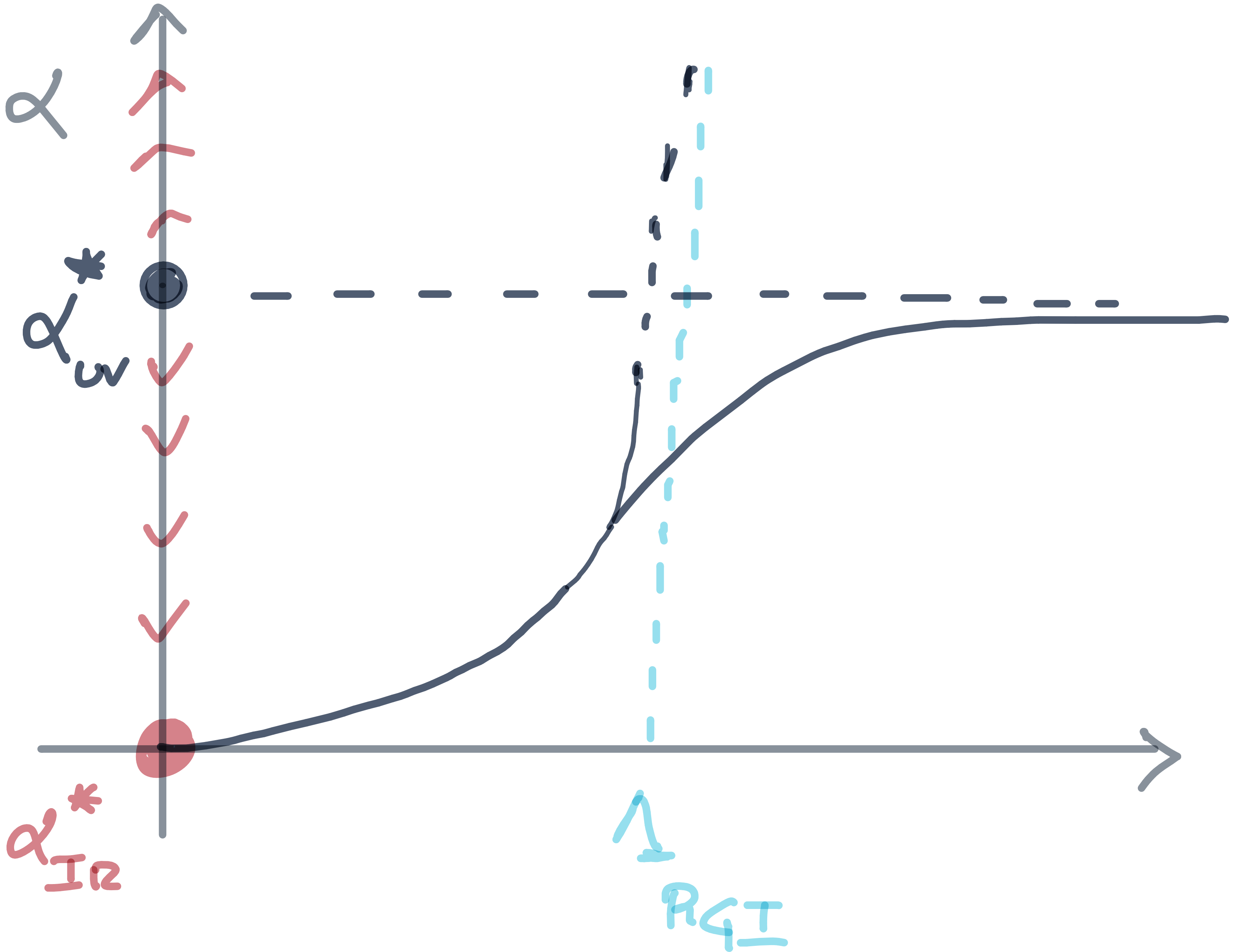
Cheng, Eichten, Li, PRD 9, 2259 (1974)

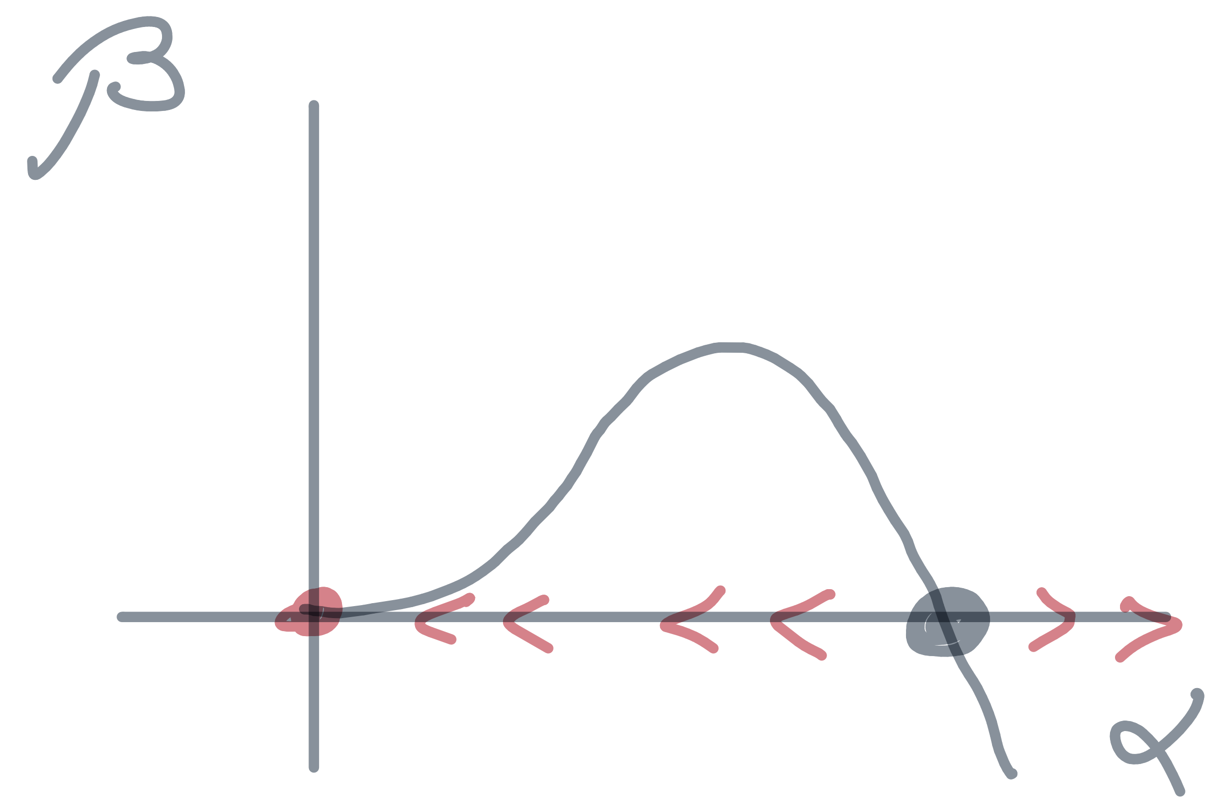
Callaway, Phys. Rept. 167, 241

Holdom, Ren, Zhang, 1412.5540

Giudice, Isidori, Salvio, Strumia, 1412.2769

Can we save a theory without freedom?





1st rigorous example
1406.2337

Asymptotic safety is the freedom alter ego.

Exact 4D Interacting UV Fixed Point

Litim and Sannino, 1406.2337, JHEP

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

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

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

Veneziano Limit

Litim and Sannino, 1406.2337, JHEP

Litim, Mojaza, Sannino, 1501.03061, JHEP

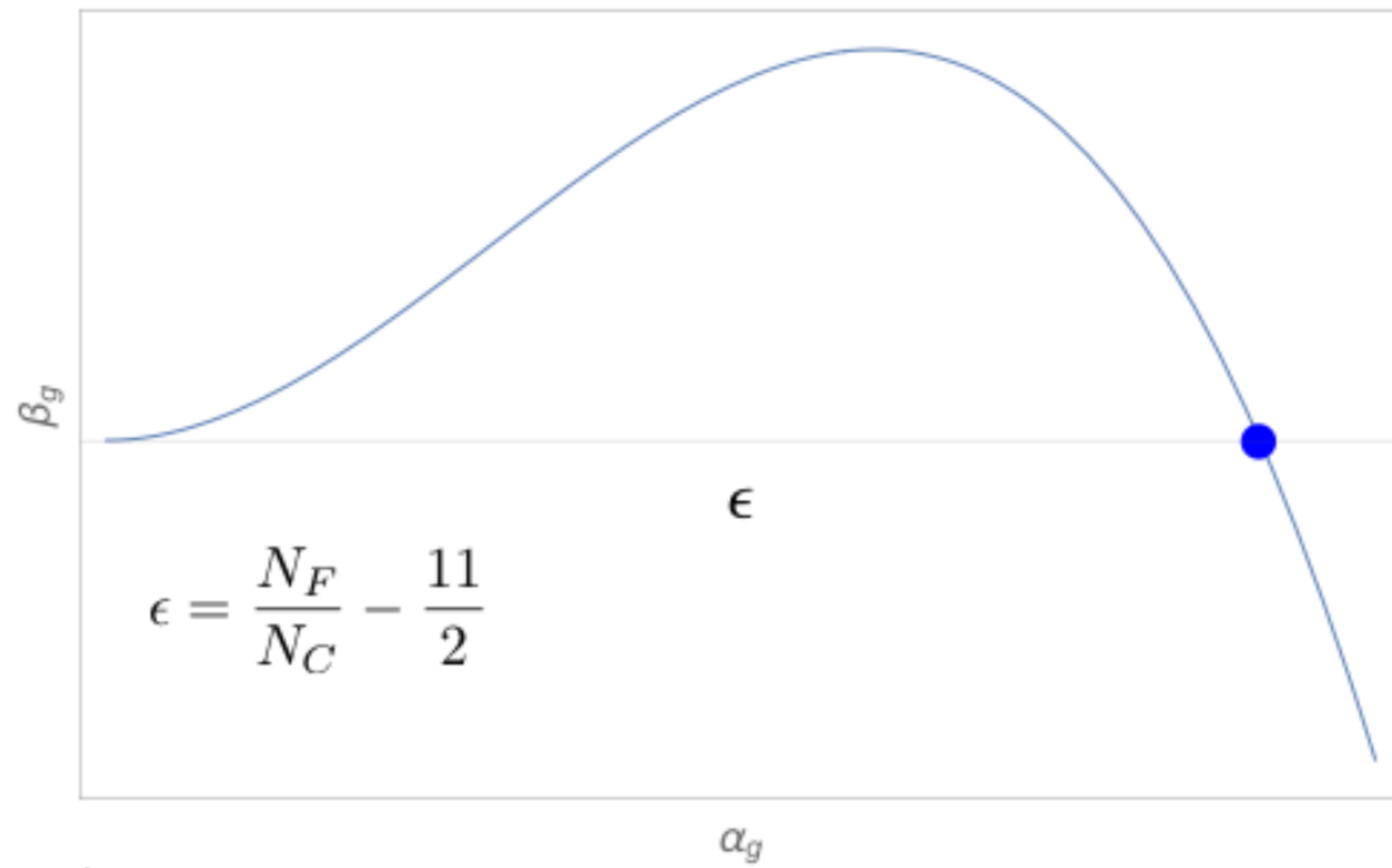
- Normalised couplings

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

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

At large N

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

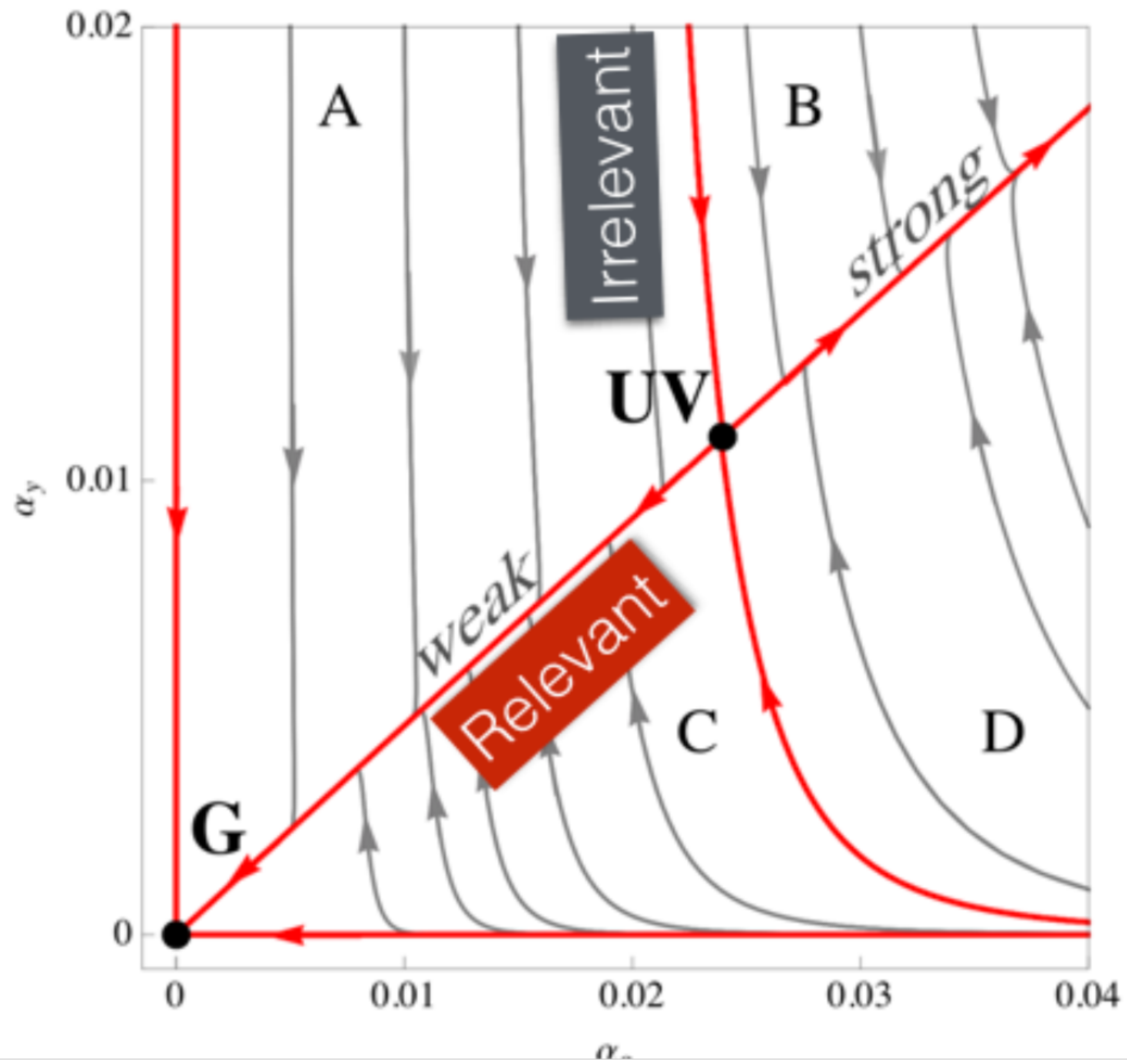


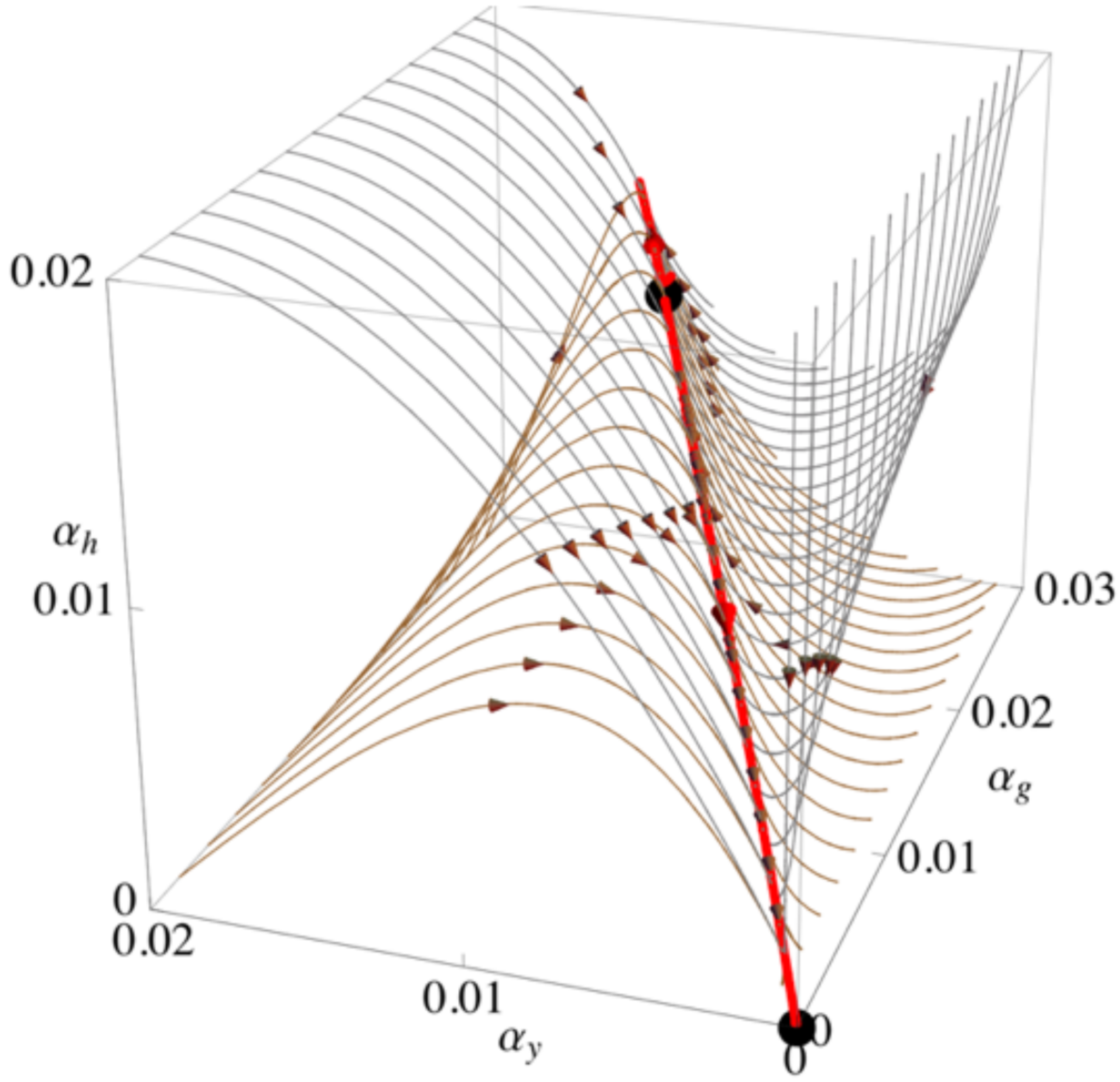
Impossible in Gauge Theories with Fermions alone

Caswell, PRL 1974

Phase Diagram

$$\vartheta_1 = -0.608\,\epsilon^2 + \mathcal{O}(\epsilon^3)$$
$$\vartheta_2 = \quad 2.737\,\epsilon + \mathcal{O}(\epsilon^2)$$
$$\vartheta_3 = \quad 4.039\,\epsilon + \mathcal{O}(\epsilon^2)$$
$$\vartheta_4 = \quad 2.941\,\epsilon + \mathcal{O}(\epsilon^2)\,.$$



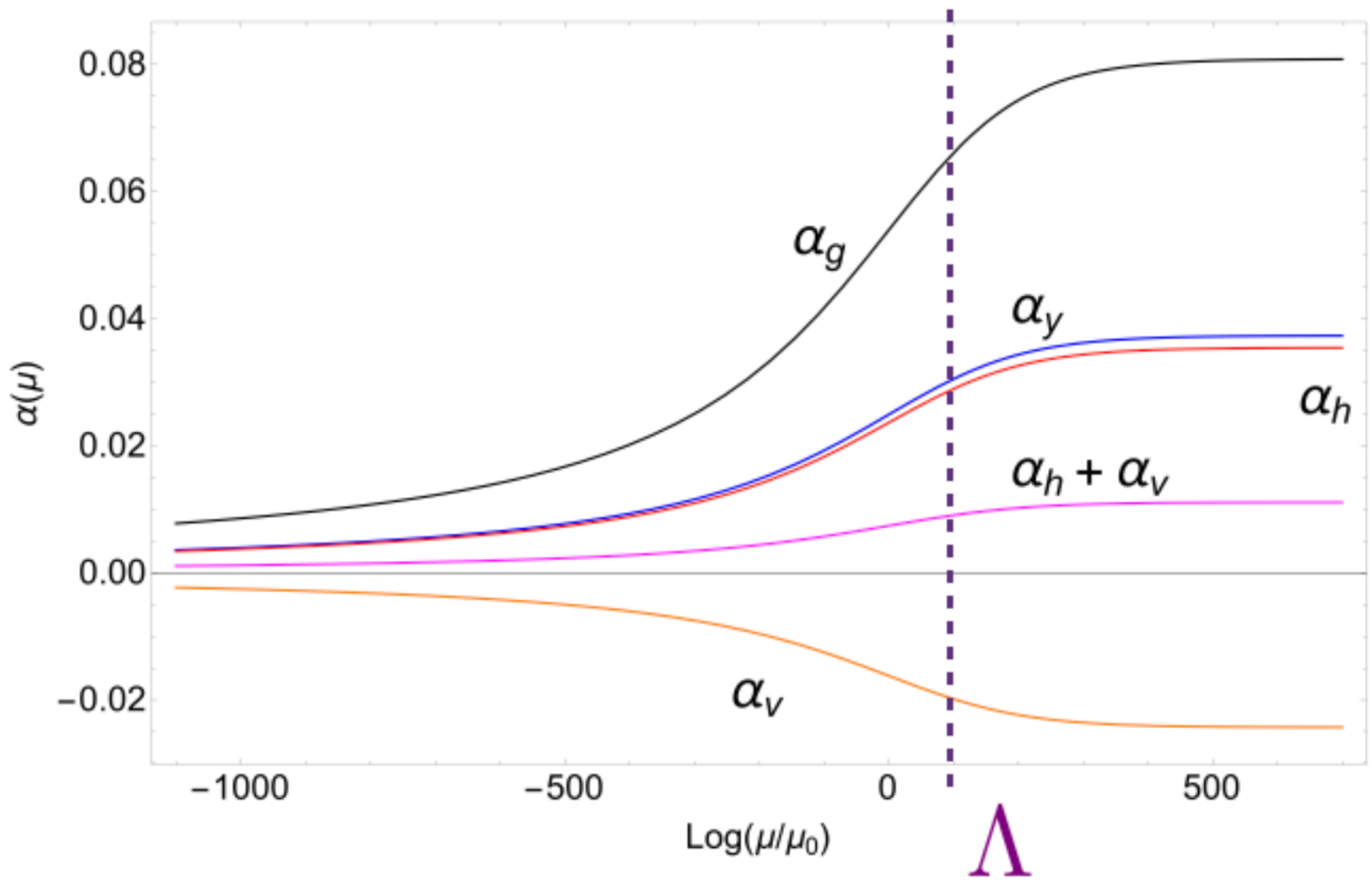


$$\vartheta_1 < 0 < \vartheta_2 < \vartheta_4 < \vartheta_3$$

Complete asymptotic safety

Litim and Sannino, 1406.2337, JHEP

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



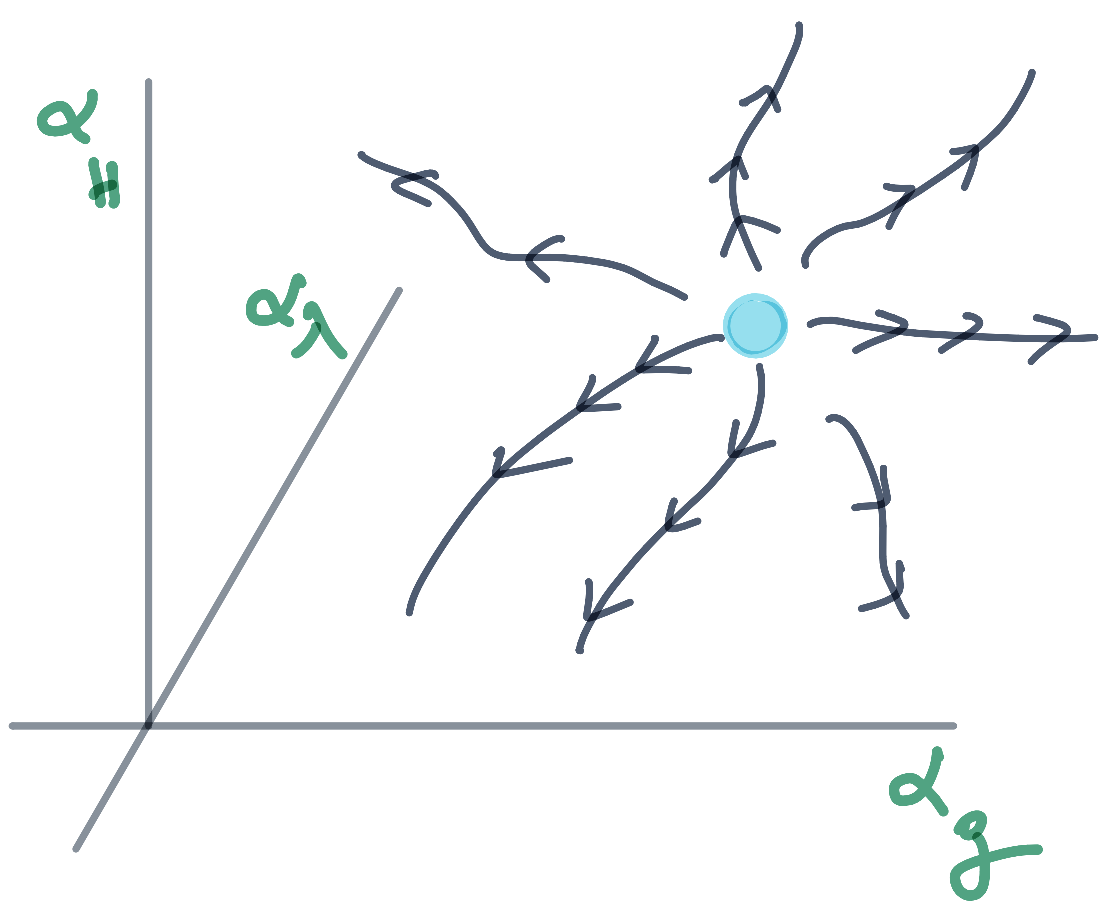
Scalars are needed perturbatively to make the theory fundamental

Fundamental theories as CFT$_s$

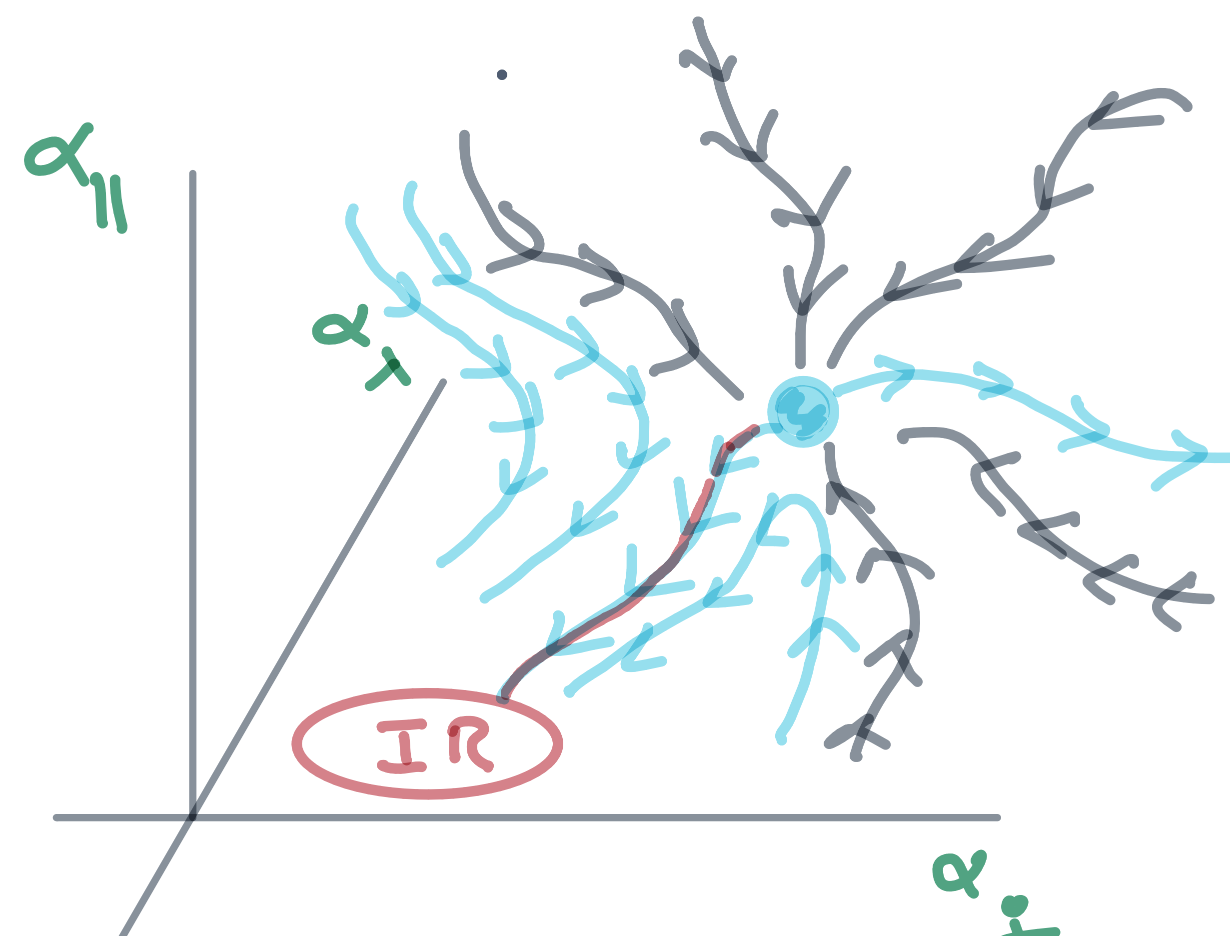
or

CFT$_s$ as lamppost

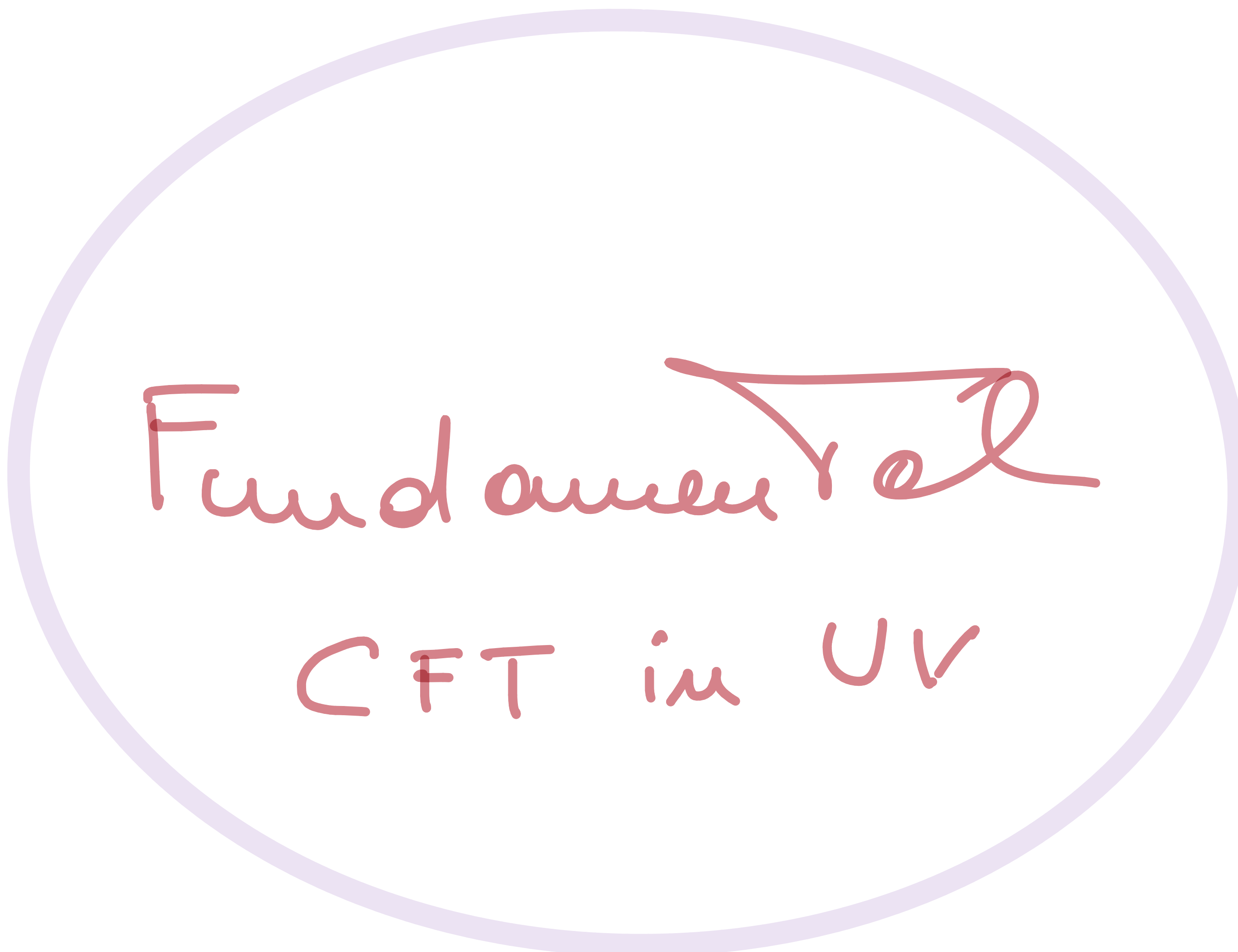
IR unpredictive



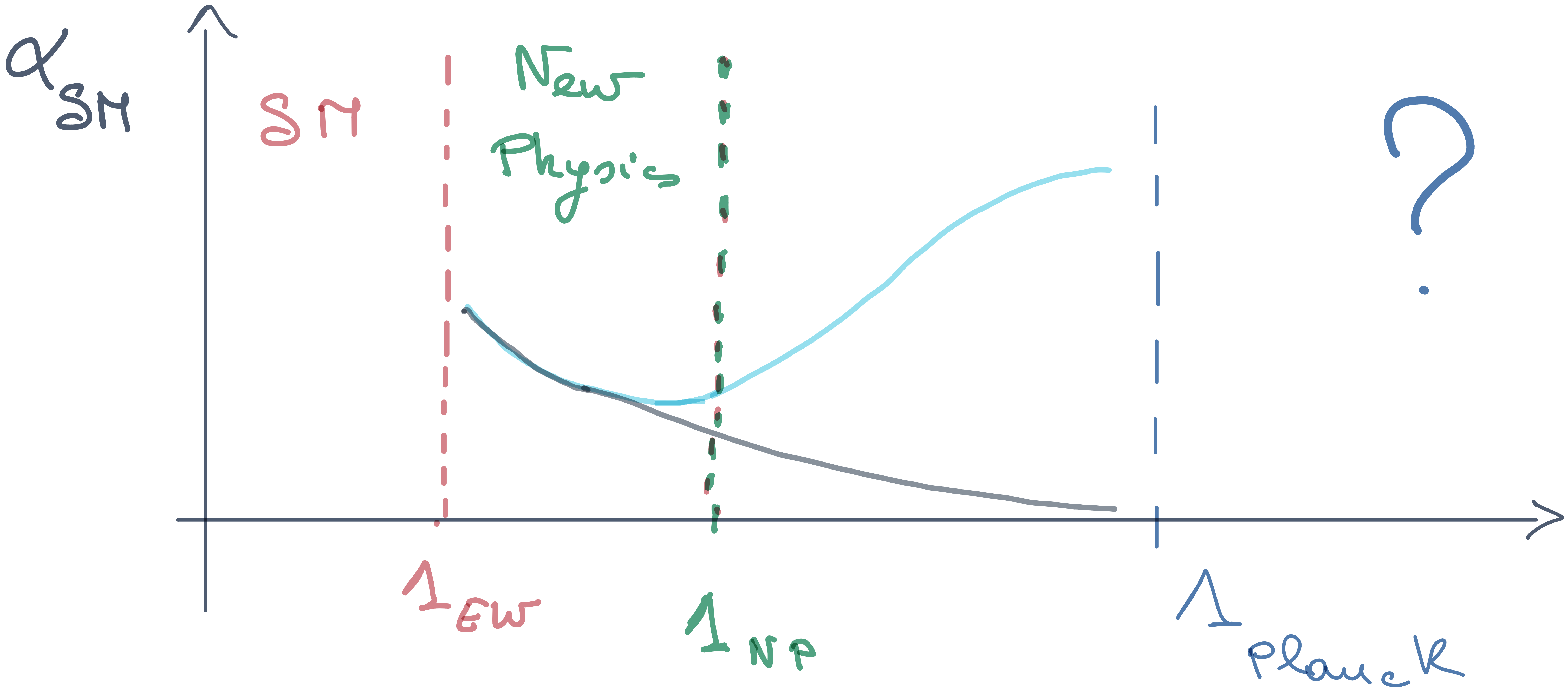
IR predictive



QFTs

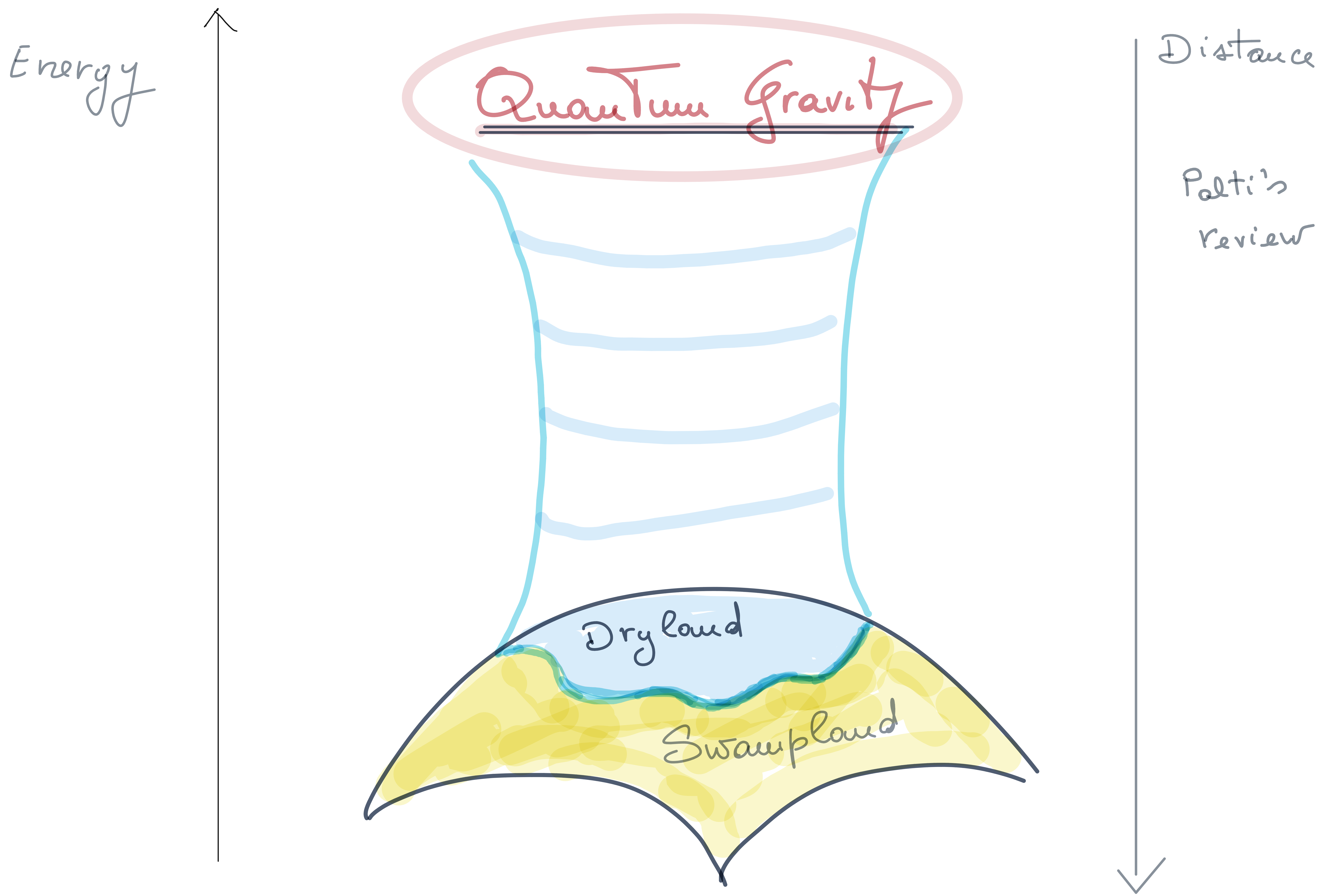


Quantum Gravity ?



- If R^2 gravity no effect on QFT
- Follow Swampland program [Palti's review]


Swampland
Claudia Prommegger


Energy
Quantum Gravity
Distance
Palti's review
Dry land
Swampland

Conjectures

- **No global symmetries**

- **Completeness conjecture**

  [Theories featuring a gauge symmetry coupled to quantum gravity must exhibit states of all charges]

- **Distance conjecture**

$$m(B) \sim m(A)\, e^{-\alpha\, \delta(A,B)}$$

- **Species scale conjecture**

$$\Lambda < \Lambda_s = \frac{M_p}{N^{1/d-2}}$$

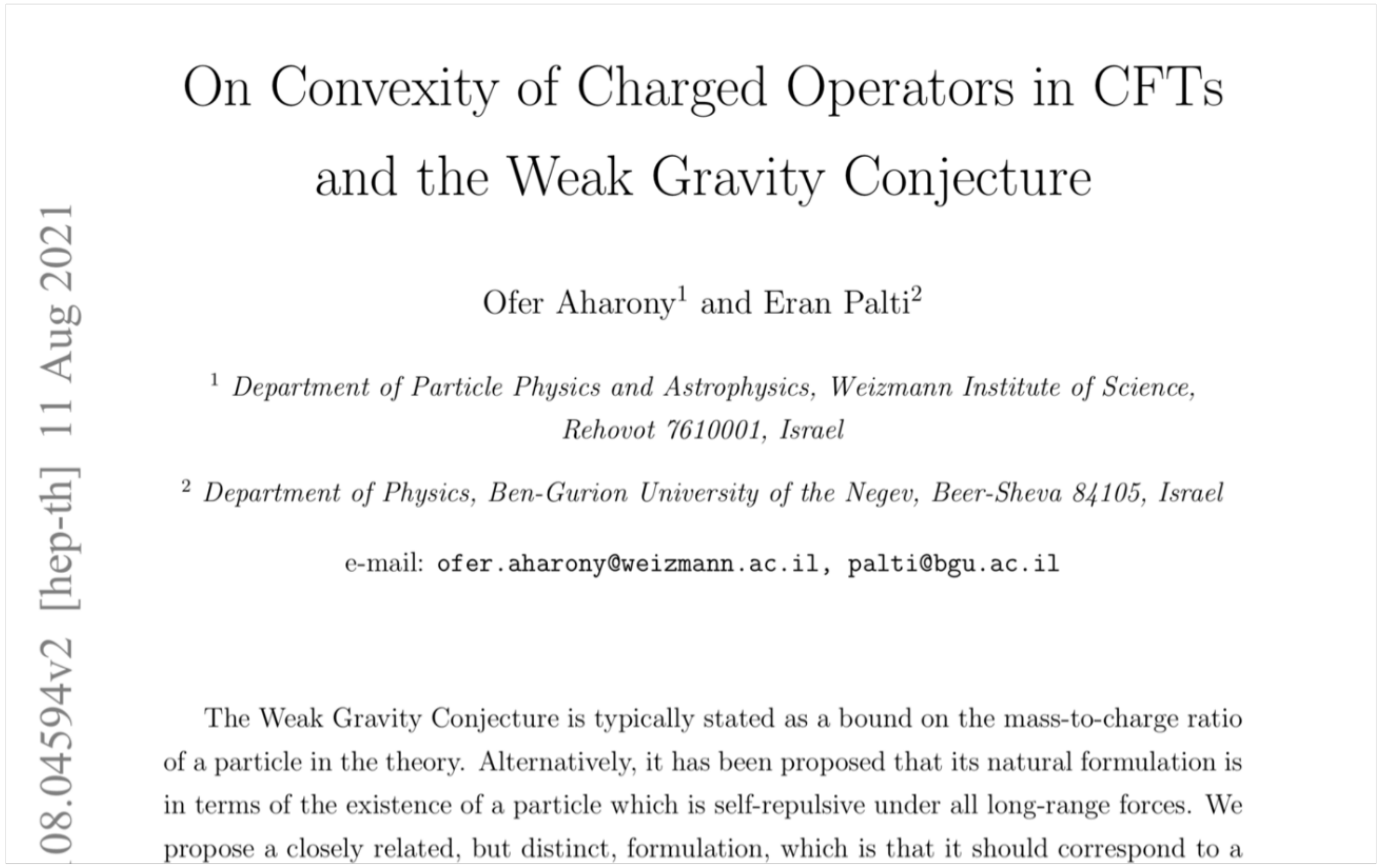
M_p = d-dim Planck scale

N particle states below a given cutoff Λ_s

- **Weak gravity conjecture**

Gravity is the weakest force

$$g^2 q^2 \geq \frac{m^2}{M_p^2} \quad \Longrightarrow \quad m \leq \# g\, q\, M_p$$



08.04594v2 [hep-th] 11 Aug 2021

On Convexity of Charged Operators in CFTs and the Weak Gravity Conjecture

Ofer Aharony[1] and Eran Palti[2]

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[2] Department of Physics, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel

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The Weak Gravity Conjecture is typically stated as a bound on the mass-to-charge ratio of a particle in the theory. Alternatively, it has been proposed that its natural formulation is in terms of the existence of a particle which is self-repulsive under all long-range forces. We propose a closely related, but distinct, formulation, which is that it should correspond to a

Sharp version of the WGC

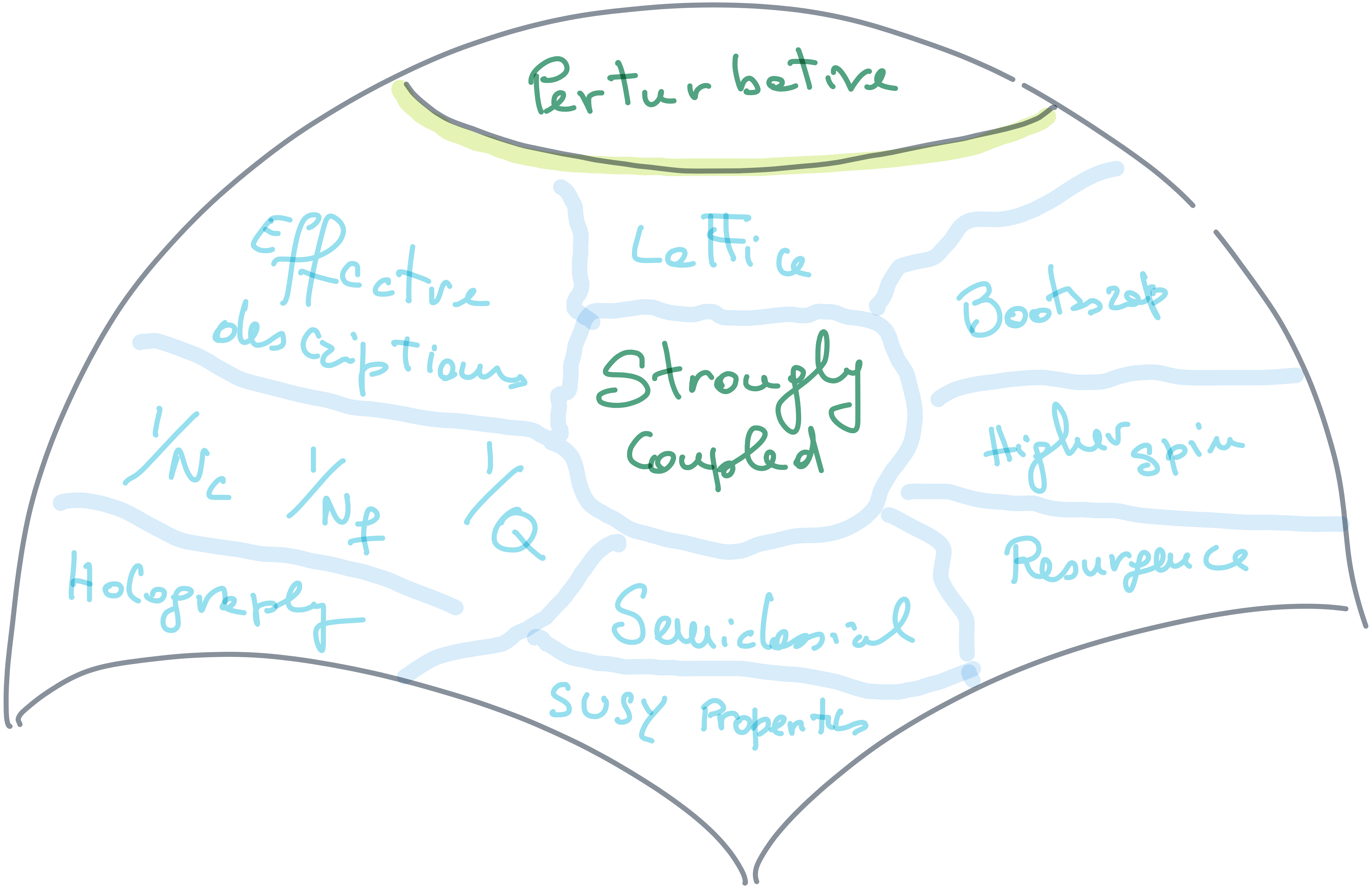
$$\Delta(q_1+q_2) \geq \Delta(q_1) + \Delta(q_2)$$

$\Delta(q)$:= Conformal dim of operators of charge q

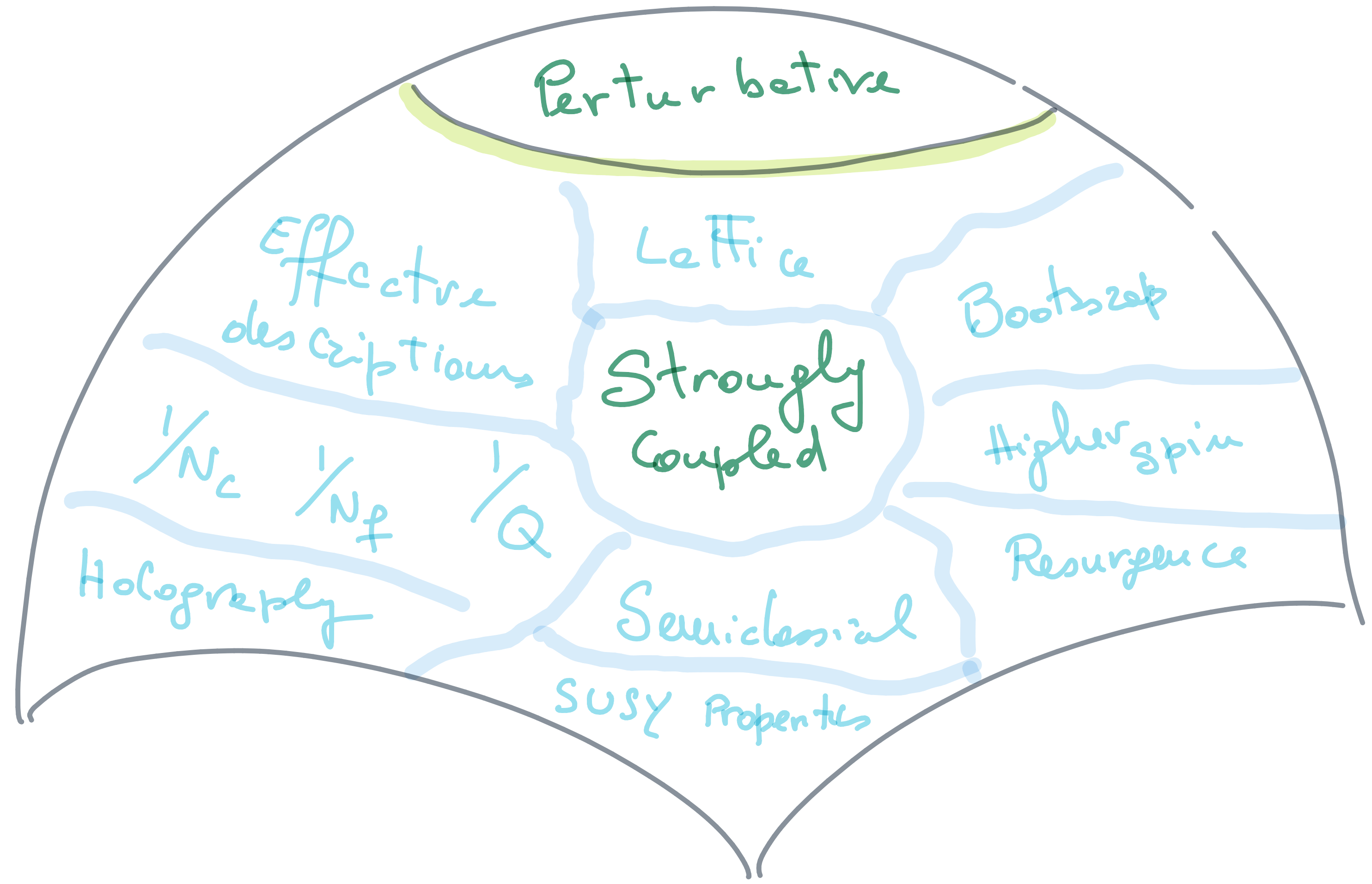
* Physical interpretation
  Positive binding energy

* Non-abelian case ≈ Most Attractive Channel (MAC) of the 80'?

Methodologies



Methodologies



Perturbation theory

* Valid up to order

$$\alpha^{1/\alpha}$$

* With multiple couplings must respect Weyl Consistency Conditions (WCC)

* Feynman Diagrammatic is cumbersome

$O(N)$ model, charged

$O(N)$ scalar theory in $d = 4 - \epsilon$

WF fixed point

$$S = \int d^d x \left[\frac{(\partial\phi_i)^2}{2} + \frac{(4\pi)^2 g_0}{4!} (\phi_i\phi_i)^2 \right] \qquad g^*(\epsilon) = \frac{3\epsilon}{8+N} + O(\epsilon^2)$$

Fix $N/2$ charges (rank of $O(N)$) with N even

$\epsilon \to 1$

Magnets, Superfluid He^4, ...

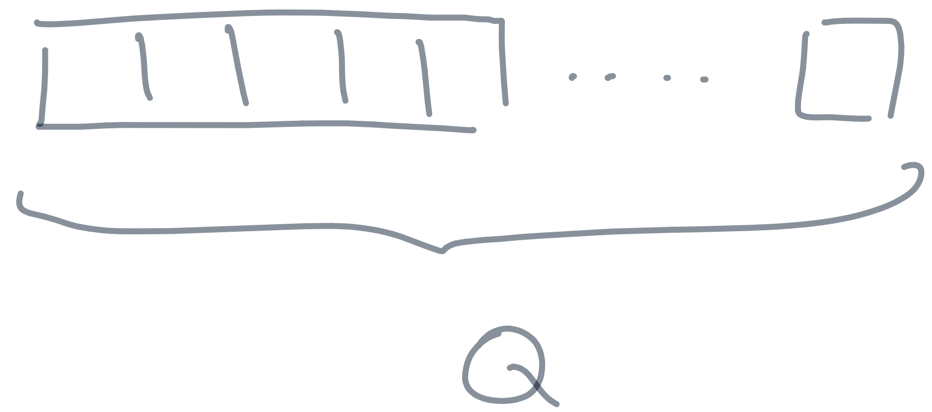
$\epsilon = 0 \quad N = 4$

SM Higgs

Antipin, Bersini, Sannino, Wang, Zhang, PRD 102 (2020) 4, 045011

Minimal scaling dimensions

$$Q = \sum_{i=1}^{N/2} Q_i$$



$$Q(\phi_i) = 1$$

$$Q\left(\phi_i \phi_j - \frac{\delta_{ij}}{N}\phi^2\right) = 2$$

Anisotropic perturbations

$\Delta_{\vec{q}}$ ⇝ stability of the system vs anisotropic perturbations

Ground state

homogeneous classical solution

$$\varphi_i = \frac{1}{\sqrt{2}}\left(\phi_{2i-1} + i\,\phi_{2i}\right) = \frac{1}{\sqrt{2}}\,v_i\,e^{i\chi_i}$$

$v_i = A_i$ → VEV

$\chi_i = -i\mu\tau$ → chemical potential

$$\vec{Q} = (Q_1, \dots, Q_{N/2}) \to (Q, 0 \dots, 0)$$

$$\langle Q|\, e^{-HT}\, |Q\rangle = \frac{1}{Z}\int D^{N/2}v\; D^{N/2}\chi\; e^{-S_{eff}}$$

$$S_{eff} = S + \mu Q + \frac{1}{2}\left(\frac{d-2}{2R}\right)^2 v_i v_i$$

conformal coupling

$$\Delta_Q = \sum_{k=-1}^{\infty} \frac{1}{Q^k} \Delta_k(A) \qquad A = gQ$$

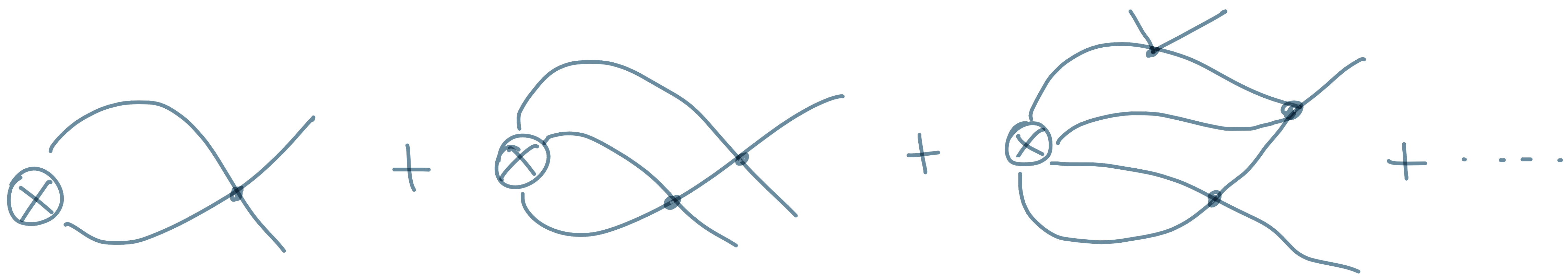
Δ_{-1}

$$S = S(\phi_0) + \frac{1}{2}(\phi - \phi_0)^2 S''(\phi_0) + \dots$$

EOM

$$\frac{4\,\Delta_{-1}(A)}{A} = \frac{3^{2/3}\,x^{1/3}}{3^{1/3} + x^{2/3}} + \frac{3^{1/3}\left(3^{1/3} + x^{2/3}\right)}{x^{1/3}} \,, \qquad x = 6A + \sqrt{-3+36A^2}$$

Resum an infinite class of diagrams



Δ_0 is trikier

$$S = S(\phi_0) + \frac{1}{2}(\phi-\phi_0)^2 S''(\phi_0) + \cdots$$

Determinant fluctuation

$$\Delta_0 = \frac{R}{2} \sum_{\ell=0}^{\infty} n_\ell \left[\omega_+(\ell) + \omega_-(\ell) + \left(\frac{N}{2}-1\right)\left(\omega_{++}(\ell) + \omega_{--}(\ell)\right) \right]$$

ℓ labels momentum eigenvalues with degeneracy n_ℓ

Dispersion Relations

	Mass
ω_+	6μ
ω_-	0
ω_{++}	2μ
ω_{--}	2μ

$c_s = \frac{1}{\sqrt{d-1}}$ (phonon)

non relativistic (magnon)

Perturbation theory

$\mathcal{A} = g Q$

Expand Δ_k for $\mathcal{A} \to 0$

Δ_{-1} Δ_0

$$
\begin{aligned}
\Delta_Q = {} & Q + \left(\frac{Q^2}{8+N} - \frac{(N+10)}{2(8+N)}Q\right)\epsilon \\
& - \left[\frac{2}{(8+N)^2}Q^3 + \frac{(N-22)(N+6)}{2(8+N)^3}Q^2 + \frac{184+N(14-3N)}{4(8+N)^3}Q\right]\epsilon^2 \\
& + \left[\frac{8}{(8+N)^3}Q^4 + \frac{-456-64N+N^2+2(8+N)(14+N)\zeta(3)}{(8+N)^4}Q^3\right. \\
& - \frac{-31136-8272N-276N^2+56N^3+N^4+24(N+6)(N+8)(N+26)\zeta(3)}{4(N+8)^5}Q^2 \\
& \left. + \frac{-65664-8064N+4912N^2+1116N^3+48N^4-N^5+64(N+8)(178+N(37+N))\zeta(3)}{16(N+8)^5}Q\right]\epsilon^3 \\
& + \left[c_5 Q^5 + c_4 Q^4 + c_3 Q^3 + c_2 Q^2 + c_1 Q\right]\epsilon^4 + \left[e_6 Q^6 + e_5 Q^5 + e_4 Q^4 + e_3 Q^3 + e_2 Q^2 + e_1 Q\right]\epsilon^5 +
\end{aligned}
$$

Full 4-loop $O(\epsilon^4)$ combining with p.r. for $Q = 1, 2, 4$

Infinite # of checks for diagrammatic computations

$d = 4 \qquad \epsilon = 0$

$$\Delta_Q = Q + \frac{1}{3} g Q(Q-1) - \frac{g^2}{18}\left(4Q^3 + (N-6)Q^2 + \frac{1}{2}(2-3N)Q\right) + \mathcal{O}(g^3)$$

CFT $\Longrightarrow$ QFT

Anomalous dimensions of Higgs operators

SM Higgs for $N=4$

Work in progress...

$Q = n$ Aharony and Palti $O(N)$ $4-\epsilon$ test

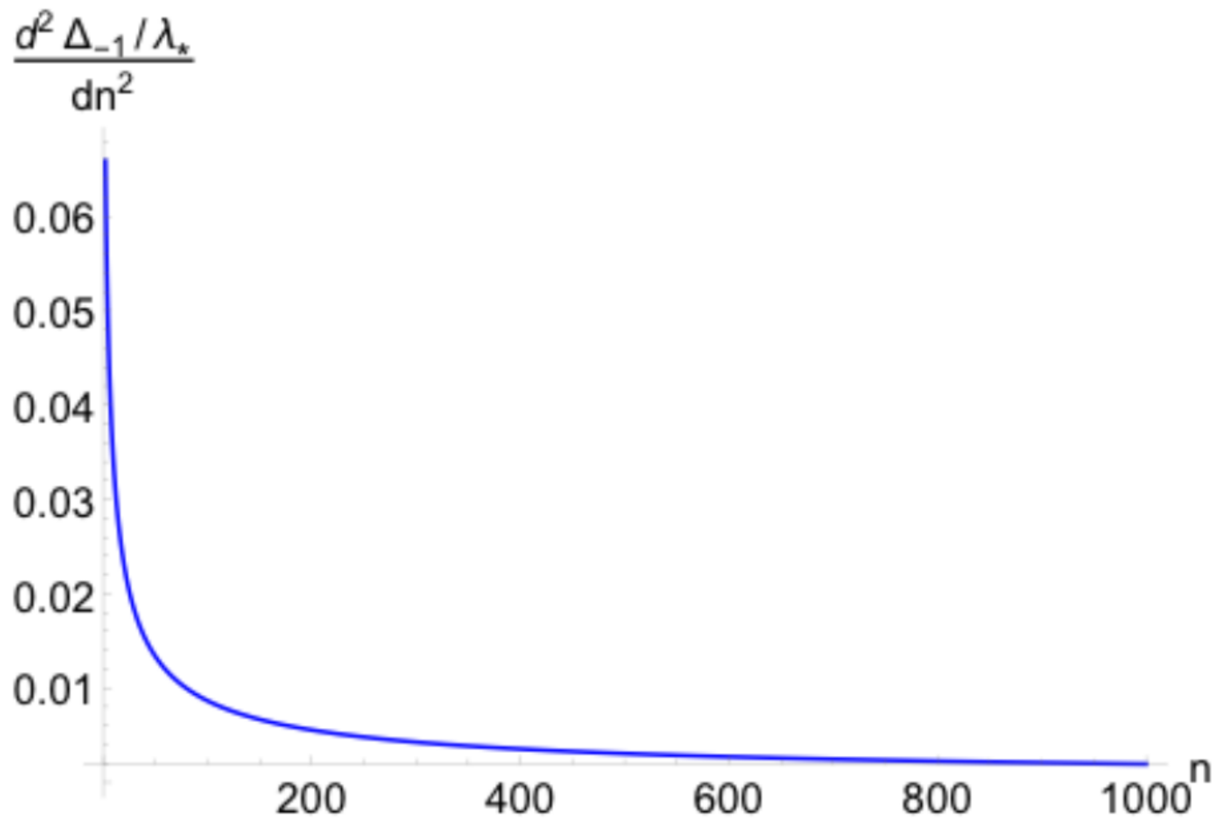
$$\gamma_{n_1,n_2} = \Delta(\varphi^{n_1+n_2}) - \Delta(\varphi^{n_1}) - \Delta(\varphi^{n_2}) > 0 \qquad O(\epsilon^3)$$

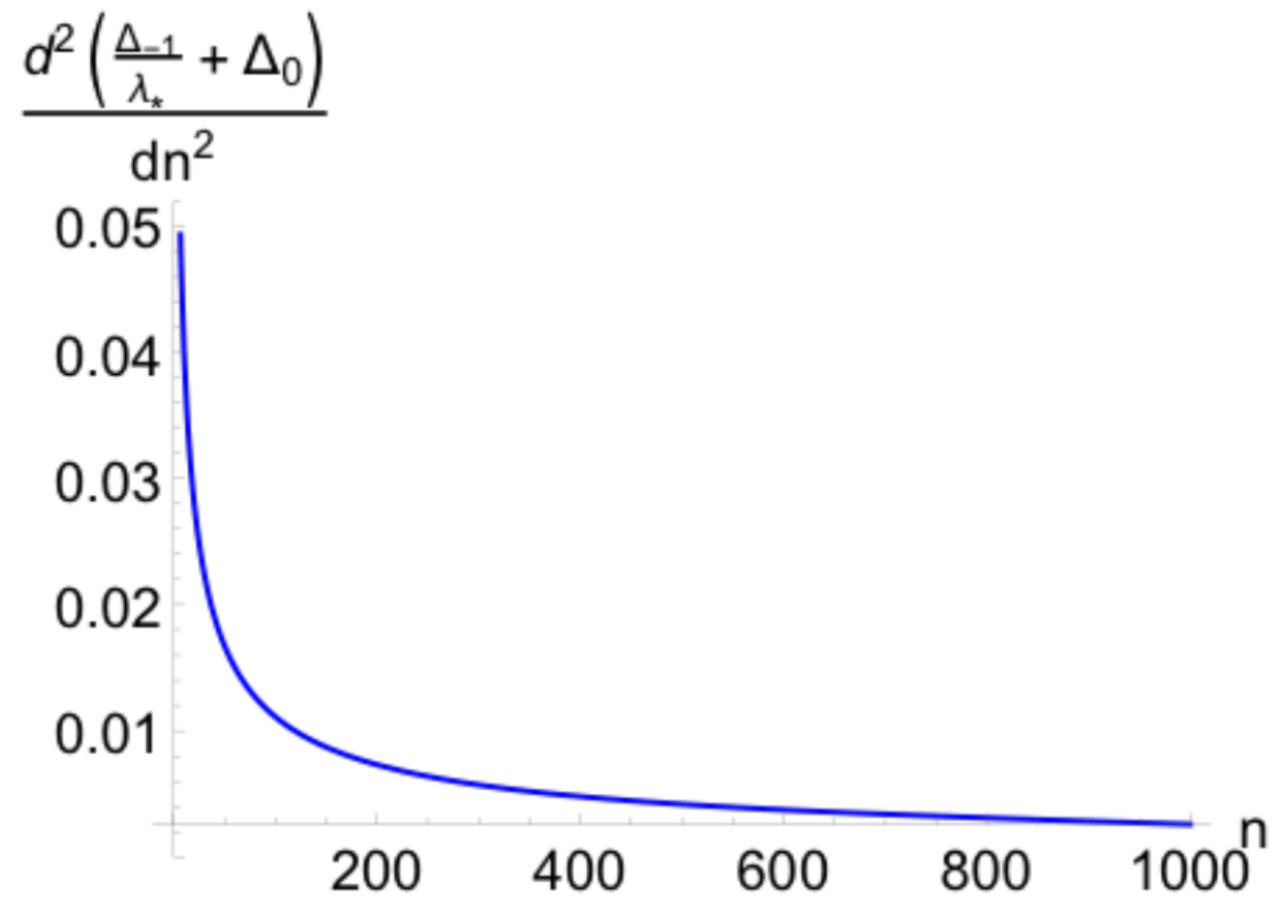
$$\Delta_\theta = \frac{1}{\lambda_*} \Delta_{-1}(\lambda_* n) + \Delta_0(\lambda_* n) + \cdots$$

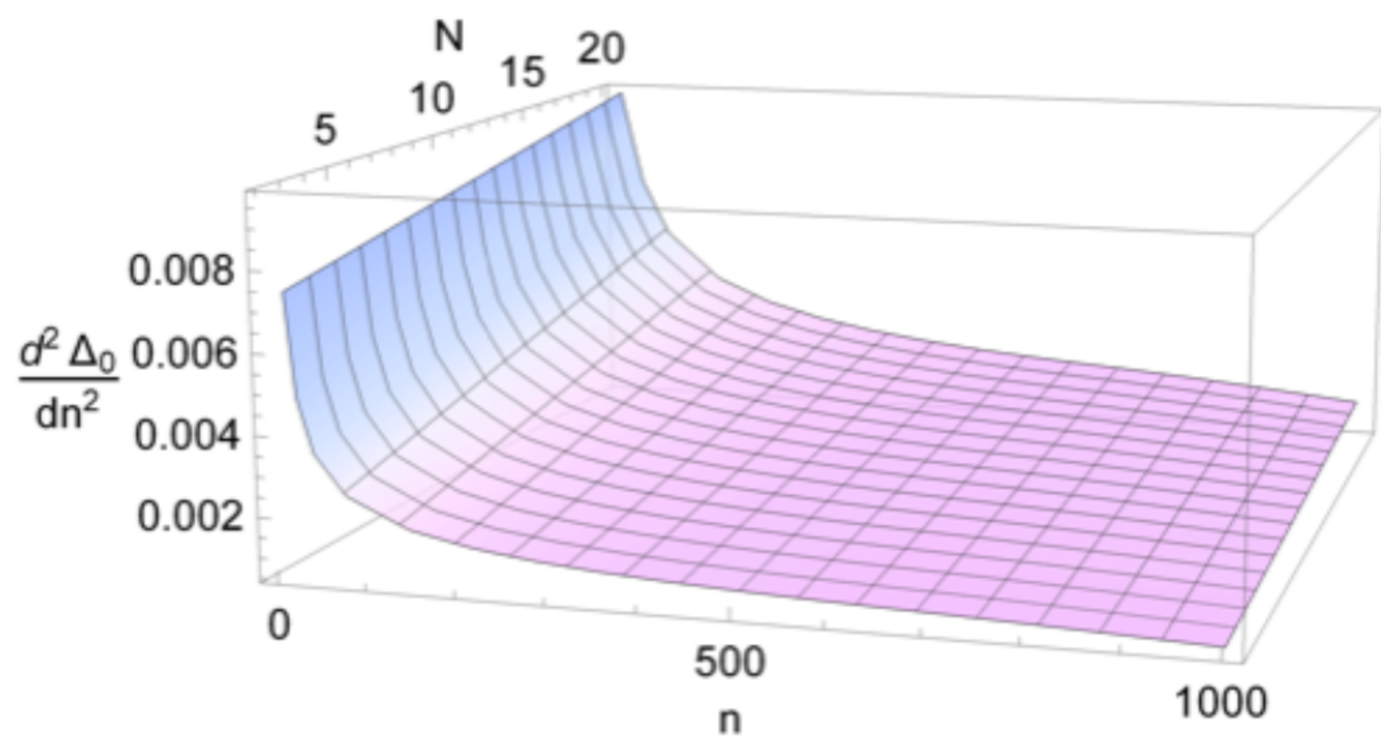
Each Term is convex

$\lambda_* = 0.1$

$N = 4$







What I did not present

- Charged (Complex) CFTs
- O(N) Cubic duality (Bersini's Talk)
- $U(N) \times U(M)$ [Intriguing for WGC]
- $d=4$ Safety at large charge
- $d=4$ QCD (near) conformal dynamics
  the dilaton story

Reorganizing Epidemiology via CFTs

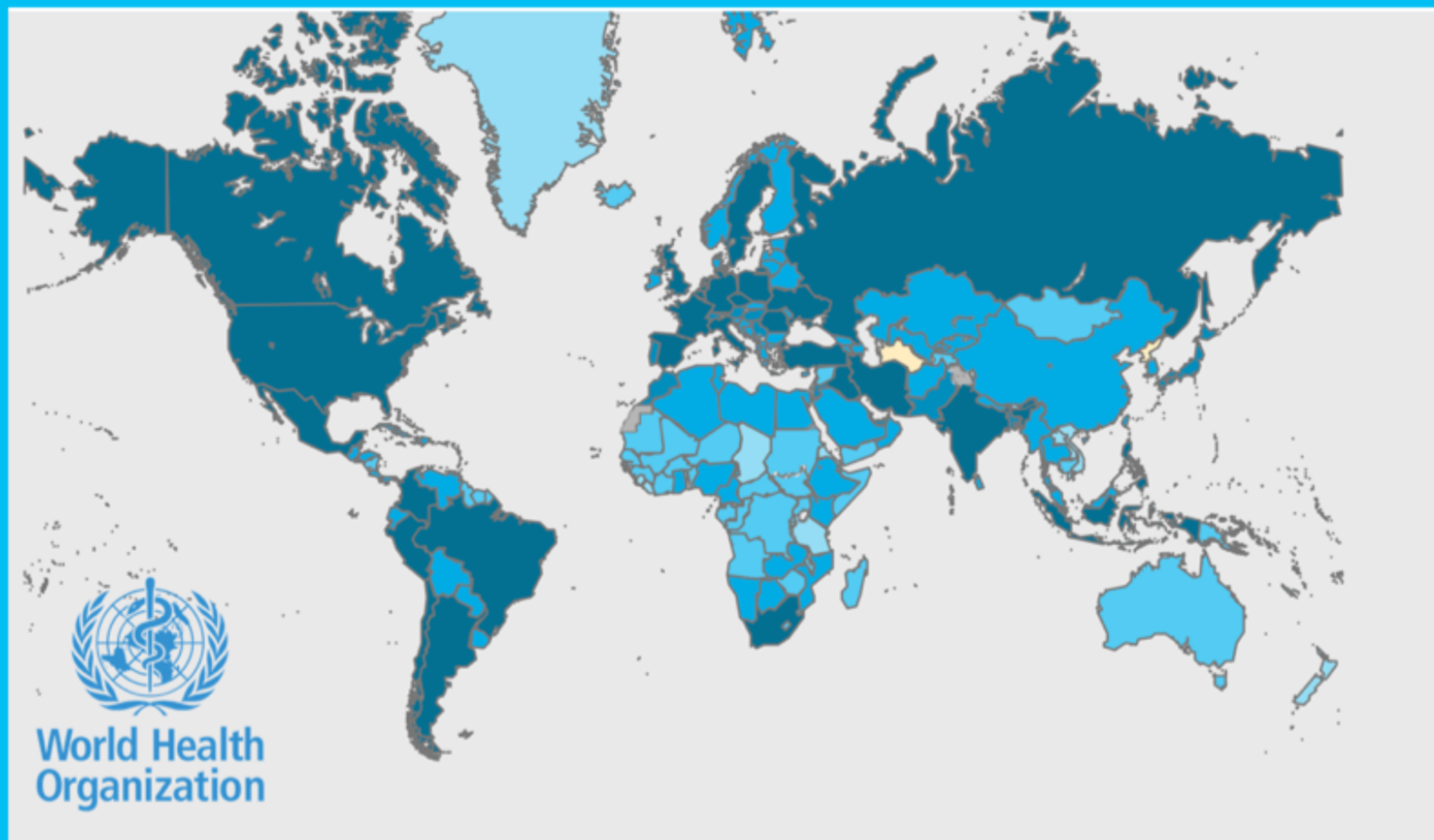
World wide situation

New cases: 515,104

Deaths: 3,386,825

Confirmed: 163,312,429

Vaccine doses: 1,407,945,776



World Health Organization
Worldometers.info
Johns Hopkins CORONAVIRUS

May 19th 2021

FROM STRING THEORY TO PANDEMICS

... the privilege to work with amazing people

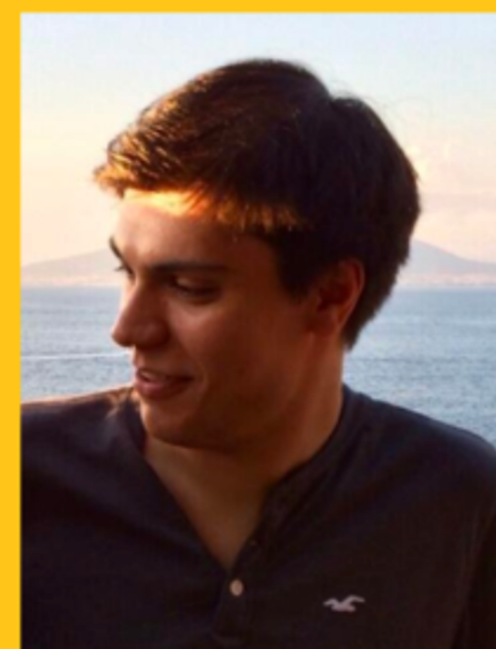
FROM HEP-TH AND -EXP TO PANDEMICS & ARTIFICIAL INTELLIGENCE












… the privilege to work with amazing people

PAPERS

frontiers

Renormalisation Group Approach to Pandemics…
M. Della Morte, D. Orlando and F. Sannino, Frontiers of Physics 8, 144 (2020)

nature SCIENTIFIC REPORTS

Interplay of social distancing and border restrictions….
G. Cacciapaglia and F. Sannino Sci Rep 10, 15828 (2020)

frontiers

RG approach to pandemics as a time-dependent SIR model
M. Della Morte and F. Sannino Frontiers of Physics 8 (2021) 583

PAPERS

nature SCIENTIFIC REPORTS

Second wave COVID-19 pandemics in Europe: A temporal...

G. Cacciapaglia, C. Cot and F. Sannino Sci Rep 10, 15514 (2020)

nature SCIENTIFIC REPORTS

Multiwave pandemic dynamics explained: How to tame ....

G. Cacciapaglia, C. Cot and F. Sannino Sci Rep 11, 6638 (2021)

nature SCIENTIFIC REPORTS

Mining Google and Apple mobility data: Temporal anatomy for..

G. Cacciapaglia, C. Cot and F. Sannino Sci Rep 11, 4150 (2021)

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nature SCIENTIFIC REPORTS

Impact of US vaccination strategy on COVID-19 wave dynamics

C. Cot, G. Cacciapaglia, A.S. Islind, M. Oskarsdottir, F. Sannino Sci Rep to appear

THE LANCET

Calling for pan-European commitment for rapid and sustained reduction in SARS-CoV-2 infections

V. Priesemann, F. Sannino et al. The lancet 397 (10269), 92-93

frontiers

Evidence for complex fixed points in pandemic data

G. Cacciapaglia and F. Sannino article/rs-70238/v1 (accepted)


PAPERS
Invited review
ELSEVIER
PHYSICS REPORTS
A Review Section of Physics Letters
The field theoretical ABC of epidemic dynamics
Giacomo Cacciapaglia[1,2], Corentin Cot[1,2], Michele Della Morte[3], Stefan Hohenegger[1,2], Francesco Sannino[4,5], Shahram Vatani[1,2]
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q-bio.PE] 25 Jan 2021

Epidemiological theory of virus variants

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Abstract:

We propose a physical theory underlying the temporal evolution of competing virus variants that relies on the existence of (quasi) fixed points capturing the large time scale invariance of the dynamics. To motivate our result we first modify the time-honoured compartmental models of the SIR type to account for the existence of competing variants and then show how their evolution can be naturally re-phrased in terms of flow equations ending at quasi fixed points. As the natural next step we employ (near) scale invariance to organise the time evolution of the competing variants within the effective description of the *epidemic Renormalization Group* framework. We test the resulting theory against the time evolution of COVID-19 virus variants that validate the theory empirically.

PAPERS

arXiv.org > q-bio > arXiv:2106.14982

PAPERS

Variant-driven multi-wave pattern of COVID-19 via Machine Learning clustering of spike protein mutations

Adele de Hoffer, Shahram Vatani, Corentin Cot, Giacomo Cacciapaglia, Francesco Conventi, Antonio Giannini, Stefan Hohenegger, Francesco Sannino

doi: https://doi.org/10.1101/2021.07.22.21260952

Submitted

“WHEN COULD WE TRAVEL AGAIN?”

AT THE END OF JANUARY WE WERE TOLD TO POSTPONE OUR TRIPS

RENORMALISATION GROUP

Renormalisation Group Approach to Pandemics…

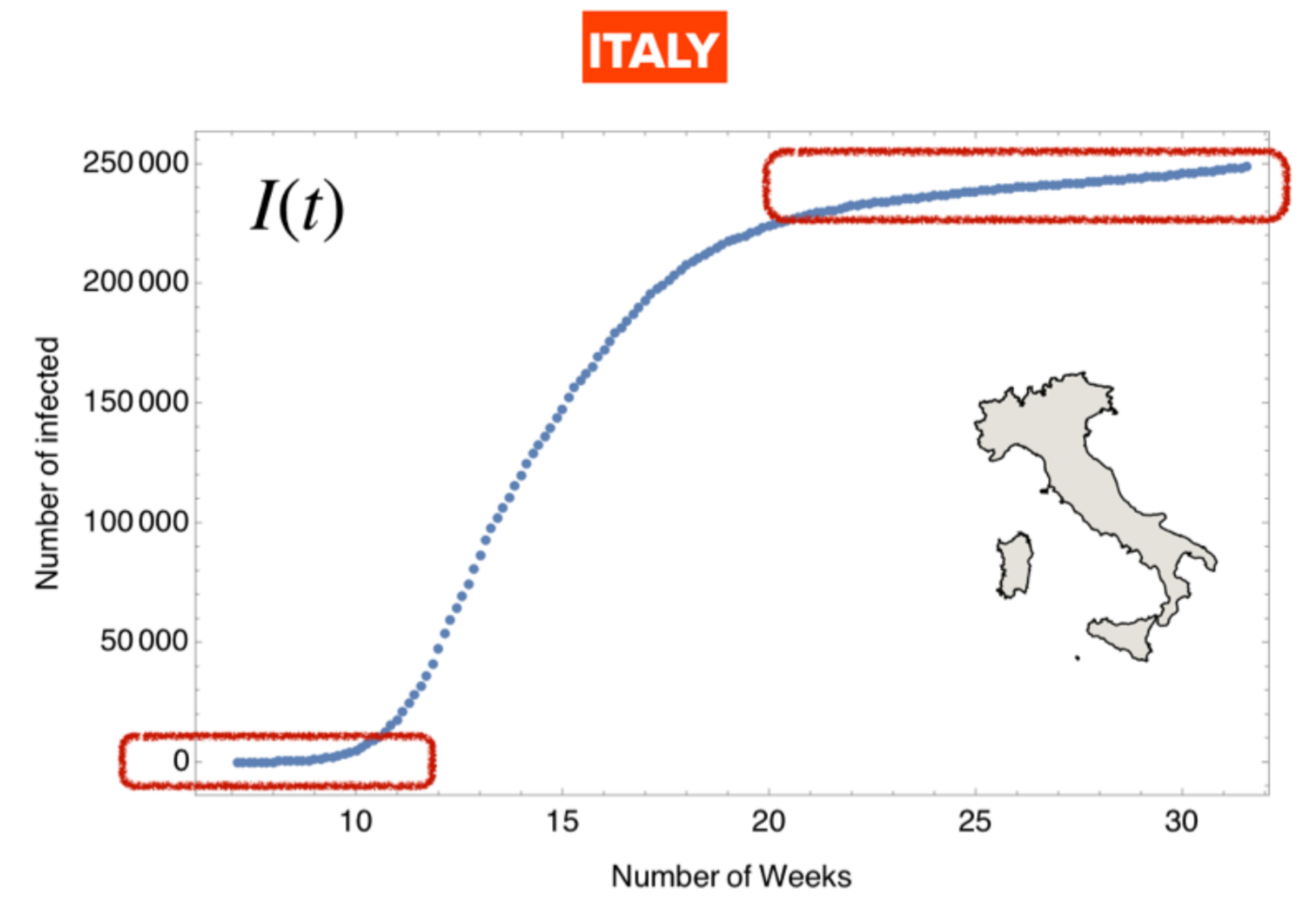
M. Della Morte, D. Orlando and F. Sannino, Frontiers of Physics 8, 144

EPIDEMIC

LARGE AND SHORT TIME SCALE INVARIANCE

- Short times = obvious time invariance
- Long time = approx time invariance
- Approx time dilation can be encoded in an effective interaction strength

$$\alpha(t) = \ln I(t)$$



EPIDEMIC RENORMALISATION GROUP (eRG) IN A NUTSHELL

- The **beta function** encodes the underlying (pandemic) dynamics

$$-\beta(\alpha) \equiv \frac{d\alpha}{dt} = \gamma\alpha\left(1 - \frac{\alpha}{a}\right)$$

- The zeros at $\alpha = 0$ and $\alpha = a$ enforce time-scale invariance at these two points

- The solution is

$$\alpha(t) = \frac{a\, e^{\gamma t}}{b + e^{\gamma t}}$$

- With b an integration constant

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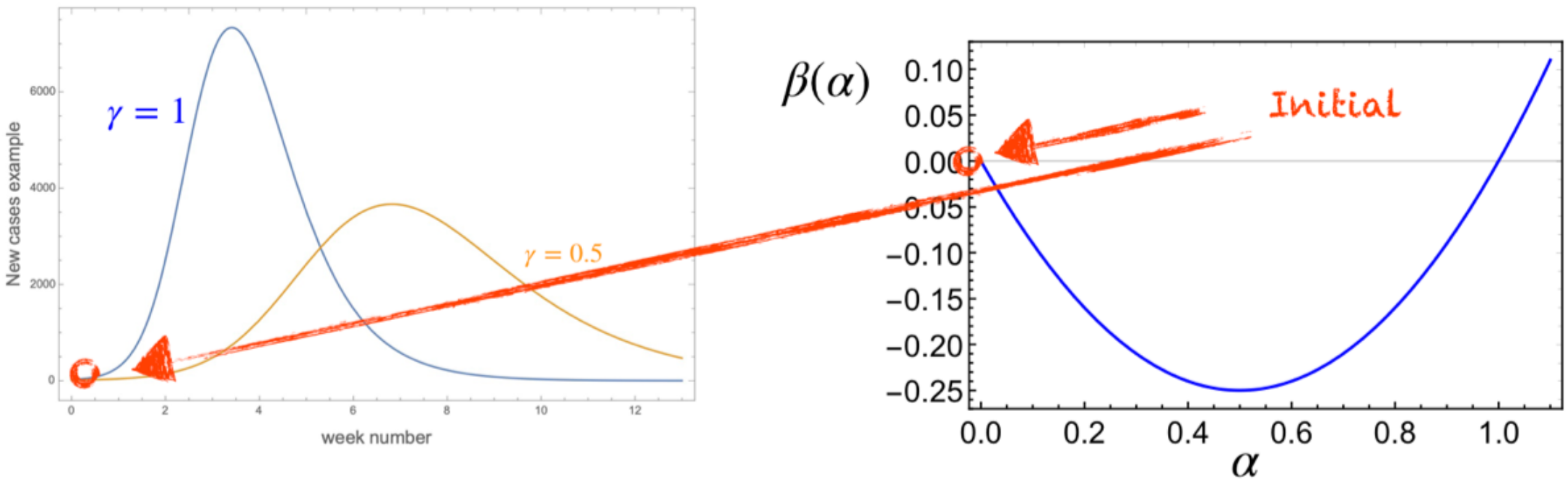

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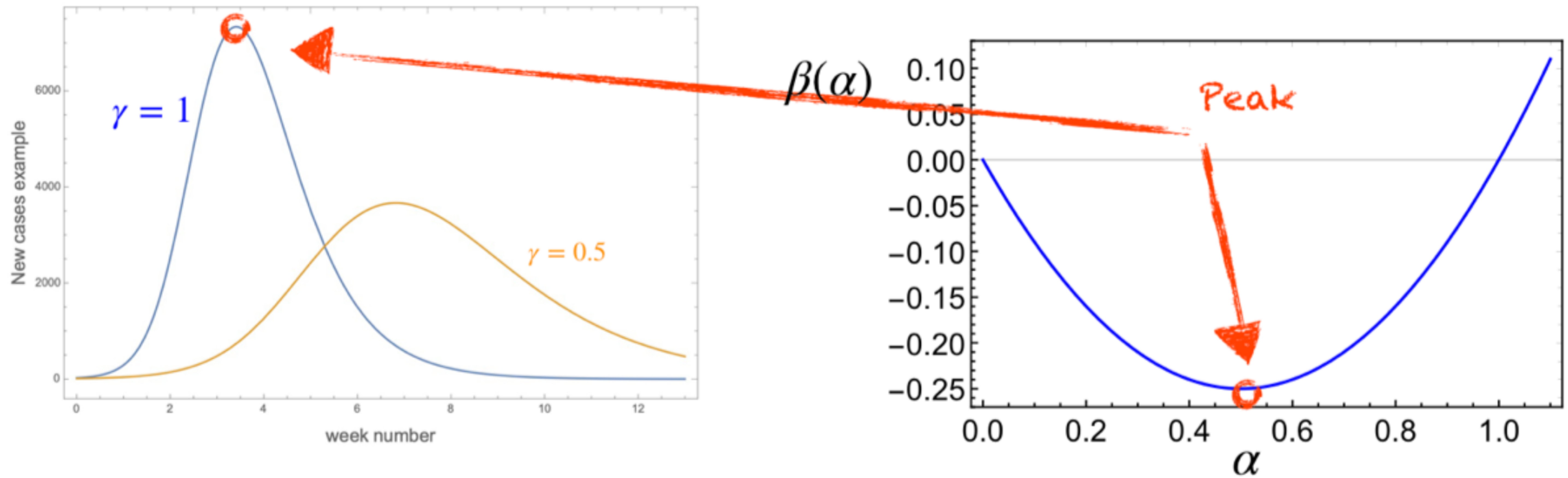

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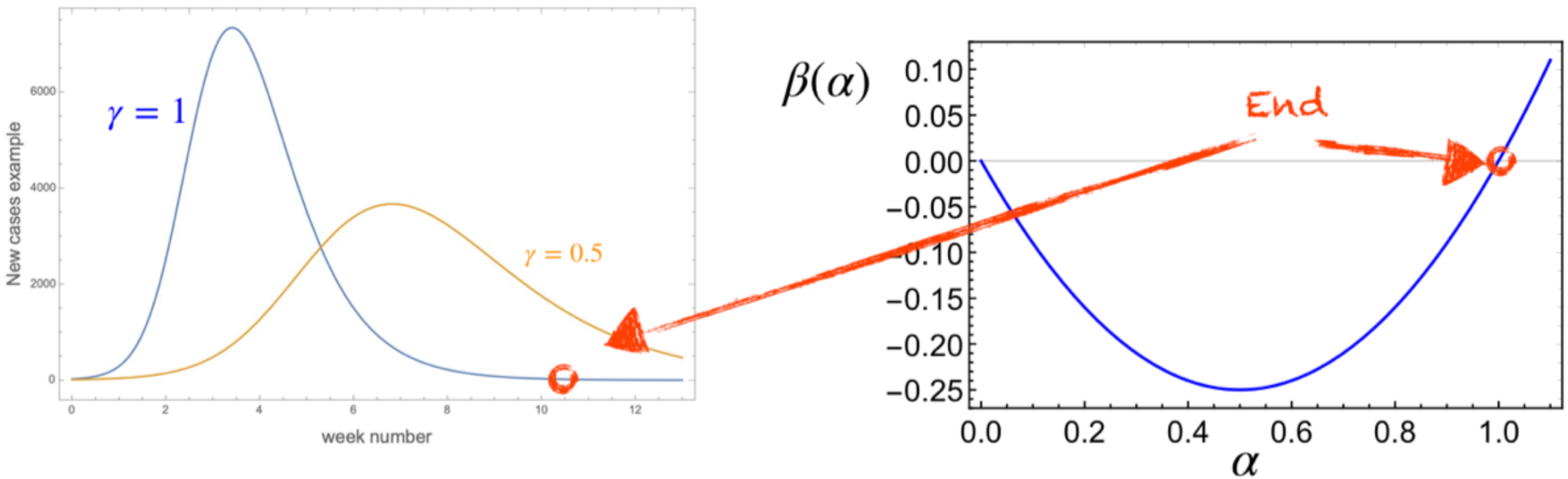
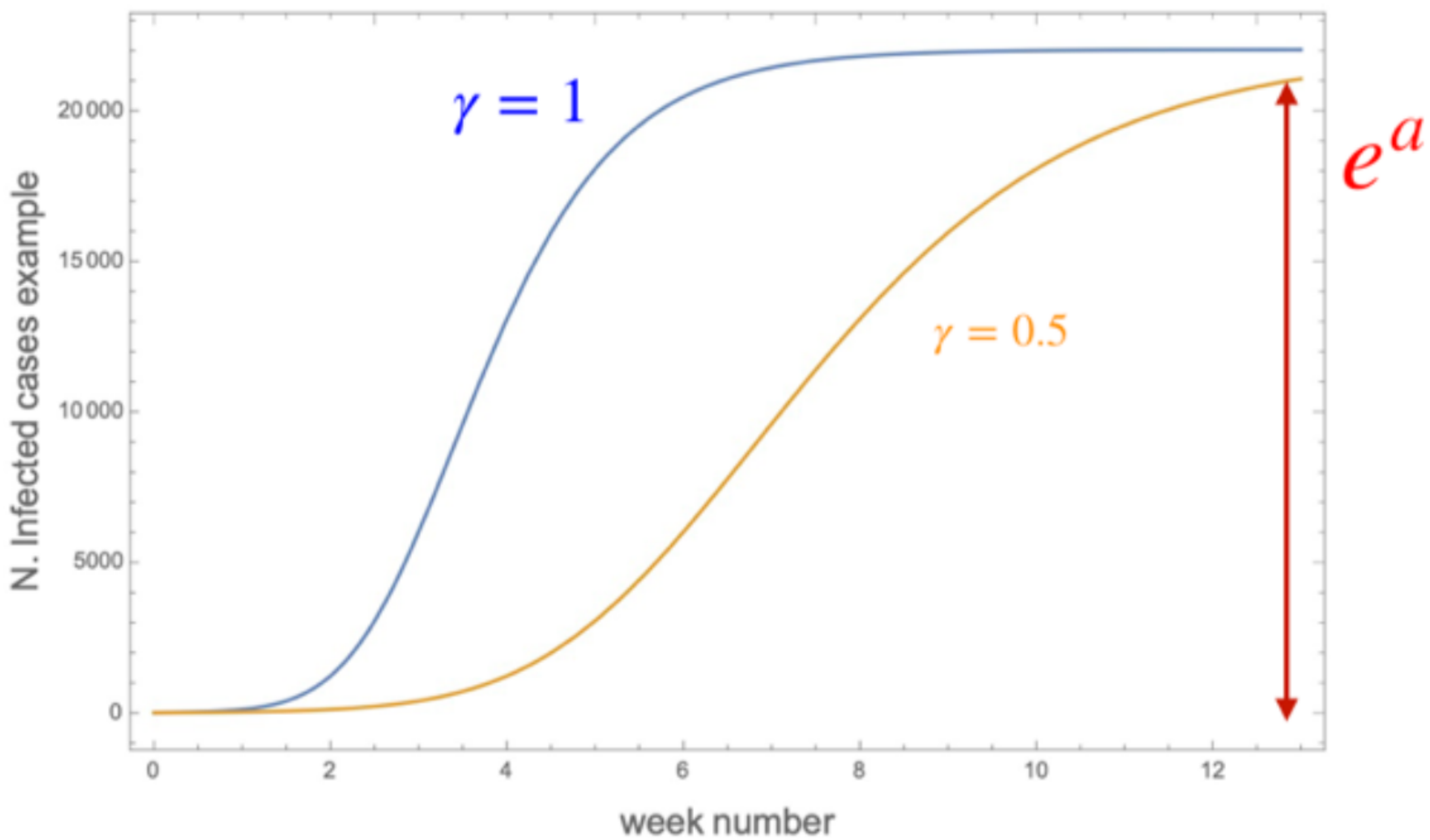
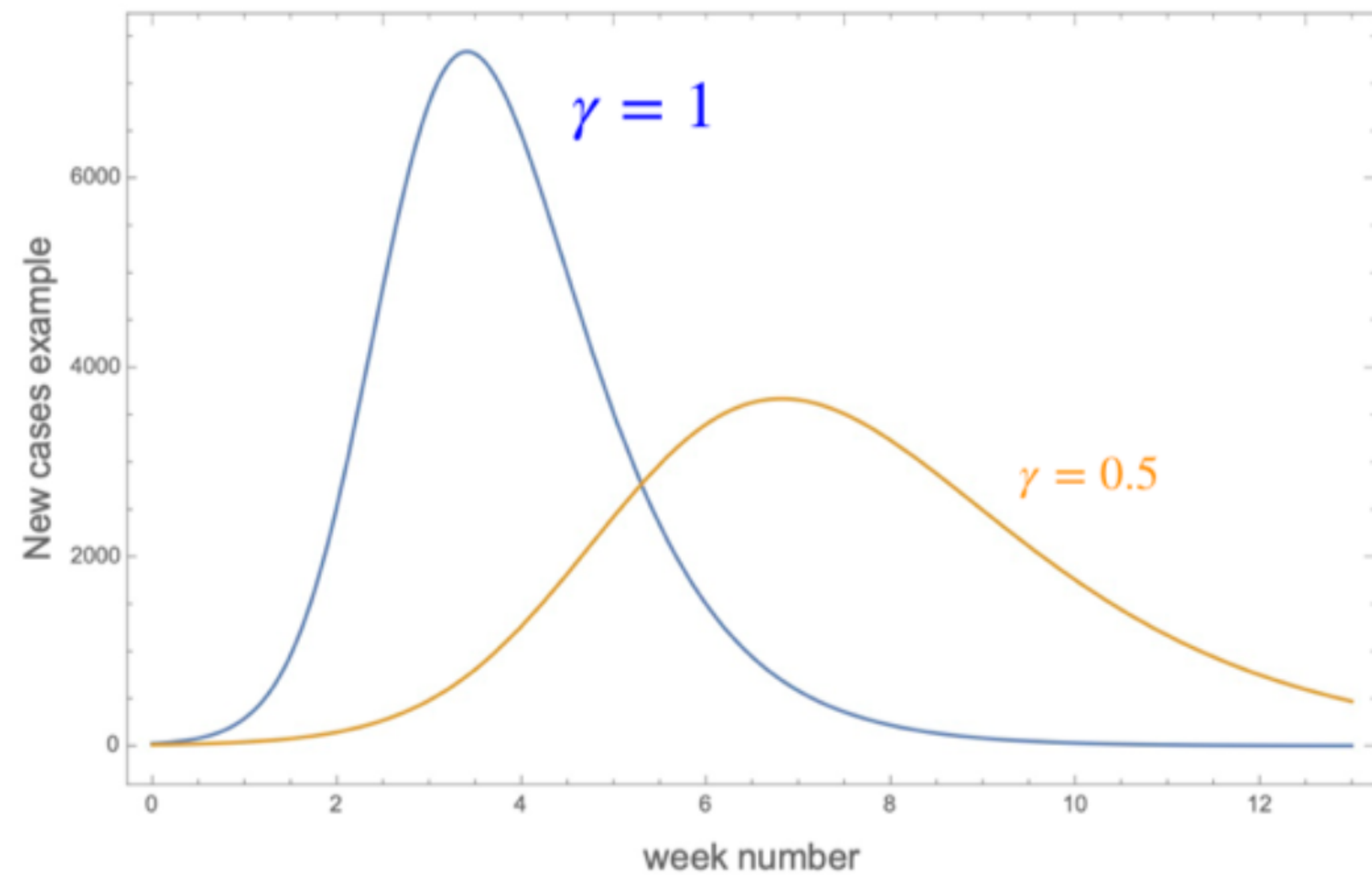


eRG

$$\alpha(t) = \frac{a\, e^{\gamma t}}{b + e^{\gamma t}}$$

- γ controls the infection rate and the flattening of the epidemic curve.



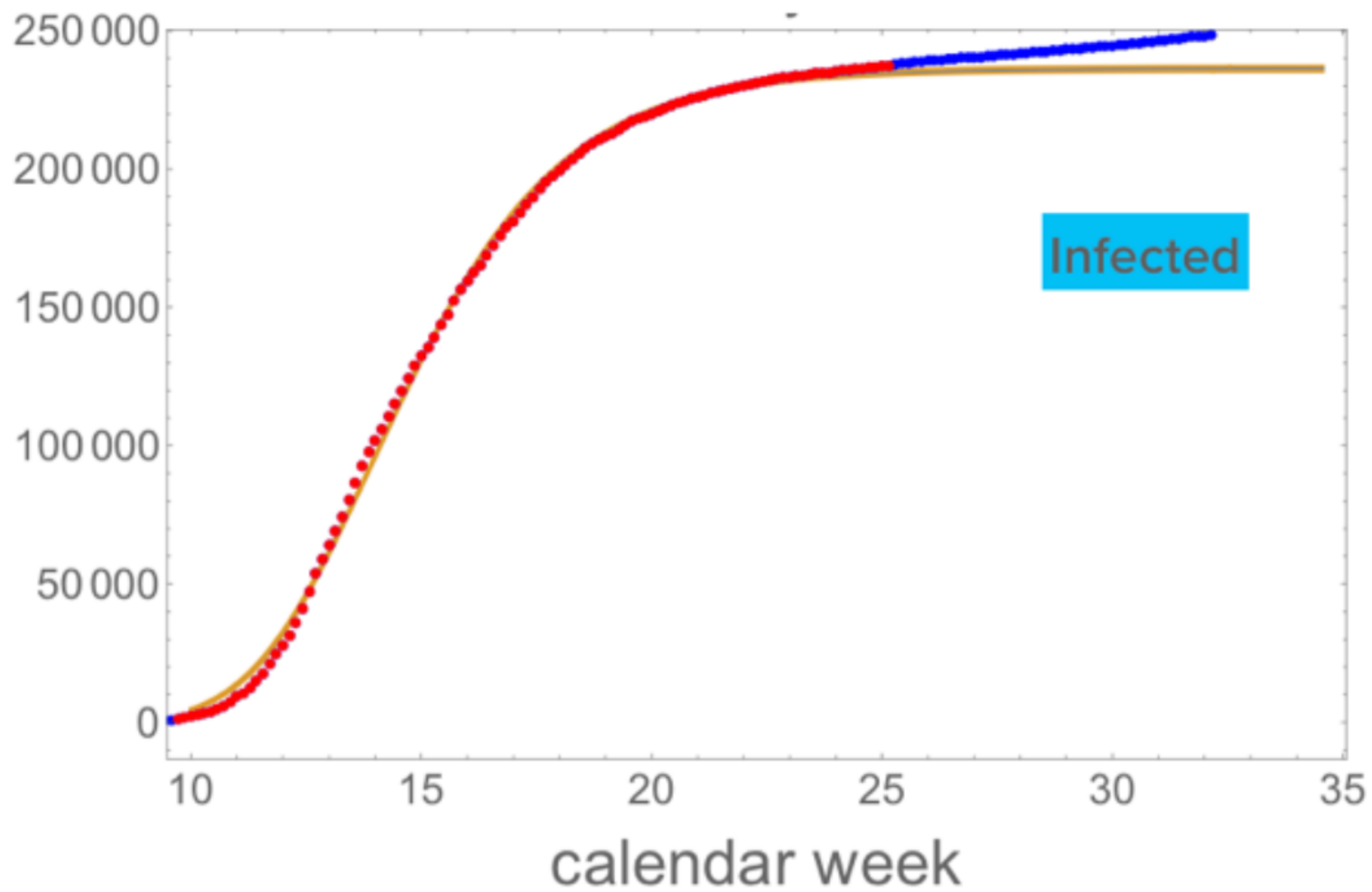


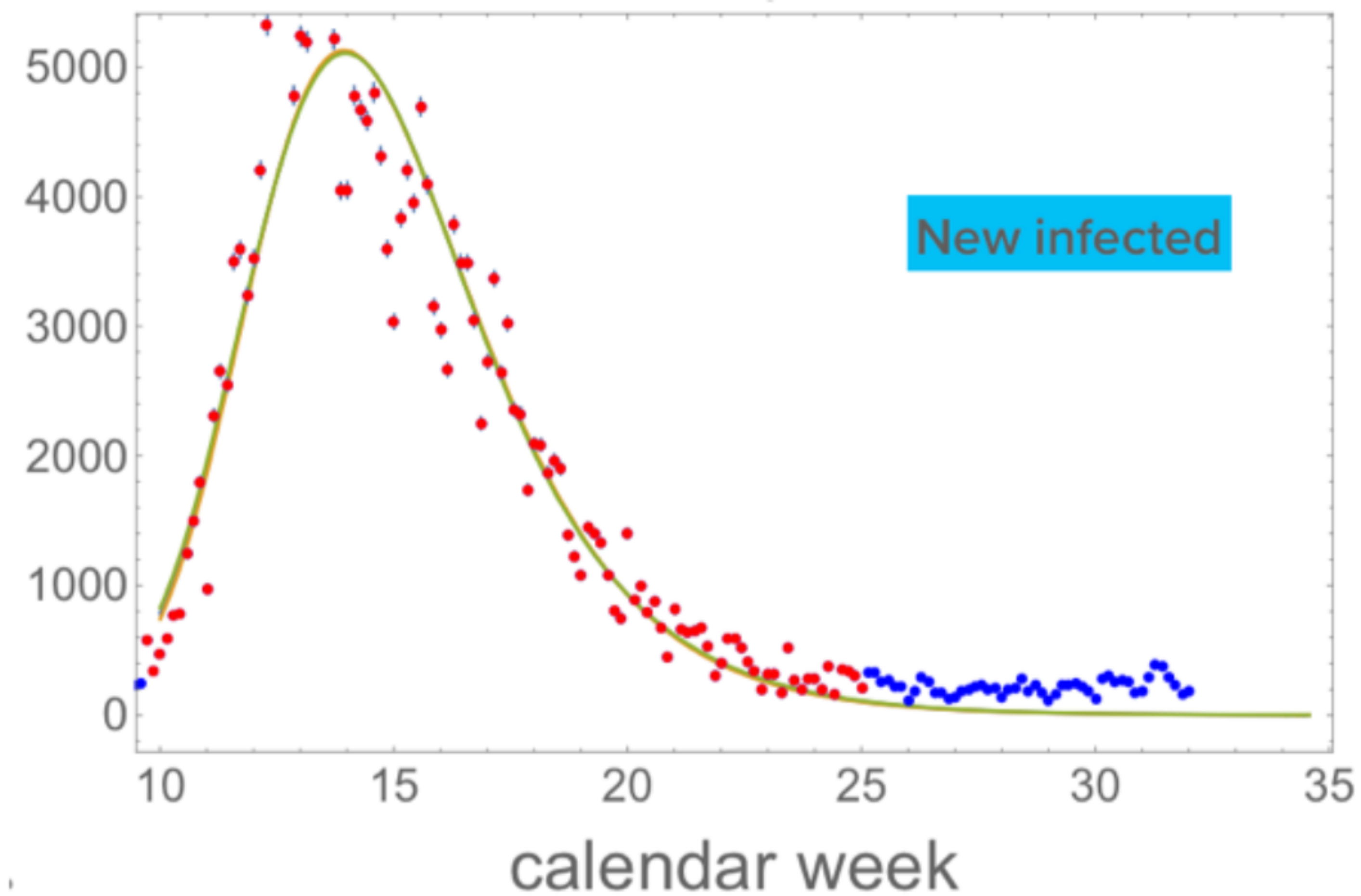
- e^a is the total number of infected

- b is a temporal shift

Time structure well reproduced

ITALY

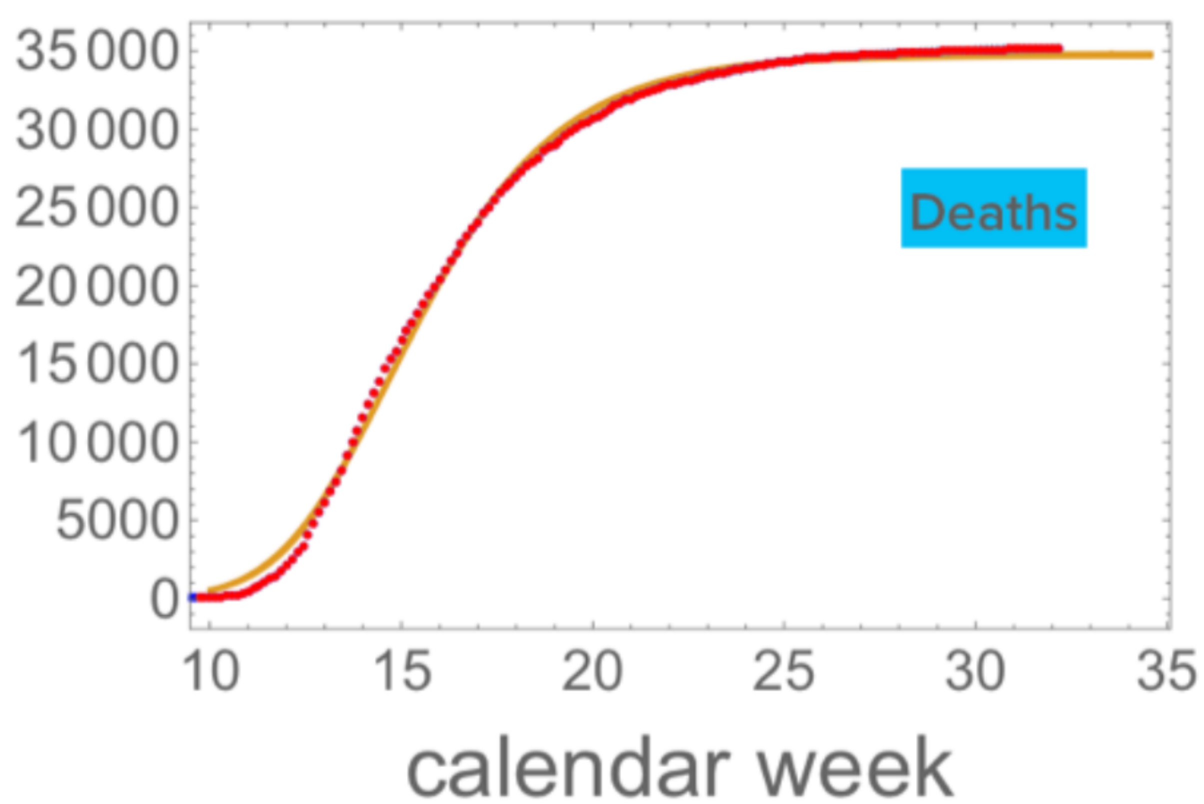




$a = 12.373 \pm 0.005$

$\gamma = 0.447 \pm 0.009$

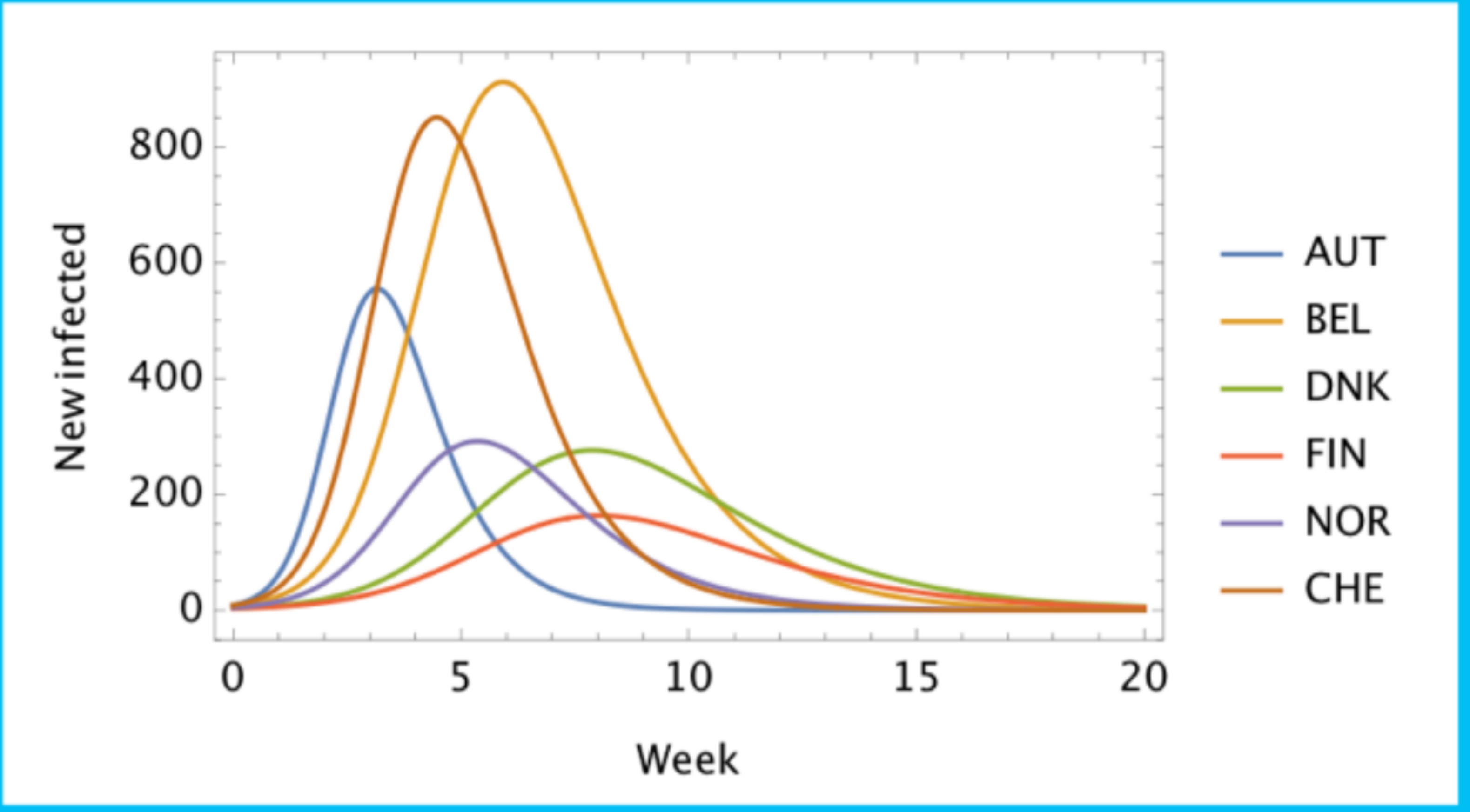
$b = 41 \pm 5$

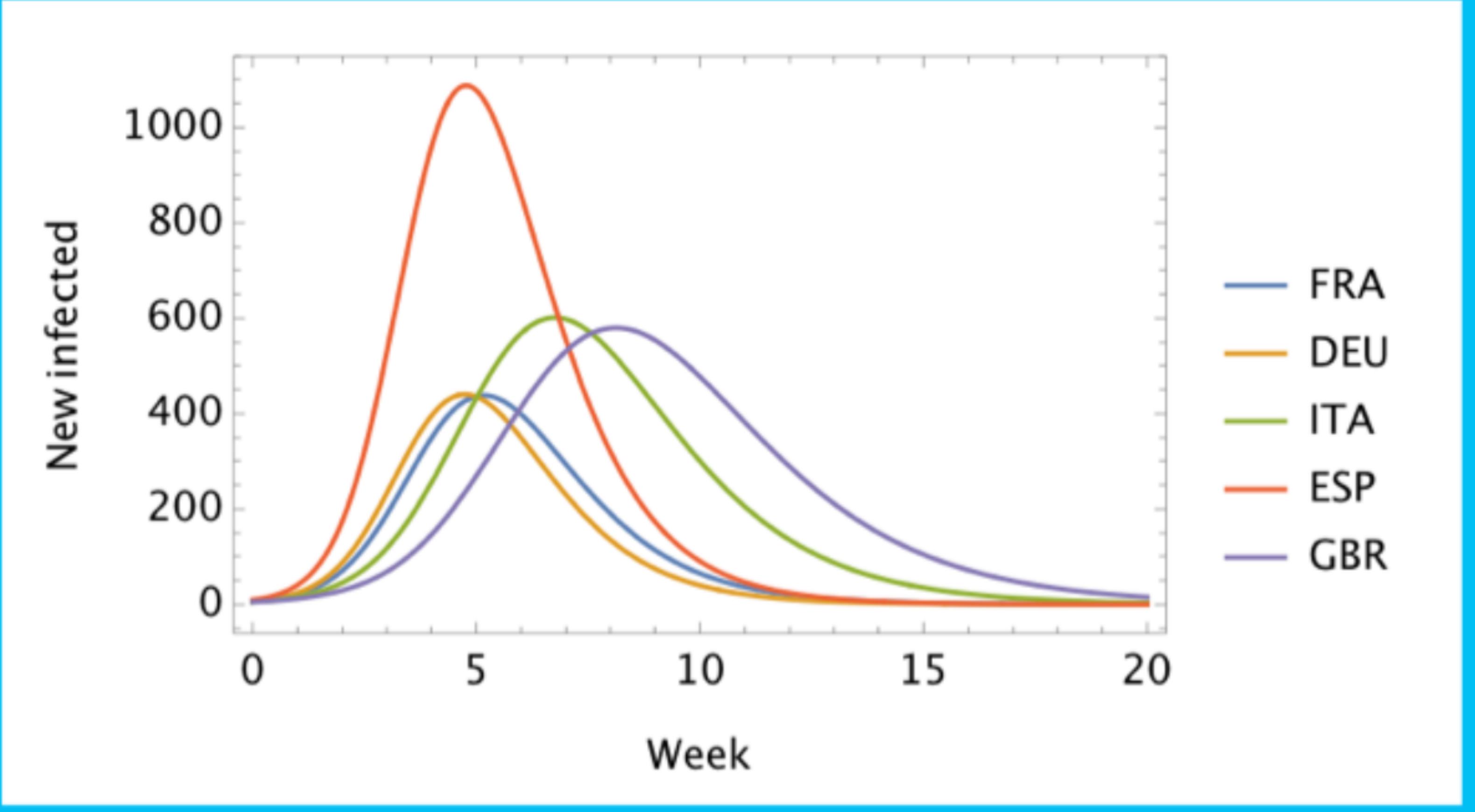


eRG

ADVANTAGES

- Analytic expressions
- Symmetry based
- 2 parameters per country
- Time structures well described
- Predictive near peak of new infected

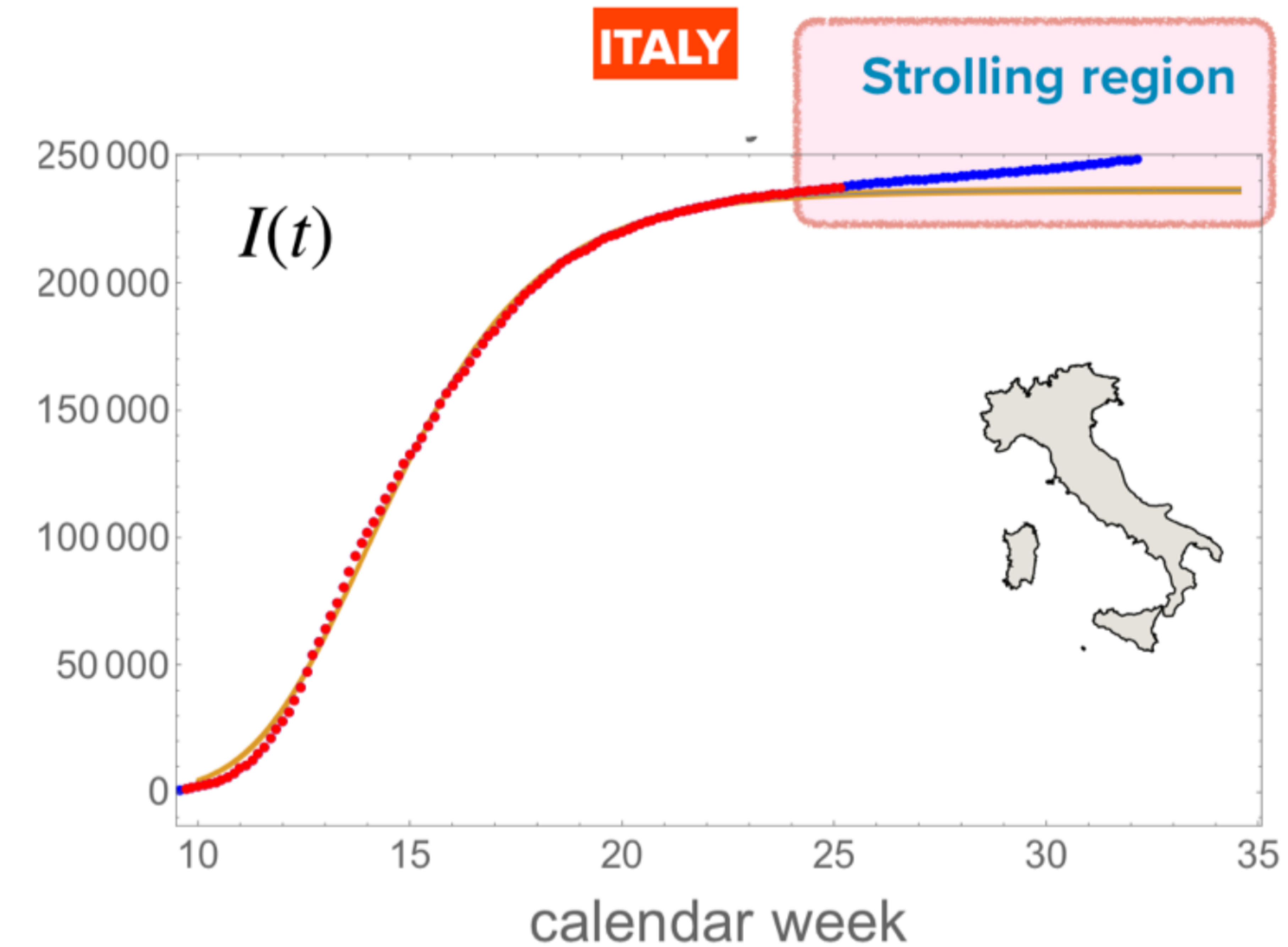




NEAR TIME SCALE INVARIANCE

EXPLAINS STROLLING PANDEMIC

- *Approx* time scale invariance
- Strolling pandemic (Sp) = linear growth
- *eRG:* natural framework for Sp



COMPLEX eRG = CeRG [it reads "Serge"]

- A tiny violation of large time scale invariance can be achieved via

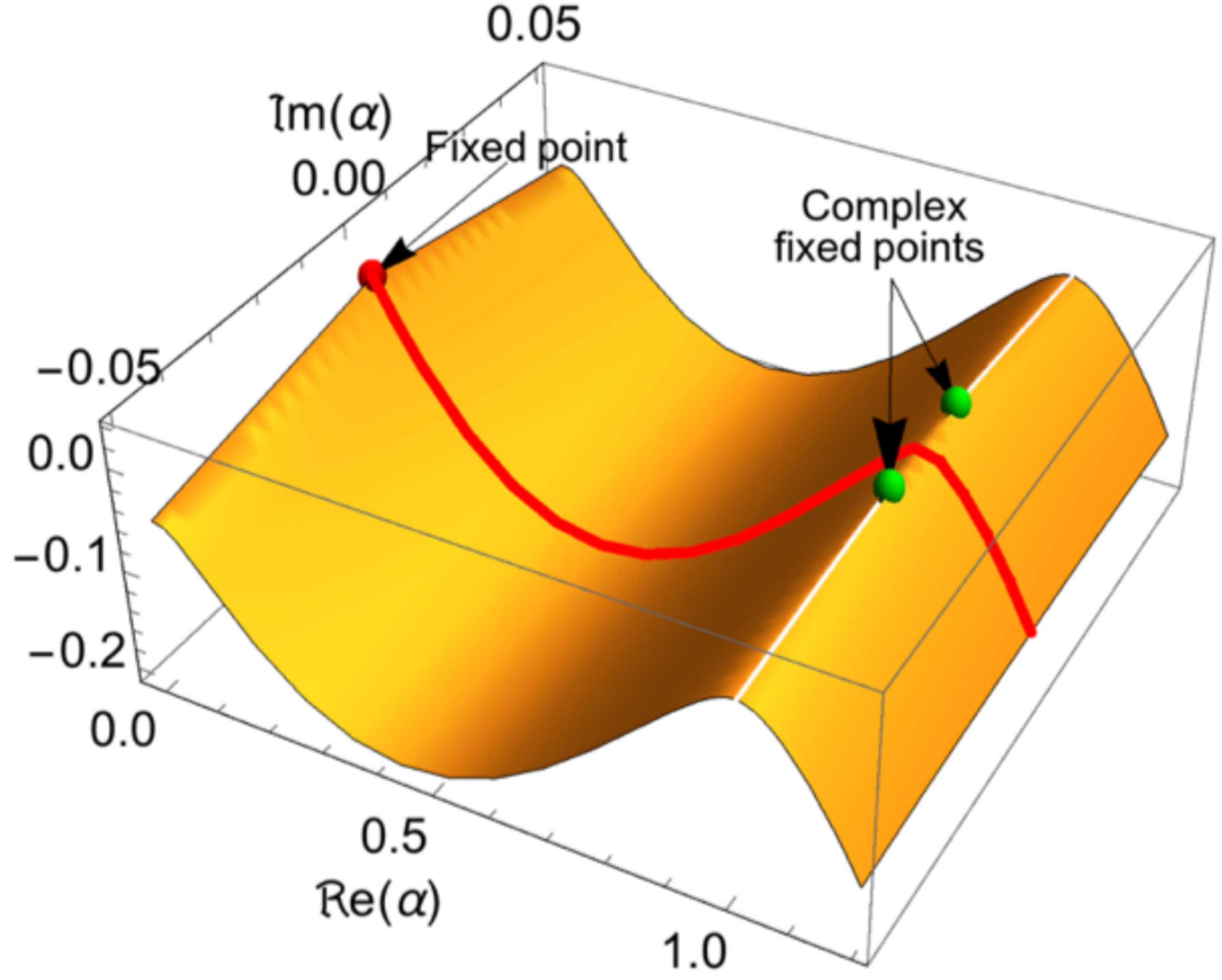
$$-\beta_{\mathrm{CeRG}}(\alpha) = \frac{d\alpha}{dt} = \alpha\left[(1-\alpha)^2 - \delta\right]^p$$

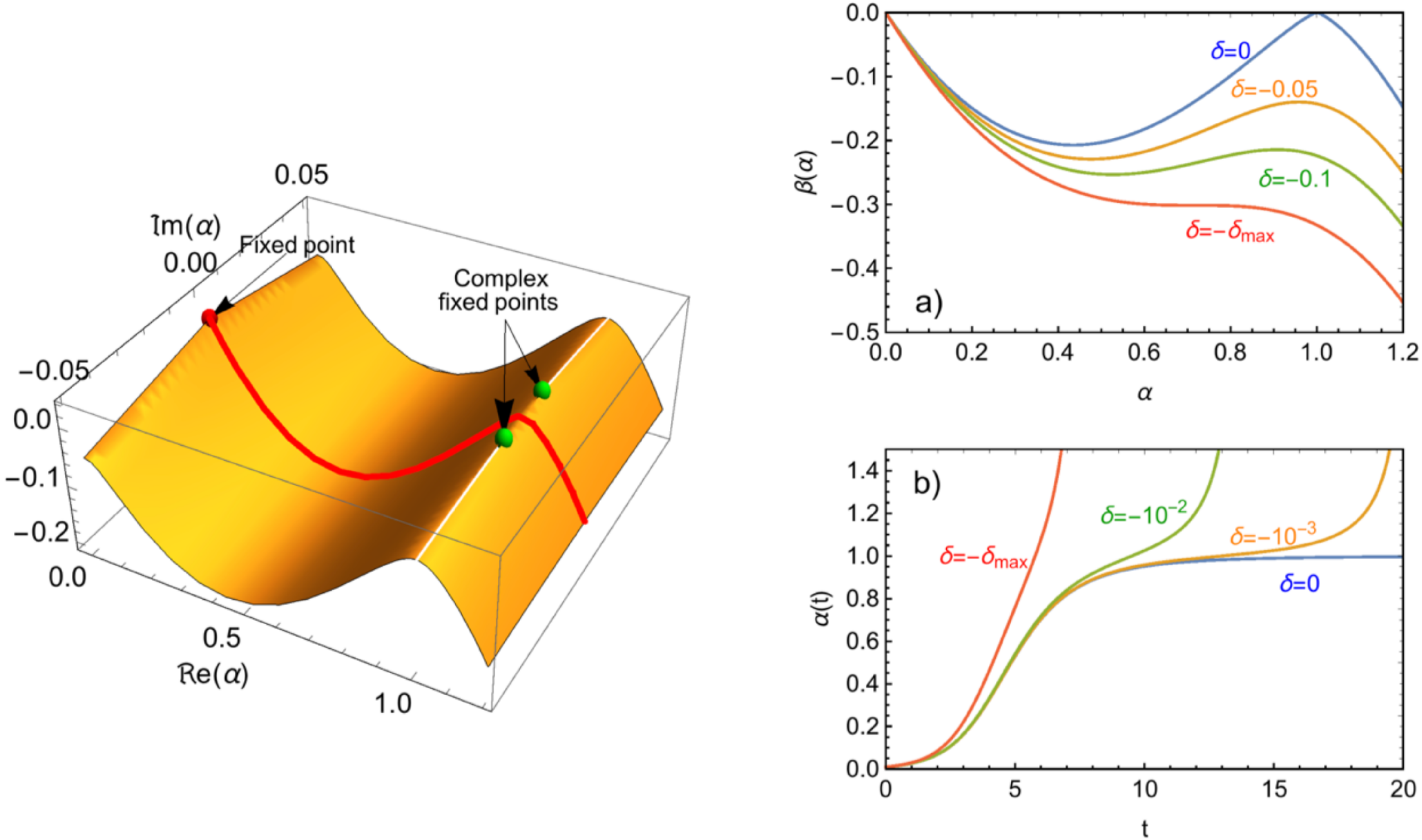
- with $|\delta| \ll 1$

- For $p = 1/2$ and $\delta = 0$ it reproduces eRG

- Complex fixed points for negative δ

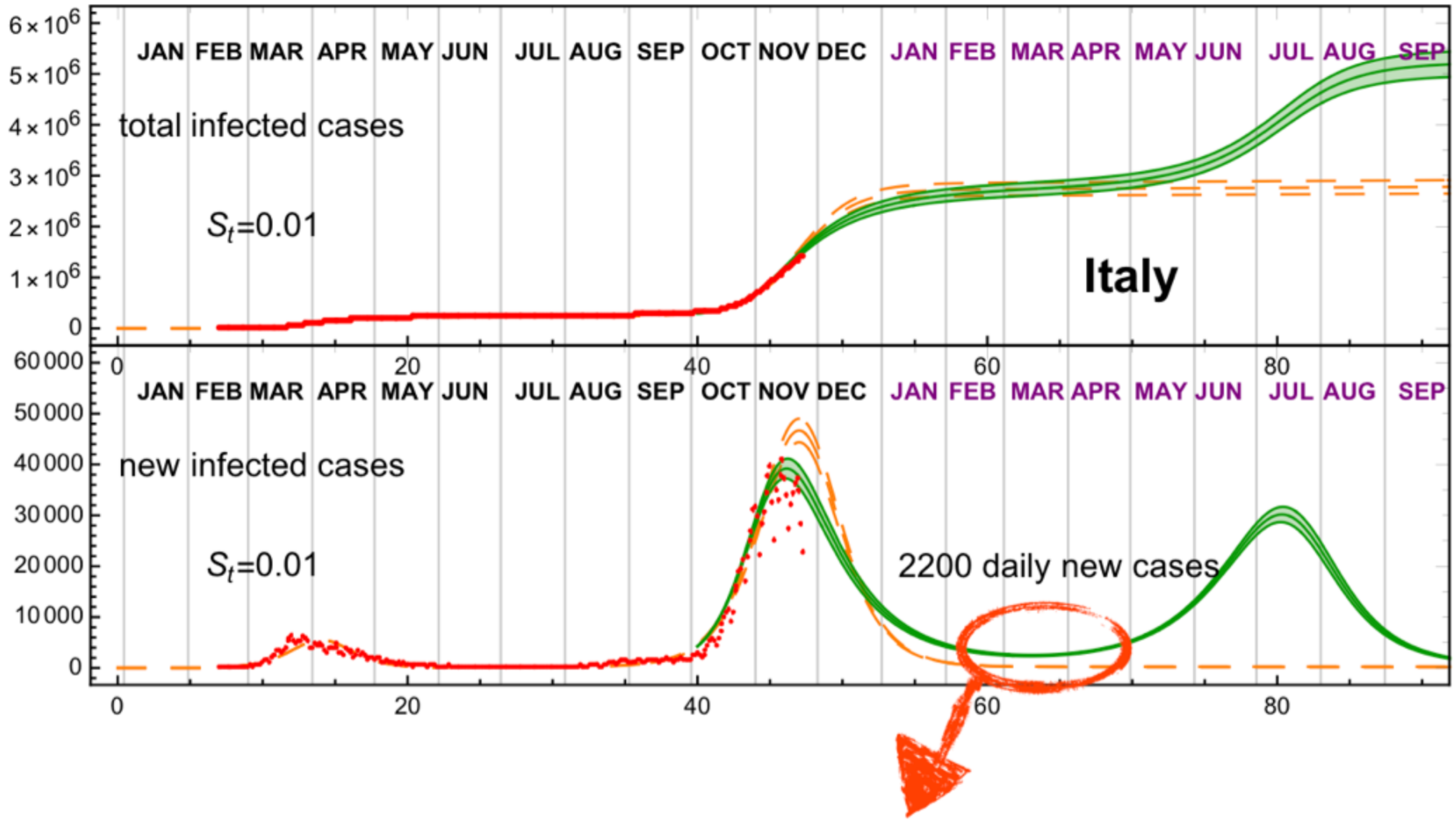
$$\alpha_0 = 0\ , \quad \alpha_1 = 1 - i\sqrt{|\delta|}\ , \quad \alpha_2 = 1 + i\sqrt{|\delta|}$$





0.05
Im(α)
Fixed point
0.00
Complex
fixed points
−0.05
0.0
−0.1
−0.2
0.0
0.5
Re(α)
1.0
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
β(α)
δ=0
δ=−0.05
δ=−0.1
δ=−δmax
a)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
α
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
α(t)
b)
δ=−δmax
δ=−10−2
δ=−10−3
δ=0
0
5
10
15
20
t

A predicting example:



Crucial to keep the number of new cases as low as possible!

Prieseman, Sannino et al, The Lancet 397, P92-93

What next?

- Dilatonic dynamics / Conformal window
- Beyond scalars
- Deeper relation to gravity
- CFT to reorganize understanding of infectious diseases. (Large viriological charge?)
- . . .