

# Challenges for quantum gravity - a perspective from asymptotic safety

September 14, 2026

Puzzles in the quantum gravity landscape, Graz

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European Research Council



**UNIVERSITÄT  
HEIDELBERG**  
ZUKUNFT  
SEIT 1386

# Rafael D. Sorkin (5.10.1945 - 12.9.2026)



Selected scientific contributions:  
developed causal set quantum gravity, conceived  
entanglement entropy, achieved deep insights into the  
Lorentzian path integral and quantum measure theory  
and much more.

An example to all of us, how to achieve profound insights  
and put forward truly innovative ideas, but remain first and  
foremost a curious and humble mind who treats everybody  
with respect and openness.

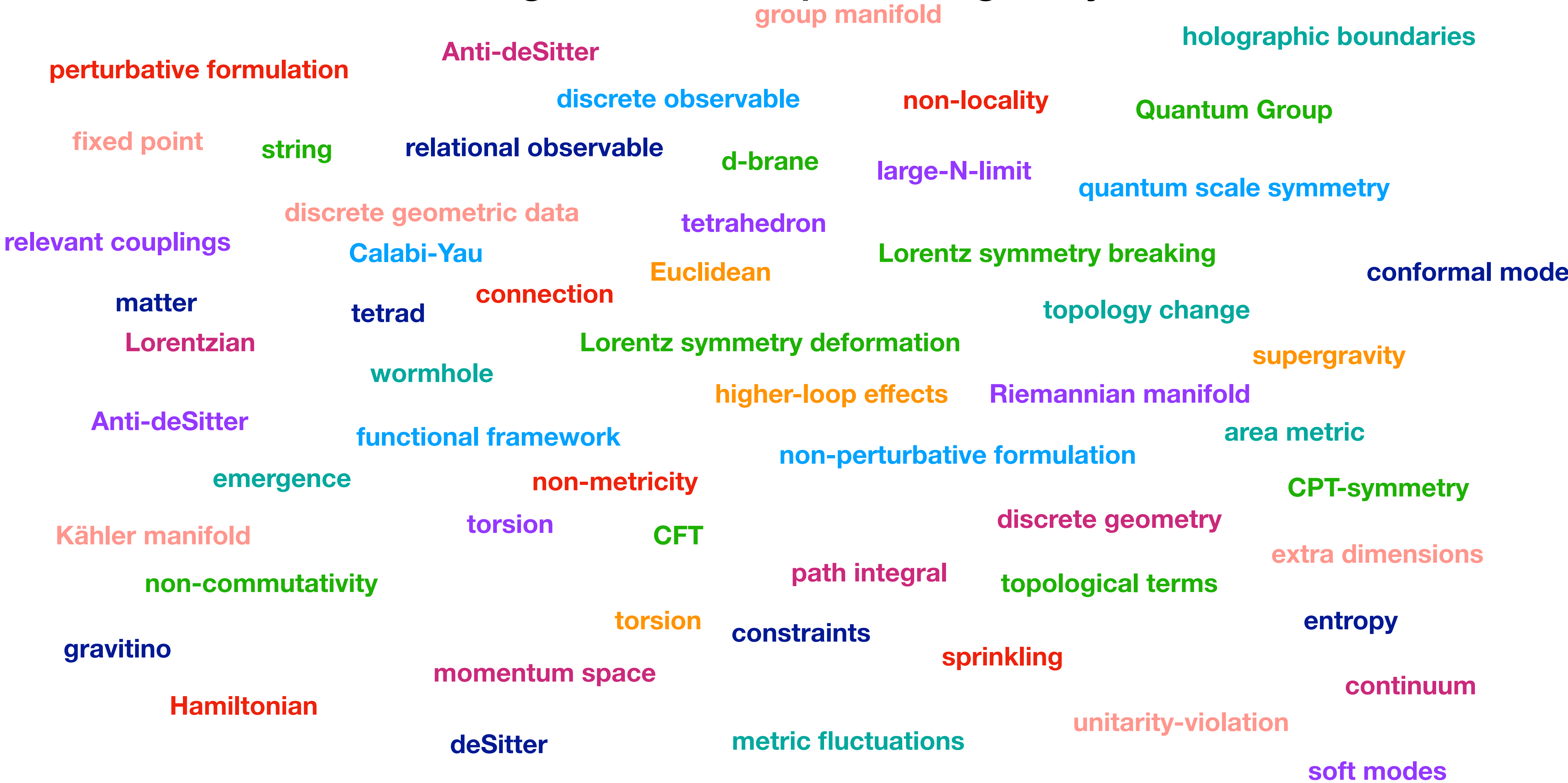
He will be truly missed!

We keep his wife Fatma and extended family in our thoughts.

# Ingredients for quantum gravity:



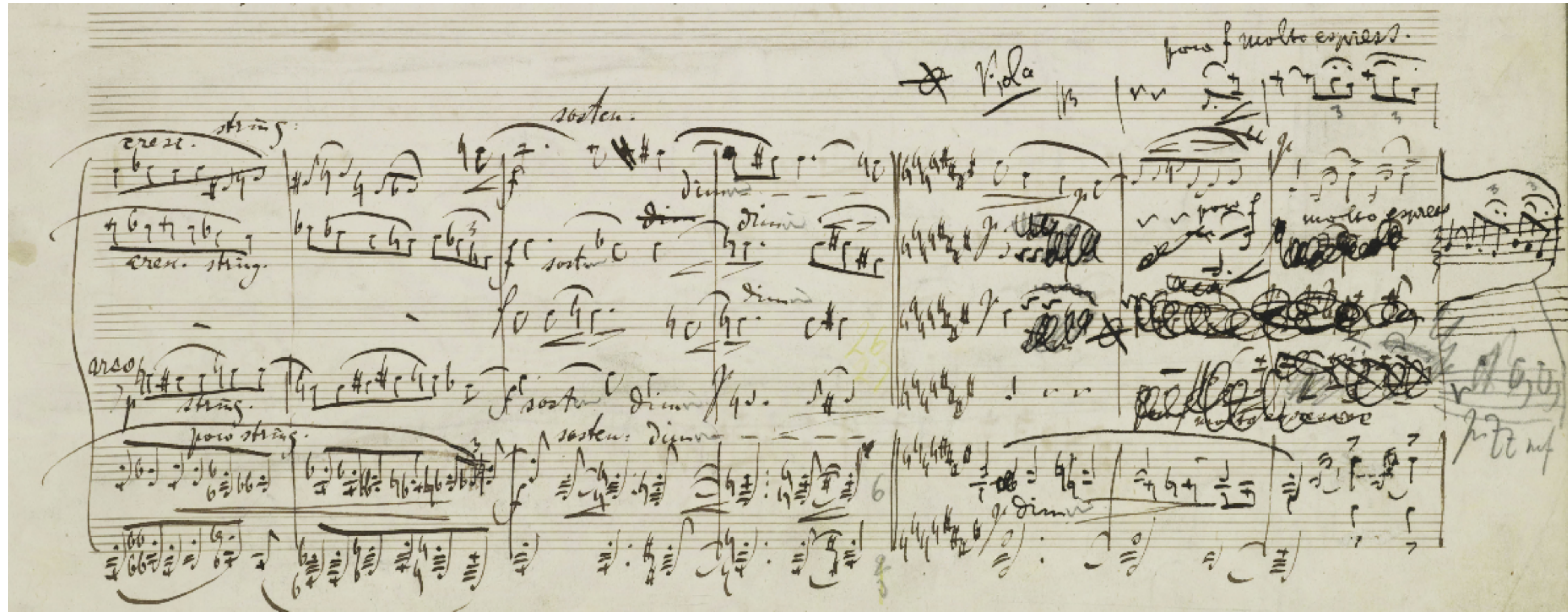
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# What composing music and developing quantum gravity have in common

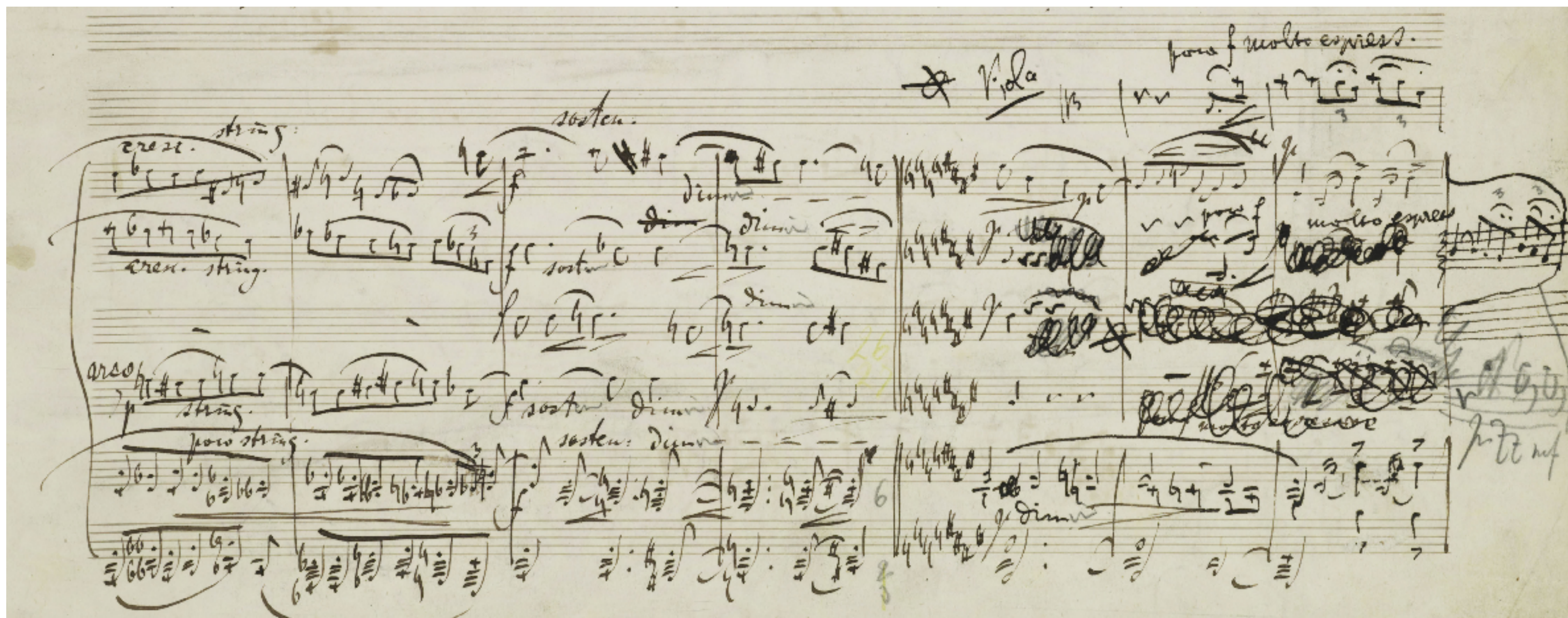
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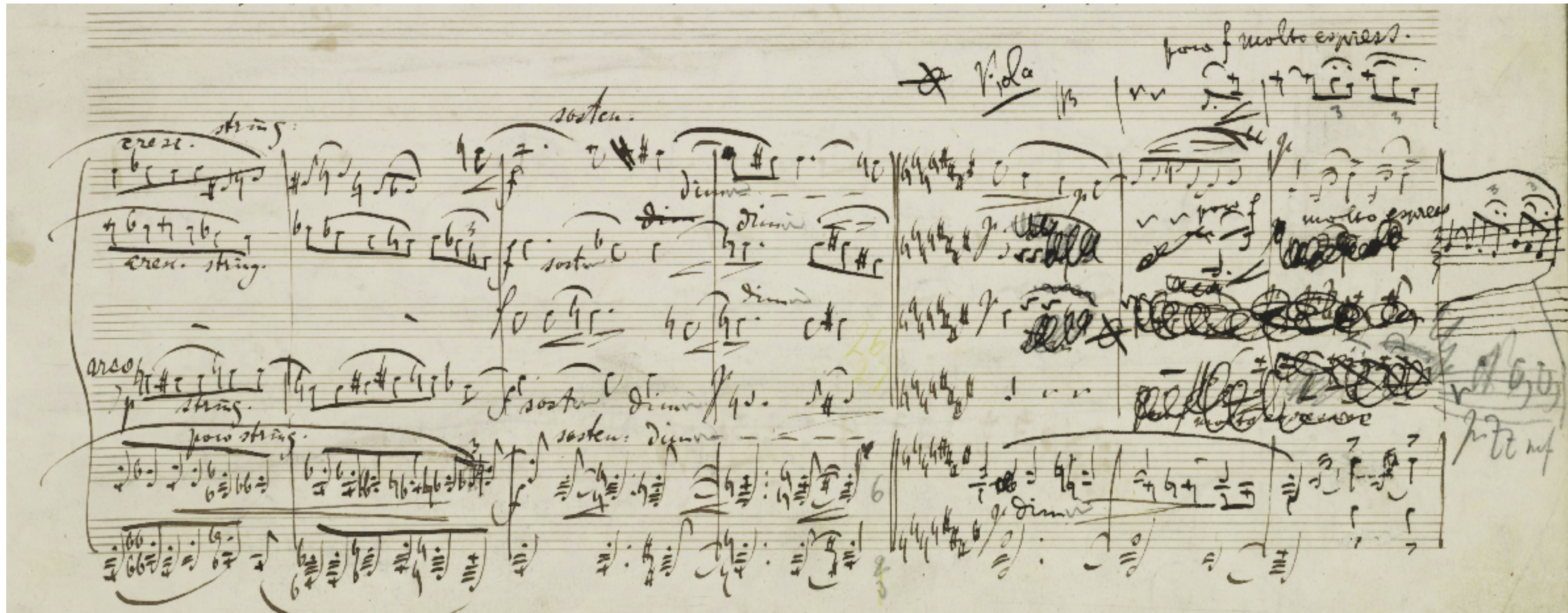




# What composing music and developing quantum gravity have in common

attributed to Johannes Brahms: “It is not hard to compose, but what is fabulously hard is to leave the superfluous notes under the table.”

quantum-gravity version: “It is not hard to come up with frameworks for quantum gravity, but what is fabulously hard is to leave the superfluous ingredients under the table.”





# Guiding ideas for the development of quantum gravity

“Forks in the road on the way to quantum gravity”

R. Sorkin '97



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Mathematical consistency

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P. A. M. Dirac: "In any region of physics where very little is known, **one must keep to the experimental basis if one is not to indulge in wild speculation that is almost certain to be wrong.**

I do not wish to condemn speculation altogether. It can be entertaining and may be indirectly useful [...]. [...] one should not completely oppose speculation, but one must take care not to get too involved in it."

# Outline

1. Asymptotic safety: key concepts
  - Predictive power of a fixed point
  - Bridging the gap between scales
2. Asymptotic safety: current status - what we know and what we do not know
3. Asymptotic safety and its phenomenology in particle physics
4. Outlook, including connection to causal sets

review finally out:  
2606.21522



# Outline

## 1. Asymptotic safety: key concepts

- Predictive power of a fixed point
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Theory

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## 2. Asymptotic safety: current status - what we know and what we do not know

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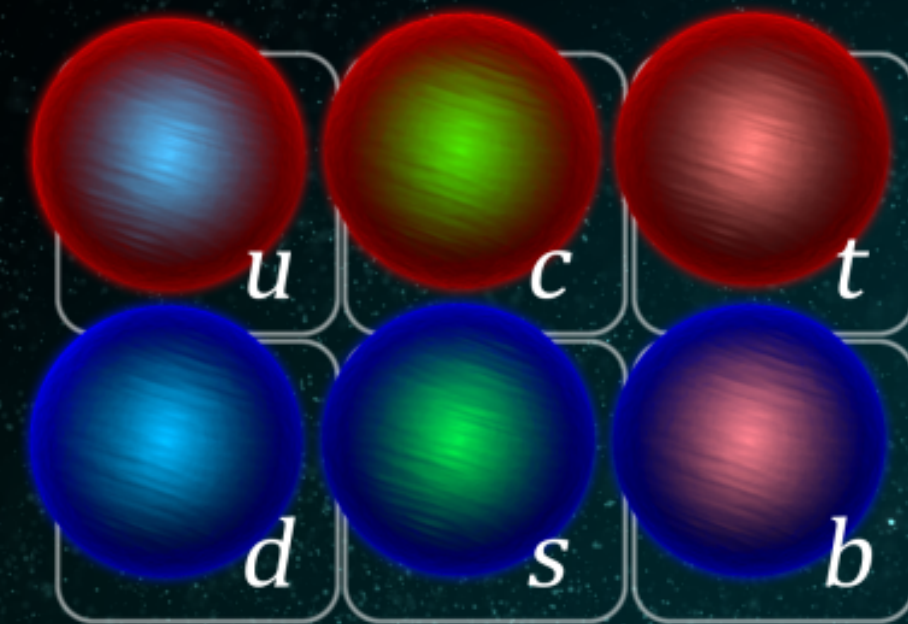
Reality

## 4. Outlook, including connections to causal sets

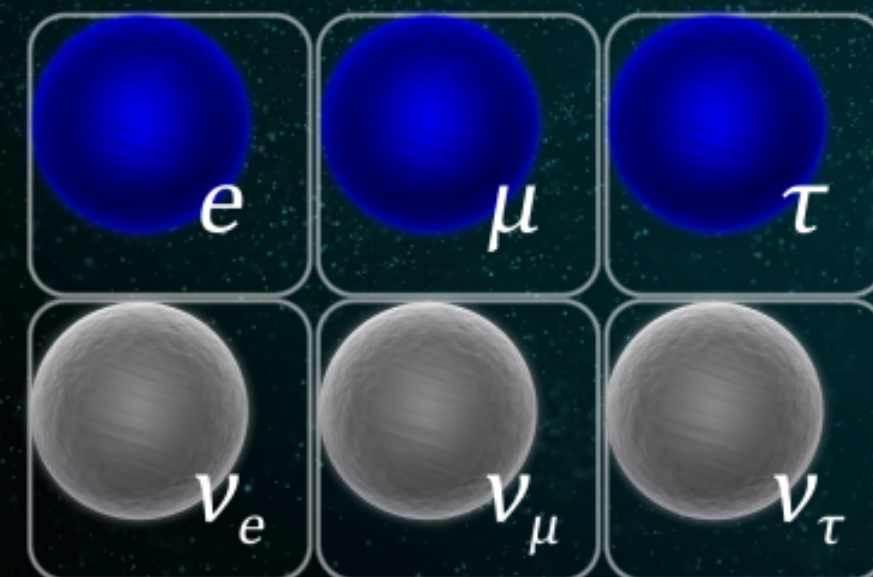
Dream



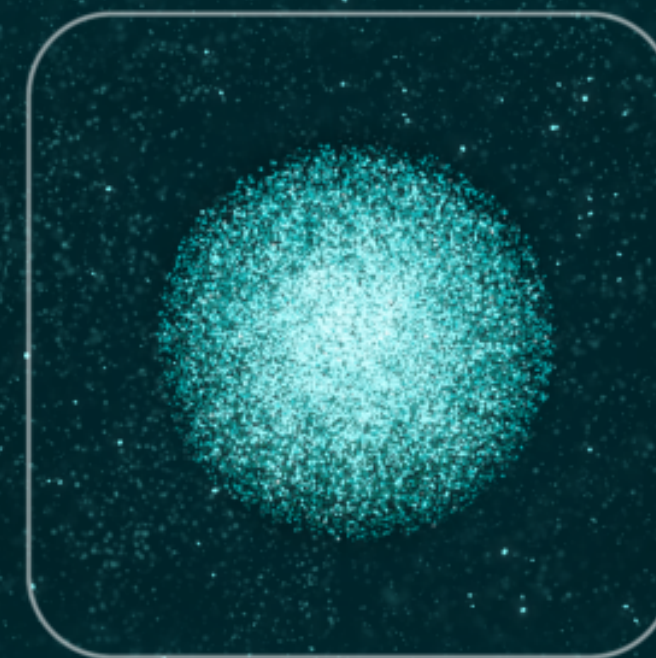
# Quantizing gravity: Motivations from particle physics



Quarks



Leptons



Higgs boson

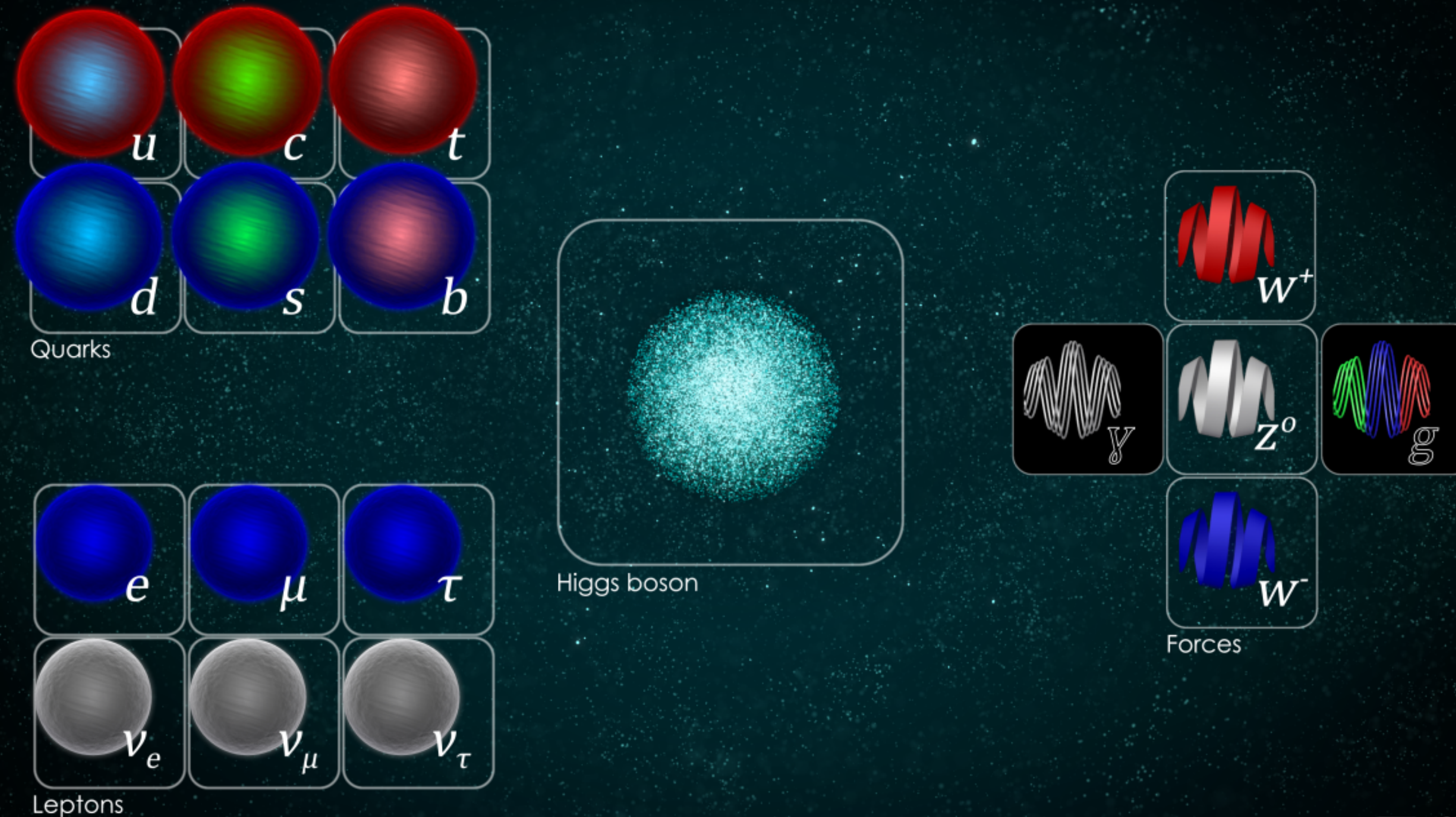


Forces

Standard Model: complete particle content since discovery of Higgs boson in 2012



# Quantizing gravity: Motivations from particle physics



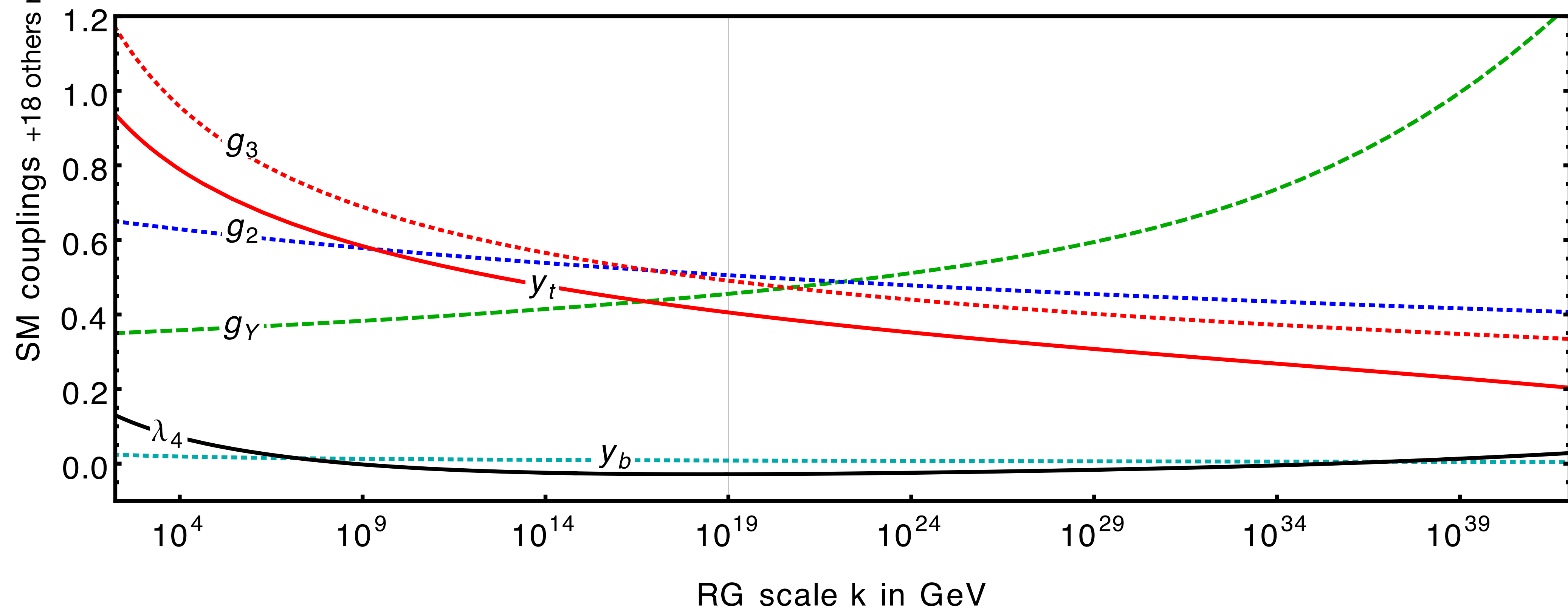
Standard Model: complete particle content since discovery of Higgs boson in 2012

Interactions determined by couplings

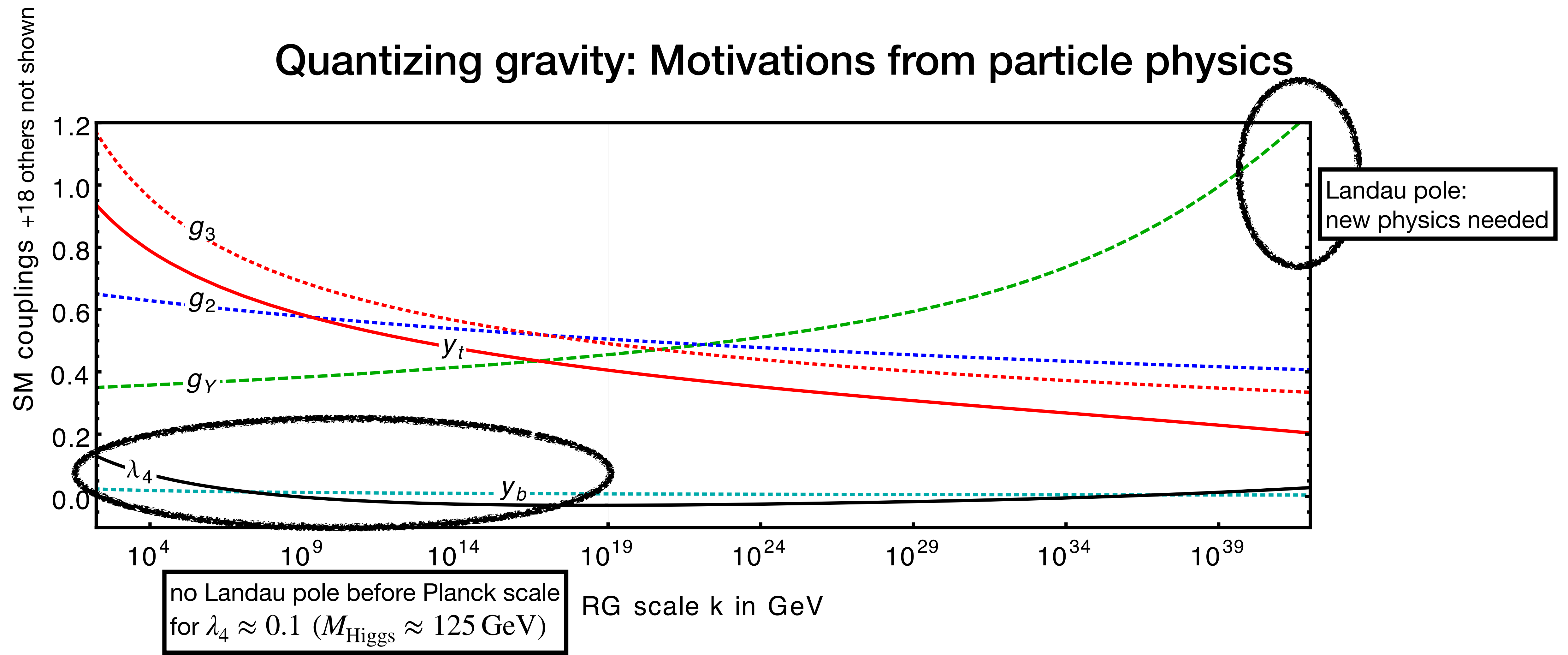
Couplings “run” as a function of energy scale (also in theories which are UV finite)



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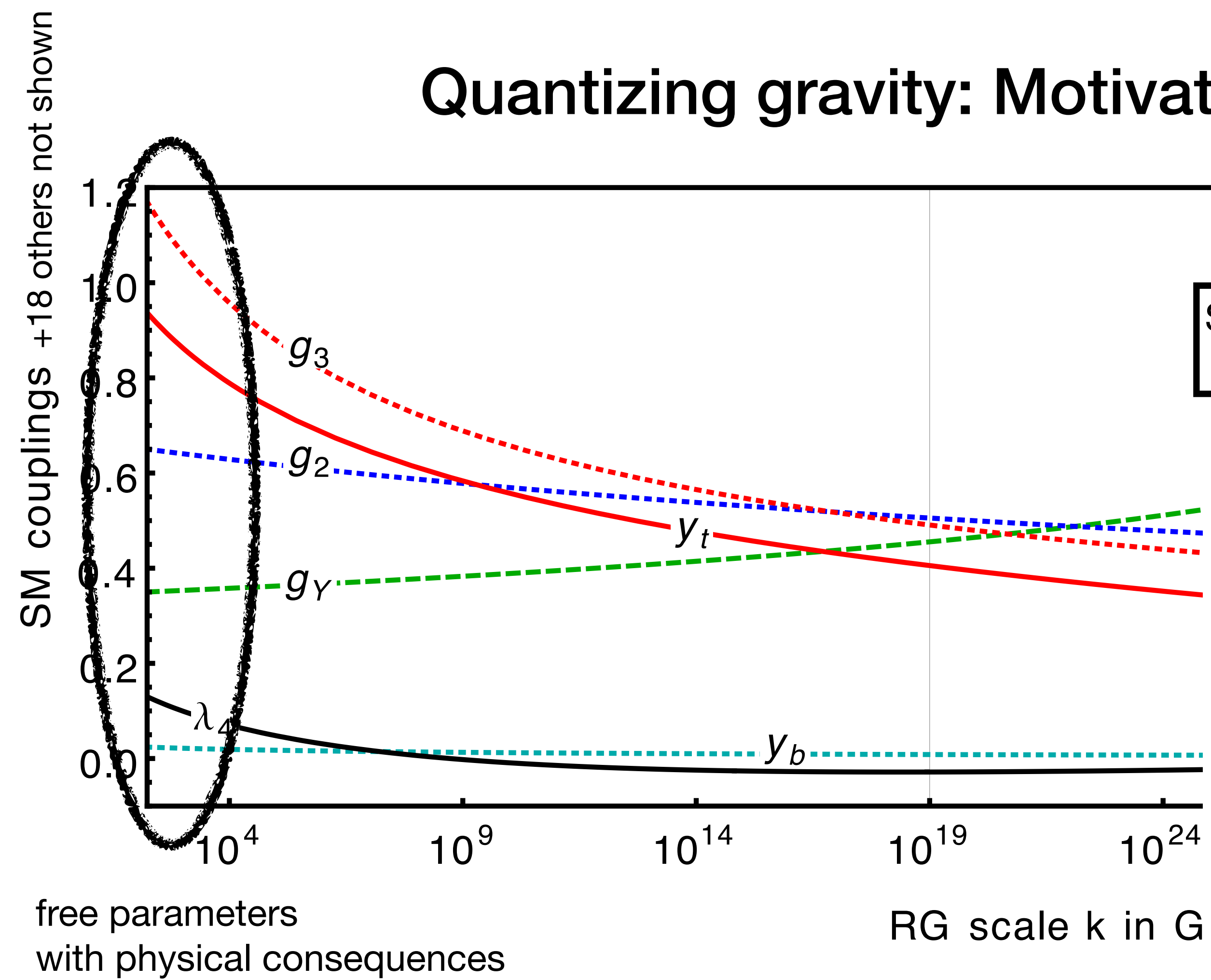


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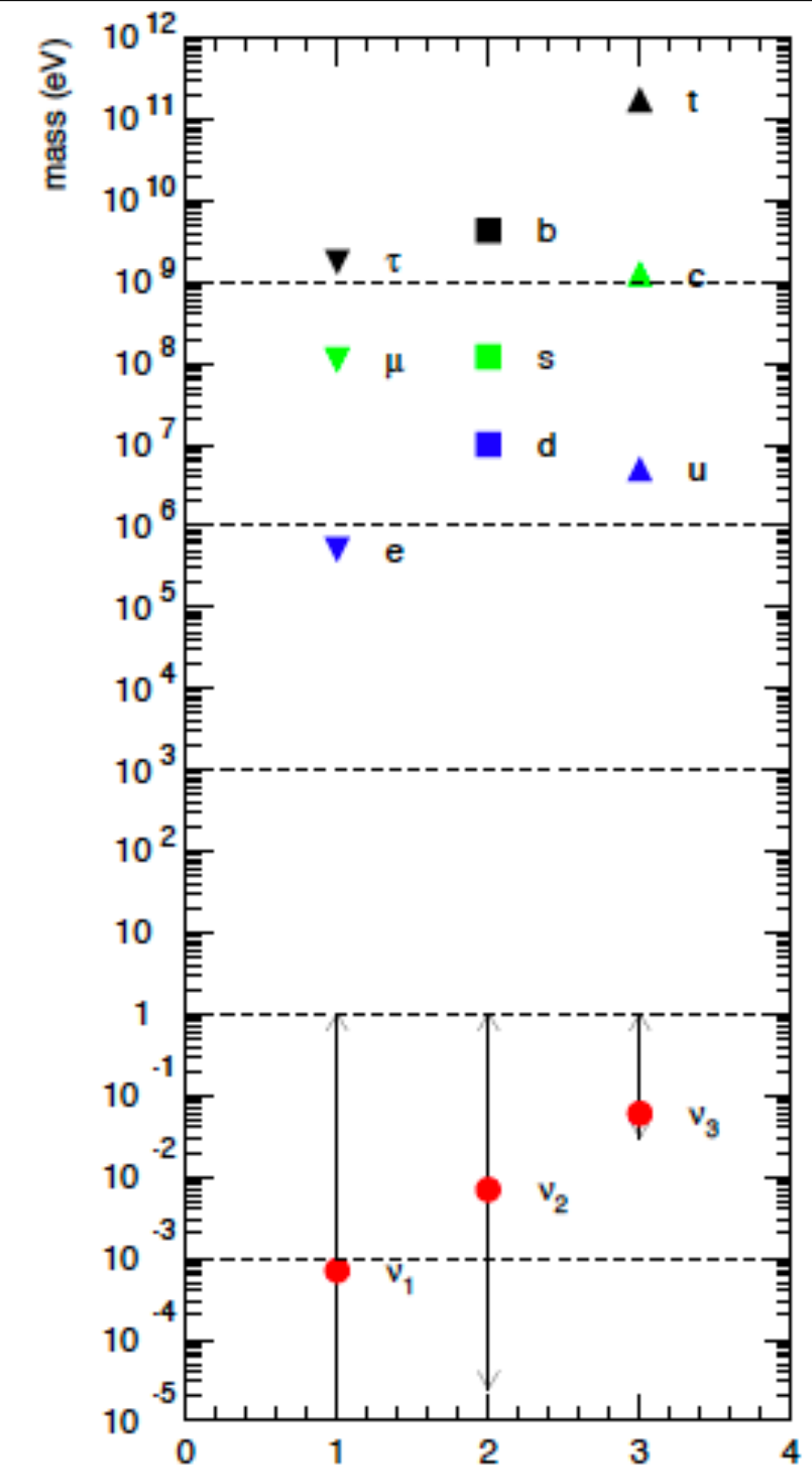


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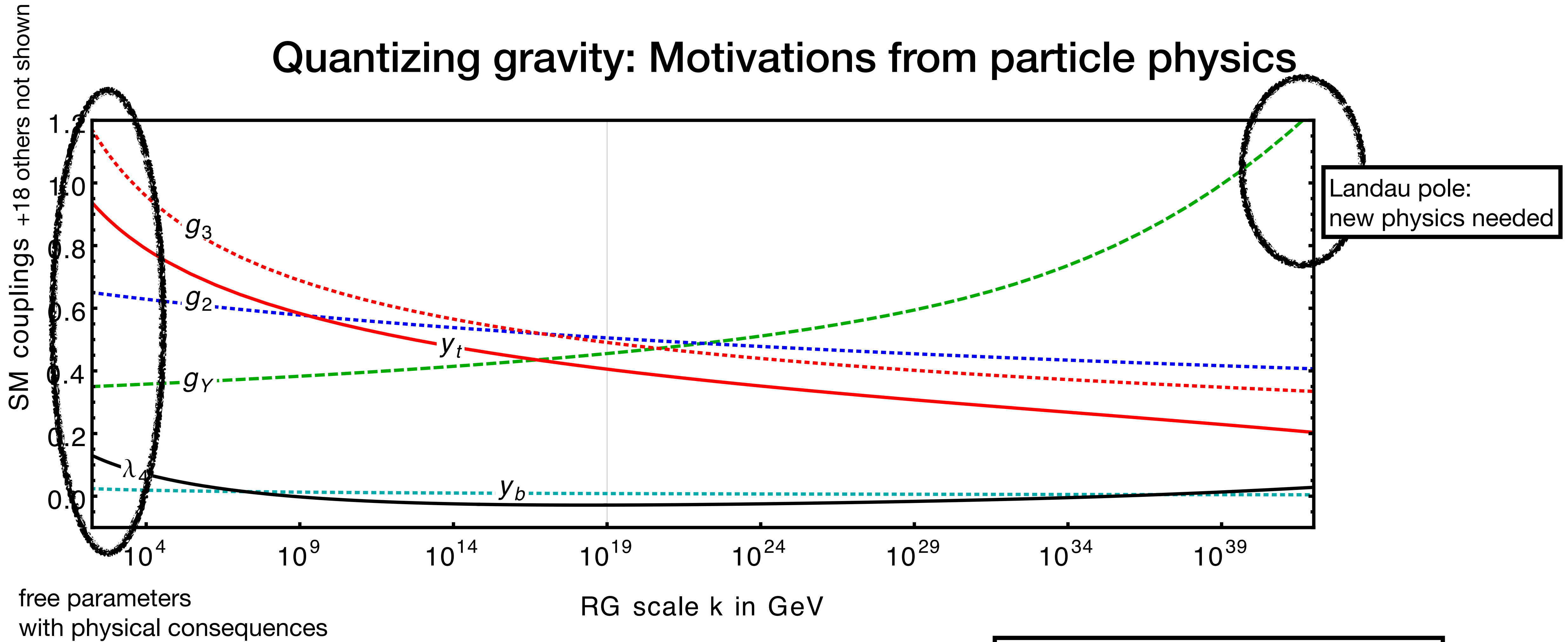
Why are neutrinos masses so tiny?  
 Why is there very little flavor mixing in the quark sector?  
 ....

Standard Model fermion masses



Landau pole:  
new physics needed

# Quantizing gravity: Motivations from particle physics



Why are neutrinos masses so tiny?  
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Can quantum gravity:  
 a) solve the Landau-pole problem  
 b) explain some of the free parameters?



# Mind the gap: quantum gravity in particle physics?

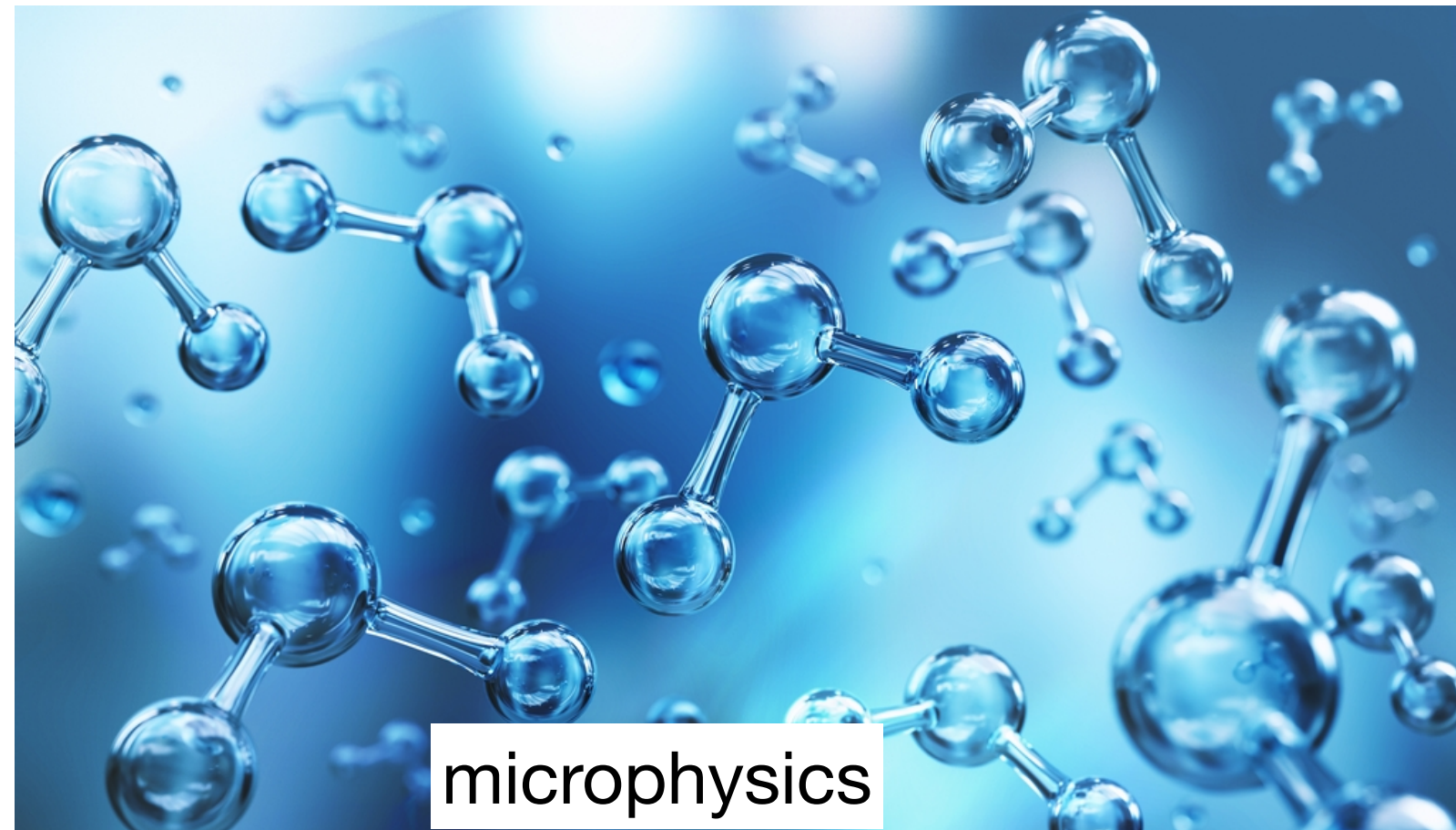
quantum gravity

particle physics

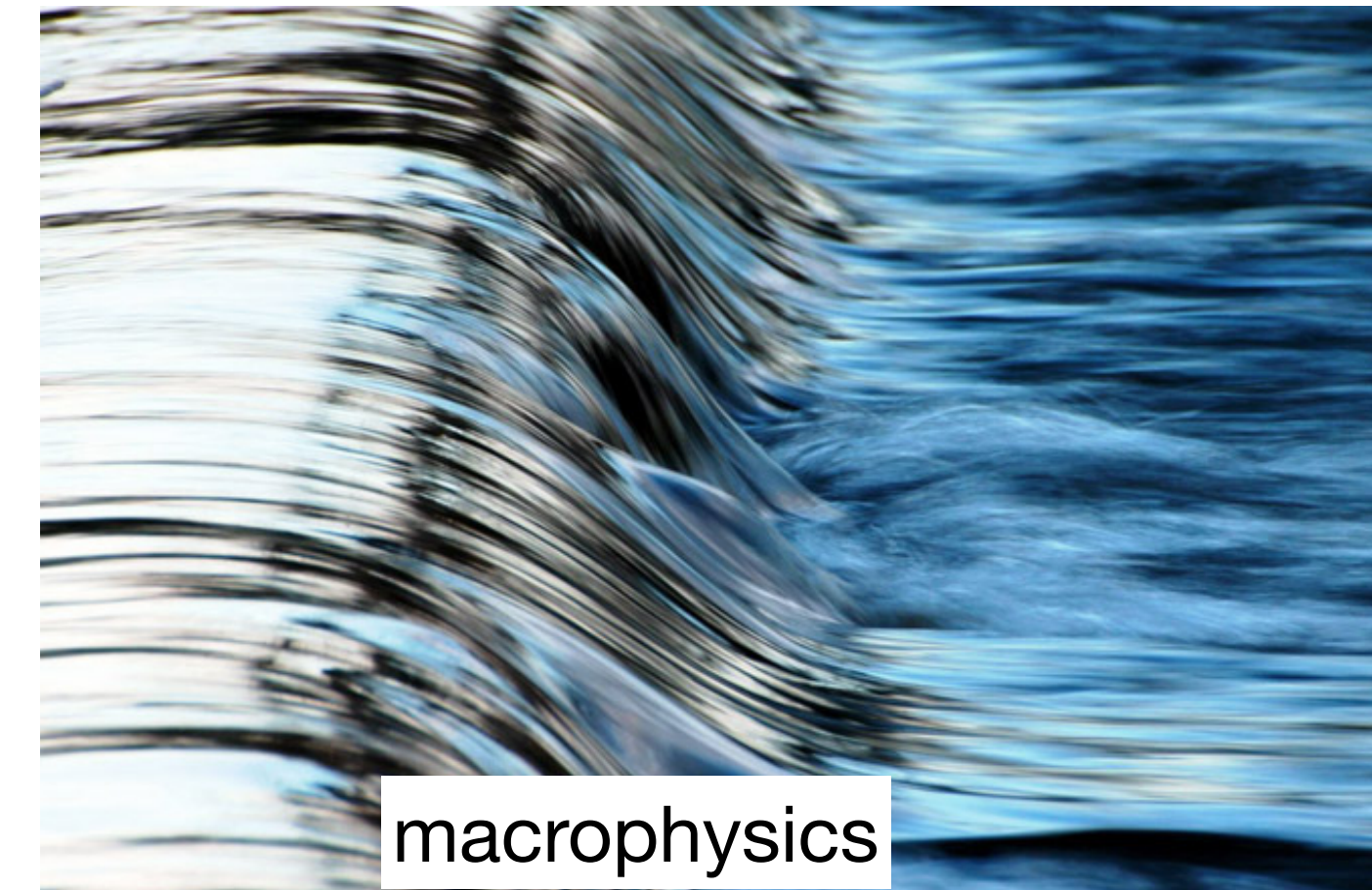
$$\ell_{\text{Planck}} \approx 10^{-35} \text{m}$$

$$\ell_{\text{LHC}} \approx 10^{-17} \text{m}$$

length scales



determines



Note: no new dynamical effects in particle physics, rather derivation of effective/phenomenological models

Suitable tool: Renormalization Group flow of couplings: all possible couplings in an effective Lagrangian evolve as function of scale

# Quantizing gravity: the problem

$$Z = \int \mathcal{D}g_{\mu\nu} e^{iS[g_{\mu\nu}]} \quad \text{with } S = \frac{1}{16\pi G_N} \int d^4x \sqrt{-g} R$$



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1-loop counterterms:

- $\sqrt{-g} \rightarrow \Lambda$
- $\sqrt{-g} R \rightarrow G_N$
- $\sqrt{-g} R^2, \sqrt{-g} R_{\mu\nu} R^{\mu\nu} \rightarrow$  new couplings [’t Hooft, Veltman ‘74]



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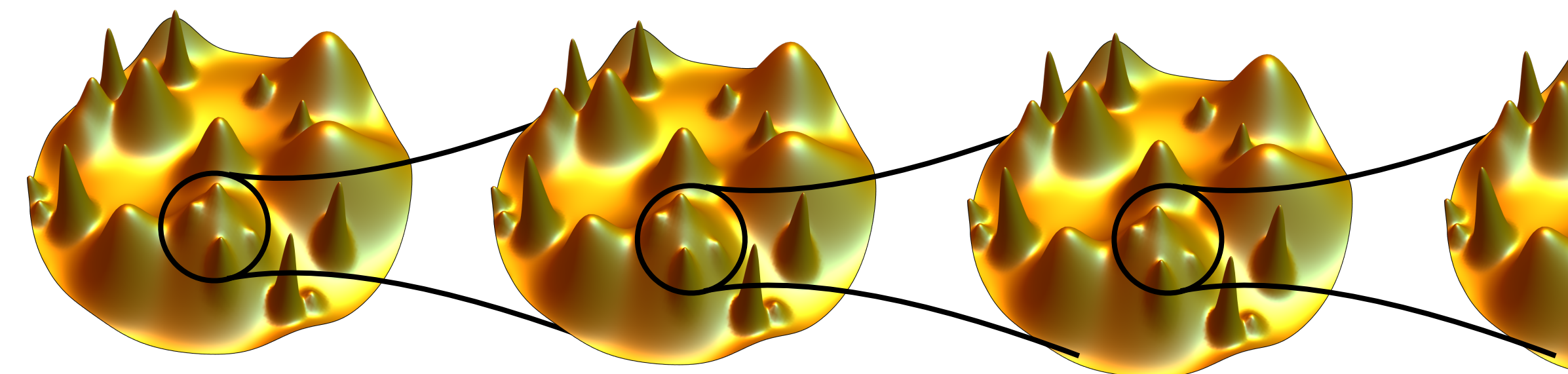
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$\Rightarrow$  predictivity breaks down

Proposed solution:

go **beyond perturbation theory** &  
add **symmetry** requirement on the couplings

Renormalization Group flow starting at fixed point  
(= scale symmetry)

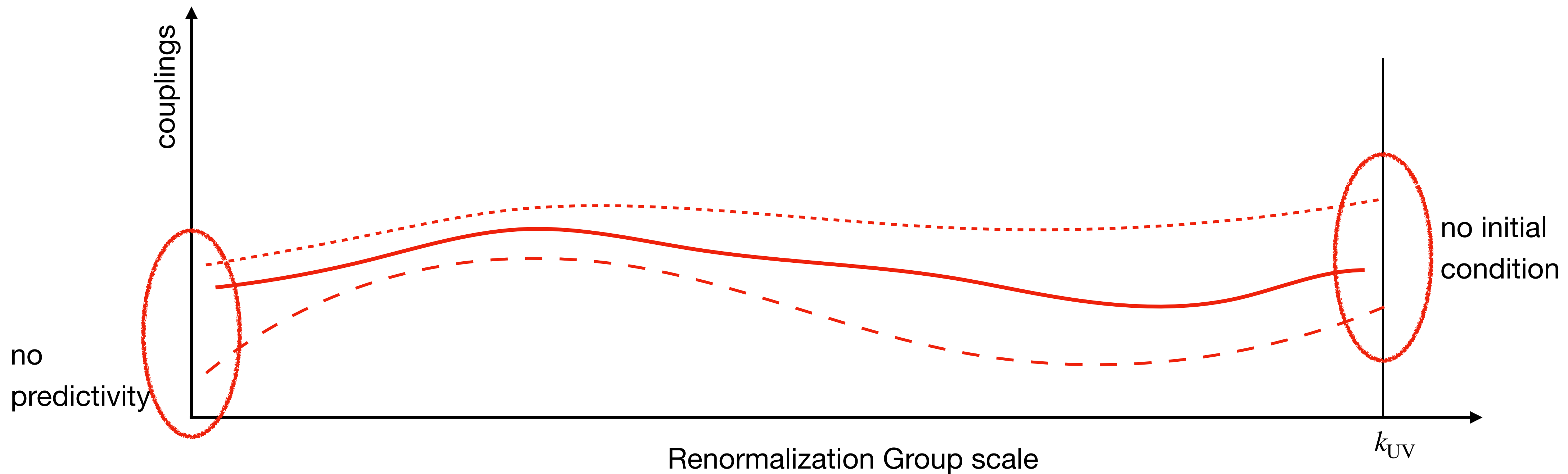




# Predictivity from scale symmetry

Couplings evolve under Renormalization Group flow

- Beta functions  $\beta_{g_i} = k\partial_k g_i(k)$  encode this evolution: calculable from a given action
- Breakdown of predictivity: Initial conditions  $g_i(k_{UV})$  are lacking

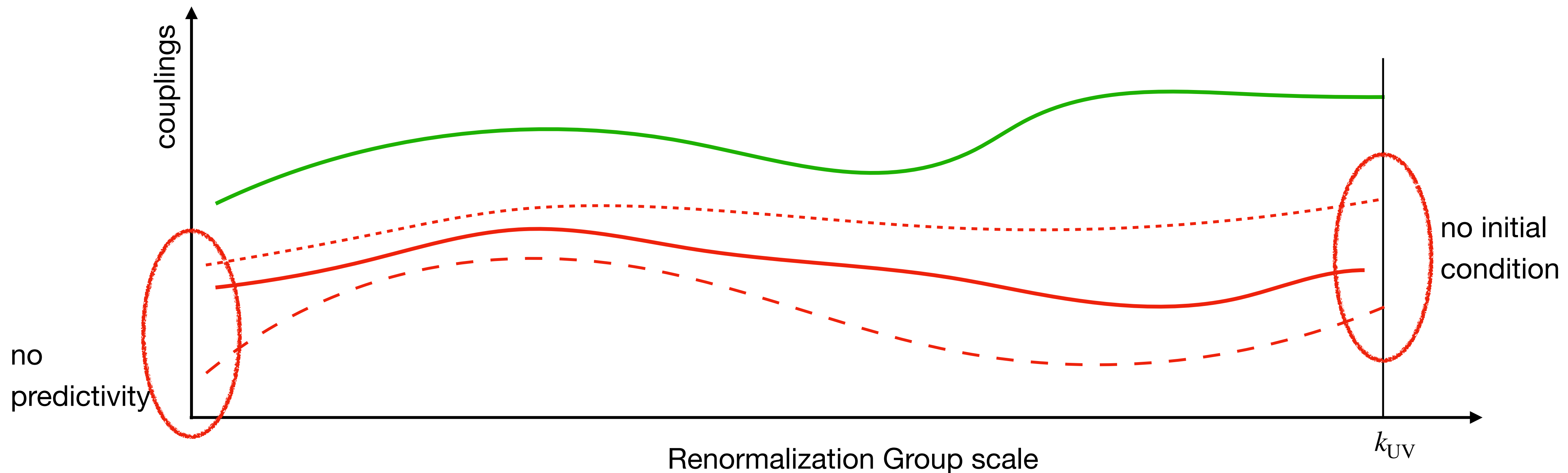


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couplings start in the vicinity of a fixed point (scale invariant regime) in the UV:  $g_i(k_{\text{UV}}) = g_{i*} + \delta g_i$

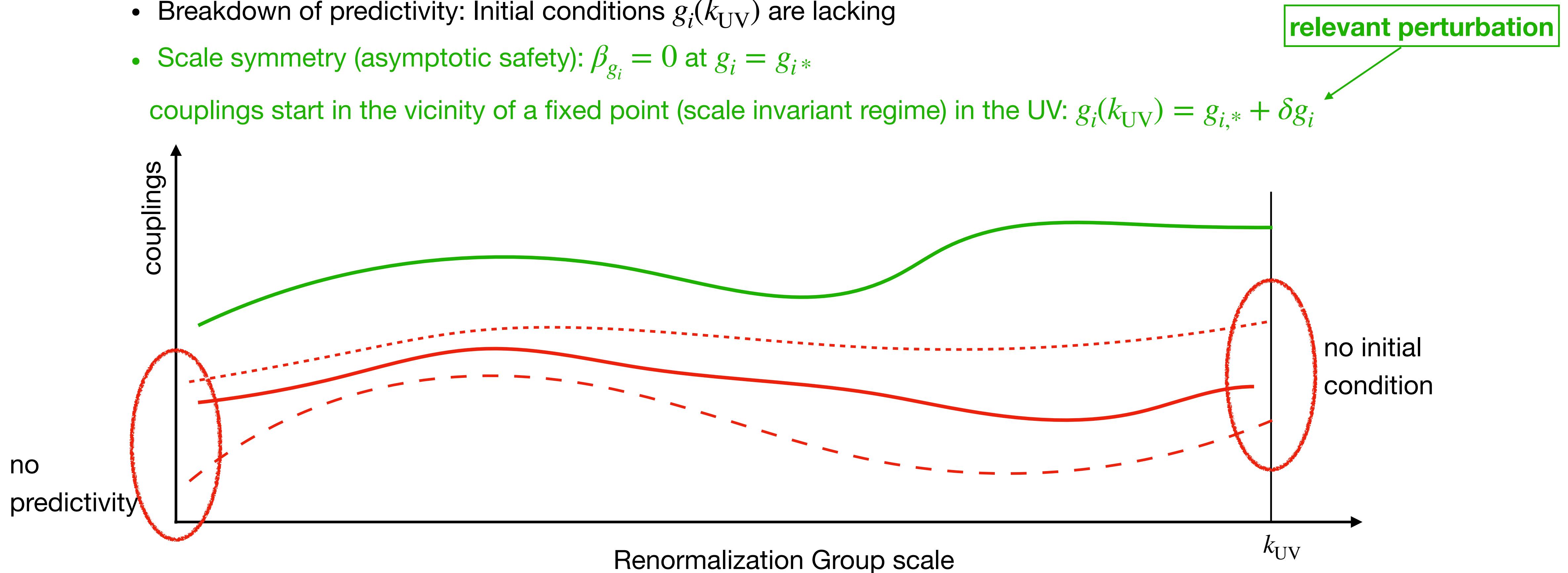


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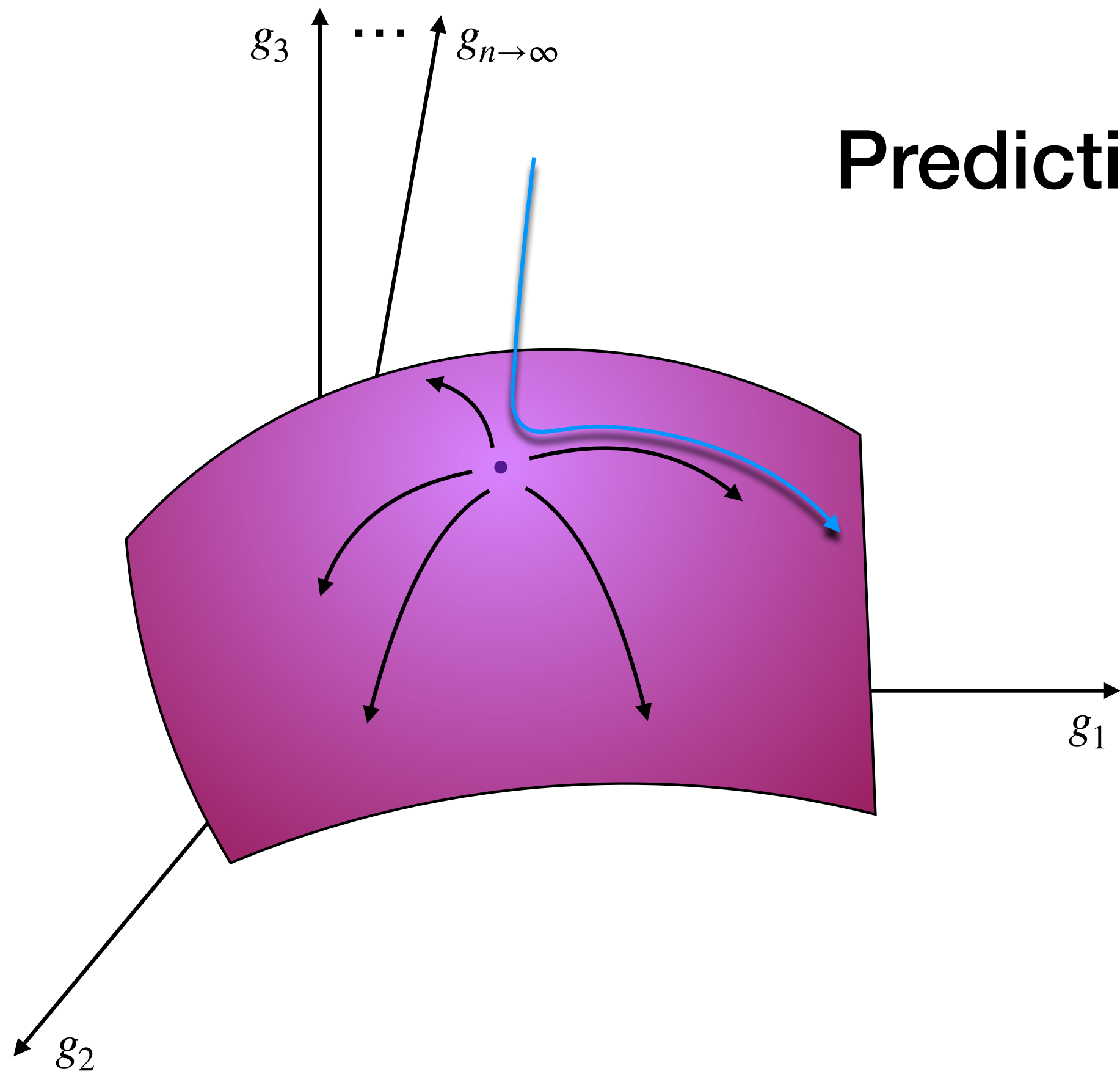
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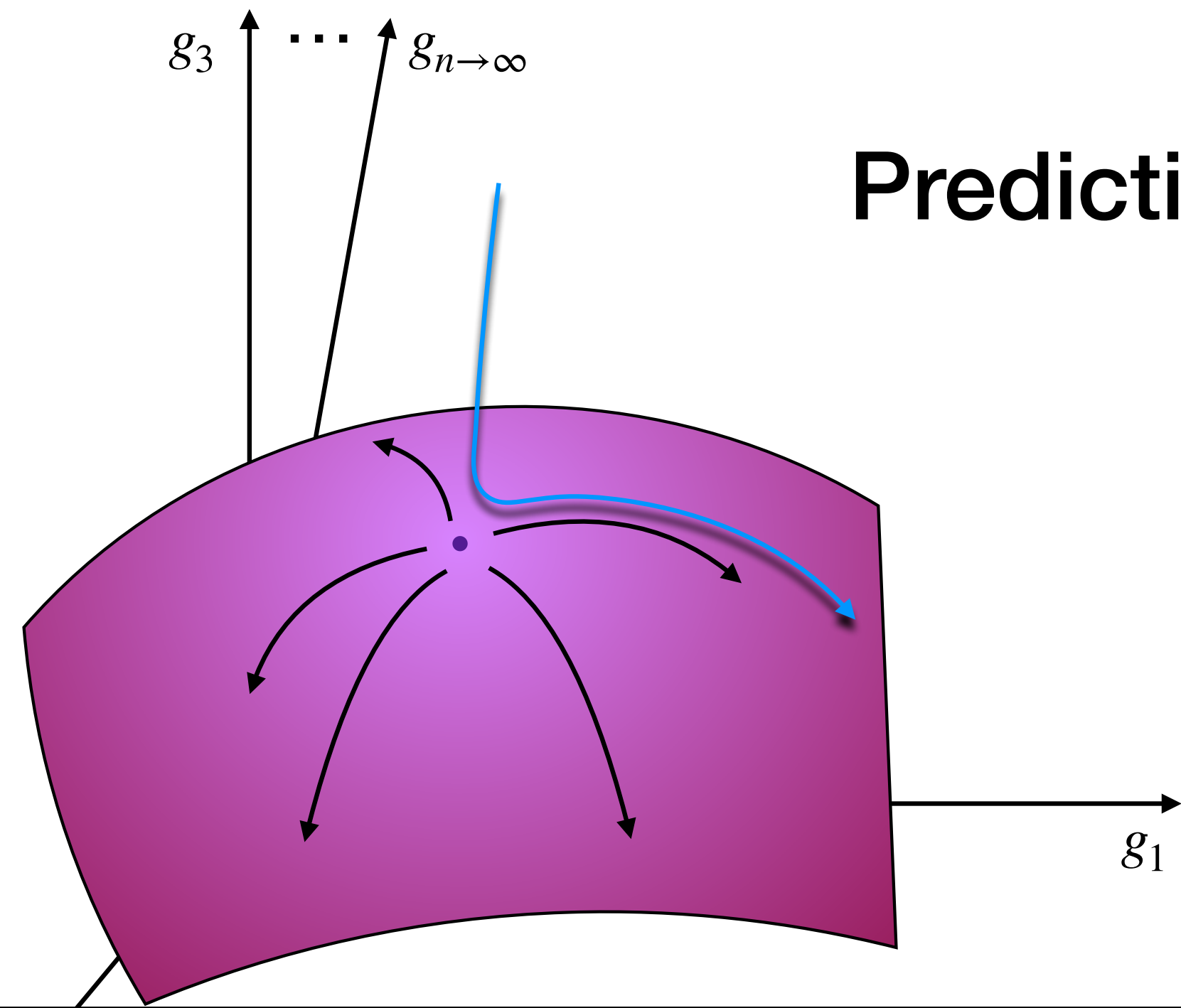


# Predictivity from scale symmetry



- Asymptotic safety condition selects low-dimensional hypersurface in space of all couplings of an EFT
- Renormalization Group flow around a fixed point:
  - “source” directions (= relevant directions)
  - “sink” directions (= irrelevant directions)

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Quantum fluctuations

screen or antiscreen interactions, e.g.,

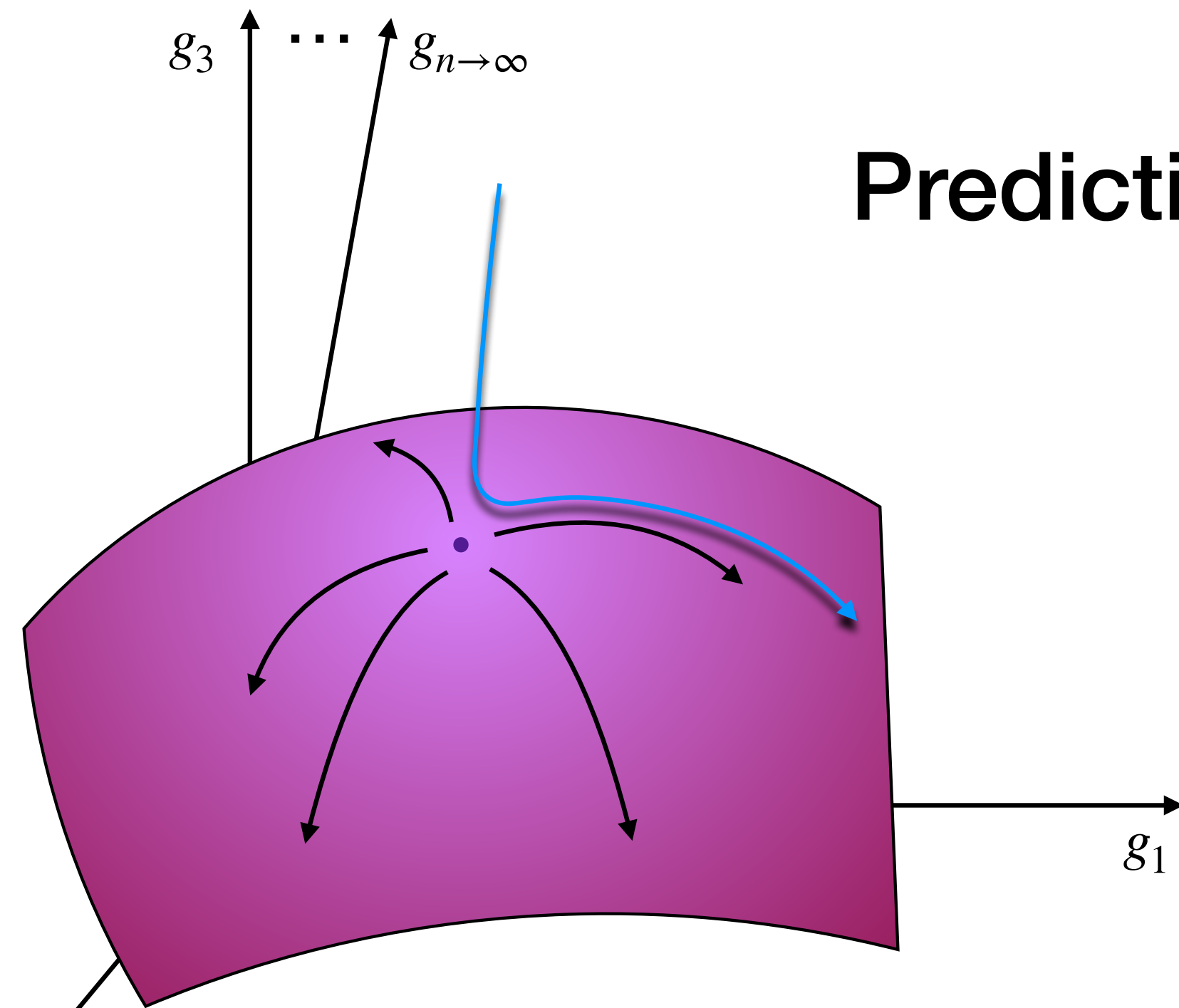
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→  $e(k)$  decreases as  $k$  is lowered

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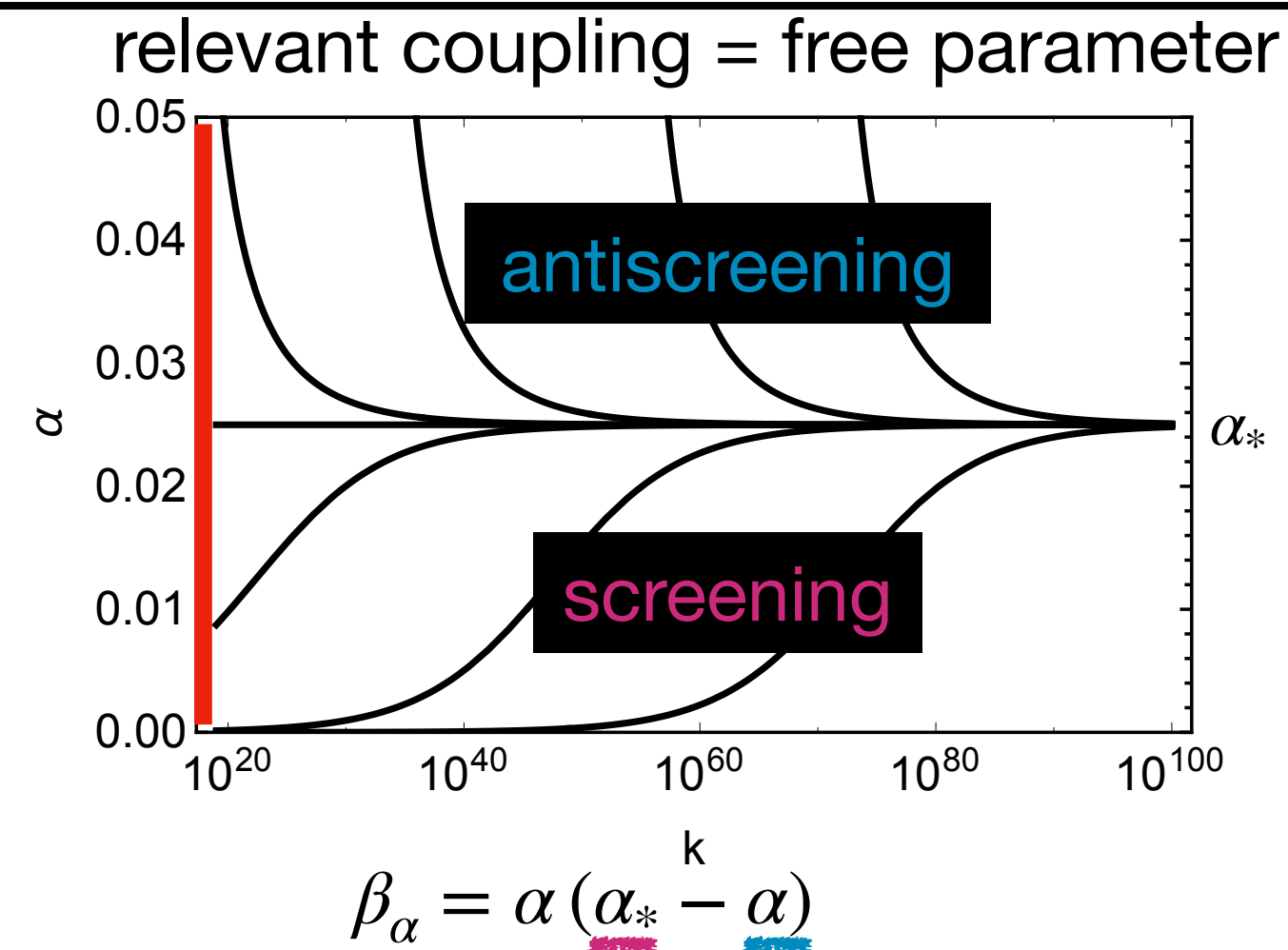
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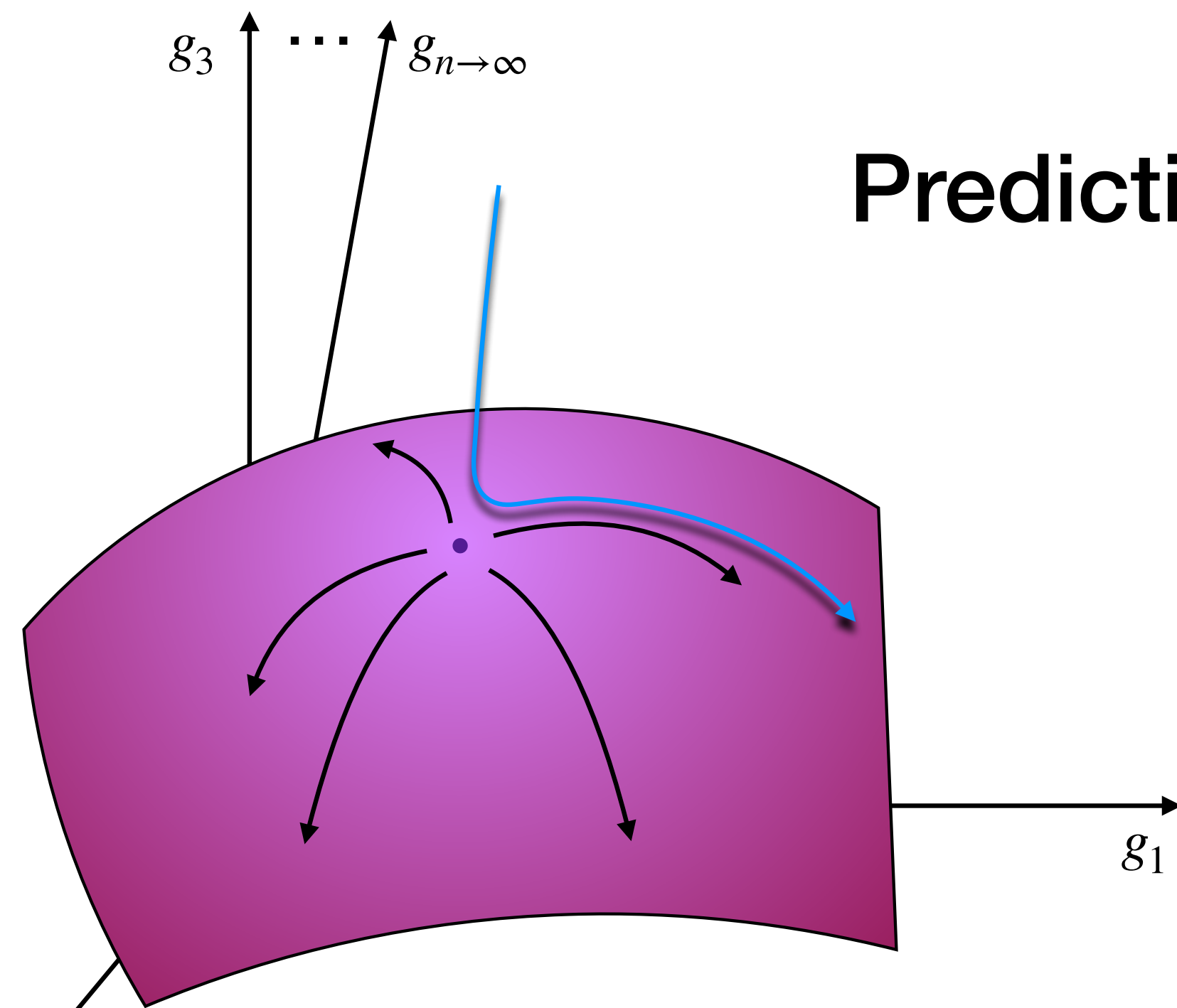
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quantum fluctuations drive coupling **away**  
**from** scale symmetry

→ a range of coupling values  
achievable at the Planck scale





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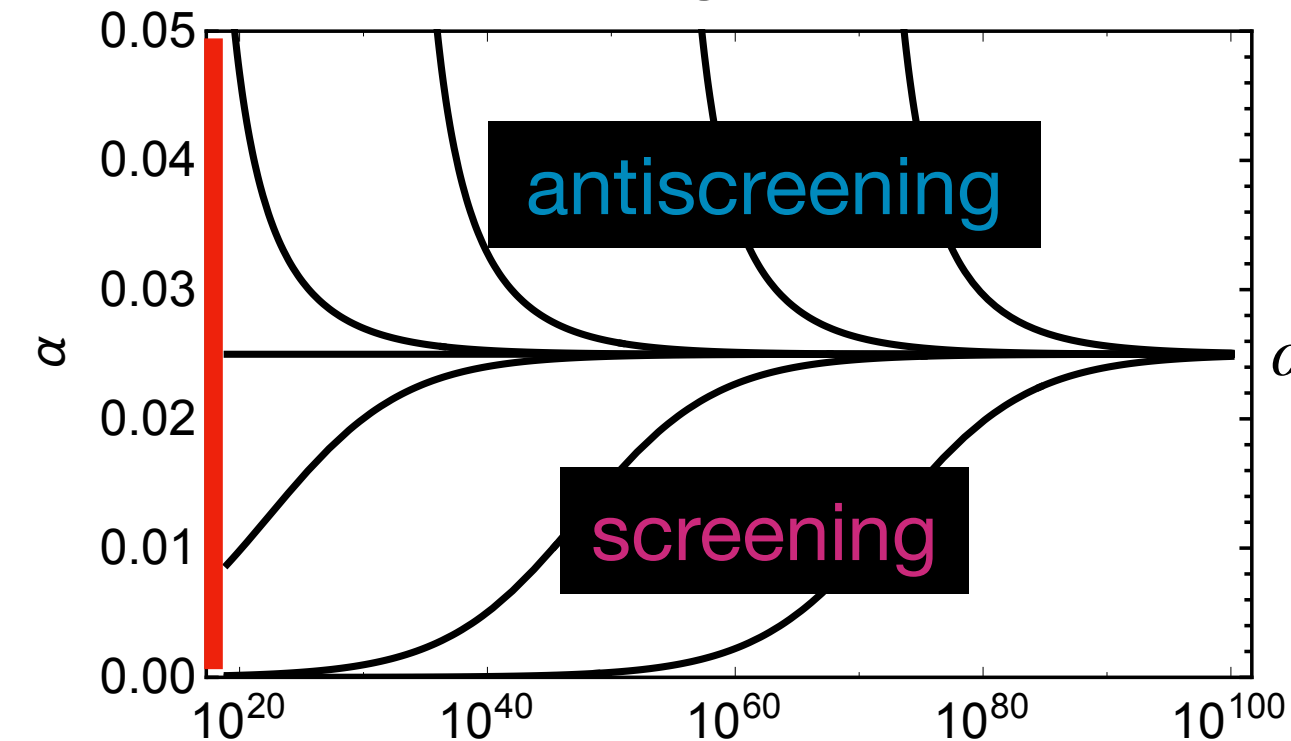
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relevant coupling = free parameter

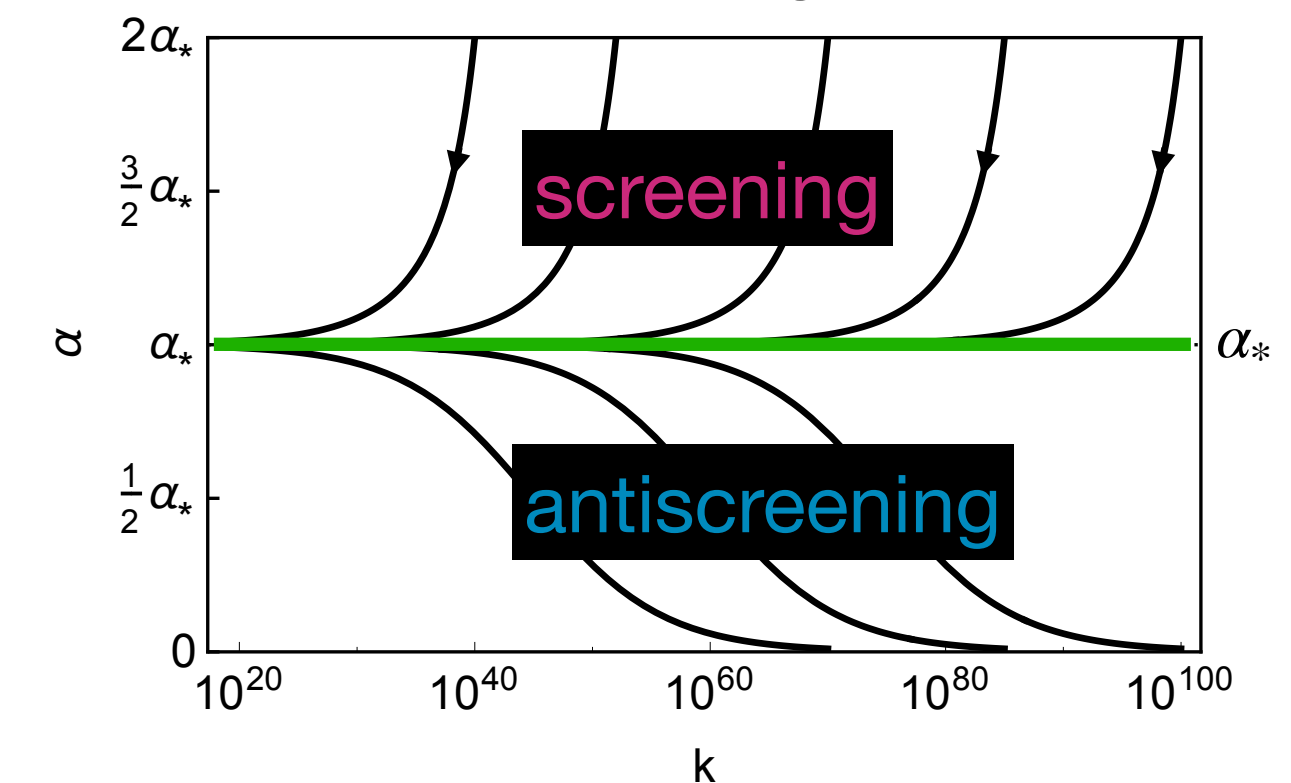


$$\beta_\alpha = \alpha \left( \alpha_* - \alpha \right)$$

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→ a range of coupling values  
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irrelevant coupling = prediction

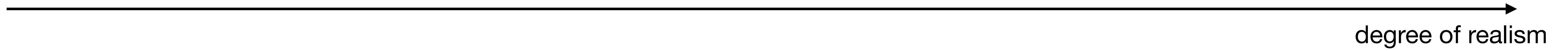


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quantum fluctuations drive coupling  
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# Current status



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S. Weinberg '76    M. Reuter '96

degree of realism

Euclidean quantum gravity:  
Existence of fixed point established  
(functional Renormalization Group:  
hundreds of papers  
lattice (dynamical triangulations;  
Ambjørn, Jurkiewicz, Loll '00):  
supporting evidence)

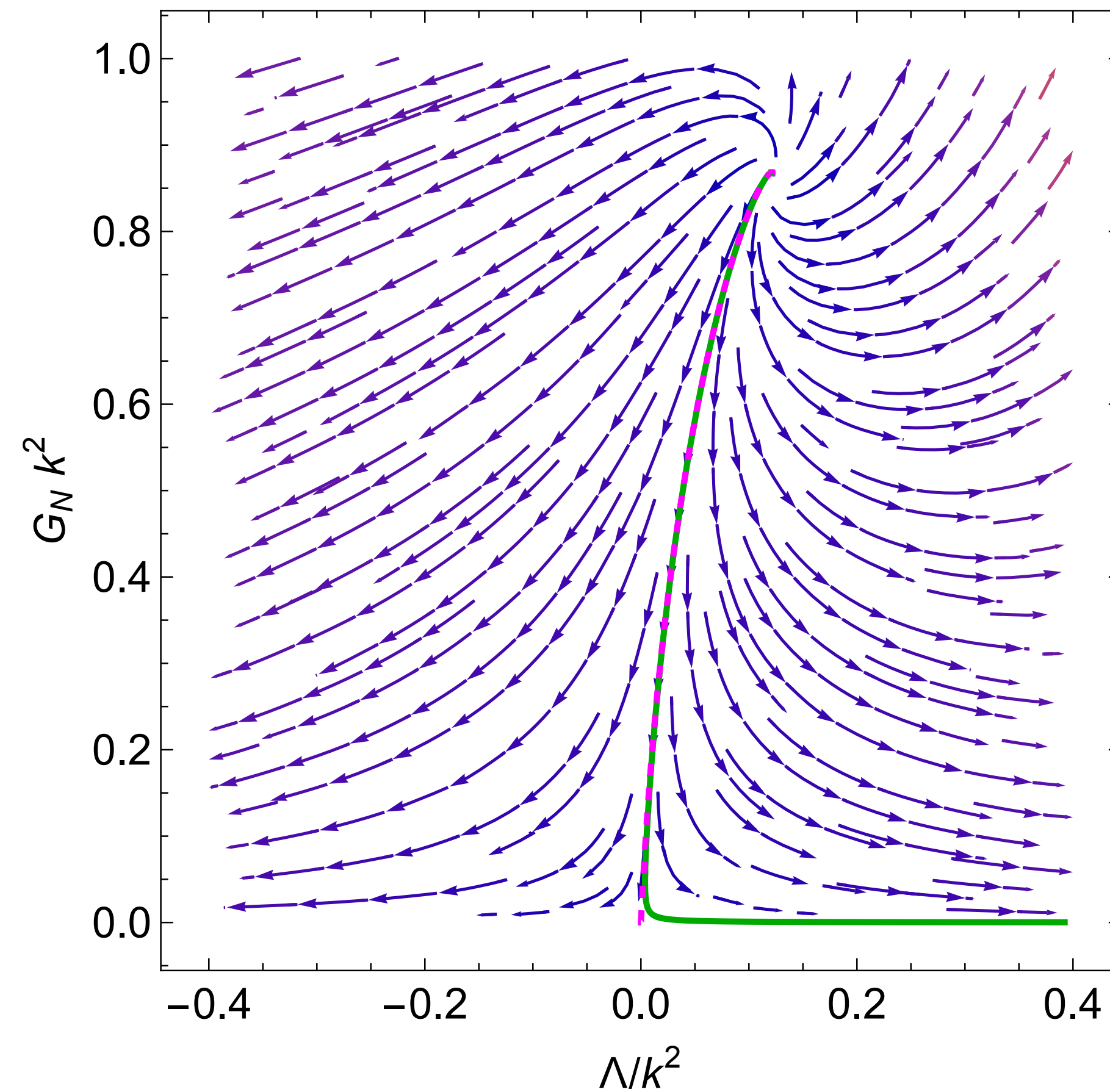


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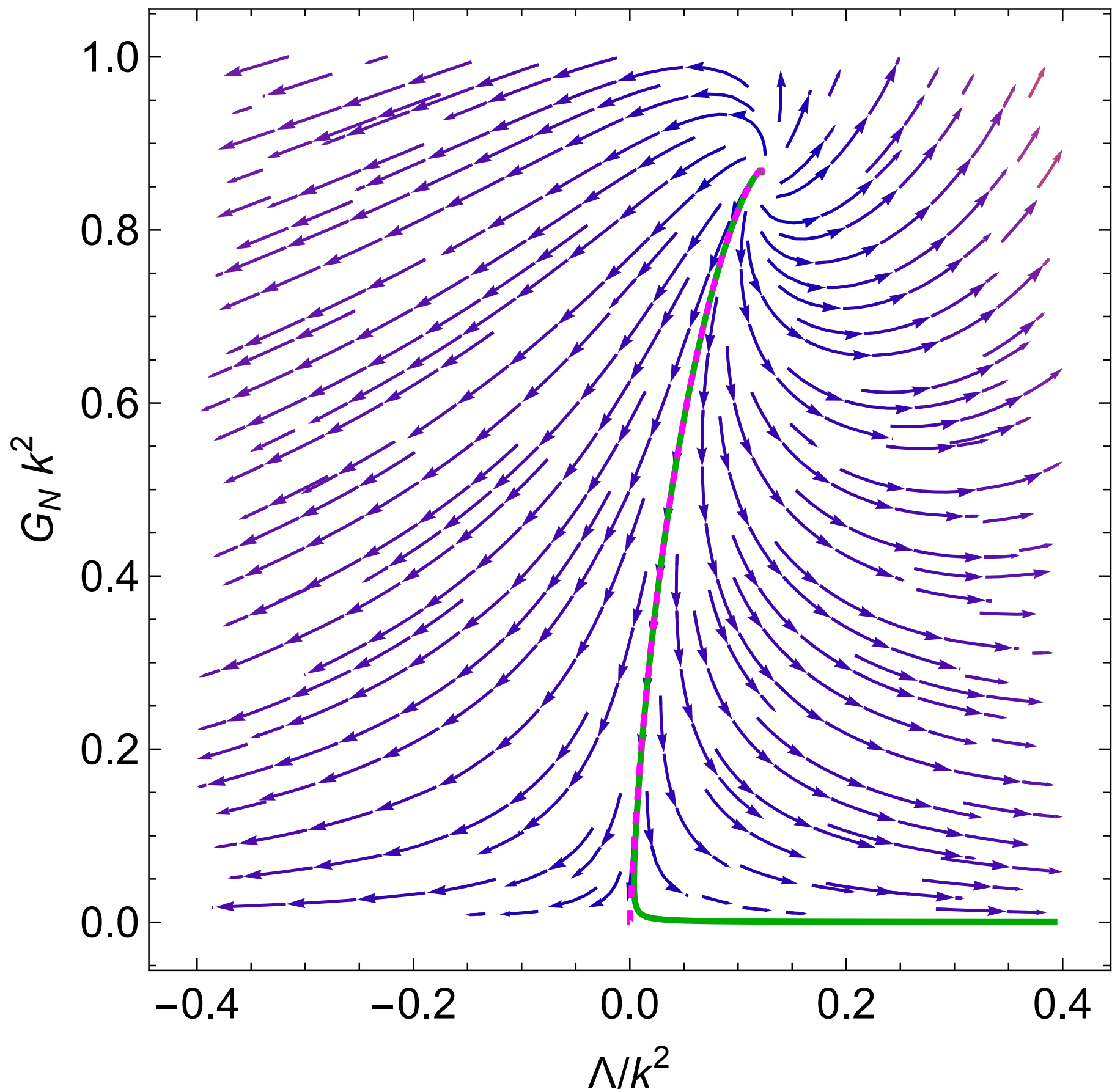


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relevant directions ( $\theta > 0$ ):  
 $\sqrt{-g}\Lambda, \sqrt{-g}R\frac{1}{16\pi G_N}, \sqrt{-g}(R^2 + \#R_{\mu\nu}R^{\mu\nu})a$   
[Benedetti, Machado, Saueressig '09;  
Falls, Litim, et al. '13, '14;  
Denz, Pawłowski, Reichert '16;  
Falls, Ohta, Percacci '20;  
Baldazzi, Falls, Kluth, Knorr '23]  
all other couplings irrelevant

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But: matter exists (and matters)

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Euclidean quantum gravity with matter:

Mounting evidence for fixed point  
of Standard Model with gravity

(functional Renormalization Group:  
~ hundred papers

lattice (dynamical triangulations):  
simple matter)



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But: matter exists (and matters)

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lattice (dynamical triangulations):  
simple matter)



Lorentzian quantum gravity:

Fixed point in simple truncations  
(with some matter)

(functional Renormalization Group:  
~ few papers

[Assant, d'Angelo, Ferrero, Knorr, Reichert, Pawłowski, Litim]  
lattice (dynamical triangulations):  
Wick-rotatable sector)



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Dona, AE, Percacci '13

Fehre, Litim, Pawłowski, Reichert '21

degree of realism

But: matter exists (and matters)

But: spacetime isn't space

Euclidean quantum gravity:

Existence of fixed point established

(functional Renormalization Group:  
hundreds of papers

lattice (dynamical triangulations;  
Ambjørn, Jurkiewicz, Loll '00):  
supporting evidence)

Euclidean quantum gravity with matter:

Mounting evidence for fixed point  
of Standard Model with gravity

(functional Renormalization Group:  
~ hundred papers

lattice (dynamical triangulations):  
simple matter)

Lorentzian quantum gravity:

Fixed point in simple truncations  
(with some matter)

(functional Renormalization Group:  
~ few papers

[Assant, d'Angelo, Ferrero, Knorr, Reichert, Pawłowski, Litim]  
lattice (dynamical triangulations):  
Wick-rotatable sector)

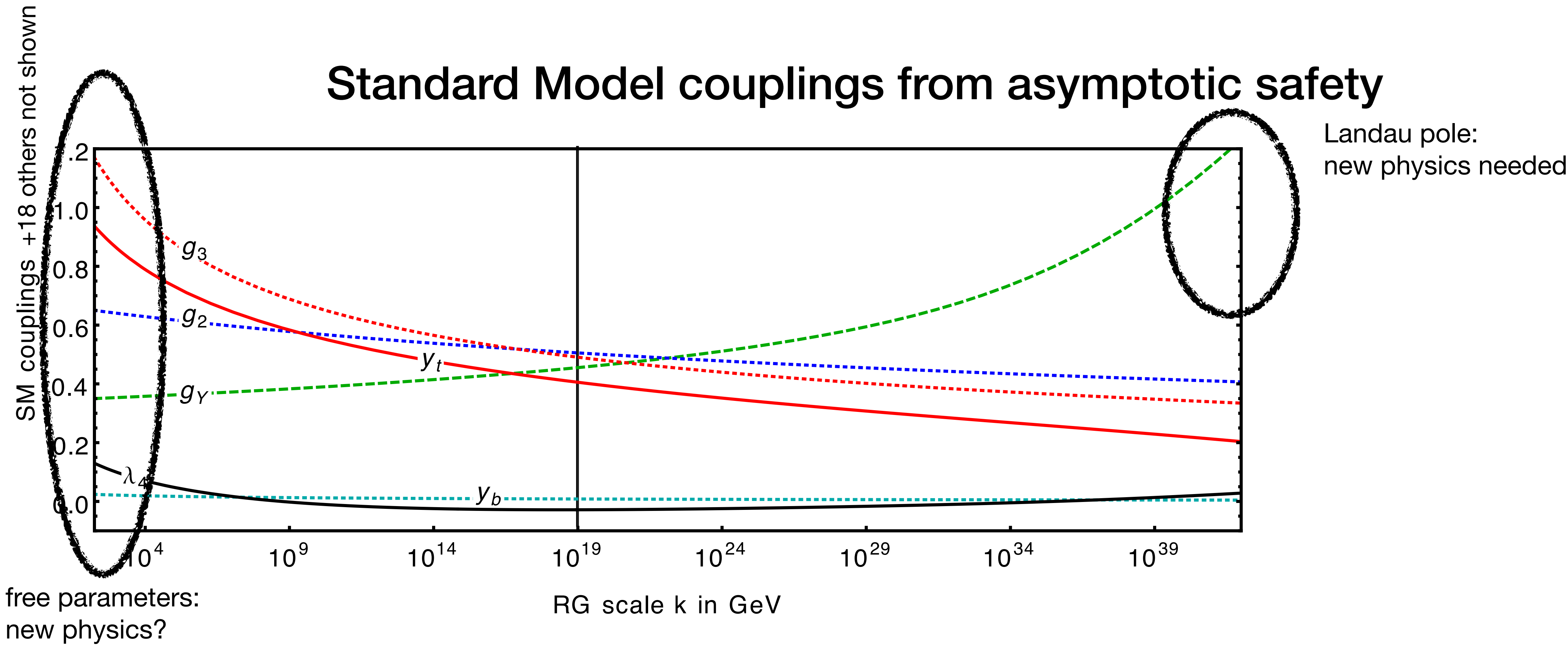


[Assant, Benedetti, Bonanno, Borissova, Christiansen, Codello, Daum, de Brito, Denz, del Porro, Donà, AE, Falls, Ferrero, Gessner, Gies, Gyftopoulos, Harst, Held, Kluth, Knorr, Kowalska, Labus, Lino dos Santos, Lippoldt, Litim, Lumma, Morris, Niedermaier, Ohta, Pauly, Pawłowski, Percacci, Pereira, Platania, Rahmede, Ray, Reichert, Reuter, Ripken, Saueressig, Schiffer, Sessolo, Silveravalle, Sprenger, Vacca, Versteegen, Wagner, Wang, Wetterich, Willaschek, Yamada, Zambelli, Zanusso and many others]

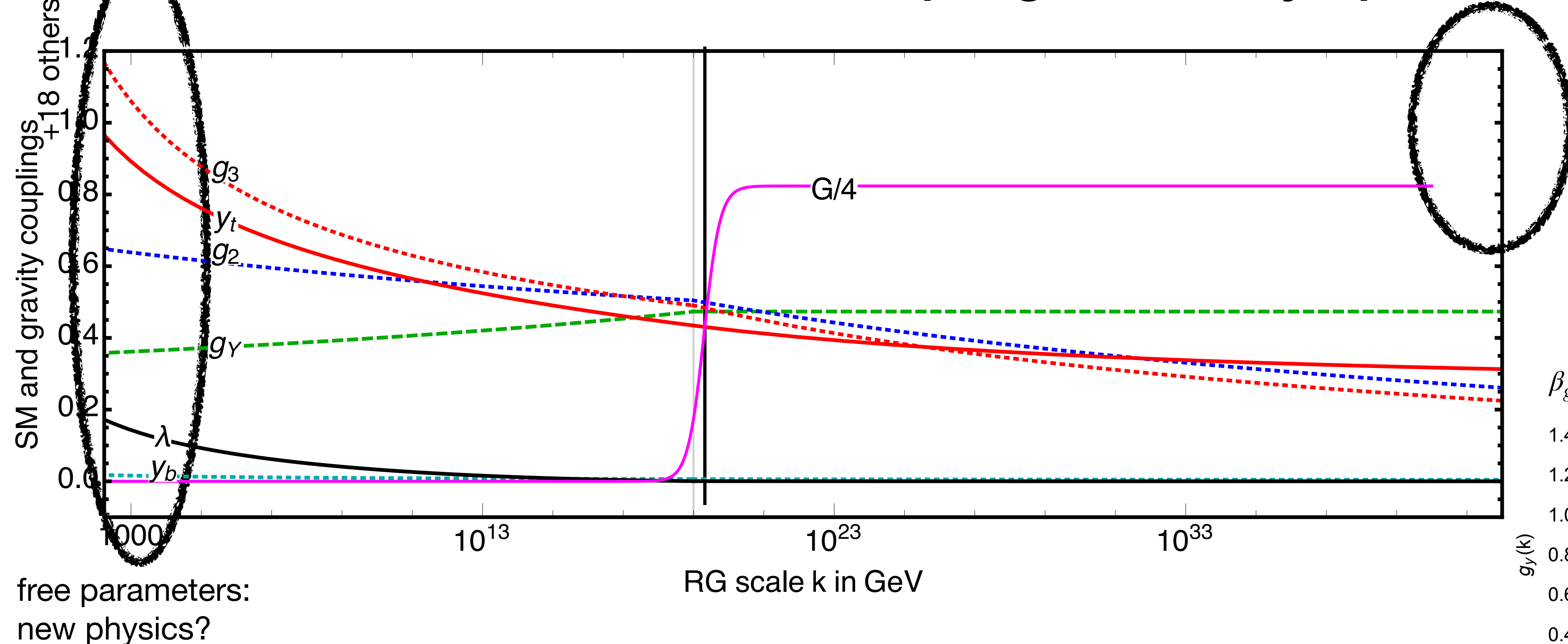


**WORK IN  
PROGRESS**

# Standard Model couplings from asymptotic safety



# Standard Model couplings from asymptotic safety

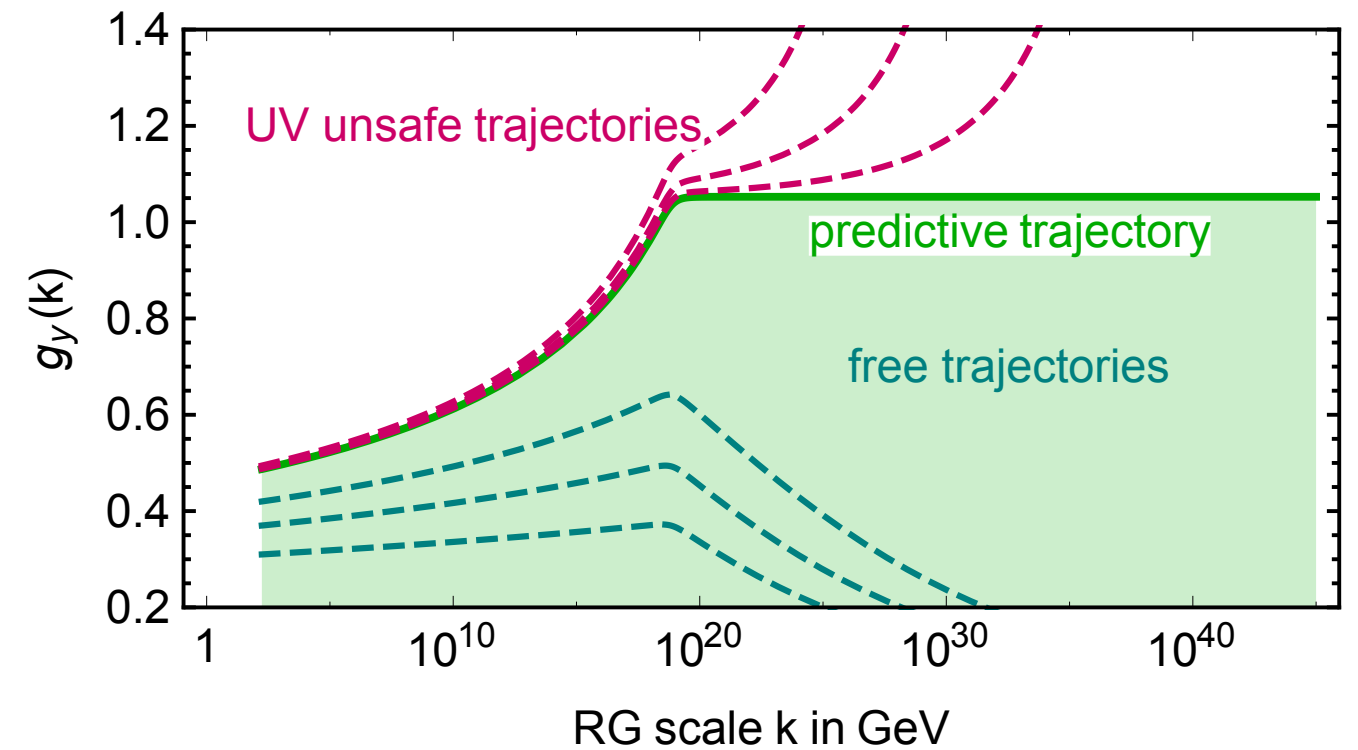


Landau pole:  
new physics needed

Abelian gauge coupling:  
bounded from above

[Harst, Reuter '11;  
AE, Versteegen '17]

$$\beta_{g_Y} = k \partial_k g_Y(k) = -\frac{5}{36\pi} G g_Y + \frac{g_Y^3}{16\pi^2} \frac{41}{6} + \dots$$

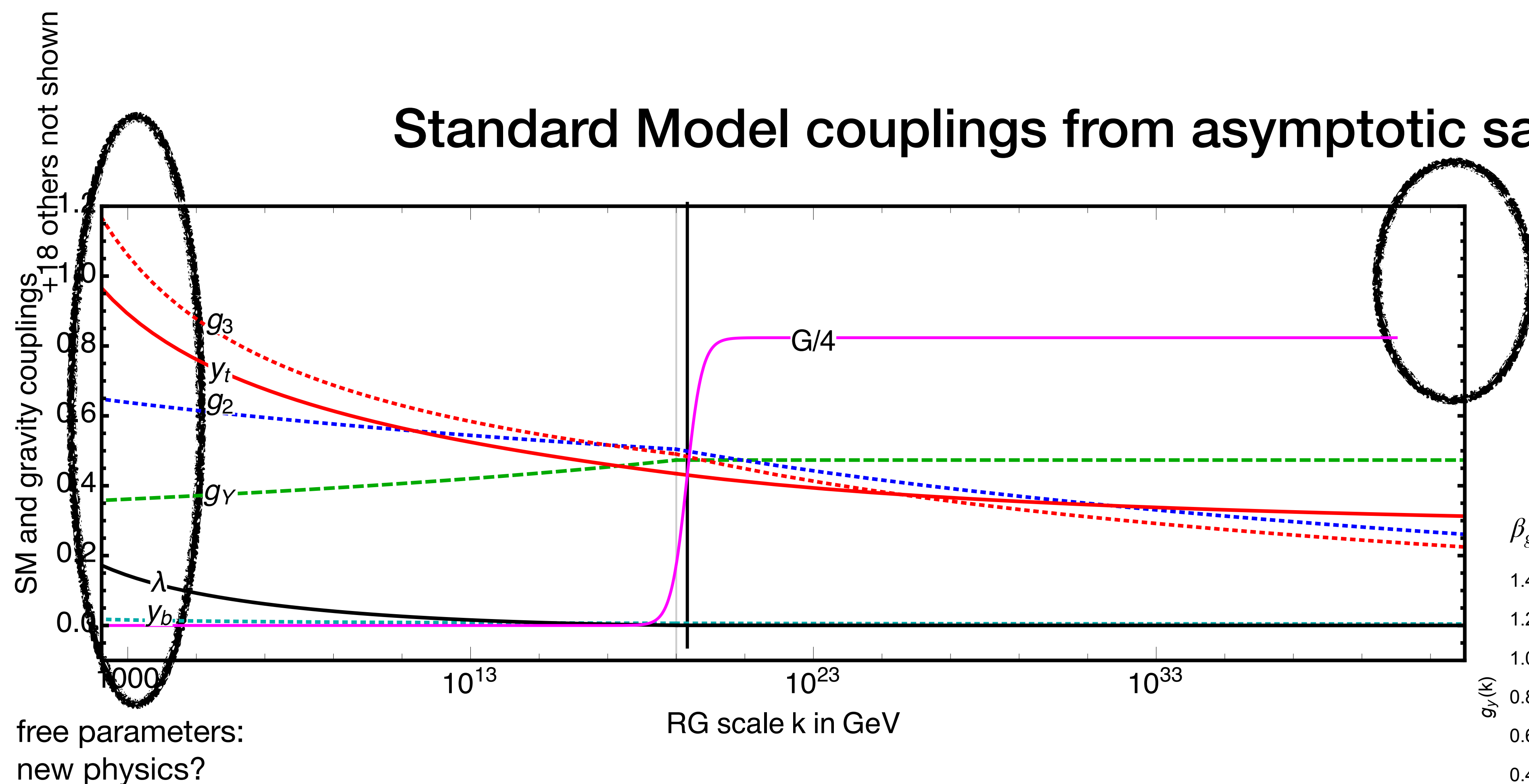


robustness checks:

[Daum, Harst, Reuter '09;  
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Zapalla '26]



# Standard Model couplings from asymptotic safety

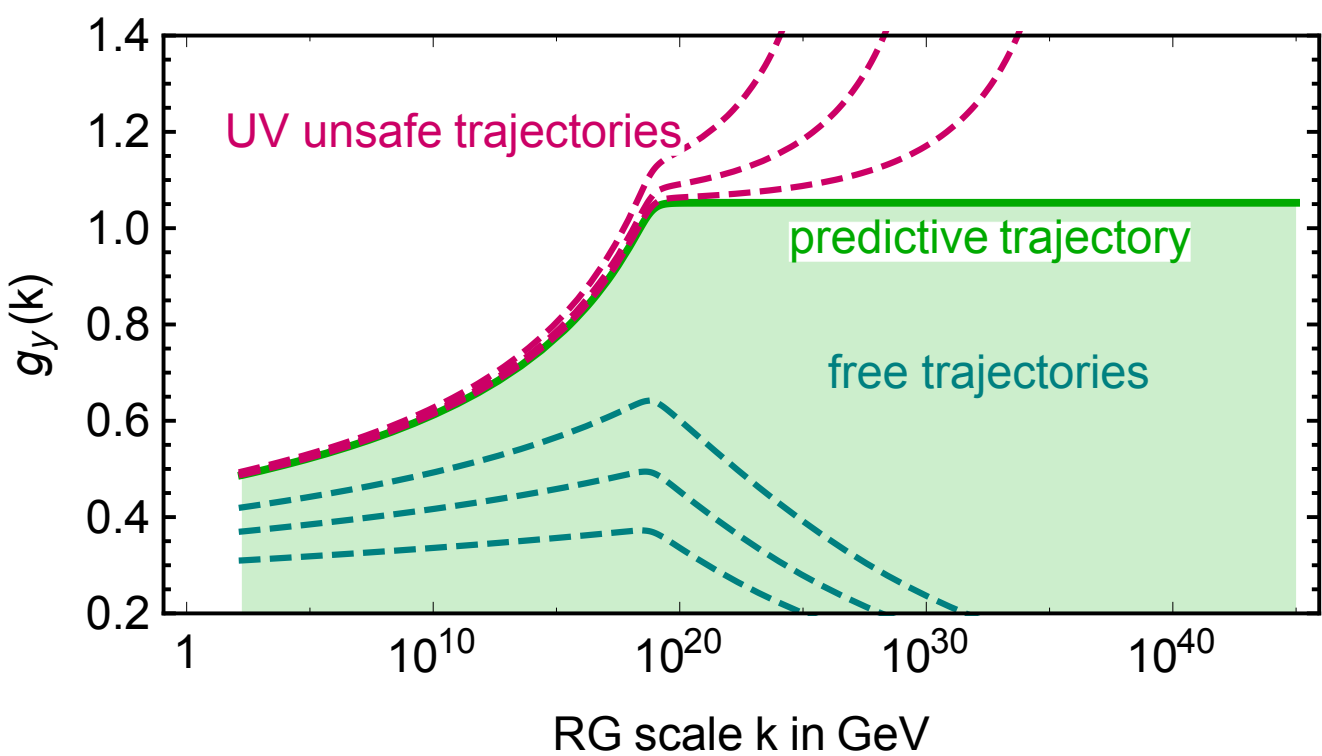


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prediction: Higgs quartic coupling

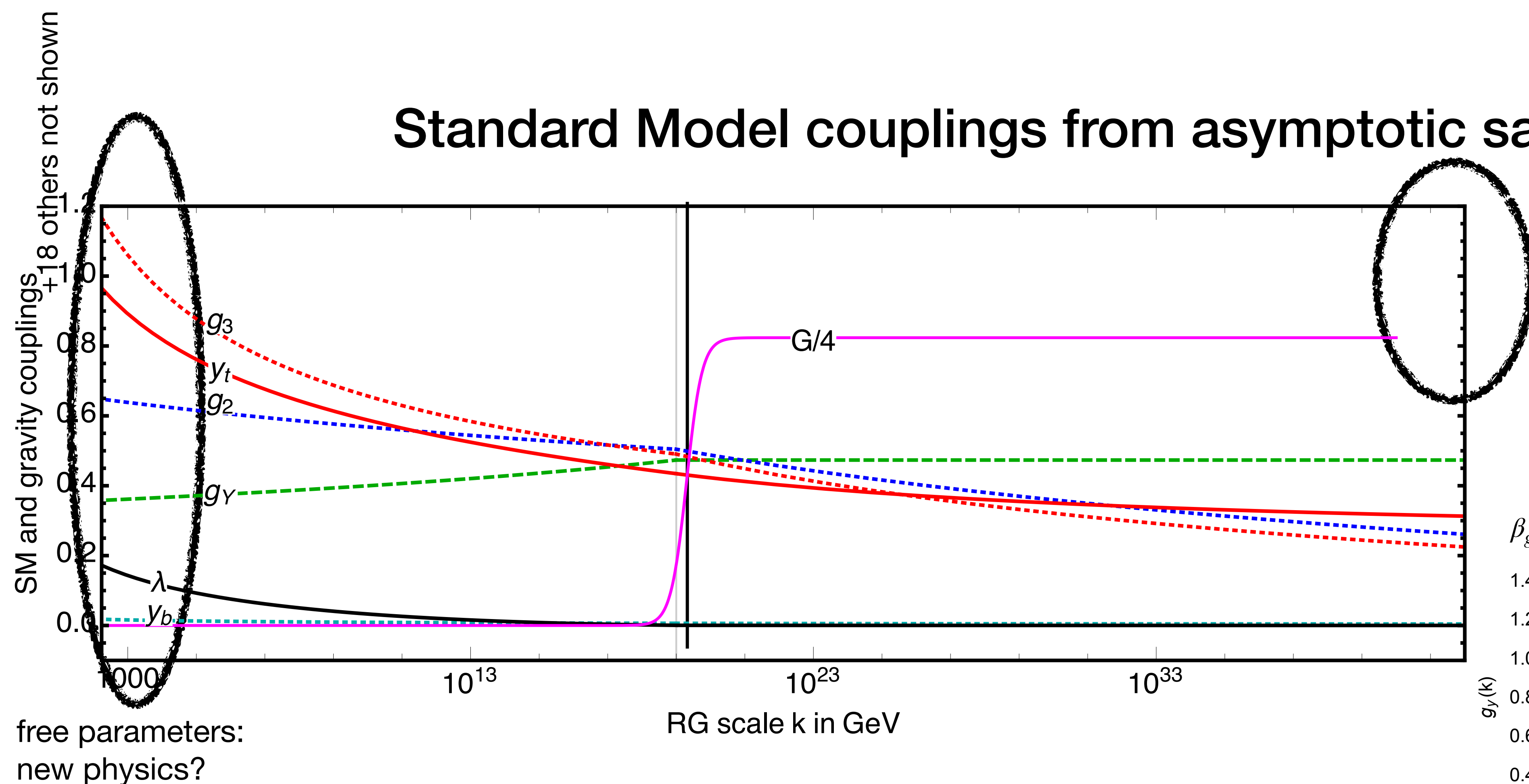
$\lambda \approx 0 @ M_{\text{Planck}} \rightsquigarrow M_H \approx 126 \text{ GeV}$   
(beware: sensitivity to top mass)

[Shaposhnikov, Wetterich, '09]

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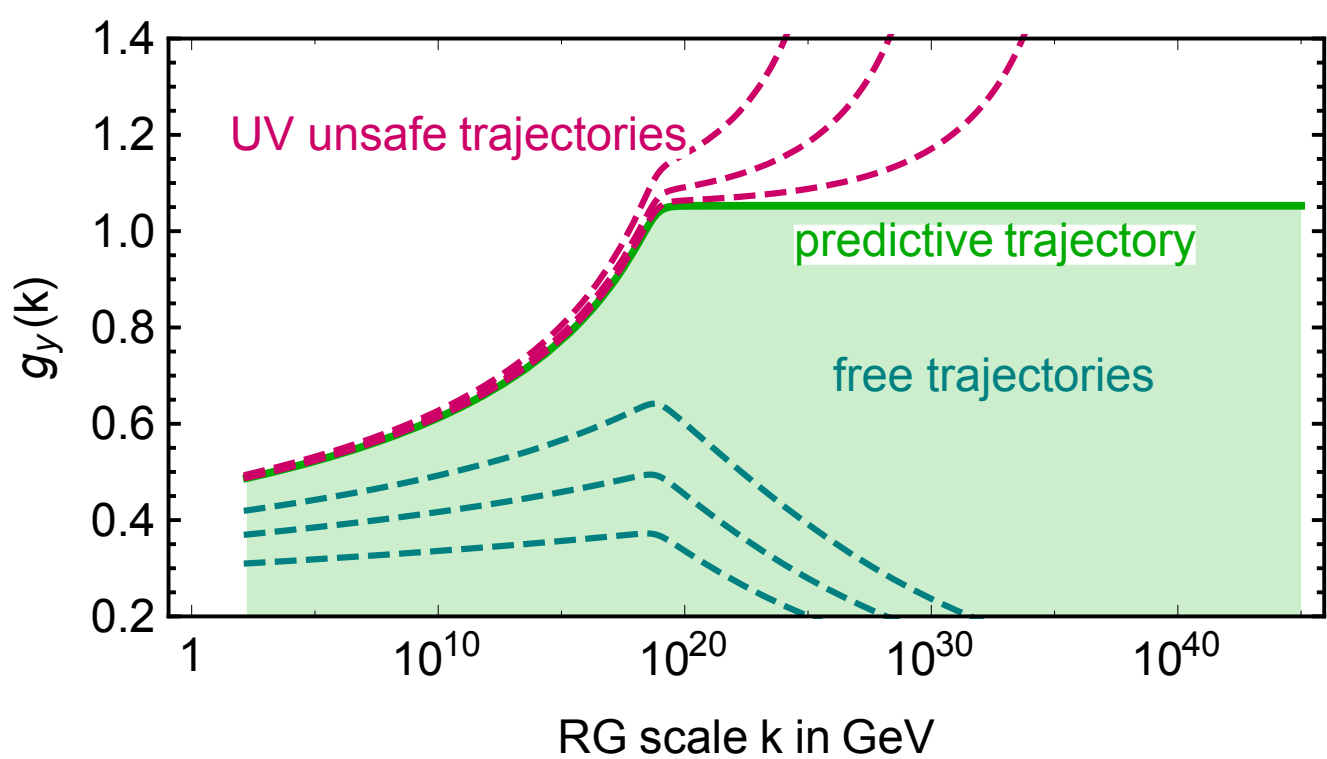


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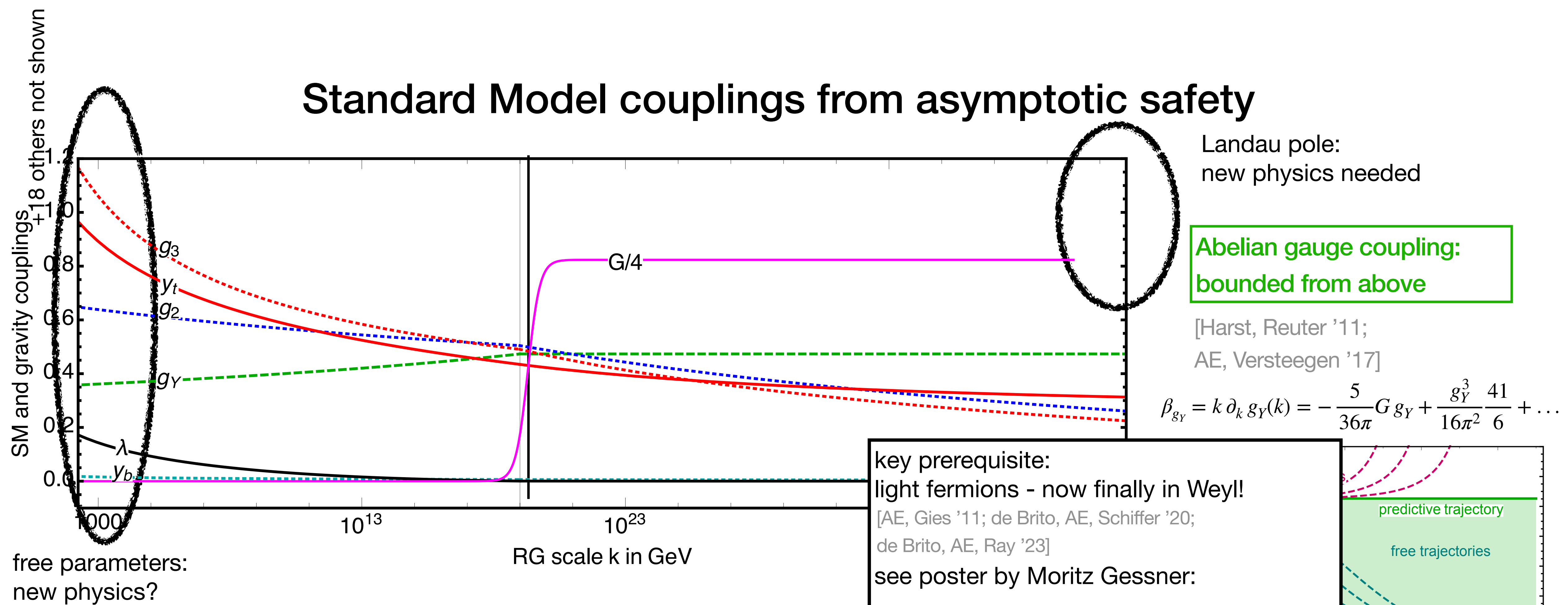
postdiction:

- top Yukawa coupling [AE, Held '17]  
 $\rightsquigarrow M_t \approx 171 \text{ GeV}$

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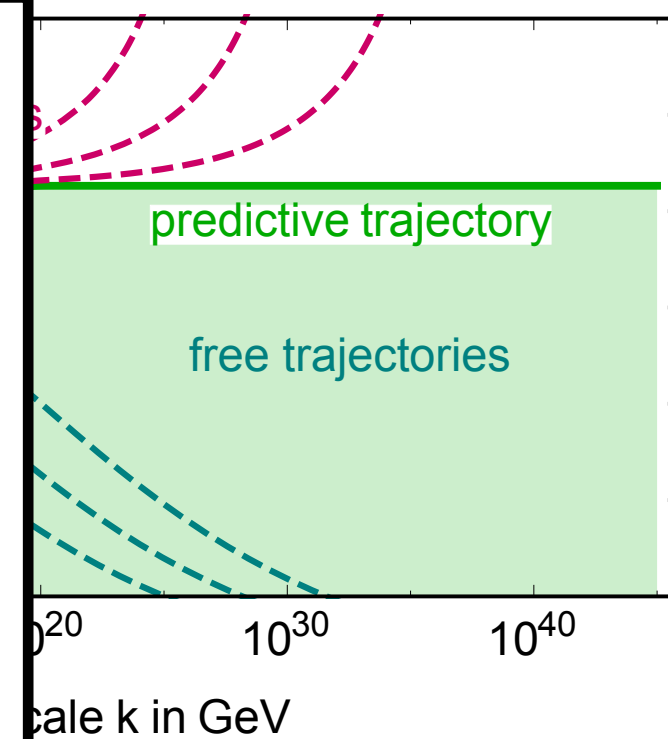
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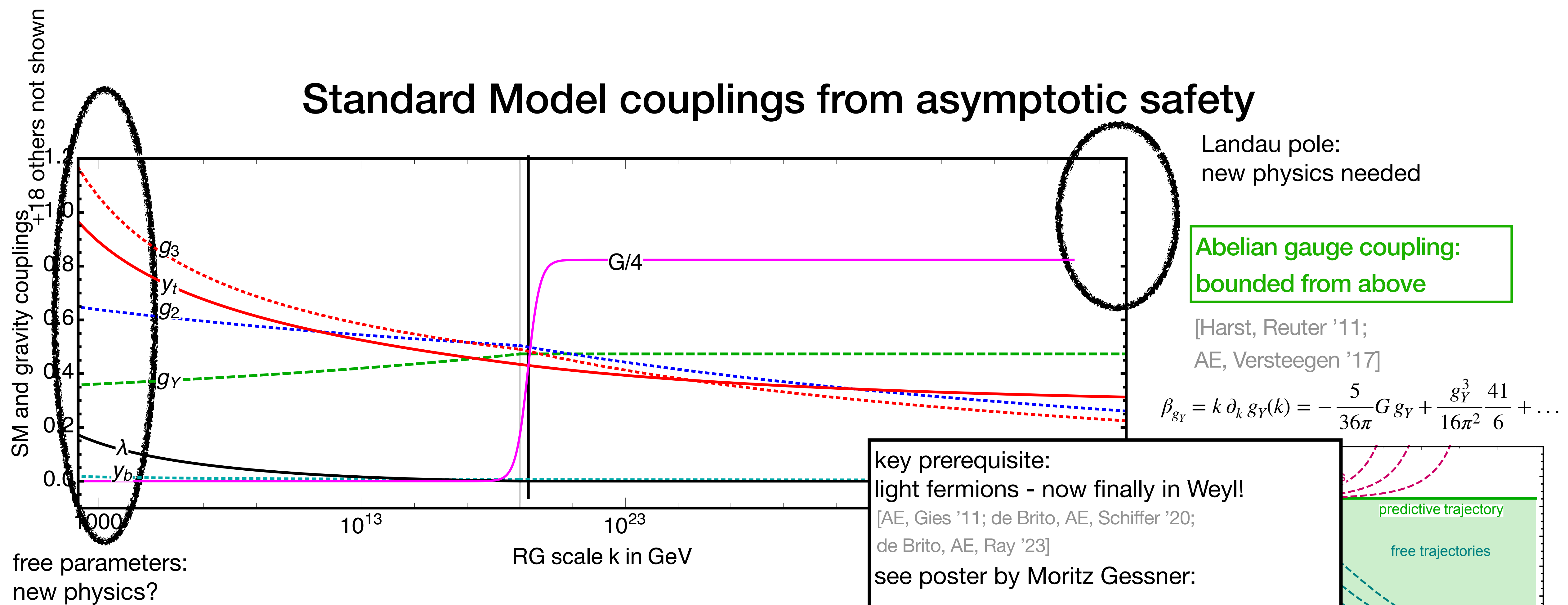
(2607.18398)

On the Structure of the Fermion Sector in  
the Asymptotically Safe Standard Model





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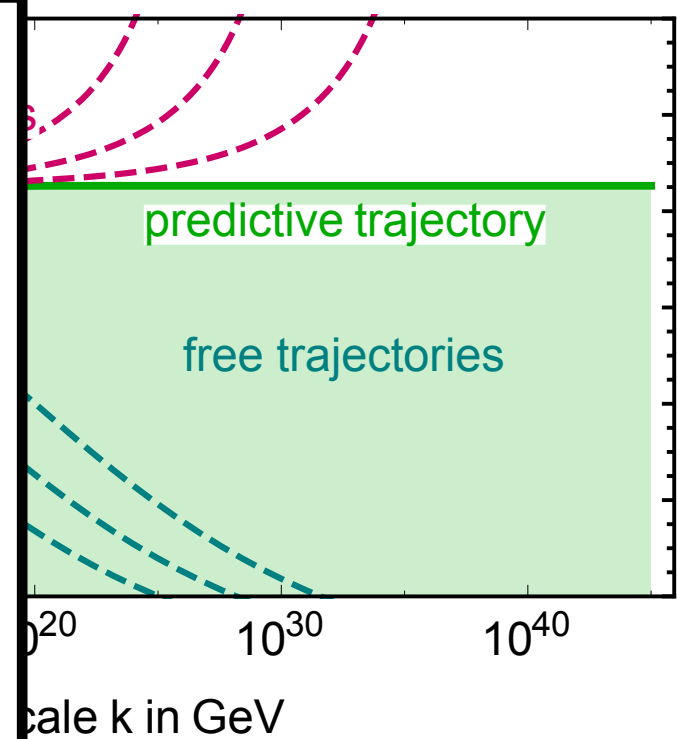
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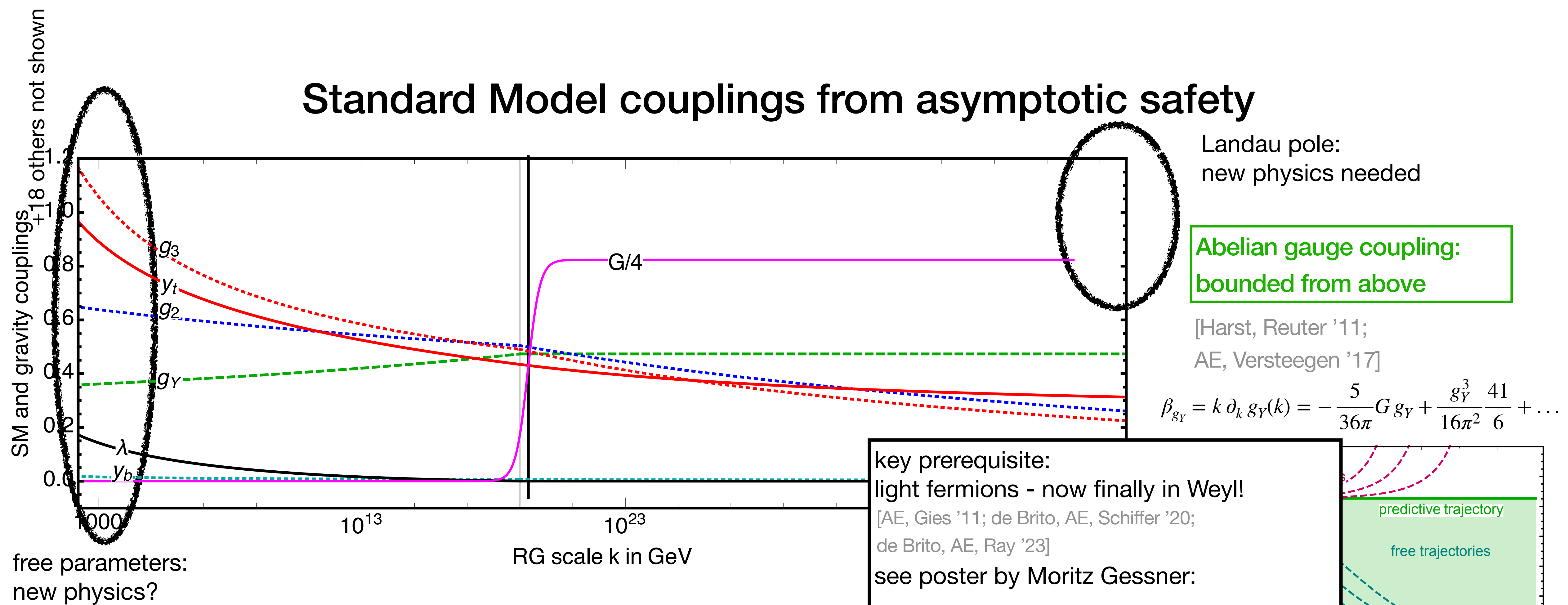
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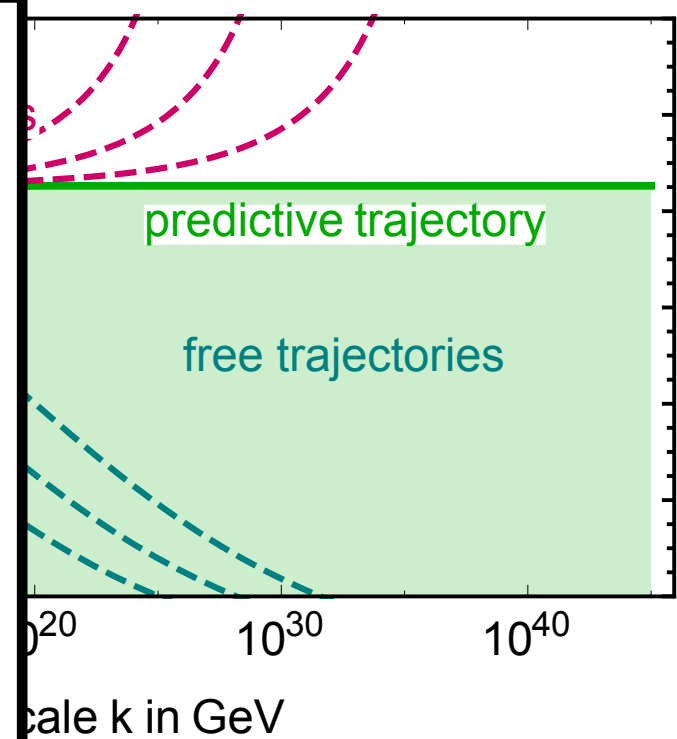
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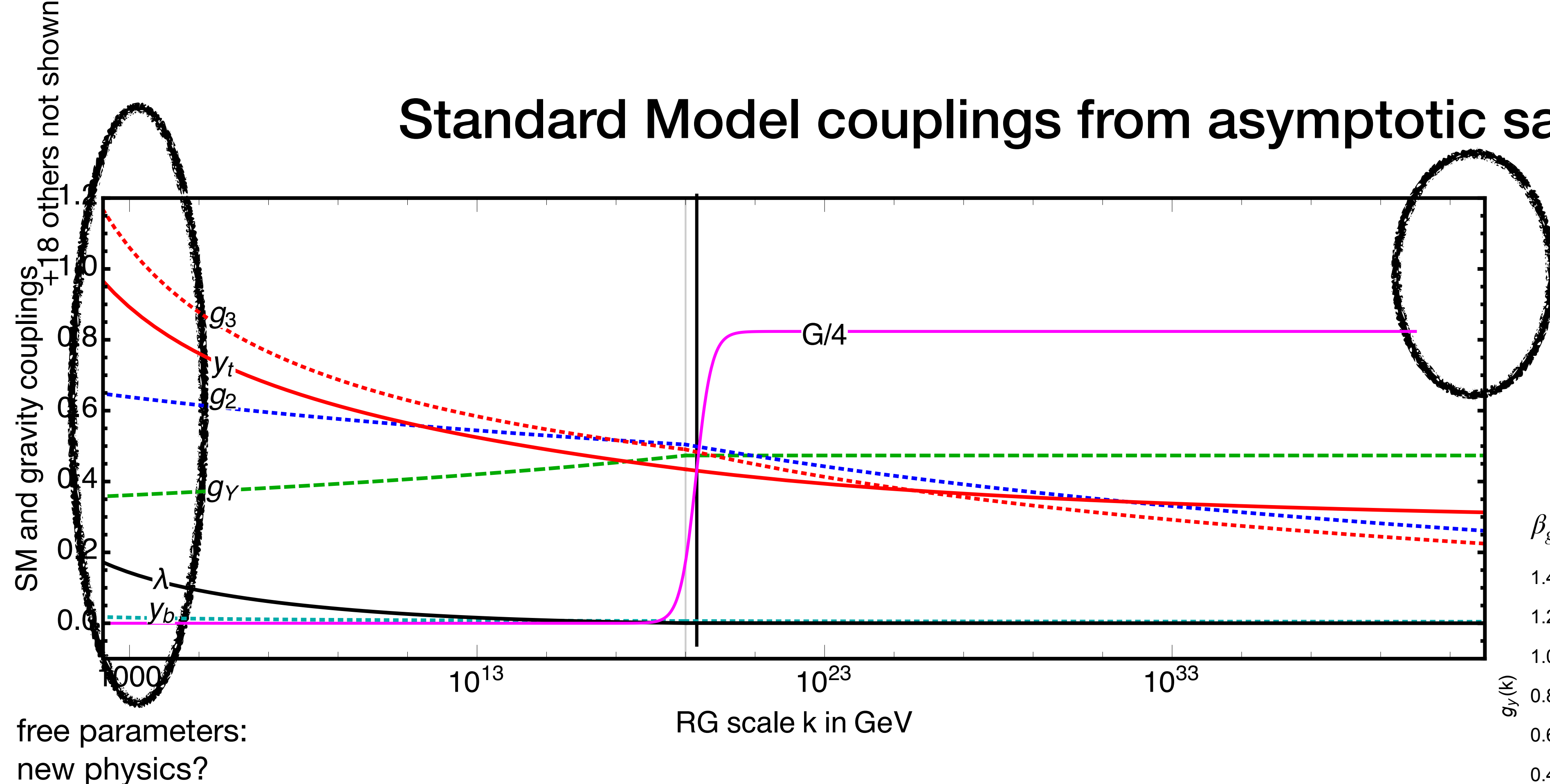
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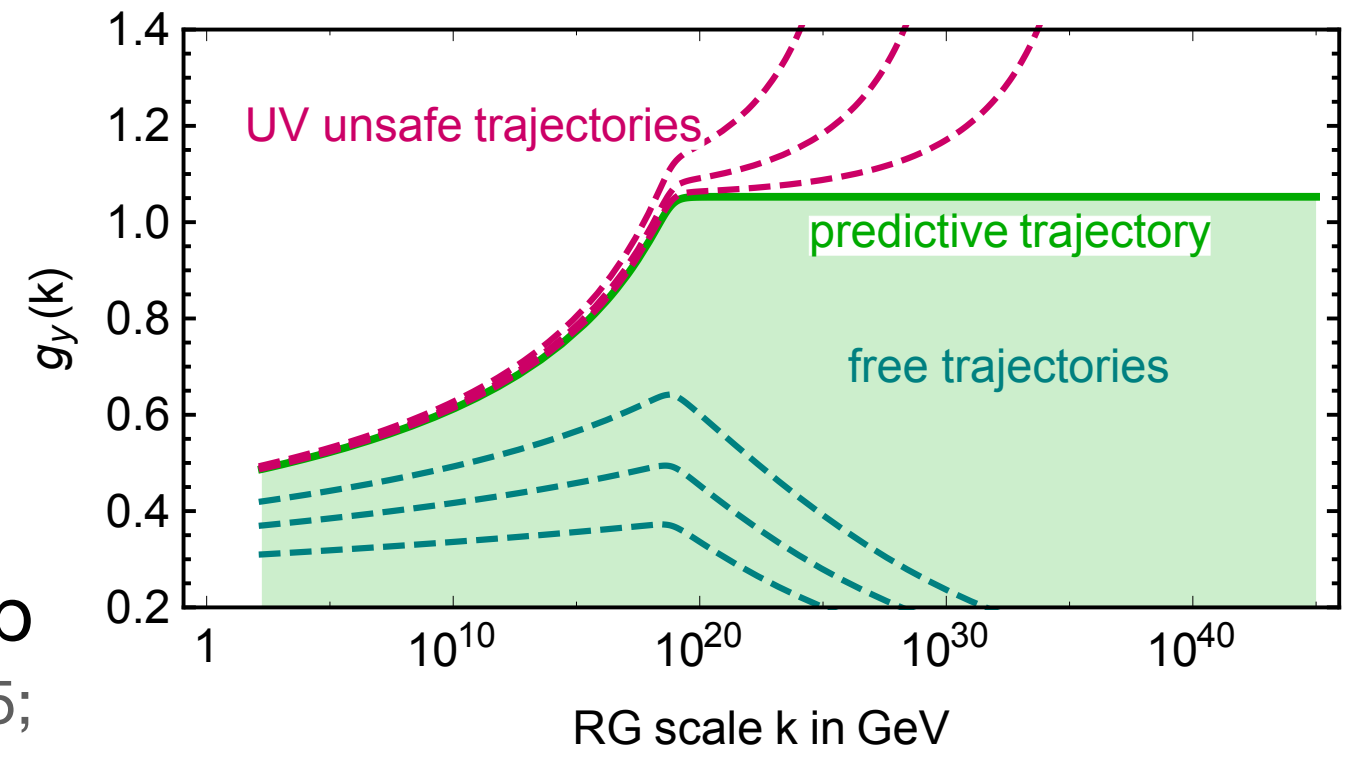


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principled approach: calculate quantum-gravity effects from functional Renormalization Group  
[Daum, Harst, Reuter '09; Narain, Percacci '09; Folkerts, Litim, Pawłowski '09; Harst, Reuter '11; Percacci, Vacca '15; Oda, Yamada '16; AE, Held, Pawłowski '16, AE, Held '17, Christiansen, AE '17; AE, Versteegen '17; AE, Hamada, Lumma, Yamada '17; Christiansen et al. '17; Pawłowski, Reichert, Wetterich, Yamada '18; AE, Pauly '18; AE, Schiffer '19; de Brito, AE, Pereira '19; Wetterich '19; de Brito, AE '21; Riabokon, Schiffer, Wagner '25; de Brito, Reichert, Schiffer '25...]

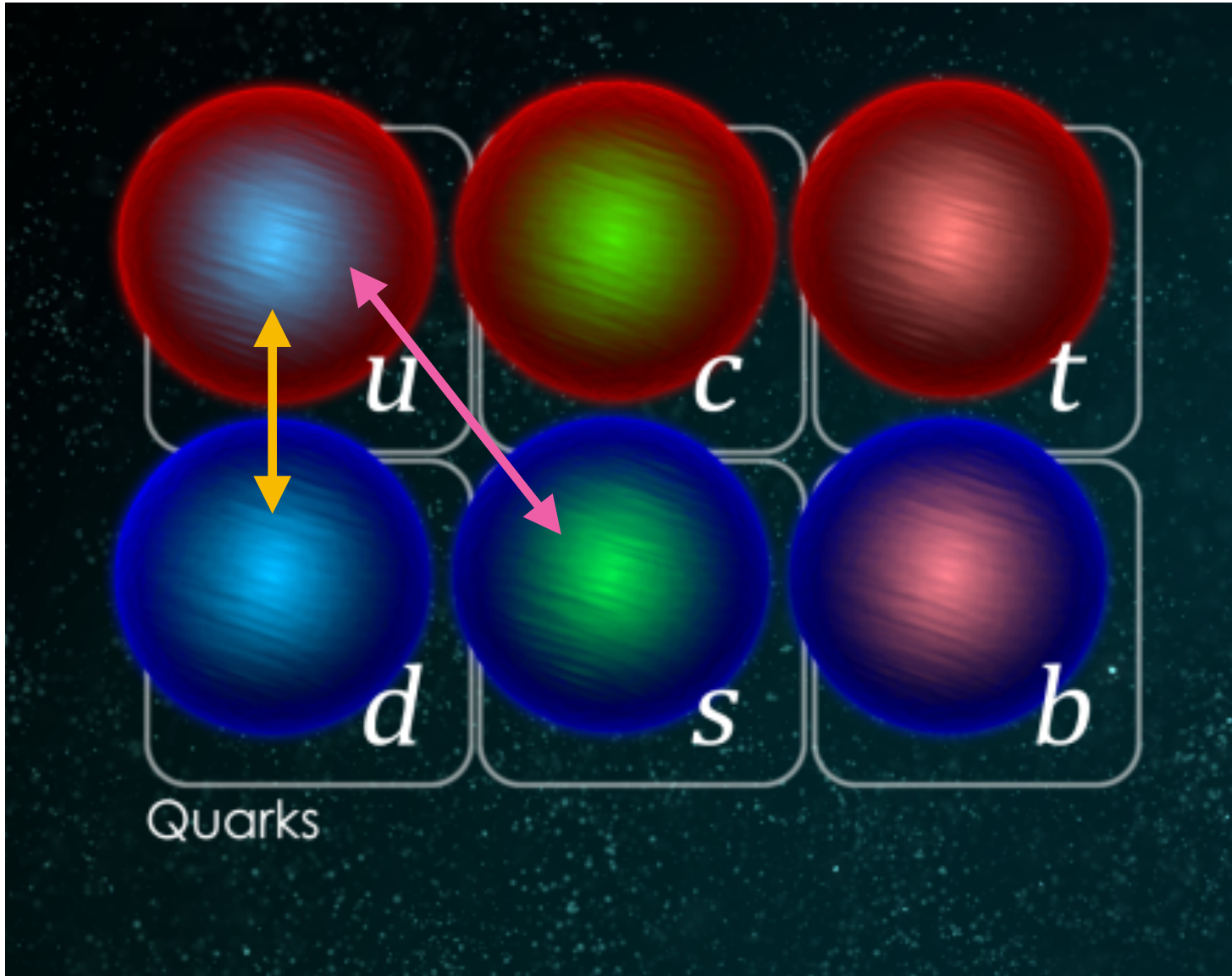
principled-parameterized approach: derive phenomenological consequences based on parameterization  
[AE, Held '18; Reichert, Smirnov '19; Kowalska, Sessolo et al. '20, '21, '22, '23, '24 '25; Alkofer, AE, Held, Nieto, Percacci, Schröfl '20; AE, Held '22; Boos '22; de Brito, AE, Frandsen, Rosenlyst, Vieira '23; Carone '25; AE, Gyftopoulos, Held '25...]



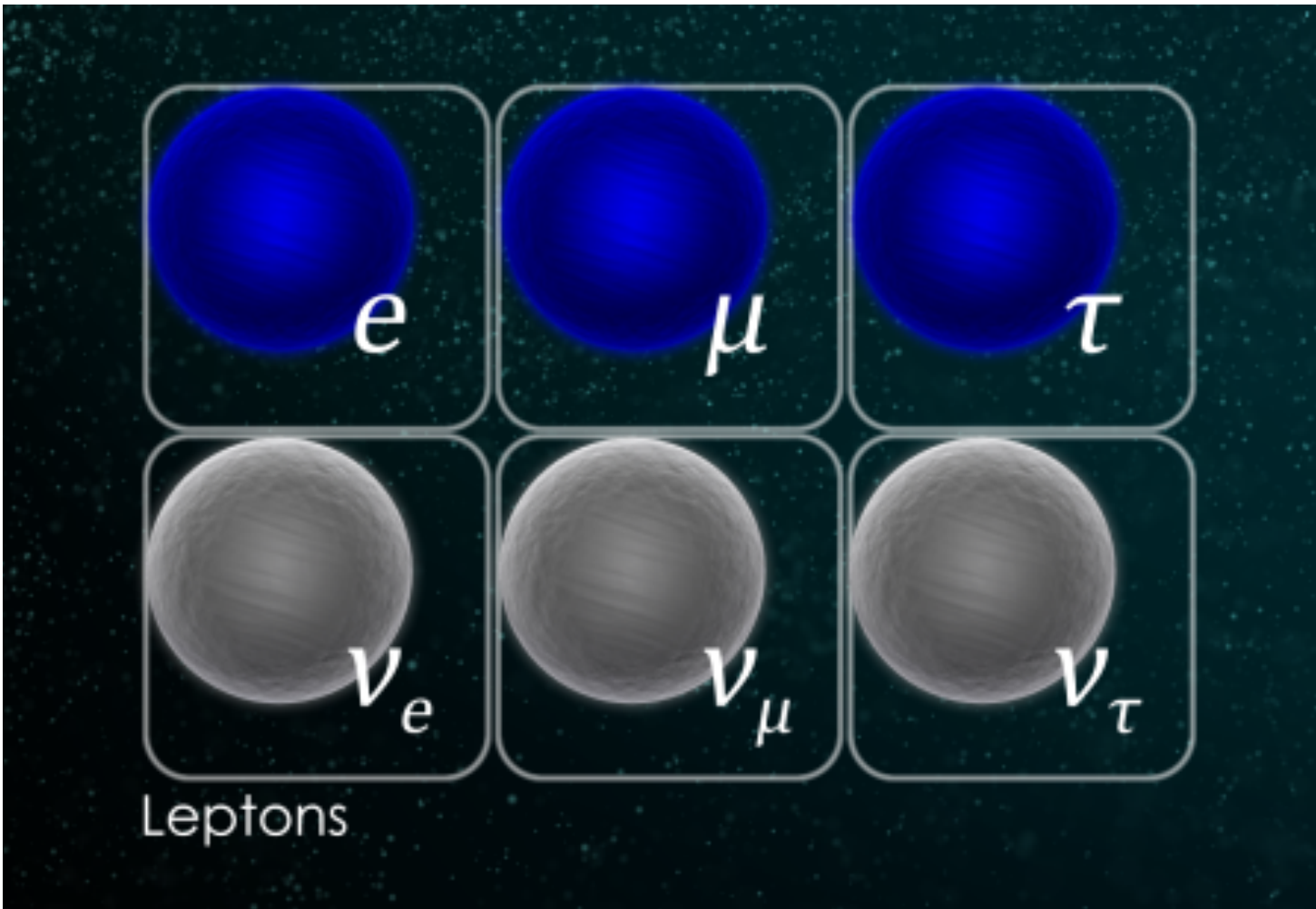
# Recent news

AE, Gyftopoulos, Held '25,  
AE, Gyftopoulos, Held, Palizban, to appear  
Buccio, AE, Gyftopoulos, Held, to appear

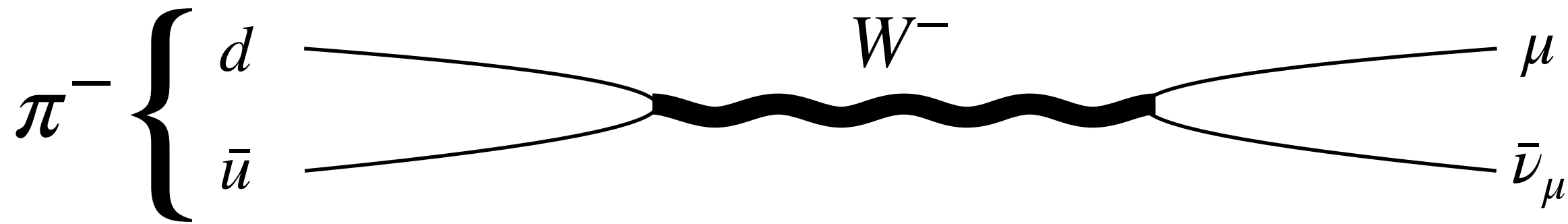
CKM



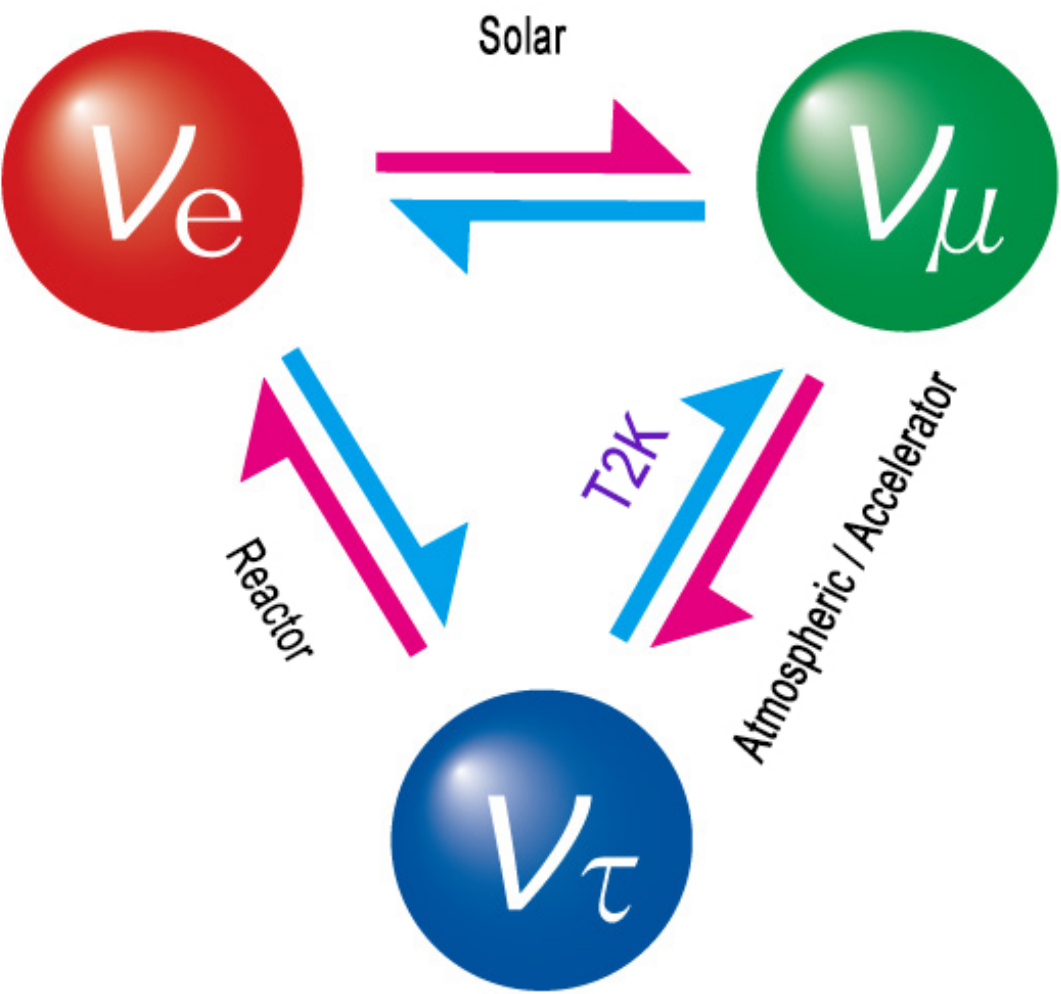
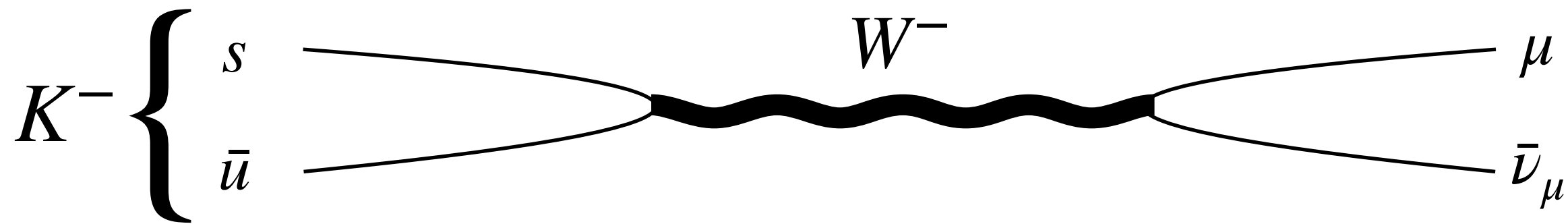
PMNS



without mixing



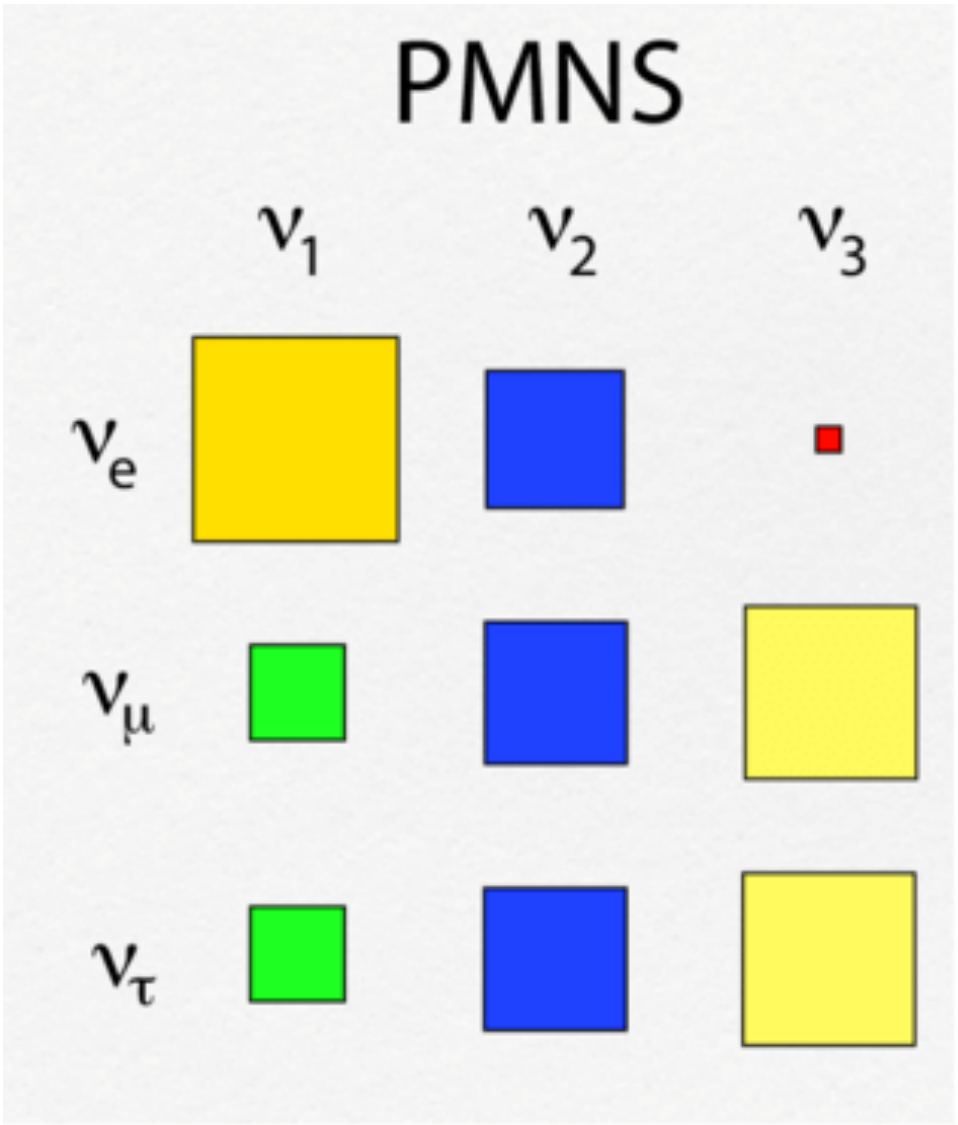
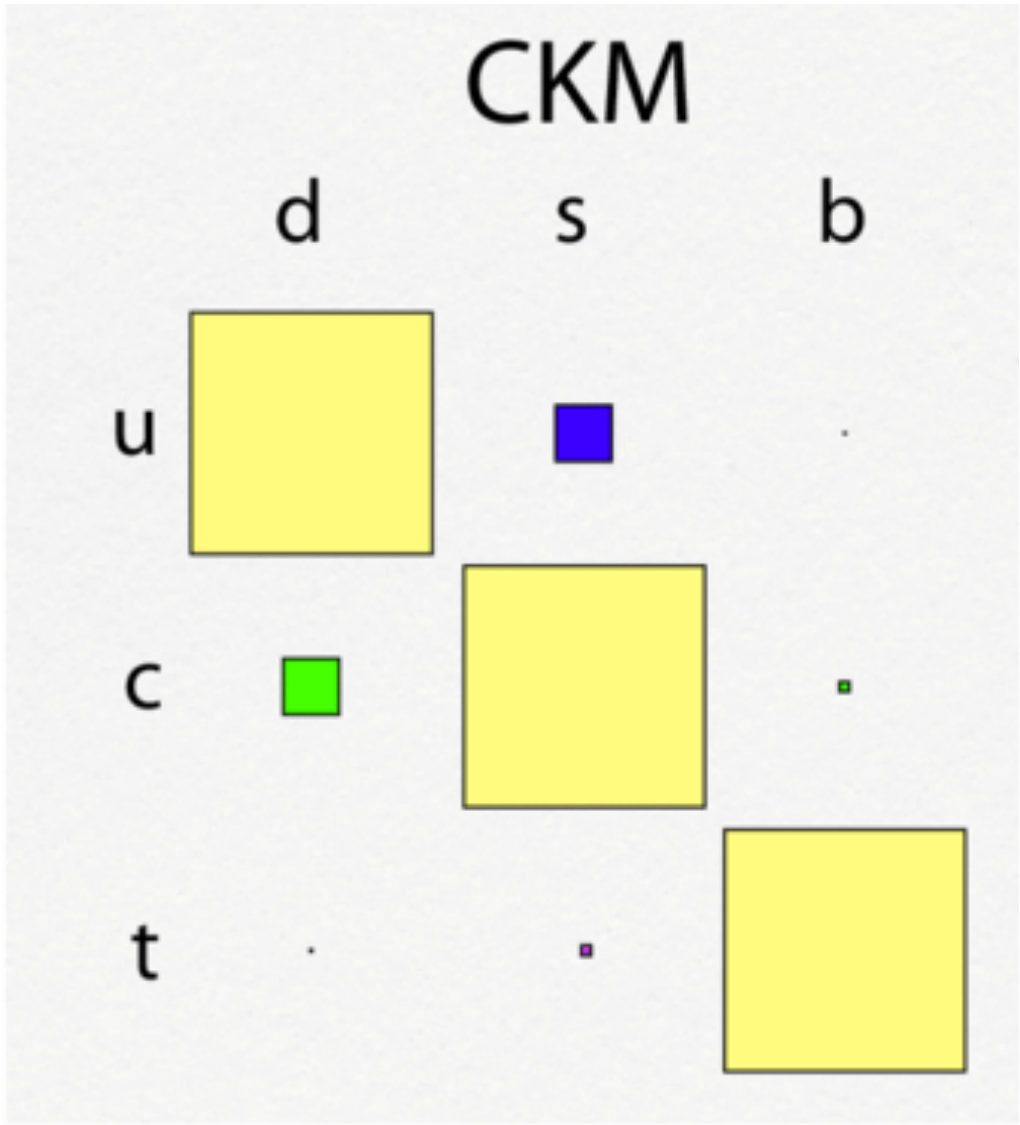
with mixing



Neutrino oscillation between three generations

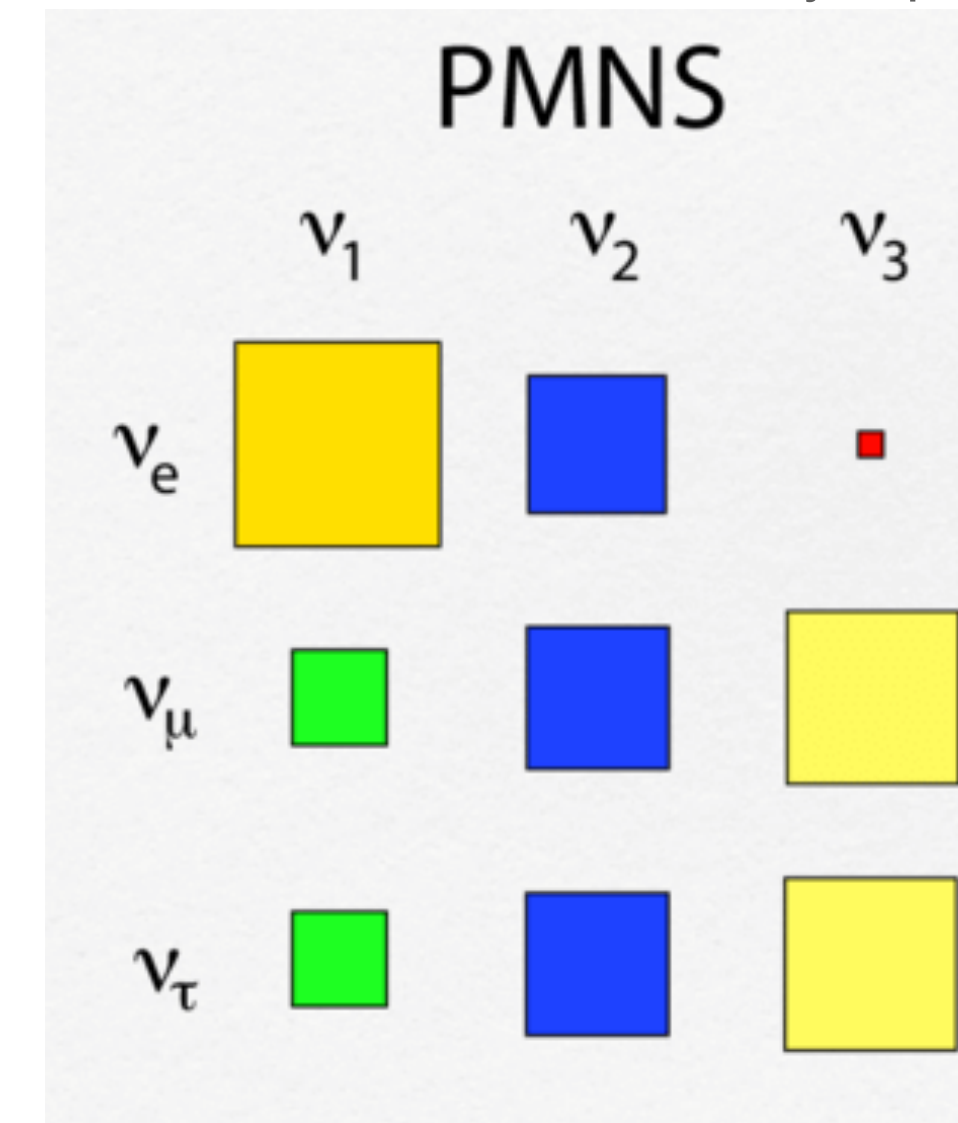
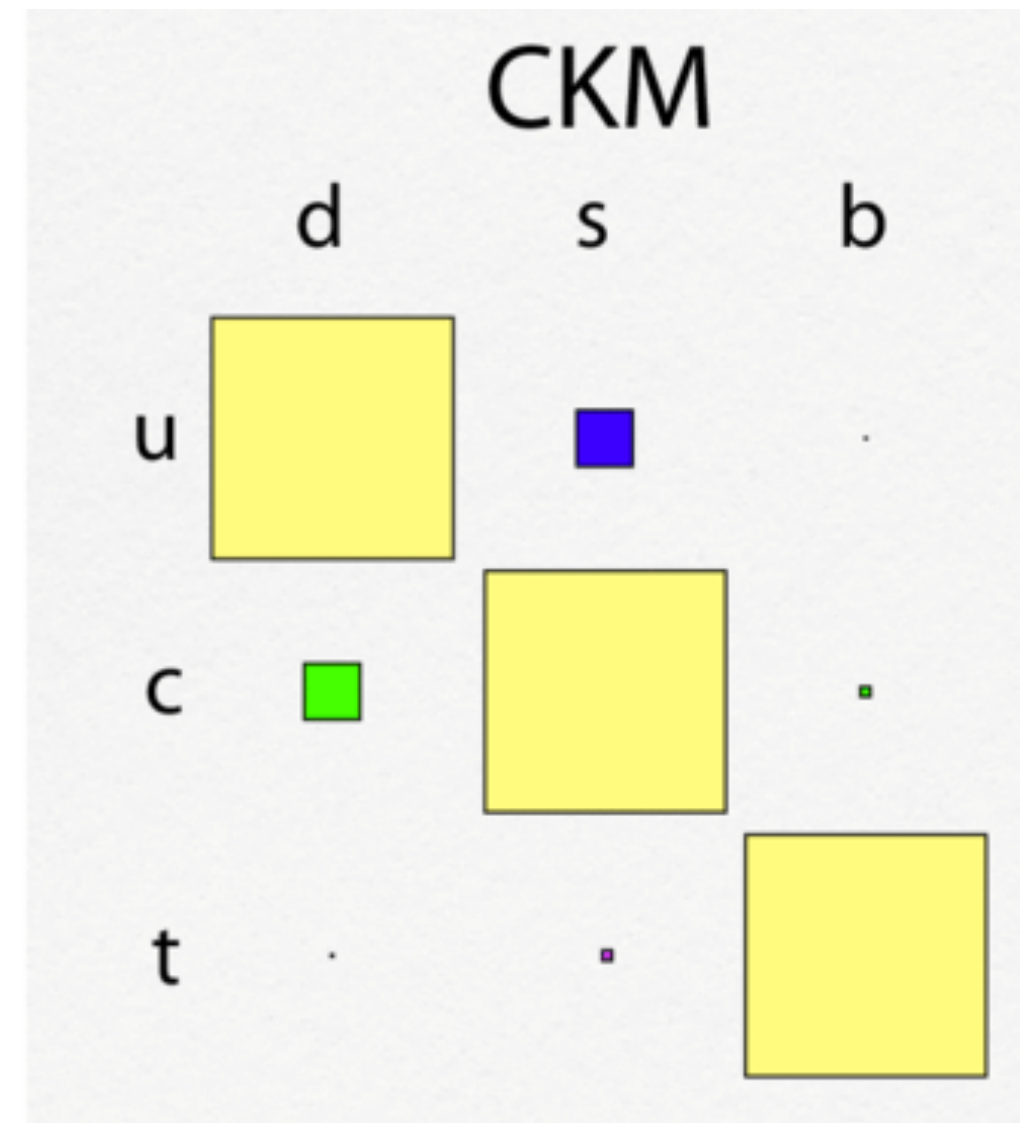
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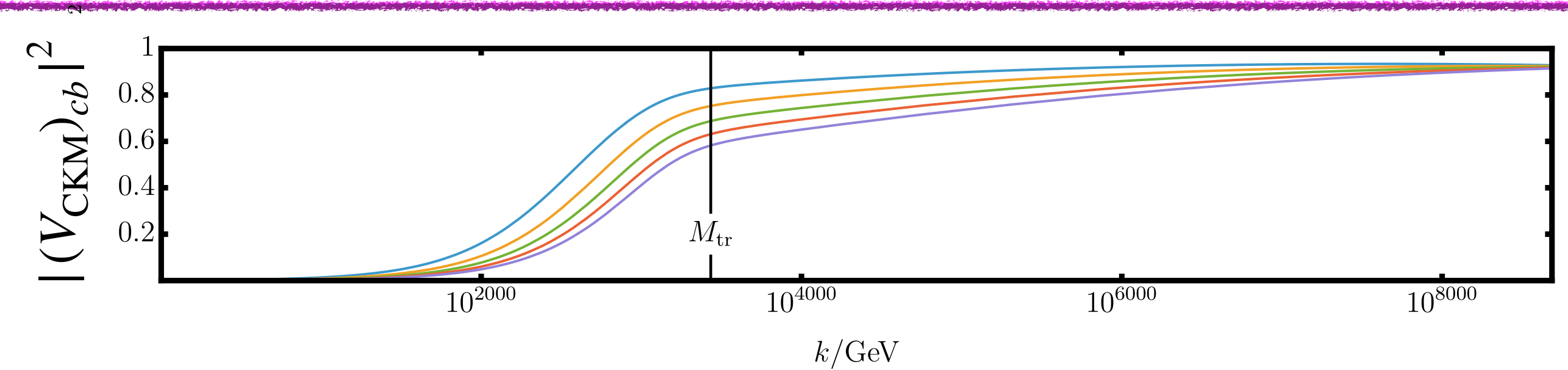
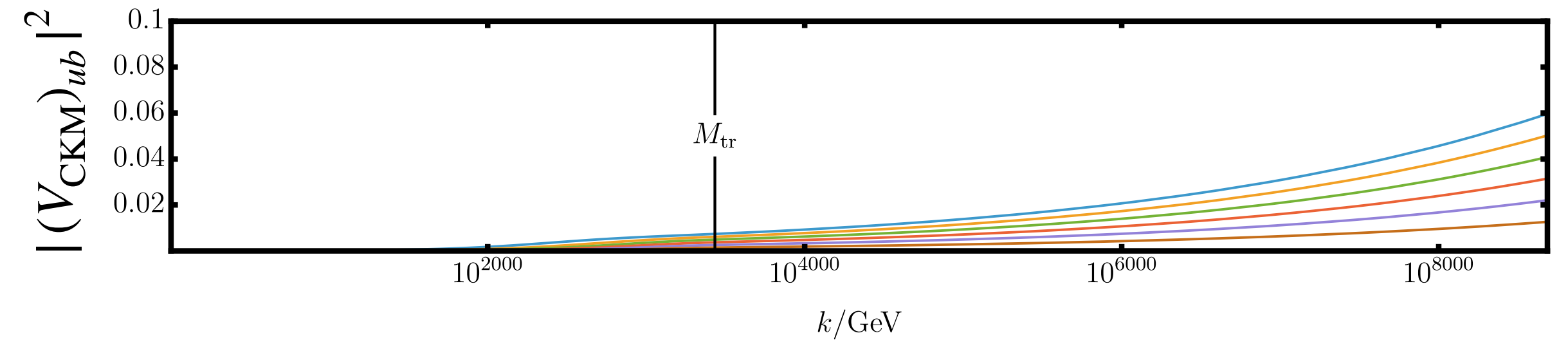
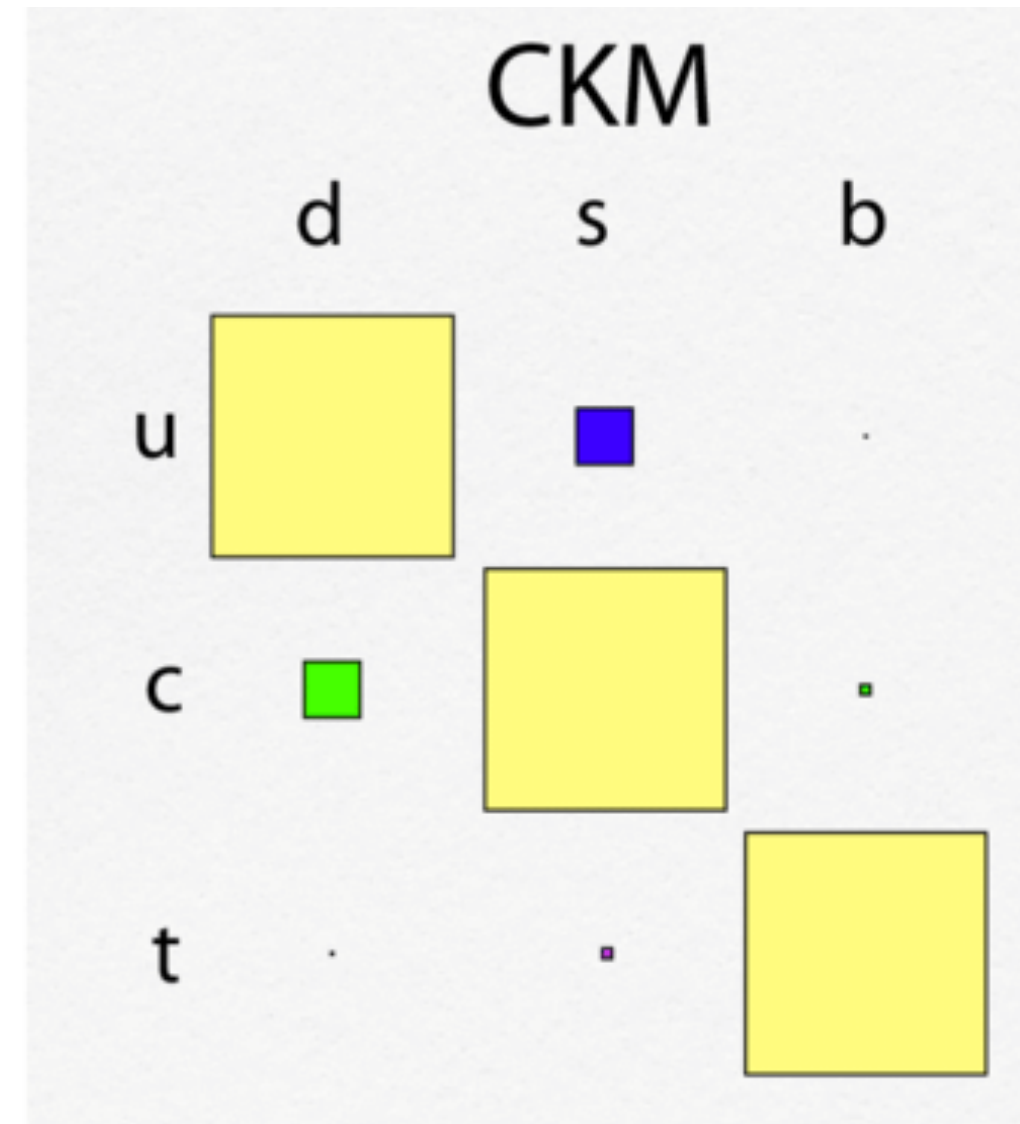
Previously known result:

- Renormalization Group flow of both matrices has an infrared attractive fixed point in the diagonal (no-mixing) configuration

[Pendleton, Ross '81, Alkofer, AE, Held, Nieto, Percacci, Schröfl '19, ]



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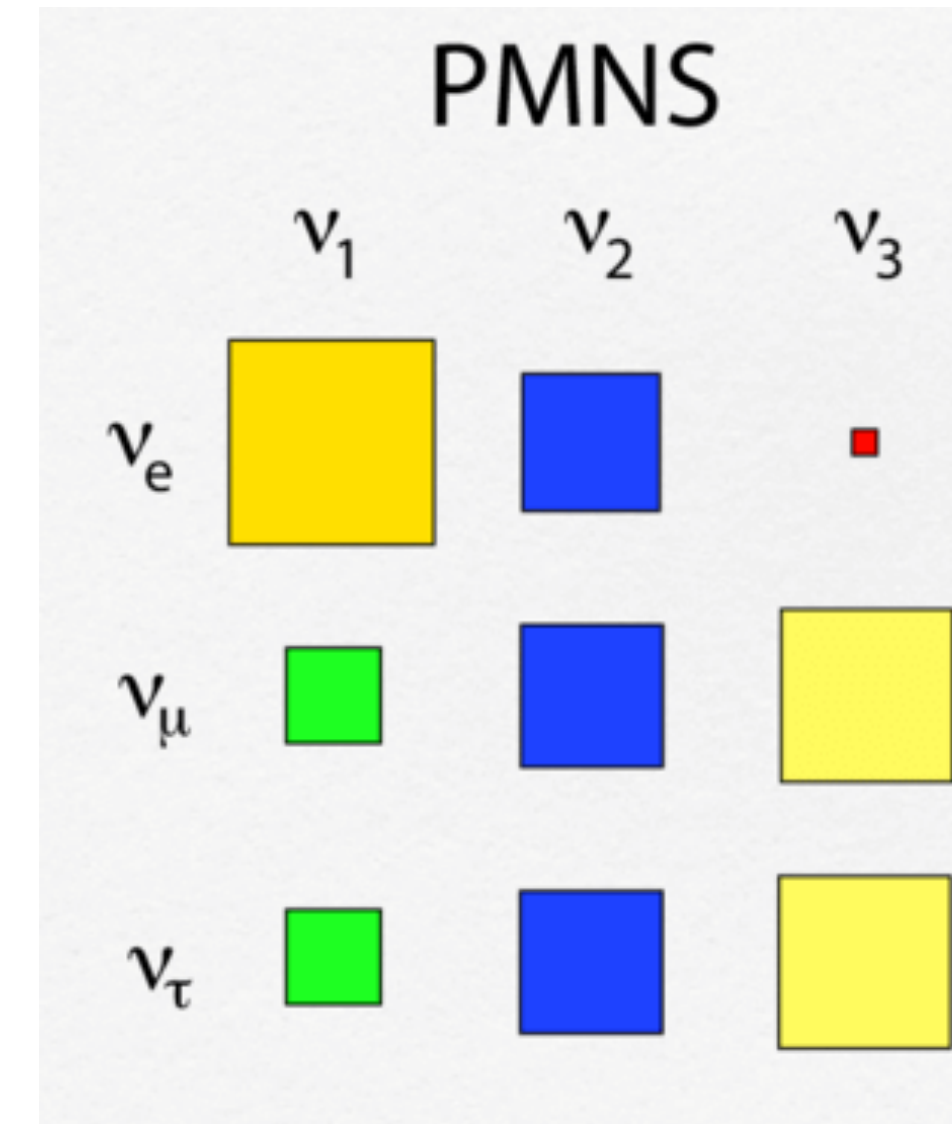
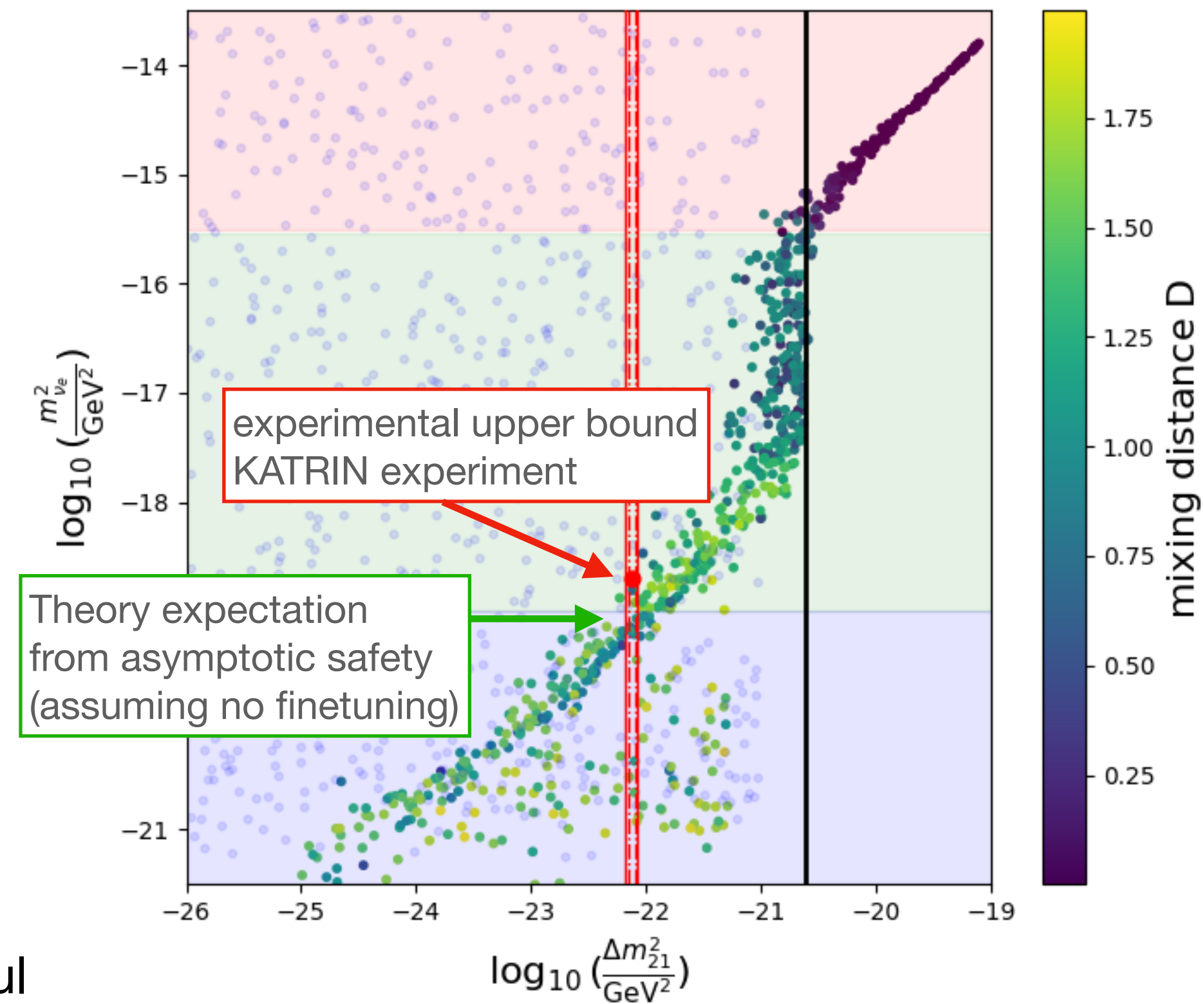
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- CKM: fixed point is approached if huge range of scales over which  $y_t \gg y_{b,c,s,d,u}$

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- PMNS: fixed point cannot be avoided, unless  $y_\nu \ll y_\tau$  (not near-degenerate neutrinos)

Buccio, AE, Gyftopoulos, Held, to appear

# How framing the question matters



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Framing A: Given the achievements of asymptotic safety, is it **the** theory of quantum gravity?

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Which framing should our PhD students learn to think in?

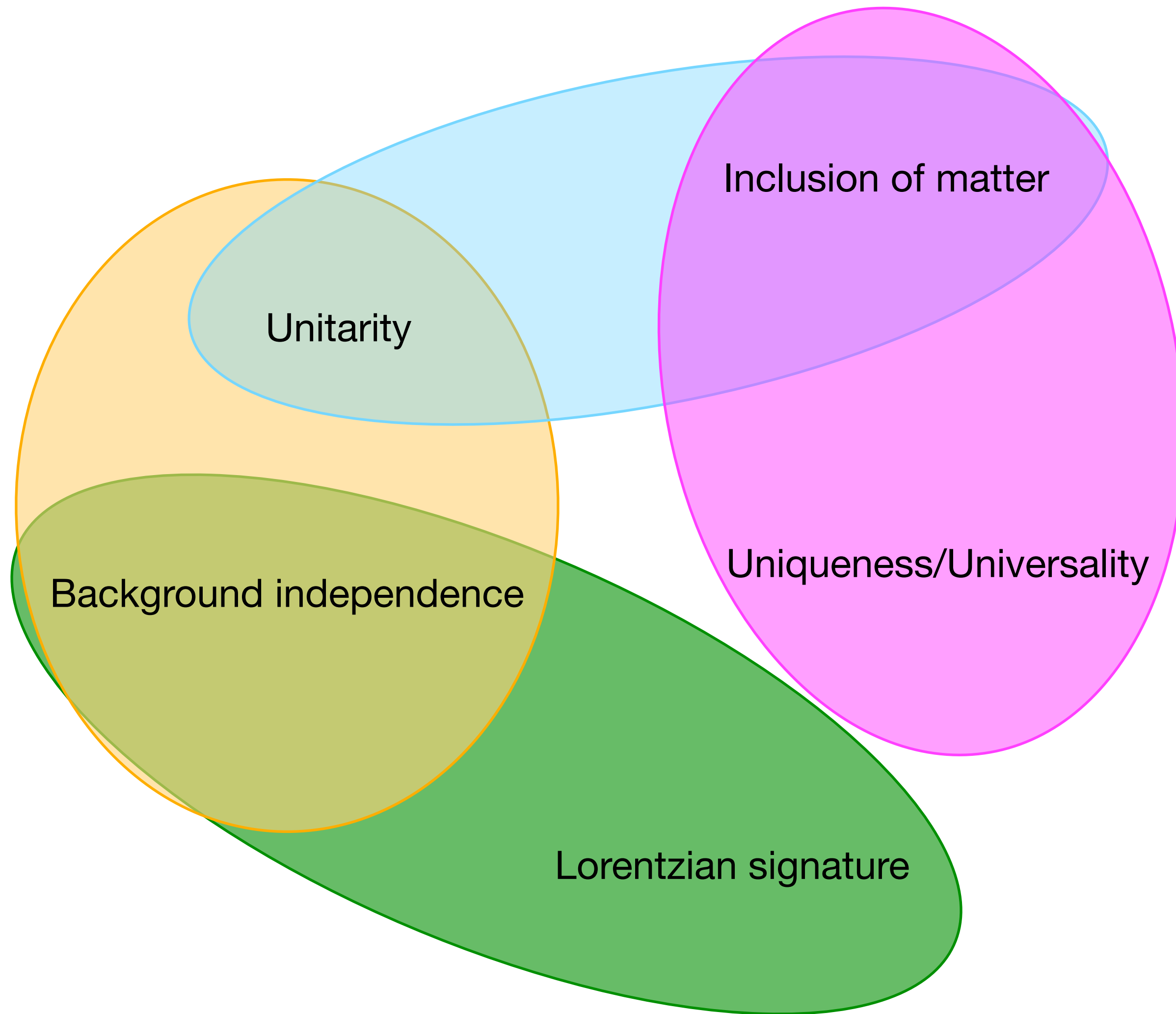


# Combining frameworks for quantum gravity





# Combining frameworks for quantum gravity



Asymptotic safety with continuum-QFT techniques  
(functional Renormalization Group)

String theory

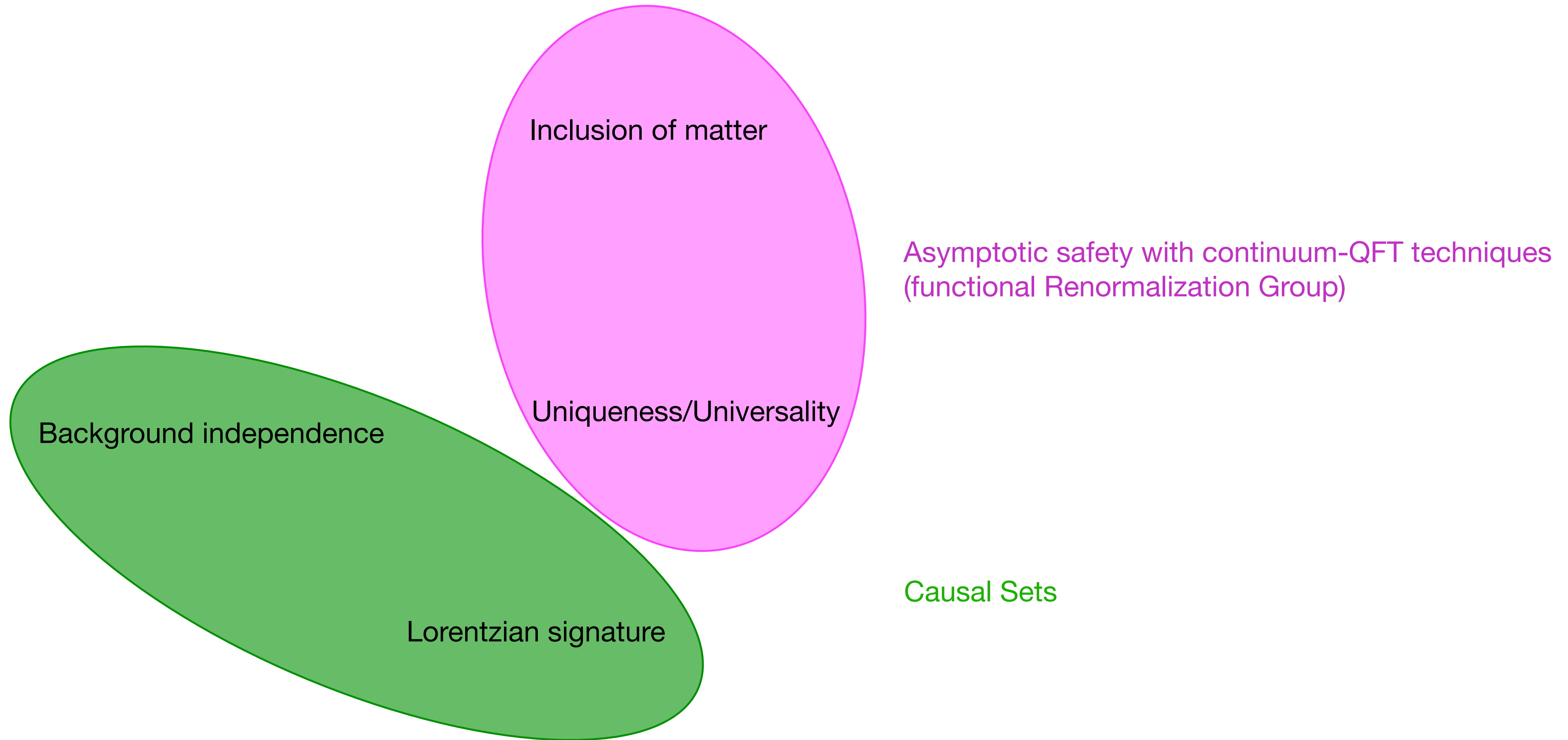
Asymptotic safety with lattice techniques  
(Causal/Euclidean Dynamical Triangulations)

Causal Sets

.....

# Causal-set/Asymptotic safety interface: Why and how?

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# Causal set quantum gravity

[Bombelli, Lee, Meyer, Sorkin '87]



# Causal set quantum gravity

Framework for dynamics: path integral

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# Causal set quantum gravity

Framework for dynamics: path integral

Configurations: causal sets

A causal set  $C$  is a set of spacetime points,  $e_i \in C$ , together with a relation  $\prec$  “precedes”, such that

- If  $e_i \prec e_j$  and  $e_j \prec e_k$ , then  $e_i \prec e_k$

(causal order of events is transitive)

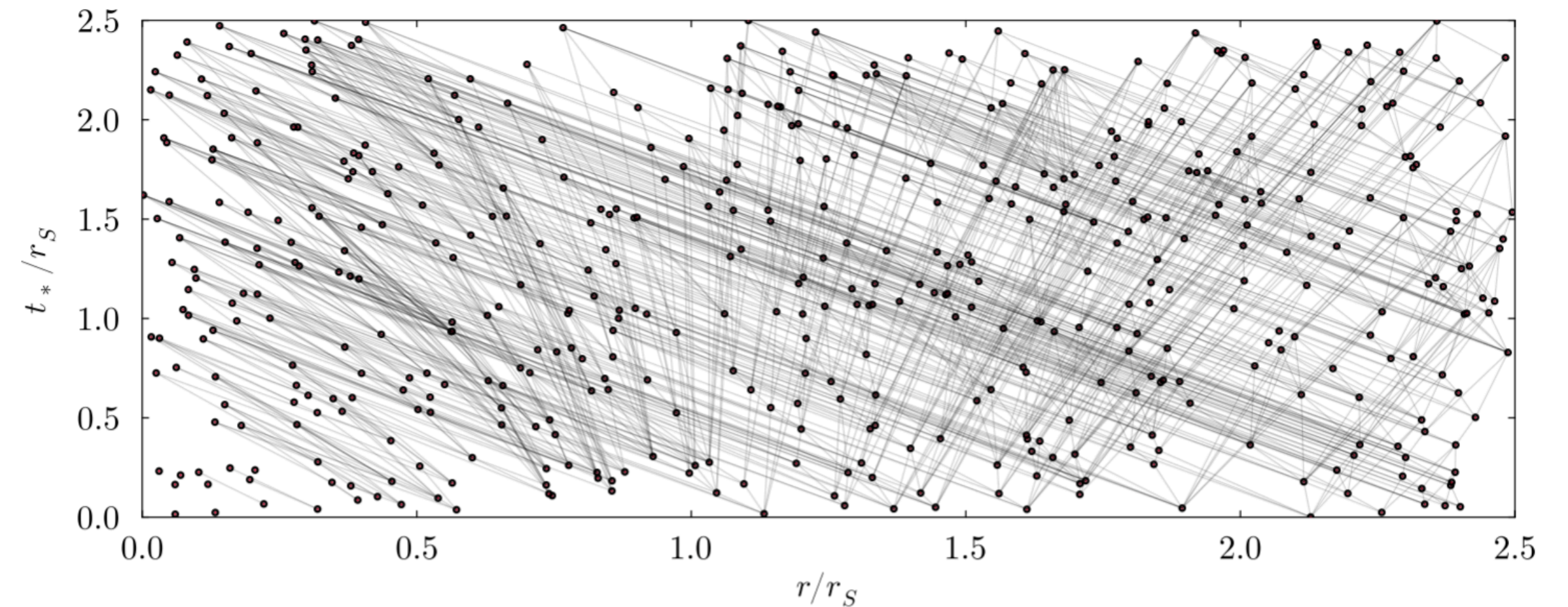
- If  $e_i \prec e_j$  and  $e_j \prec e_i$ , then  $e_i = e_j$

(no closed timelike loops)

- $|\{e_j | e_i \prec e_j \prec e_k\}| < \infty \forall e_i, e_k \in C$

(local finiteness, spacetime discreteness)

[Bombelli, Lee, Meyer, Sorkin '87]



Example: causal set approximated by 2-d slice  
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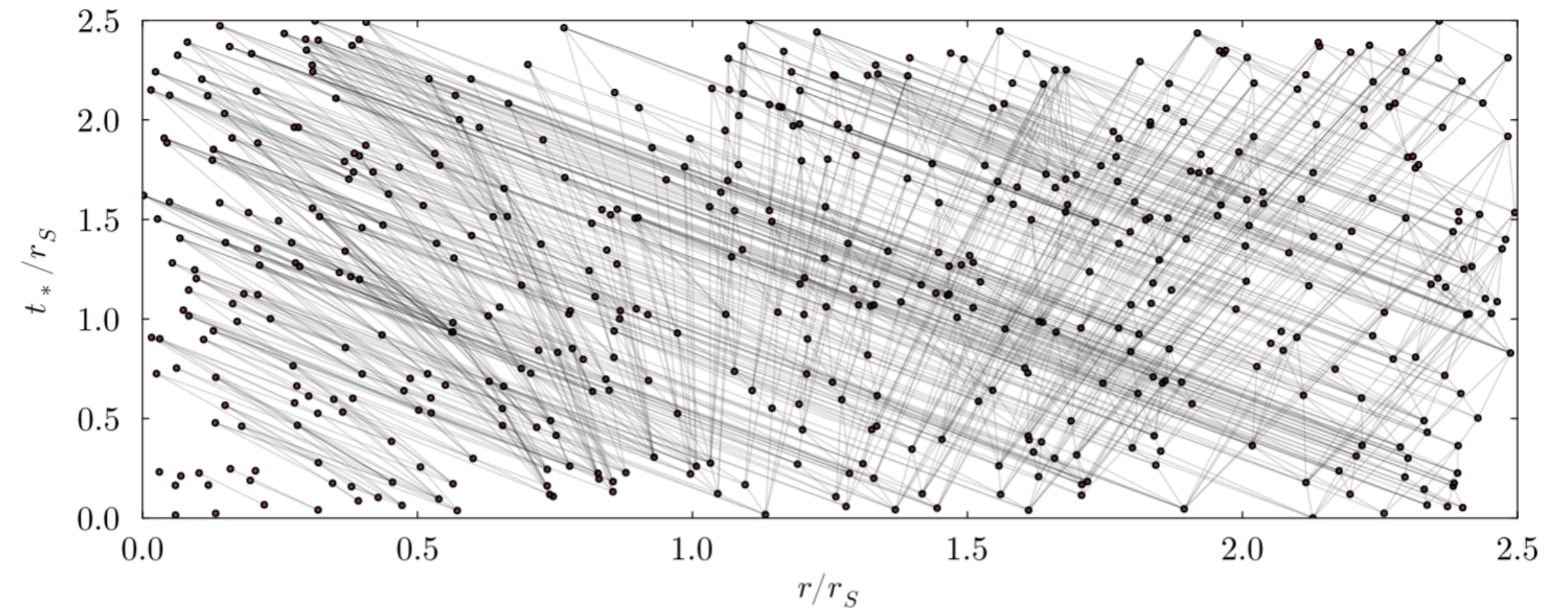
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Causal order and Lorentzian nature of spacetime take center stage

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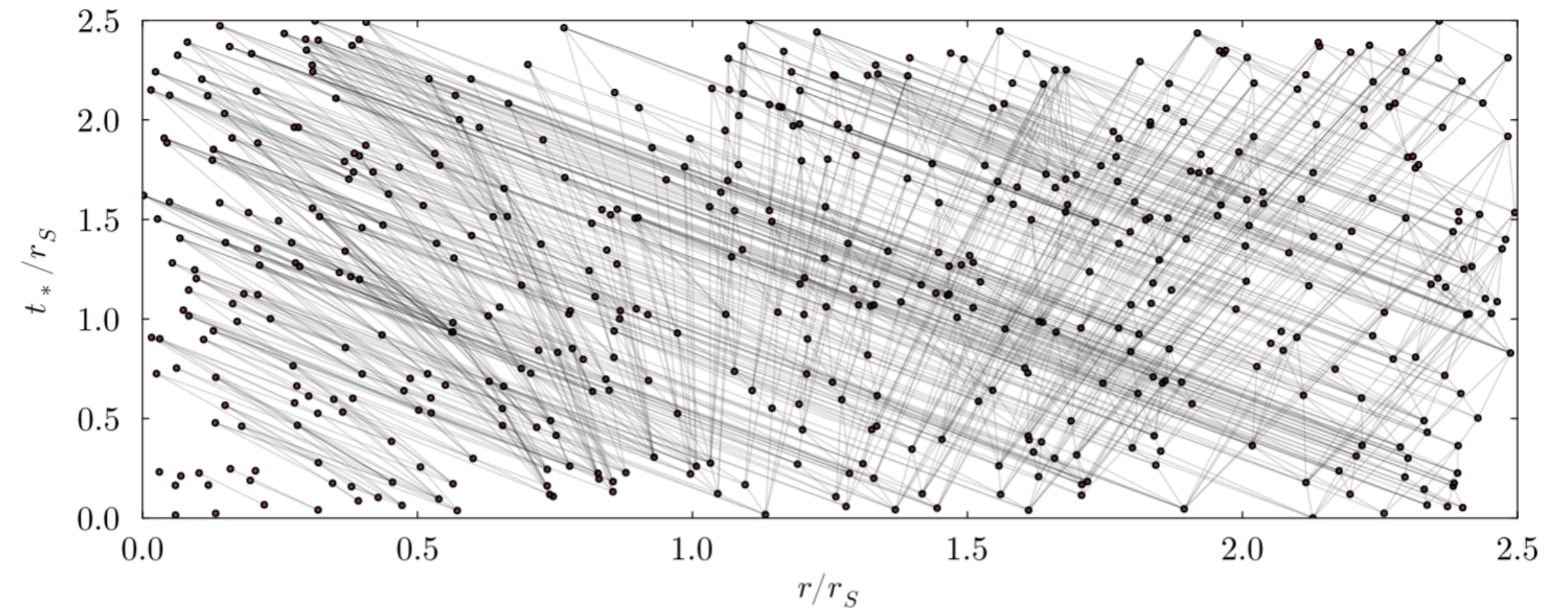
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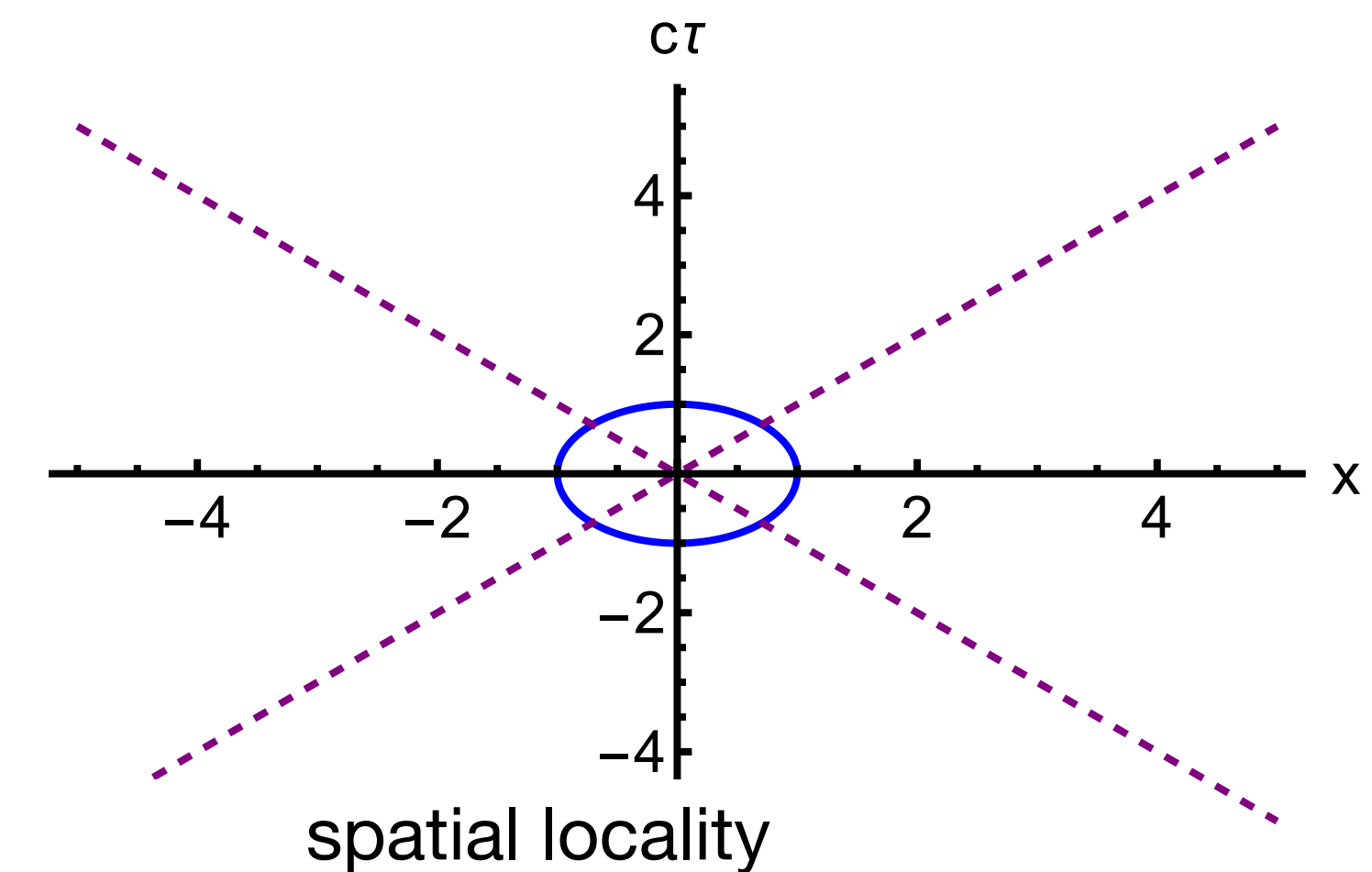
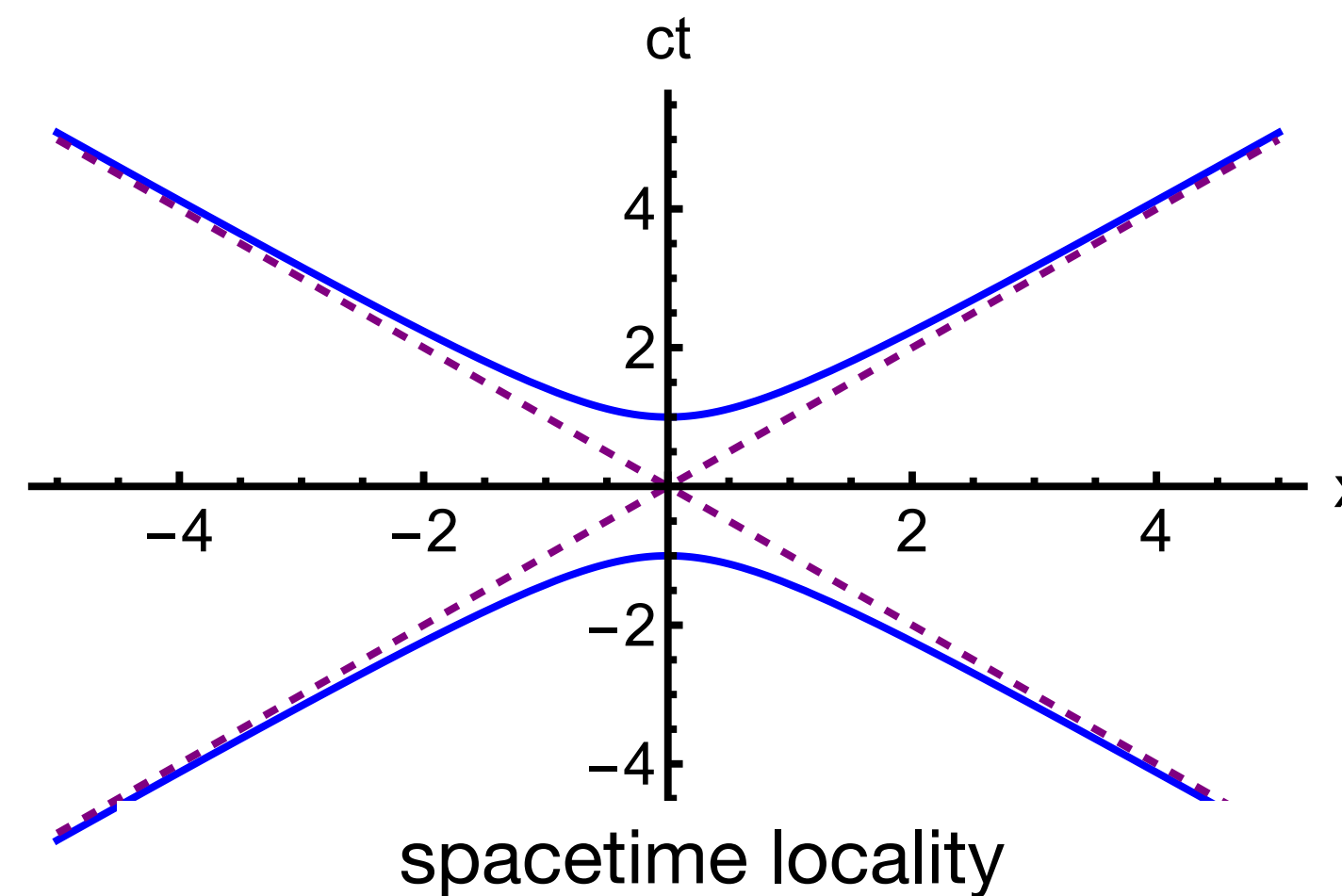
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In a causal set, the conformal factor is recovered by counting:

Embedding of causal set elements into differentiable manifold (understood as approximation to the causal set) is through random Poisson process  $\Rightarrow$  number of causal set elements proportional to spacetime volume.

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Configurations: causal sets

A causal set  $C$  is a set of spacetime points,  $e_i \in C$ , together with a relation  $<$  “precedes”, such that

- If  $e_i < e_j$  and  $e_j < e_k$ , then  $e_i < e_k$

(causal order of events is transitive)

- If  $e_i < e_j$  and  $e_j < e_i$ , then  $e_i = e_j$

(no closed timelike loops)

- $|\{e_j | e_i < e_j < e_k\}| < \infty \forall e_i, e_k \in C$

(local finiteness, spacetime discreteness)

Hawking Malament theorem: Under some (fairly generic) assumptions, the causal order of a continuum differentiable manifold encodes the metric up to a conformal factor.

In a causal set, the conformal factor is recovered by counting:

Embedding of causal set elements into differentiable manifold (understood as approximation to the causal set) is through random Poisson process  $\Rightarrow$  number of causal set elements proportional to spacetime volume.

Causal set “slogan” (R. Sorkin):

Order + number = geometry



# Causal set quantum gravity

Very far from asymptotic safety?!

What could a connection look like and why  
should it be useful?



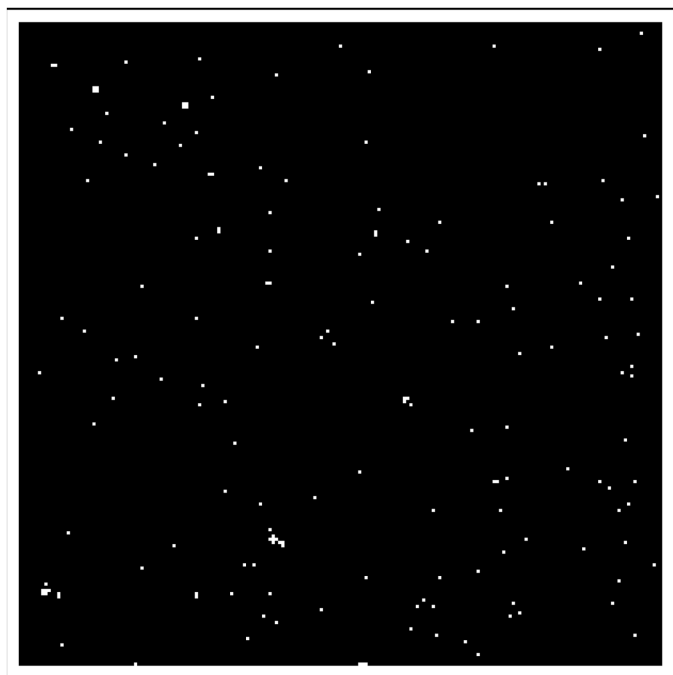
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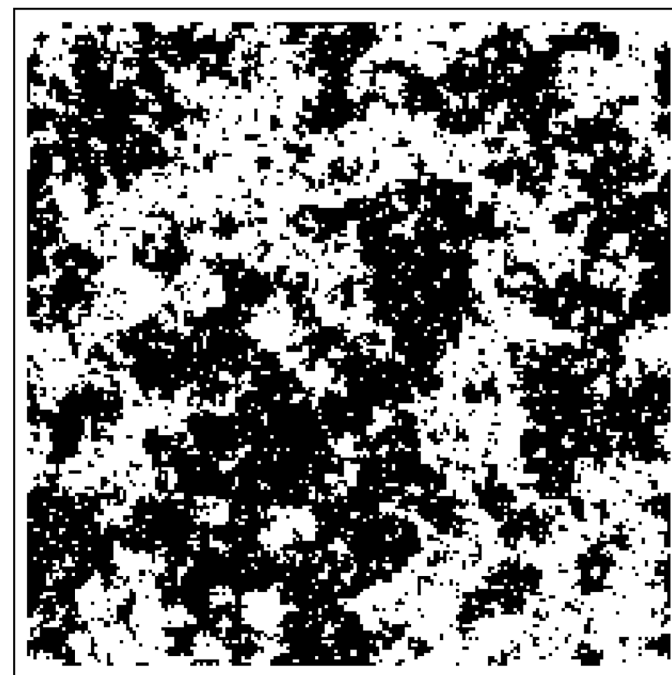
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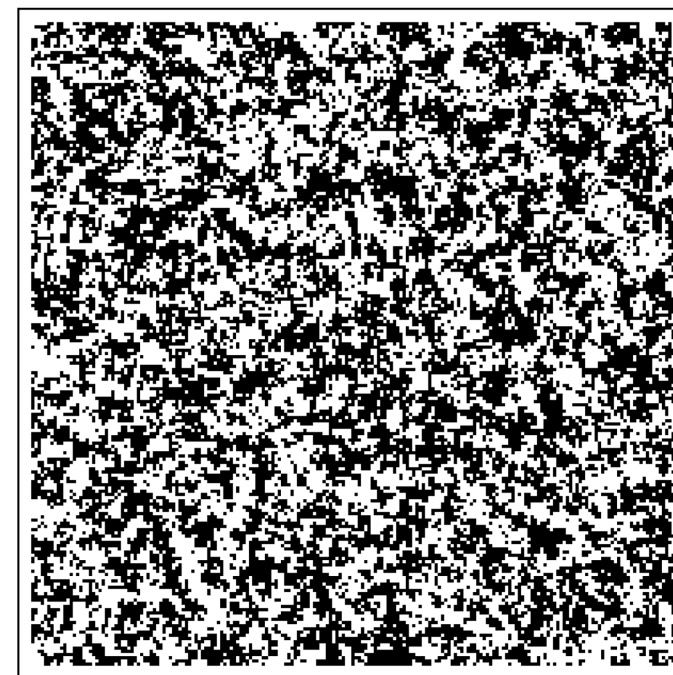
Asymptotic safety translated into discrete approaches  
= universal continuum limit, achievable at higher-order  
phase transition in phase diagram (cf. Dynamical Triangulations)



$T < T_c$



$T \sim T_c$



$T > T_c$

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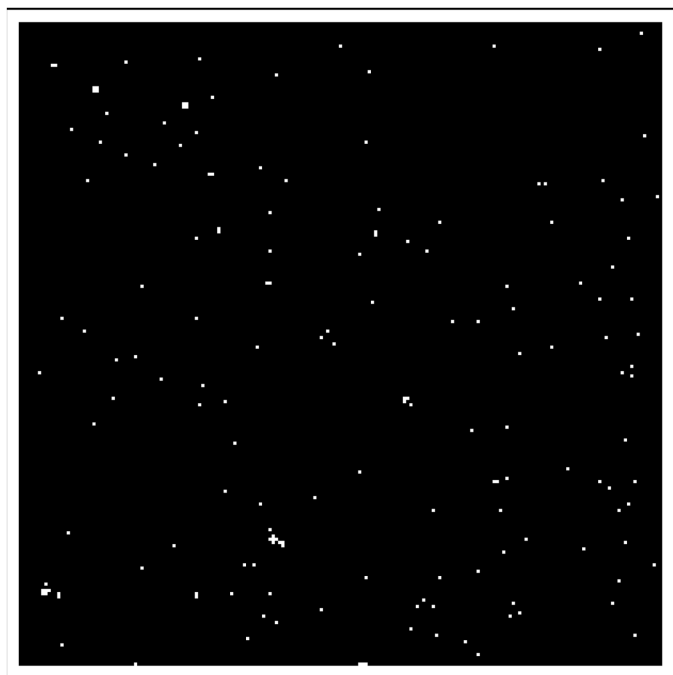
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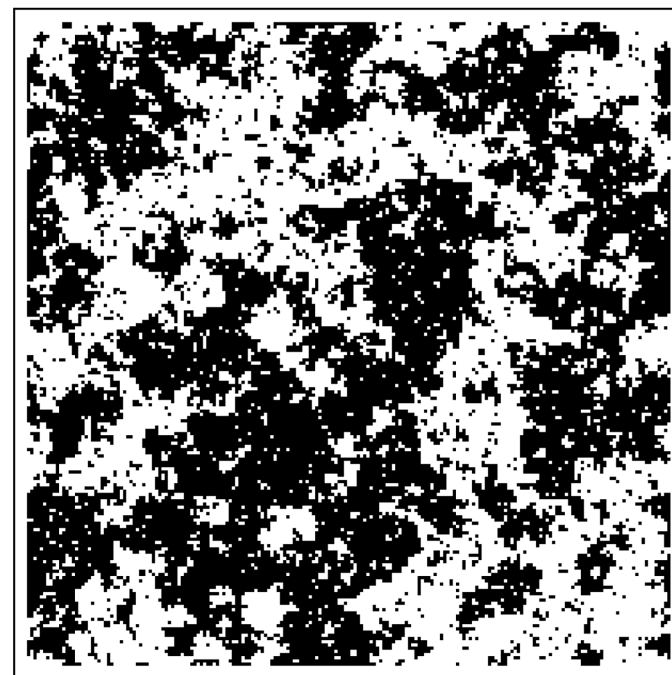
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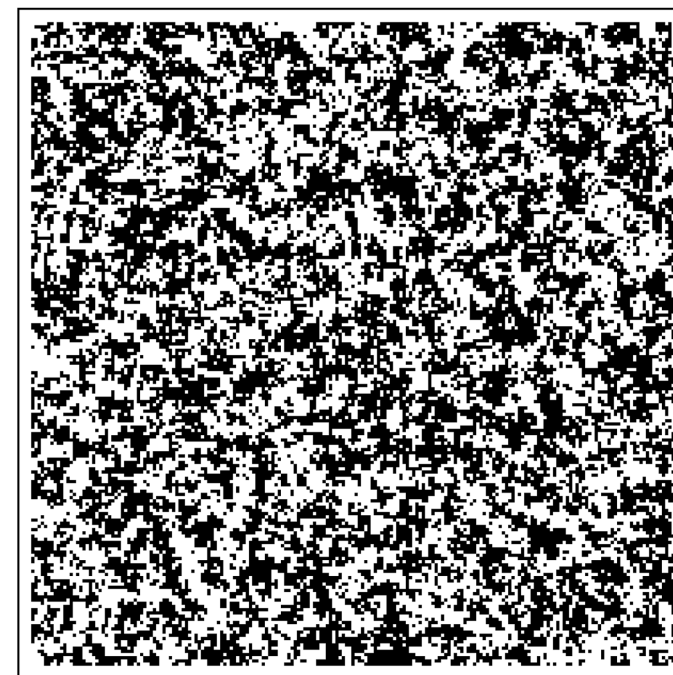
Causal sets is a fundamentally Lorentzian approach;  
Continuum functional RG in Lorentzian signature  
extremely challenging (but see poster by G. Assant  
for fantastic progress!)



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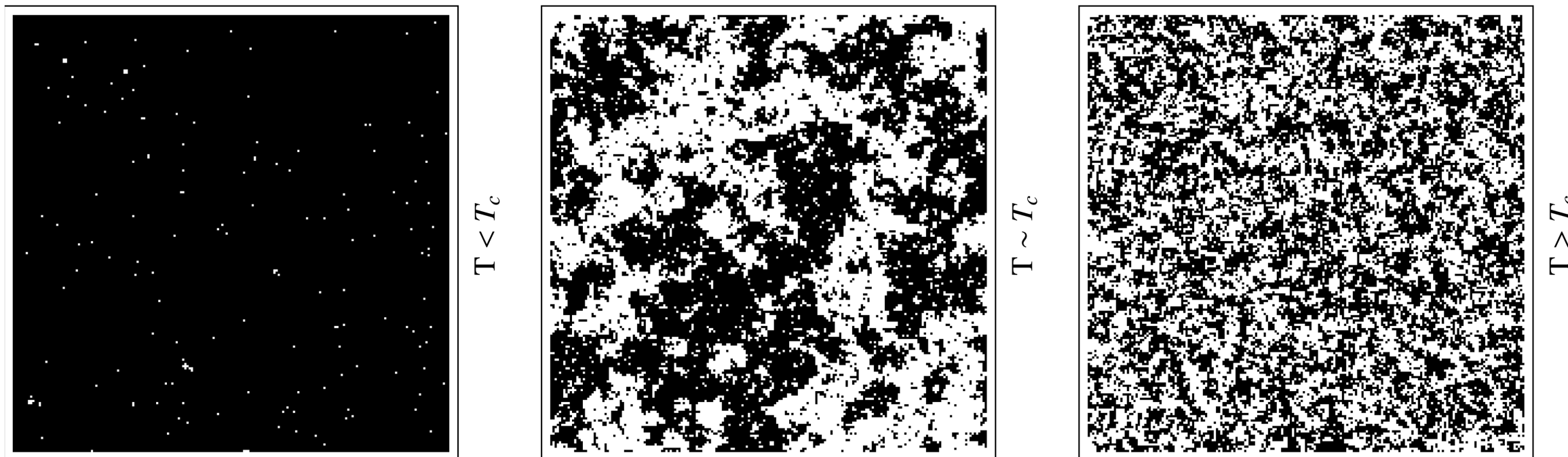
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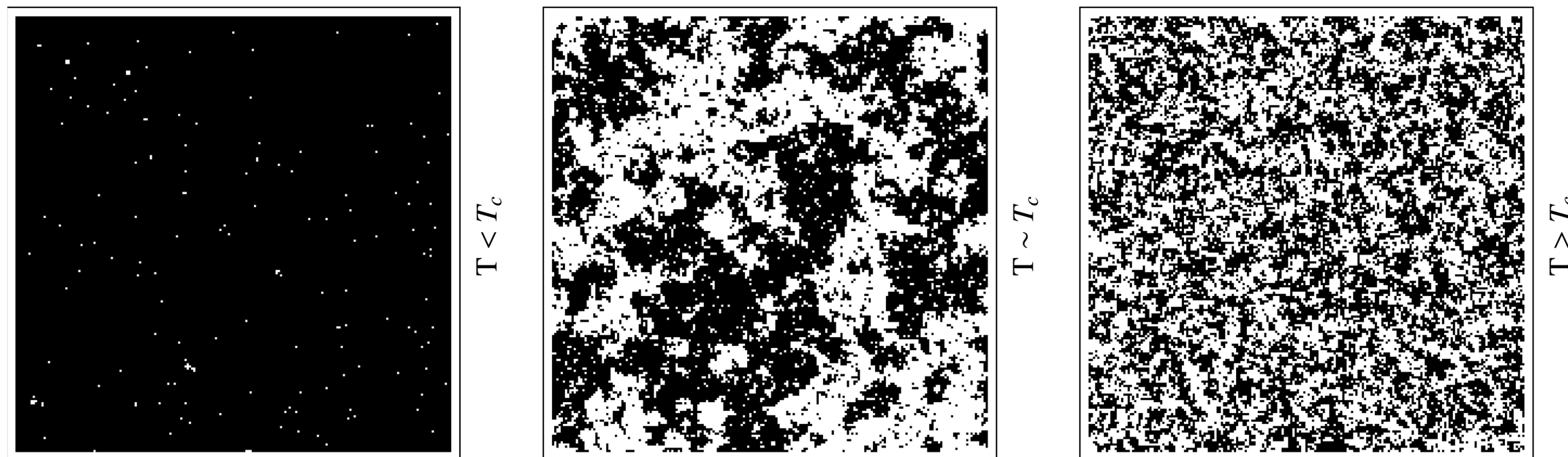
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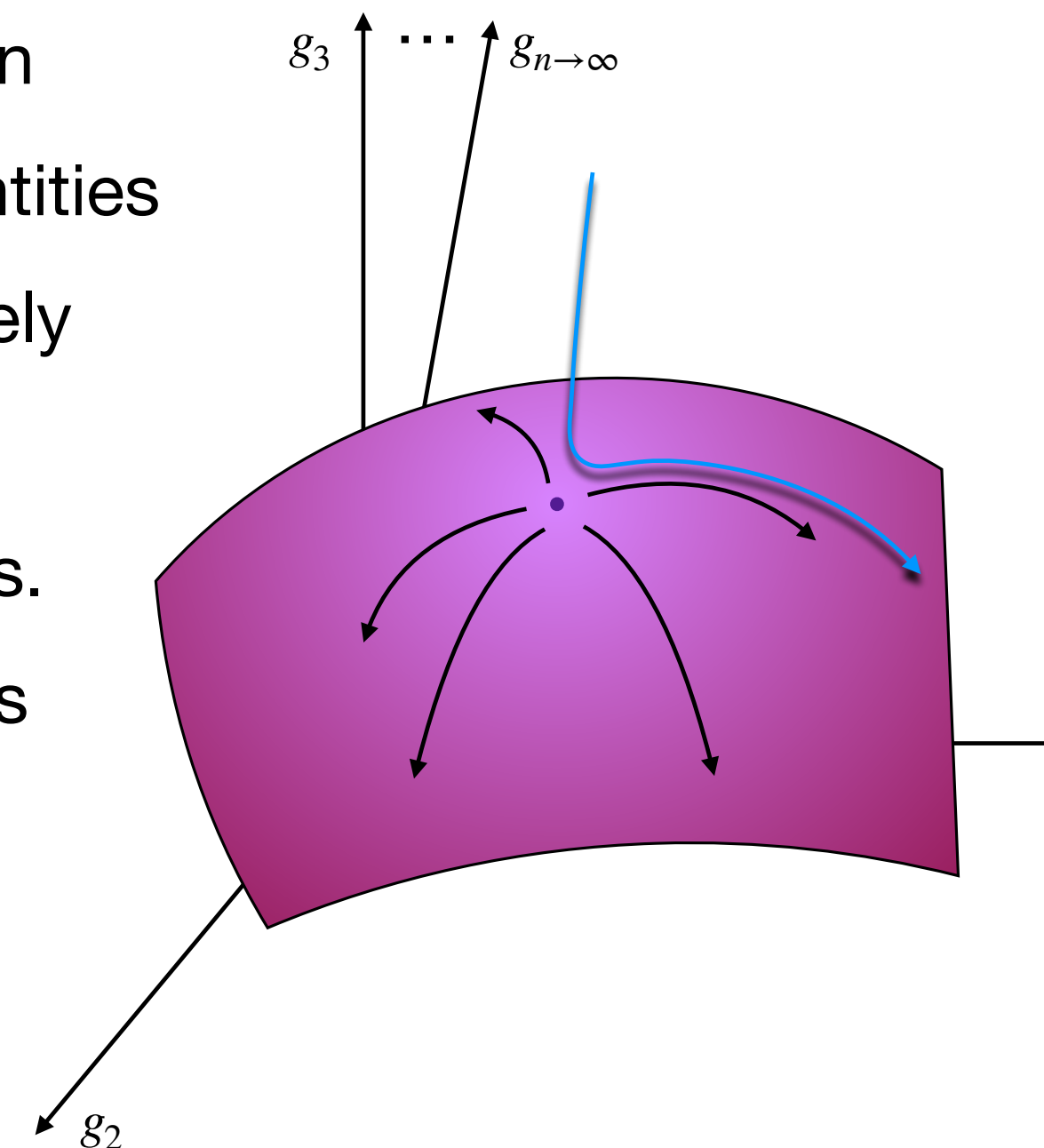


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Continuum functional RG in Lorentzian signature  
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Why is this interesting for causal sets?

Given  $C$ , building blocks for an  
action are label-invariant quantities  
on the graph. There are infinitely  
many; thus action has a priori  
infinitely many free parameters.  
Requiring continuum limit fixes  
these.





# Causal set quantum gravity

Very far from asymptotic safety?!

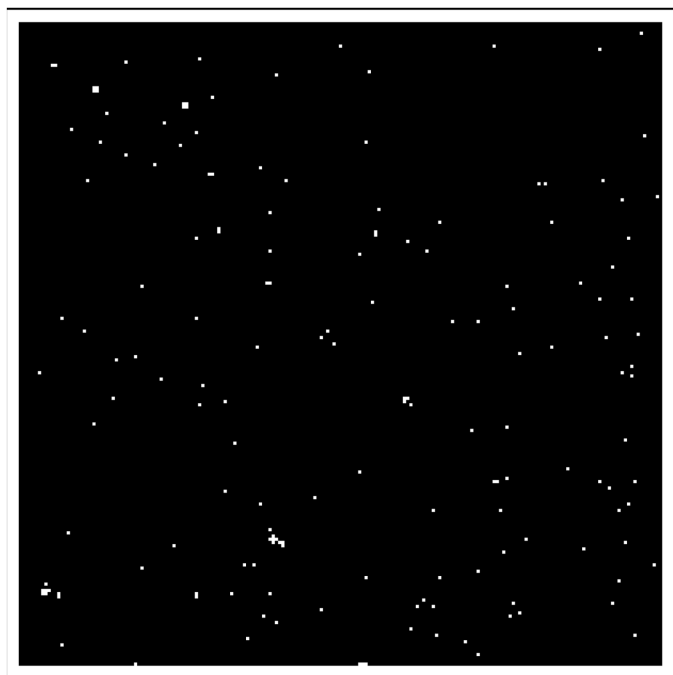
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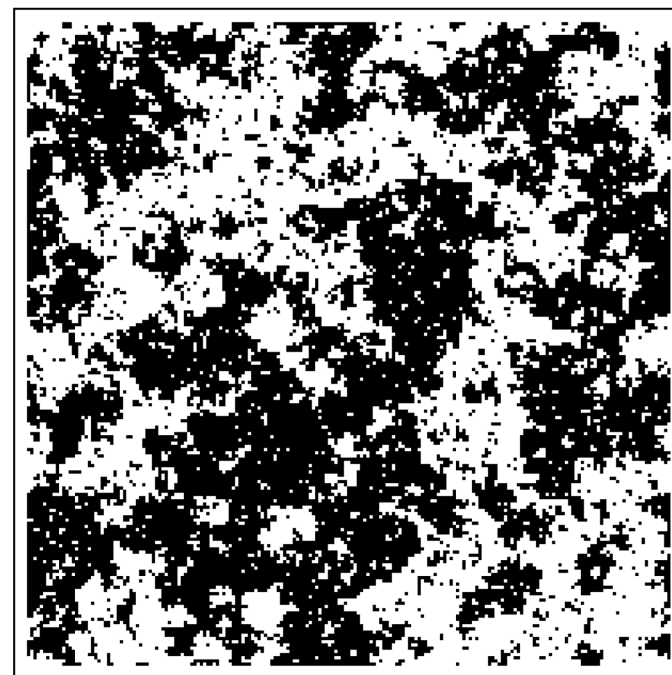
first-order phase transitions in restricted configuration spaces (2 and 3 dimensions)

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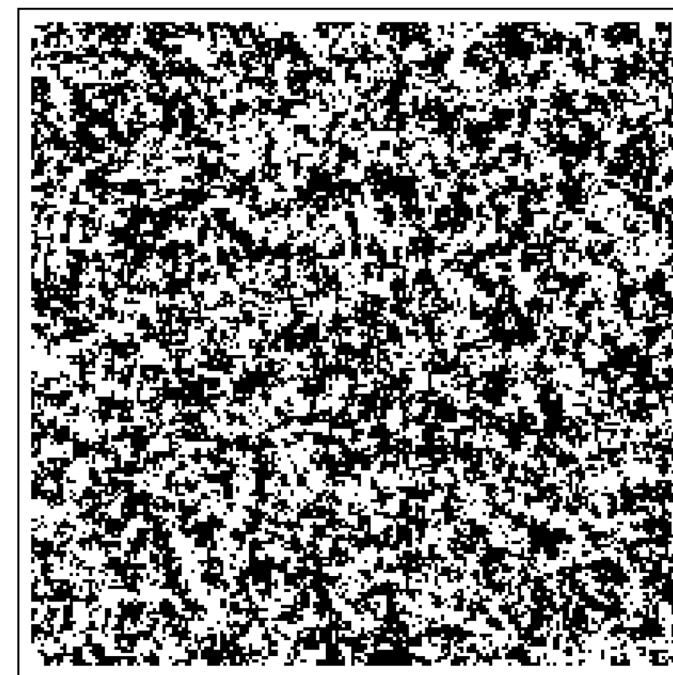
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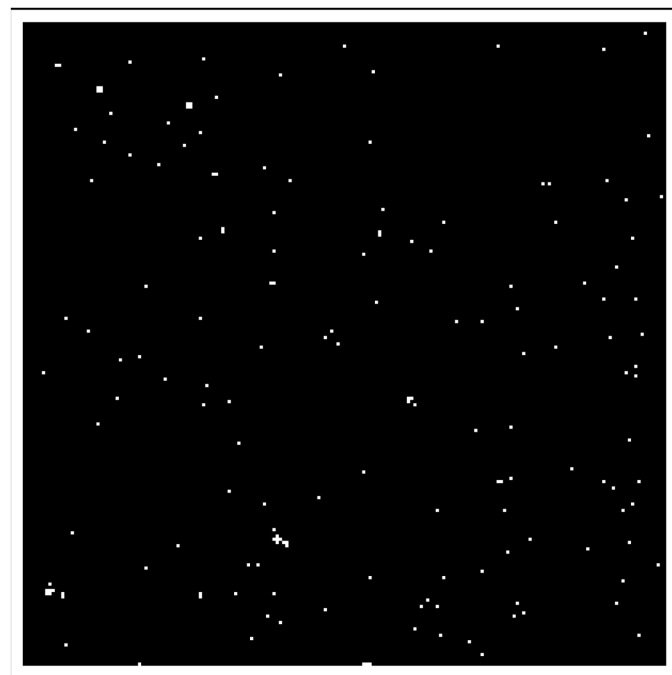
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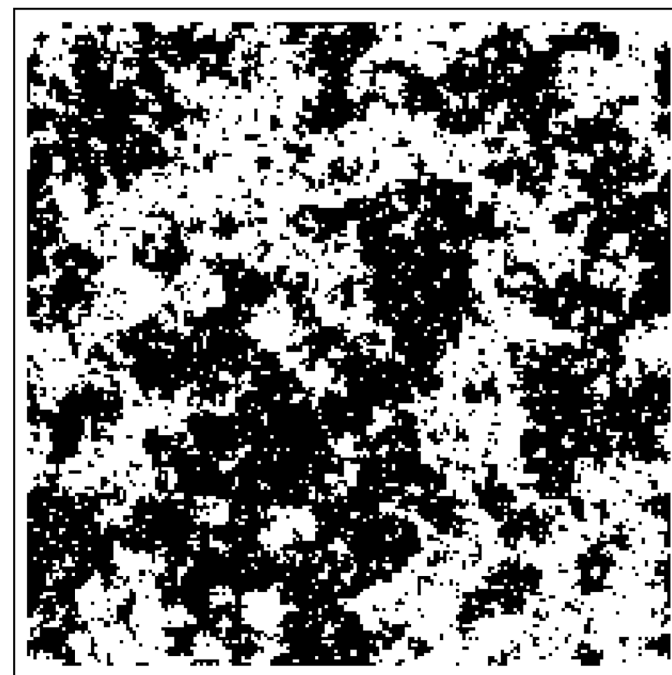
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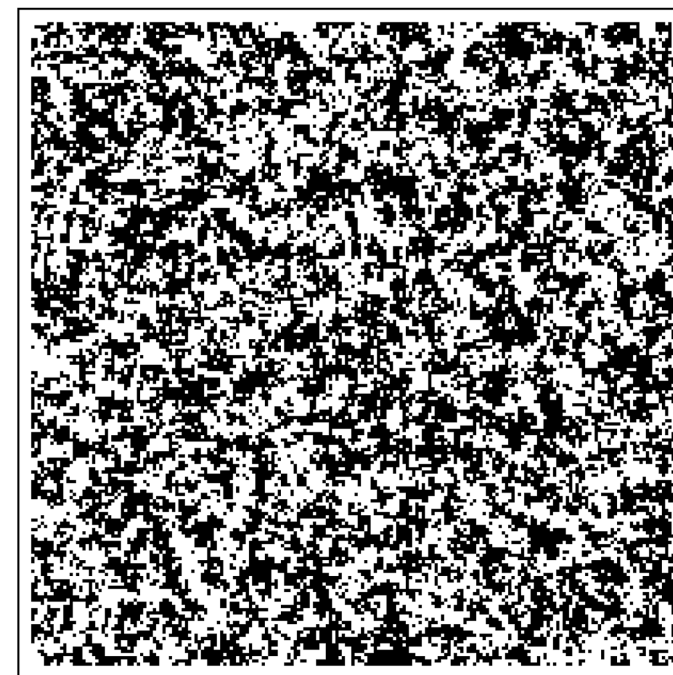
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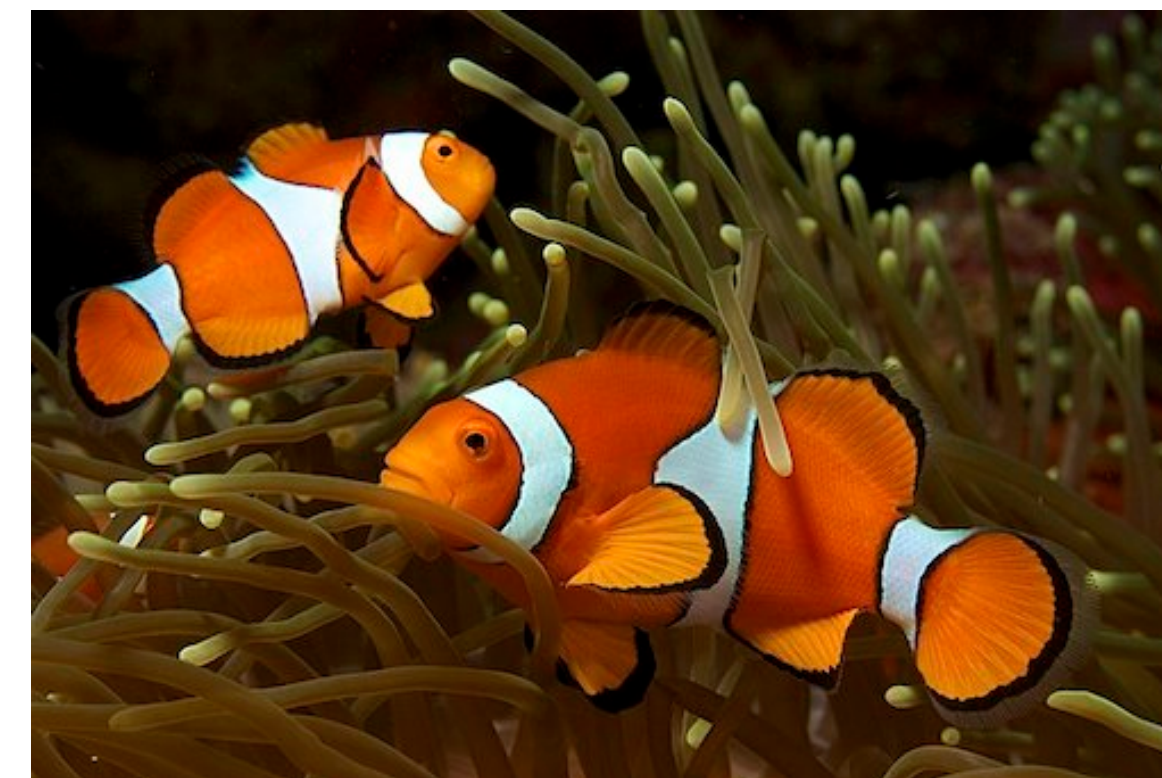
Status: [Surya '11; Cunningham, Surya '19]

first-order phase transitions in restricted  
configuration spaces (2 and 3 dimensions)

What is missing?

- additional configurations (but challenging to map out configuration space) [AE, Mack, Lee, Wagner '26]
- analogue of higher-order curvature terms [Sorkin '07; Benincasa Dowker '10; de Brito, AE, Pfeiffer '23]

Outlook: 'symbiotic' relationships between  
quantum-gravity frameworks?





# Conference: Quantum gravity 2027

September 13-17, 2027

more info coming soon - stay tuned!





# Outlook

Asymptotic safety: Scale symmetry in the UV

Predictive power for the IR

here: Standard Model of particle physics

beyond SM: not everything goes

connections to other models/frameworks produce constraints  
on the free parameters of those models/frameworks

examples:

Poster: Daniele Berruti (master's thesis)  
Horndeski Gravity in Asymptotically Safe Gravity: Bridging UV with IR



Horndeski gravity  
(e.g., in cosmology)

Poster: Moritz Gessner (2607.18398)  
On the Structure of the Fermion Sector in the Asymptotically Safe  
Standard Model



Standard Model effective field theory  
(e.g., at LHC)

Poster: Lidia Marino (2603.05064 & to appear)  
Scalarized black holes in asymptotically safe gravity



Black-hole scalarization  
(e.g., in numerical relativity, comparison with data)





# Thanks to current and former group members!



Aaron Held,  
now ENS Paris



Marc Schiffer,  
now Radboud U.



Rafael R. Lino  
dos Santos,  
now Warsaw U.



Johannes Lumma,  
now Oxford U.



Fleur Versteegen,  
now ASML



Alessia Platania,  
prof. at U. Graz



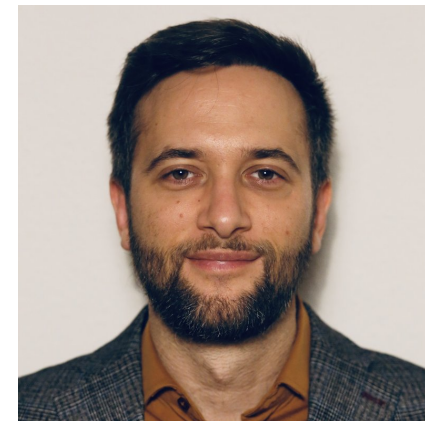
Shouryya Ray  
assist. prof.  
at U. of Faroe Islands



Martin Pauly,  
now exnaton



Héloïse Delaporte,  
now U. of Kraków



Raúl Carballo-Rubio  
associate prof.  
at U of Granada, Spain



Antonio Pereira,  
assist. prof. at  
Flum. Fed. U.,  
Brazil



Gustavo P. de Brito,  
assist. prof. at  
São Paulo State U.,  
Brazil





# Current status

S. Weinberg '76    M. Reuter '96

degree of realism 

Euclidean quantum gravity:  
Existence of fixed point established  
(functional Renormalization Group:  
hundreds of papers  
lattice (dynamical triangulations;  
Ambjørn, Jurkiewicz, Loll '00):  
supporting evidence)

Functional Renormalization Group: based on Euclidean path integral

$\Gamma_k$ : analog of classical action, but with quantum fluctuations above  $k$  included

$$k \partial_k \Gamma_k = \frac{1}{2} \text{Tr} \left[ \left( \Gamma_k^{(2)} + R_k \right)^{-1} k \partial_k R_k \right] \quad \rightarrow \quad \beta_g = k \partial_k g(k)$$

[Wetterich '93; Reuter '96]



$$\Gamma_{k \rightarrow \infty} \simeq S$$



$$\Gamma_{k \rightarrow 0} = \Gamma$$

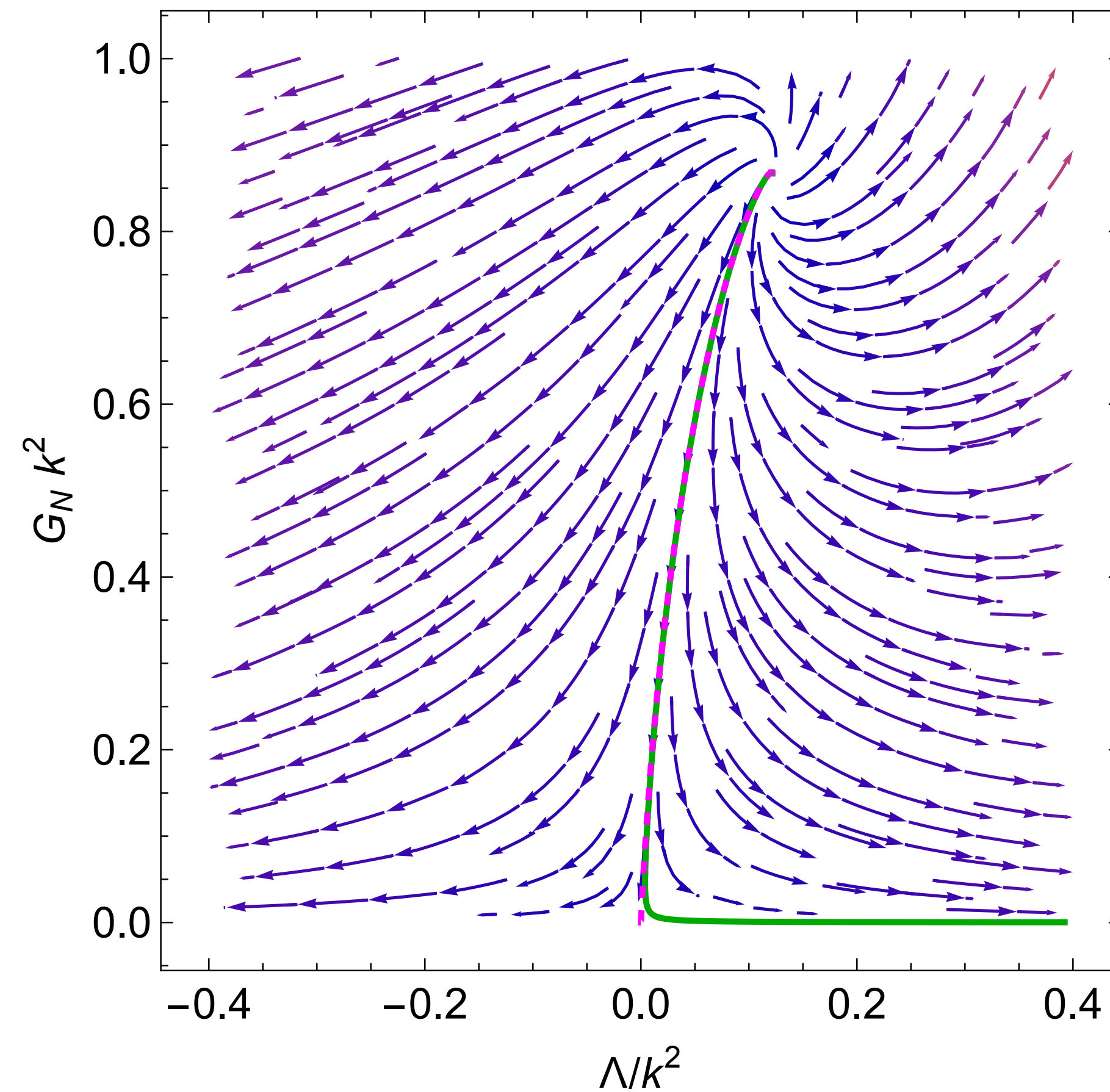
$$e^{-\Gamma_k} \simeq \int_{p^2 > k^2} \mathcal{D}g_{\mu\nu} e^{-S[g_{\mu\nu}]}$$

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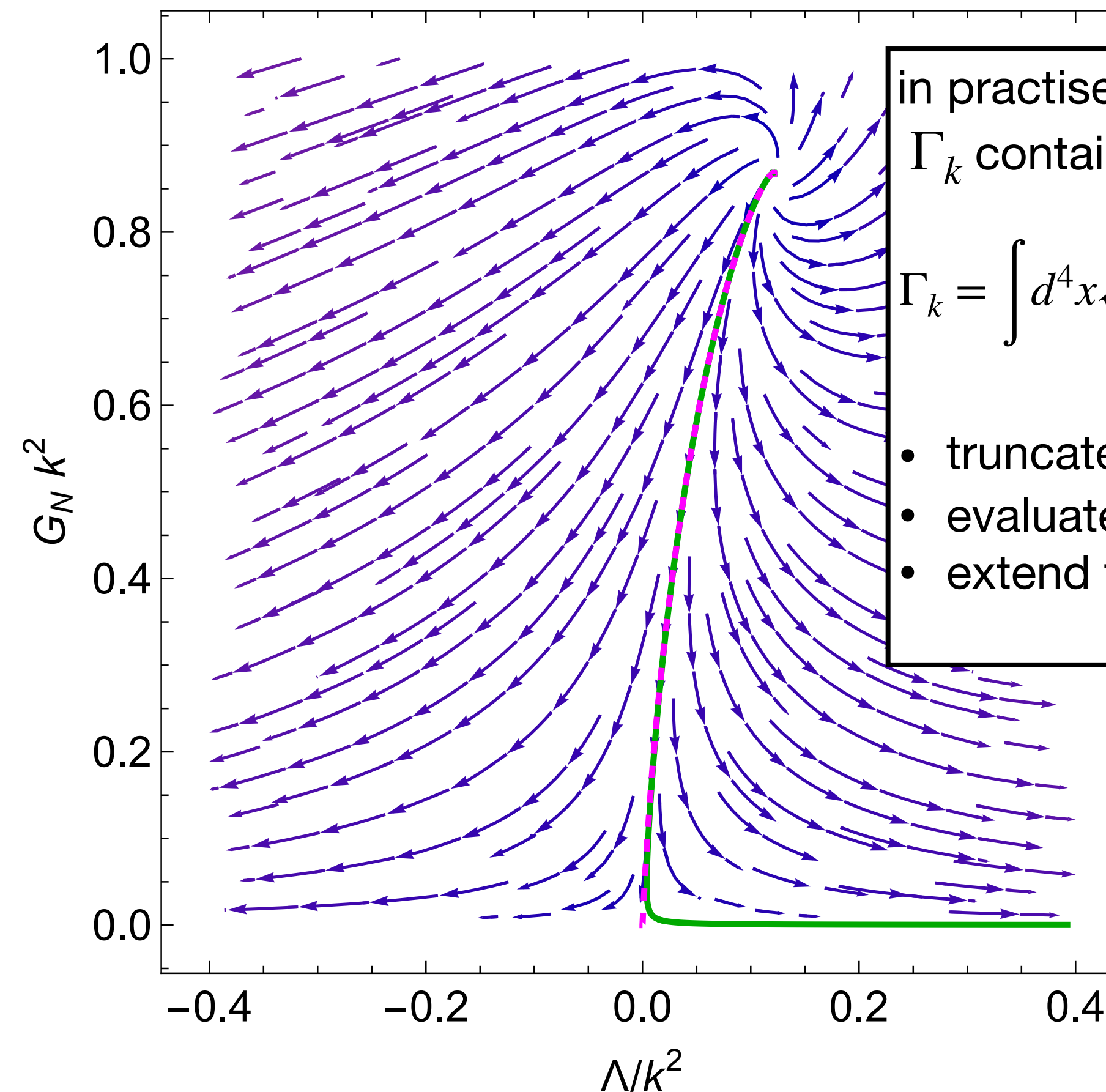


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in practise:

$\Gamma_k$  contains infinitely many interactions

$$\Gamma_k = \int d^4x \sqrt{-g} \left( \Lambda(k) + \frac{1}{16\pi G_N(k)} R + a(k) R^2 + b(k) R_{\mu\nu} R^{\mu\nu} + \dots \right)$$

- truncate  $\Gamma_k$  by including a subset of interactions
- evaluate beta functions and characterize fixed point
- extend the truncation and check stability of results

Controllable and robust results?



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Physics Reports  
Volume 910, 10 May 2021, Pages 1-114



The nonperturbative functional renormalization group and its applications

N. Dupuis <sup>a</sup>  , L. Canet <sup>b</sup>, A. Eichhorn <sup>c d</sup>, W. Metzner <sup>e</sup>, J.M. Pawłowski <sup>d f</sup>, M. Tissier <sup>a</sup>, N. Wschebor <sup>g</sup>

Quantitative precision achievable

Example: Fixed point in the Ising model, derivative expansion

| derivative expansion   | $\nu$       | $\eta$        |
|------------------------|-------------|---------------|
| $s = 0$ (LPA)          | 0.651(1)    | 0             |
| $s = 2$                | 0.6278(3)   | 0.0449 (6)    |
| $s = 4$                | 0.63039(18) | 0.0343(7)     |
| $s = 6$                | 0.63012(5)  | 0.0361 (3)    |
| $s \rightarrow \infty$ | 0.6300(2)   | 0.0358(6)     |
| conformal bootstrap    | 0.629971(4) | 0.0362978(20) |

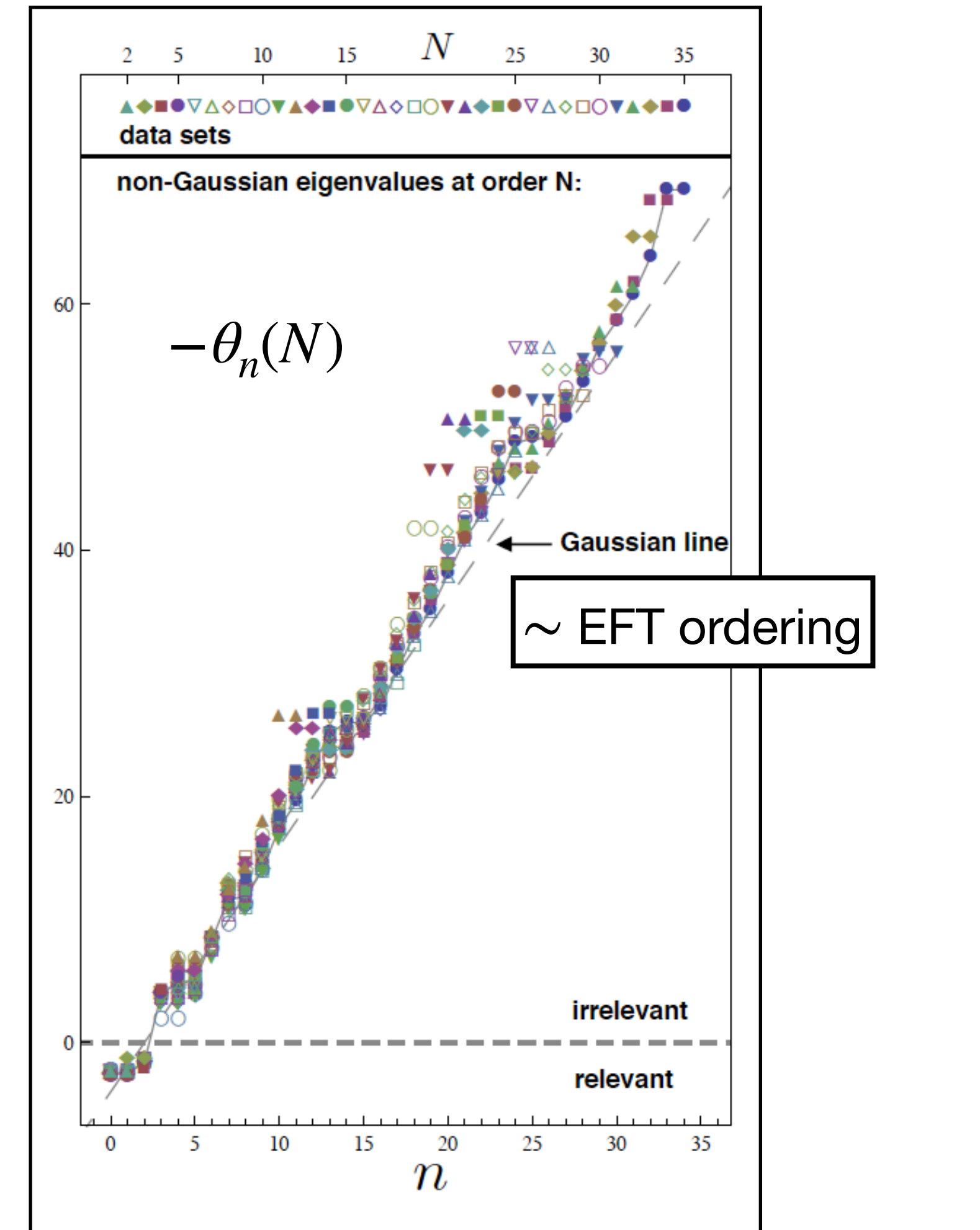
[Balog, Chaté, Delamotte, Marohnić, Wschebor '19]

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“Near-perturbative”  $\Rightarrow$  control over calculations:  
ordering of interactions follows canonical power  
counting ( $\sim$  EFT ordering)



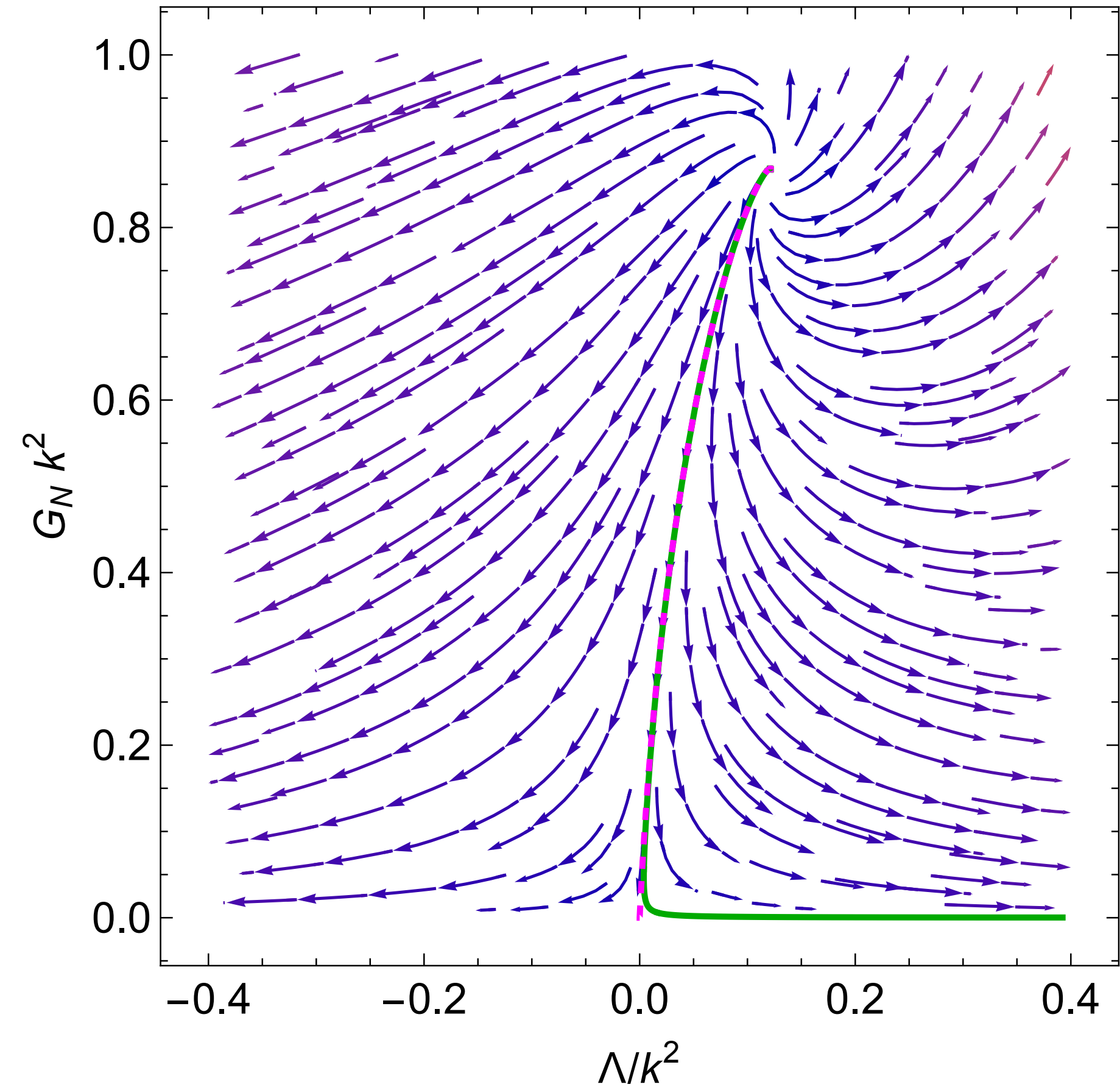
[Falls, Litim et al. '13]

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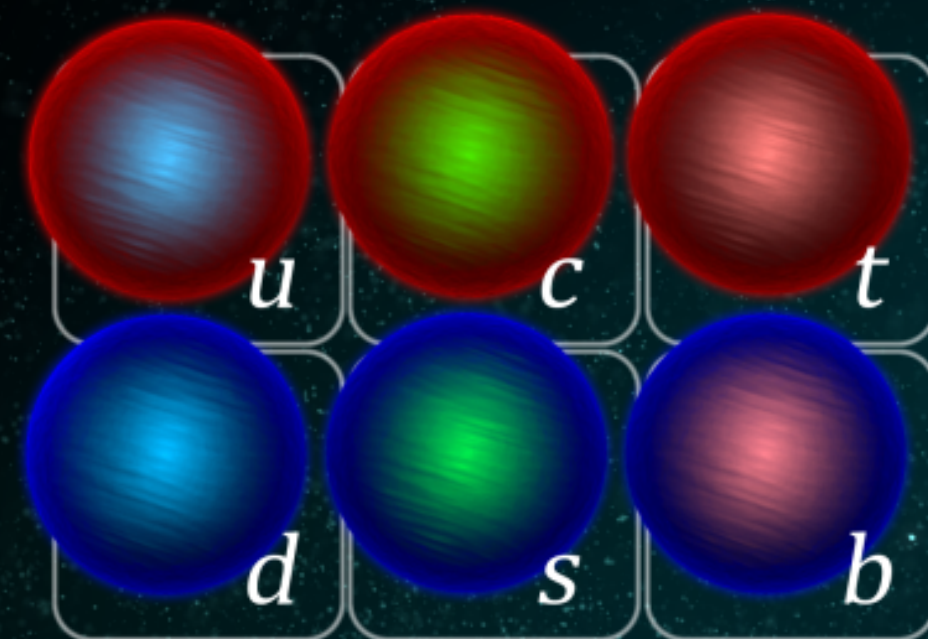
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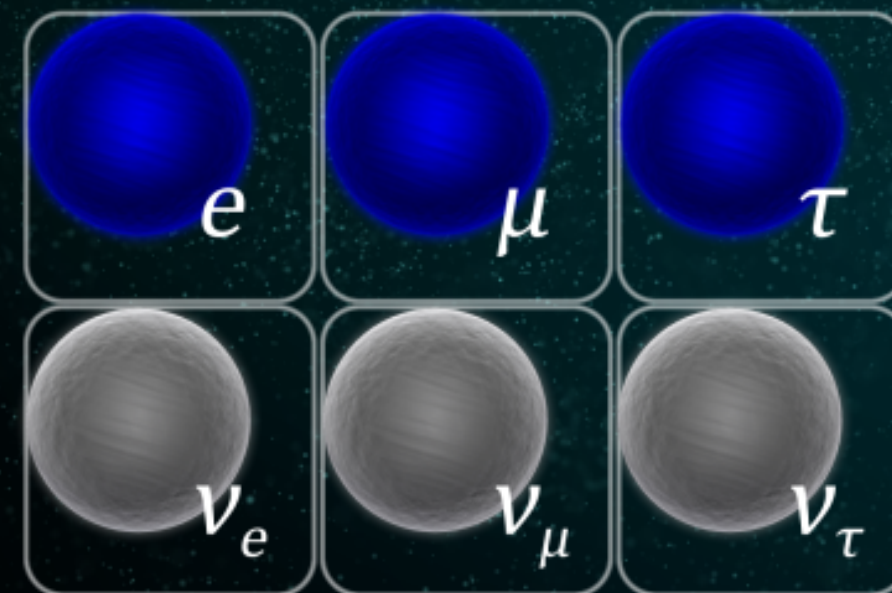
relevant directions ( $\theta > 0$ ):  
 $\sqrt{-g}\Lambda, \sqrt{-g}R\frac{1}{16\pi G_N}, \sqrt{-g}(R^2 + \#R_{\mu\nu}R^{\mu\nu})a$   
[Benedetti, Machado, Saueressig '09;  
Falls, Litim, et al. '13, '14;  
Denz, Pawłowski, Reichert '16;  
Falls, Ohta, Percacci '20;  
Baldazzi, Falls, Kluth, Knorr '23]  
all other couplings irrelevant



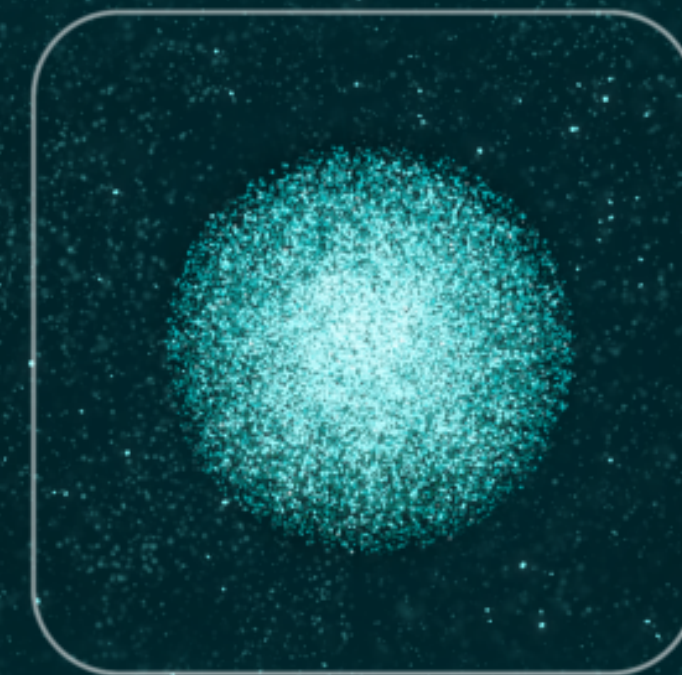
# Standard Model couplings



Quarks



Leptons



Higgs boson



Forces

## The microscopic structure of quantum space-time and matter from a renormalization group perspective

[Astrid Eichhorn](#)

[Nature Physics](#) **19**, 1527–1529 (2023) | [Cite this article](#)

[arXiv](#) > hep-th > arXiv:2212.07456

High Energy Physics – Theory

[Submitted on 14 Dec 2022]

## Asymptotic safety of gravity with matter

[Astrid Eichhorn](#), [Marc Schiffer](#)

[arXiv](#) > hep-th > arXiv:1810.07615

High Energy Physics – Theory

[Submitted on 17 Oct 2018 ([v1](#)), last revised 21 Feb 2019 (this version, v2)]

## An asymptotically safe guide to quantum gravity and matter

[Astrid Eichhorn](#)