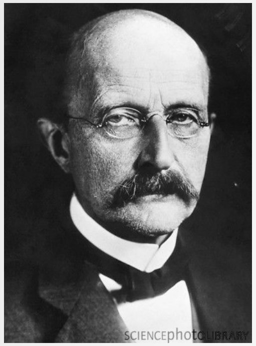
Planck 2018 Memorial Scientific Symposium



Quantum Field Theory towards the Planck scale

in search of the Theory of Everything

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Outlines

- Introduction
- Aspects of shadowing
- Scale evolution of the Standard Model
- Renormalizing gravity
- Conclusions

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Introduction: Understand Universe!

Analogy: understand human body

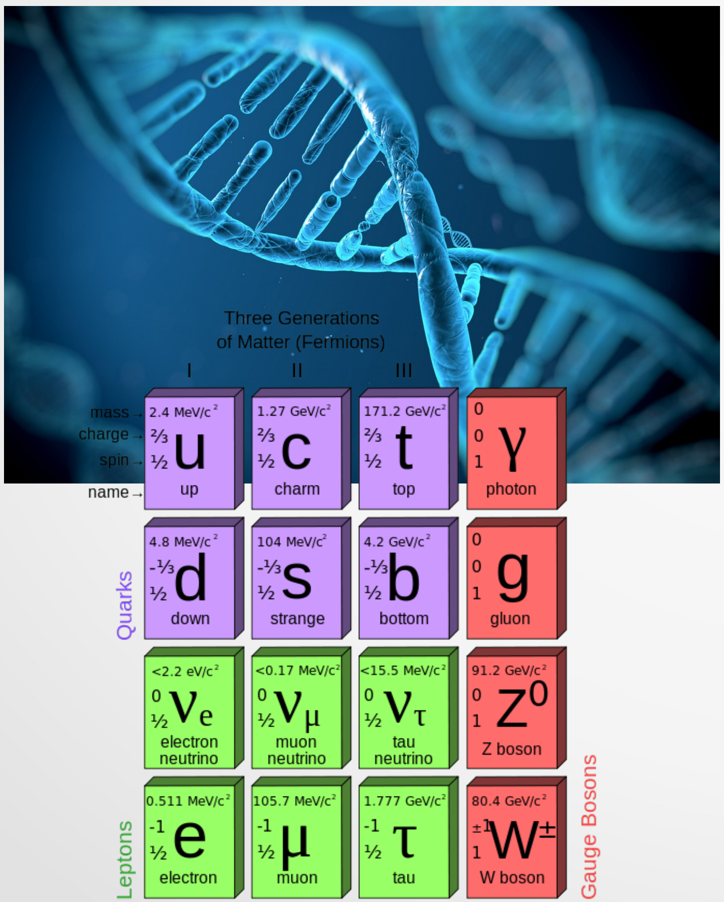
Human body in different resolutions:

- full body
- organs
- cells
- ultimate understanding: *DNA, human genome*

We see all scales from experiment

Introduction: Understand Universe!

Understand Universe



Human body in different resolutions:

- full body
- organs
- cells
- DNA, human genome

Universe's genome project:

- continuous matter
- molecules, atoms,
- nuclei, hadrons
- Standard Model
- GUT/SUSY/string theory?
- "genome": **Theory of Everything**

Introduction

Intrinsic scale of the Universe: **Planck scale**

From dimensionful constants of nature we can produce an energy scale

$$[c]=\frac{m}{s}, \quad [\hbar]=\frac{kg\, m^2}{s}, \quad [G]=\frac{m^3}{kg\, s^2}$$

$$R_{Pl}=\sqrt{\frac{\hbar G}{c^3}}\approx 10^{-35}\, m, \quad M_{Pl}=\sqrt{\frac{\hbar c}{G}}\approx 2.2\ \ 10^{-8}\, kg$$

$$E_{Pl}=M_{Pl}c^2\approx 2\cdot 10^9\, J=1.2\cdot 10^{19}\, GeV$$

Interpretation:

"resolution" of spacetime, geometry/gravity starts to dominate

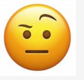
cf. talk of T.S. Biró

Introduction

Experimentally we see till Standard Model: $E \approx 10^4 \, GeV \,, \quad r \approx 10^{-20} m$

May the **Standard Model** (including right handed neutrinos) be the Theory of Everything?

- All accelerator experiments are within 3σ! ✓

- Aesthetics problem: too many parameters (19) 
- Phenomenological problem: cosmological observations (inflaton, dark matter/energy)

- Consistency problems of renormalization: Landau poles, vacuum stability, renormalization of gravity!? ✗

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Aspects of shadowing I.

What does renormalization physically mean?

… not just a property of quantum field theories!

Usually it appears in different models as

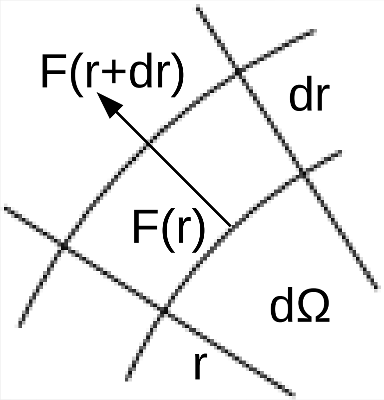
screening/shielding/shadowing/shading

- shading of sunlight
- dust/pollution/humidity in air reducing transparency
- screening of a charged ion in electrolytes
- dipole electric and magnetic screening in materials, permittivity and permeability of matter
- screening due to vacuum/statistical fluctuations ≡ *renormalization*

Aspects of shadowing: lamp brightness

Observe a light source from a distance. From energy conservation:

$$F(r)\, r^2\, d\Omega = F(r+dr)(r+dr)^2\, d\Omega$$



$$\frac{dF}{dr} = \frac{-2}{r} F \quad \Rightarrow \quad F = \frac{\alpha}{r^2}$$

Measurement instruction:

We should measure the F apparent brightness of the lamp at a distance r, then reconstruct the absolute brightness as

$$\alpha = F\, r^2$$

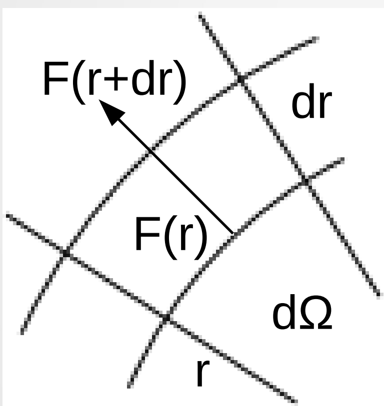
Experimental result: We measure larger α when we are closer to the light source!

Interpretation: Distance dependent source strength $\alpha(r)$!?

Aspects of shadowing: lamp brightness

Physical explanation:

If there is pollution in the air, it can shade the light source!



Dust reduces the incoming area:

$$F(r)\left(r^2 d\Omega - \sigma n r^2 dr\, d\Omega\right) = F(r+dr)(r+dr)^2 d\Omega$$

(where σ is cross section, n is particle density)

Equation for the lamp brightness $\alpha = F r^2$

$$\frac{d\alpha}{dr} = -\sigma n \alpha \quad \Rightarrow \quad \alpha(r) = \alpha_0 e^{-\sigma \int_0^r n(r')dr'} \quad \xrightarrow{\text{n const}} \quad \alpha = \alpha_0 e^{-\sigma n r}$$

Renormalization: Our model, based on *energy conservation* describes data only if the model parameter α depends on the distance. It is then a *“running coupling”.*

Models for screening

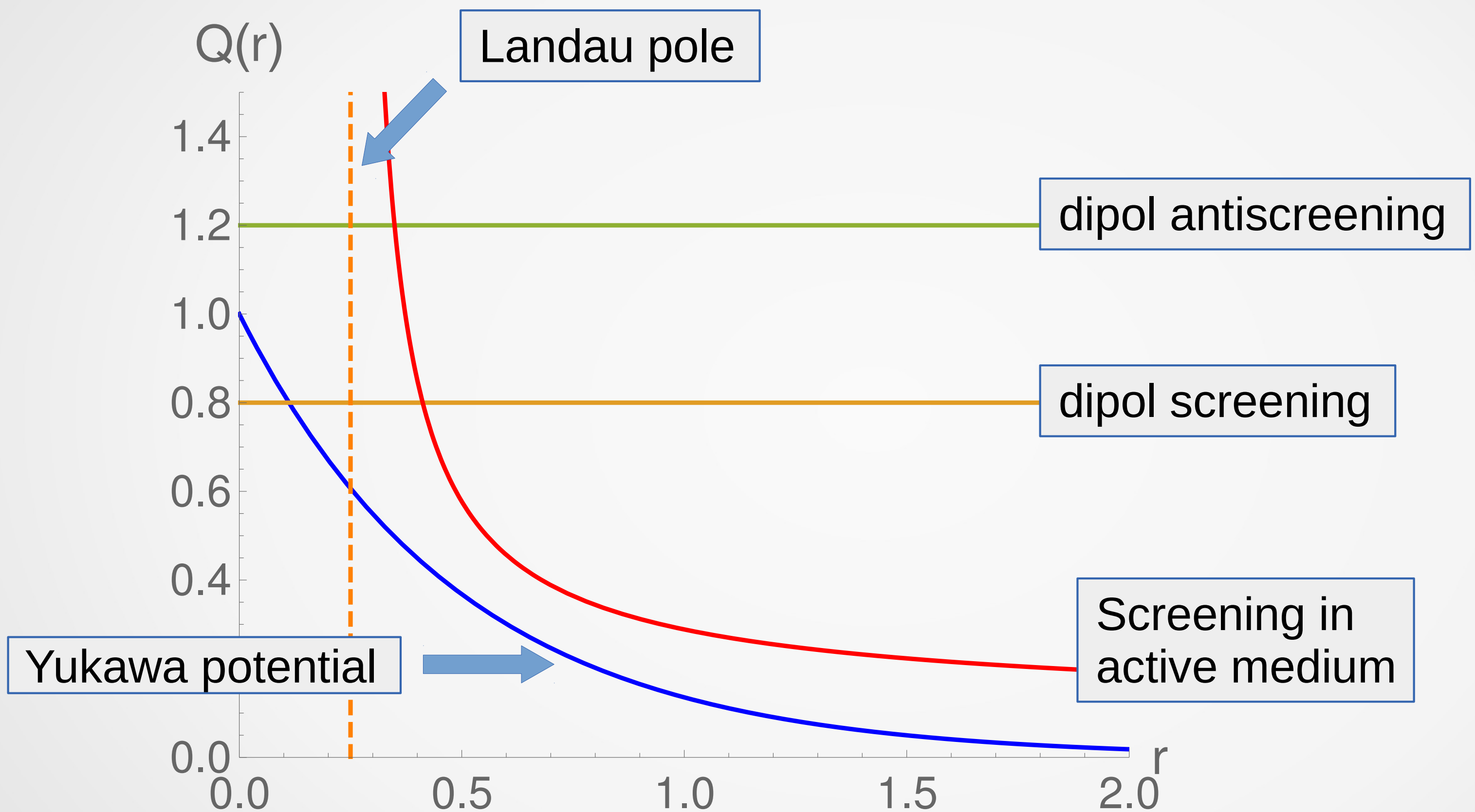
Form of the running source strength depends on the screening model

- Charge in electrolyte: $(\Delta-\kappa^2)\Phi=\frac{-\rho}{\epsilon_0}$ ➡ $\Phi=\frac{Q e^{-\kappa r}}{4\pi\epsilon_0 r}$ Yukawa potential
- Dipole screening (electrodynamics in matter): $Q\rightarrow\frac{Q}{\epsilon_r}$ r-independent
- Magnetic screening (paramagnetism): $J\rightarrow J(1+\chi)>J$ **anti-screening!**
- Dynamic screening: pollution density depends on the environment

$$n \propto \frac{\alpha}{r} \quad \Rightarrow \quad \frac{d\alpha}{dr}=-C\sigma\frac{\alpha^2}{r} \quad \Rightarrow \quad \alpha=\frac{1}{C\sigma\log(\Lambda r)}$$

… not sensible for r<1/Λ **Landau pole!**

Models for screening



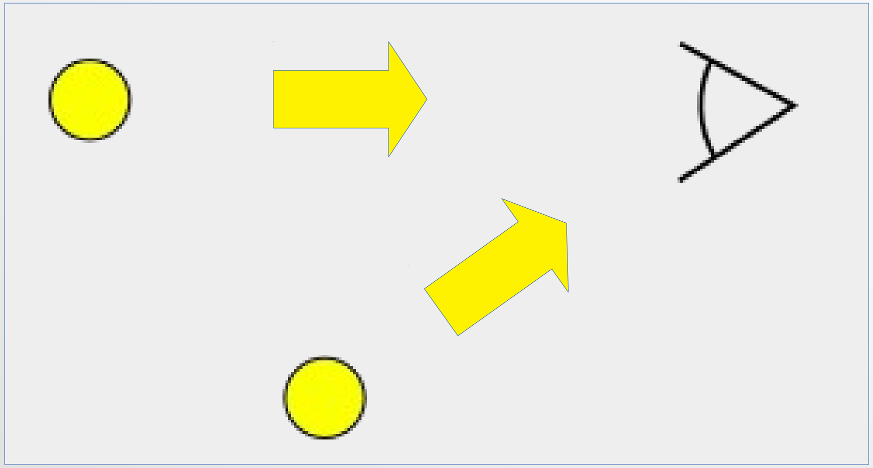
Vacuum screening in QED: $\alpha = \frac{1}{C\,\sigma \log(\Lambda r)}$ **Landau pole!**

vacuum screening ~ screening in active medium

Aspects of shadowing II.

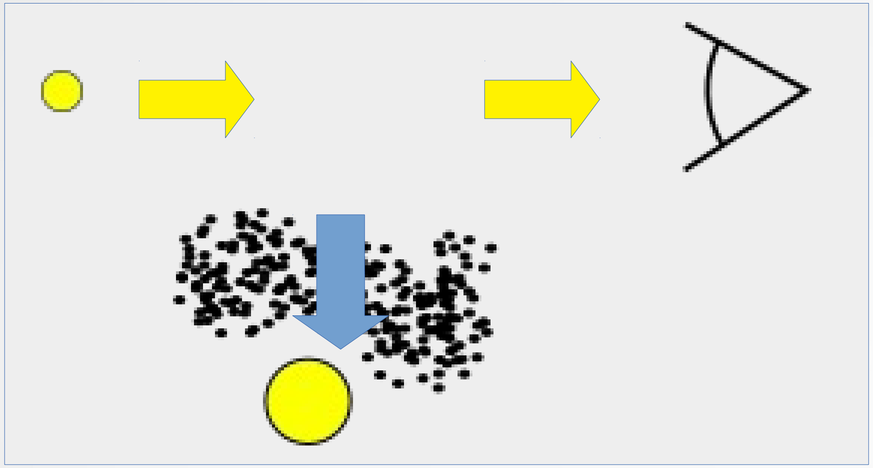
Light of a lamp screened by insects in the air

+ = ?



Light of two lamps added (superposition)

Aspects of shadowing II.



Switching on the second lamp clears the air, and the light of the first lamp will be *brighter!*

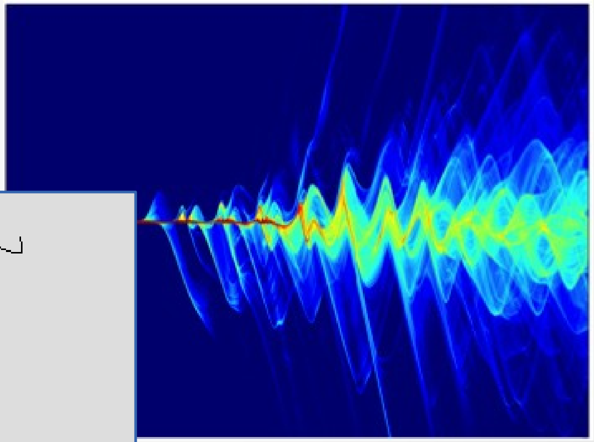
Conclusion: Active medium causes not just distance dependent source stregth (running couplings), but also effects of sources become non-independent/nonlinear.

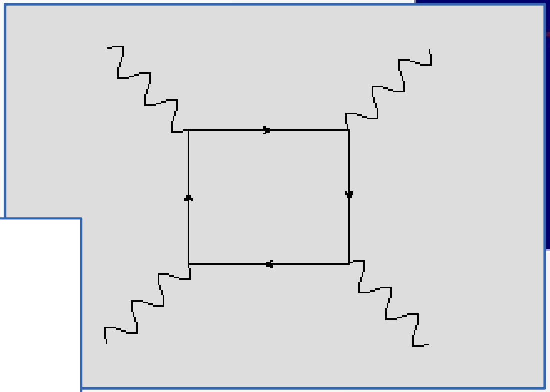
Three (and higher) body interactions appear!

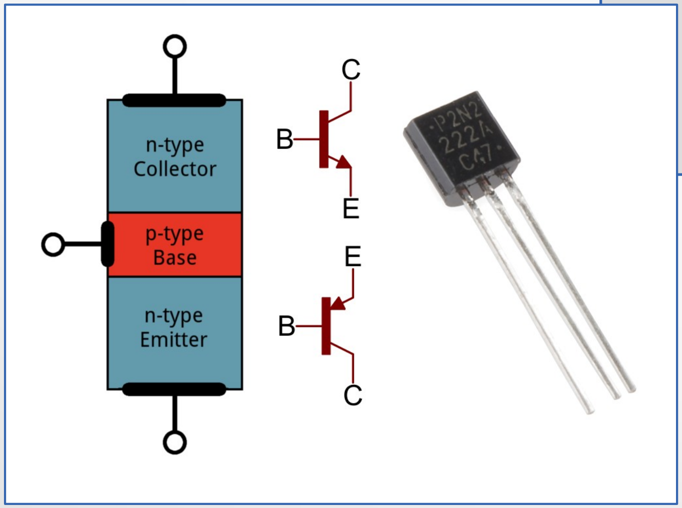
Nonlinear matter

Physical examples where matter/medium causes nonlinearity:

- Nonlinear optics, e.g. generation of higher harmonics
- Light-by-light scattering
- Transistors







Screening in Quantum Field Theories

Screening/renormalization in quantum field theories:

We try to describe observations at a given energy scale k (inverse length scale) with *classical field theory,* represented by a classical action $S_k(\Phi)$.

When we change the scale, the screening effect of *quantum fluctuations* leads to scale dependent (running) classical parameters/couplings, and appearance of new interactions.

Mathematically: Exact Renormalization Group (ERG) equation

$$\partial_k S_k = \frac{1}{2} STr\left[\partial_k R_k \left(\frac{\delta^2 S_k}{\delta\Phi\,\delta\Phi} + R_k\right)^{-1}\right]$$

- *R is the "regulator", a tool for setting the scale smoothly*
- *STr is super-trace, trace for bosons, -trace for fermions*
- *Iterated one-loop expression*

$\beta_n(g_*)>0$

ERG equation

Treatment: take a function basis, $O_n[\Phi]$, and expand the action S

$$S[k,\Phi]=\sum_{n=1}^{\infty} g_n(k) O_n[\Phi]$$

(in practice choose a finite subset: Ansatz for S)

where g_n are the generalized couplings. Then we obtain ordinary differential equation for the couplings. With $t=\log k/\Lambda$, and rescaled fields

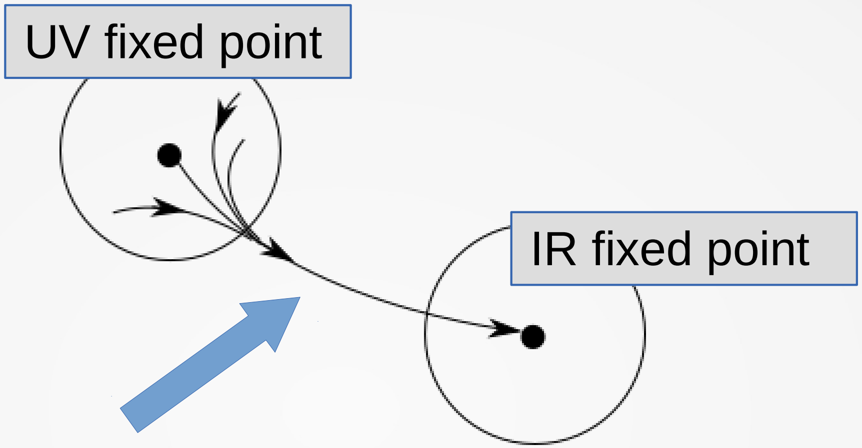
$$\frac{dg_n}{dt}=\beta_n(g)$$

where the beta-functions depend only on the couplings

- Fixed point: g_* where $\beta_n(g_*)=0$ for all n.
- irrelevant directions are $\beta_n(g_*)>0$: screening, $g_n \rightarrow g_{n*}$ at large distances
- relevant directions $\beta_n(g_*)<0$: anti-screening, coupling drives away from the fixed point

ERG equation

Generic picture



Only the relevant couplings of the
UV fixed point remain

Multi-fixed point evolution when lowering k (increasing distance):
approach a fixed point, stay in the vicinity for some scale range, then
leave it along its relevant directions

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Running in the Standard Model

Running of couplings in the Standard Model (reduced set, one loop)

Ansatz for the action: keeping only the relevant directions of SM.

gauge couplings: $$\frac{d g_1}{d \log k} = \frac{41}{96 \pi^2} g_1^3, \quad \frac{d g_2}{d \log k} = \frac{-19}{96 \pi^2} g_2^3, \quad \frac{d g_3}{d \log k} = \frac{-7}{16 \pi^2} g_3^3$$

top- Yukawa coupling: $$\frac{dh}{d \log k} = \frac{1}{16 \pi^2} \left(\frac{9}{2} h^3 - 8 g_3^2 h - \frac{9}{4} g_2^2 h - \frac{17}{12} g_1^2 h \right)$$

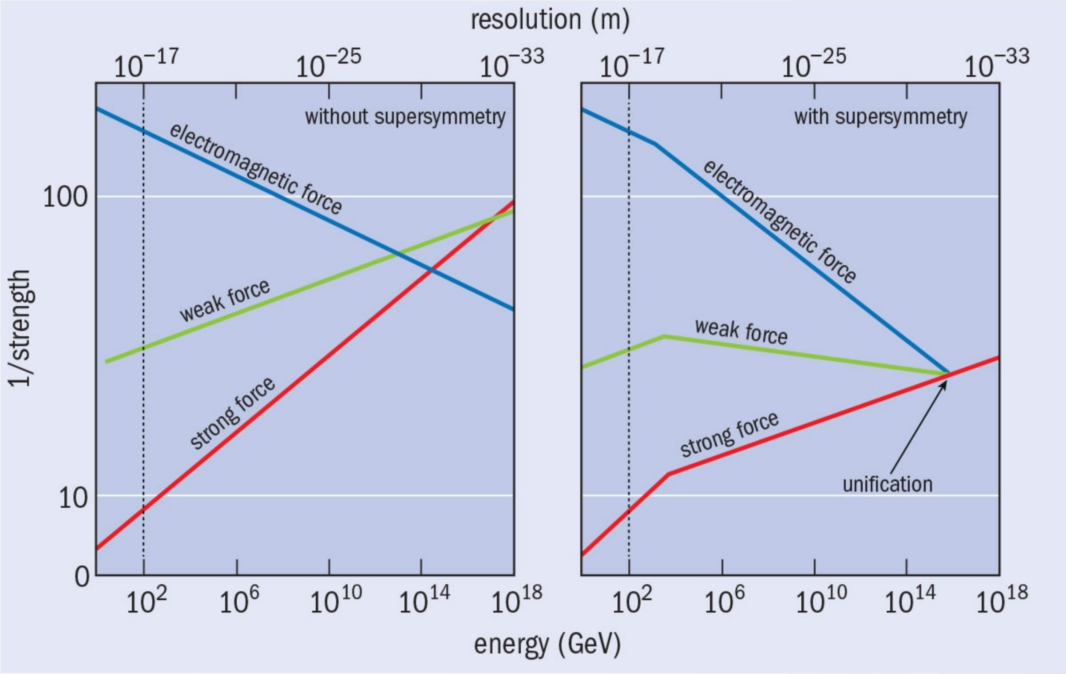
Higgs coupling: $$\frac{d \lambda}{d \log k} = \frac{1}{16 \pi^2} \left(24 \lambda^2 - 6 h^4 + 12 \lambda h^2 - 3 \lambda (3 g_2^2 + g_1^2) + \frac{3}{8} (3 g_2^4 + g_1^4 + 2 g_1^2 g_2^2) \right)$$

(where k is the energy/inverse length scale)

Running in the Standard Model

Running of gauge couplings

- QED screening, SU(2), SU(3) antiscreening *(asymtptic freedom)*
- with SUSY couplings meet
- GUT at scale $\sim 10^{15}\, GeV$
- larger gauge symmetry group (SU(5), SO(10), Sp(8),…)
- Predictions: cosmological defects, proton decay, SUSY particles



Status:

- Neither SUSY, nor GUT are not seen experimentally
- Landau pole is beyond Planck scale

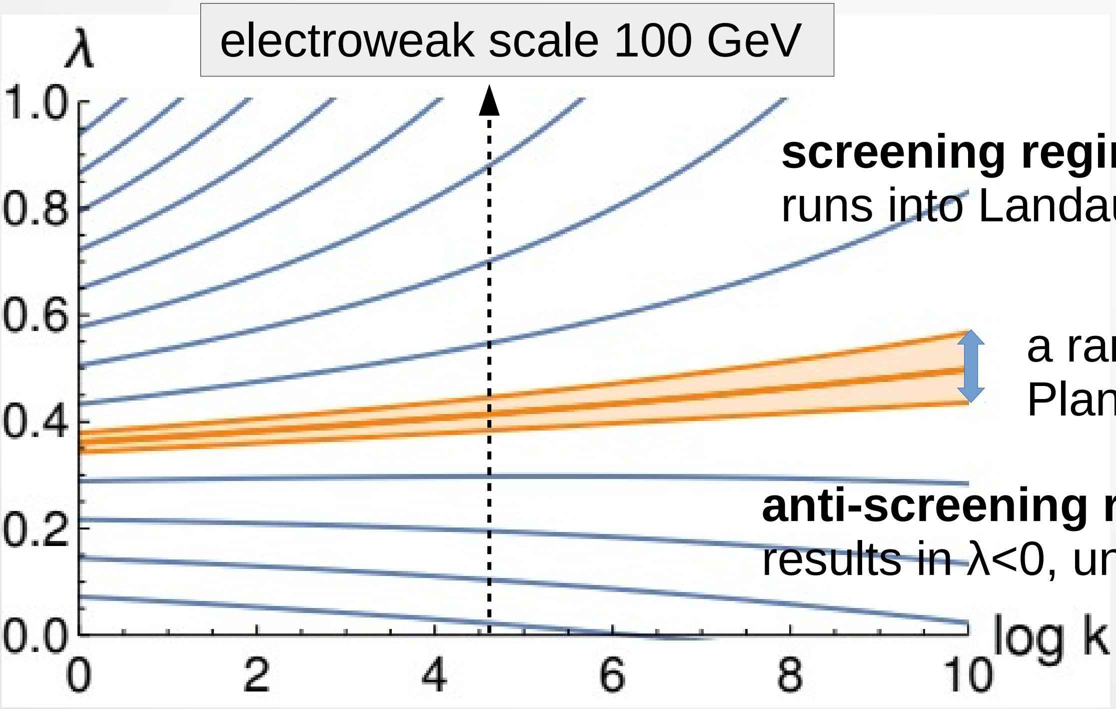
Gauge sector is not necessary to change until Planck scale

Running in the Standard Model

Running in the top-Higgs sector:

$$\frac{dh}{d\log k} = \frac{9}{32\pi^2}h^3, \quad \frac{d\lambda}{d\log k} = \frac{3}{8\pi^2}\left(4\lambda^2 - h^4\right)$$

screening: bosonic
anti-screening: fermionic fluctuations



screening regime:
runs into Landau pole

a range survives till the Planck scale

anti-screening regime:
results in λ<0, unstable vacuum

Higgs mass from Planck scale physics

M. Shaposhnikov and Ch. Wetterich Phys.Lett. B683 (2010) 196-200 [arXiv: 0912.0208]

- use Standard model one-loop running couplings
- at (near) the Planck scale require $\lambda(M_{Planck})=0$
- require measured masses and couplingst at the electroweak scale
- Higgs mass is prediction!

$$m_{Higgs} \approx 126\ GeV$$

Experimentally Higgs discovered in 2012 with $m_{Higgs}=125.09\ GeV$

Standard Model appropriate/predictive up to the Planck scale!

Beyond Planck scale

Screening of a physical quantity Q due to gravitational fluctuations:

$$\frac{dg}{d\log k} \sim g \sum C_n G^n \sim g \sum c_n M_{Pl}^{-2n}$$

- Gravity ~ geometry: anomalous dimension $\frac{dg}{d\log k} \sim \eta g \Rightarrow g \sim k^{\eta}$
- G is dimensionfull: $[M_{Pl}^2] = eV^2$
- Expansion parameter must be dimensionless: k^2 / M_{Pl}^2
- Running of the Planck mass *(dimensional analysis)* $M_{Pl}^2(k) = M_{Pl}^2 + \frac{k^2}{\xi_0}$
- The anomalous dimension: $\eta \sim \frac{k^2}{M_{Pl}^2 + k^2/\xi_0} \sim \begin{cases} \text{small for } & k \ll M_{Pl} \\ \xi_0 \quad \text{for } & k \gg M_{Pl} \end{cases}$

Beyond Planck scale

Physics:

- Gravity effects dominate for large scales; assume $\eta_\lambda > 0, \quad \eta_{others} < 0$
- Then λ decreases with scale: if $\lambda(k \gg M_{Pl}) =$ finite, then $\lambda(M_{Pl}) \to 0$
- Other couplings are asymptotically free $g(k \to \infty) \to 0$
- Below the Planck scale SM running dominate

Standard Model with anomalous dimension coming from gravity effect is appropriate for all scales!

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Renormalizing gravity

Gravity is "perturbatively non-renormalizable"

Coupling constant is dimensionfull, thus perturbative corrections to an observable O read

$$\langle O \rangle = \sum_{n=0}^{\infty} c_n \left(\frac{k^2}{M_{Pl}^2} \right)^n$$

All observables depend on the scale, all must be fine-tuned to have proper physical values.

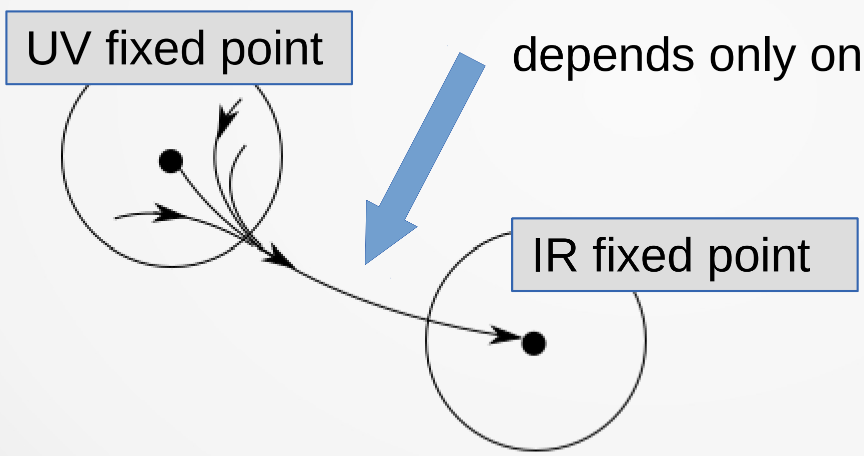
$$\Downarrow$$

Perturbatively inconclusive, ill-defined theory

Renormalizing gravity

Renormalization way of thinking: *asymptotic safety*

Assume we have a fixed point of the renormalization flow that is repulsive in n directions, and attractive in other directions.

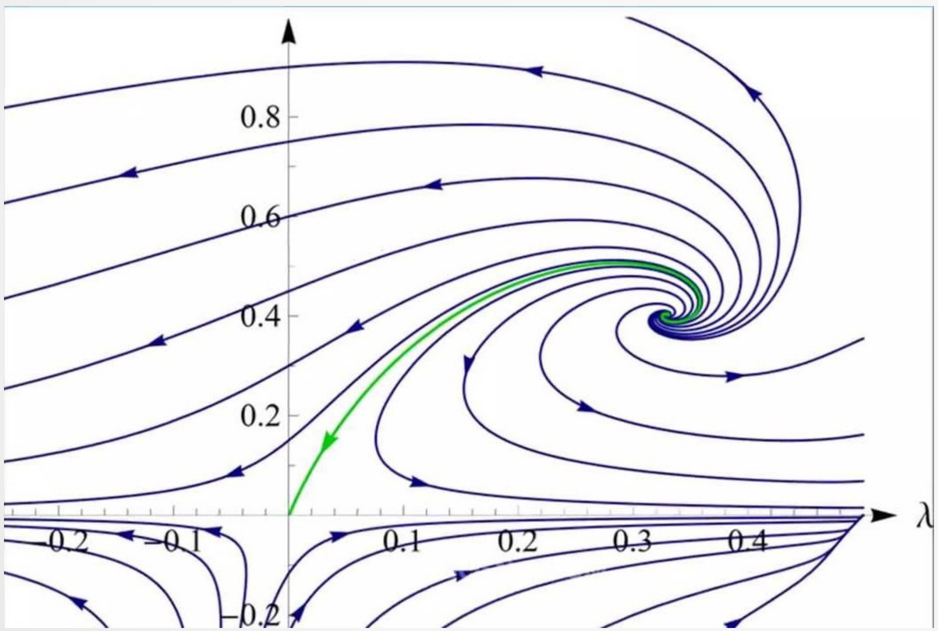


depends only on n parameters!

if we can find an UV fixed point within the Einstein-Hilbert action,
then it is enough to serve as a consistent quantum theory!

Renormalizing gravity

Present status: running in the rescaled Newton constant G and cosmological constant Λ space



We seem to have an UV fixed point and a stable IR fixed point.

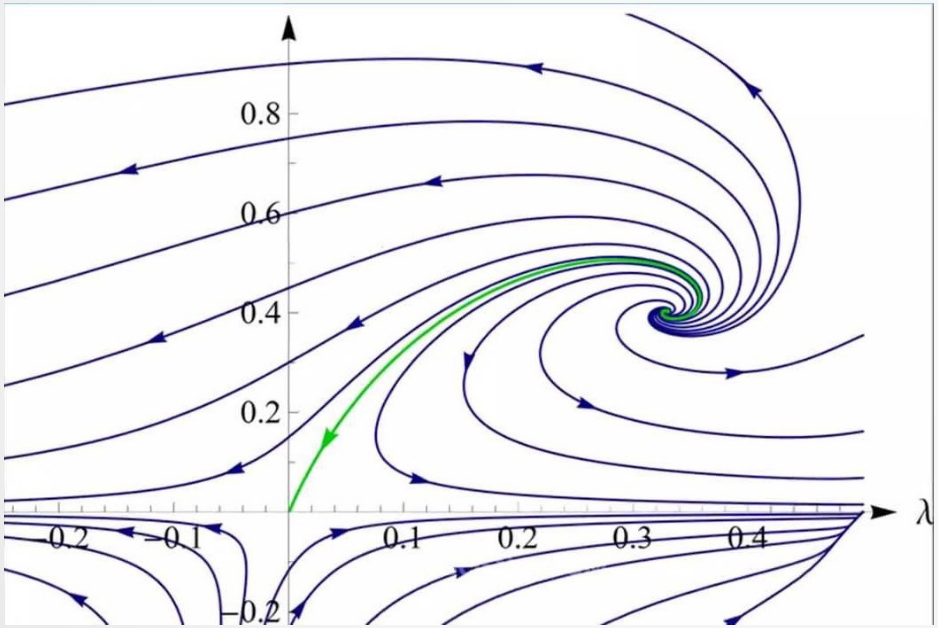
Gravity is probably *asymptotic safe*!

Standard Model + right handed neutrinos + asymptotic safe gravity

is a consistent theory for all scales!

Renormalizing gravity

Present status: running in the rescaled Newton constant G and cosmological constant Λ space



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Theory of Everything found?

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Before conclusion...

On the use of the Theory of Everything:

- We (perhaps) know the genome of Universe; can explain everything?
- … then why a Standard Model expert can not bake *pogácsa?*
- It is too complicated… (lots of quarks, electrons, gluons, photons)
- But it is not true! (*my grandma can bake very good pogácsa)*

Before conclusion...

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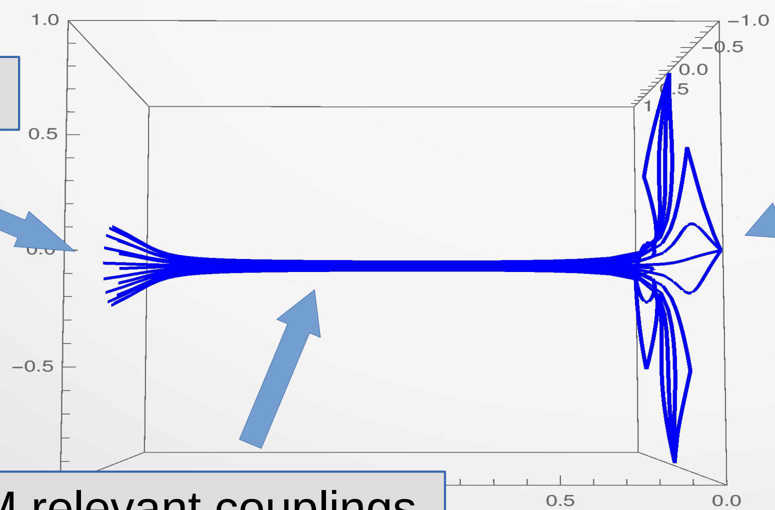
Explanation: those couplings that are irrelevant for Standard Model can be relevant in later fixed points!

SM fixed point



IR fixed point: relevant directions are the SM irrelevant ones

SM relevant couplings

The true Theory of Everything should contain **all couplings** ...

Conclusions

- Nature of forces change when we change scale; reason: **screening / renormalization**
- … this leads to running couplings, new interactions
- … fixed points dominate scale regimes
- That what is between LHC scale and Planck scale is ultimately an expermintal question
- There are numerous theoretical constructions (GUT models, SUSY models, string theories, etc.)
- BUT: **(extended) Standard Model + Einstein-Hilbert gravity** is a consistent possibility
- No Landau-pole or vacuum instability, gravity is asymptotically safe
- Prediction: Higgs-mass from plausible assumptions