Title: Connecting quantum gravity to particle physics and to the dark universe - why and how?

Speakers: Astrid Eichhorn

Series: Colloquium

Date: May 24, 2023 - 2:00 PM

URL: https://pirsa.org/23050154

Abstract: There are fascinating new insights we could achieve if we succeeded in connecting quantum gravity to particle physics in the visible and the dark universe. However, making such a connection is challenging, because the typical scale of quantum gravity is believed to be far from the typical scales in particle physics. I will exploit lever arms that could make it possible to bridge this gap in scales. To provide concrete examples for these ideas, I will review recent results on the proton lifetime in quantum gravity, the effects of asymptotically safe quantum gravity on properties of Standard Model matter and the effects of asymptotically safe quantum gravity on simple models of dark energy and dark matter.

Zoom Link: https://pitp.zoom.us/j/96545839038?pwd=UG1IVzJPWUZGa2ovOFhzdHBhOFhOdz09

Connecting quantum gravity to particle physics and to the dark universe - why and how?

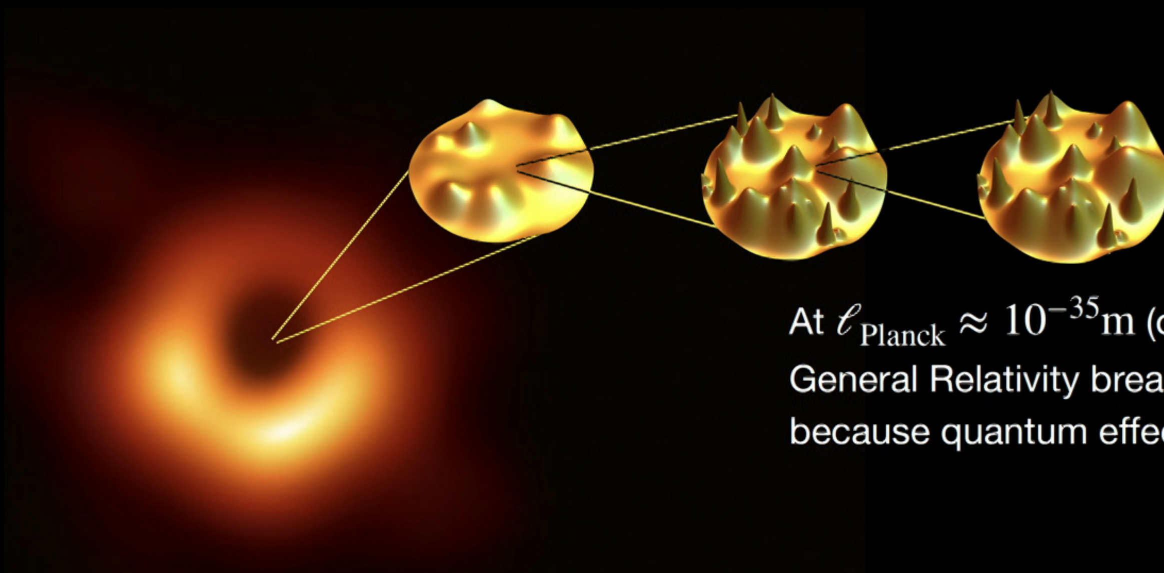
Colloquium,
Perimeter Institute, May 24, 2023

Astrid Eichhorn, CP3-Origins, University of Southern Denmark

VILLUM FONDEN

Motivation: (Some) fascinating puzzles in fundamental physics

1) What is the quantum nature of gravity?

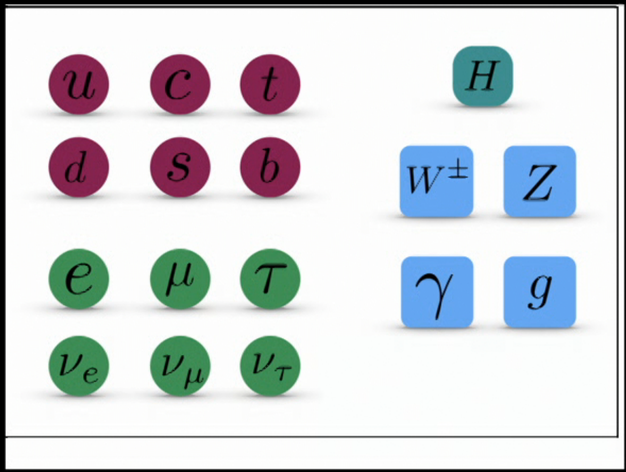


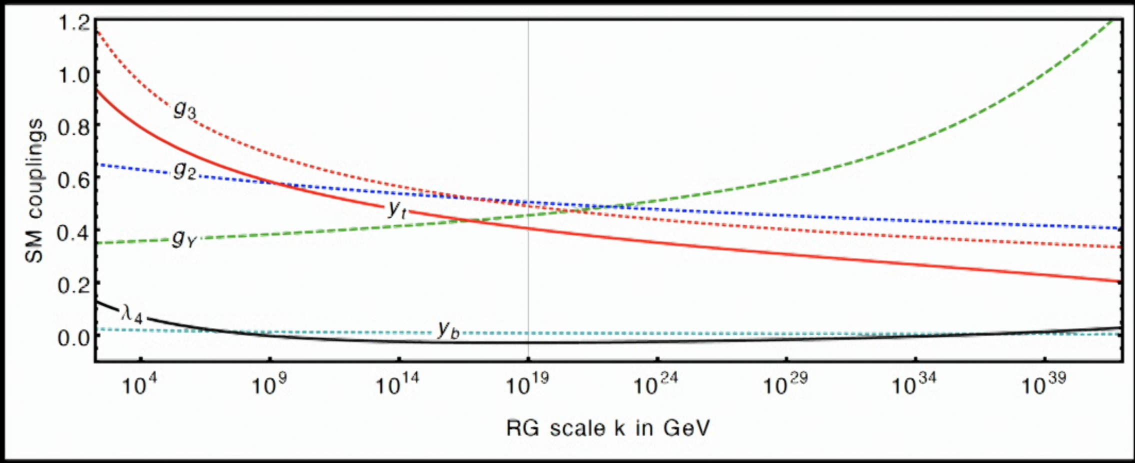
At $\ell_{\text{Planck}} \approx 10^{-35}\text{m}$ (or $M_{\text{Planck}} \approx 10^{19}\,\text{GeV}$),
General Relativity breaks down,
because quantum effects become important

Asymptotically safe gravity,
Causal Dynamical Triangulations,
Causal Sets,
Loop quantum gravity/Spin Foams,
String theory,
...

Motivation: (Some) fascinating puzzles in fundamental physics

2a) What is the missing new physics beyond the Standard Model?
2b) What fixes some/all of the free parameters in the Standard Model?





Key result from LHC: Higgs mass low enough to avoid sub-Planckian Landau pole

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3) What is the nature of the dark matter?

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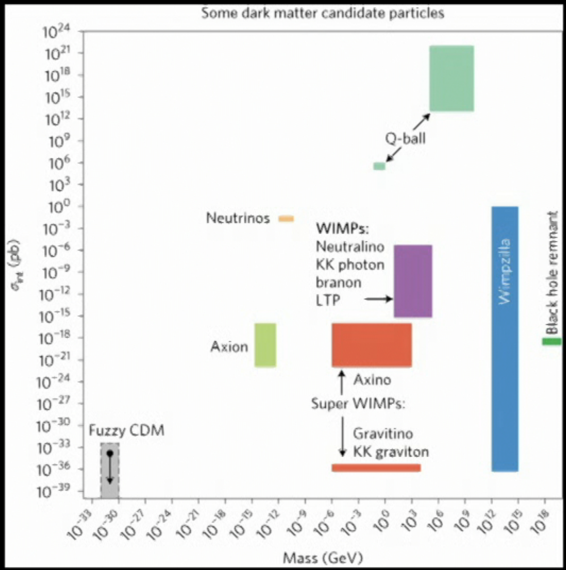
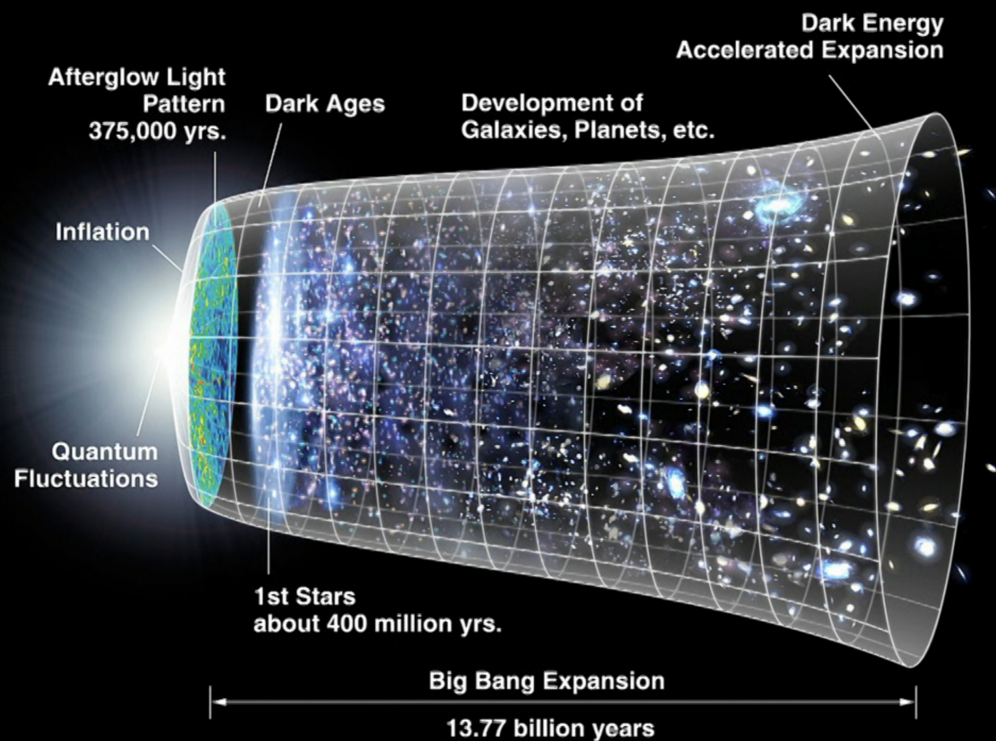


[Conrad, Reimer '17]

Too many choices!

Motivation: (Some) fascinating puzzles in fundamental physics

3) What is the nature of the dark energy?



Cosmological constant, Everpresent Lambda, Quintessence, Horndeski gravity, scalar-tensor theories, Galileon, massive gravity…

Motivation: (Some) fascinating puzzles in fundamental physics

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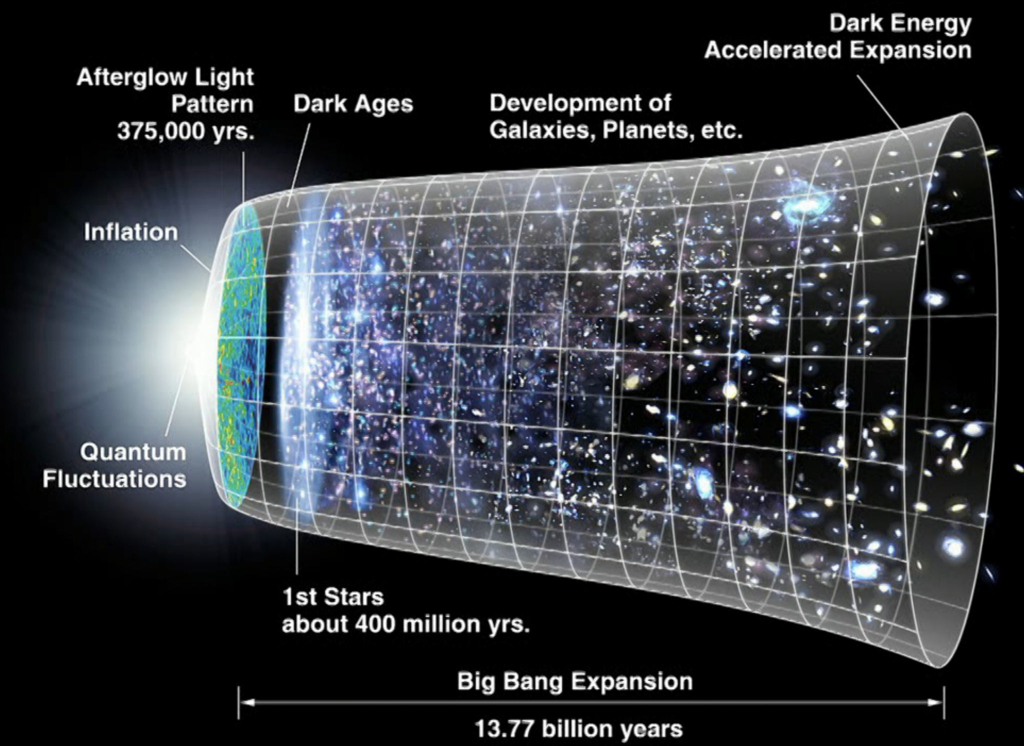

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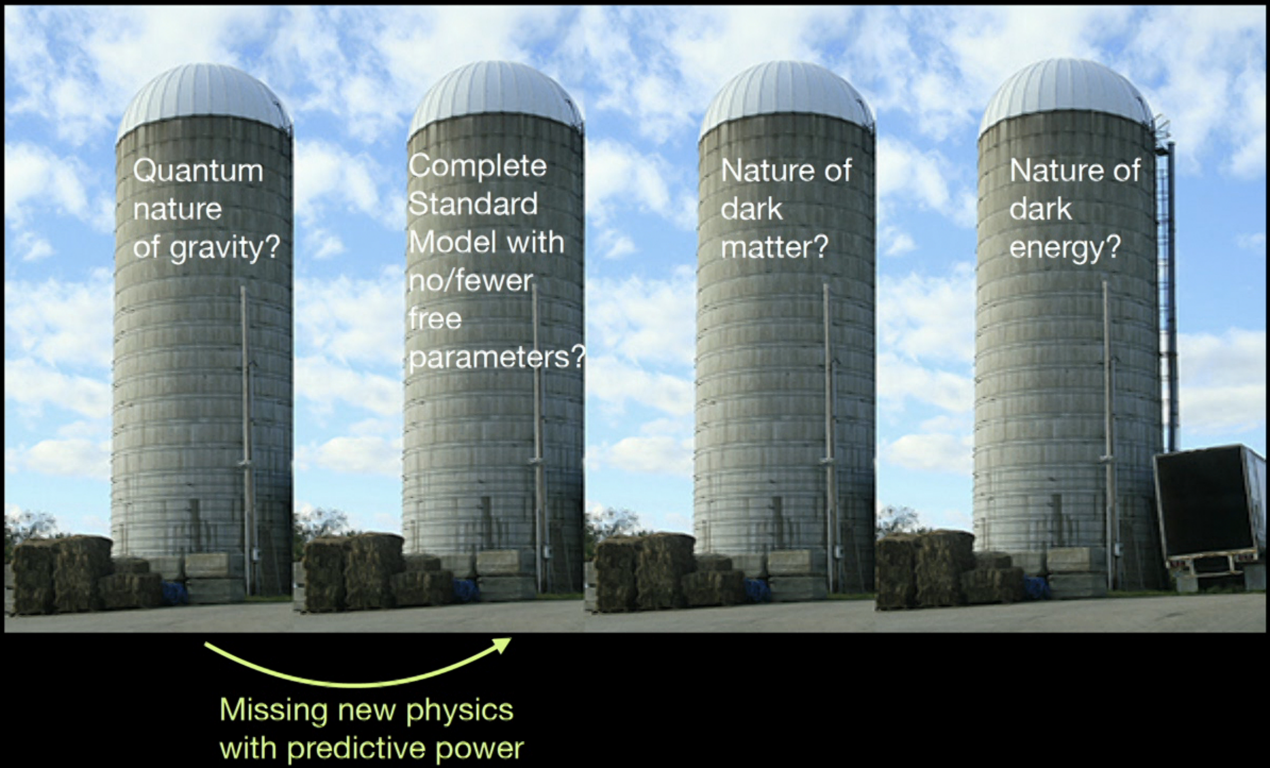

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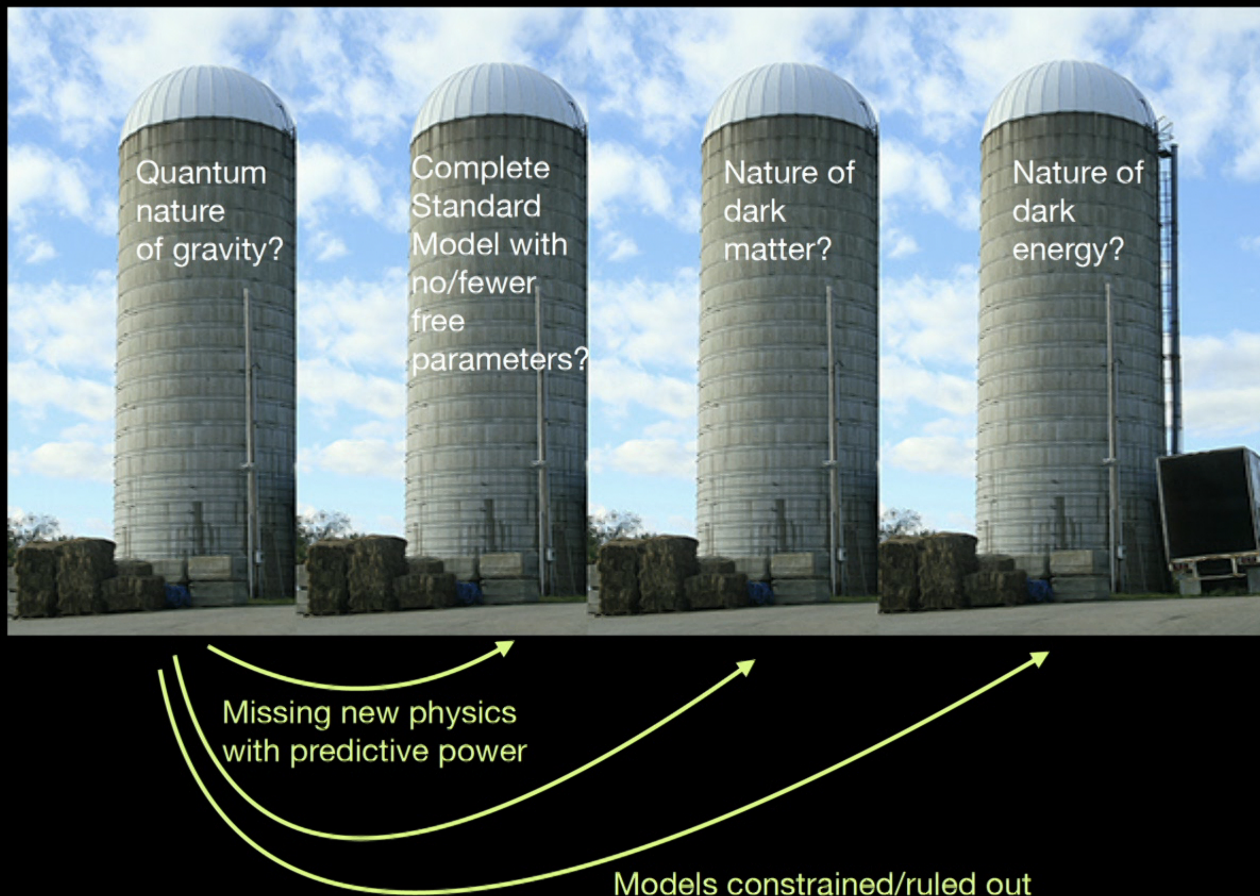

Motivation: (Some) fascinating puzzles in fundamental physics

Theories testable

Connecting quantum gravity and the Standard Model of particle physics — a challenge of scales

Where is quantum gravity important?

Connecting quantum gravity and the Standard Model of particle physics — a challenge of scales

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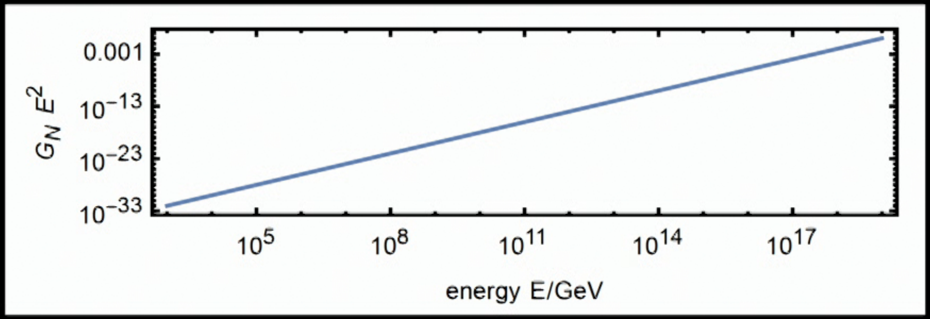
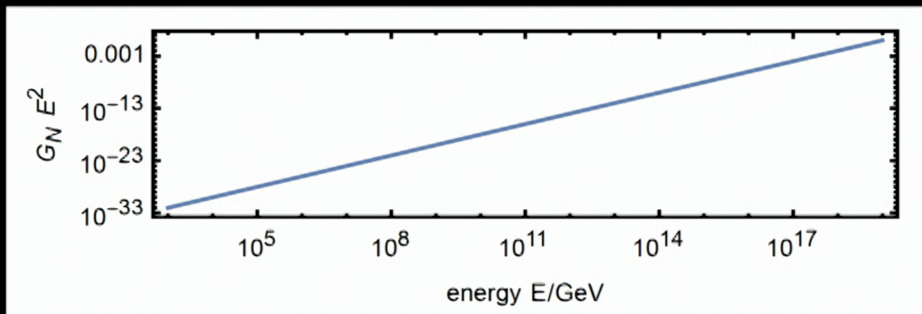


Gravity dynamically important

Gravity dynamically unimportant

Connecting quantum gravity and the Standard Model of particle physics — a challenge of scales

Where is quantum gravity important?



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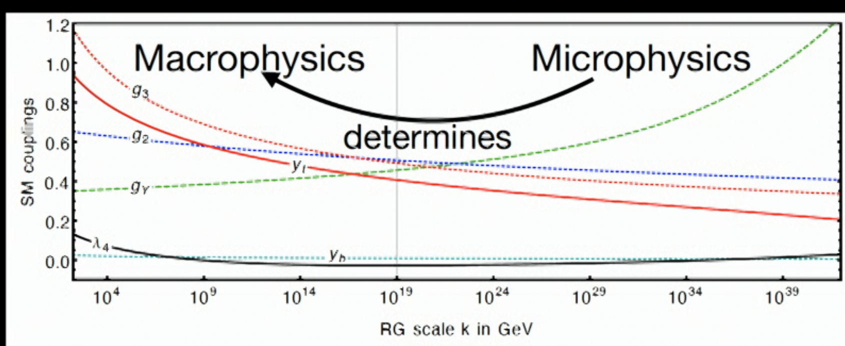

Connecting quantum gravity and particle physics — strategies to solve the challenge of scales

Connecting quantum gravity and particle physics — strategies to solve the challenge of scales

- Observables with (near) Planck-scale sensitivity

- Quantum-gravity approaches with a second scale

- Leverarm for Planck-scale physics

Observables with (near-) Planck-scale sensitivity: Proton decay and quantum gravity fluctuations

Lifetime of the proton:

- experimentally: $\tau_p > 10^{34}\,\mathrm{yrs}$

- theoretically: $\tau_p \approx M_p^{-1} \left(\frac{M_X}{M_p} \right)^4$

$\Rightarrow M_X > 2 \cdot 10^{16}\,\mathrm{GeV}$

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Proton decay through four-fermion coupling $G_{4\text{F}}$:

$$\tau_p = 16\pi M_p^{-1}\left(G_{4F}(M_P)\right)^{-2}$$
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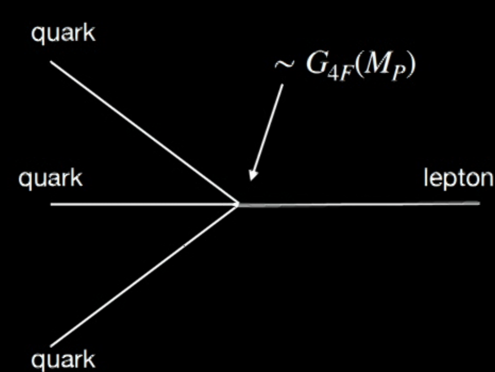

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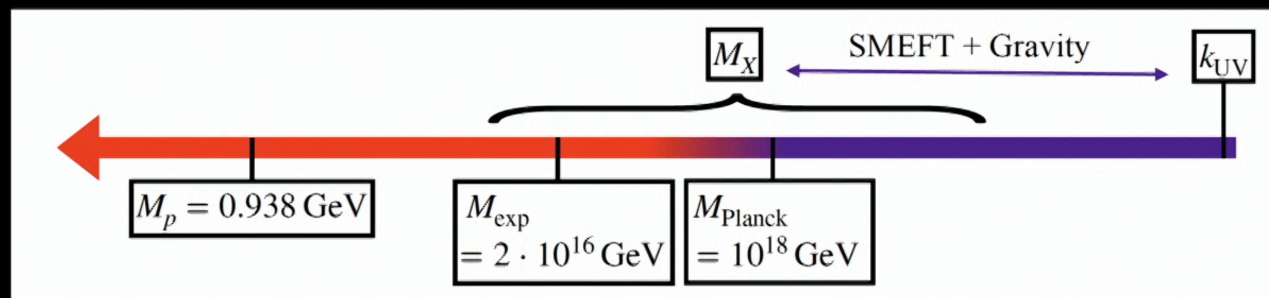
How large is $G_{4\mathrm{F}}(M_X)$? $\rightarrow$ determined by the theory at and above M_X

[AE, Shouryya Ray '23]



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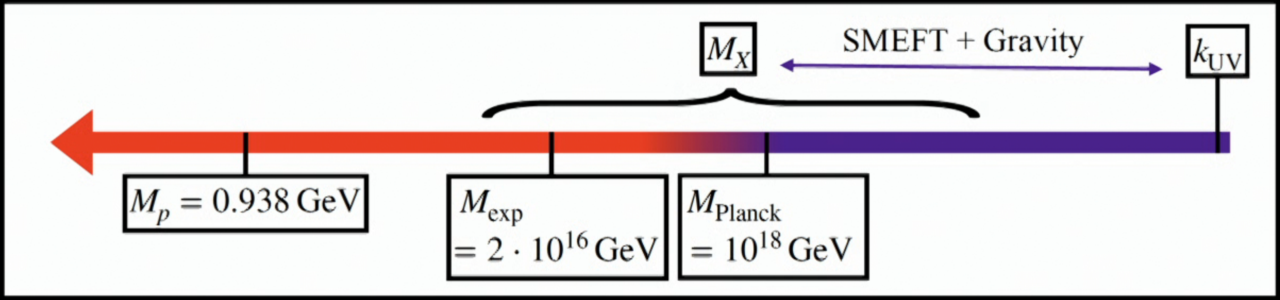

Metric fluctuations generate anomalous dimension $\eta_{4F} > 0$:

$$G_{4F}(M_X) = G_{4F}(k_{\mathrm{UV}})\left(\frac{M_X}{k_{\mathrm{UV}}}\right)^{2+\eta_{4F}}$$

$\Rightarrow$ quantum gravity suppresses proton decay

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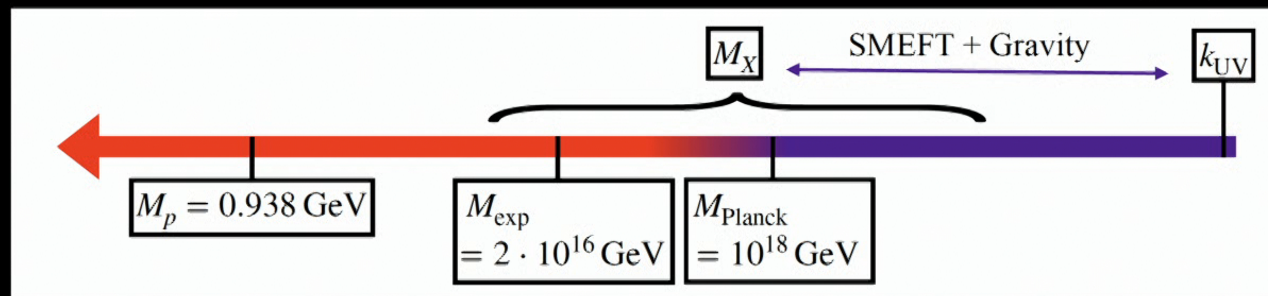

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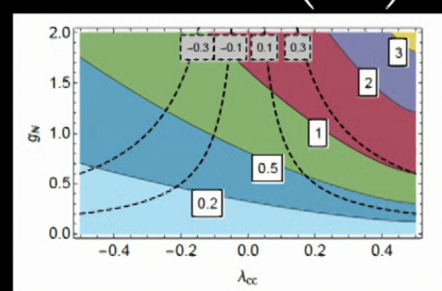
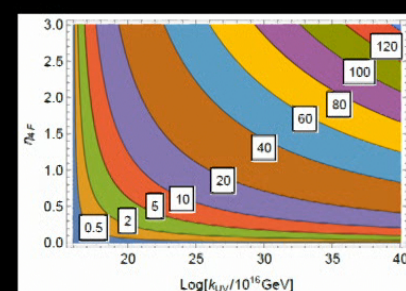




$\log\left(\frac{\tau_p}{\tau_{p,\,\mathrm{no\,QG}}}\right)$

Connecting quantum gravity and particle physics — strategies to solve the challenge of scales

- Observables with (near) Planck-scale sensitivity

  → Quantum fluctuations of the metric and proton decay

- Quantum-gravity approaches with a second scale

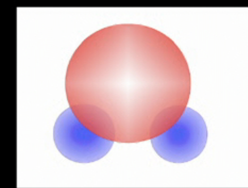
- Leverarm for Planck-scale physics

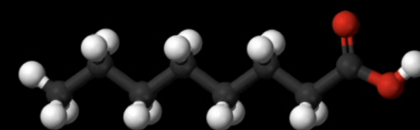
  → Asymptotically safe gravity and constraints at the Planck scale on logarithmically running couplings in and beyond the Standard Model

Bridging the gap between Planck scale and Standard-Model scales

Bridging the gap between Planck scale and Standard-Model scales

zooming out:
microscopic information gets lost

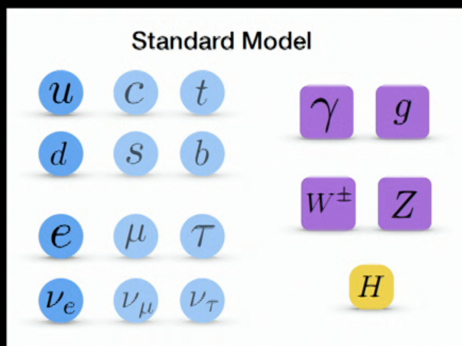




not so different at macroscopic scales

very different at microscopic scales

Bridging the gap between Planck scale and Standard-Model scales



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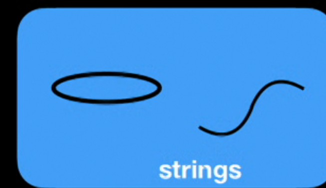
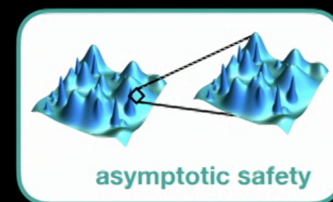




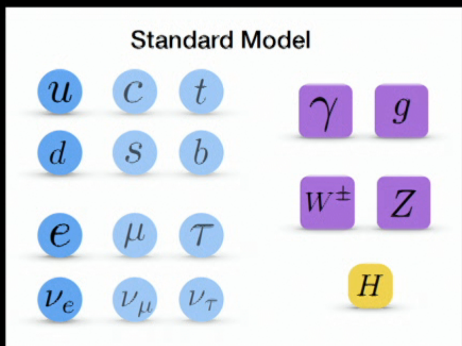
10^{-18} m ← 10^{-35} m

not so different at macroscopic scales

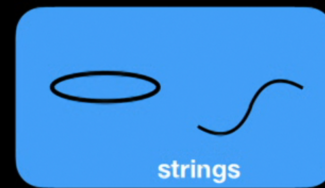
very different at microscopic scales*

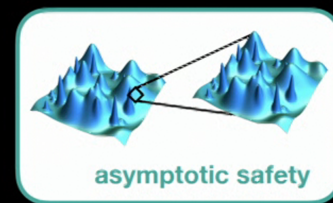
* or are they? [de Alwis, AE, Held, Pawlowski, Schiffer, Versteegen ’19; Basile, Platania ’21]

Bridging the gap between Planck scale and Standard-Model scales



zooming out:
most microscopic information gets lost



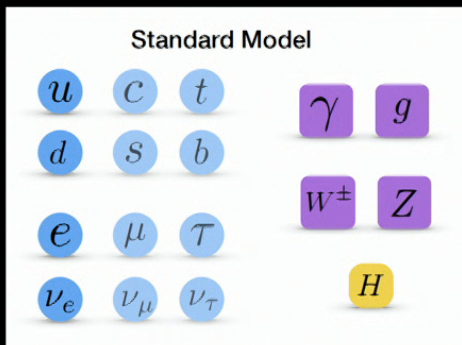


imprints of microscopic physics at macroscopic scales

very different at microscopic scales

→ identify which (beyond) Standard Model couplings are sensitive to the microphysics

Bridging the gap between Planck scale and Standard-Model scales



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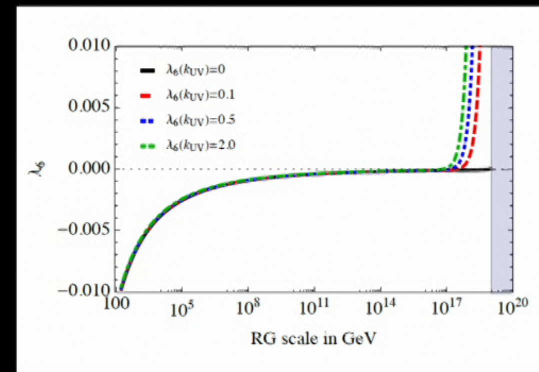
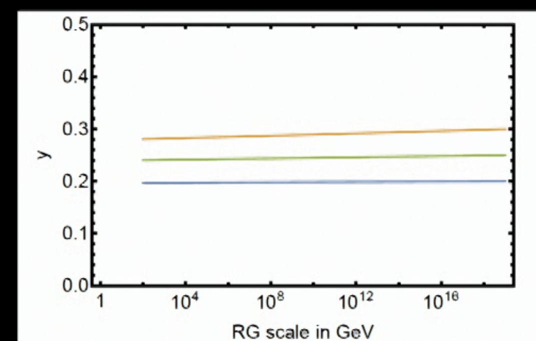


higher-order couplings: universality

imprints of microscopic physics at macroscopic scales

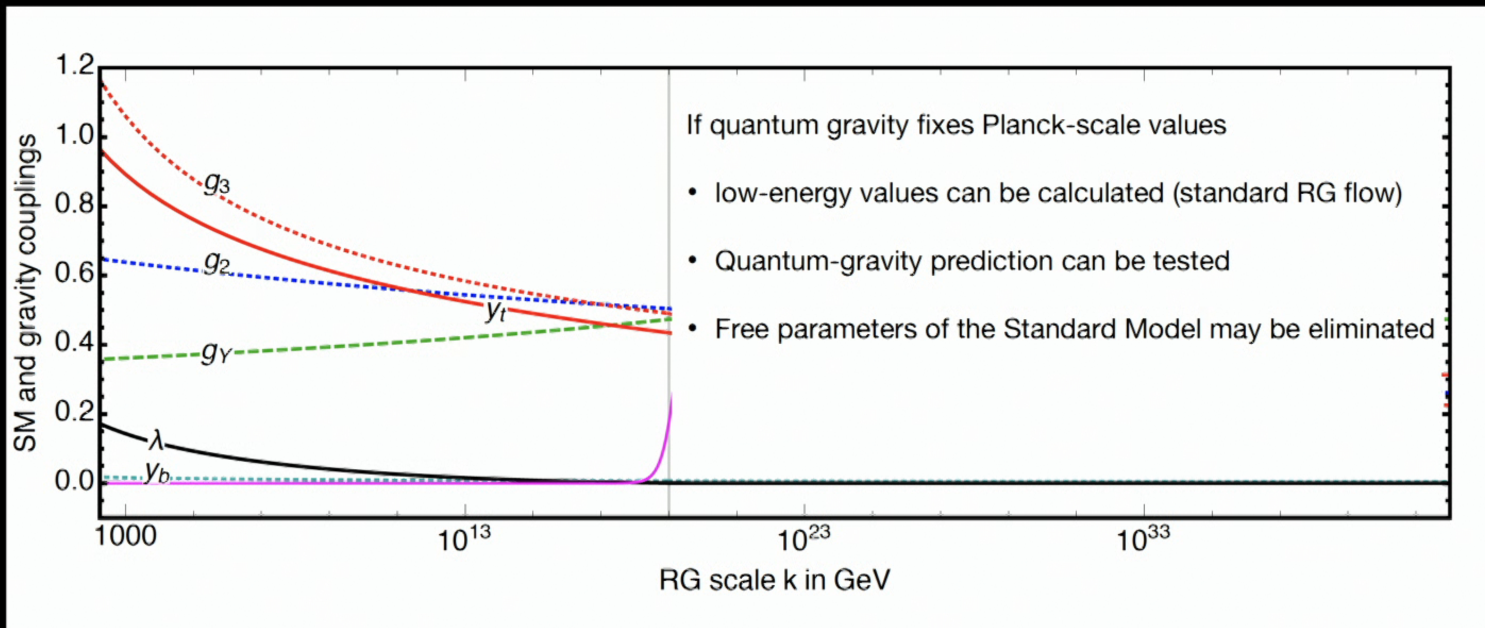
→ identify which (beyond) Standard Model couplings are sensitive to the microphysics



logarithmic scale dependence:
preserves "memory" of initial conditions
at the Planck scale

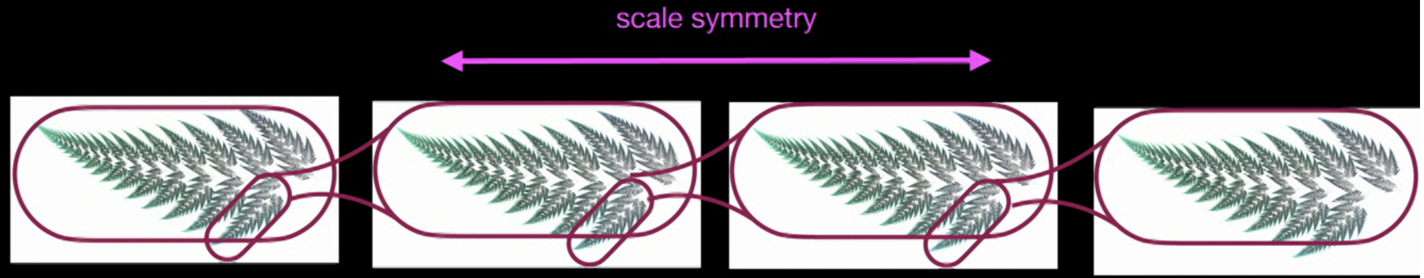
Quantum gravity and values of Standard Model couplings at the Planck scale

Standard Model couplings:
free parameters



Asymptotic safety (a.k.a. quantum scale symmetry)

Symmetry principles ubiquitous



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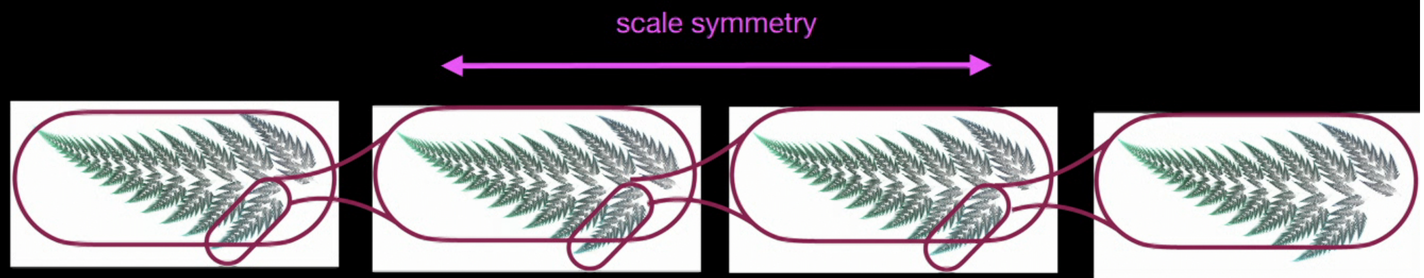
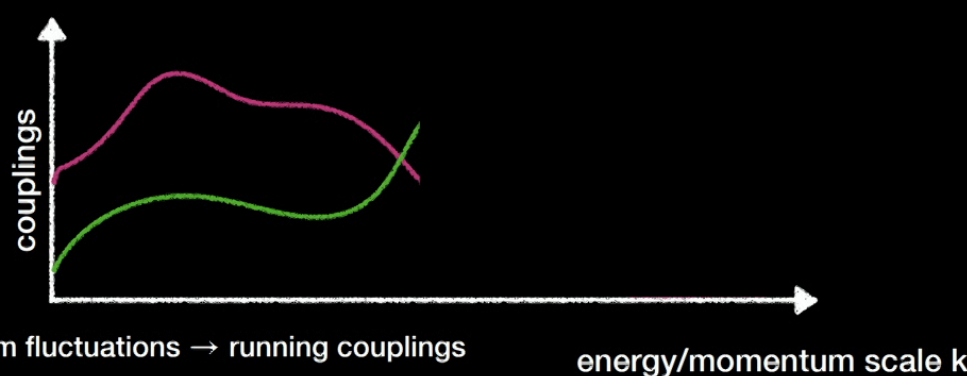
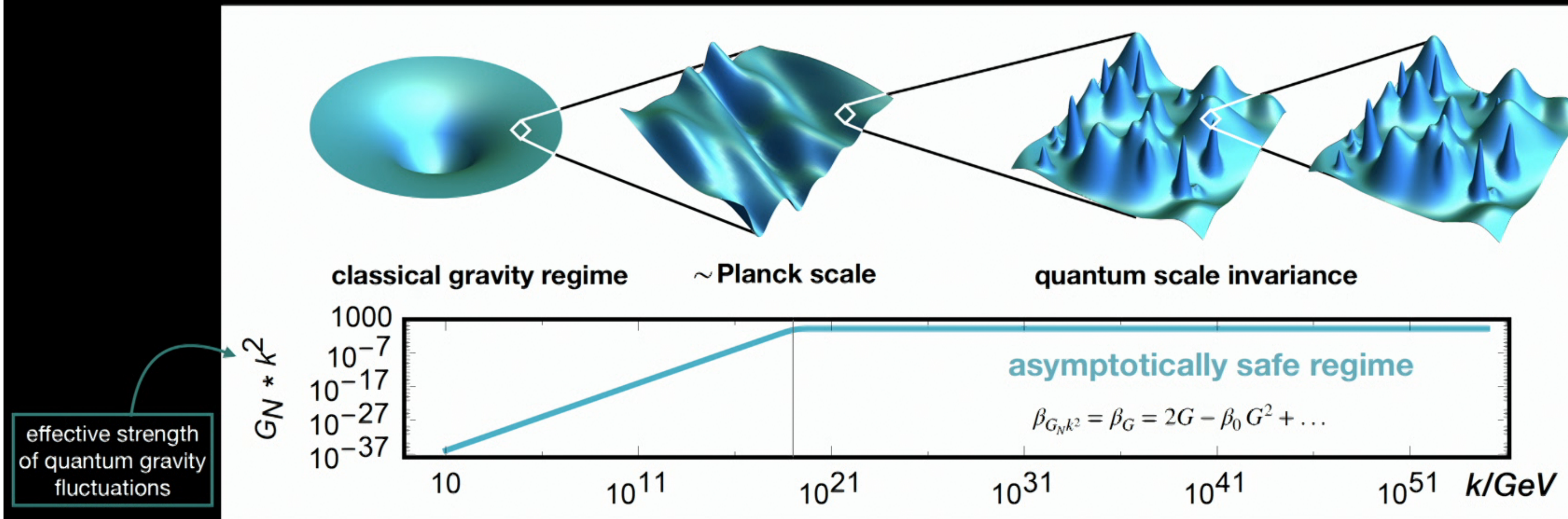




quantum fluctuations → running couplings

Asymptotic safety (aka quantum scale symmetry) in quantum gravity



Compelling theoretical evidence that gravity behaves in this way*

AE, Benedetti, Codello, Falls, Gies, Held, Knorr, Litim, Morris, Ohta, Pawlowski, Percacci, Pereira, Platania, Reichert, Reuter, Ripken, Saueressig, Schiffer, Wetterich, Yamada, Zanusso…

* unitarity and Lorentzian signature may be compatible with asymptotic safety

[Draper, Knorr, Ripken, Saueressig '20, Fehre, Litim, Pawlowski, Reichert '21, Platania '22]

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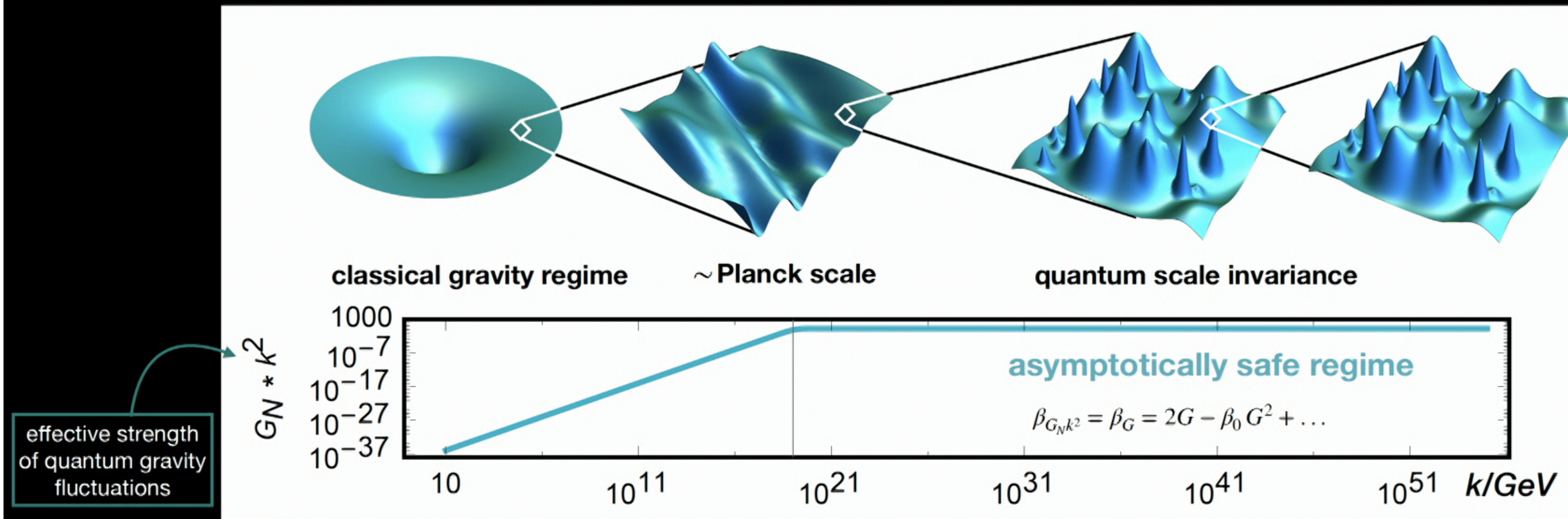

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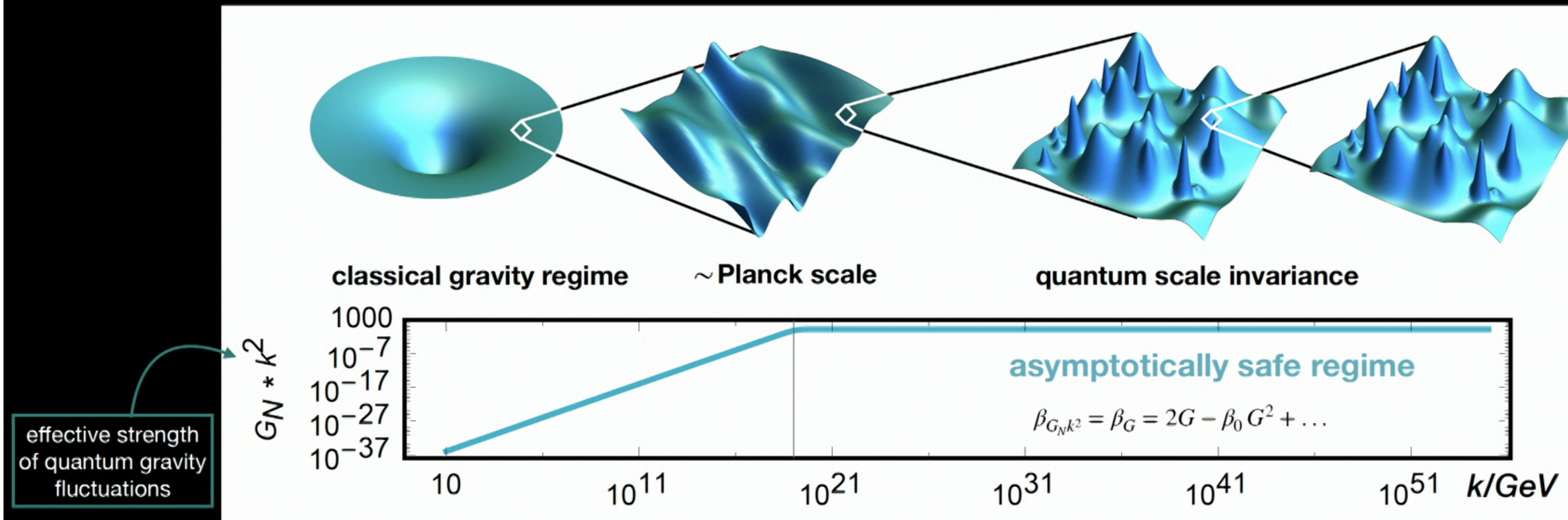
Tools to search for asymptotic safety

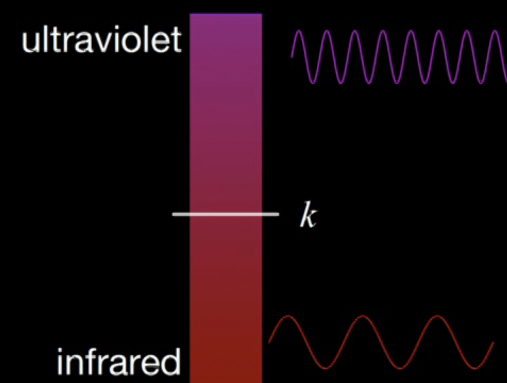


functional Renormalization Group ≈ mathematical microscope

Γ_k: analog of classical action, but with quantum fluctuations above k included

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

[Wetterich '93; Reuter '96]



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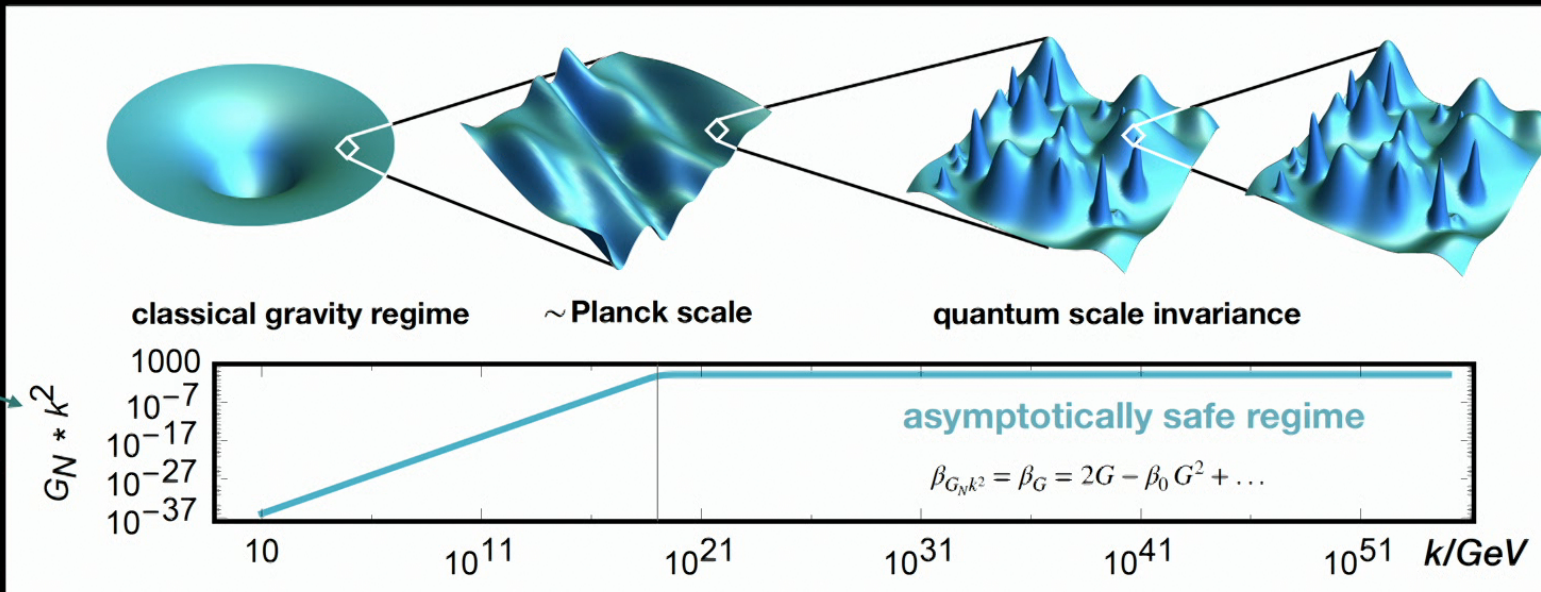
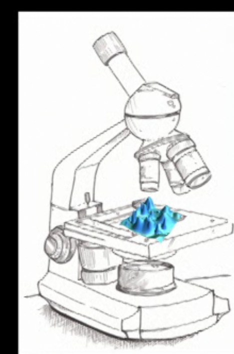


effective strength of quantum gravity fluctuations

functional Renormalization Group ≈ mathematical microscope



step 1: search for which values of couplings there is scale symmetry: $\beta_g = 0$

step 2: zoom out to connect microscopic, scale-symmetric regime to macrophysics, where experiments/observations exist: numerically integrate $\beta_g = k\,\partial_k\, g(k)$ to obtain $g(k)$

all statements in this talk in truncations of the full dynamics -> systematic uncertainties

Predictive power of asymptotic safety: Mechanism

Quantum fluctuations screen or antiscreen interactions

Standard Model examples:

Predictive power of asymptotic safety: Mechanism

Quantum fluctuations screen or antiscreen interactions

Standard Model examples:

QED: $\beta_e = k\,\partial_k\, e(k) = \dfrac{1}{12\pi^2} e^3 + \ldots$

$\rightarrow$ $e(k)$ decreases as k is lowered

Predictive power of asymptotic safety: Mechanism

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QCD: $\beta_g = k\,\partial_k\,g(k) = -\frac{7}{16\pi^2}g^3 + \ldots$

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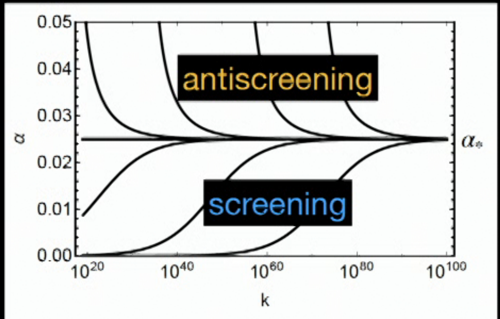
relevant couplings



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

$\beta_\alpha = \alpha\,(\alpha_* - \alpha)$

→ a range of coupling values achievable at the Planck scale

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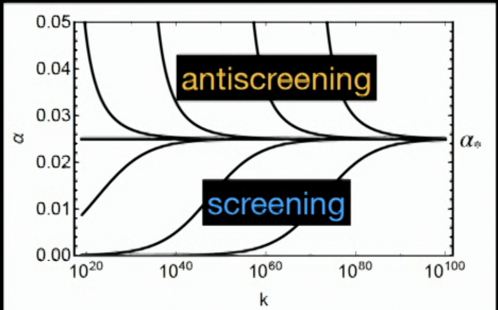

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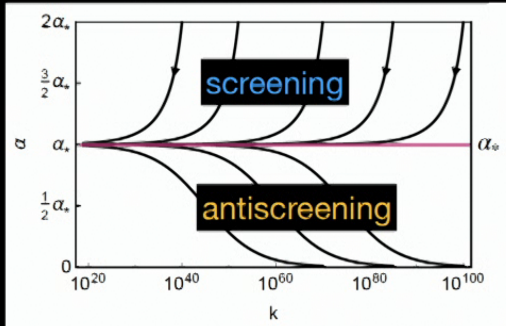


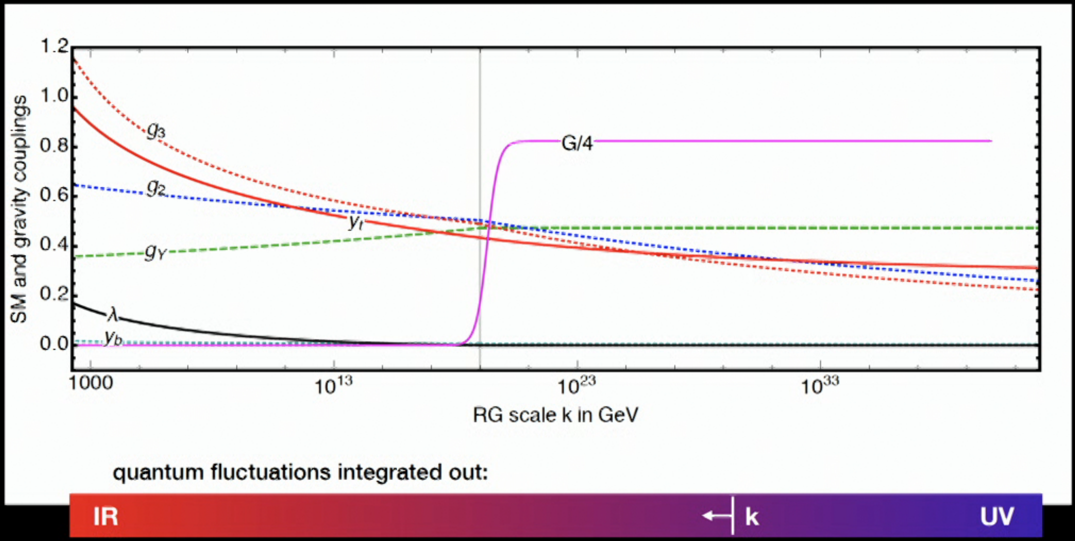
quantum fluctuations drive coupling **towards** scale symmetry

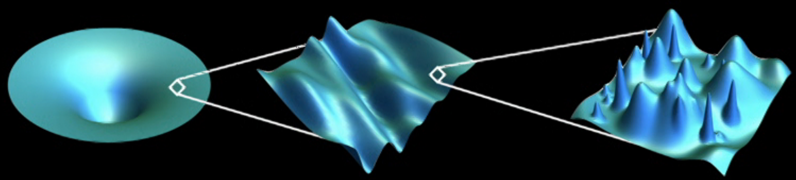
$\beta_\alpha = \alpha\,(-\alpha_* + \alpha)$

→ a unique coupling value achievable at the Planck scale

Predictive power of asymptotic safety

matter regime | dynamical decoupling of quantum gravity fluctuations | quantum scale invariant regime



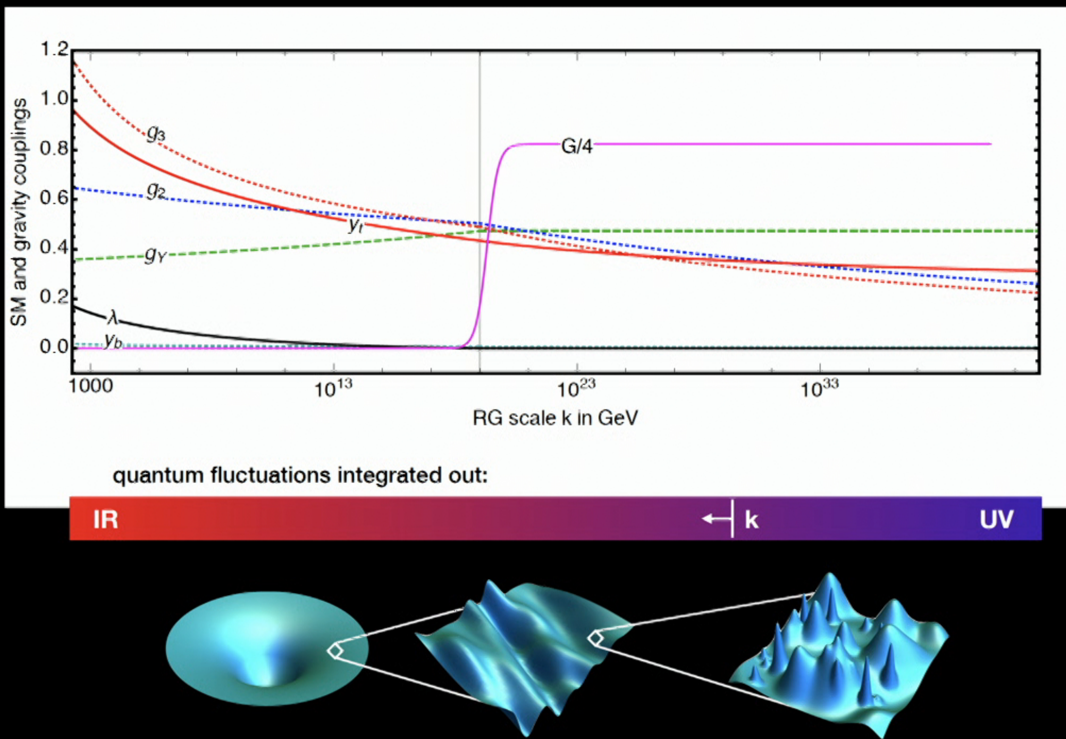


Predictive power of asymptotic safety

matter regime

dynamical decoupling of quantum gravity fluctuations

quantum scale invariant regime



Higgs quartic coupling: determines mass of the Higgs boson

[Shaposhnikov, Wetterich, '09]

Abelian gauge coupling: determines finestructure constant

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

Top Yukawa coupling determines top quark mass

[AE, Held '17]

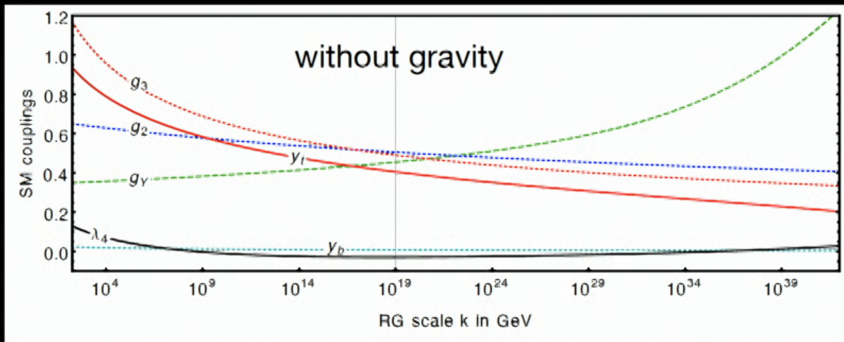
Bottom Yukawa coupling determines b- quark mass

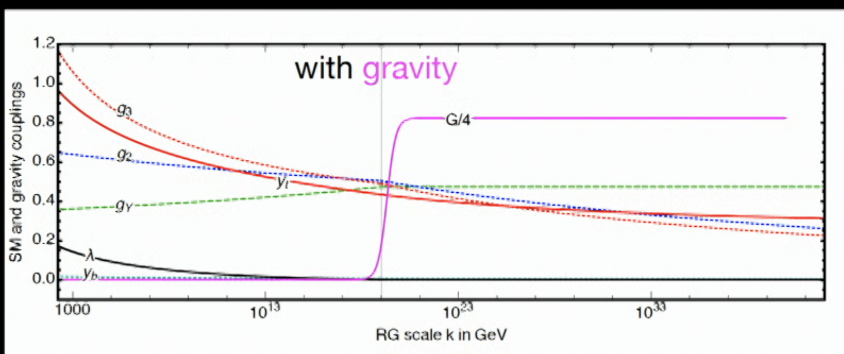
[AE, Held '18]

Neutrino Yukawa couplings determine tiny neutrino masses

[Kowalska, Sessolo '22; AE, Held '22]

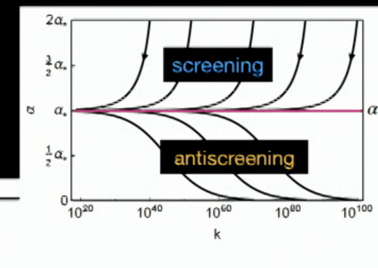
Proof of principle: Upper bound on the Abelian gauge coupling

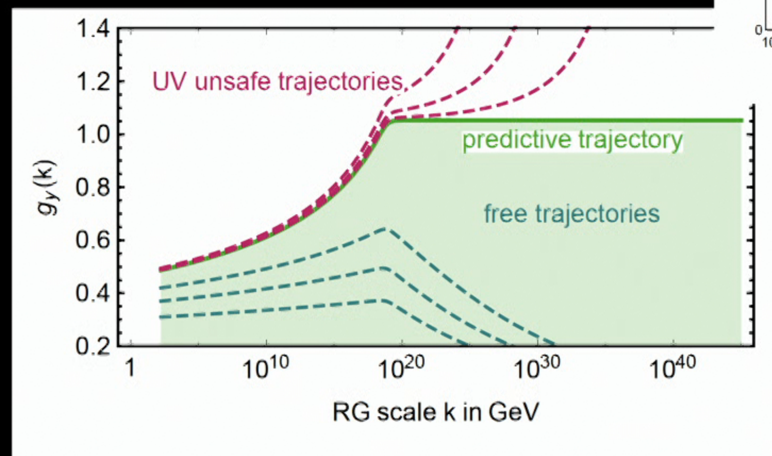




$$\beta_{g_Y} = k\partial_k g_Y(k) = \frac{41}{6\cdot 16\pi^2} g_Y^3 - \frac{G}{4\pi} g_Y + \dots$$

[AE, Versteegen '17]





Gravity and matter fluctuations compete:

strong gravity antiscreens ⇒ asymptotic freedom

strong matter screens ⇒ Landau pole

balance: asymptotic safety with a "retrodiction" that is upper bound

Principled-parameterized approach to asymptotically safe gravity-matter models

[AE, Held '18]

Principled-parameterized approach to asymptotically safe gravity-matter models

[AE, Held '18]

→ the gravitational contributions to the scale-dependence of matter couplings are not known *quantitatively* precisely

But their *qualitative* form is known

→ effects are linear in the Standard-Model couplings *(because gravity couples to the energy-momentum tensor)*

→ effects are only present beyond the Planck scale *(because gravity coupling negligible below the Planck scale)*

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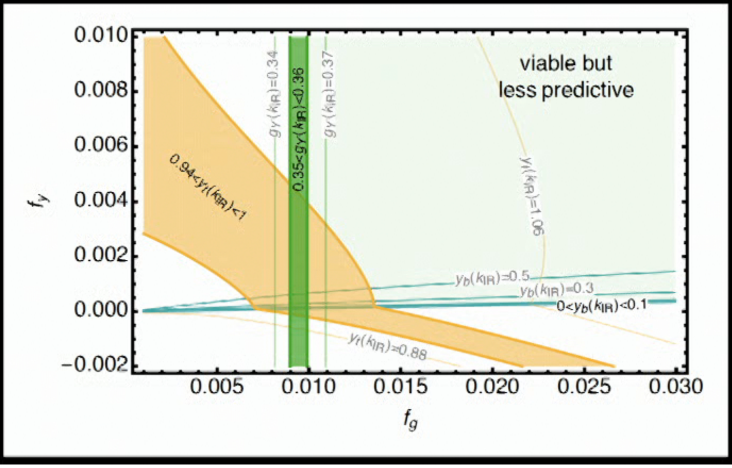
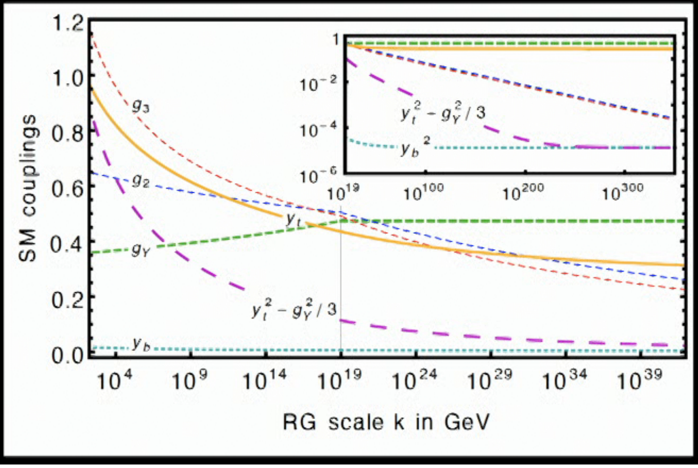
Example: third generation gauge-quark sector

$$\beta_{g_i} = -f_g\, g_i\, \theta(k - M_{\rm Planck}) + \mathcal{O}(g_i^3)$$

$$\beta_{y_f} = -f_y\, y_f\, \theta(k - M_{\rm Planck}) + \mathcal{O}(y_f^3)$$





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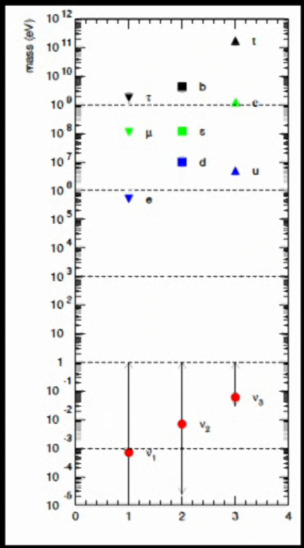
Principled-parameterized approach used in:

- Full gauge-Yukawa sector with CKM matrix elements [Alkofer, AE, Held, Nieto, Percacci, Schröfl '20]
- Muon g-2 [Kowalska, Sessolo '20]
- Higgs portal to dark matter [Reichert, Smirnov '19; AE, Pauly '20]
- BSM with gauged baryon number [Boos, Carone, Donald, Musser '22]
- Flavor anomalies [Kowalska, Sessolo '22]
- …

Beyond the Standard Model: neutrino masses

Standard Model fermion masses



[de Goueva '09]

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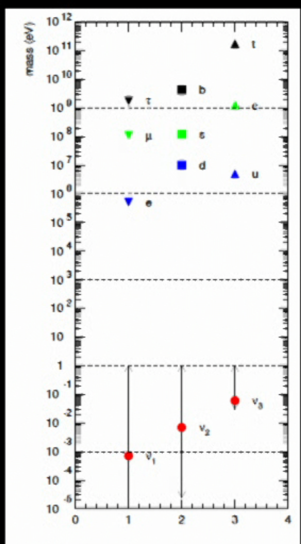

[de Goueva '09]

- Option 1:

  neutrino masses arise through a different mechanism than the other fermion masses

- Option 2:

  neutrino masses arise through the Higgs mechanism with a very small Yukawa coupling

  Dynamically small neutrino Yukawa coupling in principled-parameterized approach

  [Held '19; Kowalska, Sessolo '22; AE, Held '22]

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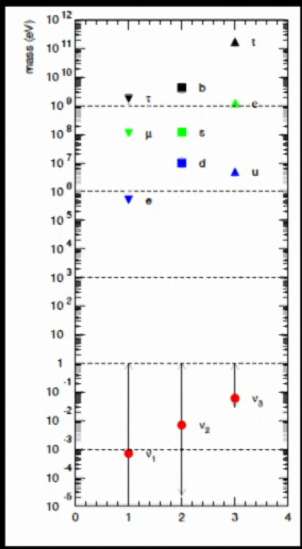

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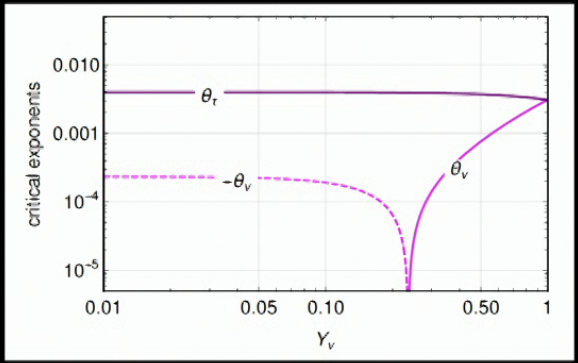

negative critical exponent: coupling decreases

scaling of the coupling $y_i \sim k^{-\theta_i}$

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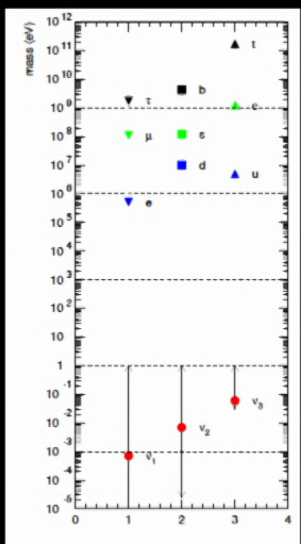

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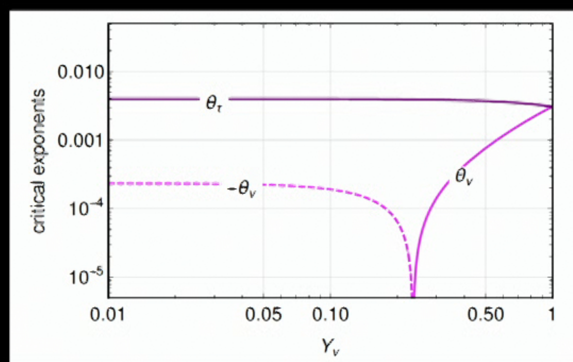

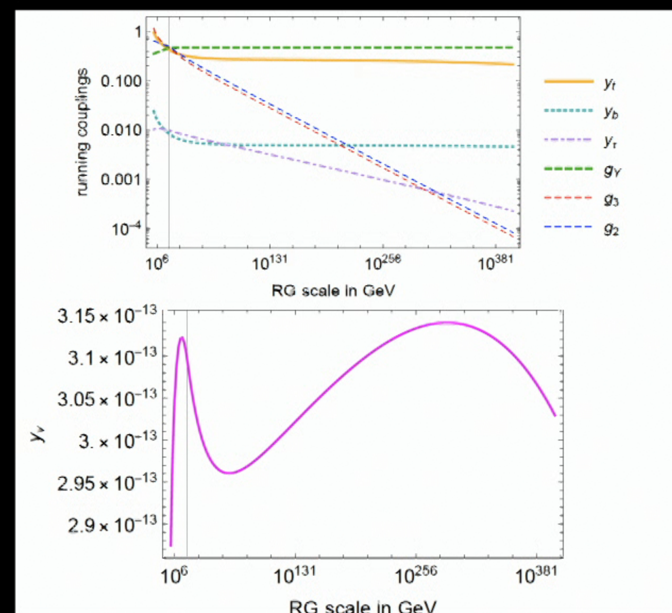

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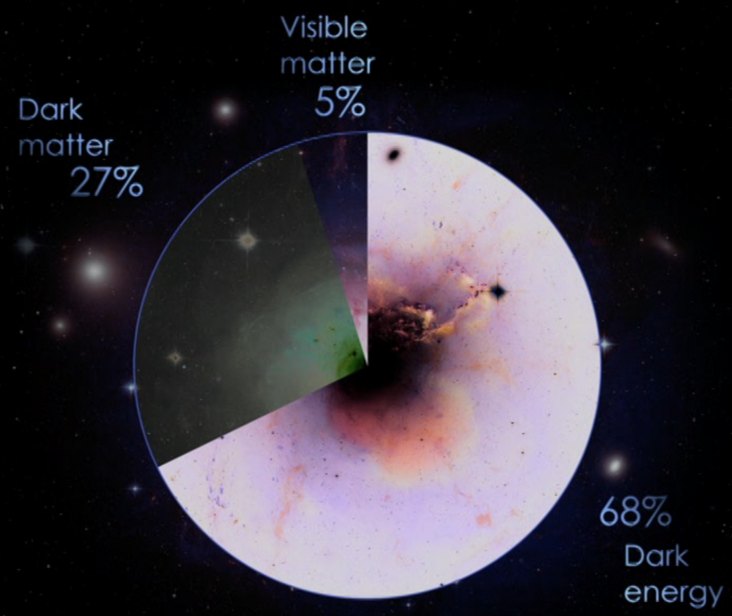
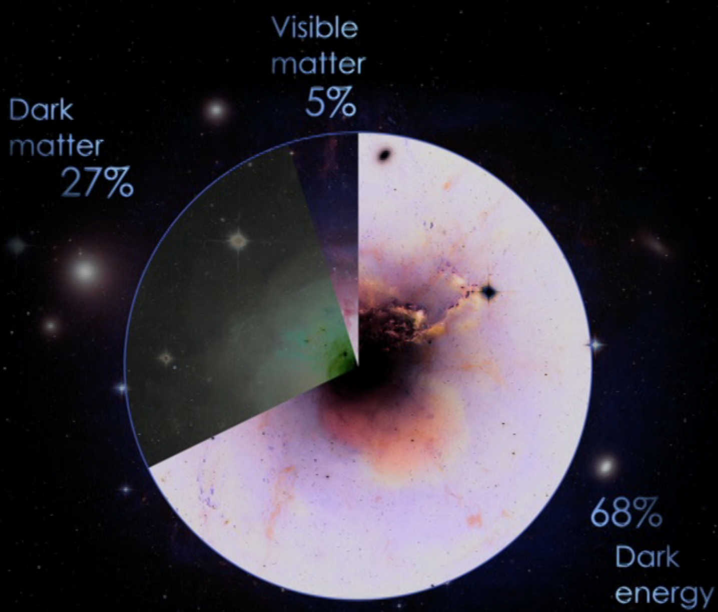
Beyond the Standard Model: the dark universe



- Dark energy: cosmological constant, many models of dark energy…
- Dark matter: primordial black holes, modified gravity (?), many models of new particles…

Beyond the Standard Model: the dark universe



- Dark energy: cosmological constant, many models of dark energy…
- Dark matter: primordial black holes, modified gravity (?), many models of new particles…
- Idea: only some explanations (or none?) compatible with asymptotically safe quantum gravity

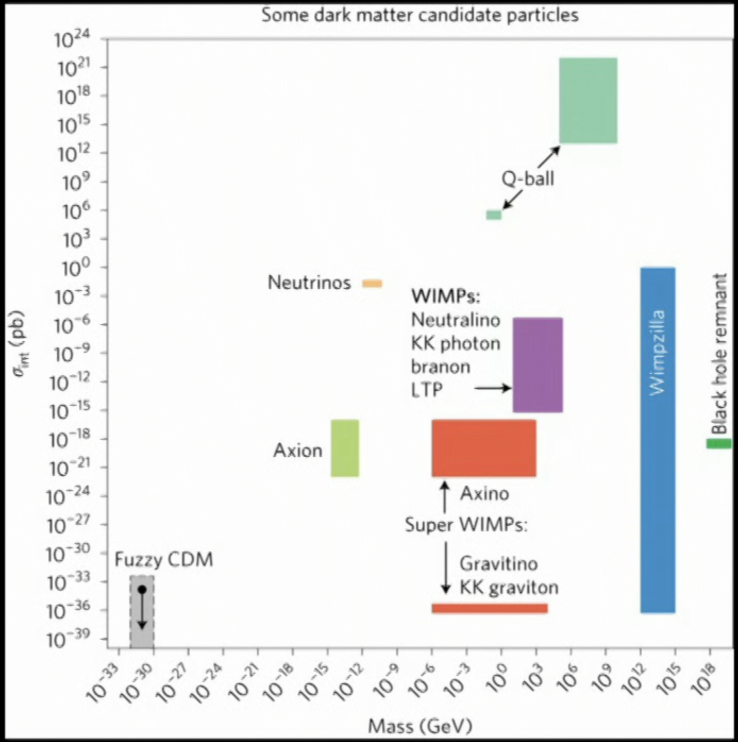
    Example: simplest Horndeski theory of dark energy: asymptotic safety predicts vanishing couplings

    [AE, Rafael R. Lino dos Santos, Fabian Wagner '23]

    Further examples: dark matter models

Beyond the Standard Model: dark matter

Some dark matter candidates



[Conrad, Reimer '17]

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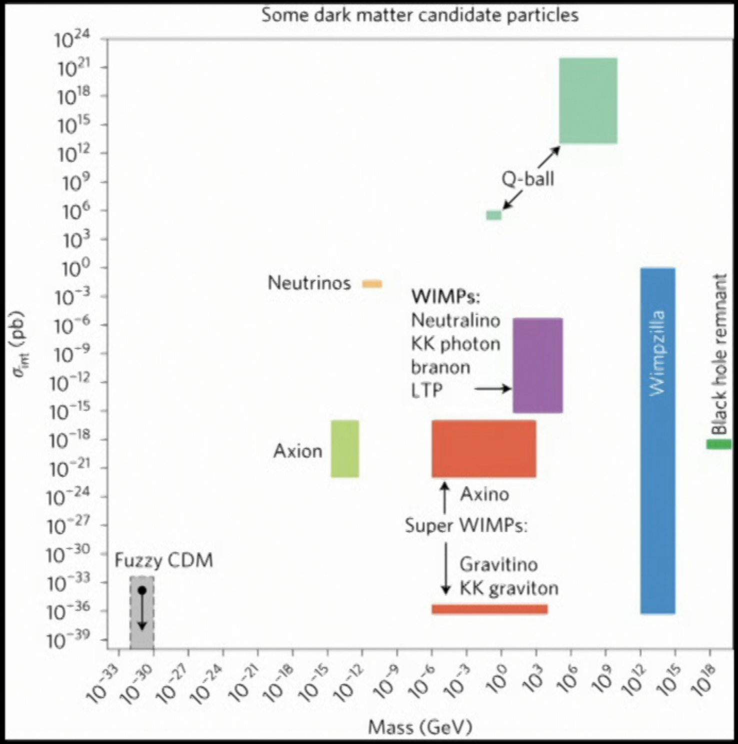
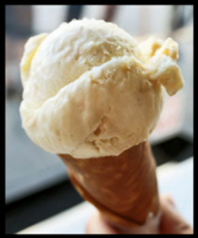


[Conrad, Reimer '17]

Too many choices!

Asymptotic safety and the Higgs portal to dark matter

The vanilla model:



Higgs portal to one singlet scalar

$$\lambda_H H^\dagger H \phi^2$$

→ production in the early universe

→ direct searches (e.g. LHC, XENON)

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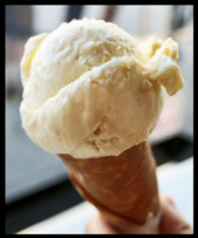

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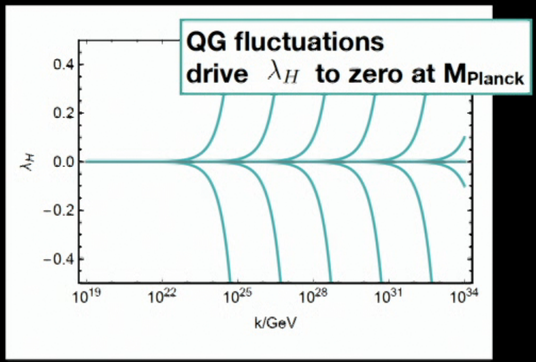
with $f_\lambda > 0$



→ single dark scalar decouples in asymptotic safety

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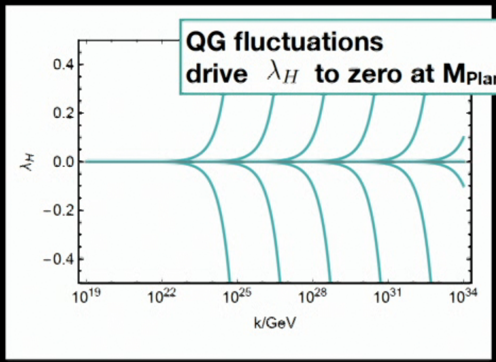

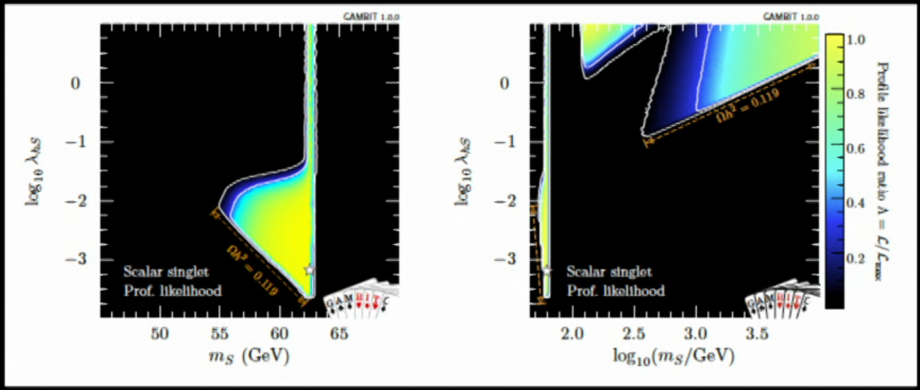

[GAMBIT coll. '17]

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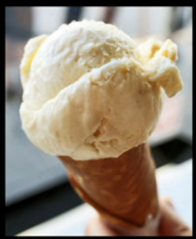

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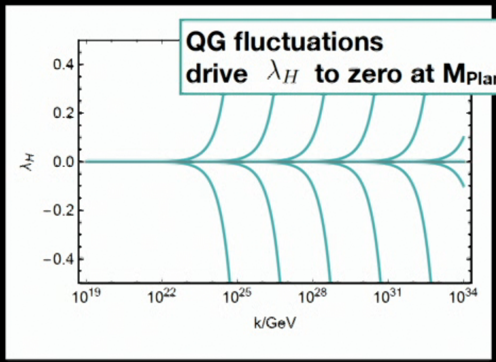

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→ Can portal be generated by adding new fields?

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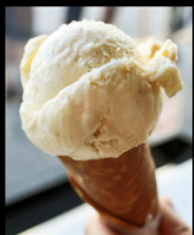

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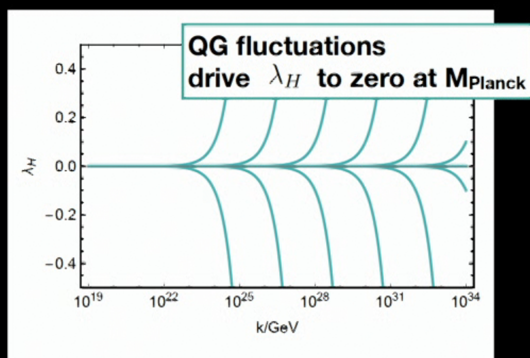

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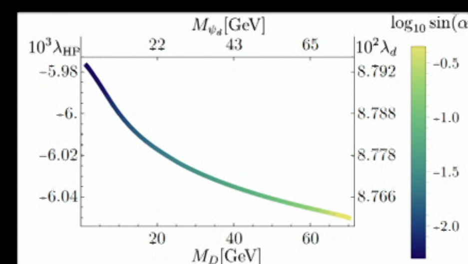
→ Strongly constrained settings

EFT of the dark sector: 6 free parameters
(scalar mass, scalar quartic, Higgs portal, mixing angle, Yukawa, non-minimal)

single free parameter in asymptotic safety



Asymptotic safety and the Higgs portal to dark matter: Summary

The vanilla model:

predictive power:
model ruled out

Extended dark sectors:

predictive power:
reduced parameter space

extra degrees of freedom

Asymptotic safety and ALPS

ALPS: axion-like particles

$$\bar{g}_a\, a(x)\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Asymptotic safety and ALPS

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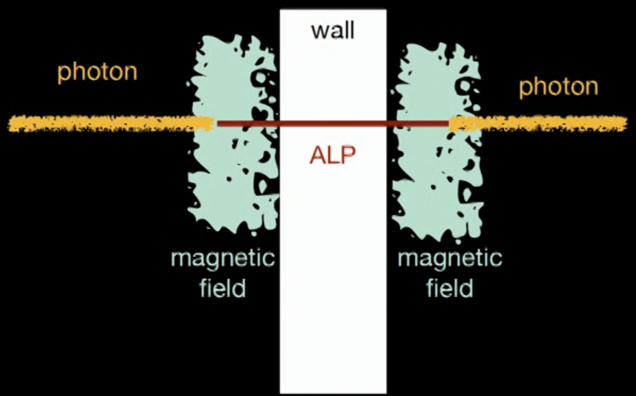
phenomenology:

- ultralight (sub-eV) dark-matter candidate
- experimental searches: light-shining-through-wall



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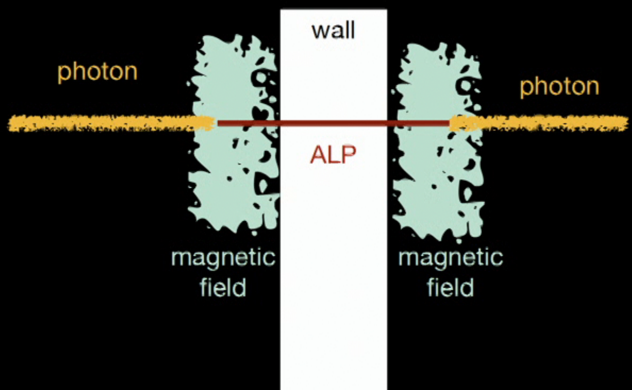
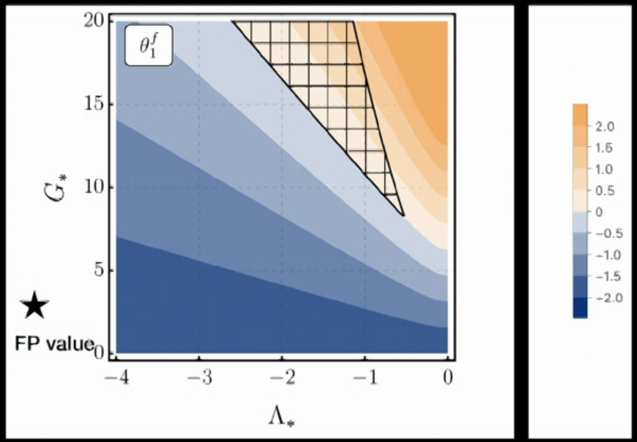


with asymptotically safe gravity: $\beta_{g_a^2} = 2g_a^2 - f_{g_a} g_a + \frac{7}{48\pi^2} g_a^4 + \ldots$

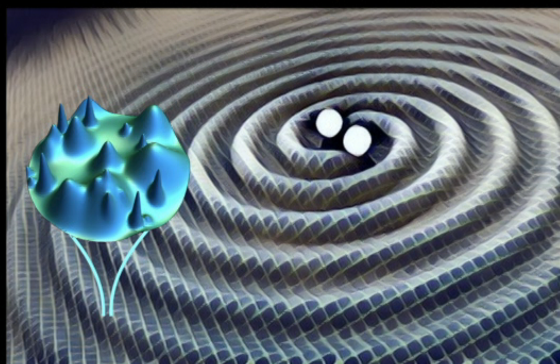
$g_{a*}^2 = 0$ unless $f_{g\,a} > 2$ (strongly-coupled quantum gravity)

[de Brito, AE, Lino dos Santos '21]



Summary

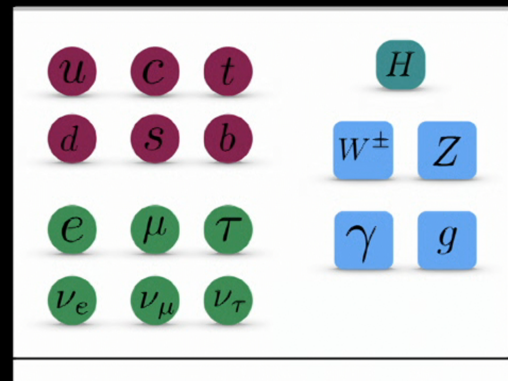
Quantum gravity

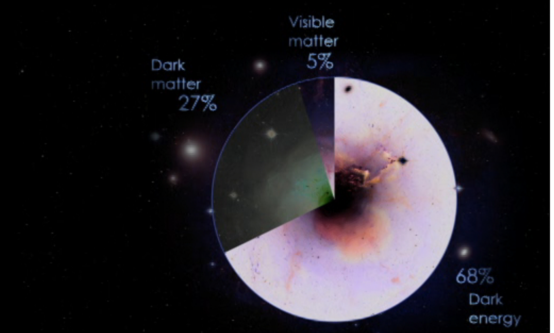


key open challenge: testability

interplay with matter makes quantum gravity testable

Particle physics in visible & dark universe





key open challenge: too many possibilities & free parameters

interplay with gravity constrains properties of matter

Outlook:

Dark matter, dark energy and matter-antimatter asymmetry in asymptotically safe quantum gravity

Gravitational-wave signatures from beyond Standard Model physics in the early universe within asymptotic safety

"Matter matters" program in other quantum gravity approaches
(e.g. towards bounds on the Higgs mass in causal sets)

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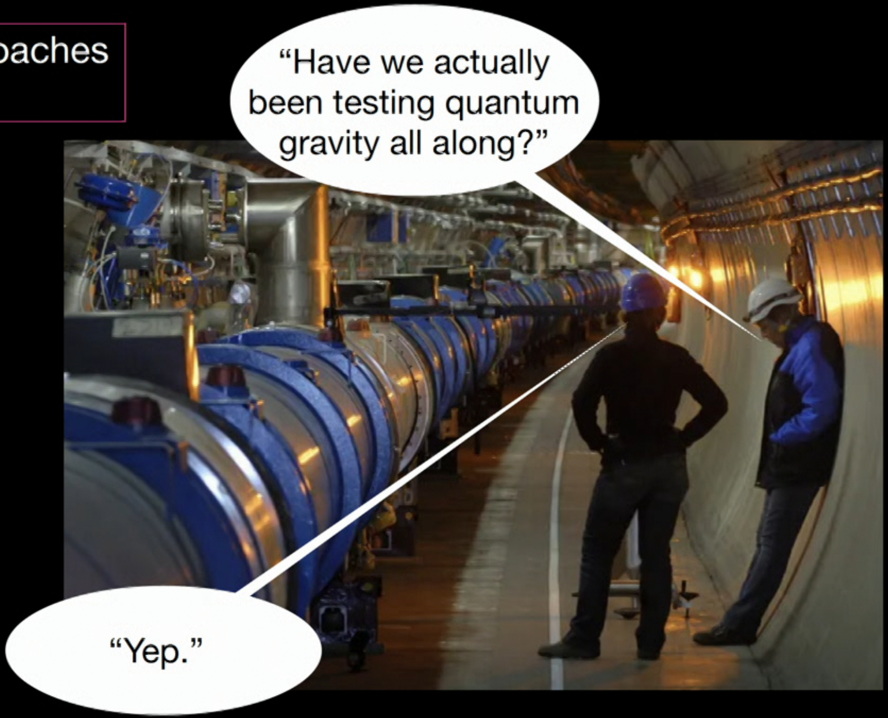

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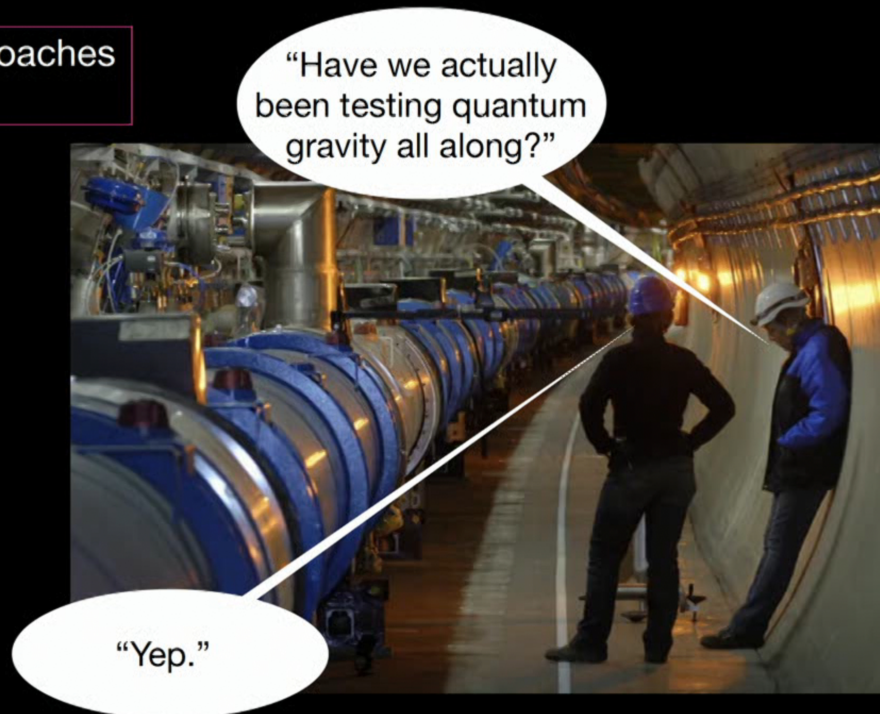

Thank you for your attention!

Thanks to former and current group members!

Aaron Held, Ademola Adeifeoba, Alessia Platania, Andreas Pithis, Antonio Pereira, Arslan Sikandar, Christopher Pfeiffer, Fabian Wagner, Fleur Versteegen, Gustavo P. de Brito, Héloïse Delaporte, Jan Kwapisz, Johanna Borissova, Johannes Lumma, Ludivine Fausten, Marc Schiffer, Martin Pauly, Nicolai Christiansen, Peter Vander Griend, Philipp Johannsen, Rafael Robson Lino dos Santos, Raúl Carballo-Rubio, Shouryya Ray, Vedran Skrinjar