Title: Quantum Gravity and its connection to observations

Speakers: Astrid Eichhorn

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

Date: May 08, 2023 - 9:30 AM

URL: https://pirsa.org/23050111

Abstract: To make progress in developing a quantum theory of gravity, we need to connect candidate theories to observations. I will review ideas on connecting quantum gravity to observations in particle physics, to searches for dark matter and to observations of black holes, in particular with the (next-generation) Event Horizon Telescope.

Zoom Link: https://pitp.zoom.us/j/94575380034?pwd=Y21DMTRqeFFGNnd5dnVBc1dac2tUQT09

Quantum gravity and its connection to observations

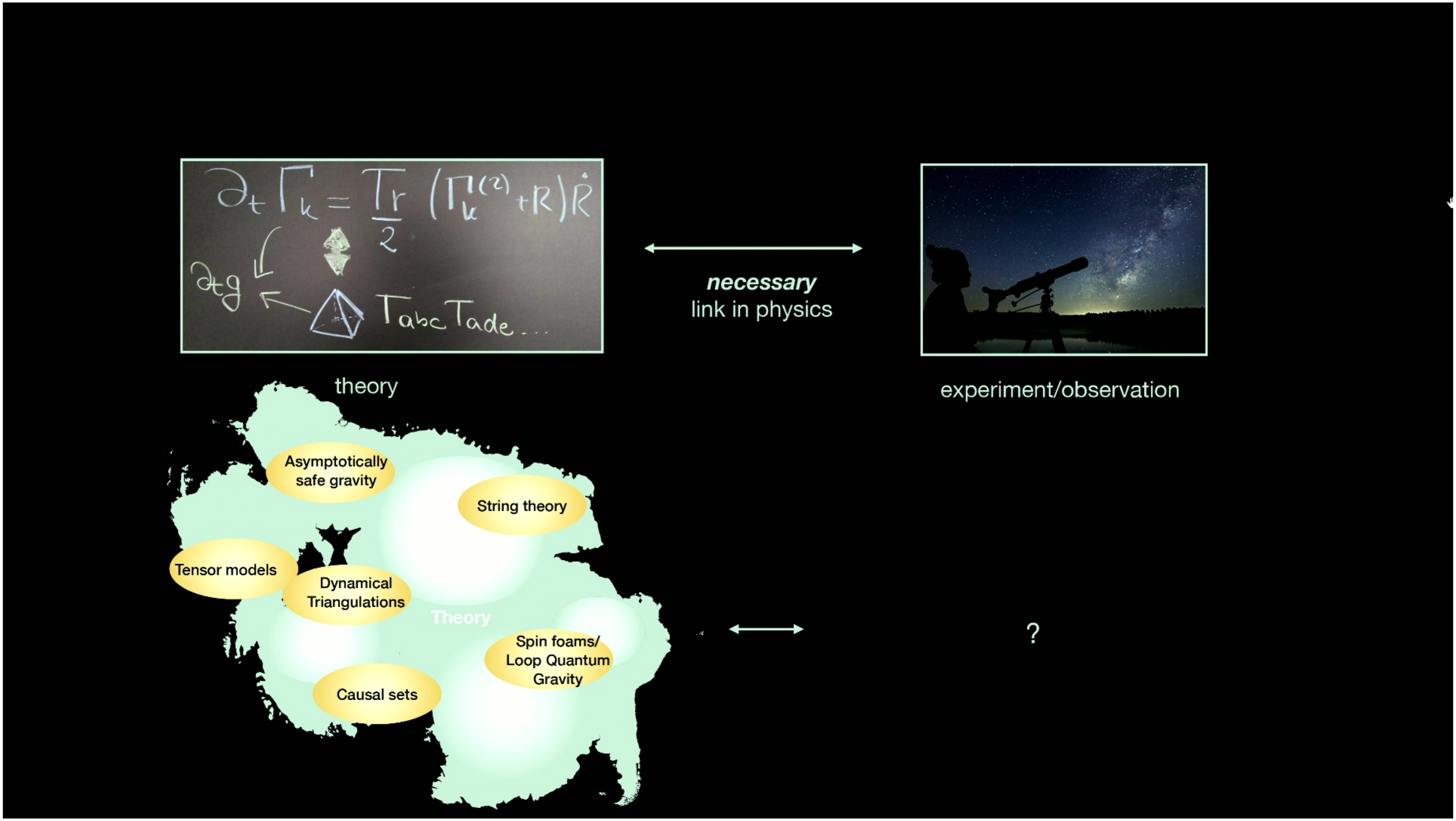
Quantum spacetime in the cosmos: from conception to reality
Perimeter Institute, May 8, 2023

Astrid Eichhorn, CP3-Origins, University of Southern Denmark

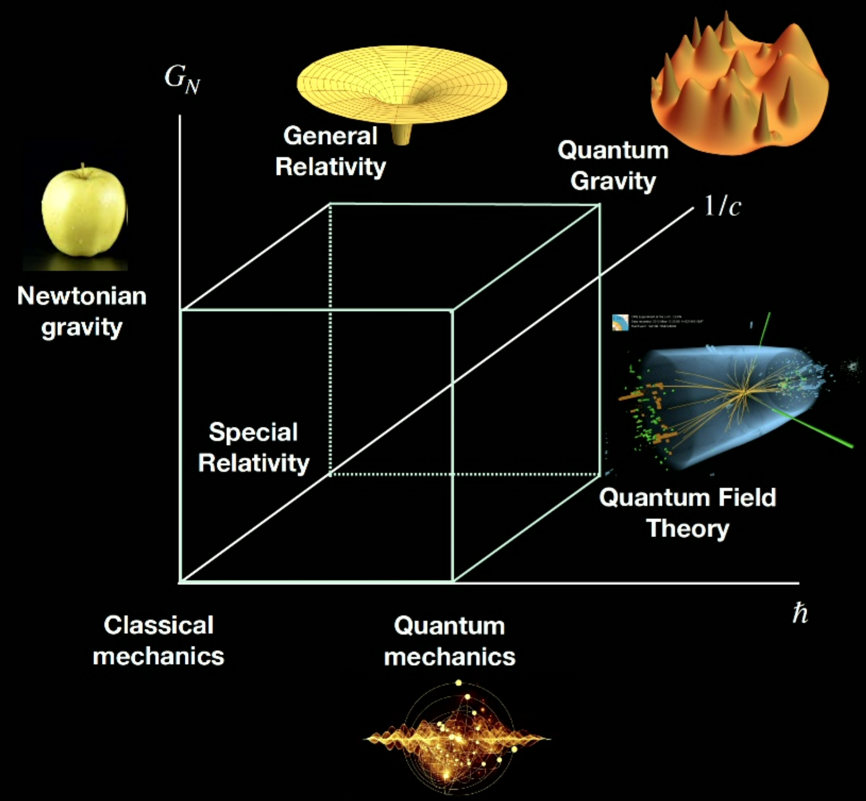
VILLUM FONDEN

CP3

SDU


theory
necessary
link in physics
experiment/observation
Asymptotically safe gravity
String theory
Tensor models
Dynamical Triangulations
Theory
Spin foams/ Loop Quantum Gravity
Causal sets
?

Why is it so challenging to test quantum gravity?



$$\ell_{\text{Planck}} = \sqrt{\frac{\hbar\, G_N}{c^3}} = 10^{-35} m \qquad (M_{\text{Planck}} \approx 10^{19}\,\text{GeV})$$

Simple/naive dimensional estimate

- lacks dynamical information
- assumes “naturalness” (but see cosmological constant)
- assumes quantum gravity comes with a single scale

Strategy:

1) be agnostic and constrain new-physics scale ℓ_{NP}
2) be pessimistic and find leverarms that make ℓ_{Planck} accessible in observations

Testing black-hole spacetimes with shadow observations

Approaches to black-hole shadows beyond GR:

i) parameterized approach:

parameterize all possible deviations of the metric from Kerr (disconnected from fundamental theory)

ii) principled-parameterized approach:

calculate black-hole shadow in models based on general principles *[AE, A Held '21 a, '21 b]*

iii) principled approach:

calculate black-hole shadow in each conceivable theory beyond GR (too much information given finite EHT resolution)

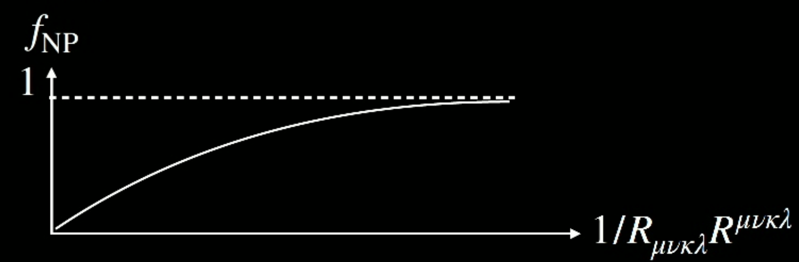
Black holes that satisfy regularity, locality and simplicity

spherically symmetric, stationary black hole [AE, Held, Johannsen ’22; axisymmetric case in AE, Held ’21]

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$f(r) = 1 - 2\frac{G_N M}{r}$$ upgrade to non-singular spacetime: $$f(r) = 1 - 2\frac{G_N M}{r} f_{\rm NP}$$

- locality: upgrade depends on local curvature scale $f_{\rm NP} = f_{\rm NP}\left(R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}(r)\cdot \ell_{\rm NP}^4\right)$
- regularity: upgrade removes curvature singularity $f_{\rm NP} = \frac{1}{\sqrt{\left(R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}(r)\cdot \ell_{\rm NP}^4\right)}} + \mathcal{O}\left(\left(R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}(r)\cdot \ell_{\rm NP}^4\right)^{-3}\right)$
- simplicity: upgrade introduces a single new-physics scale $\ell_{\rm NP}$



Black holes that satisfy regularity, locality and simplicity

spherically symmetric, stationary black hole [AE, Held, Johannsen '22; axisymmetric case in AE, Held '21]

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$f(r) = 1 - 2\frac{G_N M}{r}$$ upgrade to non-singular spacetime: $$f(r) = 1 - 2\frac{G_N M}{r} f_{\mathrm{NP}}$$

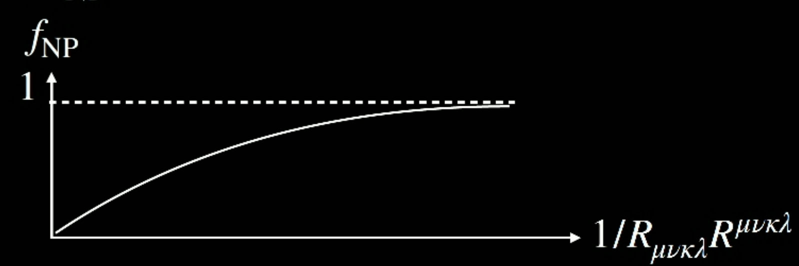
- locality: upgrade depends on local curvature scale $f_{\mathrm{NP}} = f_{\mathrm{NP}}\left(R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}(r)\cdot \ell_{\mathrm{NP}}^4\right)$
- regularity: upgrade removes curvature singularity $f_{\mathrm{NP}} = \frac{1}{\sqrt{\left(R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}(r)\cdot \ell_{\mathrm{NP}}^4\right)}} + \mathcal{O}\left(\left(R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}(r)\cdot \ell_{\mathrm{NP}}^4\right)^{-3}\right)$
- simplicity: upgrade introduces a single new-physics scale ℓ_{NP}

examples:

Dymnikova: $f_{\mathrm{NP}}[x] = 1 - e^{-1/\sqrt{x}}$

Hayward: $f_{\mathrm{NP}}[x] = 1/(1+\sqrt{x})$

Simpson-Visser: $f_{\mathrm{NP}}[x] = e^{-x^{1/6}}$



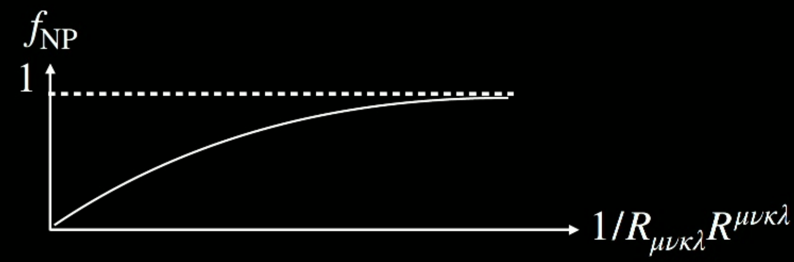
Black holes that satisfy regularity, locality and simplicity

spherically symmetric, stationary black hole

[AE, Held, Johannsen '22; axisymmetric case in AE, Held '21]

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$f(r) = 1 - 2\frac{G_N M}{r} f_{NP}$$



Does this approach cover quantum gravity theories?

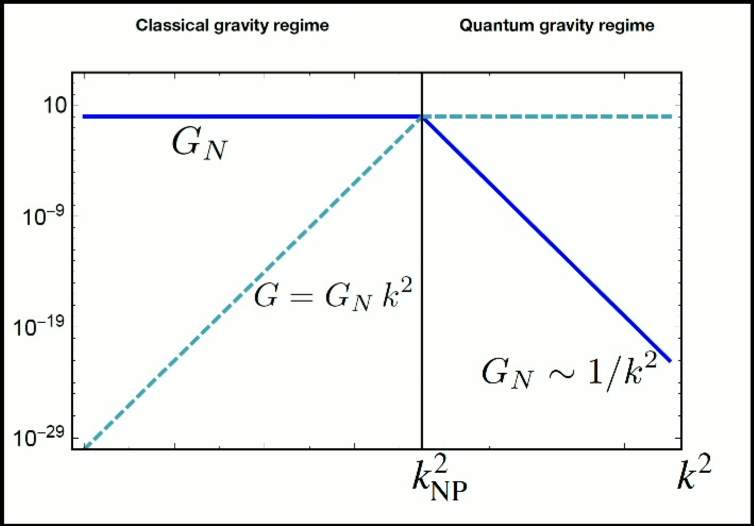
Example: Asymptotically safe quantum gravity

[Bonanno, Reuter '01, Falls, Litim '12,...., Adeifeoba, AE, Platania '18, AE, Held '22]

f_{NP} from scale-dependence of Newton coupling

$$G_N(k^2) = \frac{G_N(0)}{1 + \omega\, G_N(0)\, k^2} \qquad k^2 \sim \sqrt{R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}}$$

$$\to f_{NP} = \frac{1}{1 + \ell_{NP}^2 \sqrt{R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda}}}$$



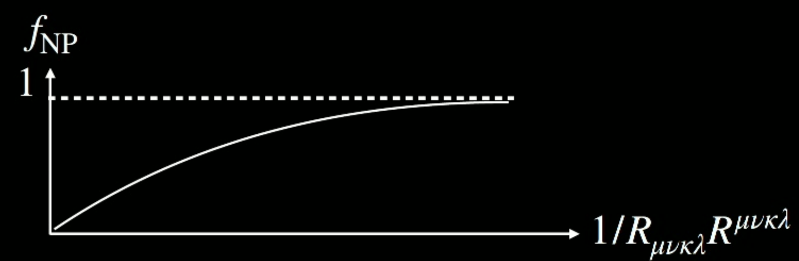
Observational consequences

spherically symmetric, stationary black hole

[AE, Held, Johannsen '22; axisymmetric case in AE, Held '21]

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$f(r) = 1 - 2\frac{G_N M}{r} f_{NP}$$

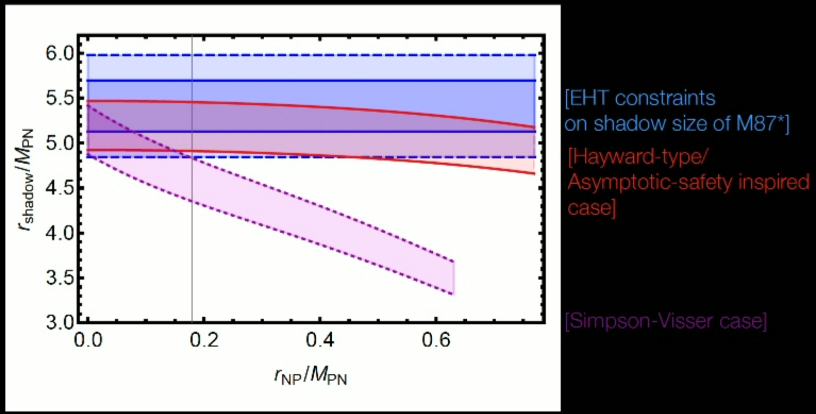


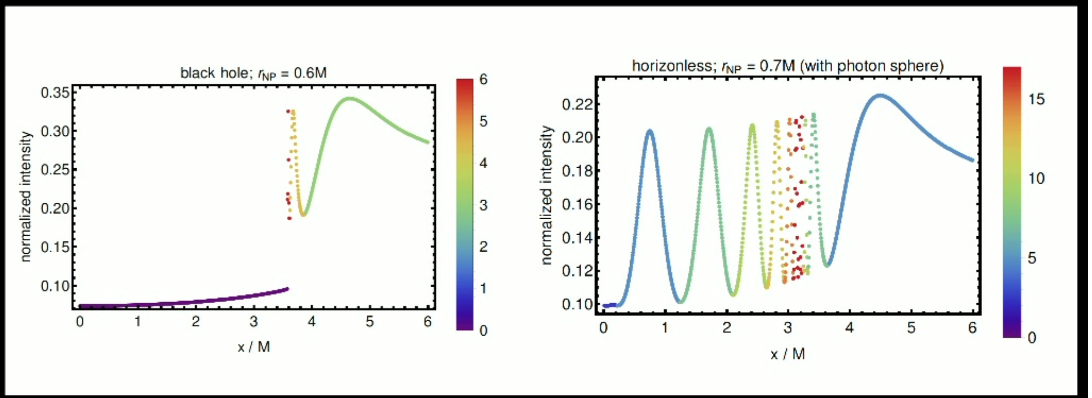
- photon sphere is more compact

$\Rightarrow$ shadow is more compact

- for $\ell_{NP} > \ell_{NP,\,crit}$, horizon is resolved

$\Rightarrow$ images show inner photon rings





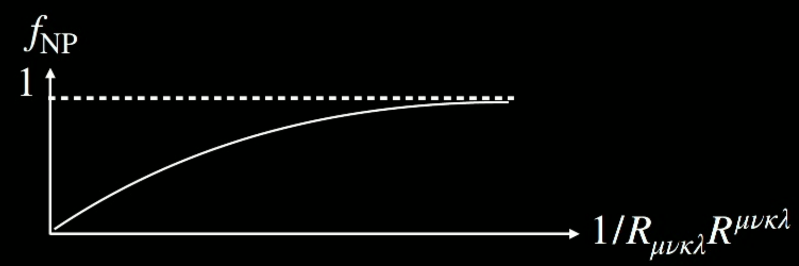
Observational consequences

spherically symmetric, stationary black hole

[AE, Held, Johannsen '22; axisymmetric case in AE, Held '21]

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$f(r) = 1 - 2\frac{G_N M}{r} f_{\mathrm{NP}}$$

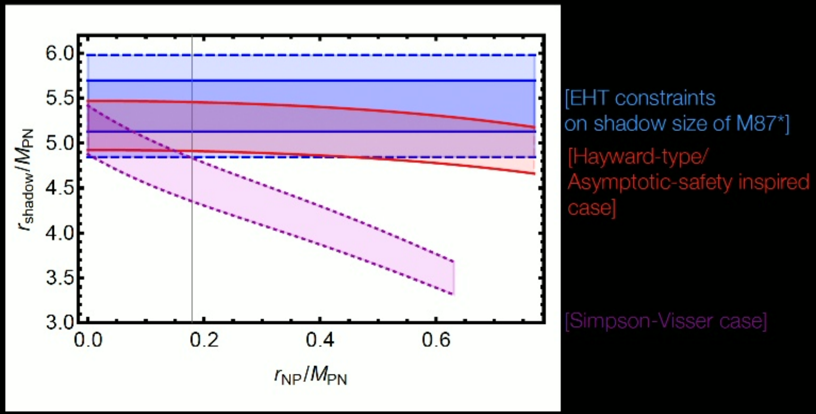


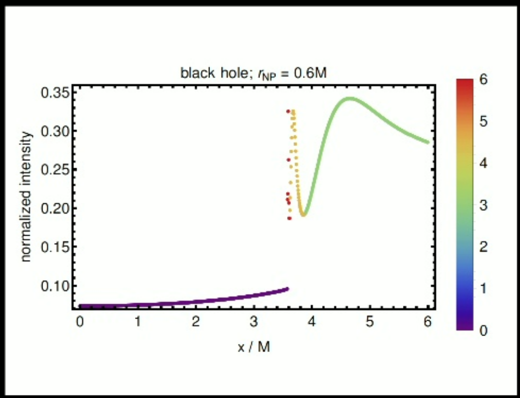
- photon sphere is more compact

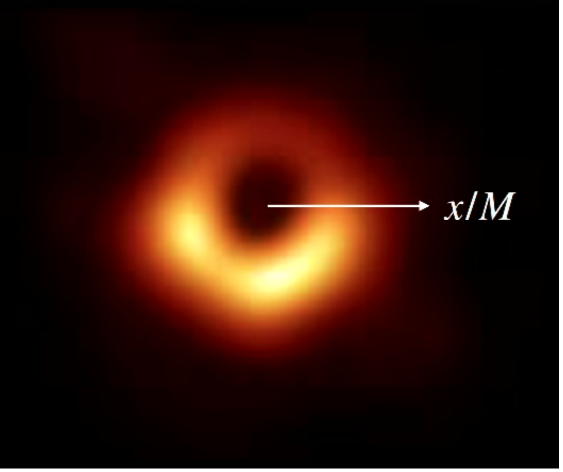
$\Rightarrow$ shadow is more compact

- for $\ell_{\mathrm{NP}} > \ell_{\mathrm{NP,crit}}$, horizon is resolved

$\Rightarrow$ images show inner photon rings

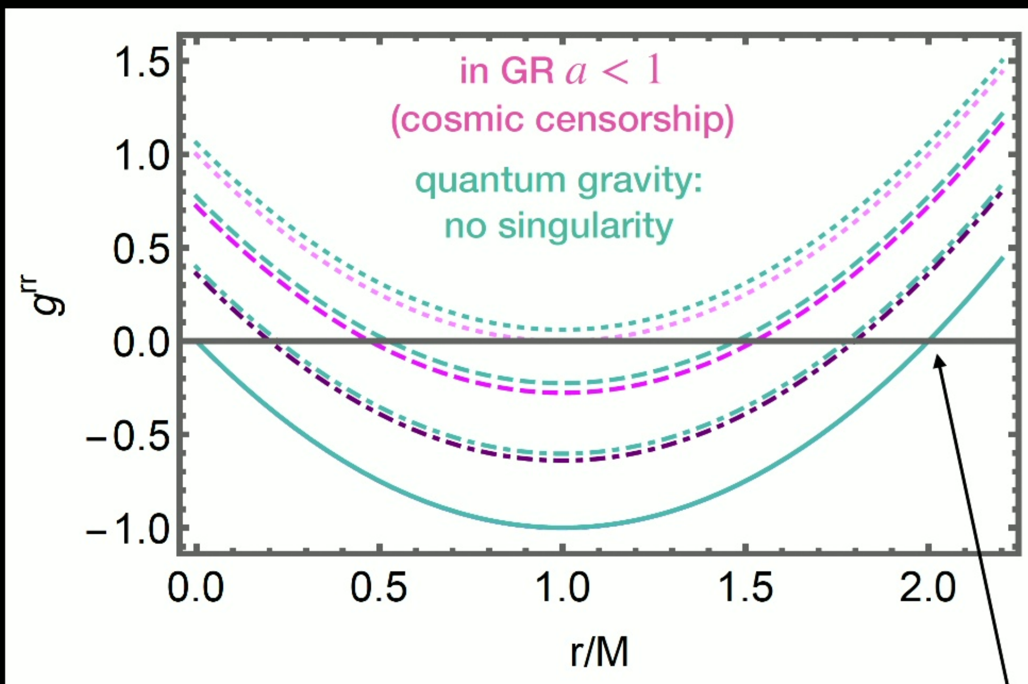






What if $\ell_{\rm NP} = \ell_{\rm Planck}$?

→ spin as a leverarm

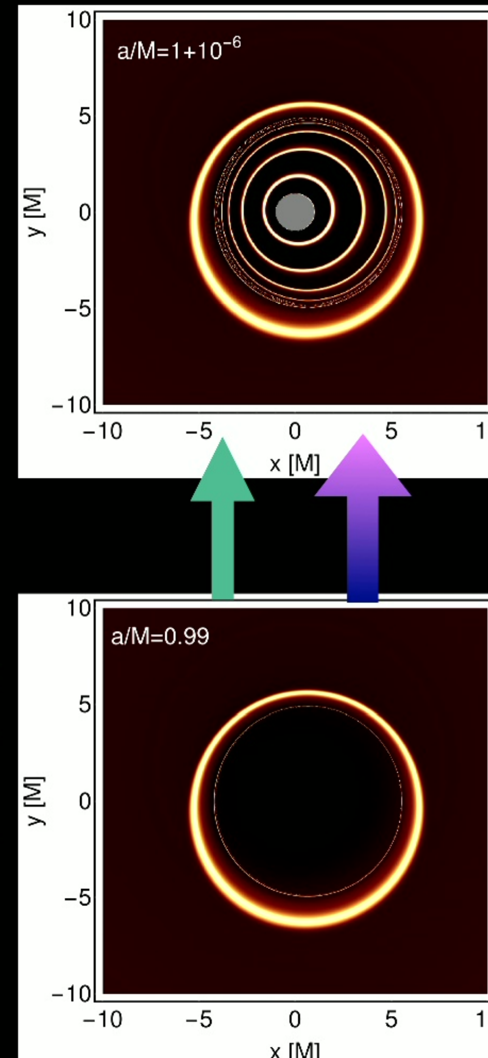


high spin
(fast rotating)

low spin
(slowly rotating)

a black hole shadow
lights up

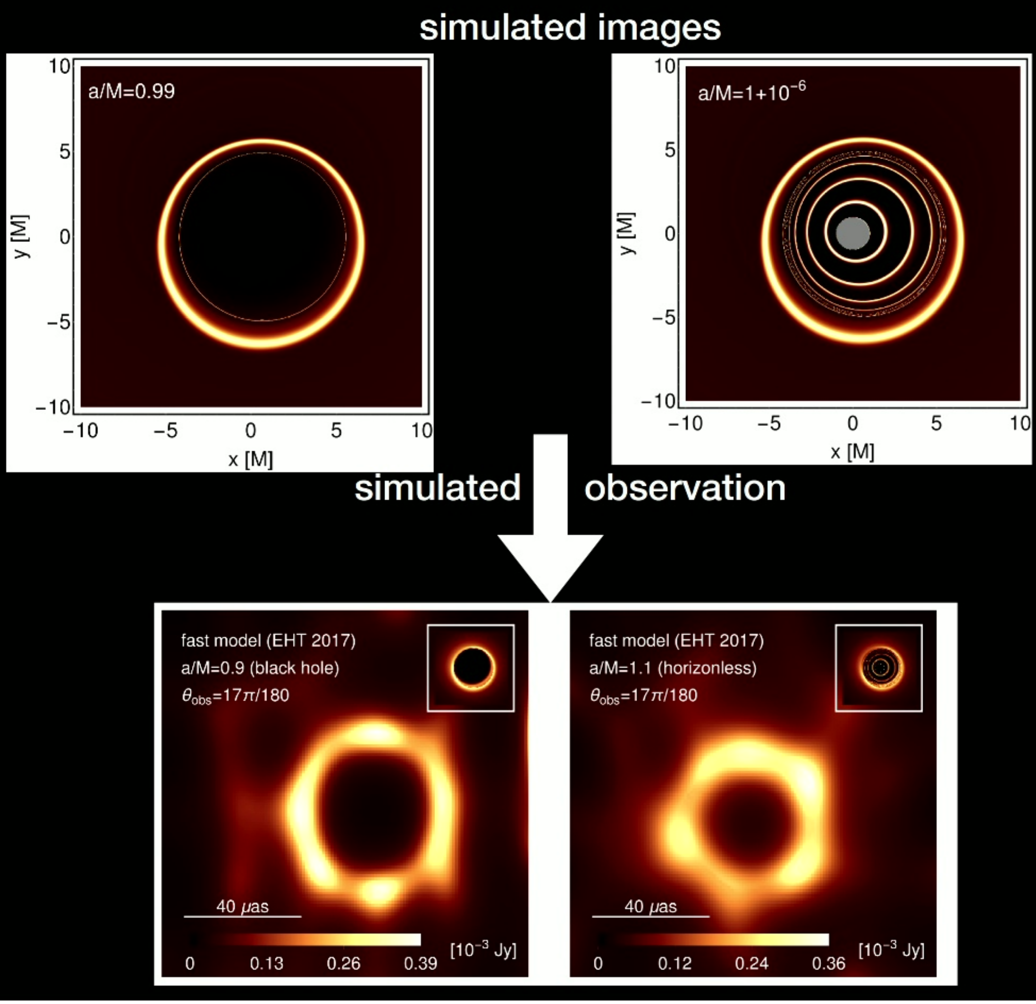
[AE, Held '22]



Caveat: For astrophysical black holes
spins $a \sim 1$ may not be achievable
(depends on dynamics beyond GR)

location of horizon:
$g^{rr} = 0$

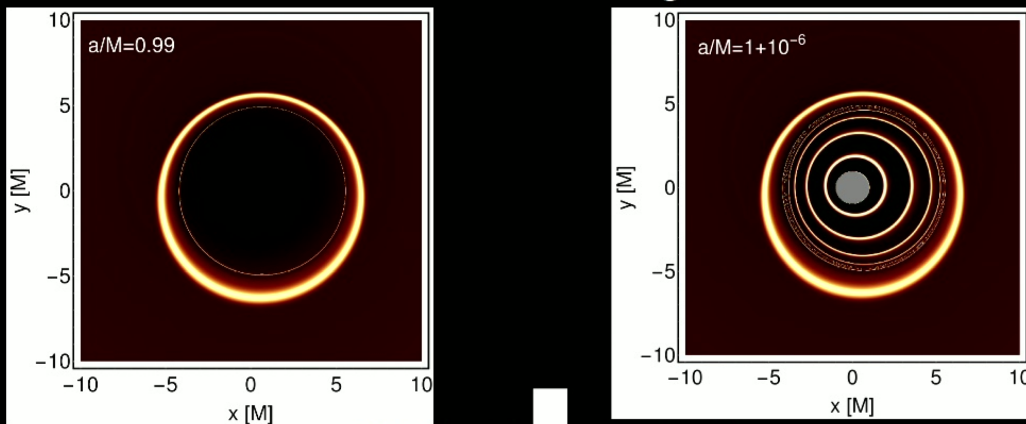
Can the (ng) EHT distinguish black holes and horizonless spacetimes?



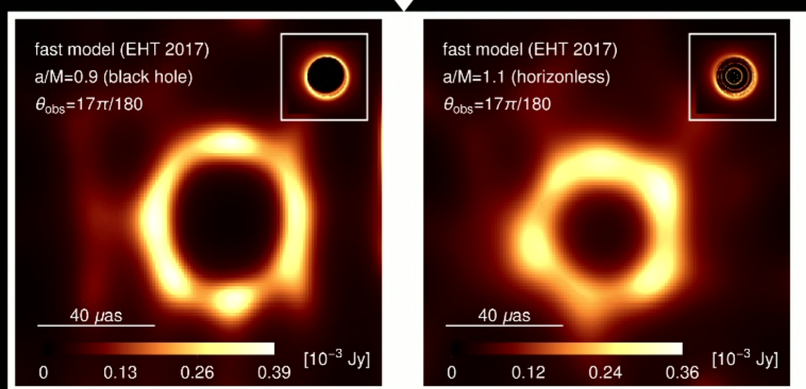
[AE, Gold, Held ’22 and AE, Held ‘22]

Can the (ng) EHT distinguish black holes and horizonless spacetimes?

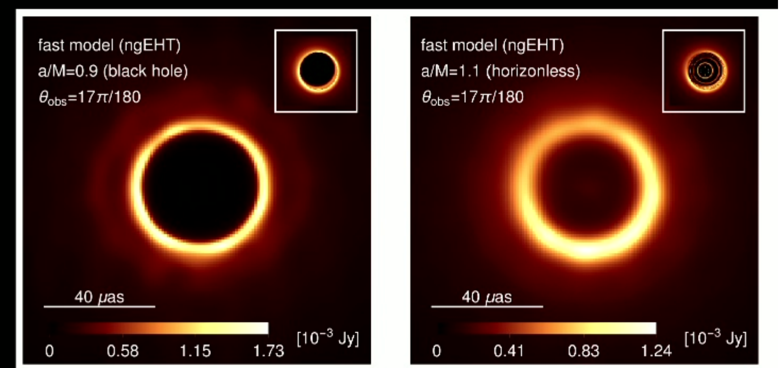
simulated images



simulated observation



simulated observation with future telescope array (next-generation EHT)

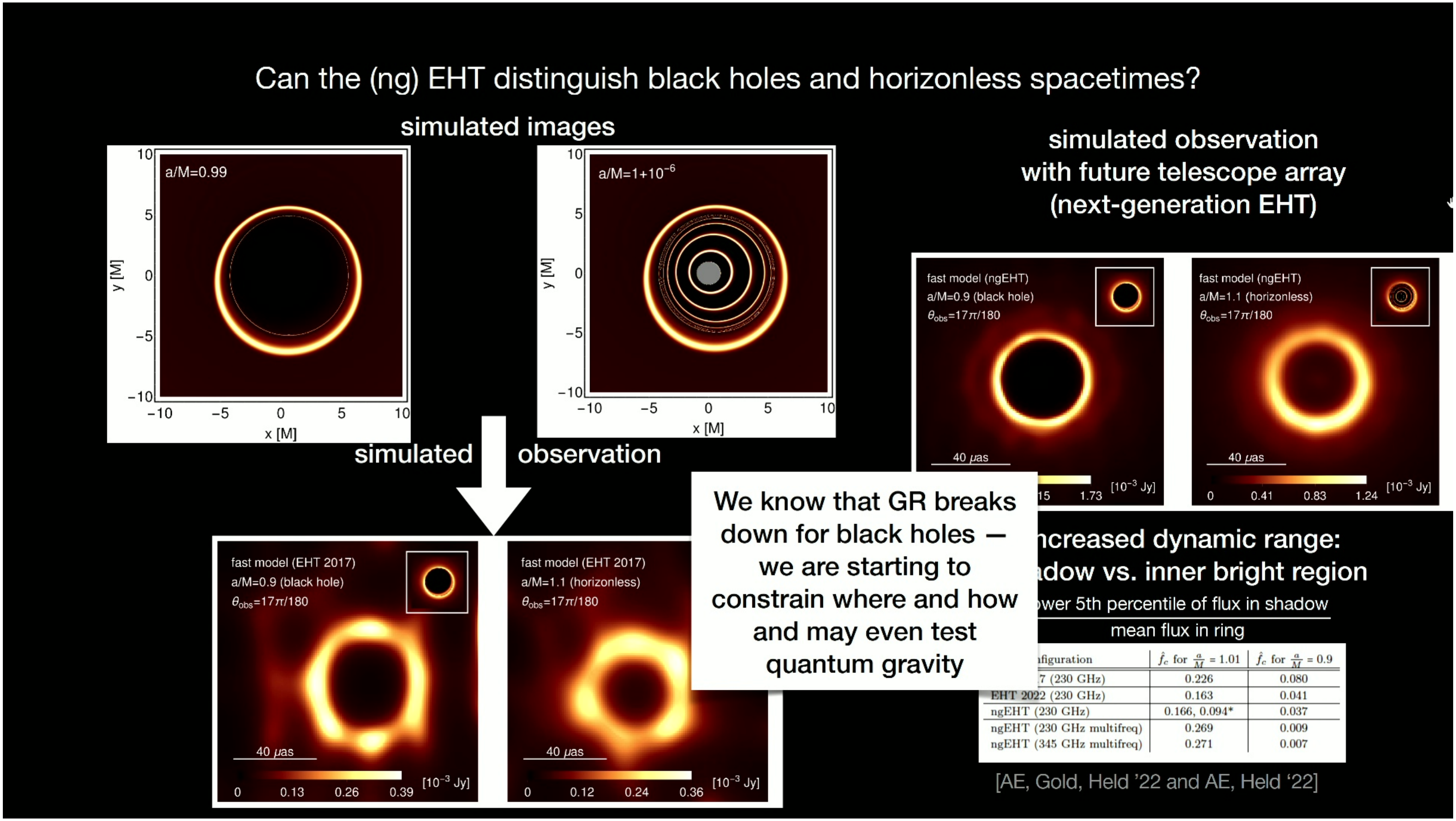


increased dynamic range: shadow vs. inner bright region

$$\hat{f}_c = \frac{\text{lower 5th percentile of flux in shadow}}{\text{mean flux in ring}}$$

array configuration	$\hat{f}_c$ for $\frac{a}{M} = 1.01$	$\hat{f}_c$ for $\frac{a}{M} = 0.9$
EHT 2017 (230 GHz)	0.226	0.080
EHT 2022 (230 GHz)	0.163	0.041
ngEHT (230 GHz)	0.166, 0.094*	0.037
ngEHT (230 GHz multifreq)	0.269	0.009
ngEHT (345 GHz multifreq)	0.271	0.007

[AE, Gold, Held '22 and AE, Held '22]


Can the (ng) EHT distinguish black holes and horizonless spacetimes?
simulated images
a/M=0.99
a/M=1+10^-6
y [M]
x [M]
simulated observation
with future telescope array
(next-generation EHT)
fast model (ngEHT)
a/M=0.9 (black hole)
θobs=17π/180
fast model (ngEHT)
a/M=1.1 (horizonless)
θobs=17π/180
40 μas
[10^-3 Jy]
simulated
observation
fast model (EHT 2017)
a/M=0.9 (black hole)
θobs=17π/180
fast model (EHT 2017)
a/M=1.1 (horizonless)
θobs=17π/180
We know that GR breaks down for black holes — we are starting to constrain where and how and may even test quantum gravity
ncreased dynamic range:
dow vs. inner bright region
ower 5th percentile of flux in shadow
mean flux in ring
nfiguration | $\hat{f}_c$ for $\frac{a}{M}$ = 1.01 | $\hat{f}_c$ for $\frac{a}{M}$ = 0.9
7 (230 GHz) | 0.226 | 0.080
EHT 2022 (230 GHz) | 0.163 | 0.041
ngEHT (230 GHz) | 0.166, 0.094* | 0.037
ngEHT (230 GHz multifreq) | 0.269 | 0.009
ngEHT (345 GHz multifreq) | 0.271 | 0.007
[AE, Gold, Held '22 and AE, Held '22]

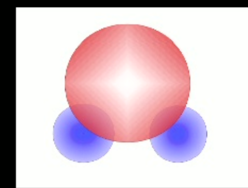
Second testing ground: particle physics

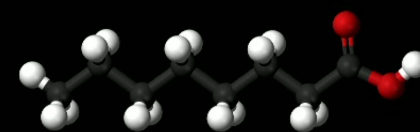
What if $\ell_{\mathrm{NP}} = \ell_{\mathrm{Planck}}$?

→ Logarithmically running couplings as a leverarm

Bridging the gap between Planck scale and Standard-Model scales

zooming out:
microscopic information gets lost

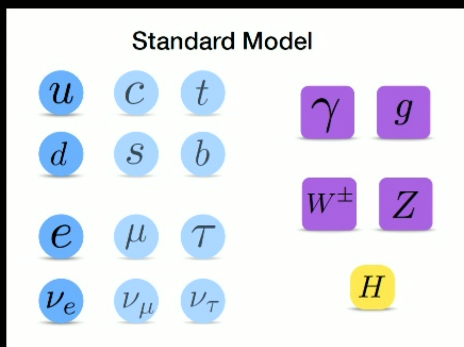




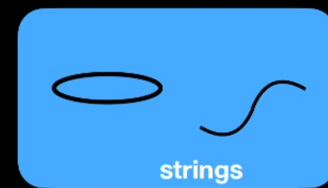
not so different at macroscopic scales

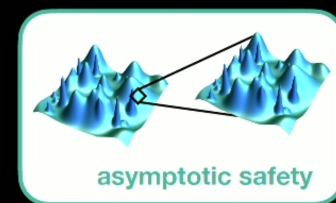
very different at microscopic scales

Bridging the gap between Planck scale and Standard-Model scales



zooming out:
microscopic information gets lost





10^{-18} m ← 10^{-35} m

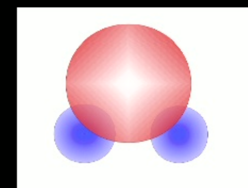
not so different at macroscopic scales

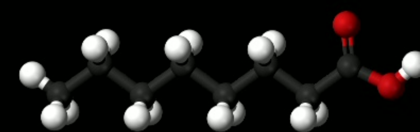
very different at microscopic scales*

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

Bridging the gap between Planck scale and Standard-Model scales

zooming out:
most microscopic information gets lost

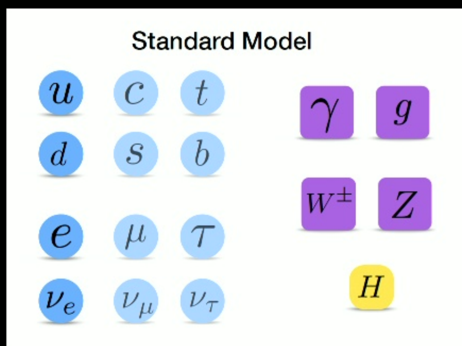




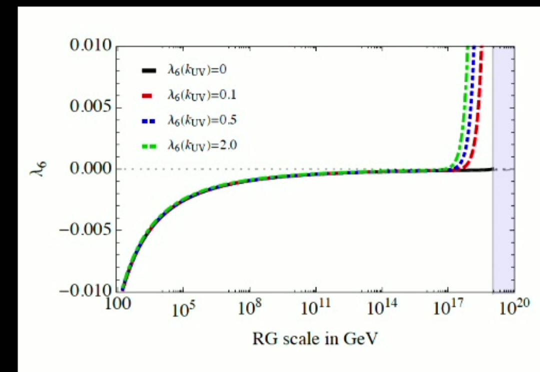
imprints of microscopic physics at macroscopic scales

very different at microscopic scales

Bridging the gap between Planck scale and Standard-Model scales



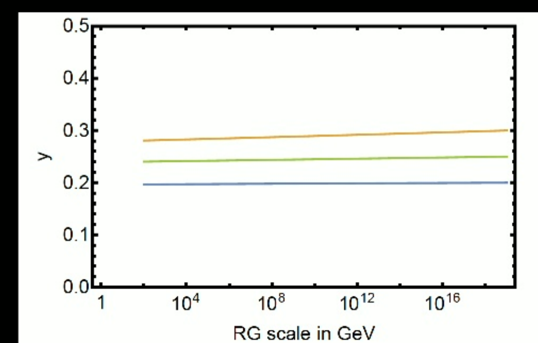
zooming out:
most microscopic information gets lost



higher-order couplings: universality

imprints of microscopic physics at macroscopic scales

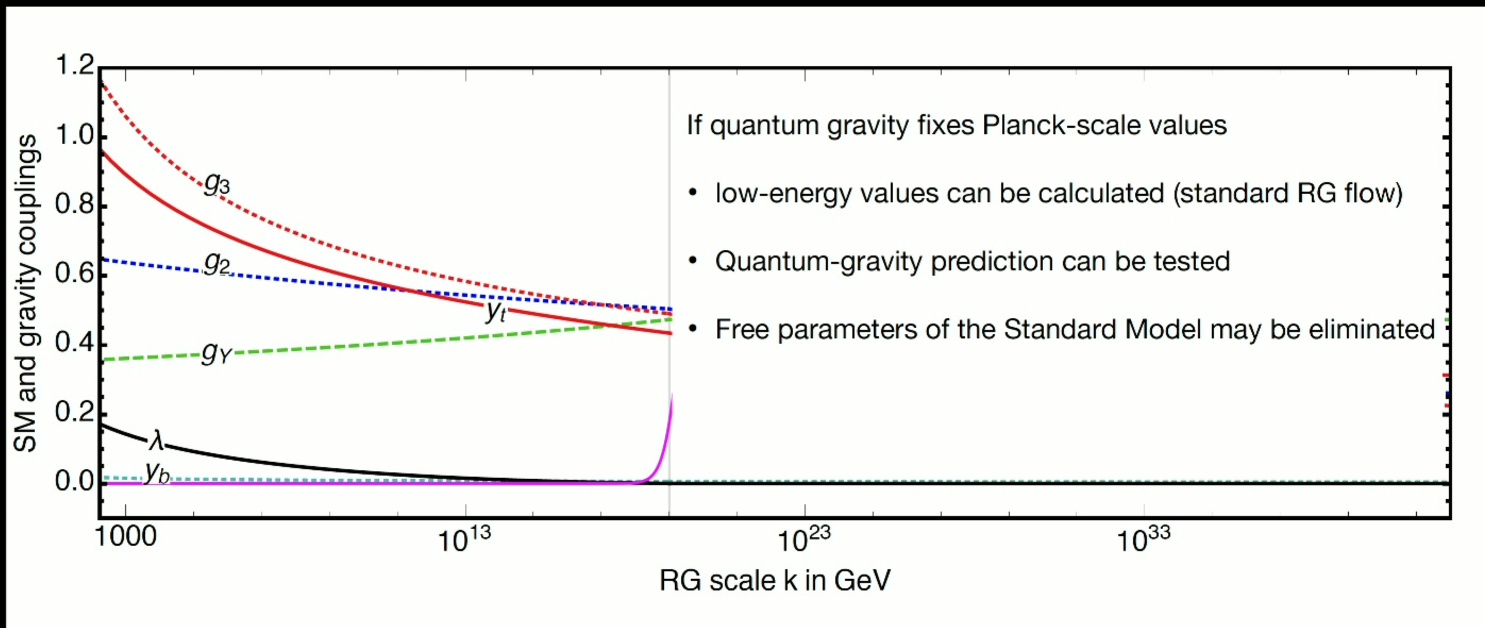
→ identify which (beyond) Standard Model couplings are sensitive to the microphysics



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



Proof of principle: Yukawa couplings

$$\beta_{y_t} = \frac{9}{32\pi^2} y_t^3 \boxed{- f_y\, y_t} + \dots$$

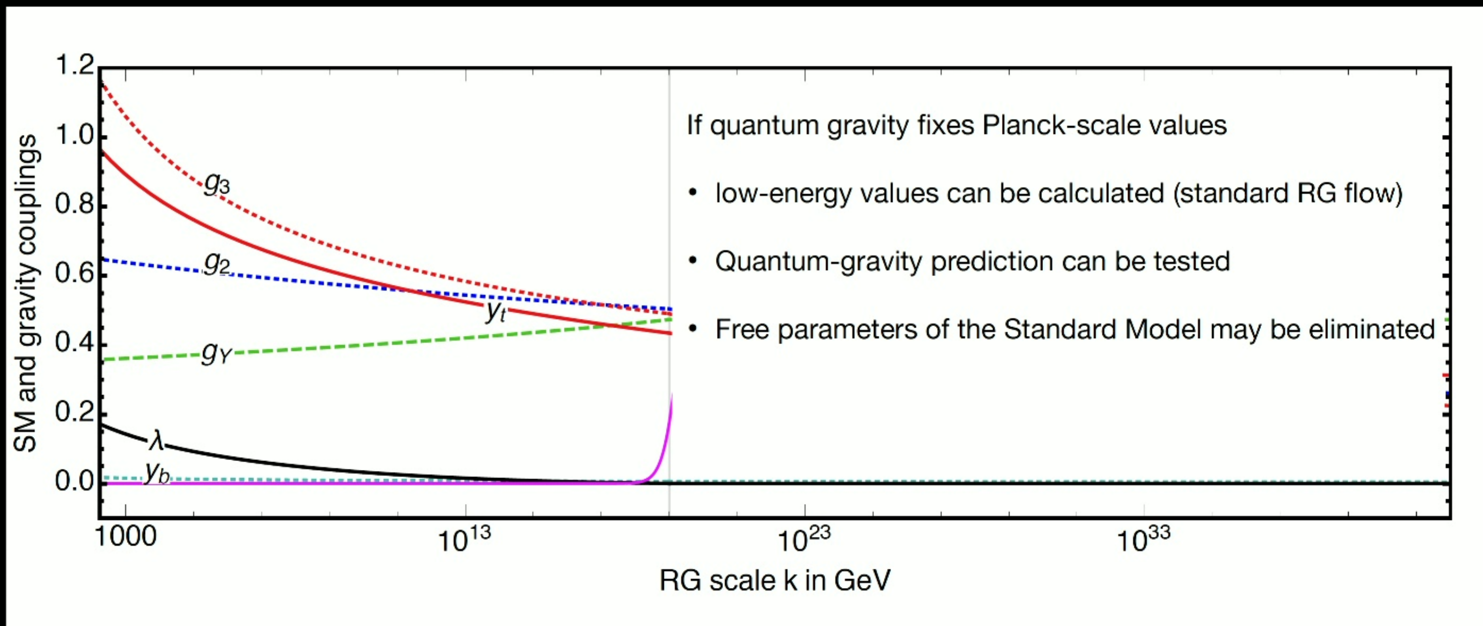
metric fluctuations
(cf. effective change in dimensionality)

$f_y = \text{const}$ above M_{pl}

$f_y \to 0$ below M_{pl}

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

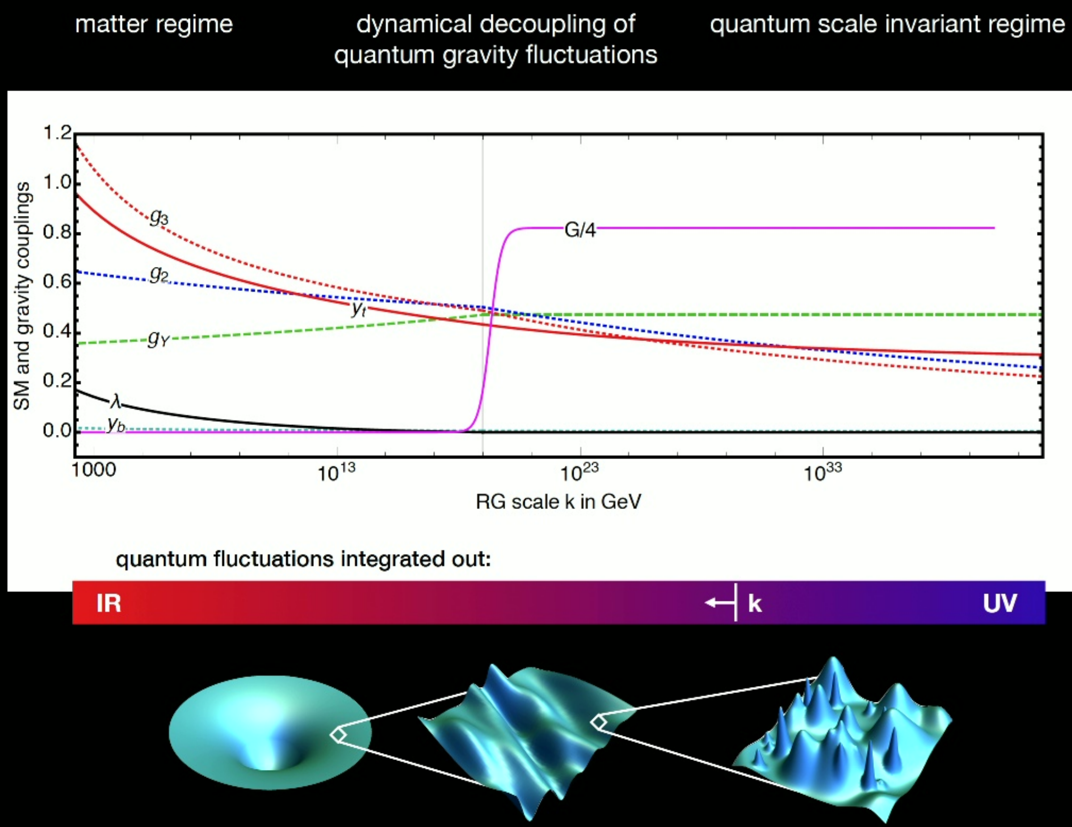
Standard Model couplings:
free parameters



Two examples:

- Asymptotically safe quantum gravity
- Causal set quantum gravity

Predictive power of asymptotic safety: Concept

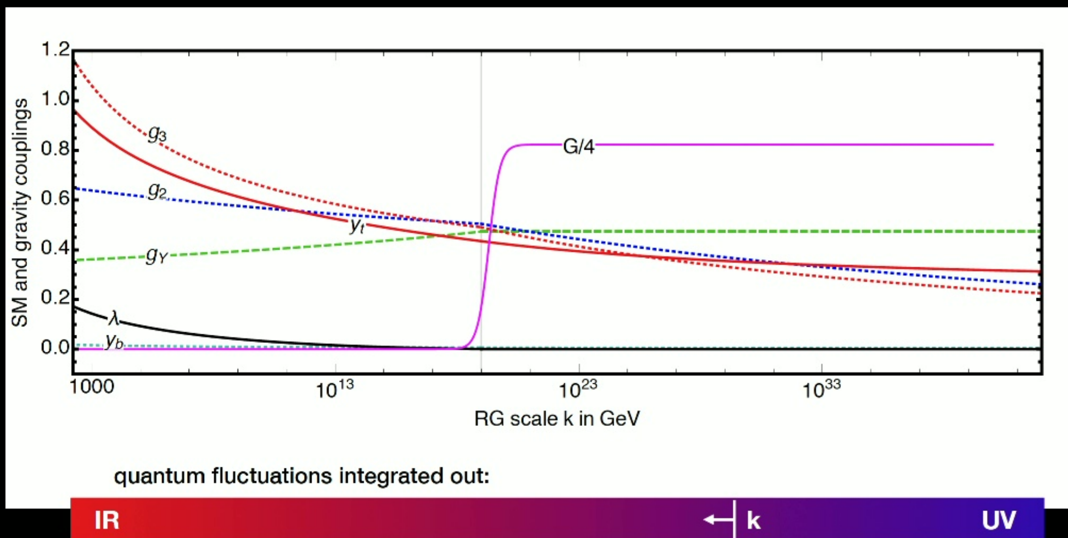


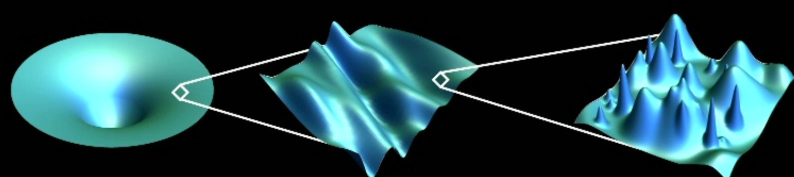
Predictive power of asymptotic safety: Concept

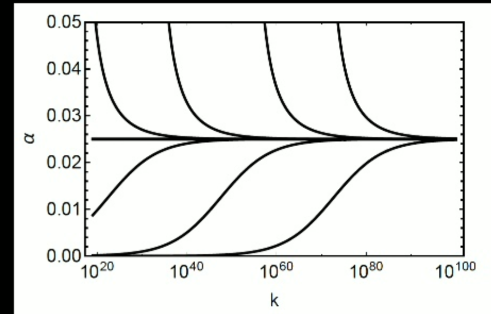
matter regime

dynamical decoupling of quantum gravity fluctuations

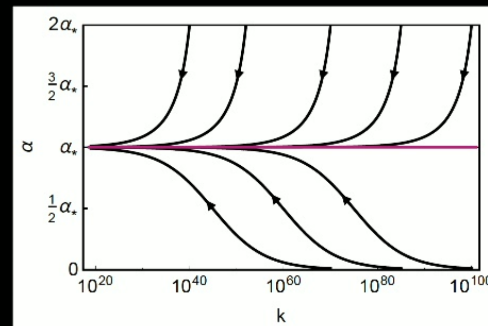
quantum scale invariant regime







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



quantum fluctuations drive coupling **towards** scale symmetry

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

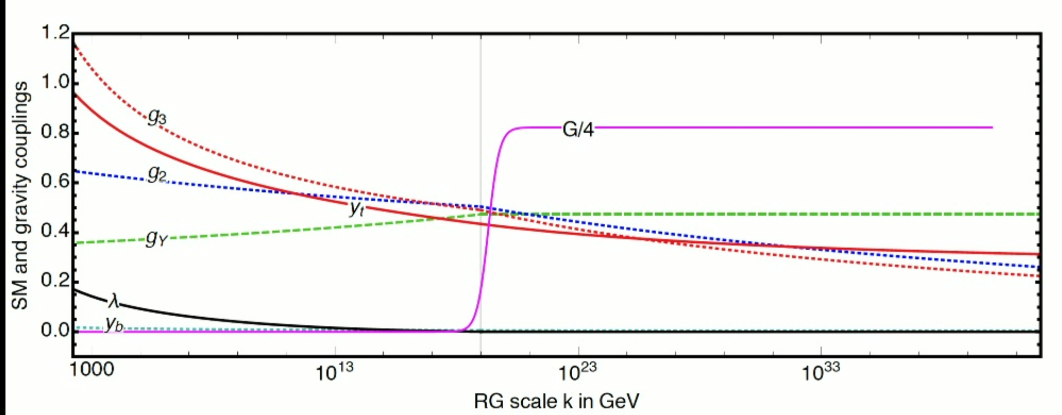
[AE, Held '22]

Predictive power of asymptotic safety: Concept

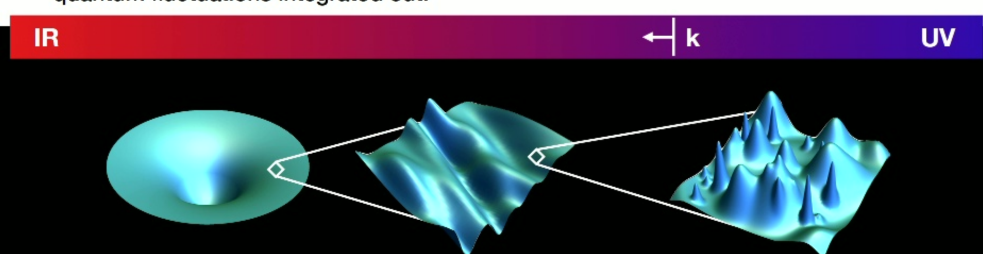
matter regime

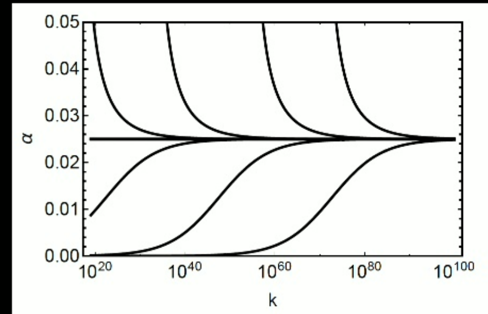
dynamical decoupling of quantum gravity fluctuations

quantum scale invariant regime

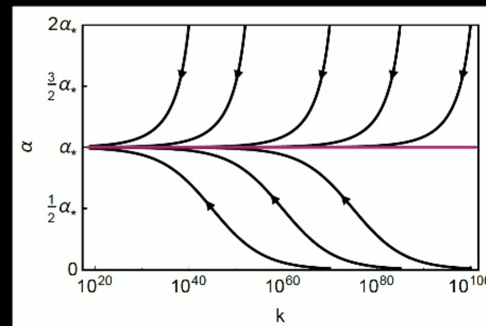


quantum fluctuations integrated out:





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



quantum fluctuations drive coupling **towards** scale symmetry

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]

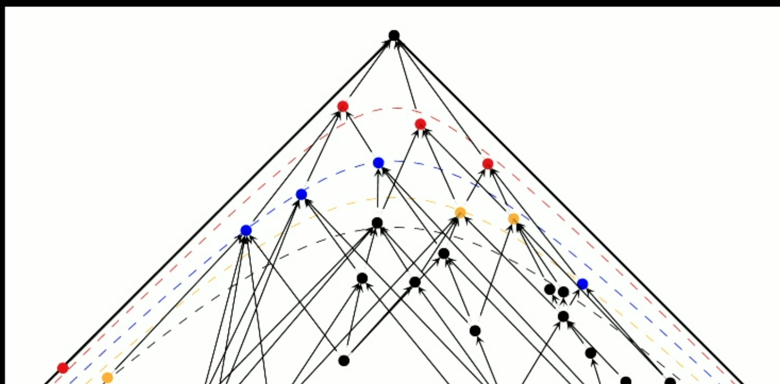
Bottom Yukawa coupling determines b- quark mass

[AE, Held '18]

Neutrino Yukawa couplings determine tiny neutrino masses

[AE, Held '22]

Towards an upper bound on the Higgs mass from causal set quantum gravity



Causal set:
discrete, Lorentzian approach: spacetime as a causal network

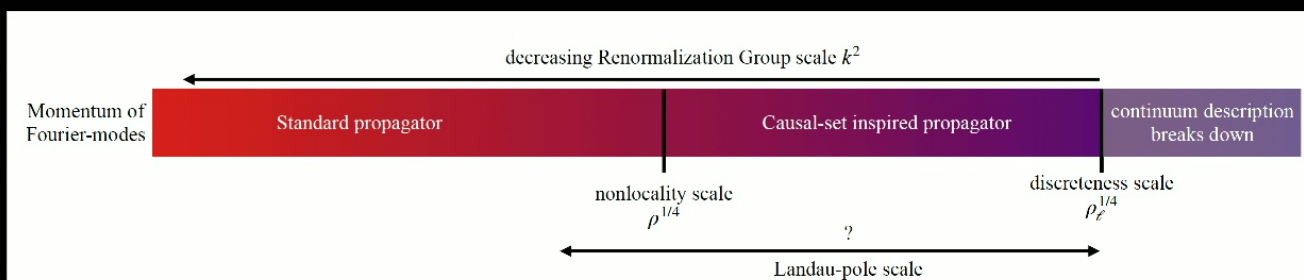
Propagator for a scalar field: [Sorkin '07]
summing over (causal) nearest neighbors

Average over different sprinklings into Minkowski spacetime:

propagator $\sim 1/p^2$ in the IR and $\sim \text{const} - \dfrac{1}{p^4}$ in the UV

use functional RG techniques to calculate running of the quartic scalar coupling

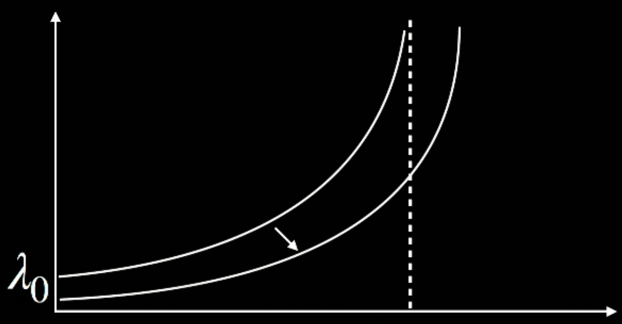
[de Brito, AE, Fausten, to appear]



Towards an upper bound on the Higgs mass from causal set quantum gravity

standard local QFT:

Landau pole in quartic coupling



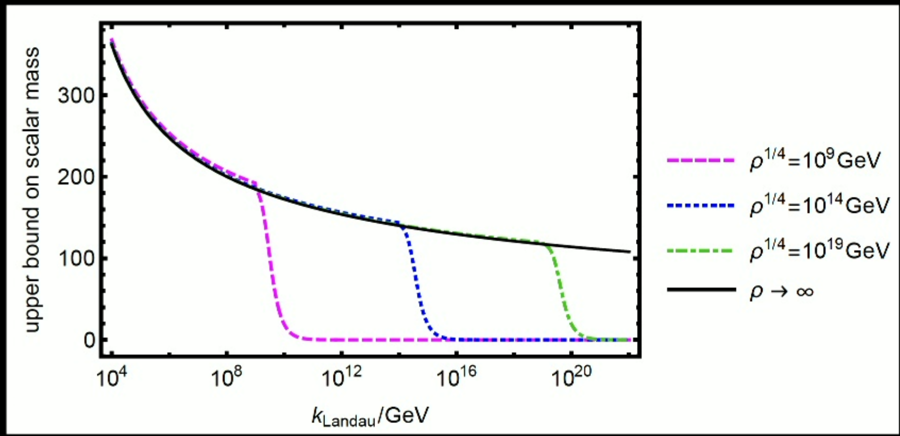
To shift k_{Landau} further into the UV, must lower λ_0.

Mass of the scalar $M = 3\lambda_0 v$

$\Rightarrow$ the further the theory extends into the UV, the lower the scalar mass

causal-set inspired case:

Landau pole in quartic coupling persists

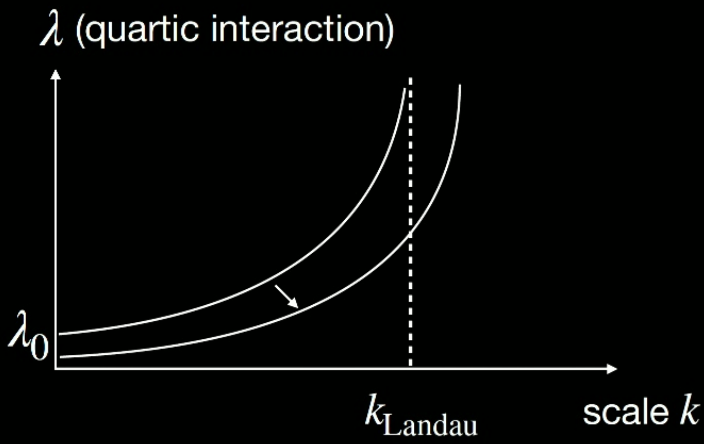


$$k_{\text{Landau}} \gtrsim \rho^{1/4}$$

Towards an upper bound on the Higgs mass from causal set quantum gravity

standard local QFT:

Landau pole in quartic coupling



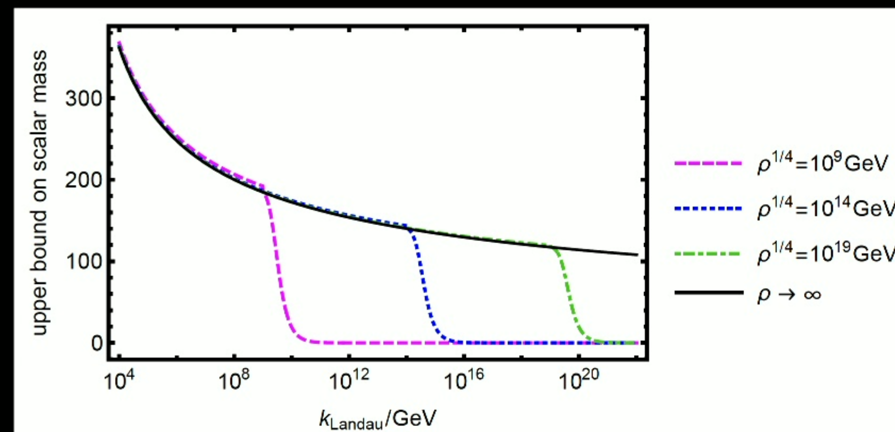
To shift $k_{\rm Landau}$ further into the UV, must lower λ_0.

Mass of the scalar $M = 3\lambda_0 v$

$\Rightarrow$ the further the theory extends into the UV, the lower the scalar mass

causal-set inspired case:

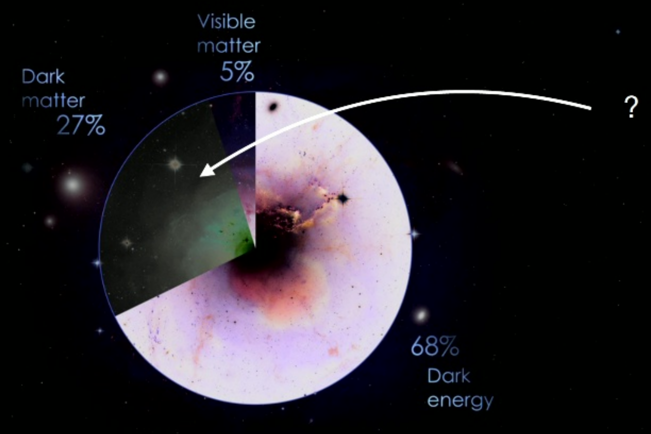
Landau pole in quartic coupling persists



$$k_{\rm Landau} \gtrsim \rho^{1/4}$$

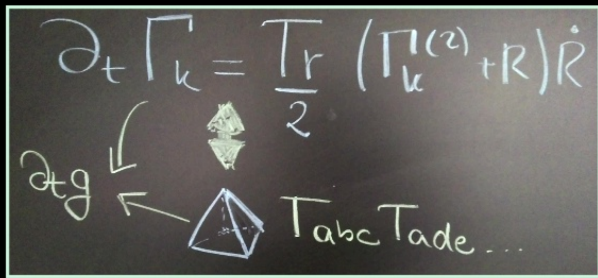
Outlook: including the other fields of the Standard Model will result in upper bound on Higgs mass as a function of ρ

Quantum gravity and particle physics beyond the Standard Model



Asymptotic safety and the dark sector

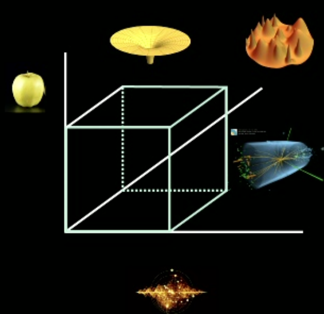
Summary:



theory

necessary
link in physics

experiment/observation



Is the Planck scale really the scale of quantum gravity?

1) be agnostic and constrain new-physics scale $\ell_{\rm NP}$

2) be pessimistic and find leverarms that make $\ell_{\rm Planck}$ accessible in observations