# Quantum Schwarzschild-(A)dS and Kerr-(A)dS Spacetimes

**Hot Topics in Modern Cosmology, Cargèse 2018**

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# Asymptotic Safety as Quantum Gravity Scenario

- Gravity perturbatively non-renormalisable (Hooft and Veltman 1974), (Goroff and Sagnotti 1986)

**Asymptotic Safety Scenario (Weinberg 1980)**

Quantum gravity described as predictive, effective field theory, valid at all energy scales

- Predictivity: ensured by the existence of a non-trivial UV fixed point (with finitely many UV-attractive directions)
- Exact equation for the flow of effective action $\Gamma_k$ for gravity (Reuter 1998)
- General Relativity contained as IR-limit of fundamental quantum action: $\Gamma_{k\to 0} \to S_{\mathrm{GR}}$

review paper e.g. (Niedermaier and Reuter 2006)

# Black Holes in Asymptotic Safety

- Extract momentum dependent running gravitational $G(k)$ and cosmological coupling $\Lambda(k)$ from flow eq.
- Ansatz: take a classical solution $g_{\mu\nu}$ and replace Newton's and the cosmological constant by functions $G_0 \to G(r)$ & $\Lambda_0 \to \Lambda(r)$, **modeling** quantum gravity effects
- Introduce scale identification $k(r)$ to translate

$$G(k), \Lambda(k) \quad \xleftrightarrow{k(r)} \quad G(r), \Lambda(r)$$

## Quantum Improved Spacetimes

**Classial solution** $g_{\mu\nu}$ equipped with **running couplings** $G(k)$ & $\Lambda(k)$ from flow eq. and a **scale identification** $k(r)$

e.g. Bonanno and Reuter 2000, Koch and Saueressig 2014, Bonanno and Saueressig 2017, Bonanno and Reuter 2006

# Set-up of this Work

- Assume the following analytical runnings:

$$G(k) = \frac{G_0}{1 + \frac{G_0}{g_*} k^2} \quad , \quad \Lambda(k) = \Lambda_0 + \lambda_* k^2$$

- Scale identification based on the classical Kretschmann scalar:

$$k(r) = \xi \left(K - K_\infty\right)^{1/4} \quad , \quad \xi = \text{const}$$

$$K = \frac{8}{3}\Lambda^2(r) + \frac{48M^2}{r^6} G^2(r)$$

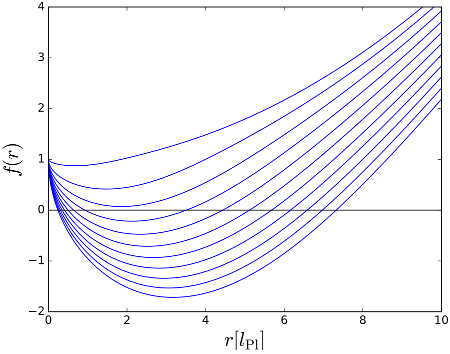
Now: study quantum improved **Schwarzschild-(A)dS** and **Kerr-(A)dS** geometries

# Horizons

Horizons are solutions of

$$1 - \frac{2MG(r)}{r} - \frac{\Lambda(r)}{3} r^2 \overset{!}{=} 0 \qquad \text{Schwarzschild-(A)dS}$$

$$(r^2 + a^2)(1 - \frac{\Lambda(r)}{3}) - 2MG(r)\, r \overset{!}{=} 0 \qquad \text{Kerr-(A)dS}$$

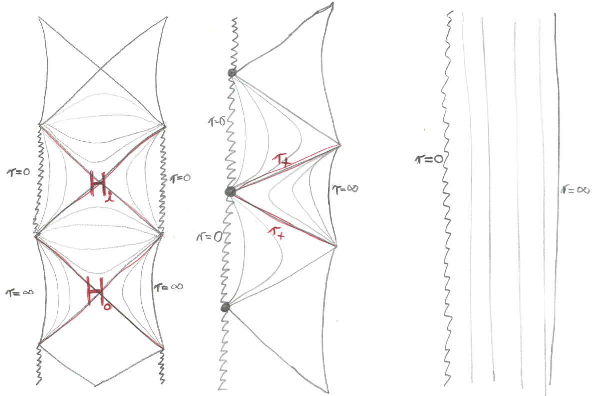



Schwarzschild-AdS as function of mass $M$

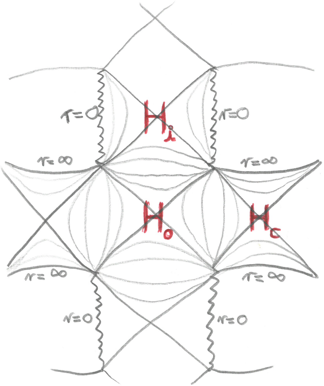
# Penrose Diagrams (AdS)

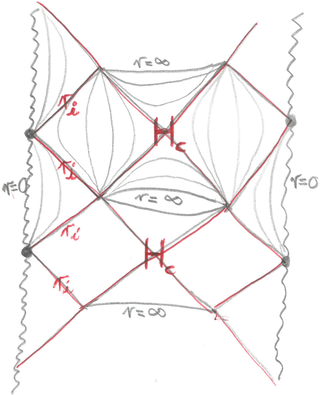
## Results:

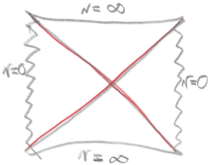
- Formal construction identical to classical Reissner-Nordström-(A)dS
- Same causal structure for Schwarzschild & Kerr geometry



# Penrose Diagrams (dS)



# Curvature Singularity

- Quantum gravity expected to alter singularity; so far: change from spacelike → timelike for Schwarzschild

**Leading order divergences of the Ricci and Kretschmann Scalars:**

| | $R$ | $K$ |
|---|---|---|
| classical Schwarzschild-(A)dS & Kerr-(A)dS | $4\Lambda_0$ | $\sim r^{-6}$ |
| quantum Schwarzschild-(A)dS | $\sim r^{-3/2}$ | $\sim r^{-3}$ |

⇒ **Weakening of the singularity**, but no resolution!

- $R \neq 0$, because running coupling create an effective stress energy tensor

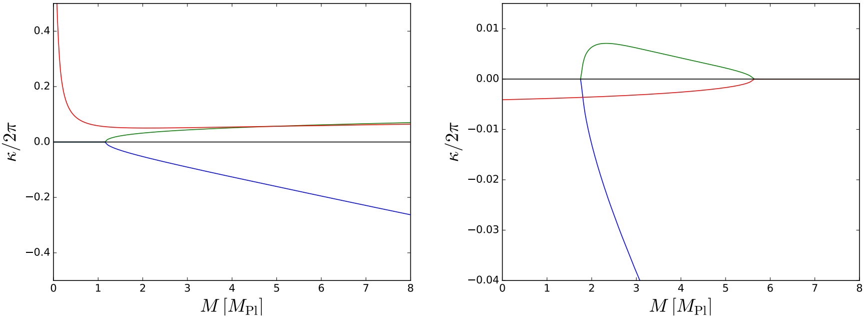
# Hawking Temperatures & Black Hole Evaporation

- The horizons can be shown to be Killing horizons $\Rightarrow$ constant surface gravity $\kappa$
- Observer in the static spacetime region with Killing vector field $K$ sees temperature

$$T_{\mathrm{H}}(r) = \frac{\kappa}{2\pi} \frac{1}{\sqrt{g(K,K)}}$$

- $\kappa$ proportional to $f'$ and $\Delta'$ evaluated at the horizon

# Hawking Temperatures & Black Hole Evaporation




## Endpoint of Evaporation Process:

Smallest, extremal black hole of Planck mass, with $T_{\mathrm{H}} = 0$
$\Rightarrow$ **Remnant**

# Conclusions

- Scale identifications based on proper distance integrals suffer from unphysical features → matching based on (classical) Kretschmann scalar
- Quantum effects lead to a unified causal structure for Schwarzschild- & Kerr-(A)dS; but massive particles travel differently
- Weakening of central curvature singularity, which is timelike in both geometries
- Endpoint of black hole evaporation a stable, cold, extremal, Planck sized black hole remnant
- All studied properties match the GR-result in the classical limit

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Pawlowski and Stock (in prep.)