IMPROVED EFFECTIVE DYNAMICS OF LOOP-QUANTUM-GRAVITY BLACK HOLE AND NARIAI LIMIT

Hongguang Liu (FAU Erlangen)

KTWiG

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In collaboration with Muxin Han

LQG Black Hole and Nariai Limit

- We propose a new model of the spherical symmetric LQG black hole with infinitely many DOFs and study the effective dynamics of both interior and exterior of the black hole
- Classical limit is recovered in low curvature regime. The black hole singularity is resolved and replaced by the non-singular bounce
- After the bounce, the evolution stabilizes asymptotically to the charged Nariai limit $dS_2 \times S^2$
- Black hole evaporation and the quantum tunneling proposes a scenario of BH--WH transition on $dS_2 \times S^2$
- $dS_2 \times S^2$ have infinite zero mode quantum degeneracy: an example of Wheeler's bag of gold

Reduced Phase Space Formulation

Couple gravity and standard matter fields to clock fields at classical level

Gaussian dust (GD)

[Kuchar and Torre 90
[Giesel and Thiemann 15

$$S_{\mathrm{GD}}\left[\rho, g_{\mu\nu}, T, S^j, W_j\right] = -\int_M \mathrm{d}^4 y \sqrt{|\det(g)|}\left[\frac{\rho}{2}\left(g^{\mu\nu}\partial_\mu T \partial_\nu T + 1\right) + g^{\mu\nu}\partial_\mu T\left(W_j \partial_\nu S^j\right)\right]$$

heat-conducting dust fluid

T, S^j clock fields
ρ, W^j Lagrange multipliers

Dirac observables = parametrizing gravity variables with values of dust fields

$T(x) \equiv \tau$ — τ physical time variable

$S^j(x) \equiv \sigma^j$ — σ^j physical space variable

[Rovelli, Dittrich,Thiemann...

Reduced Phase Space

Gravity Dirac observables

$$A(\tau,\sigma) = A(x)|_{T(x)=\tau, S^j(x)=\sigma^j}\,, \qquad E(\tau,\sigma) = E(x)|_{T(x)=\tau, S^j(x)=\sigma^j}$$

SU(2) Ashtekar-Barbero connection $A = \beta K + \Gamma$ Densitized triad

$$\{E^i_a(\sigma,t), A^b_j(\sigma',t)\} = -\frac{1}{2}\kappa\beta\ \delta^i_j \delta^b_a \delta^3(\sigma,\sigma') \qquad \kappa = 16\pi G$$

Physical Hamiltonian:

Gaussian dust

$$\mathbf{H}_0 = \int_{\mathcal{S}} \mathrm{d}^3\sigma\, \mathcal{C}(\sigma) \qquad \mathcal{C}^{GR} = \frac{1}{\kappa}\left[F^a_{jk} - \left(\beta^2+1\right)\varepsilon_{ade} K^d_j K^e_k\right]\varepsilon^{abc}\frac{E^j_b E^k_c}{\sqrt{\det(q)}} + \frac{2\Lambda}{\kappa}\sqrt{\det(q)}$$

$$\mathcal{C}^{GR}_a = \frac{2}{\kappa\beta} F^b_{jk}\frac{E^k_b E^j_a}{\sqrt{\det(q)}}.$$

Classical EoMs:

$$\frac{\mathrm{d}f}{\mathrm{d}\tau} = \{\mathbf{H}_0, f\}\,, \quad \mathbf{H}_0 = \int_\delta d^3\sigma h$$

Black holes: symmetry reduction

Dust space with $\mathcal{S} \simeq \mathbb{R} \times S^2$ with coordinate $\sigma = (x, \theta, \phi)$

[Chiou, Ni and Tang 2012
[Gambini, Olmedo, Pullin 2013

Gauss constraint is solved with gauge fixing s.t. E is diagonal:

$$E_1^1(\sigma) = E^x(x)\sin(\theta), \quad E_2^2(\sigma) = E^\varphi(x)\sin(\theta), \quad E_3^3(\sigma) = E^\varphi(x),$$
$$A_1^1(\sigma) = 2\beta K_x(x), \quad A_2^2(\sigma) = \beta K_\varphi(x), \quad A_3^3(\sigma) = \beta K_\varphi(x)\sin(\theta),$$
$$A_3^1(\sigma) = \cos(\theta), \quad A_3^2(\sigma) = -\sin(\theta)\tfrac{E^{x\prime}(x)}{2E^\varphi(x)}, \quad A_2^3(\sigma) = \tfrac{E^{x\prime}(x)}{2E^\varphi(x)}.$$

Symplectic structure

$$\Omega = -\frac{2}{\kappa\beta}\int \mathrm{d}^3\sigma \left[\delta A_j^a(\sigma) \wedge \delta E_a^j(\sigma)\right] = -\frac{16\pi}{\kappa}\int \mathrm{d}x \left[\delta K_x(x) \wedge \delta E^x(x) + \delta K_\varphi(x) \wedge \delta E^\varphi(x)\right],$$

Canonical structure:

$$\{K_x(x), E^x(x')\} = G\delta(x - x'), \quad \{K_\varphi(x), E^\varphi(x')\} = G\delta(x - x').$$

Metric is given by:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \Lambda(t,x)^2\mathrm{d}x^2 + R(t,x)^2\left[\mathrm{d}\theta^2 + \sin^2(\theta)\mathrm{d}\varphi^2\right], \quad \Lambda = \frac{E^\varphi}{\sqrt{|E^x|}}, \quad R = \sqrt{|E^x|}.$$

Black holes: symmetry reduction

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \Lambda(t,x)^2\mathrm{d}x^2 + R(t,x)^2\left[\mathrm{d}\theta^2 + \sin^2(\theta)\mathrm{d}\varphi^2\right], \quad \Lambda = \frac{E^\varphi}{\sqrt{|E^x|}}, \quad R = \sqrt{|E^x|}.$$

Physical Hamiltonian:

$$E^{x\prime} \equiv \partial_x E^x$$

$$\begin{aligned}
\mathbf{H}_0 &= \int dx\, \mathcal{C}(x), \\
\mathcal{C}(x) &= \frac{4\pi}{\kappa}\frac{\mathrm{sgn}(E^\varphi)}{\sqrt{|E^x|}}\left(-\frac{2E^xE^{x\prime}E^{\varphi\prime}}{E^{\varphi 2}} + \frac{4E^xE^{x\prime\prime} + E^{x\prime 2}}{2E^\varphi} - 8E^xK_xK_\varphi - 2E^\varphi\left[{K_\varphi}^2 + 1\right]\right).
\end{aligned}$$

The time evolution by $\boldsymbol{H_0}$ has infinitely many conserved charges from spatial diffeomorphisms,

$$\begin{aligned}
\mathcal{V}(N) &= \int \mathrm{d}x N(x)\mathcal{C}_x(x) \quad \{\mathbf{H}_0, \mathcal{V}(N)\} = 0 \\
\mathcal{C}_x(x) &= E^\varphi(x)K_\varphi'(x) - K_x(x)E^{x\prime}(x)
\end{aligned}$$

$\mathcal{C}(x)$ conserved charge when $\mathcal{C}_x(x) = 0$

1+1 dim field theory which contain infinitely many DOFs.

different from homogeneous Kantowski-Sachs models

Black holes: symmetry reduction

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \Lambda(t,x)^2\mathrm{d}x^2 + R(t,x)^2\left[\mathrm{d}\theta^2 + \sin^2(\theta)\mathrm{d}\varphi^2\right], \quad \Lambda = \frac{E^\varphi}{\sqrt{|E^x|}}, \quad R = \sqrt{|E^x|}.$$

Physical Hamiltonian:

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[Geisel, Tambornino, Thiemann 10'

General solutions of EoMs $\frac{\mathrm{d}f}{\mathrm{d}t} = \{f, \mathbf{H}_0\}$ Lemaitre-Tolman-Bondi (LTB) spacetime.

$$\Lambda(x)^2 = \frac{\left[\partial_x R(t,x)\right]^2}{1+\mathcal{E}(x)}, \quad \partial_t R(t,x) = \pm\sqrt{\mathcal{E}(x) + \frac{\mathcal{F}(x)}{R(t,x)}}$$

$\mathcal{F}$ gravitation mass
$\mathcal{E}$ unit mass energy of dust

Lemaitre-type coordinates, t, x

Schwarzschild solution is given when

arbitrary function (can be taken as x)

$$\mathcal{E}(x) = 0: \qquad R(t,x) = \left[\frac{3}{2}\sqrt{\mathcal{F}(x)}\left(\boxed{f(x)} - t\right)\right]^{2/3}, \qquad \mathcal{F} = R_s = 2GM$$

$f(x) = t$ classical singularity

Improved Hamiltonian

A $\bar{\mu}$-scheme regularization from fixed-edge-length holonomies $h_\Delta(A_1^1), h_\Delta(A_2^2), h_\Delta(A_3^3)$

$$K_\varphi(x) \to \frac{\sqrt{|E^x|}}{\beta\sqrt{\Delta}} \sin\left[\frac{\sqrt{\Delta}}{\sqrt{|E^x|}}\beta K_\varphi(x)\right], \quad K_x(x) \to \frac{E^\varphi}{2\beta\sqrt{\Delta}\sqrt{|E^x|}} \sin\left[\frac{\sqrt{\Delta}\sqrt{|E^x|}}{E^\varphi} 2\beta K_x(x)\right].$$

s.t. they give the fixed area Δ to every plaquette

The effective Physical Hamiltonian:

[Chiou, et al 2012,
[Bojowald and Swiderski 2005,
[Gambini, Olemedo, Pullin,
...

$$\begin{aligned}
\mathbf{H}_\Delta &= \int_{-\infty}^{\infty} dx\, \mathcal{C}_\Delta(x), \\
\mathcal{C}_\Delta(x) &= \frac{4\pi}{\kappa}\frac{\mathrm{sgn}(E^\varphi)}{\sqrt{|E^x|}}\Bigg(-\frac{2E^x E^{x\prime} E^{\varphi\prime}}{E^{\varphi 2}} + \frac{4E^x E^{x\prime\prime} + E^{x\prime 2}}{2E^\varphi} \\
&\quad -\frac{4E^x E^\varphi}{\beta^2\Delta} \sin\left[\frac{\sqrt{\Delta}\sqrt{|E^x|}}{E^\varphi} 2\beta K_x(x)\right] \sin\left[\frac{\sqrt{\Delta}}{\sqrt{|E^x|}}\beta K_\varphi(x)\right] - \frac{2E^\varphi |E^x|}{\beta^2\Delta}\sin^2\left[\frac{\sqrt{\Delta}}{\sqrt{|E^x|}}\beta K_\varphi(x)\right] - 2E^\varphi\Bigg).
\end{aligned}$$

Boundary term: $\mathbf{H}_{bdy} = -\frac{8\pi}{\kappa}\left(\frac{\sqrt{E^x}E^{x\prime}}{E^\varphi} - 2\sqrt{E^x}\right)\Bigg|_{x=L>0}$

0 at $x \to +\infty$ if we impose asymptotically flatness (Schwarzschild bdy condition)
0 at $x \to -\infty$ we impose the Neumann boundary condition $E^{x\prime} \sim 0 \quad \text{as} \quad x \to -\infty$

$\mathcal{V}(N^x)$ are still conserved $\mathcal{C}_\Delta(x)$ does not

$$\mathcal{V}(N^x) = \int \mathrm{d}x N^x(x)\mathcal{C}_x(x) \quad \{\mathbf{H}_\Delta, \mathcal{V}(N)\} = 0$$

with $\mathcal{C}_x(x)$ not modified

Effective dynamics

EoMs from physical Hamiltonian:

Nonlinear PDEs for $K_x(t,x)$, $K_\varphi(t,x)$, $E_x(t,x)$, $E_\varphi(t,x)$

EoMs for $E_x > 0$ and $E_{\tilde{x}} < 0$ are related by spacetime inversion $\tilde{x} \to -x, \tilde{t} \to -t$ and

$$K_{\tilde{x}}(\tilde{t},\tilde{x}) = K_x(t,x),\ K_{\tilde{\varphi}}(\tilde{t},\tilde{x}) = -K_\varphi(t,x),\ E^{\tilde{x}}(\tilde{t},\tilde{x}) = -E^x(t,x),\ E^{\tilde{\varphi}}(\tilde{t},\tilde{x}) = E^\varphi(t,x)$$

Introducing $z = x - t$, ← Stationary solutions

z parametrizes the spatial slice when fixing t, parametrizes the time evolution when fixing x.

Nonlinear PDEs →

$$\frac{\mathrm{d}}{\mathrm{d}z}\begin{bmatrix} E^x \\ E^\varphi \\ K_1 \\ K_2 \end{bmatrix} = \begin{bmatrix} f^x\left(E^x, E^\varphi, K_1, K_2\right) \\ f^\varphi\left(E^x, E^\varphi, K_1, K_2\right) \\ f_1\left(E^x, E^\varphi, K_1, K_2\right) \\ f_2\left(E^x, E^\varphi, K_1, K_2\right) \end{bmatrix}.$$

1^{st} order ODEs

Initial values at $z = z_0 \gg 0$: Schwarzschild spacetime

$$E^x(z_0) = \left(\frac{3}{2}\sqrt{R_s} z_0\right)^{4/3}, \quad E^\varphi(z_0) = \sqrt{R_s}\left(\frac{3}{2}\sqrt{R_s} z_0\right)^{1/3},$$

$$K_x(z_0) = \frac{R_s}{3 \times 2^{2/3} 3^{1/3}\left(\sqrt{R_s} z_0\right)^{4/3}}, \quad K_\varphi(z_0) = -\frac{\left(\frac{2}{3}\right)^{1/3}\sqrt{R_s}}{\left(\sqrt{R_s} z_0\right)^{1/3}}$$

z= 0 singularity

Recall Schwarzschild solution in Lemaitre coordinate with $f(x) = x$

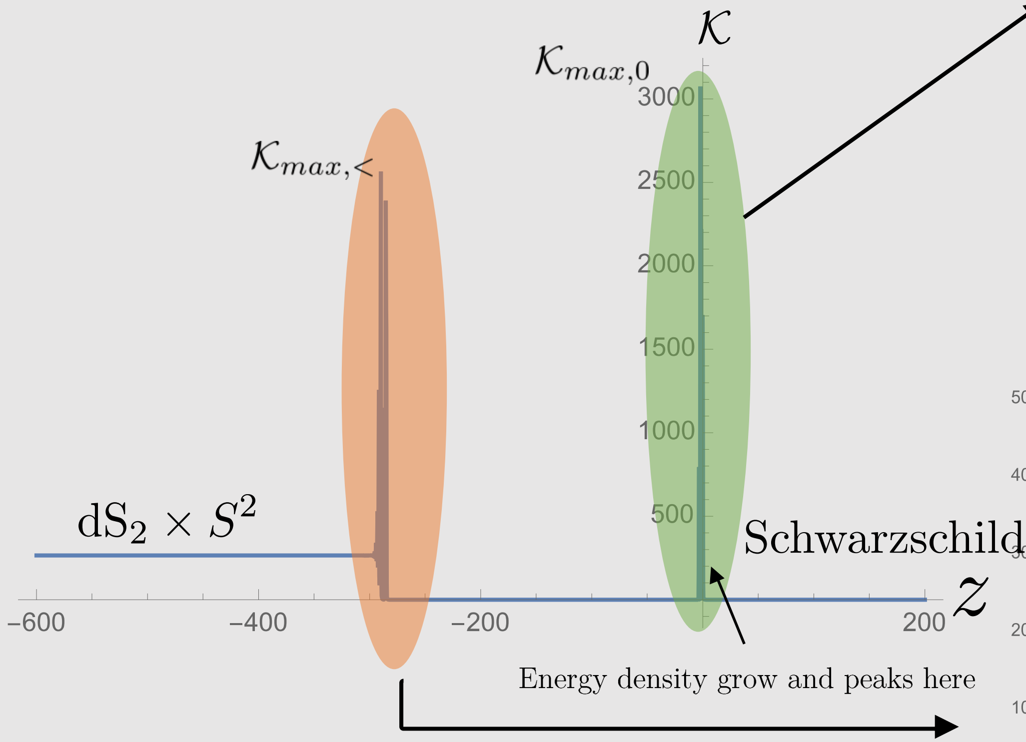
$$\frac{(E^\phi)^2}{|E^x|} = \Lambda^2 = (\partial_x R)^2 = R_s\left[\frac{3}{2}\sqrt{R_s}\,(x-t)\right]^{-2/3}, \quad \sqrt{|E^x|} = R = \left[\frac{3}{2}\sqrt{R_s}\,(x-t)\right]^{2/3}$$

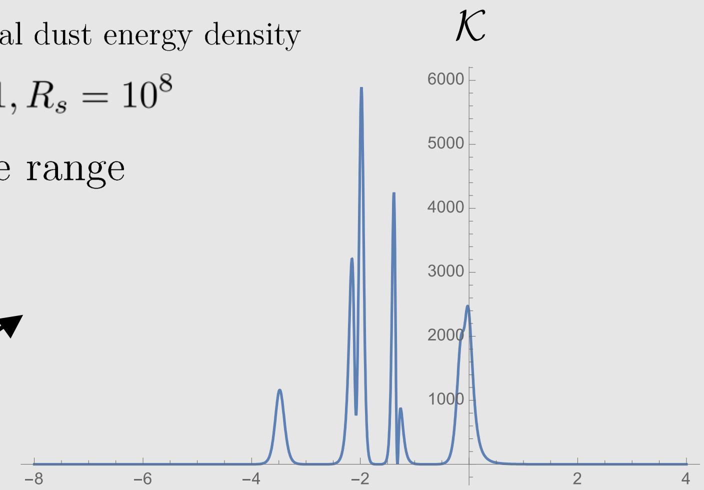
Numerical evaluation

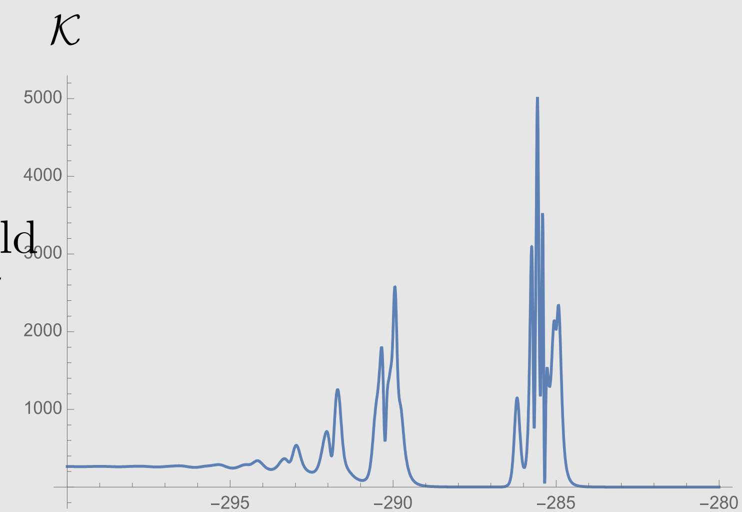
Evaluation with very tiny initial dust energy density

Numerical evaluation with $z_0 = 3 \times 10^8, \Delta = 0.1, \beta = 1, R_s = 10^8$

- The spacetime curvature is finite on the entire range
- Two local maxima for $\mathcal{K}$
- Asymptotically Schwarzschild and dS2

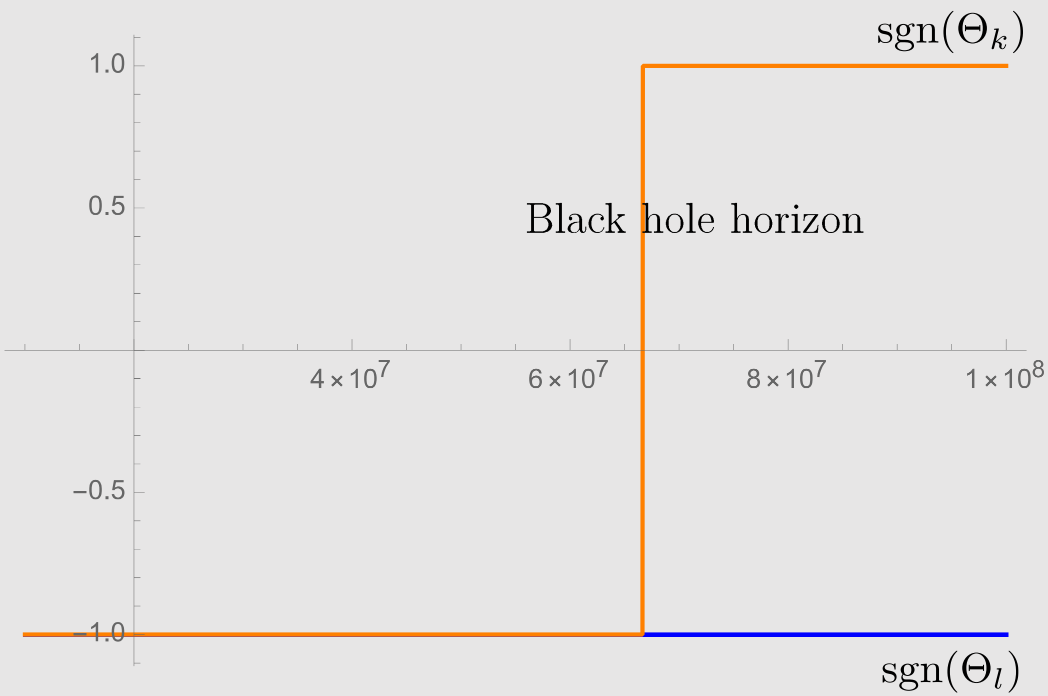






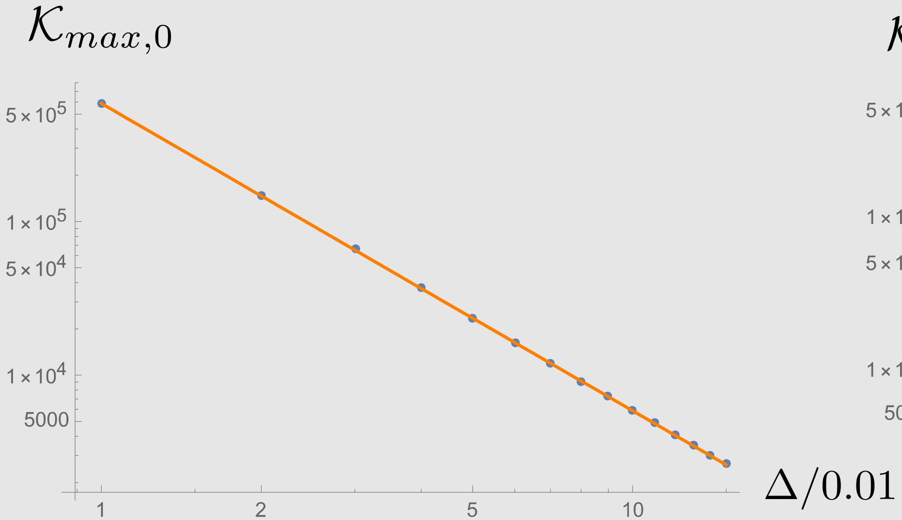
Numerical evaluation

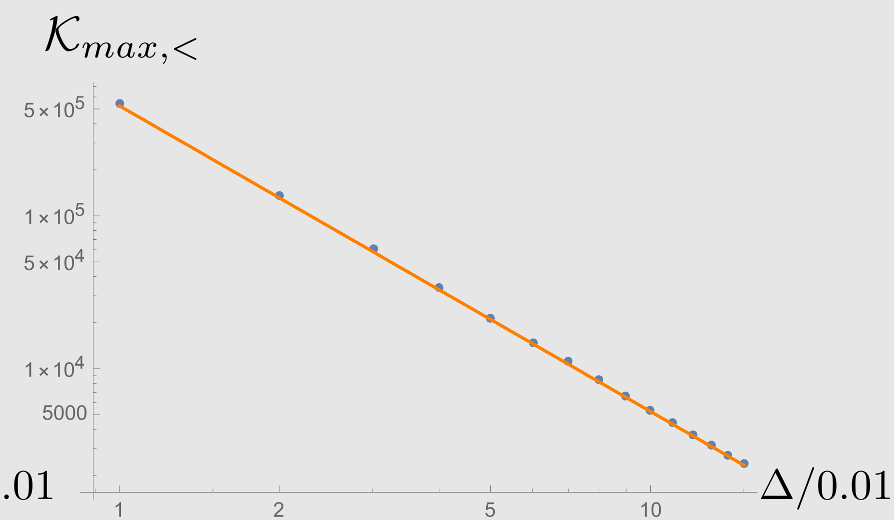
Null expansions



Quantum correction at the black hole horizon are negligible

Two local curvature maxima





$$\mathcal{K}_{max,0}\big|_{\beta=1} \simeq \frac{1}{\Delta^2} k_0(R_s), \quad \mathcal{K}_{max,<}\big|_{\beta=1} \simeq \frac{k_<(R_s)}{\Delta^2}\left[1 + \tilde{k}_<(R_s)\log(\Delta)\right]$$

$dS_2 \times S^2$ region $(z \to -\infty)$

The solution approaches $z \to -\infty$

$$E^x(z) \sim r_0^2, \quad \Lambda(z) = \frac{E^\varphi(z)}{\sqrt{E^x(z)}} \sim e^{-\alpha_1 - \alpha_0^{-1} z}, \quad z \to -\infty$$

S^2 Radius

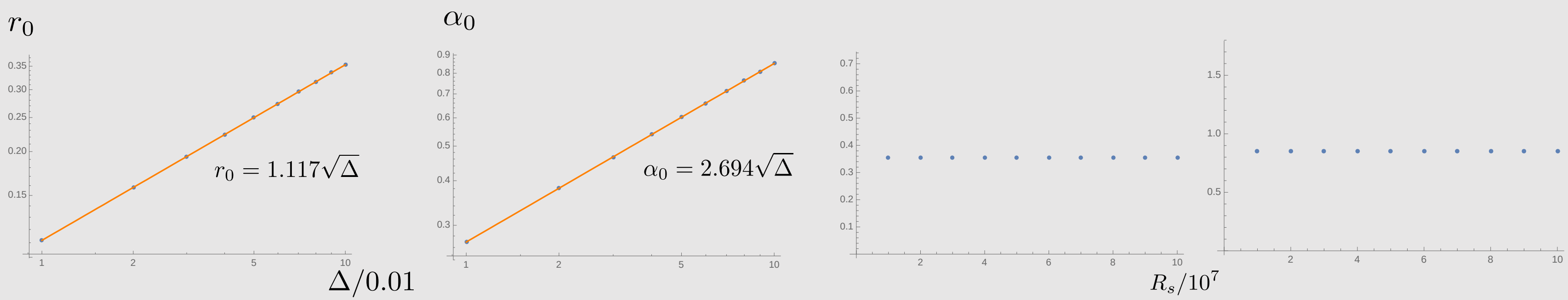
A $\mathrm{dS}_2 \times S^2$ metric: $\mathrm{d}s^2 \sim -\mathrm{d}t^2 + e^{-2\alpha_1 + 2\alpha_0^{-1}(t-x)}\mathrm{d}x^2 + r_0^2\left(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\varphi^2\right)$

dS_2 Radius

Quantum charged Nariai geometry

r_0, α_0 does not depend on R_s, and they are Planckian → stable under perturbation

$$r_0 \simeq 1.11724\Delta^{1/2}, \quad \alpha_0 \simeq 2.69371\Delta^{1/2}, \quad (\text{at } \beta = 1) \qquad \mathcal{K} \sim 4\left(\frac{1}{\alpha_0^4} + \frac{1}{r_0^4}\right) \simeq \frac{2.64325}{\Delta^2}$$



α_1 nonlinearly depend on both R_s and Δ

Quantum states $|r_0, \alpha_0; \alpha_1\rangle$ also depend also on α_1 → **infinite degeneracy**

$dS_2 \times S^2$ region $(z \to -\infty)$

The solution approaches $z \to -\infty$

$$E^x(z) \sim r_0^2, \quad \Lambda(z) = \frac{E^\varphi(z)}{\sqrt{E^x(z)}} \sim e^{-\alpha_1 - \alpha_0^{-1} z}, \quad z \to -\infty$$

S^2Radius

A $\mathrm{dS}_2 \times S^2$ metric: $\mathrm{d}s^2 \sim -\mathrm{d}t^2 + e^{-2\alpha_1 + 2\alpha_0^{-1}(t-x)}\mathrm{d}x^2 + r_0^2\left(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\varphi^2\right)$

dS_2 Radius

Quantum charged Nariai geometry

Similar geometries are found in Kantowski-Sachs black hole interior models

[Boehmer & Vandersloot 07' 08'
[Dadhich, Joe & Singh 15'

- Their $\bar{\mu}$-scheme model of black hole interior produce large quantum effect near the event horizon which is of low curvature

Quantum correction at the black hole horizon are negligible

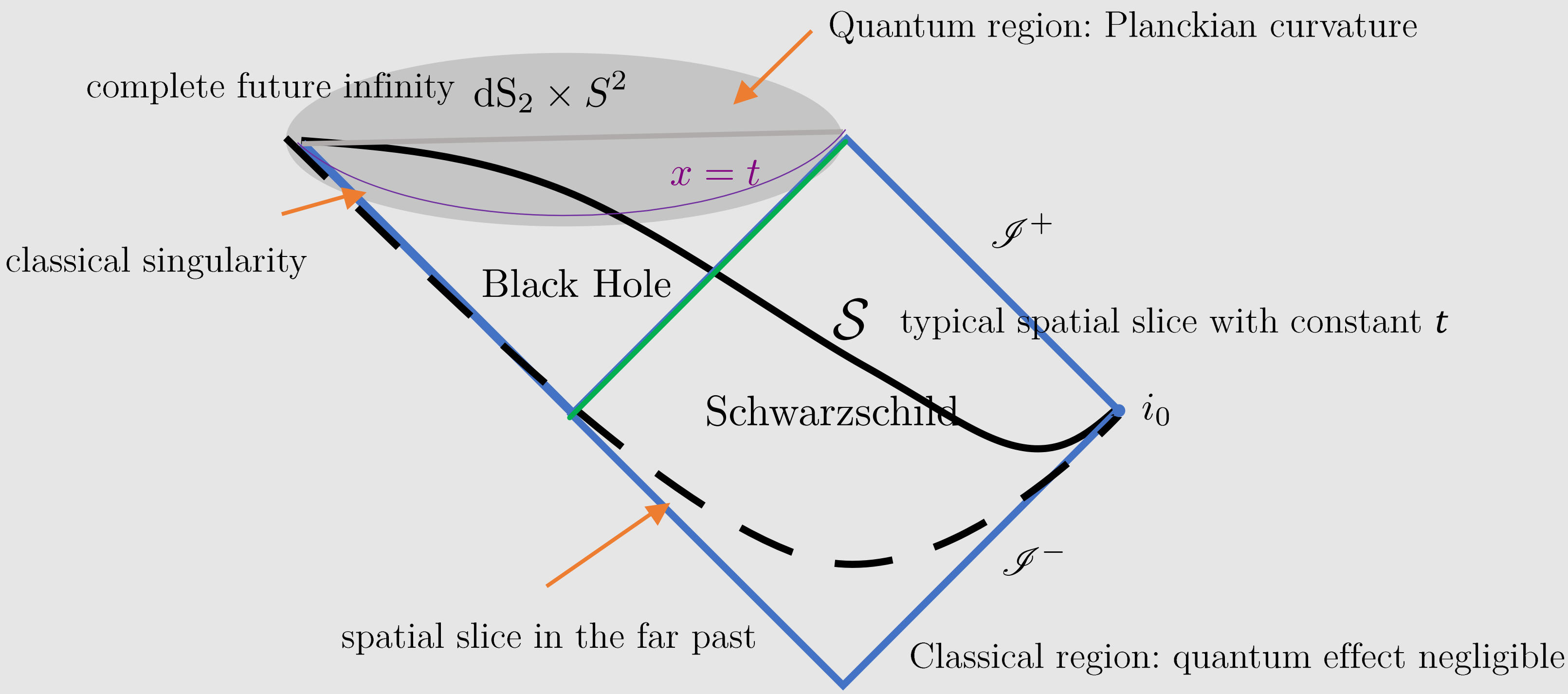
- The area of S^2 becomes smaller than the minimal area gap Δ at certain stage of the time evolution, inconsistent with the $\bar{\mu}$-scheme treatment of holonomies

We are free of these problems

S^2 area always larger than Δ

[Ashtekar, Olmedo & Singh 20'

Effective spacetime diagram

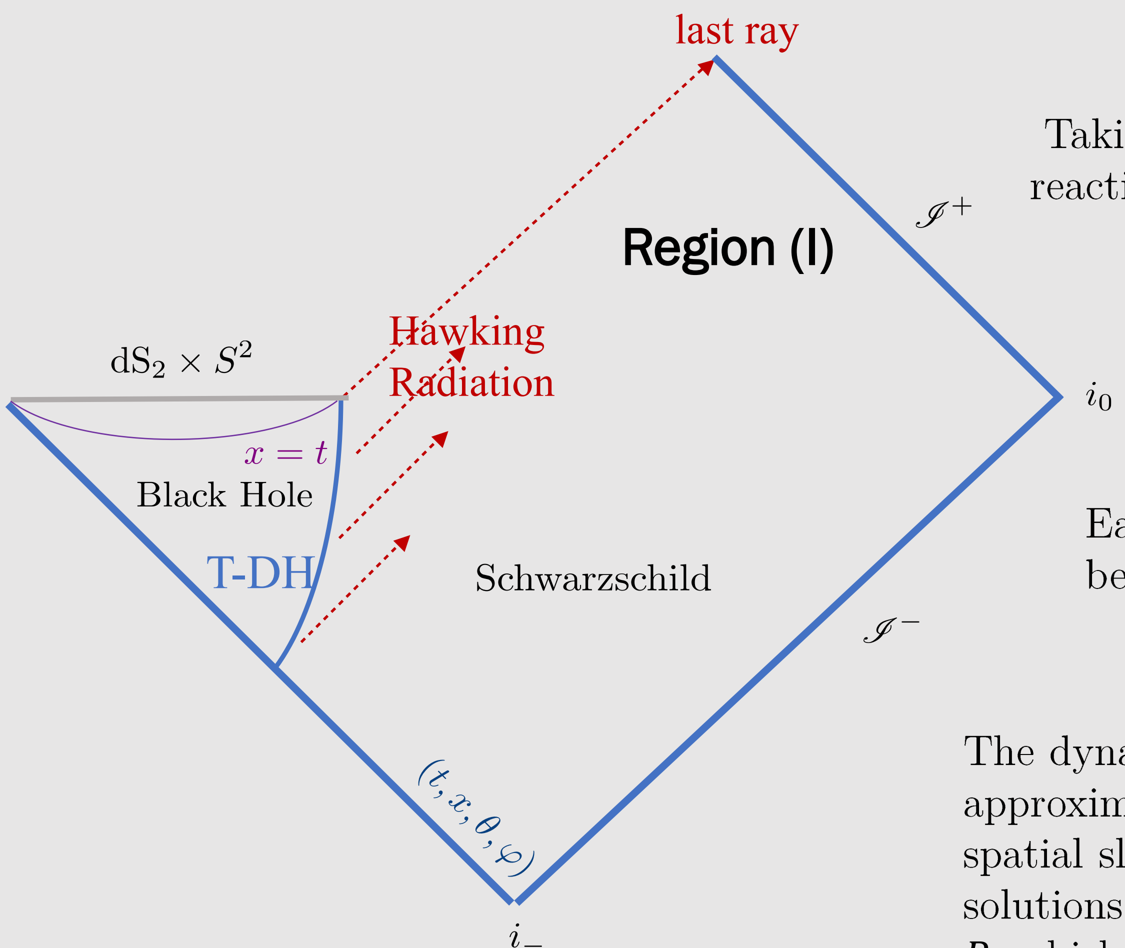


Linear perturbations are bounded from above:

$dS_2 \times S^2$ is stable classically but may be unstable quantum mechanically

Average null energy condition
from classical effective energy momentum tensor is violated by LQG effect

Black hole evaporation



trapping dynamical horizon (T-DH)

$$\Theta_k = 0, \Theta_l < 0$$

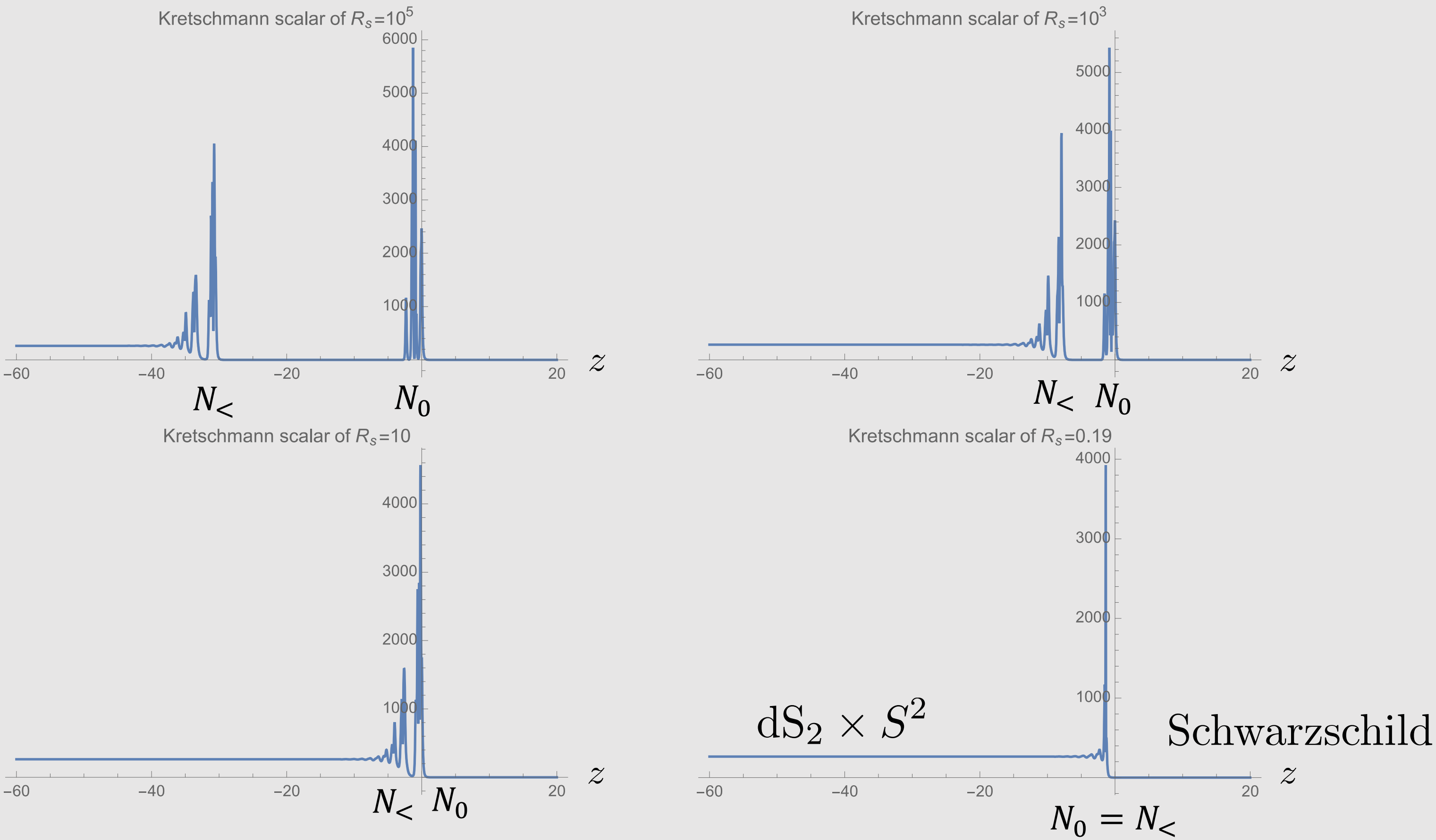
Taking into account the back-reaction from Hawking radiation

Slowly shrinking horizon

Each constant t_0 surface can be solved by effective EoMs

The dynamical black hole can be approximated by a large number of spatial slices carrying different solutions with different horizon radii R_s which is monotonically decrease as t growing.

Black hole evaporation

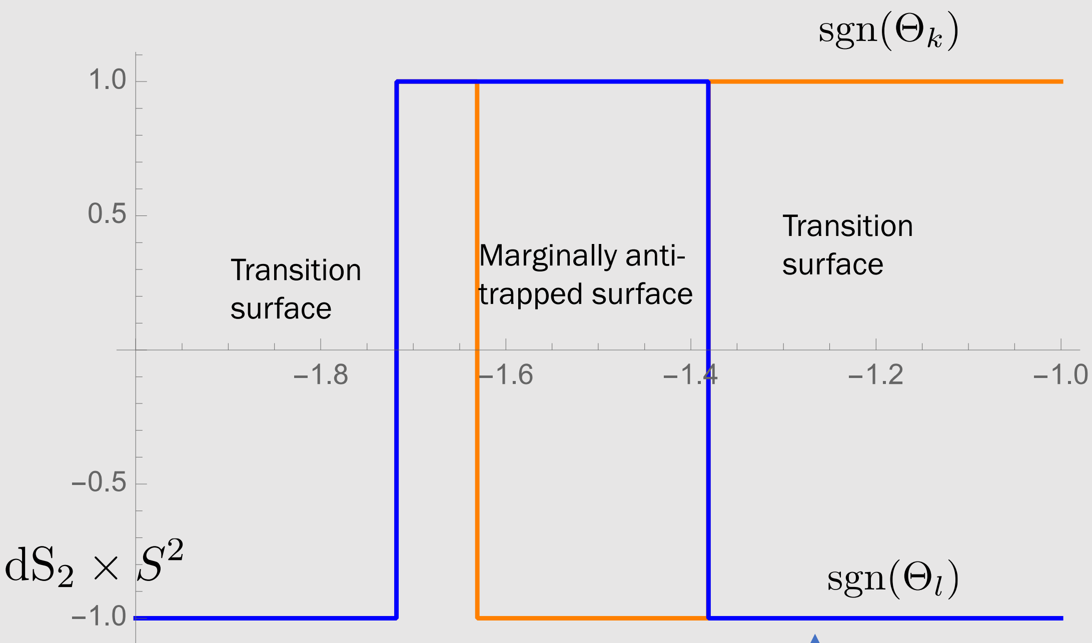


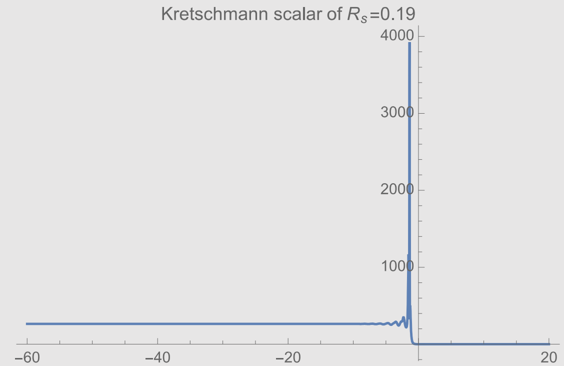
Domain wall?

Asymptotic $dS_2 \times S^2$ is invariant

Two neighborhoods $N_<$, N_0 become closer as R_s decreasing

Black hole evaporation





$N_0 = N_<$

Domain wall?

small fluctuations of geometry

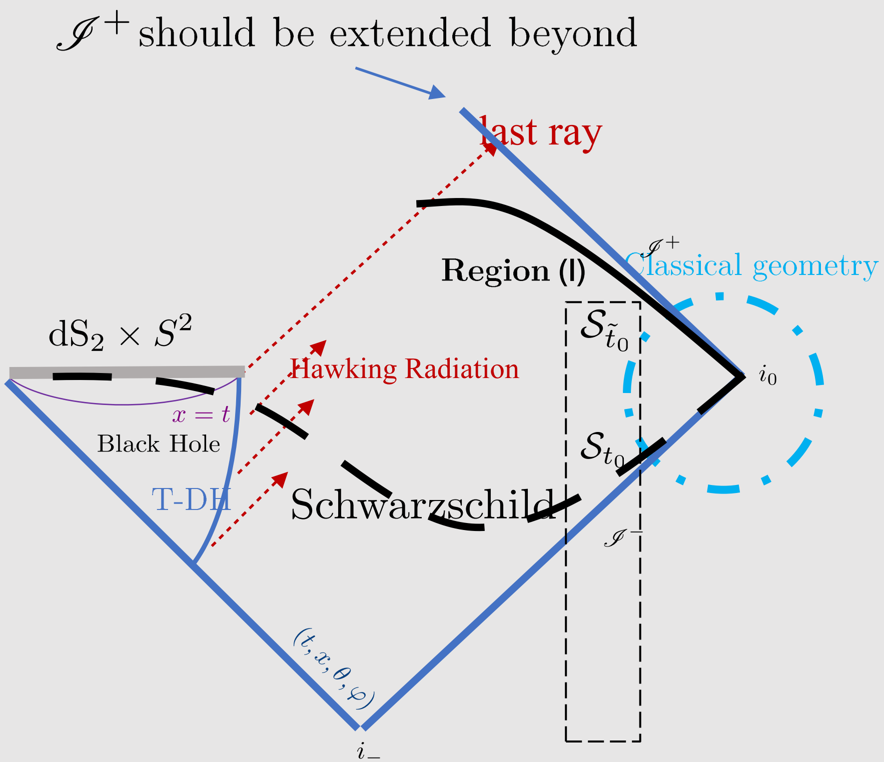
Trapping dynamical horizon disappears ⇒ Strong quantum effect
Hawking's derivation of evaporation fails

⇓

Full theory of LQG needed

$4\pi E^x > \Delta,\ 2\pi E^\varphi > \Delta$ self-consistent with $\bar{\mu}$ scheme

Black hole to white hole transition



The extension is derived using effective dynamics

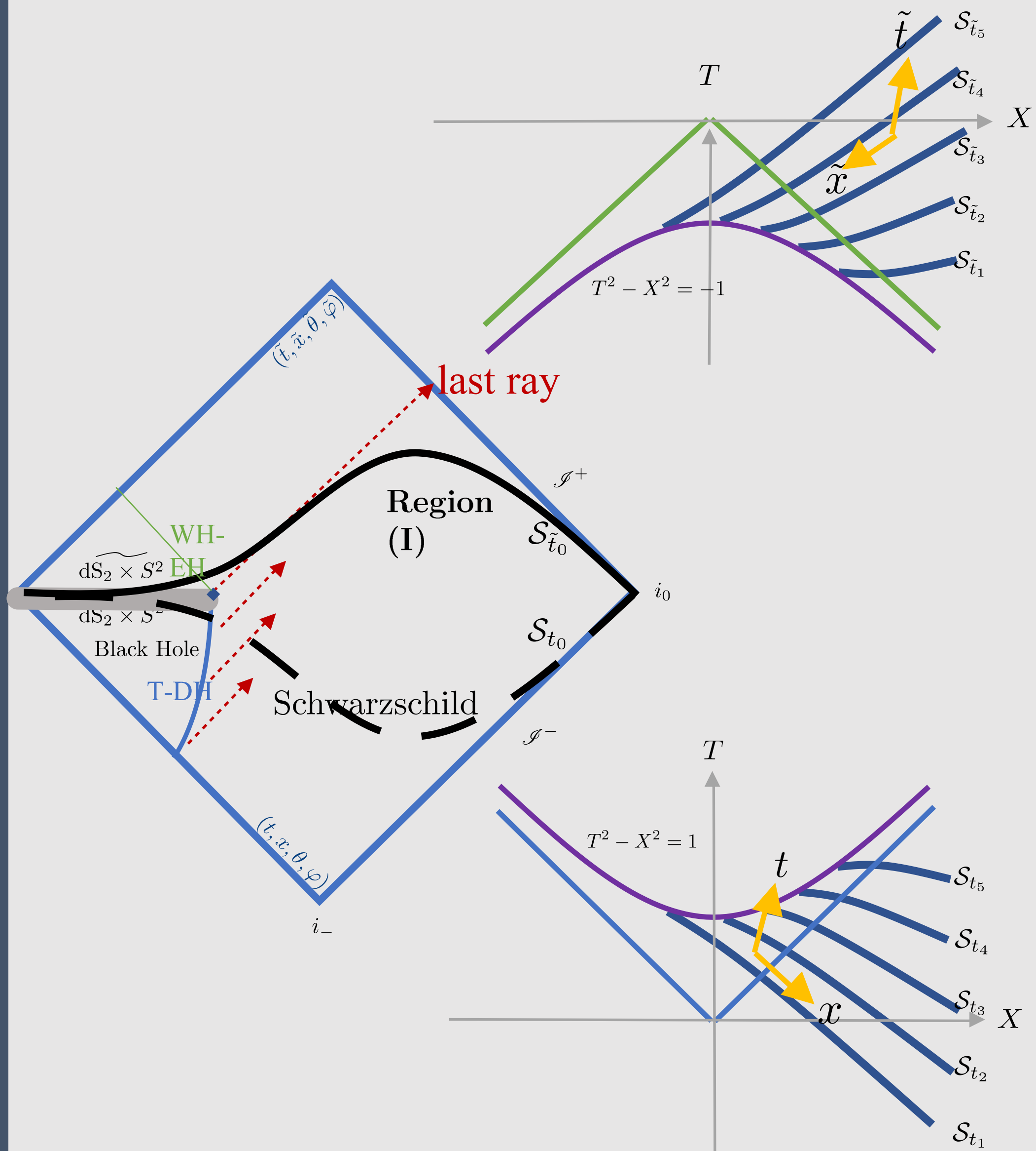
- The quantum dynamics in Region (I) near the spatial infinity i_0 can be well approximated by the quantum field theory on classical background spacetime. The dynamical effect is weak near i_0.
- For all spatial slices Region (I), their asymptotic (internal and external) geometries near the spatial infinity i_0 are classical and asymptotically flat. Their geometries are continuous extensions from geometries in the past.

$\mathcal{S}_{t_0}, \mathcal{S}_{\tilde{t}_0}$ asymptotic geometries coincide with each other, their ADM mass are approximately the same: remnant blackhole mass before Hawking radiation stops

Backreaction from Hawking radiation are ignored

[Haggard 14, Rovelli...

Black hole to white hole transition



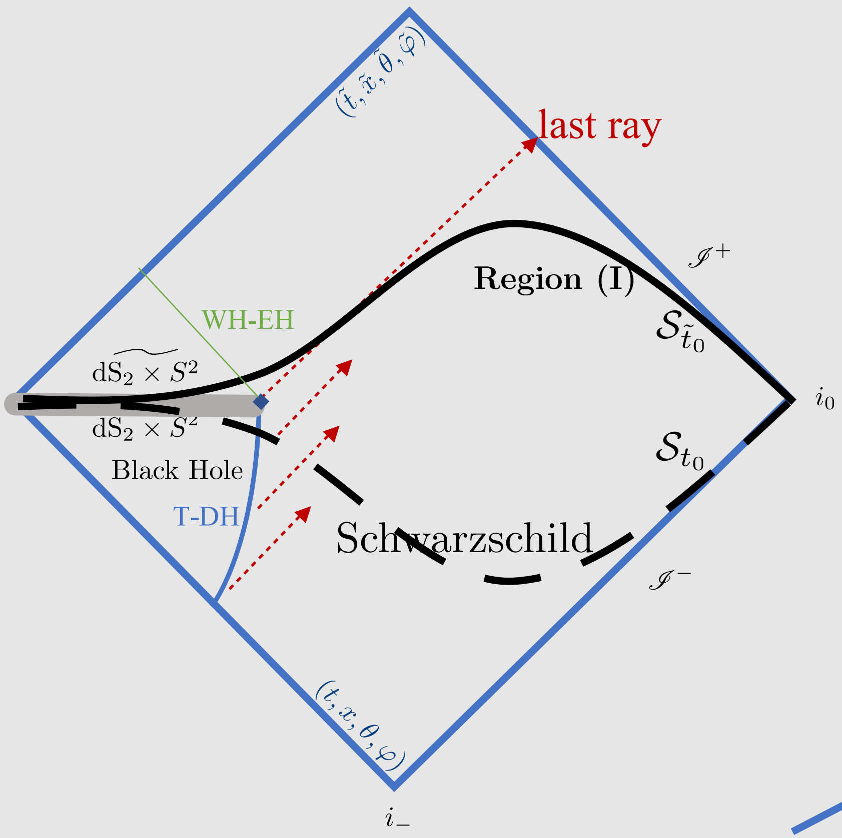
New foliation need to be introduced $(\tilde t, \tilde x, \tilde\theta, \tilde\varphi)$ by time reflection symmetry

$$t \to -t, \qquad x \to -x$$

$$\begin{aligned} E^{\tilde x}(p) &= -E^{x}(\mathscr{R}^{-1}(p)), \\ E^{\tilde \varphi}(p) &= E^{\varphi}(\mathscr{R}^{-1}(p)) \end{aligned} \qquad \mathscr{R} : \mathcal{S}_t \to \mathcal{S}_{\tilde t}$$

New boundary conditions by classical EoMs

Black hole to white hole transition



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New boundary conditions by classical EoMs

EoMs can be solved by reflection symmetry given before

White hole solution: anti-trapped region

$$\mathrm{dS}_2 \times S^2 \longrightarrow \widetilde{\mathrm{dS}_2 \times S^2}$$

Same E_a^j but opposite K_j^a

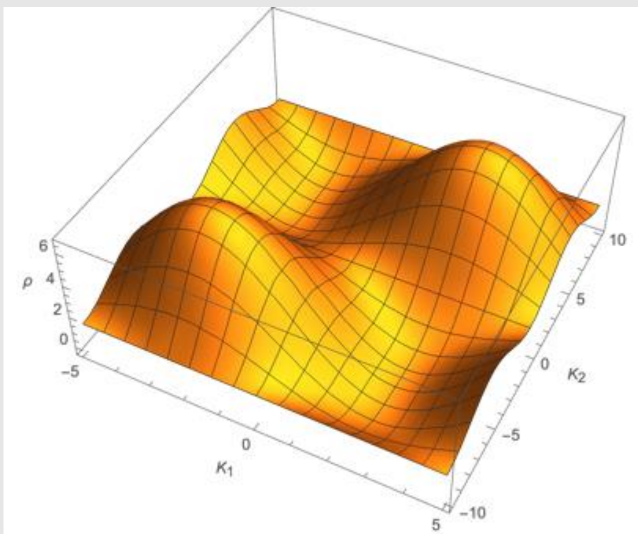
Non-classical transition allowed: quantum tunnelling?

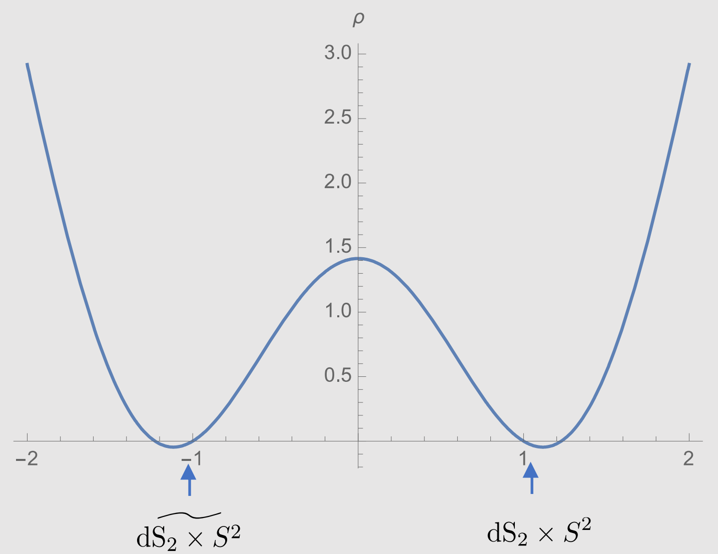
Evidence of quantum tunneling

Improved Hamiltonian density at $dS_2 \times S^2$ and $d\widetilde{S_2 \times S}^2$

Reflection symmetry of $K \to -K$

$$\rho = -\frac{\mathcal{C}_\Delta}{E^\varphi\sqrt{E^x}} = \frac{1}{2E^x} + \frac{\sin\left(2\beta\sqrt{\Delta}K_1\right)\sin\left(\beta\sqrt{\Delta}K_2\right)}{\beta^2\Delta} + \frac{\sin^2\left(\beta\sqrt{\Delta}K_2\right)}{2\beta^2\Delta}$$

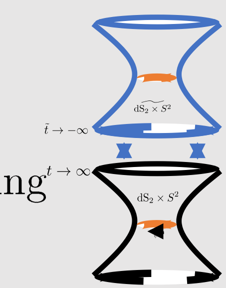




double-well effective potential of ρ

K_x fluctuations are large since E_x is small

Possible quantum tunneling



Infinitely many infrared states

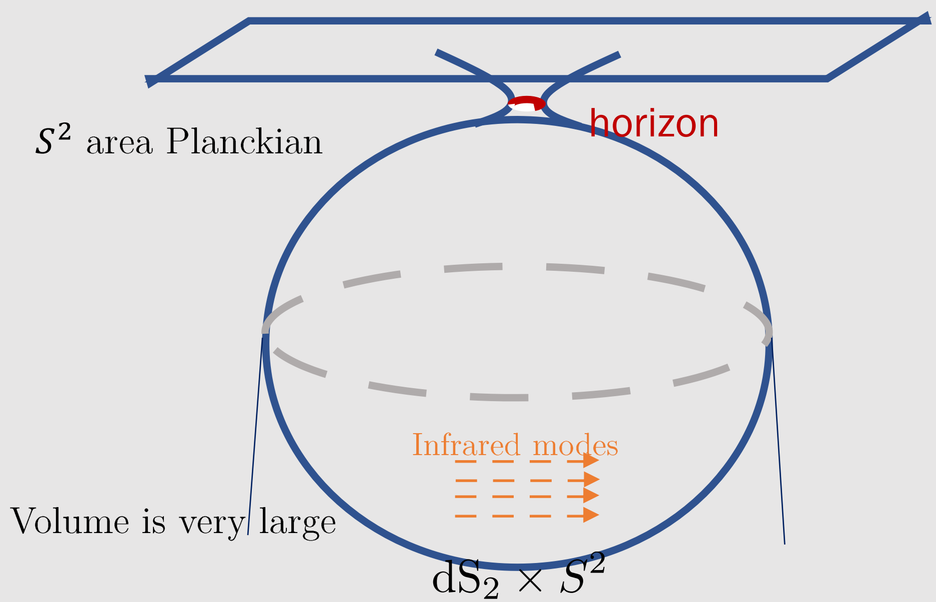
$$\rho = \mathbf{H}_\Delta / \sqrt{\det(q)} = 0 \qquad \text{in } dS_2 \times S^2$$

In terms of sates $|r_0, \alpha_0; \alpha_1\rangle \in \mathcal{H}_{\mathrm{dS}_2 \times \mathrm{S}^2}$

$$\langle r_0, \alpha_0; \alpha_1 | \hat{\rho} | r_0, \alpha_0; \alpha_1 \rangle = 0$$

All states are infrared states, soft modes, and they are infinitely many

An example of Wheeler's bag of gold



Action of diffeomorphisms

$$\widehat{e^{i\varepsilon \mathcal{V}(N)}} |r_0, \alpha_0; \alpha_1\rangle = |r_0, \alpha_0; \alpha_1'\rangle,$$

$$\alpha_1'(x) = \alpha_1(x) + \varepsilon \alpha_0^{-1} N(x) + \varepsilon \partial_x N(x)$$

$\mathcal{H}_{\mathrm{dS}_2 \times \mathrm{S}^2}$ A representation space of the group of 1-dimensional diffeomorphisms

e.g. Witt algebra

$$[L_m, L_n] = (m-n) L_{m+n}, \qquad L_n = -i e^{in\theta} \frac{\partial}{\partial \theta}$$

Outlook

- From black hole to the Nariai limit
  - Thermalization predicted from H_Δ
  - Relation with Hawking radiation
- Near the Nariai limit
  - Detailed analysis of quantum tunneling
  - Detailed analysis of infrared modes
- From the Nariai limit to white hole. Quantization of H_Δ
  - Quantum chaos and transition beyond effective theory
- Large dust energy/momentum density and dynamical collapse

Thank you