Evanescent 2D black holes

Singularity resolution via a negative central charge

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Based on on-going work with F.J. Marañón-González, J. Navarro-Salas y S. Play

Why 2D black holes?

- Black hole singularities remain one of the biggest puzzles in General Relativity
- To fully understand them we (expectedly) need Quantum Gravity
- Even at the semiclassical level there are complications (conceptual and computational)
- 2D models simplify the Mathematics, while still retaining all the relevant features:

  - Event horizons

  - Hawking radiation

  - Information paradox

The CGHS model

- Originally proposed by [Callan, Giddings, Harvey & Strominger, 1992]
- The action is

$$S_D = \frac{1}{2\pi}\int d^2x\sqrt{-g}e^{-2\phi}\left[R+4(\nabla\phi)^2+4\lambda^2\right]$$

- The equations of motion

$$2e^{-2\phi}\left[\nabla_\mu\nabla_\nu\phi+g_{\mu\nu}((\nabla\phi)^2-\nabla^2\phi-\lambda^2)\right]=0, \qquad e^{-2\phi}\left[R+4\lambda^2+4\nabla^2\phi-4(\nabla\phi)^2\right]=0,$$

allow for a (linear dilaton) vacuum solution

$$R=\nabla^2\phi=0, \qquad (\nabla\phi)^2=\lambda^2$$

and an eternal black hole solution

The CGHS model

- In lightcone coordinates $x^{\pm}$ and conformal gauge $g_{\mu\nu} = e^{2\rho}\eta_{\mu\nu}$ we have

$$e^{-2(\phi+\rho)}\left[-4\partial_+\partial_-\phi + 4\partial_+\phi\partial_-\phi + 2\partial_+\partial_-\rho + \lambda^2 e^{2\rho}\right] = 0,$$

$$e^{-2\phi}\left[2\partial_+\partial_-\phi - 4\partial_+\phi\partial_-\phi - \lambda^2 e^{2\rho}\right] = 0.$$

$$e^{-2\phi}(4\partial_+\rho\partial_+\phi - 2\partial_+{}^2\phi) = 0,$$

$$e^{-2\phi}(4\partial_-\rho\partial_-\phi - 2\partial_-{}^2\phi) = 0.$$

- This implies $\partial_+\partial_-(\rho - \phi) = 0$ and thus can solve

$$e^{-2\phi} = e^{-2\rho} = \frac{M}{\lambda} - \lambda^2 x^+ x^-,$$

$$R = 8e^{-2\rho}\partial_+\partial_-\rho = \frac{4M\lambda}{M/\lambda - \lambda^2 x^+ x^-}$$

- Can we get black holes from gravitational collapse? Yes

The CGHS model

- After adding matter

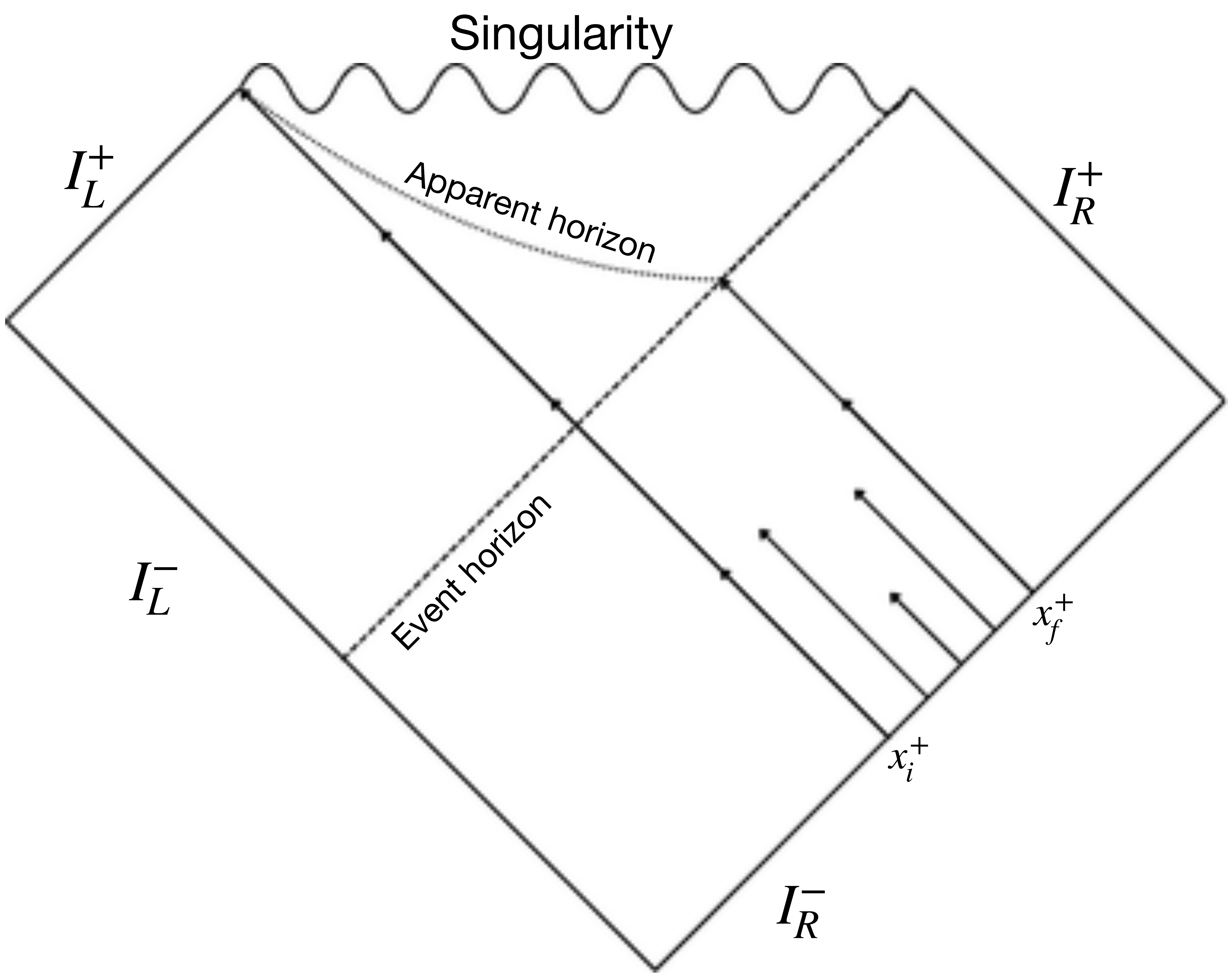
$$S_{CGHS} = \frac{1}{2\pi}\int d^2x\sqrt{-g}[e^{-2\phi}\left(R + 4\left(\nabla\phi\right)^2 + 4\lambda^2\right) - \frac{1}{2}\sum_{i=1}^{N}(\nabla f_i)^2]$$

- The equations of motion get modified accordingly; in conformal gauge

$$e^{-2(\phi+\rho)}\left[-4\partial_+\partial_-\phi + 4\partial_+\phi\partial_-\phi + 2\partial_+\partial_-\rho + \lambda^2 e^{2\rho}\right] = 0,$$
$$e^{-2\phi}\left[2\partial_+\partial_-\phi - 4\partial_+\phi\partial_-\phi - \lambda^2 e^{2\rho}\right] = 0.$$

$$e^{-2\phi}\left(-4\partial_\pm\rho\partial_\pm\phi + 2\partial_\pm^2\phi\right) = T^f_{\pm\pm} \equiv \frac{1}{2}(\partial_\pm f)^2$$

The CGHS model



$$e^{-2\phi} = -\lambda^2 x^+(x^- + P(x^+)/\lambda^2) + \frac{m(x^+)}{\lambda}$$

$$P(x^+) = \int_{x_i^+}^{x^+} dy^+ T_{++}(y^+)$$

$$m(x^+) = \lambda \int_{x_i^+}^{x^+} dy^+ y^+ T_{++}(y^+)$$

The CGHS model

- In 2D, the trace anomaly can be correlated to the central charge of the system

$$\langle T \rangle = \frac{C}{24} R$$

- In conformal gauge this can be exploited to get, via energy-momentum conservation,

$$\langle T^f_{--} \rangle_{\mathcal{I}^+} = \frac{N\lambda^2}{48} \left[1 - \frac{1}{\left(1 + \frac{P(x_f^+)}{\lambda} e^{\lambda \hat{\sigma}^-}\right)^2} \right]$$

The backreaction

- Integrating the radiation emitted to all times diverges: we haven't considered the back reaction on the black hole itself

- First approach: consider the (quantum) stress-energy tensor as a source for the metric equations; for example

$$e^{-2\phi}(2\partial_+\partial_-\phi - 4\partial_+\phi\partial_-\phi - \lambda^2 e^{2\rho}) = -\left\langle T^f_{+-}\right\rangle$$

- This modification can be derived from an effective action

$$\Gamma_+\left[g_{\mu\nu}\right] = -\frac{C_+}{96\pi}\int d^2x\sqrt{-g}R(g)\Box^{-1}(g)R(g)$$

- However, the E.O.M derived from this action are usually not analytically solvable and we break the conformal gauge

The RST solution

- [Russo, Susskind & Strominger, 1992] proposed adding a local counterterm

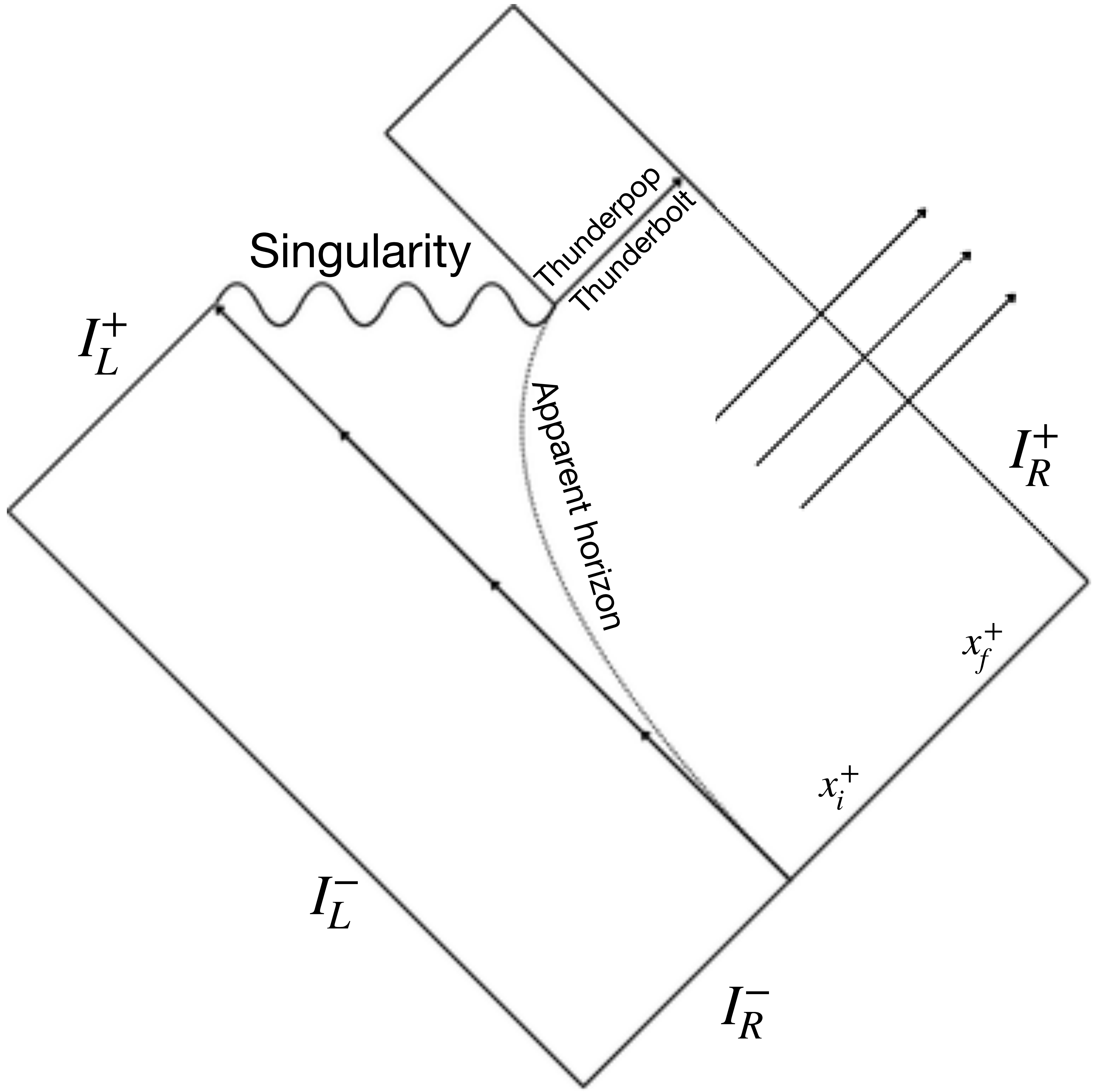
$$-\frac{N}{48\pi}\int d^2x\sqrt{-g}\phi R$$

  and taking the large N limit (for reasons I won't spoil, give me a minute)

- Doing so reinstates exact solubility (provided some boundary conditions)

- The math is ~~very boring~~ for the most part mechanical, and arrives at a vanishing black hole solution

The RST solution



The backreaction, revisited

- First of all, we can generalize [Cruz & Navarro-Salas, 1996]

$$S_{local}[g,\phi] = \frac{C_+}{24\pi}\int d^2x\sqrt{-g}[(1-2a)(\nabla\phi)^2 + (a-1)\phi R]]$$

- Not the full story; we have chosen the conformal gauge so we have to account for Fadeev-Popov ghost fields in the effective action

- This presents itself with problems:

  1. The central charge changes

  2. We have ghost fields Hawking radiation

The backreaction, revisited

- Proposal [inspired by Potaux, Sarkar & Solodukhin, 2023]: ghosts are not coupled to the original metric $g_{\mu\nu}$ but to the conformally scaled one $\hat{g}_{\mu\nu} = e^{-2\phi} g_{\mu\nu}$, which is flat on-shell (i.e. no Hawking radiation)

$$\Gamma_- \left[\hat{g}_{\mu\nu}\right] = -\frac{C_-}{96\pi} \int d^2x \sqrt{-\hat{g}} R(\hat{g}) \Box^{-1}(\hat{g}) R(\hat{g})$$

- The full effective action is then

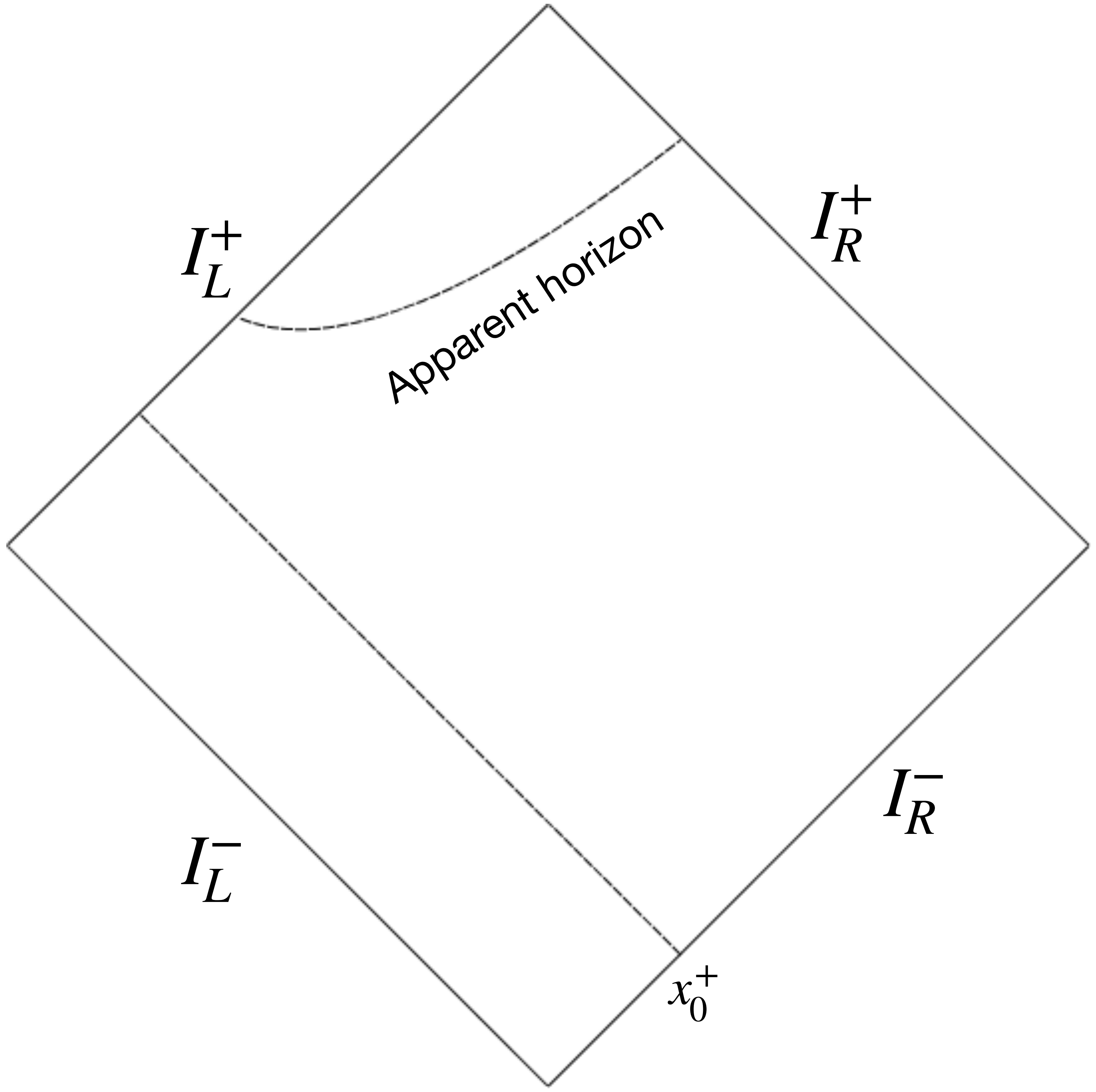
$$S_{cghs}[g, \phi, f] + \Gamma_-[\hat{g}] + \Gamma_+[g] + S_{local}[g, \phi]$$

- By imposing that flat spacetime remains a solution at the 1-loop level, the parameter a is fixed

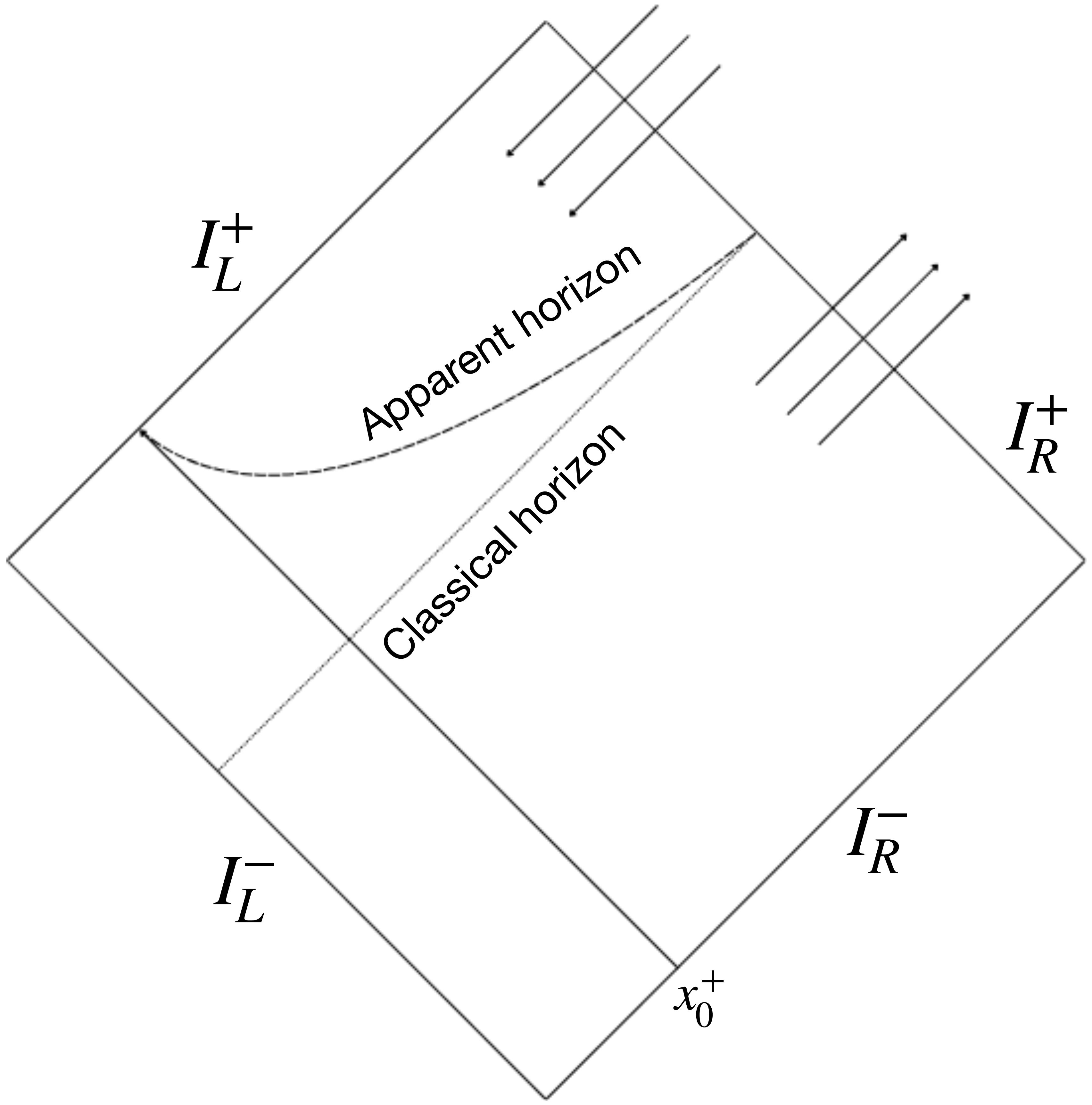
$$a = \frac{C_- + C_+}{2C_+}$$

Preliminary results

$C_+ = 0 \qquad C_- \neq 0$



$C_+ + C_- < 0$



Conclusions

- 2D black holes pose an interesting “lab environment” for testing our understanding of black hole dynamics

- The Hawking radiation process can be modeled with semiclassical theories only at the earlier stages; when energies become Planckian, we do need to go to a Quantum Gravity model

- Introducing a (non-radiating) negative central charge seems to solve the singularity outright

- This could be of great interest to the information loss problem, and could point to a picture in which the fate of gravitational collapse is ultimately determined by the content matter in the universe

Thank you very much!