Causal structure of nonhomogeneous dust collapse in effective loop quantum gravity

Michał Bobula

University of Wrocław

based on MB, T. Pawłowski 2410.22943

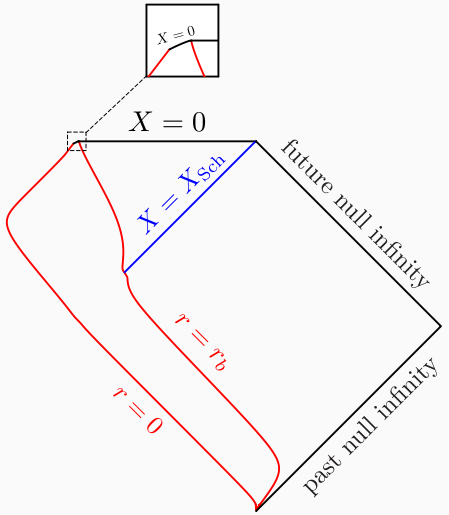
Motivation

> *"The framework falls down for everything that one has ever called a law of physics"*. Wheeler

Is it possible to obtain a description/theory free from problems that are present in General Relativity?

With no new fields or degrees of freedom?

So that it could also successfully model our universe?



Homogeneous dust ball collapse in GR.

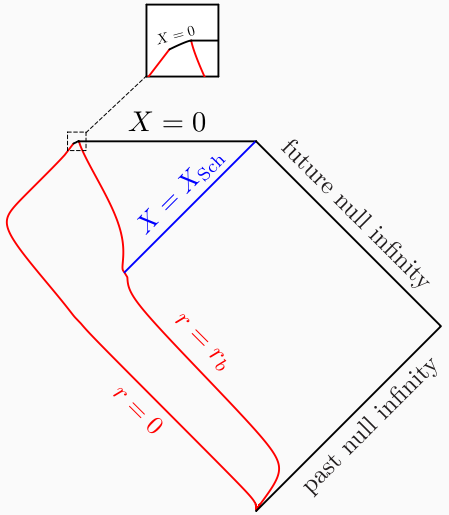
Motivation

> *"The framework falls down for everything that one has ever called a law of physics"*. Wheeler

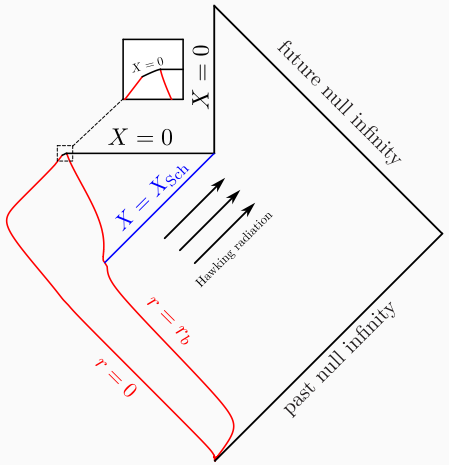
Is it possible to obtain a description/theory free from problems that are present in General Relativity?

With no new fields or degrees of freedom?

So that it could also successfully model our universe?



Homogeneous dust ball collapse in GR.



BH formation and evaporation.

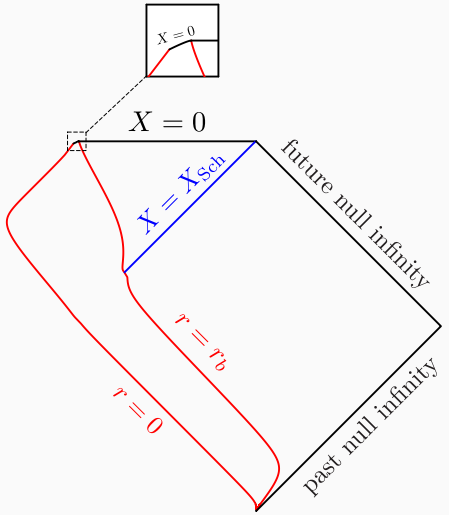
Motivation

> *"The framework falls down for everything that one has ever called a law of physics"*. Wheeler

Is it possible to obtain a description/theory free from problems that are present in General Relativity?

With no new fields or degrees of freedom?

So that it could also successfully model our universe?

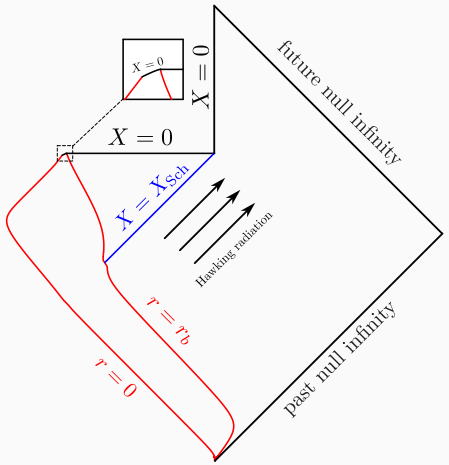


Homogeneous dust ball collapse in GR.

Ashtekar-Bojowald paradigm

[2005]
The picture of black hole formation and evaporation:

- No singularities
- No event horizon
- Global hyperbolicity



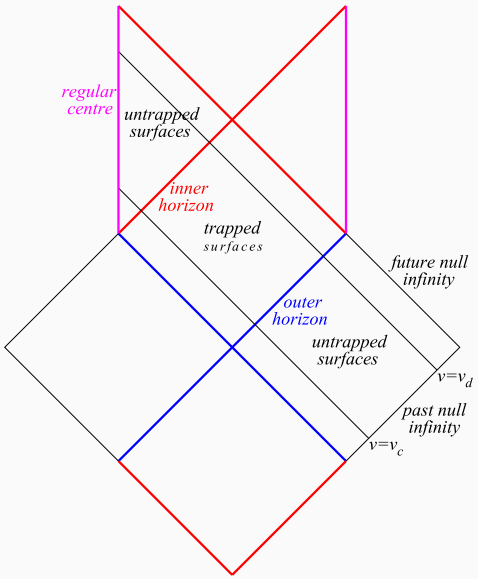
BH formation and evaporation.

Formation and evaporation of regular black holes

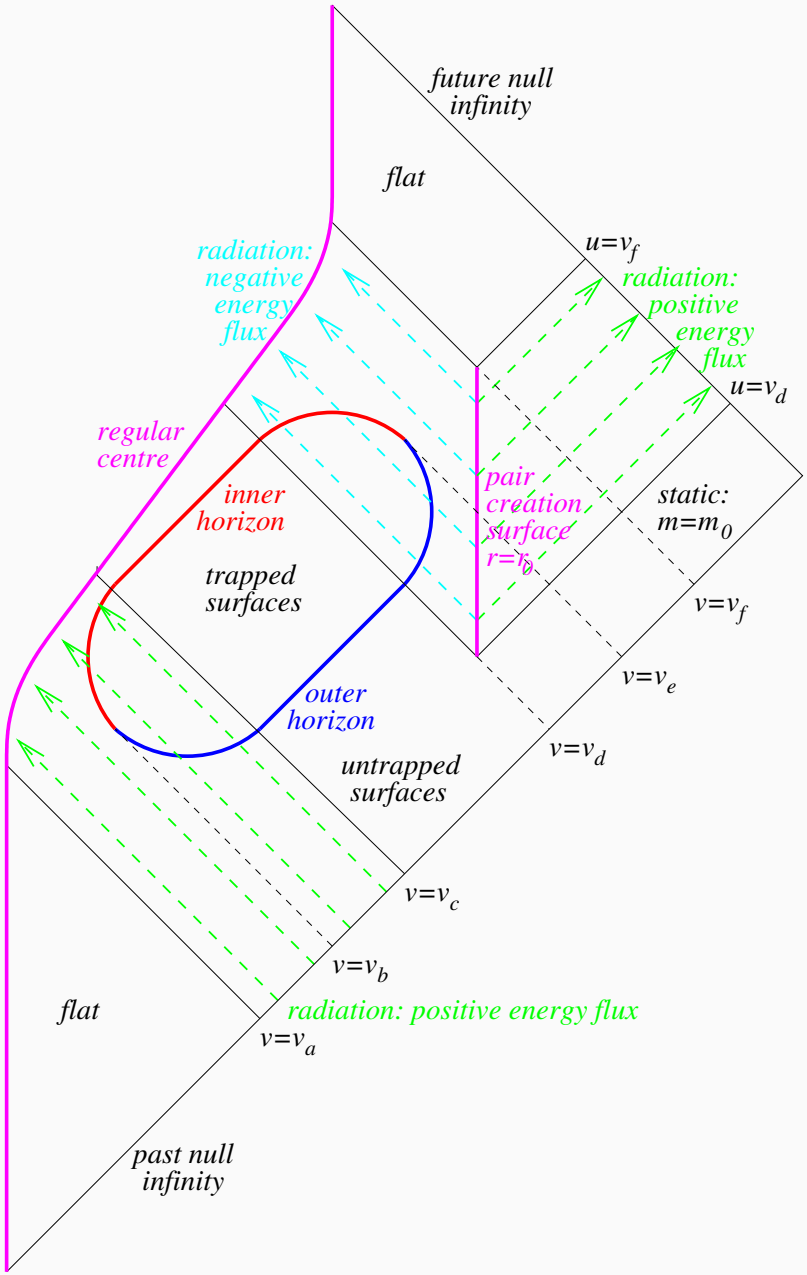
A toy model consistent with Ashtekar-Bojowald paradigm [2005] was proposed [Hayward, 2005] **No BH information paradox**.

The metric describing the static part was later known as Hayward black hole metric
$F(x) = 1 - \frac{2Mx^2}{x^3+2l^2M}$.

The static metric spacetime is not globally hyperbolic (backreaction is neglected)



How to obtain similar model (formation and evaporation) within robust field-theorethical description?



Husain-Kelly-Santacruz-Wilson-Ewing model

PHYSICAL REVIEW LETTERS **128,** 121301 (2022)

Featured in Physics

Quantum Gravity of Dust Collapse: Shock Waves from Black Holes

Viqar Husain,* Jarod George Kelly,† Robert Santacruz,‡ and Edward Wilson-Ewing§
Department of Mathematics and Statistics, University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada

(Received 29 September 2021; revised 26 November 2021; accepted 10 February 2022; published 22 March 2022)

We study the quantum gravitational collapse of spherically symmetric pressureless dust. Using an effective equation derived from a polymer quantization in the connection-triad phase space variables of general relativity, we find numerically, for a variety of initial dust configurations, that (i) trapped surfaces form and disappear as an initially collapsing density profile evolves into an outgoing shock wave; (ii) black hole lifetime is proportional to the square of its mass; and (iii) there is no mass inflation at inner apparent horizons. These results provide a substantially different view of black hole formation and subsequent evolution than found from semiclassical analyses.

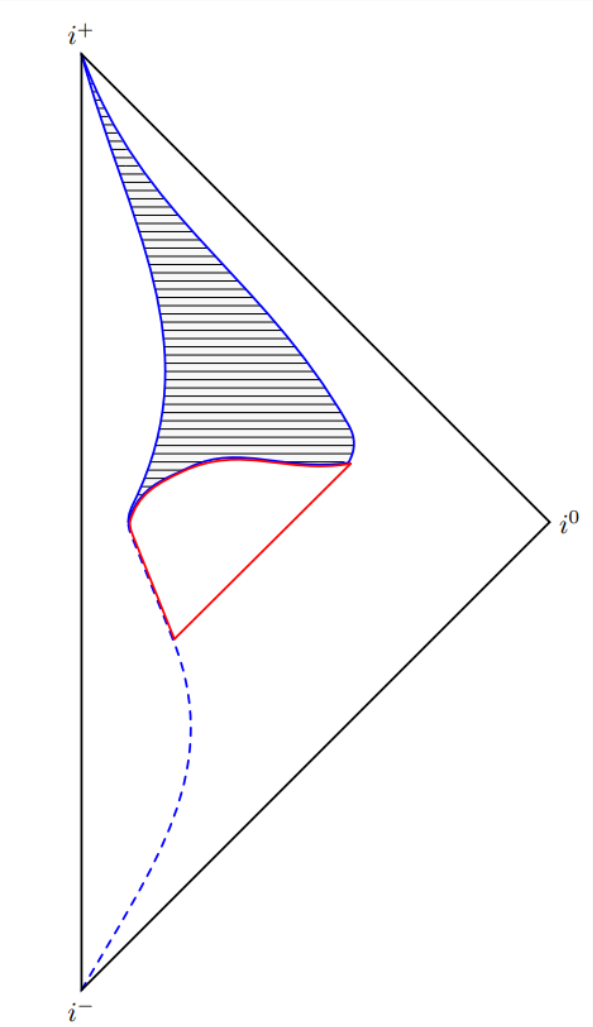
DOI: 10.1103/PhysRevLett.128.121301

Nonhomogeneous dust collapse model in effective LQG.

The authors reported shock waves (metric discontinuities) during the gravitational collapse.

This talk

What is the exact causal structure for nonhomogeneous dust collapse (numerically computed conformal diagrams)? Can the collapse take place within single asymptotic region? (Note that the backreaction was neglected.)



Consistent with Ashtekar-Bojowald paradigm? No backreaction

Model setup

- **Classical level.** Spherical symmetry. Gravity coupled to dust field.

$$\mathrm{d}\mathfrak{s}^2 = -1\,\mathrm{d}T^2 + h[T,x]\left(\mathrm{d}x + N^x\mathrm{d}T\right)^2 + x^2\mathrm{d}\Omega^2\,, \tag{1}$$

  Gauges are fixed: Painleve-Gullstrand gauge and areal gauge.

Model setup

- **Classical level.** Spherical symmetry. Gravity coupled to dust field.

$$\mathrm{d}\mathscr{s}^2 = -1\,\mathrm{d}T^2 + h[T,x]\left(\mathrm{d}x + N^x\mathrm{d}T\right)^2 + x^2\mathrm{d}\Omega^2\,, \tag{1}$$

  Gauges are fixed: Painleve-Gullstrand gauge and areal gauge.

- **Quantization and effective dynamics**. Discretization along radial coordinate $\rightarrow$ methods of LQC. Effective dynamics. Continuum limit. Marginally bound collapse $h[T,x] \rightarrow 1$. The dynamics is governed by nonlinear PDE [Husain et al. 2022]

$$\dot{\beta} = \{\beta, H^{\mathrm{eff}}_{\mathrm{phys}}\} - \frac{1}{2\gamma\sqrt{\Delta}x^2}\partial_x\left(x^3\sin^2\beta\right)\,, \quad \rho = -\frac{\mathcal{H}_{\mathrm{phys}}}{4\pi x^2} \tag{2}$$

  with the shift $N^x \sim -\frac{x}{\gamma\sqrt{\Delta}}\sin\beta\cos\beta$. GR retrieved for $\sin\beta \rightarrow \beta$. Solving the dynamics $\rightarrow$ method of characteristic equations. $\Delta = 4\sqrt{3}\pi\gamma\ell^2_{\mathrm{Pl}}$ (area gap). γ is BI parameter.

Model setup

- **Classical level.** Spherical symmetry. Gravity coupled to dust field.

$$\mathrm{d}\mathscr{s}^2 = -1\,\mathrm{d}T^2 + h[T,x]\left(\mathrm{d}x + N^x\mathrm{d}T\right)^2 + x^2\mathrm{d}\Omega^2\,, \tag{1}$$

  Gauges are fixed: Painleve-Gullstrand gauge and areal gauge.

- **Quantization and effective dynamics**. Discretization along radial coordinate $\rightarrow$ methods of LQC. Effective dynamics. Continuum limit. Marginally bound collapse $h[T,x] \rightarrow 1$. The dynamics is governed by nonlinear PDE [Husain et al. 2022]

$$\dot{\beta} = \{\beta, H^{\mathrm{eff}}_{\mathrm{phys}}\} - \frac{1}{2\gamma\sqrt{\Delta}x^2}\partial_x\left(x^3\sin^2\beta\right)\,, \quad \rho = -\frac{\mathcal{H}_{\mathrm{phys}}}{4\pi x^2} \tag{2}$$

  with the shift $N^x \sim -\frac{x}{\gamma\sqrt{\Delta}}\sin\beta\cos\beta$. GR retrieved for $\sin\beta \rightarrow \beta$. Solving the dynamics $\rightarrow$ method of characteristic equations. $\Delta = 4\sqrt{3}\pi\gamma\ell^2_{\mathrm{Pl}}$ (area gap). γ is BI parameter.

- **Conformal diagrams.** Key observation: to construct pair of null coordinates (u,v) they have to obey [MB, T. Pawłowski 2024]

$$\mathrm{d}(\mathrm{d}u) = 0 \quad \mathrm{d}(\mathrm{d}v) = 0 \tag{3}$$

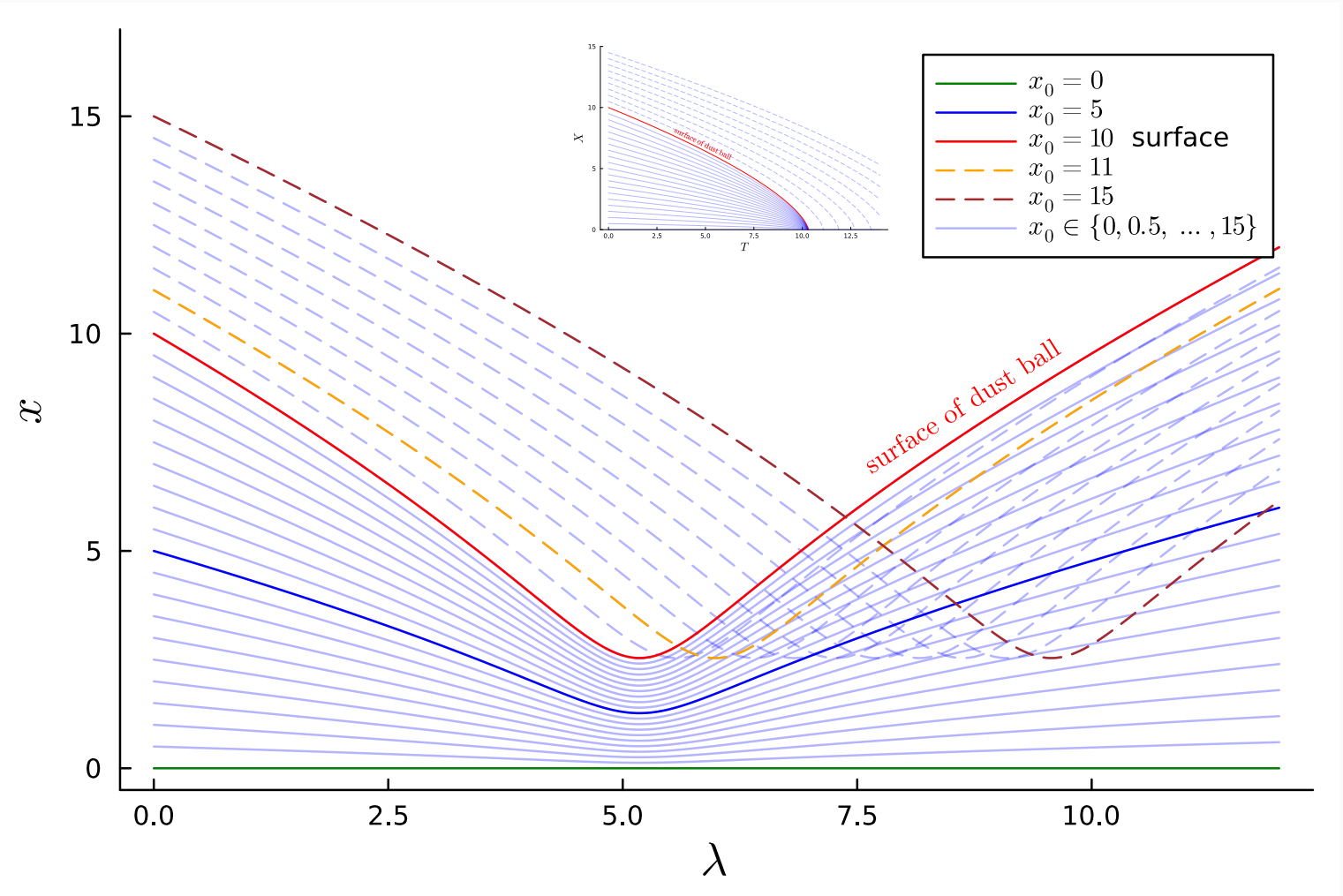
  Initial conditions for the above determine the shape of a diagram!

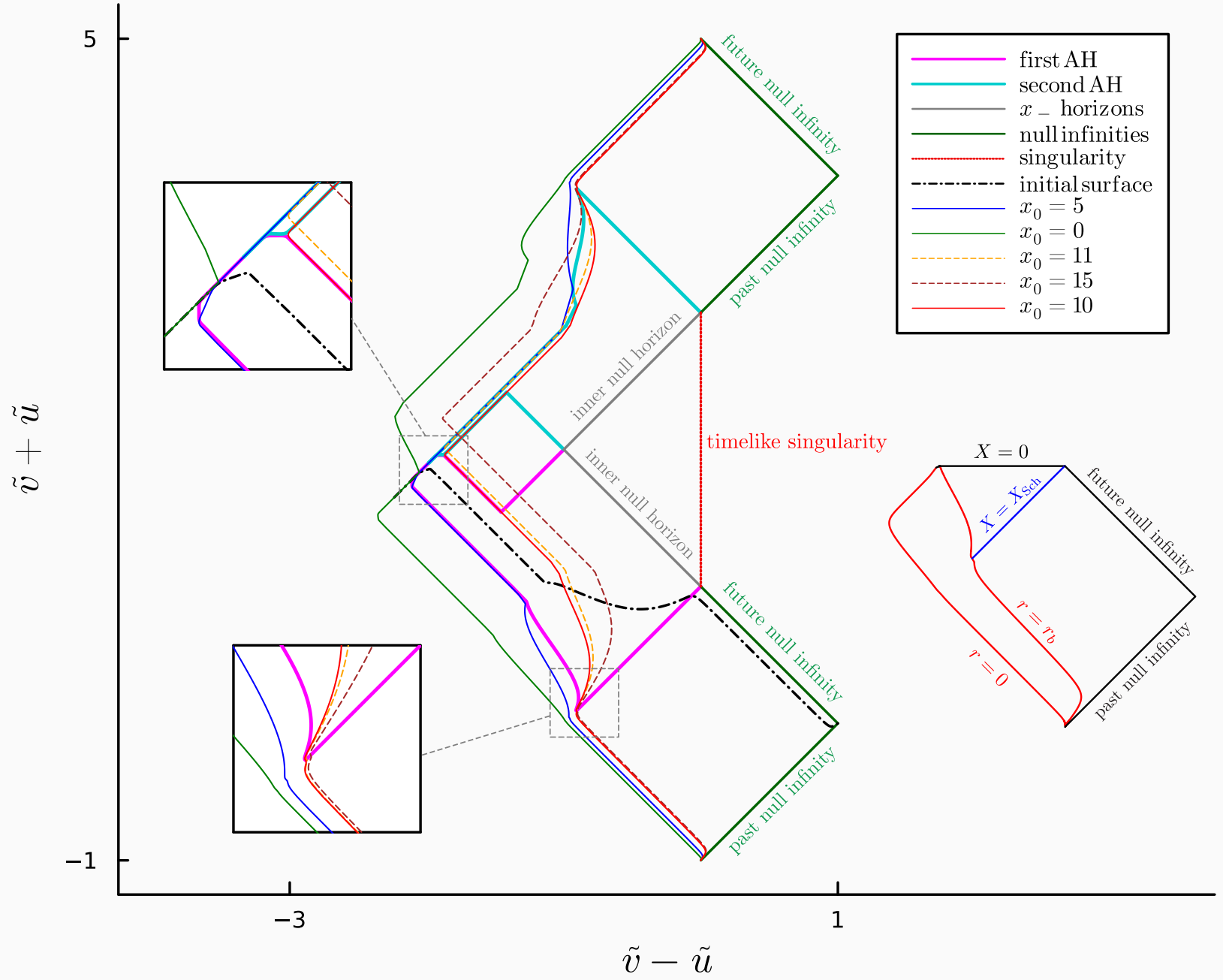
Oppenheimer-Snyder collapse

A collapse of homogeneous dust ball. Energy density at the **initial slice**

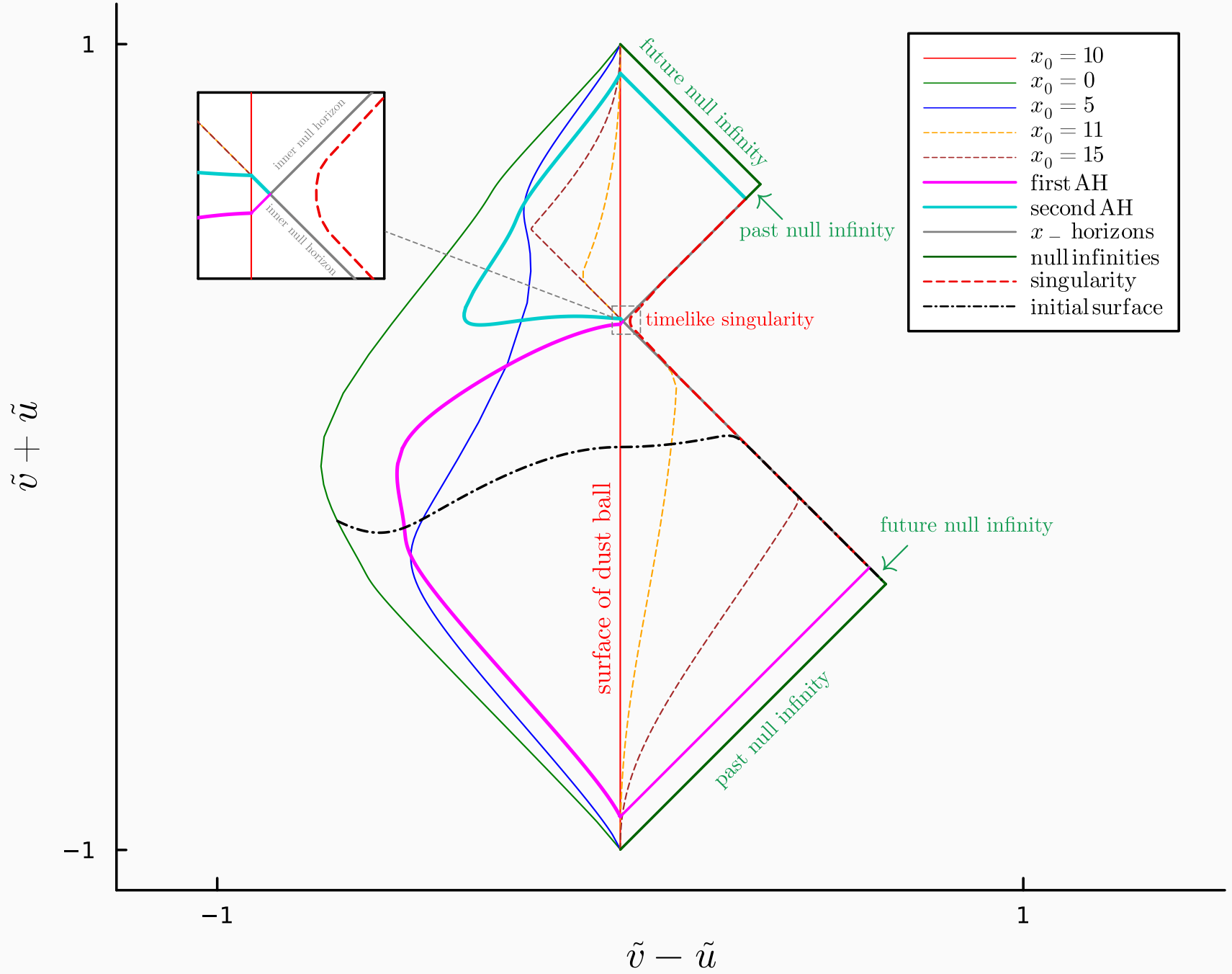
$$\rho_{\mathrm{OS}}(\lambda = 0, x_0) = \begin{cases} \rho_0 \quad \text{for} \quad x_0 \leq x_b \,, \ \text{(interior)} \\ 0 \quad \text{for} \quad x_0 > x_b \,, \ \text{(exterior)} \end{cases} \tag{4}$$

Timelike geodesics on radial coordinate x vs. affine paramerter λ plane [MB, T. Pawłowski, 2024]





Exterior: $1 - (N^x_{\rm OS})^2 = 1 - \frac{2GM}{x} + \frac{4G^2M^2\gamma^2\Delta}{x^4}$, quantum-corrected Schwarzchild spacetime


1
−1
−1
1
$\tilde{v}+\tilde{u}$
$\tilde{v}-\tilde{u}$
future null infinity
past null infinity
timelike singularity
surface of dust ball
future null infinity
past null infinity
inner null horizon
inner null horizon
$x_0 = 10$
$x_0 = 0$
$x_0 = 5$
$x_0 = 11$
$x_0 = 15$
first AH
second AH
x_- horizons
null infinities
singularity
initial surface

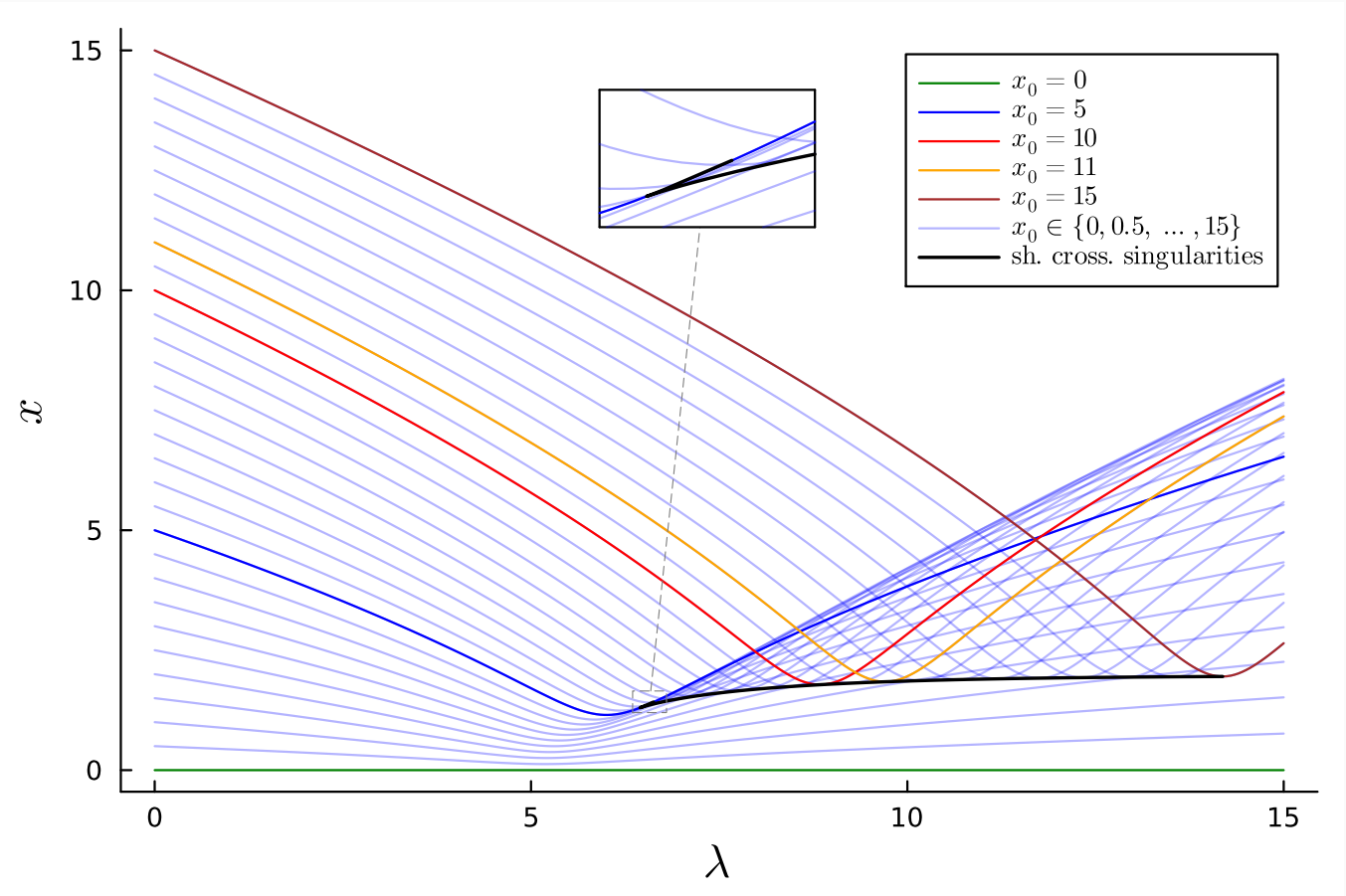
Nonhomogeneous dust collapse

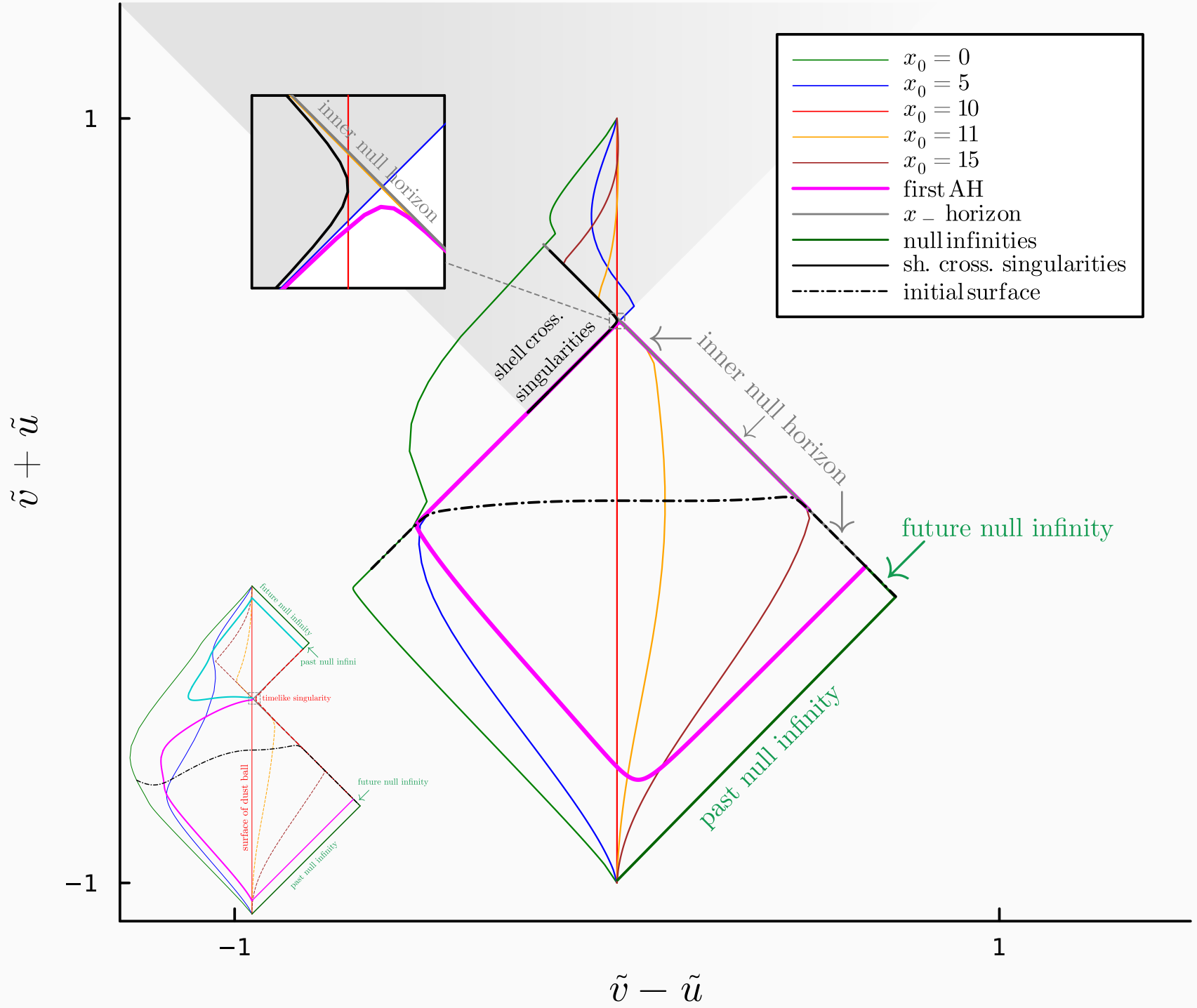
Gaussian initial dust profile

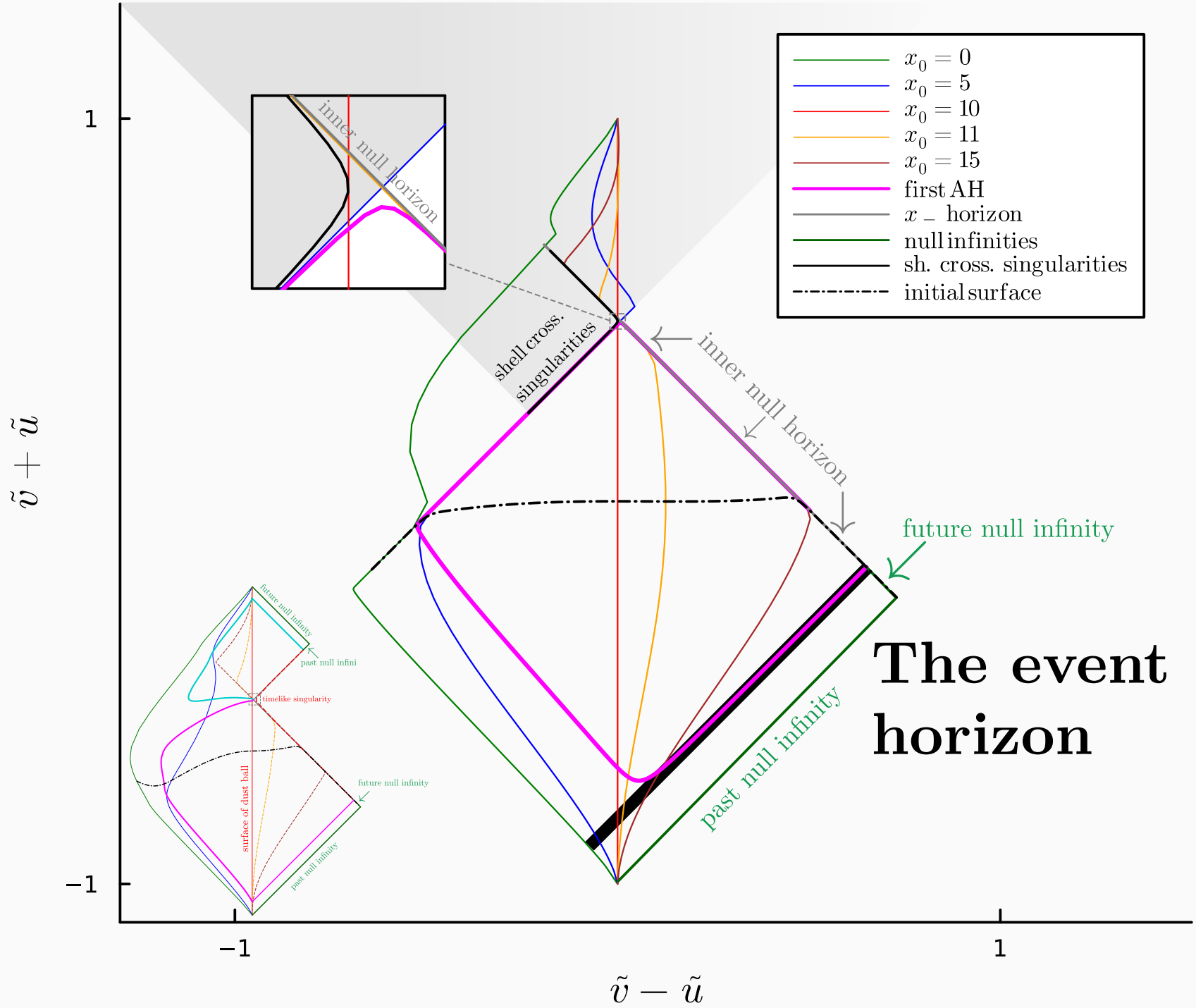
$$\rho_{\mathrm{NH}}(\lambda = 0, x_0) = \rho_0 \exp\left(\frac{-x_0^2}{2\mathcal{R}^2}\right) , \tag{5}$$

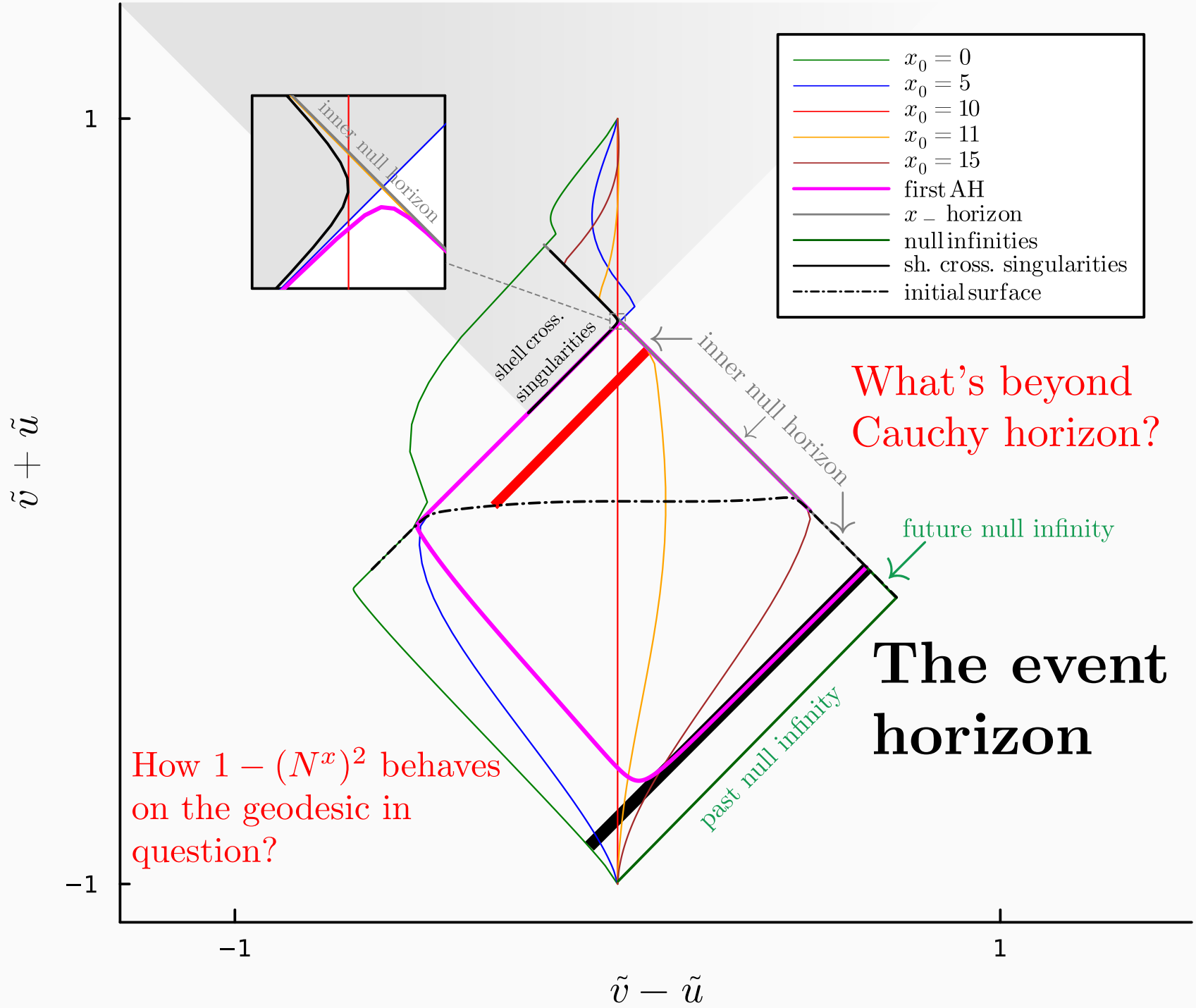
Shell-crossing singularities. (seminally studied by [Fazzini et al., 2023])

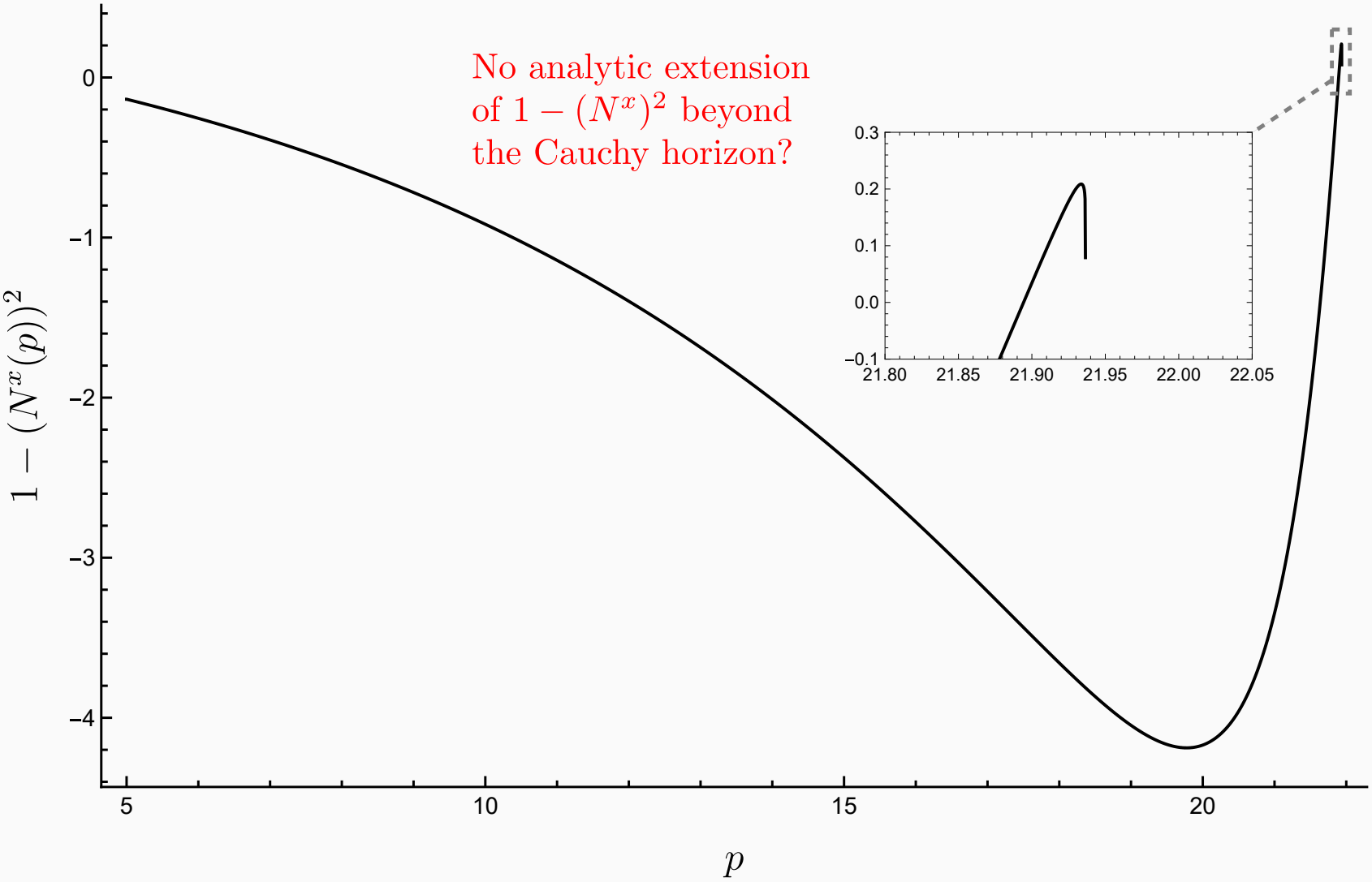
The energy denisty blows up at certain spacetime points. $\rho = -\frac{\mathcal{H}_{\mathrm{phys}}}{4\pi x^2}$




$x_0 = 0$
$x_0 = 5$
$x_0 = 10$
$x_0 = 11$
$x_0 = 15$
first AH
x_- horizon
null infinities
sh. cross. singularities
initial surface
inner null horizon
shell cross. singularities
inner null horizon
future null infinity
past null infinity
$\tilde{v} + \tilde{u}$
$\tilde{v} - \tilde{u}$
1
−1
−1
1
future null infinity
past null infini
timelike singularity
surface of dust ball
future null infinity
past null infinity


$x_0 = 0$
$x_0 = 5$
$x_0 = 10$
$x_0 = 11$
$x_0 = 15$
first AH
x_- horizon
null infinities
sh. cross. singularities
initial surface
inner null horizon
shell cross. singularities
inner null horizon
future null infinity
past null infinity
The event horizon
1
−1
−1
1
$\tilde{v} + \tilde{u}$
$\tilde{v} - \tilde{u}$
future null infinity
past null infini
timelike singularity
surface of dust ball
future null infinity
past null infinity


$x_0 = 0$
$x_0 = 5$
$x_0 = 10$
$x_0 = 11$
$x_0 = 15$
first AH
x_- horizon
null infinities
sh. cross. singularities
initial surface
inner null horizon
shell cross. singularities
inner null horizon
future null infinity
past null infinity
What's beyond Cauchy horizon?
The event horizon
How $1 - (N^x)^2$ behaves on the geodesic in question?
1
−1
−1
1
$\tilde{v} + \tilde{u}$
$\tilde{v} - \tilde{u}$



$1-(N^x)^2$ as the function of the affine parameter p on the null geodesic in question.

Conclusions

- **OS collapse scenario in reduced effective LQG**
  central singularity resolved, two asymptotic regions, timelike singularity
  Inflationary phase needed?
  collapsing matter crosses Cauchy horizon
  Hawking radiation included $\rightarrow$ Wheeler bag of gold scenario or Ashtekar-Bojowald-like picture?
  Standard model field instead of dust?

Conclusions

- **OS collapse scenario in reduced effective LQG**
  central singularity resolved, two asymptotic regions, timelike singularity
  Inflationary phase needed?
  collapsing matter crosses Cauchy horizon
  Hawking radiation included $\rightarrow$ Wheeler bag of gold scenario or Ashtekar-Bojowald-like picture?
  Standard model field instead of dust?
- **Nonhomogeneous collapse scenario in reduced effective LQG**
  The collapse cannot take place within single asymptotic region. (LQG phenomena hidden from external observer)
  Shell-crossing singularities $\rightarrow$ they should be eliminated.
  What's beyond Cauchy horizon? – still open problem.

Conclusions

- **OS collapse scenario in reduced effective LQG**
  central singularity resolved, two asymptotic regions, timelike singularity
  Inflationary phase needed?
  collapsing matter crosses Cauchy horizon
  Hawking radiation included $\rightarrow$ Wheeler bag of gold scenario or Ashtekar-Bojowald-like picture?
  Standard model field instead of dust?
- **Nonhomogeneous collapse scenario in reduced effective LQG**
  The collapse cannot take place within single asymptotic region. (LQG phenomena hidden from external observer)
  Shell-crossing singularities $\rightarrow$ they should be eliminated.
  What's beyond Cauchy horizon? – still open problem.
- **Inner horizon instabilities**

  Problem of several quantum gravitational collapse models:

  - symmetry-reduced LQG models,
  - asymptotic-safety-inspired models [Bonanno, et al., 2024]
  - quasi-topological gravity (string-theory-inspired) [Bueno et al., 2024]

  Success in both BHs & cosmology $\rightarrow$ existence of inner horizons

Conclusions

- **OS collapse scenario in reduced effective LQG**
  central singularity resolved, two asymptotic regions, timelike singularity
  Inflationary phase needed?
  collapsing matter crosses Cauchy horizon
  Hawking radiation included $\rightarrow$ Wheeler bag of gold scenario or Ashtekar-Bojowald-like picture?
  Standard model field instead of dust?
- **Nonhomogeneous collapse scenario in reduced effective LQG**
  The collapse cannot take place within single asymptotic region. (LQG phenomena hidden from external observer)
  Shell-crossing singularities $\rightarrow$ they should be eliminated.
  What's beyond Cauchy horizon? – still open problem.
- **Inner horizon instabilities**

  Problem of several quantum gravitational collapse models:

  - symmetry-reduced LQG models,
  - asymptotic-safety-inspired models [Bonanno, et al., 2024]
  - quasi-topological gravity (string-theory-inspired) [Bueno et al., 2024]

  Success in both BHs & cosmology $\rightarrow$ existence of inner horizons
- **Global hyperbolicity only with backreaction**

Conclusions

- **OS collapse scenario in reduced effective LQG**
  central singularity resolved, two asymptotic regions, timelike singularity
  Inflationary phase needed?
  collapsing matter crosses Cauchy horizon
  Hawking radiation included $\rightarrow$ Wheeler bag of gold scenario or Ashtekar-Bojowald-like picture?
  Standard model field instead of dust?
- **Nonhomogeneous collapse scenario in reduced effective LQG**
  The collapse cannot take place within single asymptotic region. (LQG phenomena hidden from external observer)
  Shell-crossing singularities $\rightarrow$ they should be eliminated.
  What's beyond Cauchy horizon? – still open problem.
- **Inner horizon instabilities**

  Problem of several quantum gravitational collapse models:

  - symmetry-reduced LQG models,
  - asymptotic-safety-inspired models [Bonanno, et al., 2024]
  - quasi-topological gravity (string-theory-inspired) [Bueno et al., 2024]

  Success in both BHs & cosmology $\rightarrow$ existence of inner horizons
- **Global hyperbolicity only with backreaction**

Thank you for your attention!