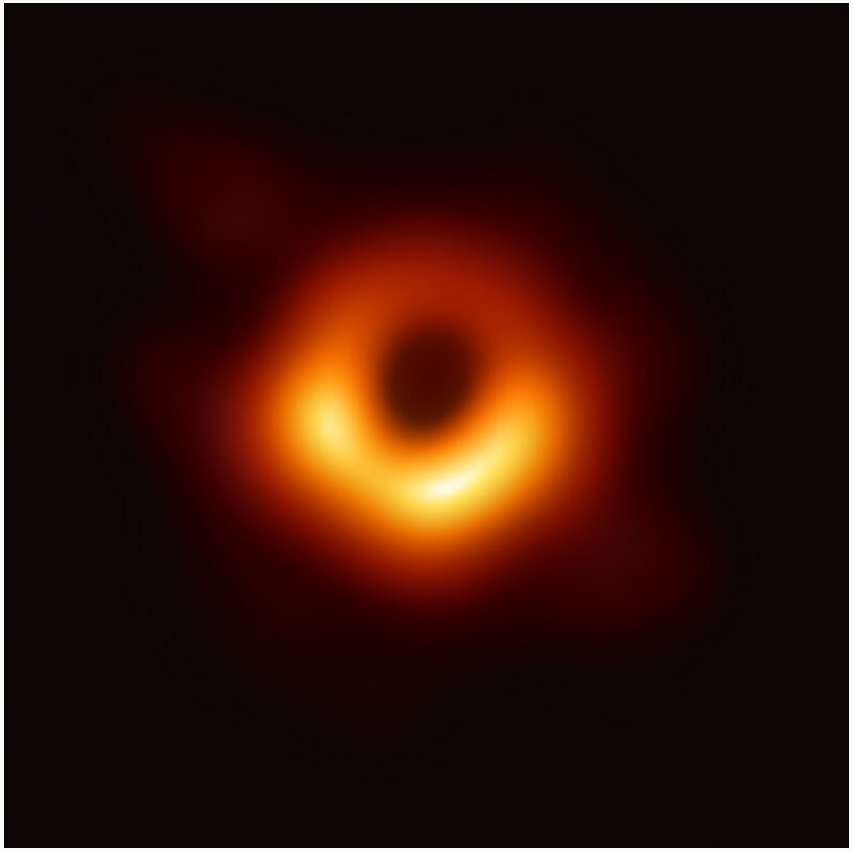
Bounce vs. long squeeze in quantum gravitational collapse

Michał Bobula

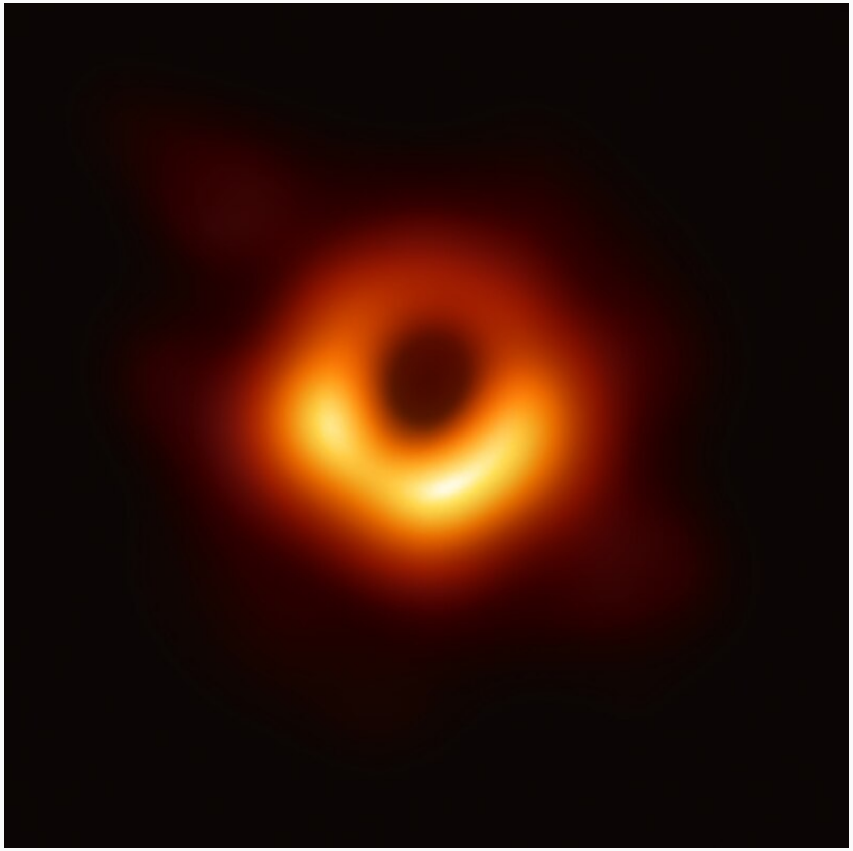
University of Wrocław

based on
MB, T. Pawłowski (2025) Phys. Rev. D 112, 064056
MB (2025) Class. Quantum Grav. 42 065027

Relativity Seminar, University of Warsaw, 7th of November 2025



Reminder: This picture does not prove that either black holes (as defined in GR) or event horizons actually exist.



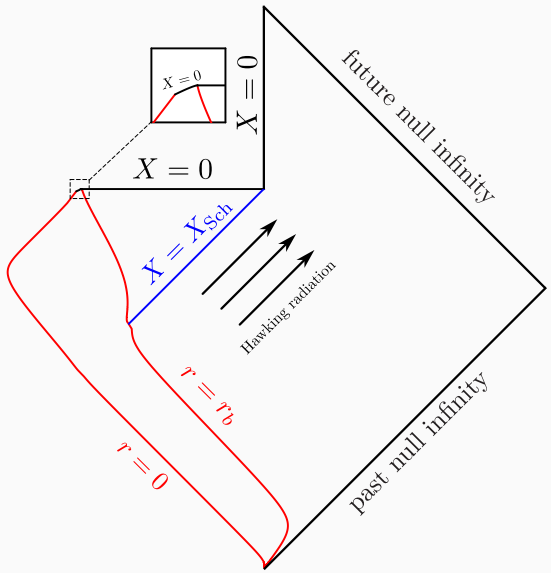
Reminder: This picture does not prove that either black holes (as defined in GR) or event horizons actually exist.

Event horizons (EH) are visible only to those who *ever were* and *ever will* be $\rightarrow$ certainly not to us!
The existence of EHs is only known after the universe has ended.

Motivation

Questions

1. How to find a consistent picture of 'black hole' formation and evaporation?
2. What are the observational signatures?



Typical inconsistent picture of BH evolution [already in Hawking '75]. Both singularity and event horizon are present. Breakdown of predictability $\rightarrow$ BH information paradox.

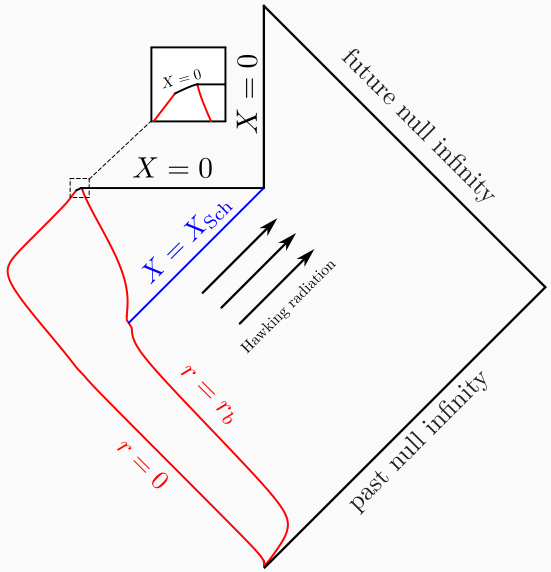
Motivation

Questions

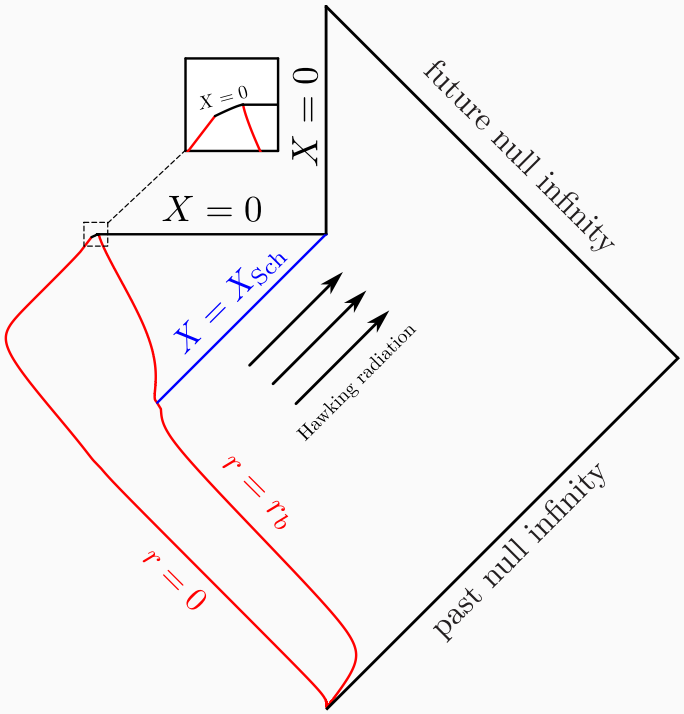
1. How to find a consistent picture of 'black hole' formation and evaporation?
2. What are the observational signatures?

This talk: Searching for the picture with:

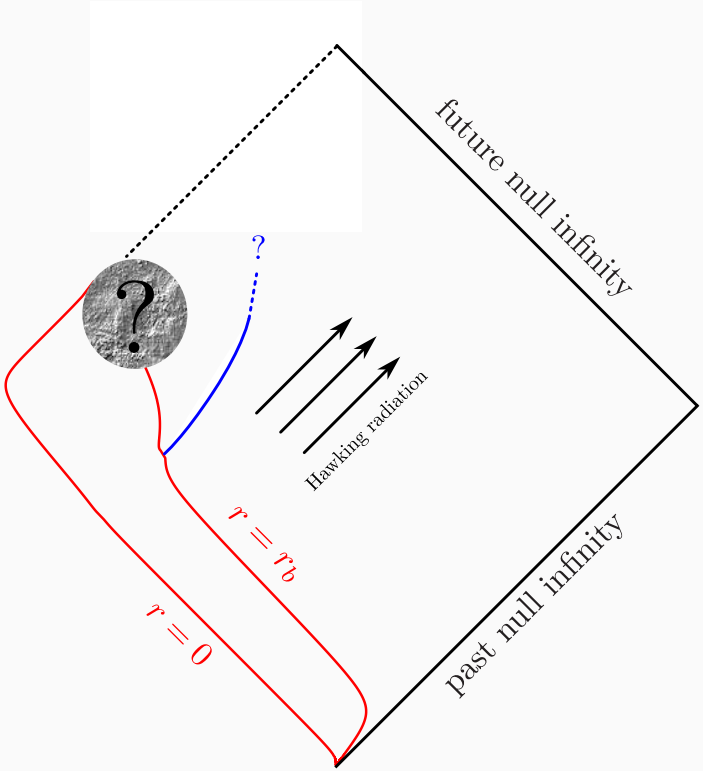
- No singularities
- No new fields or degrees of freedom other than in GR-like picture
- No event horizons [Ashtekar, Bojowald, Hayward, late Hawking, . . .]
- Predictive theory → global hyperbolicity [Geroch, Penrose, Hawking, Choquet-Bruhat, Ellis, . . .]



Typical inconsistent picture of BH evolution [already in Hawking '75]. Both singularity and event horizon are present. Breakdown of predictability → BH information paradox.



Typical inconsistent picture of BH evolution [already in Hawking '75, Parentani PRL 1994, . . .]. Both singularity and event horizon are present. Breakdown of predictability → BH information paradox.



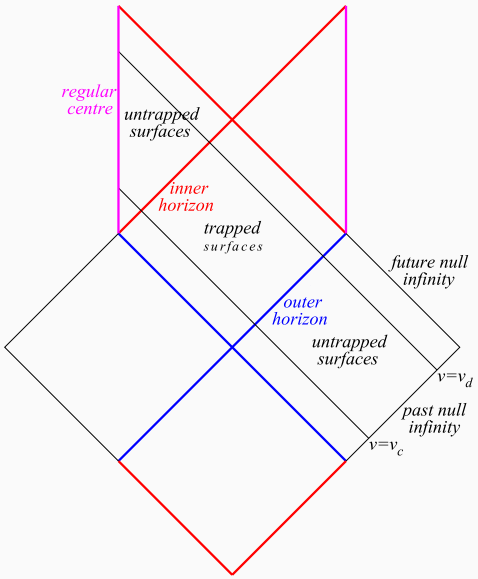
Black hole formation and evaporation in Ashtekar-Bojowald paradigm [CQG, 2005]. No singularity, no event horizon, no BH info paradox.
Fate of matter and local trapping horizon is model-dependent.
QG effects visible for the external observer!

Formation and evaporation of regular black holes

Toy model [Hayward, PRL 2005] consistent with the paradigm [Ashtekar, Bojowald, CQG 2025]

The static black hole metric (Hayward BH)
$F(X) = 1 - \frac{2MX^2}{X^3+2l^2M}$.

Spacetime of the static metric alone $\rightarrow$ no global hyperbolicity. Cauchy horizon instability.

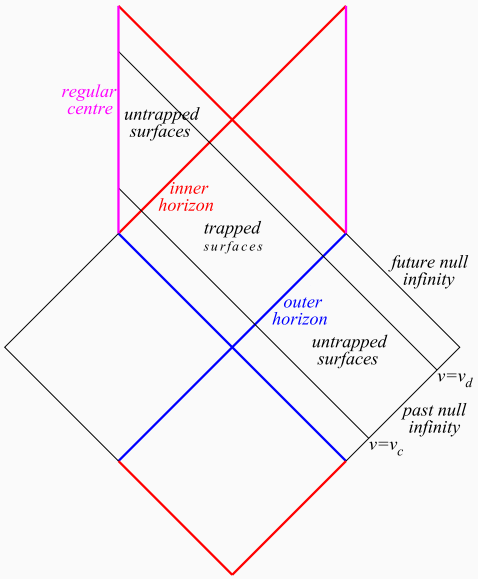


Formation and evaporation of regular black holes

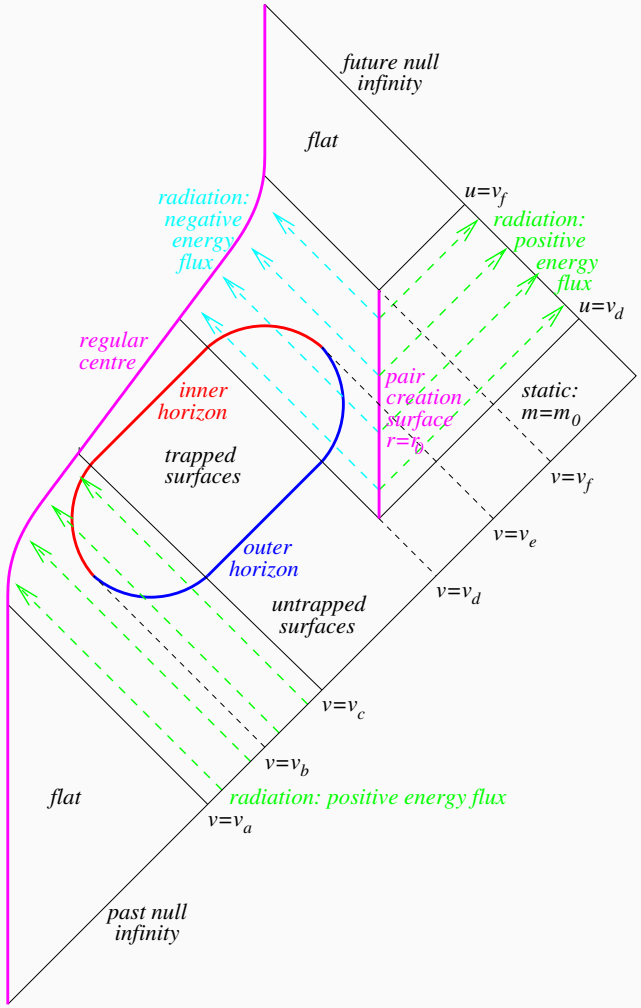
Toy model [Hayward, PRL 2005] consistent with the paradigm [Ashtekar, Bojowald, CQG 2025]

The static black hole metric (Hayward BH)
$F(X) = 1 - \frac{2MX^2}{X^3+2l^2M}$.

Spacetime of the static metric alone $\rightarrow$ no global hyperbolicity. Cauchy horizon instability.



No singularities, no event or Cauchy horizons, no BH info paradox [Hayward, PRL 2005]



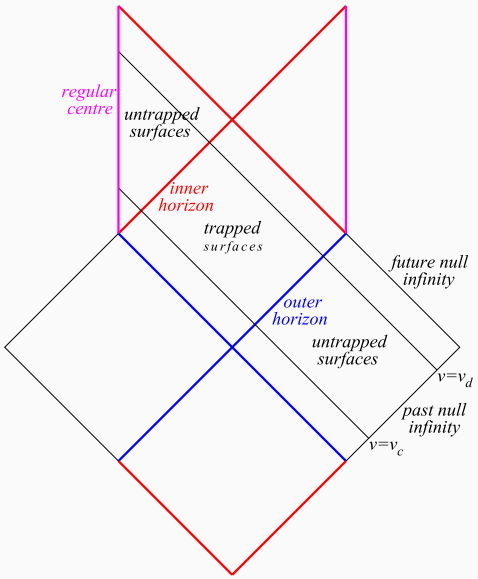
A dream scenario for any effective QG framework.

Formation and evaporation of regular black holes

Toy model [Hayward, PRL 2005] consistent with the paradigm [Ashtekar, Bojowald, CQG 2025]

The static black hole metric (Hayward BH)
$F(X) = 1 - \frac{2MX^2}{X^3+2l^2M}$.

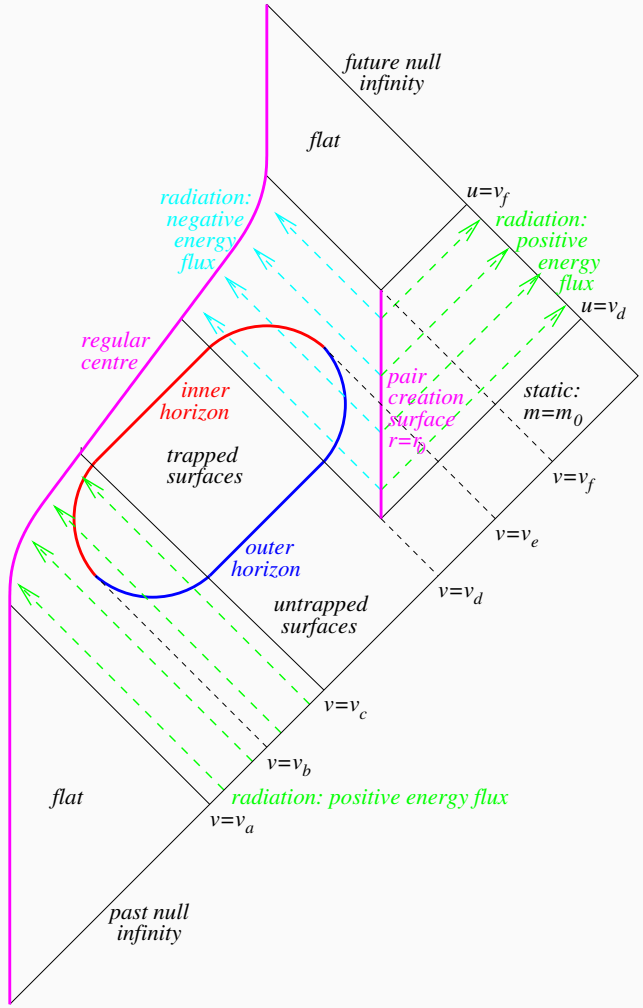
Spacetime of the static metric alone $\rightarrow$ no global hyperbolicity. Cauchy horizon instability.



In this talk

Long squeeze: detailed picture of Hayward black hole formation, however no backreaction.

No singularities, no event or Cauchy horizons, no BH info paradox [Hayward, PRL 2005]



A dream scenario for any effective QG framework.

[Submitted on 22 Jan 2014]

Information Preservation and Weather Forecasting for Black Holes

S. W. Hawking

It has been suggested [1] that the resolution of the information paradox for evaporating black holes is that the holes are surrounded by firewalls, bolts of outgoing radiation that would destroy any infalling observer. Such firewalls would break the CPT invariance of quantum gravity and seem to be ruled out on other grounds. A different resolution of the paradox is proposed, namely that gravitational collapse produces apparent horizons but no event horizons behind which information is lost. This proposal is supported by ADS-CFT and is the only resolution of the paradox compatible with CPT. The collapse to form a black hole will in general be chaotic and the dual CFT on the boundary of ADS will be turbulent. Thus, like weather forecasting on Earth, information will effectively be lost, although there would be no loss of unitarity.

Bounce

Analysis of 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.

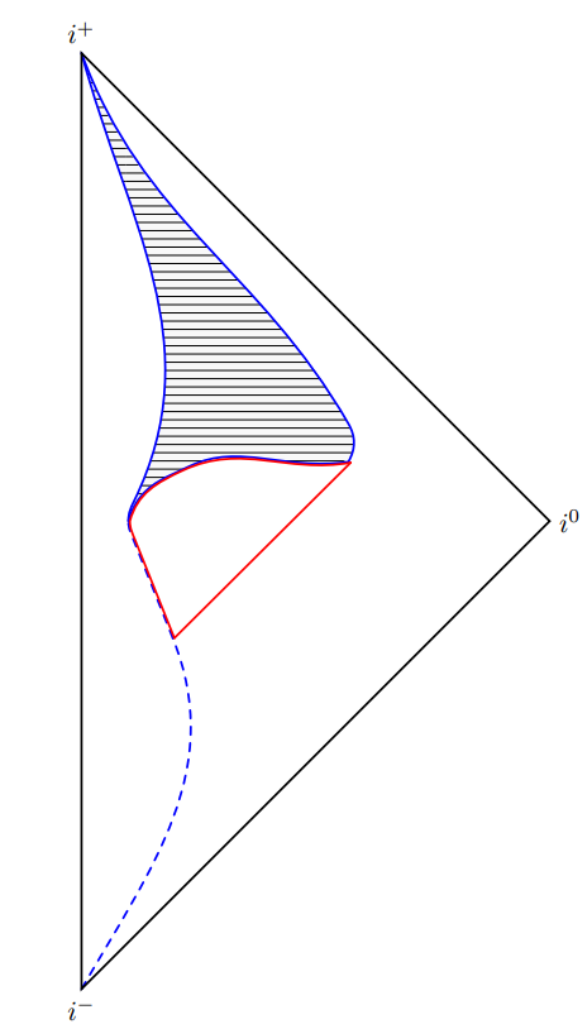
DOI: 10.1103/PhysRevLett.128.121301

Nonhomogeneous dust collapse model in effective LQG.

Tools of homogeneous and isotropic LQC applied to nonhom. case $\rightarrow$ discretization, quantization and then continuum limit

In this talk

What are numerically computed conformal diagrams for nonhomogeneous dust collapse (e.g. gaussian initial dust profile)?



Profound picture: no curv. singularities, no event horizons, one asymptotic region, shock waves

Model setup

What does it mean 'effective' in LQG frameworks?

classical GR $\xrightarrow{\text{loop quantization}}$ Loop Quantum Gravity $\xrightarrow{\text{Ehrenfest-like description (effective dynamics)}}$ deformed constraint alg., quantum-corrected traj. in class. phase space

Model setup

What does it mean 'effective' in LQG frameworks?

classical GR $\xrightarrow{\text{loop quantization}}$ Loop Quantum Gravity $\xrightarrow{\text{Ehrenfest-like description (effective dynamics)}}$ deformed constraint alg., quantum-corrected traj. in class. phase space

Husain-Kelly-Santacruz-Wilson-Ewing model [PRL, 2022]:

1. **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

What does it mean 'effective' in LQG frameworks?

classical GR $\xrightarrow{\text{loop quantization}}$ Loop Quantum Gravity $\xrightarrow{\text{Ehrenfest-like description (effective dynamics)}}$ deformed constraint alg., quantum-corrected traj. in class. phase space

Husain-Kelly-Santacruz-Wilson-Ewing model [PRL, 2022]:

1. **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.

2. **Loop quantization** $\rightarrow$ discretization along radial direction $\rightarrow$ tools of loop quantum cosmology

$$i\hbar\partial_T\Psi = \hat{\mathcal{H}}_{\text{grav}}\,\Psi \qquad \hat{\mathcal{H}}_{\text{grav}} = \sum_n \hat{\mathcal{H}}_n^{\text{LQC}} \tag{2}$$

Model setup

What does it mean 'effective' in LQG frameworks?

classical GR $\xrightarrow{\text{loop quantization}}$ Loop Quantum Gravity $\xrightarrow{\text{Ehrenfest-like description (effective dynamics)}}$ deformed constraint alg., quantum-corrected traj. in class. phase space

Husain-Kelly-Santacruz-Wilson-Ewing model [PRL, 2022]:

1. **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.
2. **Loop quantization** $\rightarrow$ discretization along radial direction $\rightarrow$ tools of loop quantum cosmology

$$i\hbar\partial_T\Psi = \hat{\mathcal{H}}_{\text{grav}}\,\Psi \qquad \hat{\mathcal{H}}_{\text{grav}} = \sum_n \hat{\mathcal{H}}_n^{\text{LQC}} \tag{2}$$

3. **Effective dynamics** $\rightarrow$ Ehrenfest-like equations $\rightarrow$ continuum limit $\rightarrow$ 1st order PDE for marginally bound collapse scenario

Model setup

What does it mean 'effective' in LQG frameworks?

classical GR $\xrightarrow{\text{loop quantization}}$ Loop Quantum Gravity $\xrightarrow{\text{Ehrenfest-like description (effective dynamics)}}$ deformed constraint alg., quantum-corrected traj. in class. phase space

Husain-Kelly-Santacruz-Wilson-Ewing model [PRL, 2022]:

1. **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.
2. **Loop quantization** $\rightarrow$ discretization along radial direction $\rightarrow$ tools of loop quantum cosmology

$$i\hbar\partial_T\Psi = \hat{\mathcal{H}}_{\text{grav}}\,\Psi \qquad \hat{\mathcal{H}}_{\text{grav}} = \sum_n \hat{\mathcal{H}}_n^{\text{LQC}} \tag{2}$$

3. **Effective dynamics** $\rightarrow$ Ehrenfest-like equations $\rightarrow$ continuum limit $\rightarrow$ 1st order PDE for marginally bound collapse scenario

Key observation for conformal diagrams

Double null coordinates (u, v) have to satisfy [MB, T. Pawłowski, PRD 2025]

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

Oppenheimer-Snyder collapse

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

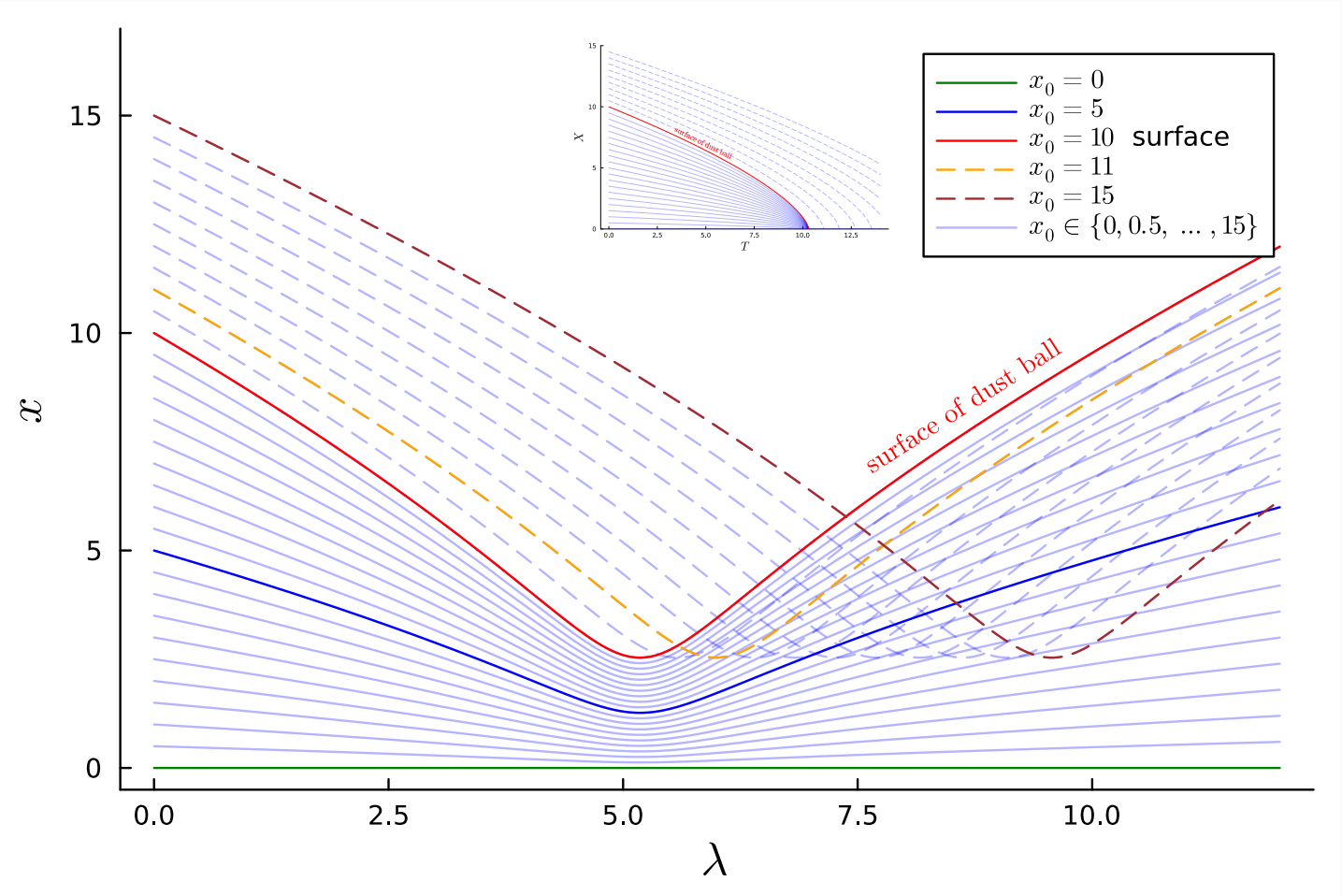
$$\rho_{\mathrm{OS}}(\lambda = 0, x_0) = \begin{cases} \rho_0 \quad \text{for} \quad x_0 \leq x_b \,, \ (\text{interior}) \\ 0 \quad \text{for} \quad x_0 > x_b \,, \ (\text{exterior}) \end{cases} \tag{3}$$

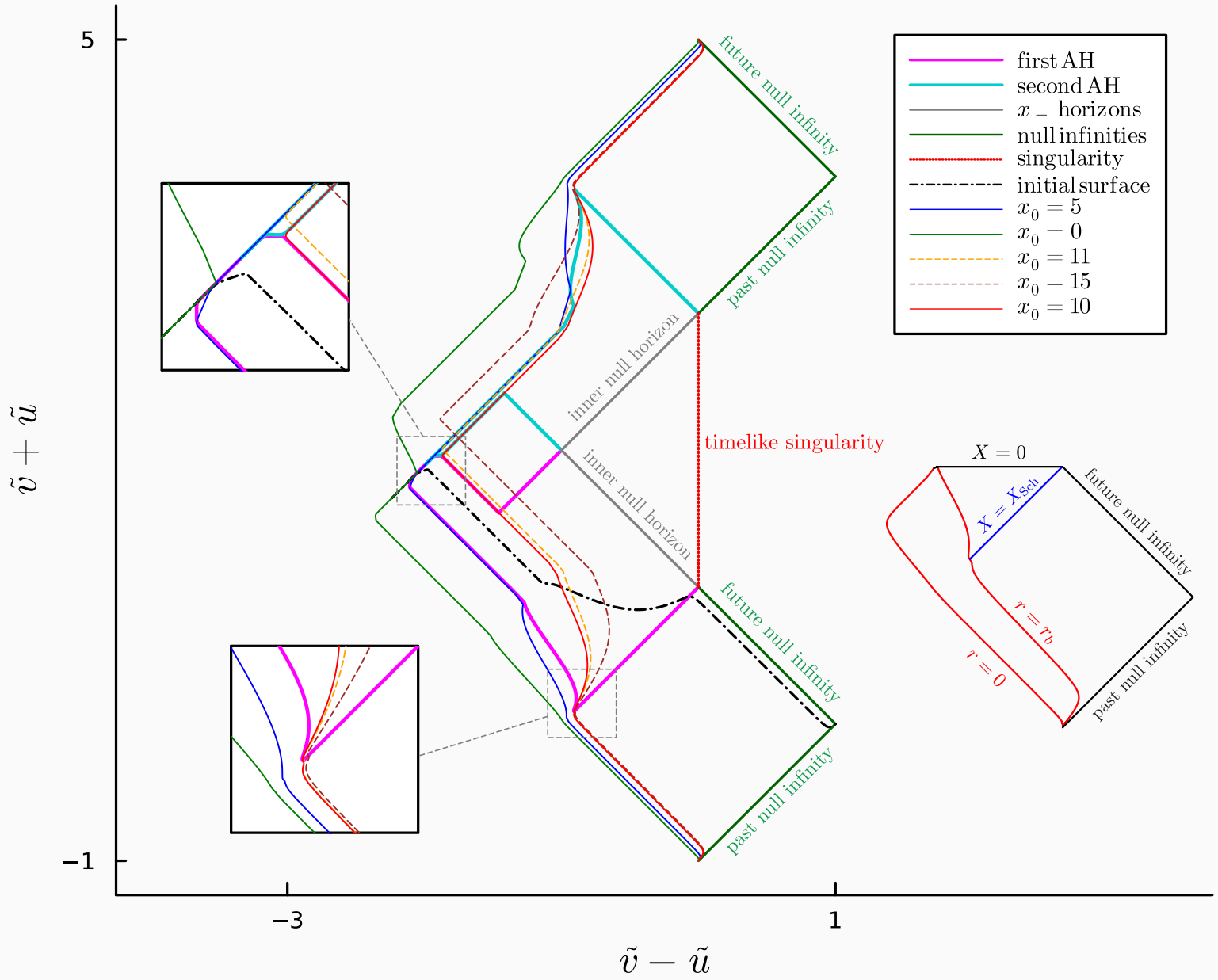
Oppenheimer-Snyder collapse

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

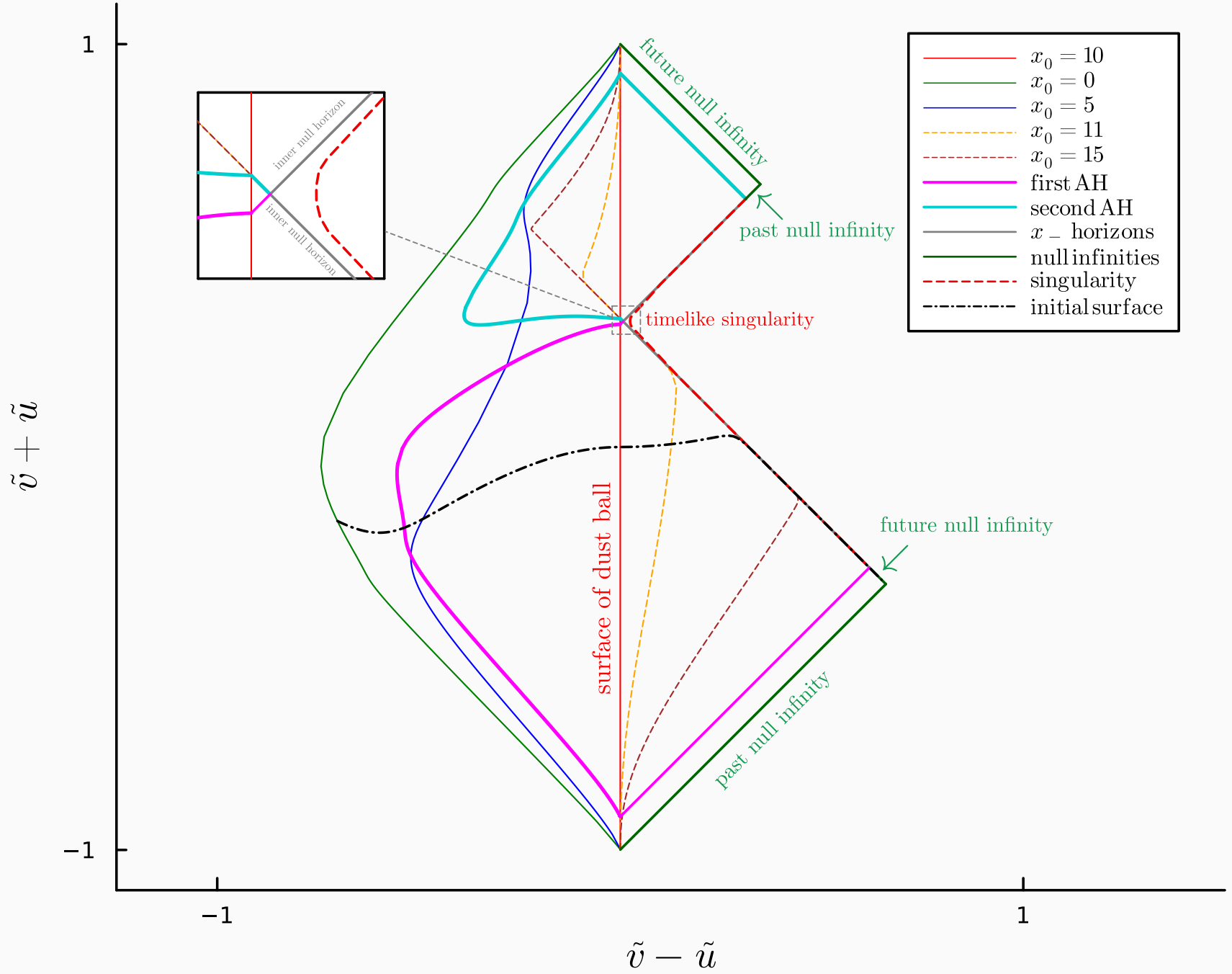
$$\rho_{\mathrm{OS}}(\lambda = 0, x_0) = \begin{cases} \rho_0 \quad \text{for} \quad x_0 \leq x_b \,, \ \text{(interior)} \\ 0 \quad \text{for} \quad x_0 > x_b \,, \ \text{(exterior)} \end{cases} \tag{3}$$

Timelike geodesics on radial coordinate x vs. affine paramter λ plane [MB, T. Pawłowski, PRD 2025]





Vacuum: $F(X) = 1 - \frac{2GM}{x} + \frac{4G^2M^2\gamma^2\Delta}{x^4}$ [Similar diagrams were obtained before by several authors]


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

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

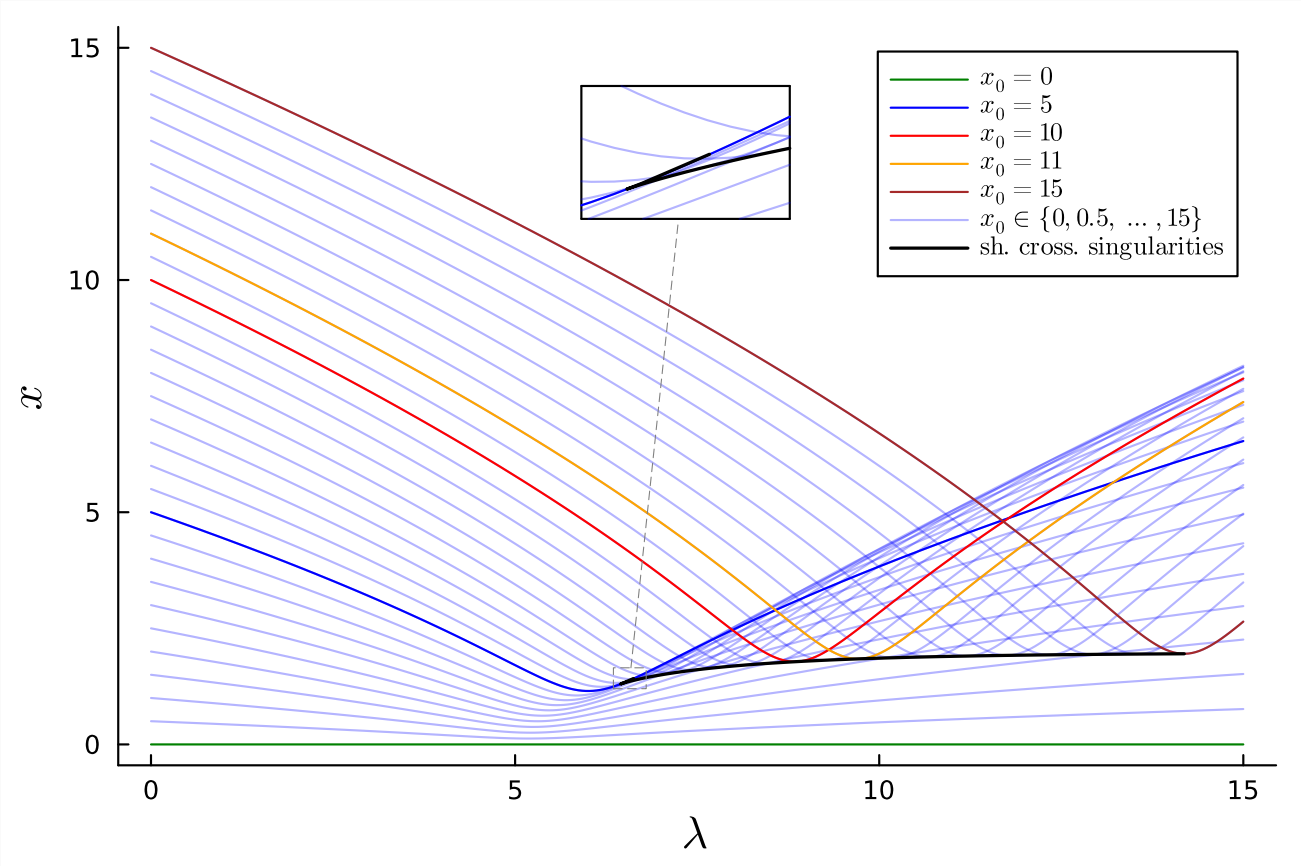
Nonhomogeneous dust collapse

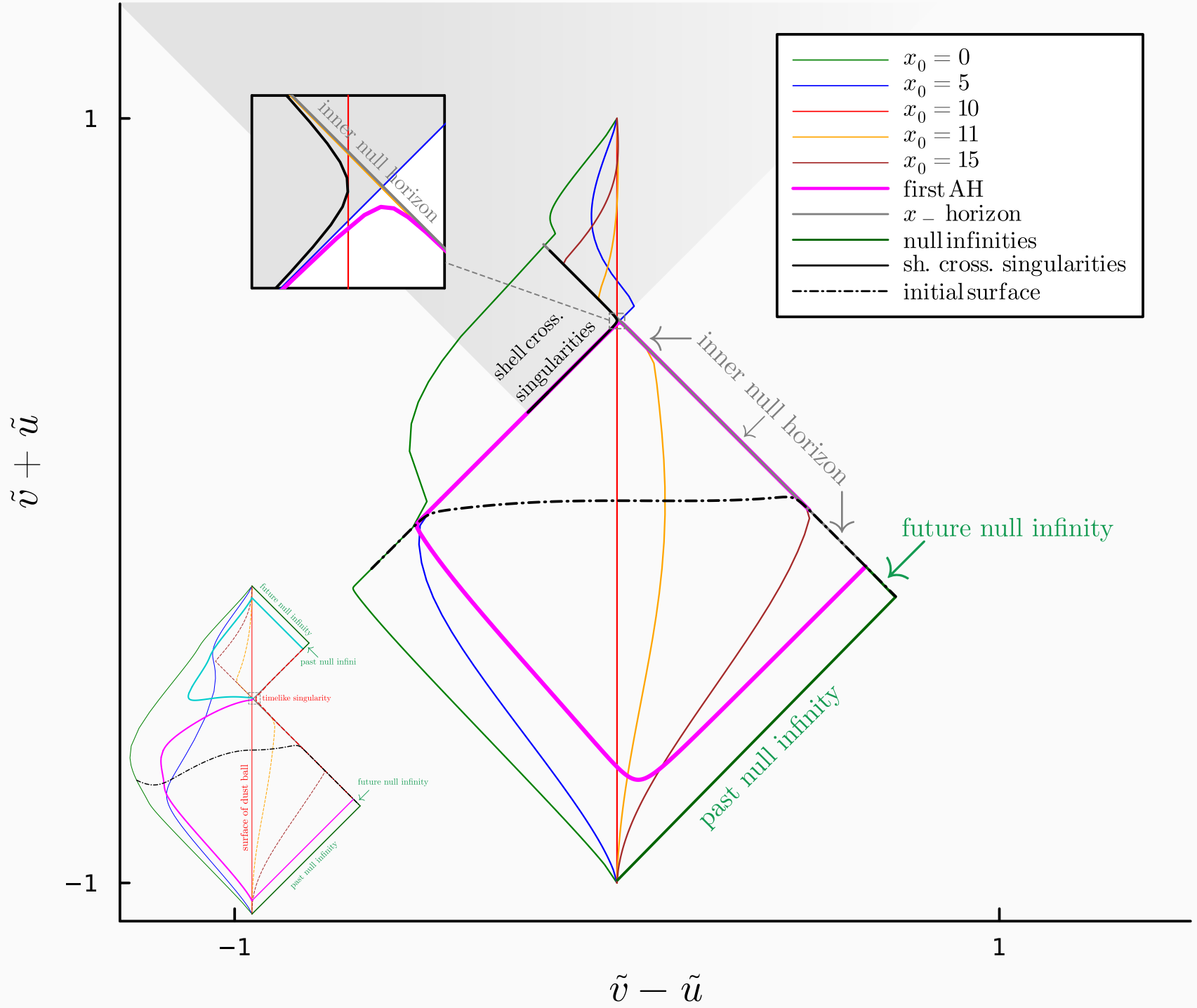
Gaussian initial dust profile

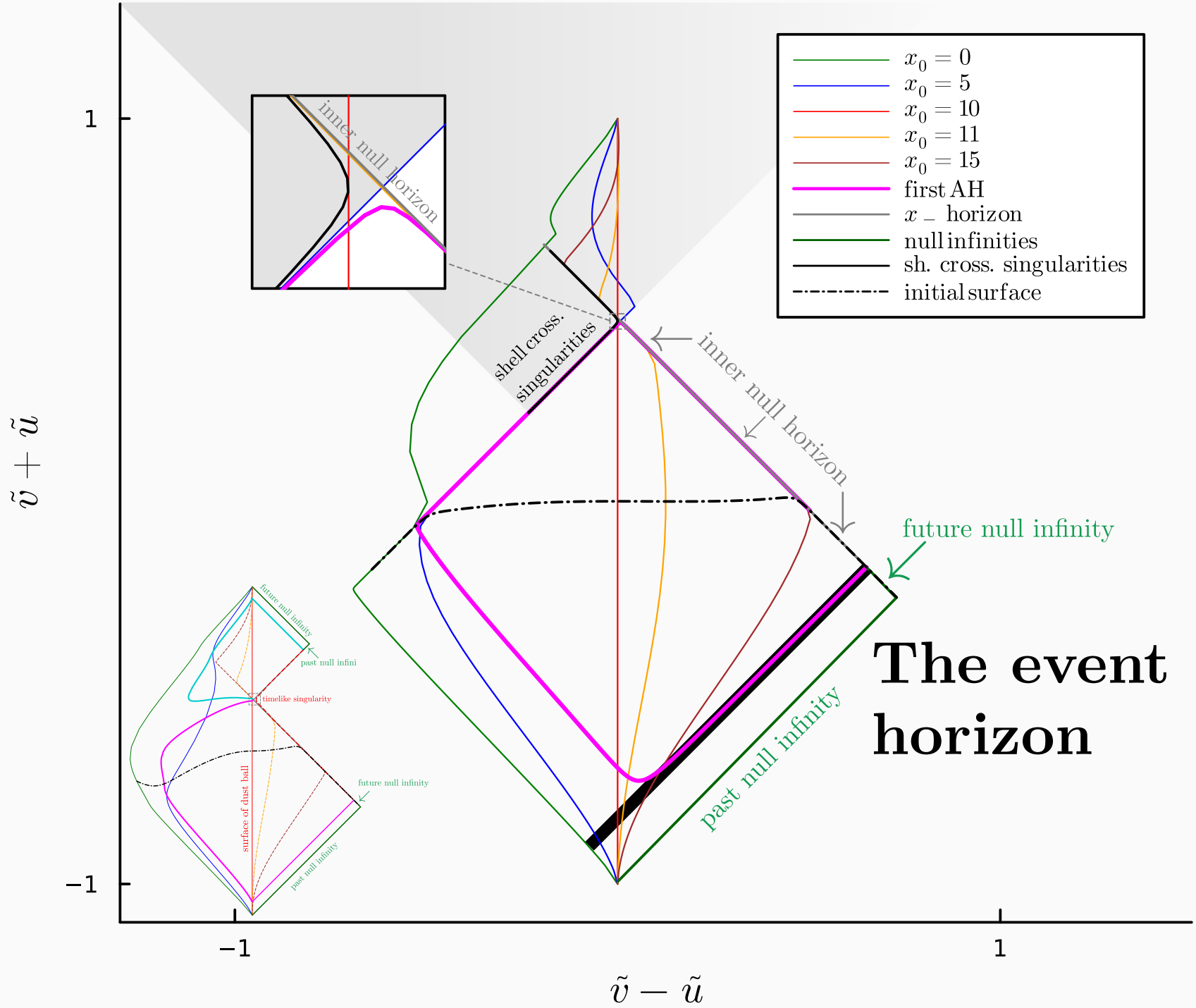
$$\rho_{\mathrm{NH}}(\lambda = 0, x_0) = \rho_0 \exp\left(\frac{-x_0^2}{2\mathcal{R}^2}\right) ,$$

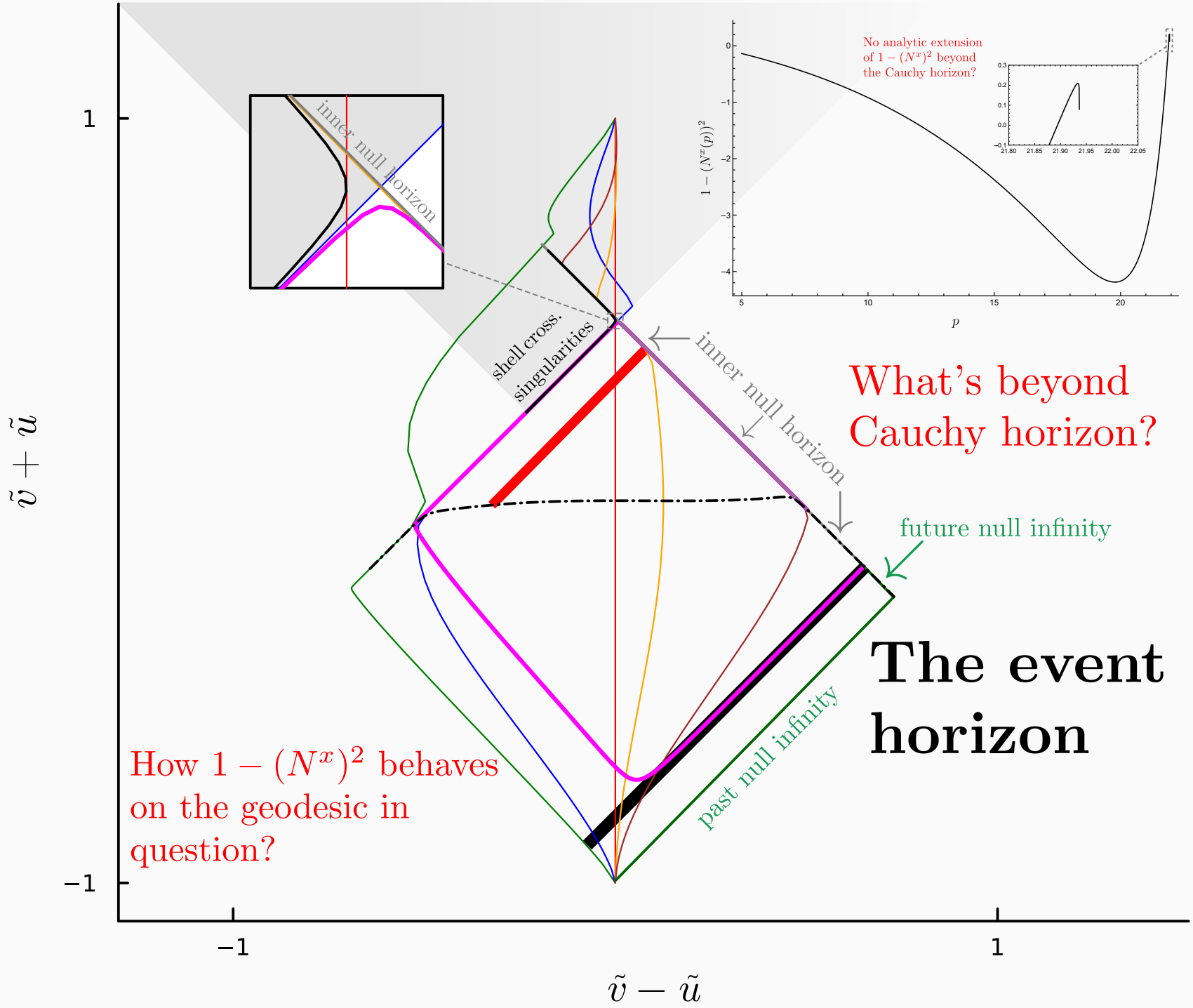
Shell-crossing singularities. (seminally studied by [Fazzini, PRD 2024])

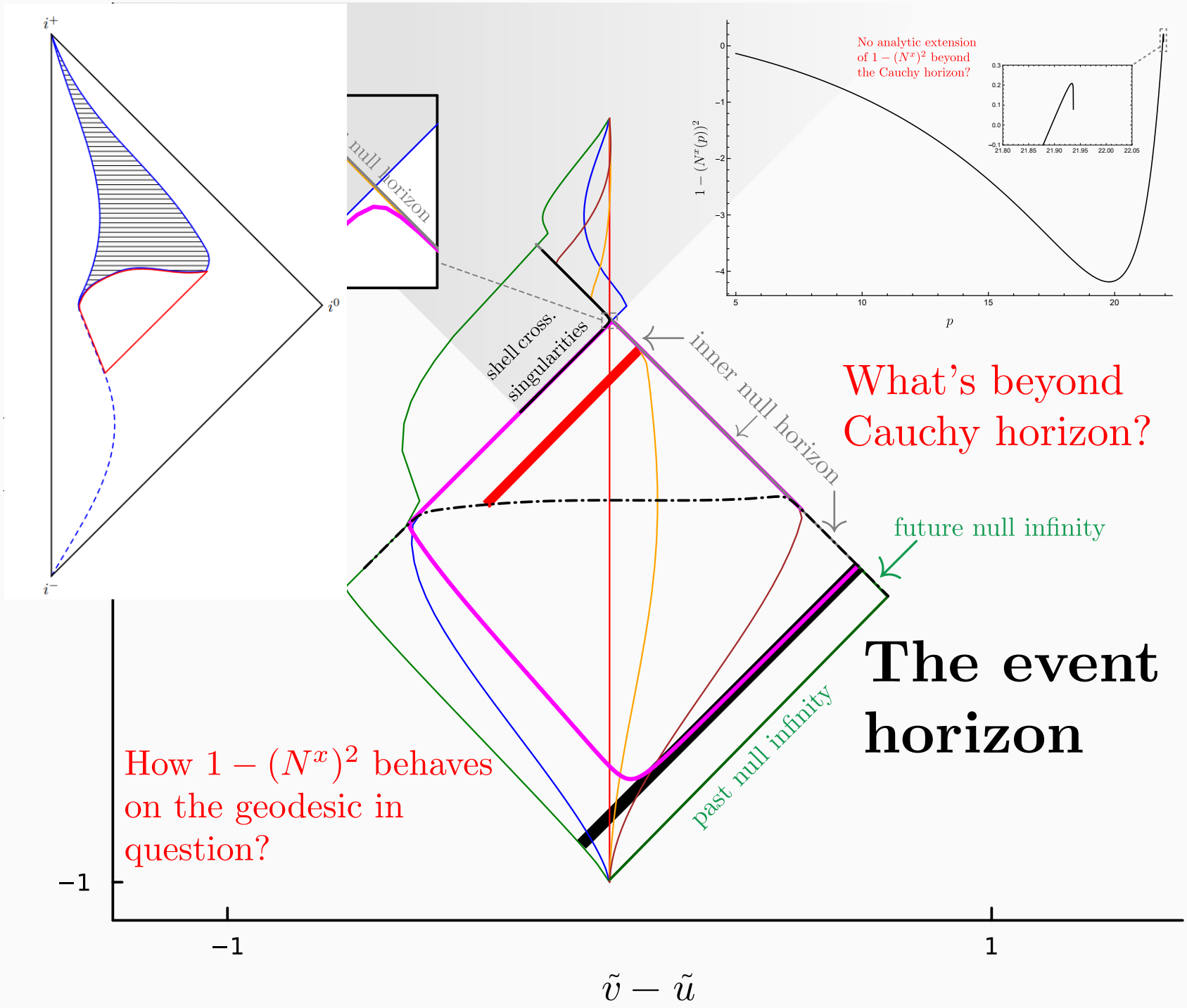
The energy denisty blows up at certain spacetime points $\rho = -\frac{\mathcal{H}_{\mathrm{phys}}}{4\pi x^2}$. The radial timelike geodesics [MB, T. Pawłowski, PRD 2025]:




$x_0 = 0$
$x_0 = 5$
$x_0 = 10$
$x_0 = 11$
$x_0 = 15$
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
$\tilde{v} + \tilde{u}$
$\tilde{v} - \tilde{u}$
1
−1
−1
1
future null infinity
past null infini
timelike singularity
surface of dust ball
future null infinity
past null infinity


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?
No analytic extension of $1-(N^x)^2$ beyond the Cauchy horizon?
$1-(N^x(p))^2$
p
$\tilde{v}+\tilde{u}$
$\tilde{v}-\tilde{u}$
1
−1
−1
1


i^+
i^0
i^-
null horizon
shell cross. singularities
inner null horizon
future null infinity
past null infinity
What's beyond Cauchy horizon?
The event horizon
No analytic extension of $1-(N^x)^2$ beyond the Cauchy horizon?
$1-(N^x(p))^2$
p
How $1-(N^x)^2$ behaves on the geodesic in question?
−1
−1
1
$\tilde{v}-\tilde{u}$

Long squeeze

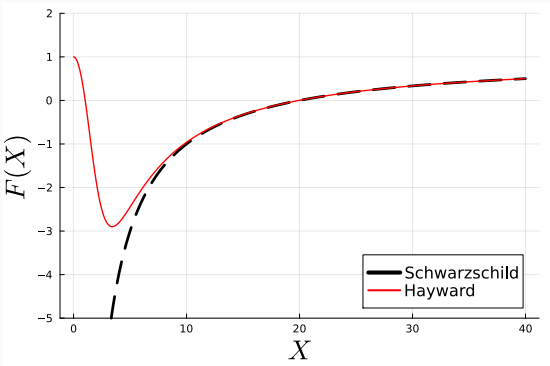
In this talk

- OS collapse. **Exterior → regular Hayward BH** No backreaction
- What is the interior and its cosmological properties?

Quantum-corrected Schwarzschild metric – Hayward black hole [Hayward, PRL 2005], **Globally hyperbolic spacetime for BH formation and evaporation**:

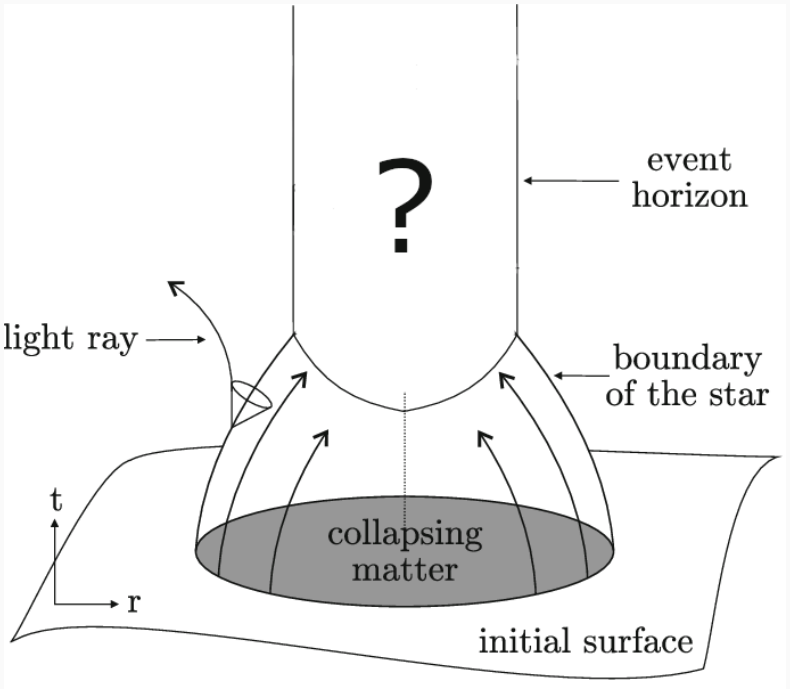
$$\mathrm{d}s^2_{\mathrm{ext}} = -F(X)\mathrm{d}t^2 + F(X)^{-1}\mathrm{d}X^2 + X^2\mathrm{d}\Omega^2 \quad (4)$$

$$F(X) = 1 - \frac{2MX^2}{X^3 + 2l^2M}.$$



What is the FRW geometry modeling the interior of the dust ball?

$$\mathrm{d}s^2_{\mathrm{int}} = -\mathrm{d}T^2 + a(T)^2\,\mathrm{d}r^2 + r^2 a(T)^2\,\mathrm{d}\Omega^2. \quad (5)$$



Dust ball interior: FRW geometry

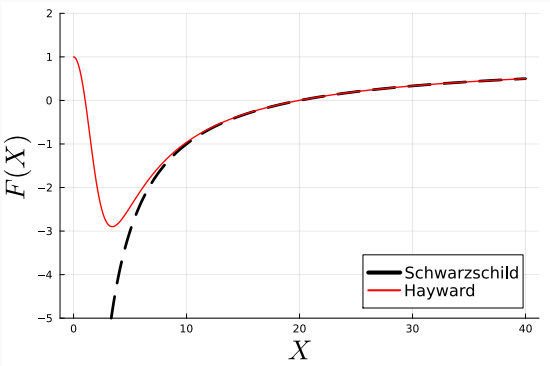
In this talk

- OS collapse. **Exterior → regular Hayward BH** No backreaction
- What is the interior and its cosmological properties?

Quantum-corrected Schwarzschild metric – Hayward black hole [Hayward, PRL 2005], **Globally hyperbolic spacetime for BH formation and evaporation**:

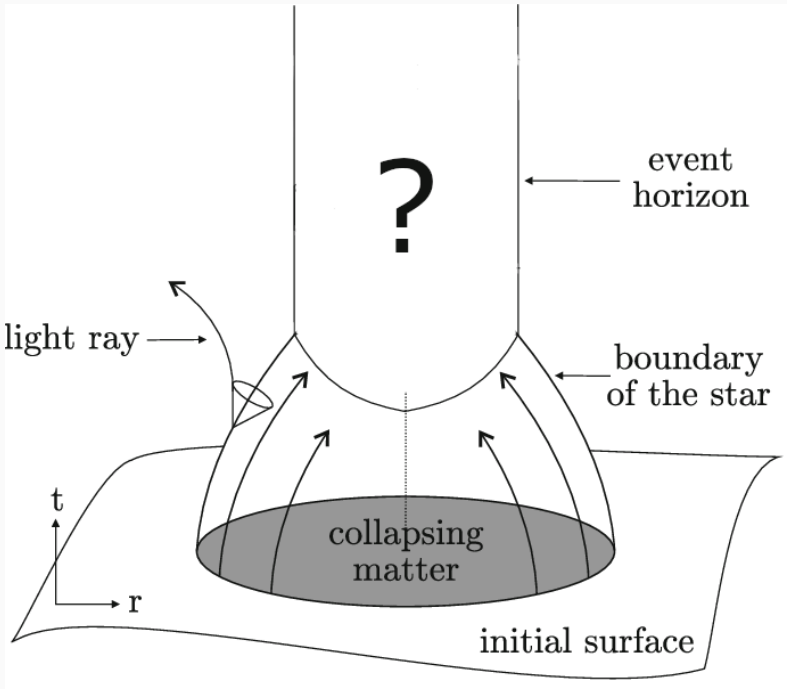
$$\mathrm{d}s^2_{\mathrm{ext}} = -F(X)\mathrm{d}t^2 + F(X)^{-1}\mathrm{d}X^2 + X^2\mathrm{d}\Omega^2 \quad (4)$$

$$F(X) = 1 - \frac{2MX^2}{X^3 + 2l^2M}.$$



What is the FRW geometry modeling the interior of the dust ball?

$$\mathrm{d}s^2_{\mathrm{int}} = -\mathrm{d}T^2 + a(T)^2\,\mathrm{d}r^2 + r^2 a(T)^2\,\mathrm{d}\Omega^2. \quad (5)$$



Dust ball interior: FRW geometry

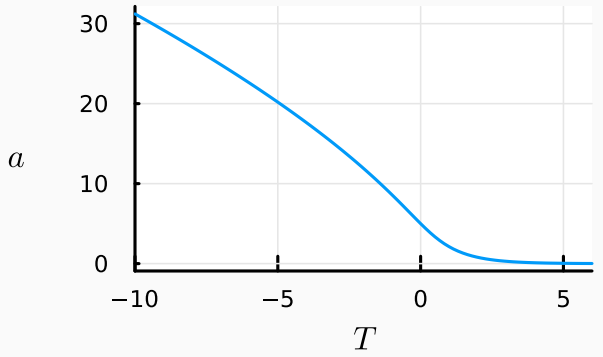
Two descriptions delivering Hayward black hole as a vacuum solution (no new fields or dof):
i) $D \geq 5$ Quasi-topological Gravity → E-H action supplemented with infinite tower of higher-curvature corrections. Eq. of motion of second order in sph. symm. [Bueno, PLB 2024]
ii) Giesel-Liu-Rullit-Singh-Weigl framework for polymerized LTB spacetimes [PRD 2025]. Hayward BH → specific Hamiltonian polymerization. Fine-tuning.

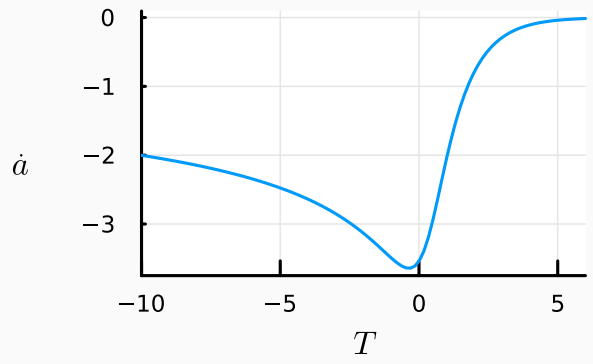
A universe out of Hayward black hole

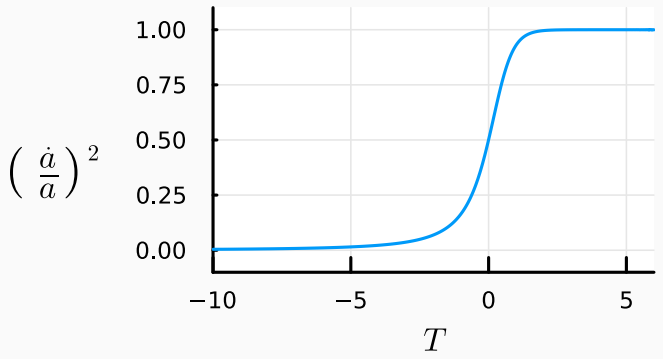
Assumptions:
i) Israel-Darmois junction conditions hold
ii) conservation of dust EM tensor
They fully determine the dynamics.

- Modified Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3 + 8\pi l^2 \rho}$$







A universe out of Hayward black hole

Assumptions:
i) Israel-Darmois junction conditions hold
ii) conservation of dust EM tensor
They fully determine the dynamics.

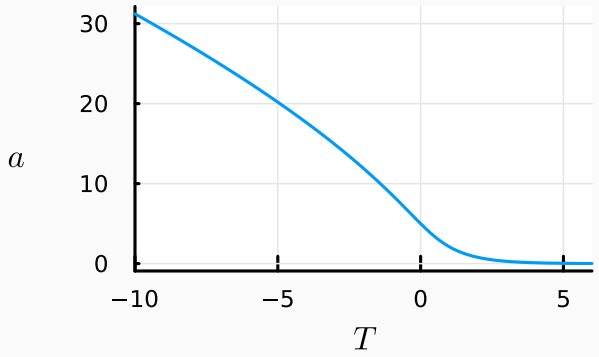
- Modified Friedmann equation

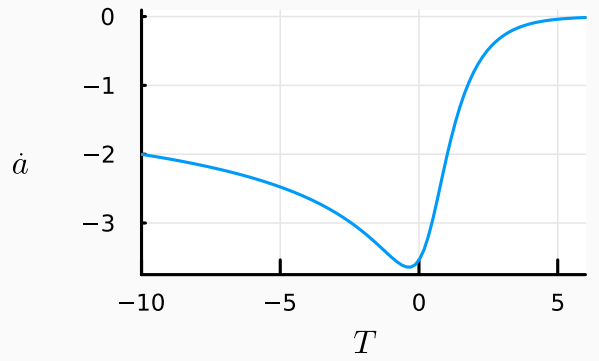
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3+8\pi l^2\rho}$$

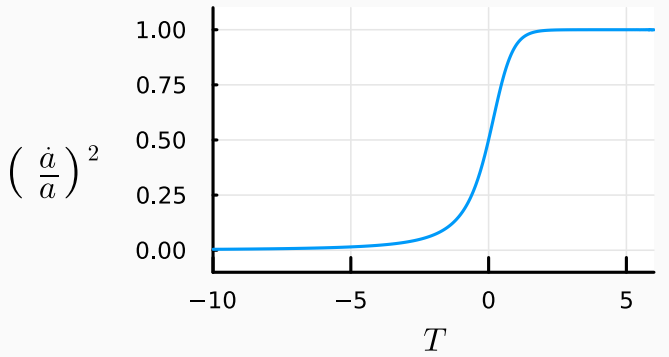
Expanding

$$\frac{8\pi\rho}{3+8\pi l^2\rho} = \frac{8\pi\rho}{3} - \frac{64}{9}\left(\pi^2 l^2\right)\rho^2 + \frac{512}{27}\pi^3 l^4 \rho^3 \ldots$$

Infinite tower of higher-order correction weighted by powers of Planck length.
2nd order truncation $\rightarrow$ bounce







A universe out of Hayward black hole

Assumptions:
i) Israel-Darmois junction conditions hold
ii) conservation of dust EM tensor
They fully determine the dynamics.

- Modified Friedmann equation

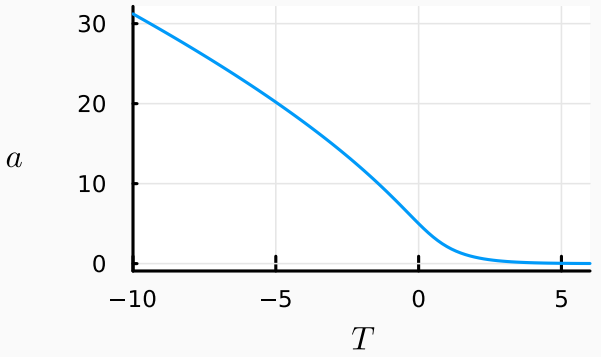
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3+8\pi l^2\rho}$$

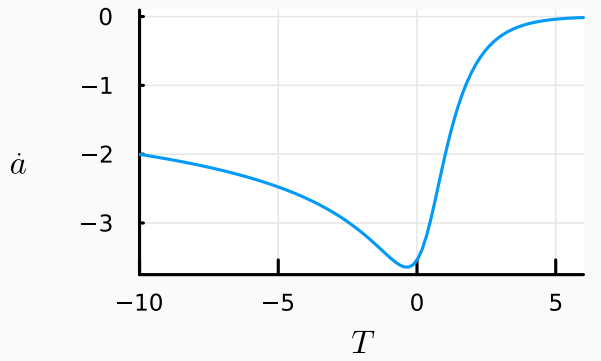
Expanding

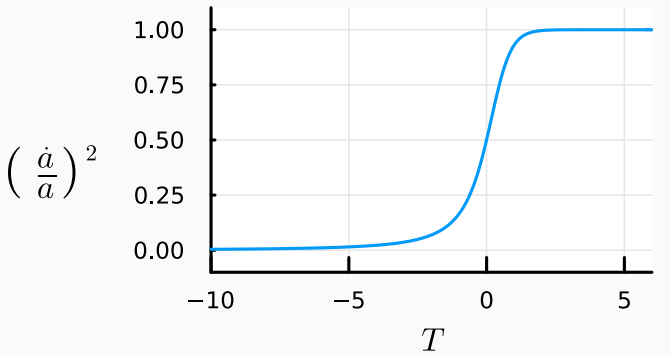
$$\frac{8\pi\rho}{3+8\pi l^2\rho} = \frac{8\pi\rho}{3} - \frac{64}{9}\left(\pi^2 l^2\right)\rho^2 + \frac{512}{27}\pi^3 l^4 \rho^3 \ldots$$

Infinite tower of higher-order correction weighted by powers of Planck length.
2nd order truncation $\rightarrow$ bounce

- No curvature singularities, even when $a \rightarrow 0$ as $T \rightarrow \infty$. Timelike geodesic completeness.







A universe out of Hayward black hole

Assumptions:
i) Israel-Darmois junction conditions hold
ii) conservation of dust EM tensor
They fully determine the dynamics.

- Modified Friedmann equation

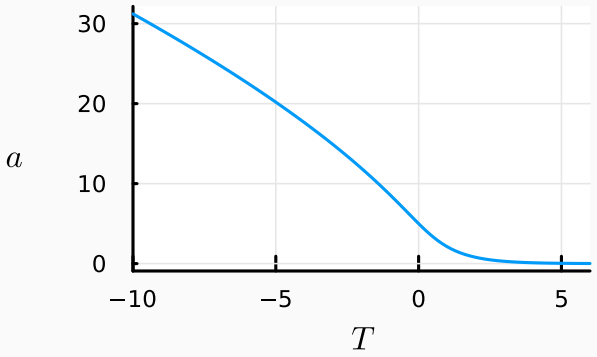
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3 + 8\pi l^2 \rho}$$

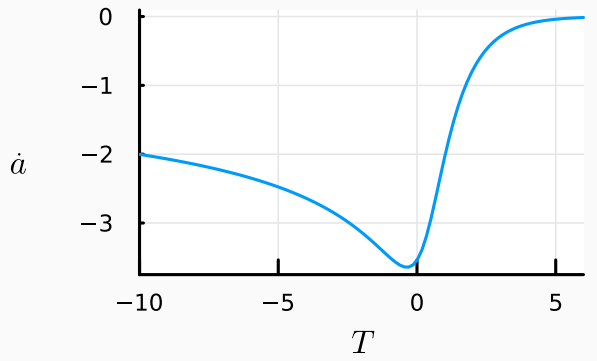
Expanding

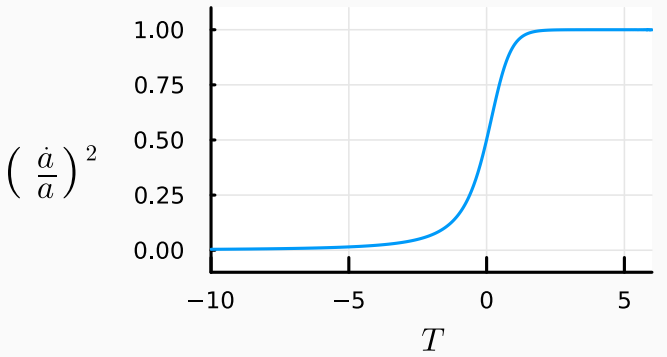
$$\frac{8\pi\rho}{3 + 8\pi l^2 \rho} = \frac{8\pi\rho}{3} - \frac{64}{9}\left(\pi^2 l^2\right)\rho^2 + \frac{512}{27}\pi^3 l^4 \rho^3 \ldots$$

Infinite tower of higher-order correction weighted by powers of Planck length.
2nd order truncation $\rightarrow$ bounce

- No curvature singularities, even when $a \rightarrow 0$ as $T \rightarrow \infty$. Timelike geodesic completeness.
- Slow roll without slow roll. No inflaton field. Graceful entrance to inflation.







A universe out of Hayward black hole

Assumptions:
i) Israel-Darmois junction conditions hold
ii) conservation of dust EM tensor
They fully determine the dynamics.

- Modified Friedmann equation

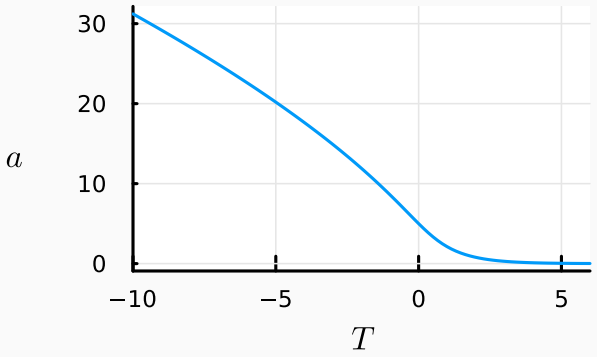
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3+8\pi l^2\rho}$$

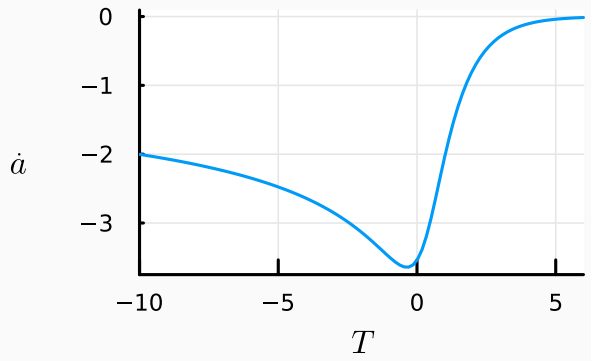
Expanding

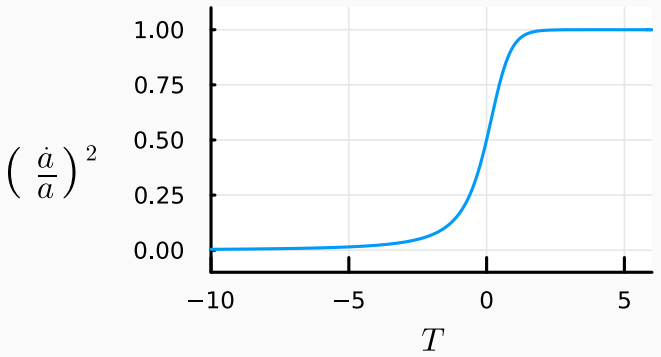
$$\frac{8\pi\rho}{3+8\pi l^2\rho} = \frac{8\pi\rho}{3} - \frac{64}{9}\left(\pi^2 l^2\right)\rho^2 + \frac{512}{27}\pi^3 l^4 \rho^3 \ldots$$

Infinite tower of higher-order correction weighted by powers of Planck length.
2nd order truncation $\rightarrow$ bounce

- No curvature singularities, even when $a \rightarrow 0$ as $T \rightarrow \infty$. Timelike geodesic completeness.
- Slow roll without slow roll. No inflaton field. Graceful entrance to inflation.
- The energy density $\rho = M/\left(\frac{4}{3}\pi r_b^3 a^3\right)$ diverges in the final collapsing point $T \rightarrow \infty$.





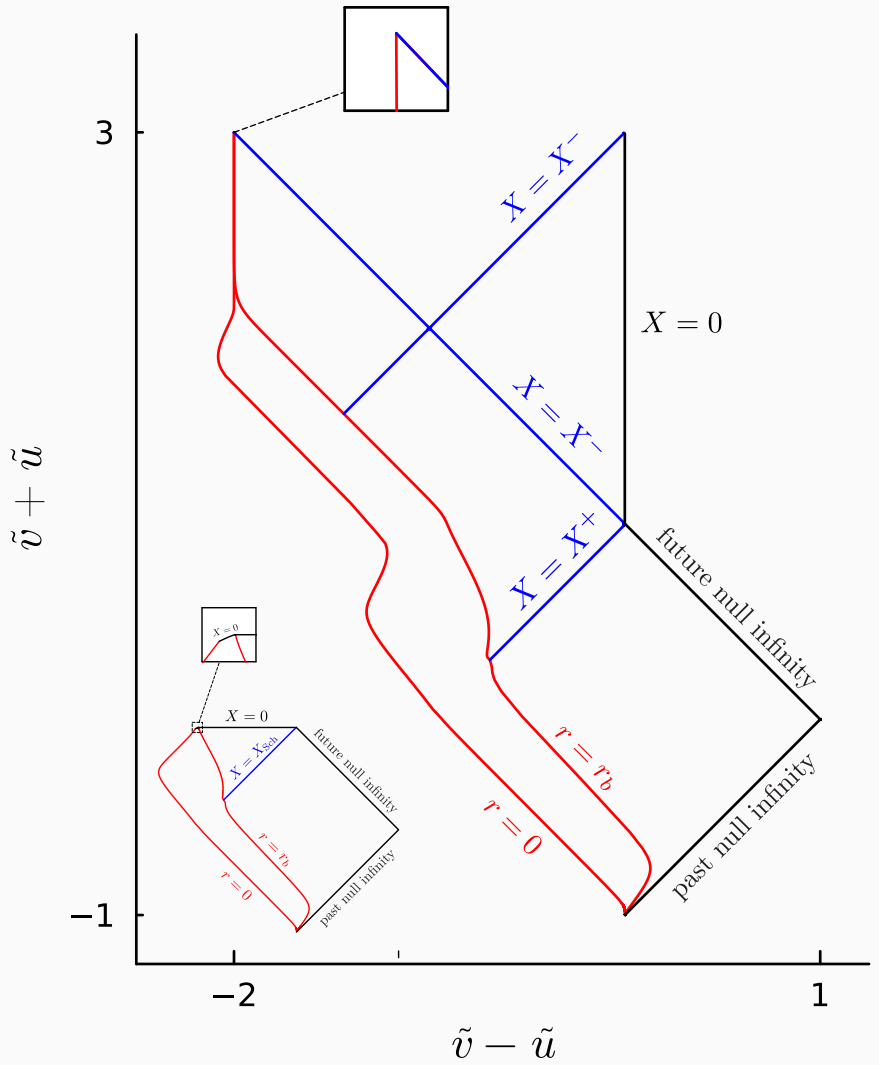


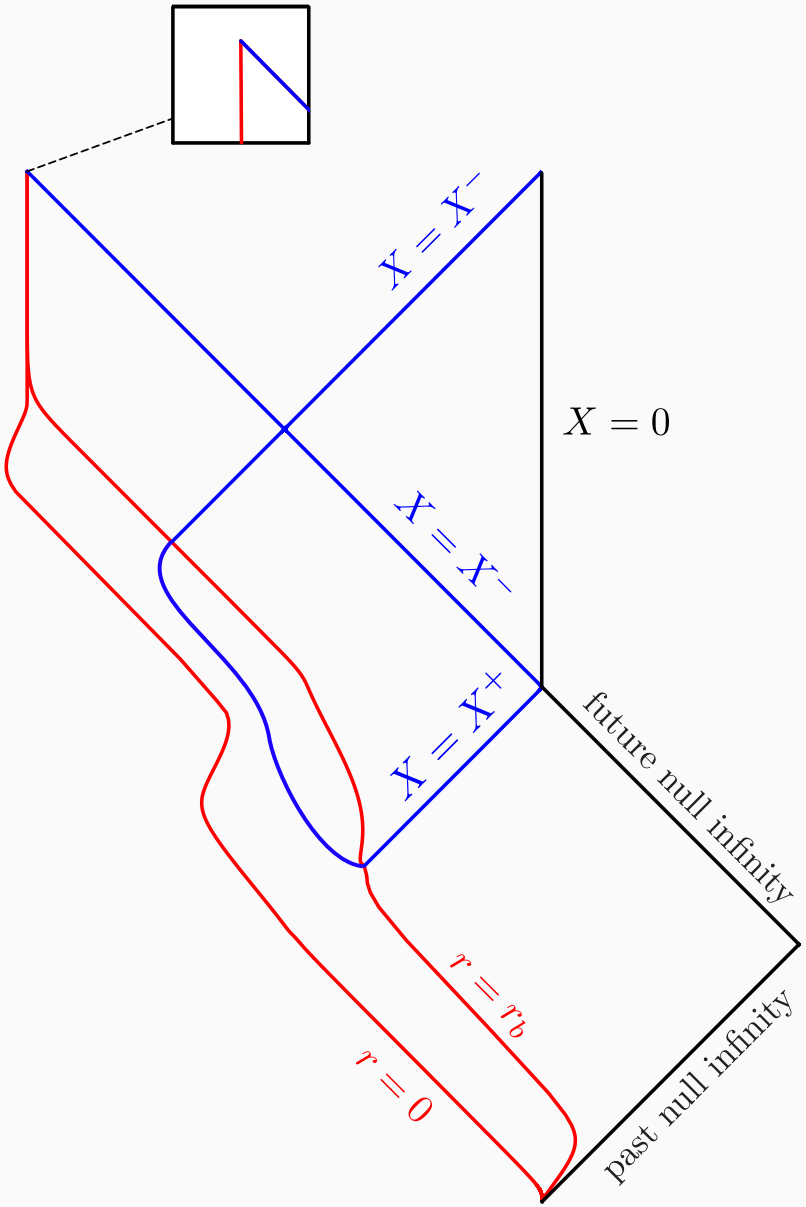
Conformal diagram for the modified OS collapse

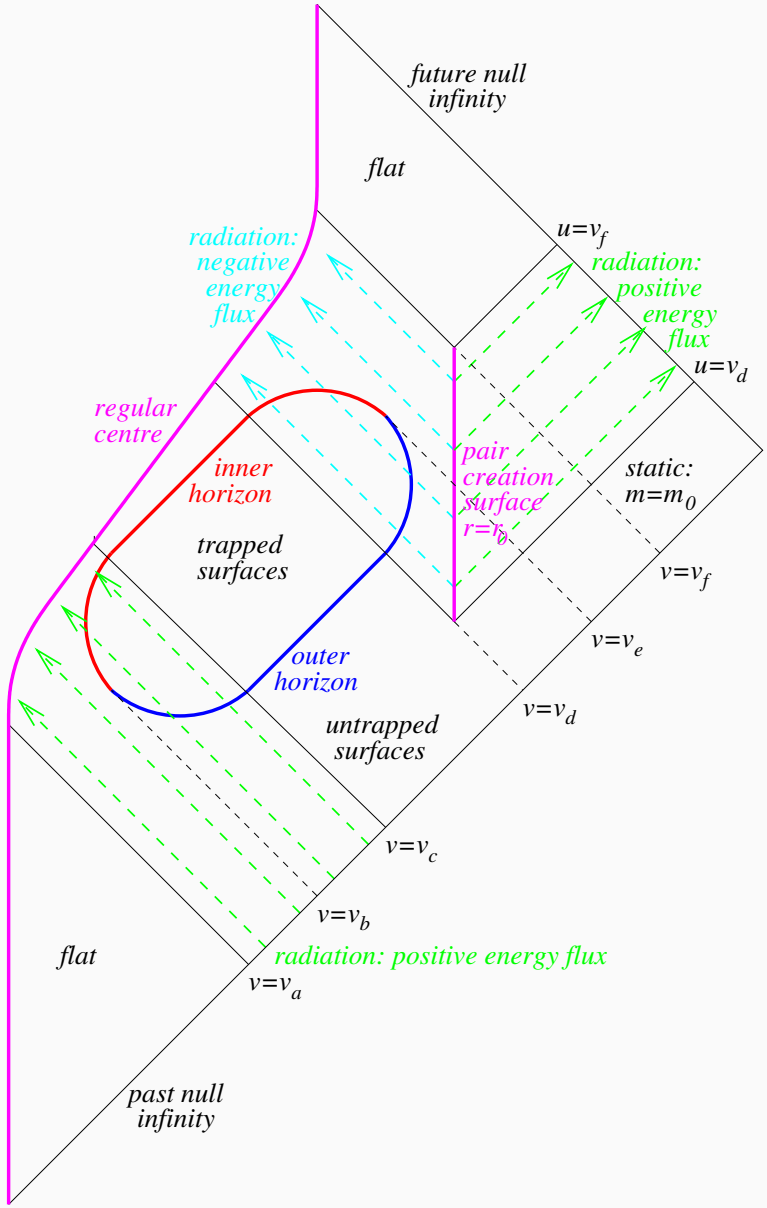
[MB, CQG 2025]

- Perpetual collapse. Long Squeeze instead of classical Big Crunch.
- The spacetime is geodesically complete.
- Cosmic inflation decelerates collapsing matter thereby prevents singularity formation.
- Lesson for cosmology. How cosmologies can circumvent Borde-Vilenkin-Guth theorem *Inflationary spacetimes are past incomplete.*
  Nonhomogeneous vacuum can serve as a completion of finite homogeneous and isotropic sector of the universe.

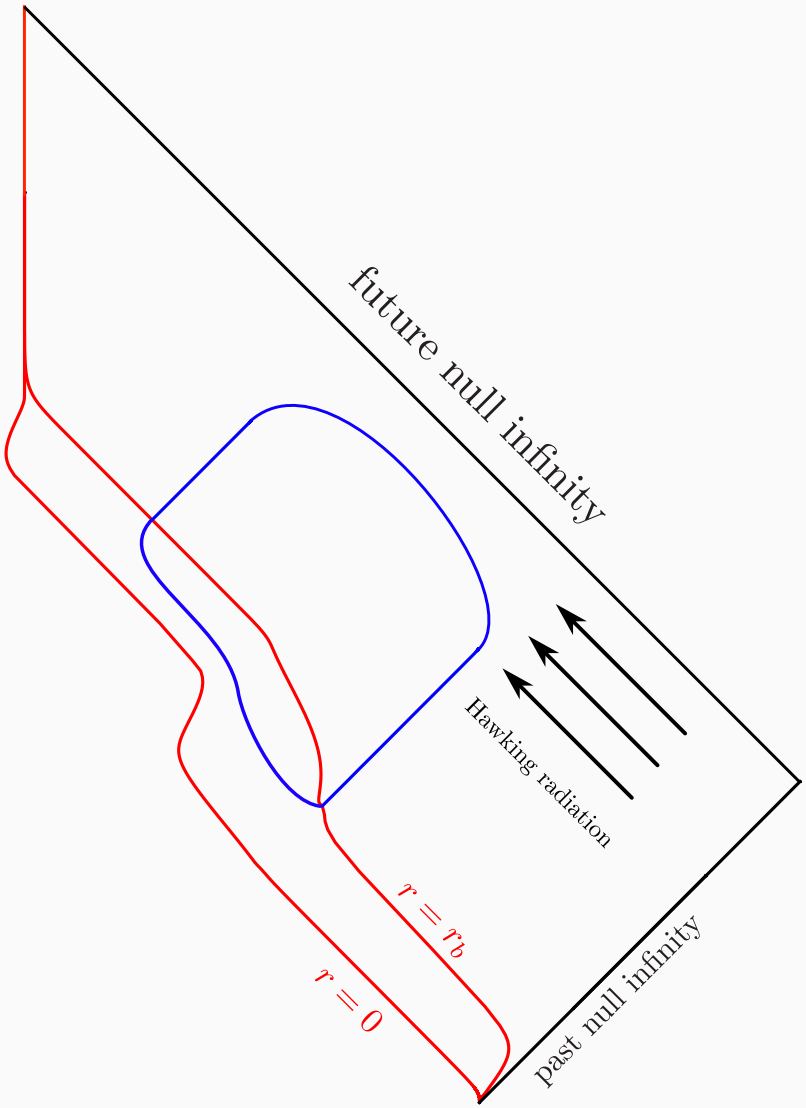
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3 + 8\pi l^2 \rho}$$

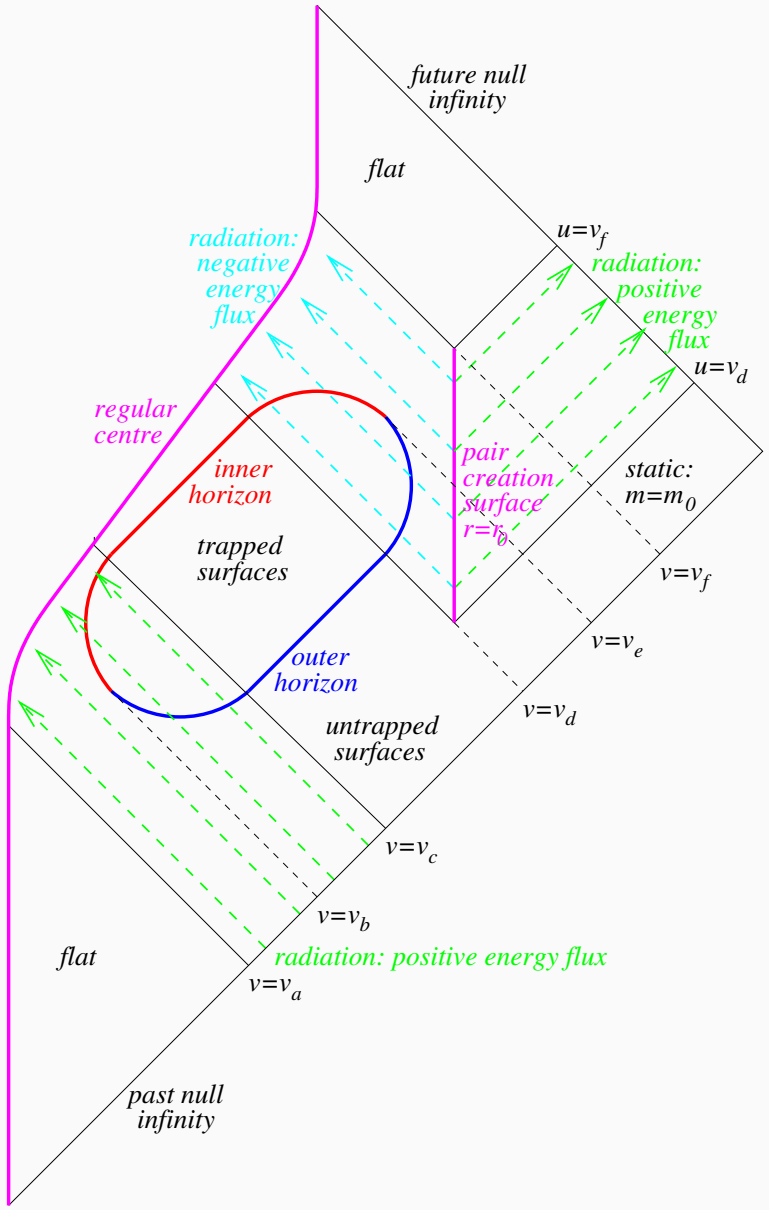




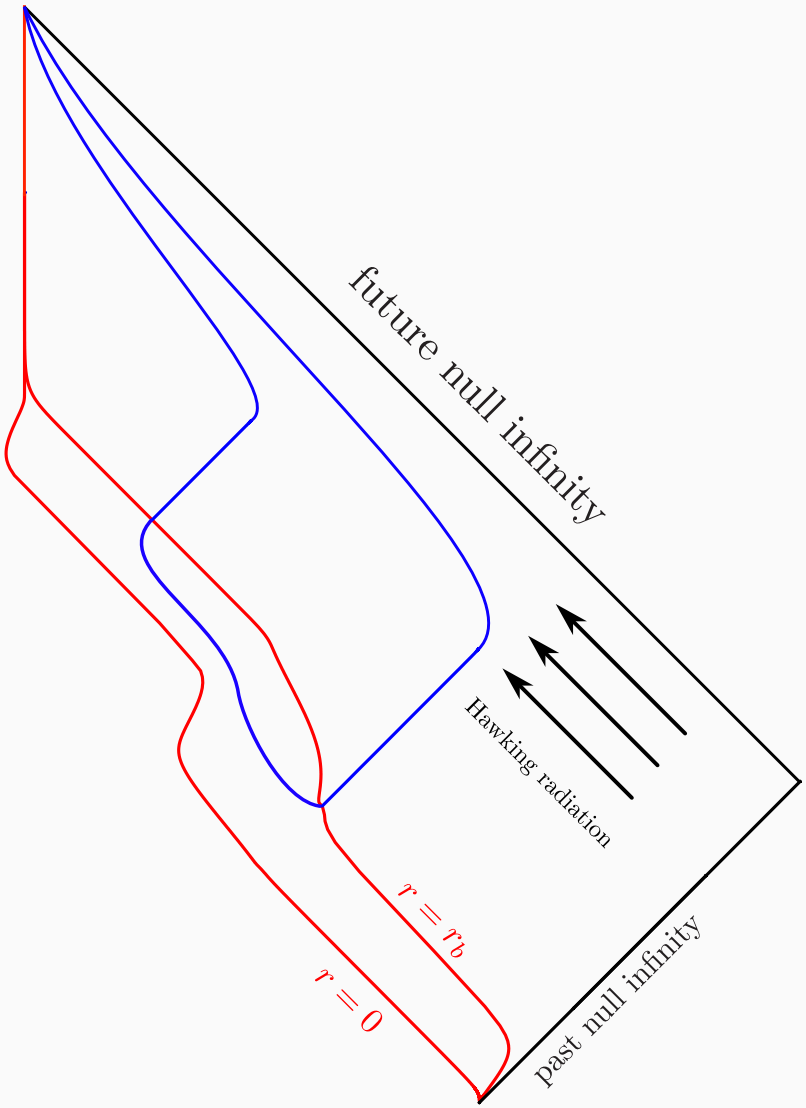


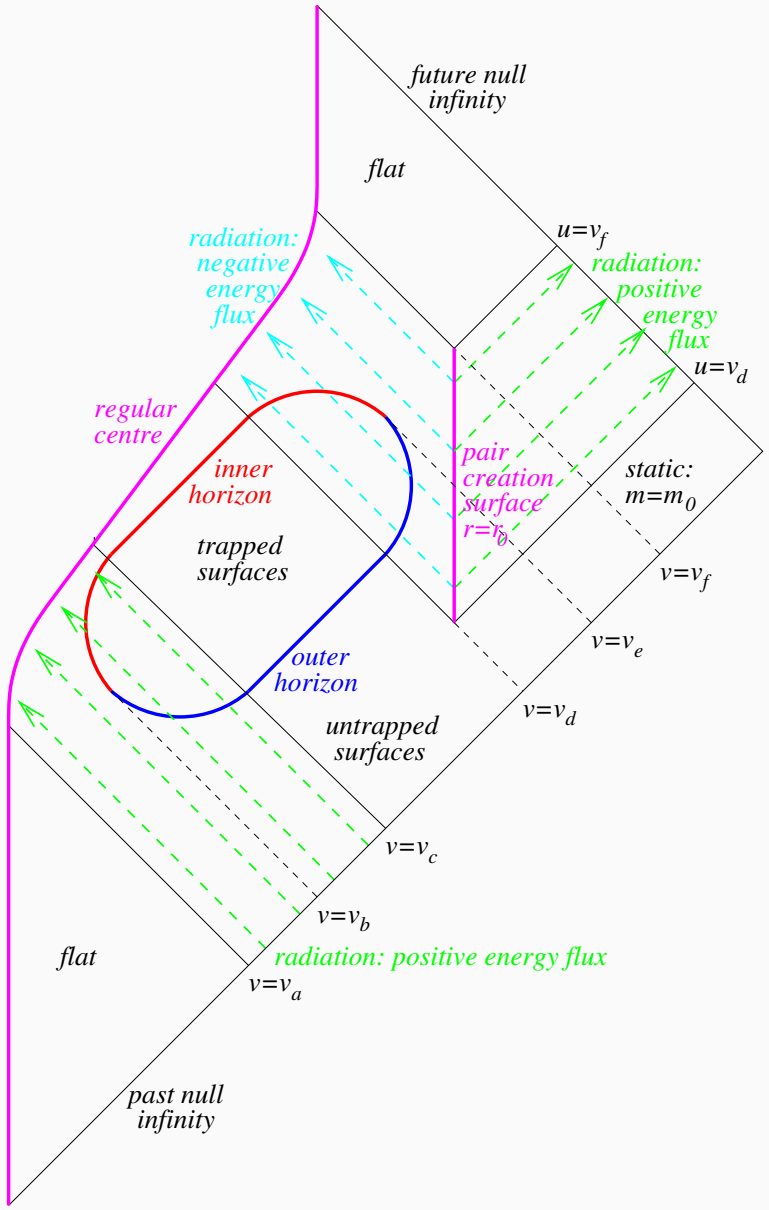
[Hayward, PRL 2005]





[Hayward, PRL 2005]





[Hayward, PRL 2005]

Discussion

- **Bounce** [MB, T. Pawłowski, PRD 2025]
  Nonhomogeneous dust collapse in effective LQG
  shell cross. singularities $\rightarrow$ *exclude large region*
  collapse cannot take place within single asymptotic region
  event horizon inevitable (highly teleological obj.)
  what is beyond Cauchy horizon $\rightarrow$ *remain open problem*

Discussion

- **Bounce** [MB, T. Pawłowski, PRD 2025]
  Nonhomogeneous dust collapse in effective LQG
  shell cross. singularities $\rightarrow$ *exclude large region*
  collapse cannot take place within single asymptotic region
  event horizon inevitable (highly teleological obj.)
  what is beyond Cauchy horizon $\rightarrow$ *remain open problem*
- **Long squeeze** [MB, CQG 2025]
  OS collapse into Hayward BH
  geodesically complete spacetime (no singularities yet EH still there)
  Slow roll without slow roll, no inflaton or new dof $\rightarrow$ *cosmic inflation prevents BH singularity formation* $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3+8\pi l^2\rho}$
  Similarities with model inspired-by Asymptotically Safe Gravity [Bonanno, PRL 2024]
  This how inflationary spacetim. circumvent Borde-Vilenkin-Guth theorem [Borde, PRL 2005]

Discussion

- **Bounce** [MB, T. Pawłowski, PRD 2025]
  Nonhomogeneous dust collapse in effective LQG
  shell cross. singularities → *exclude large region*
  collapse cannot take place within single asymptotic region
  event horizon inevitable (highly teleological obj.)
  what is beyond Cauchy horizon → *remain open problem*
- **Long squeeze** [MB, CQG 2025]
  OS collapse into Hayward BH
  geodesically complete spacetime (no singularities yet EH still there)
  Slow roll without slow roll, no inflaton or new dof → *cosmic inflation prevents BH singularity formation* $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3+8\pi l^2\rho}$
  Similarities with model inspired-by Asymptotically Safe Gravity [Bonanno, PRL 2024]
  This how inflationary spacetim. circumvent Borde-Vilenkin-Guth theorem [Borde, PRL 2005]
- **Outlook**
  Cauchy horizon instabilities → *plagues models based/inspired-by LQG, String Theory, Asymptotic Safety, success in both cosmo. and BHs only with Cauchy hor.*
  The backreaction with Hawking radiation → *seem to resolve the problem* [Hayward, PRL 2005] We need to make apparent horizon timelike again
  Global hyperbolicity only with the backreaction. → Backreaction as a necessary ingredient of predictive effective QG framework (problem absent outside sph. symm.? I doubt it)
  Brightening cosmological puzzles with black holes → ev. reg. BHs as dark matter. Is our universe geodesically complete?

Discussion

- **Bounce** [MB, T. Pawłowski, PRD 2025]
  Nonhomogeneous dust collapse in effective LQG
  shell cross. singularities → *exclude large region*
  collapse cannot take place within single asymptotic region
  event horizon inevitable (highly teleological obj.)
  what is beyond Cauchy horizon → *remain open problem*
- **Long squeeze** [MB, CQG 2025]
  OS collapse into Hayward BH
  geodesically complete spacetime (no singularities yet EH still there)
  Slow roll without slow roll, no inflaton or new dof → *cosmic inflation prevents BH singularity formation* $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3+8\pi l^2\rho}$
  Similarities with model inspired-by Asymptotically Safe Gravity [Bonanno, PRL 2024]
  This how inflationary spacetim. circumvent Borde-Vilenkin-Guth theorem [Borde, PRL 2005]
- **Outlook**
  Cauchy horizon instabilities → *plagues models based/inspired-by LQG, String Theory, Asymptotic Safety, success in both cosmo. and BHs only with Cauchy hor.*
  The backreaction with Hawking radiation → *seem to resolve the problem* [Hayward, PRL 2005] We need to make apparent horizon timelike again
  Global hyperbolicity only with the backreaction. → Backreaction as a necessary ingredient of predictive effective QG framework (problem absent outside sph. symm.? I doubt it)
  Brightening cosmological puzzles with black holes → ev. reg. BHs as dark matter. Is our universe geodesically complete?

Thank you for your attention!