Towards a Non-singular Paradigm for Black Hole Physics

Francesco Di Filippo

Goethe University, Frankfurt, Germany

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Based on:

Raúl Carballo-Rubio, FDF, Stefano Liberati, Matt Visser,

Julio Arrechea, Carlos Barceló, Alfio Bonanno, Johanna Borissova, Valentin Boyanov, Vitor Cardoso, Francesco Del Porro, Astrid Eichhorn, Daniel Jampolski, Prado Martin-Moruno, Jacopo Mazza, Tyler McMaken, Paolo Pani, Antonio Panassiti, Alessia Platania, Luciano Rezzolla, Vania Vellucci

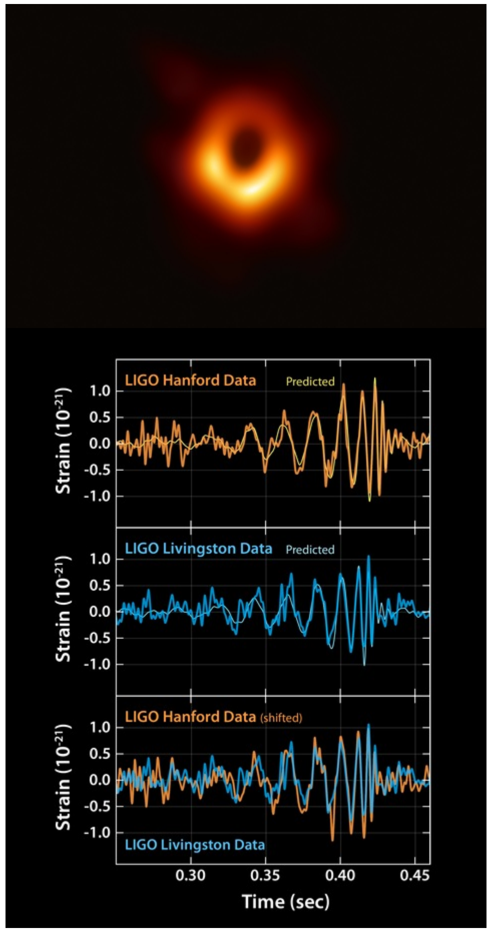
arXiv:2501.05505

Introduction

Observations coming from the LIGO/Virgo/KAGRA, the EHT, and the GRAVITY collaborations are in agreement with the prediction of general relativity.

However, there are also reasons to extend GR. In particular, the theory predicts its own breakdown due to the formation of singularities

We need a framework to study this problem



This talk will mostly be based on:

Raúl Carballo-Rubio, FDF, Stefano Liberati, Matt Visser,

Julio Arrechea, Carlos Barceló, Alfio Bonanno, Johanna Borissova, Valentin Boyanov, Vitor Cardoso, Francesco Del Porro, Astrid Eichhorn, Daniel Jampolski, Prado Martin-Moruno, Jacopo Mazza, Tyler McMaken, Paolo Pani, Antonio Panassiti, Alessia Platania, Luciano Rezzolla, Vania Vellucci

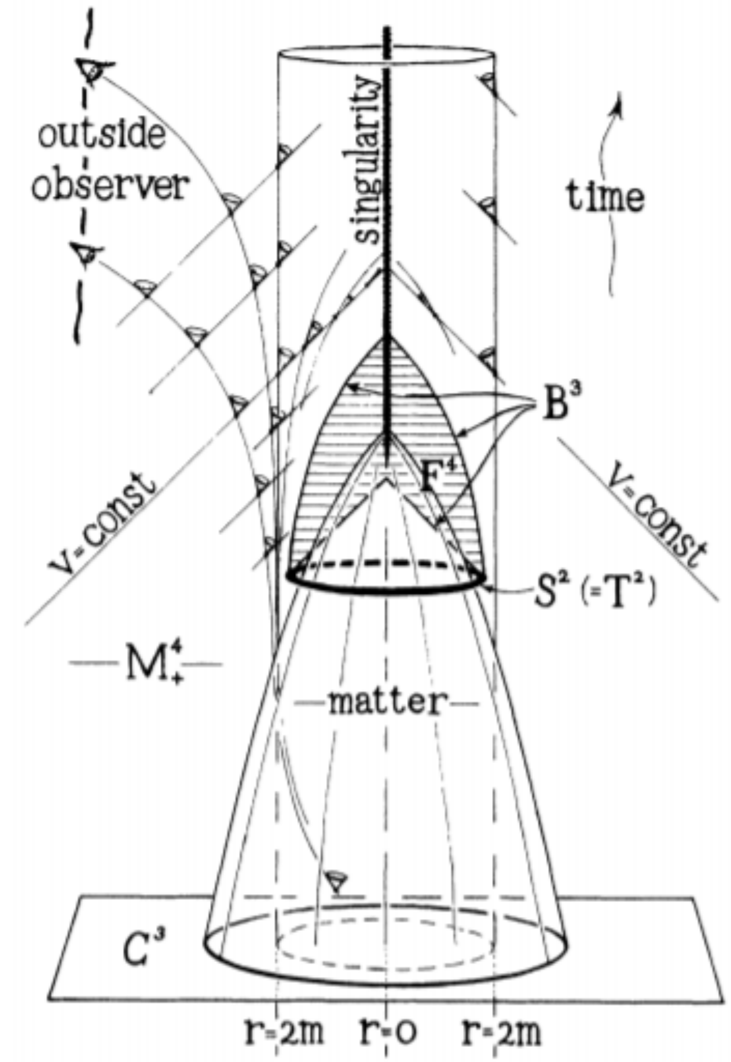
arXiv:2501.05505

Introduction

Observations coming from the LIGO/Virgo/KAGRA, the EHT, and the GRAVITY collaborations are in agreement with the prediction of general relativity.

However, there are also reasons to extend GR. In particular, the theory predicts its own breakdown due to the formation of singularities

We need a framework to study this problem



This talk will mostly be based on:

Raúl Carballo-Rubio, FDF, Stefano Liberati, Matt Visser,

Julio Arrechea, Carlos Barceló, Alfio Bonanno, Johanna Borissova, Valentin Boyanov, Vitor Cardoso, Francesco Del Porro, Astrid Eichhorn, Daniel Jampolski, Prado Martin-Moruno, Jacopo Mazza, Tyler McMaken, Paolo Pani, Antonio Panassiti, Alessia Platania, Luciano Rezzolla, Vania Vellucci

arXiv:2501.05505

Open questions

Regular black holes and black hole mimickers

- What is an adequate definition of being “non-singular”?
- Are there dynamical processes to go from regular black holes to black hole mimickers and the other way around?
- Can a geometrodynamic theory generically cure singularities?

Dynamical formation

- What are the known physical mechanisms that could lead to the formation of regular black holes and black hole mimickers?
- What are the most promising formalisms for the study of dynamical aspects?
- What are the open issues?

Instabilities

- What are the known instabilities associated with different spacetime features?
- Are instabilities shortcomings of the models, or are they informative regarding dynamics?
- What are the differences between the dynamics of classical versus semiclassical/quantum perturbations?

Observational signatures

- What are the different observational channels?
- What is the current theoretical/observational status of each channel?
- Which are the most promising channels in terms of future experiments?

Realistic astrophysical modeling

- What are the most relevant astrophysical uncertainties?
- Which ingredients do we need to go from theoretical to realistic modeling?
- Are potentially observable signatures hidden by astrophysical uncertainties?

Regular black holes vs Black hole mimickers

- What is an adequate definition of being “non-singular”?
- Are there dynamical processes to go from regular black holes to black hole mimickers and the other way around?
- Can a geometrodynamic theory generically cure singularities?

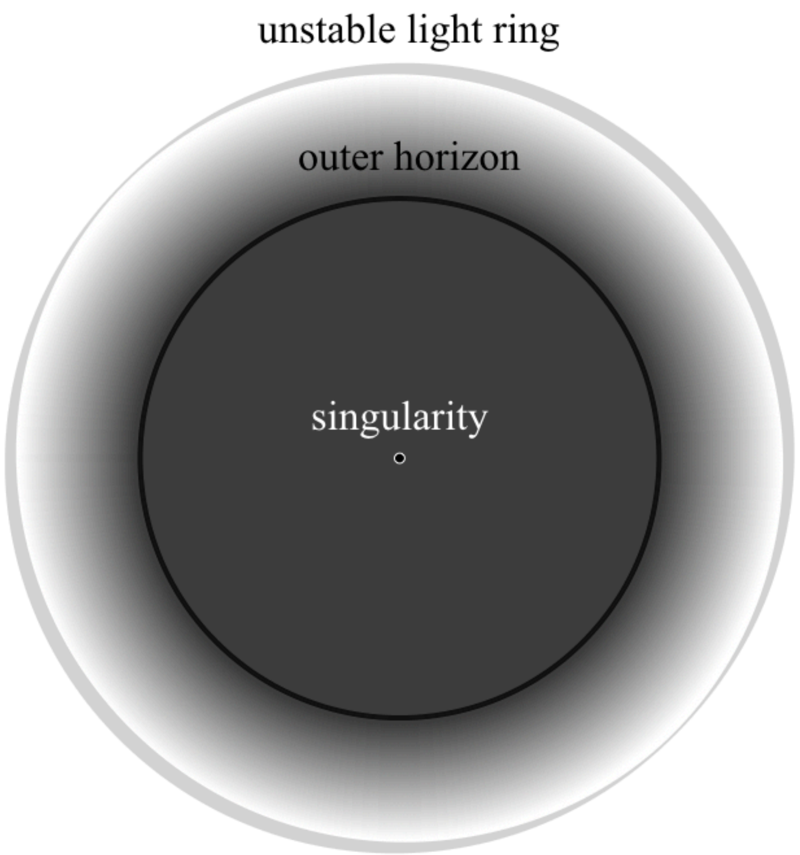
Non-singular spacetimes

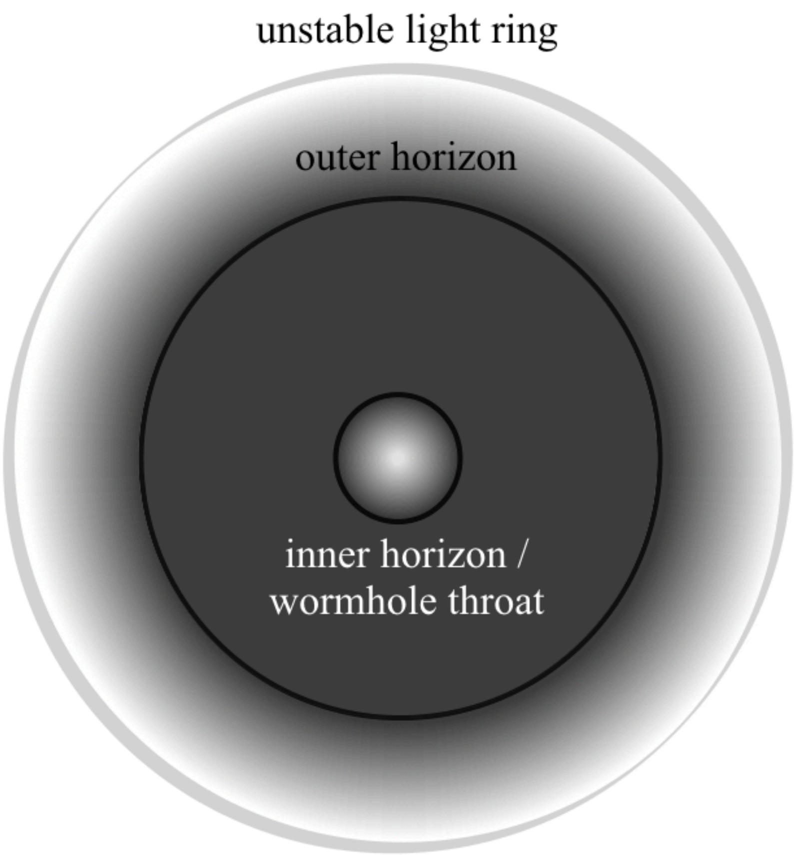
What is an adequate definition of being “non-singular”?

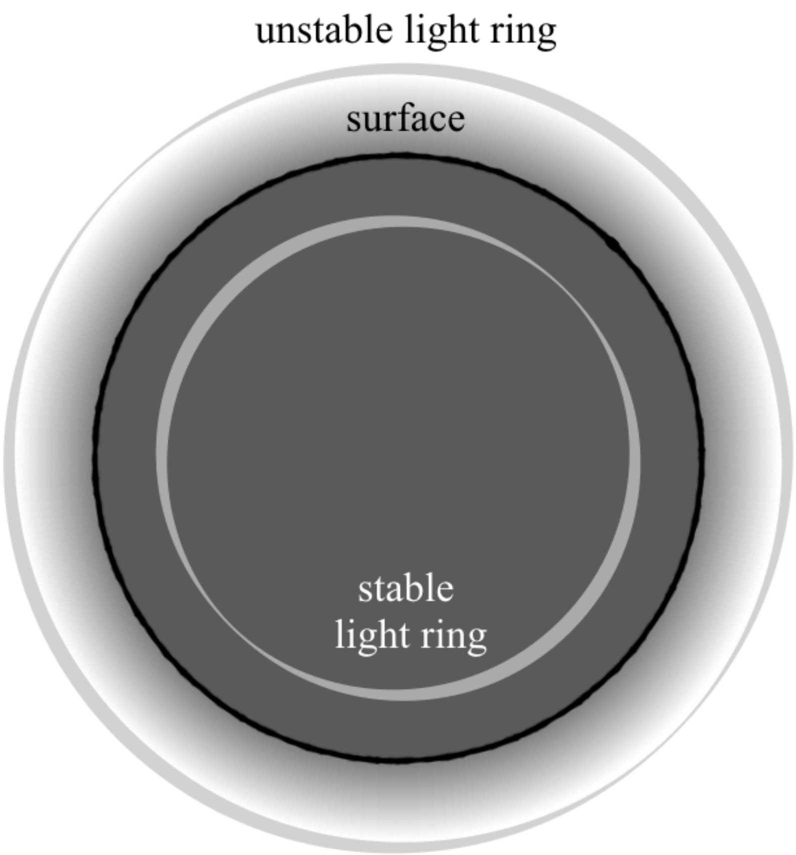
1. Completeness of physical trajectories: a predictive theory should not contain abrupt endings for physical trajectories.

2. Finiteness of physical observables: a predictive theory should yield finite values for physical observables along physical trajectories.

Non-singular spacetime







Classical Black holes

Regular Black holes

The singularity is replaced by a regular core shielded behind an inner horizon

Horizonless objects

A more extreme regular spacetime that does not have any horizon

Can a geometrodynamic theory generically cure singularities?

We assume that the tools of differential geometry and field theory are sufficient to describe non-singular scenarios.

There are (at least) two possible caveats

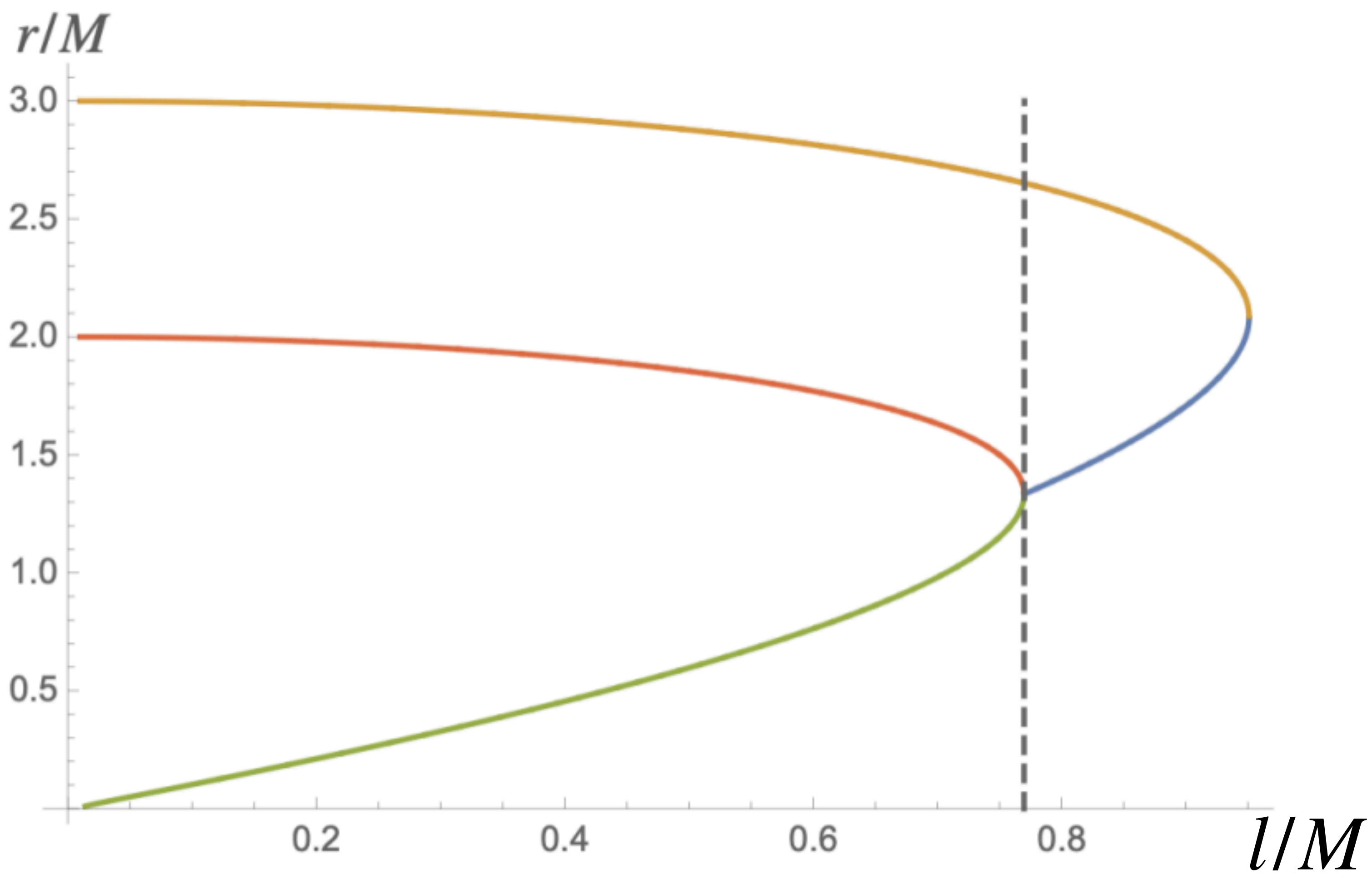
(i) A given theory might produce non-singular spacetimes from "reasonable" initial conditions while failing to do so in other cases (e.g. static vacuum solutions).

(ii) Certain physically relevant situations may necessitate alternative approaches, such as discrete geometry, to describe the interior of black holes.

A simple example

As a simple example, let us consider the geometry

$$ds^2 = -\left(1 - \frac{2Mr^2}{r^3 + 2Ml^2}\right)dv^2 + 2dvdr + r^2 d\Omega^2$$



Dynamical formation

- What are the known physical mechanisms that could lead to the formation of regular black holes and black hole mimickers?
- What are the most promising formalisms for the study of dynamical aspects?
- What are the open issues?

Instabilities

- What are the known instabilities associated with different spacetime features?
- Are instabilities shortcomings of the models, or are they informative regarding dynamics?
- What are the differences between the dynamics of classical versus semiclassical/quantum perturbations?

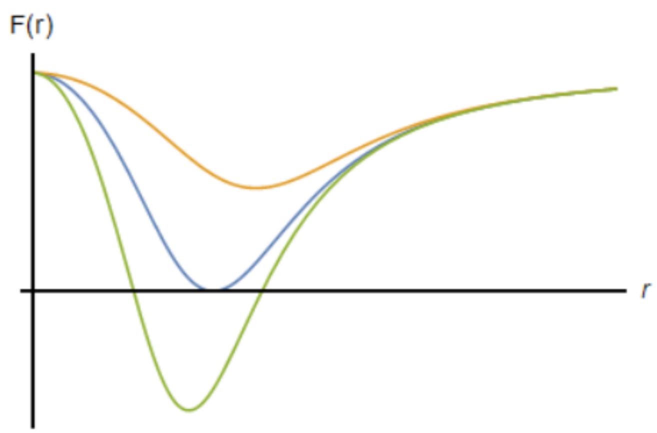
Regular black holes

Let us consider a static regular black hole

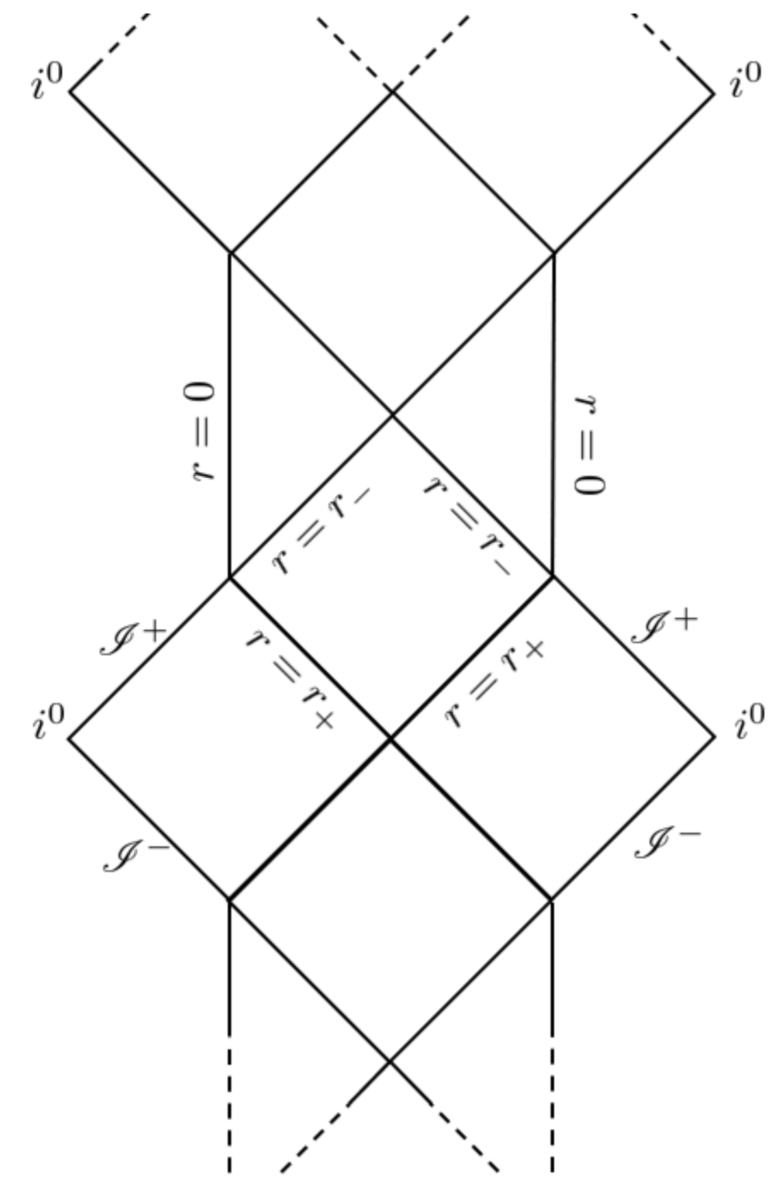
$$ds^2 = -\, e^{-2\phi(r)}F(r)dv^2 + 2e^{-\phi(r)}dvdr + r^2 d\Omega^2$$

The horizon condition is $F(r) = 0$.

- $\lim\limits_{r->\infty} F(r) = 1$
- $\lim\limits_{r->0} F(r) = 1$



There is an even number of horizons

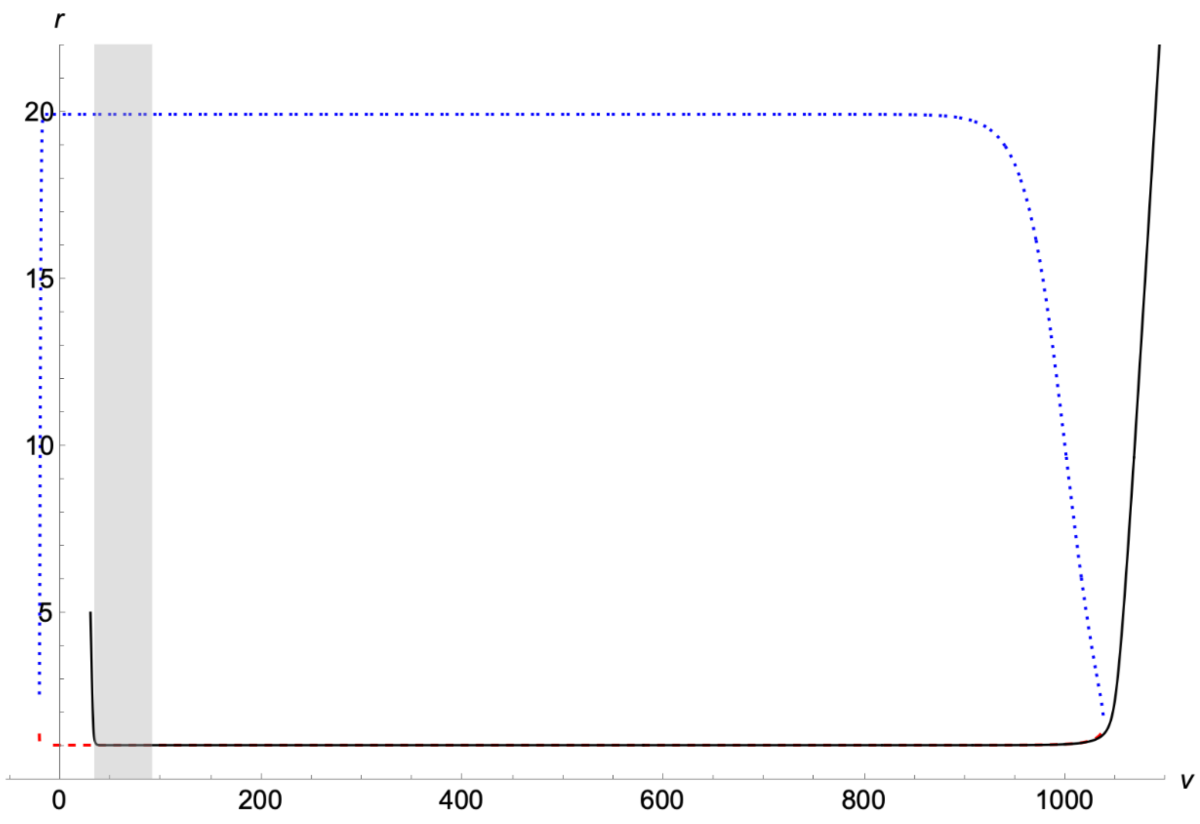


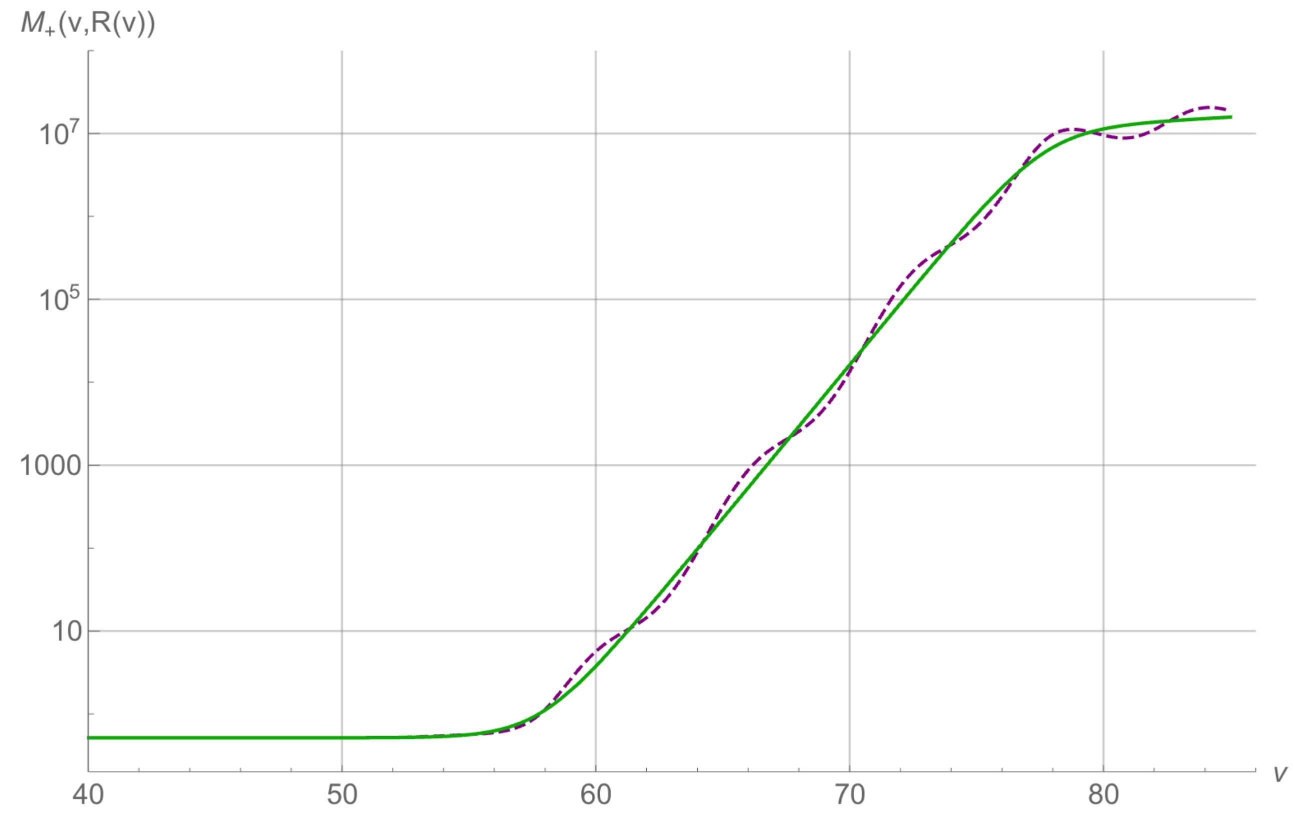
The surface gravity:

$$\kappa_\pm = \frac{1}{2} e^{-\phi(r_\pm)} \frac{dF}{dr}\bigg|_{r=r_\pm} \quad \Longrightarrow \quad \kappa_- < 0\,, \kappa_+ > 0\,.$$

Regular black holes — Mass Inflation instability

Perturbations near the inner horizon are exponentially amplified.





R. Carballo Rubio, F. Di Filippo, S. Liberati, M. Visser. *Phys.Rev.Lett.* 133 (2024) 18, 181402.

Horizonless objects — Stable light ring

Light-rings (LR) correspond to the location of circular orbits.

They play a crucial role in the study of astrophysical compact objects.

For axisymmetric spacetimes ((t, r, θ, ϕ), ∂_t and ∂_ϕ are Killing vectors), at the LRs are region null geodesics have only t and ϕ directions.

Assuming invariance under (t, φ) → (−t, −φ), and introducing the potential

$$V = \frac{1}{g_{t\phi}^2 - g_{tt}g_{\phi\phi}} \left(E^2 g_{tt} + 2E\Phi g_{t\phi} + \Phi^2 g_{\phi\phi} \right),$$

the LR conditions are

$$p_r = p_\theta = \dot{p}_\mu = 0 \iff \begin{cases} V(r,\theta) = 0 \\ \partial_\mu V(r,\theta) = 0\,. \end{cases}$$

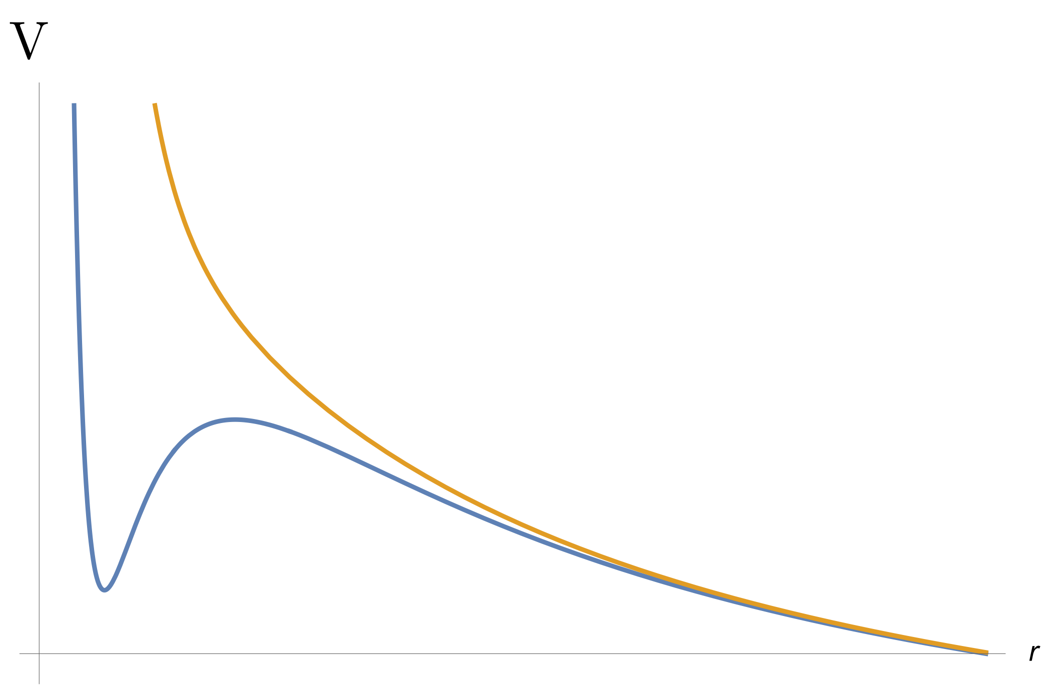
Horizonless objects — Stable light ring

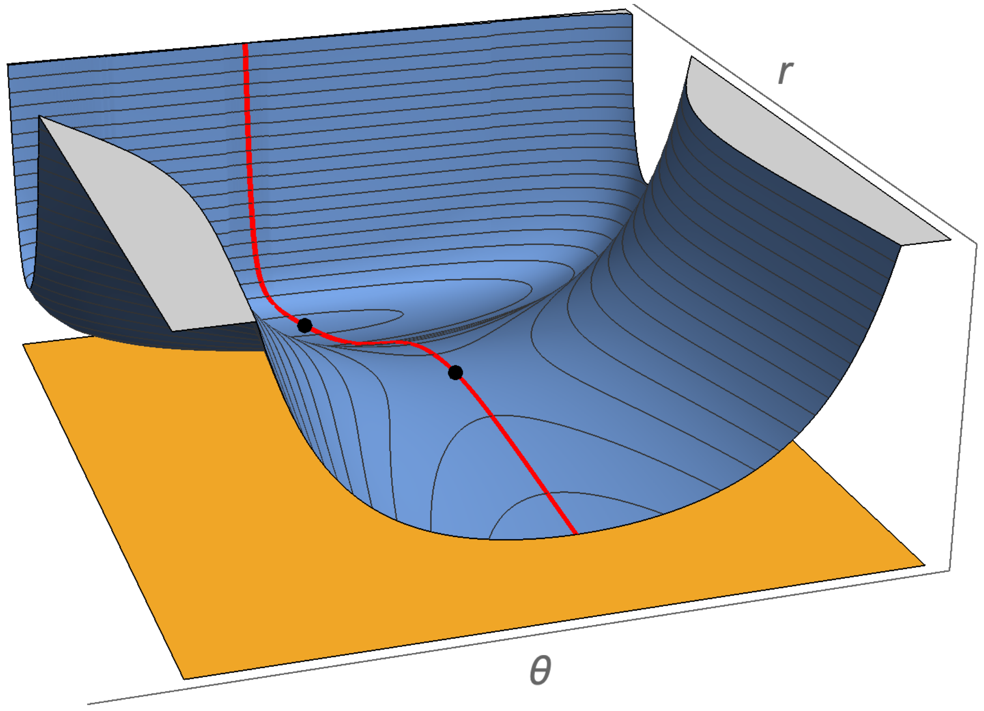
The light-rings in Kerr are saddle points of the effective potential.

Horizonless objects must have an even number of light-rings.

The inner light ring is a minimum of the effective potential [Cunha+ 2022, FDF 2024]

Stable light-rings, can lead to an unstable spacetime [Cunha+ 2022]



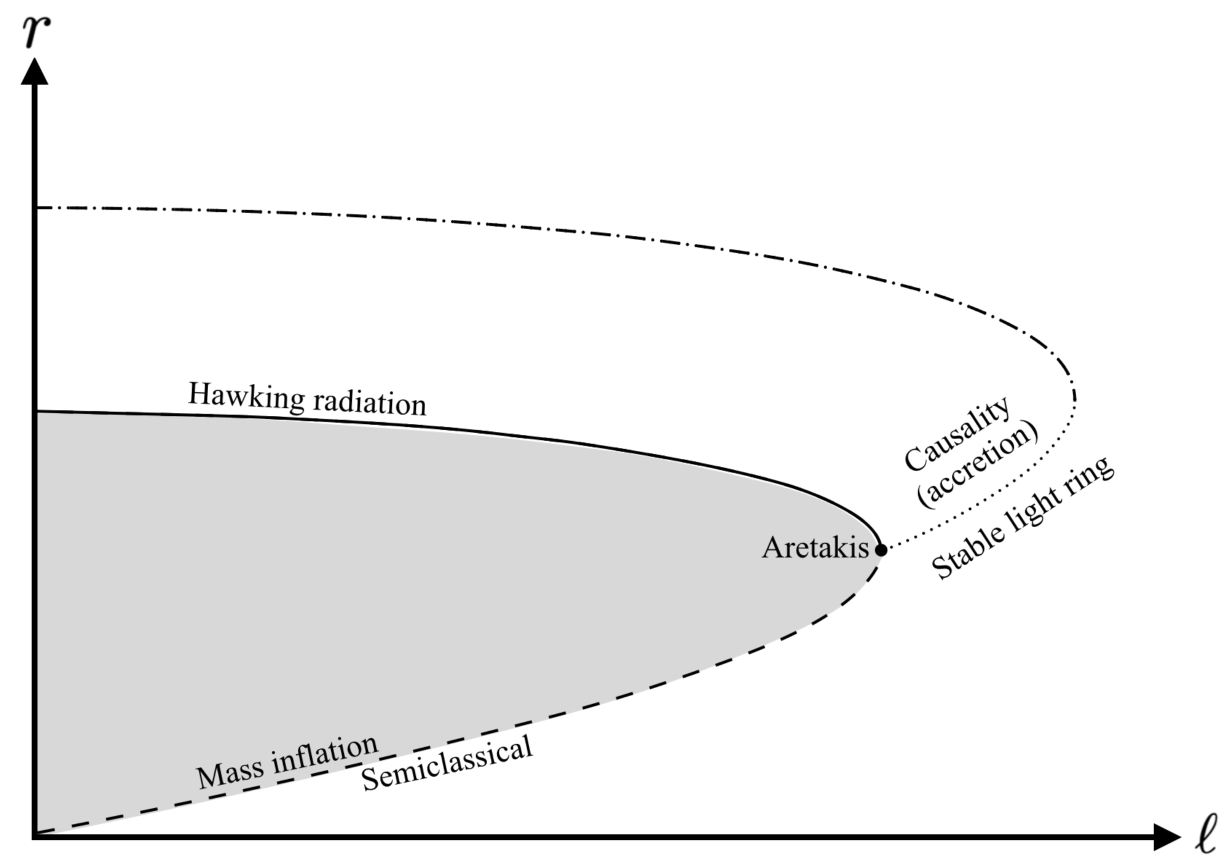


What are the known instabilities associated with different spacetime features?

1. Regular black holes:
   Mass inflation instability

2. Horizonless objects:
   Stable Light ring

3. Degenerate extremal horizons
   Aretakis instability [Aretakis 2010, Marolf 2010, Garfinkle 2011]



Is there no hope for a stable non-singular object?

What are the known instabilities associated with different spacetime features?

1. **Mass inflation instability:** Quite well understood
   - The end-point of the instability is not clear;
   - There are some regular black holes without (classical) mass inflation [Carballo-Rubio, FDF, Liberati, Pacilio, Visser 2022; Mcmaken 2023; FDF, Kolar, Kubiznak 2024].
   - Can these objects be formed dynamically?

2. **Stable light ring instability:** Not well understood (in my opinion)
   - We only have a heuristic argument;
   - Numerically shown only for some classes of boson stars [Cunha 2022]

3. **Aretakis instability:** Somewhat understood
   - Studied for singular black holes in GR

Still a lot of work to be done

Observational signatures

- What are the different observational channels?
- What is the current theoretical/observational status of each channel?
- Which are the most promising channels in terms of future experiments?

What are the different observational channels?

Regular black holes: The trapping horizons leads to a causally disconnected interior.

Modifications in the gravitational and electromagnetic waves observations are likely to be quantitative rather than qualitative.
Such modifications can be extremely suppressed.
Need to complement observations with theoretical analysis.

Horizonless objects The interior is no longer disconnected. In principle, there might be qualitatively new phenomena

1. Gravitational waves echoes
2. Thermal emission due to accretion

However, observing these effects requires more refined models
Need to complement observations with theoretical analysis.

Realistic astrophysical modeling

- What are the most relevant astrophysical uncertainties?
- Which ingredients do we need to go from theoretical to realistic modeling?
- Are potentially observable signatures hidden by astrophysical uncertainties?

Are potentially observable signatures hidden by astrophysical uncertainties?

There are many uncertainties related to astrophysics
Can we know if eventual modifications are due to new physics?

Gravitational wave observations:

We expect that astrophysical effects are not universal

Electromagnetic waves:

We can look at some features that are quite robust to astrophysical uncertainties (e.g. [Eichhorn, Held, Johannsen 2022])

Conclusions

- Still a lot to do to obatin a viable alternative to black holes.
- This is a very positive feature!
- Either we address these issues,
- or we might have observational signatures.
- Observations are extremely difficult.
- A lot of data in the future.
- Theoretical analysis need to tell us where to look

Conclusions

- Still a lot to do to obatin a viable alternative to black holes.

- This is a very positive feature!

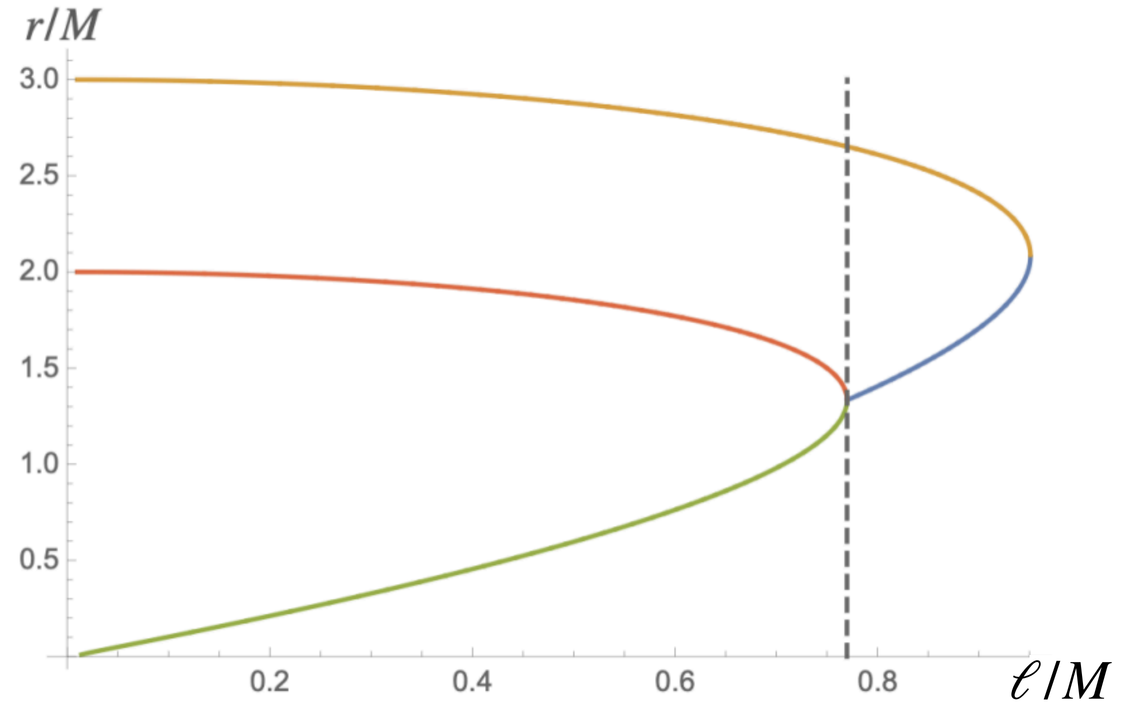
- Either we address these issues,

- or we might have observational signatures.

- Observations are extremely difficult.

- A lot of data in the future.

- Theoretical analysis need to tell us where to look



Open questions

Regular black holes and black hole mimickers

- What is an adequate definition of being “non-singular”?
- Are there dynamical processes to go from regular black holes to black hole mimickers and the other way around?
- Can a geometrodynamic theory generically cure singularities?

Dynamical formation

- What are the known physical mechanisms that could lead to the formation of regular black holes and black hole mimickers?
- What are the most promising formalisms for the study of dynamical aspects?
- What are the open issues?

Instabilities

- What are the known instabilities associated with different spacetime features?
- Are instabilities shortcomings of the models, or are they informative regarding dynamics?
- What are the differences between the dynamics of classical versus semiclassical/quantum perturbations?

Observational signatures

- What are the different observational channels?
- What is the current theoretical/observational status of each channel?
- Which are the most promising channels in terms of future experiments?

Realistic astrophysical modeling

- What are the most relevant astrophysical uncertainties?
- Which ingredients do we need to go from theoretical to realistic modeling?
- Are potentially observable signatures hidden by astrophysical uncertainties?

Raúl Carballo-Rubio, Francesco Di Filippo, Stefano Liberati, Matt Visser et al. arXiv:2501.05505

Open questions Thank You

Regular black holes and black hole mimickers
- What is an adequate definition of being “non-singular”?
- Are there dynamical processes to go from regular black holes to black hole mimickers and the other way around?
- Can a geometrodynamic theory generically cure singularities?

Dynamical formation
- What are the known physical mechanisms that could lead to the formation of regular black holes and black hole mimickers?
- What are the most promising formalisms for the study of dynamical aspects?
- What are the open issues?

Instabilities
- What are the known instabilities associated with different spacetime features?
- Are instabilities shortcomings of the models, or are they informative regarding dynamics?
- What are the differences between the dynamics of classical versus semiclassical/quantum perturbations?

Observational signatures
- What are the different observational channels?
- What is the current theoretical/observational status of each channel?
- Which are the most promising channels in terms of future experiments?

Realistic astrophysical modeling
- What are the most relevant astrophysical uncertainties?
- Which ingredients do we need to go from theoretical to realistic modeling?
- Are potentially observable signatures hidden by astrophysical uncertainties?

Raúl Carballo-Rubio, Francesco Di Filippo, Stefano Liberati, Matt Visser et al. arXiv:2501.05505