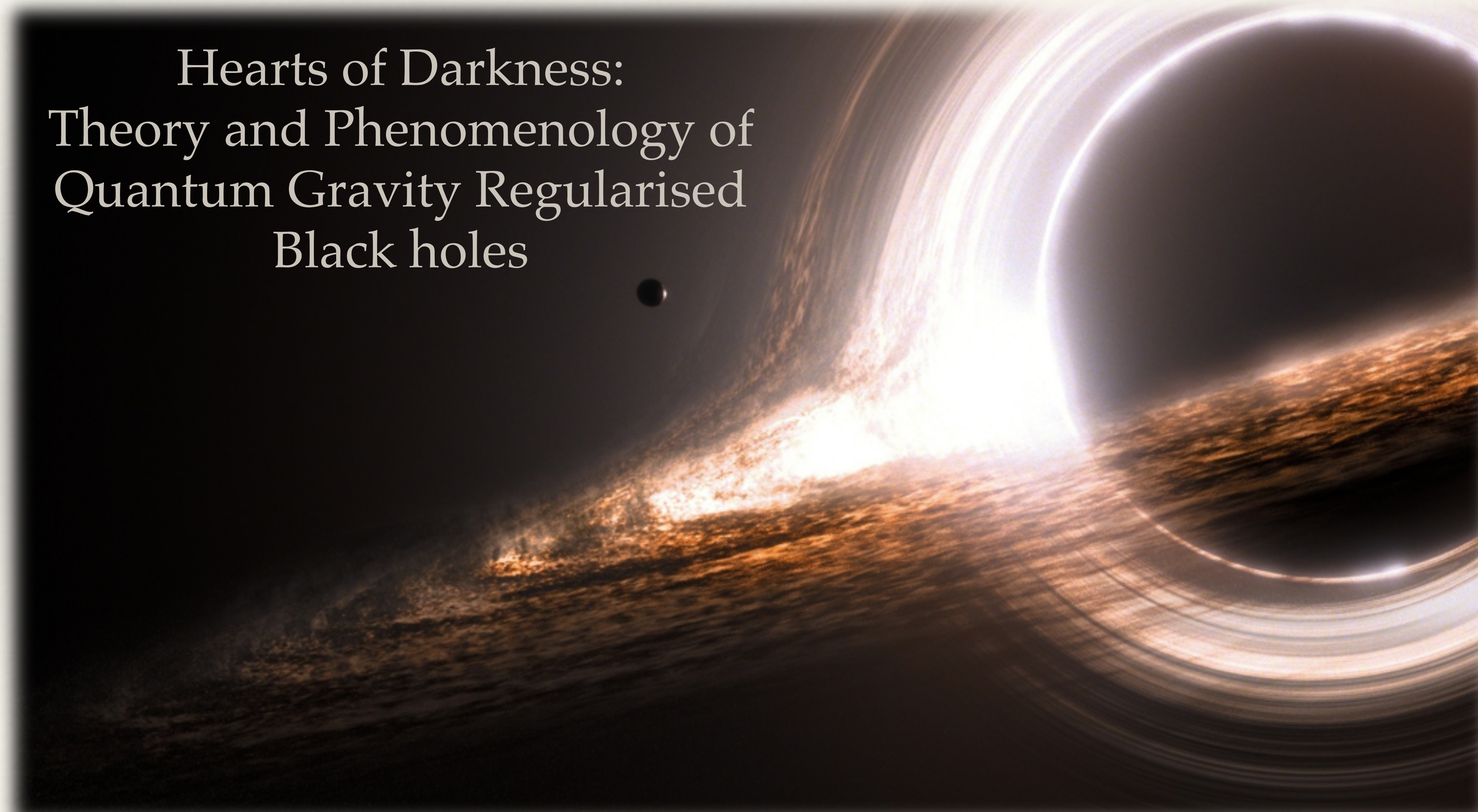
Work in collaboration with: R. Carballo-Rubio, F. Di Filippo, E. Franzin , J. Mazza, C. Pacilio, M. Visser

Copernicus Webinar and Colloquium Series

Stefano Liberati



Hearts of Darkness: Theory and Phenomenology of Quantum Gravity Regularised Black holes

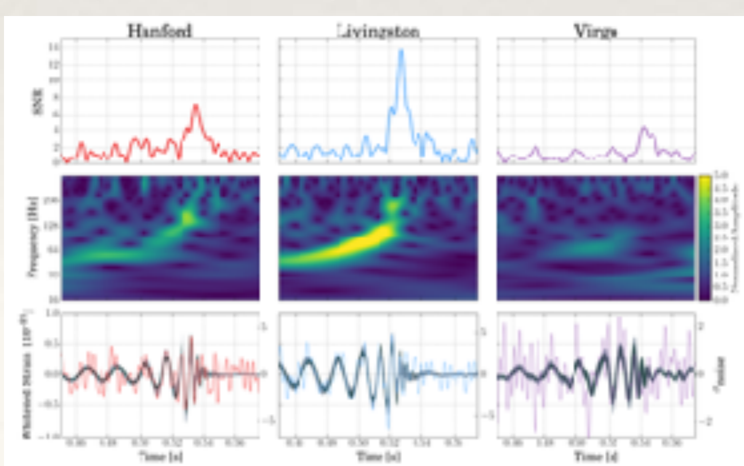
It from the cracks that light gets in… **Anthem-Leonard Cohen**

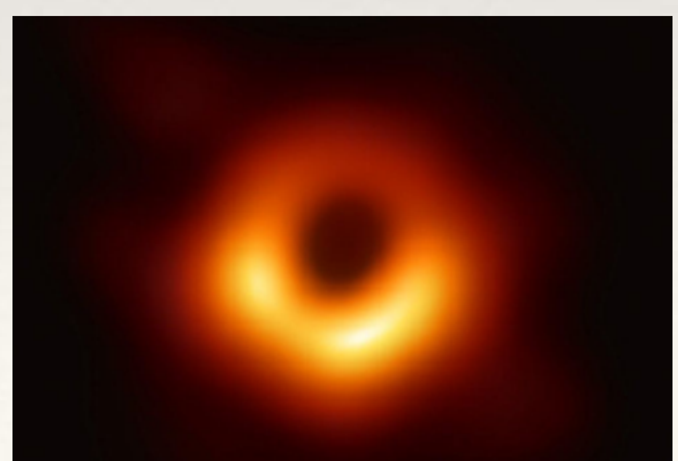
A new dawn for testing General Relativity

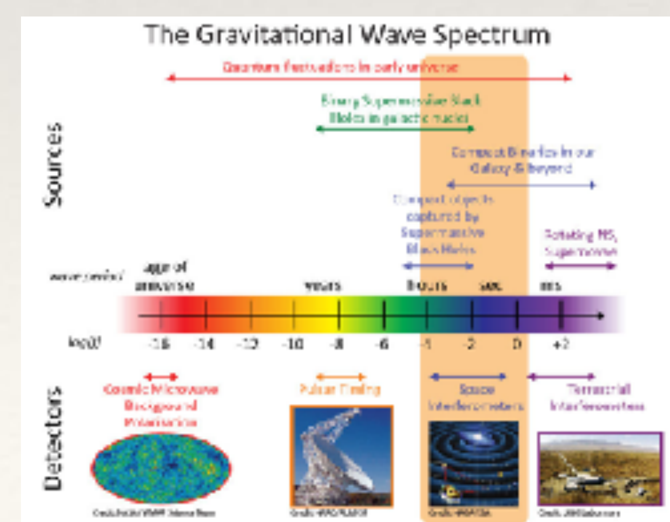
Albeit we "use" GR everyday (e.g. GPS) still it has some tantalising features and it has resisted so far any attempt to be quantised…

- The cosmological constant problem
- Faster than light and Time travel solutions
- AdS/CFT duality, holographic behaviour
- Information Problem in BH Physics

No more







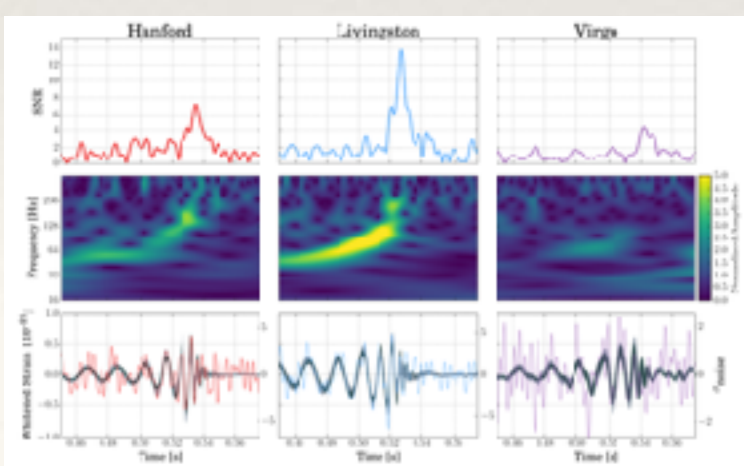
A new dawn for testing General Relativity

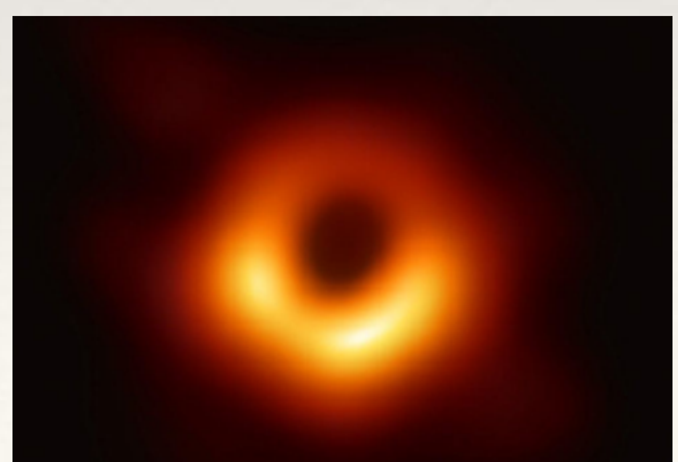
Albeit we "use" GR everyday (e.g. GPS) still it has some tantalising features and it has resisted so far any attempt to be quantised…

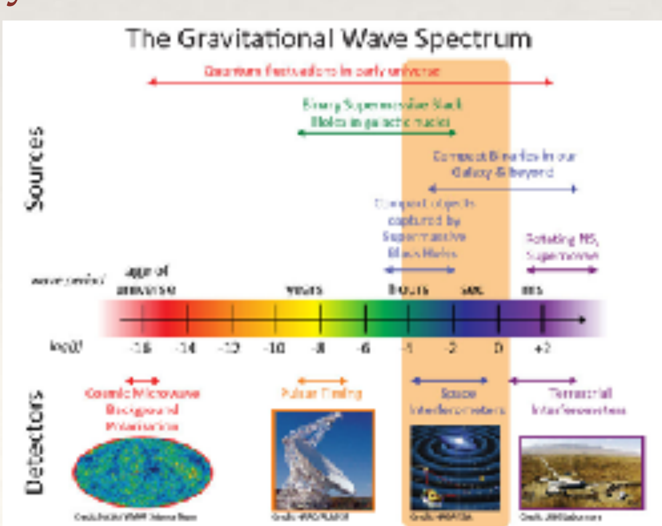
- Singularities
- Critical phenomena in gravitational collapse
- Horizon thermodynamics
- Spacetime thermodynamics: Einstein equations as equations of state.
- The cosmological constant problem
- Faster than light and Time travel solutions
- AdS/CFT duality, holographic behaviour
- Information Problem in BH Physics

There are a ubiquitous objects that are associated to most of these odd GR features:
Black Holes
Understanding them "in nature" would be key to test our understanding of gravity.
Unfortunately so fare very sparse knowledge was allowed by observations…

No more



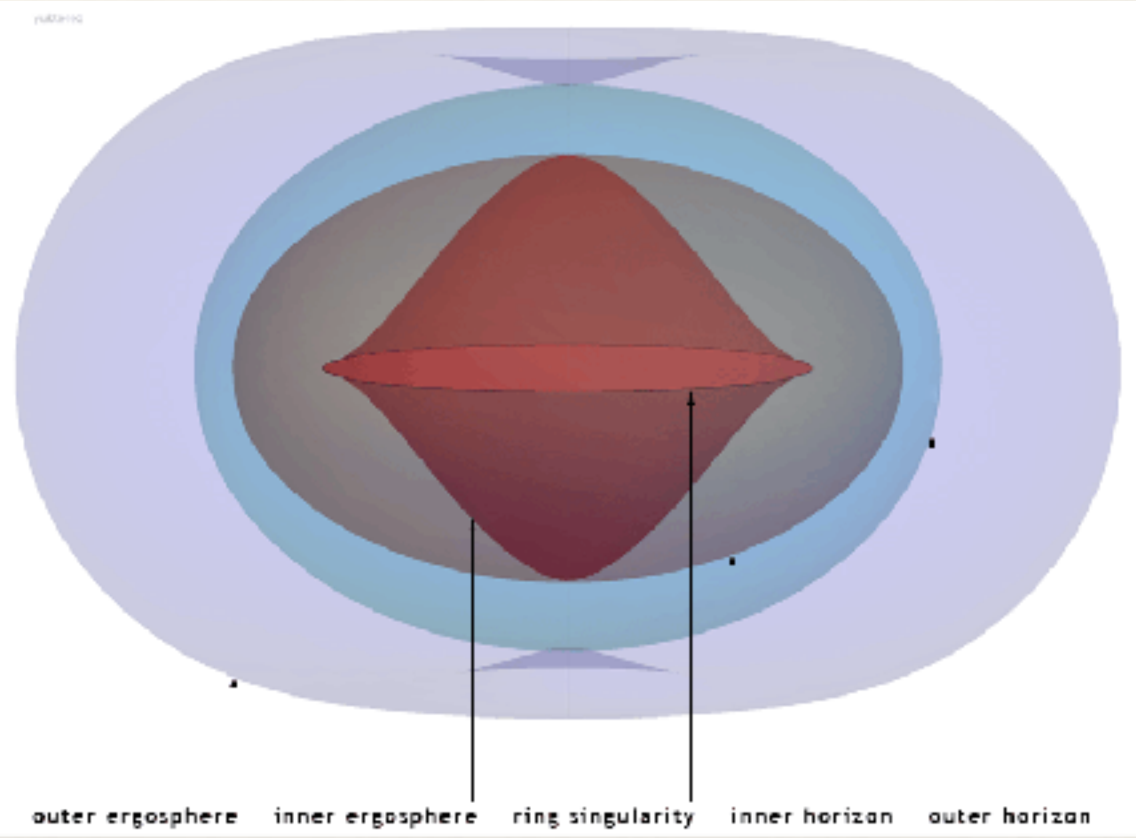




Black Holes:
the Rosetta stone of gravity

> "The **black holes** of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time."
> **Subrahmanyan Chandrasekhar**

- Albeit we are nowadays familiar with the concept of Black Holes their acceptance as a physical solution of General relativity has been far from obvious.
- Even once was understood the nature of the event horizon, BH are still characterised by "hard to digest" structures
  - Singularities: infinite curvature
  - Cauchy horizons (associated to timelike singularities and time machines): end of predictability



QG is supposed to "cure" these features:
If it does so just in a hidden QG core of Planck scale then BH will be exactly as in GR.
But what if the "cure" requires long range (in time and/or space) effects?
Then maybe we could test QG using BH… could we?

Singularity

- A singularity is where General relativity is no more predictive: we cannot describe spacetime there —> missing points.
- Penrose's theorem is what makes very confident that singularities must form inside black holes generically

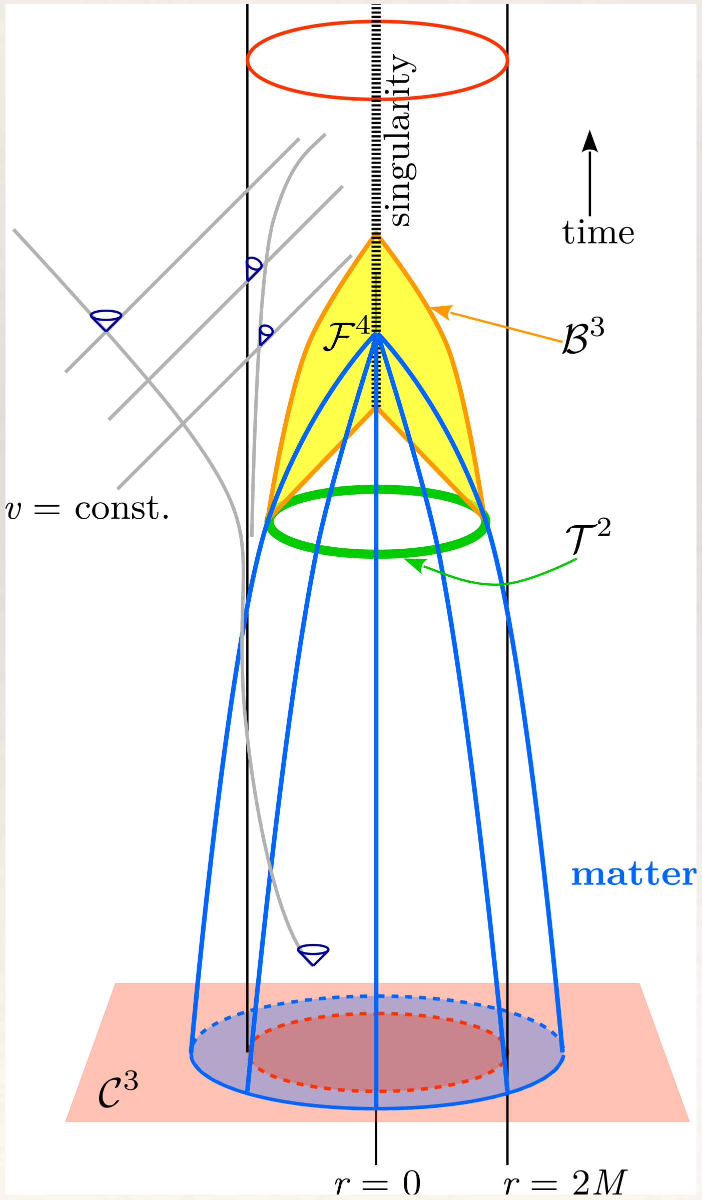
Penrose's singularity theorem

Assumptions

- The theory of gravity is GR
- The gravitational collapse becomes enough strong to have convergent light cones (trapped region)
- Matter gravitates in the standard way (no exotic/quantum matter: if p=wϱ w>-1)

Implication

Once a trapped region forms the collapse would be unstoppable and has to lead to a singularity



Avoidance of this conclusion requires at least one of the following

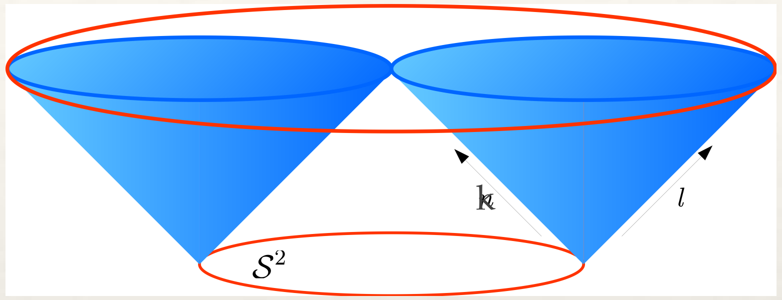
- The weak energy condition is violated.
- The Einstein field equations do not hold.
- Lorentzian geometry does not provide an adequate description of spacetime inside BHs.
- Global hyperbolicity (Cauchy evolution) breaks down.

We shall be ready to give up the first two and hold the last two…

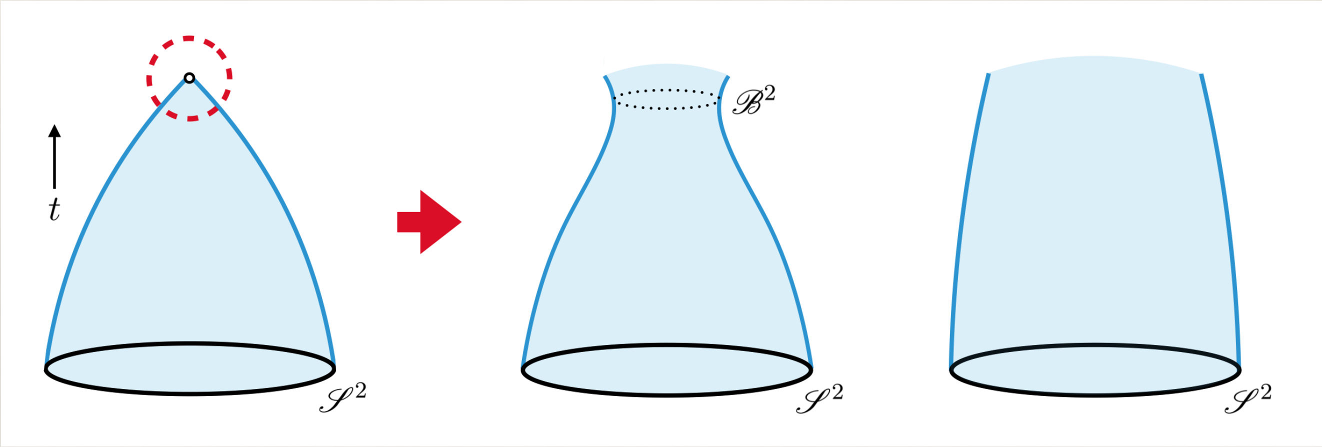
Focussing on the focussing point

- **Let's assume that QG produces a <u>space-time which is regular and entirely predictable in the sense of a Cauchy problem</u>.**
  - **No singularities both in the sense of incomplete geodesic as well as curvature singularities (metric is at least C^2).**

Penrose' theorem works by proving first that in a collapse a focussing point for outgoing light rays is reached and then by showing that this point (or sets of points) cannot be part of the spacetime. If QG removes such a focussing post what can happen? We can have



$$\theta^{(i)}_{\text{null}} = \frac{1}{\delta A}\frac{\delta A}{\delta \lambda} \,.$$



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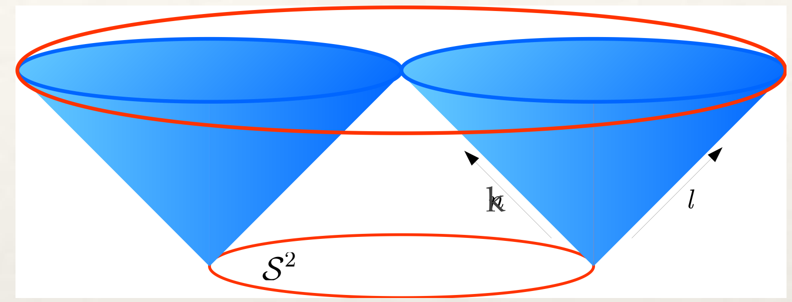

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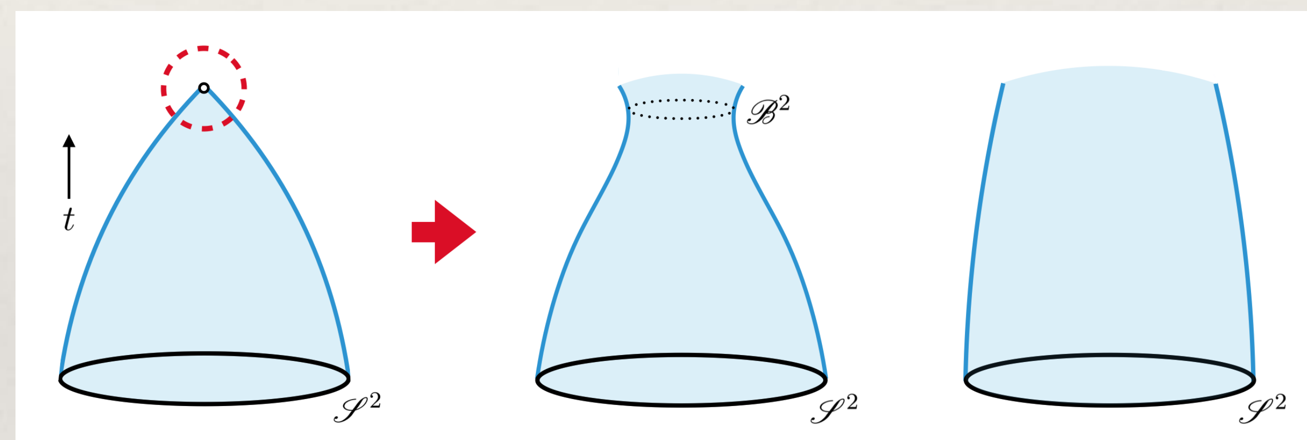

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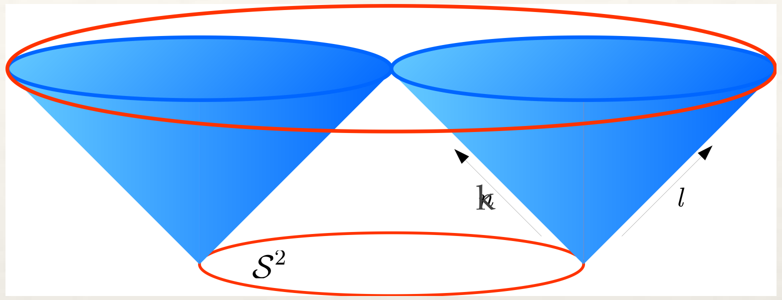

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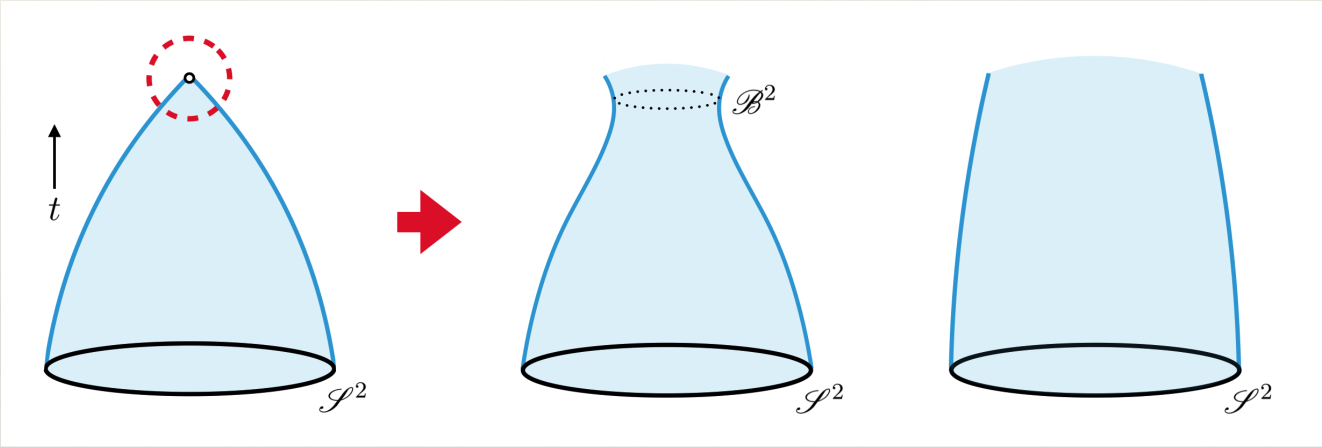

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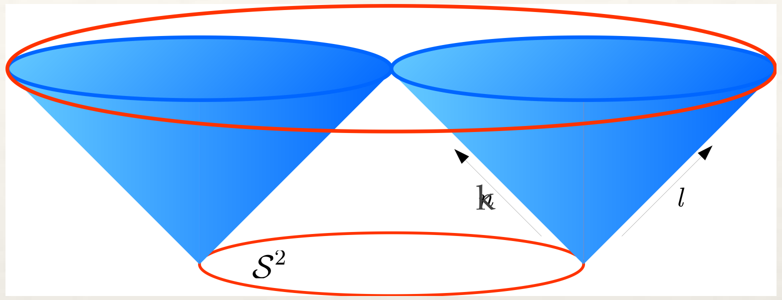

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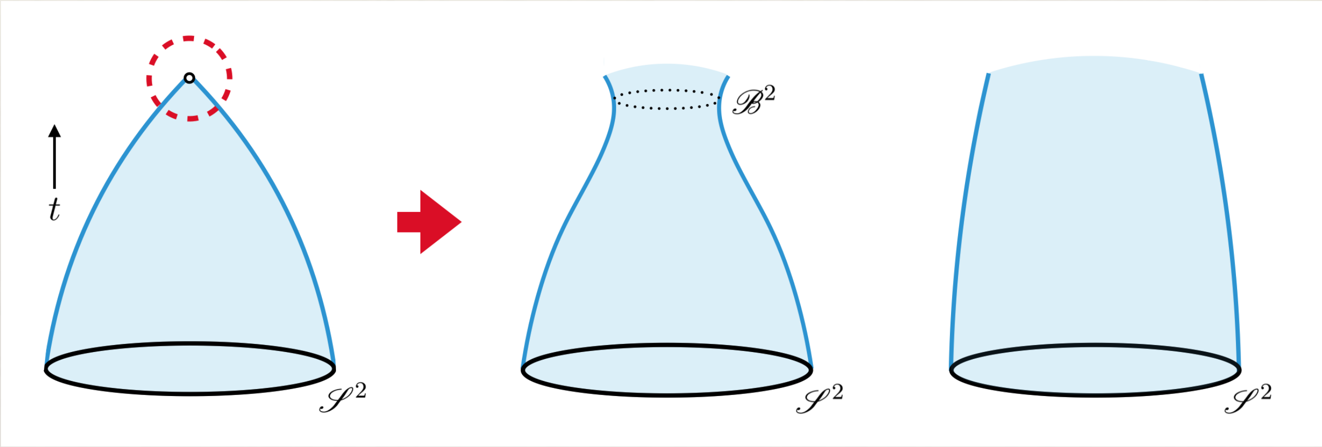

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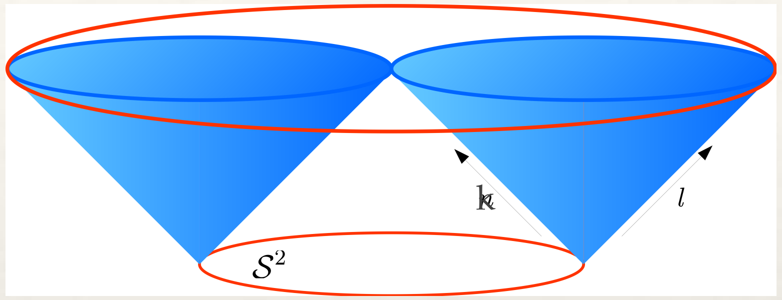

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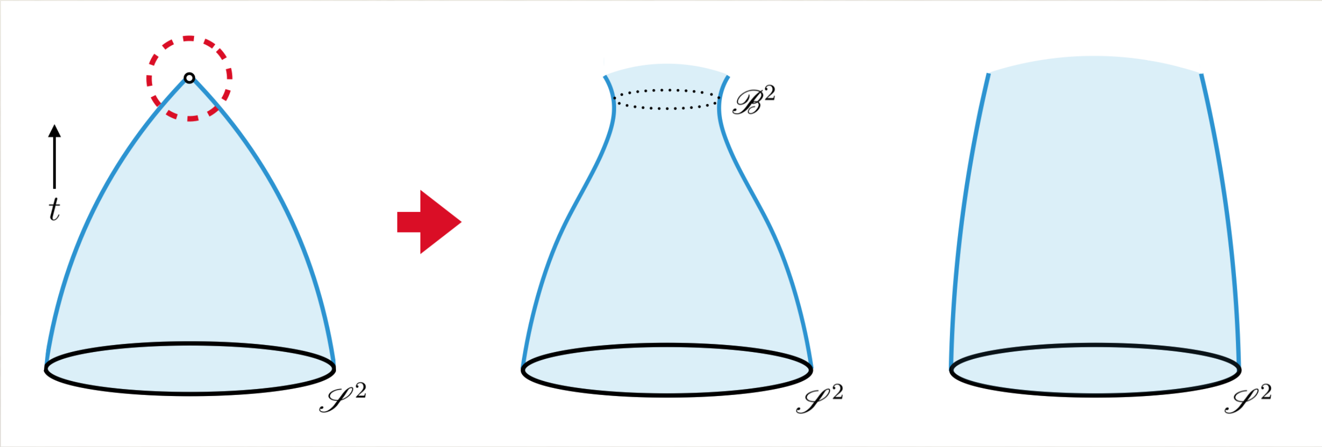

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  - **still singular at finite affine parameter for ingoing congruence**

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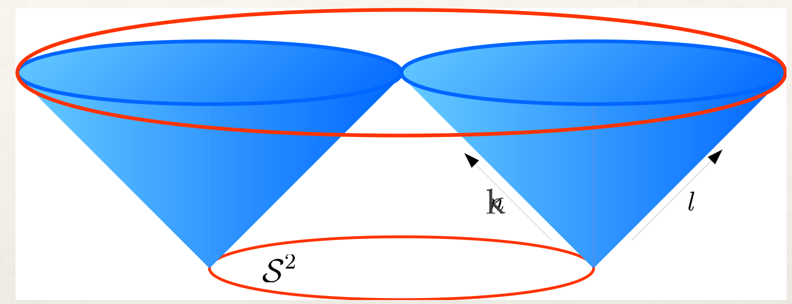

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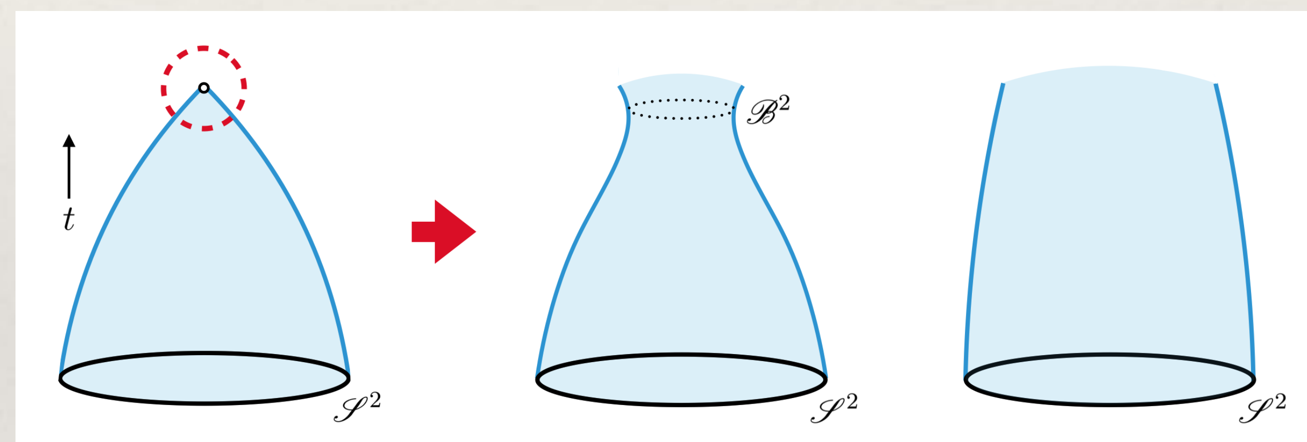

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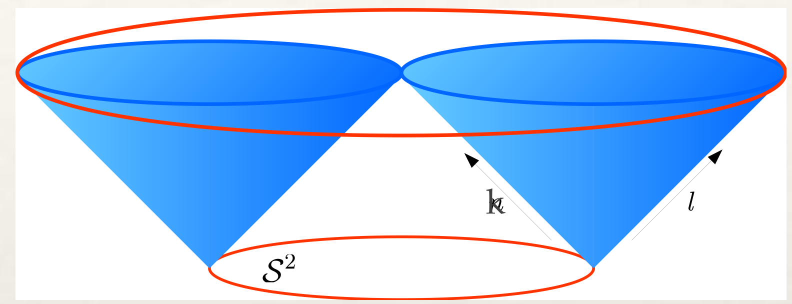

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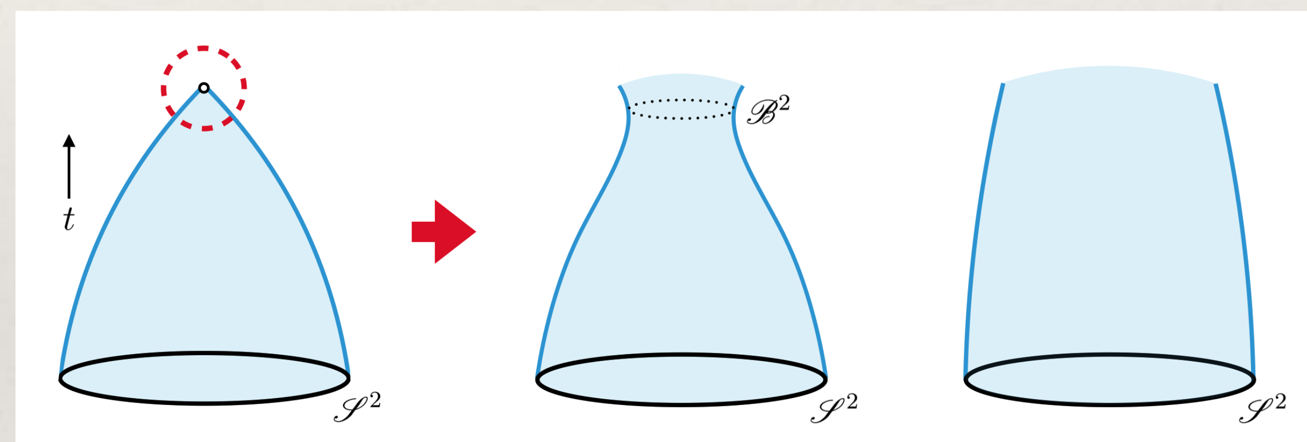


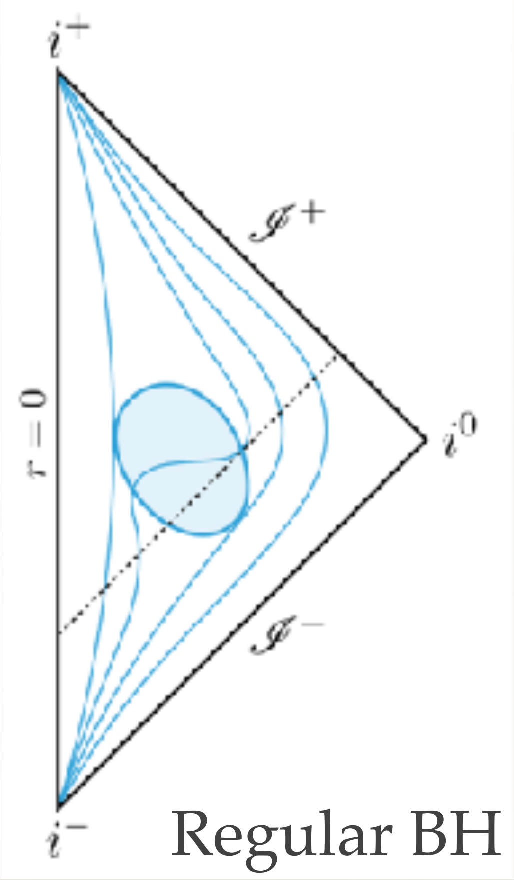
Apart from the above behaviour of the outgoing light rays we can catalogue all the possible cases by considering the radius R at which defocussing appears and the behaviour of the ingoing light rays there. We then get only

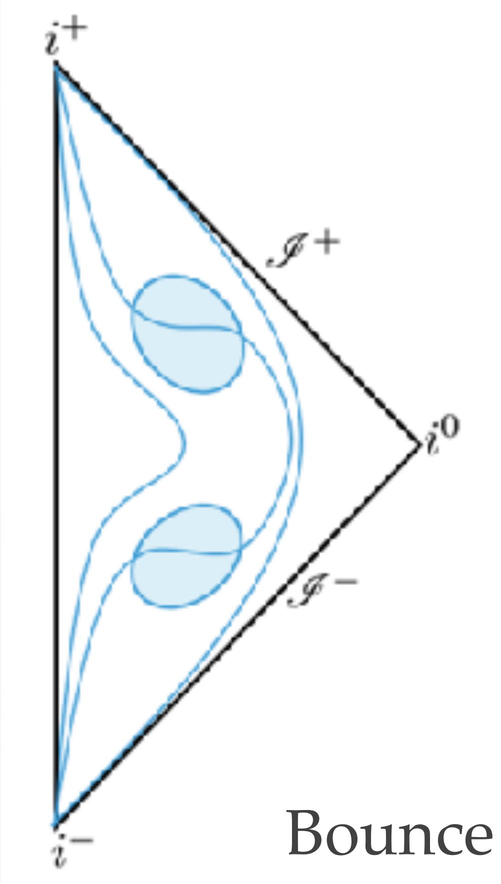
4 viable classes:

1. $(\lambda_0, R_0, \bar{\theta}^{(k)} < 0)$
2. $(\lambda_0, R_0, \bar{\theta}^{(k)} \geq 0)$
3. $(\infty, R_\infty, \bar{\theta}^{(k)} < 0)$
4. $(\infty, R_\infty, \bar{\theta}^{(k)} \geq 0)$

Class 1: Evanescent horizons

- The expansion relative to the outgoing null vector vanish and changes sign.
- The expansion of the intersecting ingoing radial null geodesics remains negative.





- We recover the geometry of an evanescent regular black hole.
- The geometry possesses an outer and an inner horizon that merge in finite time.
- This situation corresponds to a regular BH with no singularity or a bounce from a BH to a White Hole (the time reversal of a black hole)

Note: one can think of Inner Horizons as White Horizons which have been turned Inside Out

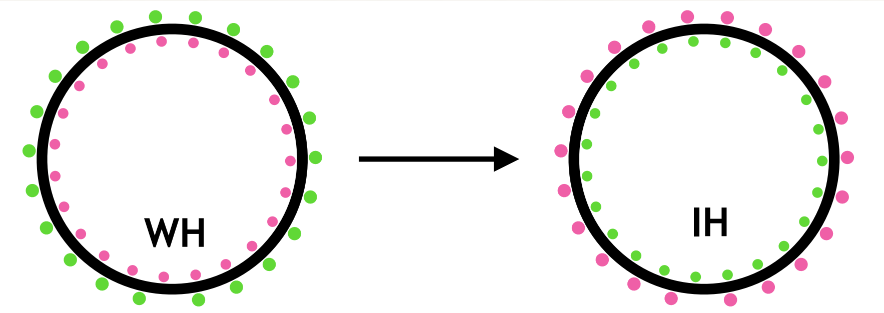


Figure by courtesy of R. Carballo-Rubio

Class 2: One way hidden wormholes

- The expansion relative to the outgoing null rays vanish and changes sign.
- The expansion of the intersecting ingoing radial null rays changes sign as well.

- The geometry possesses a minimum radius throat that resembles the one of a wormhole;
- The throat is inside a trapping horizon and can be traversed only in one direction.
- Problematic creation from gravitational collapse as topology change is incompatible with global hyperbolicity. However, if one gives up (at least in two points) metric analyticity requirement then possible to conceive a geometry with minimum finite radius locally.

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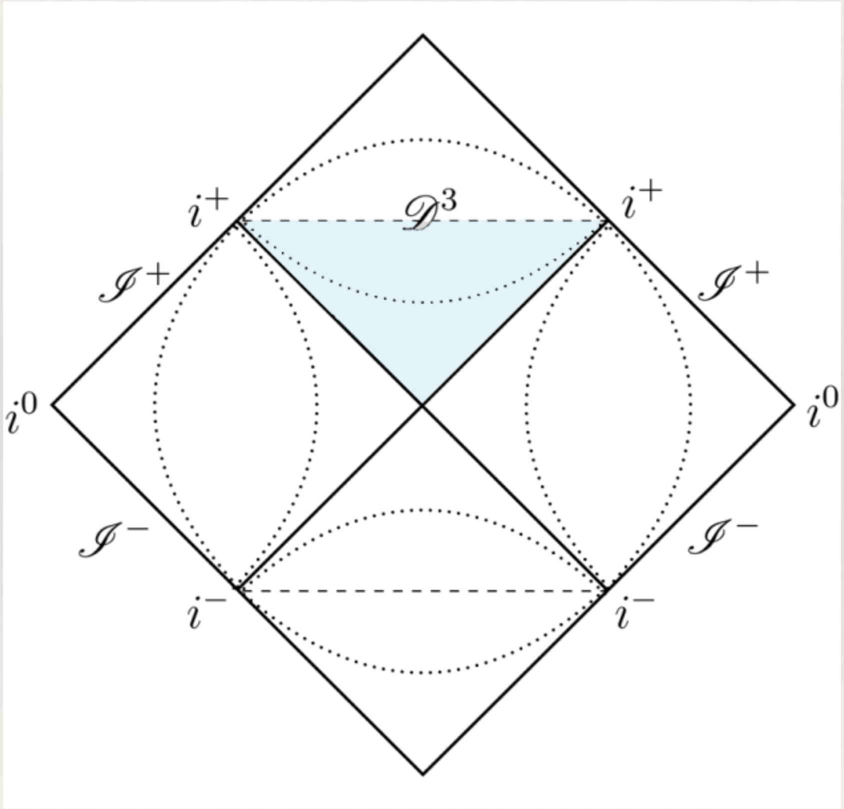

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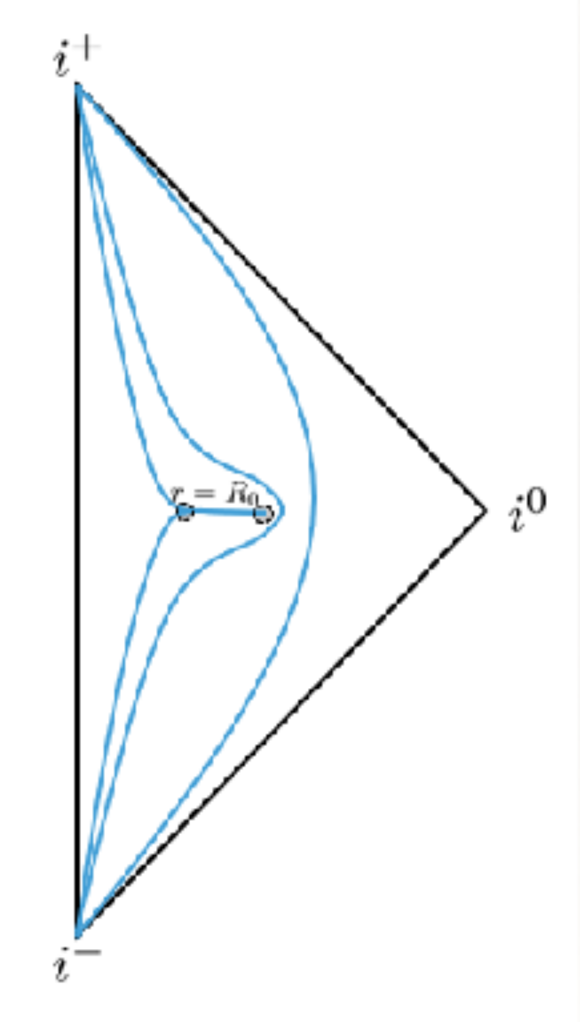
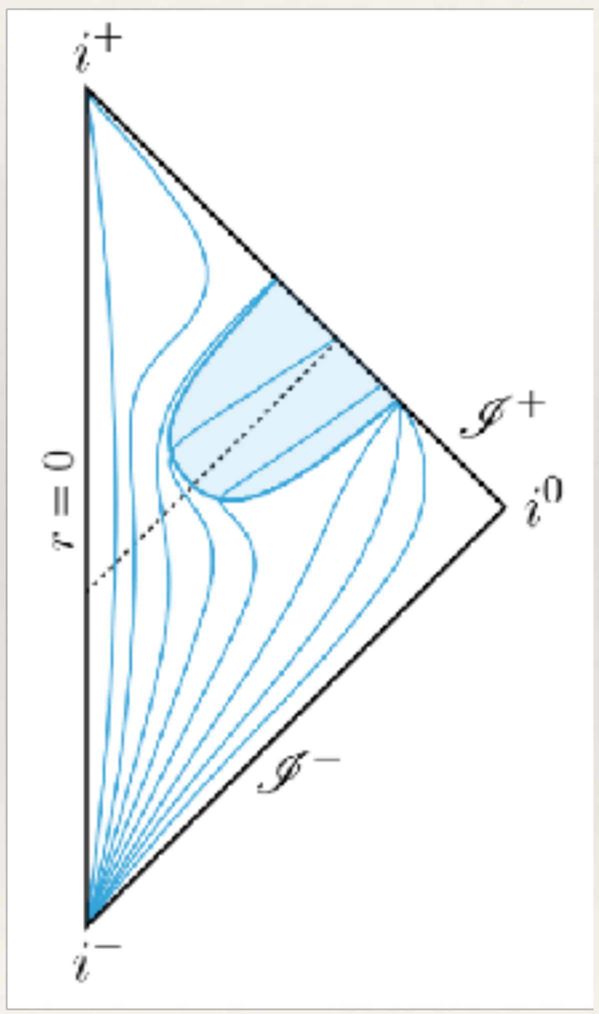


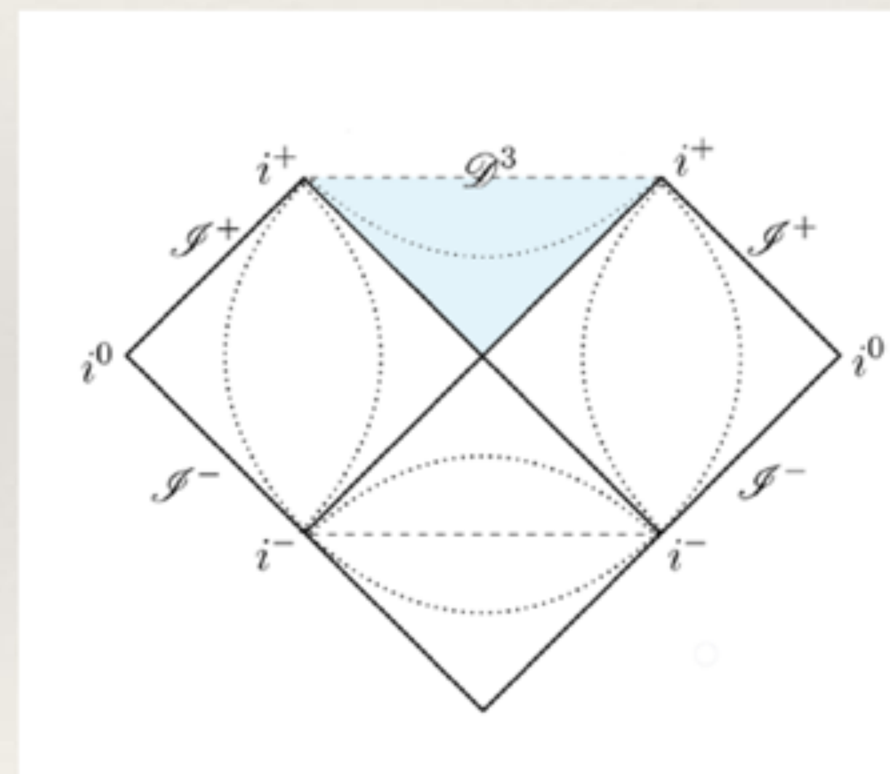
Asymptotic resolutions: Cases 3,4

- These are (idealised?) cases in which the defocussing point is pushed at infinity.

Everlasting horizons



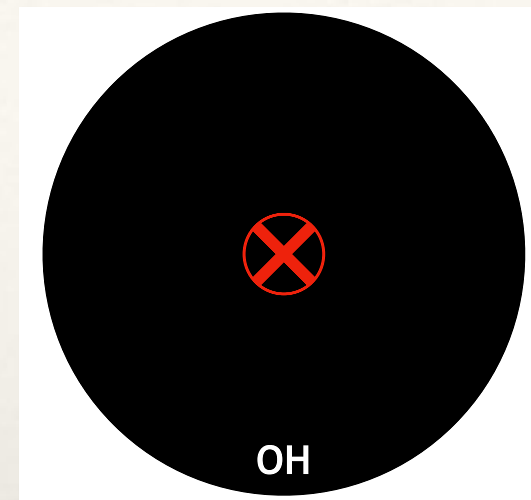
Asymptotic hidden wormholes



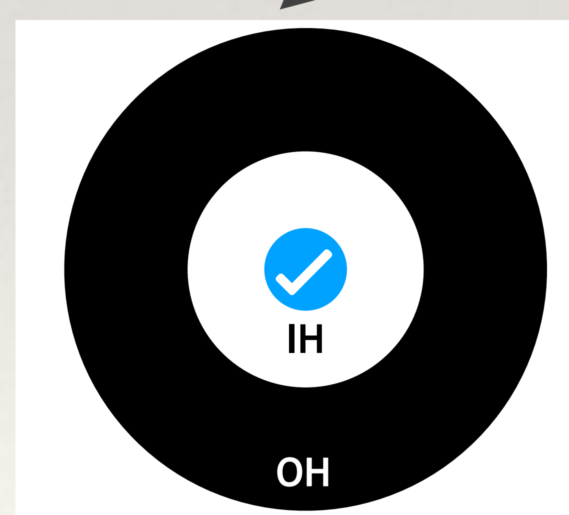
These are allowed but rather unphysical singularity resolutions.
We shall not deal with these asymptotic cases further…

First take home message

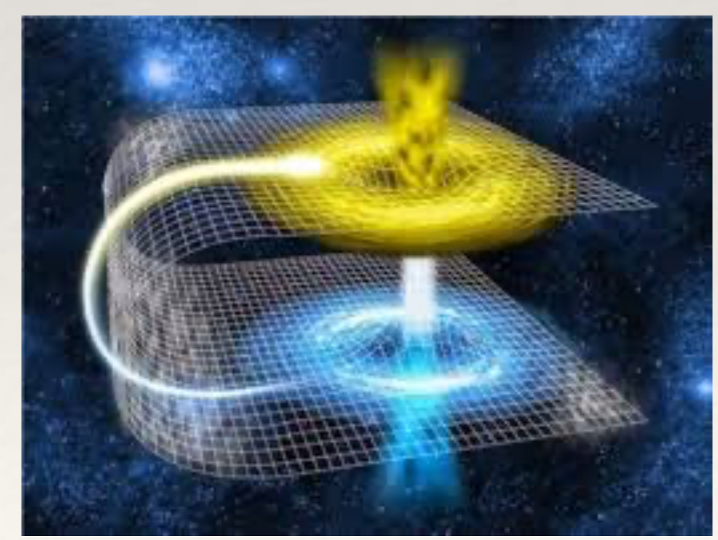
- The analysis of the singularity resolutions tells us that substantially, once a trapping horizon forms, there are two classes of singularity free solutions (local in space and time) available:
  - Simply connected topology: Regular black holes (and bounces) with inner horizons.
  - Non-simply connected topology: Hidden Wormholes (wormholes shielded by a trapping horizons)



GR



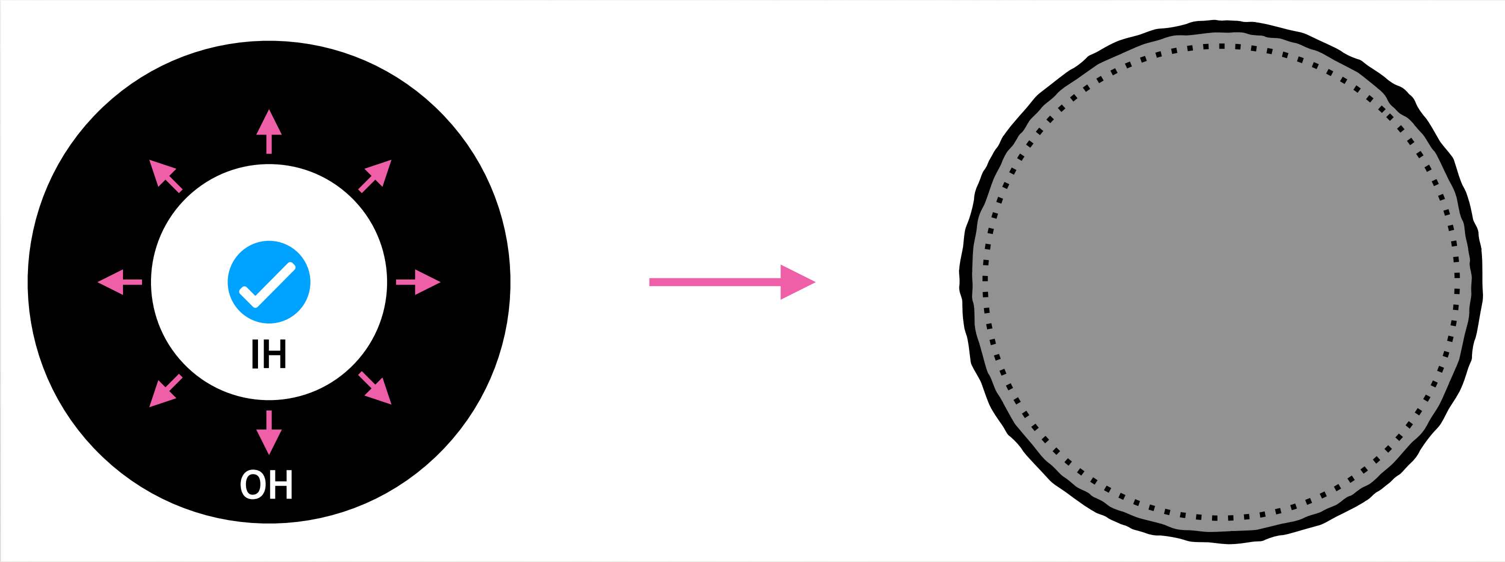
Regular BH



Figures by courtesy of R. Carballo-Rubio

Limiting cases

- In both these cases one can ask what happens if $R_0 \to r_{horizon}$ and "overtakes it"
  - The answer is simple one gets two corresponding new classes of objects
    - Horizonless Quasi-BH
    - Naked wormholes



Quasi-BH

Let us define a static and spherically symmetric quasi-black hole as a spacetime satisfying:

(i) the geometry is Schwarzschild above a given radius R that is defined to be the radius of the object,

(ii) the geometry for r ≤ R is not Schwarzschild, and

(iii) there are no event or trapping horizons.

Naked Wormhole

Easy to engineer WH-mickers by "gluing" two copies of Schw. or Kerr spacetime cut just above the horizon but in general these are not correspondent to regularised solutions.

Class 1: Simply connected spacetimes

$$ds^2 = -\left(1 - \frac{2m(r)}{r}\right) \mathrm{d}t^2 + \frac{\mathrm{d}r^2}{\left(1 - \frac{2m(r)}{r}\right)} + r^2 \left[\mathrm{d}\theta^2 + \sin^2\theta \, \mathrm{d}\phi^2\right] .$$

m(r)=Misner-Sharp Mass

Model	$m(r)$
Bardeen [44]	$M \frac{r^3}{(r^2+\ell^2)^{3/2}}$
Hayward [45]	$M \frac{r^3}{r^3+2M\ell^2}$
Dymnikova [46]	$M \left[1 - \exp\left(\frac{r^3}{\ell^3}\right)\right]$
Fan–Wang [47]	$M \frac{r^3}{(r+\ell)^3}$

- Requirements for the mass function
  $m(r) \to M$ as $r \to \infty$ and $m(r) = O(r^3)$ as $r \to 0$ (at least)
- Asymptotic flatness+Regularity at the core+Outer Horizon imply also Inner Horizon. The position of the inner and outer horizons and their surface gravity depend on m(r)
- Within GR, RBHs are non-vacuum solutions, the effective stress-energy tensor can be read off from the Einstein tensor; several interpretations in terms of non-linear electrodynamics. In general Violations of energy conditions.
- Even non-rotating RBH have inner horizons
- Rotating regular black holes (Kerr-like) can be constructed e.g. using generalised Janis–Newman procedure (albeit care is required…)

Class 1: Regular-BH limit

- Let us take Hayward RBH for concreteness: $m(r) = \dfrac{Mr^3}{r^3 + 2\ell^2 M}$, $\qquad \phi(r) = 0.$
- The effective stress energy tensor takes the form associated with an anisotropic perfect fluid

$$\rho(r) = \frac{3\ell^2}{2\pi}\left(\frac{m(r)}{r^3}\right)^2 = -p_r(r), \qquad p_t(r) = \frac{3\ell^2}{\pi}\frac{r^3 - \ell^2 M}{r^3 + 2\ell^2 M}\left(\frac{m(r)}{r^3}\right)^2 = \frac{2r^3 - 2\ell^2 M}{r^3 + 2\ell^2 M}\rho(r)\,.$$

- $2m(r) = r$ has 2 roots for $M/\ell > 3\sqrt{3}/4$ a degenerate/double root for $M/\ell = 3\sqrt{3}/4$ (at $r_* = \sqrt{3}\ell$)and no roots for $M/\ell < 3\sqrt{3}/4$

Assuming $M/\ell > 3\sqrt{3}/4$ and $M \gg \ell$ one has a RBH a ultra compact object with 4 “zones”

- The (approximately isotropic) core $[r \sim \ell < 2M]$:

$$\rho(\ell) \equiv -p_r(\ell) = \frac{3}{8\pi\ell^2}\left[1 - \mathcal{O}\left(\ell/M\right)\right] = -p_t(\ell)\,.$$

- The (mildly anisotropic) crust $[r \sim L_+ \equiv \sqrt[3]{2\ell^2 M}]$:

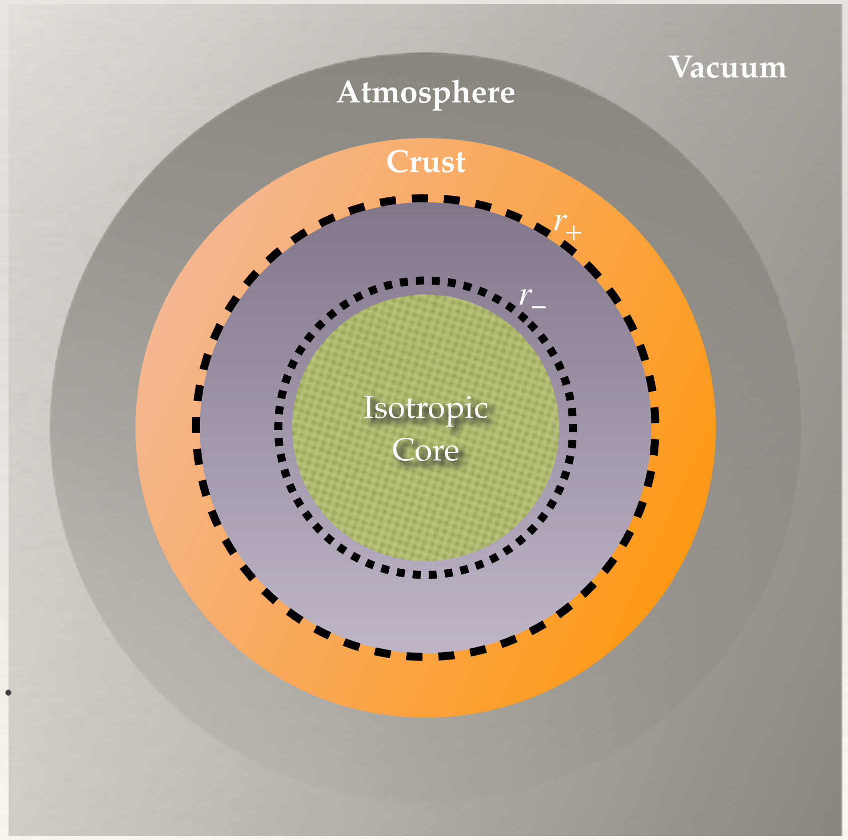
$$\rho(L_+) \equiv -p_r(L_+) = \frac{\Lambda_0}{4}\left[1 + \mathcal{O}\left(\ell/M\right)\right], \qquad p_t(L_+) = \frac{\Lambda_0}{8}\left[1 + \mathcal{O}\left(\ell/M\right)\right]\,.$$

- The (grossly anisotropic) atmosphere $[r \sim 2M]$:

$$\rho(M) \equiv -p_r(M) = \Lambda_0\left(\frac{\ell}{2M}\right)^4\left[1 + \mathcal{O}\left(\ell^2/M^2\right)\right], \qquad p_t(M) = 2\rho(M)\left[1 + \mathcal{O}\left(\ell^2/M^2\right)\right]\,.$$

- The (approximately vacuum) asymptotic region $[r \sim R \gg M]$:

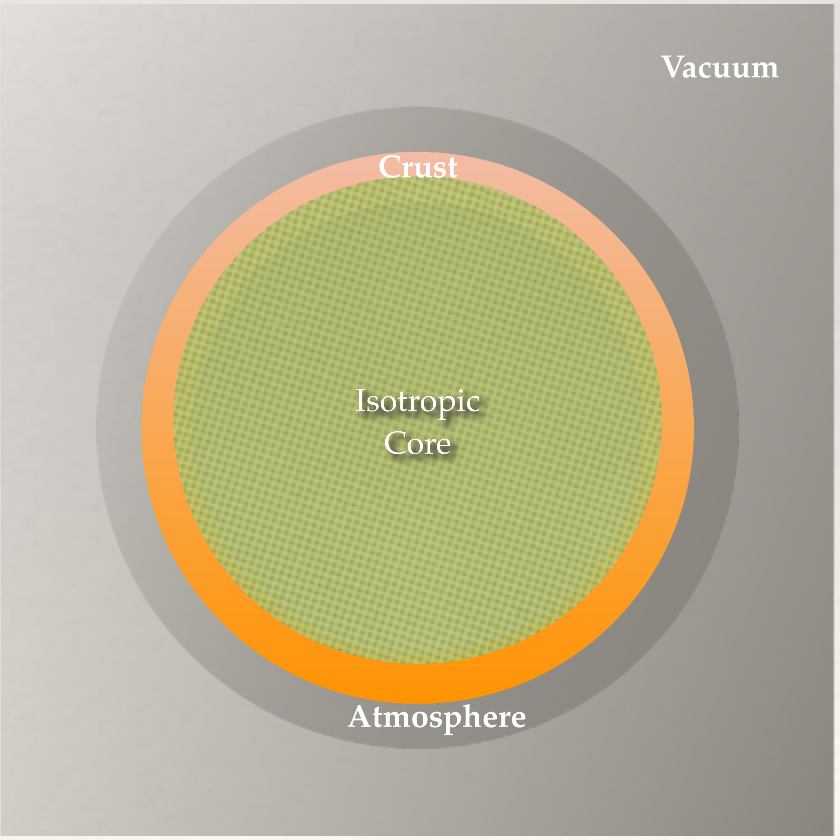
$$\rho(R) \equiv -p_r(R) = \Lambda_0\left(\frac{\ell}{2M}\right)^4\left(\frac{2M}{R}\right)^6\left[1 + \mathcal{O}\left(\ell^2 M/R^3\right)\right], \quad p_t(R) = 2\rho(R)\left[1 + \mathcal{O}\left(\ell^2 M/R^3\right)\right]\,.$$



Class 1: Quasi-BH limit

- Let us take Hayward RBH for concreteness: $m(r) = \dfrac{Mr^3}{r^3 + 2\ell^2 M}, \qquad \phi(r) = 0.$
- The effective stress energy tensor takes the form associated with an anisotropic perfect fluid
$$\rho(r) = \frac{3\ell^2}{2\pi}\left(\frac{m(r)}{r^3}\right)^2 = -p_r(r), \qquad p_t(r) = \frac{3\ell^2}{\pi}\frac{r^3 - \ell^2 M}{r^3 + 2\ell^2 M}\left(\frac{m(r)}{r^3}\right)^2 = \frac{2r^3 - 2\ell^2 M}{r^3 + 2\ell^2 M}\rho(r)\,.$$
- $2m(r) = r$ has 2 roots for $M/\ell > 3\sqrt{3}/4$ a degenerate/double root for $M/\ell = 3\sqrt{3}/4$ and no roots for $M/\ell < 3\sqrt{3}/4$

Assuming $M/\ell \lesssim 3\sqrt{3}/4$ and $M \sim \ell$. In this case, the different scales ℓ and M coalesce, the horizons disappear, with the core growing in size and the crust and atmosphere shrinking.



Similar structure to gravastars

A class 2 example: The Simpson-Visser Metametric

$$\mathrm{d}s^2 = -\left(1 - \frac{2M}{\sqrt{r^2+\ell^2}}\right)\mathrm{d}t^2 + \left(1 - \frac{2M}{\sqrt{r^2+\ell^2}}\right)^{-1}\mathrm{d}r^2 + (r^2+\ell^2)\left[\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right],$$

A.Simpson, M.Visser. JCAP 02 (2019) 042
e-Print: 1812.07114 [gr-qc]

- a two-way, traversable wormhole à la Morris-Thorne for $\ell > 2M$,
- a one-way wormhole with a null throat for $\ell = 2M$, and
- a regular black hole, in which the singularity is replaced by a bounce to a different universe, when $\ell < 2M$; the bounce happens through a spacelike throat shielded by an event horizon and is hence dubbed "black-bounce" in [6] or "hidden wormhole" as per [4].

RN extension:
E.Franzin,SL, J.Mazza, A.Simpson, M.Visser. JCAP 07 (2021) 036.
e-Print: 2104.11376 [gr-qc]

Rotating counterpart

J.Mazza, E.Franzin, SL. JCAP 04 (2021) 082 • e-Print: 2102.01105 [gr-qc]

$$\mathrm{d}s^2 = -\left(1 - \frac{2M\sqrt{r^2+\ell^2}}{\Sigma}\right)\mathrm{d}t^2 + \frac{\Sigma}{\Delta}\mathrm{d}r^2 + \Sigma\mathrm{d}\theta^2 - \frac{4Ma\sin^2\theta\sqrt{r^2+\ell^2}}{\Sigma}\mathrm{d}t\mathrm{d}\phi + \frac{A\sin^2\theta}{\Sigma}\mathrm{d}\phi^2 \tag{2.16}$$

with

$$\Sigma = r^2+\ell^2+a^2\cos^2\theta, \qquad \Delta = r^2+\ell^2+a^2-2M\sqrt{r^2+\ell^2},$$

$$A = (r^2+\ell^2+a^2)^2 - \Delta a^2\sin^2\theta.$$

WoH traversable wormhole;

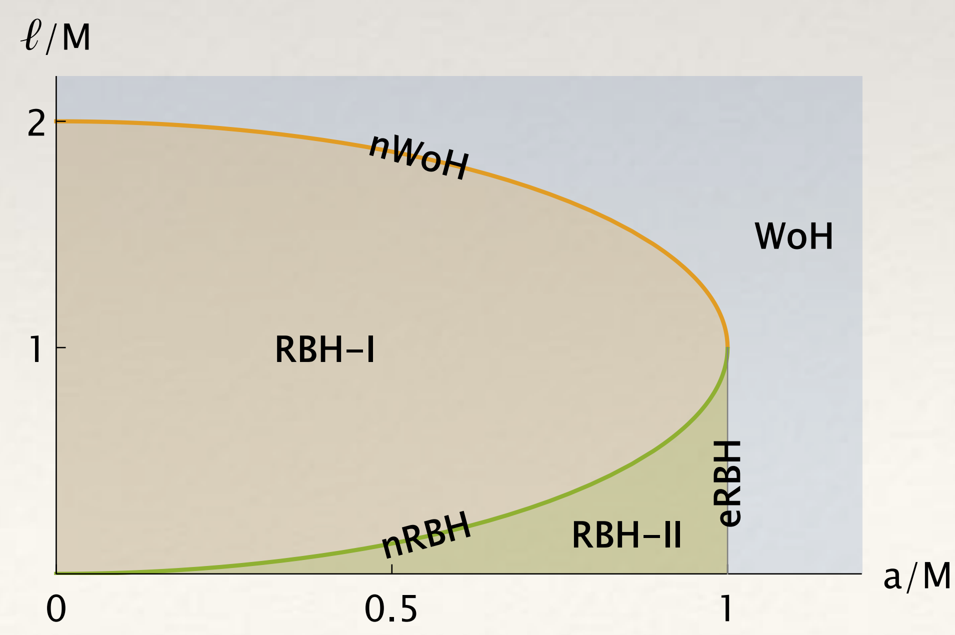
nWoH null WoH, i.e. one-way wormhole with null throat;

RBH-I regular black hole with one horizon (in the $r > 0$ side, plus its mirror image in the $r < 0$ side);

RBH-II regular black hole with an outer and an inner horizon (per side);

eRBH extremal regular black hole (one extremal horizon per side);

nRBH null RBH-I, i.e. a regular black hole with one horizon (per side) and a null throat.

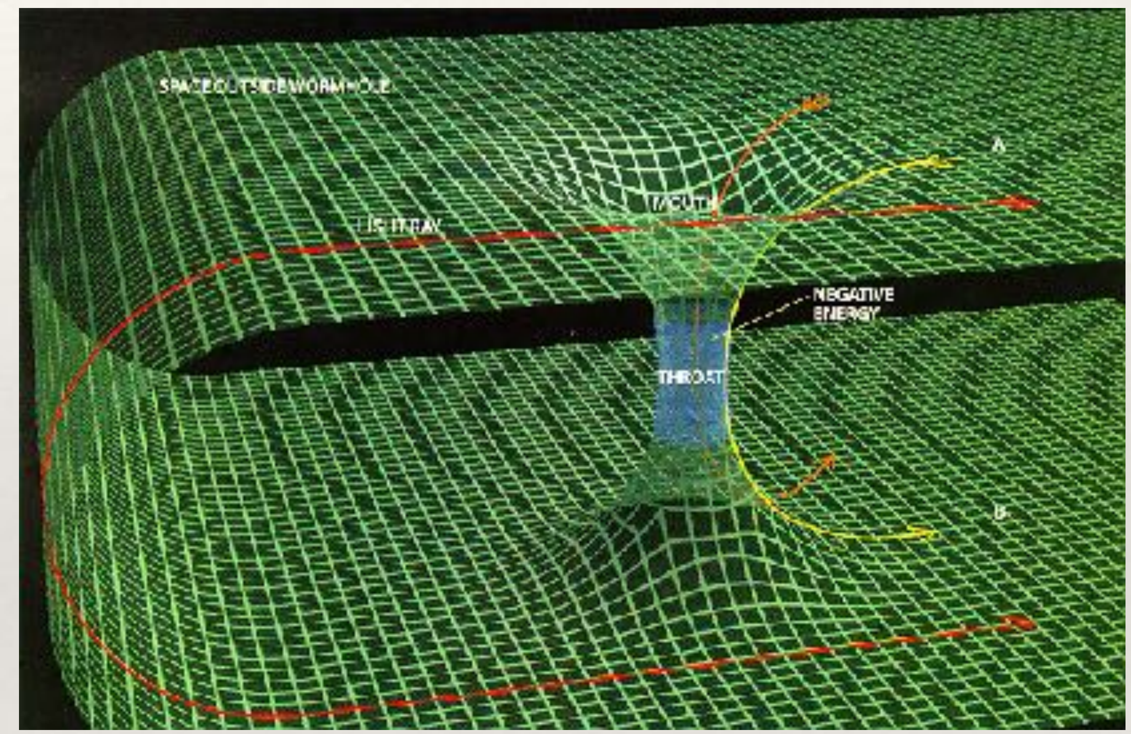


Class 2 limiting case: wormholes

$$ds^2 = -\left(1 - \frac{2M}{\sqrt{r^2+\ell^2}}\right) dt^2 + \left(1 - \frac{2M}{\sqrt{r^2+\ell^2}}\right)^{-1} dr^2 + (r^2+\ell^2)\left[d\theta^2 + \sin^2\theta d\phi^2\right],$$

$\left(1 - 2M/(\sqrt{r^2+\ell^2}\right) = 0$ has no roots for $\ell > 2M$

Similarly for the rotating case.



- Energy conditions violation at the WH throat
- Even worse Topology change is known to be unsustainable from QFT in Curved Spacetimes leading at a paroxysmal particle creation. One really needs QG…

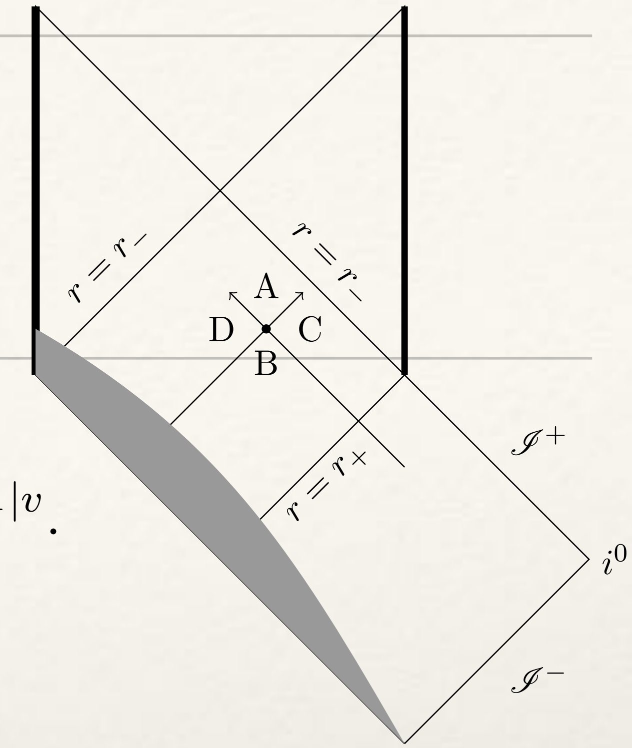
This suggest that wormholes might be generated by QG effects at the end of a gravitational collapse which somehow “bounce back” to a macroscopic regularisation radius ℓ larger than the configuration gravitational radius

Viability

- Are all these singularity resolutions equally viable?

- Already at the theoretical level all of these GR black hole mimickers present different issues…

BH Mimickers



$$m_A(r_0(v)|_{u=u_0}) \propto v^{-\gamma} e^{|\kappa_-|v}.$$

- Regular BH
  - Bouncing Geometries
  - Quasi-BH
- Hidden Wormholes
  - Traversable wormholes

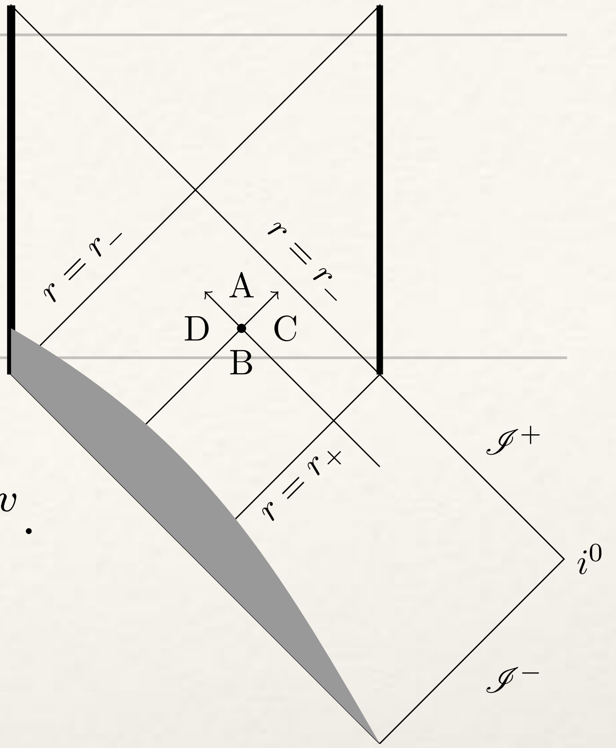
Without fine tuning there is an instability at inner horizon (mass inflation) in QG time scale, while evaporation time is generically infinite. Note also that possible cosmological constant relevant only after a time $v \sim 1/\sqrt{\Lambda}$. Similarly, ingoing Hawking flux can become relevant (see Buonanno et al. 2022) but too late for astrophysical black holes?

R.Carballo-Rubio, F.Di Filippo, SL, C.Pacilio and M.Visser,

JHEP 1807, 023 (2018). [arXiv:1805.02675 [gr-qc]].

JHEP 05 (2021) 132 • e-Print: 2101.05006 [gr-qc]

BH Mimickers



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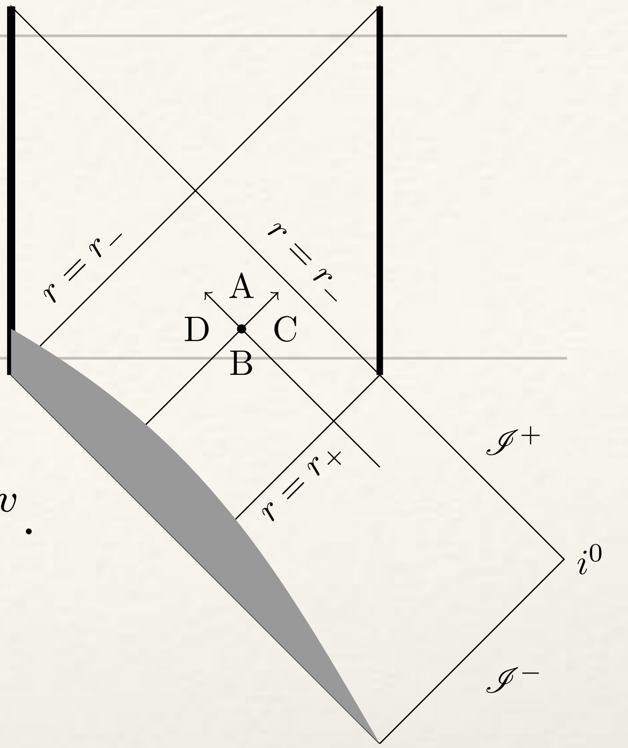

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These results suggest that or
A black hole mimicker with a non-zero inner horizon surface gravity MUST evolve toward some stable state
Options:
1) A RBH with zero IH surface gravity, $\kappa\_ = 0$
2) A bounce
3) Its quasi-BH limi
4) A hidden wormhole solution

Stable regular black holes

- Basic idea: a possible stable endpoint is a Regular BH with zero surface gravity at the IH but non zero one at the outer horizon given that mass inflation is exponential in κ_-

R. Carballo-Rubio, F. Di Filippo, S. Liberati, C. Pacilio and M. Visser, ``Regular black holes without mass inflation instability,'' JHEP \textbf{09} (2022), 118. [arXiv:2205.13556 [gr-qc]].

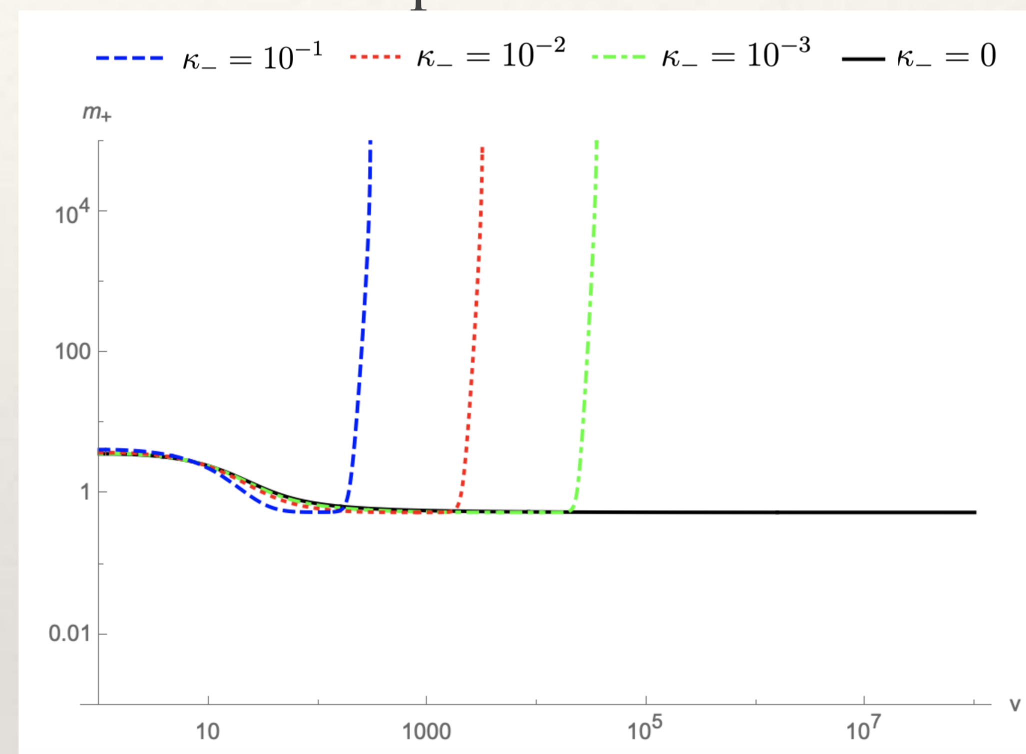
$$\mathrm{d}s^2 = -e^{-2\phi(r)}F(r)\mathrm{d}v^2 + 2e^{-\phi(r)}\mathrm{d}v\mathrm{d}r + r^2\mathrm{d}\Omega^2,$$

Misner-Sharp quasi-local mass m $\quad F(r) = 1 - \frac{2m(r)}{r}.$

$$F(r) = \frac{(r-r_-)^3(r-r_+)}{(r-r_-)^3(r-r_+) + 2Mr^3 + [a_2 - 3r_-(r_+ + r_-)]r^2}, \qquad \phi(r) = 0,$$

subject to

$$r_- \ll r_+ \sim 2M; \qquad r_- \sim |r_+ - 2M|; \qquad a_2 \gtrsim \frac{9}{4}r_+r_-.$$



E. Franzin, S.Liberati, J. Mazza and V. Vellucci, ``Stable Rotating Regular Black Holes,”. [arXiv:2207.08864 [gr-qc]].

$$ds^2 = \frac{\Psi}{\Sigma}\left[-\left(1 - \frac{2m(r)r}{\Sigma}\right)\mathrm{d}t^2 - \frac{4a\,m(r)r\sin^2\theta}{\Sigma}\mathrm{d}t\,\mathrm{d}\phi + \frac{\Sigma}{\Delta}\mathrm{d}r^2 + \Sigma\,\mathrm{d}\theta^2 + \frac{A\sin^2\theta}{\Sigma}\mathrm{d}\phi^2\right],$$

$$\Psi = \Sigma + \frac{b}{r^3}, \quad \Sigma = r^2 + a^2\cos^2\theta, \quad \Delta = r^2 - 2m(r)r + a^2, \quad A = (r^2+a^2)^2 - \Delta a^2\sin^2\theta,$$

$$m(r) = M\frac{r^2 + \alpha r + \beta}{r^2 + \gamma r + \mu}.$$

$$\alpha = \frac{a^4 + r_-^3 r_+ - 3a^2 r_-(r_- + r_+)}{2a^2 M},$$

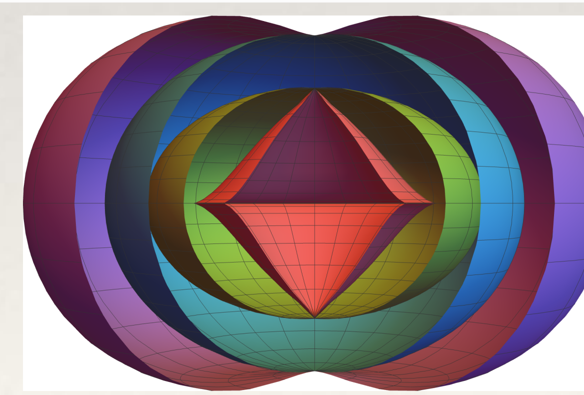
$$\beta = \frac{a^2(2M - 3r_- - r_+) + r_-^2(r_- + 3r_+)}{2M},$$

$$\gamma = 2M - 3r_- - r_+,$$

$$\mu = \frac{r_-^3 r_+}{a^2}.$$

$$r_+ = M + \sqrt{M^2 - a^2},$$

$$r_- = a^2\left[M + (1-e)\sqrt{M^2 - a^2}\right]^{-1}$$



QNM and Shadow
so far cast (mild) constraints on the parameters of the rotating metric.
(see R. Ghosh, M. Rahman and A. K. Mishra, [arXiv:2209.12291 [gr-qc]])

BH Mimickers

- Regular BH
  - Bouncing Geometries
  - Quasi-BH
- Hidden Wormholes
  - Traversable wormholes

Dynamically, it seems more natural to expect that the existence of a repulsive core would lead generally to bouncing solutions via a dominant energy condition violation, t=rather than a stable de Sitter core.

Two main features can be associated to these solutions

1. The typical timescale of the bounce

$$\mathcal{T} = \mathcal{T}^{(j)} \sim t_{\mathrm{P}}(M/m_{\mathrm{P}})^{j}, \qquad j = 1, 2.$$

where j=3 would be the standard Hawking evaporation time.

2. An unavoidable non-classical region outside the trapping horizon

If observation time scale is Δt then deviations from the classical geometries would be suppressed by the dimensionless quotient $\Delta t/\mathscr{T}$

However, in the most natural scenarios, modifications in these geometries are by construction O(1) only after the time $\mathscr{T}$.

So far indication that $\mathscr{T}$~M, so fast bounces, possible mechanism with fast bounce compatible with observations would be fast bounce only at the end of evaporation, or a series of fast dissipative bounces leading to a stable Quasi-BH

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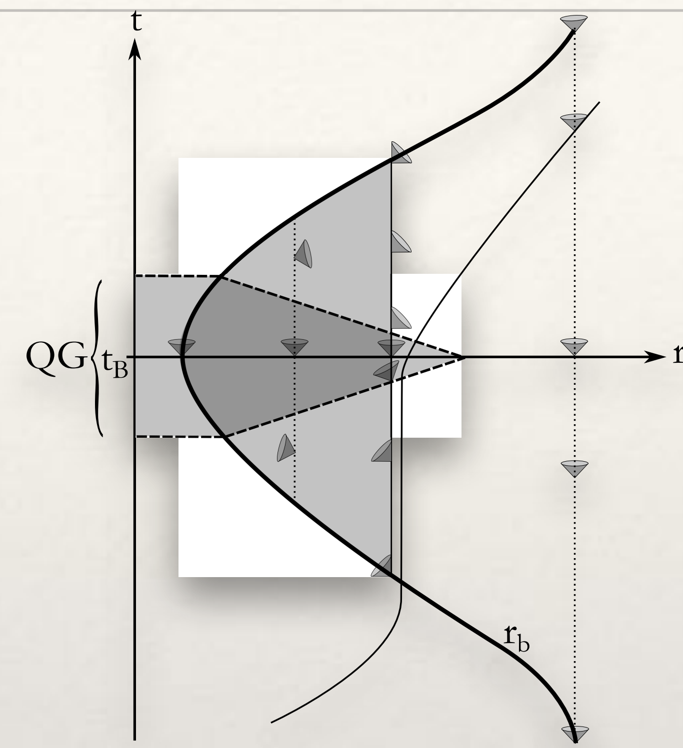

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WITHOUT COMMITTING TO A SPECIFIC MODEL THERE ARE TWO MAIN QUANTITIES THAT CAN BE USED TO CHARACTERISE THESE SOLUTIONS.

A) THE TRANSIENT TIME τ_- THAT IT TAKES FOR A COLLAPSE (OR MERGING?) TO SETTLE DOWN TO THE SOLUTION (END POINT OF BOUNCE OR RBH INSTABILITY)

B) THE DEGREE OF COMPACTNESS $\mu = 1 - \frac{r_s}{R}.$

For $\mu \ll 1$, and if the surface is at a proper radial distance $\ell \ll r_S$ from r_S, one has $\mu \approx (\ell/r_s)^2 \approx 10^{-76} (M_\odot/M)^2 (\ell/\ell_P)^2$

E.g. $\ell \sim \ell_P$ and the mass corresponding to Sgr A*, $M = 4 \times 10^6 M_\odot$, which yields $\mu \sim 10^{-91}$

<u>Ultra compact object light ring instability</u>
In the absence of an horizon there could be, inside the standard unstable light ring, another stable light ring. This structure can lead to unbounded accretion and generate an instability. However, for our UCO always inside EC violating matter. So detailed model needed.
P.V.P. Cunha,et al. [arXiv:2207.13713 [gr-qc]].

Rotating solutions: Generically for perfectly reflecting surface there is an ergoregion instability
E. Franzin, S.L, J. Mazza, R. Dey and S. Chakraborty, Phys. Rev. D 105 (2022) no.12, 124051 [arXiv:2201.01650 [gr-qc]].

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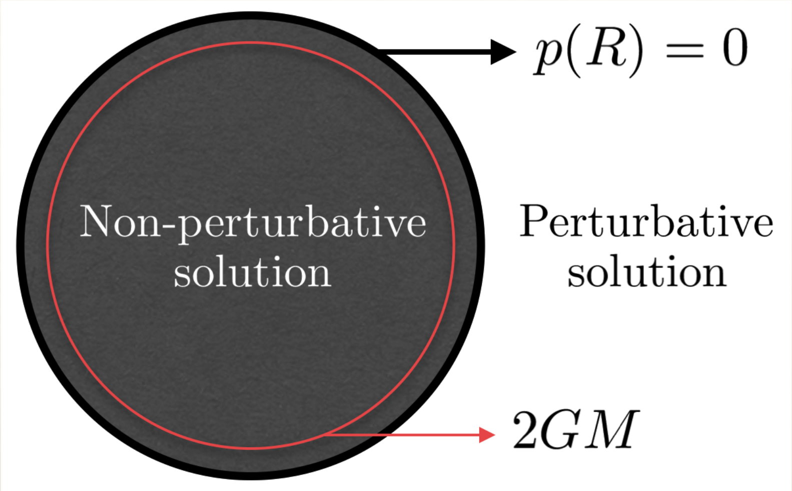

Without committing to a specific model there are two main quantities that can be used to characterise these solutions.

a) The transient time τ_- that it takes for a collapse (or merging?) to settle down to the solution (end point of bounce or RBH instability)

b) The degree of compactness $\mu = 1 - \frac{r_s}{R}$.

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- hidden wormholes are stable

Superradiance analysis:
- The superradiant range for ω does not change, the the effect gets smaller as ℓ gets bigger
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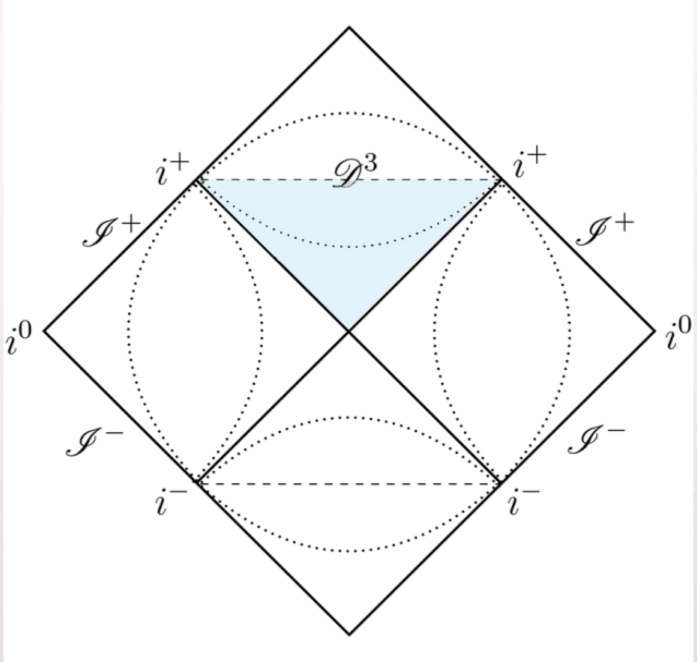

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- **It is generally assumed that standard particles of matter and waves can cross traversable wormholes without experiencing appreciable interactions with the exotic matter opening the throat. Hence, the interior of wormholes is essentially transparent**
- **This assumption would be certainly more reasonable if the exotic matter inside the wormhole comes entirely from the polarization of the quantum vacuum.**
- **The traversability property (the lack of a physical surface) represents the main difference between wormholes and quasi-black holes.**

QNM analysis:

- Slowly rotating wormholes are stable
- Fast rotating wormholes show an ergoregion instability

Superradiance analysis:

- If one does not assume symmetry on the two sides of the throat, then no superradiance (general result for axisymmetric traversable wormholes)

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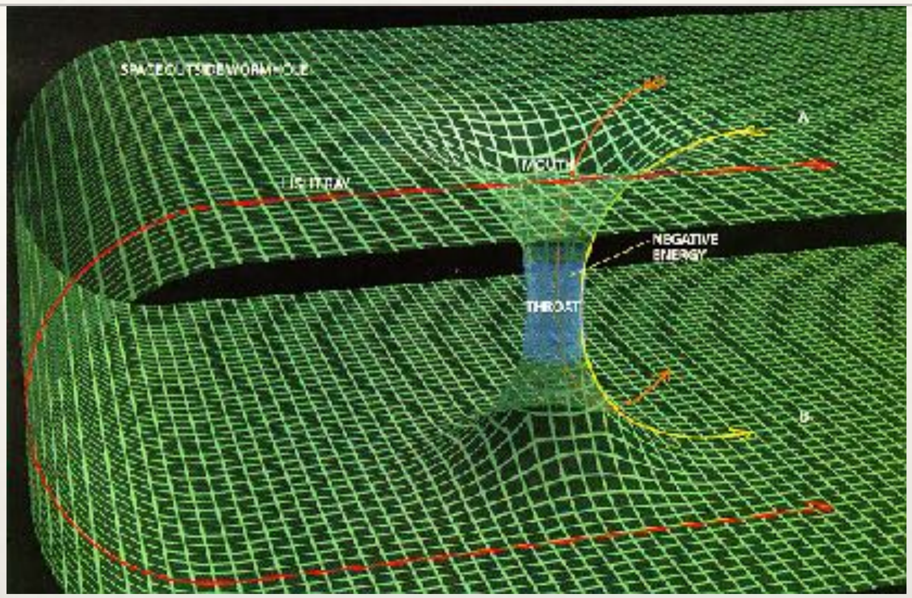

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Phenomenology: parametrising the uncertainties

Size, **$R = r_S(1 + \Delta)$**: the value of the radius below which the modifications to the classical geometry are O(1). $\Delta \geq 0$.
Note the compactness parameter $\mu = \Delta/(1 + \Delta)$. So for $\Delta \ll 1$ one has $\mu \simeq \Delta$

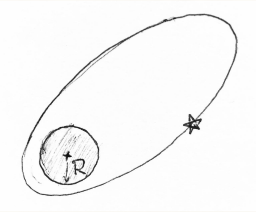
	τ_+ - Lifetime	τ_- -formation time	μ- compactness	κ-Absorption Coeff.	Γ-Elastic reflection Coeff.	$\tilde{\Gamma}$-Inelastic reflection Coeff.	$\varepsilon(r)$- Tails
Classical GR BH	∞	~10 M	0	1	0	0	0
Trapped regions (RBH+Hidden WH)	undertermined	~10 M	0	1	0	0	Non-zero
Quasi-BH	∞	Model dependent	Model dependent	Model dependent	Model dependent	Model dependent	Model dependent
Bouncing Geometries (long lived)	$\mathcal{T}^{(i)}$	Model dependent	0	1	0	0	non-zero and $r_* = O(r_S)$
Traversable Wormholes	∞	unknown	>0	Model dependent	1-κ	0	Model dependent

NOTE: ONE OF THE PARAMETERS IS NOT INDEPENDENT: E.G. INELASTIC INTERACTION PARAMETER MUST SATISFY $\tilde{\Gamma} = 1 - \kappa - \Gamma$

INCLUDING ADDITIONAL INDEPENDENT PARAMETERS WOULD PROVIDE MORE FREEDOM TO PLAY WITH THE OBSERVATIONAL DATA BUT LESS CONSTRAINING POWER. THE SET INTRODUCED IS MINIMAL, BUT STILL ABLE TO ASSES THE OBSERVATIONAL STATUS OF BLACK HOLES.

EM channels

1. Stars orbiting the BH mimicker



- **Tracking several stars we can determine the mass of Sgr A* and our distance from it. $M = 4\times10^6\ M_\odot$ and d = 8 Kpc**
- **Most close orbiting star S2 constraints the radius of Sgr A*: The periastron of S2 is 17 light hours, while the Schwarzschild radius of Sgr A* is 40 light seconds. Therefore, $\Delta \leq O(10^3)$.**

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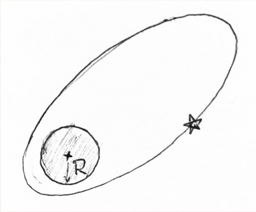

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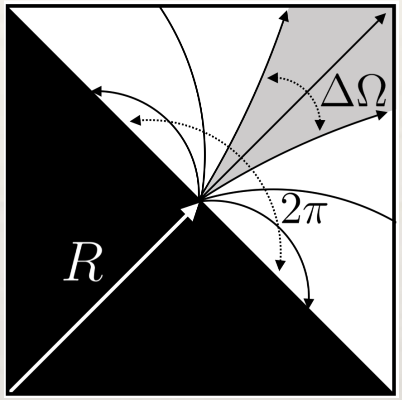
2. Infalling matter.

Naive expectation:
strong constraints from absence of thermal radiation from hard surface in the case of Quasi-BH
However quite generally radiation emitted as a consequence of smash of matter on a hard surface rather than a horizon will be subject to strong lensing. Indeed the escape solid angle is

For $r \to r_s$ $$\frac{\Delta\Omega}{2\pi} = \frac{27}{8}\mu + \mathscr{O}(\mu^2).$$

Therefore, only a small fraction of the light emitted from the surface of the object will immediately escape to infinity



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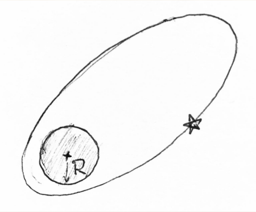

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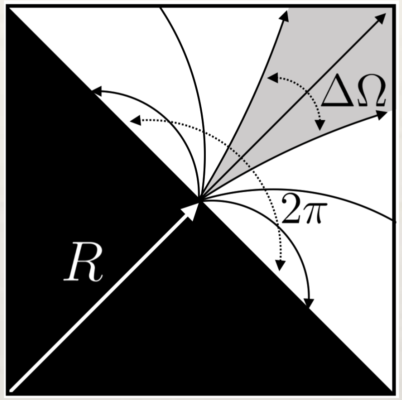

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Therefore, only a small fraction of the light emitted from the surface of the object will immediately escape to infinity

- Cataclysmic events (stars disruptions)

weak constraint due to complex physics $$\mu \leq 10^{-4}\frac{\kappa_T M_\star}{4\pi r_s^2} = \mathscr{O}(1) \times \left(\frac{10^8 M_\odot}{M}\right)^2.$$

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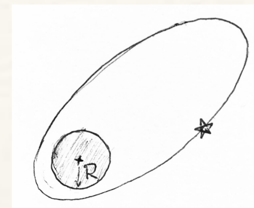

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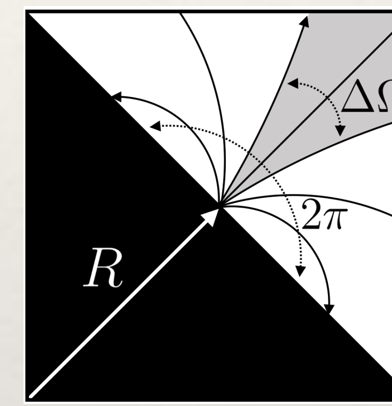

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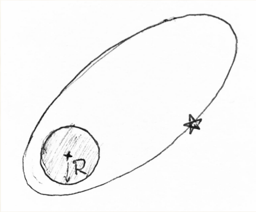

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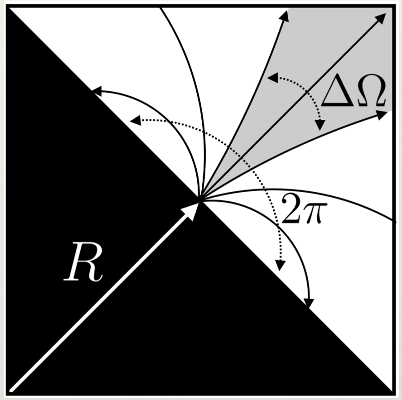

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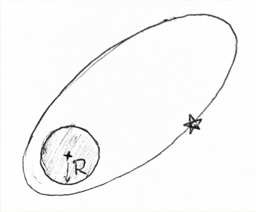

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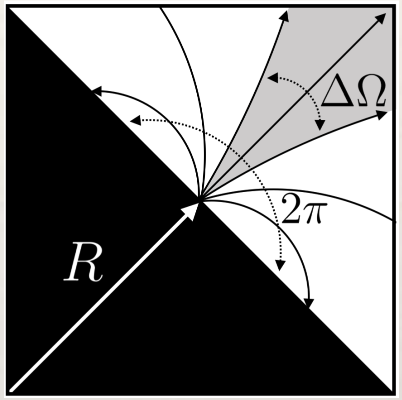

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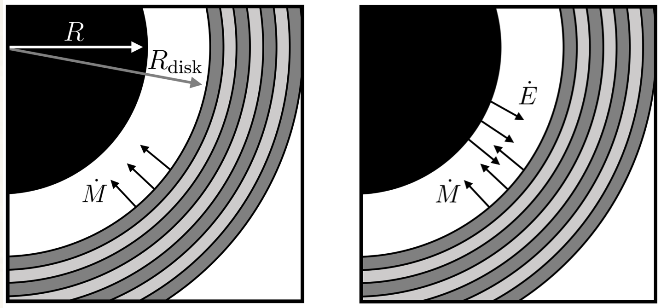

10^2 meters over a size of 10^{10} m! Still very far from Planck scale.

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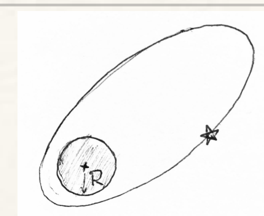

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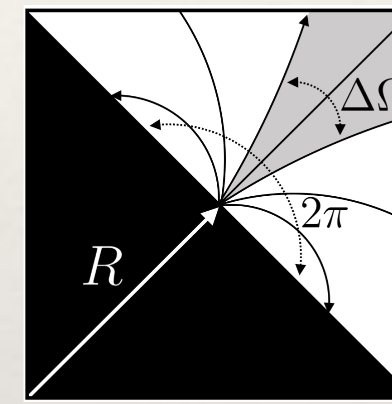

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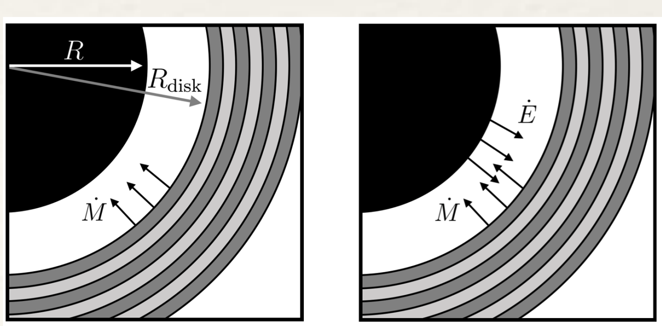


Let's analyse in detail the case of non-zero absorption
(i.e. simple case $\kappa \neq 0$ but $\Gamma = 0$)

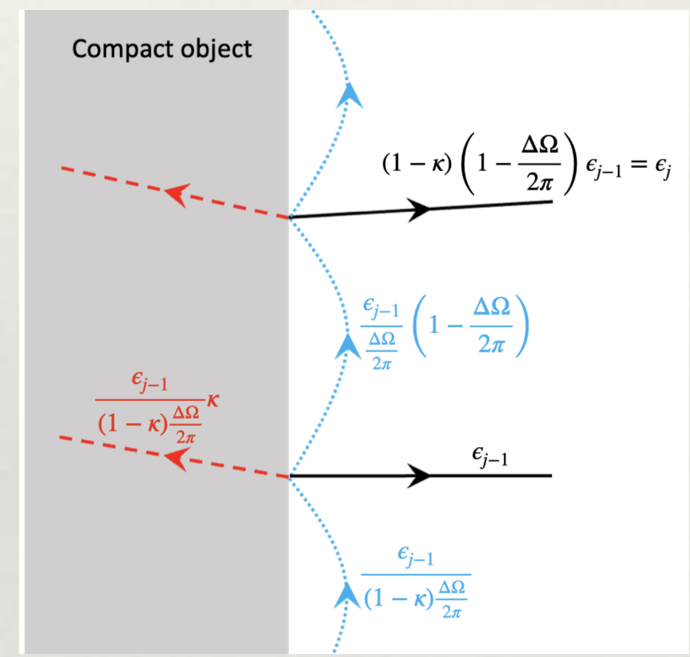
EHT Constraints from Reemission

The minimum surface luminosity expected at infinity L∞ can be estimated as

$$L_\infty > \eta \dot{M} \ \text{ where } \ \eta = \dot{E}/\dot{M}$$

An upper bound on the observed luminosity can then be translated into a constraint on the η parameter. From ETH we know $\eta < 10^{-2}$

How this translates on a bound on $\mu = 1 - 2M/r_*$?



Assuming that all the kinetic energy of infalling matter is converted to outgoing radiation, leads to the naive result $\eta = 1 - \sqrt{\mu}$

However, this does not take into account the physical relevant case in which part of the radiation is absorbed by the Quasi-BH. I.e. the case $\kappa \neq 0$.

This plus the narrow escaping angle (remember $\Delta\Omega/2\pi = 27\mu/8 + O(\mu^2)$) leads to several bounces of the radiation over the surface which can be summed up.

The net effect is $\eta(t) = \frac{\dot{E}}{\dot{M}} = \frac{\Delta\Omega}{2\pi}\frac{(1-\kappa)}{\kappa + \frac{\Delta\Omega}{2\pi}(1-\kappa)}\left\{1-(1-\kappa)^{t/\tau}\left(1-\frac{\Delta\Omega}{2\pi}\right)^{t/\tau}\right\}.$

t=time over which SGrA* has been accreting
$t \approx T_{\rm Edd} \approx 3.8 \times 10^8$ yr
τ = time for each bounce $\approx O(10M) \sim 10^2$ s

For the physical limit $\tau/T \ll \kappa < 1$ $\qquad \eta = \frac{\Delta\Omega}{2\pi}\frac{1-\kappa}{\kappa + \frac{\Delta\Omega}{2\pi}(1-\kappa)}.$

So e.g. for $\tilde{\Gamma} = 1 - \kappa = 10^{-5} \implies \mu \lesssim 10^{-7}$
or for $\tilde{\Gamma} = 1 - \kappa = 10^{-2} \implies \mu \lesssim 1$

So no meaningful upper-bound constraints can be placed for objects with large absorption coefficients

R. Carballo-Rubio, F. Di Filippo, S.L. and M.Visser,
JCAP08 (2022) no.08, 055.[arXiv:2205.13555 [astro-ph.HE]].

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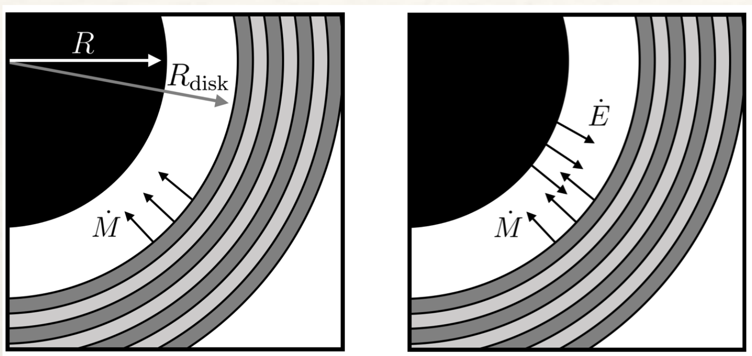

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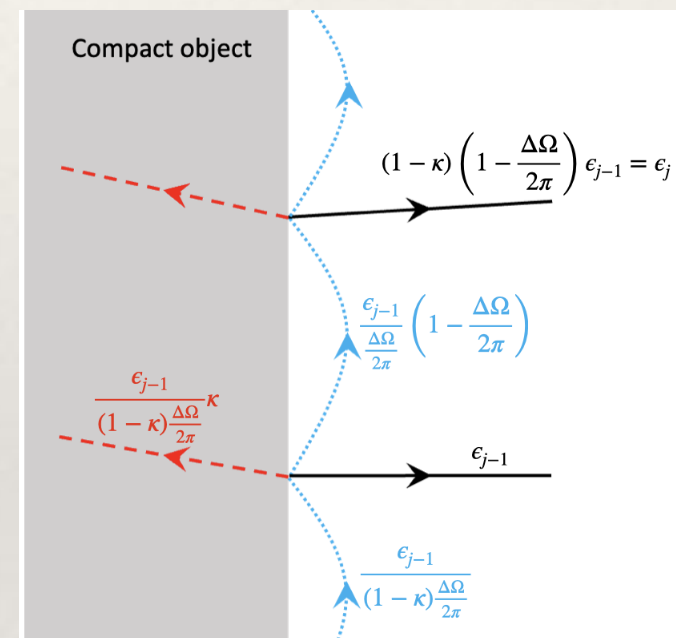

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- Zulianello, Carballo-Rubio, SL, Ansoldi: *Phys.Rev.D* 103 (2021) 6, 064071 • e-Print: 2005.01837 [gr-qc]

Extension to rotating BH

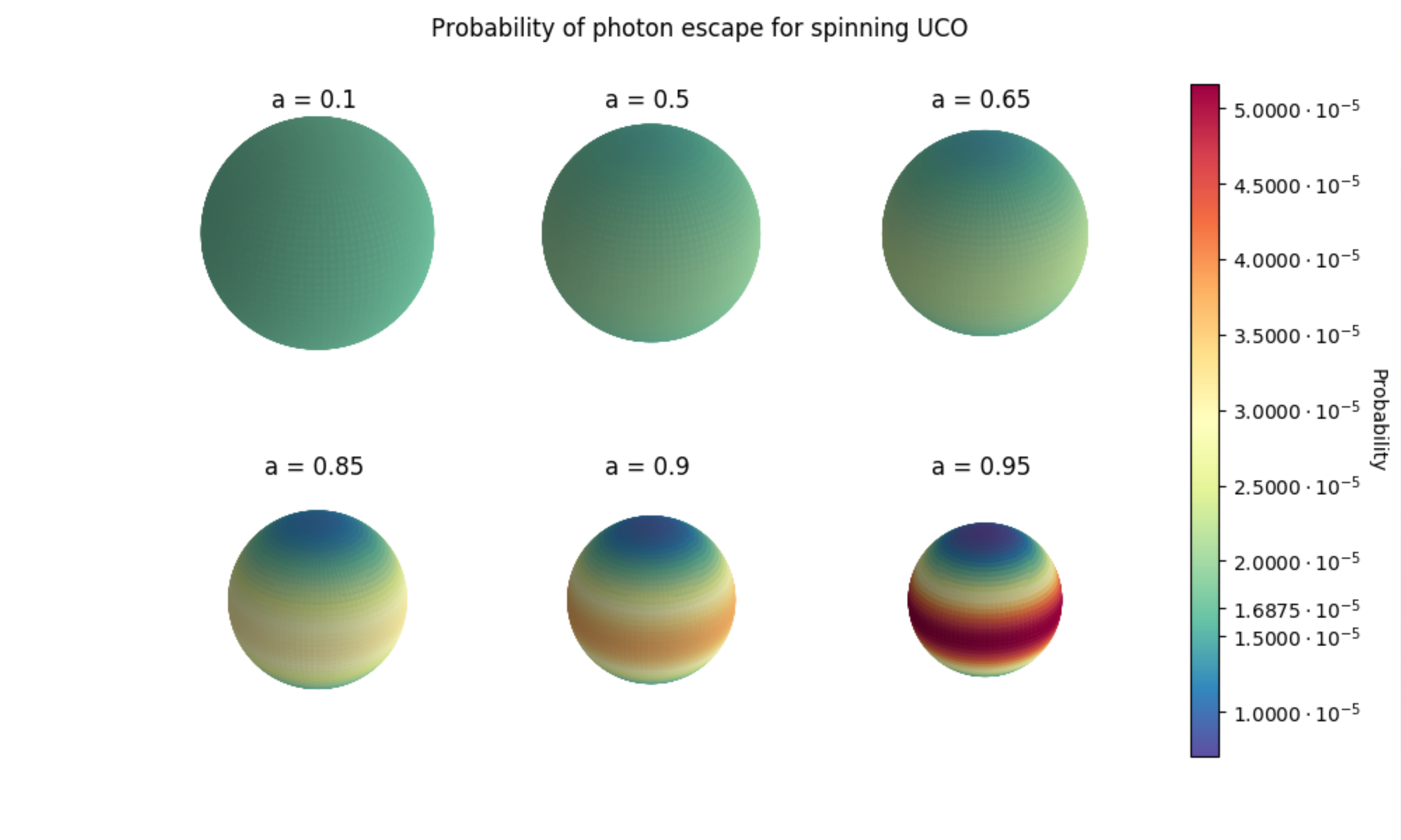
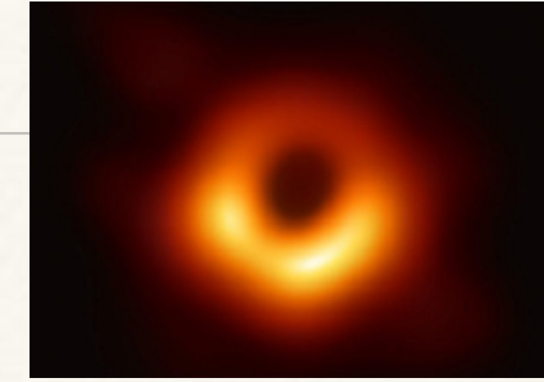


FIG. 11: Visualizations of photon escape probability for different values of a, normalized to the same color scale. The value $P = 1.6875 \cdot 10^{-5}$ corresponds to the case $a = 0$.

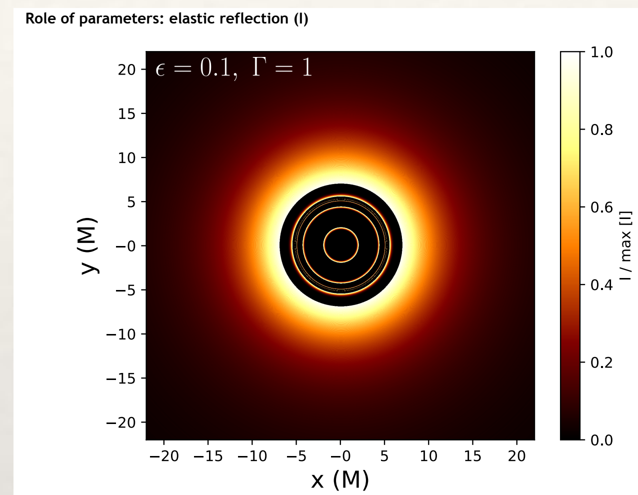
The re-emission of radiation can be enhanced or suppressed w.r.t. the non-rotating case if it happens respectively at the equator or at the poles, due to the dependence of the escaping angle to the azimuthal coordinate.

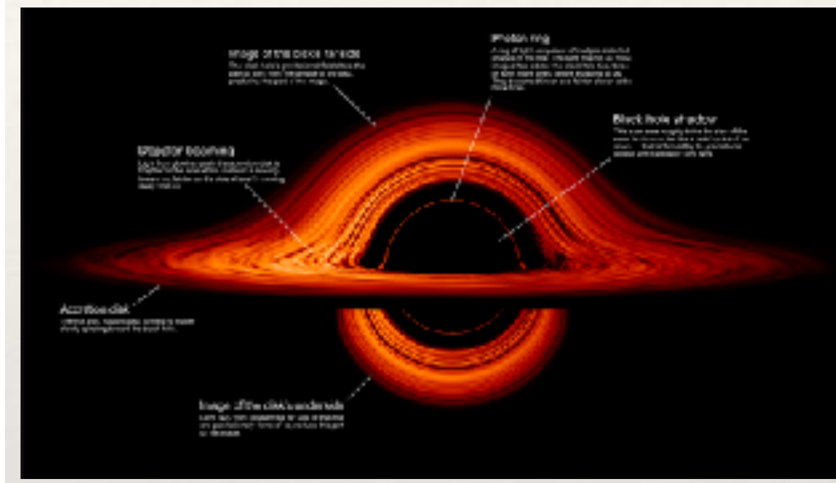
EM channels



Event Horizon Telescope actual Image of M87

EM probing of BH mimickers can come from two other forms of interaction with matter:





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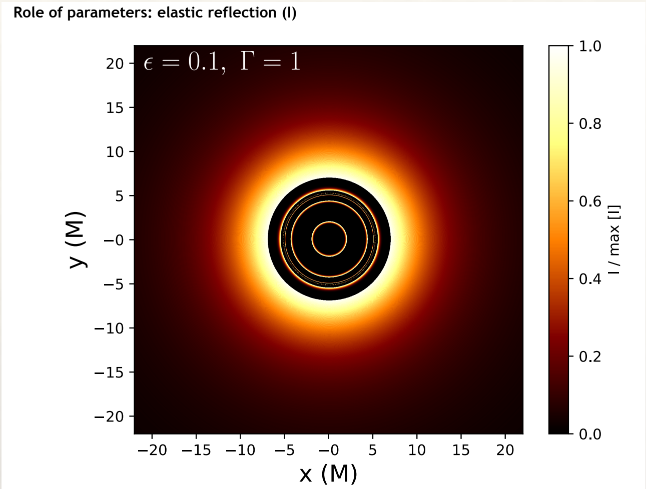
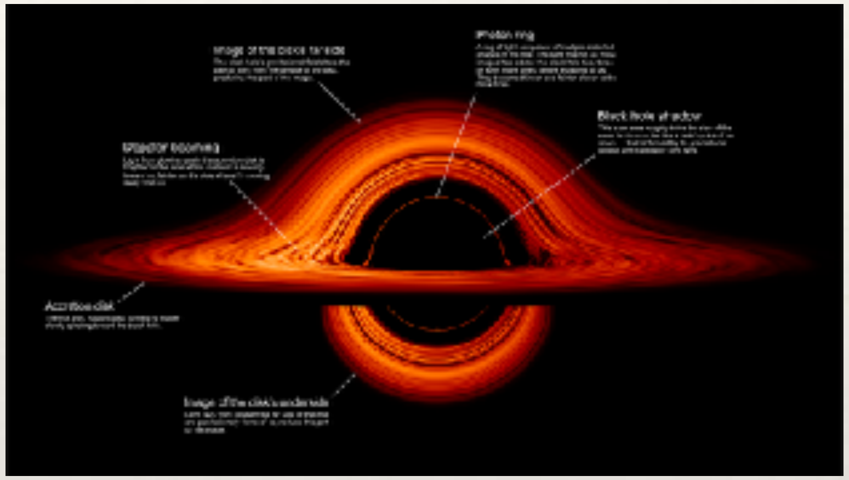
1. Hunting shadows

BH mimickers with a clean photon sphere can very easily mimic the BH shadow. However, in the case of very long tail effects strong constraints are expected. Still recent studies suggest that some models will be constrainable with better resolution.

See e.g. R. Carballo-Rubio, V. Cardoso and Z. Younsi,``Towards VLBI Observations of Black Hole Structure,'' [arXiv:2208.00704 [gr-qc]].





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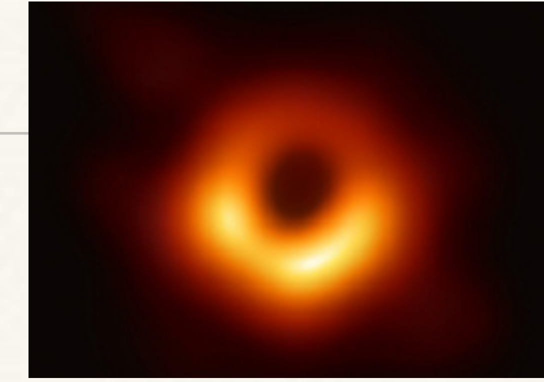

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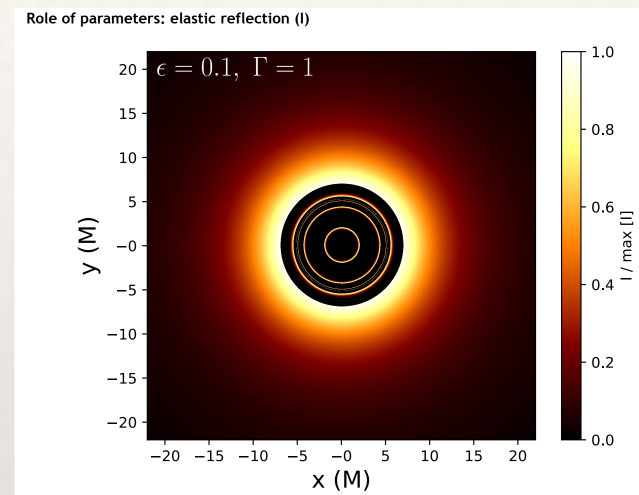

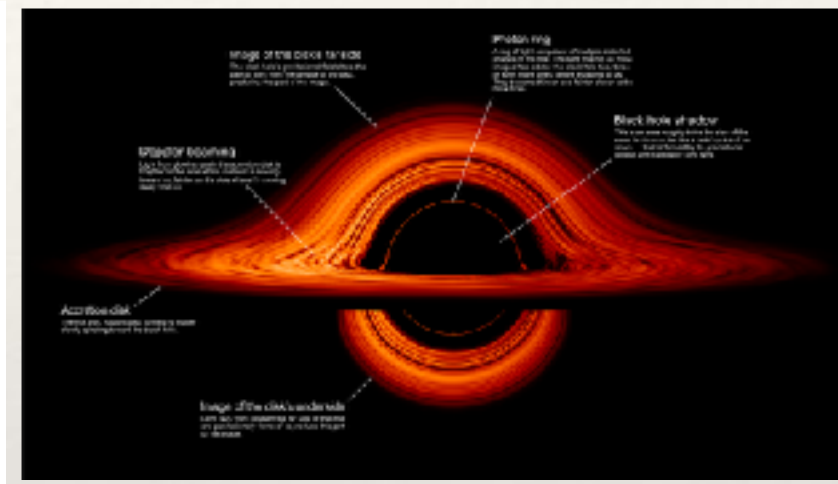

2. Burst from Bounces

- **Present calculations favour a timescale $\tau^{(1)} \sim t_p(M/M_{pl})$ with a signal expected at freq.~$1/\tau^{(1)}$. This timescale is incompatible with long living BH candidates observed but it does not imply disappearance of the object (e.g. multiple bounces leading to stable ultra-compact object).**

- **If timescale is $\tau^{(2)} \sim t_p(M/M_{pl})^2$ (long living bounce) expected UV+IR components**

UV Component~Temperature of the universe at the time of the collapse

IR Component~Size of the bouncing Object

For primordial black holes whose lifetime is of the order of the Hubble time, IR ~MeV-GeV scale UV~TeV range (cf. Barrau, Rovelli, Vidotto)

GW channel: Echoes

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- In the case of a black hole GW scattered back at the potential barrier (usually close to the light ring) are lost inside the horizon.
- For an horizonless object (quasi-BH or traversable wormhole) instead the wave can go through the center and bounce again at the potential barrier with a part transmitted at infinity and one par reflected. This generates “echoes”.

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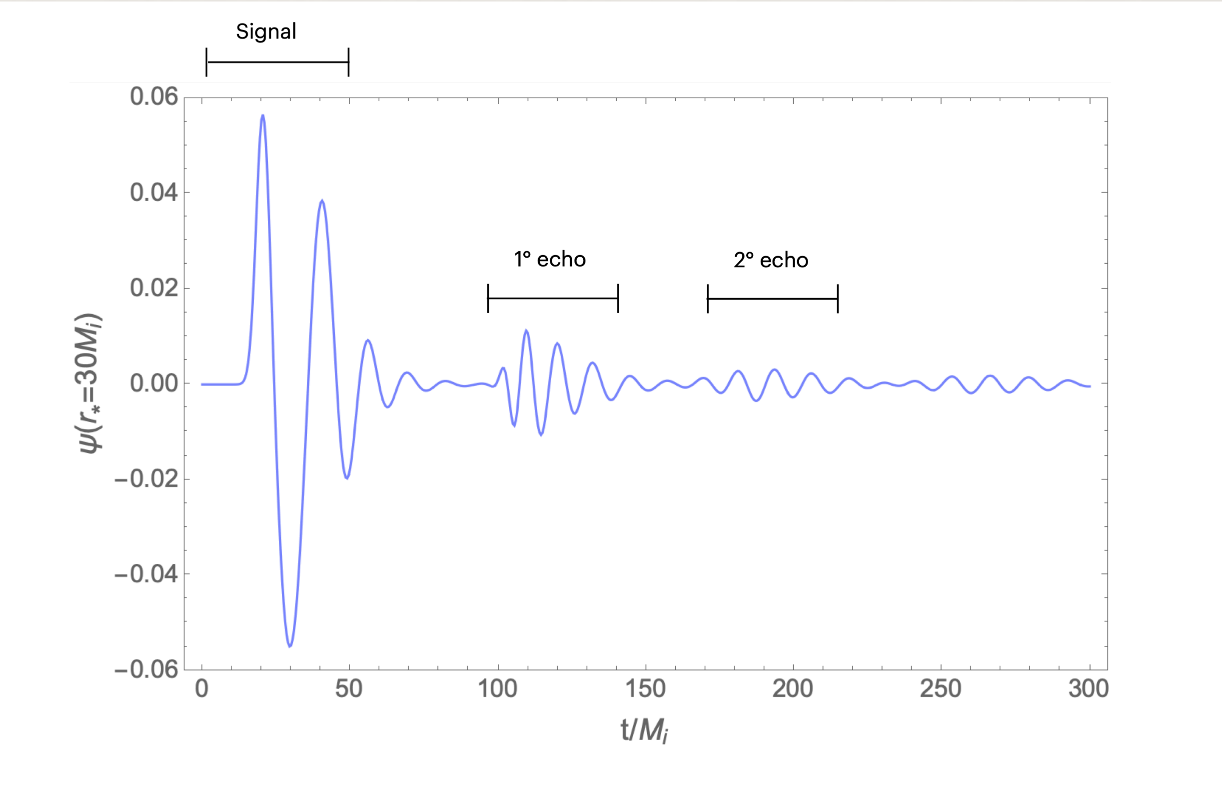
Key point: even for ultra compact objects the delay between such echoes is macroscopic (logarithmic scaling).

Time delay for an object of compactness $\Delta = r/2M_0 - 1$

$$\Delta t_{\text{echo}} = 2\int_{r_0=2M_0(1+\Delta)}^{r_{\text{peak}}\approx 3M_0} \frac{\mathrm{d}r}{1-2M_0/r} \approx 2M_0\left[1-2\Delta-2\ln(2\Delta)\right]$$

- **The amplitude of gravitational wave echoes would be proportional to Γ.**
- **A non-observation of echoes can only constrain this parameter.**
- **A positive detection of echoes could be used in order to determine also Δ.**
- **The other two parameters which are relevant for the process are τ^+, which has to be greater than the characteristic time scale of echoes (this would place a very uninteresting lower bound on this quantity), and τ_- which has to be smaller .**



So far searches for quasi-periodic signals…

Echos and Non-linear back reaction

V. Vellucci, E. Franzin and S. Liberati,
``Echoes from backreacting exotic compact objects,''
arXiv:2205.14170 [gr-qc]].

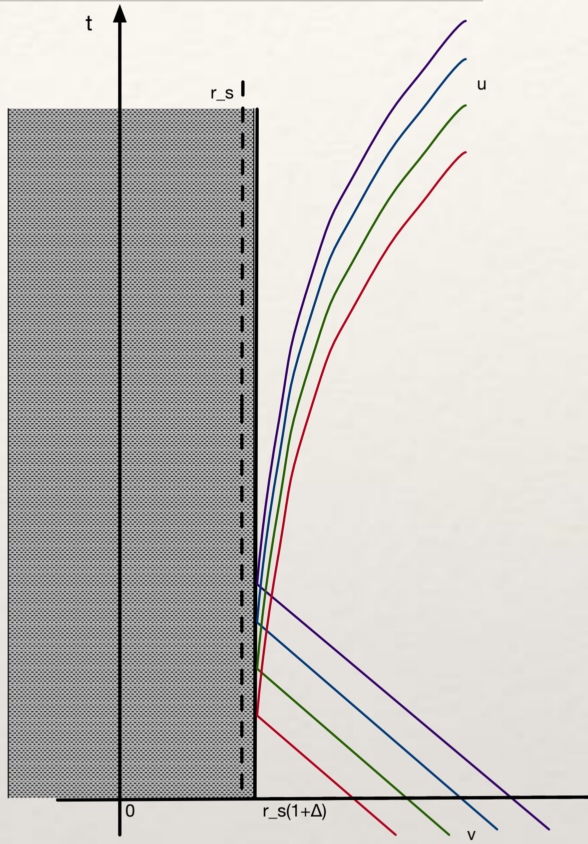
Echos and Non-linear back reaction

Non-linear interactions between the GW and the central object

- These are neglected in extant analyses. However, this appears to be inconsistent
- **For quasi-BH even modest amounts of accretion will generate a trapped region**
- The formation of a trapping horizon might be avoided by nonlinear interactions

Example: If vacuum polarisations supports a QUasi-BH in Boulware vacuum

$\text{RSET} \propto -\left(1-\frac{2M}{r}\right)^{-2}$ so even tiny change 2M→r can generate huge back-reaction.



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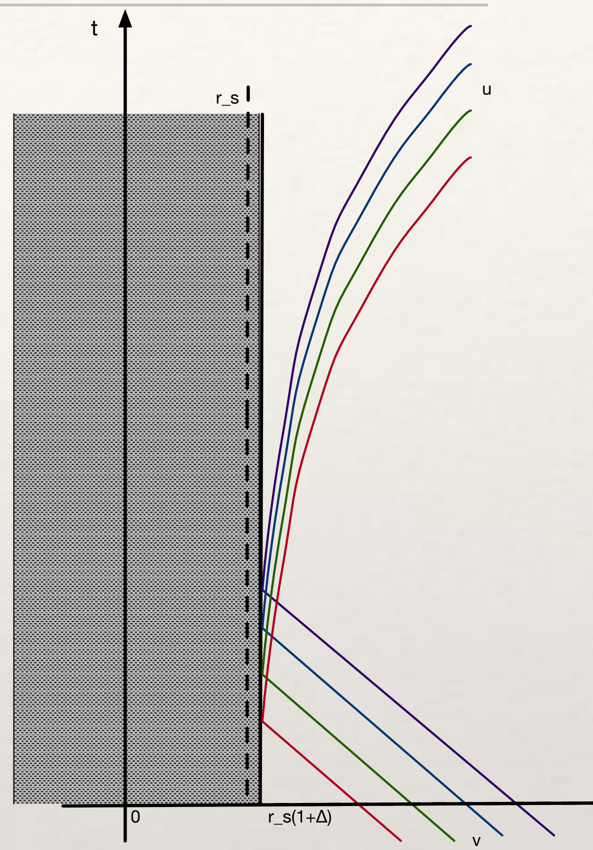

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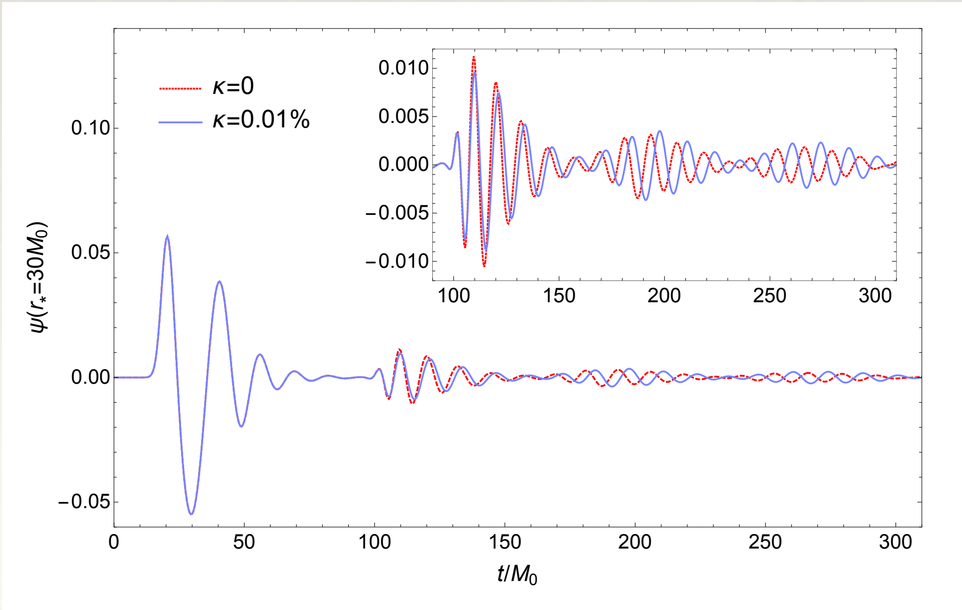
- The more compact the central object is, the larger is the fraction of the energy stored in the gravitational waves to be transferred through nonlinear interactions. I.e. large absorption $\kappa = 1 - E_{out}/E_{in}$

- A model-independent outcome of these interactions has to be the expansion of the central object in order to avoid the formation of trapping horizons.

- For very compact objects, very small ΔM corresponds to large variations in the compactness.

- So, even for $\kappa \sim 0.01\,\%$ one get noticeable delays between echoes given that the compactness of the object has to increase



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Toy modelling the back-reaction

1. The object varies its compactness up to a certain asymptotic limit (max compactness)
2. The object expands so to keep its initial compactness

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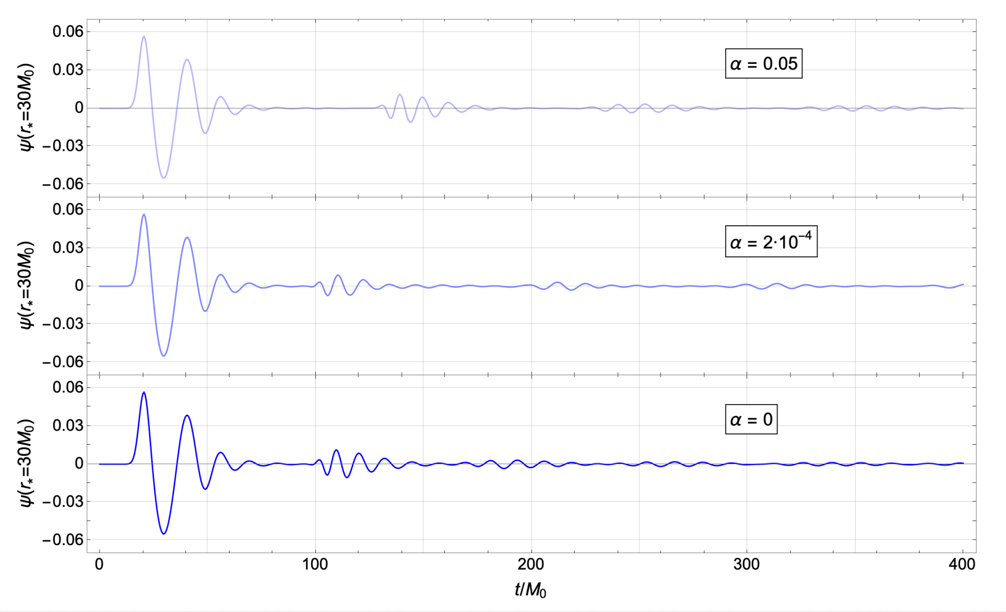
Example case 1

Assume

$$\kappa(\Delta) = \alpha\left(1 - \tanh\frac{\beta}{\Delta - \Delta_{\rm Planck}}\right)$$



Echos and Non-linear back reaction

Toy modelling the back-reaction

1. The object varies its compactness up to a certain asymptotic limit (max compactness)
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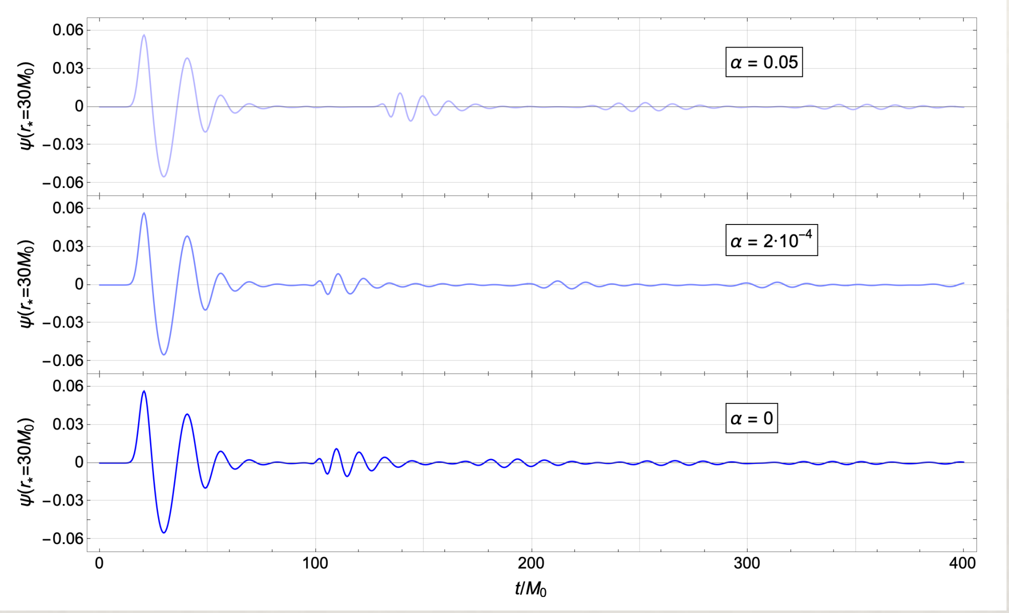

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Assume expansion law

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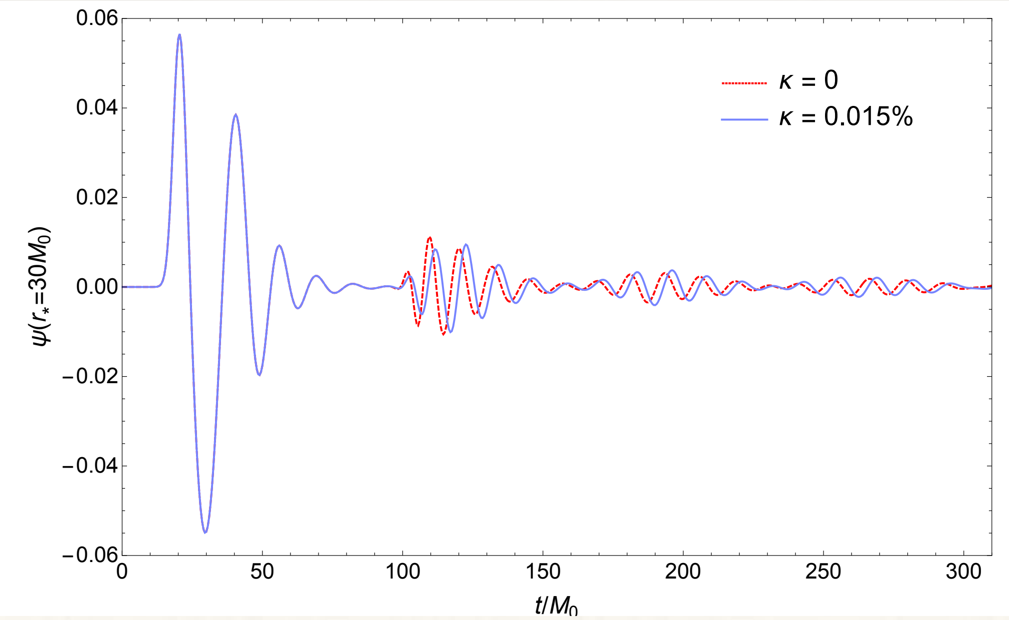

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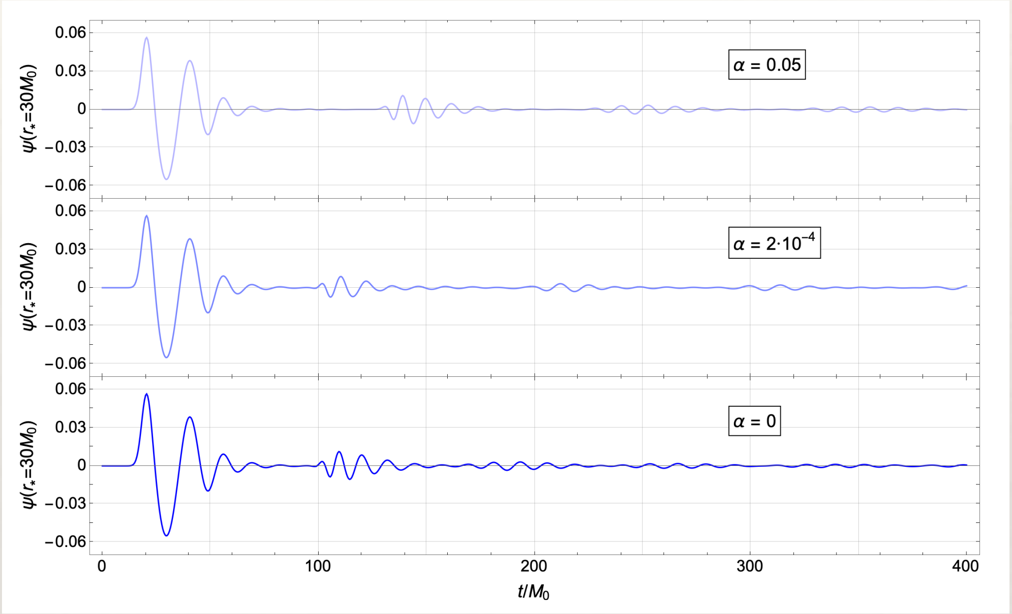

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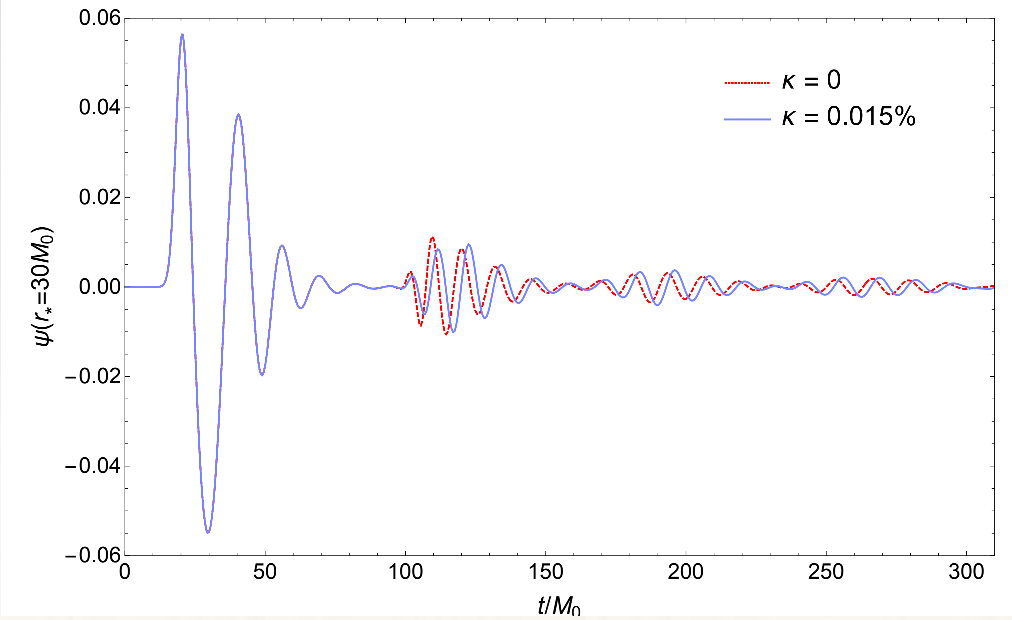

Upshot:

Case 1: Lost of signal quasi-periodicity!

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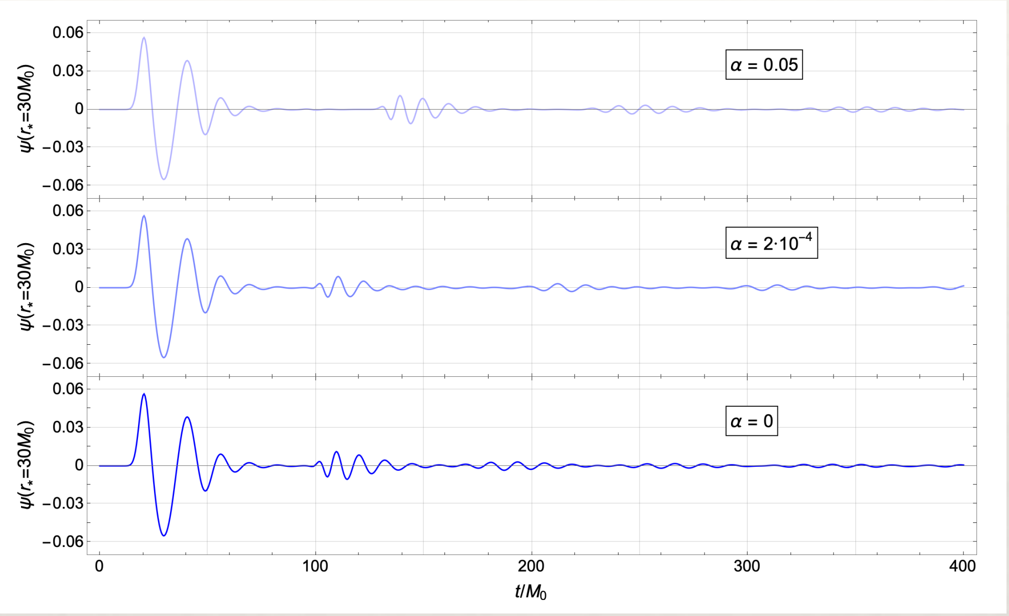

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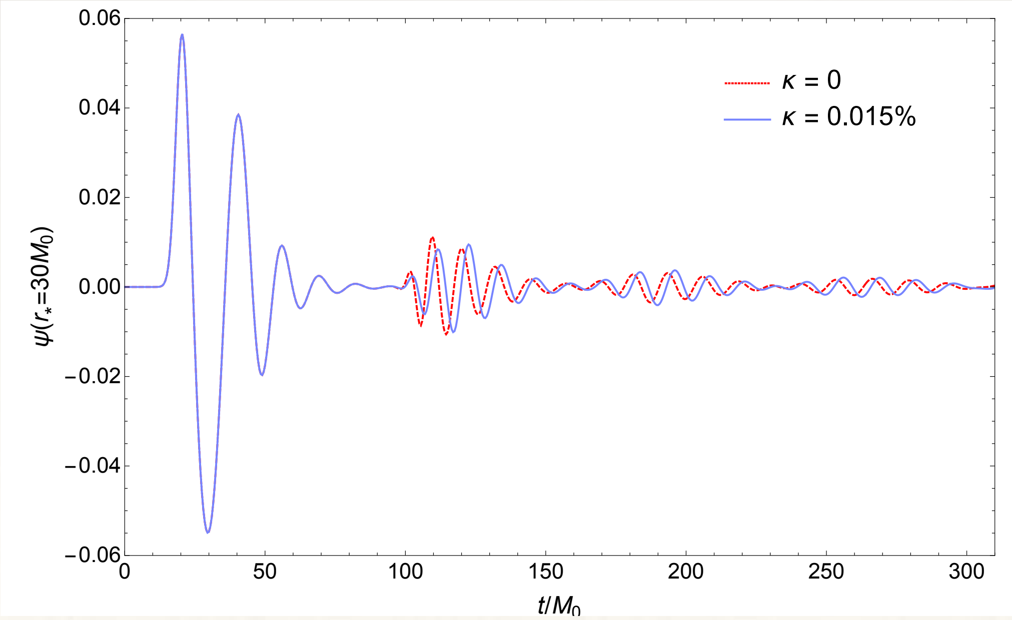

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Case 1: Lost of signal quasi-periodicity!

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We need improved analyses and model sensitive searches!

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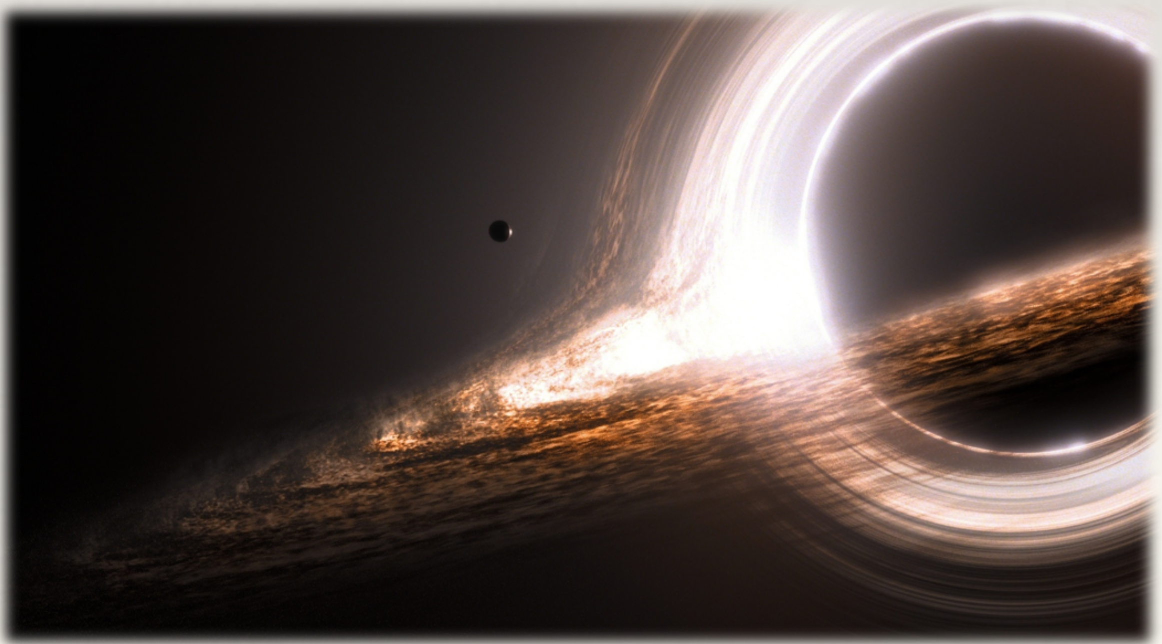

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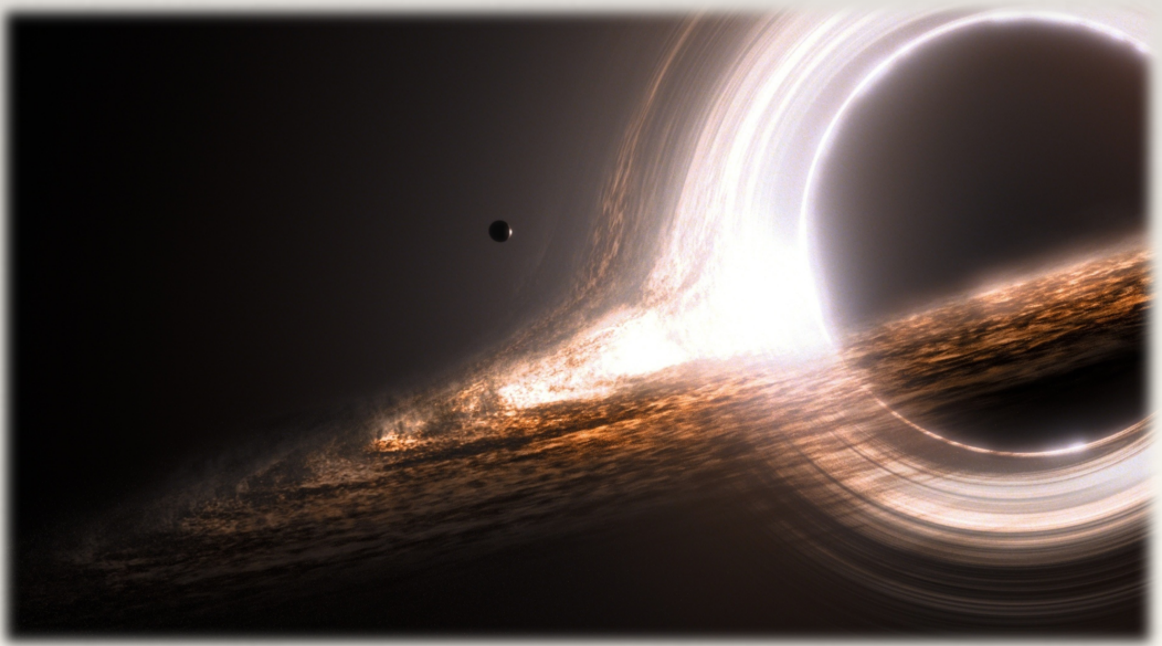
- BH are the new frontier for testing classical and quantum deviations from GR
- Basic arguments from Penrose singularity theorem show that regular spacetime resolutions of singularities are divide in two families depending on the absence/presence of a minimal radius (topology change)



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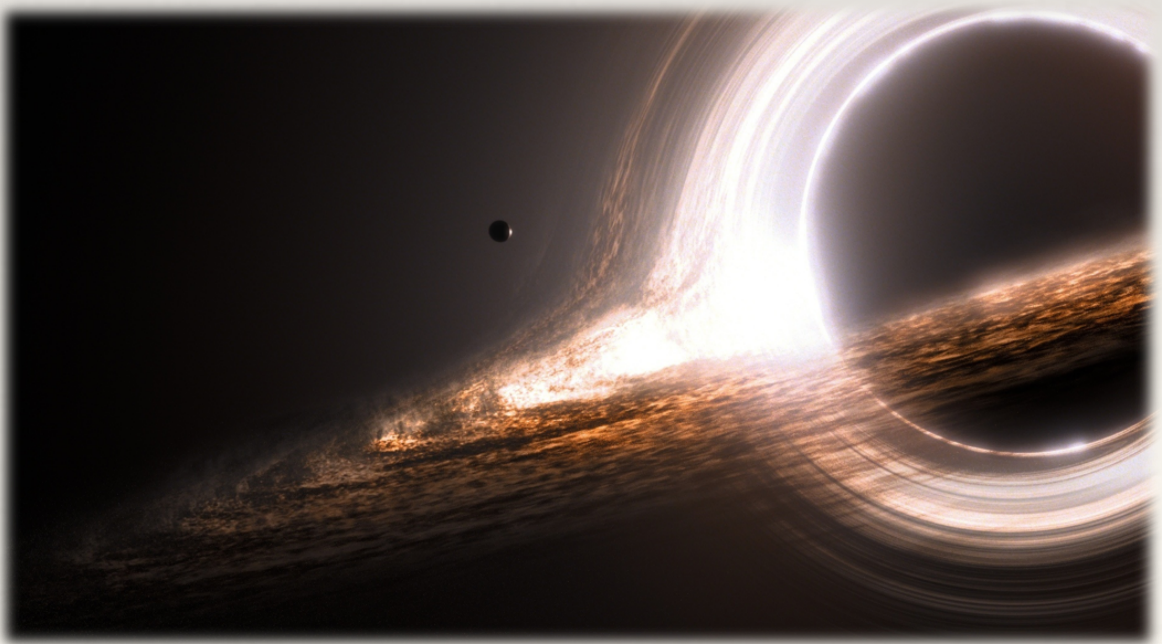

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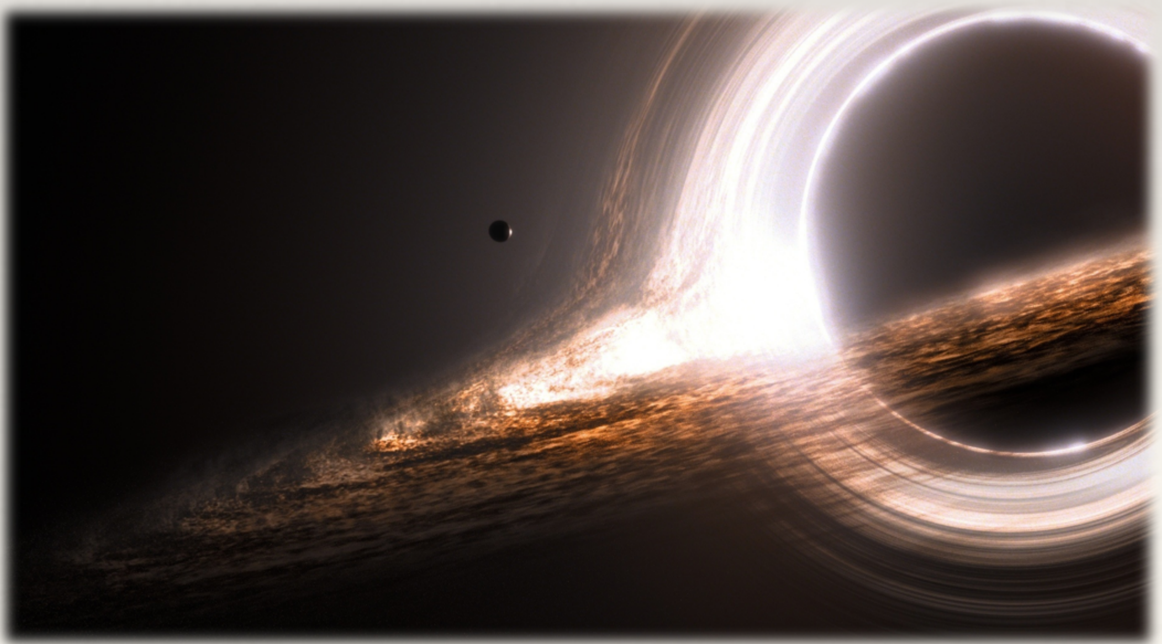

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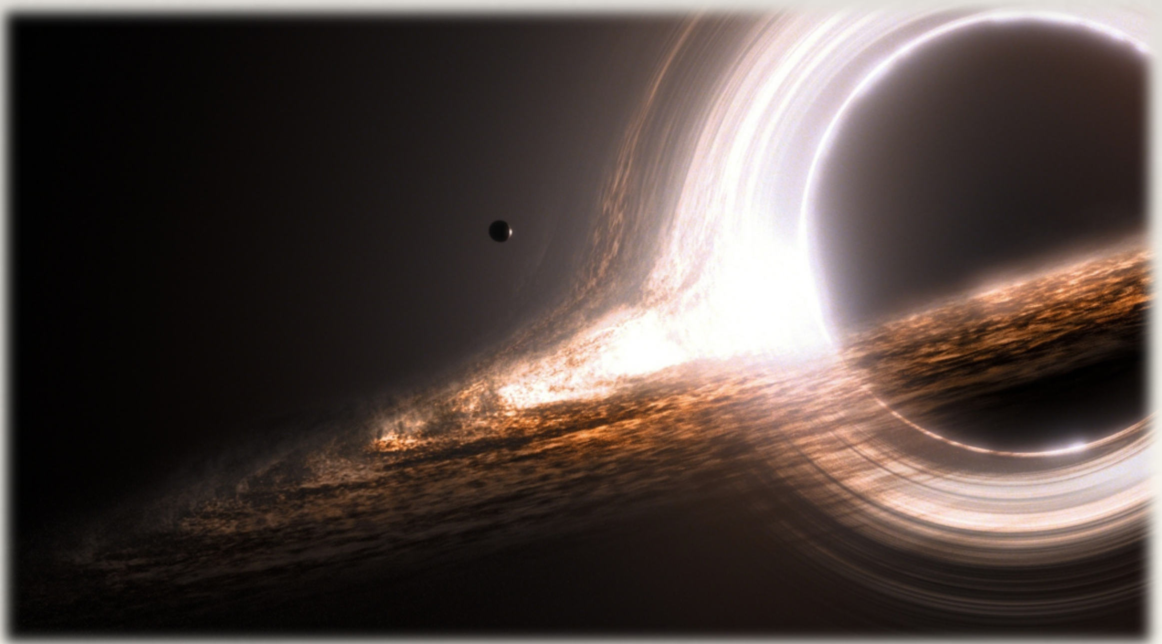

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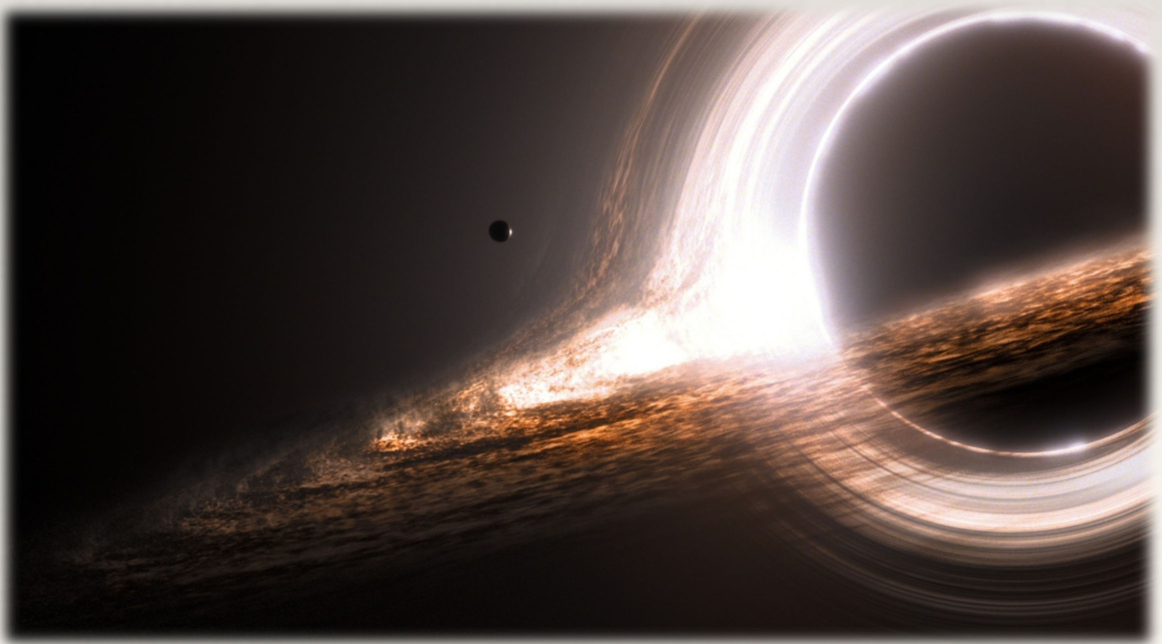
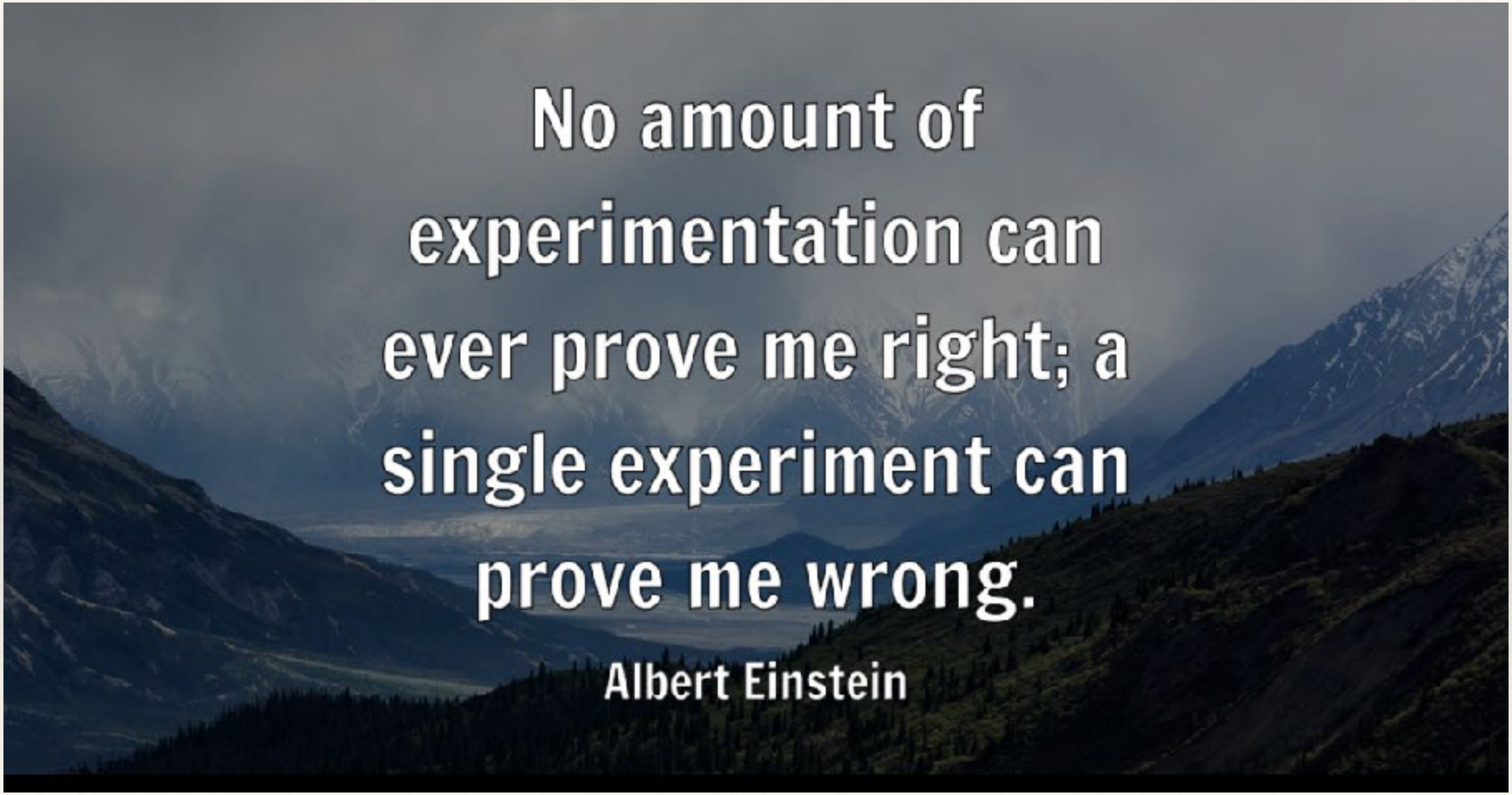


Hopefully, we might be at the dawn of a new form of QG phenomenology based on BH observations!

THANK YOU!


No amount of experimentation can ever prove me right; a single experiment can prove me wrong.
Albert Einstein