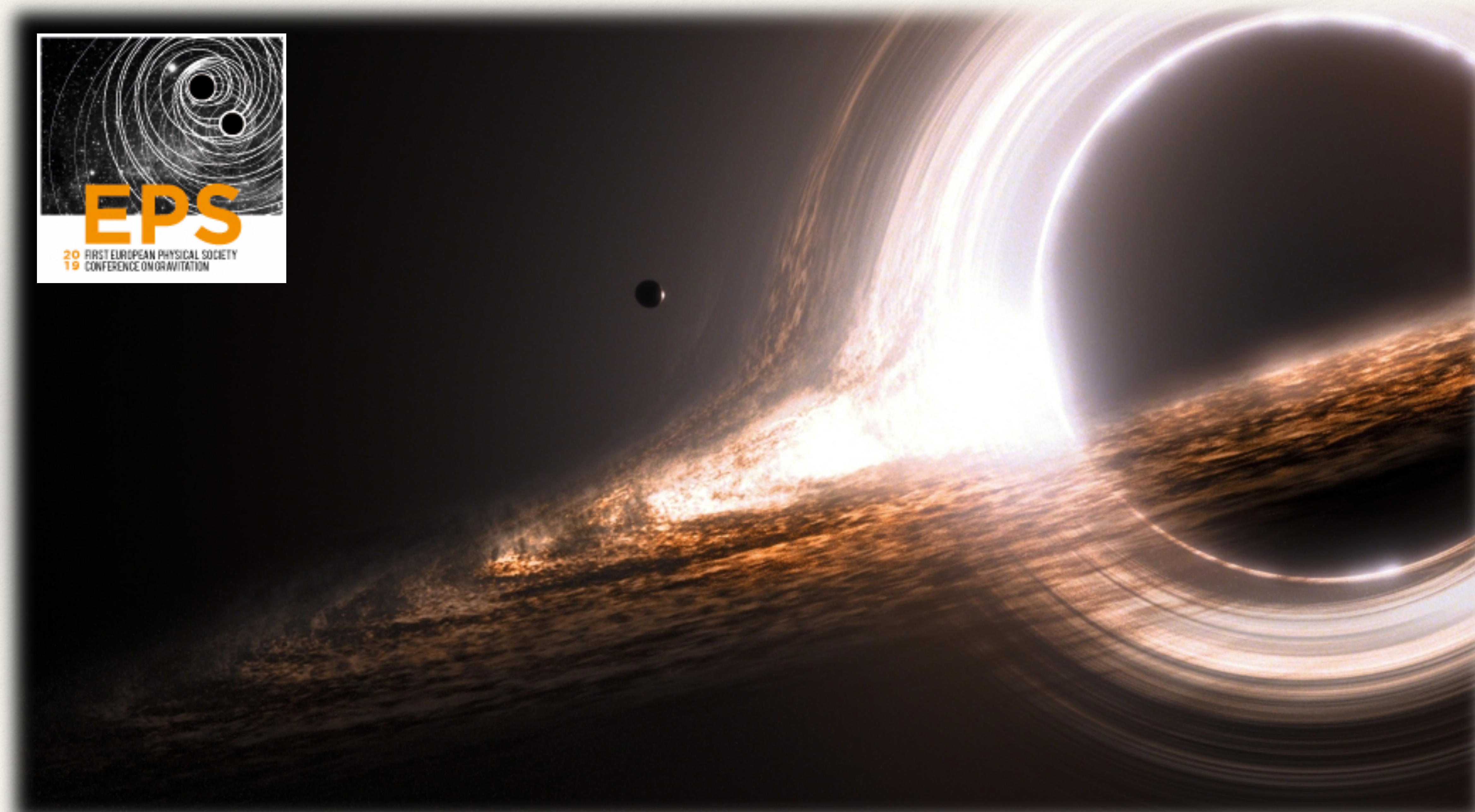
Phenomenological aspects of black holes beyond general relativity

Stefano Liberati



” Raúl Carballo-Rubio, Francesco Di Filippo, SL, and Matt Visser

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GR Black Holes

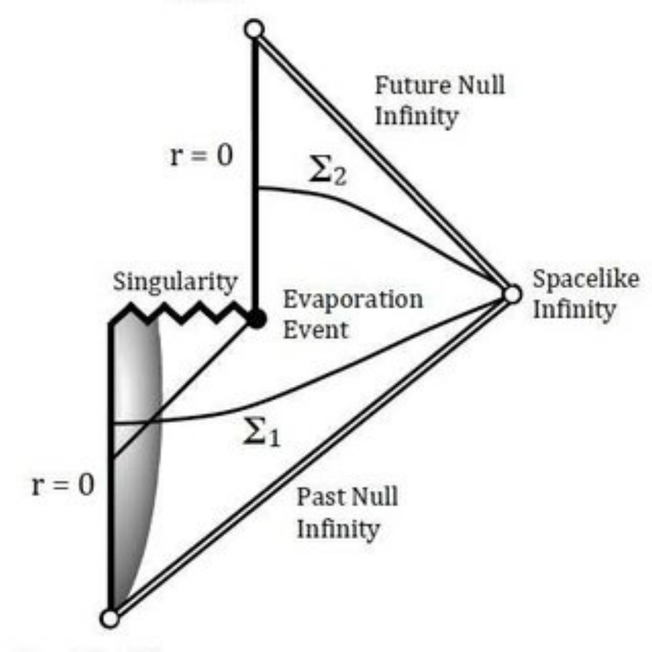
- Albeit we are nowadays familiar with the concept of Black Holes their acceptance as a physical solution of General relativity has been far from obvious.
- BH indeed are characterised by “hard to digest” structures
  - The singularity: infinite curvature
  - Cauchy horizons: end of predictability

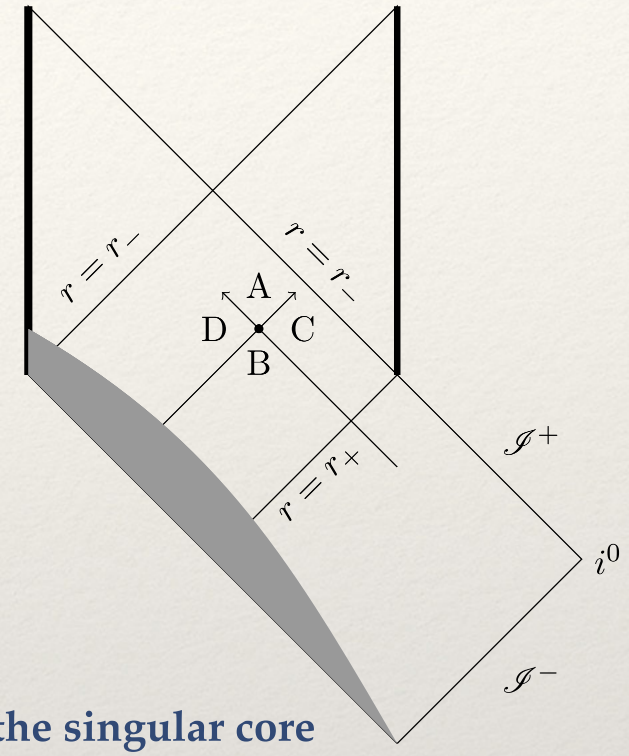
QG i supposed to “cure” these features: if it does so just in a hidden Planck core then BH will be exactly as in GR. But what if the “cure” requires long range (in time and/or space) effects? Then we can test GR using BH…

Over time several form of regularisation of these infinities have been envisaged…
(also in connection with the information loss problem)

BH Mimickers

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





Most conservative hypothesis: Replace the singular core of black holes by a smooth spacetime region in which the metric does not necessarily satisfy the Einstein equations.

Example

$$ds^2 = -e^{-2\phi(r)}F(r)\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{F(r)} + r^2\mathrm{d}\Omega^2,$$

where

$$F(r) = 1 - \frac{2m(r)}{r}.$$

This geometry reduces to Schwarzschild for $m(r) = M \in \mathbb{R}, \qquad \phi(r) = 0.$

Open issue: generic instability at inner horizon (mass inflation) while evaporation time is generically infinite.

R.Carballo-Rubio, F.Di Filippo, SL, C.Pacilio and M.Visser, JHEP 1807, 023 (2018). [arXiv:1805.02675 [gr-qc]].

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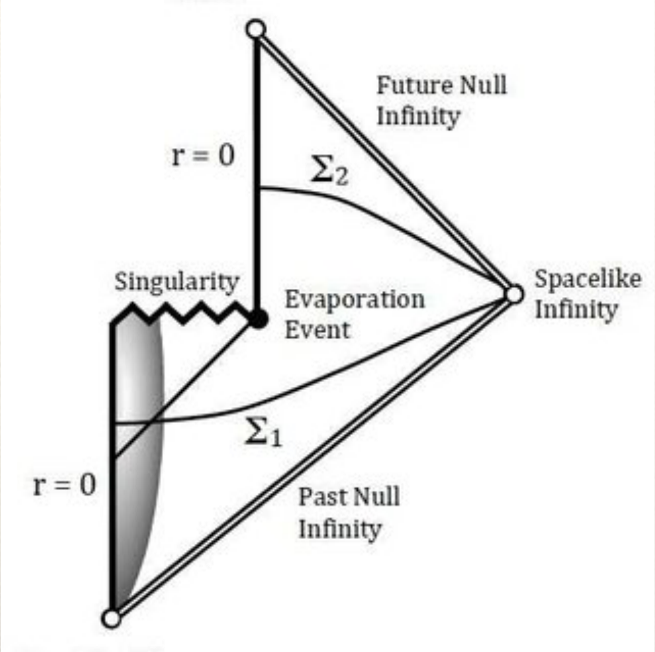

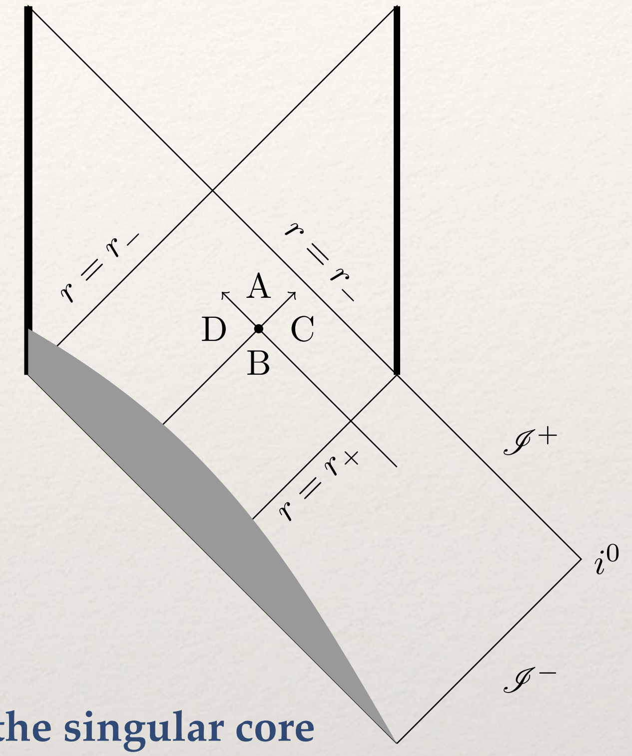

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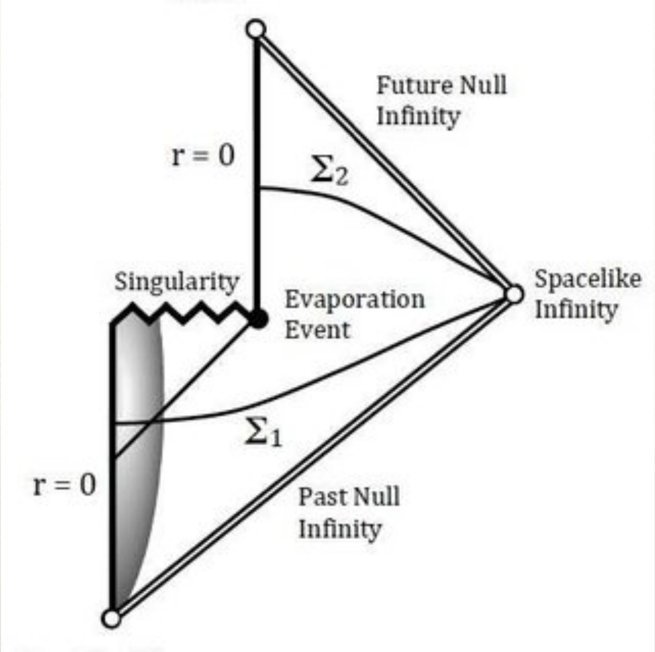

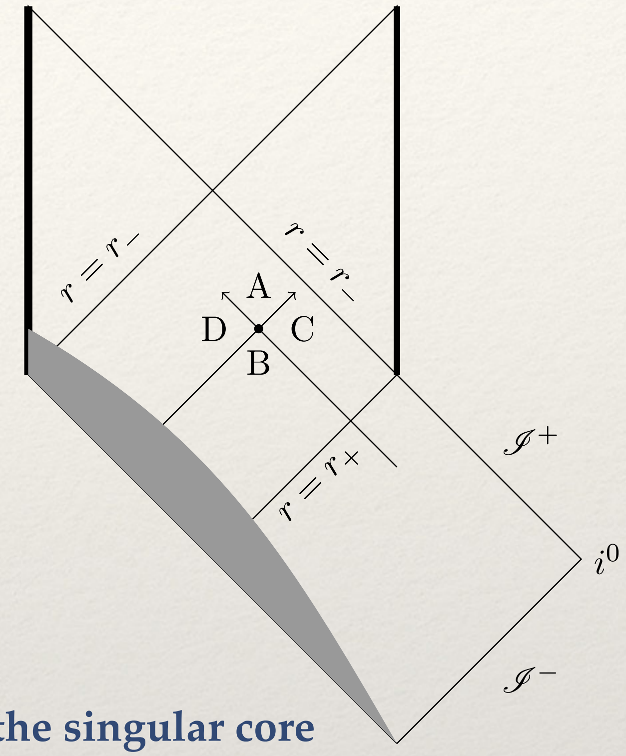

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See F. Di Filippo Poster!

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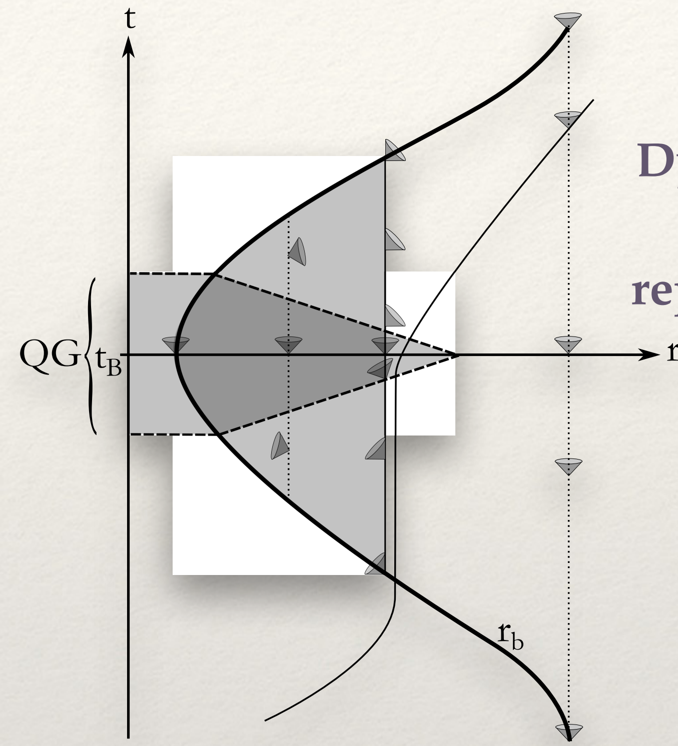

Dynamically, it seems more natural to expect that the existence of a repulsive core would lead generally to bouncing solutions

TWO MAIN FEATURES CAN BE ASSOCIATED TO THESE SOLUTIONS

THE TYPICAL TIMESCALE OF THE BOUNCE

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

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

AN UNAVOIDABLE NON-CLASSICAL REGION OUTSIDE THE TRAPPING HORIZON

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

If obs. time Delta t then deviations from the classical geometries would be suppressed by the dimensionless quotient $\Delta t/\mathscr{T}$

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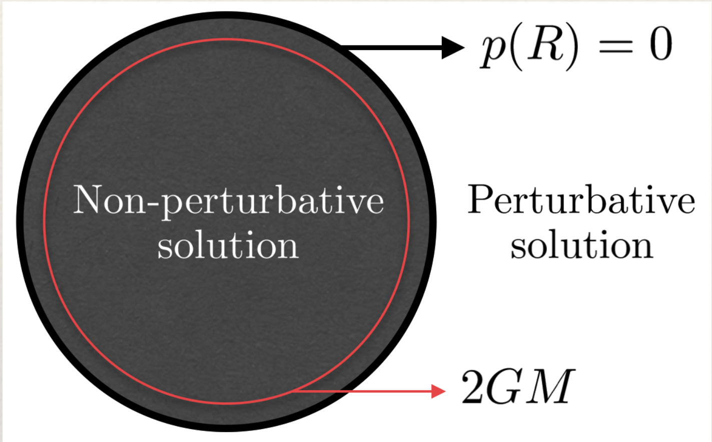
Let us define a static and spherically symmetric quasi-black hole as a spacetime satisfying:

(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.



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

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 $\mu \simeq \left(\frac{\ell}{r_s}\right)^2 \simeq 2\times 10^{-76}\left(\frac{M_\odot}{M}\right)^2\left(\frac{\ell}{\ell_P}\right)^2.$

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

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Let's consider Morris-Thorne wormholes

$$ds^2 = -e^{2\Phi(\ell)}dt^2 + d\ell^2 + r^2(\ell)\left[d\theta^2 + \sin^2\theta d\phi^2\right]$$

- **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.**

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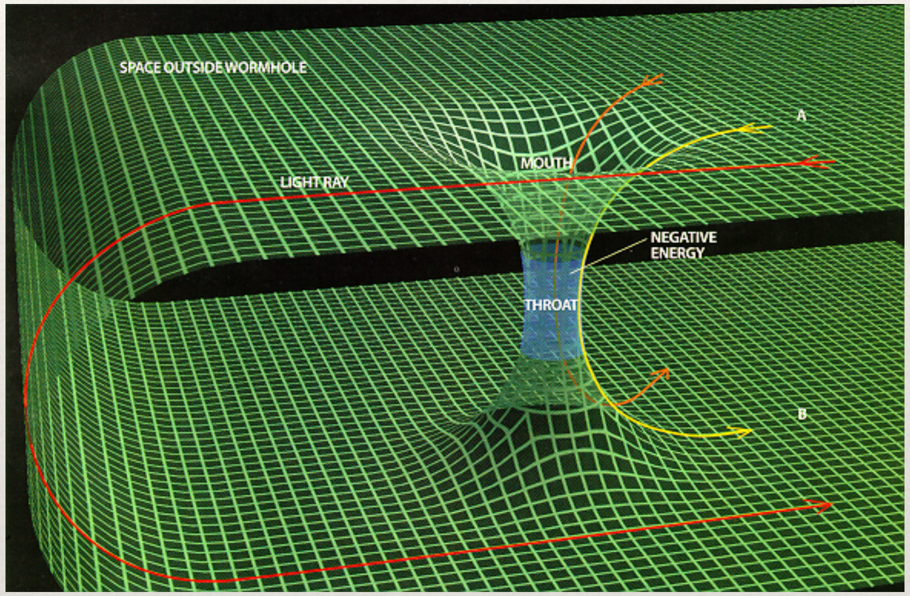

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Phenomenology: parametrising the uncertainties

Let us start with introducing two timescales:

Lifetime, τ_+: is the amount of time in which a black hole with mass M, and in vacuum, disappears completely (due to Hawking radiation, or some other effect).

Relaxation, τ_-: is the amount of time in which O(1) transient effects taking place after violent dynamical processes (formation of the black hole, merger,...) dissipate. We propose to use the reciprocal of of the imaginary part of the lowest quasi-normal mode as this governs the damping rate under excitations…

These two timescales describe the interval of time $t \in [\tau_-, \tau_+]$ in which the system is expected to be evolving slow enough such that it can maintain stable structural properties. Within this interval of time, we can define the following parameters:

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1. **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 is related to Δ as $\mu = \Delta/(1 + \Delta)$. So for $\Delta \ll 1$ one has $\mu \simeq \Delta$**
2. **Absorption coefficient, κ: measures the fraction of the energy that is lost inside the region $r \leq R$. E.g. excitation of internal degrees of freedom in the bulk, or to propagation into some other spacetime region.**
3. **Elastic reflection coefficient, Γ: if there is a certain amount of energy falling onto the object and reaching $r = R$, this coefficient measures the portion that is reflected at $r \geq R$ due to elastic interactions (i.e., energy which is not absorbed and bounces back). The coefficient for inelastic interactions is then** $\tilde{\Gamma} = 1 - \kappa - \Gamma.$
4. **Tails, $\varepsilon(r) \ll 1$: small modifications of the geometry that decay with the radius, typically polynomial but which can be modulated by functions with compact support. Hence there could be a maximum radius such that $\varepsilon(r \geq r_\star) = 0$.**

Phenomenology: parametrising the uncertainties

How can we discriminate in GW astronomy GR black holes from the above mentioned mimickers? Use parametrisation…

	τ_+	τ_-	μ	κ	Γ	$\varepsilon(r)$
Classical GR BH	∞	~10 M	0	1	0	0
Regular BH	undertermined	~10 M	0	1	0	Non-zero
Bouncing Geometries (long lived)	$\mathcal{T}^{(2)}$	Model dependent	0	1	0	non-zero and $r_* = O(r_S)$
Quasi-BH	∞	Model dependent	Model dependent	Model dependent	Model dependent	0?
Wormholes	∞	unknown	>0	Model dependent	$1-\kappa$	0?

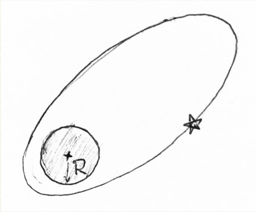
It is always possible to introduce additional parameters or functional relations.

However, in practical terms this just implies that we are including additional parameters that would provide more freedom to play with the observational data.

The set introduced is minimal, but still interesting enough to give a detailed picture of 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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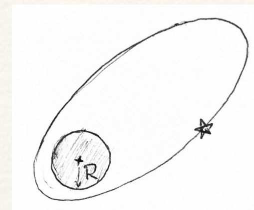

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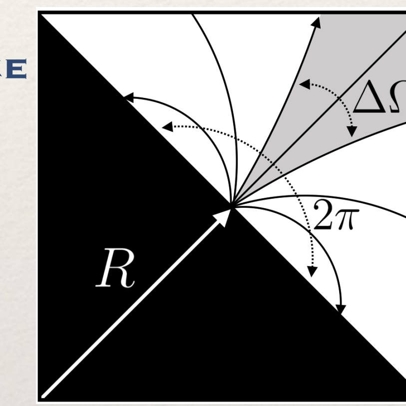
Naive expectation:
strong constraints from absence of thermal radiation from hard surface in the case of Quasi-BH.
However quite generally radiation emitted as a consequence of smash of matter on a hard surface rather than a horizon will be subject to strong lensing... indeed the escape solid angle is



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

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

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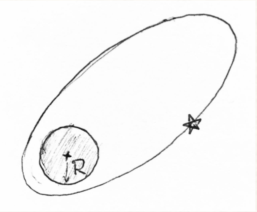

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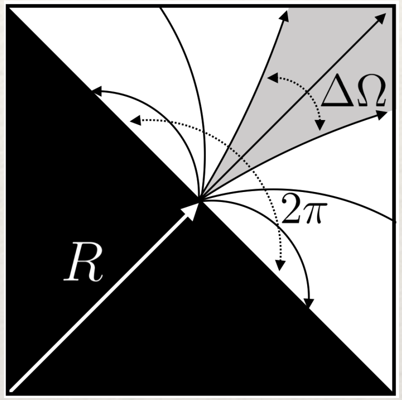

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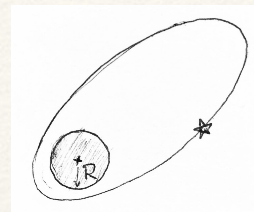

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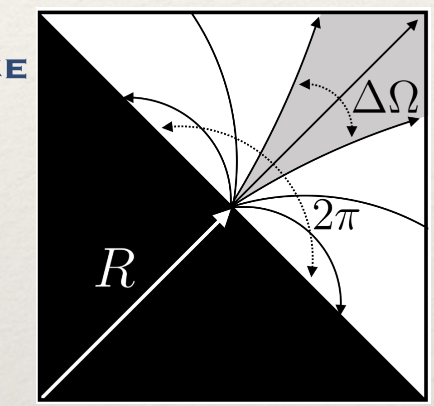

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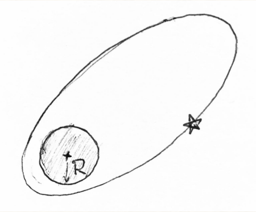

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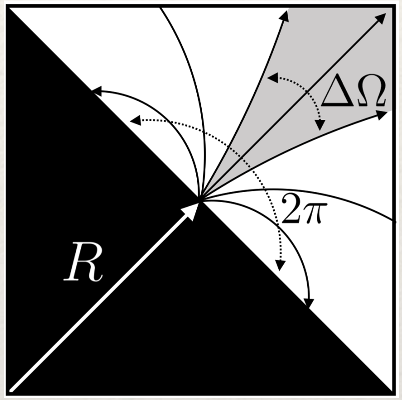

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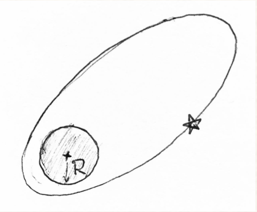

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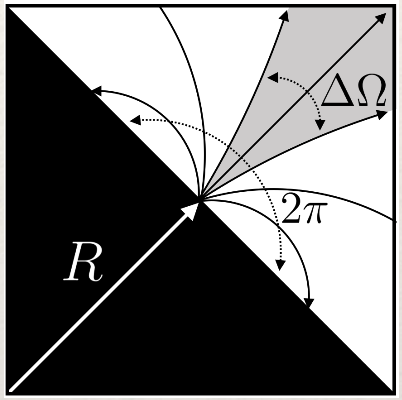

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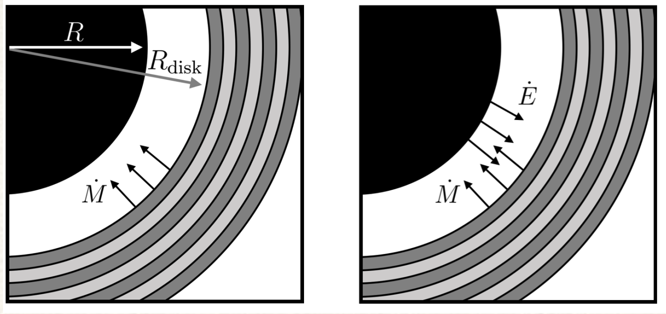
10^2 meters over a size of 10^{10} m! Still very far from Planck scale…



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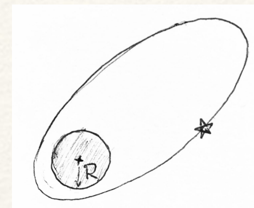

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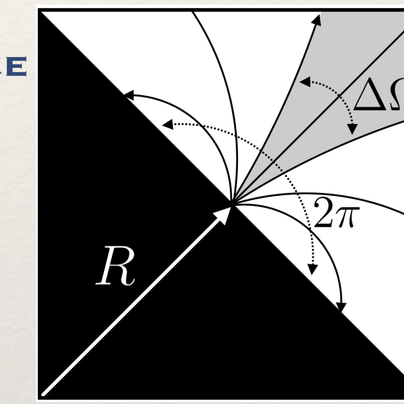

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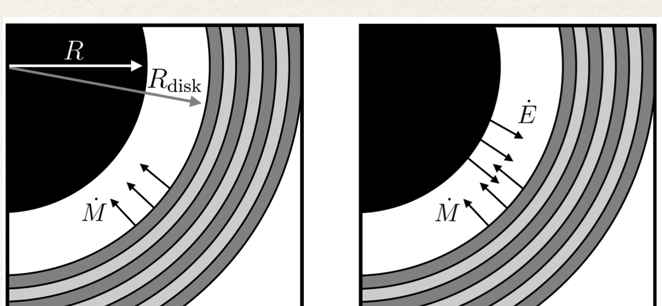
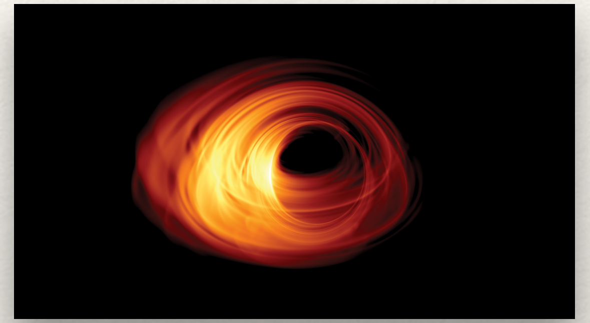


For non-zero κ and *Γ* there are several cycles of absorption and emission before radiations bounces back to disk. $$\lim_{t\to\infty}\frac{\dot E}{\dot M} = \frac{(1-\kappa-\Gamma)(1-\Gamma)\Delta\Omega/2\pi}{\kappa + (1-\kappa-\Gamma)\Delta\Omega/2\pi}.$$

This makes constraints very difficult and for <u>wormholes</u> (1-**κ**-*Γ*)=0 <u>no constraint is possible</u>!

EM channels

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



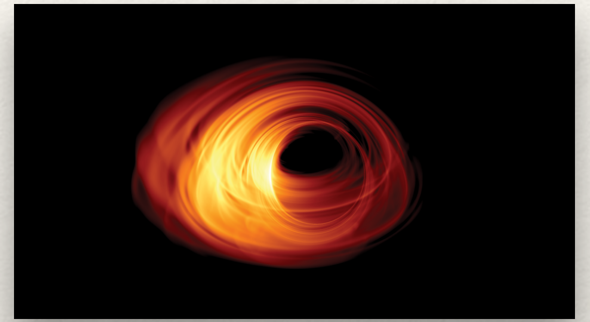
Simulated image of an accreting black hole.
Image credit: Bronzwaer, Moscibrodzka, Davelaar and Falcke, Radboud University 2017

EM channels

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

1. Hunting shadows

Detection of light that gets as close as possible to the CMO, without being captured by the gravitational field of the latter. The fate of light rays passing by is determined by their location w.r.t. the photon sphere and the observation of light rays around a black hole should reveal a shadow with the corresponding size of the photon sphere=3M in Schwarzschild, so macroscopically away from the horizon.



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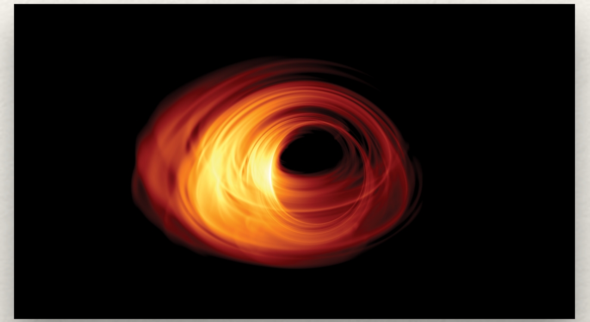

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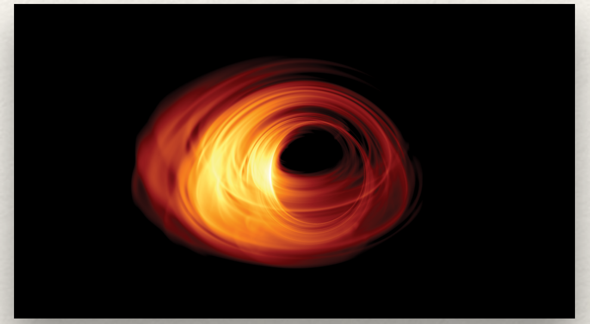

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2. Burst from Bounces

- **If timescale is $\tau^{(1)} \sim t_p(M/M_{pl})$ (short living bounce) than a signal expected at freq.~$1/\tau^{(1)}$**
- **If timescale is $\tau^{(2)} \sim t_p(M/M_{pl})^2$ (long living bounce) no signal expected**

But still UV+IR components

UV Component~T 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, it was shown that the infrared component of the signal could get up to the GeV scale and be peaked in the MeV, while the ultraviolet part of the burst is expected to be in the TeV range

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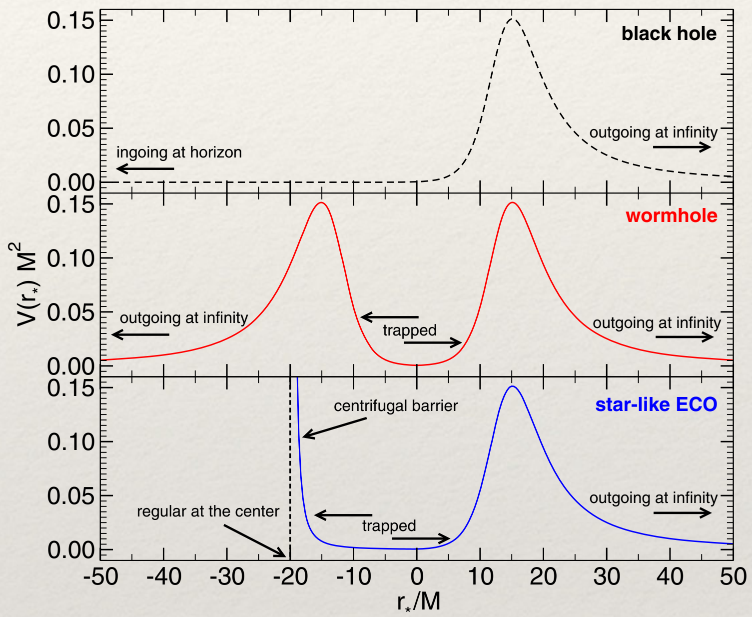

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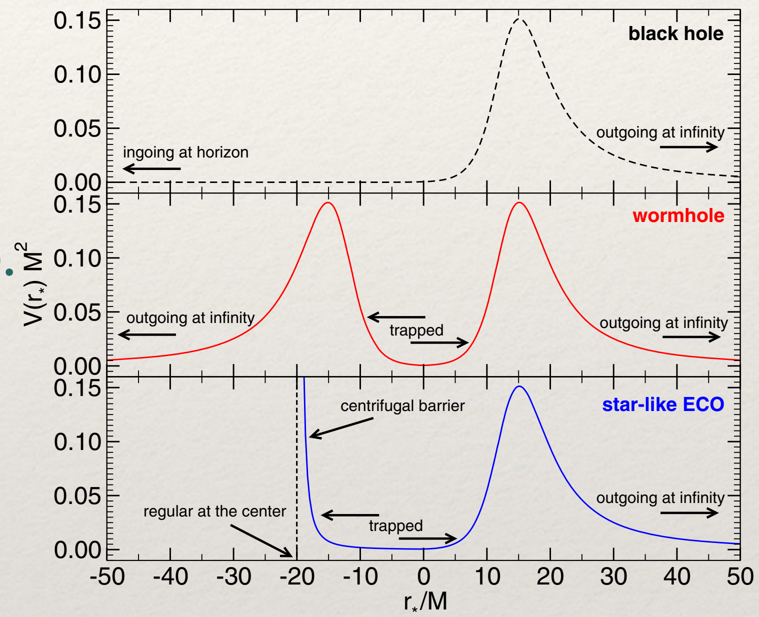

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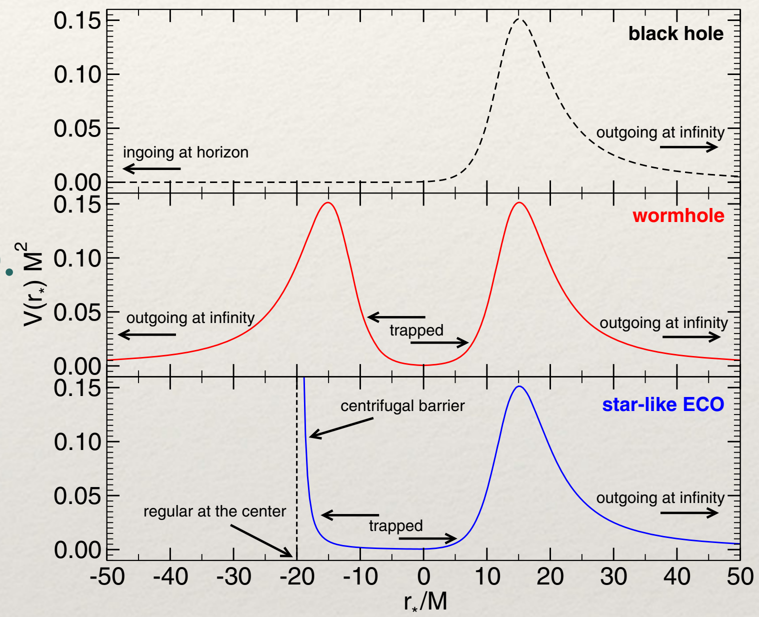

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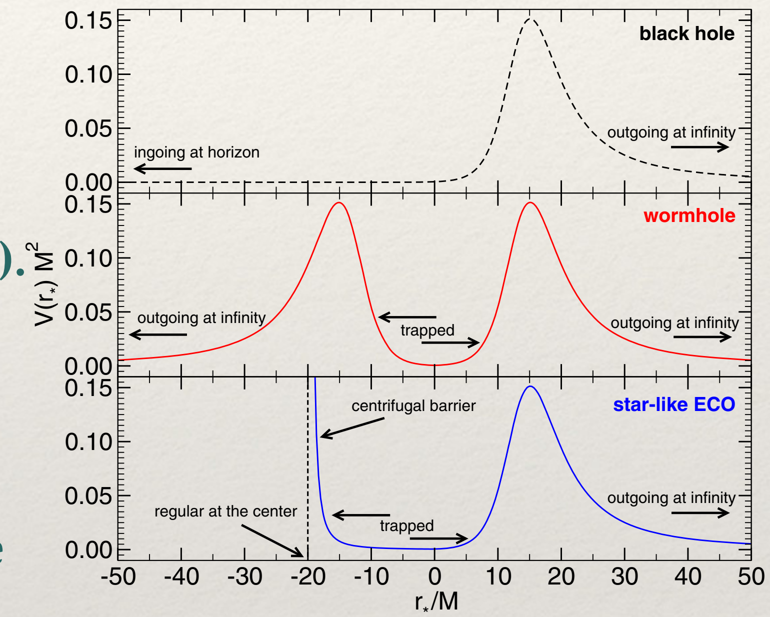

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- **The amplitude of gravitational wave echoes would be proportional to Γ.**
- **A non-observation of echoes can only constrain this parameter.**
- **A positive detection of echoes could be used in order to determine also Δ.**
- **The other two parameters 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 .**

GW channel: Echoes

What about the lensing at the surface which was so important for EM phenomenology?!?!?

THE EM LENSING AT THE SURFACE OF THE QUASI-BH DEPENDS ON TWO THINGS

- **The use of ray-optic approximation**
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RAY-OPTIC APPROX FOR GW

- **Wavelengths involved are O(M) and hence geometric optic approximation so on a region M it <u>does not apply</u> to them: they maybe even able to escape even in the case they have $L>L_*$ =maximum angular momentum for which null geodesics cross or reach the photon sphere.**
  This worth further investigation…
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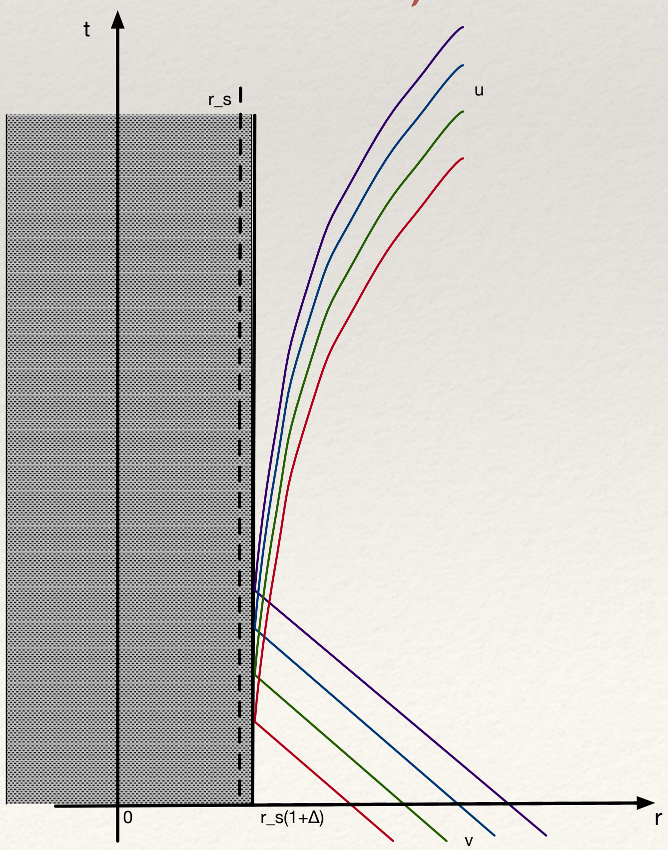
Non-linear interactions between the GW and the central object

- 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
- 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.
- 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.
- Hence the reflection coefficient Γ has to be extremely small, implying suppression of echoes…



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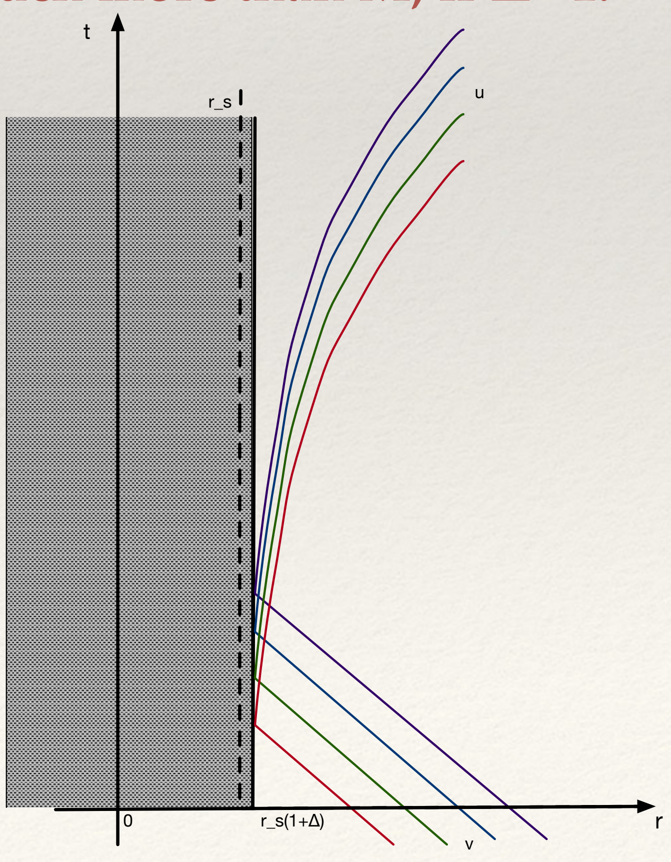
GIST: we need a more accurate analysis …



Wrapping Up...

	EM Stars	EM infalling matter	EM Shadows	EM Bursts	GW IMR	GW Echos
Regular BH	✅ ε(r)	X	X	✅ If converted to bouncing	X	X
Bouncing Geometries	✅ ε(r)	X	X	✅	✅? τ_ (short living)	✅? τ_ (short living)
Quasi-BH	X	✅ Γ, μ, κ	X	X	✅ τ_, Γ, μ (inspiral)	✅ Γ, (also μ if detected)
Wormholes	X	X (Γ+κ=1)	X	X	τ_, Γ	✅ Γ, (also μ if detected)

- It is in general very hard to constraint these mimickers for realistic parameters.
- The more compact they are the less hair they will have (see "Generalized no-hair theorems without horizons" C. Barceló, R. Carballo-Rubio, SL. arXiv:1901.06388 [gr-qc]. Check poster R. Carballo-Rubio!)
- EM signal from stars TDE, Accretion and burst for bouncing solutions together with Inspiral signals plus GW
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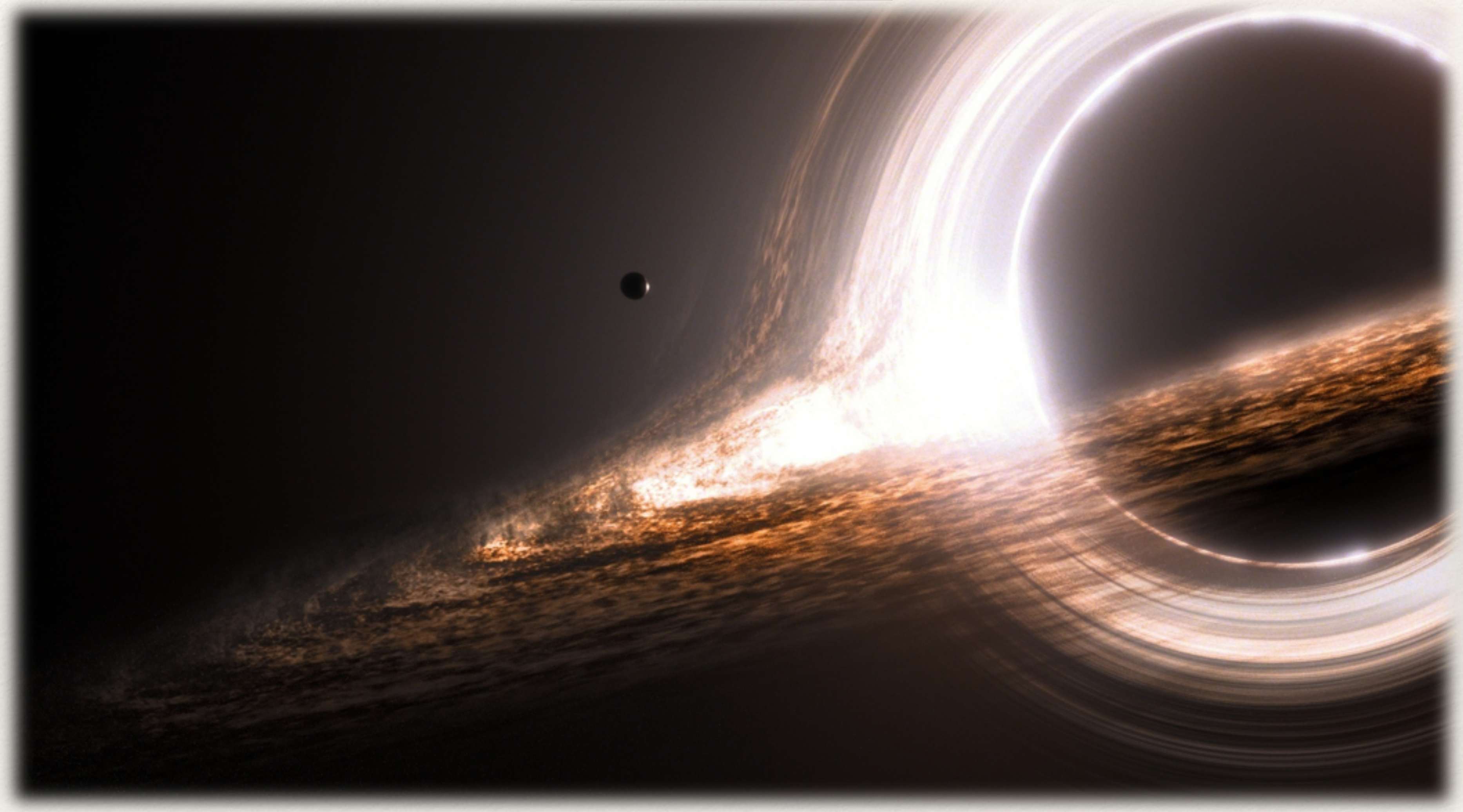
It seems clear that we are at the dawn of a new form of QG phenomenology!
It is up to us to grab this opportunity…

Thank You!

Measure what is measurable, and make measurable what is not so.
Galileo Galilei



"PHENOMENOLOGICAL ASPECTS OF BLACK HOLES BEYOND GENERAL RELATIVITY"

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Phys.Rev. D98 (2018) no.12, 124009

See also

R.Carballo-Rubio, F.Di Filippo, SL, C.Pacilio and M.Visser, JHEP 1807, 023 (2018). [arXiv:1805.02675 [gr-qc]].

C. Barceló, R. Carballo-Rubio, SL. arXiv:1901.06388 [gr-qc]