Black holes, white holes, wormholes: geometry and physics

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14:45

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Australian Government
Australian Research Council

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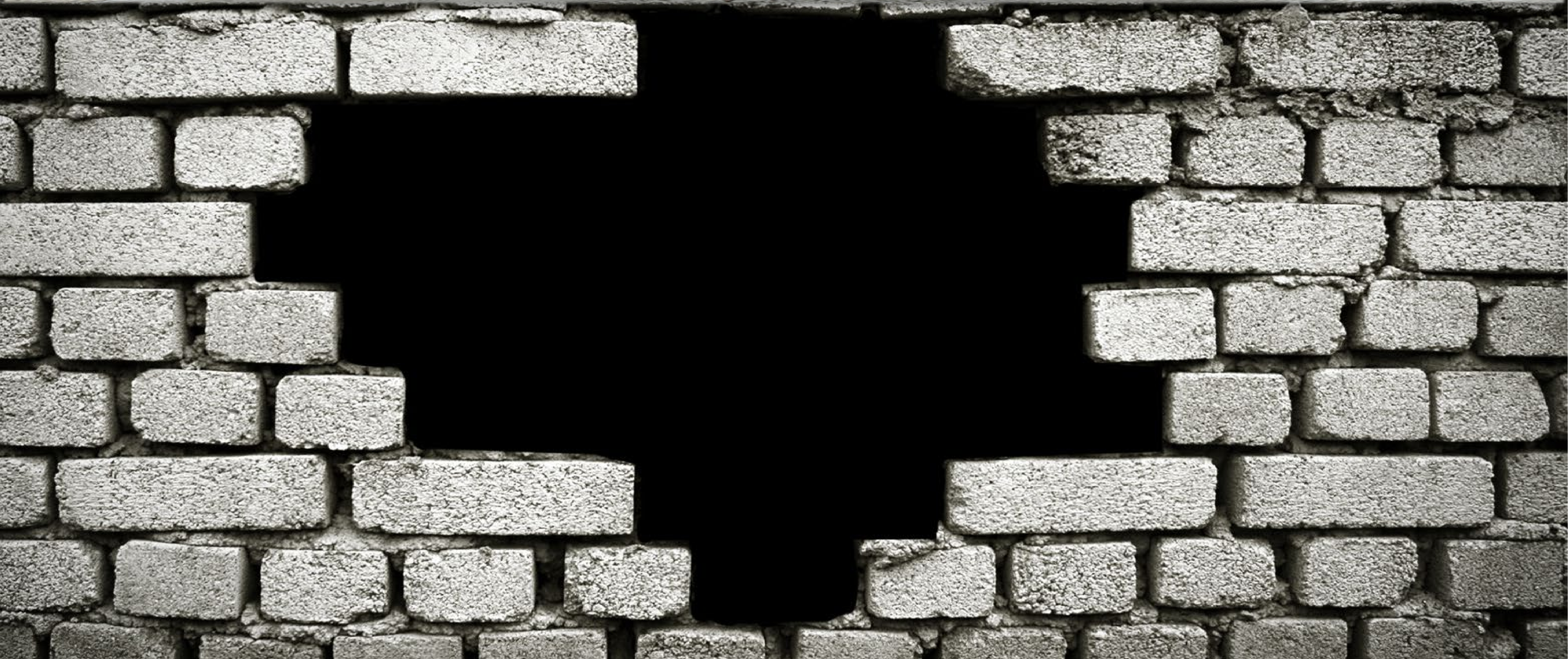
11-16 December 2022
Adelaide Convention Centre

Mann, Murk, DRT,
Black holes and their horizons in semiclassical and modified theories of gravity
Int J Mod Phys D **31**, 2230015 (2022) arXiv:2112.06515



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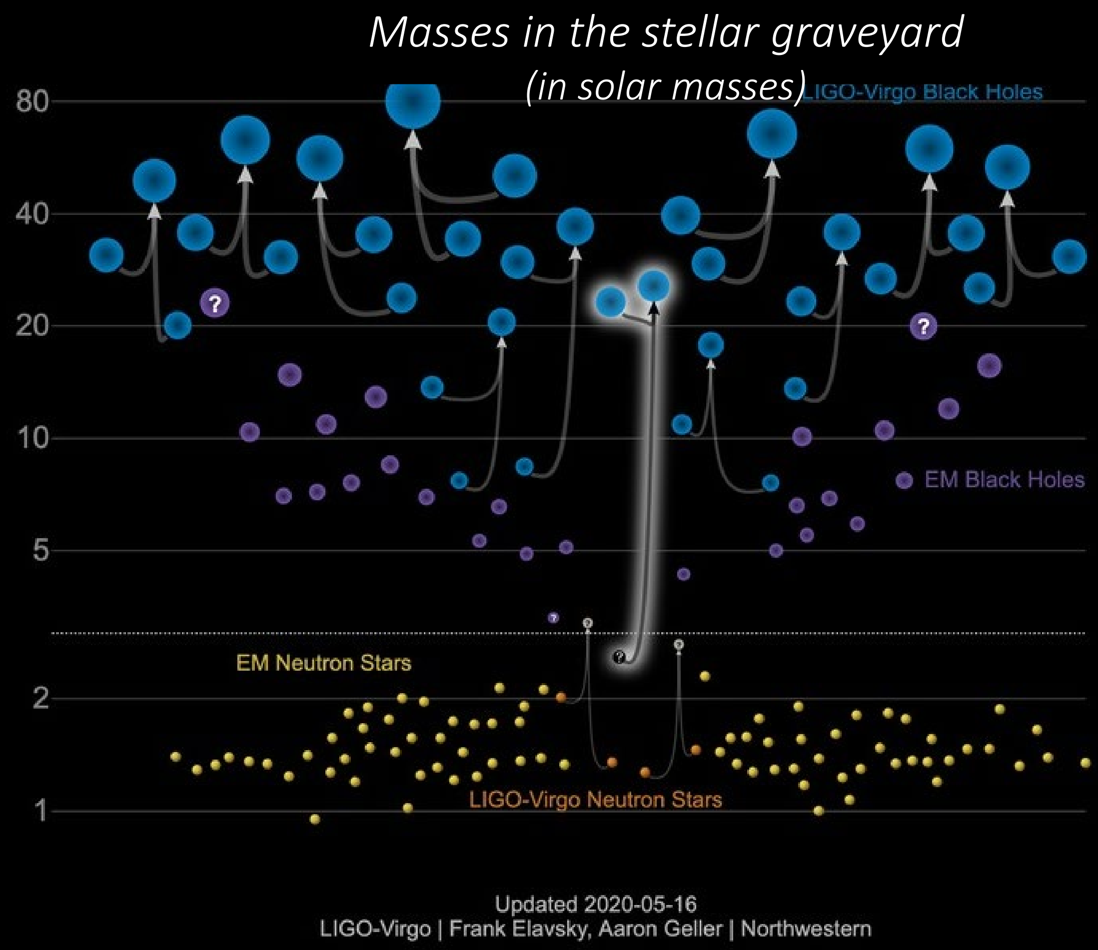
Outline

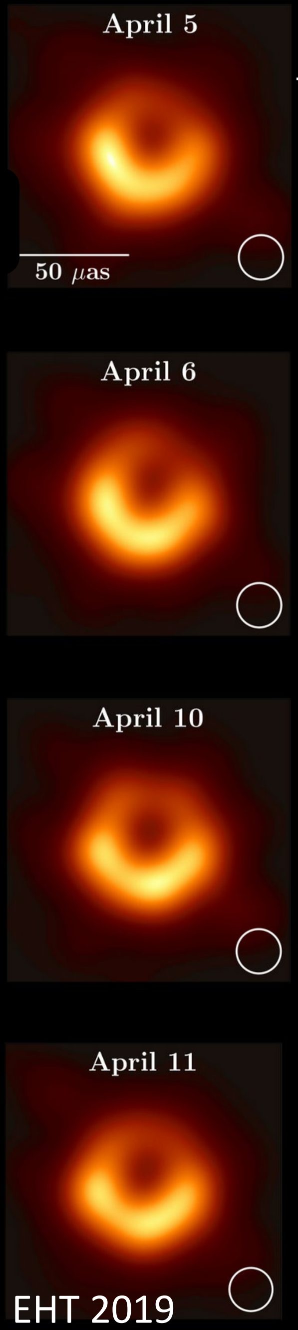
- Existence of horizons as a math question
- Admissible solutions, their properties, and the holes they describe
- Implications for black holes
- Implications for wormholes

What's next?

astrophysical black holes

known knowns





known unknowns

IOP Publishing   Classical and Quantum Gravity

Class. Quantum Grav. **36** (2019) 143001 (178pp)   https://doi.org/10.1088/1361-6382/ab0587

Topical Review

Black holes, gravitational waves and fundamental physics: a roadmap

Leor Barack[1], Vitor Cardoso[2,3,133], Samaya Nissanke[4,5,6], Thomas P Sotiriou[7,8](editors), Abbas Askar[9,10], Chris Belczynski[9], Gianfranco Bertone[5], Edi Bon[11,12], Diego Blas[13], Richard Brito[14], Tomasz Bulik[15], Clare Burrage[8], Christian T Byrnes[16], Chiara Caprini[17],

astrophysical black holes

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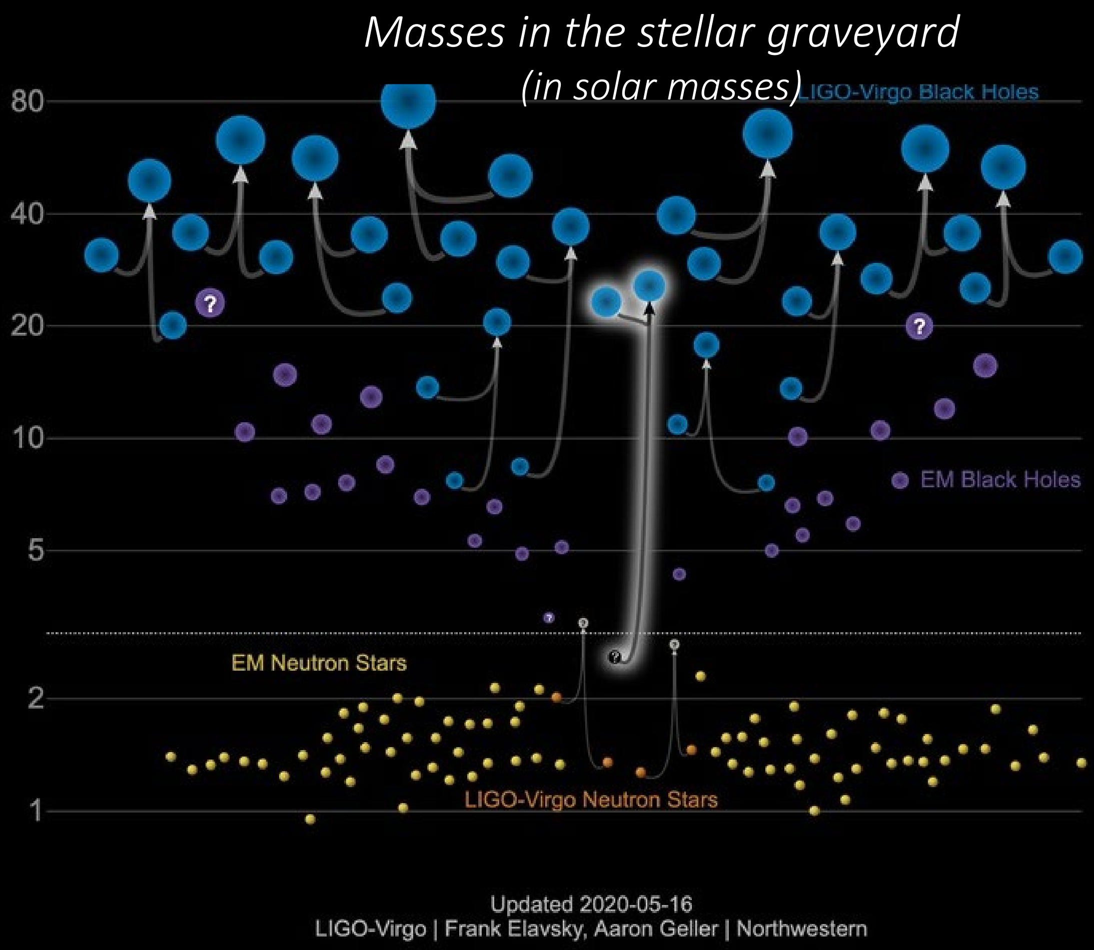
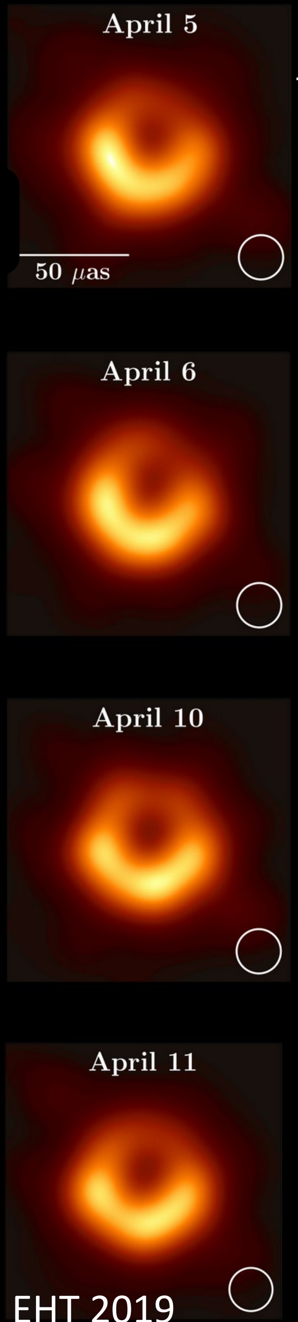




EHT 2019

known unknowns

Many definitons of a black hole:

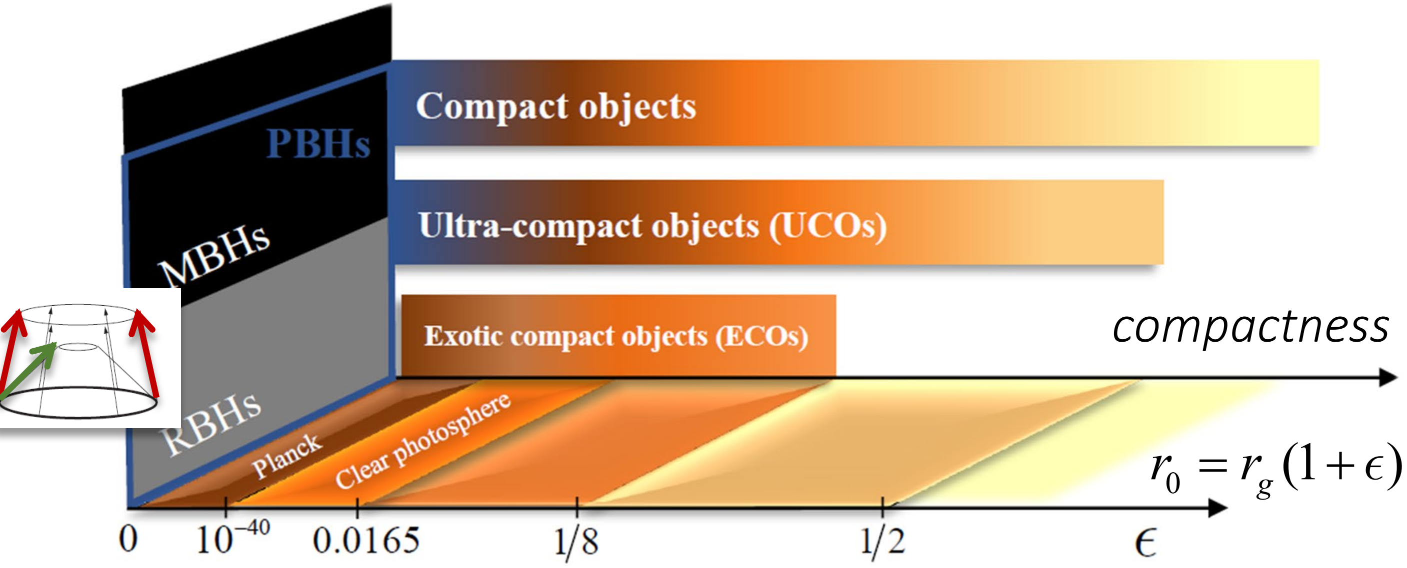
Curiel, Nature Astr. **3**, 27 (2019)

Frolov, arXiv:/gr-qc1411.6981

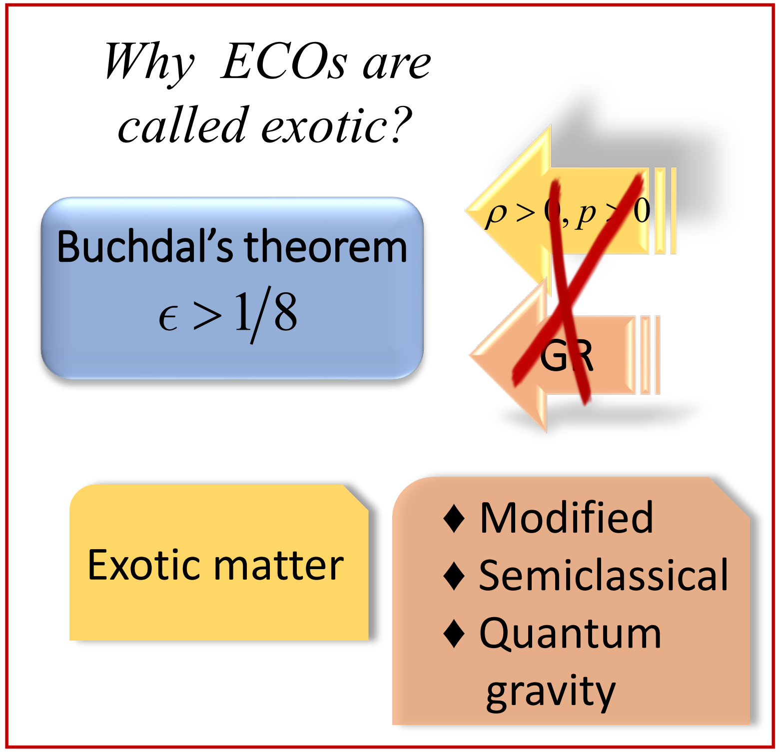
physical black hole (PBH) =
a trapped spacetime region
[that has been formed at a finite time of a distant observer]

ultra-compact objects

the zoo & physical black holes



UCO: has a photosphere
BH: has a horizon
MBH: has an event horizon
PBH: has a trapped region
ECO: non-BH UCO



Cardoso and Pani, Nat. Astron. **1**, 586 (2017)

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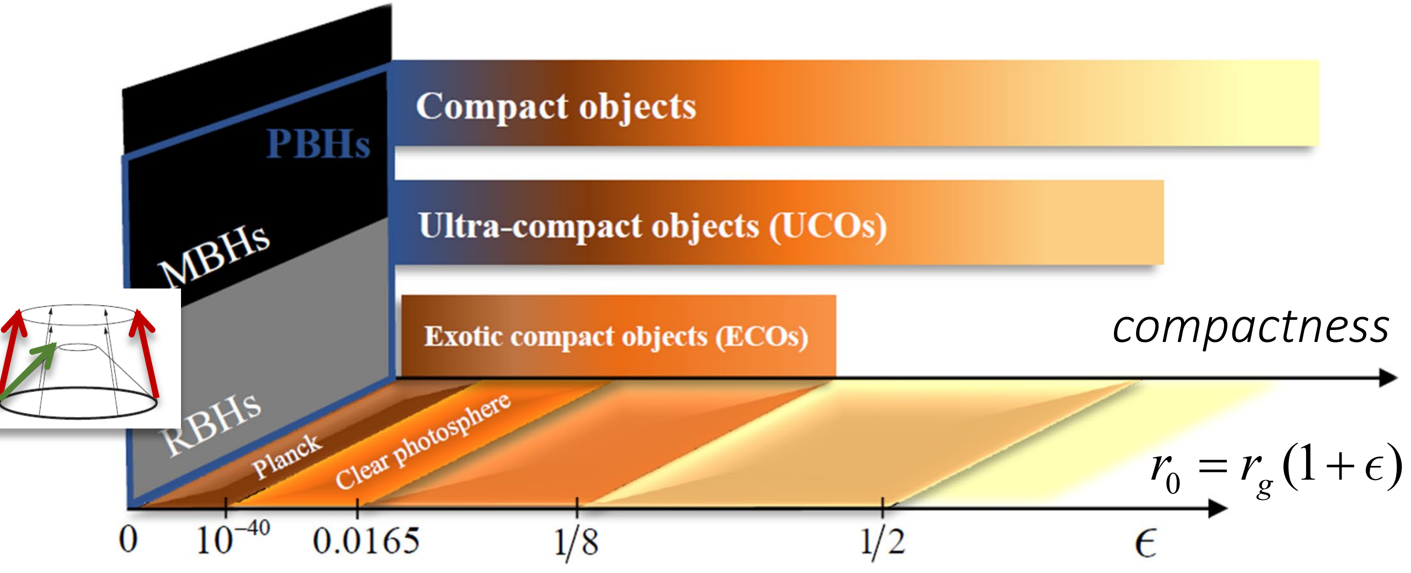

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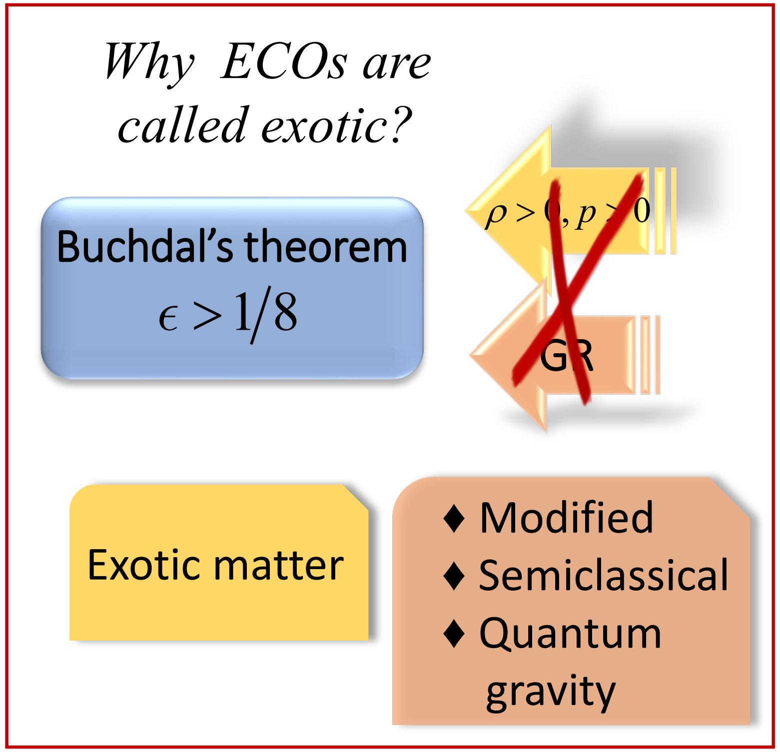

Cardoso and Pani, Nat. Astron. **1**, 586 (2017)

[1] Perpetual ongoing collapse, with an asymptotic horizon $\epsilon \to 0$

[2] Formation of a transient or an asymptotic object, where the compactness reaches a minimum at some finite asymptotic [=distant observer] time $\epsilon \to \epsilon_{\min}$

[3] Formation of an apparent horizon in finite asymptotic time $\epsilon(t_f) = 0$

4+ii

assumptions

1.The classical spacetime structure is still meaningful and is described by a metric $g_{\mu\nu}$.

2. Classical concepts, such as trajectory, event horizon or singularity can be used.

3. The metric is modified by quantum effects. The resulting curvature satisfies the semiclassical self-consistent equation

$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} = 8\pi \left\langle \hat{T}_{\mu\nu} \right\rangle_{\omega}$$

$$+E_{\mu\nu}$$

4. Dynamics of the collapsing matter is still described classically using the self-consistent metric

semiclassical physics

not assumed: global structure, singularity, types of fields, quantum state, presence of Hawking radiation

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physical black holes

(i) a light-trapping region forms at a **finite** time of a distant observer

(ii) curvature scalars [contractions of the Riemann tensor] are **finite** on the boundary of the trapped region

Worked-out consequences:

□ Spherical symmetry □ Kerr-Vaidya metrics

spherical symmetry: recap + some results

PBH: the process

- ❑ Use Schwarzschild coordinates to extract the info from divergencies
- ❑ Pick a nice form of the Einstein equations. Demand existence of real solutions
- ❑ Use null coordinates to help classification

spherical symmetry: recap + some results

PBH: the process

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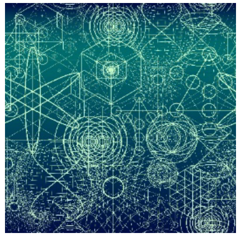
PBH: the properties

- Finite infall time (according to a distant Bob)
- Collapse of a massive thin shell takes a finite time (according to Bob),
  but most of the mass remains [?]



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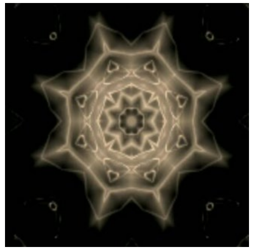
- Null energy condition is violated [in the vicinity of the outer horizon]
- A **weak firewall**: energy density for escaping* non-geodesic Alice diverges, but weakly.



- Inner apparent horizon is timelike or null.
- Some popular RBH models do not work.
- Usual proofs of instability of RBH do not apply

spherical symmetry

structure

$$ds^2 = -e^{2h} f dt^2 + f^{-1} dr^2 + r^2 d\Omega_2$$

- □ circumference: $2\pi r$
- □ physical time at infinity: t

$$f = 1 - 2M(t,r)/r$$

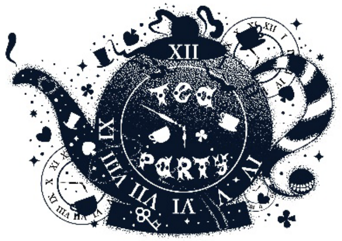
$$2M(t,r) \equiv C(t,r)$$

Misner-Sharp invariant mass

Schwarzschild radius

$$\max r_g = C(t, r_g)$$

$$C = r_g(t) + W(t,r)$$ ▶



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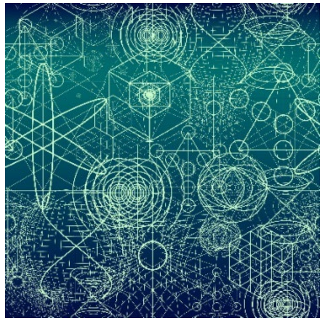
Curvature scalars

$$\mathrm{T} := T^{\mu}{}_{\mu}$$

$$\mathfrak{T} = T^{\mu\nu} T_{\mu\nu}$$



$$\mathfrak{T} := \left((\tau^r)^2 + (\tau_t)^2 - 2(\tau_t{}^r)^2\right)/f^2$$

useful

$$\tau_t := e^{-2h} T_{tt}$$

$$\tau_t{}^r := e^{-h} T_t{}^r$$

$$\tau^r := T^{rr}$$

$$\mathrm{T} := (\tau^r - \tau_t)/f$$

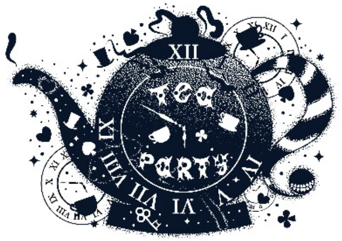
+regular terms*

Einstein equations

$$\partial_r C = 8\pi r^2 \tau_t / f,$$

$$\partial_t C = 8\pi r^2 e^h \tau_t{}^r,$$

$$\partial_r h = 4\pi r \left(\tau_t + \tau^r\right)/f^2$$



spherical symmetry

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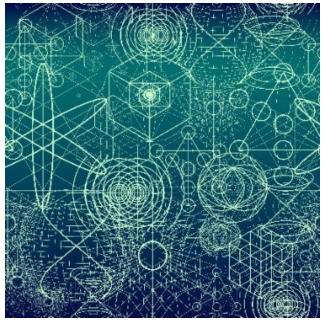

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+regular terms*

useful

$$\tau_t := e^{-2h} T_{tt}$$

$$\tau_t{}^r := e^{-h} T_t{}^r$$

$$\tau^r := T^{rr}$$

All three components go to zero or diverge in the same way

Einstein equations

$$\partial_r C = 8\pi r^2 \tau_t / f,$$

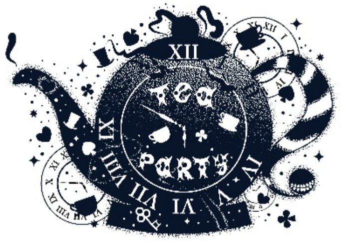
$$\partial_t C = 8\pi r^2 e^h \tau_t{}^r,$$

$$\partial_r h = 4\pi r \left(\tau_t + \tau^r\right)/f^2$$

$$\lim_{r \to r_g} \tau_a \sim \begin{cases} \pm \Upsilon^2 f^0 \\ \tau_a(t) f^k \end{cases}$$

k=0,1*

$$C = r_g(t) + W(t,r) \ \blacktriangleright$$



$$\lim_{r \to r_g} \tau_t = \lim_{r \to r_g} \tau^r = -\Upsilon^2 \qquad k = 0$$

spherical symmetry

metrics

1. The limiting form (close apparent horizon) of dynamical metrics is almost uniquely defined (both *k*=0 and *k*=1).

$$x := r - r_g$$

$$C = r_g - 4\sqrt{\pi r_g^3}\Upsilon\sqrt{x} + \dots \quad h = -\frac{1}{2}\ln\frac{x}{\xi} + \dots$$ ◀ $k=0$

(dynamical BH/WoH; more static options)

$k=1$ ▶ $$C = r - c_{32}x^{3/2} + \dots \qquad h = -\frac{3}{2}\ln\frac{x}{\xi} + \dots$$

2. BH parameters are related via evaporation rate

$$\frac{dr_g}{dt} = -4\sqrt{\pi r_g \xi}\Upsilon$$

$$\frac{dr_g}{dt} = -\frac{c_{32}\xi^{\frac{3}{2}}}{r_g}$$

spherical symmetry

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- ❑ No static *k*=0 solutions
- ❑ Vaidya metrics are *k*=0 solutions
- ❑ Reissner-Nordström, many static RBH are examples of *k*=1 solutions: $C = r_g + 8\pi r_g^2 \rho_g x + \ldots$
- ❑ Popular dynamic RBH models are *k*=0 solutions

metrics

3. Most convenient coordinates are retarded (u_-,r) for *white holes* and advanced (v_+,r) for *black holes*

$$dt = e^{-h}\left(e^{h_\pm} dv_\pm \mp f^{-1} dr\right)$$

$$ds^2 = -e^{2h_+} f dv^2 + e^{h_+} dv dr + r^2 d\Omega_2$$
$$= -e^{2h_-} f du^2 + e^{h_-} du dr + r^2 d\Omega_2$$
$$2M(t,r) \equiv C(t,r) \equiv C_-(u(t,r),r) \equiv \ldots$$

E.g, in (v,r) the metric is regular at $r_g \equiv r_+$ for $r_g' < 0$ and singular for $r_g' > 0$

$$e^{-h_+}\partial_v C_+ + f\partial_r C_+ = 8\pi r^2 \theta_v, \qquad \theta_v := e^{-2h_+}\Theta_{vv} = \tau_t,$$
$$\partial_r C_+ = -8\pi r^2 \theta_{vr}, \qquad \theta_{vr} := e^{-h_+}\Theta_{vr} = ({\tau_t}^r - \tau_t)/f,$$
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$r_g' < 0 \blacktriangleright (v,r)$	$r_g' > 0 \blacktriangleright (u,r)$
$\theta_{\text{in}} < 0, \theta_{\text{out}} < 0$	$\theta_{\text{in}} > 0, \theta_{\text{out}} > 0$
BH solutions	WH solutions

spherical symmetry

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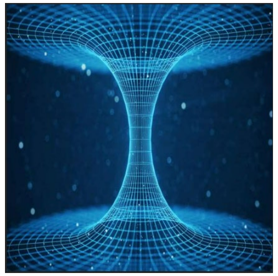
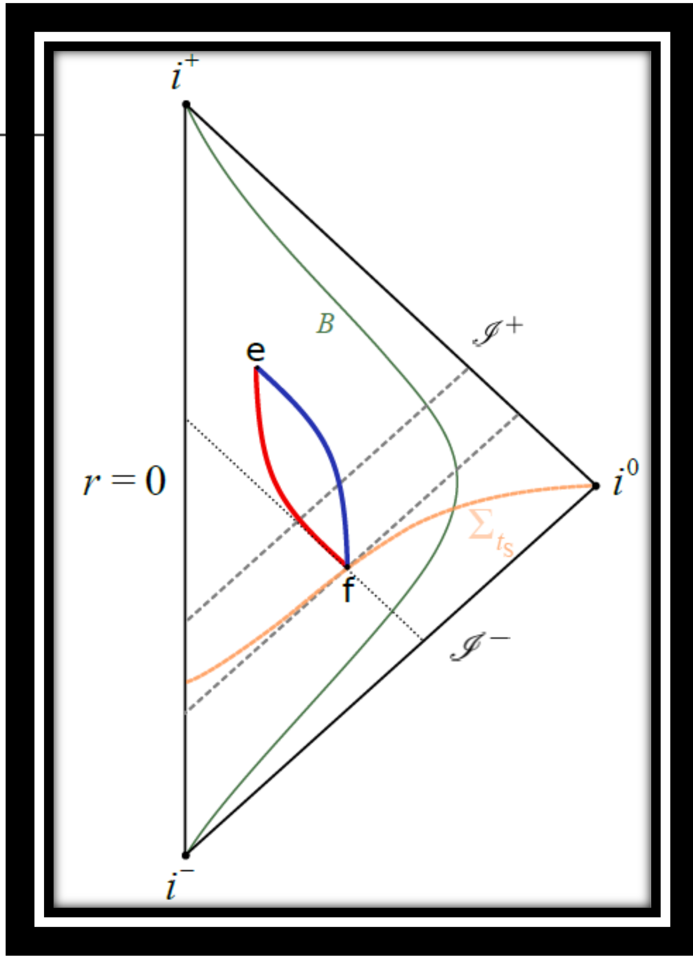


- ❑ A wormhole throat: a marginal outer trapped surface +
- ❑ Use all possible solution + impose wormhole requirements

spherical symmetry: recap + some results



PBH: the process

- Use Schwarzschild coordinates to extract the info from divergencies
- Pick a nice form of the Einstein equations. Demand real solutions
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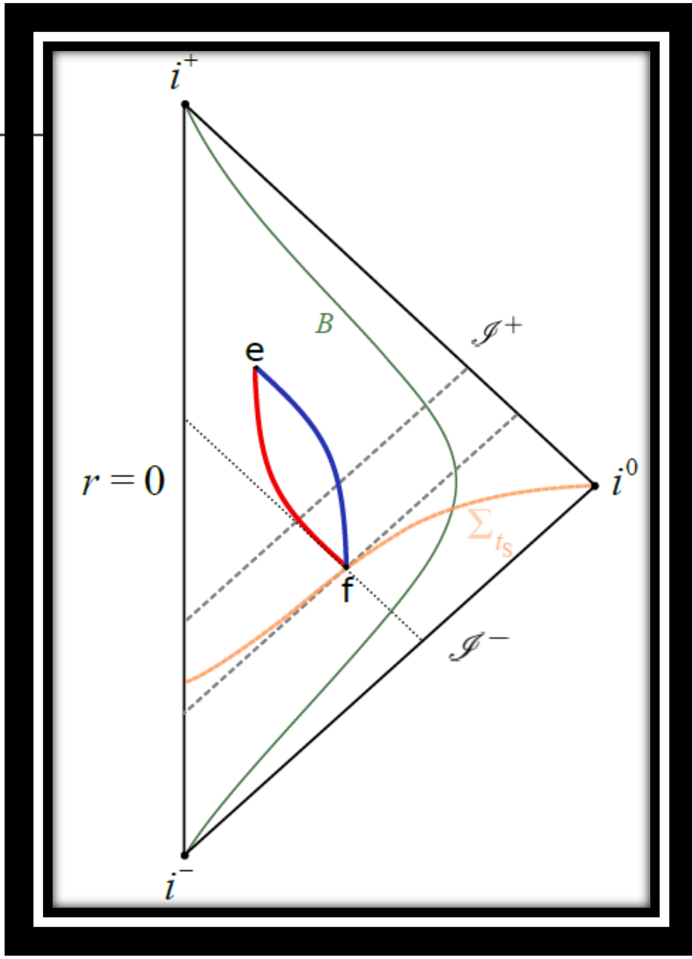
PBH: the properties

- Finite infall/collapse time (according to a distant Bob)
- Outer apparent horizon is always **timelike**
- Null energy condition is violated [in the vicinity of the outer horizon]
- Unique formation scenario.
- A weak firewall: energy density for escaping* non-geodesic Alice diverges, but weakly
- Some popular RBH models do not work.
- Generalized surface gravity: Kodama
- Interesting consistency/thermo implications
- If the 1st law+ thermality of evaporation work, then a short hair

spherical symmetry: recap + some results



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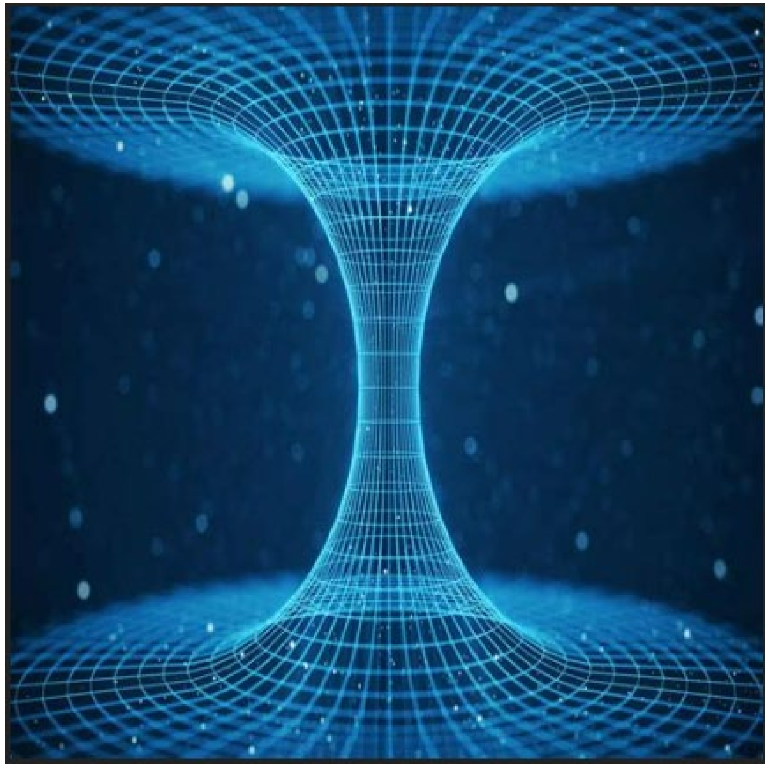
Wormholes:

- ❑ A problem

wormholes

DRT, *Inaccessibility of traversable wormholes*, Phys. Rev. D **106**, 044035 (2022)

classic sci-fi



$$ds^2 = -e^{2h} f dt^2 + f^{-1} dr^2 + r^2 d\Omega_2$$

$$ds^2 = -e^{\Phi} dt^2 + f^{-1} dr^2 + r^2 d\Omega_2$$

Schwarzschild radius

$$\max r_g = C(t, r_g)$$

- ❑ Ellis-Morris-Thorne $\quad \Phi = 0, C = b_0^2 / r$
- ❑ Simpson-Visser

$$ds^2 = -\left(1 - \frac{2m}{\sqrt{\eta^2 + a^2}}\right) dt^2 + \frac{d\eta^2}{1 - \frac{2m}{\sqrt{\eta^2 + a^2}}} + (\eta^2 + a^2) d\Omega_2,$$

- ❑ A wormhole throat: a marginal outer trapped surface +
- ❑ Use all possible solution + impose wormhole requirements

consequences

- ❑ EMT and SV wormholes are k=1
- ❑ More dynamical solutions are possible
- ❑ EMT and SV are not static limits of any of the admissible solutions
- ❑ Static limits of admissible solutions (if exist) have strong firewall and/or violate the QEI

$$\int_\gamma \mathfrak{f}^2(\tau)\rho d\tau \geqslant -B(R,\mathfrak{f},\gamma)$$

Kontou and Olum,
PRD **91**, 104005 (2015).

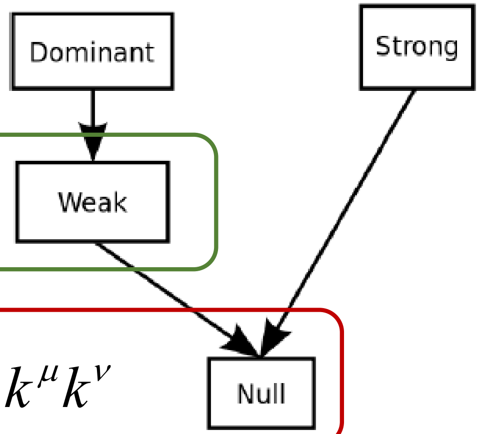
Horizon singularities & EMT
Mon 12/12, R2 @15:00


WORMHOLE 1

spherical symmetry

consequences

Energy conditions

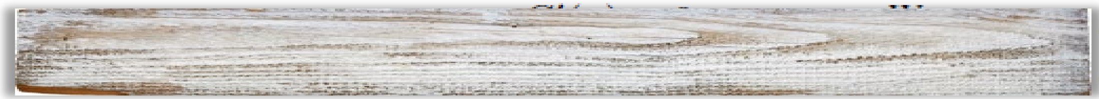


$$T_{\mu\nu}u^{\mu}u^{\nu} \geq 0$$

$$T_{\mu\nu}k^{\mu}k^{\nu} \geq 0 \Leftrightarrow R_{\mu\nu}k^{\mu}k^{\nu}$$

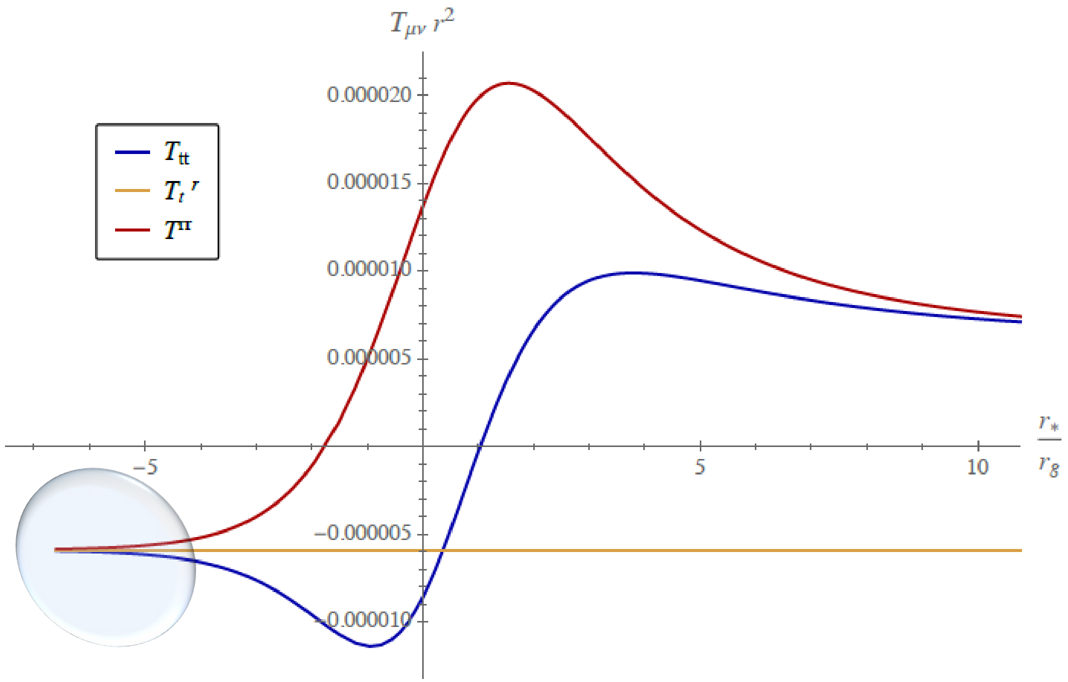
Solutions of the Einstein equations exist:
the NEC **must** be violated

$\text{sgn}(T_{tt})$	$\text{sgn}(T_t{}^r)$	Time-evolution of Vaidya mass function	Black/ White hole	NEC violation
−	−	$C'(v) < 0$	B	✓
−	+	$C'(u) > 0$	W	✓
				✗
				✗



Energy momentum (k=0)

$$T_{\hat{a}\hat{b}} = -\frac{\Upsilon^2(t)}{f}\begin{pmatrix} 1 & \pm 1 \\ \pm 1 & 1 \end{pmatrix}$$



Levi and Ori, Phys. Rev. Lett. **117**, 231101 (2016)

useful relations

(v,r) & (t,r)

$$x := r - r_g(t)$$
$$y := r - r_+(v)$$

$$ds^2 = -e^{2h} f dt^2 + f^{-1} dr^2 + r^2 d\Omega_2$$
$$f = 4\sqrt{\pi r_g}\,\Upsilon\sqrt{x} + \ldots \qquad h = -\frac{1}{2}\ln\frac{x}{\xi} + \ldots$$

$$ds^2 = -e^{2h_+} f(v,r) dv^2 + 2e^{h_+} dv dr + r^2 d\Omega_2$$
$$f = 1 - \frac{C}{r} \qquad C_+(v,r) = r_+(v) + w_1(v) y + \mathcal{O}(y^2)$$
$$h_+(v,r) = \chi_1(v) y + \mathcal{O}(y^2),$$

$$x(r_+ + y, v) = r_+ + y - r_g\big(t(v, r_+ + y)\big) = -r''_g y^2/(2r'^2_g) + \mathcal{O}(y^3).$$

- ❑ 1^{st} step in the coordinate transformation ▲
- ❑ 1^{st} terms in the expansion ▼ (use invariance of the MS mass)

(Dynamical k=1 solution: w_1=1) $$w_1 = 1 - 2\sqrt{2\pi r_g^3 |r''_g|}\,\frac{\Upsilon}{|r'_g|}$$

Parameter identification, 1.0

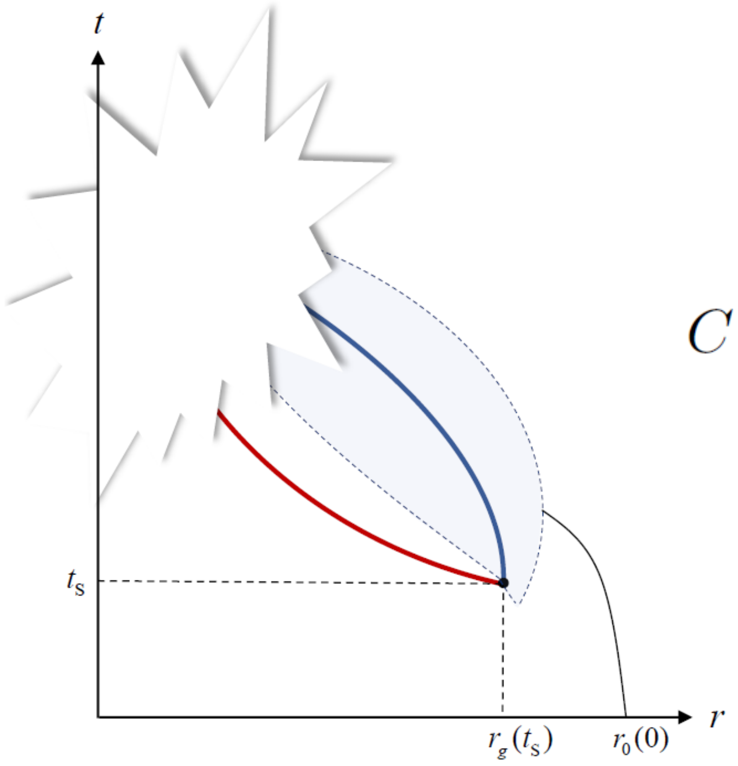
using the EMT transformation, near-horizon expansions:

(for the semiclassical evaporation law in a general form)

$$r'_g(t) = \Gamma(r_g) \qquad r'_+(t) = \Gamma_+(r_+)$$

$$\Upsilon = \frac{1}{2}\sqrt{\frac{|r''_g|}{2\pi r_g}}\,\frac{|r'_+|}{|r'_g|}$$
$$\xi = \frac{r'^4_g}{2|r''_g| r'^2_+}$$

BH formation

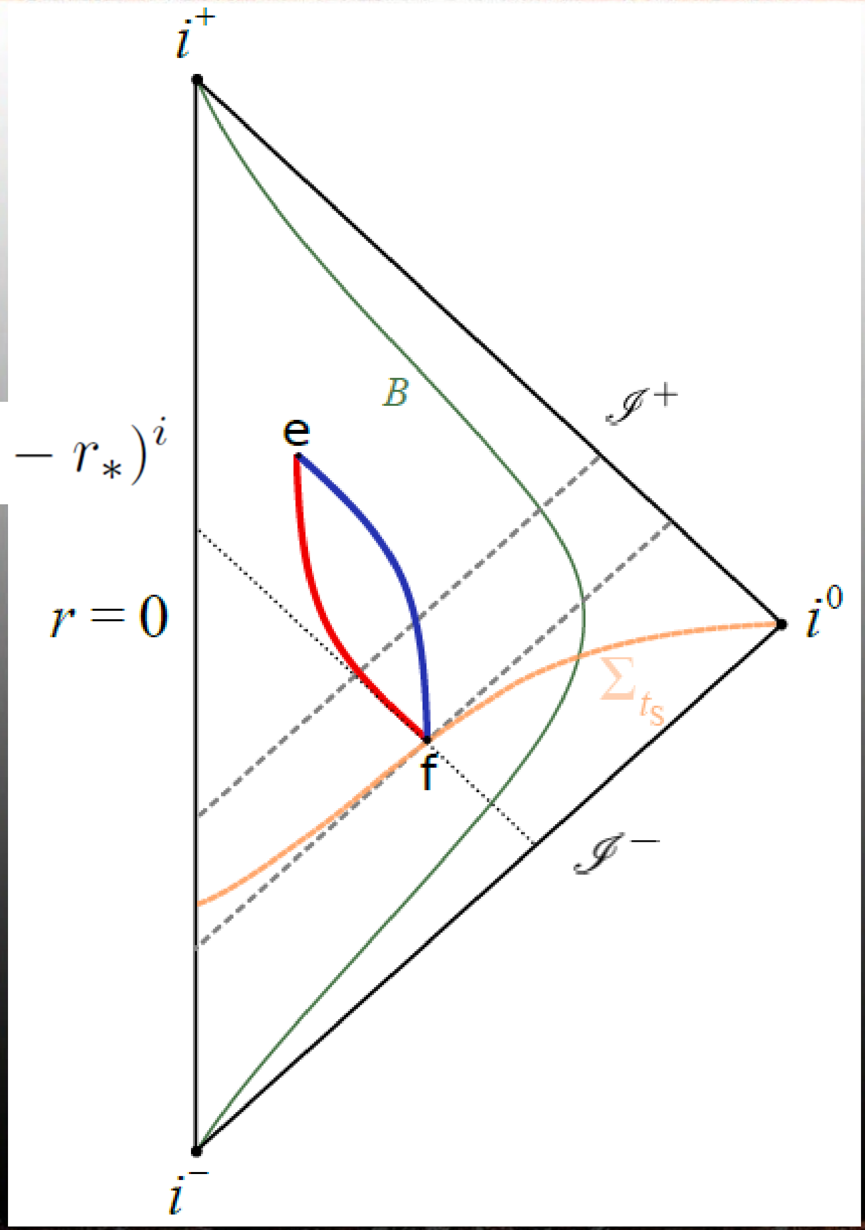


- A PBH forms as k=1 solution and then evolves as (evaporating) k=0 solution

$$C(v,r) = \Delta(v) + r_*(v) + \sum w_i(v)(r - r_*)^i$$

min gap C-r — r of min C-r

Hence up to formation of the first marginally trapped surface w_1=1



At the formation: $\Delta(v_f)=0$, $r_+(v_f)=r_*(v_f)$

After formation: $\Delta=0$, but $r_+(v)$ is not @ min

Surface gravity

Surface gravity κ is:

(a) inaffinity of null geodesics *on the horizon*

(b) and the peeling off properties of null geodesics *near the horizon*

Interpretation: the force per unit mass as measured at infinity, to keep the observer stationary just outside the horizon (c)

Stationary Killing horizon: (a)=(b)=(c)

Schwarzschild: $\kappa = 1/4M = 1/2C$

➡ Surface gravity plays a key role in BH thermo

NEC is true

- 0^{th} law: surface gravity is constant on the horizon
- 1^{st} law: $$dM = \frac{\kappa}{8\pi} dA + \omega_H dJ$$

NEC is false

Temperature

$$T = \frac{\kappa}{2\pi} \frac{\hbar c^3}{G k_B}$$

➡ Surface gravity plays a key role in the Hawking radiation

surface gravity

@ outer apparent horizon

Peeling surface gravity

$$\kappa_{\text{peel}} = \frac{e^{h(t,r)}}{r}\left(1-\partial_r C(t,r)\right)\Big|_{r=r_g}$$

- Vanzo, Acquaviva, and Di Criscienzo,
Class. Quant. Grav. **28**, 183001 (2011).
- Cropp, Liberati,Visser,
Class. Quant. Grav. **30**, 125001 (2013)

$$\kappa_{\text{peel}} = 0, \infty^*$$ both k=0,1 solutions

Kodama surface gravity

$$\kappa_{\text{K}} = \frac{1}{2}\left(\frac{C(v,r)}{r^2} - \frac{\partial_r C(v,r)}{r}\right)\Big|_{r=r_g\equiv r_+}$$

- Hayward,
Class. Quant. Grav. **15**, 3147 (1996).

$$C = r_+ + w_1(r - r_+) + \ldots$$

$$\kappa_{\text{K}} = 0$$ for k=1 solution

$$\kappa_{\text{K}} \leq 1/2r_+$$ for k=0 (w_1=1) solution

Mann, Murk and DRT,
Phys. Rev. D **105**, 124032 (2022)

universality

of BH dynamics

- If we want **the 1st law with AH**, then the metric is ``close'' to Vaidya

$$dM = \frac{\kappa}{8\pi} dA$$

$$\kappa_K = \frac{1}{2r_+} \Rightarrow w_1 = 0$$

- Use the relations between the coefficients

$$w_1 = 1 - 2\sqrt{2\pi r_g^3 |r_g''|} \frac{\Upsilon}{|r_g'|}$$

$$\Upsilon = \frac{1}{2}\sqrt{\frac{|r_g''|}{2\pi r_g} \frac{|r_+'|}{|r_g'|}}$$

$$r_+'^2 = \frac{r_g'^2}{|r_g''| r_g}$$

- Add **Page's law**

$$r_g'(t) = \Gamma(r_g) = -\frac{\alpha}{r_g^2}$$

then

$$r_+' = -\frac{1}{2}$$

$$\Upsilon = \frac{1}{2\sqrt{2\pi r_g}}$$

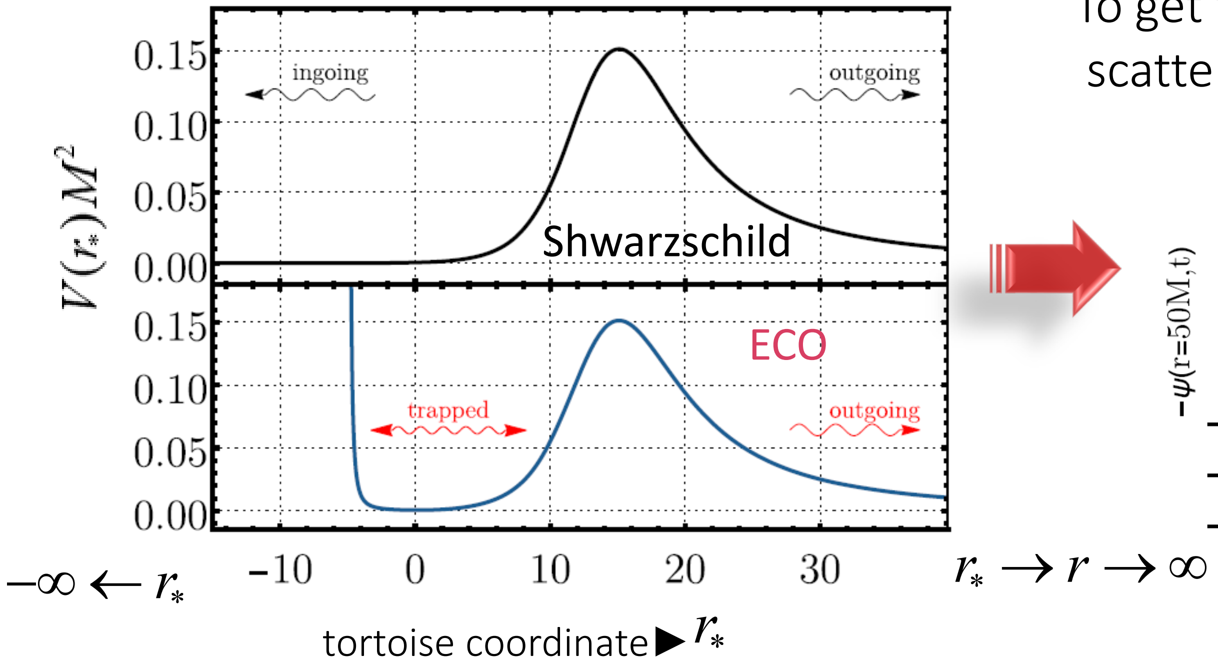
$$\xi = \frac{\alpha^2}{r_g^3}$$

Dahal, Simovic, Soranidis, DRT, soon(ish)

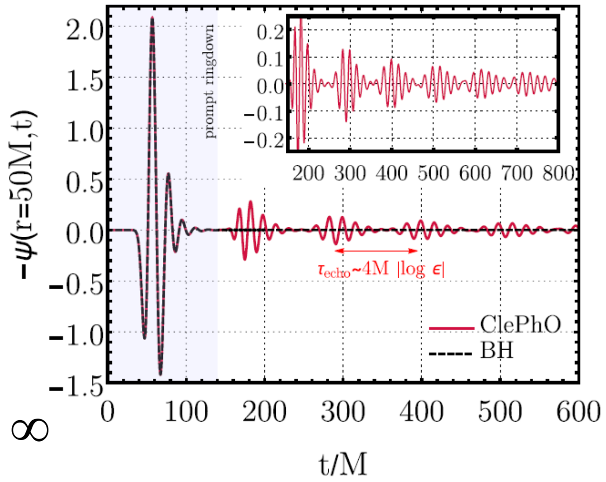
ECO vs BH

THE QUESTION

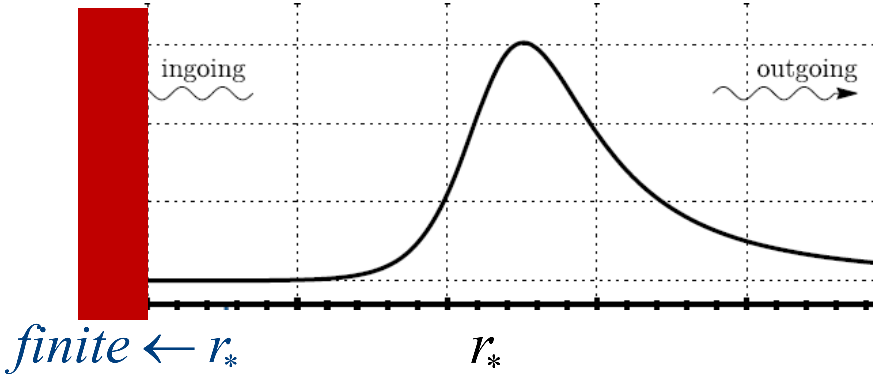
will be there a smoking gun?



To get to the QNM, waveforms:
scattering in the effective potential



Cardoso and Pani,
Liv. Rev. Rel. **22**, 4 (2019)



A missing piece

PBH give yet another potential:

what are the QNM & waveforms?