Physical black holes and their properties

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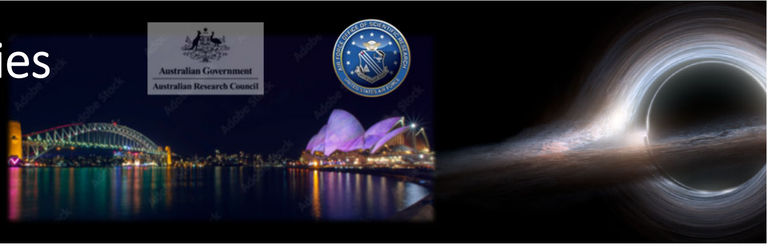
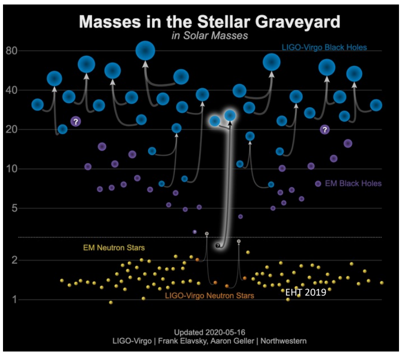
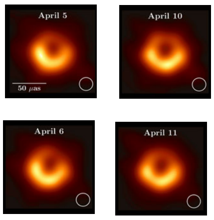


1. astrophysical black holes

known knowns





2. 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],

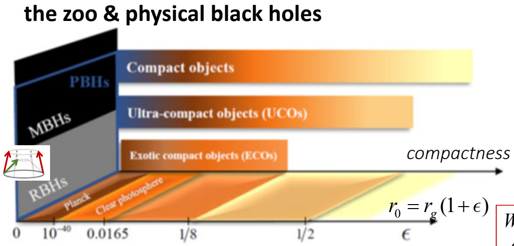
◊ There are many definitions of a black hole…
Curiel, Nature Astr. **3**, 27 (2019)

◊ physical black hole (PBH) = a trapped spacetime region
Frolov, arXiv:/gr-qc1411.6981

+form in finite time of a distant observer

3. ultra-compact objects

the zoo & physical black holes



$r_0 = r_g(1+\epsilon)$

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

[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

Why ECOs are called exotic?

Buchdal's theorem $\epsilon > 1/8$

$\rho > 0, p > 0$ — GR

Exotic matter

- Modified
- Semiclassical
- Quantum gravity

4+ii

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.

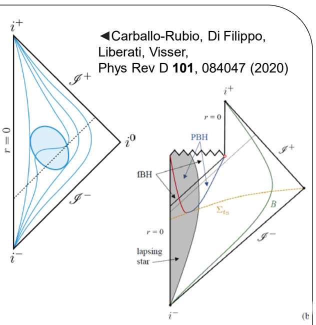
3. The metric is modified by quantum effects. The resulting curvature satisfies the semiclassical self-consistent equation

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

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

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

◄Carballo-Rubio, Di Filippo, Liberati, Visser, Phys Rev D **101**, 084047 (2020)



Physical BH [PBH]

(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

5. 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

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

Curvature scalars

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

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

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

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

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

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

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

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

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

k=0,1*

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

6. spherical symmetry

metrics

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

$x := r - r_g$

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

$k=1$ ► $C = r - c_{32} x^{3/2} + \ldots \quad h = -\frac{3}{2}\ln\frac{x}{\xi} + \ldots$

$r_g' < 0$ ► (v,r) BH solutions

$r_g' > 0$ ► (u,r) WH solutions

References

Nice coordinates:
advanced null (black hole);
retarded null (white hole)

- No static k=0 solutions
- Reissner-Nordström & many static regular BH are k=1 solutions
- Popular dynamic regular BH models are k=0 solutions (and many are not fully consistent)

2. BH parameters are related via evaporation rate

$$\frac{dr_g}{dt} = -4\sqrt{\pi r_g \xi}\,\Upsilon \qquad \frac{dr_g}{dt} = -\frac{c_{32}\xi^{\frac{3}{2}}}{r_g}$$

spherical symmetry: summary

PBH: the process

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

PBH: the properties

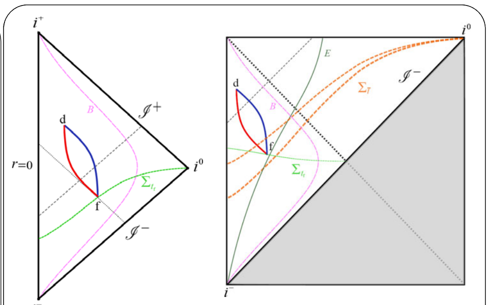
- Finite infall/collapse time (according to a distant Bob)
- Outer apparent horizon is always timelike
- Null energy condition is violated [nearthe outer horizon]
- Unique formation scenario.
- Zero angular momentum BH: no growth
- Some popular RBH models do not work.
- Generalized surface gravity: Kodama
- Interesting consistency/thermo implications
- If the 1st law+ thermality of evaporation work, then a short hair

Wormholes:

- A problem

Cosmological background:

- Fine



Schematic Penrose diagram of a transient regular black hole in the asymptotically flat (left) and asymptotically de Sitter spacetimes. The outer (blue) and inner (dark red) components of the black hole apparent horizon (timelike membranes) are indicated according to the invariant definition. The trajectory of a distant observer, Bob, is indicated in pink and labelled B. The equal (Schwarzschild) time hypersurface of formation is shown as a dashed light green line.

more interesting stuff

- Generalised Kerr-Vaidya
- Partial/general axial symmetry
- White holes
- Perturbations ►QNM
- Cosmological spacetimes
- Radiation

References

❖ Mann, Murk, Terno, *Black holes and their horizons in semiclassical and modified theories of gravity*, Int J Mod Phys D **31**, 2230015 (2022) arXiv:2112.06515
❖ Dahal, Simovic, Soranidis, Terno, arXiv:2303.15793 (2023)
❖ Dahal, Soranidis, Terno, Phys Rev D **106**, 124048 (2022)