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Physical black holes and their properties

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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

assumptions

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

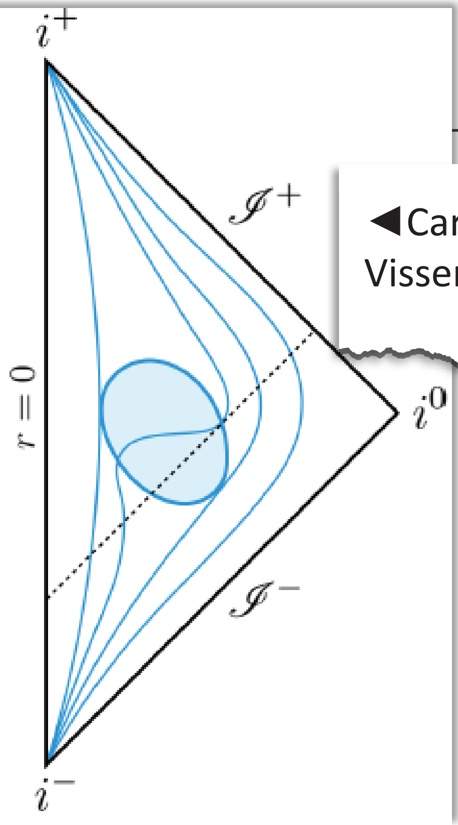
2. Classical concepts, such as trajectory, event horizon or singularity can be used.

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

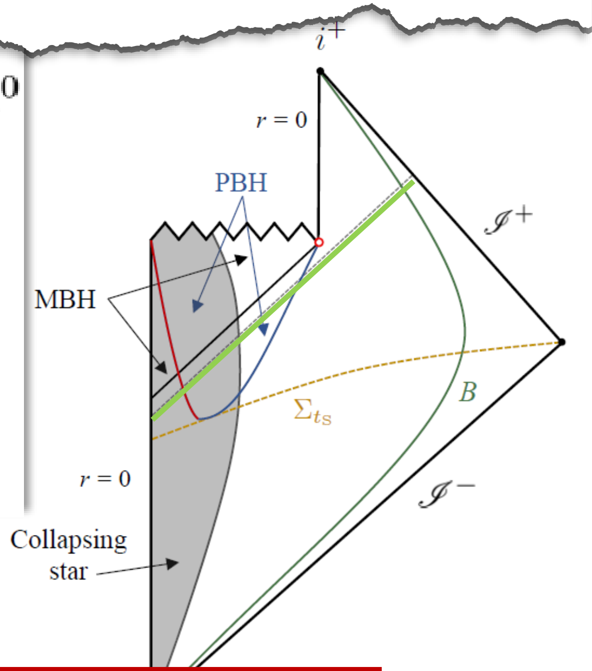
$$R_{\mu\nu}-\tfrac{1}{2}Rg_{\mu\nu}\underset{+E_{\mu\nu}}{=}8\pi\left\langle\hat{T}_{\mu\nu}\right\rangle_{\omega}$$

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

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

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

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

MS invariant mass

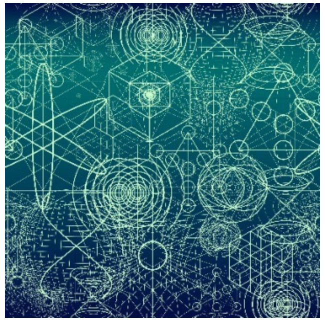
Schwarzschild radius

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

Curvature scalars

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

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



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

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

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

Einstein equations

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

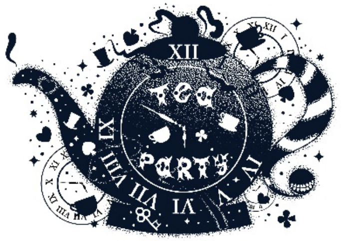
$$\partial_t C = 8\pi r^2 e^h \tau_t{}^r,$$

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

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

k=0,1*

$C = r_g(t) + W(t,r)$ ▶



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

spherical symmetry

metrics

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

$$x := r - r_g$$

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

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

$r_g' < 0 \blacktriangleright (v,r)$

BH solutions

$r_g' > 0 \blacktriangleright (u,r)$

White hole solutions

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

2. BH parameters are related via evaporation rate

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

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

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

Summary: spherical symmetry

●BH formation requires violation of the null energy condition.

● Apparent horizon is timelike. ● Definitions of the inner & outer horizon are coordinate-independent ● There is a unique formation scenario. Once a semiclassical PBH is formed, it stops growing (and is k=1 type) ● Finite redshift (but very big) ● Long(-ish) hair ● Collapse (for distant observers) happens in finite time, but… possibly not yet ● Apparent horizon is a weakly singular surface ● Surface gravity generalizations are problematic ● If Kodama surface gravity is proportional to the Hawking temperature, then physical BH form cold ● There may be no emission that matches the Hawking radiation/ Page's evaporation law