Regular black holes from pure gravity: lessons and perspectives

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Agencia Estatal de Investigación

Based on:

- [PB, Cano, Hennigar]
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- [PB, Cano, Hennigar, Murcia]
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- [PB, Cano, Hennigar, Murcia, Vicente-Cano]
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+WIP with:
Cano, Hennigar, Moreno, Murcia, van der Velde, Vicente-Cano

OUTLINE

⋆ 1. Regular black holes (RBHs)

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⋆3. RBHs from pure gravity: perspectives

$\star$ 1. Regular black holes

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    $\Rightarrow$ **regular black holes**

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  ...In the absence of a dynamical framework, all these ideas are very poorly justified
- The success of all previous attempts at embedding RBHs into actual theories has been quite limited

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All curvature invariants remain finite everywhere

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- Corrections from top-down models (e.g., String Theory) $\Rightarrow$ infinite towers of higher-curvature corrections to Einstein gravity (in String Theory, weighted by powers of α')
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- Understanding such effects is in general out of reach...

$\star$2. **RBHs from pure gravity: lessons**

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- RBHs arise as the unique spherically symmetric solutions of Einstein gravity coupled to infinite towers of higher-curvature terms
- First complete dynamical models of matter collapse leading to the formation of regular black holes

$\star$ 2.1 Quasi-topological gravities

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\begin{aligned}
\mathcal{Z}_{(1)} &= R\,,\\
\mathcal{Z}_{(2)} &= \frac{1}{(D-2)}\left[\frac{W_{abcd}W^{abcd}}{D-3}-\frac{4Z_{ab}Z^{ab}}{D-2}\right]+\frac{\mathcal{Z}_{(1)}^2}{D(D-1)}\,,\\
\mathcal{Z}_{(3)} &= \frac{24}{(D-2)(D-3)}\left[\frac{W_{ac}{}^{bd}Z_b^aZ_d^c}{(D-2)^2}-\frac{W_{acde}W^{bcde}Z_b^a}{(D-2)(D-4)}+\frac{2(D-3)Z_b^aZ_c^bZ_a^c}{3(D-2)^3}+\frac{(2D-3)W^{ab}{}_{cd}W^{cd}{}_{ef}W^{ef}{}_{ab}}{12(D((D-9)D+26)-22)}\right]\\
&\quad+\frac{3\mathcal{Z}_{(1)}\mathcal{Z}_{(2)}}{D(D-1)}-\frac{2\mathcal{Z}_{(1)}^3}{D^2(D-1)^2}\,,\\
\mathcal{Z}_{(4)} &= \frac{96}{(D-2)^2(D-3)}\left[\frac{(D-1)\left(W_{abcd}W^{abcd}\right)^2}{8D(D-2)^2(D-3)}-\frac{(2D-3)Z_e^fZ_f^eW_{abcd}W^{abcd}}{4(D-1)(D-2)^2}-\frac{2W_{acbd}W^{cefg}W^d{}_{efg}Z^{ab}}{D(D-3)(D-4)}\right.\\
&\quad\left.-\frac{4Z_{ac}Z_{de}W^{bdce}Z_b^a}{(D-2)^2(D-4)}+\frac{(D^2-3D+3)\left(Z_a^bZ_b^a\right)^2}{D(D-1)(D-2)^3}-\frac{Z_a^bZ_b^cZ_c^dZ_d^a}{(D-2)^3}+\frac{(2D-1)W_{abcd}W^{aecf}Z^{bd}Z_{ef}}{D(D-2)(D-3)}\right]+\frac{4\mathcal{Z}_{(1)}\mathcal{Z}_{(3)}-3\mathcal{Z}_{(2)}^2}{D(D-1)}\,,
\end{aligned}
$$

Quasi-topological gravities

$$
\begin{aligned}
\mathcal{Z}_{(5)} = \frac{960(D-1)}{(D-2)^4(D-3)^2} \Bigg[& \frac{(D-2) W_{ghij} W^{ghij} W_{ab}{}^{cd} W_{cd}{}^{ef} W_{ef}{}^{ab}}{40D(D^3-9D^2+26D-22)} + \frac{4(D-3) Z_a^b Z_b^c Z_c^d Z_d^e Z_e^a}{5(D-1)(D-2)^2(D-4)} \\
& - \frac{(3D-1) W^{ghij} W_{ghij} W_{acde} W^{bcde} Z_b^a}{10D(D-1)^2(D-4)} - \frac{4(D-3)(D^2-2D+2) Z_a^b Z_b^a Z_c^d Z_d^e Z_e^c}{5D(D-1)^2(D-2)^2(D-4)} \\
& - \frac{(D-3)(3D-1)(D^2+2D-4) W^{ghij} W_{ghij} Z_c^d Z_d^e Z_e^c}{10D(D-1)^2(D+1)(D-2)^2(D-4)} + \frac{(5D^2-7D+6) Z_g^h Z_h^g W_{abcd} Z^{ac} Z^{bd}}{10D(D-1)^2(D-2)} \\
& + \frac{(D-2)(D-3)(15D^5-148D^4+527D^3-800D^2+472D-88) W_{ab}{}^{cd} W_{cd}{}^{ef} W_{ef}{}^{ab} Z_g^h Z_h^g}{40D(D-1)^2(D-4)(D^5-15D^4+91D^3-277D^2+418D-242)} \\
& - \frac{2(3D-1) Z^{ab} W_{acbd} Z^{ef} W_e{}^c{}_f{}^g Z_g^d}{D(D^2-1)(D-4)} - \frac{Z_a^b Z_b^c Z_{cd} Z_{ef} W^{eafd}}{(D-1)(D-2)} + \frac{(D-3) W_{acde} W^{bcde} Z_b^a Z_f^g Z_g^f}{5D(D-1)^2(D-4)} \\
& - \frac{(D-2)(D-3)(3D-2) Z_b^a Z_c^b W_{daef} W^{efgh} W_{gh}{}^{dc}}{4(D-1)^2(D-4)(D^2-6D+11)} + \frac{W_{ghij} W^{ghij} Z^{ac} Z^{bd} W_{abcd}}{20D(D-1)^2} \Bigg] \\
& + \frac{5\mathcal{Z}_{(1)}\mathcal{Z}_{(4)} - 2\mathcal{Z}_{(2)}\mathcal{Z}_{(3)}}{D(D-1)} + \frac{6\mathcal{Z}_{(1)}\mathcal{Z}_{(2)}^2 - 8\mathcal{Z}_{(1)}^2\mathcal{Z}_{(3)}}{D^2(D-1)^2} \,.
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\boxed{\mathcal{Z}_{(n+5)} = \frac{3(n+3)\mathcal{Z}_{(1)}\mathcal{Z}_{(n+4)}}{D(D-1)(n+1)} - \frac{3(n+4)\mathcal{Z}_{(2)}\mathcal{Z}_{(n+3)}}{D(D-1)n} + \frac{(n+3)(n+4)\mathcal{Z}_{(3)}\mathcal{Z}_{(n+2)}}{D(D-1)n(n+1)}}\,.
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$$\xRightarrow{g_{ab} \to g_{ab} + \beta_2 R_{ab} + \ldots} \quad I_{\mathrm{QT}} = \int \frac{\mathrm{d}^D x \sqrt{|g|}}{16\pi G} \left[R + \sum_n \alpha_n \mathcal{Z}_n \right]$$

Quasi-topological gravities and gravitational EFT

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Here we will go **beyond** the perturbative regime...

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$\Rightarrow$ QT theories satisfy a **Birkhoff theorem**: [Oliva, Ray; PB, Cano, Hennigar, Murcia]

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every spherically symmetric vacuum solution is also static.

Birkhoff implies Quasi-topological

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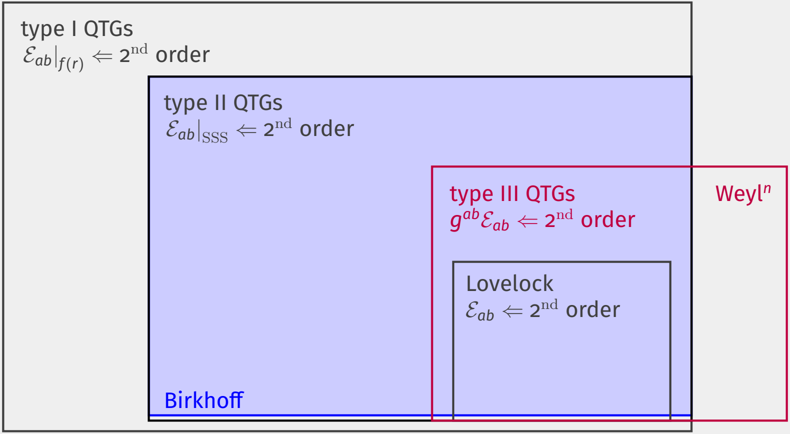

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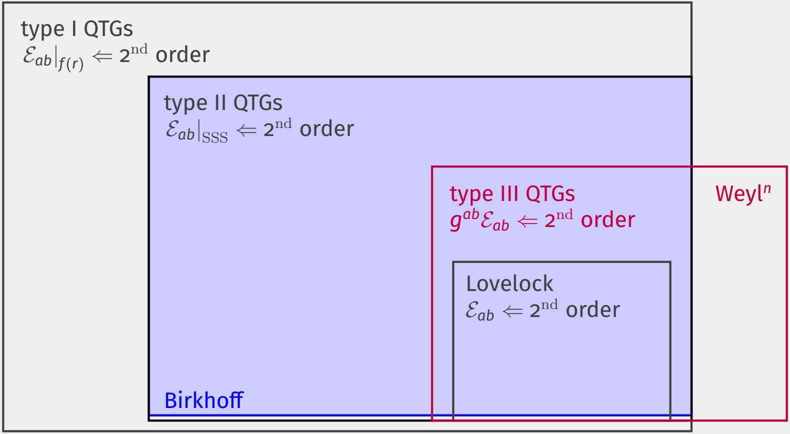

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- Overcoming this limitation $\Leftarrow$ consider **non-polynomial densities**.

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[PB, Cano, Hennigar, Murcia]

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- Similar densities of arbitrary order exist (identical recursion formulas as in the $D \geq 5$ polynomial cases).

Consider a dimensional reduction of our D-dimensional models on the $(D-2)$-sphere (both the polynomial $D \geq 5$ and non-polynomial $D = 4$ ones)

$$\mathrm{d}s^2 = \gamma_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu + \varphi(x)^2 \mathrm{d}\Omega^2_{(D-2)}$$

A unified dimensional reduction

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As long as we inquire about spherically symmetric problems, the dynamics can be studied by means of this 2d action.

$\star$2.2 RBHs from infinite towers of QT gravities

Both for polynomial $D \geq 5$ and non-polynomial $D = 4$ QT theories, the full non-linear EOM for a general spherically symmetric ansatz reduce to an algebraic equation for $f(r)$:

$$\boxed{\frac{1-f(r)}{r^2} + \sum_{n=2}^{\mathrm{n_{max}}} \alpha_n \frac{(D-2n)}{(D-2)} \left[\frac{1-f(r)}{r^2}\right]^n = \frac{2M}{r^{D-1}}}$$

where M is an integration constant proportional to the mass.

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$$f(r) \overset{r\to 0}{=} 1 - \left(\frac{2M}{\alpha_{\max}}\right)^{1/n_{\max}} r^{2-\frac{(D-1)}{n_{\max}}} + \dots$$

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Note that exponent tends to 2 as $n_{\max} \to \infty$...

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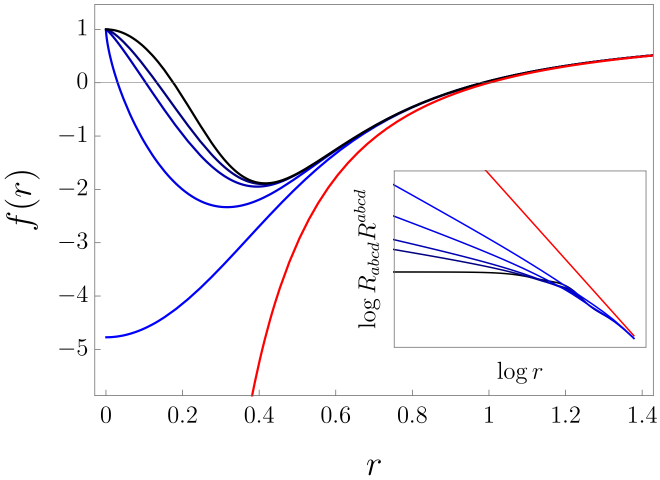
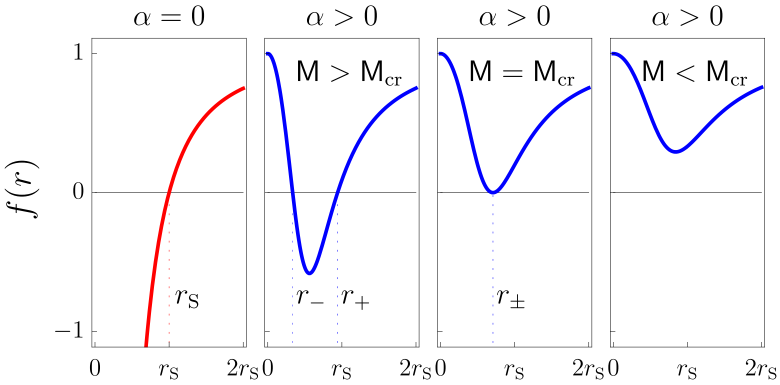
- Example:

$$\alpha_n = \frac{(D-2)}{(D-2n)}\alpha^{n-1} \quad \Rightarrow \quad f(r) = 1 - \frac{2Mr^2}{r^{D-1} + 2M\alpha}$$

(Hayward black hole)


1
0
−1
−2
−3
−4
−5
$f(r)$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
r
$\log R_{abcd}R^{abcd}$
$\log r$


$\alpha = 0$
$\alpha > 0$
$\alpha > 0$
$\alpha > 0$
$f(r)$
1
0
-1
r_S
r_-
r_+
$r_\pm$
M > M_{cr}
M = M_{cr}
M < M_{cr}
0
r_S
$2r_S$

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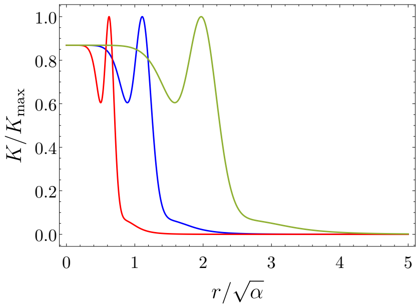
- General proof
  [Frolov, Koek, Pinedo Soto, Zelnikov]



$\star$2.3 Dynamical formation of RBHs

- Collapse of a very thin spherical shell of dust

$$T_{ab} = \sigma\delta(r - R(\tau))u_a u_b\,.$$

Inside the shell, flat spacetime.

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- Birkhoff's theorem $\Rightarrow$ the exterior is given by the unique static and spherically symmetric vacuum solution.

Find and solve the modified Israel junction conditions using the two-dimensional Horndeski effective action.

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- Continuity of the induced metric:
  $h_{AB}^{-} = h_{AB}^{+}$
- Discontinuity of boundary equations of motion:
  $\Pi_{AB}^{-} - \Pi_{AB}^{+} = 8\pi G T_{AB}$, where $\Pi_{AB} \sim \delta I_{2d}^{\mathrm{bdy}} / \delta h^{AB}$

- A shell/star that starts collapsing at some finite radius $R_0 > r_+$ keeps on decreasing its size, eventually giving rise to a regular black hole.

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- The shell/star grows up to $r = R_0$, at which point the process of collapse starts over.

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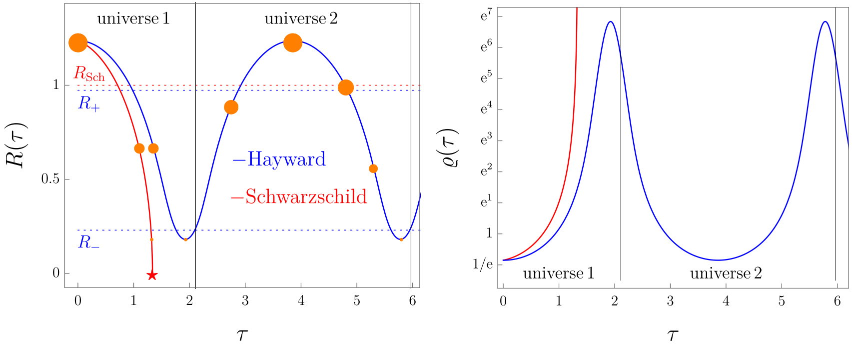

$\star$ 3. **RBHs from pure gravity: perspectives**

- **Buchdahl limit**

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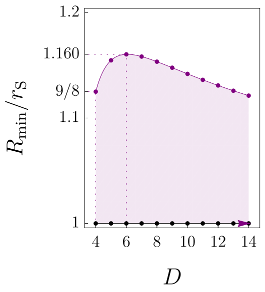

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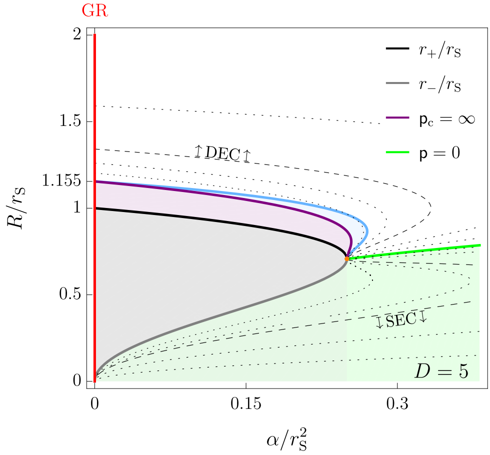
- In GR, Buchdahl's inequality is saturated by infinite-central pressure constant-density stars.
- A generalized inequality can be found for QT models with RBHs. This is also saturated by infinite-central pressure, constant-density stars at least for broad classes of such models.

Space of constant-density stars



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- One way to avoid this $\Rightarrow$ impose the dominant energy condition on matter (non-negative energy density for every observer and non-spacelike local energy flow).

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- One way to avoid this $\Rightarrow$ impose the dominant energy condition on matter (non-negative energy density for every observer and non-spacelike local energy flow). More generally, this suggests that less-naive matter couplings may be needed in order to preserve regularity beyond the vacuum sector.

Dynamical stability $\star^{\text{(WIP)}}$

[PB, Cano, Carballo-Rubio, Hennigar, Murcia, Vicente-Cano]

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  $\Rightarrow$ study classical+semiclassical perturbations
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  $\Rightarrow$ study gravitational perturbations
- Stability on other backgrounds?
  $\Rightarrow$ can be healed by including explicit non-local $f(\Box)$ terms

Evaporation $\star^{\text{(WIP)}}$

[PB, Cano, Hennigar, Moreno, Murcia, van der Velde]

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Evaporation process

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- Take 0 ⇒ black body approximation:

Evaporation $\star^{(\mathrm{WIP})}$

[PB, Cano, Hennigar, Moreno, Murcia, van der Velde]

Evaporation process

- Take 0 $\Rightarrow$ black body approximation:
  - $\star$ early times: analogous to Schwarzschild

Evaporation $\star^{\text{(WIP)}}$

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Role of "overextremal" horizonless solutions?

More to come

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- ⋆ This framework allows us to address many questions regarding the fate/viability of regular black holes.

The End