Dynamical formation of regular black holes

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"Black holes and their symmetries"
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Universitat de Barcelona

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Agencia Estatal de Investigación

Based on:

- [PB, Cano, Hennigar]
  arXiv:2403.04827. PLB 861 (2025) 139260
- [PB, Cano, Hennigar, Murcia]
  arXiv:2412.02740. PRD 111 (2025) 10, 104009
- [PB, Cano, Hennigar, Murcia]
  arXiv:2412.02742. PRL 134 (2025) 18, 181401
- [PB, Cano, Hennigar, Murcia, Vicente-Cano]
  arXiv:2505.09680. PRD xxx (2025) xx, xxxxxx

+ work in progress

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  $\Rightarrow$ Fundamental question: how do they get resolved?

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- Possibility 2: They can be resolved within a regime in which the classical metric description holds $\Rightarrow$ **regular black holes**

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  ...In the absence of a dynamical framework, all these ideas are very poorly justified

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All curvature invariants remain finite everywhere (in particular at $r = 0$).

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  $\Rightarrow$ regular black holes are not the general solutions of these theories

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- Understanding such effects is in general completely out of reach...

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

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- Quasi-topological theories constructed at curvature orders: $n = 3$ [Oliva, Ray; Myers, Robinson], $n = 4$ [Dehghani, Bazrafshan, Mann, Mehdizadeh, Ghanaatian, Vahidinia], $n = 5$ [Cisterna, Guajardo, Hassaine, Oliva] and $\forall n$ (and $\forall D \geq 5$) [PB, Cano, Hennigar; Moreno, Murcia].

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Let W_{abcd} denote the Weyl tensor and Z_{ab} the traceless part of the Ricci tensor, then:

$$
\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]+\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}
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\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^b_a Z^c_b Z^d_c Z^e_d Z^a_e}{5(D-1)(D-2)^2(D-4)} \\
& - \frac{(3D-1) W^{ghij} W_{ghij} W_{acde} W^{bcde} Z^a_b}{10D(D-1)^2(D-4)} - \frac{4(D-3)(D^2-2D+2) Z^b_a Z^a_b Z^d_c Z^e_d Z^c_e}{5D(D-1)^2(D-2)^2(D-4)} \\
& - \frac{(D-3)(3D-1)(D^2+2D-4) W^{ghij} W_{ghij} Z^d_c Z^e_d Z^c_e}{10D(D-1)^2(D+1)(D-2)^2(D-4)} + \frac{(5D^2-7D+6) Z^h_g Z^g_h 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^h_g Z^g_h}{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^d_g}{D(D^2-1)(D-4)} - \frac{Z^b_a Z^c_b Z_{cd} Z_{ef} W^{eafd}}{(D-1)(D-2)} + \frac{(D-3) W_{acde} W^{bcde} Z^a_b Z^g_f Z^f_g}{5D(D-1)^2(D-4)} \\
& - \frac{(D-2)(D-3)(3D-2) Z^a_b Z^b_c 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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Here we will go **beyond** the perturbative regime...

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- The full non-linear EOM of a general Quasi-topological gravity

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- Hence, $N(r,t) = N(t)$, $f(r,t) = f(r)$ and without loss of generality we can set $N(t) = 1 \Rightarrow$ our theories satisfy a **Birkhoff theorem**: *every spherically symmetric vacuum solution of our theories is also static.*

[Oliva, Ray; PB, Cano, Hennigar, Murcia]

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- 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 related to the mass.

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

Schwarzschild black hole singularity resolution

[PB, Cano, Hennigar]

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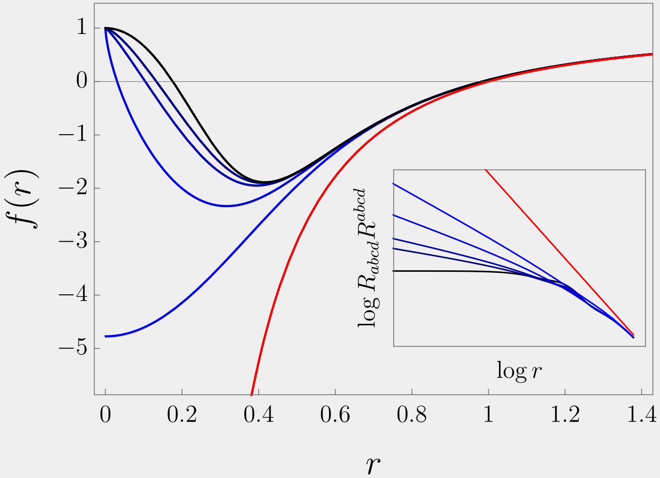
- Example:

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

Schwarzschild black hole singularity resolution

[PB, Cano, Hennigar]



Schwarzschild black hole singularity resolution

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Schwarzschild black hole singularity resolution

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- Our regular black holes are solutions to actual theories, so we can ask now: **how do they form?**

Regular black holes from thin shell collapse

[PB, Cano, Hennigar, Murcia]

We consider the collapse of a very thin spherical shell of dust

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

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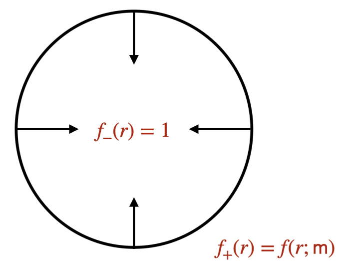
- Goal: find the trajectory of the shell $R(\tau)$



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- Master equation for the shell motion

$$\boxed{m = \int_0^M \frac{\mathrm{d}M'}{\sqrt{\dot{R}^2 + f(R, M')}}}$$

where:

1. $m \equiv$ shell's proper mass
2. $M \equiv$ spacetime total mass
3. $\dot{R} \equiv$ shell's proper velocity
4. $f(R, M) \equiv$ metric function for a spacetime of mass M evaluated at the shell radius

- Case 1: Einstein gravity,

$$f(R,M) = 1 - \frac{2M}{R^{D-3}} \Rightarrow \dot{R}^2 + V(R) = \frac{M^2}{m^2} - 1\,, \qquad \boxed{V(R) = -\frac{M}{R^{D-3}} - \frac{m^2}{2R^{2(D-3)}}}$$

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The potential does not diverge at $R = 0$!

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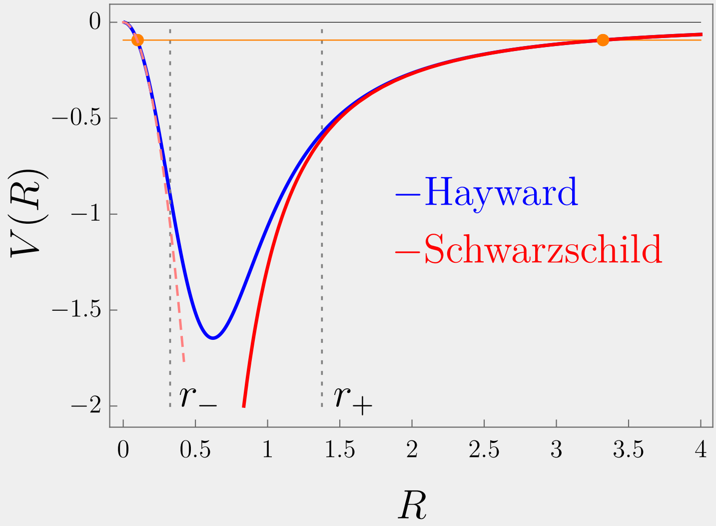

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- The shell grows up to $r = R_0$, at which point the process of collapse starts over.

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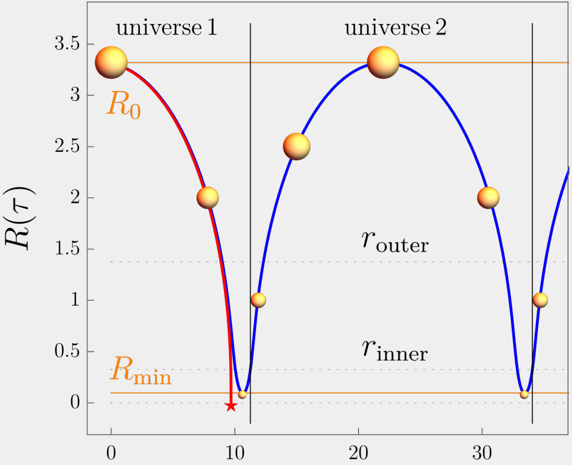

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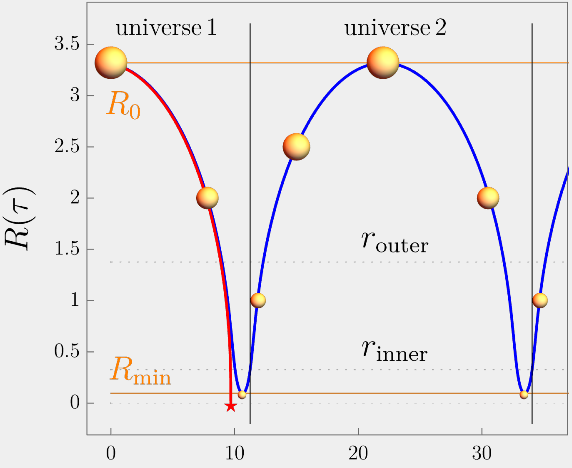

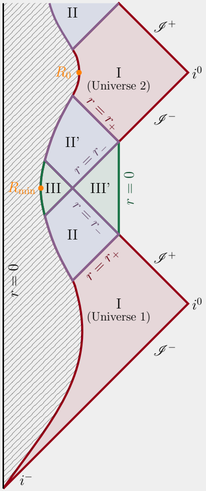

Regular black holes from Oppenheimer-Snyder collapse

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- First junction condition:

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  Cold dark matter bouncing universe model

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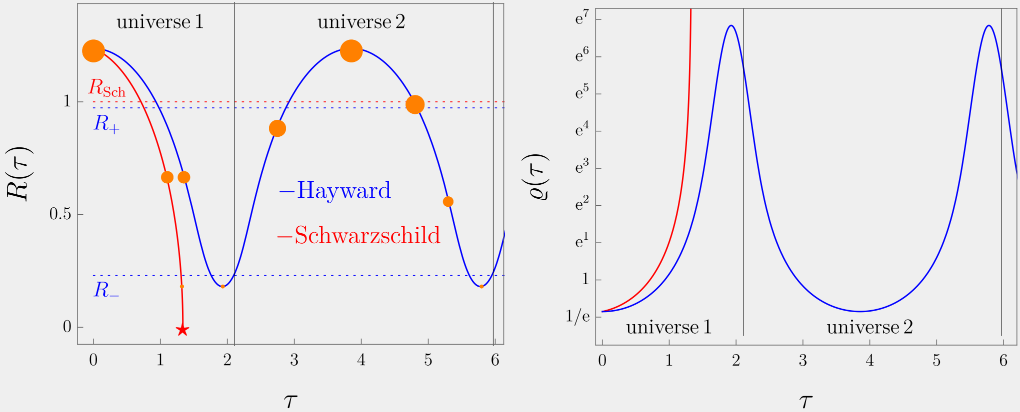

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- The resulting regular black holes are the only vacuum spherically-symmetric solutions of these theories (Birkhoff theorem holds).
- First fully dynamical models in which the collapse of matter leads to the formation of regular black holes!

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The End