Regular Black Holes from Pure Gravity

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Ministerio de Ciencia e Innovación
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Based on:

- [PB, Pablo A. Cano, Robie A. Hennigar]
  arXiv:2403.04827

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  $\Rightarrow$ They occur in the interior of black holes
- Expected to be an artifact of an incomplete description...
  $\Rightarrow$ Fundamental question: how do they get resolved?

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$\Rightarrow$ Not actual GR solutions: postulated metrics as theoretical test beds

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$$f(r) \overset{r\to\infty}{=} 1 - \frac{m}{r^{D-3}} + \ldots$$

- ...but the curvature singularity gets replaced by a de Sitter core

$$\boxed{f(r) \overset{r\to 0}{=} 1 - \frac{r^2}{\alpha} + \ldots}$$

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  $\Rightarrow$ e.g., no Maxwellian limit
- Requires fine tuning of parameters
  $\Rightarrow$ regular black holes are not the general solutions of these theories

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- Perhaps those would resolve singularities somehow
- Understanding such effects is in general completely out of reach...

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- The result is a generic resolution of the Schwarzschild singularity!
- Regular black holes arise as (the unique) exact solutions of Einstein gravity $+$ infinite towers of higher-curvature terms

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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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$$
\begin{aligned}
\mathcal{Z}_1 &= +R\,,\\
\mathcal{Z}_2 &= +R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}\,,\\
\mathcal{Z}_3 &= +(D-4)R_a{}^b{}_c{}^d R_b{}^e{}_d{}^f R_e{}^a{}_f{}^c + \frac{3(3D-8)}{8(2D-3)}R_{abcd}R^{abcd}R - \frac{3(3D-4)}{2(2D-3)}R_a{}^c R_c{}^a R - \frac{3(D-2)}{(2D-3)}R_{acbd}R^{acb}{}_e R^{de} + \frac{3D}{(2D-3)}R_{acbd}R^{ab}R^{cd}\\
&\quad + \frac{6(D-2)}{(2D-3)}R_a{}^c R_c{}^b R_b{}^a + \frac{3D}{8(2D-3)}R^3\,,\\
\mathcal{Z}_4 &= -\frac{384(D-8)R^a_b R^c_a R^d_c R^b_d}{(D-2)^5(D^3-8D^2+48D-96)} - \frac{1152R_{ab}R^{ab}R_{cd}R^{cd}}{(D-2)^5(D^3-8D^2+48D-96)} - \frac{64(D^3-10D^2+40D+24)RR^c_a R^b_c R^a_b}{(D-1)(D-2)^5(D^3-8D^2+48D-96)}\\
&\quad + \frac{24(D^4-6D^3+20D^2+104D-64)R^2R_{ab}R^{ab}}{(D-1)^2(D-2)^5(D^3-8D^2+48D-96)} - \frac{(D^5+6D^4-64D^3+416D^2+176D-480)R^4}{(D-1)^3(D-2)^5(D^3-8D^2+48D-96)} - \frac{96(D+2)RR^{ab}R^{cd}W_{acbd}}{(D-1)(D-2)^4(D-3)(D-4)}\\
&\quad - \frac{6(2D^5-D^4-31D^3+20D^2+20D-16)R^2W_{abcd}W^{abcd}}{(D-1)^2(D-2)^3(D-3)(D-4)(2D^4-17D^3+49D^2-48D+16)} + \frac{96(2D^4-7D^3-7D^2+18D-8)RR^a_b W_{ac}{}^{de}W_{de}{}^{bc}}{(D-1)(D-2)^3(D-3)(D-4)(2D^4-17D^3+49D^2-48D+16)}\\
&\quad + \frac{384R^c_a R^{ab}R^{de}W_{bdce}}{(D-2)^4(D-3)(D-4)} - \frac{48(7D^2-10D+4)R^{ab}R^{cd}W_{ac}{}^{ef}W_{bdef}}{(D-2)^3(D-3)(2D^4-17D^3+49D^2-48D+16)}\\
&\quad - \frac{8(2D^4-15D^3+26D^2+27D-58)RW_{ab}{}^{ef}W^{abcd}W_{cdef}}{(D-1)(D-2)^2(D-3)(D-4)(D^2-6D+11)(D^3-9D^2+26D-22)} - \frac{48(7D^2-10D+4)R^c_a R^{ab}W_b{}^{def}W_{cdef}}{(D-2)^3(D-3)(2D^4-17D^3+49D^2-48D+16)}\\
&\quad + \frac{96R^{ab}W_a{}^{cde}W_{bc}{}^{fg}W_{defg}}{(D-2)^2(D-3)(D-4)(D^2-6D+11)} - \frac{3(3D-4)W_{ab}{}^{cd}W_{cd}{}^{ef}W_{ef}{}^{gh}W_{gh}{}^{ab}}{(D-2)(D-3)(D^5-14D^4+79D^3-224D^2+316D-170)}\,,
\end{aligned}
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\begin{aligned}
\tilde{\mathcal{Z}}_5 = &+\frac{512(-64-12D+D^2)R_a{}^cR^{ab}R_b{}^dR_c{}^eR_{de}}{(-4+D)(-2+D)^6(-128+32D+D^3)} + \frac{5120(4+D)R_{ab}R^{ab}R_c{}^eR^{cd}R_{de}}{(-4+D)(-2+D)^6(-128+32D+D^3)} \\
&- \frac{640(4608+3712D-2880D^2+664D^3-126D^4+7D^5)R_a{}^cR^{ab}R_b{}^dR_{cd}R}{(-4+D)(-2+D)^6(-1+D)(-128+32D+D^3)(-96+48D-8D^2+D^3)} \\
&- \frac{1920(-768-320D+280D^2-58D^3+11D^4)R_{ab}R^{ab}R_{cd}R^{cd}R}{(-4+D)(-2+D)^6(-1+D)(-128+32D+D^3)(-96+48D-8D^2+D^3)} \\
&- \frac{160(4096-27136D+7168D^2+160D^3-64D^4+116D^5-16D^6+D^7)R_a{}^cR^{ab}R_{bc}R^2}{(-4+D)(-2+D)^6(-1+D)^2(-128+32D+D^3)(-96+48D-8D^2+D^3)} \\
&+ \frac{40(30720-20992D-41216D^2+17920D^3-2784D^4+656D^5+28D^6-8D^7+D^8)R_{ab}R^{ab}R^3}{(-4+D)(-2+D)^6(-1+D)^3(-128+32D+D^3)(-96+48D-8D^2+D^3)} \\
&- \frac{(155648+231424D-530176D^2+136384D^3-14336D^4+4272D^5+1296D^6-204D^7+16D^8+D^9)R^5}{(-4+D)(-2+D)^6(-1+D)^4(-128+32D+D^3)(-96+48D-8D^2+D^3)} \\
&- \frac{240(-80-100D+8D^2+7D^3)R^{ab}R^{cd}R^2W_{acbd}}{(-4+D)(-3+D)(-2+D)^5(-1+D)^2(96-48D+7D^2)} \\
&- \frac{10(-128+896D-2552D^2+3900D^3-2970D^4+425D^5+710D^6-243D^7-10D^8+8D^9)R^3W_{abcd}W^{abcd}}{(-4+D)(-3+D)(-2+D)^4(-1+D)^3(16-48D+49D^2-17D^3+2D^4)(16-56D+69D^2-27D^3+4D^4)} \\
&+ \frac{240(64-256D+260D^2+292D^3-795D^4+516D^5-35D^6-42D^7+8D^8)R^{ab}R^2W_a{}^{cde}W_{bcde}}{(-4+D)(-3+D)(-2+D)^4(-1+D)^2(16-48D+49D^2-17D^3+2D^4)(16-56D+69D^2-27D^3+4D^4)} \\
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&- \frac{11520R_a{}^cR^{ab}R_d{}^fR^{de}W_{becf}}{(-3+D)(-2+D)^5(96-48D+7D^2)} \\
&- \frac{20(3632-7644D-4296D^2+23905D^3-23526D^4+8466D^5+560D^6-1437D^7+478D^8-70D^9+4D^{10})R^2W_{ab}{}^{ef}W^{abcd}W_{cdef}}{(-4+D)(-3+D)(-2+D)^3(-1+D)^2(11-6D+D^2)(-22+26D-9D^2+D^3)(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)} \\
&- \frac{240(128-704D+1464D^2-1240D^3+60D^4+503D^5-221D^6+28D^7)R_a{}^cR^{ab}RW_b{}^{def}W_{cdef}}{(-4+D)(-3+D)(-2+D)^4(-1+D)(16-48D+49D^2-17D^3+2D^4)(16-56D+69D^2-27D^3+4D^4)} \\
&- \frac{15360R_a{}^cR^{ab}R_b{}^dR^{ef}W_{cedf}}{(-3+D)(-2+D)^5(96-48D+7D^2)} \\
&+ \frac{960(4-12D+11D^2)R_a{}^cR^{ab}R^{de}W_{bd}{}^{fg}W_{cefg}}{(-4+D)(-3+D)(-2+D)^4(16-56D+69D^2-27D^3+4D^4)} \\
&+ \frac{160(-232+550D-253D^2-242D^3+221D^4-62D^5+6D^6)R^{ab}RW_a{}^{cde}W_{bc}{}^{fg}W_{defg}}{(-4+D)(-3+D)(-2+D)^3(-1+D)(11-6D+D^2)(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)} \\
&+ \frac{320(4-12D+11D^2)R_a{}^cR^{ab}R_b{}^dW_c{}^{efg}W_{defg}}{(-4+D)(-3+D)(-2+D)^4(16-56D+69D^2-27D^3+4D^4)} \\
&- \frac{80(12-28D+17D^2)R^{ab}R^{cd}W_{ac}{}^{ef}W_{bd}{}^{gh}W_{efgh}}{(-3+D)(-2+D)^3(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)} \\
&- \frac{15(-528+482D+241D^2-425D^3+194D^4-39D^5+3D^6)RW_{ab}{}^{ef}W^{abcd}W_{cd}{}^{gh}W_{efgh}}{(-4+D)(-3+D)(-2+D)^2(-1+D)(85-99D+48D^2-11D^3+D^4)(-170+316D-224D^2+79D^3-14D^4+D^5)} \\
&- \frac{80(12-28D+17D^2)R_a{}^cR^{ab}W_b{}^{def}W_{cd}{}^{gh}W_{efgh}}{(-3+D)(-2+D)^3(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)} \\
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&- \frac{4(-5+4D)W_{ab}{}^{ef}W^{abcd}W_{cd}{}^{gh}W_{ef}{}^{ij}W_{ghij}}{(-3+D)(-2+D)(-1150+2954D-3202D^2+1934D^3-705D^4+155D^5-19D^6+D^7)}\,.
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&-\frac{20(3632-7644D-4296D^2+23905D^3-23526D^4+8466D^5+560D^6-1437D^7+478D^8-70D^9+4D^{10})R^2W_{ab}{}^{ef}W^{abcd}W_{cdef}}{(-4+D)(-3+D)(-2+D)^3(-1+D)^2(11-6D+D^2)(-22+26D-9D^2+D^3)(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)}\\
&-\frac{240(128-704D+1464D^2-1240D^3+60D^4+503D^5-221D^6+28D^7)R_a{}^cR^{ab}RW_b{}^{def}W_{cdef}}{(-4+D)(-3+D)(-2+D)^4(-1+D)(16-48D+49D^2-17D^3+2D^4)(16-56D+69D^2-27D^3+4D^4)}\\
&-\frac{15360R_a{}^cR^{ab}R_b{}^dR^{ef}W_{cedf}}{(-3+D)(-2+D)^5(96-48D+7D^2)}\\
&+\frac{960(4-12D+11D^2)R_a{}^cR^{ab}R^{de}W_{bd}{}^{fg}W_{cefg}}{(-4+D)(-3+D)(-2+D)^4(16-56D+69D^2-27D^3+4D^4)}\\
&+\frac{160(-232+550D-253D^2-242D^3+221D^4-62D^5+6D^6)R^{ab}RW_a{}^{cde}W_{bc}{}^{fg}W_{defg}}{(-4+D)(-3+D)(-2+D)^3(-1+D)(11-6D+D^2)(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)}\\
&+\frac{320(4-12D+11D^2)R_a{}^cR^{ab}R_b{}^dW_c{}^{efg}W_{defg}}{(-4+D)(-3+D)(-2+D)^4(16-56D+69D^2-27D^3+4D^4)}\\
&-\frac{80(12-28D+17D^2)R^{ab}R^{cd}W_{ac}{}^{ef}W_{bd}{}^{gh}W_{efgh}}{(-3+D)(-2+D)^3(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)}\\
&-\frac{15(-528+482D+241D^2-425D^3+194D^4-39D^5+3D^6)RW_{ab}{}^{ef}W^{abcd}W_{cd}{}^{gh}W_{efgh}}{(-4+D)(-3+D)(-2+D)^2(-1+D)(85-99D+48D^2-11D^3+D^4)(-170+316D-224D^2+79D^3-14D^4+D^5)}\\
&-\frac{80(12-28D+17D^2)R_a{}^cR^{ab}W_b{}^{def}W_{cd}{}^{gh}W_{efgh}}{(-3+D)(-2+D)^3(176-600D+775D^2-482D^3+161D^4-28D^5+2D^6)}\\
&+\frac{240R^{ab}W_a{}^{cde}W_{bc}{}^{fg}W_{de}{}^{hi}W_{fghi}}{(-4+D)(-3+D)(-2+D)^2(85-99D+48D^2-11D^3+D^4)}\\
&-\frac{4(-5+4D)W_{ab}{}^{ef}W^{abcd}W_{cd}{}^{gh}W_{ef}{}^{ij}W_{ghij}}{(-3+D)(-2+D)(-1150+2954D-3202D^2+1934D^3-705D^4+155D^5-19D^6+D^7)}\,.
\end{aligned}
$$

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$$I_{\mathrm{EFT}} = \int \frac{\mathrm{d}^D x \sqrt{|g|}}{16\pi G}\left[R + \sum_n \beta_n \mathrm{Riem}^n\right] \overset{g_{ab}\to g_{ab}+\beta_2 R_{ab}+\dots}{\Longrightarrow} I_{\mathrm{QT}} = \int \frac{\mathrm{d}^D x \sqrt{|g|}}{16\pi G}\left[R + \sum_n \alpha_n \mathcal{Z}_n\right]$$

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Here we will go beyond the EFT regime...

Quasi-topological Black Holes

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

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to a couple of algebraic equations:

$$N(r) = 1\,, \qquad \boxed{\frac{1-f(r)}{r^2} + \sum_{n=2}^{\mathrm{n}_{\max}} \alpha_n \left[\frac{1-f(r)}{r^2}\right]^n = \frac{m}{r^{D-1}}}$$

where m is an integration constant related to the mass.

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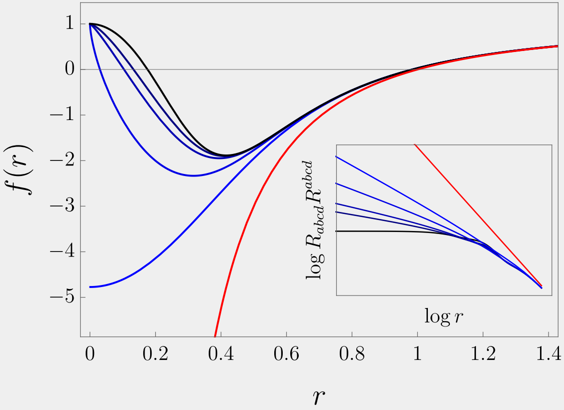

Regular Black Holes Bacchanalia

[PB, Cano, Hennigar]

α_n	$f(r)$
α^{n-1}	$1-\frac{mr^2}{r^{D-1}+\alpha m}$
$\frac{\alpha^{n-1}}{n}$	$1-\frac{r^2}{\alpha}\left(1-e^{-\alpha m/r^{D-1}}\right)$
$n\alpha^{n-1}$	$1-\frac{2mr^2}{r^{D-1}+2\alpha m+\sqrt{r^{2(D-1)}+4\alpha m r^{D-1}}}$
$\frac{(1-(-1)^n)}{2}\alpha^{n-1}$	$1-\frac{2mr^2}{r^{D-1}+\sqrt{r^{2(D-1)}+4\alpha^2m^2}}$
$\frac{(1-(-1)^n)\Gamma\left(\frac{n}{2}\right)}{2\sqrt{\pi}\Gamma\left(\frac{n+1}{2}\right)}\alpha^{n-1}$	$1-\frac{mr^2}{\sqrt{r^{2(D-1)}+\alpha^2m^2}}$

Hayward, Bardeen-like, Dymnikova-like, etc., black holes as particular cases

In sum

The Schwarzschild black hole singularity gets generically resolved in $D \geq 5$ by the effect of infinite towers of higher-curvature densities, no tricks involved.

The End

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- Straightforward extensions to include matter with $T_r^r = T_t^t$
- What about $D = 4$?

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