Resolution of black hole singularities in Palatini gravity

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- Fundamentally different from singularities on the fields living on a fixed space-time background! (e.g. Coulomb's divergence).
- If space-time breaks down when a singularity, how can we even speak of a singularity as something occurring at some "location"?.
- It is hard to rigorously capture the intuitive notion of a singularity (the theorems on singularities offer little clue about this).

Curvature divergences

- If we see space-time singularities as indicative of a physically troublesome region, a natural guess is that something is going on ill with the geometry.
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- Difficulty 1: theorems on singularities still apply. Pay the price of violation of energy conditions.
- Difficulty 2: nothing in the singularity theorems speak of curvature invariants.

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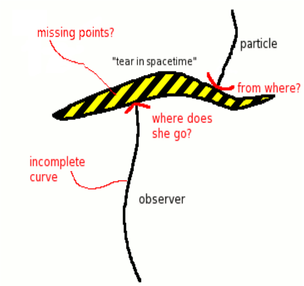

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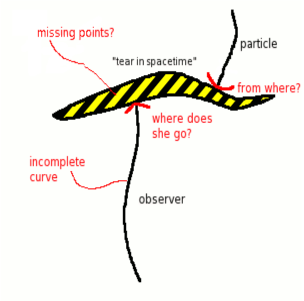

- That observers may experience intense tidal forces or large deformations is irrelevant as long as they exist.

- Thus:
  - In a singular space-time there exist geodesic curves which cannot be extended to arbitrarily large values of the affine parameter (i.e., they start or terminate at some finite value).
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- Assumptions/approach of our research:
  - The fundamental criterium to be considered for space-time singularities is geodesic completeness.
  - Space-time singularities are an artifact of the classical description provided by GR, which breaks down at high curvature/short-scales: modified gravity.
  - The bulk of “quantum gravity” effects can be captured by some effective theory of gravity in which singularities are avoided.

Background geometry

- Consider the following electrovacuum geometry (derived first in 1207.6004 [gr-qc] (PRD))

$$ds^2 = -A(x)dv^2 + \frac{2}{\sigma_+}dvdx + r^2(x)d\Omega^2$$

where

$$\begin{aligned} A(x) &= \frac{1}{\sigma_+}\left[1 - \frac{r_S}{r}\frac{(1+\delta_1 G(r))}{\sigma_-^{1/2}}\right] \; ; \; \delta_1 = \frac{1}{2r_S}\sqrt{\frac{r_q^3}{l_\varepsilon}} \; ; \; \sigma_\pm = 1 \pm \frac{r_c^4}{r^4(x)}; \\ G(z) &= -\frac{1}{\delta_c} + \frac{1}{2}\sqrt{z^4-1}\left[f_{3/4}(z) + f_{7/4}(z)\right] \end{aligned}$$

where $r_c = \sqrt{l_\varepsilon r_q}$: "core" radius, l_ε some length scale, $r_q^2 = 2G_N q^2$: charge radius, $r_S = 2M_0$: Schwarzschild radius, $\delta_c \simeq -0.572$ a constant.

  - For $z = r/r_c \gg 1 \to$ Reissner-Nordström space-time:

$$A(x) \approx 1 - \frac{r_S}{r} + \frac{r_q^2}{2r^2} + O\left(\frac{1}{r^4}\right)$$

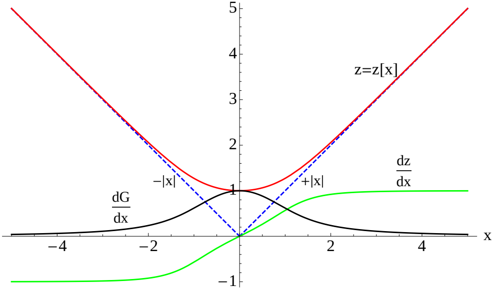
  - For $z \simeq 1$ (N_q: number of charges):

$$A(x) \simeq \frac{N_q}{4N_c}\frac{(\delta_1 - \delta_c)}{\delta_1 \delta_c}\sqrt{\frac{r_c}{r - r_c}} + \frac{N_c - N_q}{2N_c} + \dots$$

- From $\left(\frac{dr}{dx}\right)^2 = \frac{\sigma_-}{\sigma_+^2}$ we find

$$r^2(x) = \frac{x^2 + \sqrt{x^4 + 4r_c^4}}{2}$$

which has a minimum at $x = 0$. This is reminiscent of a wormhole geometry.



- WH structure persists regardless of the fact that the curvature scalars at the wormhole throat be all finite ($\delta_1 = \delta_c$) or divergent ($\delta_1 \neq \delta_c$).

Theories and approach

- This space-time is an exact solution of quadratic gravity [1207.6004 [gr-qc] (PRD)]:

$$S_{Quad} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left[R + l_\epsilon^2(aR^2 + R_{\mu\nu}R^{\mu\nu})\right] - \frac{1}{16\pi}\int d^4x\sqrt{-g}F_{\mu\nu}F^{\mu\nu}$$

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- and also of Born-Infeld gravity [1311.0815 [hep-th] (PRD)]:

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- Standard electromagnetic Maxwell field as matter $\to$ energy conditions are satisfied.
- Formulated in the Palatini approach: metric and connection as independent fields:
  - Second-order field equations.
  - Vacuum equations are Minkowski or (A)dS solutions $\to$ no extra propagating dofs.
  - In GR (and Lovelock), metric and Palatini formulations coincide.

Geodesics

- A geodesic curve $\gamma^\mu = x^\mu(\lambda)$ with tangent vector $u^\mu = \frac{dx^\mu}{d\lambda}$ and affine parameter λ satisfies (e.g. Chandrasekhar's book):

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0$$

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  - The metric defines a natural connection (Christoffel) and defines a set of geodesics.
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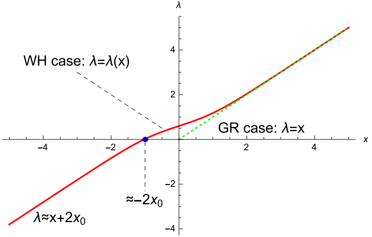
- Rewrite the geodesic equation in terms of the geodesic tangent vector

$$\frac{1}{\sigma_+^2}\left(\frac{dx}{d\lambda}\right)^2 = E^2 - A\left(\kappa + \frac{L^2}{r^2(x)}\right)$$

where $k = 0(1)$ for null (time-like) geodesics.

- Radial null geodesics ($k=0, L=0$) integrate this equation as

$$\pm E\cdot\lambda(x)=\begin{cases} {}_2F_1[-\frac{1}{4},\frac{1}{2},\frac{3}{4};\frac{r_c^4}{r^4}]r & \text{if } x\geq 0 \\ 2x_0-{}_2F_1[-\frac{1}{4},\frac{1}{2},\frac{3}{4};\frac{r_c^4}{r^4}]r & \text{if } x\leq 0 \end{cases}$$



- The affine parameter $\lambda(x)$ extends over the real axis and the space-time, no matter the behaviour of curvature scalars.
- In GR: $r(\lambda)=\pm E\lambda$, the affine parameter is only defined on the positive/negative side of the real axis because $r(\lambda)$ is positive.

- For null and time-like geodesics with $L \neq 0$, see the geodesic equation as a classical particle in a one effective dimensional potential

$$V(x) = A\left(\kappa + \frac{L^2}{r^2(x)}\right)$$

which near the WH behaves as $V(x) \approx -a/|x|$, with $a = \left(\kappa + \frac{L^2}{r_c^2}\right)\frac{N_q(\delta_c - \delta_1)r_c}{2N_c\delta_c\delta_1}$.

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  - If $\delta_1 > \delta_c$ (Reissner-Nordström-like configurations) an infinite potential barrier arises which prevents any geodesic from reaching $x = 0$ (same as in GR).
  - If $\delta_1 < \delta_c$ (Schwarzschild-like configurations) the potential becomes infinitely attractive as $x \to 0$ and yields

$$\frac{d\lambda}{dx} \approx \pm\frac{1}{2}\left|\frac{x}{a}\right|^{\frac{1}{2}} \to \lambda(x) \approx \pm\frac{x}{3}\left|\frac{x}{a}\right|^{\frac{1}{2}}$$

    complete! $\to$ compare to GR result $\lambda(r) \approx \pm\frac{2}{3} r \left(\frac{r}{r_S}\right)^{\frac{1}{2}}$ incomplete! (again because $r > 0$).
  - If $\delta_1 = \delta_c$ (no curvature divergences) depending on $E > V_{max}$ geodesics either bounce or oscillate through the WH.

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- Thus... null and time-like complete! $\to$ the presence of the wormhole is essential for this.

- Consider $f(R) = R - \lambda R^2$ with anisotropic fluid $T_\mu{}^\nu = \text{diag}[-\rho, -\rho, \alpha\rho, \alpha\rho]$ (equivalent to some models of non-linear electrodynamics), [1509.02430 [hep-th], 1511.03755 [gr-qc]]:

$$ds^2 = \frac{1}{f_R}\left(-A(x)dt^2 + \frac{1}{A(x)}dx^2\right) + r^2(x)d\Omega^2$$

where $f_R = 1 - 1/z^{2+2\alpha}$, $r = r_c z$, $r_c^{2+2\alpha} \equiv (4\lambda)\kappa^2(1-\alpha)C$.
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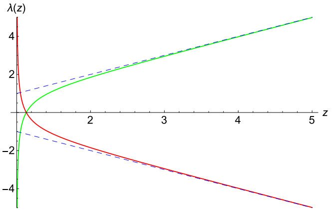
- Radial null geodesics complete [same for time-like and with angular momentum]

$$\pm E\tilde{\lambda}(z) = -\frac{z}{\sqrt{1 - z^{-2(\alpha+1)}}} + 2z\, {}_2F_1\left(\frac{1}{2}, -\frac{1}{2(\alpha+1)}; 1 - \frac{1}{2(\alpha+1)}; z^{-2(\alpha+1)}\right)$$



Infinite affine time → these wormholes lie beyond the reach of any observer or signal!.

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THANK YOU FOR YOUR ATTENTION!