Kilometer-scale ultraviolet regulators and astrophysical black holes

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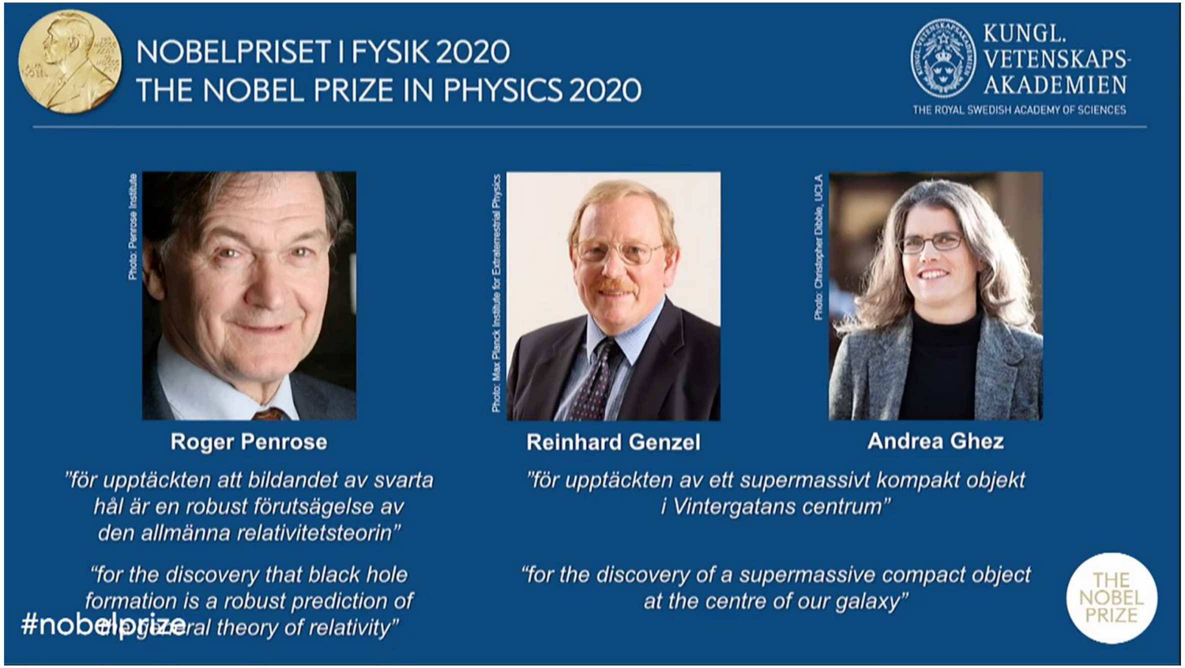

Black hole formation appears to be a **robust prediction** of general relativity. Considerable problem!

$$ds^2 = -F(r)dt^2 + \frac{dr^2}{F(r)} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2 \,, \quad F(r) = 1 - \frac{2GM}{r}$$

→ Do black holes really contain spacetime singularities? (Schwarzschild: $r = 0$)

Why look into regular BH models?

Common belief: quantum gravity somehow resolves singularities. But be careful:

- Stable quantum gravity ground state from singularities (Horowitz & Myers, GRG 1995).
- Bousso bound and incomplete surfaces (Bousso & Shahbazi-Moghaddam, PRD 2023).
- Extremal Kerr horizon can be singular in higher-derivative gravity (Horowitz et al, PRL 2023).

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Today: **phenomenological approach** ~~fundamental quantum gravity~~

- Bardeen (GR5 Proc 1968), Dymnikova (CQG 1992), Hayward (PRL 2006)
- Loop quantum black hole (Modesto, CQG 2006)
- Non-commutative geometry-inspired (Nicolini et al, PLB 2006)
- UV-complete black holes (Modesto et al, PLB 2011)
- Generating rotating versions (Azreg-Aïnou, PRD 2014)
- ...
- Quantum corrections from T-duality (Nicolini et al, PLB 2019)

and many more!

Typical challenges

Regular BHs are no exact vacuum solutions. Energy-momentum tensor violates strong energy condition but respects weak energy condition.	} by design
Mass inflation instability at inner horizon. Geodesic (in)completeness.	} "technicalities"
Horizon disappearance for over-regular black holes. No meaningful constraints from supermassive BHs.	} phenomenology

We have barely scratched the surface of interesting regular BH models.

Our claim: **mass-dependent regulators** can change phenomenology appreciably.

Step 1/4: Schwarzschild metric

$$F(r) = 1 - \frac{2GM}{r}$$

- ✓ exact vacuum solution
- ✓ unique solution
- ✗ singularity at $r = 0$
- ✗ unbounded curvature

Next step: regularize this metric somehow.

Step 2/4: Regular metric

$$F(r) = 1 - \frac{2GM}{r} \frac{r^3}{r^3 + L^3}$$

- ✔ regular at $r = 0$
- ✔ pheno: $L < \mathcal{O}(\mu\mathrm{m})$

- ✘ not an exact solution
- ✘ curvature is not bounded in M: $\sim \frac{GM}{L^3}$
- ✘ has horizon: $[L/(2GM)]^3 < 4/27$

Next step: want to avoid trans-Planckian curvatures.

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* Limiting curvature conjecture (Markov JETP Lett 1982, Polchinski Nucl Phys B 1989).

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Problem: inconsistency* for kilometer-scale regulators.

*inconsistency: mass gap

	horizon condition
Bardeen	$GM \geq 1.30\ell$
Dymnikova	$GM \geq 0.88\ell$
Bonanno-Reuter	$GM \geq 3.50\ell$
Hayward	$GM \geq 1.30\ell$
Simpson-Visser	$GM \geq 0.50\ell$
Frolov	$GM \geq 0.98\ell$

"No black hole, if regulator $>>$ Schwarzschild radius."

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Next step: let's remove inconsistency for kilometer-scale regulators!

Step 4/4: Improved Hayward metric

$$F(r) = 1 - \frac{2GM}{r} \frac{r^3}{r^3 + 2GM\ell^2 f\left(\frac{\ell}{2GM}\right)}$$

- ✓ regular at $r = 0$
- ✓ $\mu\mathrm{m}$-pheno possible
- ✓ curvature bounded by $\approx 1/\ell^2$
- ✓ has horizon: $[\ell/(2GM)]^2 f < 4/27$
- ✗ not an exact solution

New ingredient: **mass-dependent regulator** $f(\ell/(2GM))$

This mass-dependent regulator can change phenomenology appreciably.

$$L^3 \;\to\; 2GM\ell^2 f\left(\frac{\ell}{2GM}\right)$$

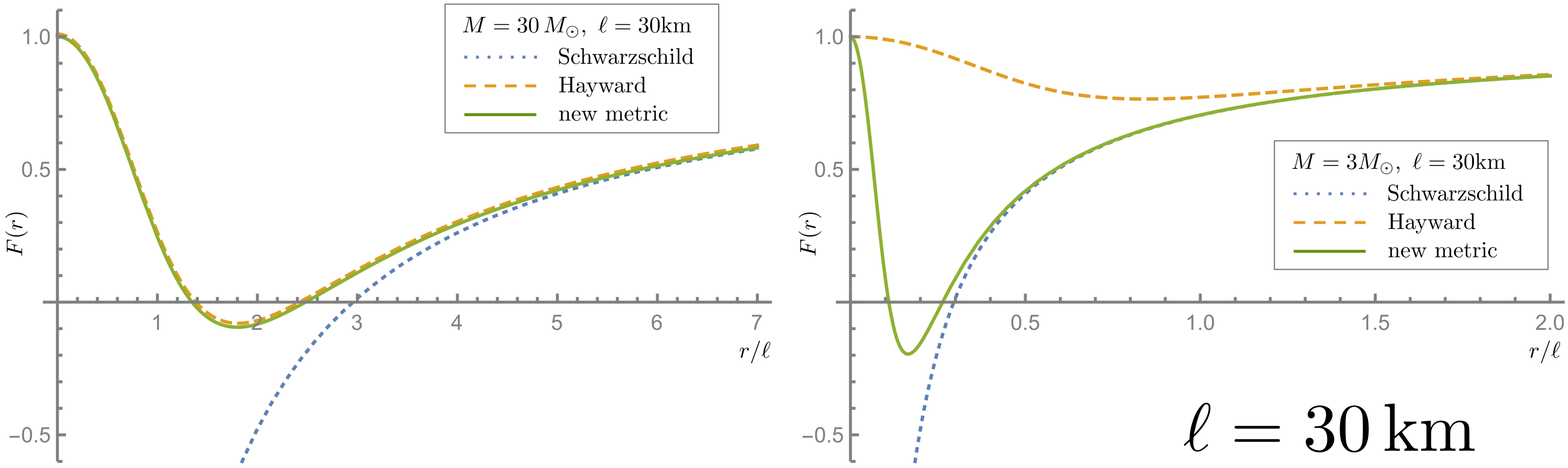
- Smooth recovery. Fixed M, vanishing ℓ : overall regulator needs to vanish.
- Limiting curvature conjecture. Finite ℓ, large M: need that $f \to 1$.
- Tabletop consistency. Finite ℓ, small M: need that $f \lesssim 1$ to avoid more stringent bound.

We find that the function $f = \dfrac{1}{1 + \left(\frac{\ell}{2GM}\right)^4}$ satisfies these criteria (but there are others, too).

Important: Maximum size of effect is not changed (compared to the metric with $f = 1$).

Rather: Size of effect can be maximal for very large regulators while still allowing black holes.

Mass-dependent regulators = new way to look at regular black holes!



So far: Kilometer-scale regulators destroy black hole horizons. But: we can **solve that**!

Mass-dependent regulators support **large, percent-level effects** in horizon & photon sphere shifts.

Search for M-dependent regulators and constrain shape of f rather than r-dependence of geometry.

Thank you for your attention! Jens Boos & Chris Carone, 2311.16319 [gr-qc]