Testing black-hole near-horizon effects and pseudo-complex general relativity with gravitational Waves

Alex Nielsen

Max Planck Institute for Gravitational Physics - AEI

Hanover, Germany

Motivation

- Einstein’s theory of general relativity is one of the most successful scientific theories of all time.
- Only with very careful measurements can we notice that the Solar System is not described by Newtonian Gravity.
- General relativity predicts its own incompleteness (for black holes and the Big Bang).
- Black hole entropy and the information paradox suggest there may be something going on at (or near) the horizon.
- With binary mergers, observation is now ahead of theory.

Testing gravity with GWs

- Compact and dynamic

$$\frac{v}{c} \sim \sqrt{\frac{GM}{c^2 r}} \sim \left(\frac{\pi G M f_{GW}}{c^3}\right)^{1/3}$$

- Curvature scale corrections to gravity?

$$R_{abcd} R^{abcd} l_p^4 \sim \frac{3}{4} \frac{\hbar^2 c^2}{G^2 M^4} \ll 1$$

- Horizon scale corrections to gravity?

$$\langle B | \hat{T}_{ab} | B \rangle \Rightarrow \infty$$

Flux correlations

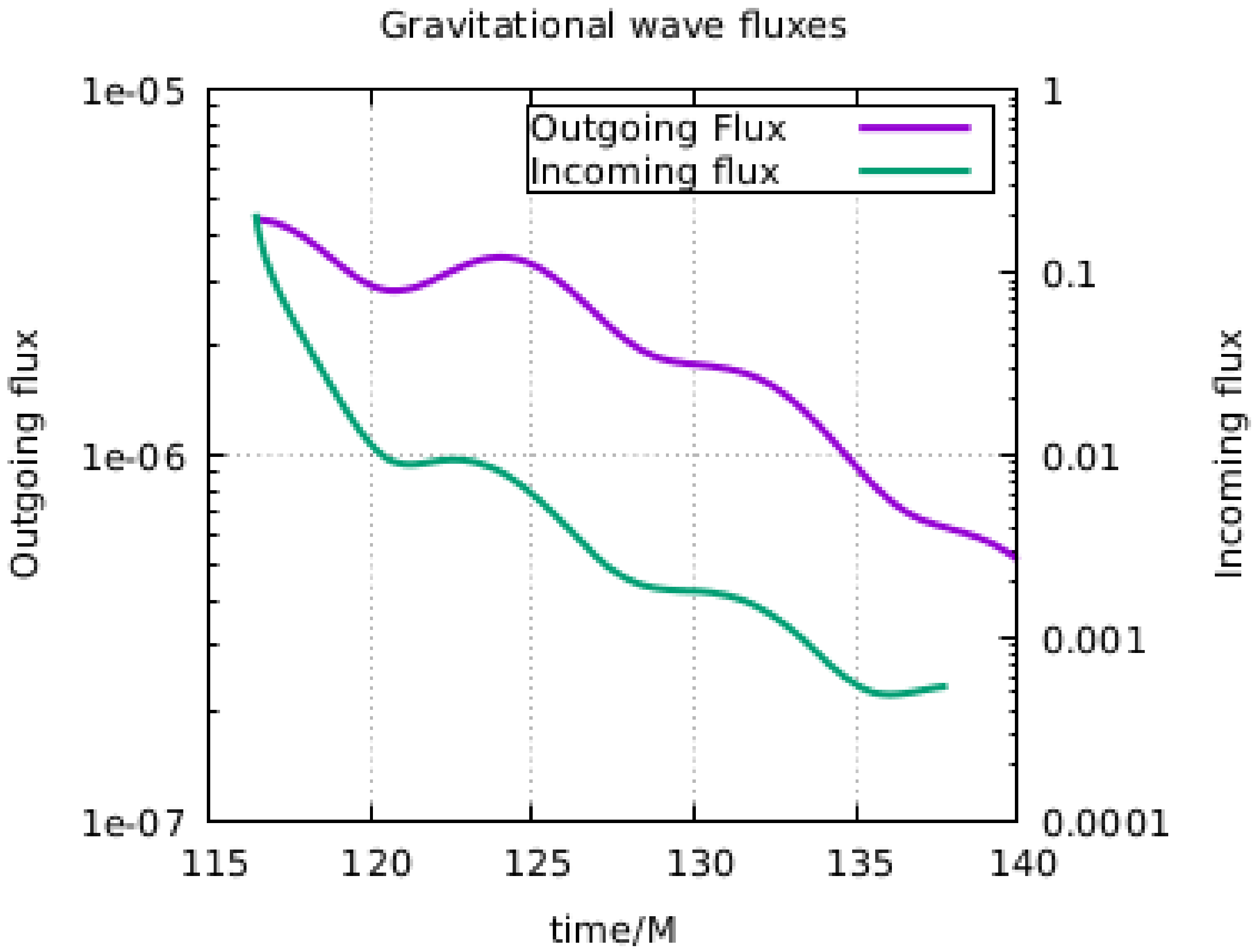


Image: Gupta, Krishnan, Nielsen, Schnetter PRD97 (2018) 084028

Modified GR solutions and pcGR

$$-g_{tt} = 1 - \frac{2M}{r} + \frac{1}{r}\int \xi \, dr$$

Full Kerr-like solution derived (Casper et al. 2012 for pcGR)

$$\begin{aligned}
g_{tt} &= -\left(1 - \frac{\psi}{\Sigma}\right) \quad , \quad g_{rr} = \frac{\Sigma}{\Delta} \quad , \quad g_{\theta\theta} = \Sigma \ , \\
g_{\phi\phi} &= \left((r^2 + a^2) + \frac{a^2\psi}{\Sigma}\sin^2\theta\right)\sin^2\theta \ , \\
g_{t\phi} &= g_{\phi t} = -a\frac{\psi}{\Sigma}\sin^2\theta \ ,
\end{aligned}$$

Form of ξ is bound by Solar System tests, but not by near horizon physics….yet

Solutions without horizons

Take a dimensionless parameter, b:

$$b = -\left(\frac{r}{M}\right)^n \frac{\int \xi \, dr}{2M}$$

Provides effective correction to the mass M:

$$m(r) = M\left(1 + b\left(\frac{M}{r}\right)^n\right)$$

For sufficiently large b values there are no horizons and hence no black holes

$$b > \gamma^n\left(1 - \frac{\chi^2}{2\gamma} - \frac{\gamma}{2}\right) \quad \gamma = \frac{n + \sqrt{n^2 - (n^2 - 1)\chi^2}}{n+1}$$

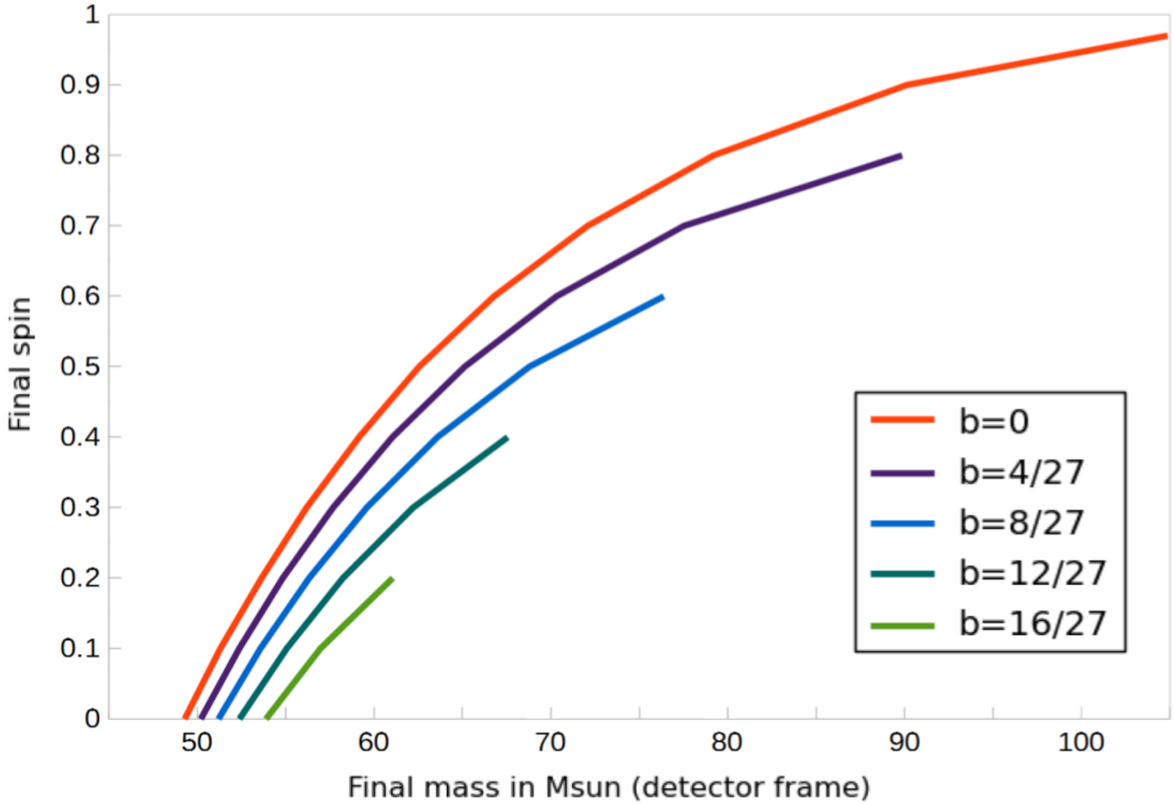
For n=2 and no spin, b_{crit} = 16/27

Light ring and ringdown

Solve for light ring location:

Geodesic: $$(\omega a+1)^2(m-m'r)-\omega^2 r^3=0$$

Null: $$2m-r+4\omega ma+\omega^2(r^3+ra^2+2ma^2)=0$$



Post-Newtonian terms in inspiral

Expand gravitational wave phase as power series in frequency domain:

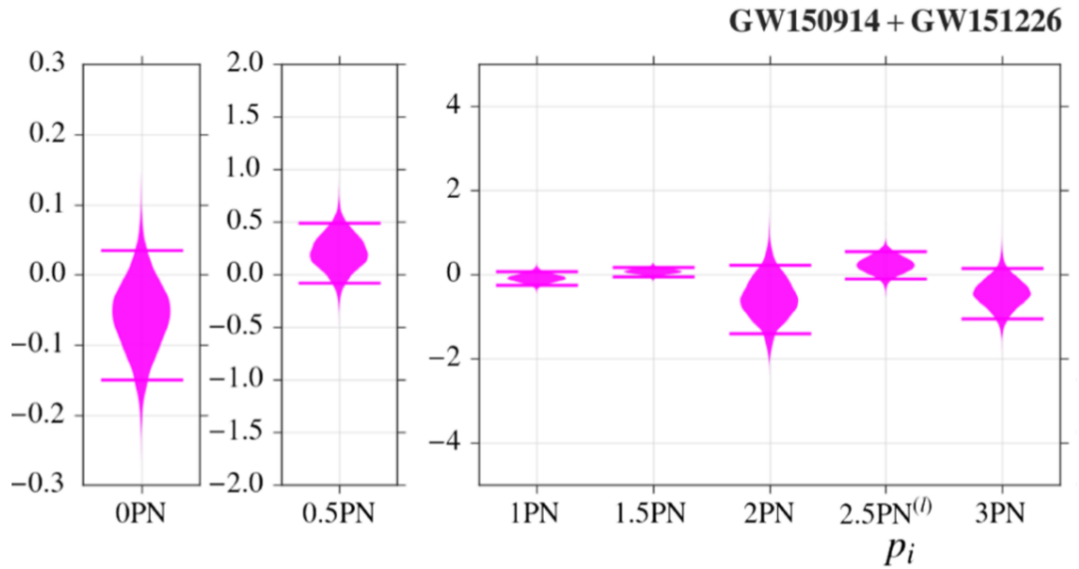
$$\Psi(f) = \sum_n p_n \times (\pi M f_{GW})^{n/3}$$

pcGR correction:

$$nPN\ term = \frac{20b(n+2)(n+1)(1+q^n)}{3(n-4)(2n-5)(1+q)^n}(\pi M f_{GW})^{2n/3}$$

For n=2, q=1, gives about a 25% correction to the value of the GR 2PN term.

Bounds on post-Newtonian coefficients



From Fig 7,
LVC PRX 6 (2016) 041015

n	b_crit	PcGR p_n	GR p_n	Delta p_n	90% confidence range
1	0.5	20/9	6.44	34%	(-20%, 5%)
2	16/27	320/27	46.2	26%	(-130%, 15%)
3	27/32	-225/8	-652	4.3%	(-110%, 10%)

Summary

- Gravitational wave observations allow tests of near-horizon properties.
- Simple properties can be calculated in many models, including pcGR.
- The LIGO observations already disfavour some regions of pcGR parameter space (while still consistent with vacuum GR).

Thank you

Further details: Nielsen and Birnholtz, Astron.Nachr. 339 (2018) no.4, 298-305

Deviations at the horizon

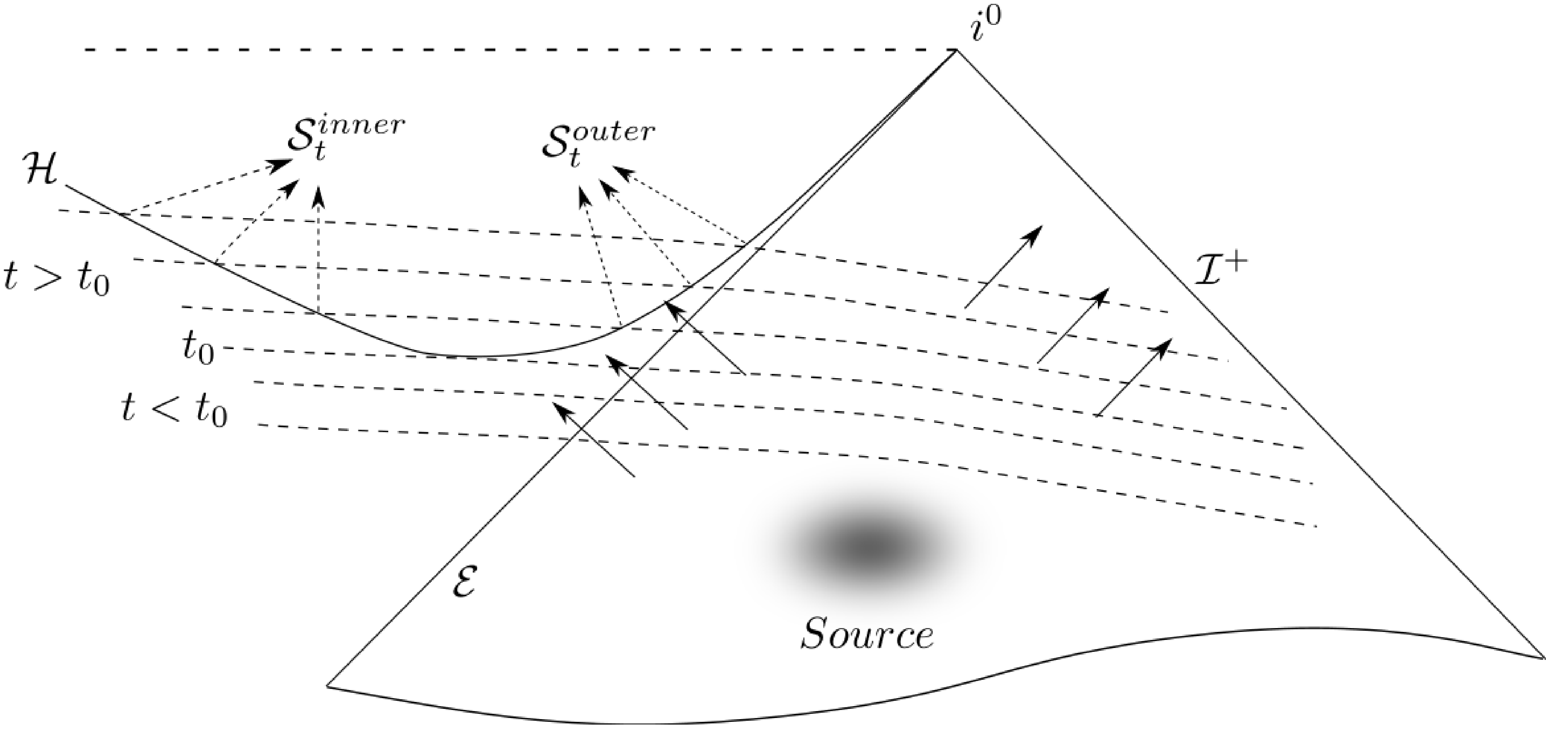
- **Light return time**

$$t_{Schwarzschild} = 2M \ln\left(\frac{r_2 - 2M}{r_1 - 2M}\right) + t_{flat}$$

- **Light scattering time**

$$t_{Scatter} = t_{Hubble} \frac{10^{-22}}{\frac{r_{surface}}{2M} - 1} \frac{M}{M_{Sun}}$$

Horizon correlations



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EMRIs, ISCO and EHT

Generalisation of (circular) Kepler law, r-cmpt of geodesic eqn

$$(\omega a+1)^2(m-m'r)-\omega^2 r^3=0$$

Fig 9 of Schönenbach et al 2012

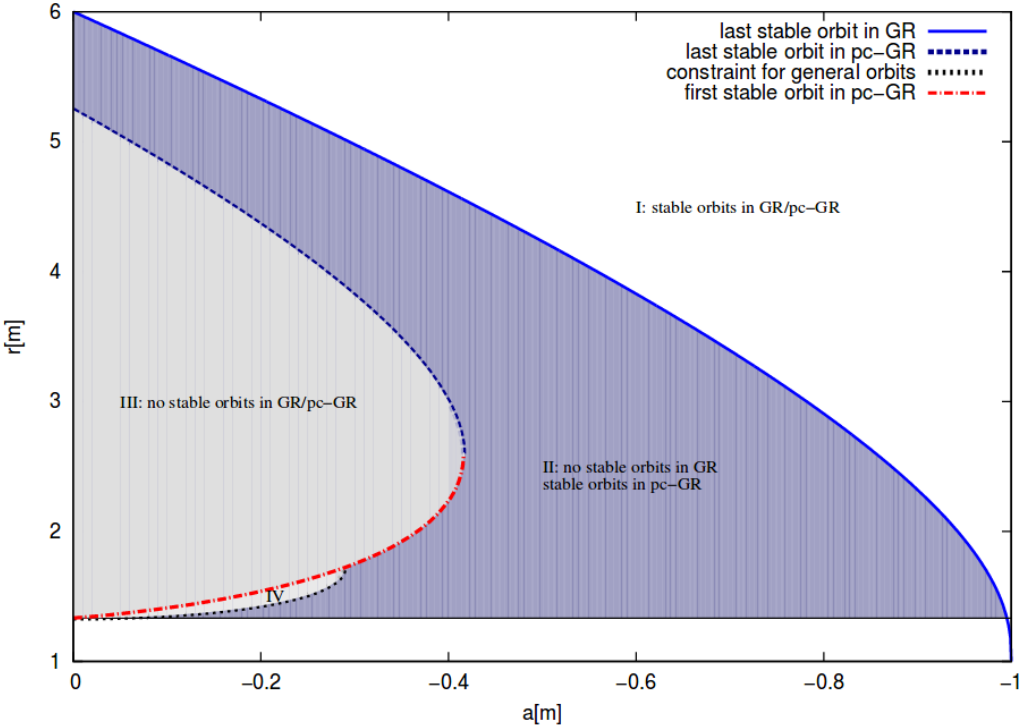
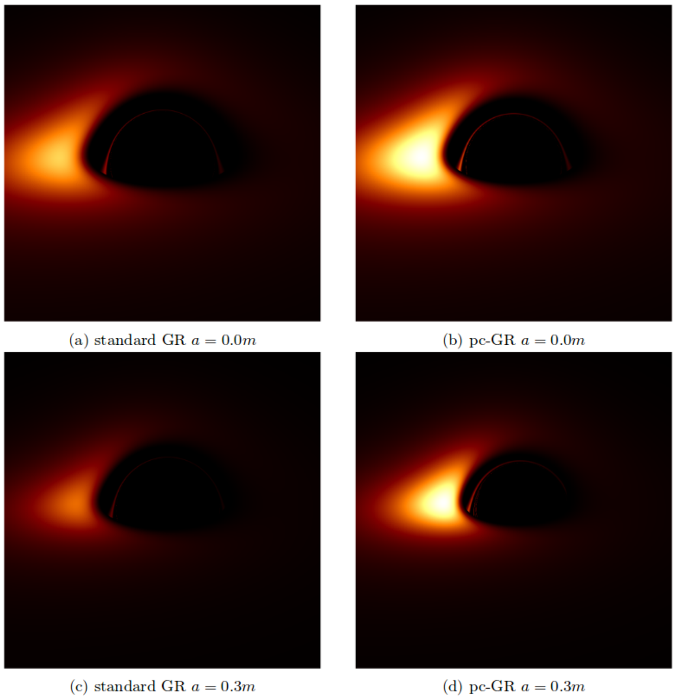


Fig 2 of Schönenbach et al 2014



Results from EHT due ~ 2018?