Black hole horizon fluxes and gravitational waves

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Einstein's Theory of Gravity

$$G_{ab} = 8\pi G T_{ab}$$

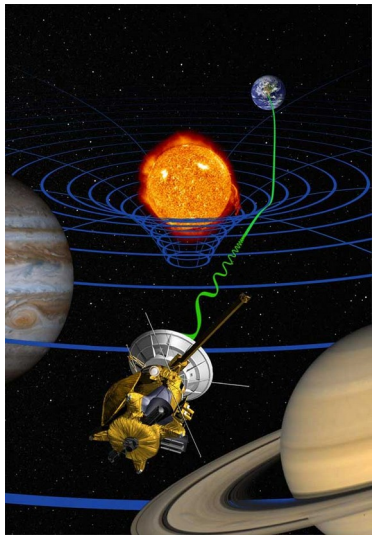
Source: Leor Baeck Institute

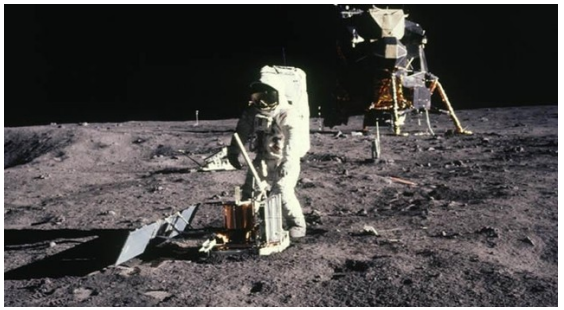
In 1915 Einstein didn’t know about...

- Other galaxies
- Expansion of the universe
- The Big Bang
- Neutron stars and pulsars
- Black holes, quasars and AGNs
- Compact binaries
- Space travel
- GPS
- Atomic clocks
- Lasers
- Particle accelerators
- Dark matter
- Dark energy
- Quantum mechanics / Quantum Field theory

Einstein's Theory of Gravity

$$G_{ab} = 8\pi G T_{ab}$$





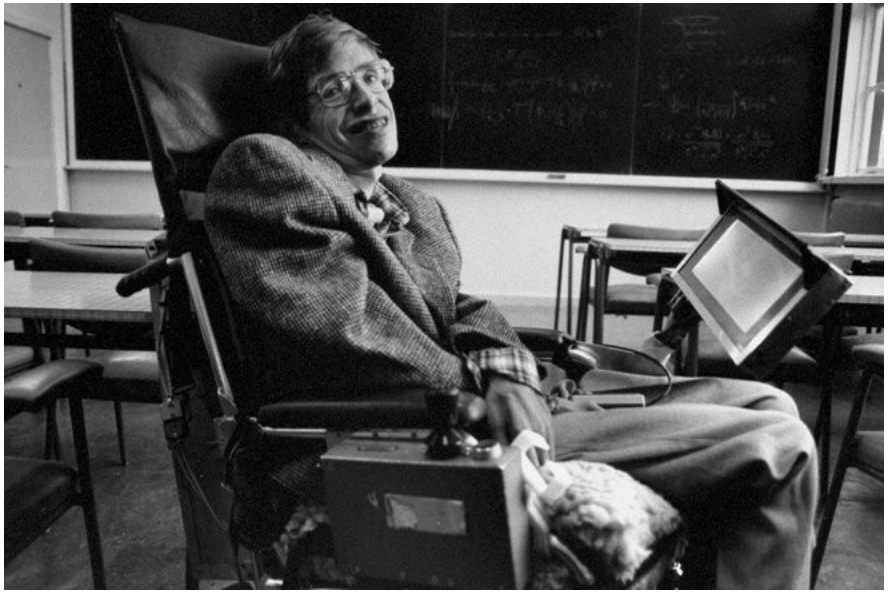
Source: NASA

Source: Leor Baeck Institute

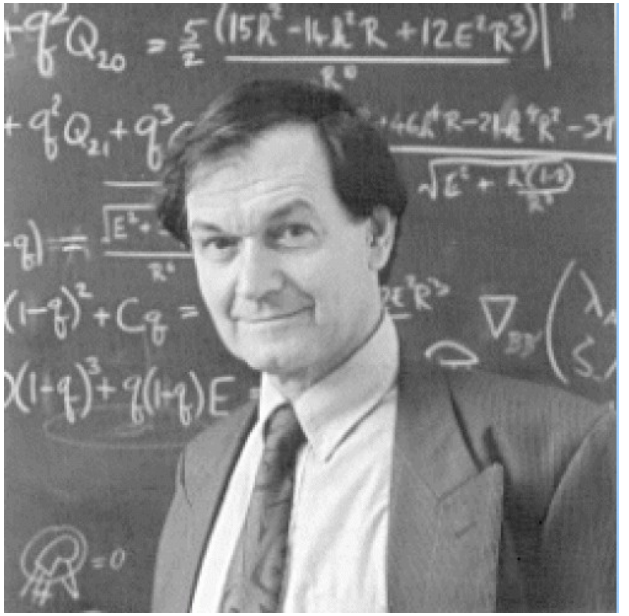
LIGO-Virgo – Gravitational waves

Quelle: LIGO Lab, Caltech

Warum genau Schwarze Löcher?



Stephen Hawking



Roger Penrose

Singularity theorems

Under certain conditions (metric gravity, energy conditions, trapped surfaces) Einstein gravity must breakdown somewhere (Penrose 1965, Hawking 1966).

Either

Conditions of the theorem are never met in our universe
=> **NEW PHYSICS!**

or

Einstein gravity breaks down somewhere
=> **NEW PHYSICS!**

or

Both!
=> **NEW PHYSICS!**

Can the new physics be restricted to very near the singularity?

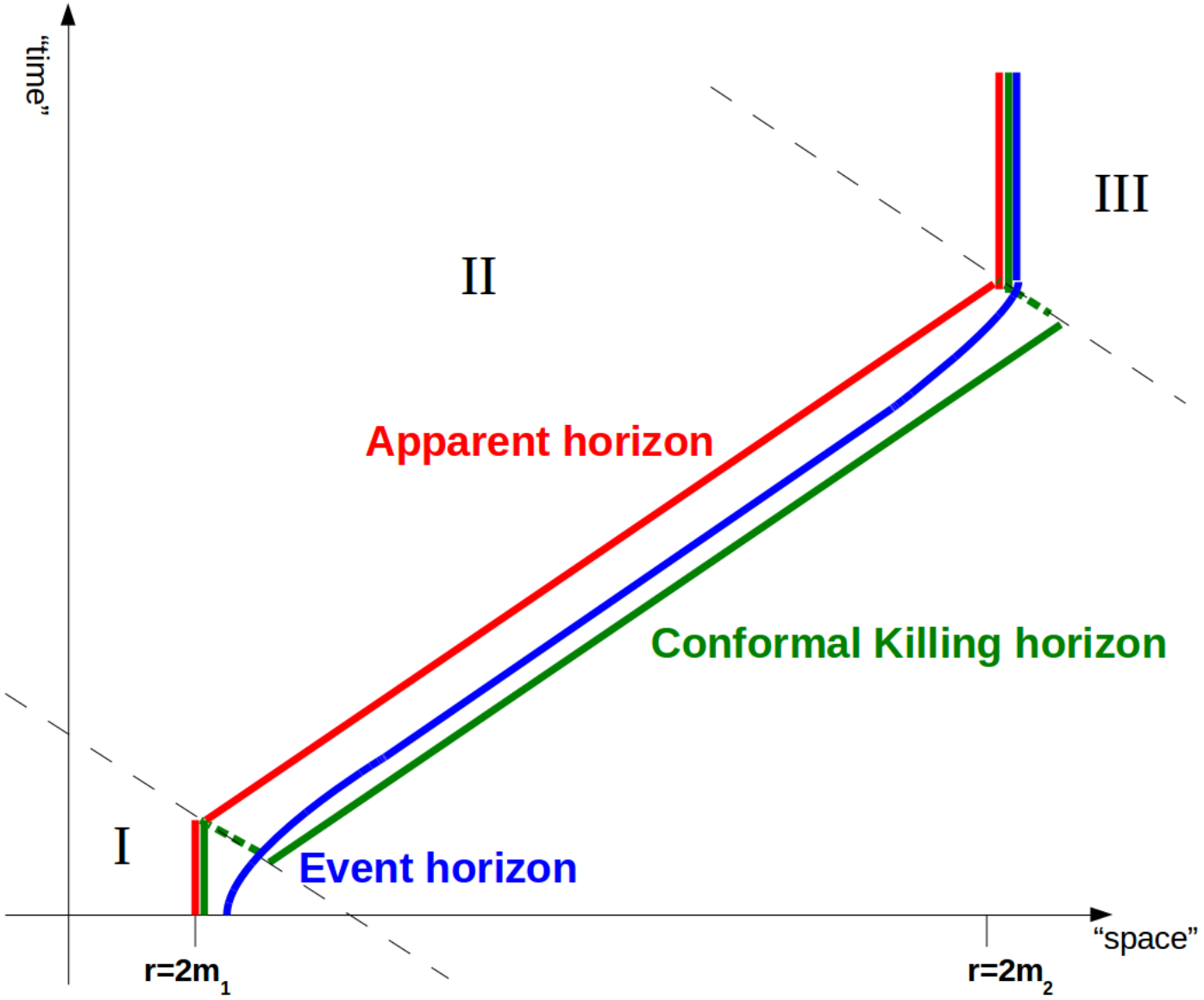
- LIGO-Virgo GWs not sensitive to Planck scale gravity
- But are sensitive to horizon scale gravity
- Standard static quantum vacuum diverges at the horizon in Schwarzschild *(Boulware 1975)*
- Decelerated collapse to Schwarzschild from Boulware leads to large back reaction *(Barcelo et al. 2007)*
- Kerr vacua not well understood
  (no regular stationary state, Kay and Wald 1991)

Black hole information

- Information appears to be lost *(Hawking 1976)*

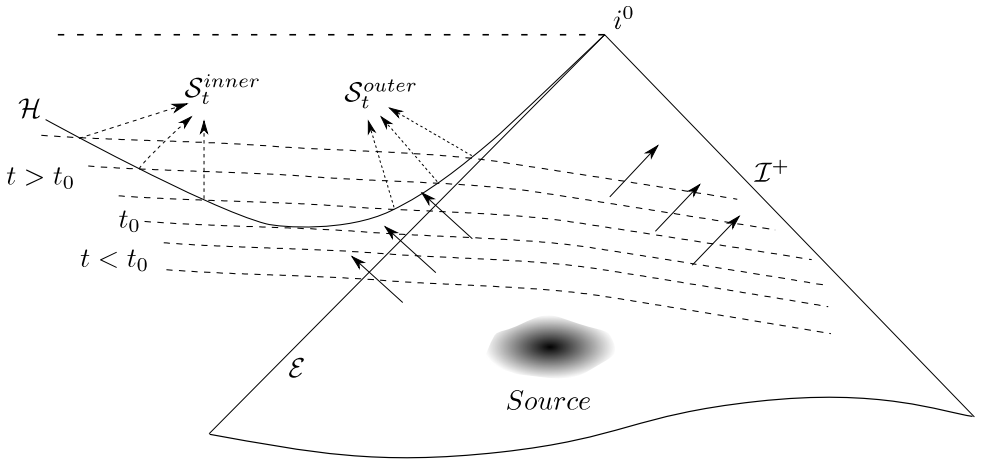
- External state cannot both be a pure state and fully entangled with the interior; firewalls? *(Almheiri, Marolf, Polchinski, Sully 2012)*

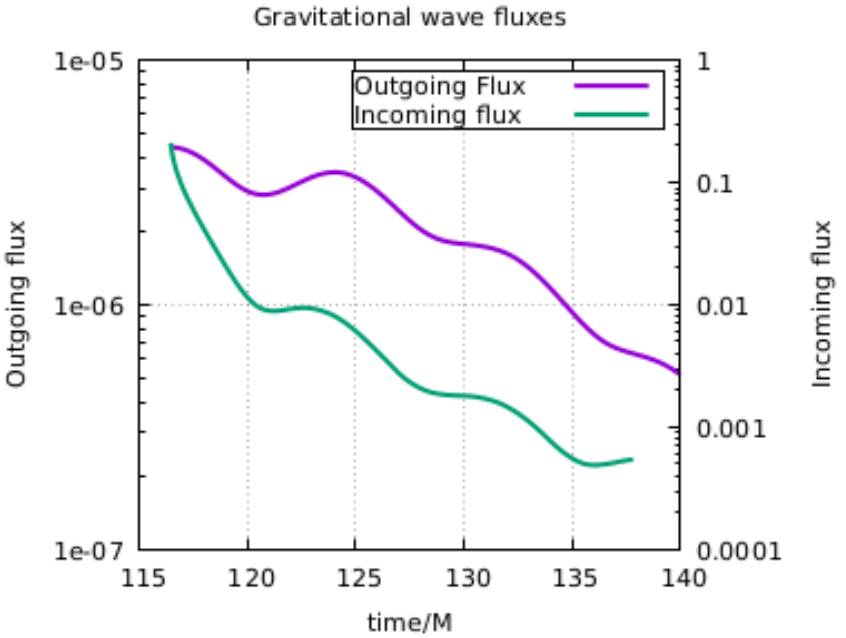
Different black hole horizons



Nielsen, Shoom, CQG 35 (2018) 105008

Black hole horizon fluxes in GR





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

LVC standard tests

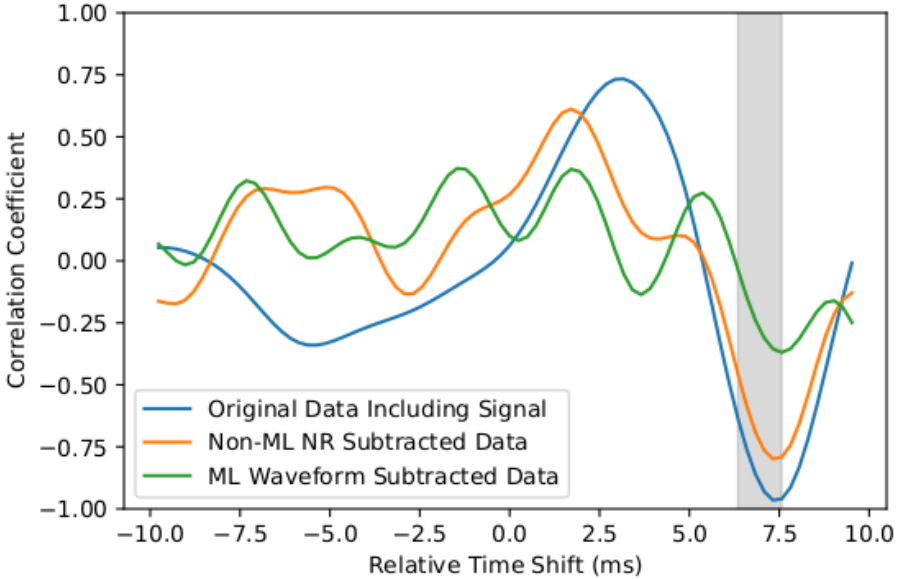
- Parameterised tests
- Inspiral-merger-ringdown tests
- Dispersion tests
- Residual tests

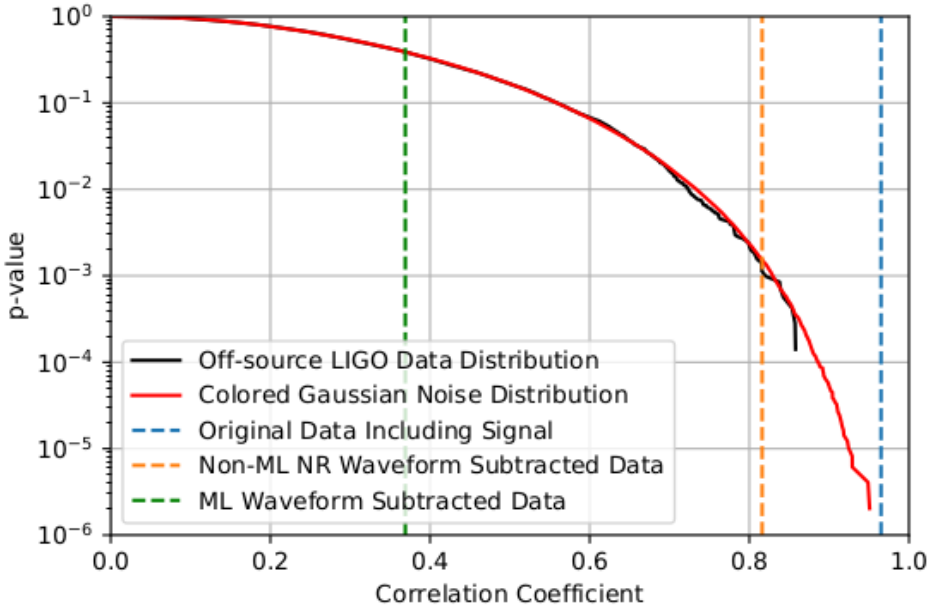
LVC PRL 16 (2016) 221101
LVC PRX 6 (2016) 041015
LVC 1811.00364

GW1501914 residual correlations

Already studied in *LVC PRL 16 (2016) 221101*

(see also *Green and Moffat PLB 784 (2018) 312)*





Nielsen, Nitz, Capano, Brown: arXiv:1811.04071
https://github.com/gwastro/gw150914_investigation

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

Post-Newtonian terms in inspiral

Expand gravitational wave phase as power series in frequency domain:

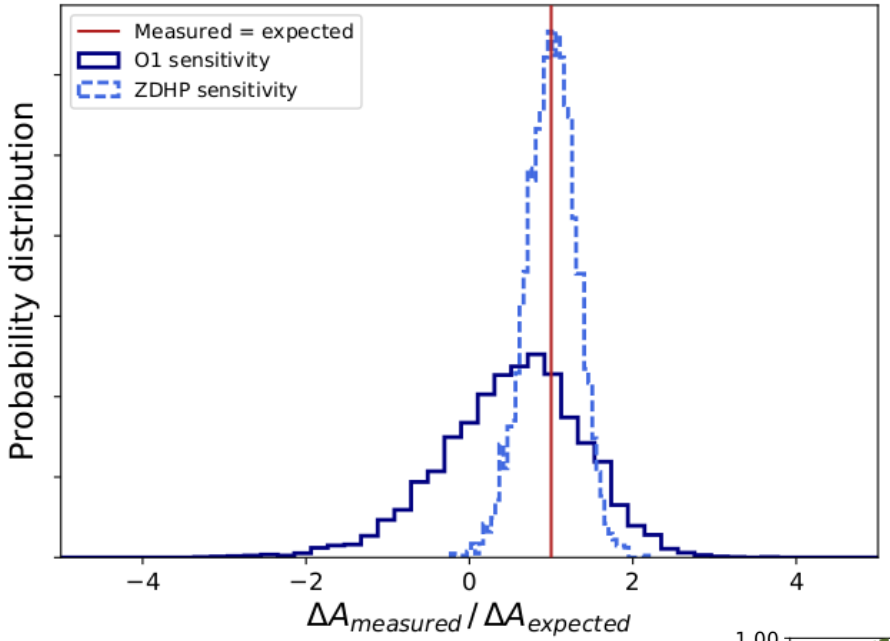
$$\Psi(f) = \sum_n p_n \times (\pi M f_{GW})^{n/3}$$

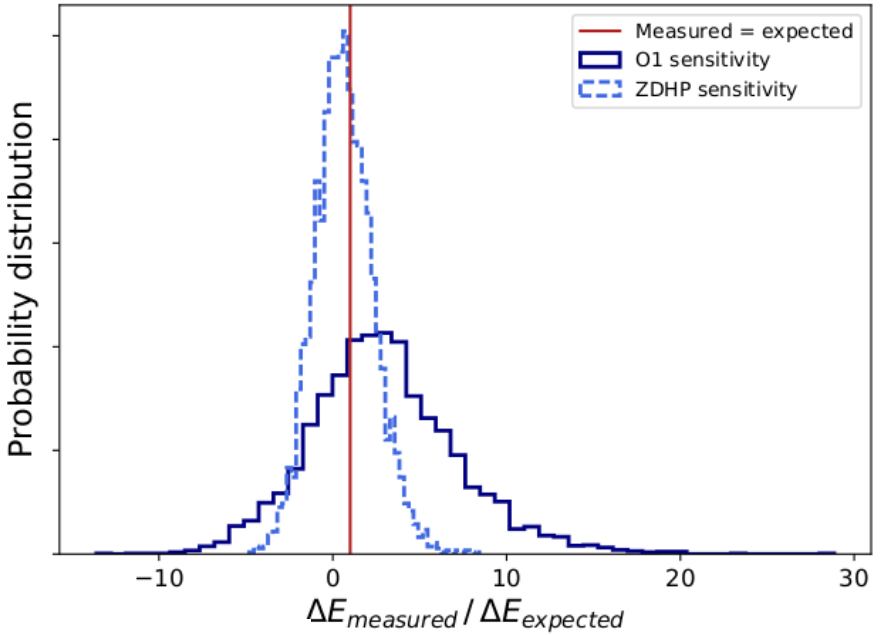
pcGR correction:

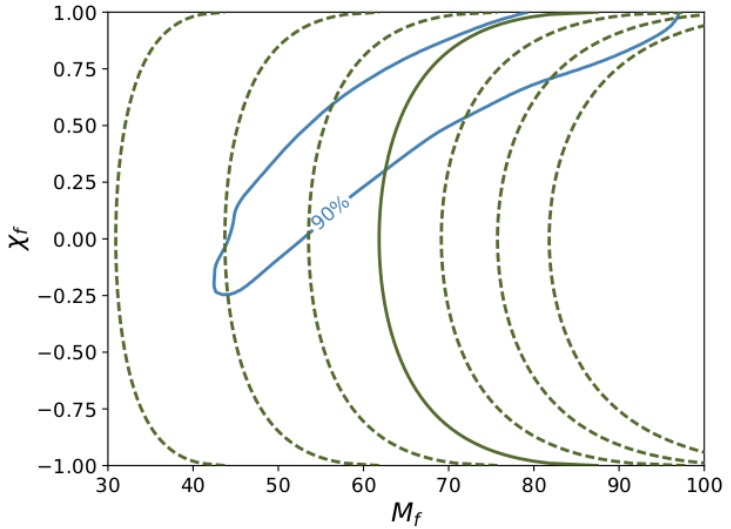
$$nPN\ term = \frac{20\, b\,(n+2)(n+1)(1+q^n)}{3(n-4)(2n-5)(1+q)^n} (\pi M f_{GW})^{2n/3}$$

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

Black hole area theorem



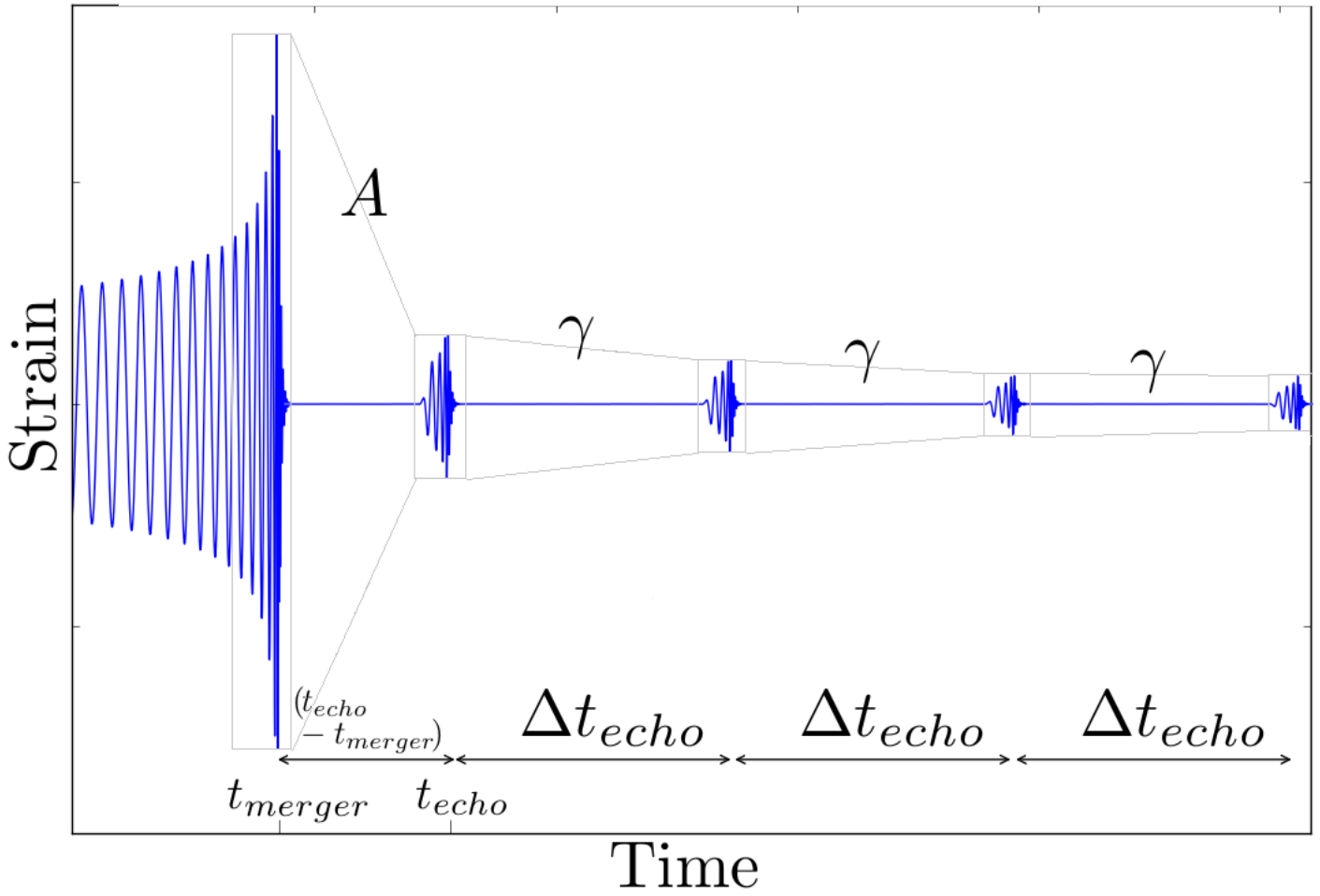


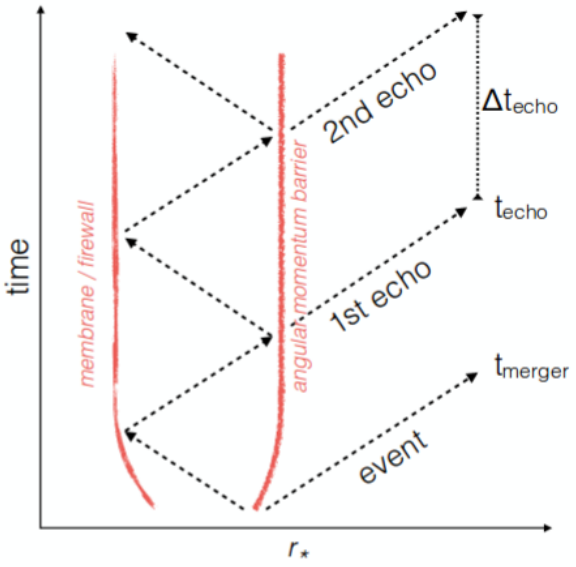


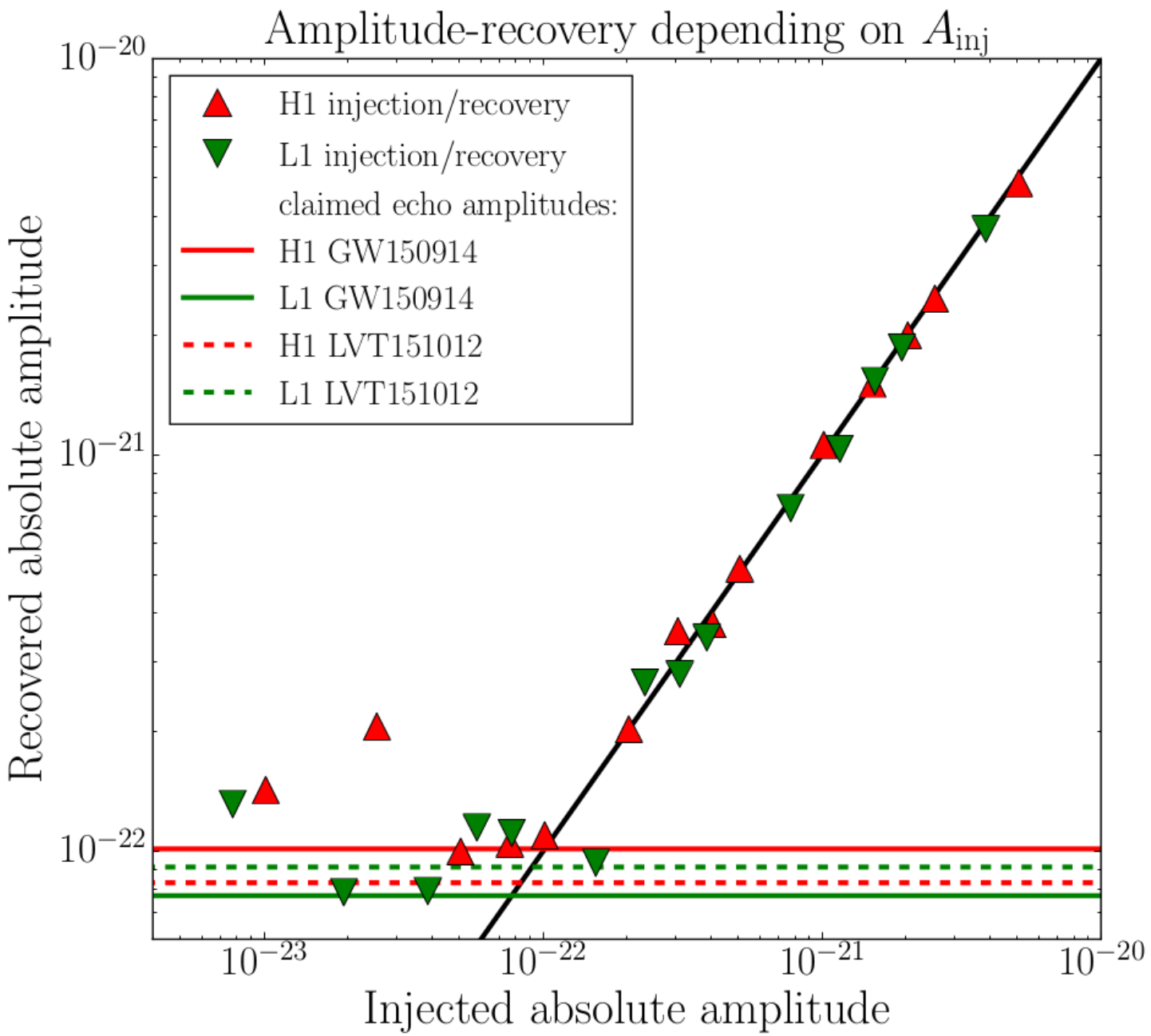
Cabero, Capano, Fischer-Birnholtz, Krishnan, Nielsen, Nitz, Biwer PRD 97 (2018) 124069

Echo-cavity formed by near horizon structure and the light ring

Simplified model of Abedi, Dykaar and Afshordi (ADA) from arXiv: 1612.00266.

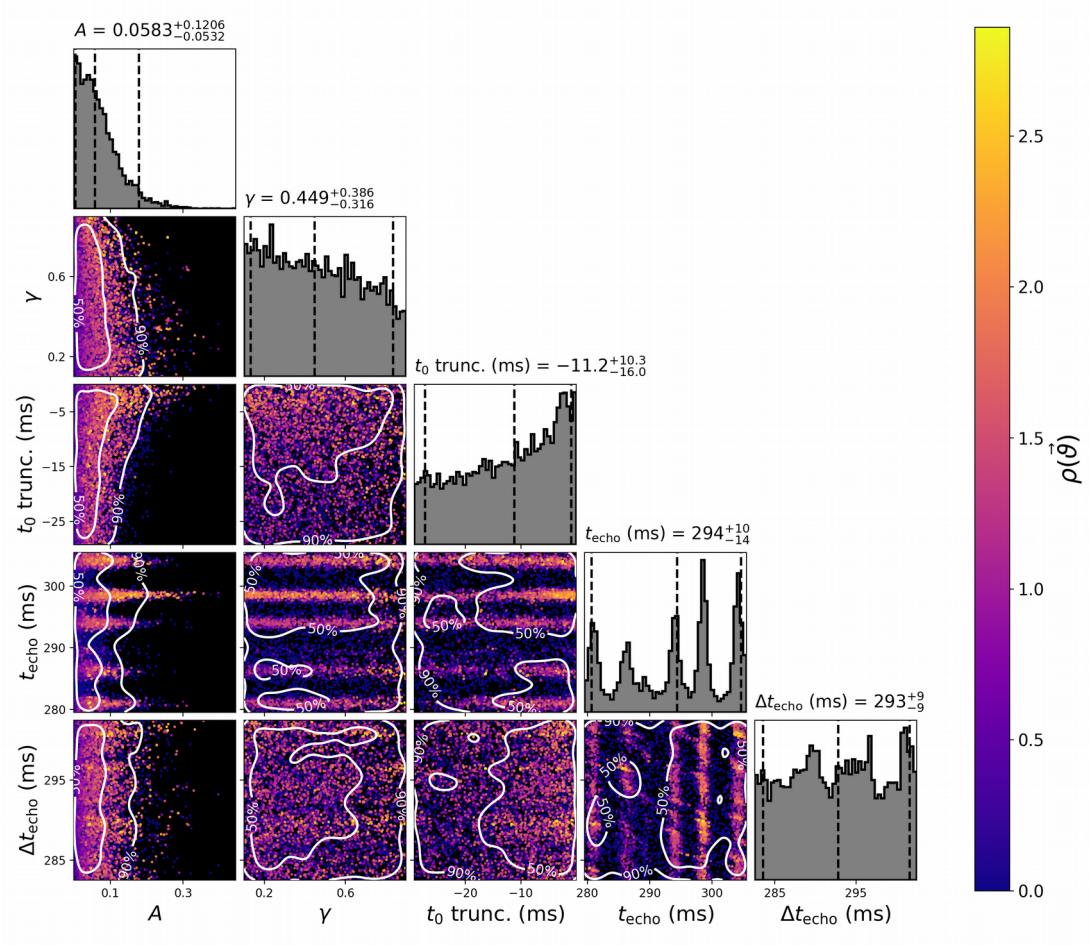






Westerweck, Nielsen, Fischer-Birnholtz, Cabero, Capano, Dent, Krishnan. Physical Review D 97 (2018) 124037

Bayesian pycbc_inference on echoes



	Log Bayes factor
GW150914	-1.8056
LVT151012	+1.2499
GW151226	0.4186

Nielsen, Capano, Birnholtz, Westerweck: arXiv: 1811.04904

Conclusions

- Rich structure of GR effects still waiting to be discovered.
- No evidence (yet) of deviations from GR.
- A focus on dynamical black hole models might help with model selection and paradoxes.

Thank you