Title: A model-independent search for gravitational-wave echoes

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Abstract: Exotic compact objects (e.g. boson stars, dark matter stars, gravastars), and certain quantum modifications to black holes (e.g. firewalls) are speculated to give out ``echoes'' or bursts of radiation appearing at regular time intervals due to a perturbation by any infalling matter or field. In particular, these echoes are also expected to appear soon after their formation. The presence (or absence) of gravitational-wave echoes following observations of coalescences of compact binaries by detectors like Advanced LIGO and Virgo, might be able to directly probe (or constrain) the nature of the remnant compact object. For a large class of these objects, the echoes are expected to appear at time scales that are amenable to a search. However, there can be a substantial variation in the detailed waveform models, and this might make a template-based search inffective. We propose and demonstrate a model-independent search method that relies only on the constancy of the time difference between subsequent echoes.

A ~~model-independent~~ model-agnostic search for gravitational-wave echoes

Archisman Ghosh
Nikhef, Amsterdam

Quantum black holes in the sky?
Perimeter Institute, 2017 November 08

With: Michiel Rollier, Ka Wa Tsang, Anuradha Samajdar, Chris Van Den Broeck, Michalis Agathos, Katerina Chatziioannou, Tyson Littenberg, Miguel Correia, Vitor Cardoso

Echoes: recapitulation of salient features

Horizon-scale corrections $\Rightarrow$ secondary bursts of radiation.

Modulated and distorted train of "echoes".

A large class of exotic compact objects.

$$\Delta t = nM \log(M/l)$$

n=8: wormholes

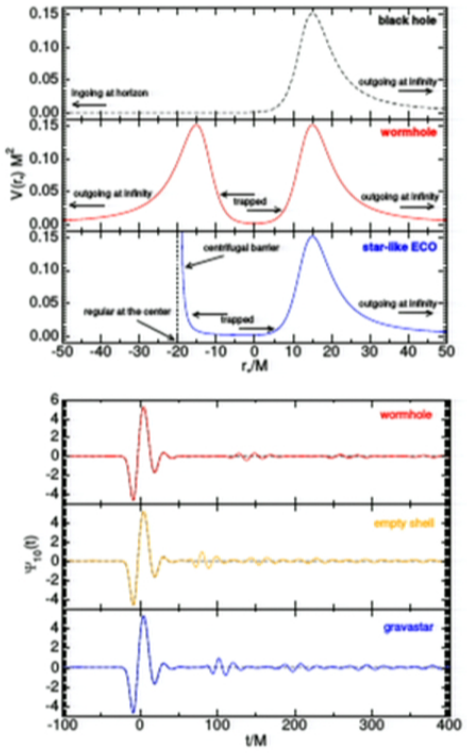
n=4: empty shell

n=6: thin-shell gravastars

Planck-scale corrections can appear relatively soon.

For an event like GW150914, $\Delta t = \mathcal{O}(100\,\mathrm{ms})$, at aLIGO design can hope to see first few echoes.

Cardoso *et al* (2016)



Necessity for model-agnostic search for echoes

- Form of echoes not sufficiently modelled.
- There can be a substantial variation in the waveform parameters:

  damping
  widening
  phase modulation

- One feature expected to be reasonably robust: constancy of time difference between the subsequent echoes.
- One can have echo-like signatures from objects not envisaged in literature.
- Agnostic of detailed models: look for repeated coherent burst of radiations – coherent between the detectors and also between the subsequent echoes.

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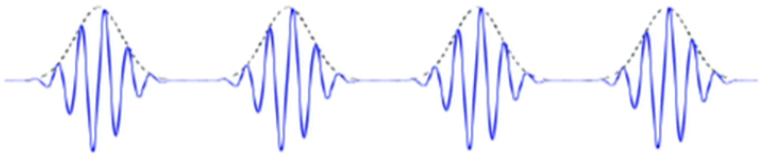
To look for coherence between subsequent echoes

- Use wavelets that are combs of sine-Gaussians to reconstruct the signal

$$\Psi(t; A_n, f_0, \tau, t_n, \phi_n) = \sum_{n=0}^{N_{\text{echoes}}} A e^{-(t-t_n)^2/\tau_n^2} \cos\left(2\pi f_0 (t - t_n) + \phi_n\right)$$

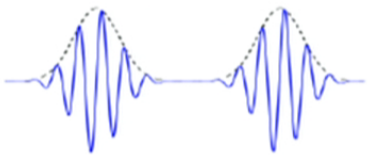
With:

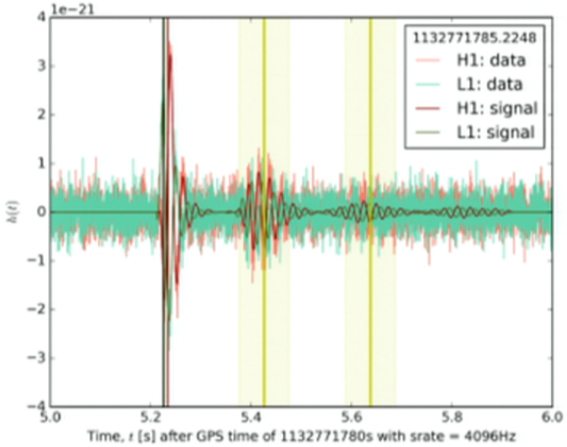
$A_n = \gamma^n A$	damping
$\tau_n = w^n \tau$	widening
$t_n = t_0 + n\Delta t$	time between subsequent echoes
$\phi_n = \phi_0 + 2\pi f_0 n\Delta t + n\Delta\phi$	phase shift subsequent echoes



♣ Start with a double Gaussian:

a comb with only two teeth.

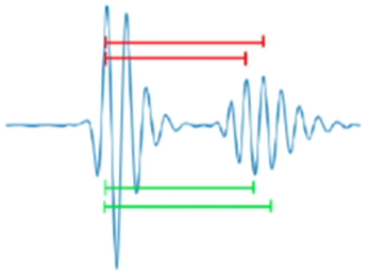




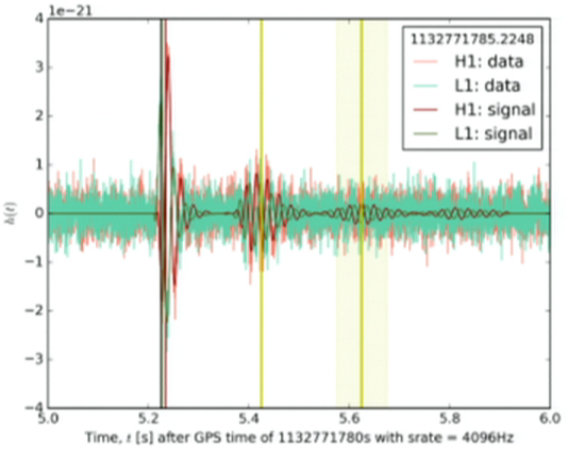
♣ Step over Δt to look for echo:

in-phase or out-of-phase correlation between t and $t + \Delta t$?

DISCLAIMER!



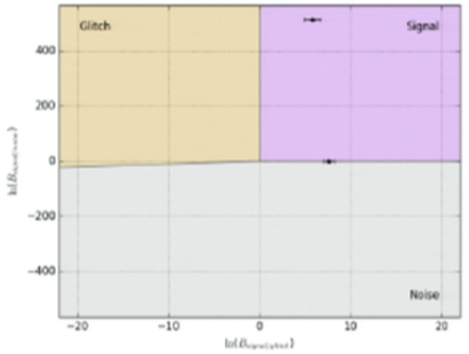
Tentative results



Sample over Δt instead

Relative phases: $\{0, \pi\}$

Very sensitive to relative phase!



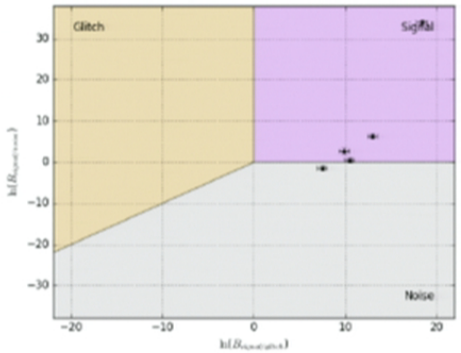
In progress and on our to-do list

- Sample efficiently over all parameters
  - time, phase difference, relative amplitudes.
- A full background still to be calculated.
- The double Gaussian to standard single Gaussian model evidences.

Outlook: search for echoes with current and future detectors

What kinds sensitivities do we need? How loud echoes do we need?

- Can pick-up SNR $\gtrsim 8$
- Combined SNR in echoes $\gtrsim 8$



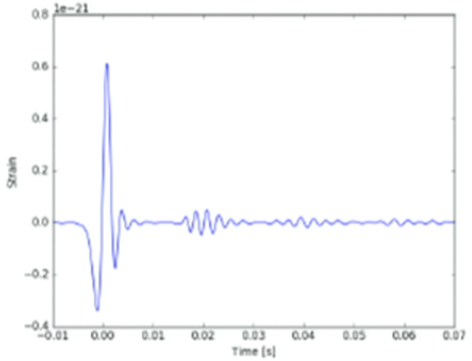
Total SNRs: 100, 71, 50, 35, 25

GW150914 peak strain at Adv-LIGO design

First echo: 9.91

Two echoes: 10.28

Three echoes: 10.37



Questions to theoreticians from the point of view of searches

♣ Are there exotic compact objects that do not leave any detectable signature pre-merger, but only leave their imprint as post-merger echoes?

♣ What features of available models should we trust? What features of models should we be more agnostic about?