Title: From Quadratic Gravity to Observation

Date: Nov 09, 2017 02:20 PM

URL: http://pirsa.org/17110087

Abstract: : Astrophysical black hole candidates might be horizonless ultra-compact objects. Of particular interest is the plausible fundamental connection with quantum gravity. The puzzle is then why we shall expect Planck scale corrections around the horizon of a macroscopic black hole.
Taking asymptotically free quadratic gravity as a possible candidate of UV completion of general relativity, I will show how the would-be horizon can be naturally replaced by a tiny interior as dictated by the dynamics. The new horizonless 2-2-hole, as a quite generic static solution sourced by sufficiently dense matter, may then be the nearly black endpoint of gravitational collapse. In the era of gravitational wave astronomy, echoes in the post-merger phase provide a great opportunity to probe such scenario.
Given the uncertainties associated with the waveform of echoes, I will discuss some model-independent search strategies, where the primary task is to find the time delay between echoes. The search range is then motivated by the Planck scale deviation outside the would-be horizon.

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From Quadratic Gravity to Observation

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Quantum Black Holes in the Sky?

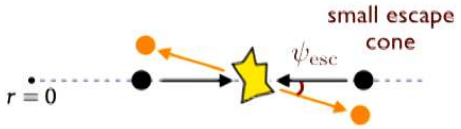
Perimeter Institute, November 9, 2017

collaboration with Bob Holdom, arXiv: 1512.05305, 1605.05006, 1612.04889
collaboration with Randy S. Conklin and Bob Holdom, 1712.xxxxx

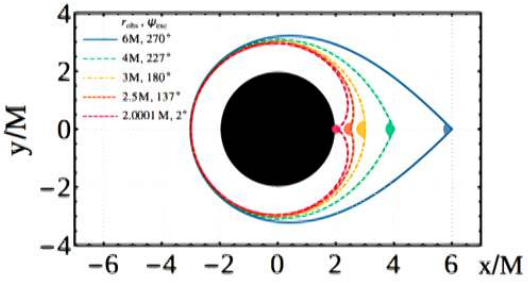
Q: Do astrophysical black holes have event horizons?

A: Maybe not if they resemble BHs closely from the exterior…

Efficient trapping (appear black)

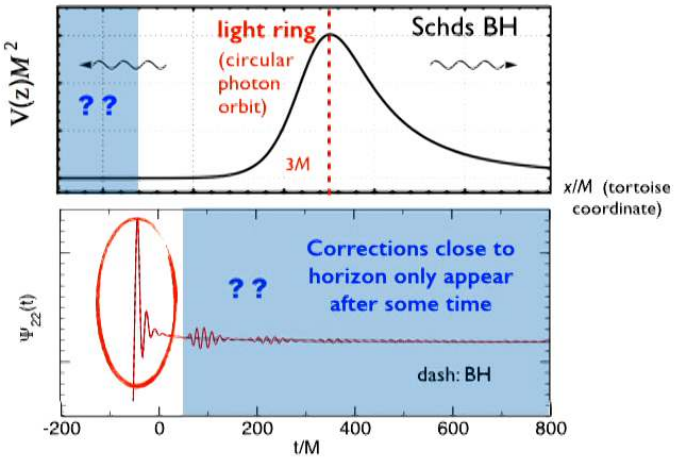


$$\sin\psi_{\rm esc} = 3M\sqrt{3f_0}/r_0.\ f_0 = 1-2M/r_0.$$



Similar ringdown at early time

$$\frac{d^2\psi}{dx^2} + (\omega^2 - V)\psi = 0 \quad M\omega_{\rm RD} \approx 0.37 - i0.089$$



Cardoso and Pani, arXiv:1707.03021 [gr-qc]

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Event horizon: information loss paradox?

- Need drastic modification close to the horizon
- Maybe the event horizon is *never formed*??
- Fundamental connection with quantum gravity??

Why quantum gravity effects around the horizon of macroscopic black holes??

- Puzzling in view of effective theory: the big hierarchy between the cutoff ($M_{\rm Pl}$) and the curvature scale at horizon ($M_{\rm Pl}^2/M$)??

$$S_{\rm GR} = \int d^4x\sqrt{-g}\left[M_{\rm Pl}^2\left(-\Lambda+\frac{1}{2}R\right)+c_1R^2+c_2R_{\mu\nu}R^{\mu\nu}+...\right]$$

- Can *ultracompact horizonless objects* be produced in a ***natural*** way (rather than put in by hand)?

Outline

- A novel horizonless 2-2-hole
  - *Asymptotically free quadratic gravity: a new perspective*
  - *Ultracompact horizonless solutions sourced by dense matter*
- Search strategies for echoes
  - *Search for generic features related to the time delay*
  - *Reduce noise with window functions*
  - *Interesting hint from the LIGO data!*
- Summary and outlook

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Asymptotically free extension of GR

GR is non-renormalizable: graviton loops create more powers of derivatives

$$S_{\rm GR} = \int d^4x\sqrt{-g}\left[M_{\rm Pl}^2\left(-\Lambda+\frac{1}{2}R\right)+c_1R^2+c_2R_{\mu\nu}R^{\mu\nu}+...\right] \qquad g_{\mu\nu}=\eta_{\mu\nu}+h_{\mu\nu}$$

($1/M_{\rm Pl}^2k^2$ propagator)

Quantum Quadratic Gravity: an old candidate of quantum gravity, generalize GR with all quadratic curvature terms

$$S_{\rm QQG} = \int d^4x\,\sqrt{-g}\left(\frac{1}{2}\mathcal{M}^2R-\frac{1}{2f_2^2}C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta}+\frac{1}{3f_0^2}R^2\right)$$

- Perturbatively renormalizable Stelle, PRD 16, 953 (1977)

  Power counting changes behaviors: $1/k^4$ propagator softens UV divergence

- Asymptotically free Fradkin, Tseytlin, NPB 201, 469 (1982); Avramidi, Barvinsky, PLB 159, 269 (1985)

$$\frac{df_2^2}{dt}=-\left(\frac{133}{10}+a_m\right)f_2^4, \quad \frac{1}{f_2^2}\frac{dw^2}{dt}=-\left[\frac{5}{12}+w\left(5+\frac{133}{10}+a_m\right)+\frac{10}{3}w^2\right] \qquad w=f_2^2/f_0^2, \quad a_m>0$$

Wait … "the ghost problem" ?

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Standard picture: running couplings remain weak at the mass scale $\sim |f_i\mathcal{M}|$, the perturbative spectrum has a *massive, spin-2 ghost* (different from the Faddeev-Popov ghost)

$$\frac{-i}{k^2(k^2-M_2^2)} = \frac{1}{M_2^2}\left(\frac{i}{k^2} - \frac{i}{k^2-M_2^2}\right) \qquad M_2^2 = \tfrac{1}{2}f_2^2\mathcal{M}^2$$

Negative energy *(vacuum instability)* or negative norm *(unitarity problem)*??

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Negative energy *(vacuum instability)* or negative norm *(unitarity problem)*??

May not be the end of the story!

If $\mathcal{M}$ is small and f_i^2 gets strong at some higher scale $\Lambda_{\rm QQG} > \mathcal{M}$, perturbative poles could be drastically modified by strong interactions. Taking into account non-perturbative effects, **the theory in the strong phase could be well-defined!**

- *Holdom, Ren, PRD 93, no. 12, 124030 (2016); IJMPD 25, no. 12, 1643004 (2016)* *(Gravity Research Foundation 2016 essay competition, fourth prize)*
- Donoghue, arXiv:1609.03523, 1609.03524, 1704.01533

A QCD analogy for quadratic gravity

Holdom, Ren, PRD 93, no. 12, 124030 (2016); IJMPD 25, no. 12, 1643004 (2016)

	QCD	QQG ($\mathcal{M} \lesssim \Lambda_{\rm QQG}$)
UV behavior	perturbatively renormalizable, asymptotically free	
Strong scale	gauge coupling strong at $\Lambda_{\rm QCD}$	gravitational couplings strong at $\Lambda_{\rm QQG}$
Nonperturbative effects	the perturbative gluon removed from the physical spectrum and a mass gap developed as controlled by $\Lambda_{\rm QCD}$	$\mathcal{M} \neq 0$: all perturbative poles removed from the physical spectrum and a mass gap now controlled by $\mathcal{M}$
		$\mathcal{M} = 0$: the massless graviton pole emerges as the only light state in the physical spectrum
IR effective description	color singlet states described by Chiral Lagrangian	massless graviton described by GR with the derivative expansion, $m_{\rm Pl} \sim \Lambda_{\rm QQG}$

GR emerges as the low energy effective theory!

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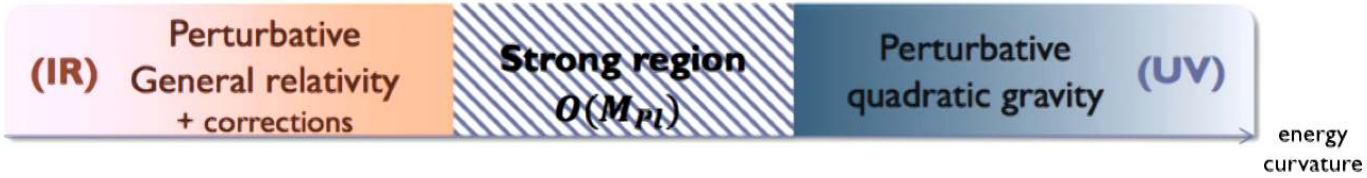
A new picture for gravity



Large corrections to black holes?

Find solutions in *Classical Quadratic Gravity*, a theory with the same limits for small and large curvatures

$$S_{\rm CQG} = \frac{1}{16\pi}\int d^4x\,\sqrt{-g}\left(m_{\rm Pl}^2 R - \alpha C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \beta R^2\right) \qquad \alpha,\beta \sim \mathcal{O}(1)$$

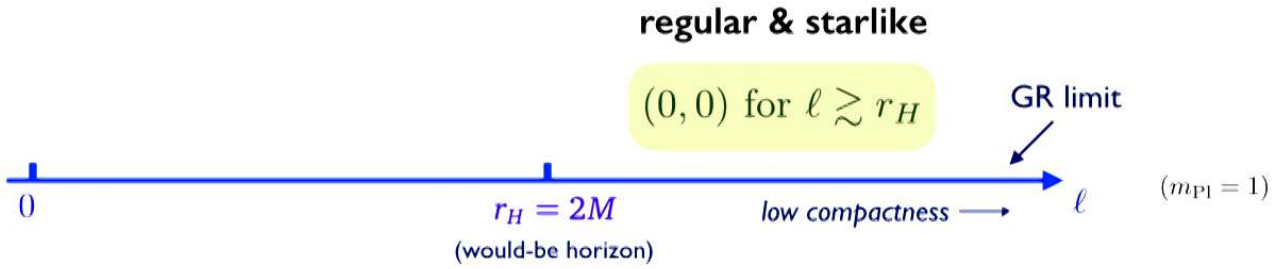
Previous works treated this as a truncation and had problems with higher order terms when describing solutions with arbitrarily large curvatures.

Our new perspective allows exploration of solutions containing both sub-Planckian and super-Planckian curvature regions.

Static spherically symmetric solutions

$$ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$

No Birkhoff's theorem. Find asymptotically-flat numerical solutions sourced by matter distributions with increasing compactness, e.g. a spherical thin-shell (M, ℓ) *Holdom, Ren, PRD 95, no. 8, 084034 (2017)*



Series expansion around the origin

(s,t)	behavior at $r=0$	GR	generic CQG
$(0,0)$	non-singular	none	a_2, b_2

$$A(r) = a_s r^s + a_{s+1} r^{s+1} + \ldots$$
$$B(r) = b_t (r^t + b_{t+1} r^{t+1} + \ldots).$$

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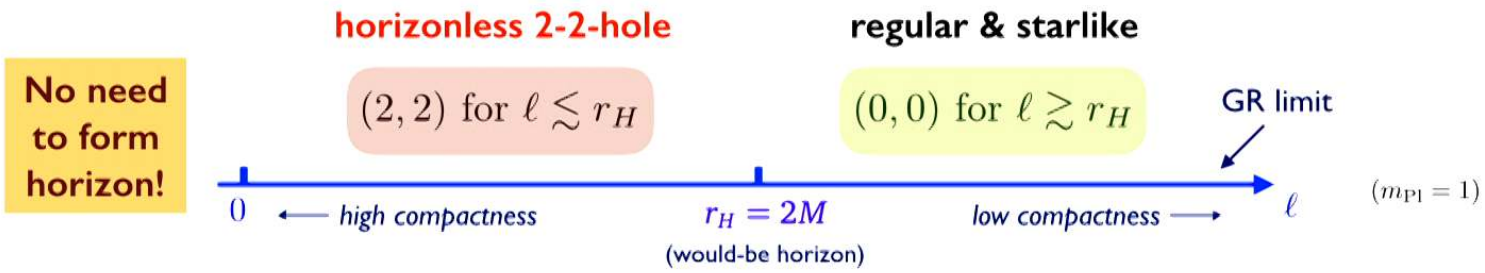


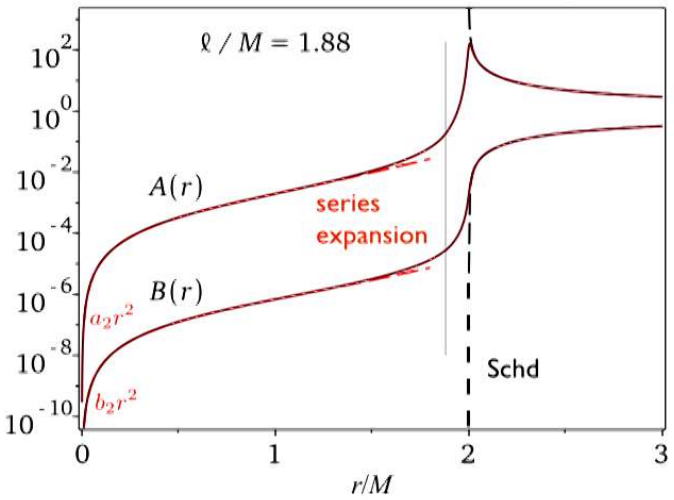
Series expansion around the origin

A brand new family, the *most generic solutions*

(s,t)	behavior at $r=0$	GR	generic CQG
$(0,0)$	non-singular	none	a_2, b_2
$(2,2)$	vanishing metric	NA	a_2, a_5, b_3, b_4, b_5

$$A(r) = a_s r^s + a_{s+1} r^{s+1} + \ldots$$
$$B(r) = b_t (r^t + b_{t+1} r^{t+1} + \ldots).$$

= Super-Planckian curvature interior + transition region + Sub-Planckian curvature exterior



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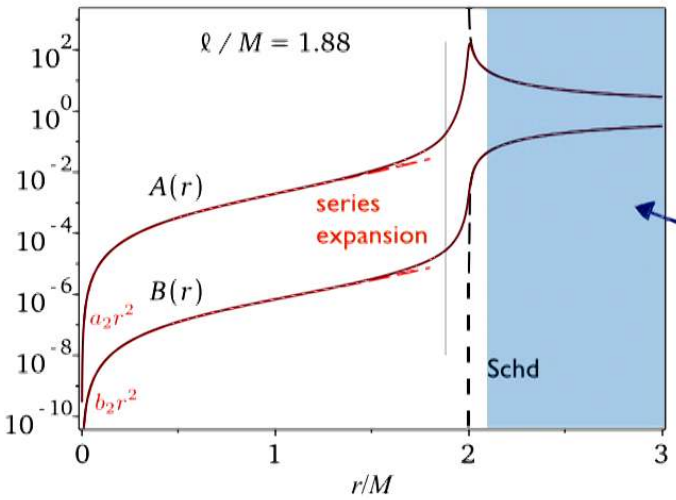


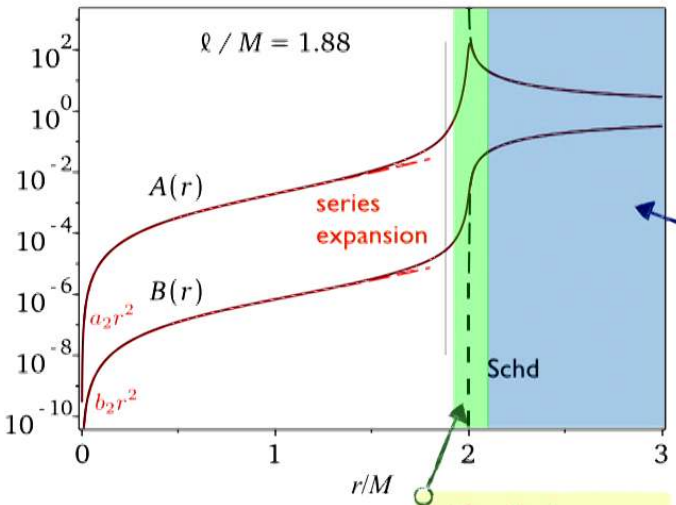
Schd scaling

$$A_M(r) = A_{\varrho M}(r\varrho)$$

$$B_M(r) = B_{\varrho M}(r\varrho)$$

(exponentially small corrections, curvatures highly suppressed for large objects)

= Super-Planckian curvature interior + transition region + Sub-Planckian curvature exterior



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Deviation at Planck distance

(natural candidates for *ultracompact horizonless objects*)

8

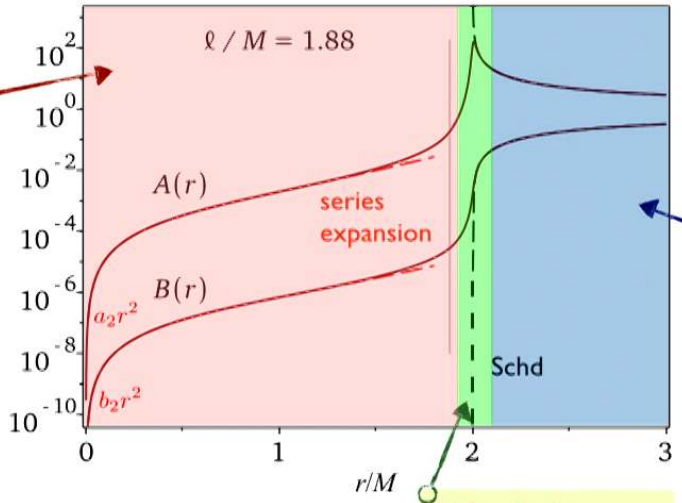
= Super-Planckian curvature interior + transition region + Sub-Planckian curvature exterior

Novel scaling

$A_M(r) = \varrho^2 A_{\varrho M}(r\varrho)$

$B_M(r) = \varrho^2 B_{\varrho M}(r\varrho)$

- Small *B(r)*: very large gravitational redshift
- Small *A(r)*: shrinking radial size (Planck proper length)



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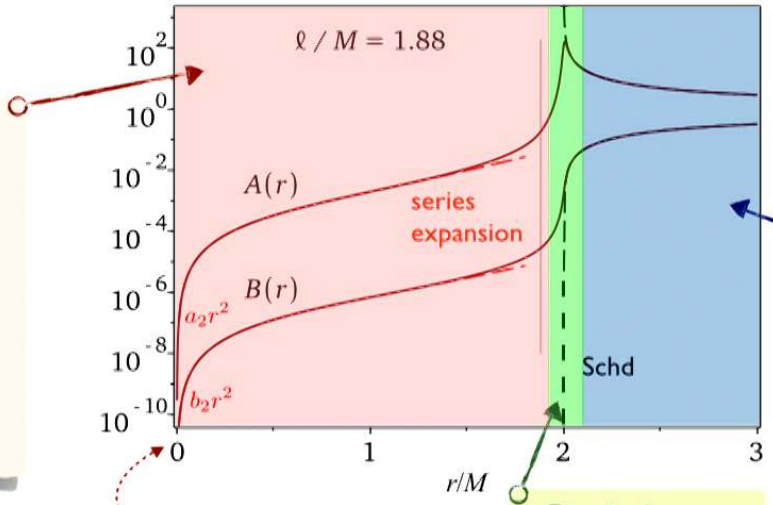

timelike curvature singularity

$(R_{\mu\nu\rho\sigma})^2 \propto 1/r^8, \;\; (C_{\mu\nu\rho\sigma})^2 \propto 1/r^4$

Geodesic-incompleteness?! *Regular* as probed by finite energy wave-packets (*reflecting Dirichlet boundary condition*)

Deviation at Planck distance

(natural candidates for *ultracompact horizonless objects*)

Schd scaling

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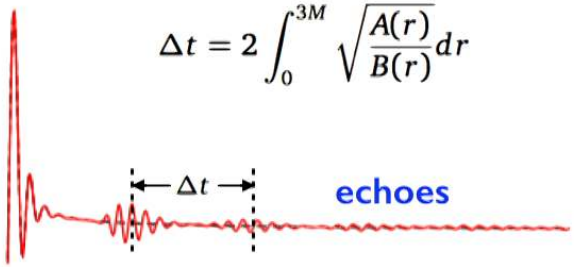
(exponentially small corrections, curvatures highly suppressed for large objects)

Post-merger echoes for 2-2-holes

light ring modes

$$\Delta t = 2\int_0^{3M}\sqrt{\frac{A(r)}{B(r)}}dr$$



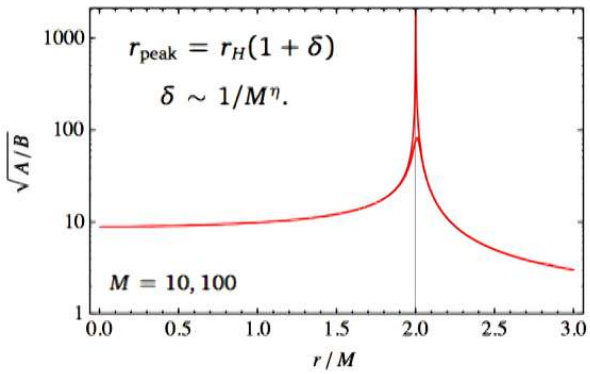
A new time scale for quantum gravity:

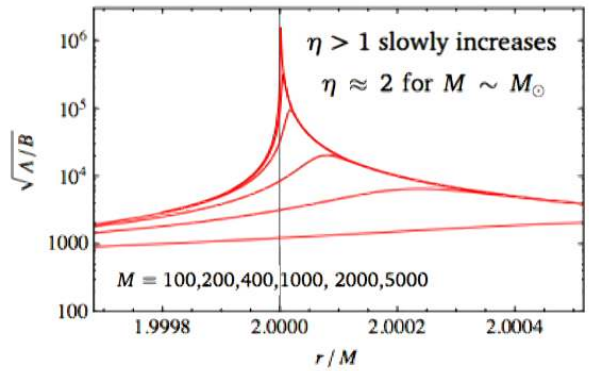
contribution mainly from exterior, with only $\log(M/m_{Pl})$ dependence on the mass hierarchy

$$700 + 7\ln\frac{M}{30M_\odot} \lesssim \frac{\Delta t}{M} \lesssim 860 + 9\ln\frac{M}{30M_\odot}$$

For $M \sim 30\,M_\odot$ Δt is in the 100-125 ms range.

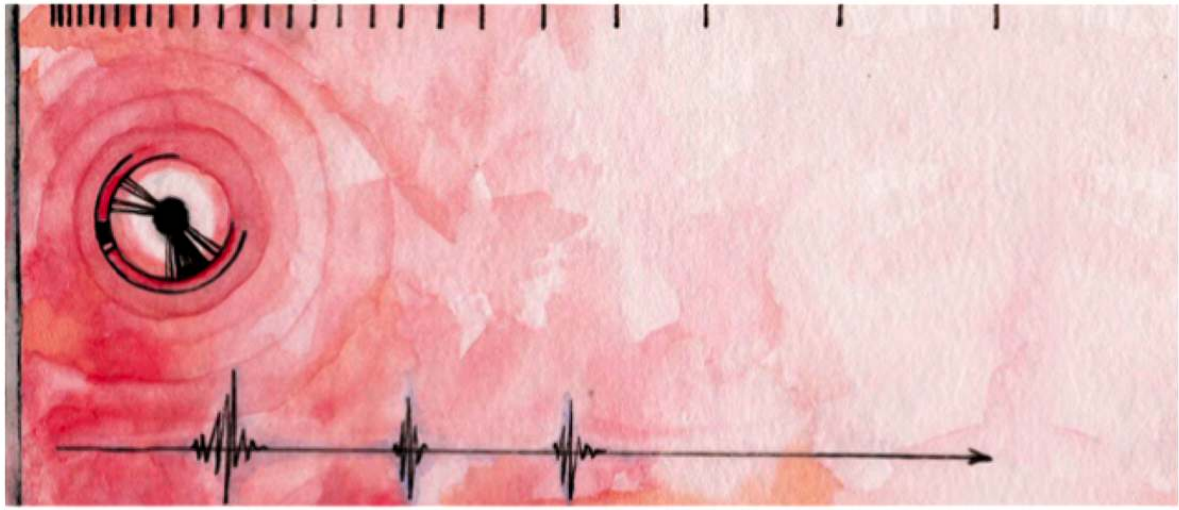
longer than the damping time of BH dominant ringdown $O(1ms)$ and shorter than the duration of strain data $O(10s)$.





Search strategies for echoes

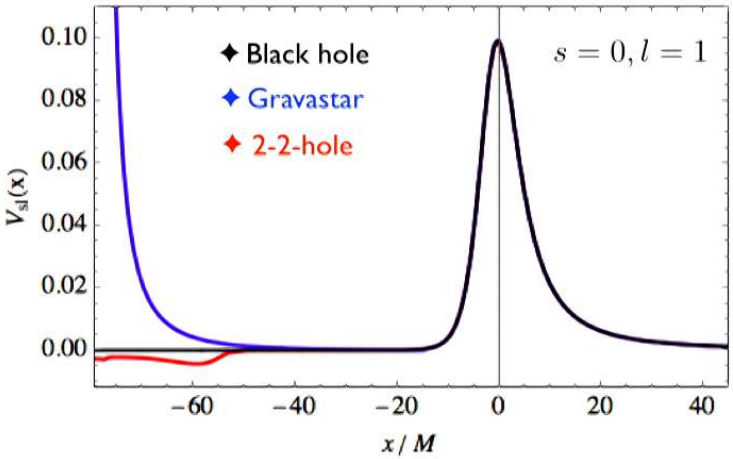
Conklin, Holdom, Ren, arXiv: 1712.xxxxx



Potential in wave equations

$$\left(\partial_x^2 - \partial_t^2 - V_{ls}(x)\right)\Psi_{ls}(x,t) = 0\,, \quad \frac{dx}{dr} = \sqrt{\frac{A(r)}{B(r)}}$$

$$V_{ls}(r) = B(r)\frac{l(l+1)}{r^2} + \frac{1-s^2}{2r}\frac{B(r)}{A(r)}\left(\frac{B'(r)}{B(r)} - \frac{A'(r)}{A(r)}\right)$$



- Ultracompact stars: potential blows up at the origin
- 2-2-holes: interior potential deviates from BH by a small step (dominated by the *l*-independent term)

Ultracompact objects could have quite different potential shape (interior) as well as the boundary conditions. Need to find *common features*…

Transfer function in frequency space

Green function: $\frac{d^2G_\omega(x,x')}{dx^2} + (\omega^2 - V(x))G_\omega(x,x') = \delta(x-x').$ $G_\omega(x,x') = \frac{\psi_{\rm left}(\min(x,x'))\psi_{\rm right}(\max(x,x'))}{W(\psi_{\rm left},\psi_{\rm right})}.$

Transfer function: $\mathcal{K}(\omega) = 1/W(\omega)$, $W(\omega) = \psi_{\rm left}\psi'_{\rm right} - \psi'_{\rm left}\psi_{\rm right}$ *(intrinsic feature of ultracompact objects)*

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- Truncated black holes (with a wall at x_0)

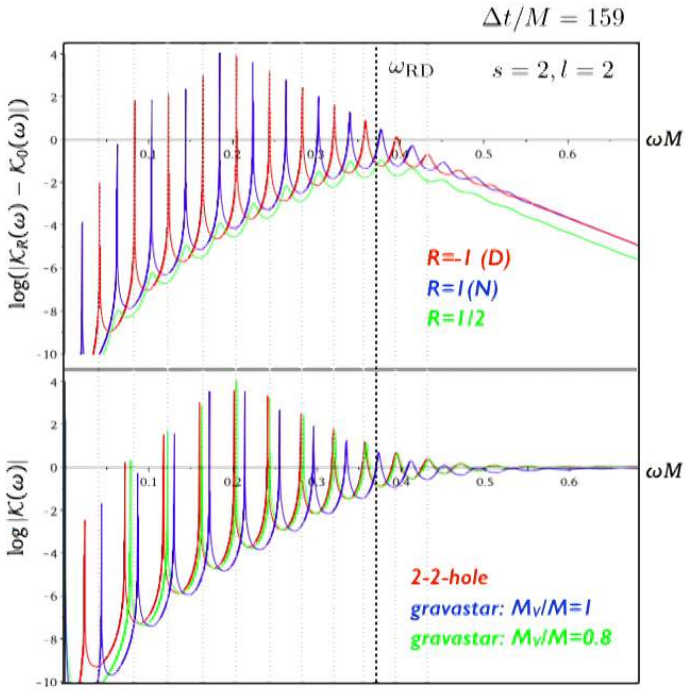
$$\psi_{\rm left}\to\begin{cases}\frac{1}{2i\omega}e^{-i\omega_V x_0}\left(e^{-i\omega_V(x-x_0)}+R\,e^{i\omega_V(x-x_0)}\right), & x=x_0\\ A_{\rm out}(\omega)e^{i\omega x}+A_{\rm in}(\omega)e^{-i\omega x}, & x\to\infty\end{cases}$$

$$\psi_{\rm right}\ \to\ e^{i\omega x},\qquad x\to\infty,\qquad \omega_V=\sqrt{\omega^2-V(x_0)}$$

$$\mathcal{K}(\omega)=\frac{1}{W_{\rm BH}(\omega)}\frac{2i\omega}{(1-R_{\rm BH}Re^{-2i\omega x_0})}=\frac{T_{\rm BH}}{1-R_{\rm BH}Re^{-2i\omega x_0}}$$

Mark, Zimmerman, Du, Chen, PRD 96, no. 8, 084002 (2017)

- Generalization to gravastar and 2-2-hole: low frequency modes more affected



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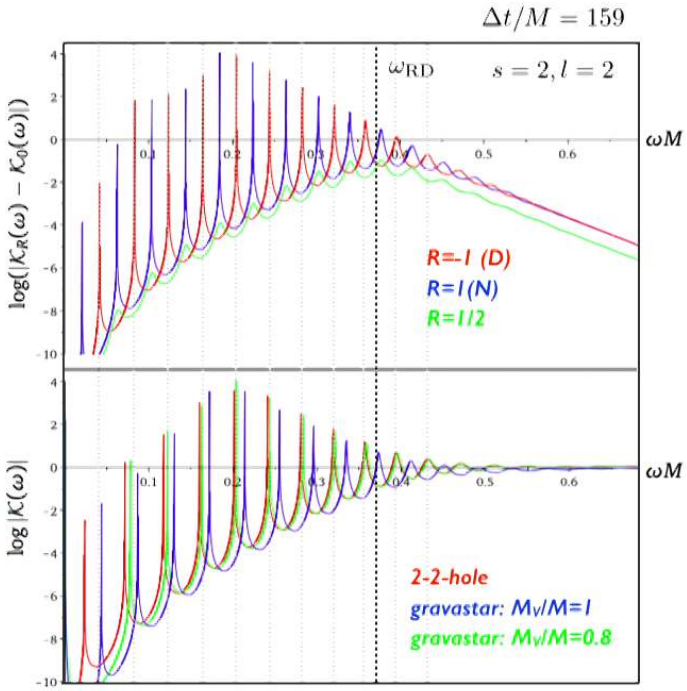
- Generalization to gravastar and 2-2-hole: low frequency modes more affected

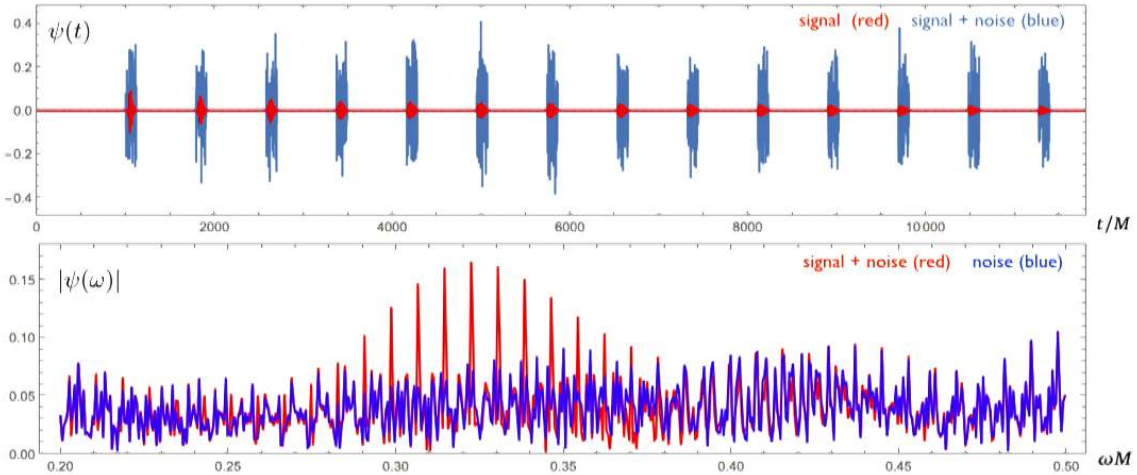
- **Common features**: evenly spaced resonances ($\Delta\omega\approx 2\pi/\Delta t$), gradually increasing width, peaked below ringdown. Search for **the resonance structure in the intermediate frequency range close to ringdown** (help to reduce the initial condition dependence).



Reduce noise with window functions

Time window

- A few echoes are enough
- Parameters: time delay Δt, width t_w, offset t_0, number of echoes N_E
- Signal largely enhanced in intermediate frequency range (close to BH ringdown)



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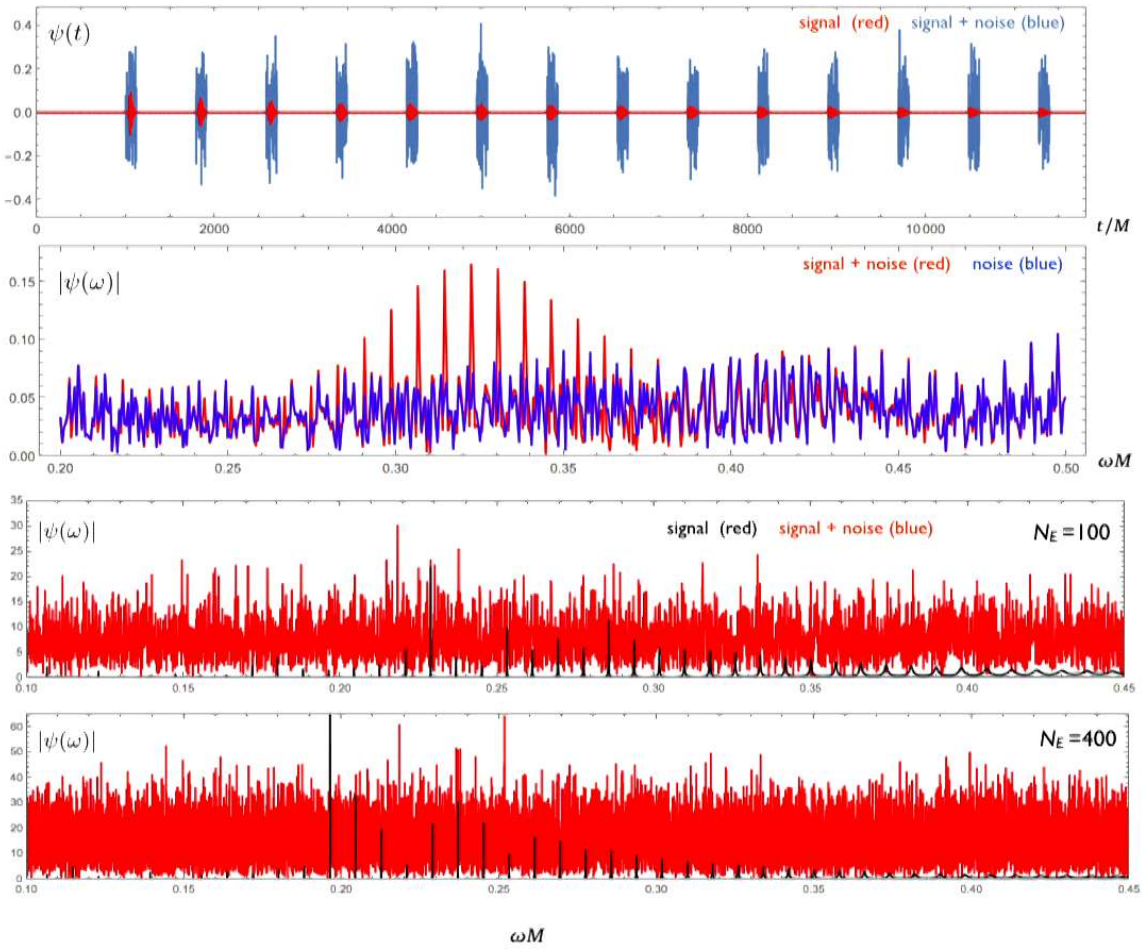
Frequency window

- Need high frequency resolution, i.e. large N_E (number of points between resonances)
- Parameters: spacing $\Delta\omega$, width ω_w, offset ω_0, bandpass $\omega_{\min/\max}$



Using correlation to find the best Δt

- Implement windows and find the amplitudes for windowed data
- Optimize *correlation of multiple data sets* with respect to shift of window
- Find preferred time delay from the correlation by varying other parameters (window widths, echoes number, frequency bandpass, …)

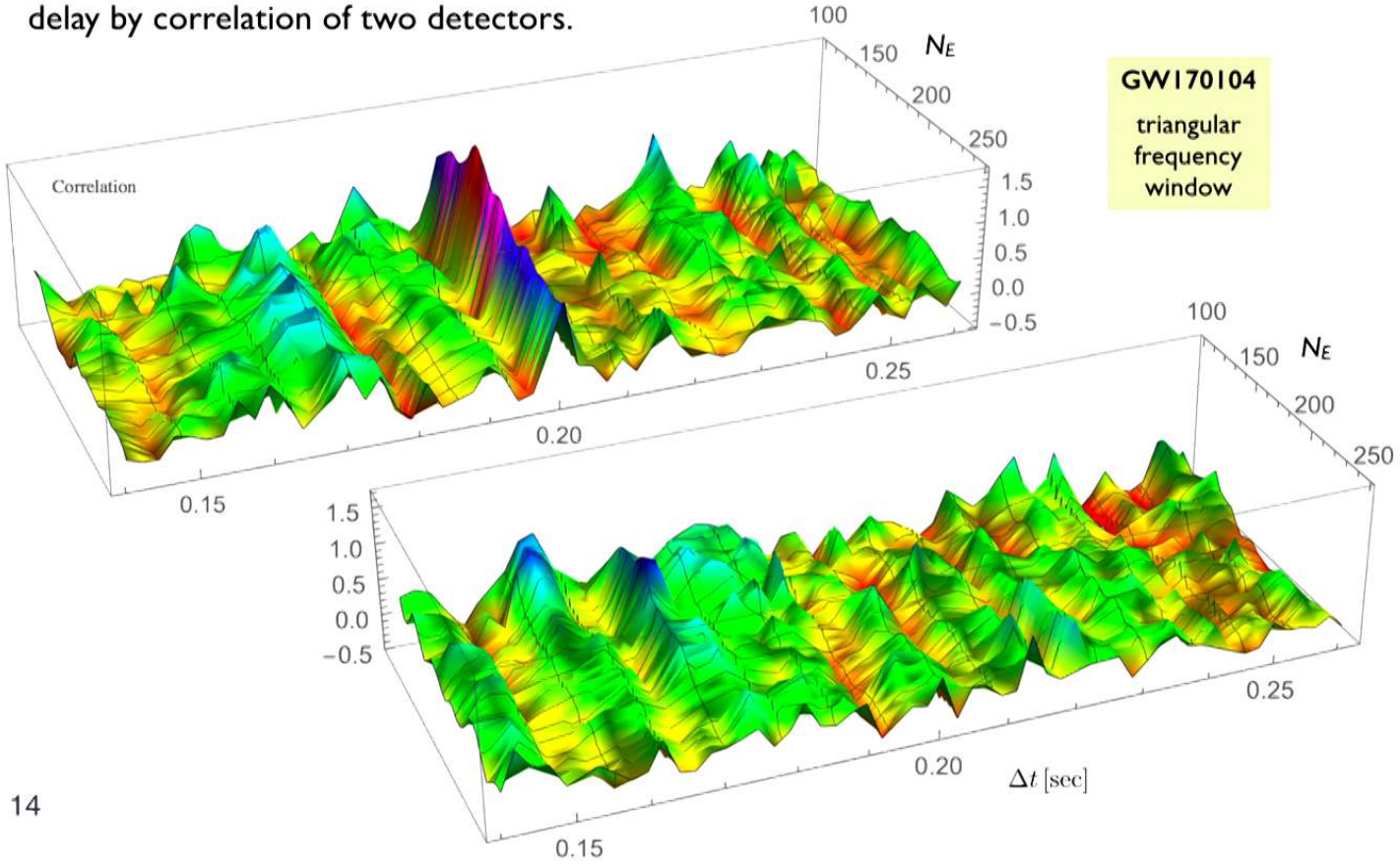
Three methods

(tested by toy models with Gaussian noise)

Optimal time window	*Triangular frequency window*	*Square time + frequency window*
• Optimal width t_w, with Hann window. Correlation with offset t_0.	• Narrow width ~ $0.1\Delta\omega$. Mean of nonzero windowed data.	• Scan over different t_w, ω_w. Total sum of windowed data.
• Autocorrelation, use late peaks to avoid window artifacts	• Correlation with offset ω_0	• Assume expected t_0. Correlation with offset ω_0
• Prefer N_E~15-40	• Prefer N_E~100-250	• N_E~10-20 works (may apply to a wider range of N_E)

Interesting hints from the LIGO data!

Apply the three methods to the four LIGO BBH events. Whitened data after merger for the signal search, data before merger for comparison. Search for the best time delay by correlation of two detectors.

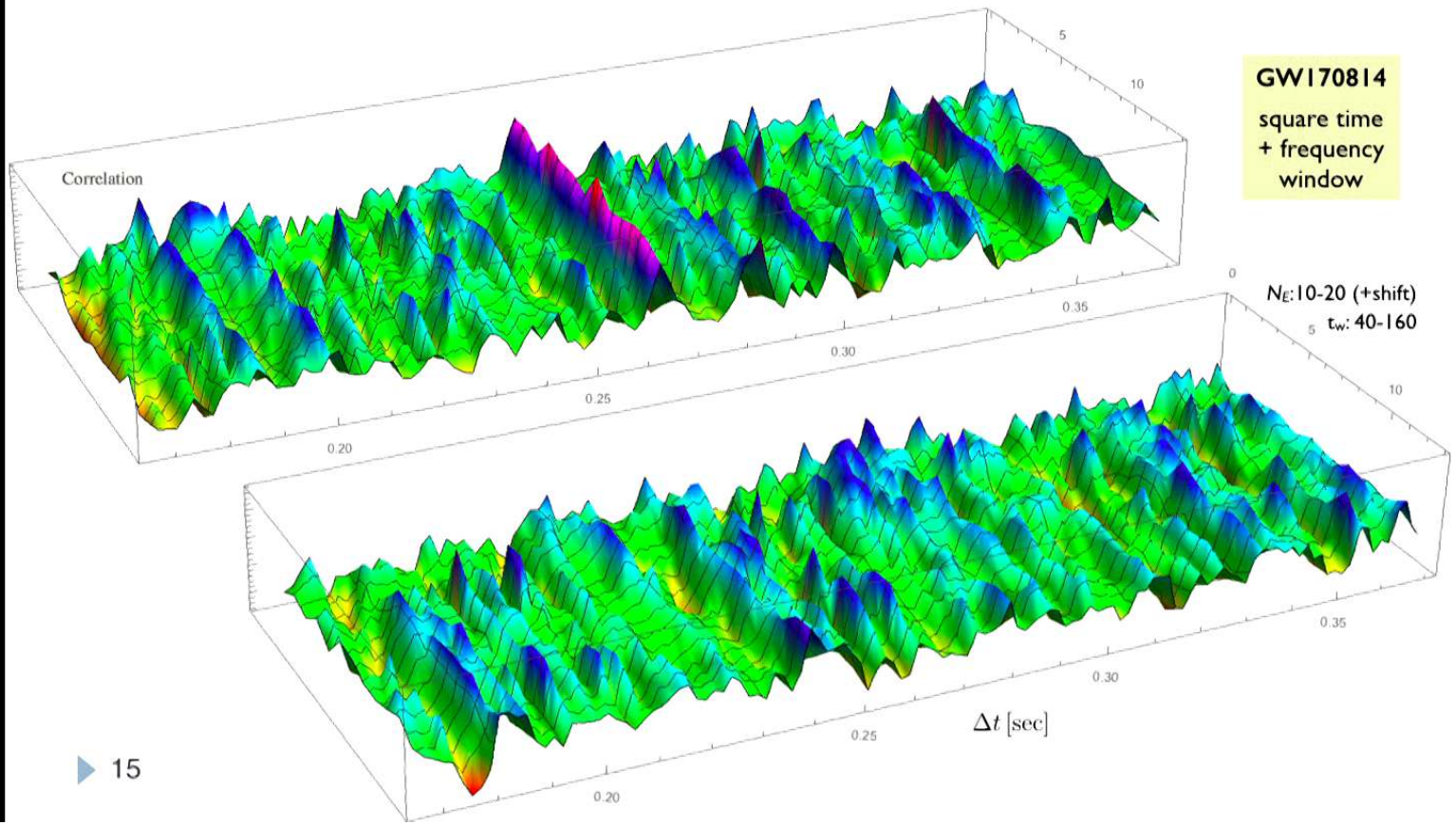


GW170104

triangular frequency window

Interesting hints from the LIGO data!

Persistence of the time delay peak with variation of window parameters (echoes numbers, time shift of data, window width, shape), ways of whitening data…



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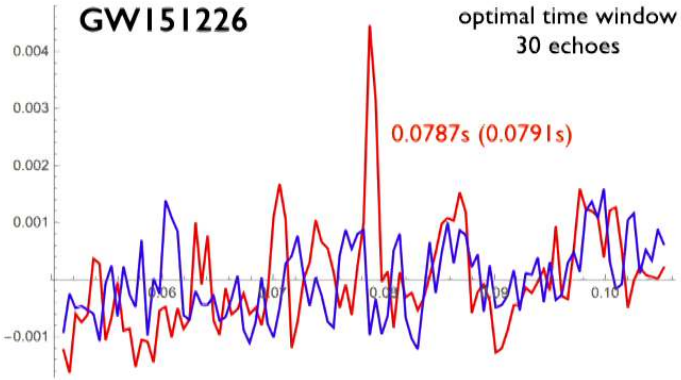
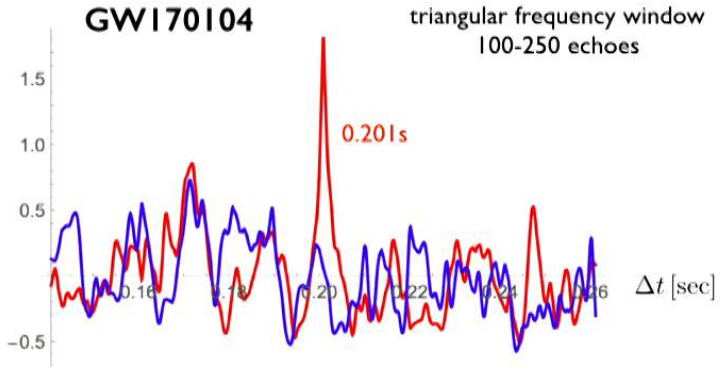
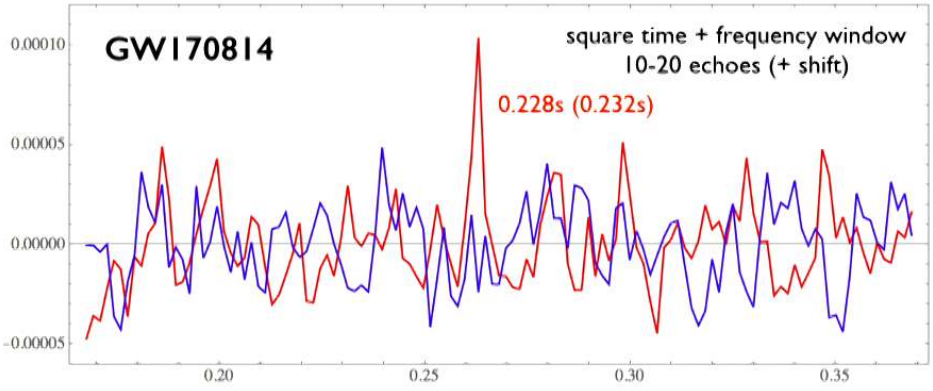
Interesting hints from the LIGO data!

Preliminary results for the LIGO BBH events: data after merger (signal: red), data before merger (background: blue).





Events	$\Delta t/M$	$M/M_\odot$
GW151226	550-760	21.1-29.3
GW170104	650-790	51.7-63
GW170814	740-820	56.3-62.6



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