Astrophysics and fundamental physics with gravitational waves.

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Potsdam-Golm, Germany

3-7 July, 2017, Orsay

Overview

GW landscape

Basis of parameter estimation

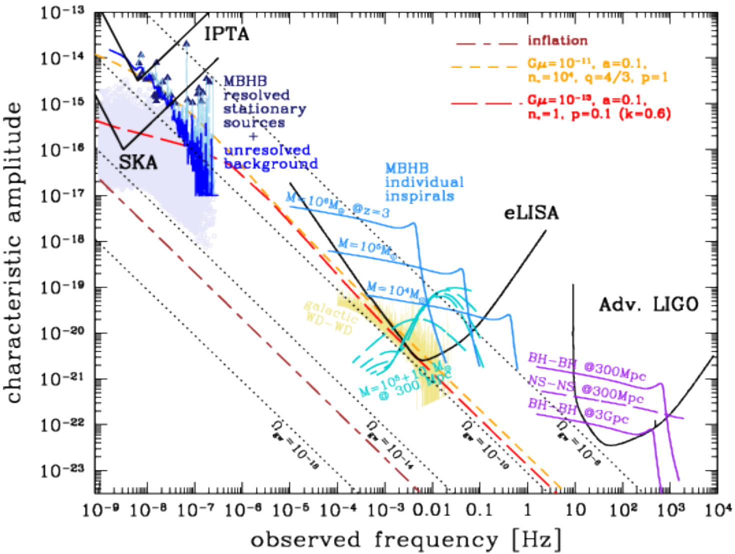
Testing GR with LIGO

Testing GR with LISA

References

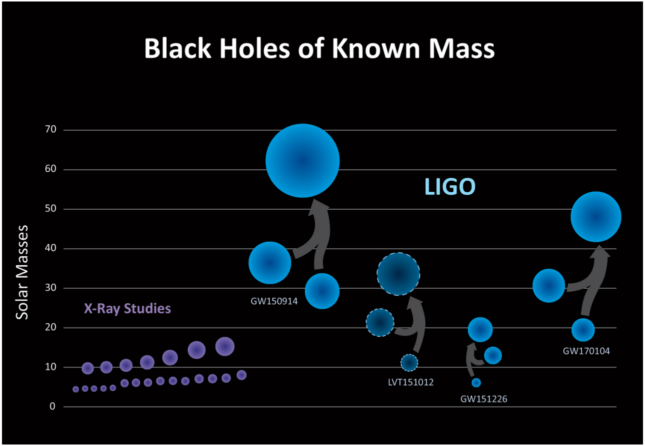
- LSC+Virgo, Phys. Rev. Lett. 116, 221101 (2016)
- LSC+Virgo, Phys. Rev. X 6, 041015 (2016)
- LSC+Virgo, Phys.Rev.Lett. 116 241102 (2016)
- LSC+Virgo, Phys.Rev. X6 041014 (2016)
- LSC+Virgo, Phys. Rev. Lett. 118, 221101 (2017)
- Berti et al., Class.Quantum Grav. 32, 243001 (2015)
- Agathos et al., Phys. Rev. D 89, 082001 (2014)
- Li et al., Phys. Rev. D 85, 082003 (2012)
- Ghosh et al. Phys. Rev. D 94, 021101(R) (2016)
- Will Phys. Rev. D57 2061 (1998)
- Mirshekari et al. Phys. Rev. D 85, 024041 (2012)
- Blanchet, Sathyaprakash, Phys.Rev.Lett. 74 1067 (1995).
- Arun et al. Phys.Rev. D74 024006 (2006)
- Mishra et al. Phys.Rev. D82 064010 (2010).

Gravitational waves landscape



[credits: A. Sesana]

Detection of GW with LIGO



[Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)]

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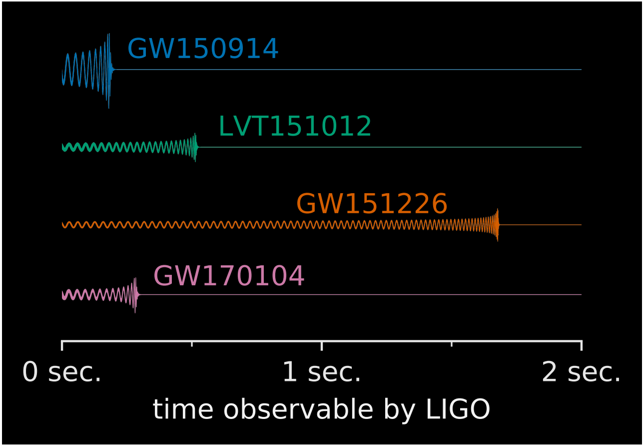
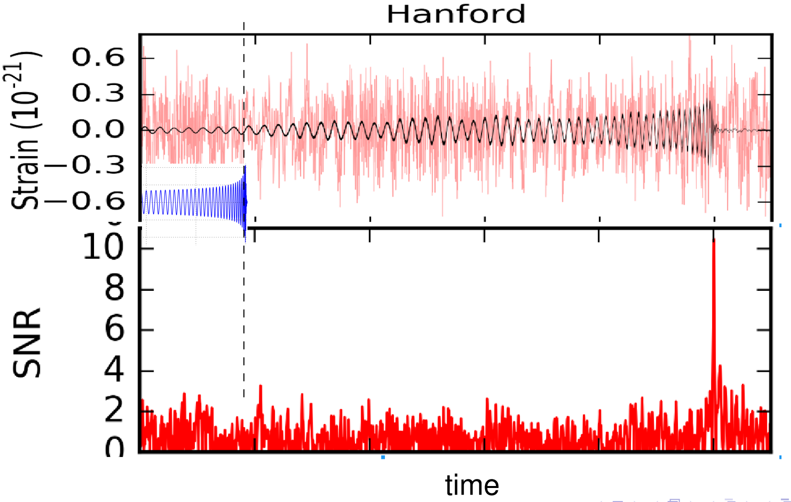


[Image credit: LIGO/B. Farr]

Matched filtering

We are searching for a signal of a specific shape buried in the noise: matched filtering.



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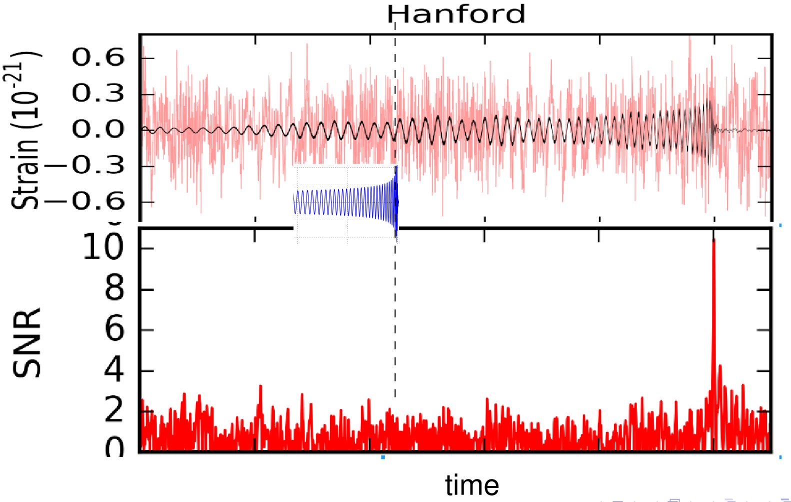

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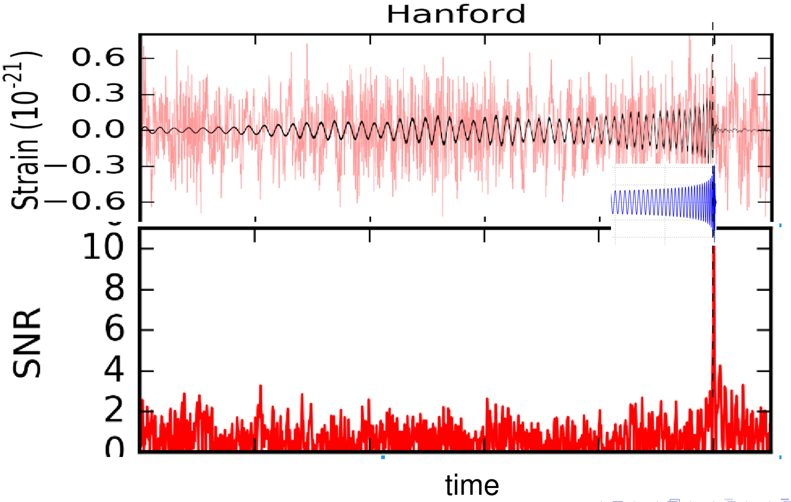
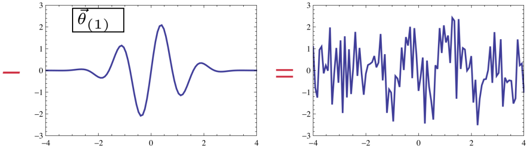
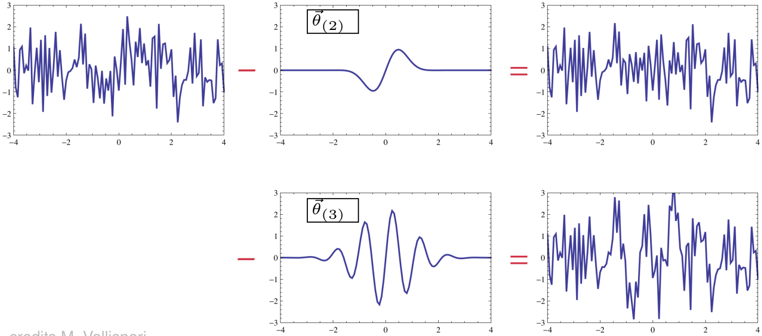


Matched filtering and parameter estimation

noise = data - signal

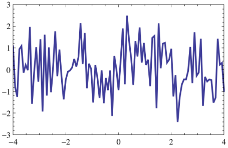


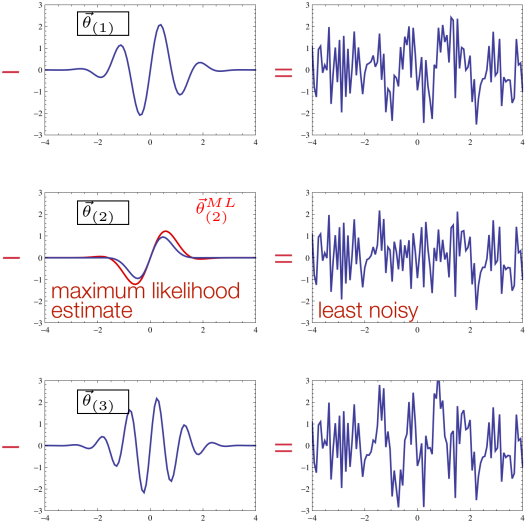


credits M. Vallisneri

Matched filtering and parameter estimation

noise = data - signal
p(signal parameters)
= p(noise residuals)



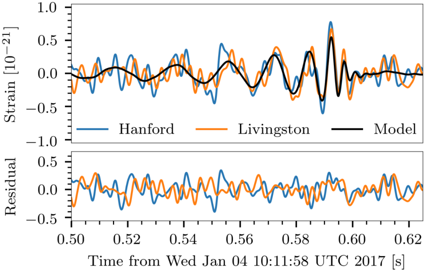


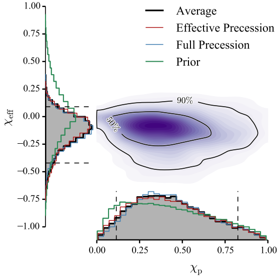
credits M. Vallisneri

Parameter estimation

prior

$$p(\theta|d) = \frac{p(d|\theta)p(\theta)}{p(d)}$$





[LSC+Virgo PRL (2017)]

Parameter estimation

likelihood

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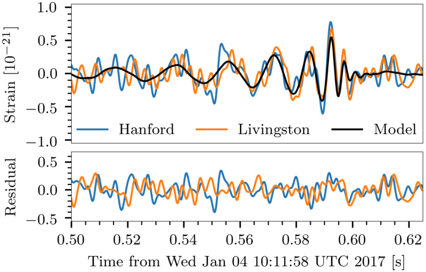

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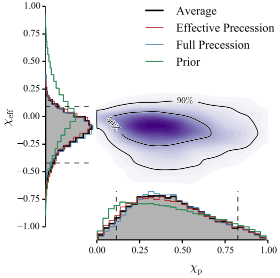
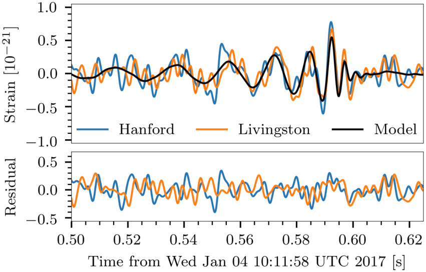
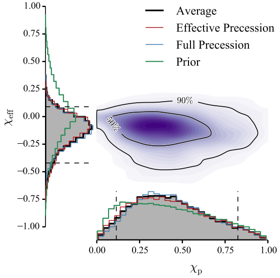


Parameter estimation

posterior

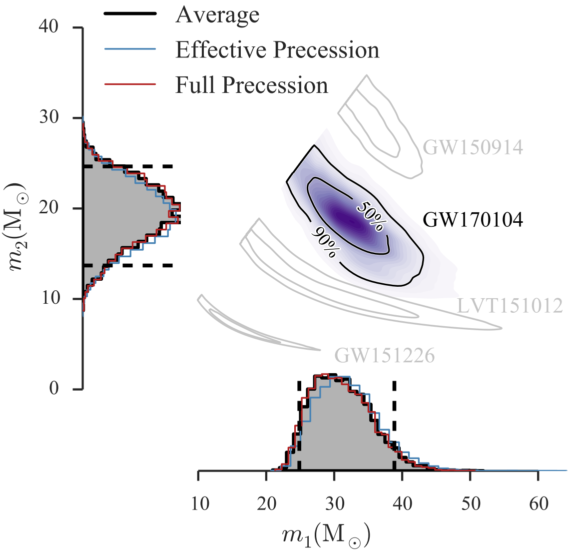
$$p(\theta|d) = \frac{p(d|\theta)p(\theta)}{p(d)}$$





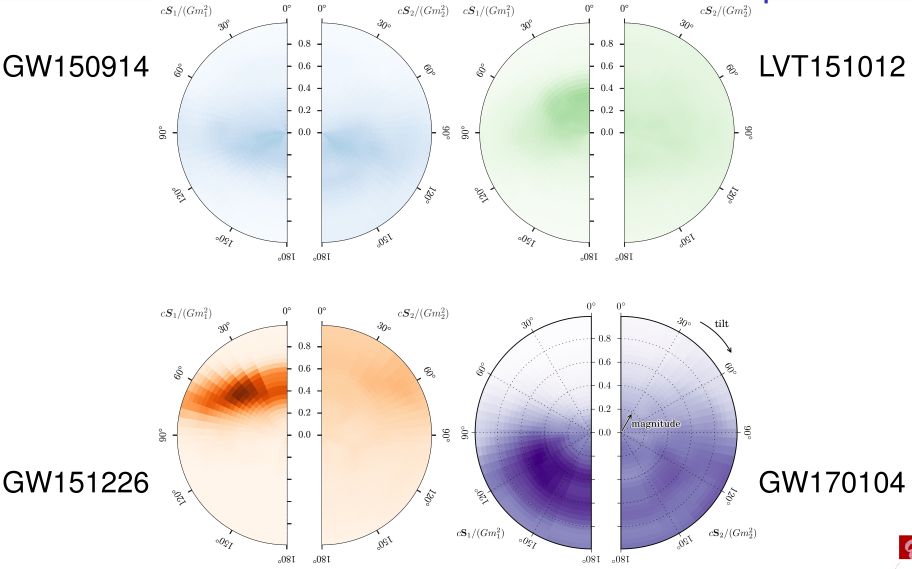
[LSC+Virgo PRL (2017)]

Inferred parameters of binary systems: masses



[LSC+Virgo PRL (2017)]

Inferred parameters of binary systems: spins



[LSC+Virgo PRL (2016, 2017)]

Testing GR with GWs

- GWs are predicted in virtually any metric theory of gravity
- Compare GR's GWs with (usually parametrized) alternative theories
- Perform phenomenological consistency test for different aspects:
  - binary dynamics (encoded in the phase of GW signal)
  - polarization of GW (in GR only two polarizations "+", "x")
  - propagation of GWs
- Alternative theories can introduce extra-fields, curvature terms, preferred foliation, graviton mass.
- No full solution for 2-body problem in non-GR
- Do we observe BHs of GR or something else (exotic objects)?

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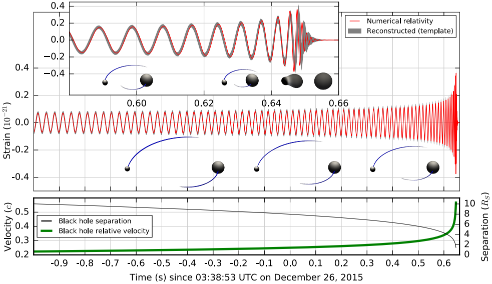
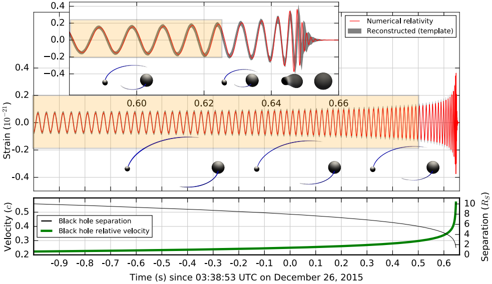
Testing inspiral phase



[Credit: SXS collaboration]

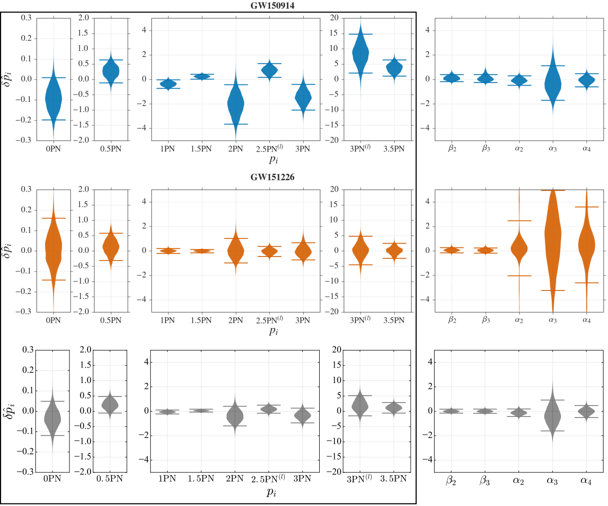
Testing inspiral phase



[Credit: SXS collaboration]

- Inspiral part: size of bodies $\ll$ separation, orbital velocity $v \ll c$, semi-analytic description.
- Waveform $h(f,\theta) = A(f;\theta)e^{i\phi(f;\theta)}$, $\phi(f;\theta) = \phi_o + \sum \phi_k(\theta)(\pi M f)^{(k-5)/3}$. $\theta = \{m_1, m_2, \mathbf{s_1}, \mathbf{s_2}\}$
- Do the coefficients depend on masses, spins as predicted by GR?
- Tidal effects during inspiral: BH mimickers (boson stars, gravastars, ...)

Parametrized test

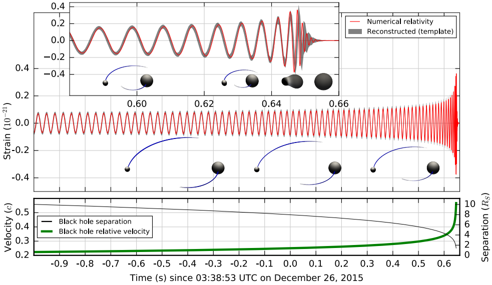


Inspiral

- Waveform: $h(f,\theta) = A(f;\theta)e^{i\phi(f;\theta)}$,
- $\phi = \phi_o + \sum \phi_k(\theta)(\pi M f)^{(k-5)}$, $\theta = \{m_1, m_2, \mathbf{s_1}, \mathbf{s_2}\}$
- $\phi_k = \phi_k^{GR}(1 + \delta\phi_k)$

[LVC PRL(2016), PRX(2016), PRL(2017)]

Consistency test for inspiral and merger & ring down



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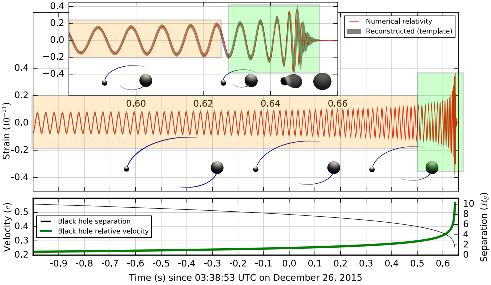
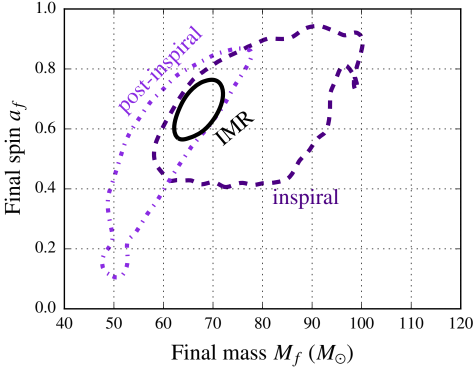


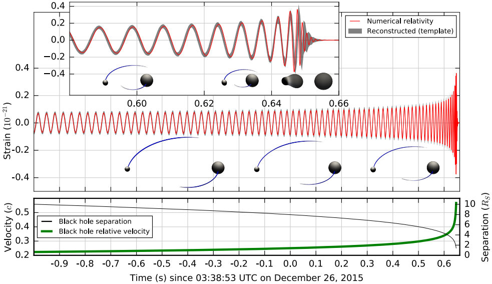
- We check consistency between inspiral and post-inspiral parts of the signal
- We perform independent analysis of two parts of the signal and estimate $m_1, m_2, \mathbf{s_1}, \mathbf{s_2}$
- Assuming GR we evaluate the mass and the spin of the remnant from each part of the signal

Consistency check

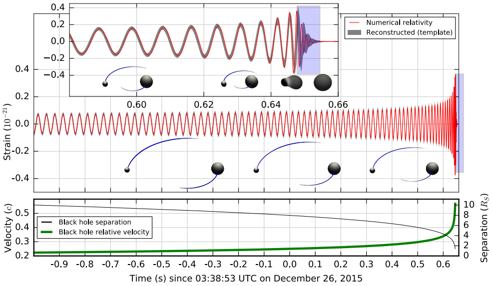


Verify self-consistency by comparing final mass and spin predicted from the “inspiral” and from the “post-inspiral”
[Ghosh+, 2016]
[LVC PRL(2016)]

Ringdown

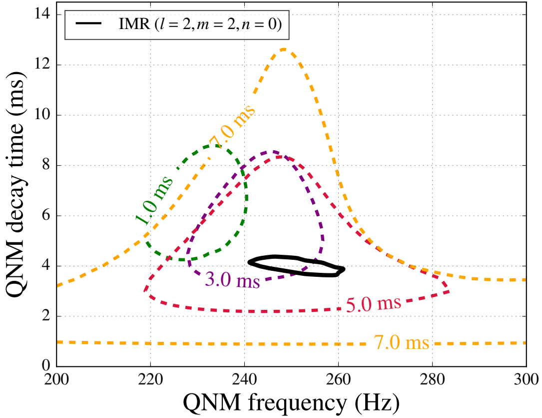

Numerical relativity
Reconstructed (template)
0.60
0.62
0.64
0.66
Strain (10^{-21})
Black hole separation
Black hole relative velocity
Velocity (c)
Separation (R_S)
Time (s) since 03:38:53 UTC on December 26, 2015

Ringdown



- Ringdown: superposition of exponentially damped eigen frequencies of a remnant BH (linear perturbation of Kerr BH)
- Hard to identify linear post-merger regime dominated by RD (τ after maximum)

Ringdown



[LVC PRL(2016)]

- Attempt to estimate the least damped mode and compare with expectation based on estimation of the mass and spin (M_{remn}, a_{remn}) of the remnant BH.

Propagation effect: massive graviton

- Graviton is massless spin-2 particle. If graviton has non-zero mass: $E^2 = (pc)^2 + (m_g c^2)^2$
- Dispersion of the gravitational wave (low frequencies propagate slower)
- Modification of the GW phase: $\delta\phi = -\frac{\pi M D}{\lambda_g^2 (1+z)}$

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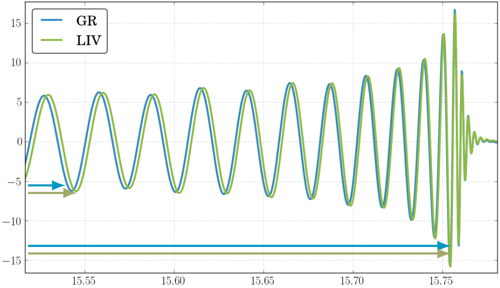
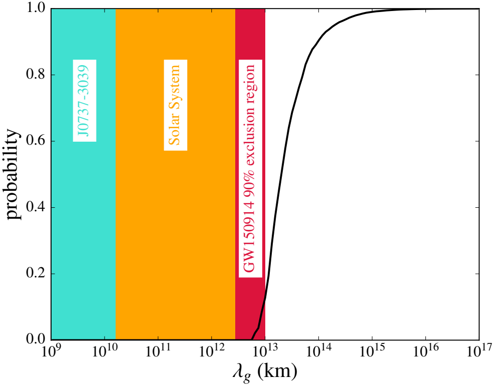


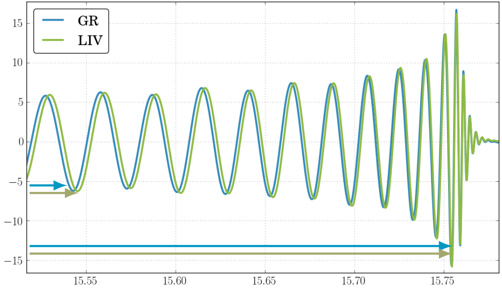
Bound on mass of graviton



Bounds on the Compton wavelength $\lambda_g = h/(m_g c)$ of a hypothetical theory, assuming that the dispersion is a dominant effect [LVC PRL(2016)]

Propagation effect: Lorentz invariance violation

- Anomalous dispersion of gravitational waves (violation of local Lorentz invariance): $E^2 = (pc)^2 + A(pc)^\alpha$
- We neglect other modifications which could come from the Lorentz invariance violation (could be accompanied by dipolar radiation)
- Could be subluminal or superluminal (depends on the sign of A and $\alpha <> 1$)



subluminal

Propagation effect: Lorentz invariance violation

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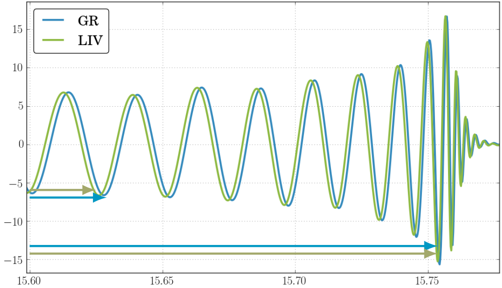
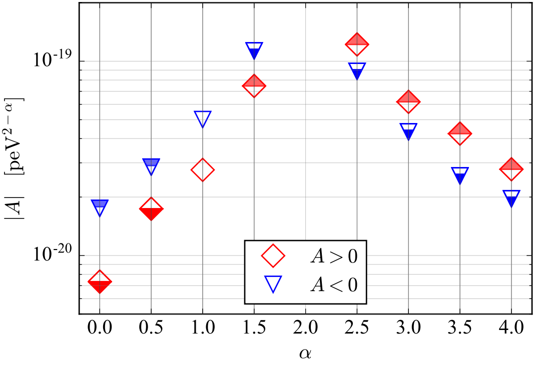


superluminal

Bounds on Lorentz invariance violation

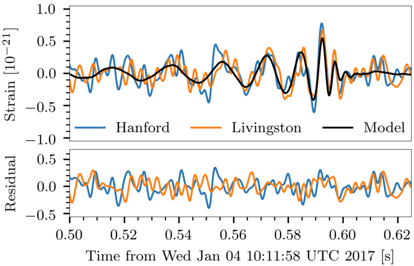


[LVC PRL(2017)]

$$\delta\phi = \begin{cases} -\beta(\pi M f)^{-1} - \zeta_\alpha(\pi M f)^{\alpha-1}, & \alpha \neq 1 \\ -\beta(\pi M f)^{-1} + \zeta_1 \log(\pi M f), & \alpha = 1 \end{cases}$$

where $\zeta_\alpha \propto D_\alpha M^{1-\alpha}/\lambda_A^{2-\alpha}$, $\lambda_A = hA^{\frac{1}{\alpha-2}}$, $D_\alpha = \frac{1+z}{H_0}\int_0^z \frac{(1+z')^{2-\alpha}}{\sqrt{\Omega_m(1+z')^3+\Omega_\lambda}}$

Residuals



- Basis of matched filtering: noise = data - signal
- Is data consistent with the noise after subtraction of the best matched template?

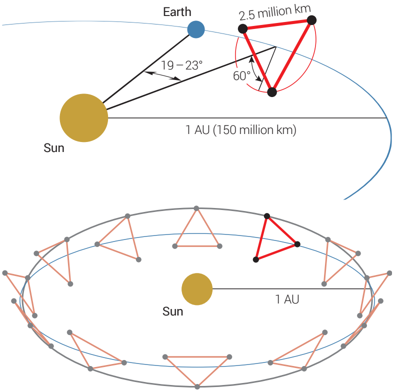
Fitting factor FF - overlap with signal maximized over the all parameters

$$SNR^2_{\rm res} = (1 - FF^2)FF^{-2}SNR^2_{\rm det}$$

- GW150914, measured: $SNR_{\rm res} \leq 7.3$, $SNR_{\rm det} \approx 25.3 \rightarrow FF \geq 0.96$. We have fitted at least 96% of the signal.

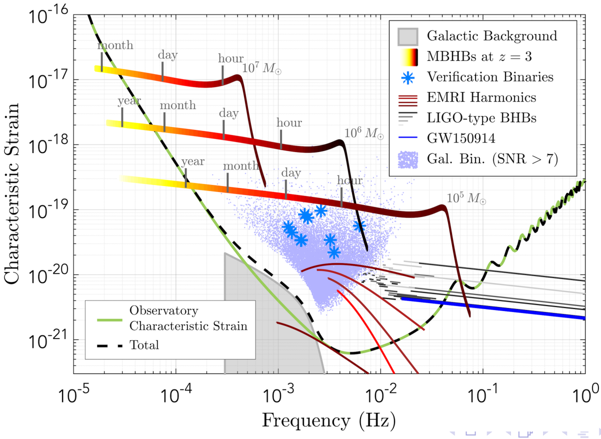
LISA

- LISA is a space-based mission to be launched $\approx$ 2034
- LISA was officially approved end of June as L3 mission.



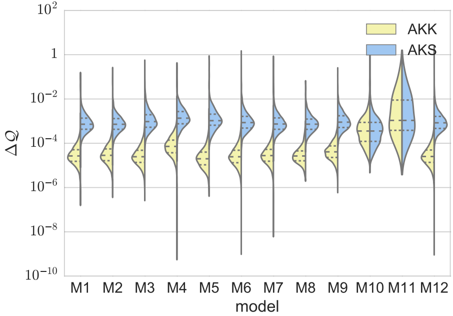
Sources in LISA's band

- LISA will detect the merging massive $M > 10^5 M_\odot$ black hole binaries (SNR could be few $\times 10^3$. Extreme Mass Ratio Inspirals (inspiral and plunge of a stellar mass object (BH) into massive BH.



Testing GR with LISA

- Testing GR: all the test performed by LIGO but here with much better accuracy (much higher SNR)
- For merging supermassive BHs ($M > 10^6 M_\odot$) we can easily detect RD part of the signal $\rightarrow$ test "no hair" theorem
- EMRIs: similar to geodesy. small BH performs $10^4 - 10^6$ orbits in close vicinity of MBH $\rightarrow$ the spacetime is encoded into the GW phase $\rightarrow$ can check if the massive centrl object is indeed Kerr BH.



[Babak+ 2017]

Summary

Testing GR with GWs

- LIGO has detected 4 GW signals from merging binary black hole systems
- We can use the detected GW signals to verify GR
- SNR is low: usually can test consistency with GR $\rightarrow$ all detected GW signals are consistent with the predictions of GR (upper limit on the Lorentz invariance vioaltion and on the mass of graviton)
- LISA: space based mission will detect similar signals but with much higher SNR. In addition EMRIs will measure the multipolar stricture and confirm (?) "Kerrness" of compact massove objects in galactic nuclei