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Compact binaries, sky localization & all that

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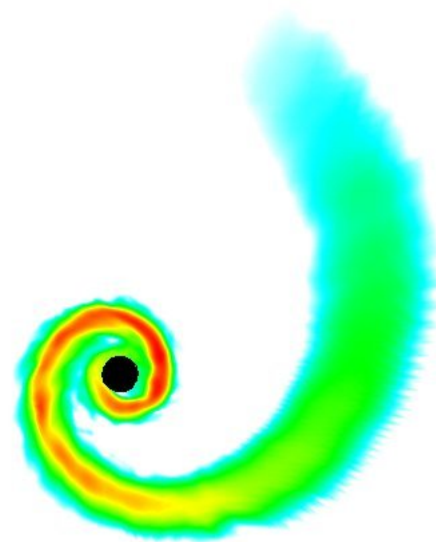

Sukanta Bose

Acknowledgments:
LIGO Sci. Collab. Members;
NRTT, NSF

Based on:
LIGO-DCC-G1602275
LIGO-DCC-G1600931
LIGO-DCC-G1601432
LIGO-DCC-G1500545
LIGO-DCC-G1500496

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Outline

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- The synergy of EM astronomy and GW astronomy: GW transients meet time-domain EM light curves

- Challenges posed:
  - Dealing with non-Gaussian GW data
  - Difficulties of rapid follow-up to catch a fading light curve
  - Large sky localization patches

- Using higher order statistics to understand nature of noise transient and its source.

EM counterpart prospects of GWs: Short GRBs

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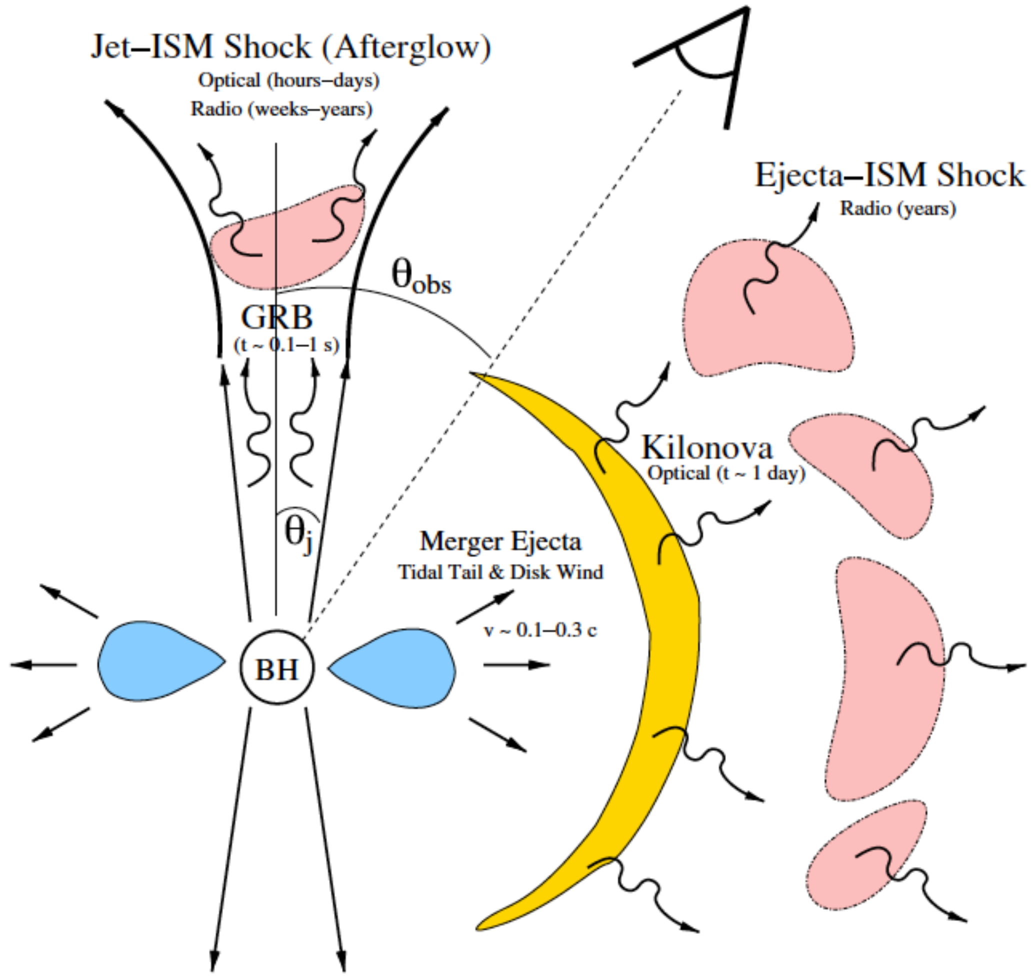
- Among known sources, CBCs involving neutron stars present the best EM counterpart prospects.
- Short duration gamma-ray bursts (SGRBs) have been conjectured to have CBC-NS as progenitors.
- The CBC-NS model is consistent with multiple types of EM counterparts, e.g., prompt emissions (in γ–ray and X-ray), optical and radio afterglows, and kilonovae.



[Metzger & Berger, Astrophy. J., 746:48 (2012).

Can EM observations complement GWs?

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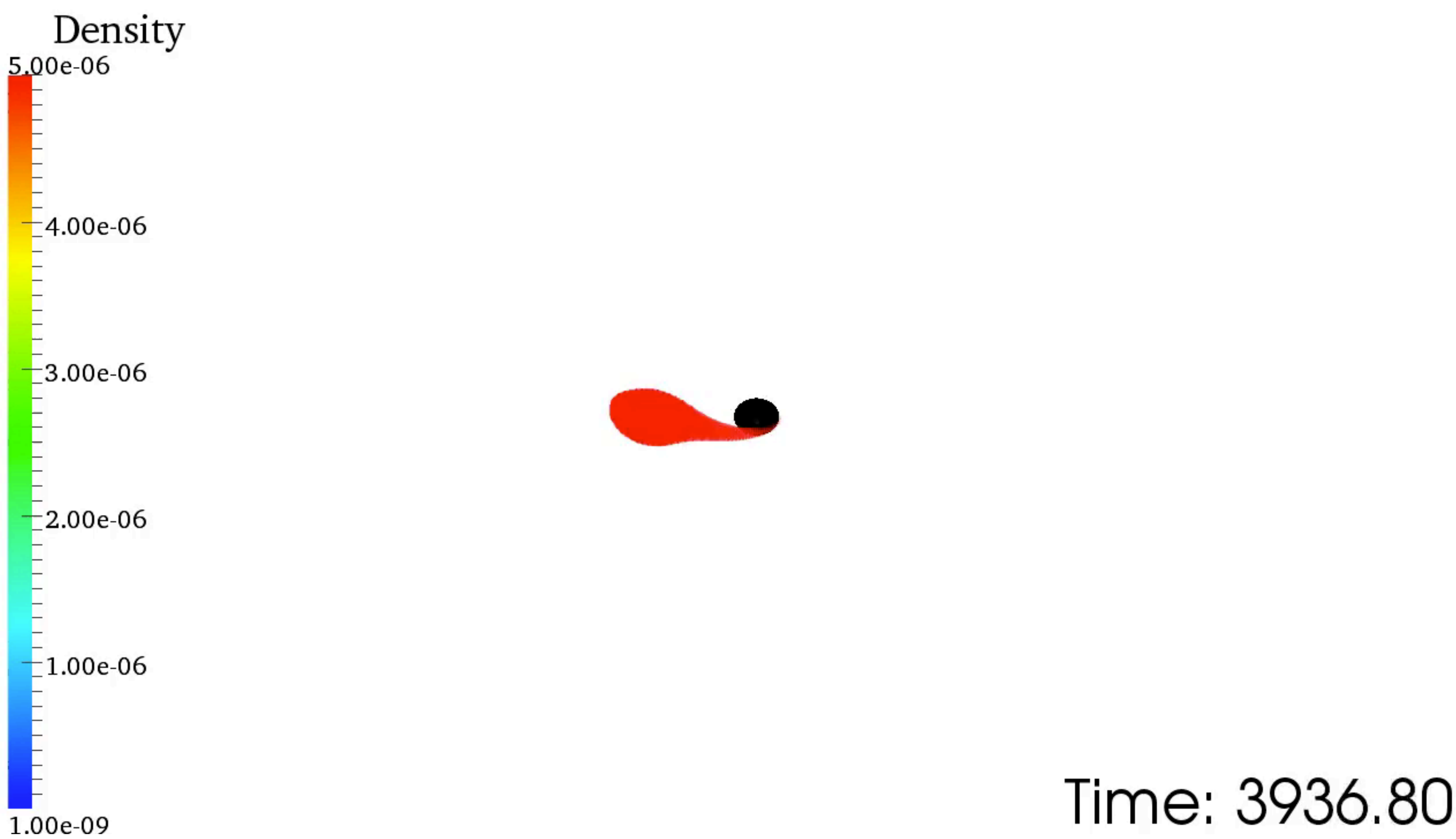
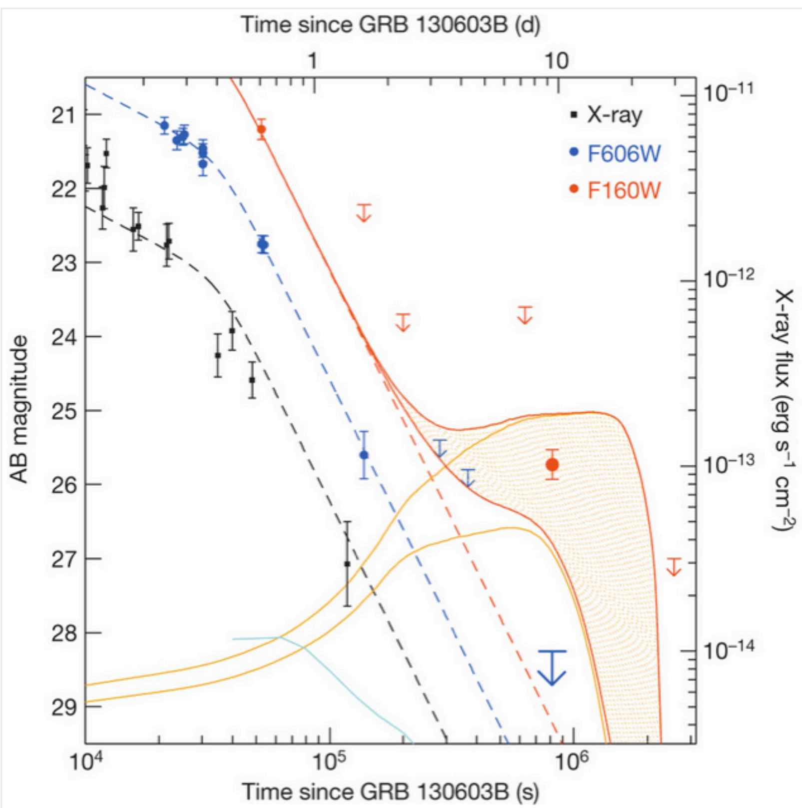
Neutrino luminosity (erg/s)

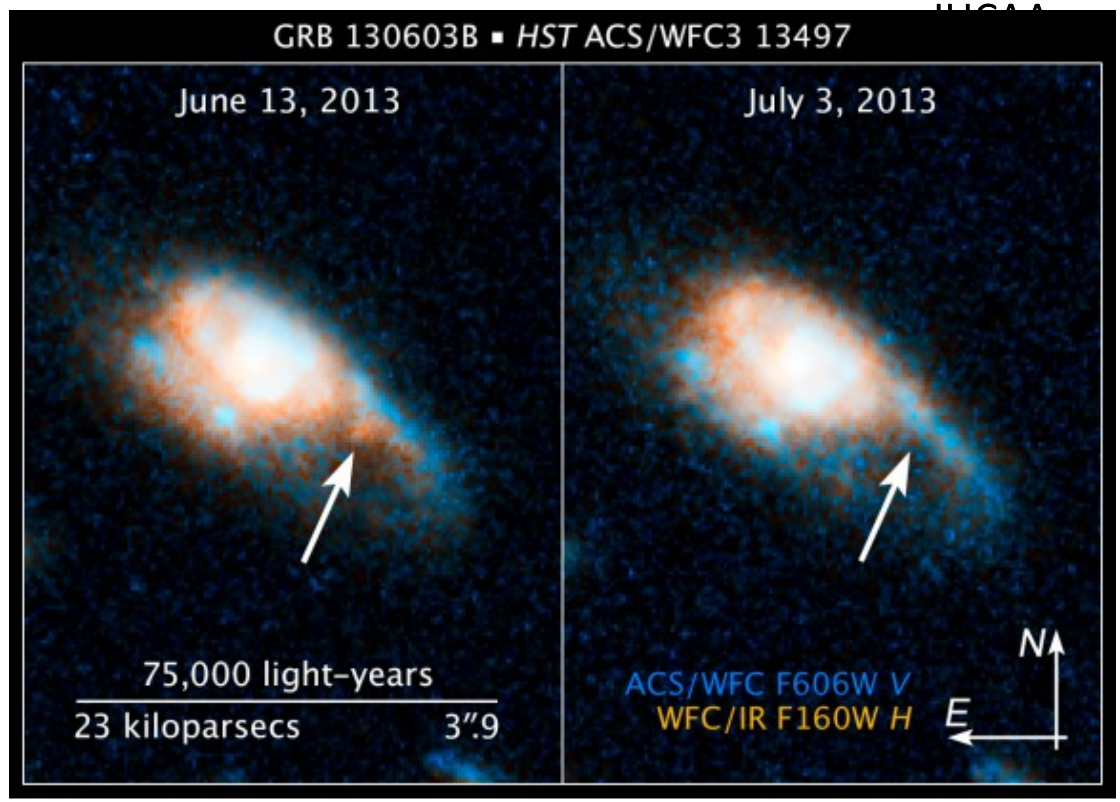


[Courtesy: Matt Duez, SXS Coolab.]

The first kilonova in GRB 130603B?

- Late-type galaxy at z ~ 0.35
- No late-time optical counterpart (rules out Ni-decay emission as in a supernova)
- Single late-time near-infrared emission.





- N-IR emission consistent with kilonova models of CBC-NS with ejected mass ~ $10^{-2} – 10^{-1}$ Msun.

[Tanvir et al., , Nature doi:10.1038/nature12505 (2013); E. Berger+, Astrophy. J. 774(2), (2013)]

LSST can complement GW detectors for coincident observations.

Post-merger oscillations

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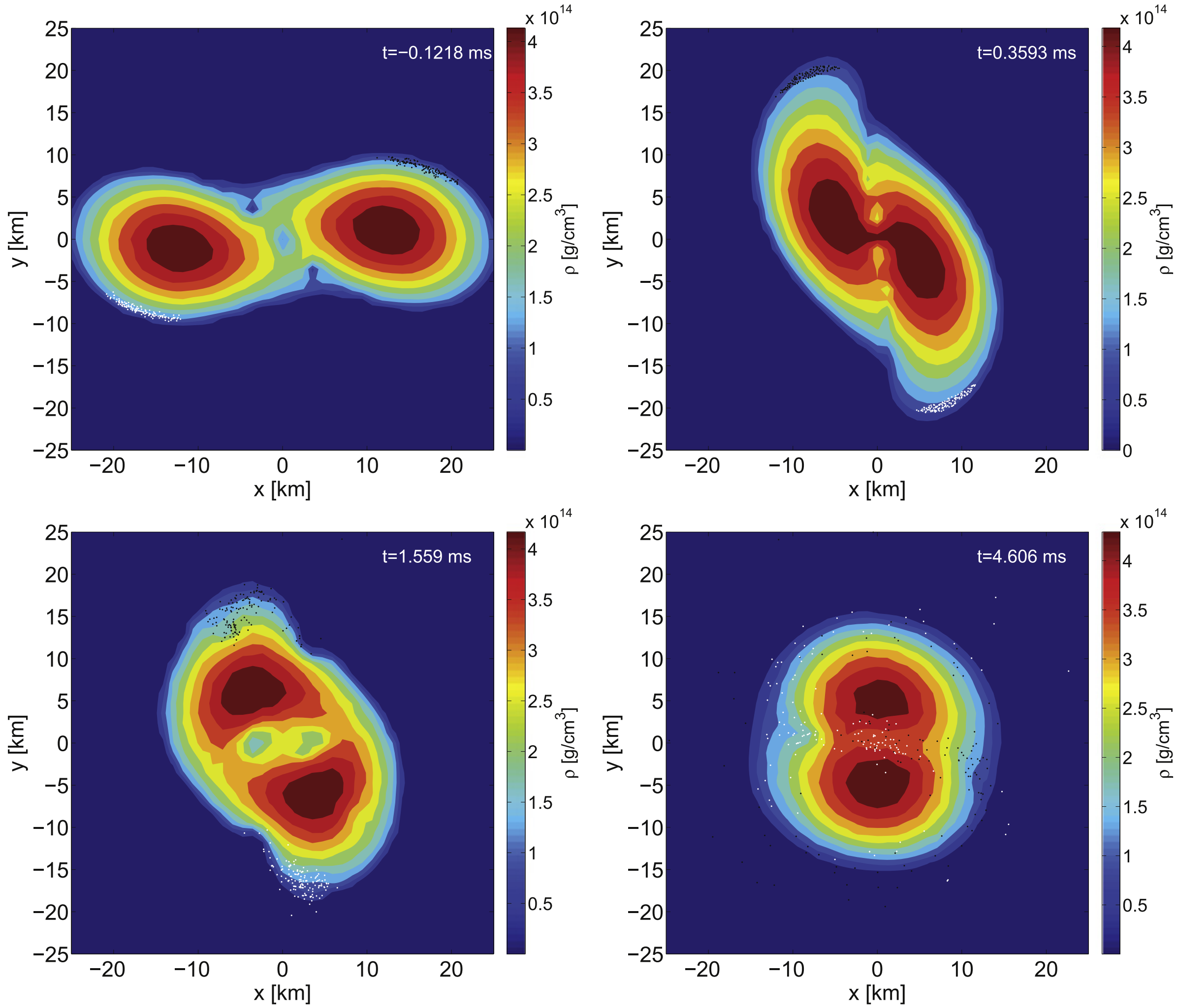

[Clark+, CQG 33 (2016)]

Some results-I (preliminary)

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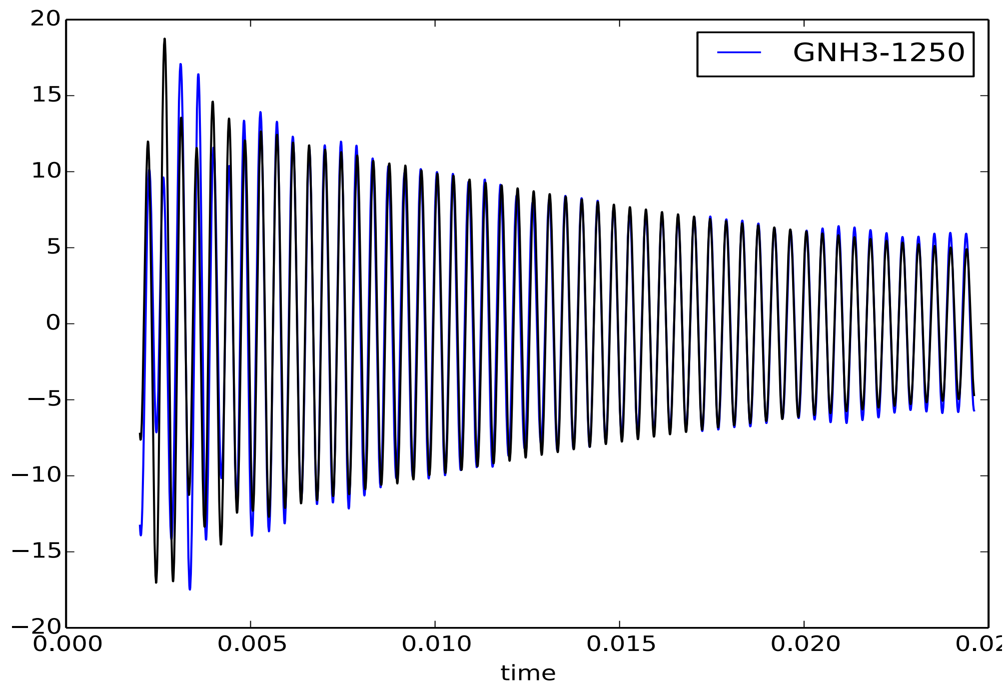
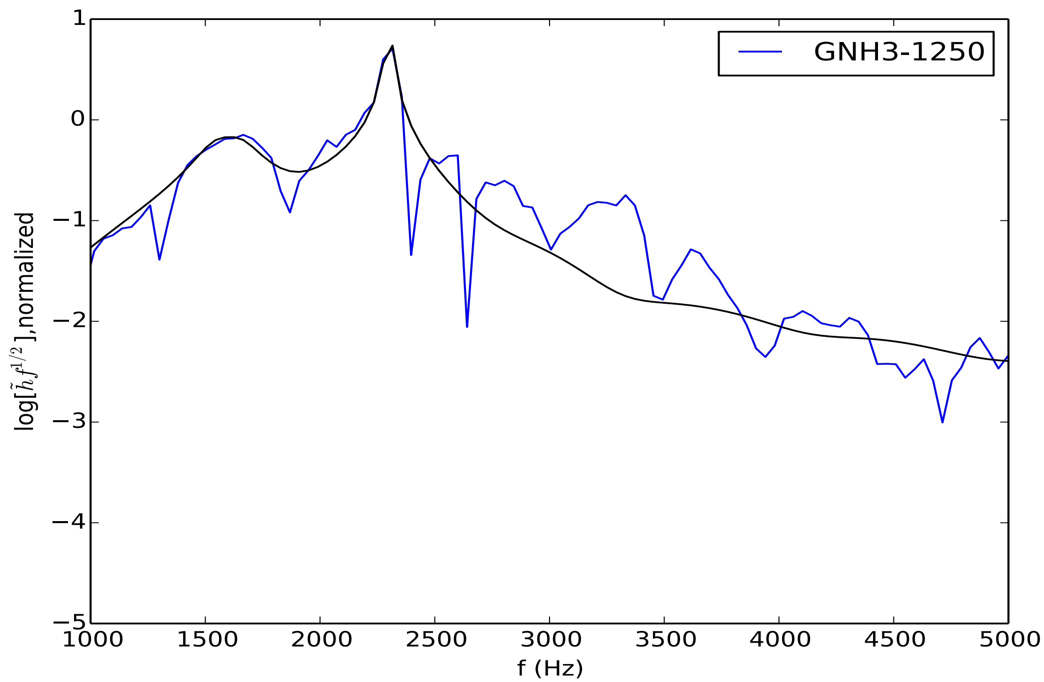
- We have *analytically* modelled (in black below) NR post-merger waveforms (in blue, with emphasis on frequencies f_1 and f_2 (also called f_{peak}).

- This has been done for a set of EOS, e.g., GNH3, H4, ALF2, SLy.

EOS: *GNH3*, $m_1 = m_2 = 1.25\ M_{sun}$.





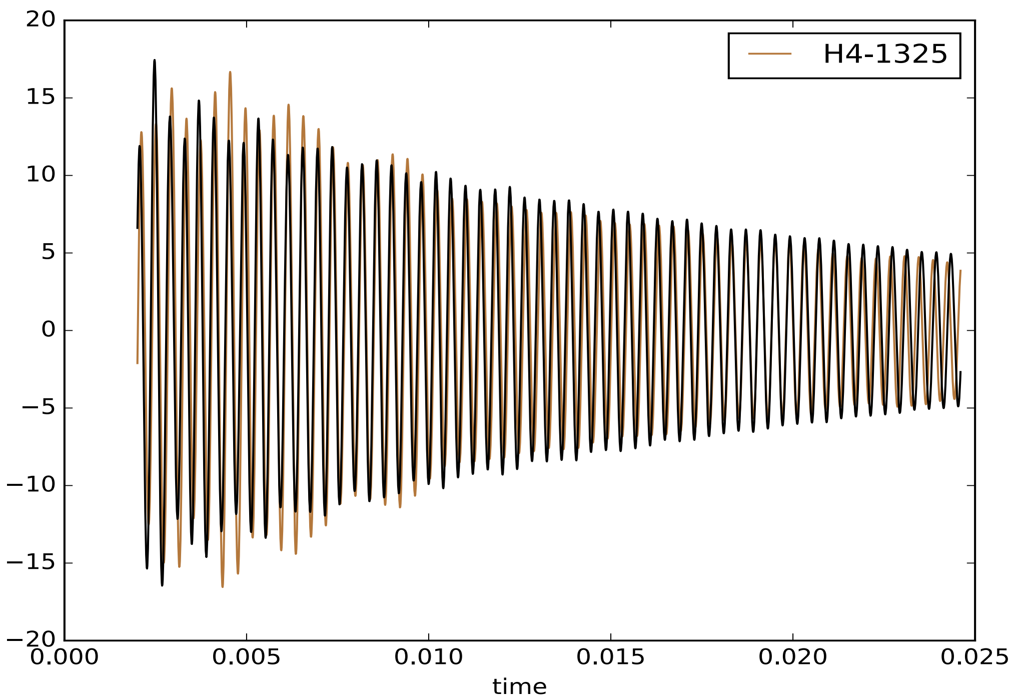
S. Bose, K. Chakravarti, L. Rezzolla, B. Sathyaprakash, K. Takami, LIGO-DCC-G1602275.

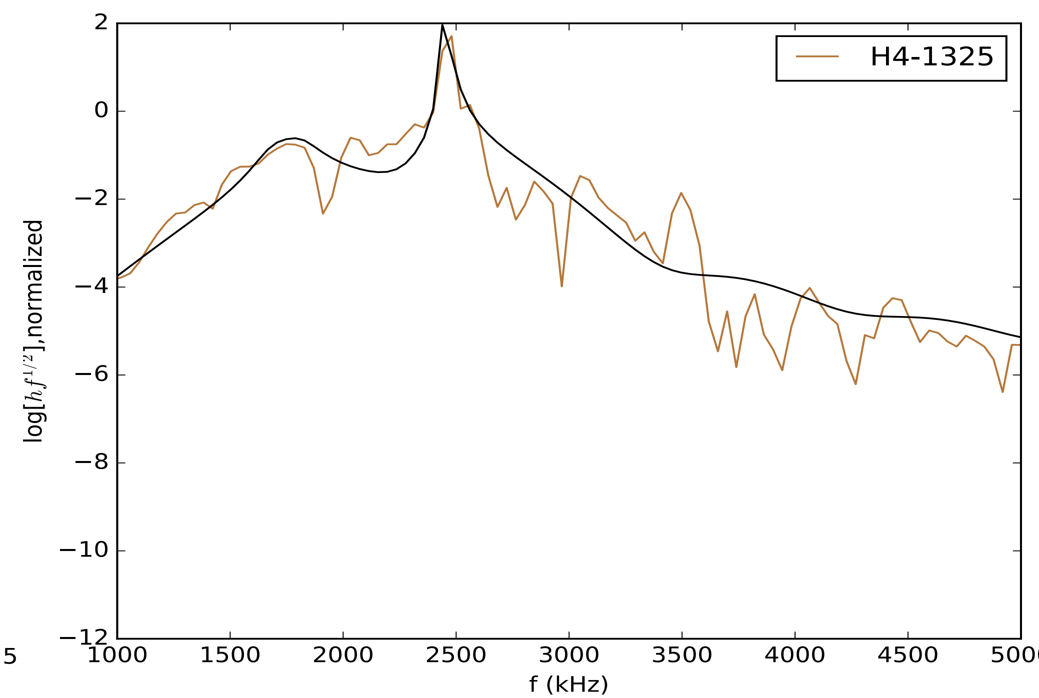
Some results-II (preliminary)

IUCAA

- We have *analytically* modelled (in black below) NR post-merger waveforms (in brown, with emphasis on frequencies f_1 and f_2 (also called f_{peak}).
- This has been done for a set of EOS, e.g., GNH3, H4, ALF2, SLy.

EOS: *H4, m_1 = m_2 = 1.325 M_{sun}.*





S. Bose, K. Chakravarti, L. Rezzolla, B. Sathyaprakash, K. Takami, LIGO-DCC-G1602275.

GW sky localization error regions

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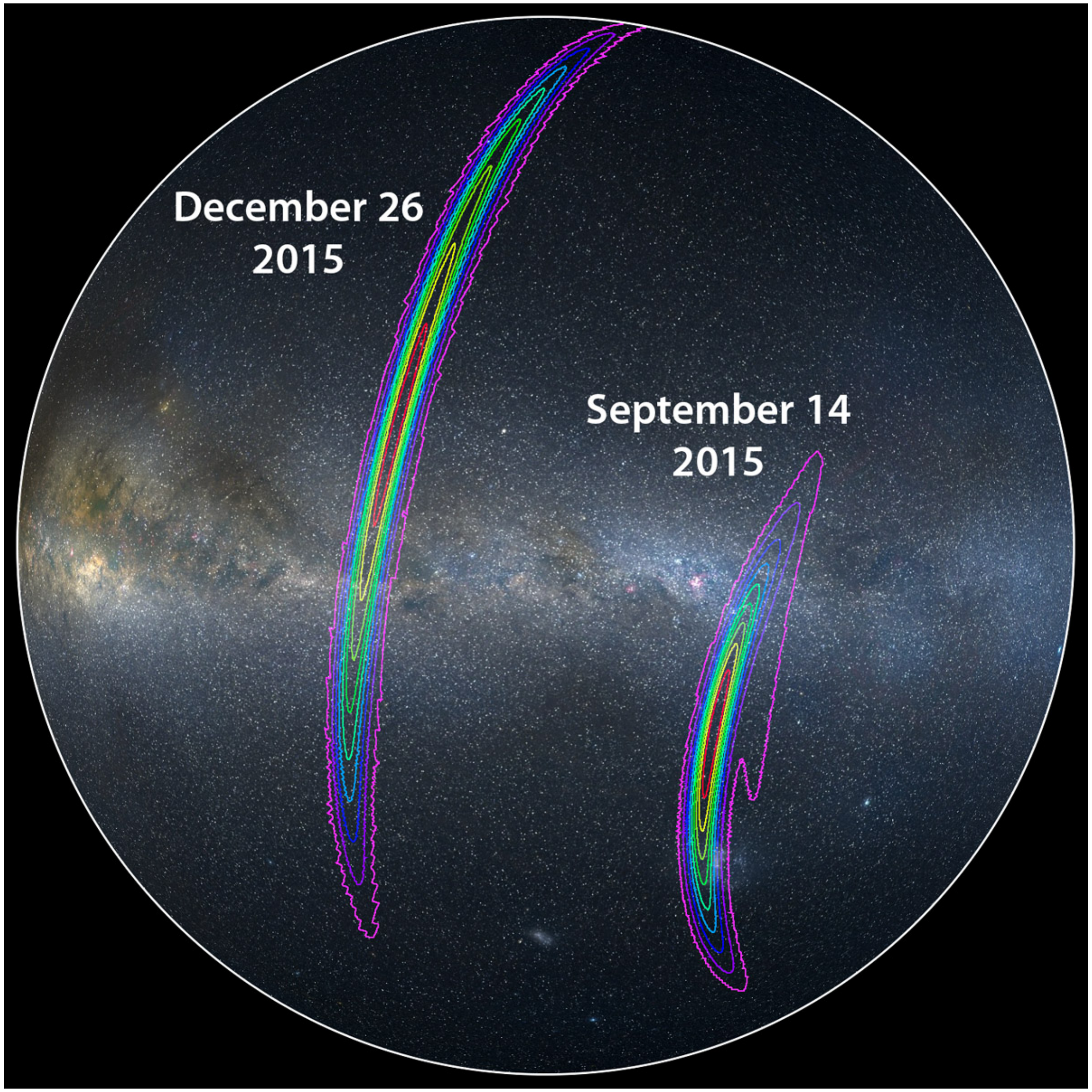
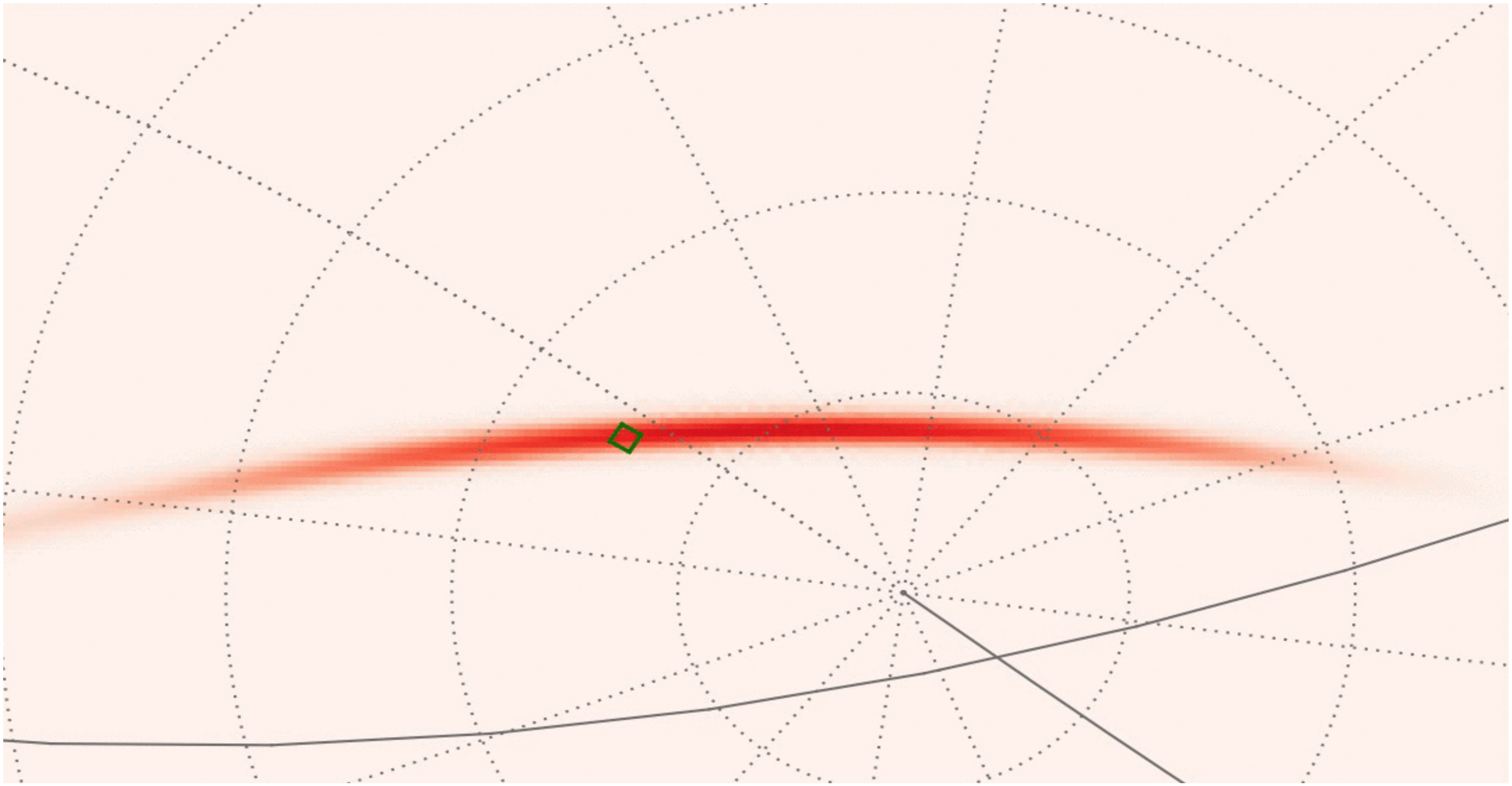


[Courtesy: Singer et al.]

Scheduling telescope observations



J. Rana, A. Singhal, B. Gadre,
V. Bhalerao, S. Bose, arXiv:1603.01689

Need to work on providing GW alerts in advance of merger!

Non-Gaussian noise

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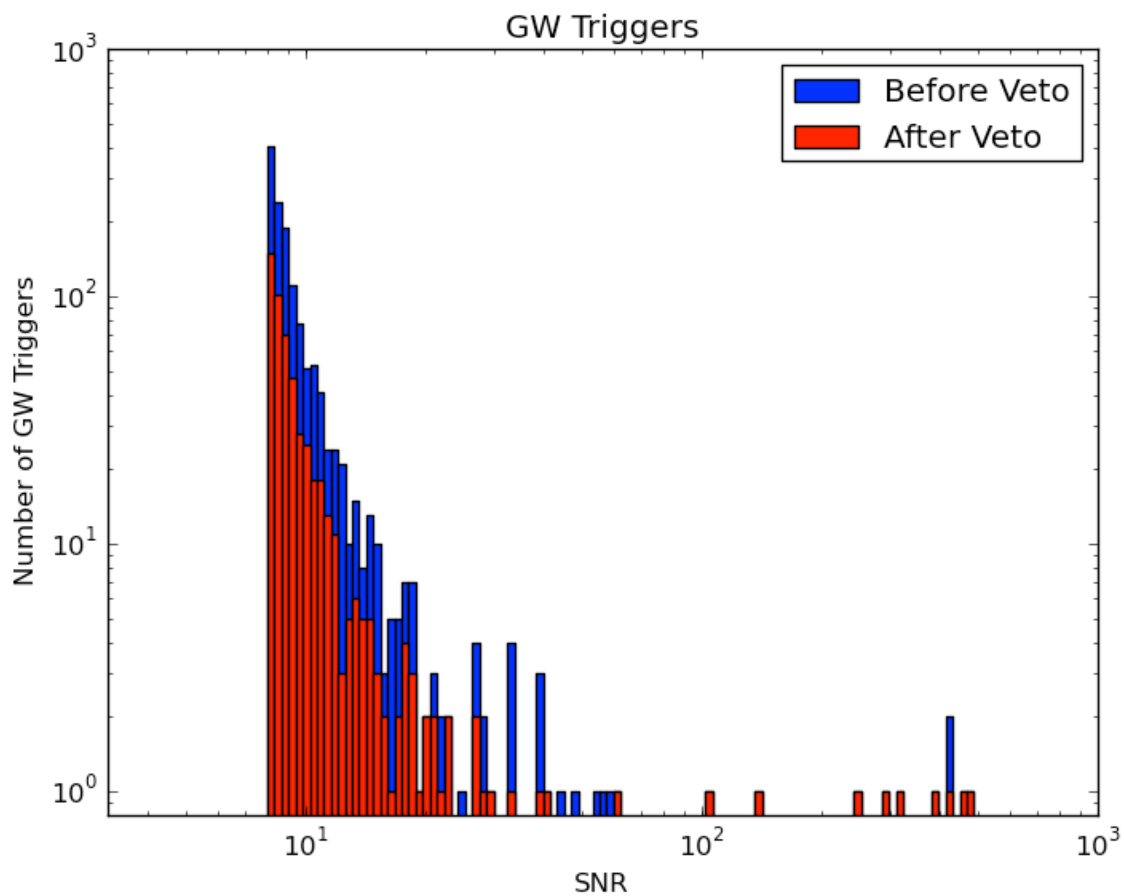
Example from an aLIGO Engg. Run:



[Courtesy: Bernard Hall and N. Mazumder]

Time-frequency plots of GW150914

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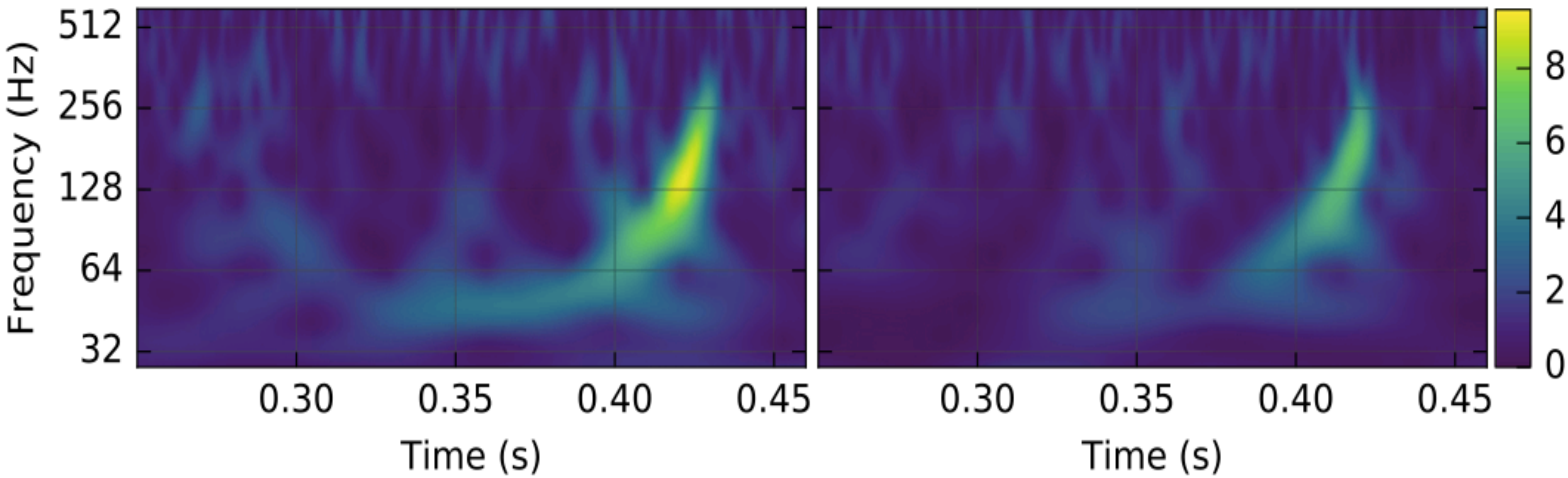

Hanford, Washington (H1)

Livingston, Louisiana (L1)

Abbott et al. (LVC), Observation of Gravitational Waves from a Binary Black Hole Merger," Phys. Rev. Lett. 116, 061102 (2016).

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On the other hand …transient noise

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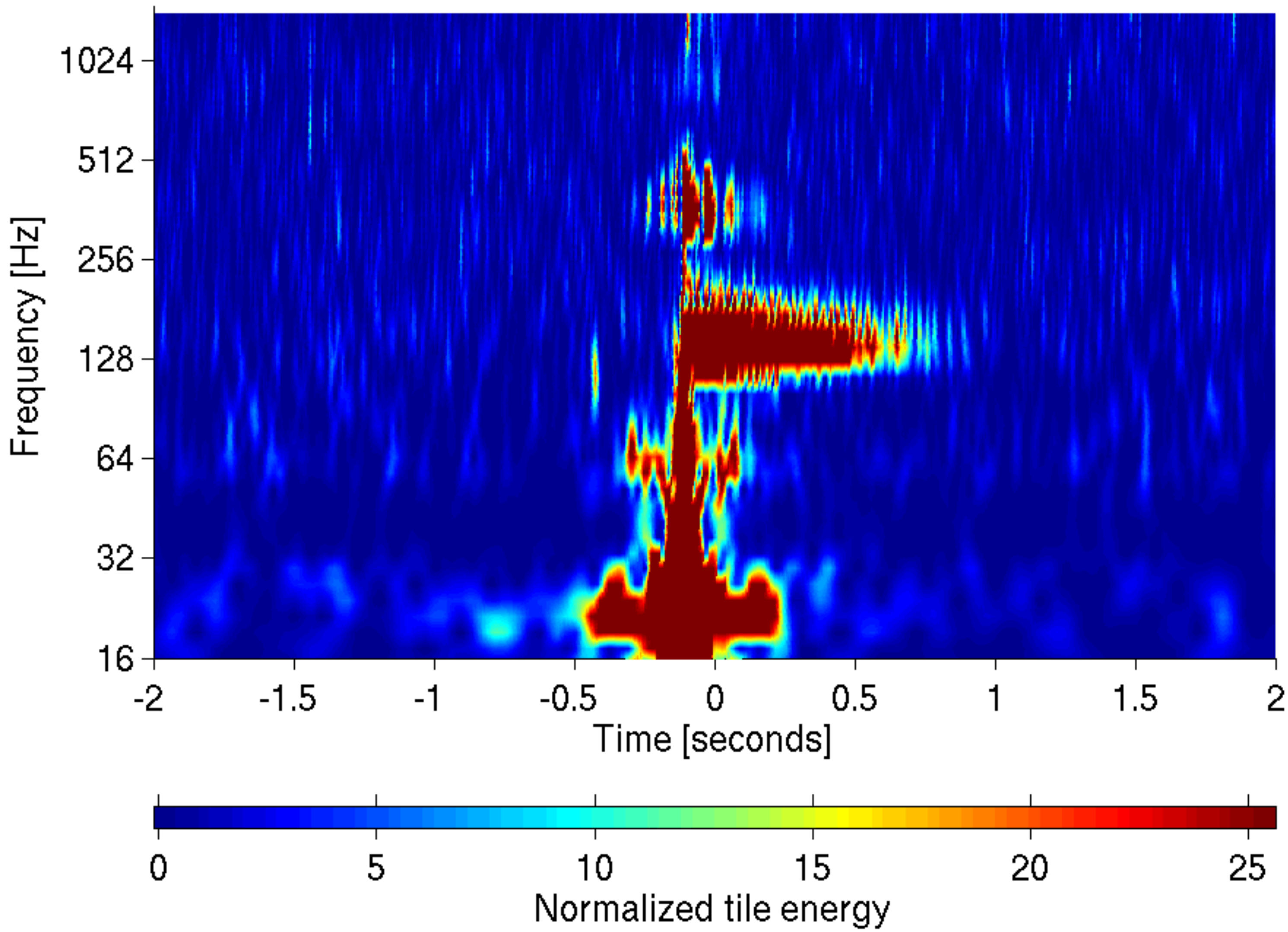

Chirping Sine-Gaussian glitches

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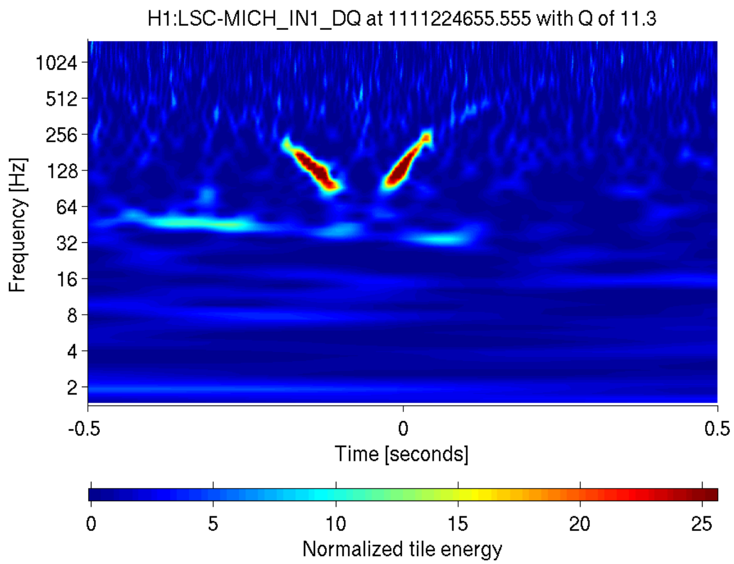

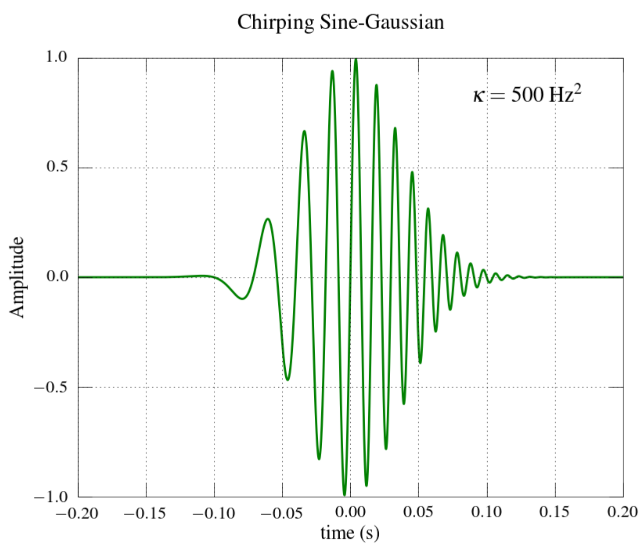

$$s(t) = e^{-t^2/\tau^2} \sin\left(2\pi f_0 t + \pi\kappa t^2\right),$$

where $\tau = Q/(2\pi f_0)$,

Q = Quality factor,

f_0 = Central frequency,

κ = Chirp-rate (in Hz^2) of chirping sine-Gaussian.

SB, Dhurandhar, Gupta, Lundgren, arXiv:1606.06096 [gr-qc].

Sine-Gaussian glitches

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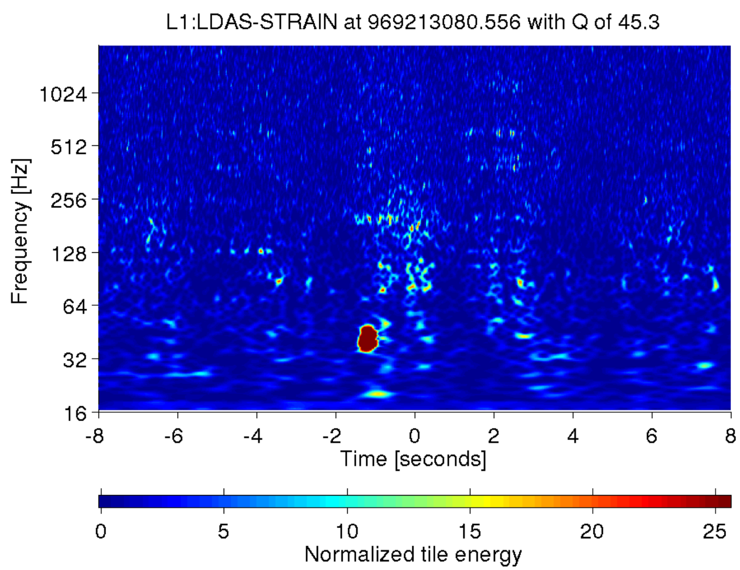
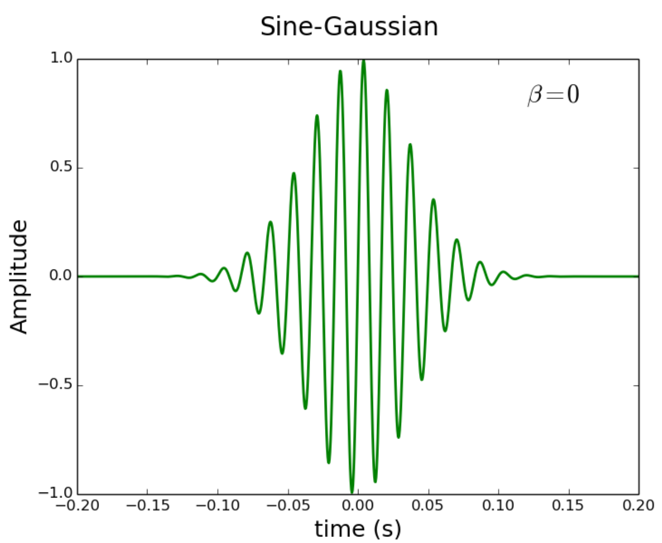




$$s(t) = e^{-t^2/\tau^2} \sin(2\pi f_0 t),$$

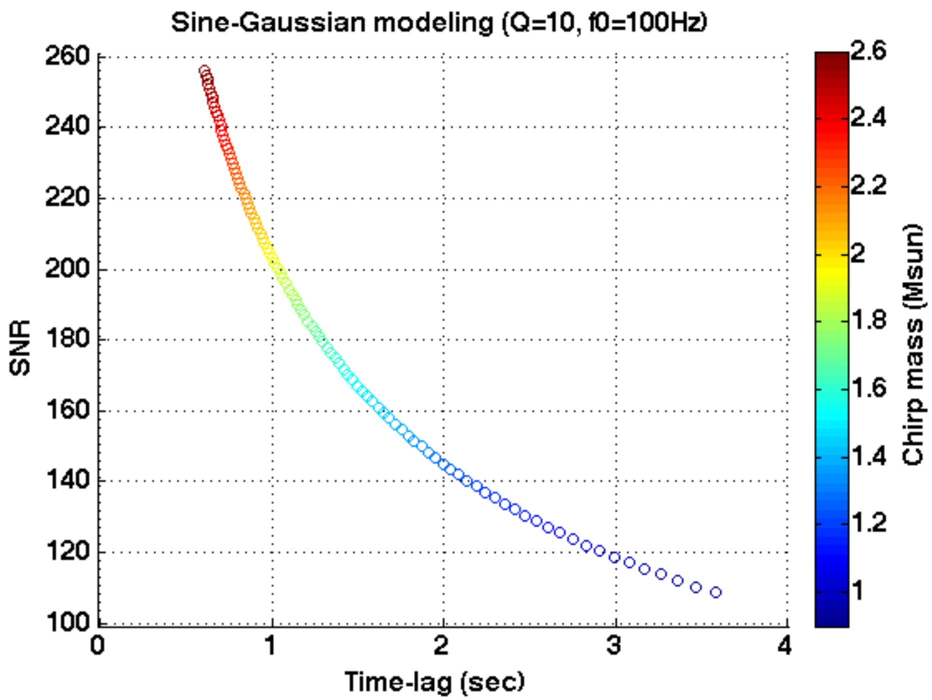
where $\tau = Q / (2\pi f_0)$

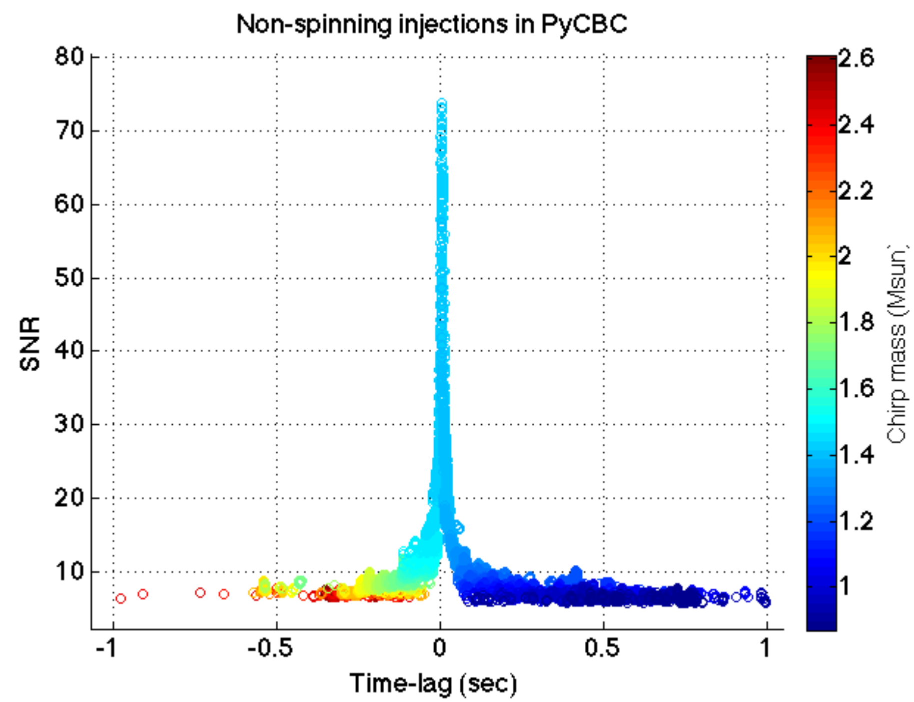
Q = Quality factor,

f_0 = Central frequency of sine-Gaussian

SB, Dhurandhar, Gupta, Lundgren, arXiv:1606.06096 [gr-qc].

Response of a CBC template-bank to a *CBC signal*





Prediction from theoretical modeling of effect of a sine-Gaussian glitch on CBC template SNRs and time-lags.

The above plot shows what a search pipeline produces *for a CBC signal.*

SB, Dhurandhar, Gupta, Lundgren, arXiv:1606.06096 [gr-qc].

Total mass, symmetrized mass-ratio & chirp mass:

$$M = m_1 + m_2, \quad \eta = \frac{m_1 m_2}{M^2}, \; M_c = \eta^{3/5} M \, .$$

Why the time-lag?

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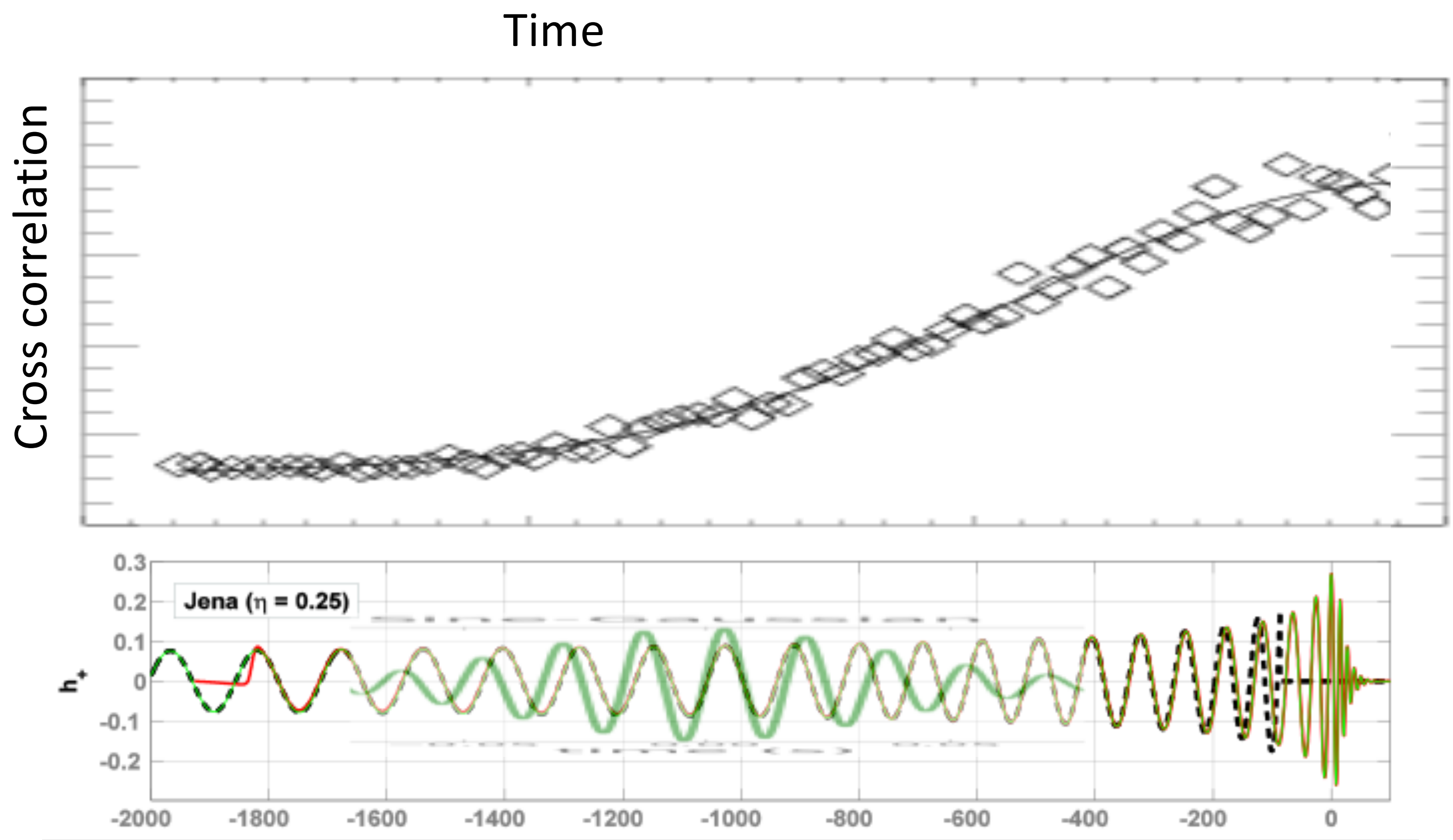

Time lag

Response of a CBC template-bank to a *CBC signal*

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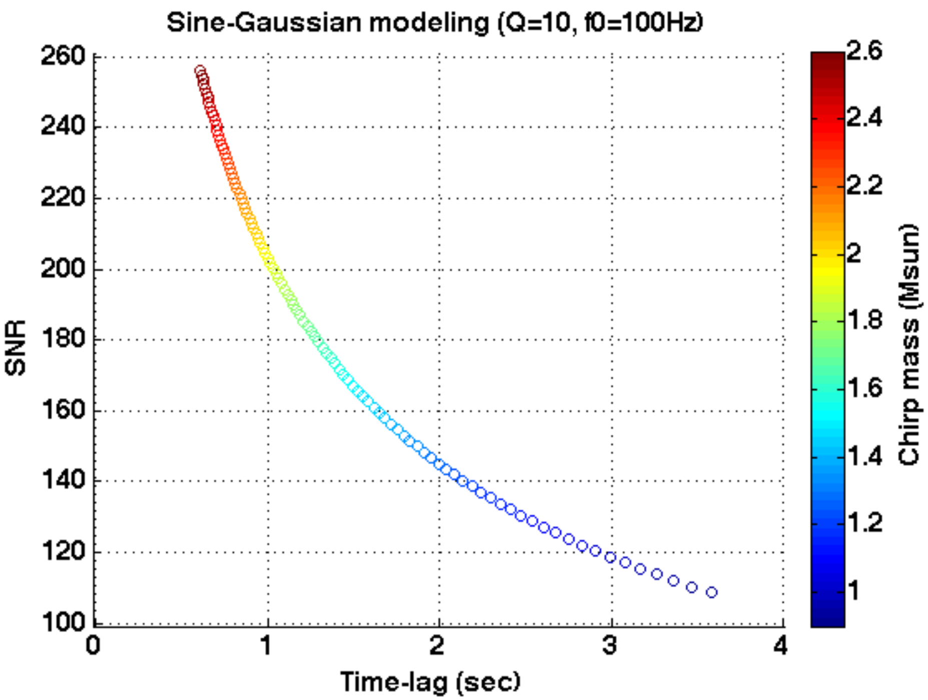
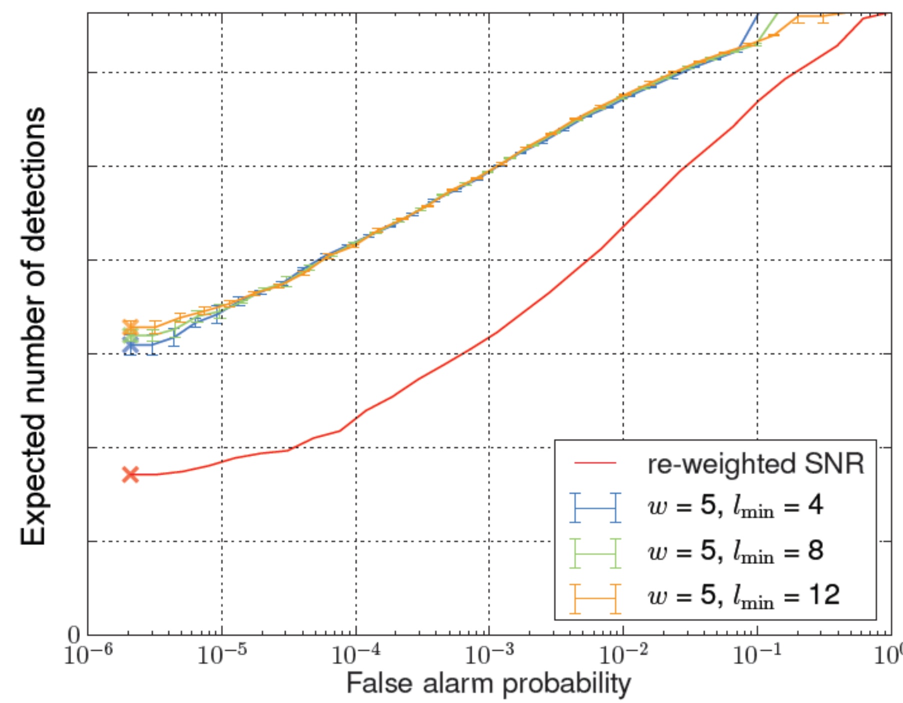


Prediction from theoretical modeling of effect of a sine-Gaussian glitch on CBC template SNRs and time-lags.



The above plot shows what a search pipeline produces *for a CBC signal.* The above difference is perhaps one clue as to why machine learning tools are now able to discriminate better glitches from signals. *[S. Kapadia, R. Dent,, LIGO-G1500537.]*

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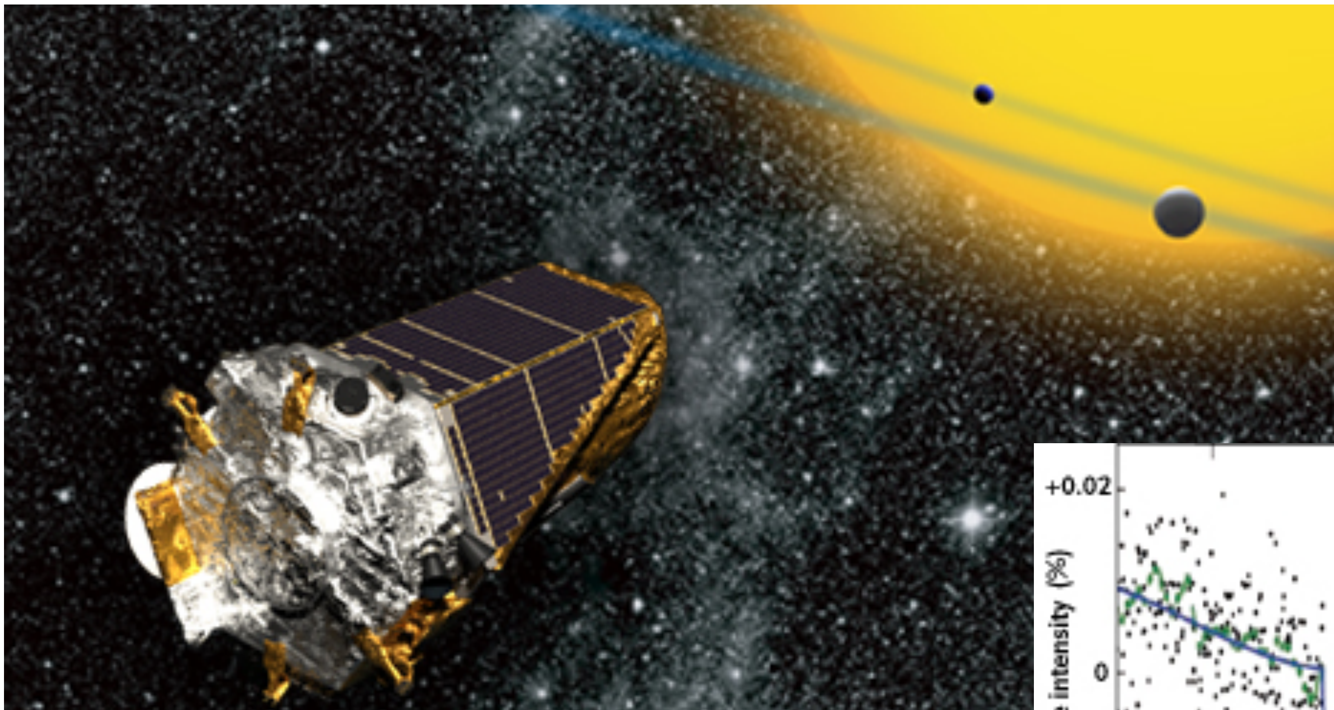
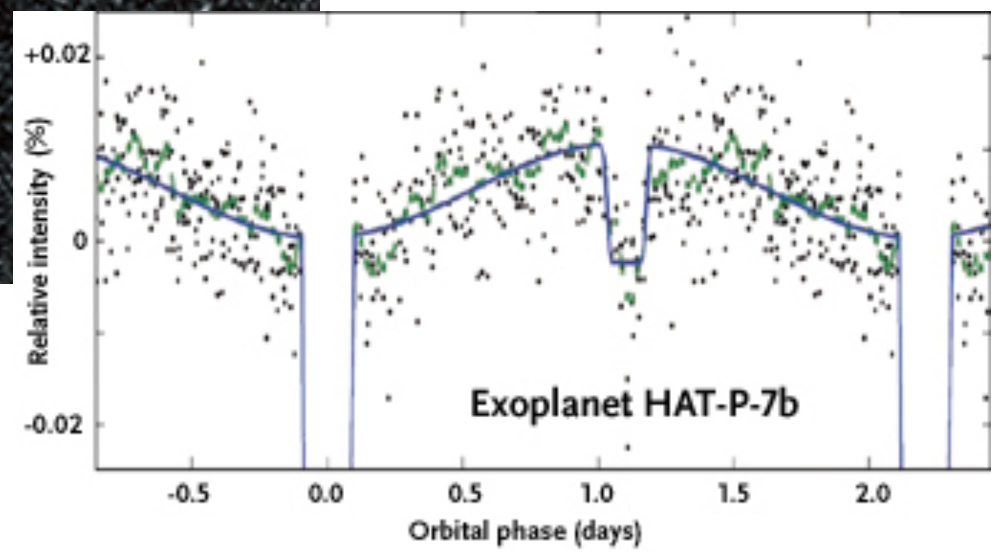
GW applications in other areas of science?



The Kepler mission



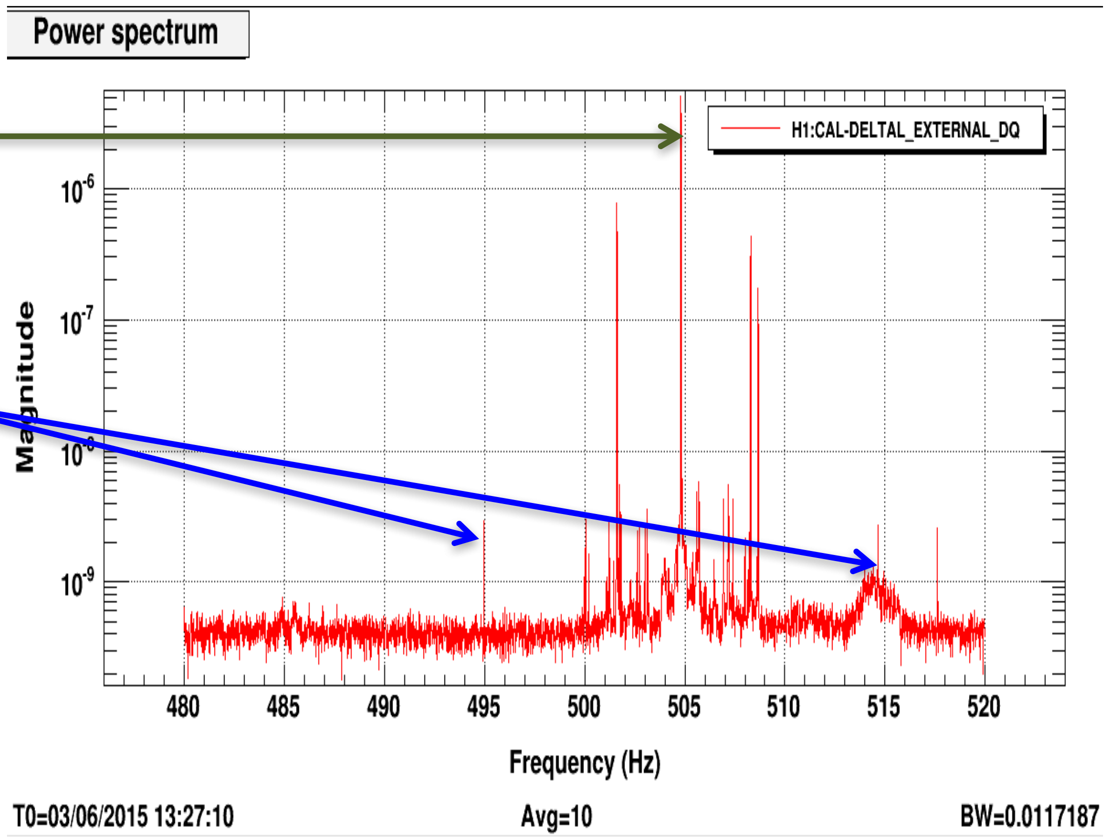
GW methods have aided exo-planet discoveries!

S. Seader et al., Astrophys.J.Sup. 206 (2013) 25.

HOSA: Nonlinear noise couplings as possible sources of glitchiness

Violin mode at ~505Hz…

…couples, e.g., with the 10Hz bounce mode of the test mass.



Bounce mode (f_2=10Hz) of H1 ITMY couples with its violin mode (f_1=505Hz) to create a side-band at (f_3=495Hz).

1. *SB*, B. Hall, N. Mazumder, S. Dhurandhar, A. Gupta, A Lundgren, *published* [LIGO-G1500496].
2. Abbott et al. (LVC), Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914, arXiv:1602.03844 [gr-qc]; 3. J. Aasi et al. (LSC), CQG 32, 115012 (2015);
4. L. Nuttall et al., CQG 32, 245005 (2015); 5. V. Tiwari et al. (LSC), CQG 16, 165014 (2015).

Transient nature of nonlinear coupling: *Bispectrum (fixed range)*

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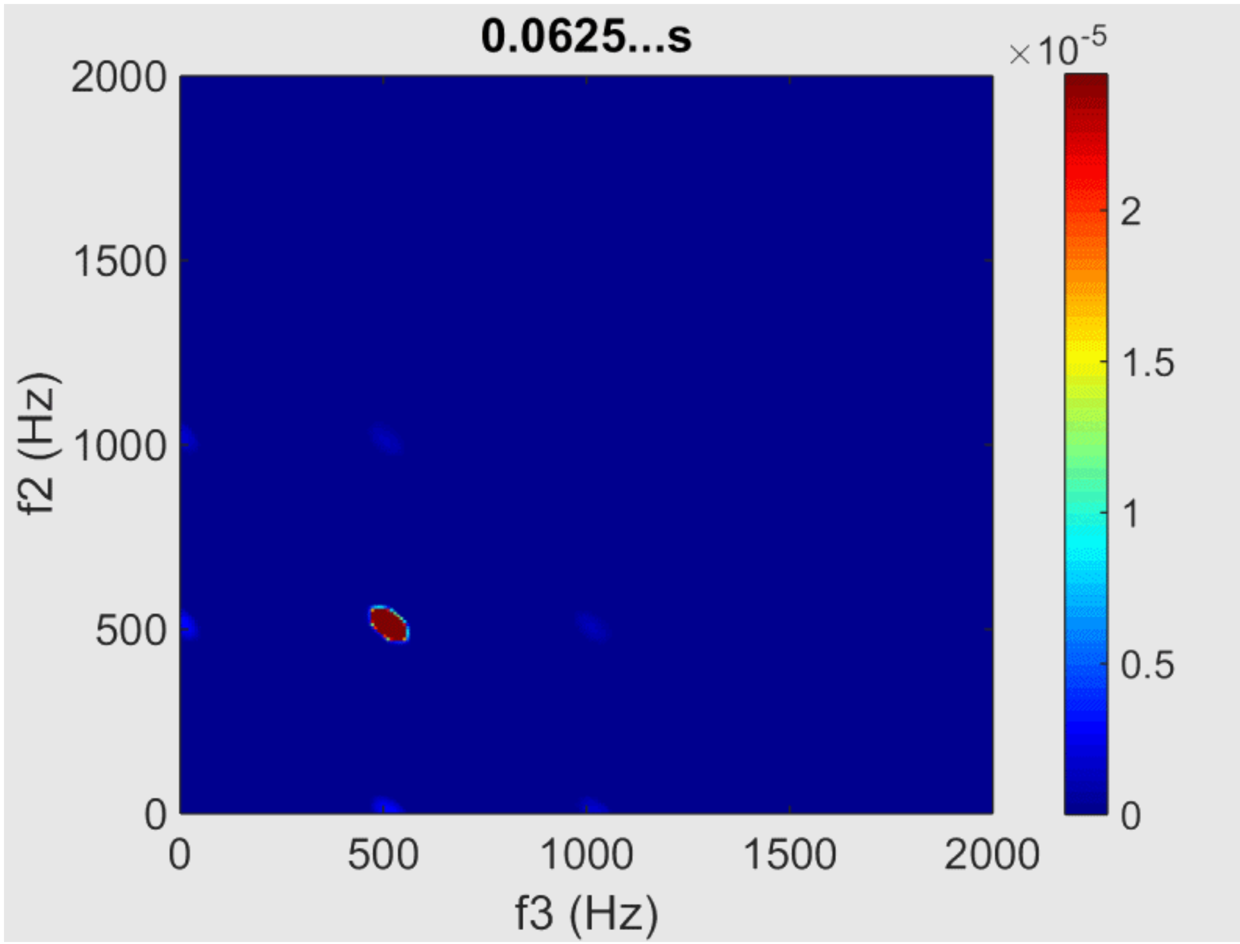

Animation made by *Bernard Hall* [LIGO-G1500496].

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Higher order statistics

Presence of QPC can be detected by the bispectrum:

Biphase

$$B(f_1,f_2) = \frac{1}{M}\sum_{k=1}^{M} X_k(f_1) Y_k(f_2) Z_k^*(f_1+f_2),$$

$$= \frac{1}{M}\sum_{k=1}^{M} A_k^x(f_1) A_k^y(f_2) A_k^z(f_1+f_2)\, e^{i\left(\phi_k^x(f_1)+\phi_k^y(f_2)-\phi_k^z(f_1+f_2)\right)}, \quad (4)$$

where *X* and *Y* are the Fourier transforms (FTs) of data, e.g., in two auxiliary channels that may or may not have nonlinear couplings, and *Z* is the FT of the GW channel. The normalized bispectrum is the bicoherence:

$$r(f_1,f_2) = \frac{B(f_1,f_2)}{\frac{1}{M}\sqrt{\sum_{i=1}^{M}\left|X_i(f_1)Y_i(f_2)\right|^2 \sum_{i=1}^{M}\left|Z_i(f_1+f_2)\right|^2}}.$$

Plots show the absolute values of *B* and *r*.

- V. Chickarmane, G. Gonzalez, LIGO-G020327;
- S. Penn, LIGO-G060139.

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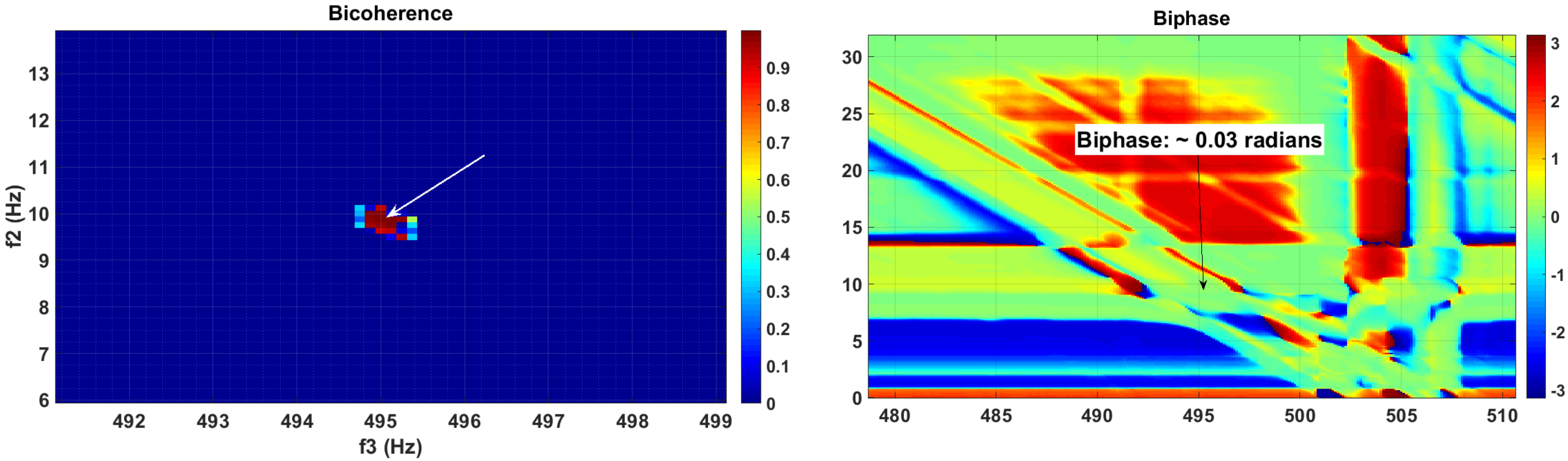
Some examples of nonlinear noise couplings - I

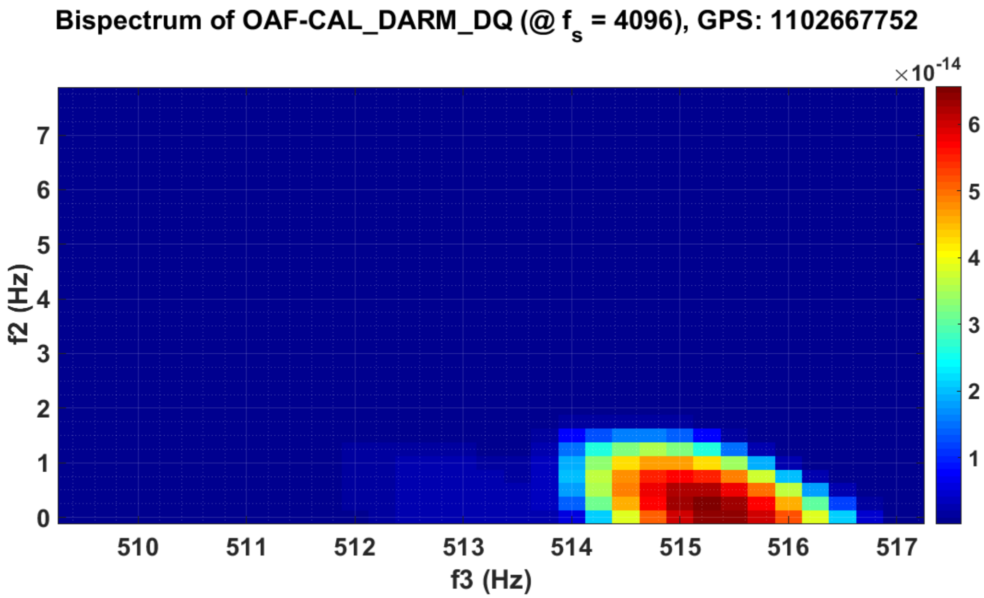


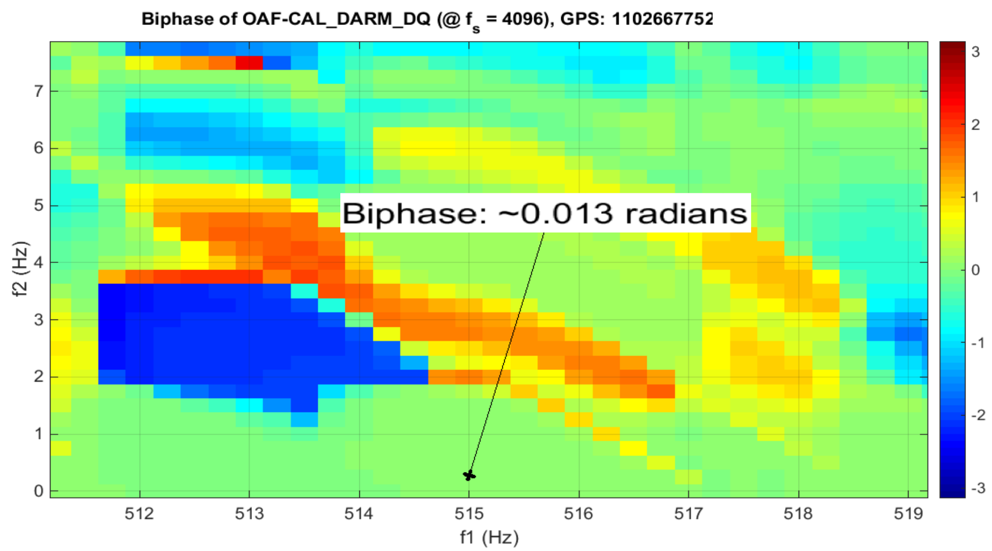
Case 1: Bounce mode (f_2=10Hz) of H1 ITMY couples with its violin mode (f_1= 505Hz) to create a side-band at (f_3=495.Hz).

[SB, B. Hall, N. Mazumder, S. Dhurandhar, A. Gupta, A. Lundgren, arxiv.org/abs/1602.02621 .]

Some examples of nonlinear noise couplings - II

IUCAA





Case 2: Microseismic (f_2=0.15Hz) in L1 couples with its violin mode (f_1= 515.5Hz) to create a side-band at (f_3=515.35Hz).

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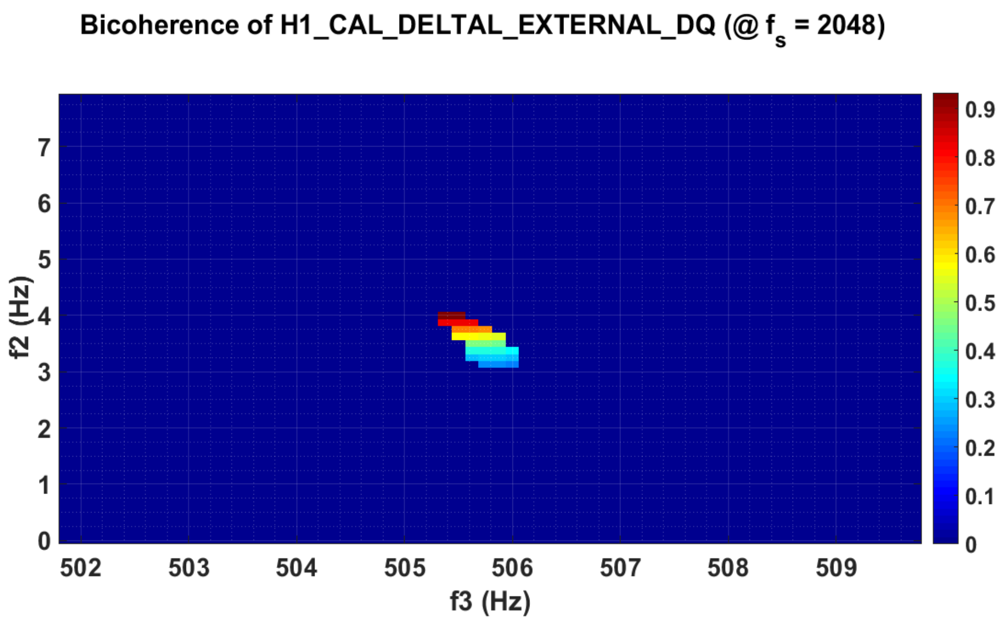
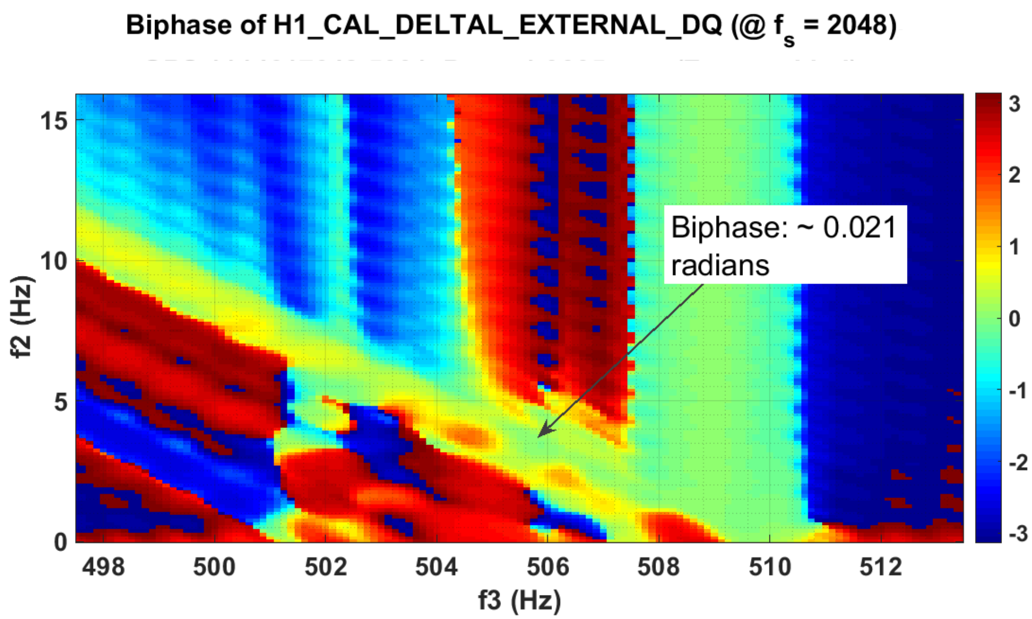
Some examples of nonlinear noise couplings - III

IUCAA





Case 3: A suspension mode (f_2=3.8Hz) of H1 couples with its violin mode (f_1= 509Hz) to create a side-band at (f_3=505.2Hz).

 f_3(Hz)

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Take home messages

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- Coincident EM/particle and GW observations are the future, but face challenges.
- Speed is of essence: GW data analysis (battling non-Gaussianity, large search space); complying, fast slewing EM observatories scanning possibly large sky patches.
- Learning from machines: If the pattern of trigger times of multiple templates was found useful by a machine, then humans can use that information to target detector / observatory noise sources.
- Scope for learning from each other.