MAX PLANCK INSTITUTE
FOR GRAVITATIONAL PHYSICS
(ALBERT EINSTEIN INSTITUTE)

Modelled searches in LIGO data
for
Compact Binary Coalescences

Ofek Birnholtz

on behalf of LIGO & VIRGO Collaborations

Gravitational Waves and Compact Objects Workshop

הטכניון מכון טכנולוגי לישראל TECHNION Israel Institute of Technology

23 November 2016

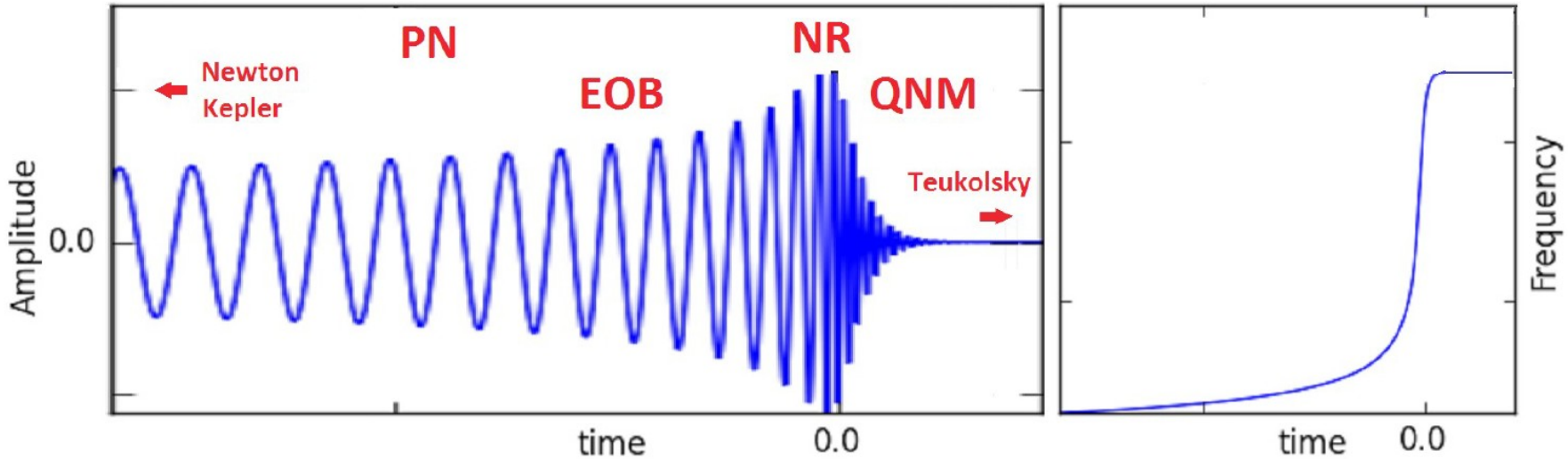
LVC References

[1] GW150914 Detection, arXiv:1602.03837
[2] CBC Searches, arXiv:1602.03839
[3] Parameter Estimation (PE), arXiv:1602.03840, arXiv:1606.01210
[4] Testing GR, arXiv:1602.03841
[5] Detector Characterization (DetChar), arXiv:1602.03844
[6] Basic Physics, arXiv:1608.01940
[7] GW151226, arXiv:1606.04855
[8] O1 BBH, arXiv:1606.04856

Modelled CBC Searches

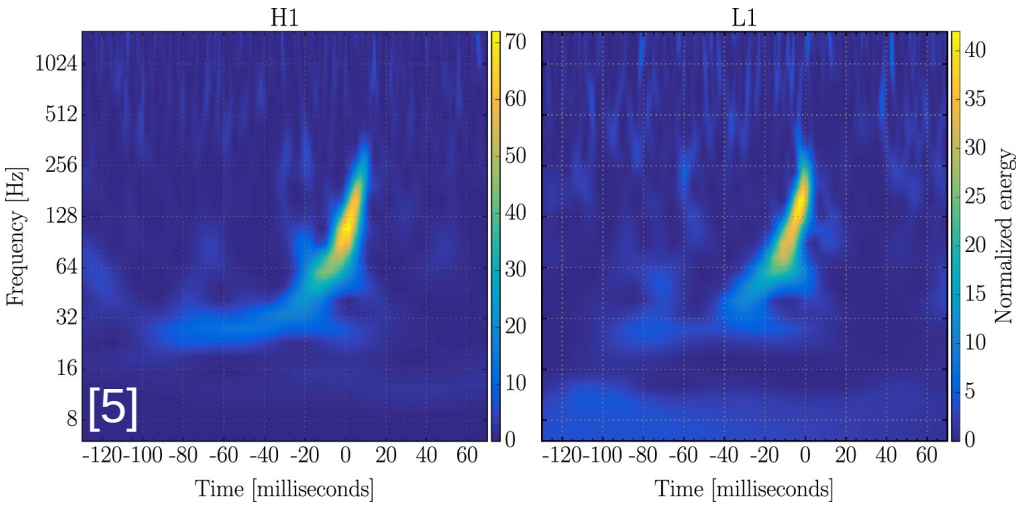
- What we search for
- How we do it
- What we do when we find it

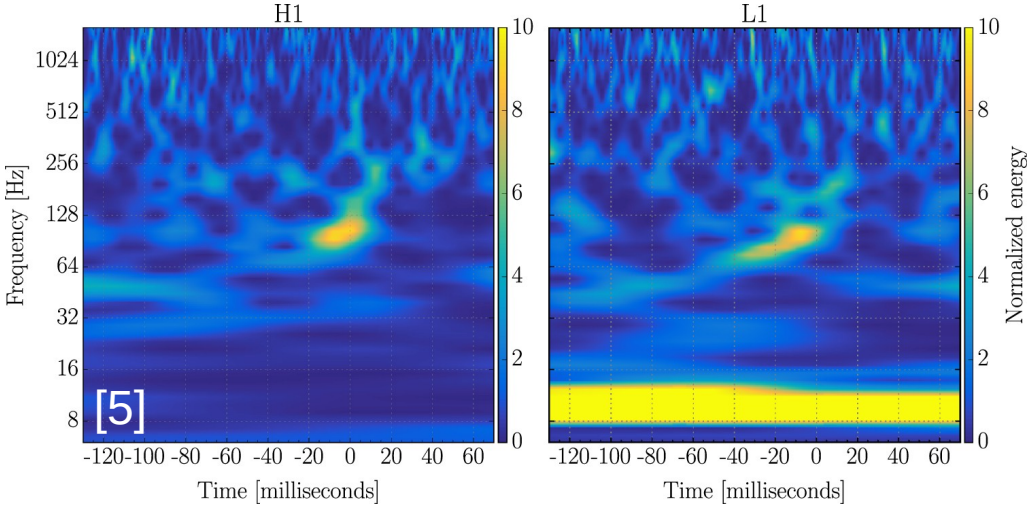
What a signal looks like

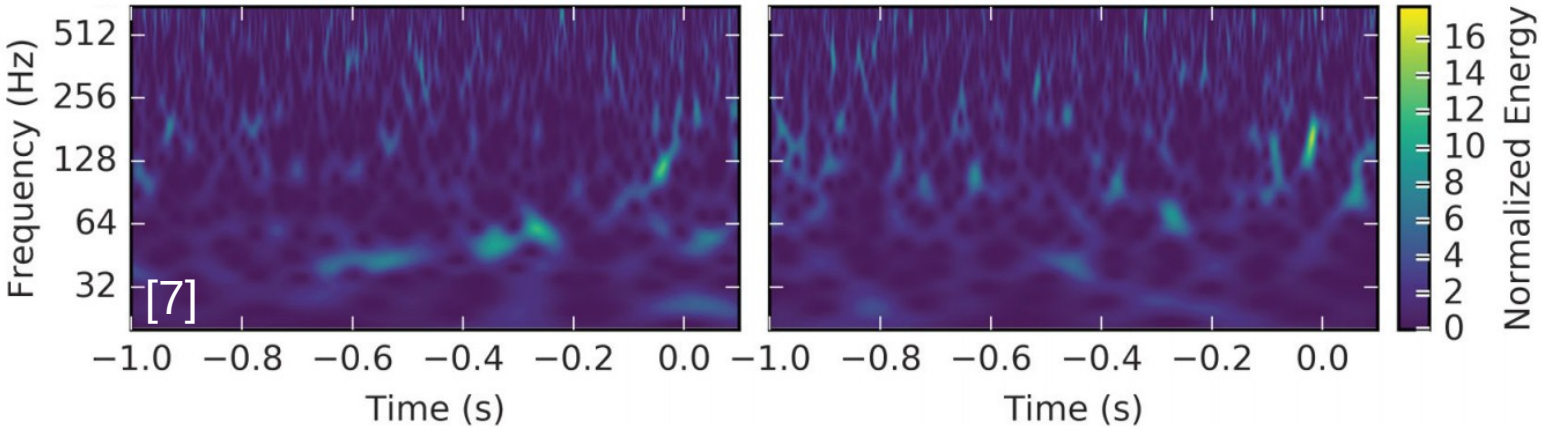


- The post-Newtonian parameter x : $\sqrt{x} = v/c = \omega r/c = \sqrt[3]{\pi G M f_{GW}}/c$
- For $x \sim 0.1$: $\frac{M}{20\,\mathrm{M}_\odot} \sim \frac{100\,\mathrm{Hz}}{f_{GW}}$
- $M = m_1 + m_2$ $\left(\frac{G\,\mathrm{M}_\odot}{c^3} \sim 5\mu s\right)$

What a signal ***really*** looks like







The window

- The Quadrupole Formula: $h_{ij} = \frac{2\,G}{c^4\,d_L}\frac{\mathrm{d}^2 Q_{ij}}{\mathrm{d}t^2}$

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} = \frac{c^3}{16\pi\,G}\iint |\dot{h}|^2 \mathrm{d}S = \frac{1}{5}\frac{G}{c^5}\sum_{i,j=1}^{3}\frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3}\frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3}$$

- Defining the chirp mass:

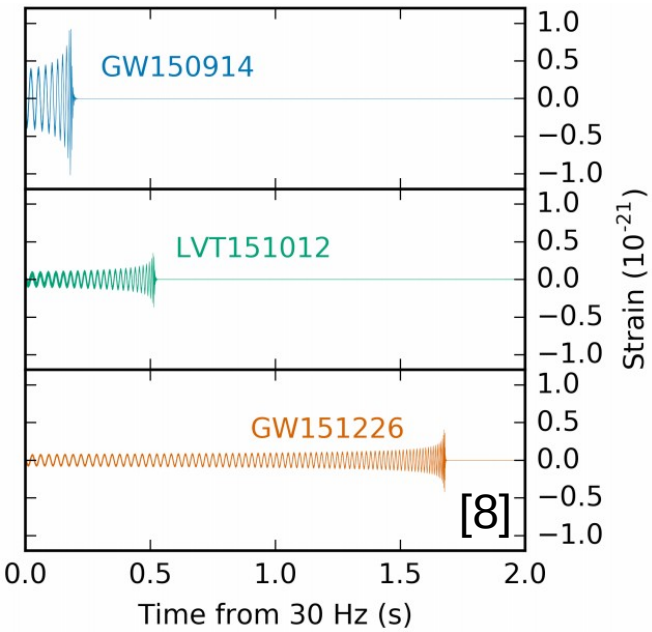
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

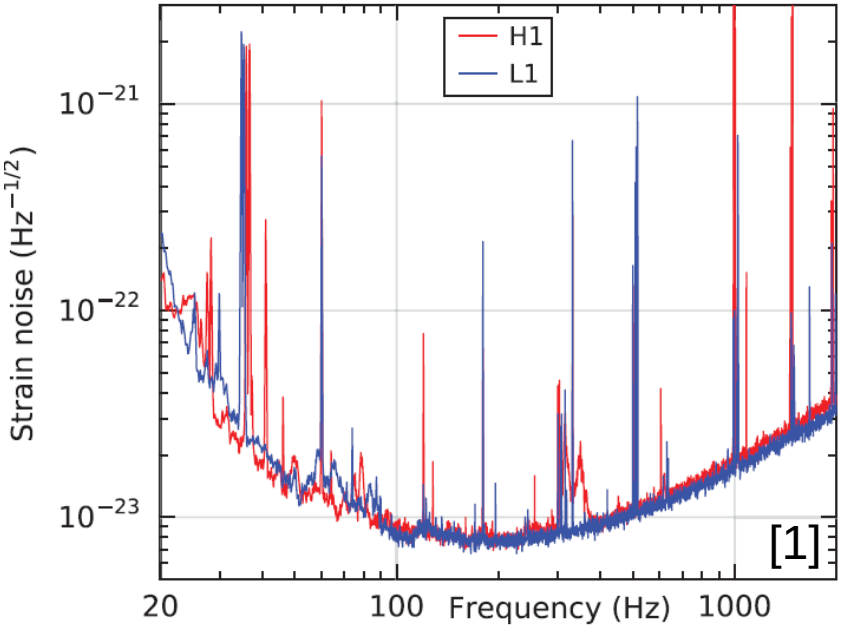
- Frequency evolution:

$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{G\,\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

- Time in the band:

$$\tau_0 = \frac{5}{256}\left(\pi f_{ref}\right)^{-8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{-5/3}$$





Matched Filtering

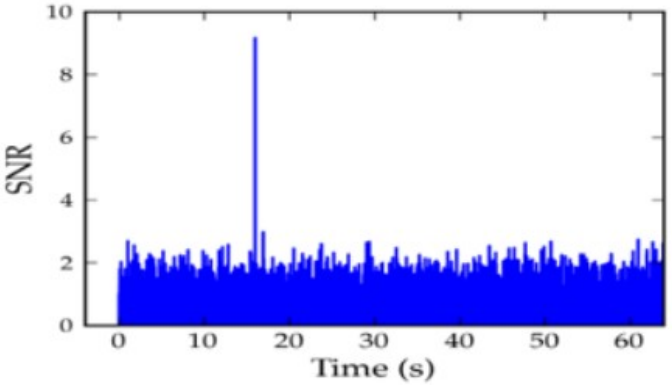
- Measure the Noise Power Spectrum Density (PSD) $S_n(f)$
- Define Scalar product

$$<a|b> = 4\int_0^\infty \frac{\tilde{a}^*(f)\,\tilde{b}(f)}{S_n(f)}df$$

- Signal-to-(Gaussian)Noise Ratio (SNR) of template h in measured strain s

$$\rho = \frac{|<h|s>|}{\sqrt{<h|h>}}$$

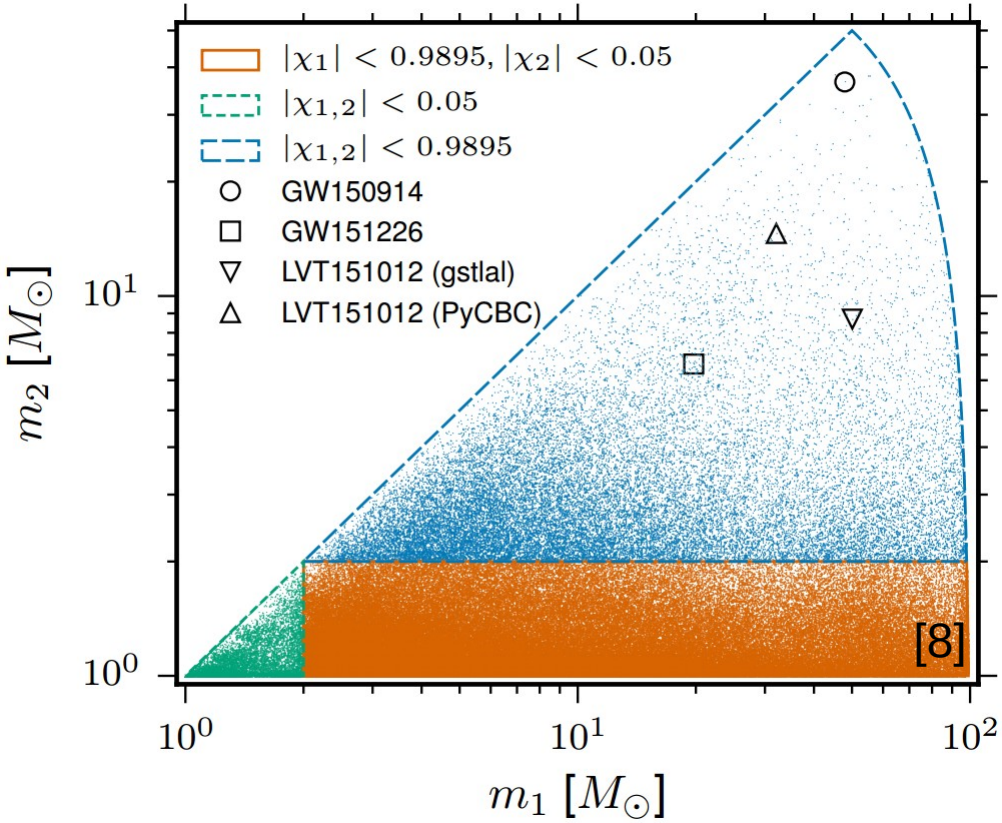
- Find ***Triggers***, which maximize $\rho(t)$



Courtesy of A. H. Nitz

The Template “Über”-bank

- 4 free parameters:
  - $m_{1,2}$ masses
  - $\chi_{1,2} = \frac{c\,\mathbf{S}_{1,2}\cdot\hat{\mathbf{L}}}{G\,m_{1,2}^2}$ aligned spins
- 2 waveform models:
  - TaylorF2 $M < 4\mathrm{M}_\odot$
  - SEOBNRv2 $M > 4\mathrm{M}_\odot$
- 2 population methods:
  - Geometric $\mathcal{M} < 1.5\mathrm{M}_\odot$
  - Stochastic $\mathcal{M} > 1.5\mathrm{M}_\odot$



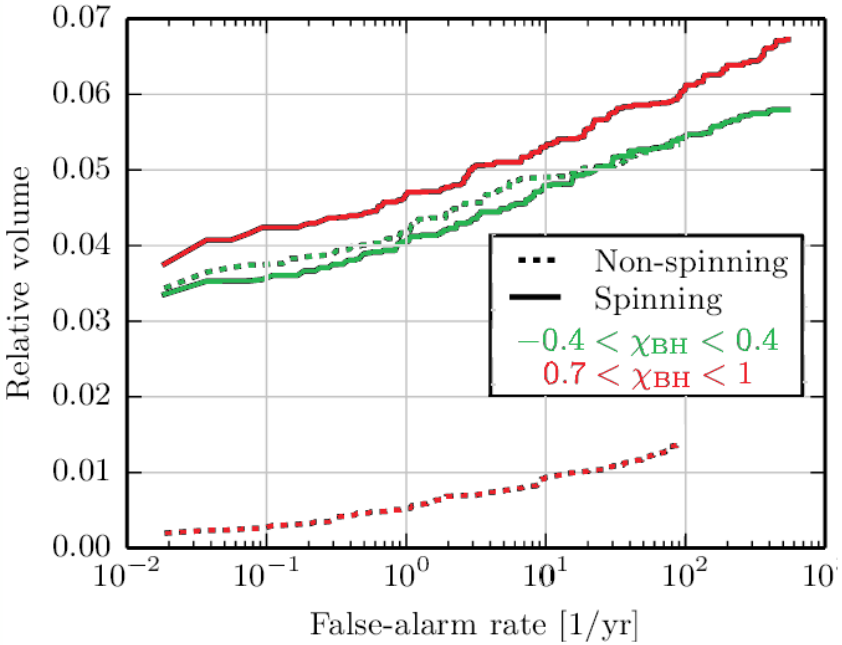
- Mismatch >3% for <1% of signals (ER8 PSD)
- ~250,000 templates

Precession

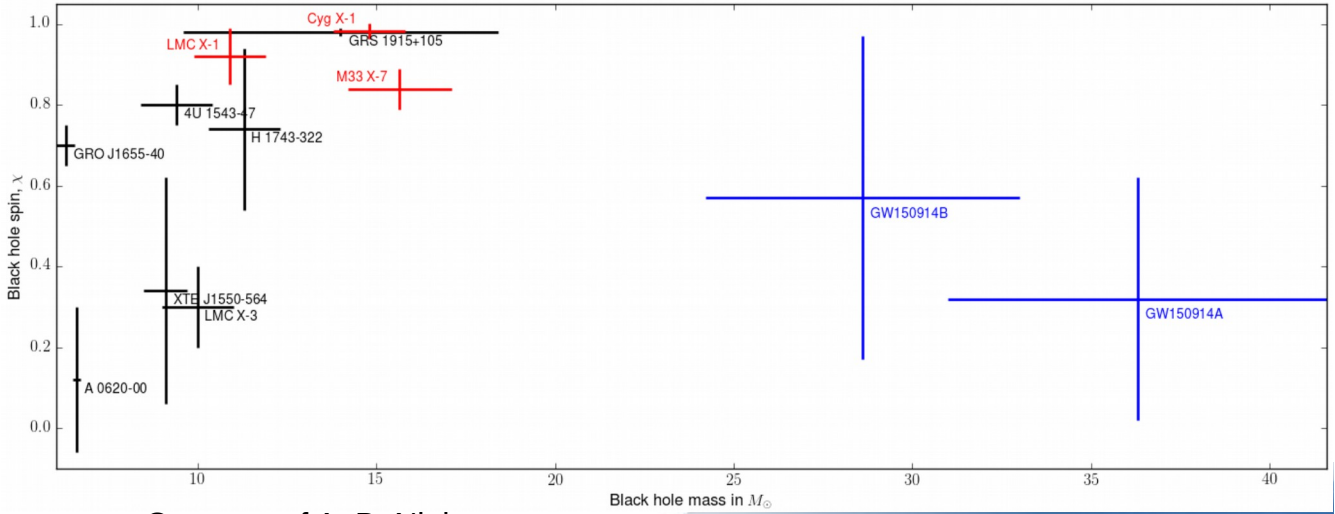
- Überbank effectual if only little precession
- Generally, precession adds ~10 spin+sky free parameters

↓ ↓

Aligned search
+
precession in post-analysis



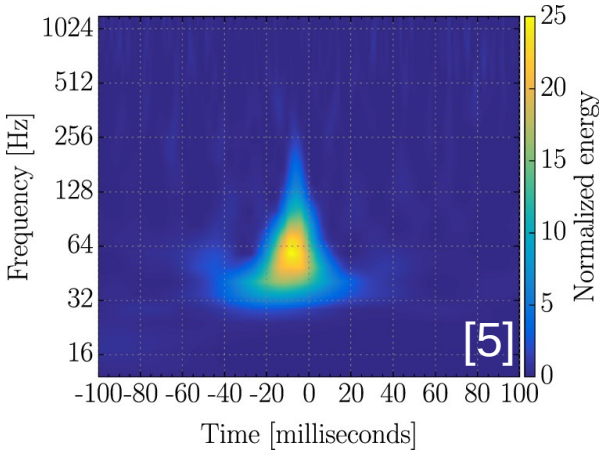
T. Dal Canton et. al, PRD 90, 082004, 2014



Courtesy of A. B. Nielsen

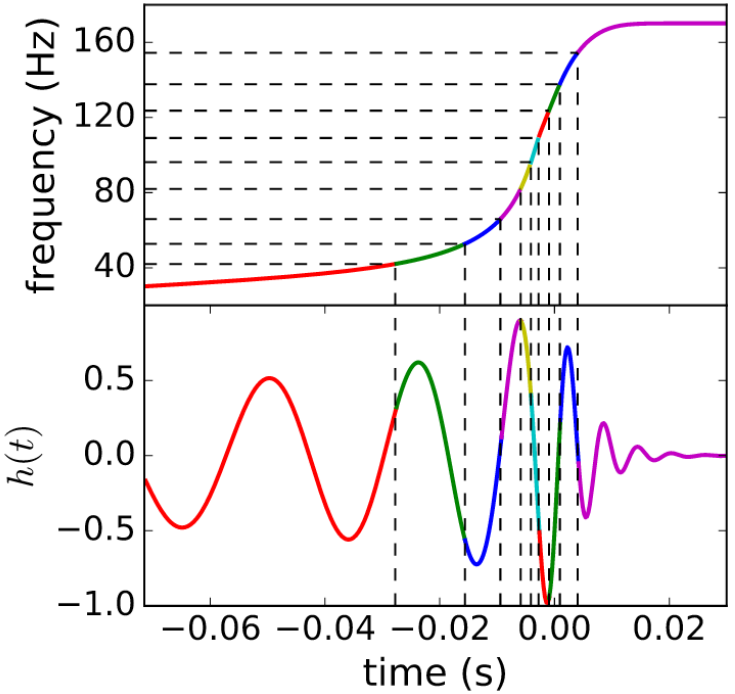
χ^2-test

- Background **not** Gaussian
  - Many loud triggers
  - Remove triggers with SNR > 300



- Measure distance to template:
  - Divide template h to bins $\{h_i\}$
  - Bins of equal power $\{<h_i|s>\}$
  - Calculate SNR bin-by-bin
  - Variance:

$$\chi_r^2 = \frac{p}{2p-2}\frac{1}{<h|h>}\sum_{i=1}^{p}\left|<h_i|s> - \frac{<h|s>}{p}\right|^2$$

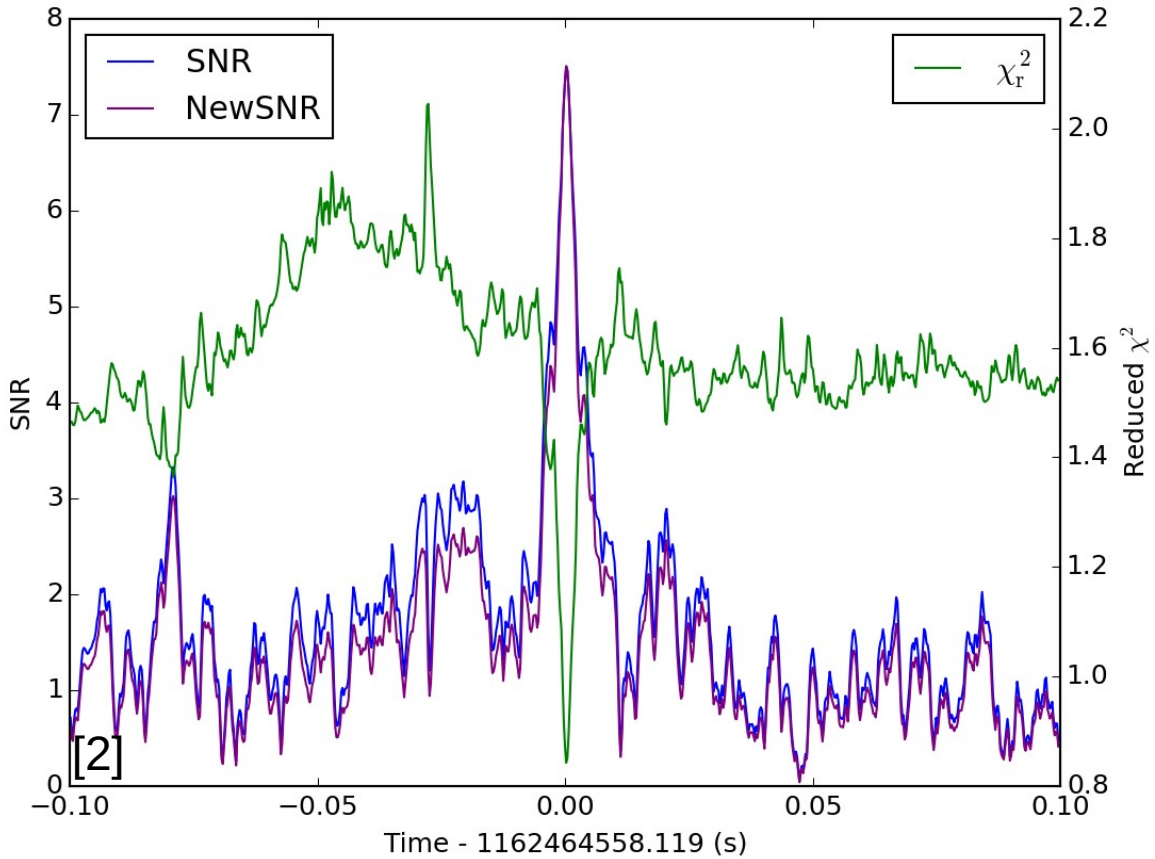


Courtesy of C. D. Capano

χ^2-test

- Penalize triggers using χ^2:

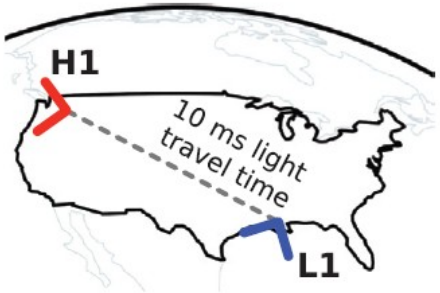
$$\tilde{\rho} = \rho \cdot \left[\frac{1 + \left(\max\left\{ \chi_r^2, 1 \right\} \right)^3}{2} \right]^{-\frac{1}{6}}$$



Coincidence test

- Still many significant triggers in each detector
- If astrophysical, should trigger *both*
  - light-travel-time 10ms
  - template auto-correlation time 5ms

  => 30ms window for trigger coincidence



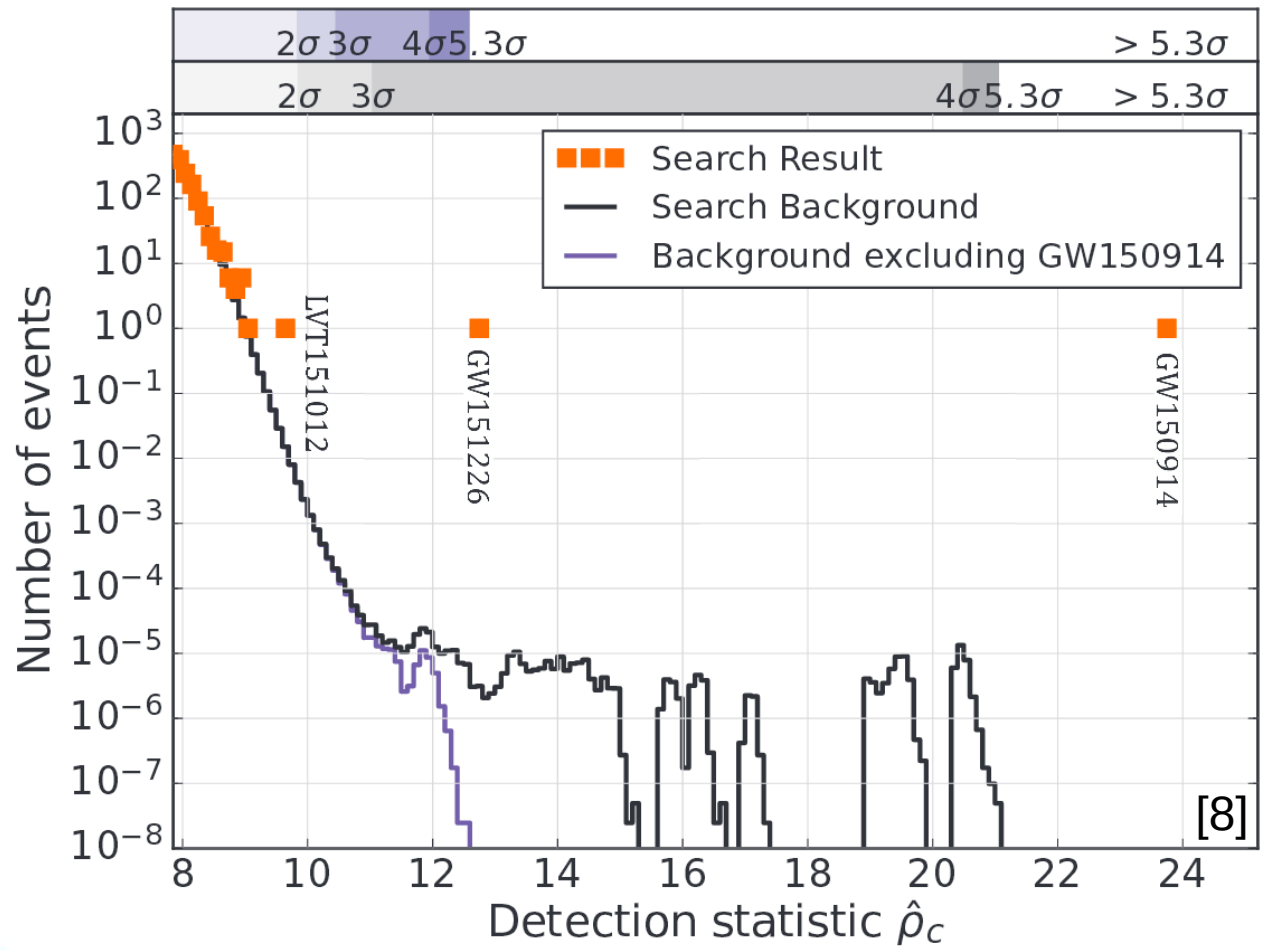
- Must be same template
- Combined coincident SNR (incoherent):

$$\tilde{\rho}_c = \sqrt{\tilde{\rho}_H^2 + \tilde{\rho}_L^2}$$

Background estimation

- Estimated using single-detector triggers
- By time-sliding between detectors
  - Ns = 10^7
  - Δt = 100ms
- How many louder?

$$\mathrm{FAR}(\tilde{\rho}_c) \sim \frac{n_b(\tilde{\rho}_c)}{N_S T}$$

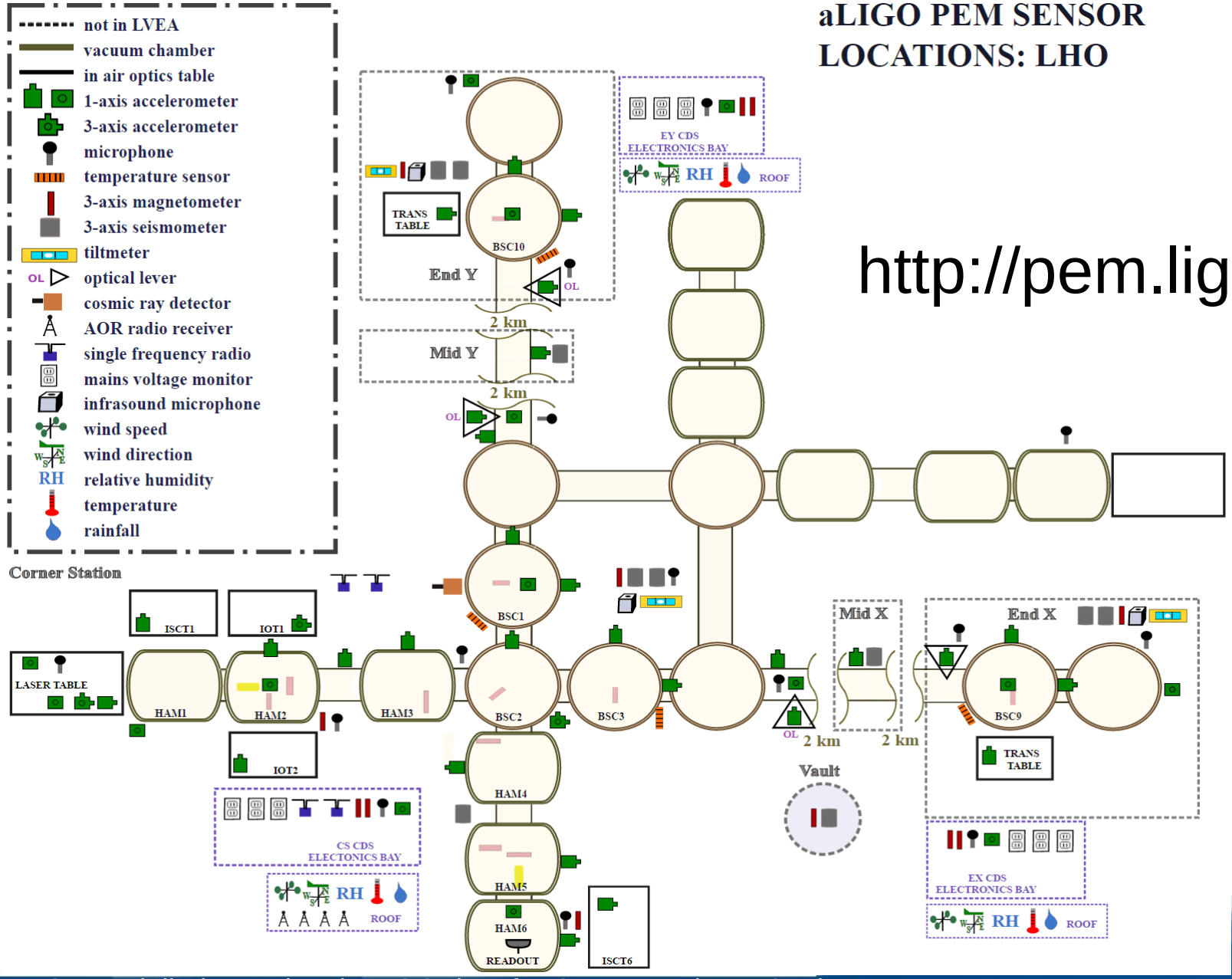


Data Quality

- Monitor possible external sources: earthquakes, lightnings, solar events, traffic...

- Auxiliary Channels:
  - ~200K Channels – mostly internal to detectors
  - Physical Environmental Monitoring (PEM): RF, microphones, magnometers, barometers, thermometers, wind & rain, cosmic ray detector...

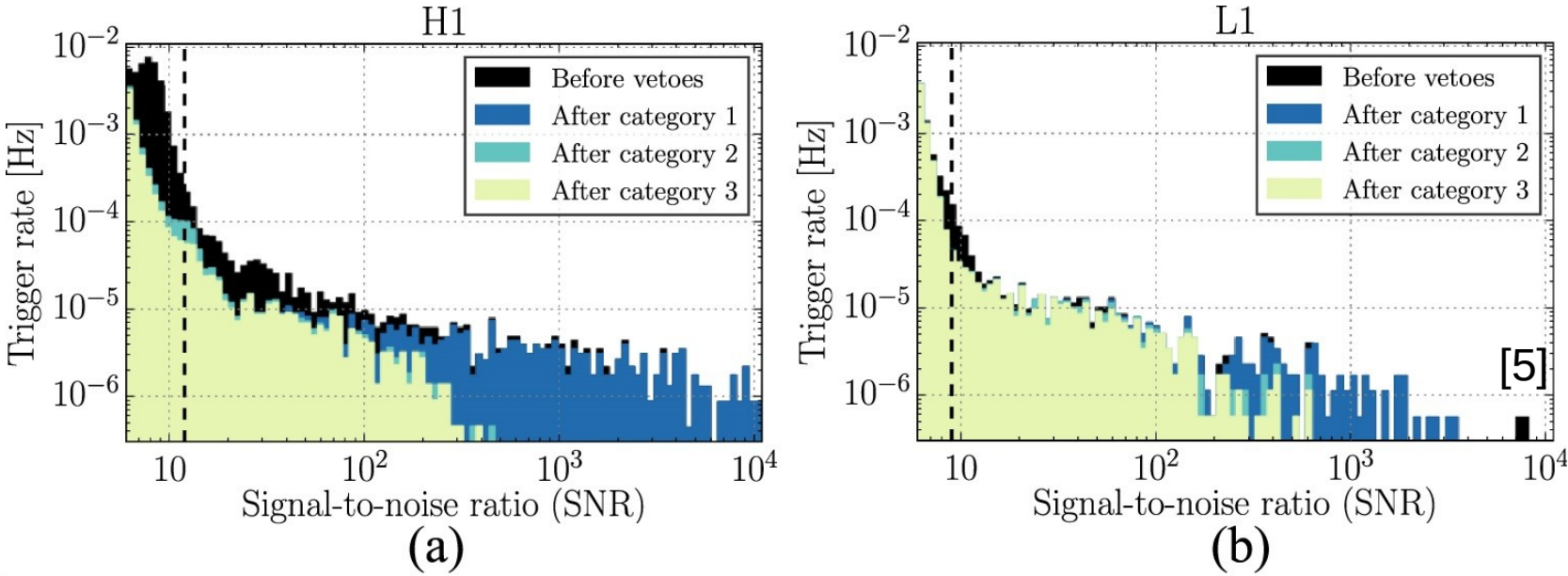
PEM at LHO



http://pem.ligo.org

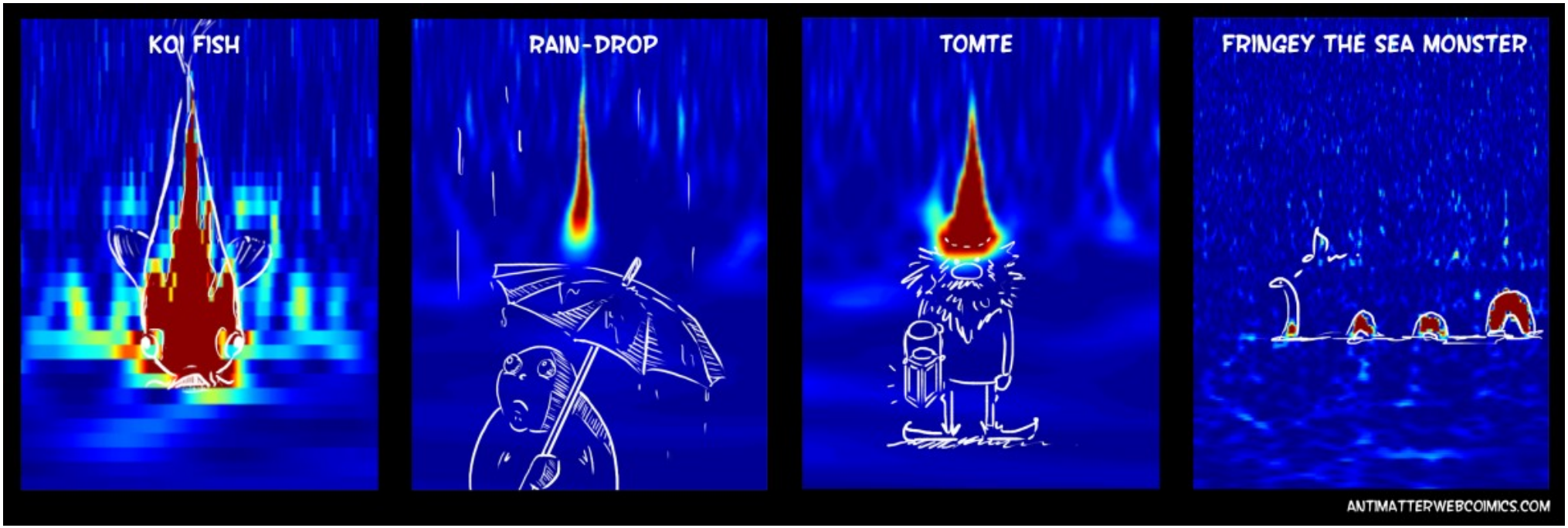
Data Veto Categories

- 1: critical issue in key detector component
  - global
- 2: active noise source with known physical coupling
  - search-specific
  - must be demonstratedly advantageous
  - must be safe
- 3: other



Characterizing Glitches

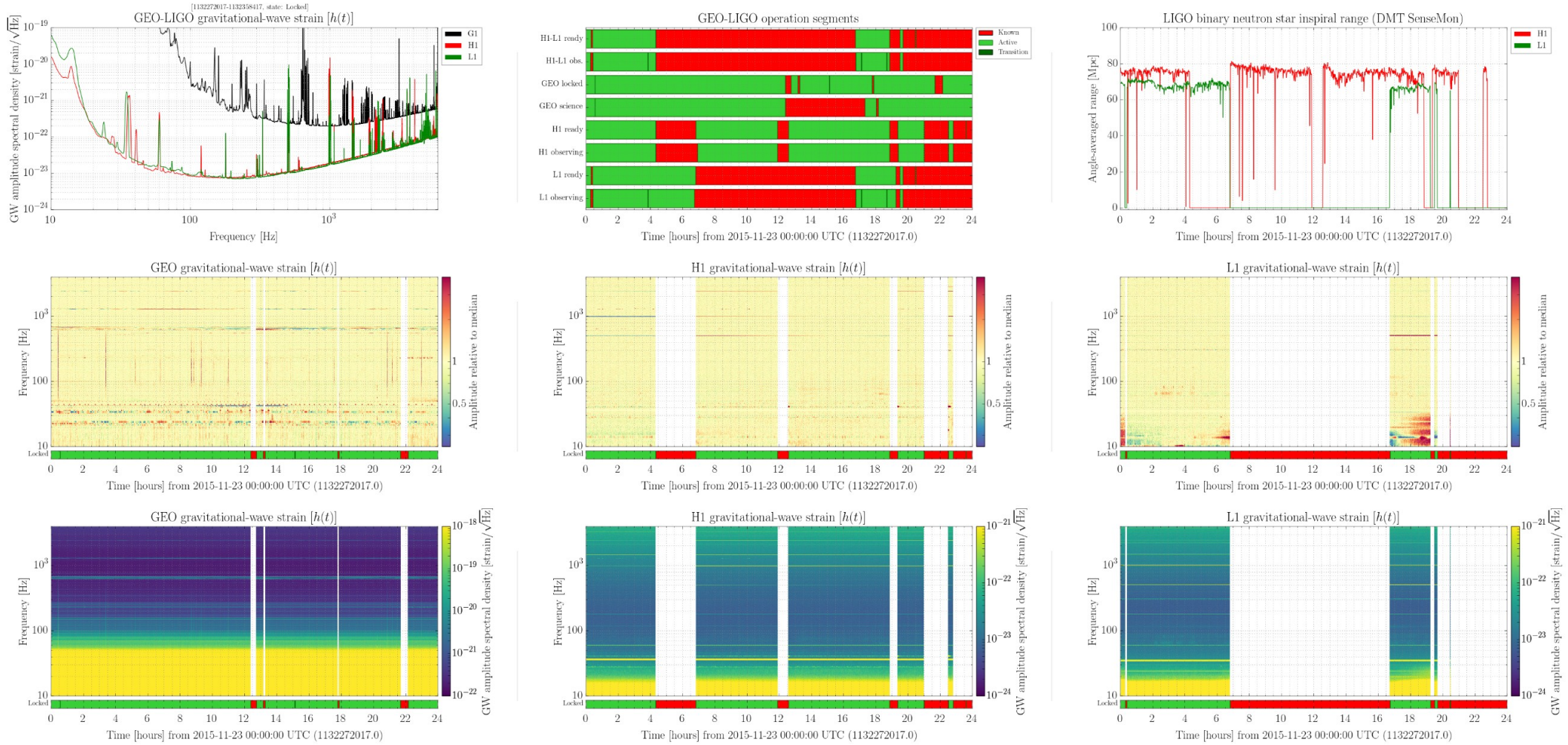
Begins manually…



… and continues to machine learning algorithms

Data Summary Page

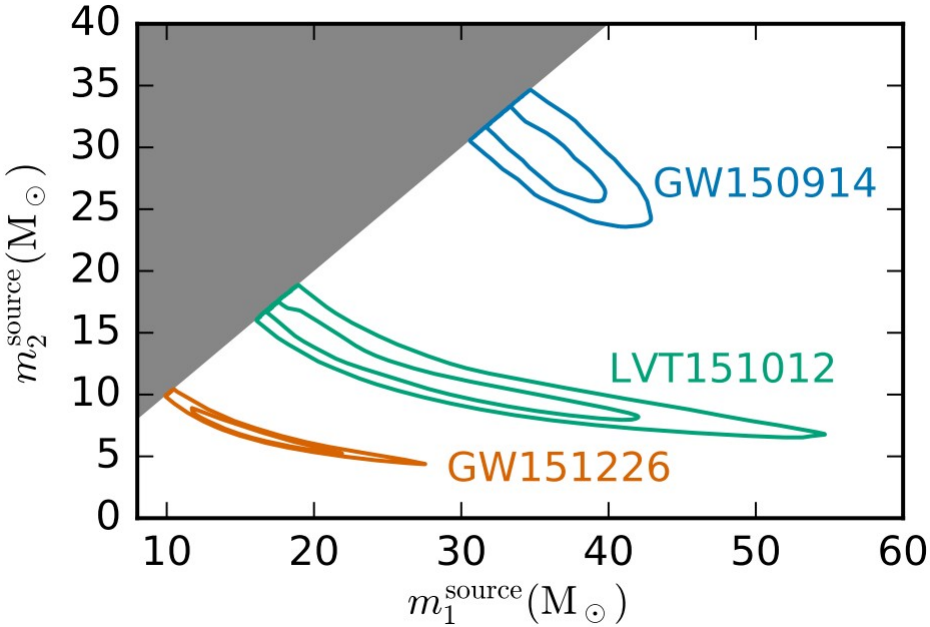
https://ldas-jobs.ligo.caltech.edu/~detchar/summary/day/20151123/

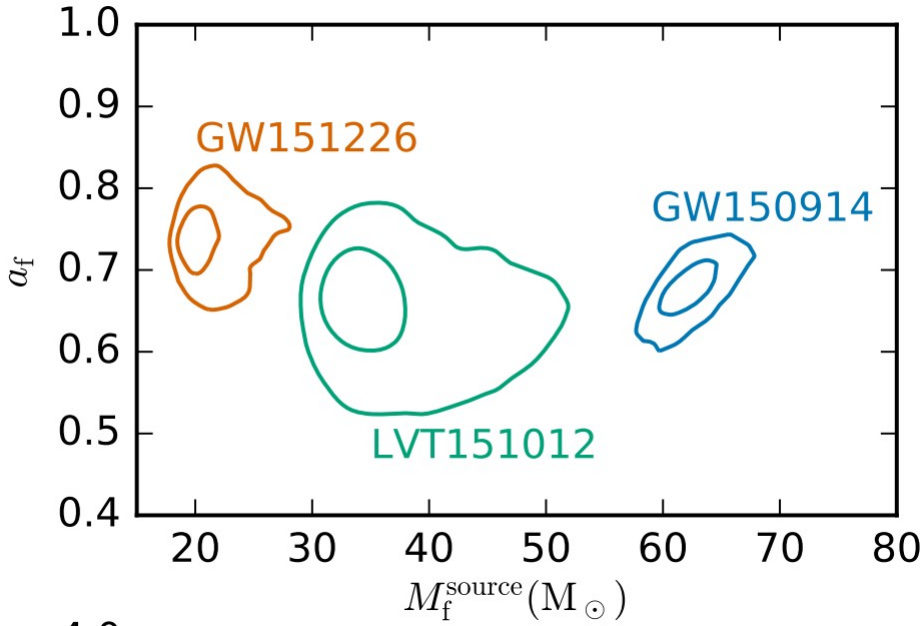


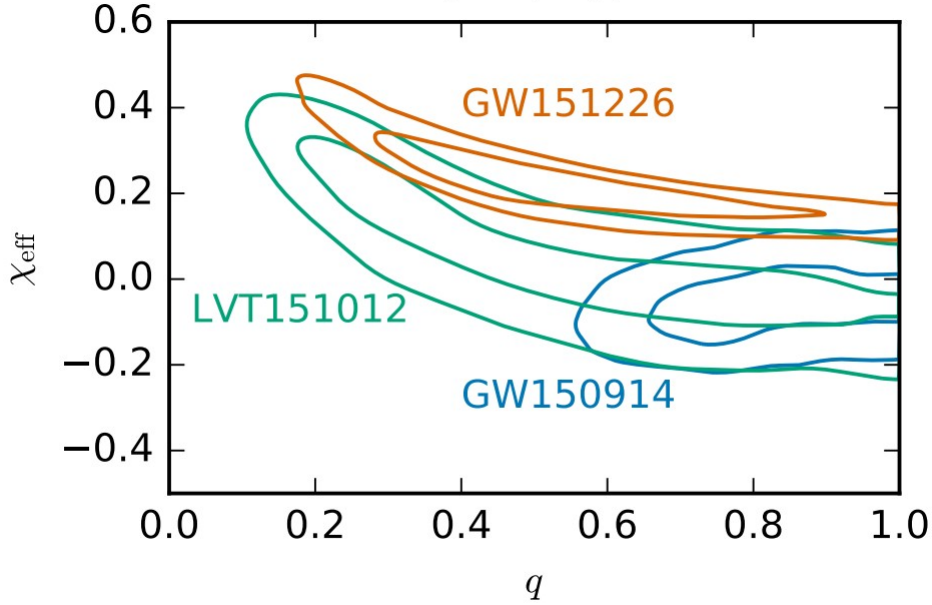
Parameter Estimation (PE)

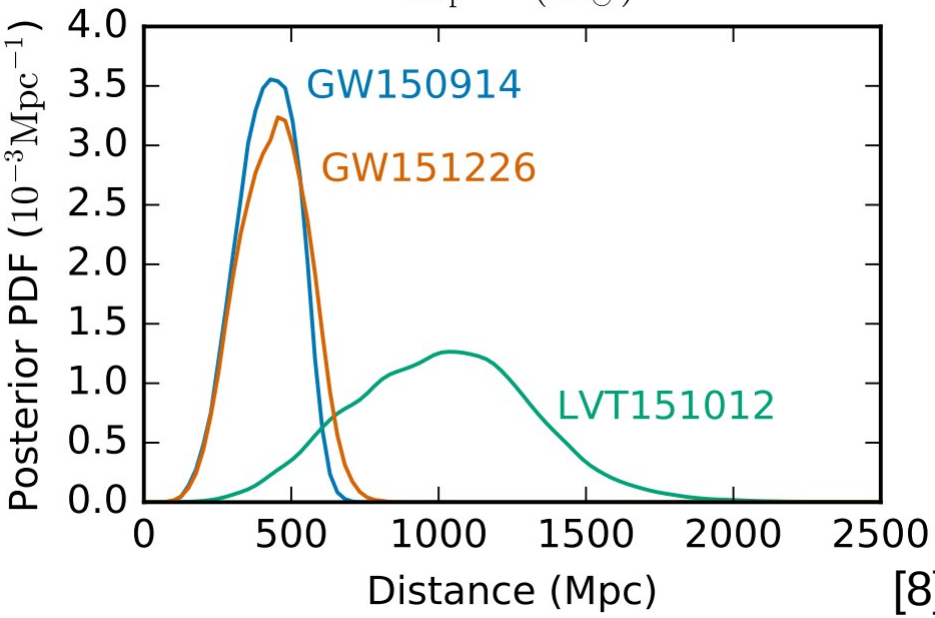
- Follow-up on Events
- “Opposite” problem to Searches:
  - maximum resolution, few triggers
- Stochastic Sampling Engines:
  - Markov Chain Monte-Carlo
  - Nested Sampling
- Priors from identified trigger (time)

PE – sample results









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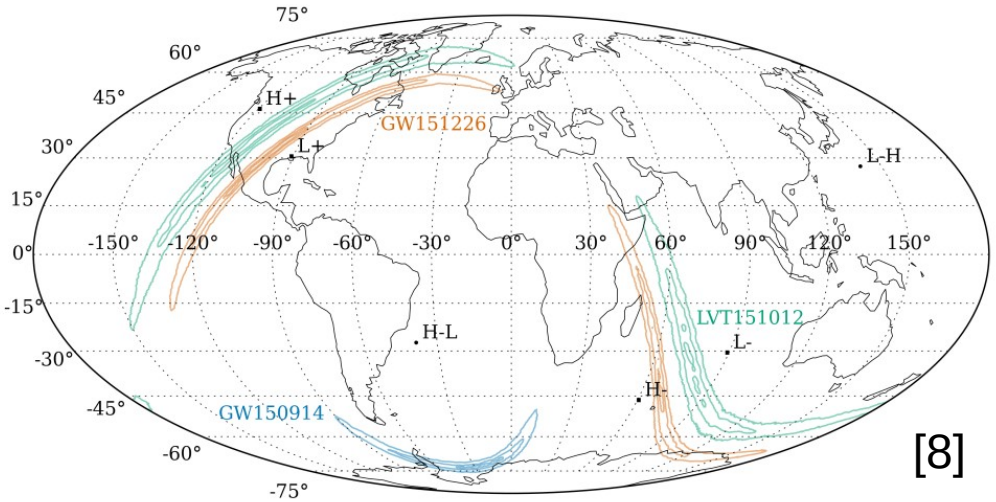
PE – richer physics

- Sky Location
- More waveform approximants:
  - IMRPhenomD
  - Precession: IMRPhenomP, SEOBNRv3
    - Little precession / small mass ratio
    - Effective spin
- Modified waveforms:
  - Eccentricity
  - Matter effects, NS E.O.S
  - Modifications to GR
- Focus on particular parts (inspiral, ringdown...)



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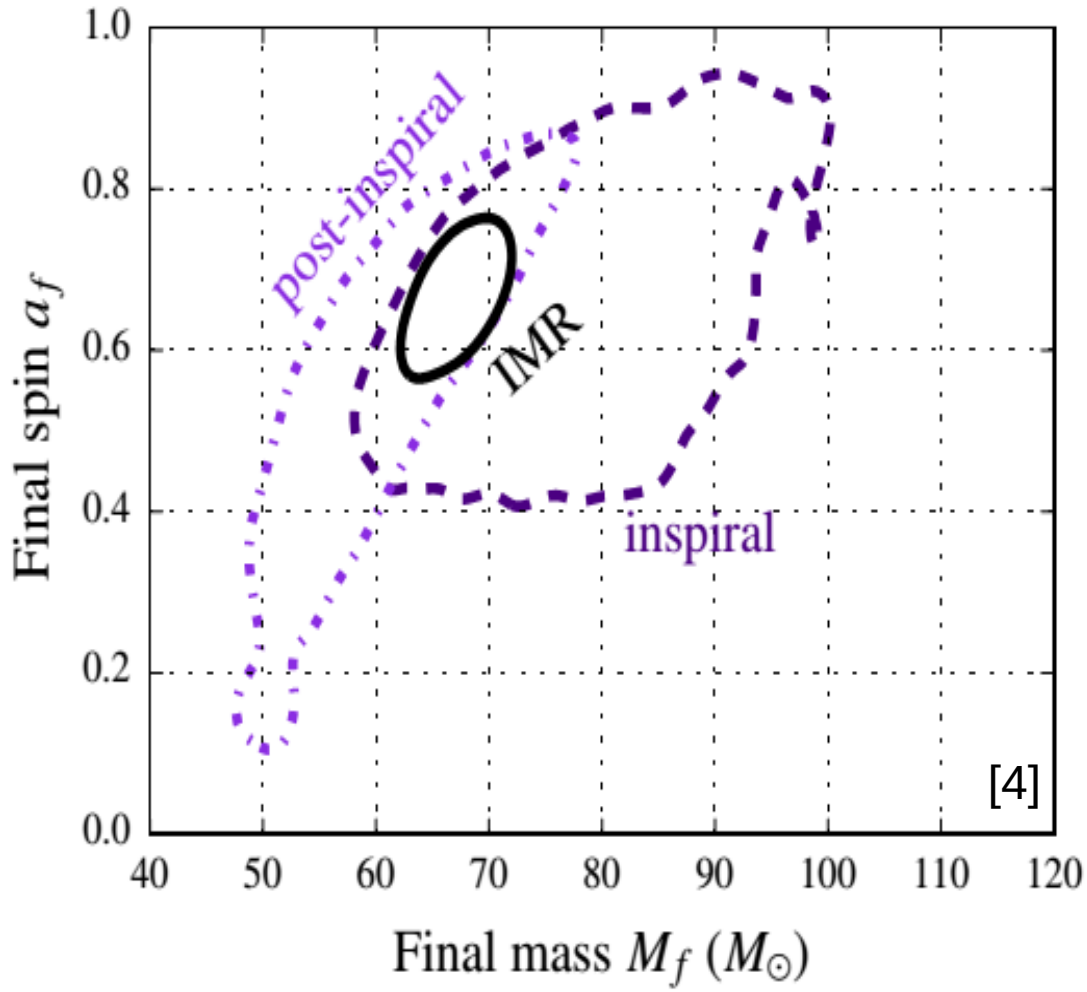
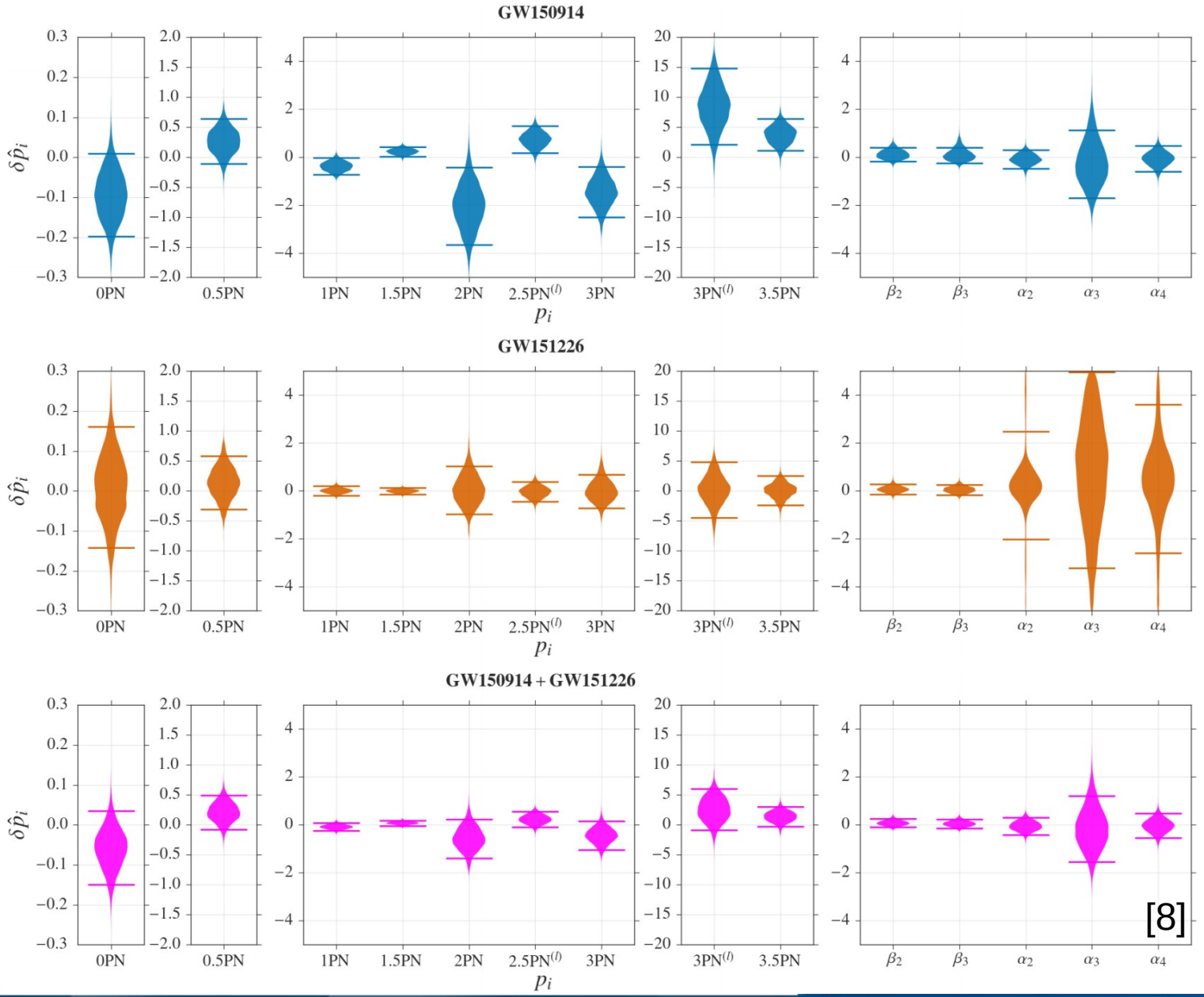
Testing GR Consistency



Testing GR Modifications



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What next?

- New sources: Neutron Stars, BH-NS
- Matter effects: Tides, Disruptions, E/M Fields…
- New waveforms: Precession, GR modifications
- 3rd detector => signal coherence
- Louder SNR, Higher modes
- With new data come new surprises:
  - New noise analyses, new reduction techniques
  - New tests constrain theory => new theories…

2nd Observation Run (O2): Next week!

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