Neutron Star Gravitational-Wave Transient Searches

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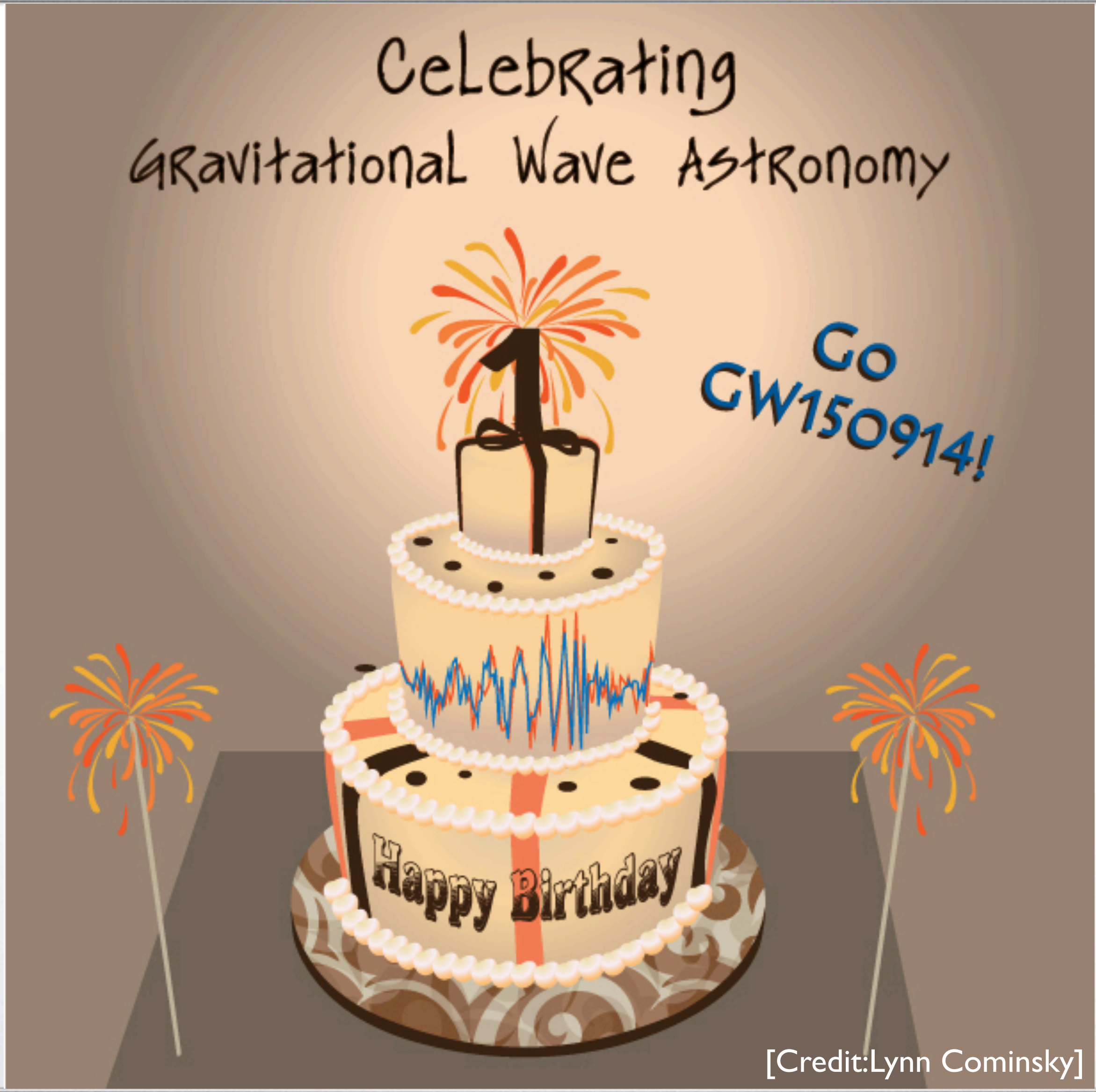
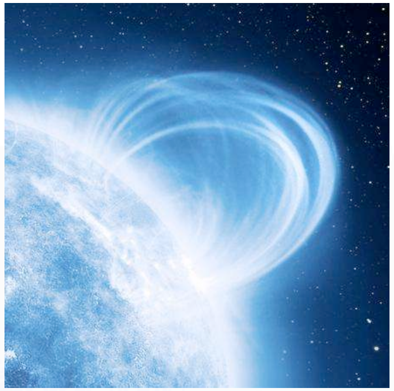


LIGO

Violent Phenomena



AXPs, SGRs, hyperflares, 15% (?) of short GRBs, dynamical/secular instabilities, pulsar glitches, fall-back accretion onto newborn NSs, proto-magnetar deformations, QPOs...

Post-merger of binary NS coalescences

Violent Phenomena

- Expected or known to be associated with gravitational-wave emission
- Challenge: many uncertainties (emission mechanism, waveform), low event rates,...
- Vision: GW signals associated with these phenomena would convey unique information on the NS equation of state

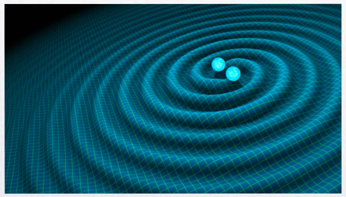
GW Searches

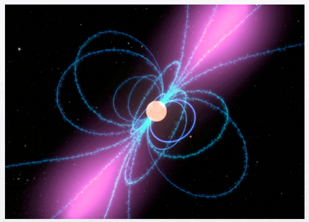
Transient Signals

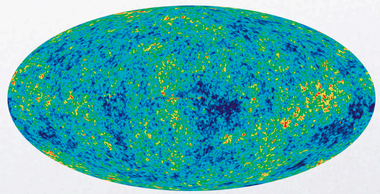
- Model → Compact Binary Coalescence
- No model → Burst

Continuous Signals

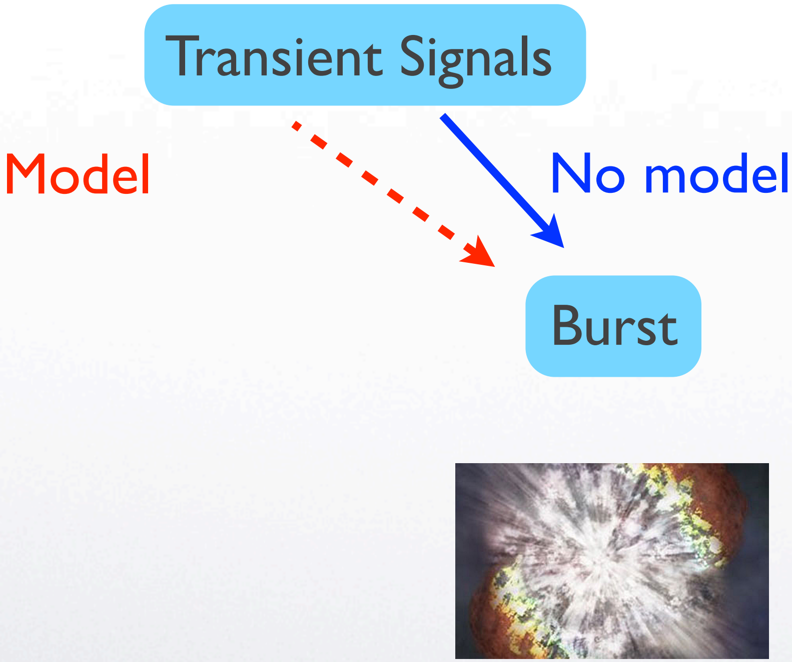
- Model → Continuous Waves
- No model → Stochastic





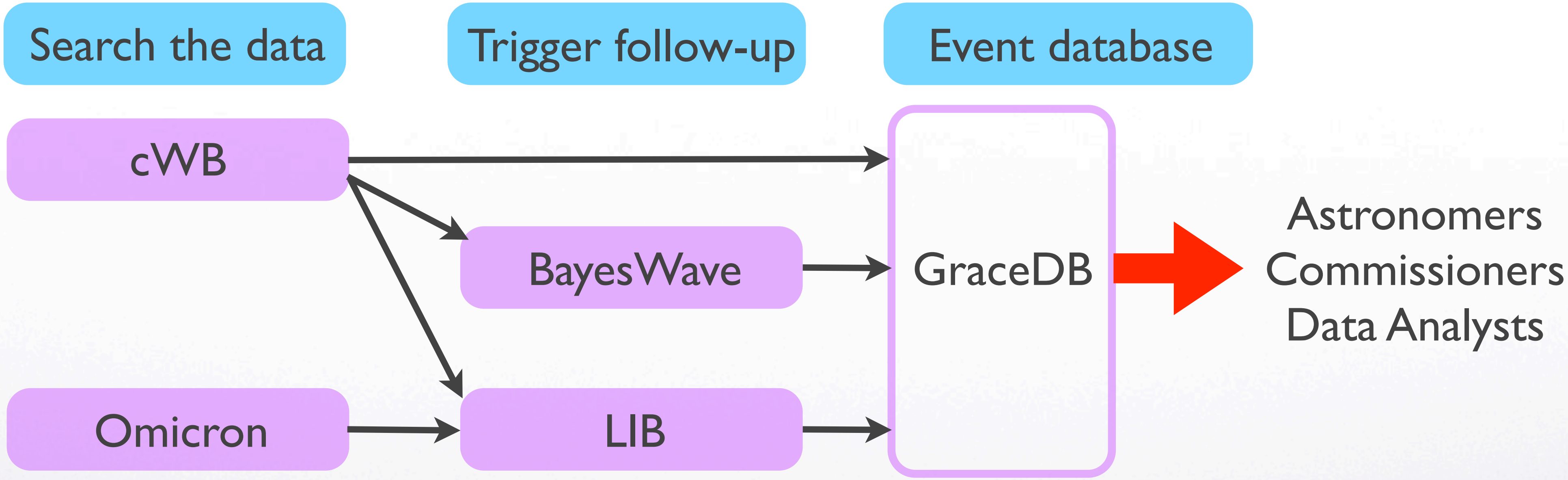


GW Searches



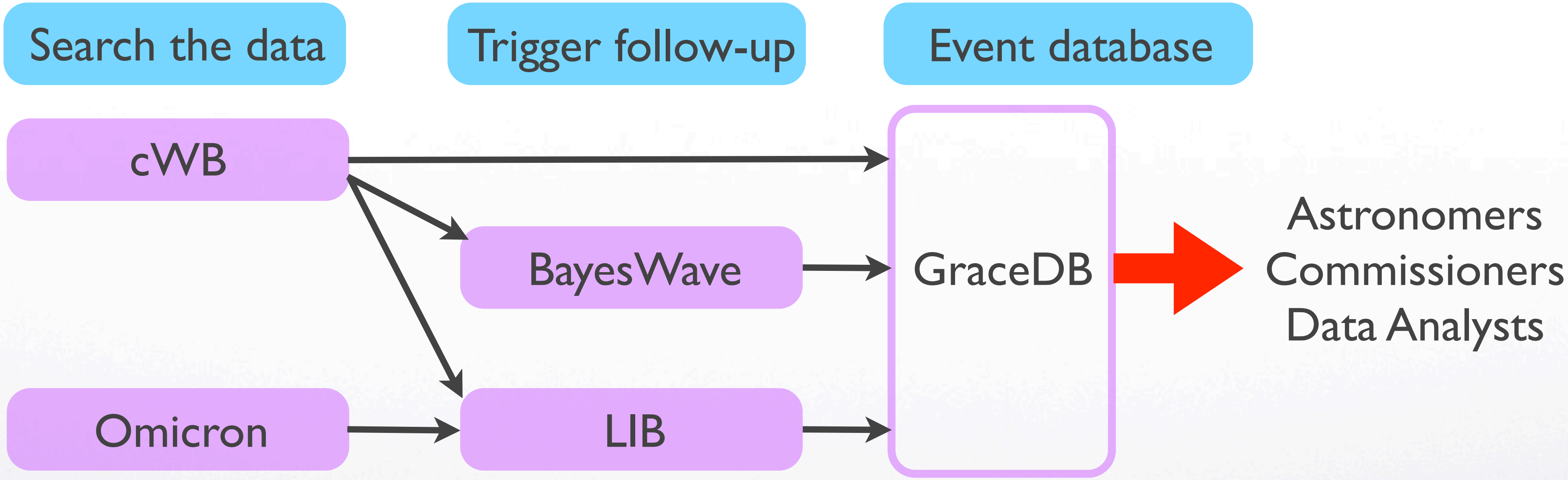
- All-sky, all-time searches
- NS dedicated search

Search Plan: All-Sky



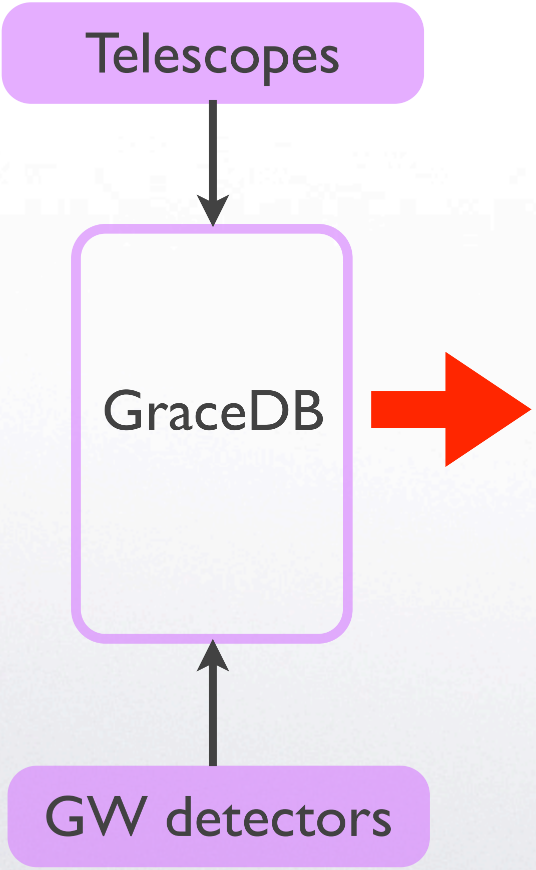
- Target transient signals with ms to s duration over 32-4096 Hz
- Independent validation of results

Search Plan: All-Sky



- Long-duration (10-500s) transient GW events: cWB, X-SphRad, STAMP
- 24-2000 Hz band (24-1000Hz for X-SphRad)

Triggered Search Plan



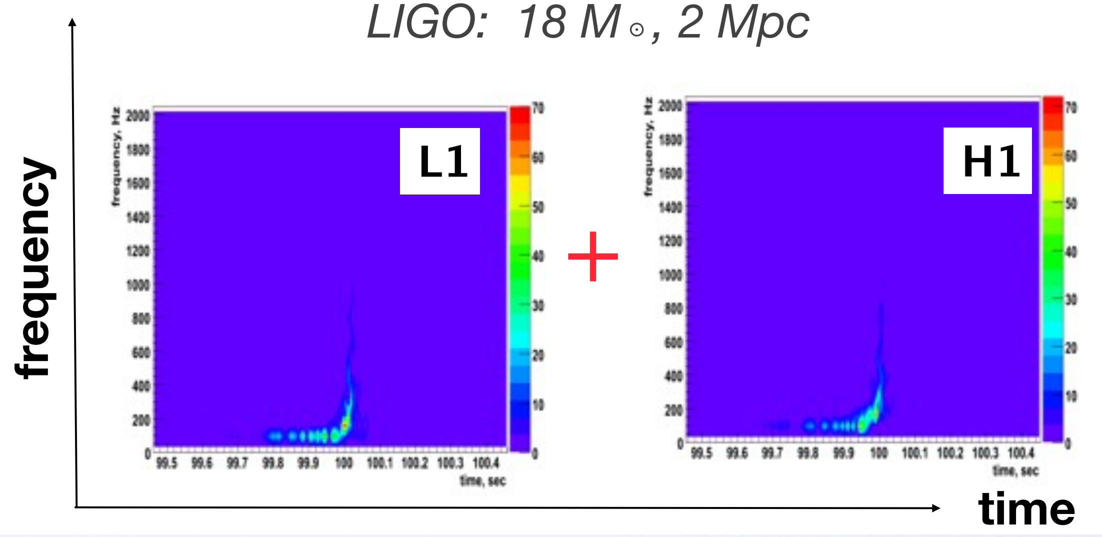
<u>NS dedicated GW search</u>

1. Hyperflares in Galactic magnetars:
   - long-duration GRB-like analyses
   - follow-up short-duration candidate signals with standard burst reconstruction tools
2. Post-merger of NS-NS remnants:
   - standard burst tools to characterise and reconstruct short-duration, high-frequency signal
   - open-mind about targeting any later long-duration bursts from stable remnants

Coherent Burst Search

- Seek excess power in time-frequency domain (instead of matched filtering) by identifying clusters of “hot” pixels in time-frequency maps
- Decompose data with multi-resolution basis (wavelets, short Fourier transforms)

Example: simulated BBH in Initial LIGO: 18 $M_\odot$, 2 Mpc

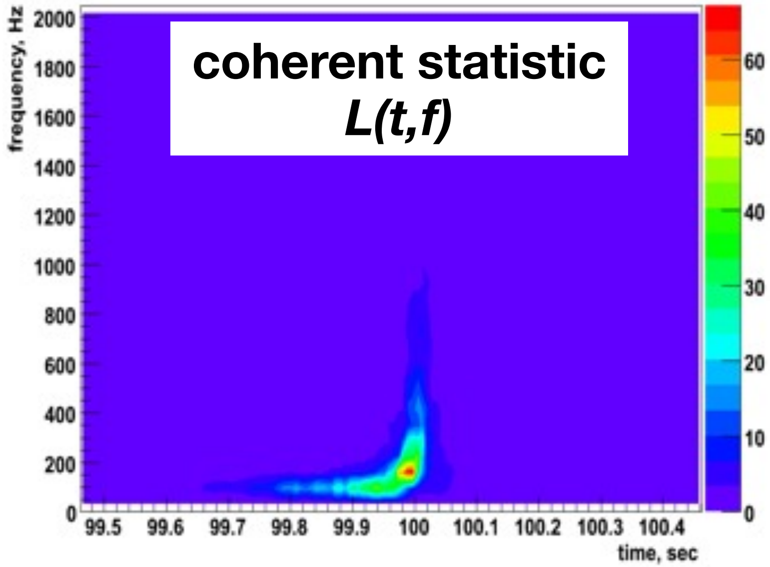


Coherent Burst Search

- Coherent analysis: likelihood maximized over waveform, sky-location

$$L(t,f) = \max_{h_+,h_\times,\theta,\phi} \sum_k \frac{x_k^2[t,f] - (x_k[t,f] - \xi_k[t,f])^2}{\sigma_k^2(f)}$$

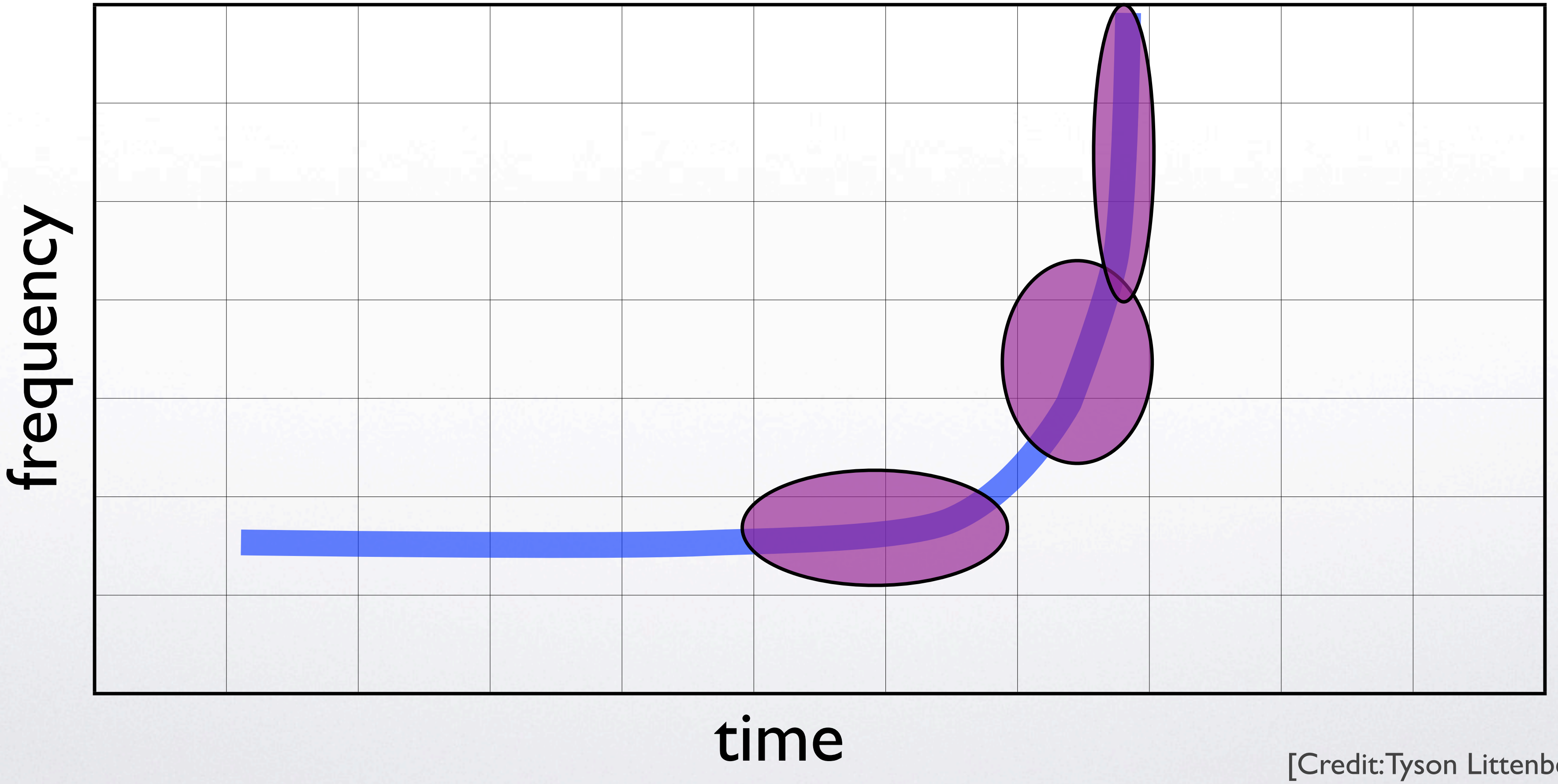
$\xi_k = h_+ F_{+,k} + h_\times F_{\times,k}$ - k^{th} detector response



Klimenko et al, CQG 25:114029,2008

- Noise fluctuations can be eliminated based on their non-correlation between detectors

Clustering



[Credit: Tyson Littenberg]

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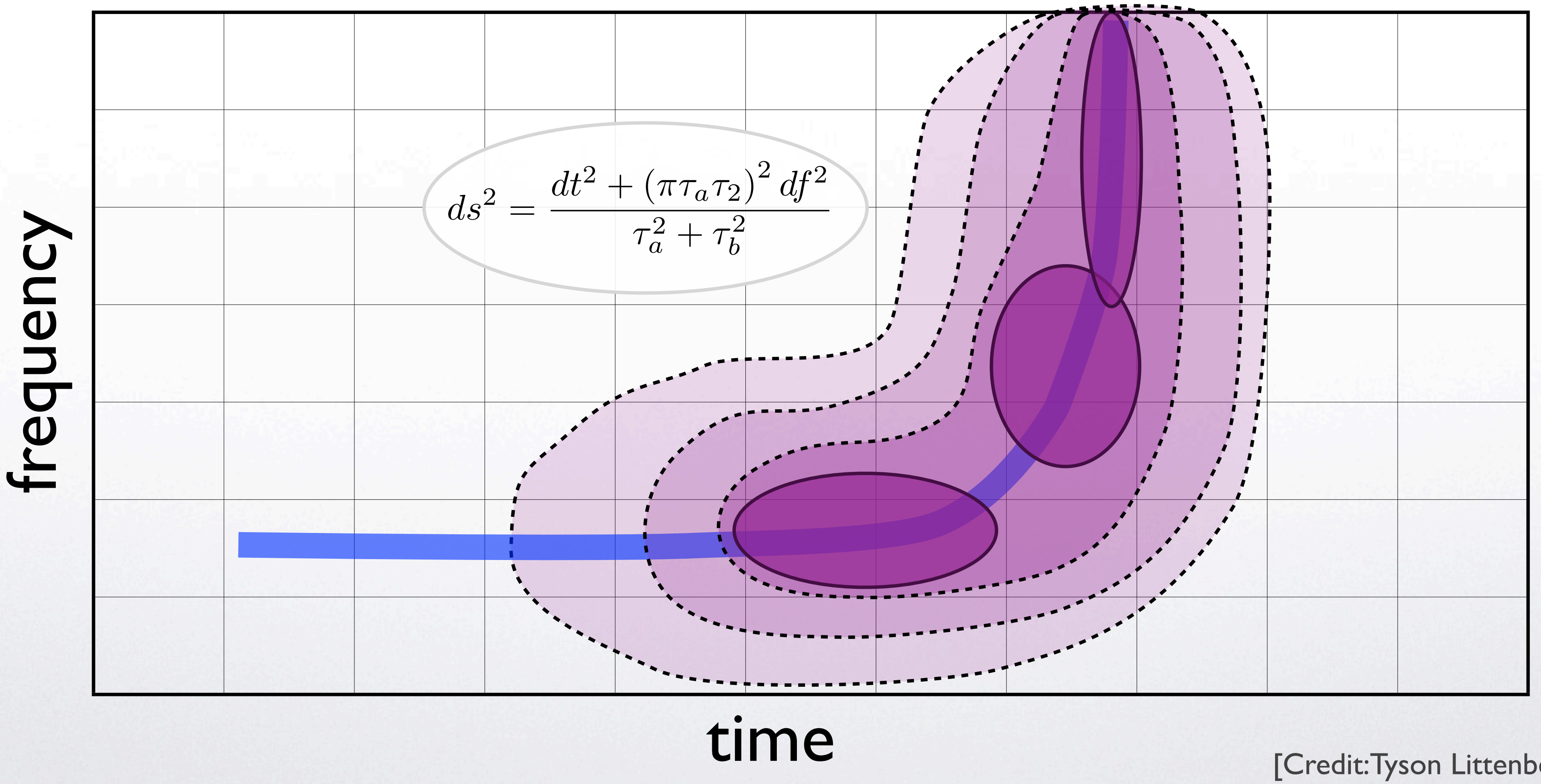

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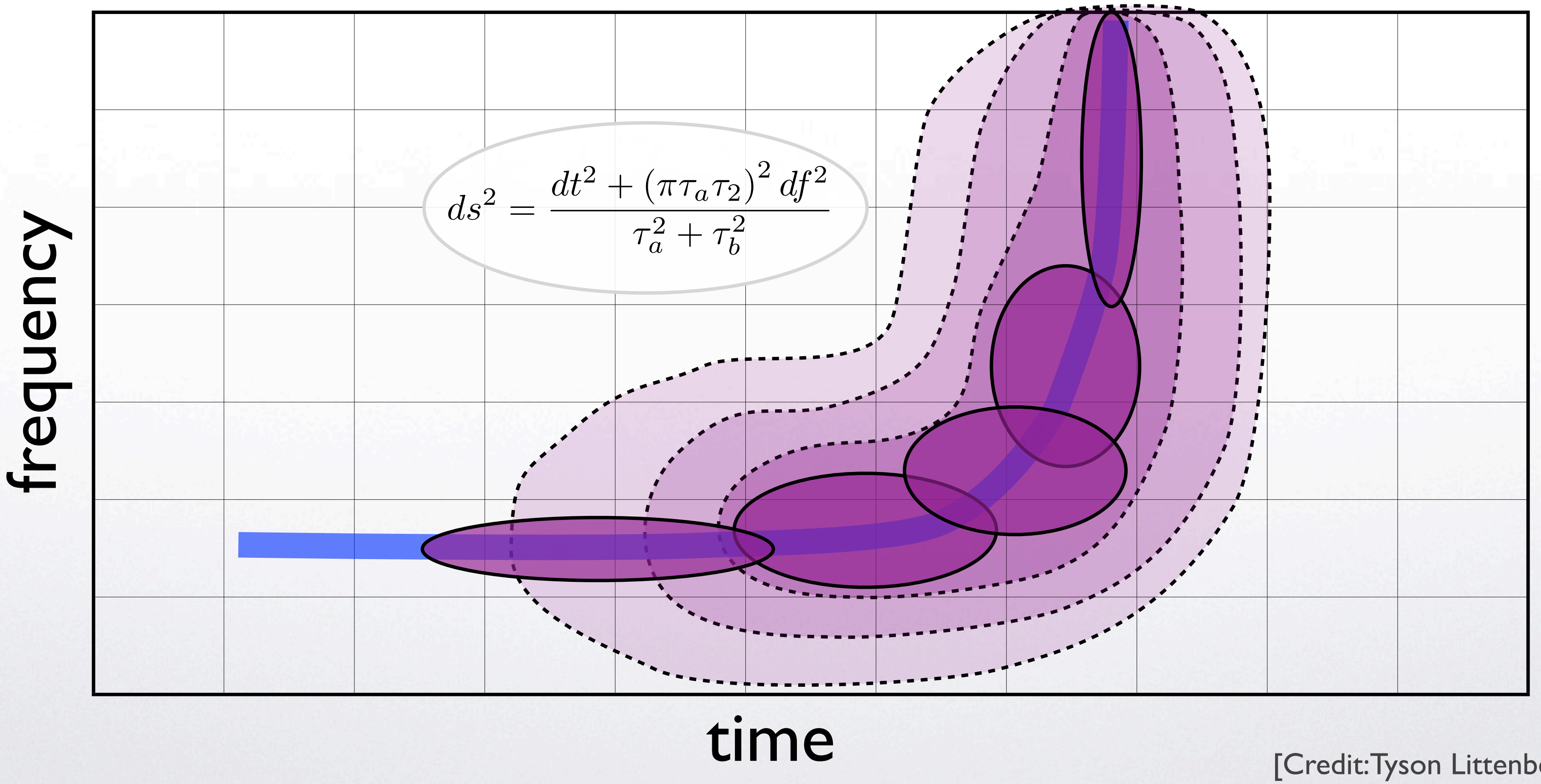

[Credit: Tyson Littenberg]

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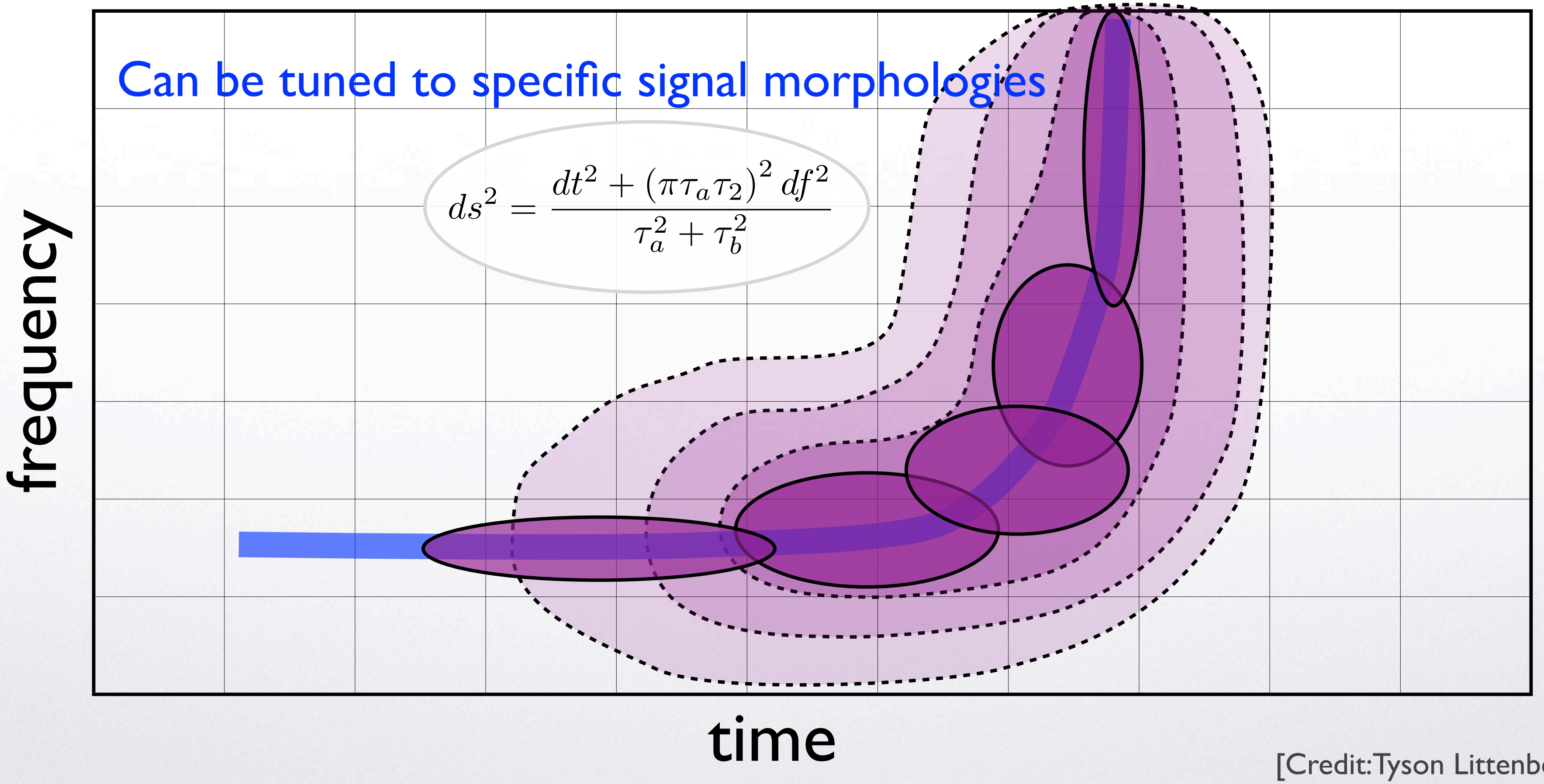

[Credit: Tyson Littenberg]

Follow-up Analyses

BayesWave: operates in the Fourier domain, using a trans-dimensional Reversible Jump Markov Chain Monte Carlo to build linear combinations of sine-Gaussians

- Glitch model fits data separately in each interferometer with an independent linear combination of wavelets
- Signal model reconstructs the candidate event at the center of the Earth, taking into account the response of each detector
- Uses a parametrized phenomenological model (BayesLine) for the instrument noise spectrum, simultaneously characterizing the Gaussian noise and instrument/astrophysical transients

[Cornish+, CQG **101,** 135012 (2015), Littenberg+, PRD **91**, Phys. Rev. D 91, 084034 (2015)]

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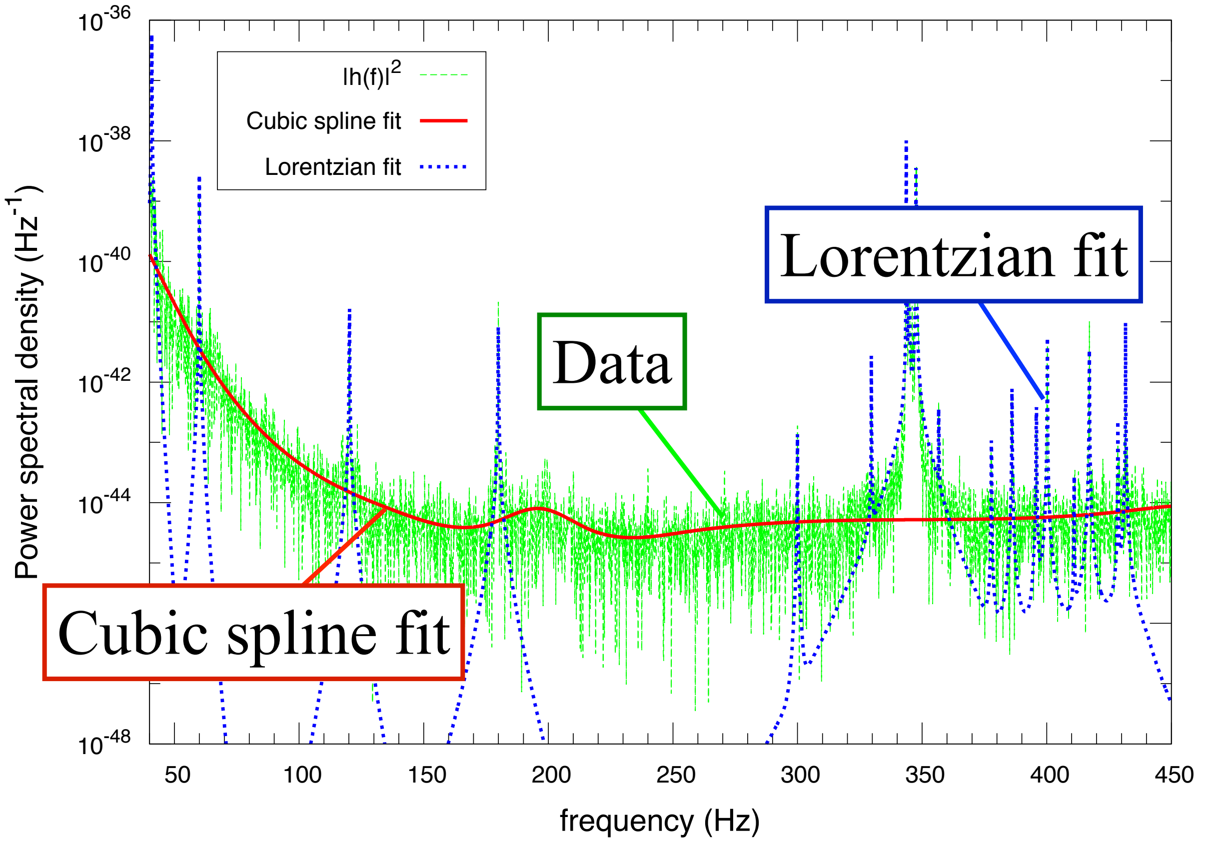
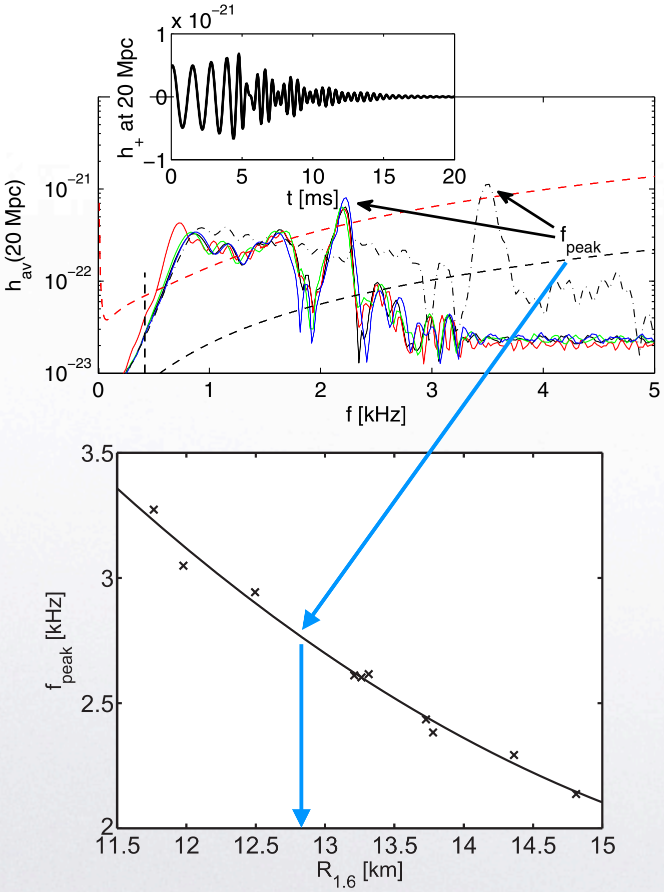


NS-NS Follow-Ups



- Quasi-stable (hyper-)massive NS remnant
- Merger/post-merger dynamics produce a rich GW spectrum:
  - Emission dominated by post-merger ~ f-mode oscillations (f_{peak})
  - Subdominant emission from (2,0)-mode coupling & short-lived bar structure
- Locate f_{peak} → constrain NS EOS

[Bauswein+, PRL **101,** 011101 (2012), Clark+, CQG **33,** 085003 (2016)]

NS-NS Follow-Ups

Year	Instrument	$\mathrm{SNR}_{\mathrm{full}}$	D_{hor} (Mpc)	$\dot{N}_{\mathrm{det}}$ (year^{-1})
Now-2020	aLIGO	$2.99^{3.86}_{2.37}$	$29.89^{38.57}_{23.76}$	$0.01^{0.03}_{0.01}$
2020+	A+	$7.89^{10.16}_{6.25}$	$78.89^{101.67}_{62.52}$	$0.13^{0.20}_{0.10}$
2027-28	LV	$14.06^{18.13}_{11.16}$	$140.56^{181.29}_{111.60}$	$0.41^{0.88}_{0.21}$
2035+	ET-D	$26.65^{34.28}_{20.81}$	$266.52^{342.80}_{208.06}$	$2.81^{5.98}_{1.33}$
2035+	CE	$41.50^{53.52}_{32.99}$	$414.62^{535.221}_{329.88}$	$10.59^{22.78}_{5.33}$

Notation: $50\mathrm{th}^{10\mathrm{th}}_{90\mathrm{th}}$ percentile over the 50 waveforms used

- Finite simulation time and numerical damping of the post-merger oscillations likely lead to an underestimate of the total SNR

[Clark+, CQG **33,** 085003 (2016)]

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NS-NS Follow-Ups

Use input from models: Fourier-domain principal component analysis model for 50 NS-NS waveforms takes from high-dimensional (and costly) parameter space to dominant waveform features.

Year	Instrument	$\mathcal{M}$	$\delta f_{\rm peak}$ (Hz)	$\delta R_{1.6}^{\rm stat}$ (m)	$\delta R_{1.6}$ (m)
Now-2020	aLIGO	$0.93_{0.91}^{0.96}$	$135.7_{98.6}^{184.9}$	$363.4_{235.2}^{476.2}$	$429.1_{507.9}^{317.0}$
2020+	A+	$0.93_{0.89}^{0.96}$	$136.4_{98.6}^{180.8}$	$359.7_{227.5}^{496.6}$	$425.5_{313.0}^{526.6}$
2027-28	LV	$0.93_{0.90}^{0.96}$	$139.0_{96.7}^{184.6}$	$375.3_{228.9}^{478.5}$	$420.9_{509.5}^{318.2}$
2035+	CE	$0.91_{0.93}^{0.96}$	$138.1_{98.6}^{188.3}$	$363.9_{234.7}^{483.5}$	$424.9_{514.1}^{319.8}$
2035+	ET-D	$0.94_{0.92}^{0.97}$	$138.8_{105.3}^{185.3}$	$401.8_{230.6}^{506.7}$	$443.1_{536.1}^{318.1}$

[Errors at SNR=5]

[Clark+, CQG **33,** 085003 (2016)]

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[Clark+, CQG **33,** 085003 (2016)]

Overview

- NS transients do not have an analytic/numerical mapping between physical parameters and strain
- Solid GW search plan in place wherein inference is still possible:
  - Reconstructions without templates
  - Identification of robust GW signal features
  - Interplay with NS models (NR, but not only)
- Promising scenarios to constrain the NS equation of state

References

- coherent WaveBurst: Klimenko+, CQG **25**, 114029 (2008).
- Omicron-LAL-Inference-Bursts: Lynch+, arXiv:1511.05955.
- BayesWave/BayesLine: Cornish+, CQG **32**, 135012 (2015), Littenberg+, PRD 91, PRD **91**, 084034 (2015).
- STAMP: Thrane+, PRD **83**, 083004 (2011).
- X-Pipeline/X-SphRad: Sutton+, NJPh **12**, 053034 (2010), Was +, PRD **86**, 022003 (2012); Edwards+, JoP: CS **363**, 012025 (2012), Edwards, PhD Thesis, Cardiff University (2013).

- And special thanks to James Clark!