IWAVE - a novel adaptive filtering method and its application to short and long-duration gravitational wave searches

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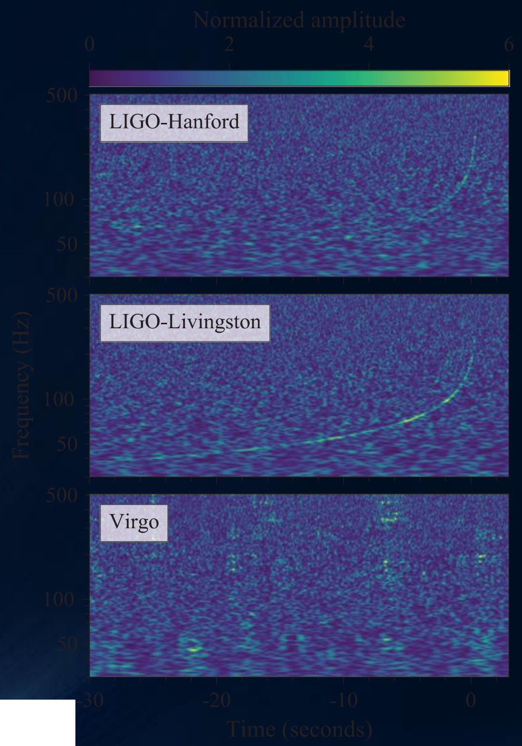
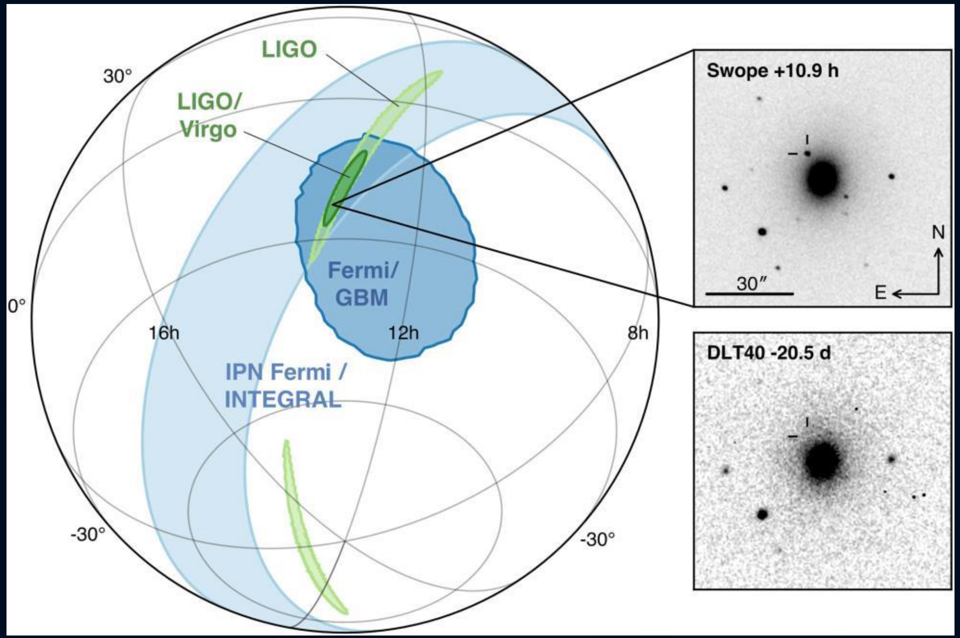
IOP JOINT APP, HEPP AND NP CONFERENCE, LIVERPOOL, 10 APRIL 2024





[Phys. Rev. Lett., **119**, 161101 (2017)
B. P. Abbott et al. Ap. J. Lett. **848**, L12 (2017)]

The University Of Sheffield.

Iterative **W**ave **A**ction-angle **V**ariable **E**stimator

- New type of PLL addresses dynamic characterisation of evolving pseudo-sinusoidal signals in noisy data streams [E. J. Daw, I.J. Hollows, E.L. Jones, R. Kennedy, T. Mistry, T.B. Edo, M. Fays, L. Sun, Rev. Sci. Instrum. **93**, 044502 (2022)]
  - Adaptive element is a filter rather than an oscillator or counter
  - Not computationally intensive
  - Both prefiltering and IWAVE are in ANSI C - run easily and fast on LIGO clusters
  - IWAVE has advantages over other PLLs (SOGI-PLL, EPLL)
    - Produces a benign output when unlocked
      - Controlling a parameter of a gravitational wave interferometer in a closed loop feedback system
    - Tracks amplitude and frequency in a single feedback loop
    - Initialised with just initial frequency, f_0, and response time, τ, parameters with clear physical meaning
  - Used to study violin modes in LIGO silica suspensions [A.V. Cumming, B. Sorazu, E.J. Daw, et al. , Classical and Quantum Gravity, *37*(19), 195019 (2020)]
    - can characterise, simultaneously, multiple oscillations having similar frequencies using a cross-subtraction method

IWAVE method

- IWAVE core iteration algorithm

$$y^n = e^{-w}e^{i\Delta}y_{n-1} + (1 - e^{-w})x_n$$

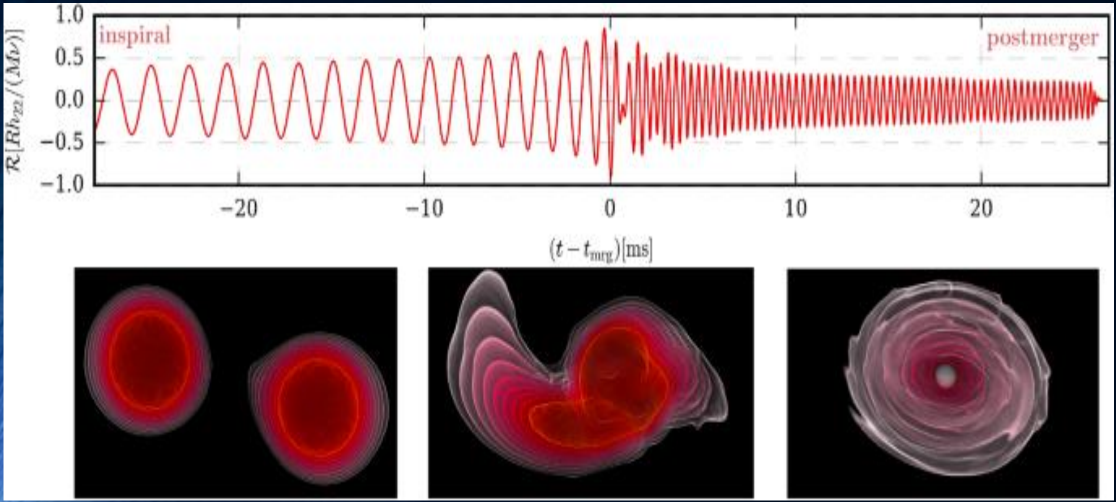
  responds resonantly at frequency Δ. $w = {}^{t_s}/_{\tau}$ where t_s is the sampling period and τ is the response time

- Infinite impulse response (IIR) filter generating the *n*th output using the current input x_n, the previous output y_{n-1} and a multi-input, multi-output (MIMO) filter
- More recent data weighted more heavily
- $\mathcal{Z}$-transform weighs data samples exponentially and is the analogue of the discrete Fourier transform

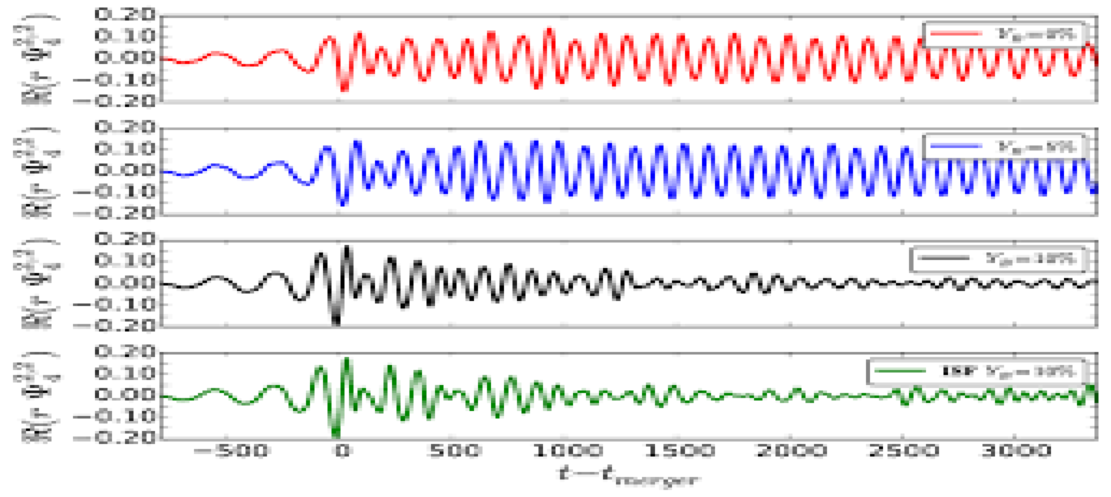
Post binary neutron star mergers

Gravitational waves from:

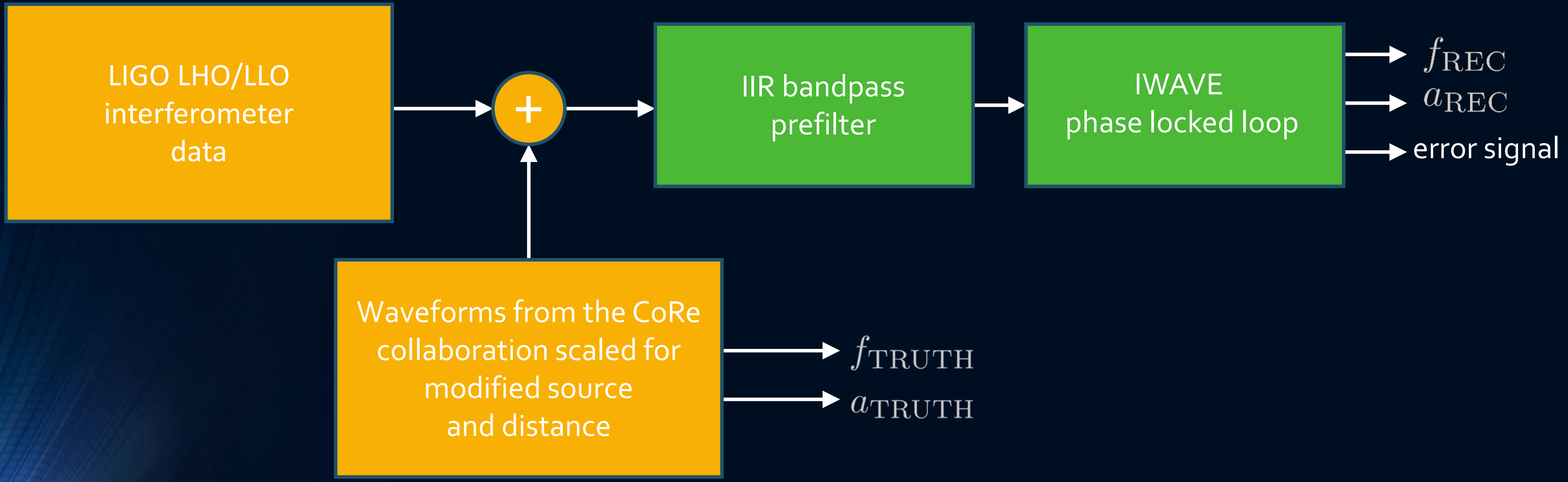
Hypermassive (> 3 $M_{\odot}$) neutron star remnant collapsing to black hole ≤ 1 s [Dietrich et al. RG **53**, 1 (2021)]



Supramassive (2-3 $M_{\odot}$) remnant collapsing in 10 s – 100000 s [Bezares et al., PR D **100**, 044049 (2019)]



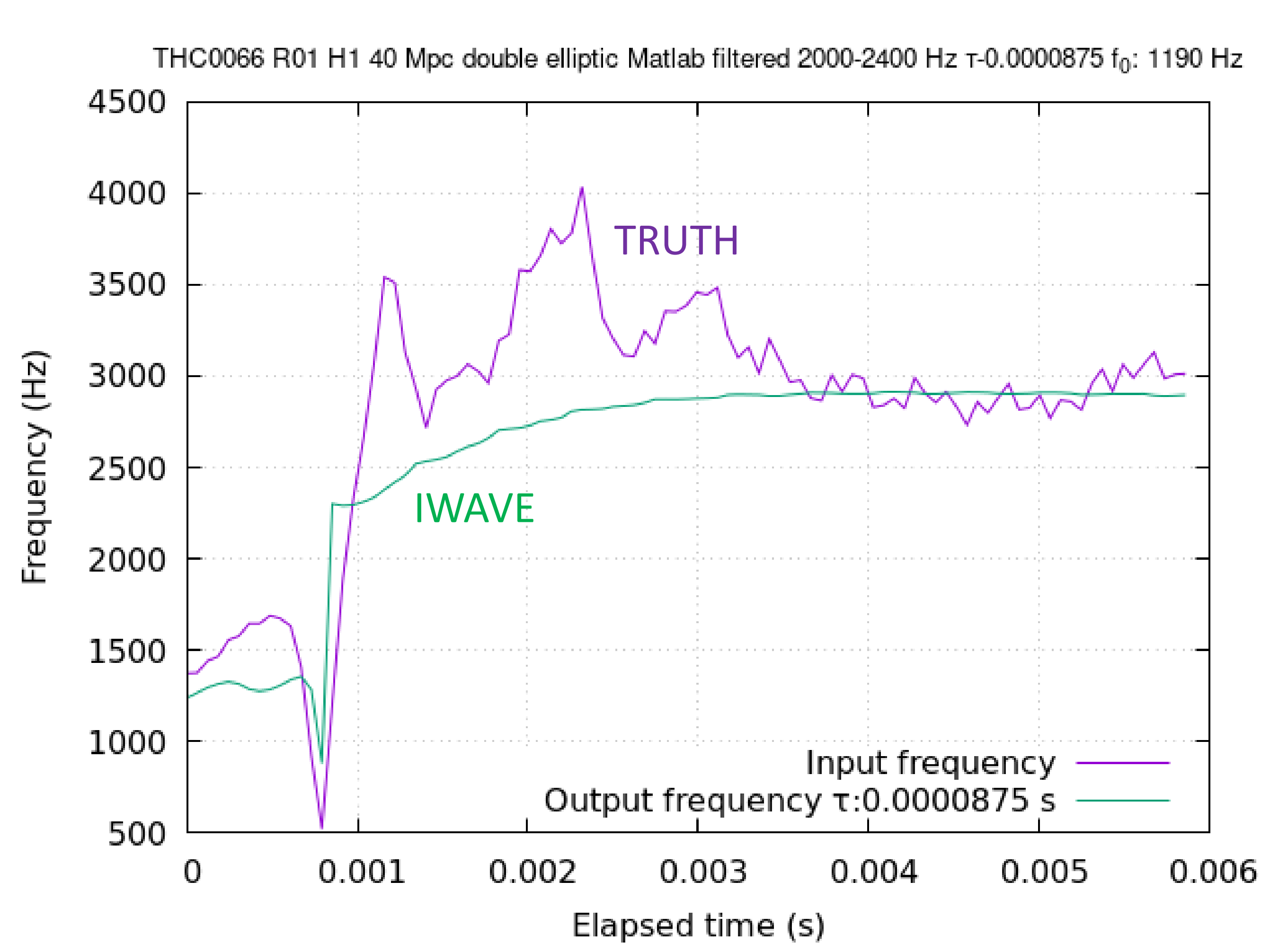
Experiments to test IWAVE on short duration GW data



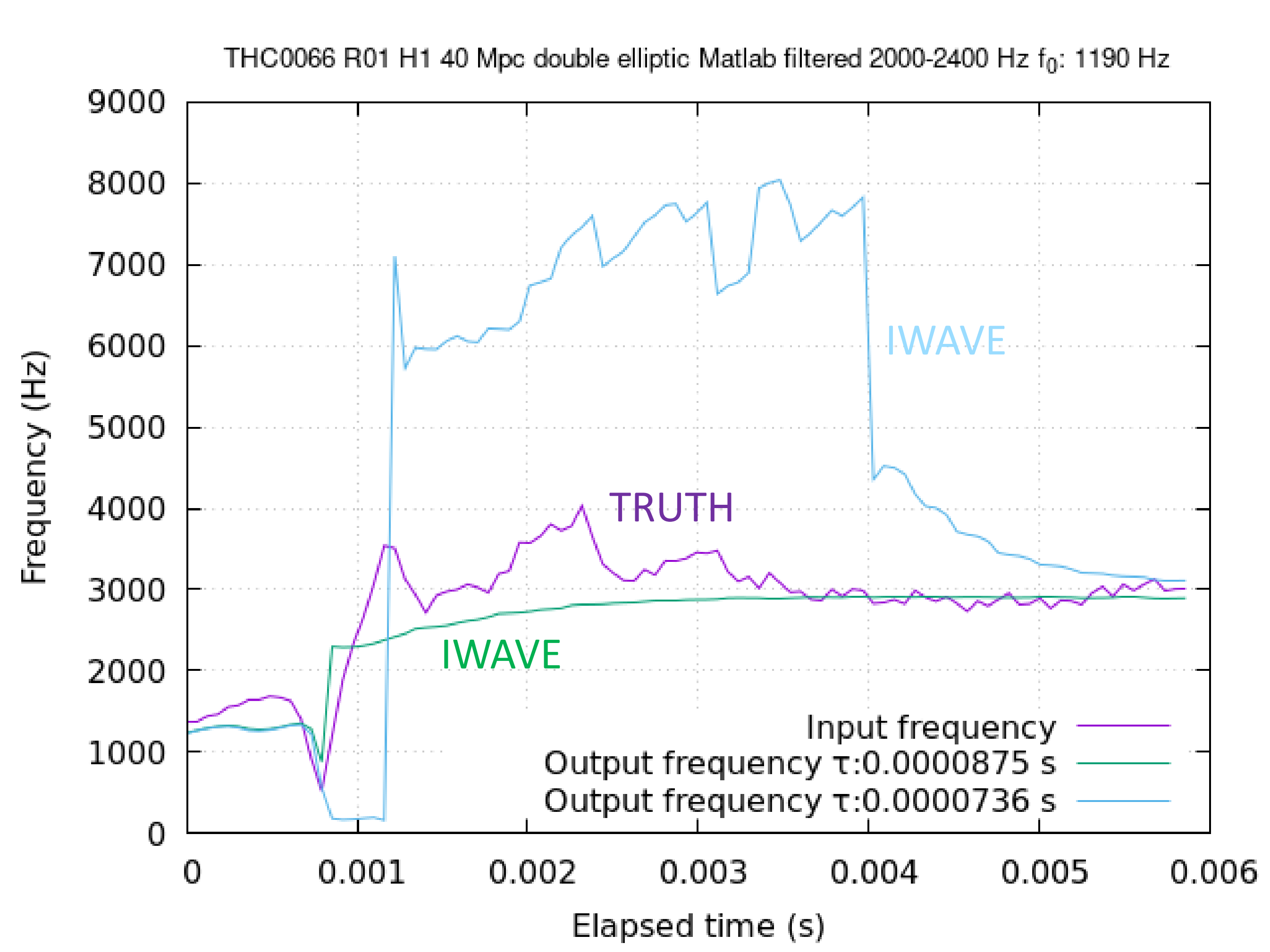
CoRe catalogue waveforms added to interferometer data at the merger time of GW170817 and GW190425

[A. Gonzalez et al., Class. Quantum Grav. 40 (2023) 085011]

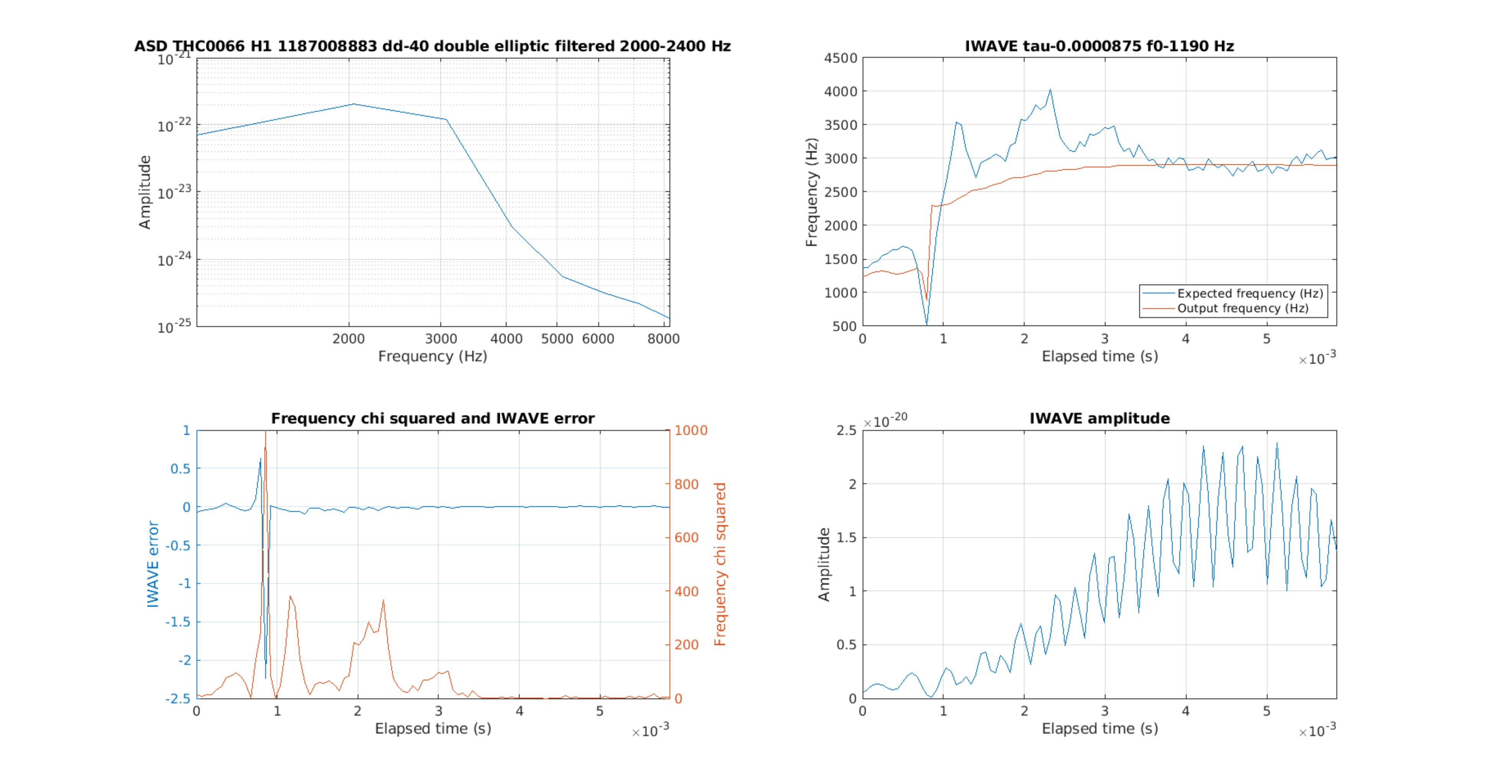
CoRe database THC_0066 simulation at 40 Mpc injected into LIGO Hanford data and double filtered 2000-2400 Hz



CoRe database THC_0066 simulation at 40 Mpc
Effect of changing τ



THC_0066 ASD, error signal, output frequency, amplitude



Unless signal-to-noise ratio is very high, a phase locked loop loses and re-acquires lock on the signal it is tracking

IWAVE tracking of simulated long duration GW signals

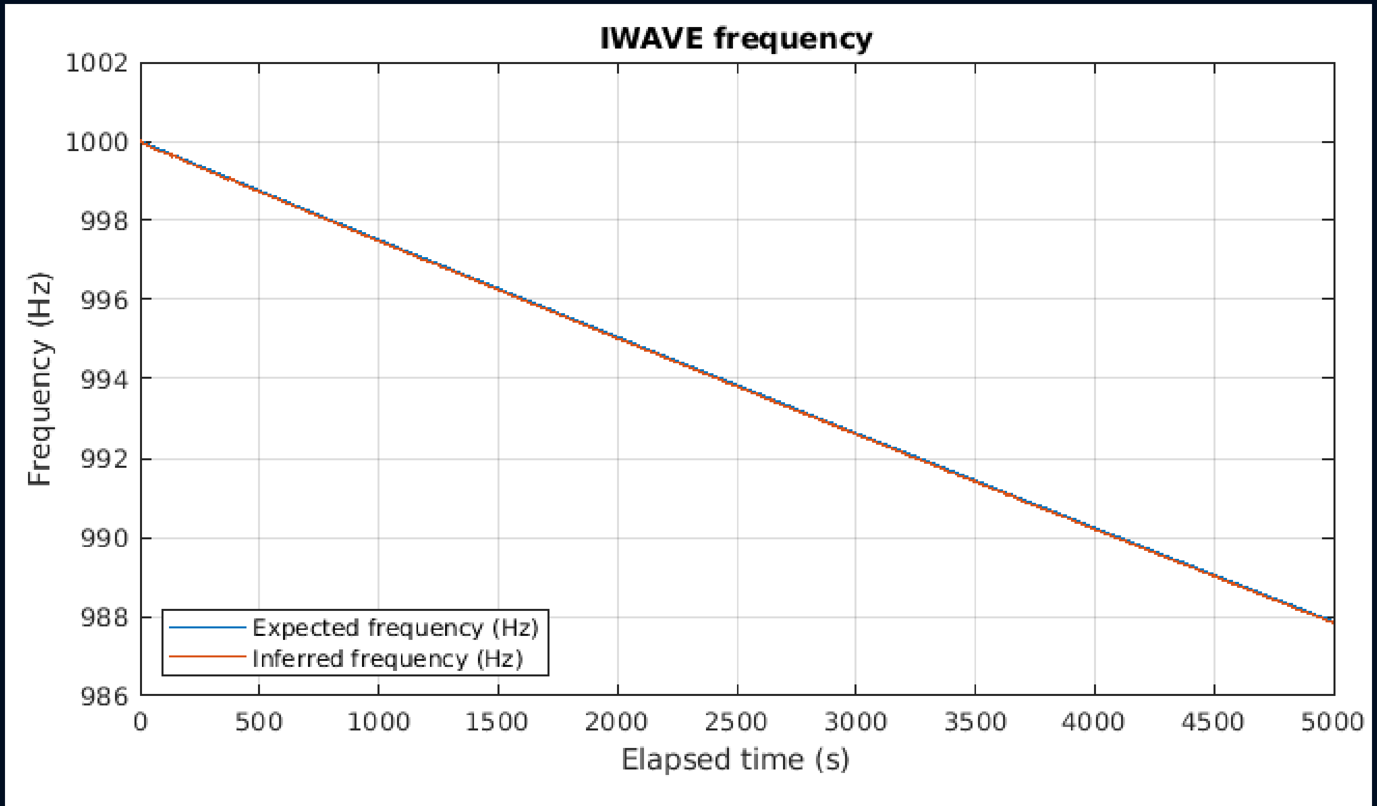
Simulated magnetar data at LIGO Hanford and Livingston observatories with added Gaussian noise for a range of distances 0.4 – 2.0 Mpc [Scripts developed by LVK Collaboration colleagues, K. Wette, and see L. Sun and A. Melatos, Phys. Rev. D 99, 123003 (2019)]

Highly deformed magnetar signal with parameters:

- f_0 1000 Hz, later 950 Hz to avoid violin modes
- Sample data length 5000 s
- Signal spin-down timescale 100000 s
- Braking index 5 $\dot{f} - 0.025\ Hz^{-1}$
- Ellipticity 0.01
- Gaussian noise ASD 1e-23 $Hz^{-1/2}$
- SNR 1:100

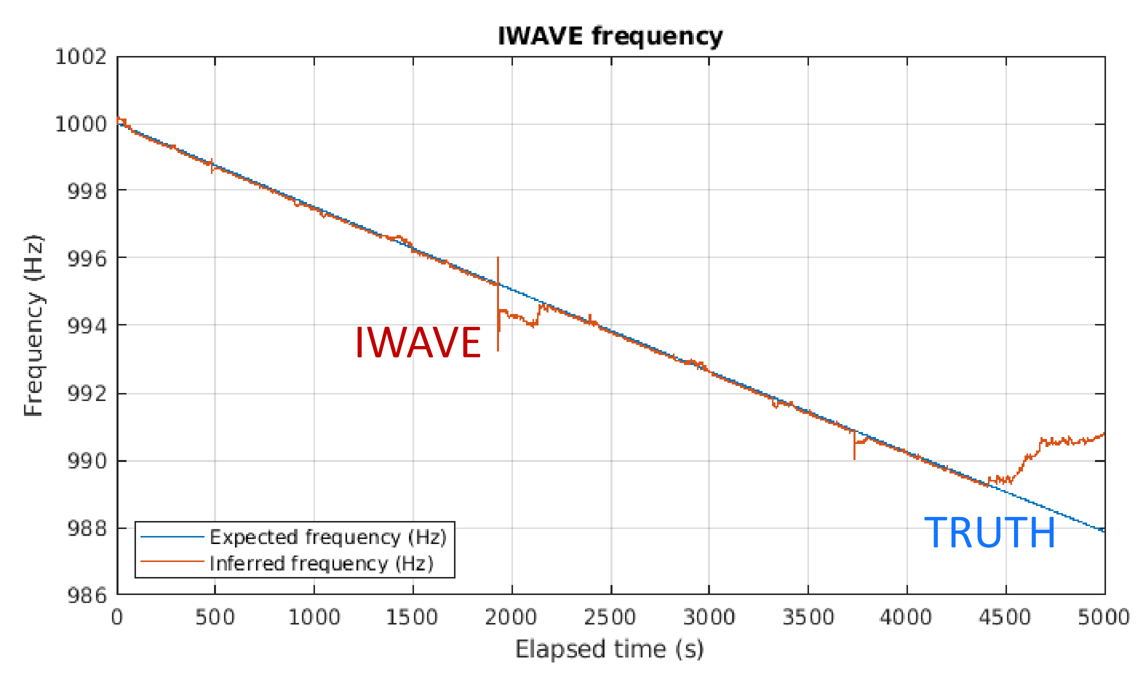
Optimised response time, τ s

Unfiltered signal at 0.4 Mpc τ: 3.565205 s

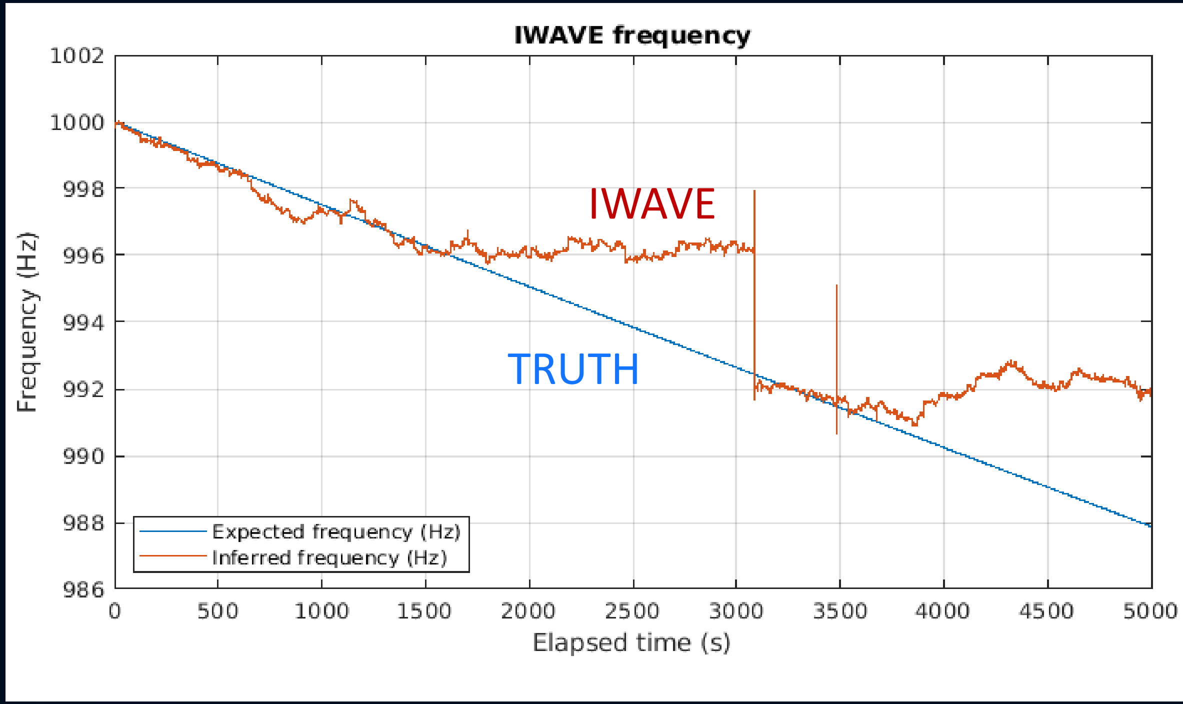


Filtered simulated magnetar signals

1.0 Mpc τ: 4.373448 s

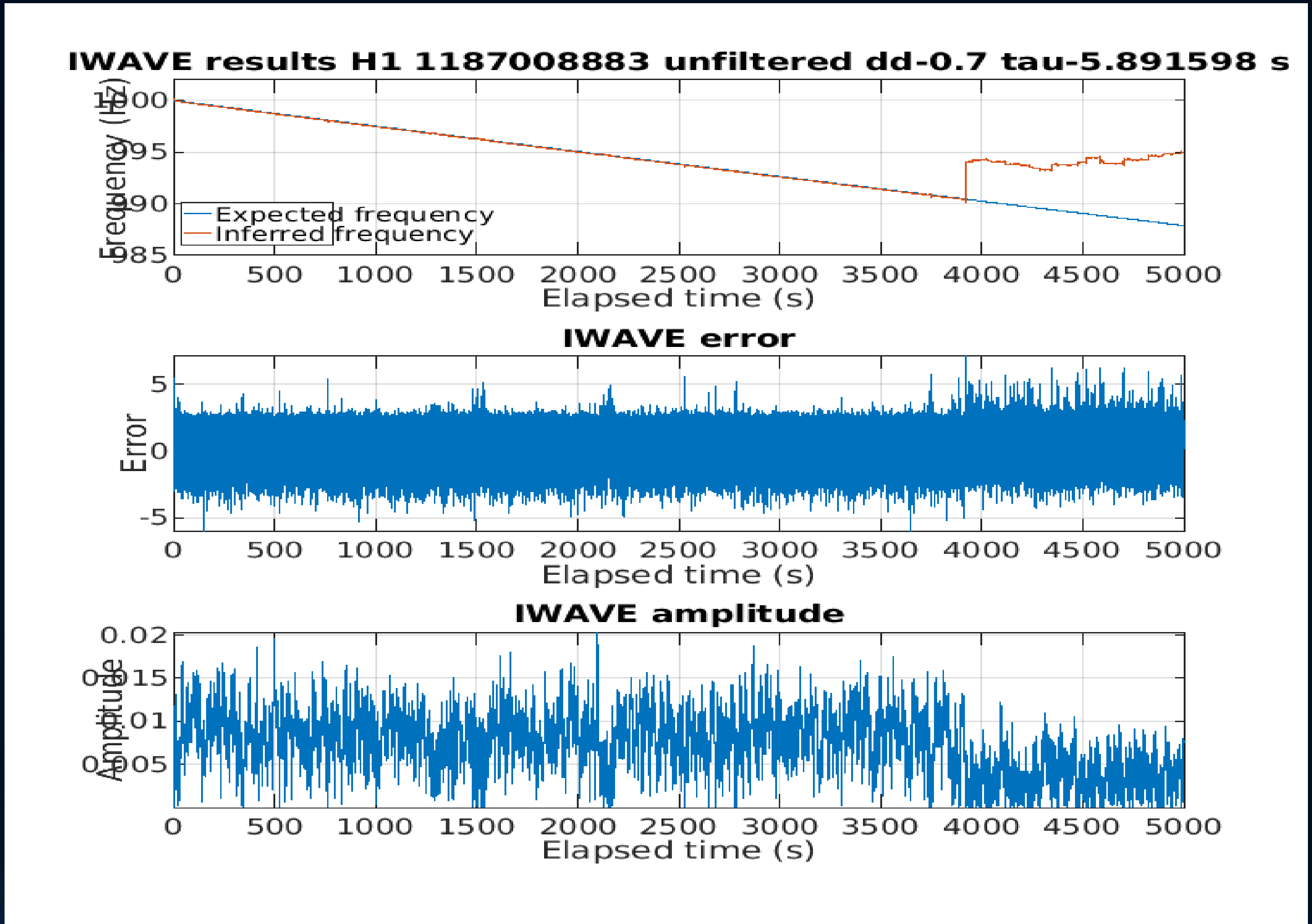


2.0 Mpc τ: 3.776350 s



- Chebyshev1 filter 986-1002 Hz passband
- Signal evolution at 1.0 Mpc and 2.0 Mpc corresponds to strain sensitivity of c. 1.03×10^{-23} and 5.16×10^{-24} respectively [P. D. Lasky, N. Sarin, and L. Sammut, LIGO Document No. T1700408, 2017]

How do we know when IWAVE is locked?



Investigating whether, as the SNR approaches some critical value, the locked and unlocked states become indistinguishable

Conclusions and challenges

- Encouraging but …
  - Current need for optimisation of response time, τ
  - Define detection statistics and test threshold/ figure of merit
  - Develop pipeline
  - How to combine data from several detectors?
- Divide data into narrower frequency bands, significantly reducing the rms of the noise
- Use more or more sophisticated filters in banks
- Deploy many frequency/τ combinations
- Inject magnetar signals into interferometer data
- IWAVE likely to be most effective in conjunction with template-based methods

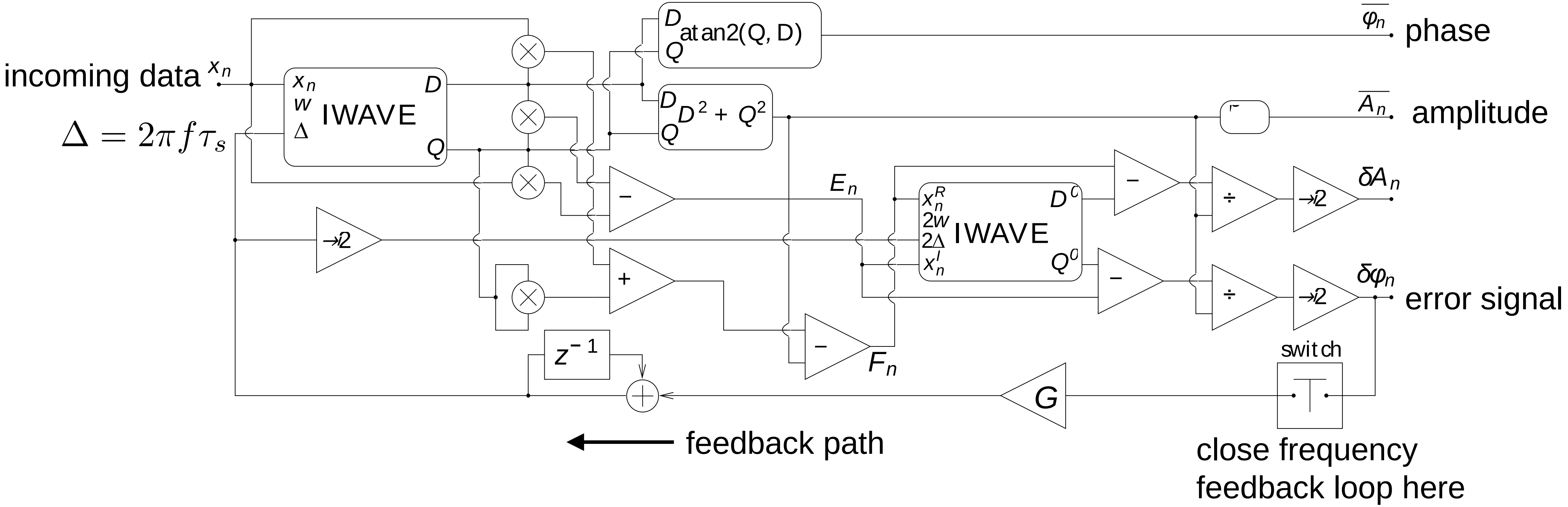
IWAVE documents

- The IWAVE method is described in detail in the paper: E. J. Daw, I.J. Hollows, E.L. Jones, R. Kennedy, T. Mistry, T.B. Edo, M. Fays, L. Sun, Rev. Sci. Instrum. **93**, 044502 (2022)
- Full treatment of the mathematics: I. J. Hollows, The mathematics of the IWAVE algorithm, https://git.ligo. org/edward.daw/iwave/-/blob/master/documents/paper_rsi/iwavepaper_mathematics.pdf; accessed 4 June 2021.
- Software library implementing IWAVE in C with MATLAB and Python wrappers : E. J. Daw, IWAVE git repository, https://git.ligo.org/edward.daw/iwave, 2021
- The magnetar simulation-specific code in C: /home/ian.hollows/public_html/magnetarSim
- Work on the simulations available in an ALOG: https://iwavecw.ligo-la.caltech.edu/logbook/index.php?startPage=1 (with thanks to Dwayne Giardina, Caltech)

Thank you for listening

Do you have any questions?

IWAVE adaptive filtering scheme



Closed-loop transfer function to frequency fluctuations for the critically damped adaptive servo tracking the wave frequency.

$$H(s) = \left(\frac{\frac{1}{2\tau}}{s + \frac{1}{2\tau}} \right)^2$$