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The impact of calibration uncertainty on supernova searches and parameter estimation

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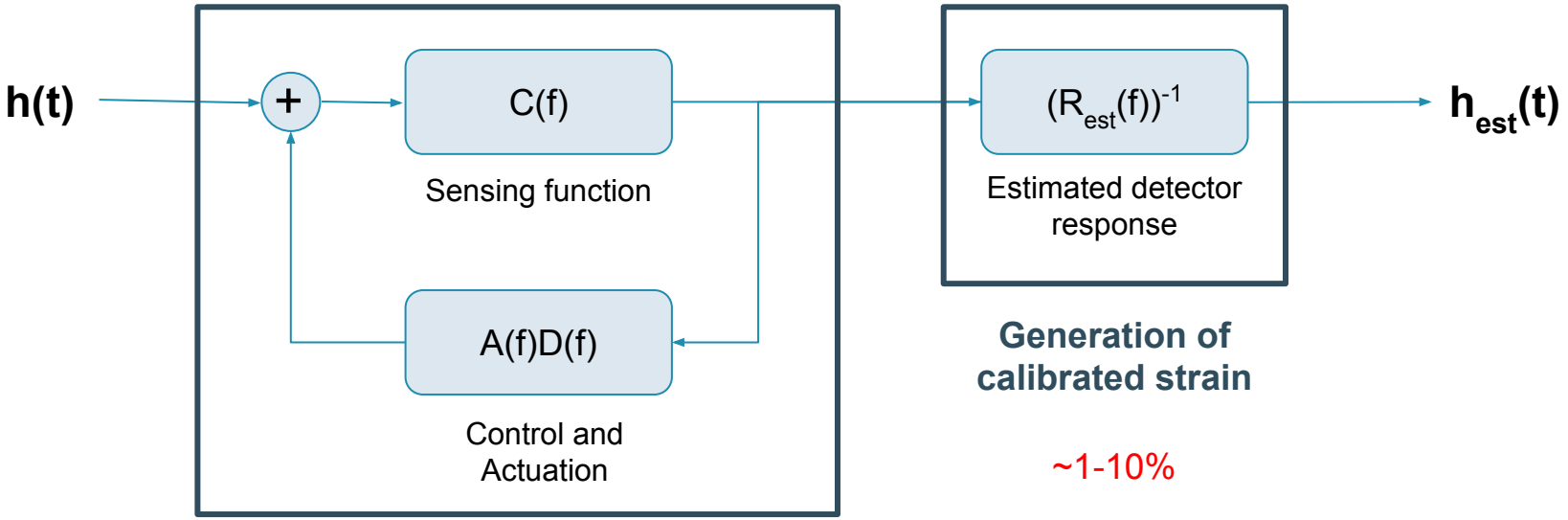
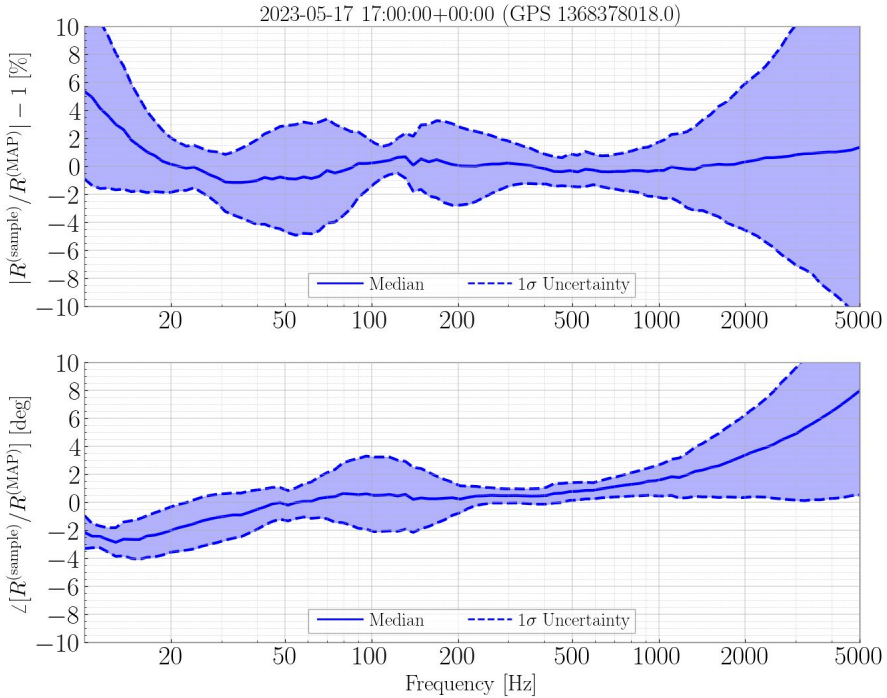
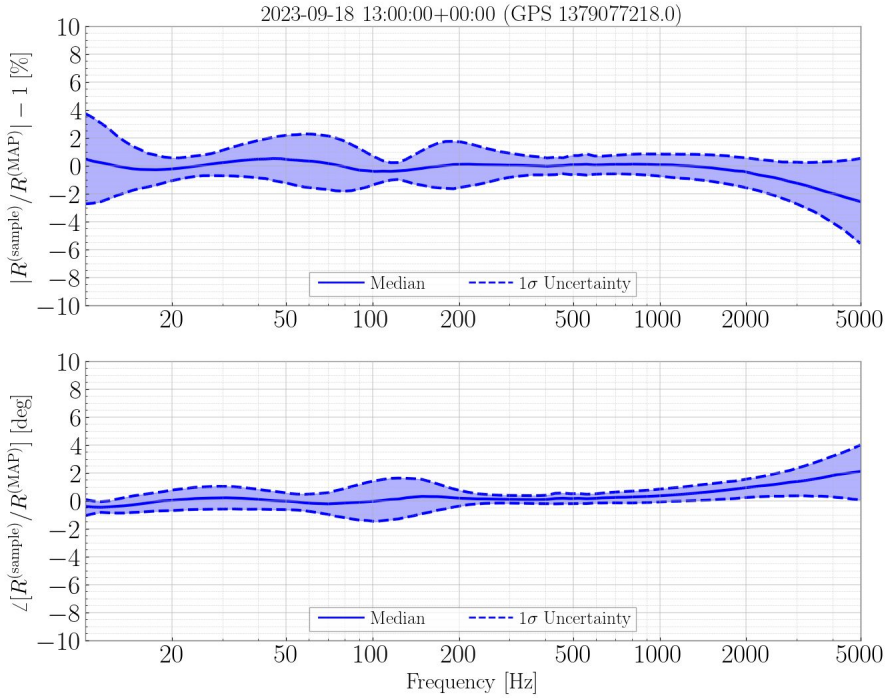
Calibration of GW detectors

Detector Calibration



Calibration Uncertainty (ER15 vs O4a)





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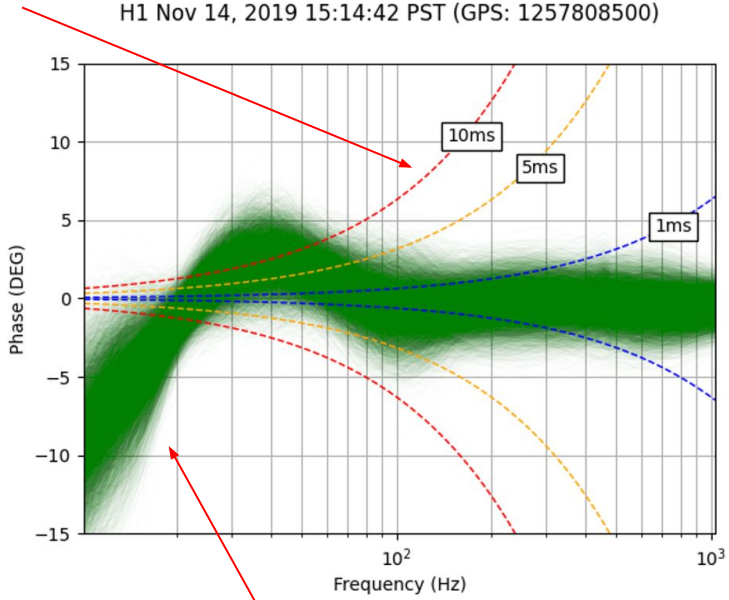
Old Model

- Calibration Error (CE) modelling
  - Amplitude scaling
  - Time jittering
  - Good approximation for narrowband signals
- Does not correspond to physical CEs

Frequency dependence of time jittering



Measured frequency dependence of phase CEs (smoothed by Gaussian Process Regression (GPR))

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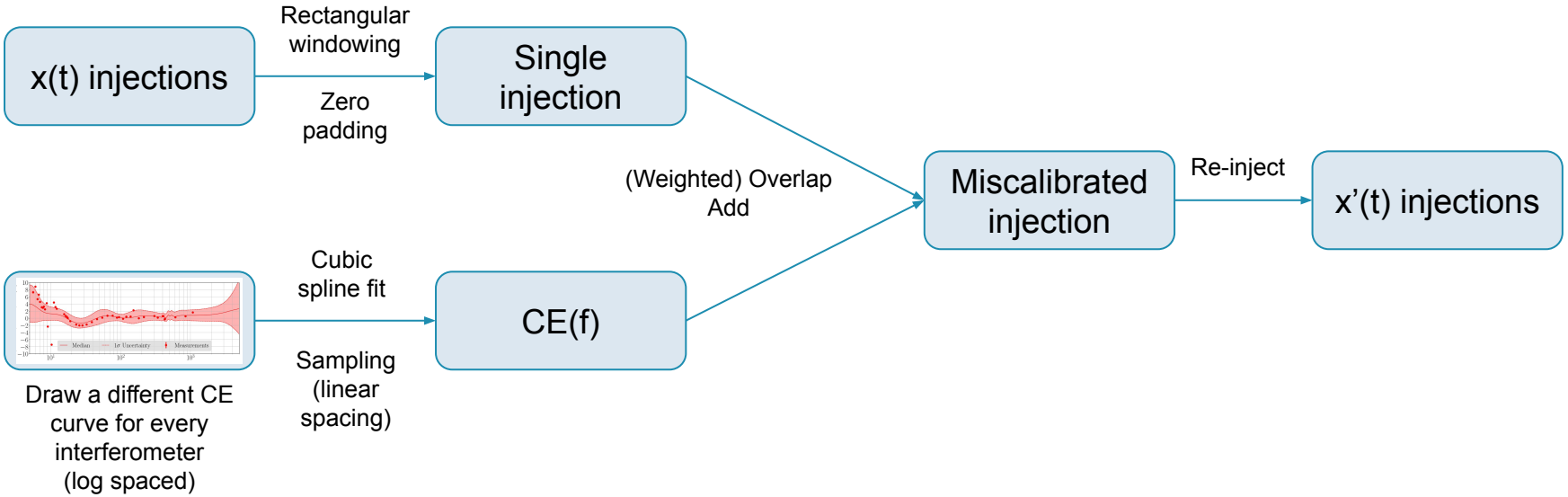
Impact on coherent WaveBurst

Simulation of physical calibration errors

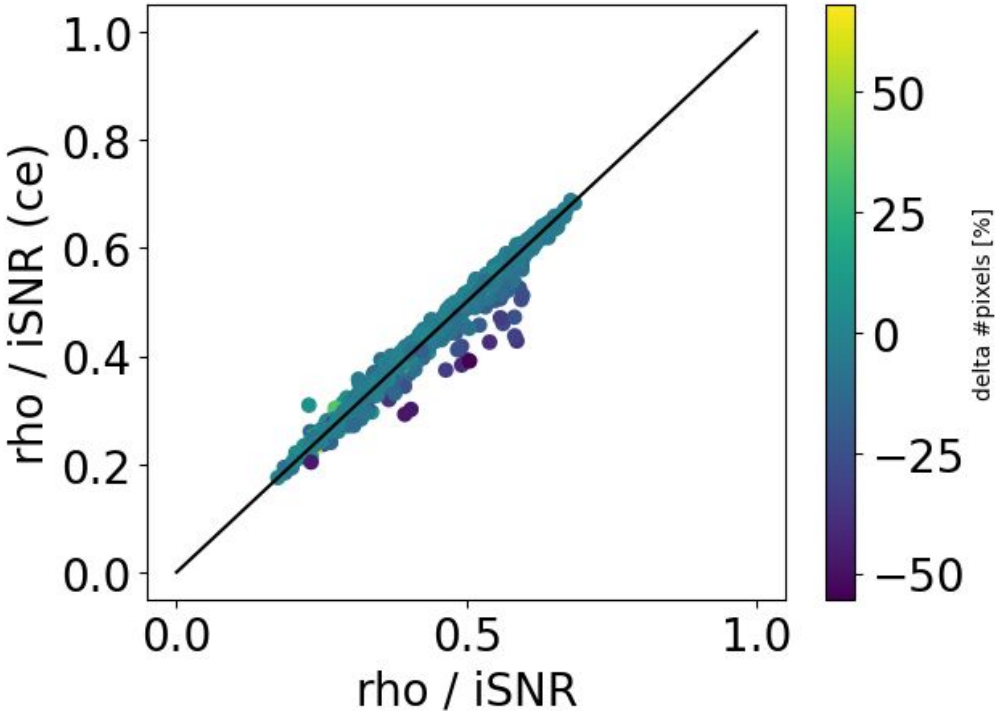


Impact on unmodeled search pipelines

- Calibration Error (CE) is different in each detector
  - Fraction of the signal is no longer coherent
  - Roughly proportional to the CE
- 2G detectors
  - SNR of detected events < 40
  - For CE < 10%: incoherent signal has SNR < 4
  - Low impact expected
- 3G detectors
  - SNR ~ 100
  - Residual signal no longer consistent with the noise

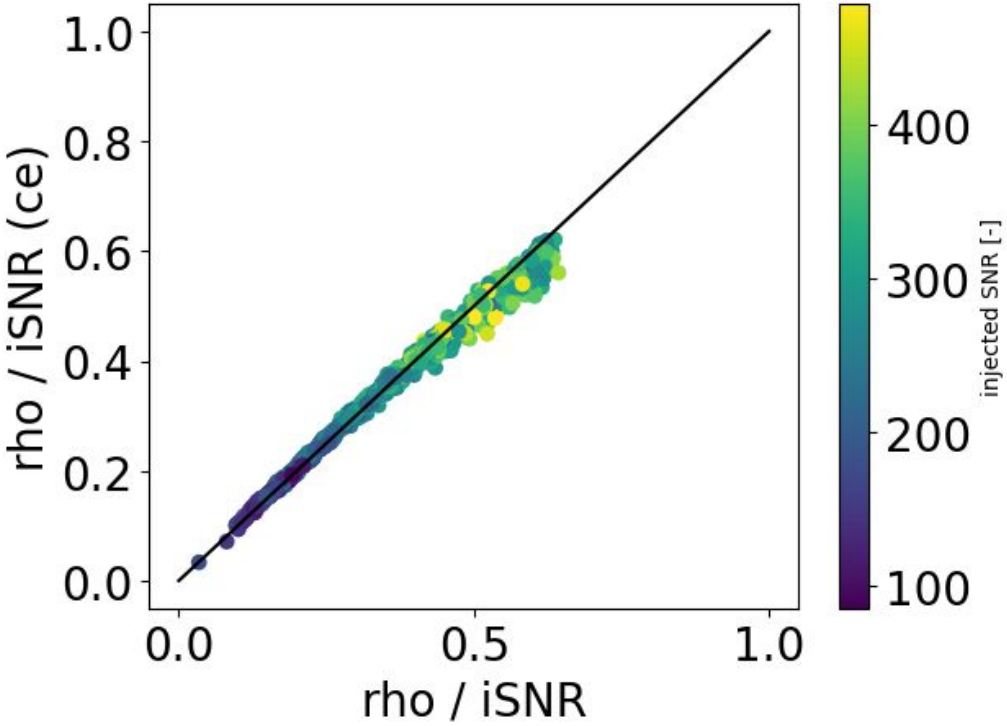
Worst Case Phase Errors O3

- mesa20 waveform at 420 pc
- Moderate SNR (~40)
  - Most triggers unaffected
  - A few triggers have a loss up to 10%
  - Big difference in #pixels
  - Most likely some clusters of pixels are around a threshold value



Worst Case Phase Errors O3

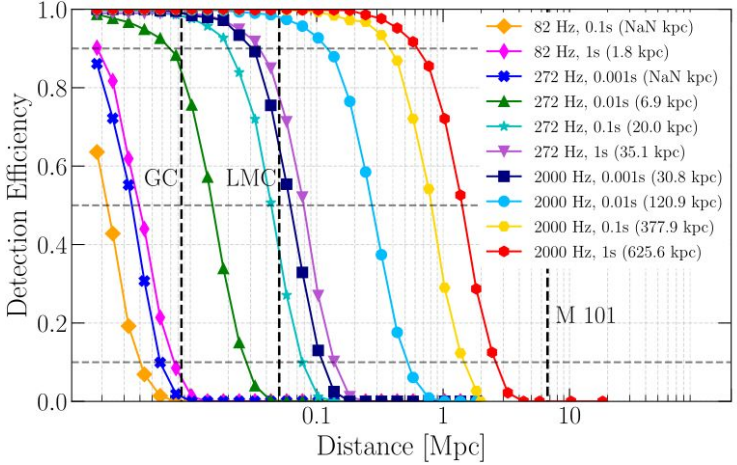
- s14 waveform at 30 pc
- High SNR (~200)
  - #pixels barely changes
  - Residual signal too small to affect likelihood / noise power
- Extremely high SNR (~400)
  - Only the coherent portion of the signal is detected
  - Residual signal becomes comparable to the noise



Detection efficiency

- Impact on the 50% detection efficiency SN2023ixf ~ 1%
- Using calibration errors from the injected GPS times
- Corresponds to a marginalisation over the calibration uncertainty
- Could be run as a default in offline targeted search

Figure taken from [1]



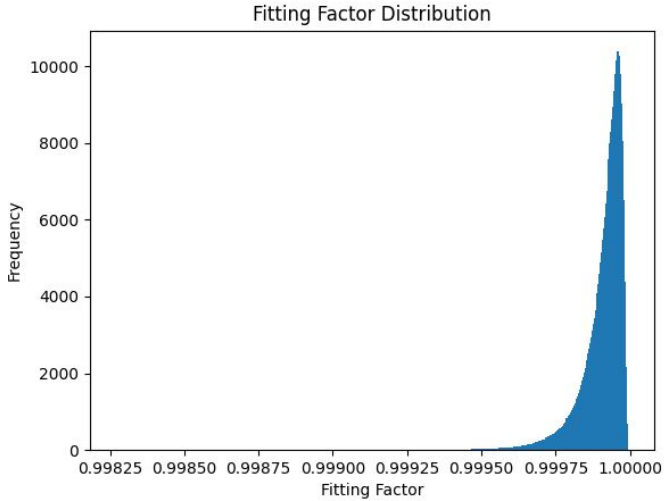
Waveform	d50 (CE)	d50 (No CE)	Diff
s11	1.37E+00	1.38E+00	-0.72%
SFHx	1.35E+01	1.35E+01	0.00%
D15-3D	4.43E+00	4.44E+00	-0.23%
mesa20	1.32E+00	1.32E+00	0.00%
mesa20_pert	1.70E+00	1.69E+00	0.59%
s18_3d	8.24E+00	8.26E+00	-0.24%
s3.5_pns	4.16E+00	4.17E+00	-0.24%
s13	9.91E-01	9.88E-01	0.30%
s25	8.94E+00	8.96E+00	-0.22%
NR	1.06E+01	1.06E+01	0.00%

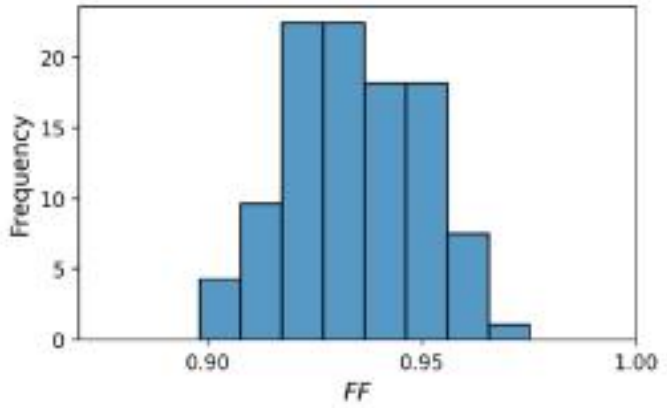
Impact on parameter estimation

Core-bounce: Fitting Factor

- 10000 O3 calibration curves at a bad GPS time in H1
- 864 waveforms from Abdikamalov 2024 catalog [2]
- Fitting factor > 0.9995
- Much larger than the current modelling errors [3]
- Fitting factor is very sensitive to phase, less to amplitude errors

See Claudia's talk!





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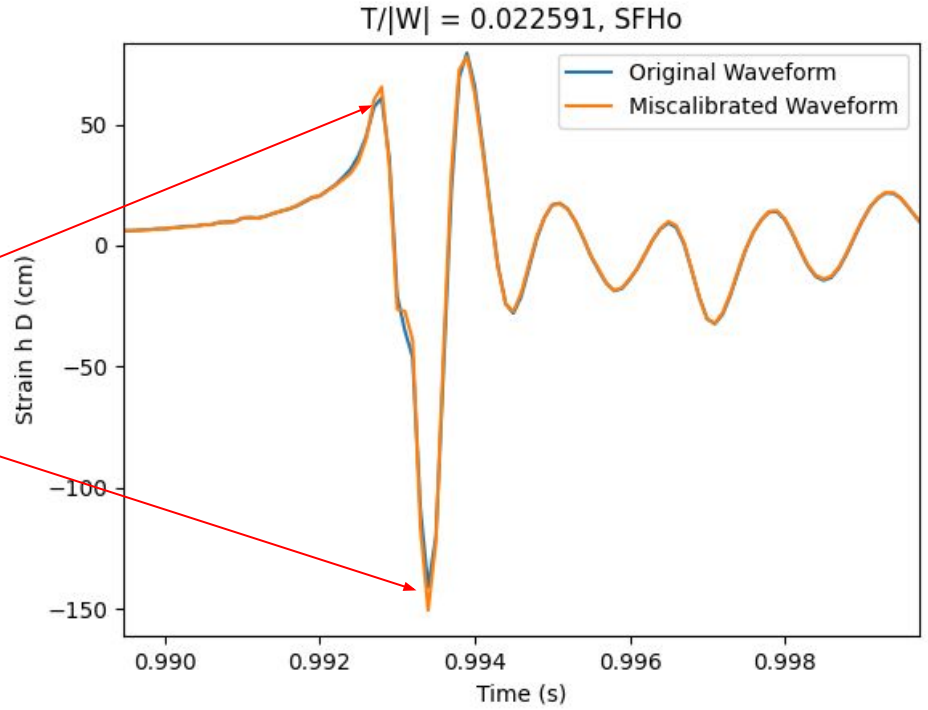
Core-bounce: time-domain

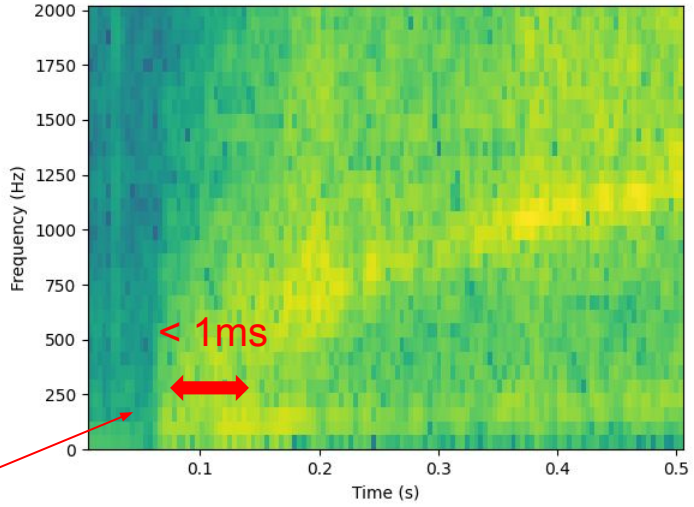
- Example parameters
  - T / |W| = 0.026
  - EOS: LS220
  - FF = 0.9998
- Frequency dependent calibration error → relative difference in peak amplitudes!
- Potential bias in T / |W|



High-frequency signature

- Amplitude errors do not fundamentally change the TF structure
  - Relative amplitude errors can cause some jitter on the slope estimate
- Phase error ~ frequency dependent delay

$$\tau = \frac{\phi}{2\pi f} \approx 1ms \frac{\phi}{10^\circ} \frac{20\,Hz}{f}$$



- Low frequency has the highest jitter

$$\frac{\delta\hat{s}}{\hat{s}} \approx \frac{\tau}{\Delta t} \approx 1\%$$

Much lower than current confidence levels [4]

SASI

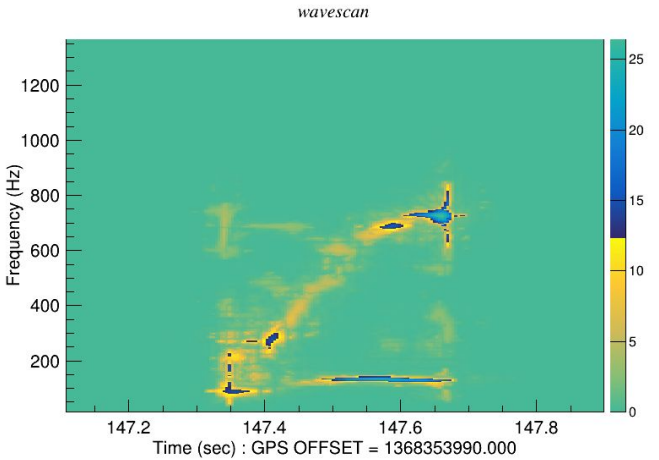
- Reconstructed event for SN2023ixf in L1
  - Virtually indistinguishable between
- Loss of pixels could impact detectability for SASI for medium SNR

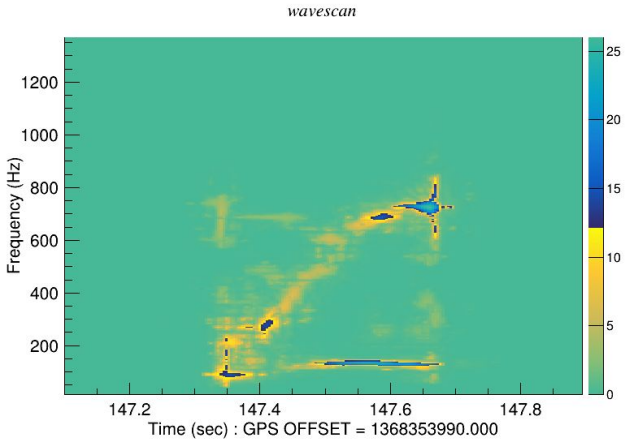
$$\rho_{norm} = \frac{\sum_{i \in SASI} \rho^i}{\sum_i \rho^i} \qquad [5]$$

- Sharp feature in calibration error could shift estimated peak frequency

$$f = \frac{\sum_{i \in SASI} f_c^i \rho^i}{\sum_i \rho^i}$$

See Vicente's talk!





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Conclusion

Conclusion

- Developed plugin for cWB that simulates **realistic** CEs
- Impact on detection statistics
  - Only significant effects are well above detection threshold (~10)
  - Negligible impact on detection efficiency
- Impact on PE
  - Fitting factors are small compared to model uncertainty
  - Precision tests of T / |W| might be affected with 3G
- Future work
  - Include sharp features in the calibration error
  - Run the full pipeline: cWB with CE → PE (SASI, g-mode)

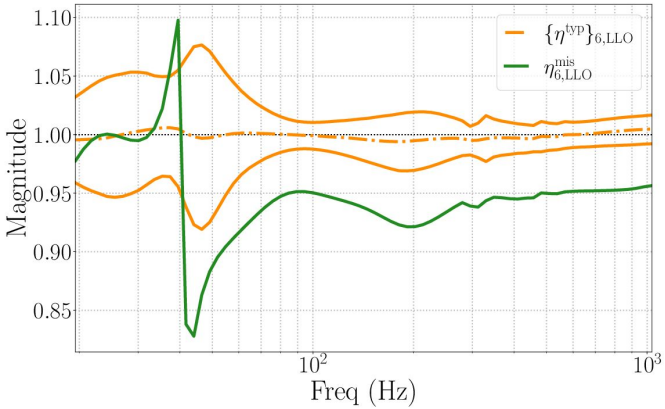
References

- [1] Abac, A. G., “Search for Gravitational Waves Emitted from SN 2023ixf”, The Astrophysical Journal vol. 985, no. 2, Art. no. 183, IOP, 2025. doi:10.3847/1538-4357/adc681.
- [2] Abylkairov, Y. S., Edwards, M. C., Orel, D., Mitra, A., Shukirgaliyev, B., and Abdikamalov, E., “Evaluating machine learning models for supernova gravitational wave signal classification”, Machine Learning: Science and Technology, vol. 5, no. 4, Art. no. 045077, IOP, 2024. doi:10.1088/2632-2153/ada33a.
- [3] Villegas, L. O., Moreno, C., Pajkos, M. A., Zanolin, M., and Antelis, J. M., “Parameter estimation from the core-bounce phase of rotating core collapse supernovae in real interferometer noise”, Classical and Quantum Gravity, vol. 42, no. 11, Art. no. 115001, IOP, 2025. doi:10.1088/1361-6382/add235.
- [4] Casallas Lagos, A., Antelis, J. M., Moreno, C., Zanolin, M., Mezzacappa, A., and Szczepańczyk, M. J., “Characterizing the temporal evolution of the high-frequency gravitational wave emission for a core collapse supernova with laser interferometric data: A neural network approach”, Phys.Rev.D 108 (2023) 8, 084027. doi:10.1103/PhysRevD.108.084027
- [5] Lin, Z., Rijal, A., Lunardini, C., Morales, M. D., and Zanolin, M., “Characterizing a supernova's standing accretion shock instability with neutrinos and gravitational waves”, Physical Review D, vol. 107, no. 8, Art. no. 083017, APS, 2023. doi:10.1103/PhysRevD.107.083017.

Backup slides

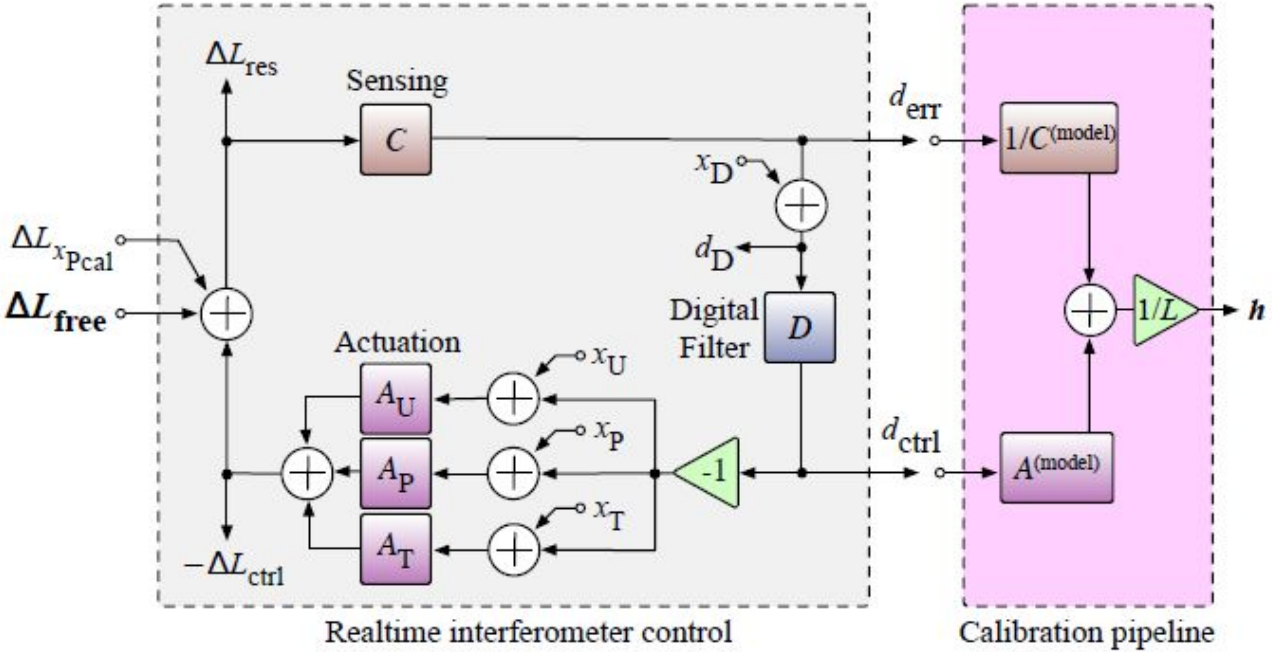
Open Issues we are checking

- Sharp features in CE(f) are not simulated
  - Smoothness requirement on CE(f)
    - Depends on DFT-size and zero-padding
    - Check should be implemented
  - Gaussian Process Regression
    - Logarithmic smoothness
    - $$k\left(\log(f), \log(f')\right) = \gamma_1^2 + \gamma_2^2 \exp\left(-\frac{\left(\log(f) - \log(f')\right)^2}{2\ell^2}\right)$$
- Sharp features do exist
  - Switch between actuation and sensing function
  - Finite Impulse Response Filters (FIRs)



Huang et al. 2022, arXiv:2204.03614

DARM Loop



Source: Ling Sun et al 2020 Class. Quantum Grav. 37 225008

Full signal: Fitting Factor

- Waveforms of O4 search
- Lower fitting factor than core-bounce