GWFAST: a Fisher-matrix Python code for third-generation gravitational-wave detectors

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Based on *Astrophys. J. Supp.* 263 (2022) 1, 2.

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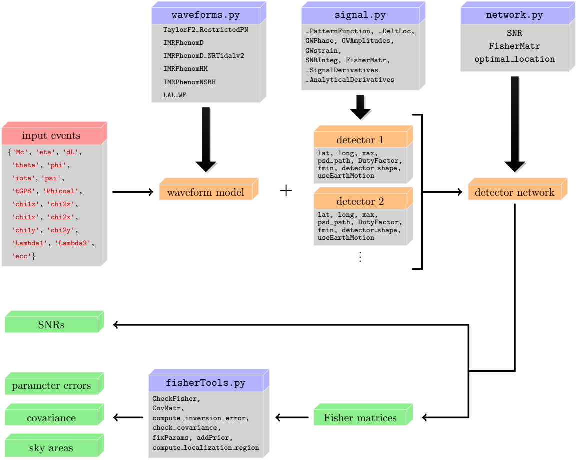
XIII ET Symposium – Cagliari 2023

GWFAST structure

GWFAST is a Fisher code particularly tuned towards high computational speed, user friendliness, and accuracy in derivative evaluation

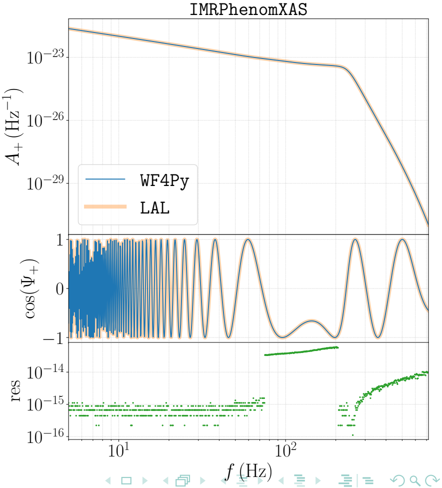


GWFAST: waveforms

Waveforms are the first building block of the analysis, allowing to translate the source parameters into an actual signal!

In the `waveform.py` module GWFAST provides a pure Python implementation of various state–of–the–art approximants, whose a adherence with LAL has been carefully checked.

We released them also as a separate module, WF4Py, which features: TaylorF2, IMRPhenomD, IMRPhenomD_NRTidalv2, IMRPhenomHM, IMRPhenomNSBH, IMRPhenomXAS (more coming!)

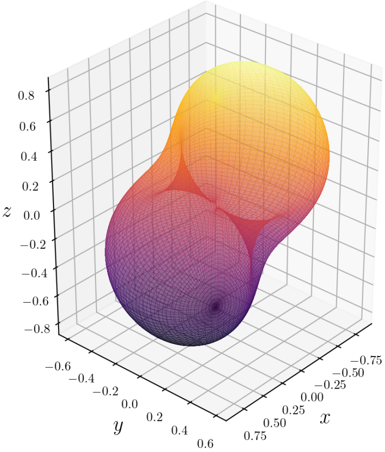


GWFAST: signal

Once the waveform is provided we need to project the signal onto the detector

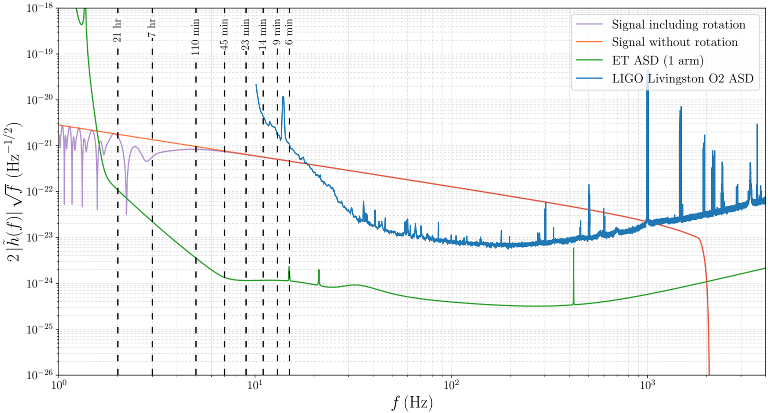
In **GWFAST** this is done within the **GWSignal** class in the **signal.py** module. This class is in a sense the abstract representation of the detector, initialised providing the position, orientation, shape and noise amplitude/power spectral density.

The key element of the **GWSignal** class are the so–called antenna pattern functions, which give the angular sensitivity of a GW detector.



GWFAST: signal

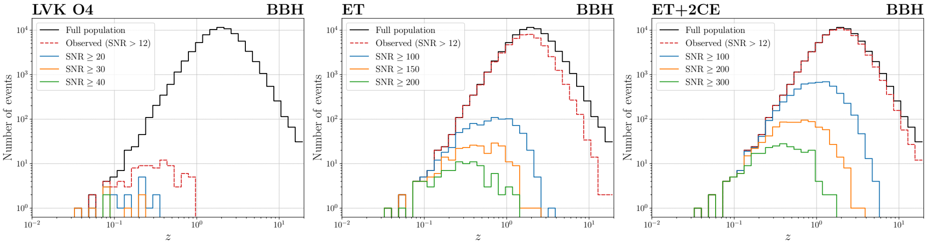
Using the signal class it is possible e.g. to plot how a GW signal would look like in the band of a detector!



GWFAST: network and SNRs

If considering more than one instrument, it possible to easily build a detector network in GWFAST though the DetNet class in the network.py module!

Having a GWSignal or DetNet it is then possible to compute e.g. the signal–to–noise ratios (SNRs) for one or multiple events, which already provide very useful information to characterize GW detectors!



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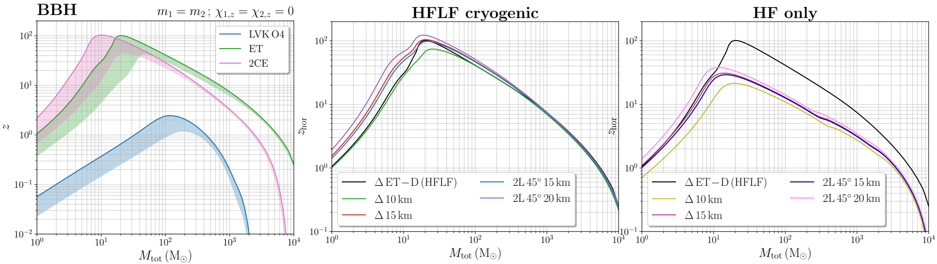
GWFAST: detection horizons

GWFAST also offers the possibility to compute the optimal location in the sky for a signal to be observed by a single detector or a network of identical detectors. Together with the possibility to compute the SNRs, this allows us to get a very useful metric: the detection horizon!



GWFAST: Fisher matrix

The key feature offered by `GWFAST` is the possibility to compute the Fisher matrices for one or multiple events.

The fundamental ingredient for it are derivatives, which are computed using *automatic differentiation* with with

This allows for efficient vectorization and exquisite numerical accuracy

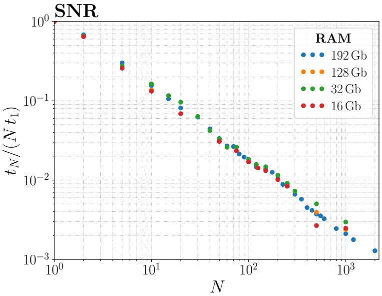
$$f(x) = \sin\left(\ln\left(\sqrt{x}\right)\right)$$

```
eps = 1e-5
print((f(10.+eps) - f(10.))/eps - fp(10.))
```

```
0.003476493
```

```
JAXfp = jax.grad(f)
print(JAXfp(10.) - fp(10))
```

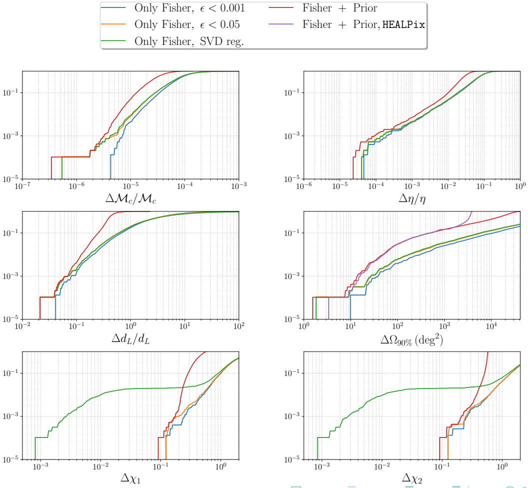
```
0.0
```



GWFAST: covariance matrix

A delicate point is the inversion of the Fisher matrix to obtain the covariance matrix.

In GWFAST we offer various ways of checking the FIM (e.g. eigenvectors and eigenvalues), as well as to compute the covariance. In particular, we employ the mpmath library for precision arithmetic, and provide the possibility to evaluate the condition number and inversion error $\epsilon = \Gamma \cdot \Gamma^{-1}$



Thanks for your attention. . . now let's get our hands dirty with some coding!

GW parameter estimation: MCMC timing for PE

Performing a full Bayesian PE for a GW signal via an MCMC sampling of the likelihood is computationally expensive

Signal	Sampler	n_ℓ	$n^{\rm eff}_{\rm samples}$
BBH	`DYNESTY`	2.2×10^8	15000
	`BILBY-MCMC`	3×10^8	5000
BNS	`BILBY-MCMC`	2.5×10^9	5000

Ashton, Talbot (2021)

With `BILBY` it can take $\gtrsim \mathcal{O}(1\ \text{day/ev})$ to perform the estimation

Full PE is not feasible for 10^5 events

GWFAST checks

To asses the reliability of **GWFAST** we performed the PE analyses on the samples of real GW events with high SNR and good sky location, finding consistent results