Detection and measurement prospects at the Einstein Telescope: forecasts with GWFAST

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Mainly based on ApJ 941 208 (2022) and ApJS 263 2 (2022), in collaboration with: Michele Mancarella, Stefano Foffa, Michele Maggiore

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XXV SIGRAV Conference – Trieste, 2023

Outline

1. Introduction
   - State–of–the–art of GW observations at 2G detectors
   - 3G detectors: how big is the leap?
   - Fisher codes: why and how?
2. Forecasts @3G detectors with **GWFAST** for CBCs: BBH, BNS and NSBH at ET and ET+2CE
3. Forecasts @3G detectors with **GWFAST** on specific science cases:
   - Primordial black holes
   - Nuclear physics

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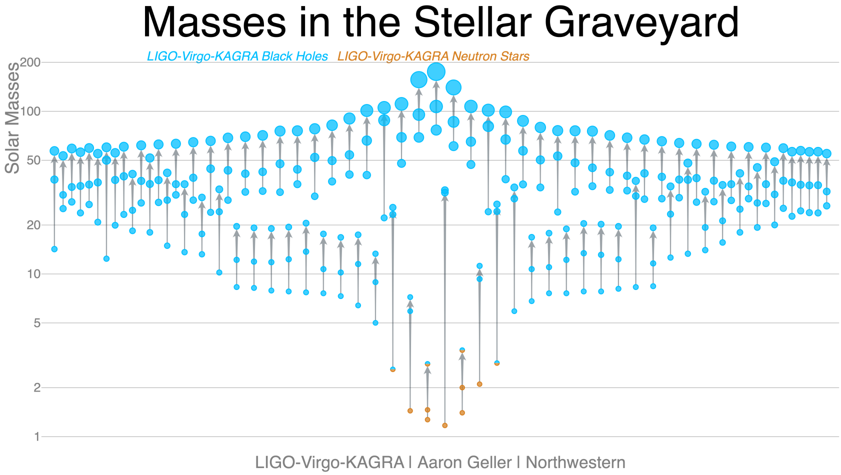
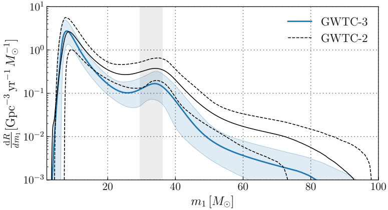
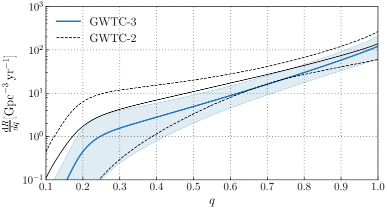
Introduction: 2G GW detectors, where we stand

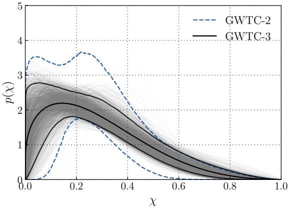


Introduction: 2G GW detectors, where we stand

Thanks to LVK detections, we now have information on the distribution of BBH up to $z \sim 1$, and some hints for BNS and NSBH







$$R_{0,\mathrm{BBH}} = 10.3 - 27\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$
$$R_{0,\mathrm{BNS}} = 10 - 1700\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$
$$R_{0,\mathrm{NSBH}} = 7.8 - 140\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

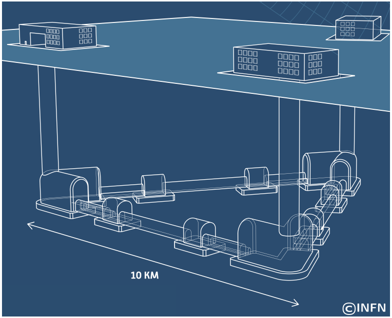
LVK Collaboration, 2111.03634 (2021)

Introduction: 3G GW detectors

2G detectors offer outstanding possibilities...
...but the potential of 3G detectors is unprecedented

ET:

Between 100 m and 300 m underground;
Six 10 km detectors arranged in a triangle with "xylophone" design:
– Cryogenic for LF and high power at HF; – No blind spots;
– Sensitive to both GW polarizations;
Proposed more than 10 years ago (Punturo et al. (2010), Hild et al. (2011)).



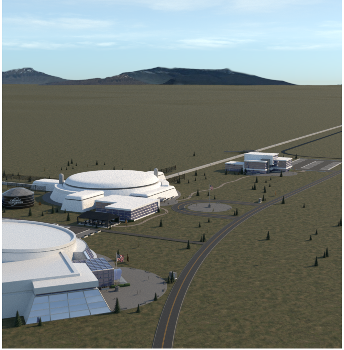
Science case in Maggiore et al. (2020), see Branchesi et al. (2023) for an updated science case, also studying different designs!

Introduction: 3G GW detectors

2G detectors offer outstanding possibilities...
...but the potential of 3G detectors is unprecedented

CE:

Two facilities of 40 km and 20 km: length reduces many noise sources (shot, radiation pressure,...);
Tunable design:
– can be optimized for CBCs;
– can be optimized for BNS PM;
CE white paper in 2019 (Reitze et al. (2021)) and CE Horizon Study document recently published (Evans et al. (2021))

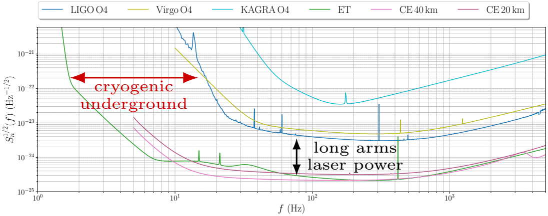


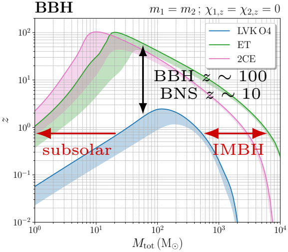
White paper recently submitted to NSF cmte. Evans et al. (2023)

Introduction: 3G GW detectors

2G detectors offer outstanding possibilities...
...but the potential of 3G detectors is unprecedented

Thanks to their technological advancements and the bigger facilities, ET and CE will have a broader frequency range and sensitivities improved more than 10 times compared to LVK





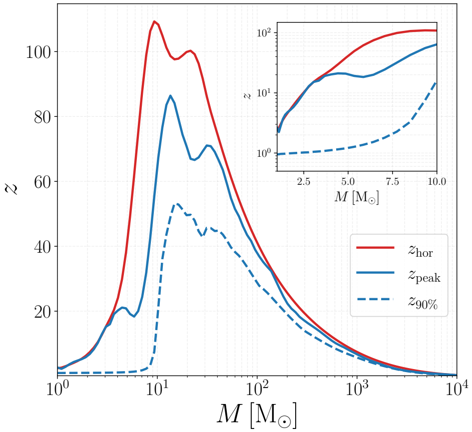
Assessing the capabilities of 3G detectors is fundamental to take informed decisions!

Introduction: 3G GW detectors

Other than the number of detections and horizon, a key metric is the estimation of the errors on the source parameters' reconstruction

The fact that we can detect many far mergers does not mean that we can perform a good PE for all of them

Mancarella, FI, Gerosa, 2023



Introduction: why Fisher matrix?

One of the key challenges when performing studies for ET and CE that emerged in recent years is the number of detectable sources

Network	BBH/yr	BNS/yr	NSBH/yr
LVK–O4	$\mathcal{O}(10^2)$	$\mathcal{O}(1-10)$	$\mathcal{O}(1-10)$
ET	$\mathcal{O}(10^4)$	$\mathcal{O}(10^3-10^5)$	$\mathcal{O}(10^3-10^4)$
ET+2CE	$\mathcal{O}(10^4-10^5)$	$\mathcal{O}(10^4-10^5)$	$\mathcal{O}(10^3-10^5)$

Currently used Bayesian parameter estimation codes, like `BILBY`, can take $\mathcal{O}(1\,\mathrm{day/ev})$ to perform the analysis with an MCMC…

…and we do not have 10^5 days :'(

Introduction: Fisher matrix

In the linearized signal approximation / high–SNR limit, the GW likelihood can be approximated near the peak as a multivariate Gaussian with covariance

$$\mathrm{Cov}_{ij} = \Gamma^{-1}_{ij}\,, \quad \Gamma_{ij} \equiv -\left.\langle \partial_i \partial_j \log \mathcal{L}(s \,|\, \boldsymbol{\theta}) \rangle_n \right|_{\boldsymbol{\theta}_0} = \left.(\partial_i h(\boldsymbol{\theta}) \,|\, \partial_j h(\boldsymbol{\theta}))\right|_{\boldsymbol{\theta}_0}$$

Γ_{ij} being the Fisher matrix

The key ingredients are then computing derivatives and...speed!

Introduction: public Fisher codes

Various groups all across the world started to tackle the problem, and by now there are three public codes that can perform such a complex analysis exploiting the Fisher matrix formalism:

GWBENCH: a novel Fisher information package for gravitational-wave benchmarking

S. Borhanian[1,2]

[1] *Institute for Gravitation and the Cosmos, Department of Physics, Pennsylvania State University, University Park, PA 16802, USA*
[2] *Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, 07743, Jena, Germany**
(Dated: August 31, 2021)

GWFISH: A simulation software to evaluate parameter-estimation capabilities of gravitational-wave detector networks

Jan Harms[1,2], Ulyana Dupletsa[1,2], Biswajit Banerjee[1,2], Marica Branchesi[1,2], Boris Goncharov[1,2], Andrea Maselli[1,2], Ana Carolina Silva Oliveira[3], Samuele Ronchini[1,2], and Jacopo Tissino[1,2]
[1] *Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*
[2] *INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy and*
[3] *Department of Physics, Columbia University in the City of New York, New York, NY 10027, USA*
(Dated: May 6, 2022)

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

Francesco Iacovelli[1], Michele Mancarella[1], Stefano Foffa[1] and Michele Maggiore[1]

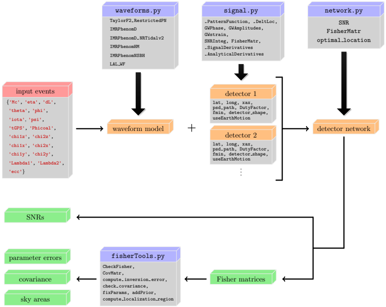
[1] *Département de Physique Théorique, Université de Genève, 24 quai Ernest Ansermet, 1211 Genève 4, Switzerland*

see also TiDoFM, Li et al. (2022) and Pieroni et al. (2022)

Introduction: GWFAST

GWFAST is particularly tuned towards high computational speed, user friendliness, and accuracy in derivative evaluation, in particular:

- ⟹ derivatives are computed using automatic differentiation with JAX
- ⟹ the code is written in pure Python (also the waveforms!)
- ⟹ vectorization is exploited to handle multiple events at a time, even on a single CPU

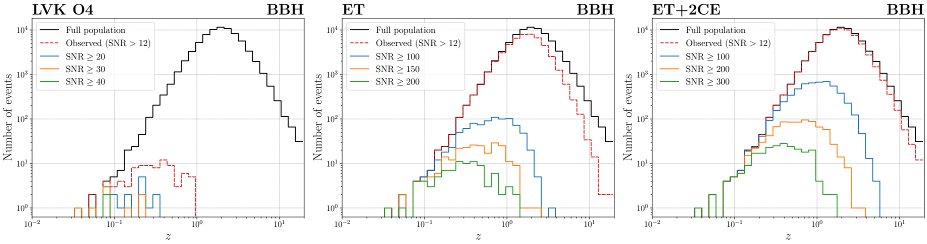


GWFAST needs $\lesssim 1$ day **to run the PE on** 10^5 **events!**

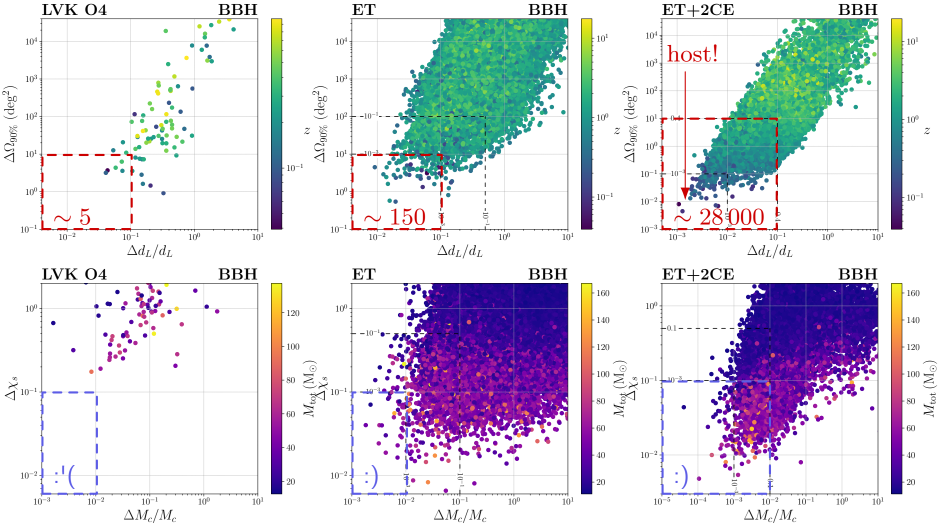
We also published a complete online documentation, see https://gwfast.readthedocs.io/en/latest/

Forecasts with GWFAST: BBHs at 3G detectors

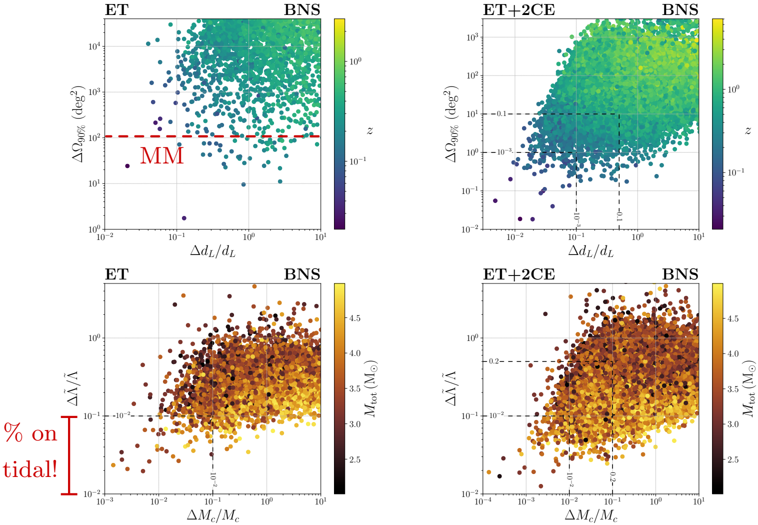
Simulating synthetic merger populations, based on the latest LVK results, through **GWFAST** it is possible to assess the capabilities of GW detectors, comparing among different networks and configurations and for different sources



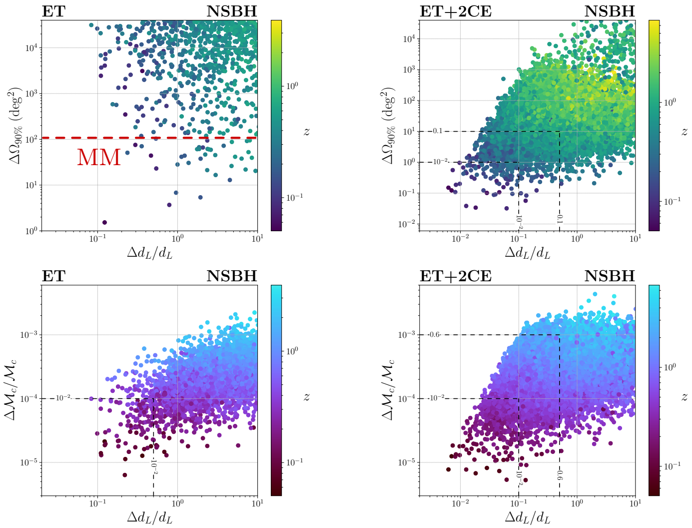
Forecasts with GWFAST: BBHs at 3G detectors



Forecasts with GWFAST: BNSs at 3G detectors



Forecasts with GWFAST: NSBHs at 3G detectors



ET science case

Astrophysics

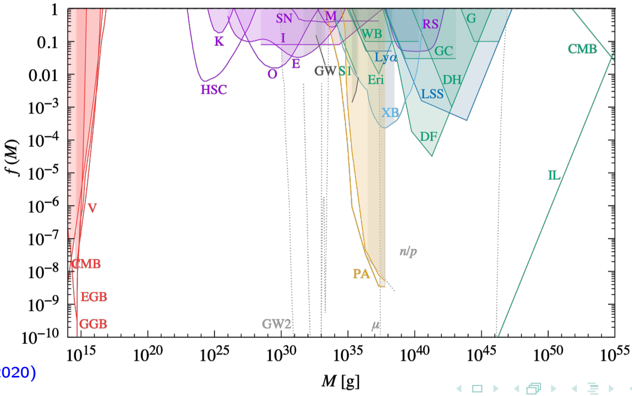
- BH properties (origin, evolution, demography)
- NS properties (interior structure, demography)
- Multi-band and -messenger astronomy (joint GW/EM observations, ET+LISA synergy, neutrinos)
- New astrophysical sources (CCSNe, isolated NS, stochastic background)

Fundamental physics and cosmology

- Tests of GR and compact objects (PN, near-horizon, exotic objects)
- DM (PBHs, axion clouds, accretion on CO)
- DE and modified gravity
- Cosmological stochastic background

Primordial Black Holes

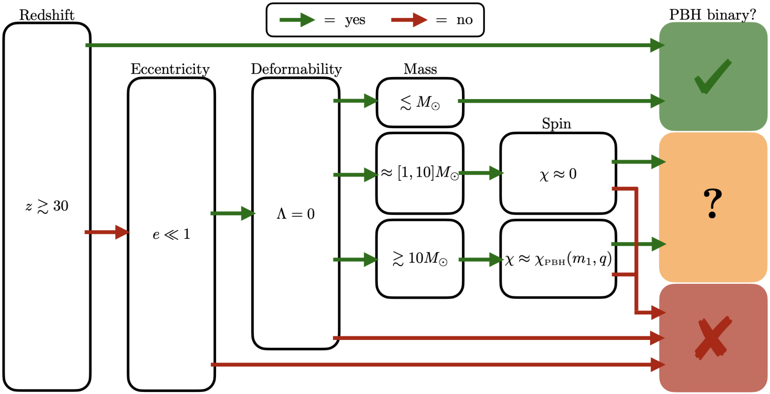
PBHs can form from the collapse of inhomogeneities in the radiation–dominated era. PBHs could explain at least a fraction of the dark matter in our universe, be the seed of SMBHs at high z, and could give rise to CBC events



Carr, et al. (2020)

Primordial Black Holes: binaries signatures

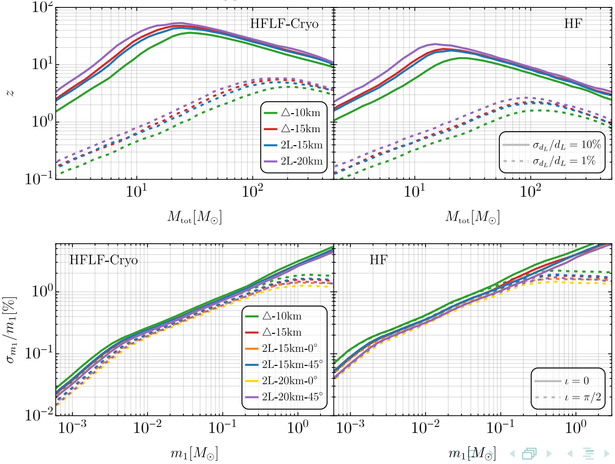
PBHs binaries could be difficult to tell apart from the ABH ones, but they have some characteristic features



Franciolini, et al. (2021)

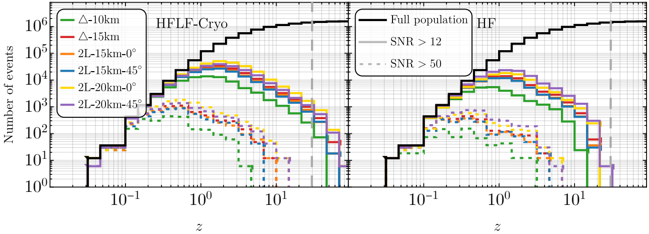
Primordial Black Holes: smoking–gun signatures

ET could reach an outstanding accuracy in the reconstruction of some relevant source parameters, such as mass, but some others are tricky Franciolini, FI, Mancarella, Maggiore, Pani, Riotto, 2023



Primordial Black Holes: population

We also simulated a PBH population that saturates the upper bounds provided by current GWTC–3 GW data Franciolini, et al. (2022)

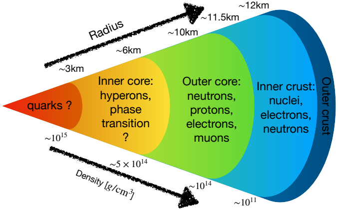


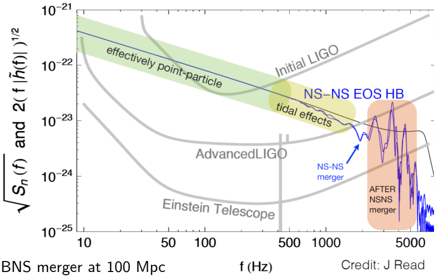
	$N^{\rm tot}$	$N^{\rm SS}$	$N^{z>10}$	$N^{z>30}$	$N^{\rm LMG}$	$N^{\rm UMG}$
Intrinsic population	1 920 000	708 487	1 400 384	795 904	300 220	7774
Configuration	$N^{\rm tot}_{\rm det}$	$N^{\rm SS}_{\rm det}$	$N^{z>10}_{\rm det}$	$N^{z>30}_{\rm det}$	$N^{\rm LMG}_{\rm det}$	$N^{\rm UMG}_{\rm det}$
△-10km-HFLF-Cryo	13 347	1650	336	17	2638	235
△-15km-HFLF-Cryo	30 912	4281	1099	91	6443	376
2L-15km-45°-HFLF-Cryo	24 900	3345	824	66	5132	332
2L-15km-0°-HFLF-Cryo	26 585	3580	940	65	5517	356
2L-20km-45°-HFLF-Cryo	35 524	5206	1434	140	7550	374
2L-20km-0°-HFLF-Cryo	45 650	6745	1962	187	9809	465
LVKI-O5	49	7	0	0	10	1

Franciolini, FI, et al. 2023

Nuclear physics: NS interior and observations

The largely improved sensitivity at high frequencies of 3G detectors will allow to look deeply into the BNS mergers (including the PM phase!), that can provide extremely valuable information on the NS structure

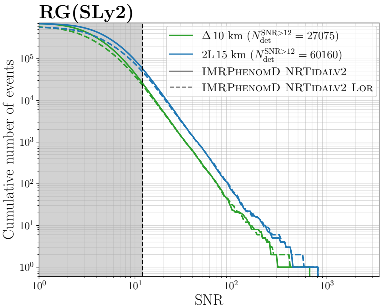


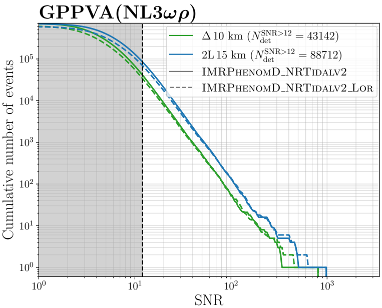


Even a few detections can give high evidence for the correct EoS model! Pacilio, et al. 2021

Nuclear physics: NS observations varying the EoS

The EoS can potentially have a strong impact on the number of detections, since it sets a limit to the maximum NS mass...



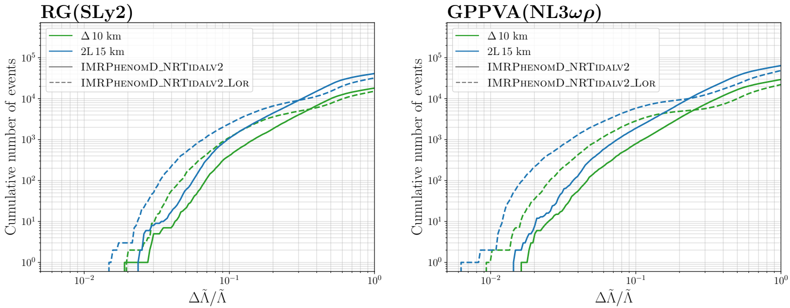


...but this obviously depends on the underlying mass distribution

FI, Mancarella, Mondal, Puecher, Dietrich, Gulminelli, Maggiore, Oertel, 2023

Nuclear physics: NS observations varying the EoS

Depending on the EoS the reconstruction of the tidal deformability parameters can be different, with softer EoSs posing a more difficult challenge, but…

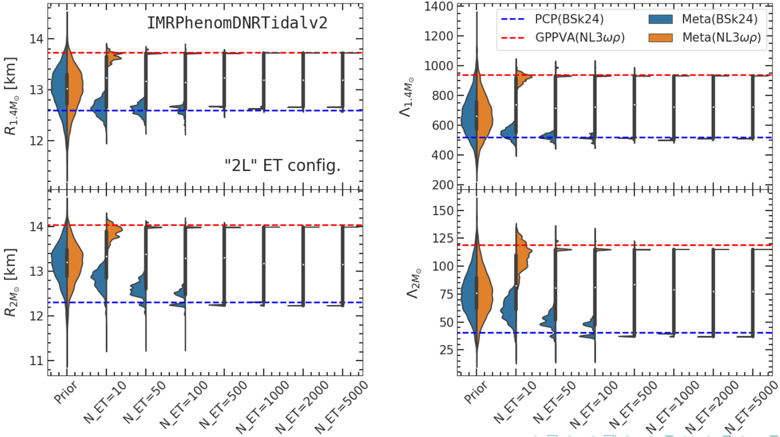


…already from the main post-merger peak we can improve the reconstruction of the Λs at the population level

Puecher, et al. 2022

Nuclear physics: NS properties reconstruction

A few detections are already enough to reconstruct specific features of NSs in the $R-M$ plane, and with $\mathcal{O}(10^3)$, attainable in a few moths at ET alone, the precision is exquisite



Conclusions

- 3G detectors have an unprecedented potential, capable of triggering fundamental discoveries
- Performing parameter estimation for 3G detectors is a key challenge, and the Fisher forecasts are just a first step, but...
- ...they provide a useful approximation, which can be used to explore and asses the capabilities of future detectors, with dedicated analyses

We developed and keep working on GWFAST let people explore the vast science case of 3G detectors, use it!

Contact: Francesco.Iacovelli@unige.ch

Thanks for your attention, questions?

I am available at Francesco.Iacovelli@unige.ch

GW parameter estimation: the GW likelihood

A GW signal as observed by a detector can be expressed as

$$s(t) = h_0(t) + n(t)$$

The likelihood for its parameters, choosing a waveform model h, is

$$\mathcal{L}(s \mid \boldsymbol{\theta}) \propto \exp\{- \left(s - h(\boldsymbol{\theta}) \,|\, s - h(\boldsymbol{\theta})\right)/2\}$$

where the inner product for any two time–domain signals is

$$(a \,|\, b) = 4\,\mathrm{Re}\left\{\int_0^\infty \mathrm{d}f\, \frac{\tilde{a}^*(f)\,\tilde{b}(f)}{S_n(f)}\right\} \implies \mathrm{SNR} = (h_0 \,|\, h_0)^{1/2}$$

GWFAST: derivatives

Usually derivatives are computed using finite difference techniques, but this has some limitations, consider e.g.

$$f(x) = \sin\left(\ln\left(\sqrt{x}\right)\right) \implies f'(x) = \cos\left(\ln\left(\sqrt{x}\right)\right)/2x$$

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

```
0.003476493
```

Every function with a closed form expression, however complex, is built from simple operations $(+, -, \times, \div)$, and well–known functions $(\exp, \cos, \ln, \dots)$ whose derivative is trivial.

What a pity a machine cannot understand it... wait, it can!

GWFAST: derivatives

Automatic differentiation is a technique to make a machine compute derivatives of any order in a pseudo–analytic way, iteratively applying the *chain rule* on a given function.

`GWFAST` uses the module `JAX` for automatic differentiation, that applied to our example function gives

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

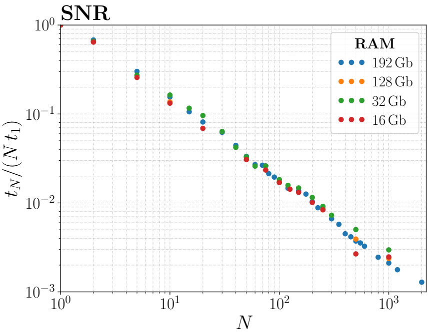
```
0.0
```

The only requirement is to write the function in a way the machine can understand, in our case pure `Python`... but `LAL` is written in `C`

GWFAST: vectorization

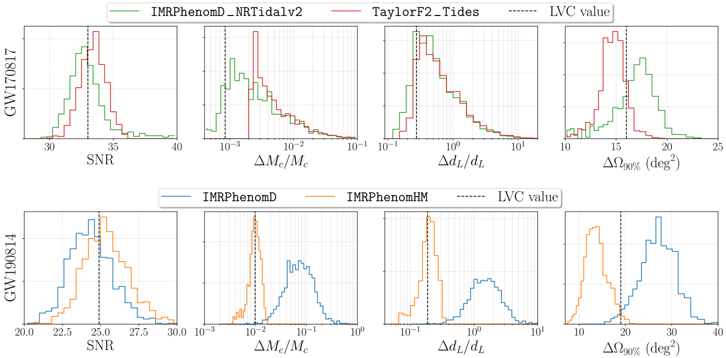
Having a pure `Python` code and using `JAX`, it is possible to exploit what is called *vectorization*, i.e. the possibility to perform calculations for multiple events at a time even on a single CPU, not resorting to `for` loops.

This makes `GWFAST` ideal to handle large catalogs!



GWFAST vs. real events

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



Contact: Francesco.Iacovelli@unige.ch

GWFAST vs. Mathematica

To asses the performance of the derivative computation, we compared the output of `GWFAST` with an independent code written in `Wolfram Mathematica`, capable of computing analytical derivatives with respect to all parameters