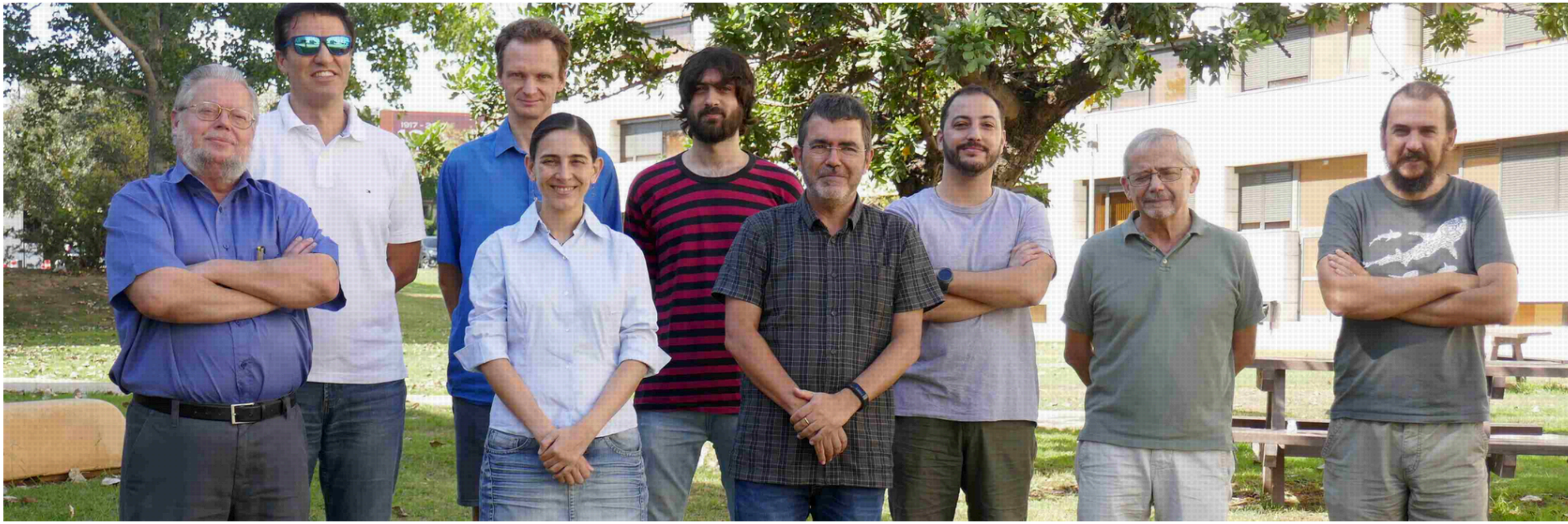
A brief overview of the activities of the Valencia Virgo Group

José Antonio Font
Universitat de València
www.uv.es/virgogroup

The Valencia Virgo Group

www.uv.es/virgogroup

M.A. Aloy M. Obergaulinger N. Sanchis A. Torres



J.M. Ibáñez I. Cordero J.A. Font A. Marquina P. Cerdá

D. Guerra

F. Di Giovanni

M. Miravet

Activities of the VVG

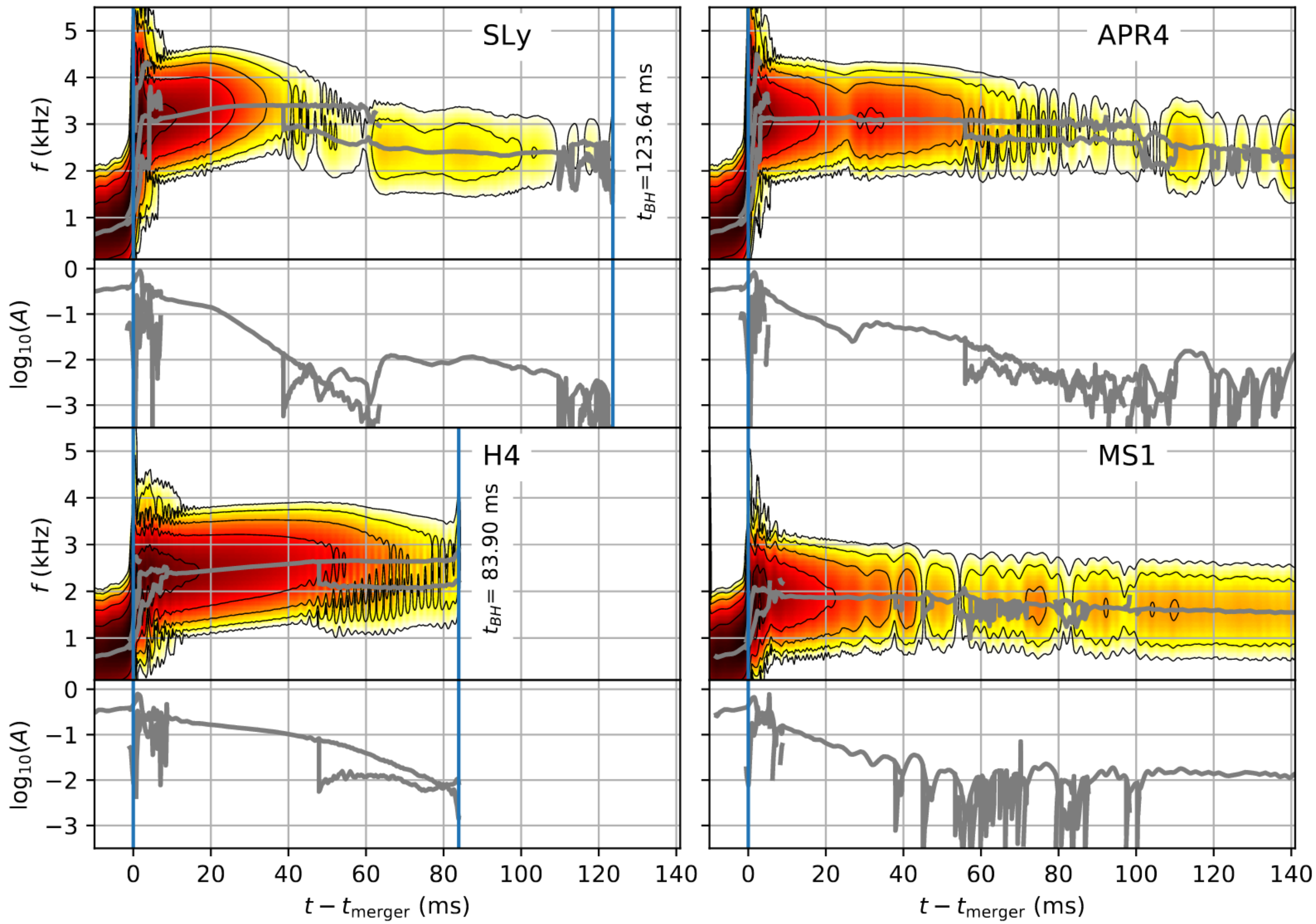
- Long-term experience in numerical simulations of astrophysical sources of gravitational radiation, i.e., **waveform generation through numerical relativity simulations**.

  RNS, BNS, BBH, CCSNe, BH accretion, fundamental fields (BH mimickers).

- **Data analysis** with TV techniques for GW denoising and waveform reconstruction. ROF model. (With ICCUB.) Machine learning for GW DA (with U. Minho).
- **Detector characterization** - classification methods for noise transients (glitches) in GW detectors and blips denoising (Dictionary Learning).
- **Parameter estimation** (CCSNe, BBH mergers, "exotic" mergers).
- **EM follow-up**: EM observations of GW counterparts during O3 (with UIB & IAA).
- **3G:** UVEG participates in the ET ESFRI proposal (just submitted).
- **Outreach**.
- **Service work** (Advanced Virgo detchar shifts, reviews).

NR simulations & waveform generation (R&D)

BNS: Excitation of **inertial modes** in long-lived simulations of HMNS

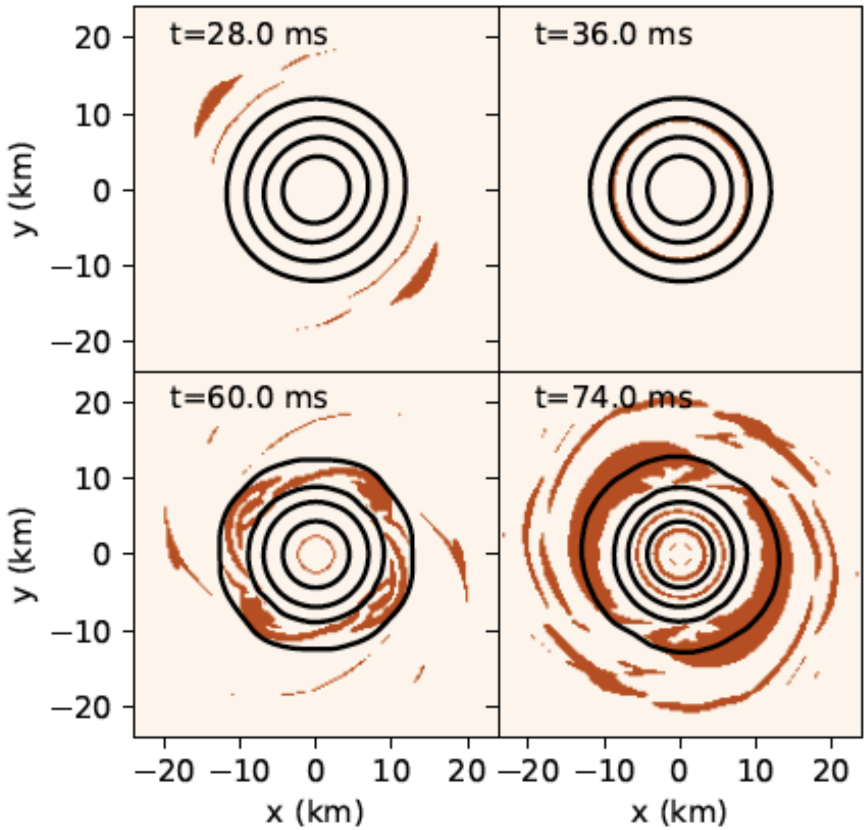


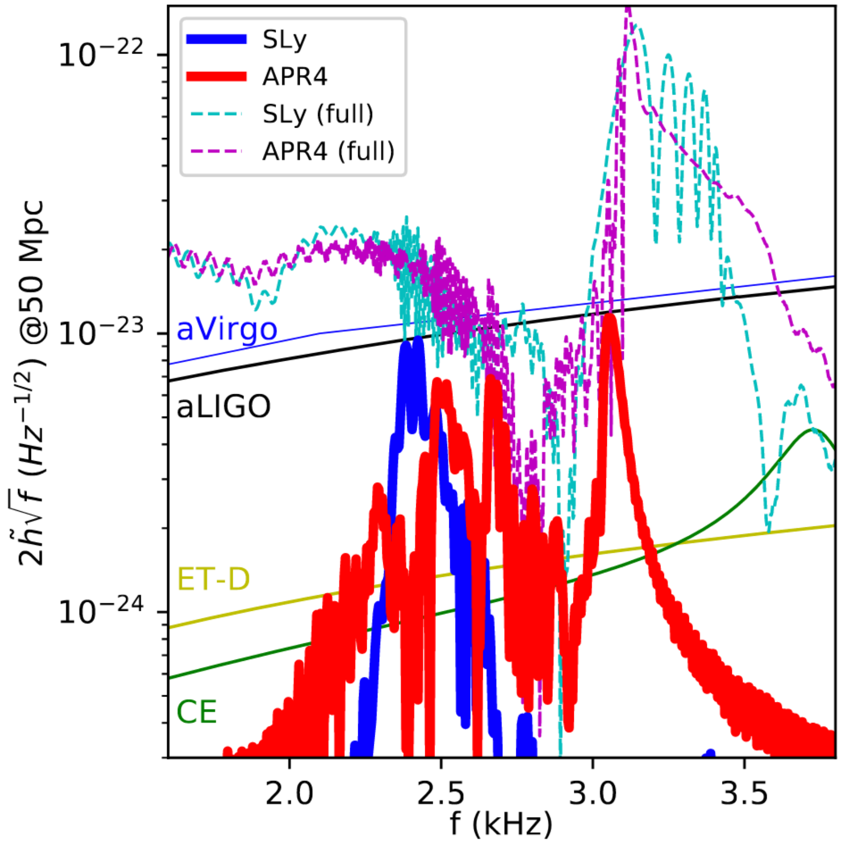
Collaboration VVG+Parma+AUTh

De Pietri et al, PRL (2018); PRD (2020)

NR simulations & waveform generation (R&D)

BNS: Excitation of **inertial modes** in long-lived simulations of HMNS





Detection of inertial modes in HMNS may provide an opportunity to infer the rotational and thermal properties of remnants.

De Pietri et al, PRL (2018); PRD (2020)

NR simulations & waveform generation (R&D)

Spinning Bosonic Stars: different stability properties found in the scalar/vector case, related to their toroidal/spheroidal morphology.

Collaboration VVG+Aveiro+CENTRA

Sanchis-Gual et al, PRL (2019)
Di Giovanni et al, PRD submitted (2020)

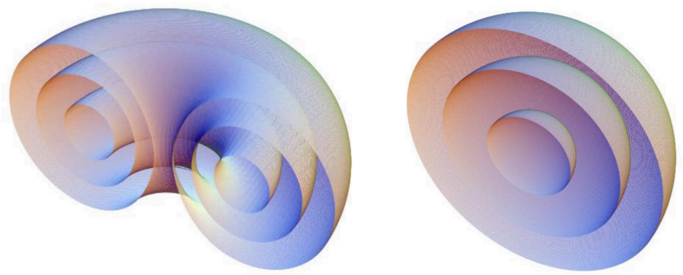
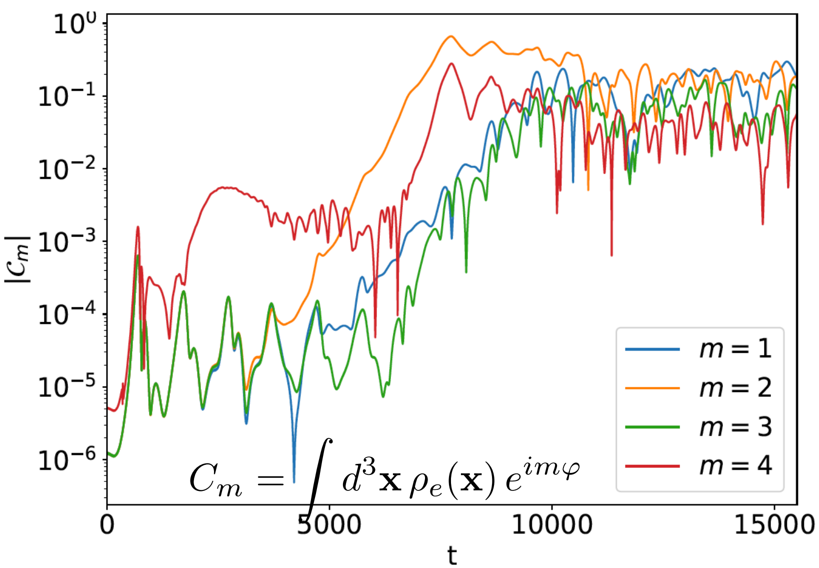
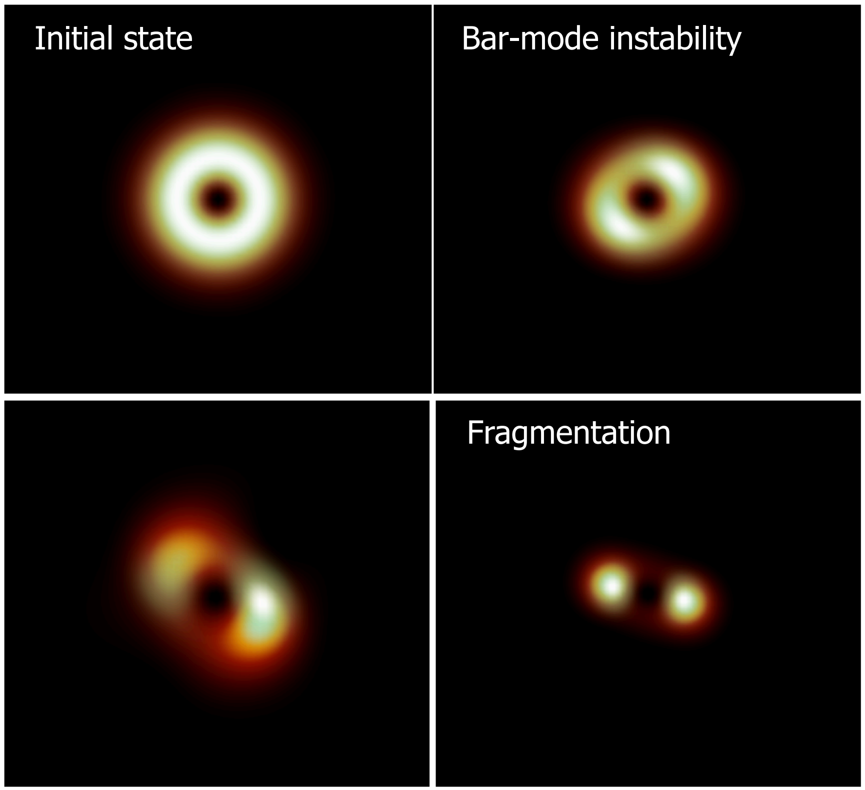


FIG. 1: Surfaces of constant energy density for illustrative SBSs: (left panel) scalar configuration 2_S; (right panel) vector configuration 1_P. The toroidal *vs.* spheroidal nature is clear.



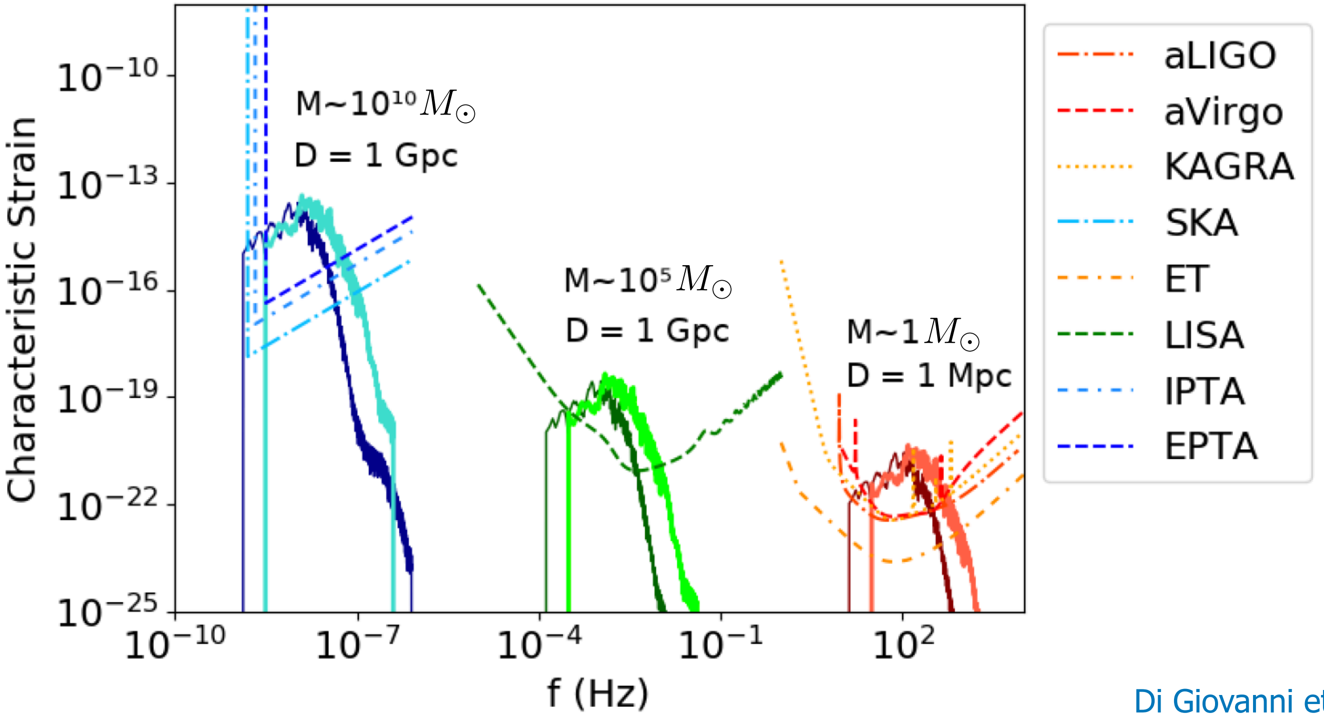


Snapshots of time evolution of a rotating BS showing its initial toroidal form and subsequent fragmentation.

In complete analogy with the dynamical evolution of **bar-mode unstable neutron stars.**

NR simulations & waveform generation (R&D)

Spinning Bosonic Stars: characteristic GW strain and **detectability** prospects.



Di Giovanni et al (2020) arXiv:2010.05845

$$h_{\rm char}(f) = \frac{1+z}{\pi D(z)}\sqrt{2\frac{dE}{df}[(1+z)f]}$$

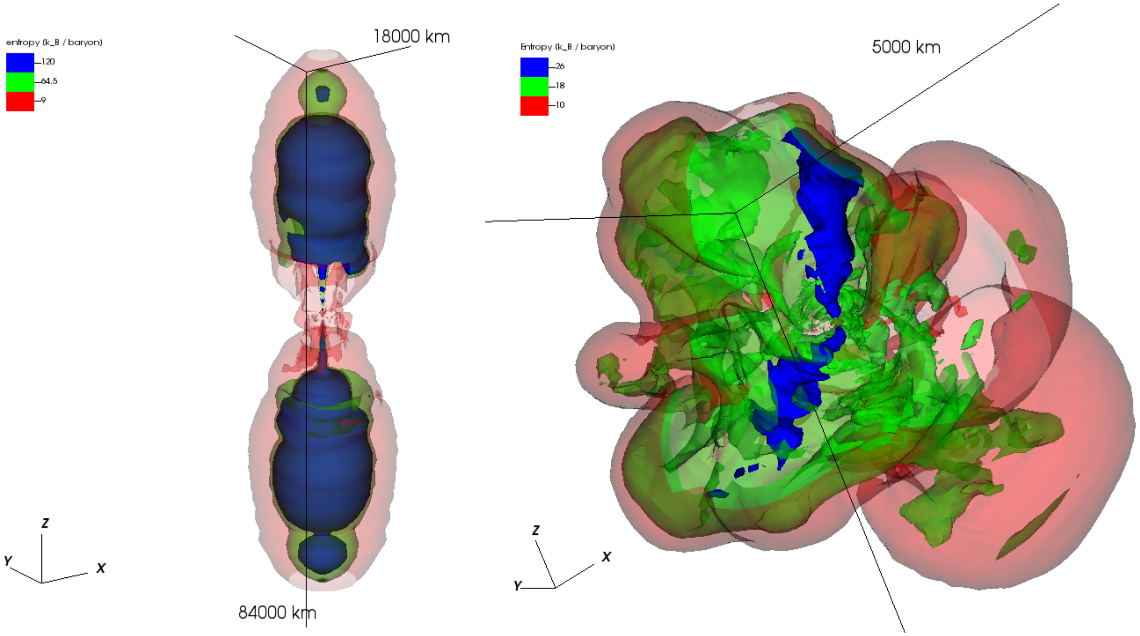
Our results indicate that GW observations of SBSs might be within the reach of future experiments, offering a **potential means to establish the existence of such hypothetical stars** and to place tight constraints on the mass of the bosonic particle.

NR simulations & waveform generation (R&D)

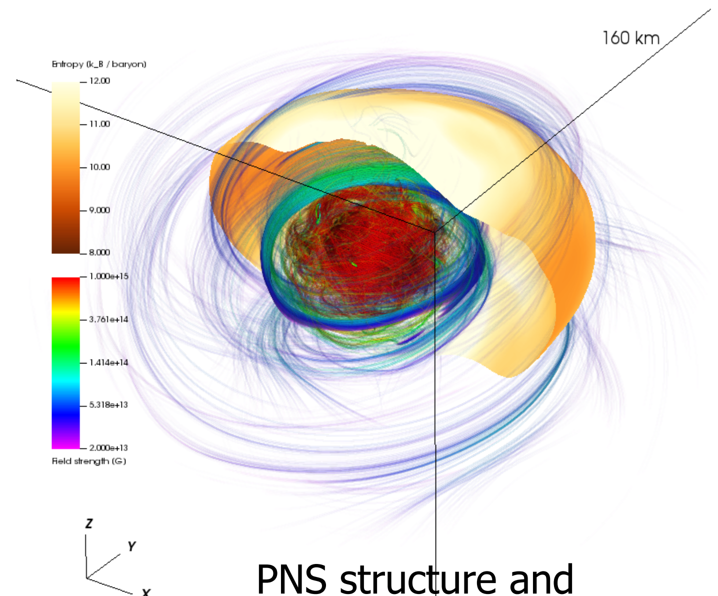
CCSN explosions: **promising source of GWs.** Might be one of the next discoveries of current or future ground-based GW observatories. Most common CCSNe are **neutrino-driven explosions,** expected to be observable with Advanced LIGO and Virgo within our galaxy at a rate of about three per century (Gossan et al (2016); Adams et al (2013)).

M. Obergaulinger is performing state-of-the art 2D and 3D simulations of rapidly rotating and strongly magnetized stars ($35M_{sun}$ ZAMS) with self-consistent M1 neutrino transport.

SN explosions driven by neutrinos and/or magneto-rotational stresses (mildly relativistic outflows). [Bugli et al (2020), Obergaulinger & Aloy (2020a,b), Aloy & Obergaulinger (2020)].



Entropy in two 3D models

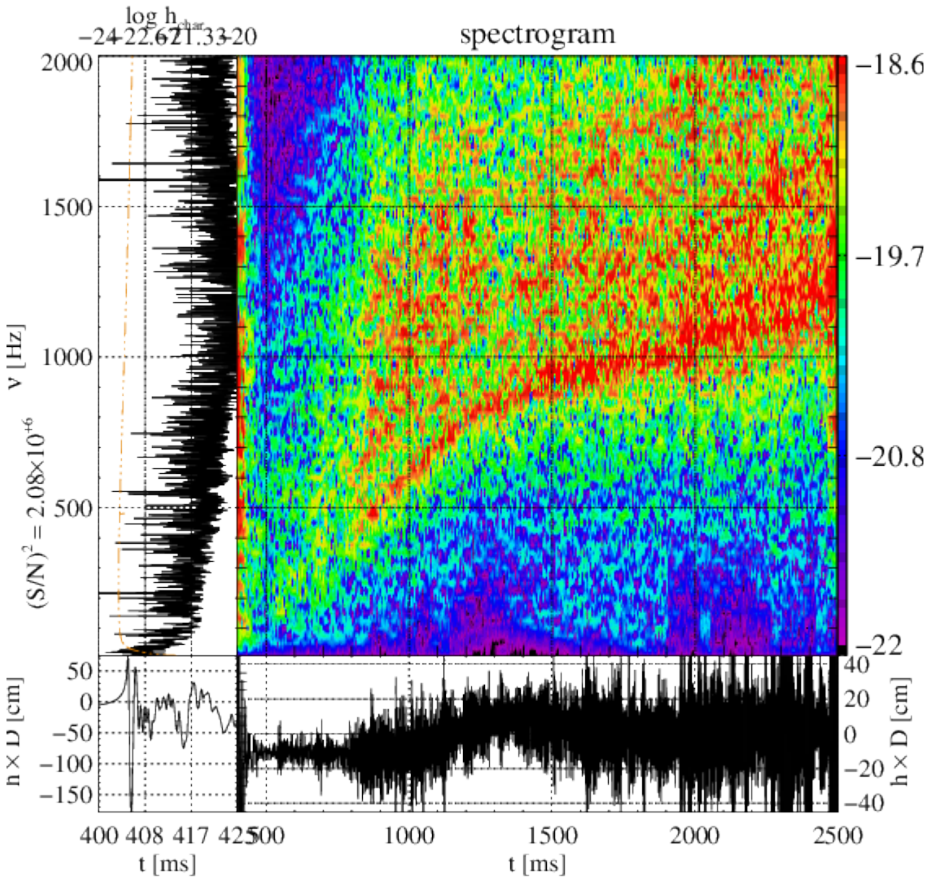


PNS structure and magnetic-field lines

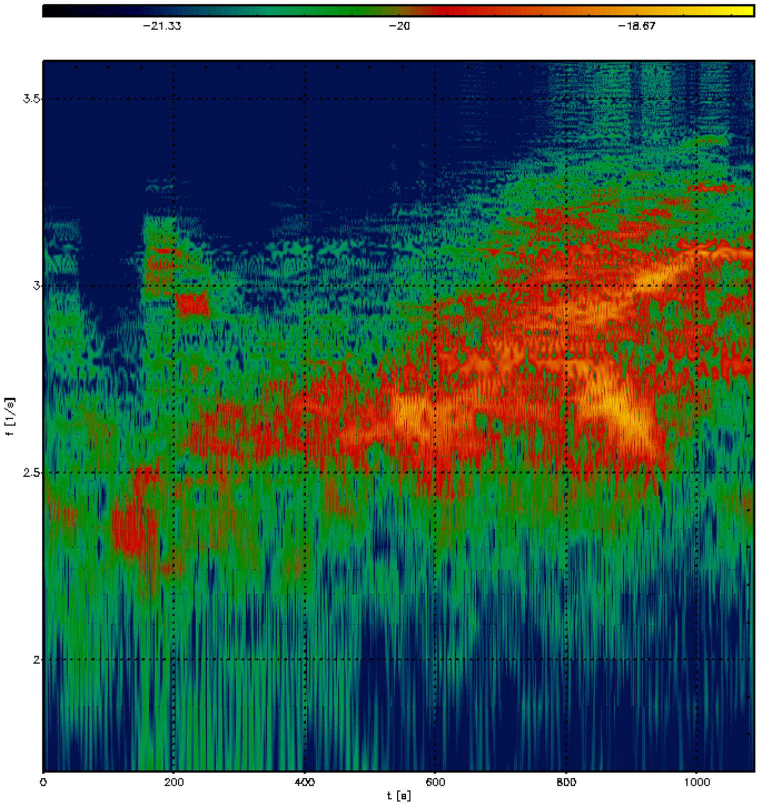
NR simulations & waveform generation (R&D)

GWs from Core Collapse Supernovae.

- strong GW emission in the LVK-relevant frequency range
- **waveforms** of 2D and 3D models **provided to LVK SN group for analysis**



2D model spectrogram



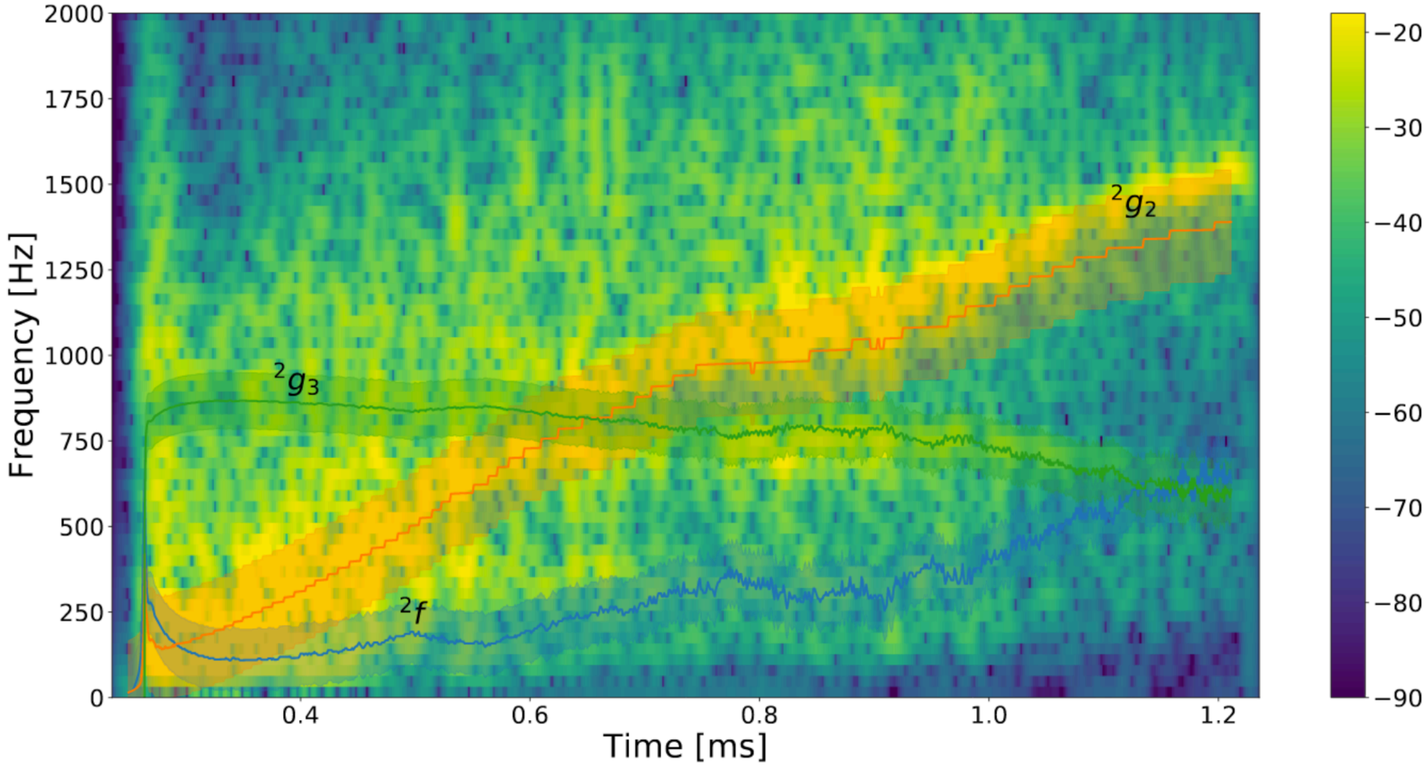
3D model spectrogram

Obergaulinger & Aloy (2020)

GW asteroseismology of PNS stars

Numerical simulations of CCSNe reveal that the **main source of GWs is the excitation of PNS oscillation modes during post-bounce evolution.**

Our recent work (Torres-Forné et al (2018, 2019)) has established that **features in GW spectrograms can be matched to specific PNS eigenmodes.**



GW spectrogram from the collapse of a $20M_{sun}$ progenitor (Cerdá-Durán et al, ApJL (2013))

GW asteroseismology of PNS stars

We derive **universal relations** that relate the frequencies of most common oscillation modes (buoyancy-driven g-modes, pressure-driven p-modes and the f-mode) with fundamental properties of the system (surface gravity of the PNS or mean density in post-shock region).

Torres-Forné et al, PRL (2019)

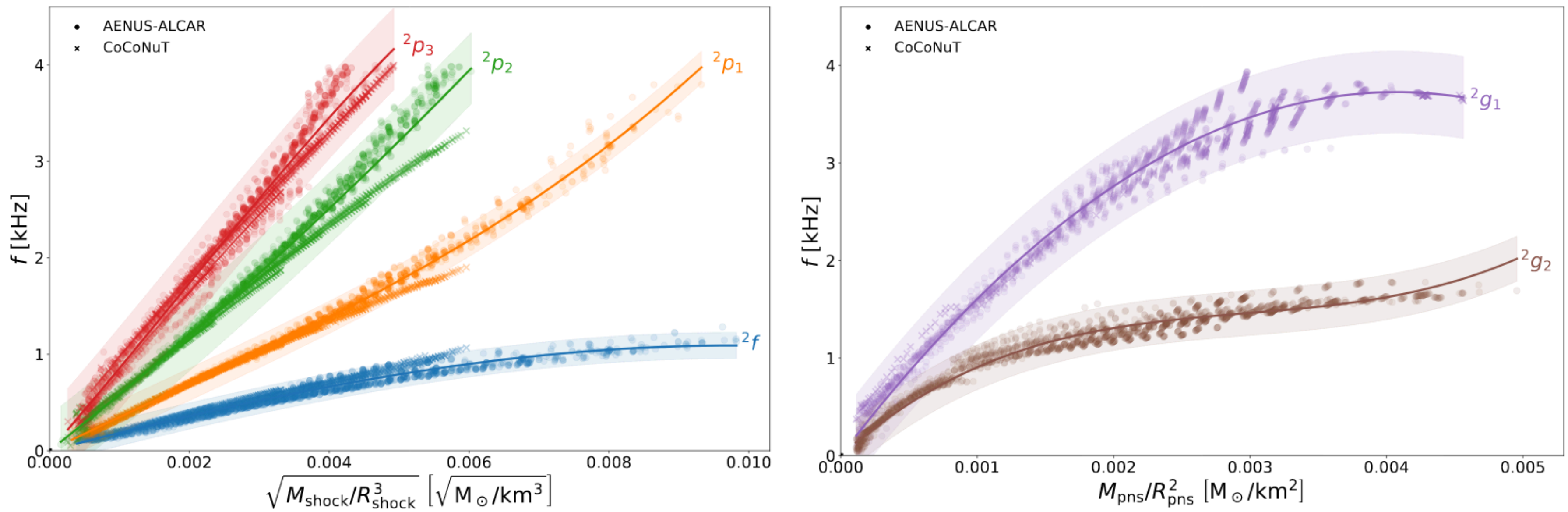


FIG. 2. Fits of the different modes. The left panel shows the f-mode and the first three p-modes while the right panel shows the first two g-modes. The results from AENUS-ALCAR and CoCoNuT are represented with solid circles and crosses, respectively. Shaded areas indicate 2σ error intervals.

These relations are independent of EoS, neutrino treatment, and progenitor mass and hence can be used to build methods to **infer PNS properties from GW observations alone**.

Work in progress in **collaboration** with M.A. Bizouard and N. Christensen (**Artemis - OCA**) and R. Meyer and P. Maturana (**U. of Auckland**). [Presentation at the LVK SN call October 29.]

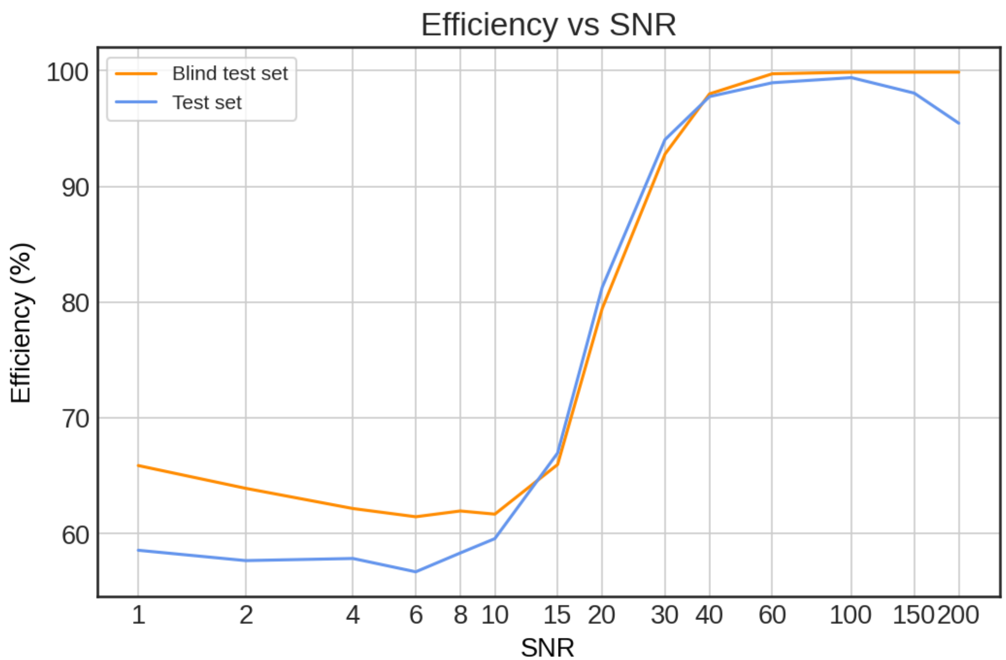
CNN to detect GWs from CCSNe

First employed by Astone et al (2018); recently improved with the help of former UV undergraduate student Melissa López (member of the Virgo Collaboration through the Utrecht group).

Improvements:

Collaboration VVG+Roma+GSSI+Utrecht

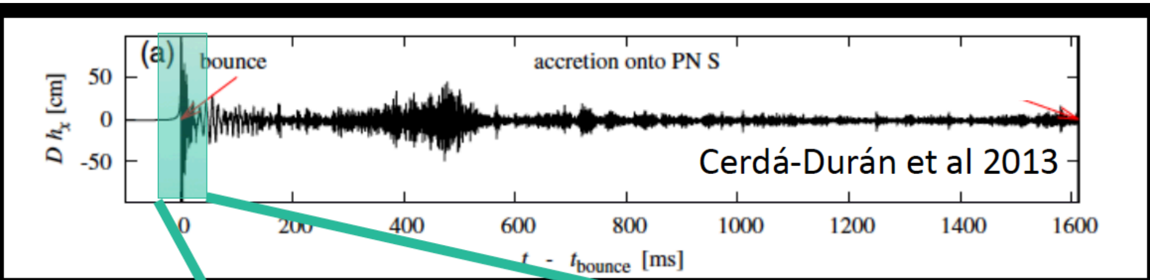
* CNN extended from ~3000 to about ~10000 parameters
* Injections in real data from O2 (three-detector network)
* Training with ~26000 phenomenological waveforms
* Tests using phenomenological waveforms not included in the training set (blind set) and using waveforms from 3D simulations of CCSNe (test set)



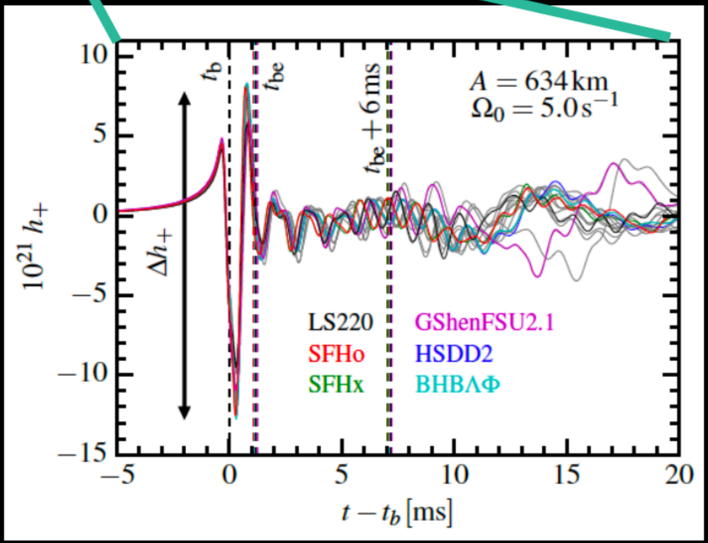
False alarm probability is about 5% for SNR<15 and much smaller for higher SNR values.

Paper currently in preparation.

PE in rapidly rotating CCSN



Cerdá-Durán et al 2013



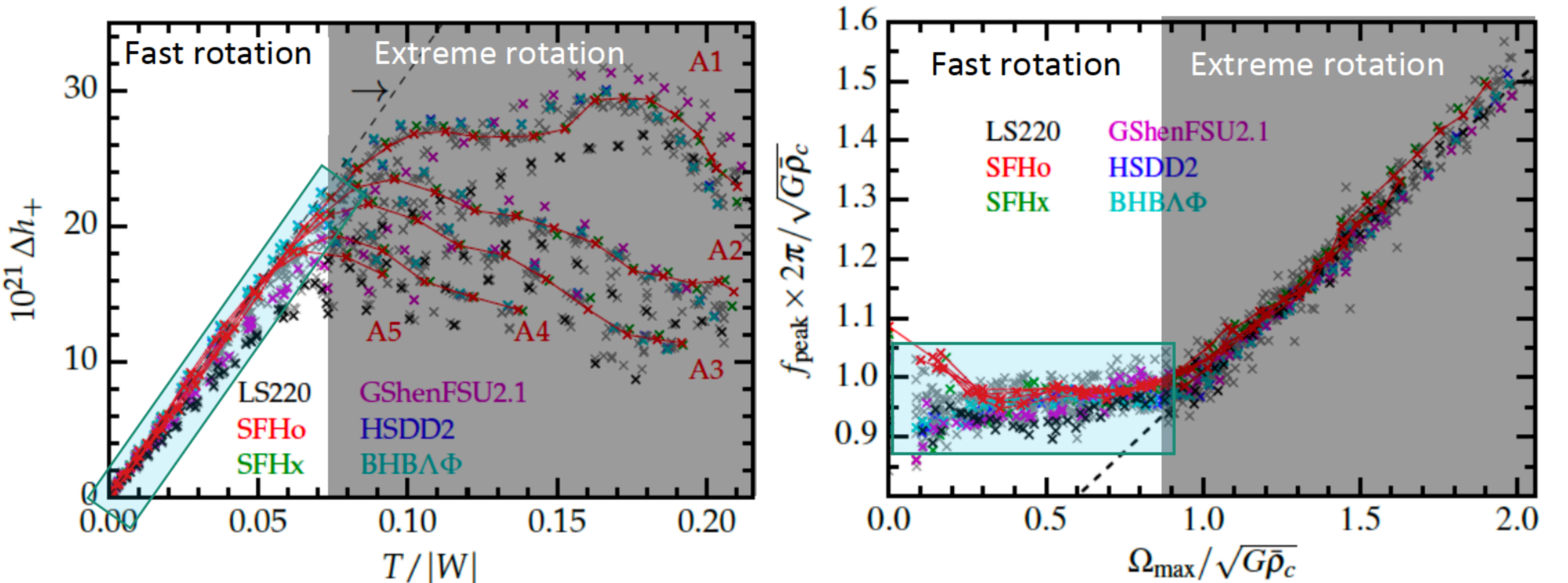
Richers et al 2017

- Only first few ms
- Only rotating models (zero for non-rotating): <1% SNe
- Main features:
  - Peak with amplitude Δh_+
  - Several oscillations with frequency f_{peak}
- Richers et al catalog:
  - 2D GR simulations
  - 1824 waveforms
  - 18 different EOS

Q: What can we learn from performing PE on Δh_+ and f_{peak} ?

A: We can estimate the source parameters: ρ_c and $\dfrac{T}{|W|}$

PE in rapidly rotating CCSN



Richers et al (2017)

$$\Delta h_+ \propto \frac{T}{|W|}$$

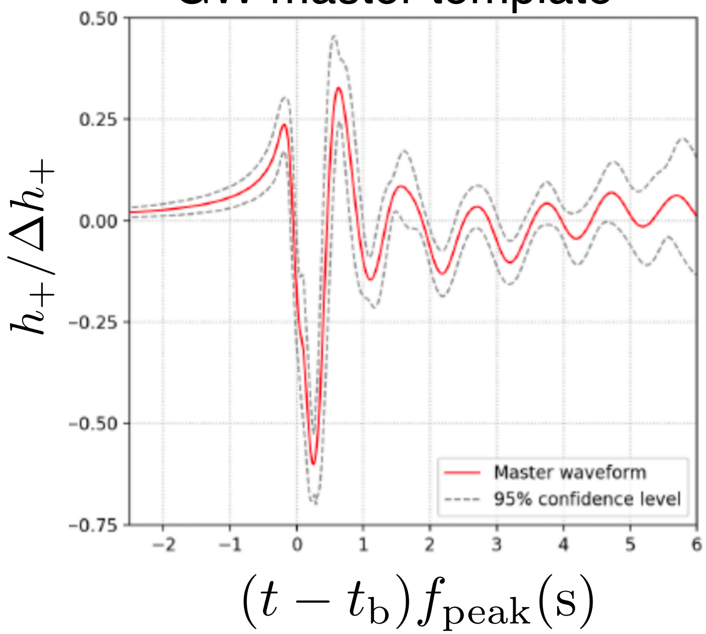
$$f_{\rm peak} \propto \frac{1}{\sqrt{\bar{\rho}_{\rm c}}}$$

Q: What can we learn from performing PE on Δh_+ and $f_{\rm peak}$?

A: We can estimate the source parameters: $\rho_{\rm c}$ and $\frac{T}{|W|}$

PE in rapidly rotating CCSN

GW master template



Master template: average of 420 waveforms.

Waveform generator depends on 3 intrinsic parameters: inclination, Δh_+ and $f_{\rm peak}$

We can do **parameter estimation.**

Injections in Gaussian noise with PSD from LH network

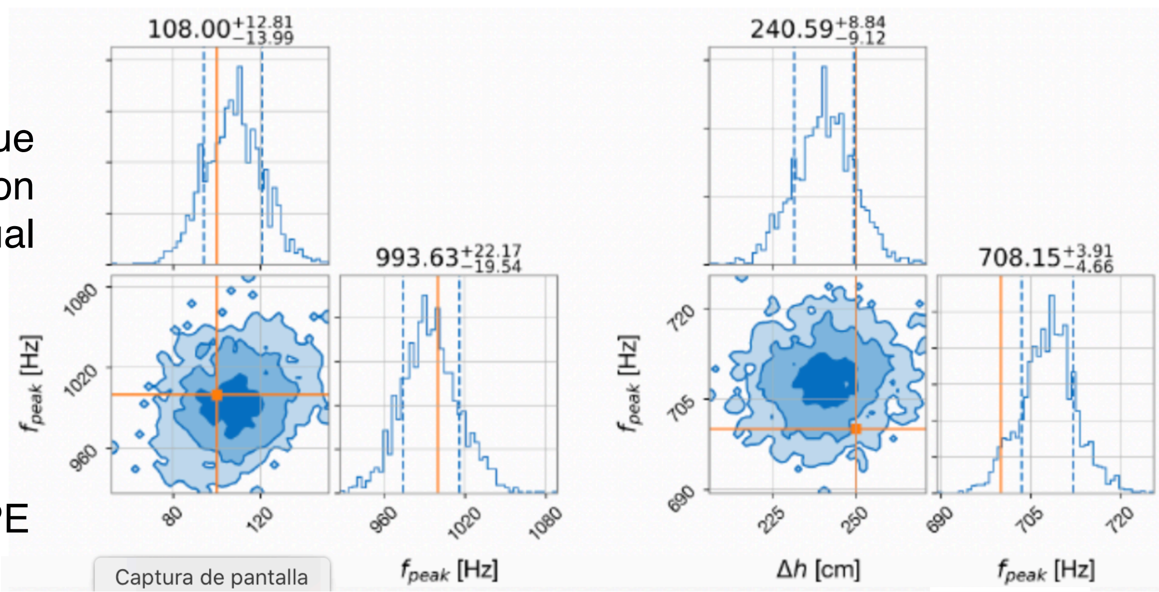
Parameters:

- Event time, sly location and distance fixed (EM + neutrinos).
- Inclination known (simplification)
- 2 parameters: Δh_+ and $f_{\rm peak}$

Injection using **MT @10 kpc.** For true parameters template matches injection perfectly. Not the case for individual waveforms (MT uncertainties).

Future runs:

- Inclination
- Dependence on distance
- Incorporate MT uncertainties in PE
- Estimate source parameters.



GWs from BBH mergers surrounded by scalar-field clouds

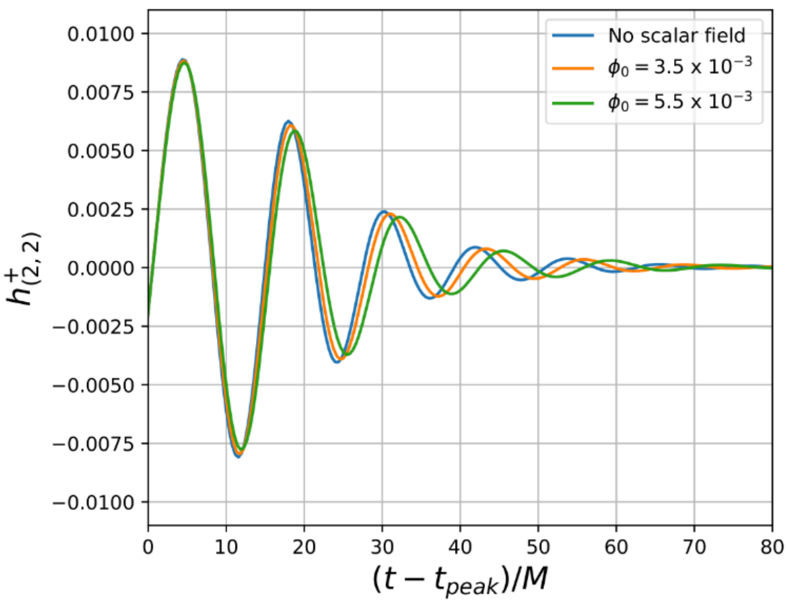
S. Choudhary et al (2020): Gravitational waves from binary black hole mergers surrounded by scalar field clouds: Numerical simulations and observational implications. **Collaboration VVG+IUCAA.**

GW observations of BBH mergers can constrain the physical characteristics of scalar field clouds parameterized by mass and strength that may surround them.

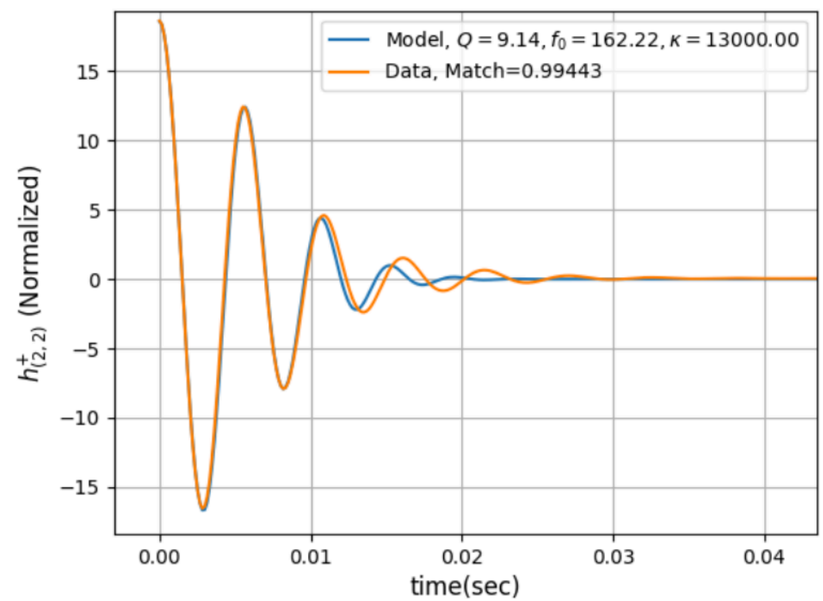
NR simulations of BBH systems dressed in such clouds, focusing on GW signals emitted at merger-ringdown phase. Waveforms can be modeled as chirping sine-Gaussians, matches in excess of 95%.

$$g(t; f_0, Q, \kappa) \equiv A e^{-4\pi^2 f_0^2 t^2/Q^2} \cos(2\pi f_0 t + \kappa t^2)$$

NR merger-ringdown signals



Chirp sine-Gaussian fit

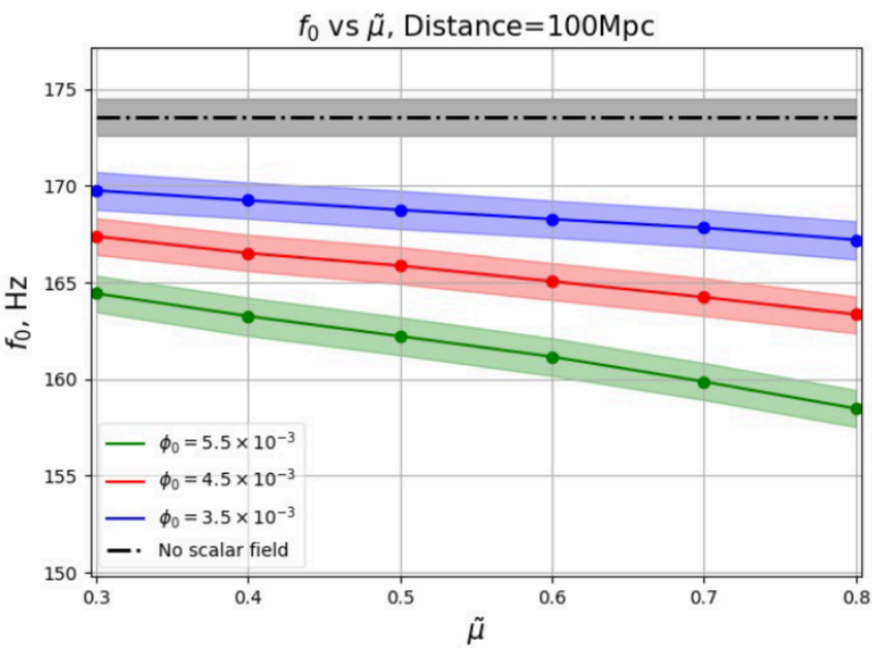


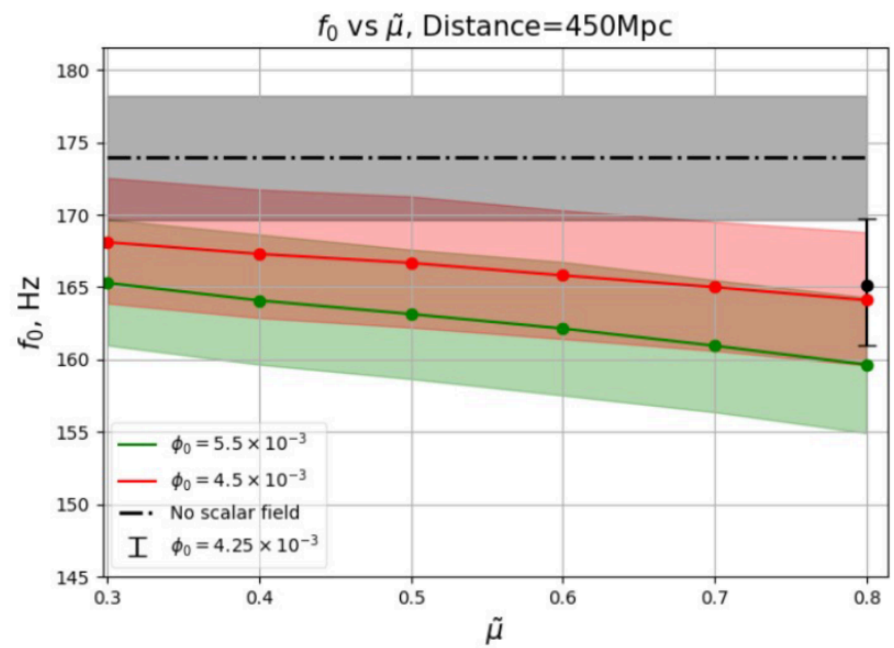
This observation enables one to employ Bayesian studies for estimating the parameters of such binaries.

Observations of BBH mergers @ 450 Mpc will allow to distinguish BBHs without any scalar field from those with a field strength ~5.5×10^{-3}, at any fixed value of the dimensionless particle mass ∊[0.3,0.8], with 90% confidence or better, in single detectors with Advanced LIGO/Virgo type sensitivities.

S. Choudhary et al (2020)
arXiv:2010.00935

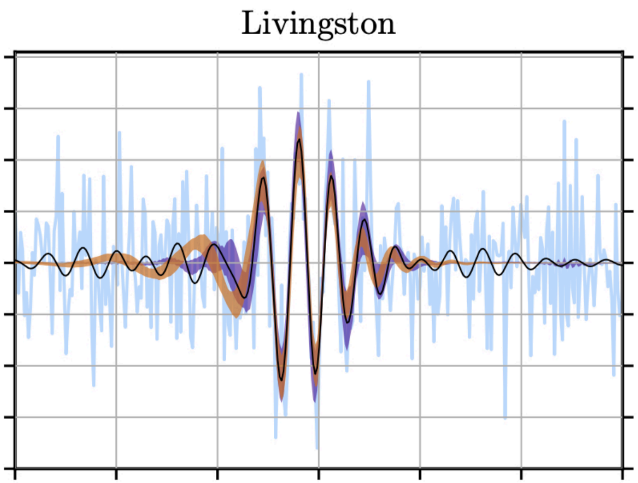
$$\tilde{\mu} \equiv \frac{GMm_s}{\hbar c}$$





GW190521: Confusing head-on and precessing BBH mergers?

Collaboration VVG+IGFAE



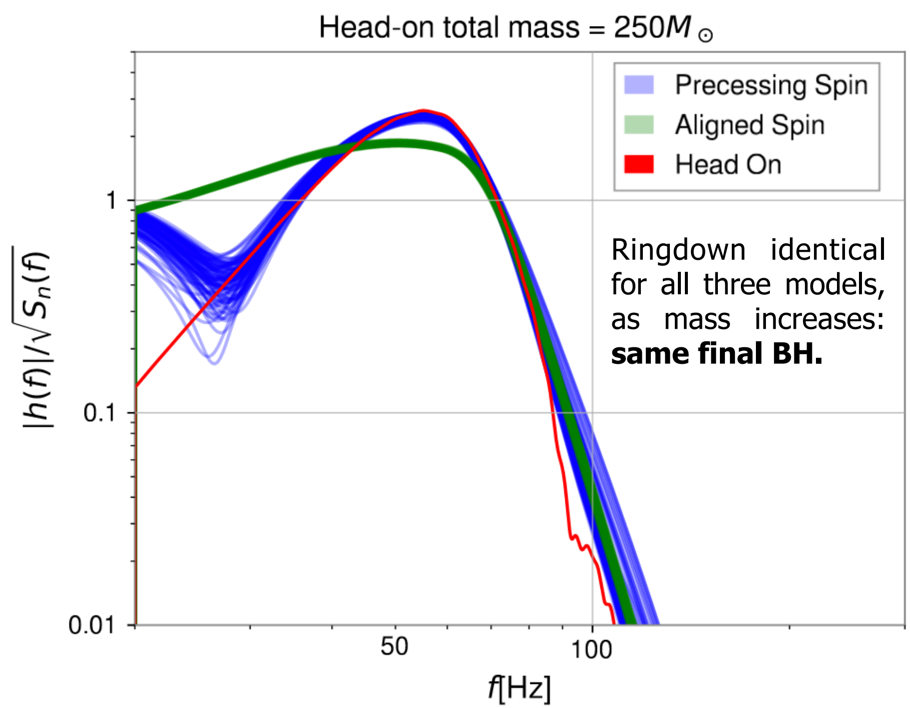
LIGO-Virgo interpretation:
- quasi-circular precessing BBH merger
- IMBH remnant
- Primary BH sitting in the PISN gap

However, barely any power in the inspiral. Quasi-circular inspiral uncertain. Different interpretations:
- Eccentricity? (Romero-Shaw et al (2020), Gayahtri et al (2020))
- Head-on? (Calderon-Bustillo et al (2020a))
- Exotic compact objects? (Calderon-Bustillo et al (2020b).

In Calderón-Bustillo et al (2020a) we found that **precession can mimic extreme eccentricity**. A **degeneracy** between the GW signals from quasi-circular precessing BBH mergers and those from head-on collisions, was found.

Consequences on estimated parameters:

- 130-310M_{sun} head-on collisions might be identified as a precessing quasi-circular IMBH binary, located at a much larger distance.
- A head-on merger with masses outside the PISN gap may be mistaken by a vanilla binary with masses in the gap.

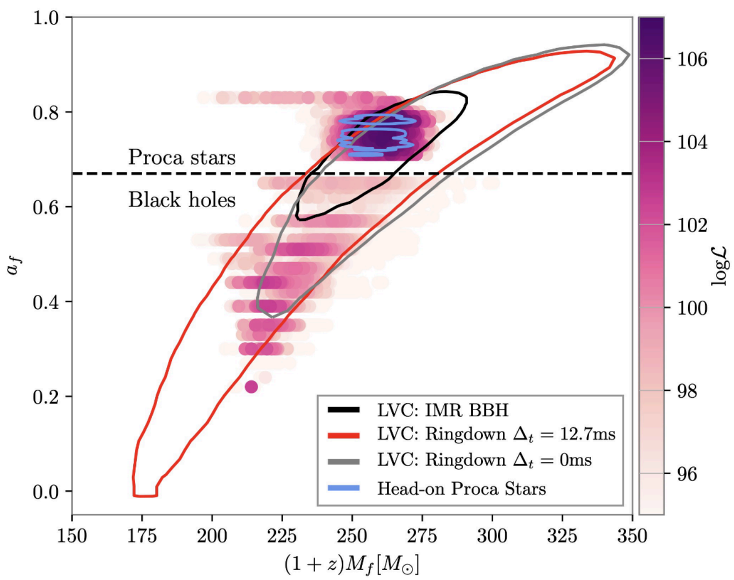


GW190521: merger of Proca stars?

The geometry of BBH head-on collisions makes it **difficult to reach the high spin of the GW190521 remnant**, a~0.7, for mass ratios 1<q<4, due to the lack of orbital angular momentum and the Kerr limit on the BH spin (a≤1) imposed by the cosmic censorship conjecture.

Exotic compact objects are not subject to this limit and may mimic BBH signals, leading to a degeneracy in the emitted GW signals.

In Calderón-Bustillo et al (2020b) we show that GW190521 is consistent with NR GW signals from head-on collisions of two (equal mass and spin) Proca stars. **Collaboration VVG+IGFAE+Aveiro.**



See Nico Sanchis-Gual talk on Tuesday.

Final BH mass: $M_{\mathrm{BH}} = 231^{+13}_{-17} M_\odot$

Distance: $d_L = 571^{+348}_{-181}\mathrm{Mpc}$

Knowing the BH mass allows to estimate the **mass of the ultra-light vector boson** constituent of the Proca stars:

$$\mu_{\mathrm{V}} = 8.72^{+0.73}_{-0.82} \times 10^{-13}\mathrm{eV}$$

Proof-of-concept demonstration of close degeneracy between these two theoretical models (BH vs PS) **with a real GW event.**

Confirmation of the Proca star interpretation would provide the first evidence for a long sought **dark matter particle.**

Data analysis - TV methods + Machine Learning

At the VVG we have started a program to apply **total-variation methods** for GW denoising and signal reconstruction. Applied to both signals and glitches. Also in combination with learned dictionaries.

Torres-Forné et al (2014): simulated CCSN and BBH signals. Gaussian noise. TV.
Torres-Forné et al (2016): simulated CCSN and BBH signals. Gaussian noise. TV + DL.
Torres-Forné et al (2018): simulated CCSN and BBH signals. Real noise (O1). TV + DL.
Llorens-Monteagudo et al (2019): simulated glitches. Gaussian noise. TV + DL.
Torres-Forné et al (2020): O1 blip glitches. TV + DL.

Rudin-Osher-Fatemi (ROF) model of a variational problem.

Ongoing work to incorporate those approaches into the **cWB pipeline** (led by P. Barneo ICCUB, in collaboration with M. Drago (GSSI).

See J. Portell's talk on Monday afternoon.

Collaboration recently started with Antonio Onofre's group at U. Minho (Portugal) to apply ML techniques to GW data analysis and parameter estimation.

See Onofre's talk on Monday afternoon where preliminary results will be presented.

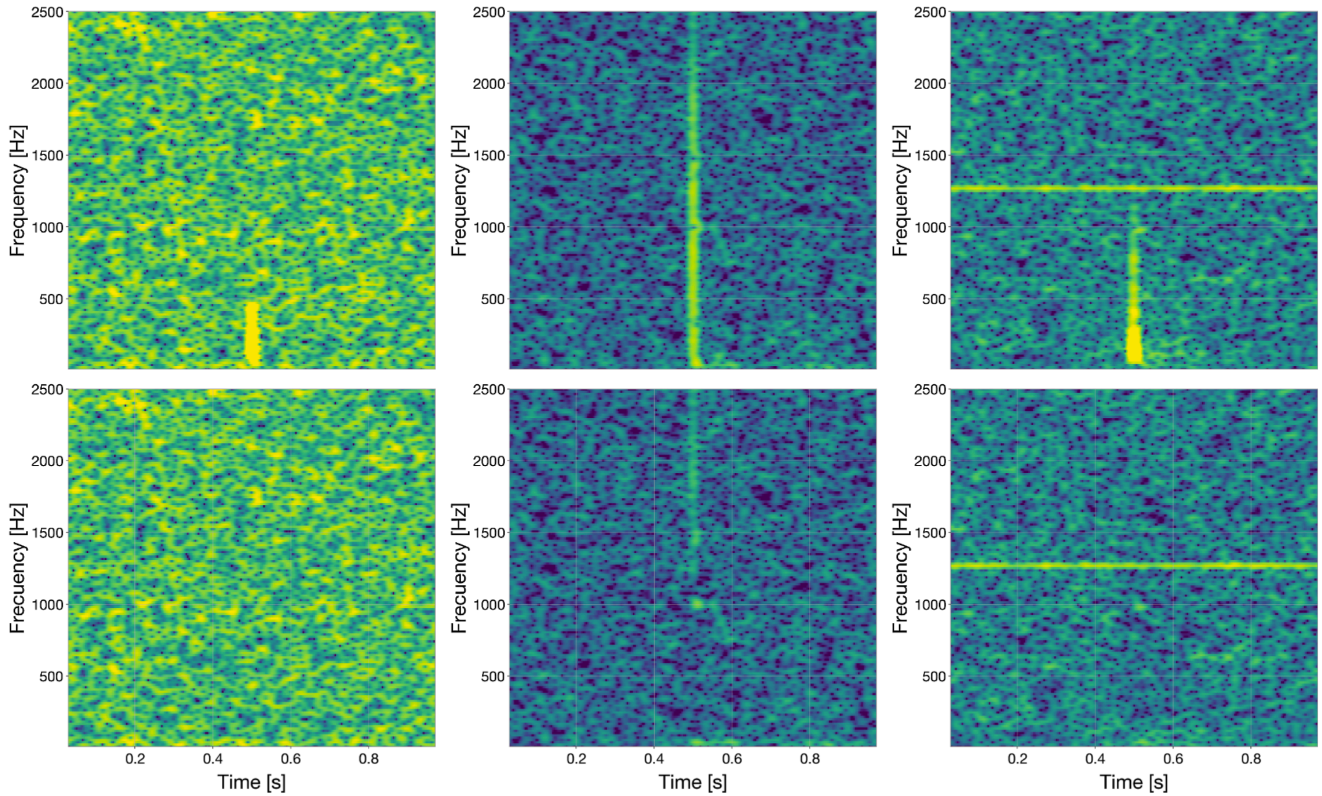
Glitch denoising - blips in O1 Advanced LIGO data

Application of dictionary learning to denoise LIGO's blip noise transients. Torres-Forné et al (2020)

Data streams of GW detectors polluted by transient noise features ("glitches") of instrumental and environmental origin. We investigate the use of **TV methods and learned dictionaries** to mitigate the effect of transients in the data. Focus on **"blip"** glitches, most common glitch in the LIGO detectors.

Dictionary-learning methods are a **valid approach** to model and subtract most of the glitch contribution, particularly at frequencies below ~1kHz.

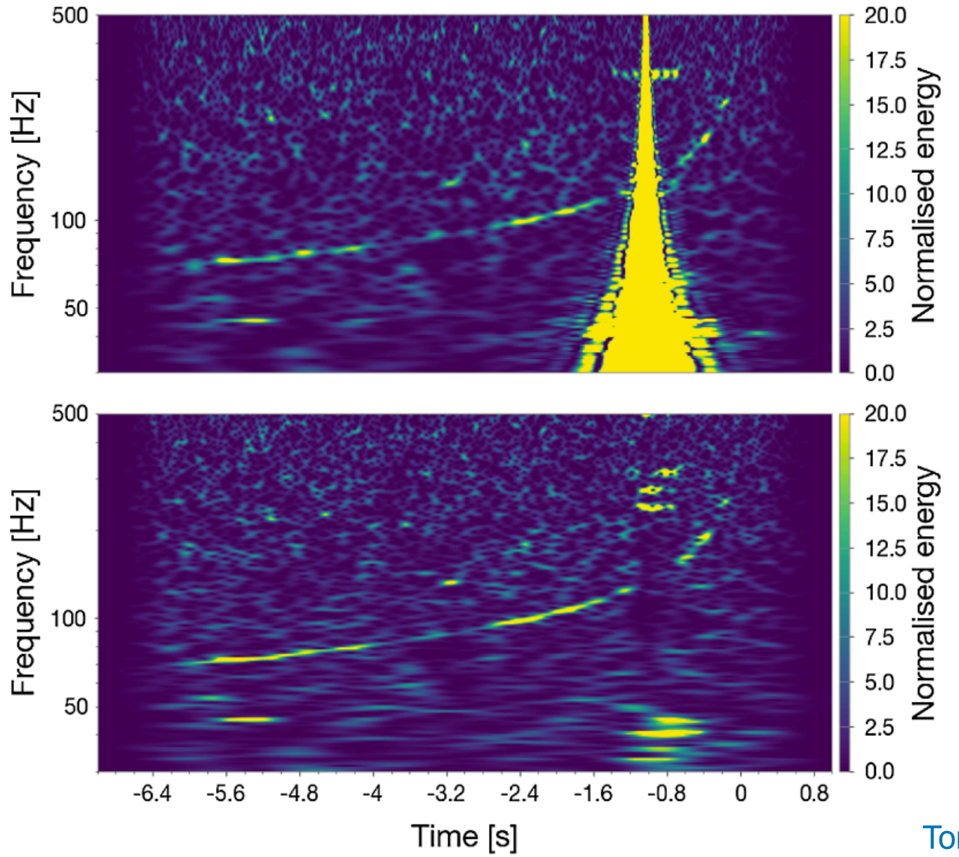
Collaboration VVG+Pisa.



Before

After

Glitch denoising



Torres-Forné et al, PRD (2020)

FIG. 6. Time-frequency diagram of 8 seconds of data corresponding to the GW170817 signal. The times shown are relative to August 17, 2017 12:41:04 UTC. The top panel shows the original data from LIGO-Livingston. The bottom panel displays the data after subtracting the glitch using a single blip-trained dictionary with 256 samples.

Outreach

- Led by **Isabel Cordero-Carrión**.
- **National coordination of the 5 LVK Spanish groups in announcements of exceptional events and associated press releases.**
- VVG active in social networks (Facebook: https://www.facebook.com/VirgoValenciaGroup/, Twitter: @VirgoValencia).
- VVG group members participate in outreach talks and workshops (Pint of Science 2019, "Ogmios: contando revoluciones", etc), high-school talks, radio interviews (Onda Cero, RNE, CV Radio, A Punt), newspapers (El País, El Mundo, La Razón, La Vanguardia, ABC, Levante-EMV) and activities related to the International Day of Women and Girls in Science.
- Participation in the LOC of the 1st International Gravitational Waves Outreach Group Meeting, https://indico.ego-gw.it/event/29/ held as a satellite event of the GR22-Amaldi13 conference in Valencia in 2019 (https://gr22amaldi13.com/).
- Nikhef has donated a mini-interferometer to the VVG as a token for our service in translating outreach documentation into Spanish.

Much more information of our outreach activities on VVG website: www.uv.es/virgogroup

Outreach

Artistic interpretation of GW190521. Turquoise and orange mini-grids represent the dragging effects due to the individually rotating BHs. The estimated spin axes, or self-rotations, of the BHs are indicated with the corresponding coloured arrows. The background suggests a star cluster, one of the possible environments in which GW190521 could have occurred.

Image credit: Raúl Rubio / Virgo Valencia Group / The Virgo Collaboration

Astronomy Picture of the Day, September 8, 2020 (https://apod.nasa.gov/apod/ap200908.html)