LIGO-Virgo Gravitational Wave Astronomy @ IGFAE

Virtual IGWM, Oct 19 2020

Thomas Dent

with V. Villa-Ortega, I. Musco, J. Sadiq, J. Calderon Bustillo, J. Alvarez-Muñiz, E. Zas, ...

Image Credit: NASA/GSFC

IGFAE research themes

THE STANDARD MODEL TO THE LIMITS

The Standard Model (SM) is our best construction of the microscopic reality at the most fundamental level. The degree of consistency with experiment is astonishingly good.

Our Institute has played a fundamental role in this broad field of research.

COSMIC PARTICLES AND FUNDAMENTAL PHYSICS

Astroparticle Physics, as well as the connections between Particle Physics and Cosmology, are experiencing a new golden age.

Our Institute has been one of the pioneers in the Pierre Auger Observatory, a giant air shower array in Argentina.

NUCLEAR PHYSICS FROM THE LAB TO IMPROVE PEOPLES HEALTH

The participation of IGFAE in new international facilities such as FAIR offers unprecedented opportunities to contribute to understanding the nature of the strong interaction in the non-perturbative regime, the structure of the nuclear many-body systems and their astrophysical implications.

- New IGFAE research line since Oct 2018, funding from *María de Maeztu Research Unit*
- SOMMa Excellence Alliance (Severo Ochoa Centres + *MM* Units)

New arrivals

- Ilia Musco
  - IGNITE short-term fellow, expertise on numerics of primordial BH formation in GR
- Jam Sadiq
  - MdM postdoc, former Fulbright PhD at RIT (NY, USA), main work on NR methods & efficient precision modelling of GW from precessing BH mergers
- Juan Calderon Bustillo
  - La Caixa / Marie Curie Junior Leader (formerly CUHK & Monash), work on numerical relativity, BBH searches, parameter estimation, beyond-GR new physics, ...
  - Ongoing collaboration with CUHK students
  - Upcoming call for a junior postdoc collaborator

Ground-based GW network & sources

- Global network

  LIGO / Virgo : O3 2019-20, further runs 2022+

  GEO600 : technology prototyping & cover LIGO breaks

  KAGRA : observing/commissioning 2020+

  LIGO-India : construction pending

Continuous Wave sinusoidal GW from rotation of neutron stars	**Compact Binary Coalescence** transient inspiral-merger-ringdown waveforms well modelled
Stochastic Background superposition of weak unresolved sources / early Universe	**Burst** transient unmodelled / irregular waveforms : CCSuperNovae, ...

IGFAE-GW main projects

- CBC detection searches
  - T Dent, V Villa-Ortega, J Sadiq, J Calderon Bustillo
  - All-sky searches for binary mergers with using PyCBC analysis toolbox
- CBC source modelling & parameter estimation
  - J Calderon Bustillo, J Sadiq, I Musco
  - Numerical / hybrid solutions of GR & beyond-GR theories
  - Alternative interpretations of ‘BH binary’ detections
- CBC Rates/Populations
  - T Dent co-chairs LVK Rate/Pop subgroup: simulation campaigns to measure search sensitivity
- Multi-messenger HEν/CR followup
  - J Alvarez-Muñiz, F Pedreira, E Zas
  - Followup of all low latency LIGO-Virgo transient candidate events with Pierre Auger observatory

What is PyCBC ?

- Open-source git repository https://github.com/gwastro/pycbc
- Library of Python functions for transient GW data analysis
  - leverages LAL & LALSimulation functionality
- Modular toolkit for quick GW/DA investigations
- Codes for detecting & estimating parameters of (B)BH-(B)NS merger signals
- Optimized low-latency all-sky search – ‘PyCBC live’
- Optimized offline all-sky search – ‘hyperbank’
- DetChar tool for prompt diagnosis of detector issues affecting CBC search
- Technical subgroup of CBC

https://www.lsc-group.phys.uwm.edu/ligovirgo/cbcnote/PyCBC

Online documentation

https://pycbc.org/pycbc/latest/html/pycbc.html#module-pycbc.detector

pycbc.detector module

This module provides utilities for calculating detector responses and timing between observatories.

class **pycbc.detector.Detector**(*detector_name*) [source]

Bases: `object`

A gravitational wave detector

antenna_pattern(*right_ascension, declination, polarization, t_gps*) [source]

Return the detector response.

Parameters:

- **right_ascension** (*float or numpy.ndarray*) – The right ascension of the source
- **declination** (*float or numpy.ndarray*) – The declination of the source
- **polarization** (*float or numpy.ndarray*) – The polarization angle of the source

Returns:

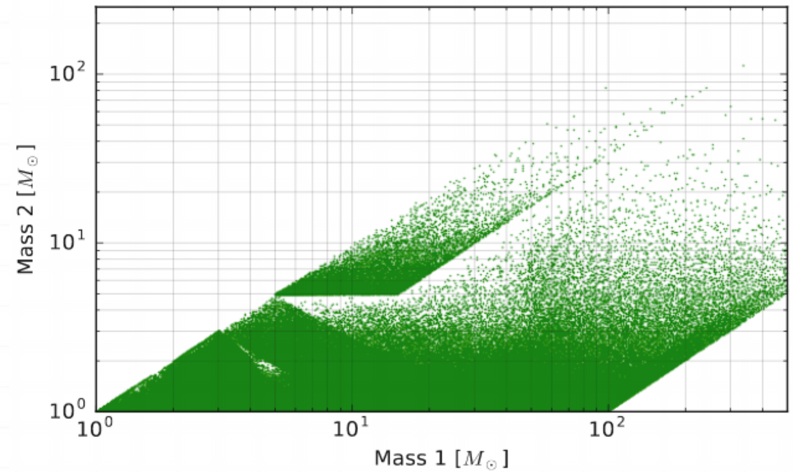
- **fplus** (*float or numpy.ndarray*) – The plus polarization factor for this sky location / orientation
- **fcross** (*float or numpy.ndarray*) – The cross polarization factor for this sky location / orientation

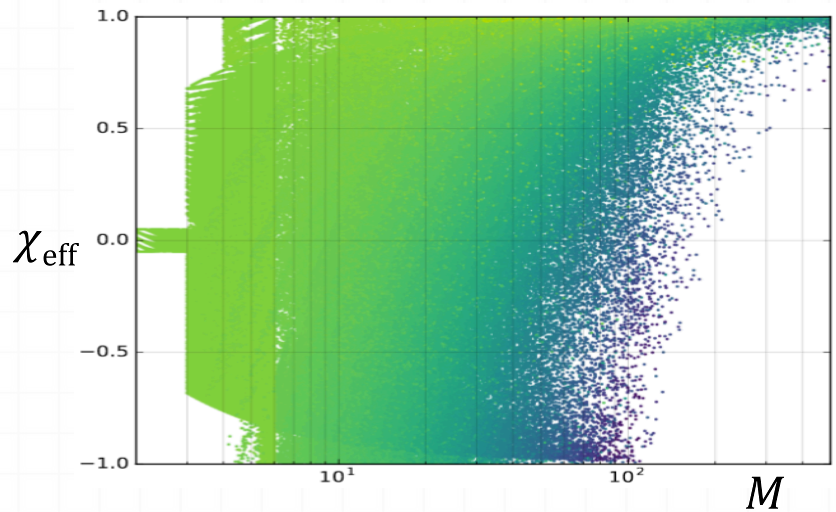
light_travel_time_to_detector(*det*) [source]

Return the light travel time from this detector

PyCBC offline search

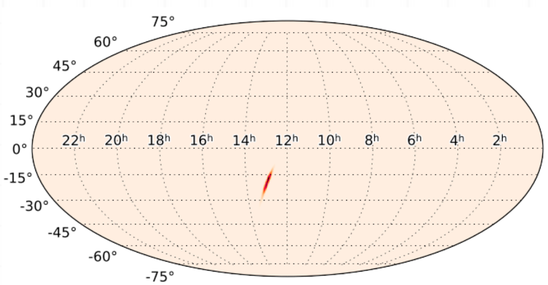
- Correlate data against 400,000 templates via FFT
- Check consistency between detectors : mass, spin, merger time, phase, amplitude ...
- Find significance of events by comparing to time-shifted analyses
- Estimate search sensitivity by adding $\gtrsim 10^4$ simulated signals to data ('injections')



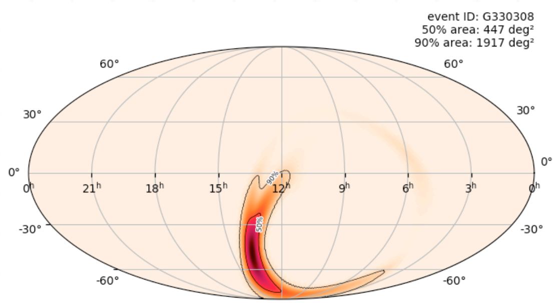


PyCBC Live

- Produce triggers/candidate detections with latency few×10s via overlapping FFTs
- Upload to GraceDB for EM followup



GW170817



S190421ar
(O3a candidate)

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	FAR (yr^{-1})	Links	UTC Submitted
G298107	EM_COINC	CBC	pycbc	AllSky	H1,L1,V1	1187008882.4434	1.291e-05	407.51 per year	Data	2017-08-17 16:11:22 UTC

Coinc Tables

End Time (GPS)	1187008882.4434 s
Total Mass	2.7567 $M_\odot$
Chirp Mass	1.1976 $M_\odot$
SNR	28.3072
False Alarm Probability	0.000e+00

Single Inspiral Tables

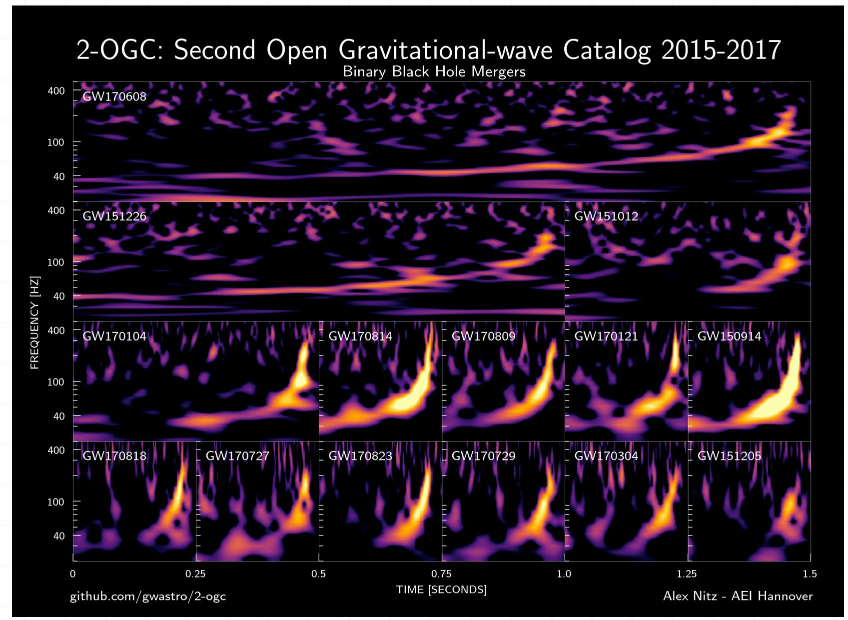
IFO	L1	V1	H1
Channel			
End Time (GPS)	1187008882.443359375 s	1187008882.445068359 s	1187008882.446777344 s
Template Duration	74.4328308105 s	None s	74.4328308105 s
Effective Distance	70.254651 Mpc	None Mpc	52.250165 Mpc
COA Phase	−3.0009944 rad	None rad	0.59536642 rad
Mass 1	1.4574227 $M_\odot$	1.4574227 $M_\odot$	1.4574227 $M_\odot$
Mass 2	1.2993017 $M_\odot$	1.2993017 $M_\odot$	1.2993017 $M_\odot$
η	0.24917751	0.24917751	0.24917751
F Final	None Hz	None Hz	None Hz
SNR	24.330324	None	15.745832
χ^2	1.0659677	None	1.0236512

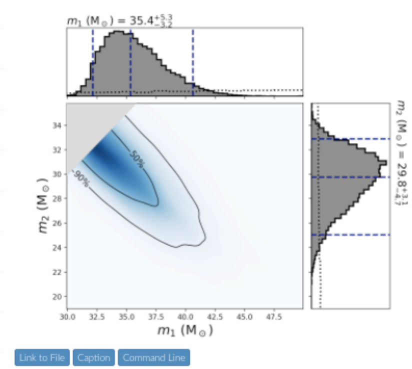
https://gracedb.ligo.org/superevents/S190421ar/view/

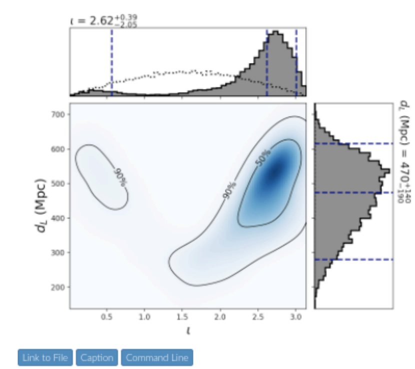
2-OGC: Open Gravitational-wave Catalog of binary mergers

- ❑ Reproducible analysis of open O2 LIGO-Virgo data
- ❑ Confirm 3 additional BBH beyond LVC catalog, 1 further ‘marginal’ BBH candidate
- ❑ Full parameter estimates for all events
- ❑ Data release including sub-threshold events & PE samples

https//dx.doi.org/10.3847/1538-4357/ab733f
https://github.com/gwastro/2-ogc

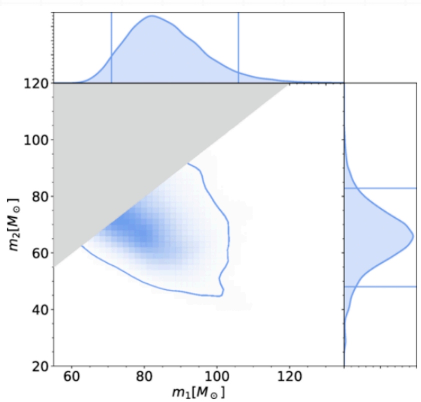


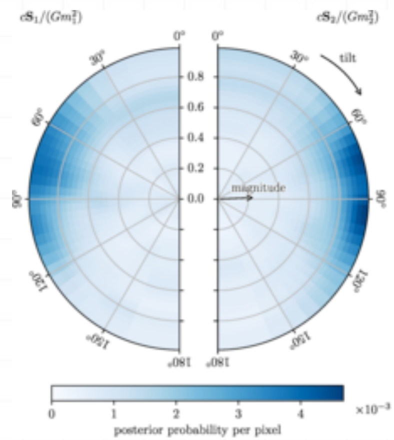


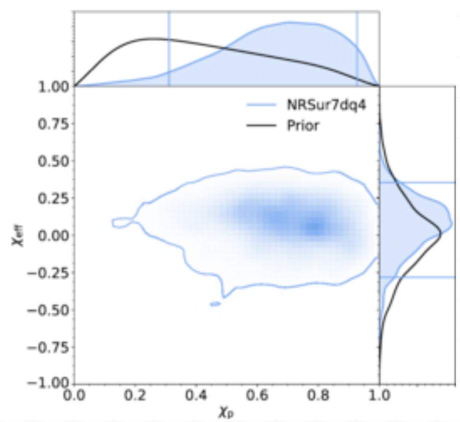


GW190521

- Highest mass BBH event so far
- Detected by low latency pipelines including PyCBC Live
- TD, JCB on editorial teams for Detection & Implications papers





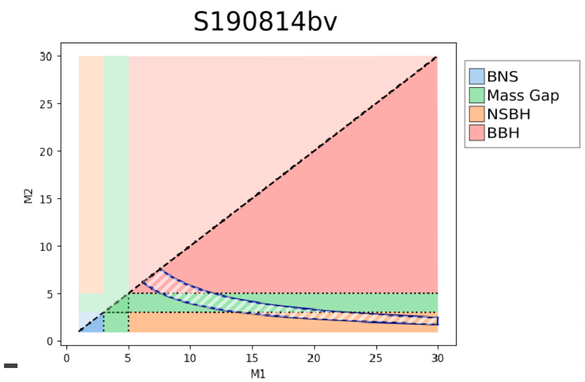


- Hints for new astrophysics (hierarchical / eccentric merger) ?

Phys.Rev.Lett. 125 (2020) 10, 101102
Astrophys.J. 900 (2020) 1, L13

Ongoing projects

- Deployment of 3-detector searches for final O3 results
- Low latency source classification using PyCBC Live triggers
- Renovating coherent GRB search (PyGRB) with PyCBC-based code
- Making search robust(er) to glitches & non-stationary data – gating, short-term PSD variation ..
- Extending search for 'non-standard' signals : precessing, HM, IMBH, sub-solar ...
- Collaboration with AEI Hannover, Portsmouth, IIT Bombay, others ..



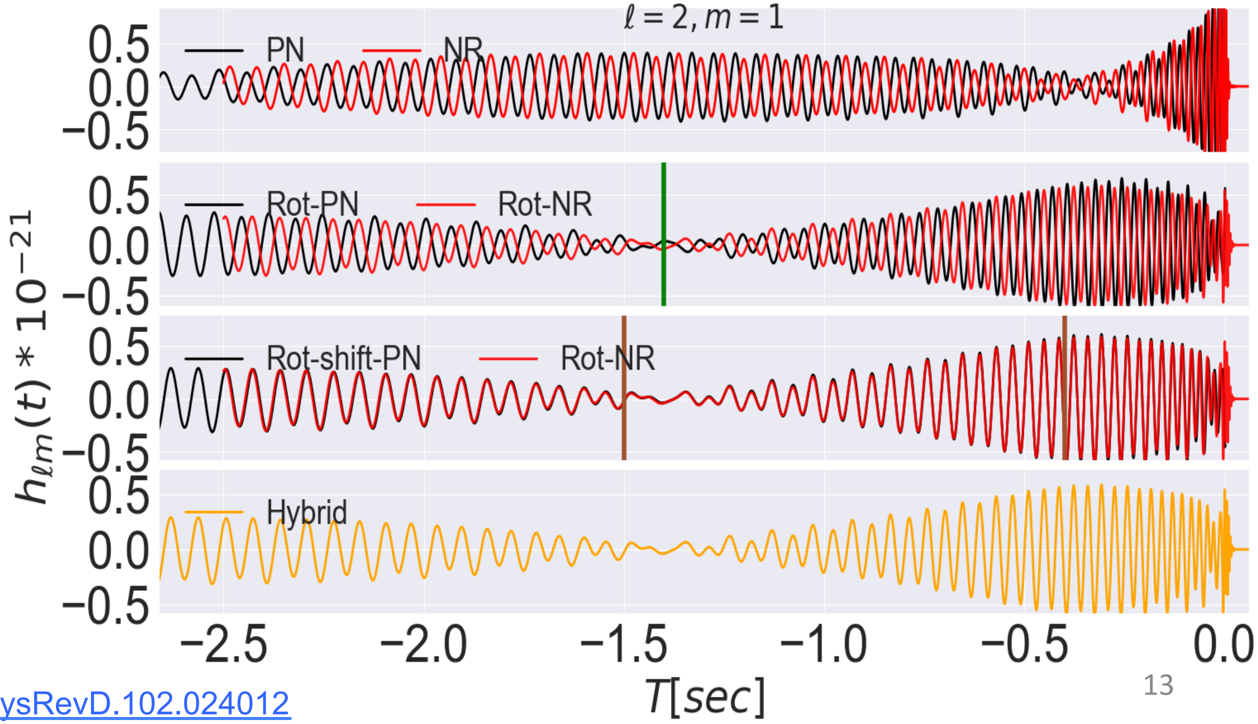
Automated Hybridization of Post-Newtonian and Numerical Waveforms for Precessing Black hole Binaries

Motivation

- Hybrid precessing waveforms benefit from both numerical (accurate but shorter, late inspiral to merger part) and analytical (accurate for early inspiral phase) waveforms to detect & characterize BH binaries in future GW observations
- Due to precessions (mixing of amplitude and phase in modes) hybridization is difficult. We are using simplicity of co-precessing frame (frame where precessing system behaves like a non-precessing one)

Hybridization Procedure

- Fix time co-precessing frame rotation (at green line)
- Alignment of time and phase in hybrid interval (brown lines)
- Hybrid construction

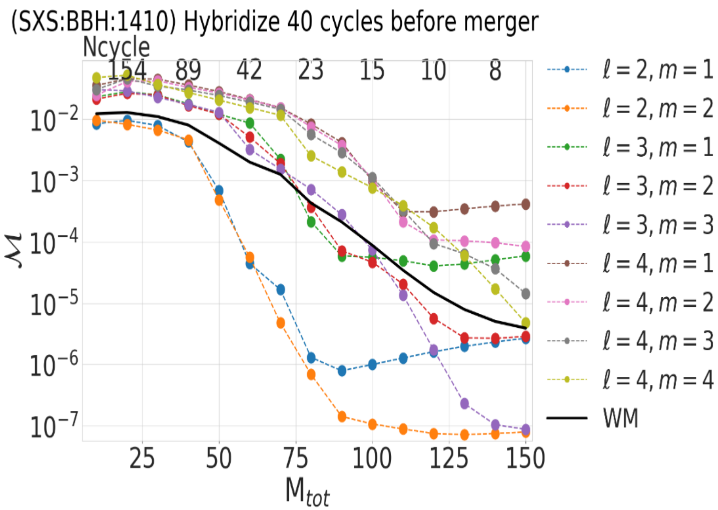


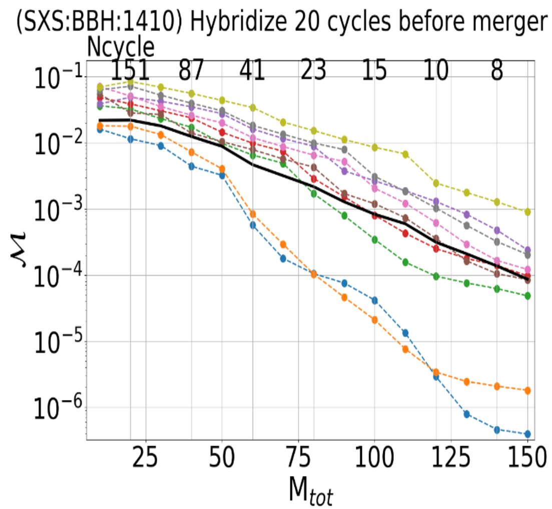
J. Sadiq et al. https://doi.org/10.1103/PhysRevD.102.024012

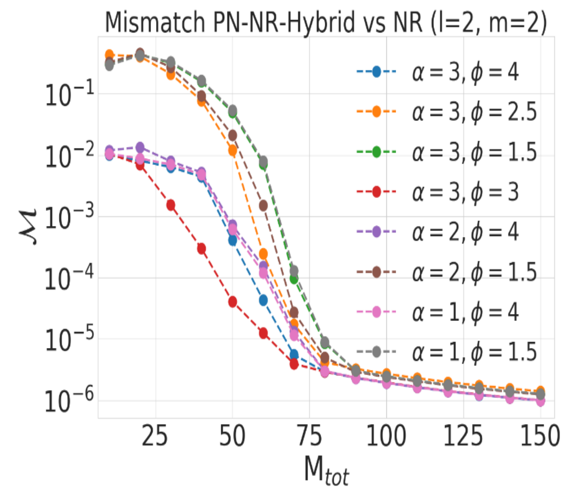
Accuracy of Hybrid and Future Goals

Mismatch (measure of accuracy)

- Depends on length of NR waveform & choice of hybrid interval
- Depends on pN waveform order : α -> amplitude, φ -> phase







Future

- Use hybrid waveforms for PE studies
- Use model waveforms (EOB/Phenom) in place of pN, compare accuracy of hybrids
- Improve accuracy by hybridizing in co-precessing frame & consistently rotate back to inertial frame
- Use hybrids to construct surrogate waveforms

Juan Calderon Bustillo

- **La Caixa Junior - Leader Marie Curie Fellow @IGFAE**
- **Adjunct Assistant Professor @The Chinese University of Hong Kong (CUHK)**

Team

- **Students: Mr. Samsong Leong, Ms. Sonja Choi (CUHK)**
- **Postdoc: upcoming call**

Science Activities

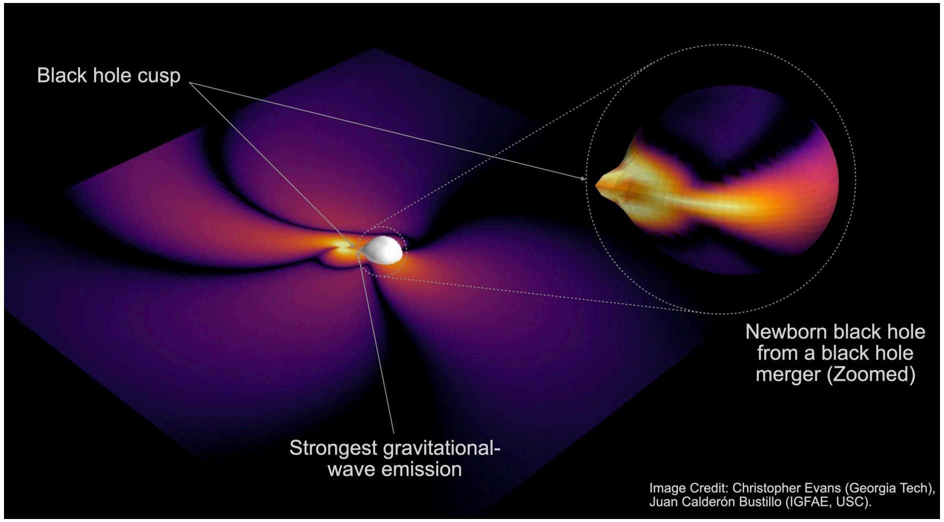
- **LIGO-Virgo data analysis: searches for binary black holes, parameter estimation**
- **Numerical Relativity and ringdown studies (with Monash U.)**
- **Improved searches for binary black holes (with IITP Mumbai)**
- **Search for new physics in Advanced LIGO and future detector data (with Aveiro and Valencia)**
- **Cosmology and Hubble parameter estimates (with Postdam and Monash U)**

Ringdown, higher harmonics and numerical relativity

Goals

- Understand relation between black hole horizon dynamics and GW emission
- Identification of Kerr vs. exotic nature of compact objects

Software: Einstein Toolkit, Bilby



- **Explicit demonstration of horizon dynamics affecting ringdown emission**

  (Nature Comms. Phys 3, (170), 2020)

- **Improved test of the no-hair theorem on GW150914**

  (arXiv: 2010.01857)

- **Impact of higher gravitational-wave modes in cosmology :** Percent-level measurements of H0 with single BNS events in 2.5-gen detectors

  (arXiv 2006.11525)

Searches for gravitational waves

- **Prototype search for binary black holes using higher harmonics**
  (PRD 97 023004, 2018)
- **Updated upper limits on intermediate-mass black hole mergers**
  (PRD, 102 044035, 2020)

Search for new (astro)physics

- **Search for black hole mimickers and new physics in Advanced LIGO data**
- **Understanding possible source degeneracies ; measurability of beyond-standard parameters**

- **Putative ultra-light boson from GW190521**
  (arXiv: 2009.05376)
  With Aveiro + Valencia (JCB, Nico Sanchis-Gual, Toni Font, Carlos Herdeiro, Eugen Radu, Alex Torres-Forne)
- **Highly eccentric BBH mergers can be confused with precessing ones**
  (arXiv: 2009.01066)
  With Aveiro + Valencia (JCB, Nico Sanchis-Gual, Toni Font, Alex Torres-Forne)
- **GW190521 consistent with an eccentric black-hole merger**
  (arXiv: 2009.04771)

Ultra-light boson mass estimate from GW190521

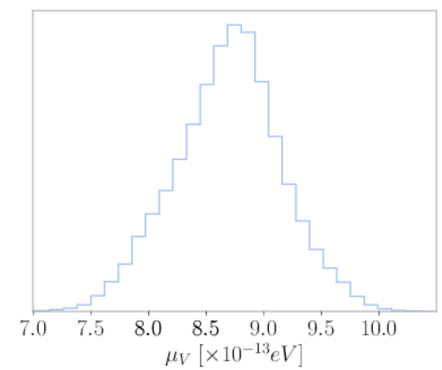
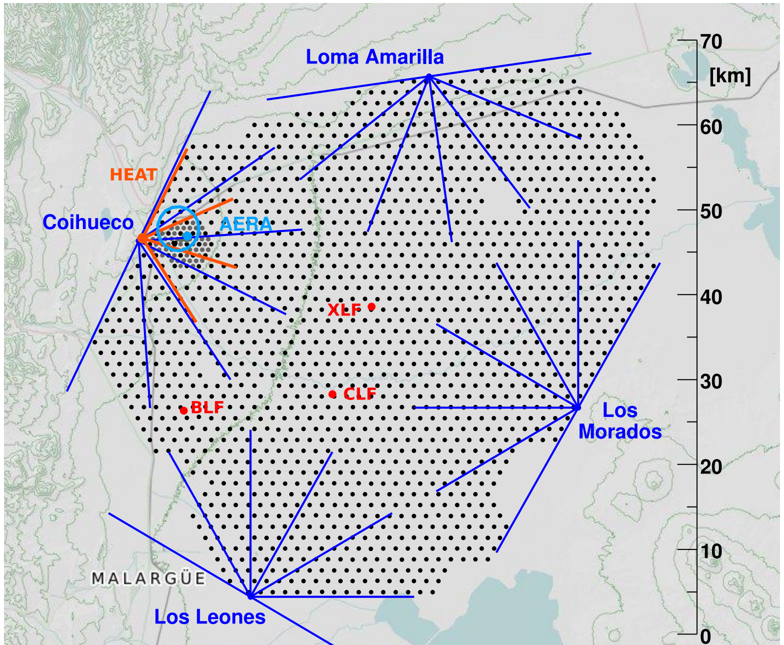


FIG. 4. **Posterior distribution for the values of the bosonic field associated to GW190521.** The top panel shows the oscillation frequency of the bosonic field ω/μ_V. The bottom panel shows the mass of the ultra-light boson μ_V. We assume a merger of two equal-mass and equal-spin Proca stars.

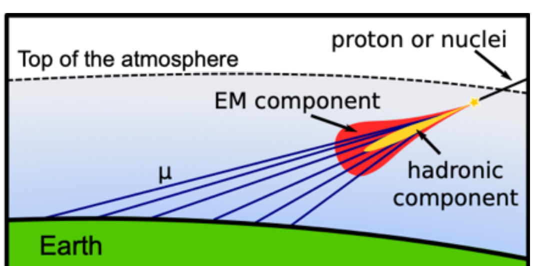
Pierre Auger Observatory : Ultra-High Energy neutrino follow-up of GW events



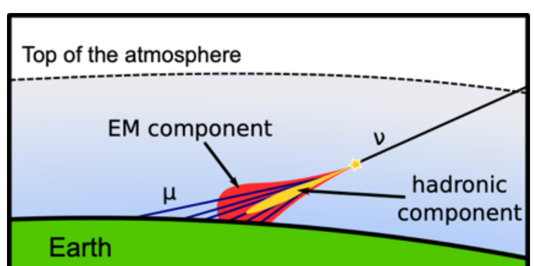
SD 1500 = Surface detector 1600 water Cherenkov stations (**3000 km²**)
SD 750 = infilled array (27 km²)
FD = Fluorescence Telescopes
AERA radio detector

- Surface Detector Pierre Auger Observatory sensitive to **Ultra-High Energy Neutrinos (E > 10^{17} eV)**
- **Neutrino sensitivity largest in inclined directions** w.r.t. vertical to ground $\theta \in (60^o, 95^o)$ increasing with θ. Peaking in $\theta \in (90^o, 95^o)$ due to Earth-Skimming tau neutrinos.
- **30% of the sky viewed instantaneously**
- Follow-up of LIGO/Virgo GW alerts performed with **15 min. latency (at most)**
- **No UHE neutrino candidates found so far**

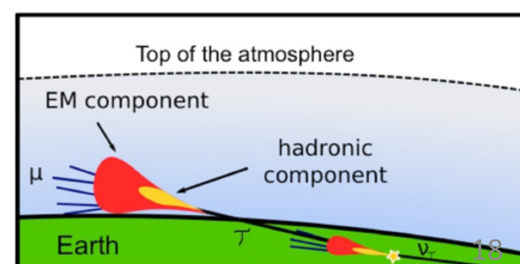
COSMIC-RAY



DOWNWARD-GOING ν
$\theta \in (60^o, 95^o)$

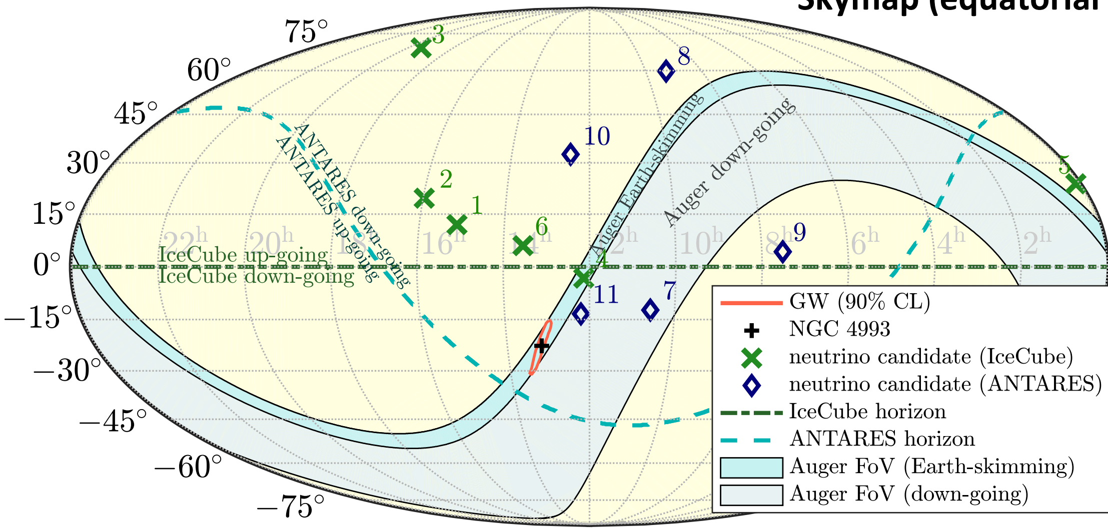


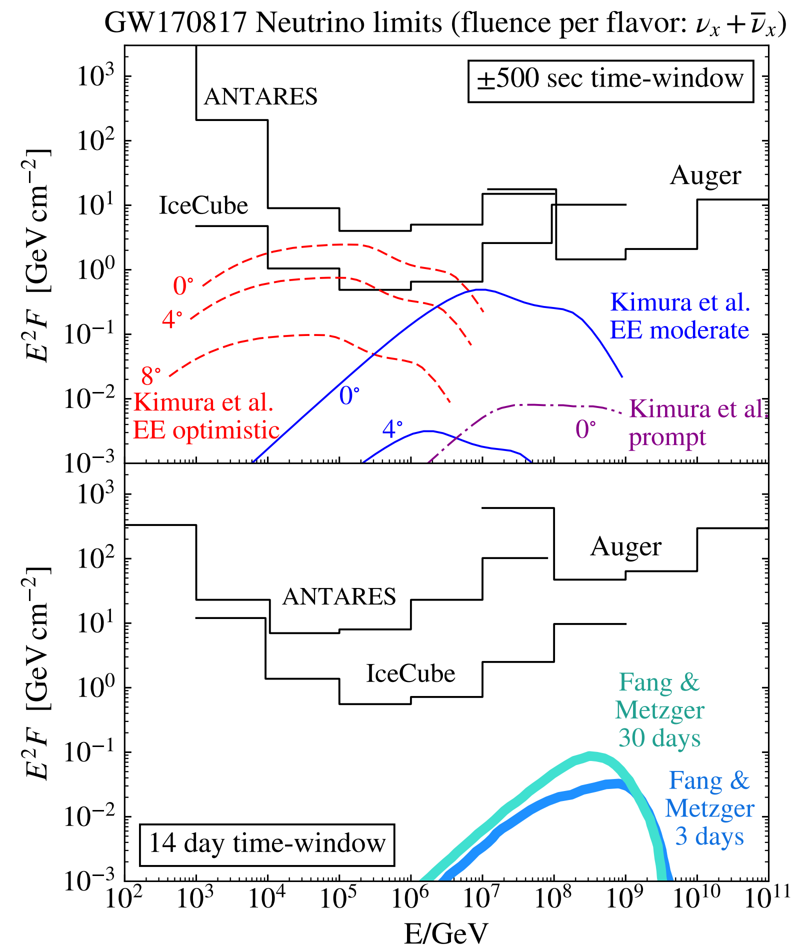
EARTH-SKIMMING ν_τ
$\theta \in (90^o, 95^o)$



Follow-up of GW 170817 in UHE neutrinos with Auger

Skymap (equatorial coords)





GW170817 BNS was in an **optimal position (Earth-Skimming channel)** in the sky for UHE neutrino detection with Auger at the time of merger.

⇒ **best limits** to UHE neutrino flux from BNS.

No observation of UHE neutrinos consistent with GRB jet not aligned with Earth's direction > 20°

IGFAE Auger + LIGO multi-messsenger group:
Jaime Alvarez-Muñiz, Francisco Pedreira, Enrique Zas

ANTARES, IceCube, Pierre Auger, LIGO & Virgo
Astrophys. J. Lett. **850**, L35 (2017)

Follow-up of BBH in UHE neutrinos with Auger

NO ν candidates found:

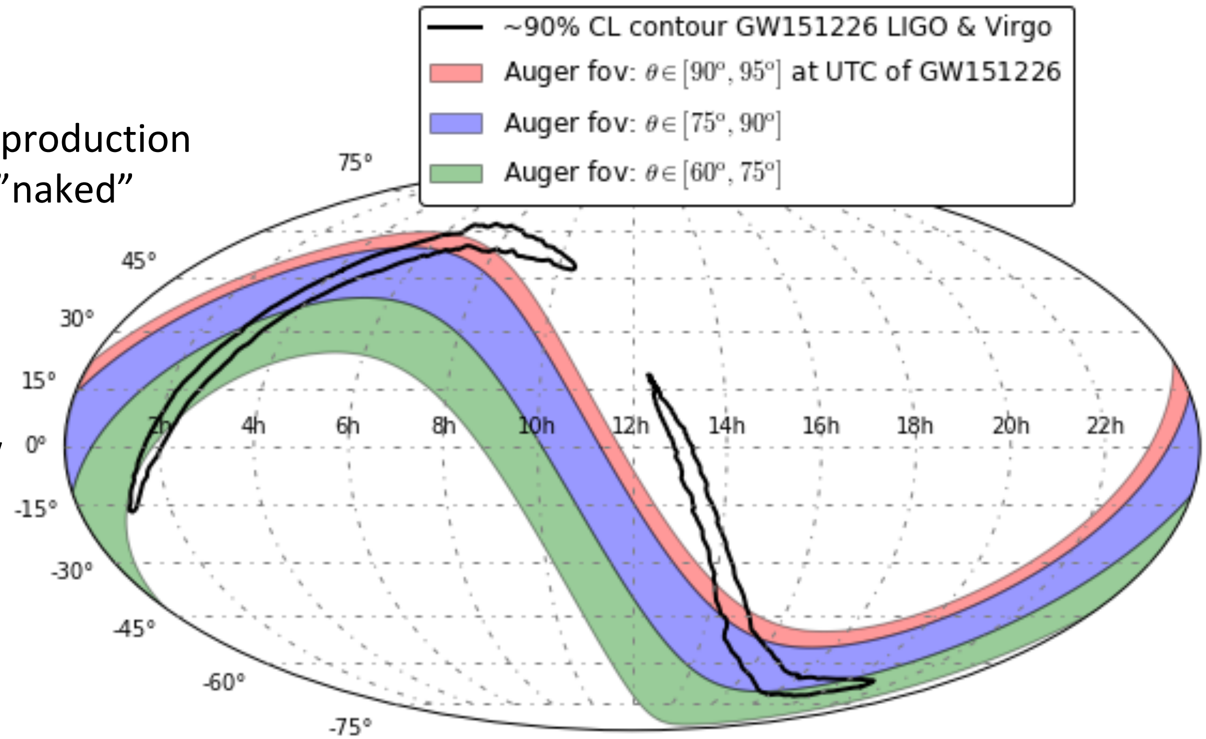
⇒ Constraints on energy emitted in UHEν: less than a few solar masses.

⇒ Consistent with NO neutrino production expected if BBH systems are "naked"

~ 40% of contour of GW151226 in Field-of-View of Auger at merger time

Example: follow-up of GW151226

Skymap (equatorial coords.)

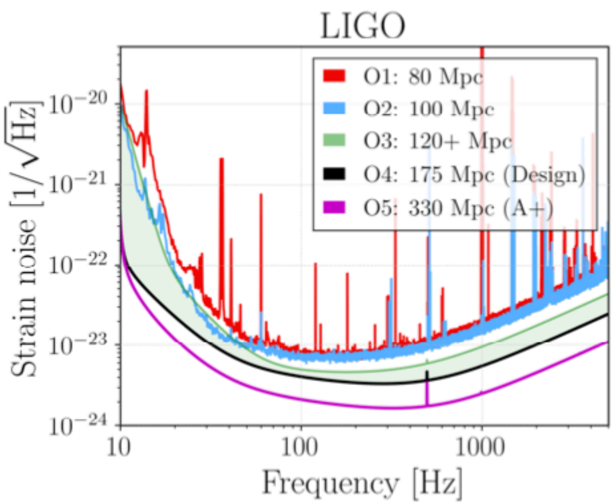


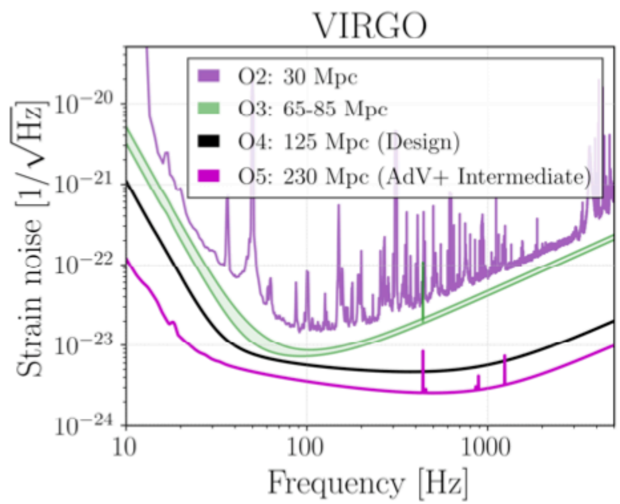
Pierre Auger Collaboration,
Phys. Rev. D **94**, 122007 (2016)

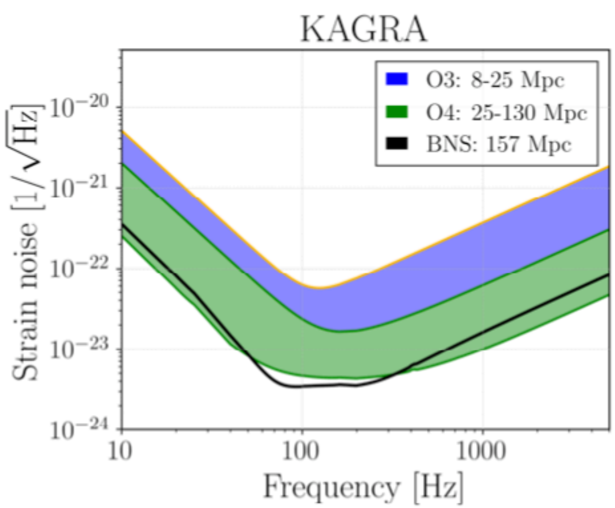
IGFAE Auger + LIGO multi-messsenger group:
Jaime Alvarez-Muñiz, Francisco Pedreira, Enrique Zas

EXTRA SLIDES ...

Upcoming science runs







- O3 run to start early 2019, duration ~1 year
- Advanced LIGO design sensitivity by 2021-22

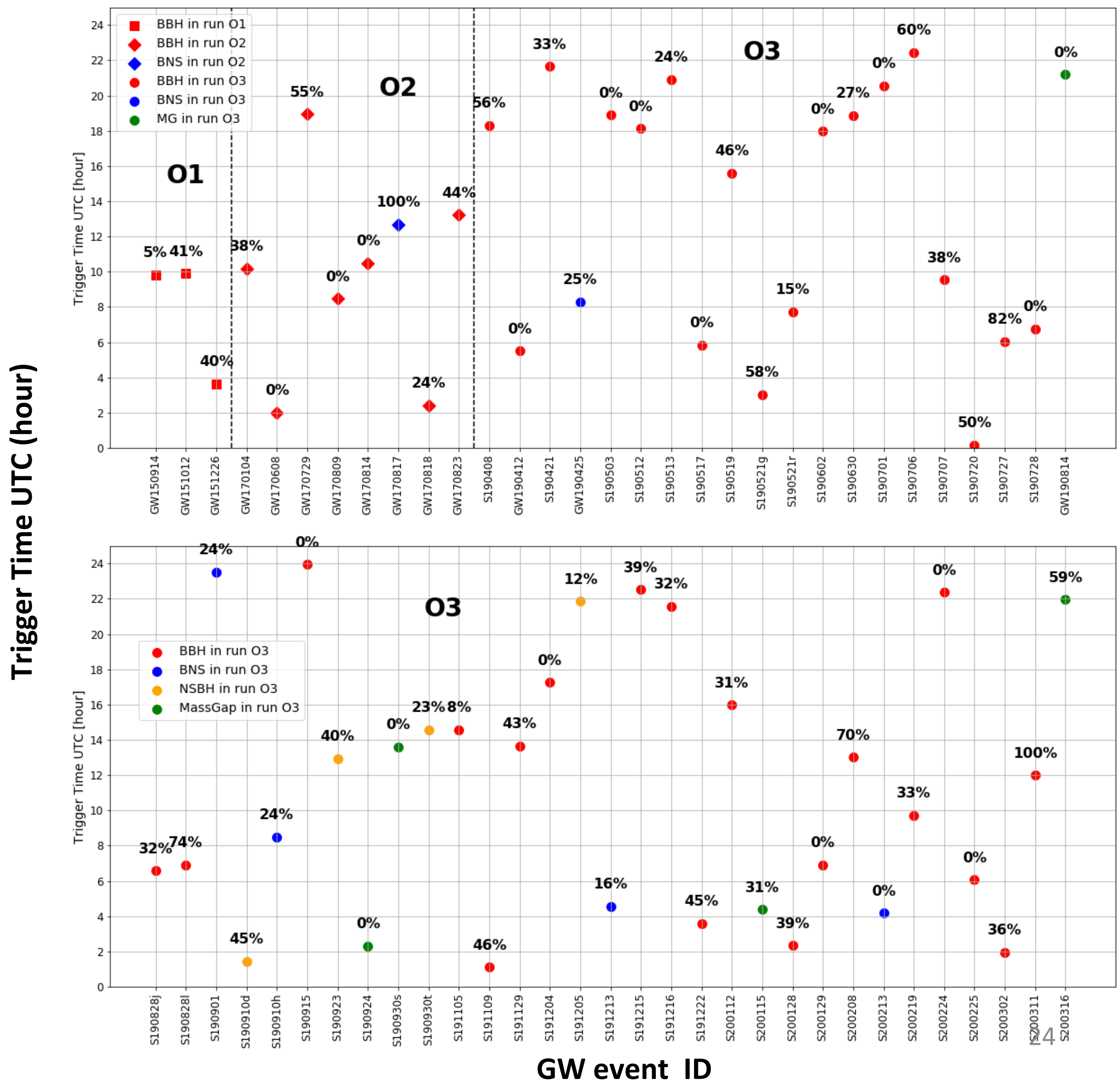
Instrumentation for Advanced(+) interferometers

- Mid-2020 : LHCb upgrade over, window of opportunity for IGFAE members to engage in detector hardware development
- Contribute to reaching & surpassing Advanced design sensitivities
- Expertise in microelectronics, silicon radiation detectors and readout, sensor photodiodes, monitoring and control systems
- In contact with Virgo spokesperson

Follow-up of BBH in UHE neutrinos with Auger

All BBH or BNS or NS-BH candidates alerted by LIGO/Virgo in O1, O2 & O3 followed-up with Auger

(numbers on top of each dot indicate fraction of 90% C.L. contour in the field-of-view of Auger at merger time)



Francisco Pedreira
PhD Thesis. Dec 2020.