Technical and scientific contributions of ICCUB to Virgo

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ICCUB and Virgo

- **ICCUB joined Virgo on July 2018**
- **Full members of the Virgo Collaboration since July 2019**

- Initial focus: computing
  - Virgo had to deal with ~50 MB/s during O3 (~1 year) → ~1PB
  - Grid-like computing network (main centers: Bologna and Lyon)
  - Apply our expertise on **LHCb** and **Gaia**
    (massive, high-throughput data handling and processing)
- …but actually much more active on:
  instrumentation, data analysis, science case

The ICCUB Virgo team

Name	FTE	Activity
Jordi Portell i de Mora	15%	Group leader, **coordination** of ICCUB tasks on Virgo; Pablo's advisor
Juan Trenado	15%	Support to ICCUB Virgo group **coordination** and management
Mark Gieles	10%	Development of **science case** for Virgo@ICCUB
David Gascón Fora	10%	Coordinate ICCUB tasks on Virgo **instrumentation and electronics**
Pablo Barneo	**100%**	PhD on **data analysis** (denoising in bursts pipeline); **DetChar**, outreach
Gerard Guixé	**90%**	PhD on **instrumentation** (SAT electronics for AdV+)
Andreu Sanuy	**50%**	**Instrumentation**: SIN/QNR quadrant photodiodes for AdV+
Tomas Andrade	**40%**	**Data analysis**: eccentric waveforms for BHBs
Javier Castañeda Pons	10%	Support to **software and computing**
Joan Mauricio	5%	**Advisor** of Gerard's PhD
Esther Pallarés	5%	Local contact point for **outreach**

Additional ICCUB expertise related to GW

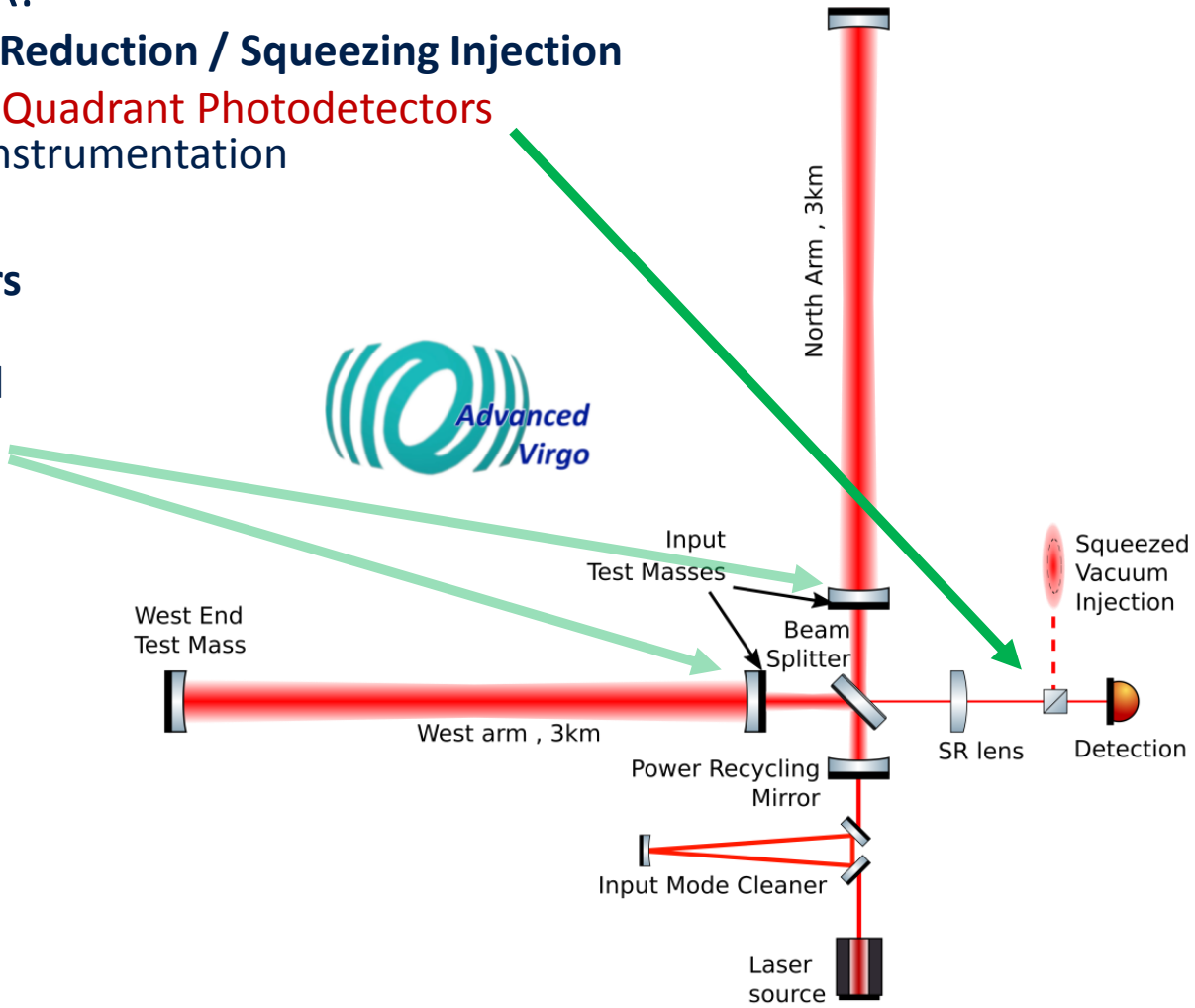
- Names:
  - Roberto Emparan
  - Licia Verde
  - Domènec Espriu
  - Jaume Garriga
  - Cristiano Germani
  - Arnau Rios
  - Jordi Miralda
  - Nikos Triantafyllou (PhD)
  - Diego Cruces (PhD)
- Activities:
  - **Extreme mass ratio mergers**
  - **Primordial BHs**
  - **Dynamical BBH formation** (N-body & population synthesis)
  - Pulsar Timing Arrays (**PTAs**) and $\mathbf{H_0}$
  - Low-frequency GWs (**LISA**)

Outline of next slides

- Instrumentation and electronics
  (Virgo)
- Computing
  (Virgo, in agreement with LIGO)
- Data analysis
  (Virgo, applicable to LIGO)
- Science case
  (Virgo and beyond)

Instrumentation and electronics

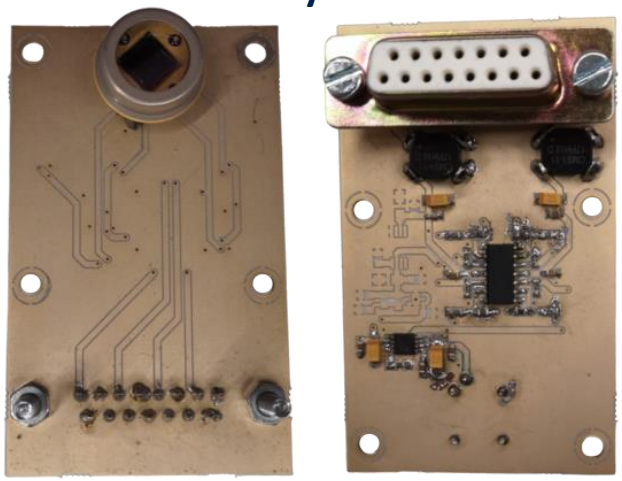
- Work on SIN/QNR:
  - **Quantum Noise Reduction / Squeezing Injection**
  - Development of Quadrant Photodetectors and associated instrumentation
- Work on SAT:
  - **Superattenuators**
  - Development of highly integrated data acquisition electronics card

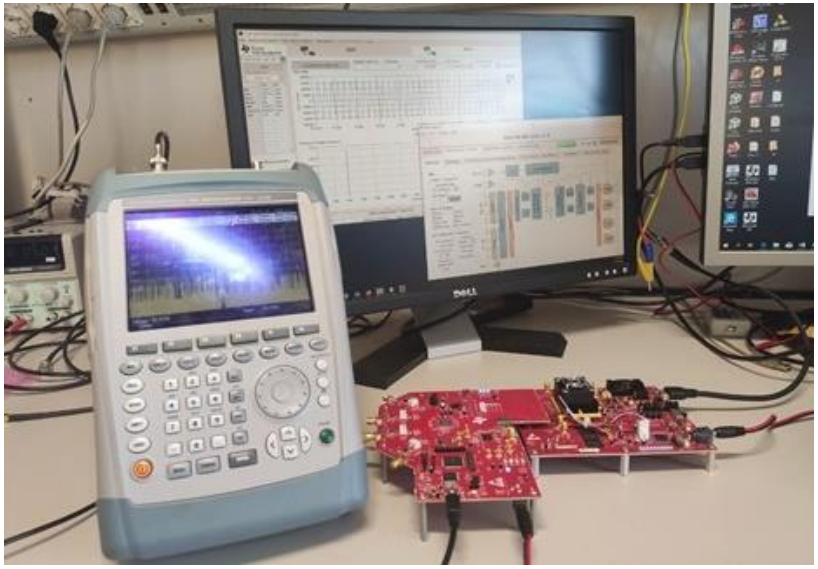


Instrumentation and electronics

DC quadrants + electronics, Squeezing Injection subsystem, Quantum Noise Reduction system

- Selection of DC quadrants for green laser beam (532 nm), operated at low frequency
- Development of low-noise electronics to interface with the ADC designed by Annecy
- Devices to be operated in vacuum; outgassing control as in Space projects. Alternative: electronics in a box with air (not baseline)



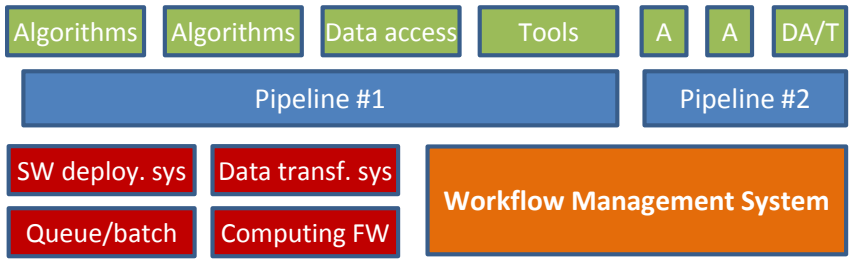


Electronics for suspended masses

- Design of new high-freq. data conversion+processing board for AdV+
- Currently designing firmware+hardware for the new generation of boards
- Future creation of new software+control electronics for the Einstein-Podolsky-Rosen Virgo demonstrator
- During Phase I, electronics will be implemented in the EPR squeezing demonstrator; if these show good results, they will be later used during Phase II of AdV+

Computing

- Overall Virgo computing approach needed several improvements for O3
  - Software development and deployment, ease of use, efficiency of computing centres…
  - Data distribution, reliability and availability
  - Workload + workflow management

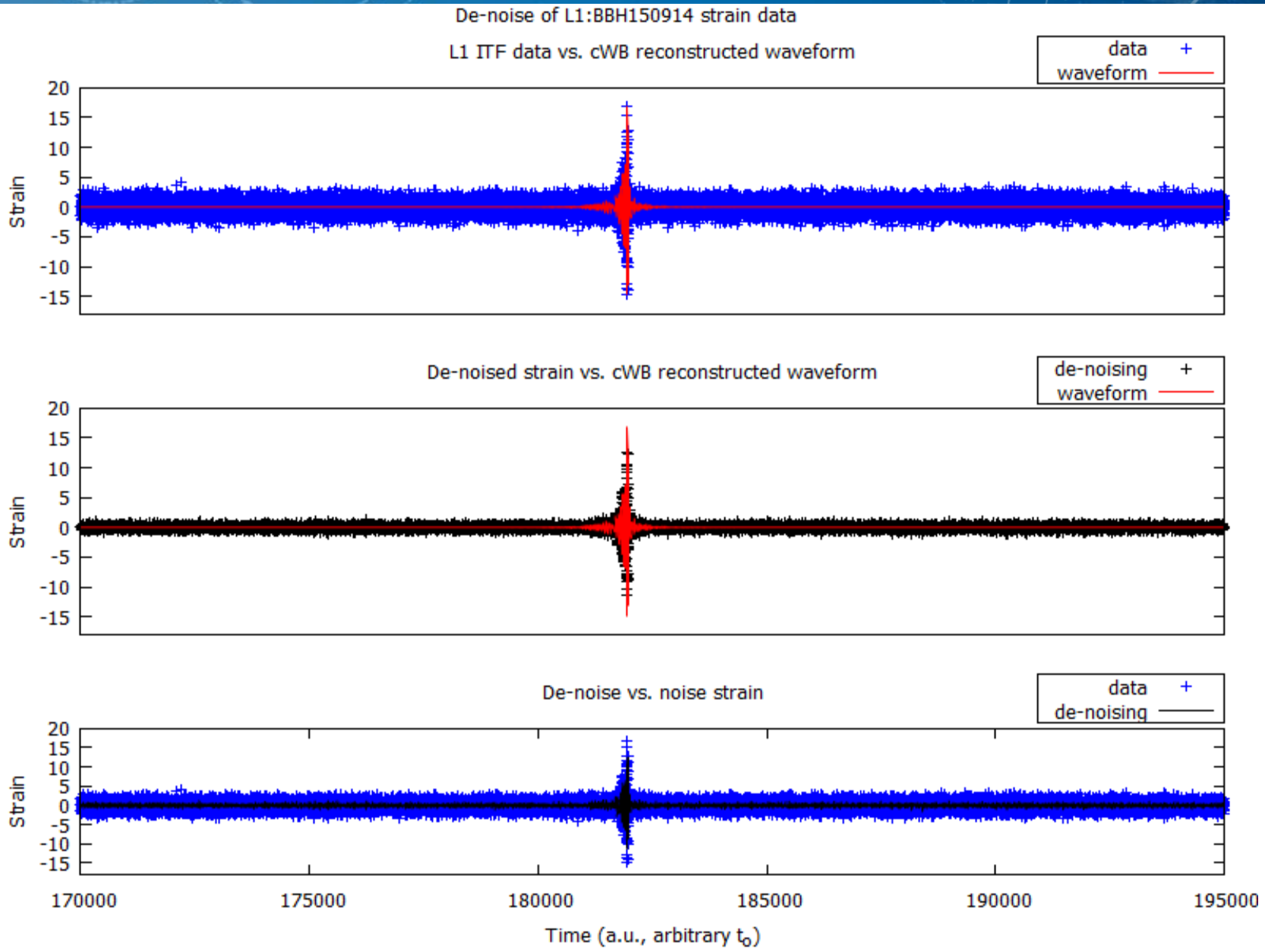


- Coordination and meetings
  - **DIRAC workshop** (Nov'18), **AdV Computing Kick-Off Meeting** (Feb'19), **ECC**
  - **Computing Model** revision, discussions on CVMFS, Rucio, DIRAC…
  - In general: **Look for better Virgo+LIGO computing coordination**
- Software development, building and distribution
  - SVN → **Git** migration
  - CMT (unmaintained) → **CMake + Conda**
  - Work on **porting offline pipelines to GRID**
- Our DIRAC expert left ICCUB a while ago
  - Work on computing quite on stand-by
  - **Now hiring** a full-time software engineer to resume our activities

Data analysis

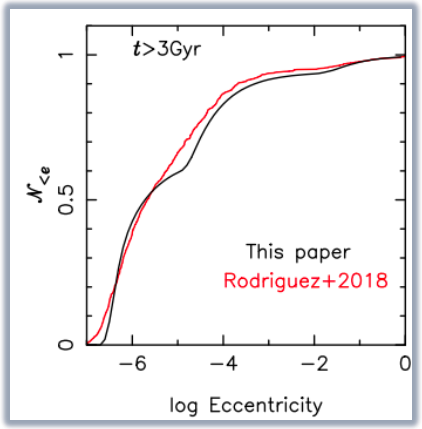
- Developing a method to **de-noise** the GW data taken by the International Gravitational Wave Network (IGWN): Virgo/LIGO/KAGRA (LVK)
- Based in **total variation techniques**:
  continuation of de-noising proposals and tests done by Univ. Valencia
- Choice: regularized version of Rudin-Osher-Fatemi method (**rROF**),
  to be implemented in the **cWB** pipeline (coherent Wave Bursts) of LVK
- Aim: reduce the noise contained in the data
  → **identify more** and/or **better analyze** GWs
- A **parametrization** system has been developed to adjust the de-noising efficiency to a given set of data, while preserving the signal.
- The **implementation** of the rROF de-noising in the cWB pipeline is **complete**.
  The results achieved on O1 data are under revision and evaluation.

Data analysis: de-noising example (O1)



Science case (I)

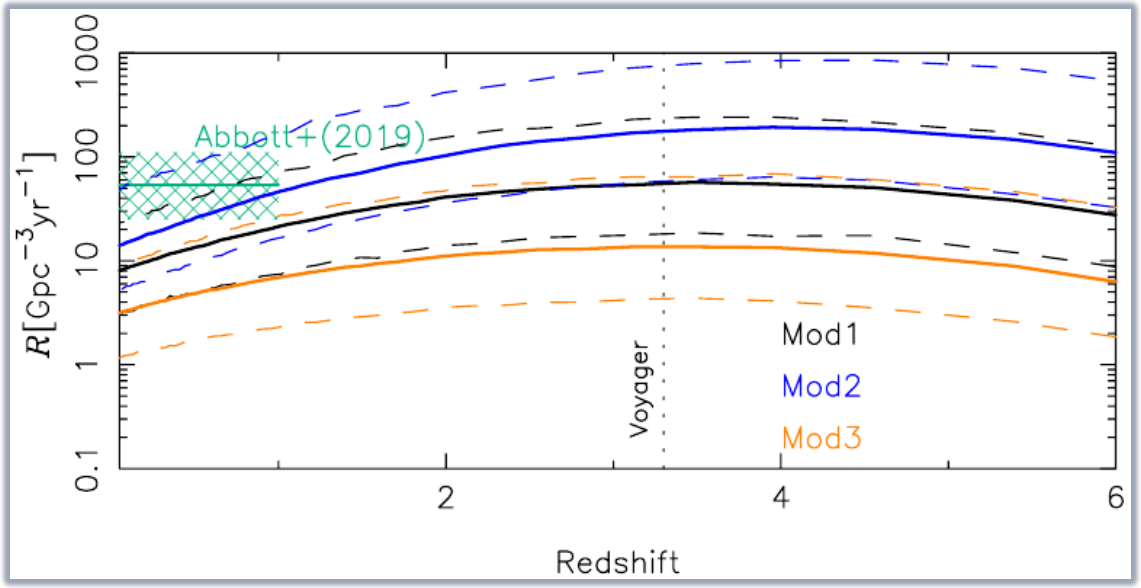
- We developed a **population synthesis code** (*clusterBHBdynamics* or *cBHBd*, Antonini & Gieles 2020) which computes the **evolution of a star cluster and its BH population in < 1 second**.
  With recipes, we couple the evolution of dynamically active BH binaries (BHBs) to the evolution of the cluster to follow BHB mergers.
- cBHBd provides, **for each cluster**, the **evolution** of:
  - **3 types of BHB mergers** (in-cluster, ejected, and GW captures)
  - **Total mass** of the BHB
  - **Eccentricity**
- Excellent agreement found with time consuming star-by-star N-body methods (see figure at right) that shows the eccentricity distribution at the LIGO-Virgo frequency of all mergers after 3 Gyr coming from a massive globular clusters, modelled with N-body Monte Carlo method by Rodriguez et al. and our code.



- High eccentricities (e > 0.05) at Virgo/LIGO freqs. are only predicted by the dynamical formation channel → they are a "smoking gun" signal that can soon be inferred from the data!

Science case (II)

- We apply cBHB to a globular cluster population model, using a model for the cluster formation history across cosmic time + initial cluster mass function constrained by the GC mass density in the Universe today, and a simple model for GC mass loss.
- The figure shows the resulting **merger rate vs. redshift** for 3 assumptions of the initial cluster density: canonical cluster densities ~10^4 Msun/pc^3 in black (model 1), and lower/higher densities (blue/orange).
- By assuming an equal contribution of our 3 cluster densities to the merger rate, we find at *z=0* a BHB merger rate of $7.2^{+21.5}_{-5.5}$/Gpc^3/yr.



This can be compared to the O1+O2 rate of $R=53.2^{+55.8}_{-28.2}$ (same units and assuming no variation with redshift), or $R=19.7^{+57.2}_{-15.9}$ (allowing for redshift evolution), and the O3 rate.

Science case (III)

- The merger rate as a function BH mass in the middle panel shows that the shape of the MF is best matched for the highest density clusters, i.e. when the rates are also closest to the observed rates!
- **If** we assume all mergers are dynamically made, **then** the GW data tells us that clusters formed with a high density (~10^5 Msun/pc^3). **Astrophysics with GWs!**
- We find an absence of BHs with m~<15 Msun, hence another channel must make these.
- Our best fit redshift dependence is $R \sim (1+z)^{\lambda}$, with λ = 1.6+/-0.5, i.e. in between constant (λ = 0) and following the cosmic SFH ($\lambda \sim 2.7$).
  Good agreement with preliminary O3 analyses (yet large error bars, both in model + data)
- Future work:

  More detailed **prediction for eccentric mergers** and **search for eccentric BHBs** in the data.

  Team up with a group working on this eccentric BHBs search,
  e.g. with Univ. Valencia on **preparation of templates**

- Additional lines of research:

Continue work concerning the possible measurement of some cosmological parameters in PTA via studying the influence of the universe expansion beyond taking into account the usual redshift. Extension to LISA is also planned.

Conclusions

- ICCUB Virgo group (and GW group, in general) is growing:
  ~20 people (11 of which are members of Virgo)
- Mostly on Virgo, but also beyond: PTA, LISA, cosmology
- Technology + data analysis + science
- Science case becoming well defined
- Collaborations with Univ. Valencia (rROF, science case)
- Funding: currently María de Maeztu; application next year to national program
- **We're hiring**!
  - **Postdoc position** in Fundamental Physics and Astrophysics from Gravitational Waves
    http://icc.ub.edu/job/116
  - **PhD position** in Fundamental Physics and Astrophysics from Gravitational Waves
    http://icc.ub.edu/job/104
  - **Software engineer** working at the Virgo Collaboration
    http://icc.ub.edu/job/114

Thank you

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on behalf of the Virgo ICCUB group