# OBS div 10 report

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# Goals of Division 10

- Data analysis methods for LVK network in place.
- Some problems arise when moving to 3G era:
  - Longer signals
  - Overlapping signals
  - Rising computational costs; very likely need not just faster but newer methodologies
  - Noise characterisation
  - Others?

***Identify drawbacks of current methods***

***Works on new methods***

***Develop a common infrastructure to tackle this***

# Blue Book: status

- A first draft has been concluded before the summer
  - Several people contributed to the writing
- Several reviewers have been individuated; two accepted and sent us their report
- The comments are being taken into account by the writers of the different sections
- The final draft is nearly done.

# Blue Book contents

- Challenges
- Innovative methods: machine learning applications
- Signal detection methods
- Parameter estimation methods
- Peculiarities of a triangular ET
- Simulation and Mock Data Challenges

# Challenges I

- ***Long duration CBC signals***
  - Good sensitivity down to 5 Hz & frequency evolving slowly at low frequencies → signals much longer than for current ITFs

| | BNS standard | BBH (30+30 Mo) | SSM (0.8+0.8 Mo) |
|---|---|---|---|
| **LIGO-Virgo** | 160 s | 0.9 s | 400 s |
| **ET** | 6420 s | 40 s | 16000 s |

  - Computational cost can dramatically increase
  - Earth motion  and rotation
  - Noise stationarity and glitches

# Challenges II

- ***Overlapping signals***

  - Higher sensitivity and larger detection frequency band → chances of observing overlapping signals will increase

| Rate | Number of BBH mergers | Number of BNS mergers | Number of any type |
|---|---|---|---|
| Low rate | $8^{+10}_{-5}$ | $16^{+16}_{-8}$ | $25^{+23}_{-12}$ |
| Median rate | $13^{+14}_{-7}$ | $62^{+58}_{-27}$ | $76^{+77}_{-33}$ |
| High rate | $21^{+21}_{-11}$ | $157^{+144}_{-66}$ | $178^{+164}_{-75}$ |

TABLE III. Typical numbers of compact binary mergers happening during the time a BNS signal is in band.

| Run | BBH-BBH | BBH-BNS | BNS-BNS |
|---|---|---|---|
| Low rate | 5 | 57 | 416 |
| Median rate | 11 | 304 | 6752 |
| High rate | 15 | 1594 | 41306 |

TABLE IV. Number of pairs of binary coalescence events with both SNRs between 15 and 30, and such that their mergers occur within 2 seconds or less from each other. Arxiv 2102.07544v1

  - Detection will be affected as signals merging at near times could be difficult to distingue

  - Parameter Estimation will be affected if assuming a single-signal model to model the data
    - in general overlaps are a problem when the merger times are very close (< 1 second), SNRs of overlapped signals are comparable, and if in addition to these two, one signal is much smaller (heavy BBH) than the other (long BNS)
    - even with few cases parameters offsets can have a big impact on estimating common parameters from a set of signals (GR, PP)

# Challenges III

- ***Noise Background estimation***

  - ET data polluted by a large number of signals → problem with PSD of the instrument and noise False Alarm Rate estimation
  - First studies based on MDCs indicate small effects on CBC detection; other studies find a significant contribution of simoultaneous signals on noise spectra estimation at low frequencies.
  - FAR cannot be simply estimated with the method of time slides; use of null stream for triangular configuration could help.

# Challenges IV

- Source subtraction for CBCs
  - CBCs will mask the cosmological background → need a subtraction of individual detected signals
  - Possible problems with uncertainity on source parameters of subtracted signals → emergence of an extra residual background.
  - Possible new methods to be further esplored.

# Innovative methods: ML applications

Pipeline for transient noise signal (glitches) classification

Study for CBC detection for early warning

Many effort on parameter estimation application to fasten the procedure

Different activities on going on burst signal detection/classification (to be tested on next MDCs)

# Data Analysis methods for Compact Binary Coalescences

- Current methods rely on matched-filtering → efforts are being applied to check if the same methods are possible for 3G detectors.
- LVK pipelines are being applied: first results indicate that there should not be any relevant decrease in the detection efficiency
  - To cope with the long signals, approaches like decomposition in several frequency bands or SVD could be doable.
  - Effects on angular response variation over time are to be investigated in full detail; preliminary results indicate that this will not be a major concern.
- MDC in real scenario demonstrates that Machine Learning could eventually match the detection sensitivity of traditional matched-filtering techniques, while being faster and with low computational cost.
- Traditional LVK searches are found to be computationally faisible with the current methods with present-day computational resources
  - New searches – precession, tidal effects etc – could require improved technology or new DA solutions.

# Data Analysis methods for Gravitational Wave Background

- Current methods (isotropic and non isotropic pipelines) rely on cross-correlation of pairs of detector to cancel the intrinsic noise and extract the common GW signal.
- These methods assume that the signal is small compared to the noise, when for ET the signal will be comparable to the noise or larger. Thus, we have to change the detection statistics by incorporating the variance term coming from the GW signal.
- Another promising possibility for ET in its triangle configuration is to calculate the difference between (one-third of) the null stream PSD and the individual detector PSD.

# Data Analysis methods for Continous Wave Searches

- In principle, current algorithms for the search of CWs will be mostly applicable to ET data as well
- In practice, a continued effort is ongoing in order to improve search sensitivity for wide-parameter space searches (e.g. directed and especially all-sky)
- This must be done by keeping the computational cost under control.
  - Any promising new computing architecture will be explored in relation to CW searches (GPU – ongoing, Field Programmable Gate Arrays (FPGA)?,…)
- Two CW-related potential issues, specific for ET, must be investigated:
  - The impact of the CBC astrophysical background on CW algorithms
    - Better noise estimation?
    - Sensitivity reduction in some frequency band?
  - Superposition (in frequency) of specific sources, e.g. the population of ultra-light boson clouds around rotating black holes
    - Does this have an impact on current search algorithms?
    - Can we design algorithms that exploit this superposition to improve detection efficiency?

# Data Analysis methods for Burst signals

- Current method relies on excess power from more detectors and combine coherently.
  - More efficient wrt a time coincidence between detectors
- Main problem: noise excesses mimicking GWs
  - Machine learning application to assess significance (cWB+XGBoost, cWB+GMM)
- Application of dedicated searches for specific sources (like for Supernovae: Triggered on EM information, or pre-selecting Time-Frequency patterns)

# Parameter estimation methods

Loud signals in 3G; parameter estimater becomes not just more expensive but harder!

Long signals; impossible computational demands:

- hardware advancements necessary too (GPUs, FPGAs, quantum computing,...)
- particularly for BNSs, even more rapid estimates necessary for early warning etc.

Promising avenues:

automated techniques, ***machine learning*** based:

- Neural posterior estimation – directly output posterior density distributions
- Nested sampling enhanced with normalising flows
- Markov chain monte carlo methods coupled with machine learning

***Others:***

***Relative binning*** –

making frequency grid sparser, effectively reducing cost of single likelihood computation

# Peculiarities of a triangular ET

- Benefits of sky-indipendent null stream to cancel out the GW signals:
  - Noise estimation: possibility of removing the background of confusion noise (unresolvable and resolvable signals) in the detectors at frequencies where the correlated noise is negligible.
  - On–source PSD measurement, desirable for coping with non-stationarity.
  - Glitch identification: glitches do not cancel out in the null stream, thus giving the opportunity to identify and reduce them to the Gaussian noise background.

# Impact of Correlated noise

- Correlated noise (magnetic coupling) will dominate ET ASD below 15
  - GWB searches will be affected up to 30 Hz.
  - Lightning strikes will produce numerous correlated glitches.
- Additional noise couplings (i.e. with seismic noise) in triangular ET can deeply impact GWB search between 20Hz-40Hz.
- PE can be affected as well in triangular ET.
  - The effect varies with the sign of the correlation coefficient between the detectors, being most probably negative due to the triangular geometry.
  - → need to account for correlated noise for PE at low frequencies.

# Simulation and Mock Data Challenges

- MDCs provide a common training simulated data set used to test, develop, optimize or compare data analysis and parameter estimation techniques. The aim is to assess both the science potential and the requirements for computing infrastructure with ET.
- The first ET MDC contains one month of data with Gaussian noise and a realistic population of all types of CBCs (BBHs, BHNSs and BNSs)
- Next MDCs will include other sources (CWs, bursts, stochastic background), glitches, correlated noise for different noise PSDs and detector configurations (triangle or 2Ls)