Virgo-LIGO Data analysis activities at IP2I Lyon

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Why?

- The confirmation of the existence (and the subsequent study and understanding) of Gravitational Waves (GW) is of utmost importance for:
  - Testing general relativity
  - Studying the deep sky with a brand-new (non-electromagnetic) source of signals
    - This has immediate and far-reaching consequences in the domains of astrophysics, cosmology, nuclear matter, particle physics
- The only detectable GWs on earth can be of astrophysical origin
- We must resort to the most violent astrophysical events
  - Coalescent compact binaries are good GW radiators
  - They occur frequently in the universe and they are the loudest expected GW sources (in their frequency band)
  - Best candidates are Black Holes (BHs) and Neutron Stars (NSs)

The power of Compact Binary Coalescences (also known as CBCs)

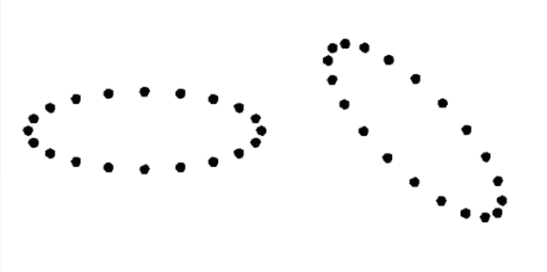
- The direct observation of CBC signals has multiple implications
  - Confirmation of the existence of gravitational waves
  - Direct determination of the rate of these occurrences in the observable space
    - Assessment on rates and population of BH and NS
  - CBC waveforms encode much more information
    - Masses and spins of the individual object and the final object
      - Test the uncertain BH mass distribution and the maximum allowed mass for a NS
    - Information on tidal deformations
      - Constrain nuclear matter of state for NS
  - Help in constraining other cosmological facts
    - Infer the Hubble constant via an estimation of the redshift of the GW
    - Check counterparts for completing the information on the source (multi-messenger astronomy)
      - Electromagnetic: Direct redshift information, check for coincident gamma ray burst emission for BN-X mergers
      - Neutrinos: information from inner regions of astrophysical engines
  - Probe dark matter candidates in coalescences
    - Primordial black holes, axions, ultralight bosons forming compact self-gravitating configurations…
  - Possible deviation from GR expectations…

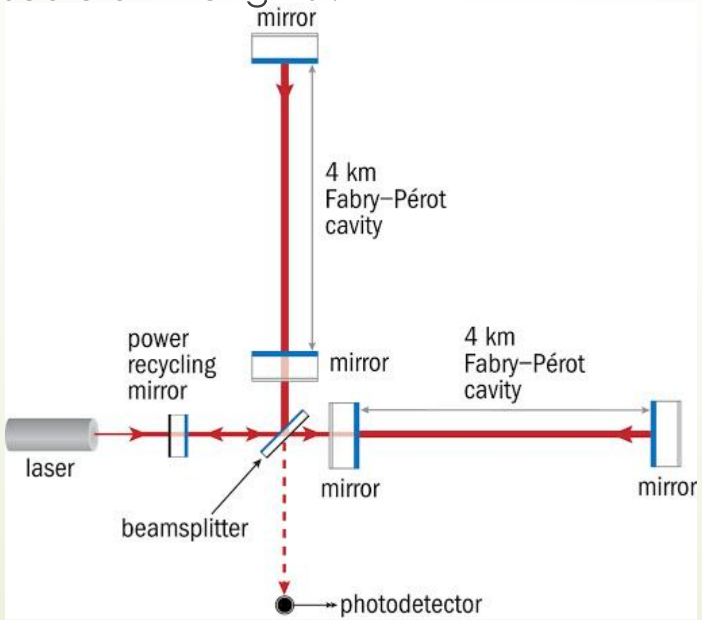
Keep in mind: not only CBC…

- There are different types of searches for GW signals in LIGO-Virgo
  - Many other astrophysical sources: pulsars, supernovae, unknown sources?
- Transient sources
  - Coalescences of compact binaries (known waveform assumed)
  - Generic GW bursts (poorly modeled)
- Persistent sources
  - Continuous waves (from pulsars)
  - Stochastic (relic GW from early evolution of the Universe)

How? Principle

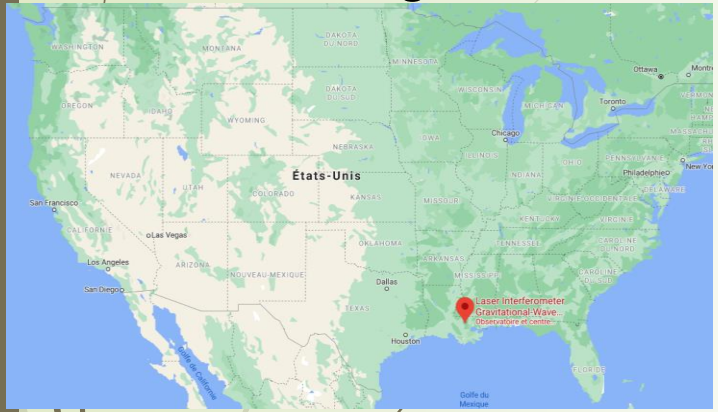
- Gravitational waves are distortions of the spacetime curvature happening in a plane orthogonal to the wave direction
  - Their passage induces an apparent distortion of the mutual distances of particles in our reference frame
- Use an interferometer to study them
  - The wave amplitude is physically represented by a (dimensionless) strain
  - Measure the strain ($O(10^{-21}$!!) by the shift in wave-phase
    - Need Km-scale arm lengths !





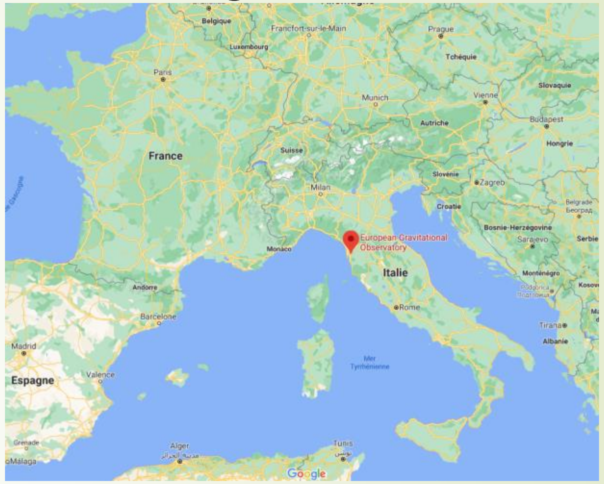
How? Detectors running in O3 (2019-2020)

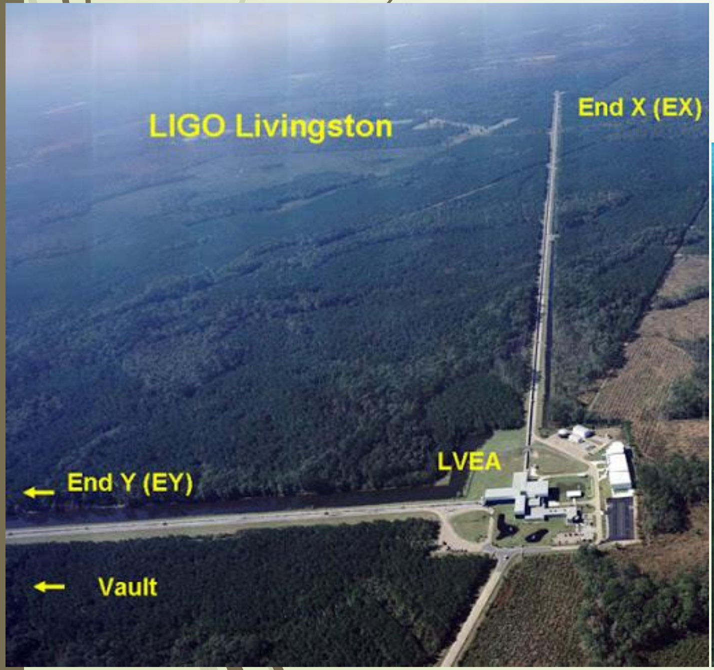
LIGO Livingston

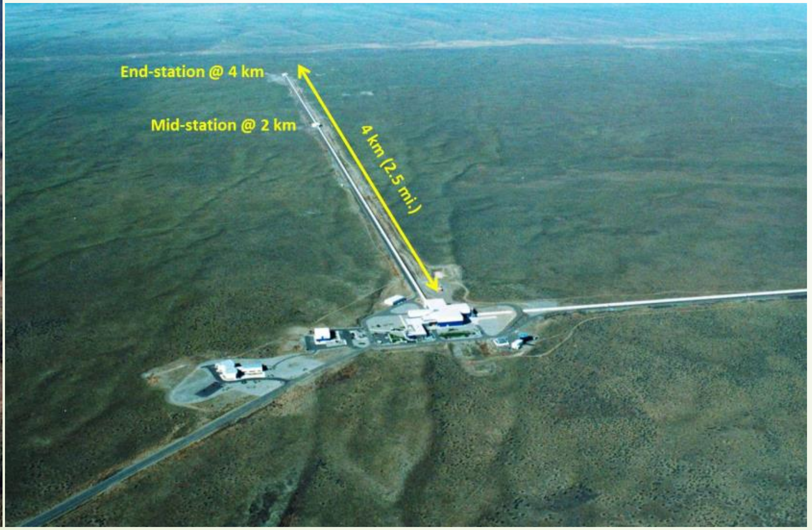


LIGO Hanford

Virgo

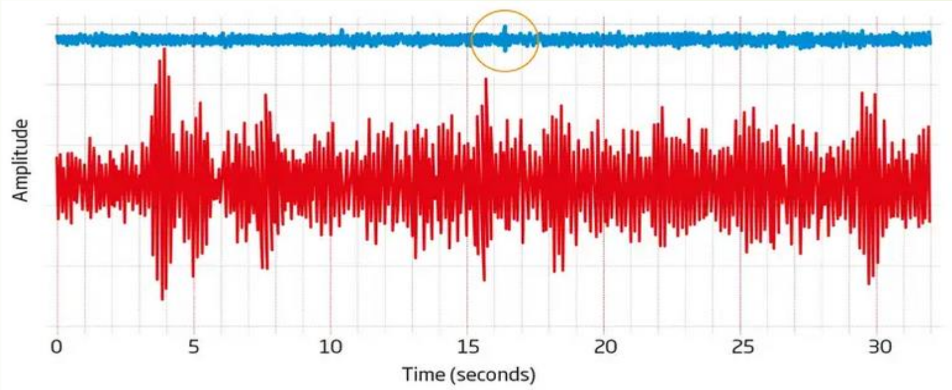




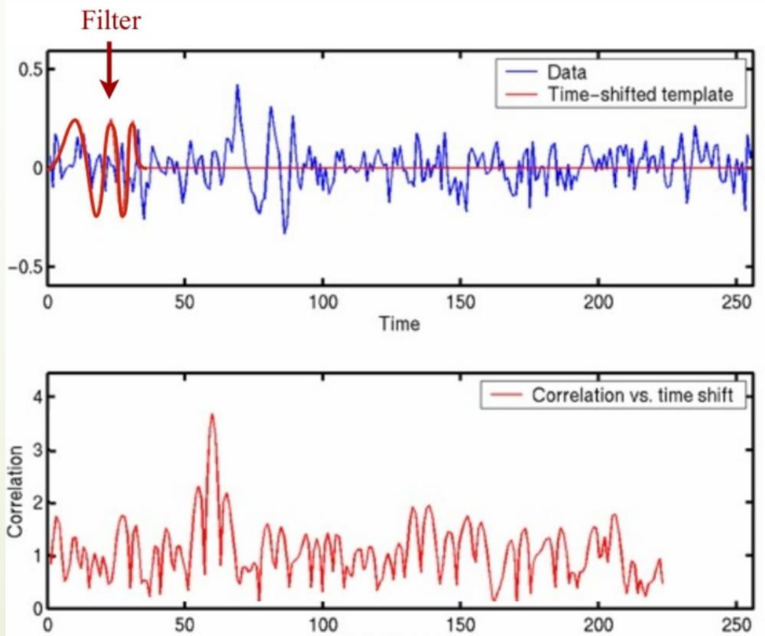


How? Data analysis (1/2)

- The time series (h(t)) from the interferometers' signals are very sensitive to many undesired "earthly" effects: seismic noise, human noise, optical noise



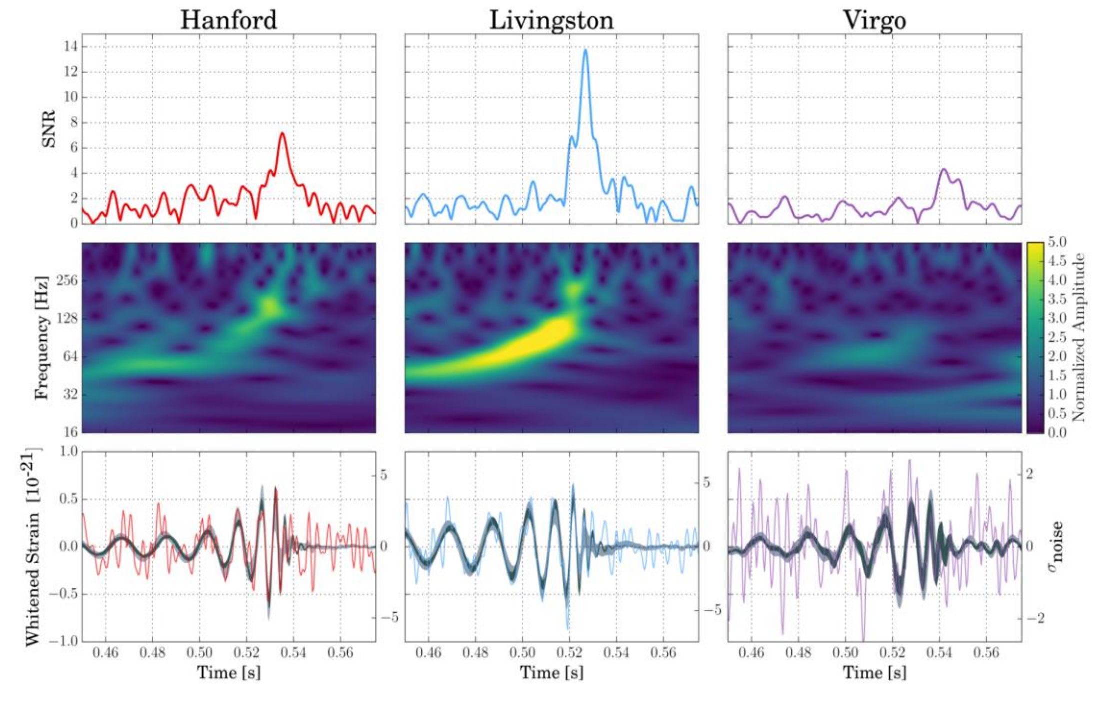
- The signals we look for are transient events of typical durations 0.5-100 seconds
  - The kind of waveform and duration are quite different according to the type of coalescence
    - BH-BH, BH-NS, NS-NS
    - function of their masses, possibly their spins
- Strategy for digging out a signal
  - h(t) is whitened
  - known noise subtracted
  - The signal is calibrated
  - the presence of waveforms looked for by matched filtering techniques (using known waveforms as signal templates)

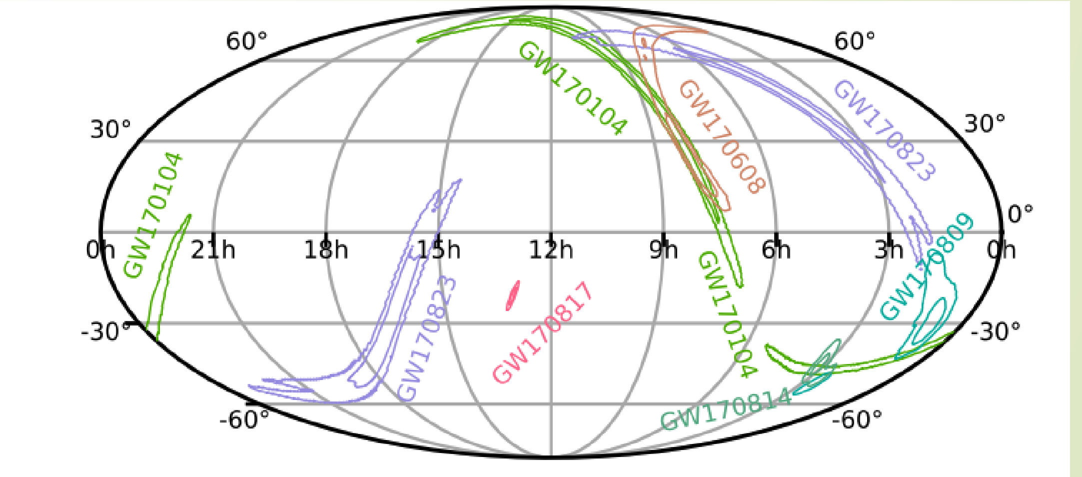


How? Data analysis (2/2)

- Use the coincidences of multiple detectors to drastically reduce local noise
  - Check if the same template waveforms is consistent with data across time-shifted h(t) from different detectors
  - Information from many places on earth also allows sky localization
- Several observations of CBC signals have been already made by LIGO-Virgo in the O2 (2016-2017) run
- More observations in O3 from the improved sensitivities of the detectors
  - A few papers on exceptional events already out

Example event GW170814

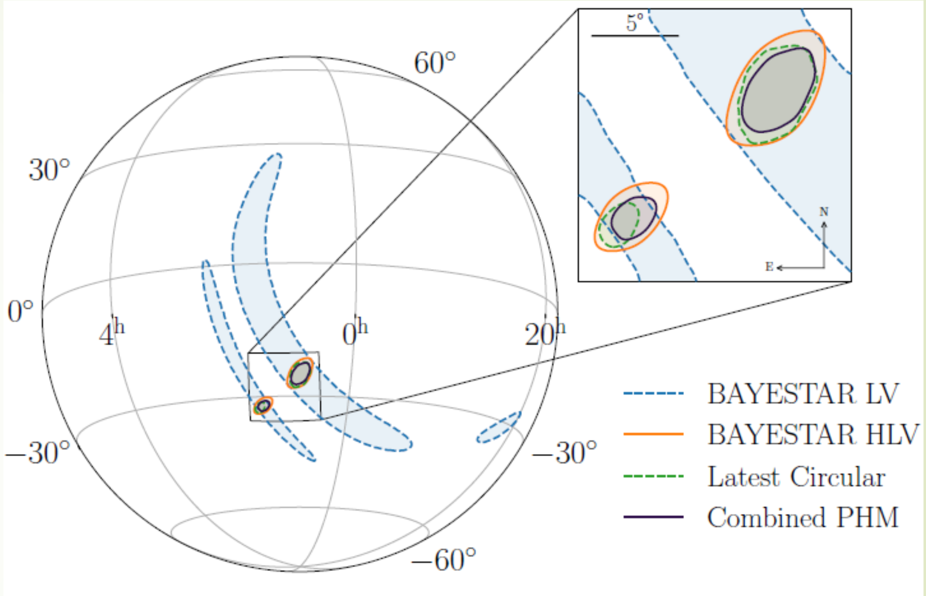




Online and offline data analysis(CBC)

- Analyses running « **online** » (low-latency, fast-response) for alerts
  - Three pipelines during O2
    - GstLAL, PyCBC from LIGO groups
    - MBTA from Virgo groups (LAPP, Urbino)
  - Essential for multi-messenger astronomy

- Analyses running « **offline** » for publications
  - Use of the official final data calibration
  - Use updated data-quality vetoes
  - Refined monitoring of efficiency and fake rate
  - Better determination of the parameters
  - Only two pipelines during O2
    - Only the LIGO ones



Example event GW190814

- GW signal (BH-? coalescence)
- Most asymmetric coalescence to date
- Spatial resolution: 18.5 deg^2

Who?

- Analysis-wise, the LIGO and Virgo collaboration(s) (LVC) work together
- The data stream is accessible for analysis to any of the groups belonging to the LVC
  - I.e. Virgo data are accessible to scientific groups belonging to LIGO, and vice-versa
- Meetings to present and discuss the results, as well as to plan publications and dedicated studies, are common

- The IP2I group has entered recently (2019) the Virgo collaboration and is contributing to the LVC CBC analysis via the Multi-Band Template Analysis (MBTA)
  - Two persons full time to analysis, previous experience from high energy physics
  - One student recently joined
  - Work in collaboration with members from groups in Annecy, Strasbourg, Urbino
  - This group also participates to the characterization of the detector and monitoring of the quality of the data (in collaboration with EGO/LAL)

Analysis timeline and activities

- Main current aim: port the MBTA pipeline offline for the search of CBC signals
  - Participate to the analyses (and subsequent papers) of the O3 observation run (2019-2020)
  - First Virgo analysis on offline detection of coalescent binaries
- Task is not straightforward: many new challenges for offline…
  - Handle massive runs and test performance on simulation before looking at the data
- …but also opportunities
  - No tight latency constraints, may loosen thresholds to increase in acceptance w.r.t. the online version, use more background time to reach lower fake rate values for significant events,…
- A lot has happened since last year
  - Analysis ported and running at the French CCIN2P3
    - Tuning of parameters, configuration, analysis flow and strategy
    - Systematic characterization of the analysis on simulation, comparison with other groups
    - Successfully run over all the O3 data
  - Work now ongoing for the interpretation of the results
  - Group integrated in the LVC CBC community; regular reports ongoing

Multi-Band Template Analysis

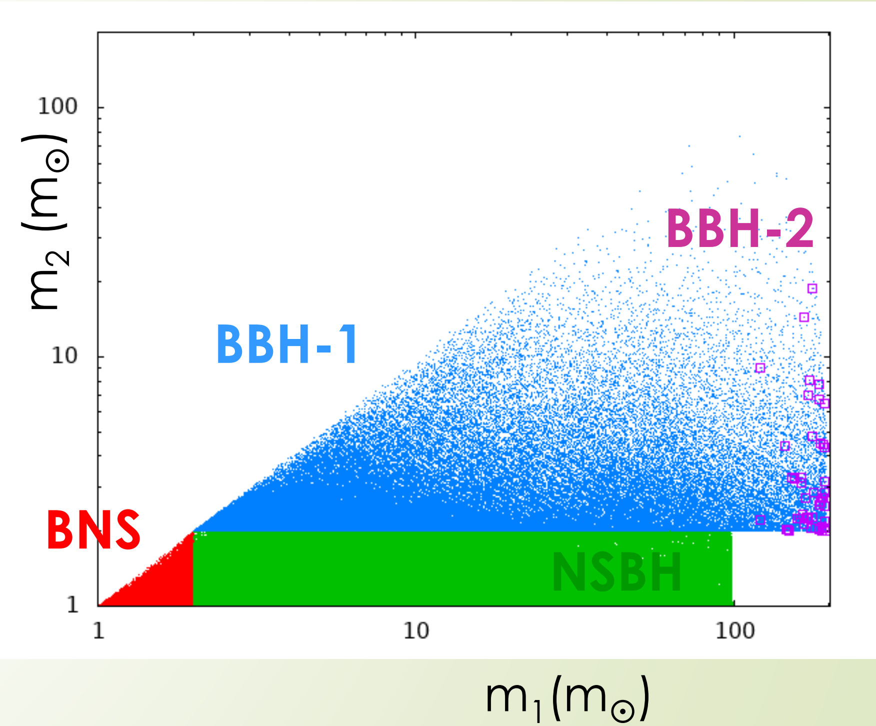
- Novelty: use several matched filters to extract the GW signal from the data by a split in the frequency domain
  - Split across two (or more) frequency bands

$$S(t,M) = \int_{f\,min}^{f\,max} h(f)T(M,f)df = \int_{f\,min}^{fc} h(f)T(M,f)df + \int_{fc}^{f\,max} h(f)T(M,f)df$$

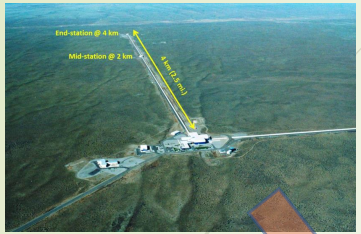
- Bands chosen so to ~equally share the signal-to-noise ratio (SNR)
  - Each band is analyzed independently, and the results are then combined coherently
- Reduce computational costs, with ~no loss in SNR wrt single-band analyses
  - Less number of templates needed, the size of the FFT is reduced

Multi-Band Template Analysis

- The filtering is done by testing a huge number of signal templates from known astrophysical sources (NS-NS, BH-NS, BH-BH)
- Template banks:
  - BNS: 26170 templates
  - BHNS: 522934 templates
  - BBH: 169427(standard)+9000(ungated) templates
- The searches are performed independently
- Results put together a posteriori
  - Computationally very intense



Multi-Band Template Analysis



Data pre-processing
- Frequency filtering
- Adding injections
- Gating channels

$h'_j(t)$

MBTA filtering
- Low+high frequency
- Corrections to data
- Background determination
- Build coincidences
- Clustering

Single triggers

Coincidences

FAR

$h'_j(t)$+injections

MBTA filtering
- Low+high frequency
- Corrections to data
- Build coincidences
- Clustering

Single triggers

Coincidences

Final analysis, interpretation

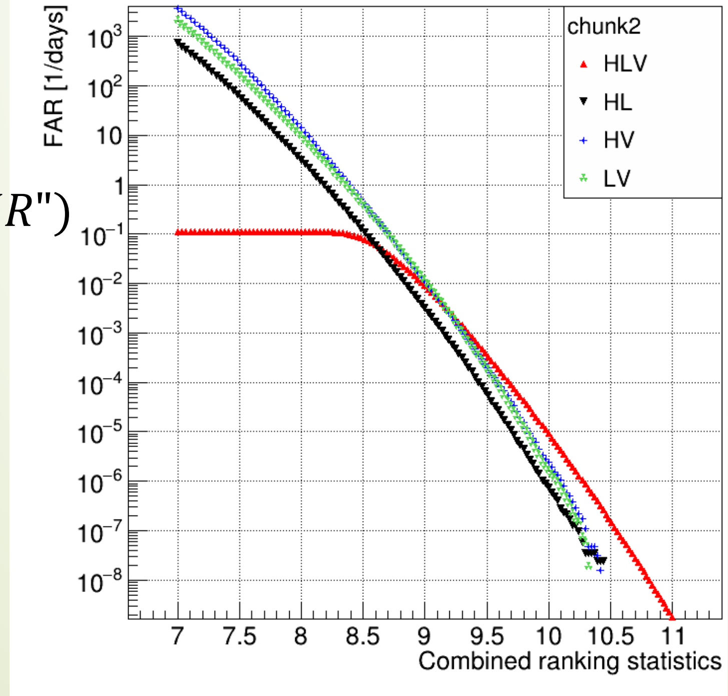
Plots
Tables
Web pages
Presentations

- Full chains running at the CCIN2P3
  - 1 year of data taking analyzed
  - 60K injections/week analyzed in parallel

Background determination by using the data

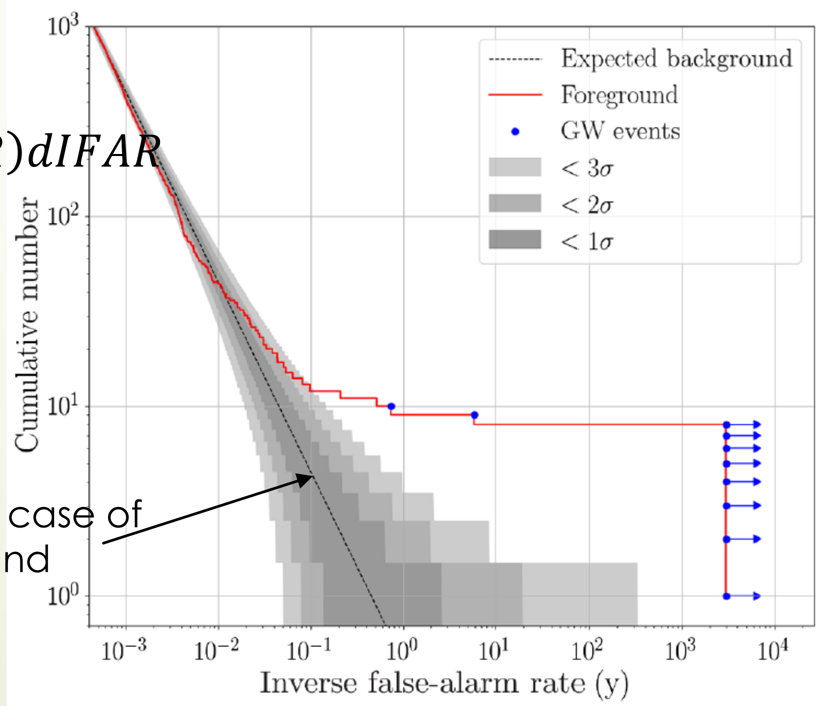
- In order to determine the fake rate (FAR), the probability of getting an accidental coincidence between two (or three) detectors above a certain SNR threshold is determined by using single trigger information
  - They are overwhelmingly dominated by background, but real signals can be subtracted
  - Combinatorial approach: count the rate of random combinations of single triggers from the same template and coming from two (or three) different detectors which gives rise to a combined SNR larger than a threshold
- Real astrophysical signals would appear as outliers in a cumulative FAR/IFAR plot

$FAR("SNR")$



$$\int_y^\infty n(IFAR)dIFAR$$

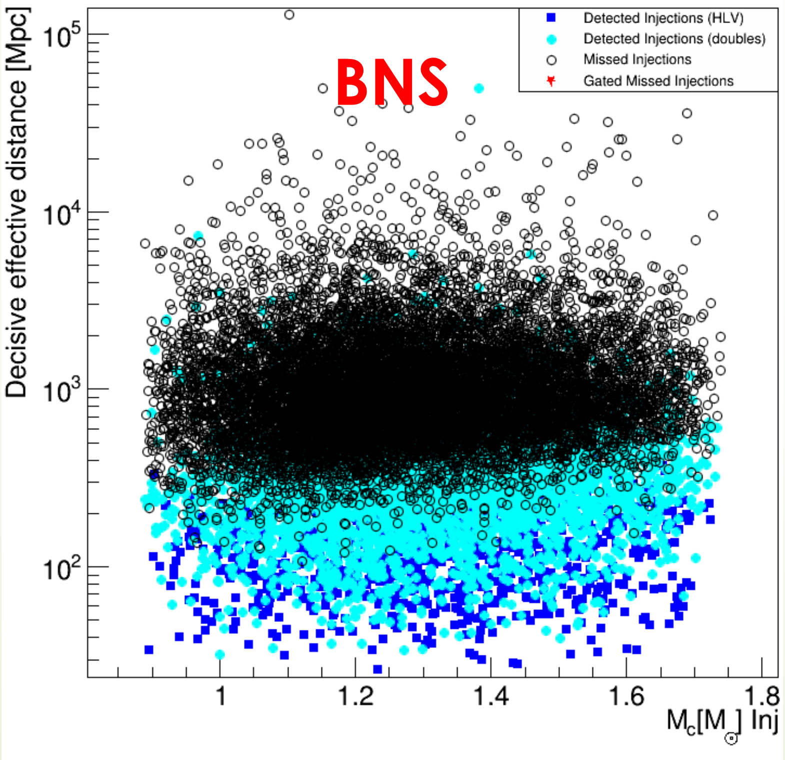
Expectation in case of only background

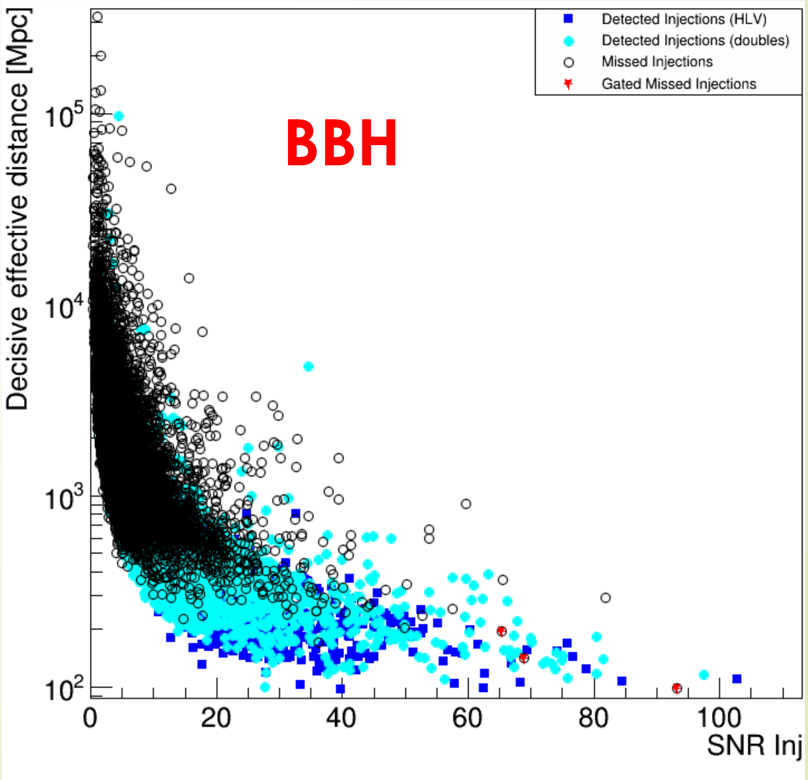


Performance on simulation (1/2)

- The detection chain is systematically tested on simulated "injections"
  - Known waveforms superimposed to background at known times
- The ability to detect them is investigated as a function of several parameters

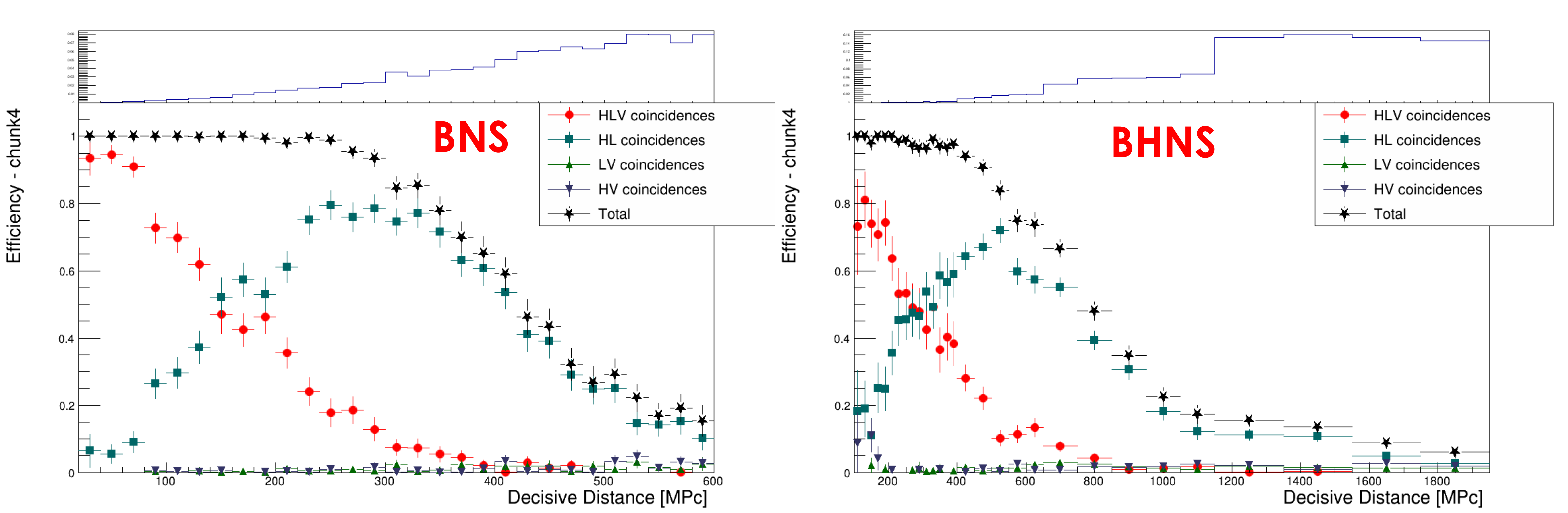
BNS:=[1 M⊙,2 M⊙]x [1 M⊙,2 M⊙]
BHNS:=[1 M⊙,2 M⊙]x [2 M⊙,100 M⊙]
BBH:=[2 M⊙,200 M⊙]x [2 M⊙,200 M⊙]





Performance on simulation (2/2)

- The "hit and miss" plots are easily converted in efficiency figures
  - Needed to quantify performance
  - Presentable differentially in the interesting variable(s)



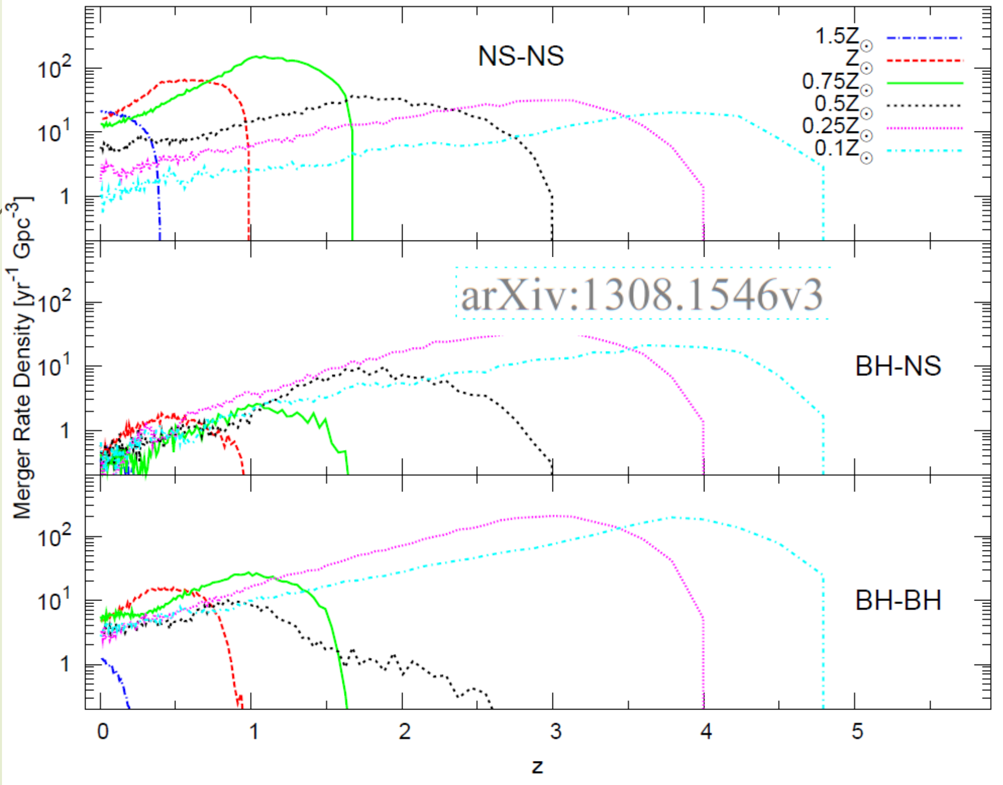
Stay tuned

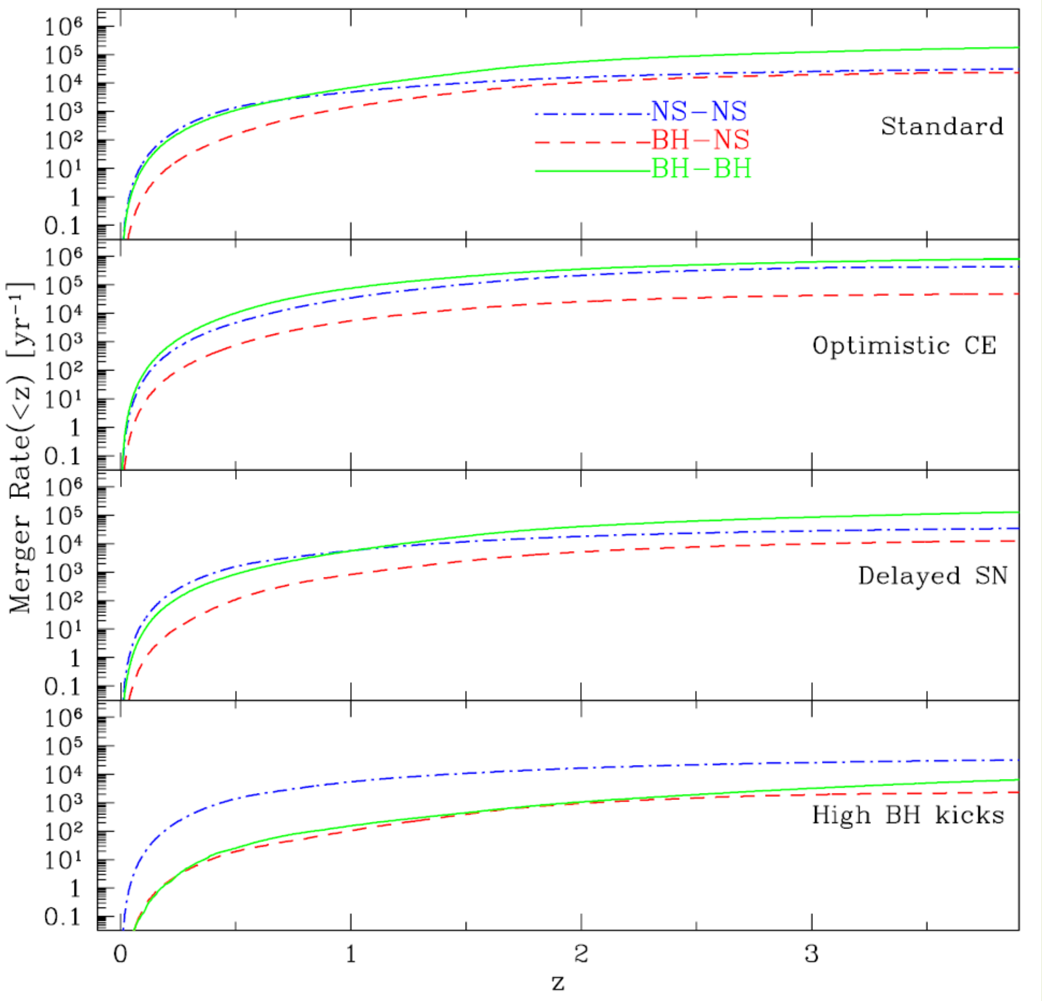
- New group at IP2I has joined the existing Virgo activities
  - 2 people, started 1.5 years ago
  - Now reinforced with one more student
- Mainly dedicated to LIGO-Virgo data analysis
- Well on track to participate to O3 data analysis for CBC searches
  - We are regularly presenting our results on candidates in O3 data
  - Participate to the O3 catalog papers, possibly on rates and population papers
  - Contribute to other papers on exceptional events (if any ☺)
- Busy and exciting times, stay tuned…

Backup

Predicted rates

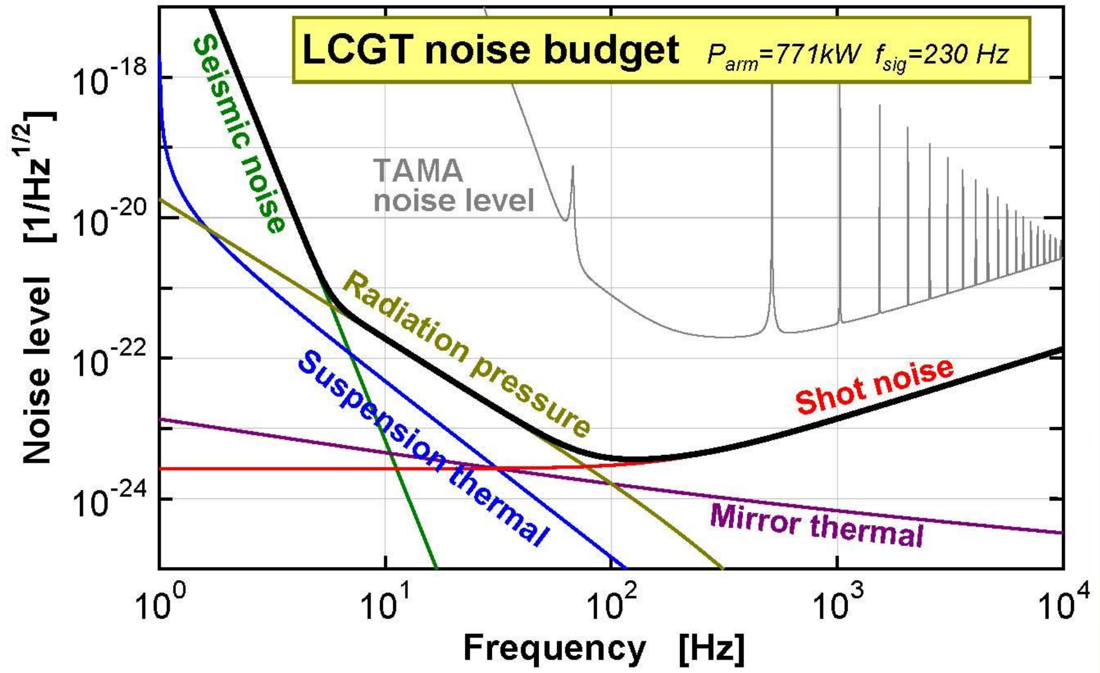
- Study merger event rates as a function of redshift and metallicity, in several binary evolution scenarios. Results from arXiv:1308.1546v3

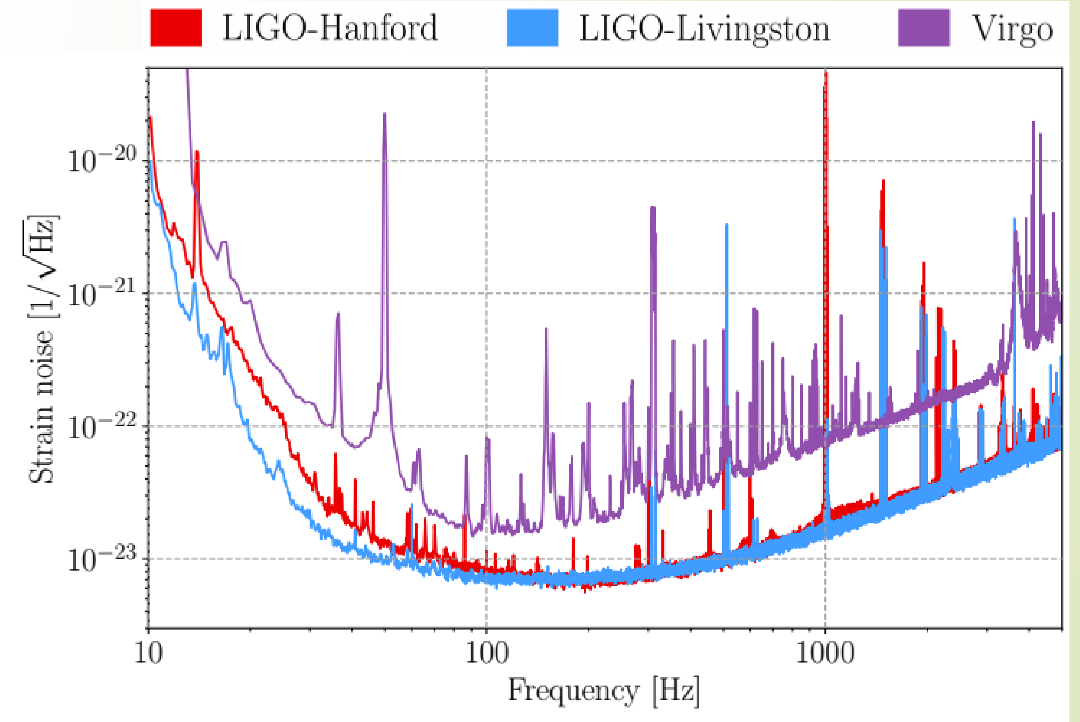




Noise profile

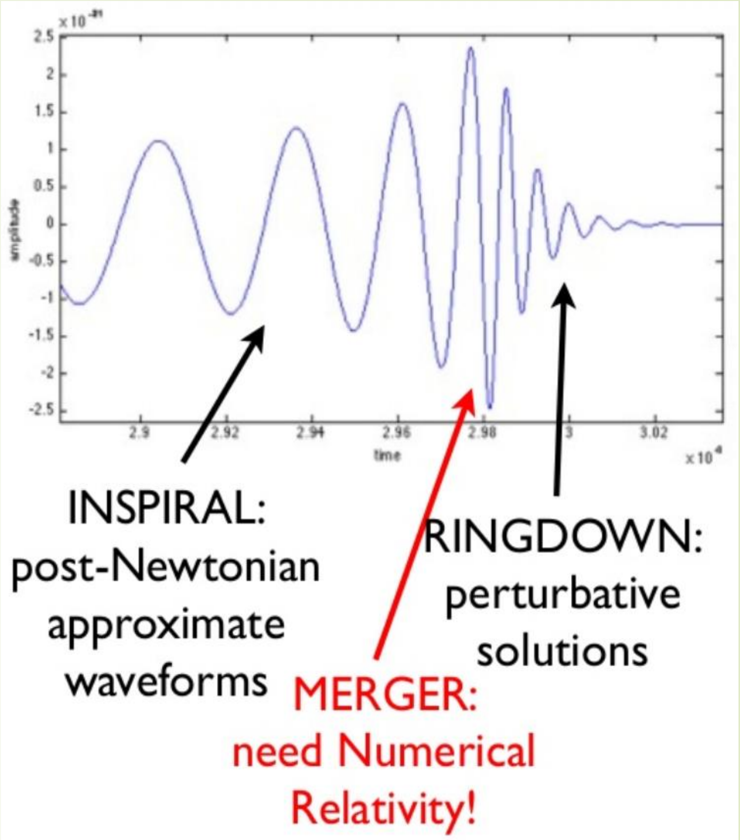
- At low frequencies dominated by seismic noise
- At high frequency we lose sensitivity because of the limited arm length, making the shot noise from individual photons become the dominant noise source
- Typical sensitivity to CBC signals in the 10-1000 Hz regime





Waveforms basics

- Typical frequency scales with 1/M
- For massive systems (>50 $M_\odot$) merger and ringdown features may contribute significantly to the signal SNR
- Spins, as well as matter effects, may add complications
- The number of parameters to describe a CBC waveform, $\boldsymbol{\theta}$, is large
  - Coalescence time and phase
  - Masses m1 and m2
  - Distance (=amplitude of the signal)
  - Spins s1 and s2
  - Sky position (RA and dec (α and δ), for instance)
  - Inclination of the orbiting plane (ι and ψ: inclination and orientation)
  - Eccentricity (typically small $\rightarrow$ neglected)
  - Matter distribution and parameters of the EOS (irrelevant for a search)



$$h(t;\boldsymbol{\theta}) = F_+(\alpha,\delta,\psi;t)\,h_+(t;\boldsymbol{\theta}) + F_\times(\alpha,\delta,\psi;t)\,h_\times(t;\boldsymbol{\theta})$$

Directional sensitivities of the interferometers

Strains from the GW

$$h(t;\boldsymbol{\theta}) = A(t;\boldsymbol{\theta})\cos\Phi(t;\boldsymbol{\theta}) = -\left(\frac{G\mathcal{M}}{c^2 r_{\rm eff}}\right)\left(\frac{5G}{c^3}\frac{\mathcal{M}}{t_c - t}\right)^{1/4}\cos\Phi(t;\boldsymbol{\theta})$$

Chirp mass

pN-corrected GW phase

$$r_{\rm eff} := r\left[F_+^2(\alpha,\delta,\psi)\left(\frac{1+\cos^2\iota}{2}\right)^2 + F_\times^2(\alpha,\delta,\psi)\cos^2\iota\right]^{-1/2}$$

Effective distance: a degenerate parameter encoding several ones