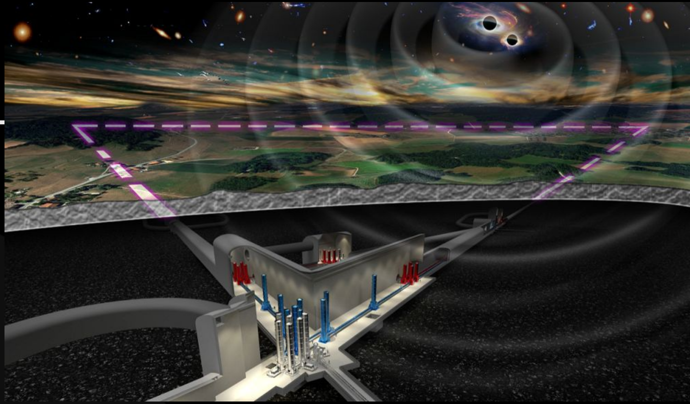
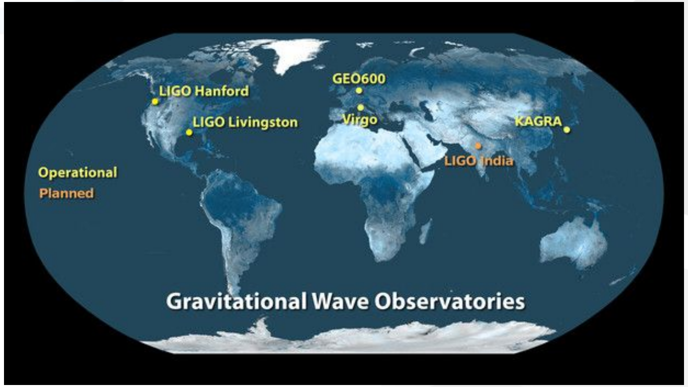
Einstein Telescope: a 3rd-generation gravitational-wave detector

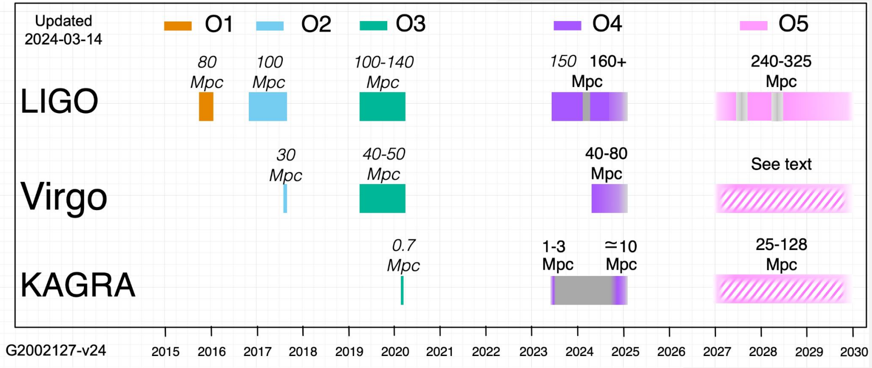


6th Univers du pôle A2C, 21 June 2024

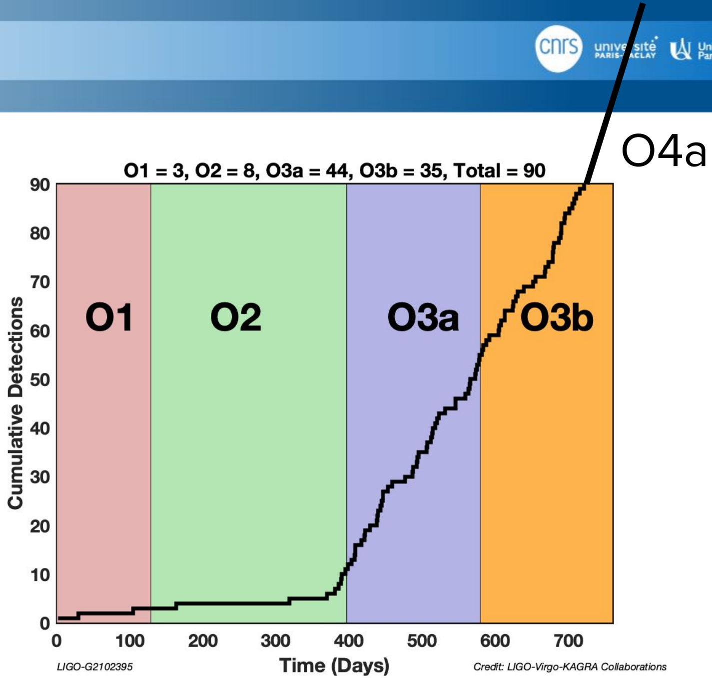
Adrian Macquet - GW group

GW astronomy today



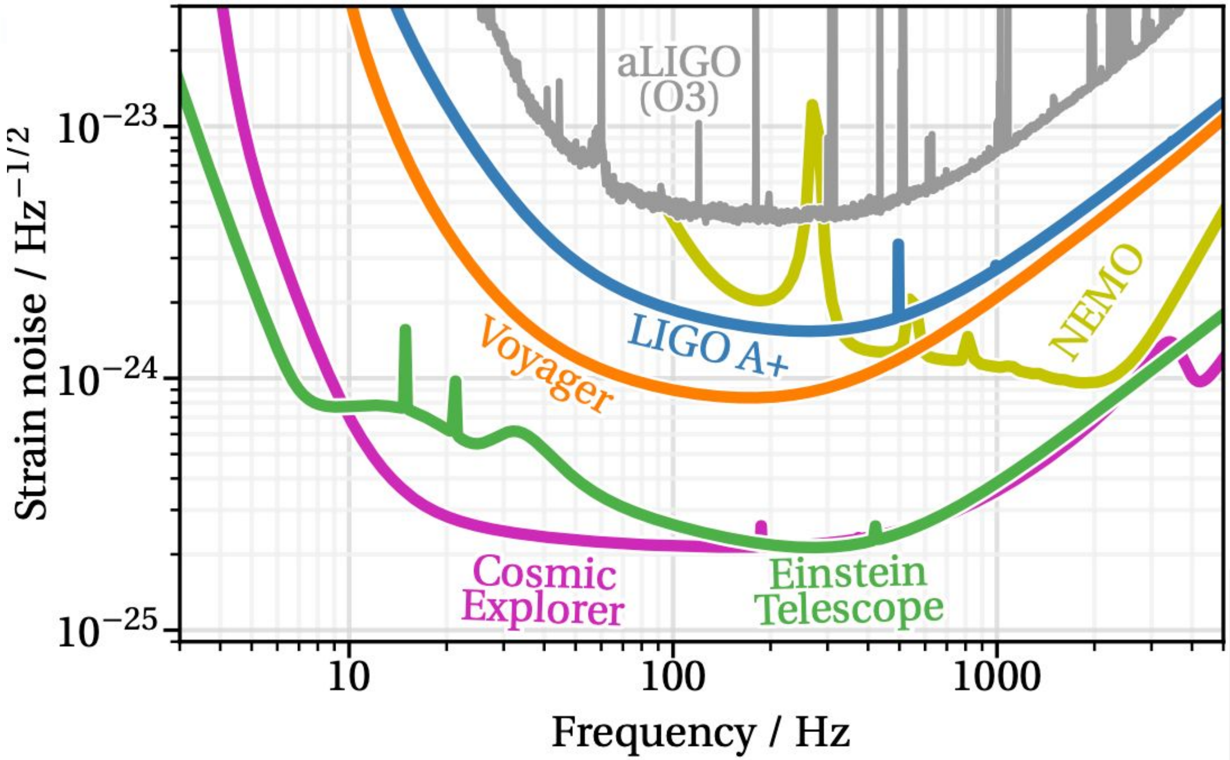


Credit: LVK



- ➔ 2024: ~200 detections (90 published from O1+O2+O3 and ~100 public alerts in O4).
- ➔ All from CBC sources.

3rd generation GW detectors



Sensitivity of different GW detectors (credit: Cosmic Explorer)

Einstein Telescope / Cosmic Explorer (CE)

➔ ~10 times more sensitive.

➔ Sensitive to lower frequencies (o(1 Hz)).

Science goals of ET

GW detectors sensitive to the amplitude -> detection volume x 1000.

Properties of compact objects

- ➔ Tighter constraints on population properties and evolution vs redshift (up to z=20)
- ➔ Lower frequencies: higher masses (IMBH)
- ➔ Tests of GR.

Multi-messenger astronomy

- BNS post-merger
- Core-collapse supernovae
- Magnetar flares / Fast radio bursts.

➔ Properties and phenomenology of NS.

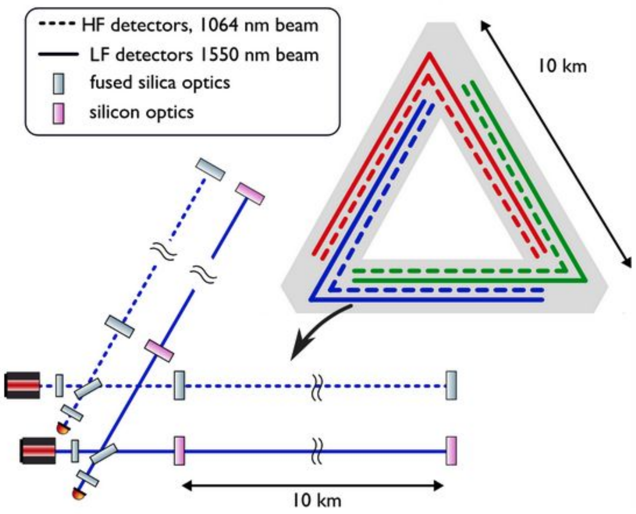
Stochastic GW background

- Astrophysical + cosmological component.
- Constrain cosmological models and scenarios.
- Window of observation before CMB.

Design of ET

Dual-recycled Fabry-Perot-Michelson interferometers

- **Longer arms (>= 10 km).**
- **Underground (~100m).**
  - ➢ Mitigation of seismic noise.
- **2 sets of detector (xylophone):**
  - ➢ HF: high laser power.
  - ➢ LF: cryogenic.
- **Triangular configuration.**
  - ➢ Good sky coverage.
  - ➢ Null stream.

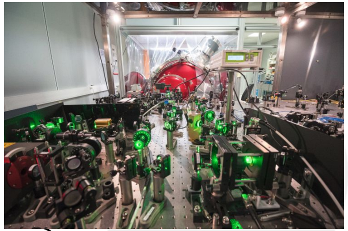


Schematic optical layout of ET (credit: Rowlinson et al., Phys. Rev. D 103, 023004 (2021))

<u>Current design:</u> 6 V-shaped nested interferometers forming an equilateral triangle.

ET activities @ IJCLab in a nutshell

Instrumental activities

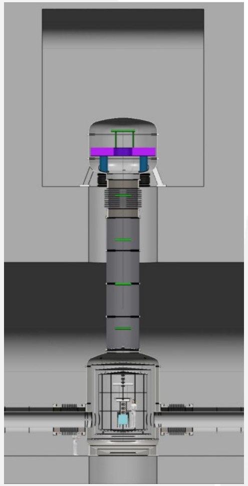


- Optics : squeezing
  ⇒ squeezing source @ 1064 nm
  ⇒ filtering cavities for LF and HF
  } tests on CALVA
  ⇒ pyGWINC (simulation code)

- Interferometer
  ⇒ noise characterization

- Vacuum and Cryogenics (mechanical workshop)
  ⇒ design of vacuum towers with EGO
  ⇒ design of cryostat with KIT

  (MAVERICS team)
  ⇒ mirror surface in-situ characterization and cleaning



Observational Science activities

- Mock Data Challenge (MDC)
- Multi-messenger follow-up (in particular for GRBs)
- Predictions for supernovae
- Synergies with LISA and 2G detectors
- Test of General Relativity (theory group)

General activities

- Computational infrastructure (IT group)
- Sustainability
- Project office (organization)

Data analysis challenges

- LVK: ~1 CBC signal per day (O5).
- ET: ~1 signal per minute.

Much more signals in the data -> analyses need to cope with that.

➔ Overlapping signals: disentanglement and Parameter Estimation (PE).

➔ CBC foreground mask other sources (stochastic background / other transients).

➔ Computational cost: PE is expensive

  ➢ Need rapid PE for EM follow-up (chirp mass and sky position).

ET Mock Data Challenge

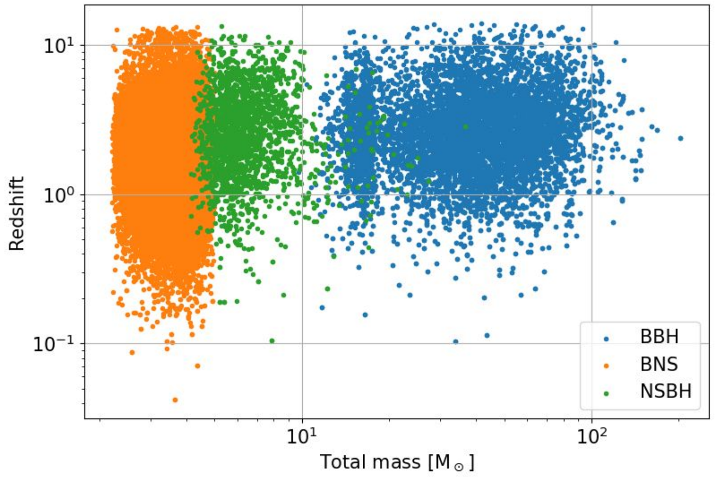
Dataset simulating ET data (expected noise + realistic signal distribution)

Goal: test data analysis techniques and study signal recovery.

- ➢ Validate science objectives.
- ➢ Anticipate potential issues.

Current MDC (T. Regimbau et al.):

- 1 month of data.
- Gaussian noise at ET design sensitivity.
- CBC distribution from most recent population models (~70000 signals).



Distribution of signals in ET MDC

Searches for Compact Binary Coalescences (CBC)

Modeled searches (matched filtering):

- Optimal detection statistic.
- Well-suited for CBCs.

- Computationally expensive.
- Sensitive to errors in the waveform.
- Parameter space dependant on the template bank.

Unmodeled searches (excess of power):

- Sub-optimal.
- Suited for weakly modelled signals.

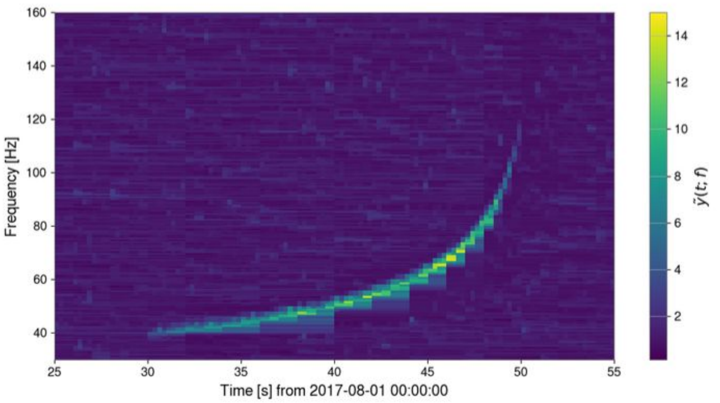
- Computationally cheaper.
- Sensitive to a wide variety of signals.

Can we use an unmodelled search to search for CBC signals in ET?

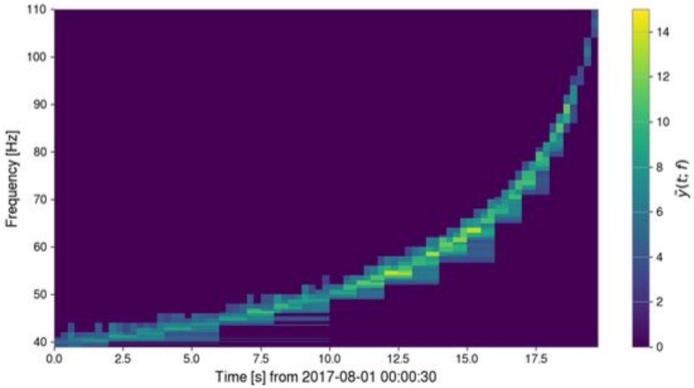
Search method

<u>Unmodelled search:</u> look for generic excess of power in detectors' data.

- Time-frequency representation.
- Pattern recognition algorithm.
- Cross-correlation between several detectors



TF-representation of the data



Extracted signal

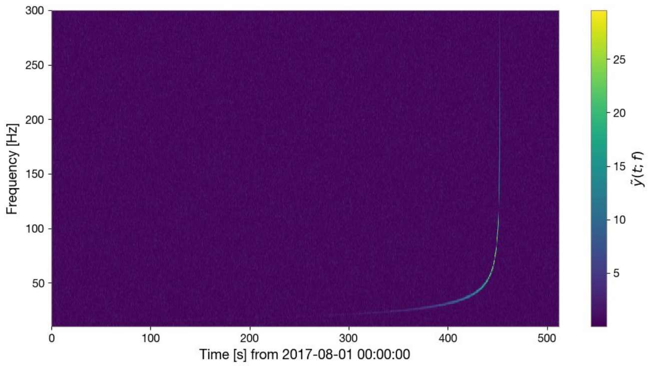
Estimation of the chirp mass

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

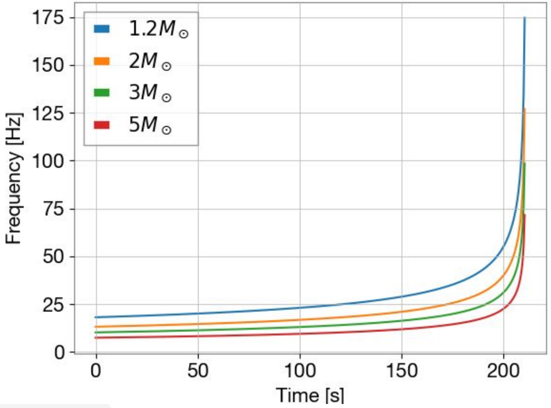
- Primary parameter of the waveform (controls amplitude and frequency evolution).
- Proxy for the total mass -> nature of compact object and potential EM counterpart.

➔ Compute time-frequency templates depending only Mc.

➔ Fit templates onto spectrogram and keep highest SNR.

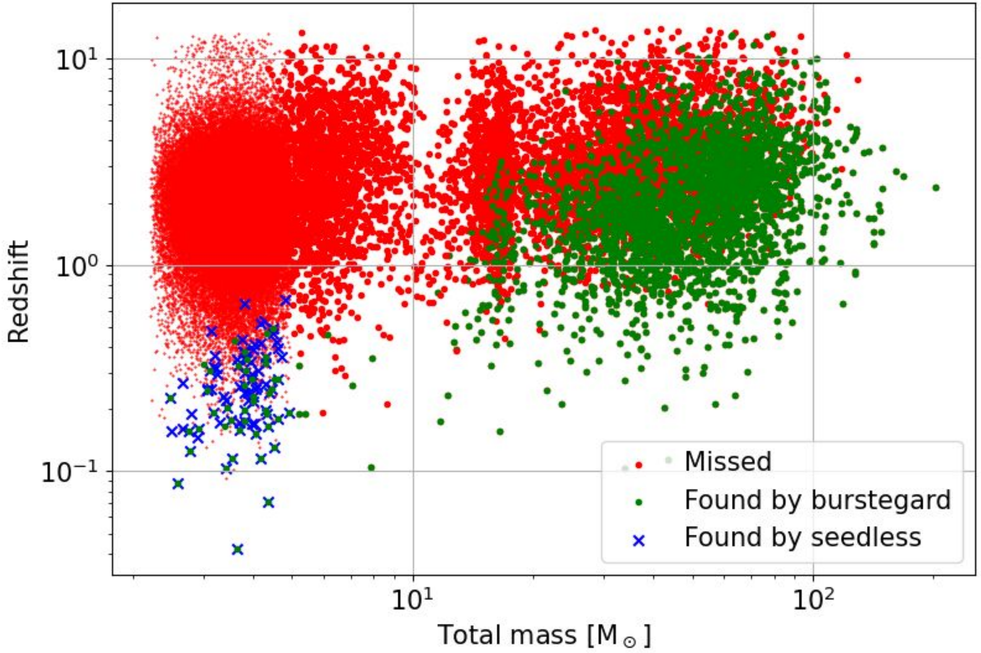


Spectrogram containing a loud BNS signal



Examples of templates fitted on the spectrogram

Results: detection of CBC

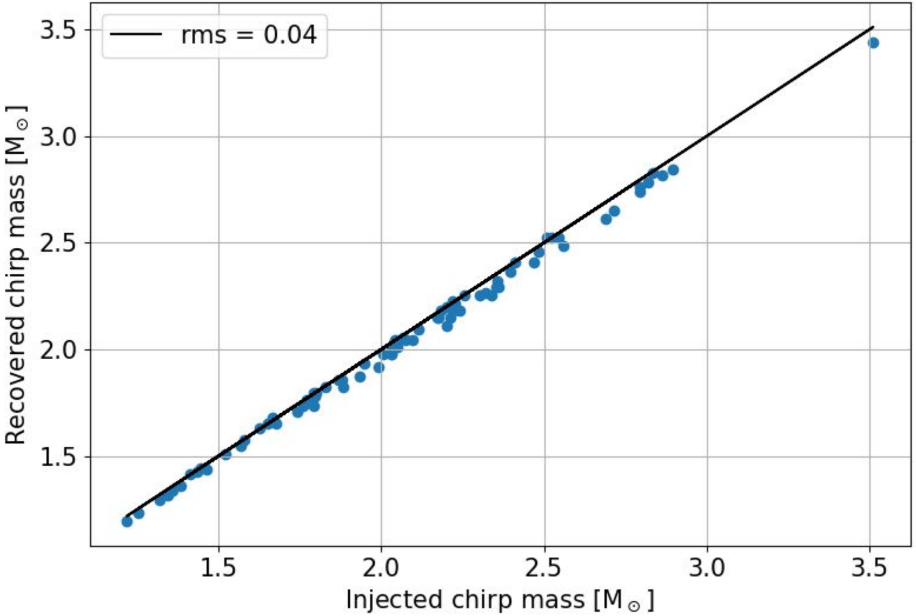


Detected vs missed signals in the MDC

- 38% of BBH recovered
  - 88% for M > 100 solar masses
- 70 BNS recovered
  - 2.6 per days.

➔ **Not as efficient as dedicated CBC searches but still sensitive (especially for large masses).**

Results: estimation of the chirp mass

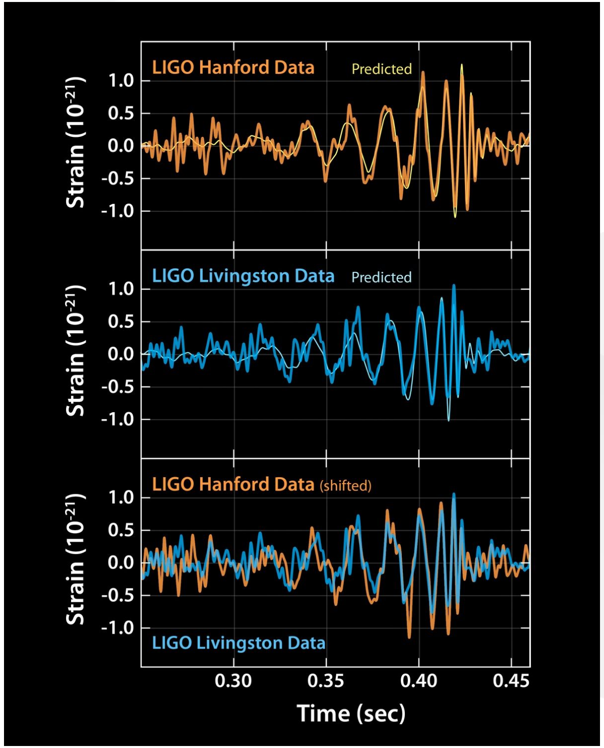


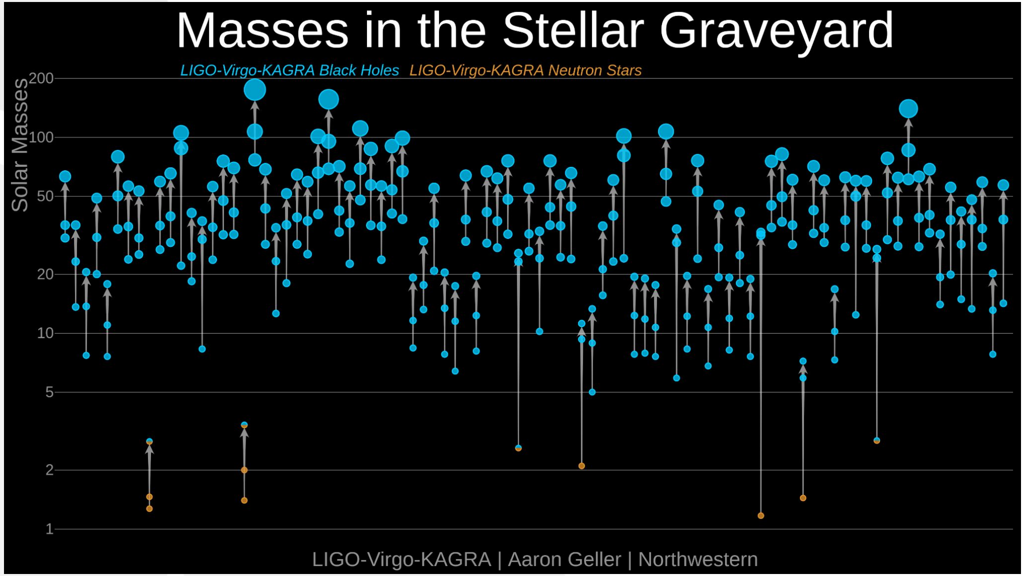
- ➔ Chirp mass (detector frame) well estimated for all detected BNS (rms error 1.4%).
- ➔ Fast analysis (~10s per 500s of data).
- ➔ Fast estimation of the chirp mass useful for MM astronomy (early warnings to EM observatories).

Conclusion

- ET will be ~10x more sensitive than Advanced LIGO/Virgo.
  - ➢ Huge potential for astrophysics, cosmology, NS physics, tests of GR…
- Many instrumental challenges to overcome in next decade.
  - ➢ IJCLab involved in squeezing, vacuum + leadership.
- Much more signals in the data: data analysis techniques have to be adapted.
  - ➢ "Burst" searches could be used for CBC detection and fast PE of the chirp mass.
  - ➢ Complementary to matched-filtering based searches.

<u>Next steps:</u> tests on more realistic MDCs (non-Gaussian noise, calibration errors, non-CBC sources…).


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern