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# Searching for Compact Object Collisions with Latencies of Seconds

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## Compact Object Mergers

- Orbiting bodies lose energy to gravitational radiation.
- For most of the system's evolution the radiated wave has simple, easily modelled, structure.
- For compact objects (black holes, neutron stars), orbital speeds get close to c.
- Near merger, size and deformability of objects becomes significant, dynamics of spacetime, too.







#### Compact Object Mergers as Laboratory

- GWs are created by the movement of mass and momentum, not electric charges and currents.
- Essentially all intervening material between us and the source will be transparent to the GWs.
- They carry substantially different information about their sources than electro-magnetic (EM) radiation and carry that information from regions of the sources invisible with other energy forms.
- ► GWs provide the promise of exposing the dynamics of the central engines of GRBs and other high-energy astrophysical phenomena





#### Compact Object Mergers as Laboratory

- ▶ General relativity (GR) only tested in weak-field limit
- Strong-field regime appears inaccessible to laboratory experiments
- The universe is a dynamic place, and cataclysmic events regularly occur in which spacetime curvature is driven into the strong-field regime.
- GWs provide the promise of the first experimental probe of strong-field gravity.
- Is GR the correct theory of gravity in the strong-field regime?
- What is the most stable form of matter at very high densities?







# NS-NS Mergers – EM Radiation

Following the merger:

- ▶ Rapid accretion 1 s → collimated relativistic jet (SGRB).
- Optical after-glow from interaction of jet with surrounding medium (red) observable ~days-weeks with θ<sub>obs</sub> < 2θ<sub>jet</sub>.
- ▶ Jet decelerates → isotropic radio afterglow ~weeks-months, and years.
- r-process "kilonova": isotropic optical emission lasting few days (yellow).







- GW antennas are mostly omni-directional (and, in any case, generally cannot be steered).
- GW antenna data rates are sufficiently low that a continuous archive can be kept indefinitely.
- Therefore, GW antennas do not impose pressure on analysis timescale (can be done when convenient, when we're happy with it, etc.)
- Generally not true for EM telescopes: directional and/or data rates are too high to retain continuous archive indefinitely.
- Creates a time pressure:
  - Small amounts of data can be archived from omni-directional telescopes for later analysis, if it can be identified before being discarded from the ring buffer.
  - Directional telescopes need to be pointed at regions of the sky of greater interest before the flash fades away.





- The success rate for simultaneous GW-EM detections remains unknown.
- But the facilities exist, the marginal cost of trying is microscopic, and the knowledge to be gained from success is potentially very high.
- ► The ultimate timescale would seem to be the GRB jet timescale of O(1 s).
- Reducing the latency of GW analysis would seem to be scientifically beneficial until it is reduced as small as that.
- History of GW compact object search latency
  - LIGO S1: O(years) (offline only).
  - LIGO/Virgo S5/VSR1: O(months) (offline only).
  - LIGO/Virgo S6/VSR3: O(1 h). See LSC and Virgo, A&A 541, A155 (2012), arXiv:1112.6005.

Currently: O(100 s).







- MBTA latency in S6/VSR3. From LSC and Virgo, A&A 541, A155 (2012), arXiv:1112.6005.
- Does not include 20 min to 40 min of manual follow-up.





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• MBTA latency in ER7 (mode is  $\sim$  65 s).







 GstLAL latency in ER7. Approximately 14 s is required for calibration, data distribution, and posting of alert.







▶ GstLAL latency in ER7 exhibiting data-dependent variation.

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## Latency Reduction Techniques

- Mostly an accidental side-effect of work done to accommodate template banks for second-generation antennas.
- Better sensitivity at low frequency  $\rightarrow$  longer templates.
- ► Longer templates → better orbital frequency resolution → more templates.
- ► Low-mass LIGO template banks increase from O(10<sup>4</sup>) templates of 45 s to O(10<sup>6</sup>) templates of 1800 s.
- Virgo spectrum was shallower than LIGO's so Advanced Virgo's increase is less dramatic.
- For initial Virgo, need to accommodate large template banks already led to development of MBTA. See Beauville, F. *et al.* 2008, Class. Quantum Grav., 25, 045001





## Latency Reduction Techniques

- Advanced LIGO led to development of GstLAL.
- Replace templates with linear combinations of template fragments, either frequency domain (MBTA) or time domain (GstLAL).
- Template bank rank reduction via lossy compression of fragments: Cannon *et al.*, Phys. Rev., D82:044025, 2010, arXiv:1005.0012
- Filtering cost reduction via composite detection: Cannon *et al.*, Phys. Rev., D83:084053, 2011, arXiv:1101.0584
- Latency reduced by overlapping FFTs or brute-force  $n^2$  convolutions.
- Causal significance measurement: Cannon *et al.*, Phys. Rev., D88:024025, 2013, arXiv:1209.0718; Cannon *et al.*, arXiv:1504.04632.





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Noise spectrum estimate for all instruments at time of candidate. Horizon distances (given the candidate's masses) and SNR densities will be indicated.







- Location of candidate with respect to noise model in SNR- $\chi^2$  plane (one plot per instrument).
- Note broken matplotlib installation on this computer (plot labels will be fixed for O1).





H1 Signal  $P(\chi^2 / \text{SNR}^2 | \text{SNR})$ 10<sup>0</sup> 10<sup>2</sup> 10<sup>1</sup> 10<sup>-1</sup> 10<sup>0</sup> 10<sup>-1</sup>  $\chi^2\,/{\rm SNR^2}$ 10-2 10-2 10<sup>-3</sup> 10-4 10-3 10-5 10-6 10-7 10-4 10<sup>1</sup> 10<sup>2</sup> SNR

 Location of candidate with respect to signal model in SNR-χ<sup>2</sup> plane (one plot per instrument).

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- False-alarm probability vs. ranking statistic in experiment to date.
- with candidate's ranking statistic value marked.





## Limitations

- Antenna health monitoring not fully automated, only preliminary data quality information is available.
  - False-alarm probabilities are still accurate, but sensitivity might suffer.
  - This is being actively improved: see Reed Essick's talk next.
- GstLAL template bank is whitened and compressed using static noise spectrum to define inner product.
  - Data are still whitened with adaptive spectrum, so SNR distribution is correct and stable.
  - Can quantify how poorly the compressed template bank approximates ideal template bank but have no plan for automating the response.
- Chicken-or-egg issues in the definition of the ranking statistic cause poor sensitivity for first O(week) of observing — require a warm-up following cold-starts.





#### The Future: Early Warning?



 Early warning detectability: event rate vs. amount of advance notice (2nd generation detectors).





# Conclusion

- Search latencies reduced enormously to O(100 s)
- Low latency compact object merger searches to be executed in O1 are modern, high-sensitivity pipelines.
- Two-site physical redundancy (GstLAL in North America, MBTA in Europe) assures high up-time.
- ► Two independently-developed pipelines provide cross validation.
- Latencies still 1.5 orders of magnitude higher than the shortest physical timescales of interest.





Bonus Slides











- Location of candidate with respect to noise model in SNR- $\chi^2$  plane (one plot per instrument).
- ► Note broken matplotlib installation on this computer (plot labels will be fixed for O1).







 Location of candidate with respect to signal model in SNR-χ<sup>2</sup> plane (one plot per instrument).







- ► False-alarm probability vs. ranking statistic in experiment to date.
- with candidate's ranking statistic value marked.