Searches for Gravitational Waves from Compact Binary Coalescences with LIGO and Virgo

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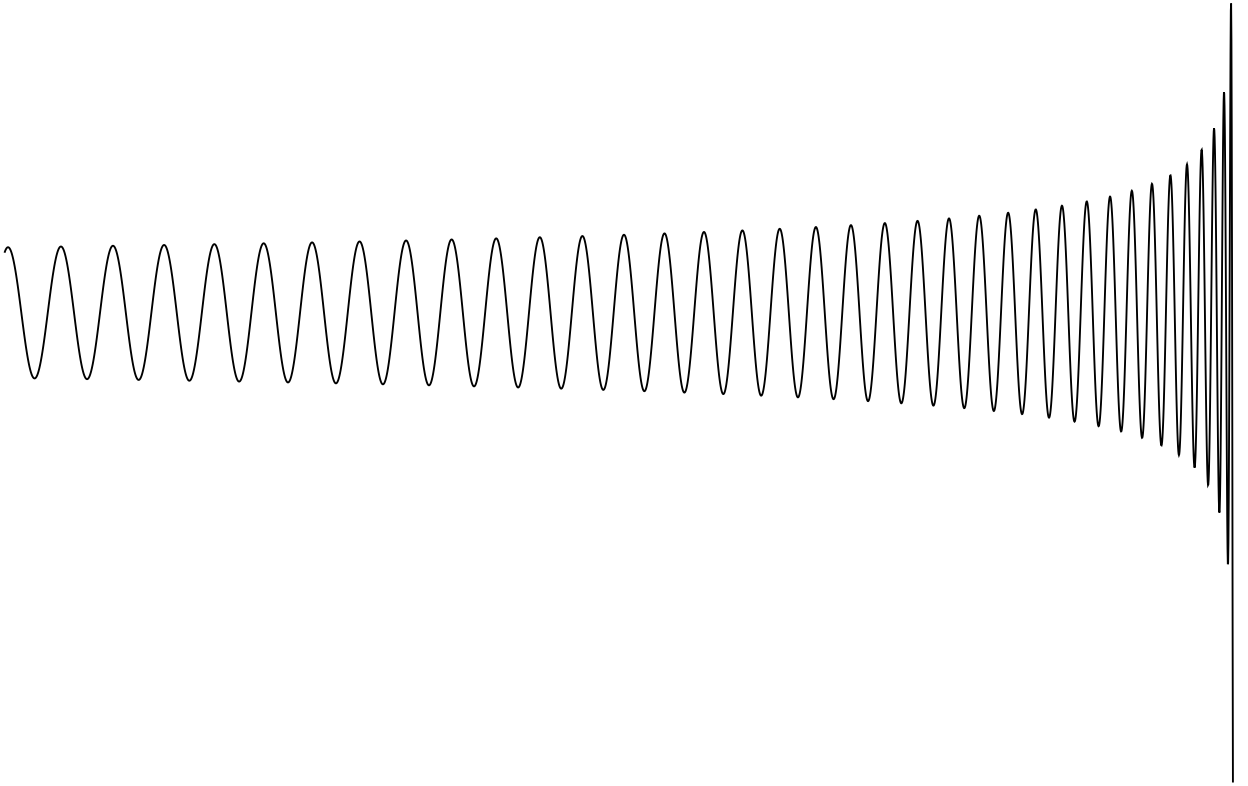
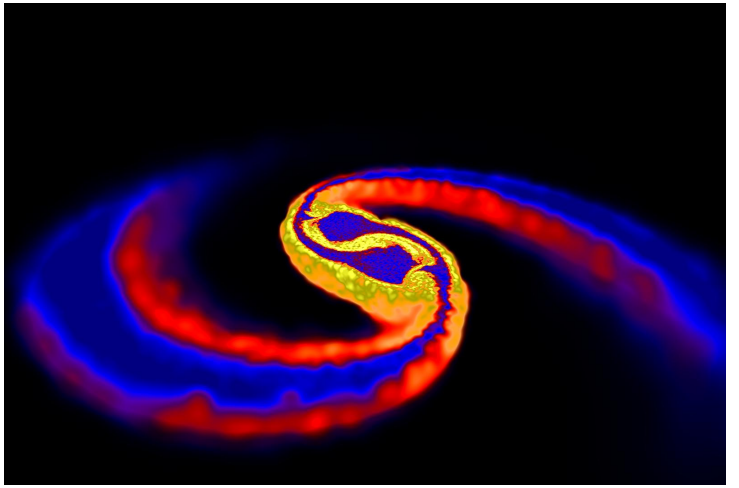
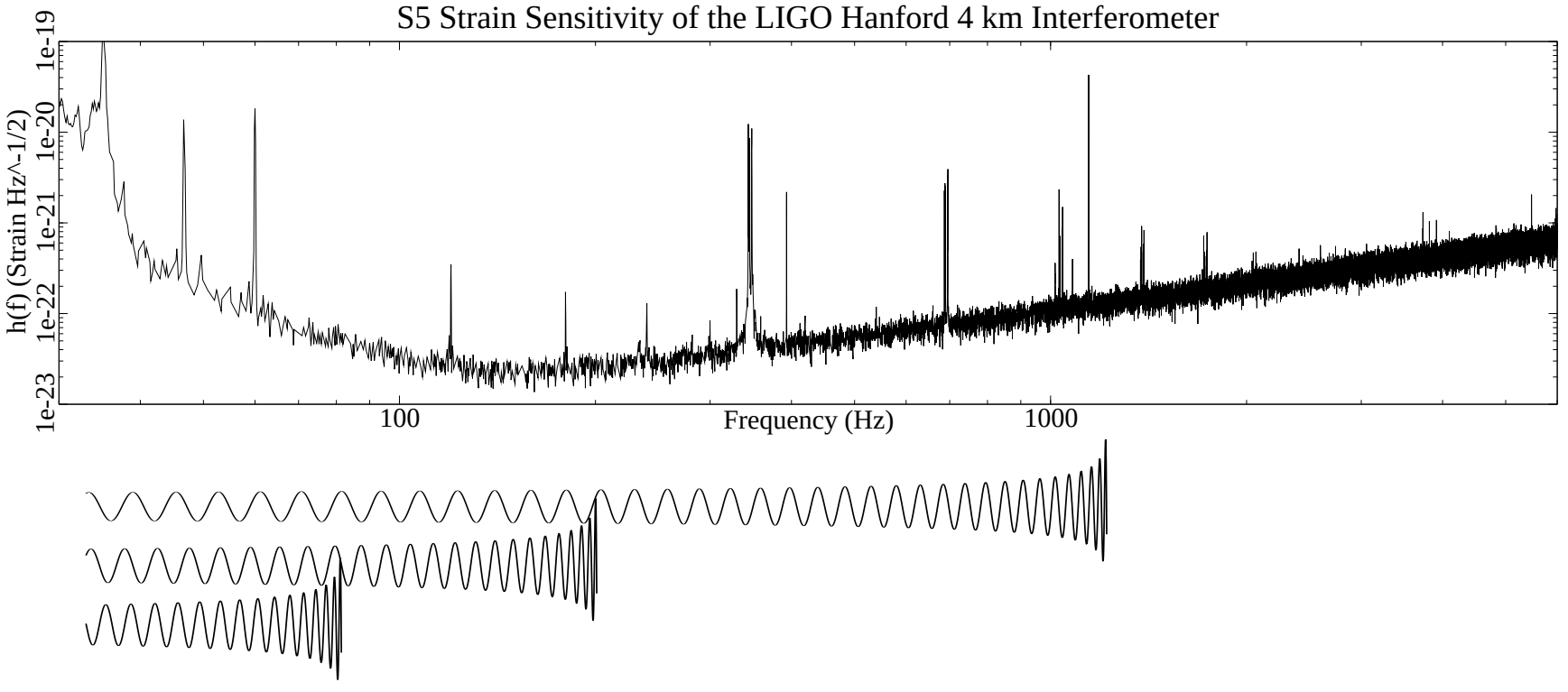
What the searches are targeting

- Binary systems of massive compact objects in close orbits: neutron stars (NS), black holes (BH), primordial black holes (PBH).
- Orbits decay by radiating energy as gravitational waves.
- Component objects eventually collide and merge.





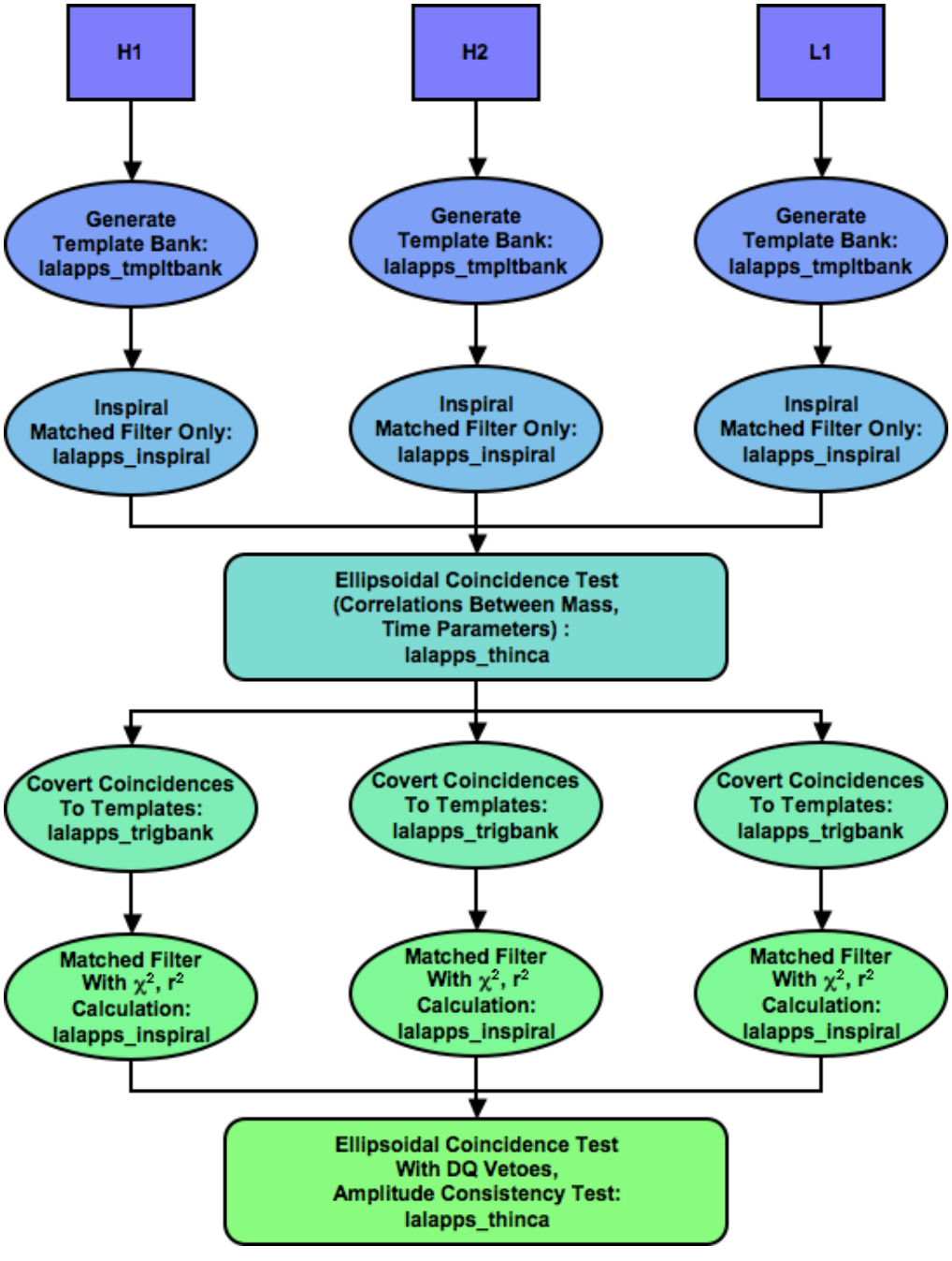
NS–NS merger. Credit: Daniel Price and Stephan Rosswog



- Initial LIGO and Virgo, etc., are sensitive to the last few tens of seconds or less of the gravitational wave signal before the merger.
- Classes:
  - low-mass systems, total mass $\in 2\,\mathrm{M}_\odot \ldots 35\,\mathrm{M}_\odot$, e.g., neutron star – neutron star, neutron star – black hole, black hole – black hole.
  - high-mass systems, total mass $\in 25\,\mathrm{M}_\odot \ldots 100\,\mathrm{M}_\odot$,
  - black-hole ring-downs, mass $\in \sim 85\,\mathrm{M}_\odot \ldots \sim 390\,\mathrm{M}_\odot$.

How the search is conducted

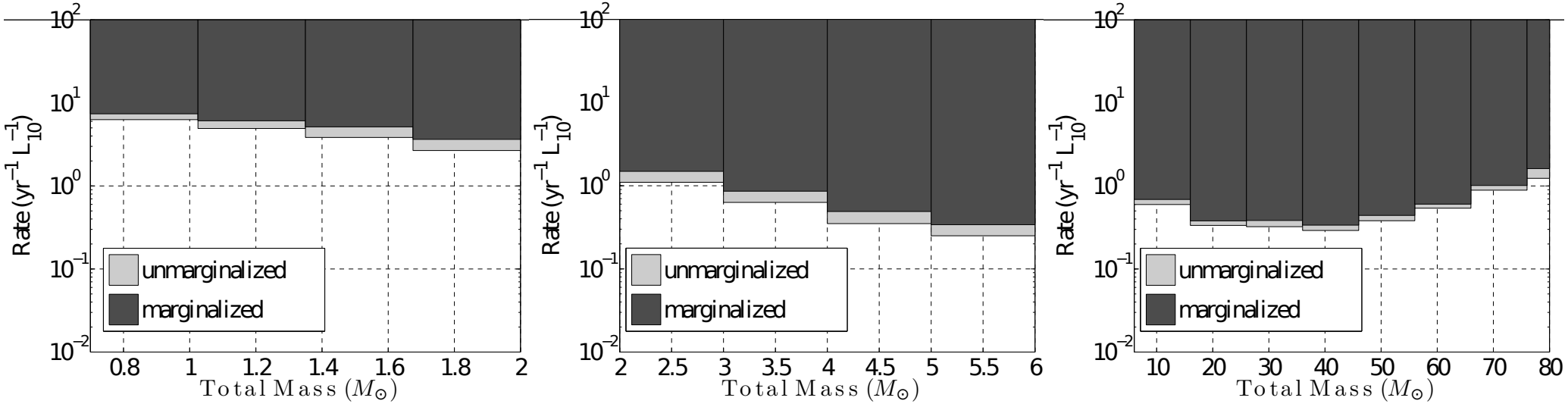
- A “template bank” of waveforms spanning the parameter space is constructed.
- Using a frequency-domain noise-weighted inner product, the strain output of each instrument is projected onto each of the template waveforms, yielding an SNR time series for each template.
- A thresholding and clustering algorithm is applied to each SNR time series, and a list of the template waveforms that matched the data above threshold and the times at which they matched is collected.
- Coincidence in time and waveform parameters is demanded across multiple instruments; subsets of the instruments are allowed in several combinations.
- Large time offsets are applied to the event lists prior to coincidence to estimate false-alarm rate.
- Simulated signals are added to the data streams in software to measure the detection efficiency.



Recent publications

Third and fourth science runs (S3 & S4)

- Six analyses: for each of S3 & S4: PBH/PBH (0.3–1 $\mathrm{M}_{\odot}$), NS/NS (1–3 $\mathrm{M}_{\odot}$), BH/BH (3–35 $\mathrm{M}_{\odot}$).
- Phys.Rev. D77:062002 (2008); arXiv:0704.3368.
- No detections; assuming binary systems with components whose masses are Gaussian distributed around $0.75\mathrm{M}_{\odot}$, $1.4\mathrm{M}_{\odot}$, and $5.0\mathrm{M}_{\odot}$ respectively, set 90% confidence event rate upper limits of $4.9\mathrm{a}^{-1}\mathrm{L}_{10}^{-1}$, $1.2\mathrm{a}^{-1}\mathrm{L}_{10}^{-1}$, and $0.5\,\mathrm{a}^{-1}\mathrm{L}_{10}^{-1}$ respectively ($\mathrm{L}_{10} = 10^{10} \times$ the blue light luminosity of the Sun)



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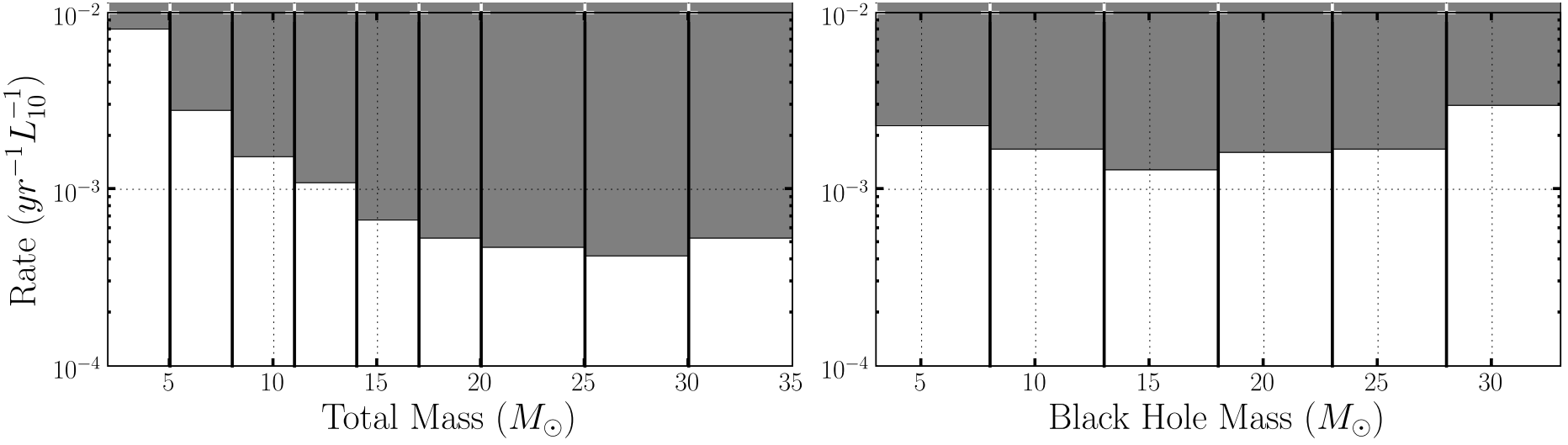
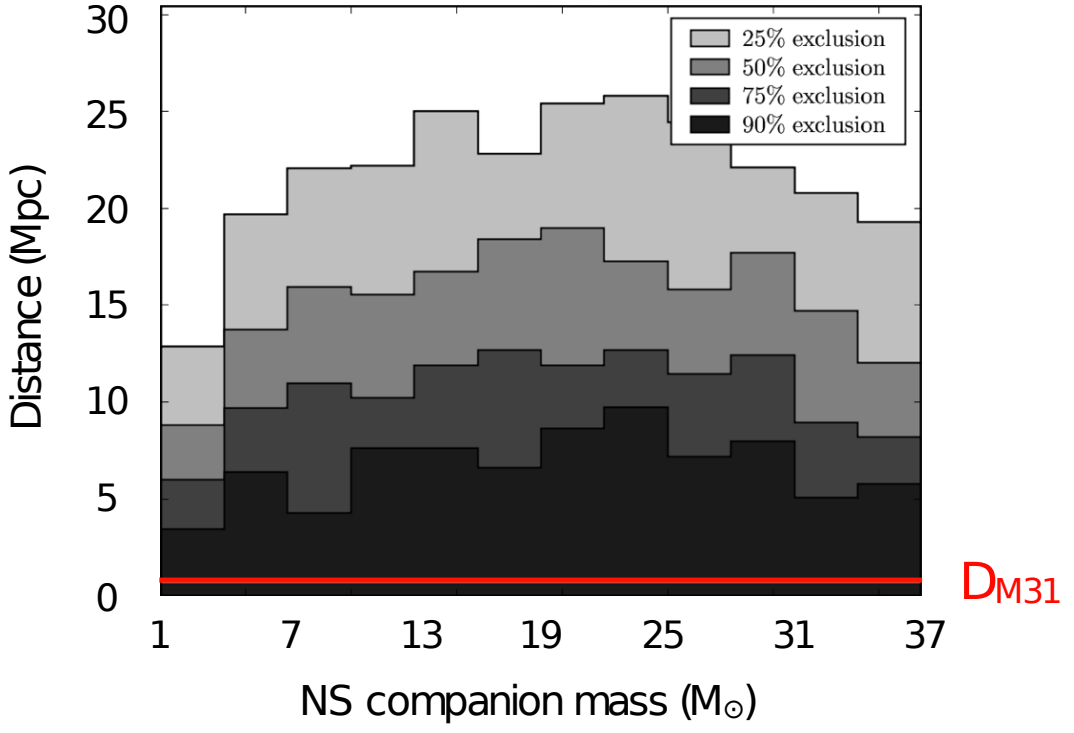
LIGO's fifth science run (S5)

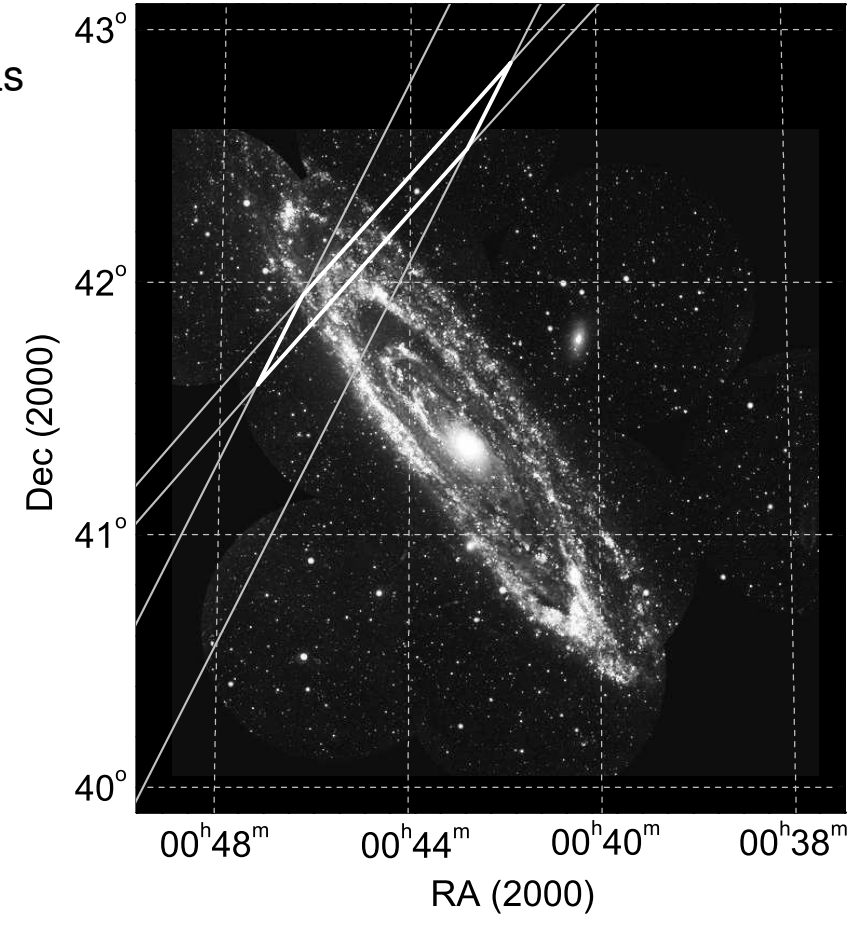
- Results from first 18 months of data in "low mass" regime — $M_{\rm total} \in [2\,{\rm M}_\odot, 35\,{\rm M}_\odot]$, $M_{1,2} \geq 1\,{\rm M}_\odot$ — to appear in Phys.Rev. D; available as arXiv:0901.0302 (1st year) and arXiv:0905.3710 (update from months 12–18).
- Sensitive to a distance of up to $150\,{\rm Mpc}$ depending on mass.
- No detections; assuming a compact binaries population with a Gaussian mass distribution representing binary neutron star systems, black hole-neutron star binary systems, and binary black hole systems, set 90%-confidence upper limits of $1.4 \times 10^{-2}\,{\rm a}^{-1}{\rm L}_{10}^{-1}$, $3.6 \times 10^{-3}\,{\rm a}^{-1}{\rm L}_{10}^{-1}$, $7.3 \times 10^{-4}\,{\rm a}^{-1}{\rm L}_{10}^{-1}$ respectively.



Gamma-Ray Burst GRB 070201 in fifth science run (S5)

- Short GRB: possible compact binary merger, possible SGR.
- Error box for location of electromagnetic source covers a portion of M31 (at $D \sim 770\,\mathrm{kpc}$).
- LIGO null result excludes compact binary merger in M31 as source with confidence $> 99\%$.
- Ap.J. 681(2):1419–1430 (2008); arXiv:0711.1163

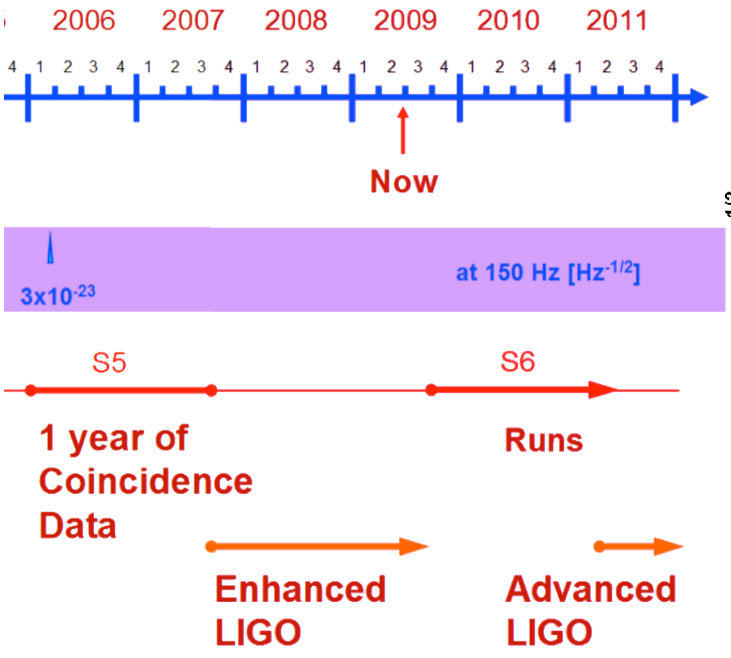


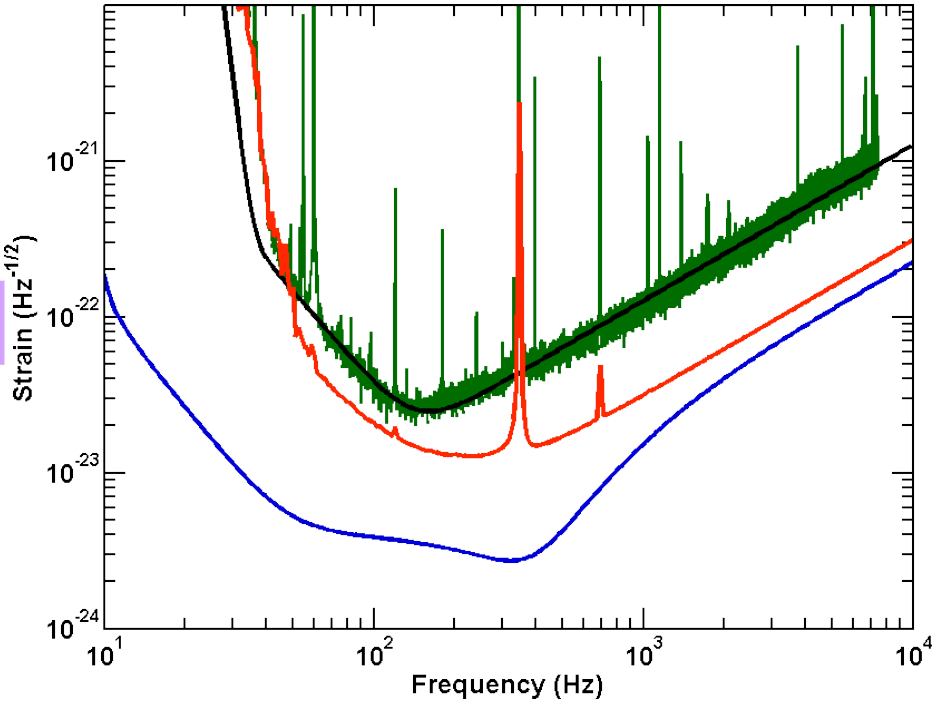


GRB 070201 error box. Credit: Mazets et al., arXiv:0712.1502

S6/VSR2 and Advanced Detector Preview

- The newly constructed Enhanced LIGO interferometers will be used for sixth science run, expected to begin in July and last for about 1.5 years.
- Following S6, the Advanced LIGO interferometers will be installed. Advanced LIGO is fully funded, construction of components was begun a year ago and is progressing on schedule and within budget.
- Advanced LIGO Science run to begin by 2014.
- First detection possible in S6 (knock on wood!), detection is believed to be certain with Advanced LIGO — $200\ \mathrm{Mpc}$ range, plausible NS/NS event rates of nearly 1/week.



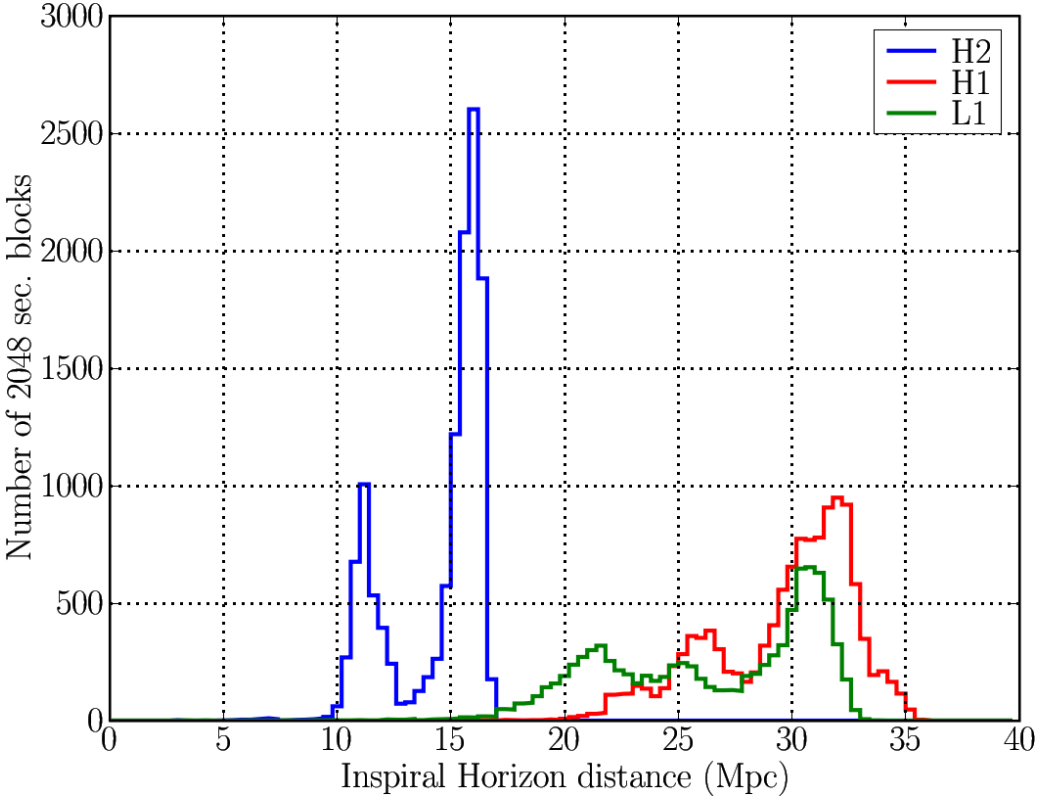


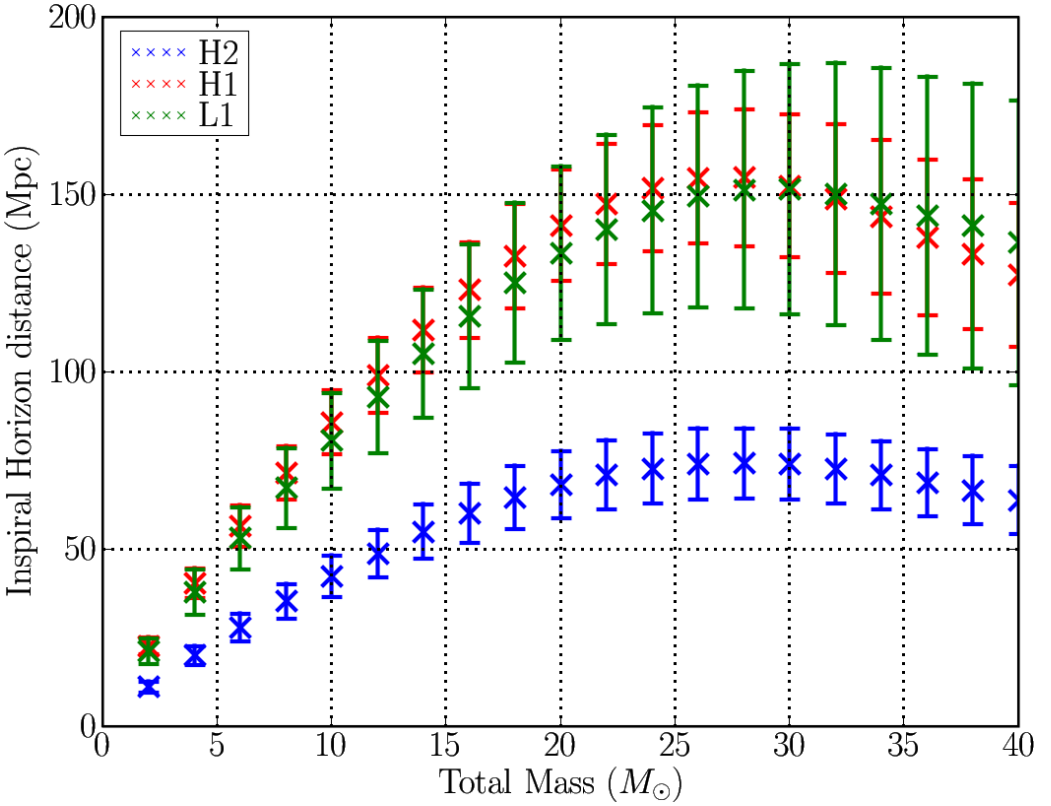
New Analysis Techniques in Development

- Detector improvements increase our sensitivity. Software improvements do, too!
- Multi-dimensional event classification for better discrimination of signals from noise.
- Coherent methods, to impose better multi-instrument waveform consistency, estimate direction to source, etc..
- Low-latency techniques (even sub-template latency) for rapid candidate event identification and correlation with EM transients.
- Smarter data management techniques to eliminate data volume bottlenecks allowing pipeline's internal thresholds to be lowered.
- Hardware-accelerated signal processing techniques using GPUs to make more computational resources available for Monte Carlo simulation studies, etc..
- Studies of event populations — not just the "loudest event" — might allow a statistical detection: believable evidence of an excess of events without being able to identify which events, specifically, are the gravitational waves.

Extra Slides ...

- First calendar year low-mass horizon distance — distance at which an optimally-oriented source would be seen at SNR 8.





Publication plans for fifth science run

- LIGO's fifth science run spanned Nov 4, 2005, to Sept 30, 2007.
- Virgo's first science run (VSR1) spanned May 18, 2007, to October 1, 2007 (last ~ 4.5 months of S5).
- Agreement between collaborations allows full data sharing.
- S5/VSR1 searches in progress:
  - low-mass search in LIGO months 12–18
  - low-mass LIGO-Virgo search in months 19–24
  - LIGO-only high-mass search — $M_{\mathrm{total}} \in [25\,\mathrm{M}_{\odot}, 100\,\mathrm{M}_{\odot}]$ — in full 2 years
  - externally-triggered GRB search in full 2 years (18 short GRBs in S5 after data quality cuts)
  - black hole ring-down search in full 2 years
- When setting rate upper limits, results will be combined using previous runs as Bayesian priors. I.E., there will be a series of low mass upper limits published, the last of which will provide the complete result for the entire S5 run.