Searching for Compact Object Collisions with Latencies of Seconds

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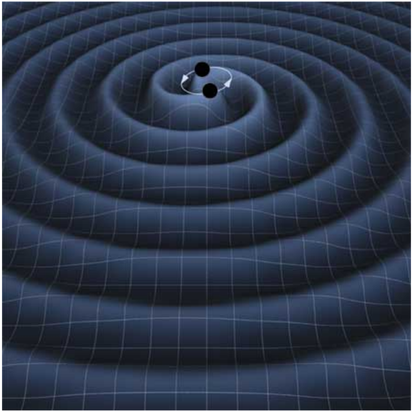
Compact Object Mergers

- 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

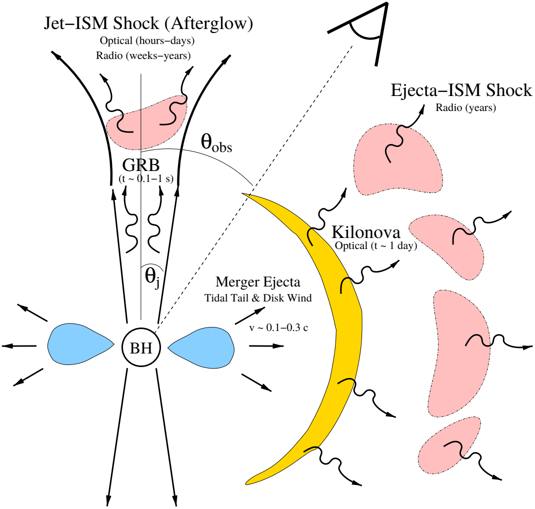
Compact Object Mergers as Laboratory

- 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:

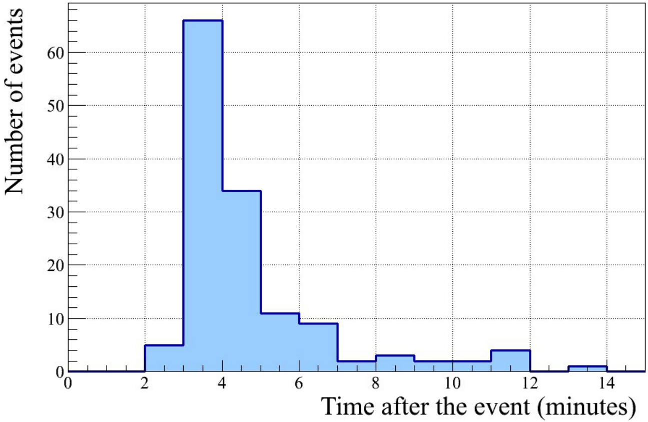
- Rapid accretion 1 s → collimated relativistic jet (SGRB).
- Optical after-glow from interaction of jet with surrounding medium (red) observable ∼days–weeks with $\theta_{\rm obs} < 2\theta_{\rm jet}$.
- Jet decelerates → isotropic radio afterglow ∼weeks–months, and years.
- r-process “kilonova”: isotropic optical emission lasting few days (yellow).



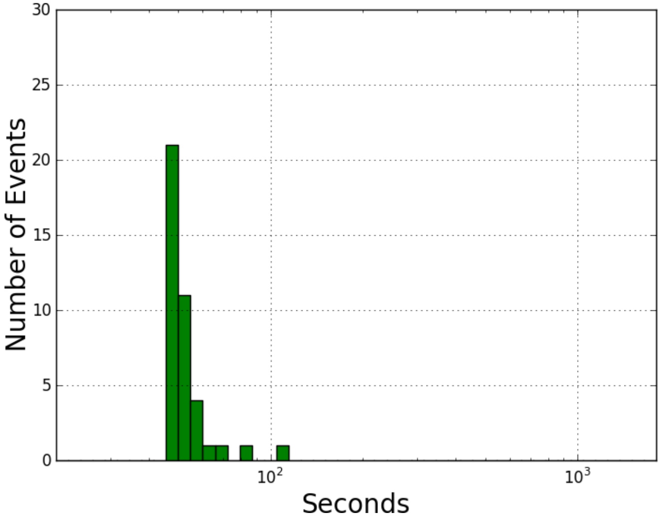
(from Metzger, B., Berger, E., 2011, arXiv:1108.6056)

- 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.

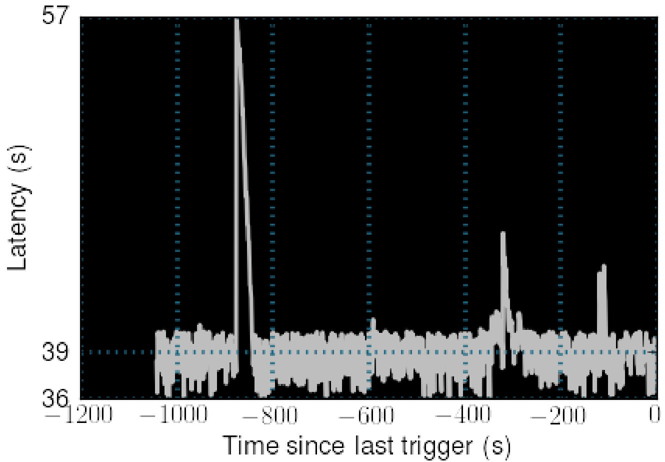
- The success rate for simultaneous GW-EM detections remains unknown.
- But the facilities exist, the marginal cost of trying is microscopic, and the knowledge to be gained from success is potentially very high.
- The ultimate timescale would seem to be the GRB jet timescale of O($1\,\mathrm{s}$).
- 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($1\,\mathrm{h}$). See LSC and Virgo, A&A 541, A155 (2012), arXiv:1112.6005.
    - Currently: O($100\,\mathrm{s}$).



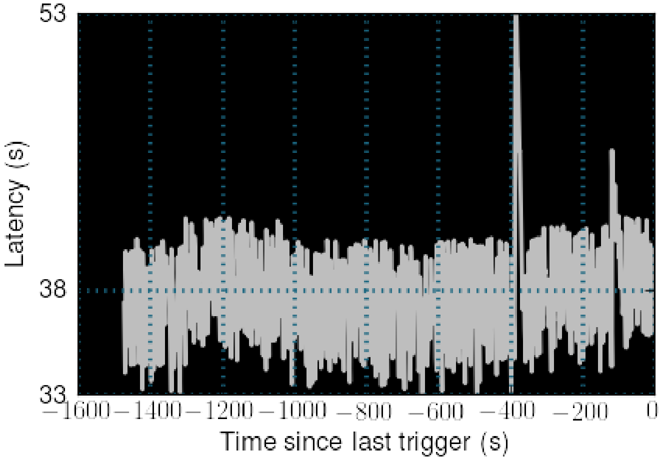
- MBTA latency in S6/VSR3. From LSC and Virgo, A&A 541, A155 (2012), arXiv:1112.6005.
- Does not include 20 min to 40 min of manual follow-up.



- MBTA latency in ER7 (mode is $\sim 65\,\mathrm{s}$).



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



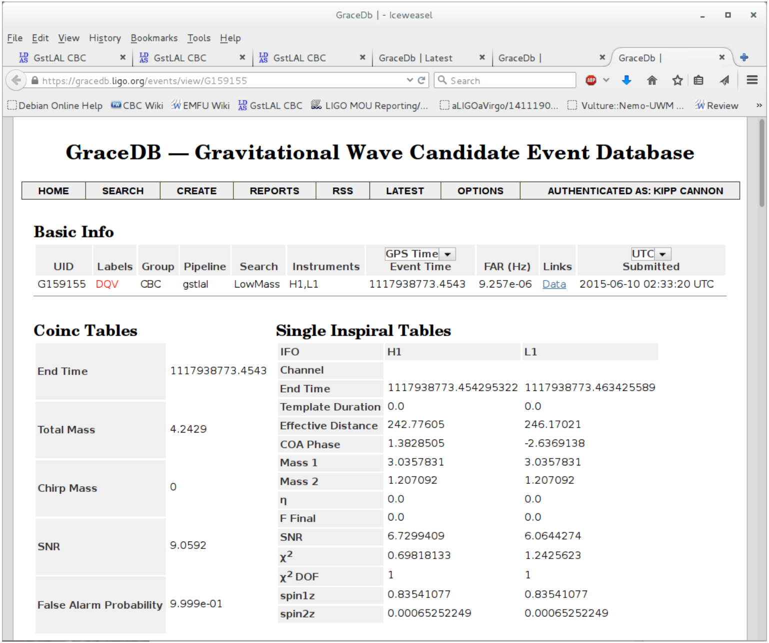
- GstLAL latency in ER7 exhibiting data-dependent variation.

Latency Reduction Techniques

- Mostly an accidental side-effect of work done to accommodate template banks for second-generation antennas.
- Better sensitivity at low frequency → longer templates.
- Longer templates → better orbital frequency resolution → more templates.
- Low-mass LIGO template banks increase from $O(10^4)$ templates of $45\,\mathrm{s}$ to $O(10^6)$ templates of $1800\,\mathrm{s}$.
- 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.



GraceDB — Gravitational Wave Candidate Event Database

Basic Info

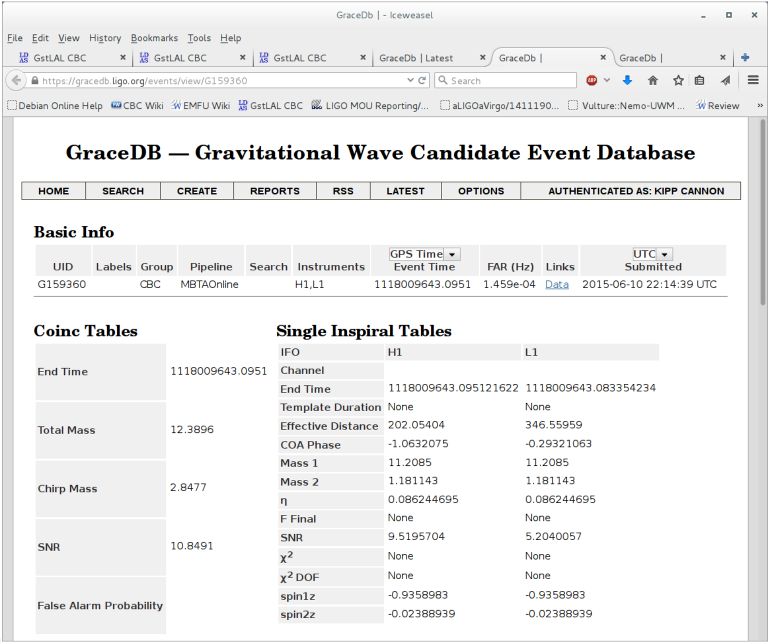
UID	Labels	Group	Pipeline	Search	Instruments	GPS Time ▾ Event Time	FAR (Hz)	Links	UTC ▾ Submitted
G159155	DQV	CBC	gstlal	LowMass	H1,L1	1117938773.4543	9.257e-06	Data	2015-06-10 02:33:20 UTC

Coinc Tables

End Time	1117938773.4543
Total Mass	4.2429
Chirp Mass	0
SNR	9.0592
False Alarm Probability	9.999e-01

Single Inspiral Tables

IFO	H1	L1
Channel		
End Time	1117938773.454295322	1117938773.463425589
Template Duration	0.0	0.0
Effective Distance	242.77605	246.17021
COA Phase	1.3828505	-2.6369138
Mass 1	3.0357831	3.0357831
Mass 2	1.207092	1.207092
η	0.0	0.0
F Final	0.0	0.0
SNR	6.7299409	6.0644274
χ^2	0.69818133	1.2425623
χ^2 DOF	1	1
spin1z	0.83541077	0.83541077
spin2z	0.00065252249	0.00065252249



GraceDB — Gravitational Wave Candidate Event Database

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Basic Info

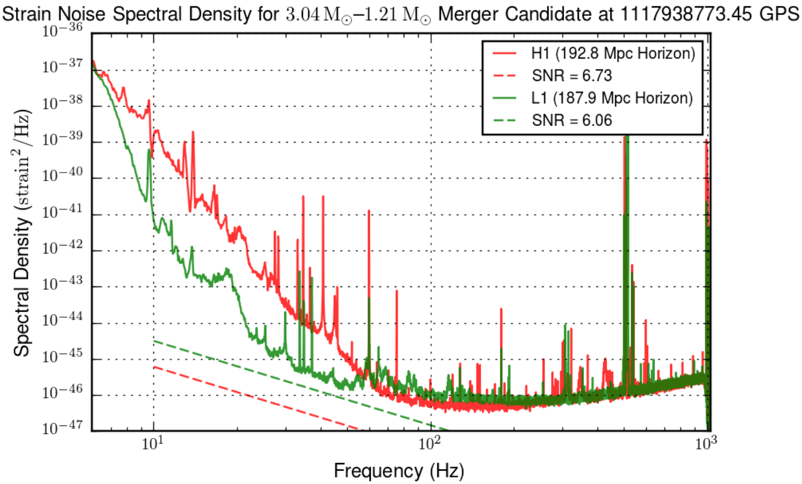
UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G159360		CBC	MBTAOnline		H1,L1	1118009643.0951	1.459e-04	Data	2015-06-10 22:14:39 UTC

Coinc Tables

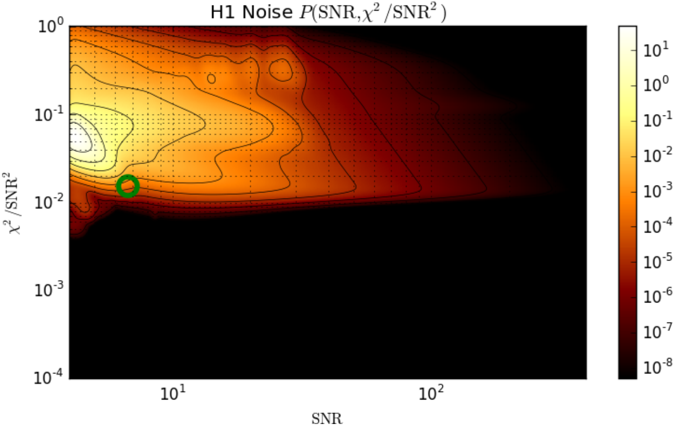
End Time	1118009643.0951
Total Mass	12.3896
Chirp Mass	2.8477
SNR	10.8491
False Alarm Probability	

Single Inspiral Tables

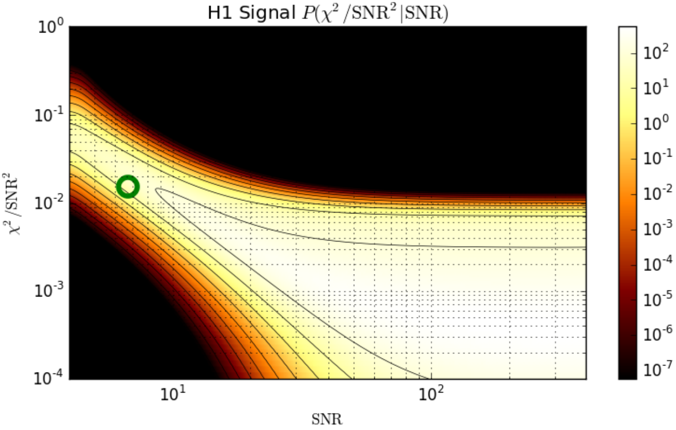
IFO	H1	L1
Channel		
End Time	1118009643.095121622	1118009643.083354234
Template Duration	None	None
Effective Distance	202.05404	346.55959
COA Phase	-1.0632075	-0.29321063
Mass 1	11.2085	11.2085
Mass 2	1.181143	1.181143
η	0.086244695	0.086244695
F Final	None	None
SNR	9.5195704	5.2040057
χ^2	None	None
χ^2 DOF	None	None
spin1z	-0.9358983	-0.9358983
spin2z	-0.02388939	-0.02388939



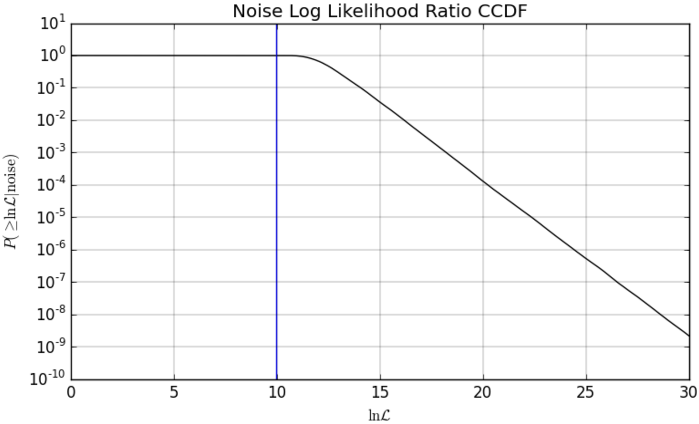
- Noise spectrum estimate for all instruments at time of candidate. Horizon distances (given the candidate's masses) and SNR densities will be indicated.



- Location of candidate with respect to noise model in SNR-χ^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^2 plane (one plot per instrument).

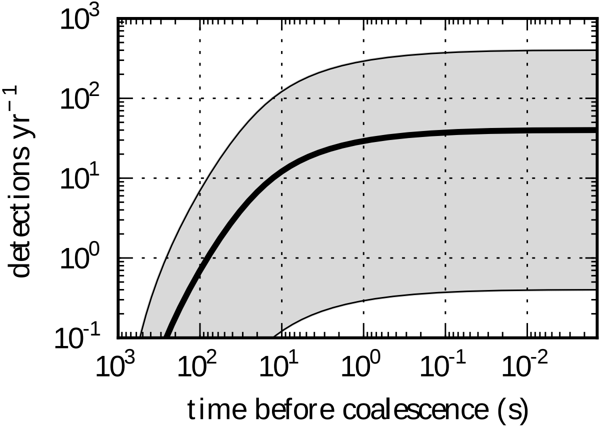


- False-alarm probability vs. ranking statistic in experiment to date.
- with candidate's ranking statistic value marked.

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?



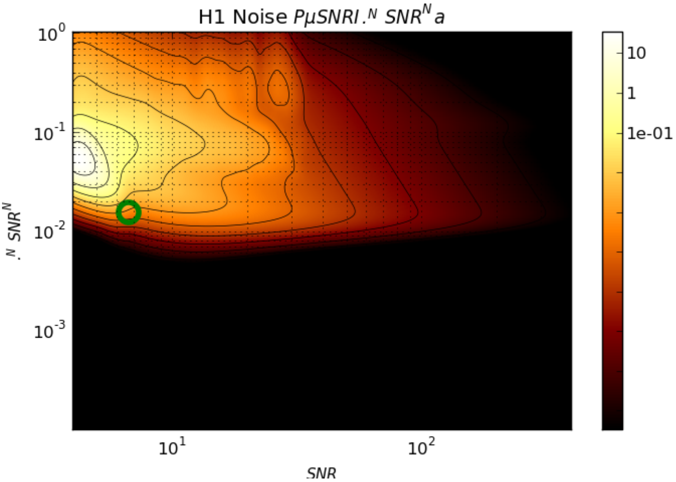
(from Cannon *et al.*, Ap. J., 748(2):136, 2012, arXiv:1107.2665)

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

Conclusion

- Search latencies reduced enormously to O($100\,\mathrm{s}$)
- 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



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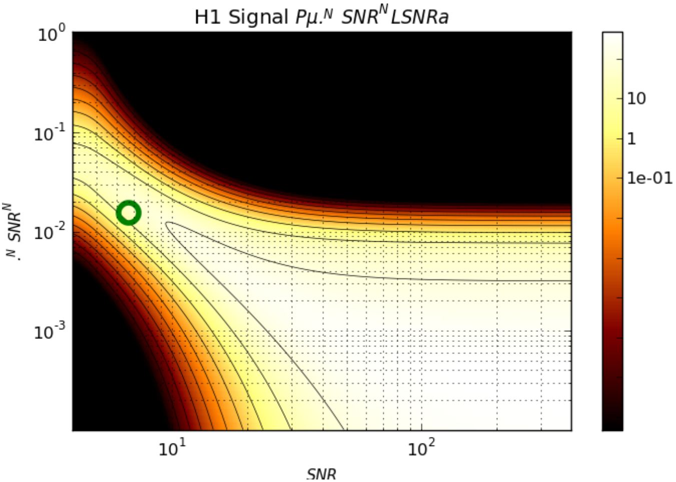
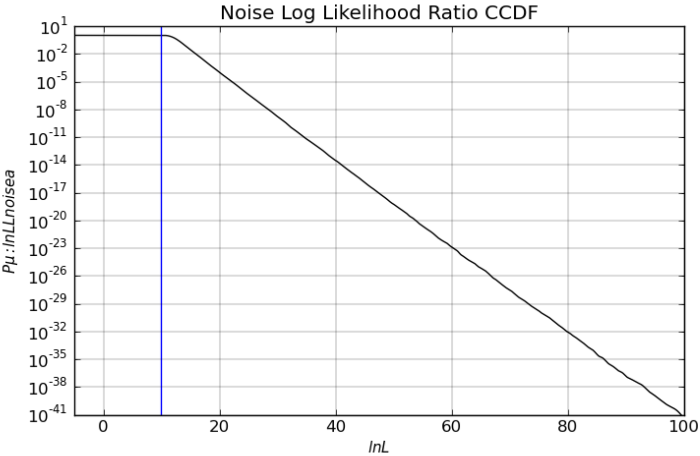


- Location of candidate with respect to signal model in SNR-χ^2 plane (one plot per instrument).



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