Searching for Gravitational Waves with LIGO

Andrés C. Rodríguez
Louisiana State University

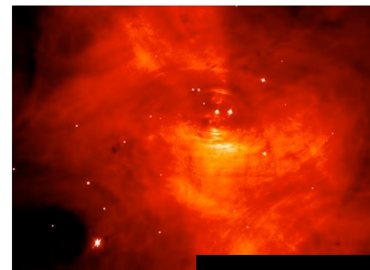
on behalf of the LIGO Scientific Collaboration

Outline

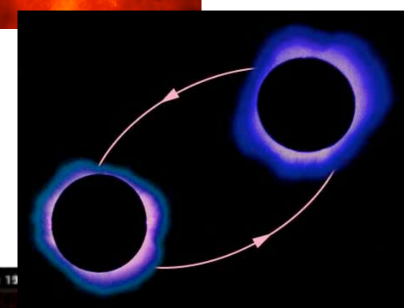
- **Sources of Gravitational Waves**
- **Coalescing binaries**
  - **Binary neutron stars**
  - **Binary black holes**
- **Gravitational wave bursts**
  - **Unmodelled bursts**
  - **Astronomically triggered searches**

Gravitational Wave Sources

• different frequencies, different temporal patterns, different data analysis methods:



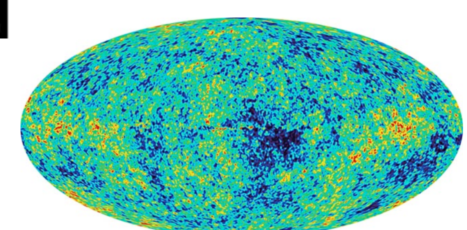
• periodic sources: rotating stars (pulsars),…



• inspiraling sources: compact binary systems (neutron stars, black holes, MACHOs…)

• burst sources: supernovae, collisions, black hole formations, gamma ray bursts…

• stochastic sources: early universe, unresolved sources...



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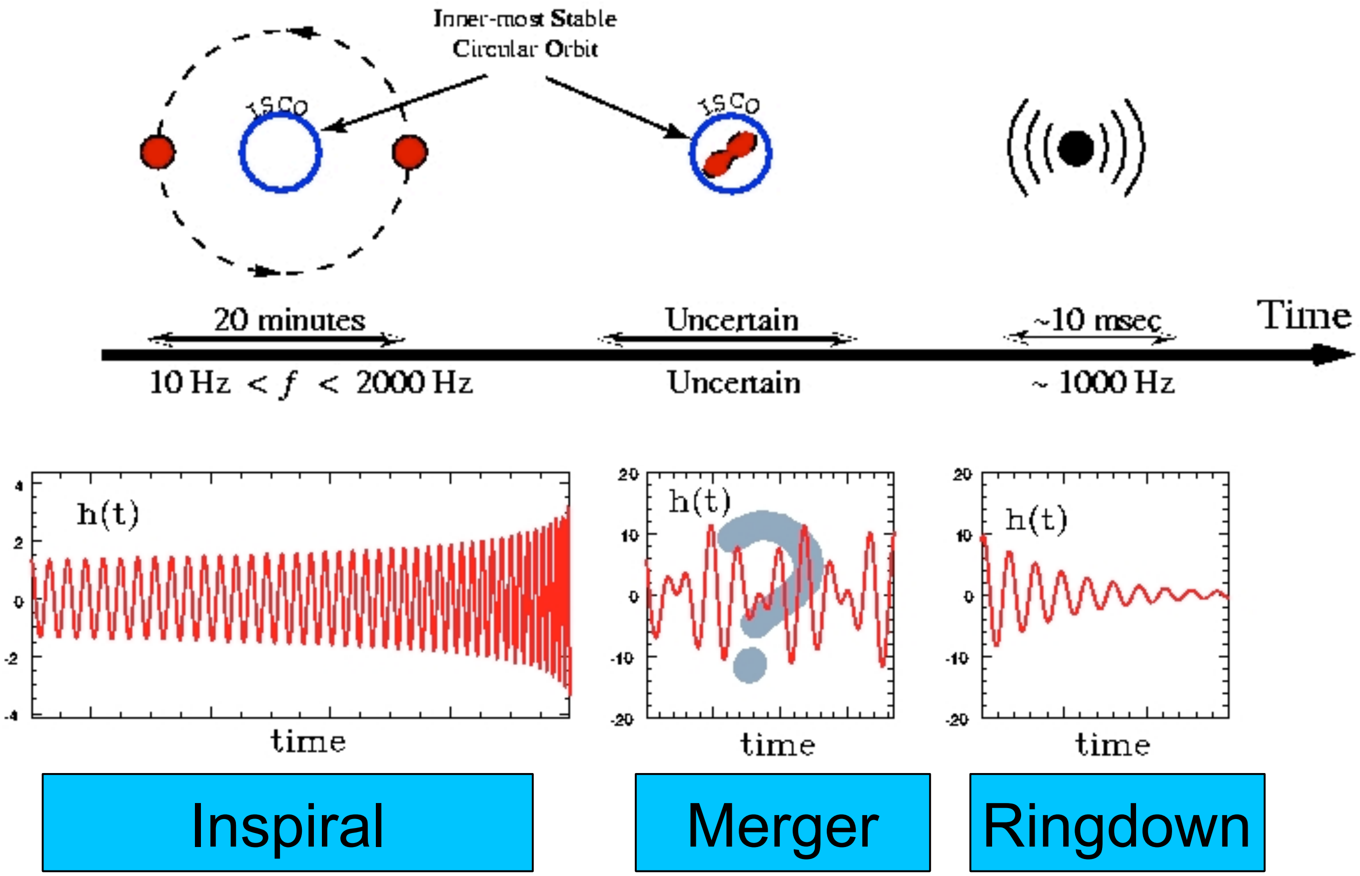
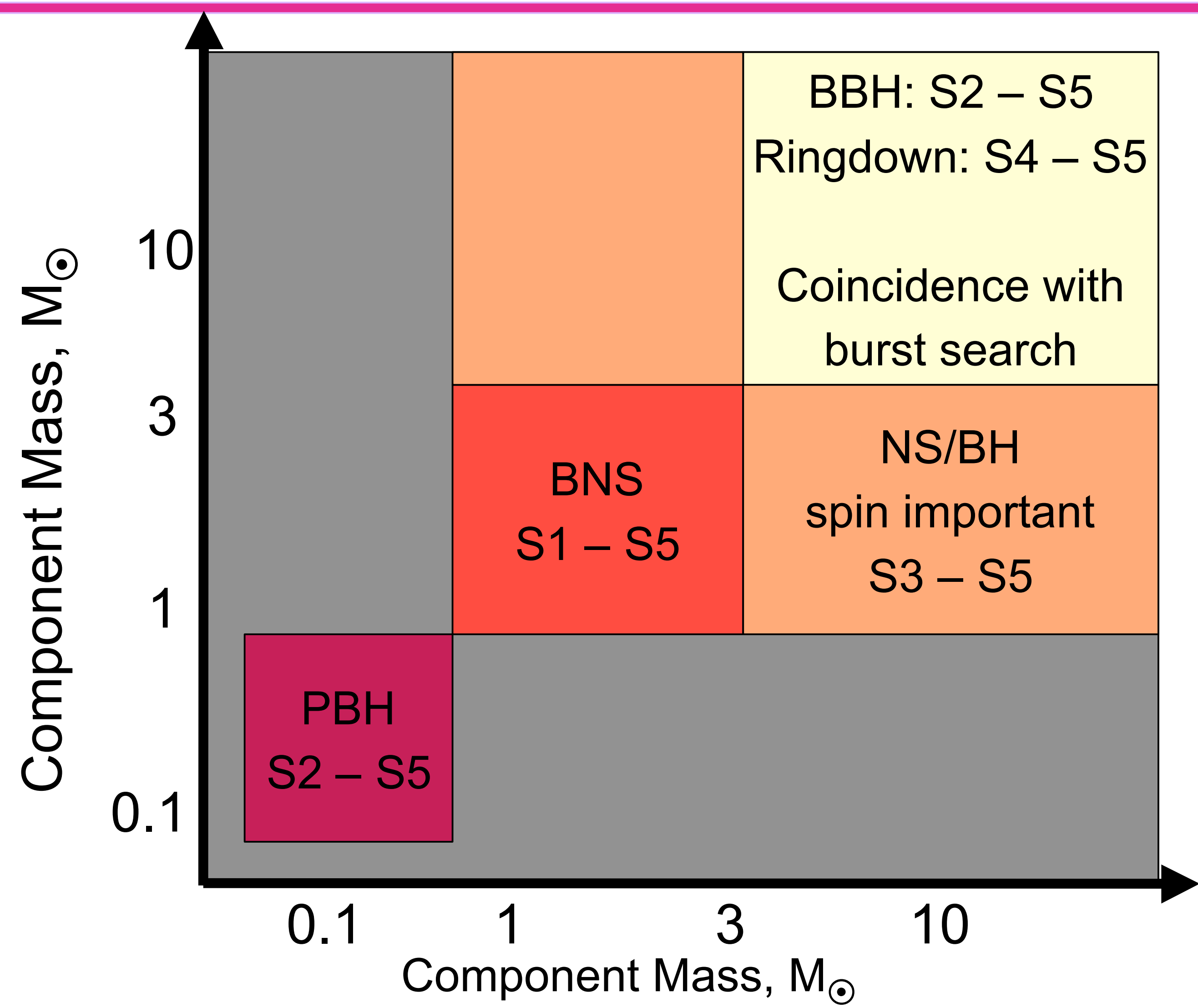
Coalescing Binaries

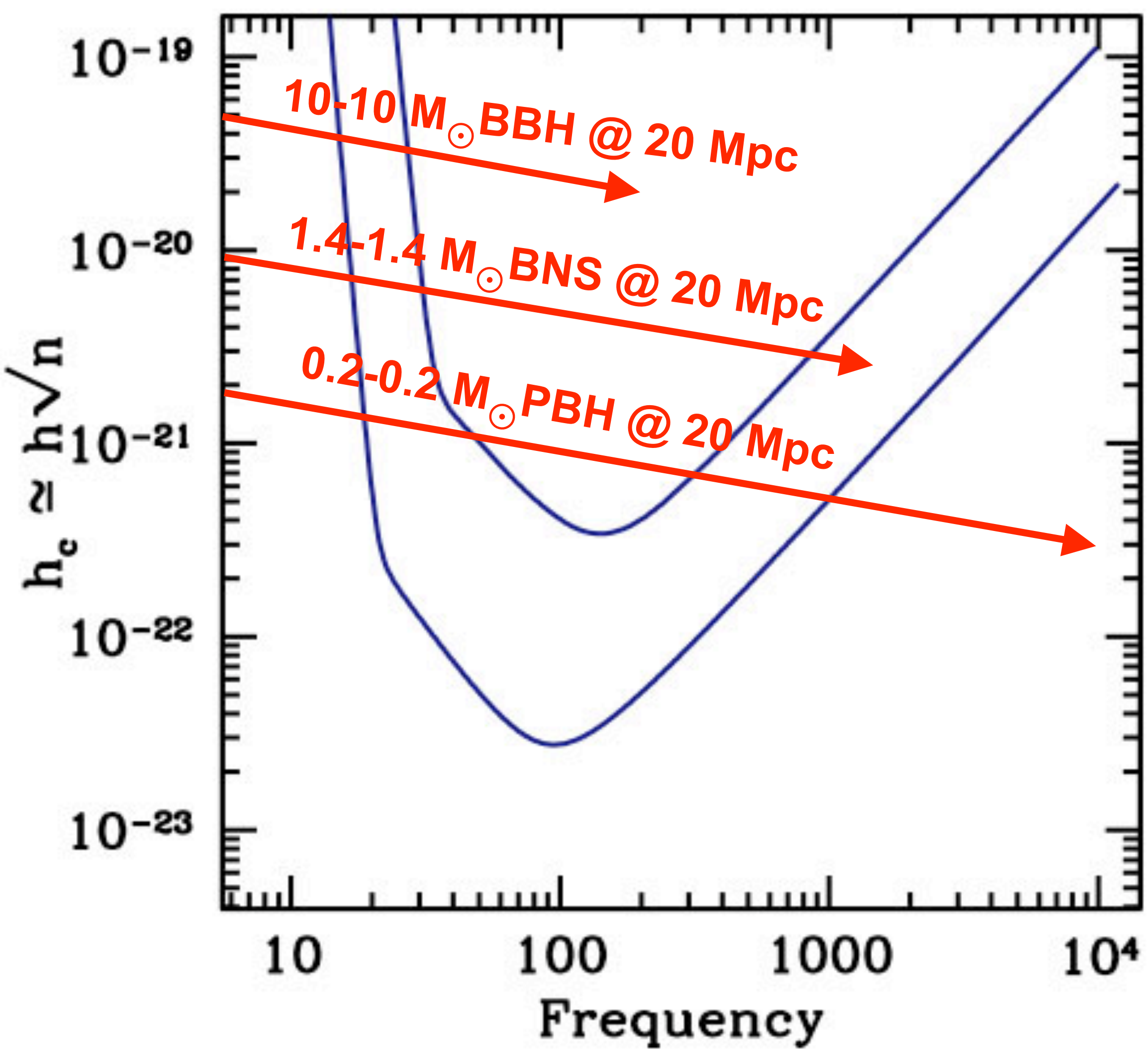
- LIGO is sensitive to gravitational waves from neutron star and black hole binaries



Target Sources



Target Sources



- Binary Neutron Stars
  - Estimates give upper bound of 1/3 year for LIGO during S5
- Binary Black Holes
  - Estimates give upper bound of 1/year for LIGO during S5
  - Merger occurs in band

Search for binary systems

- Analysis pipeline begins with a discrete bank of templates from each detector, ends with surviving events w/ χ^2, snr, & coincidence based on surviving templates.

- Vetoes applied (instrumental & statistical) throughout.

- Inspiral events "triggers" relay info on original template + snr, χ^2, coalescence time, effective distance.

- Pipeline characterized by a Monte-Carlo method
  - » simulated inspiral signals injected into the time series to determine efficiency at each snr: software + hardware

- Estimate false alarm probability of resulting candidates: detection?

- Compare with expected efficiency of detection and surveyed galaxies: upper limit

Search: Binary Neutron Stars

- S2 Observational Result - (published -*Phys. Rev. D. 72, 082001 (2005))*
  - Rate < 47 per year per Milky-Way-like galaxy
  - 0.04 yr of data
  - 1.27 Milky-Way like galaxies for 1.4 – 1.4 $M_\odot$
- S3 search complete
  - Under internal review
  - 0.09 yr of data
  - ~3 Milky-Way like galaxies for 1.4 – 1.4 $M_\odot$
- S4 search complete
  - Under internal review
  - 0.05 yr of data

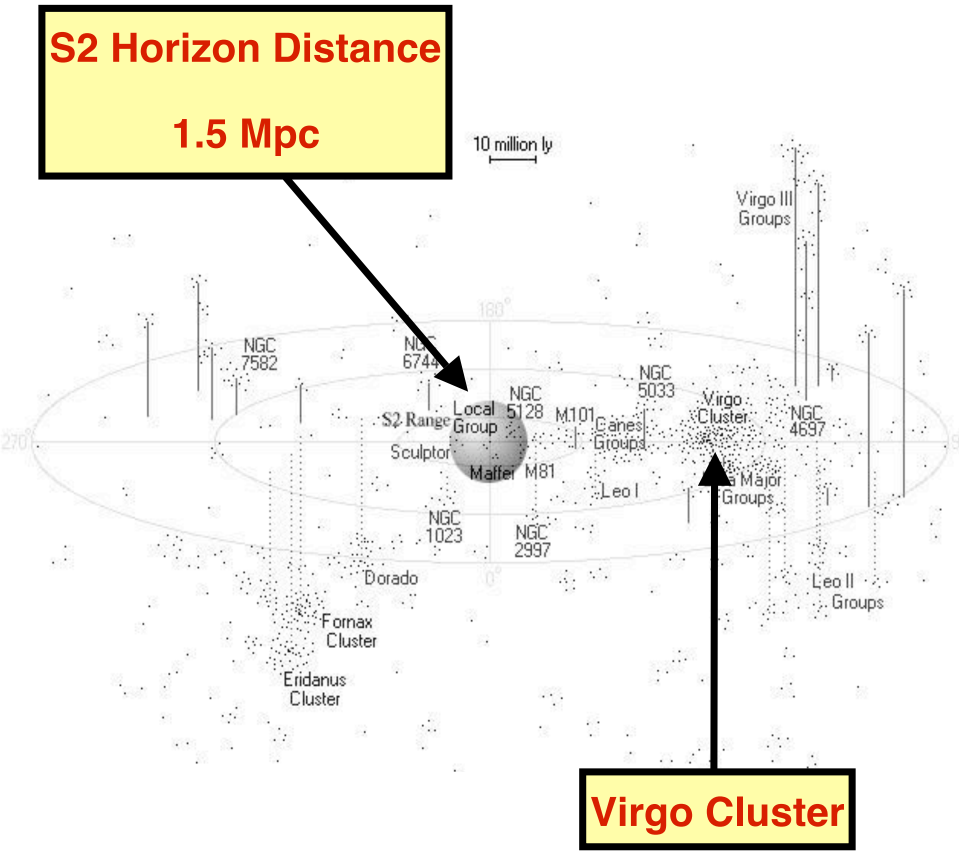
Search: Binary Black Holes

- S2 Observational Result (published in *Phys. Rev. D. 73, 062001 (2006)*)
  - Rate < 38 per year per Milky-Way-like galaxy

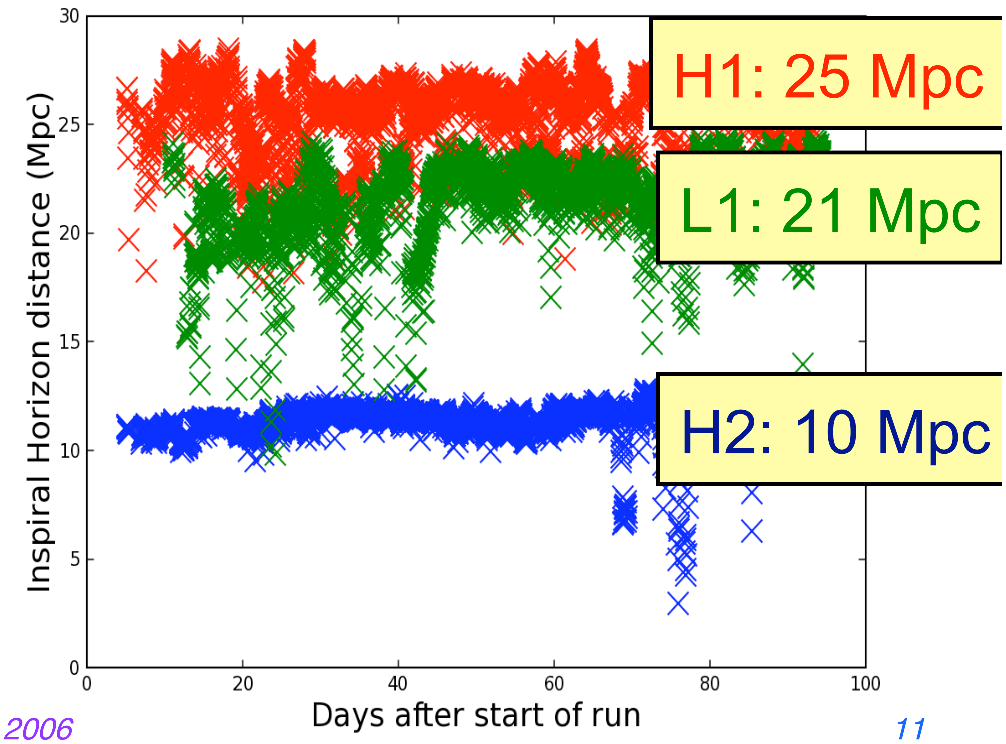
- S3 search complete
  - Under internal review
  - 0.09 yr of data
  - ~5 Milky-Way like galaxies for 5-5 $M_\odot$
- S4 search complete
  - Under internal review
  - 0.05 yr of data
  - ~150 Milky-Way like galaxies for 5-5 $M_\odot$

S5 Binary Neutron Stars

- First three months of S5 data have been analyzed



- Horizon distance
  - Distance to 1.4-1.4 $M_\odot$ optimally oriented & located binary at SNR 8



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Gravitational Wave Bursts

- **Produced during cataclysmic events involving stellar-mass (1-100 $M_{\odot}$) compact objects:**
  - **Core-collapse supernovae**
  - **Accreting/merging black holes**
  - **Gamma-ray burst engines**
  - **Unexpected ...**

- **Probe interesting new physics and astrophysics:**
  - **dynamical gravitational fields, black hole horizons, matter at supra-nuclear density, ...**
- **Uncertain waveforms complicate detection.**

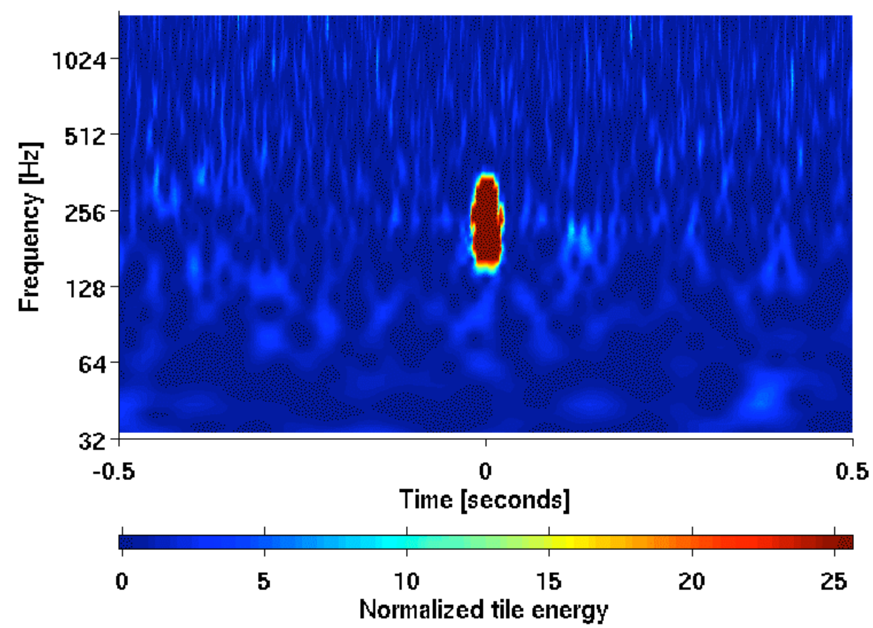
Search for Burst sources (untriggered)

- Use a wavelet algorithm to search for triple coincident triggers
- Calculate waveform consistency to measure confidence
- Set a threshold for detection for low false alarm probability
- Compare with efficiency for detecting simple waveforms

Excess power detection

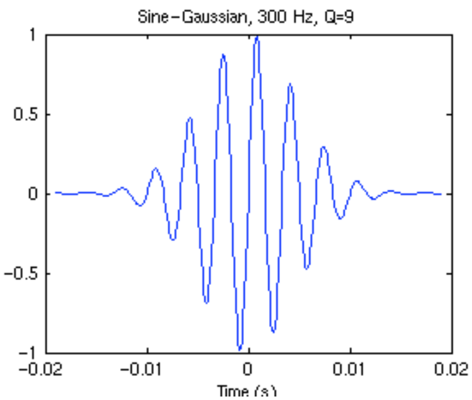
- Look for transient increase in power in some time-frequency region:
  - Minimal assumptions about signal
  - Duration: 1 to 100 ms
    - Characteristic time scale for stellar mass objects
  - Frequency: 60 to 2,000 Hz
    - Determined by detector's sensitivity
  - Many different implementations
    - Fourier modes, wavelets, sine-Gaussians
    - Multiple time/frequency resolutions
    - Provide redundancy and robustness

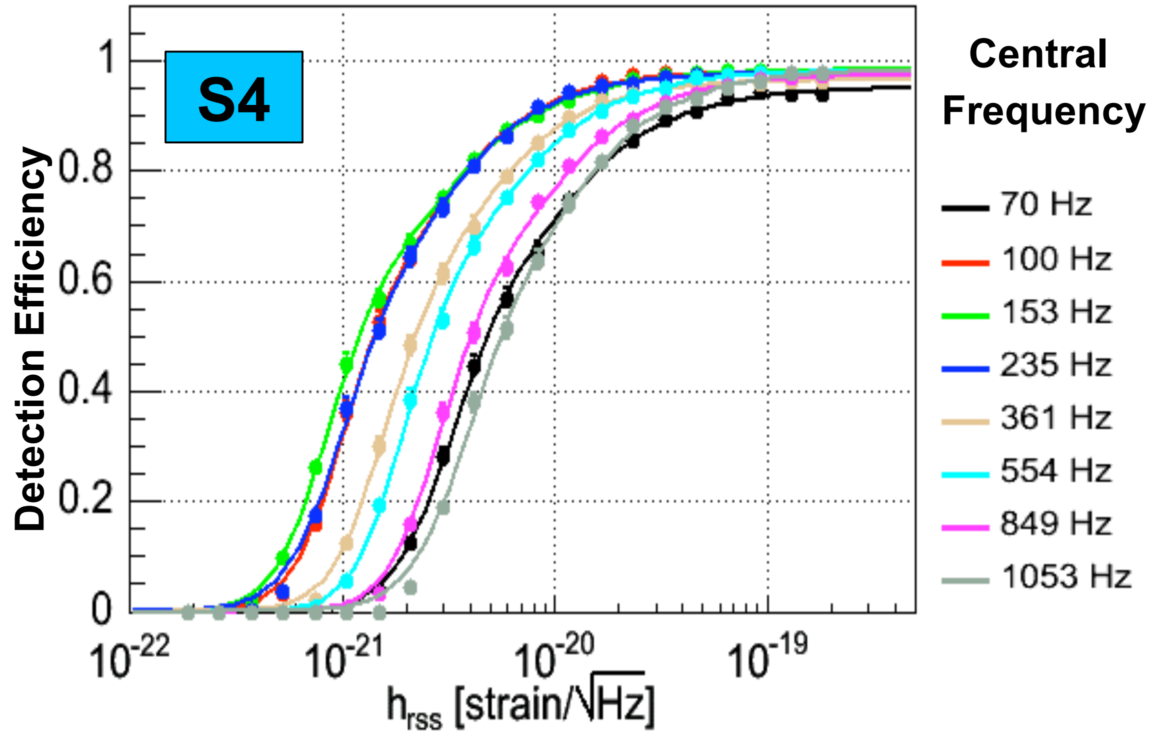
Simulated burst signal



Detection Efficiency

- Evaluate efficiency by adding simulated GW bursts to the data.
  - Example waveform





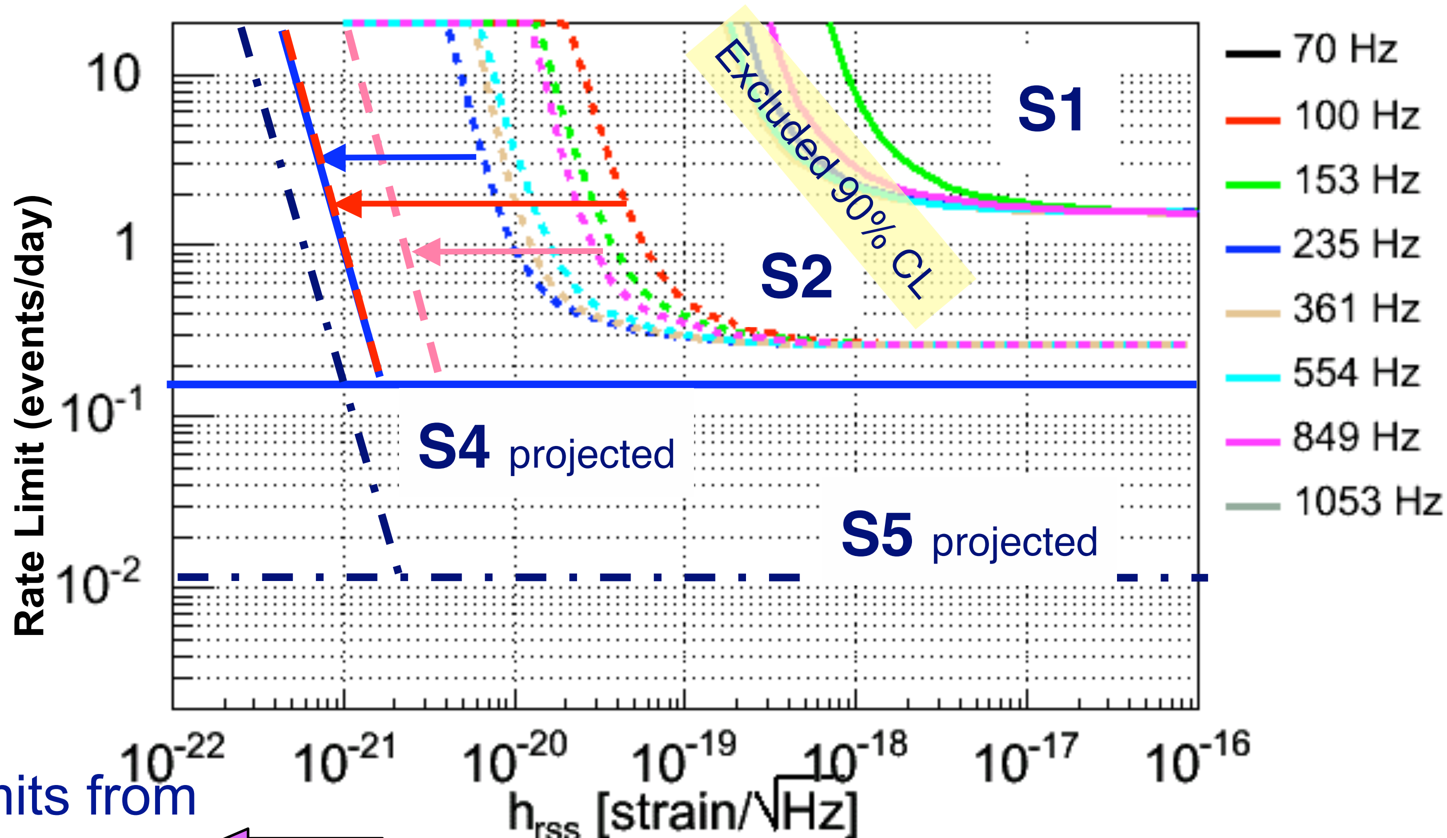
- S5 sensitivity: minimum detectable in band energy in GW
  - E_{GW} > 1 Msun @ 75 Mpc
  - E_{GW} > 0.05 Msun @ 15 Mpc (Virgo cluster)

Upper Limits

- No GW bursts detected through S4
  - set limit on rate vs signal strength.

$$R \propto \frac{1}{\epsilon(h_{\rm rss})\, T}$$

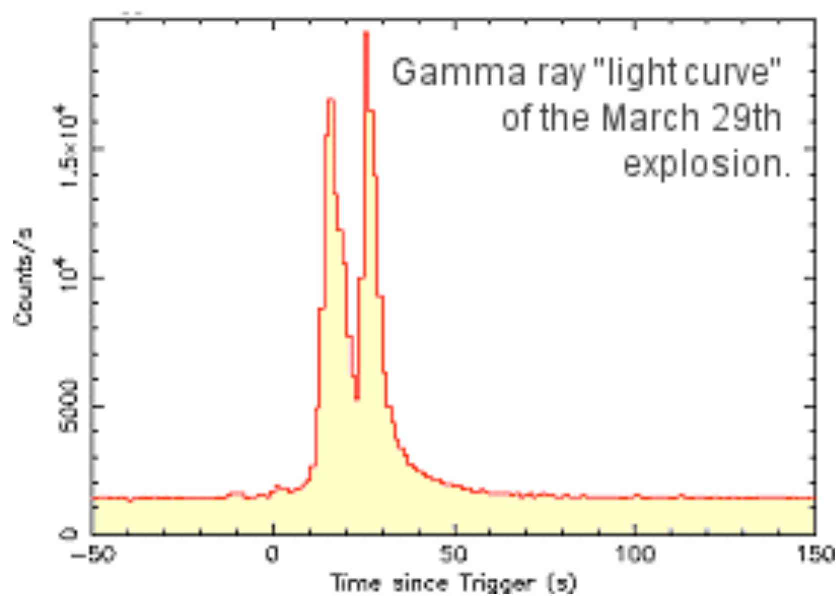
Lower rate limits from longer observation times



Lower amplitude limits from lower detector noise

Search for Burst sources (triggered)

- Follow up GRB triggers looking at cross-correlation from data in at least two detectors.
- For a set of GRBs, search for cumulative effect with statistical tests.
- Follow up times around interesting astronomical triggers, particularly gamma-ray bursts
  - Compare results with those from time shifts
- No loud signals seen
- Look for cumulative effect
  - Use binomial test to compare to uniform distribution
- No significant difference from expectation



Burst Search Results

- Analysis of data from first three science runs (S1-S3) complete:

1. B. Abbott et al. (LSC), *First upper limits from LIGO on gravitational wave bursts.* Phys. Rev. D **69**, 102001 (2004).
2. B. Abbott et al. (LSC), *A Search for Gravitational Waves Associated with the Gamma Ray Burst GRB030329 Using the LIGO Detectors.* Phys. Rev. D **72**, 042002 (2005).
3. B. Abbott et al. (LSC), *Upper Limits on Gravitational Wave Bursts in LIGO's Second Science Run.* Phys. Rev. D **72**, 062001 (2005)
4. B. Abbott et al. (LSC), T. Akutsu et al. (TAMA), *Upper Limits from the LIGO and TAMA Detectors on the Rate of Gravitational-Wave Bursts.* Phys. Rev. D **72**, 122004 (2005)
5. B. Abbott et al. (LSC), *Search for gravitational wave bursts in LIGO's third science run.* Class. Quant. Grav. **23**, S29-S39 (2006)

- Results from S4 being finalised.
- S5 search in progress.

Conclusions

- Analysis of LIGO data is in full swing
  - No gravitational waves discovered so far, but results are becoming astrophysically interesting.
  - In the process of acquiring one year of coincident data at design sensitivity.
  - “Online” analysis & follow-up provide rapid feedback to experimentalists.
  - Results from fourth and fifth LIGO science runs are appearing.
- Inspiral searches
  - S2 Results published, S3/S4 published results in the near future.
  - S5 sensitivity makes exciting time for gravitational wave astronomy and astrophysics.
- Burst searches
  - Rate and amplitude sensitivities continue to improve.

Thank you