Astrophysically Triggered Searches for Gravitational Waves

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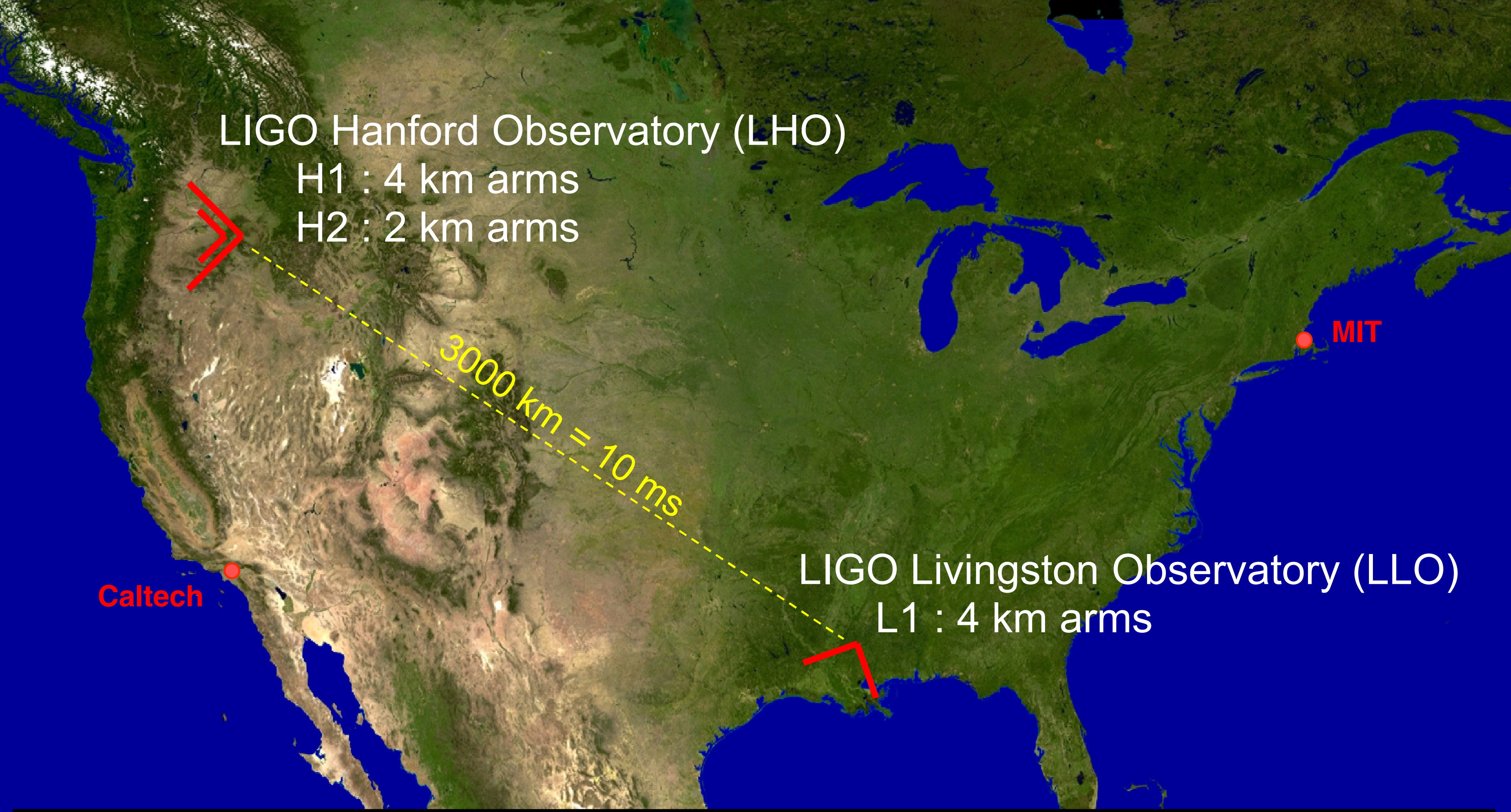
LIGO Scientific Collaboration

LIGO Scientific Collaboration

- LIGO = Laser Interferometer Gravitational wave Observatory
  - A flagship project of the National Science Foundation.
  - 3 detectors at 2 sites.
- 2-stage project:
  - Initial LIGO (now operating!)
  - Advanced LIGO (2015+)
    - 10 x more sensitive than Initial LIGO.
- LIGO Scientific Collaboration (LSC)
  - 500+ scientists and 40+ institutions worldwide
  - LIGO + GEO 600 (Hannover)
- Most recent data taking: Science Run 5 ("S5")
  - Nov 2005 – Oct 2007
  - >1 year of coincident LIGO operation at design sensitivity

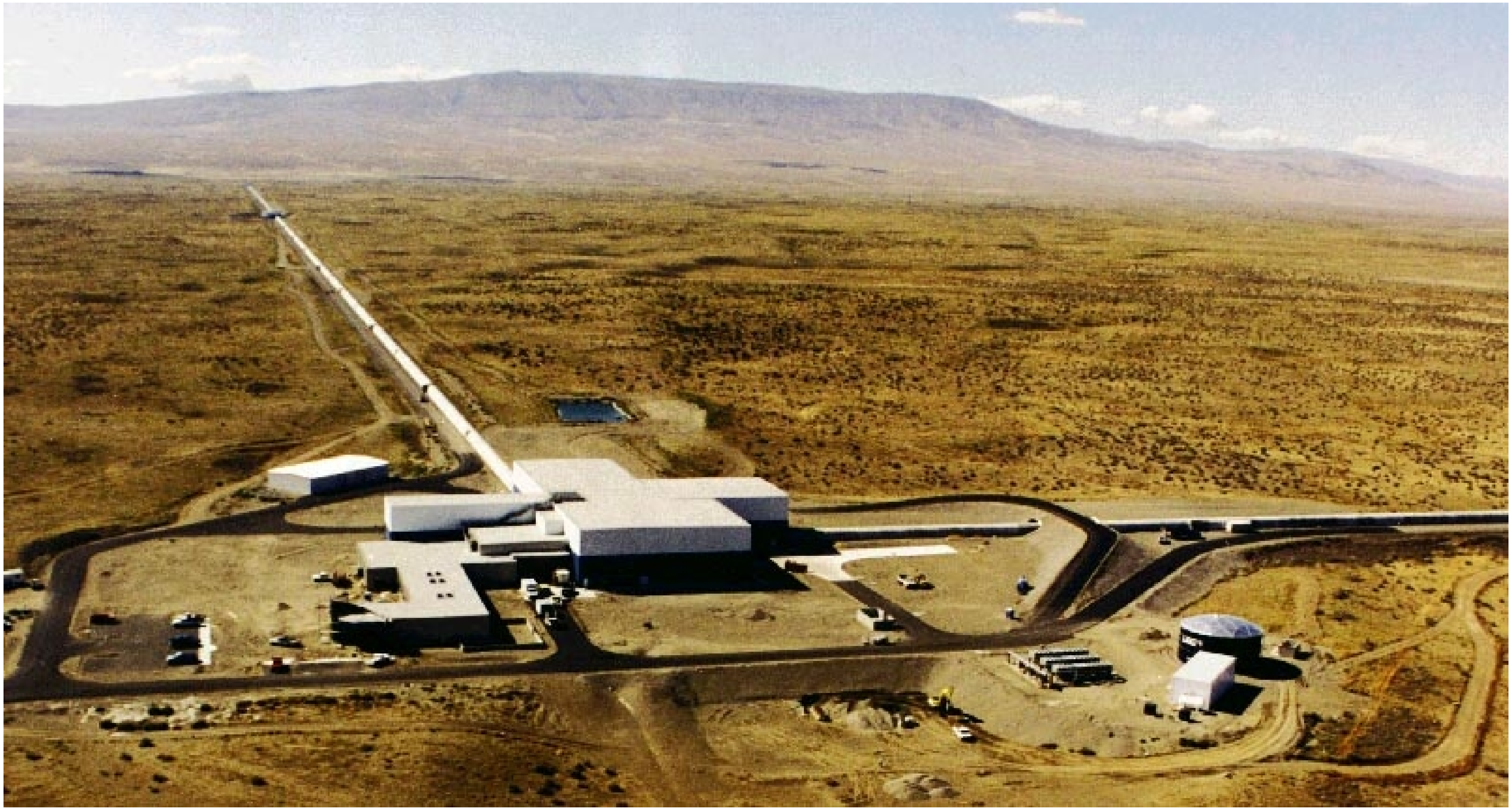
LIGO Scientific Collaboration

The LIGO Observatories



- Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov
- NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

LIGO Hanford Observatory

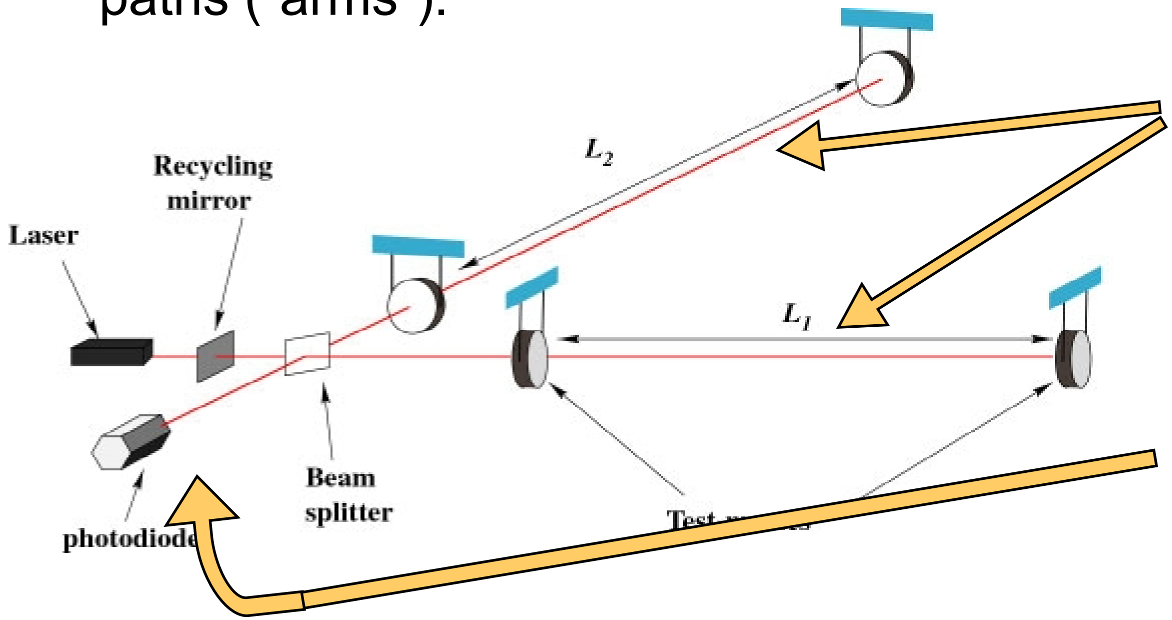


LIGO Livingston Observatory

GEO 600 Observatory

Interferometric GW Detectors

- Take advantage of the tidal nature of GWs.
- A laser is used to measure the relative lengths of two orthogonal paths ("arms").

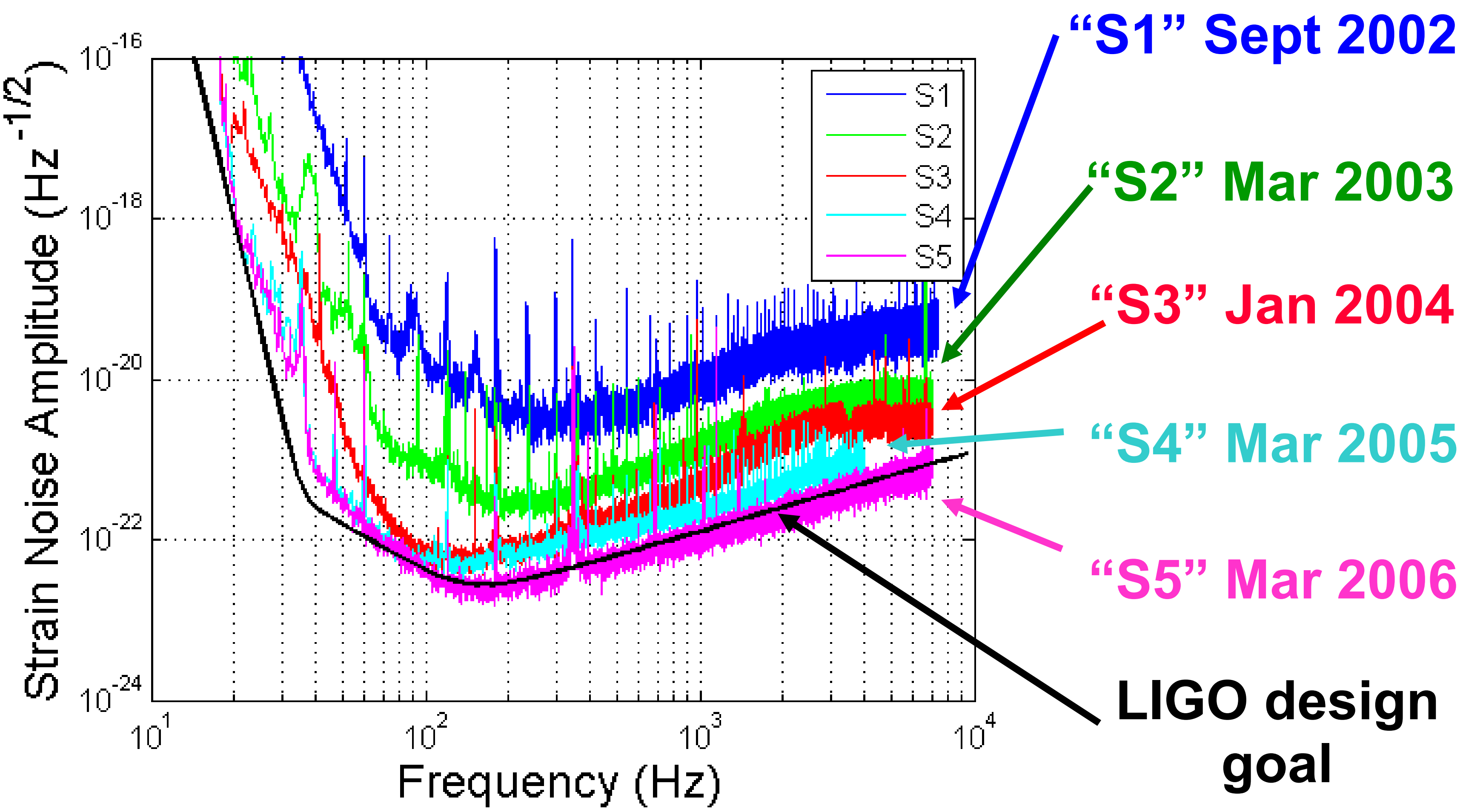


As a wave passes, the arm lengths change in different ways …

… causing the interference pattern at the photodiode to change.

- LIGO: L = 4 km. Can measure $dL/L < 10^{-21}$
  - $dL < 10^{-18}$ m ~ 1/1000 the size of a proton

Progress in Sensitivity



LIGO's Targets

- Searches for continuous emission
  - Distorted neutron stars
  - Stochastic background (analogous to CMB)
- Searches for transient signals
  - “chirp” signal of inspiralling neutron-star or black-hole binaries
  - “bursts” from supernovae, perturbed black holes, etc.

- Number of direct, confirmed detections of gravitational waves: 0
  - Need to use every scrap of information we can get to maximise sensitivity of our searches.

- This talk: describe LIGO searches for transient GW signals that use information from astronomical “triggers” (e.g., GRB alerts).

Astrophysical Triggers

- Establish association between gravitational waves and
    - Gamma-ray bursts (GRBs)
        - Short hard GRBs -- coalescing NS-NS / NS-BH binaries
    - Soft gamma-ray repeater (SGR) flares
    - Optical transients such as supernovae
    - Neutron star quasi-normal modes
    - Neutrino events
        - Galactic supernova -- optical, neutrino, GW signature
    - …
- Correlation in time & direction between the GW signal and the astrophysical trigger event gives
    - Better background rejection, higher sensitivity to GW signals
    - More confident detection of GWs (eventually)
    - Ready association of detected GW signal with known astrophysical system will help extract maximum scientific information information.

Information from External Observations

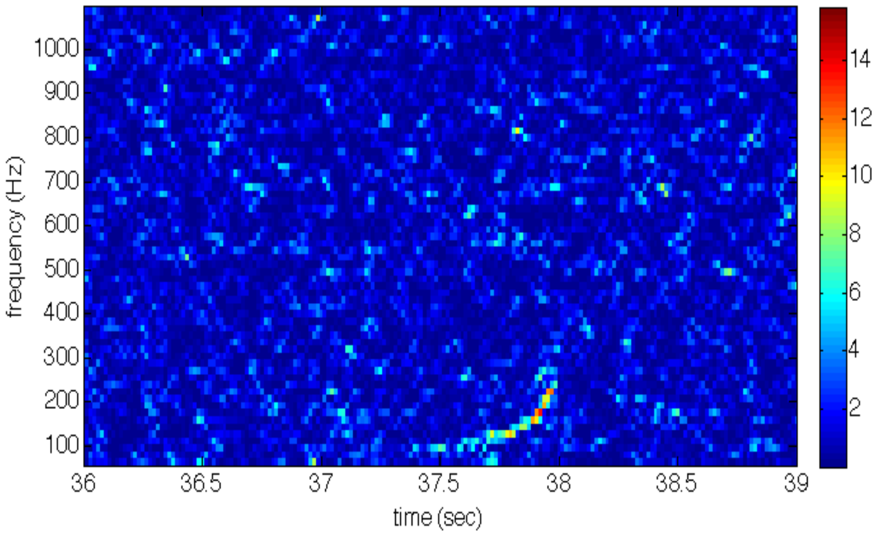
- Trigger time
  - Search within an astrophysically motivated time window.
  - Higher detection probability at fixed false alarm probability.
  - Stronger limits in the absence of a detection.
- Source direction
  - Search only the relevant portion of the sky, or
  - Veto candidates not consistent with the time delay between detectors.
- Frequency range
  - Frequency-band specific analysis of the data set (e.g., SGR QPOs)
- Progenitor type
  - Model-dependent searches can be performed in some cases, e.g., matched-filter for inspiral signal for short hard GRBs.

Search Methods

- When the signal waveform is known in advance (e.g., a binary inspiral progenitor of short GRBs):
  - Matched filtering

- When the signal waveform is unknown (i.e., usually):
  - Cross-correlation of data from pairs of detectors (S2-S4 GRBs)
  - Excess power power analysis of each detector separately.
  - Coherent combinations of data from several GW detectors (aperture synthesis)
    - Next "big thing" in externally triggered searches.

Excess power map: A simulated 1.4-10.0 Mo neutron star – black hole inspiral at an effective distance of 37 Mpc, added to simulated H1-H2 noise

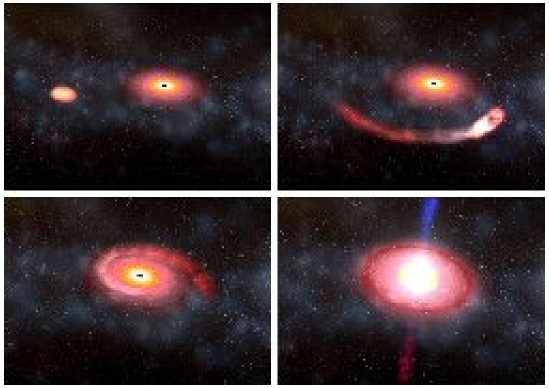


Chatterji et al., 2006 PRD 74 082005;
Klimenko et al., 2005 PRD 72 122002;
Rakhmanov M, 2006 CQG 23 S673

Sources: Gamma Ray Bursts (GRBs)

- Short-duration GRBs (less than ~2 s)
  - coalescing compact binaries; e.g., neutron star—black hole merger
  - SGR flares
- Long-duration GRBs
  - Supernovae / hypernovae
- GRB central engine: accreting solar-mass BH
  - Potentially strong GW emission?
- Inspiral phase of binary coalescence well-modeled
  - matched filtering techniques
- Merger phase of coalescence and hypernovae not well-understood
  - burst search techniques

Courtesy of NASA



The black hole first stretches the neutron star into a crescent, swallowing it, and then gulping up crumbs of the broken star in the minutes and hours that followed.

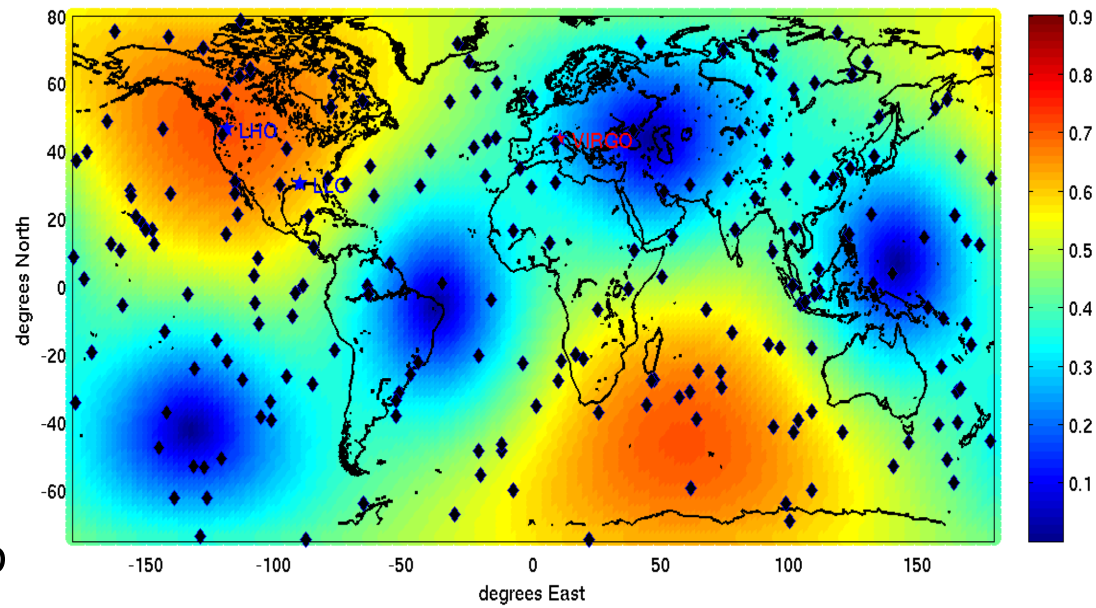
- Review: Nakar, E, 2007, Phys. Rep., 442, 166
- GRB060218/SN2006aj (Campana, S. et al. 2006, Nature, 442, 1008)
- GRB031203/ SN2003lw (Malesani, D et al. 2004, ApJ, 609, L5)
- GRB980425/SN1998bw (Galama, T. J. et al. 1998, Nature, 395, 670)
- GRB030329/SN2003dh (Hjorth, J. et al. 2003, Nature, 423, 847)

Sources: S5 GRBs

>200 GRB triggers, mostly from Swift, some from IPN, INTEGRAL and HETE-2

- **~70%** with double-IFO coincidence LIGO data
- **~40%** with triple-IFO coincidence LIGO data
- **~25%** with redshift
- **~10%** short-duration GRBs
- all but a handful have position information
- **~ 50** occurred during joint operation with Virgo (to be analysed jointly)

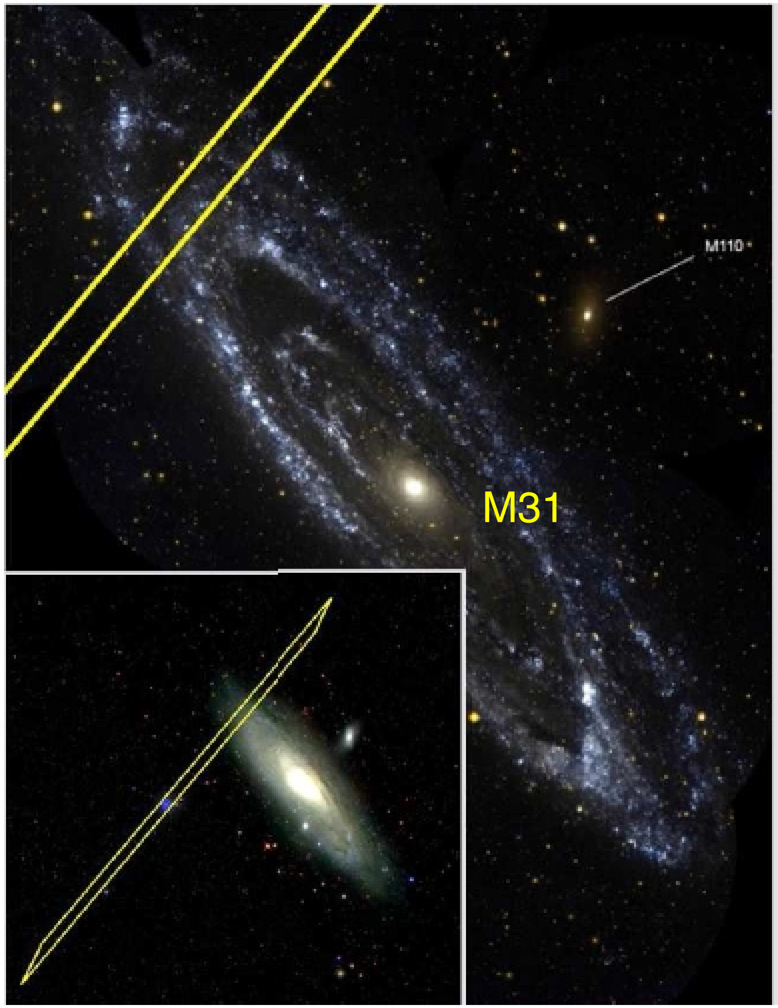
Polarization-averaged LHO antenna factor F_{ave}



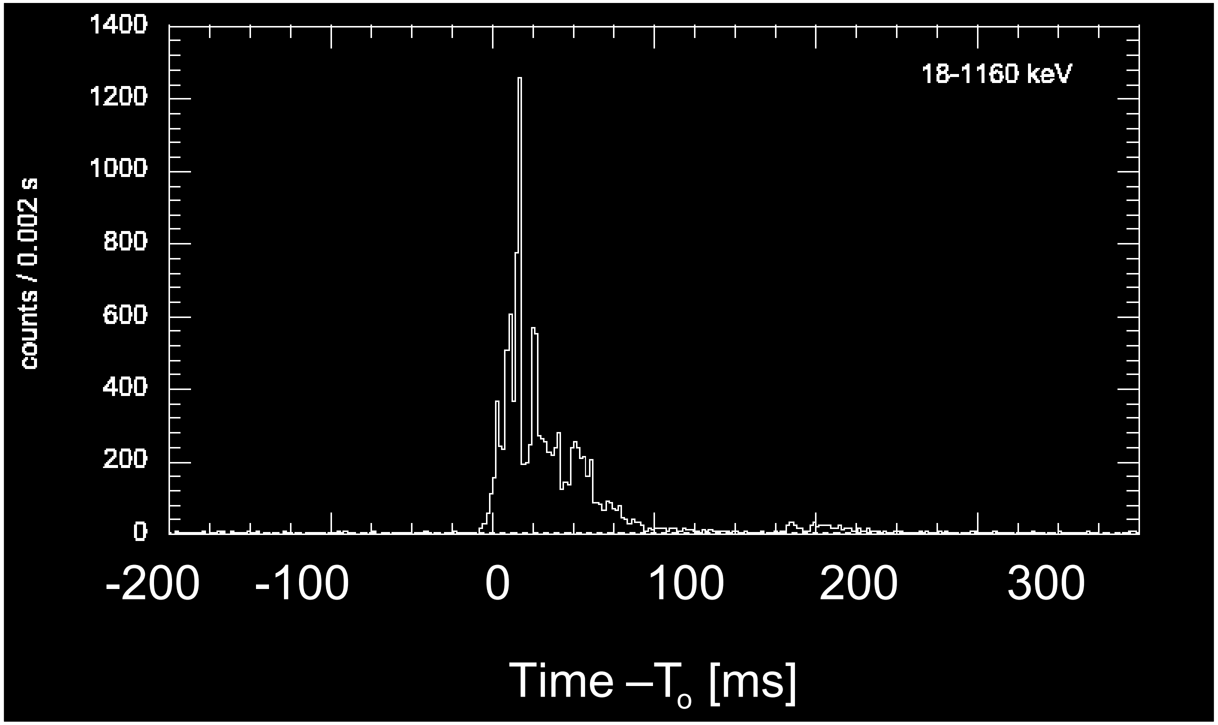
LIGO sensitivity depends on GRB position

Special case: GRB070201

- A short hard gamma-ray burst on 01 Feb. 2007
  - Detected by Konus-Wind, INTEGRAL, Swift, MESSENGER satellites
- Sky position consistent with outer arms of M31 / Andromeda
  - $E_{iso} \sim 10^{45}$ erg at M31 distance (770 kpc)
- Possible progenitor: NS/NS or NS/BH merger
  - Emits strong gravitational waves
- Another possibility: SGR
  - Much weaker GW emission



Electromagnetic Observations



- An “intense short hard GRB” (GCN 6088)
- Duration ~0.15 s, followed by a weaker, softer pulse with duration ~0.08 seconds
- Dec = 42.308 deg
- R.A. = 11.089 deg

Sources: GRBs (GRB070201 Result)

- LIGO H1 and H2 detectors on during GRB070201

- Short-hard GRB search strategy
  – Exercise matched filtering techniques for inspiral waveform search
  – Use burst search techniques to cover unmodeled waveforms (merger phase or exotic inspiral waveform types; SGR GW emission)

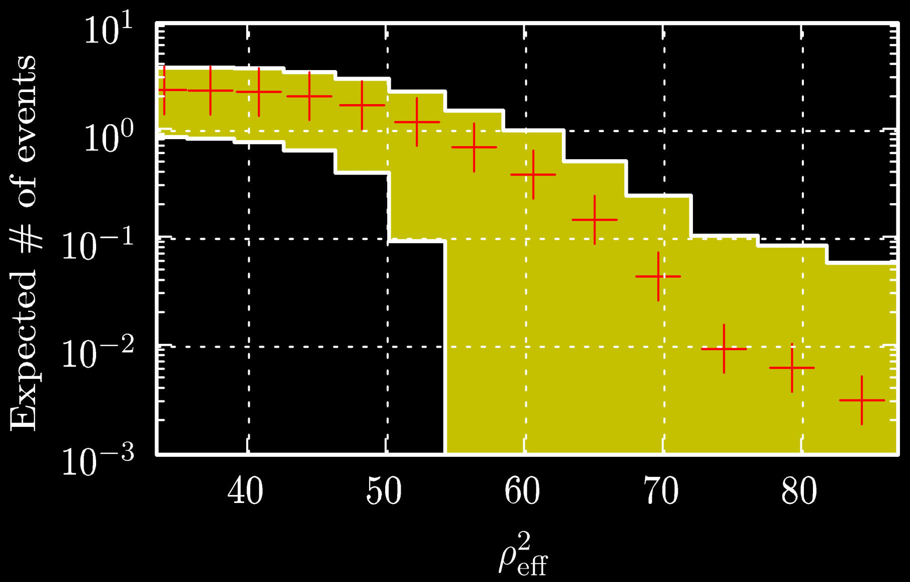
- A detection of GWs could
  – confirm the progenitor (e.g. coalescing binary system)
  – determine the distance to the GRB source

Matched filter search for inspiral

- Cross-correlate data with known signal waveform
  – Function of masses m_1, m_2 of the binary components
  – Look for strong correlation (high SNR) in [-2min,1min] window around GRB time
  – Compare SNRs to those measured in 3-min windows in "background" data a few hours around the GRB time.
  – Unusually high SNR near GRB time = possible GW detection.

Background:

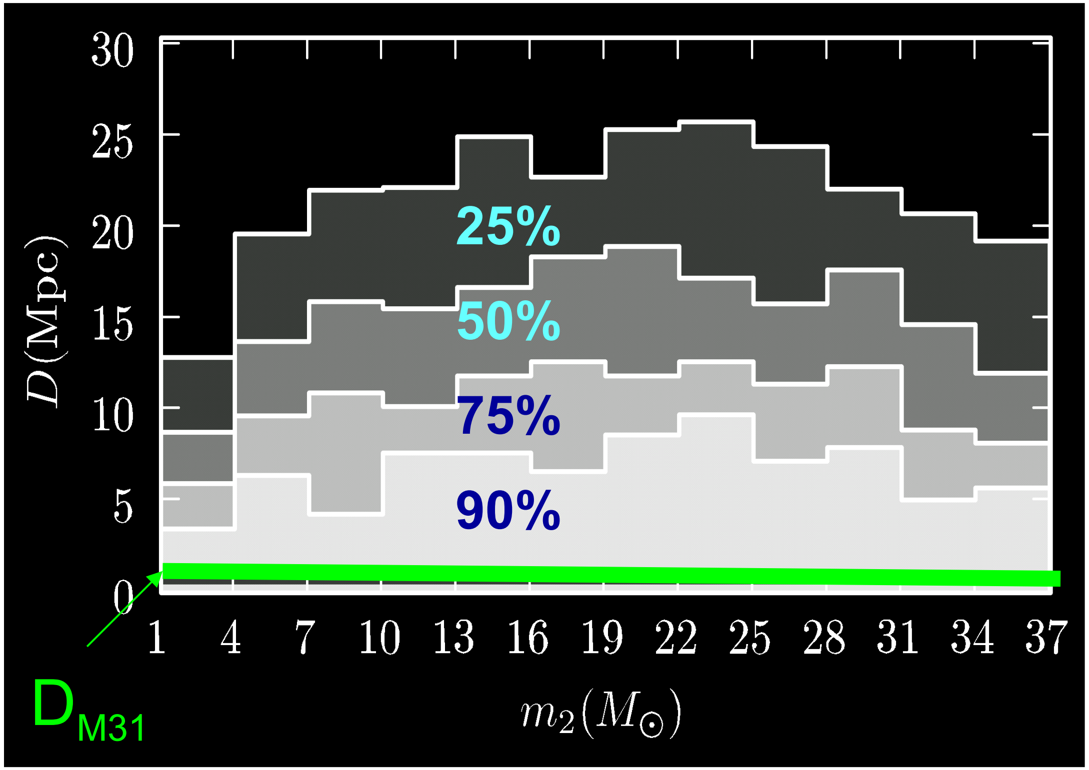
Compact Binary Inspiral Search



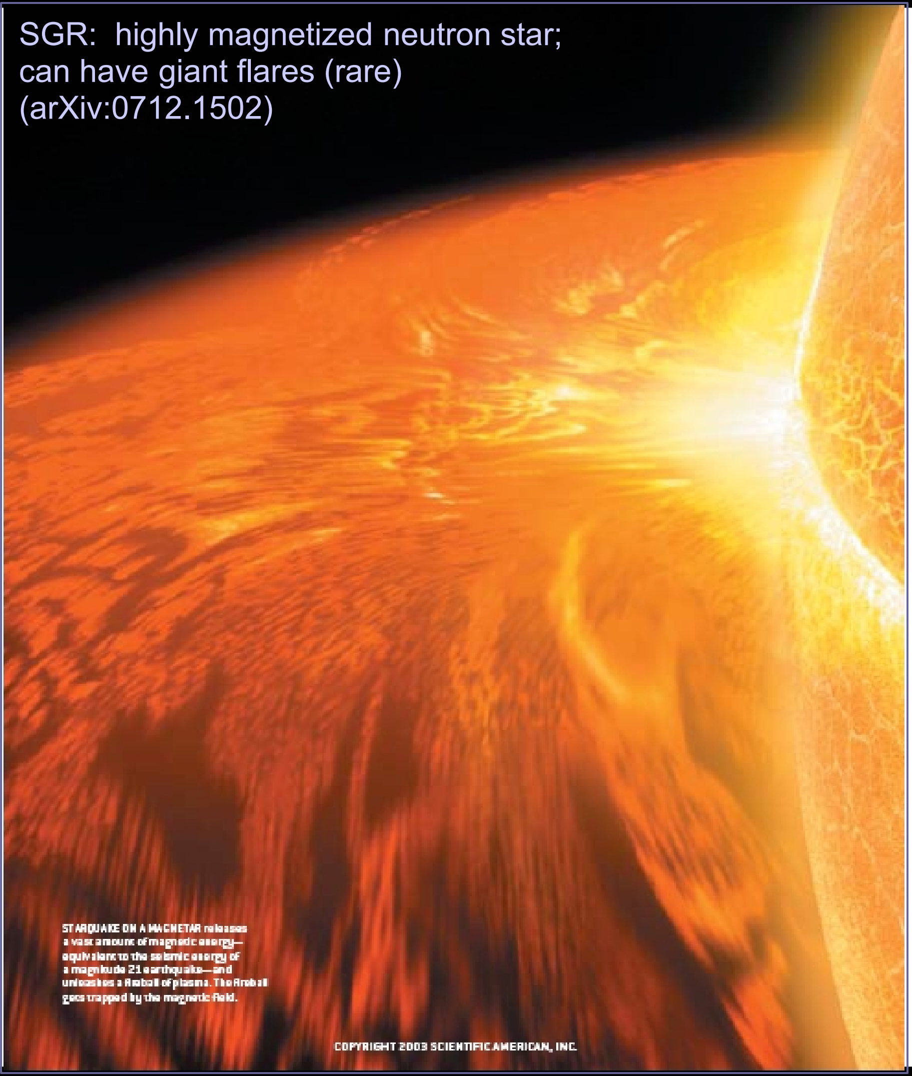
A cumulative histogram of the expected number of background triggers in 180 s based on the analysis of the off source times (+)

Results: Binary Inspiral Search

- No plausible gravitational waves identified (no high SNR triggers near GRB)
- Exclude compact binary progenitor with masses $1\,M_\odot < m_1 < 3\,M_\odot$ and $1\,M_\odot < m_2 < 40\,M_\odot$ with D < 3.5 Mpc away at 90% CL
- Exclude any compact binary progenitor in our simulation space at the distance of M31 at > 99% confidence level



Soft Gamma-ray Repeater in M31?

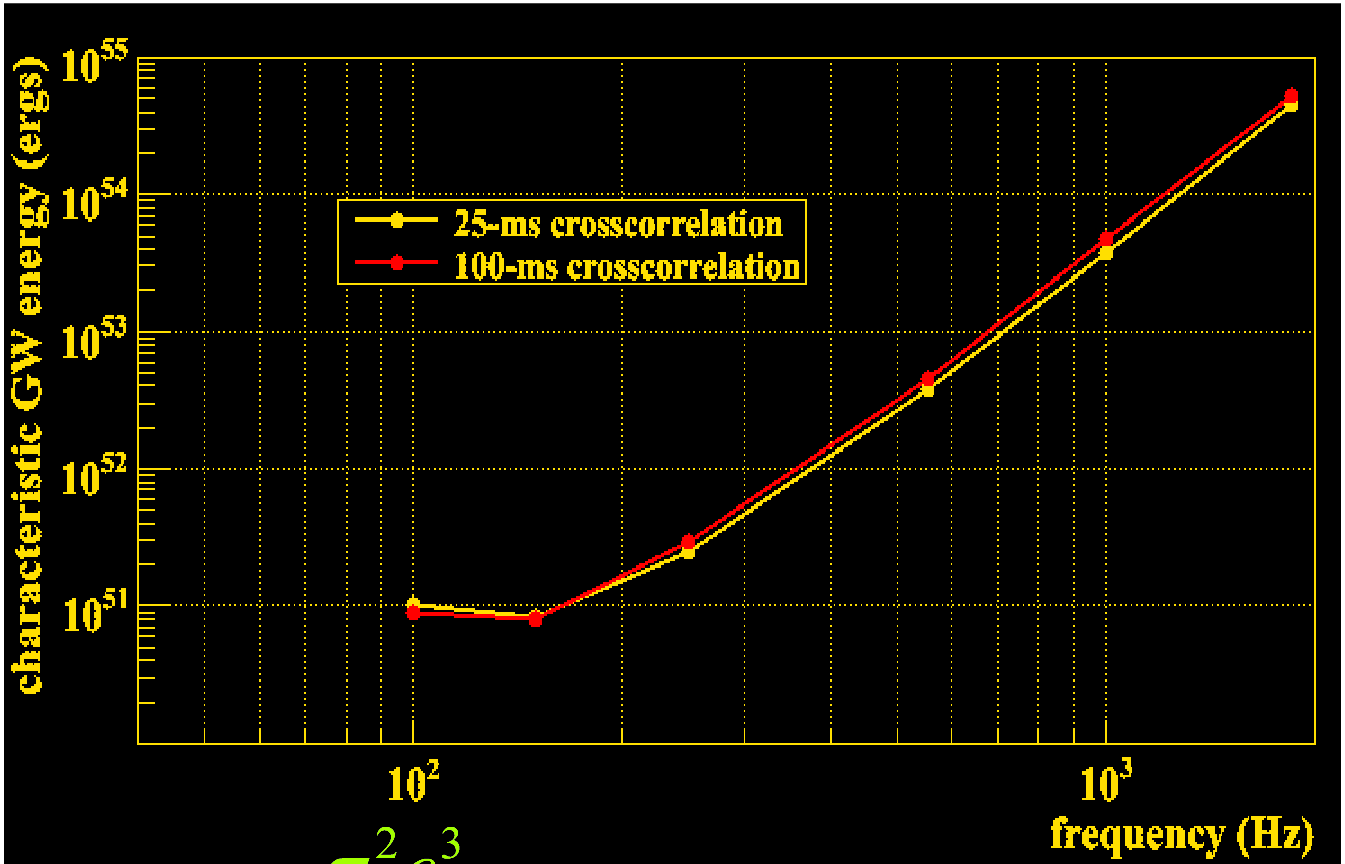


Scientific American, February 2003

- Giant flare from an SGR:
  - a hypothesized explanation for GRB 070201
  - Energy release in gamma rays consistent with SGR model (assuming isotropic emission, with source at D = 770 kpc):
- $$E_{\gamma,\mathrm{iso}} = \phi \times 4\pi D^2 \approx 10^{45}\ \mathrm{ergs}$$
- SGR models predict energy release in GWs to be no more than $\sim 10^{46}$ ergs

Model-independent burst search result

- Measure correlation between H1 and H2 detector data streams in 25ms and 100ms intervals.
- No waveform model needed.
- Energy limits cannot exclude SGR in M31.



$$E_{\mathrm{GW}} \approx \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{\mathrm{rss}}^2 \sim 4.4 \times 10^{-4}\ \mathrm{M}_{\mathrm{sun}}$$

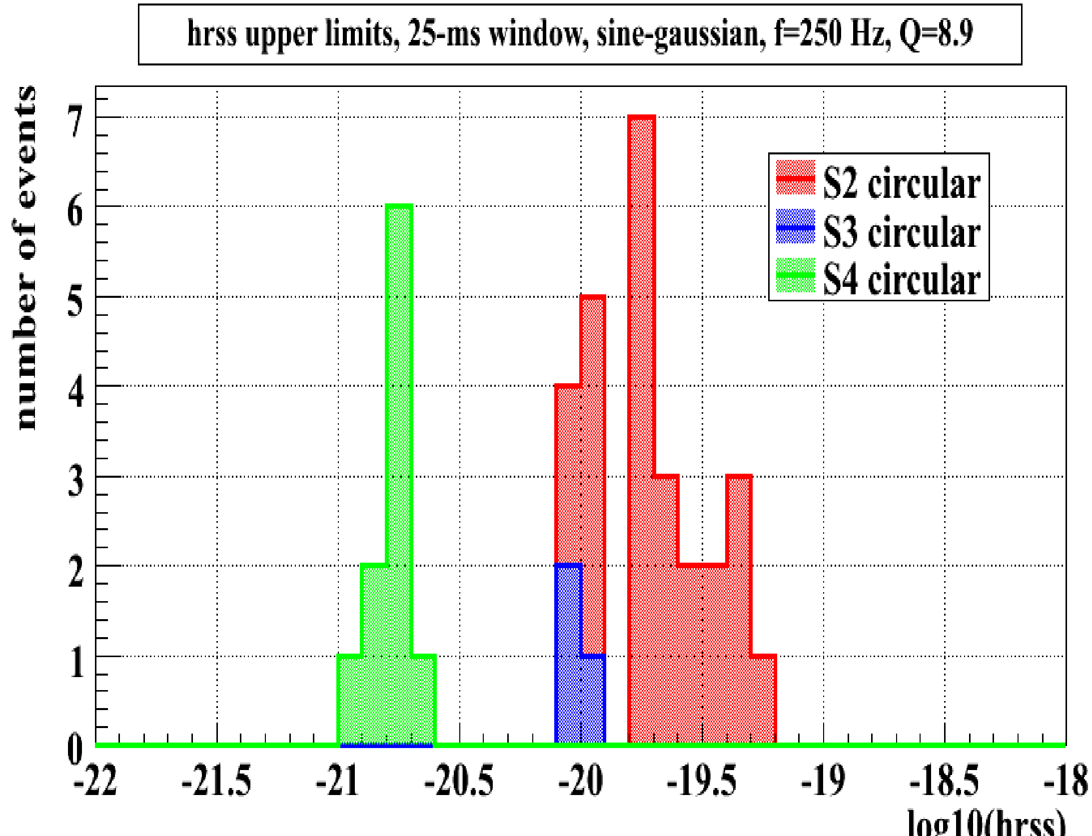
Conclusions on GRB070201

- “Implications for the Origin of GRB 070201 from LIGO Observations” (arXiv:0711.1163; to appear in ApJ)
  - No plausible gravitational waves were identified
  - Excluded compact binary progenitor in M31
  - Corresponding limits on isotropic energy emission in GW do not exclude an SGR model in M31

- Search ongoing for gravitational waves associated with
  - The sample of 213 GRB triggers contemporaneous with LIGO S5 run
  - Other external triggers…

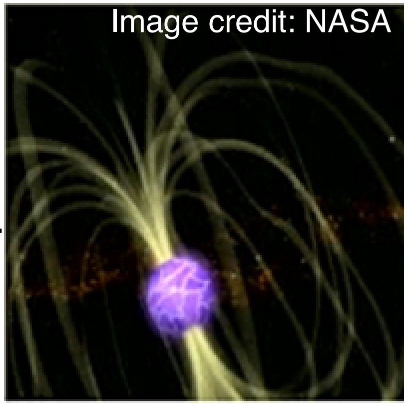
Sources: GRBs (LIGO S2-S4 Results)

- Search for short-duration gravitational-wave bursts (GWBs) coincident with GRBs
  - Analysis based on pair-wise cross-correlation of two interferometers
  - Target GWB durations: < 100 ms; Bandwidth: 40-2000 Hz
  - No GW signals found for any of the 39 GRBs studied.



$$h_{\rm rss} \equiv \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2\right) dt}$$

Sources: Soft Gamma-ray Repeaters (SGRs)



- Possibly highly magnetized neutron stars
- Emit short X- & gamma-ray bursts at irregular intervals
- Occasional giant flares (e.g. SGR1806-20, Dec 27, 2004
  - $<10^{47}$ erg/s peak EM luminosity
  - Up to 15% of GRBs can be accounted for as SGR flares
- May induce catastrophic non-radial motion in stellar matter
  - Galactic SGRs are plausible sources for detection of GWs
- X-ray lightcurve of some giant flares showed quasiperiodic oscillations (QPOs)
  - possibly due to seismic modes of neutron star (Israel et al. 2005, Watts & Strohmayer 2006)
  - well-defined frequencies
- Strategy: Search for instantaneous broadband GW emission at the burst time, and also GWs associated with QPO frequencies.

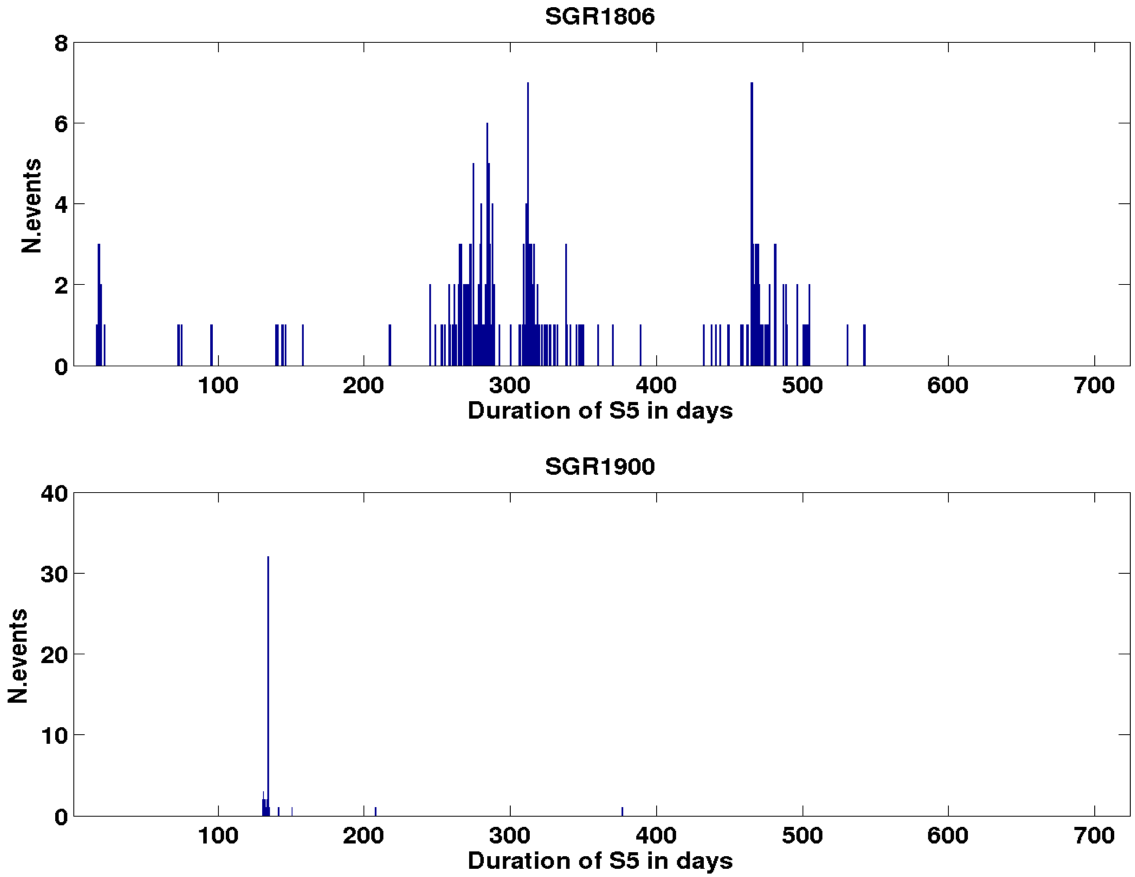
S5 SGR Burst Search

Search for GWs associated with two known Galactic SGRs: 1806 (204 events) & 1900 (58 events).

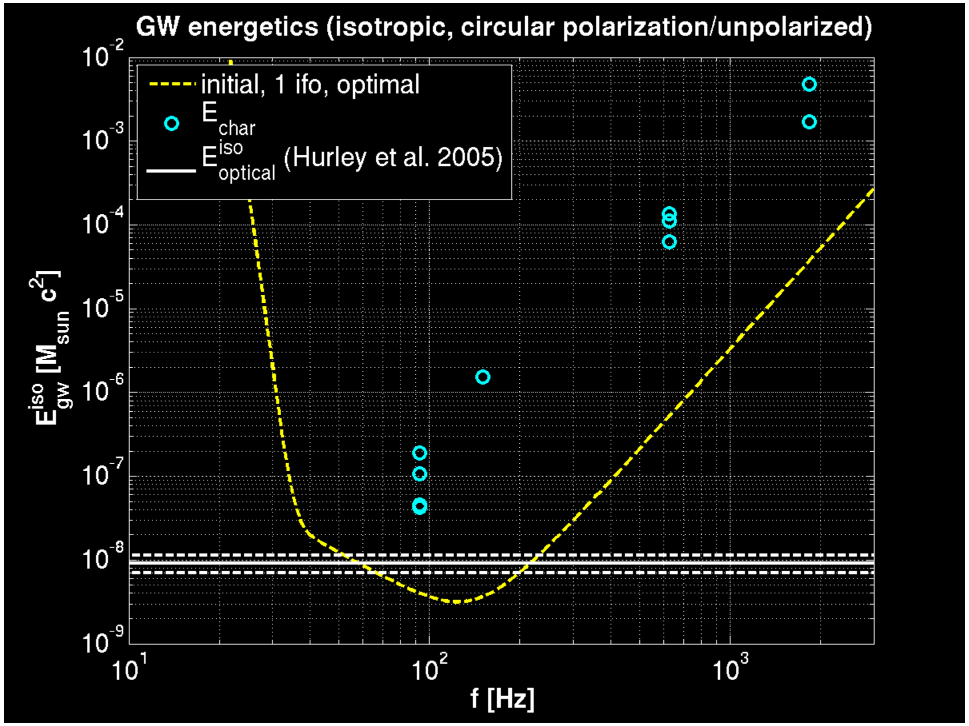
Transient Search

1. Unmodeled emission strategy: Search up to 1 kHz, with durations set by EM timescales.

2. Ringdown emission strategy: Search between 1-3 kHz, durations set by model predictions. Ringdown waveform injections.



SGR 1806-20: Dec 2004 Flare QPO Search

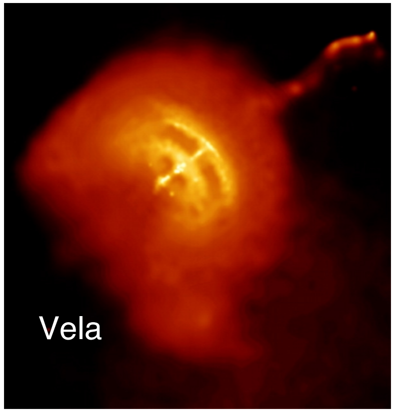


$E(GW)_{iso}$,- characteristic energy radiated in the duration and frequency band we searched (90 % CL)

- Distance [6 - 15] kpc
- Energy ~10^{46} erg
- Plausibly mechanically driven
- For the 92.5Hz QPO observation (150s-260s)
  - $E_{iso,90\%} = 4.3 \times 10^{-8} M_{\odot} c^2$
  - Comparable to the energy released by the flare in the electromagnetic spectrum
  - Abbott *et al.* PRD 76 062003, 2007
- S5: Repeat search for SGR 1806-20 and SGR 1900+14.

Sources: Pulsar Glitches

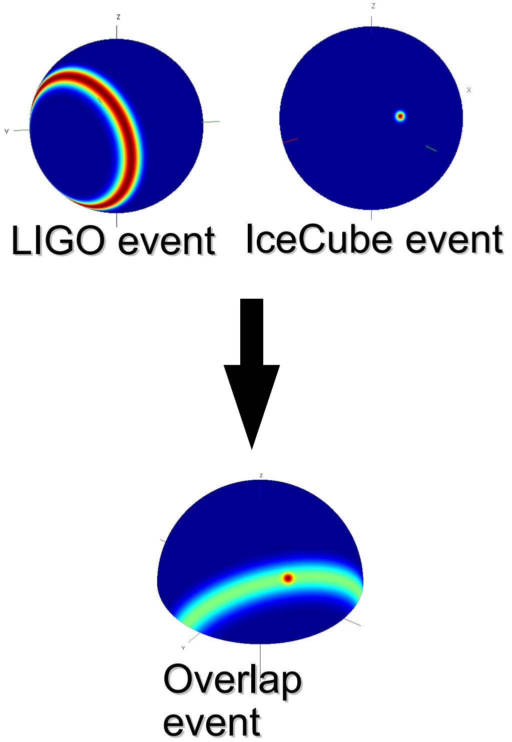
- Radio and anomalous X-ray pulsars exhibit "glitches" in their inferred spin-down rates
  - relaxation of ellipticity in crust / star-quake (younger pulsars)
  - de-coupling of fluid core and solid crust as superfluid vortex lines come un-pinned (older pulsars)
  - phase transitions from hadronic to quark matter, deep in neutron star core
- Glitch may excite non-radial oscillatory modes (~1-3 kHz for the f-mode) which are then damped by GW emission.
- Bayesian model selection search looks for decaying sinusoids around the time of the glitch
  - Clark *et al.*, PRD 76 043003 2007
- Search is being applied to LIGO S5 data from a Vela glitch on 12 August 2006 (PSR B0833-45).



Chandra image

Sources: Neutrinos

- Galactic Supernovae:
  - LIGO/VIRGO is set up to receive SNEWS alert
  - New information on neutrino mass
- High energy neutrinos:
  - May be emitted along with GWs from
    - long GRBs (if progenitor is hypernova)
    - compact binary merger
- Source direction available to ~1 degree.
- LIGO/IceCube coincidence study:
  - Two-stage coincidence:
    - Temporal coincidence
    - Spatial coincidence on sky
  - Aso *et al.*, ArXiv:0711.0107



Other Sources

- Optical Transients
  - High uncertainty in trigger time (several hours)
  - Well-known sky position
    - directional analysis methods are applicable
  - Core collapse supernovae detected during S5 are subject to analysis
  - Uncertainty in trigger time: may not always have data from multiple detectors

- Low Mass X-ray Binaries
  - Low mass star + compact object (neutron star or black hole)
  - GW observations may be used to derive constraints on
    - r-modes in young neutron star
    - accreting onto neutron star

Input needed

- Settle on choice of on-source interval.
  - Traditional: 180 sec asymmetric on-source window.
- Waveforms!
  - Frequency ranges, durations, polarization, any similar info can be used to improve sensitivity
- What ***not*** to bother looking for?

Conclusions

- Published Results
  - GWs coincident with GRBs using S2, S3 and S4 data: no detections
  - SGR1806-20 hyperflare QPO search limits comparable to the emitted energy in the electromagnetic spectrum
  - Search for gravitational-waves coincident with GRB070201:
    - Does not exclude present models of SGRs at the M31 distance.
    - Rules out a compact binary progenitor in M31 at > 99% confidence.

- Expected for S5
  - Network methods are expected to yield better upper limits (if no detection)
  - Large GRB (and also SGR) dataset allows for more significant statistical studies
  - Explore sources beyond gamma-ray emitters