Review of GW Data Analysis

Patrick Sutton

Cardiff University, for the

LIGO Scientific Collaboration

& the Virgo Collaboration

Outline

- LIGO-Virgo Detector Network
- Rules of Thumb for GWs
- Externally Triggered Searches
  - General Procedures
  - Examples
- Future Prospects
- Goals for 2009-2011

Gravitational-wave detectors

Worldwide network of km-scale detectors, operating at/near "initial" design sensitivity.

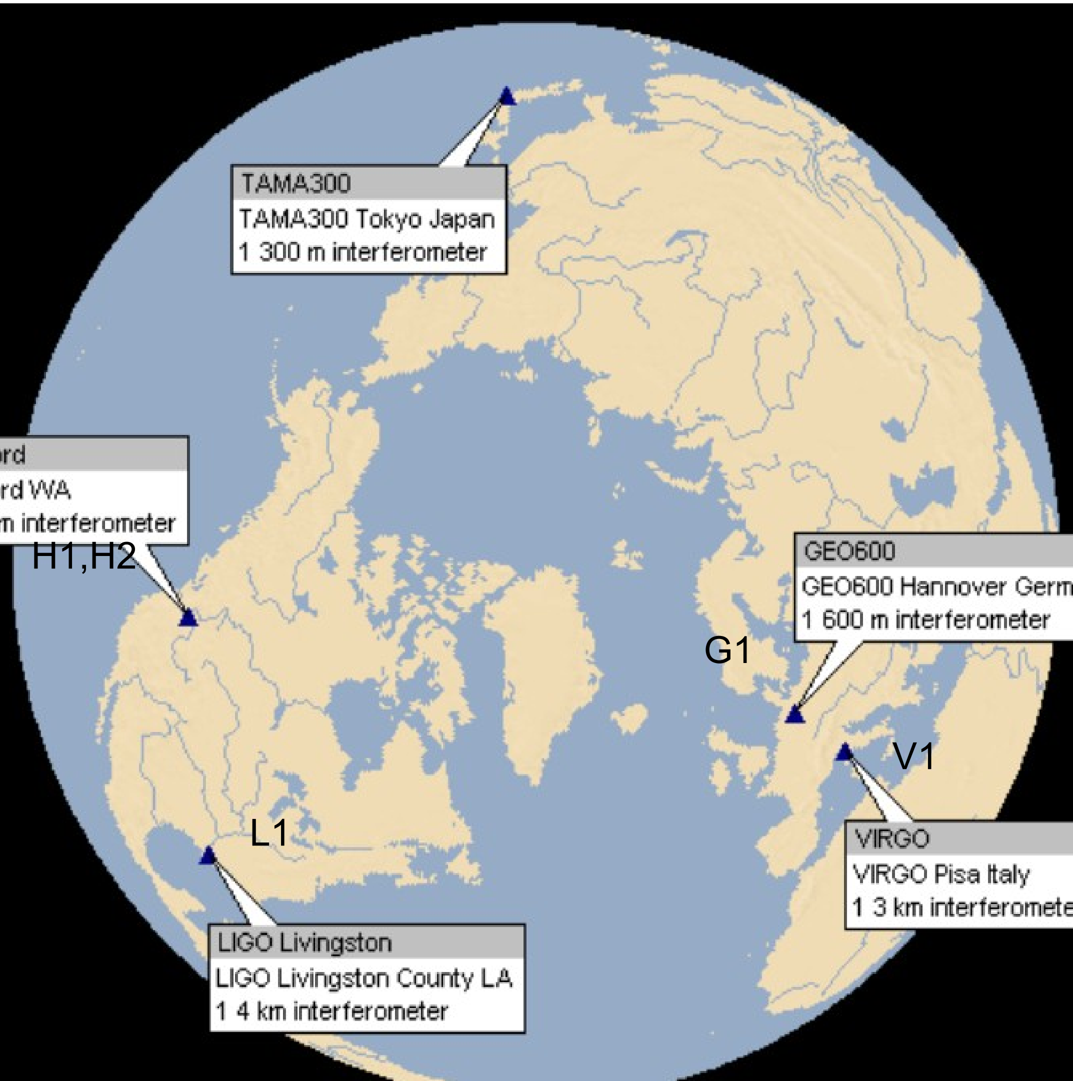
Chances of detection: *plausible* but *not probable*

~ 0.1 / yr for a BNS

~ 0.01 / yr galactic SN

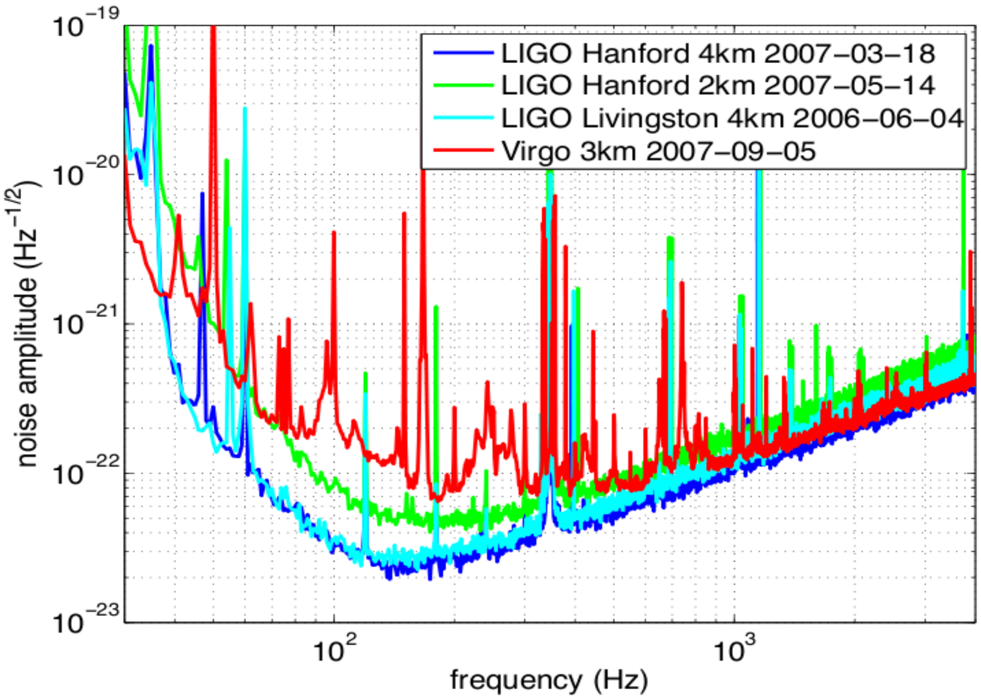
Advanced detectors (c.2014+) should have regular detections

40/yr BNS



The near future

- About to start 1.5 yr data-takir run at (hopefully) 2 x better sensitivity than initial design target.
- Number of direct, confirmed detections of gravitational waves: 0
  - "not probable" ...
  - 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).



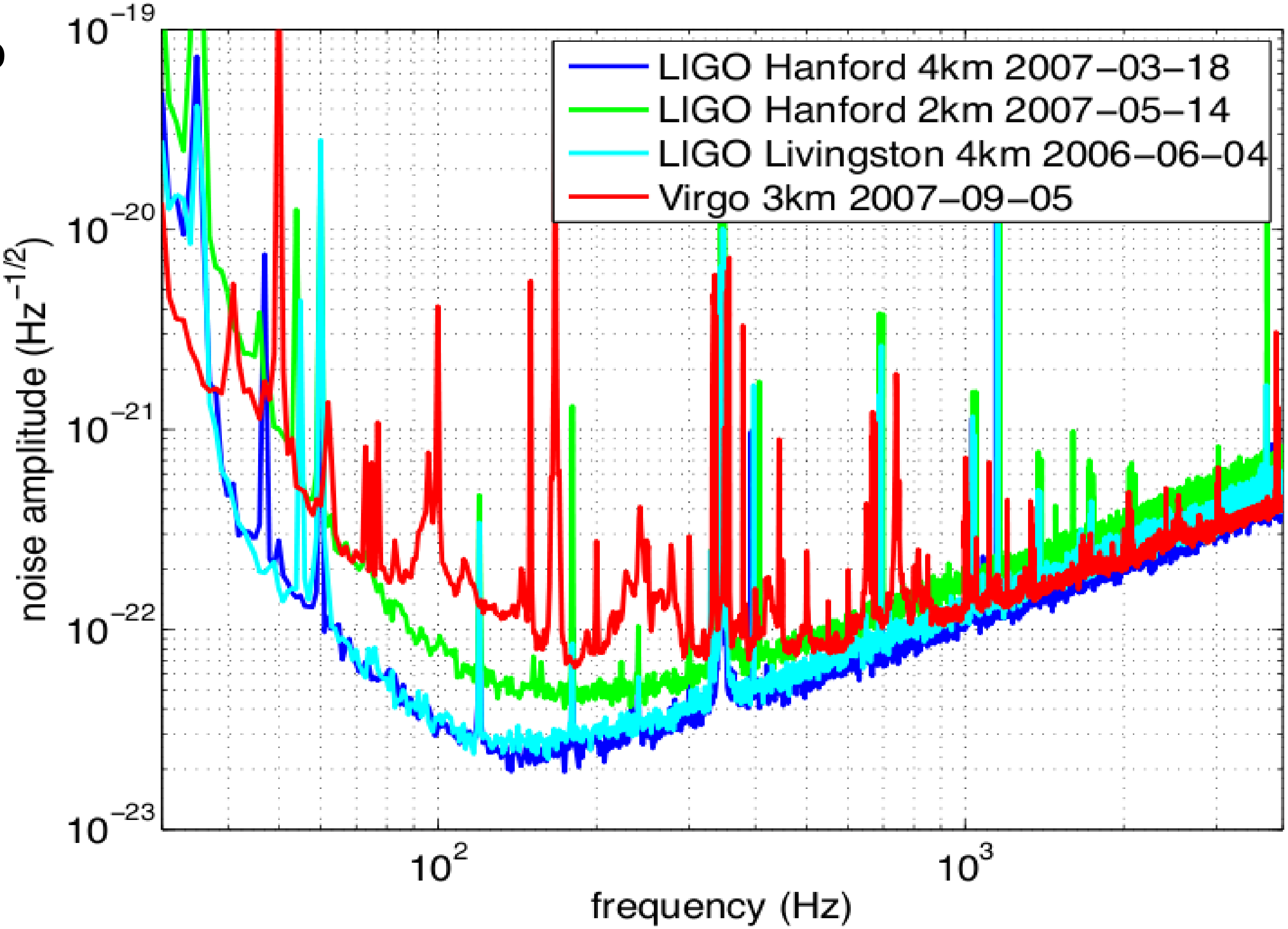
- LIGO Science Run 5 + Virgo Science Run 1 (S5-VSR1)
  - 4 Nov 2005 - Oct 1 2007.

Astrophysical Triggers

- Establish association between gravitational waves and
    - Gamma-ray bursts (GRBs)
    - Soft gamma-ray repeater (SGR) flares
    - Optical transients such as supernovae
    - Neutron star quasi-normal modes
    - Neutrino events (low- and high-energy)
    - …
- 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 ("*the whole is greater than the sum of the parts*").

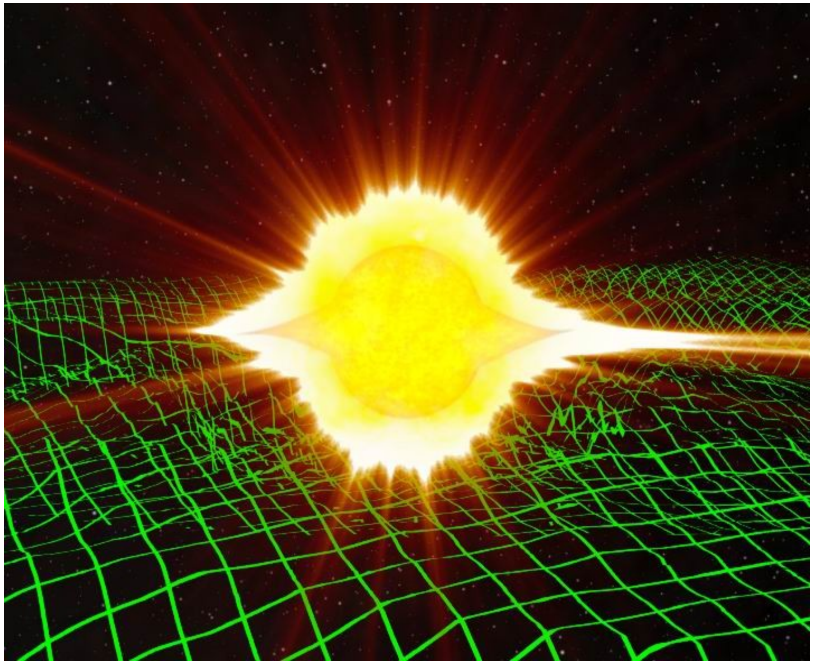
GW detection: basics

- Most sensitive to GWs around 100 – 300 Hz ("the bucket").
- High frequency: minimum detectable GW energy at distance D scales as $E_{GW} \sim f^4 D^2$.
- Energetics favors detecting in the bucket.



Source characteristics

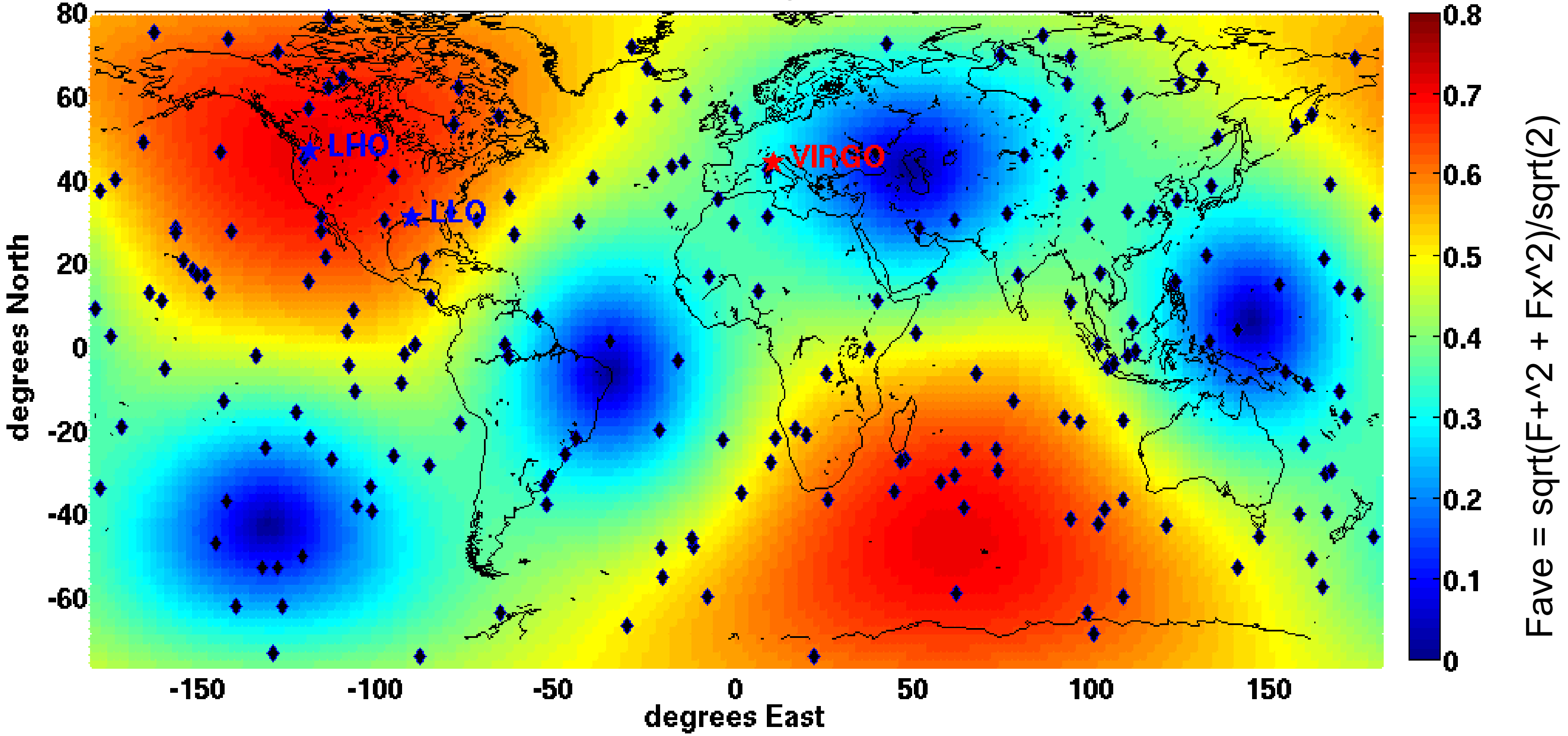
- LIGO-Virgo most sensitive at 100 - 300 Hz. Strong GWs at these frequencies would come from bulk motion of solar-mass compact objects.
  - neutron stars, black holes
  - energetics: catastrophic is better than persistent



- GW emission dominated by time-varying quadrupole moment.
  - Best emitter: a rotating dumbbell (i.e., a binary)
  - Worst emitter: spherically symmetric source (no GW emission!)

Sky Location

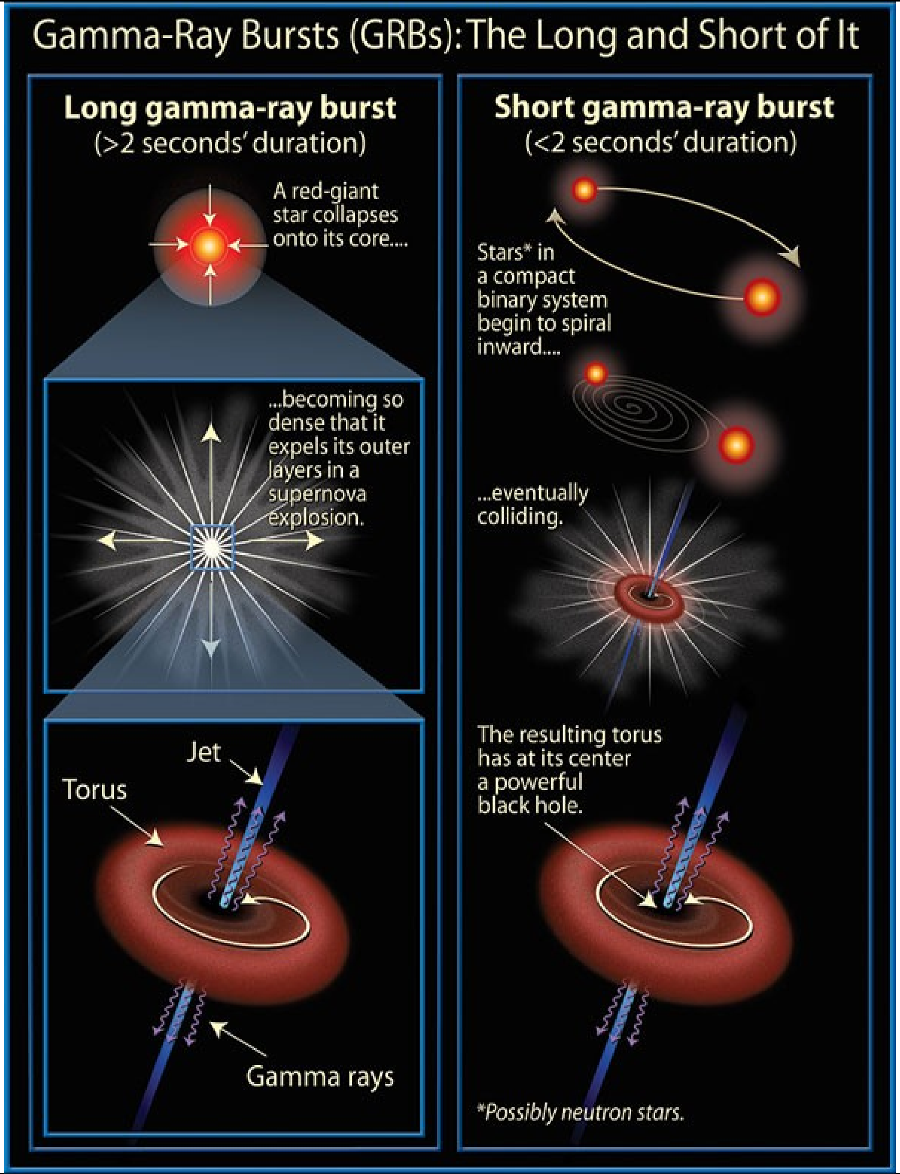
- Sensitivity to GWs also depends on direction of source relative to detector, polarization content of the GW.
- Polarization-averaged antenna response of LIGO-Hanford:
  - dots show location of GRBs during S5-VSR1



Gamma-ray bursts

Long GRBs:

- Core-collapse "hypernovae"
- Modelling is complicated (e.g., Ken Kotake's talk)
- GW emission not well understood.
- Use "burst" detection methods (less sensitive, more robust)



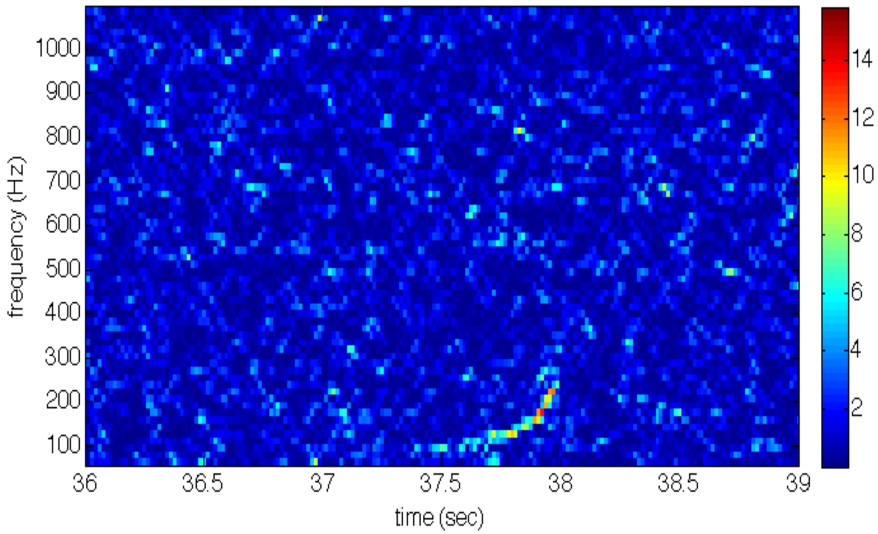
Short GRBs:

- Coalescence of NS-NS or NS-BH binaries.
- Inspiral due to GW emission, clean signal: post-Newtonian expansions, numerical relativity.
- Use "matched filtering" (more sensitive, but only for precise waveform)

Search Methods

- When the signal waveform is unknown (i.e., usually):
  - Cross-correlation of data from pairs of detectors (S2-S4 GRBs)
  - Excess power analysis, usually coherent combinations of data from several GW detectors (aperture synthesis)
  - Both look for any GW signal in th sensitive band of the detectors (~ 60 – 2000 Hz) with duration from ~1 ms to ~1 sec.
- When the signal waveform is known in advance (e.g., a binary inspiral progenitor of short GRBs):
  - Matched filtering

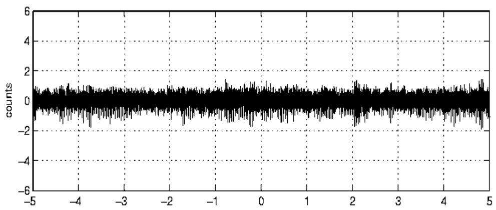
Excess power map: A simulated 1.4-10.0 Mo neutron star – black hole inspiral at an effective distance of 37 Mpc, added to simulated H1-H2 noise



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

- Optimal procedure for finding known signal in Gaussian noise.
- Essentially, correlate data with expected waveform ("template"):

Data



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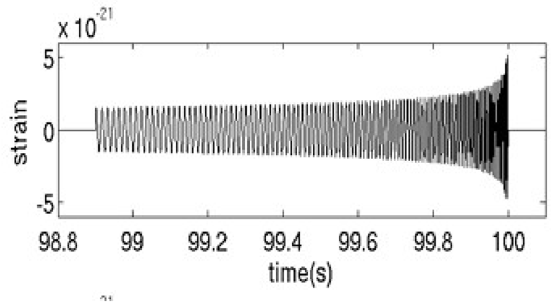
Template



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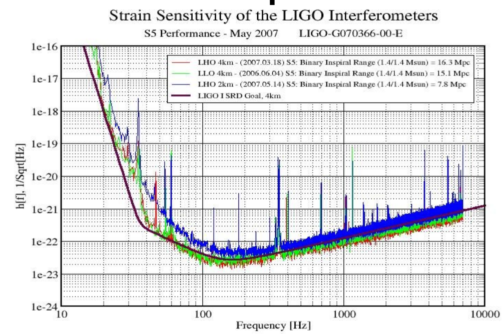
Power Spectrum



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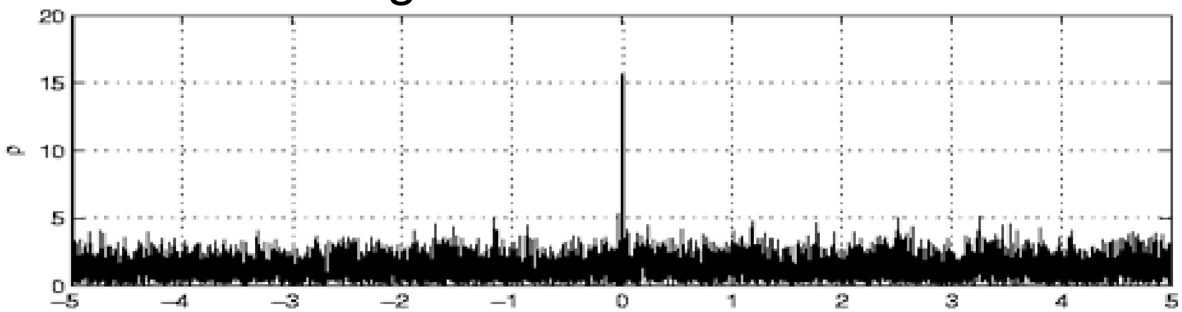
Signal to Noise Ratio

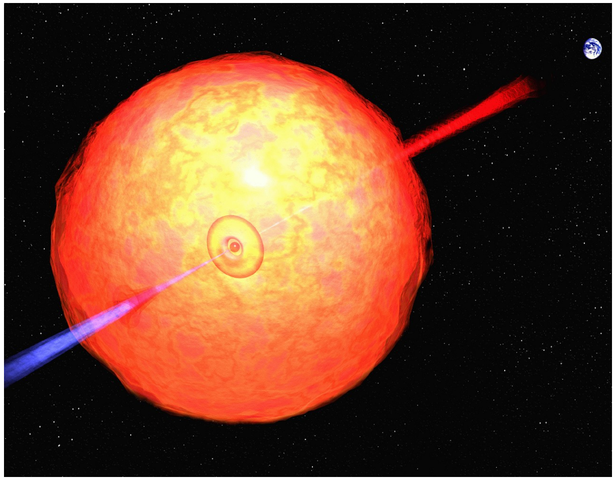


The catch(es) ...

- General issues to keep in mind (Frederique Marion's talk):
  - The data are non-stationary, containing many "glitches".
  - Real GW events are rare and weak.
- Coincidence is our most powerful tool to reduce the background.
  - Need to see signals in multiple detectors at the same time (within light travel time between sites).
- Also apply consistency tests were possible, e.g.:
  - Matched-filter search: χ^2 test of fit of transient to the template.
  - Burst search: data from all 3 sites consistent with a GW having only two polarizations, data in different detectors shows correlation.
- Tuning:
  - Estimate background rate from time slides.
  - Estimate efficiency by adding simulated GWs to the data.
  - Searches tuned to maximize efficiency at fixed background rate (e.g., 0.1/yr for bursts).

How astrophysical triggers help

- Know time of event
  - Search within an astrophysically motivated time window.
    - GRB bursts: [-120,+60] s
    - GRB inspirals: [-5,+1] s
  - Higher detection probability at fixed false alarm probability.
- Often know sky position
  - Only look there!
  - Can account for time delay, antenna response of instrument in consistency tests
- 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.

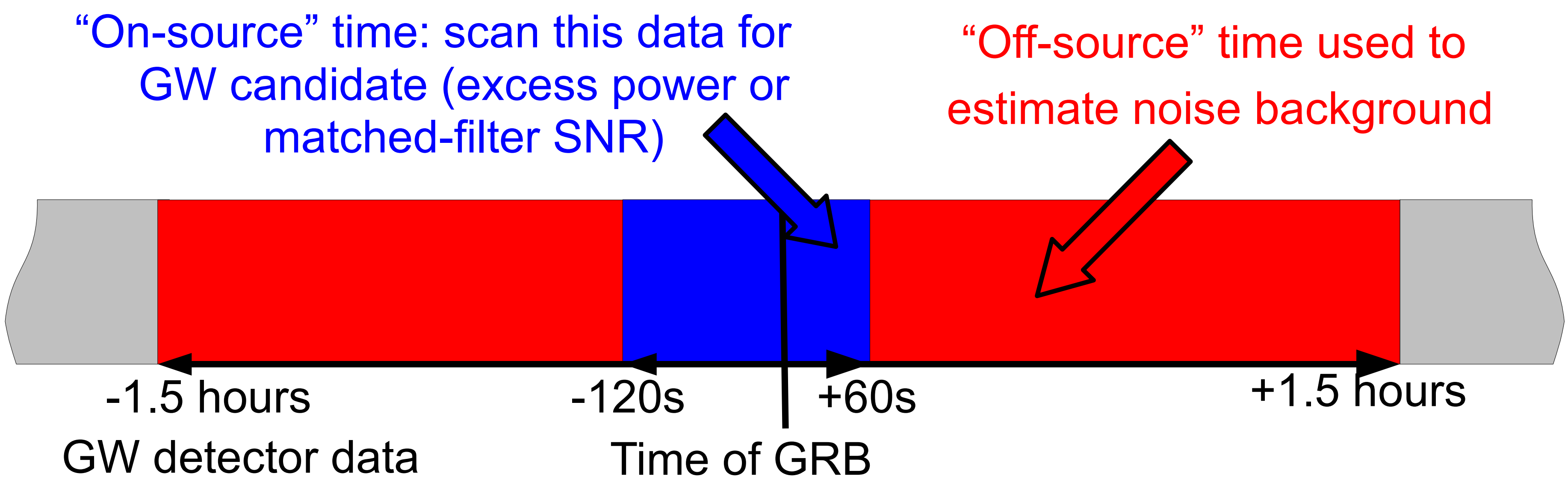


- Sensitivity improvement:
  - Often a factor of ~2-3 in amplitude / 4-10 in energy.

What we *don't* use (GRBs)

- GRB duration
  - except for classification of long/short GRB for matched filtering search
- Temporal structure of the EM emission
  - Including, *e.g.*, late-time flares or other activity.
- Redshift
  - Likely use: *ignore* GRBs with known z (unless *very* low, <0.1)!
- Fluence
  - etc.

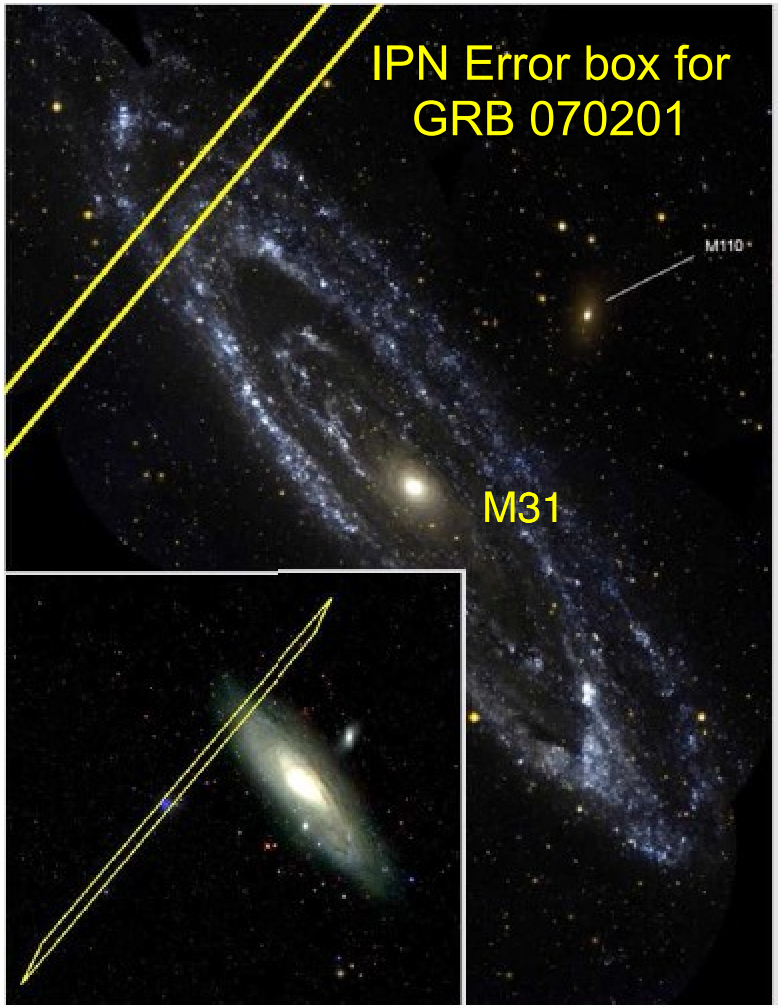
A typical triggered search



- Estimate significance of on-source events by comparing to off-source.
  - Possible GW detection := significant event
- Estimate minimum detectable GW signal amplitude by adding simulated GWs to the data and re-analysing.
  - Upper limit := signal amplitude/energy at which 90% of simulations are louder than the loudest on-source event.

Example: 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

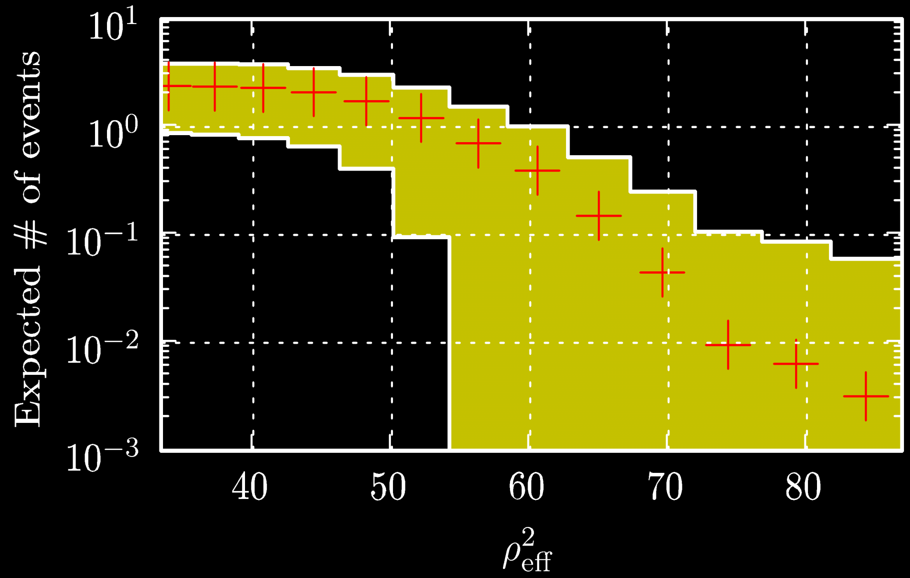


Matched filter search for inspiral

- 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:

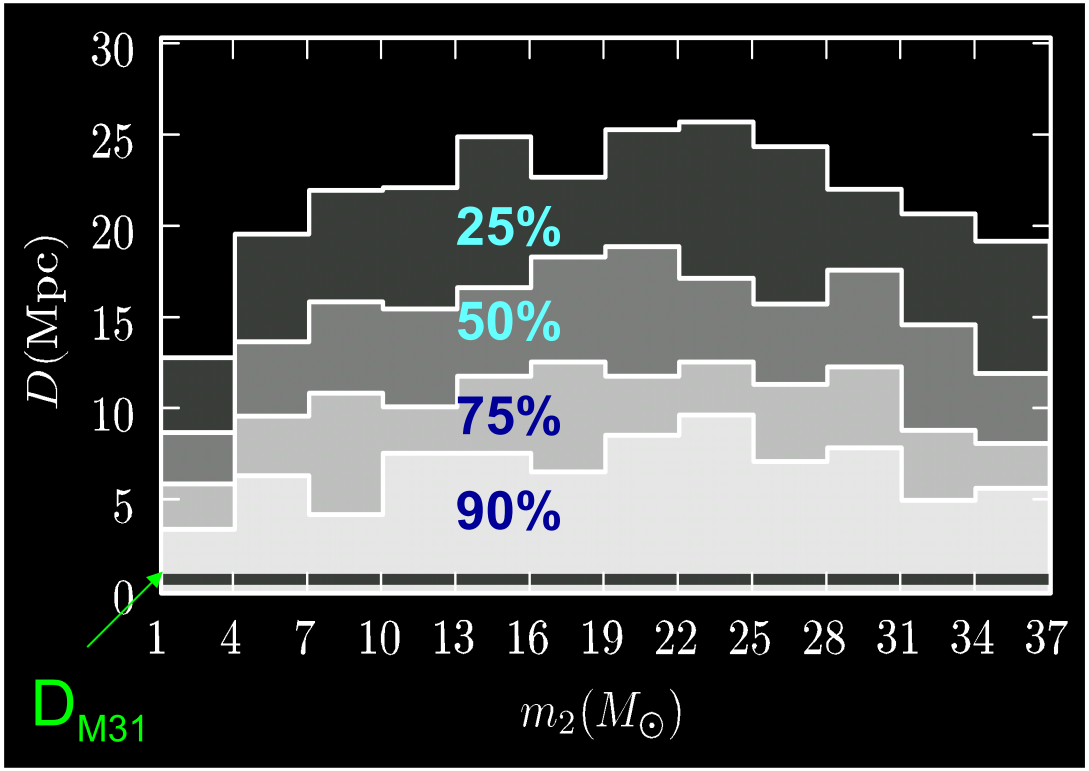
Compact Binary Inspiral Search



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

Results: inspiral search

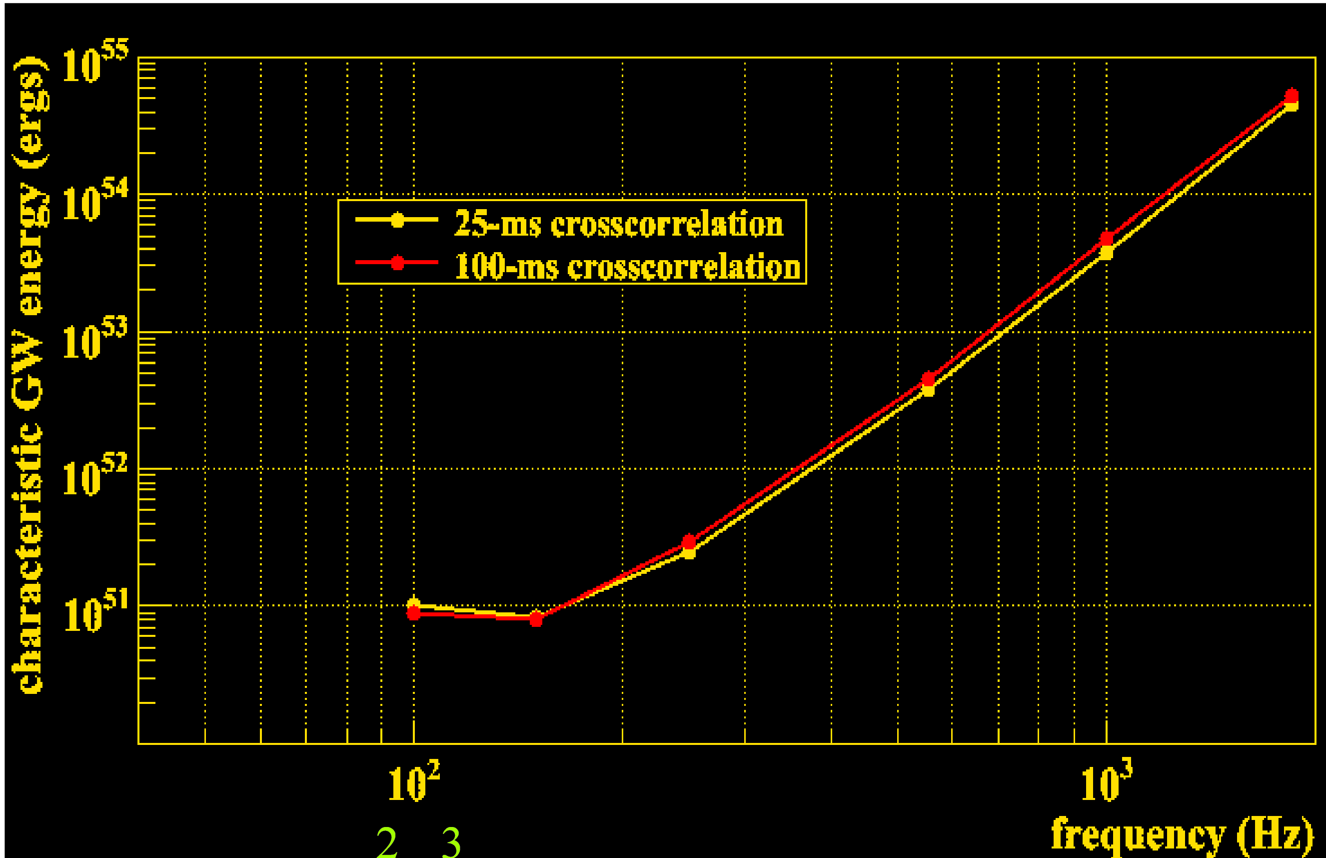
- No plausible gravitational waves identified (no high SNR triggers near GRB)
- Exclude compact binary progenitor with masses $1\ M_\odot < m_1 < 3\ M_\odot$ and $1\ M_\odot < m_2 < 40\ M_\odot$ with D < 3.5 Mpc away at 90% CL
- Exclude any compact binary progenitor in our simulation space at the distance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



- **Abbott et al., ApJ 681 (2008) 1419.**

Results: burst search

- Measure correlation between H1 and H2 detector data streams in 25ms and 100ms intervals.
- No waveform model needed.
- Plot: Energy limits vs. GW frequency from cross-correlation analysis
  - Energy limits cannot exclude SGR in M31.
- EM: $E_{iso} \sim 10^{45}$ erg at M31 distance.

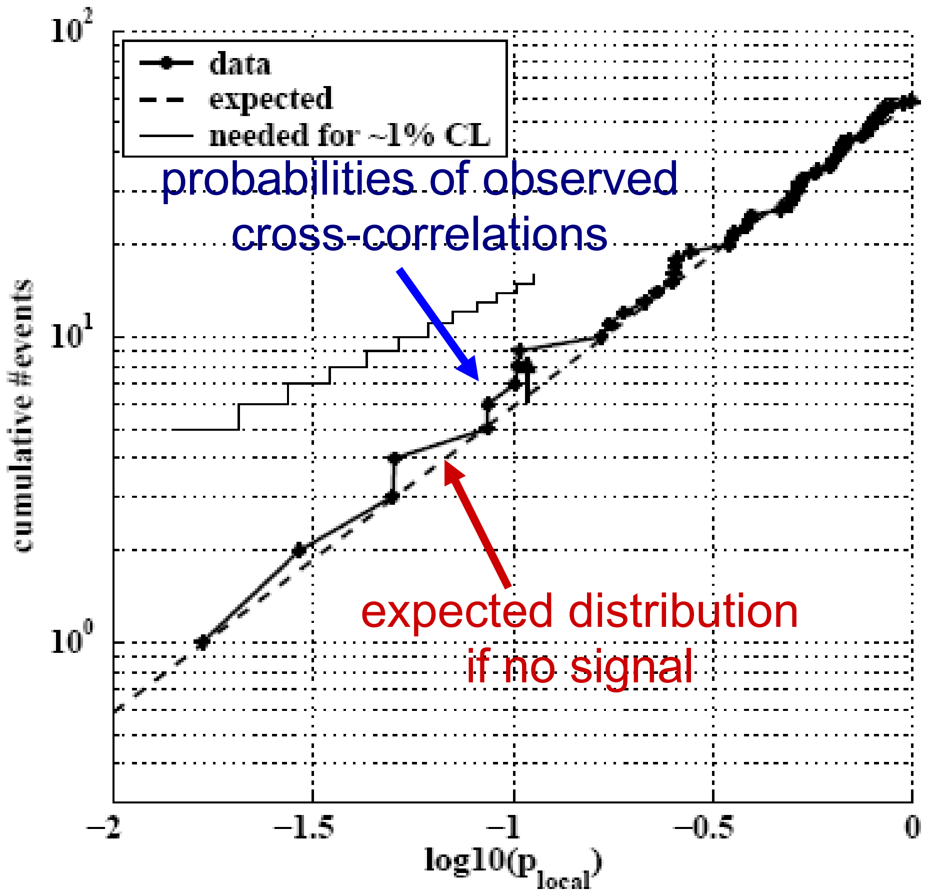


$$E_{GW} \approx \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{rss}^2 \sim 4.4 \times 10^{-4}\ \mathrm{M_{sun}}$$

Statistical search

- Statistical search for cumulative effect of many weak GWs associated with GRBs.
  - Plot: binomial test comparing distribution of probabilities of most significant events to that expected for null hypothesis.
- Local probability, p_{local} = probability of background yielding maximum cross correlation measured in the on-source.
- Distribution under null hypothesis (dashed line)
- Most significant excess has a 1 in ~7 chance of occurring model.

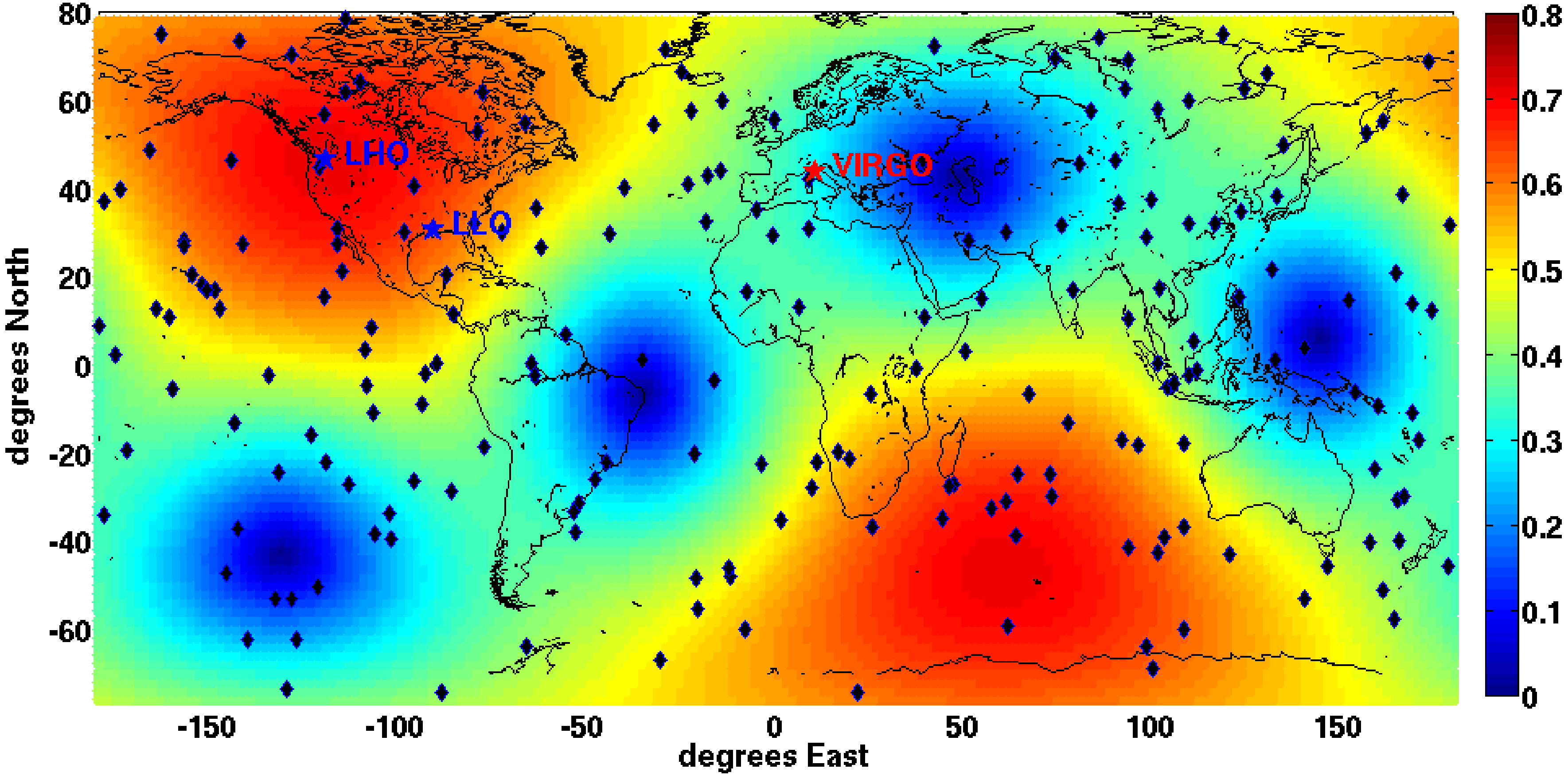
36 GRBs from S2-S4



Abbott et al., PRD **77** 062004 (2008)

S5-VSR1 GRB set

- Nov 2005 – Oct 2007: 212 GRBs (analysis in progress)
  - 137 with 2+ LIGO-Virgo detectors operating.
  - ~25% with redshift ~10% short



Burst search: sensitivity

- For narrowband signals, can convert upper limit on GW amplitude h_{rss} to lower limit on distance assuming some E_{GW}:

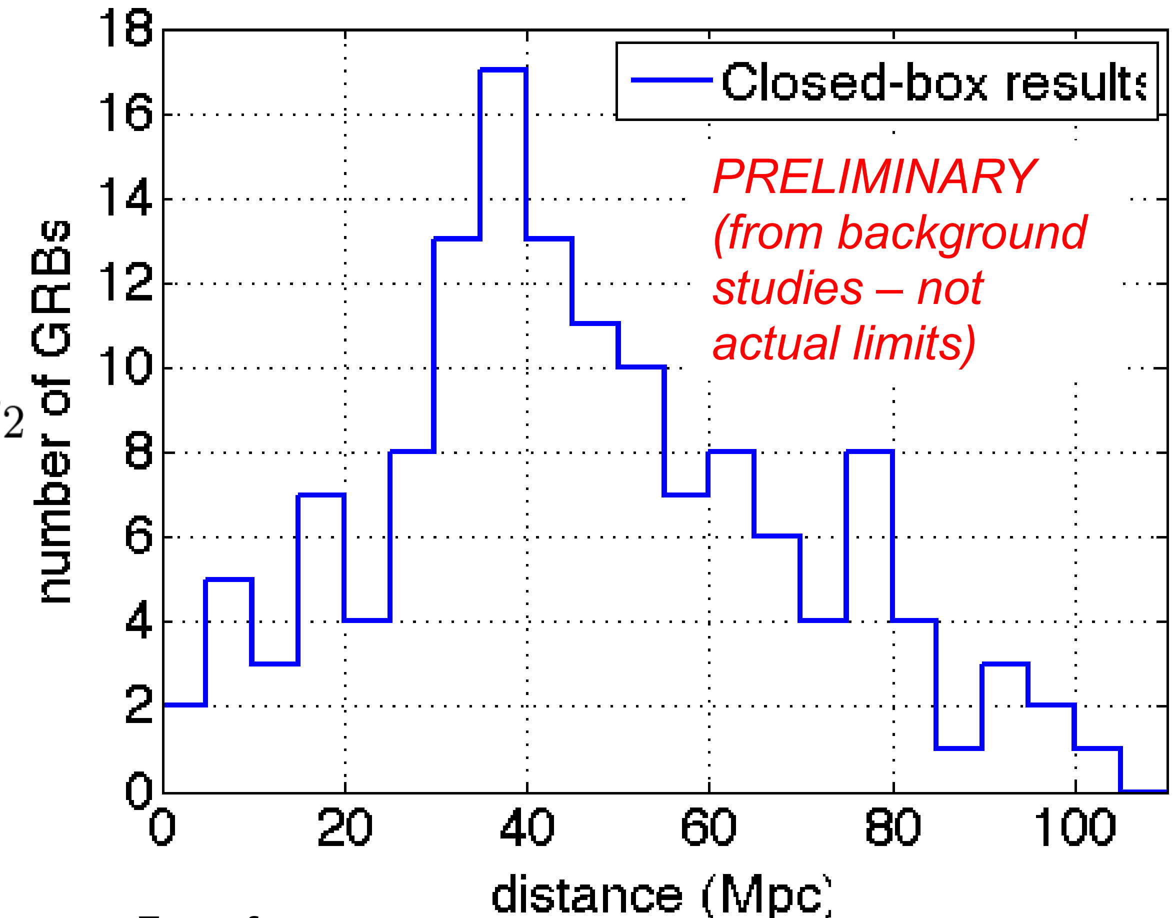
$$D = \left(\frac{G}{\pi^2 c^3} \frac{E_{GW}}{f_0^2 h_{rss}^2} \right)^{1/2}$$

- Plot: using

$E_{GW} = 0.1\ M_{\odot}\ c^2$

$= 1.8\times10^{53}$ ergs

(optimistic!)



E_{GW} references:

Short GRBs: Merger of NS-BH: 0.01-0.1 Msol c^2 in 100-200Hz

Long GRBs: Van Putten, ~0.2 Msol c^2 in LIGO-Virgo band

Rate density of GRBs

Rate references:

[1] E. Liang, et al., ApJ. 662, 1111 (2007)

[2] R. Chapman,et al., MNRAS 382, L21 (2007)

- **Typical distance limits:**

$$D \sim 15 \text{ Mpc} \left(\frac{E_{\rm GW}^{\rm iso}}{0.01 M_\odot c^2} \right)^{1/2}$$

- **Long GRBs**:
  – Local rate density of low-luminosity long GRBs is estimated at R_{obs} ~ 300 - 700 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [1,2].
  – *A priori* probability of observing GWs from a low-luminosity GRB during S5-VSR1:

$$\langle N_{\rm long} \rangle \simeq R_{\rm long}^{\rm obs} \left(\frac{4}{3} \pi D^3 \right) T \frac{\Omega}{4\pi}$$

$$\langle N_{\rm long} \rangle \simeq 1.0 \times 10^{-3} \left(\frac{R_{\rm local}^{\rm obs}}{500 \text{ Gpc}^{-3} \text{yr}^{-1}} \right) \left(\frac{E_{\rm GW}^{\rm iso}}{0.01 M_\odot c^2} \right)^{3/2}$$

0.01 $M_o c^2$ probably optimistic!

Rate density of GRBs

- **Short GRBs**: Local rate density R_{obs} ~ 8-30 Gpc^{-3} yr^{-1} [3]

$$\langle N_{\rm short}\rangle \;\simeq\; 2.0\times10^{-5}\left(\frac{R^{\rm obs}_{\rm short}}{10\ {\rm Gpc}^{-3}{\rm yr}^{-1}}\right)\left(\frac{E^{\rm iso}_{\rm GW}}{0.01M_\odot c^2}\right)^{3/2}$$

- **S6-VSR2**: Distance sensitivity x2, more GRBs from Fermi's larger field of view. Detection rates increase by factor ~40:

$$\langle N_{\rm long}\rangle \;\simeq\; 5.6\times10^{-2}$$
$$\langle N_{\rm short}\rangle \;\simeq\; 1.0\times10^{-3}$$

Rate references:

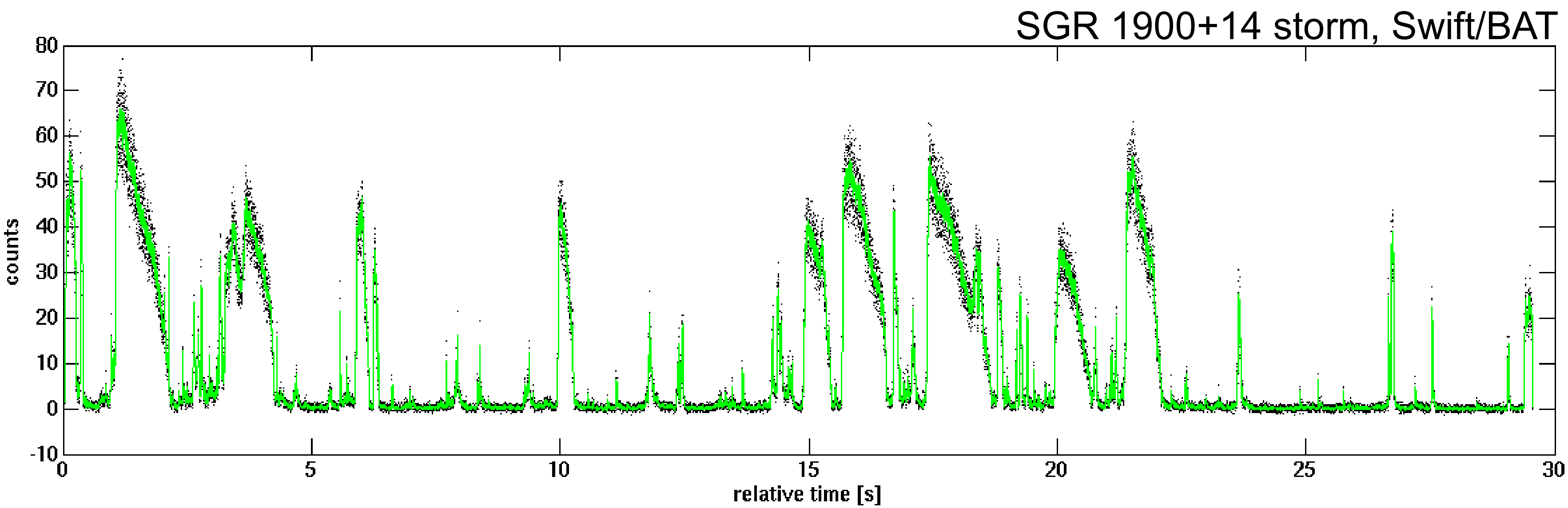
[3] D. Guetta & T. Piran (2005), astro-ph/0511238

Other triggered searches

(a non-exhaustive list)

SGR 1900+14 Storm

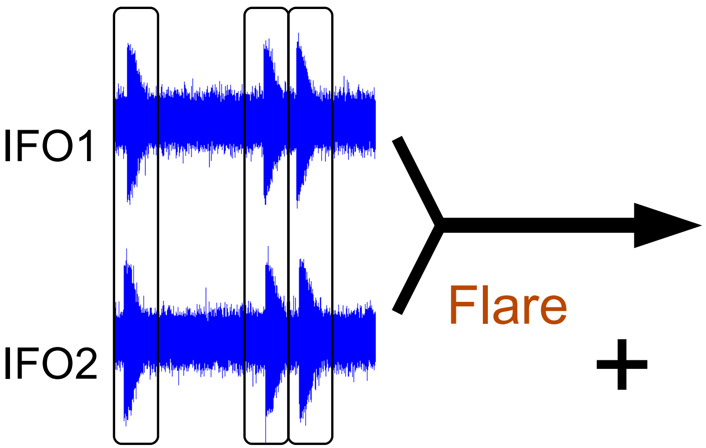
2006 March 29 SGR 1900+14 storm: >40 bursts in ~30 s.

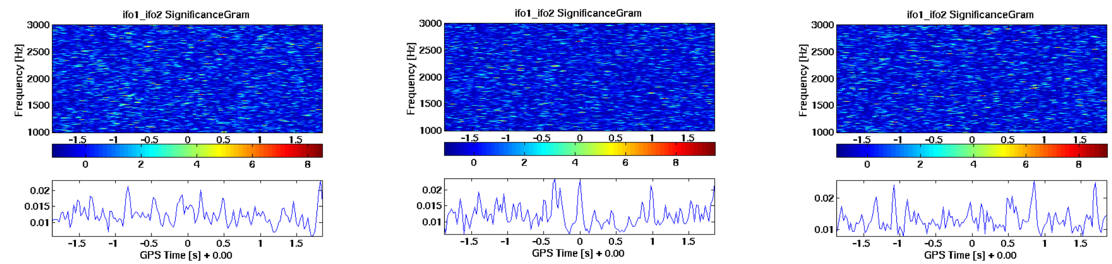


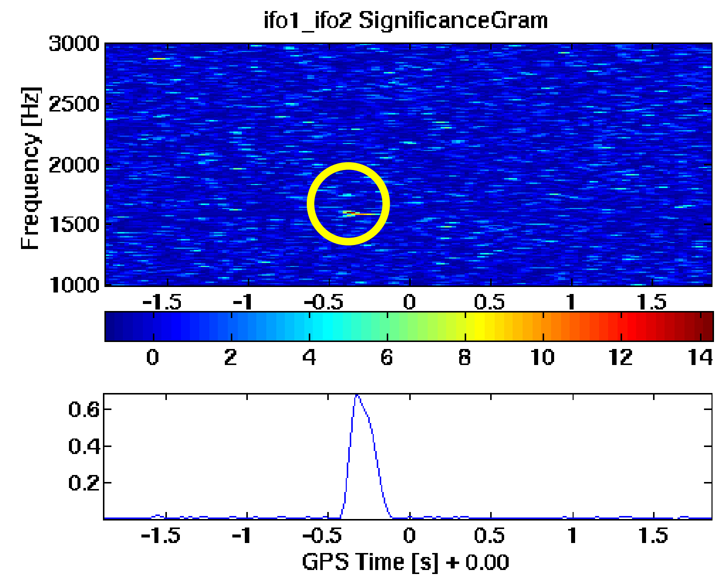
New GW search approach:

- "Stack" the GW data around the times of individual flares to build up weak GW signals associated with the flares.
  - Improve limits on E_{GW} by an order of magnitude (2×10^{45} erg to 6×10^{50} erg, depending on GW waveform type).
  - Abbott et al., arXiv/0905.0005.

“Power stacking” search

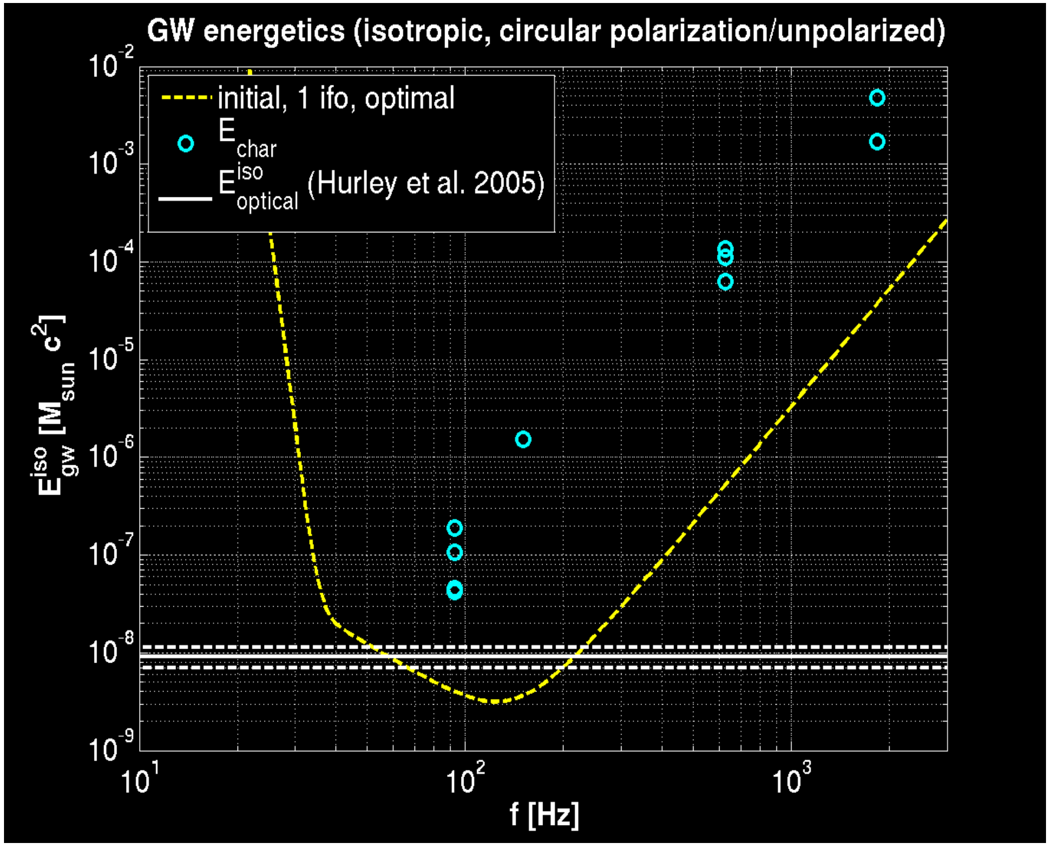






- Add up time-frequency energy maps centred on multiple flare times.
- Build up weak GWs associated with each flare to potentially detectable level.
  - Pro: Suited for unmodeled search
  - Pro: Less timing precision needed
  - Pro: N^1/4 amplitude sensitivity gain
  - Con: Less sensitive than coherent time-series stacking

SGR 1806-20 QPO Search



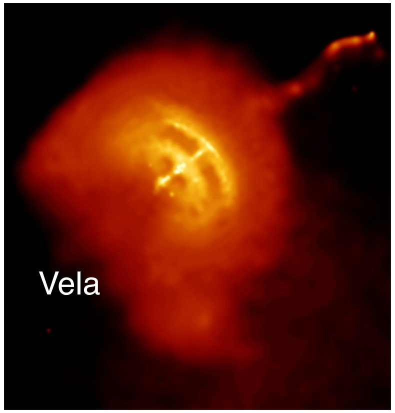
$E(GW)_{iso}$,- characteristic energy radiated in the duration and frequency band we searched (90 % CL)

Abbott *et al.* PRD 76 062003, 2007

- Target Dec 27 2004 giant flare.
- X-ray lightcurve showed quasiperiodic oscillations (QPOs)
  - possibly seismic modes of neutron star (Israel et al. 2005, Watts et al. 2006)
- Search for GWs associated with QPO frequencies.
- 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
- Will repeat for S5-VSR1 flares.

Sources: Pulsar Glitches

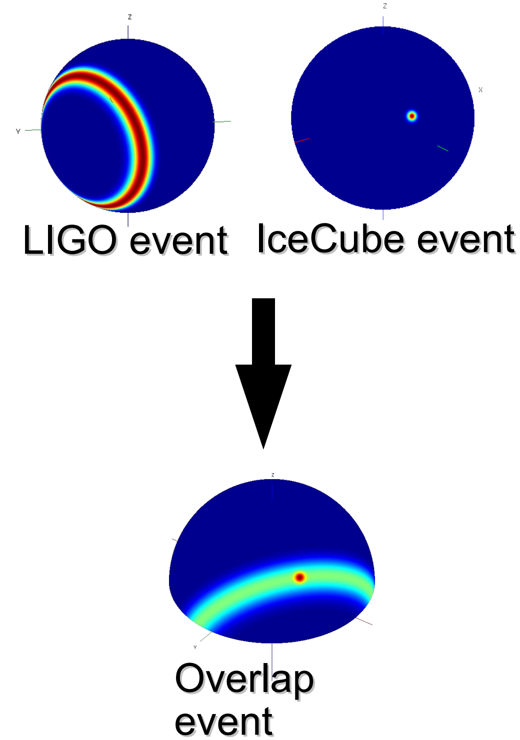
- Radio and anomalous X-ray pulsars exhibit “glitches” in their inferred spin-down rates
  - relaxation of ellipticity in crust / star-quake (younger pulsars)
  - de-coupling of fluid core and solid crust as superfluid vortex lines come un-pinned (older pulsars)
  - phase transitions from hadronic to 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
- 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 two-stage coincidence study:
  - Temporal coincidence
  - Spatial coincidence on sky
    - novel approach of combining sky maps for reconstructed signal direction
  - Aso *et al.*, arXiv:0711.0107



Other Sources

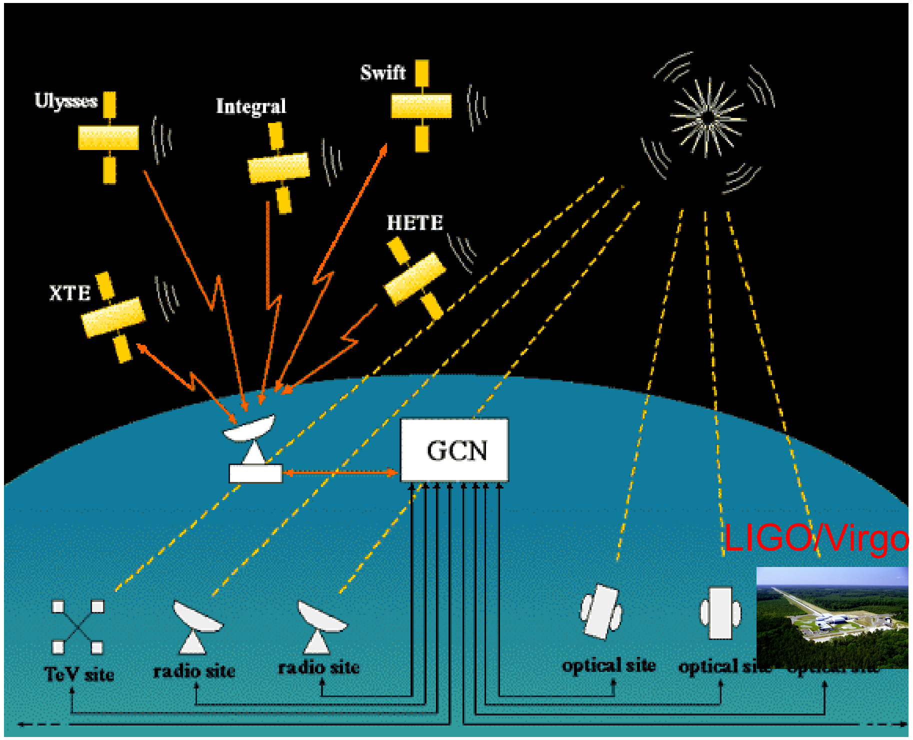
- Optical Transients
  - High uncertainty in trigger time (several hours)
  - Well-known sky position
    - directional analysis methods are applicable
  - Core collapse supernovae detected during S5 are subject to analysis
  - Uncertainty in trigger time: may not always have data from multiple detectors

- 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

What's next: S6-VSR2

- LIGO-Virgo to start next data taking run (S6-VSR2) in mid 2009.
- Big goal for data analysts: online/low latency searches.

- GRB & SGR - triggered burst searches:
  - automatically run, triggered by GCN notice / SNEWS alert
  - Goal: ~1 day latency from receipt of event trigger to final results



http://gcn.gsfc.nasa.gov/

What's next: S6-VSR2

Untriggered bursts search:

- Full analysis of data in < 30 min.
- Estimate sky direction for GW candidates, send to external observatories or EM follow-up.
  - Essentially from triangulation, optimistically to a few degrees
- Pursuing goals of multi-messenger astronomy: increased confidence in detections, extracting more science.
  - Procedures and infrastructure still being worked out.

Summary

- LIGO & Virgo have looked for GWs associated with various externally observed astrophysical phenomena for several years, using several different techniques.
  - GRBs: cross-correlation algorithm, excess-power algorithm, coherent analysis, statistical studies.
  - SGRs: excess power, power-stacking search, QPO search.
  - No detections (yet).
- S5-VSR1 analyses in progress
  - Searches for both binary inspirals (short GRBs) and unmodelled bursts (all GRBs), SGR flares.
  - Extending to new sources: HEN, LEN, SN, pulsar glitches, etc.
- S6-VSR2 goal:
  - low-latency analysis of triggers (~24 hr).

How *you* can help.

- Reliable knowledge about the source can help improve the sensitivity of our searches, and make sure we're follwing up all the phenomena that we should be.
- Example: GRBs
  - Traditional: We look for GW burst signals in the window [-2, +1] min around the GRB. Can we tighten this?
  - Should we be looking at late-time flares?
- Waveforms!
  - Frequency ranges, durations, polarization, any similar info can be used to improve sensitivity.
- What ***not*** to bother looking for?