Gravitational-Wave Data Analysis: Lecture 3

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Gravitational Wave Astronomy Summer School
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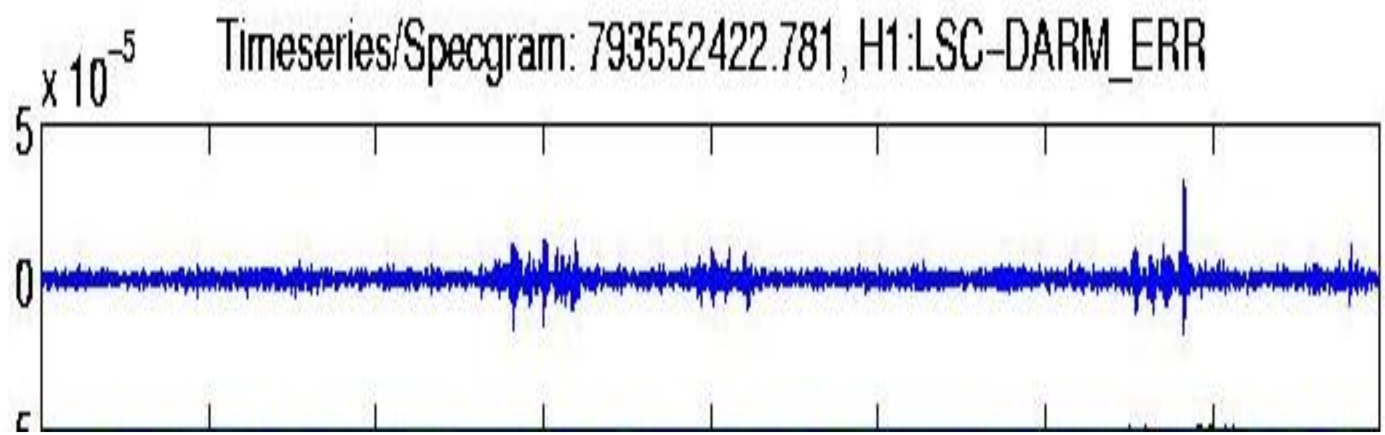
Outline for Today

- **Gaining confidence in a signal candidate**
  - Consistency tests
  - Data quality and vetoes
  - Validation of instrument response
  - Connections with other observations
- **Some notes on data analysis for space-based detectors**

Checking an Apparent Signal

How do we know whether a signal in the data is a real GW?



Available tools:

- Consistency of the signal with a source model (if there *is* a model)
- Coincidence / consistency of signals in multiple GW detectors
- Absence of instrumental problems at the time of the signal
- Validation of instrument response and data analysis software
- Association with a known astrophysical object / event

Consistency with Source Model?

Inspiral: (Matched filter already supposes a source model)
Chi-squared test
Sanity of filter output and/or chi-squared time series

Cont.-wave: Does it show the expected Doppler modulation?
Is it present all the time?

Stochastic: Does the signal have the expected spectrum?
Is it on all the time?

Burst: Is it isolated in time?

These are not all *absolute* requirements, but agreement with the "expected" source model can add confidence

Coincidence / Consistency Tests

Having multiple detectors is extremely valuable

Signals should arrive at consistent times

- LIGO Hanford vs. Livingston: within ±10 ms
- LIGO vs. Virgo: within ±27 ms
- Also get sky position information from having multiple detectors

Signals should have consistent properties

- Same or similar templates, if a matched-filter search
- Consistent frequencies, durations
- Consistent amplitudes (allowing for different orientations)

Background Estimation

Background = expected "detection" rate of false events

Depends on criteria for a "trigger"

e.g. threshold on some measure of signal strength

Any analysis involves a trade-off between sensitivity and background

How can we determine the background?

Simple method: product of average trigger rates in each detector and coincidence time window

More reliable: **Analysis of time-shifted data**

- Choose time shifts longer than maximum light travel time, so any real GW in the data is no longer coincident
- Incorporates the consistency tests used in the actual analysis
- Follows time variability better

Can only get an *estimate* of the background

Using many different time shifts, get high statistics

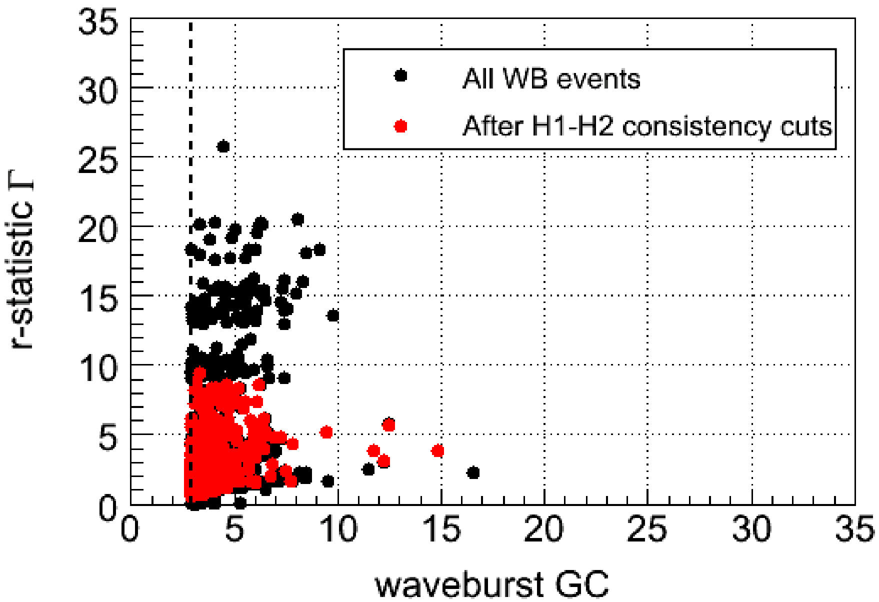
Data Quality

We attempt to catalog various environmental and instrumental conditions, then study relevance using *time-shifted* triggers

Example from LIGO S4 all-sky burst search:

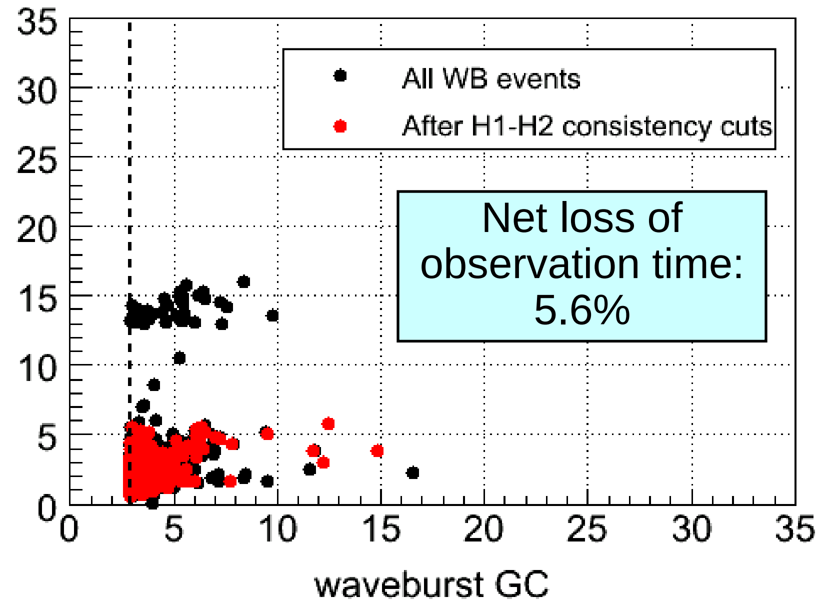
<u>Minimal data quality cuts</u>

Require locked interferometers
Omit hardware injections
Avoid times of ADC overflows



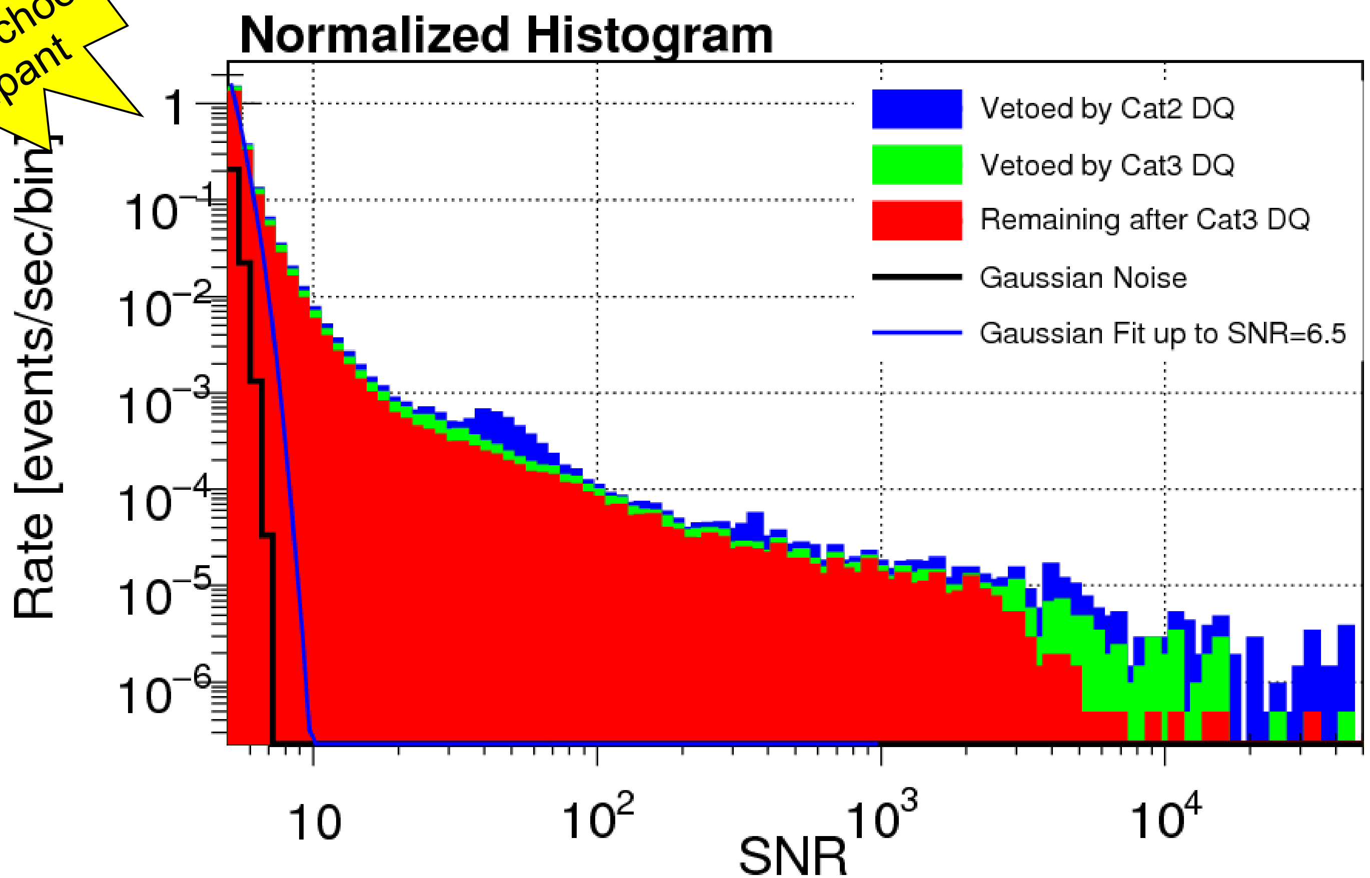
<u>Additional data quality cuts</u>

Avoid high seismic noise, wind, jet
Avoid calibration line drop-outs
Avoid times of “dips” in stored light
Omit last 30 sec of each lock



LIGO Livingston S6C example

Figure by Jess McIver – 2009 summer school participant

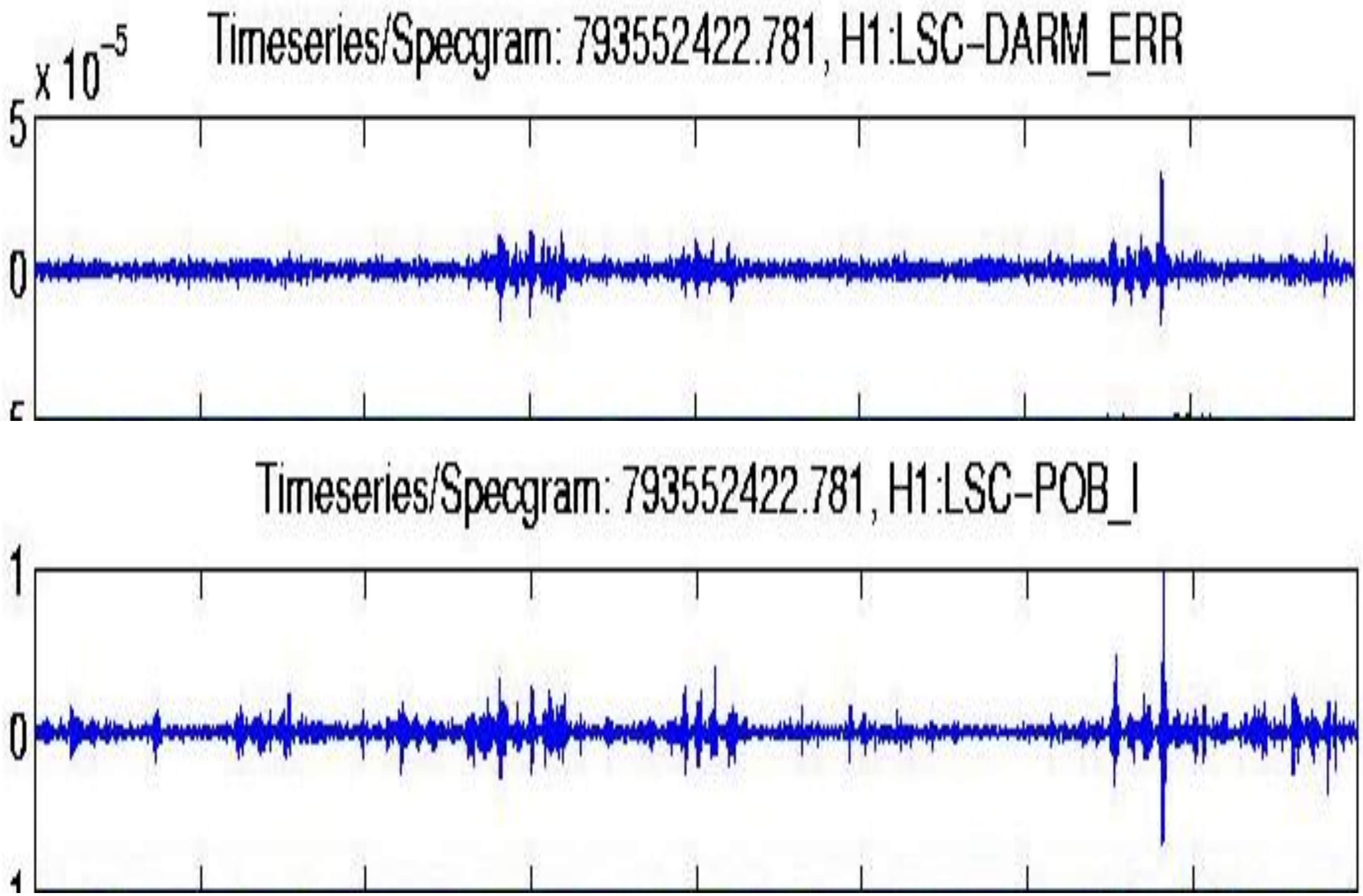


Omega Pipeline triggers

Non-Stationary Noise / Glitches

GW channel

Beam splitter pick-off



Vetoes

If there is a significant glitch in a selected auxiliary channel, then veto any trigger found at the same time in the GW channel

Goals:

- Reduce background level
- Prevent triggers from rare, large environmental effects
- Study additional auxiliary channels for following up a detection candidate

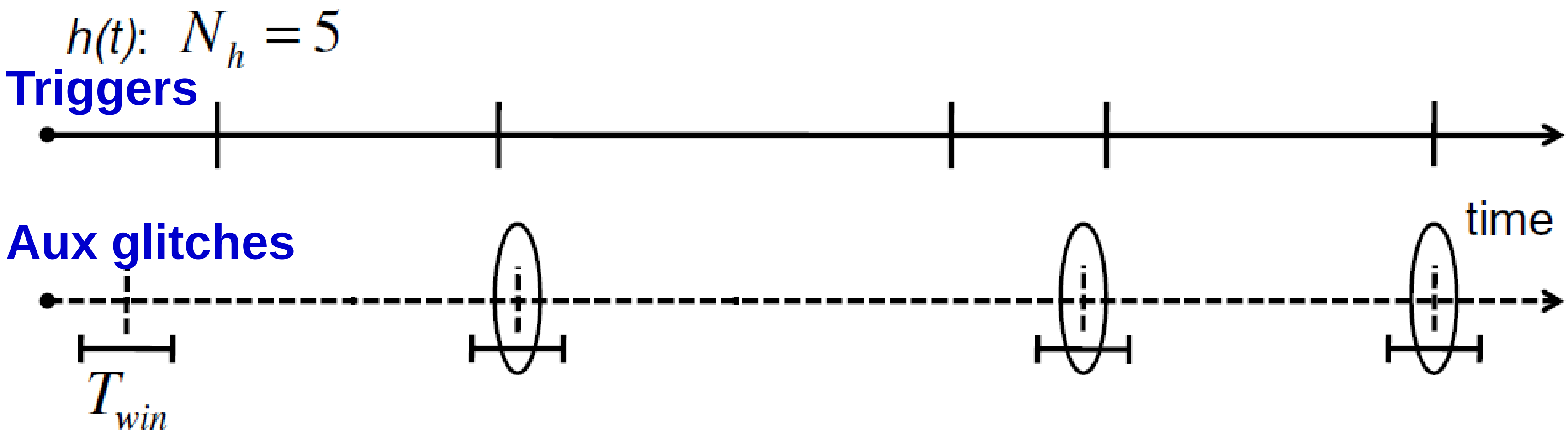
Only want to do this for relevant auxiliary channels

- Ideally, with known physical coupling mechanism to GW channel
- Or, established statistically with single-detector triggers or time-shifted coincidence triggers from GW channel

Measures of relevance

- Veto efficiency : what fraction of GW triggers are vetoed
- Use percentage : what fraction of times identified for vetoing actually do veto a GW trigger
- Deadtime : how much observation time is vetoed

Veto Illustration



This aux channel, with this window, has a *veto efficiency* of 60%

Its *use percentage* is 75% , and its *deadtime* is ~24%

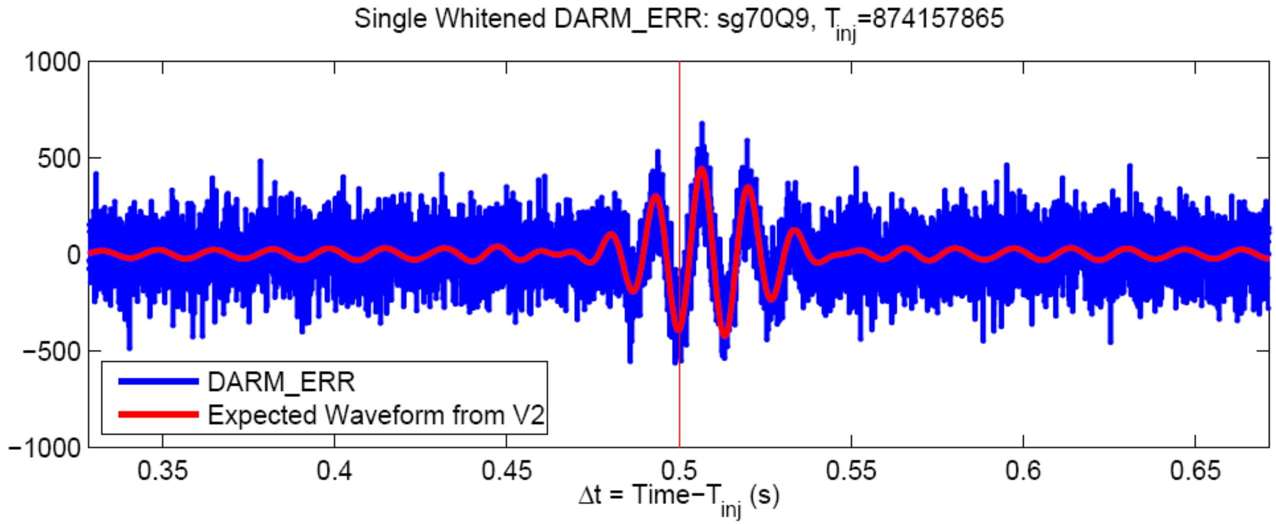
Seems to be a good veto since its efficiency and use percentage are higher than you'd expect by chance

* In reality, need higher statistics to be more sure that a veto condition is well established

Validating the Detector: Hardware Signal Injections

Shake the mirrors to mimic a GW signal

Can inject an arbitrary waveform



Also used to inject simulated pulsar signals continuously

Goals:

End-to-end test of interferometer and data analysis software

Checks calibration

Useful for veto “safety” checks

Connections with Other Observations

Many (most?) sources of gravitational waves are expected to release energy in other forms too

⇒ Search for GW bursts or inspirals associated with astrophysical events/objects observed by other means

Targets:

Gamma-ray bursts (GRBs)

Magnetar (SGR/AXP) flares

Supernovae

Anomalous optical transients

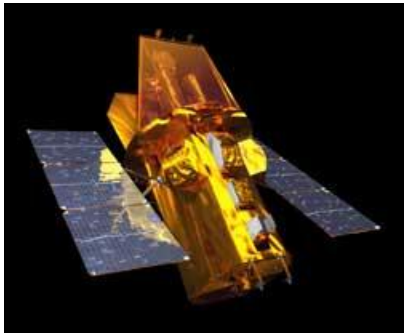
Pulsar spin-frequency glitches

LMXB X-ray intensity variations

High-energy neutrinos

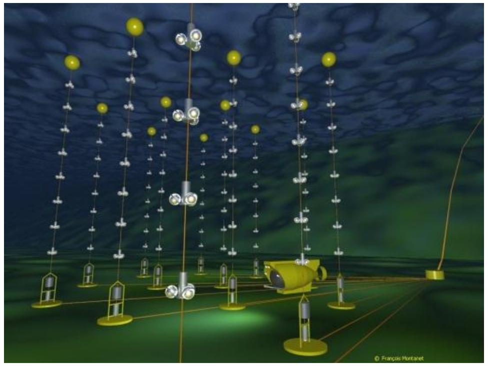
Low-energy neutrinos

Radio bursts



Swift

Palomar 48" Schmidt – Now the Ochsin telescope



ANTARES

Green Bank

Multi-Messenger Advantages

If an event has already been detected, then GW searches:

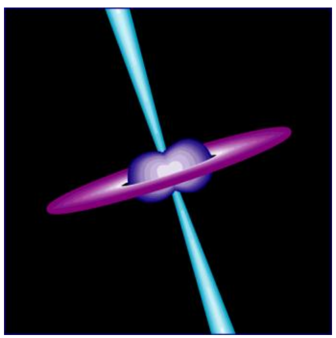
- know *when* to look at the data
- know *where* in the sky to look
- may know *what kind* of GW signal to search for
- may know the distance to the source

As a result,

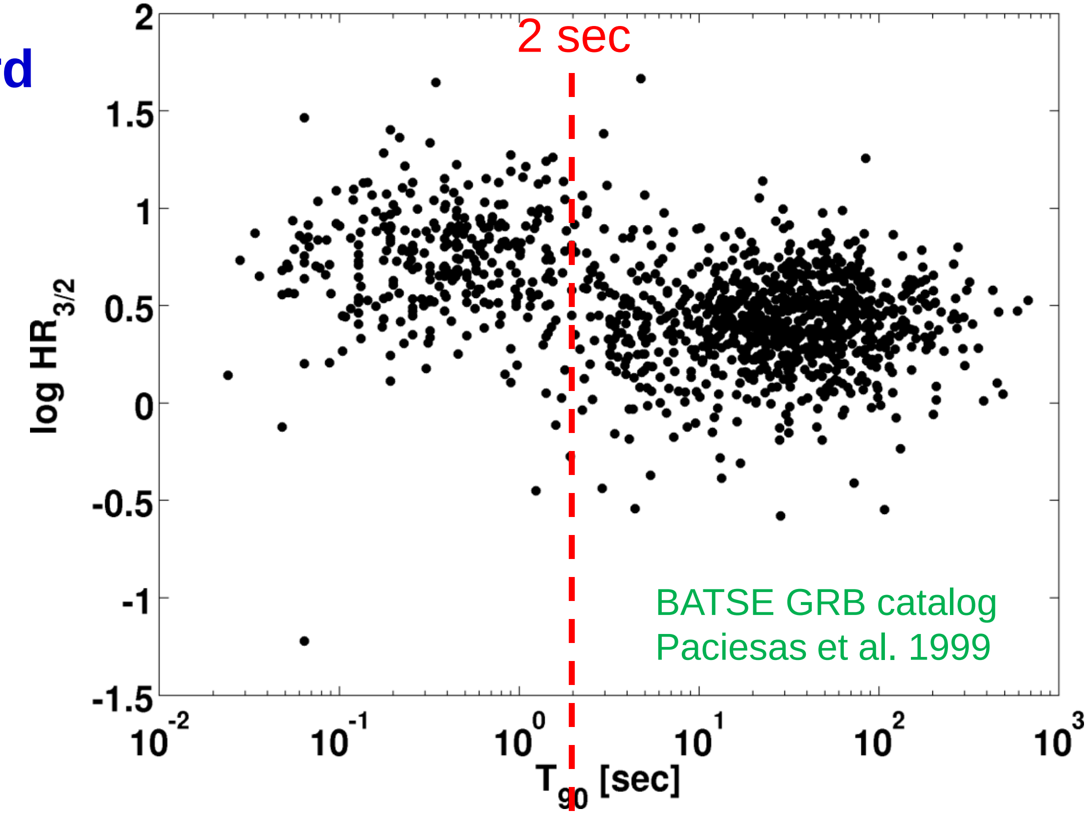
- Background is suppressed, so a weaker GW signal can be confidently detected
- The extra information from the combined observations will reveal more about the astrophysics of the source
- *Non*-detection of a GW signal can still provide interesting information, e.g. an upper limit on energy emitted in GWs

Gamma-Ray Bursts

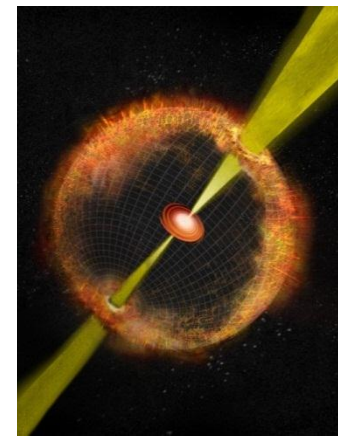
Short - Hard GRBs



Credit: P.J.T. Leonard (NASA/GSFC)



Long - Soft GRBs



Credit: Bill Saxton, NRAO/AUI/NSF

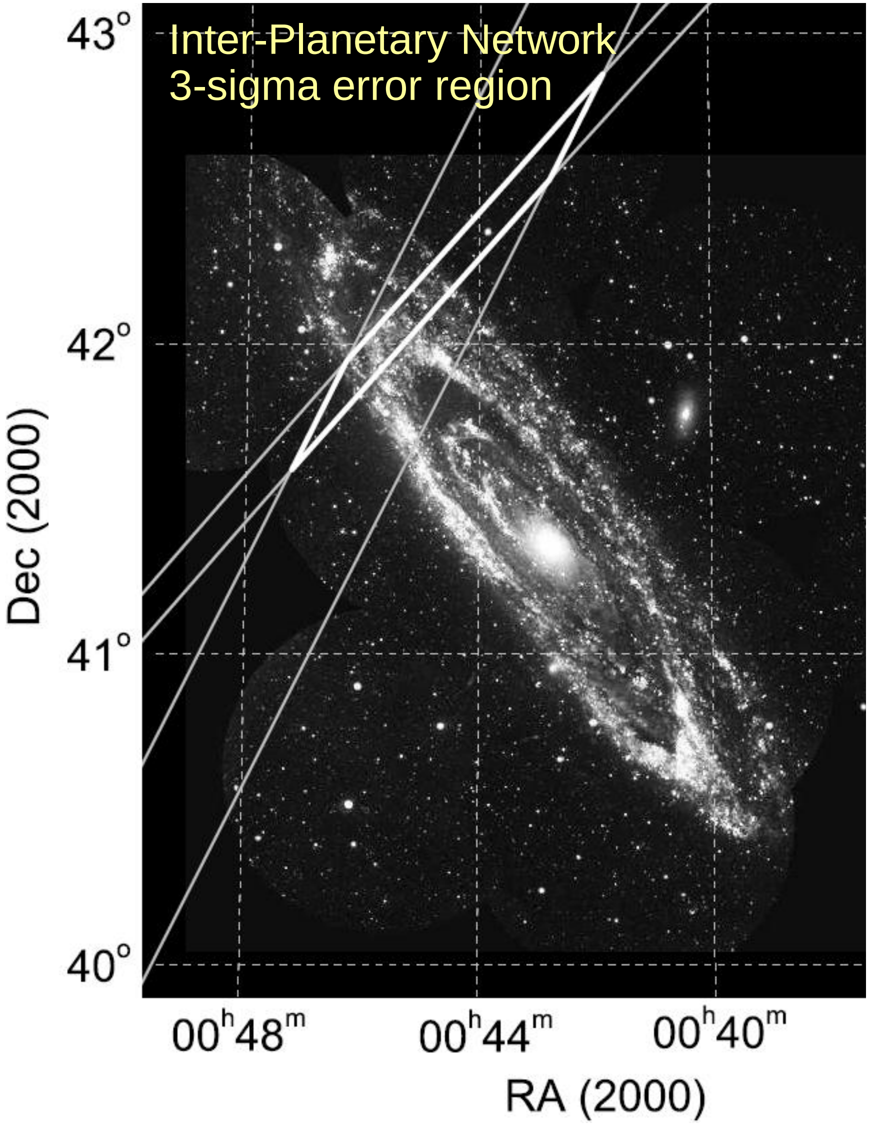
Most thought to be from **binary mergers** involving a neutron star

Some from giant flares from soft gamma repeaters (magnetars)

Most thought to be from the **collapse of high-mass stars** with rapidly rotating cores

Supernovae seen in some cases

Example: GRB 070201



Very intense short-hard GRB

- Leading candidate for such GRBs: binary mergers

Position error box overlapped M31 (Andromeda Galaxy)

Inspiral GW signal from that distance would be detectable

- Both Hanford detectors were on

No GW inspiral detected $\Rightarrow$ **evidently not a binary merger in M31**

- No GW burst signal detected by more generic search, either

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

Systematic GRB–GW Searches

Most recently, analyzed 154 GRBs reported during 2009-10
while 2 or 3 LIGO/Virgo detectors were taking good data

GW "burst" search

Done for 150 GRBs

Coherent burst search allowing for arbitrary GW waveform

Assumed circular polarization since rotational systems are efficient GW emitters and the γ rays are believed to be beamed

Compact binary coalescence search

Done for 26 short or "short-like" GRBs

Coherent matched filtering search for inspiral waveforms from a binary with at least one neutron star

Abbott et al., arXiv:1205.2216

Space and Time Windows

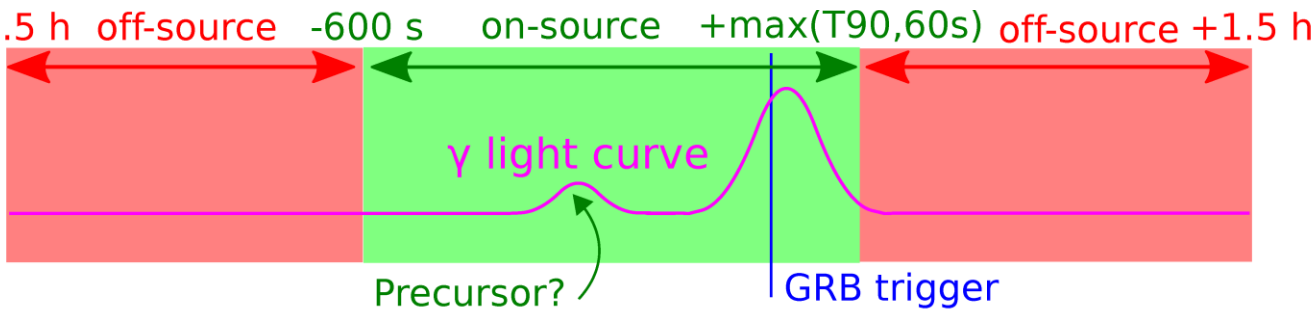
Searched over sky region reported for the GRB

GRBs reported by *Swift* and other satellites are generally well localized

GRBs detected by Fermi GBM have large error regions

Time window allowed for relative time offset from GRB trigger

Burst:

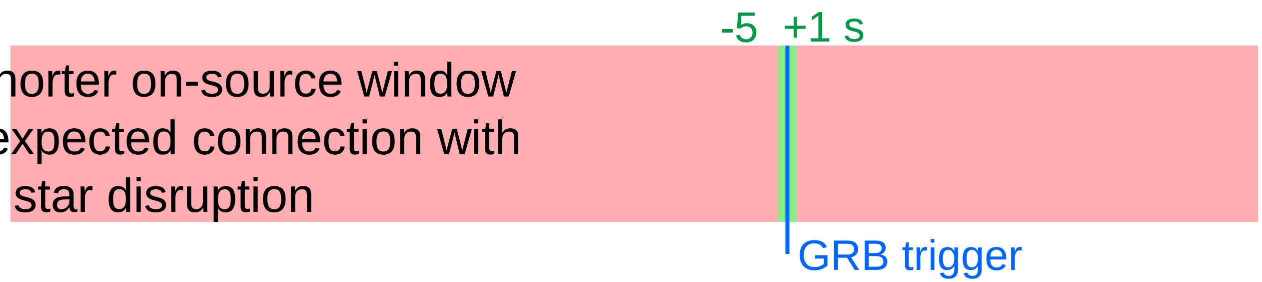


Generous "**on-source**" window allows for seen or unseen precursor

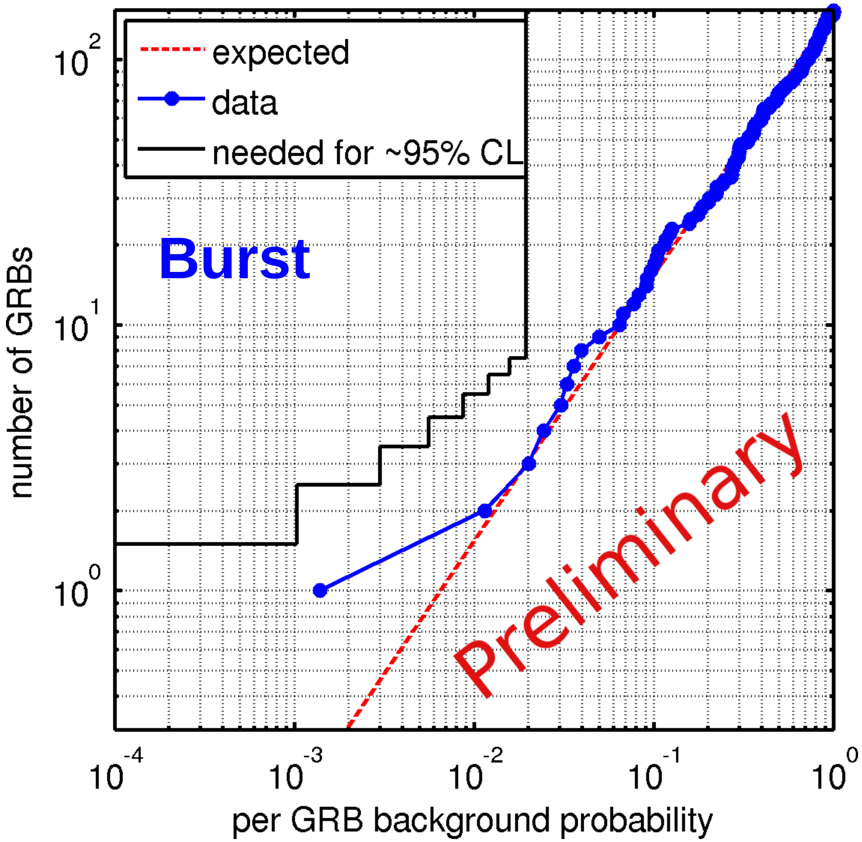
e.g. GRB 060124 precursor was 570 s early *[Romano et al. 2006]*

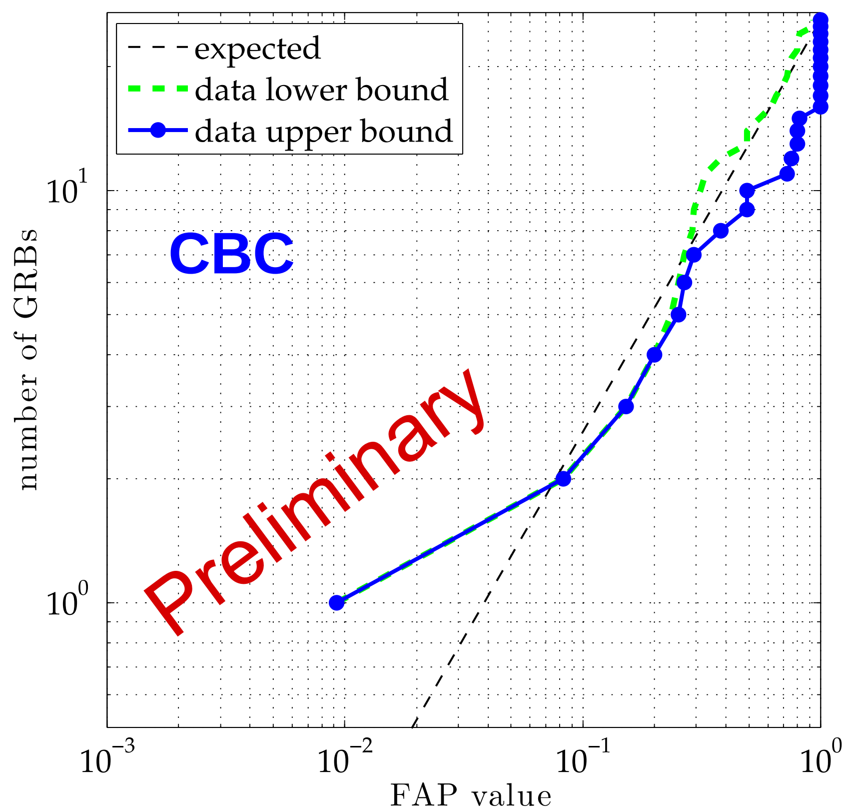
CBC:

Much shorter on-source window due to expected connection with neutron star disruption



GRB–GW Search Results





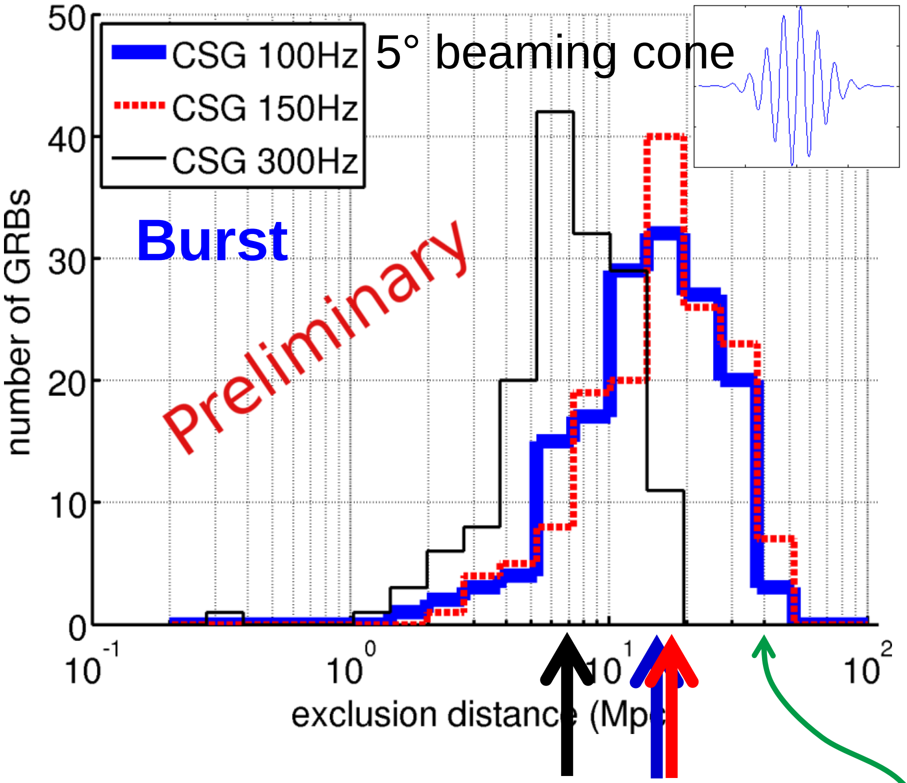
No individual GRB stands out compared to the background

No subset of the most significant GRBs stands out either

“Weighted binomial test” statistic is consistent with uniform distribution

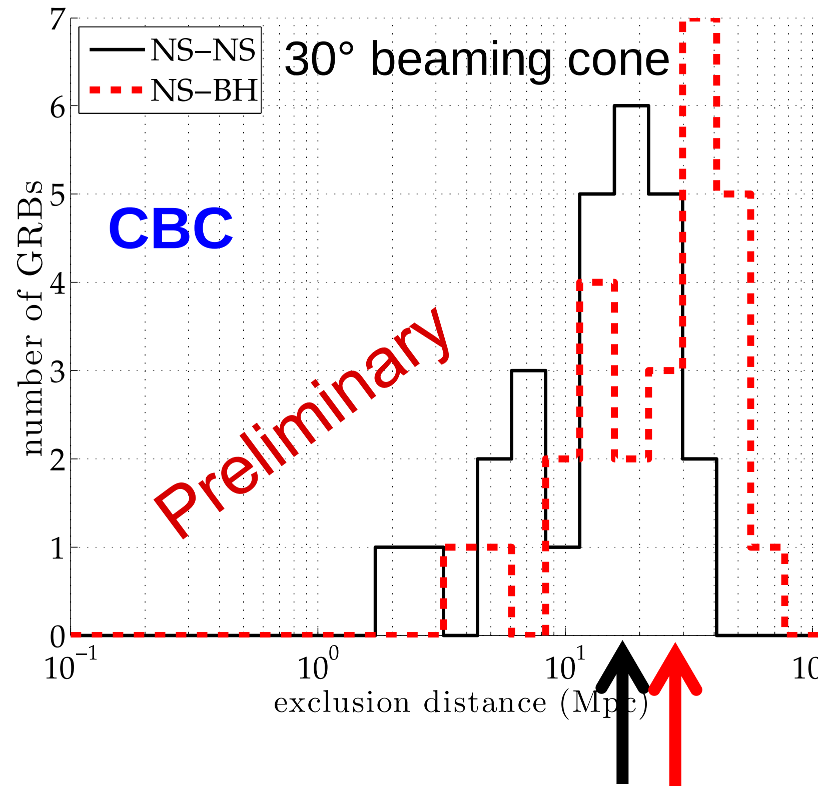
GRB Progenitor Exclusion Distances

Assuming sine-Gaussian waveform with optimistic but possible $E_{GW} = 0.01\ M_{\odot}c^2$



Median distances: 7, 15,17 Mpc

Assuming coalescence of NS-NS or NS-BH binary

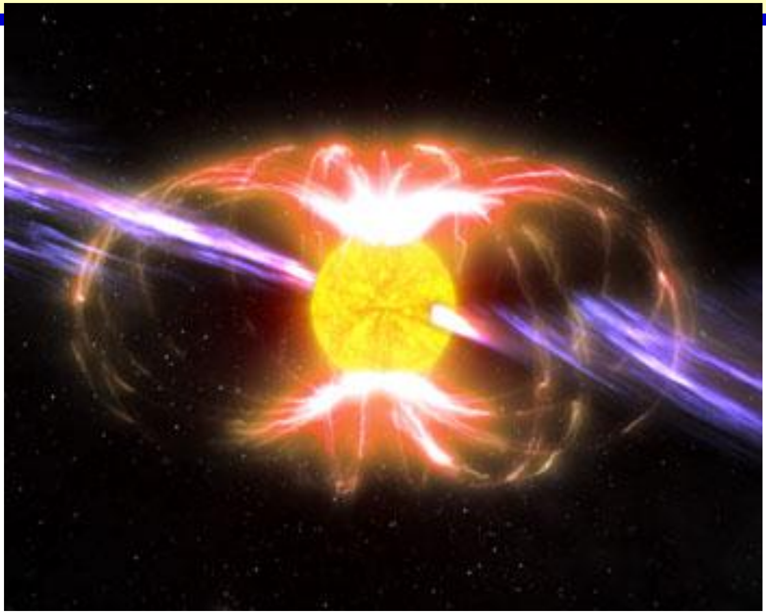


Median distances: 17, 29 Mpc

Distance to GRB 980425 / SN 1998bw

e.g. Kulkarni et al., Nature 395, 663

Magnetar Flares



Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are believed to be magnetars

Neutron stars with magnetic field ~10^{15} G interacting with crust

Occasionally emit flares of soft gamma rays

Ordinary flares E_{EM} ~ 10^{42} erg

Some SGRs have produced a ***giant flare*** with energy ~10^{46} erg

Thought to be associated with cracking of the crust (“starquake”) or magnetic reconnection

Quasiperiodic oscillations seen in X-ray emission after giant flares

May excite non-radial oscillation modes that couple to GW emission

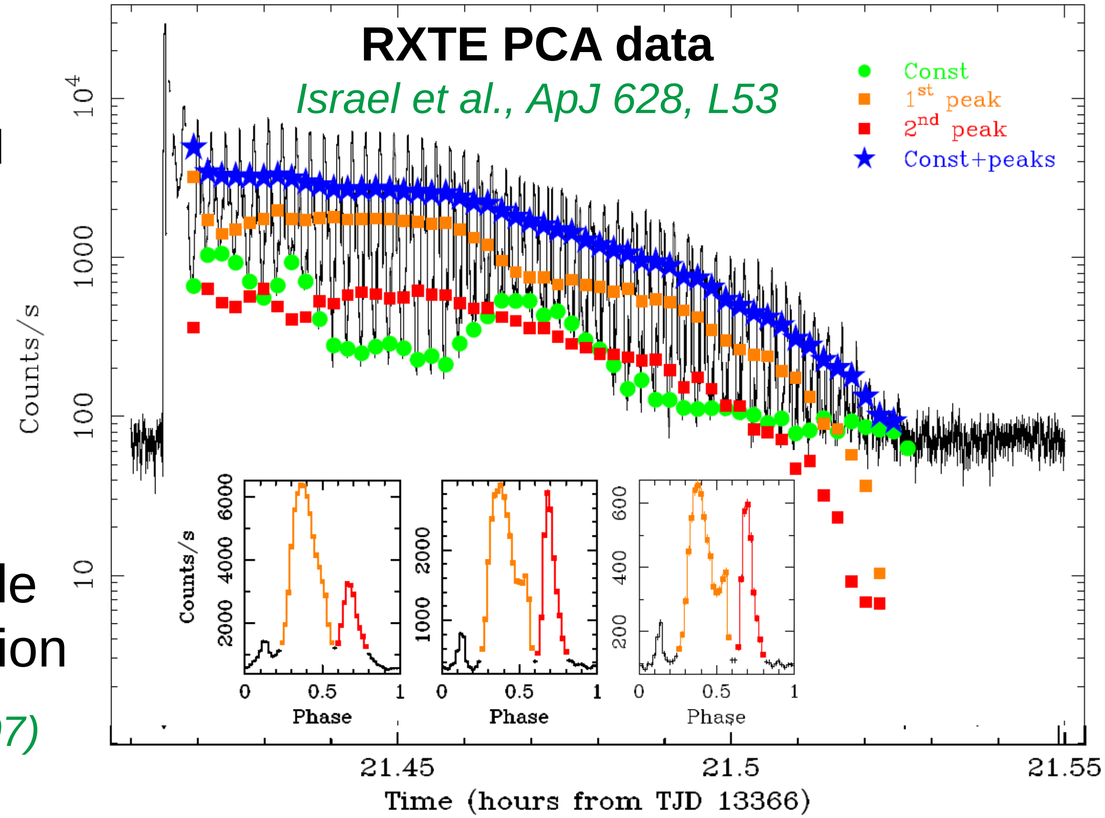
Searches for GW Signals from Magnetars

Long-lived quasiperiodic GWs after giant flare ?

December 2004 giant flare of SGR 1806–20

Searched for GW signals with same frequencies and time spans as X-ray QPOs detected by RXTE and RHESSI:

92.5, 150, 626, 1837 Hz



GW energy limits comparable to total EM energy emission

Abbott et al., PRD 76, 062003 (2007)

Searches for GW Signals from Magnetars

GW bursts at times of magnetar flares ?

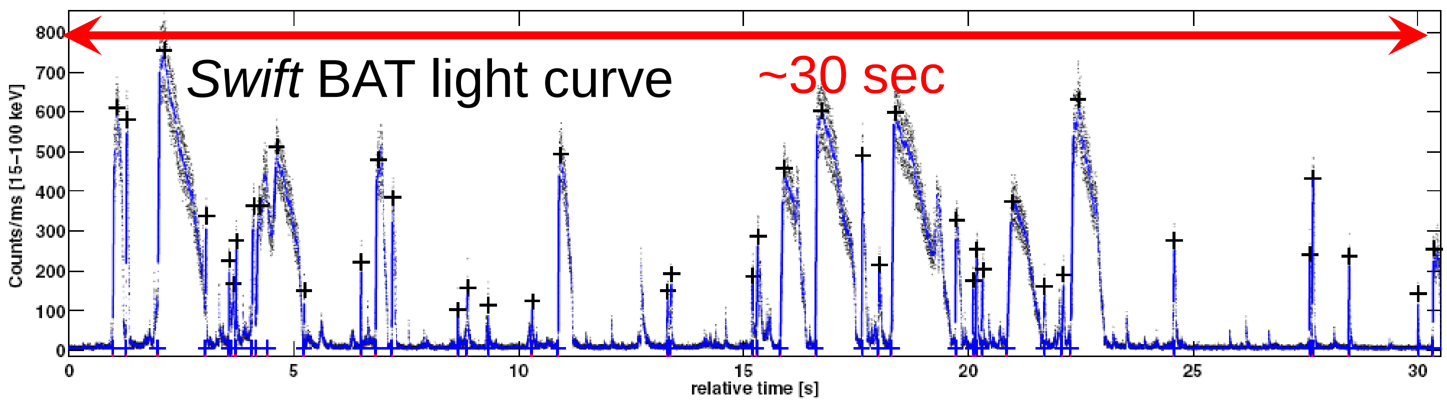
2004 giant flare plus other flares from SGR 1806–20 and 5 others

Excess-power search for neutron star *f*-modes ringing down (~1.5–3 kHz) as well as for arbitrary lower-frequency bursts

For certain assumed waveforms, GW energy limits are as low as few × 10^{45} erg, comparable to EM energy emitted in giant flares

Abbott et al., PRL 101, 211102 ; Abadie et al., ApJ 734, L35

Also a “stacked” search for repeated emission from SGR 1900+14 “storm” on March 29, 2006 – tighter GW energy upper limits under this model



Abbott et al., ApJ 701, L68

Known Pulsars in LIGO/Virgo Band

Fully coherent analysis at twice the spin frequency

Relies on having good radio (or X-ray) timing, ideally during the period of GW data collection

Vela – using Virgo data
Abadie et al., ApJ 737, 93

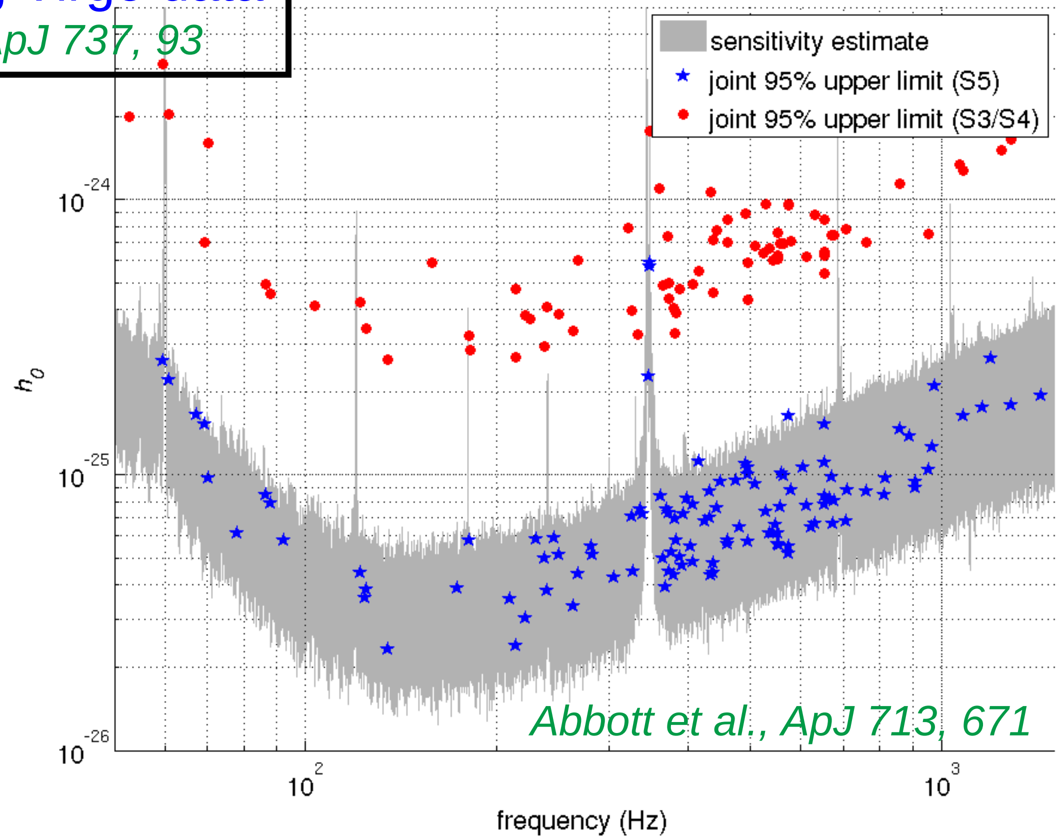
Lowest upper limit on strain:

$$h_0 < 2.3 \times 10^{-26}$$

Lowest upper limit on ellipticity:

$$\varepsilon < 7 \times 10^{-8}$$

Reached spin-down limit for Crab, Vela, and J0537–6910



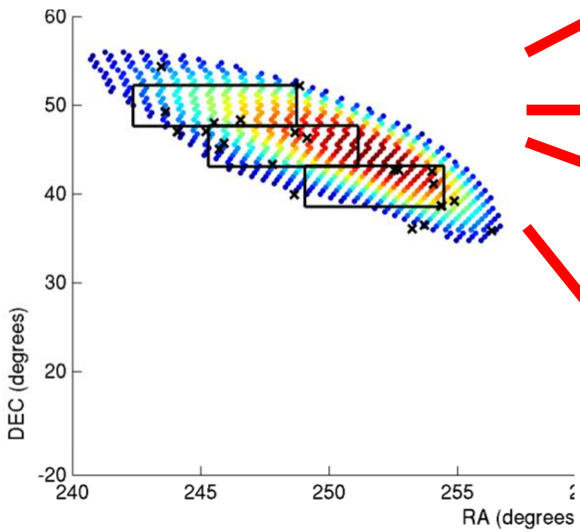
Abbott et al., ApJ 713, 671

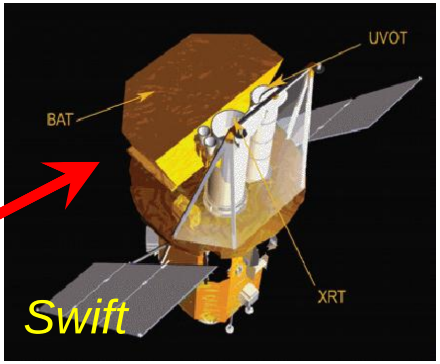
Electromagnetic Follow-Ups to GW Triggers ("LoocUp")

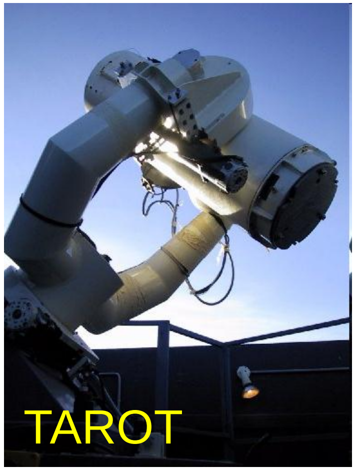
Analyze GW data promptly to identify possible event candidates and reconstruct their apparent sky positions; alert telescopes

Try to capture an EM transient that would otherwise have been missed !

First tried in last LIGO/Virgo science run

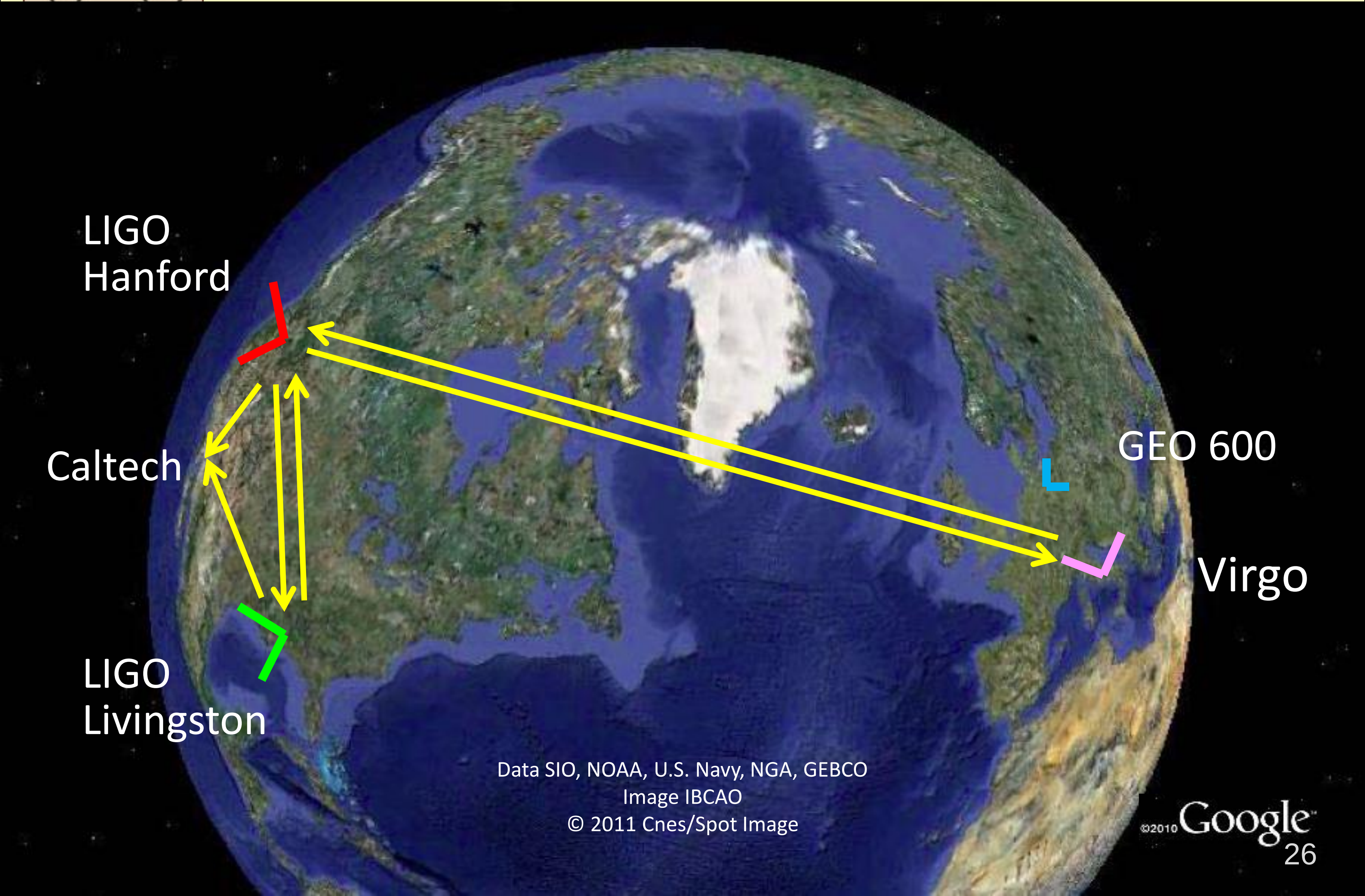




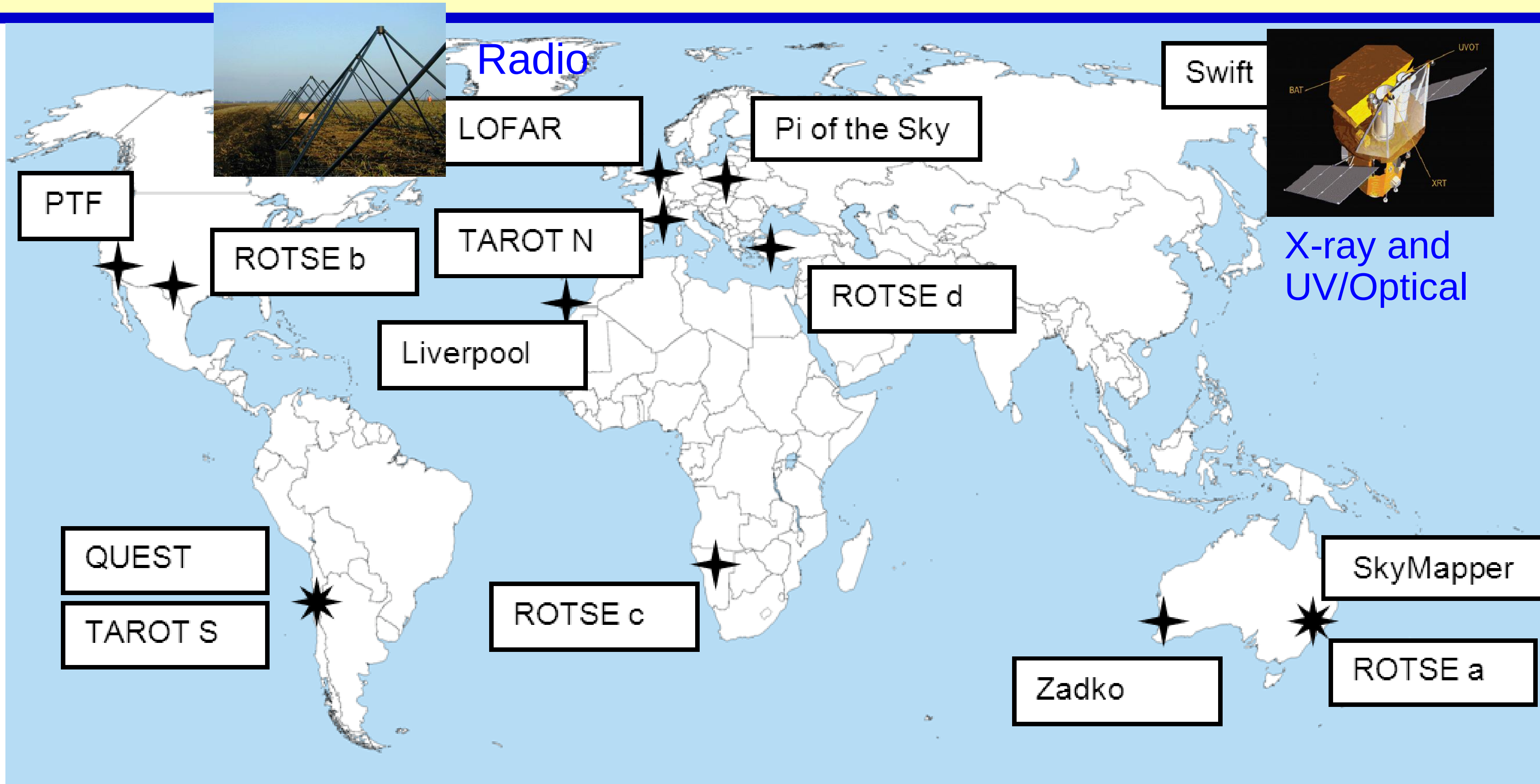


Other telescopes...

Low-Latency Calibration and Data Transfer



Observing Partners During 2009–2010



Mostly (but not all) robotic wide-field optical telescopes

Many of them used for following up GRBs, surveying for supernovae and other optical transients

EM Follow-up Operations

“Live” for two running periods

S6/VSR2: 17 Dec 2009 to 8 Jan 2010

S6/VSR3: 2 Sept to 20 Oct 2010

Target trigger rates

S6/VSR2: 1 per day of 3-site science mode

S6/VSR3: 0.25 per day of 3-site science mode

Tighter requirements for Swift, PTF

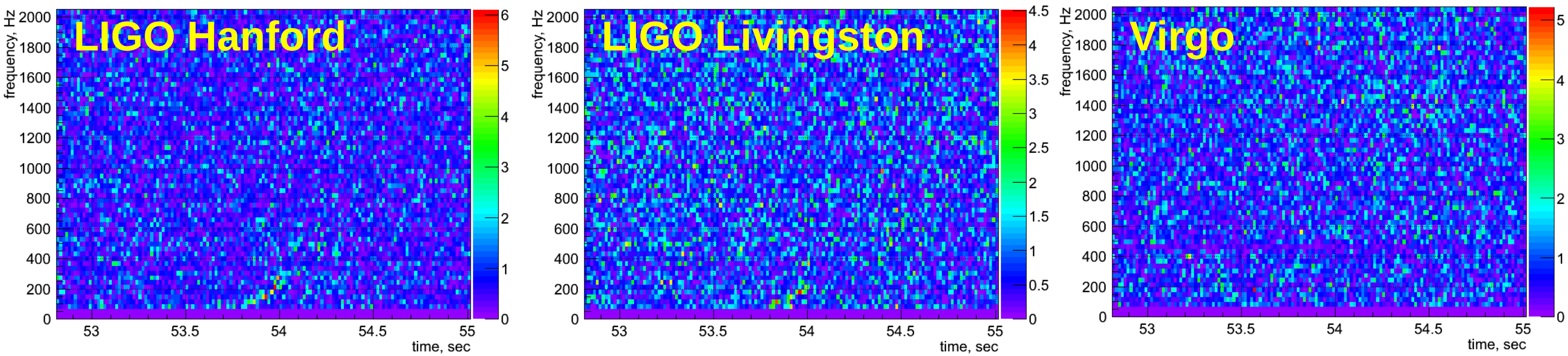
Sent alerts to scopes, which took images when possible

Sent specific coordinates chosen for that scope’s FOV

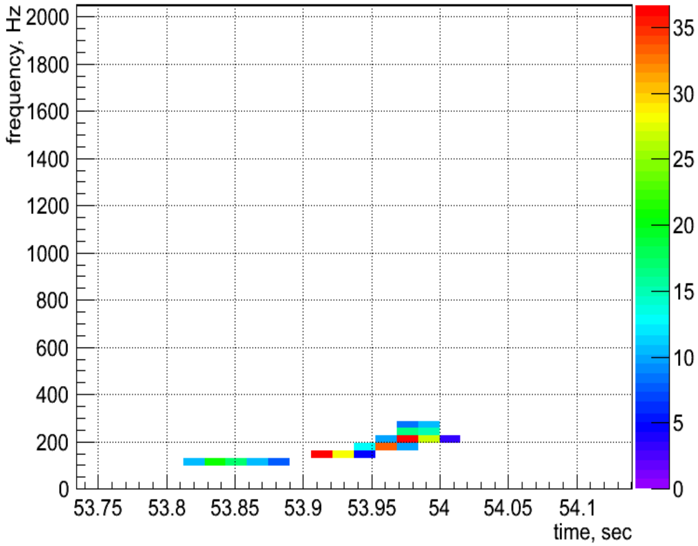
9 event candidates were followed up by at least one scope

Some Excitement: Sept. 16, 2010

Coherent WaveBurst time-frequency pixel maps:



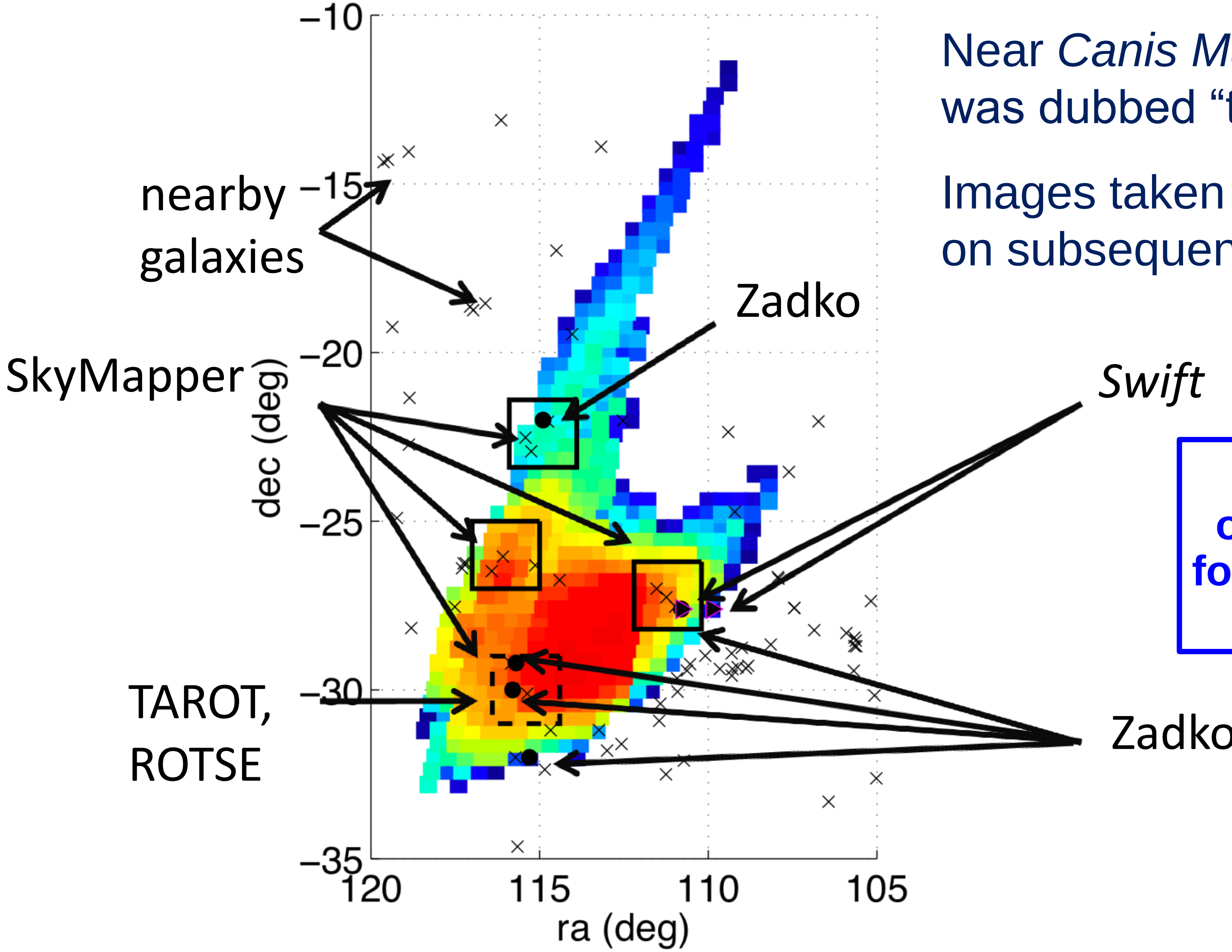
Likelihood detection statistic:



What could it be?

- A binary black hole inspiral / merger
- A noise fluctuation
- A "blind injection" (simulated signal injected into the interferometer)

Regions Imaged by Telescopes



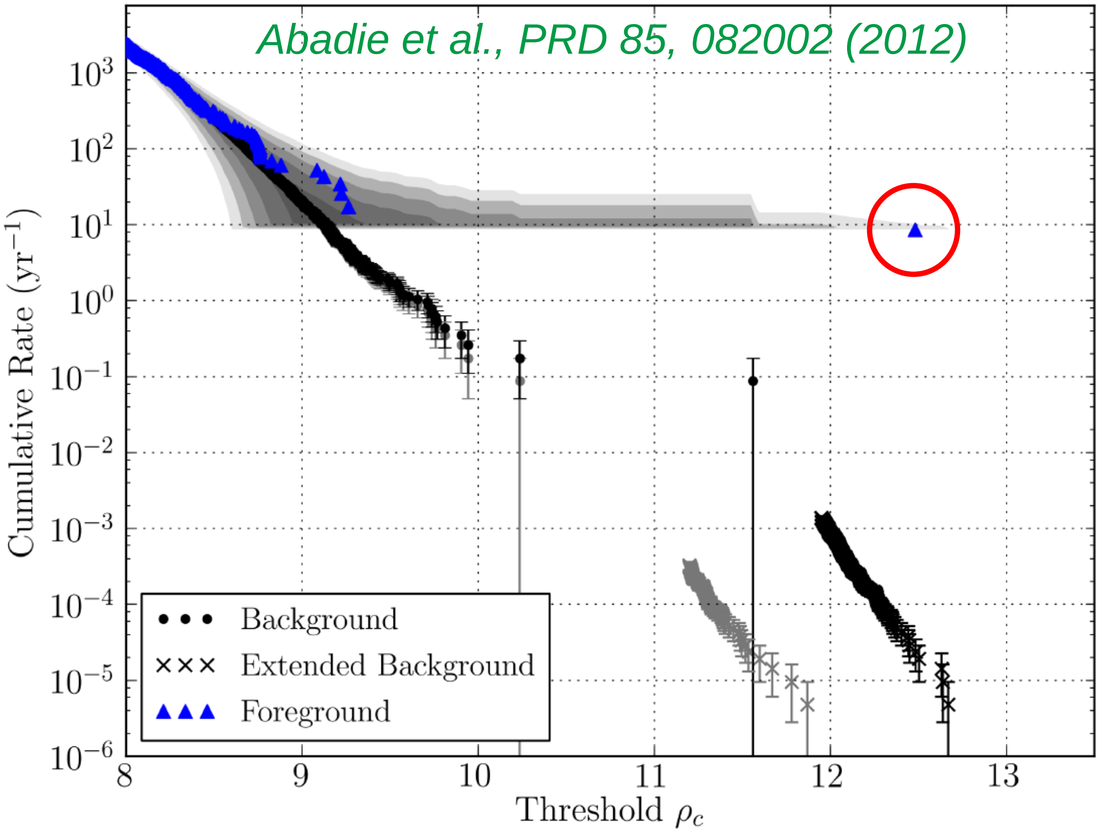
Near *Canis Major* ➔ event was dubbed "the Big Dog"

Images taken ASAP, and on subsequent nights

No significant optical transient found in telescope images

Significance of the "Big Dog" Event Candidate

Modest significance in GW burst search,
but highly significant in matched filter inspiral search



Over next 6 months:

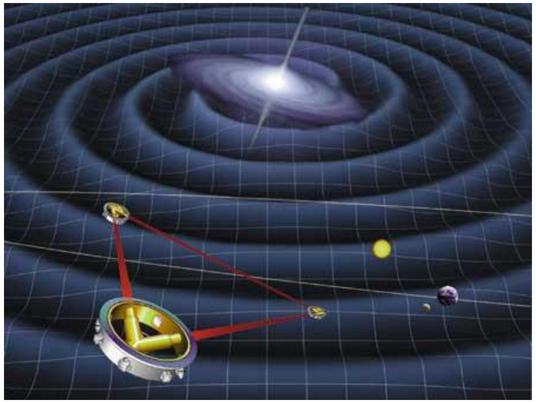
- Refined background estimation techniques – estimated 1 in 7000 y
- Did binary parameter estimation studies
- Wrote and polished a Phys Rev Letter

"Opened the envelope" in March 2011…

It was a blind injection

For more of the story: http://www.ligo.org/news/blind-injection.php

Some Notes on (e)LISA Data Analysis
(from the point of view of a LIGO person)



Much longer arms

➔ **Searches at much lower frequencies**

- Use TDI (Time Delay Interferometry) to cancel laser frequency noise
- GW wavelength comparable to arm lengths
  ➔ Response functions are non-trivial

Fewer instrumental noise sources

- Not clear whether data quality and vetoes will be a significant issue

Lots of signals !

- Dealing with overlapping signals is a major challenge

Strong signals

- Much more emphasis on parameter estimation
- Long-duration signals can be tracked as constellation orientation changes

Opportunities to associate GW signals with EM sources