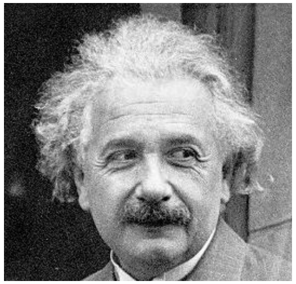
# Gravitational Wave Bursts and Multimessenger Astronomy

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/ Goddard) and T. Nielsen (Univ. of Hawaii)

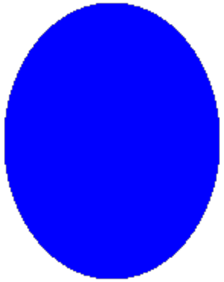
# What you've heard so far…

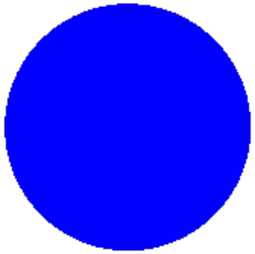


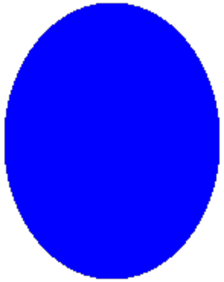
The Einstein field equations of GR have wave solutions !

- Emitted by a rapidly changing configuration of mass
- Travel away from the source at the speed of light
- Change the effective distance between inertial points — i.e. the spacetime metric — transverse to the direction of travel

**Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and *shrink* the space**

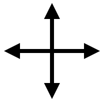




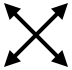


…

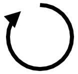
"Plus" polarization



"Cross" polarization

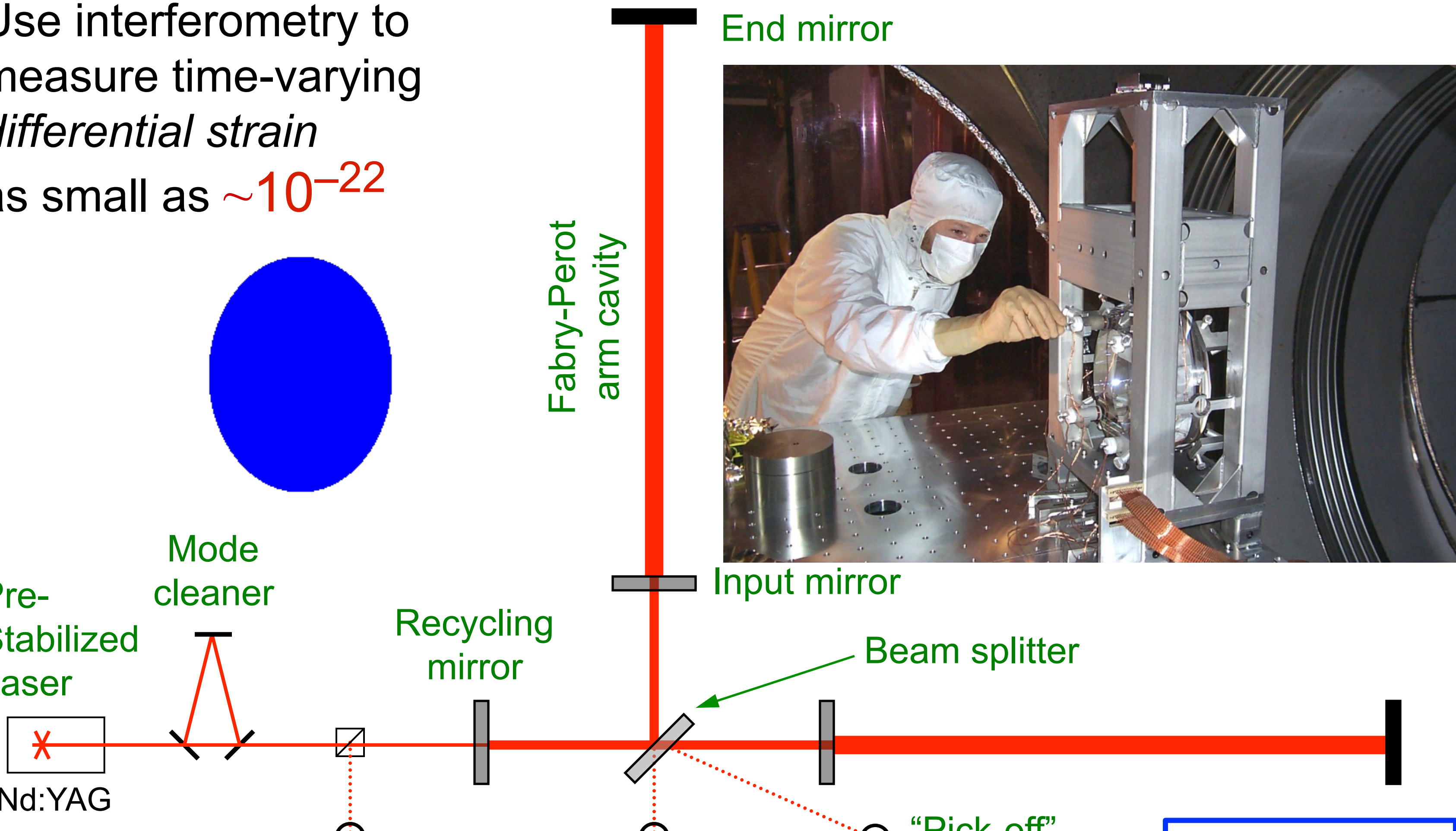


Circular polarization



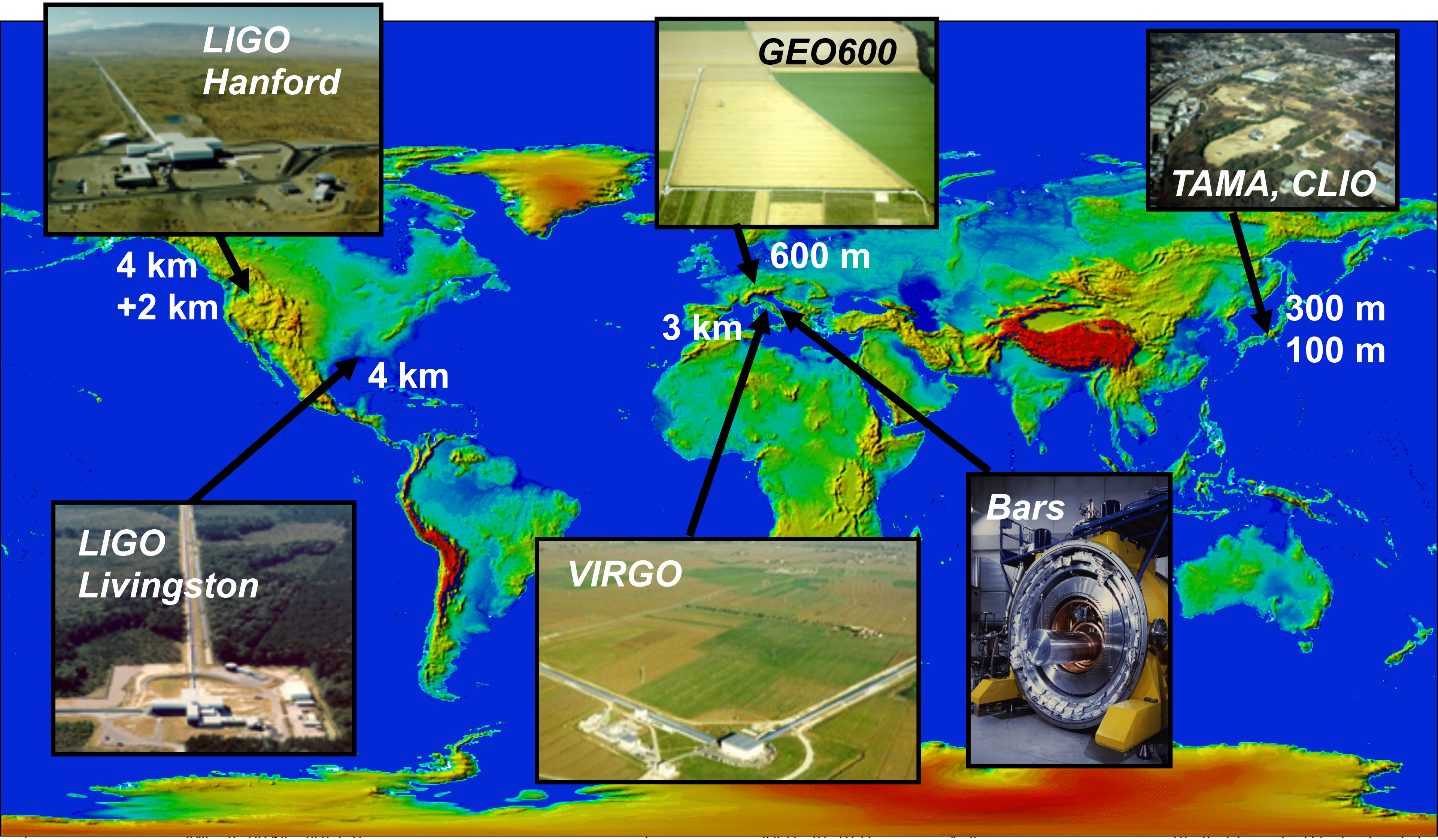
# What you have heard so far…

Use interferometry to measure time-varying *differential strain* as small as $\sim 10^{-22}$

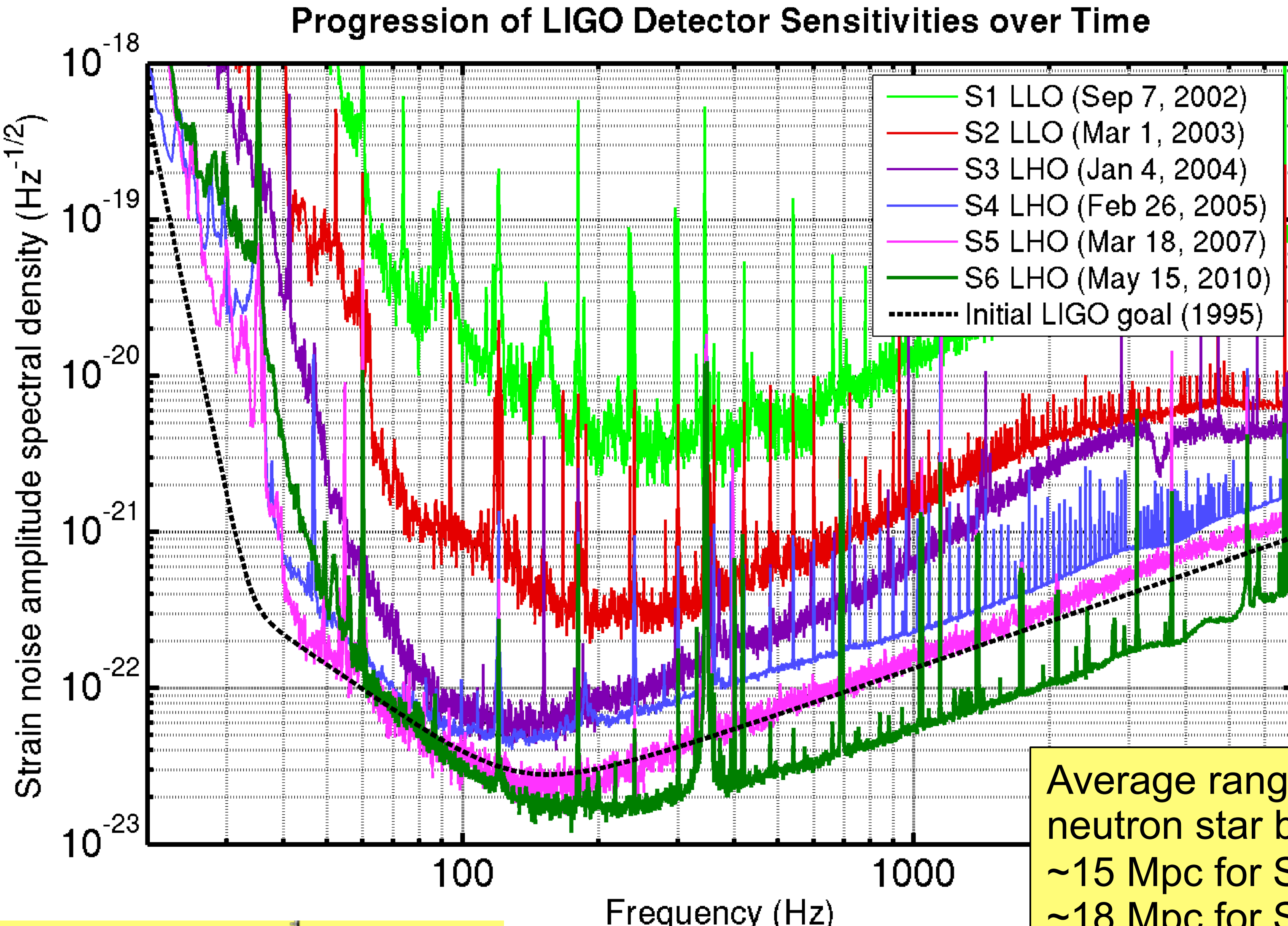



**Weakly directional response**

# The Global GW Detector Network in the Recent Past



# LIGO Noise vs. Frequency – So Far

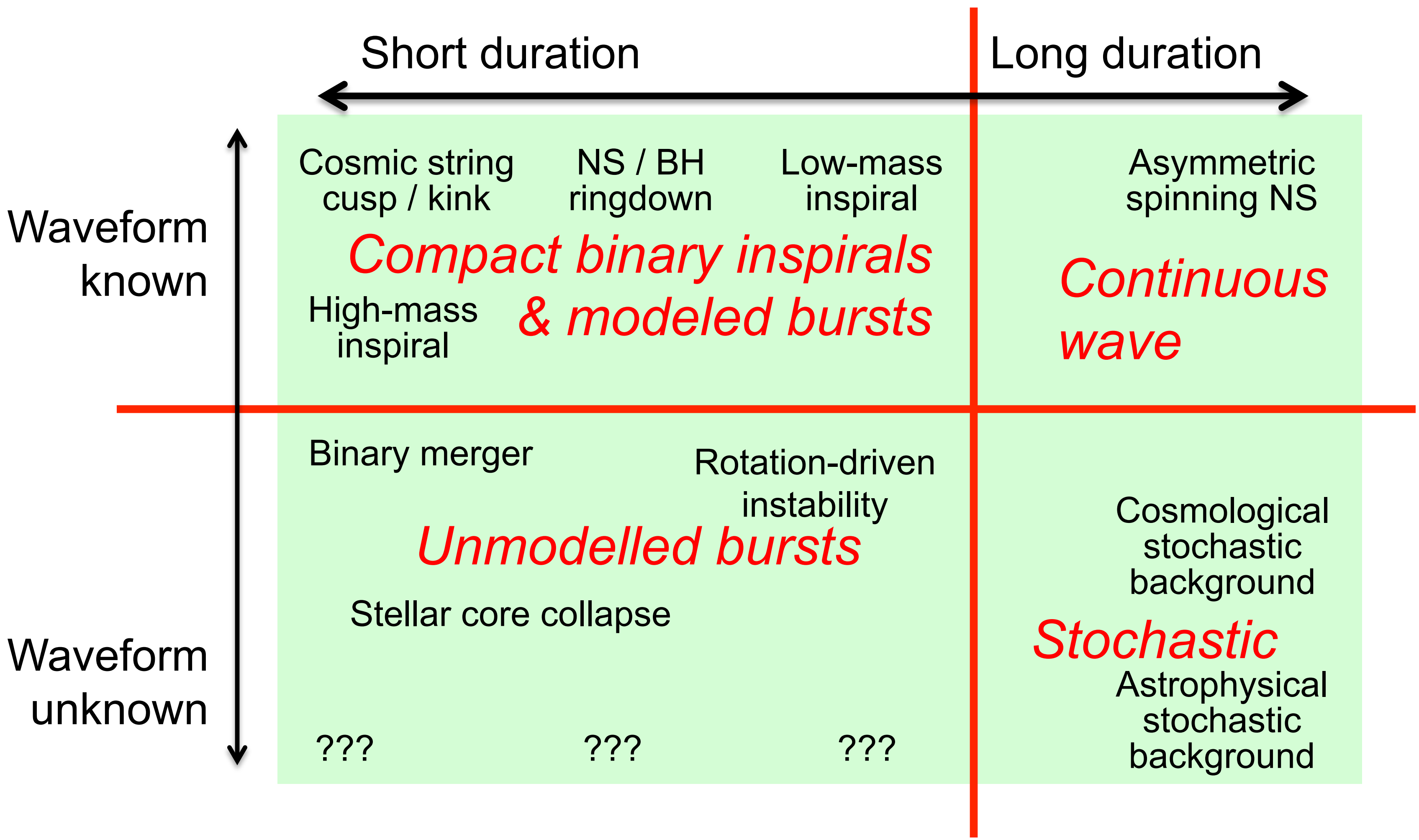



Average range for neutron star binary:
~15 Mpc for S5,
~18 Mpc for S6

$$< n(f) n*(f') > = \frac{1}{2} \times \delta_{ff'} S(f)$$

# Gravitational Wave Sources…

…and the LSC VIRGO working groups



# Gravitational Wave Burst Searches

# GW Burst Philosophy

We're listening to the whole sky – who knows what's out there?

- Models are OK, but don't put *too* much faith in them!

Goal: be able to detect *any* signal

- … if it has sufficient power within the sensitive frequency band of the detectors
- … and is "short"

# Target Signals for GW Burst Searches

## Modelled burst search

Targets:

- Black hole ringdown
- Neutron star ringdown, pulsar glitches
- Cosmic string cusp

Use matched filtering

Issues generally similar to binary inspiral searches

## Generic burst search

Targets:

- High-mass binary black hole merger
- Long duration GRBs/collapsars
- SGR flares (magnetars/AXPs)
- Core collapse supernova
- Signals deviating from model expectations (i.e. alternative models of gravity (e.g. Brans-Dicke theory))
- Other unexpected or unmodelled sources

Use robust detection methods that do not rely on having a model of the signal

# Types of GW Burst Searches

## All-sky, all-times search

Analyse all available data for GW bursts arriving from any direction

## Externally triggered searches

Analyse GW data more deeply using information from:

- Known astrophysical events (GRBs, magnetar flares, pulsar timing glitches…)
- Candidate transient signals (high-energy neutrinos, radio bursts, …)

## All-sky GW search with rapid EM follow-up

Reconstruct apparent sky positions of GW event candidates

Try to catch optical, X-ray, and/or radio transient counterpart

# Coherent Burst Analysis

## Assuming that general relativity is correct,

**Each detector measures a linear combination of $h_+(t)$ & $h_\times(t)$**

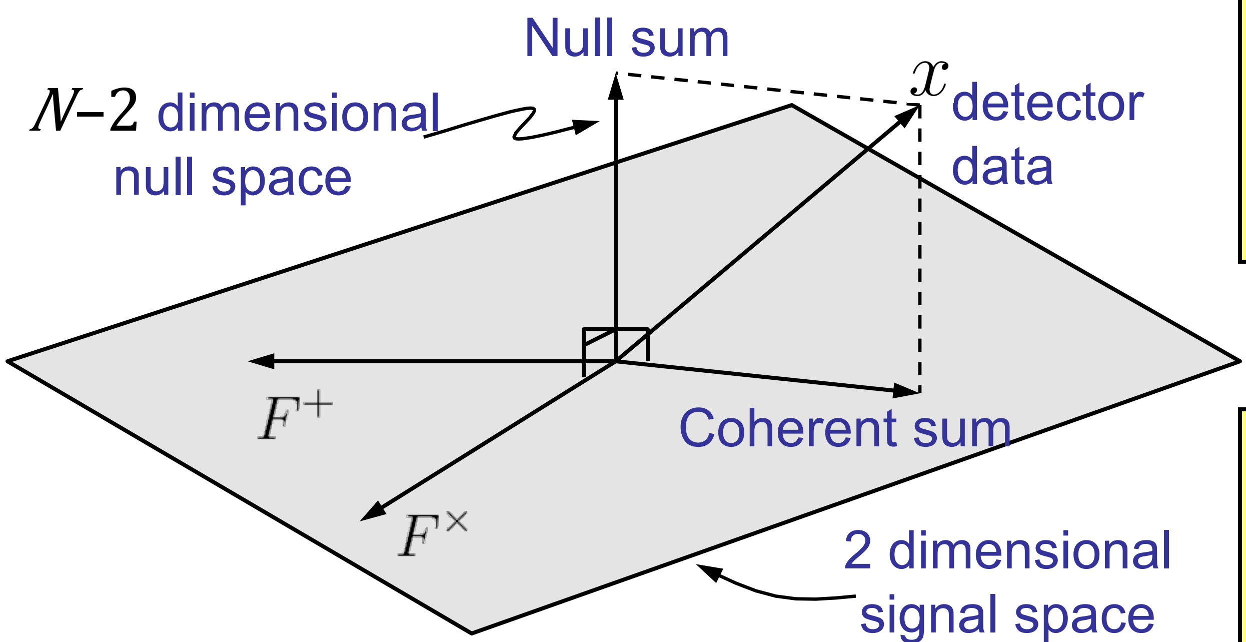
$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

*data* = *response* × *signal* + *noise*

$\Rightarrow$ Data from 2 sites can uniquely determine $h_+(t)$ and $h_\times(t)$ for an arbitrary signal, *in the absence of noise and if the arrival direction is known*

$\Rightarrow$ Data from 3 or more sites *over-determines* $h_+(t)$ and $h_\times(t)$ if the arrival direction is known

# Geometric View of Coherent Analysis




**Coherent sum:**
Find linear combination of detector data that maximizes signal to noise ratio

**Null sum:**
Linear combination of detector data that has no GW signal—provides consistency test

$$h_{maxlike} = (F^T F)^{-1} F^T x$$

F is the antenna response matrix and x is the data vector on slide 11

**Treat this as a maximum likelihood problem**

Find most likely $h_+(t)$ & $h_\times(t)$ , maximizing over arrival directions

Regulator penalizes physically unlikely signal hypotheses

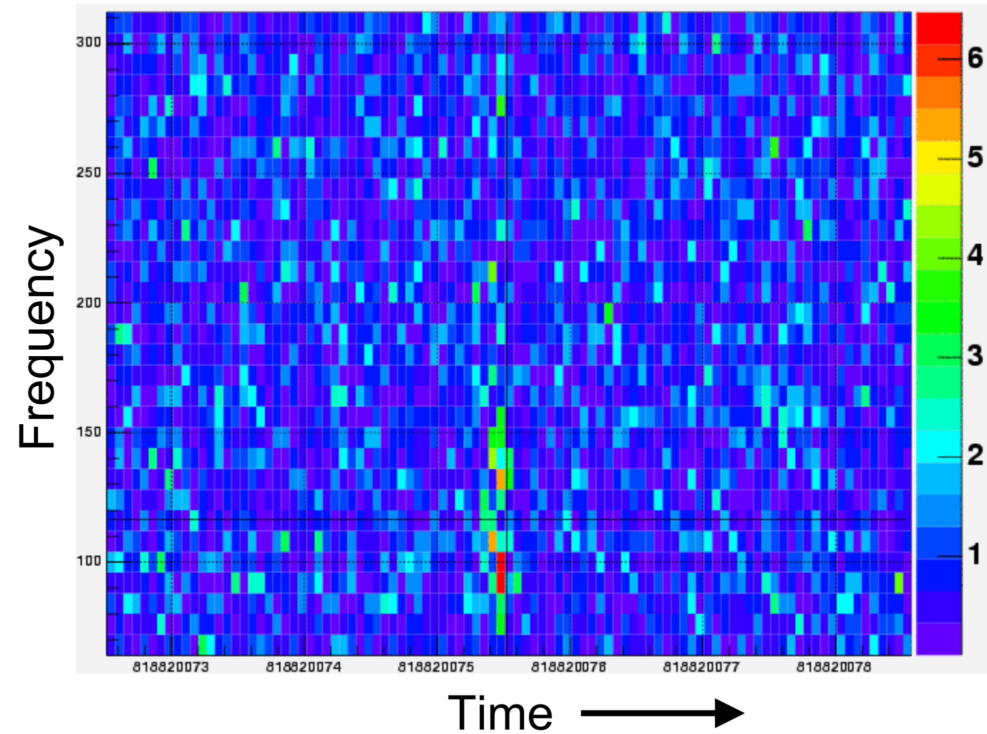
# "Excess Power" Burst Search Methods

**Decompose data stream into time-frequency pixels**

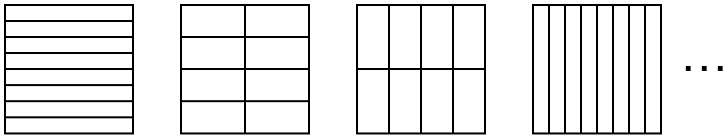
- Fourier components, wavelets, "Q transform", etc.
- Several implementations of this type of search

Normalize relative to noise **as a function of frequency**

Look for "hot" pixels or clusters of pixels




Can use multiple ($\Delta t, \Delta f$) pixel resolutions




$$SNR \sim \frac{hrss}{\sqrt{S(f0)}}$$

$$hrss = \sqrt{\int dt[h_+^2(t) + h_\times^2(t)]}$$

S(f0) is the noise power spectrum from slide 5 evaluated at the central frequency of the signal

# Signal Consistency Tests

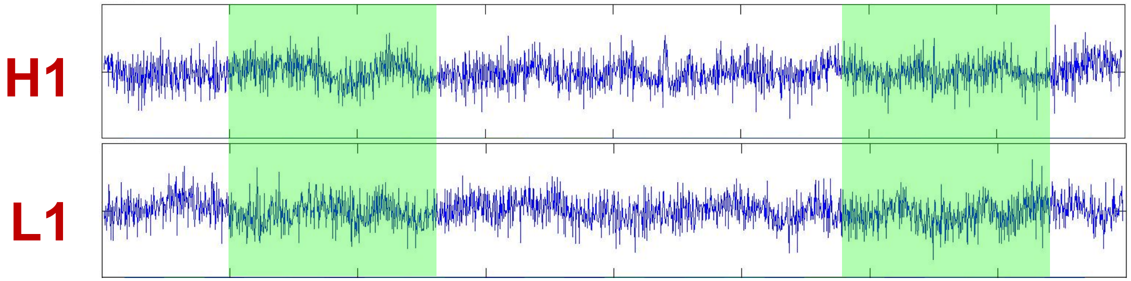
**Crucial since a GW burst in a single detector may look just like an instrumental glitch !**

## Coincidence

Require signals in different detectors to have compatible times, frequencies, amplitudes and/or other waveform properties

## Cross-correlation

Look for same signal buried in two data streams



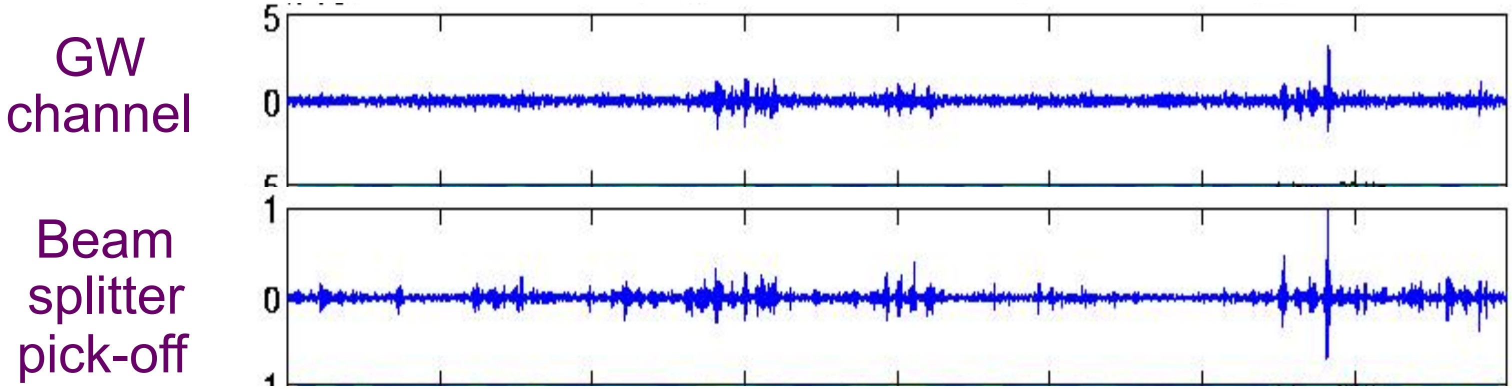

Checks for consistent *shape*, regardless of relative amplitude
Rejects background noise fluctuations

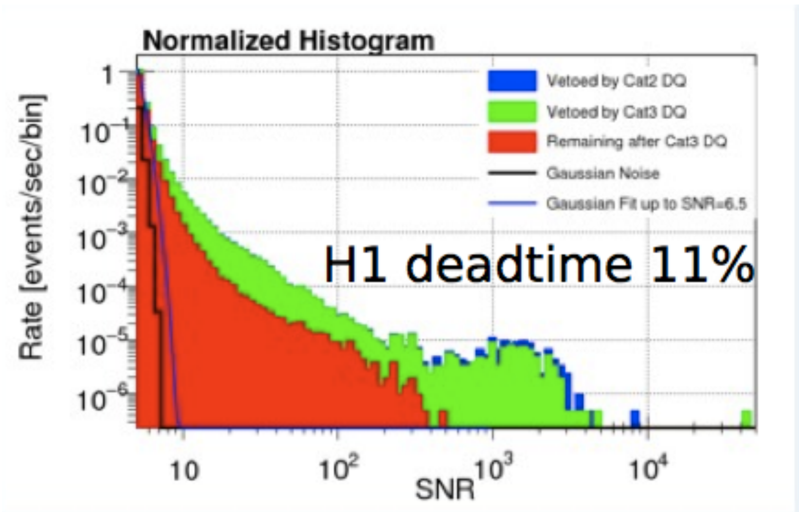
Best to integrate over a time interval comparable to the target signal

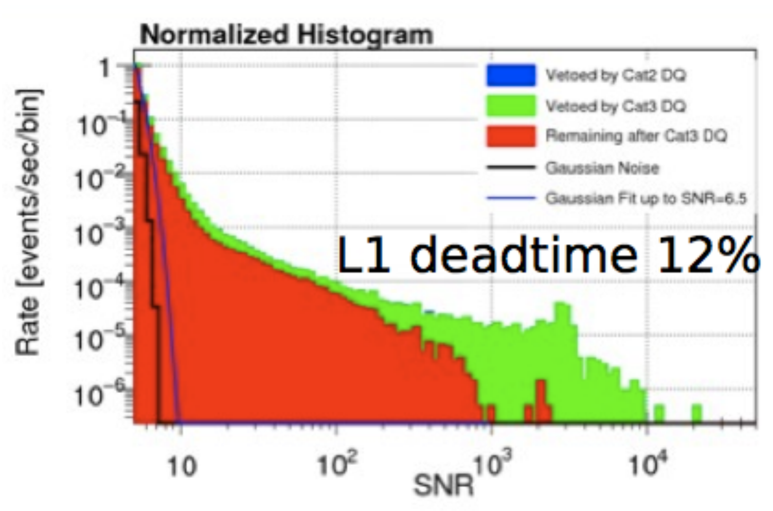
**We need to be robust against non-stationary noise**

**Solution: Data quality and Vetoes**

Reduce trigger rate, possibly allow thresholds to be lowered, and help us judge whether an event candidate may be real



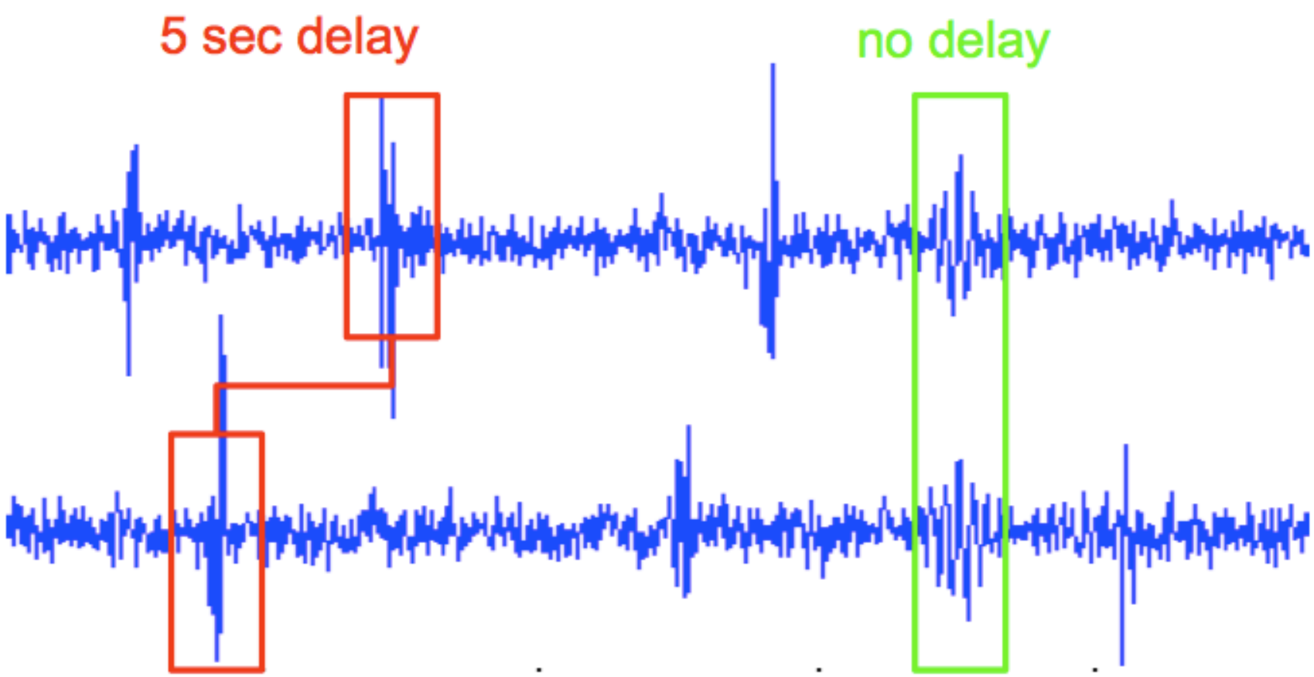



# Estimating background

- Background from time slides
- Efficiency estimated by adding simulated signals to the data
- Tune search parameters to maximise efficiency at fixed false alarm rate

- Reanalyse with artificial dealys (>>1s) between detectors
- Any resulting ‘events’ are non GW in origin



# All-Sky Generic GW Burst Search

**Analysed all LIGO and Virgo collected since 2005 when at least two detectors were running**

- Total live observation time:  636 days
- LIGO+Virgo coherent analysis
- GEO data often available for investigating possible event candidates

**Sensitive to arbitrary GW signals in the range 64–5000 Hz**

- Background measured by analyzing data with artificial time shifts
- Event selection thresholds tuned for low false alarm probability

**No event survived all selection cuts**

We set upper limits on burst rate vs. amplitude for representative waveforms using Monte Carlo

Abadie et al., PRD, arXiv:1202.2788

# All Sky Burst Search Results

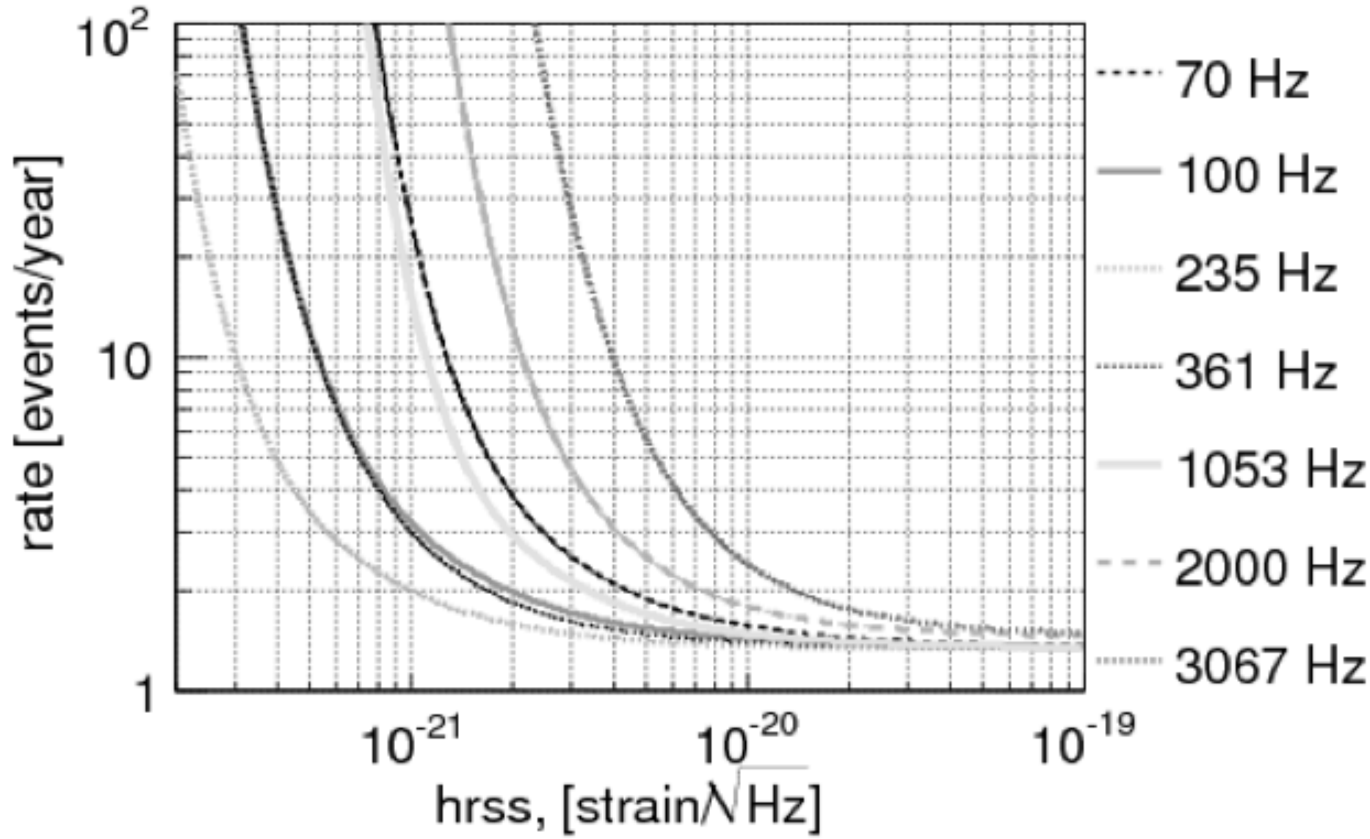
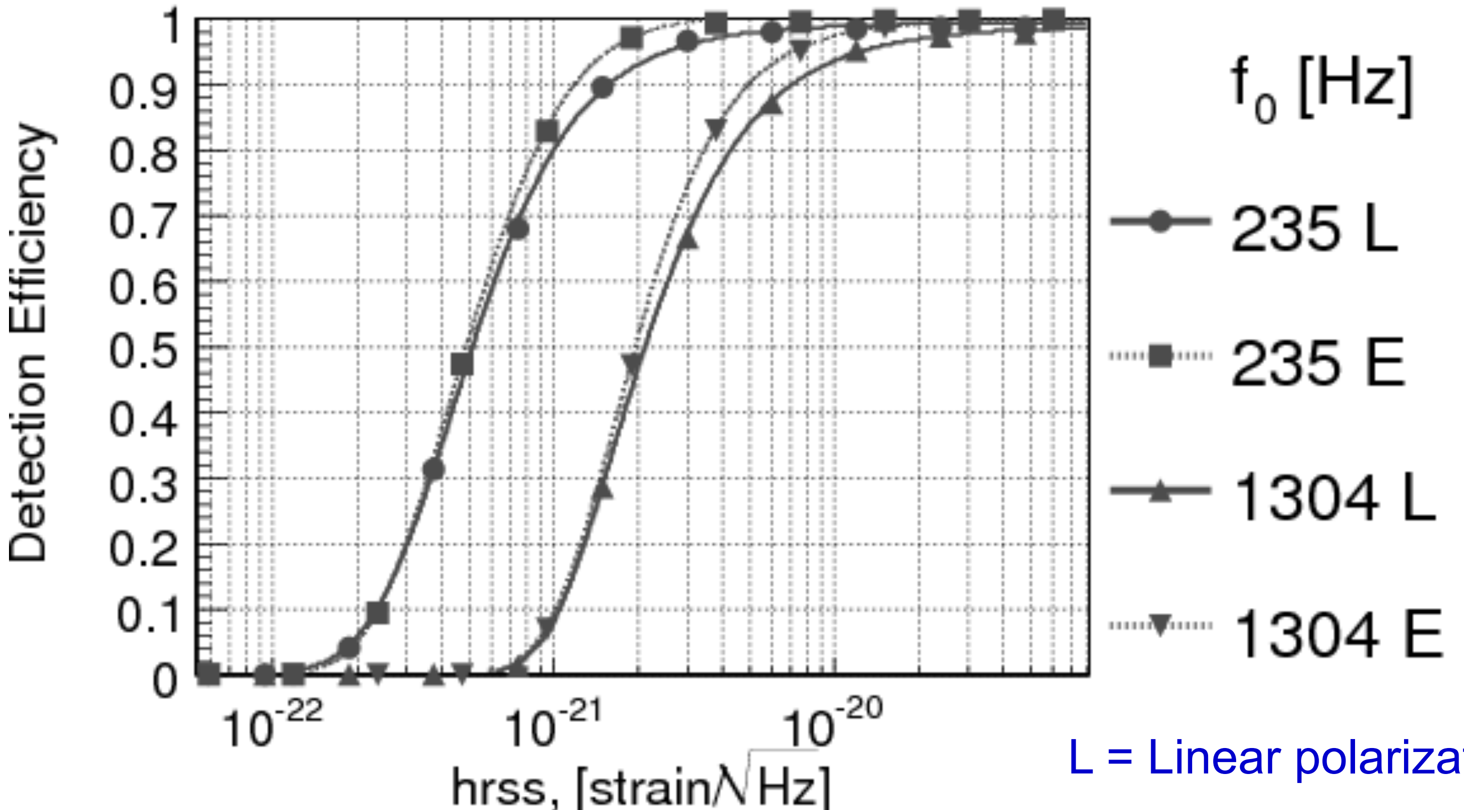



FIG. 5: Upper limits at 90% confidence on the rate of gravitational-wave bursts at Earth as a function of $h_{rss}$ signal amplitude for selected sine-Gaussian waveforms with $Q = 9$. The results include all the LIGO and LIGO–Virgo observations since November 2005.

# Sample Detection Efficiency Curves

For simulated signals with random times and sky positions added to real detector noise




(GW burst amplitude measure)

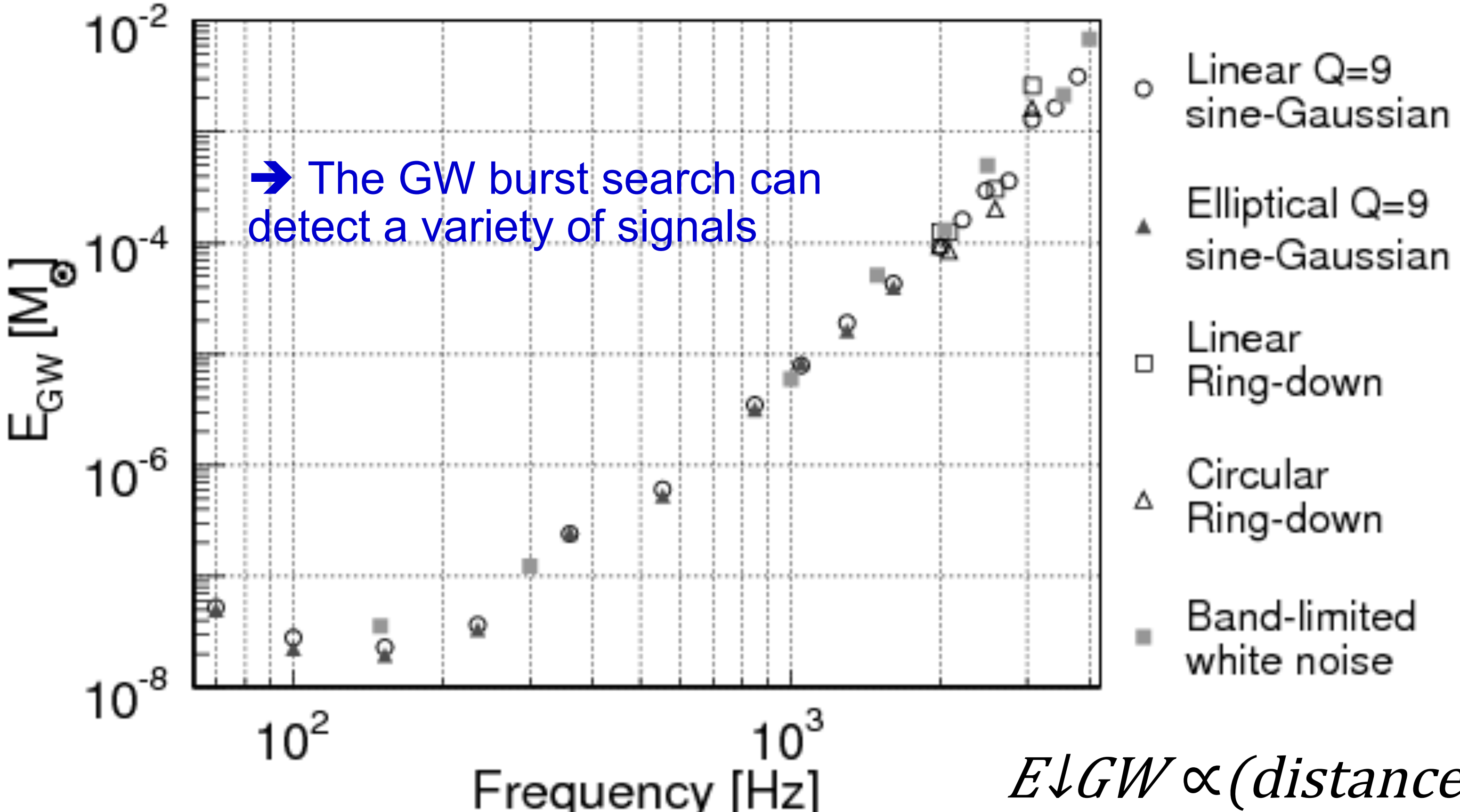
L = Linear polarization at Earth

E = Elliptical polarization from random inclination of axis of presumed rotating source

# Search Sensitivity in Energy Units

GW energy emission assuming a Galactic source (10 kpc) that could have been detected with 50% efficiency

*3-detector LIGO+Virgo network data, S6/VSR2+3 run*



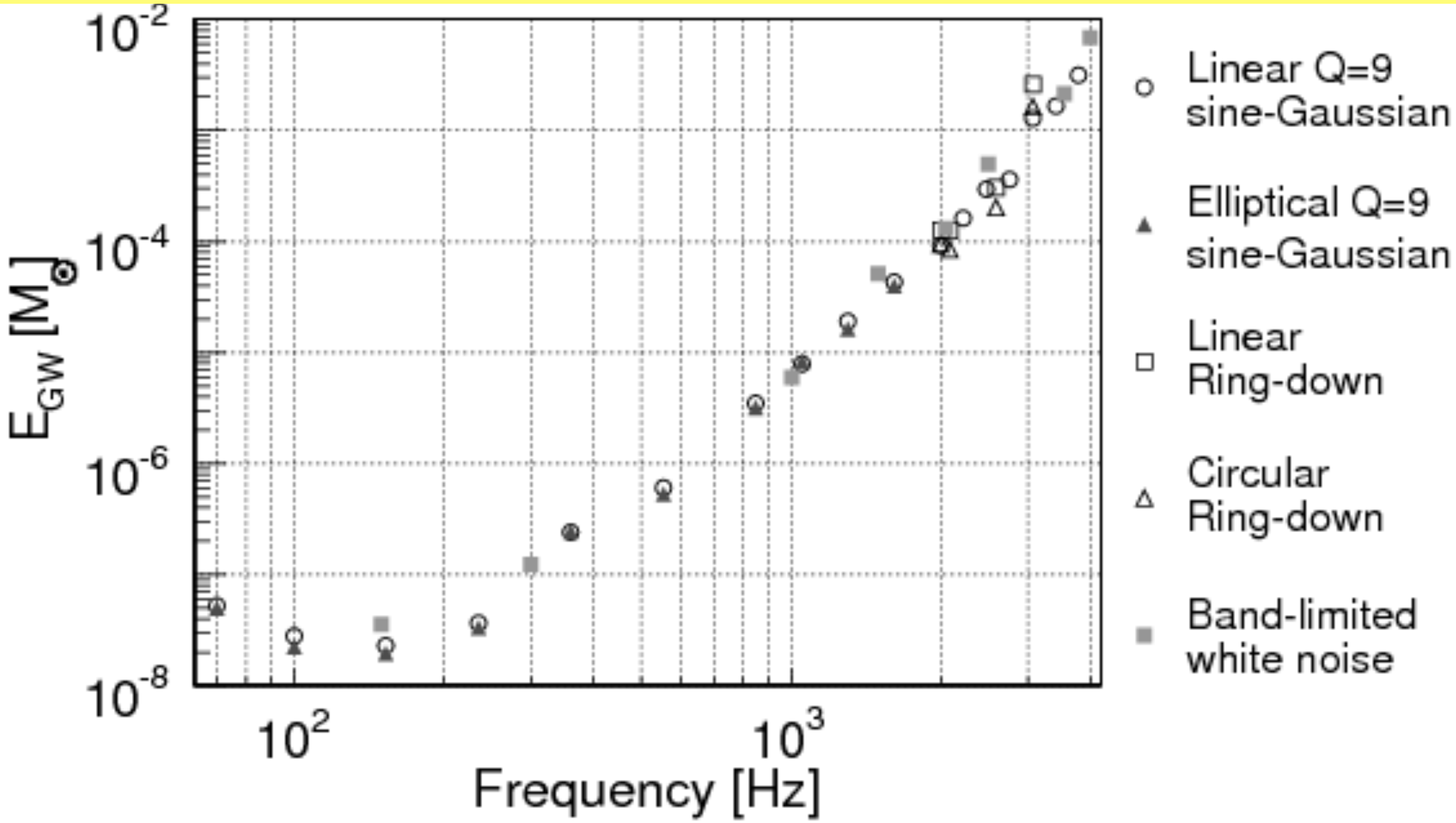

$$E_{GW} \sim \frac{\pi^2 c^3}{G} \times (f \times dist \times hrss)^2$$

$E↓GW \propto (distance)↑2$ for other distance

# Search Sensitivity in Energy Units

- Core-collapse supernovae are around 1e-8 - 1e-7 Msun (typically) up to 1e-4 Msun (extreme cases) emitting between 100-1000 Hz
- SGR flares are <~ 1e48 erg (probably less) around 1000 Hz
- BNS and extreme long GRB models can give 1e-2 Msun around 100-200 Hz.

(1Msun ~ 2e54 erg)



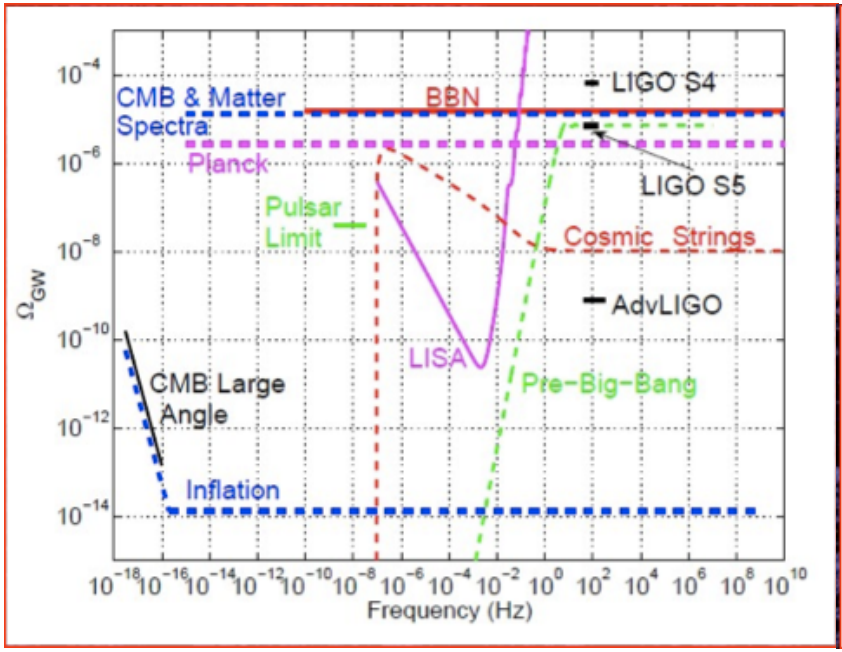
# Cosmic String Burst Search

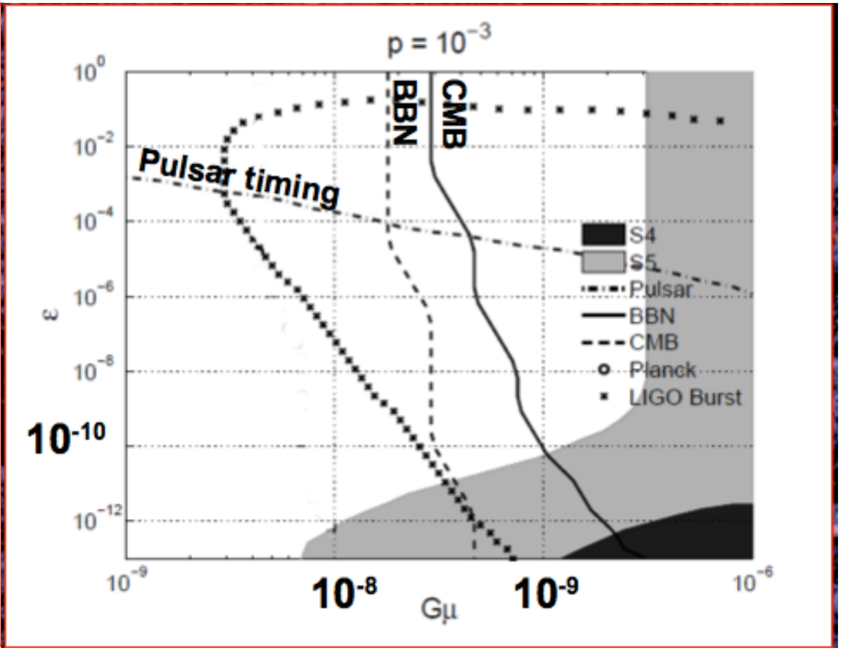
**Cosmic strings are topological defects left over from the early universe**

- May form in phase transitions, or come directly from string-theory cosmological models

**Cosmic strings are expected to have *cusps* which emit strong bursts of GWs**

- Known waveform ➔ can use matched filtering



# Externally Triggered (extTrig) Burst Searches

# Multi-messenger Advantages

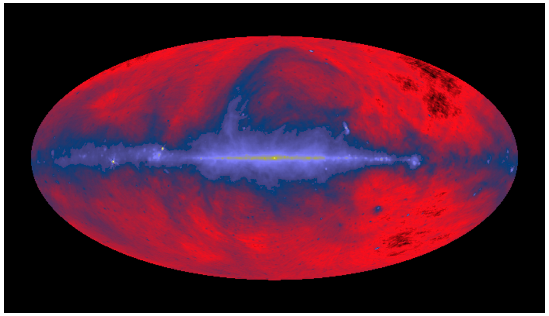
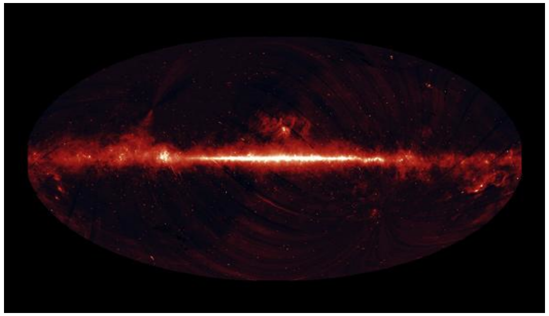
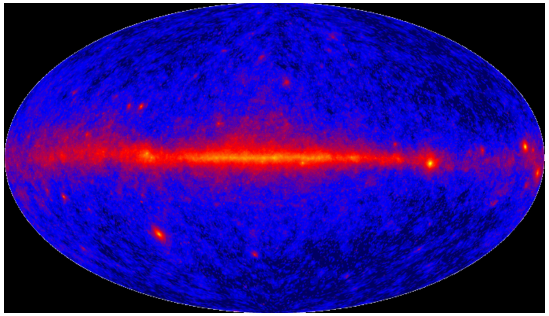
**If an event has already been detected, then GW searches:**

- 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,**

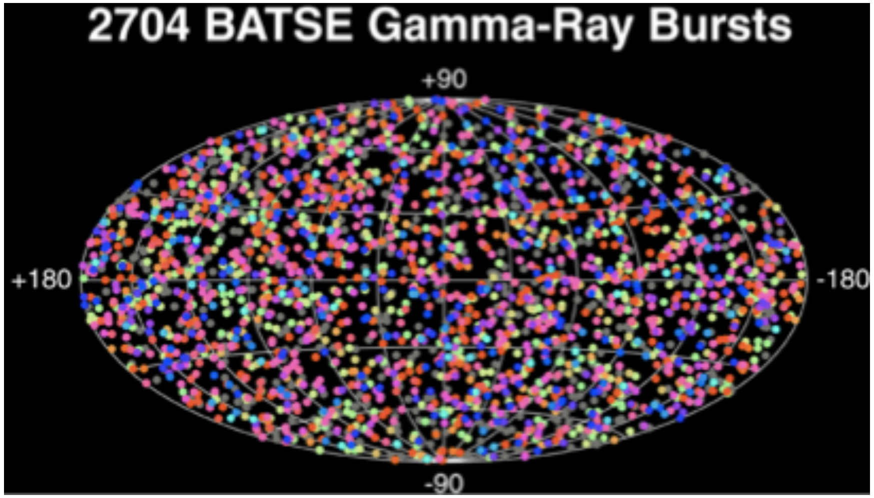
- Background is suppressed, so a weaker GW signal can be confidently detected
- The extra information from the combined observations will reveal more about the astrophysics of the source
- *Non*-detection of a GW signal can still provide useful information

# Example

| Radio Sky | Infrared Sky | Gamma-Ray Sky |
| --- | --- | --- |
|  |  |  |
| • $\lambda \sim 10^{3}$ m<br>• Molecular clouds, (Masers), CMB, quazars, Pulsars<br>• Transmitted through atmosphere | • $\lambda \sim 10^{-5}$ m<br>• Dust, probe interstellar environment<br>• Partially transmitted through atmosphere | • $\lambda \sim 10^{-12}$ m<br>• Gamma-ray bursts, pulsars, supernovae, cosmic rays<br>• Completely absorbed by atmosphere |

# Gamma-Ray Bursts

- Gamma-ray bursts: isotropically distributed bursts of γ-rays (~100keV) , ~once a day
- First detection in 1967 from Vela satellites (monitoring nuclear tests)
- Characterised by duration and spectral hardness
  - Long (>2s) , soft spectra (lower energy photons)
  - Short (<2s), hard spectra (higher energy photons)




# GRBs

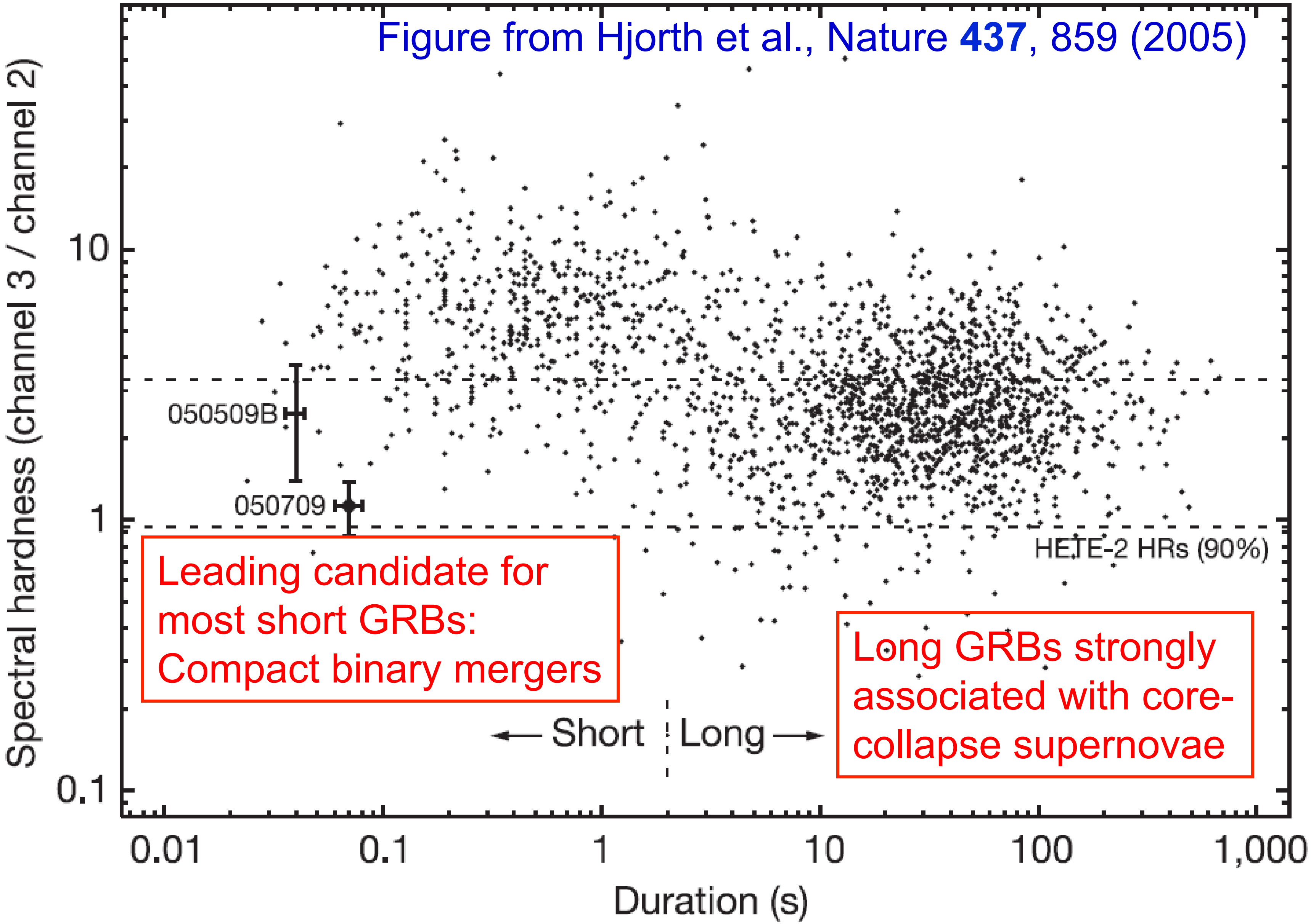


Figure from Hjorth et al., Nature **437**, 859 (2005)
Spectral hardness (channel 3 / channel 2)
10
1
0.1
050509B
050709
HETE-2 HRs (90%)
Leading candidate for most short GRBs: Compact binary mergers
Long GRBs strongly associated with core-collapse supernovae
← Short
Long →
0.01
0.1
1
10
100
1,000
Duration (s)

# Multi-Messenger Bursts: Emission Mechanisms

**Gamma rays**

- From “internal” or “external” shocks

**X-ray afterglow**

- “Fireball model” – expands into local medium
- Typically stronger for long GRBs than for short

**Optical afterglow**

- Supernova or supernova-like emission
- Reprocessing of energy by local medium

**Radio afterglow**

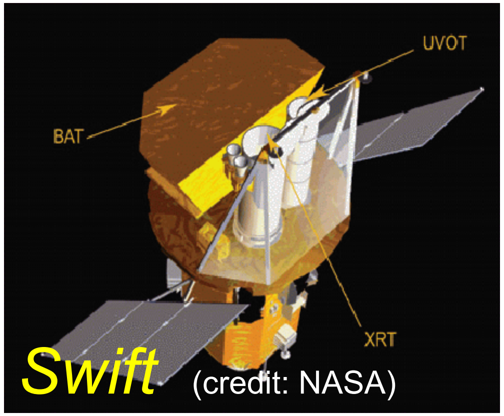
**High-energy neutrinos**

- Expected from accelerated protons in shocks

**Gravitational waves**

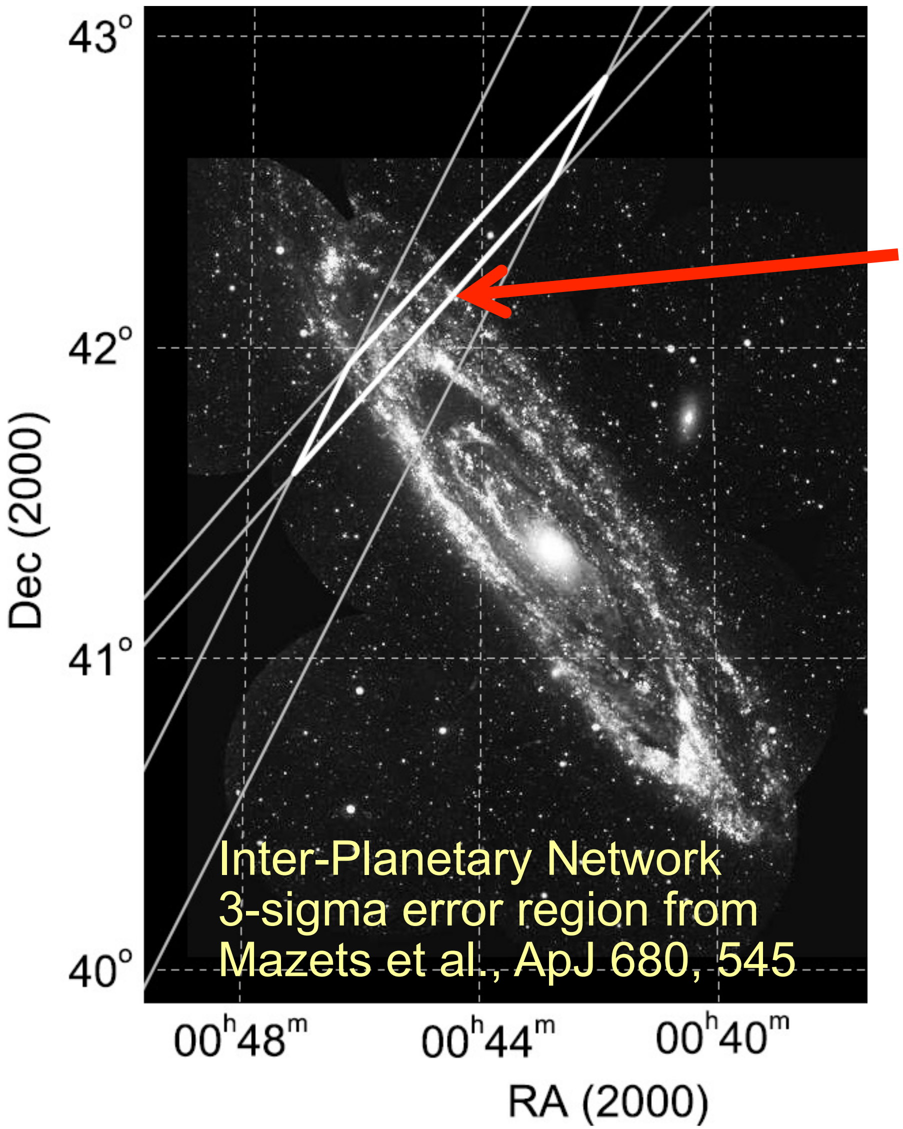
- Should be detectable *if* source is really close, especially for short GRBs


Can indicate host galaxy !




Reveal central engine !

# GRB 070201




**Short, hard gamma-ray burst**

Leading model for short GRBs: merger involving a neutron star

**Position was consistent with being in M31 (Andromeda galaxy)**

**Both LIGO Hanford detectors were operating**

- Searched for inspiral & burst signals

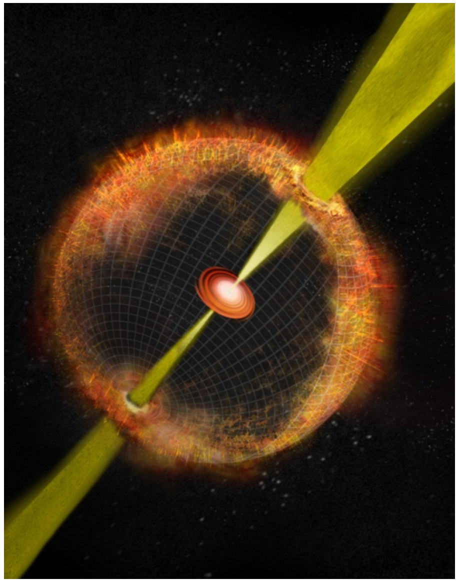
**No plausible GW signal found ➔ very unlikely to be a merger in M31**

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

Similar analysis done for GRB 051103

Abadie et al., arXiv:1201.4413

# Systematic GRB GW Burst Search



Credit: Bill Saxton, NRAO/AUI/NSF

**Both long and short GRB progenitors could emit detectable GWs**

Short: binary mergers, neutron star quakes

Long: massive star core collapse

**Huge energy release**

Can be ~$10^{51}$ erg in gamma rays !

**Redshifts known for *some* GRBs, but not most**

Could include an occasional nearby, low-luminosity GRB ?

**Previously published search results:**

S2/S3/S4 LIGO – 39 GRBs    Abbott et al., PRD 77, 062004 (2008)

S5/VSR1 LIGO+Virgo – 137 GRBs    Abbott et al., ApJ 715, 1438 (2010)

# Space and Time Windows

**Searched over sky region reported for the GRB**

GRBs detected by Fermi GBM have large error regions

Also GRBs reported by *Swift* and other satellites

**Time window allowed for relative time offset from GRB trigger**

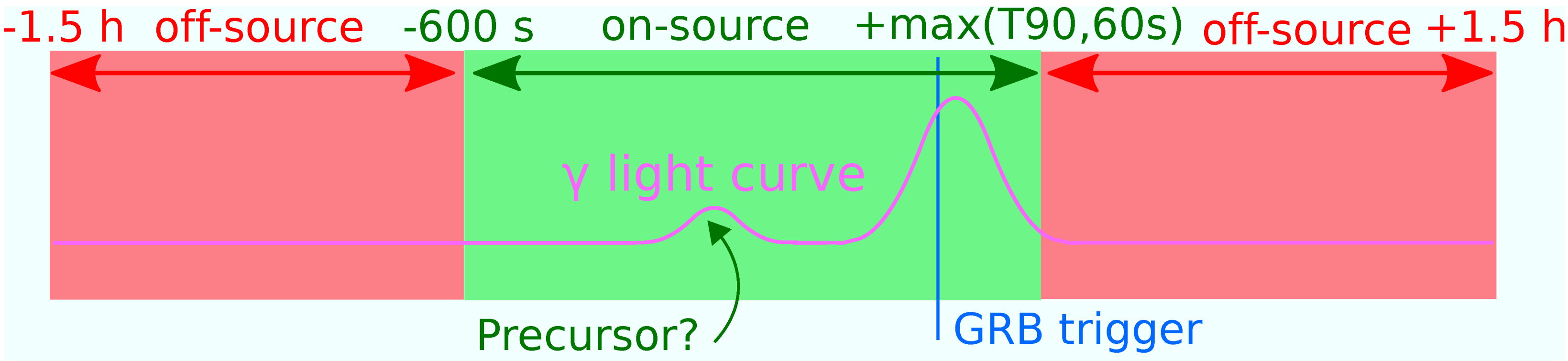
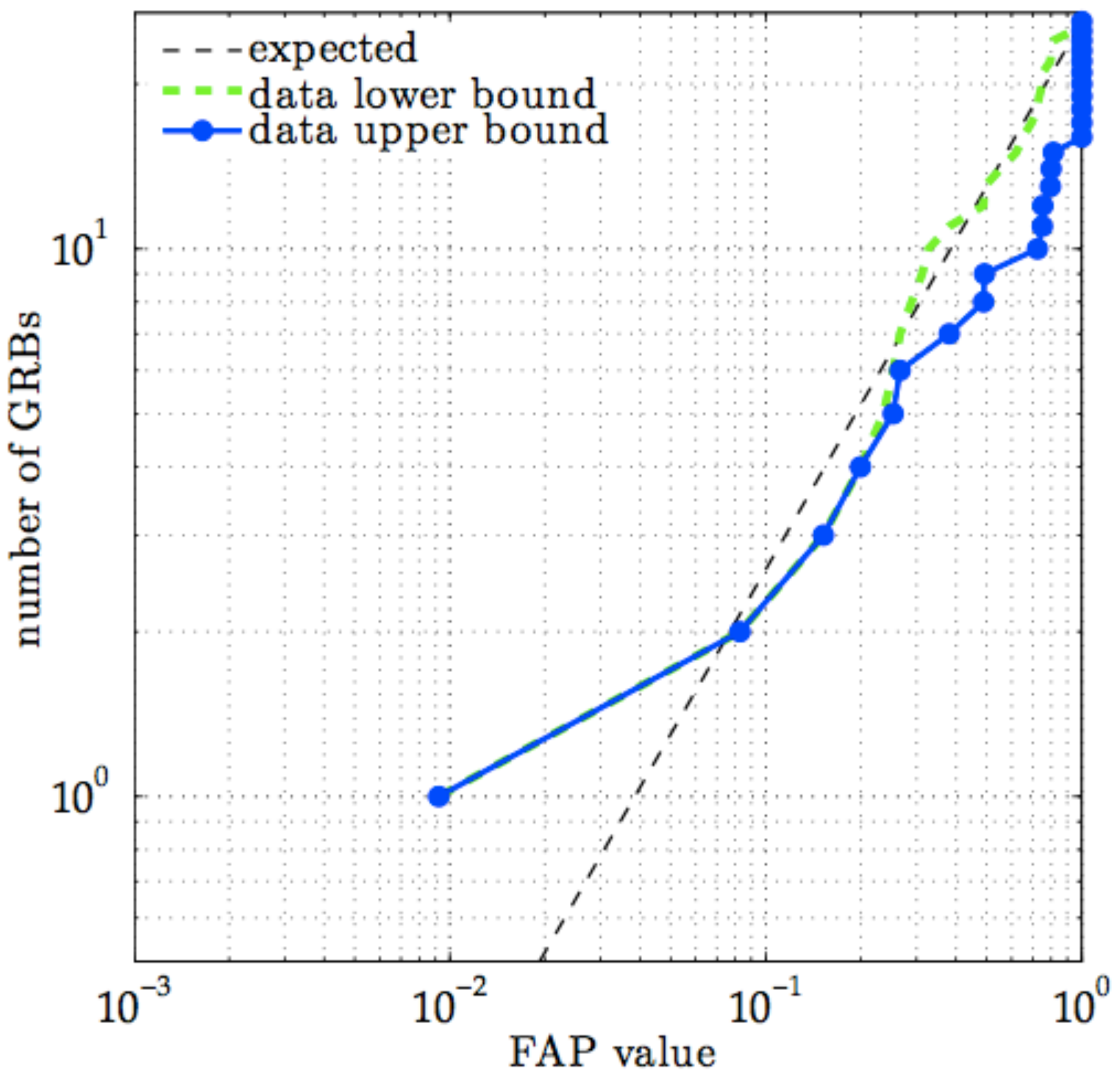



*Figure courtesy of M. Wąs*

"Off-source" time used to measure background GW trigger probability in detector data with similar properties

# S6/VSR2+3 Search Results




**No individual GRB stands out compared to the background**

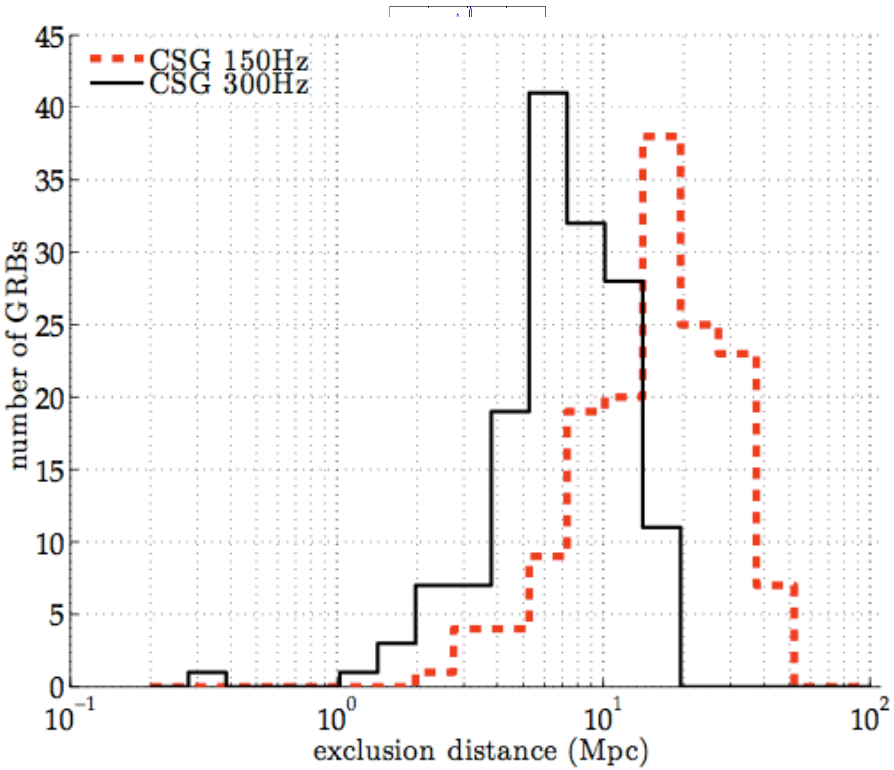
**No subset of the most significant GRBs stands out either**

- Consistent with uniform distribution

**arXiv 1205:2216**

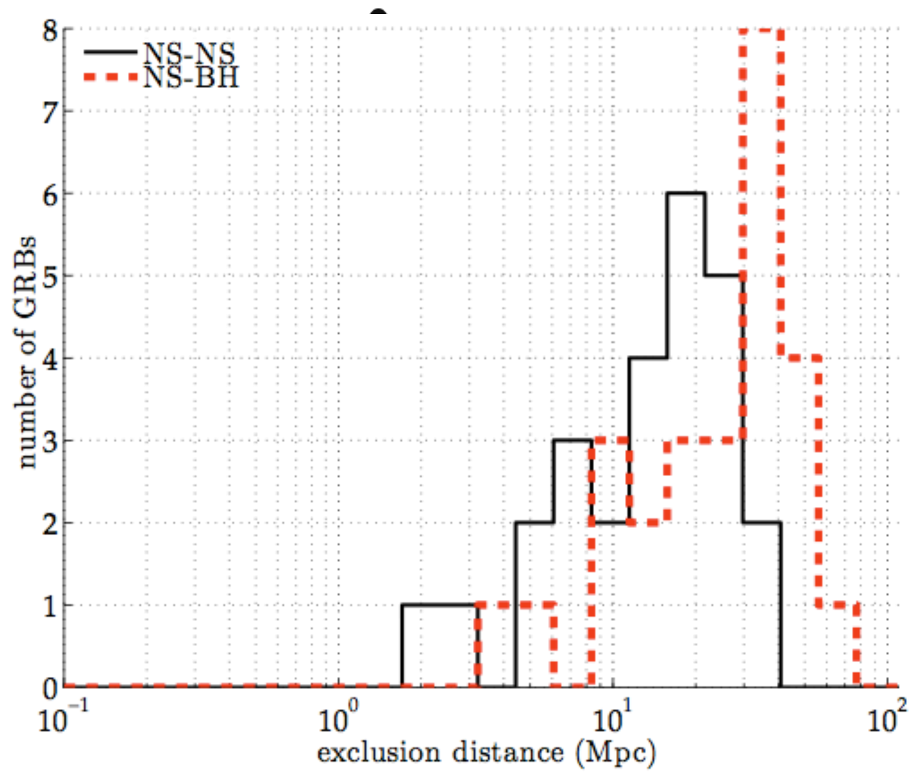
# GRB Progenitor Exclusion Distances

## Assuming sine-Gaussian with $E_{GW} = 0.01\ M_{\odot}c^2$



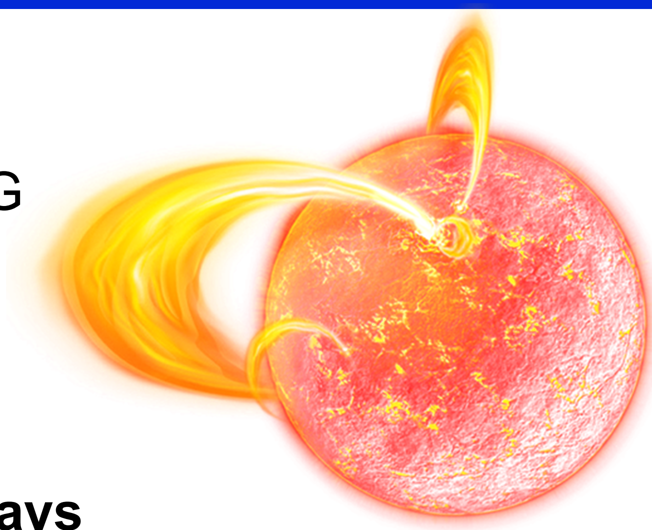

## Assuming binary inspiral

but using unmodeled burst search*




* Expect matched filtering search to have a factor of ~2 better sensitivity for binary inspiral signals

# Soft Gamma Repeater (SGR) Flares



**SGRs are believed to be magnetars**

- Neutron stars with magnetic field ~$10^{15}$ G interacting with crust
- Anomalous X-ray pulsars (AXPs) are essentially the same thing

**Occasionally emit flares of soft gamma rays**

- Ordinary flares $E_{EM} \sim 10^{42}$ erg
- Some SGRs have produced a *giant flare* with energy ~$10^{46}$ erg

**Thought to be associated with cracking of the crust**

- Probably excite vibrational modes of the neutron star
- Quasiperiodic oscillations seen in X-ray emission after giant flares

**Some vibrational modes couple to gravitational waves !**

- Can probe what is going on with the star

# 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 associated with X-ray QPOs
- GW energy limits are comparable to total EM energy emission

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

**GW bursts at times of flares ?**

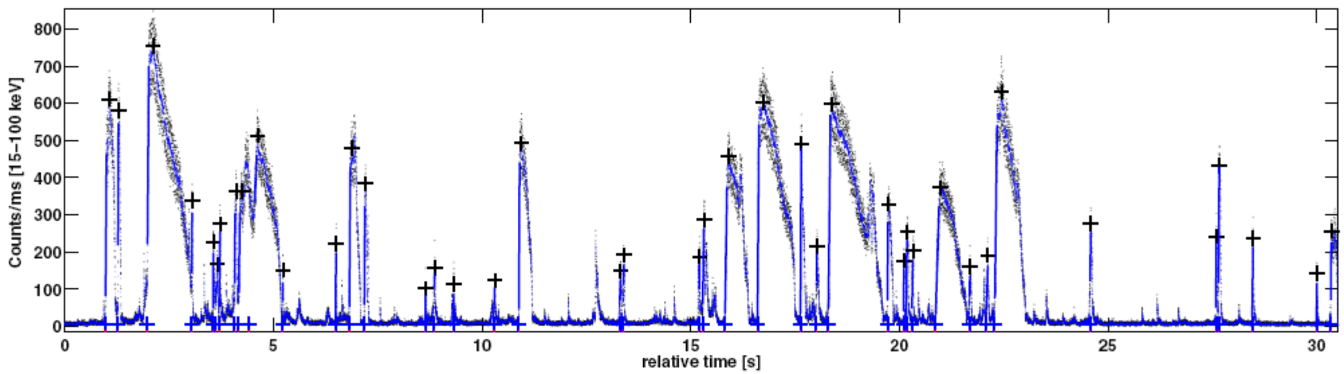
- 2004 giant flare plus 190 other flares from SGR 1806–20 and SGR 1900+14 during first calendar year of LIGO S5 run
- Excess-power search for neutron star *f*-modes ringing down (~1.5–3 kHz), also for arbitrary lower-frequency bursts
- For certain assumed waveforms, GW energy limits are as low as few $\times 10^{45}$ erg, comparable to EM energy emitted in giant flares

*Abbott et al., PRL 101, 211102 (2008)*

# Searches for GW Signals from Magnetars

## Repeated GW bursts associated with multiple flares ?

- “Storm” of flares from SGR 1900+14 on 29 March 2006



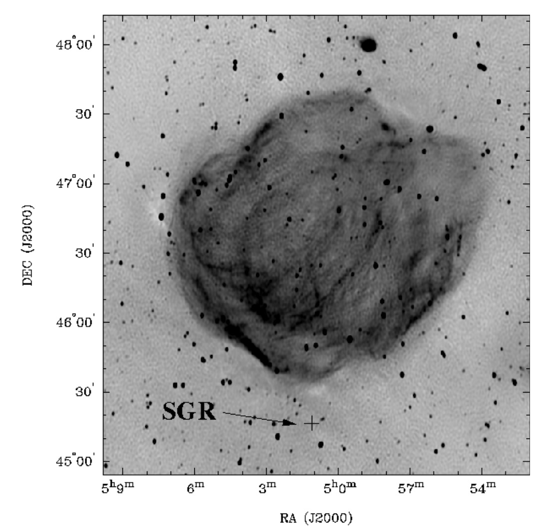

- “Stack” GW signal power around each EM flare
- Gives per-burst energy limits an order of magnitude lower than the loudest-event analysis —as low as few × $10^{45}$ **erg**

*Abbott et al., ApJ 701, L68 (2009)*

*Abadie et al., ApJ734, L35 (2011)*

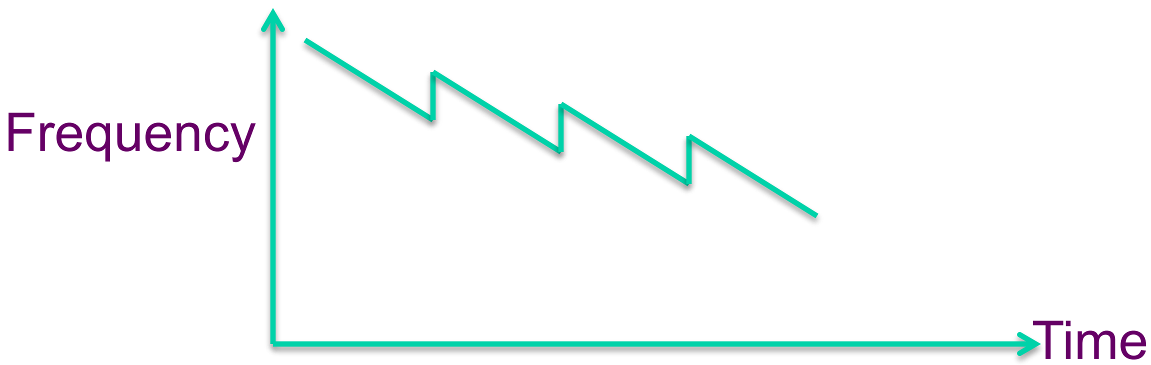
## More flares, new magnetars

- Including SGR 0501+4516 at ~1–2 kpc
- Closer source gives sensitivity to lower energies !
- Hoping for a giant flare from a nearby SGR



# Pulsar Glitches

**Some pulsars exhibit “glitches” in pulse frequency**




**Mechanism for glitches is unclear**

- Crust cracking?
- Coupling of differentially rotating crust and core?
- Rearrangement of superfluid vortices?

**May excite quasinormal vibrational modes**

- Some modes couple to GW emission !

**Searches done – Abadie et al., ApJ 737 L93 (2011)**

Vela pulsar glitch in August 2006 : $\Delta\nu/\nu = 2.6 \times 10^{-6}$

# Supernovae

**Several possible GW emission mechanisms**

- Rotating collapse and bounce
- Rotational instabilities
- Convection
- Standing accretion shock instability
- Protoneutron star $g$-modes

  ...

Review: C. D. Ott, Classical & Quantum Gravity 26, 063001 (2009)

**Relative strength of GW emission mechanisms depends on what drives the supernova explosion**

- Leading possibilities: MHD with rotation, neutrinos, acoustic waves

**➔ Detection or non-detection of GWs can distinguish !**

- Especially in conjunction with neutrino signal

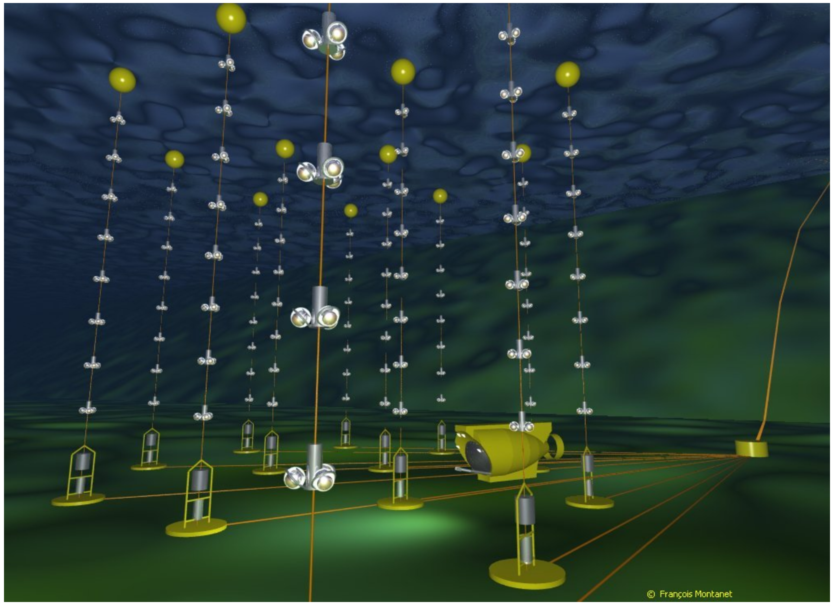
**Current detectors can probably only see SNe in our galaxy**

- Advanced detectors may go out to a few Mpc – non-negligible rate

# Neutrinos

Many EM-GW sources potentially missed:

- EM signature of many sources may be tightly beamed (e.g., pulsars, GRBs) so we miss the EM signal
- Absorption in interstellar/galactic medium




**Neutrinos**: expect neutrino emission from supernovae, GRBs, SGRs. Also potentially have ν emission from prompt stellar collapse to black hole (otherwise invisible) or from 'fizzled' SNe

Neutrino detectors have ~1° field of view, point on the sky, GW detectors have ~5° field of view.

Perform coincidence analysis using neutrino sky-location, time of trigger

Relation between ν trigger time & GW emission uncertain: use multiple coincidence windows

# Seeking Electromagnetic Counterparts with Rapid Follow-up Observations

# Prospects for EM Counterparts

**GW sources release a lot of energy**

e.g. compact binary merger: ~$10^{53}$ erg or more

**Many ways for *some* of that energy to go into EM emissions**

Relativistic jets with internal or external shocks [Piran, RMP 76, 1143]
Radioactive decay of ejected material [Metzger et al., MNRAS 406, 2650]
Magnetic field rearrangement [Thomson & Duncan, ApJ 561, 980]
Plasma excitation by GWs [Moortgat & Kuijpers, PRD 70, 023001]
Poynting flux from orbit in B field [McWilliams & Levin, arXiv:1101.1969]

⋮

**Likely to be detectable *if* an appropriate telescope is pointed in the right direction at the right time**

Optical and radio surveys only cover part of the sky at any given time

**Multiple benefits:**

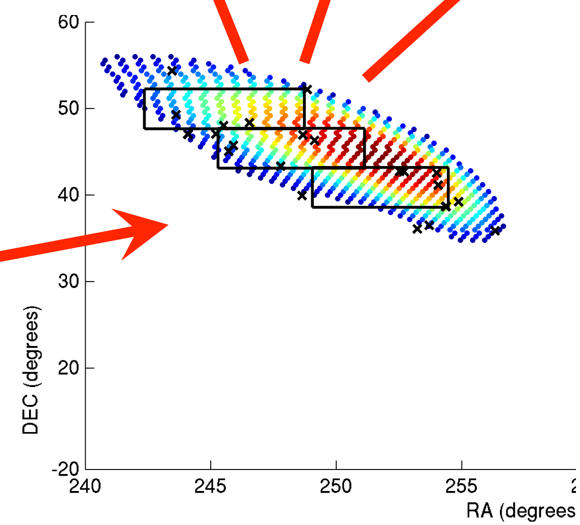
Confirm a GW event candidate → confidently detect weaker events
Obtain more comprehensive optical, X-ray and/or radio observations
Get information about the progenitor and astrophysics

# EM Follow-ups: The Basic Idea



...

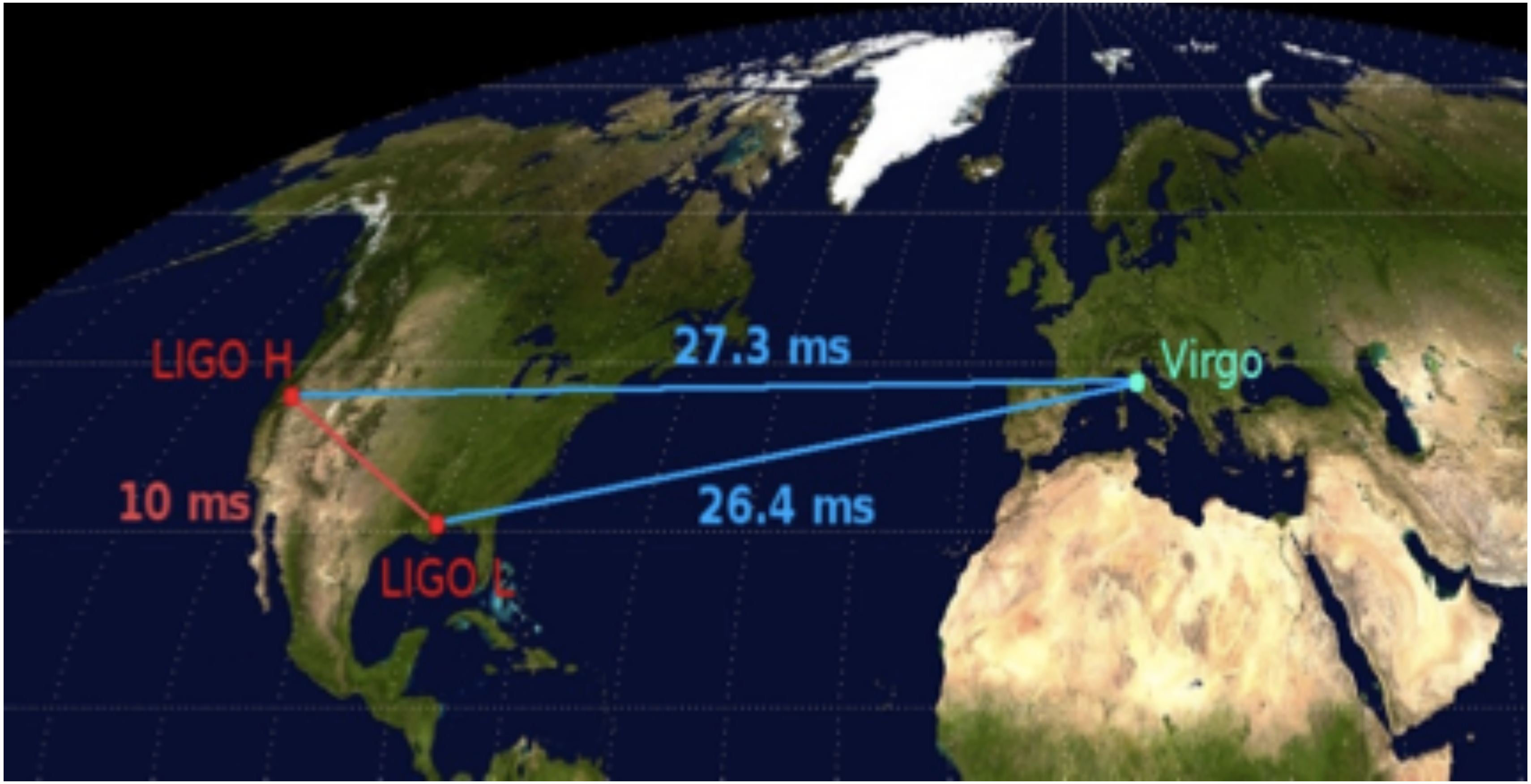
Analyze GW data, select candidates




[e.g. see Kanner et al., CQG 25, 184034]

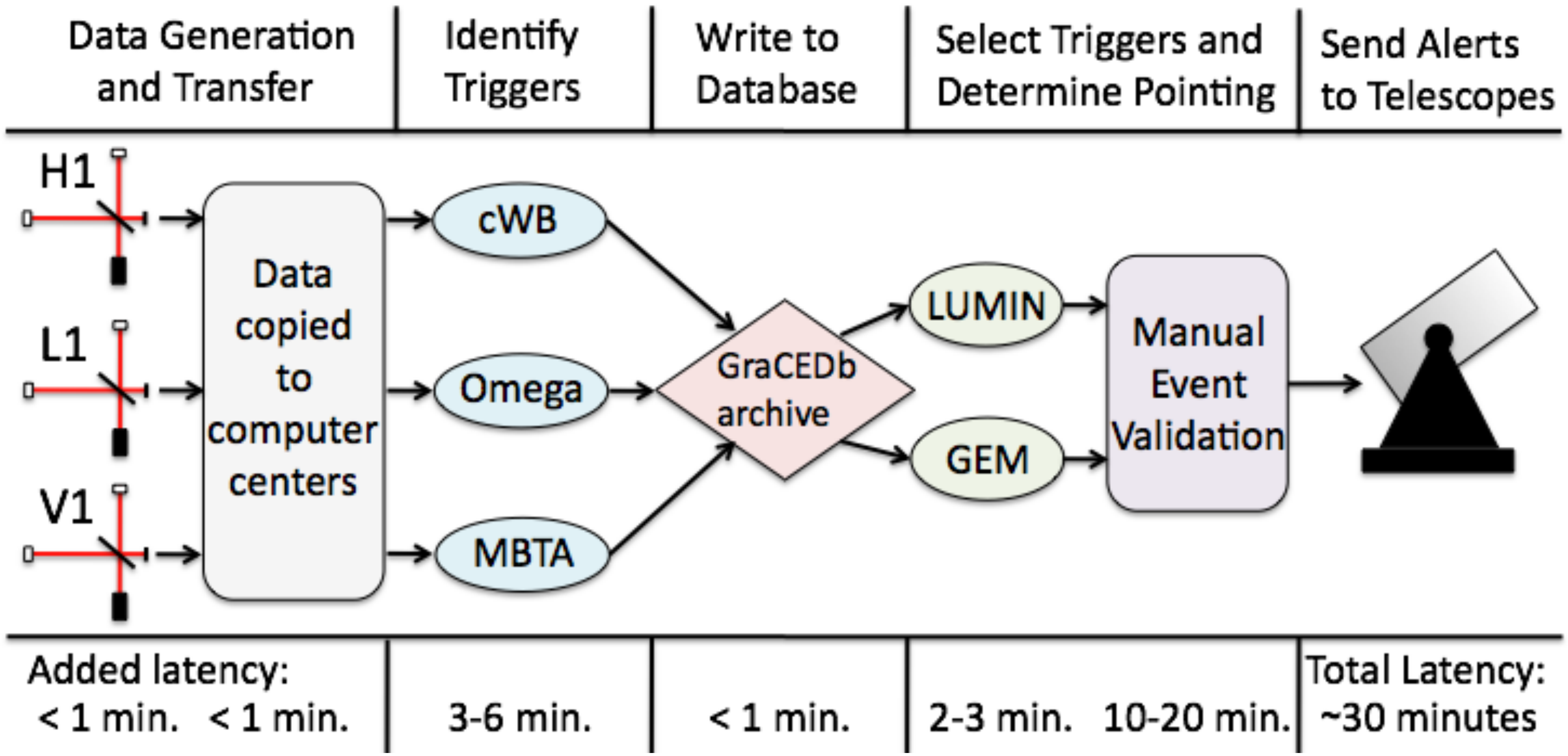
# Multi-detector network

We analyze GW data from 3 sites to find possible candidates




A 2 detector site is unable to provide satisfactory sky localisation

# First Implementation: 2009–2010




LUMIN and GEM selected significant event candidates,
alerted humans (on call 24/7 in shifts) to complete manual validation,
chose target coordinates and communicated with telescopes

LSC+Virgo+others, A&A in press, online at DOI: 10.1051/0004-6361/201118219

# Online Data Analysis

## Burst Search

Two search algorithms: *Coherent WaveBurst* and *Omega Pipeline*

Sensitive to essentially any signal with duration up to ~1 s

Fully coherent analysis considering all possible sky positions

## Inspiral Search

Search algorithm: *MBTA* (multi-band template analysis)

Consider binaries with at least one neutron star

Coincidence analysis, then use relative arrival times of triggers to triangulate sky position

Each search pipeline calculates a detection statistic

- Background estimated using time-shifted data

Search output: "triggers" with event time, significance (false alarm rate), sky probability map

# Data Quality Checks

**Check that nothing out of the ordinary is happening at the sites which could cause us to question the data**

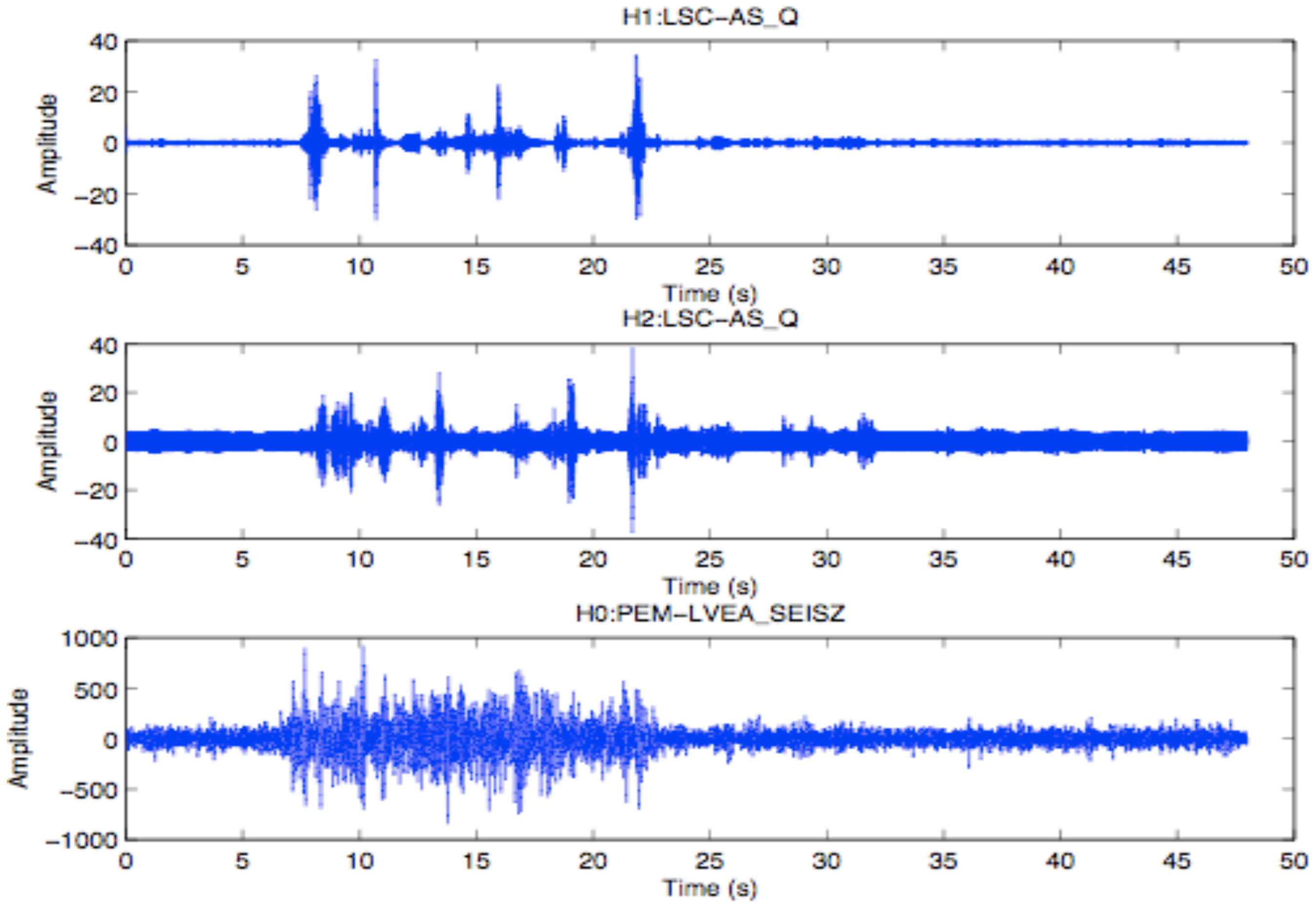
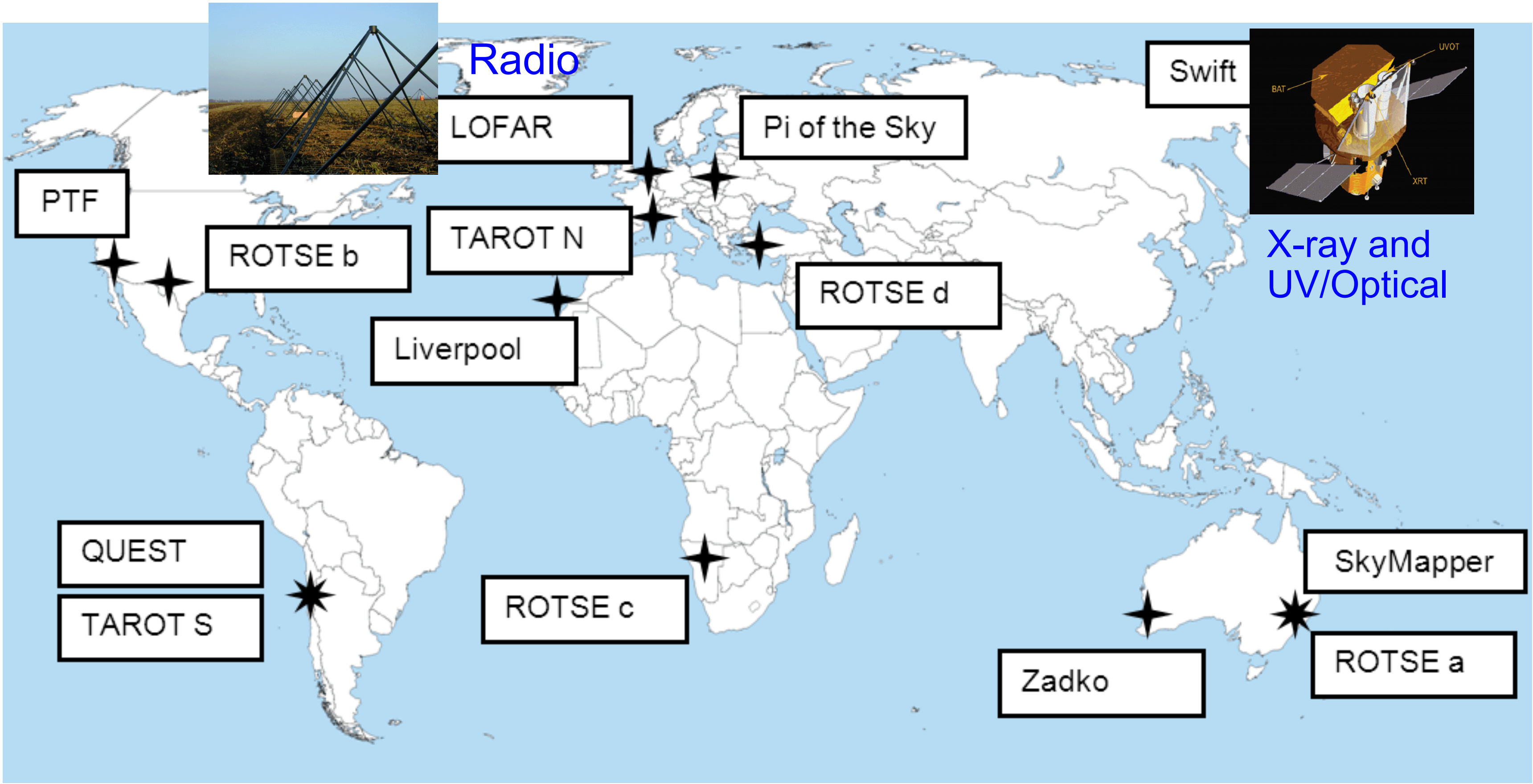



Figure taken from CQG:22.S1059

# 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

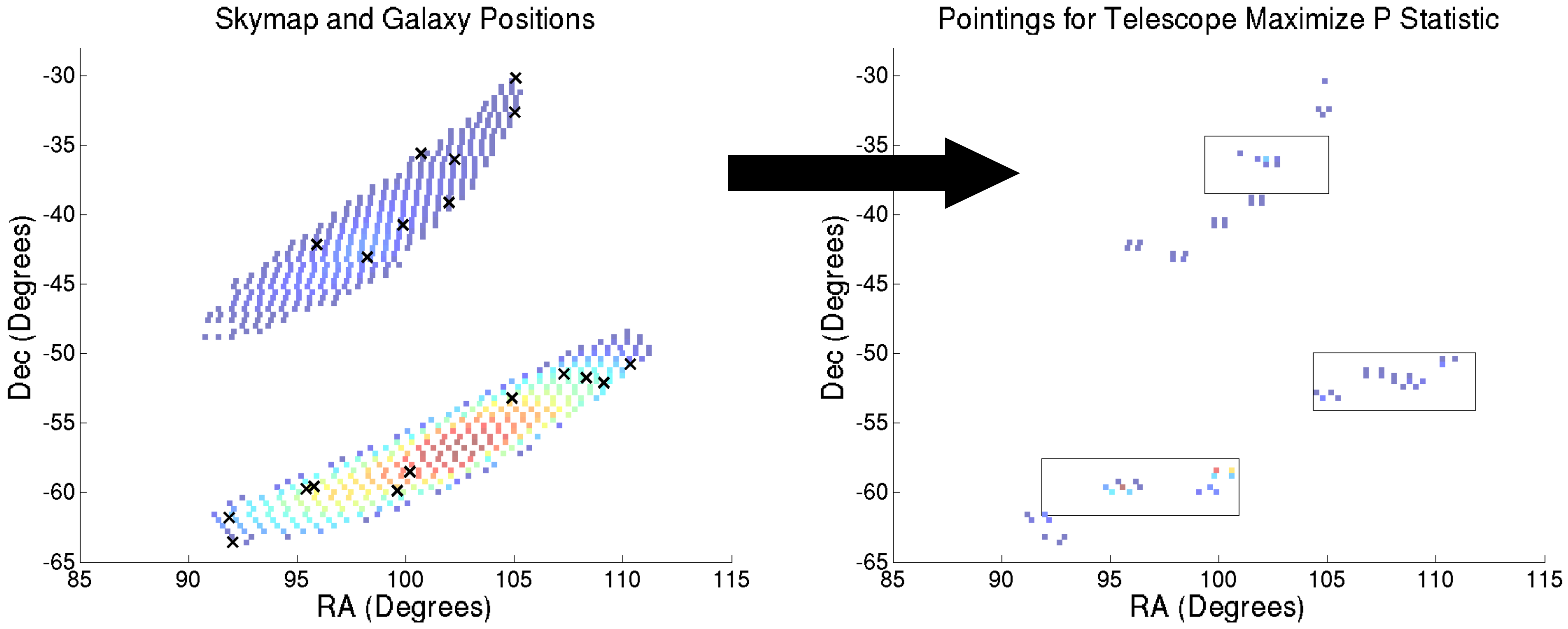
# LUMIN Galaxy Targeting

**Use positions of known galaxies within 50 Mpc**

[White et al., CQG 28, 085016]

Weight by blue light luminosity, and inversely by distance

MBTA: only consider galaxies closer than measured effective distance for the trigger



# Follow-up Target Position

The sky position error region may contain many hundreds of galaxies, therefore we need a way of ranking them

Since nearby galaxies are thought to be the most likely host of observable sources, we use a galaxy catalogue (GWGC (White et al. 2011)) and restrict ourselves to the distance our detectors can see (~ 50 Mpc)

Galaxies are weighted similar to:

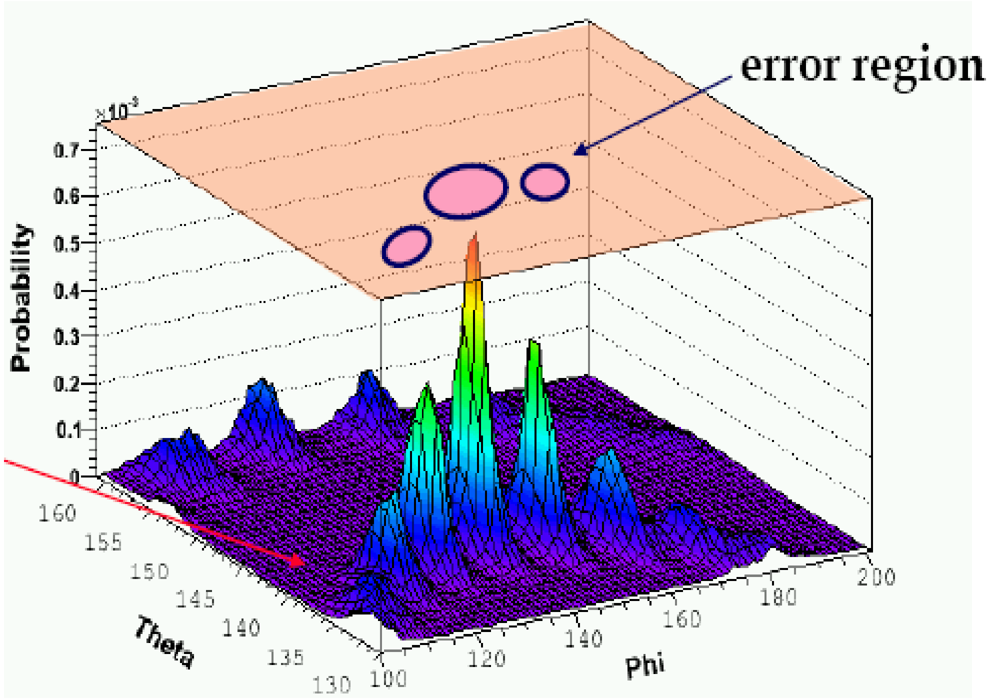
$$R = e^{-\frac{\chi^2}{2}} \frac{L}{d}$$

L - luminosity of the galaxy
d - distance to the galaxy
$X^2$ - chi-squared match between the measured and predicted arrival time of the signal in each detector

Nuttall and Sutton, 2010, Physical Review D. 82, 102002

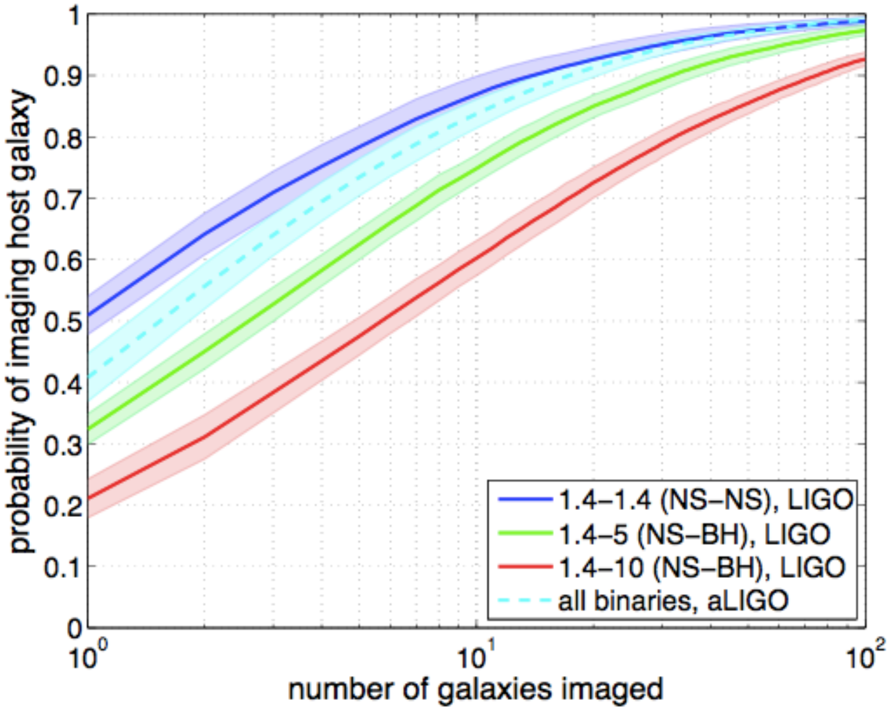
# Position Reconstruction

- We use the time delays between the 3 interferometers to construct a sky position error region
- The error region is ~1-4 deg$^2$ for a "loud" event and anywhere between 20-100 deg$^2$ for a "quiet" event



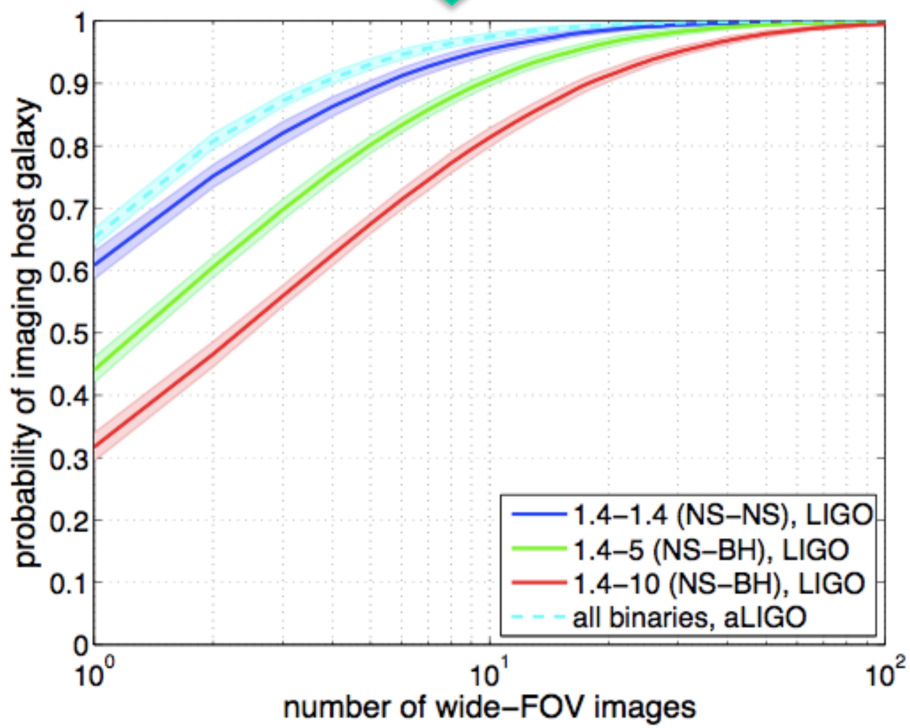

The moon is ~ 0.2 deg$^2$ and the whole sky is ~ 40,000 deg$^2$

# How often do we pick the right galaxy?




**Initial LIGO**: If we were to image the top 5 potential hosts the chances of picking the right galaxy are between **~50%** to **~80%**

**ADVANCED LIGO**: If we were to group galaxies and image the top 5 potential groups the chances of imaging the right group are between **~70%** and **~90%**



# Some Excitement: Sept. 16, 2010

## 2:50 a.m. EDT: My cell phone beeps — it's a LUMIN alert

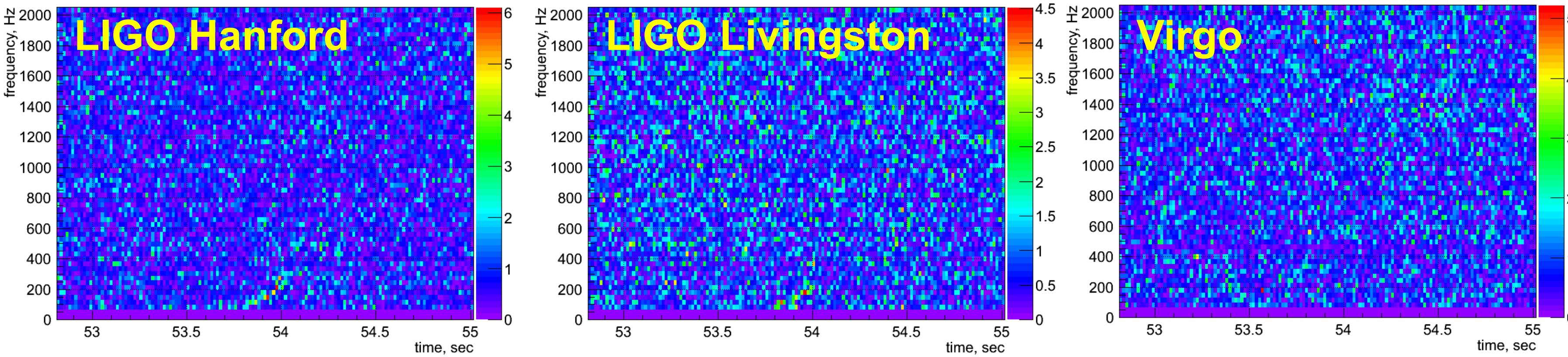
### LUMIN Events Page

| Id | GPS | DQ | Energy | Event Rate | Frequency | Status | Scopes | View Times | Trigger Details | ETG | Checklist |
|---|---|---|---|---|---|---|---|---|---|---|---|
| G19377 | 968654557.950 | Clear | ρ = 4.338 | 0.00 Events/day | 176.3 Hz | alert | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | cwb classic | GO G19377 |
| G19375 | 968653612.555 | Clear | Ω = 2.64 | 51.20 Events/day | 620.5 Hz | processed | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | omg | |
| G19373 | 968652026.594 | Clear | Ω = 2.69 | 34.13 Events/day | 429.0 Hz | processed | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | omg | |
| G19374 | 968651665.369 | Clear | Ω = 2.64 | 49.70 Events/day | 1387.6 Hz | processed | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | omg | |
| G19371 | 968651363.119 | Clear | ρ = 3.151 | 1.69 Events/day | 1619.2 Hz | processed | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | cwb linear | |
| G19370 | 968651228.193 | Clear | Ω = 2.71 | 31.05 Events/day | 915.1 Hz | processed | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | omg | |
| G19363 | 968647079.328 | Clear | Ω = 2.80 | 14.47 Events/day | 420.5 Hz | processed | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | omg | |
| G19351 | 968643536.786 | Clear | ρ = 2.939 | 1.33 Events/day | 1147.1 Hz | processed | Text: PT π Q Ra Rb Rc Rd S TN TS Z<br>Plot: PT π Q Ra Rb Rc Rd S TN TS Z | plot | Details | cwb linear | |

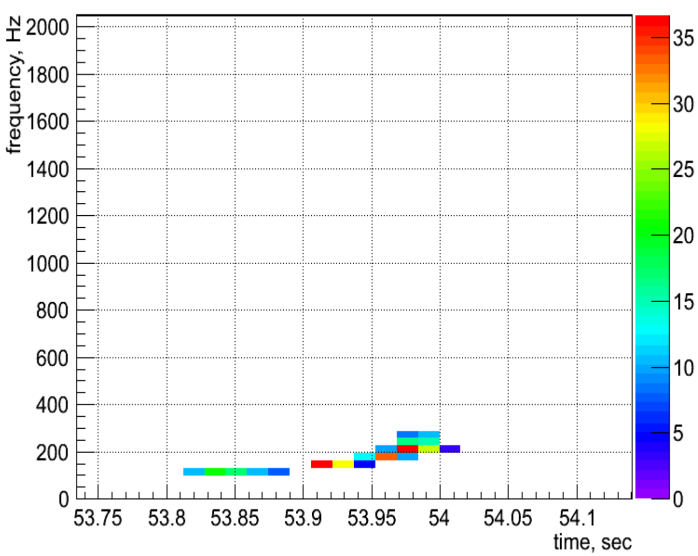

| | | | |
|---|---|---|---|
| 968654557.950 | Clear | ρ = 4.338 | 0.00 Events/day |

# What Does the Signal Look Like?

## Coherent WaveBurst time-frequency pixel maps:




## Likelihood detection statistic:

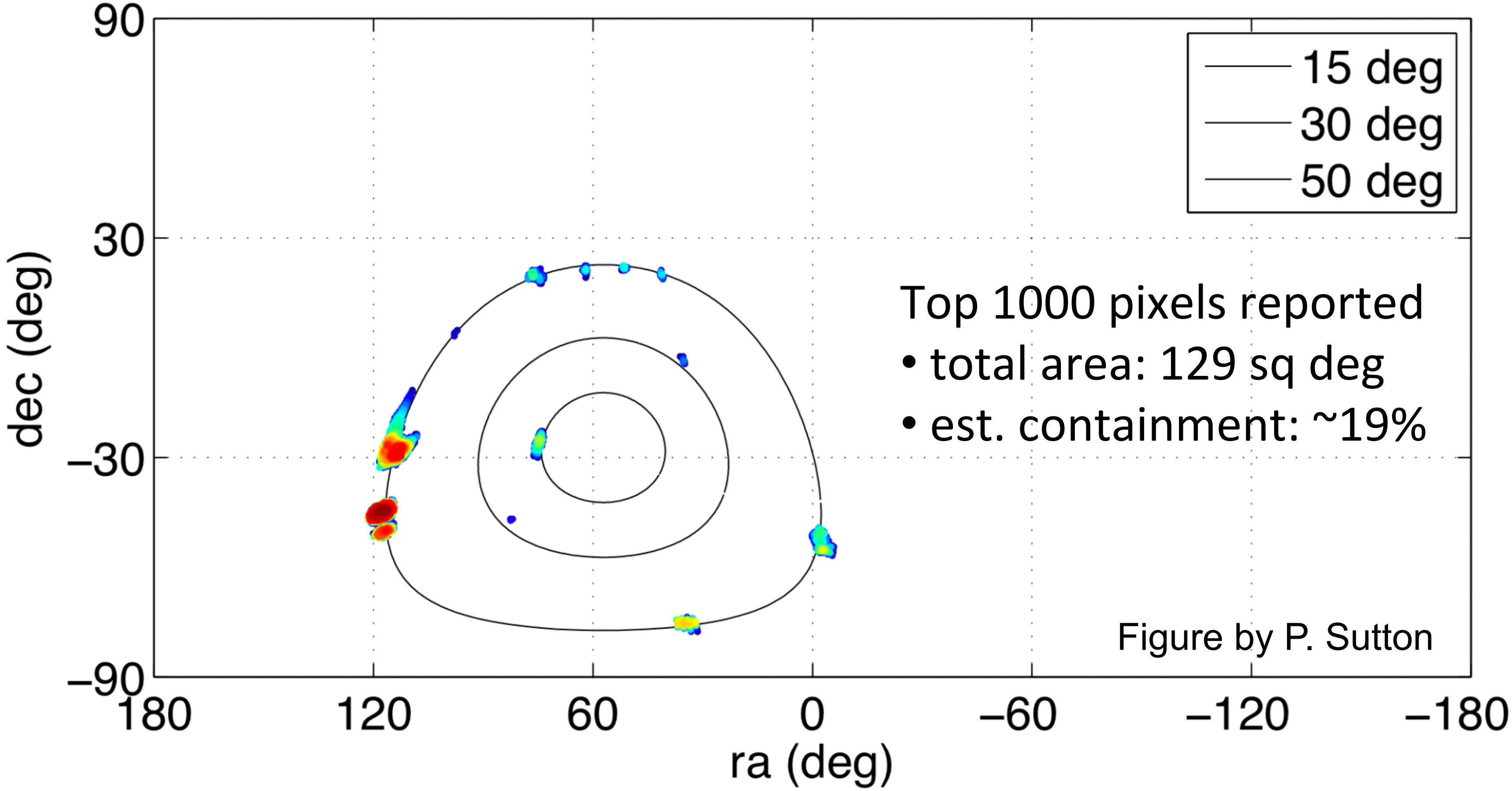



What could it be?

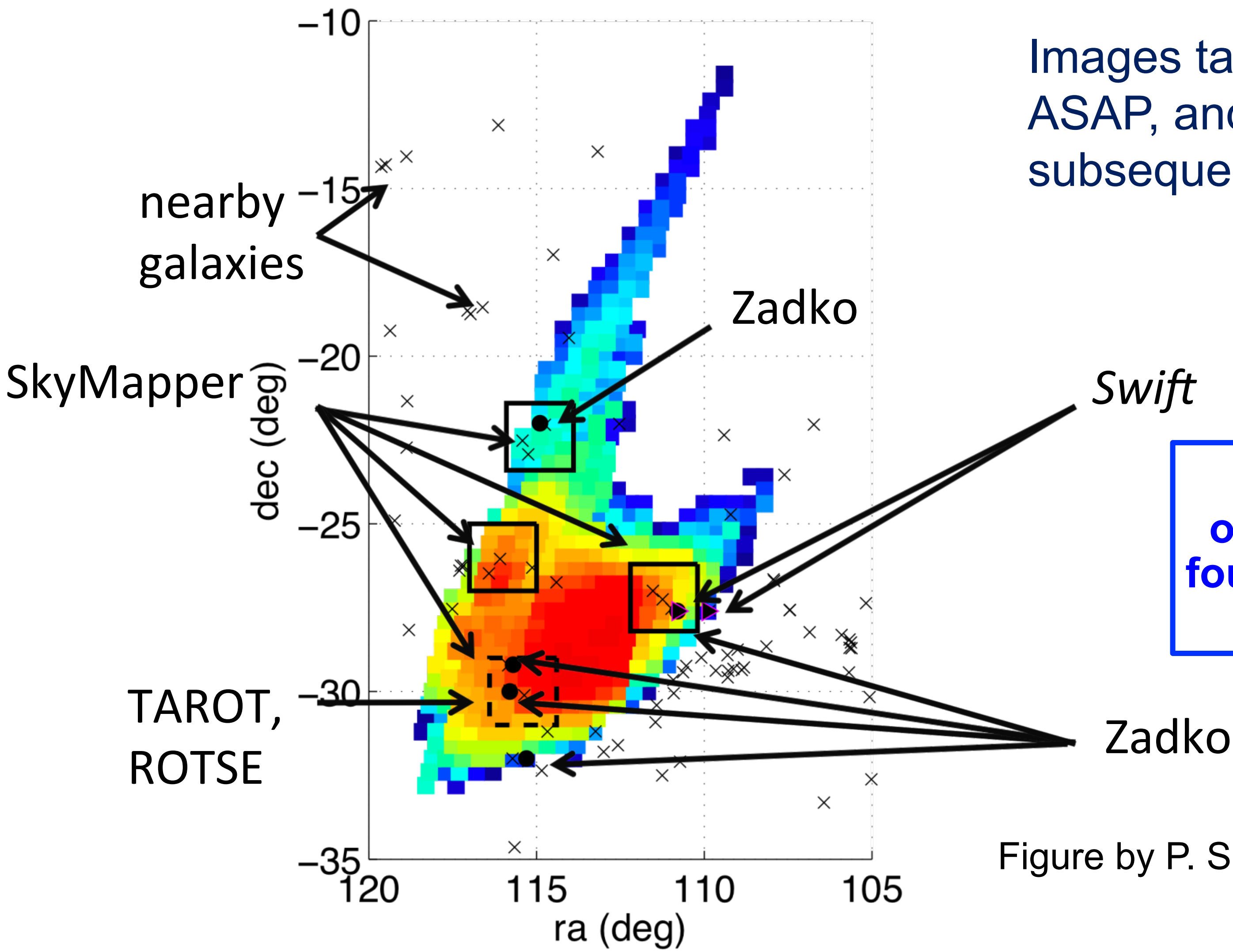
- A binary black hole inspiral / merger
- A noise fluctuation
- A “blind injection” (simulated signal injected into the interferometer)

# Where is it Coming From?

**Coherent WaveBurst probability sky map:**



# Regions Imaged by Telescopes



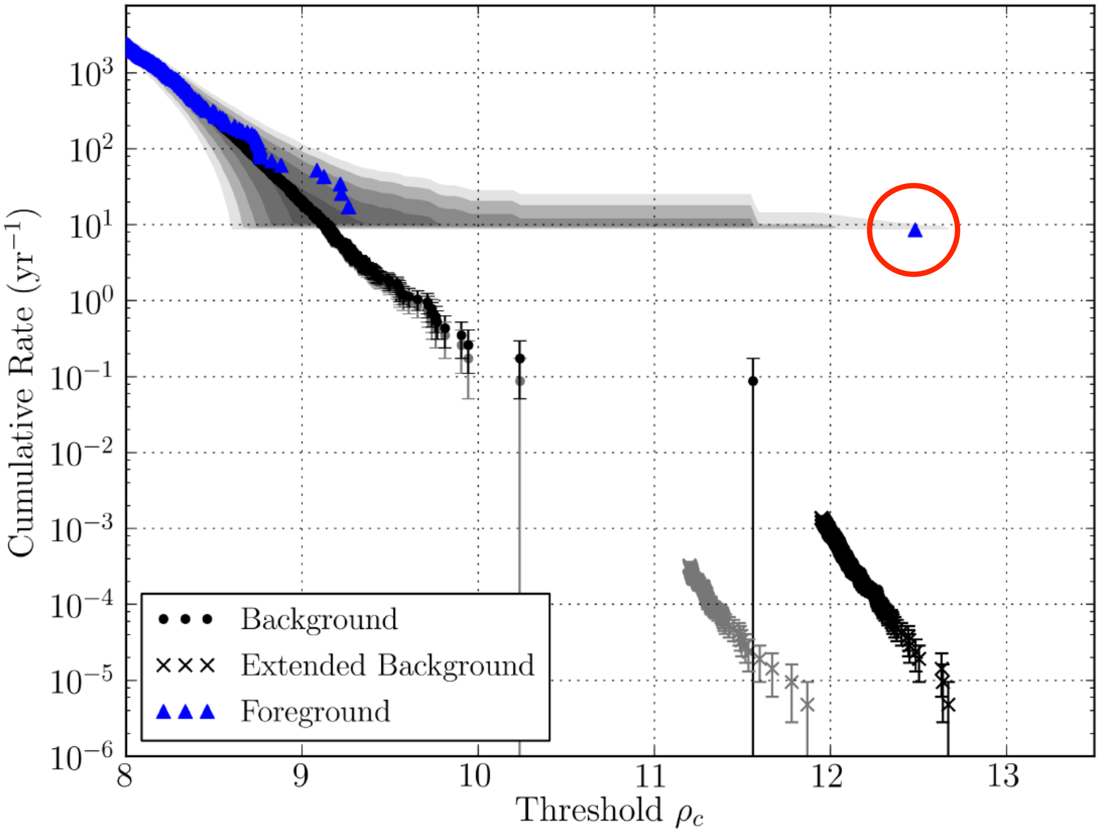

Images taken ASAP, and on subsequent nights

**No significant optical transient found in telescope images**

Figure by P. Sutton

# Significance of the Event Candidate

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




Over the winter:

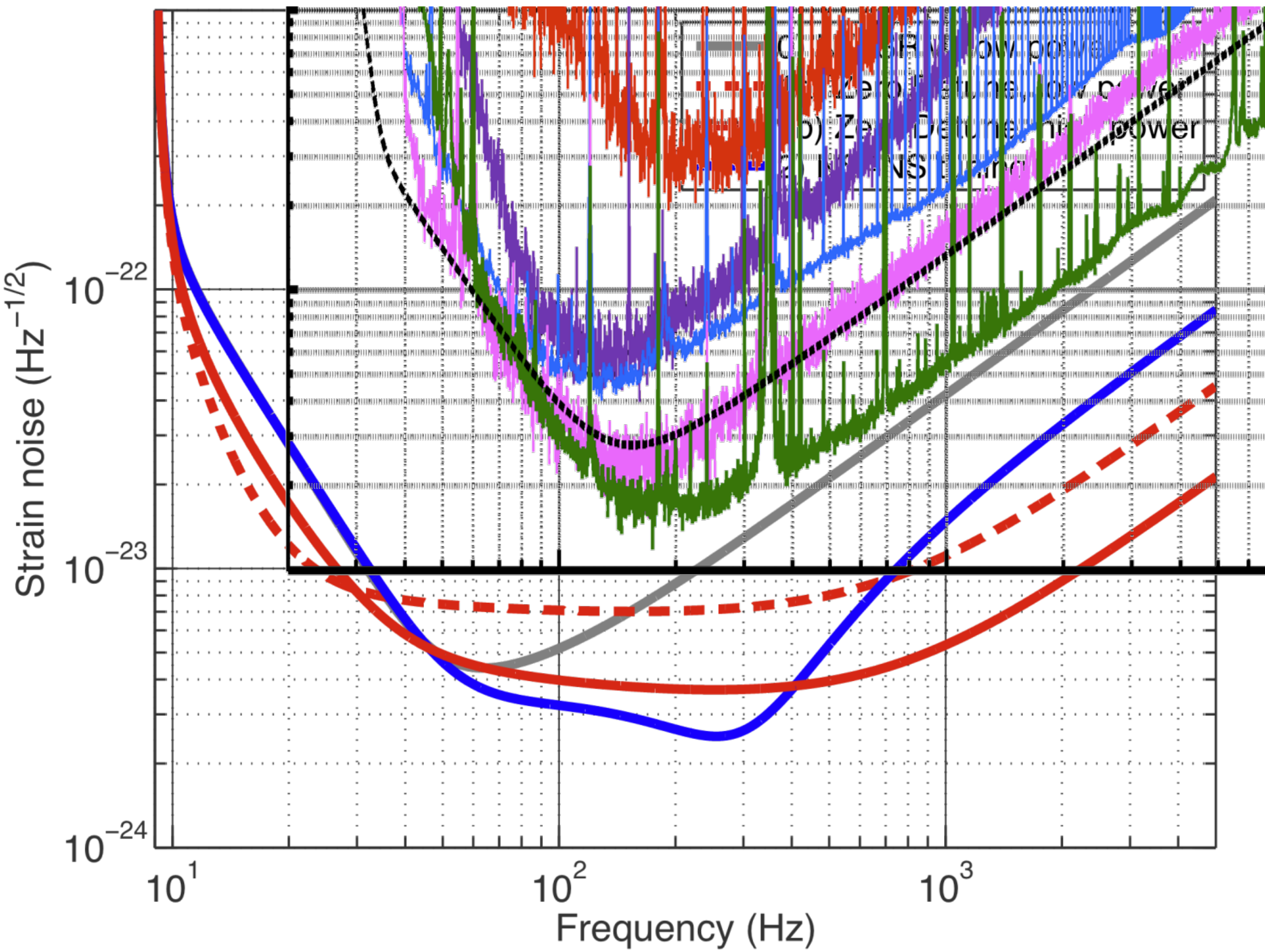
- Refined background estimation techniques – estimated 1 in 7000 y
- Did binary parameter estimation studies
- Wrote and polished a Phys Rev Letter

Finally "opened the envelope" last March…
It was a blind injection

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

# Advanced LIGO

# Projected Performance of Advanced LIGO




**Orientation-averaged detection range for binary inspirals**

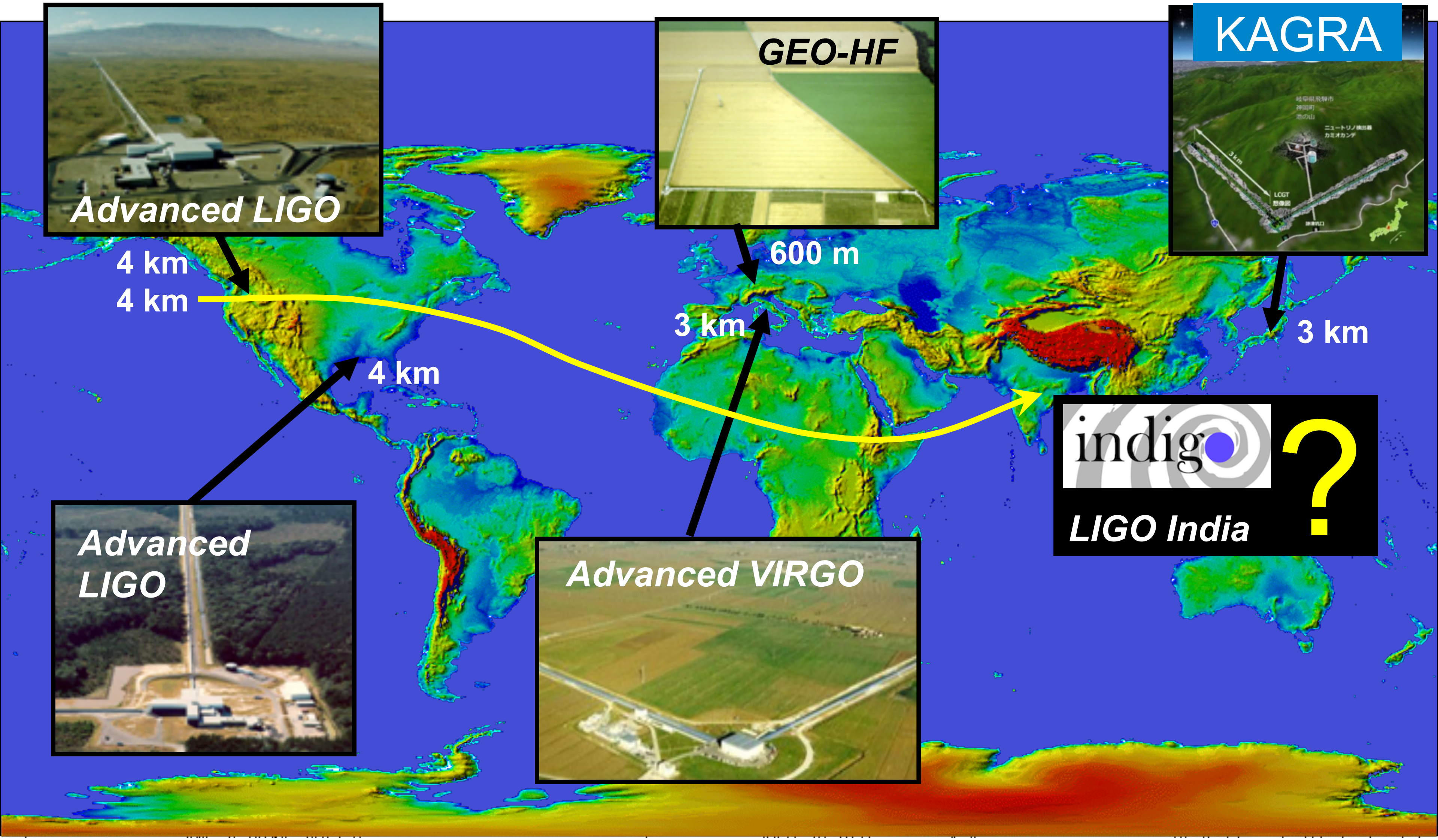
| case | NS-NS | BH-BH (30 $M_\odot$) |
|---|---|---|
| No SRM | 150 Mpc | 1.60 Gpc |
| 0-det low P | 145 Mpc | 1.65 Gpc |
| 0-det high P | 190 Mpc | 1.85 Gpc |
| NS-NS tuned | 200 Mpc | 1.65 Gpc |

**Best guess: LIGO and Virgo will detect dozens of events per year**

**Factor of ~10 better amplitude sensitivity than initial detectors**

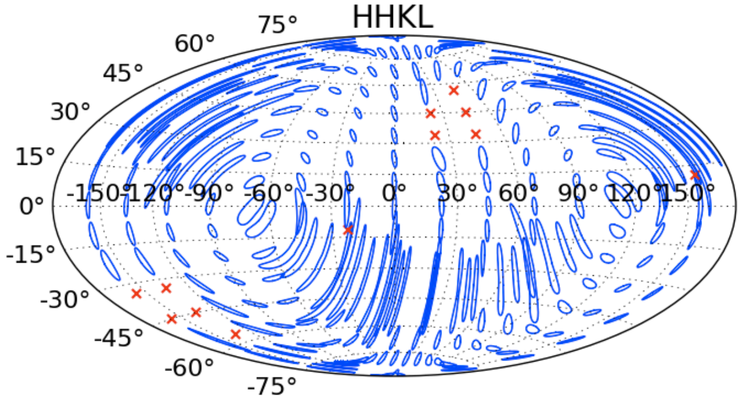
**→ Factor of ~1000 greater volume of space**

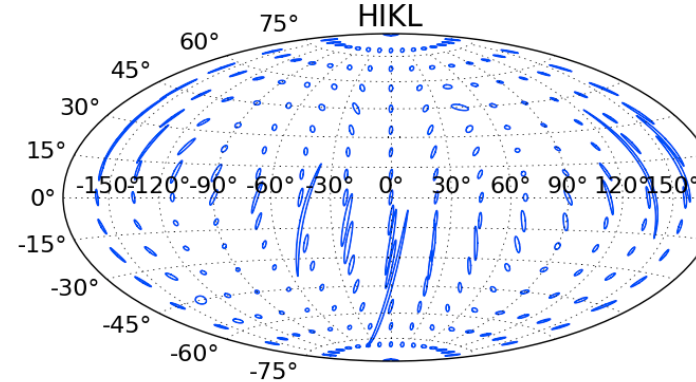
# Advanced GW Detector Network, Circa 2020



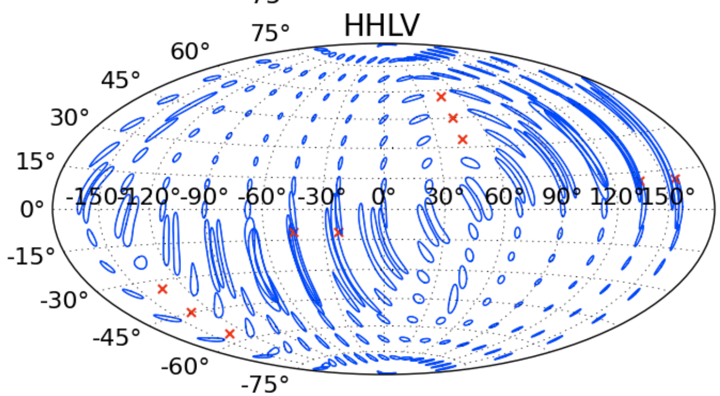
# Localisation

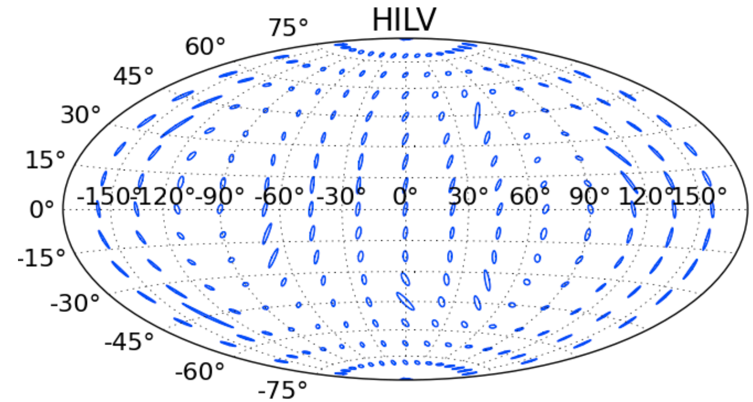
H – Hanford
I – India
K – Kagra
L – Livingston
V –Virgo

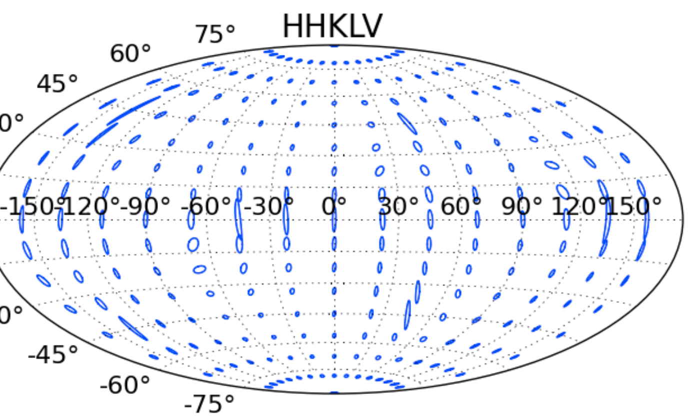


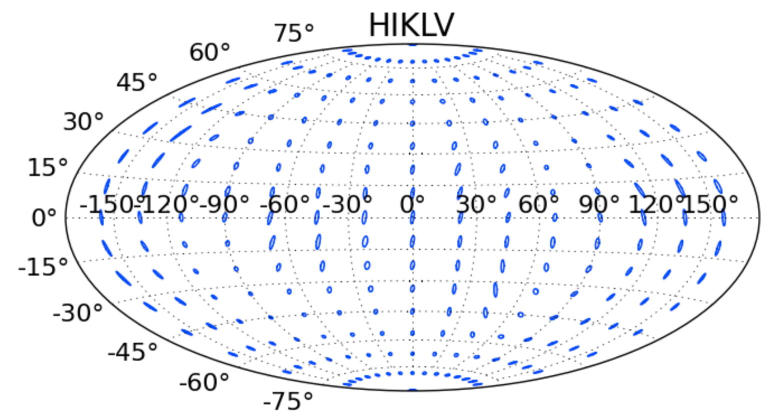




- face on BNS at 160 Mpc
- ellipses contain the 90% localisation regions



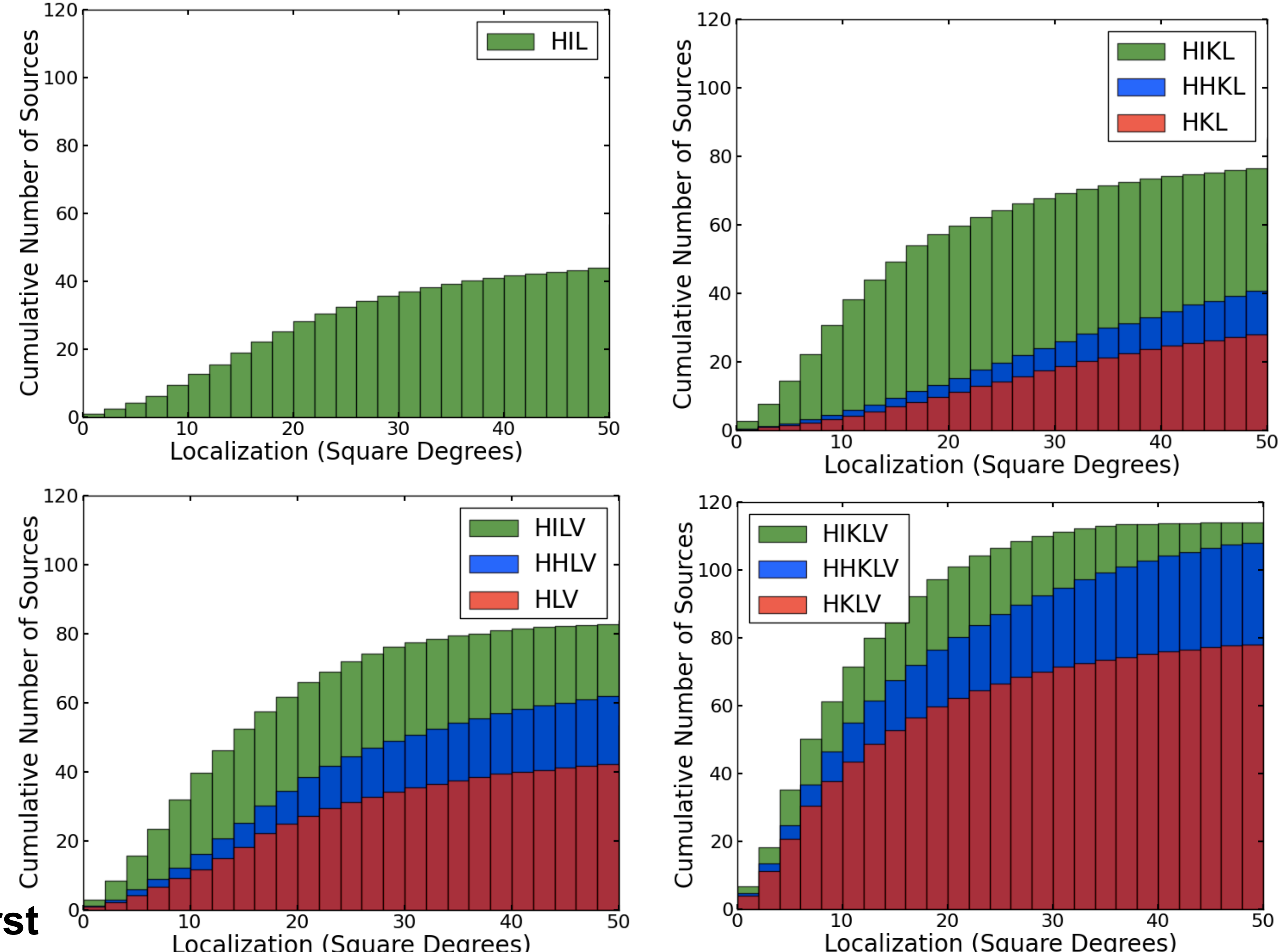




**Fairhurst arXiv:1205.6611**

# Localisation

All results assume a rate of 40 events per year at SNR 8 or higher in a single detector




**Fairhurst**
**arXiv:1205.6611**

# Summary

## Gravitational wave observing has begun

- Initial interferometric detectors operated successfully for a number of years
- Many results published — upper limits and astrophysical interpretations
- Including very inclusive searches for BW bursts
- Rapid EM follow-up project was a highlight of the most recent science run

## Currently upgrading to Advanced LIGO & Advanced Virgo

- Expected to start taking science data in ~2015
- KAGRA will join the network later

## Preparing for detections

- Calls for a change in mindset
- Planning for follow-up observations to get as much information as possible about these remarkable astrophysical events