Gravitational Wave Burst Searches

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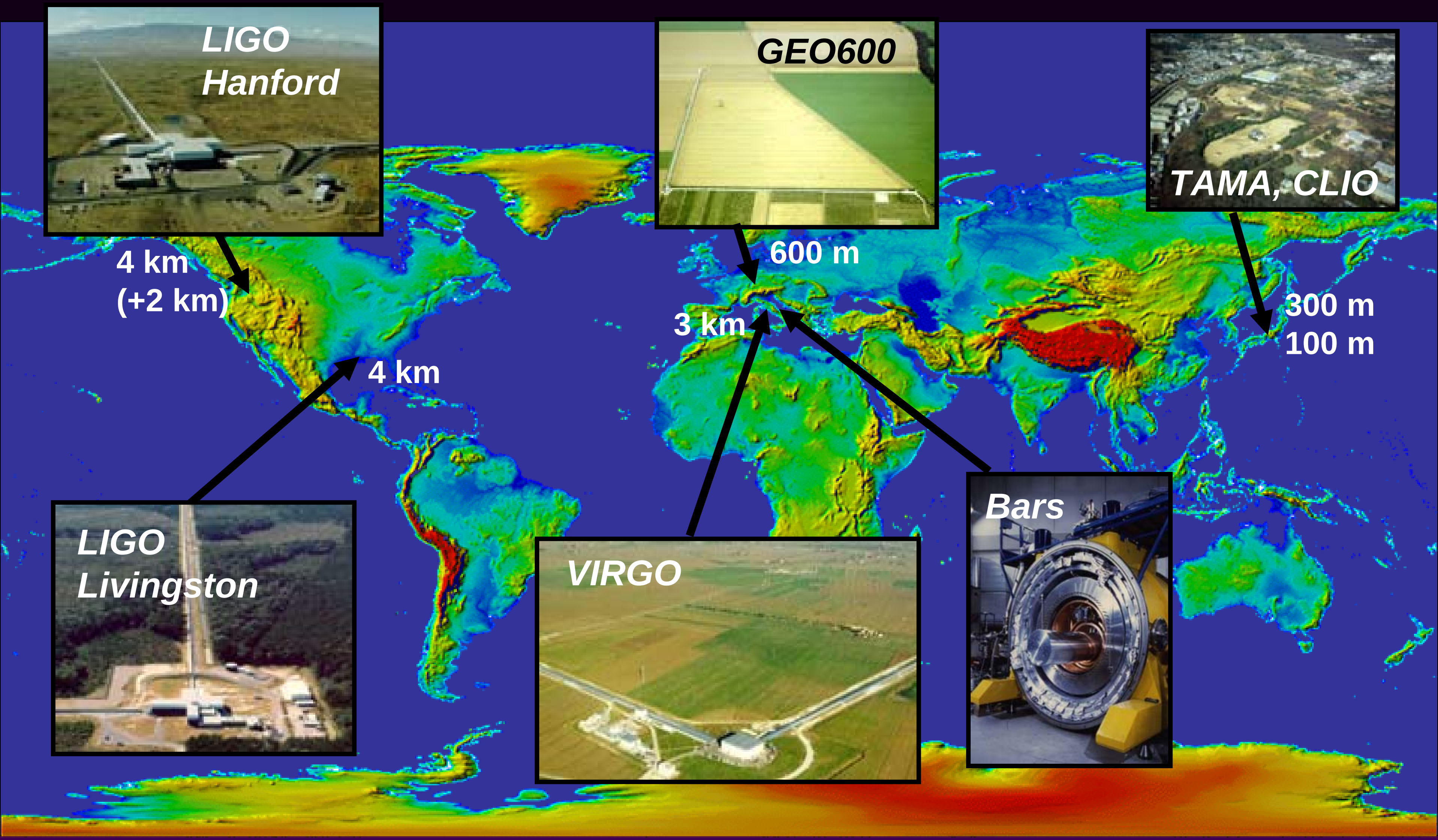
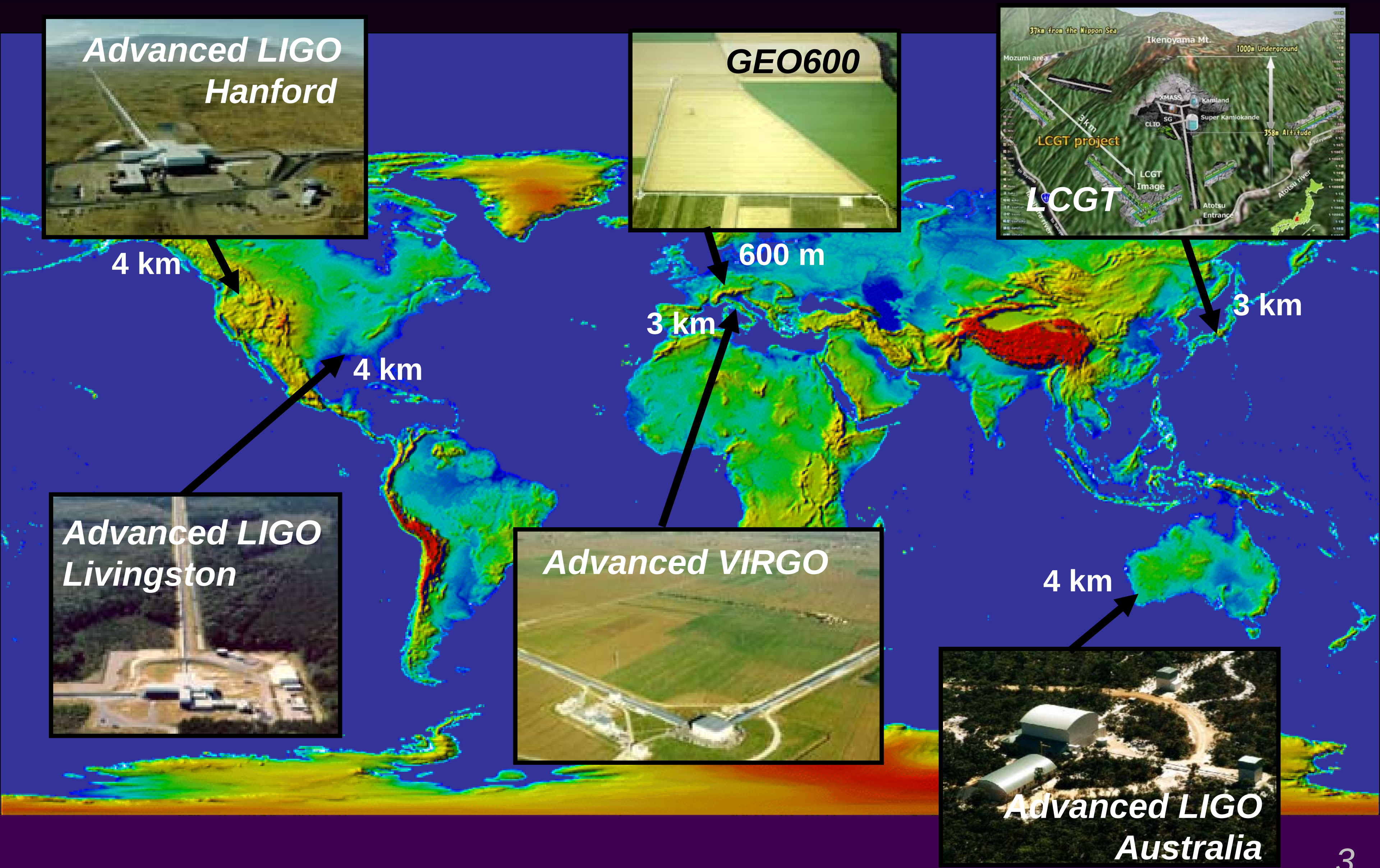
LIGO-G1000998-v3

Worldwide Network of Gravitational Wave Detectors

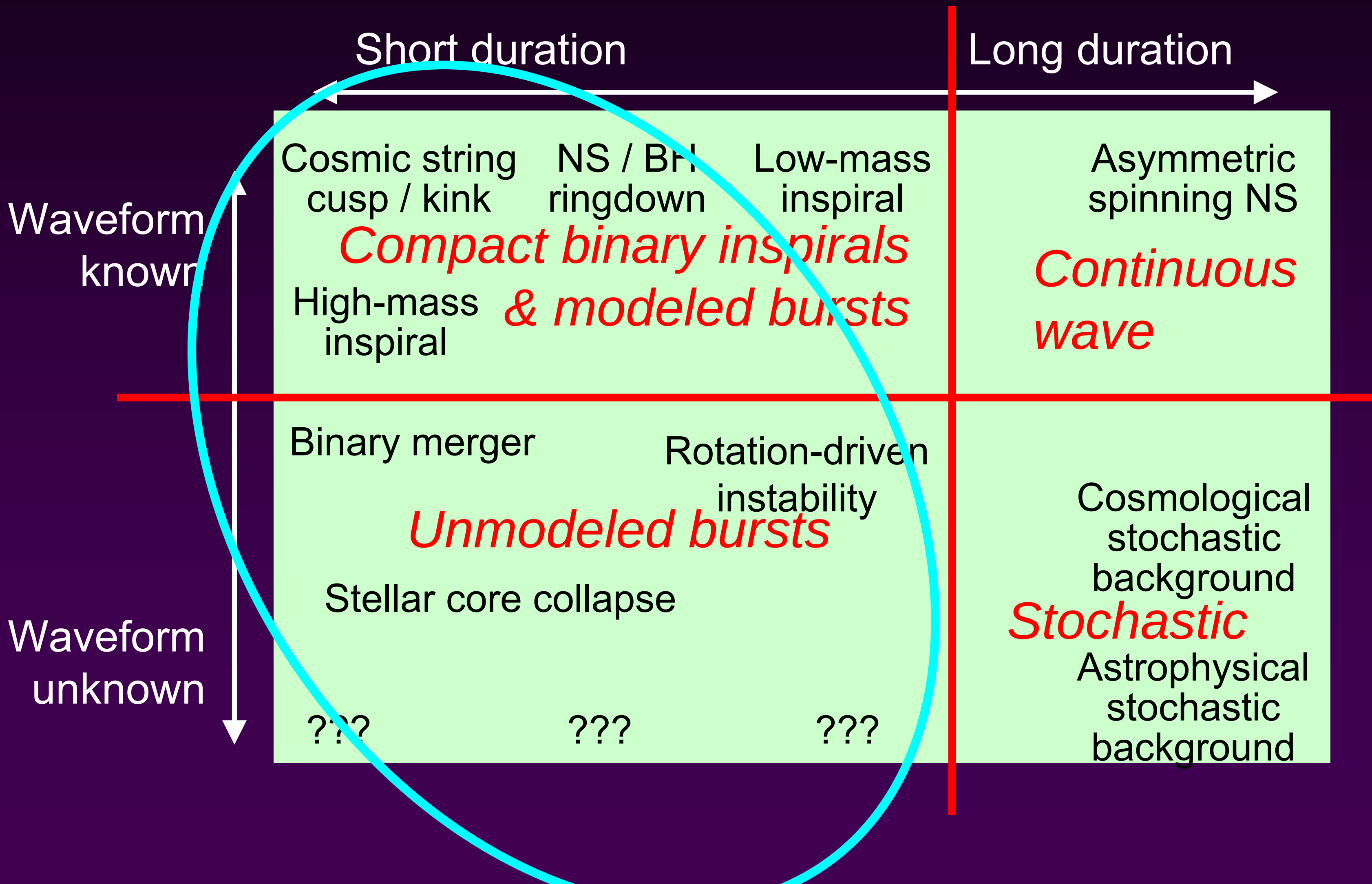


Worldwide Network of GW Detectors in ~2015 ?



Gravitational Wave Sources...

and LSC – VIRGO data analysis working groups



GW Burst Search Toolkit

GW Burst Search 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"

Types of GW Burst Searches

Modeled burst search

Targets:

- Black hole ringdown
- Neutron star ringdown
- Cosmic string cusp
- Parabolic encounter

Can use matched filtering

- Issues generally similar to CBC searches
  (see Duncan Brown's talk)

Generic burst search

Targets:

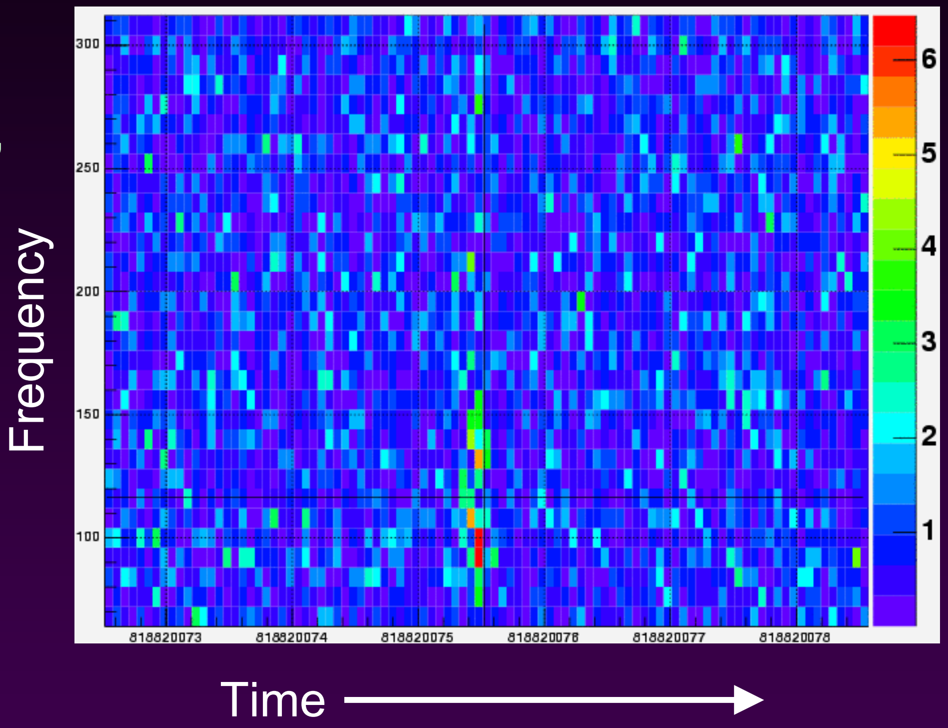
- High-mass binary BH merger
- Core collapse supernova
- Signals deviating from model expectations
- Other unexpected or unmodeled sources

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

“Excess Power” Burst Search Methods

Decompose data stream into time-frequency pixels

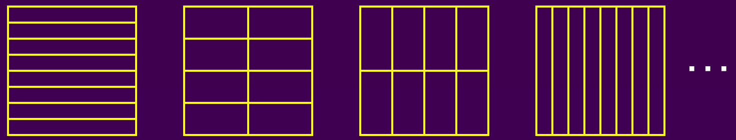
- Fourier components, wavelets, “Q transform”, etc.
- Several implementations of this type of search



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



Signal Consistency Tests

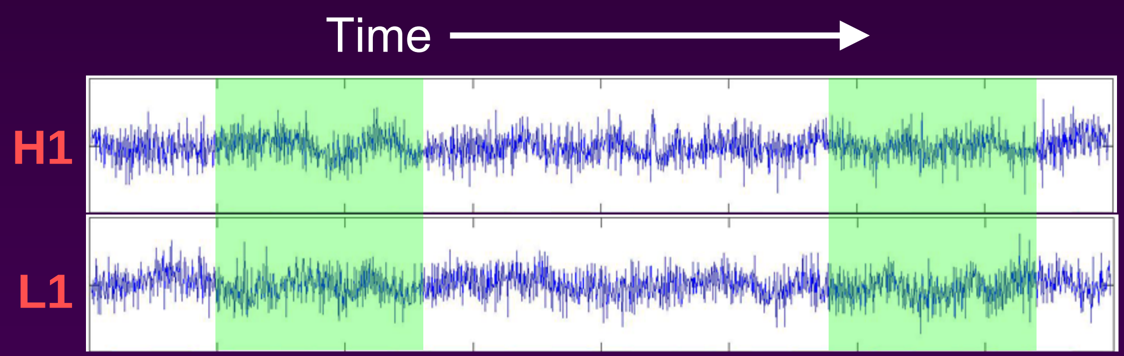
Crucial since a GW burst may look just like an instrumental glitch !

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
- Integrate over a time interval comparable to the target signal

Coherent Analysis

Assuming that general relativity is correct,

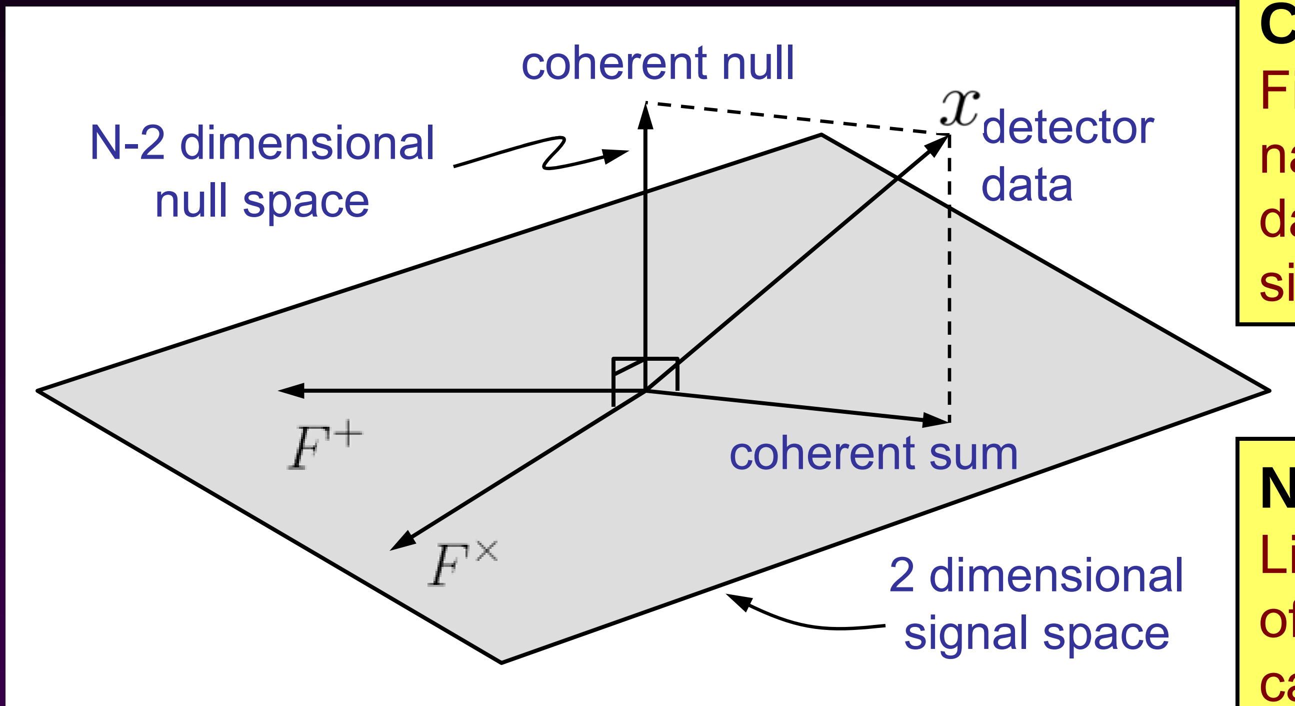
Each detector measures a linear combination of $h_+(t)$ & $h_\times(t)$

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

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

Coherent Analysis



Coherent sum:
Find linear combinations of detector data that maximize signal to noise ratio

Null sum:
Linear combinations of detector data that cancel the signal provide useful consistency tests

Can treat this as a maximum likelihood problem

- Maximize over arrival directions
- Regulator can penalize physically unlikely signal hypotheses

Actually Searching for GW Bursts

Multiple burst search methods are in active use

- Mathematical arguments about optimality only go so far
- Implementation details are critical
- Data conditioning, robustness against non-stationary noise, …

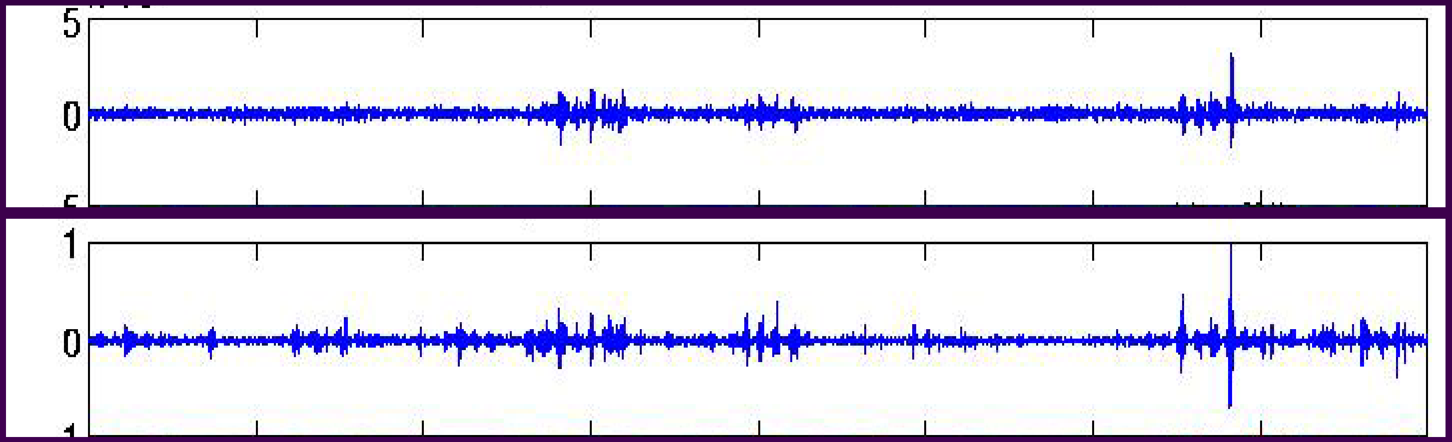
Some degree of competition and cross-pollination

Big emphasis on data quality and vetoes

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

GW channel

Beam splitter pick-off



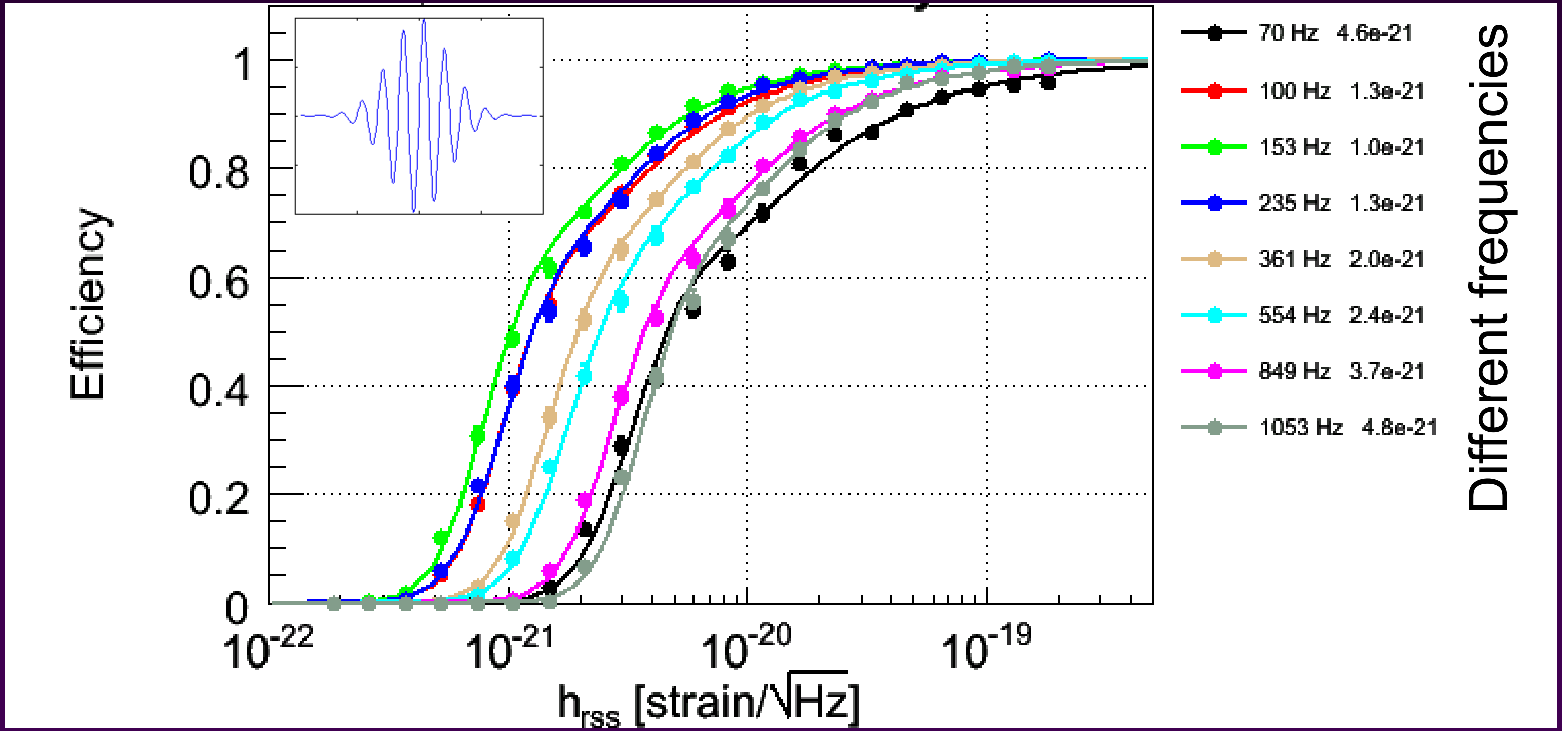
Evaluating Detection Efficiency

Test / tune searches using simulated signals

- Astrophysically modeled for *some* searches
- Ad-hoc: Sine-Gaussians, Gaussians, white noise bursts

$h(t) = h_0 \sin(2\pi f t) \exp(-2(\pi f t/Q)^2)$ $h_{rss} = h_0 (Q/4f)^{1/2} / \pi^{1/4}$

Linearly polarized; random sky position & polarization angle



"All-Sky" Burst Searches

All-Sky Burst Search

Most general search for transient GW signals

Coherent search methods using data from times with 2 or more LIGO/Virgo detectors in science mode

- Effective observation time of 429 days during S5 / VSR1
- GEO data available for investigating possible event candidates

Sensitive to arbitrary GW signals in the range 50–6000 Hz

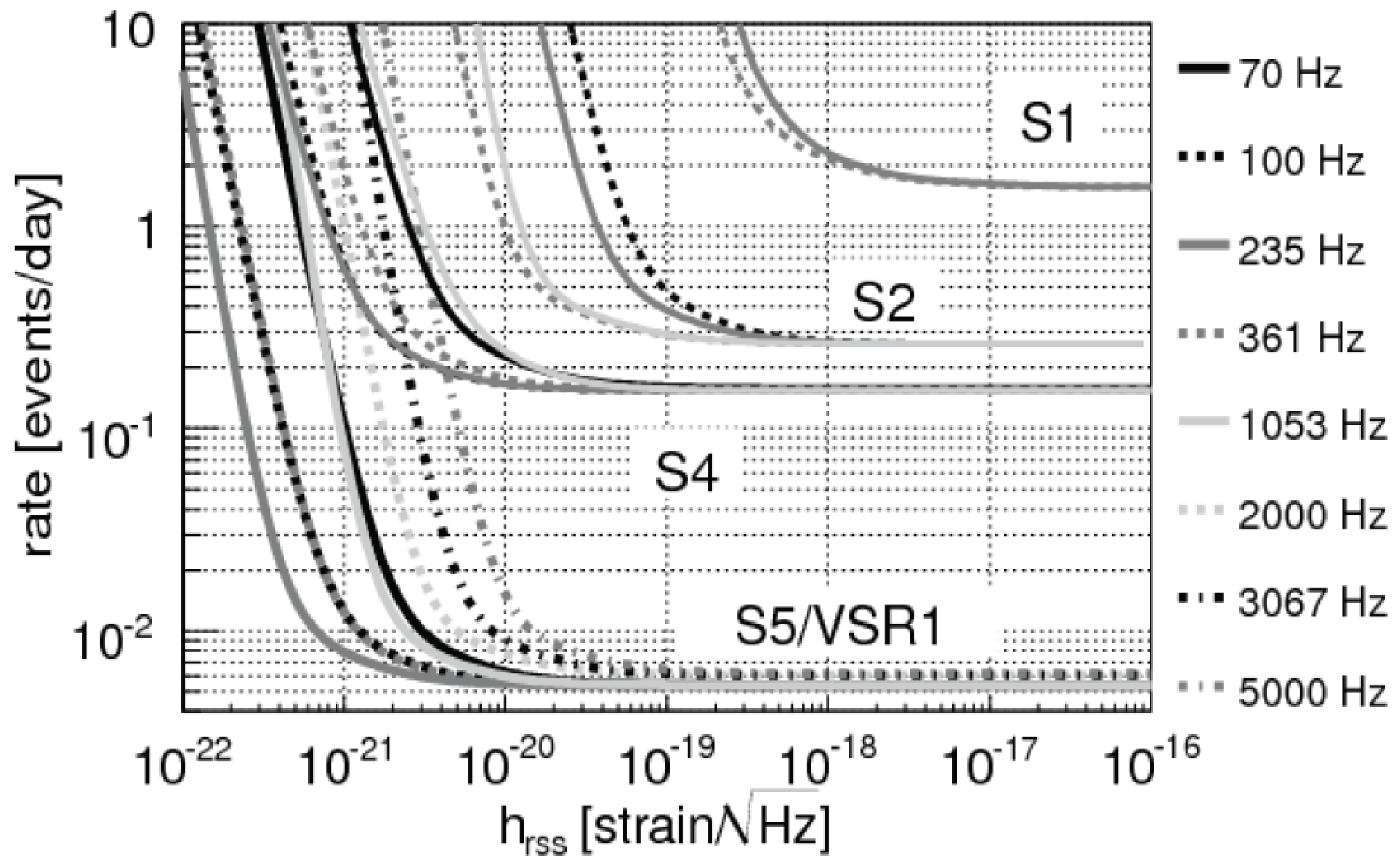
No events survived all selection cuts

- Most promising event candidate turned out to be an intentional (but unknown to analysts) “blind injection”

Set upper limits on burst rate vs. amplitude for representative waveforms

Abadie et al., PRD 81, 102001 (2010)

All-Sky Burst Search Results



Abadie et al., PRD 81, 102001 (2010)

GW energy sensitivity for a 153 Hz burst:

~2×10^{-8} $M_{\odot}c^2$ at 10 kpc , ~0.05 $M_{\odot}c^2$ at 16 Mpc

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

See talk by Xavi Siemens

Externally Triggered Burst Searches

Multi-Messenger Advantages

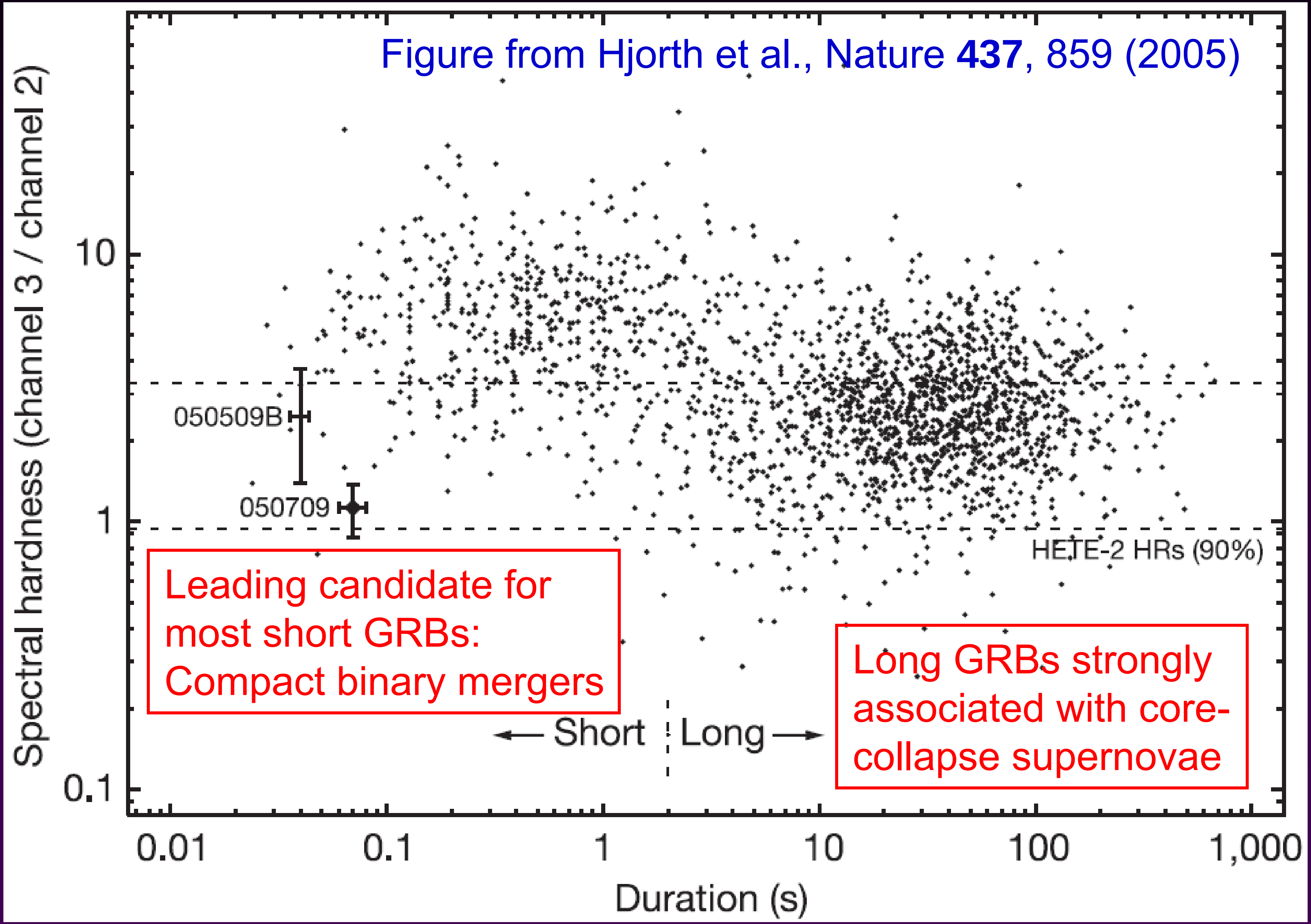
If an event has already been detected, then GW searches:

- 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

Gamma-Ray Bursts



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

Can indicate host galaxy !

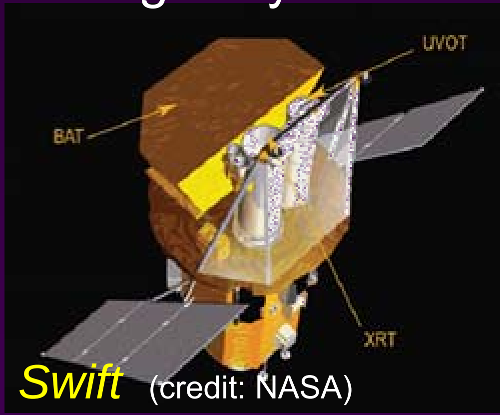
High-energy neutrinos

- Expected from accelerated protons in shocks

Gravitational waves

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

Reveal central engine !



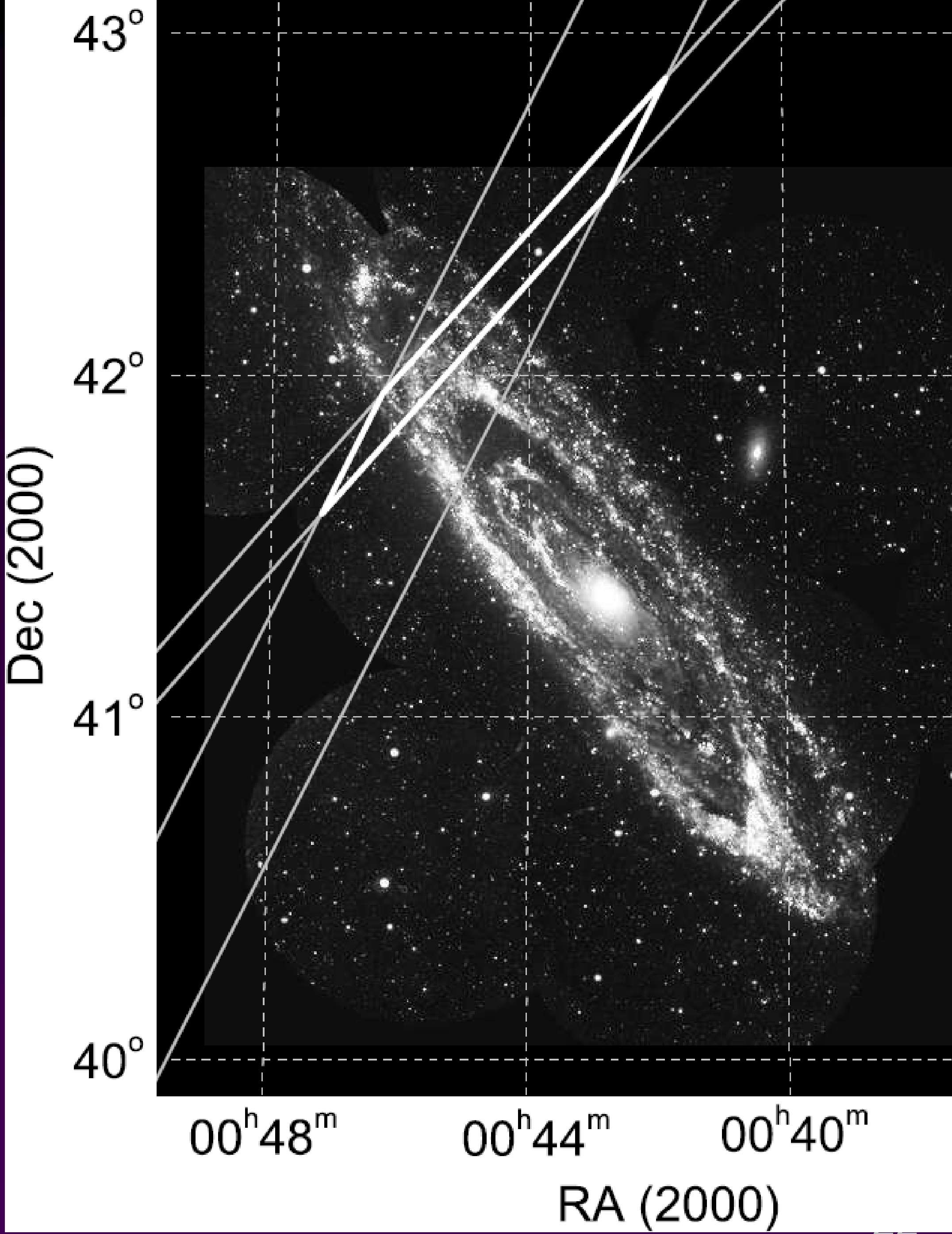
(credit: NASA)

GRB 070201

Very bright short GRB
detected by Konus-Wind, INTEGRAL, MESSENGER, and *Swift*

Consistent with being in M31, at a distance of ~770 kpc

Both LIGO Hanford detectors were on !



Inter-Planetary Network 3-sigma error region from Mazets et al., ApJ 680, 545

Searches for a GW Signal from GRB 070201

Searched for an inspiral signal

- No GW inspiral signal found

Also searched for an arbitrary GW burst signal

- Cross-correlated data streams with time windows of 25 and 100 ms
- Compared to background estimated from off-source times
- No GW burst signal found
- Model-dependent limits on GW energy emission as low as $5\times10^{-4}\ M_{\odot}$

Both searches described in *Abbott et al., ApJ 681, 1419 (2008)*

➔ Conclusion: most likely an SGR giant flare in M31

- Mazets et al., ApJ 680, 545 ; Ofek et al., ApJ 681, 1464

Search for GW Bursts Associated with Other GRBs

There were 137 GRBs (35 with redshifts) during the S5/VSR1 run with data from two or more LIGO+Virgo detectors

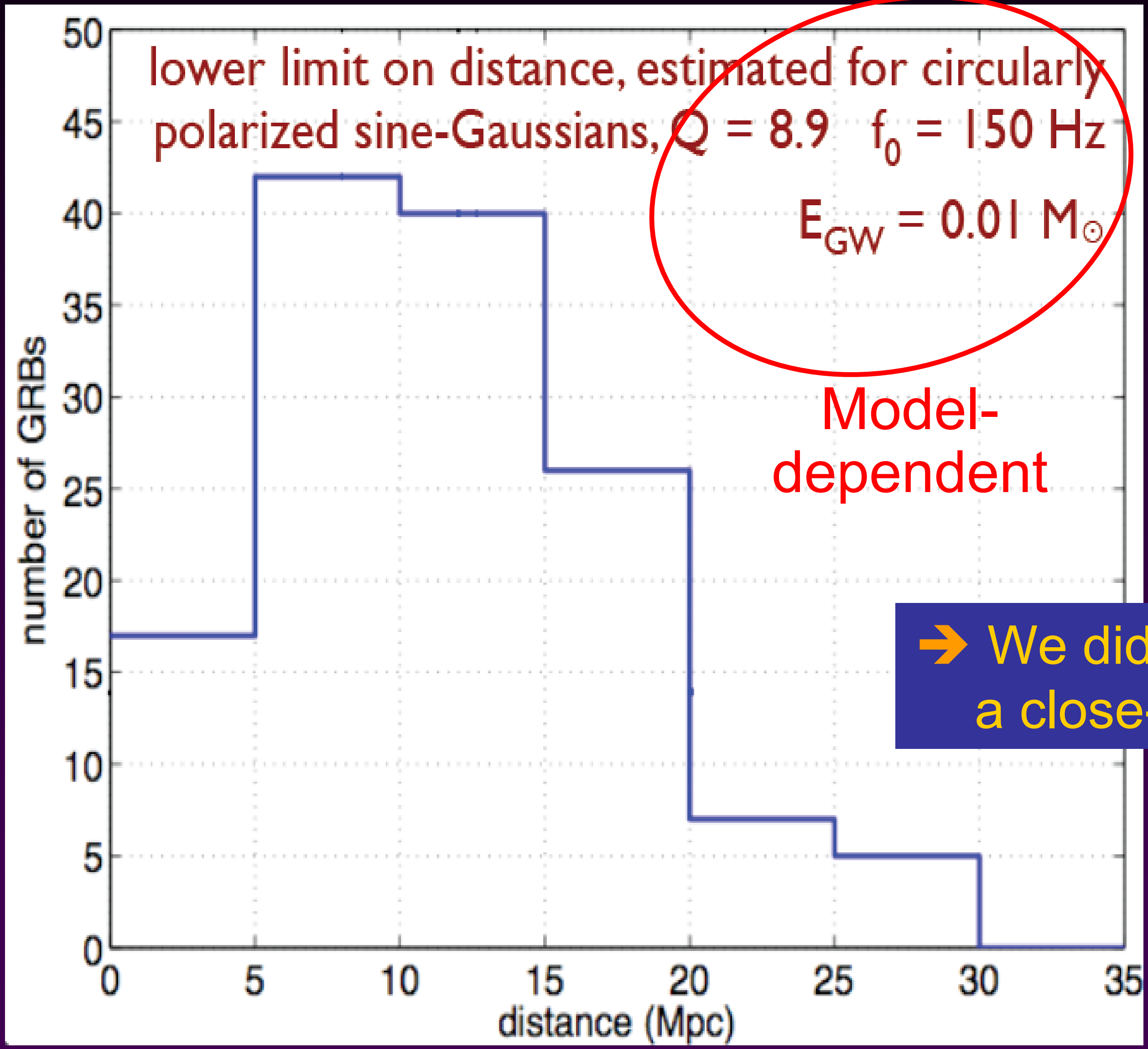
All 137 were checked for associated GW bursts

- Consider [–120,+60] second time window around time of GRB
- Coherent multi-detector burst search with 2, 3, or 4 detectors
- "Loudest event" analysis

Abbott et al., ApJ 715, 1438 (2010)

➔ No significant signal found for any individual GRB, and no statistical excess for any subset

Lower Limits on Distance to Each S5/VSR1 GRB



Model-dependent

➔ We didn't get lucky with a close-enough event

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 ?

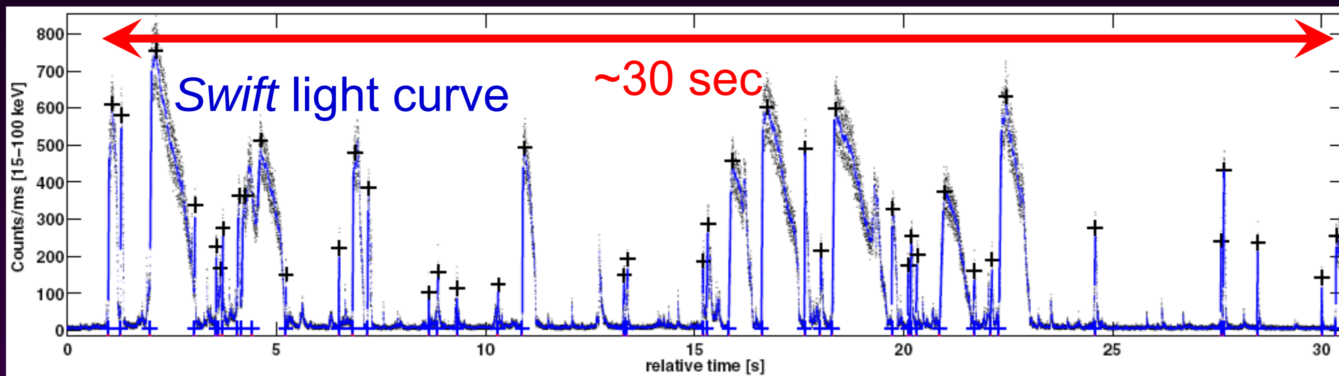
- 2004 giant flare plus 190 other flares from SGR 1806–20 and SGR 1900+14 during first calendar year of LIGO S5 run
- Excess-power search for neutron star *f*-modes ringing down (~1.5–3 kHz), also for arbitrary lower-frequency bursts
- For certain assumed waveforms, GW energy limits are as low as few × 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

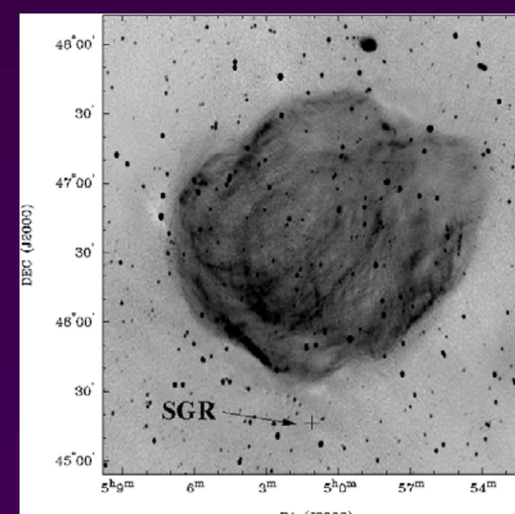


- "Stack" GW signal power around each EM flare
- Gives per-burst energy limits an order of magnitude lower than the loudest-event analysis —as low as few × 10^{45} erg

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

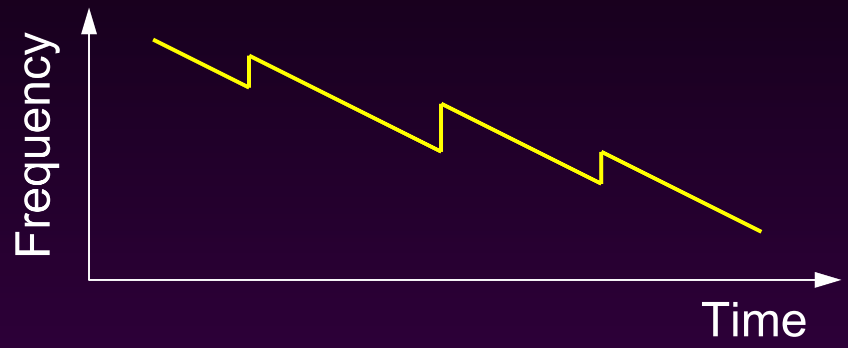
In progress: More flares, new magnetars

- 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 are in progress

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

New Directions in Burst Searches

Special Targets, Additional Messengers

More astrophysically targeted (and interpreted) searches for binary black hole mergers, neutron star ringdowns

Joint searches with neutrinos

- See talk by Szabi Marka

Joint searches with radio transients

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

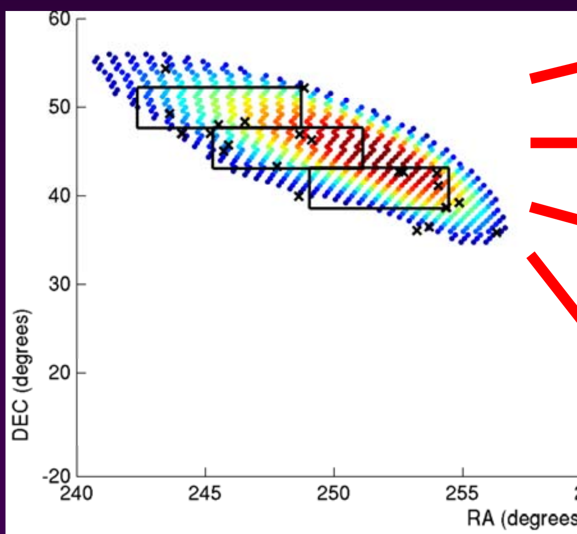
Current detectors can probably only see SNe in our galaxy

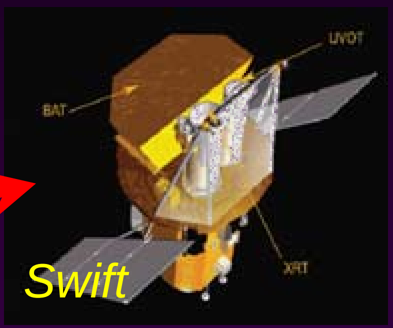
- Advanced detectors may go out to a few Mpc – non-negligible rate

Electromagnetic Follow-Ups to GW Triggers

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

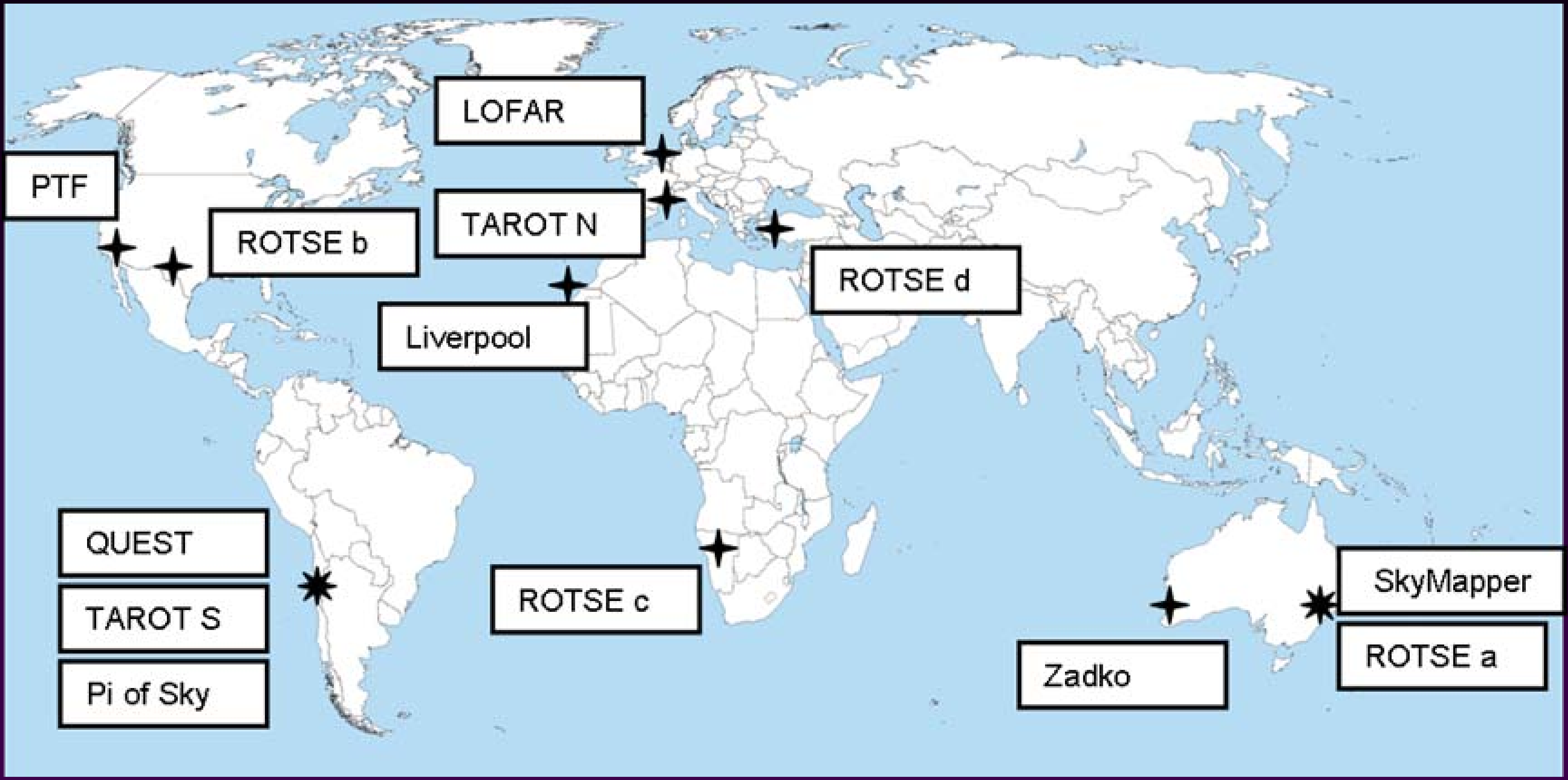
- Try to capture an EM transient that would otherwise have been missed !
- *Swift*, wide-field optical telescopes (LOOC-UP), medium-aperture optical telescopes, radio telescopes





Other telescopes...

EM Follow-Ups: Participating Scopes



Program active now in the latter part of the S6/VSR3 run

- Combines automated processing with human data quality checks

Average latency for sending alerts to scopes: ~30 minutes

Testing Alternative Theories of Gravity

Searching as broadly as possible should also allow for the possibility that GR is not correct !

Wave Propagation Speed

In ATGs, GW speed may be different from speed of light

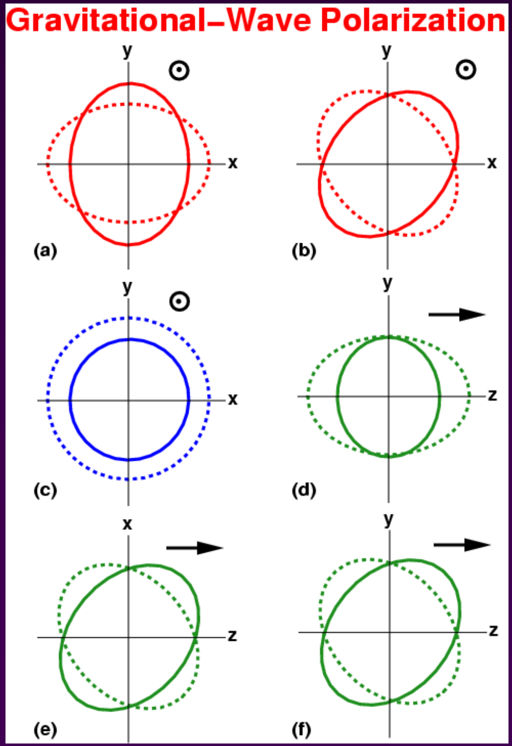
- Powerful test: compare timing of GW signal and EM or neutrino signal from a GRB or supernova

Polarization Content

GR has two modes; ATGs allow more

- Multi-detector network can separate modes, at least in principle

Can use regular burst search algorithm and evaluate efficiency given an ATG, *or* a search that explicitly allows for ATG



C. Will, Living Reviews in Relativity

Summary

Gravitational waves can provide unique information about astrophysical events

- Direct probe of the central engine of the event

We are pursuing many types of GW burst searches

- All-sky searches
- GW searches triggered by GRBs, SGR flares, supernovae, ...
- Joint searches with neutrinos, radio telescopes
- Electromagnetic follow-up observations of GW event triggers

Prepared to detect a signal – but no luck yet

Even non-detection of a GW signal can be interesting

- Constraints on astrophysical event types and emission mechanisms

Building capabilities for the advanced GW detector era

- GW signals *will* be detected – let's do as much as we can with them!