Results from LIGO observations II

GW Bursts & Stochastic Backgrounds

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for the

LIGO Scientific Collaboration

Outline

- Overview of gravitational-wave (GW) searches by the LIGO Scientific Collaboration:
  - » GW Bursts
  - » Stochastic GW Background

- This talk: hit some of the highlights.

- *No GW identified so far … but stay tuned!*

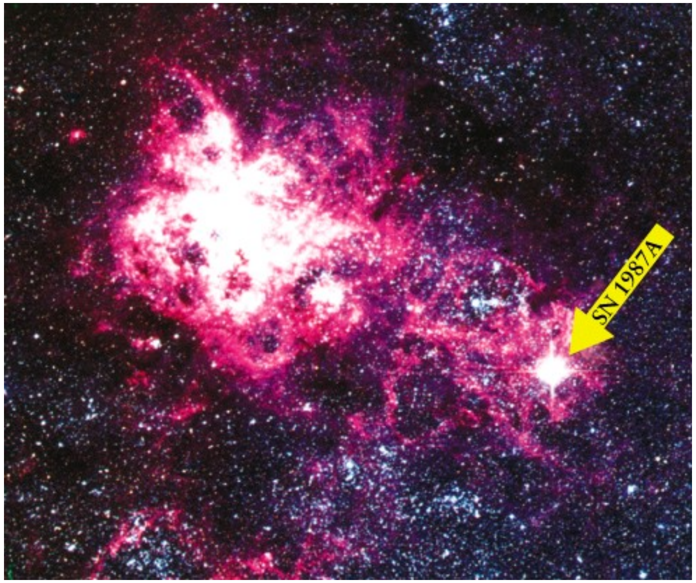
Gravitational-Wave Bursts

Gravitational-Wave Bursts

- Catastrophic events involving solar-mass (1-100 M_o) compact objects.
  - core-collapse supernovae
  - accreting/merging black holes
  - gamma-ray burst engines
  - other … ???

- Sources typically not well understood, involving complicated (and interesting!) physics.
  - Dynamical gravity with event horizons
  - Behavior of matter at supra-nuclear densities

- Lack of signal models makes GWBs more difficult to detect.



SN 1987 A

Burst Search Techniques

Two main types of burst searches:

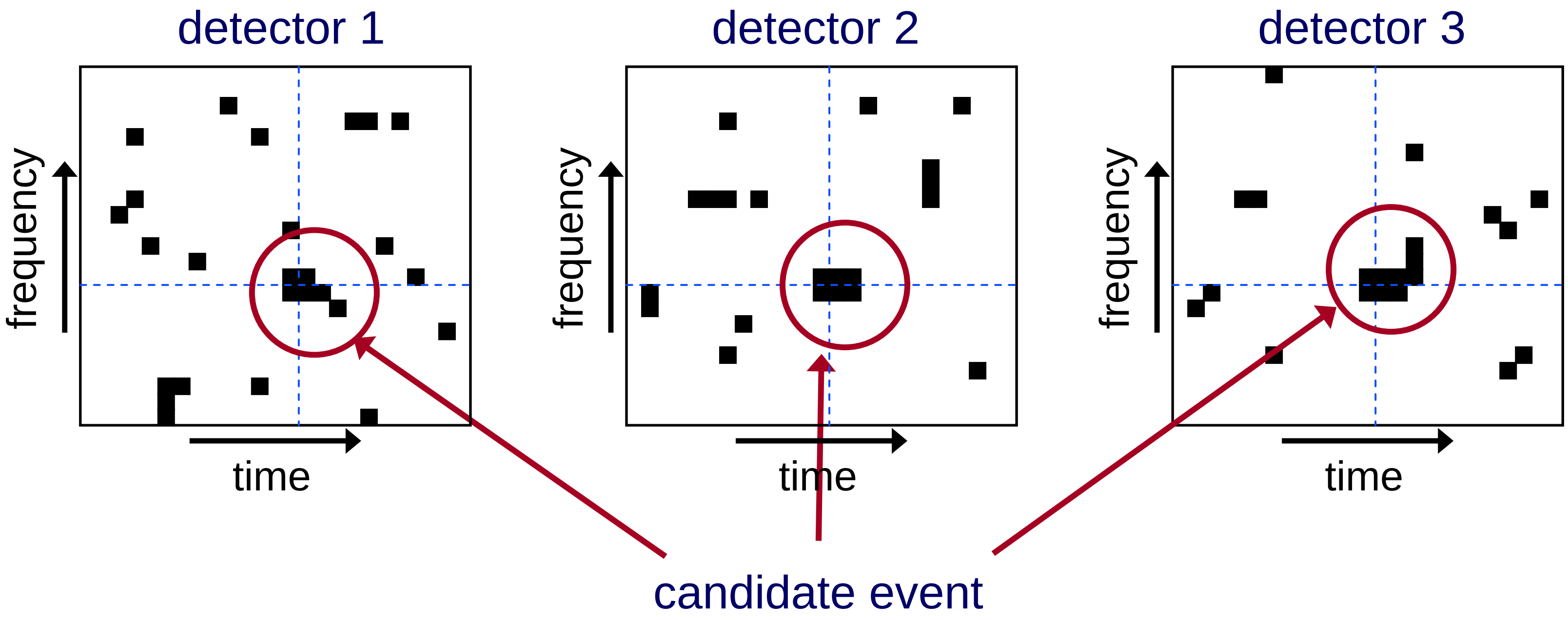
- Untriggered: Scan ~all data, looking for excess power indicative of a transient signal.
  - » Robust way to detect generic waveforms.
- Triggered: Scan small amount of data around time of astronomical event (e.g., GRB), by cross-correlating data from pairs of detectors.
  - » Exploits knowledge of time of and direction to astronomical event.

Always: Use techniques that make minimal assumptions about the signal.

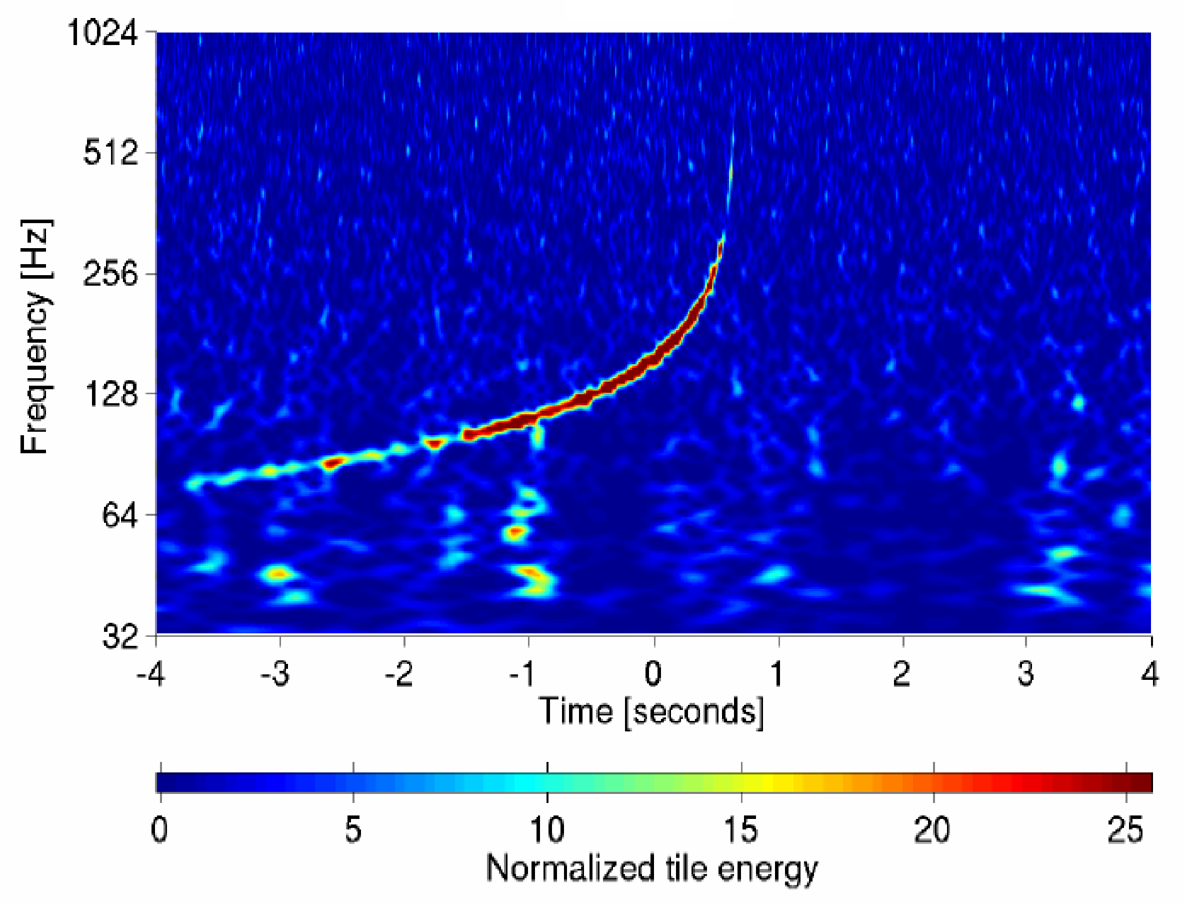
- » Be open to the unexpected!

Excess power detection

- Look for transient jump in power in some time-frequency region:
  - frequency ~ [60,2000] Hz
  - duration ~ [1,100] ms
  - Require candidate signal to be seen in all detectors.



Example: “Q Pipeline”



Simulated binary inspiral signal in S5 data

from Chatterji, session W11:

The Q Pipeline search for GWBs with LIGO

Removing Spurious Events

- Waveform-independent detection algorithms also pick up noise “glitches”.

- Follow-up tests for consistency with GWs:
  - amplitude consistency (as measured by the two co-aligned Hanford detectors)
  - require cross-correlation of data from pairs of detectors exceed threshold:

$$r_k = \frac{\sum_i (x_i-\bar{x})(y_{i+k}-\bar{y})}{\sqrt{\sum_i (x_i-\bar{x})^2}\sqrt{\sum_i (y_{i+k}-\bar{y})^2}}$$

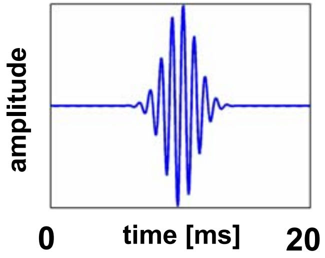
Cadonati CQG *21* S1695 (2004)

- Also apply cuts on data quality, and “veto” candidate GWs occurring in coincidence with identifiable noise events.

Detection Efficiency

Test sensitivity by adding simulated GWBs to the data.

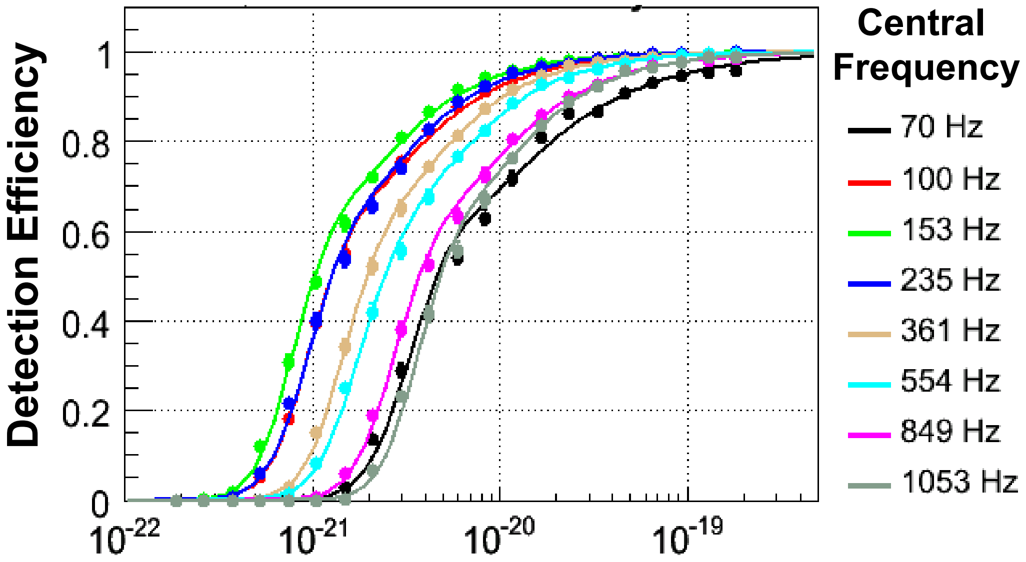
- » Eg: Gaussian-modulated sinusoid.



Astrophysical interpretation:

Minimum detectable in-band energy in GWs (in S5):

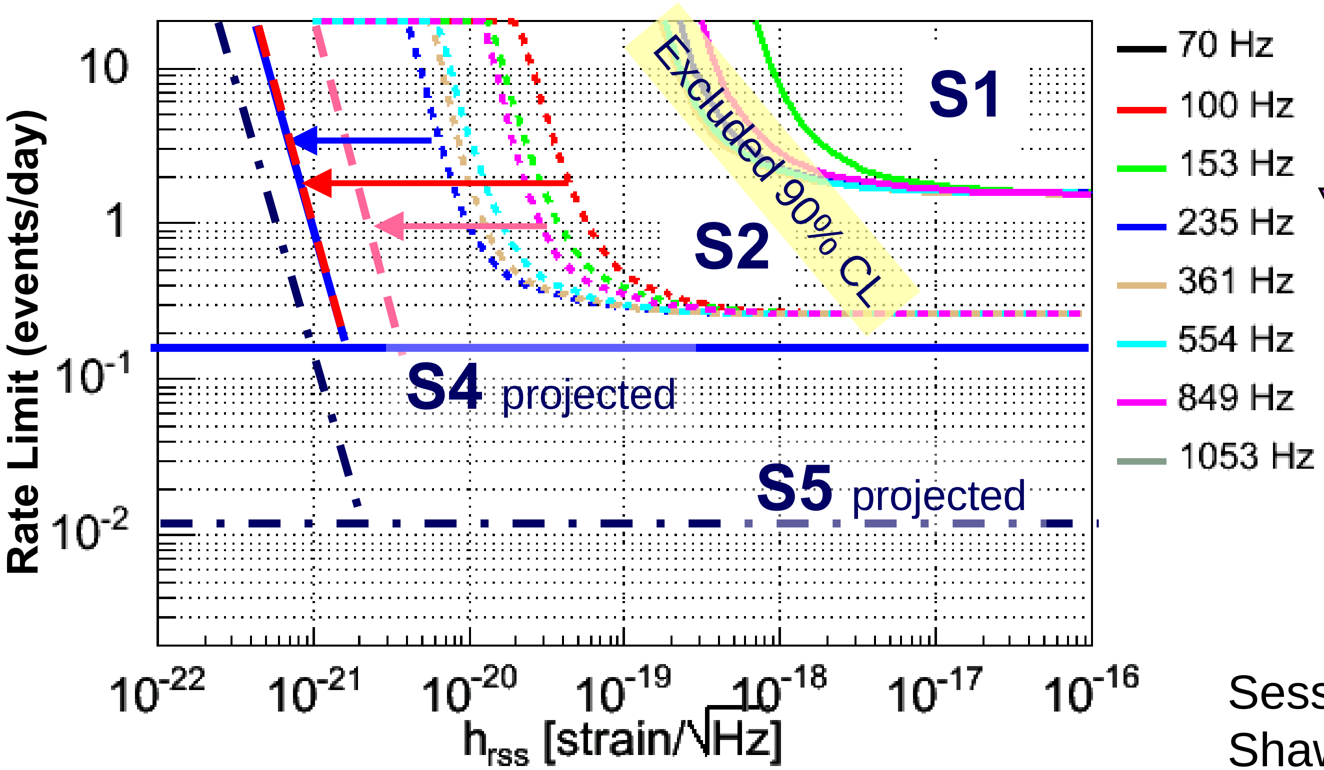
- » $E_{GW} > 1\ M_o$ at r ~ 75 Mpc
- » $E_{GW} > 0.05\ M_o$ at r ~ 15 Mpc (~ distance to Virgo cluster)


Science Run 4 (Shawhan, Session W11)

$$h_{rss} = \sqrt{\int |h(t)|^2 dt}$$

Progress in Upper Limits

- No GWBs detected through S4.
- Set limits on GWB rate as a function of amplitude.



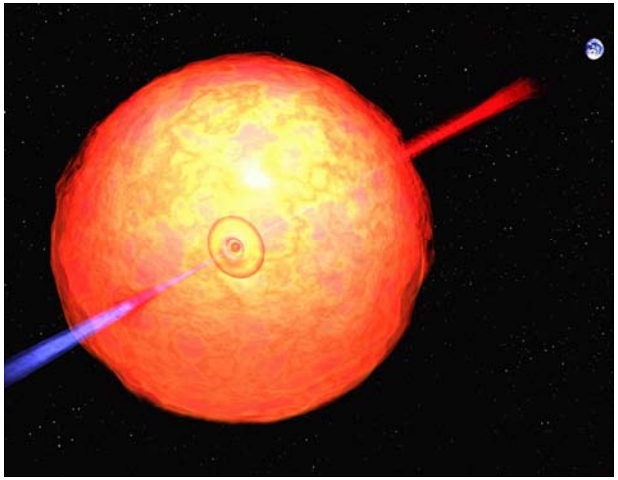
Lower rate limits from longer observation times

Lower amplitude limits from lower detector noise

Session W11:
Shawhan – Science Run 4
Yakushin – Science Run 5

Astronomically Triggered Searches

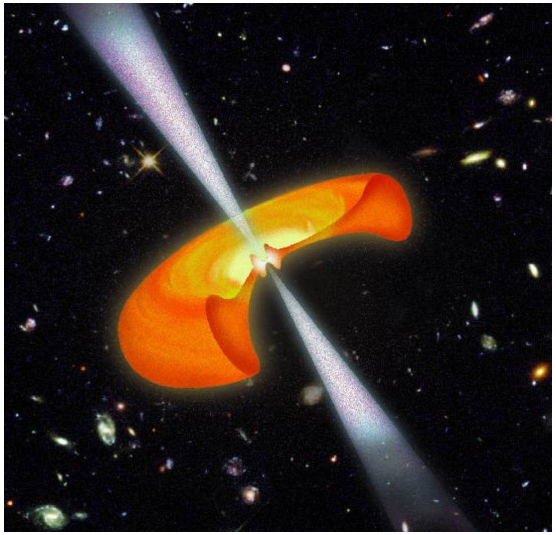
- Follow-up on interesting astronomical events.
  - GRBs: Sannibale/Leonor, Deitz, Session W11
  - Massive flare from SGR 1806: Matone, poster.



- Know time of event
  - Can concentrate efforts to probe sensitively small amount of data around the event time.
- Often know sky position
  - Can account for time delay, antenna response of instrument in consistency tests
- Sensitivity improvement:
  - Often a factor of ~2 in amplitude.

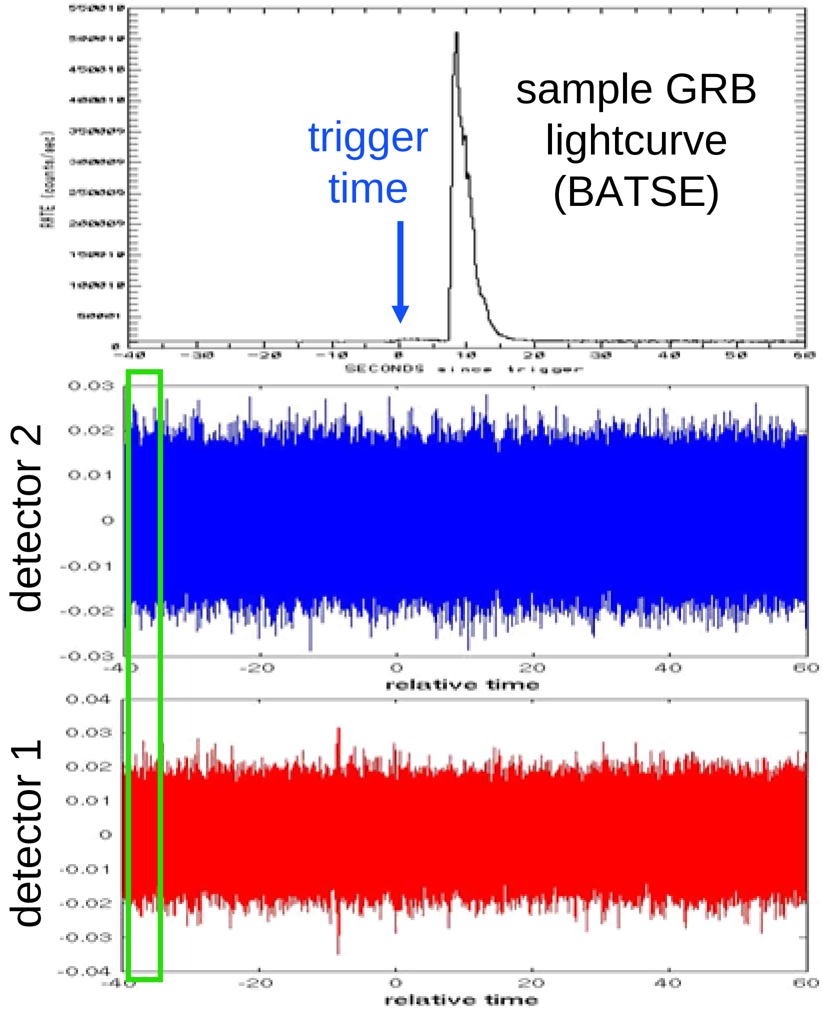
Gamma-Ray Bursts

- Bright bursts of gamma rays
  - occur at cosmological distances
  - seen at rate ~1/day.
- Long duration > 2s
  - associated with “hypernovae” (core collapse to black hole)
  - Hjorth et al, Nature **423** 847 (2003).
  - Leonor/Sannibale, Session W11
- Short duration < 2 s
  - Binary NS-NS or NS-BH coalescence?
  - Gehrels et al., Nature **437**, 851–854 (2005).
  - Dietz, Session W11



Strongly relativistic - Interesting targets for LIGO!

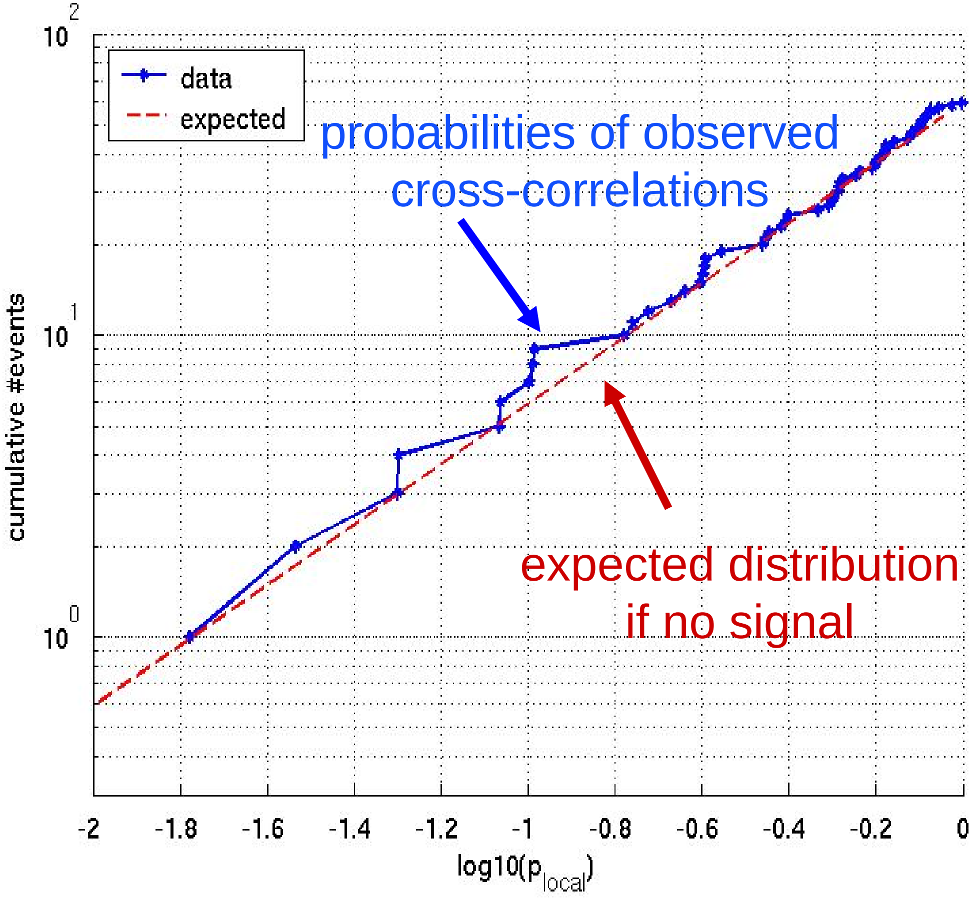
Procedure: GRBs



- Use triggers from satellites
  - » Swift, HETE-2, INTEGRAL, IPN, Konus-Wind
  - » Include both “short” and “long” GRBs
- Cross correlate data between pairs of detectors around time of event
  - » 25 – 100 ms target signal duration
  - » [-2,+1] min around GRB
- Compare largest measured CC to background distribution of CCs (from neighboring times with no GRB signal).
  - » Improbably large CC equals candidate GWB

Statistical Tests

- No loud signals seen so far.
- Look also for weak cumulative effect from population of GRBs.
    - » Use binomial test to compare to uniform distribution.
- No significant deviation from expected distribution.
    - » Significance of deviation in plot at right ~50%.



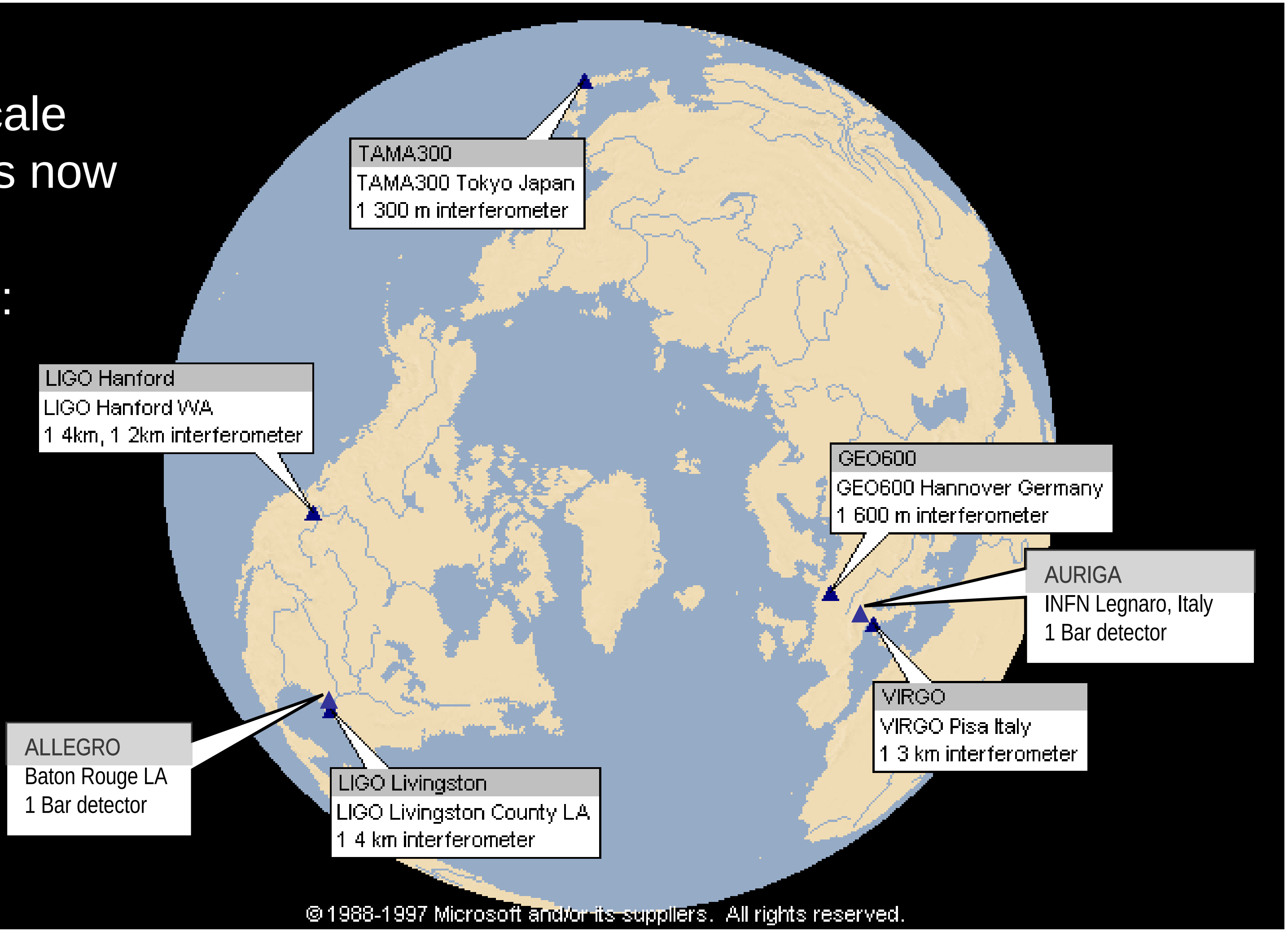
probabilities of observed cross-correlations

expected distribution if no signal

Leonor / Sannibale, Session W11

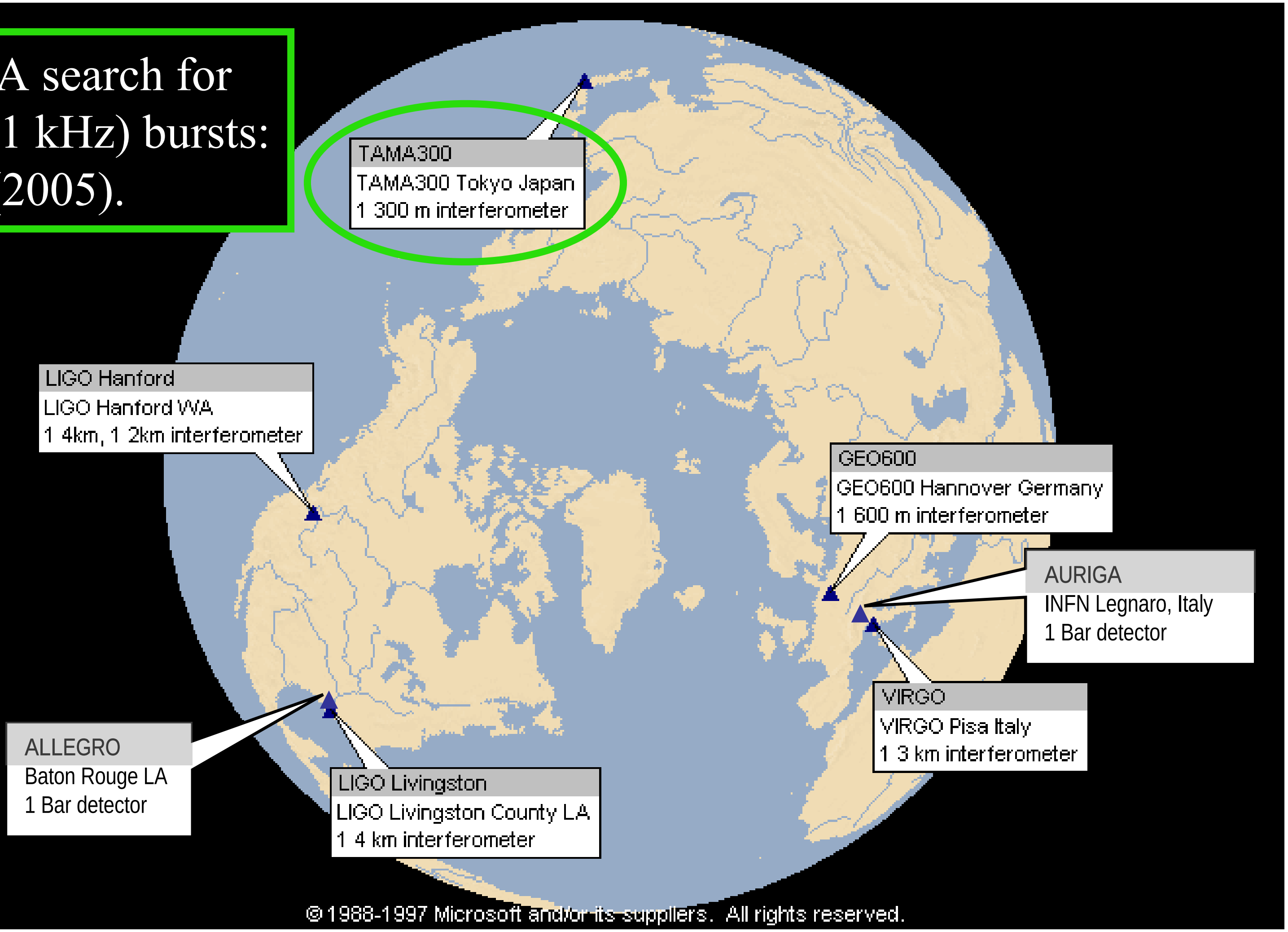
Other Efforts: Joint Searches

- Several km-scale detectors, bars now in operation
- Network gives:
  - » Detection confidence
  - » Direction by triangulation
  - » Waveform extraction



Other Efforts: Joint Searches

Joint LIGO-TAMA search for high-frequency (~1 kHz) bursts: PRD **72**, 122004 (2005).



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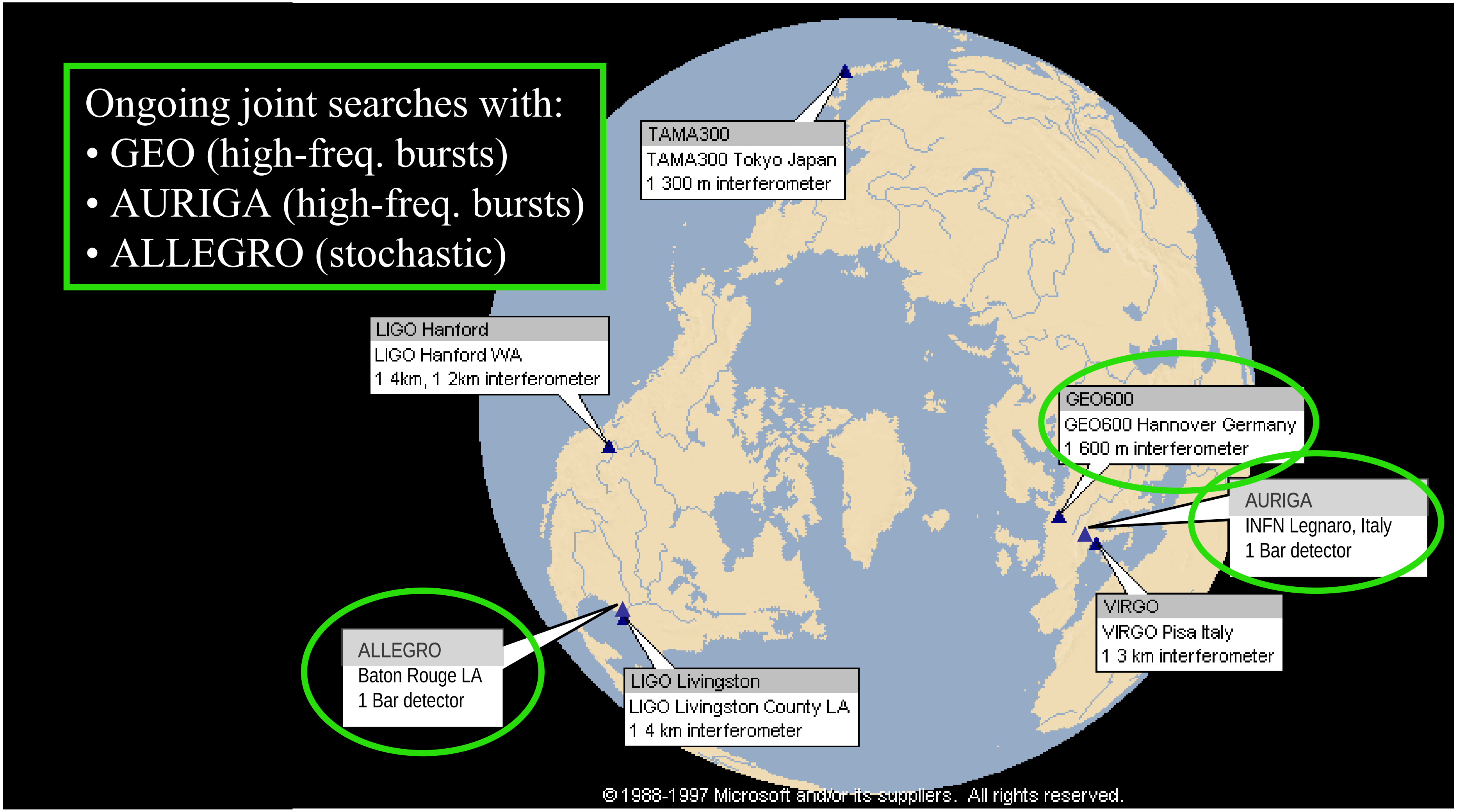
Other Efforts: Joint Searches

Ongoing joint searches with:
- GEO (high-freq. bursts)
- AURIGA (high-freq. bursts)
- ALLEGRO (stochastic)



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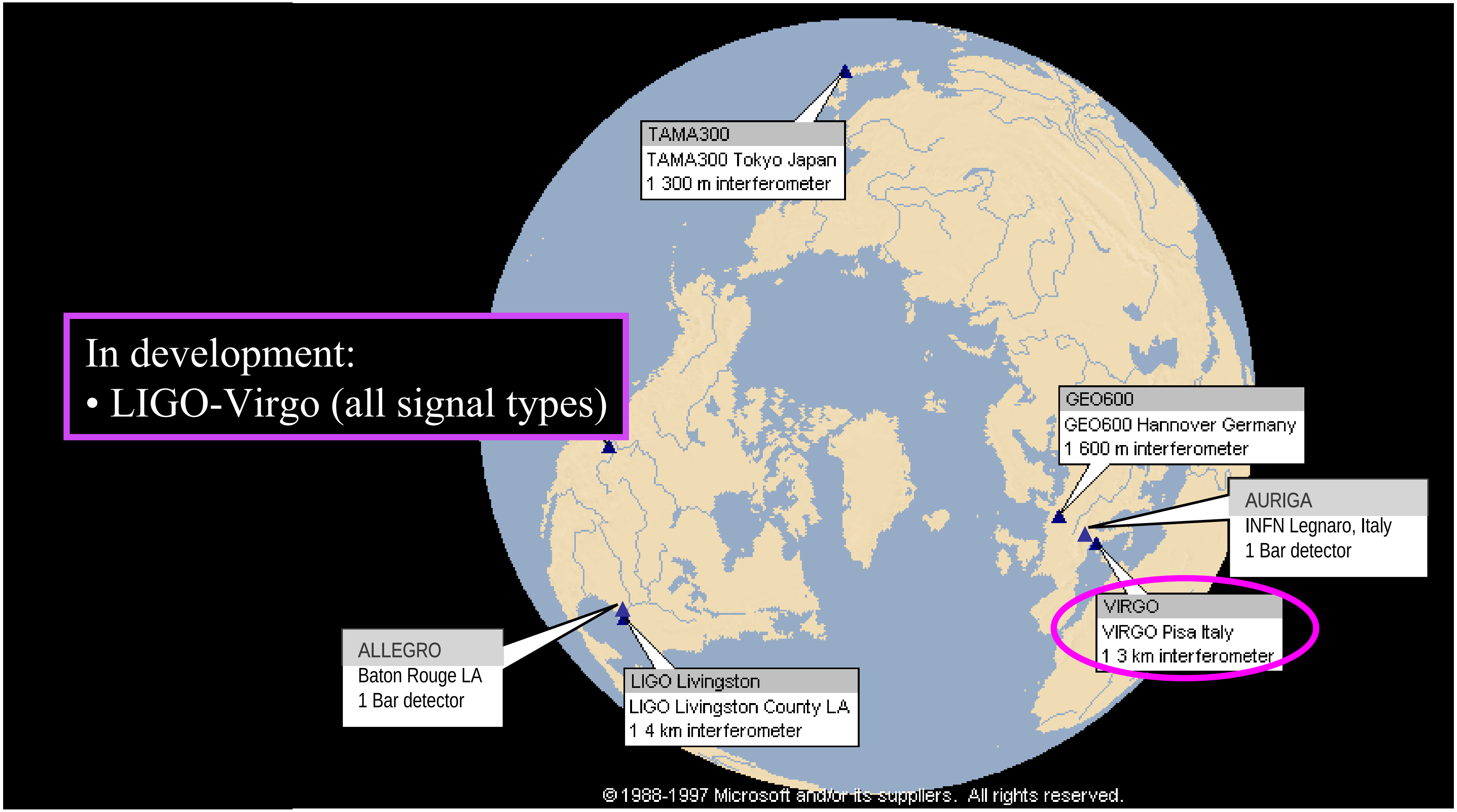
Other Efforts: Joint Searches

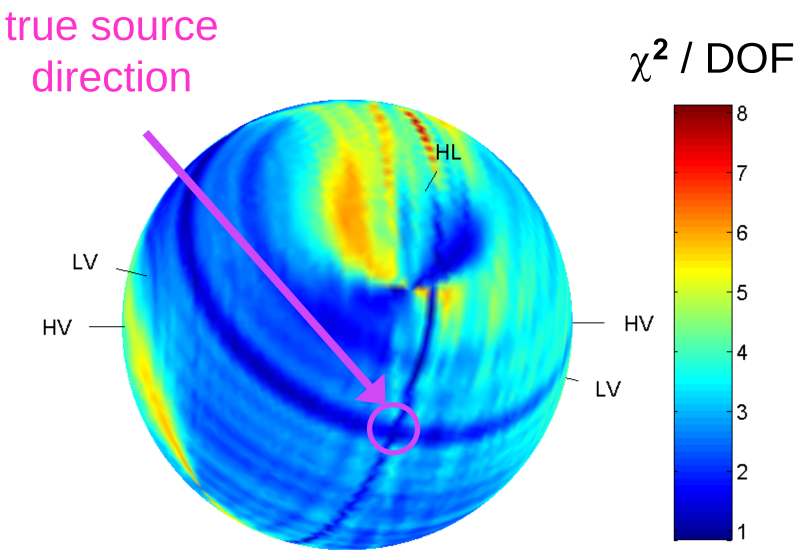


In development:

- LIGO-Virgo (all signal types)

Other Efforts

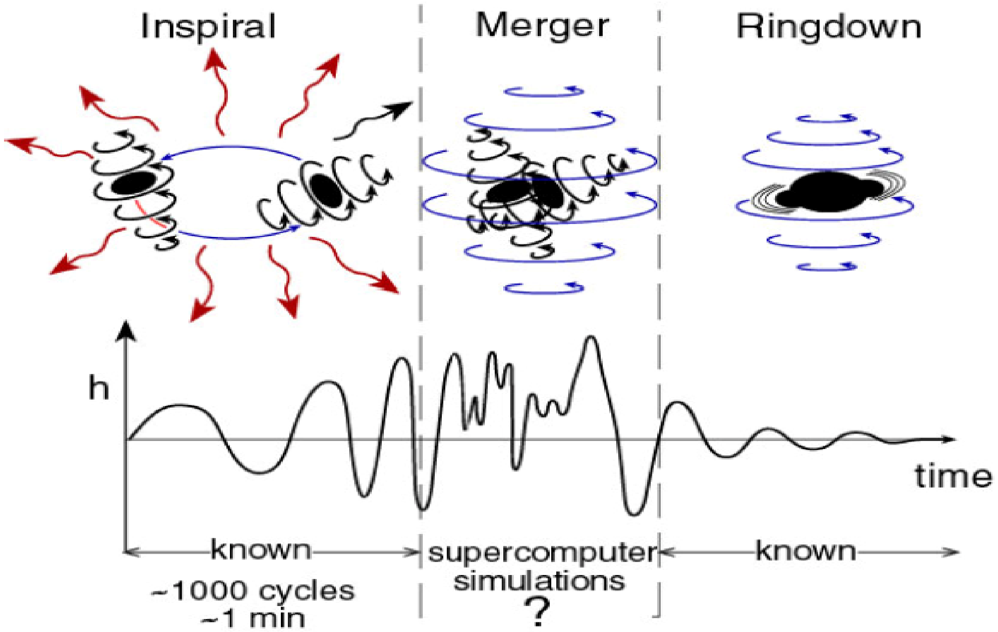
- Coherent analysis with the global network (under development):
  - » for detection, source location, waveform extraction
  - » Klimenko et al, PRD **72** 122002 (2005)



χ^2 consistency with a GWB as a function of direction for a simulated supernova

Other Efforts

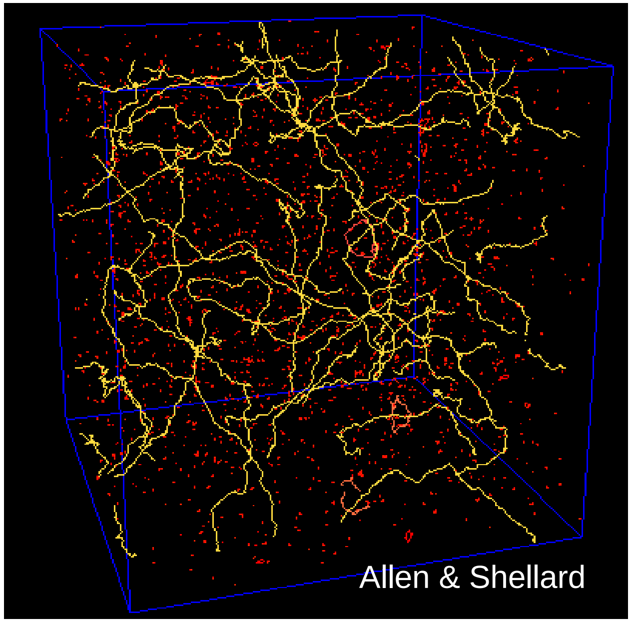
- Inspiral-burst-ringdown search (under development)
  - Joint inspiral-burst group effort (excess power + optimal filtering)
  - Targets likely (and interesting!) signal



Credits: Kip Thorne

Other Efforts

- GWBs from cosmic string cusps
  - Siemens, session S11: *Search Techniques for GWBs from cosmic strings*.
  - optimal-filtering search (waveform known)
- "Online" analysis
  - quick look for loud GWBs
  - rapid feedback on detector performance.

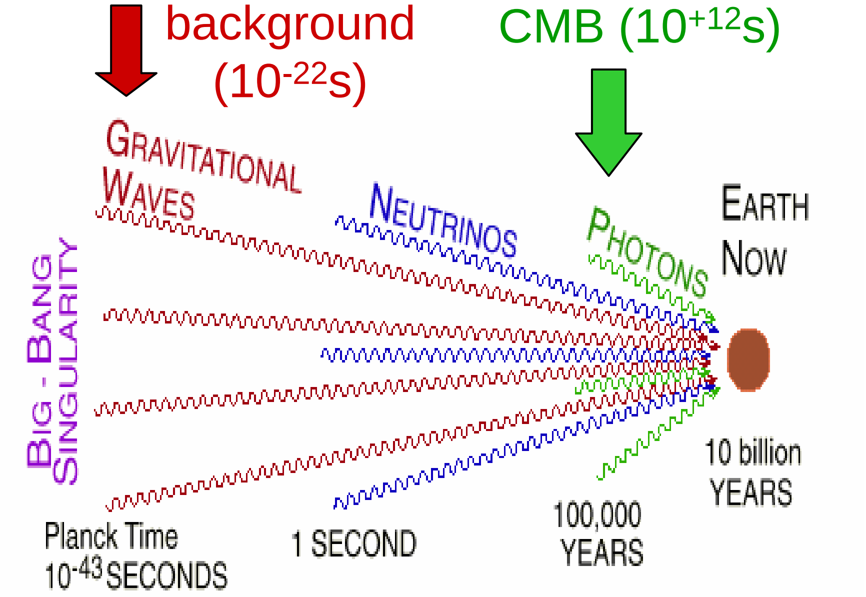


Simulation of a network of cosmic strings.

Stochastic Gravitational-Wave Backgrounds

Stochastic GW Backgrounds

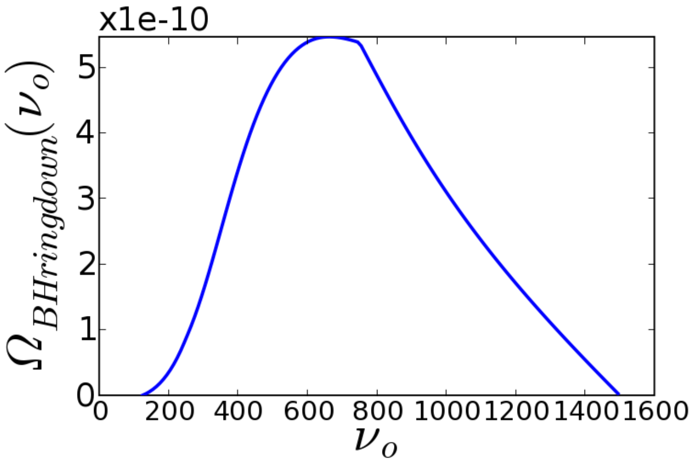
- Cosmological background from Big Bang (analog of CMB)



cosmic GW background (10^{-22}s)

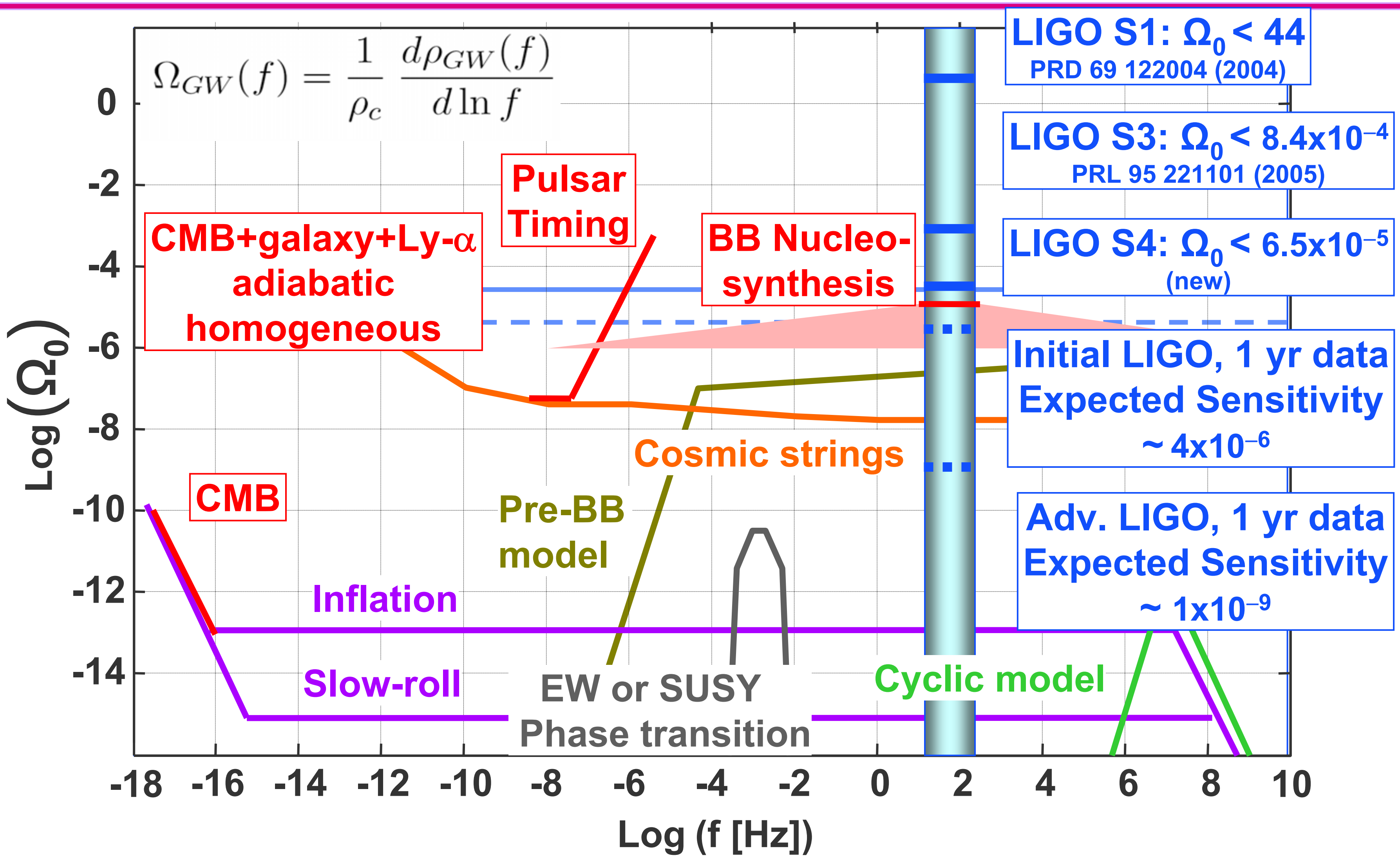
CMB (10^{+12}s)

- Astrophysical backgrounds due to unresolved individual sources
  - E.g.: BH mergers, inspirals, supernovae



GW spectrum due to cosmological BH ringdowns (Regimbau & Fotopoulos)

Predictions and Limits



$$\Omega_{GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{GW}(f)}{d\ln f}$$

LIGO S1: $\Omega_0 < 44$
PRD 69 122004 (2004)

LIGO S3: $\Omega_0 < 8.4\times10^{-4}$
PRL 95 221101 (2005)

LIGO S4: $\Omega_0 < 6.5\times10^{-5}$
(new)

Initial LIGO, 1 yr data Expected Sensitivity
$\sim 4\times10^{-6}$

Adv. LIGO, 1 yr data Expected Sensitivity
$\sim 1\times10^{-9}$

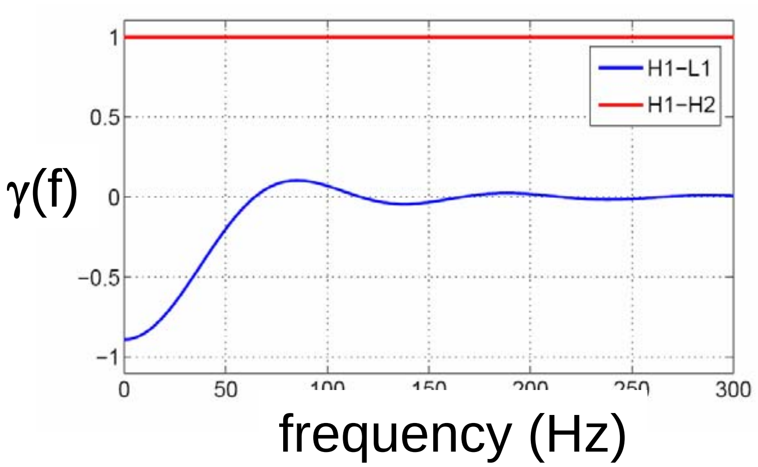
Isotropic Search Procedure

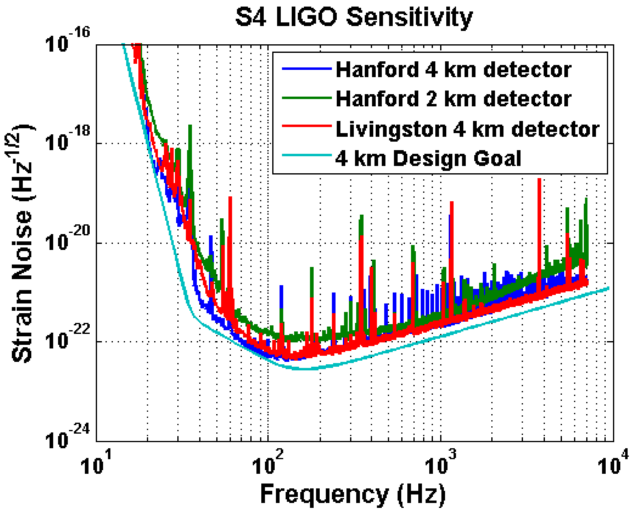
- Cross-correlate two data streams x_1 and x_2
- For isotropic search optimal statistic is

$$Y = \int_{-\infty}^{\infty} df\, \tilde{x}_1^*(f)\, \frac{\gamma(f)\, \Omega_{GW}(f)}{N f^3\, P_1(f)\, P_2(f)}\, \tilde{x}_2(f)$$

"Overlap Reduction Function"
(determined by network geometry)

Detector noise spectra

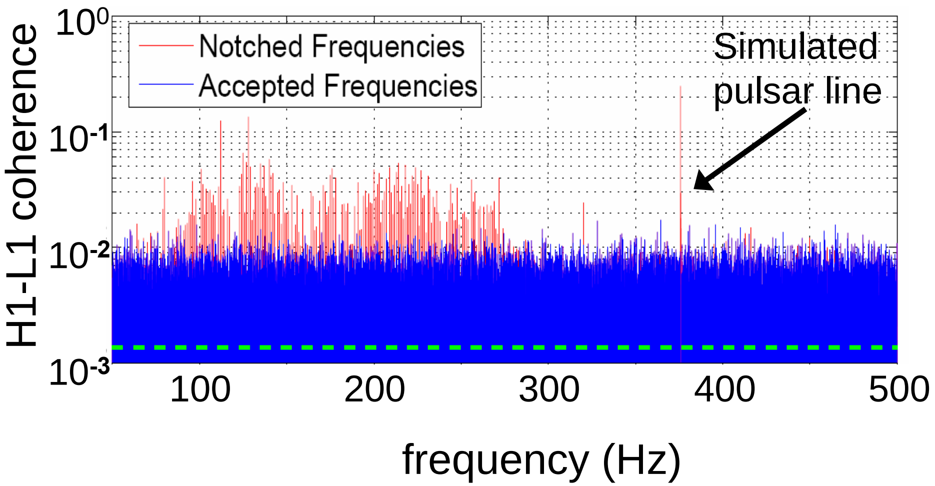




Technical Challenges

- Digging deep into instrumental noise looking for small correlations.
- Need to be mindful of possible non-GW correlations
  - common environment (two Hanford detectors)
  - common equipment (could affect any detector pair!)

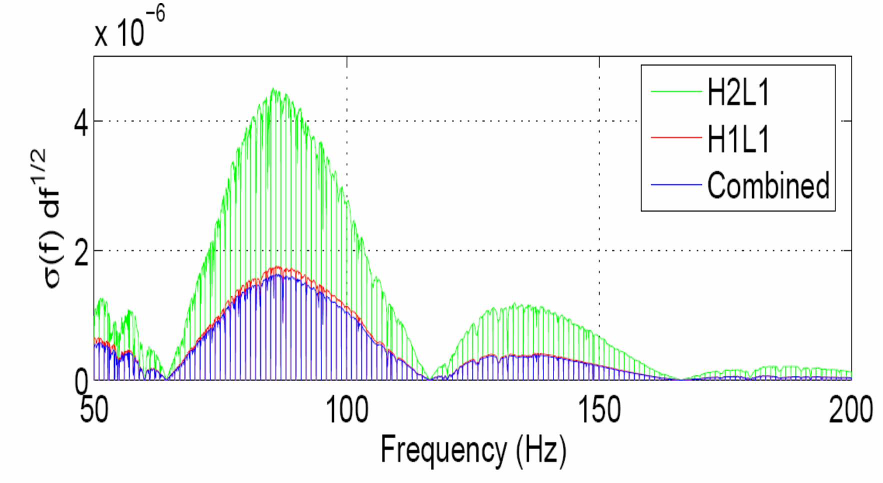
- Example:
  - Correlations at harmonics of 1 Hz.
  - Due to GPS timing system.
  - Lose ~3% of the total bandwidth (1/32 Hz resolution).



S4 Analysis Details

- Cross-correlate Hanford-Livingston
  - Hanford 4km – Livingston
  - Hanford 2km – Livingston
  - Weighted average of two cross-correlations (new in S4).
  - Do not cross-correlate the Hanford detectors.

S4: Sensitivity vs Frequency

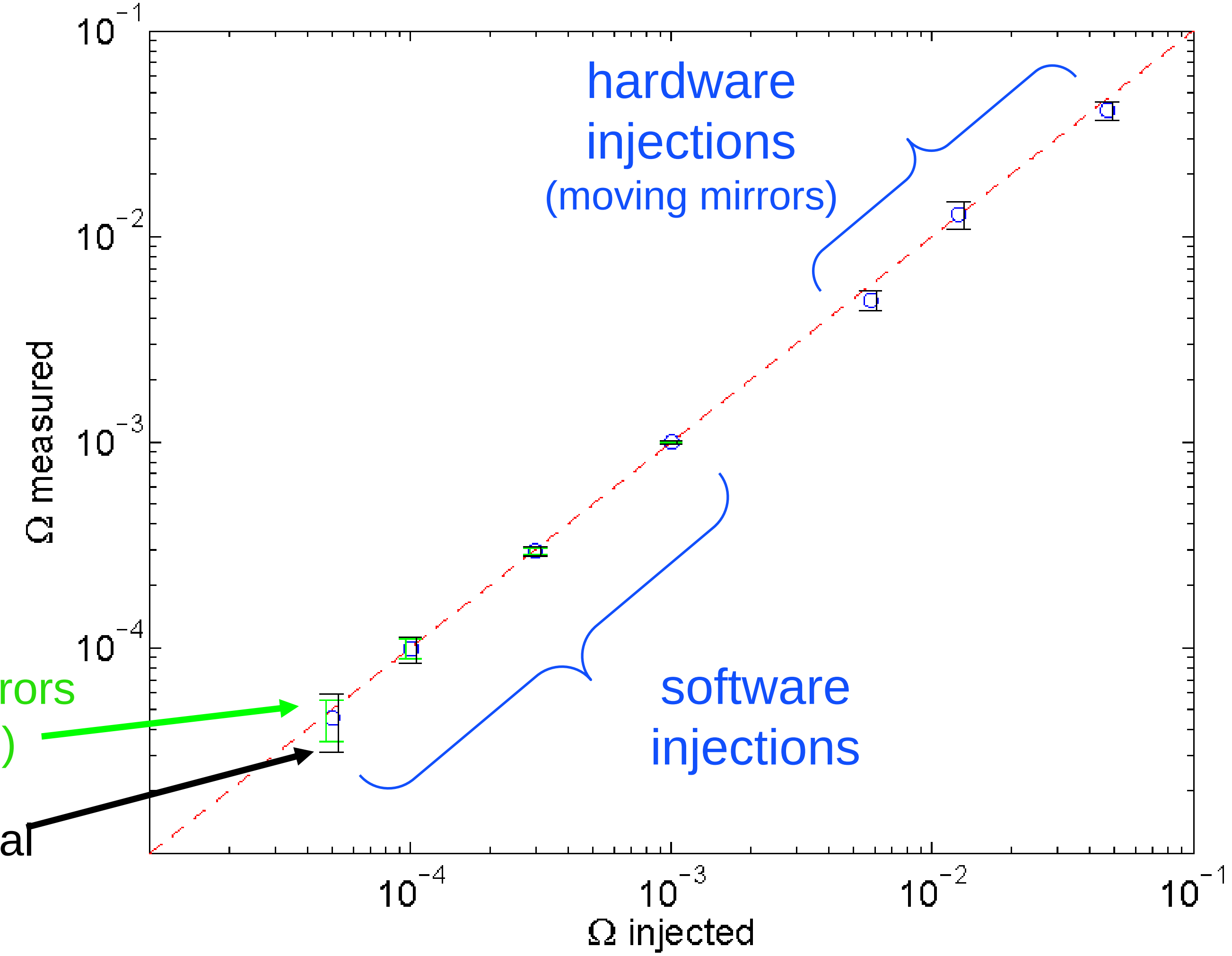


- Data quality:
  - Drop segments when noise changes quickly (non-stationary).
  - Drop frequency bins showing instrumental correlations (harmonics of 1 Hz, bins with pulsar injections).

- Bayesian UL: **$\Omega_{90\%} = 6.5 \times 10^{-5}$**
  - Use S3 posterior distribution for S4 prior.
  - Marginalized over calibration uncertainty with Gaussian prior (5% for L1, 8% for H1 and H2).

Signal Recovery

Demonstrated ability to estimate Ω_{GW} accurately:



hardware injections (moving mirrors)

software injections

standard errors (10 trials)

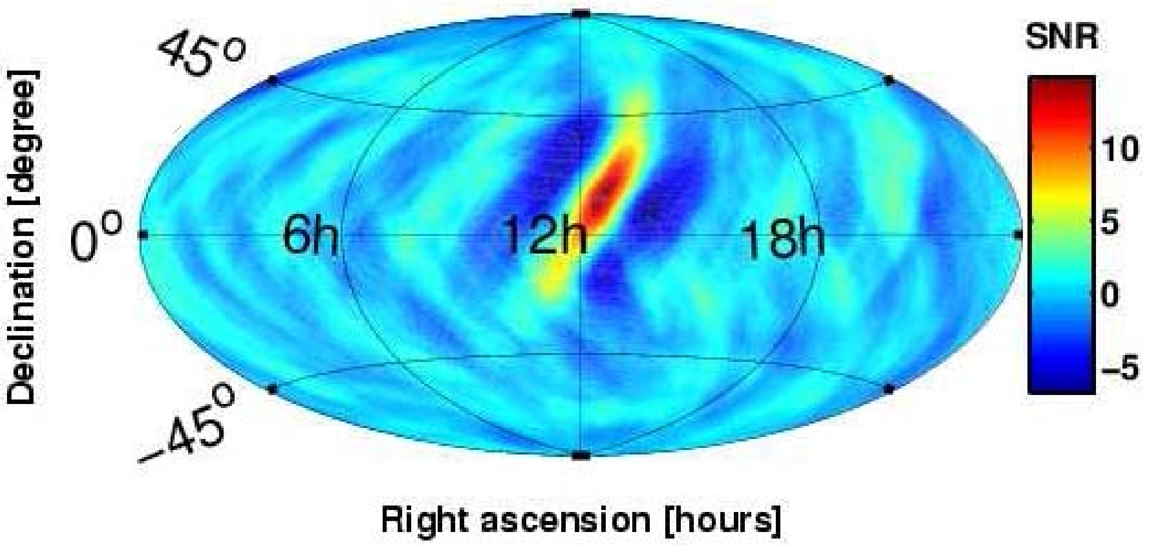
theoretical errors

Other Activities

- Suppressing correlated noise for the co-located Hanford detectors.
  - » Fotopoulos, Proc GWDAW 10, in preparation.
- S4 L1-ALLEGRO (bar detector) search
  - » Results forthcoming.
- Search at LIGO Free Spectral Range (37.5 kHz).
- Directional search (“GW Radiometer”)
  - » Use cross-correlation kernel optimized for unpolarized point source
  - » Ballmer, gr-qc/0510096

Radiometer: Proof-of-Principle

- Analysis of a simulated point source at the position of the Virgo galaxy cluster (12.5h,12.7°).
  - » simulated H1-L1 data



Summary

- Results from LIGO searches for GWBs and a stochastic background in Science runs 4, 5 are now appearing.
  - Significant improvements in interferometer sensitivity since S3.
  - In the process of accumulating 1 year of data (S5).

- Stochastic search: further improvements
  - Combined limits from Handford 4km - Livingston and Hanford 2km - Livingston measurements.
  - Latest result: $\Omega_{GW} < 6.5\text{x}10^{-5}$ (12 x better than S3).
  - Expect to surpass Big Bang nucleosynthesis limit in S5.

- Bursts:
  - Rate and amplitude sensitivity continuing to improve.
    - Minimum detectable in-band energy: $E_{GW} \sim O(1)\ M_o$ at $r < O(100)$ Mpc.
  - “Online” analysis & event follow-up for rapid feedback to experimentalists.

- Novel searches and methods in development by each group.
  - Stochastic: directional, high-frequency, noise cancellation, network searches.
  - Bursts: network searches, coherent analyses, population studies with GRBs, inspiral-burst-ringdown, cosmic strings.