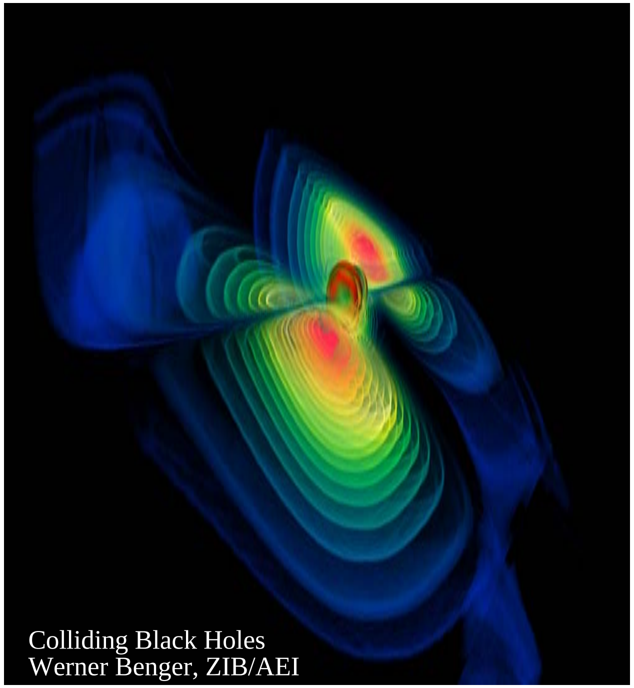
The LIGO-TAMA Joint Search for Gravitational-Wave Bursts



Patrick Sutton
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for the
LIGO and TAMA Collaborations

LIGO-G040503-00-Z

Outline

- Background of LIGO-TAMA Joint Effort
- Network Analyses
- LIGO-TAMA Network
- Bursts Search
  - » Target Population & Goals
  - » Methodology
  - » Current Status & Outlook
- GRB and Inspiral Searches

Background

LIGO-TAMA Timeline

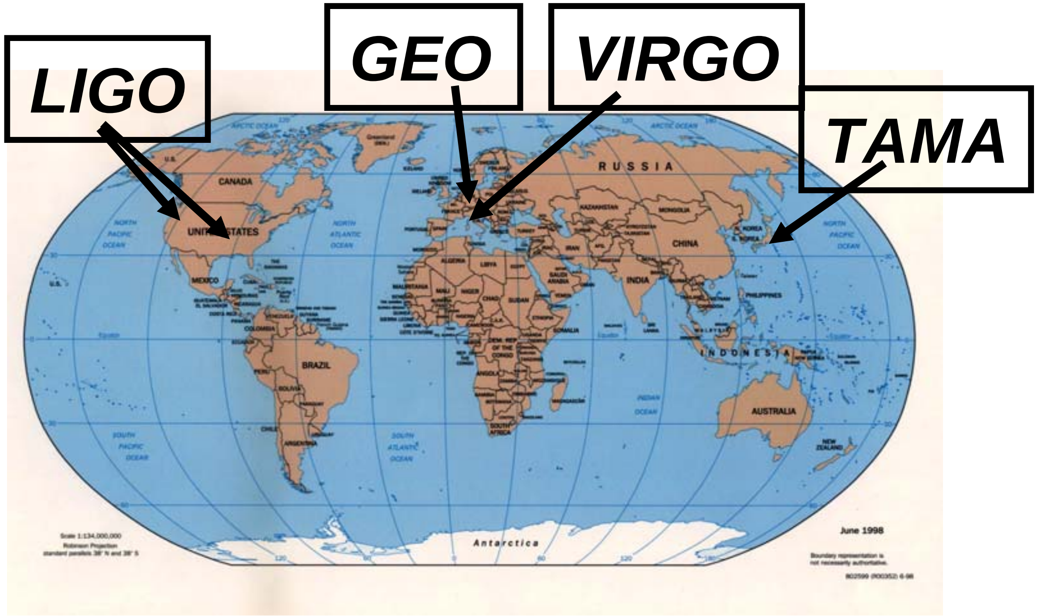
- August 2000: TAMA's first long data-taking run, "DT4".
- August 2002: LIGO's first science run, "S1".
- December 2002: LIGO & TAMA sign "Memorandum of Understanding" for joint searches for gravitational-wave transients.
  - » "*... to work toward practical and optimized methods for doing coincidences between TAMA and LIGO detectors…*"
  - » Develop expertise, foster collaborative relationships

LIGO-TAMA Timeline

- Three searches have come out of the LIGO-TAMA agreement:
  - » Un-modeled gravitational-wave bursts (this talk)
  - » Inspiralling galactic neutron-star binaries
  - » Gravitational waves from "monster" GRB 030329
- Summer, 2003: Began joint search for bursts in S2/DT8 data, focusing on high frequencies (700-2000Hz).
  - » Complementary to LIGO-only search: 100-1100Hz
  - » Results to be released at GWDAW-9 (next month).
  - » Inspiral & GRB 030329 analyses began fall 2003; in progress.

Collaborative Searches

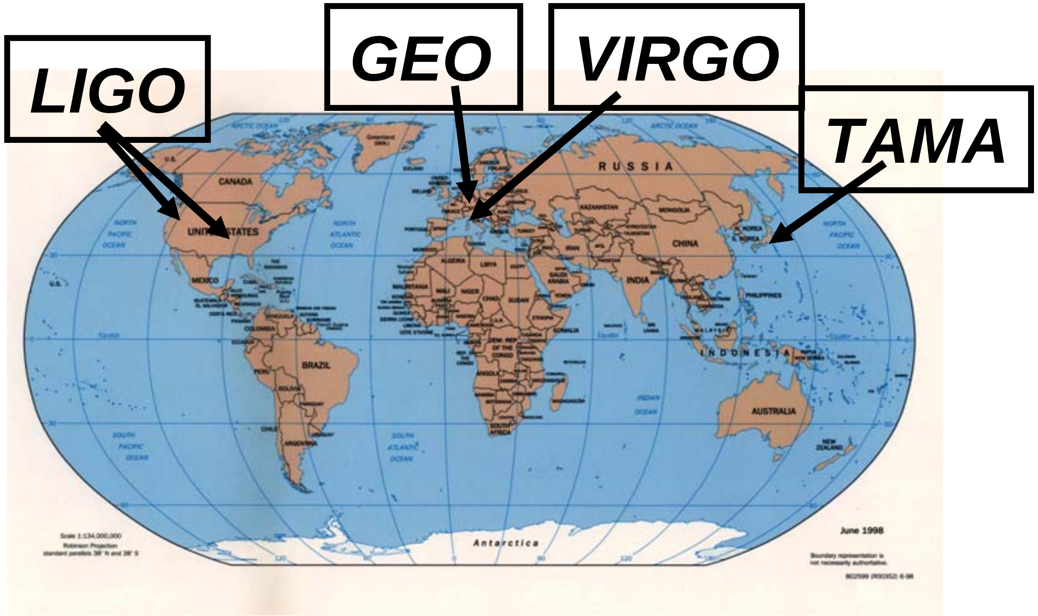
- Most confident detection and maximum exploitation of gravitational waves may come from cooperative analyses by the various observatories:



  » Reduction in false alarm rate due to extra coincidence (~1/century)
  » Increase in total usable observation time
  » Extract sky direction, polarization with 3+ sites (eg., Gursel & Tinto PRD *40* 3884 1989).
  » Better sky coverage.
  » Better frequency coverage.
  » Independent hardware, software, and algorithms minimize chances of error.

Collaborative Searches

- Unfortunately, these benefits don't come without hard work. Physical and technical challenges abound.



Different detectors see:

» … different polarization combinations.

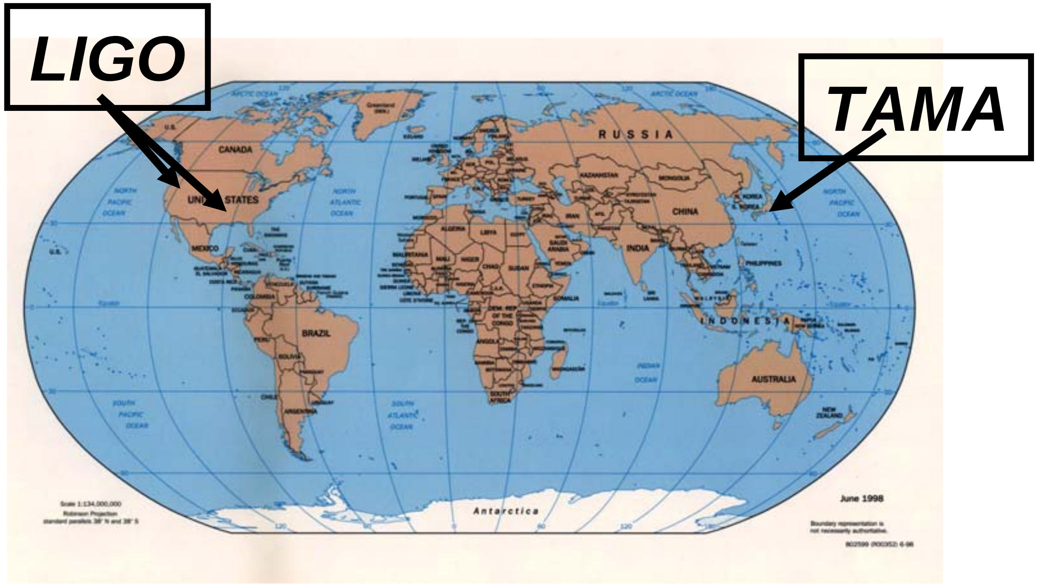
» … different parts of the sky.

» … different frequency bands.

» Different search algorithms, file formats, sampling frequencies, etc.

Collaborative Searches

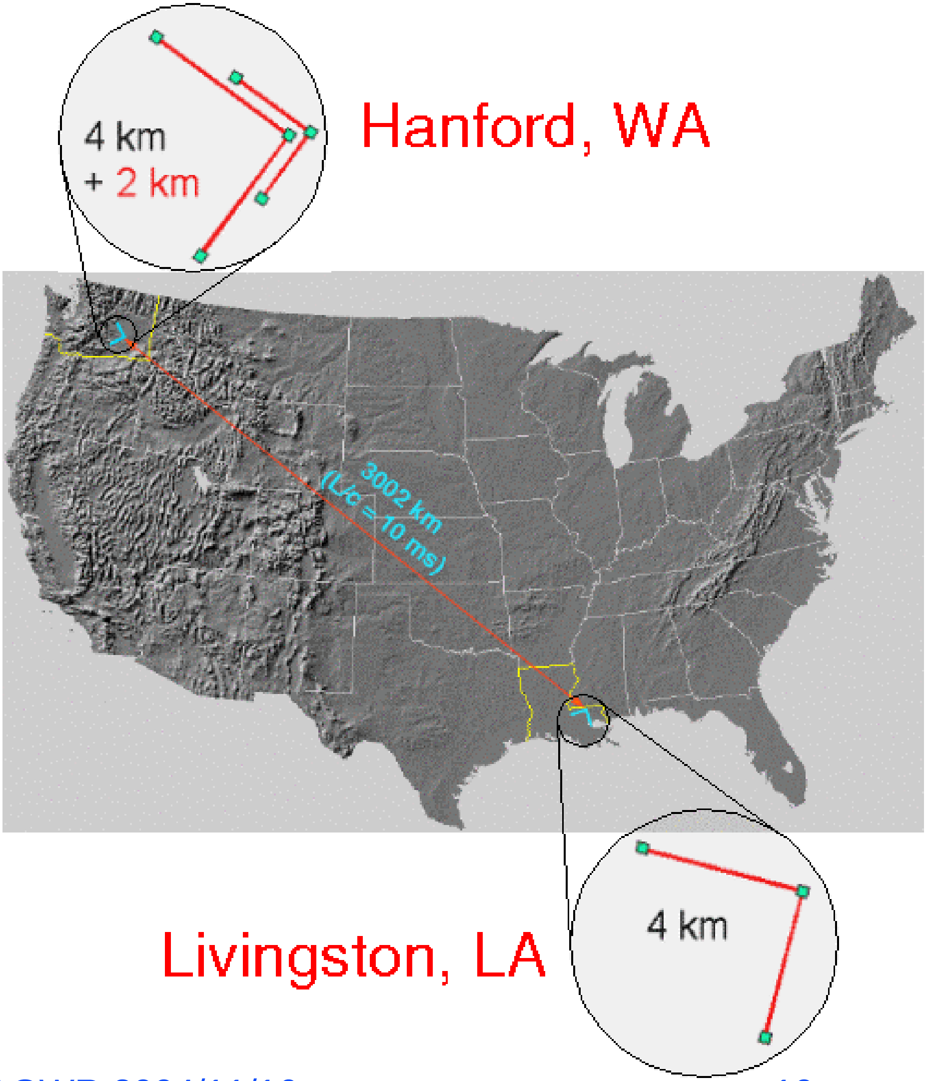
- This talk: Examine some of these challenges for a bursts analysis of LIGO and TAMA data.



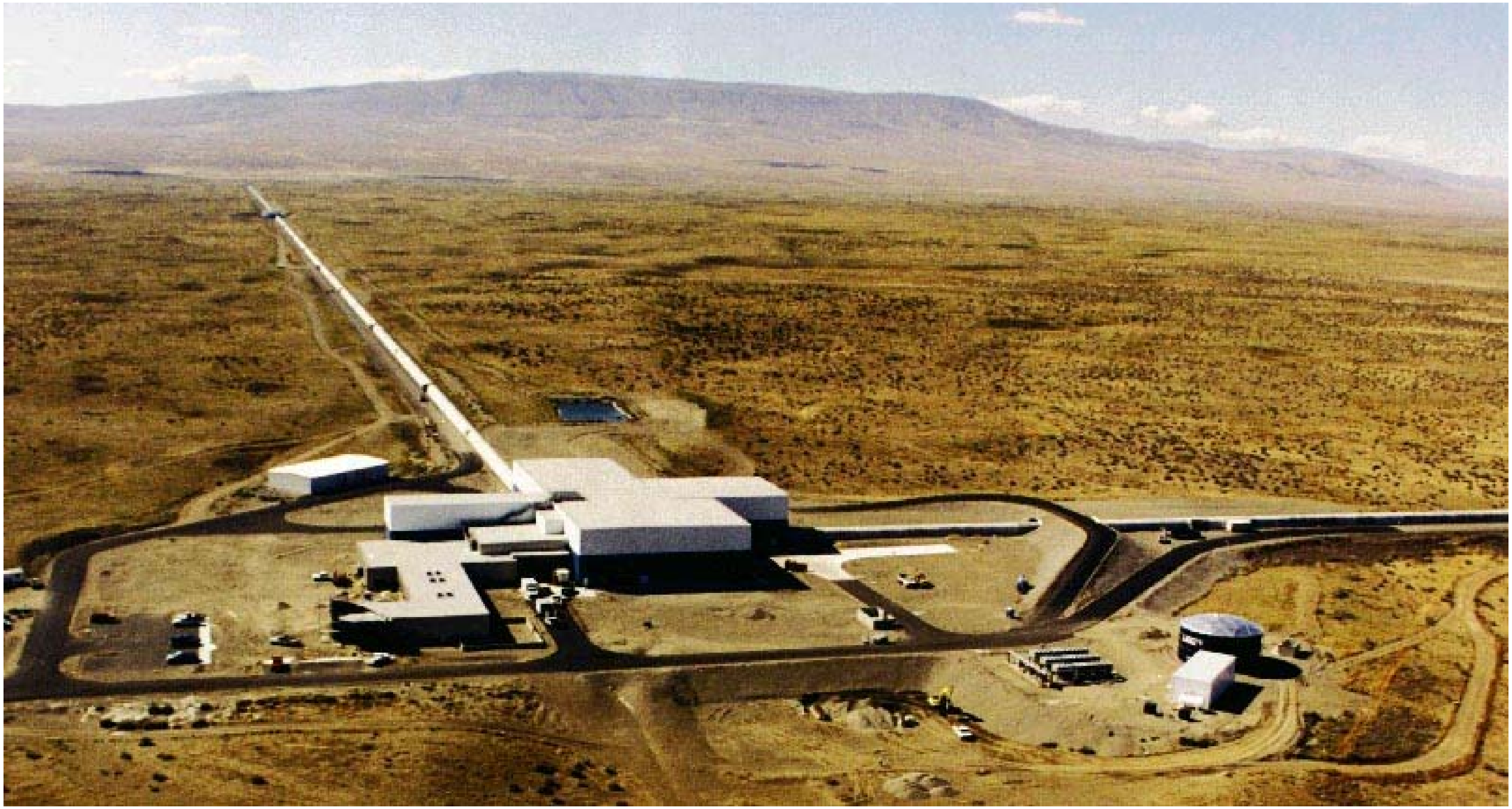
LIGO & TAMA Detectors

The LIGO Project

- Flagship project of NSF.
- 3 detectors at 2 sites.
- First operations 1999.
- Scientific data taking runs:
  - » S1: Aug–Sept 2002
  - » S2: Feb-Apr 2003
  - » S3: Oct 2003 – Jan 2004
  - » S4: Feb-March 2005



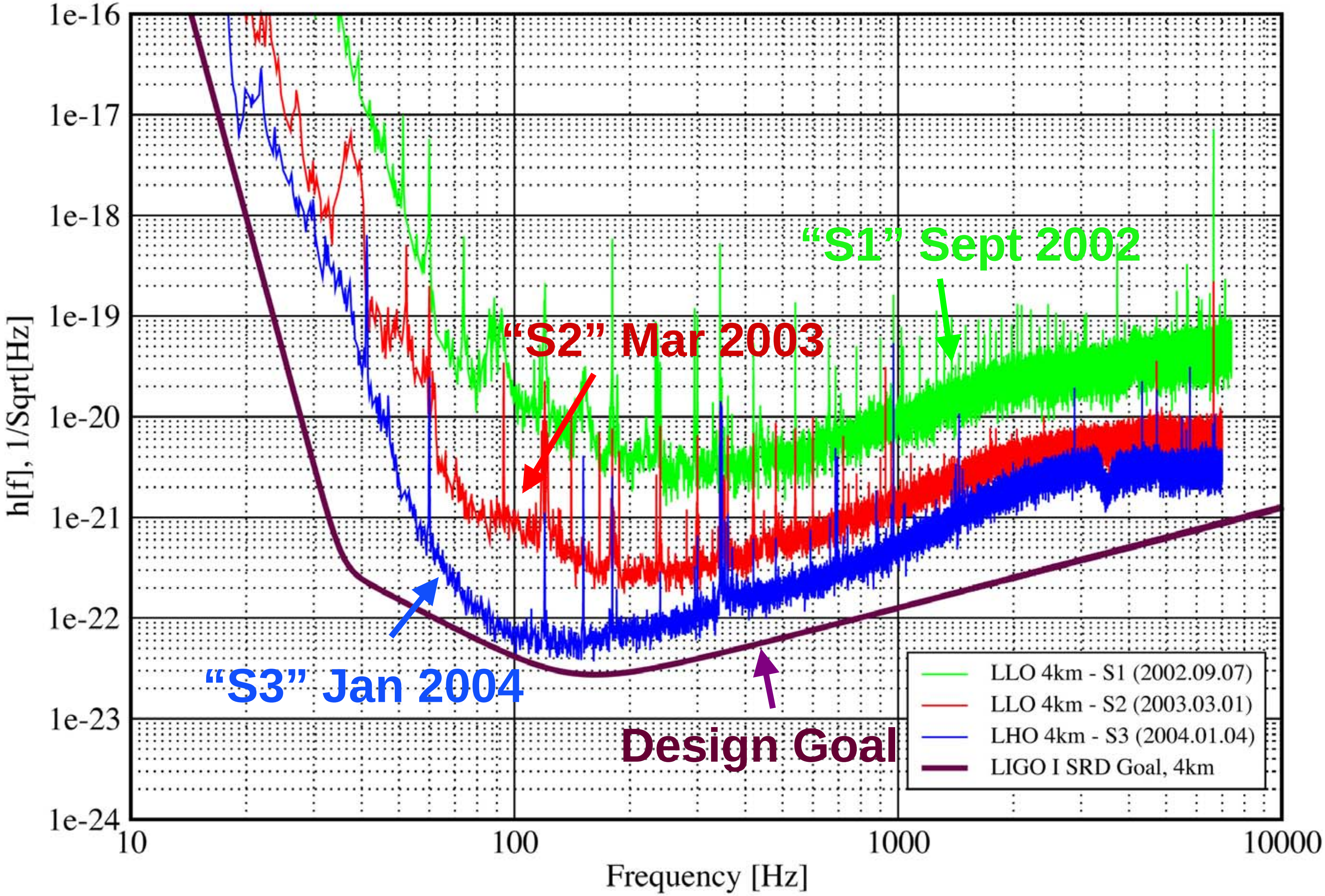
LIGO Hanford



LIGO Livingston

Best Strain Sensitivities for the LIGO Interferometers

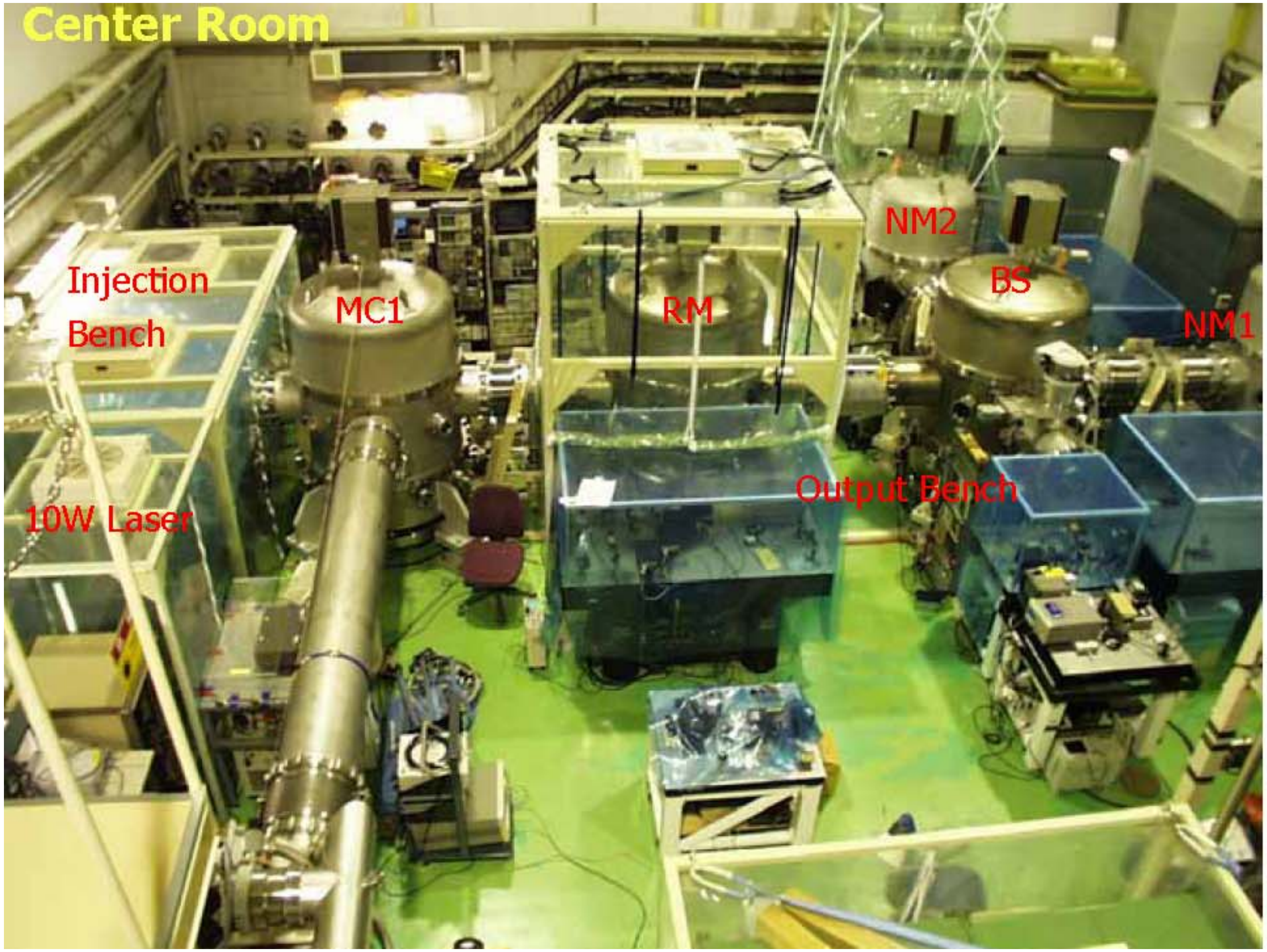
Comparisons among S1, S2, S3 LIGO-G030548-02-E



TAMA300

- At Mitaka campus of NAOJ, near Tokyo
- Recycled Fabry-Perot Michelson interferometer (same as LIGO)
- Arm length: 300m
- First observation run Sept. 1999

Inside TAMA

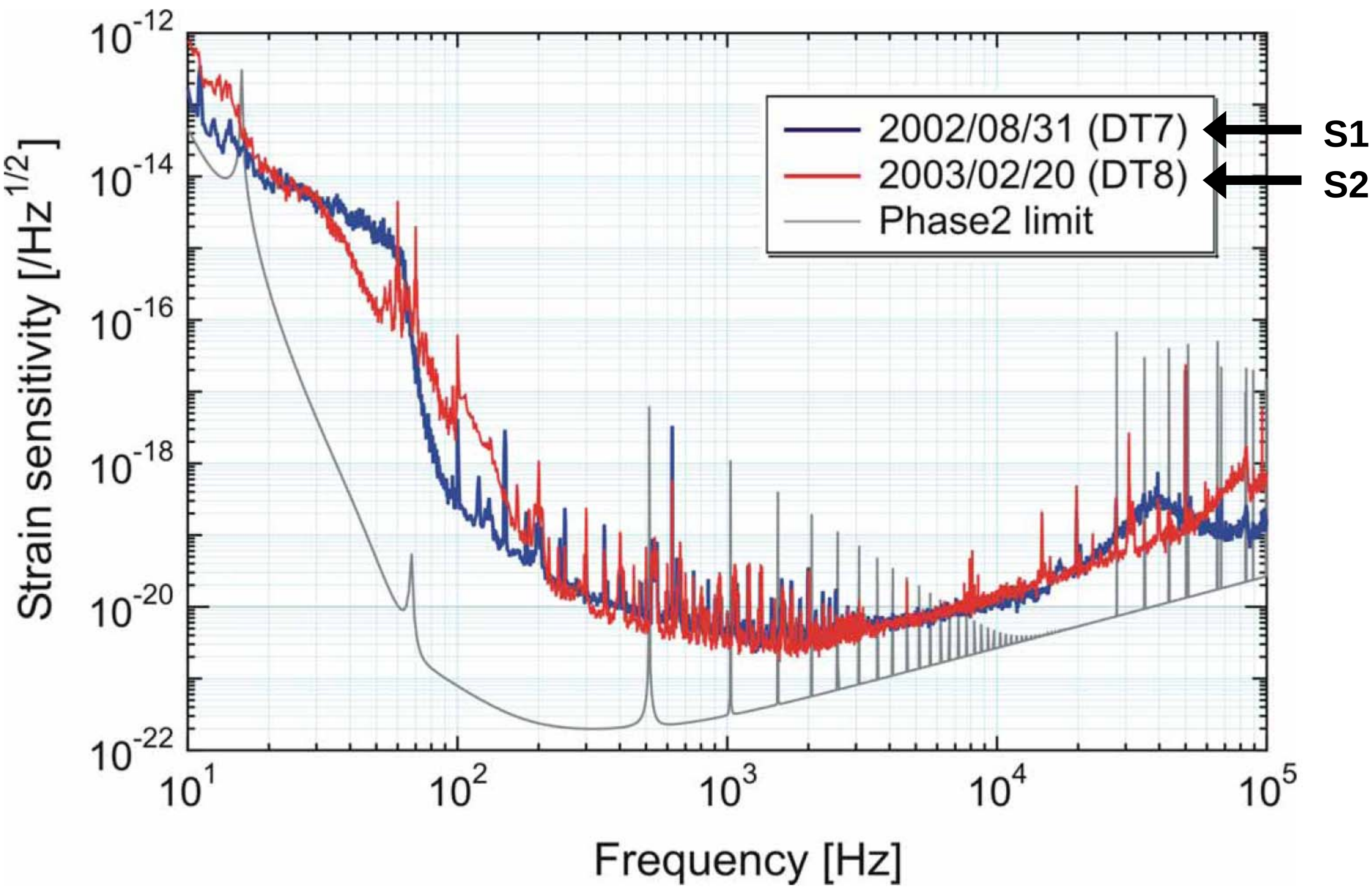


Center Room
Injection Bench
MC1
RM
NM2
BS
NM1
10W Laser
Output Bench

Tunnel
300m Tube

End Room
EM1

TAMA Noise Spectra

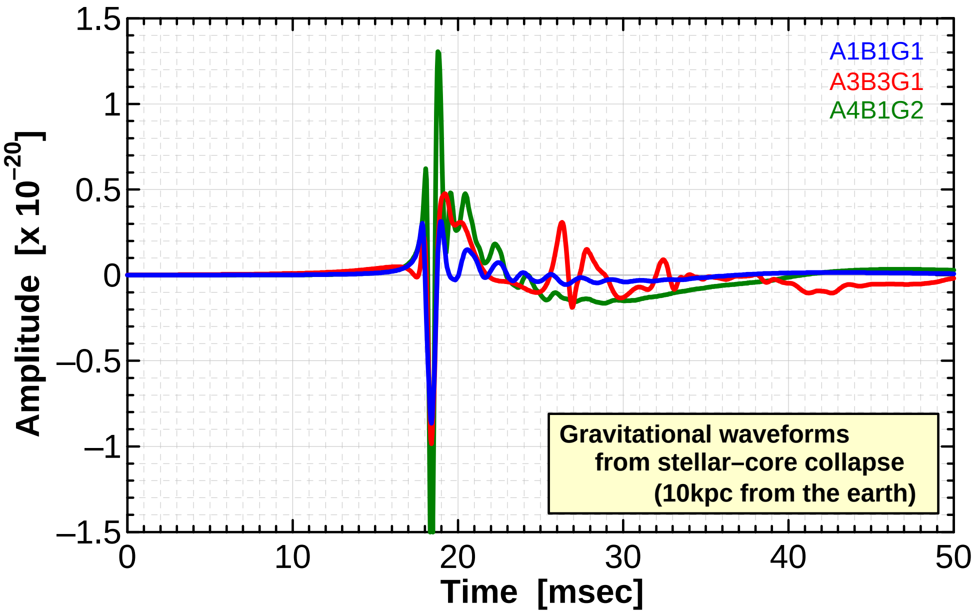


Searching for Gravitational-Wave Bursts

Gravitational-Wave Bursts

Catastrophic events involving solar-mass compact objects can produce transient “bursts” of gravitational radiation (GWBs) in the LIGO frequency band:

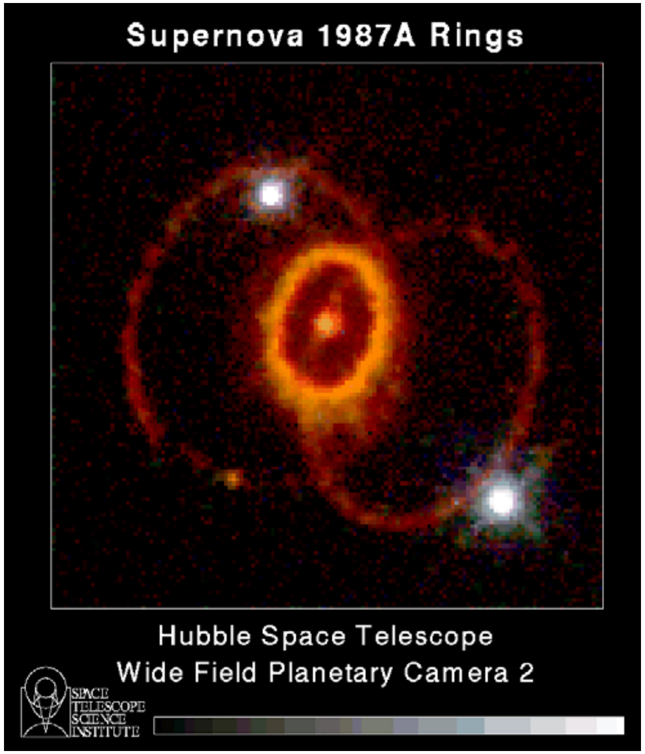
- » core-collapse supernovae
- » merging, perturbed, or accreting black holes
- » gamma-ray burst engines
- » cosmic string cusps
- » others?



possible supernova waveforms
T. Zwerger & E. Muller, Astron. Astrophys. *320* 209 (1997)

Philosophy & Goals

- Precise nature of GWB signals typically unknown or poorly modeled.
  - » Can't base our search on having precise waveforms.
  - » Use techniques to detect excess power in data due to generic GWB signals.
  - » Tune for best sensitivity to GWBs of duration ~1-100ms, frequency ~100-2000Hz.
- Science goal:
  - » Bound the rate of detectable events.
- Practical goal:
  - » Establish methodology, validate procedures. (No sources expected.)

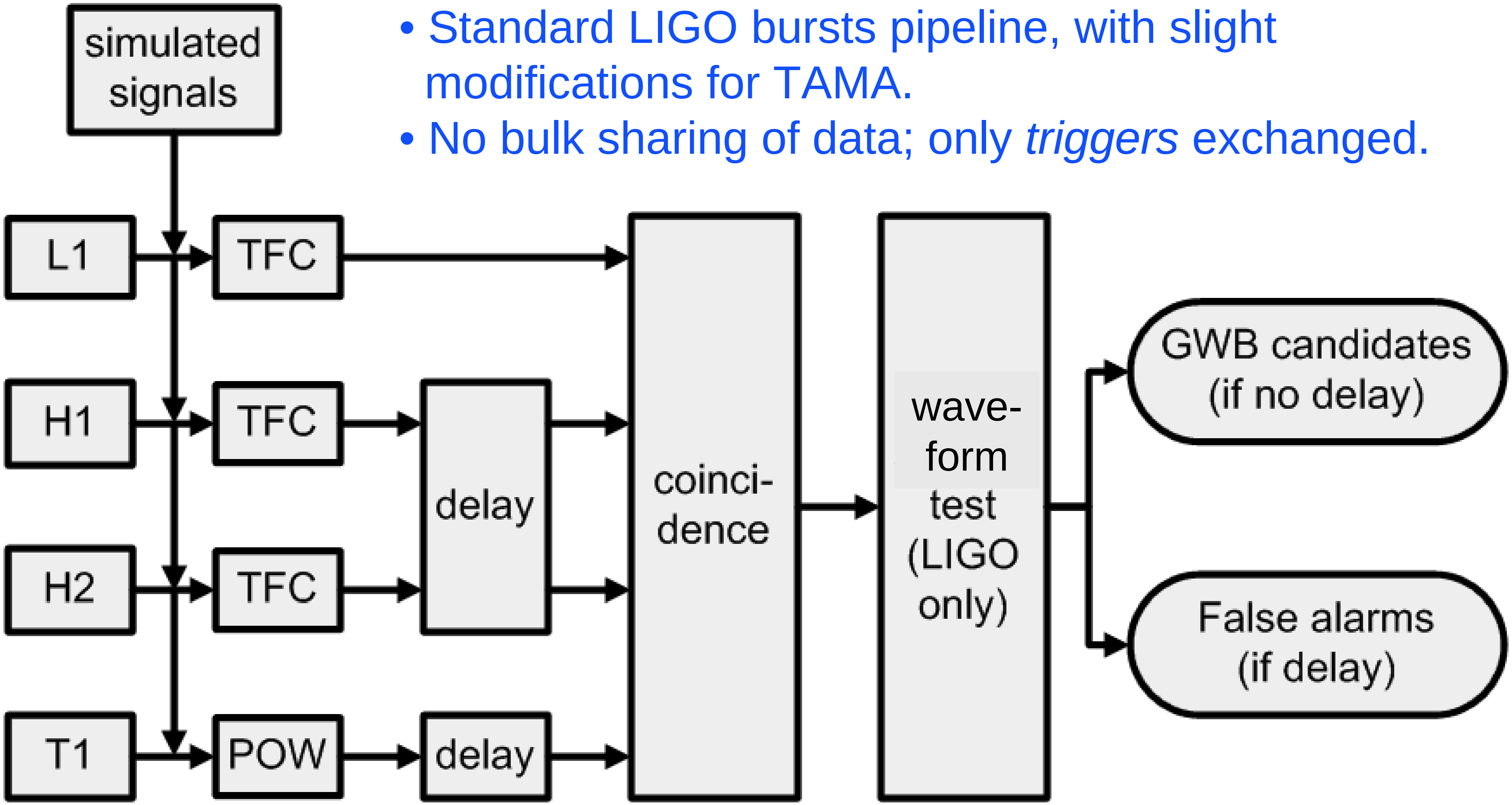


Analysis Procedure

- Based on coincidence.
  - » Candidate GWBs must be observed simultaneously by all operating detectors.
- Each group analyses own data and generates lists of possible GWB events, called “triggers”.
  - » Exchange triggers, look for coincidences in TAMA and LIGO
  - » Use waveform consistency test in LIGO, vetoes in TAMA to reduce false alarm rate
  - » Estimate rate of false alarms by repeating analysis with artificial time lags between detector sites (5-115s).
- Detection / Upper Limits.
  - » Significant excess of coincidences compared to false alarm rate is possible detection; otherwise set upper limit on GWB rate as a function of signal amplitude.
- Estimate network sensitivity using coordinated signal injections.
- Blind analysis.
  - » Set all thresholds, etc. by looking only at time-shifted data (no GWBs) or with 10% subset of data (“playground”) which is discarded in final analysis

Analysis Pipeline

- Standard LIGO bursts pipeline, with slight modifications for TAMA.
- No bulk sharing of data; only *triggers* exchanged.

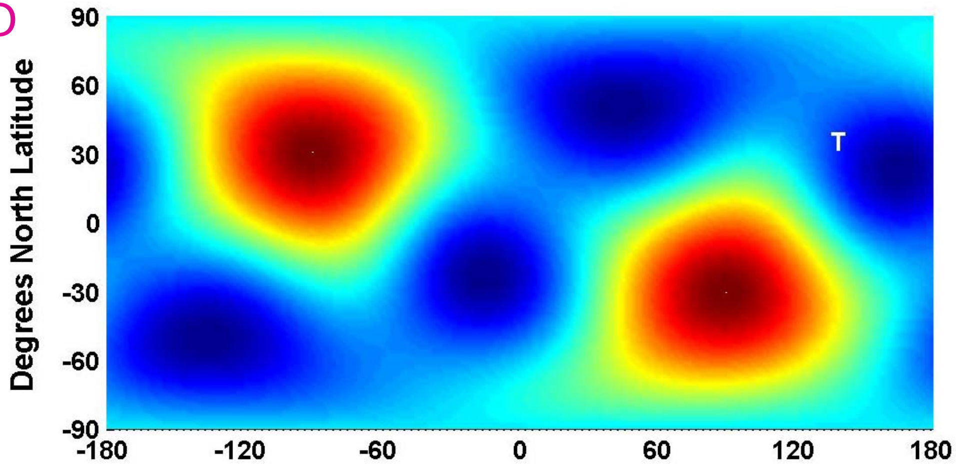


Complications

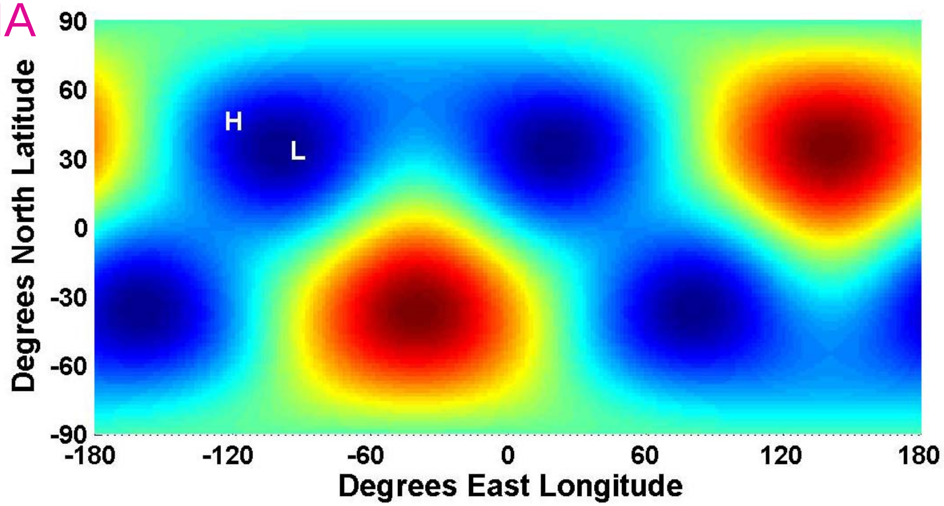
- Physical differences between LIGO & TAMA:
  - » Different sensitivities (noise spectra)
  - » Strongly non-aligned detectors
- Technical:
  - » Different signal-detection algorithms for different IFOs (comparing apples to oranges)
- Present to some extent in all searches, but worst for bursts search.

Antenna Patterns

LLO



TAMA



LIGO and TAMA look with best sensitivity at different parts of the sky:

- » Lower efficiency for coincident detection → limited by minimum of antenna responses.
- » Polarization dependence may weaken waveform-consistency test (under study) → restrict to LIGO.

(This plot: ρ^2. Equal power in uncorrelated polarizations)

Alignment & Efficiency

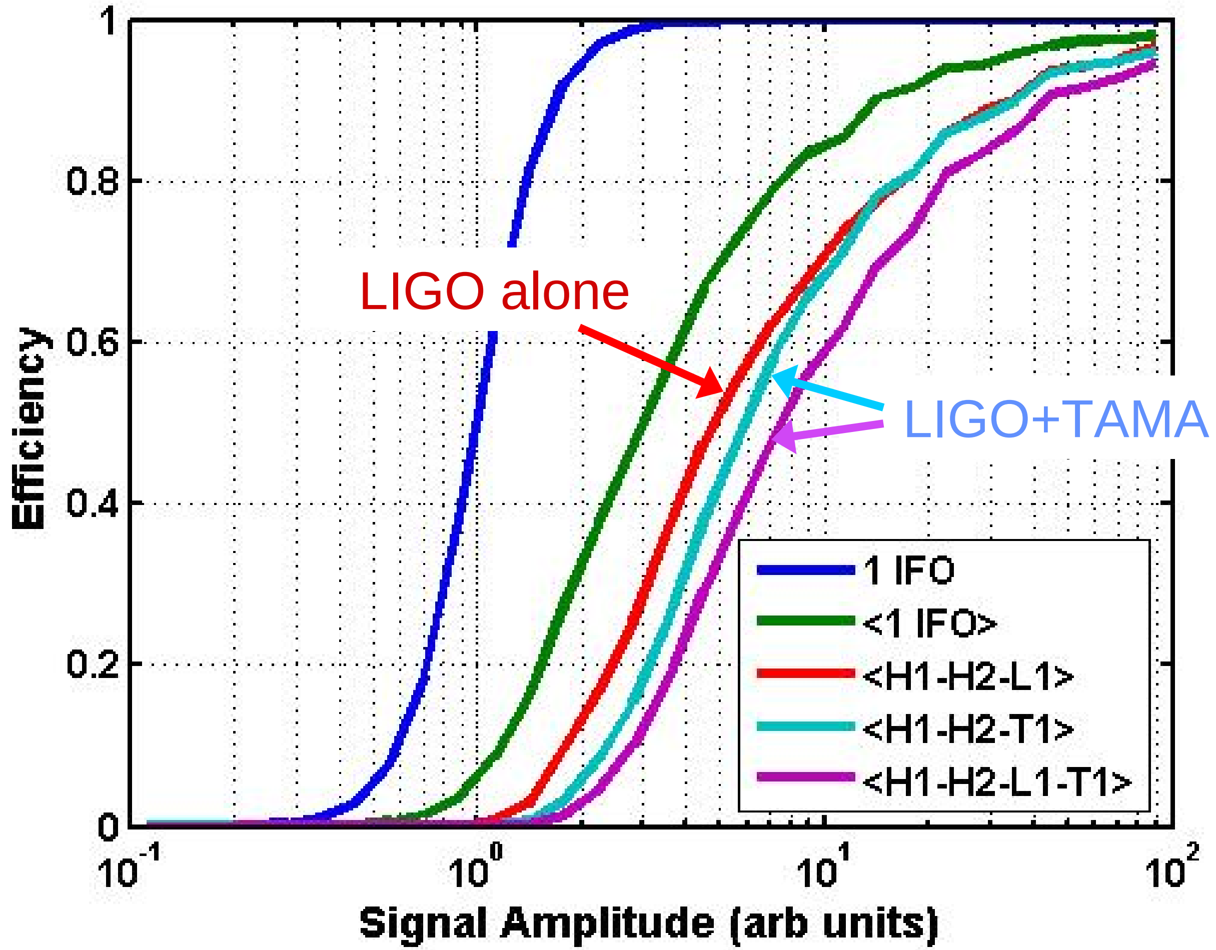
Simple Monte Carlo to compare efficiencies of different combinations of IFOs

Assumptions:

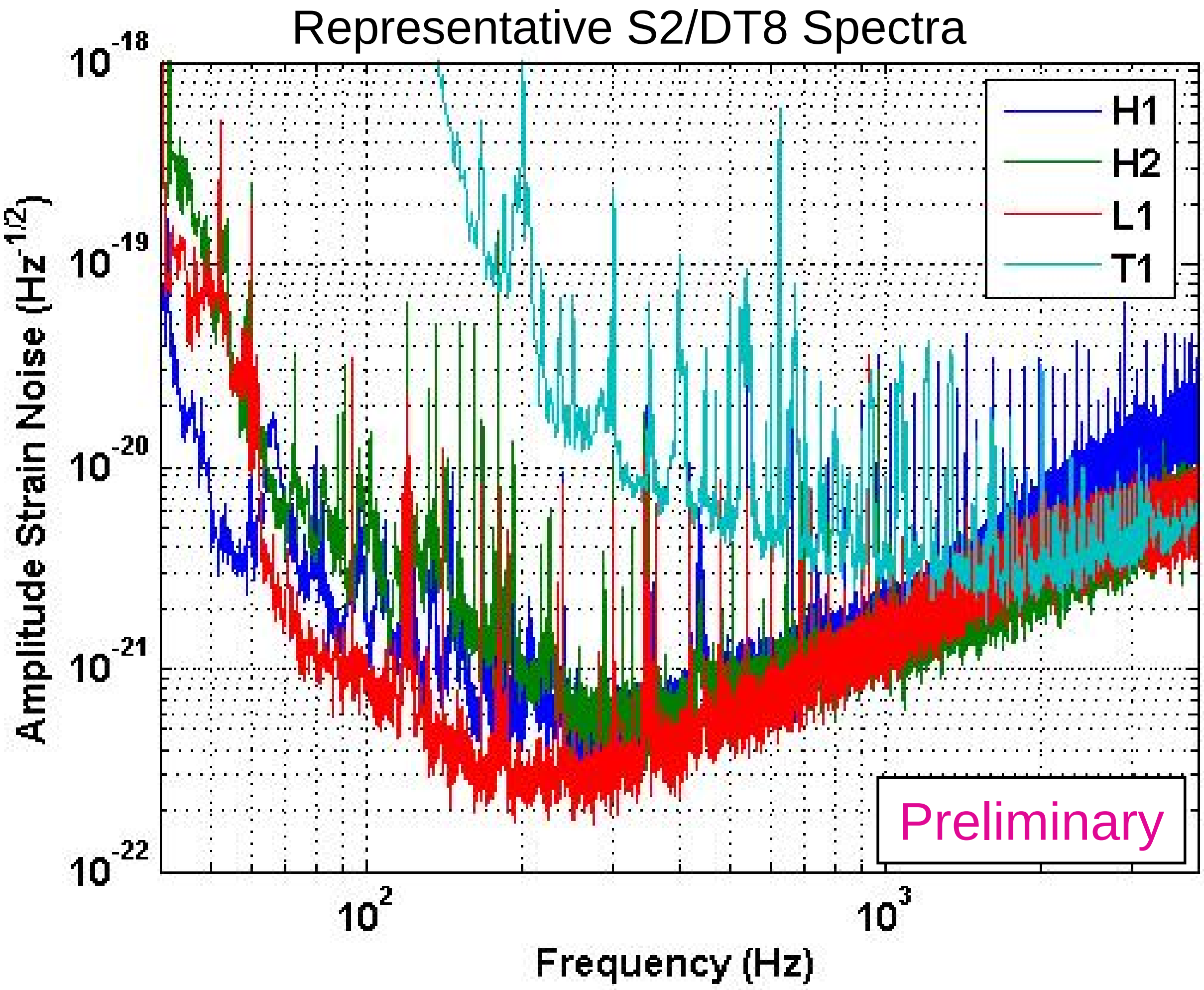
- » IFOs identical except for alignment
- » Represent each by typical efficiency curve
- » Hit with linearly polarized GWB with random sky position, polarization

Conclusion:

- » Expect up to ~50% loss of amplitude sensitivity. Accept as “cost of doing business”.



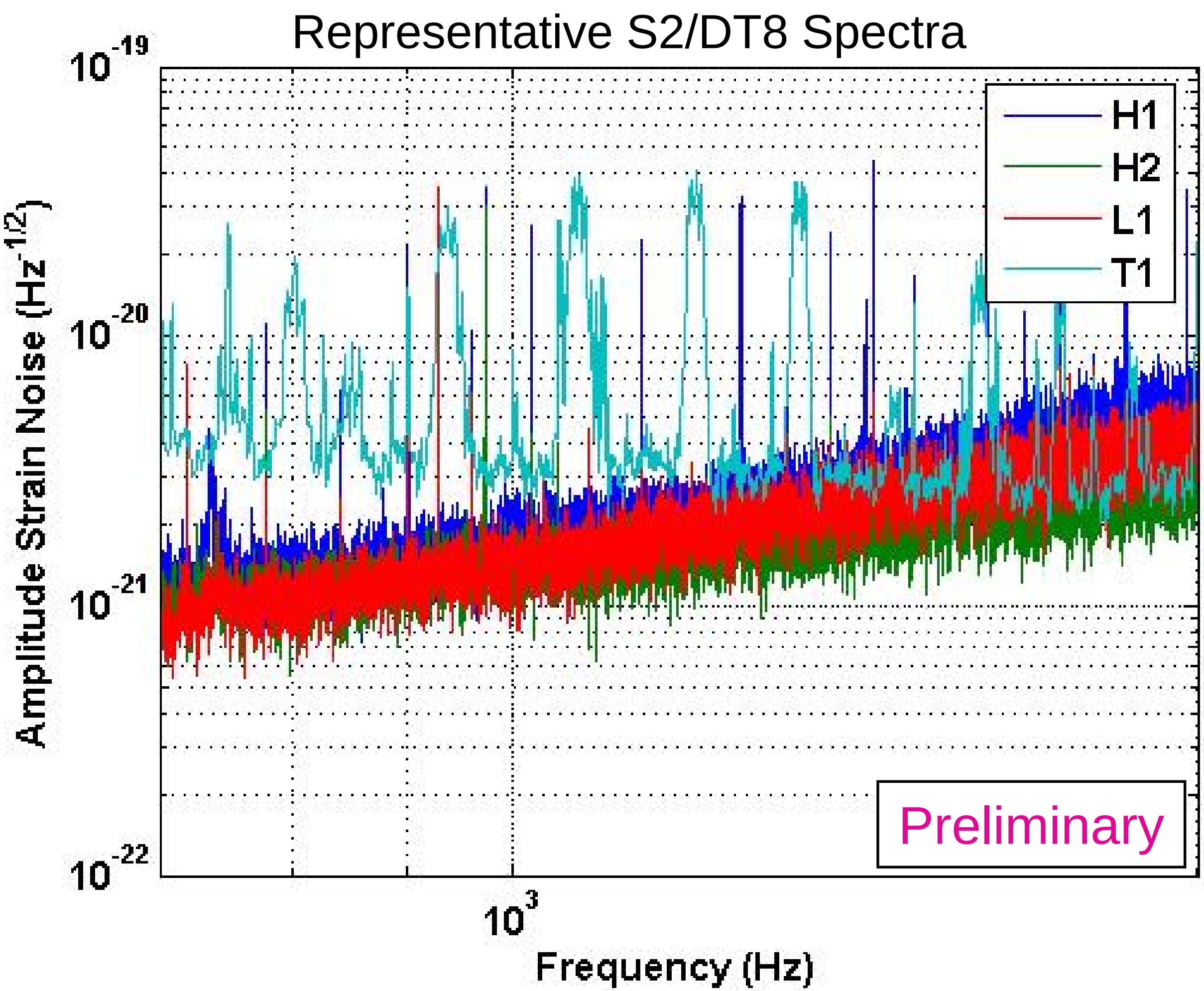
S2/DT8 Noise Spectra



Best *joint* sensitivity near minimum of noise envelope

Focus on [700,2000]Hz (ms scale signals)

S2/DT8 Noise Spectra



Best *joint* sensitivity near minimum of noise envelope

Focus on [700,2000]Hz (ms scale signals)

Near 700Hz: expect sensitivity limited by TAMA

Near 2000Hz: expect similar sensitivities

S2/DT8 Duty Cycles

H1	74%	1040hr
H2	58%	818hr
L1	37%	523hr
T1	81%	1150hr

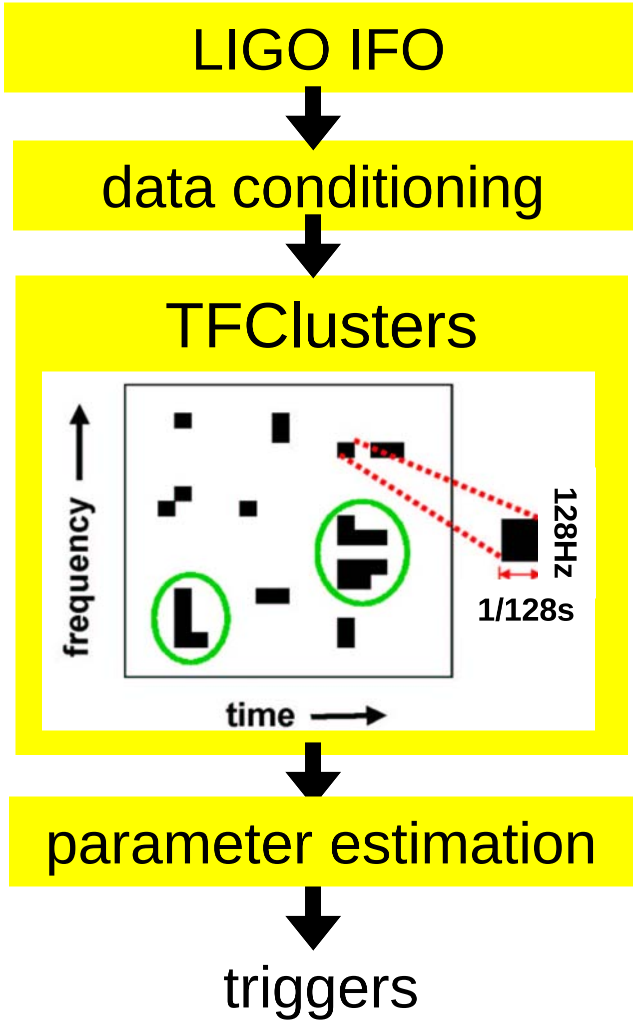
H1-H2-L1-T1	18%	250hr
H1-H2-L1	4%	62hr
H1-H2-T1	23%	325hr
total	45%	637hr

- LIGO-TAMA has *double* the total usable data set of LIGO alone
  - » Better chance of "getting lucky" in a search
  - » Cut rate upper limits in half
- Response: Analyze all H1-H2-(L1 or T1) data
  - » H1-L1-T1, H2-L1-T1: small amount of data, much higher false rate. Ignore.

LIGO: TFClusters

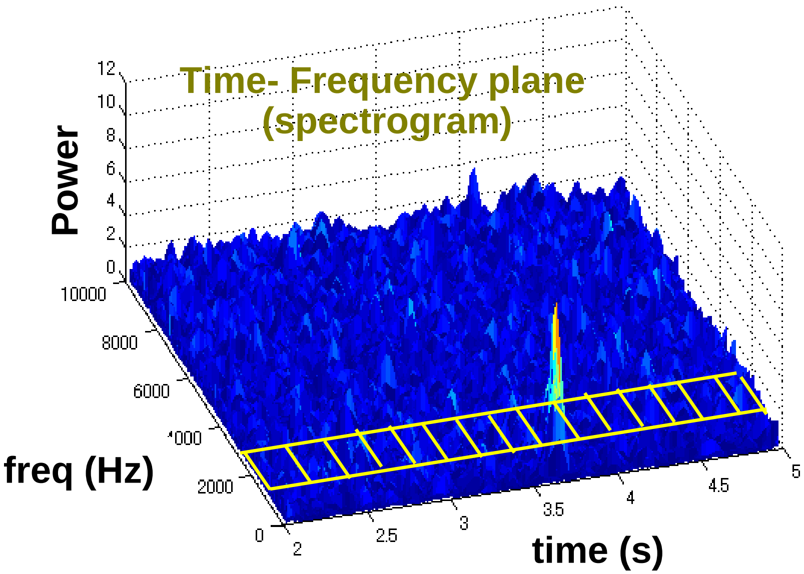
- Prefiltering with high-pass, linear-predictor error filters.
- Construct time-frequency spectrogram, trigger on clusters of pixels which are "loud" compared to average noise level.
- Triggers characterized by central time, duration, frequency, bandwidth, SNR
  - » Keep only triggers overlapping [700,2000]Hz.

Sylvestre, PRD *66* 102004 (2002)



TAMA: Excess Power

- Prefiltering for line removal.
- Construct spectrogram, normalize by background, sum over fixed set of frequency bins at each time step. Trigger if SNR>3.
- Combine contiguous segments above threshold into single trigger.
- Triggers have central time, duration, SNR. No frequency info.

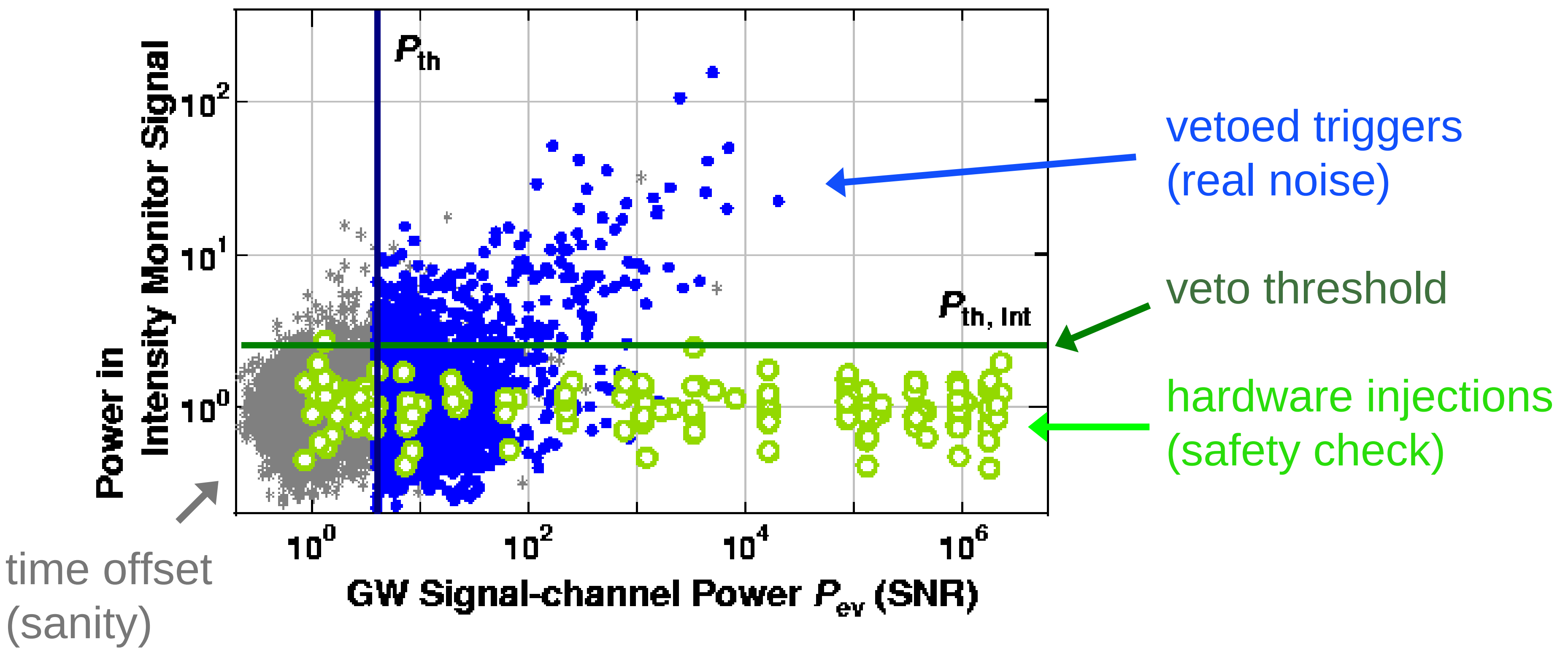


Anderson, Brady, Creighton, and Flanagan, PRD *63* 042003 (2001)

Ando *et al* gr-qc/0411027

TAMA: Intensity Veto

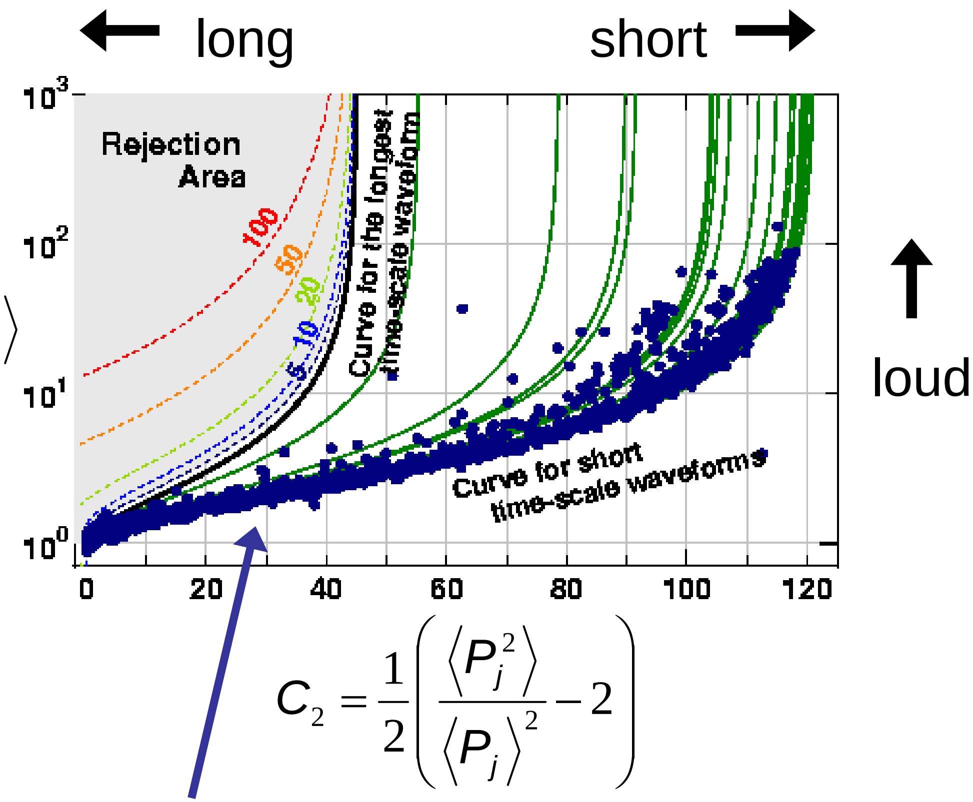
- Glitches in light intensity in TAMA power recycling cavity seen to be associated with event triggers.
  - » Remove ("veto") event triggers when simultaneous glitch in recycling cavity.



TAMA: Time-Scale Veto

- Distinguish GWBs from noise glitches by their time-scale:
  - » GW from gravitational core collapse < 100 msec,
  - » Noise caused by IFO instability > a few sec
- Compare averaged noise power (C_1) to second-order moment variability (C_2)
  - » Guide with simulations

$$C_1 = \langle P_j \rangle$$



$$C_2 = \frac{1}{2}\left(\frac{\langle P_j^2 \rangle}{\langle P_j \rangle^2} - 2\right)$$

simulations (safety check)

Coincidence & False Alarms

- Simulations tell us that we can determine arrival time of short signals to < 10ms.
- Measured arrival time differences for real signals will be dominated by light travel time between detectors:
  - » LHO – LLO < 10 ms
  - » LHO – TAMA < 25ms
  - » LLO – TAMA < 33ms
- Coincidence: Require events to be seen in detectors simultaneously within light travel time + ~10ms safety margin.
- False alarms rates from time-shifts.
  - » LIGO-only 3X search typically tune for ~10^{-6}Hz false alarm rate.
  - » LIGO-TAMA 4X false rate ~10^{-9}Hz with similar thresholds.

Waveform Consistency

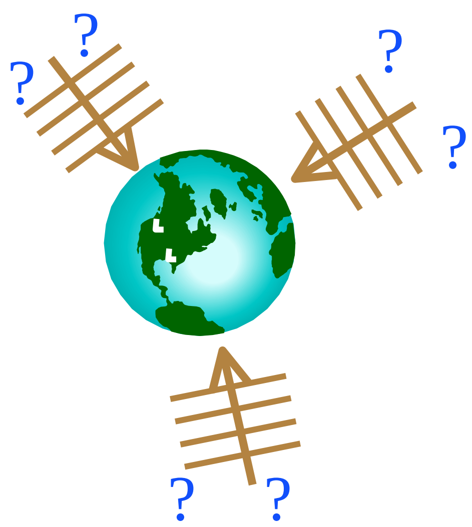
» Test consistency of waveform as seen by different detectors.

» Require cross-correlation of normalized data from pairs of detectors exceed threshold:

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

("Pearson r-statistic")

» Strong reduction of false alarm rate (~99%) with no loss of efficiency



» Evaluate r over different physical time-lags (+/-10ms)

» Evaluate r over range of potential signal durations (<100ms)

Cadonati CQG *21* S1695 (2004)

Simulations

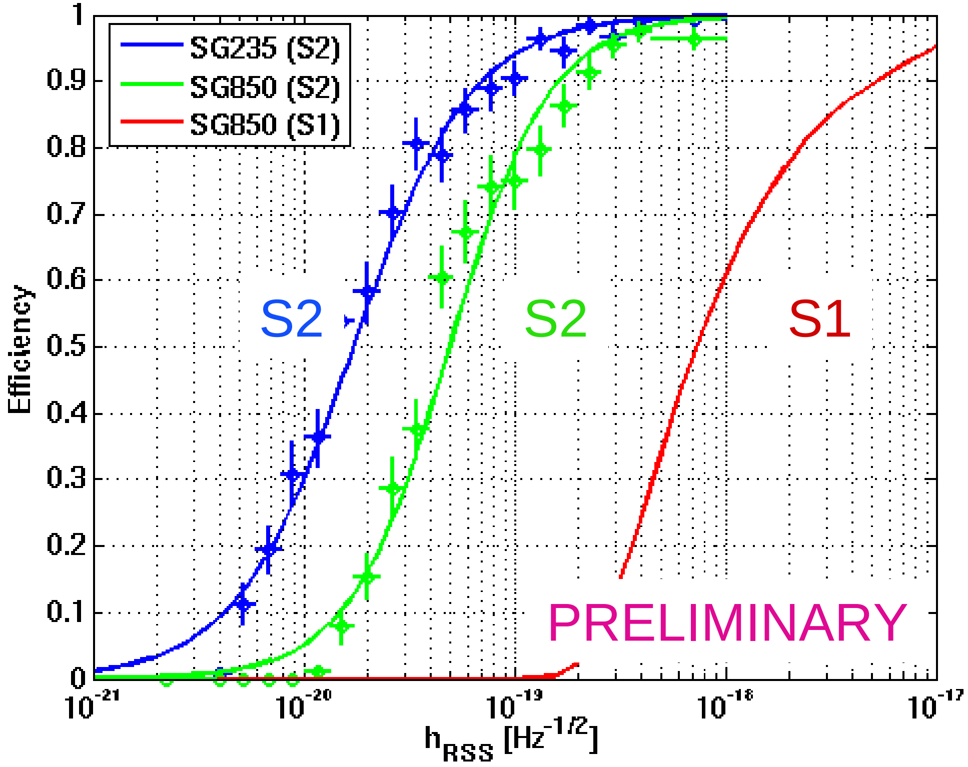
- Use: Need to tune search codes, set LIGO-TAMA coincidence windows, estimate network sensitivity.

- Procedure: Generate set of data files (frames) containing simulated GWBs, including sky position and polarization, for coherent addition to data streams.
  - » *Exchange of actual data files is very effective at avoiding confusion over definitions of signals, etc.*
  - » Use simple Gaussian-modulated sinusoids (narrowband) for this first analysis.
    - – Isotropic sky distribution, random linear polarization
    - – Data includes effects of time delay, antenna response, signal polarization.

Efficiency Examples

Example: sine-Gaussians (LIGO efficiency only) with "WaveBurst" ETG

Expect LIGO-TAMA sensitivity in the same ballpark as LIGO-only.



WaveBurst: Klimenko et al. gr-qc/0407025

Current Status

- Full data set has been analysed and final upper limits have been calculated.
  - » Currently doing double- (triple-,…) checks of analysis codes
  - » In process of approving results for release at GWDAW-9 (December).
- In the meantime…

Expected Upper Limits

Network	T (days)	$R_{90\%}$(1/day)
H1-H2-L1-T1	7.0	0.35
H1-H2-T1	10.9	0.22
H1-H2-L1	2.1	1.2
Combined LIGO-TAMA	20.0	0.12

Assuming no detections, low background, 90% rate upper limit from Feldman-Cousins[0] procedure is

$$R = 2.44 / T$$

Other Searches:

LIGO[1] alone: ~0.27/day

IGEC[2] (T~1yr): ~1.4/yr

[0] Feldman & Cousins, PRD *57* 3873 (1998)

[1] Expected

[2] Astone et al PRD *68* 022001 (2003)

Bursts Search Summary

- TAMA-LIGO joint search for GWBs in S2 is in final stages.
  - » High-frequency search complementary to LIGO-only search at low frequencies.
  - » Hope to present results at GWDAW-9 (December in Annecy).
- Saw both costs and benefits to adding extra detector
  - » Reduction of false alarm rate
  - » Increase in observation time
  - » Some loss of sensitivity
  - » Technical hurdles – must work harder even for straightforward search.
  - » Think benefits outweigh costs.
- Future searches?
  - » Exploring value of joint S3+ search with LIGO, TAMA, GEO representatives.
  - » Would like to implement, eg, Gursel-Tinto method for extracting sky direction & polarization.

The Near Term

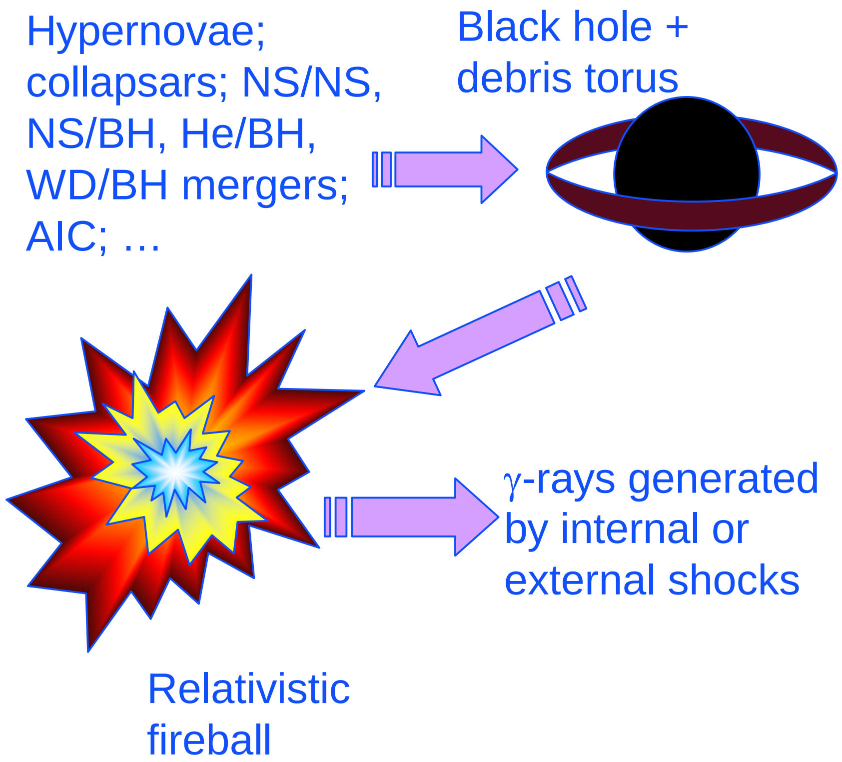
- LIGO commissioning continuing
  - » Hanford: H1 sensitivity continuing to improve since S3.
  - » Livingston: Installation of “HEPI” active seismic isolation system dramatically reducing effects of ground noise.
    - – L1 stayed in lock while train passed (!)
    - – Promises increased duty cycle in future runs
- TAMA: Currently working on noise reduction.
- Next observation runs:
  - » S4 February-March 2005 (one month), TAMA also operational
  - » S5 later in 2005 (~six months)
- Advanced LIGO approved by the National Science Board

Gravitational Waves from GRB 030329

Joint GRB 030329 Search

- LIGO and TAMA are also conducting a joint search for gravitational-wave emission by the nearby GRB 030329, which happened during S2/DT8.
- Goals:
  - » Detect or place upper limits on strength of GW emission by central engine of "nearby" Gamma-Ray Burst 030329.
  - » Exercise technique.
  - » Complementary to LIGO-only analysis using H1-H2 data.
    - – TAMA: Better alignment, slightly worse sensitivity below 1kHz.
- Key person:
  - » Szabi Marka (Columbia University)

GRBs & GWBs



GRB review: Meszaros, Ann. Rev. Astron. Astrophys. *40* (2002)
Slide by Finn.

- GRB 030329
  - Detected by HETE-2, Konus-Wind, Helicon/KoronasF
  - Especially close: z = 0.1685; d_L=880Mpc
  - Strong evidence for *supernova origin of long GRBs*.
  - H1, H2, T1 operating during, preceding burst (but not L1)
- Radiation from a broadband burst at this distance?
  - Assume flat spectrum to 1 KHz
  - $E_{GW} > 10^5 M_o$ for detection
- Exercise analysis

Analysis Methodology

- Cross-correlate h_{H1}, h_{T1} near GRB trigger time…
  - » Near: τ in [-120s,+60s]
- … and look for cross correlation exceeding threshold
  - » Signal correlated, noise uncorrelated
- Set threshold on cross-correlation for maximum false alarm probability of 0.1.

Slide by Finn.

$$c(\tau, \Delta t, T) = \int_{-T}^{+T} h_{H1}(t_0 + \tau + \Delta t)\, h_{T1}(t_0 + \tau)\, dt$$

Δt in [-5,+5] ms for timing uncertainties
T in [4,128] ms for short GW bursts
t_0 is trigger time

- *Methodology applicable to GW burst search associated with* any *externally generated trigger* (e.g., SN, neutrino burst, etc.)

For x-corr style analyses cf. L. Finn, S. Mohanty, J. Romano, Phys. Rev. D *60* 121101 (1999)
P. Astone *et al.*, Phys. Rev. D 66 102002 (2002): NAUTILUS & EXPLORER + 47 GRBs from BeppoSAX: $h_{rms} < 6.5\times10^{-19}$ at 95% confidence.

Current Status

- Marka uses same pipeline as for LIGO-only H1-H2 analysis
  - » No special TAMA treatment, except for data conditioning
  - » Same tuning procedures, etc.
- Preliminary results for H1-TAMA comparable to H1-H2
  - » similar efficiencies, false rates
- To be done:
  - » More comprehensive simulations
  - » Improved data conditioning and vetoes for TAMA data.

Joint Search for Galactic Neutron-Star Inspirals

Joint Inspiral Search

- LIGO and TAMA are also conducting a joint search for inspirals from galactic neutron-star binaries.

- Goals:
  - » Detection, or place upper limits on neutron star inspiral rate in the Milky Way.
  - » Exercise technique.

- Key people:
  - » Stephen Fairhurst (University of Wisconsin at Milwaukee)
  - » Hirotaka Takahashi (Osaka University, Niigata University)

Inspiral Analysis Strategy

- LIGO S2 inspiral analysis only uses data from time when IFOs at both sites (LLO and LHO) are "on".
  - » LIGO's one-site only data is not used (~700hr in S2).
- Both LIGO and TAMA sensitive to binary NS inspirals in the Milky Way.
- Analyze LIGO single-site data in coincidence with TAMA.

Analysis Procedure

- LIGO and TAMA data analyzed separately
  - » Use existing inspiral analysis infrastructure
- Inspiral triggers (mass, SNR, χ^2, time) exchanged and searched for coincidence.
  - » Currently tuning coincidence parameters (mass and time) with software injections.
  - » Time-lag analysis gives false rate.
- Efficiencies measured using signal injections.
- Detection / upper limit
  - » Expect rate upper limit comparable to LIGO S2 result.