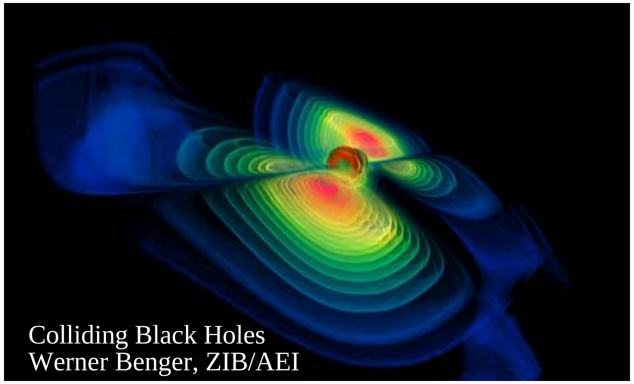
Upper Limits from LIGO and TAMA on Gravitational-Wave Bursts

Patrick Sutton

LIGO Laboratory, Caltech

for the

LIGO and TAMA Collaborations



Colliding Black Holes
Werner Benger, ZIB/AEI

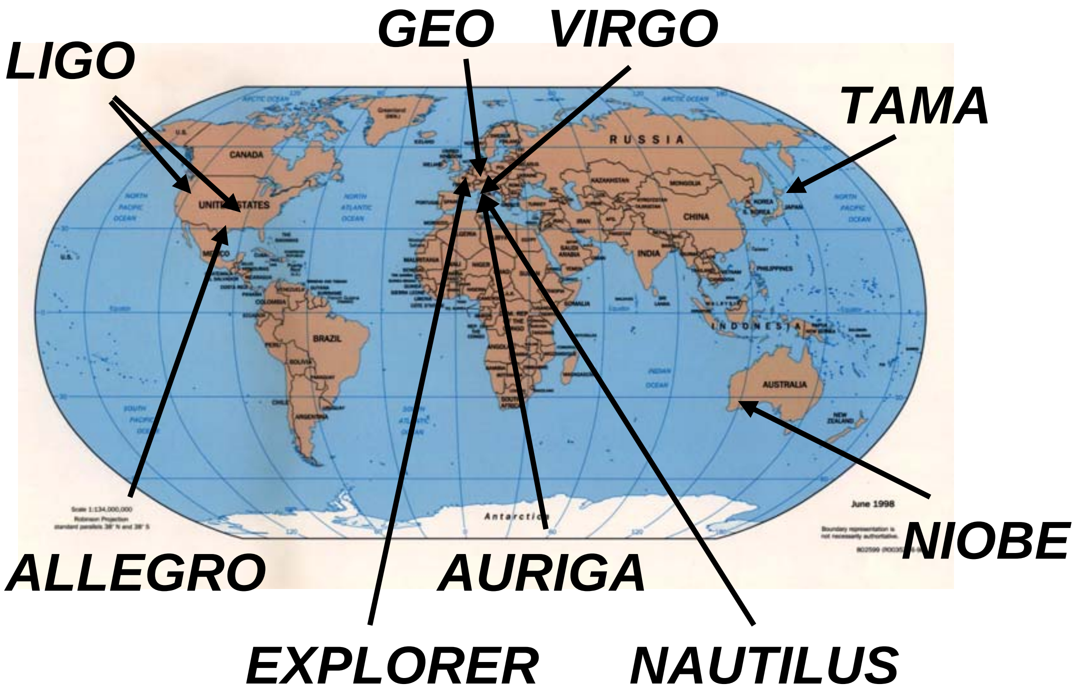
LIGO-G040527-00-Z

Outline

- Collaborative Searches
- LIGO-TAMA Network
- Analysis Overview
- Upper Limits & Outlook

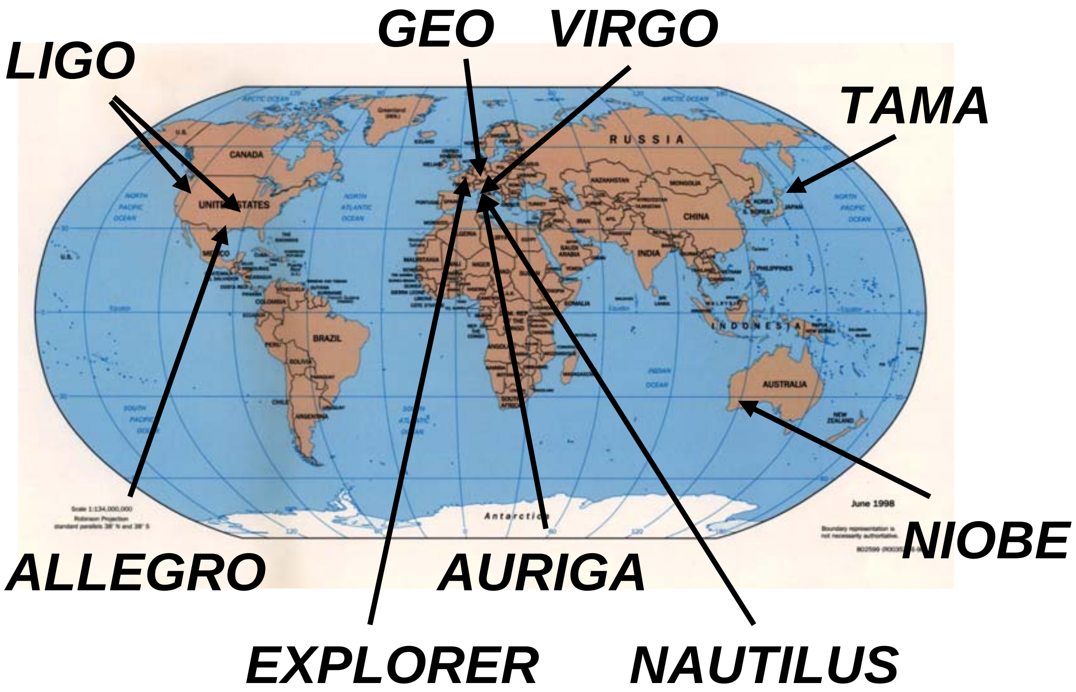
Collaborative Searches

- 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.
  - » 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

- Many of these benefits and costs are evident in the LIGO-TAMA joint bursts search.

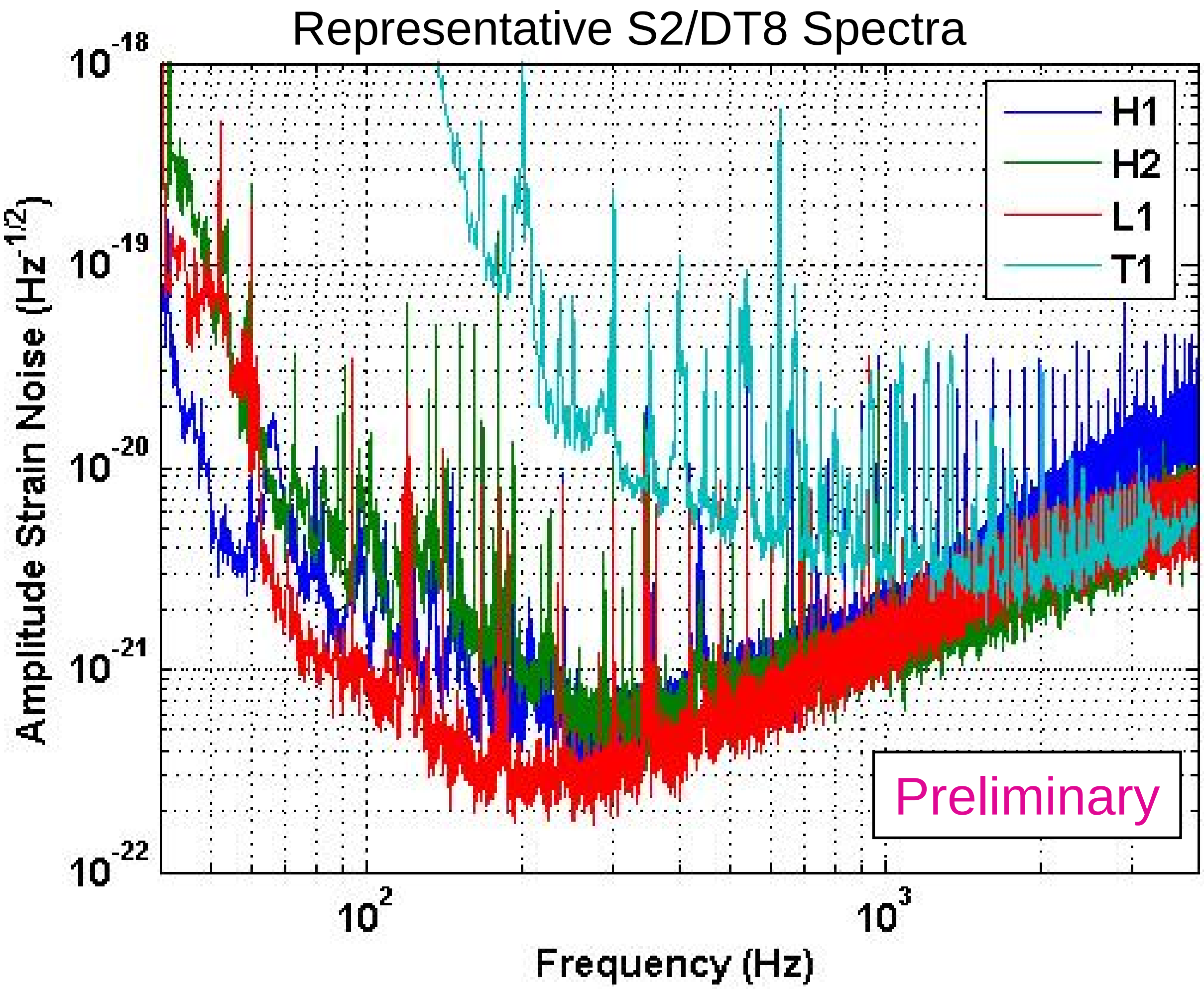
LIGO-TAMA Timeline

- GWDAW 7, 2002: LIGO & TAMA sign agreement for joint analysis of data for gravitational-wave transients.

- Summer 2003: Began joint bursts search using Science Run 2 / Data Taking Run 8 data (Feb – Apr 2003).
  - » Trigger-based coincidence analysis.
  - » Look for generic short-duration GWBs at high frequencies (~1kHz).
    - – Complementary to TAMA-only DT8 search & LIGO-only S2 search in 100-1100Hz

- Fall 2003: Inspiral & GRB 030329 analyses started (in progress).
  - » Inspiral session: Takahashi & Fairhurst

LIGO-TAMA Network

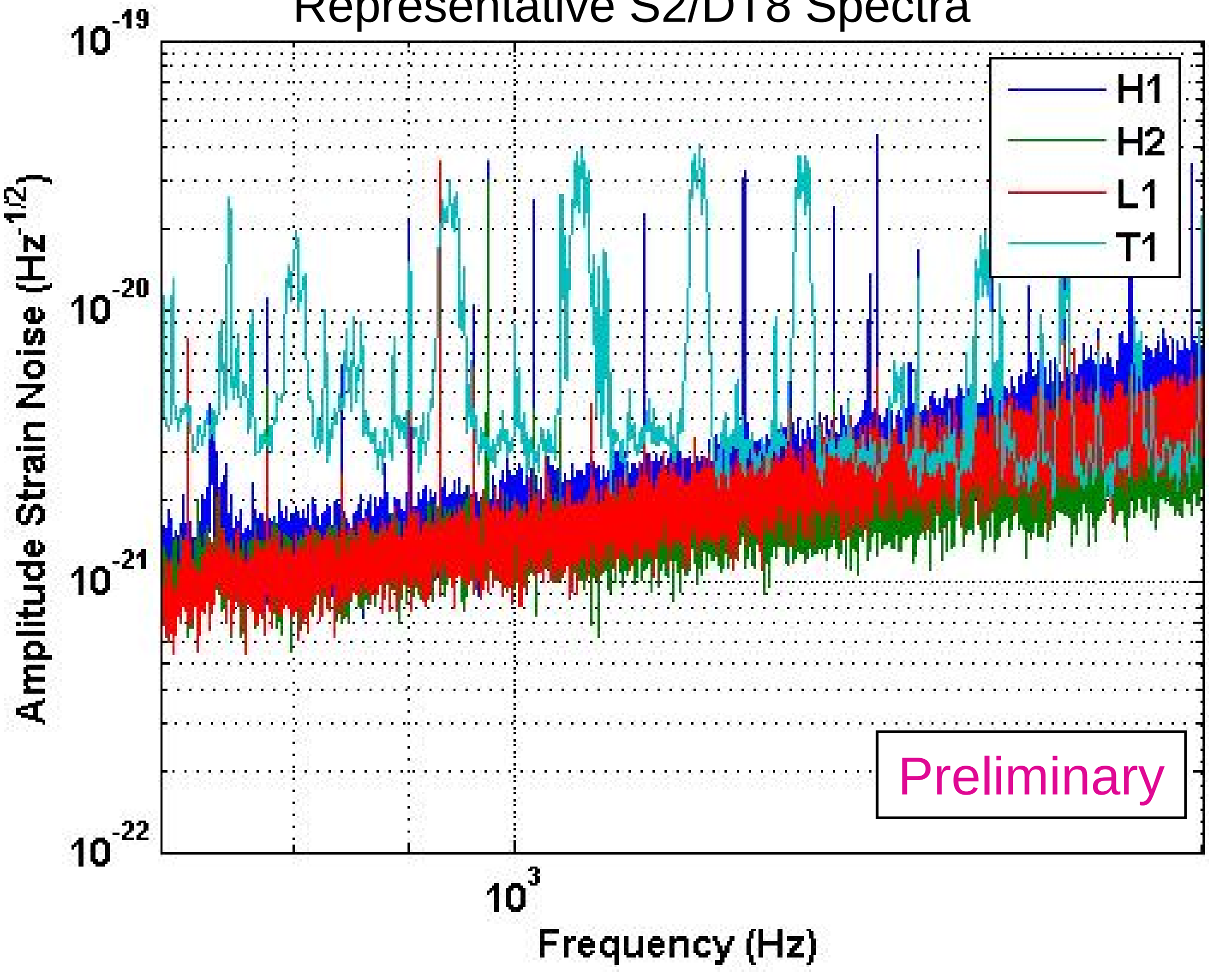


Best *joint* sensitivity near minimum of noise envelope

Focus on [700,2000]Hz

LIGO-TAMA Network

Representative S2/DT8 Spectra



Best *joint* sensitivity near minimum of noise envelope

Focus on [700,2000]Hz

Near 700Hz: expect sensitivity limited by TAMA

Near 2000Hz: expect similar sensitivities

S2/DT8 Duty Cycles

- Data sets analyzed (3+ IFOs):

H1-H2-L1-T1	15%	215hr
H1-H2-L1-**n**T1	3%	46hr
H1-H2-**n**L1-T1	23%	324hr
total	41%	585hr

(after data-quality cuts)

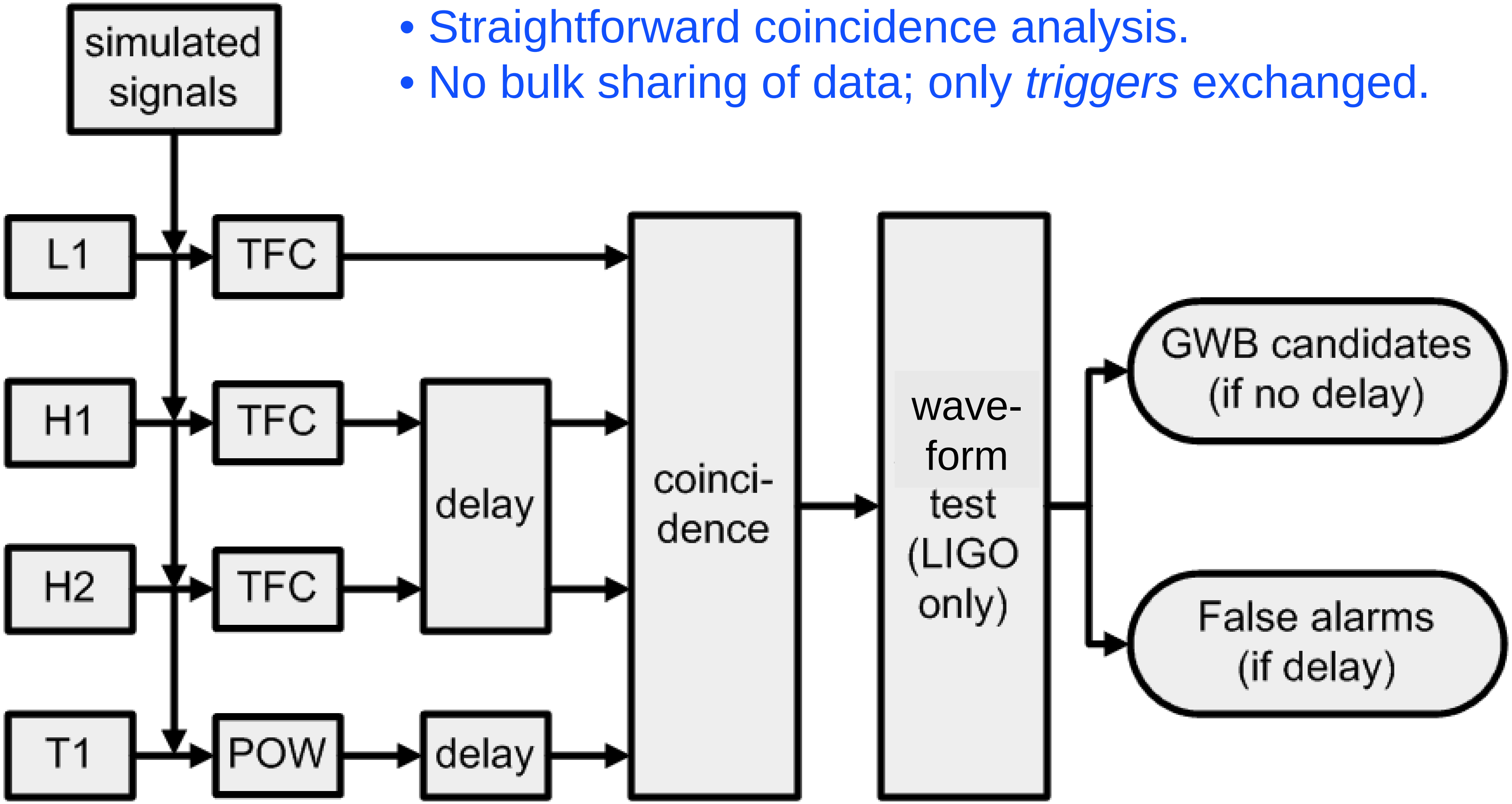
nT1 ≡ T1 not operating

nL1 ≡ L1 not operating

- 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

Analysis Procedure

- Straightforward coincidence analysis.
- No bulk sharing of data; only *triggers* exchanged.



Trigger Generation

- LIGO: TFClusters+BurstDSO algorithm:
  - » 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.
  - » Peak time, duration, frequency, bandwidth, SNR; keep only triggers overlapping [700,2000]Hz.
  - » Sylvestre, PRD **66** 102004 (2002).

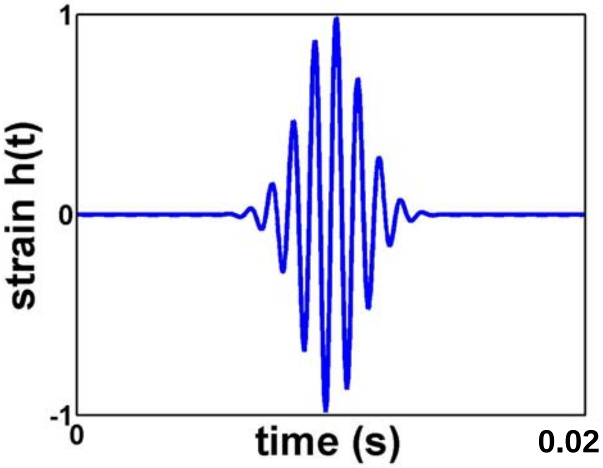
- TAMA: Excess-Power algorithm:
  - » Prefiltering for line removal.
  - » Construct spectrogram, normalize by background, sum over fixed set of frequency bins in [230, 2500]Hz at each time step. Trigger if SNR>4.
  - » Combine contiguous segments above threshold into single trigger with peak time time, duration, SNR.
  - » Vetoes:
    - – glitches in light intensity in power recycling cavity
    - – time-scale veto to distinguish short-duration GWBs from detector nonstationarity
  - » Ando *et al.*, gr-qc/0411027, Anderson, *et al.*, PRD **63** 042003 (2001)

Coincidence & False Rate

- Require candidate GWBs to be seen in all detectors simultaneously.
  - Timing accuracy of ~1ms for short signals (from simulations).
  - Use coincidence window = light travel time + ~10ms safety margin.
- R-Statistic: LIGO coincidences tested for waveform consistency.
  - Cross-correlation test (Cadonati, CQG **21** S1695 (2004)).
  - Strong reduction of false alarm rate (>90%) with no loss of efficiency
- Estimate false alarm rate using unphysical time shifts.
  - LIGO 2-site network = 47 lags in (-115s,+115s)
  - LIGO-TAMA 3-site network = 47^2 = 2209 lags in (-115s,+115s).

Simulations

- Inject simulated GWBs to tune analysis and estimate network sensitivity.
  - » Procedure: Simulated h(t) signals written to frame files, added to raw data streams. Include effects of antenna response, sky position, and polarization.
  - » Signals: Use Gaussian-modulated sinusoids for this first analysis.
    - – $Q = 8.9$, $f_0 = \{700, 849, 1053, 1304, 1615, 2000\}$Hz
    - – Isotropic sky distribution, random linear polarization



Tuning

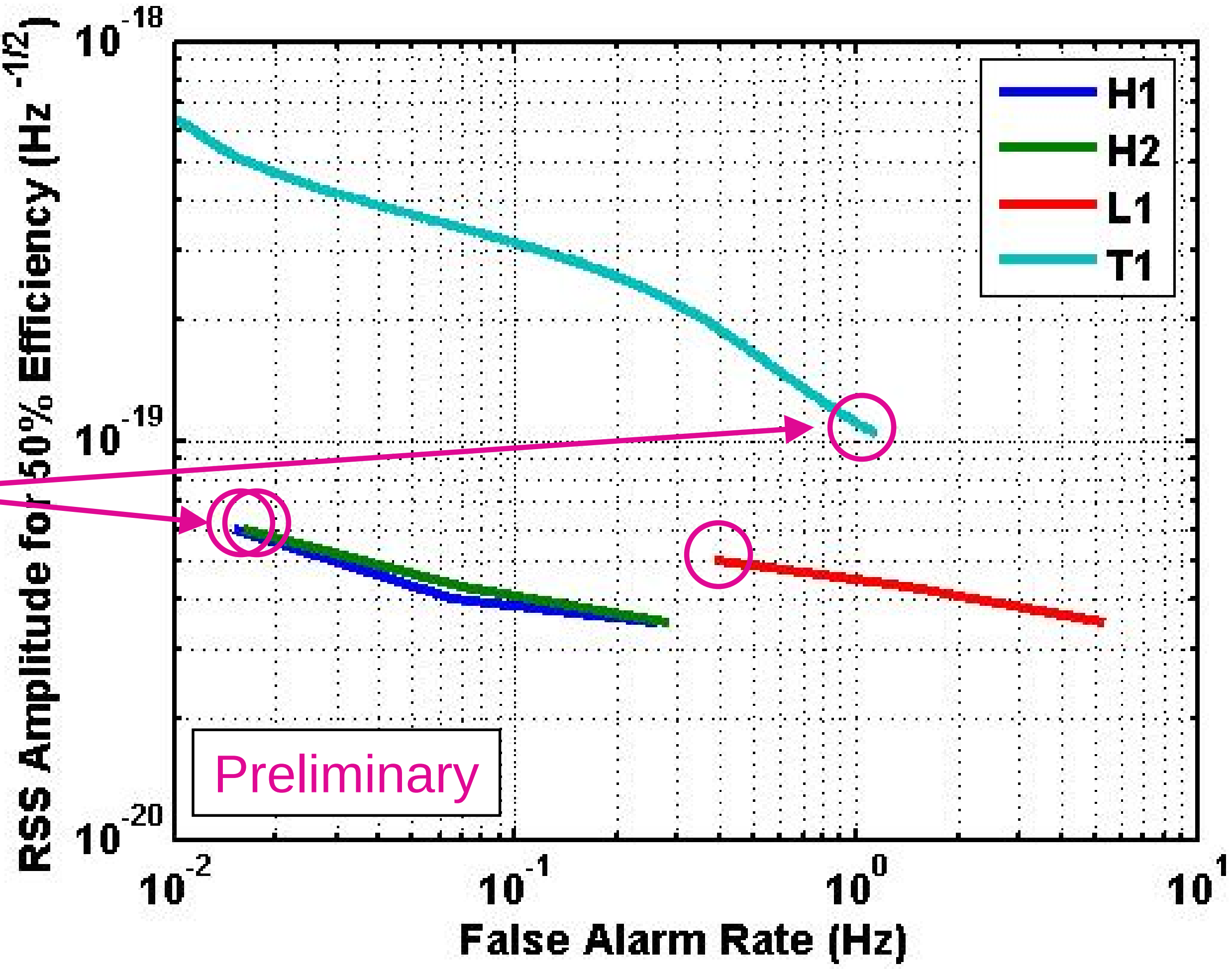
- Tune for best efficiency at each false rate:
  - » Select TFClusters, Power thresholds to match efficiencies across detectors
    - – Similar in spirit to IGEC procedure (Astone *et al.*, PRD **68** 022001 (2003))
  - » Select r-statistic threshold to ensure false rate for << 1 event over livetime (efficiencies not affected).

- Blind analysis.
  - » Set all thresholds, etc. by looking only at time-shifted data (no GWBs) or with 10% subset of data (“playground”) which is not used for upper limits

Efficiency vs False Rate

Y-axis: sine-Gaussian amplitude at which detection probability is 0.5
(with frequency, sky & polarization averaging)

Chosen single-IFO operating points

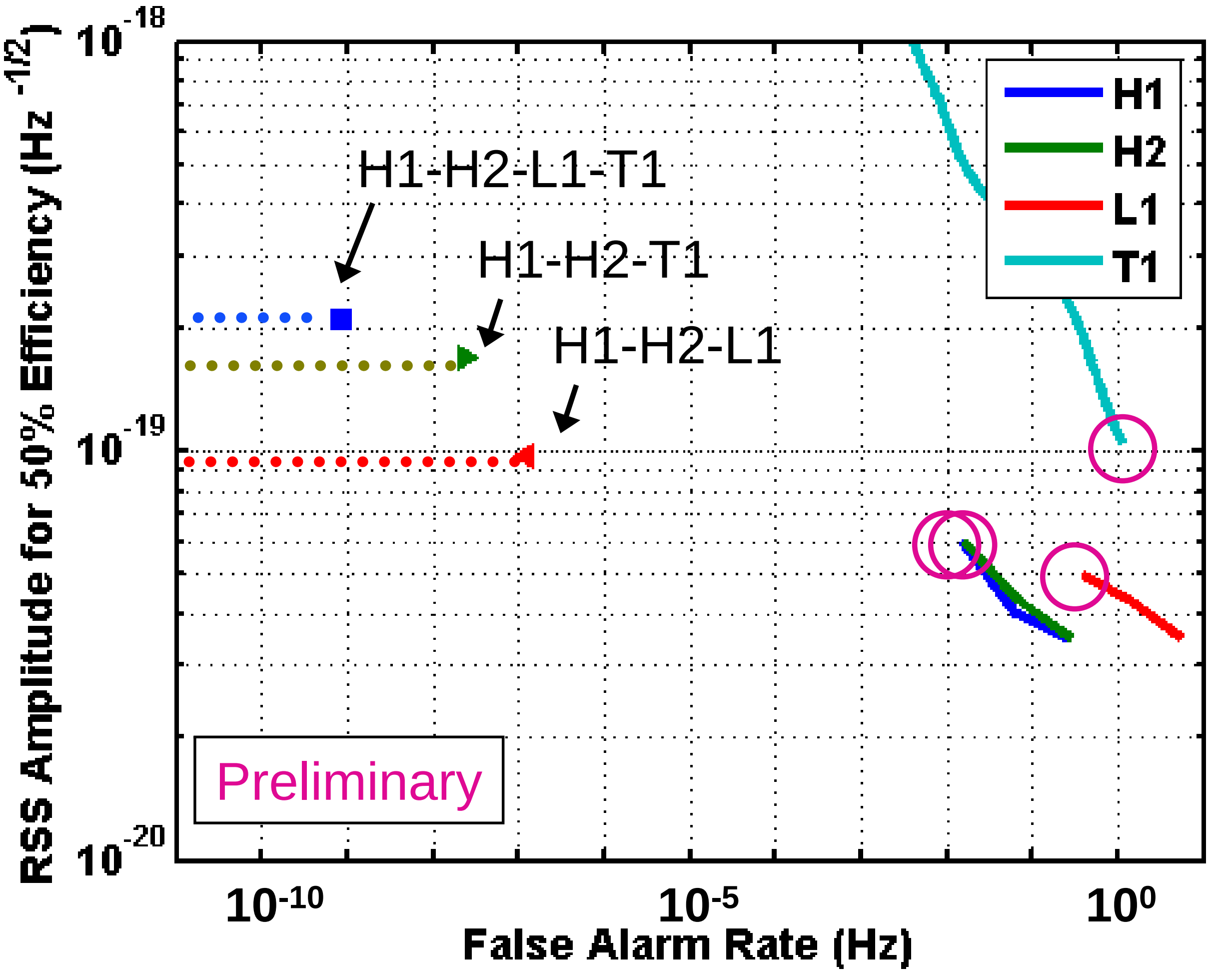


Efficiency vs False Rate

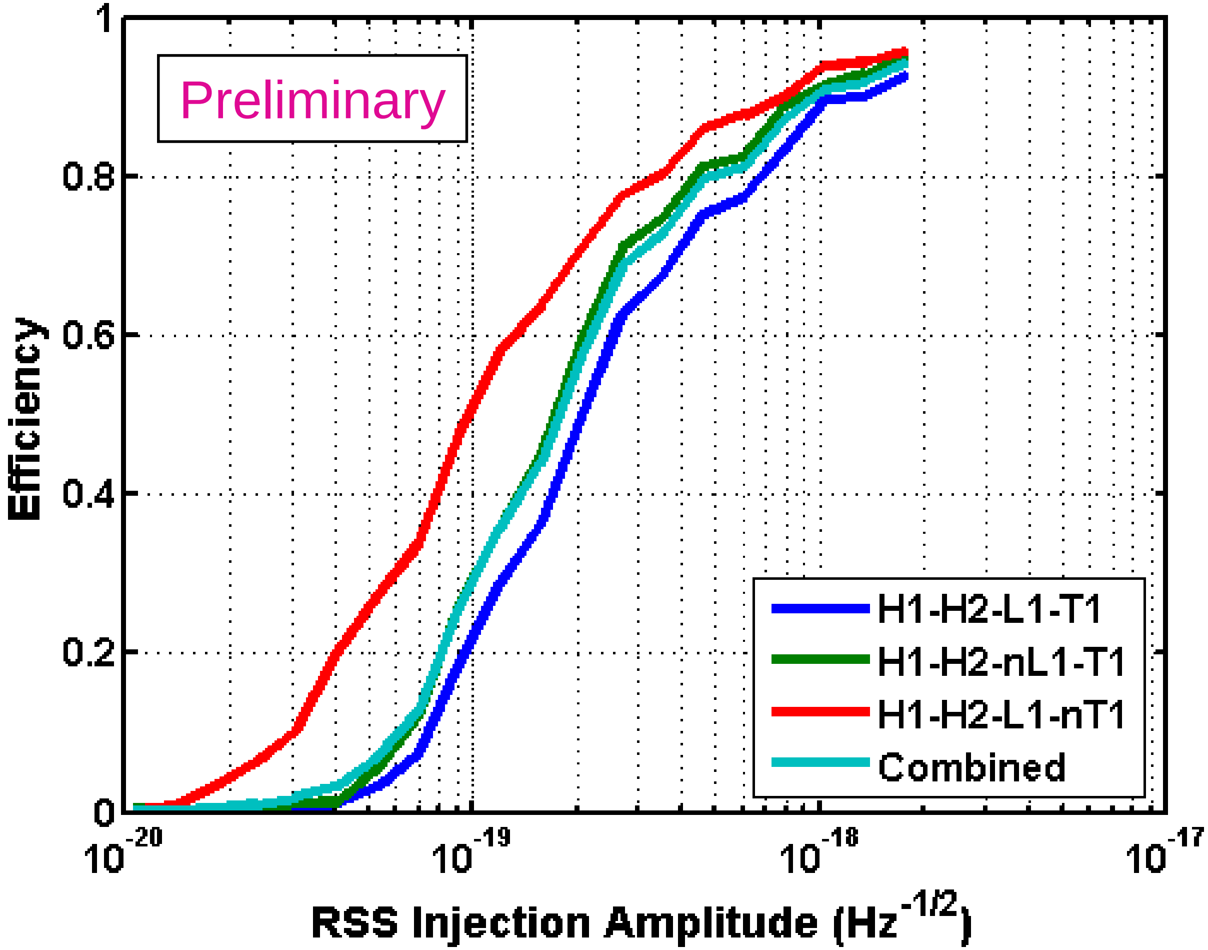
LIGO-TAMA network performance.

Plotted false rates are upper limits (no surviving coincidences from time lags).

O(1/century) false rates achievable.



Network Efficiency



From sine-Gaussian simulations

(with sky & polarization averaging)

Different network combinations have similar efficiency (factor ~2 in 50% point).

Full Data Set Results

Preliminary

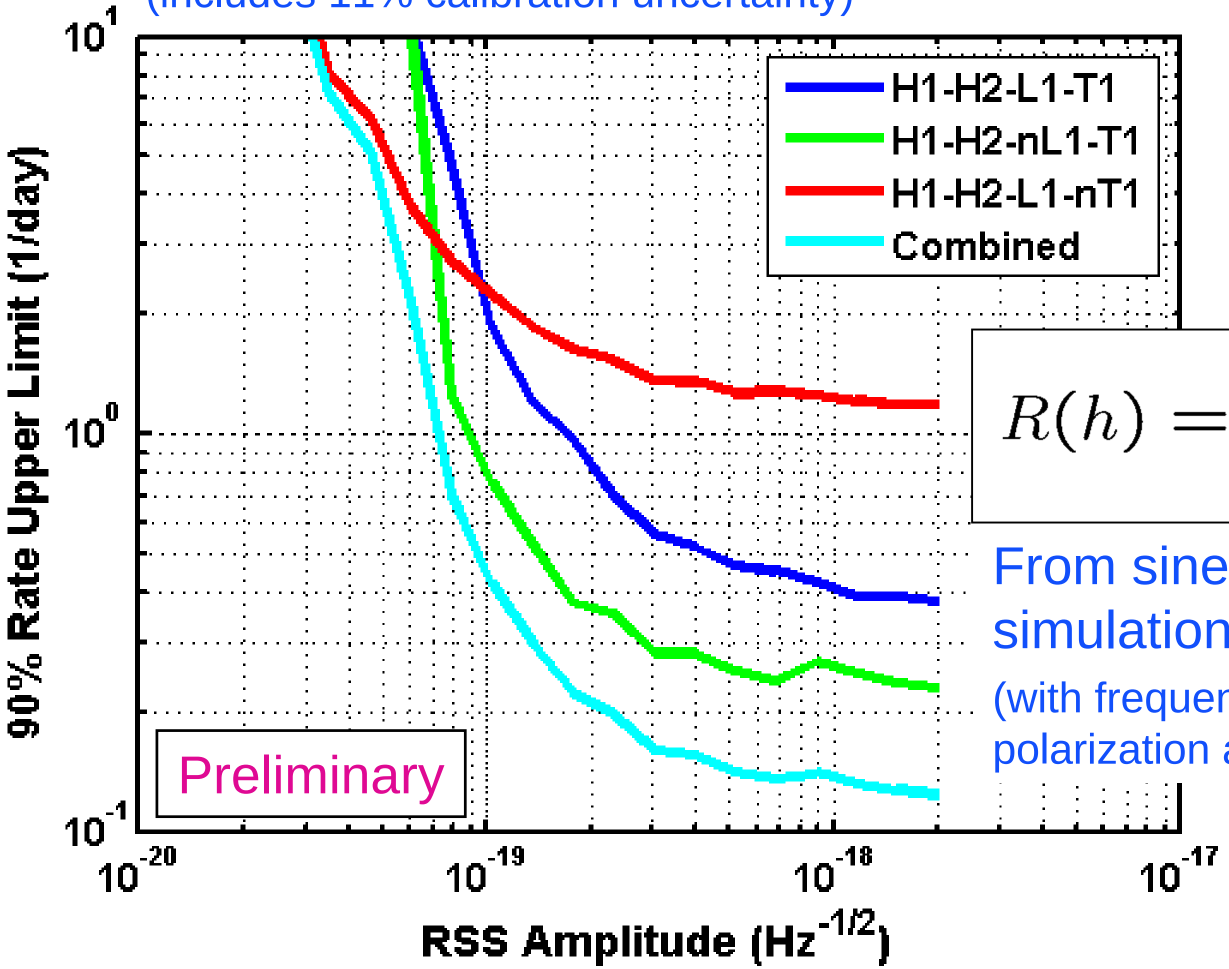
- No surviving coincidences (no GWB candidates).

Network	T (day)	N_{bck}	$R_{90\%}$(1/day)*	$h_{50\%}$ ($Hz^{-1/2}$)
H1-H2-L1-T1	6.9	<5e-4	0.35	2.1×10^{-19}
H1-H2-**n**L1-T1	10.7	<0.023	0.23	1.7×10^{-19}
H1-H2-L1-**n**T1	2.1	<0.023	1.14	0.97×10^{-19}
Combined LIGO-TAMA	19.7	<0.046	0.12	1.8×10^{-19}

*Set upper limits using Feldman & Cousins, PRD **57** 3873 (1998), with N_{bck}=0 (conservative).

R vs h Upper Limits

(includes 11% calibration uncertainty)



$$R(h) = \frac{R_{90\%}}{\epsilon(h)}$$

From sine-Gaussian simulations

(with frequency, sky & polarization averaging)

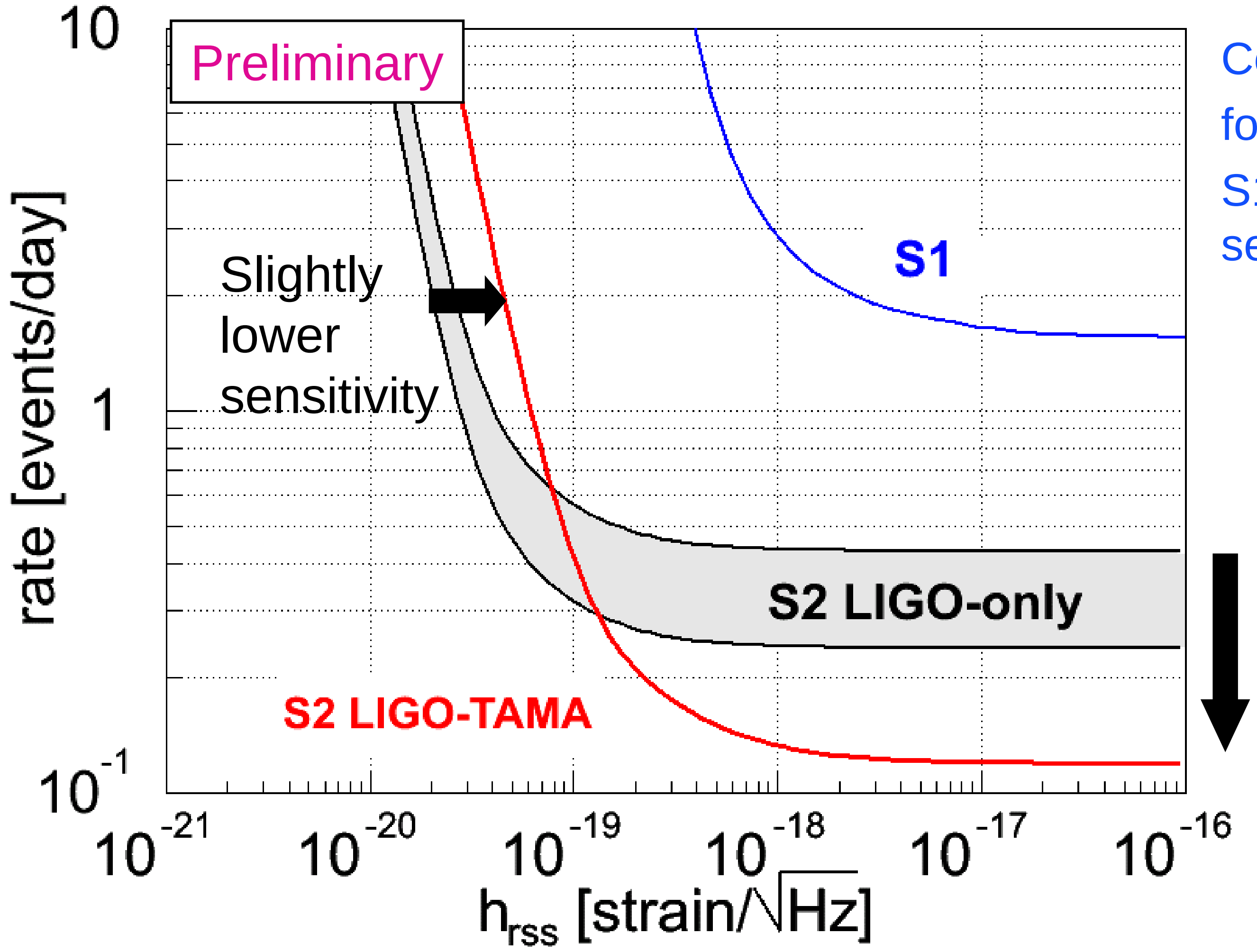
Upper Limit Comparisons

Preliminary

Network	T (day)	$R_{90\%}$(1/day)	band (Hz)
LIGO-TAMA	19.7	0.12	700-2000
LIGO-only	10.0	0.24-0.43	100-1100
IGEC*	707.9	0.0041	694-930

*5-bar search from 1997-2000, Astone *et al*., PRD **68** 022001 (2003). Sensitivity restricted to signals with significant power at resonant frequencies of bars (lowest 694Hz, highest 930Hz).

Upper Limit Comparisons



Slightly lower sensitivity

Compare results for 849Hz SG to S1, S2 LIGO-only searches.

Increased observation time

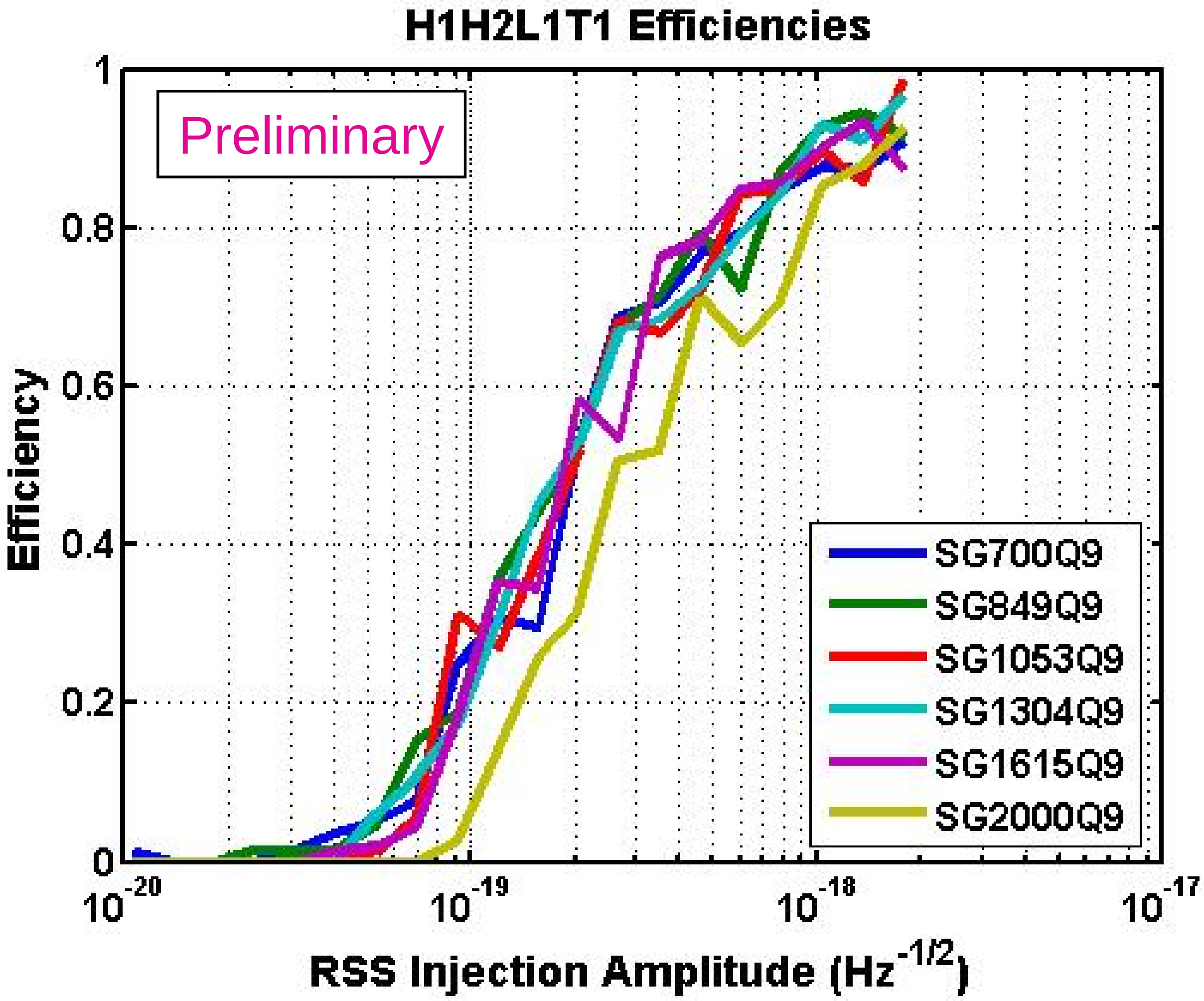
Bursts Search Summary

- TAMA & LIGO have conducted the first 4-IFO search for GWBs.
  - High-frequency search complementary to LIGO-only search at low frequencies.
- No GWB candidates were found.
  - Rate upper limit of 0.12/day.
  - $h_{rss}^{50\%} = 1.8\text{x}10^{-19}\text{Hz}^{-1/2}$ averaged over networks, analysis band.
  - Paper in preparation.

Preliminary

- Saw both costs and benefits from joint analysis
  - Reduction of false alarm rate (4X)
  - Increase in observation time (3X & 4X)
  - Sensitivity restricted to common (high-frequency) band.
  - Technical hurdles – must work harder even for straightforward search.
  - Think benefits are worth effort.
- Exploring possible joint S3+ search with LIGO, TAMA, GEO.
  - Examining scientific value of joint search.
  - Considering ways to improve on S2/DT8 analysis to take fuller advantage of network.

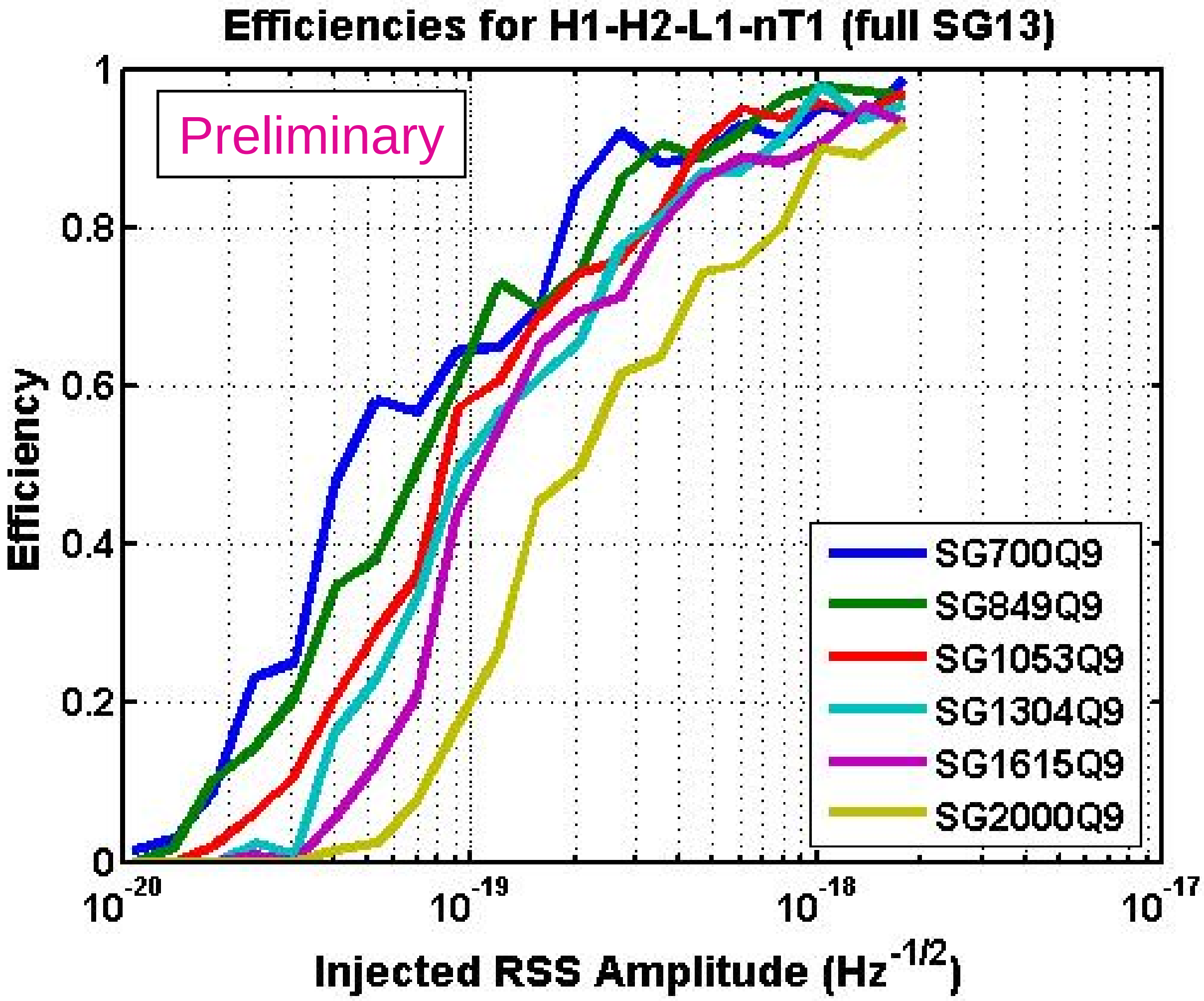
Network Efficiency, by f_0



Efficiency of 4X detection, by central frequency of signal

Sensitivity ~constant across band.

Network Efficiency, by f_0



Efficiency of LIGO 3X detection, by central frequency of signal

Improvement at lower frequencies – TAMA limits sensitivity there.