Gravitational Wave Observations with Interferometers: Results and Prospects

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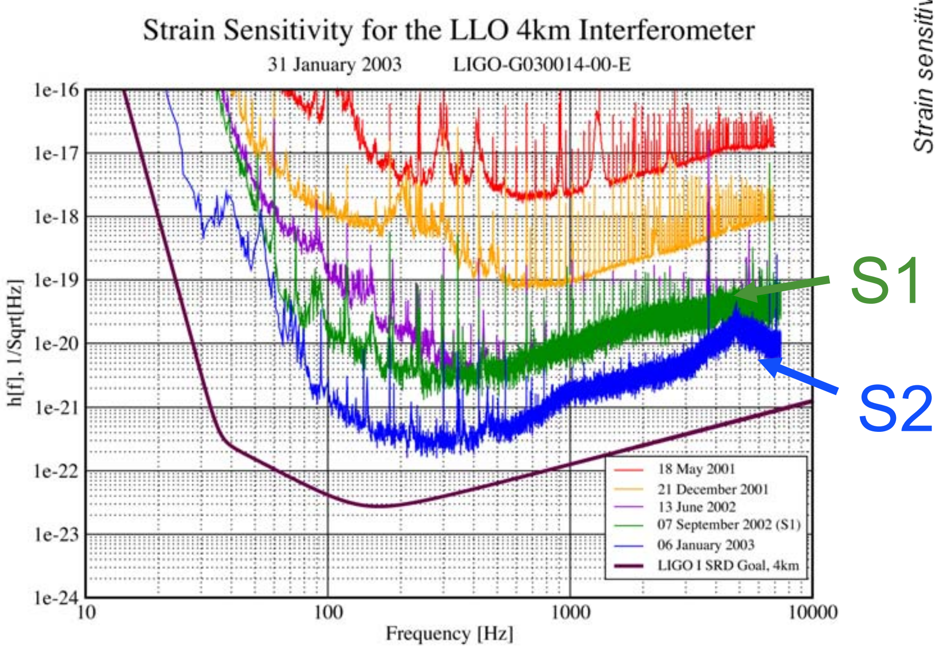
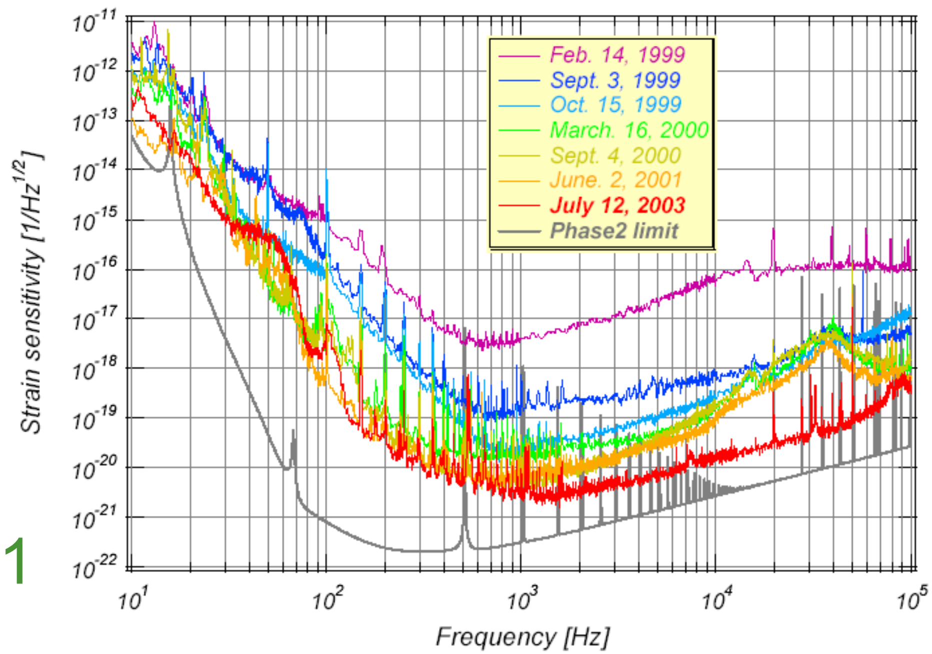
GW interferometers

- TAMA
  - » First observations Sept 1999
  - » >80% duty cycle over DT8/S2 run (Feb-Apr 2003)
- GEO600
  - » Advanced features—fused silica suspensions, signal recycling, etc.
  - » Stable lock in signal recycled mode – preparing for first observations in this mode
- Virgo
  - » First arm locked Oct 2003
- LIGO
  - » First full interferometer lock Oct 2000
  - » Total of three interferometers at two sites--L1, H1, H2 (2km)
    - – Essentially identical orientation

Detector Sensitivity Progression

- Steady improvement in LIGO interferometers
  - Example: Livingston interferometer (L1)

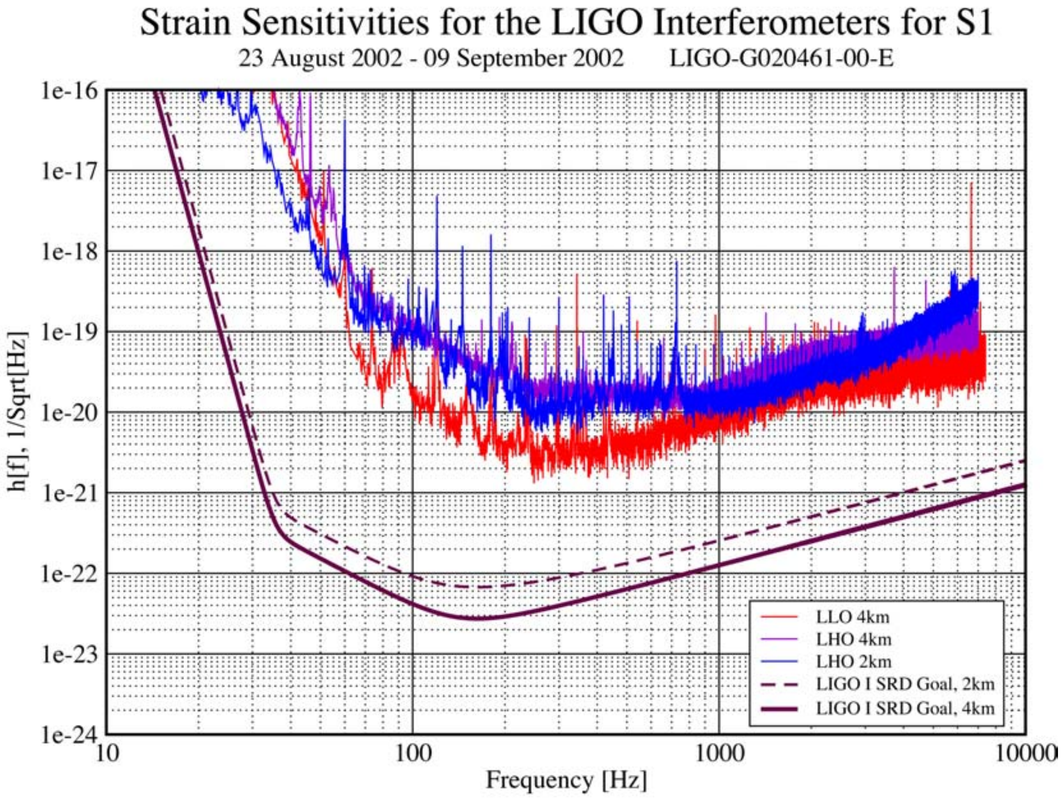




- TAMA interferometer
  - Installation of improved seismic isolation, planned for next year, should aid at low frequencies

First LIGO Science Run (S1)

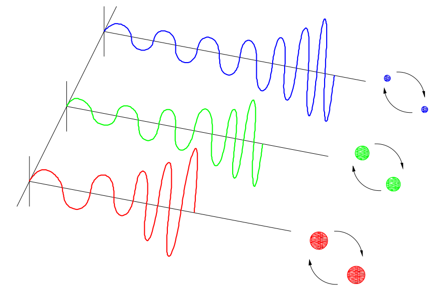
- August 23 - September 9
  (~400 hours duration)
- 1st coincidence interferometer observations since 1989 ("100 hour run")
  - » Three LIGO interferometers, plus GEO (Europe) and TAMA (Japan)
- Hardware reliability good for this stage in the commissioning
  - » Longest locked segment for LIGO interferometer: 21 hrs

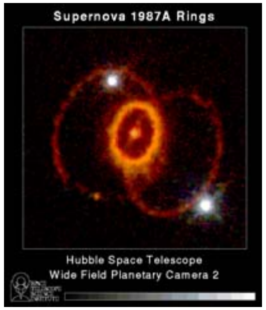


	LLO-4K	LHO-4K	LHO-2K	3x Coinc.	GEO600
Duty cycle	42%	58%	73%	24%	97%

Astrophysical Searches with Interferometer Data

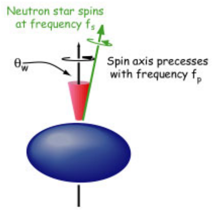
- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates



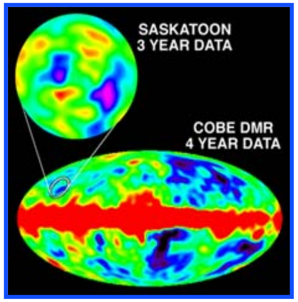


- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation
  - » prompt alarm (~ one hour) with neutrino detectors

- Pulsars in our galaxy: *"periodic"*
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)
  - » r-modes, LMXBs

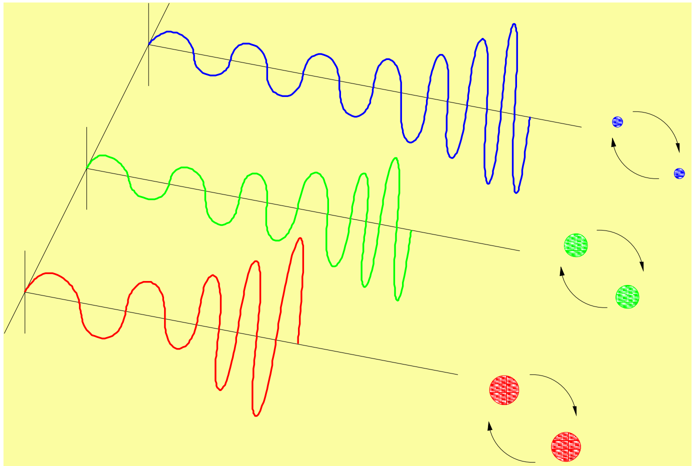


- Cosmological Signals *"stochastic background"*



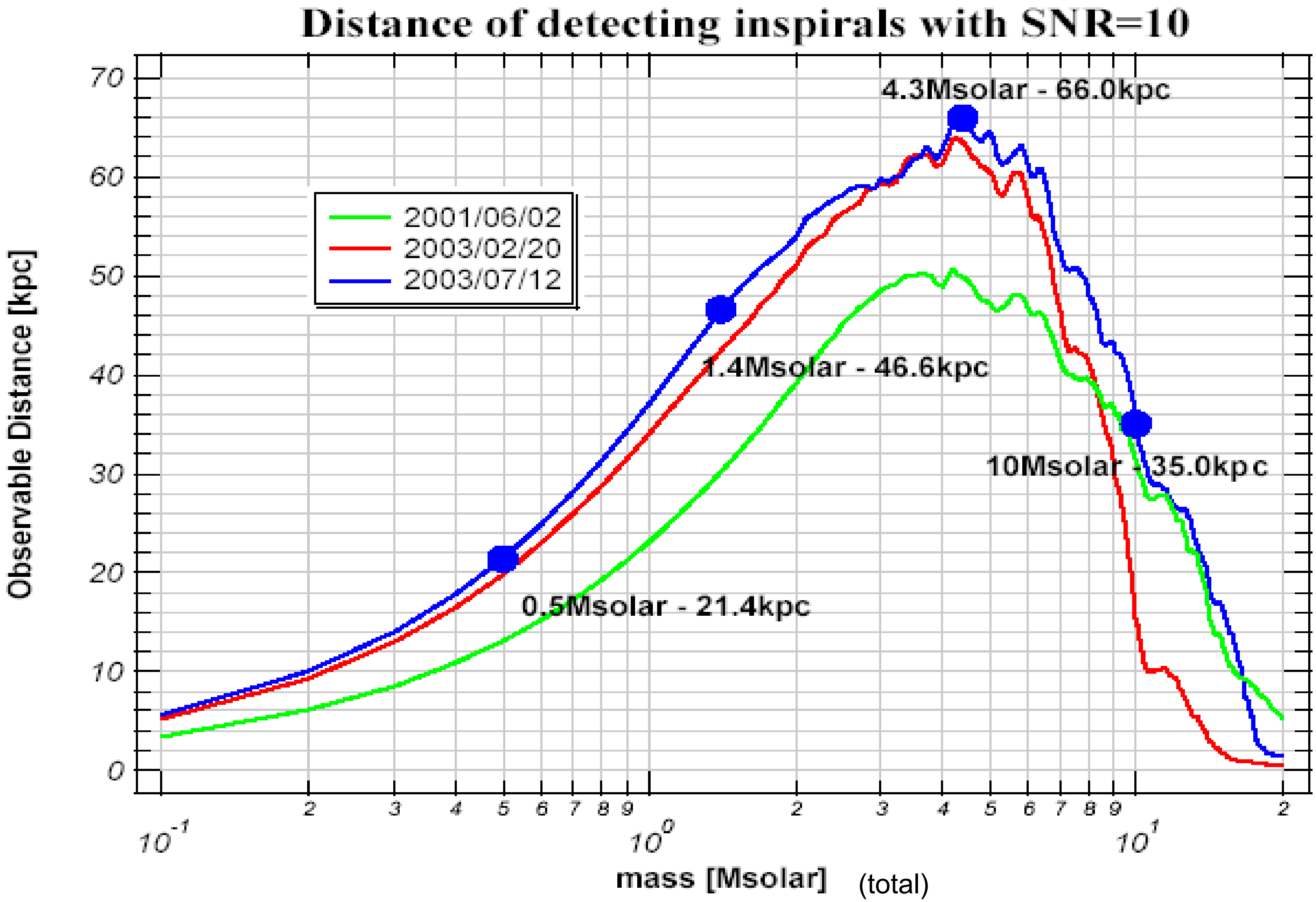
Compact Binary Coalescence

- Search technique: *matched templates*
  - » Neutron Star – Neutron Star
    - – waveforms known with confidence
  - » Black Hole – Black Hole
    - – need better waveforms

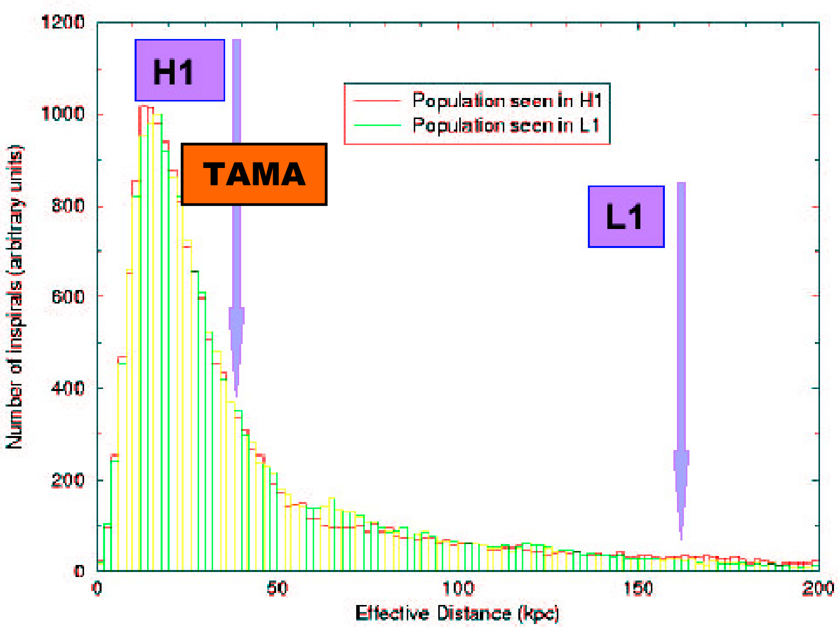


- TAMA DT6 search
  - » $m_1+m_2 < \sim 10\ M_\odot$
- LIGO S1 Search
  - » Discrete set of templates labeled by (m1, m2)
    - – $1.0\ M_\odot < m1, m2 < 3.0\ M_\odot$
    - – 2110 templates
    - – At most 3% loss in SNR

TAMA Range for Binary Inspirals



Results of S1 Inspiral Search



- Monte Carlo simulation to determine efficiency for detecting galactic events
- Simulated Galactic Population includes Milky Way, LMC and SMC
- LMC and SMC contribute ~12%

LIGO S1 Upper Limit

R < 170 / yr / MWEG

(Milky Way Equivalent Galaxy)

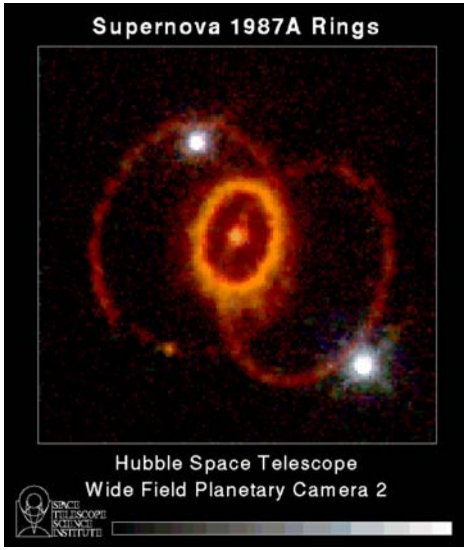
TAMA DT6 Upper Limit

R < 120 / yr

- Theoretical prediction :
  $R \sim 10^{-4} - 10^{-6}$ / yr / MWEG (??)
- Potential for improvement :
  - » 100-300 x increase in range (~20 Mpc)
  - » 100 x observation time

Short GW Burst Sources

- Known sources -- Supernovas & GRBs
  - Coincidence with observed electromagnetic observations.
    - No close events occurred during S1
    - Second science run – We are analyzing data near the very bright and close GRB030329 (both Hanford detectors and TAMA operating)



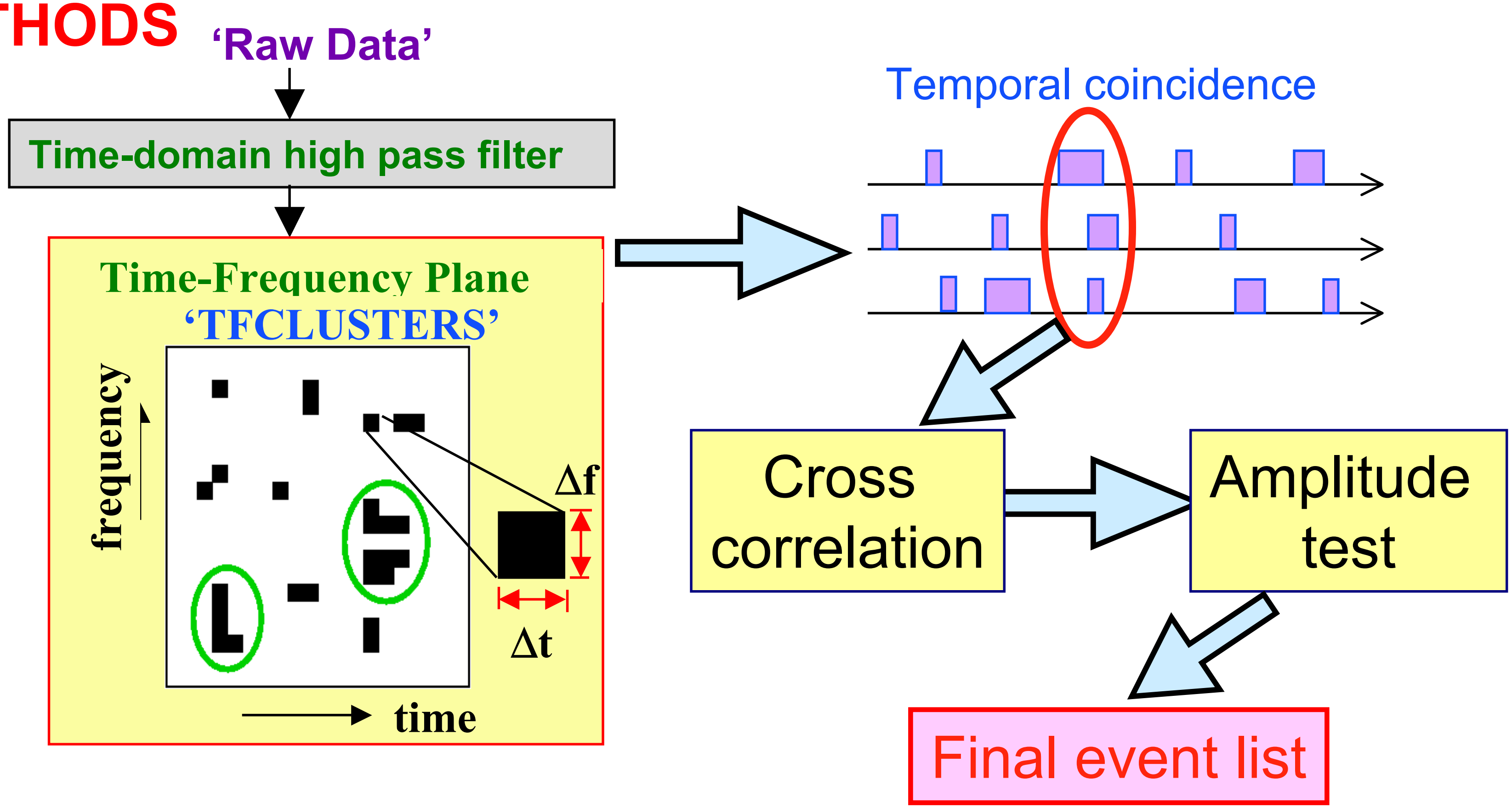
- Unknown phenomena
  » Emission of short transients of gravitational radiation of unknown waveform (e.g. black hole mergers).

S1

‘Unmodelled’ Burst Search

GOAL search for waveforms from sources for which we cannot currently make an accurate prediction of the waveform shape.

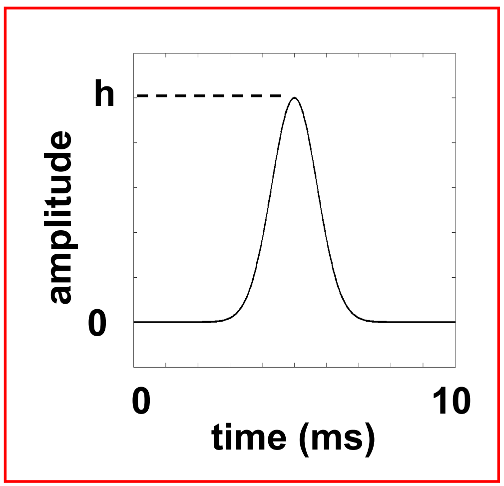
METHODS



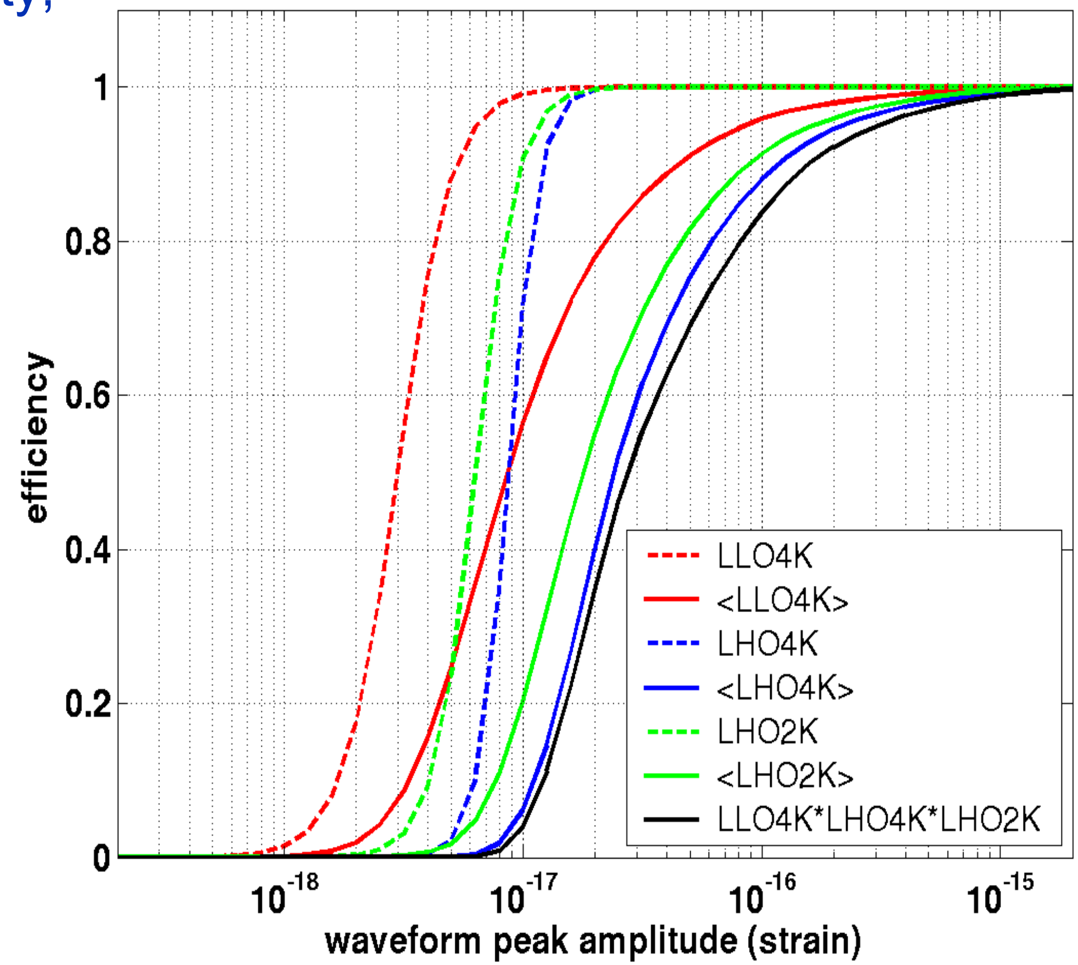
Determination of Efficiency

To determine sensitivity, inject "representative" waveforms into actual data and run through the analysis pipeline

1ms Gaussian burst



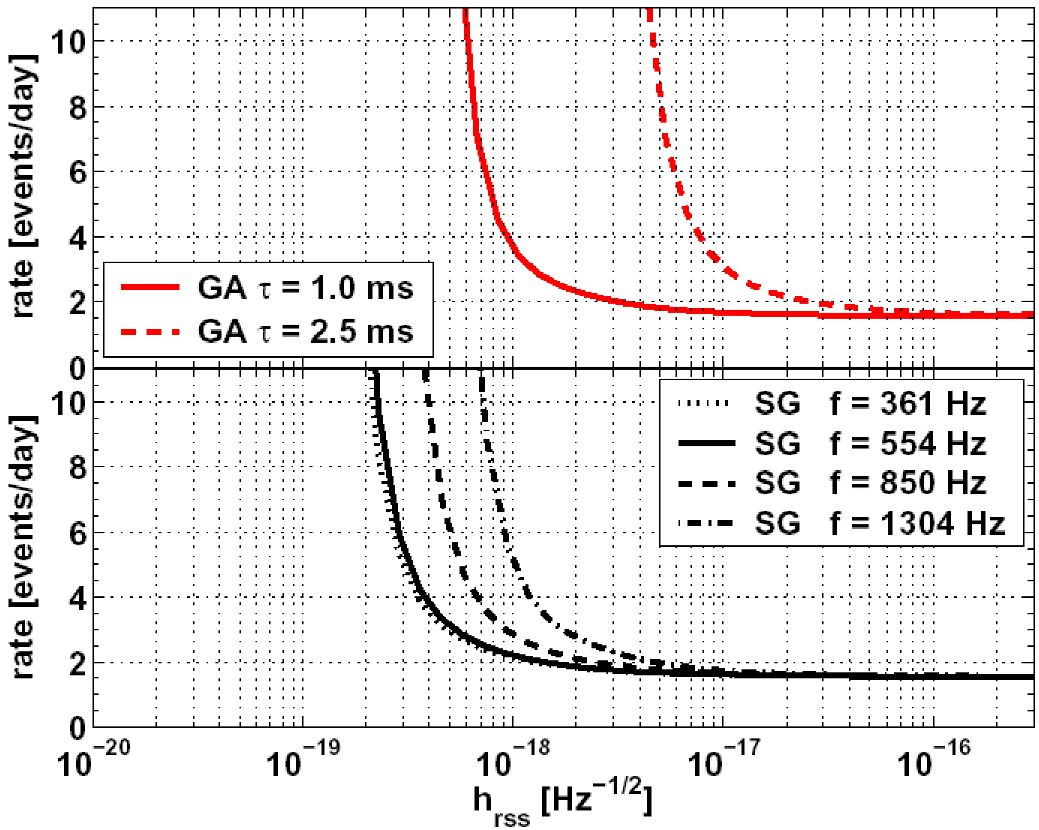
Detection efficiency vs. amplitude, averaged over source direction and polarization



LIGO S1 Upper Limit

ex: 1ms gaussian bursts

Excluded regions in rate-amplitude plane



- Not as good as the best bar results to date, due to their
  - » Longer observation time
  - » Higher sensitivity near 1 kHz
- Broaden parameter space of waveforms searched
  - » Longer duration bursts
  - » Astrophysically motivated
- Prospects for improvement :
  - » 300-1000x detector sensitivity
  - » 300x in observation time
  - » 3x analysis improvements (?)
  - » ?x improved gaussianity

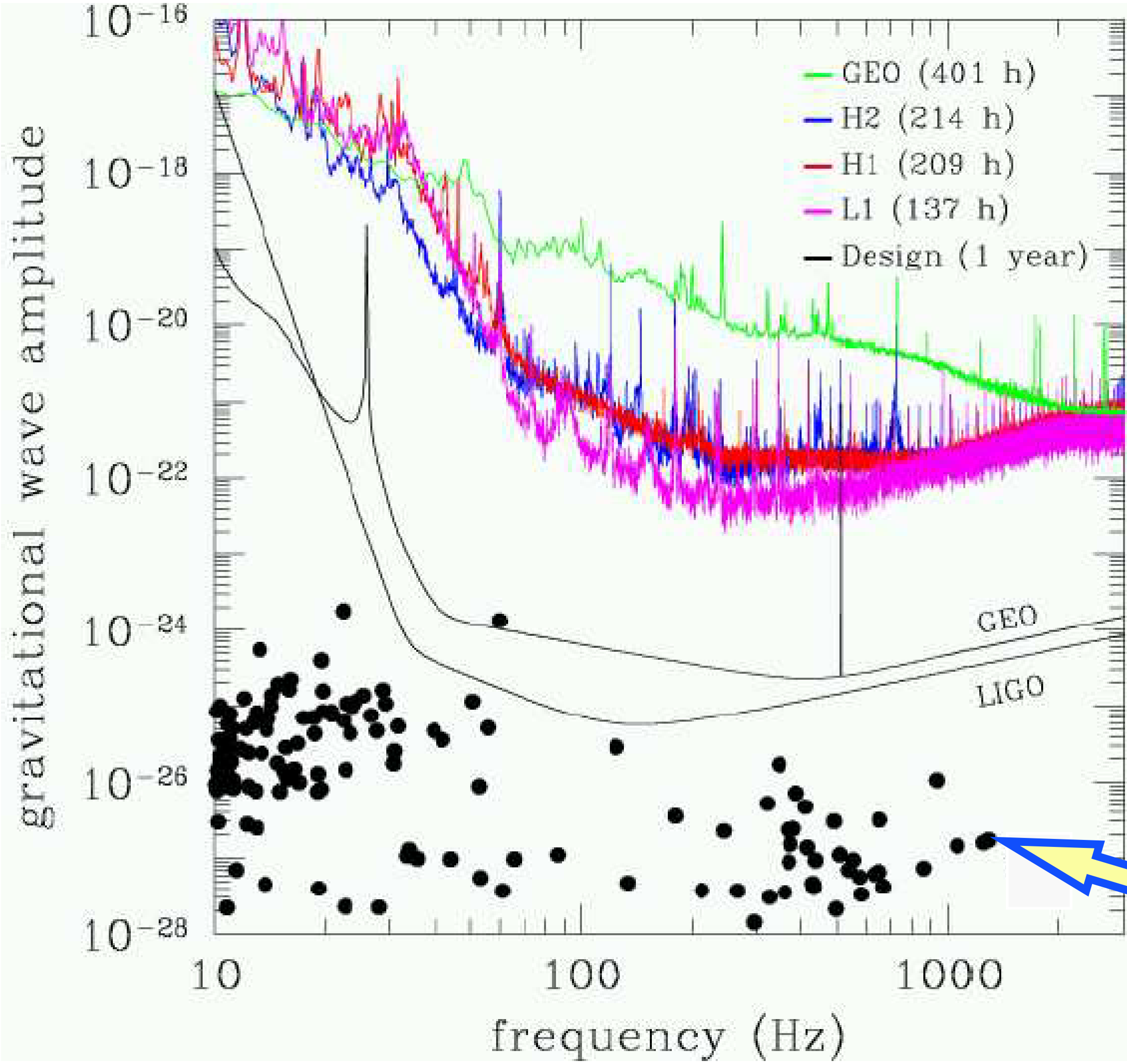
CW Sources and Search Methods

- Neutron stars in our galaxy:
  - » Search for observed neutron stars (known location and frequency)
  - » Low mass X-ray binaries (known location, rough frequency range)
  - » Unobserved NS's (unknown location, unknown frequency)
- Search Challenges
  - » Frequency modulation of signal due to Earth's motion
  - » Amplitude modulation due to the detector's antenna pattern
  - » All sky search represents significant computational challenge
- Search methods
  - » Time Domain
    - – Computationally easy but best suited to known sources
  - » Frequency Domain
    - – Best suited for large parameter space searches

TAMA Search for SN1987A

- Evidence of modulated emission at 467.5 Hz
  - » GW emission expected at 935 Hz
  - » Highest sensitivity region of TAMA300
- DT6: ~1000 hours of observation in 2001
- Search over ~ 0.1 Hz bandwidth
- Upper limit
  - » $h < 5 \times 10^{-23}$
  - » 99% confidence level

Directed Search in LIGO S1



NO DETECTION EXPECTED
at S1 sensitivities

- Compare searches using time and frequency domain algorithms
- Confront challenge of coherent analysis of detectors with different orientations on different continents

PSR J1939+2134
1283.86 Hz

S1 Result: PSR J1939+2134

- Upper limit for targeted pulsar
  - » Comparison of frequency domain and time domain searches
- 95% upper limits on h:

IFO	Frequentist FDS	Bayesian TDS
GEO	1.9×10^{-21}	2.2×10^{-21}
LLO	2.7×10^{-22}	1.4×10^{-22}
LHO-2K	4.0×10^{-22}	2.4×10^{-22}
LHO-4K	5.4×10^{-22}	3.3×10^{-22}

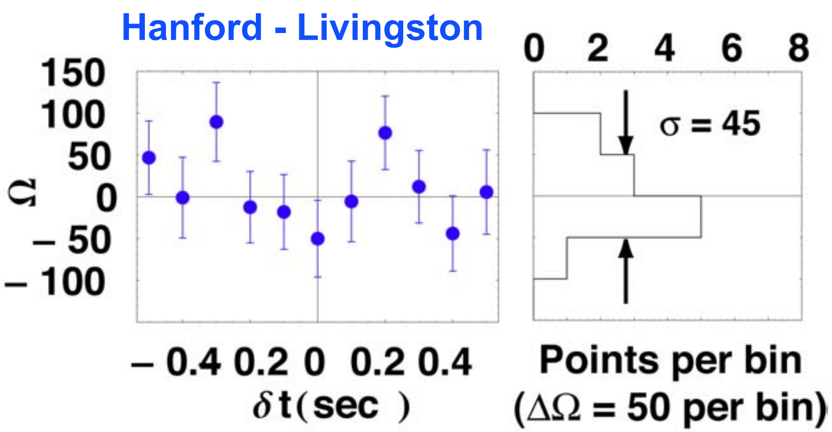
- Spindown estimate: $h < 1.8 \times 10^{-27}$
- Prospects for improvement:
  - » 100-1000x from detector sensitivity (depending on frequency)
  - » 10x from observation time

Stochastic Background

- Strength specified by *ratio of GW energy density to closure density*:

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

- Detect by *cross-correlating* output of two interferometer detectors
  - » Use widely separated detectors to minimize correlated environmental noise



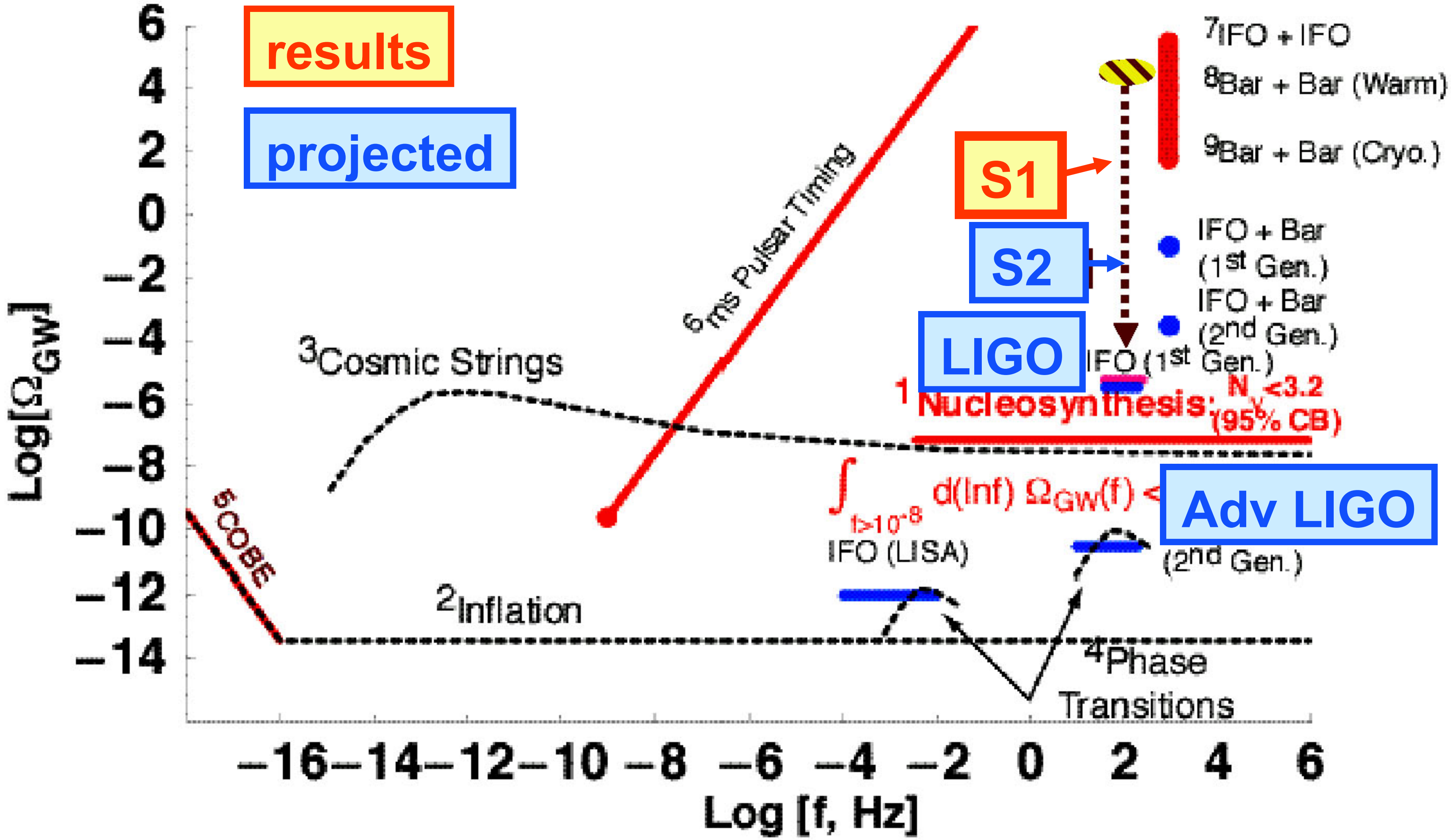
LHO 2km-LLO 4km

61 Hours of S1 data

Ω_{GW} (40Hz - 314 Hz) < 23

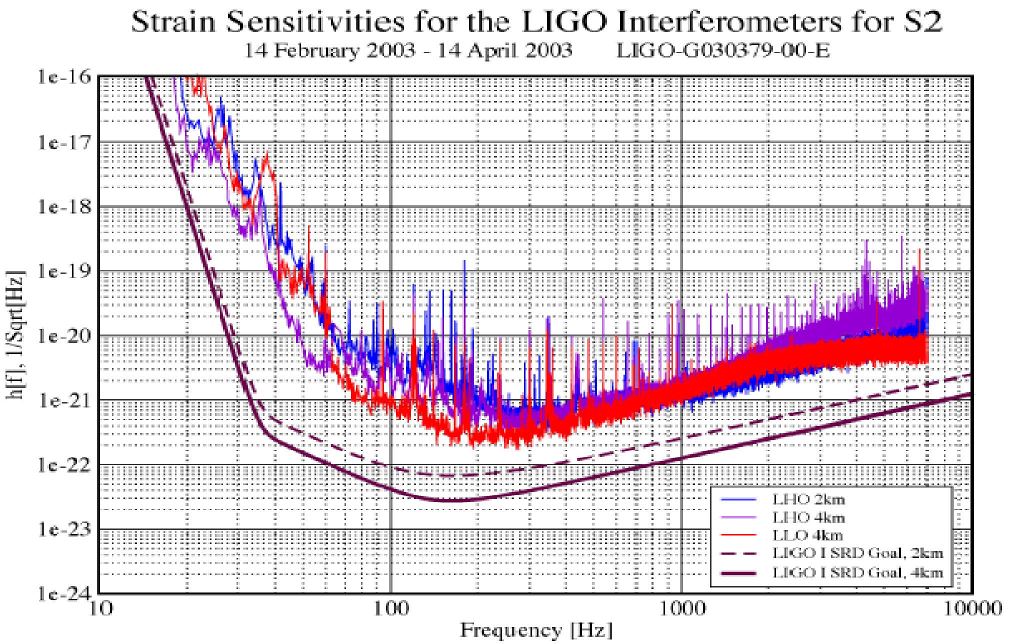
- Prospects for improvement in Ω :
  - » 10^6 x from detector sensitivity improvements ($\Omega \sim h^2$)
  - » 10 x from observation time

Stochastic Background: *measurements and predictions*



Second LIGO Science Run (S2)
TAMA Data-taking 8 (DT8)

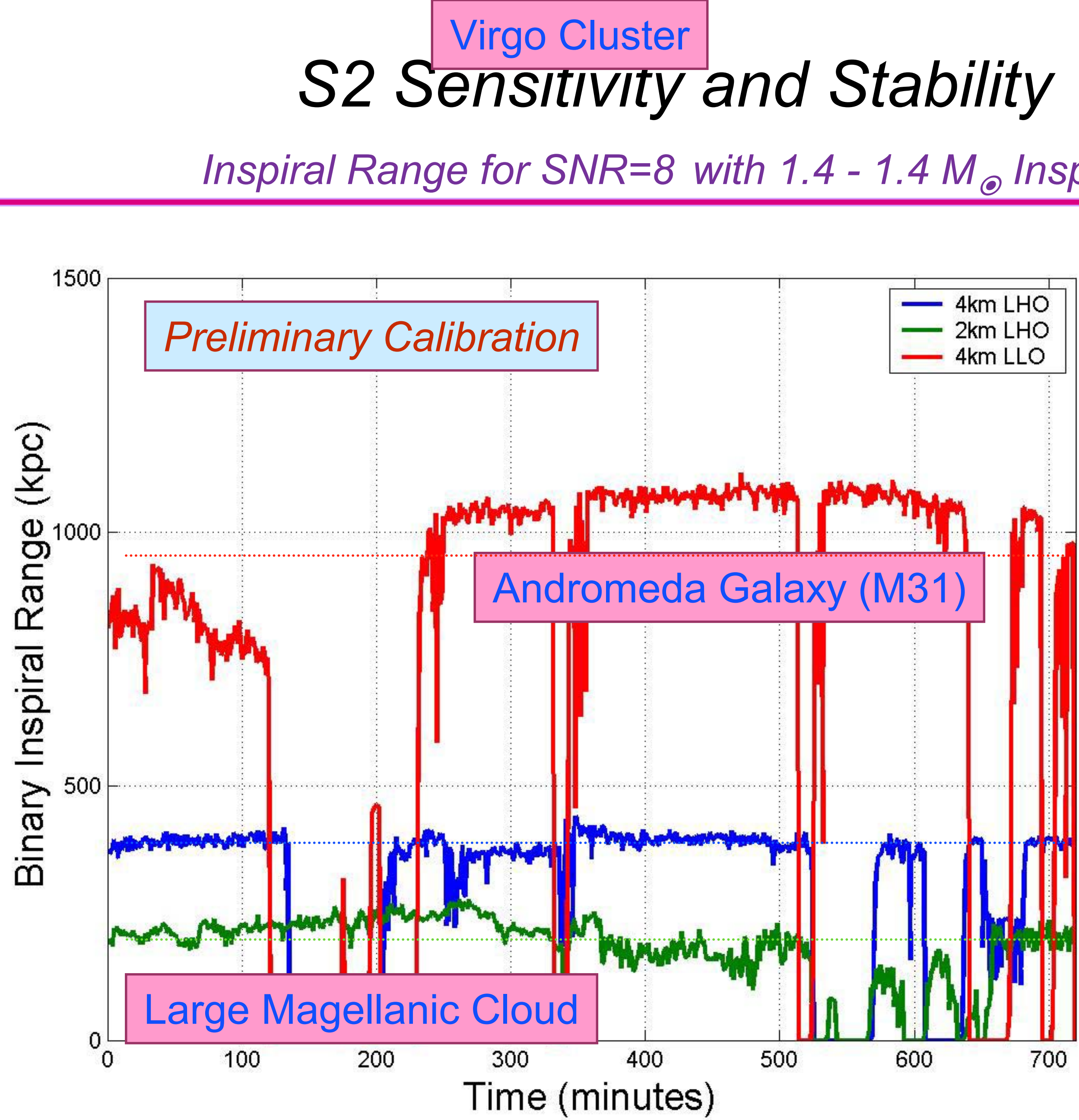
- February 14 – April 14, 2003 (~ 1400 hours)
- Three LIGO interferometers and TAMA (Japan)
- ~10x sensitivity improvement over S1
- Duty cycle similar to S1
  - » Increased sensitivity did not degrade operation
  - » Longest locked stretch ~ 66 hours (LHO-4K)



	LLO-4K	LHO-4K	LHO-2K	3x Coinc.
Duty cycle (cf. S1)	37% (42%)	74% (58%)	58% (73%)	22% (24%)

S2 Sensitivity and Stability

Inspiral Range for SNR=8 with 1.4 - 1.4 $M_\odot$ Inspiral



"Typical" 12 hours

Third LIGO Science Run (S3)

- October 31, 2003 – January 5, 2004
- Three LIGO interferometers, with some participation by TAMA and GEO
- Improvements relative to S2
  » Sensitivity better by 3-4x for LHO interferometers
  » Duty cycle improved for LHO interferometers (>80% for H1 so far)
  » Reduction of acoustic nose coupling (possible source of correlated noise at LHO)
  » Sensitivity and duty cycle for LLO interferometer ~ S2 level

“Schedule” for Full Sensitivity Operation

- TAMA
  - » Installation of new seismic isolation system in 2004
  - » Should lead to improved duty cycle and low f sensitivity
- GEO600
  - » Harder to predict schedule because of new technologies
  - » Observations may take a backseat to technology development
- Virgo
  - » First full interferometer lock within a few months
  - » One year commissioning to bring to full sensitivity (my guess!)
- LIGO
  - » Installation of external preisolator at LLO in early 2004
  - » Full sensitivity operation by the end of 2004

Potential for Current Generation of Interferometers

» My personal assessment

- Binary inspirals
  - » NS-NS range ~20 Mpc
  - » BH-BH range ~100 Mpc
- Continuous waves from neutron stars
  - » Minimum h ~ few x 10^{-26}
- Stochastic background
  - » Minimum $\Omega \sim 10^{-6}$
- Generic bursts
  - » Minimum $E_{GW} < 1 M_{\odot}$ for source at 100 Mpc
  - » Less certain than other projections