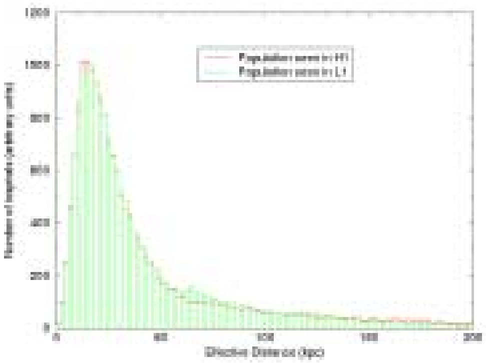
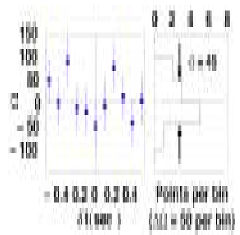
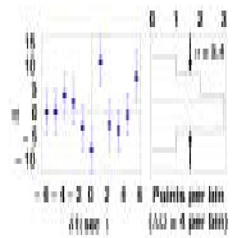
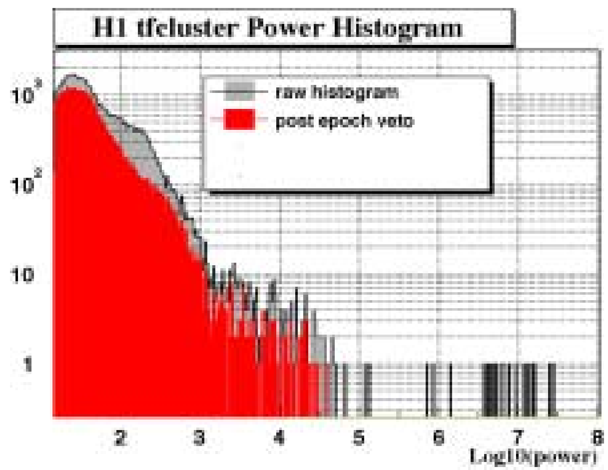
LIGO: First results from the S1 Science Run

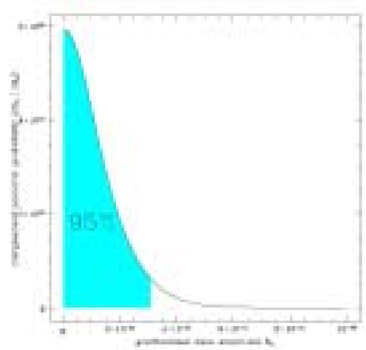






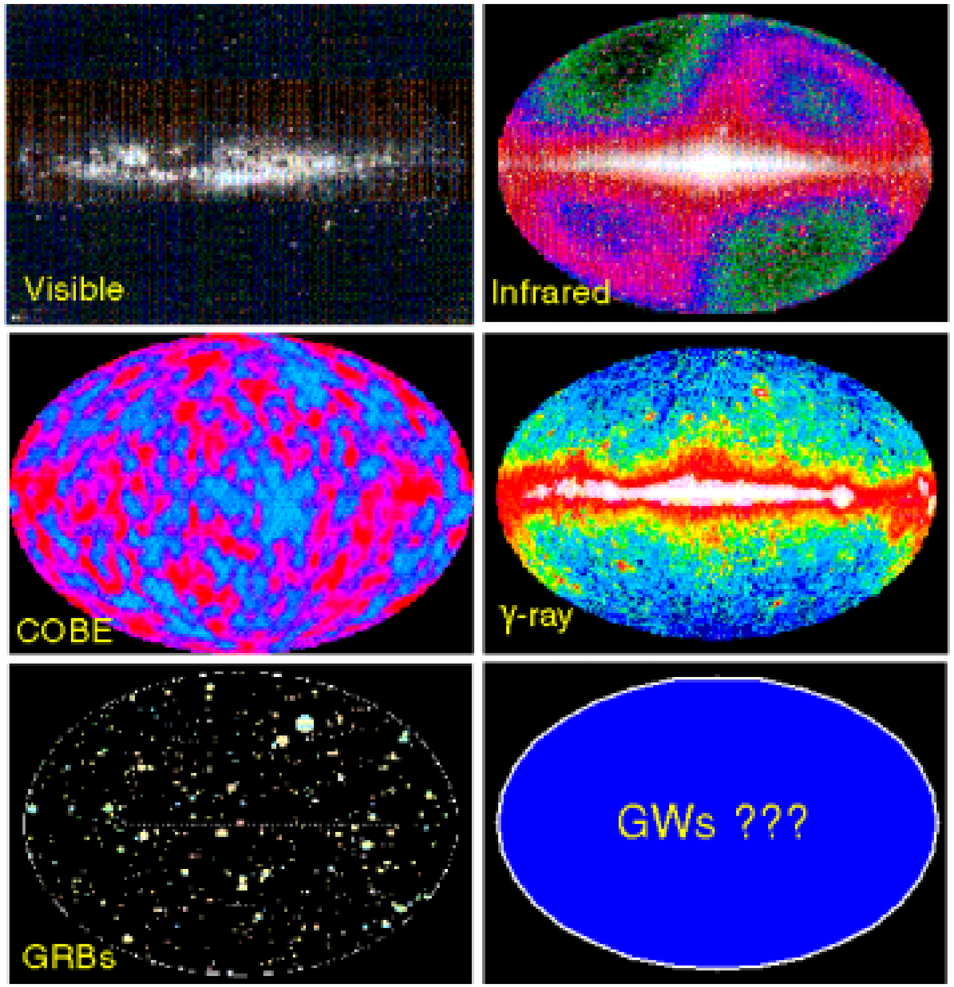
Albert Lazzarini
On behalf of the LIGO Scientific Collaboration
http://www.ligo.org

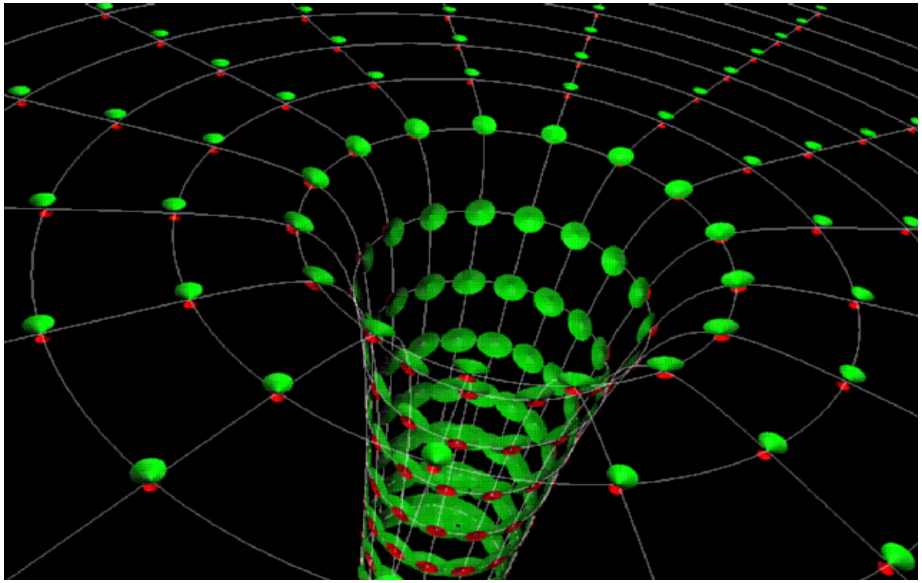




AAAS Symposium: *"Looking Beyond Earth"*

New Window on Universe





GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

EXPECTED SOURCES:

1. **BURST & TRANSIENT SOURCES - *SUPERNOVAE***
2. **COMPACT BINARY SYSTEMS - *INSPIRALS***
3. **ROTATING COMPACT STARS -*"GW" PULSARS***
4. **STOCHASTIC GRAVITATIONAL WAVE BACKGROUND**

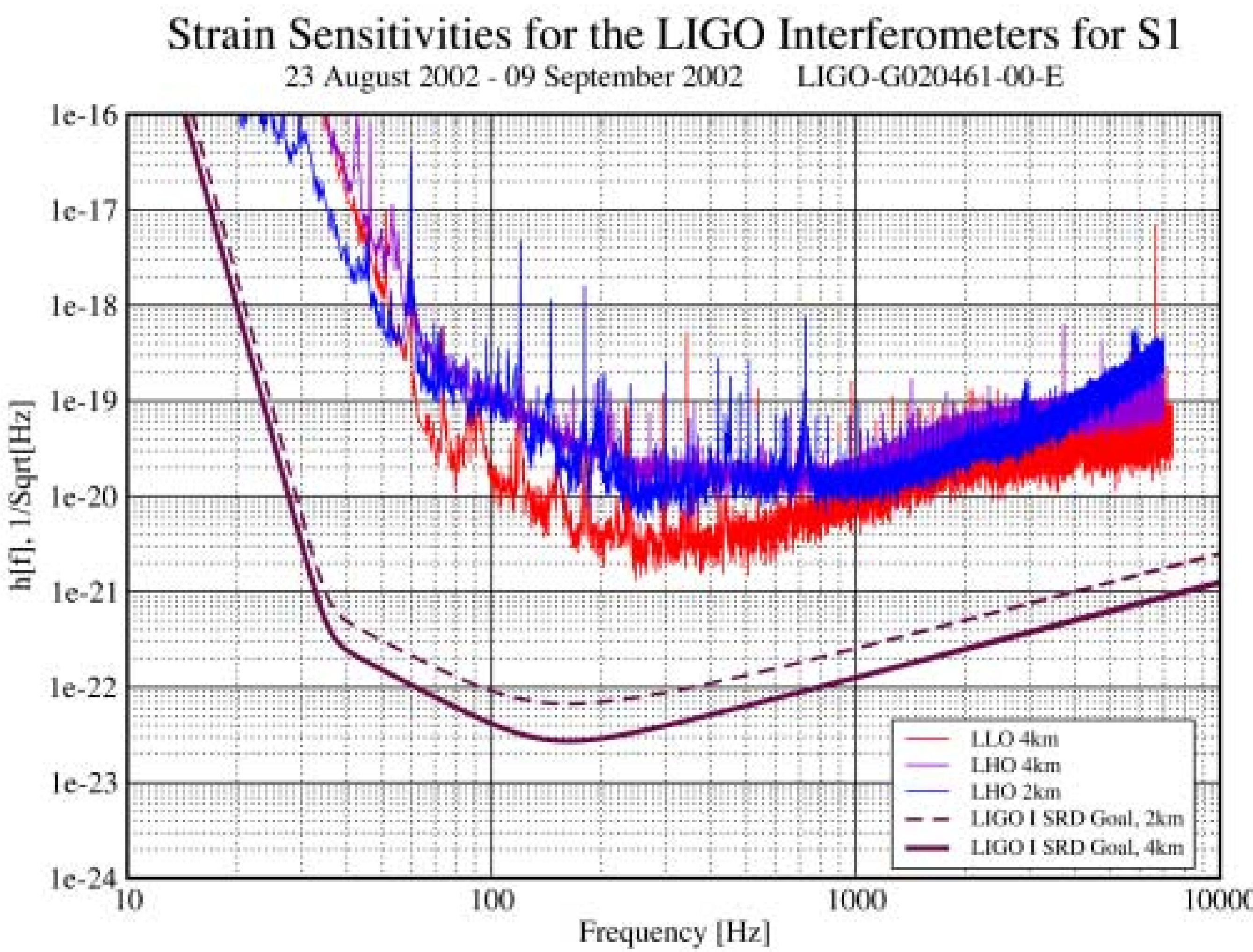
POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

LIGO Sensitivity for S1

LIGO
S1 Run

"First Upper Limit Run"

- **Aug – Sept 2002**
- **17 days**



Data Analysis According to Source Characteristics

- Deterministic signals -- ***Binary coalescences, Periodic sources***
  - »Amplitude and frequency evolution parameterized
  - »Set of templates covering parameter space matched to data

- Statistical signals -- ***Stochastic gravitational wave background***
  - »Cross-correlation of detector pairs, look for correlations above statistical variations

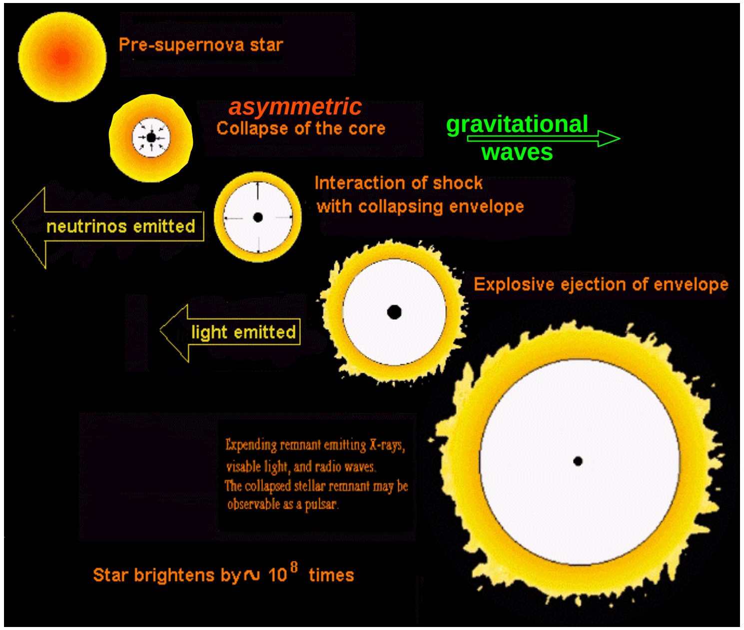
- Unmodeled signals -- ***Supernovae, Gamma Ray Bursts, …***
  - »Non-parametric techniques
    - Excess power in frequency-time domain
    - Excess amplitude change, rise-time in time domain

- *In all cases: coincident observations among multiple detectors*

LIGO Gravitational wave burst searches

Burst Working Group

- Target: gravitational wave bursts of transient nature
  - **No waveform model**
  - Bound on *rate vs. strength*
- *EVENT TRIGGERS* used to look for candidate events:
  1. *"TFCLUSTERS":* adaptively identifies clusters of excess power in time-frequency space
  2. *"SLOPE":* identifies rapid increases in amplitude of a filtered time series
- Determine detection efficiency via simulation
- **Require coincidence between 3 interferometers**



SN Rate
1/50 yr - Milky Way
3/yr - out to Virgo cluster

Upper Bound ∝ N / (ε(h) T)

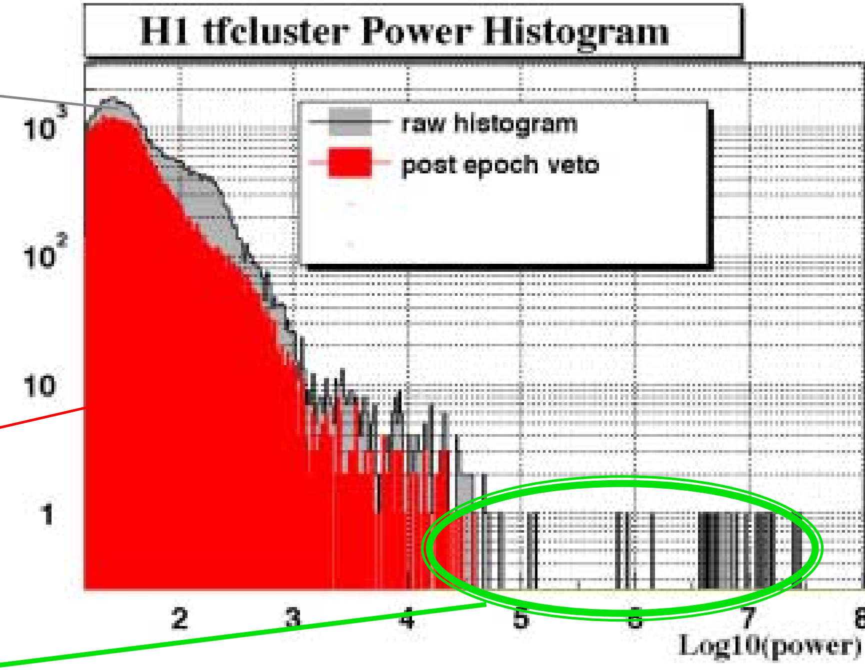
- N: number observed events
- ε(h): detection efficiency for amplitude h
- T: observation time -- *livetime*
- Proportionality constant depends on confidence level (CL) -- of order 1 for 90%

Data processing flow

Burst Working Group

- Prototypical of other event-based searches -

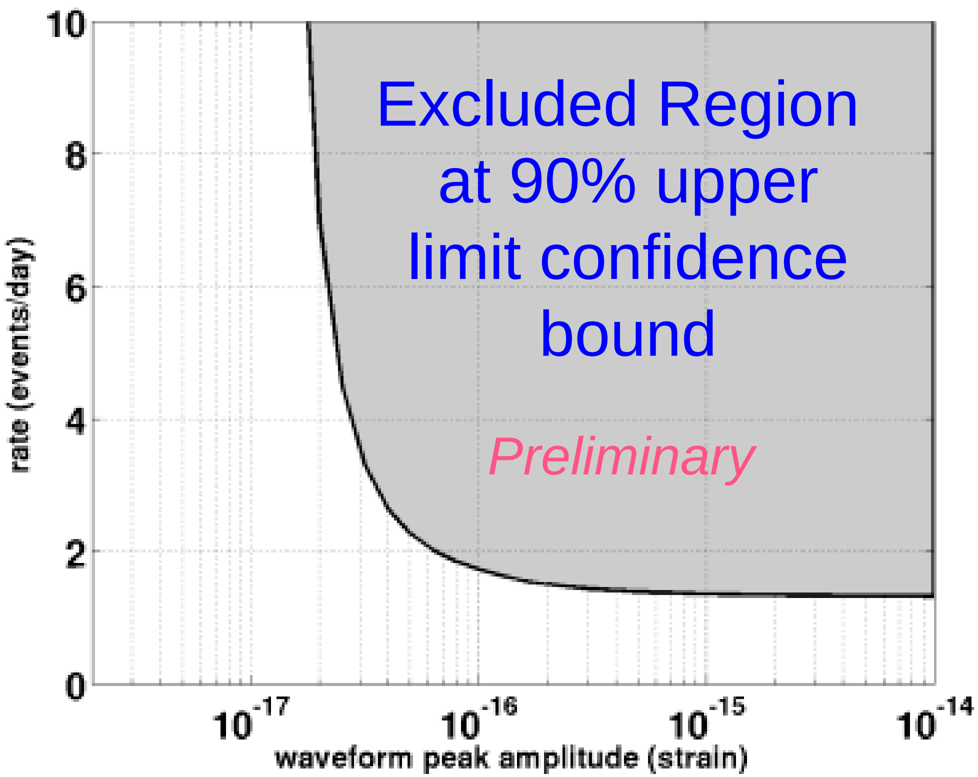
1. Event Trigger -> candidate gravitational wave event
2. Diagnostic Triggers -> indicators of instrumental or environmental artifacts
3. Interferometer Trigger-> Event Triggers *__not vetoed__* by Diagnostic Triggers
   - Vetoes eliminate particularly noisy data



4. Coincident Events: Require *simultaneity* in all interferometers
   - Within **time** window: require same time for event within experimental bounds
     - Greater of light travel time between detectors (+/- 10 ms) or filter time resolution
   - Within **frequency** window: for time-frequency methods, e.g. TFCLUSTERS filter

Burst Searches -- Preliminary Results

Burst Working Group



Able to exclude gravitational wave bursts of peak strength ***h*** above rate ***r***

Burst model --
- » 1 ms width Gaussian pulse
- » Linear polarization with random orientation
- » Arriving from random directions

Upper limit in *strain* compared to prior (cryogenic bar) results:
- » S1: $h < 5 \times 10^{-17}$ - **this result**
- » IGEC 2000[1] **:** $h < 1 \times 10^{-17}$
- » Astone et al.[2] 2001: $h \sim 2 \times 10^{-18}$

- Upper limit in *rate* constrained by observation time:
  - » S1: 17d - **this result**
  - › IGEC - 90d (2X coinc.), 260d (3X coinc.)
  - › Astone - 90d

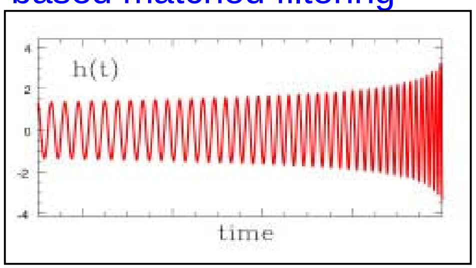
Work planned for future observations
- *Correlations with gamma ray bursts*
- *Observed Type II SNe*

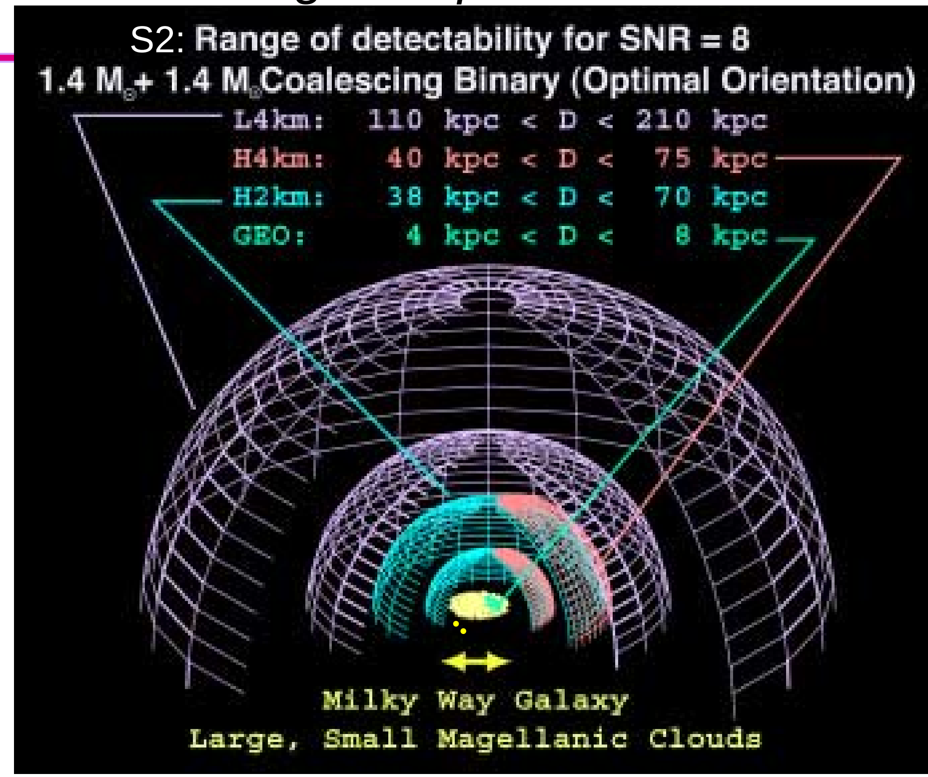
[1] *Int.J.Mod.Phys. D9 (2000) 237*
[2] *Class.Quant.Grav. 19 (2002) 5449*

Coalescing Binaries

Inspiral Sources Working Group

- Three source targets:
  - » Neutron star binaries (1-3 M_{sun})
    - ✓ Neutron star search complete
  - » Black hole binaries (> 3 M_{sun})
    - – Black hole search will be done in next science run, S2
  - » MACHO binaries (0.5-1 M_{sun})
    - – MACHO search under way
- Search method
  - » Template based matched filtering



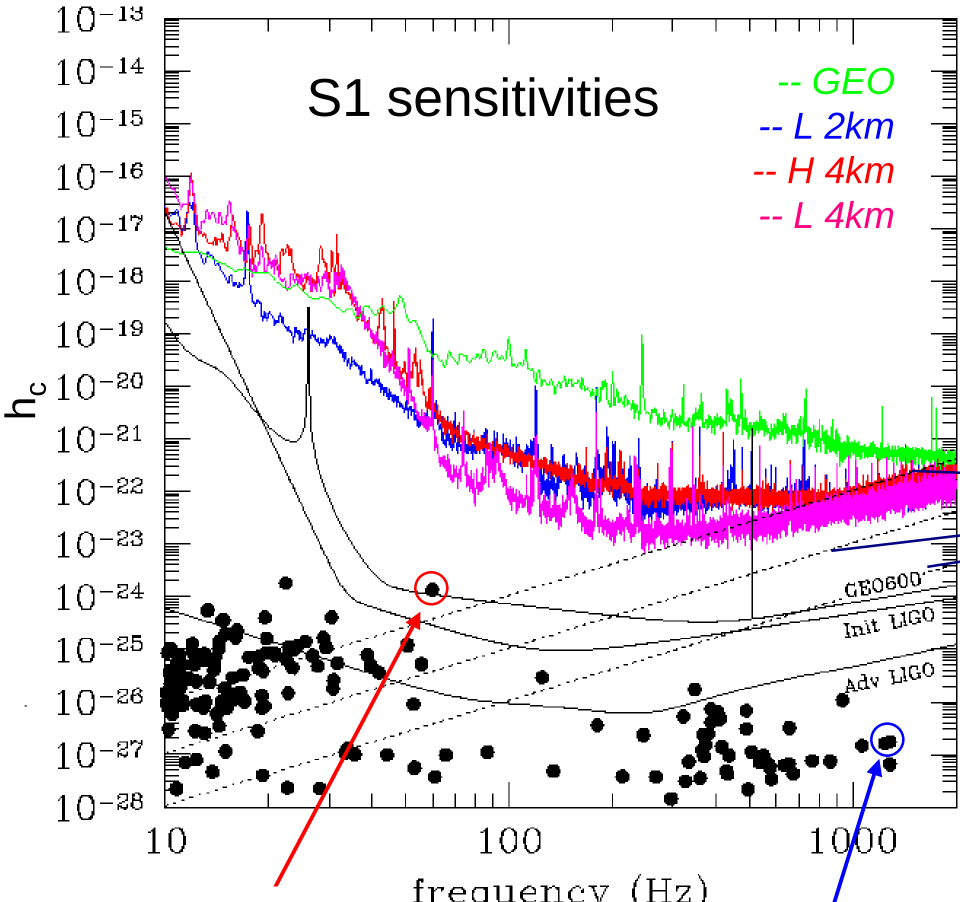


- Limit on binary neutron star coalescence rate:
  - » *$R_{90\%}$ (Milky Way) < 2.3 / (0.35 x 295.3 hr) = 170 /yr*
- Use triggers from H 4km and L 4km interferometers: *T = 295.3 hours*
  - » Monte Carlo simulation efficiency: *ε = 35%*
  - » 90% confidence limit = *2.3 / (ε T)*
- *26X lower than best published observational limit -- 40m prototype at Caltech[1]:*
  - » *$R_{90\%}$ (Milky Way) < 4400 /yr*

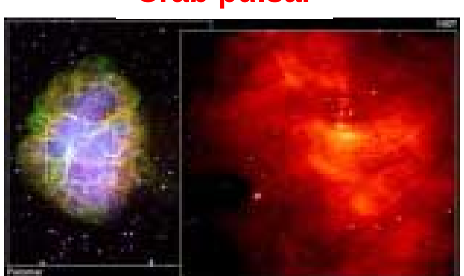
[1] *1994 data, Allen et al., Phys.Rev.Lett. 83 (1999) 1498*

Establishing limits on gravitational waves radiated by periodic sources

Periodic Sources Working Group



Crab pulsar



- h_c: Amplitude detectable with 99% confidence during observation time T:

  $$h_c = 4.2\,[S_h(f)/T]^{1/2}$$

- *Limit of detectability for rotating NS with equatorial ellipticity, $\varepsilon = \delta I/I_{zz}$:*

  10^{-3}, 10^{-4}, 10^{-5} @ 10 kpc

- ***Known** EM pulsars*
  - *Values of h_c derived from measured spin-down*
    - *IF spin-down were entirely attributable to GW emissions*
    - *Rigorous astrophysical upper limit from energy conservation arguments*

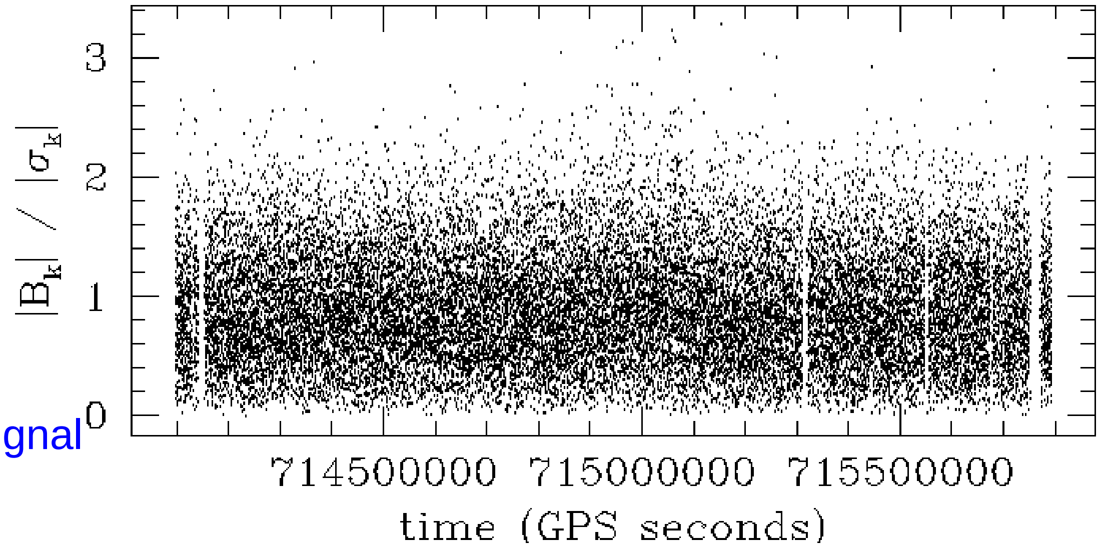
PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1.0519 10^{-19} s/s
D = 3.6 kpc

Graphic by R. Dupuis, Glasgow

Two complementary analysis approaches
Periodic Sources Working Group

- Time-domain search -- process signal to remove frequency variations due to Earth's motion around Sun
  - »Targeted searches
  - »Handles missing data
  - »Adaptable to complicated phase evolutions.
  - »Upper limit interpretation straightforward
    - – Compare result to what would be expected from noise without signal

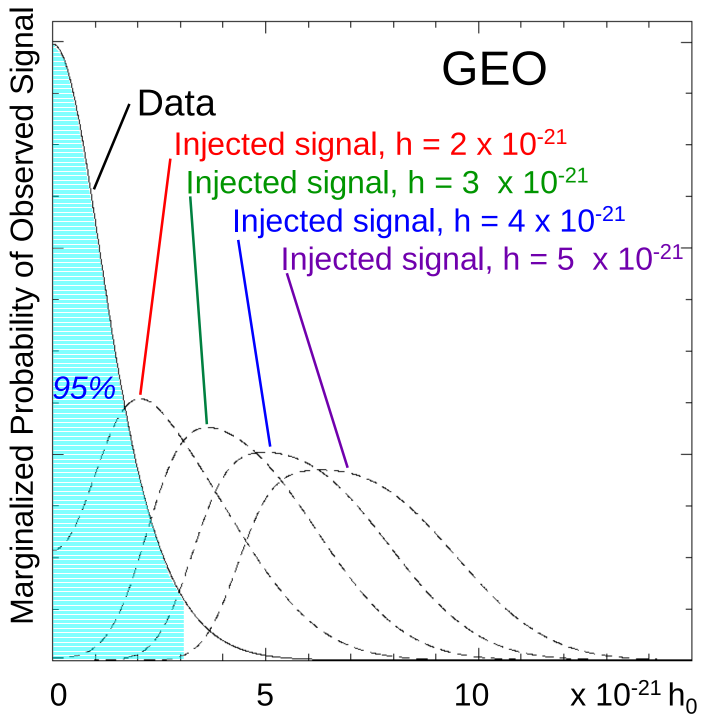
GEO -- Time series of amplitude near 1283 Hz (PSR J1939)

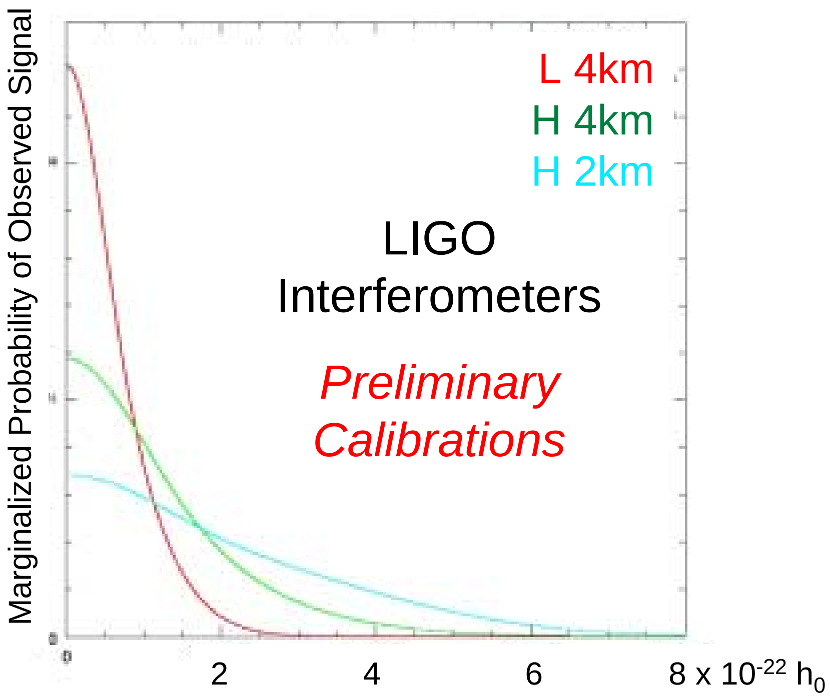


- Frequency-time domain search -- permits searches over large parameters space when signal characteristics uncertain
  - »Standard matched filtering technique
    - – Cross-correlation of signal with template, look for correlated power
  - »Analysis still progress

Preliminary results -- (EM pulsar) PSR J1939

Periodic Sources Working Group





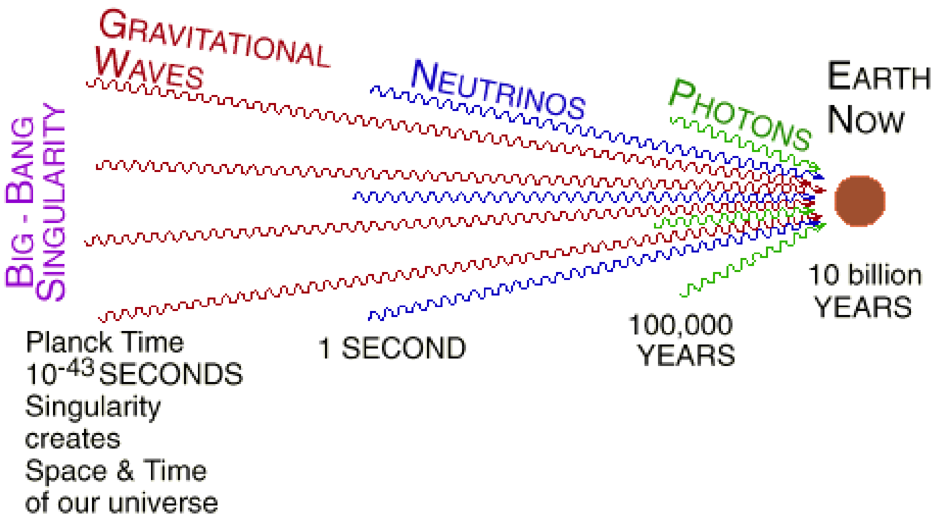
- ***Time domain analysis: No evidence of signal from PSR J1939 at f = 1283.86 Hz***
- 95% of the probability lies below:
  - GEO: $h_{max} < 3 \times 10^{-21}$
  - H 2km: $h_{max} < 5 \times 10^{-22}$
  - H 4km: $h_{max} < 3 \times 10^{-22}$
  - ***L 4km:*** $\boldsymbol{h_{max} < 2 \times 10^{-22}}$ **($\boldsymbol{\varepsilon < 7 \times 10^{-5}}$ @ 3.6 kpc)**

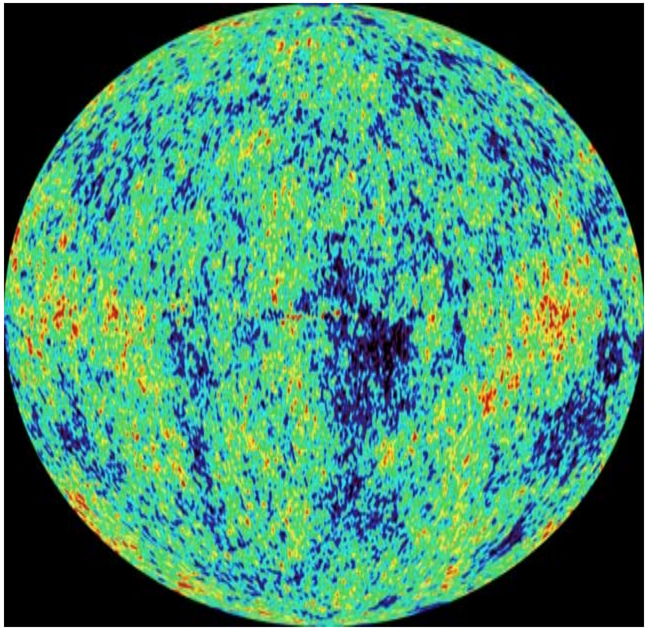
Ref. -- $h_{max} < 3 \times 10^{-20}$ *for PSR J1939 -- Hough, J. et al., Nature,* ***303*** *(1983) 216*

$h_{max} < 3 \times 10^{-24}$ *at f =921.35 (+/- 0.03) Hz - Astone, Phys.Rev. D65 (2002) 022001 (untargeted search)*

Stochastic Background Sources

Stochastic Background Sources Working Group





Analog from cosmic microwave background -- WMAP 2003

- Detect by cross-correlating interferometer outputs in pairs
  - Hanford - Livingston, Hanford - Hanford
- Good sensitivity requires:
  - $\lambda_{GW} \geq$ **2D (**detector baseline)
  - f $\leq$ 40 Hz for L - H pair
- Initial LIGO limiting sensitivity**:** Ω **<10^{-5}**

$$\int_0^\infty d(\ln f)\ \Omega_{GW}(f) = \frac{\rho_{GW}}{\rho_{critical}}$$

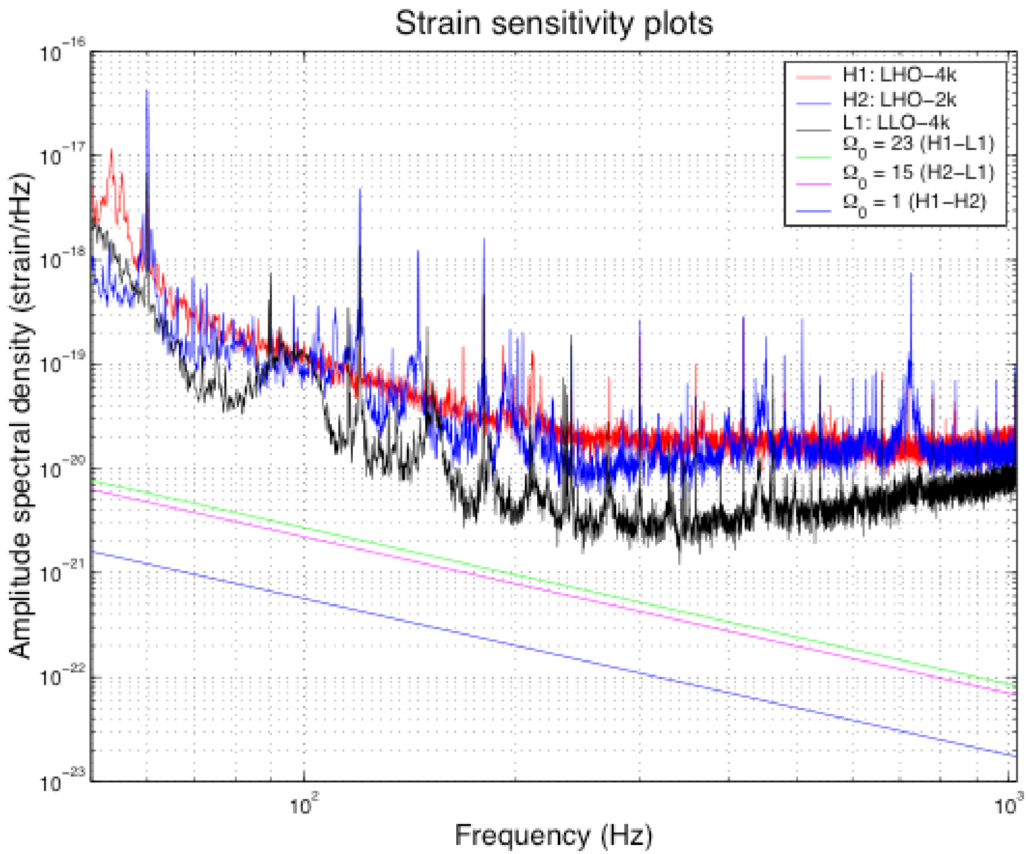
The integral of [1/f•Ω_{GW}(f)] over all frequencies corresponds to the fractional energy density in gravitational waves in the Universe

Stochastic Gravitational Wave Background

Stochastic Background Sources Working Group

- Current best upper limits:
  - » Inferred: From Big Bang nucleosynthesis: (Kolb et al., 1990) $\int \Omega_{GW}(f)\ d\ln f < 1\times10^{-5}$
  - » *Measured:* Garching-Glasgow interferometers (Compton et al. 1994): $\Omega_{GW}(f)\ <\ 3\times10^{5}$
  - » *Measured*: EXPLORER-NAUTILUS (cryogenic bars -- Astone et al., 1999) $\Omega_{GW}(907Hz)\ <\ 60$

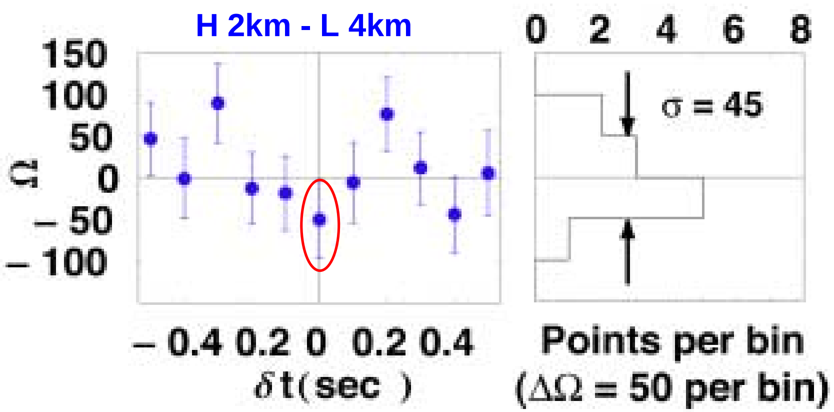
Cross-correlation technique enables one to “dig” signal below individual interferometer noise floors

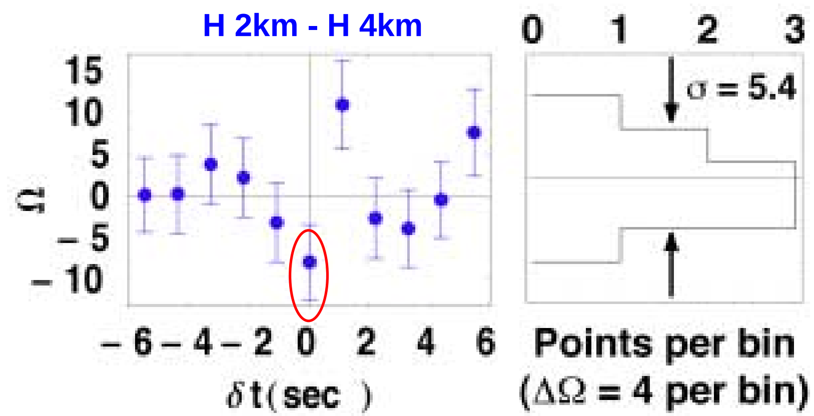


Stochastic Gravitational Wave Background

Stochastic Background Sources Working Group

- Preliminary results from 7.5 hr of data -





- Introduce non-astrophysical time lags (>20ms) to determine backgrounds *(off-source)*
  - *δt = 0 sec (on-source)* measurements consistent with *off-source* backgrounds
- Extrapolated S1 H 2km - H 4km result covers **240 Hz bandwidth, is ~10X better** than best published result for *direct measurement* of Ω_{GW} (Astone et al., 1999, cryogenic bar, 907 Hz).

Interferometer Pair	**Extrapolated Upper Limit for S1 (by scaling 7.5 hrs to 150 or 100 hrs)**	**T_{obs}**
H 2km - H 4km	**Ω_{GW} (40Hz - 300 Hz) < 5 (90% C.L.)**	**150 hr**
H 4km - L 4km	**Ω_{GW} (40Hz - 314 Hz) < 70 (90% C.L.)**	**100 hr**
H 2km - L 4km	**Ω_{GW} (40Hz - 314 Hz) < 50 (90% C.L.)**	**100 hr**

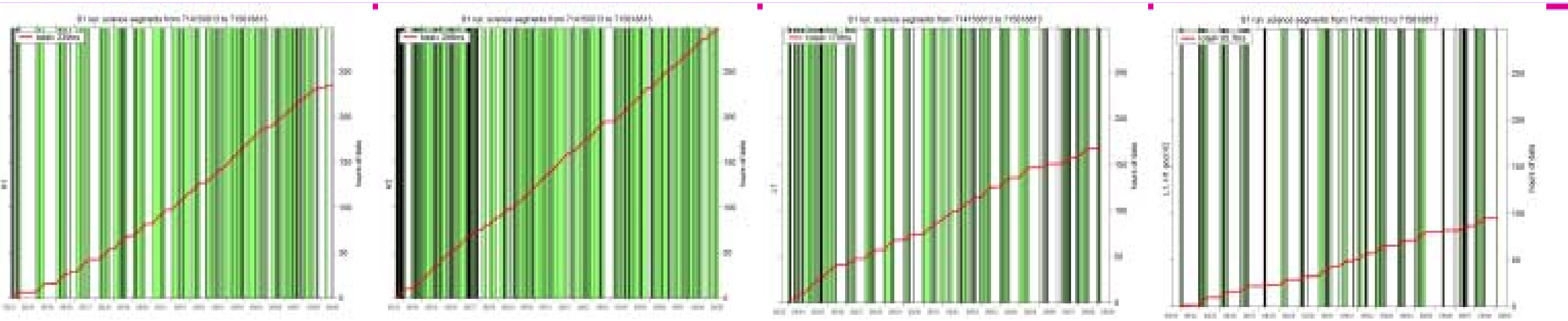
LIGO Science Has Started

- LIGO has started taking data
- LIGO had its first science run last Summer
  - » Collaboration has carried out preliminary analysis
    - ✓ Bursts & Transients
    - ✓ Compact binary coalescences
    - ✓ Periodic sources
    - ✓ Stochastic background
  - » First results papers to be circulated by March 2003
- Second run *began* 14 February (*last Friday*)
  - » Will last through 14 April
  - » Sensitivity will be ~10x better than S1
  - » Duration will be ~ 4x longer
  - » LIGO:
    - – *Bursts: rate limits: 4X lower rate & 10X lower strain limit*
    - – *Insprials: reach will exceed 1Mpc -- includes M31 (Andromeda)*
    - – *Periodic sources: limits on* $h_{max} \sim$ *few x* 10^{-23} ($\varepsilon \sim$ *few x* 10^{-6} *@ 3.6 kpc*)
    - – *Stochastic background: limits on* $\Omega_{GW} <$ *few x* 10^{-3}
  - » *FIVE INTERFEROMETERS ARE COLLABORATING INTERNATIONALLY*
    - – GEO (UK/Germany) and TAMA (Japan) observing jointly with LIGO

In-Lock Data Summary from S1

Red lines: integrated up time Green bands (w/ black borders): epochs of lock

H1: 235 hrs H2: 298 hrs L1: 170 hrs 3X: 95.7 hrs



- **August 23 – September 9, 2002: 408 hrs (17 days).**
  - **H1 (4km): duty cycle 57.6% ; Total Locked time: 235 hrs**
  - **H2 (2km): duty cycle 73.1% ; Total Locked time: 298 hrs**
  - **L1 (4km): duty cycle 41.7% ; Total Locked time: 170 hrs**

- **Double coincidences:**
  - **L1 && H1 : duty cycle 28.4%; Total coincident time: 116 hrs**
  - **L1 && H2 : duty cycle 32.1%; Total coincident time: 131 hrs**
  - **H1 && H2 : duty cycle 46.1%; Total coincident time: 188 hrs**

- **Triple Coincidence: L1, H1, and H2 : duty cycle 23.4% ;**
  - **Total coincident time: 95.7 hrs**