Analysis of the first LIGO data

Erik Katsavounidis
LIGO Laboratory
MIT
On behalf of the LIGO Scientific Collaboration
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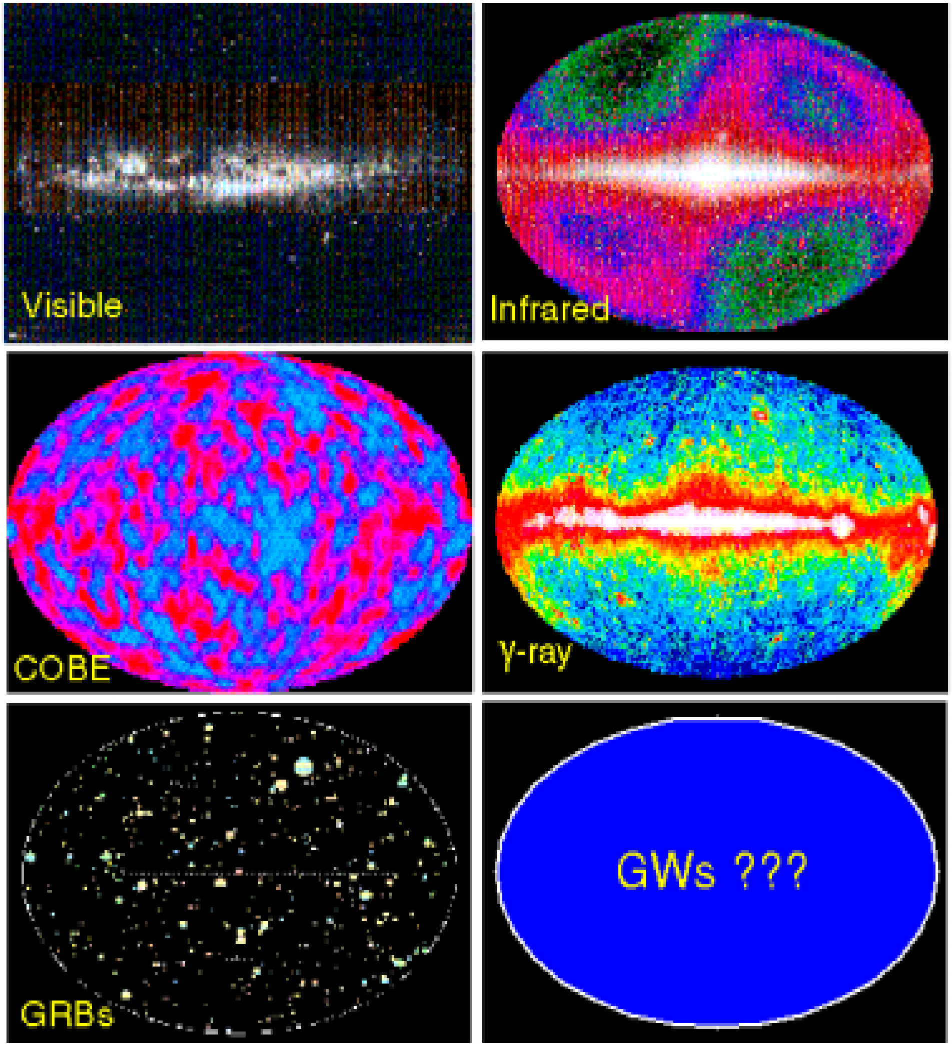
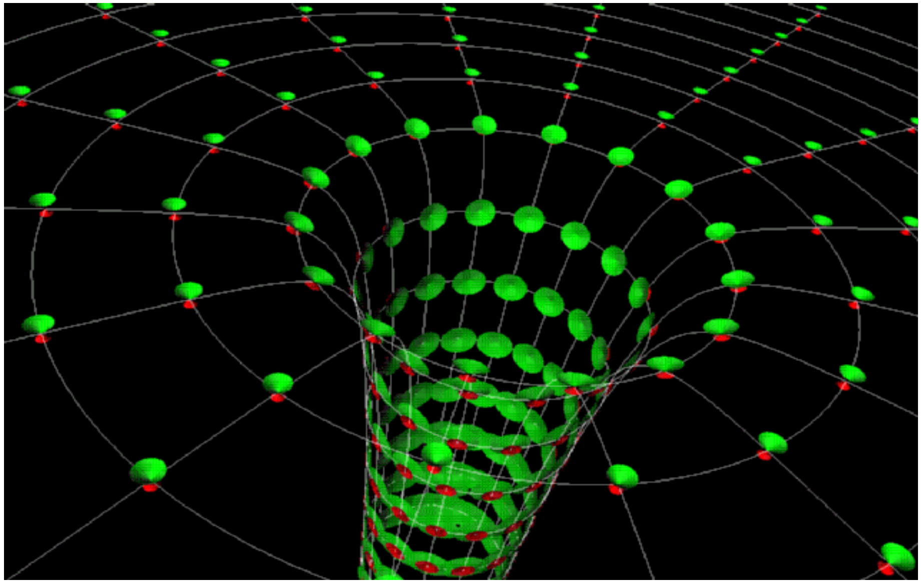
New Window on Universe





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. **STOCHASTIC GRAVITATIONAL WAVE BACKGROUND**
4. **ROTATING COMPACT STARS – *“GW”PULSARS***

POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Sensitivity in First Science Run

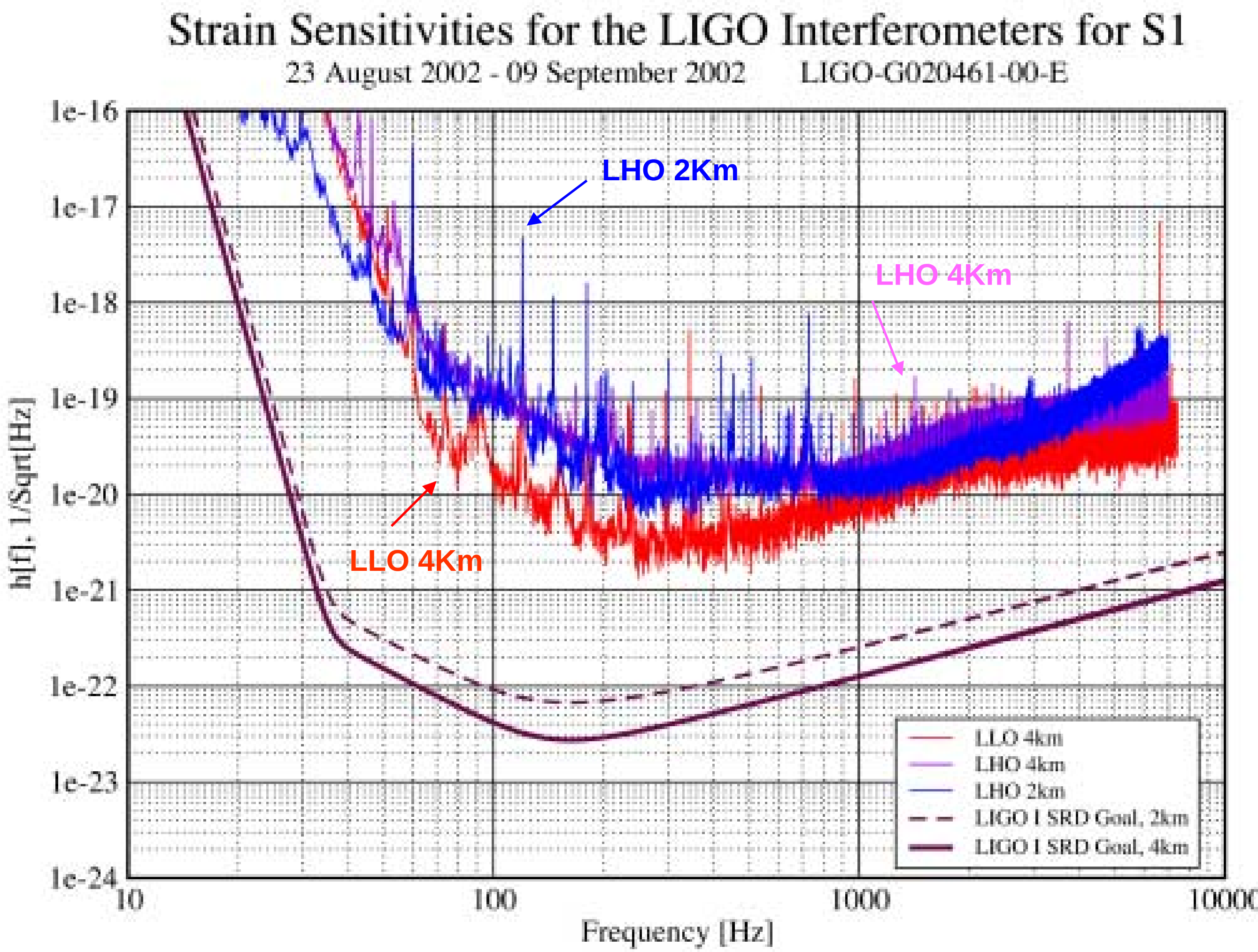
LIGO S1 Run

"First Upper Limit Run"

- **23 Aug–9 Sept 2002**
- **17 days**
- **All interferometers in power recycling configuration**

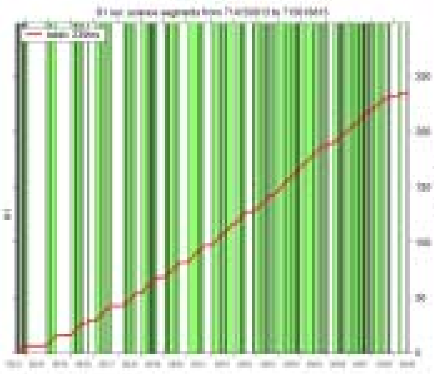
GEO in S1 RUN

Ran simultaneously
In power recycling
Lesser sensitivity

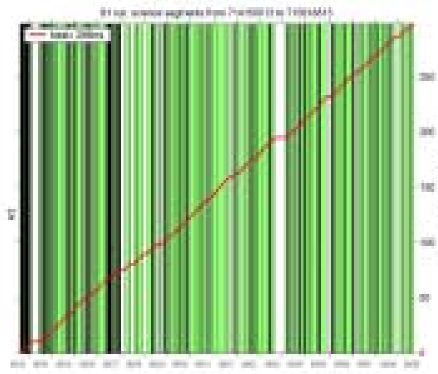


In-Lock Data Summary from S1

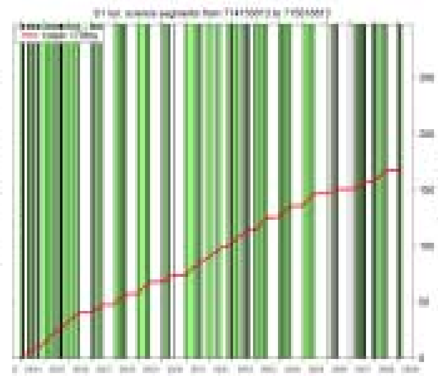
H1: 235 hrs



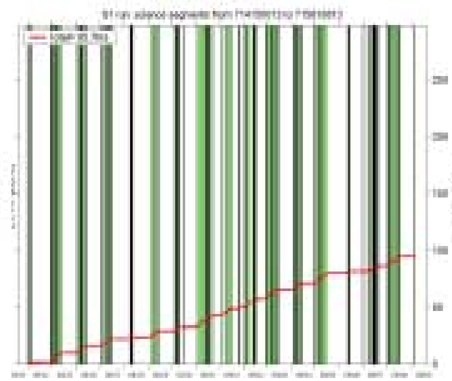
H2: 298 hrs



L1: 170 hrs



3X: 95.7 hrs



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

- **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 95.7 hours

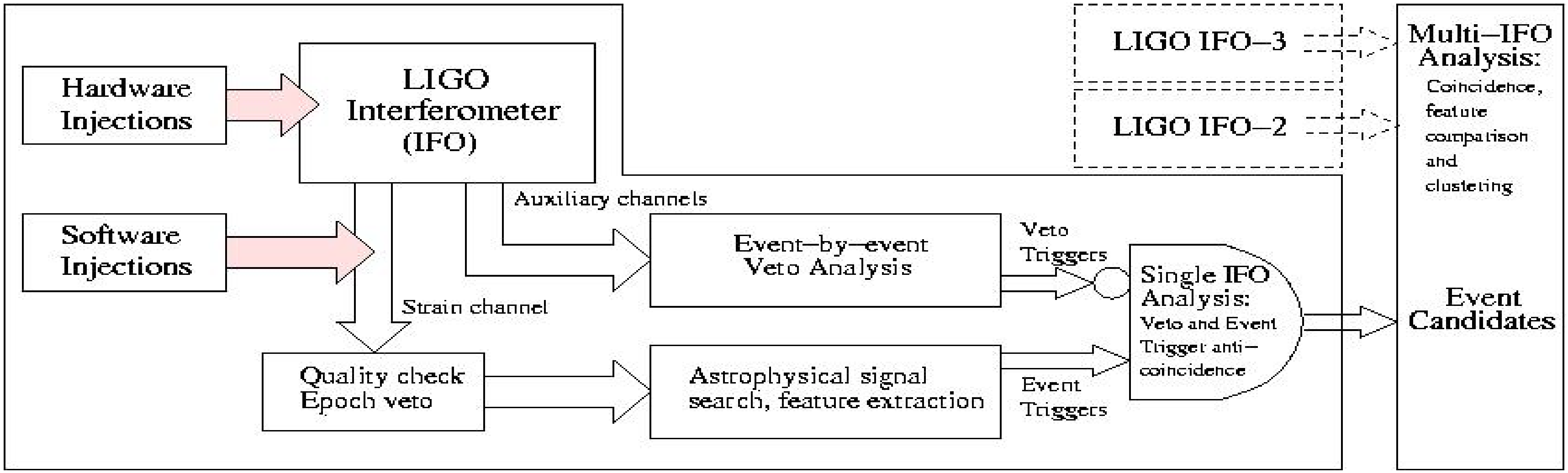
Issues in Data Analysis

- **Interferometric data:** continuous time series (16KHz) of anti-symmetric port measures the strain of a gravitational wave.
- Additional **auxiliary** channels report on servo systems and instruments' environment.
- Instrument **calibration** at the 10% level:
  - » Response tracking: continuous fixed sinusoidals.
  - » Transfer function mapping: complete sweep sine calibration.
- Analysis **emphasis**:
  - » Establish **methodology**, **no** sources expected.
  - » End-to-end **check and validation** via software and hardware **injections** mimicking passage of a gravitational wave.

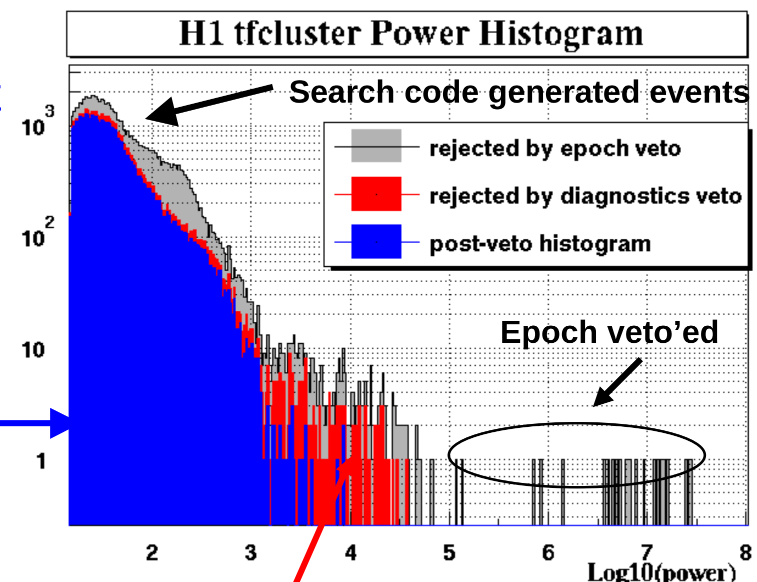
LIGO Search for Gravitational Wave Bursts

- **Sources:** **known** and **unknown phenomena** emitting short transients of gravitational radiation of **unknown waveform** (supernovae, black hole mergers).
- **Analysis goals:** **broad** frequency **band** search to (a) establish a **bound on their rate** at the instruments, (b) interpret bound in terms of a source and population model on a **rate vs. strength** exclusion plot.
- **Search methods:**
  - » **Time domain** algorithm ("SLOPE"): identifies rapid increase in amplitude of a filtered time series (threshold on 'slope').
  - » **Time-Frequency domain** algorithm ("TFCLUSTERS"): identifies regions in the time-frequency plane with excess power (threshold on pixel power and cluster size).

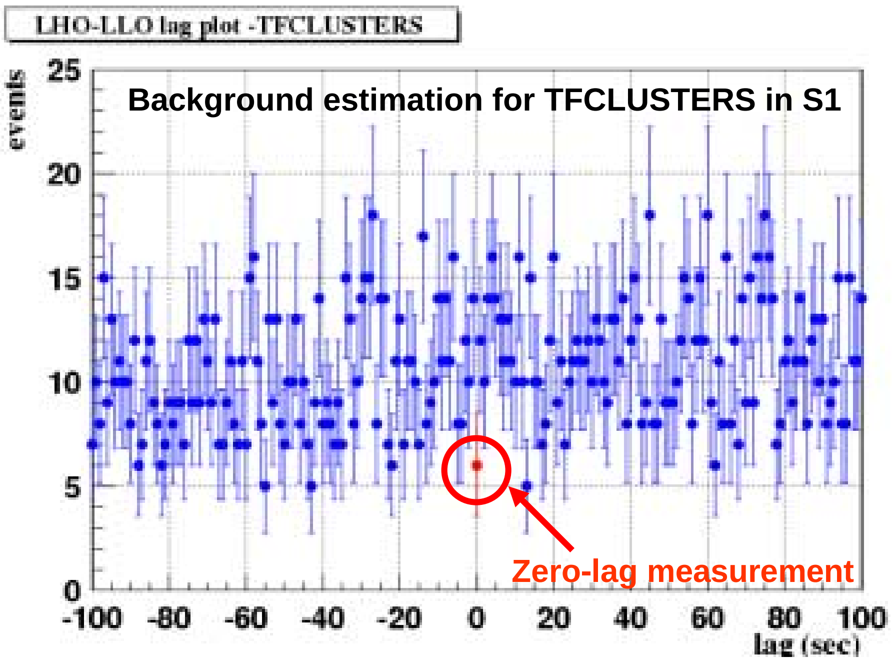
Bursts Search Pipeline

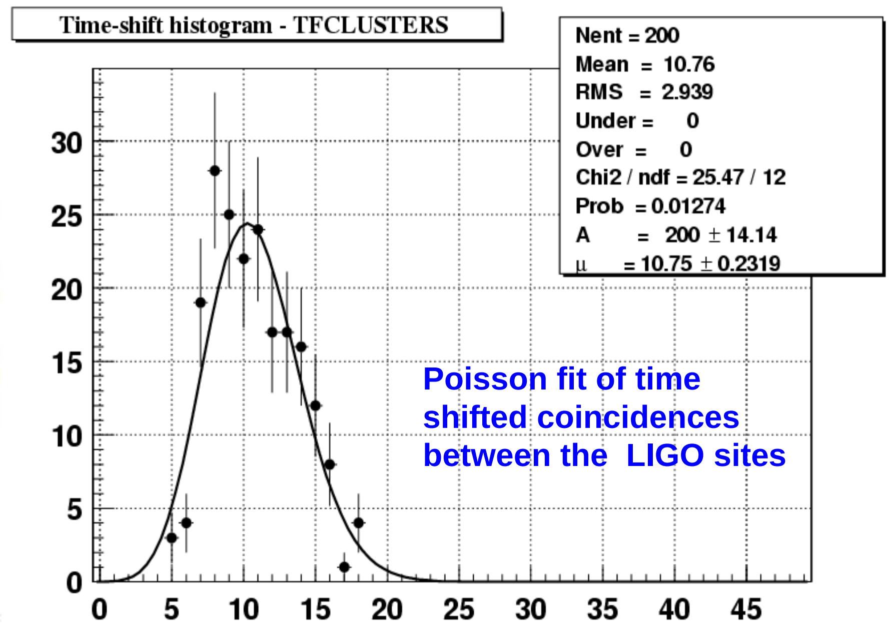


- basic assumption: **multi-interferometer response** consistent with a plane wave-front incident on network of detectors.
- **design the capability to veto** data epochs and events based on quality criteria and auxiliary channels.
- essential: use **temporal coincidence** of the 3 interferometer's 'best candidates'
- **correlate frequency** features of candidates (time-frequency domain analysis).



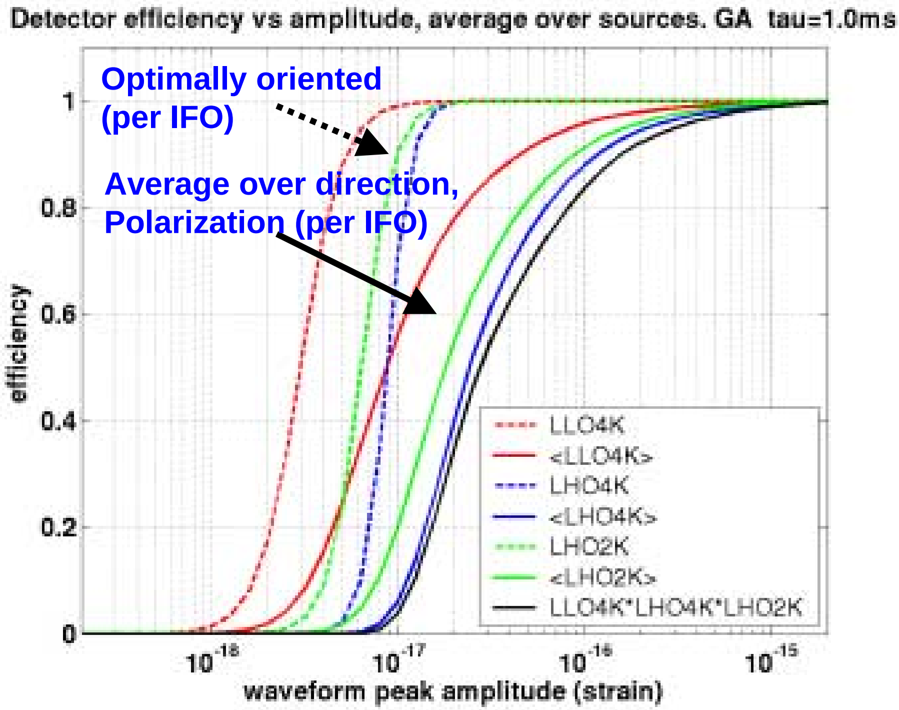
Upper Limit on Rate of Bursts

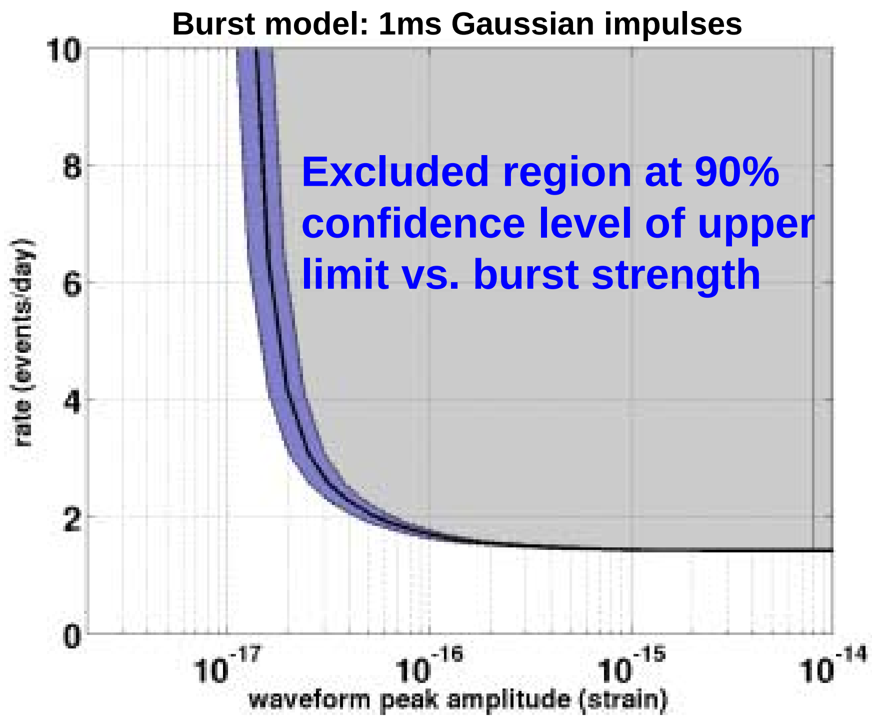




- **End result** of analysis pipeline: **number of triple coincidence events.**
- Use **time-shift** experiments to establish number of **background events.**
- Use **Feldman-Cousins** to set **90%** confidence upper limits on rate of foreground events:
  - » TFCLUSTERS: <**1.4** events/day
  - » SLOPE: <**5.2** events/day

LIGO Rate vs. Strength Plots for a Burst Model





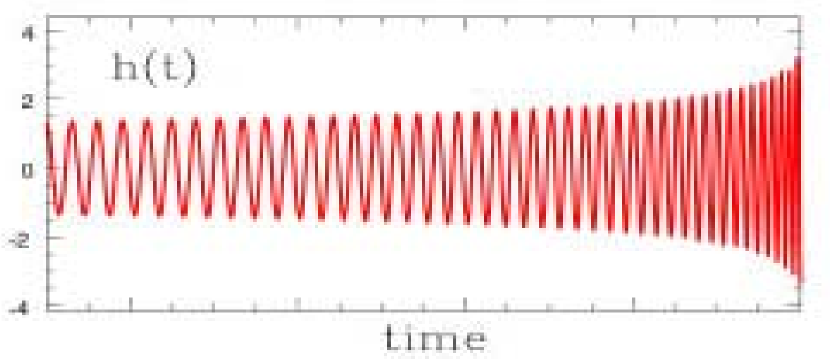
- Determine **detection efficiency** of the end-to-end analysis pipeline via **signal injection** of various morphologies.
- Assume a **population** of such sources **uniformly** distributed on a sphere around us: establish upper limit on **rate** of bursts as a function of their **strength.**

LIGO Burst Search Results and the Future

- Search and raw results **sensitive** to a wide variety of waveform morphologies and **broad frequency features** (as long as signal has significant strain amplitude in LIGO's frequency band).
- Strain upper limit assuming a burst model is for the case of 1ms Gaussian pulses at **1.4** events/day rising up as the detection efficiency reduces (50% efficiency point is at **$h\sim3x10^{-17}$**).
- In the near future:
  - » Use multiple-interferometer information on **amplitude** of putative signal and **correlation** statistic of their raw time-series.
  - » Improve **time-resolution** of event trigger generators.
  - » Pursue rigorously an **externally triggered** (by GRB's, neutrinos) search for bursts (exercised during S1).

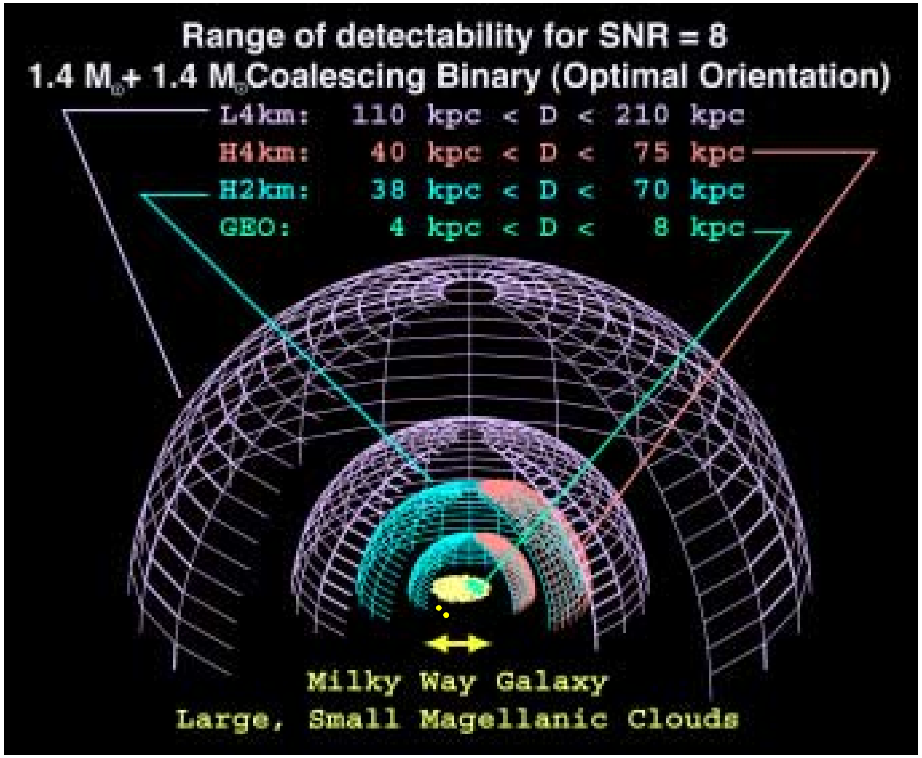
Search for Inspirals

- **Sources:** orbital-decaying **compact binaries: neutron star** known to exist and emitting gravitational waves (Hulse&Taylor).
- **Analysis goals:** determine an **upper limit** on the **rate** of **binary neutron star** inspirals in the universe.
  - » Search for black hole binaries and MACHOs will be pursued in the future
- **Search method:** system can be **modeled**, waveform is calculable:
  - » use optimal **matched filtering**: correlate detector's output with template waveform



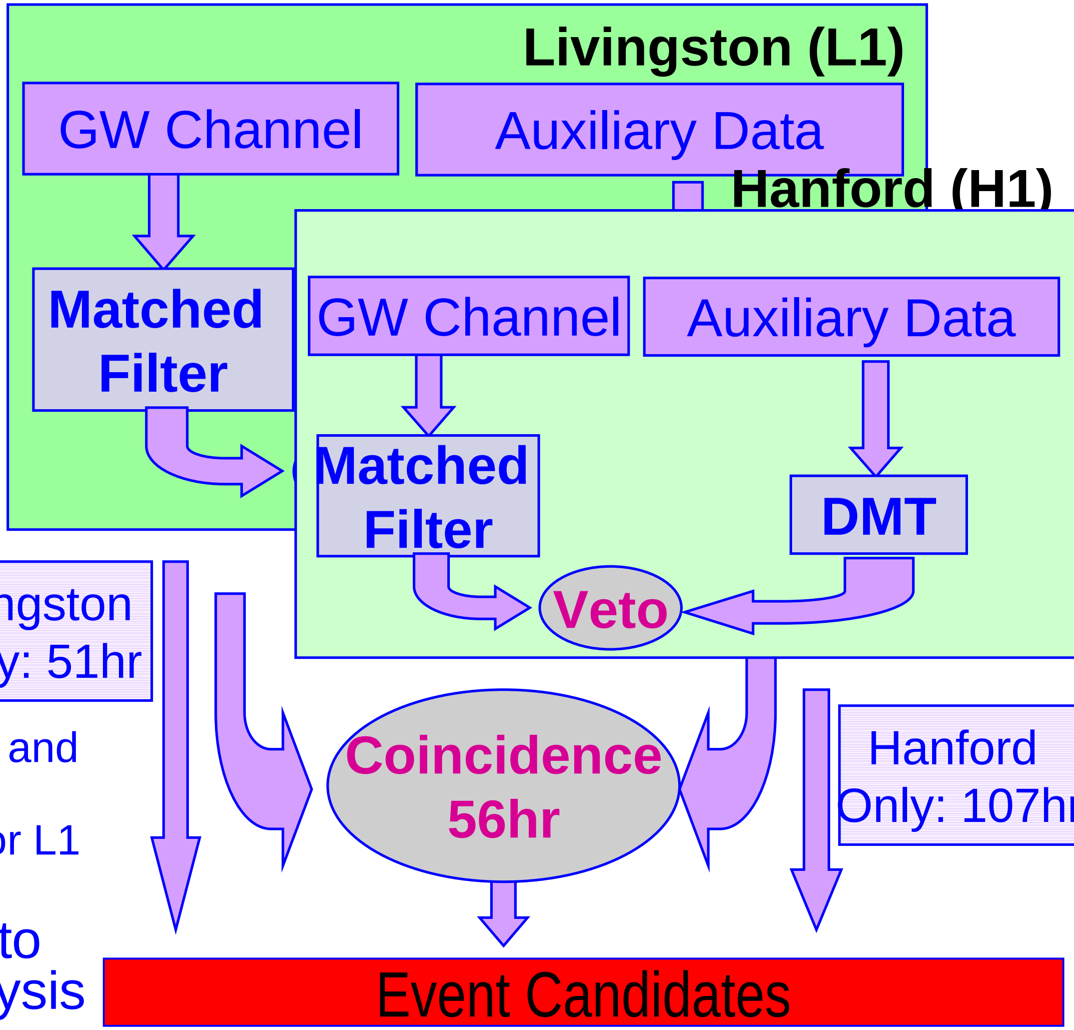
Sensitivity to Inspirals in S1

- 1-3M_{sun} **neutron star** search
  - Second-order post-Newtonian template waveforms for **non-spinning** binaries
  - Discrete set of 2110 templates designed for at most 3% loss in SNR
- **Range** of detectability of a 2x1.4 M_{sun} optimally oriented inspiral at SNR = 8
  - **L1:** 110 kpc < D < 210 kpc
  - **H1:** 40 kpc < D < 75 kpc
  - **H2:** 38 kpc < D < 70 kpc
- Sensitive to inspirals in
  - **Milky Way, LMC & SMC**



Inspiral Search Pipeline

- Use **L1** and **H1**
- Matched filter trigger:
  - » **Threshold on SNR**, and compute χ^2 : small values indicate that SNR accumulates in manner consistent with an inspiral signal.
  - » **Threshold on** χ^2, record trigger
  - » Triggers are **clustered** within duration of each template
- Auxiliary data triggers
  - **Vetoes** eliminate noisy data
- Event Candidates
  - » Coincident in time, binary mass, and distance when H1, L1 clean
  - » Single IFO trigger when only H1 or L1 operate
- Use **Monte Carlo** simulations to calculate efficiency of the analysis
  - » Model of sources in the Milky Way, LMC,SMC



Results of the Inspiral Search

- Upper limit on binary neutron star coalescence rate
- Use all triggers from Hanford and Livingston: 214 hours
  - » Cannot accurately assess **background** (be conservative, **assume zero**).
  - » Use **maximum signal-to-noise ratio** statistic to establish the rate limit.
  - » Monte Carlo simulation **efficiency** = 0.51
  - » 90% confidence limit = **2.3/ (efficiency * time).**
  - » Express the rate as a rate per **Milky Way Equivalent Galaxies** (MWEG).

$R < 2.3 / (0.51 \times 214 \text{ hr}) = 1.64 \times 10^2 \text{ /yr/(MWEG)}$

- Previous observational limits
  - » Japanese TAMA → R < 30,000 / yr / MWEG
  - » Caltech 40m → R < 4,000 / yr / MWEG
- Theoretical prediction
  - » $R < 2 \times 10^{-5}$ / yr / MWEG

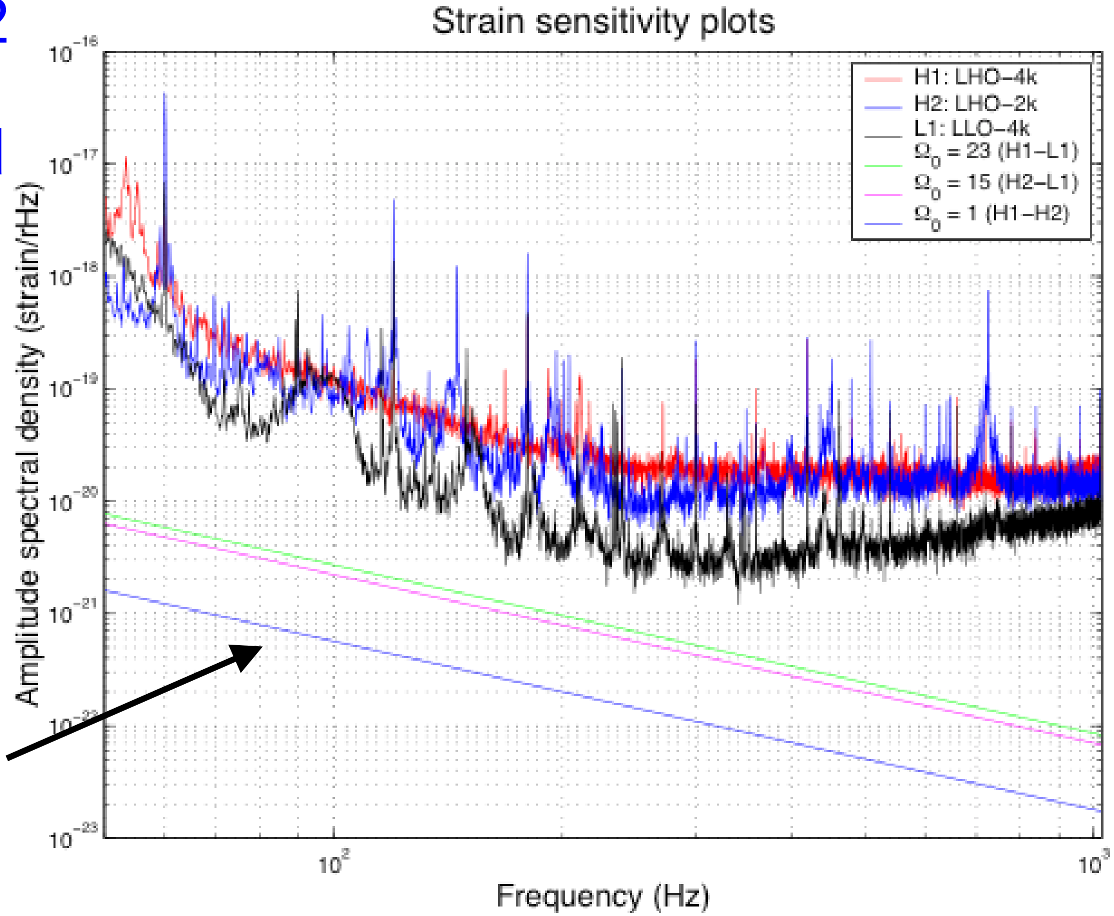
LIGO Search for Stochastic Radiation

- **Sources:** **early universe**, **many** weak unresolved **sources** emitting gravitational waves independently so that a **random** type of radiation described by its **spectrum** (isotropic, unpolarized, stationary and Gaussian) impacts on the detectors.
- **Analysis goals:** **constrain** contribution of stochastic radiation's energy ρ_{GW} to the total energy required to close the universe $\rho_{critical}$:

$$\int_0^\infty (1/f)\,\Omega_{GW}(f)\,df = \frac{\rho_{GW}}{\rho_{critical}}$$

LIGO Methods for the Stochastic Search

- Optimally filtered **cross-correlation** of detector pairs: L1-H1, L1-H2 and H1-H2
- Detector **separation** and **orientation** reduces correlations at high frequencies ($\lambda_{GW} \geq$ 2xBaseLine): **overlap reduction function**
  - » H1-H2 best suited
  - » L1-H1(H2) significant <50Hz
- Achievable **sensitivities to Ω** by detector pairs in **S1**



Results of Stochastic Search

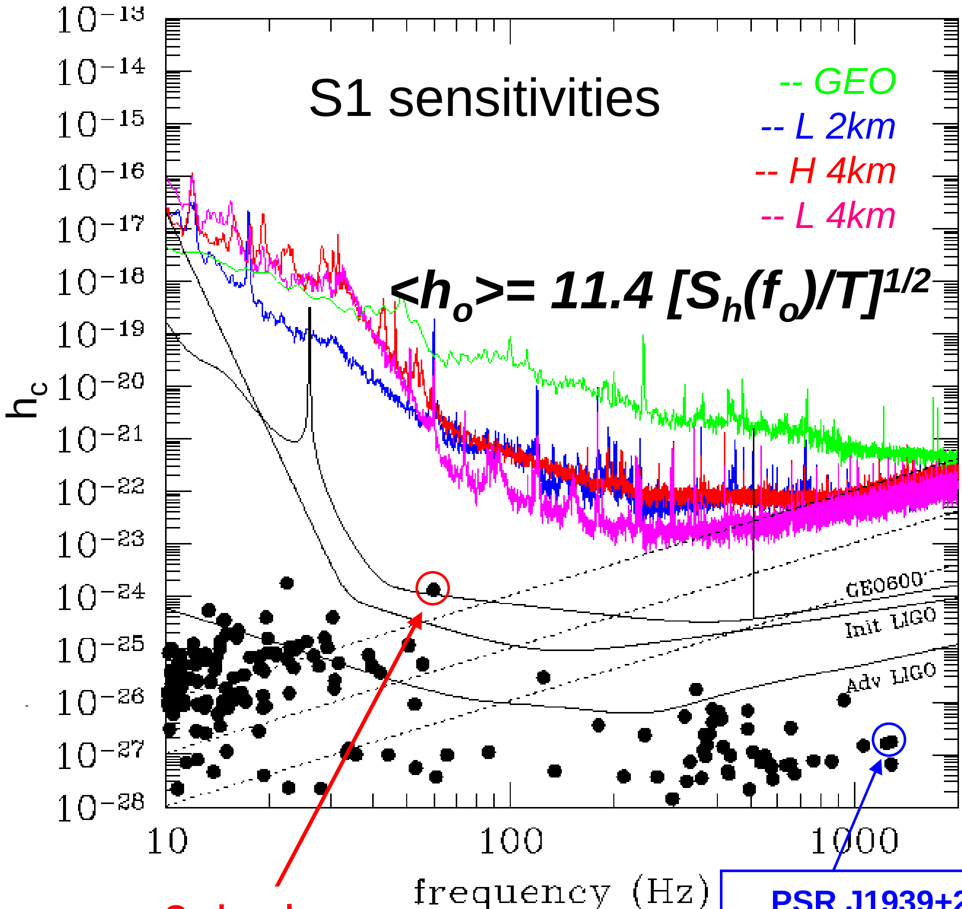
Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 72.4	62.3 hrs
LHO 2km-LLO 4km	still in progress	61.0 hrs

- Non-negligible LHO 4km-2km (H1-H2) cross-correlation; currently being investigated.
- Previous best upper limits:
  - » *Measured:* Garching-Glasgow interferometers : $\Omega_{GW}(f) < 3\times10^{5}$
  - » *Measured*: EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(907Hz) < 60$

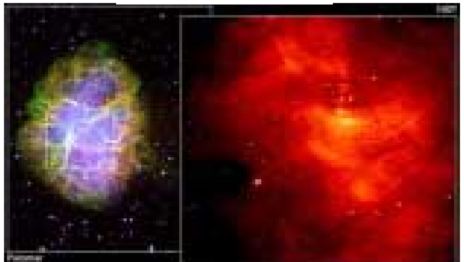
Search for Continuous Waves

- **Sources:** **known rotating neutron stars** emitting gravitational waves due to small distortions of their shape (small ellipticity).
- **Analysis goals:** given the position, frequency and spin-down parameter of a known pulsar establish **an upper limit on the amplitude** of its continuous wave emission.
- **Achievable sensitivities:** power spectral densities of the instruments determine the detectability level of a continuous wave amplitude $\langle h_o \rangle = 11.4\ [S_h(f_o)/T]^{1/2}$.

LIGO Expectations for Continuous Waves



Crab pulsar



PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1.0511 10^{-19} s/s
D = 3.6 kpc

- **Detectable amplitudes** with a 1% false alarm rate and 10% false dismissal rate by the interferometers during S1 (colored curves) and at design sensitivities (black curves).
- **Limits** of detectability for rotating NS with equatorial ellipticity $\varepsilon = \delta I/I_{zz}$: ***$10^{-3}$, 10^{-4} , 10^{-5} @ 8.5 kpc.***
- **Upper limits** on **$\langle h_o \rangle$** from spin-down measurements of known radio pulsars (filled circles).

S1: NO DETECTION EXPECTED

Graphic by R. Dupuis, Glasgow

Algorithms for CW Search

- Central **parameters** in detection algorithms:
  - » **frequency modulation** of signal due to Earth's motion relative to the Solar System Barycenter, intrinsic frequency changes.
  - » **amplitude modulation** due to the detector's antenna pattern.
- Search for **known pulsars** dramatically reduces the parameter space:
  - » computationally feasible.
- **Two** search **methods** used:
  - » **Frequency-domain** based.
  - » **Time-domain** based.

Illustration of methods for PSR J1939+2134

Frequency domain

- Fourier Transforms of time series
- Detection statistic: **F ,** maximum likelihood ratio wrt unknown parameters
- use signal injections to measure F 's pdf
- use frequentist's approach to derive upper limit

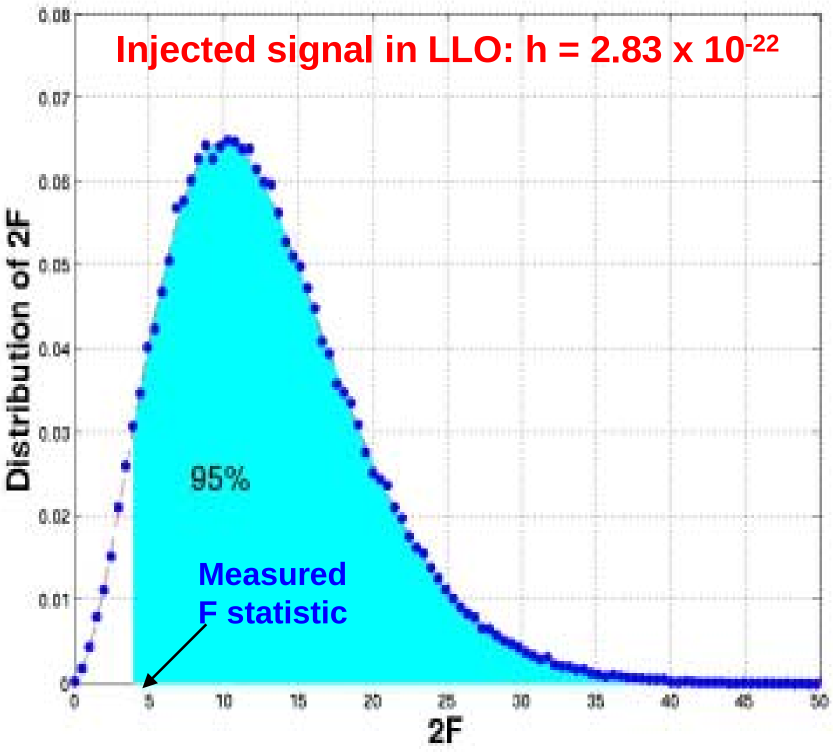
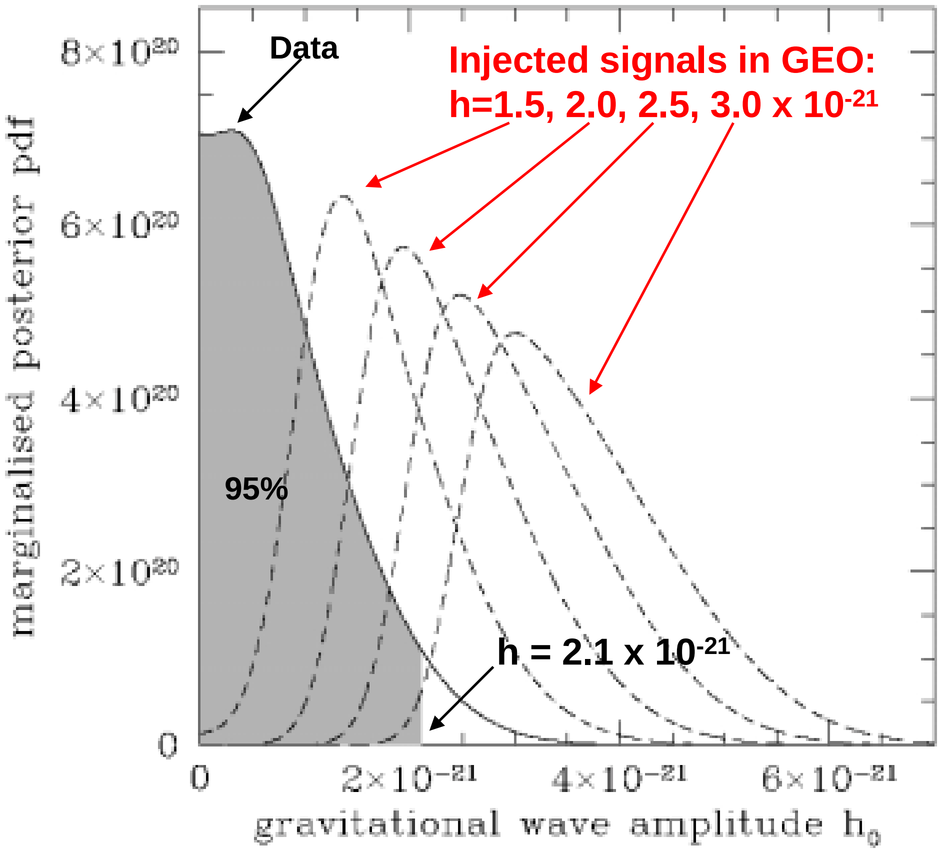


Illustration of methods for PSR J1939+2134

Time domain

- time series is heterodyned
- noise is estimated
- Bayesian approach in parameter estimation: express result in terms of posterior pdf for parameters of interest



Results of Search for CW

- **No evidence** of continuous wave emission from **PSR J1939+2134**.
- Summary of **95% upper limits** on h:

IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.94\pm0.12)\times10^{-21}$	$(2.1\pm0.1)\times10^{-21}$
LLO	$(2.83\pm0.31)\times10^{-22}$	$(1.4\pm0.1)\times10^{-22}$
LHO-2K	$(4.71\pm0.50)\times10^{-22}$	$(2.2\pm0.2)\times10^{-22}$
LHO-4K	$(6.42\pm0.72)\times10^{-22}$	$(2.7\pm0.3)\times10^{-22}$
Joint	-	$(1.0\pm0.1)\times10^{-22}$

- $h_o<1.0\times10^{-22}$ constrains **ellipticity $< 7.5\times10^{-5}$** ($M=1.4M_{sun}$, $r=10$km, $R=3.6$kpc)
- Previous results for PSR J1939+2134: **$h_o < 10^{-20}$** (Glasgow, Hough et al., 1983), **$h_o < 3.1(1.5)\times10^{-17}$** (Caltech, Hereld, 1983).

LIGO Science Has Started

- LIGO has started taking data
- LIGO had its **first science run** ("S1") last summer
  - » Collaboration has carried out **first analysis** looking for:
    - ✓ Bursts
    - ✓ Compact binary coalescences
    - ✓ Stochastic background
    - ✓ Periodic sources
- **Second science run** ("S2") began 14 February and will end 14 April:
  - » Sensitivity is ~10x better than S1
  - » Duration is ~ 4x longer
    - – Bursts: rate limits: 4X lower rate & 10X lower strain limit
    - – Inspirals: reach will exceed 1Mpc -- includes M31 (Andromeda)
    - – Stochastic background: limits on $\Omega_{GW} < 10^{-2}$
    - – Periodic sources: limits on h_{max} ~ few x 10^{-23} (ε ~ few x 10^{-6} @ 3.6 kpc)
- Ground based interferometers are **collaborating internationally**:
  - » LIGO and GEO (UK/Germany) during "S1"
  - » LIGO and TAMA (Japan) during "S2"