The Laser Interferometer Gravitational Wave Observatory

LIGO at the threshold of science operations

Albert Lazzarini
LIGO Laboratory

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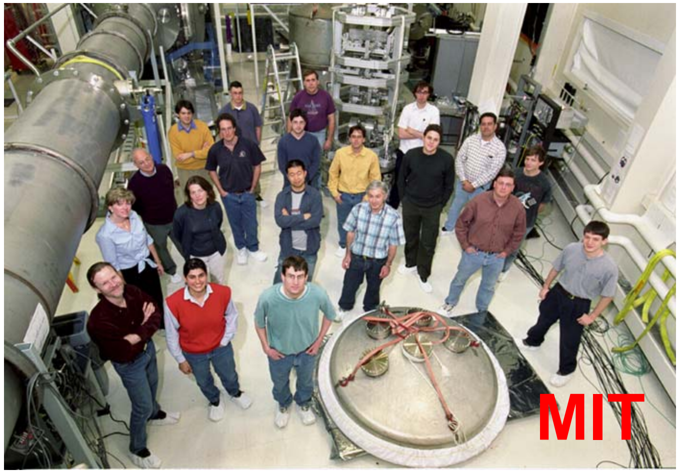
Pune, India

Acknowledgements: LIGO Laboratory



…just a few of the many individuals that have contributed to LIGO

LIGO Scientific Collaboration

LIGO I Development Group: 22 Institutions, 26 Groups, 281 Members

http://www.ligo.caltech.edu/LIGO_web/lsc/lsc.html

US Universities:

- Caltech
- Carleton College
- Cornell University
- California State University Dominguez Hills
- University of Florida
- Hobart & William Smith College
- Louisiana State University
- Louisiana Techinical University
- University of Michigan
- MIT
- Oregon
- Pennsylvania State University
- Southern University
- Syracuse University
- University of Texas-Brownsville
- University of Wisconsin-Milwaukee

US Agencies & Institutions

- FNAL (DOE)
- Goddard-GGWAG (NASA)
- Harvard-Smithsonian

International Members:

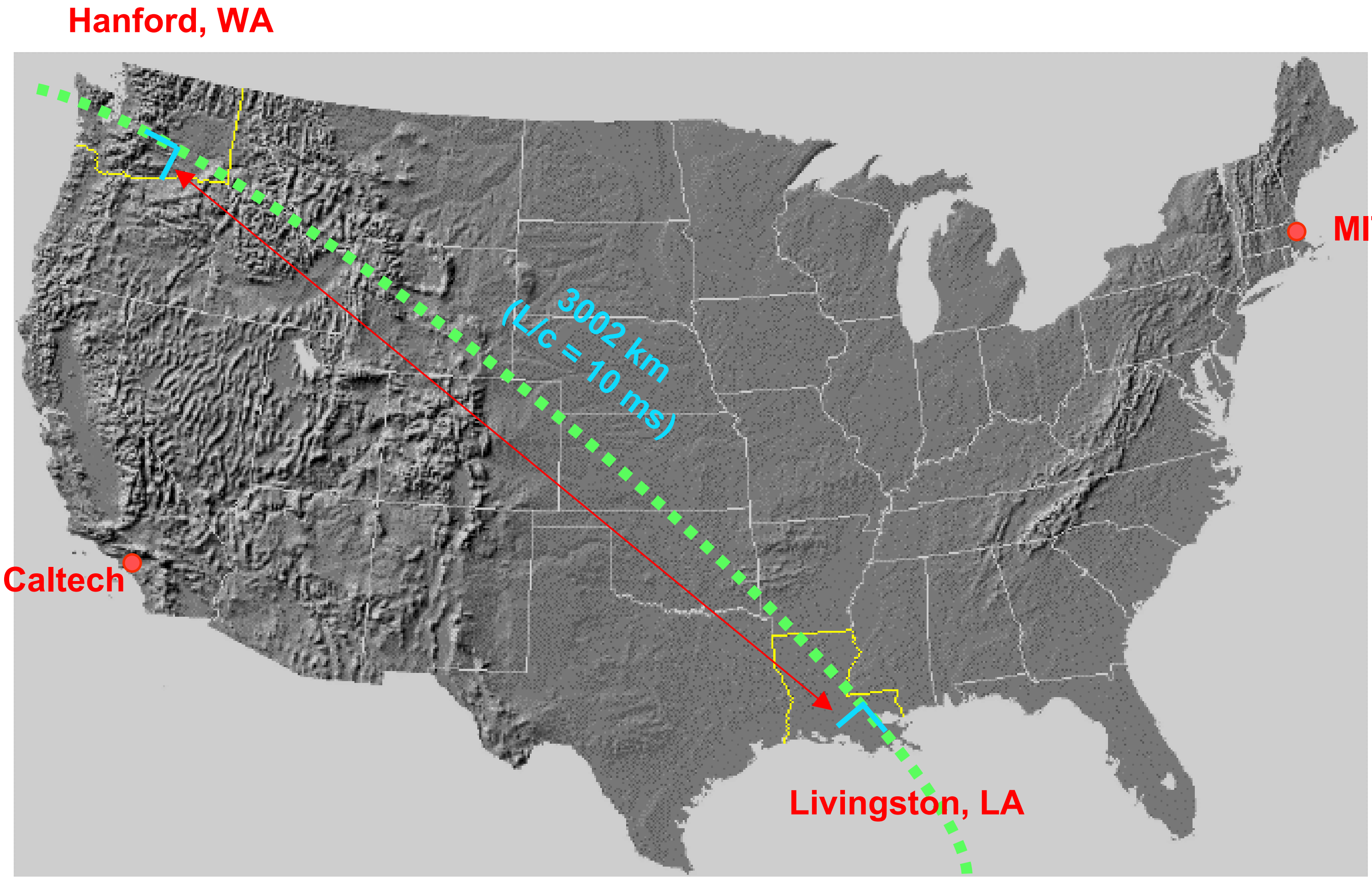
- ACIGA (Australia)
- GEO 600 (UK/Germany)
- ***IUCAA (Pune, India)***

International partners (have MOUs with LIGO Laboratory):

- *TAMA (Japan)*
- *Virgo (France/Italy)*

The LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites



LIGO Observatories

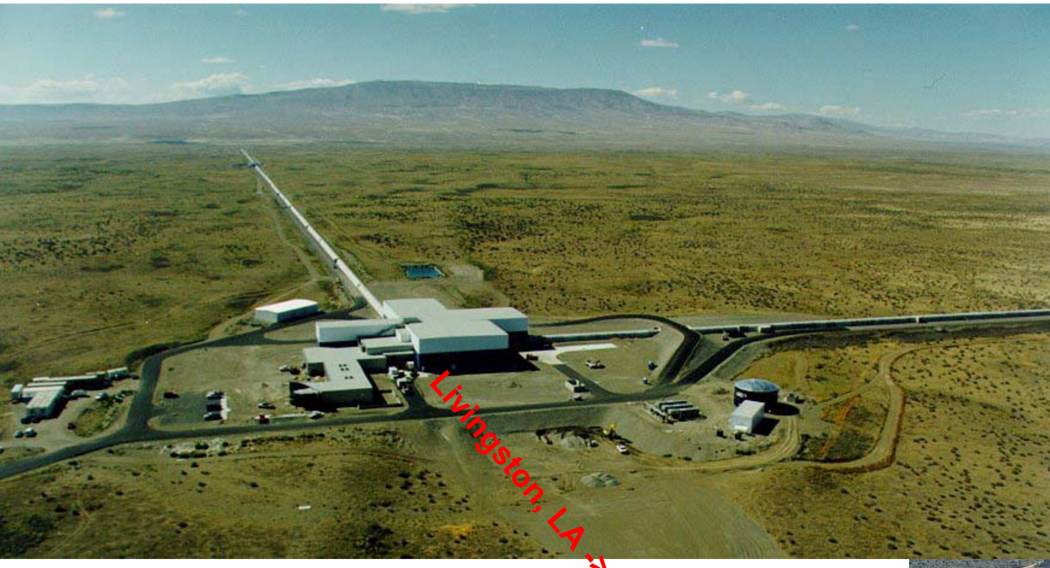
GEODETIC DATA (WGS84)

h: -6.574 m *X arm: S72.2836°W*

ϕ: N30°33'46.419531" *Y arm: S17.7164°E*

λ: W90°46'27.265294"

Livingston Observatory
Louisiana
One interferometer (4km)



Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

GEODETIC DATA (WGS84)

h: 142.555 m *X arm: N35.9993°W*

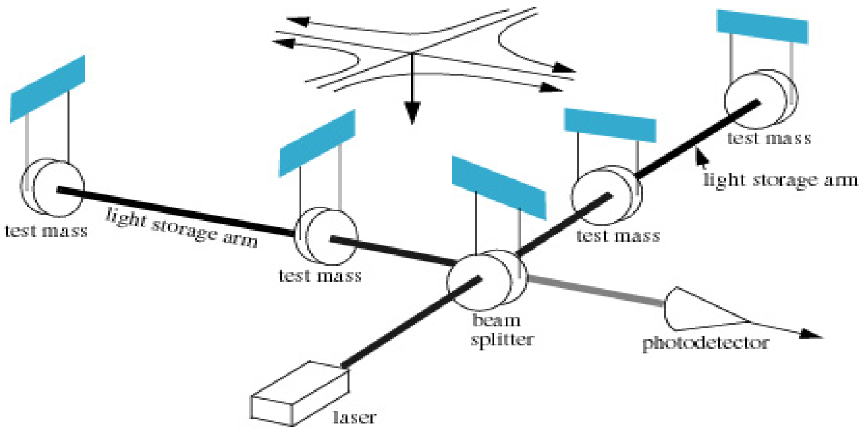
ϕ: N46°27'18.527841" *Y arm: S54.0007°W*

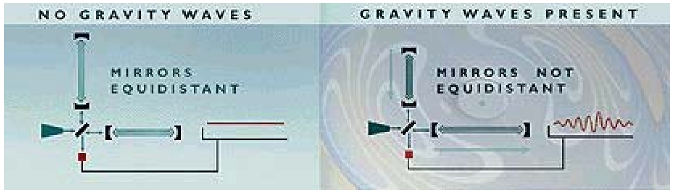
λ: W119°24'27.565681"

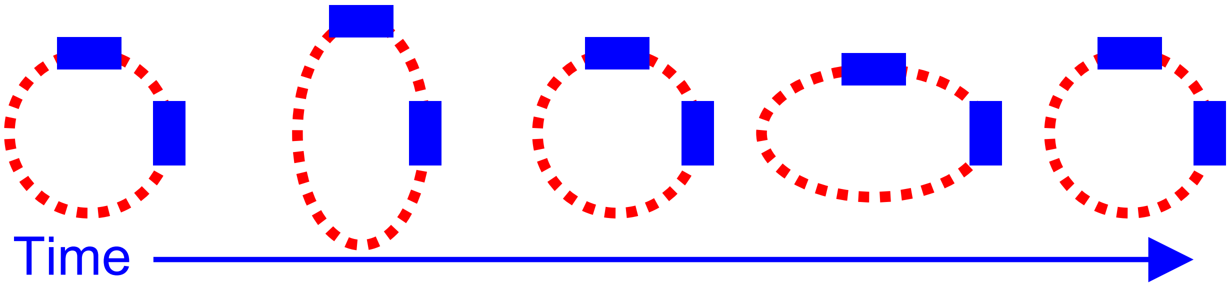
Interferometric GW Detectors

Principle of Detection:

- A gravitational wave causes the interferometers arm lengths to vary by stretching one arm while compressing the other, in the plane perpendicular to direction of travel.





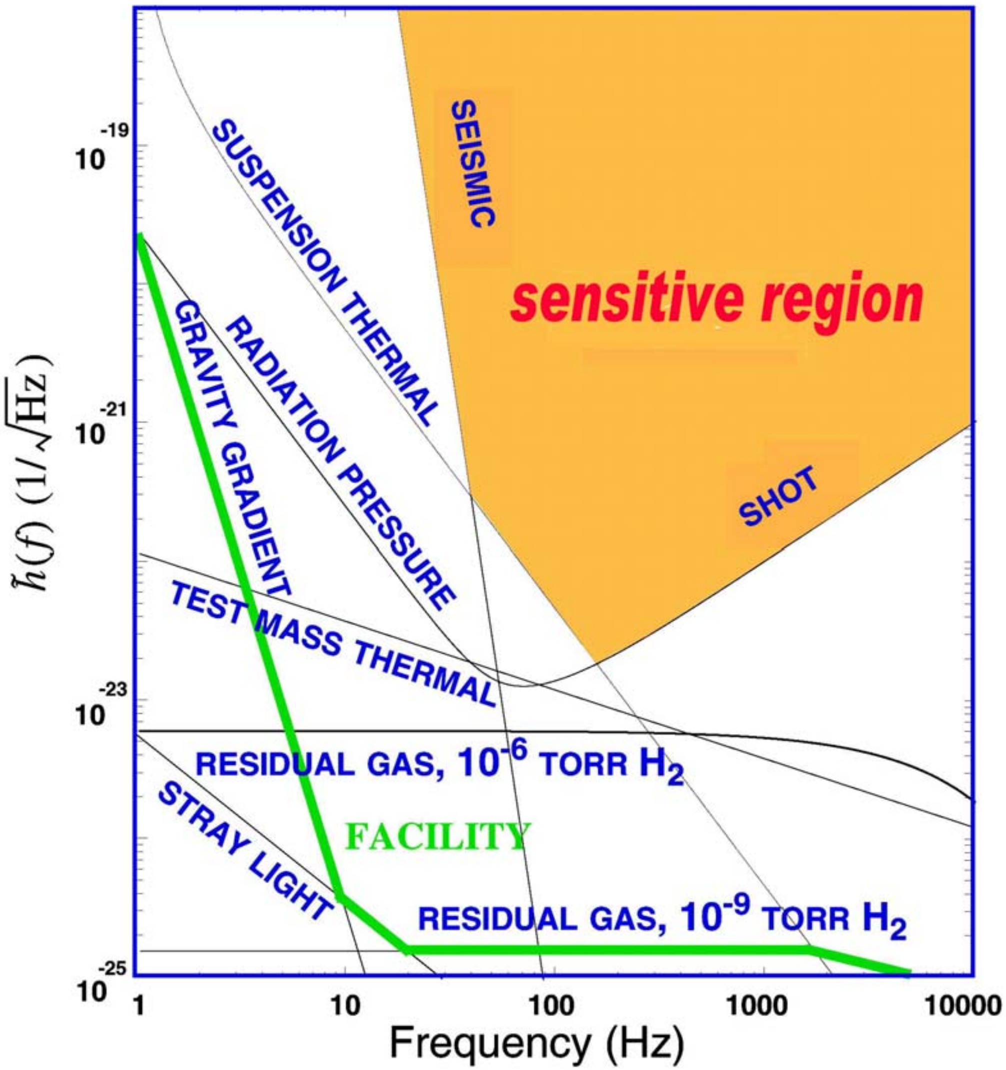


LIGO First Generation Detector

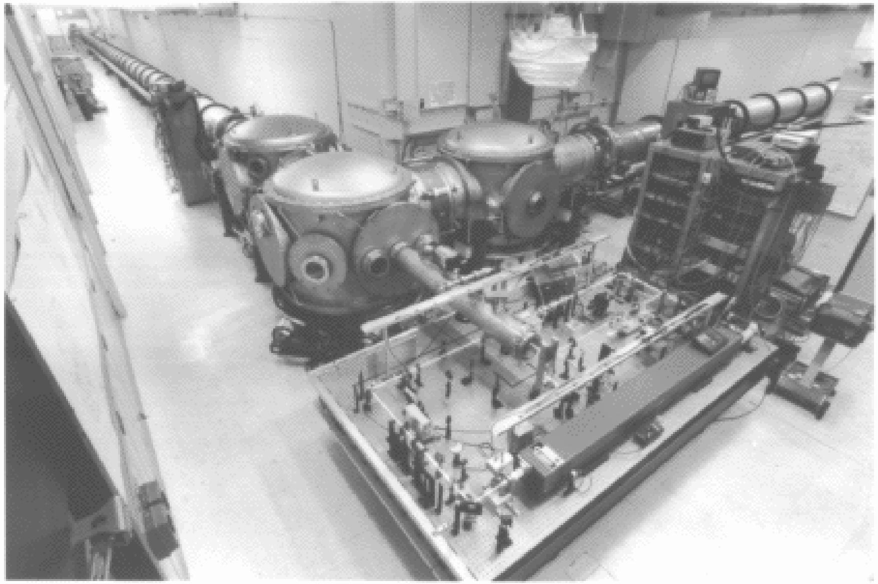
Limiting noise floor

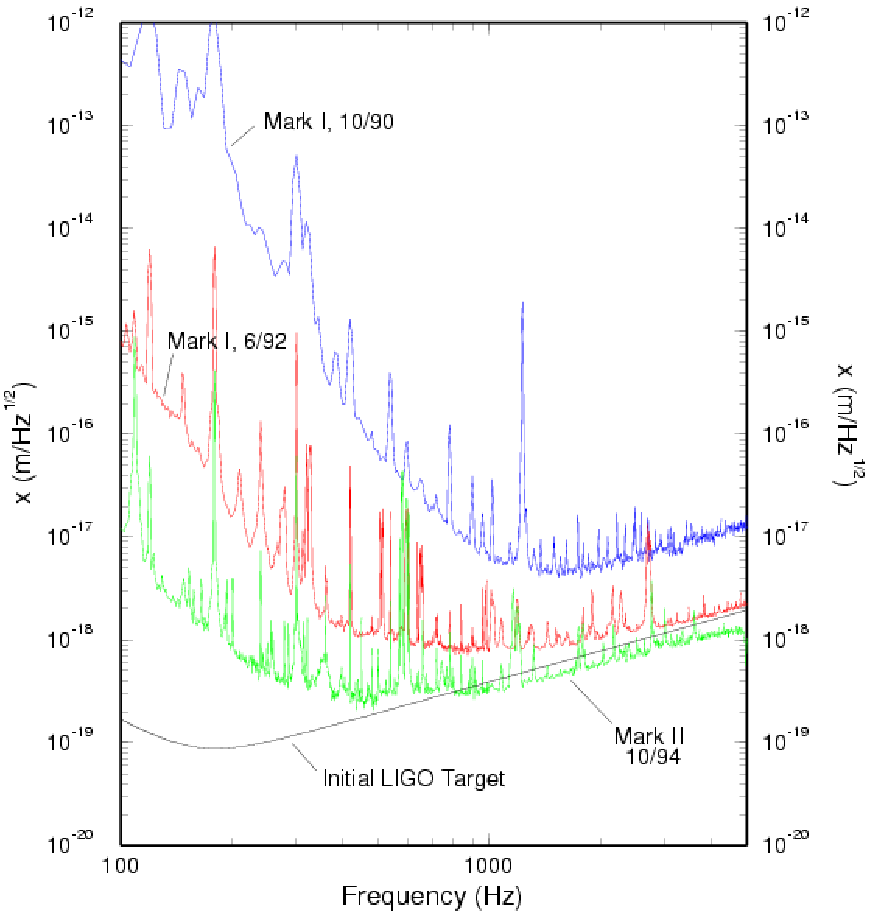
- **Interferometry is limited by three fundamental noise sources**
  - **<u>seismic noise</u> at the lowest frequencies**
  - **<u>thermal noise</u> (Brownian motion of mirror materials, suspensions) at intermediate frequencies**
  - **<u>shot noise</u> at high frequencies**

- **Many other noise sources lie beneath and must be controlled as the instrument is improved**



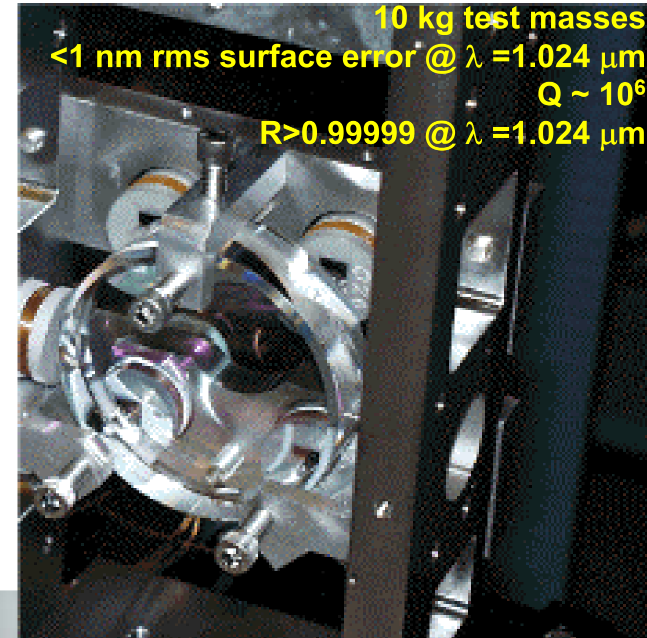
The Early Years:
Caltech 40 Meter Interferometer

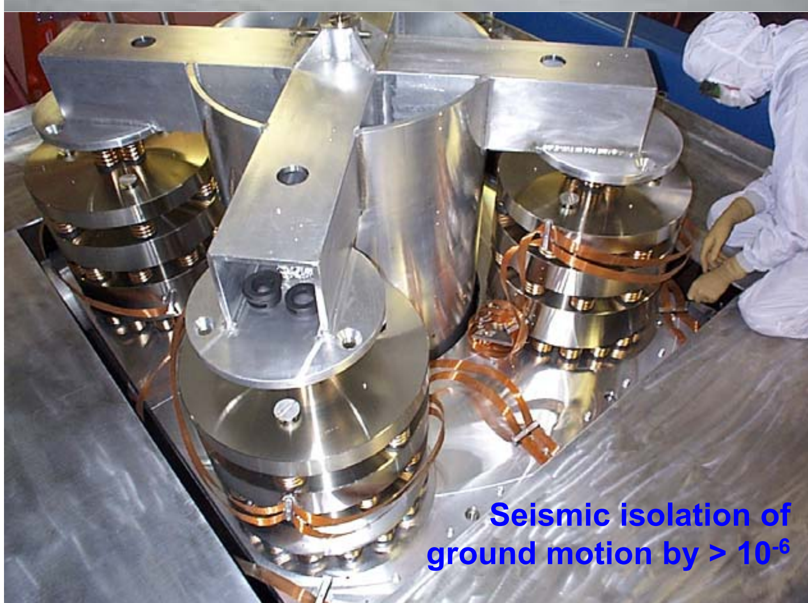




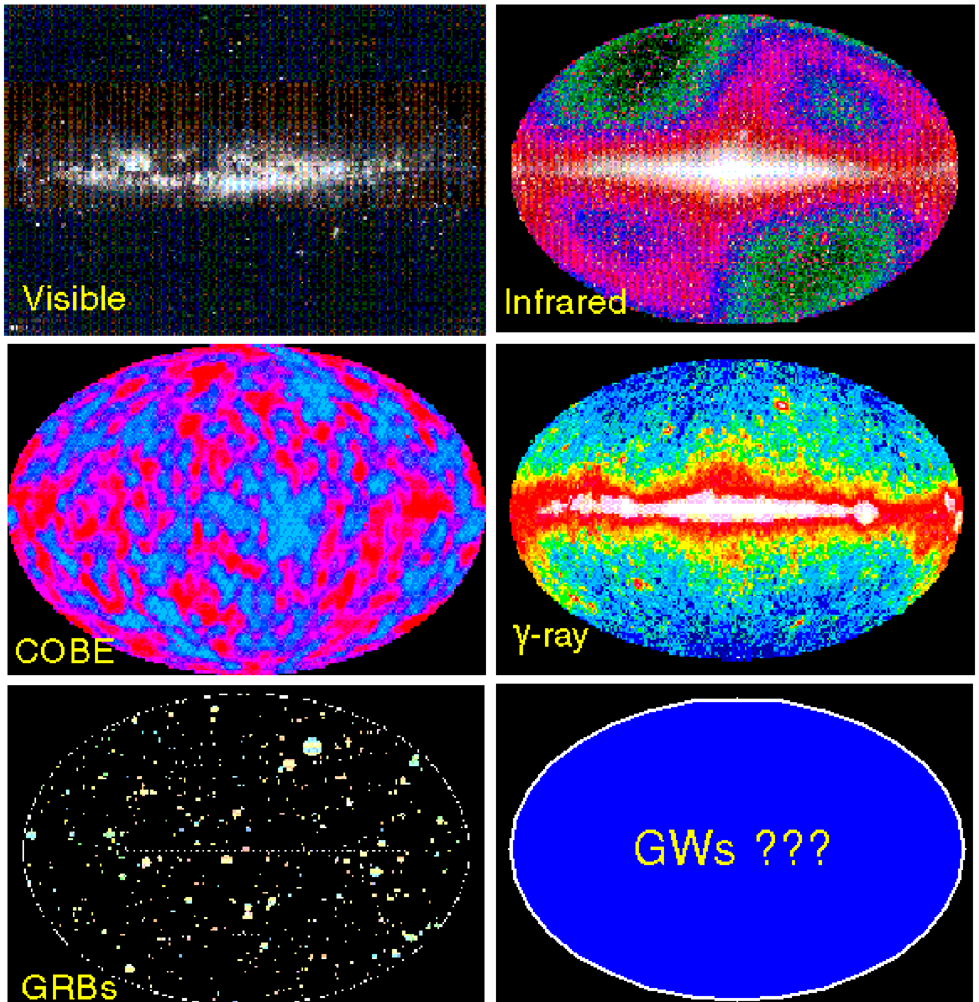
- $1/100^{th}$ scale prototype for LIGO.
- Characterized fundamental noise sources.
- Critical as a technology proving ground.

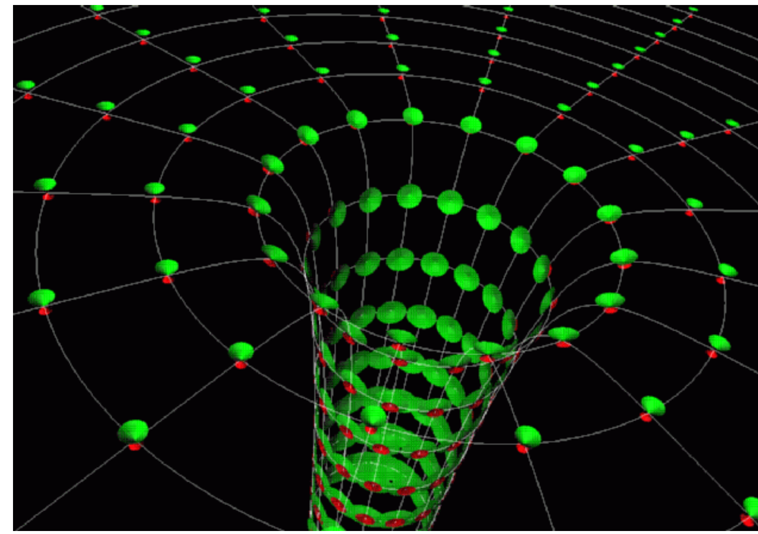
Interferometric GW Detectors





New Window on Universe



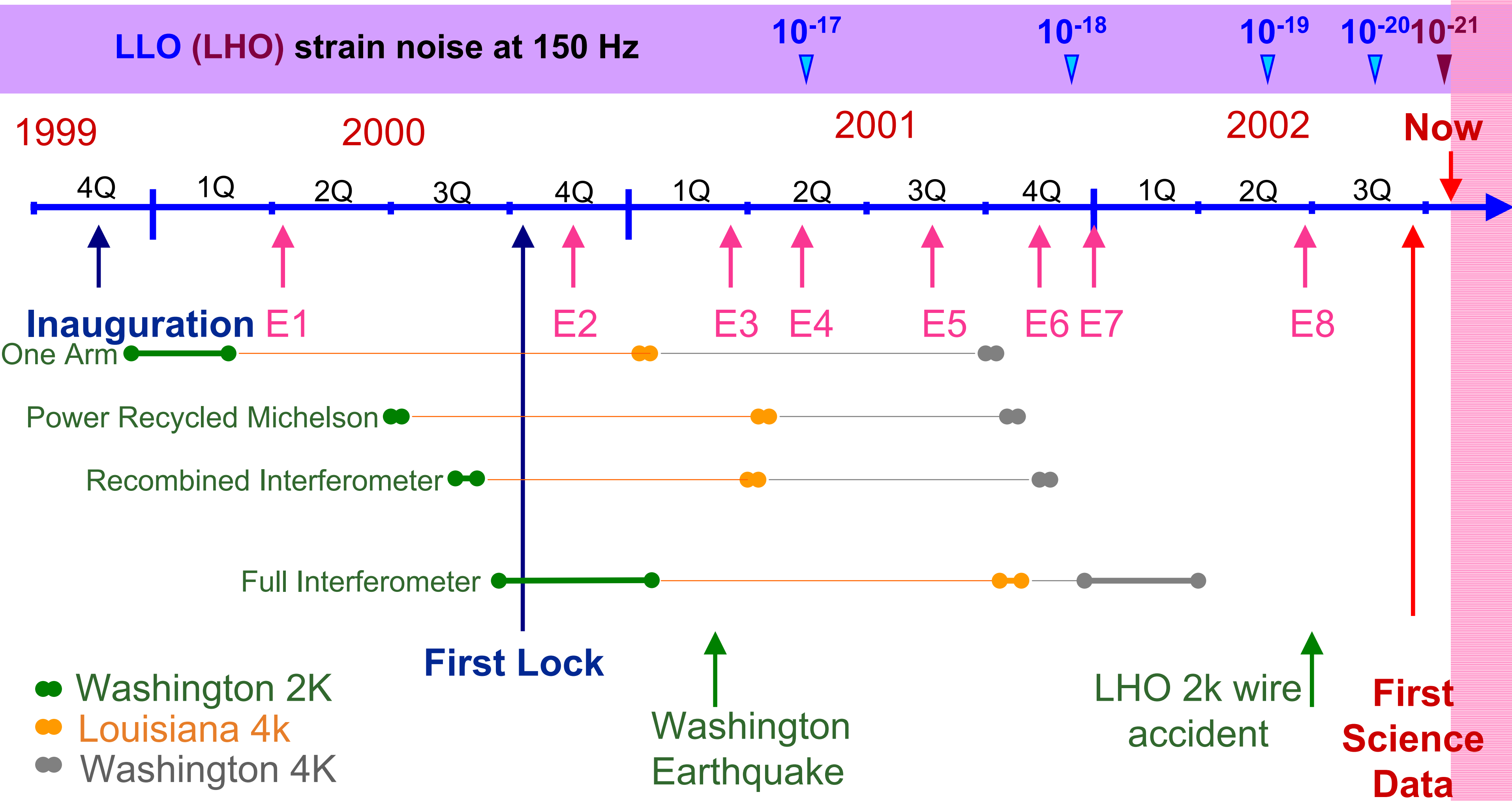


GRAVITATIONAL WAVES WILL GIVE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

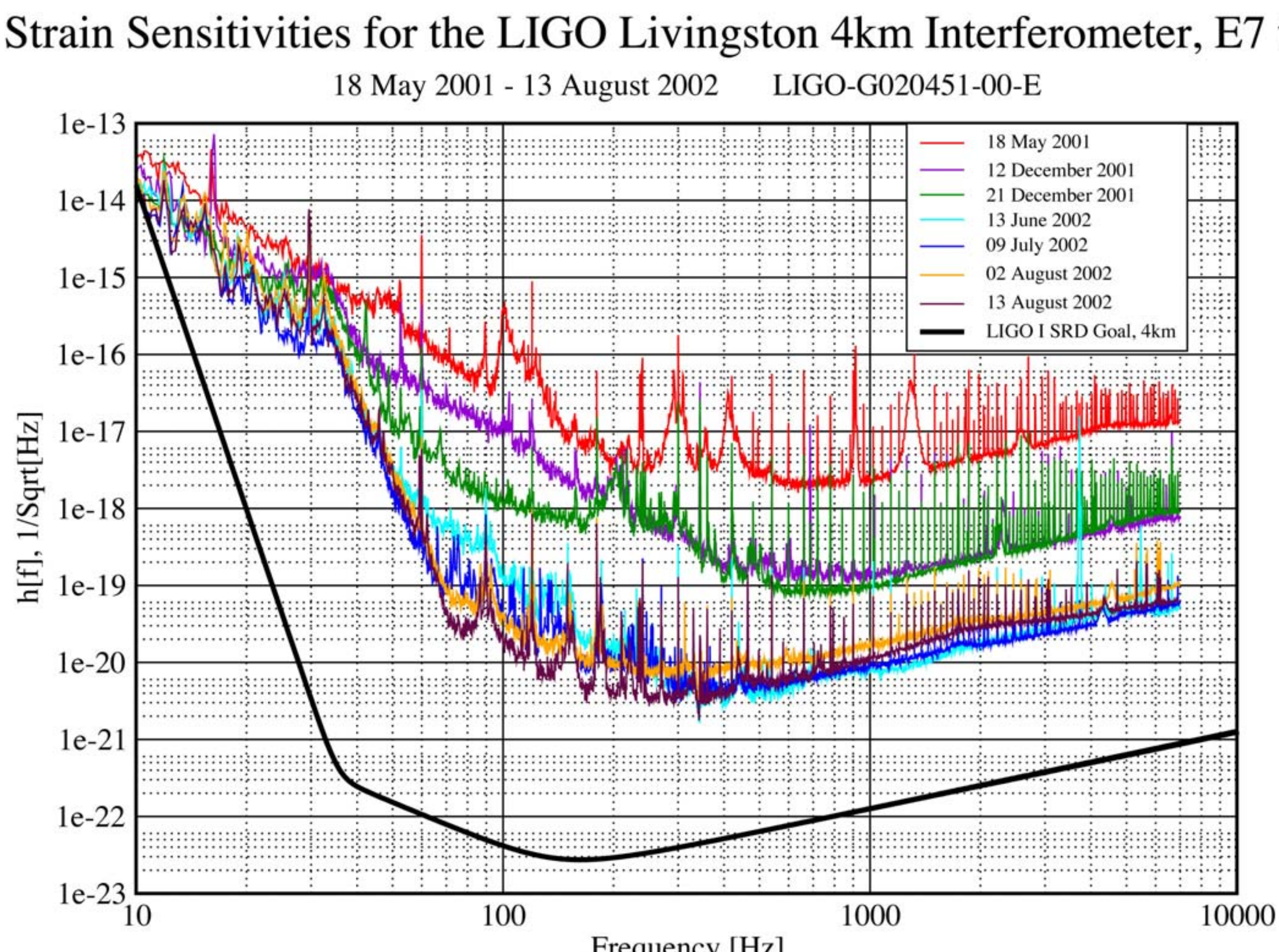
EXPECTED SOURCES: BLACK HOLES, SUPERNOVAE, PULSARS AND COMPACT BINARY SYSTEMS.

POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Timeline to Science



Sensitivity has steadily improved throughout commissioning

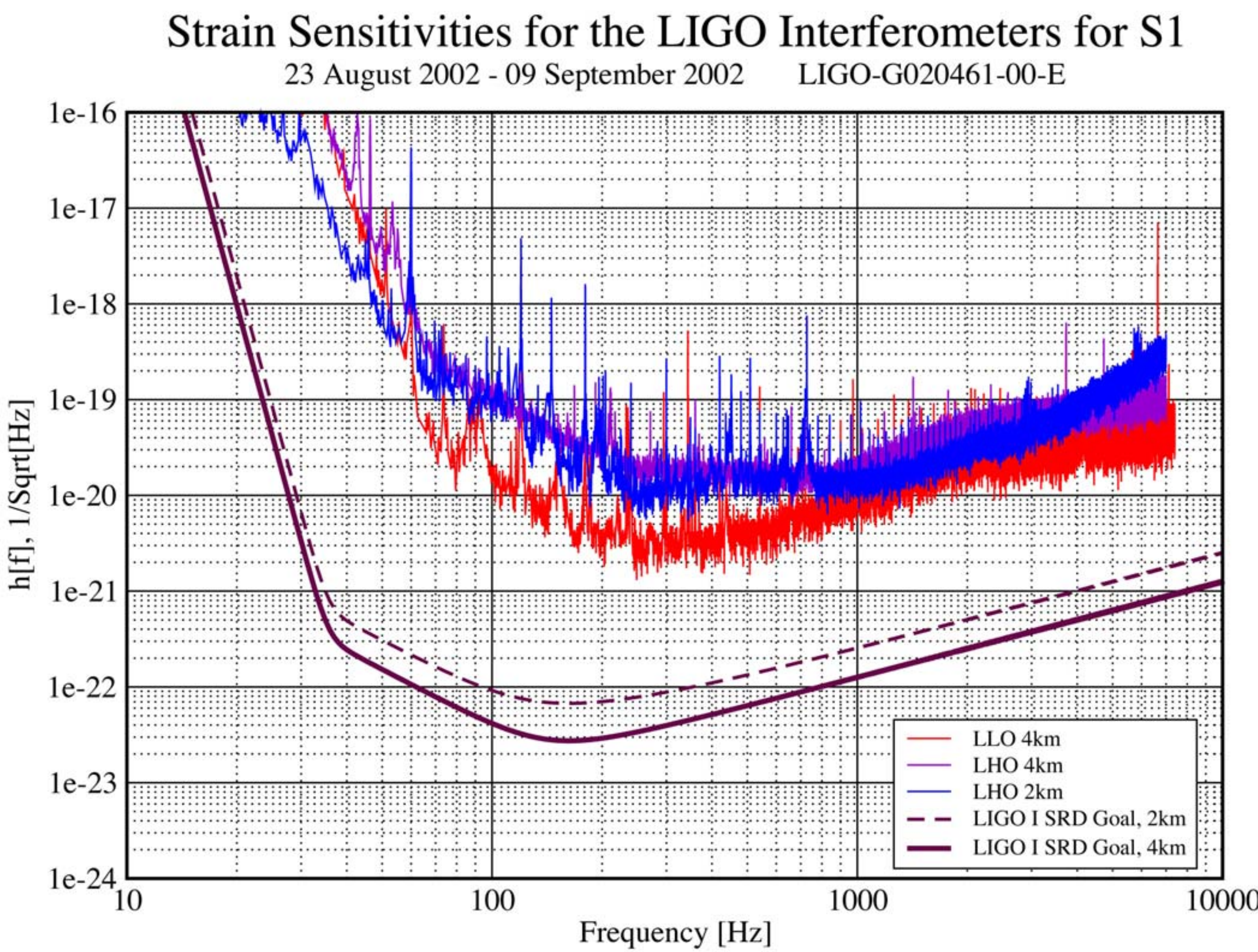


LIGO Sensitivity at Start of S1

LIGO
S1 Run

"First Upper Limit Run"

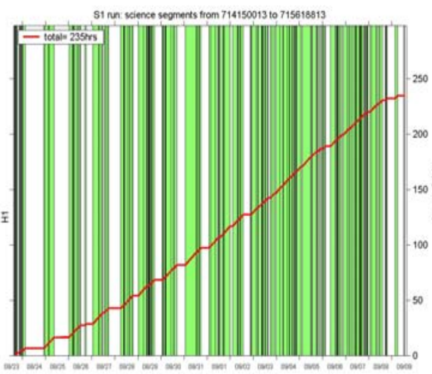
Aug – Sept 02



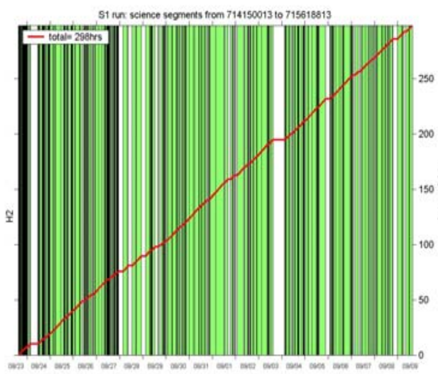
In-Lock Data Summary from S1

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

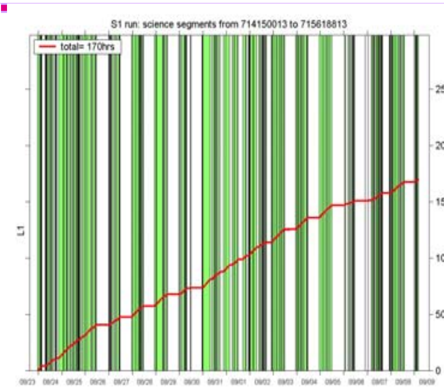
H1: 235 hrs



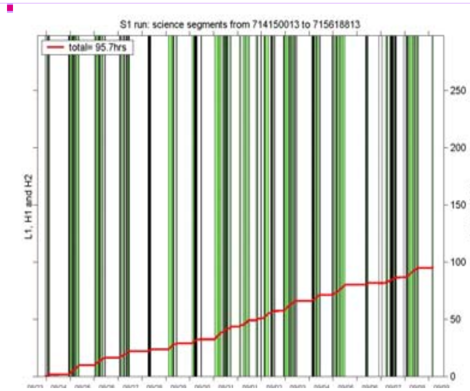
H2: 298 hrs



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**

LIGO First Science Run Synopsis

- ***LIGO is now more sensitive than any prior broadband instrument***
- *Analysis is in progress*
  - » First pass analysis used ~2.5% of full data set to optimize thresholds, refine algorithms, techniques
  - » Collaboration is now analyzing full S1 data set

    ⇒***Not yet ready to quote astrophysical results***

    ⇒*Results are being reviewed internally by the collaboration*

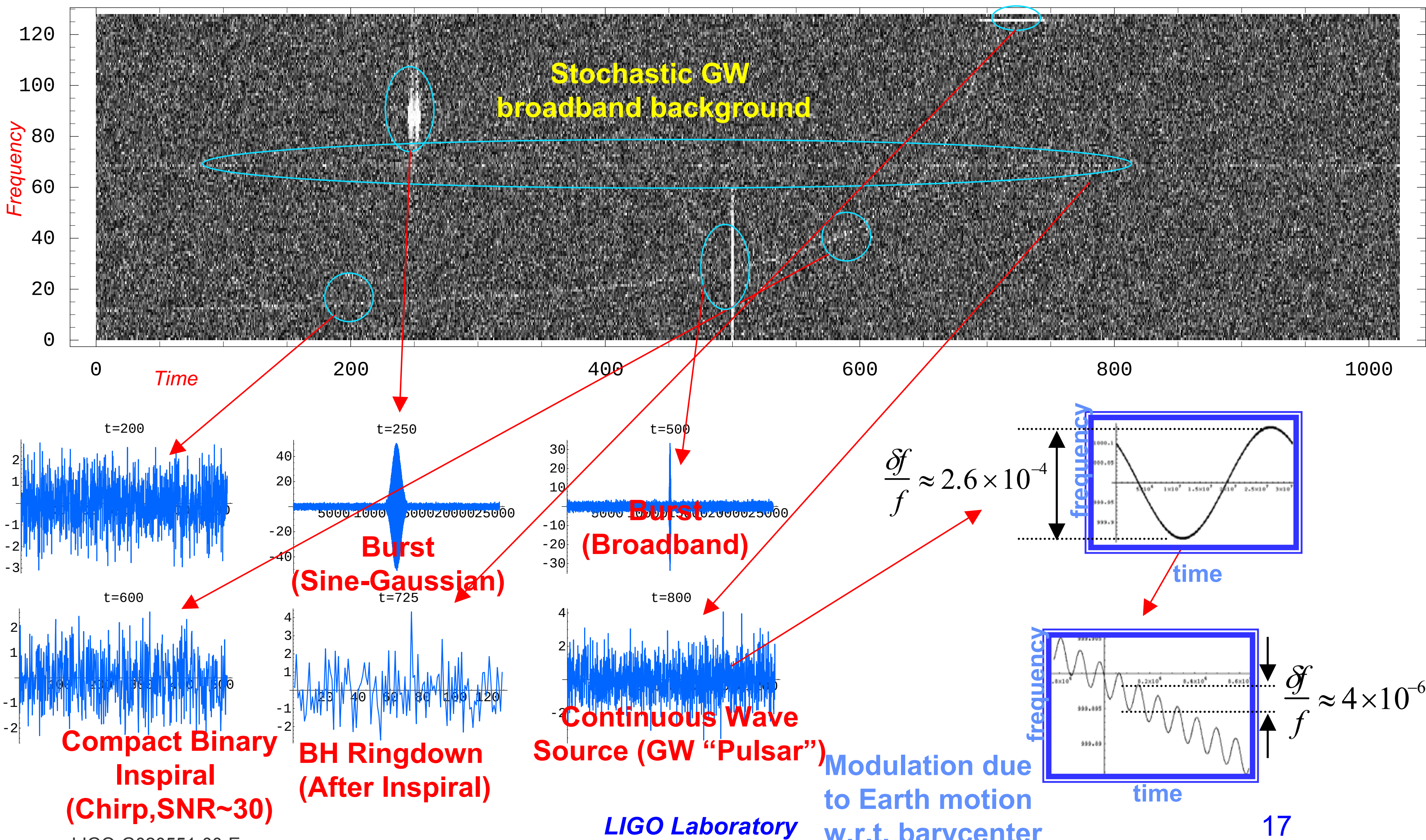
  - – Pre-prints should be available by February 2003
  - – First papers to be submitted by the end of March 2003

Organization of data analysis working groups according to source characteristics

- Signals with parametrizable waveforms
  - » Deterministic
    Periodic : http://www.lsc-group.phys.uwm.edu/pulgroup/
    Inspiral: http://www.lsc-group.phys.uwm.edu/iulgroup/
  - » Statistical
    Stochastic background:
    http://feynman.utb.edu/~joe/research/stochastic/upperlimits/

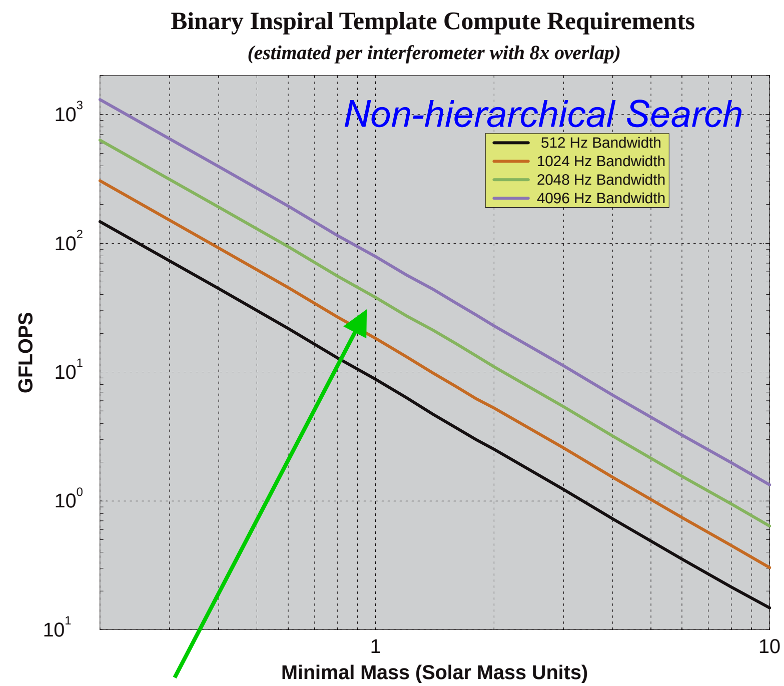
- Unmodeled sources
  - » Bursts and transients:
    http://www.ligo.caltech.edu/~ajw/bursts/bursts.html

Time-Frequency Characteristics of GW Sources



LIGO Data Analysis

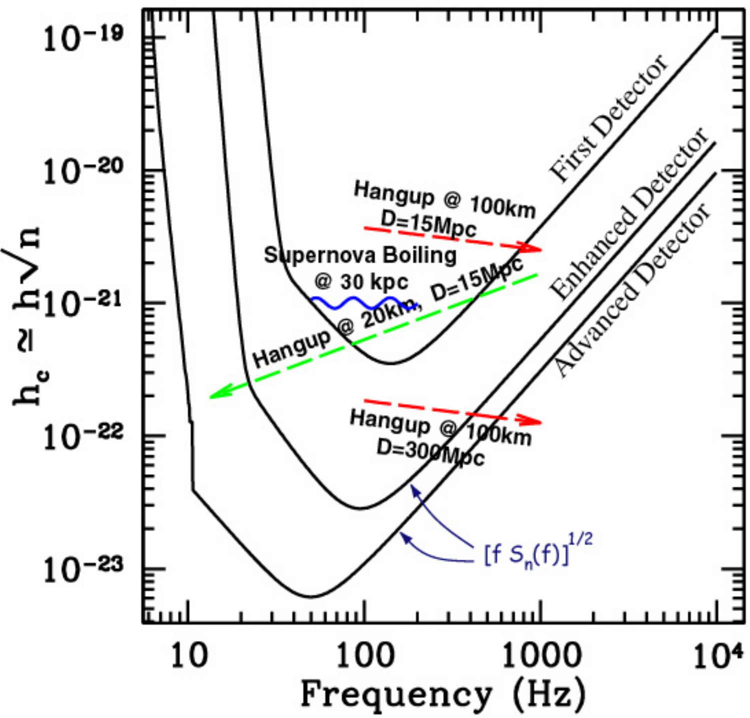
- **Different source searches -> different analysis methods**
- **Searches for (short) transient signals**
  - » Inspiral: optimal filtering.
  - » Bursts: time-frequency methods.
- **Searches for (long) periodic signals**
  - » Fourier transforms over Doppler shifted time intervals.
- **Search for stochastic GW background**
  - » Optimally weighted cross-correlated data from different detectors.
- **Detector characterization**
  - » Provide understanding of instrumental couplings to GW channel.
  - » Provide calibration for data analysis



LIGO's computational needs dominated by binary inspiral …
100 GFLOPS @ 1 Solar Mass

Burst Sources

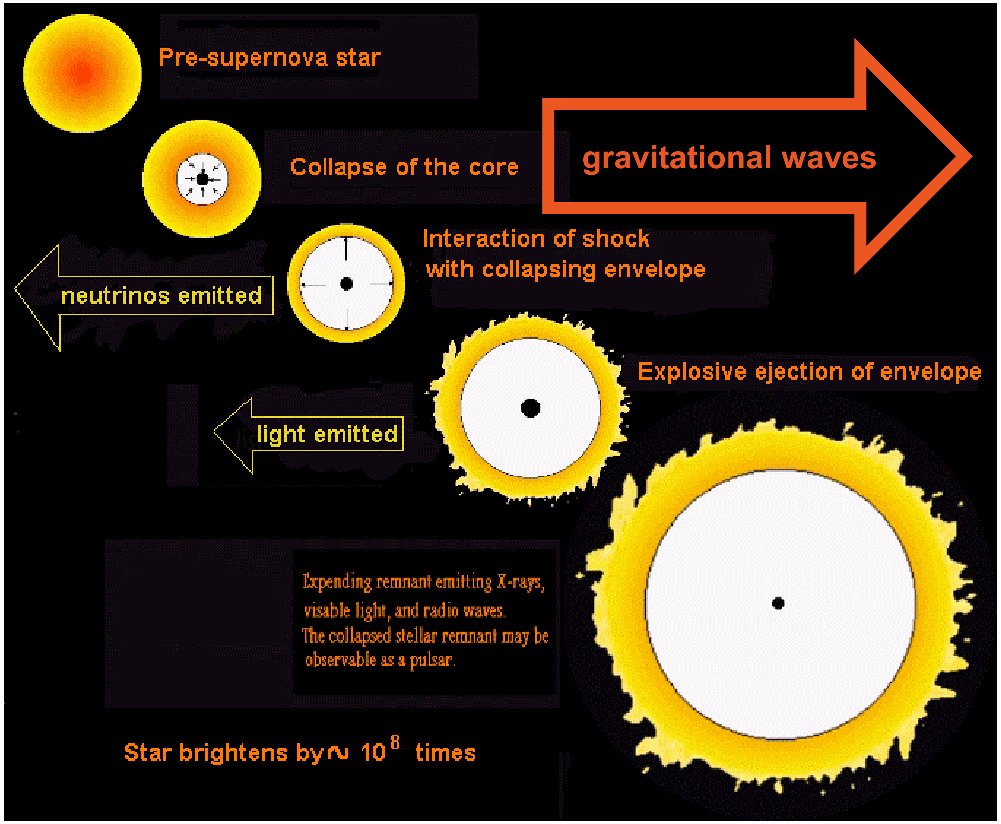
Sensitivity of LIGO to burst sources



Rate

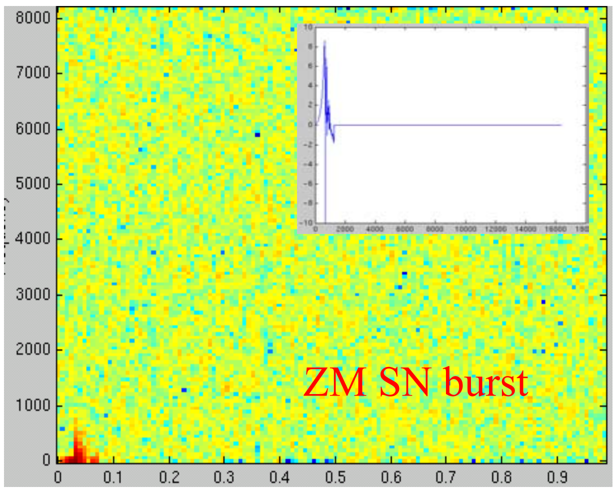
1/50 yr - our galaxy

3/yr - Virgo cluster



Time frequency characterization of signals

- Exploiting a broadband detector -



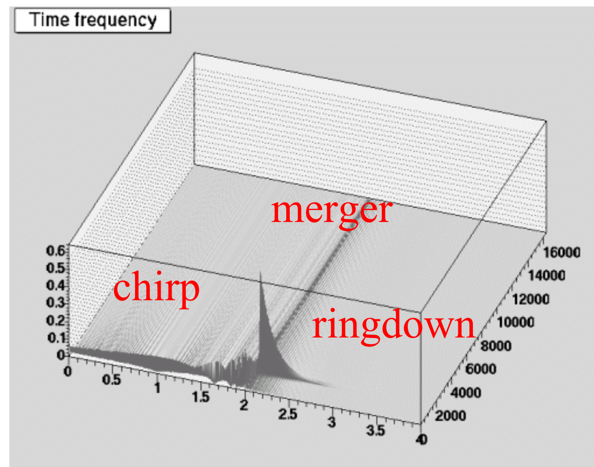
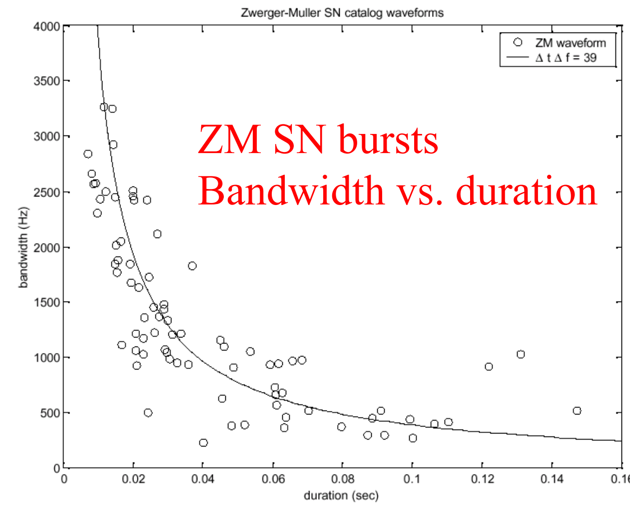


Fig. 3 Spectrogram of a composite signal

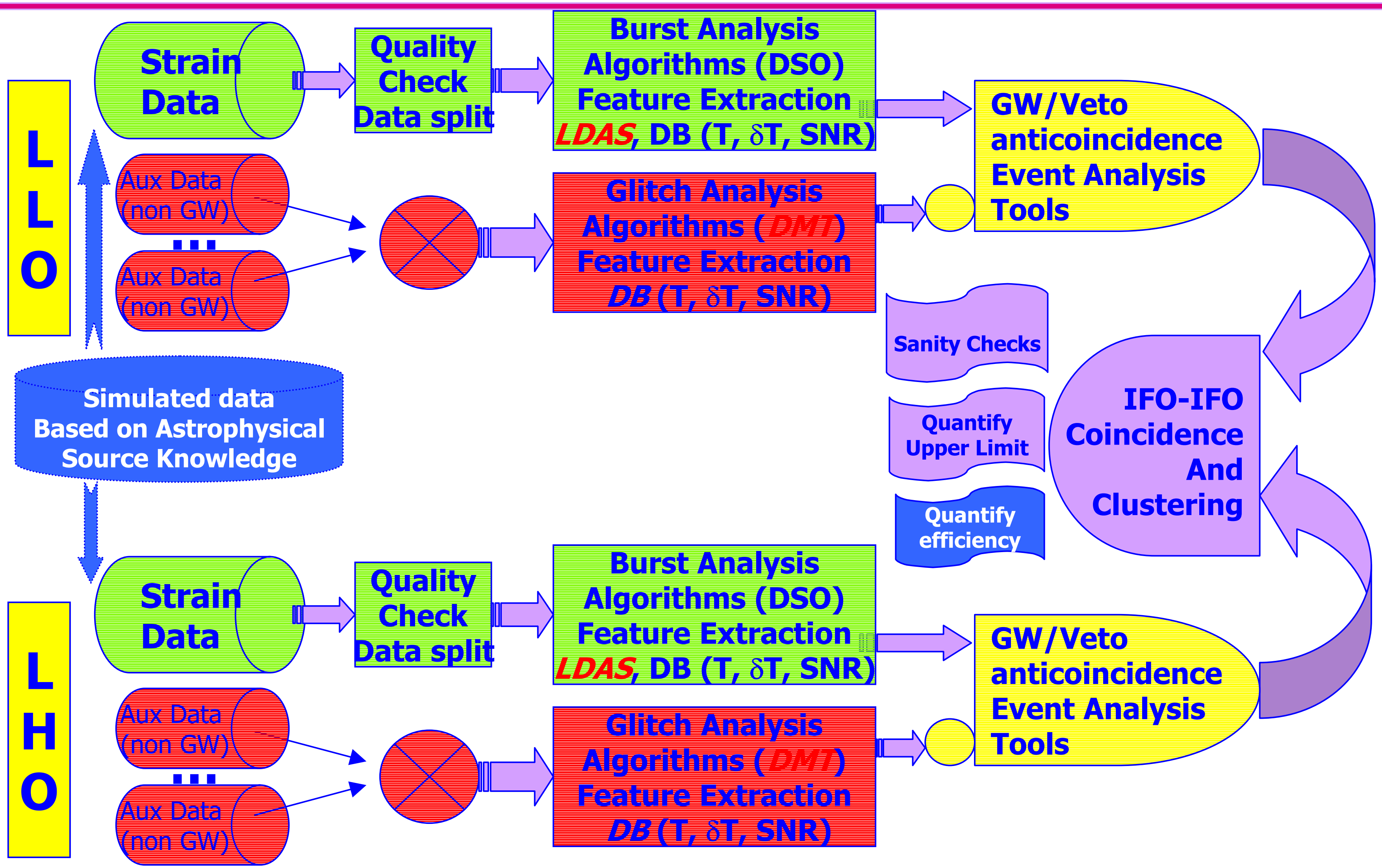


Generic statements about the sensitivity of searches to poorly-modeled sources can be made from the t-f “morphology”…

- longish-duration, small bandwidth (ringdowns, Sine-Gaussians)
- longish-duration, large bandwidth (chirps, Gaussians)
- short duration, large bandwidth (merger)
- In-between (Zwerger-Muller or Dimmelmeier SN waveforms)
    - These SN waveforms are *distance*-calibrated; all others are parameterized by a peak or rms strain amplitude

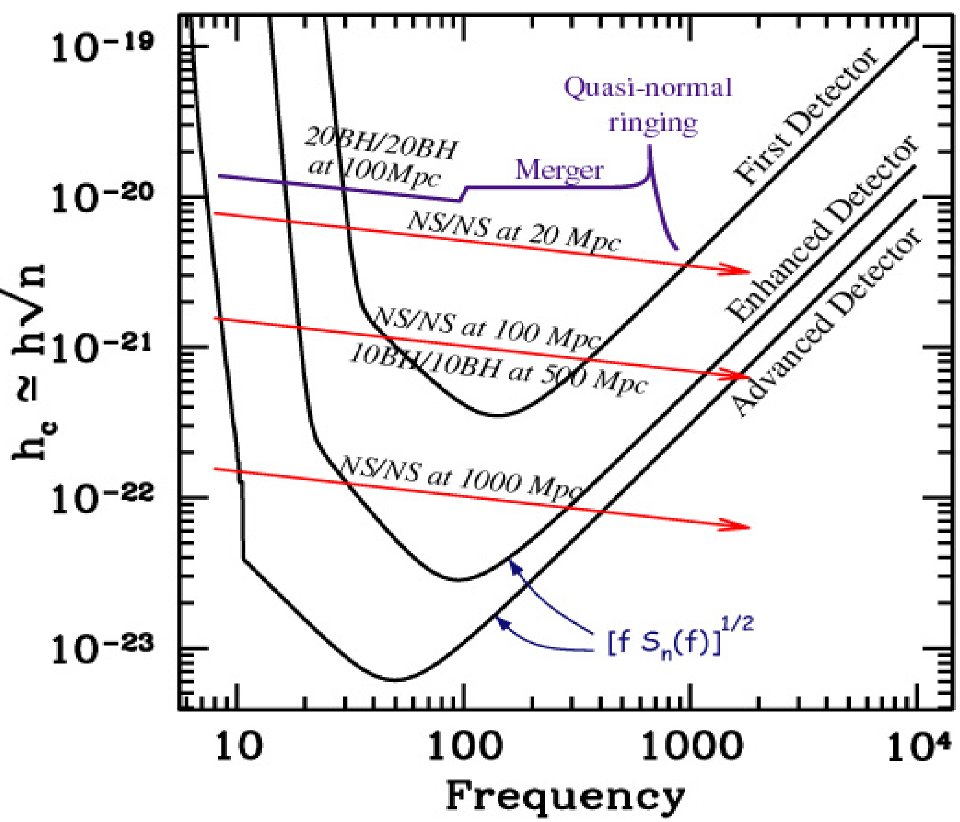
Astrophysical Search Pipeline

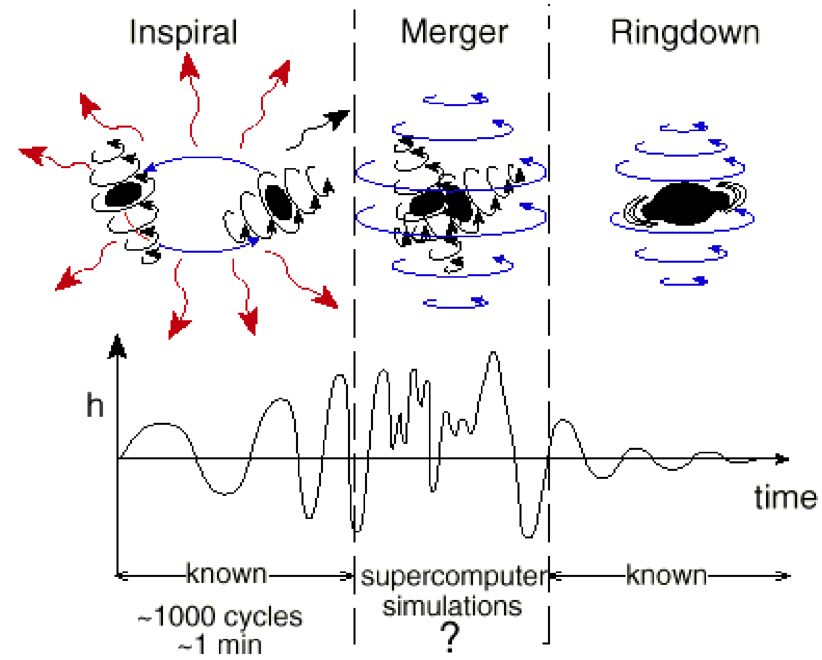
- example: burst group analysis -



Compact Binary Sources

Sensitivity of LIGO to coalescing binaries





Brief Summary of Detection Capabilities of Mature LIGO Interferometers

• **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4M_\odot$ for NS and $\sim 10M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

	NS/NS	NS/BH	BH/BH in field	BH/BH in globulars
$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	10^{-6}–10^{-5}
$\mathcal{D}_{\rm I}$	20 Mpc	43 Mpc	100	100
$\mathcal{R}_{\rm I}$, yr^{-1}	$1 \times 10^{-4} - 0.03$	$\lesssim 1 \times 10^{-4} - 0.3$	$\lesssim 3 \times 10^{-3} - 0.5$	$0.03 - 0.5$
$\mathcal{D}_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
$\mathcal{R}_{\rm WB}$, yr^{-1}	0.5 – 100	$\lesssim$ 0.5 – 1000	$\lesssim$ 10 – 2000	100 – 2000

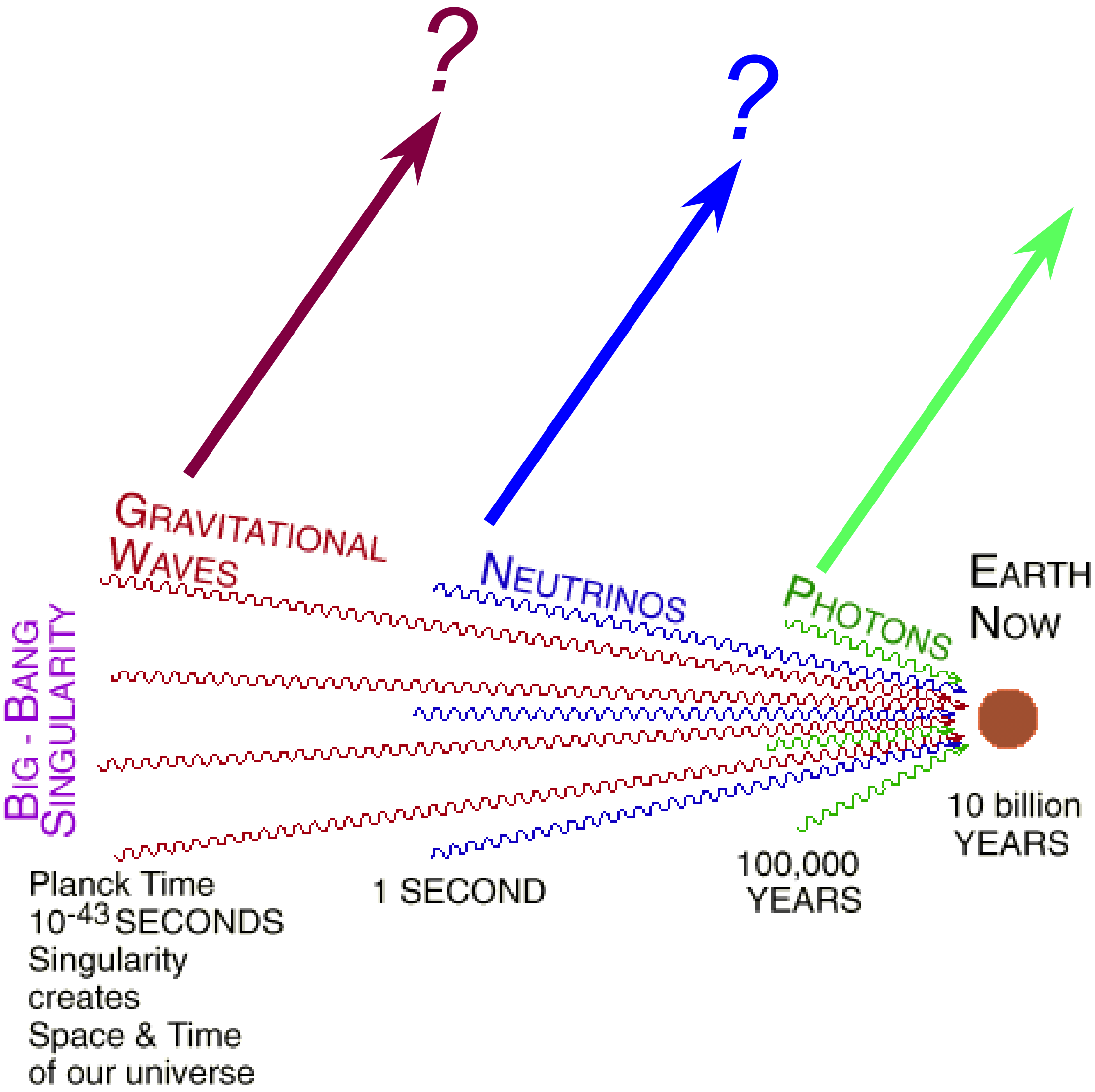
Inspiral search

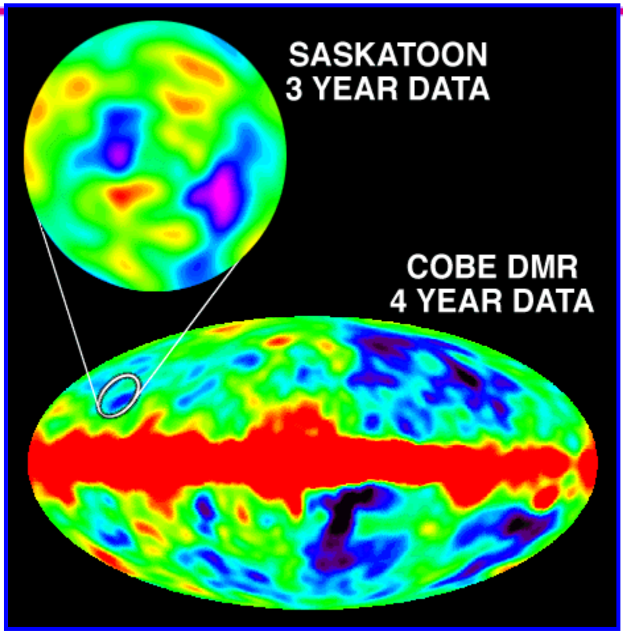
- Dual approach - *uses a pipeline process similar to burst search*
  - » Conventional optimal Wiener filtering with chirp templates
    - – Flat search
      - Implemented for analysis of 1994 40m data, TAMA data
  - » Fast Chirp Transform (FCT)
    - – Starting with stationary phase approximation to phase evolution, linearize phase behavior locally to recast filter as multi-dimensional FFT
    - – Generalize FT: $\chi_{FT}(t) = \int df \;\; h[f] \;\; e^{2\pi i f t} \longrightarrow \chi_{CT}(t) = \int df \;\; h[f] \;\; e^{i\phi(f)}$
    - – Express phase as series in f: $\phi(f) = 2\pi f \tau + \delta\phi(f); \delta\phi(f) = \sum_{m>1} k_m [f\tau_m]^m$
    - – Discretize to FFT, FCT:

$$\chi_{FFT}(k) = \sum_{j=0}^{N_0-1} h[j] \;\; e^{2\pi i (\frac{jk}{N_0})} \longrightarrow \chi_{FCT}(k, \{l_p\}) = \sum_{j=0}^{N_0-1} h[j] \;\; e^{2\pi i \left[\frac{jk}{N_0} + \sum_{p>1} l_p \left(\frac{j}{N_0}\right)^p\right]}$$

- Hierarchical search - under development
  - » ***IUCAA group is a key contributor to this effort***
- Multiple interferometer coincidences at the event level
  - » Coherent processing of strain vector from multiple interferometers still to be implemented

Stochastic Background Sources

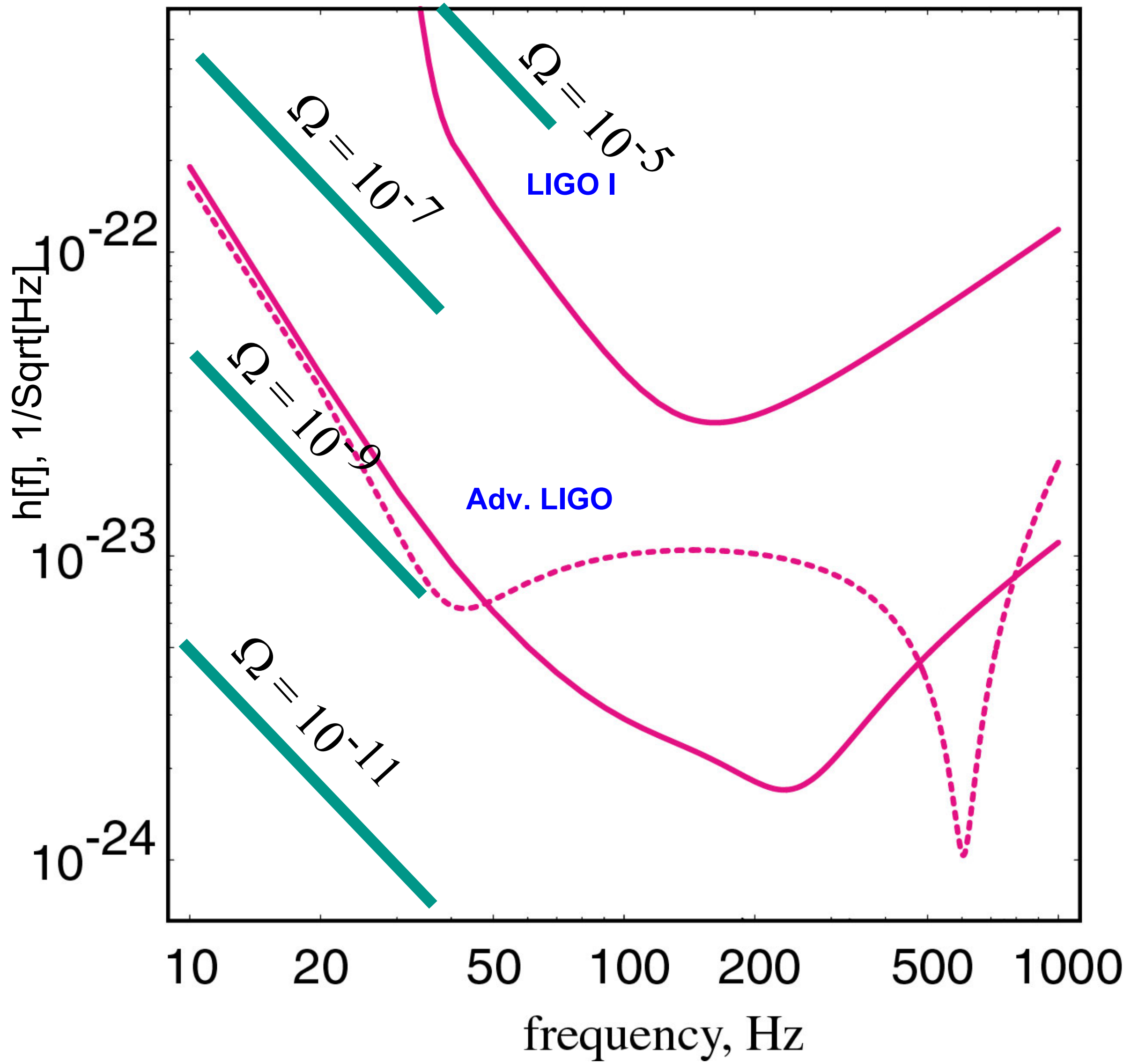




Analog from electromagnetic spectrum

Stochastic Gravitational Wave Background

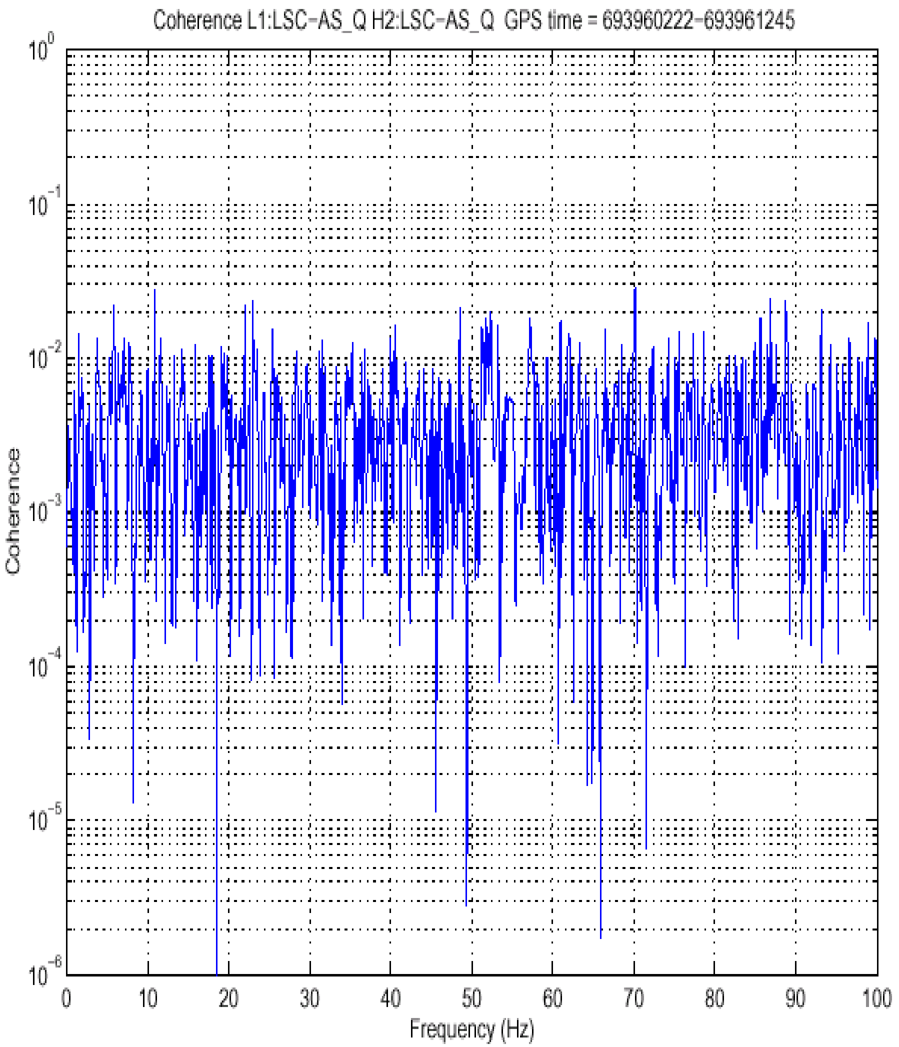
- Detect by
  - » cross correlating output of Hanford + Livingston 4km IFOs
- Good sensitivity requires
  - » (GW wavelength) $\gtrsim$ **2x** (detector baseline)
  - » f $\lesssim$ 40 Hz
- Initial LIGO sensitivity:
  - » $\Omega \gtrsim 10^{-5}$
- Advanced LIGO sensitivity:
  - » $\Omega \gtrsim$ **5×10^{-9}**

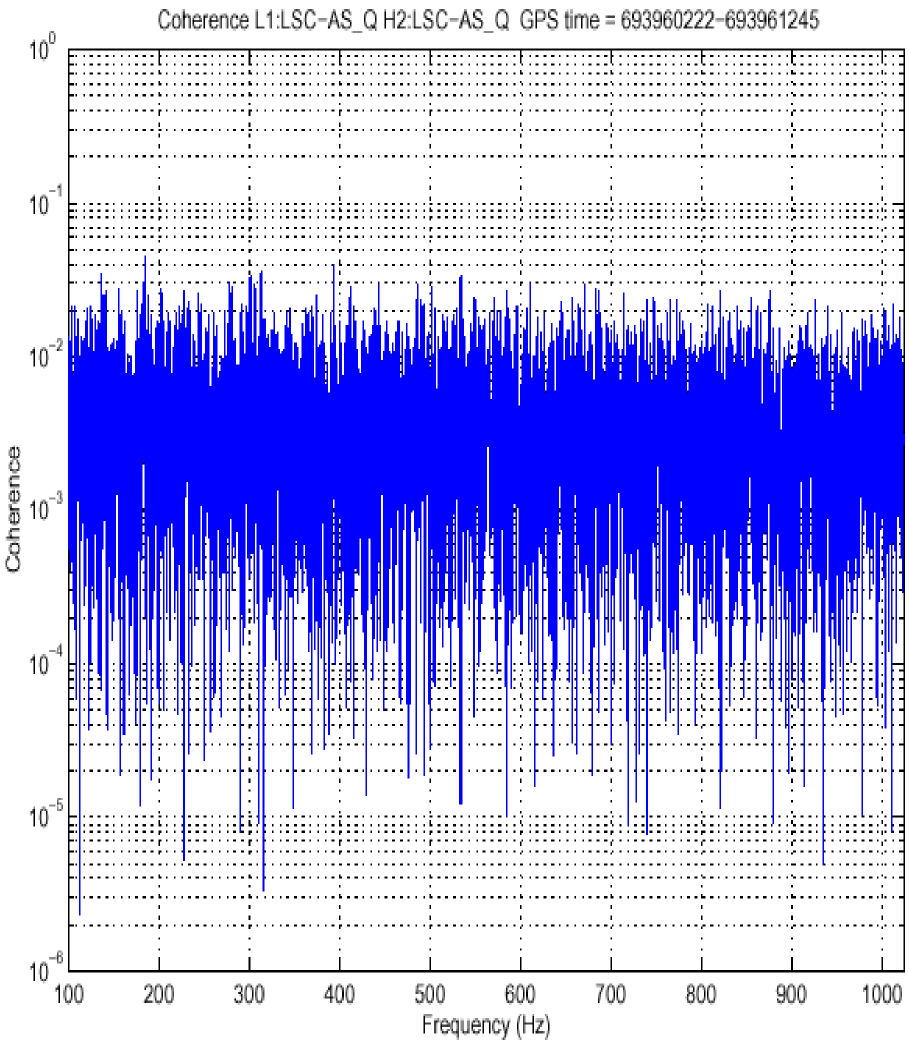


LIGO Stochastic Upper Limit Group Activities

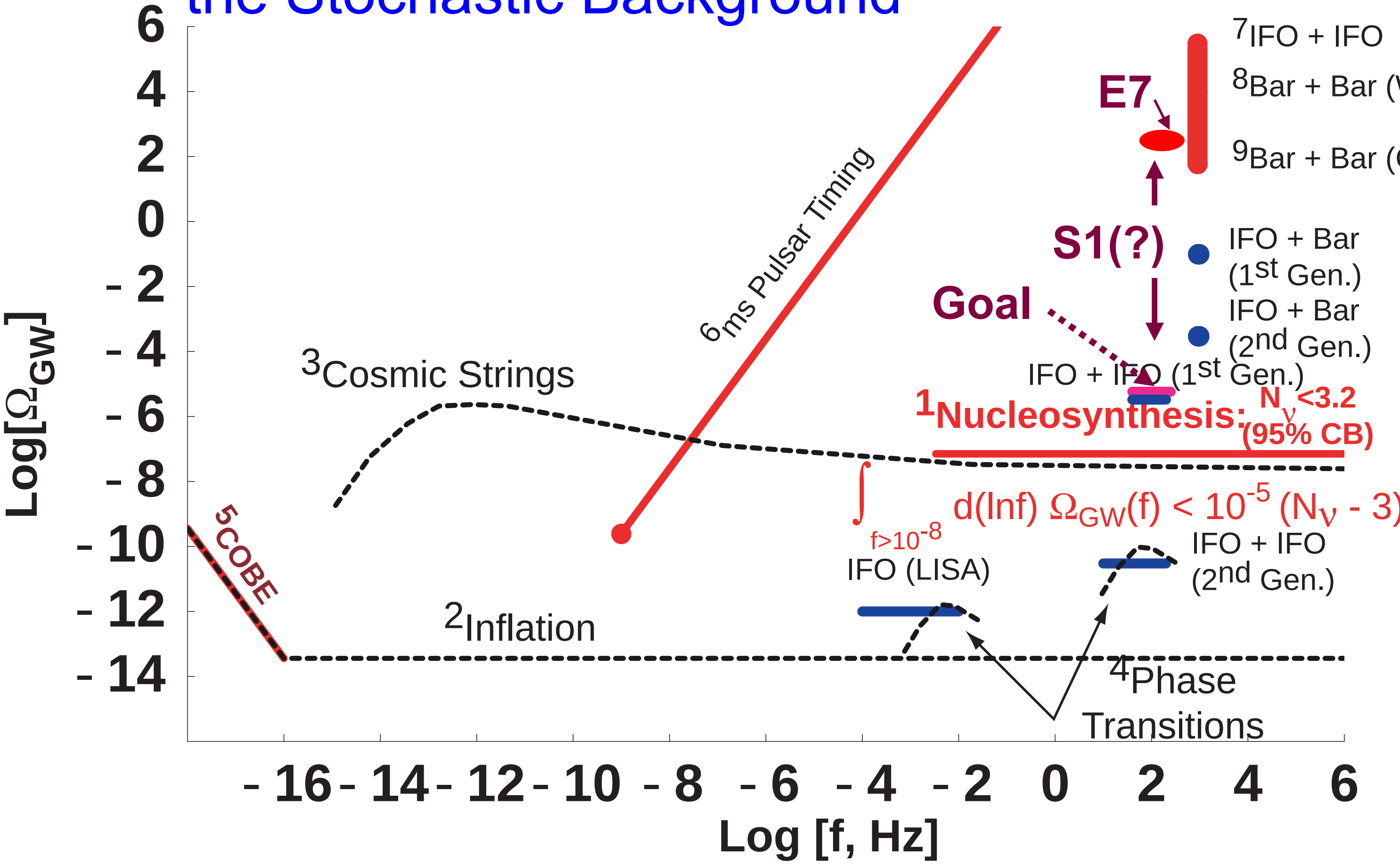
- Analytic calculation of expected upper limits (~100 hrs):
  - Ω for LHO 2k-LHO 4k will provide the most stringent *direct observational* upper limit to date
- Coherence measurements of GW channels show little coherence for LLO-LHO 2k correlations
- Investigation of effect of line removal for LHO 2km-LHO 4km correlations (e.g., reduction in instrumental correlated noise)
- Injection of simulated stochastic signals into the data and extraction from the noise to validate end-to-end capability of analysis
- Correlations between LLO with ALLEGRO bar detector
  - » *ALLEGRO was rotated into 3 different positions during earlier E7 run*
  - » *Analysis in progress*

Coherence plots (LLO 4km - LHO 2km) of strain channel for a few minutes of data





Measurements of the Stochastic Background

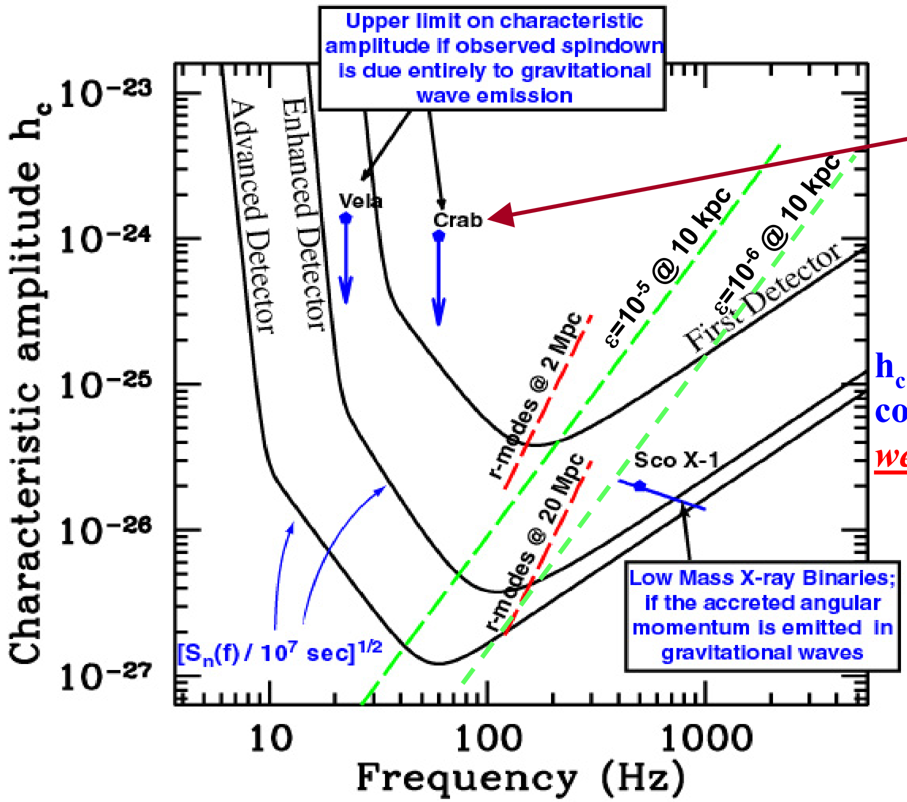


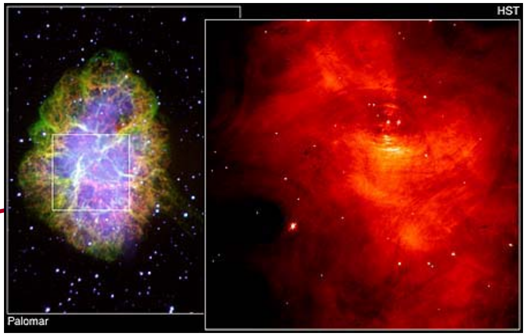
1 Kolb & Turner (The Early Universe, 1990)
Burles, Nollet,Trunan, Turner (PRL 82, 1999)
2 Grishchuk (SPJETP 40, 1975)
3 Allen & Brustein (gr-qc9609013)
Allen (gr-qc9604033)
4 Kamionkowski, Kosowoski &Turner (PRD 49, 1994)
5 Allen & Koranda (PRD 50, 1994)
6 Thorsett & Dewey (PRD 53, 1996)
Kaspi, Taylor, Ryba (ApJ 428, 1994)
7 Compton, Nicholson, Schutz, Proc. MG7 (1994)
8 Hough, Pugh, Bland, Drever, Nature 254 (1975)
9 Astone, et. al., Astr. Astroph. 351 (1999)

Periodic Sources

Target signals: slowly varying instantaneous frequency, e.g. rapidly rotating neutron stars in different moments of their evolution.

Sensitivity of LIGO to continuous wave sources





h_c: the amplitude of the weakest signal detectable with 99% confidence with 4 months of integration, *if the phase evolution were known.*

$$h_c = 2.3 \times 10^{-25} \frac{\varepsilon}{10^{-5}} \frac{I_{zz}}{10^{45}\, g\, cm^2} \frac{8.5\, kpc}{R} \left(\frac{f_0}{500\, Hz} \right)^2$$

Data must be corrected for each source position on the sky

** Graphs from Brady, Creighton, Cutler, and Schutz, gr-qc/9702050*

Periodic source searches

Upper Limit Group

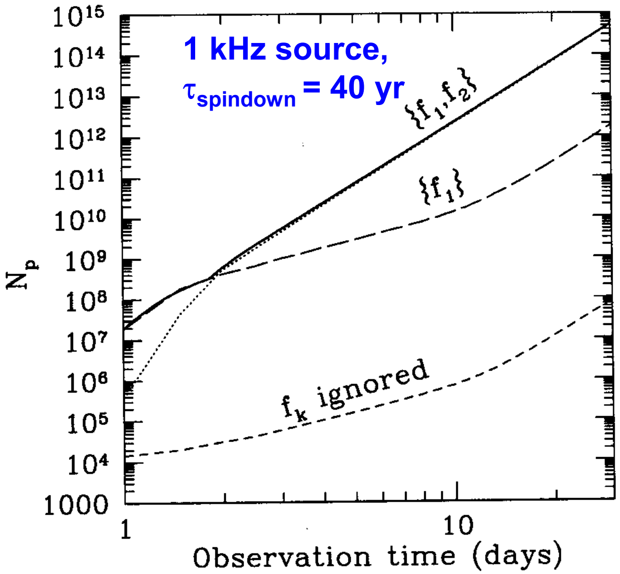
3 source categories and 4 algorithms

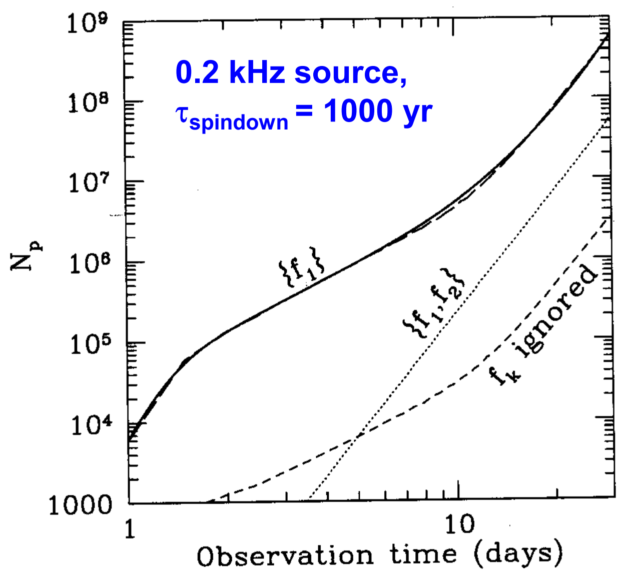
- » All sky unbiased
  - – Sum short power spectra (no doppler correction)
- » Known pulsar
  - – Heterodyne narrow BW
  - – Coherent frequency domain
- » Wide area search
  - – Hierarchical Hough transform

THE CHALLENGE

Generally the phase evolution of the source is not known and one must perform searches over some parameter space volume

- The number of templates grows dramatically with the coherent integration time baseline and the computational requirements become prohibitive:





On a 1TFLOPS computer it would take more than 10^4 yr to perform an all-sky search for f < 1000 Hz for an observation time of 4 months.

** Graphs from Brady, Creighton, Cutler, and Schutz, gr-qc/9702050*

LIGO First Science Run Synopsis

- **Quick-look** based on ~2.5% sampling of data over 17 days plus Monte Carlo simulations injected into data subset is complete -- results under internal review
- Compact object inspiraling waveforms
  - » Coverage will include the Milky Way, plus LMC, SMC
  - » Typical sensitivity for a binary neutron star population.
- Bursts/transient events
  - » 96 hours of 3X coincidence
  - » 2 different (complementary) filters applied to data
    - – frequency-time clustering algorithm (“tfclusters”)
    - – time-domain slope detector (“slope”)
    - – Calibration/efficiency using astrophysically motivated SNe waveforms, wavelets, etc.
- Continuous wave sources
  - » Initial searches target known EM sources, e.g.:
    - - PSR J1939+2134 (P= 1.557 ms, search and analysis in progress)
    - – Sco X-1 (in progress - 500 Hz - 600 Hz, multi-parameter search)
- Stochastic background
  - » Limiting sensitivity for Ω will be better than previous direct GW observational determinations with resonant bars (narrowband)

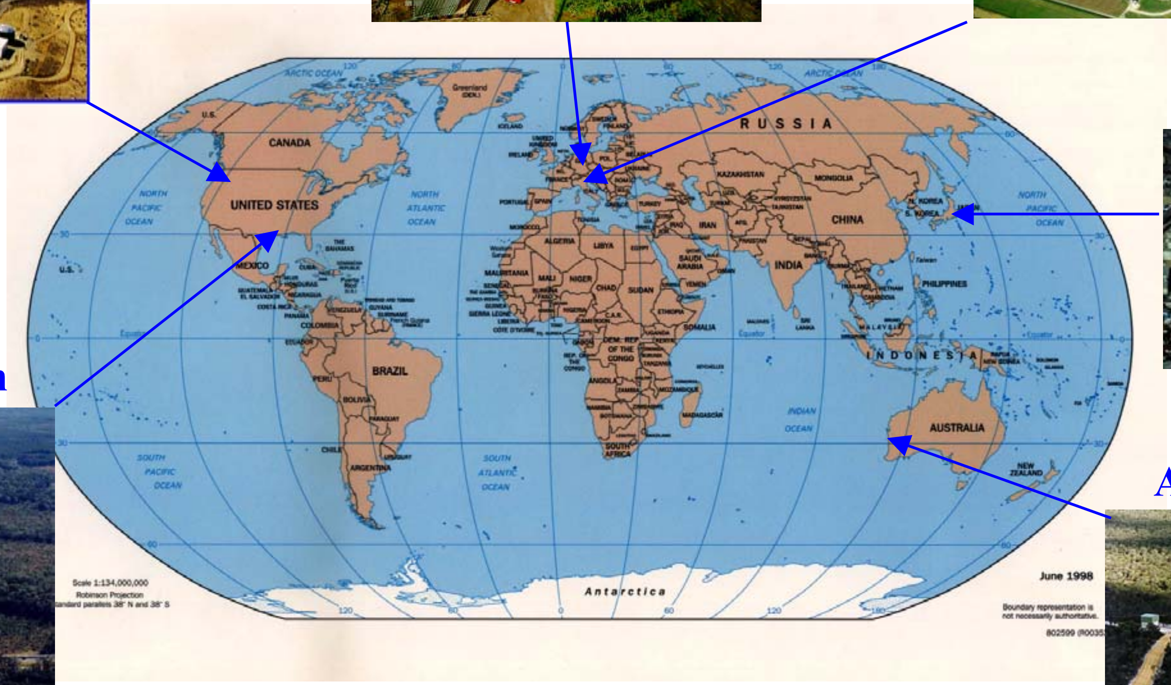
Growing International Network of GW Interferometers

LIGO-LHO: 2km, 4km

GEO: 0.6km

VIRGO: 3km

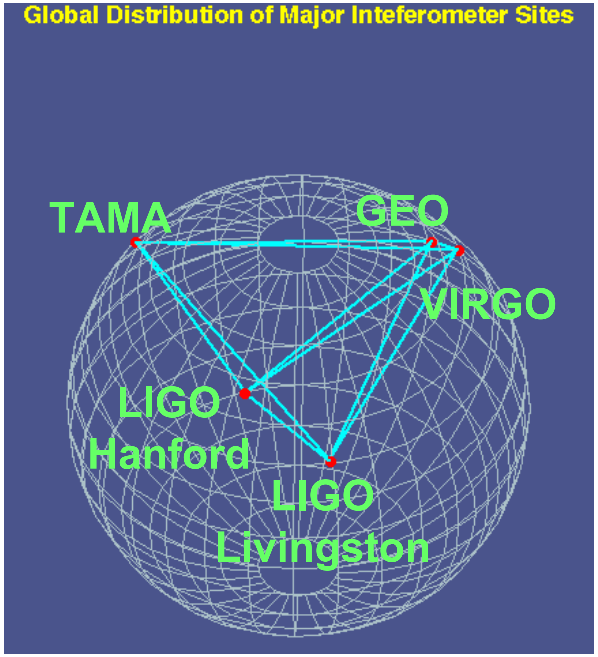
TAMA: 0.3km

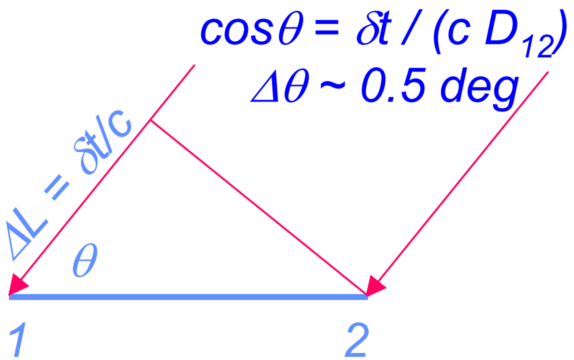


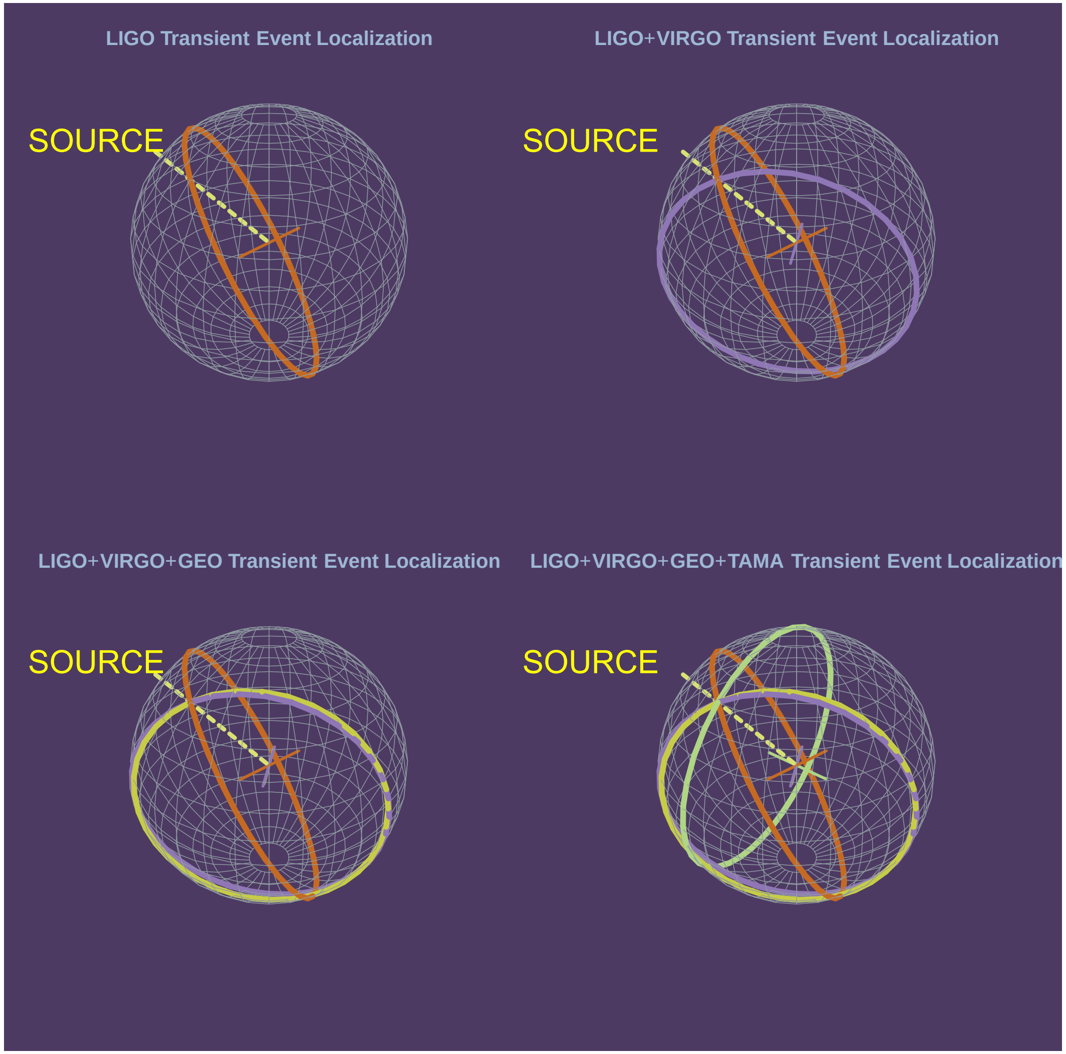
LIGO-LLO: 4km

AIGO: (?)km

Event Localization With An Array of GW Interferometers

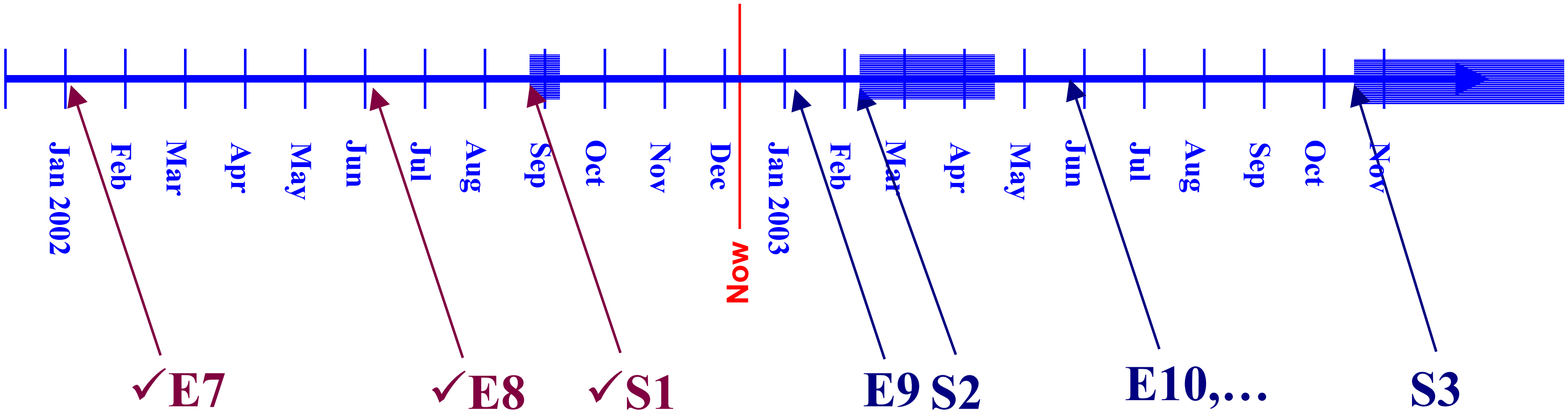






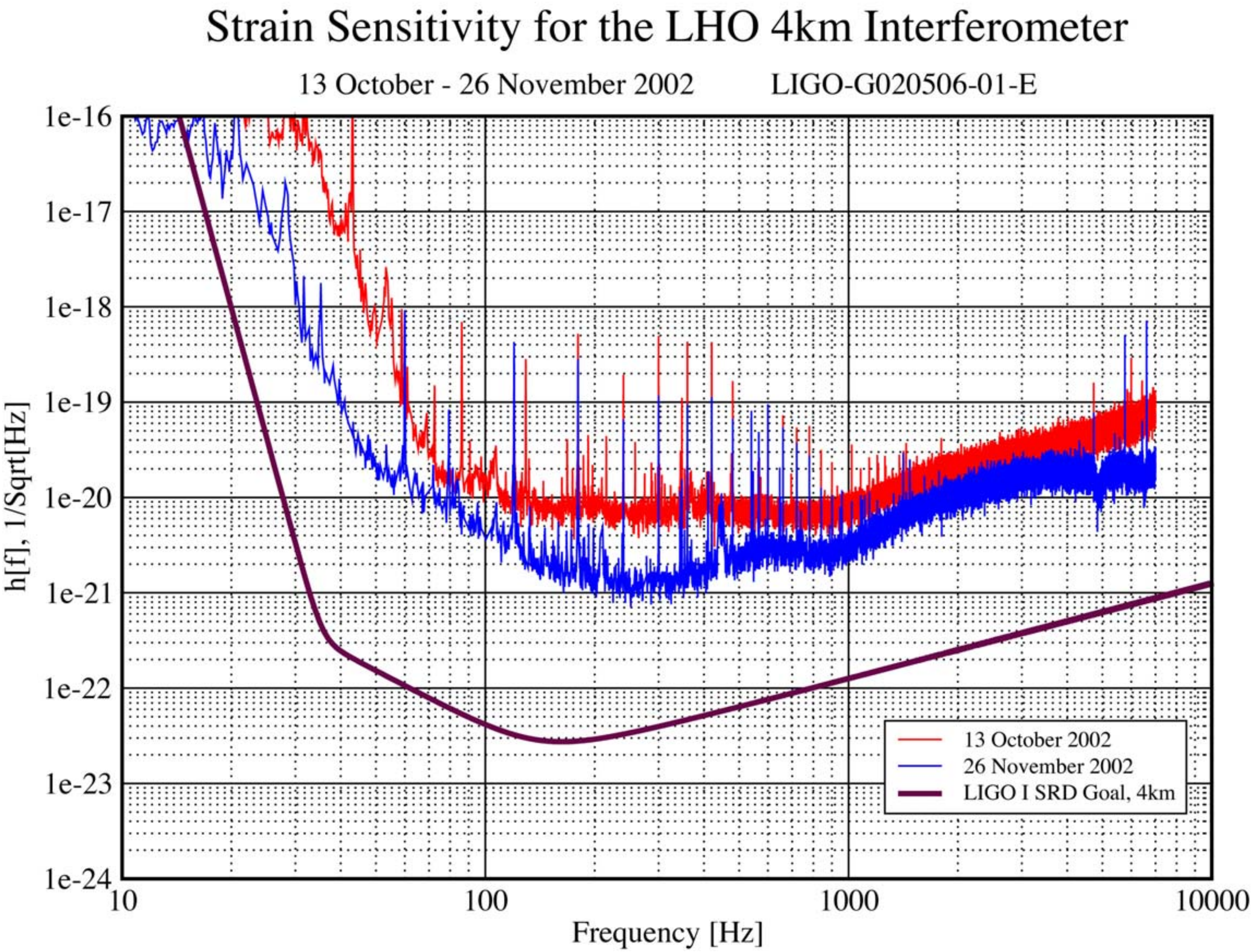
LIGO Run Schedule

- Science runs are interspersed with engineering runs and commissioning to bring interferometer to design sensitivity

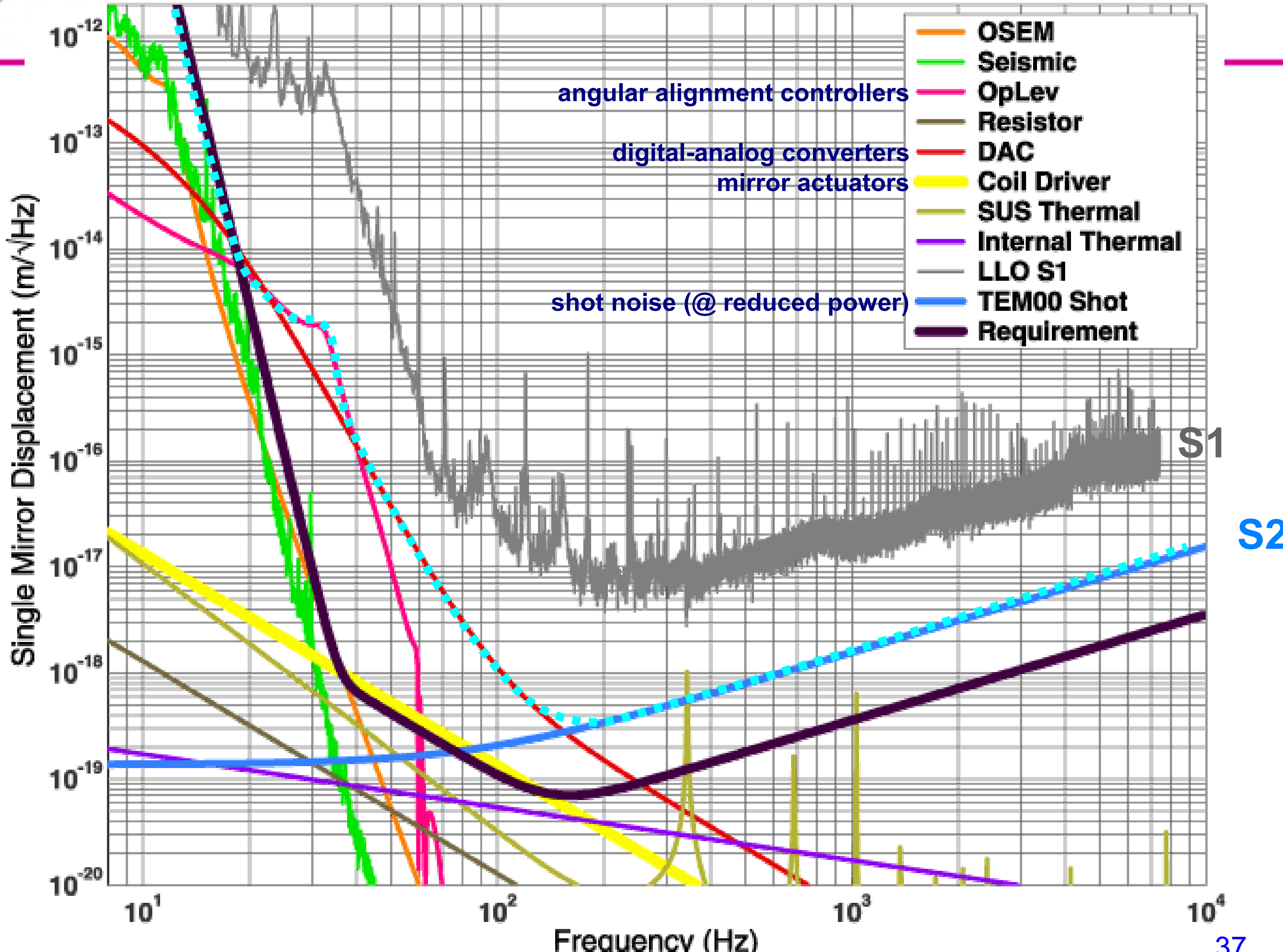


LIGO Interferometer sensitivities continue to improve!!

Recent LIGO Hanford 4 km sensitivity data

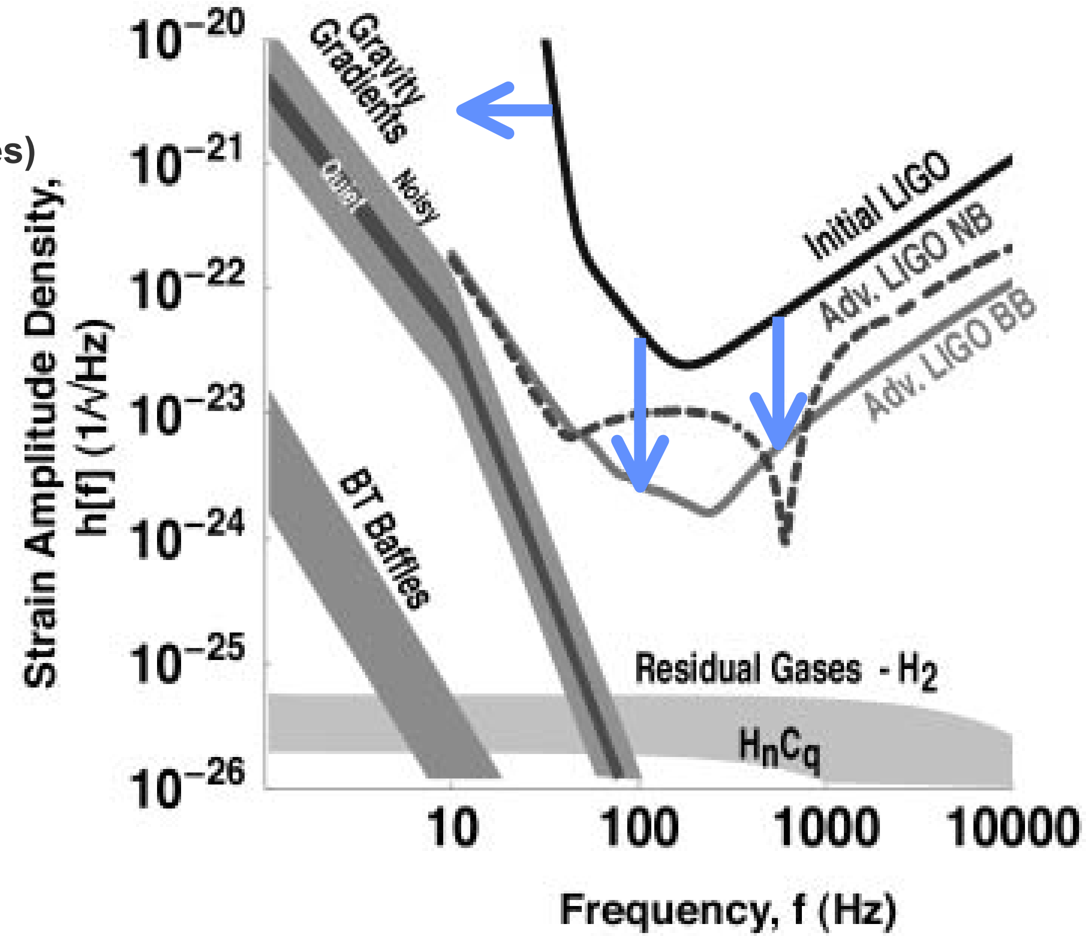


Targeted Noise Spectrum for S2



A Look to the Future: Advanced LIGO

- **Inherent facility limits**
  - » Gravity gradients (seismic waves)
  - » Residual gas (vacuum)
  - » Provides room to improve sensitivity, increase bandwidth
- **Advanced LIGO**
  - » R&D underway
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15th
  - » Shot noise 1/10th

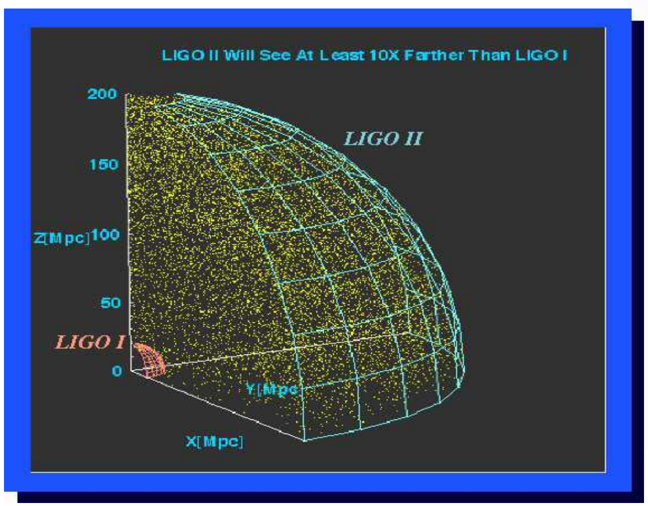


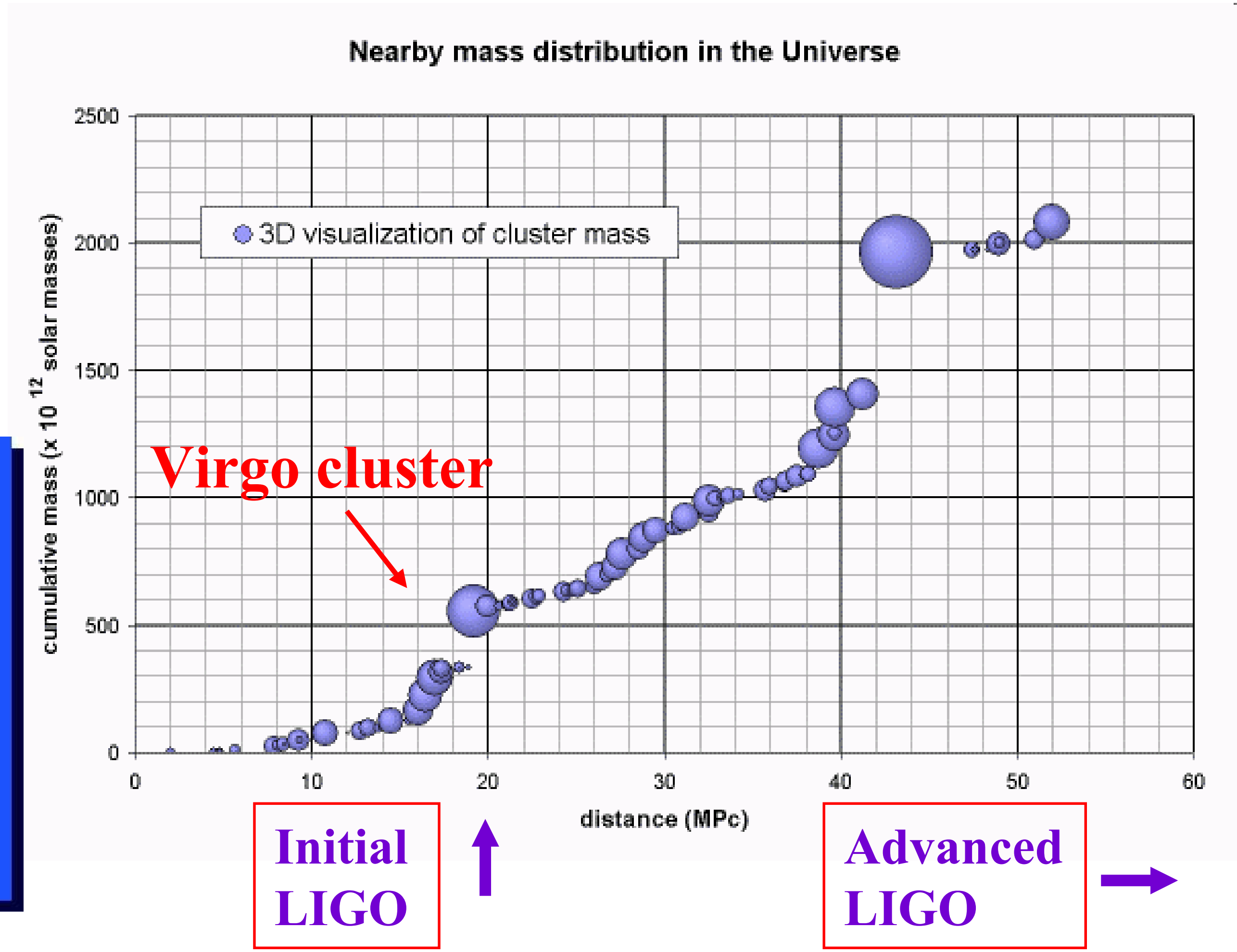
Advanced LIGO:

Cubic Law for "*Window*" on the Universe

Improve amplitude sensitivity by a factor of 10x…

…number of sources goes up 1000x!





Conclusion

- LIGO scientific operation started with S1 Aug-Sep 2002
  - » LIGO has started taking data !!!!
  - » Collaboration is currently carrying out the data analysis
    - – Periodic (CW) sources
    - – Compact binary coalescences
    - – Bursts
    - – Stochastic background

- ***First results should be announced in Feb-Mar 2003***

- Detector performance, commissioning continuing to improve towards design sensitivity

- Second run scheduled 14 Feb - 15 Apr 2003
  - » Sensitivity should be almost ***10x better than S1***

- Planning for second generation interferometers is ongoing
  - » Proposal for an Advanced LIGO interferometer is under preparation now
  - » Will include significant GEO participation with UK/German funds