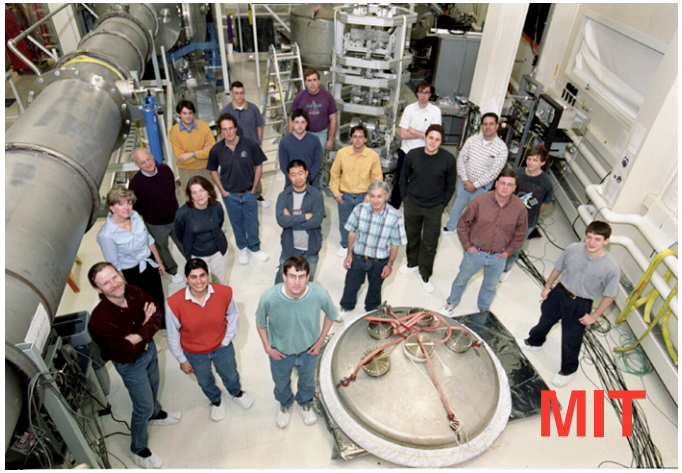
The Laser Interferometer Gravitational Wave Observatory

LIGO at the threshold of science operations

Albert Lazzarini
LIGO Laboratory

Carnegie Centiennial Symposium on Astrophysics
21 November 2002
Pasadena, Califonria

Acknowledgements: LIGO Laboratory



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

LIGO Scientific Collaboration

LIGO I Development Group: 21 Institutions, 26 Groups, 281 Members

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

US Universities:

- Caltech
- Carleton
- Cornell
- Cal State University Dominguez Hills
- Florida
- Louisiana State
- Louisiana Tech
- Michigan
- MIT
- Oregon
- Penn State
- Southern
- Syracuse
- Texas-Brownsville
- Wisconsin-Milwaukee

International Members:

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

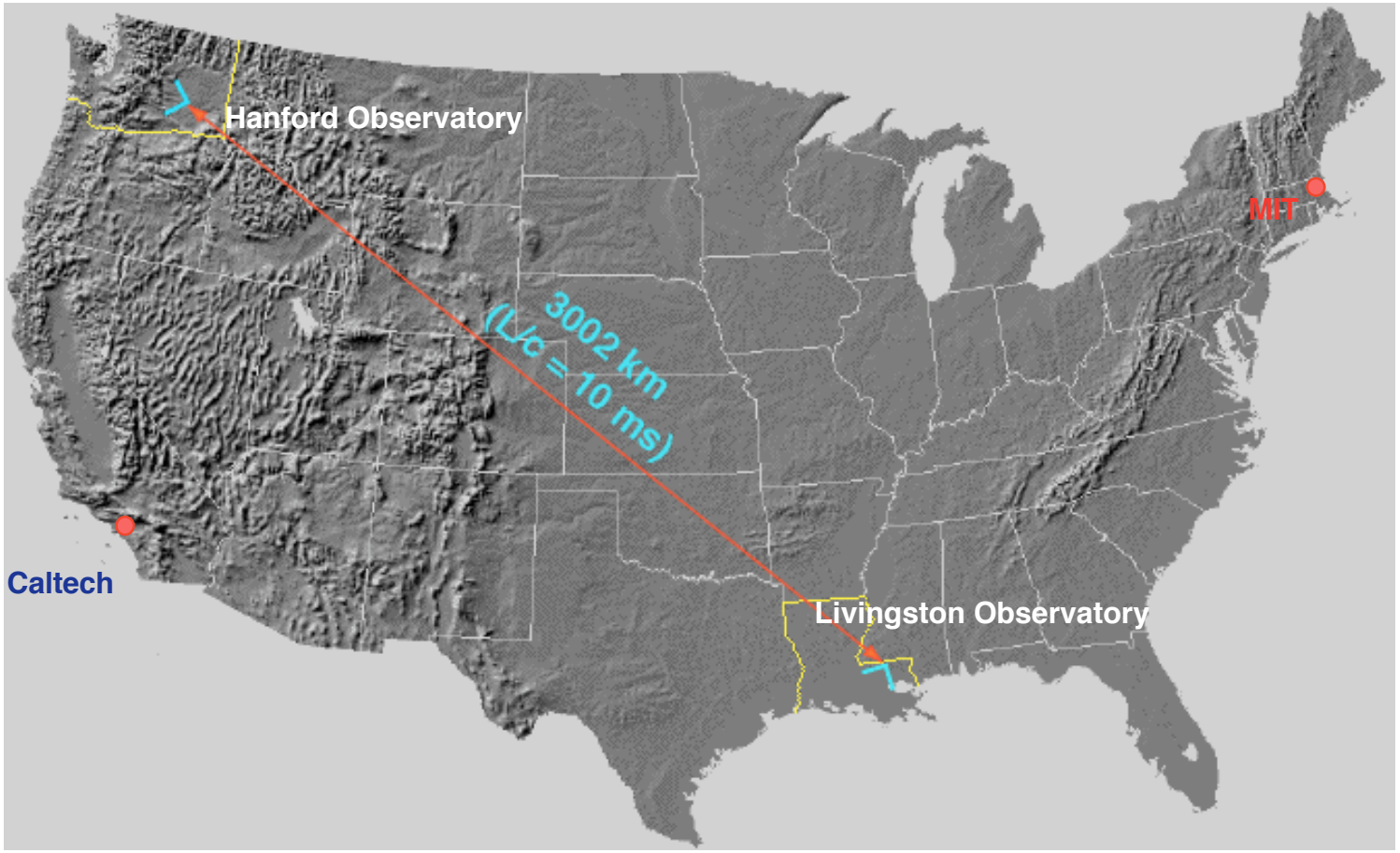
US Agencies & Institutions

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

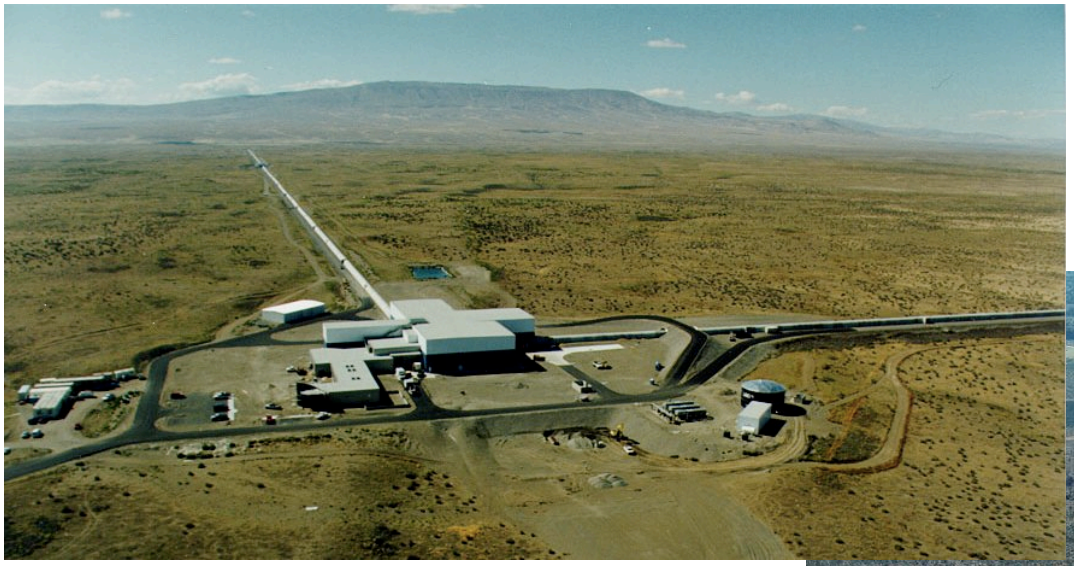
International partners (have MOUs with LIGO Laboratory):

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

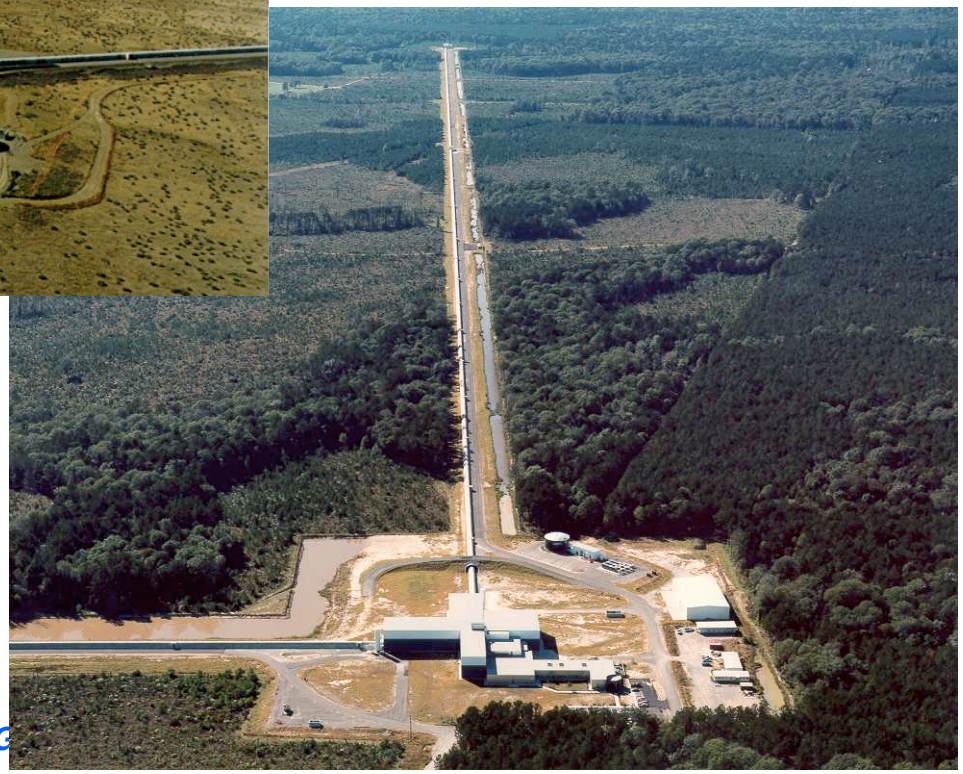
The LIGO Laboratory Sites



LIGO Observatories

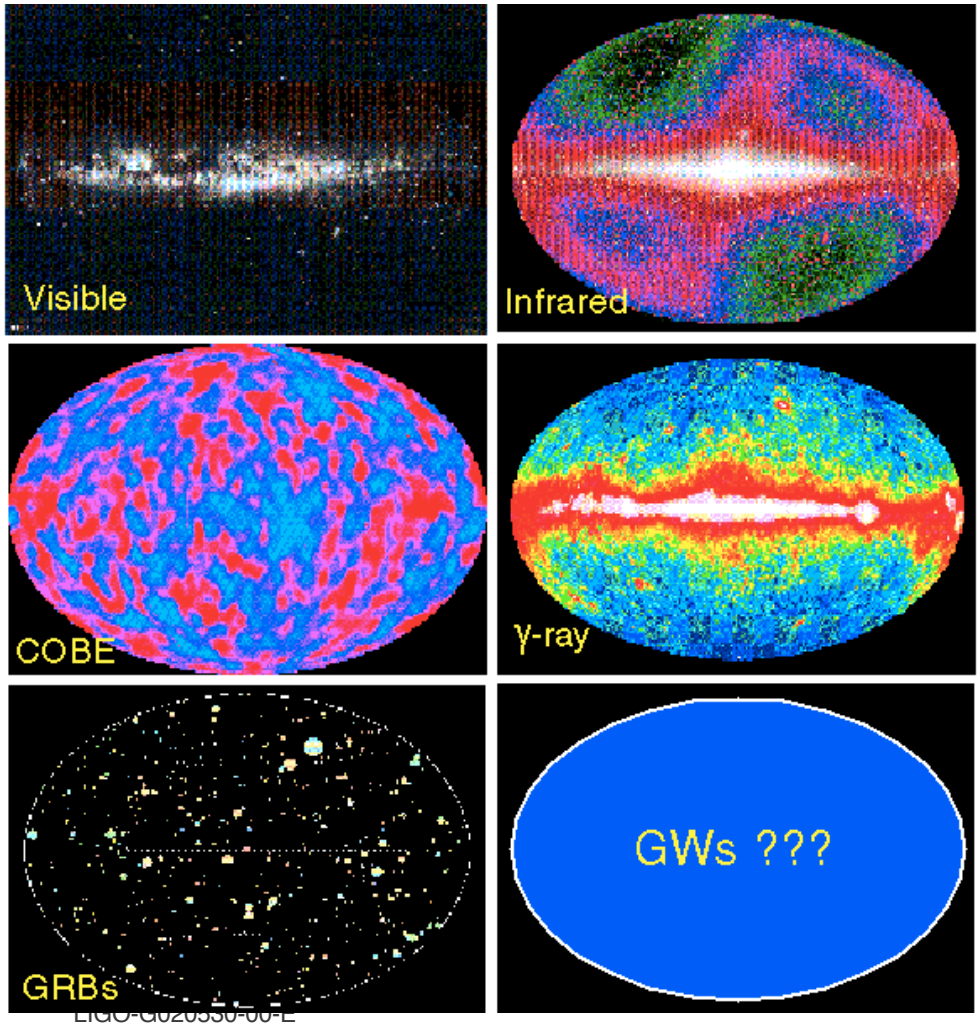


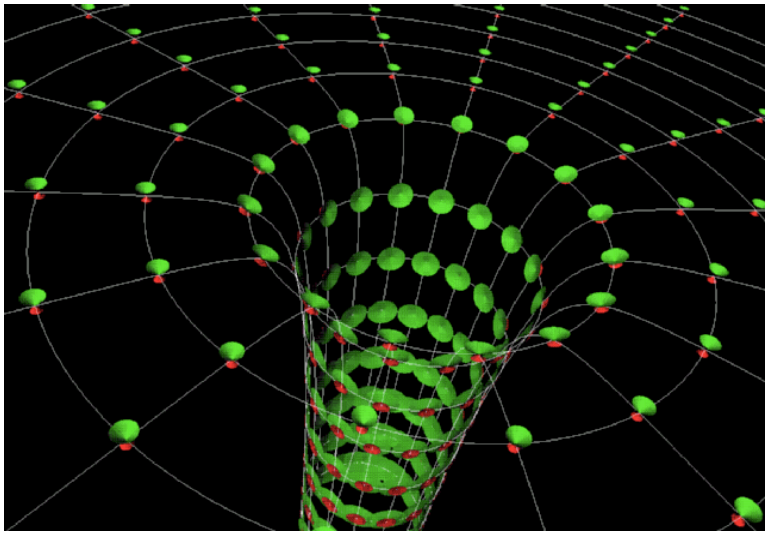
Livingston Observatory
Louisiana
One interferometer (4km)



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

New Window on Universe





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

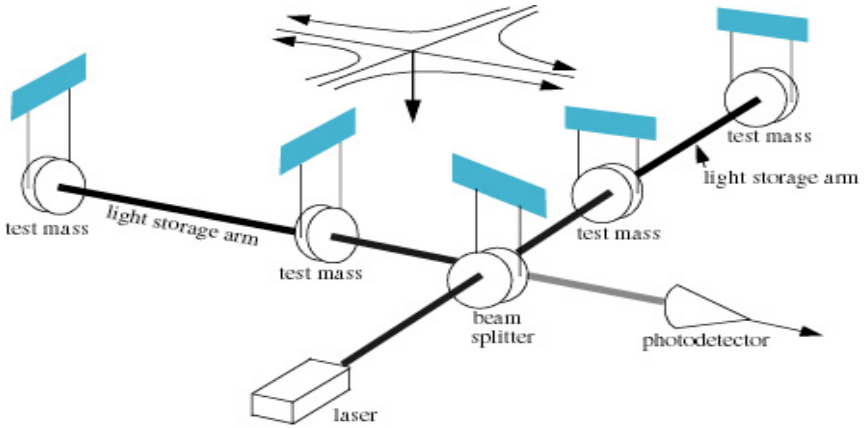
EXPECT SOURCES: BLACK HOLES, SUPERNOVAE, PULSARS AND COMPACT BINARY SYSTEMS.

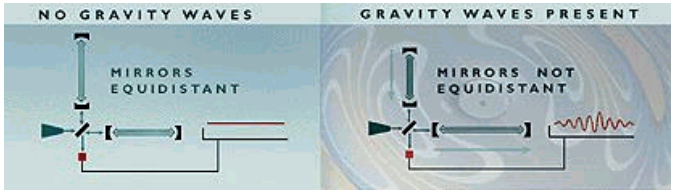
POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

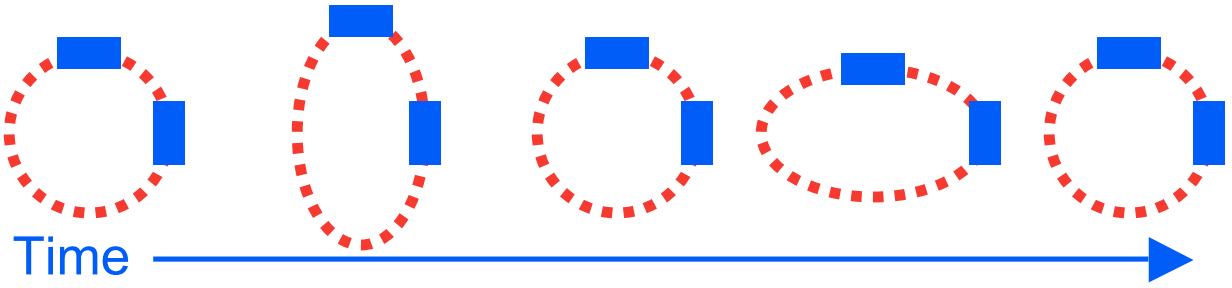
Interferometer GW Detectors

Principle of Detection:

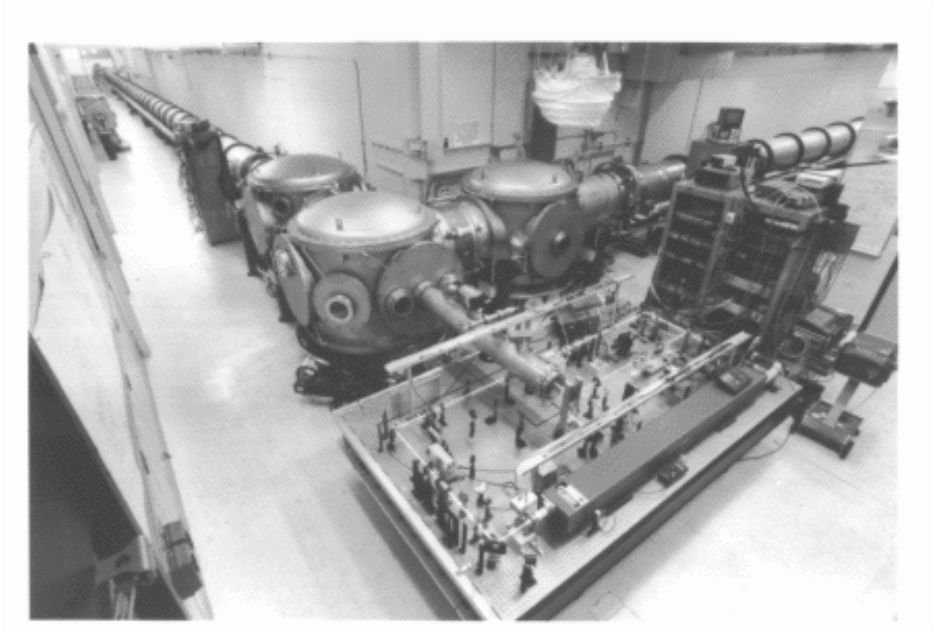
- A gravitational wave causes the interferometers arm lengths to vary by stretching one arm while compressing the other, in the plane perpendicular to direction of travel.

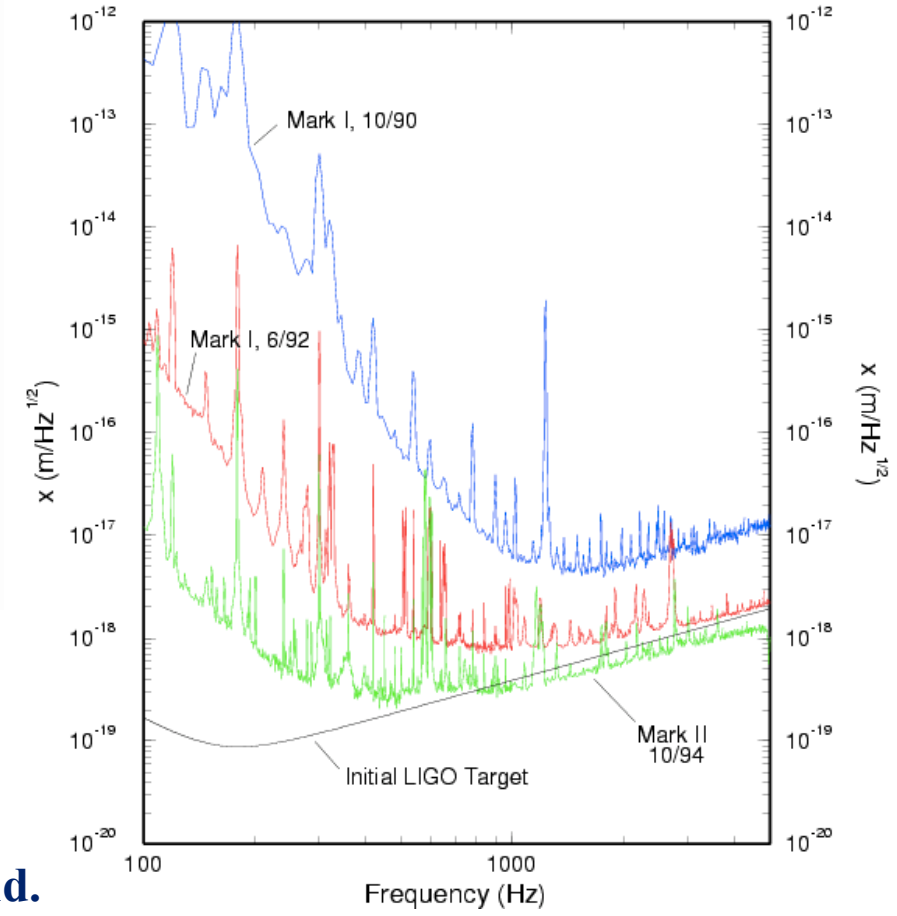






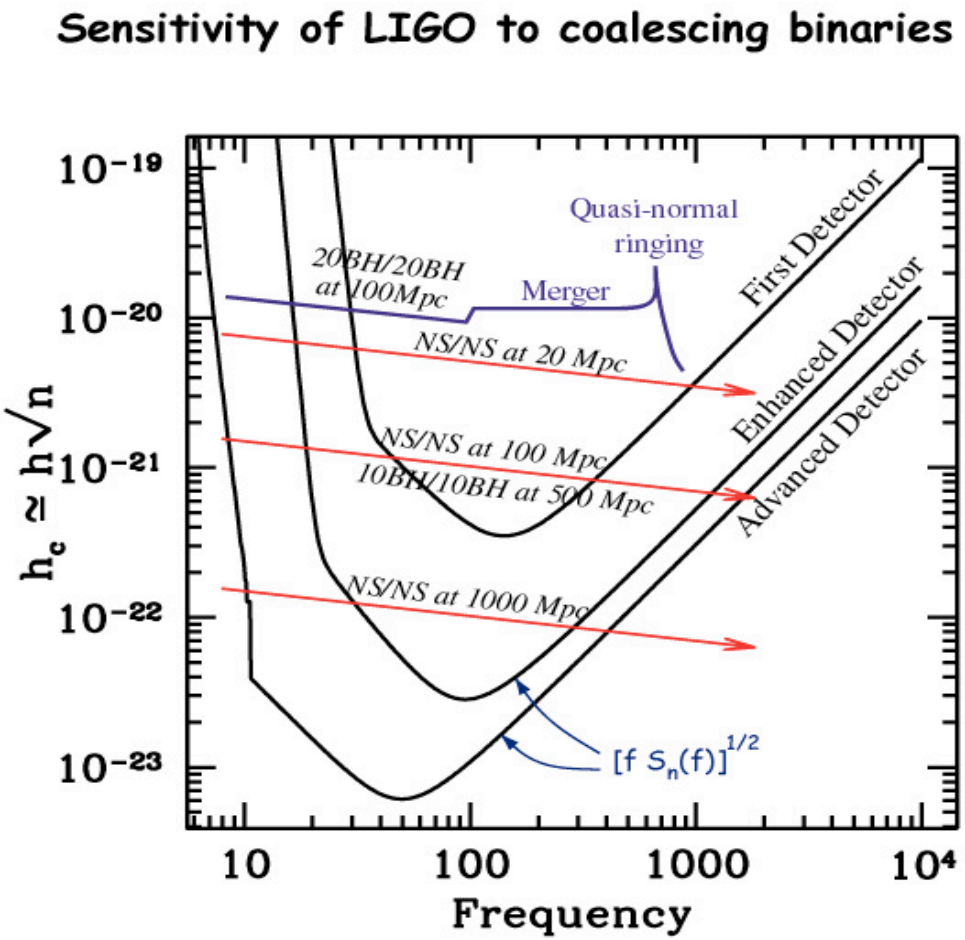
The Early Years:
Caltech 40 Meter Interferometer

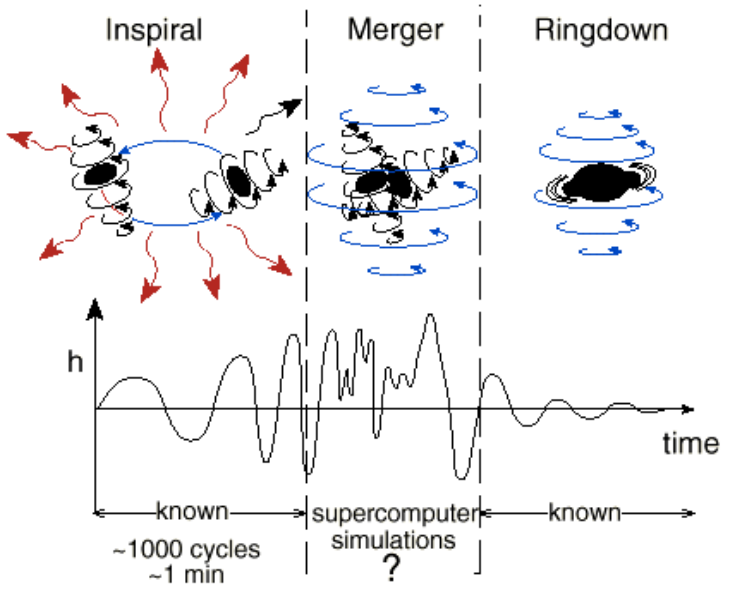




- **1/100th scale prototype for LIGO.**
- **Characterized fundamental noise sources.**
- **Instrumental as a technology proving ground.**

Compact Binary Sources





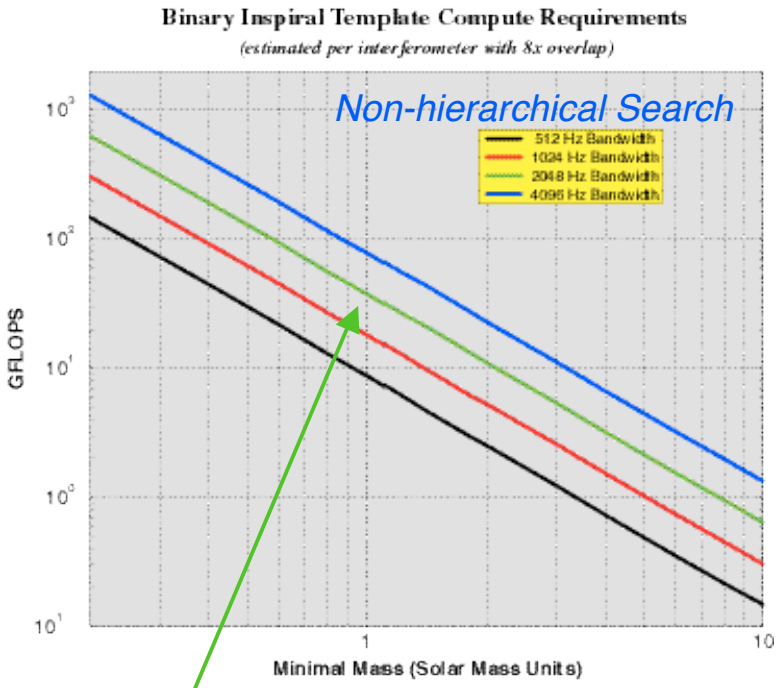
Brief Summary of Detection Capabilities of Mature LIGO Interferometers

• **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}
$D_{\rm I}$	20 Mpc	43 Mpc	100	100
$\mathcal{R}_{\rm I}$, yr^{-1}	1×10^{-4} – 0.03	$\lesssim 1\times10^{-4}$ – 0.3	$\lesssim 3\times10^{-3}$ – 0.5	0.03 – 0.5
$D_{\rm WB}$	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

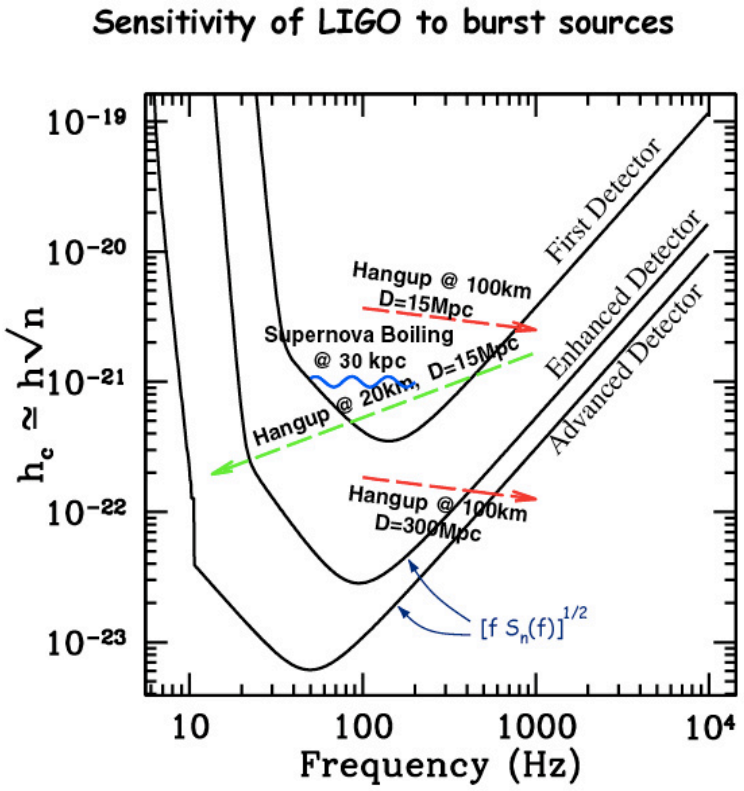
LIGO Data Analysis

- **Different scientific topics - 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 understand of instrumental couplings to GW channel.
  - » Provide calibration for data analysis



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

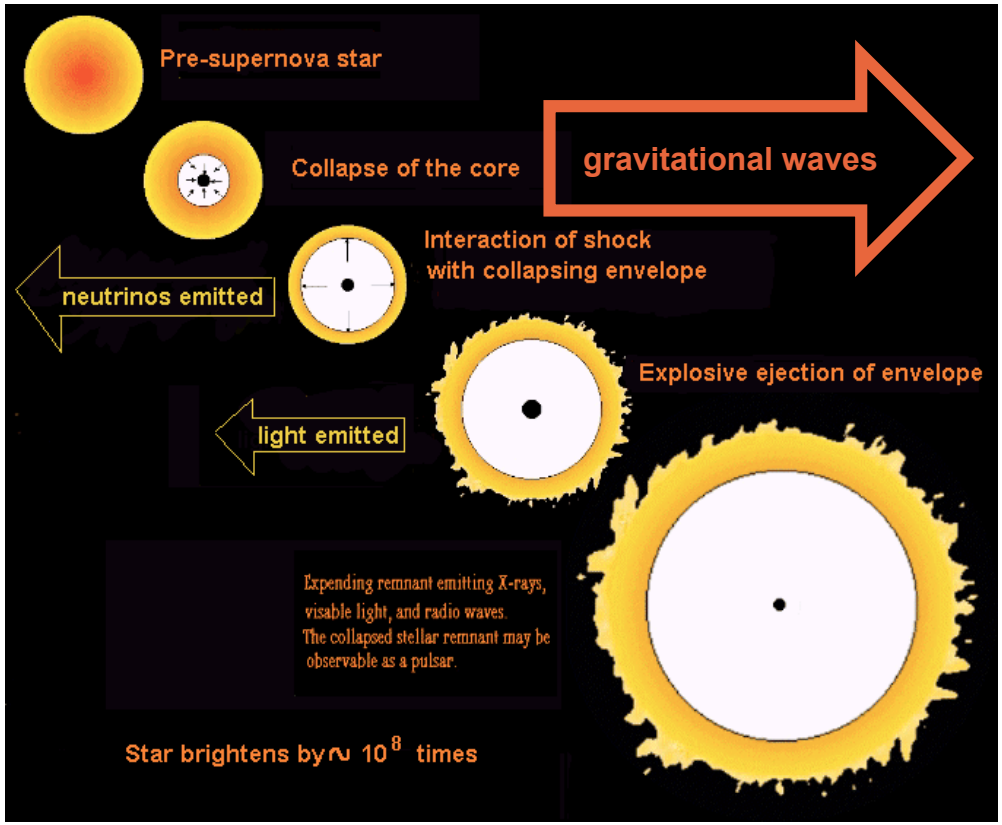
Burst Sources



Rate

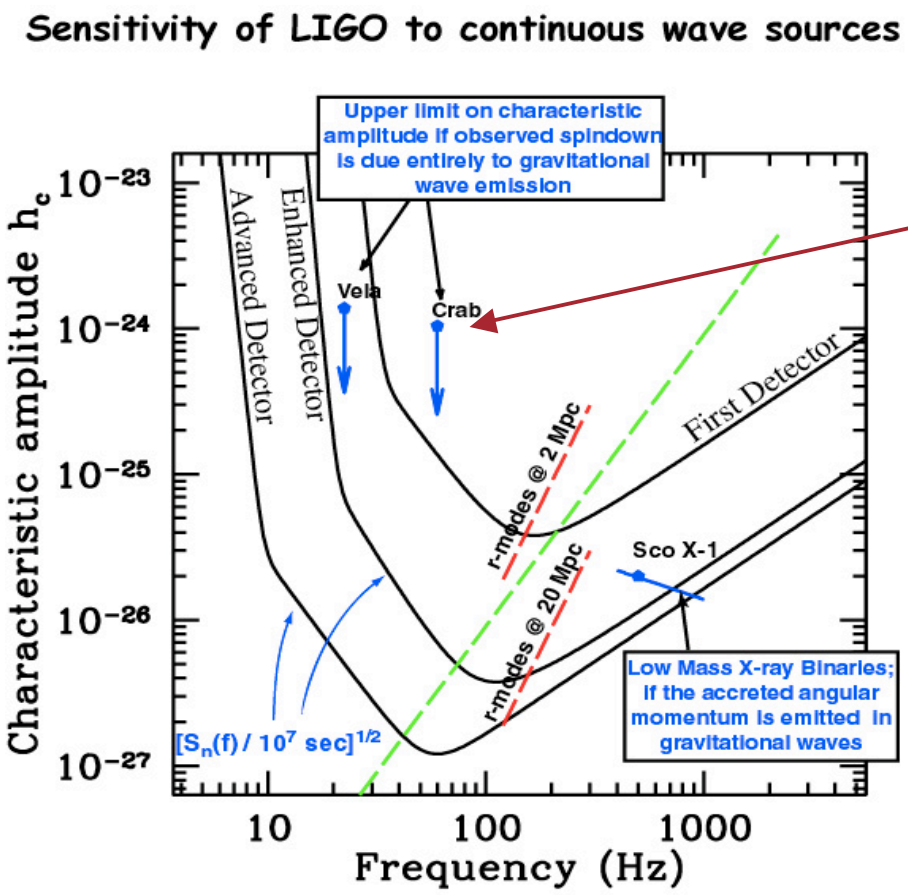
1/50 yr - our galaxy

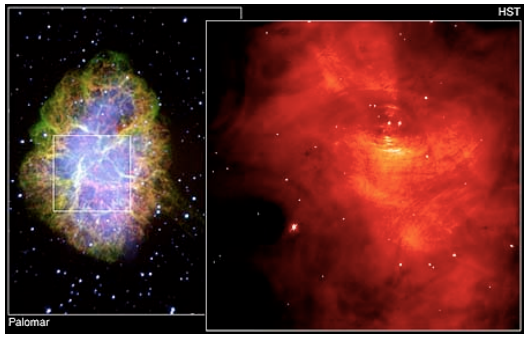
3/yr - Virgo cluster



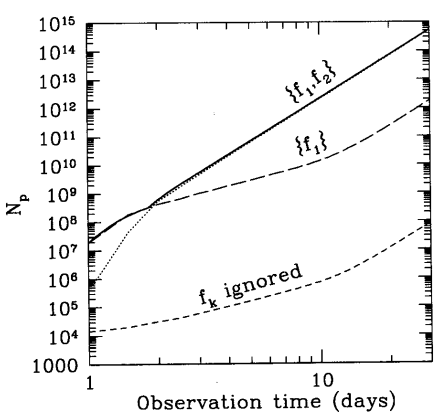
Periodic Sources

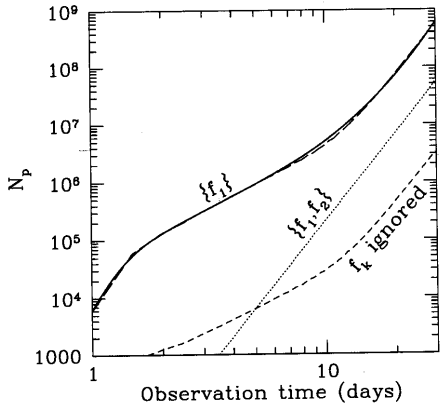
On a 1TFLOPS computer it would take more than 10,000 yr to perform an all-sky search over a 1000 Hz band for an observation time of 4 months.





Data must be corrected for each source position on the sky



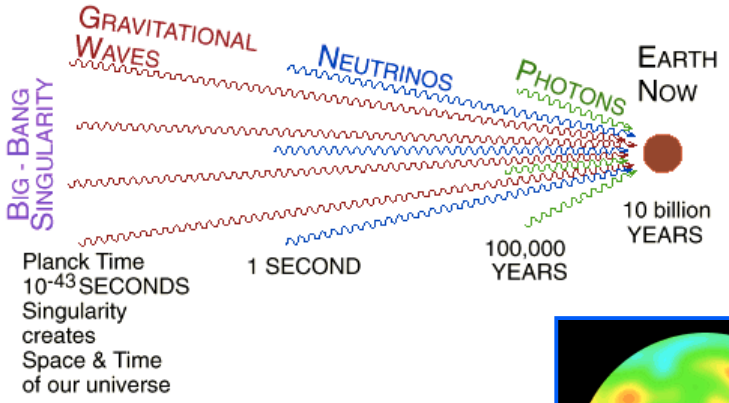


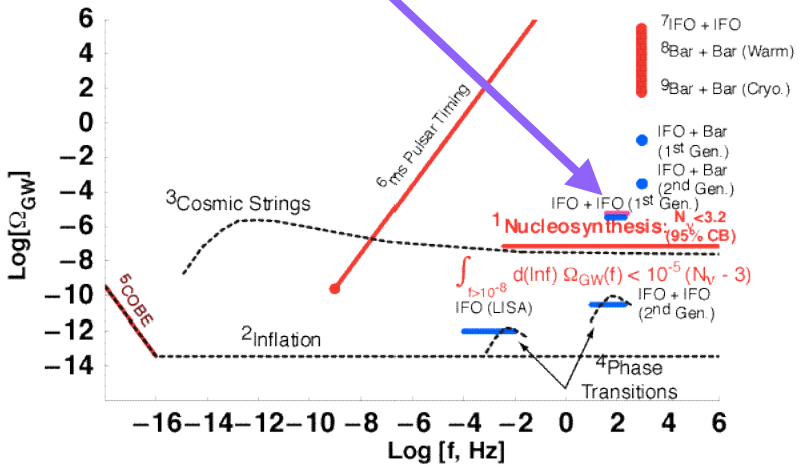
** Graphs from Brady, Creighton, Cutler, and Schutz, gr-qc/9702050*

Stochastic Background Sources

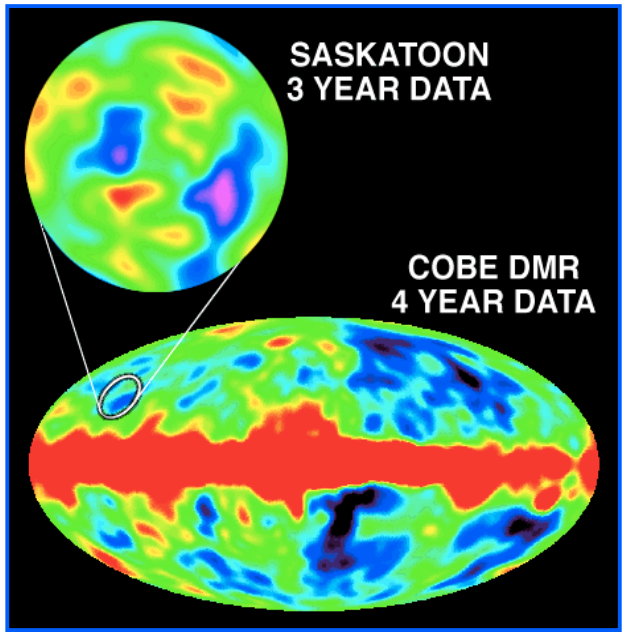
Upper limit possible with initial LIGO interferometers:

$Omega_{GW}$ ~10^{-5}



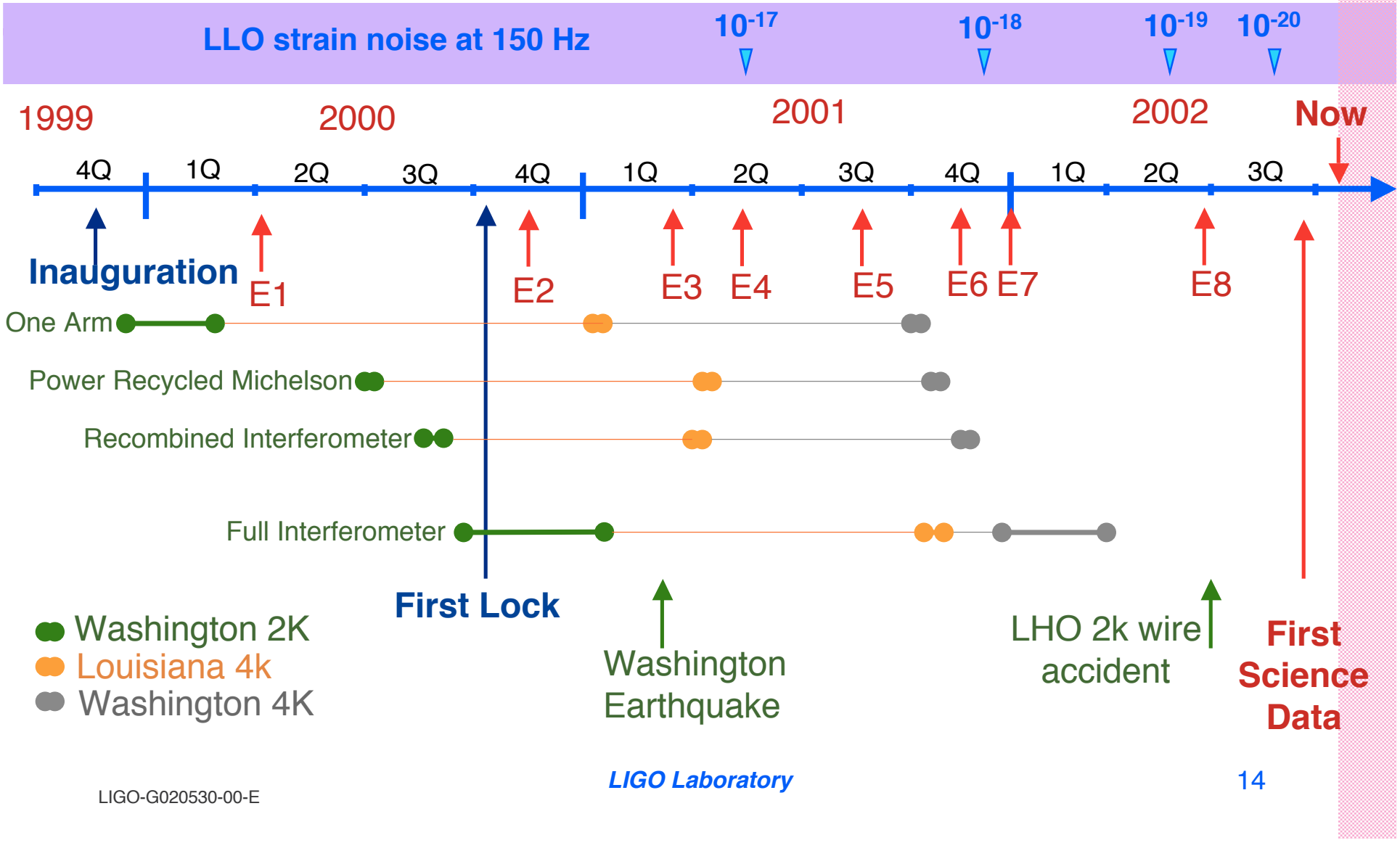


[1] Kolb & Turner (The Early Universe, 1990)
Burles, Nollet,Trunan, Turner (PRL 82, 1999)
[2] Grishchuk (SPJETP 40, 1975)
[3] Allen & Brustein (gr-qc9609013)
Allen (gr-qc9604033)
[4] Kamionkowski, Kosowoski &Turner (PRD 49, 1994)
[5] Allen & Koranda (PRD 50, 1994)
[6] Thorsett & Dewey (PRD 53, 1996)
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)

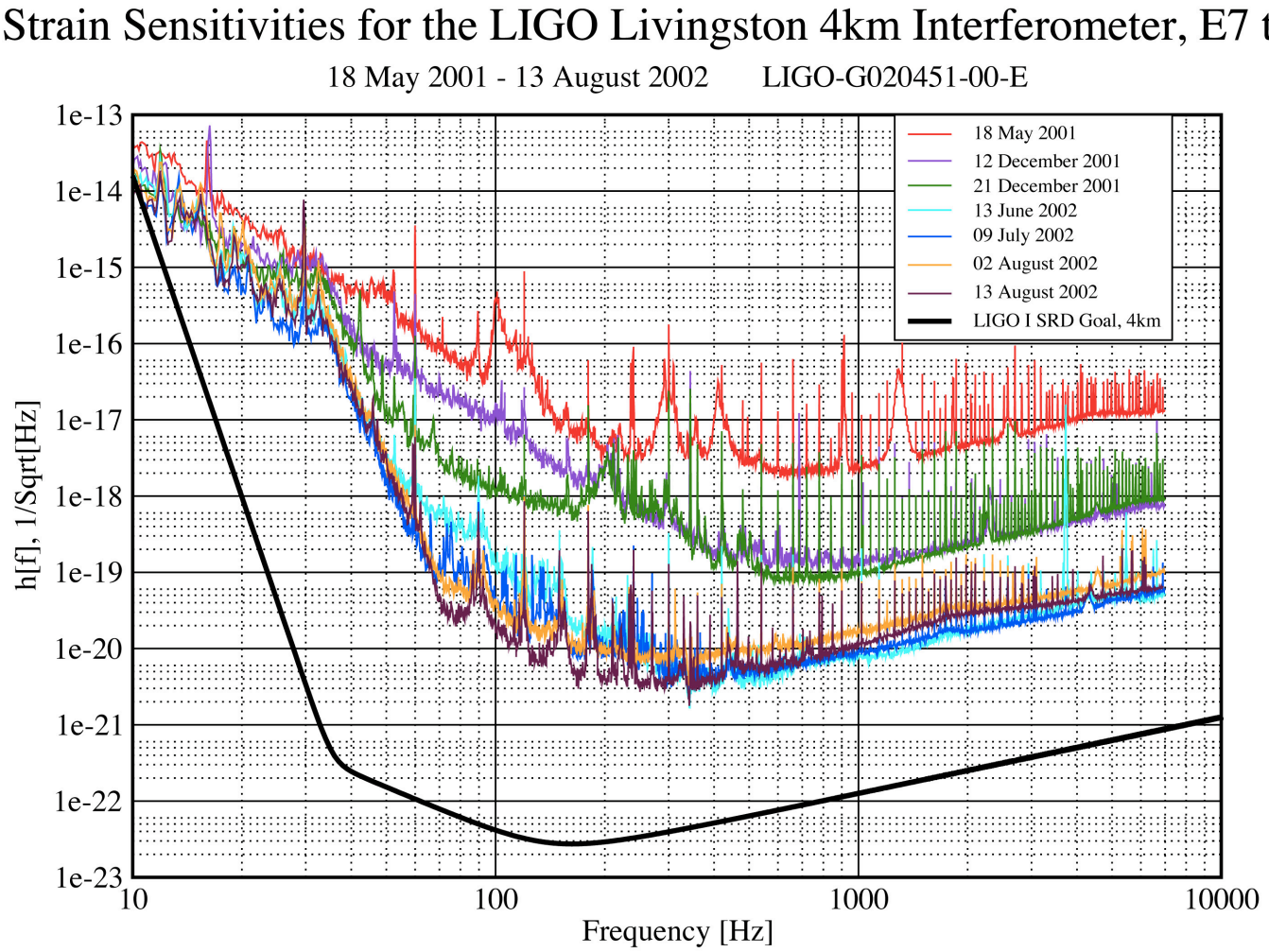


Analog from electromagnetic spectrum

Time Line


LLO strain noise at 150 Hz
10-17
10-18
10-19
10-20
1999
2000
2001
2002
Now
4Q
1Q
2Q
3Q
4Q
1Q
2Q
3Q
4Q
1Q
2Q
3Q
Inauguration
E1
E2
E3
E4
E5
E6
E7
E8
One Arm
Power Recycled Michelson
Recombined Interferometer
Full Interferometer
First Lock
Washington 2K
Louisiana 4k
Washington 4K
Washington Earthquake
LHO 2k wire accident
First Science Data

Sensitivity has steadily improved throughout commissioning

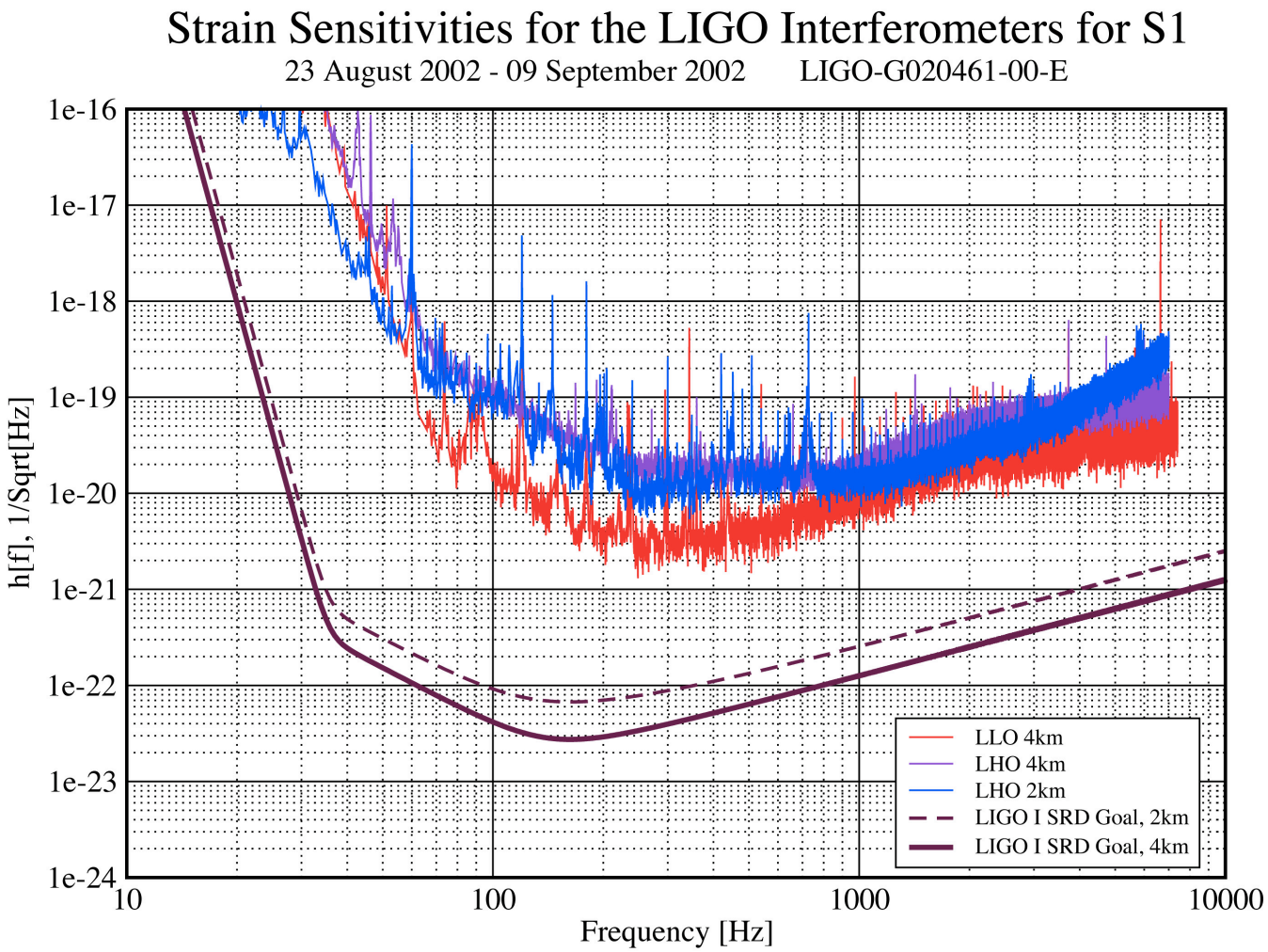


LIGO Sensitivity at Start of S1

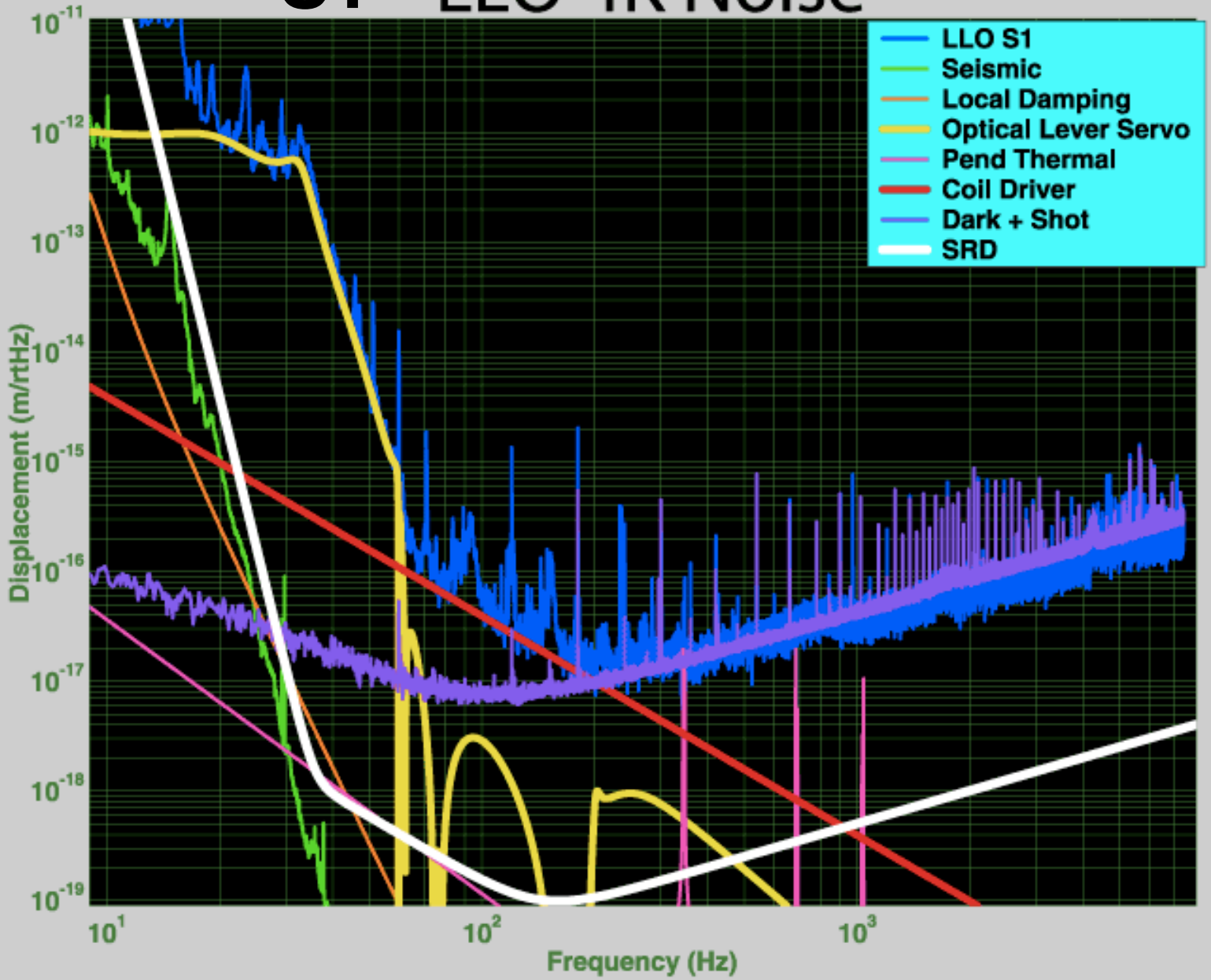
LIGO
S1 Run

"First Upper Limit Run"

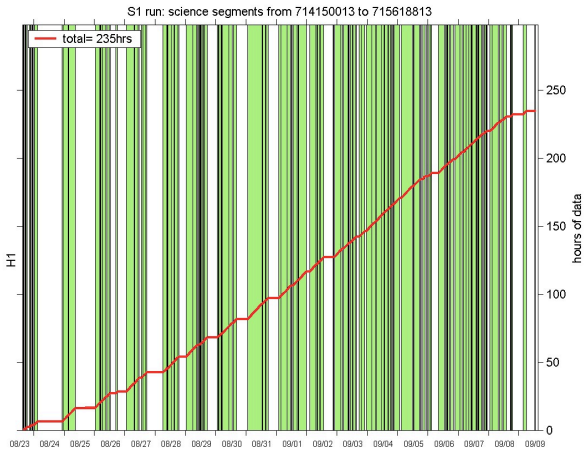
Aug – Sept 02

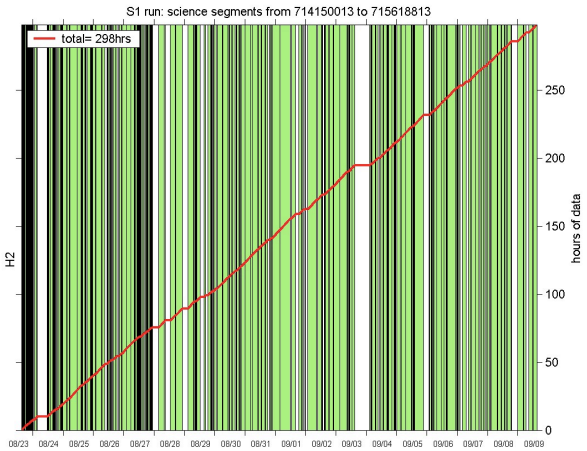


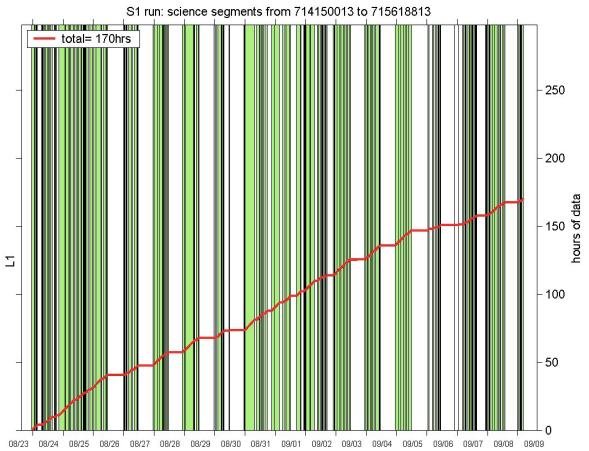
S1 LLO 4K Noise



In-Lock Data from S1





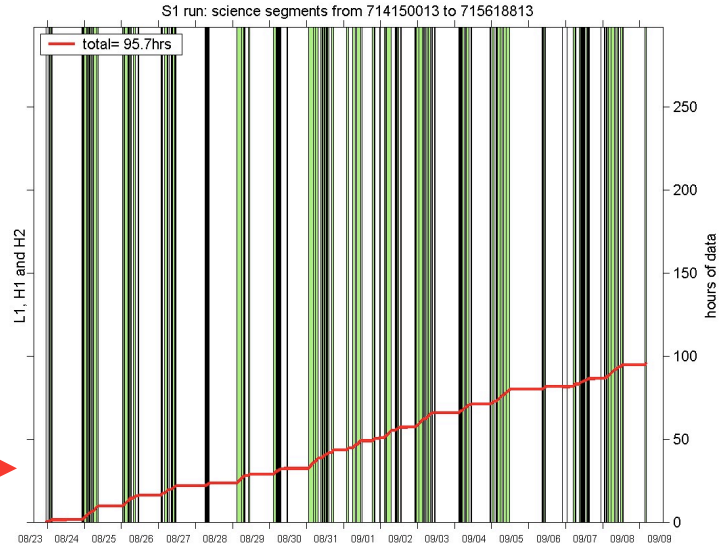


Livingston 4km: 170 hrs of lock

Hanford 4km: 235 hrs of lock

Hanford 2km: 298 hrs of lock

Triple Coincidence: 95.7 hrs



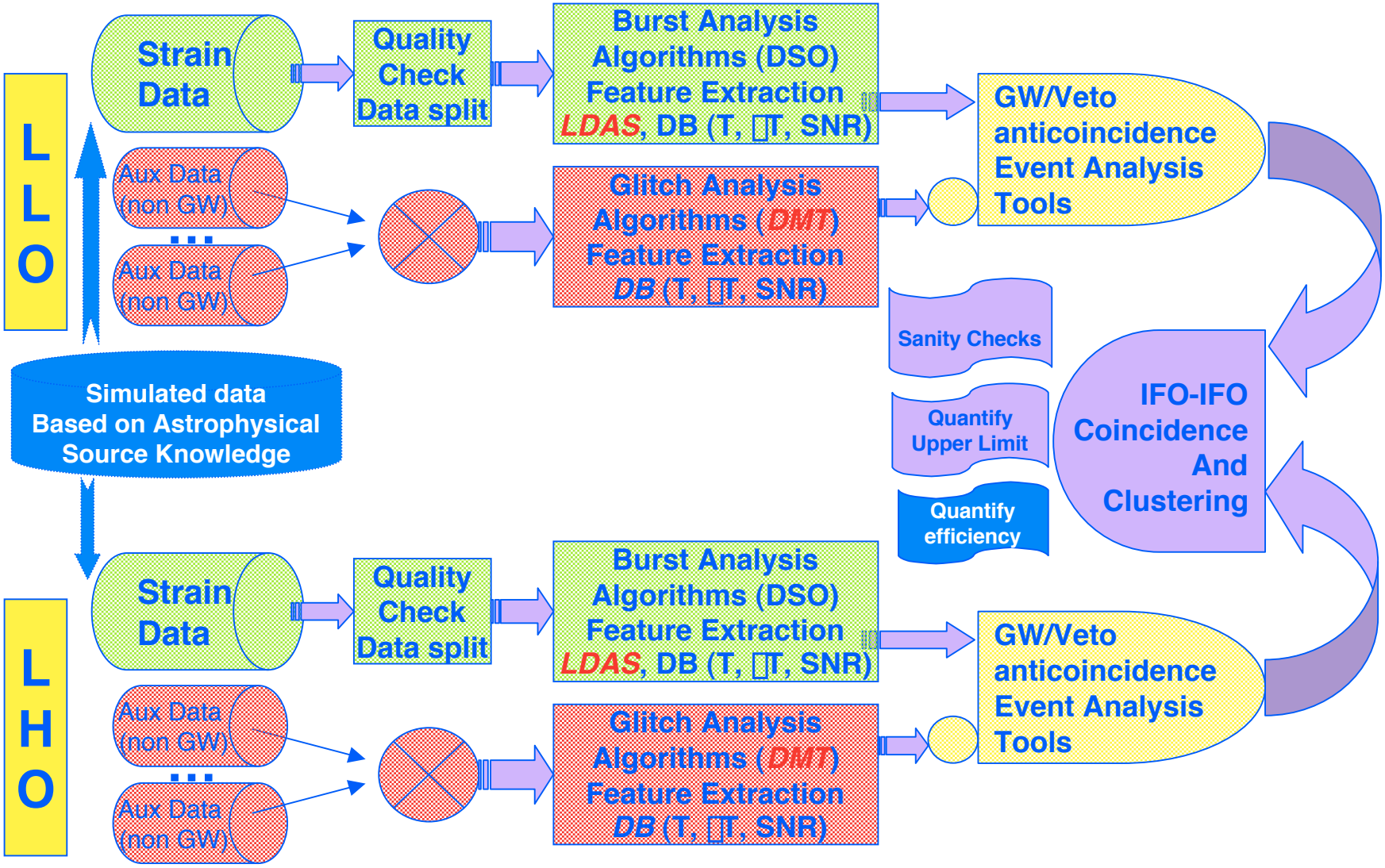
LIGO Laboratory

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

Astrophysical Search Pipeline

- example: burst group analysis -

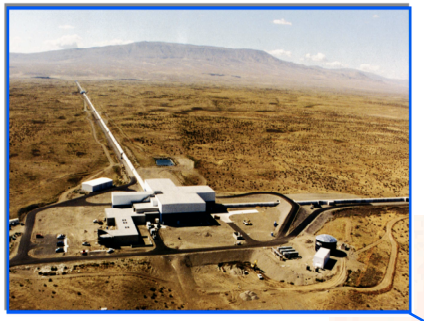


LIGO First Science Run Synopsis

- Projections based on ~2.5% sampling of data over 17 days
- Compact object inspiraling waveforms
  - » Detectable to D = 150 kpc (covers the Galaxy, plus LMC, SMC)
  - » Typical sensitivity for a binary neutron star population.
- Bursts/transient events
  - » 96.5 hours of 3X coincidence
  - » Expected false alarm rate < **XX** events/hr
- Continuous wave sources
  - » Single-interferometer integrated strain sensitivity expected to be $h_{rms} \sim Y \times 10^{-YY}$
  - » For CW sources with characteristic frequencies near minimum of sensitivity curve at 300 Hz
- Stochastic background
  - » Limiting sensitivity □ > 1, but significantly better than previous observational determinations

Growing International Network of GW Interferometers

LIGO-LHO: 2km, 4km



GEO: 0.6km

VIRGO: 3km

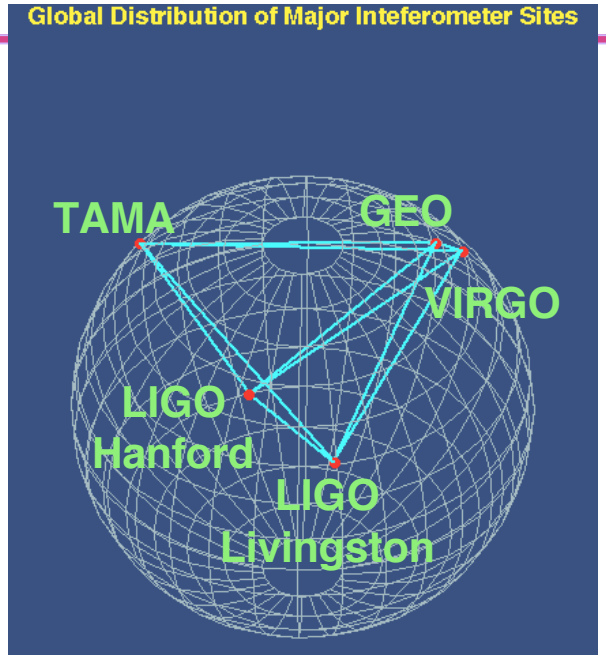
TAMA: 0.3km

LIGO-LLO: 4km

AIGO: (?)km

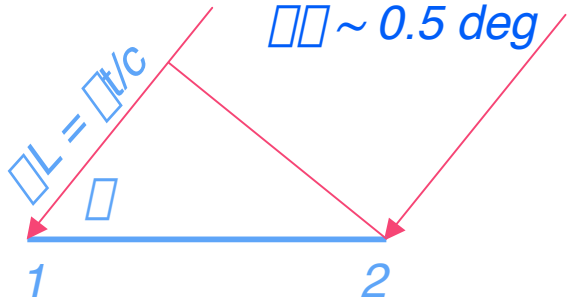
LIGO Laboratory

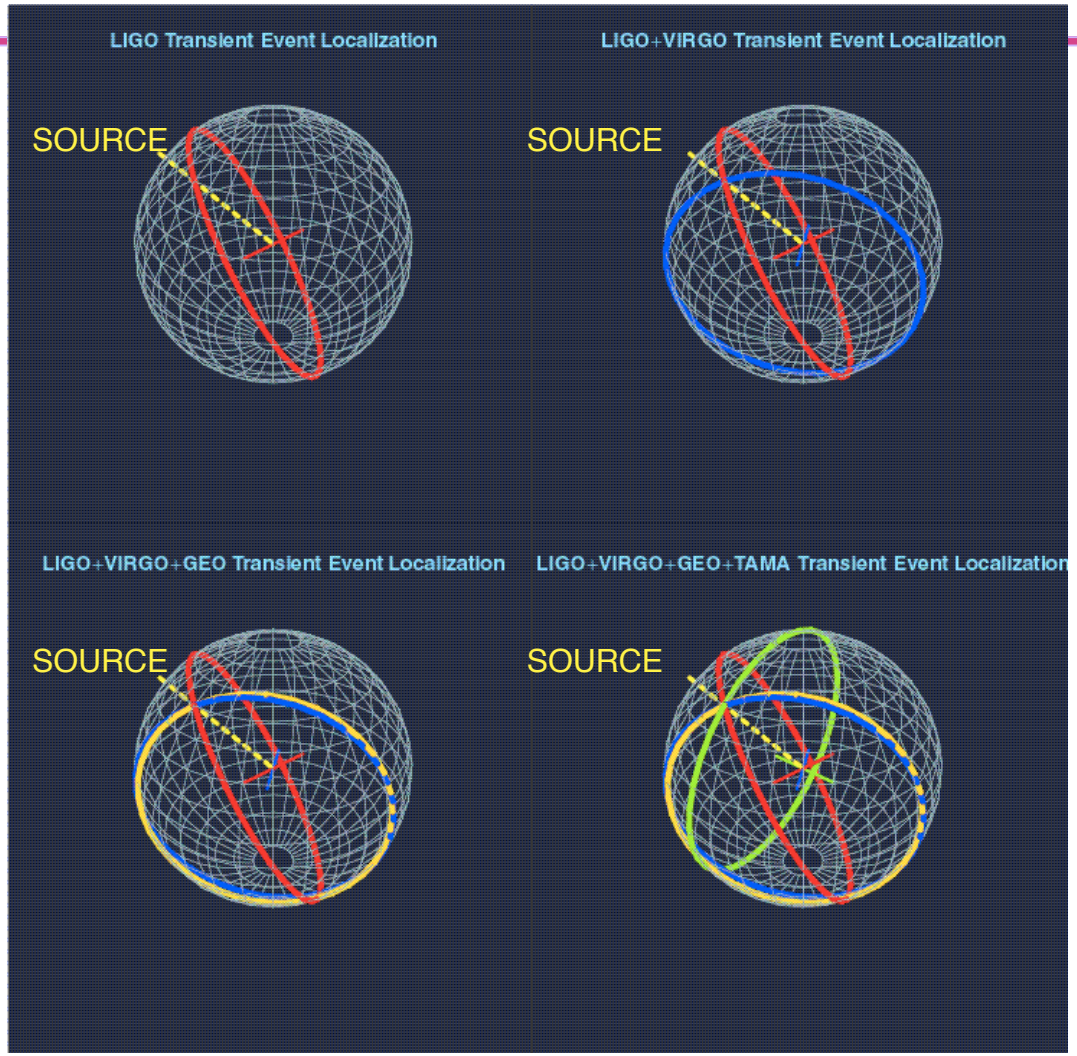
Event Localization With An Array of GW Interferometers



$\cos\theta = \delta t / (c\, D_{12})$

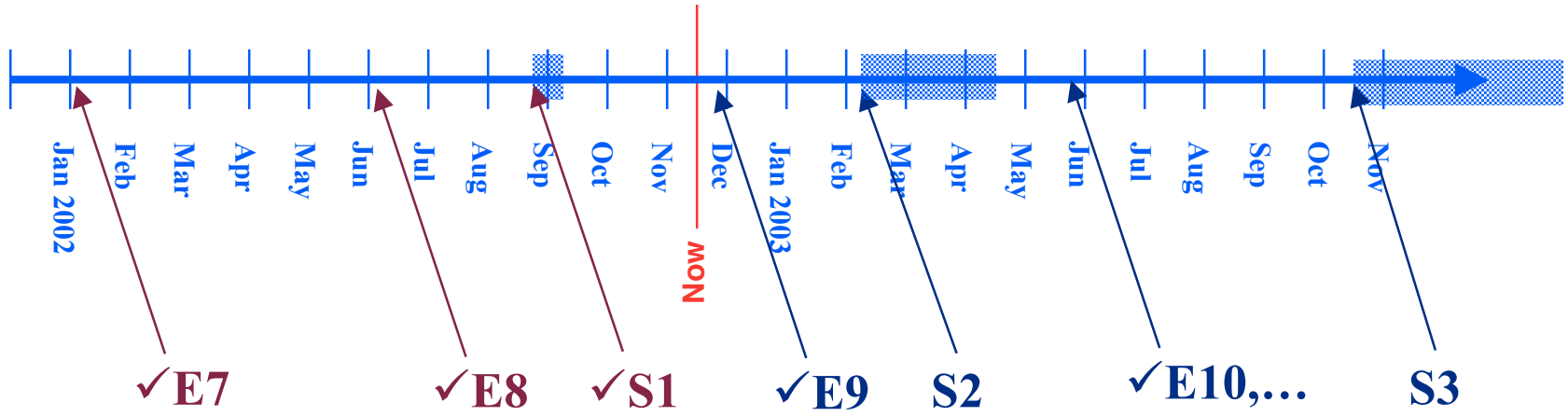
$\theta\theta \sim 0.5$ deg



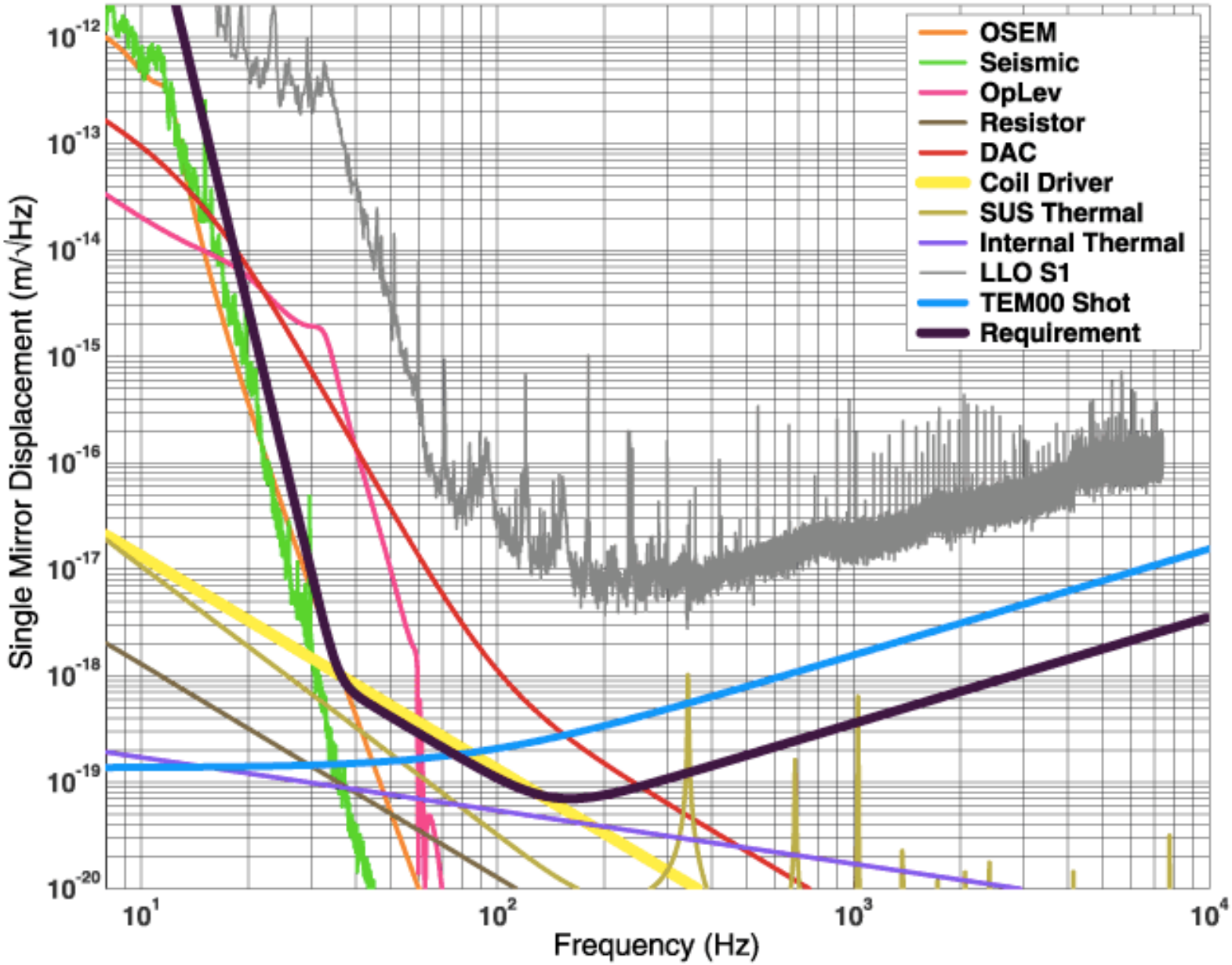


LIGO Run Schedule

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

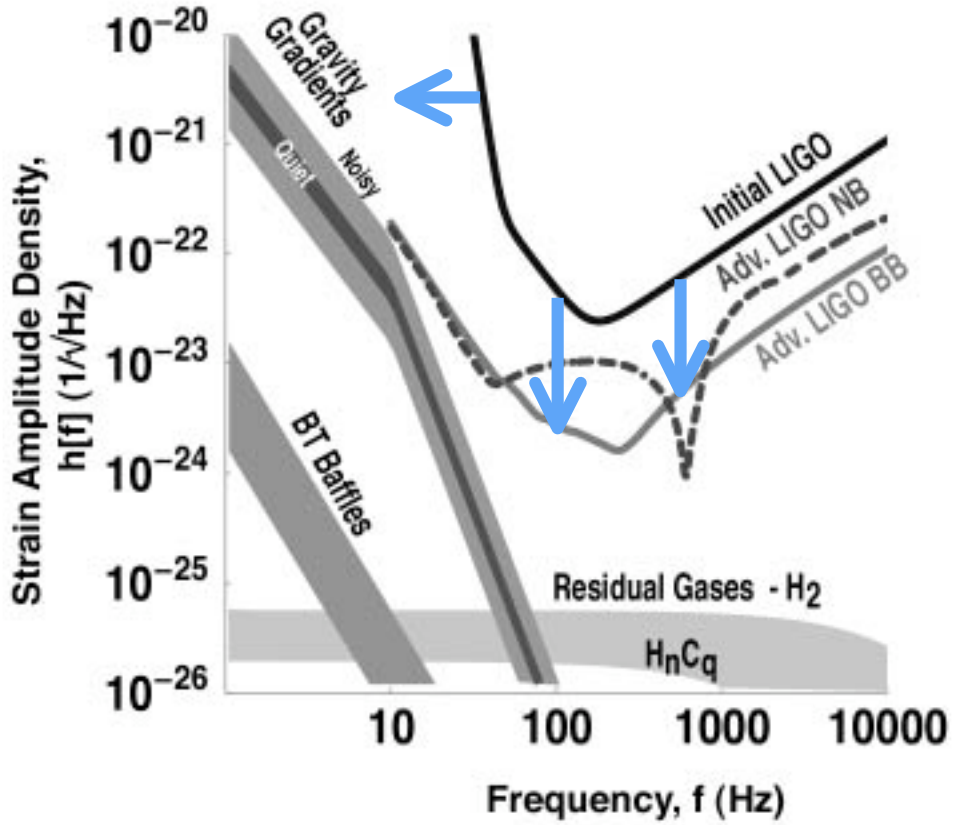


Estimated Noise limits for S2



A Look to the Future

- **Inherent facility limits**
  - Gravity gradients (seismic waves)
  - Residual gas (vacuum)
  - Room to improve…
- **Advanced LIGO**
  - R&D underway…
  - Seismic noise 40→10 Hz
  - Thermal noise 1/15th
  - Shot noise 1/10th

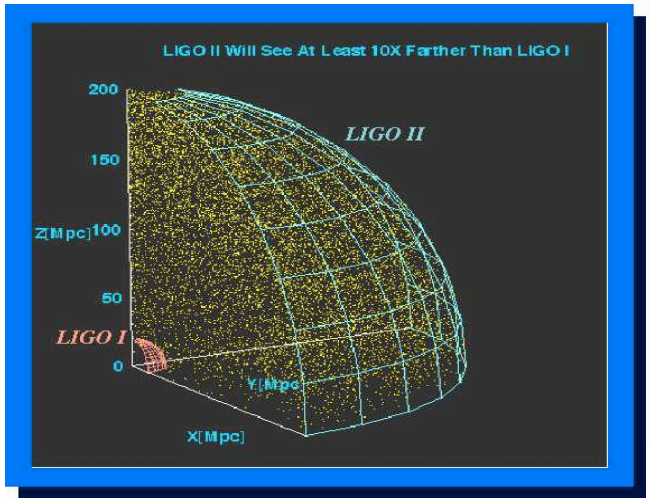


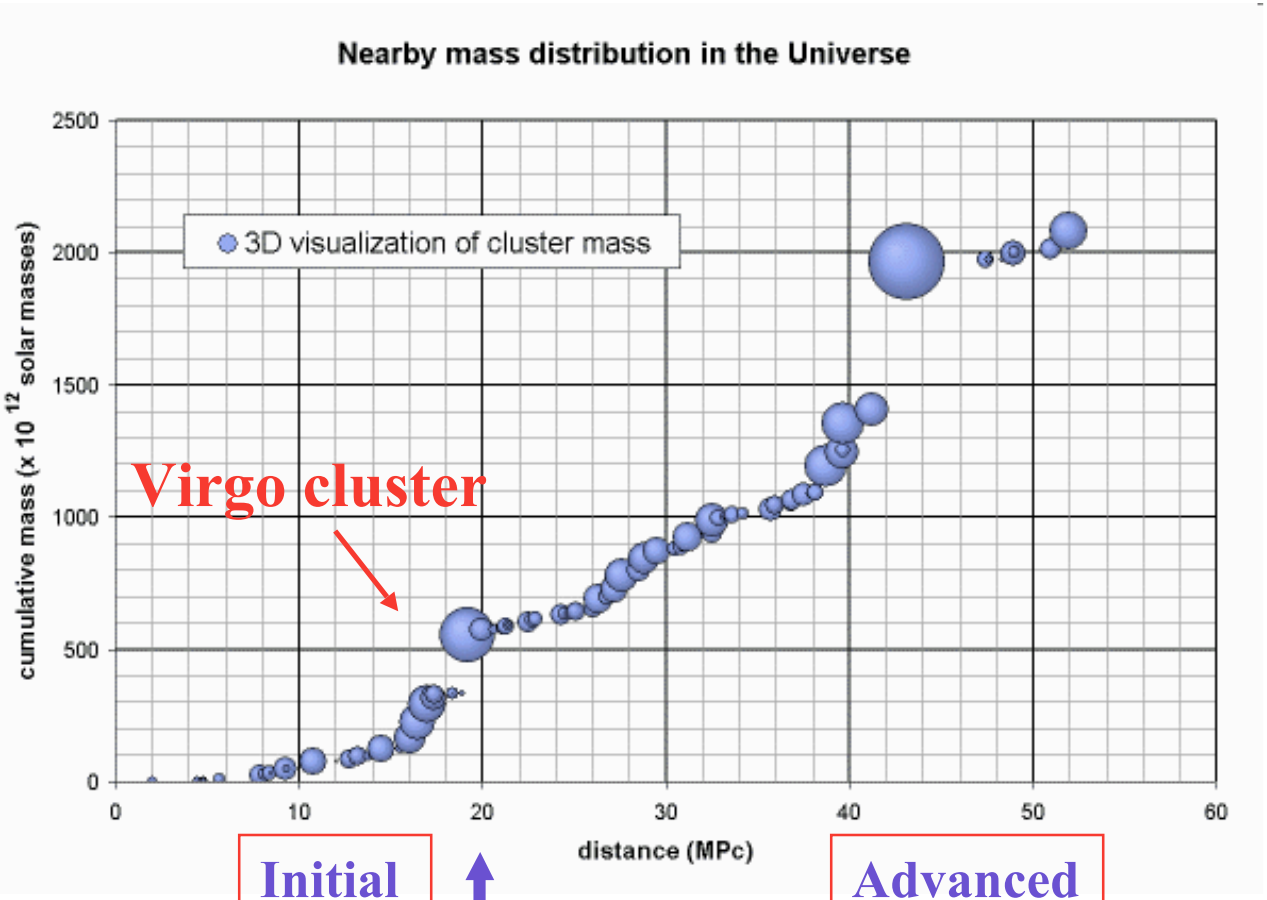
Advanced LIGO:

Cubic Law for "*Window*" on the Universe

Improve amplitude sensitivity by a factor of 10x…

…number of sources goes up 1000x!





LIGO Science Has Started

LIGO is taking and analyzing data

- LIGO had a successful first science run this summer
  - » Collaboration is currently carrying out the data analysis!
- LIGO is taking its first steps to providing new scientific insight into the workings of the Universe.
- ***LIGO is taking and analyzing data***