

The LIGO Experiment: Status and First Results

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- **Gravity Waves: Sources and Detection**
- **LIGO Data Analysis and Results**
- **Outlook: Advanced LIGO**

Gravitational Waves

- Predicted by General Relativity: source = energy tensor
- Quadrupolar radiation, two polarizations + and x
- Amplitude is characterized by dimensionless strain h :

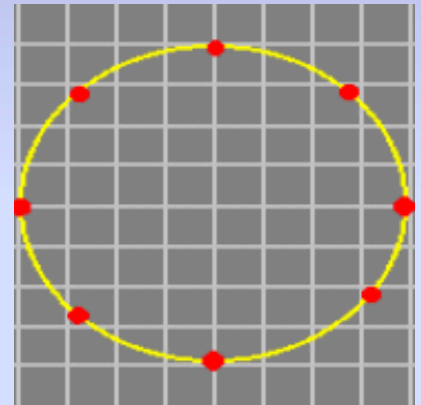
$$h = \frac{\Delta L}{L}$$

Note: Effect is tidal

- Strength at earth: $h \sim \frac{G}{c^4} \frac{\ddot{Q}}{r}$

$$\ddot{Q} \cong 4E \quad \text{non-spherical part of kinetic energy}$$

- For $r \sim 100$ Mpc, $E \sim M_{\odot}$: $h \sim 10^{-22} - 10^{-21}$



Gravitational Wave Detection

Strain sensitivity from shot noise:

$$\delta h \sim \frac{\delta x}{L} \sim \frac{\lambda}{L_0 b \sqrt{\dot{N} \tau}}$$

δx is change in length L

Wavelength $\lambda = 1 \mu\text{m}$

Arm length $L_0 = 4 \text{ km}$

Number of bounces $b = 100$

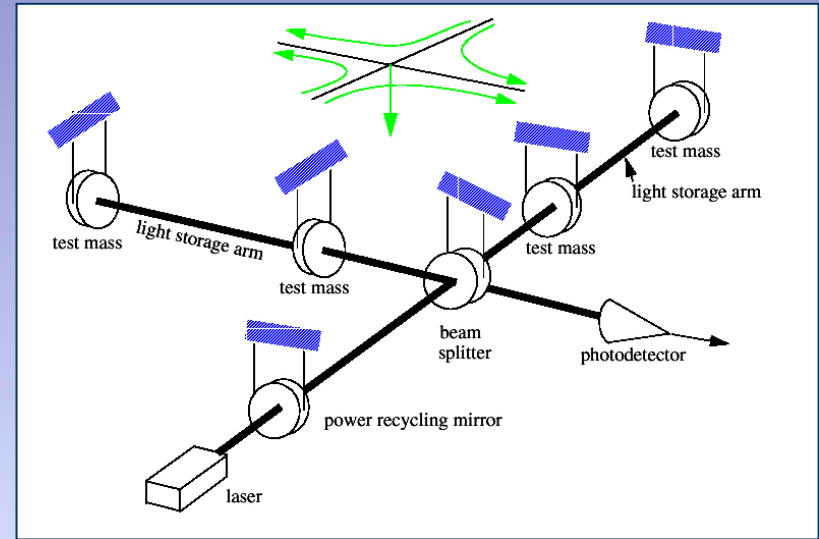
Number of photons per second for 300 W
at the beam splitter $dN/dt = 10^{21} \text{ sec}^{-1}$

Strain sensitivity = 6×10^{-22} for integration time $\tau = 0.01 \text{ sec}$

In practice λ is not sufficiently stable:

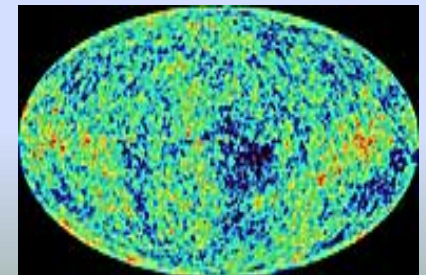
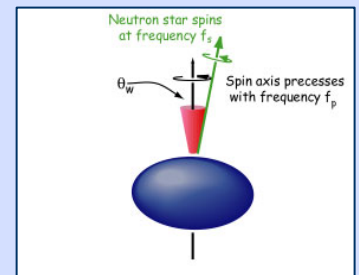
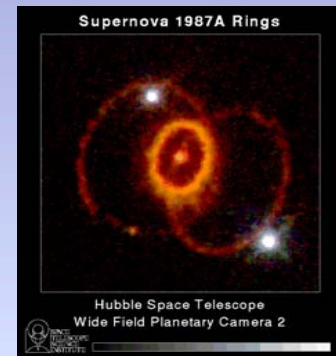
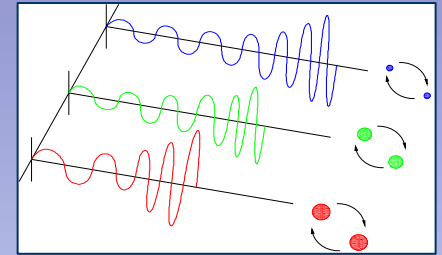
Compare length of two arms interferometrically!

At low frequencies the sensitivity is limited by seismic and thermal noise and at high frequencies by the arm cavity rolloff



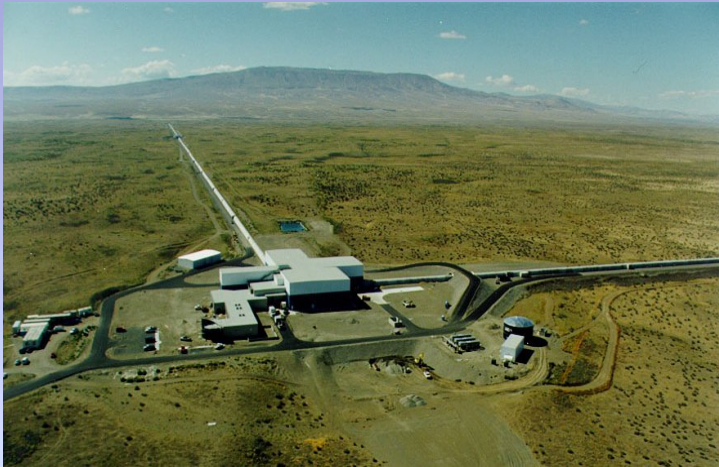
Gravitational Waves Sources

- **Compact binary inspiral:** *“chirp”*
 - NS-NS waveforms are well described
 - BH-BH waveforms are improving
 - test strong field GR, study equation of state
- **Supernovae / GRBs:** *“burst”*
 - all-sky untriggered searches
 - burst signals in coincidence with signals in electromagnetic radiation/neutrinos
 - study stellar collapse, pulsar formation
- **Pulsars in our galaxy:** *“continuous”*
 - search for observed neutron stars
 - all-sky search computing challenging
- **Cosmic Background:** *“stochastic”*
 - metric fluctuations amplified by inflation, phase transitions in early universe, brane-world effects
 - unresolved foreground sources



LIGO Observatories

Hanford, WA (H1=4km, H2=2km)



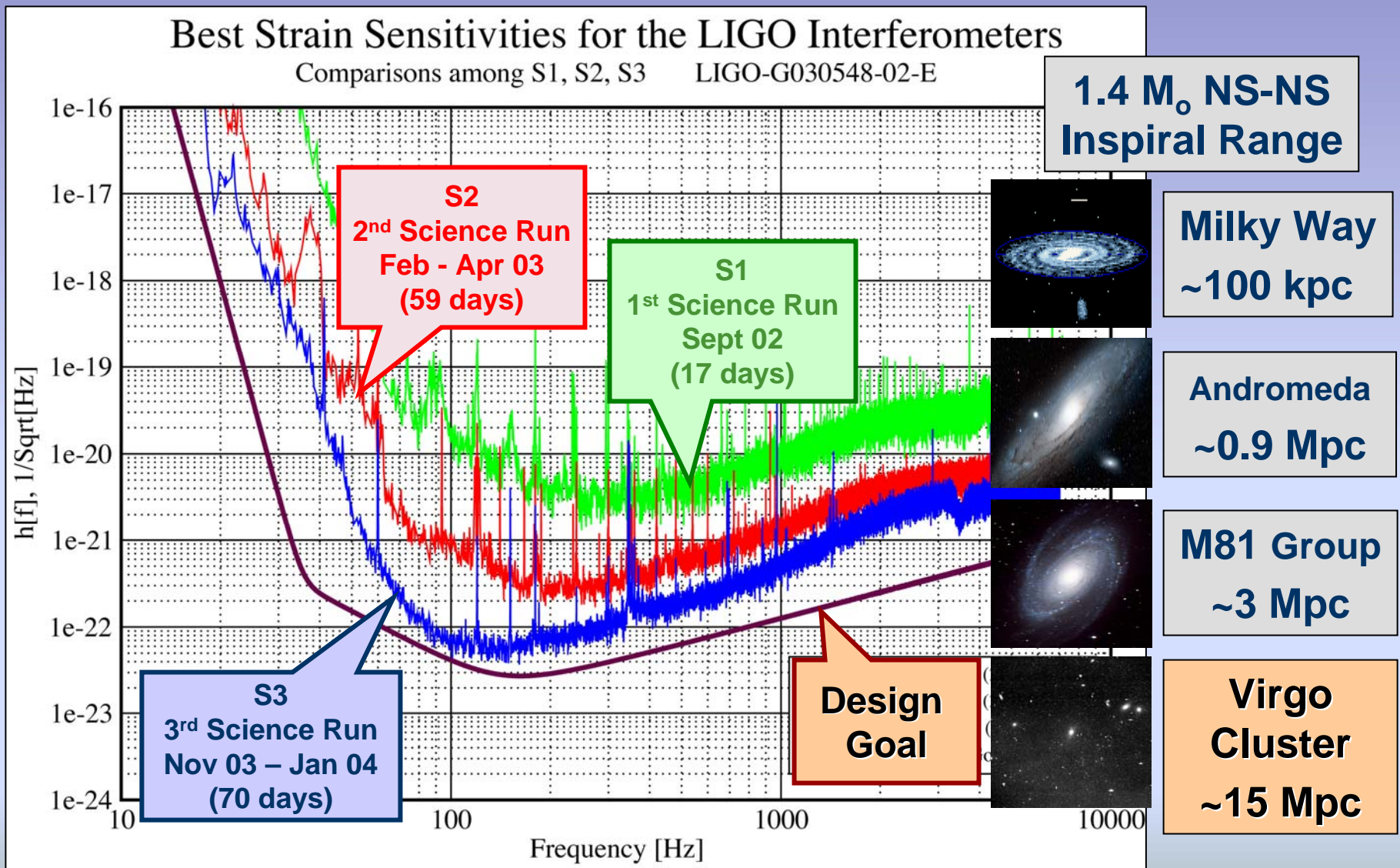
- *Interferometers are aligned to be as close to parallel to each other as possible*
- *Observing signals in coincidence increases the detection confidence*
- *Measure the direction to the source, the propagation speed and polarization of the gravity waves*



Livingston, LA (L1=4km)



Sensitivity Improvement



Overview of LIGO results

No evidence for gravity wave signals to date. Set upper limits:

- **NS-NS binary inspirals**
 - Know wave form. Use matched filtering.
S1: $R_{90\%} < 170$ events/year/Milky Way Equivalent Galaxy - PRD 69(2004)122001
S2: $R_{90\%} < 50$ events/year/MWEG **Preliminary**
- **Un-modeled bursts**
 - Wave form not known. Use coincidences between two or more ifo's.
S1: $R_{90\%} < 1.6$ events/day with $h_{rss} \sim 10^{-17}$ - 10^{-19} $\text{Hz}^{-1/2}$ - PRD 69(2004)102001
S2: Sensitivity improved by over 1 order of magnitude. Search result pending.
 - Coincidence with GRB030329 - 800 Mpc away. Data from two Hanford ifo's.
S2: $h_{rss} < 6 \times 10^{-21}$ $\text{Hz}^{-1/2}$ around most sensitive frequency region **Preliminary**
- **Known pulsars in our galaxy. From radio wave observation: $f, df/dt, d^2f/dt^2$**
 - Time domain method: heterodyne with known phase evolution and fit for GW amplitude and other source-observer parameters
S1: Search for pulsar J1939+2134 $h_0 < (1.4 \pm 0.1) \times 10^{-21}$ - PRD 69(2004)082004
S2: Search for 28 known pulsars $h_0 < 10^{-24}$ - 10^{-22} **Preliminary**

Characterization of a Gravitational Wave Background Radiation

- Assuming GWB is isotropic, stationary, and Gaussian the strength is fully specified by *the ratio of energy density in GWs to the critical density*

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

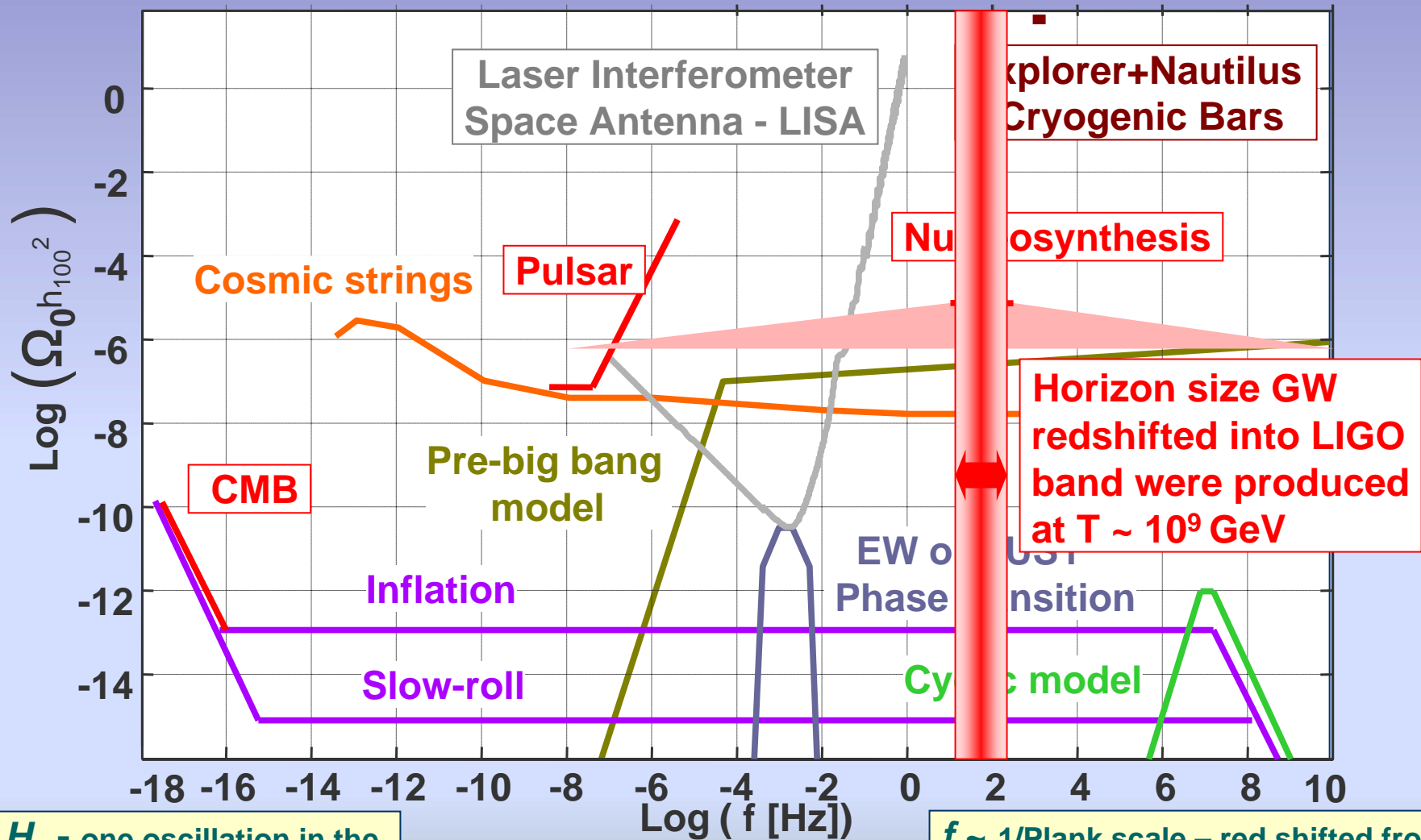
- $\Omega_{gw}(f)$ in terms of the strain power spectrum, $S_{gw}(f)$:

$$S_{gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{gw}(f)$$

- Strain amplitude scale:

$$h(f) = S_{gw}^{1/2}(f) = 5.6 \times 10^{-22} h_{100} \sqrt{\Omega_0} \left(\frac{100\text{Hz}}{f} \right)^{3/2} \text{Hz}^{1/2}$$

Gravitational Wave Background: Predictions and Experimental Limits



Horizon size GW redshifted into LIGO band were produced at $T \sim 10^9$ GeV

$f \sim H_0$ - one oscillation in the lifetime of the universe

$f \sim 1/\text{Plank scale}$ - red shifted from the Plank era to the present time

Stochastic GW Data Analysis

- Assume that detector noise $n_i(f)$ dominates the output, $P_i(f)$ - noise power spectrum
- Cross-correlate outputs from two interferometers $s_i(t) = h_i(t) + n_i(t)$
- Operator $Q(t)$ weights the cross-correlation according to the signal-to-noise ratio at each frequency
- Overlap reduction function $\gamma(t)$ accounts for separation and angle between two detectors

$$Y = \iint dt_1 dt_2 s_1(t_1) Q(t_1 - t_2) s_2(t_2)$$

$$\bar{Y} = \frac{T}{2} \int df \gamma(|f|) S_{gw}(|f|) \tilde{Q}(f)$$

$$\sigma_Y^2 \approx \frac{T}{4} \int df P_1(|f|) |\tilde{Q}(f)|^2 P_2(|f|)$$

$$\tilde{Q}(f) \propto \frac{\gamma(f) S_{gw}(f)}{P_1(f) P_2(f)} \quad \begin{array}{l} \text{Signal} \\ \text{Noise} \end{array}$$

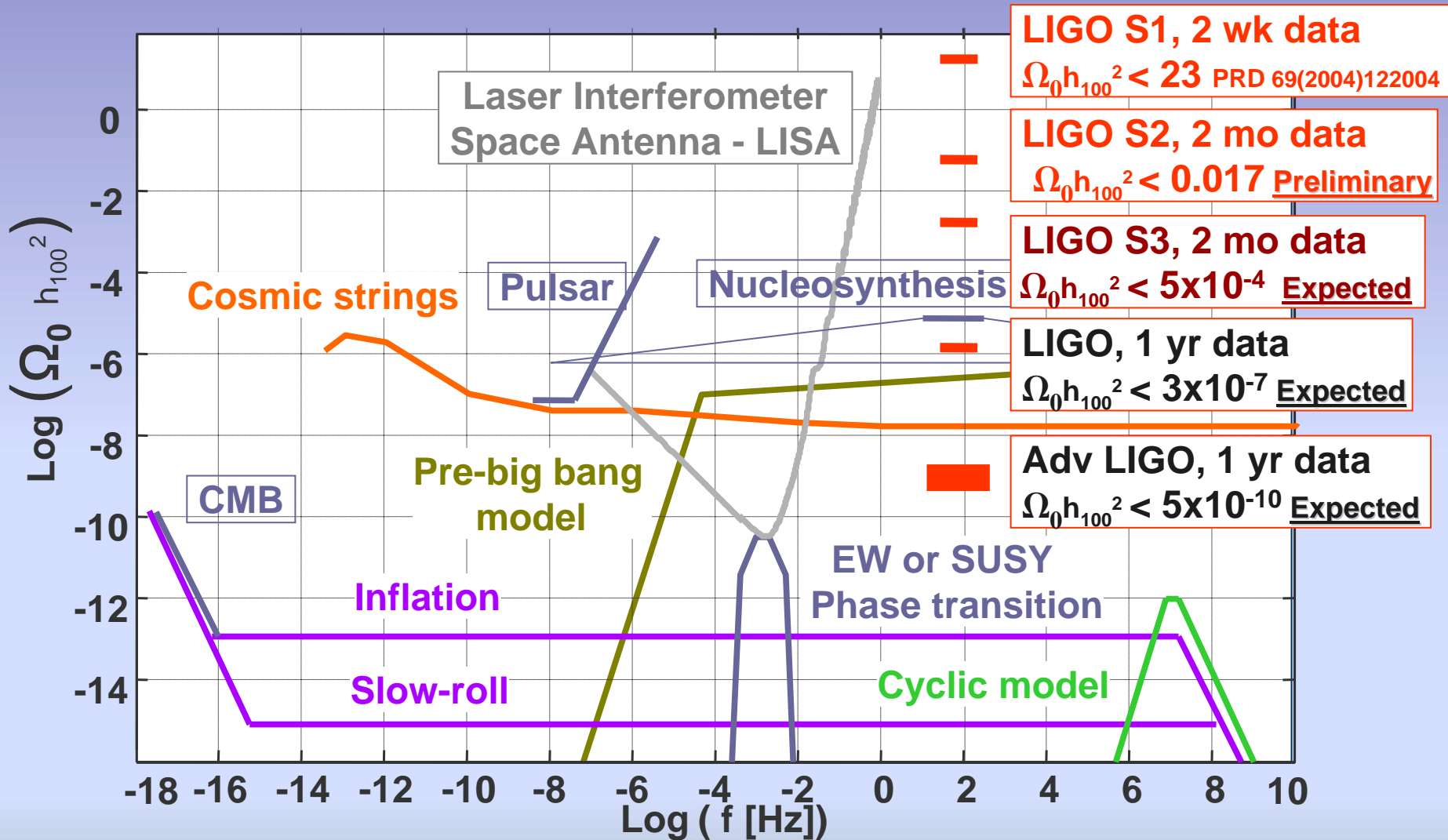
$$S_{gw}(f) \propto 1/f^3 \text{ for } \Omega(f) = \Omega_0 = \text{const}$$

$$SNR = \frac{\bar{Y}}{\sigma_Y} \propto \Omega_0 \sqrt{T}$$

Instrumental Noise Sources

- **Power lines are coherent between LLO and LHO on time scale of 1 minute but became incoherent on time scale of analysis**
- **DAQ timing is based on GPS. Data are buffered on each site. Produces very small but correlated signal at 16Hz and harmonics.**
- **Stable clocks, e.g. 70 Hz sync rates of computer monitors**
- **Correlated frequencies are left out from correlation integral**
- **No broadband correlation between the sites has been seen so far. Possible source is correlated magnetic field disturbance, e.g. from lightning strikes.**
- **Broadband correlation between two LHO detectors:**
 - **acoustic noise: beam clipping and back scattering**
 - **up conversion from nonlinear coupling: low frequency signals from seismic motion and power lines**

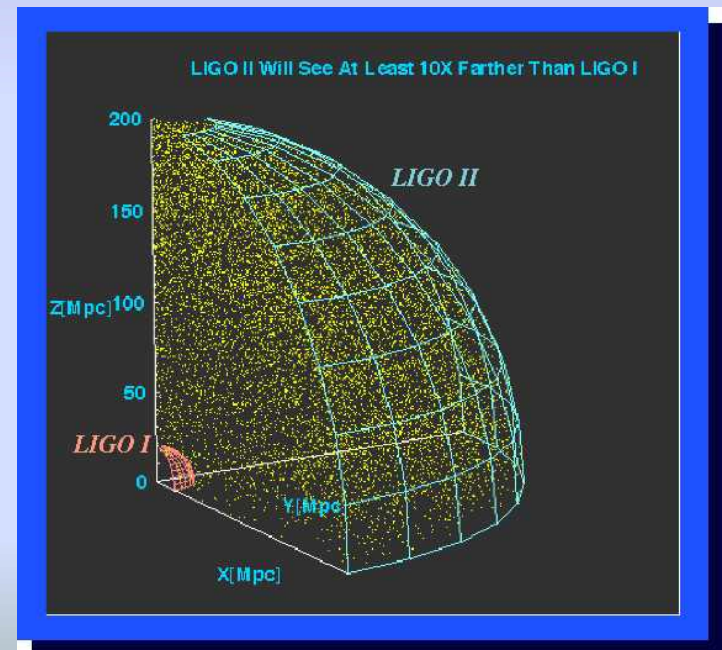
LIGO Results and Expected Sensitivity



Looking Ahead

- LIGO was always planned for a series of upgrades; the second generation detector is Advanced LIGO, with a factor of ~ 10 improvement in strain sensitivity
- Proposal has been submitted to the NSF
- Expecting to begin data taking in 2011.

Because LIGO measures GW amplitude, an increase in strain sensitivity by 10 gives an increase in sampling volume and event rate by ~ 1000



What Will We See?

