The LIGO Experiment: Status and First Results

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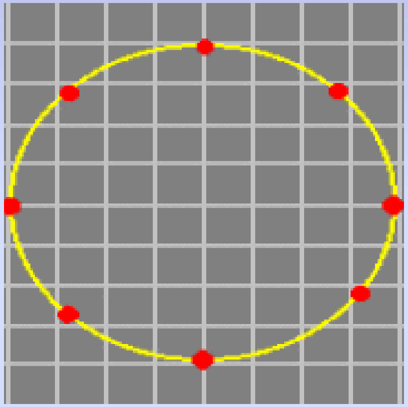
- **Gravity Waves: Sources and Detection**
- **LIGO Data Analysis and Results**
- **Outlook: Advanced LIGO**

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:** $h \sim \frac{G}{c^4}\frac{\ddot{Q}}{r}$

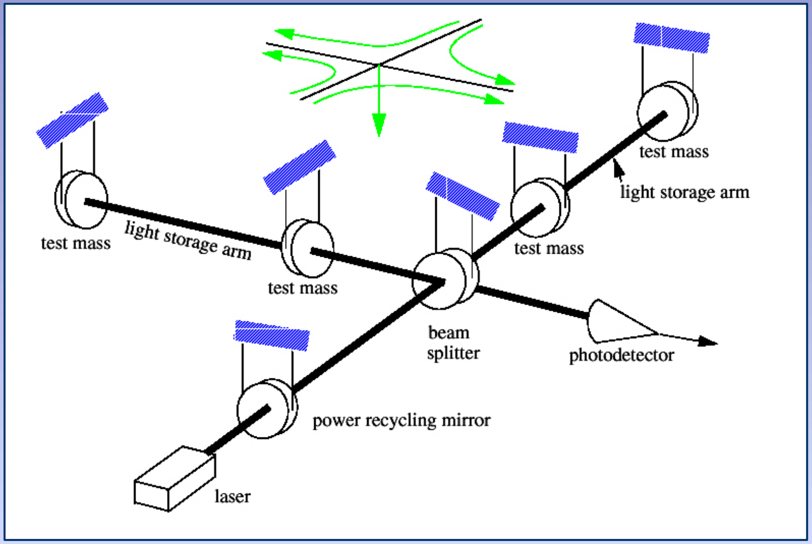
$\ddot{Q} \cong 4E$ ***non-spherical part of kinetic energy***

- **For r ~ 100 Mpc, $E \sim M_o$: $h \sim 10^{-22} - 10^{-21}$**

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 λ = 1 μm

Arm length L_0 = 4 km

Number of bounces b = 100

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

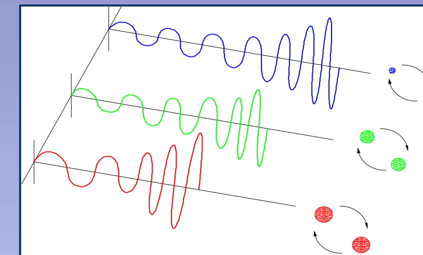
Strain sensitivity = 6×10^{-22} for integration time τ = 0.01 sec

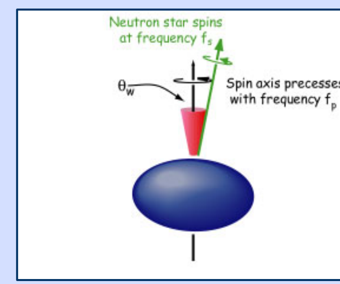
In practice λ is not sufficiently stable: Compare length of two arms interferometrically!

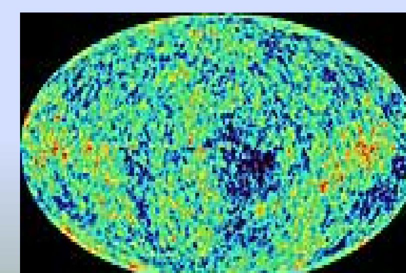
At low frequencies the sensitivity is limited by seismic and thermal noise and at high frequencies by the arm cavity rolloff

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**

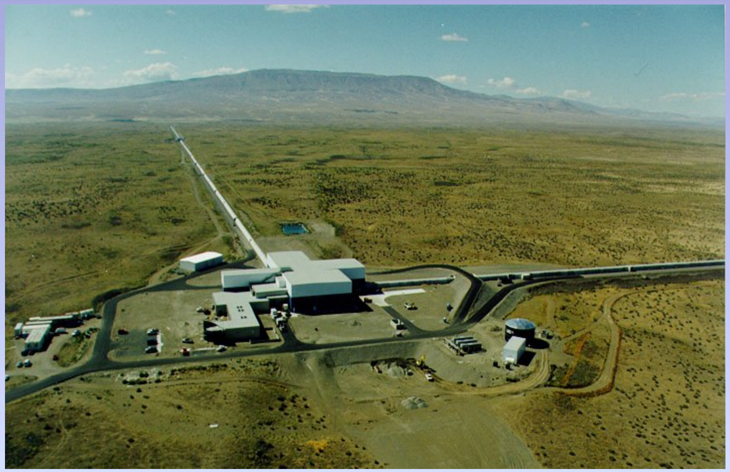




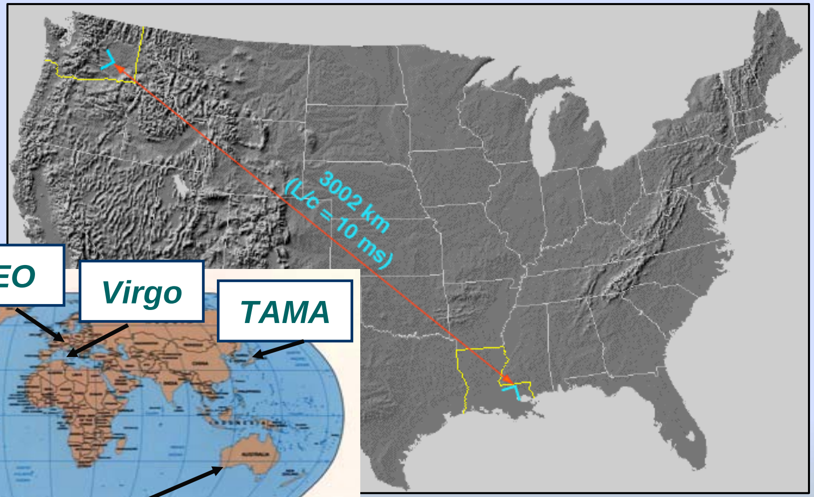


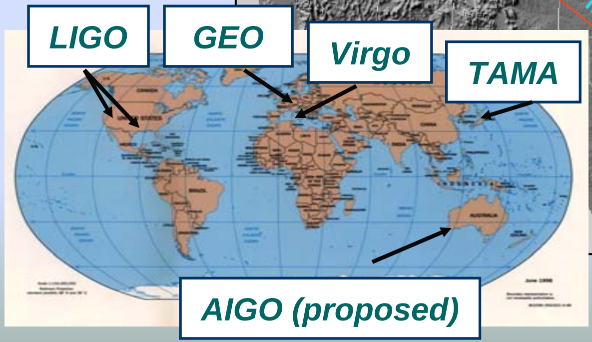
LIGO Observatories

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



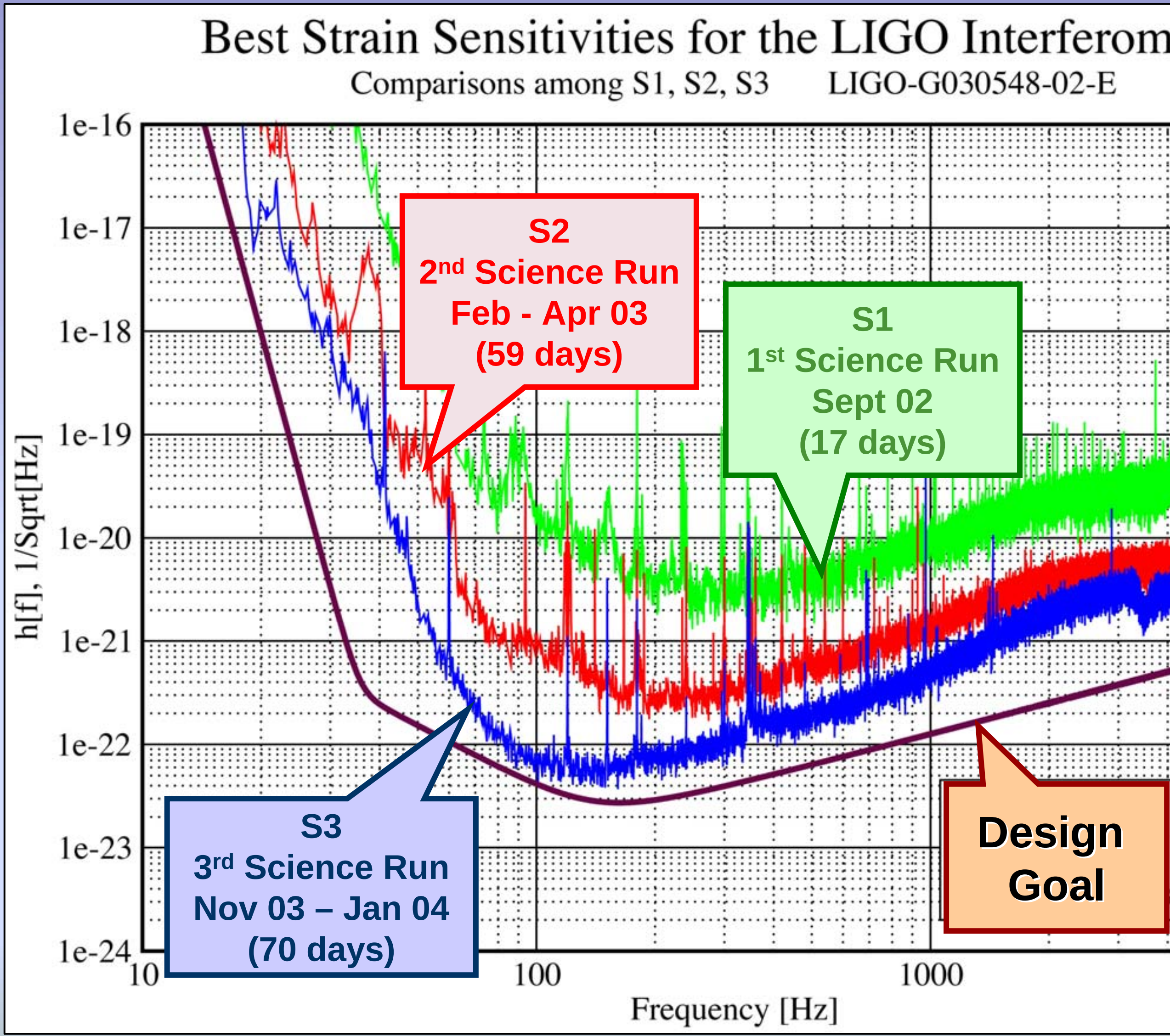
- *Interferometers are aligned to be as close to parallel to each other as possible*
- *Observing signals in coincidence increases the detection confidence*
- *Measure the direction to the source, the propagation speed and polarization of the gravity waves*



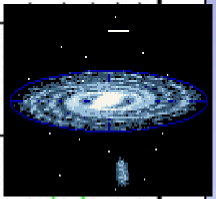


Livingston, LA (L1=4km)

Sensitivity Improvement



1.4 M_o NS-NS Inspiral Range



Milky Way ~100 kpc

Andromeda ~0.9 Mpc

M81 Group ~3 Mpc

Virgo Cluster ~15 Mpc

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} $Hz^{-1/2}$ - 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: $h_{rss} < 6 \times 10^{-21} Hz^{-1/2}$ 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***

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

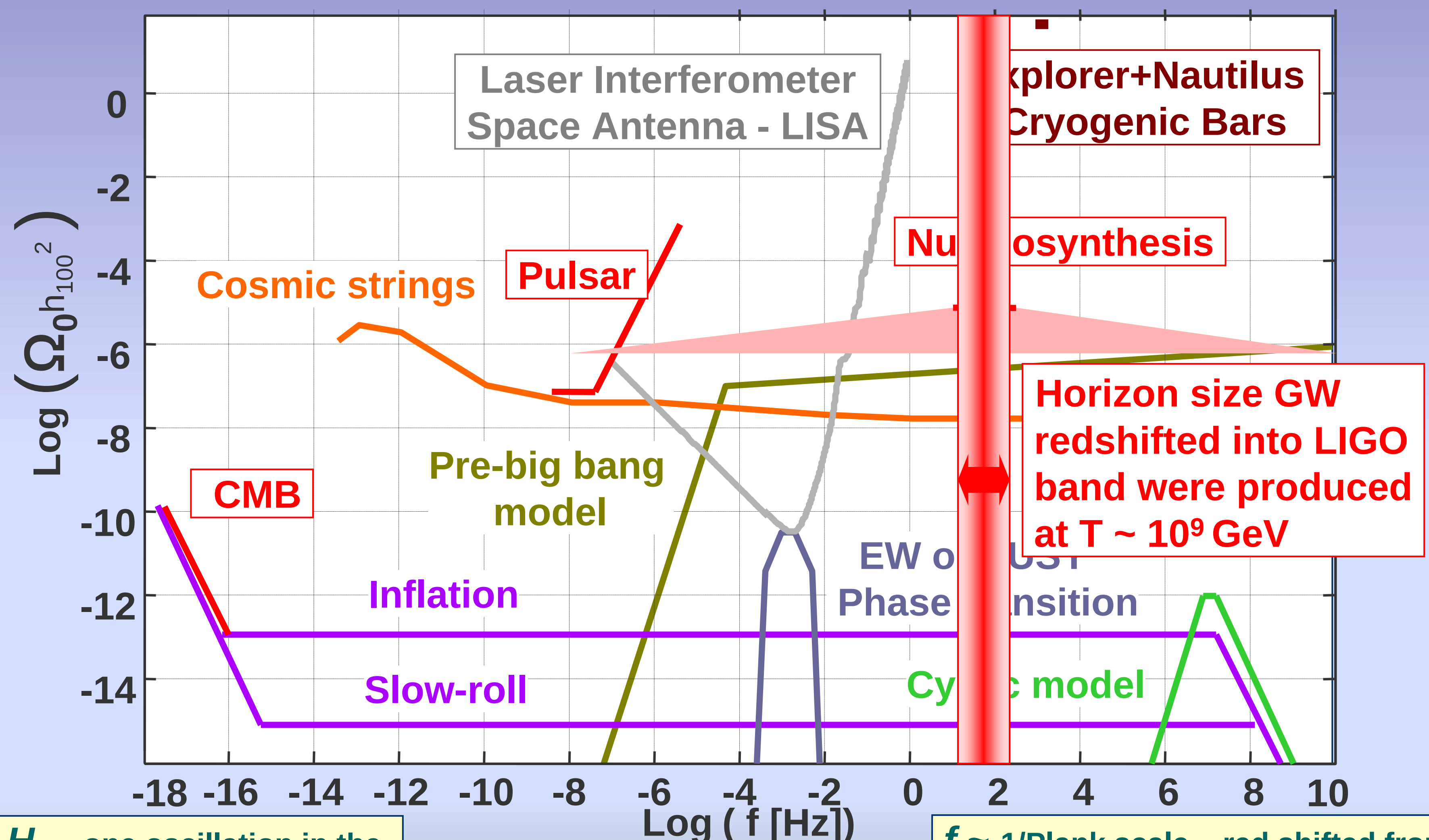
- **$\Omega_{gw}(f)$ in terms of the strain power spectrum, $S_{gw}(f)$:**

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

- **Strain amplitude scale:**

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

Gravitational Wave Background: Predictions and Experimental Limits



***f* ~ H_0 - one oscillation in the lifetime of the universe**

***f* ~ 1/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**

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

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

- **Cross-correlate outputs from two interferometers *$s_i(t) = h_i(t) + n_i(t)$***

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

- **Operator *$Q(t)$* weights the cross-correlation according to the signal-to-noise ratio at each frequency**

$$\tilde{Q}(f) \propto \frac{\gamma(f) S_{gw}(f)}{P_1(f) P_2(f)}$$

Signal

Noise

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

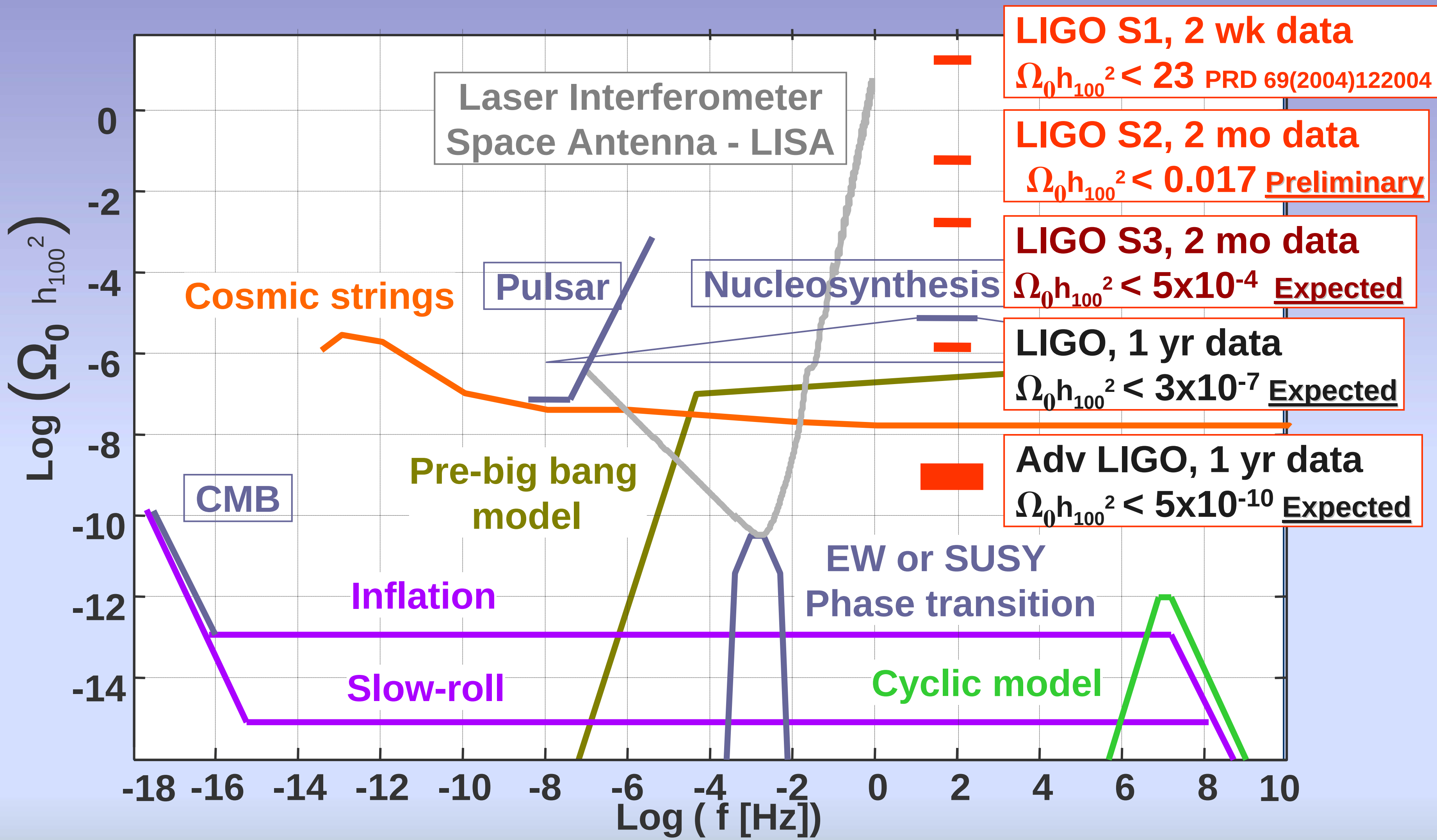
- **Overlap reduction function *$\gamma(t)$* accounts for separation and angle between two detectors**

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

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**

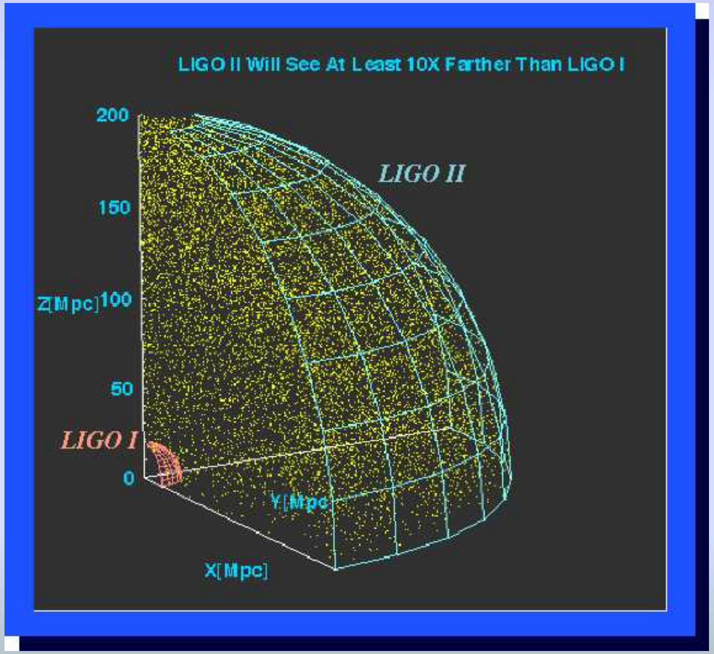
LIGO Results and Expected Sensitivity



Looking Ahead

- **LIGO was always planned for a series of upgrades; the second generation detector is <u>Advanced LIGO</u>, 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 <u>amplitude</u>, an increase in strain sensitivity by 10 gives an increase in sampling volume and event rate by ~1000



Advanced LIGO

Increased laser power: 10 W → 180 W
Improved shot noise

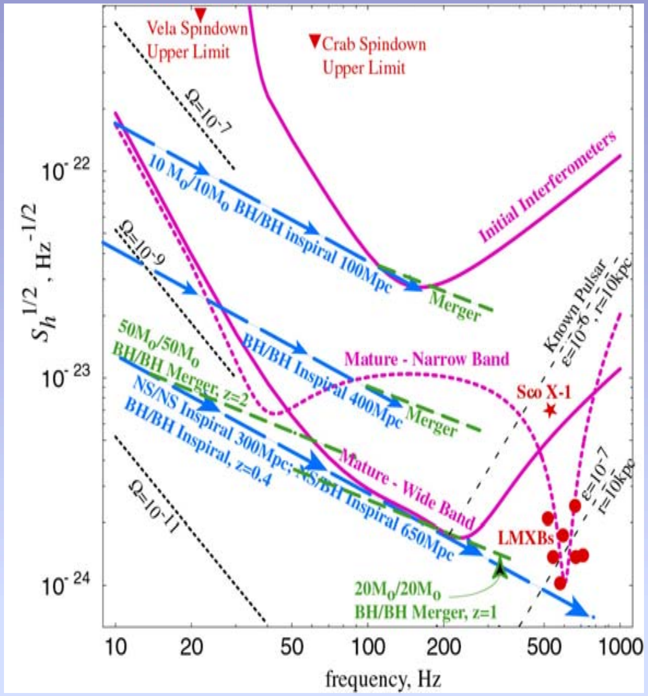
Increased test mass: 10 kg → 40 kg
Compensates increased radiation pressure noise

Potentially new test mass material:
Fused silica → Sapphire
Lower internal thermal noise in detection band

New suspensions:
Single → Quadruple pendulum
Lower suspension thermal noise in bandwidth

Improved seismic isolation: Passive → Active
Brings seismic "wall" to ~10 Hz

Signal recycling: Tunable sensitivity



What Will We See?