Outline

• **Introduction:**
  – What are Gravitational Waves?
  – The brief history of LIGO
  – The Advanced LIGO project

• Where are we now?

• Where are we going?
The weakness of Gravity

- Gravitational waves produced by orbiting masses:

$$h_{\mu\nu} = \frac{2G}{c^4d} \ddot{I}_{\mu\nu}$$

- For 2 $1.4M_{\text{Sun}}$ Neutron stars, at 1 Mpc (3 million light years):

$$h = \frac{\text{dL}}{L} \approx 3 \times 10^{-21} \left( \frac{f}{100\text{Hz}} \right)^{2/3}$$

$$\text{Flux}_{GW} \sim 1 \text{ mWatt} / \text{ m}^2$$
The wave’s field

- “Ripples in Space-Time”

- Measureable effect:
  - Stretches/contracts distance between test masses perpendicular to propagation

Amplitude:
\[
d\frac{L}{L} = h
\]
A short history of LIGO

- Electromagnetically coupled broad-band gravitational wave antenna, R. Weiss, MIT RLE QPR 1972
- NSF funding and construction in the 1990's
- Design sensitivity and observation in 2005
Noise Cartoon

- LASER
- beamsplitter
- test mass (mirror)
- Residual gas scattering
- Seismic Noise
- photodiode
- Quantum Noise
- "Shot" noise
- Radiation pressure
- Wavelength & amplitude fluctuations
- Thermal (Brownian) Noise
Initial LIGO Sensitivity

Seismic, through Auxiliary Loop Control Noise

- Non-linear up-conversion

Stefan Ballmer, Caltech
... taken apart...
What is Advanced LIGO?

- Two completely new interferometers in the US LIGO vacuum enclosures and infrastructure in Louisiana and Washington

- 3rd interferometer, to be installed in India in a new LIGO-India Observatory

- Compared to initial LIGO, a factor of 10 better sensitivity, down to 10Hz
• Initial LIGO (1\textsuperscript{st} gen.) 20 Mpc

• Adv LIGO (2\textsuperscript{nd} gen) \sim200Mpc
Interferometer Sensitivity

Michelson Interferometer
+ Fabry-Perot Arm Cavities
+ Power Recycling
+ Signal Recycling

end test mass

$\delta h \approx \frac{\lambda}{L \Delta \phi}$

$\frac{dL}{L} \approx 1.2 \times 10^{-20} \text{ m Hz}^{-1/2}$

Laser

125 W

6 kW

800 kW

4000 m

50/50 beam splitter

GW signal

1064 nm

$\sim 2 \times 10^{-12} \text{Hz}^{-1/2}$

$5 \times 10^{-24} \text{Hz}^{-1/2}$

(Numbers for aLIGO design)
Advanced LIGO Noise Budget

Strain [\mu m / \sqrt{Hz}]

Frequency [Hz]

- Quantum noise
- Seismic noise
- Gravity Gradients
- Suspension thermal noise
- Coating Brownian noise
- Coating Thermo-optic noise
- Substrate Brownian noise
- Excess Gas
- Total noise
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1) Installation

- Beamsplitter Suspension
- Baffle installation
- HAM 2 IO
- Seismic Isolation installation
Mating of suspension and seismic isolation

Quadruple Pendulum
Optics Suspension

Internal Seismic Isolation Platform

Quadruple Pendulum Optics Suspension
Transmission telescope installation
2) Integrated Testing

- Hierarchical testing process is key to rapid success

- Currently testing two significant items:
  - A 4km long arm (‘One Arm Test’ or OAT)
  - An input mode cleaner and pre-stabilized laser (MC-PSL)
One-Arm Test (OAT)

- A single, complete 4km arm at Hanford Observatory
- Two complete chambers: Optics, suspensions, seismic isolation
- Arm-length stabilization system using second color of light
  » New for aLIGO; addresses biggest initial challenge – locking
One-Arm Test

- Successful by every measure
  - Locking came very quickly
  - Very stable locks

- Allows whole-interferometer integration with $\frac{1}{2}$ interferometer

\[ Ch\ 6: \ H2:ISC-ALS_EY_PDH_DC\_OUT16 \]

\[ \sim 15\text{min} \]
Mode Cleaner – Pre-Stabilized Laser

- A 200W Nd:YAG laser, from AEI Hannover, Germany
- A suspended-mirror ring cavity, ~15m length, in transmission
- The two most complex vacuum chambers in aLIGO
Mode Cleaner – Pre-Stabilized Laser

**Goals:**

» **Achieve robust operation** of the Input Mode Cleaner

» Evaluate the **thermal effects** in IMC and FI: transmission, isolation ratio, absorption, mode distortion, drift

» Optimize **low frequency** performance of seismic isolation
Livingston mode cleaner first lock, 7/28/2012
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LIGO-India

- aLIGO currently has 2 sites, 3 interferometers

- 3 sites with long baselines scientifically more valuable
  » Better source localization

- Goal: build the 3rd LIGO interferometer on Indian soil

- LIGO Lab provides components for one Advanced LIGO interferometer

- India provides the infrastructure, “shipping & handling,” staff for installation & commissioning, operating costs for 10 years beyond construction
The localization accuracy for binary neutron stars located at 160 Mpc
In August the National Science Board approved a change in scope, enabling plans for the relocation of one detector to India.

The NSB resolution empowers the NSF to make the decision to proceed with LIGO-India.

Discussions now: How will LIGO India be implemented and managed.
What’s next?

- Installation complete:
  » Livingston May 2013, Hanford Sept 2013
- ‘Acceptance’ (definition: 2-hour lock):
  » Livingston April 2014, Hanford May 2014
- Full-Interferometer locking may come quite quickly…
- …but lots of follow-up work only possible with whole interferometer required
Timeline

- **US interferometer acceptance:**
  - Summer 2014

- **First science run near design sensitivity:**
  - maybe 2016

- **LIGO-India:**
  - Facility construction begins: Aug 2014
  - First science run (all interferometers): 2020
Conclusion

- Advanced LIGO **hardware installation** progressing at good pace

- **Integrated tests successful** (one-arm & mode cleaner)

- **LIGO-India** has passed major thresholds in the US – it’s moving forward
Thank you!