# LIGO: illuminating gravity

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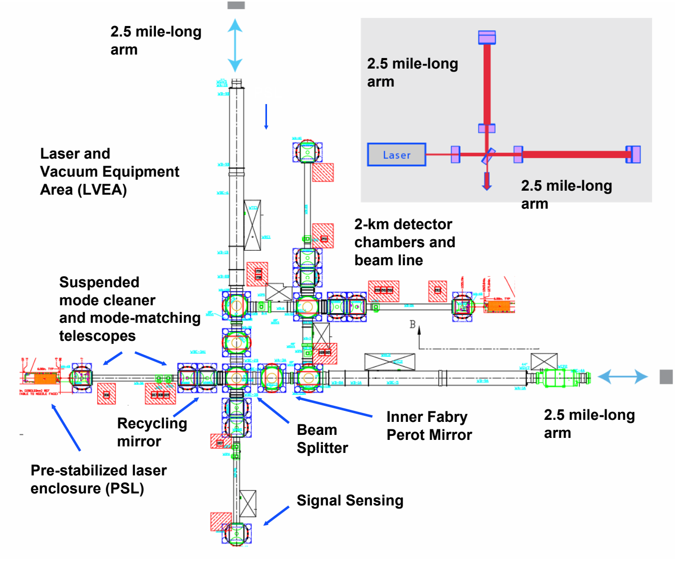
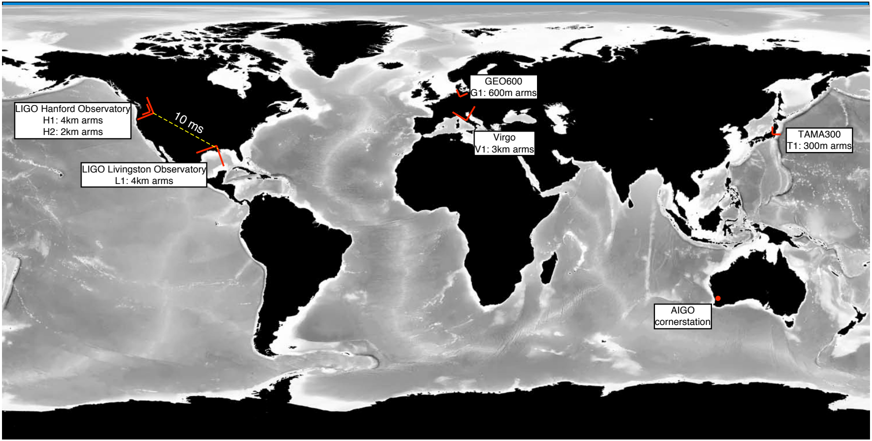
# Interferometry

Figure: Blueprints for initial LIGO: sense changes between $x$ and $y$



# Interferometry

Figure: Worldwide network allows sky localization and coincident detection that checks against terrestrial noise




Credit: NASA's Earth Observatory

# Interferometry

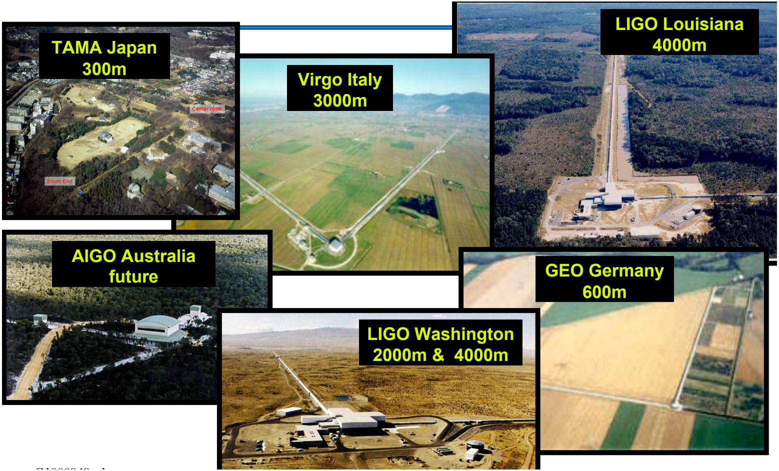



Figure: In reality: LIGO and VIRGO advancing; TAMA moving to LCGT; GEO now running as GEO HF with squeezing; AIGO Australia may be LIGO South

# Theoria & praxis

## Advanced LIGO instrumentation

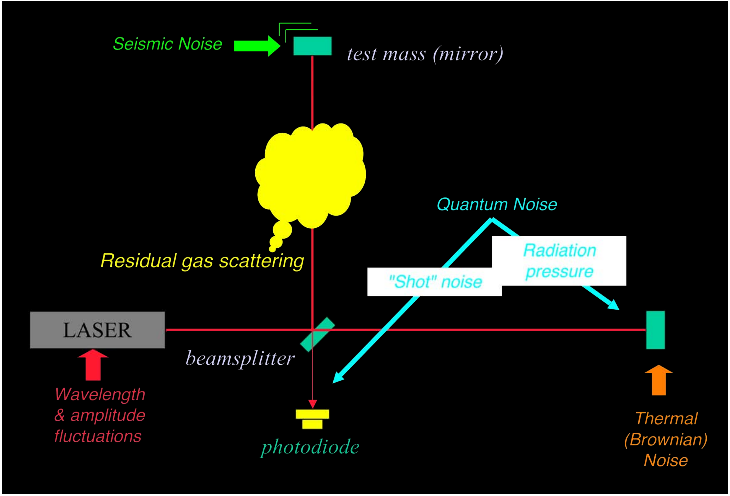
*Power recycled Michelson interferometer with Fabry-Perot arms*

Figure: Advanced LIGO upgrades

| Parameter | LIGO | Advanced LIGO |
|---|---|---|
| Stored Laser Power | 20 kW | 800 kW |
| Mirror Mass | 10 kg | 40 kg |
| Interferometer Topology | Power-recycled Fabry-Perot arm cavity Michelson | Dual-recycled Fabry-Perot arm cavity Michelson |
| GW Readout Method | RF heterodyne | DC homodyne |
| Optimal Strain Sensitivity | $3 \times 10^{-23}$ / rHz | Tunable, better than $5 \times 10^{-24}$ / rHz in broadband |
| Seismic Isolation Performance | $f_{low}$ ~ 50 Hz | $f_{low}$ ~ 10 Hz |
| Mirror Suspensions | Single Pendulum | Quadruple pendulum |

# Theoria & praxis

Figure: Sources of noise that limit LIGO



# Theoria & praxis

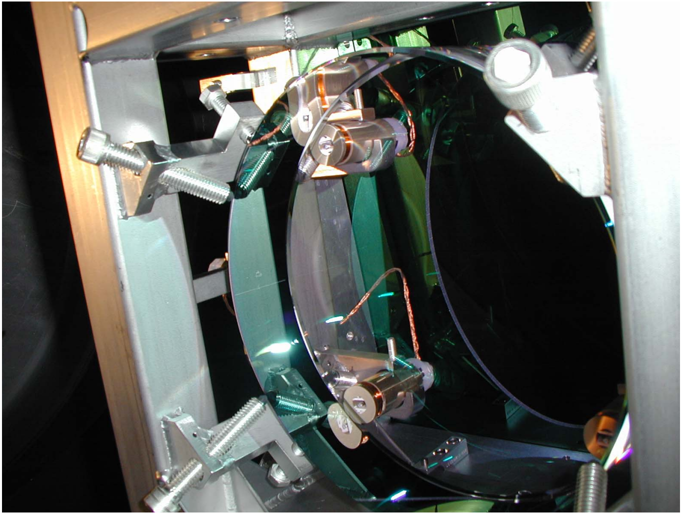
Figure: LIGO Hanford laser vacuum equipment area: **almost** noise-proof, showing beam tubes, BSC and HAM chambers, and clean rooms

# Theoria & praxis

Figure: Stablized laser (Nd:YAG, 1064 nm, 20 W) with frequency-stabilizing reference cavity and pre-mode cleaner

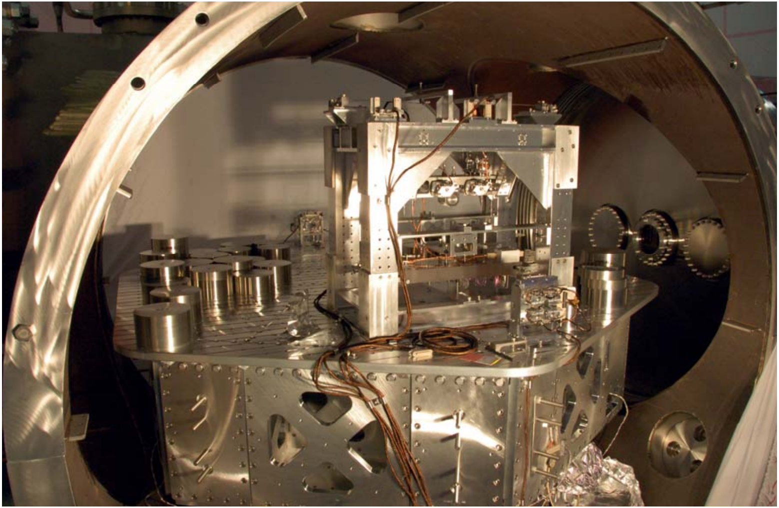
# Theoria & praxis

Figure: Initial LIGO core optic: 25 cm wide, 10 cm thick, surface-uniformity 2 nm rms, absorption 2 ppm, magnetically-actuated



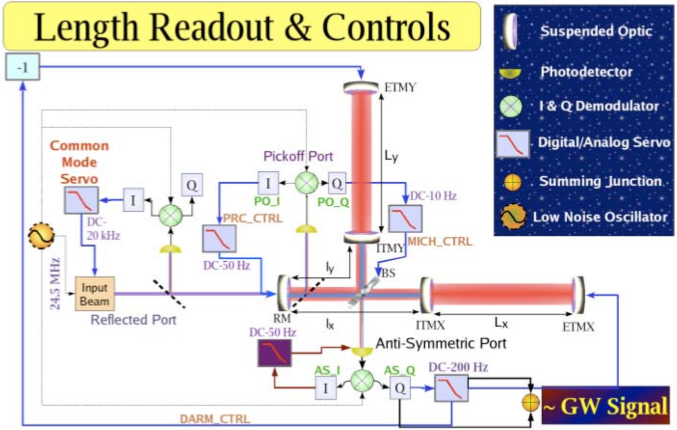
# Theoria & praxis

Figure: Output mode cleaner extracts pure, unscattered light in the $TEM_{00}$ Gaussian beam shape that contains gravitational wave signals



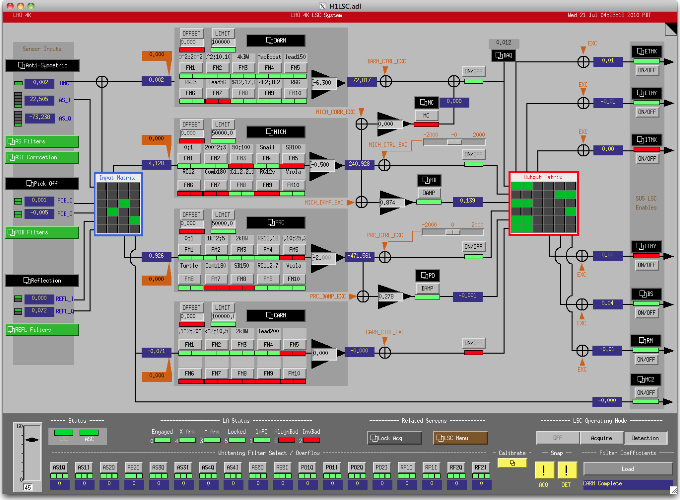
# Length sensing and control channels

Figure: Schematic servo loops for four core optic parameters (DARM, CARM, MICH, PRC respectively the differential motion of the end mirrors ETMX and ETMY, their common motion, and differential and common for the inner mirrors ITMX and ITMY)



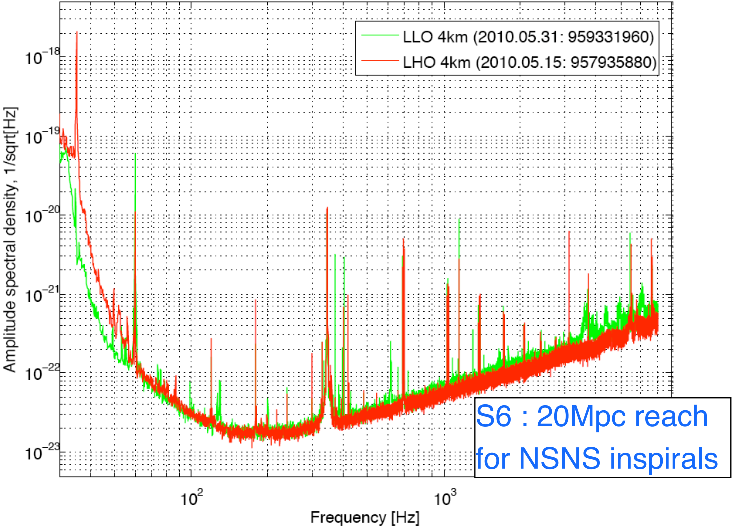
# Length sensing and control channels

Figure: DARM (differential arm) and MICH (inner Michelson) servo in the EPICS-based MEDM control screen; LIGO records about 3e4 channels and uses most in digital servos



# Noise curve

Figure: Noise curve for enhanced LIGO, showing better high frequency performance at LHO (Hanford) with stronger laser and better low frequencies at LLO (Livingston) thanks to seismic isolation

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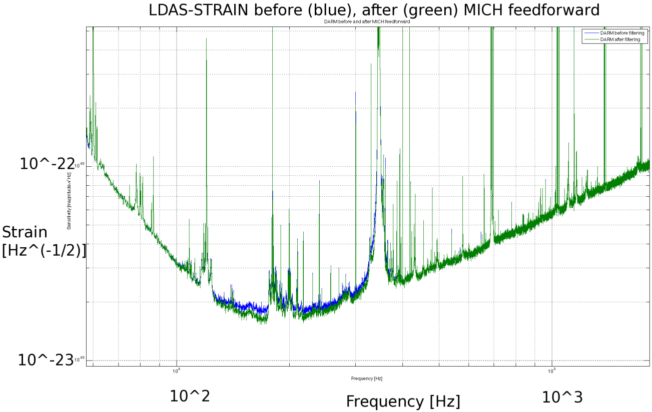
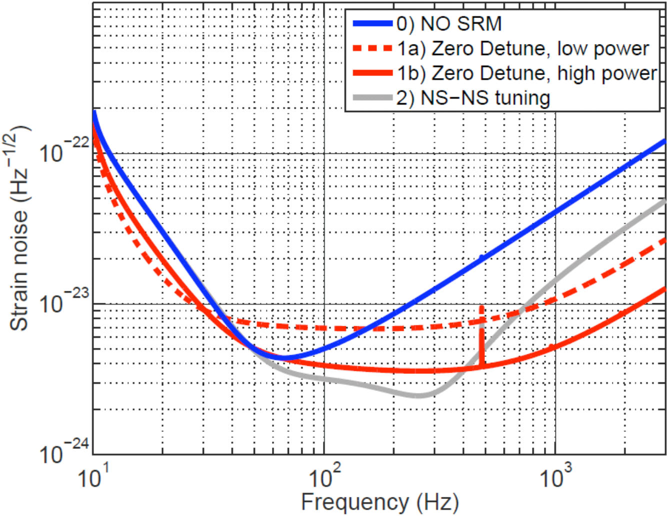
# Noise curve

Figure: Noise after a new automated filtering algorithm for feedforward subtraction of an auxiliary channel, possible both in real time and in post processing



# Noise curve

Figure: Predicted noise curve for advanced LIGO, showing gains simply due to better seismic isolation, laser, and test mass as well as with signal recycling mirror (SRM)



# Advanced LIGO

**Advanced LIGO upgrades**
100+ W laser
4 passive + 3 active stage suspension for seismic isolation
40 kg fused silica test masses
electrostatic mirror actuation
signal recycling
*Range may improve from 20 to 200 Megaparsec*
*(for 1.4-1.4 solar mass inspirals)*

# Advanced LIGO

Figure: Removing old: deinstall makes way for new in view inside BSC vacuum chamber holding core optic suspension

# Advanced LIGO

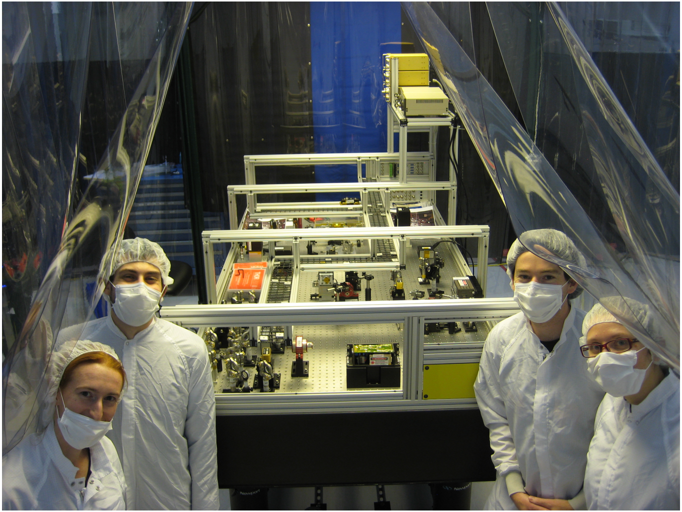
Figure: Side-by-side comparison of external seismic isolation on top of blue pillars: old (left), new HEPI (right)

# Quantum squeezing

*Explore beyond-Advanced LIGO techniques*
Heisenberg uncertainty allows any distribution of Δx, Δp
(conjugate variables *x*, *p*)
such that $\int (\Delta x)(\Delta p) dxdp = \hbar/2$
Squeezing is a nonlinear effect that tailors Δx, Δp.
Phase and amplitude are conjugate; desire phase data
3 to 6 dB quantum vacuum squeezing experiment

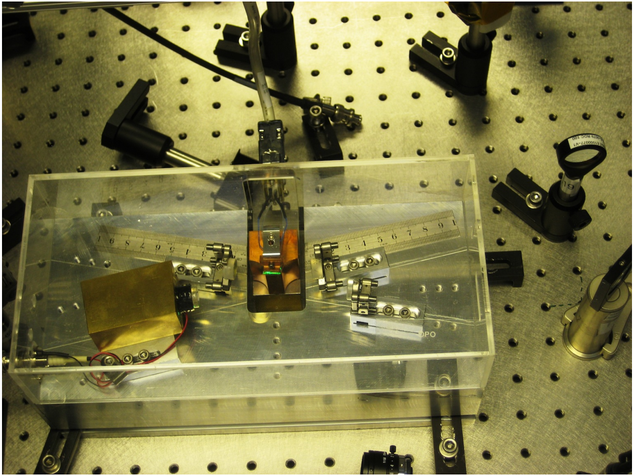
# Quantum squeezing

Figure: (Some) squeezers (Sheila, Grant, Conor, Lisa) in front of optics table containing lasers and opto-electronics for generating squeezed vacuum



# Quantum squeezing

Figure: Optical parametric oscillator (OPO) contains PPKTP crystal in a doubly-resonant bowtie-shaped cavity, which makes frequency-mirrored photons to cancel the phase noise of noisy virtual photons – squeezed vacuum emerges



# Conclusions

*Conclusions*

1. General relativity predicts gravitational waves
2. Advanced LIGO installation is now!
3. Gravitational waves will reveal an invisible cosmos

*Acknowledgments*
Thanks to the National Science Foundation, LIGO Scientific Collaboration, LIGO Hanford Observatory, Marco Cavaglia, Sheila Dwyer, Conor Mow-Lowry, Dani Atkinson, Lisa Barsottii, Dale Ingram, Keita Kawabe, Mike Landry, Daniel Sigg, Dick Gustafson, Greg Mendell, Fred Raab, and Keith Riles.

# Bibliography


- R. Adhikari, Ph.D. thesis, Massachusetts Institute of Technology (2004).
- S. Ballmer, Ph.D. thesis, Massachusetts Institute of Technology (2006).
- B. Abbott and et al, Phys. Rev. D **76**, 082001 (2007).

# General relativistic gravitational waves

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}, \text{ where } |h_{\mu\nu}| \ll |\eta_{\mu\nu}|$$

$$-\frac{1}{2}\Box\left(h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^{\lambda}_{\lambda}\right) = \frac{8\pi G}{c^4}T_{\mu\nu} \equiv 0$$

$$\rho_{gw} = \frac{c^2}{16\pi G}\left\langle |\partial_t h_+|^2 + |\partial_t h_\times|^2 \right\rangle$$

$$P = \frac{G}{5c^5}\left\langle \left(\partial_t^3 I_{ij}\right)^2 \right\rangle$$

$$\rightarrow P \approx \left(5.5 \times 10^{-54}\ \mathrm{W}^{-1}\right)\left\langle \left(\partial_t^3 I_{ij}\right)^2 \right\rangle$$

[Adhikari(2004), Ballmer(2006)]

# Sources and neutron stars

| | Definite waveform | Indefinite waveform |
|---|---|---|
| Short duration | Inspiral[1] | Burst[2] |
| Long duration | Pulsar[3] | Stochastic[4] |

Inspiral[1]: *compact binary coalescence*
Burst[2]: *supernova*
Pulsar[3]: *continuous wave*
Stochastic[4]: *gravitational wave background*

# Sources and neutron stars

**Neutron stars**

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2}{r} \epsilon$$

$$\tau_{gw}(f) \equiv \frac{f}{|4\dot{f}|}$$

$$h_0(f) = \frac{1}{r} \sqrt{\frac{5 G I_{zz}}{8 c^3 \tau_{gw(f)}}}$$

[Abbott and et al(2007)]

# Interferometers

$$T_s = \int_0^{\frac{2L_s}{c}} \sqrt{|g_{ss}|}dt$$

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$$\sqrt{|g_{xx}|} \approx \left(1 - \frac{h_+}{2}\right)$$

$$\sqrt{|g_{yy}|} \approx \left(1 + \frac{h_+}{2}\right)$$

[Adhikari(2004), Ballmer(2006)]

# Interferometers

# Interferometers

$$T_y - T_x = \int_0^{\frac{2L}{c}} \frac{h_+(t, x(t)) + h_+(t, y(t))}{2} dt,$$

$$\Delta\phi = \omega(T_y - T_x),$$

$$P \propto E^2 \left|1 + e^{i\Delta\phi}\right|^2 = 2E^2(1 + \cos\Delta\phi)$$

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$P$ power illuminates photodiode
*(improve by higher laser power and power recycling)*
$\Delta\phi$ determines fringe phase shift
*(improve by increasing storage time in arms)*

# Syllabus

**Enhanced LIGO instrumentation**

*Power recycled Michelson interferometer with Fabry-Perot arms*

- Hanford, Washington and Livington, Lousiana observatories
- 4 km perpendicular beam tubes
- $10^{-9}$ torr vacuum
- 20 W Nd:YAG 1064 nm laser
- 10 kg fused silica primary optics
- 4 stage seismic isolation
- Laser frequency stabilization
- Angular sensing and control (wavefront sensors, optical levers)
- Length sensing and control (magnet coils, common mode)
- Pre, input, and output mode cleaning
- Power recycling
- Digitally filtered servos and readout