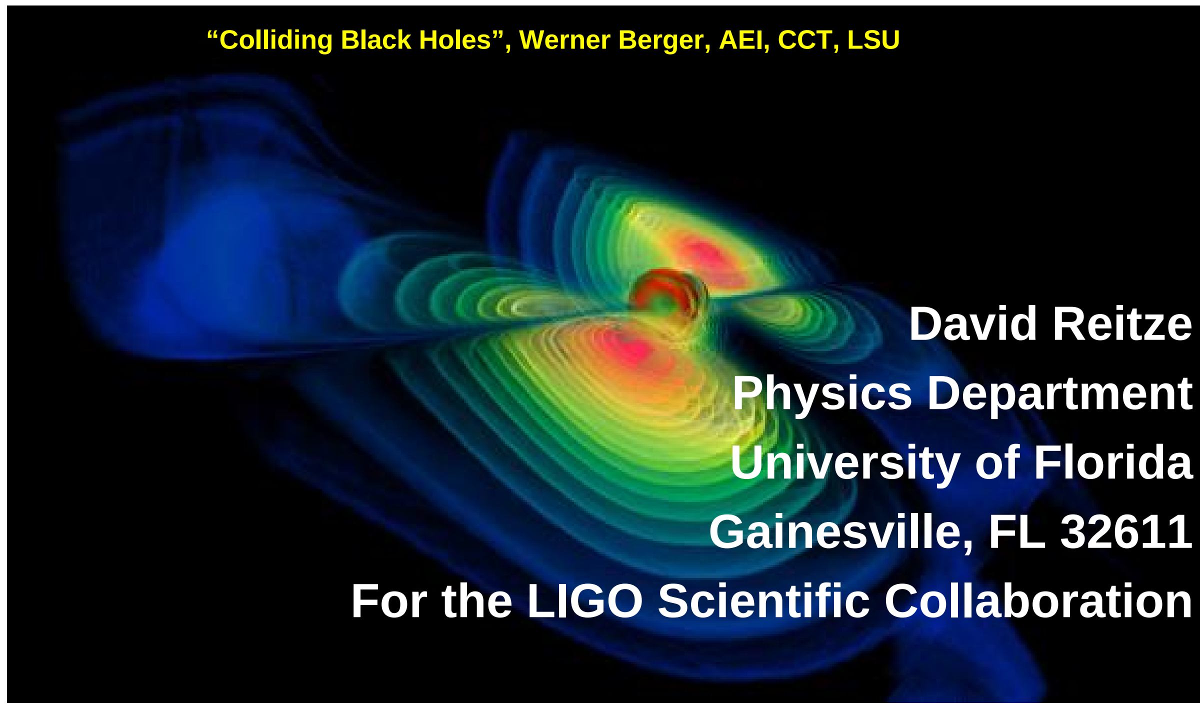
Science with LIGO



“Colliding Black Holes”, Werner Berger, AEI, CCT, LSU

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For the LIGO Scientific Collaboration

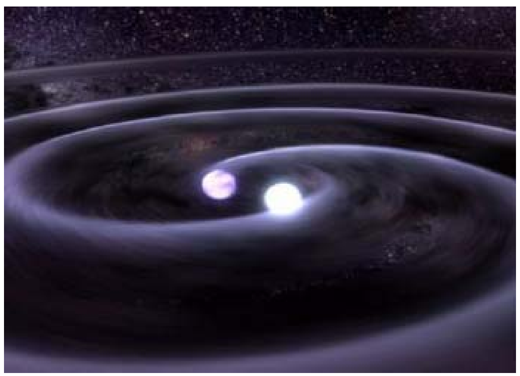
Support: NSF

Outline

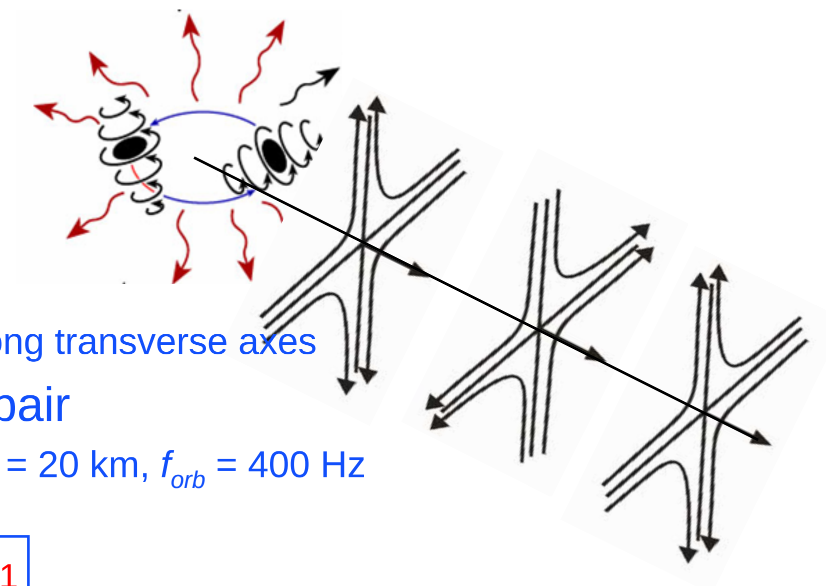
- The present: LIGO
  - » Gravitational waves, interferometry, sensitivity, science
- The future: Advanced LIGO
  - » Why AdvLIGO?
- The physics of Advanced LIGO
  - » Signal recycling
  - » SQL and thermal noise
  - » Springs, instabilities, and such
- The nuts and bolts of Advanced LIGO
  - » Improvements over LIGO
  - » Lasers, optics, seismic isolation, interferometer control, thermal management
- Outlook and Conclusions

Gravitational waves and astrophysics

- Predicted by Einstein in 1916, GWs are propagating fluctuations in the curvature of space-time
- Emissions from accelerating non-spherical mass distributions



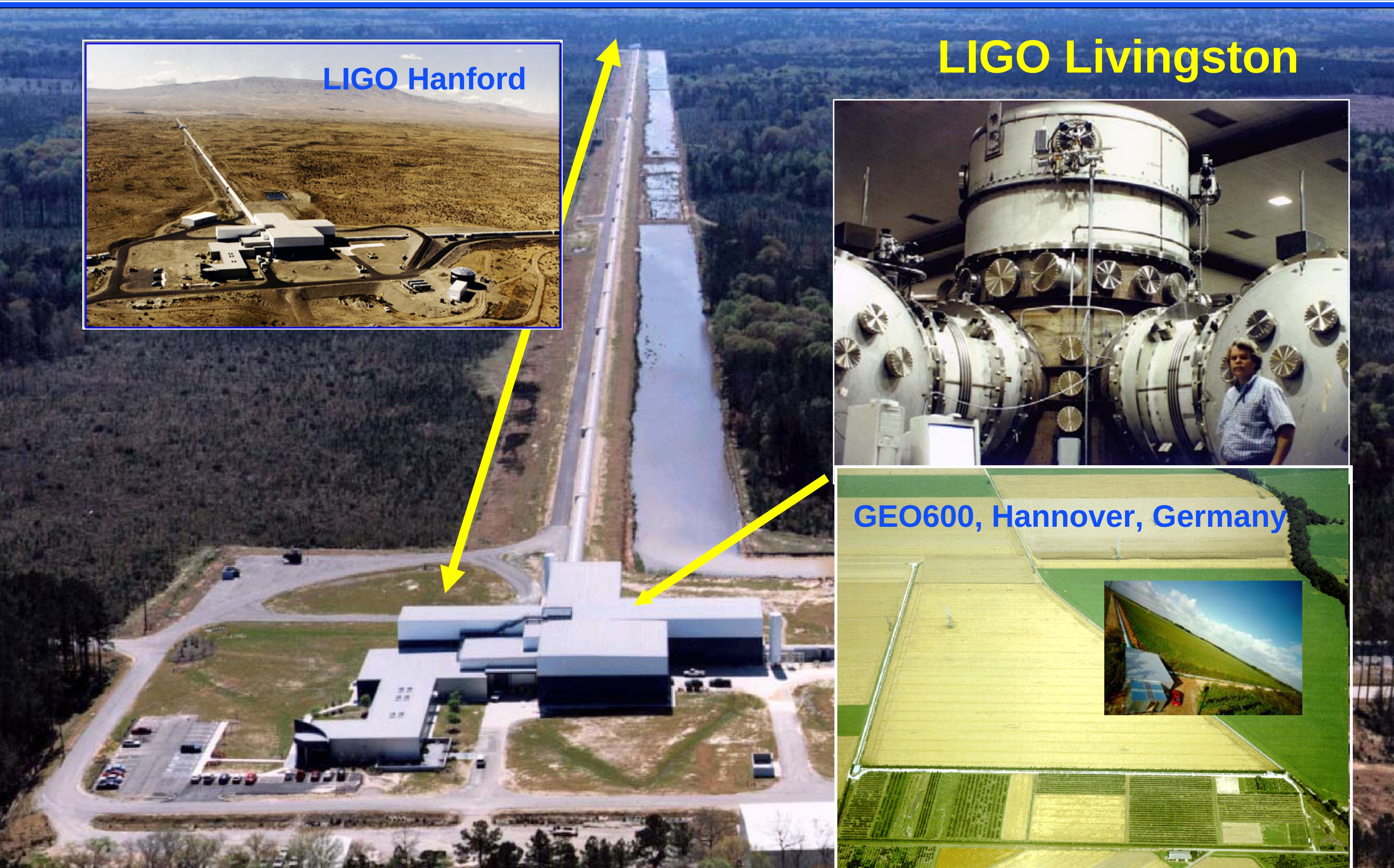
$$\Rightarrow \quad h_{\mu\nu}(\omega,t) = \frac{2G}{r\,c^4}\ddot{I}_{\mu\nu}(\omega,t) \quad \Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$



  - » Propagate at the speed of light
  - » Two polarizations: h_+ and h_x
  - » Differential contraction and expansion along transverse axes
- Sense of scale: binary neutron star pair
  - » M = 1.4 $M_\odot$, r = 10^{23} m (15 Mpc, Virgo), R = 20 km, f_{orb} = 400 Hz

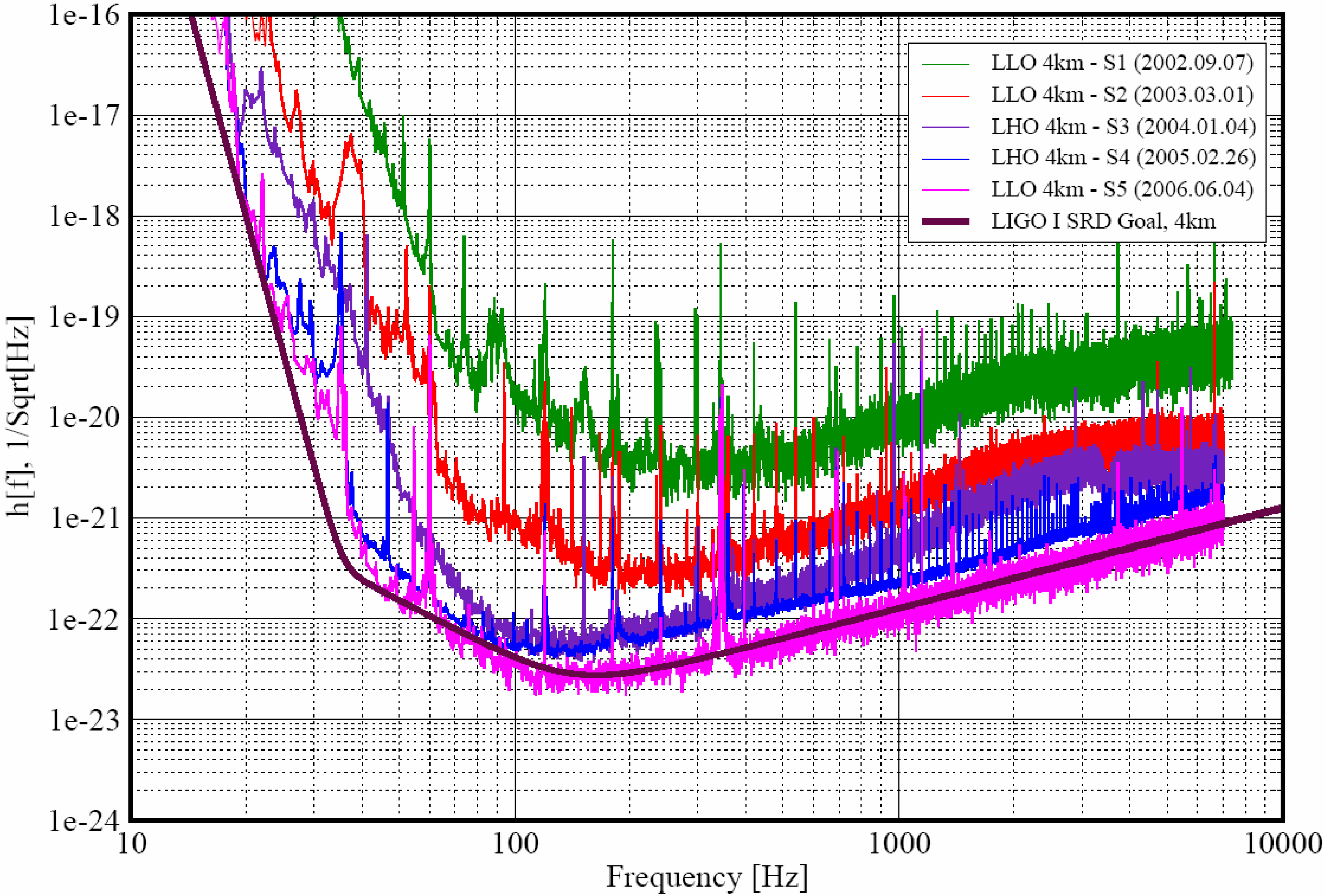
→ $h \sim 10^{-21}$

LIGO today



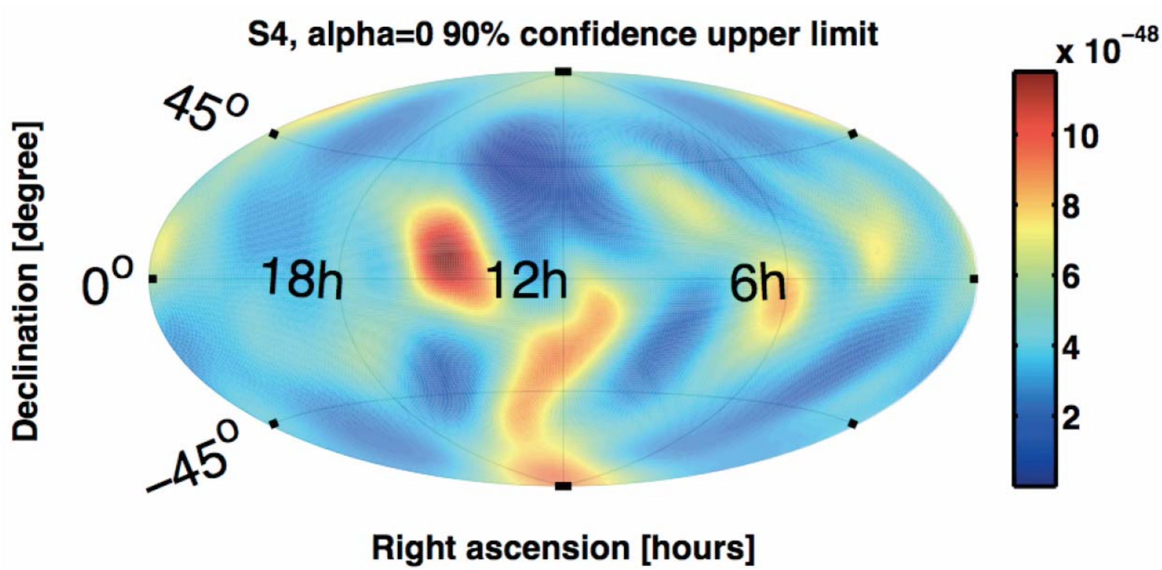
Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-02-Z



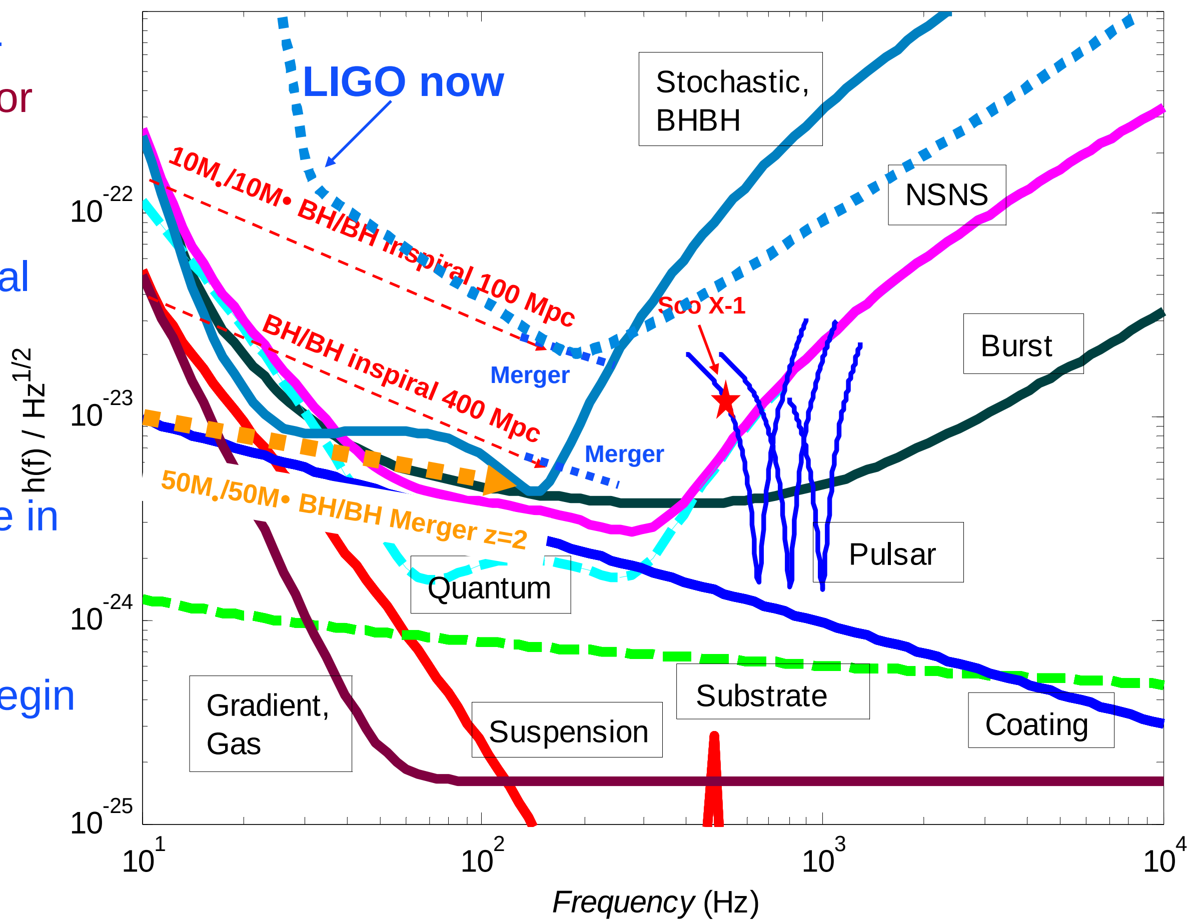
A snapshot of some recent results by the LIGO Scientific Collaboration

- Thus far, no detection of gravitational waves
- Summary of observational results in talk by Gabriela Gonzalez yesterday (E6.00003)
- Many results on searches of GW emissions from pulsars, binary NS/NS and BH/BH, stochastic sources, will be presented in sessions:
  - » R12, Gravitational Waves for and by LIGO (Monday,10:45AM)
  - » T11, Gravitational Wave Astronomy (Monday, 1:30 PM)
  - » U11, Gravitational Wave Astronomy II and Compact Objects (Monday,3:30 PM)
- One example: upper limit all-sky map from a stochastic background of point sources
  - » LIGO's 4th Science Run
  - » Flat spectrum: $H(f) = H_0$
  - » 90% confidence level

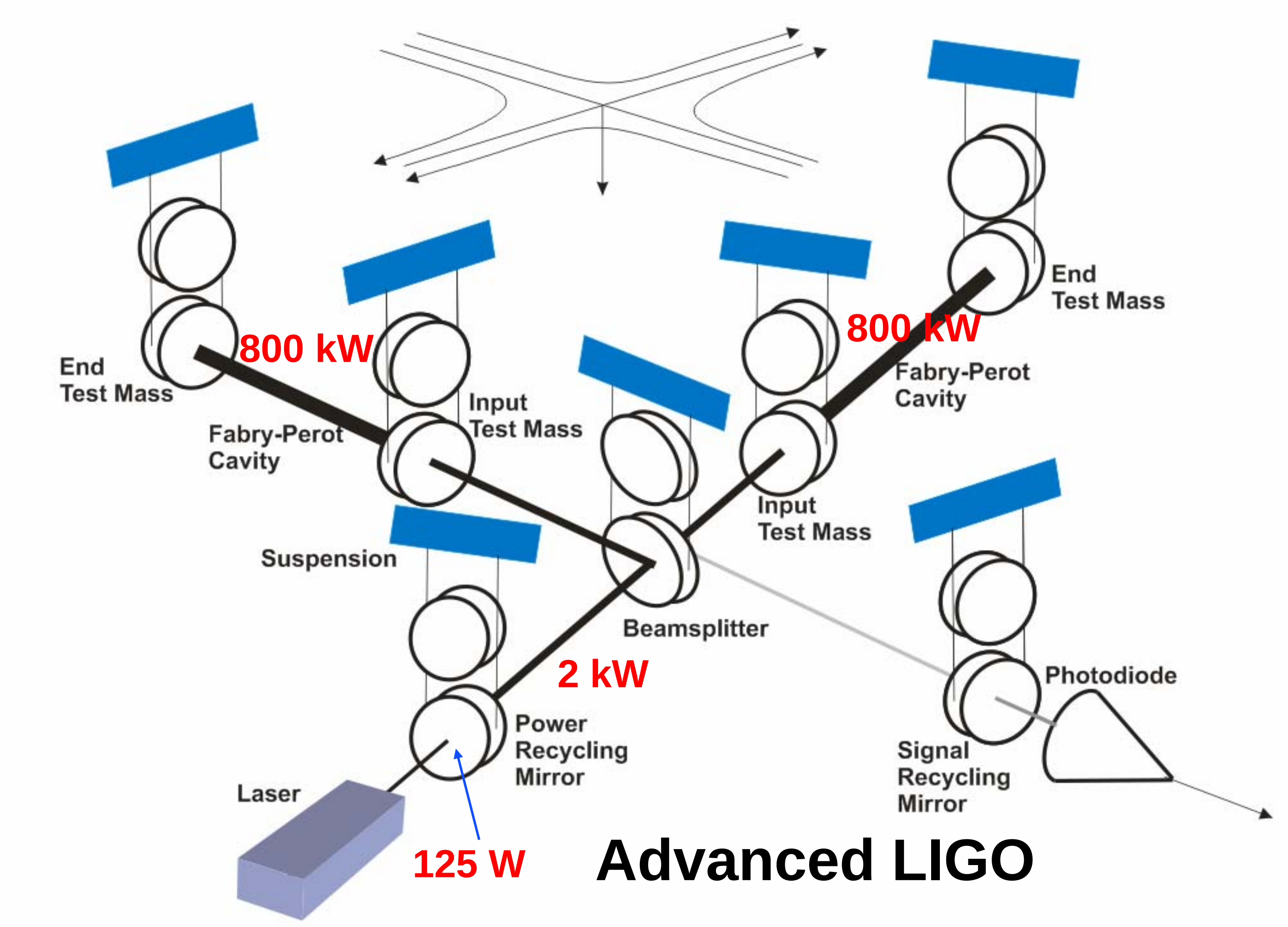


Advanced LIGO

- LIGO is currently detection rate-limited at 0.01 events per year for NS/NS inspirals
- Advanced LIGO will increase sensitivity (hence rate) over initial LIGO
  - » range $r \sim h$
  - » Event rate $\sim r^{3}$
- Most probable NS/NS event rate in Advanced LIGO is 40/yr
- Anticipate funding to start in October 2007, construction to begin in 2011



Advanced LIGO

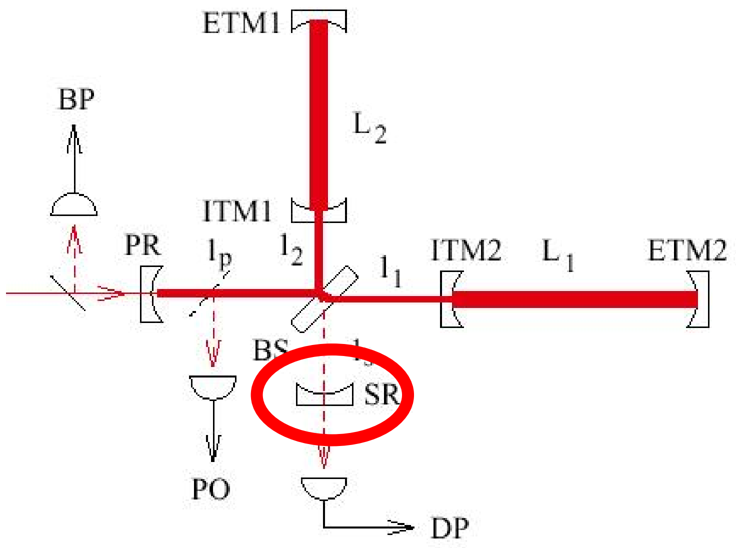


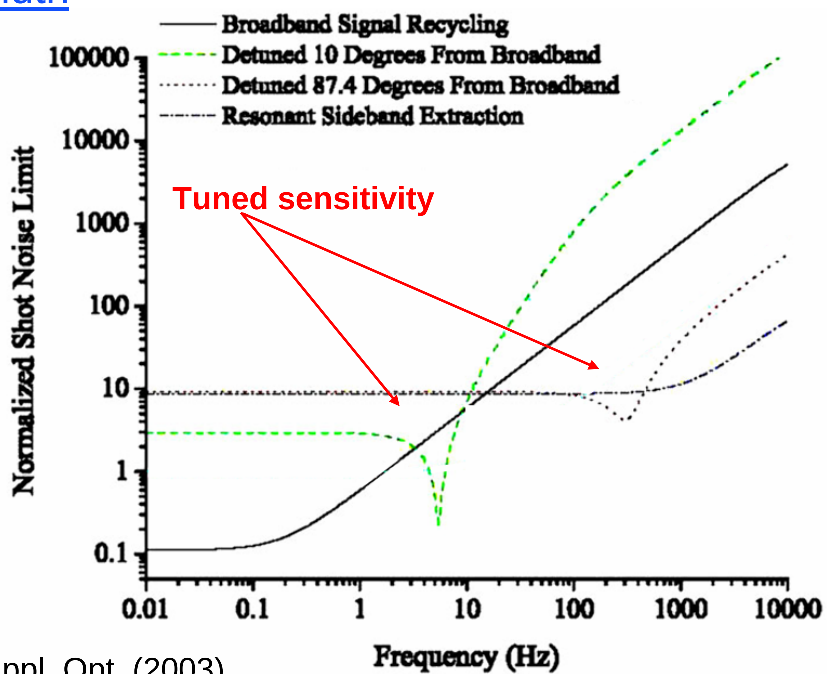
Advanced LIGO
Detector Physics

Signal recycling

Concept: SR: Drever, 1983; Meers, 1988
RSE: Mizuno, 1993

- In LIGO, GWs modulate the laser field in the arm cavities
  - » monochromatic GWs → GW ‘side bands’
  - » GW side bands leave the interferometer and beat against RF sidebands, generating a signal
- A ‘signal recycling’ mirror at the dark port forms a resonant cavity with the coupled arm cavities allowing build-up of the GW side bands
- Detuning the signal recycling cavity tunes the sensitivity curve and allows for enhanced sensitivity in a narrow bandwidth





Experimental Demonstrations:
Strain, et al, Delker, et al., Mason, et al., Shaddock, et al., Appl. Opt. (2003).

Beyond the Standard Quantum Limit…

A. Buonanno and Y. Chen, PRD 64, 042006 (2001)

- Standard Quantum Limit
  - » competition between radiation pressure (RP) and shot noise (SN); limit given by

$$h_{SQL}(f) = \sqrt{\frac{8\hbar}{4\pi^2 f^2 L^2 M}}$$

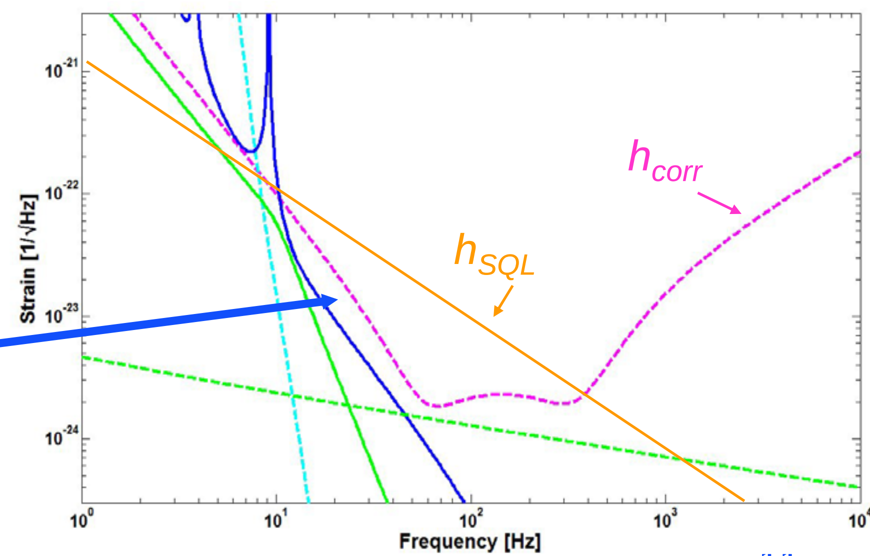
    - – This assumes no correlations between SN and RP

- Signal recycling induces photon 'back-action' on mirrors
  - » Quantum noise is dynamically correlated, leading to $h(f) < h_{SQL}(f)$ in a limited frequency range:

$$h_{corr} = h_{SQL} \frac{\Delta b_\zeta}{\sqrt{2\kappa}}$$

- Quantum correlations:

$$\frac{\Delta b_\zeta}{\sqrt{2\kappa}} < 1$$

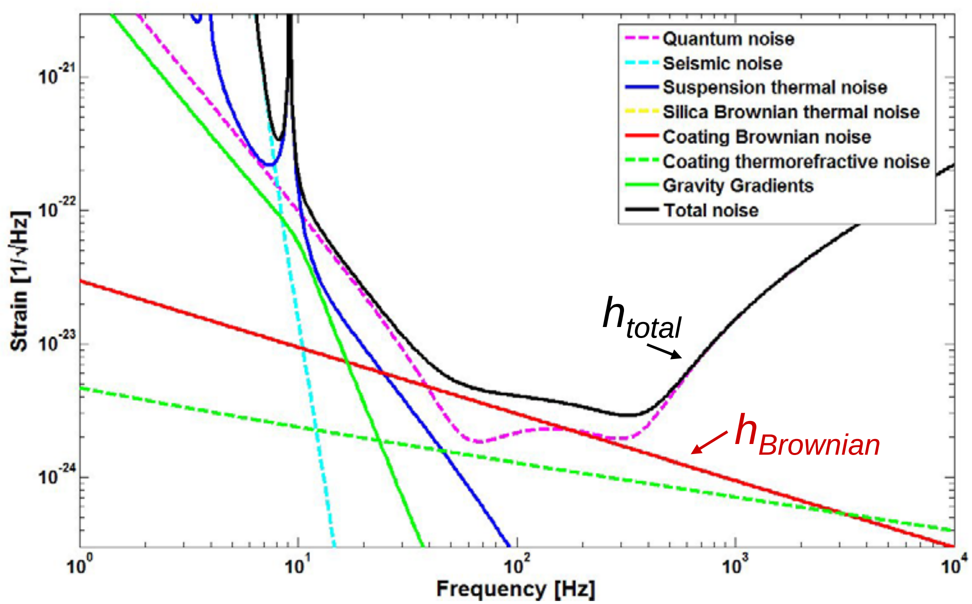


… And back (thermal noise)

- Thermal noise in the suspensions, mirrors, and coatings degrades sensitivity
  - » Brownian and thermo-elastic noise
- Advanced LIGO is dominated by *Brownian thermal noise of the mirror coatings*

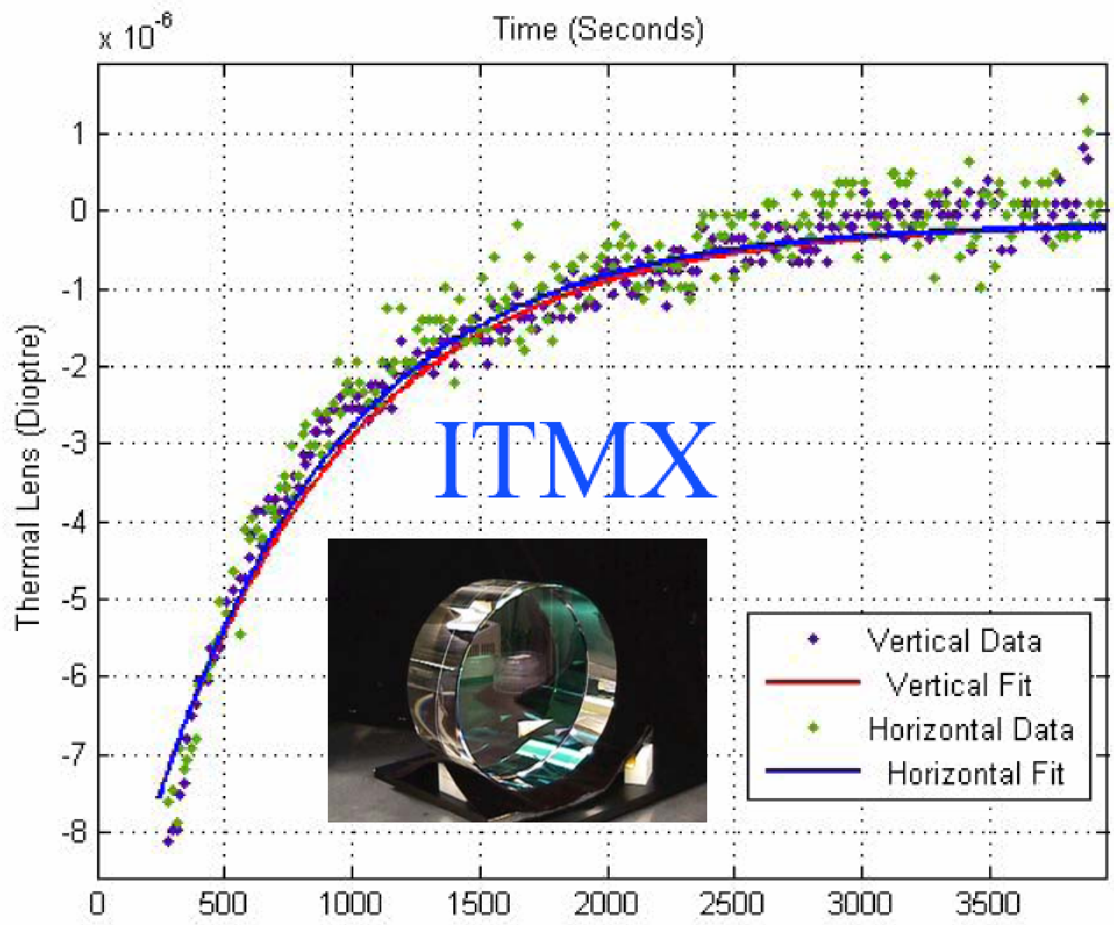
$$h_{Brownian} = \sqrt{2k_B T \phi_{eff} \frac{1-\sigma^2}{\pi^3 f \, wY}}$$

- Major effort under way to develop better coatings for Advanced LIGO
  - » 30% reduction in Brownian coating noise via doping of HR coatings with TiO_2



Thermal effects in LIGO

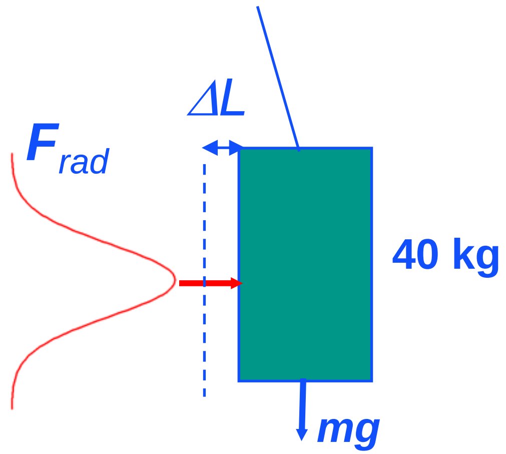
- High quality low absorption fused silica substrates
  - » ~ 2 -10 ppm/cm bulk absorption
  - » ~ 1-5 ppm coating absorption
    - – Different for different mirrors
    - – Can change with time
  - » All mirrors are different
  - » Unstable recycling cavity
  - → Requires adaptive control of optical wavefronts
- ~100 mW absorption in current LIGO interferometers
  - » Effects are noticeable!
- Will be worse in AdvLIGO
  - » ~ 1 W absorbed power into input test masses



Optical springs and instabilities

- Stored arm cavity power: 800 kW on resonance
  - » Radiation pressure on resonance:

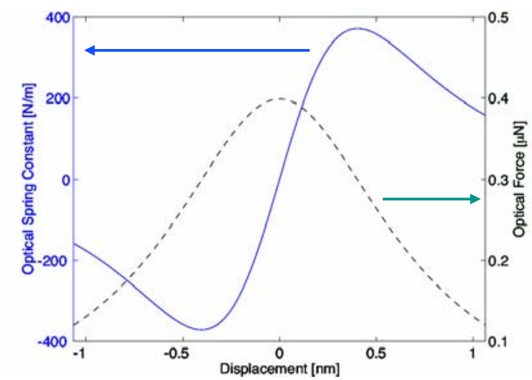
    $F_{rad} = 2P_{cav}/c \sim 6$ mN
  - » Leads to (uncontrolled) **ΔL ~ 10s of µm**



- 3 types of potential instabilities
  - » Optical 'spring' effect
    - – From dynamic force as mirrors go through resonance Sheard, et al., Phys. Rev. A**69** 051801 (2004)

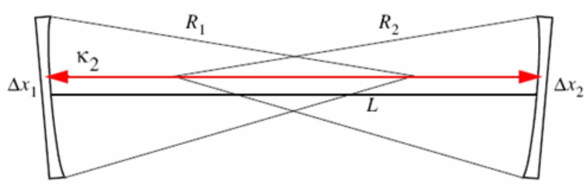
$$k_{tot} = k_{mech} + k_{opt}$$

$$k_{\rm opt} = -\frac{d}{dx}\left[\frac{(2R_2 + A_2)T_1 P_{\rm in}}{|1-\sqrt{R_1 R_2}e^{-i(4\pi x/\lambda)}|^2 c}\right]$$



  - » Angular 'tilt' Instabilities
    - – From misaligned cavities: $\tau = \frac{2P_{cav}\Delta x}{c}$

      Sidles and Sigg, Phys. Lett. A **354**,167-172 (2006)



  - » **Parametric Instabilities**

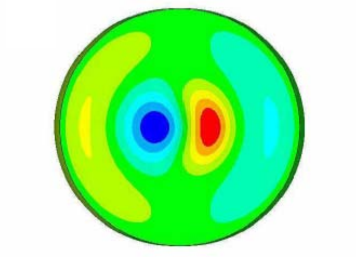
Parametric instabilities

- Coupling of intracavity photon-acoustic modes
  - » High intracavity powers excite acoustic modes in the mirrors (Stokes mode)
  - » Instability depends on
    - – Intracavity power
    - – Substrate material
      - Speed of sound, mechanical Q
    - – Cavity parameters
      - Length, mirror RoC
- Parametric Gain; R> 1 leads to instability

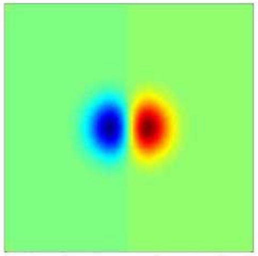
$$R = \frac{2PQ_m}{mcL\omega_m^2}\left(\frac{Q_1\Lambda_1}{1+(\Delta\omega_1/\delta_1)^2} - \frac{Q_{1a}\Lambda_{1a}}{1+(\Delta\omega_{1a}/\delta_{1a})^2}\frac{\omega_{1a}}{\omega_1}\right)$$

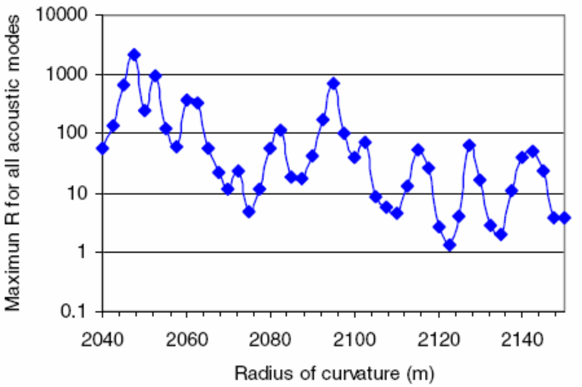
V. B. Braginsky, et al., *Phys. Lett. A*, 305, 111, (2002);
C. Zhao, et al, *Phys. Rev. Lett.* 94, 121102 (2005).

TM acoustic mode



TEM 10 mode





In AdvLIGO: mitigate via acoustic damping, thermal ROC tuning, 'tranquilizer' cavities

Advanced LIGO Subsystems ('Nuts and Bolts')

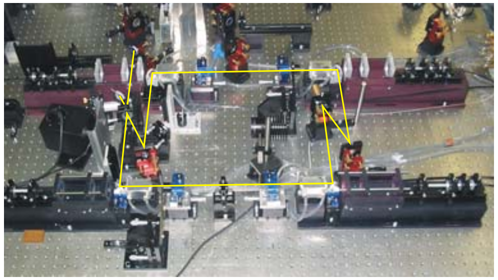
What is Advanced about Advanced LIGO?

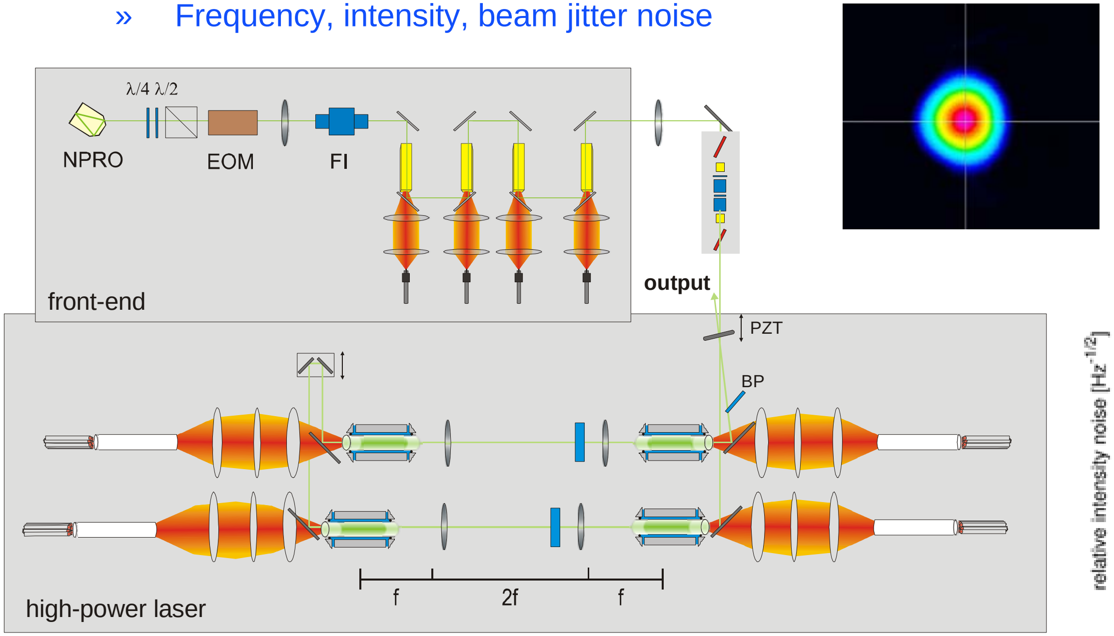
Parameter	*LIGO*	*Advanced LIGO*
Input Laser Power	10 W	180 W
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	f_{low} ~ 50 Hz	f_{low} ~ 10 Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum

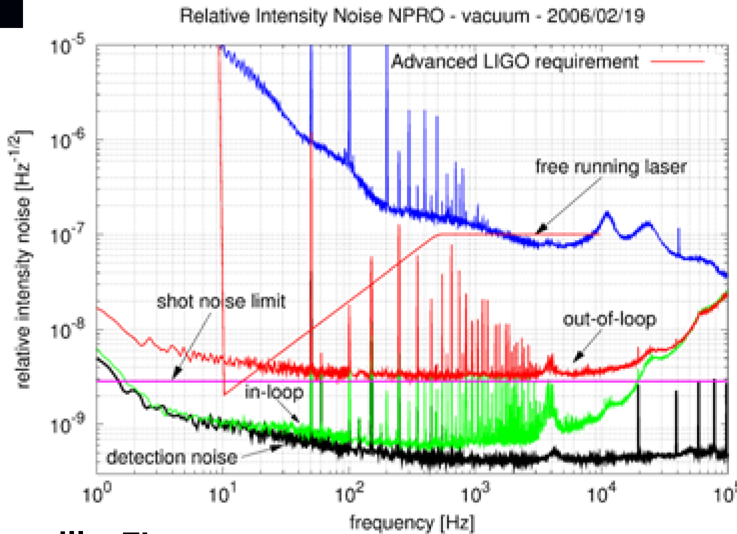
Advanced LIGO pre-stabilized laser

Frede et al, *Opt. Express* **22** p459 (2007)

- 180 W amplitude and frequency stabilized Nd:YAG laser
- Two stage amplification
  - » First stage: MOPA (NPRO + single pass amplifier)
  - » Second stage: injection-locked ring cavity
- Developed by Laser Zentrum Hannover and MPI at Hannover
- Well along toward meeting performance specs
  - » Frequency, intensity, beam jitter noise

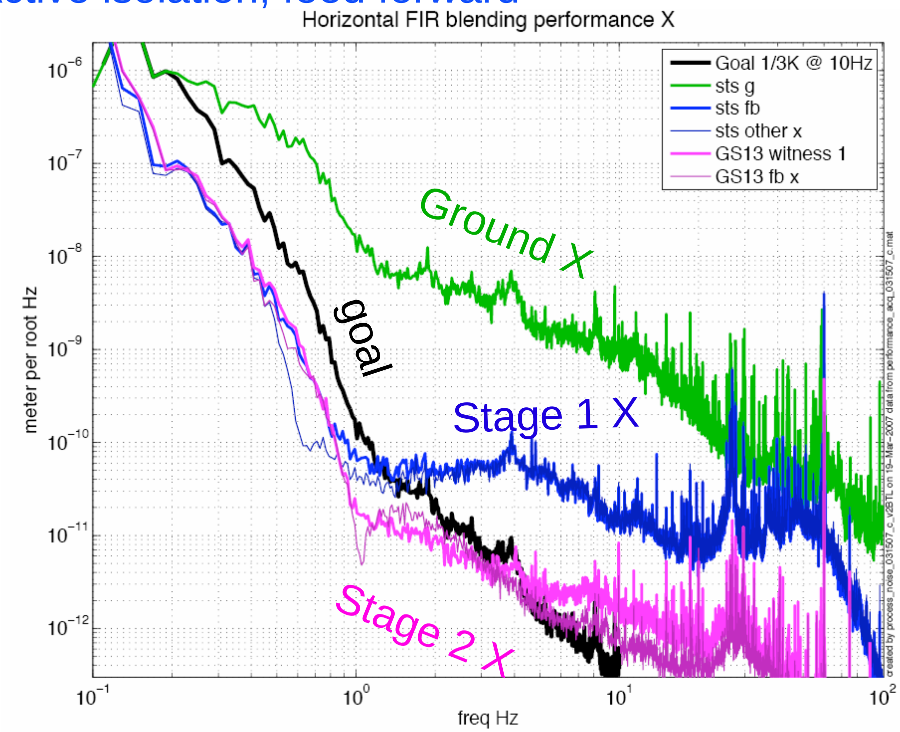


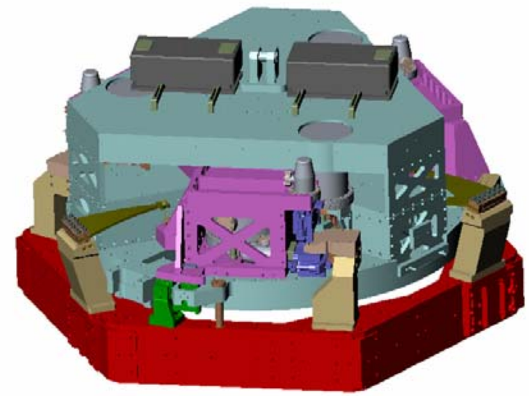




Seismic isolation

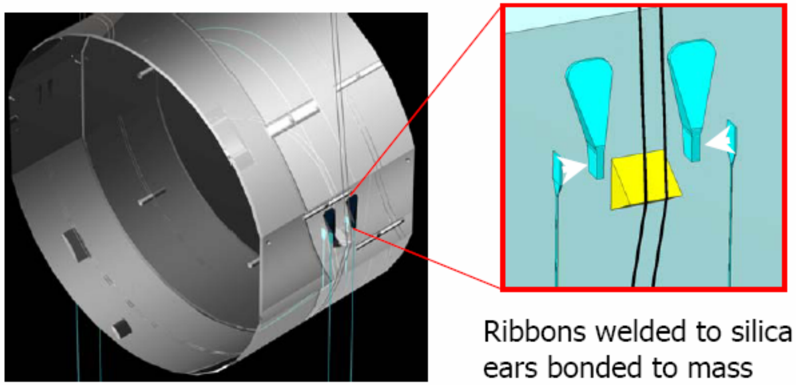
- To open Advanced LIGO band at low frequencies, a complete redesign of the seismic isolation system is needed
- Required Isolation
  - » 10x @ 1 Hz
  - » 3000x @ 10 Hz
- Active isolation, feed forward





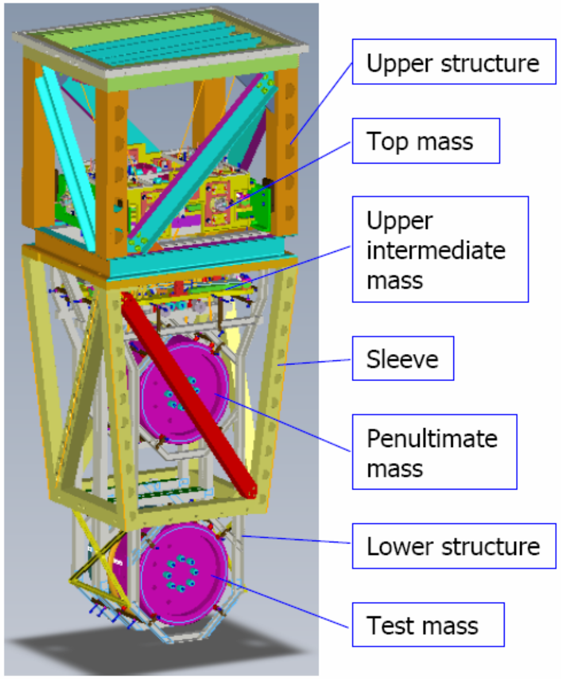
Advanced LIGO suspensions

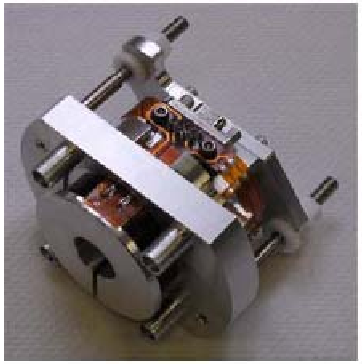
- Quad controls prototype installed at LASTI and undergoing testing
- Noise prototype in fabrication
  - » Lowest mode predicted @ 100 Hz
- Fiber pulling/welding and OSEM sensors undergoing characterization



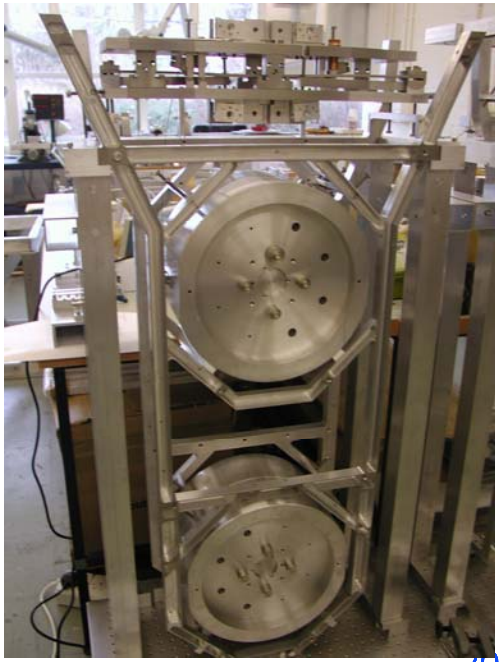
Ribbons welded to silica ears bonded to mass

Quad Noise Prototype

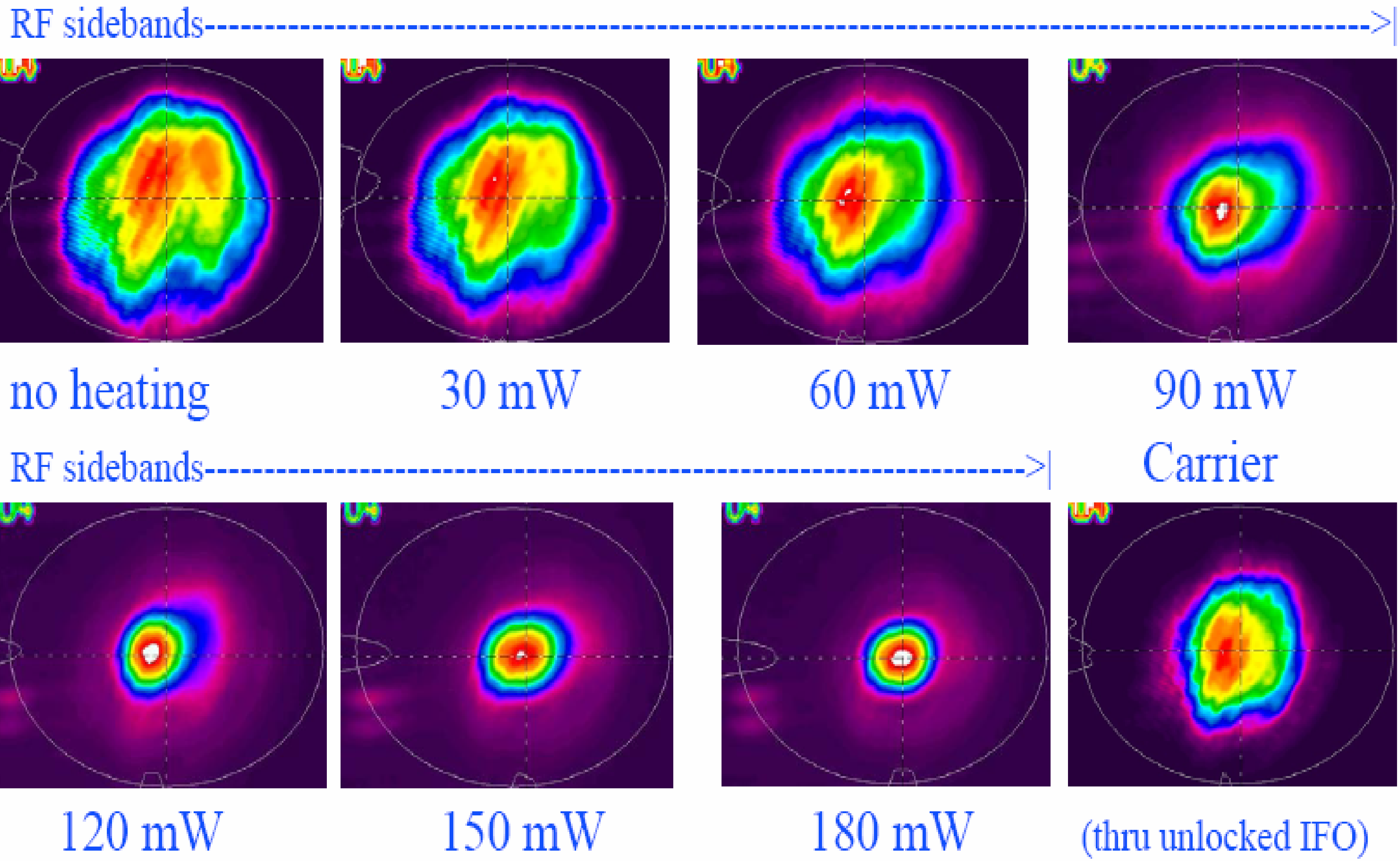




Noise Prototype OSEM (Prototype Unit)



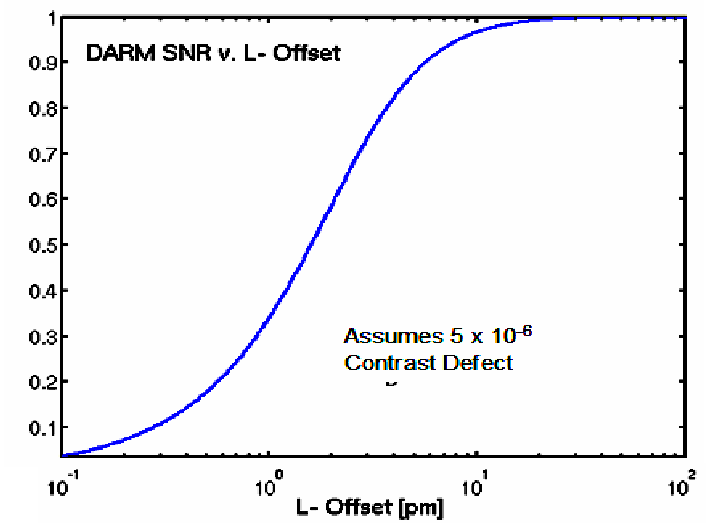
Thermal compensation



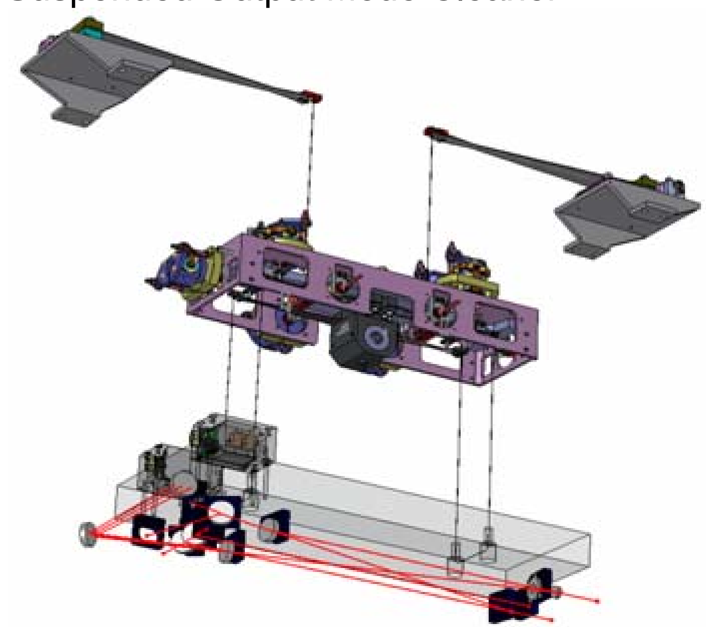
GW signal readout in Advanced LIGO

- Current LIGO uses ‘RF readout’ scheme
  - » Modulated carrier (dark under quiescent conditions) beats against ‘bright’ RF sideband
    - – Mode overlap between RF and carrier
    - – Places stringent requirements on RF phase noise
      - Impossible to meet for Advanced LIGO
- Advanced LIGO will use DC readout: GW-modulated light directly read out by dark port photodiode
  - » Requires *very clean* carrier light → output mode cleaner to filter carrier
  - » Offset arms by 10-20 pm
  - » Advantage: reduces noise couplings

Signal

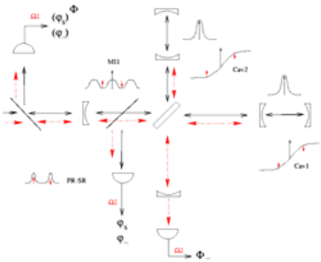


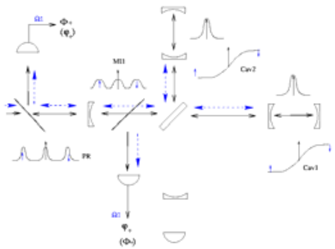
Suspended Output Mode Cleaner



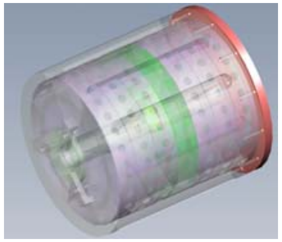
If there were more time…

- Length control system
- Alignment control system

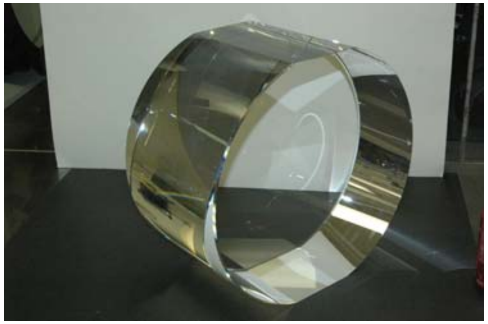




- High power electro-optic modulators and optical isolators
  - » New nonlinear optical materials and thermally compensated designs
  - » Session K12, Experimental Gravity (Sunday, 1:15 pm)



- State-of-the-art fused silica test masses
  - » Low absorption
  - » Sub-angstrom polishing



- Control and data system

Conclusions

- LIGO is running at design sensitivity
- We are 80% through the S5 Science Run
  - » One year of two site coincidence data
  - » Some preliminary results at this conference
- Advanced LIGO design is mature
  - » Anticipate upgrade to begin in 2011; operations in 2014

Acknowledgments

- **Members of the LIGO Laboratory, members of the LIGO Science Collaboration, National Science Foundation, PPARC, MPG, DFG**

More Information

- **http://www.ligo.caltech.edu; www.ligo.org**

LIGO

LSC

The LIGO Scientific Collaboration

NAOJ

UNIVERSITY of GLASGOW

GEO 600

UTB TSC

Syracuse University

MONTANA STATE UNIVERSITY

California Institute of Technology

WASHINGTON STATE UNIVERSITY

NORTHWESTERN UNIVERSITY

UF UNIVERSITY of FLORIDA

LSU

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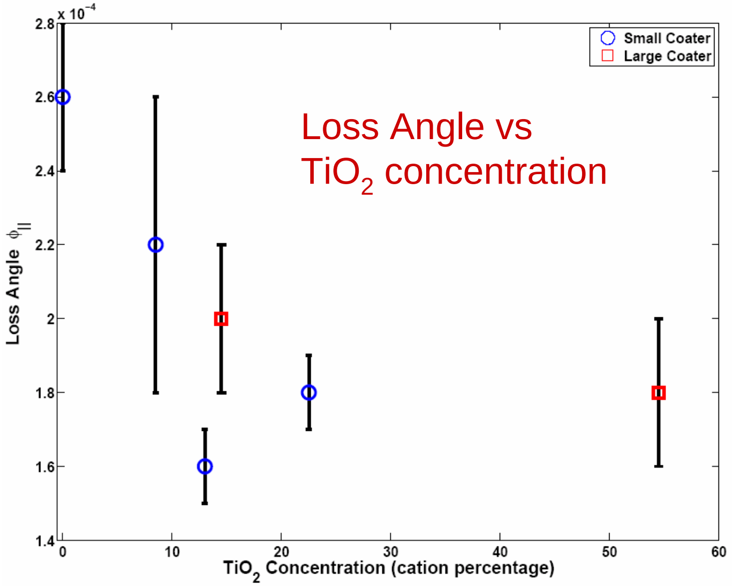
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Massachusetts Institute of Technology

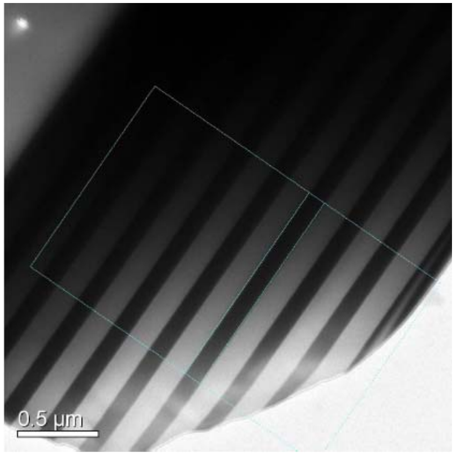
THE UNIVERSITY OF WESTERN AUSTRALIA

The importance of mirror coatings

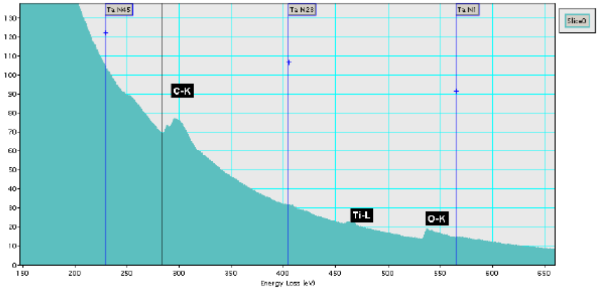
- Making a better optical coating is a major focus of the LSC
  - » Efforts in coating development, coating characterization
    - – Mechanical loss (reduction of thermal noise)
    - – Optical absorption (thermal effects)
- Mechanical loss
  - » Efforts focused on incorporation of dopants to relieve coating stress
  - » TiO_2-doped Ta_2O_5 has shown promise



Harry, et al, CQG **24**, 405 (2007)



Electron Energy Loss Spectroscopy



X-Ray Florescence Results