LIGO

# Optics Working Group Overview

**Volker Quetschke on behalf of the OWG**

**University of Florida**

**Instrument Science Plenaries I, October 22, 2007**

UNIVERSITY OF FLORIDA

# Optics Working Group Mission Statement



The Optics Working Group (OWG) of the LSC pursues research related to the development and implementation of optical components for ground-based gravitational wave detectors.

- Optical components for AdvLIGO
- Possible upgrades in subsystems of AdvLIGO
- Longer term research into ways around significant limitations in current detectors.

LIGO

# Outline

Parts/Systems

- UF - eLIGO TriMod phase modulator / high power Faraday isolator
- UF – MZ parallel modulation / high intensity coating test / MC mirrors
- Caltech – TCS

Techniques

- ANU – digitally enhanced heterodyne interferometry
- UWA/Gingin – parametric interactions

Measurements/Characterizations/Calculations

- All LSC – Coating overview
- TNI – TNI results
- LASTI - Coating Characterization
- Syracuse - Scatter Imaging Lab
- Embry-Riddle – Thermo-optic noise measurements
- CalTech - Scattering Loss in LIGO I optics
- Sannio – Coating Research

Tools

- MIT - Opticle

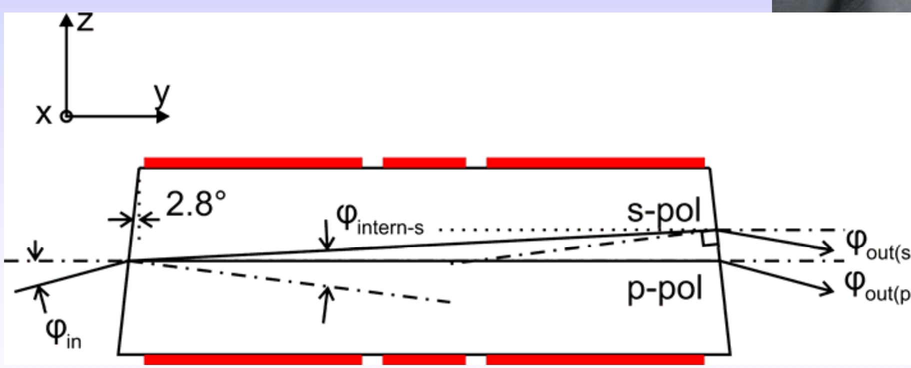
Parts/Systems

Development/improvement of optical components

# eLIGO modulator

- Requirements: Survive high power densities and show no/low thermal lensing effects.

eLIGO electro-optic modulator
- Single crystal
- Three separate electrodes
- Three modulation frequencies

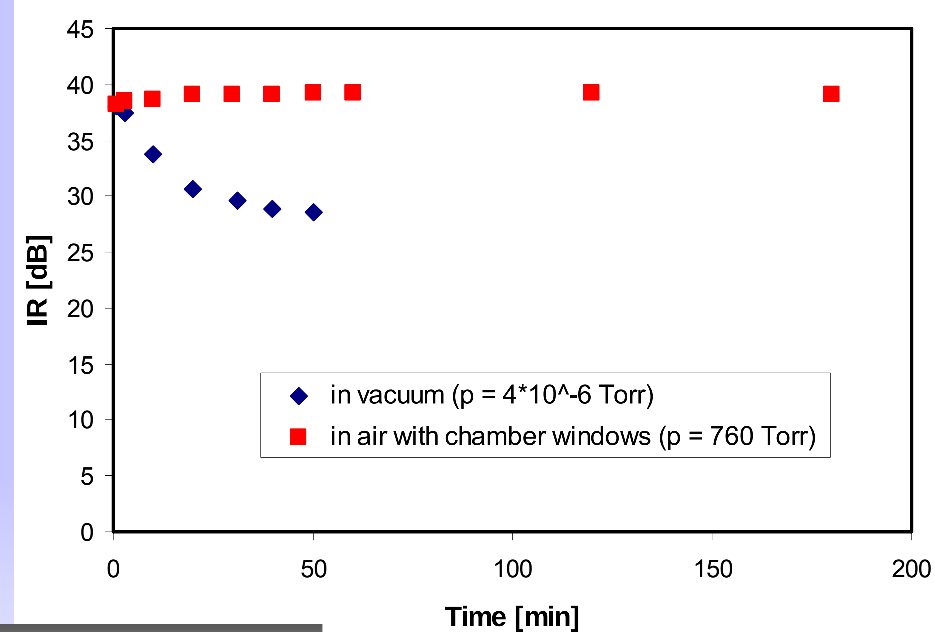



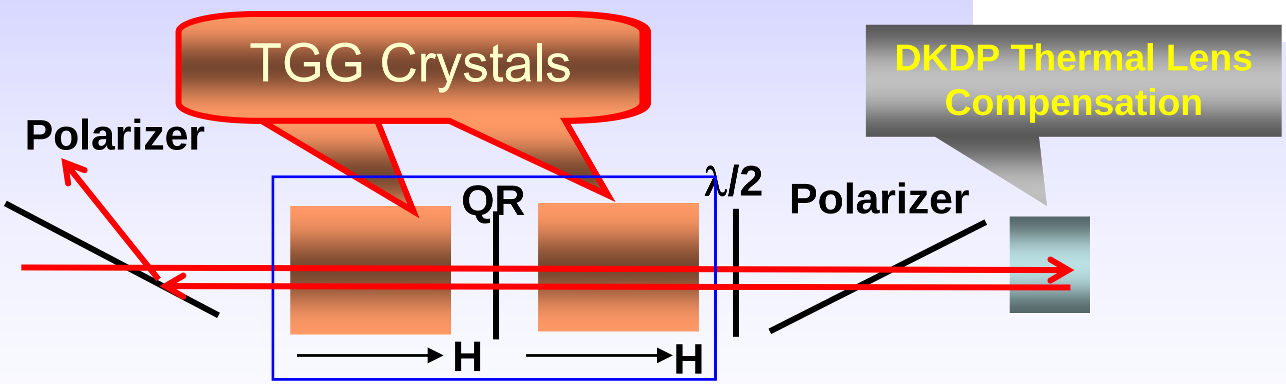

- Wedged crystal separates the polarizations and acts as a polarizer.
  - This avoids cavity effects and reduces amplitude modulation.

**See OWG Parallel Session,**
**Wednesday, Volker Quetschke - Enhanced LIGO Modulator**

# Faraday isolator

- High power requirements drive development of Faraday isolator (FR). eLIGO 30W / AdvLIGO 135W
  - Thermal lens compensation *via* negative *dn/dT* material: deuterated potassium dihydrogen phosphate, $KD_2PO_4$, or ‘DKDP’).
- Calcite wedge polarizers are used
- Current eLIGO version is “real-life” prototype for AdvLIGO



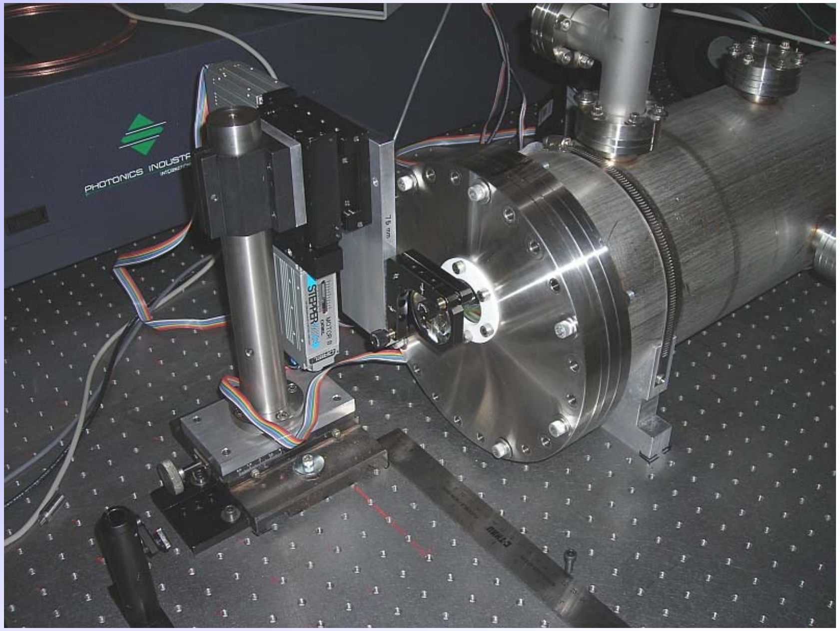

**Vacuum issues**

- >40 dB suppression in Air
- ~ 30 dB suppression in vacuum

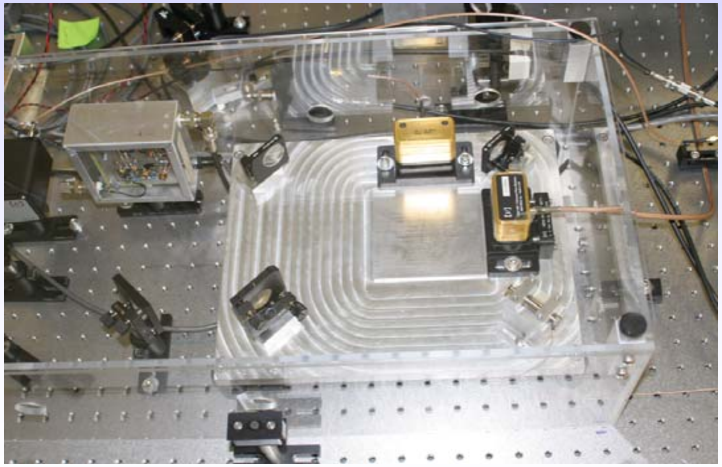
**See OWG Parallel Session, Wednesday,**
**Antonio Lucianetti - Enhanced LIGO and Advanced LIGO Faraday Isolator**

# LIGO Coating Damage Test Setup / MZ improvements

- Requirements: Survive high power densities.

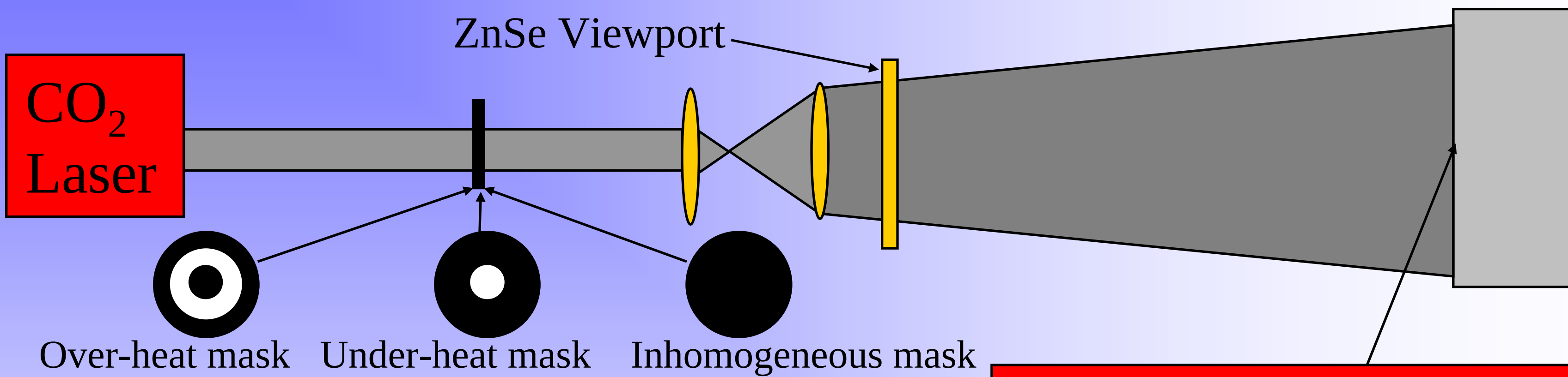


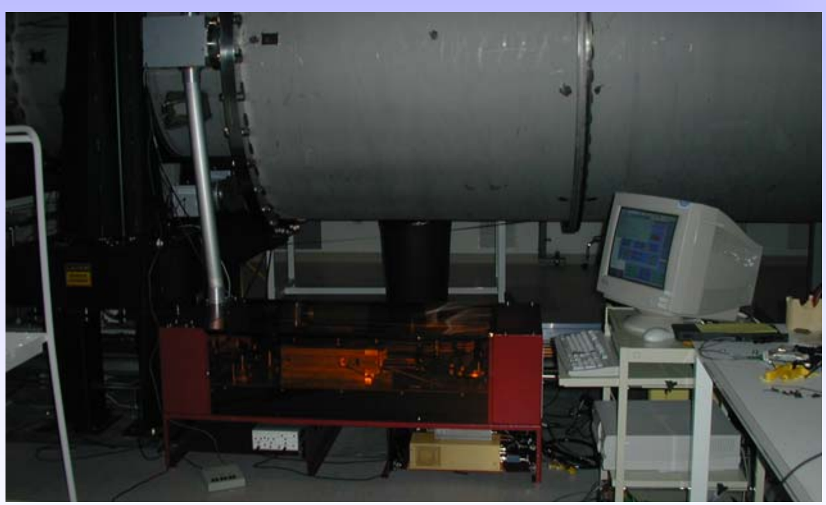
Test setup for coating damage tests (in preparation)
- 45 W laser
- 30 um beam radius
- Vacuum system

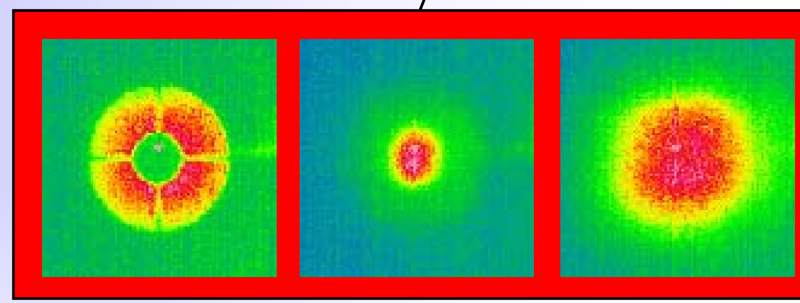


Advanced LIGO modulation
- Mach-Zehnder configuration
  - Avoids sidebands on sidebands

# Thermal Compensation System





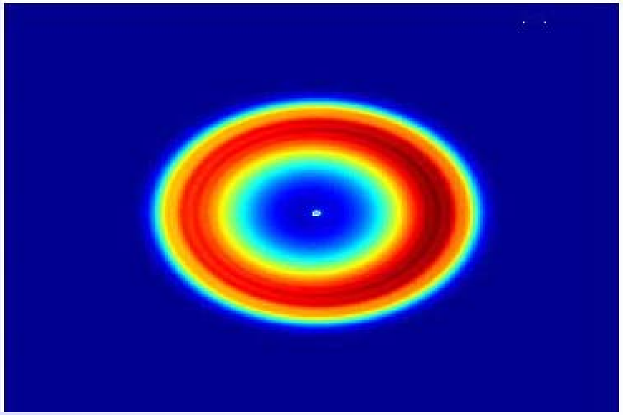
Over-heat pattern

Under-heat pattern

Raw Heating pattern

# eLIGO TCS status

- Increase in TCS laser power
  - 35W Synrad lasers
- Intensity stabilization of laser
  - PD - AOM Servo loop
  - Better electronics
- More efficient annulus
  - Previous: mask ≈ 30% efficient annulus
  - Now: axicon ≈ 99% efficient annulus
- Chillers
  - Quieter and more remote locations
- "Optical lever wavefront sensor" ?
  - Thermo-elastic surface deformation measurement using OL



**Axicon annulus mode (simulation)**

**See OWG Parallel Session, Wednesday,**
**Aidan Brooks - Enhanced and Advanced LIGO Thermal Compensation System**

# Gold Coatings for TCS

- Gold coating on test mass barrels reduces radial temperature gradients due to gold's low emissivity.
- Good idea but must test thermal noise implications.
- *First step*: Measure the loss angle of gold. This has now been done. (Embry-Riddle)

100 nm gold on top of 2 nm titanium (for adhesion).

Substrate is 3" diam. fused silica disk.

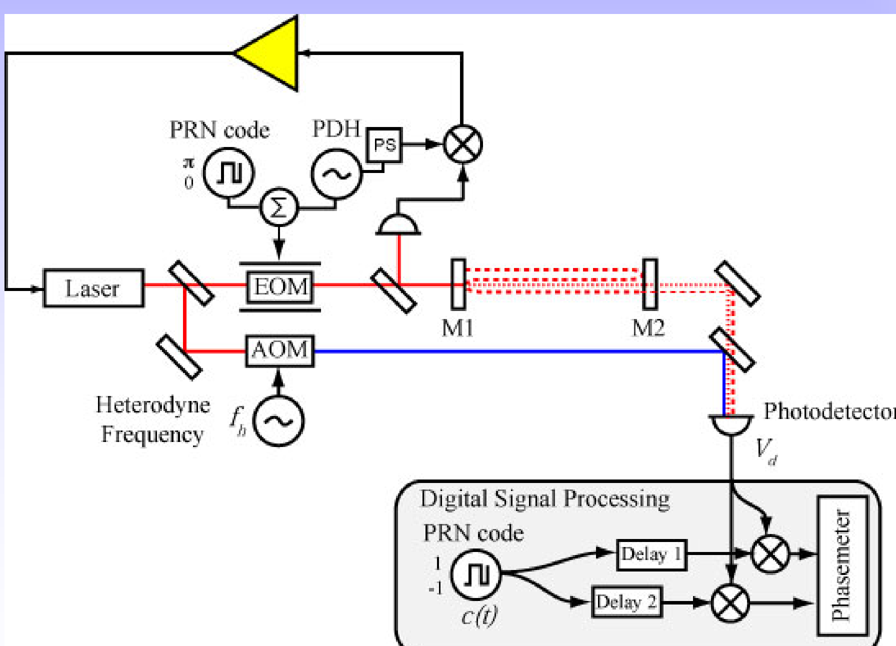
- *Second step*: Apply Levin model for finite TM to calculate thermal noise. First results are in (Phil Willems). More detailed modeling may be required.

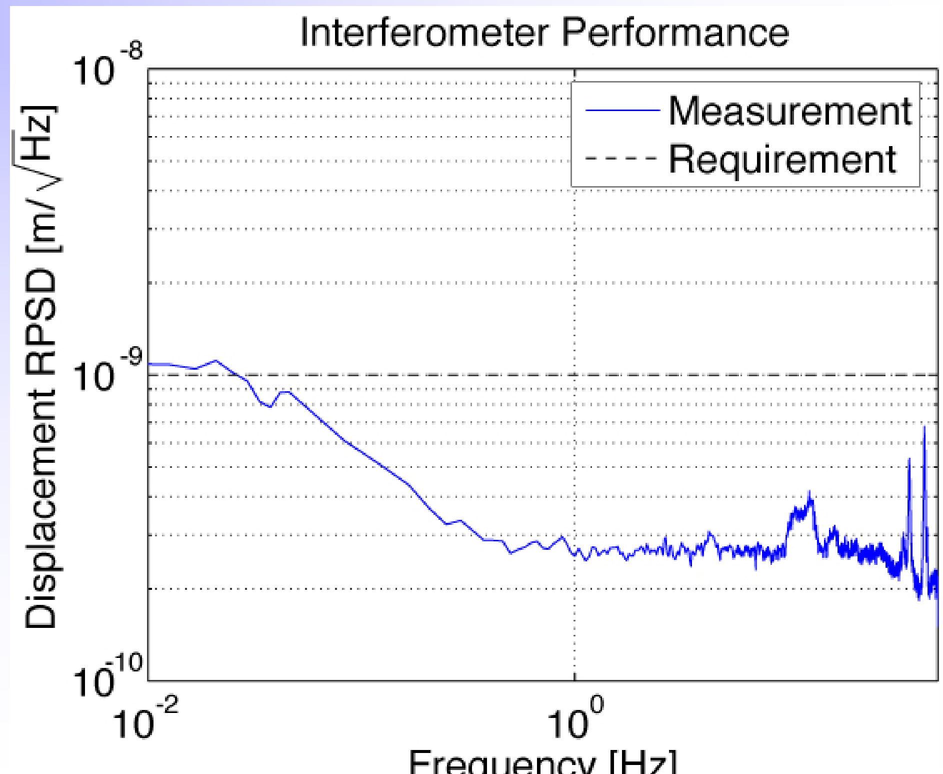
# Techniques

Methods and Experiments to improve or characterize Detector properties

# ANU
# Digitally Enhanced Heterodyne Interferometer

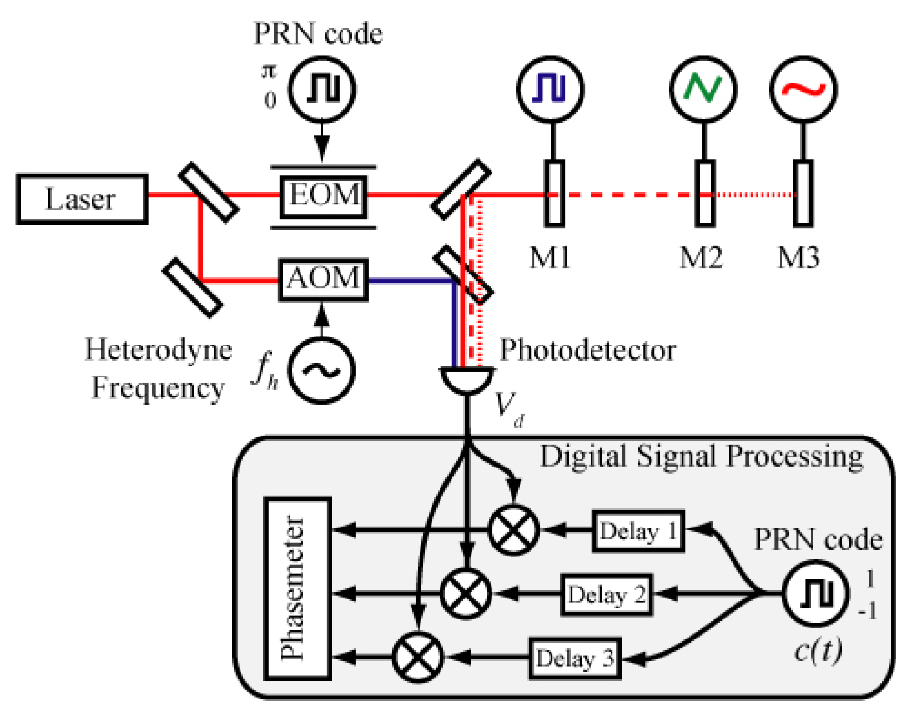
- Goal: Reduce relative test mass motion to below 10 nm in the band 0.01 Hz to 1 Hz
- Solution: Direct test mass readout using digital interferometry [1]
- Was demonstrated with a new technique which combines standard heterodyne interferometry with digital (pseudo random noise) modulation enabling the read out of mirror position with interferometric sensitivity without cavity locking. [1] D.A. Shaddock, OPL, accepted, 10/2007

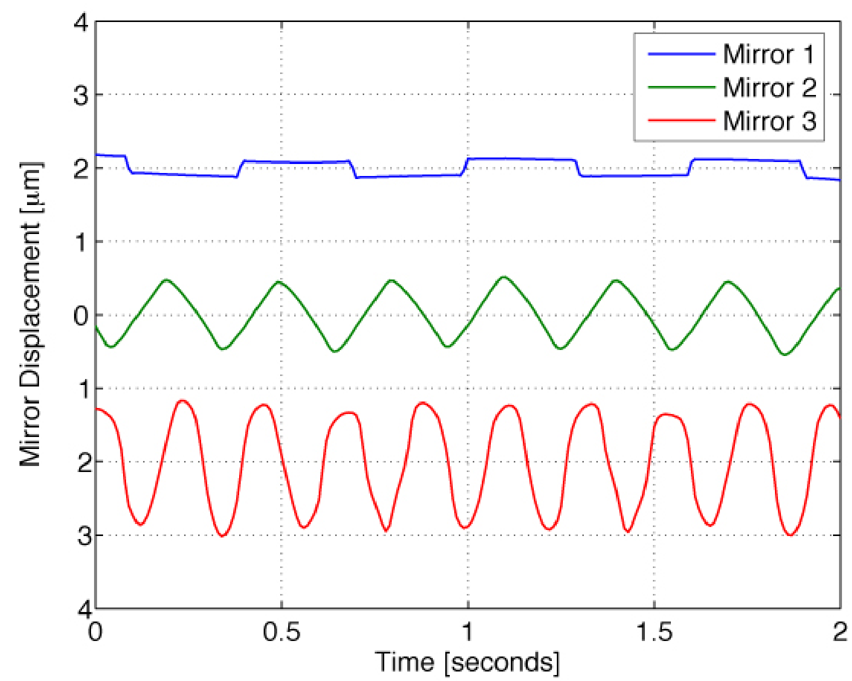


# ANU
# Digitally Enhanced Heterodyne Interferometer

- Multiplexing is possible
- Example for 3 mirror readout



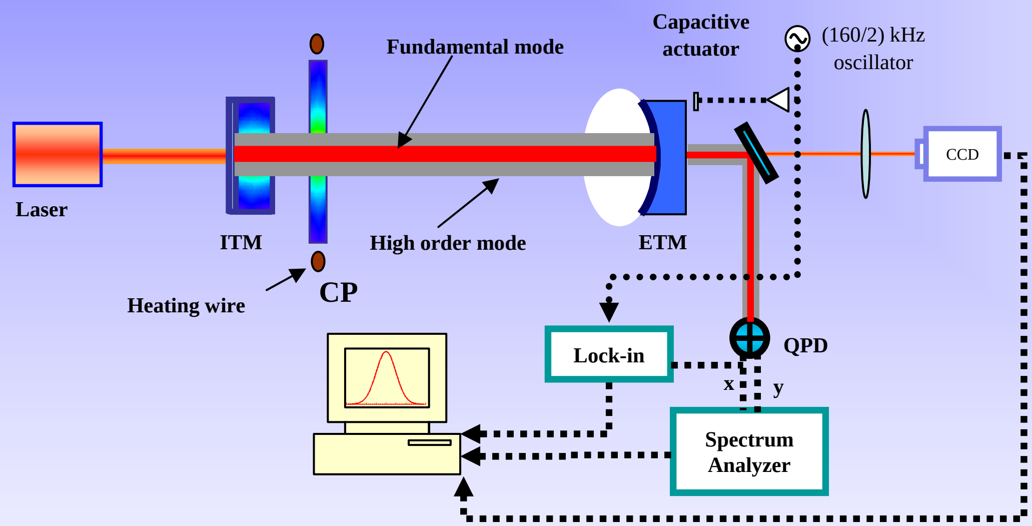




**See OWG Parallel Session, Wednesday,**
**David Rabeling - Digital Interferometry for Lock Acquisition in Adv. GW Detection**

# Gingin High Optical Power Facility

## First Observation of 3-mode Parametric Interactions

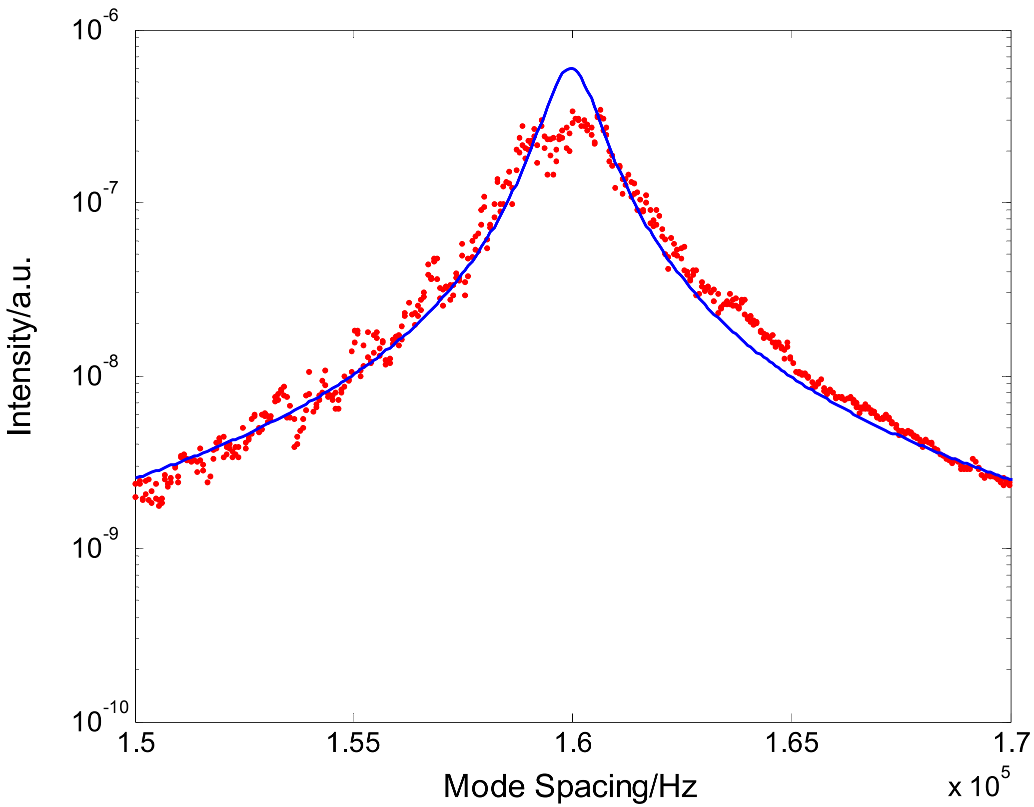
### *Experimental setup*




- The end test mass (ETM) was resonantly excited at the acoustic resonance.
- The fused silica compensation plate (CP) was heated to tune the cavity mode spacing.
- The cavity tuning and the anti-Stokes TEM01 mode excitation were measured by the CCD and quadrant photodiode (QPD) at the back of the ETM.

# First Observation of 3-mode Parametric Interactions

## *Result*




- Red dotted line: Measured power of the TEM01 mode as a function of the frequency difference between the TEM00 and TEM01 modes (mode spacing).
- Blue solid line: Predicted Lorenzian parametric interaction response based on independent measurement of the optical cavity TEM01 mode linewidth. (FWHM linewidth of 1.3 kHz)
- The peak power is at the frequency difference corresponding to a cavity g-factor of 0.967.

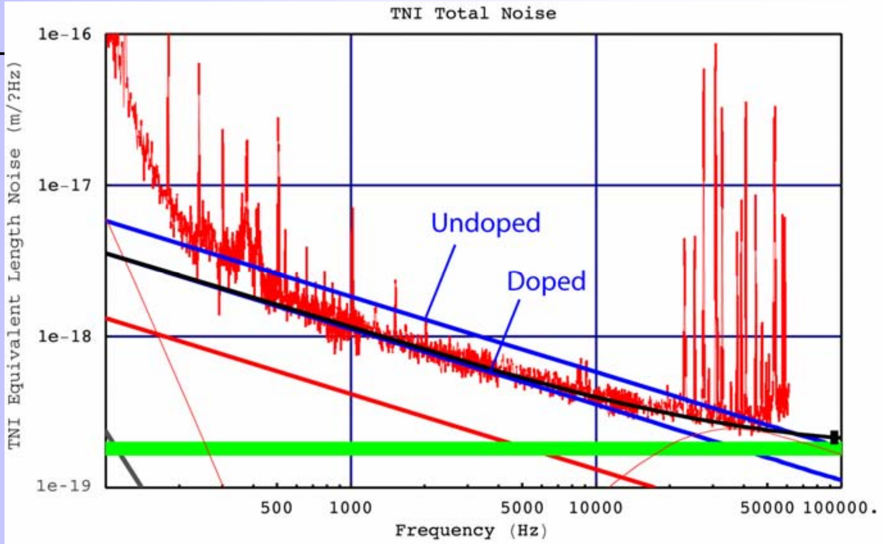
# Measurements/Characterizations/Calculations

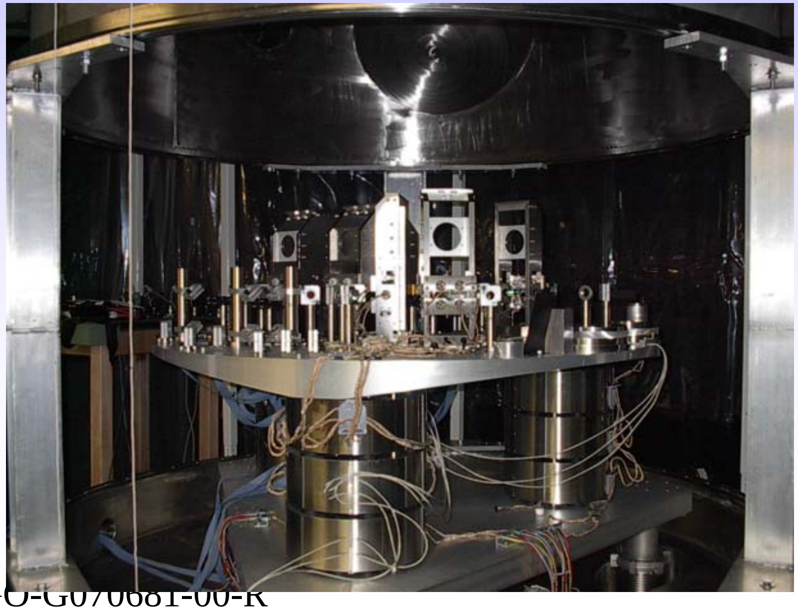
# Coating overview

- See IS Plenary III, Wednesday, 17:40 Coating Research Overview - Sheila Rowan

# LIGO Thermal Noise Interferometer (TNI)

- Recent results:
  - Broadband measurement of doped-tantala/silica, periodic coating
  - Ring dampers for suppression of parametric instabilities
  - Homogeneity experiment: Coating thermal noise vs. spot position
- Lab move:
  - Reassembly/optical-alignment complete
  - Servo recommissioning in progress

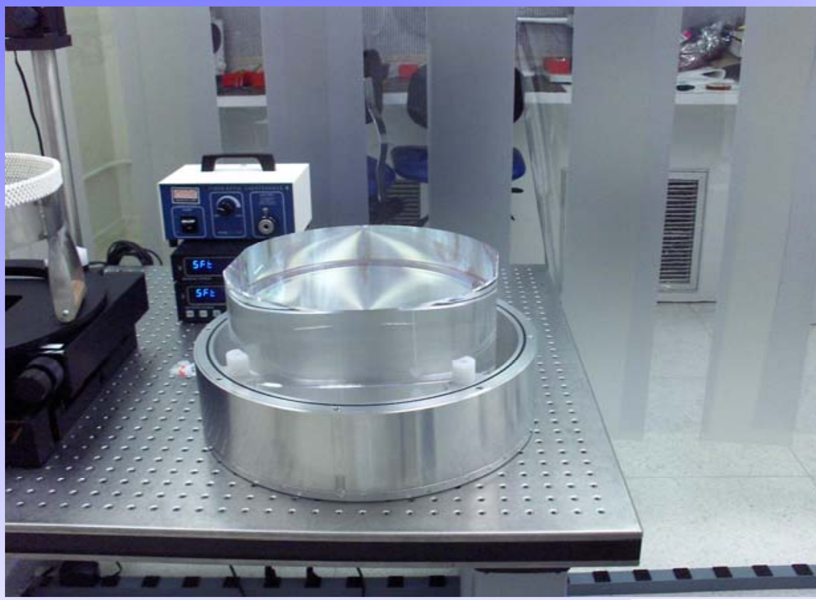


- Future plans:
  - Optimized, undoped coatings - in progress
  - Optimized coatings with doping - funding approved contingent on optimized, undoped results
  - Direct measurement of thermo-optic noise
  - Photothermal measurements of thermophysical properties in advanced coatings
  - Gold coatings for ring dampers
  - Direct measurement of charging noise and testing of charge mitigation schemes

**See IS Plenaries IV, Thursday, 10:40 TNI Update - Eric Black**

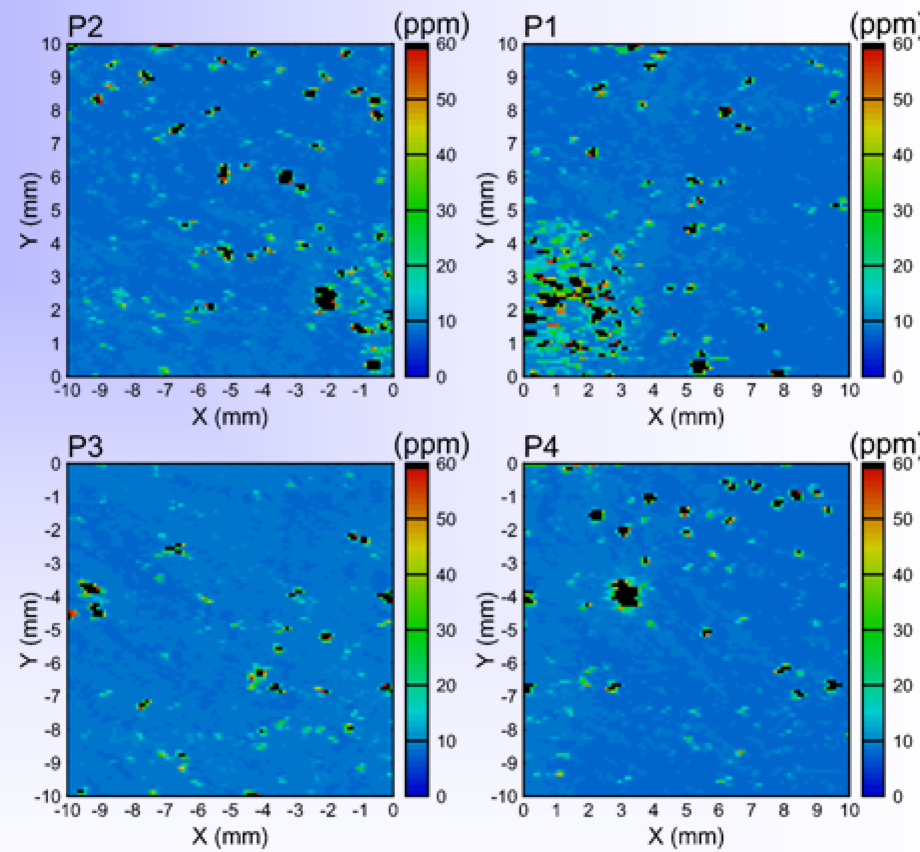
# LASTI Optic



# LASTI - ETM
## Coating Characterization at Caltech

**SCATTER**

HR side was measured on the RTS bench at Caltech by using a focused beam and an integrating sphere. The beam waist = 125 microns. The integrated polar angle range is from 1.5º to 78º,corresponding to a spatial bandwidth of 250 – 9200 cm-1.



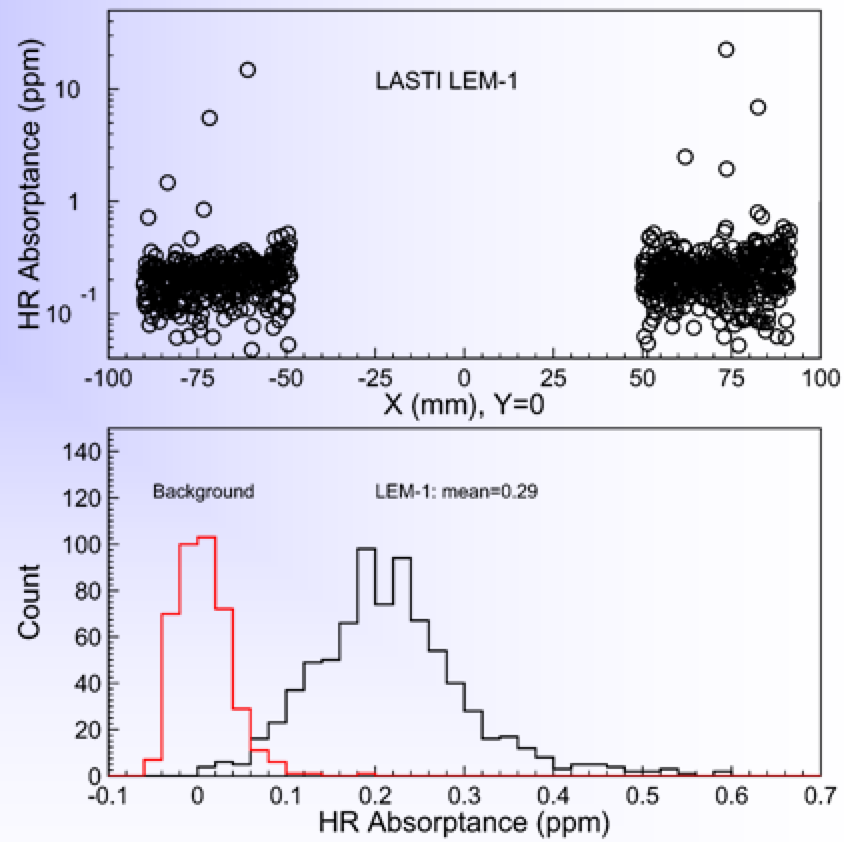
# LASTI - ETM

## Coating Characterization at Caltech

### ABSORPTION

The HR coating absorption was measured on the RTS bench by using the photo-thermal common–path interferometer (PCI) method. The heating source is a 30 W CW Nd:YAG laser, and the probe beam from a He-Ne laser.

Measured absorption: 0.3±0.1 ppm.



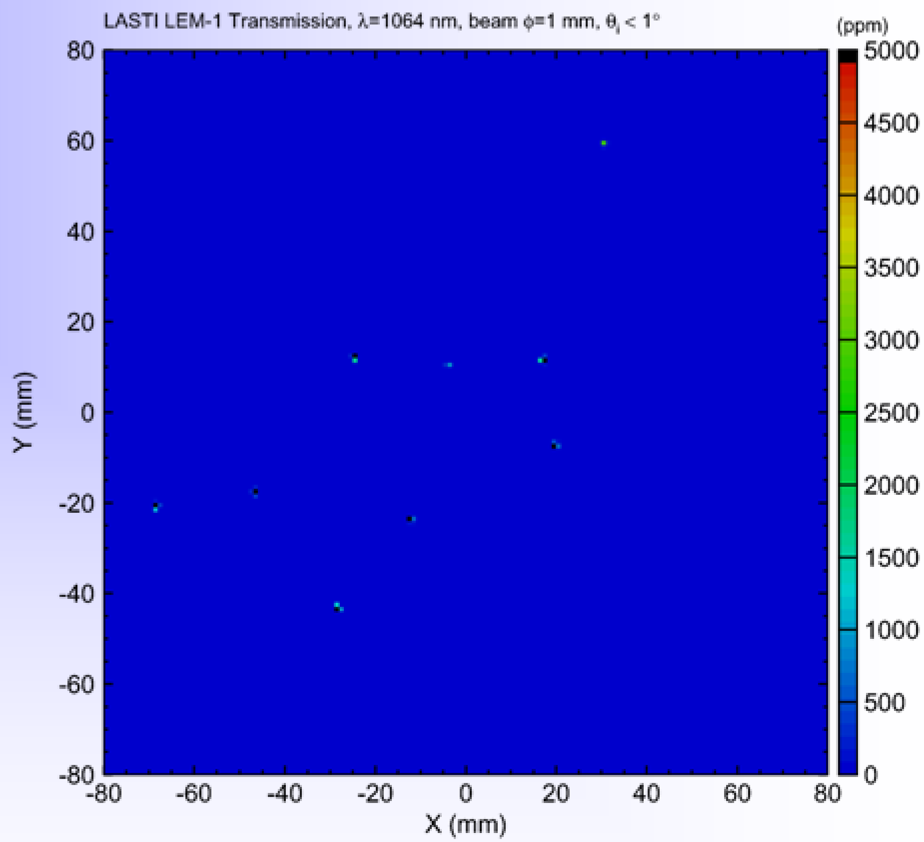
# LASTI - ETM
## Coating Characterization at Caltech

**TRANSMISSION**

The transmission was measured by using a collimated beam of 1 mm in diameter and an 1 mm scan step at the center part of 160 × 160 mm$^2$. Transmission showed good uniformity

Found 9 high transmission points (bubbles)

The contribution of the points is about 1/3 of the overall average of transmission and is non-negligible.

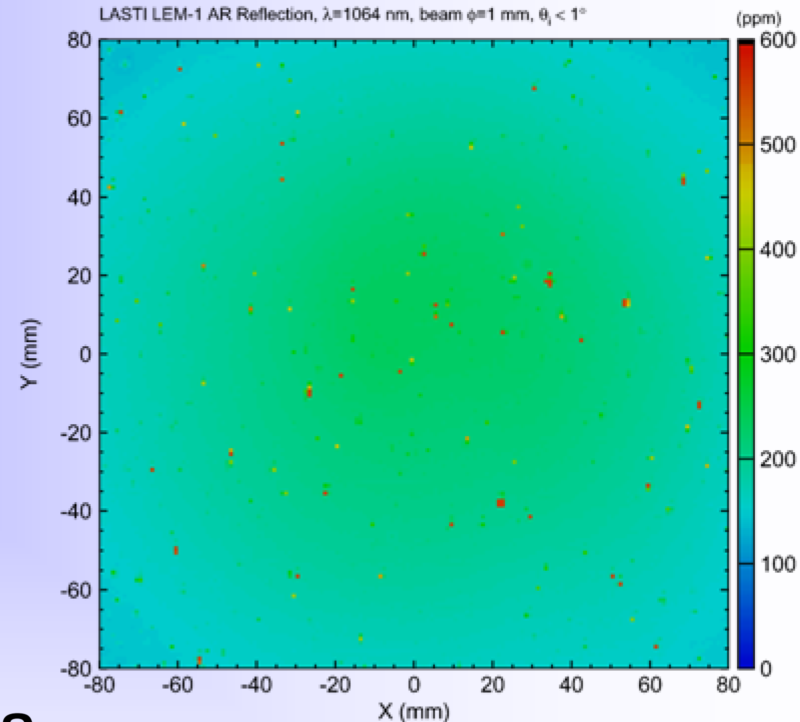



# AR REFLECTION

LIGO

## AR REFLECTION

The reflection of the AR coating was measured with a 1mm dia. collimated beam at the central part of 160 mm × 160 mm. The map shows 230 ppm at center, 160 ppm at edge and an average of 180 ppm.




## RESULTS

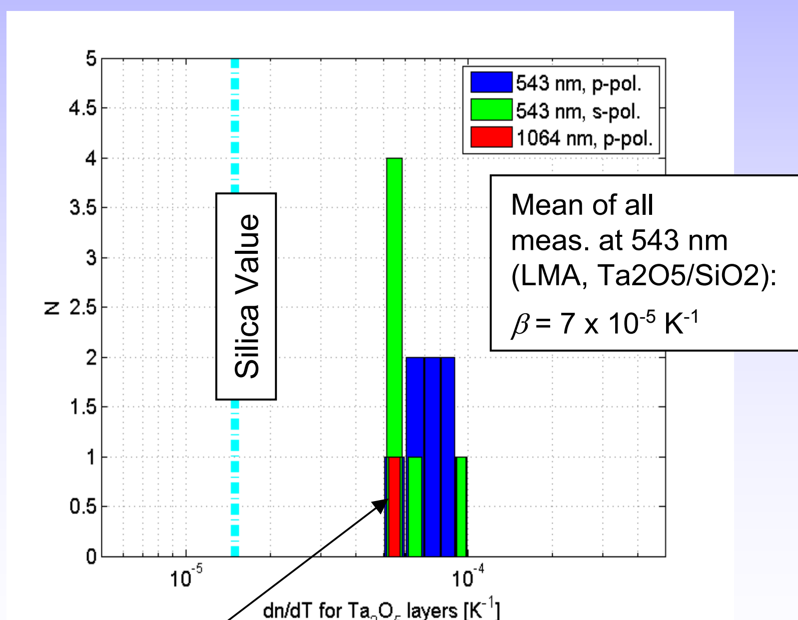
- The coating satisfied the LASTI coating requirements
- The absorption and scatter results were consistent with the measurements from LMA
- AR uniformity needs to be improved
- High transmission points (bubbles) need to be investigated

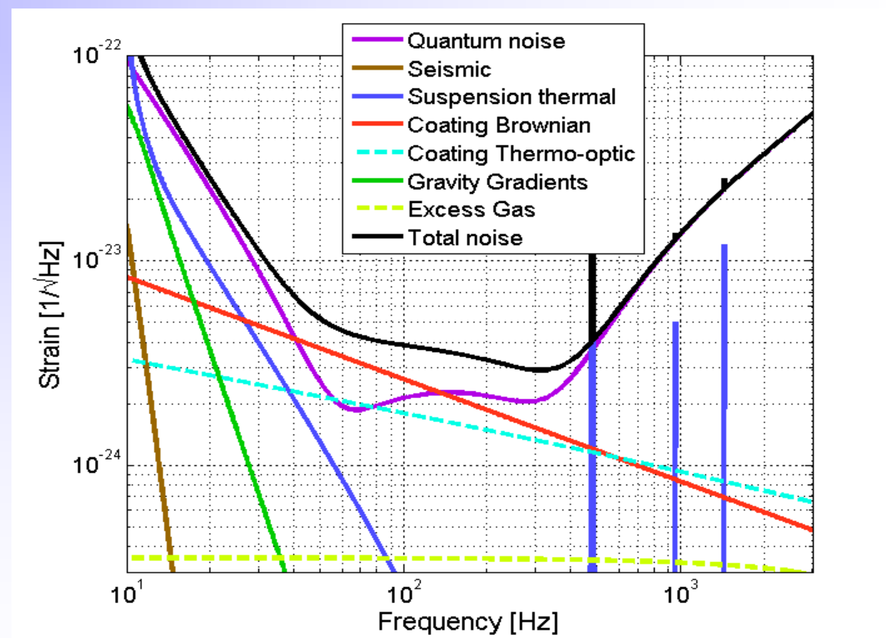
# Research at Syracuse scatter imaging lab

- Goals:
  - Imaging off-angle scatter from LIGO optics in lab
  - Measure total scatter per solid angle
  - Image scatter to
    - Allow accounting: power in points vs background glow
    - Check patterns, how they change with angle
  - Once shaken down, take sensor to sites, improve on existing measurements
  - Use input from OWG and coating WG for direction
- Progress:
  - Have, or on order:
    - class 100 cleanroom, 0.5W CW single-mode Crystalaser, astronomical CCD, lenses, rot stage, 1” AdvLigo sample
  - Lab set up should be complete in November

# Thermo-optic noise measurements
(Embry-Riddle)

- Equilibrium Temp. fluctuations drives coating parameters:
  - Thermal expansion coefficient: $\alpha$ ⇨ Thermoelastic noise.
  - Thermorefractive coefficient: $\beta$ ⇨ Thermorefractive noise.
- Thermorefractive coefficient of Tantala dominates the noise and is also the least well known parameter. So, we must measure it.




*New* 1064 nm meas. (LMA 5**)

# Scattering Loss

**See OWG Parallel Session, Wednesday, Hiro Yamamoto - Scattering Loss**

- LIGO I mirror loss estimation
  - Scattering loss per mirror in LIGO I arm (Power Recycling gain, etc) : 40~50ppm
  - Loss($\lambda$>5mm) ~ 10~15ppm/mirror
  - Loss($\lambda$<0.1mm) ~ 10~30ppm/mirror??
  - Loss($\lambda$~1mm) ~ not well unerstood
- LIGO I mirror surface quality - some inconsistencies
  - $\lambda$>5mm : PSD(coated surface) ~0.1 PSD(polished surface)
  - $\lambda$<0.1mm : mesured loss ~ 10 x estimation by polished surface data
  - $\lambda$~1mm : not well understood
- Advanced LIGO loss requirement < 35ppm / mirror
  - Loss($\lambda$>5mm) ~ 20~25 ppm/mirror with RMS < 0.7nm
  - Need to understand LIGO I mirror losses and to suppress losses or change the AdvLIGO specification to be more telerant to extra loss
- Loss in stable Michelson cavity
  - Due to far field propagation in the cavity, ~500 ppm loss by diffraction with w(ITM)=6cm.
  - With asymmetric arm configuration (w(ITM)=5.5cm,w(ETM)=6.2cm), this is suppressed to ~50ppm.

# OWG Research @ Sannio University, I



- Optimization of coating layer thicknesses. Goal : lowest noise @ prescribed transmittance;
- Plain-Tantala based optimized coating mirror proto-types manufactured at LMA (fall 2006), scheduled for testing at TNI;
- Thermorefractive (TR) & thermoelastic (TE) noise computed and found to be comparable to Brownian in doped-Tantala coatings (2007);
- Thickness optimization for doped-Tantala coatings implemented, total (B+TR+TE) noise included (2007);
- MATHEMATICA code developed; port to BENCH planned;

LIGO

# OWG Research @ Sannio University, II

- Hyperboloidal-Beams and related representations (goal: mitigate tilt instability affecting nearly flat Mexican-Hat mirror cavities);
- Abstract coating and substrate noise lower bounds achievable through beam-shaping, coping with diffraction-loss bound. Main results (2007):
  - -Absolute (variational closed-form) lower bounds for coating & substrate noises under the (unphysical) 0-diffraction loss approximation;
  - -Shannon dimension of the space of all diffraction-loss admissible fields no greater than $a^2/L\lambda$ (arm cavity Fresnel number),
  - -Within the current Adv-LIGO baseline design ($a=16cm$), one could do better than mexican-hat by a factor $\sim 2.6$ (in terms of coating noise) while satisfying the 1ppm diffraction loss constraint. at-mirror design
- Supports independent results by Bondarescu & Chen on optimized mirror-shapes (Caltech, PhD thesis, 2007)

**See OWG Parallel Session, Wednesday,**
**Innocenzo Pinto - Coating Research at Sannio Status**

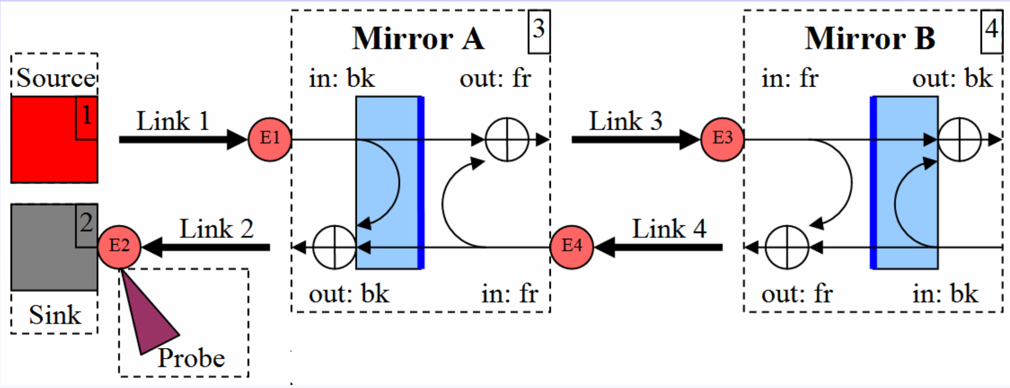
# Tools

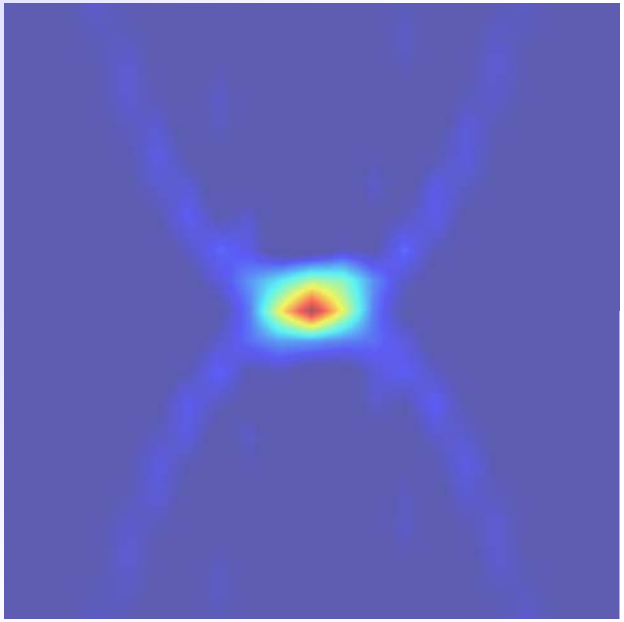
New tool to calculate detector/subsystem responses

LIGO

# Optickle

- Optickle is a frequency domain model for idealized optical systems. It can compute
  - Longitudinal and angular transfer functions, including radiation pressure
  - Quantum noises
  - DC signals



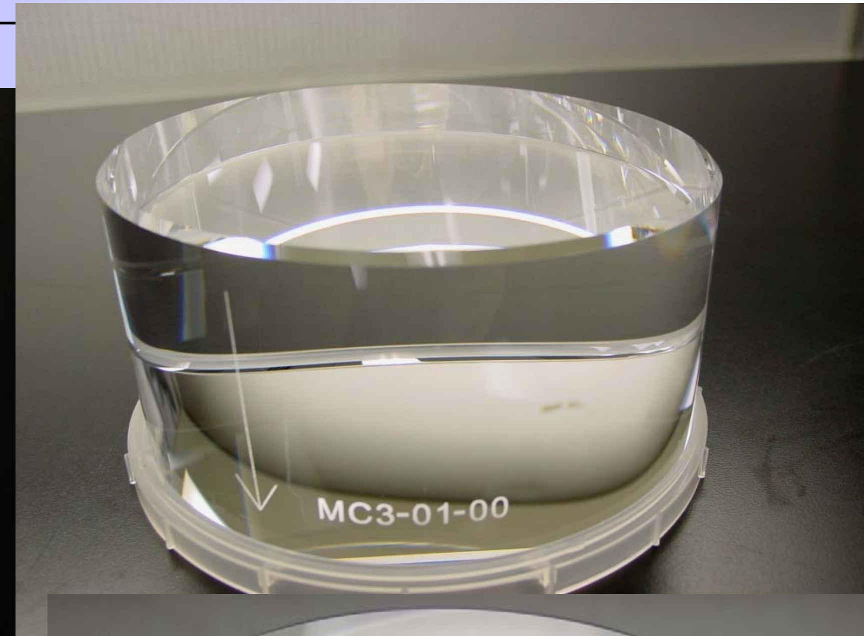
**See OWG Parallel Session, Wednesday, Matt Evans -- Optickle**

# Summary

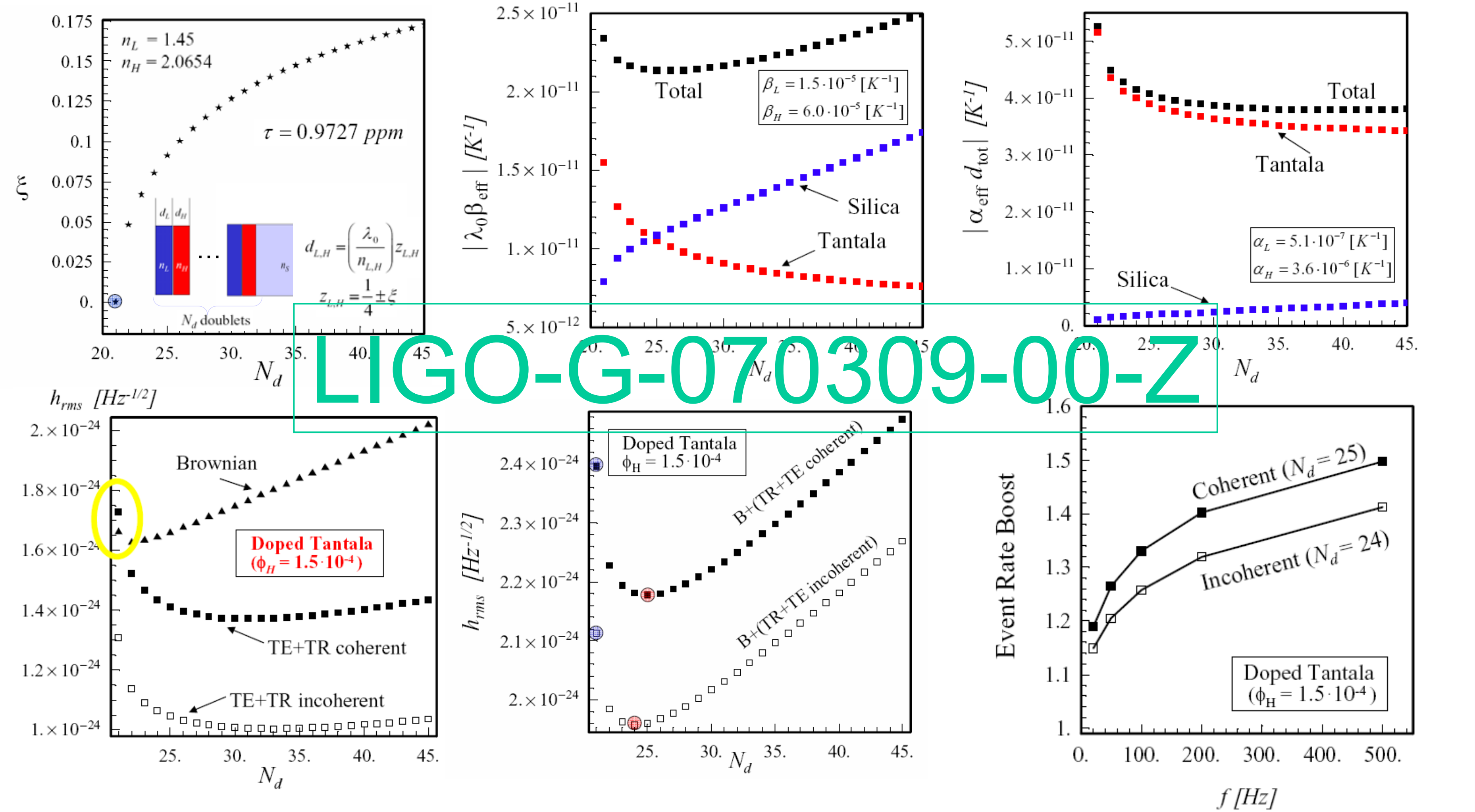
- New Components, Techniques, Measurements and Tools provide the basis for:
  - Improvements for current and future GW detectors
  - A lot of exciting research

# Supplements

# Input Optics – First AdvLIGO MC mirrors (still uncoated)



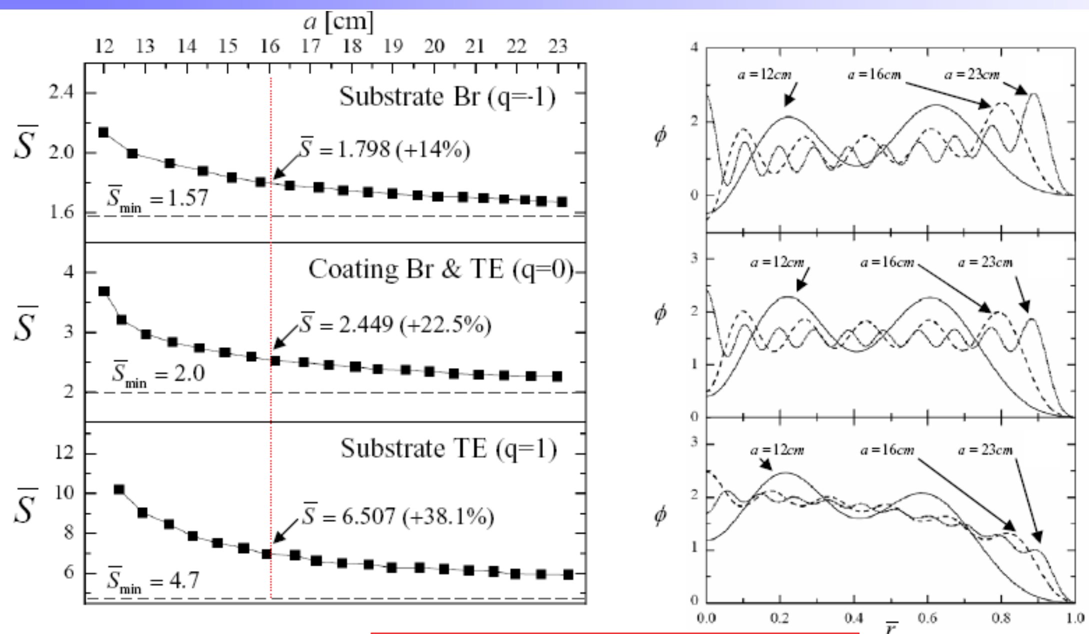

# OWG Research @ Sannio University, Ia



# OWG Research @ Sannio University, IIa

LIGO

LSC




$\text{number of modes} = N_T \approx N_D = 2a^2 / \lambda L$

| | $\overline{S}_{SLP} / \overline{S}_{min}$ | $\overline{S}_{MB} / \overline{S}_{min}$ | $\overline{S}_{GB} / \overline{S}_{min}$ |
|---|---|---|---|
| Substrate (Br) | 1.145 | 2.044 | 2.97 |
| Coating (Br+TE) | 1.225 | 3.227 | 6.92 |
| Substrate (TE) | 1.381 | 4.455 | 13.66 |

$a = 16cm\ (N_D = 14)$ ; $\mathcal{L}_T = 1ppm$ ; $w_{MB} = (N_D)^{-1/2}$ (minimum spreading)

LIGO-P-070066-01-Z