LIGO: At the forefront of optical materials research*

Stephen C. McGuire
Department of Physics
Southern University and A&M College
Baton Rouge, Louisiana 70813

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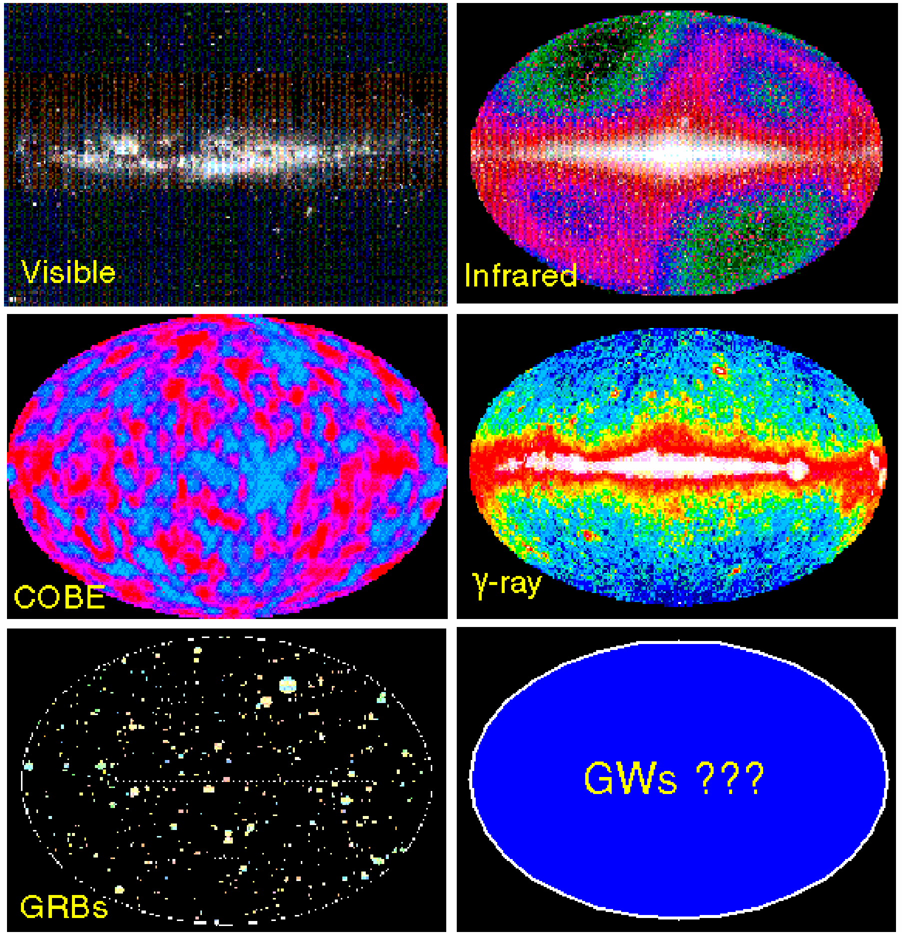
TALK OUTLINE

- **LIGO, the experiment**

  (Laser Interferometer Gravitational-wave Observatory)
- **SUBR-LIGO Materials Research**
- **Broader Educational Impacts**
- **Summary and Future Work**

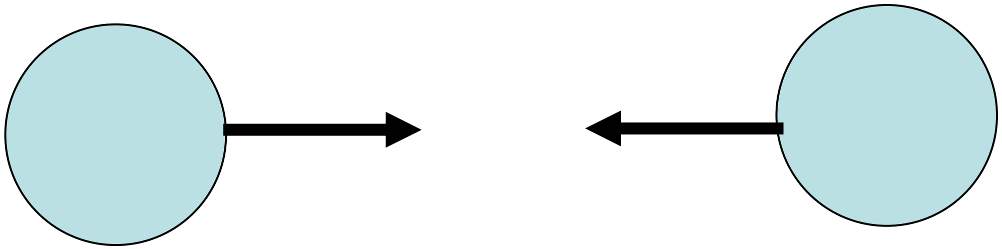
Scientific Mission of LIGO

- LIGO's quest, ~400 yrs after invention of optical astronomical telescopes, is to create a radically new way to perceive the universe, by directly listening to the vibrations of space itself
- LIGO consists of large, high-tech, earth-based, detectors that act like huge microphones, listening for "space quakes" created by the most violent events in the universe.



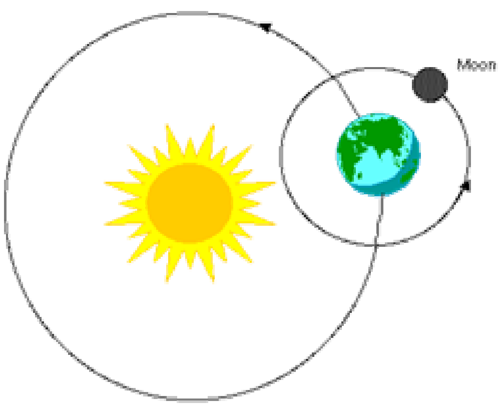
Photos courtesy of NASA.

Newton’s gravitation



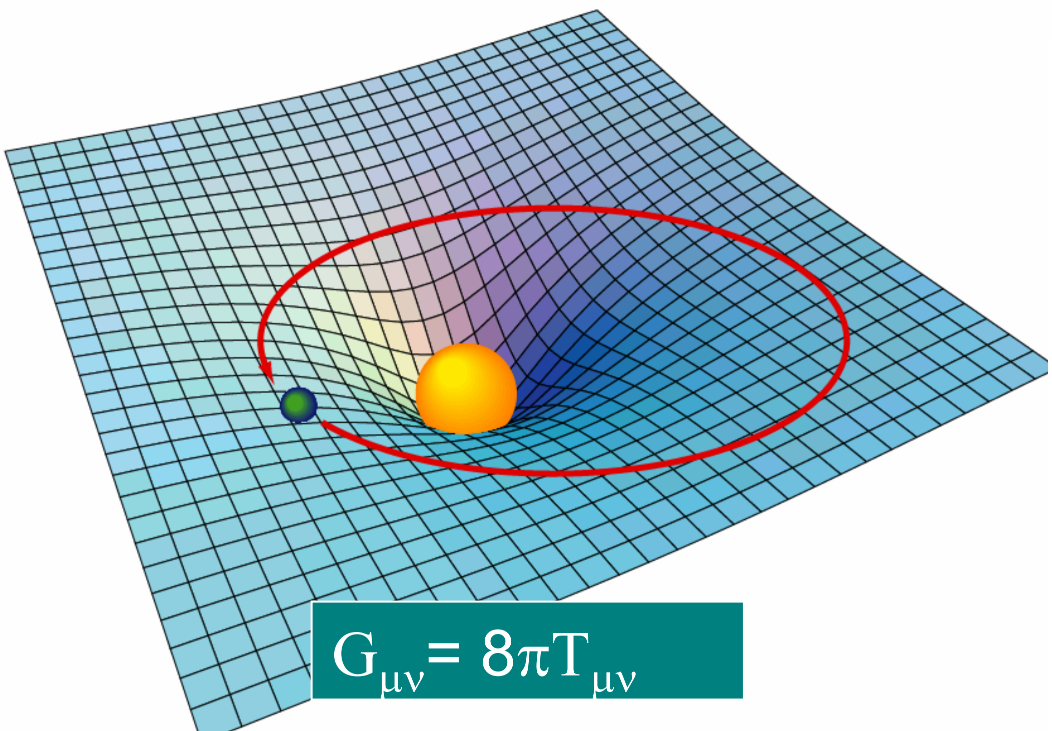
Newton’s law: $F=Gm_1m_2/r^2$

Explains why things fall down, and planetary motion.



General Relativity

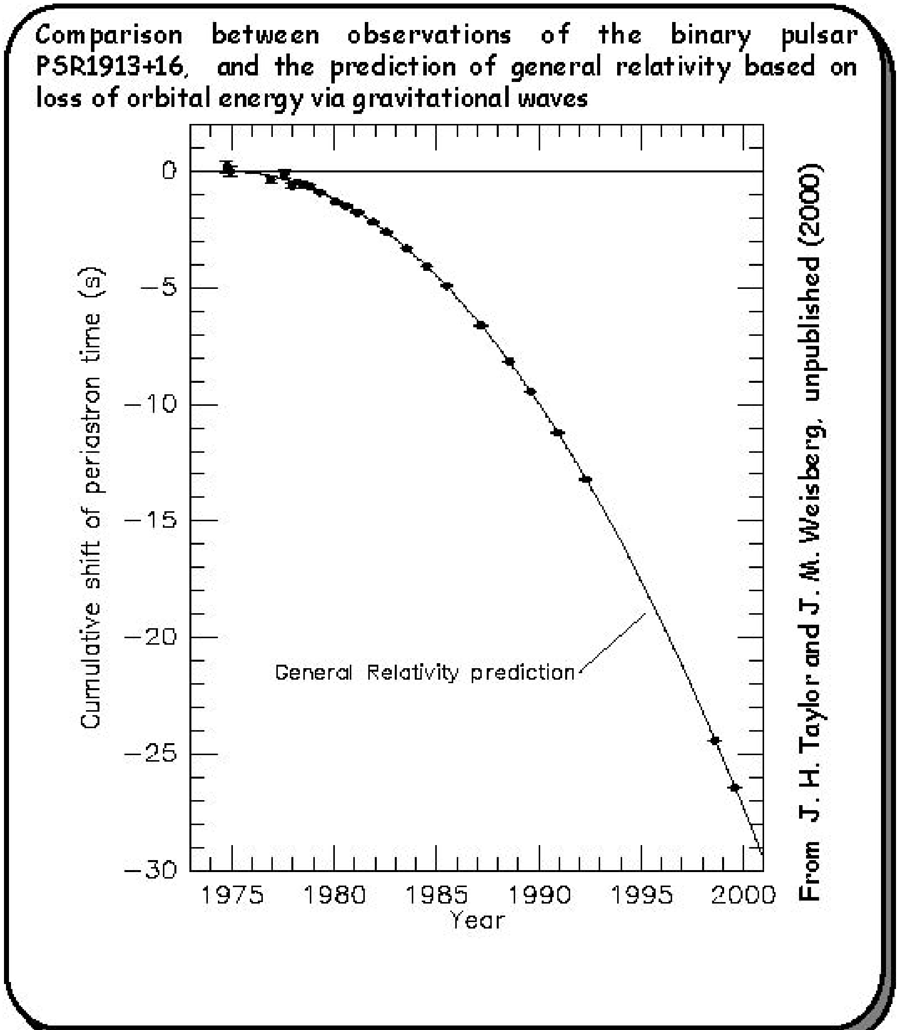
Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object



$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

- **Imagine space as a stretched rubber sheet.**
- **A mass on the surface will cause a deformation.**
- **Another mass dropped onto the sheet will roll toward that mass.**

Hulse-Taylor Experiment

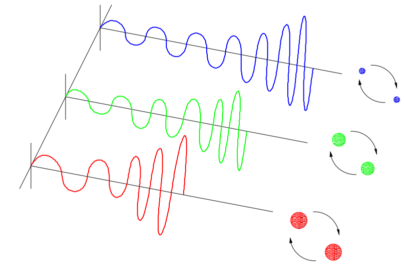


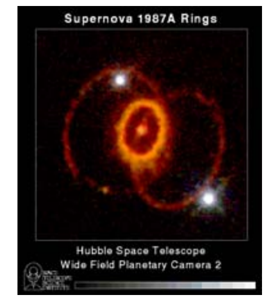
Russell Hulse and Joseph Taylor carefully observed two binary pulsar systems for more than 15 years. They determined the rate at which the orbital parameters were changing and compared these rates of change to those predicted as a consequence of the emission of gravitational radiation.

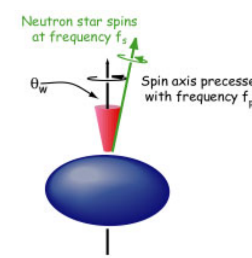
1993 Nobel Prize in Physics!

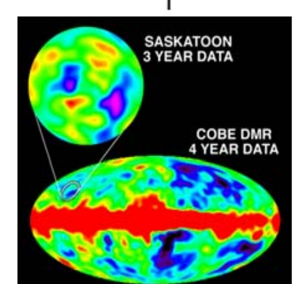
Astrophysical Sources of Gravitational Waves

- Compact binary inspiral: *"chirps"*
  - NS-NS
  - BH-BH
- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors
- Pulsars in our galaxy: *"periodic signals"*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes
- Cosmological Signals *"stochastic background"*

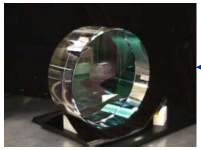




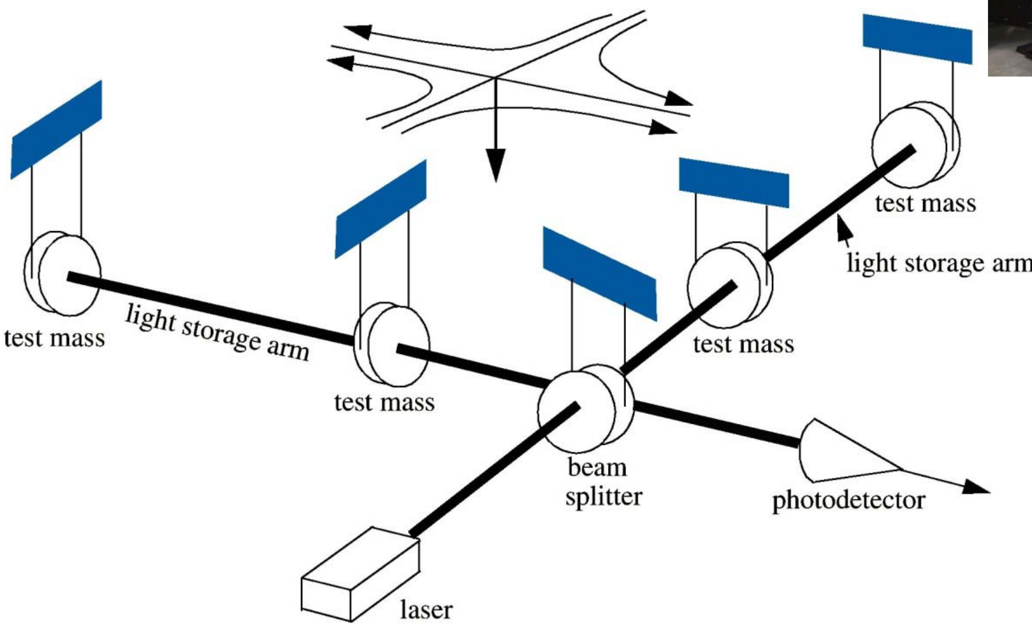




Gravity-wave Detection



suspended mirrors



Strain = h = δL/L

LIGO (4 km), stretch (squeeze) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^4 Hz. It can detect waves from a distance of 600 $\times 10^6$ light years

LIGO

How Small is 10^{-18} Meter?

	One meter, about 40 inches
$\div$10,000	*Human hair, about 100 microns*
$\div$100	*Wavelength of light, about 1 micron*
$\div$10,000	*Atomic diameter, 10^{-10} meter*
$\div$100,000	*Nuclear diameter, 10^{-15} meter*
$\div$1,000	*LIGO sensitivity, 10^{-18} meter*

Laser Interferometer Gravitational-wave Observatory Sites

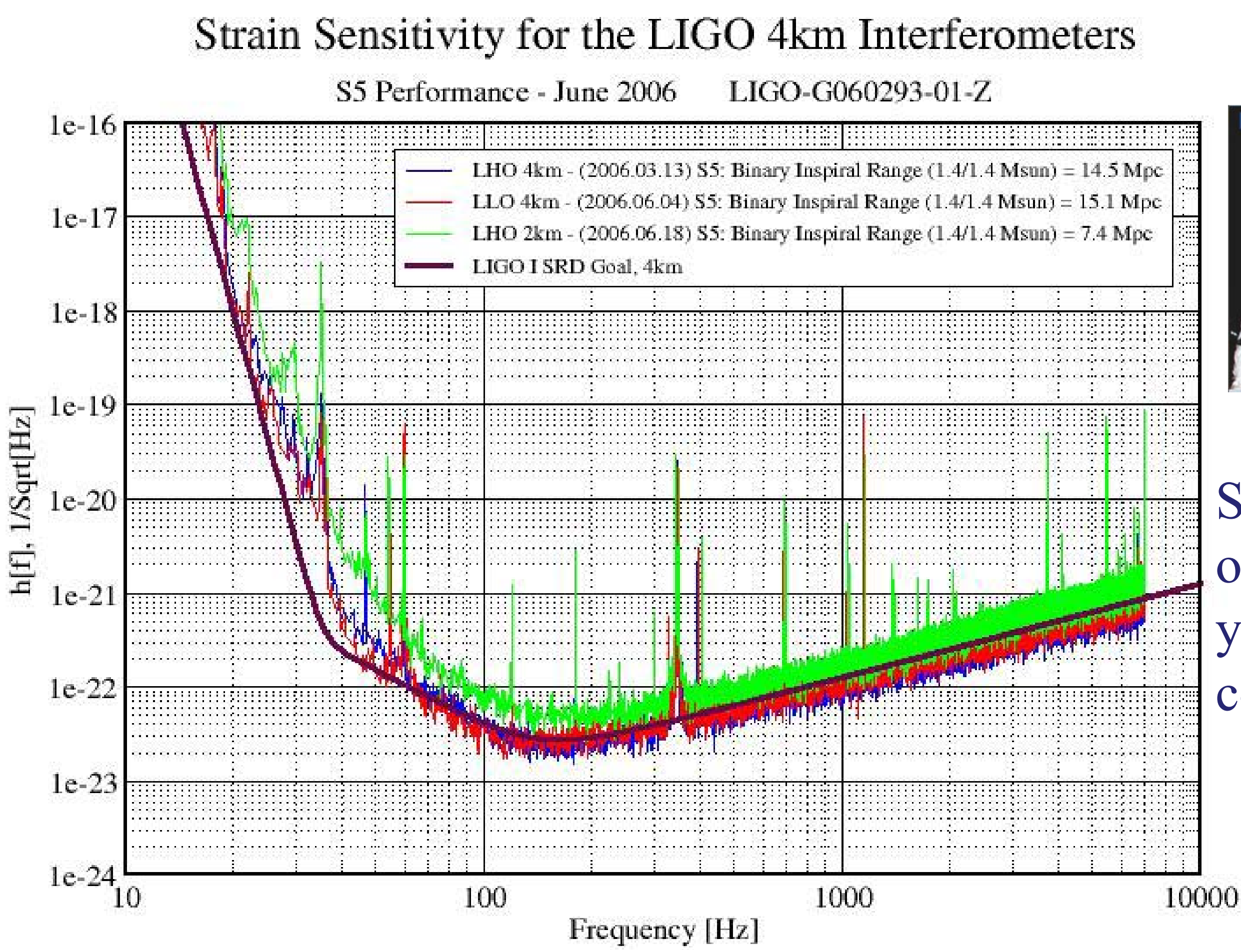
Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for about 550 LIGO Scientific Collaboration (LSC) members worldwide.

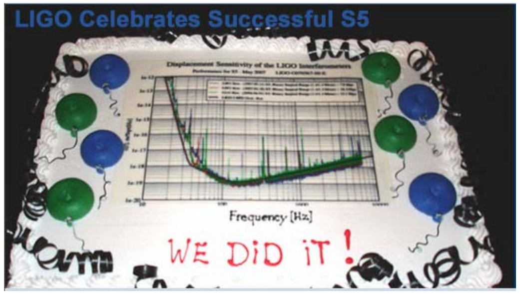
LIGO Scientific Collaboration

- Australian Consortiu for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orlean
- University of Maryland
- Max Planck Institute for Gravit

- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technolog
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern U. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washingt

Strain Sensitivity Curve

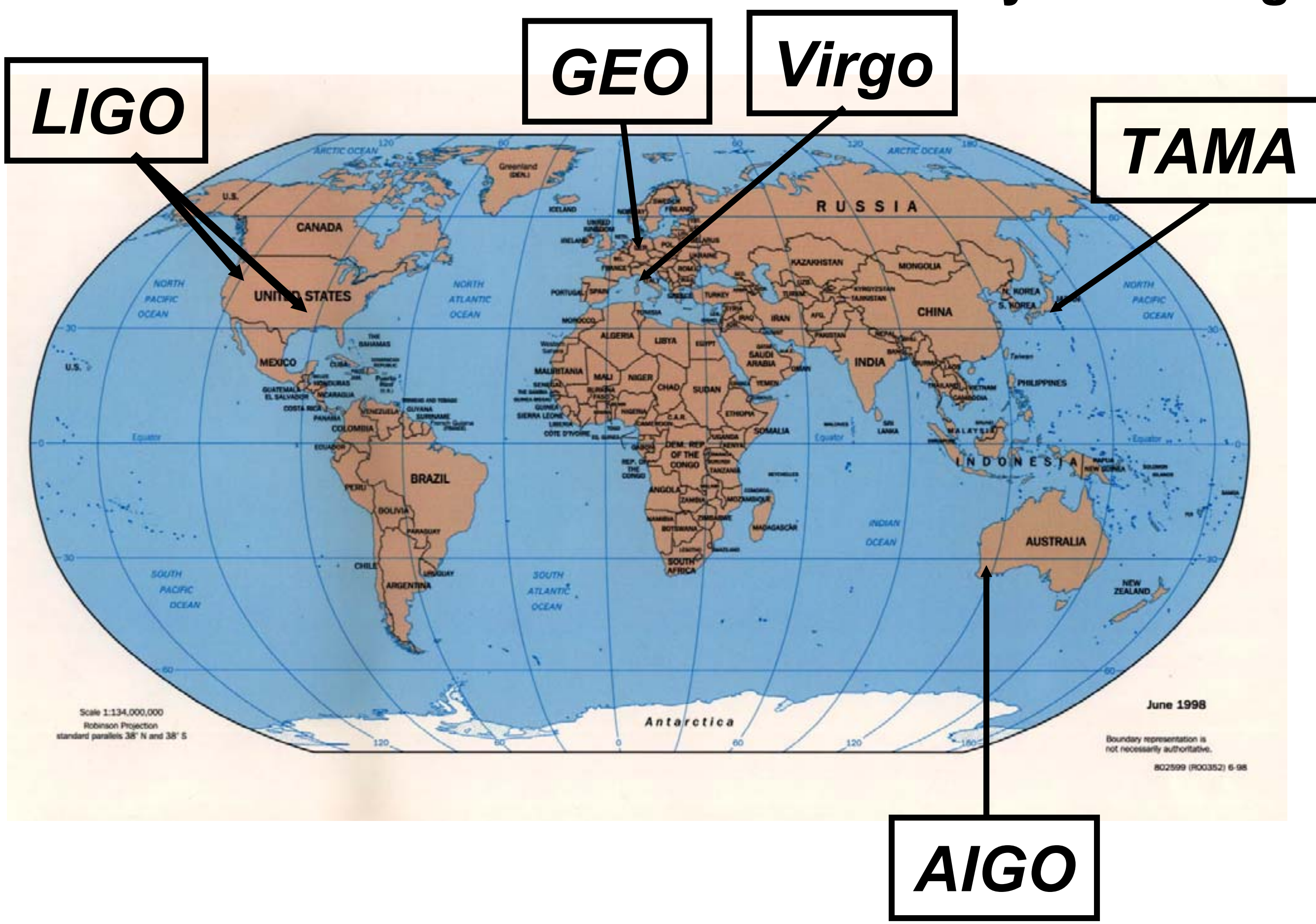




Successful completion of S5 science run, one year of triple coincidence operation!

Interferometers
international network

Simultaneously detect signal (within msec)

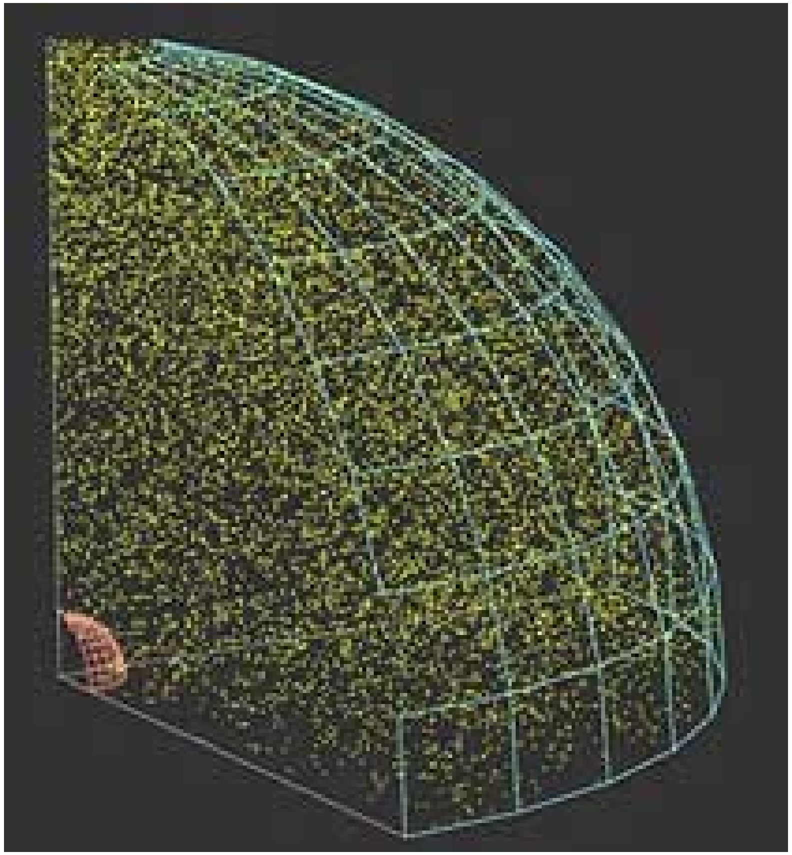


detection confidence

locate the sources

decompose the polarization of gravitational waves

Advanced LIGO

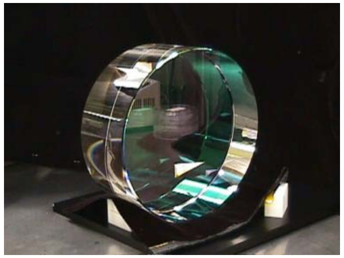


- Advanced LIGO will have more than a factor of 10 greater sensitivity than initial LIGO.
- This means that the event rates will be more than 1,000 times greater!
- Expected start in 2008.

Science from the first few hours of Advanced LIGO observing should be comparable to 1 year of initial LIGO!

SUBR Science Focus

Trace element measurements in substrates and coatings



Objective:

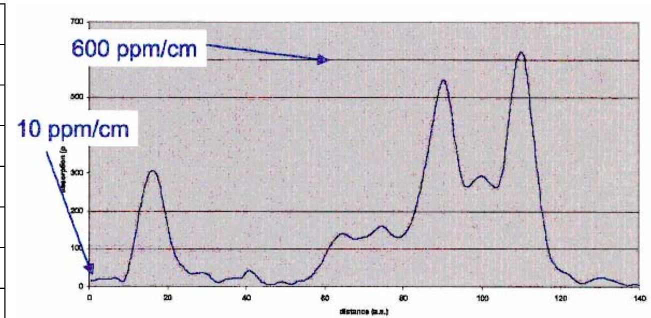
Obtain physical correlations between chemical impurities (Ti, Cr, Fe, Co, etc.) and optical absorption characteristics of materials under consideration for use as test masses and optical coatings in advanced LIGO.

HEM™ Process

Crystal Systems, Inc.

Sapphire substrate

Mass	**40 kg**
Physical dimension	**31.4 cm x 13 cm**
Optical homogeneity	**< 10 nm rms**
Microroughness	**< 0.1 nm rms**
Internal scatter	**< 10 ppm/cm**
Absorption	**10 - 40 ppm/cm***
Thermal noise	**Q > 2 x 10^8**
Birefringence	**< 0.1 rad**
Polish	**< 0.9 nm rms**



LIGO

COLLABORATORS

SOUTHERN UNIVERSITY And Agricultural & Mechanical College

E. E. Doomes, L.L. Henry, S. C. McGuire, M. J. Baham and E. Preddie
Department of Physics, Southern University and A&M College
Baton Rouge, LA

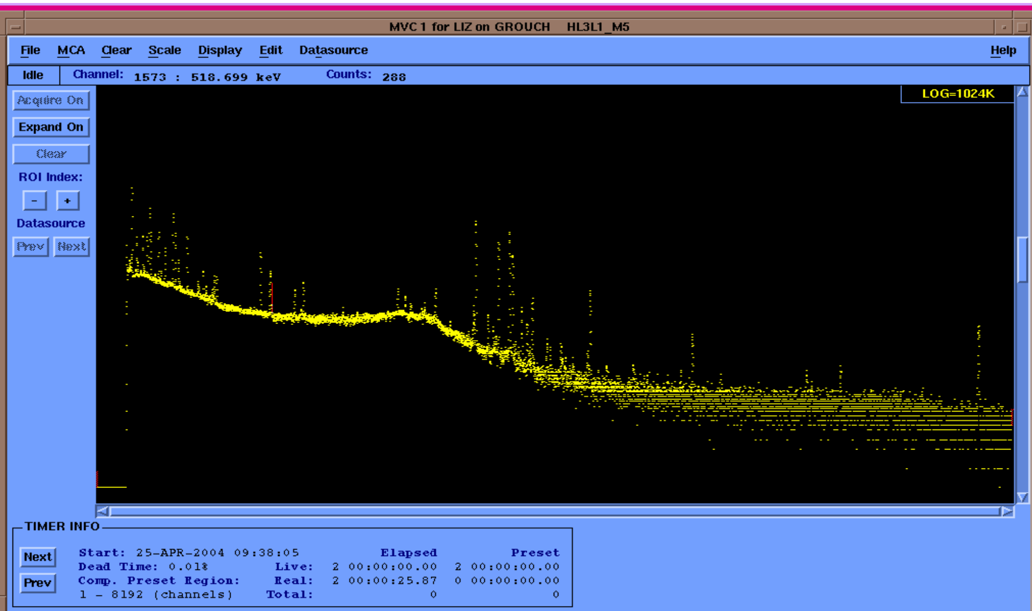
G. P. Lamaze and E. A. Mackey
NIST, Chemical Sciences and Technology Laboratory
Gaithersburg, MD

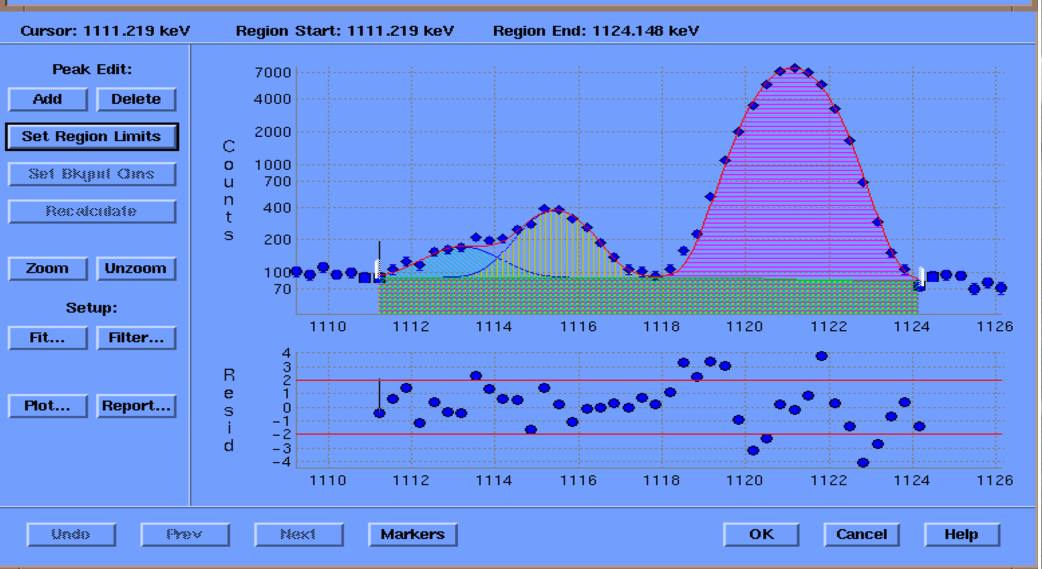
S. Brennan, K. Luening, P. Pianetta, A. Singh
Stanford Synchrotron Radiation Laboratory
SLAC/HBCU Partnership Program
Menlo Park, CA

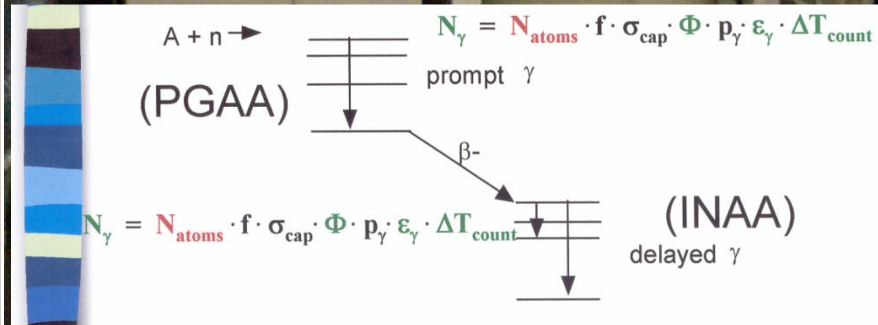
R. Tittsworth (deceased) and Amitava Roy
Center for Advanced Microstructures and Devices/LSU
Baton Rouge, LA

S. Cliff, K. H. Jackson, M. Jimenez-Cruz
Advanced Light Source
Lawrence Berkeley Laboratory
Berkeley, CA

INAA γ-Ray Spectroscopy at NIST CSTL







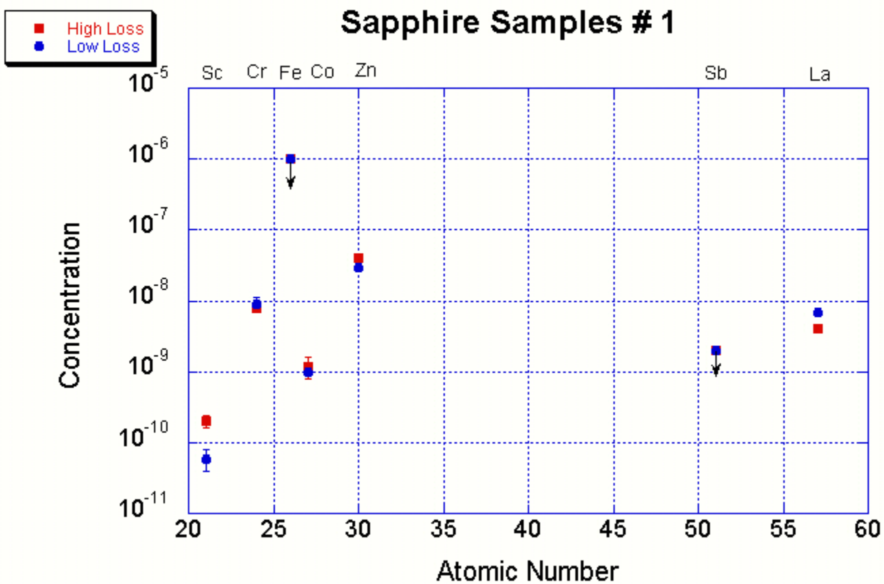
NIST INAA Measurements

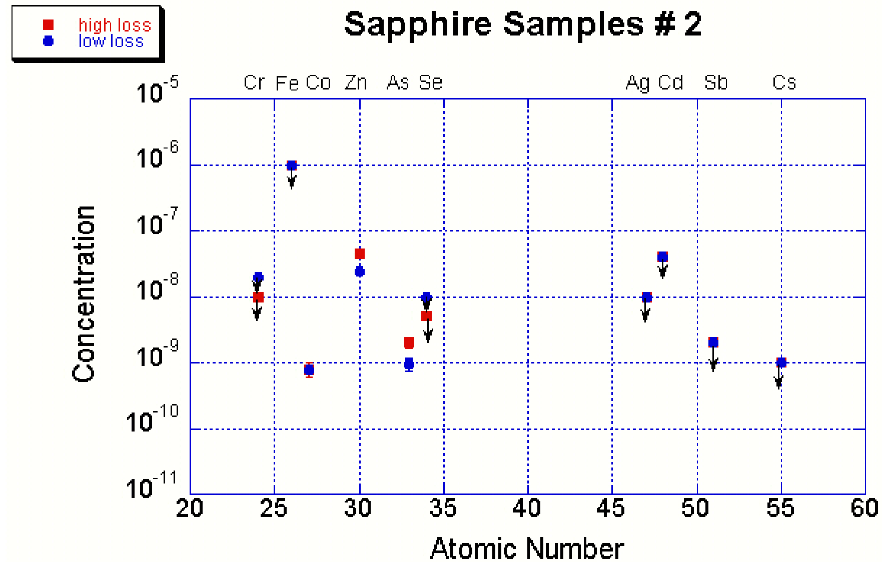
Mass fraction estimates based on comparison with SRM 2709 San Joaquim Soil.*

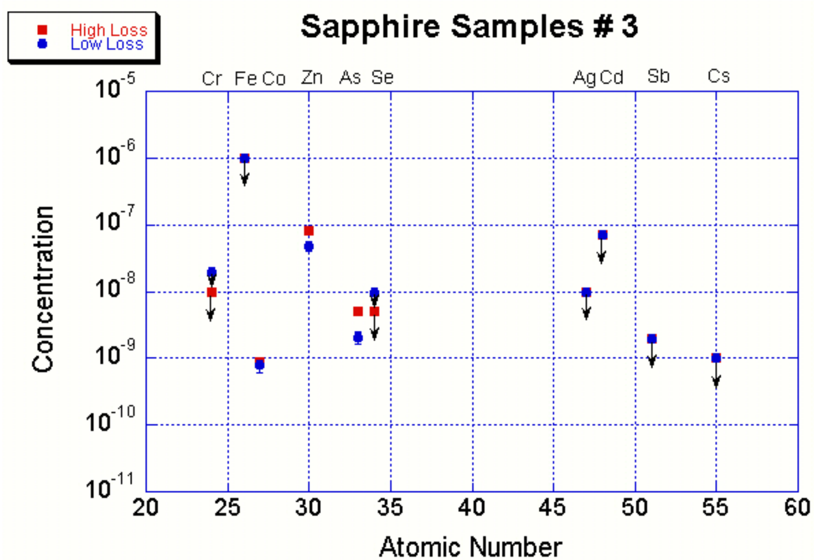
Element	Low Loss sample	High Loss sample	SRM 1575a	Certified Value
Sc	0.06 ± 0.02 ppb	0.20 ± 0.04 ppb	10.8 ± 0.8 ppb	10.1 ± 0.3 ppb
Cr	9 ± 2 ppb	8 ± 1 ppb	0.36 ±0.03 ppm	0.3 - 0.5 ppm range
Fe	≤ 1 ppm	≤ 1 ppm	45 ± 2 ppm	46 ± 2 ppm
Co	≤ 1 ppb	1.2 ± 0.4 ppb	68 ± 3 ppb	61 ± 2 ppb
Zn	30 ± 3 ppb	40 ± 4 ppb	39 ± 2 ppm	38 ± 2 ppm
Sb	≤ 2 ppb	≤ 2 ppb	10 ± 3 ppb	not certified
La	7 ± 0.4 ppb	4 ± 0.4 ppb	53 ± 7 ppb	not certified

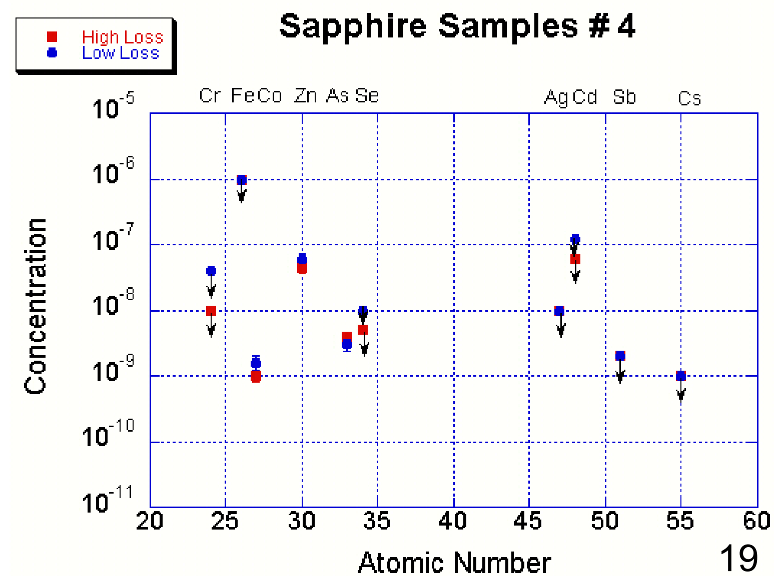
S. C. McGuire, G. P. Lamaze and E. A. Mackey, *Trans. Am. Nucl. Soc.* **Vol. 89,** 773 (2003).

NIST INAA Measurements

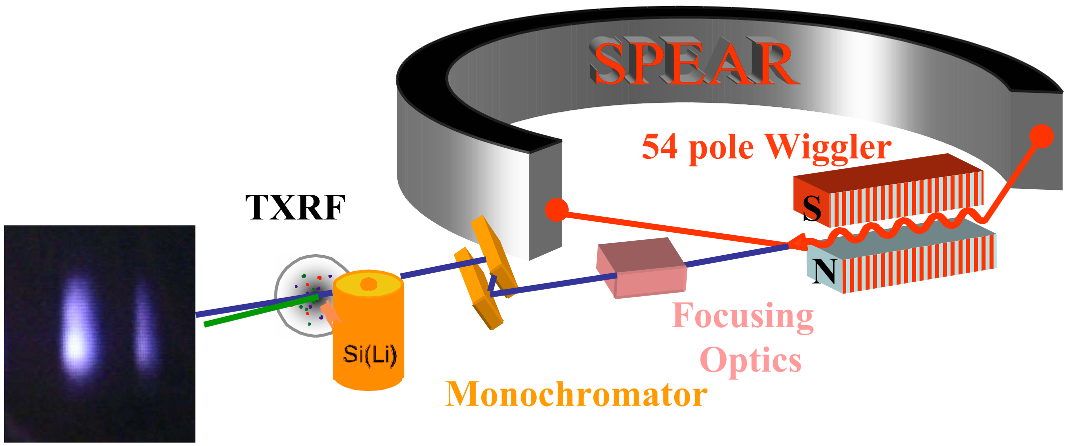








Synchrotron Radiation TXRF Facility at SSRL



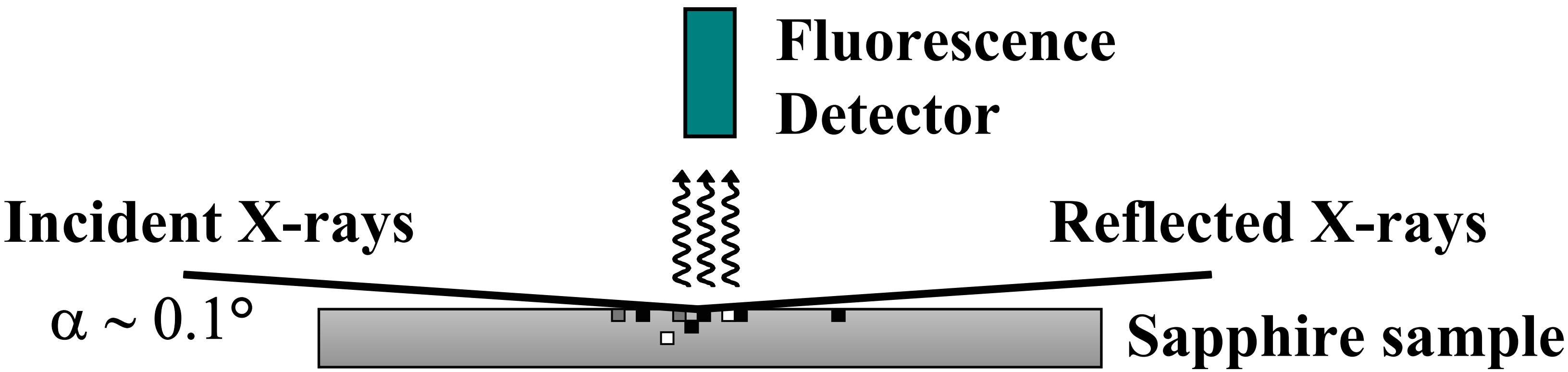
Collaborators:

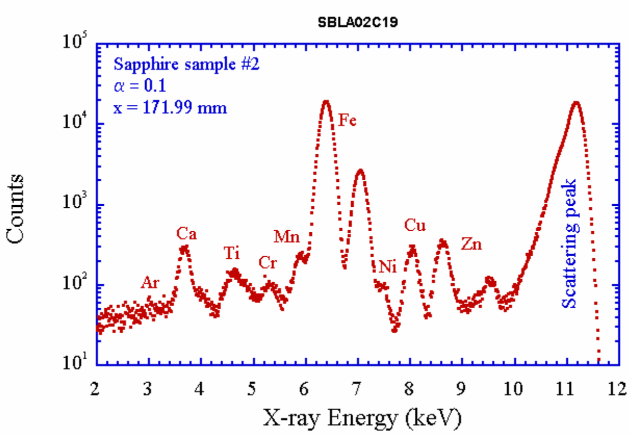
SSRL:
- P. Pianetta
- K. Luening
- S. Brennan
- A. Singh

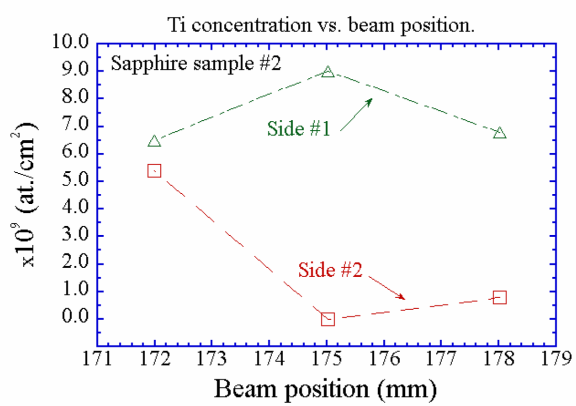
Southern Univ.
- S. C. McGuire
- M. Baham
- E. Preddie

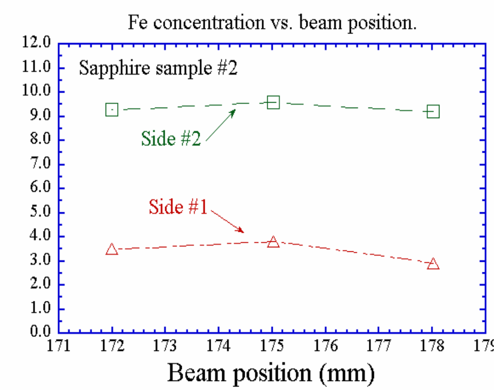
X-ray energy: 11.3 keV
Angle of incidence ~ 0.08°
Detector: Si(Li)—no parasitic peaks
Automatic critical angle measurement
Wafers: Small pieces to 200 mm
Cleanroom mini-environment

Total X-ray Reflection Fluorescence (TXRF)









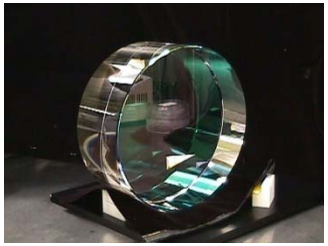
Initial results

- Synthetic sapphire measurements show typical broad range of elements at sub-ppm levels.
- Excellent sensitivity for the elements of primary interest.
- First-time measurements of transition metal and higher-Z elements at sub-ppm levels in synthetic sapphire.
- Correlations between absorption and trace element content not evident.
- Successful implementation of a program of research-based trace element measurements for advanced LIGO optics.
- Fused silica substrate down select in March 2005
- Application of work to losses in coatings on fused silica in progress.

SUBR Science Focus, cont.

Objective:

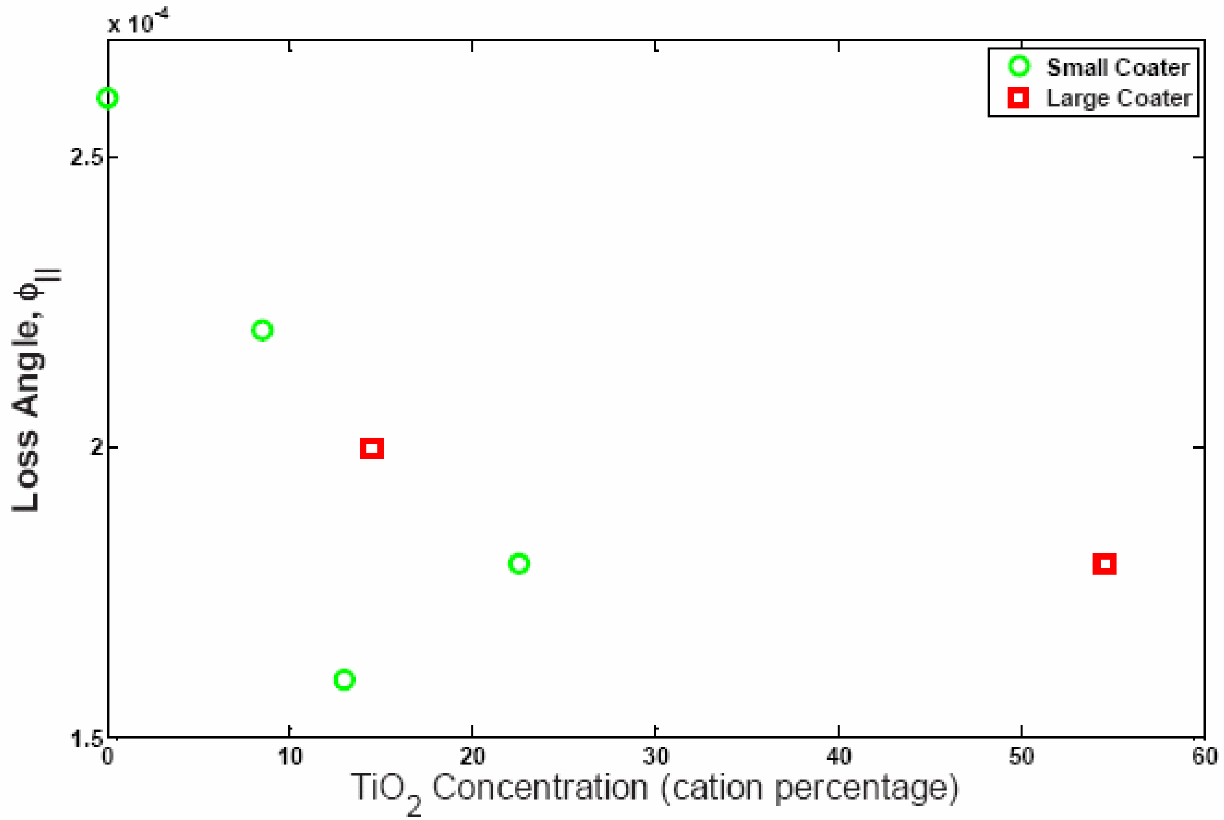
Obtain physical correlations between chemical impurities and/or dopants (Ti, Cr, Fe, Co, etc.) and optical absorption characteristics of **materials** under consideration for use as **test masses** and **optical coatings** in advanced LIGO.



Current Focus:

Composition and chemical structure of titania (TiO_2)-doped multilayer (SiO_2/Ta_2O_5) mirror coatings.

Motivation



Plot of loss angle as a function TiO_2 concentration in tantala. See Reference LIGO-G060384-00-R.

Coatings Characterization Methods

X-ray absorption spectroscopy of doped and undoped multilayer (SiO_2/Ta_2O_5) coatings on fused silica (SiO_2) substrates

• X-ray Fluorescence (XRF)	CAMD
• Extended X-ray absorption fine structure (EXAFS)	CAMD
• X-ray absorption near edge spectroscopy (XANES)	CAMD

X-ray Absorption Spectroscopy (XAS)

XANES (X-ray Absorption Near-Edge Spectroscopy)

<u>Information Provided</u>

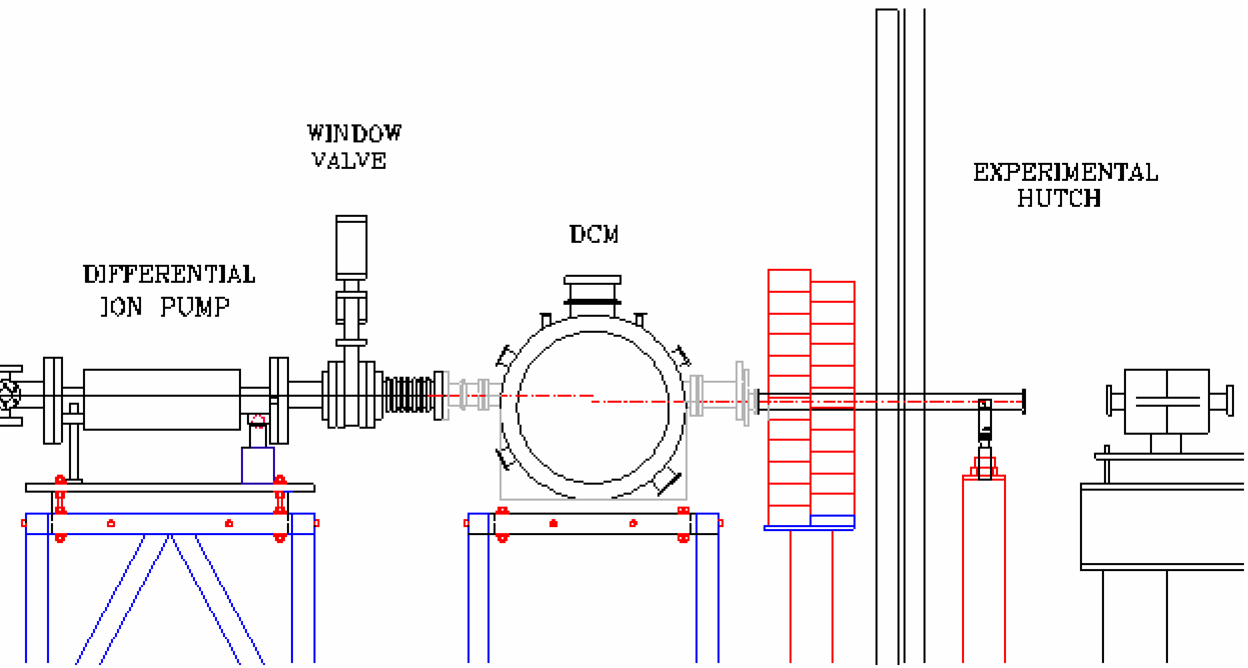
Presence or absence of specific bonds
Oxidation state of the absorber
Bond length
Orientation

EXAFS (Extended X-ray Absorption Fine Structure)

<u>Information Provided</u>

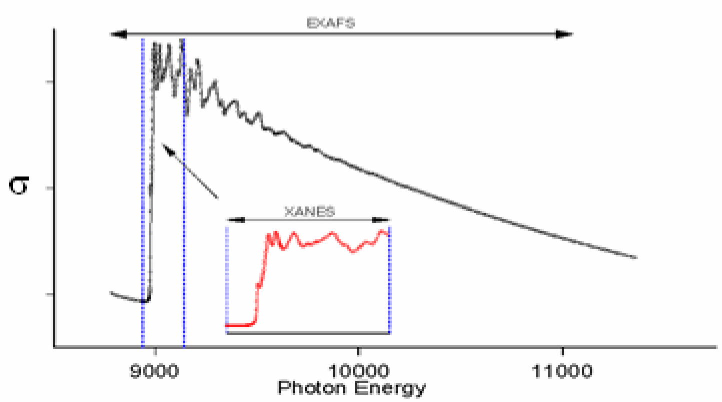
Identity of neighbors
Neighbor coordination numbers
Interatomic distances
Thermal or static disorder

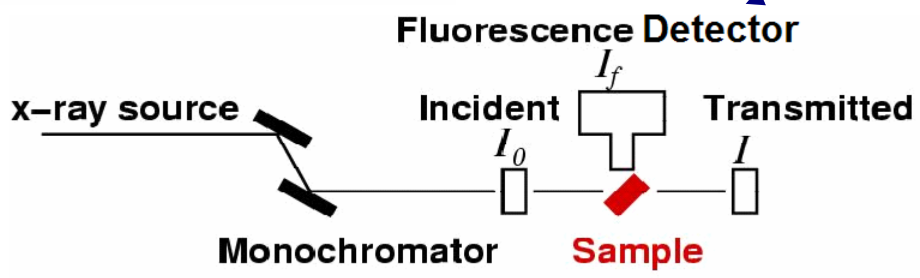
EXAFS and XANES at CAMD



CAMD Experimental Hall

13 element Ge photon detector array





X-ray Absorption Cross Section

$$\sigma = \frac{4\pi^2}{\omega} \sum_f |< f | \hat{\mathbf{e}} \cdot \mathbf{p}\, e^{i\mathbf{k}\cdot\mathbf{r}} | i >|^2 \, \delta(E_i - E_f + \omega) \qquad (1)$$

where

$\boldsymbol{\omega}$ = incident light frequency

$\hat{\mathbf{e}}$ = incident light polarization

$\mathbf{p}$ = momentum operator

$\mathbf{k}$ = wave vector of the incident light

$| i >$ = initial state wave function

$| f >$ = final state wave function

E_i = initial state energy

E_f = final state energy

Only the dipole contribution is considered in equation (1) so that we can write:

$$\sigma = \frac{4\pi^2}{\omega} \sum_f |< f | \boldsymbol{D} | i >|^2 \, \delta(E_i - E_f + \omega) \qquad (2)$$

EXAFS Equation

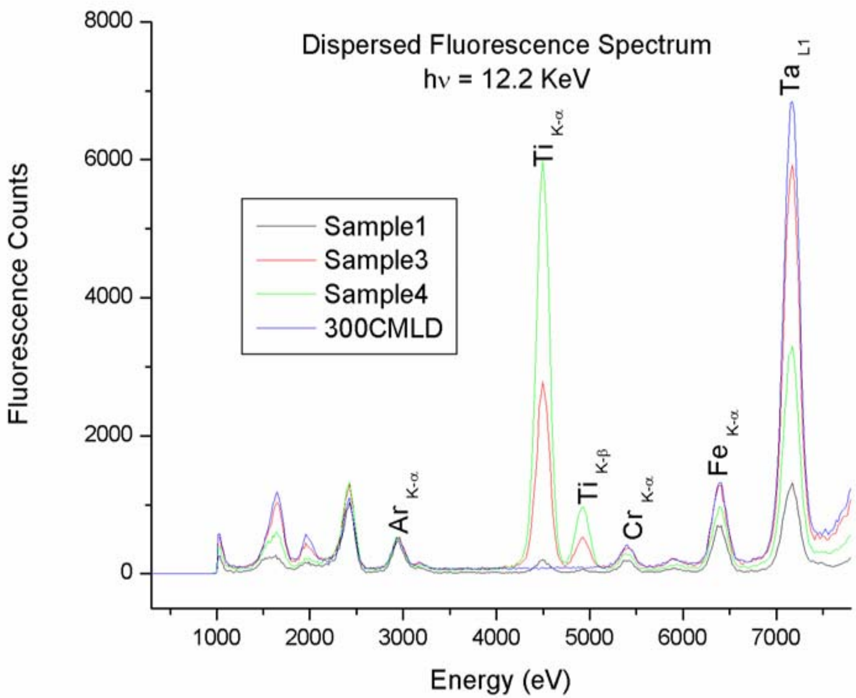
$$\chi(k) = \sum_j \frac{N_j f_j(k) e^{-2R_j/\lambda(k)} e^{-2k^2\sigma_j^2}}{kR_j^2} \sin[2kR_j + \delta_j(k)]$$

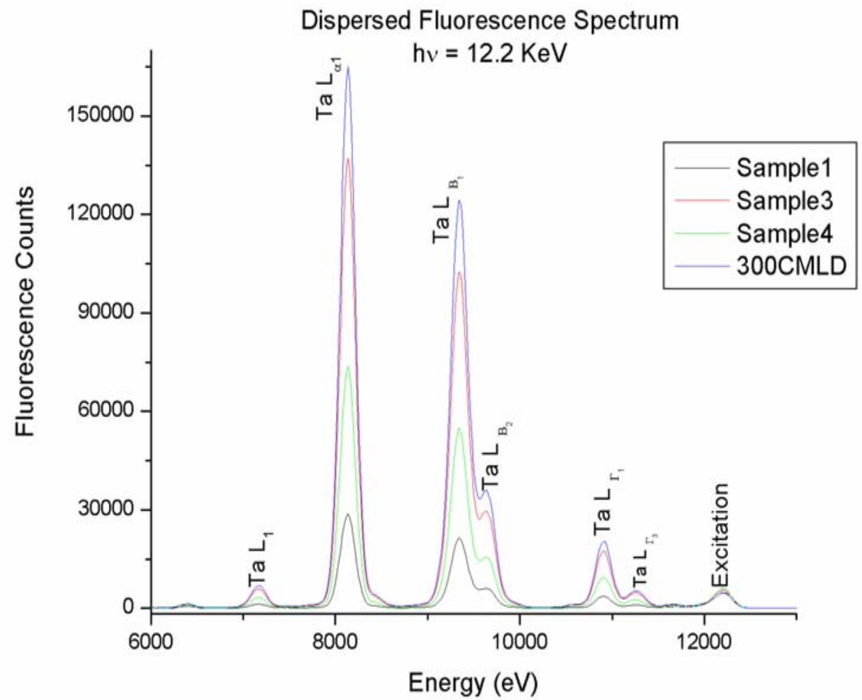
If we know the *scattering* properties of the neighboring atom: $f(k)$ and $\delta_j(k)$, and the mean-free-path $\lambda(k)$ we can determine:

R	distance to neighboring atom.
N	coordination number of neighboring atom.
σ^2	mean-square disorder of neighbor distance.

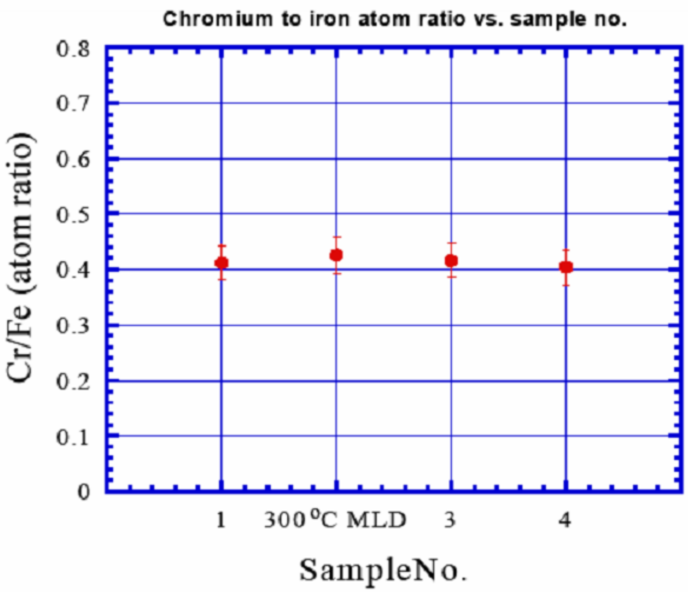
Since the scattering amplitude $f(k)$ and phase-shift $\delta_j(k)$ depend strongly on atomic number, XAFS is also sensitive to *Z* of the scattering atom.

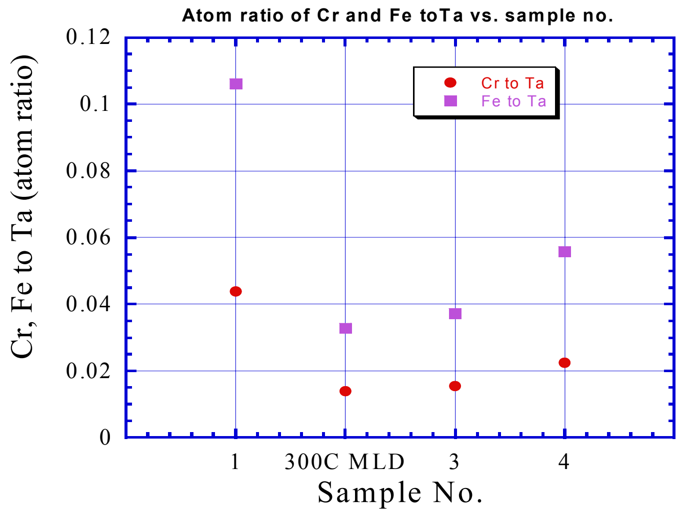
Recent XRF Spectra

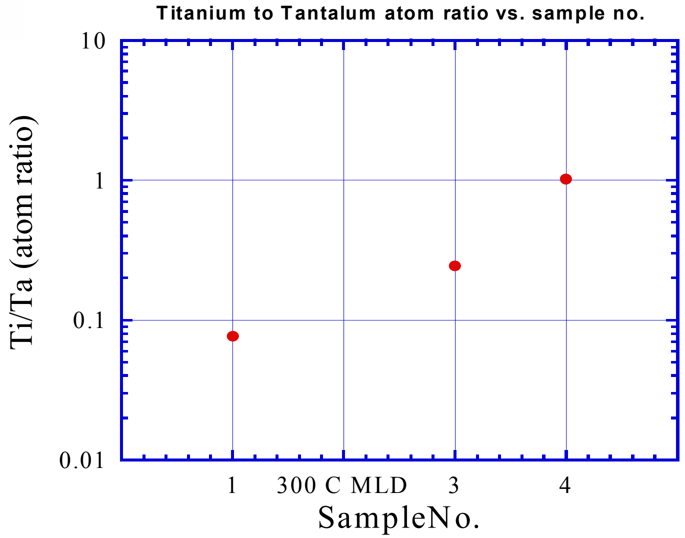




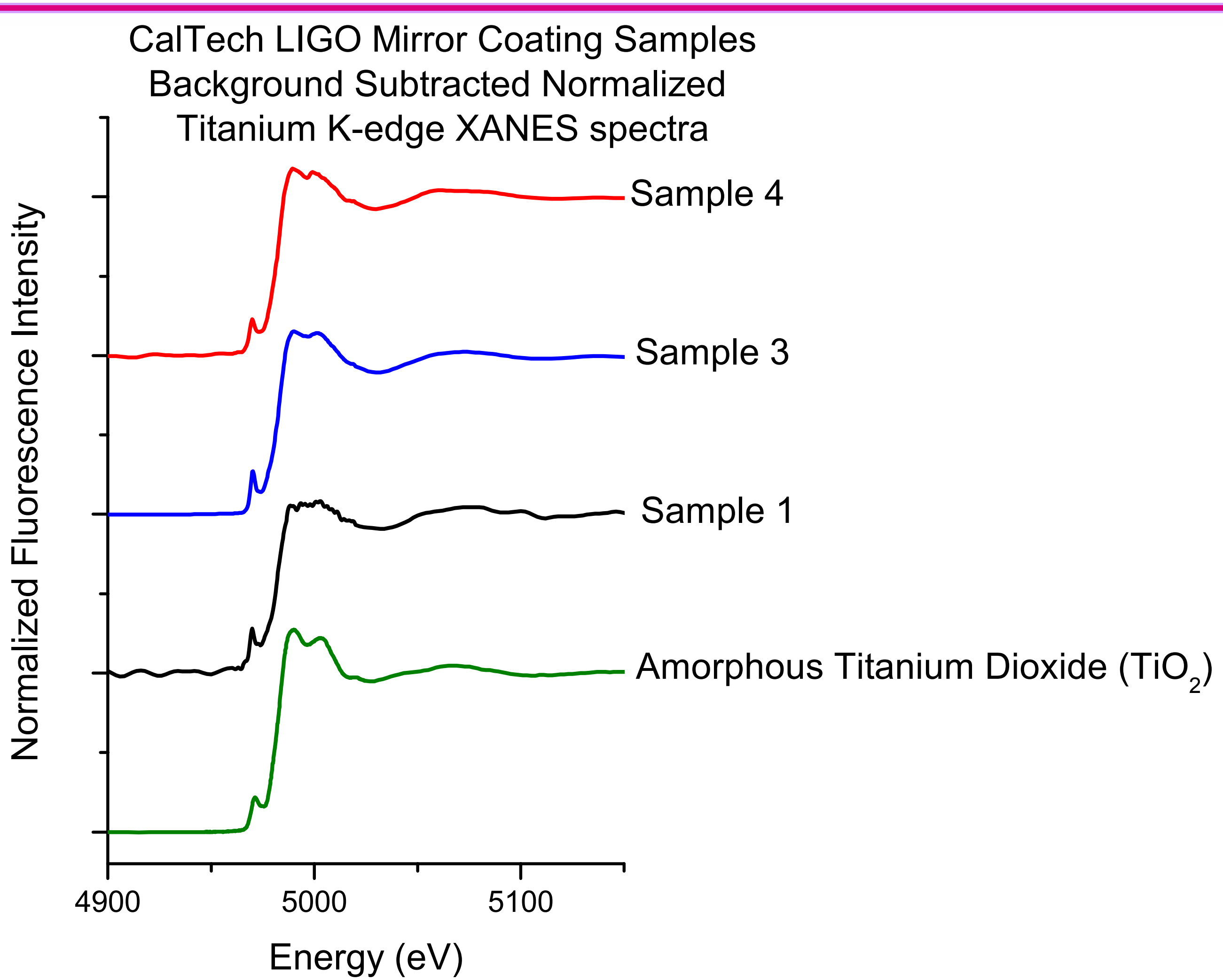
Atomic ratio plots





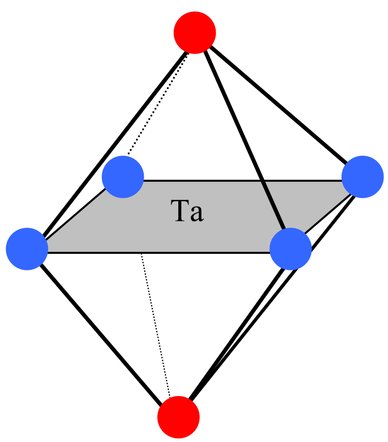


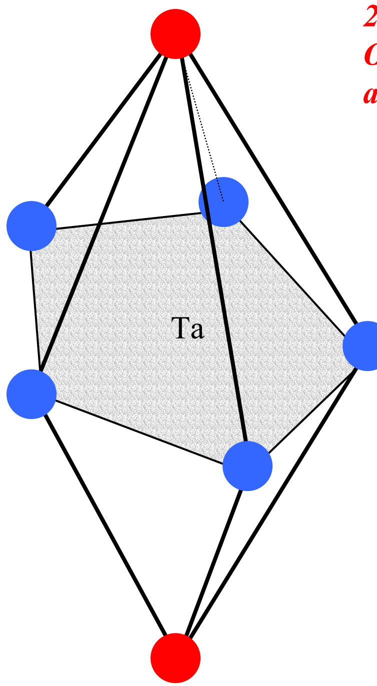
Titanium K-edge XANES



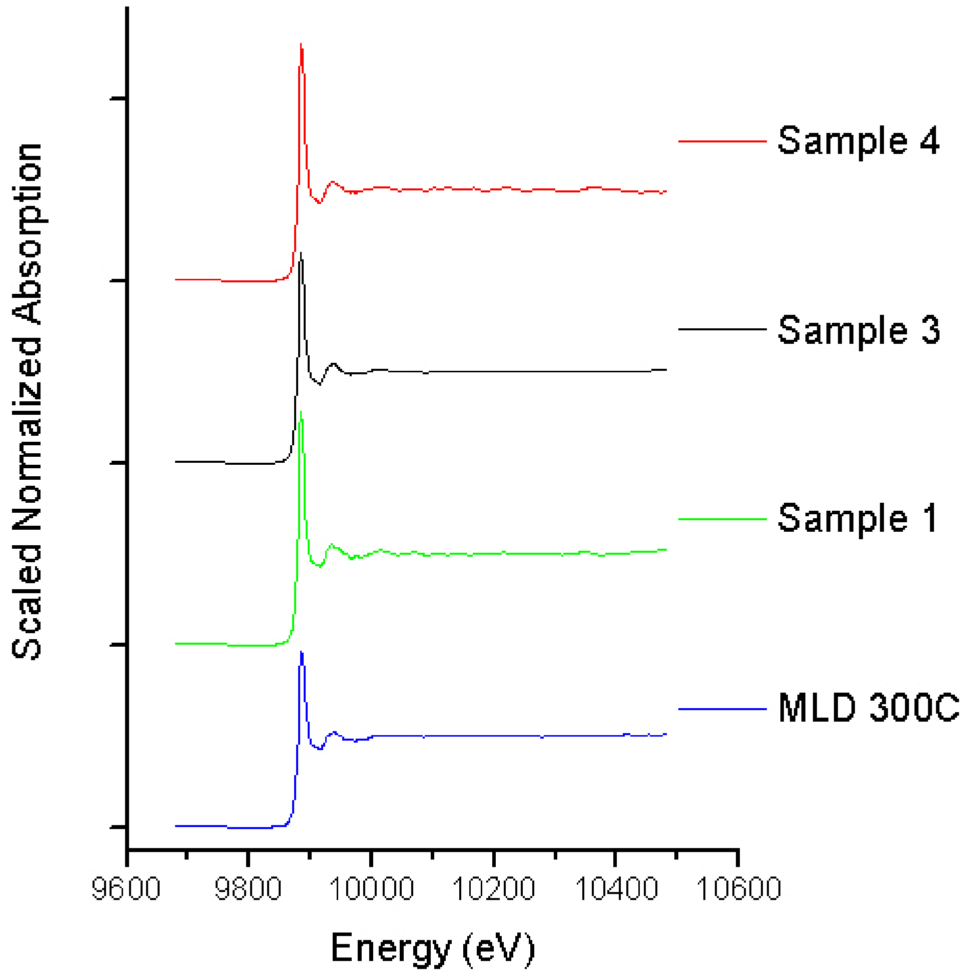
Modeling of Spectra

Tantala spectra were modeled based on β-Ta_2O_5, which consists of TaO_4 (left) and TaO_5 (right) building blocks

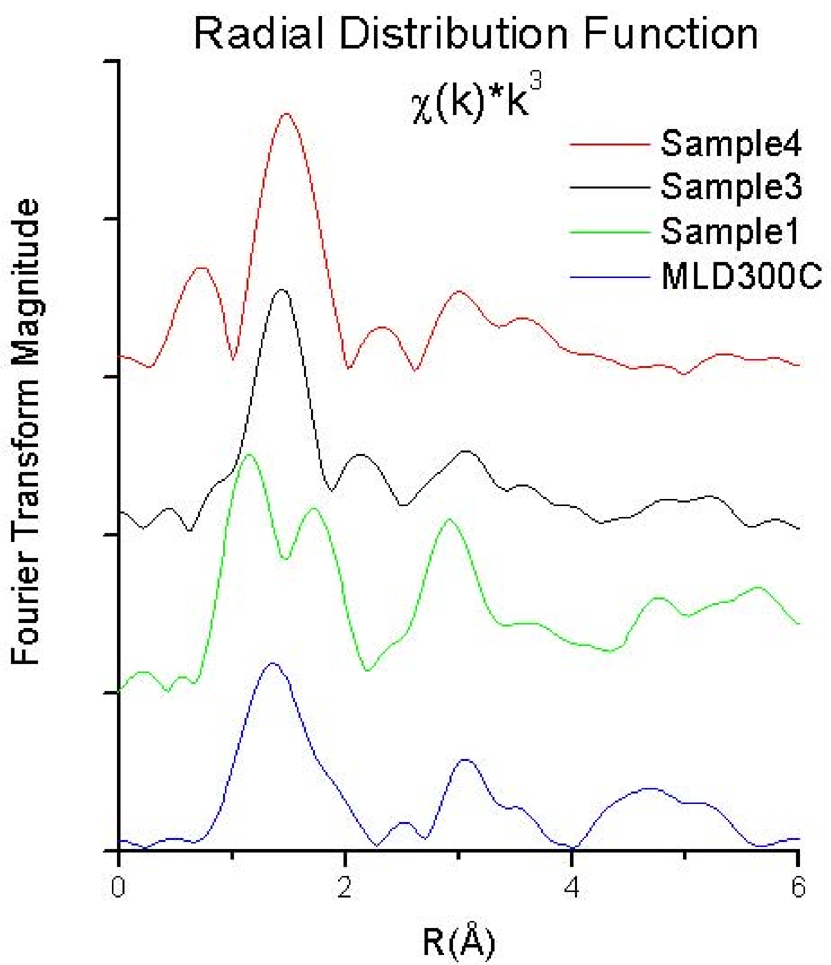


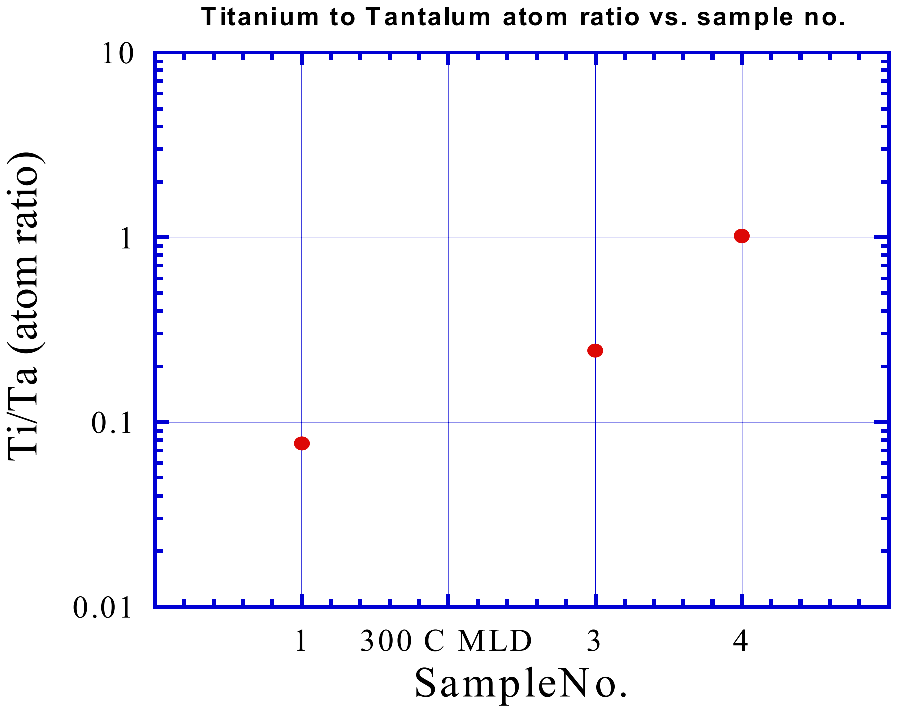


Tantalum EXAFS in Energy Space

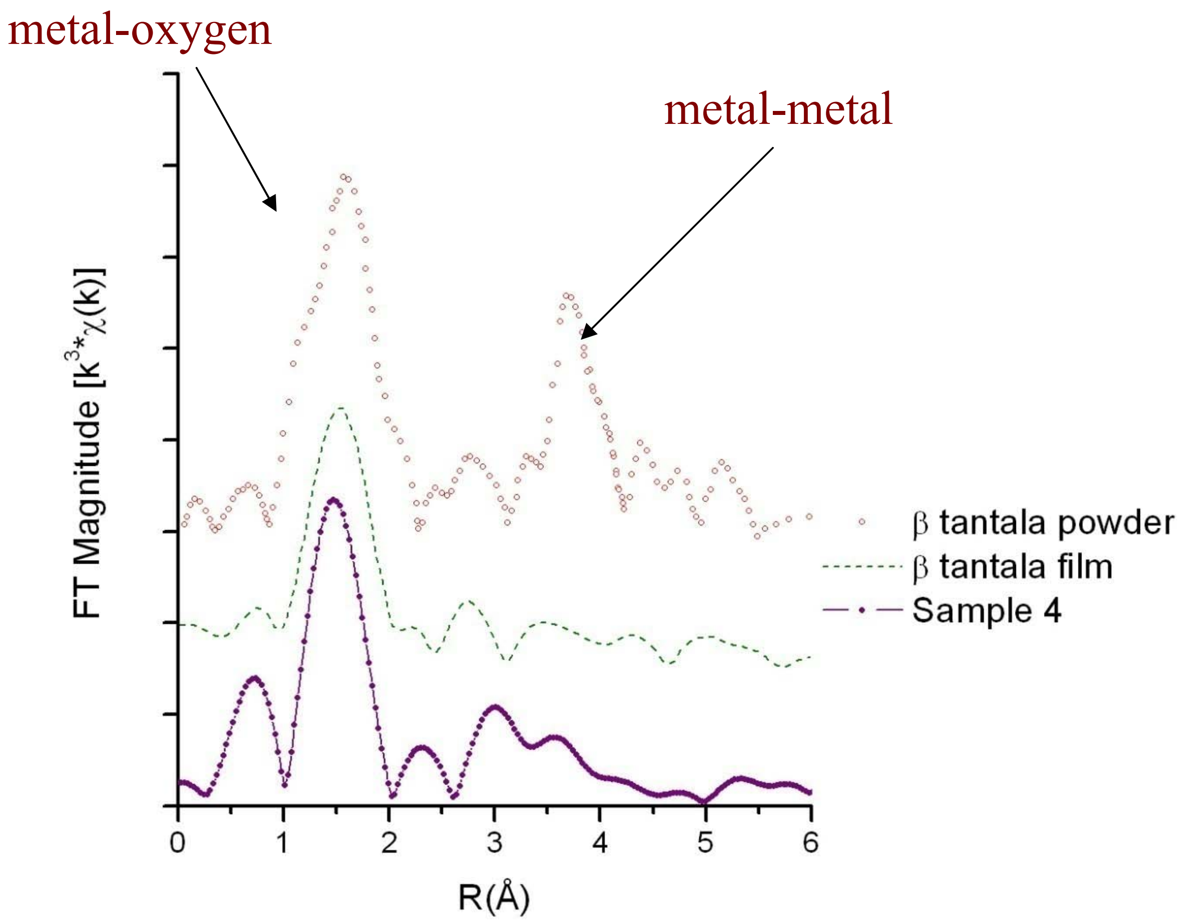


Tantalum EXAFS in R Space

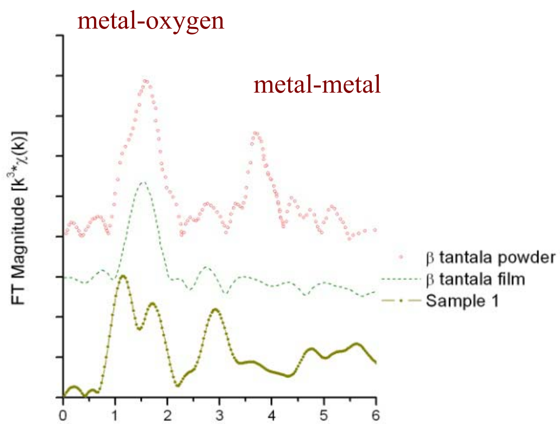


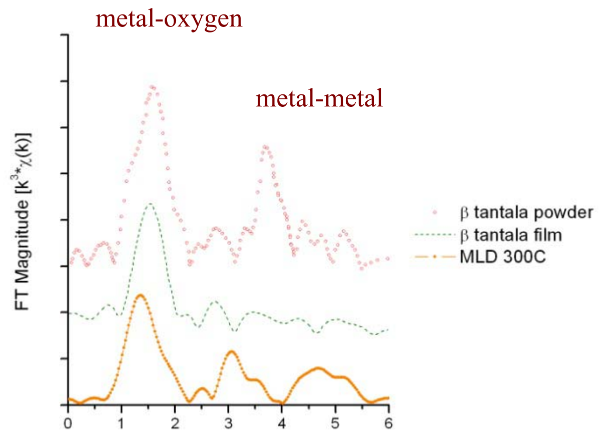


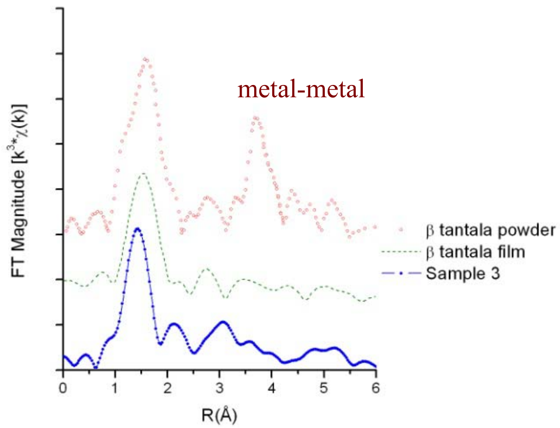
Tantalum EXAFS in R Space

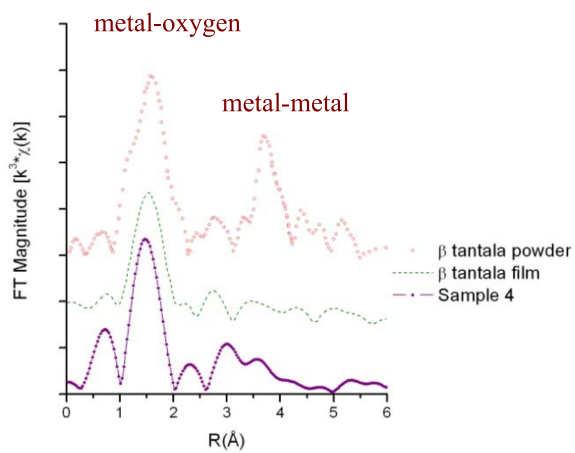


Tantalum EXAFS in R Space

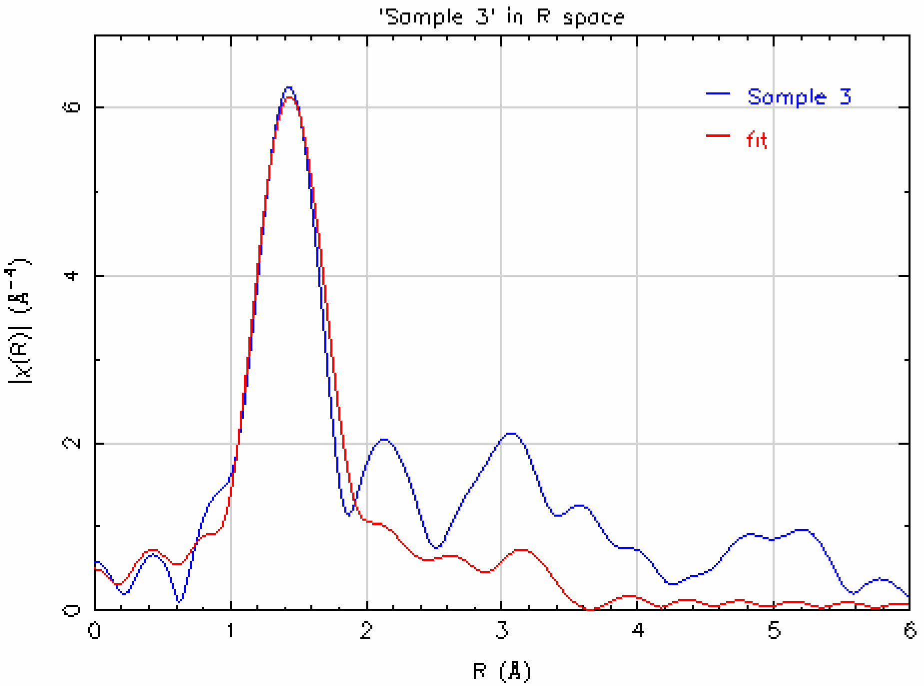


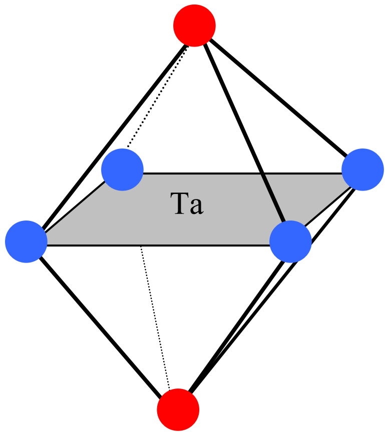






FEFF Modeling of Spectra Example





Fit is based on a cage of 6 oxygen atoms

(average r = 1.90Å)

surrounding the absorbing Tantalum atom

Tantalum EXAFS Findings

- All the samples have maxima in the radial distribution functions between one and two Å, assigned to Ta-O bonds.
- The undoped substrate, MLD300ºC, Sample 3 and Sample 4 have short range (>2.5 Å) radial distribution functions that are consistent with those seen in amorphous films or powders of Ta_2O_5.
- In Sample 1 the radial distribution function has a pronounced peak at 2.9 Å, which likely results from metal-metal (Ta-Ta and/or Ta-Ti). Sample 1 also has a split in the Ta-O peak, which is indicative of distinguishable radial and axial Ta-O bond distances.
- Physically reasonable results obtained for first coordination shell model for sample 1; work ongoing for outer coordination shells

LIGO

Educational Impacts

SOUTHERN UNIVERSITY And Agricultural & Mechanical College

Cacey S. Stevens

California Institute of Technology
MURF Summer Intern 2006

Mentor: Eric Black

"Thermal Noise Interferometer Test Mass Coating Studies"

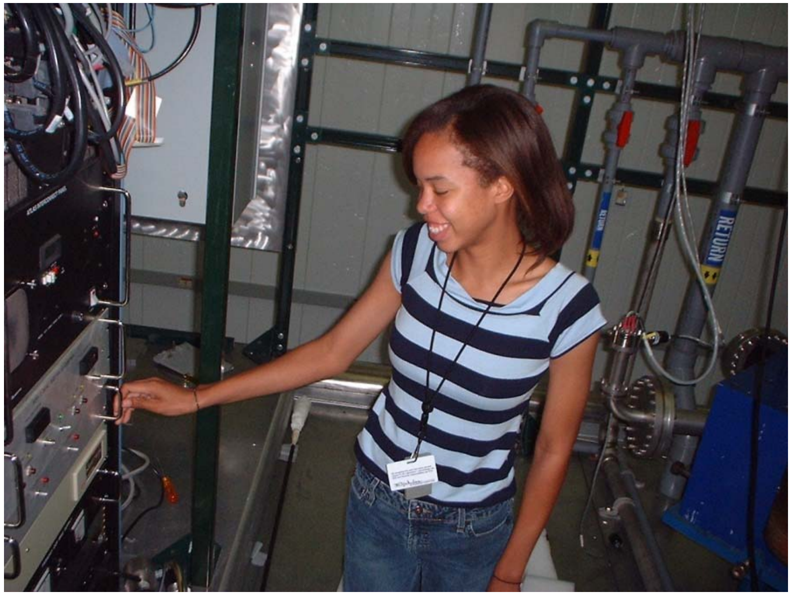


Photo courtesy of Argonne National Laboratory (DOE).

CALTECH

APS physics

Timbuktu Academy Scholar

American Physical Society Minority Undergraduate Scholarship Award Winner 2005-2007

LIGO Science Education Center Partnership

"Using Exhibit-Based Teaching and Learning to Enhance Science Literacy"

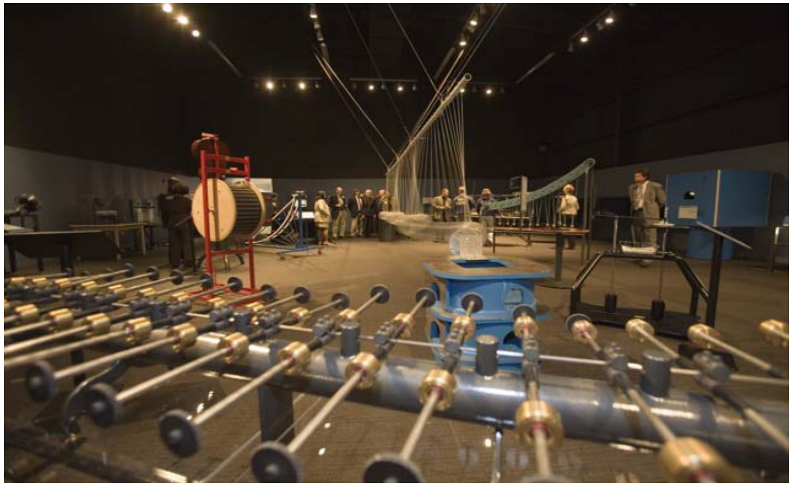
MISSION

- **To develop a Center at the LIGO Livingston Observatory (LLO) equipped with interactive exhibits in LIGO-related science.**

- **To integrate the LLO Center, its exhibits and activities, into pre-service and in-service education at Southern University Baton Rouge (SUBR).**

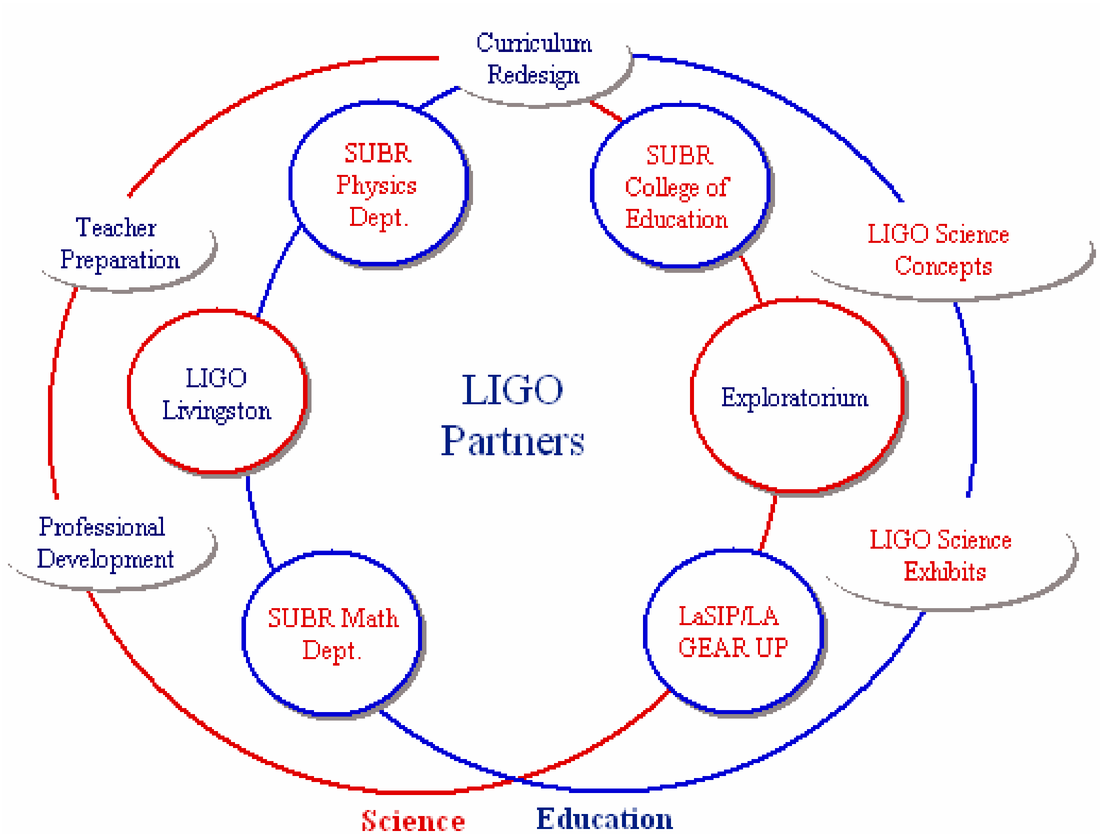
LIGO Science Education Center (SEC)

"Using Exhibit-Based Teaching and Learning to Enhance Science Literacy"



LIGO Science Education Partners

"Using Exhibit-Based Teaching and Learning to Enhance Science Literacy"



SUBR LSC PHYSICS GROUP

S. C. McGuire
E. E. Doomes
J. N. Johnson
K. L. Joseph
A. J. Alexander

PROJECT MISE

(Modeling Inquiry-Based Science Education)

J. Meyinnsse
L. Stubblefield
B. Remble

In-service teacher preparation

SUBR Inquiry Workshop

MISE Workshop at LLO

College of Education

Department of Physics

Department of Mathematics

Joint Faculty Meetings

SUBR Inquiry Workshop

Findings cont. and Future Work

- Clear signals are observable for the primary elements of interest, Ti and Ta, with excellent energy resolution and counting statistics.
- Relatively minor amounts Fe and Cr appear in a constant ratio for all samples.
- Experiments are applicable to the investigation of other dopants such as hafnia.
- Grazing incidence EXAFS (GIXAFS) beam measurements needed to avoid signals from the substrate. Emphasis on contributions from surface atoms.
- Complementary microbeam experiments are planned to determine spatial (x-y) uniformity of the element distributions.
- Two-dimensional profiles of sample surfaces with AFM.

Summary

- Southern University plays a unique role in the optical materials research of Advanced LIGO and science education within the LIGO project.
- Significant improvements in our research infrastructure are being realized as a result of our collaboration with LIGO.
- Ongoing major enhancements to our science teacher preparation programs are being created and supported by the LIGO Science Education Partnership.

Work supported by NSF Grants No(s).

PHY-0101177, PHY-0701652 and PHY-0355471

Board of Regents Grant No. 05-231SUBR-CMSS

For more information see…..

LIGO Web site: http://www.ligo.caltech.edu
See for example: **Einstein's Messengers Video**

LIGO Science Education Center: http://www.ligo-la.caltech.edu

Southern University LIGO Web site: http://ligoscience.subronline.net

Einstein@home: http://einstein.phys.uwm.edu/
http://www.einsteinathome.org/

*Work supported by NSF Grants No. PHY-0101177, PHY-0701652 and PHY- 0355471; Louisiana Board of Regents Grant No. 05-231SUBR-CMSS