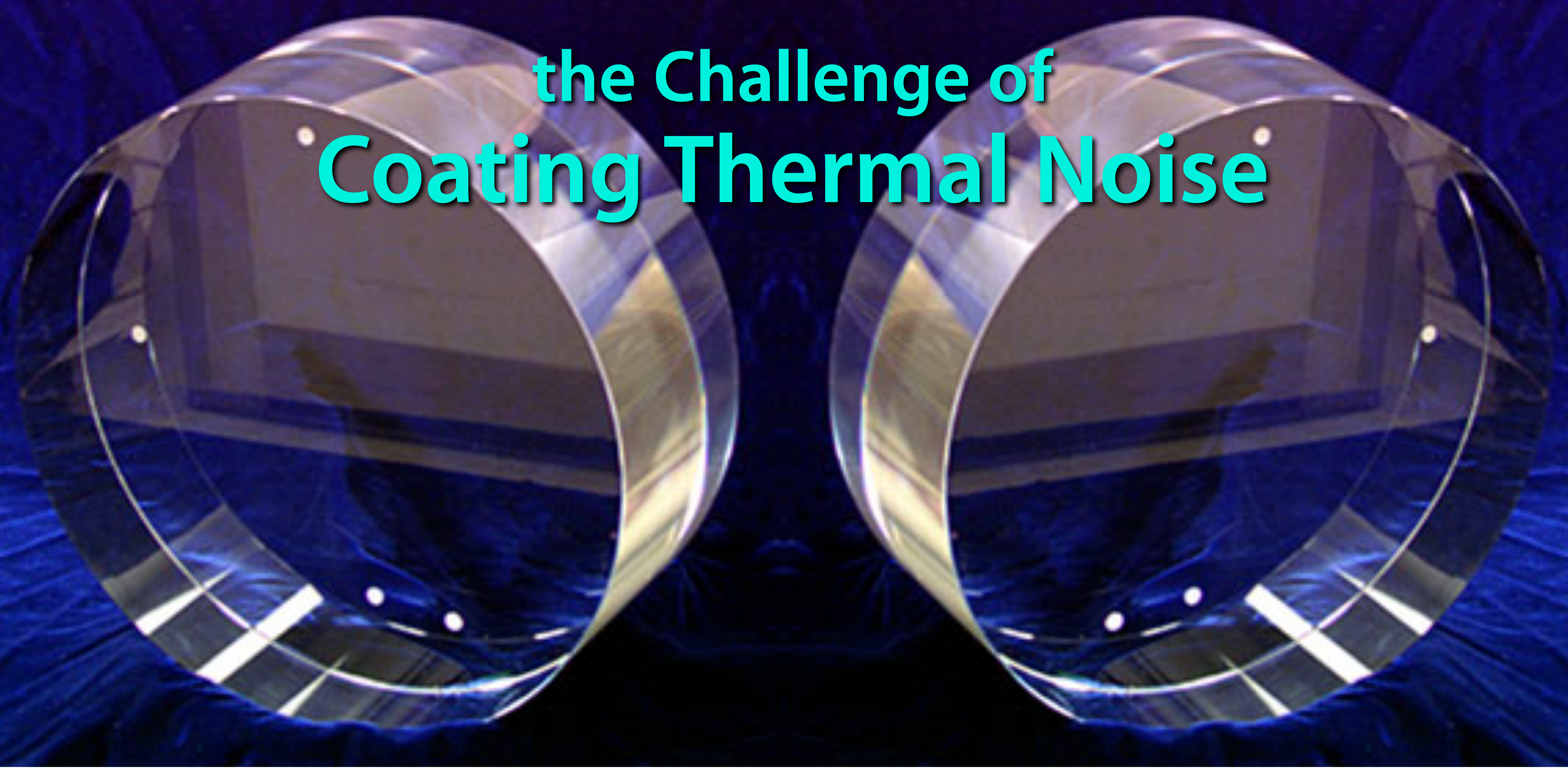
Gravitational Wave Detectors…



the Challenge of
Coating Thermal Noise

LSC LIGO Scientific Collaboration

By Professor Steven Penn
Hobart and William Smith Colleges,
and the LIGO Science Collaboration

CCRG/Astronomy Lunch Talk • RIT • 25 May 2016 • LIGO-G1601208

LIGO

LSC

LIGO Scientific Collaboration

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UNIVERSITY OF STRATHCLYDE

Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE

MICHIGAN

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique

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MONTANA STATE UNIVERSITY

SOUTHERN UNIVERSITY Agricultural & Mechanical College

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

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Caltech

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Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU LOUISIANA STATE UNIVERSITY

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HWS Gravity Lab

David Niedzwiecki,
Sean Kipperman,
Raghuvir Kasturi,
Jing Lou,
Jacob Podkaminer,
Christine Luongo,
Matt Scanlon,
Paul Stevens,
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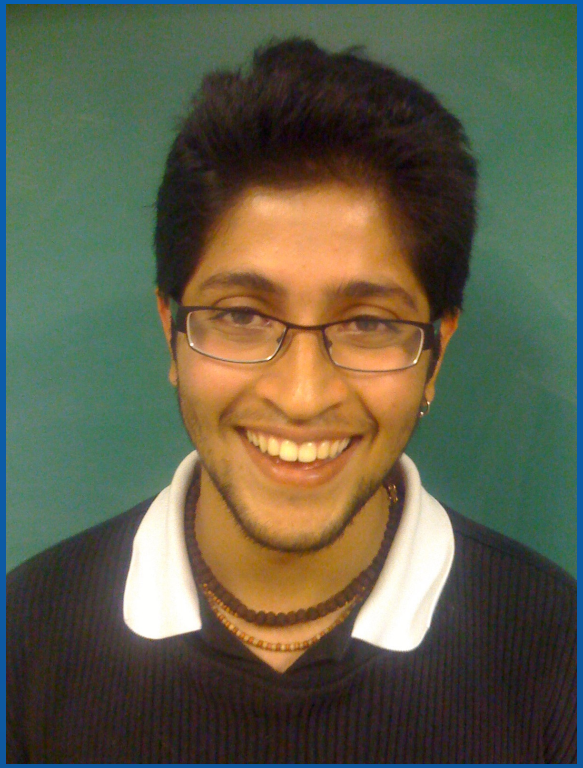
Magdy Gad



Outline

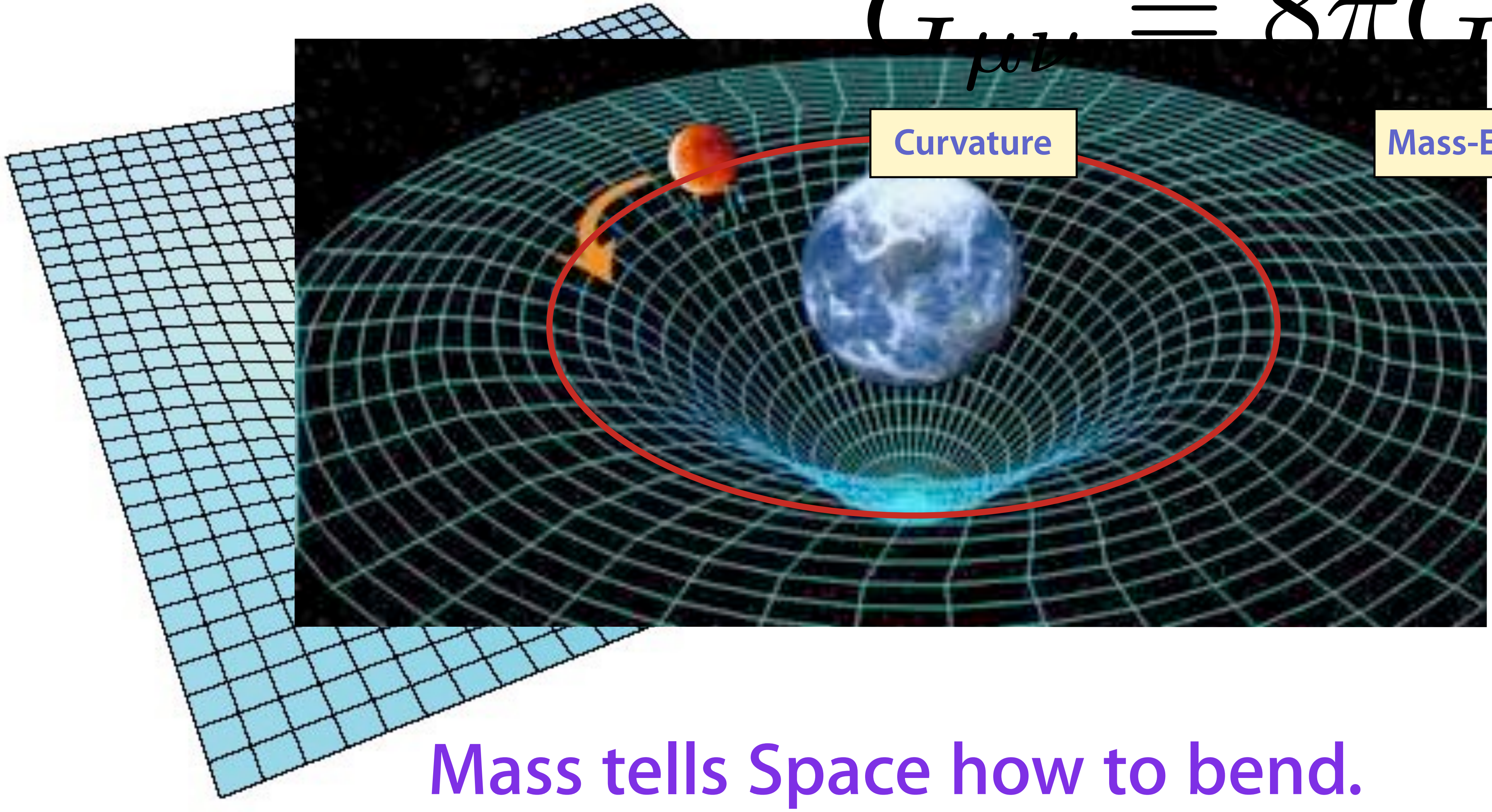
- Summary of GR and GW150914
- The Advanced LIGO Detector
    - Laser system
    - Seismic & Suspension System
    - Test Mass Mirrors & Thermal Noise
- Thermal noise & Dissipation
- Coating thermal noise
    - Amorphous Coatings
    - Crystalline Coatings
- Future Detectors
    - A+
    - Voyager
    - Cosmic Explorer

General Relativity & Gravity

Einstein developed the General Theory of Relativity in which the "force" of gravity arises from curvature in the space-time.

The Einstein Equation

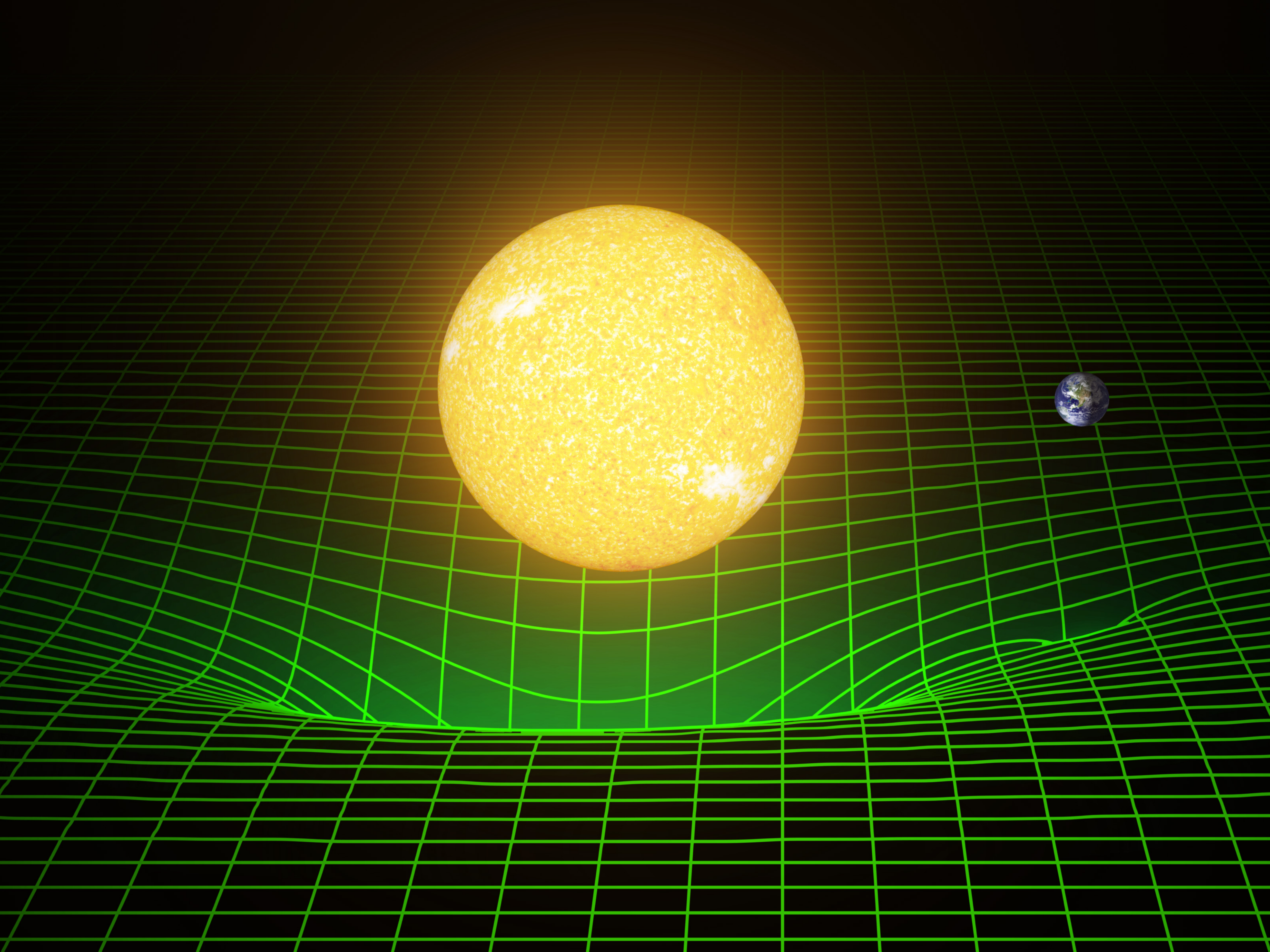
$$G_{\mu\nu} = 8\pi G\ T_{\mu\nu}$$



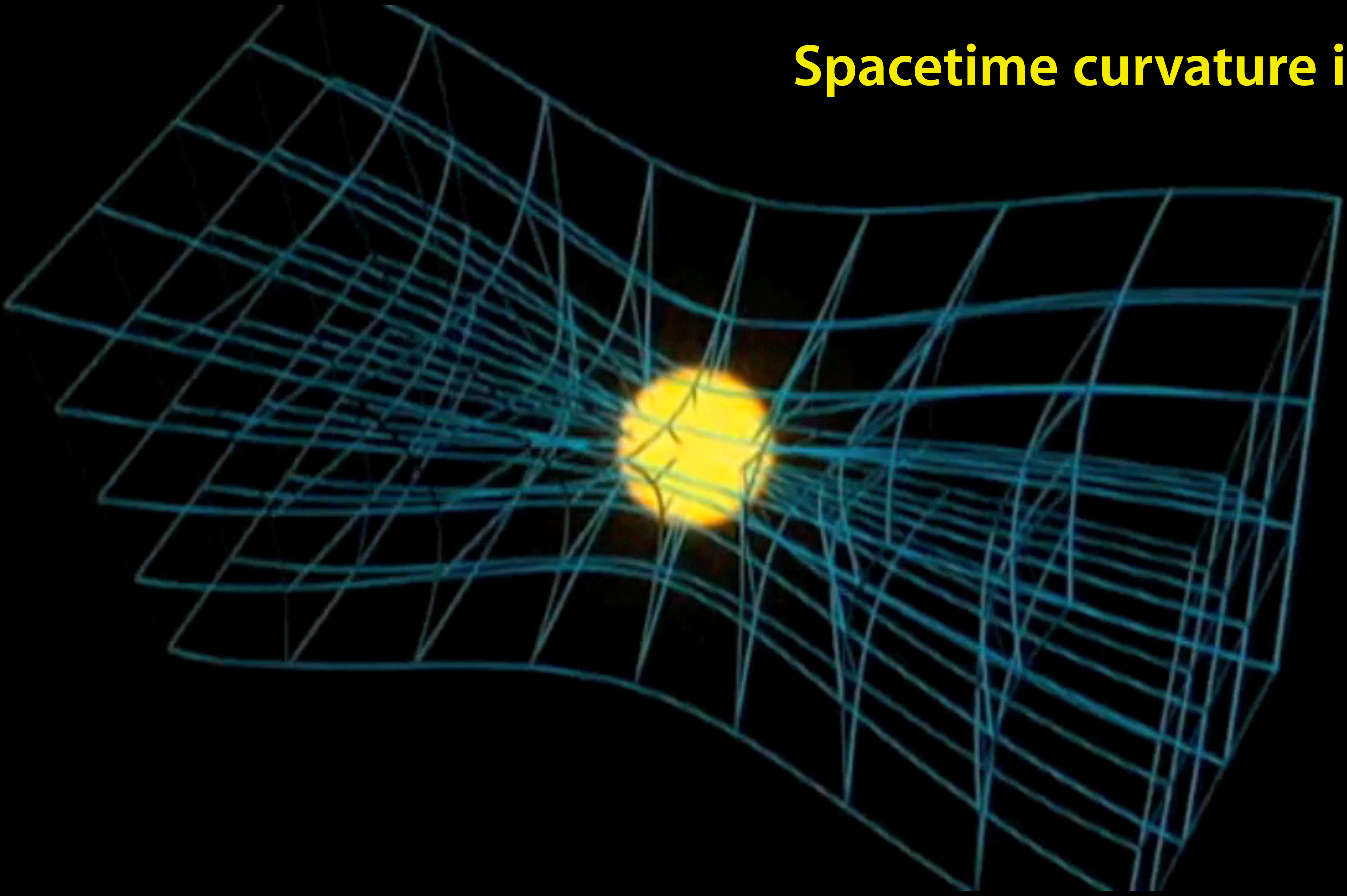
Curvature

Mass-Energy Density

Mass tells Space how to bend.
Space tells mass how to move.



Spacetime curvature in 3D



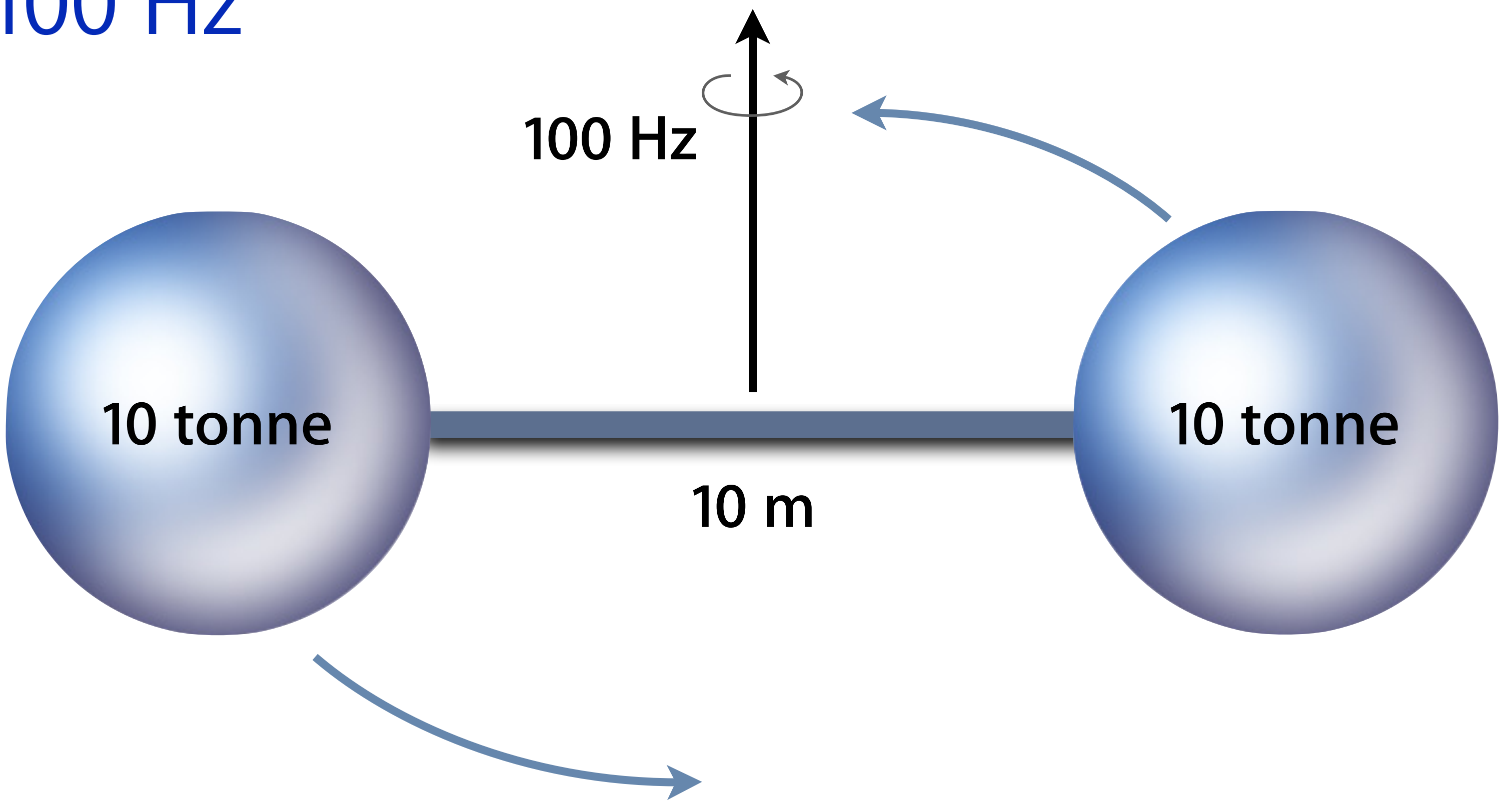
Acceleration of the mass produces a wave of curvature that propagates through spacetime.

Movie clip borrowed from *Making Waves*

Can We Make Gravitational Waves?

Make an “oscillating mass quadrupole”:

- 1m tungsten spheres (10^4 kg),
- 10 m carbon nanotube composite rod,
- Spin at 100 Hz

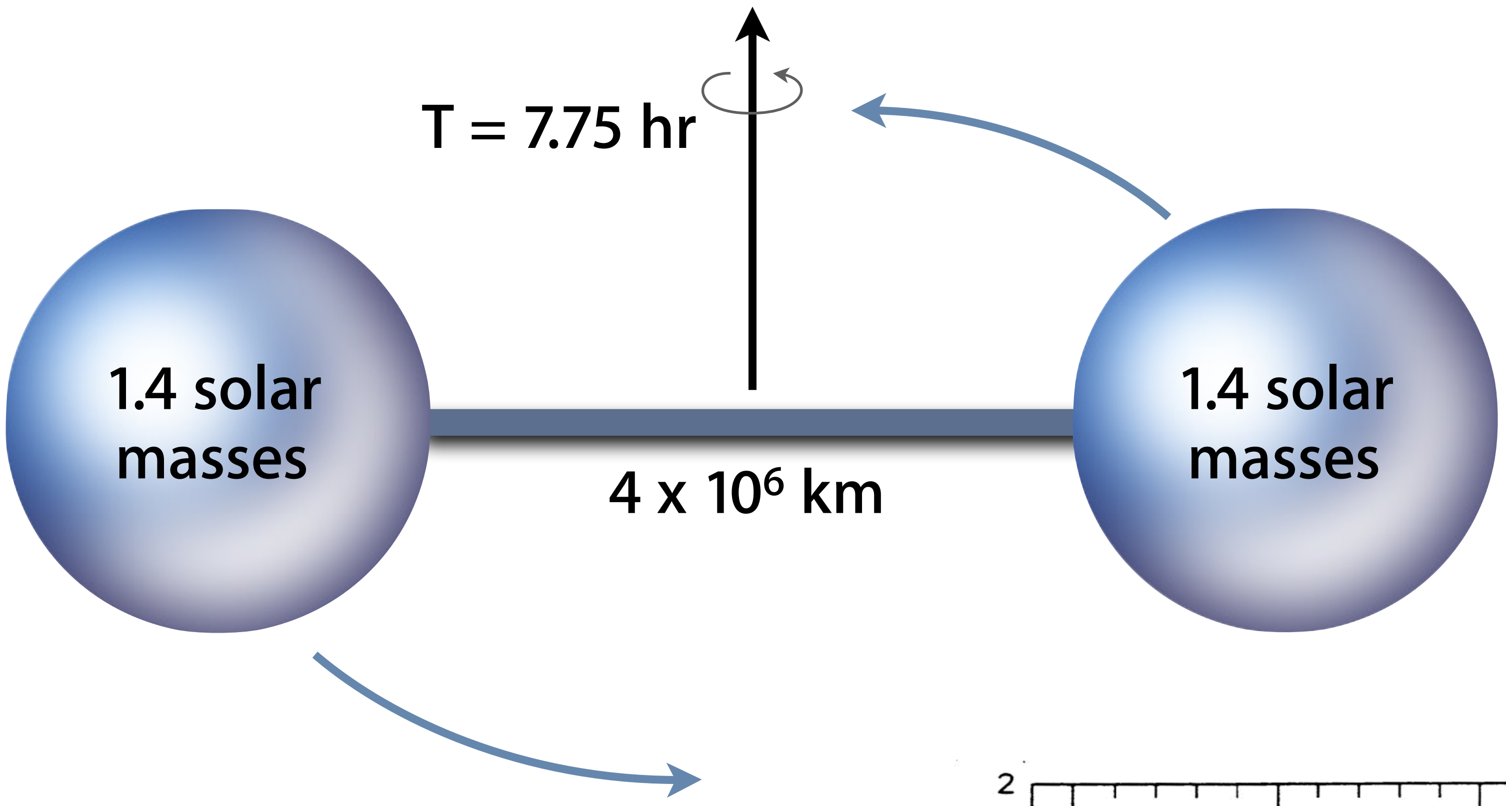


Strain at one wavelength is only 10^{-39}.

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

$$\approx 10^{-44}\ \mathrm{N}^{-1}$$

Hulse-Taylor Binary Pulsar 1913+16



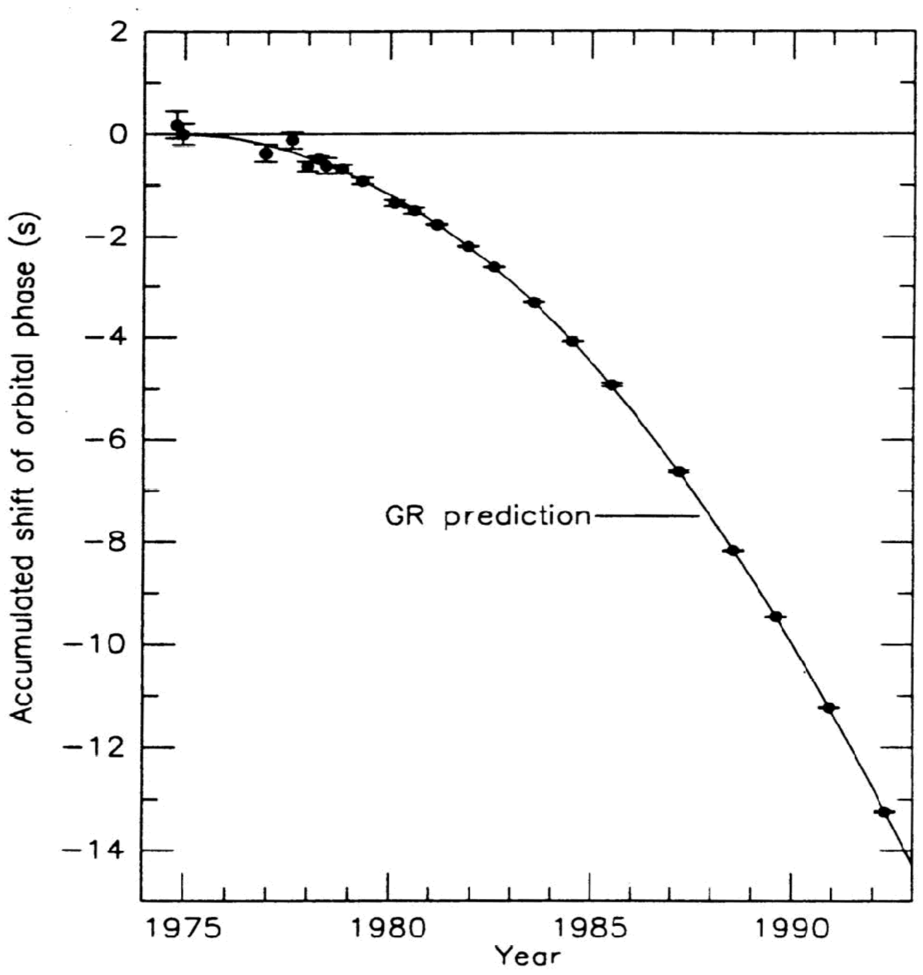
T = 7.75 hr

1.4 solar masses

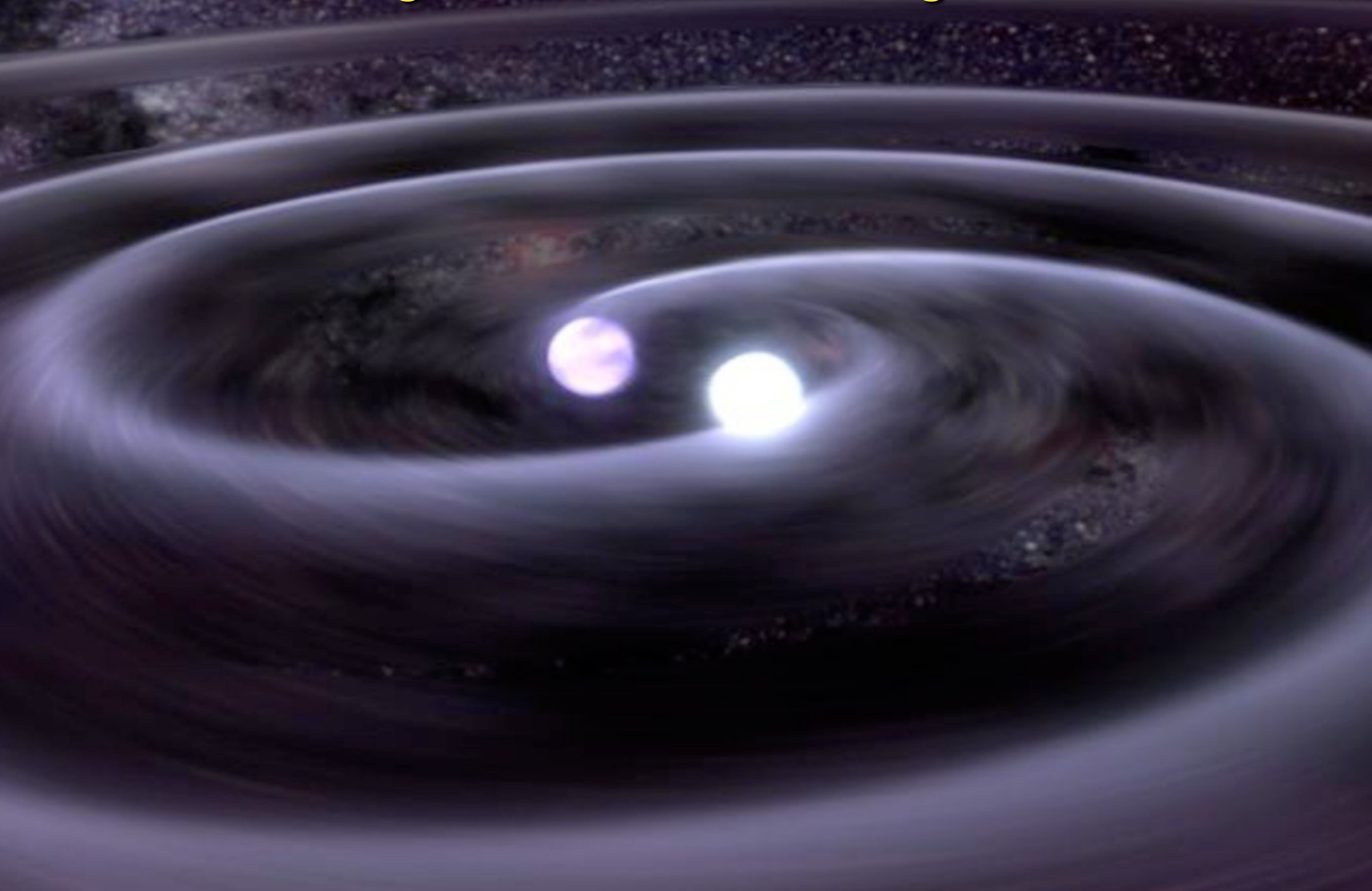
4×10^6 km

1.4 solar masses

- Binary neutron star (PSR 1913+16) discovered in 1974 by Joe Taylor and Russell Hulse.
- System is slowly losing energy. Orbital period of 7.75 hours decreases by 76 μs per year.
- Inspiral and coalescence in 300 million years.
- Predicted energy from GW radiation precisely matches the calculated loss. **No fitting!**



The inspiral of a binary system of compact massive objects (BH NS WD) can generate an observable gravitational wave.



Why look for Gravitational Waves?

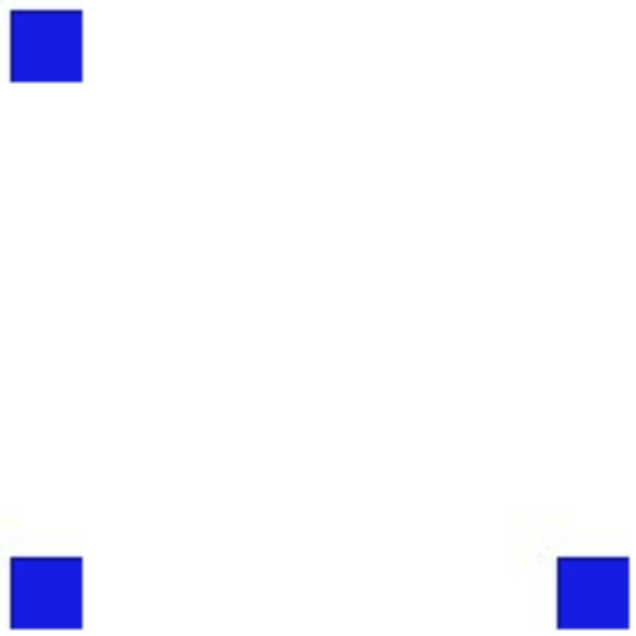
- Test the General Theory of Relativity
  - Strong field limit
  - Gravitational Wave speed

- Explore GW sources not visible to E-M telescopes
  - Black Holes
  - Neutron Stars
  - Supernovae
  - Early Big Bang

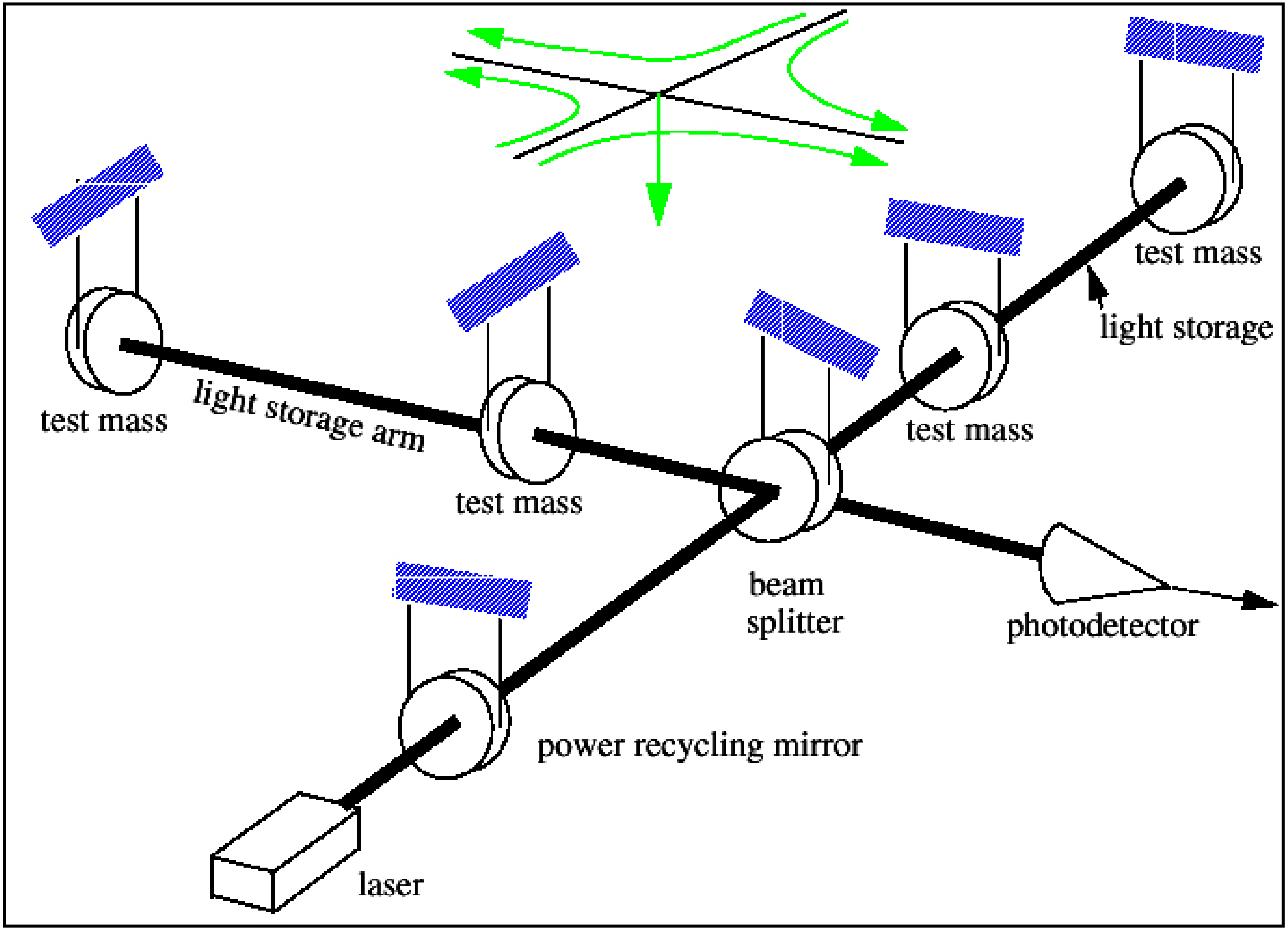
- New Window on Universe = Expect Surprises

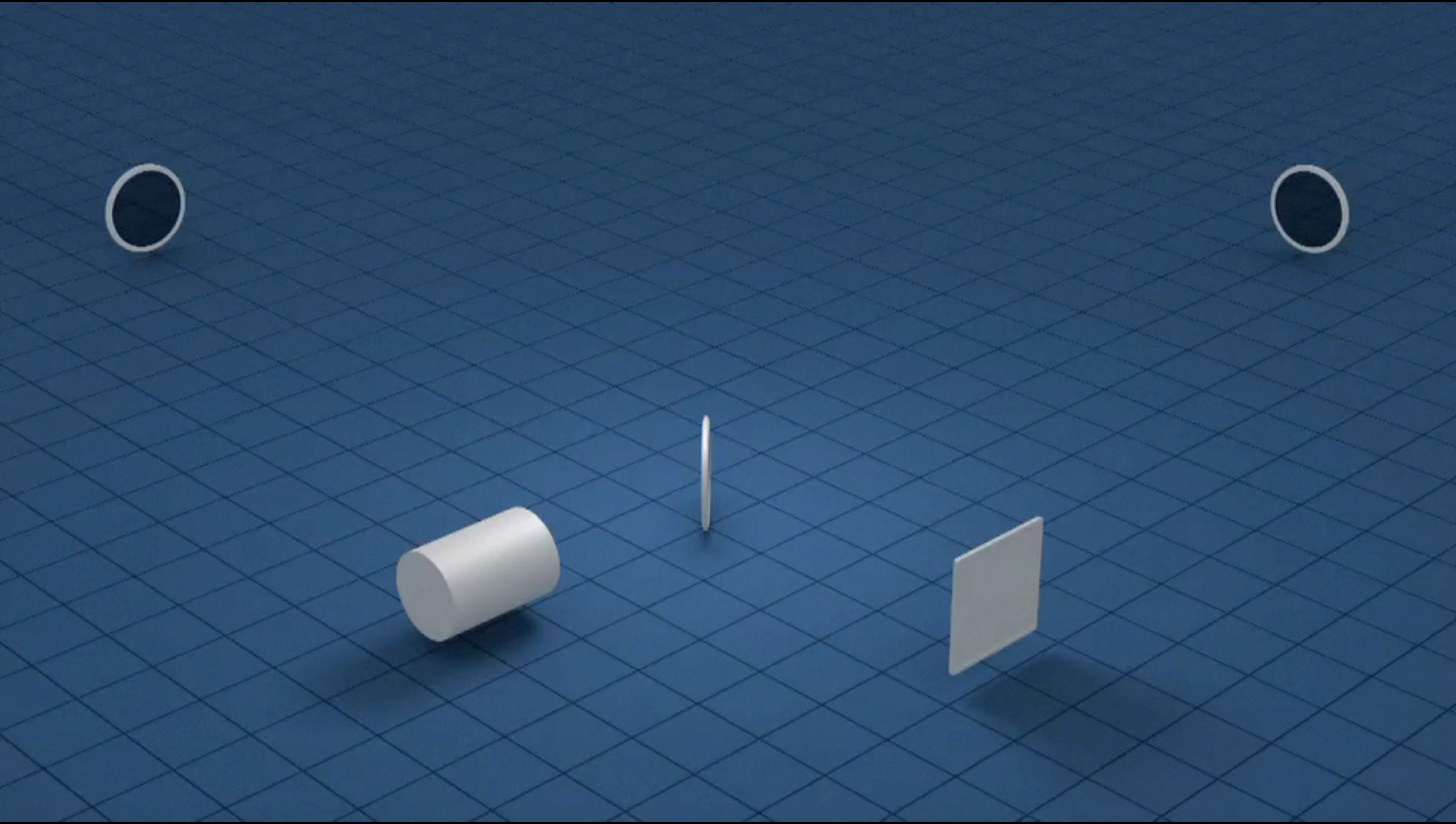
- Challenging Measurement:
  - BNS Inspiral in Virgo Cluster produces a strain $\approx 10^{-21}$
  - “Frequent” detection requires a strain sensitivity $\approx 10^{-22}$

Gravitational Wave moves Test Masses in Quadrupole form

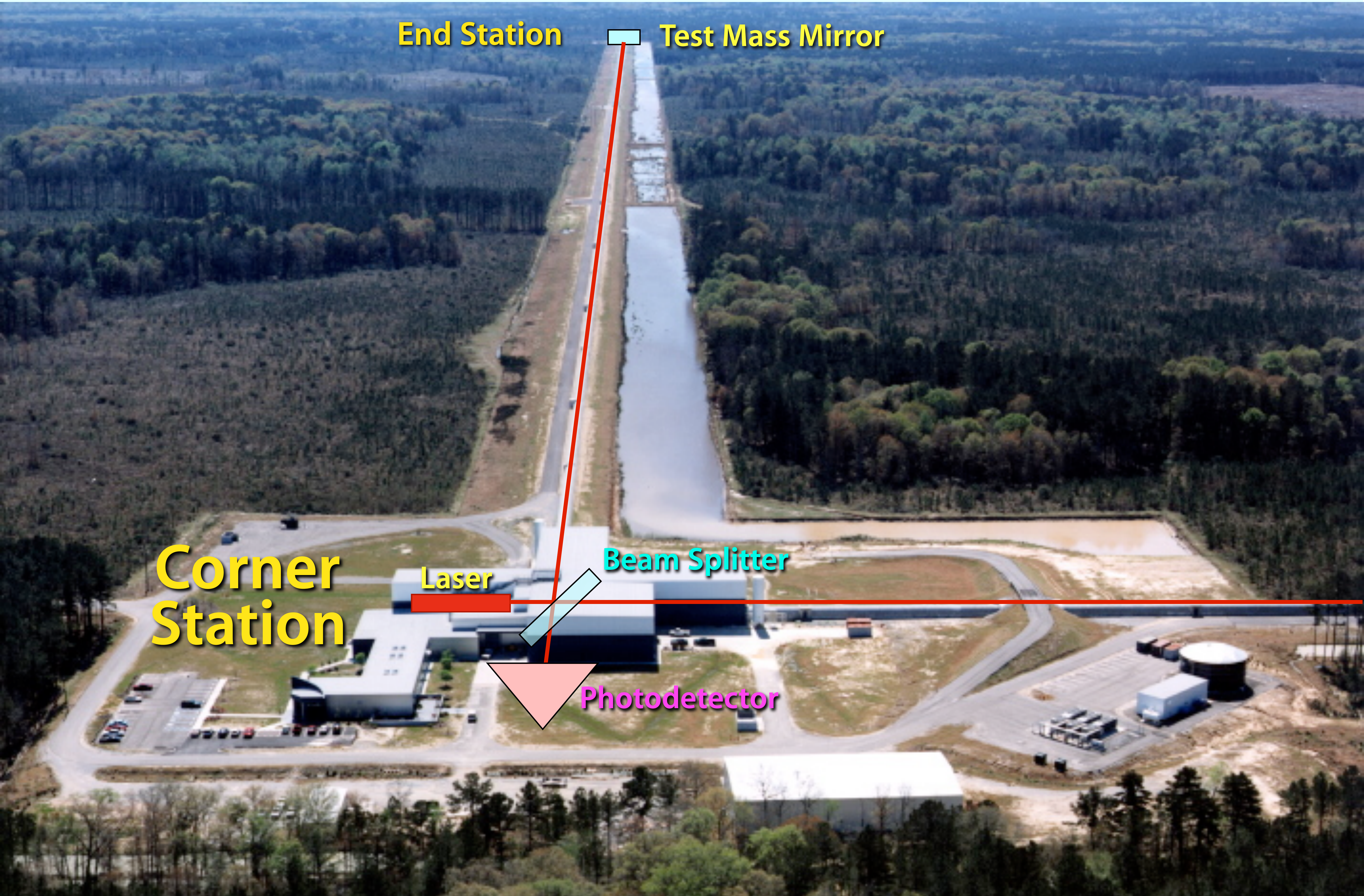


Basic Interferometer





LIGO Livingston




Corner Station
LIGO Livingston
End Station

LIGO Hanford

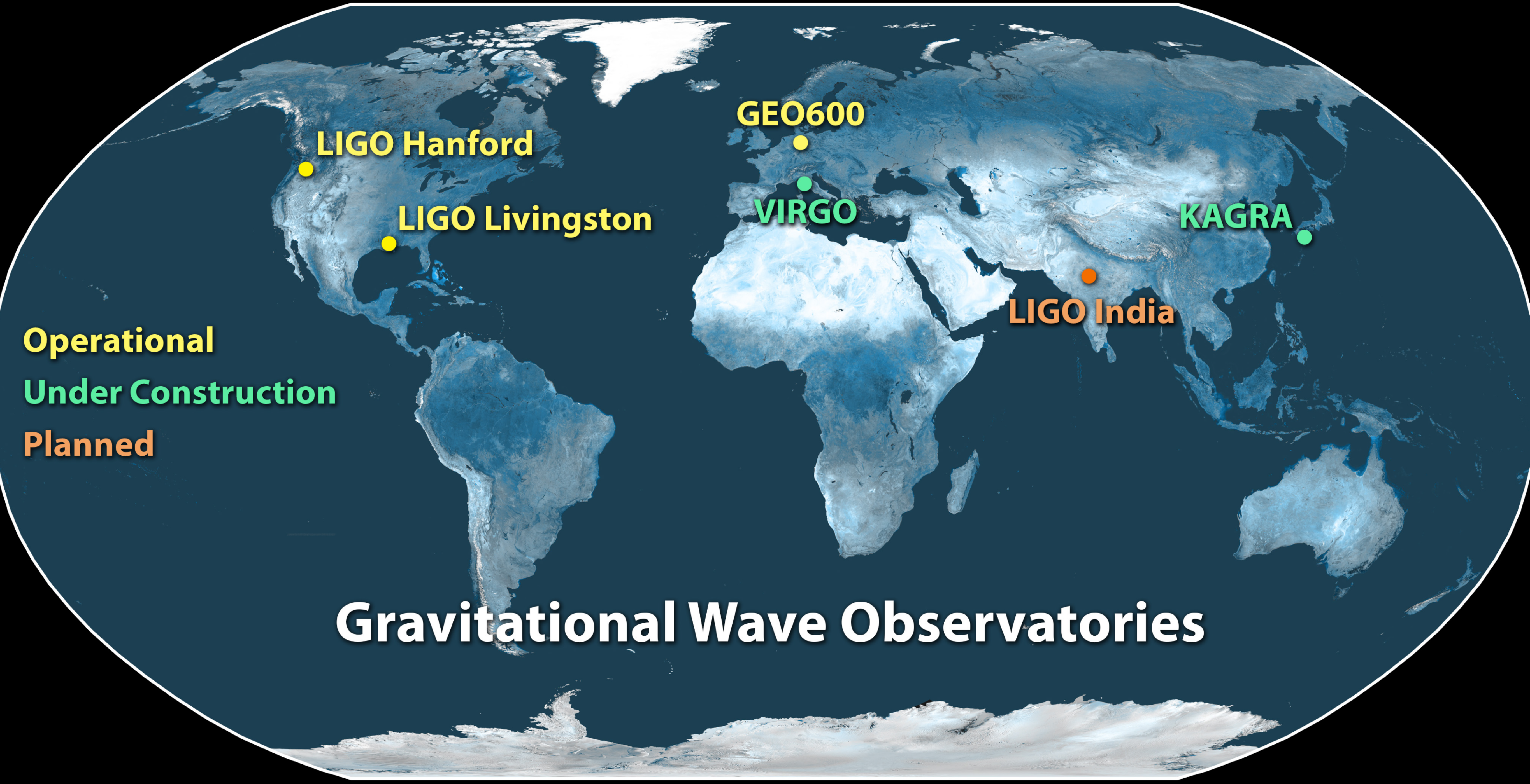
LIGO Observatory Sites

LIGO Hanford
4 km & 2 km IFO

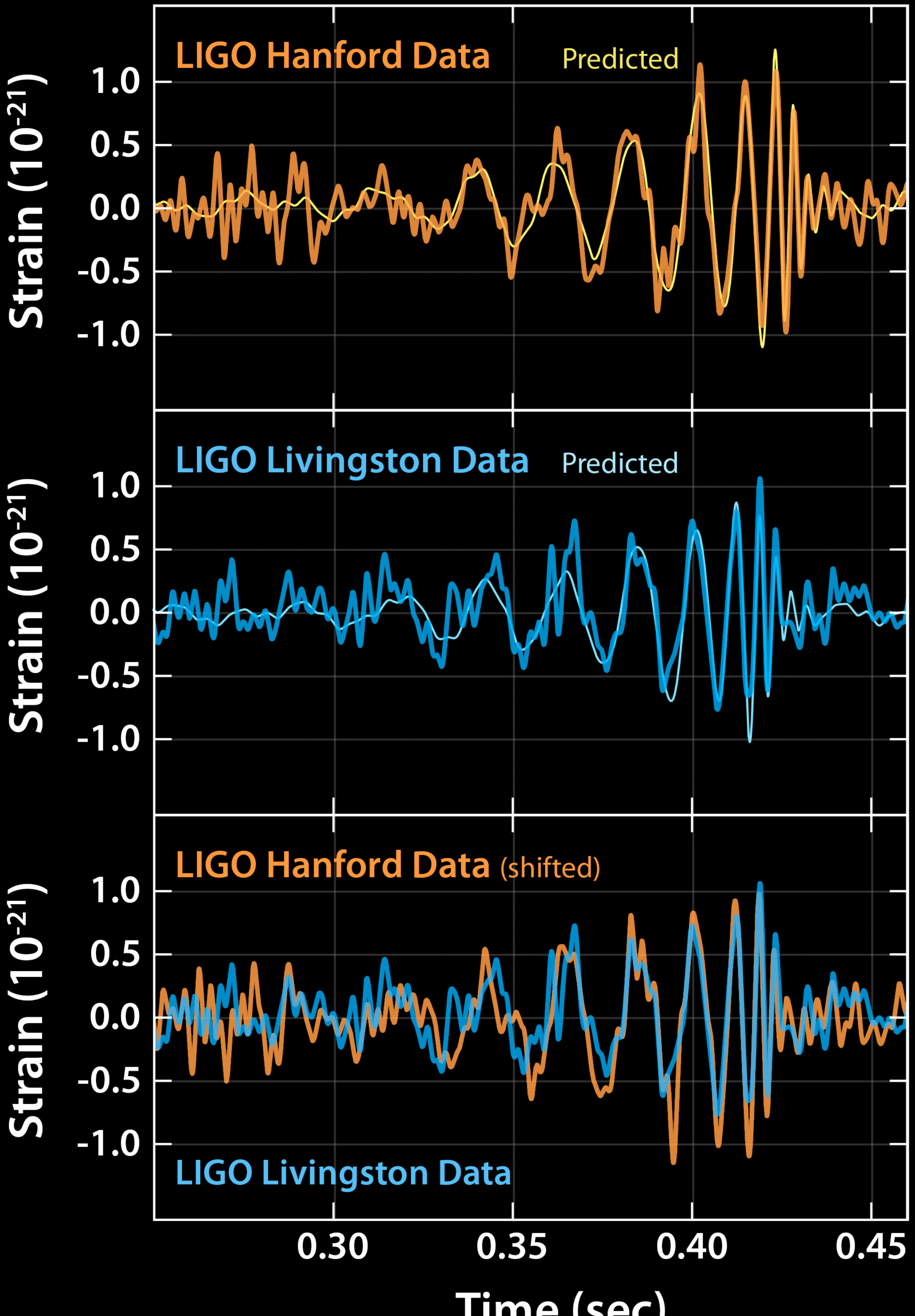
3000 km, 10 ms

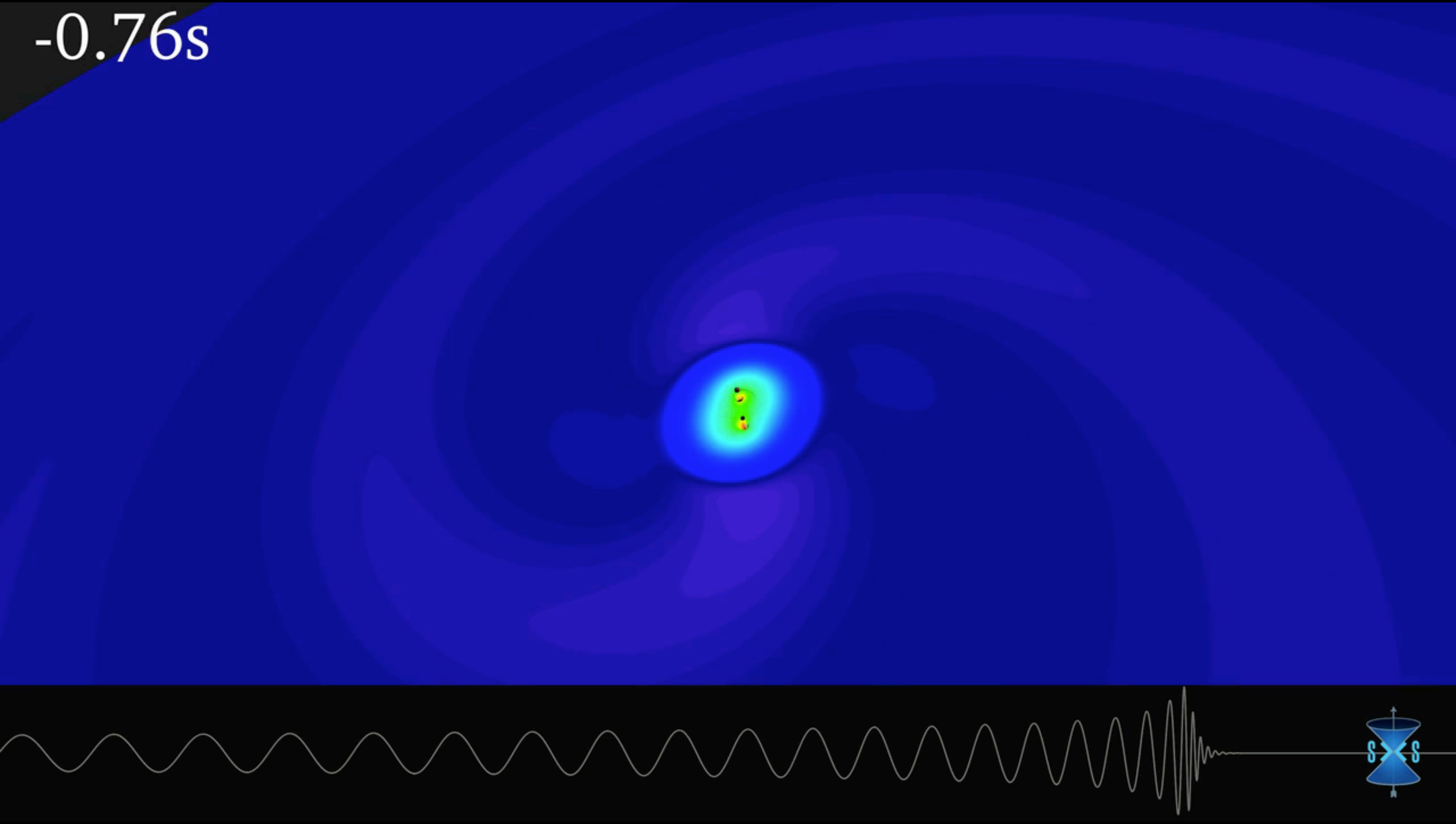
Detector separation minimizes background noise coherence and provides directional information via relative signal timing.

LIGO Livingston
4 km IFO



The Global Network


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


-0.76s
S S

Facts on the detection

Input Black Hole Masses: 29 & 36 solar masses
Final Black Hole Masses: 62 solar masses
Radiated Energy: 3 solar masses
Final Spin Energy: 4 solar masses

Event Distance: 1.3 Gly

Peak Strain: 10^{-21}
Mirror deflection: 5×10^{-18} m, 0.005 proton diameters

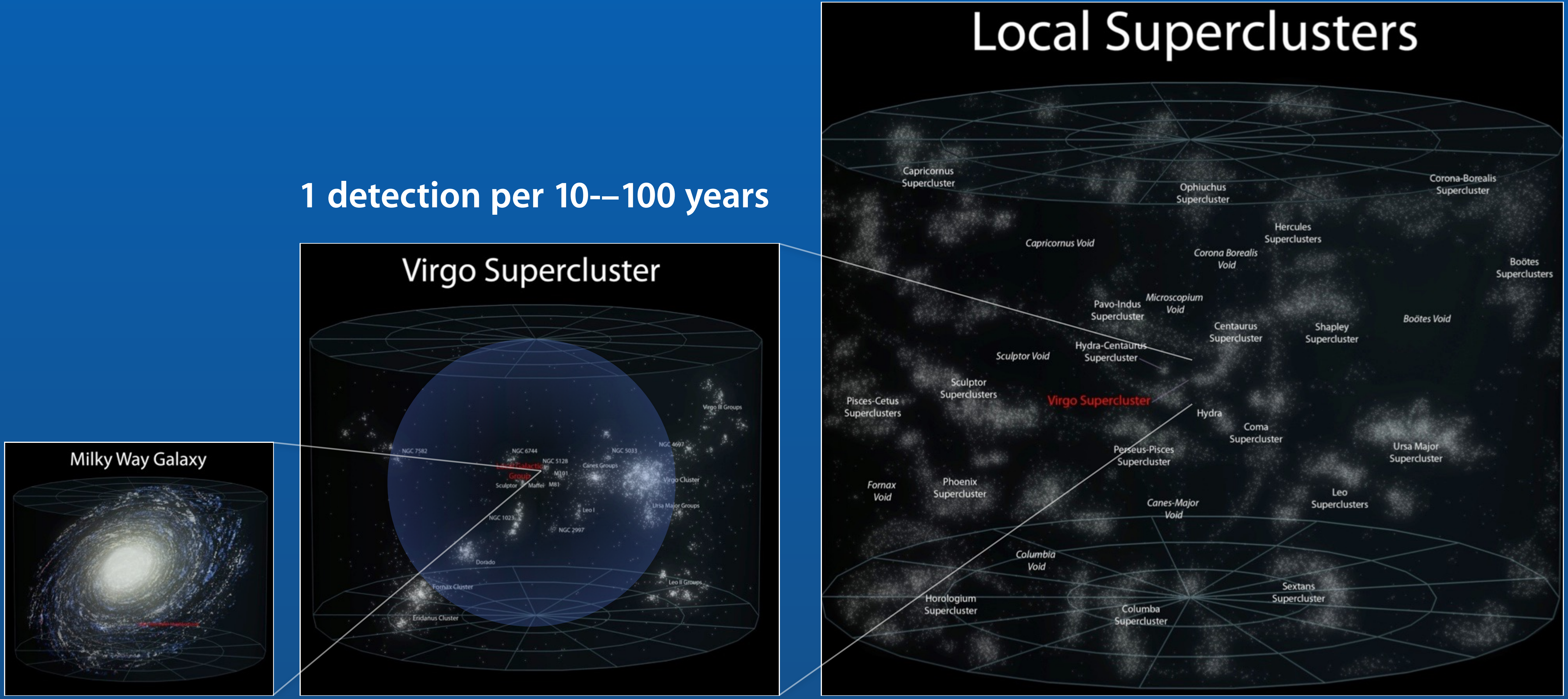
False Alarm Rate: 1/200,000 yrs

Signal-to-Noise Ratio: 24
Frequency Range: 35 –250 Hz

Advanced LIGO

10––100 detections per year

1 detection per 10––100 years



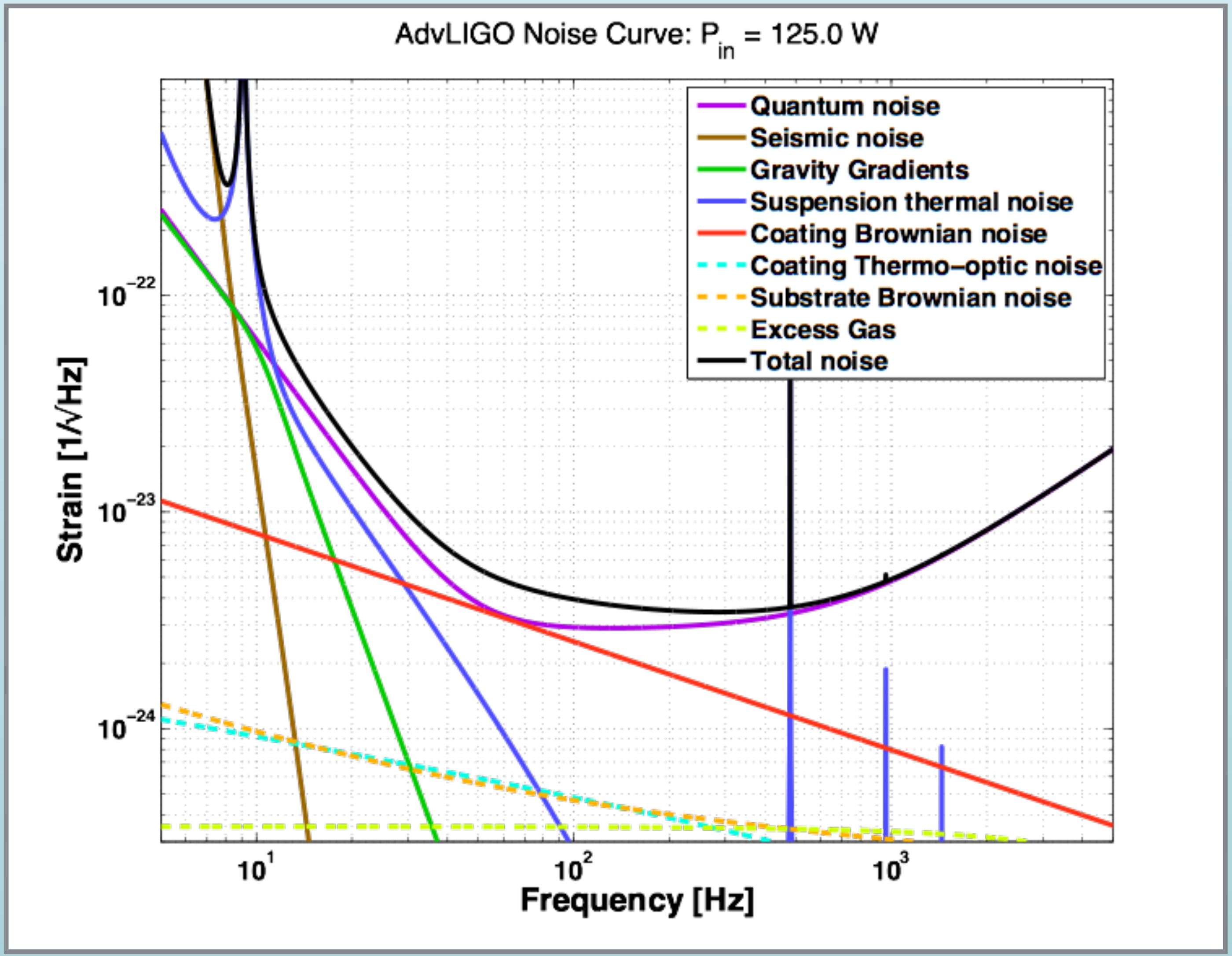
Graphic: M. Evans

Initial LIGO Reach

Advanced LIGO Reach

Advanced LIGO Improvements

Seismic Noise Wall:
$h < 10^{-22}$ for f > 10 Hz



Shot Noise:
Stored laser power
to increase 25x

Noise approaches
Quantum Limit
across most of band

Limited by Thermal Noise
in Test Mass Mirrors
≈ 4 – 40 Hz band

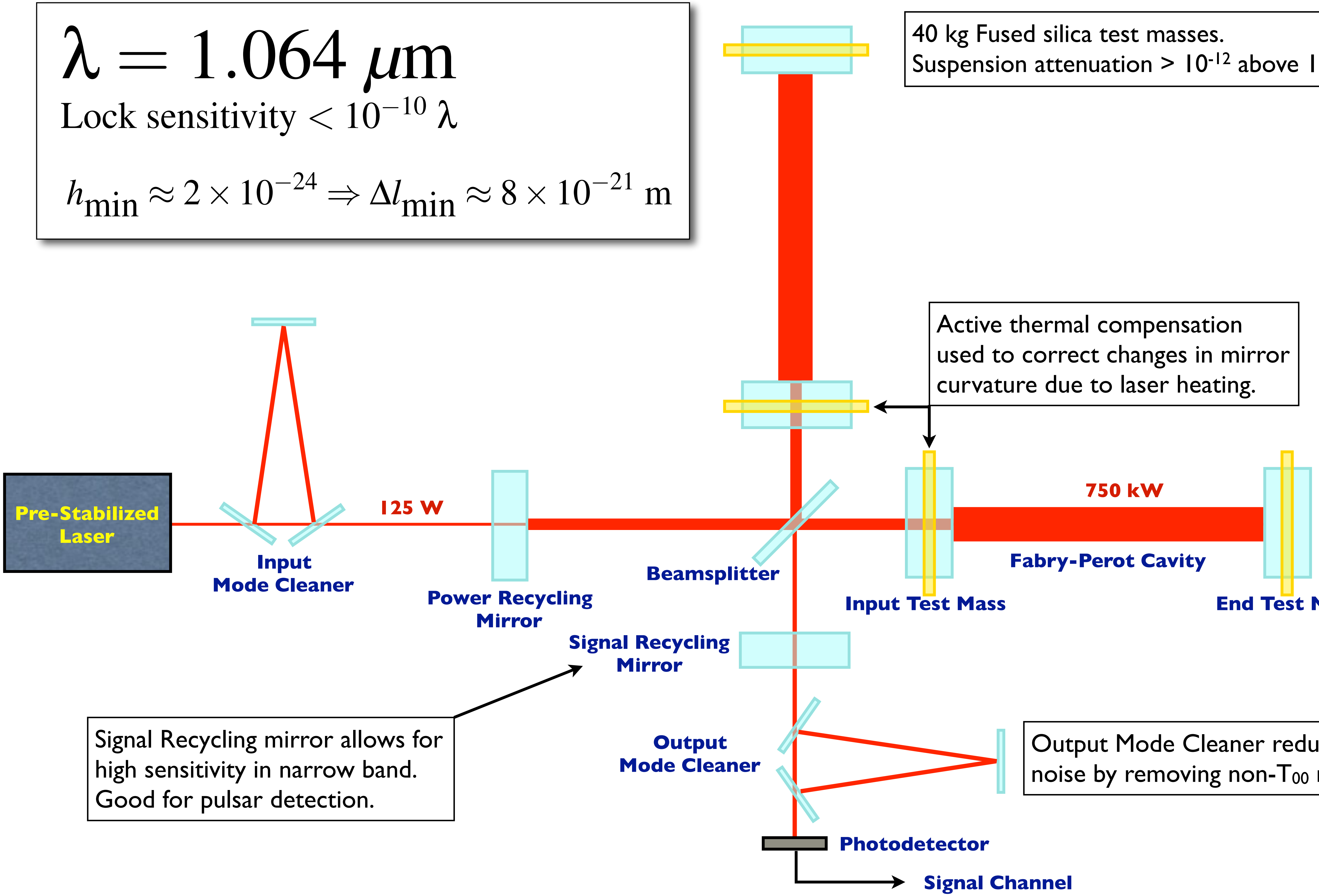
Adv. LIGO Optical Layout

$$\lambda = 1.064\ \mu\mathrm{m}$$

Lock sensitivity $< 10^{-10}\ \lambda$

$$h_{\mathrm{min}} \approx 2 \times 10^{-24} \Rightarrow \Delta l_{\mathrm{min}} \approx 8 \times 10^{-21}\ \mathrm{m}$$

40 kg Fused silica test masses.
Suspension attenuation > 10^{-12} above 10 Hz.



Active thermal compensation used to correct changes in mirror curvature due to laser heating.

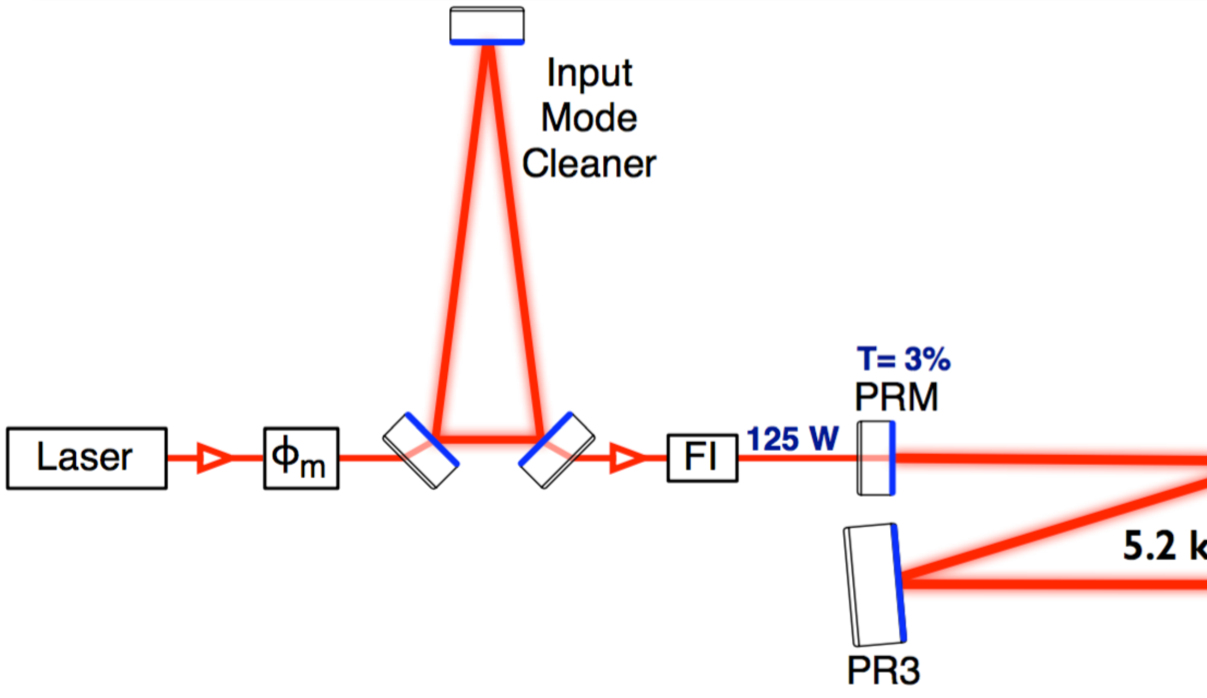
Signal Recycling mirror allows for high sensitivity in narrow band. Good for pulsar detection.

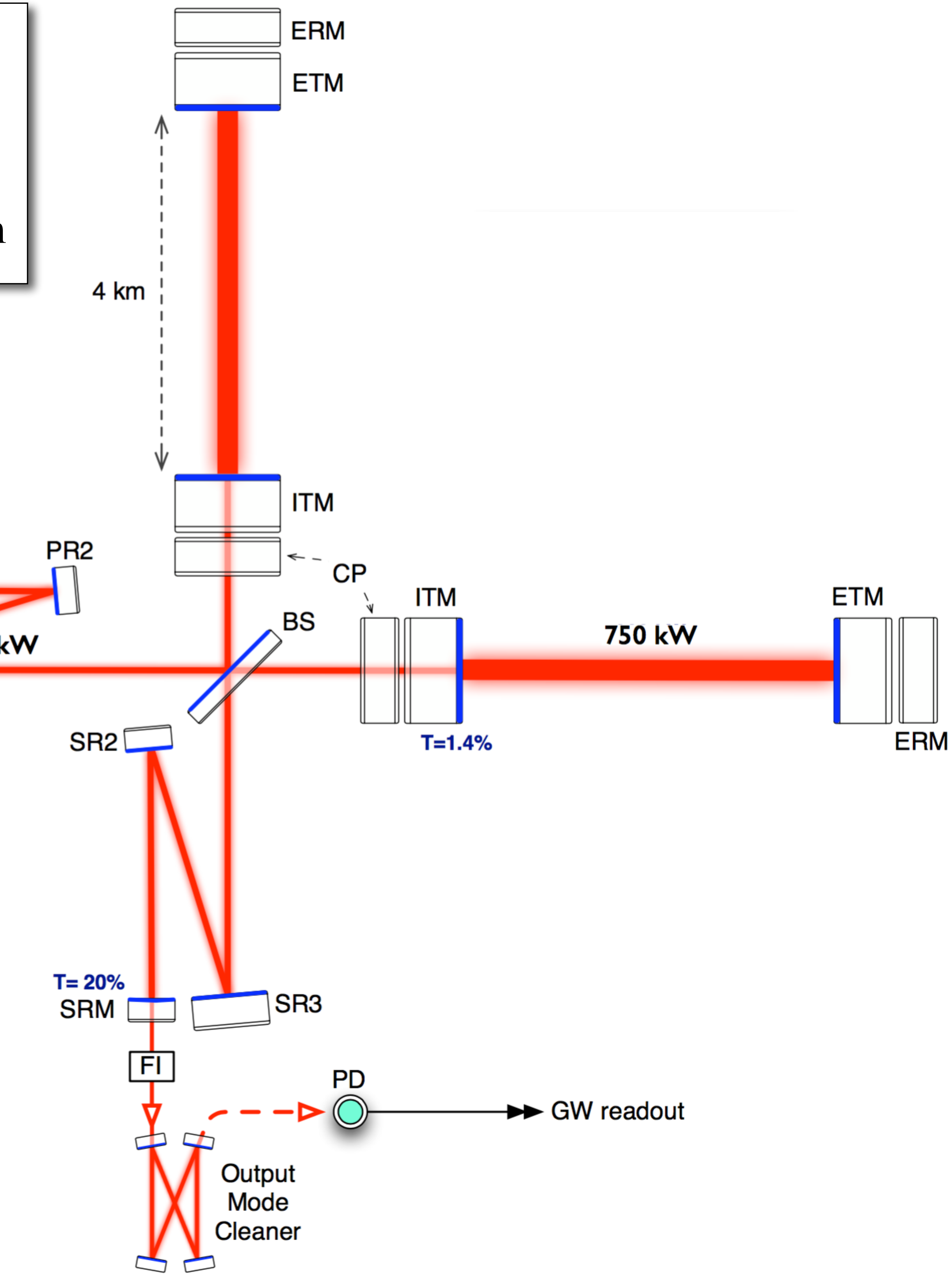
Output Mode Cleaner reduces noise by removing non-T_{00} modes.

$$\lambda = 1.064\ \mu m$$

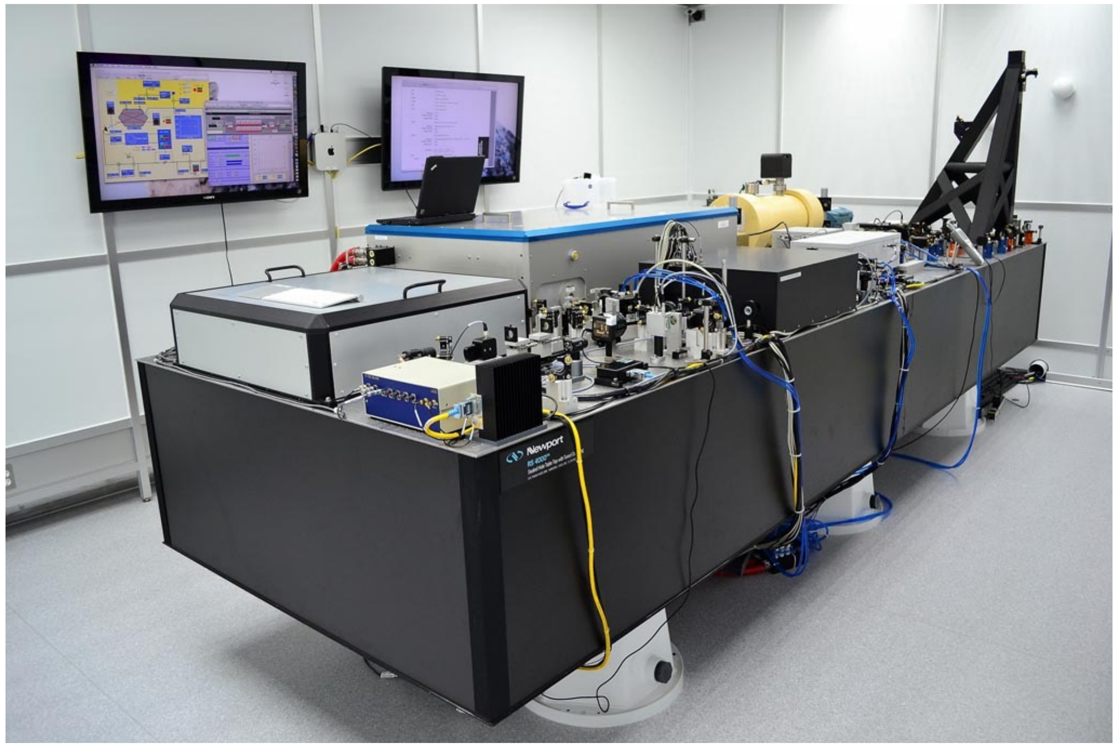
Lock sensitivity $< 10^{-10}\,\lambda$

$$h_{\text{min}} \approx 2 \times 10^{-24} \Rightarrow \Delta l_{\text{min}} \approx 8 \times 10^{-21}\ \text{m}$$



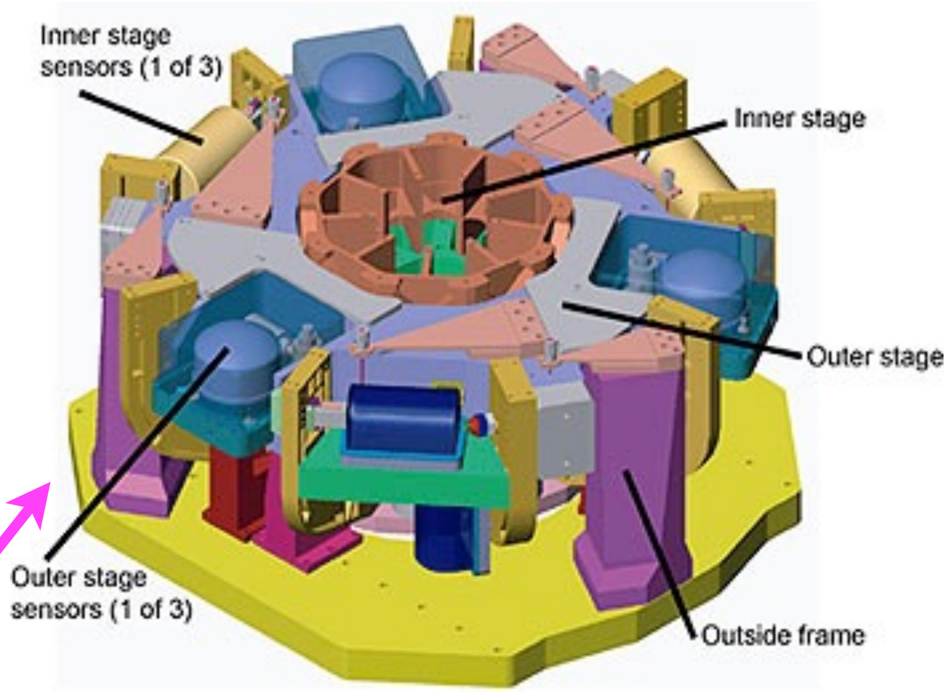


200 W Nd-YAG Laser by Max Planck AEI

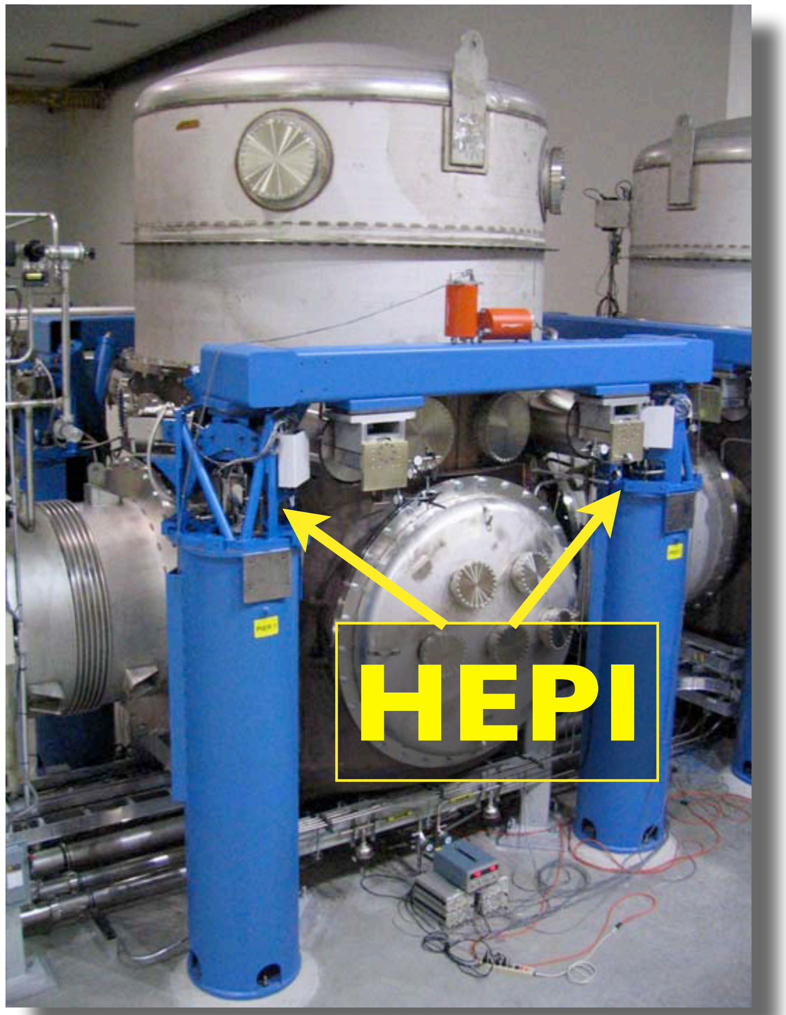


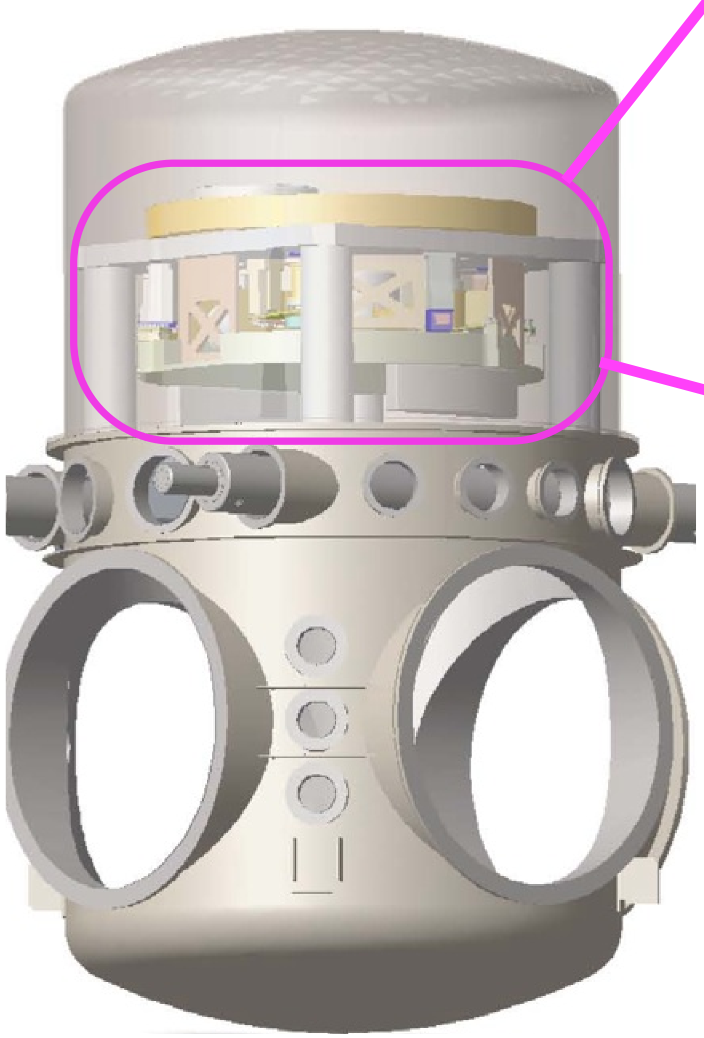
Adv. LIGO Seismic Isolation

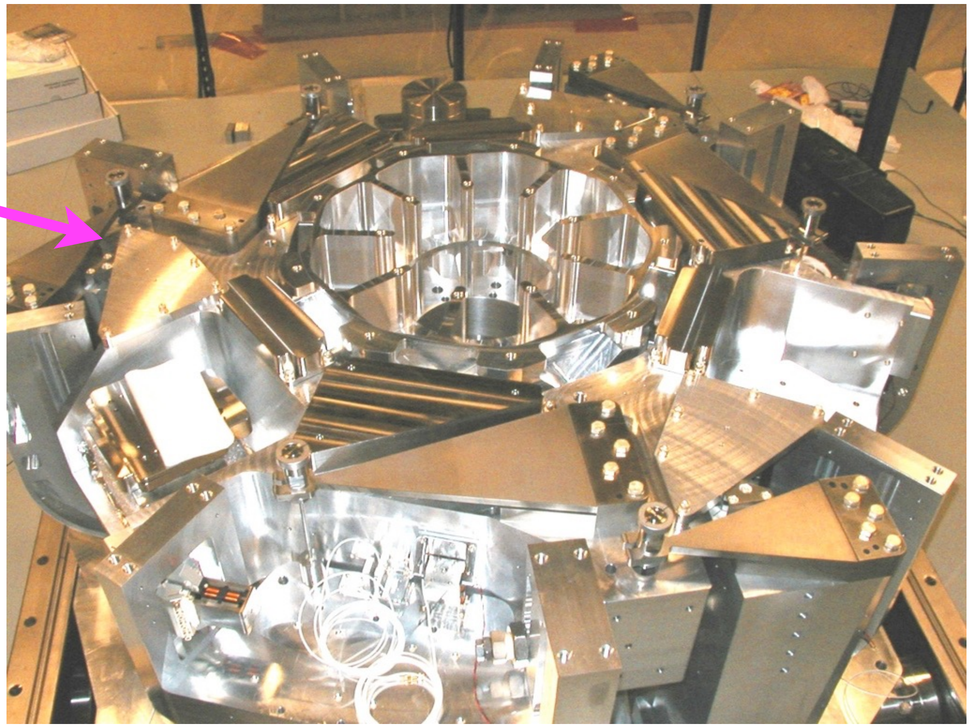
- HEPI isolation of chamber supports
  - Overdetermined 6 DOF compensation in 0.1 – 10 Hz range
  - About 0.1 – 0.001 micron/s velocity over range
- Internal Chamber Isolation Stacks
  - Two isolation stages per stack
  - Passive isolation above 3 Hz. Active isolation below 30 Hz.
  - Supports Quad pendulum in BSC chambers
  - Supports Optical tables in HAM chambers



BSC Chamber



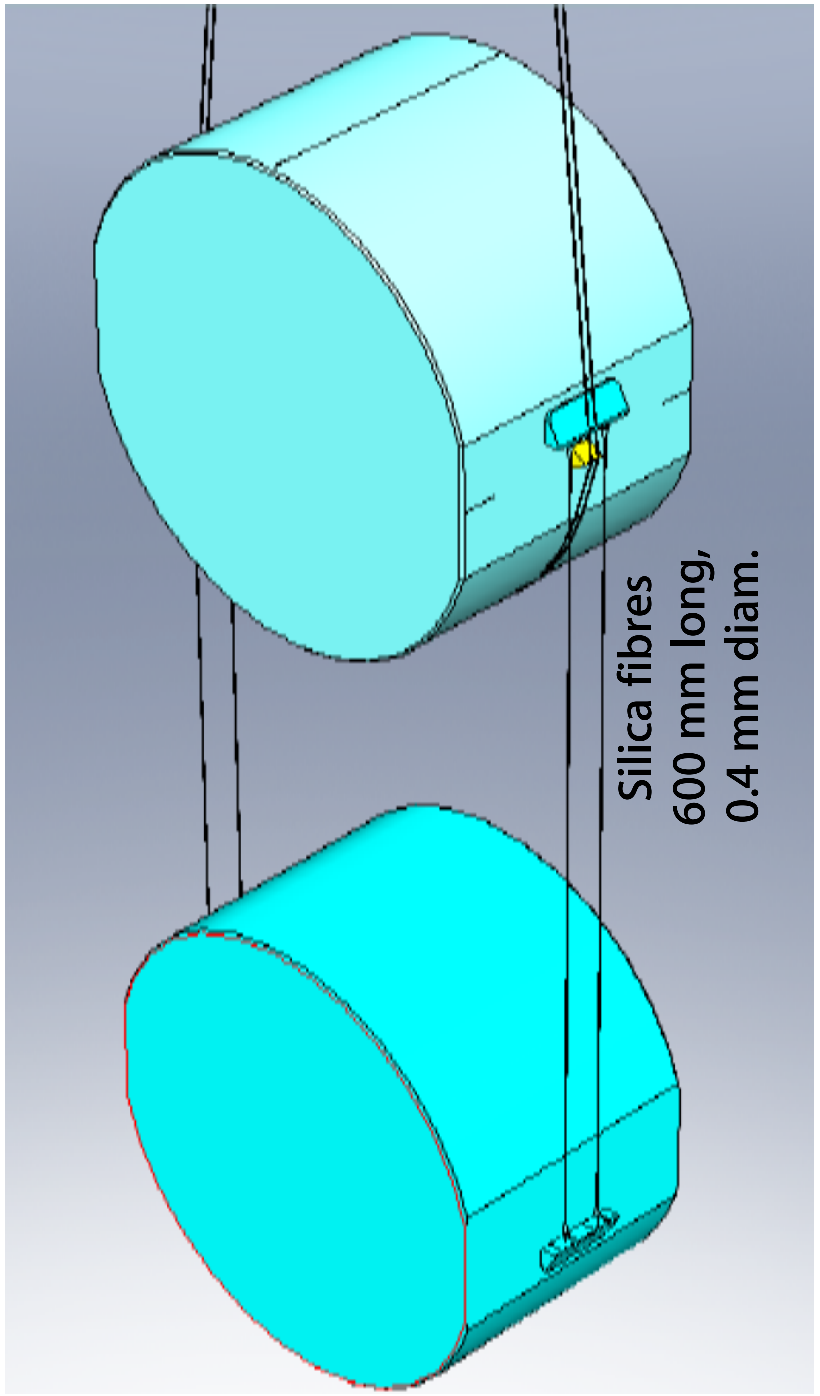




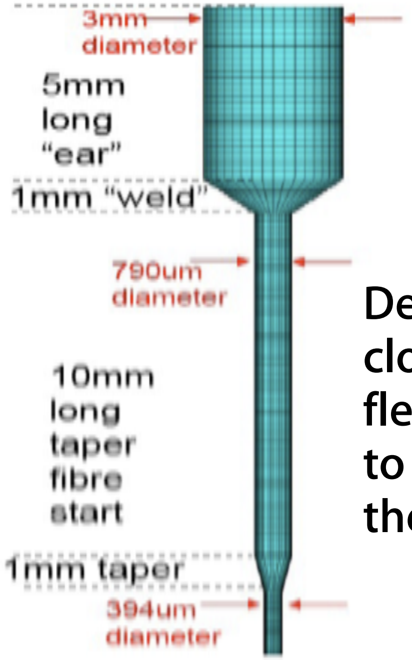
Advanced LIGO Suspensions

Quad Pendulum Design

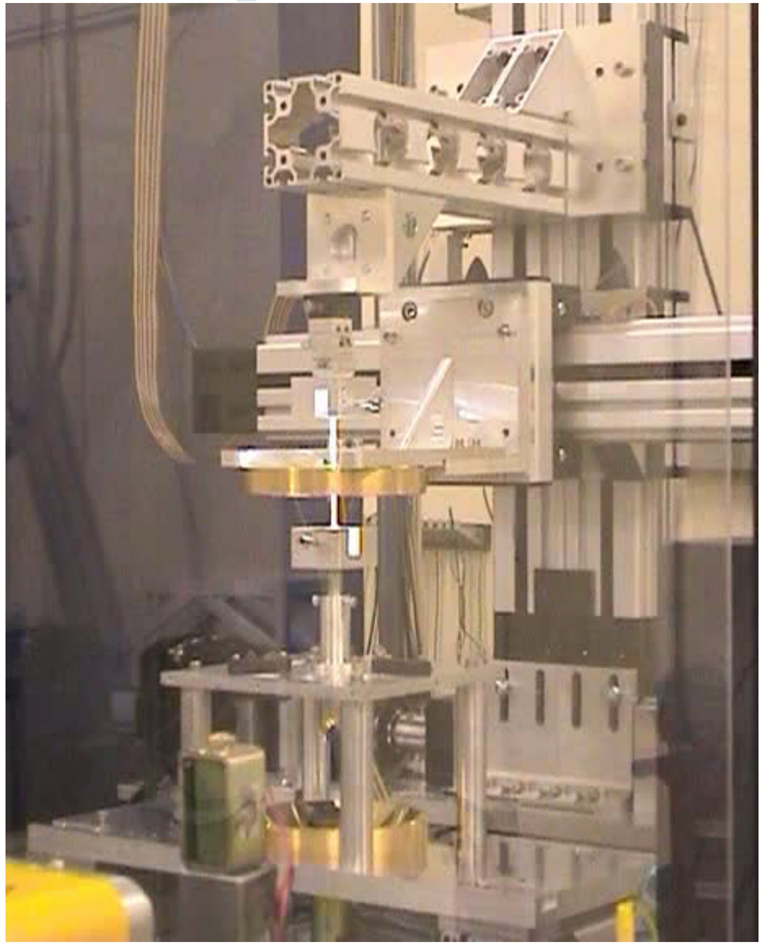
- Fused silica test masses will be supported by fused silica fibers.
  - Fibers welded to silica "ears" which are silicate bonded to the test mass.
  - Glasgow has developed a laser fiber drawing and welding apparatus.
- No Actuation on bottom test mass.
  - Actuation on upper test mass. Actuate against the reaction mass.
  - Marionette control of lower test mass
- Upper two pendula masses are Maragen Steel anti-springs and reaction masses.
- Prototype is now being assembled and tested at MIT in LASTI.



Mirror: 40 kg silica mass



Detail of fibre shape close to weld: thick flexure region used to minimize thermoelastic noise



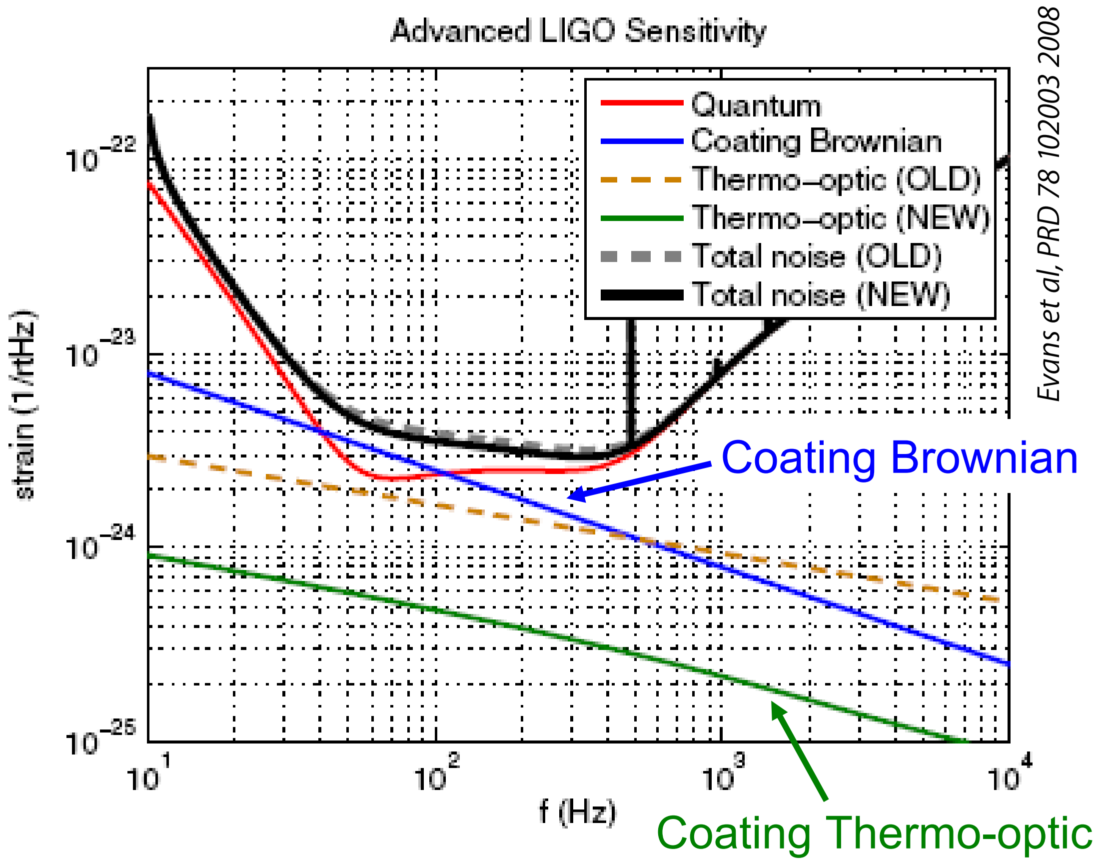
Mirrors polished to sub-nm accuracy
0.5 ppm absorption
R > .99999

Image Credit: LIGO Laboratory, MIT/Caltech

LIGO Coating Thermal Noise History

The Problem

- Initial LIGO mirror coatings are alternating layers of tantala/silica
- Tantala has high mechanical loss (internal friction).
  - 4 μm of tantala noisier than 15 cm silica.
- Dominant noise at most sensitive frequencies



Coating Brownian

Coating Thermo-optic

Evans et al, PRD 78 102003 2008

Current Solution

Titania-doped tantala / Silica

- 40% lower loss
- Layer thicknesses optimized for low loss, equal reflectivity

Ongoing Research

- Amorphous coatings:
  - Annealing / Heated-substrate
  - Dopants
  - Structural measurements
- Crystalline Coatings:
  - AlGaAs
  - AlGaP

LIGO Coating Thermal Noise Future

- Reductions in coating thermal noise required
- Upgrades to aLIGO detectors
  - A+: room temperature, 1064nm (could we change wavelength?)
  - Voyager - 120 K, Si optics, 1550nm / 2μm (20K possibility?)

  - For reference, aLIGO ETM coating loss (2 +/- 0.1)E-4
    - loss of Ti:Ta2O5 = 2.4E-4
    - loss of SiO2 = 5E-5

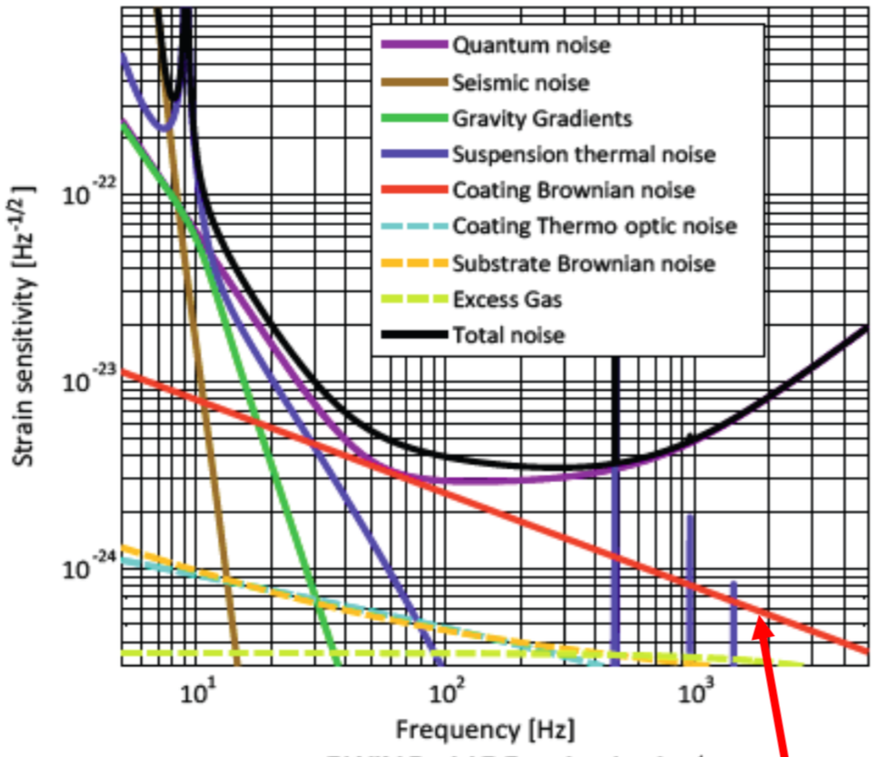
Temperature

Coating thickness

$$S_x(f,T) \approx \frac{2k_B T}{\pi^2 f}\frac{d}{w^2\,Y}\phi\left(\frac{Y'}{Y}+\frac{Y}{Y'}\right)$$

Laser beam radius

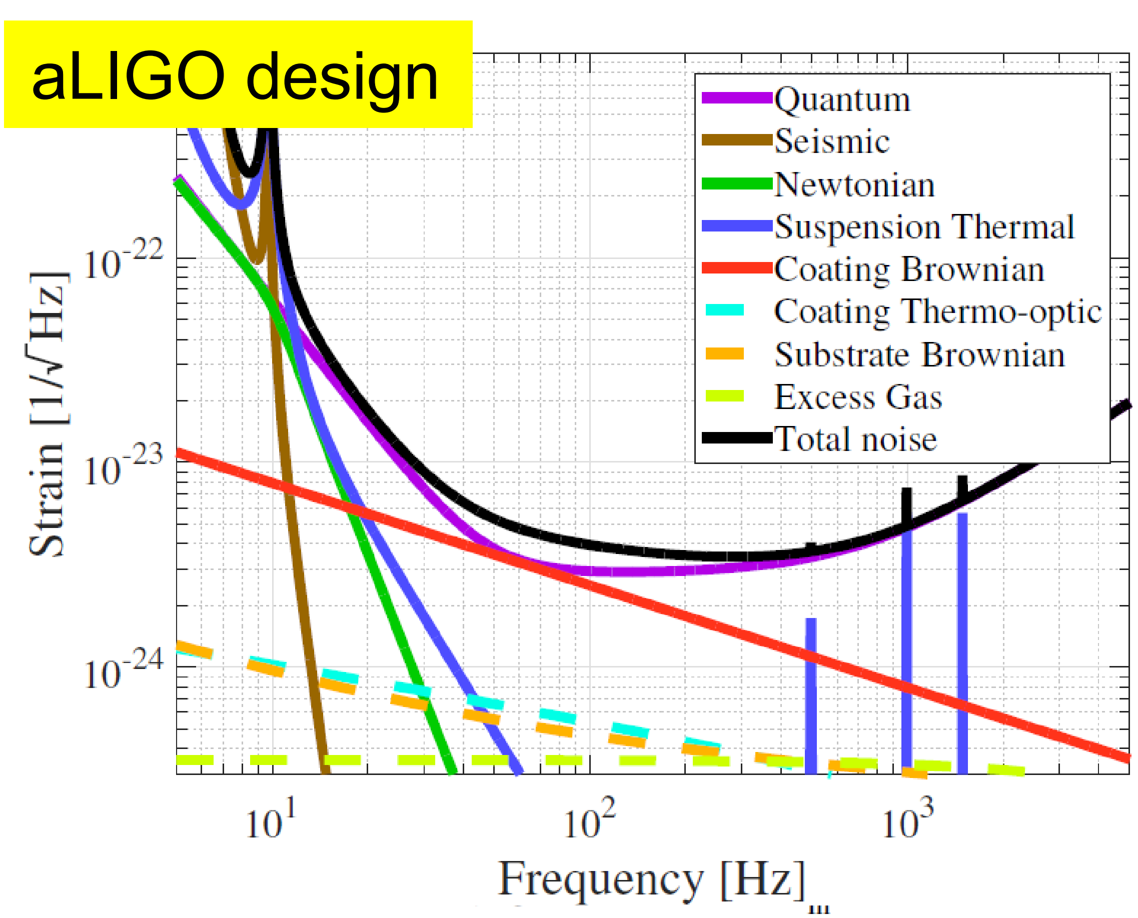
Coating mechanical loss

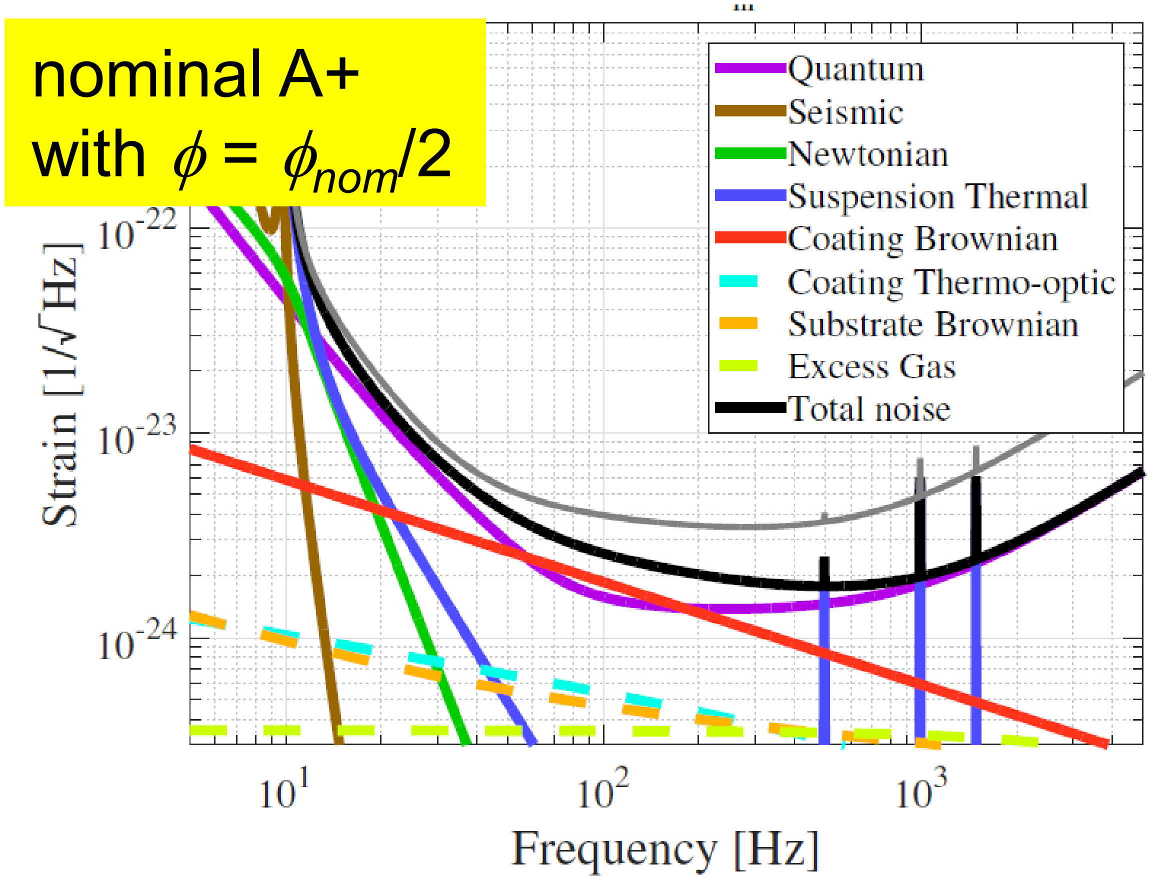


GWINC aLIGO noise budget

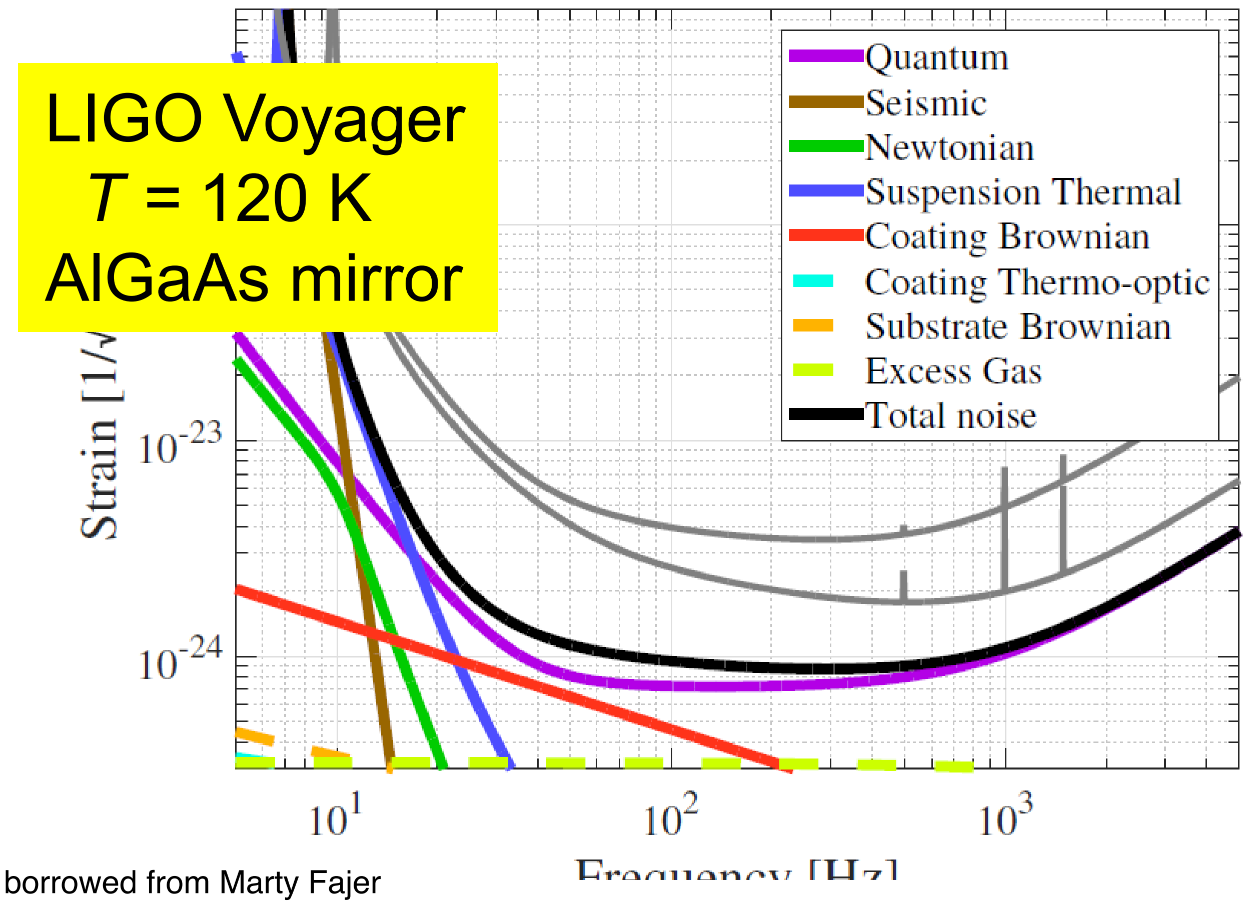
Coating thermal noise

Reduced Elastic Loss in LIGO Mid-Band


aLIGO design


nominal A+

with $\phi = \phi_{nom}/2$


LIGO Voyager

T = 120 K

AlGaAs mirror

coating elastic loss

coating thickness

$$S_x(f,T) \approx \frac{2k_BT}{\pi^2 f}\,\frac{d}{w^2 Y}\,\phi\left(\frac{Y'}{Y}+\frac{Y}{Y'}\right)$$

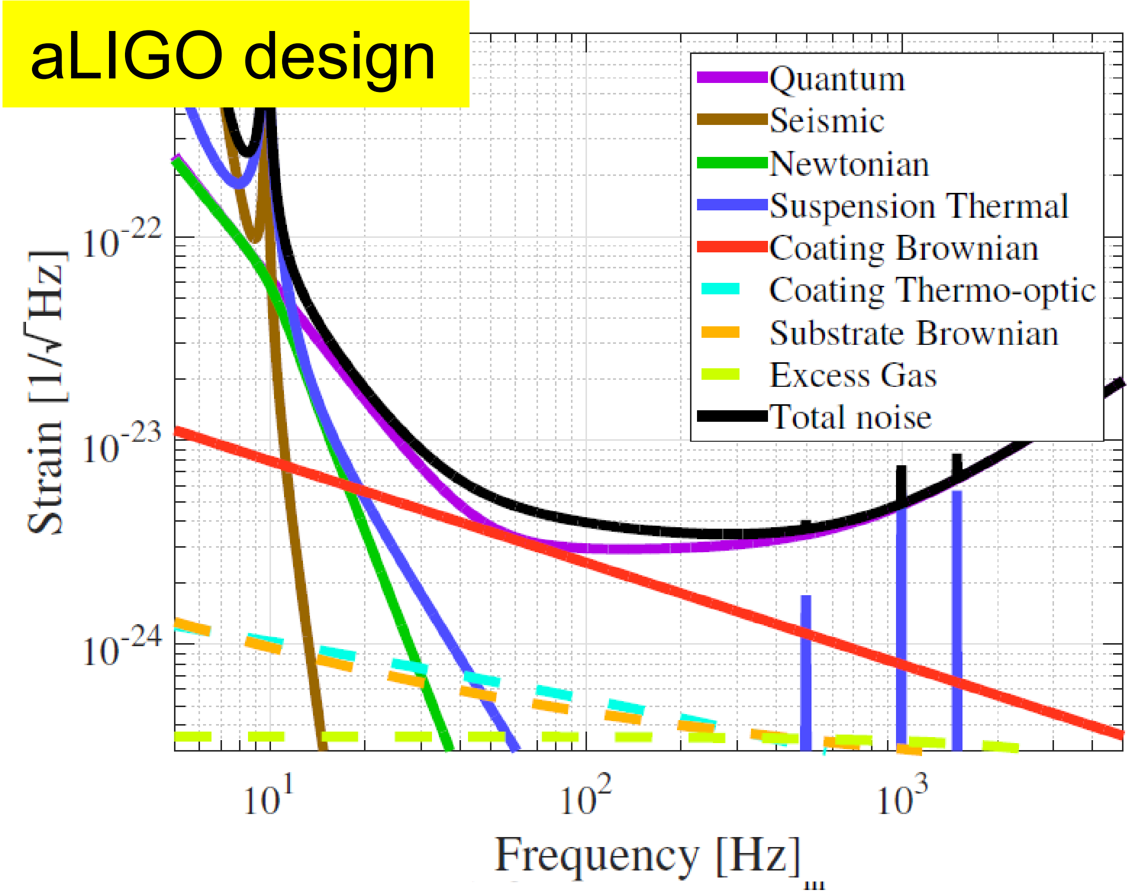
beam radius

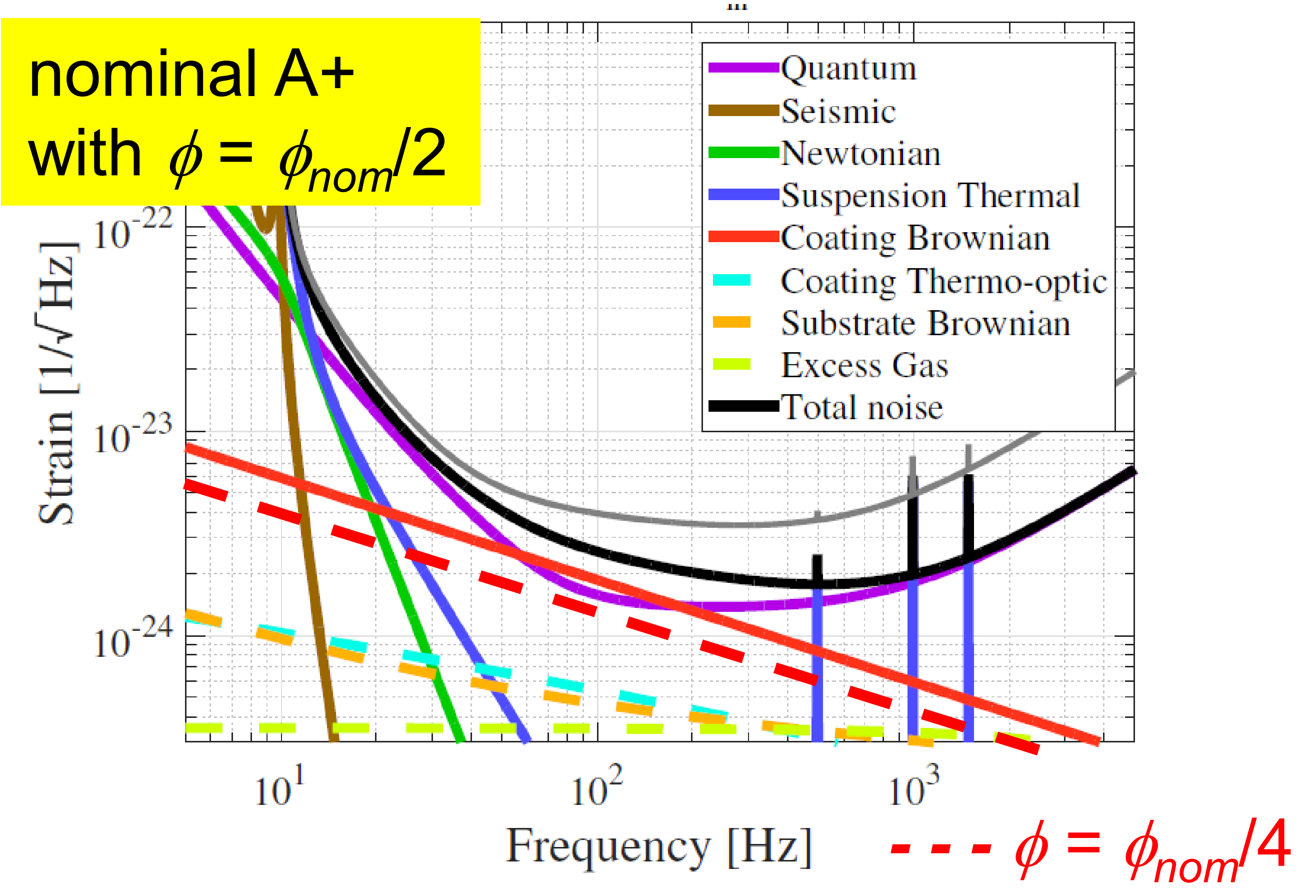
$$\phi_{\mathrm{TiO_2:Ta_2O_5}} = 2\times10^{-4}$$
$$\phi_{\mathrm{SiO_2}} = 4\times10^{-5}$$
$$\phi_{\mathrm{AlGaAs}} = 2.4\times10^{-5}$$

Plots from LIGO-T15TBI-v1, I.S. White Paper

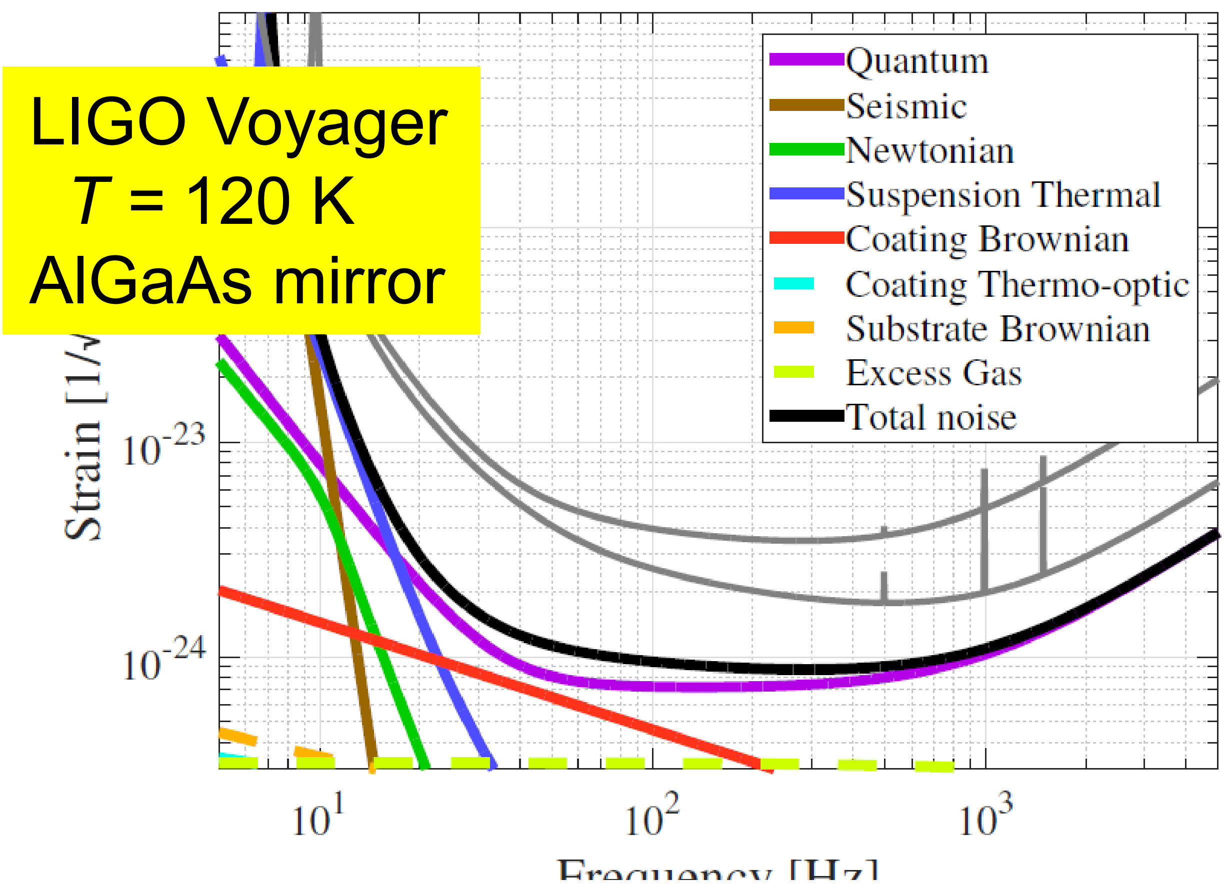
Slide borrowed from Marty Fajer

Reduced Elastic Loss in LIGO Mid-Band


aLIGO design


nominal A+ with $\phi = \phi_{nom}/2$

- - - $\phi = \phi_{nom}/4$


LIGO Voyager
T = 120 K
AlGaAs mirror

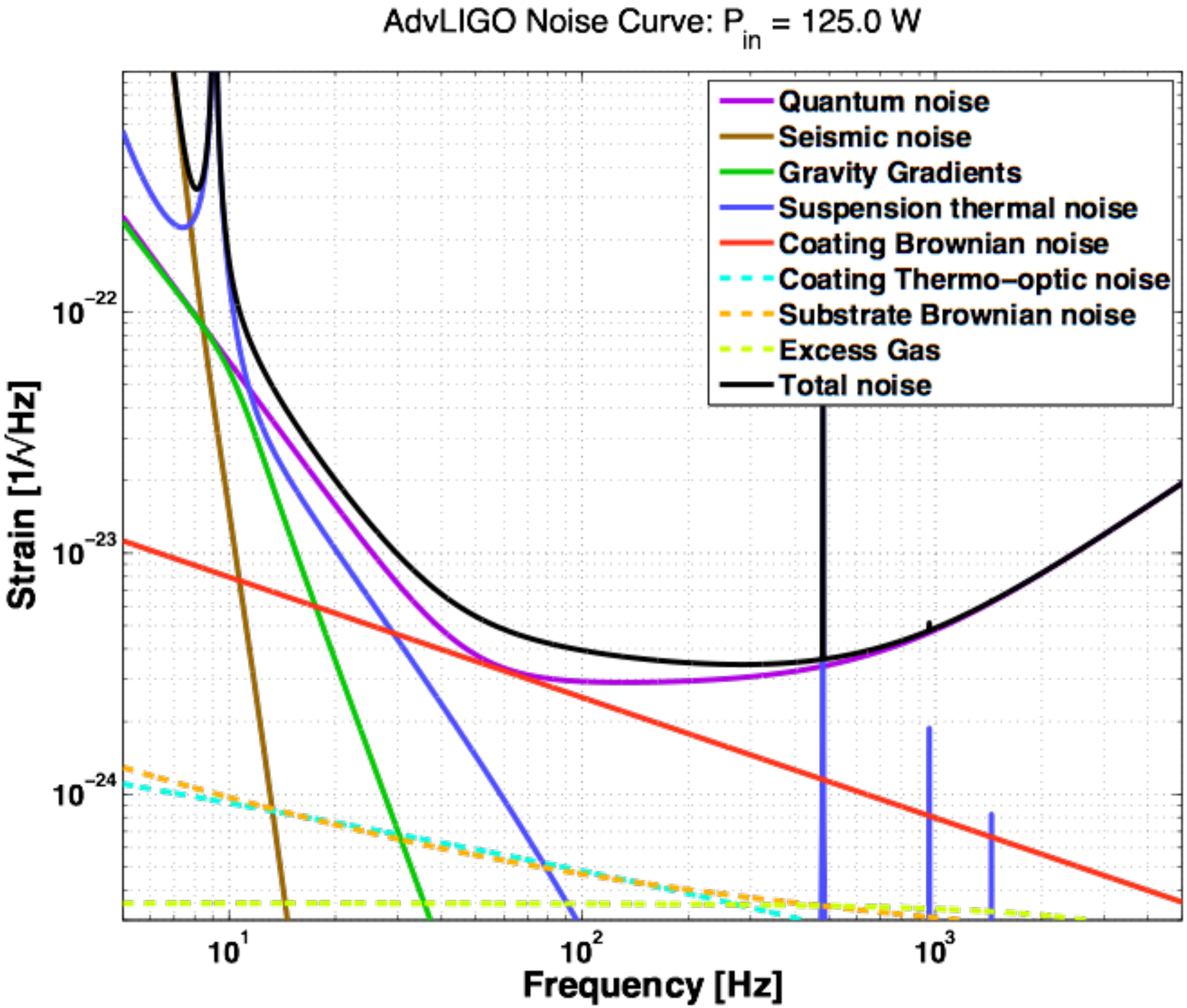
$$S_x(f,T) \approx \frac{2k_BT}{\pi^2 f}\,\frac{\overset{\text{coating thickness}}{d}}{\underset{\text{beam radius}}{w}^2 Y}\,\overset{\text{coating elastic loss}}{\phi}\left(\frac{Y'}{Y}+\frac{Y}{Y'}\right)$$

$$\boxed{\begin{aligned}\phi_{\mathrm{TiO_2:Ta_2O_5}} &= 2\times10^{-4}\\ \phi_{\mathrm{SiO_2}} &= 4\times10^{-5}\\ \phi_{\mathrm{AlGaAs}} &= 2.4\times10^{-5}\end{aligned}}$$

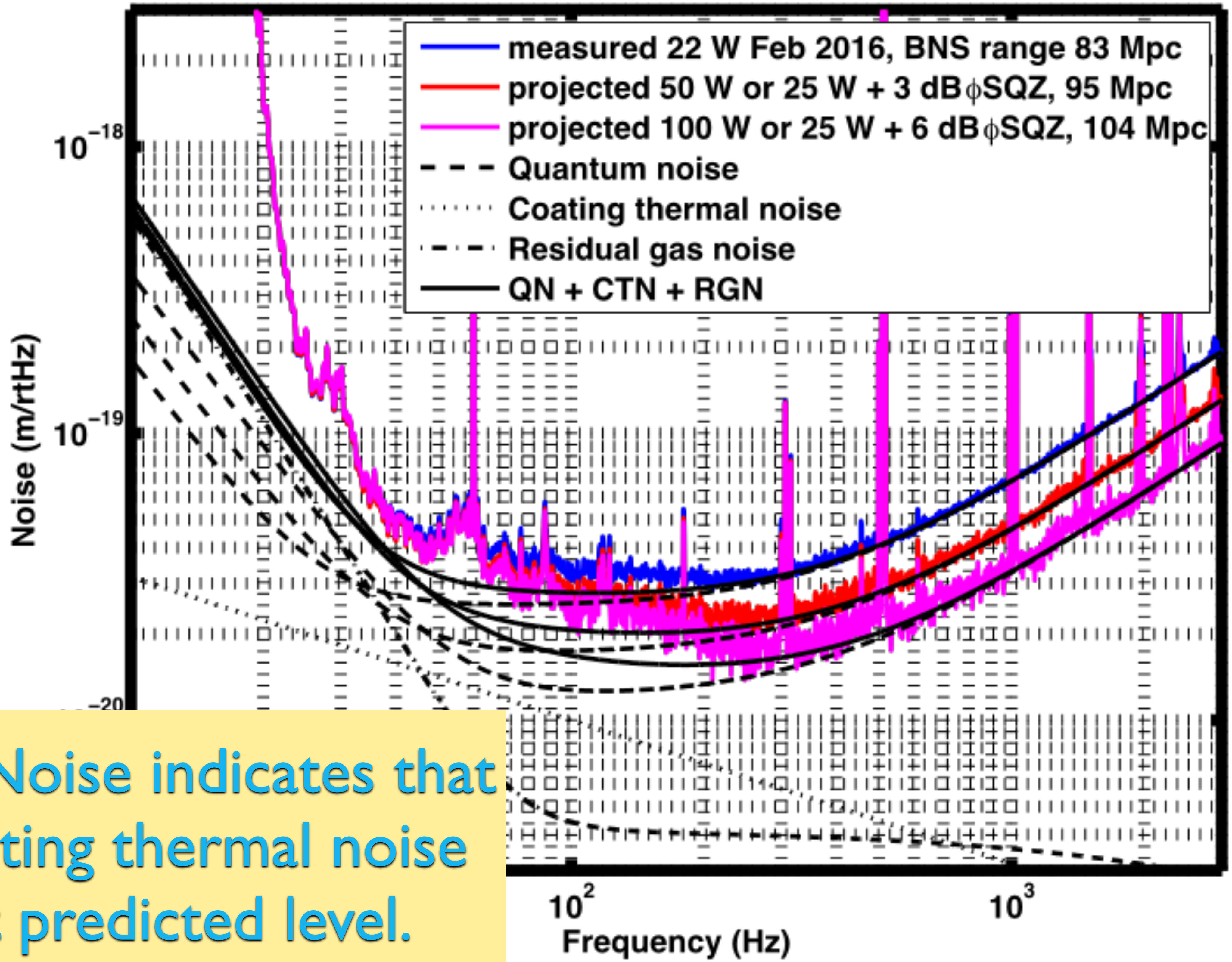
Plots from LIGO-T15TBI-v1, I.S. White Paper

Slide borrowed from Marty Fajer

The Challenge: Coating Thermal Noise



The Challenge: Coating Thermal Noise

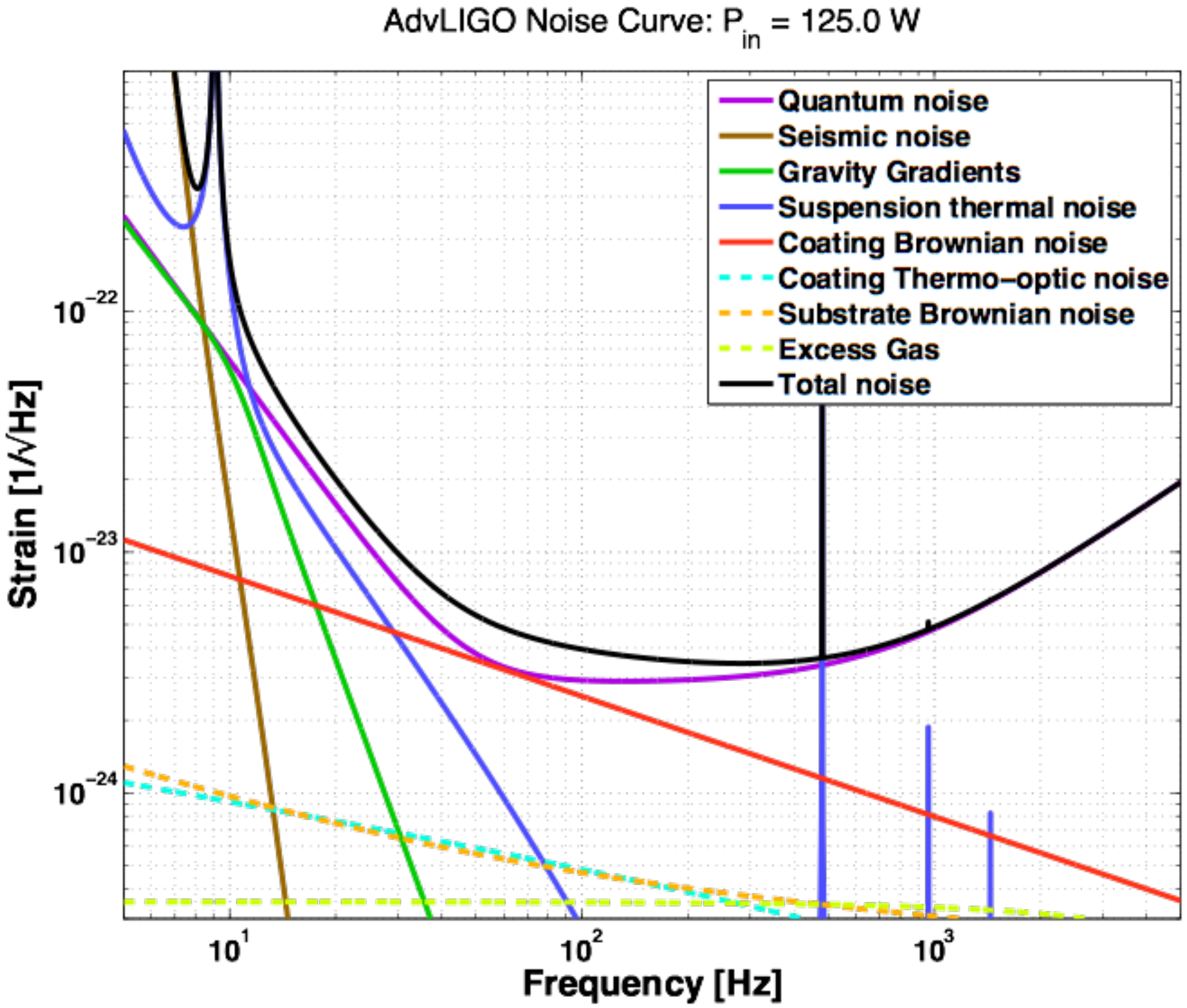


IFO Noise indicates that Coating thermal noise at predicted level.

Borrowed from P. Fritschel, G1600705-v1

Thermal Noise

Thermally-activated motion of the mirror that couples into the interferometer signal.

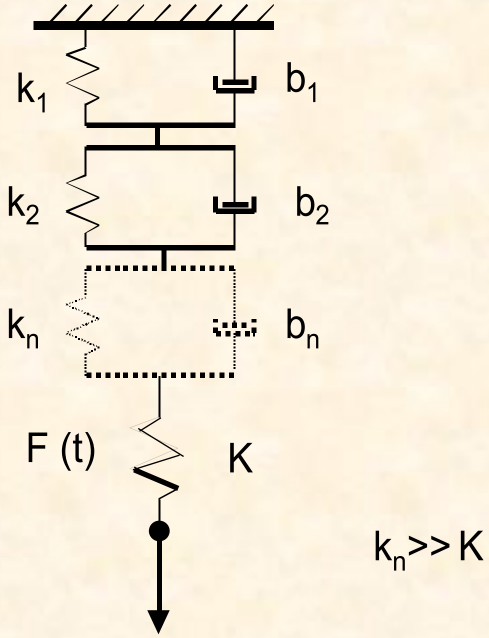


- Motion on resonance is the elastic response. Notch filtered.
- "Thermal Noise" is the off-resonance motion = inelastic response. Dissipation causes the off-resonant motion.
- Fluctuation-Dissipation Theory describes the spectrum of a dissipative system.

Fluctuation-Dissipation Theorem

- Start with a linear systems (ie. damped H. O.)

$$F_{\rm ext}(f) = m\ddot{x} + b\dot{x} + kx$$



- Define the impedance, Z, as $F_{\rm ext}(f) = Z\, v(f)$

  or the admittance, Y, as $Y(f) \equiv Z^{-1}(f)$

- The Fluctuation-Dissipation Theorem states

$$F^2_{\rm Therm}(f) = 4k_{\rm B}T\,\Re\big(Z(f)\big) \qquad x^2_{\rm Therm} = \frac{k_{\rm B}T}{\pi^2 f^2}\Re\big(Y(f)\big)$$

- Model material with a complex spring constant,

$$k\big(1 + i\phi(f)\big) \qquad x^2(f) = \frac{4k_{\rm B}T}{k}\,\frac{\phi}{2\pi f\left[\left(1 - f^2/f_0^2\right)^2 + \phi^2\right]}$$

Dissipation: Double Well Potential

Asymmetric Double Well Potential (ADWP): Thermal excitation to the higher energy state and dissipation when the system relaxes. The relaxation time is assumed to obey an Arhenius process

$$\tau = \tau_0 e^{U/kT}$$

where *U* is the potential barrier height (or Activation Energy)

- At the loss peak

$$\log \omega = -\log \tau_0 - U/kT$$

- Frequency dependence of the loss peak gives the activation energy, *U*

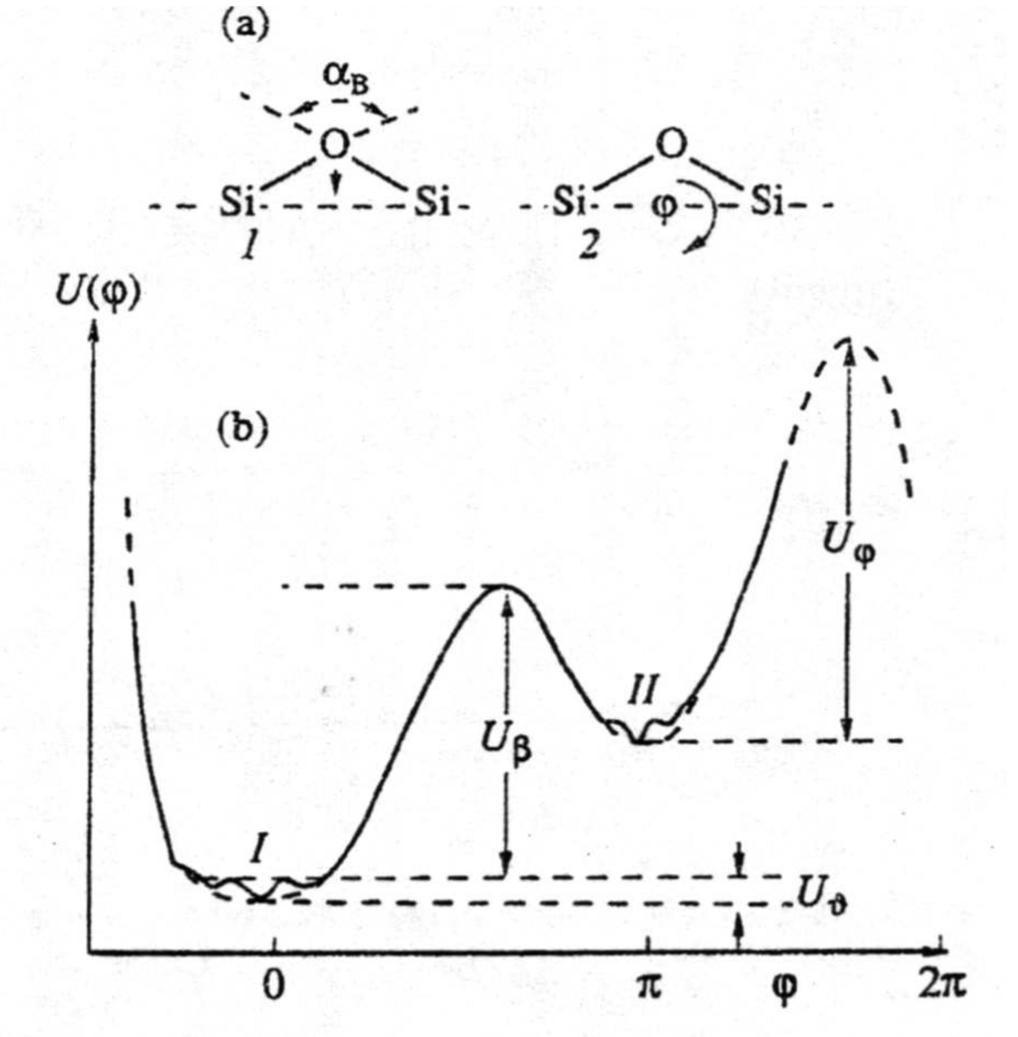


Fig. 7. (a) Two types of Si–O–Si mobility: (*1*) variable bond angle α_B (bending of the Si–O–Si unit), (*2*) rotation about the Si–Si axis; (b) potential energy vs. angle of rotation of the Si–O–Si unit: (*I*) ground state, (*II*) excited state.

Gilroy & Phillips

Dissipation: Debye Loss Model

Dissipation mechanism has a Relaxation time, τ. Sample oscillation frequency is ω.

Maximum loss peak when $\omega\tau$=1 (Debye condition)

This gives a loss peak with the form

$$\phi = \phi_0 \frac{2\omega\,\tau}{1+(\omega\,\tau)^2}$$

Dissipation in Amorphous Materials

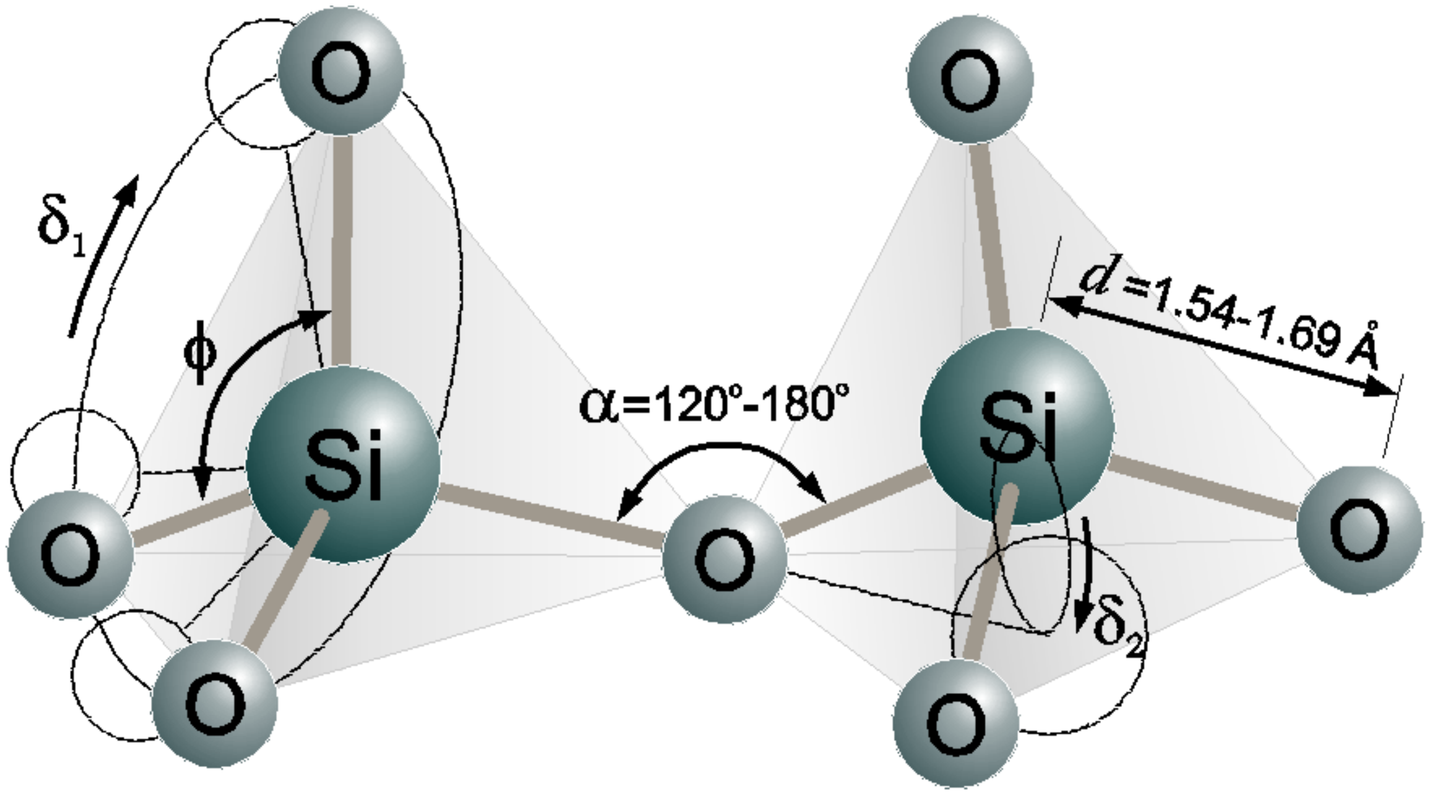
- For amorphous materials there is a distribution of barrier heights, $g(U)$.
- The total loss is

$$\phi \propto \int_0^\infty \frac{\omega\,\tau}{1 + (\omega\,\tau)^2}\, g(U)\, dU$$

- Assuming an exponential barrier height distribution, $g(U) = \frac{1}{U_0} e^{-U/U_0}$ then

$$\phi \propto f^{kT/U_0}$$

Silica Structure



SiO_2 forms tetrahedral structure

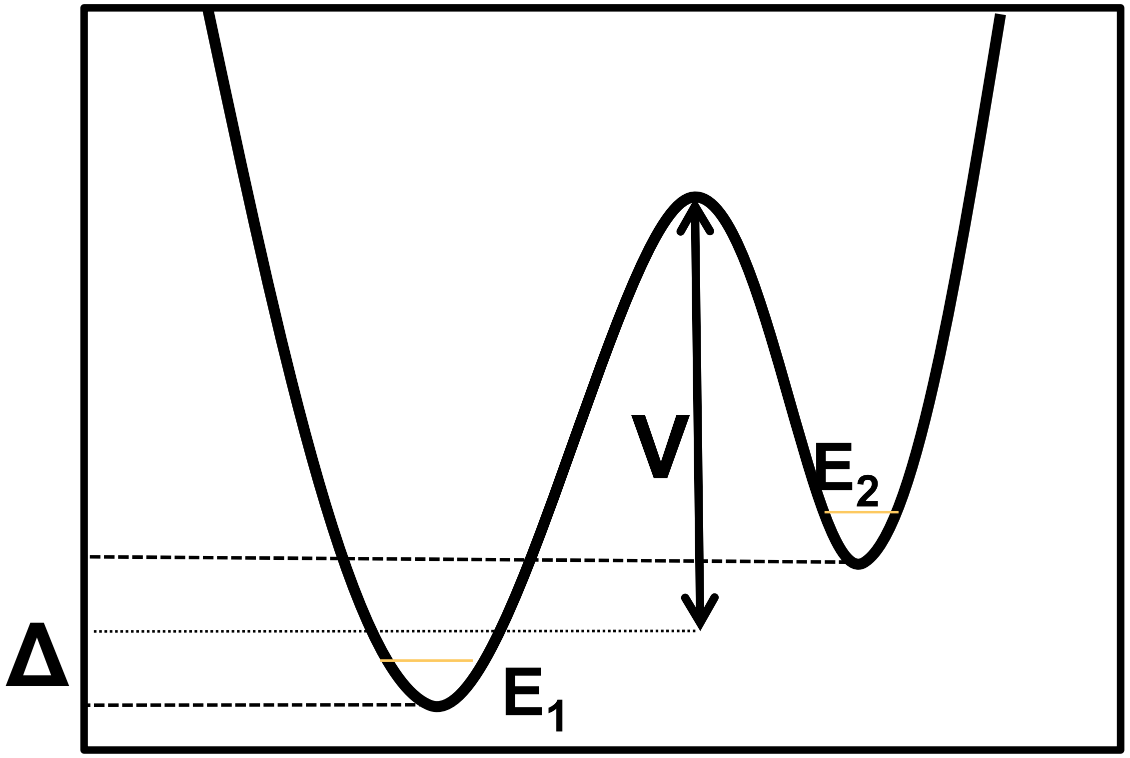
Tetrahedron bonds "fixed" at 109°. Si-O-Si bonds range from 120–180°.

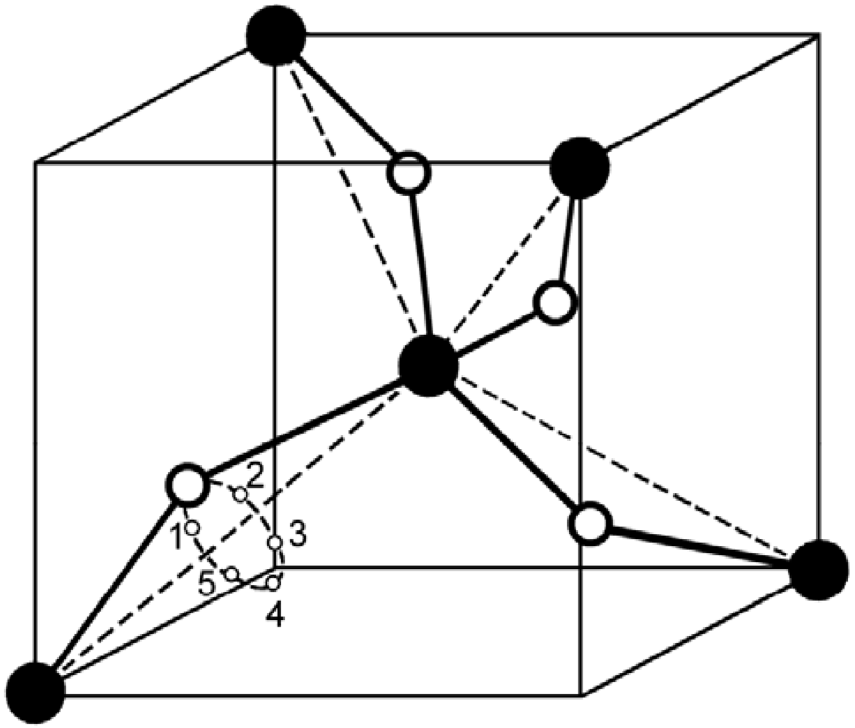
Loss Mechanisms:

- Si-O-Si bond angle shift.
- Rotation about Si-O bond
- Breaking Si-O bond

Low-frequency losses in amorphous dielectrics

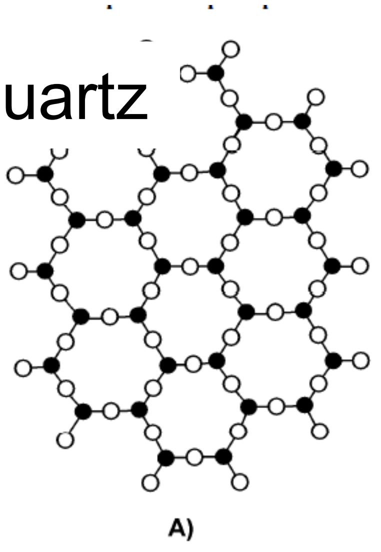
- Conventionally associated with low energy excitations (LEEs)
  - conceptualized as two-level systems (TLS)

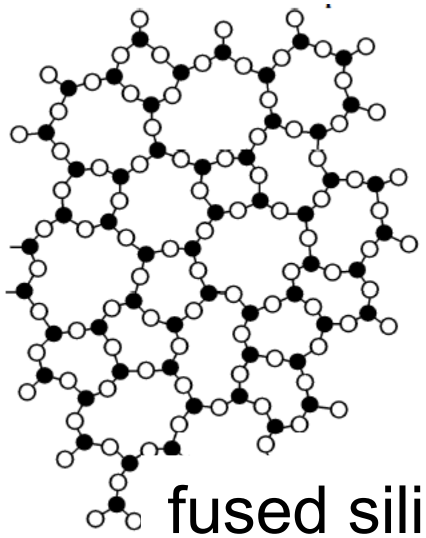




Oversimple picture: bond flopping

crystal quartz





fused silica

(●= Si, ○ = O).

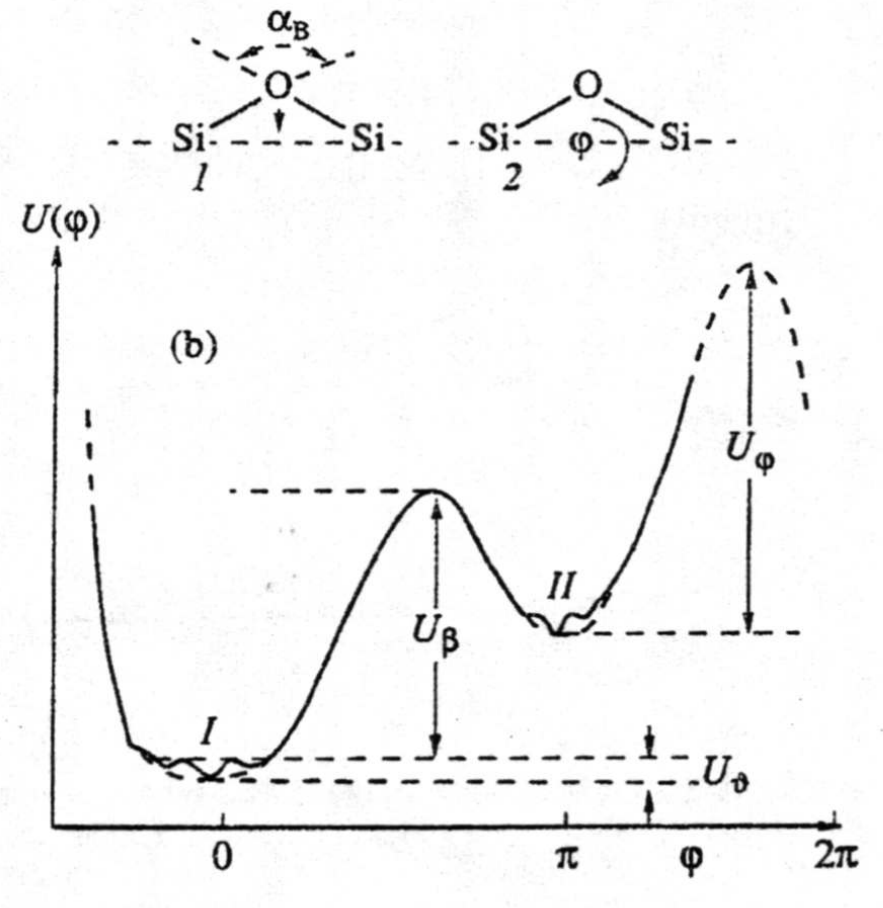
Distribution of TLS in silica due to disordered structure

figures from B.S. Lunin monograph

Slide borrowed from Marty Fajer

Silica Loss Peaks

- Silica forms larger structures, chains, and rings with a distribution of sizes depending on impurity level and thermal processing.
- The ϑ peak = shift in Si-O-Si bond angle. A kink or flexure of the silica chain.
- The β peak = rotation about Si-O bond. Torsional oscillation of section of silica chain.
- The α peak = breaking Si-O bonds. Glass-liquid transition.



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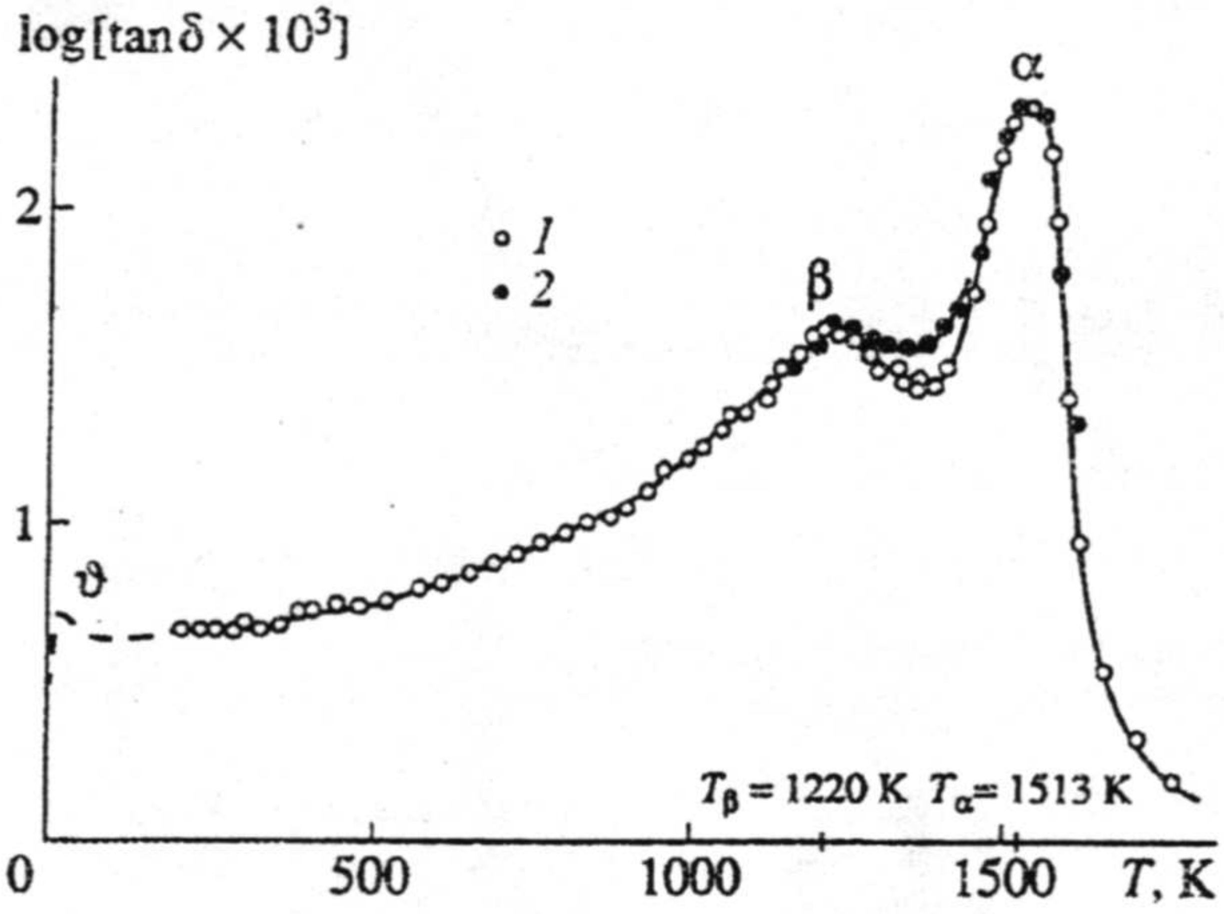


Fig. 2. Internal friction spectrum of vitreous silica (Kyshtym quartz) at ν = 1 Hz; tan δ—mechanical loss tangent; (*1*) present work, (2) earlier data [48].

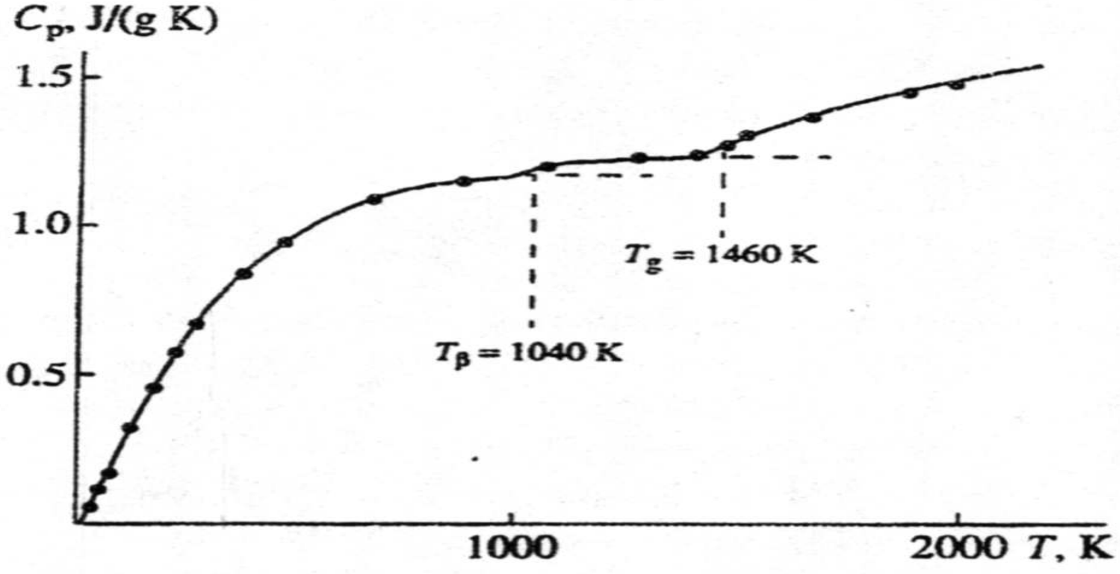
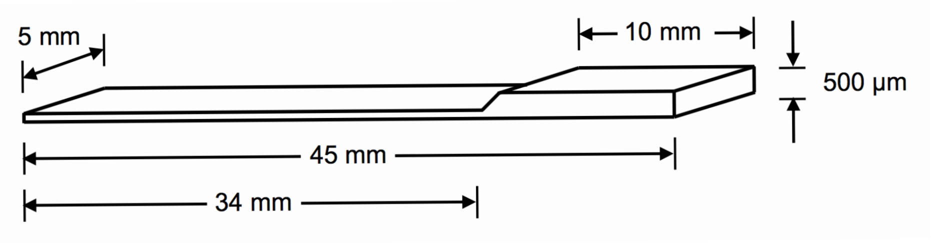
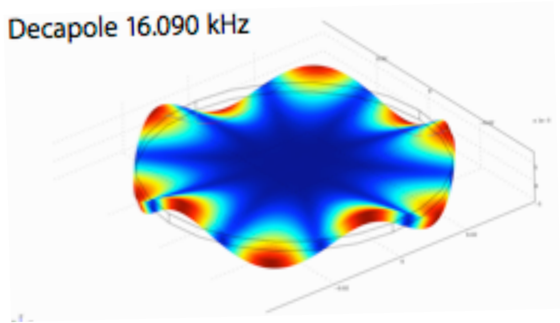


Fig. 3. Heat capacity of vitreous silica as a function of temperature [15].

Bartenev 1996

Methodologies





- Mechanical loss measurements
  - Cryogenic Measurements on Cantilevers [Glasgow]
  - Room temperature measurements on thin disks [HWS & AU]
- Structural measurements
  - Bond length and element distribution: EXAFS; FEM; EELS, XRD, NMR [Stanford & Glasgow]
  - Elastic modulus measurements [Caltech & Glasgow]
- Direct Thermal Noise Measurements
  - Optical Cavities [Caltech & Florida]
  - Thermo-optic measurements [ERAU & Whitman]
- Theoretical Models [Florida]
  - Young's Modulus and loss approaching observed values.

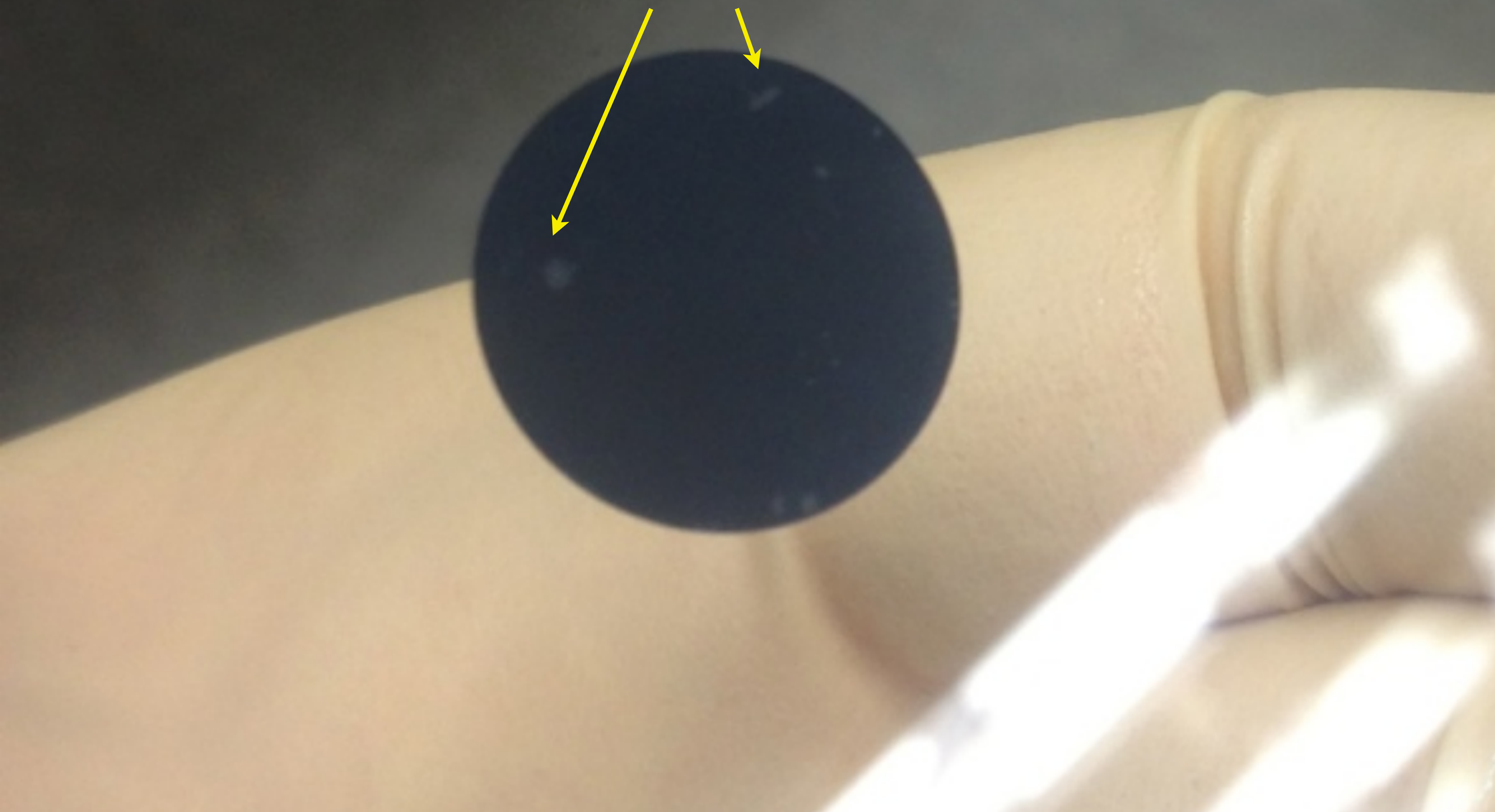
Crystalline Coatings

- AlGaAs
  - Low mechanical loss ≈ 2 x 10^{-5} in optical cavity measurements.
    [Cole, et al., *Nature Photonics*, vol. 7, pp. 644–650, Aug. 2013]
  - Size limitations:
    - 1.6 cm —> 15 cm in 3 years,
    - Move to aLIGO test mass size, at least 5-10 years (G.Cole)
  - Adhesion flaws:
    - Repeated measurements of 1.6 cm coatings. Lowest loss ≈ 1.2 x 10^{-4}
    - G. Cole believes the problem is fixed
    - New samples due this summer of a full-reflection stack
- AlGaP
  - Can be grown directly on silicon substrate
  - Stanford work (led by A. Lin) developed methods to minimize defects. Research suspended as A. Lin graduated.
  - Research in Glasgow continues in cooperation with local company

AlGaAs Sample

6.83 micron thick, 1.63 cm diameter

Areas of poor adhesion?

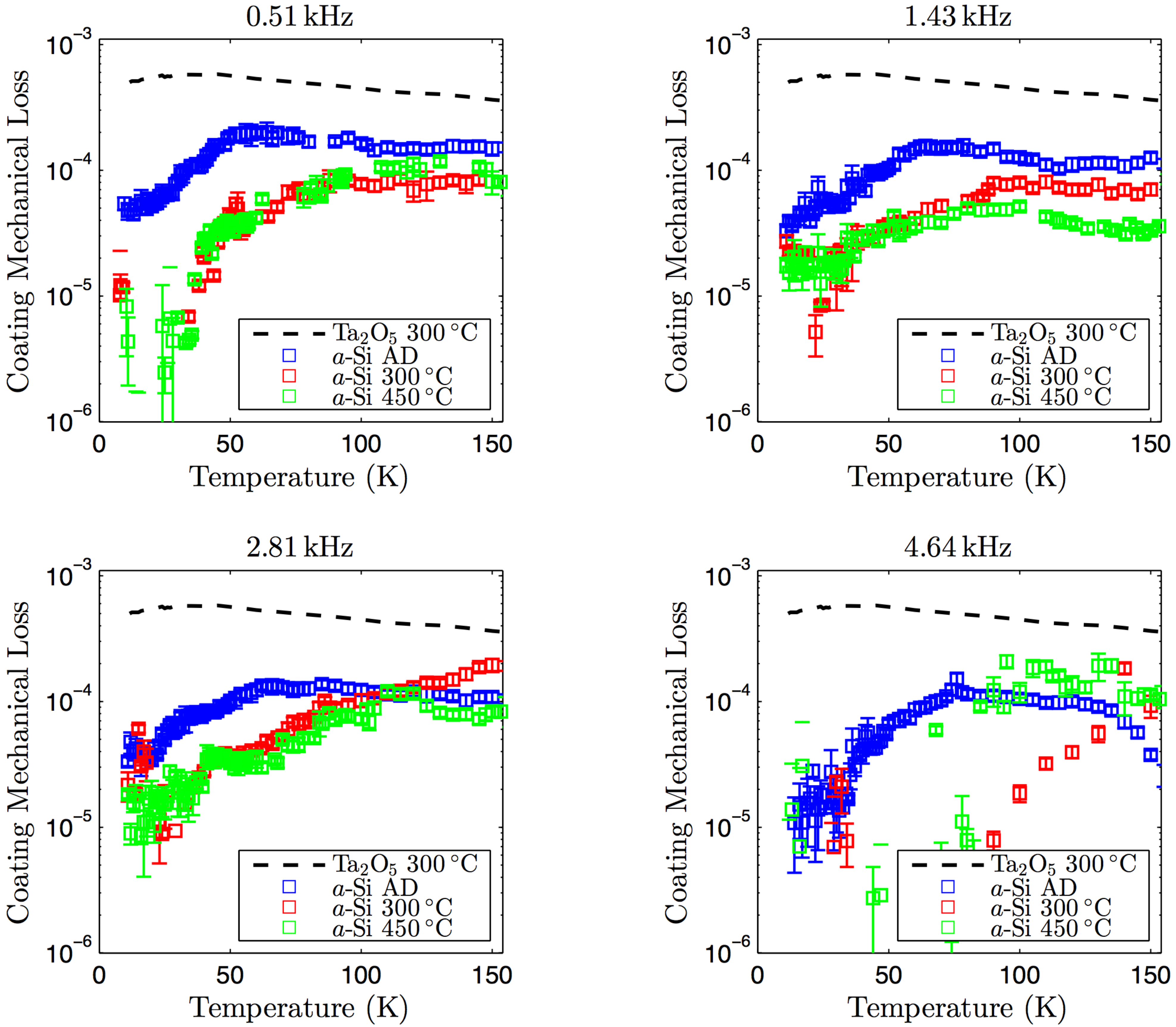


a-Silicon Coatings

- Future (Voyager, ET) to Silicon Test mass and 1.5 μm
- a-Silicon coating applied via IBS should have good optical properties
- Hot-wire CVD infused H (1 at.%) in Silicon coating yields low mechanical loss (<= 10^{-6}) [Liu, et al. PRL 78, 4418 (1997)].
- Research led by Peter Murray (Glasgow) [next slide]
  - Loss at cryogenic temperatures at few 10^{-5} rising to 10^{-4} at 300 K.
- New results from Liu [PRL 113, 025503 (2014)] for a-Silicon loss using EBD on heated substrate

a-SILICON COATING LOSS

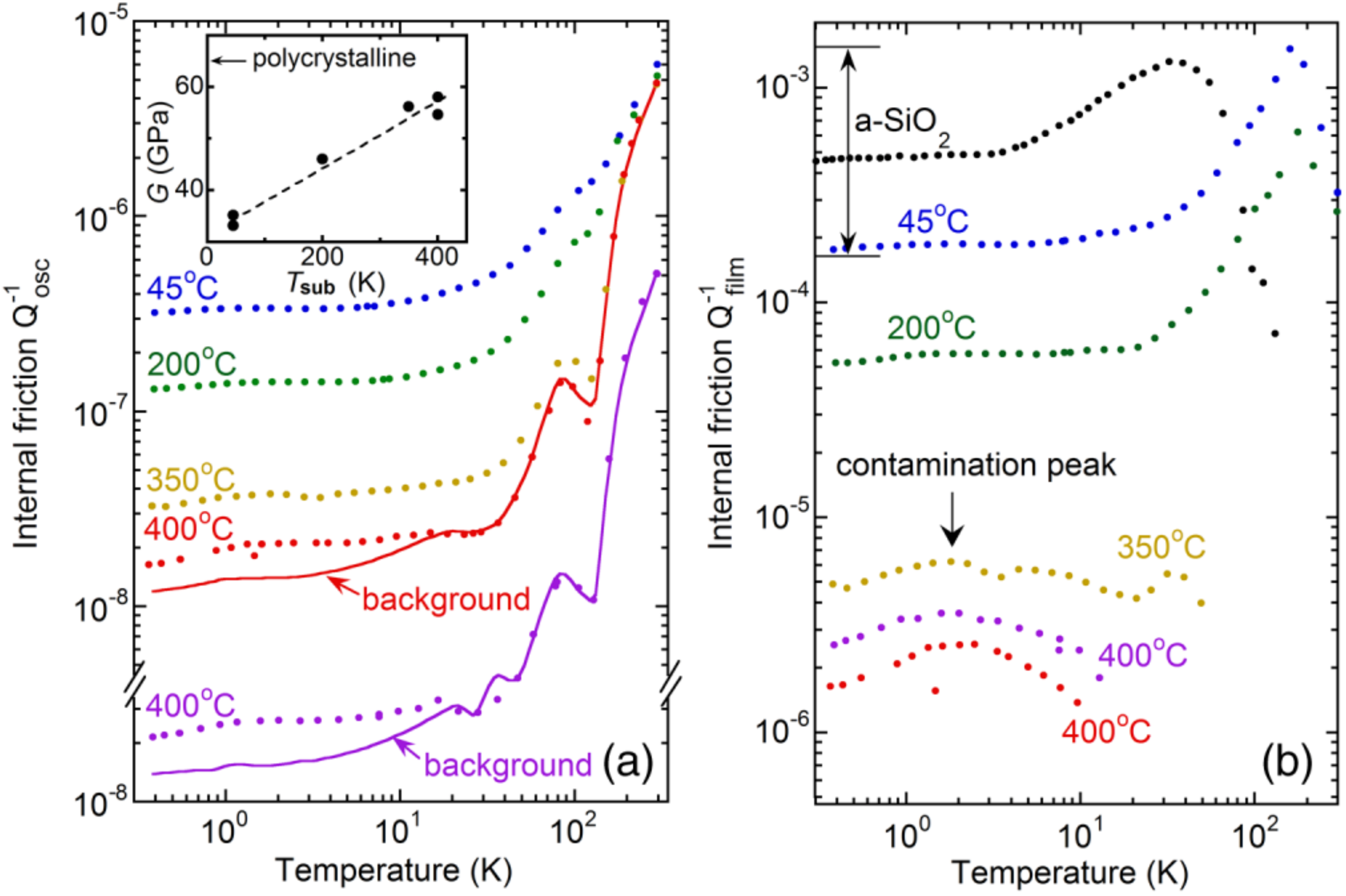
P. MURRAY (GLASGOW), et alia



a-SILICON COATING LOSS

XIAO LIU, et alia (2014)

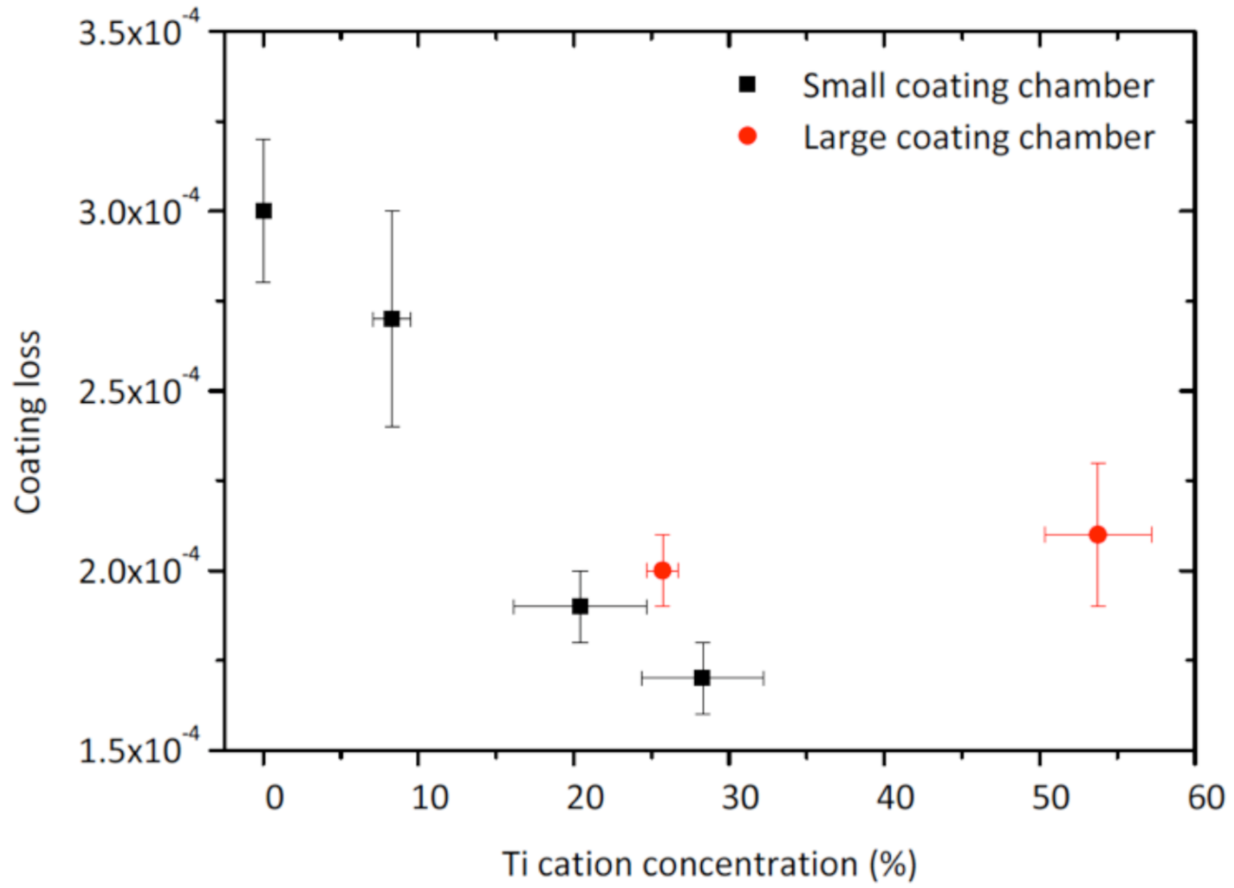
Heated Substrate: e-beam deposition



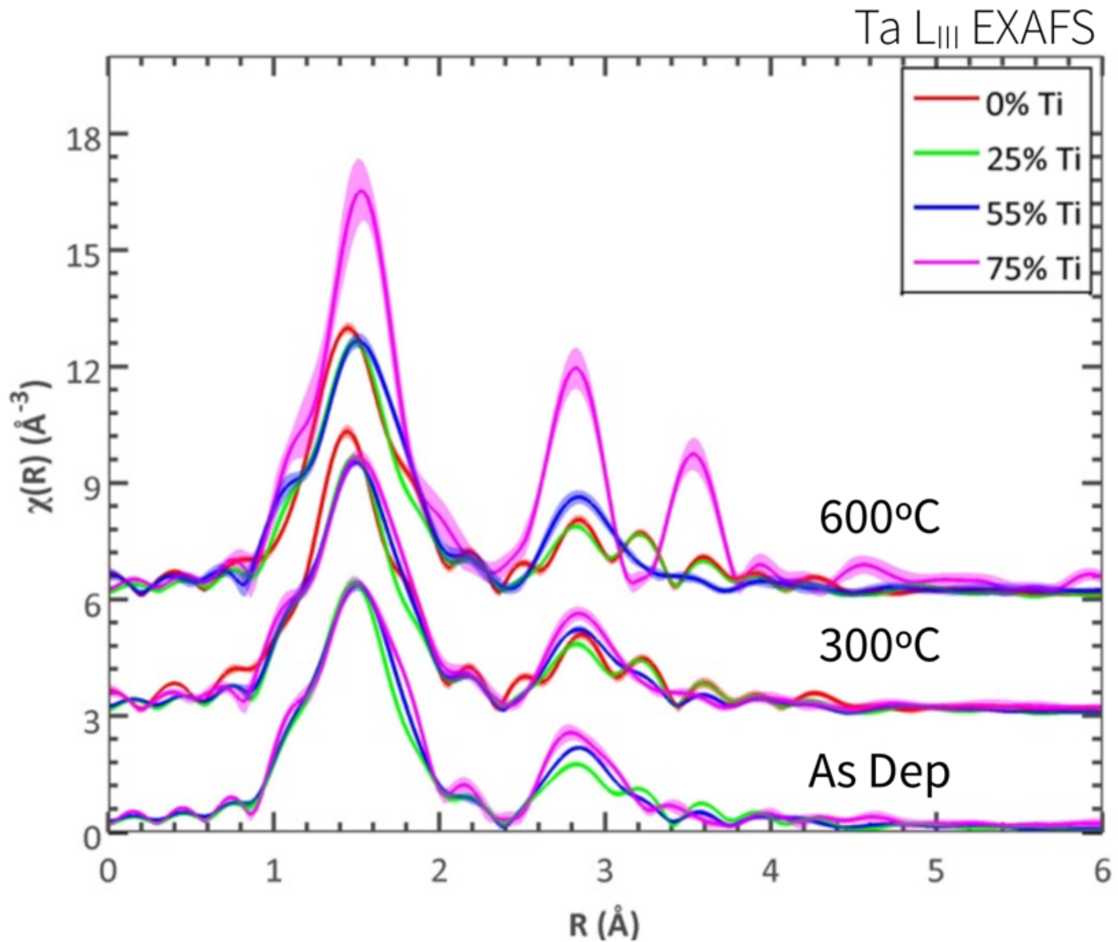
a-Silicon Coatings

- From Liu [PRL 113, 025503 (2014)] *“A densely packed and near perfect tetrahedrally bonded amorphous system can be physically constructed without requiring H by growing a-Si at a higher T, which we suggest was the dominant reason for removing the TLSs in both a-Si and a-Si:H. … Recent theoretical work suggests that amorphous solids consist of local regions of enhanced bond angle regularity embedded in a more disordered matrix with TLSs forming at the interfaces between those regions”*

Amorphous Coatings



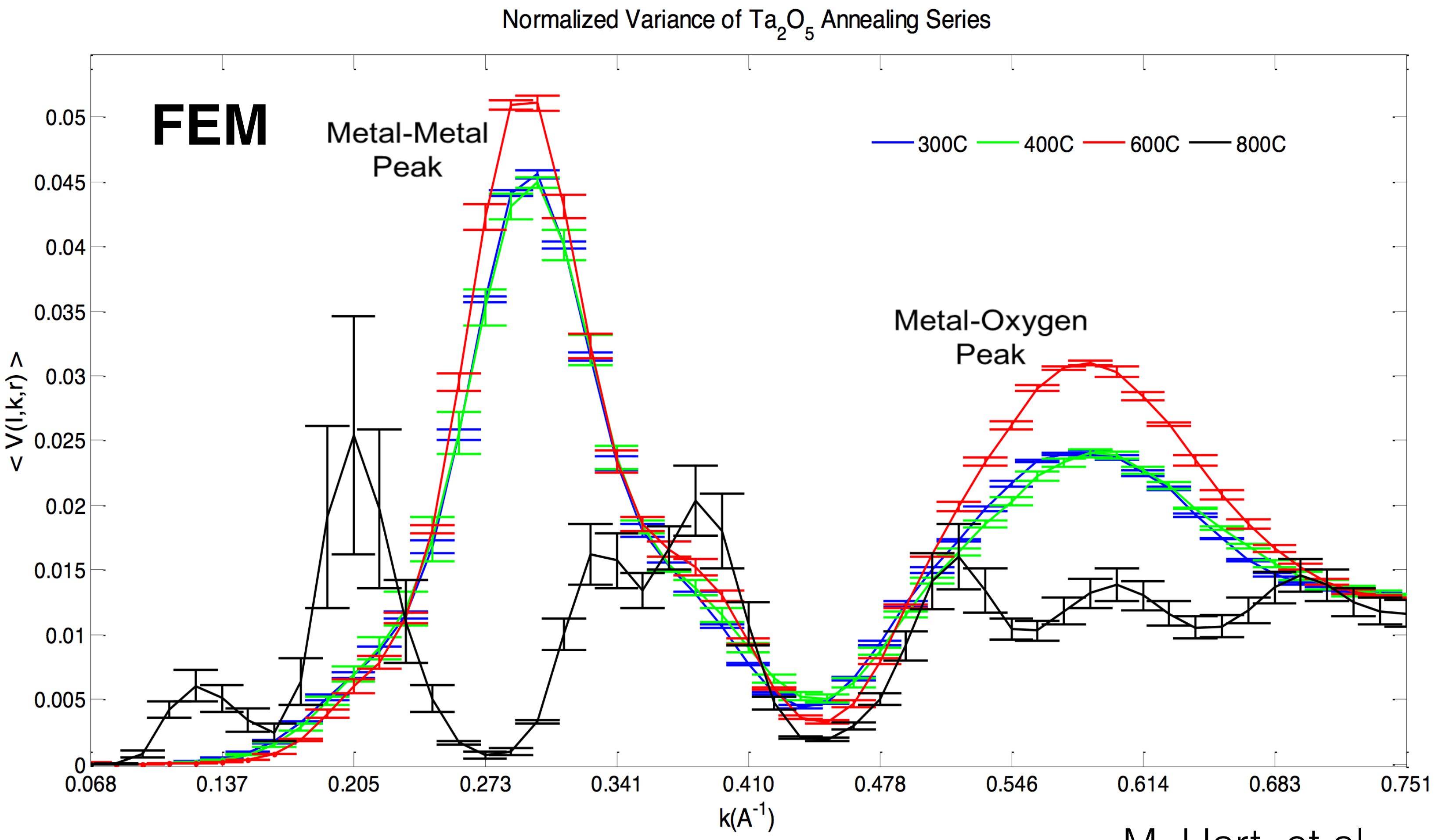
- Ti-doped Ta
  - Mechanical loss reduced 40% as Ti doped to 25%.
  - Doping also used to stabilize a coating against thermal damage.



- Annealing
  - Increased thermal stress can damage the coating or induce crystallization.
  - Annealing increases order
  - Reduces density variations,
  - Can correct O_2 deficiency,
  - Increases bandgap.

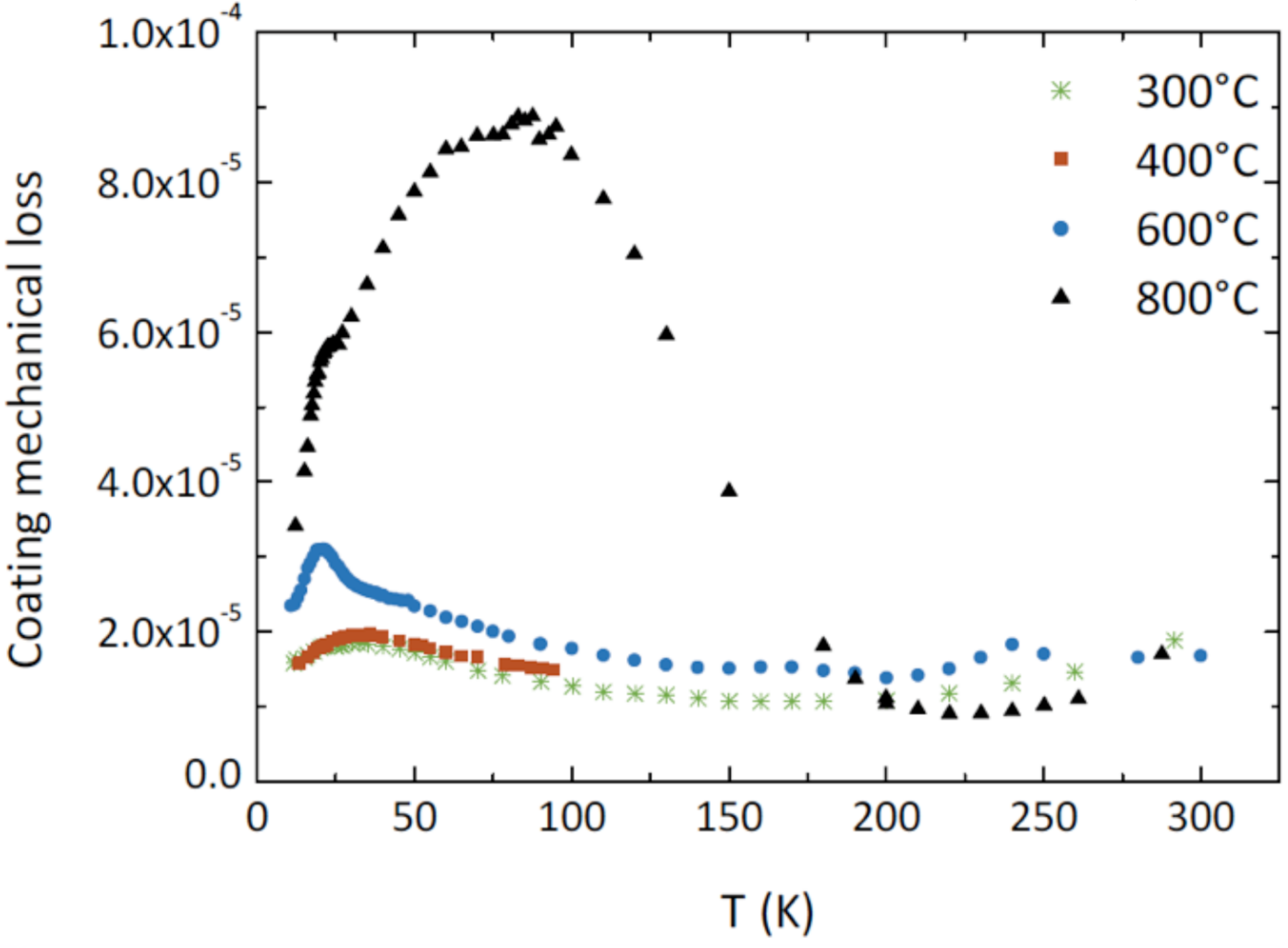
R. Bassiri, et al.

Amorphous Coatings



M. Hart, et al.

- Annealing Ta
  - Bond distribution narrows
  - Cryogenic Loss Peak narrows.
  - Crystallization (800 C) destroys that order and raises the mechanical loss.



I W Martin et al, CQG. 27 225020, 2010

Amorphous Coatings

- Developing a better coating.
  - Low loss dielectric, transparent at 1064 nm.

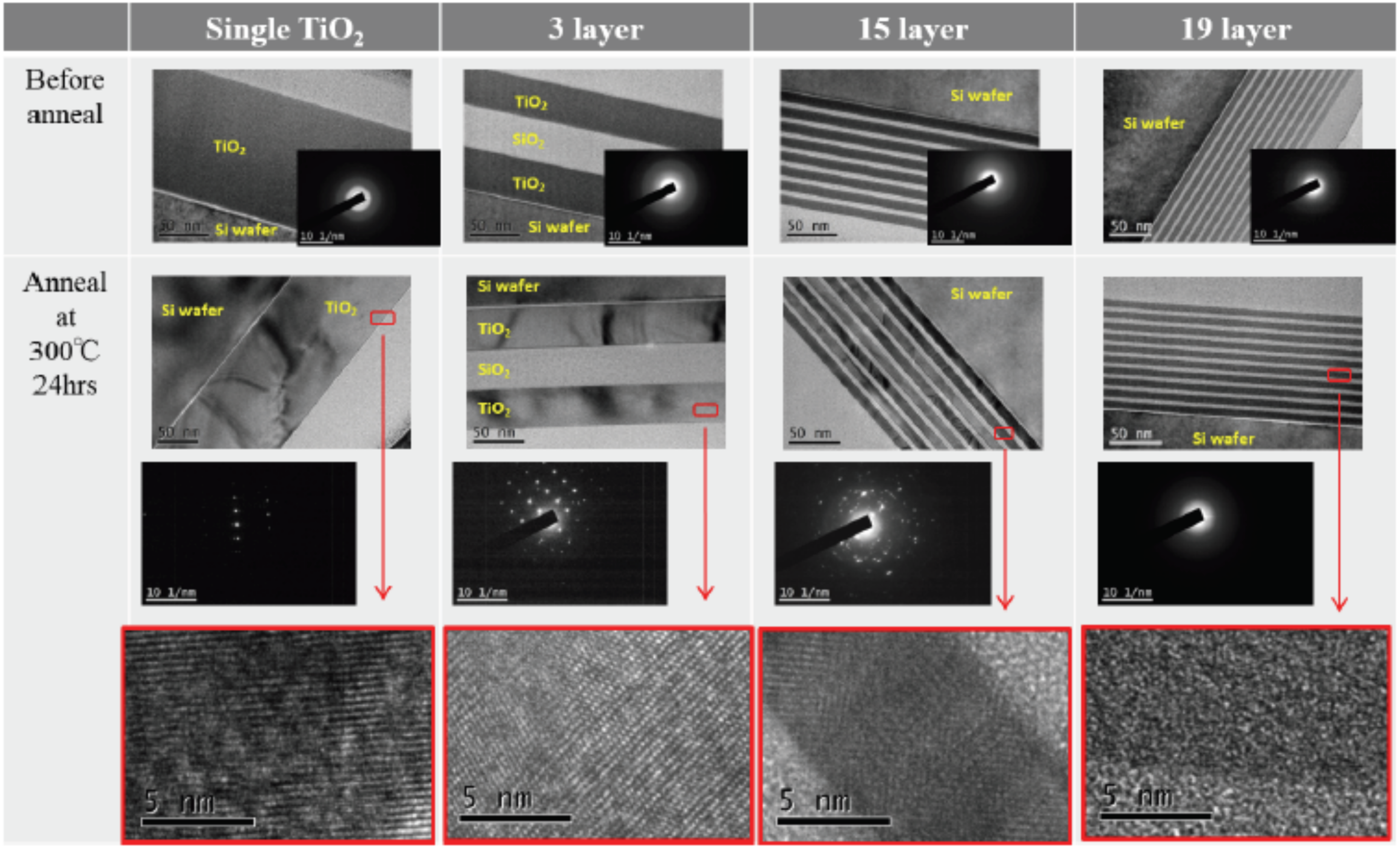
- Low loss, High-K Dielectric (semiconductor industry)
  - Studies narrowed to Stabilized Hafnia and Zirconia.
  - Stabilization: Silica-doped Hafnia, Silica-doped Zirconia, Zirconia-doped Zirconia
  - Stabilized Hafnia is currently used. (Not sure why.)

- High fluence, 1064 nm laser, minimizing damage.
  - Laser-induced damage studies focus on Hafnia & Zirconia
  - Annealed stabilized Hafnia has higher LIDT

R. Bassiri, et al.

I. Pinto, R. DeSalvo, S. Chao — Nanolayer coatings

TEM Before/After Annealing



[S. Chao et al., LIGO-G1300921]

TEM shows that no significant across-interface diffusion occurs during annealing

New Sannio Coating facility to move beyond few nm layer limit to <= 1 nm.
However the loss limit for Stabilized Titania may be ≈ 10^{-4}.

Prospects for Better Coatings

- **A+** (≈ 5 years) upgrade to Advanced LIGO
  - AlGaAs not ready (probably). … see Voyager
  - IBS high index coatings
    - Hafnia-Silica:
      - Loss, with annealing, higher that aLIGO
      - Requires better high temperature stability (?)
    - Zirconia-Silica, Zirconia-Tantala:
      - Stable to 800 C. Loss reduced strongly with annealing but substrate/coating loss must be isolated.
      - Absorption (10 ppm) too high. (Garilynn says CSIRO reduced absorption with annealing soak of days or weeks.)
    - Titania-silica nanolayers:
      - Development timeline for the new coating facility
      - Gains of stabilized Titanium probably not enough.

Prospects for Better Coatings

- **Voyager** (≈ 10-15 years) New Cryogenic Facility
  - AlGaAs coating size should be ready. Scattering acceptable??
  - AlGaP: ??
  - a-Silicon:
    - Optical quality should be acceptable
    - Can heated substrate coating or post-coating annealing be used to bring loss down to 10^{-6} scale?

- **LIGO Next Generation & ET:** It seems clear that coatings will be part of the design challenges for future generations.

- Materials research is slow but critical. Do we need a better organized, better funded US effort for materials/thermal noise?


S MBER 14, 2015