BLT interferometers: Big, Low-temperature, and Transparent

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Better acronym ?

Big Low-temperature Interferometer of Transparent Silicon

BLITS

Concept originated at Aspen Workshop this February

- **B**ig silicon mass was discussed again,
- **L**ow-temperature is a fundamental advantage, on paper,
- **T**ransparency of silicon at ~1.5 microns was pointed out by Stan Whitcomb, which changed the game. (No configuration changes required.)

- The concept is ‘in play’, and several European groups, including EGO, (and STREGA?) are pursuing similiar ideas. (Several talks at GR17 a few weeks ago revealed significant research efforts.)

Main Motivation: greater sensitivity

So far, have considered only the binary NS inspiral ***range*** of a detector.

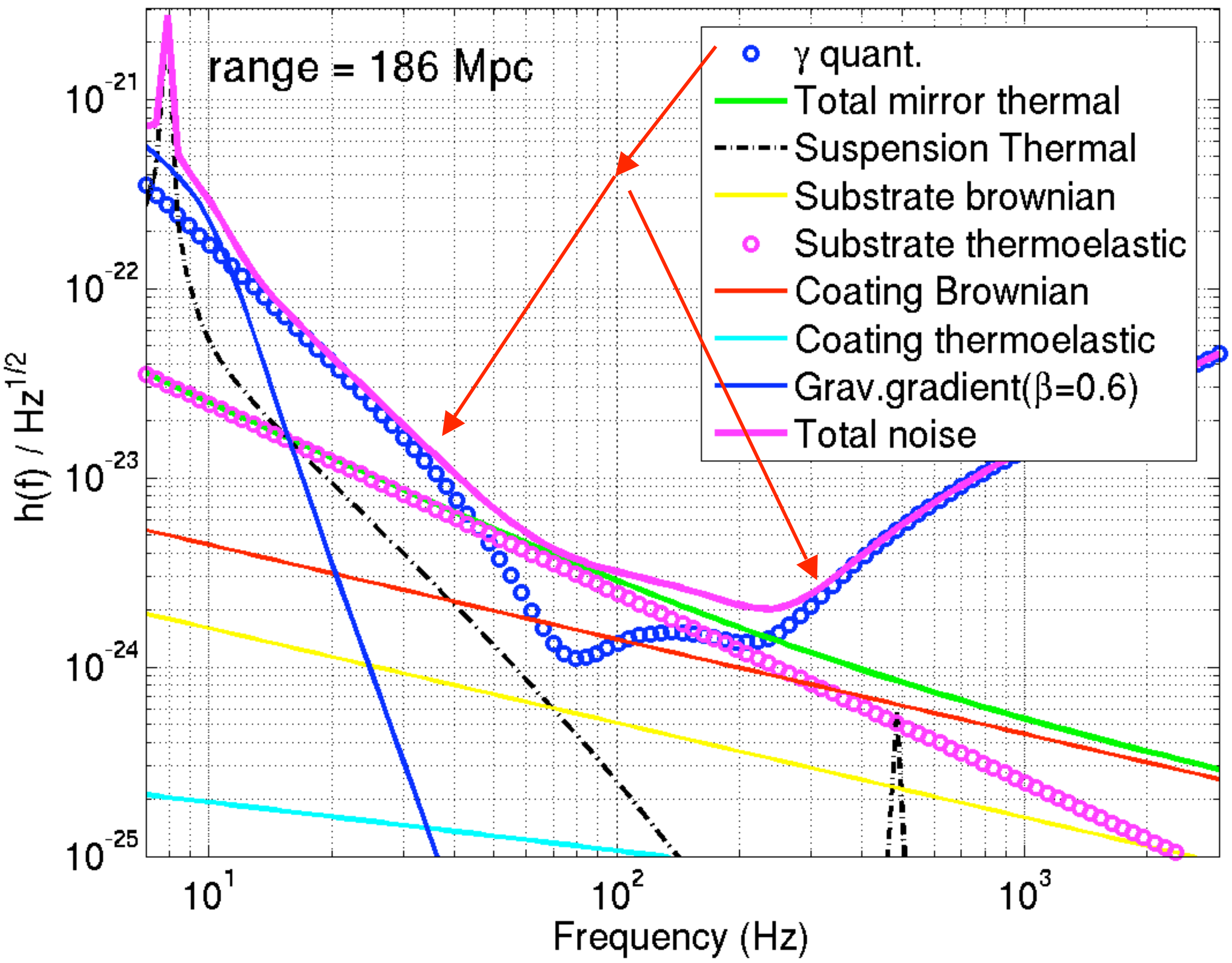
Will show that several of the fundamental mechanisms that limit the range of advanced LIGO can be suppressed in this concept.

`bench`

- The `bench` program was written by Sam Finn, now augmented by Peter Fritschel, with Gregg Harry)
  - it tallies the *fundamental* (i.e. predictable) noise sources for a interferometric gravitational wave detector,
  - calculates the (minimum) predictable noise of the detector, in the form of its amplitude spectral density (asd)
  - makes use of the known NS-NS ***inspiral*** waveform, (which includes its absolute strain), and
  - calculates the farthest distance, or ***range***, at which the inspiral is detectable

Results for recent adLigo design

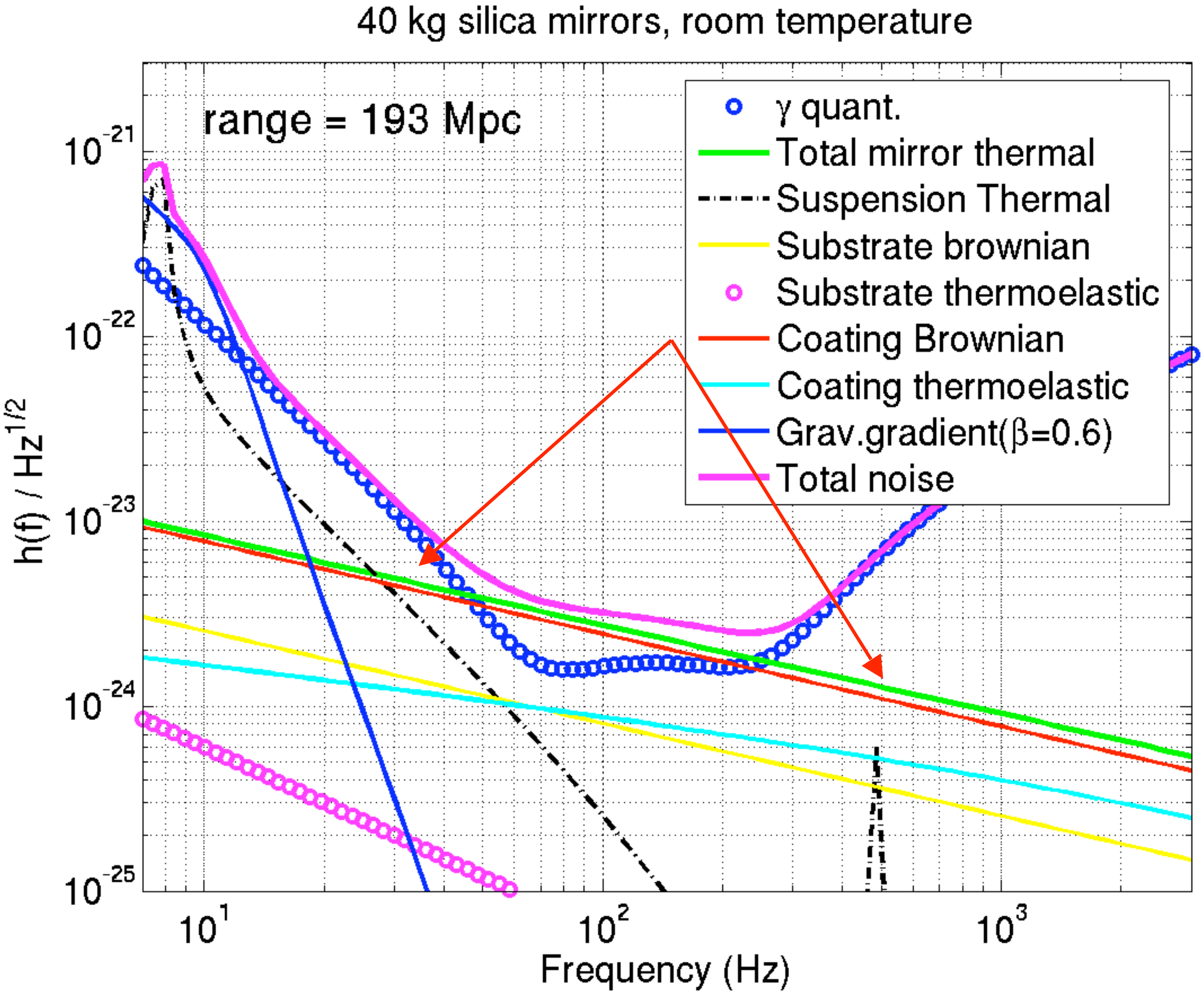
bench20: for 40 kg sapphire mirrors



Sapphire

test
masses at
room temperature

Silica


40 kg silica mirrors, room temperature
range = 193 Mpc
γ quant.
Total mirror thermal
Suspension Thermal
Substrate brownian
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Coating Brownian
Coating thermoelastic
Grav.gradient(β=0.6)
Total noise
h(f) / Hz^1/2
10^-21
10^-22
10^-23
10^-24
10^-25
10^1
10^2
10^3
Frequency (Hz)

“γ quan.” in graph <=> combined quantum noise

- photon shot noise at high frequencies
  - Can decrease this noise by <u>higher power</u> in the arm cavities, BUT for detection of binary inspirals, further increases, from case shown, don’t help because improvement is <u>essentially canceled</u> by the increase in:
- quantum “back action” noise at low frequencies
  - Which is the lowest possible (quantum) random-**<u>force</u>** applied to the mirrors by the ‘measuring’ light beam.
  - Back action noise can be **decreased**, at a given power, by
    - By “Quantum non-demolition” etc, techniques
    - By **<u>Bigger</u>** test masses

The other important noise:

- "<u>substrate thermoelastic noise</u>", discovered by Vladimir Braginsky and … collaborators
- It is a <u>fluctuation</u> of the mirror's surface caused by the mechanical <u>dissipation</u> in the substrate, or main mirror, caused by the coupling of <u>elastic</u> compression-expansion to irreversible <u>heat</u> flow.
- It can be drastically, and predictably, reduced by operating at cryogenic temperatures.

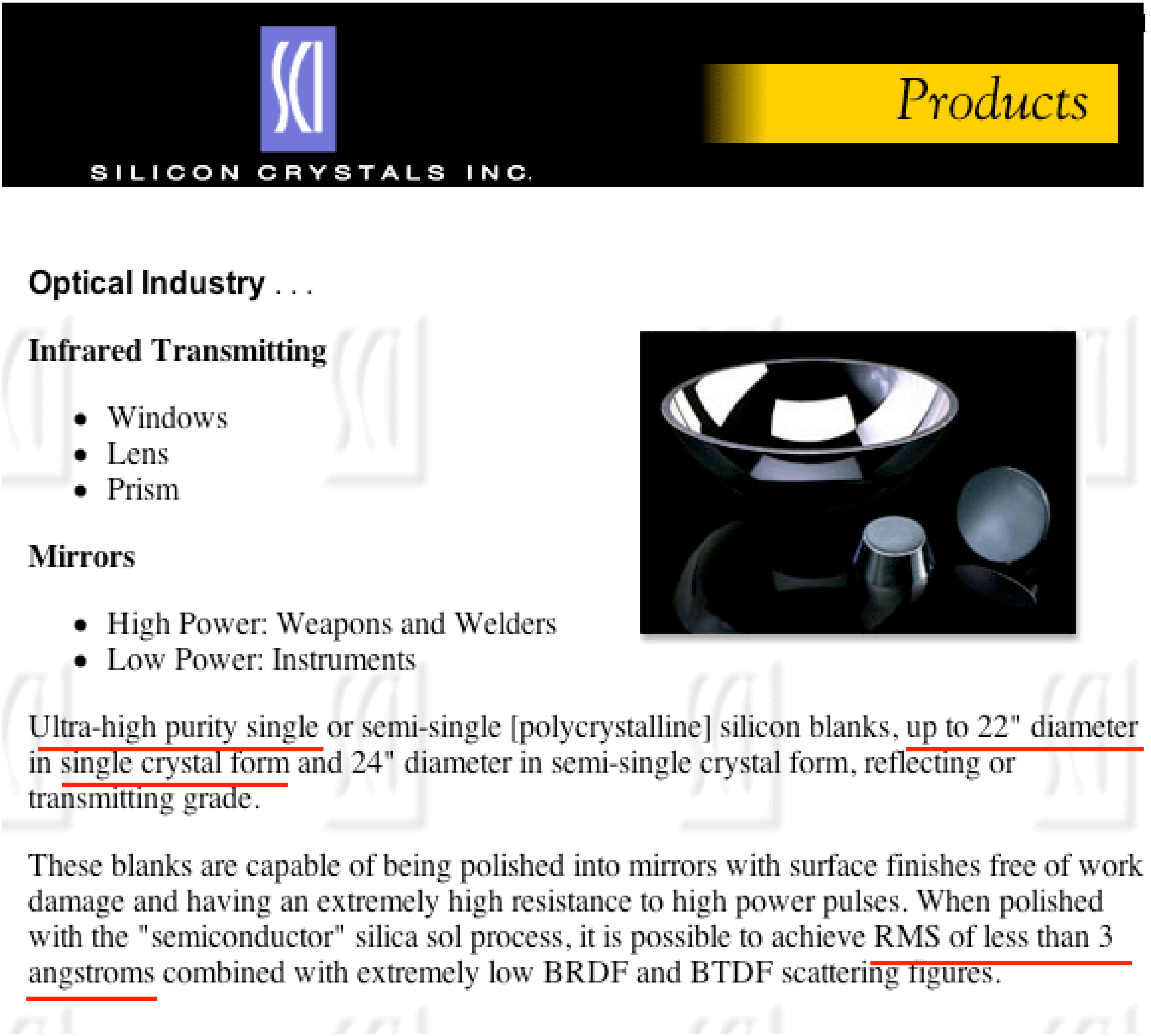
So, “Big, Low-temperature, Transparent ”, or **BLT** proposal

- A good way to get much “**B”**igger test masses (mirrors) is a better material : **silicon crystals**
- **Cryogenic** (“L”ow-temp) operation renders substrate noise negligible.
- use a **conventional** “**T**”ransparent interferometer configuration, which requires changing the laser **wavelength** to ~ 1.56 microns

Second Motivation - use Silicon : the most advanced material (?)

- The (inflation adjusted) industrial investment in the silicon processing is orders of magnitude larger than for any other material (excepting steel?)
  - Highest purity
  - Biggest single crystals
    - Now: Diameter up to 22 inches (52 cm)
    - **Now: Mass up to 300 kilograms** (limited by furnace size)
  - Excellent techniques for surface finish and flatness (needed for device fabrication)

E.g., the diameter and polish claimed by one company



Optical Industry . . .

Infrared Transmitting

- Windows
- Lens
- Prism

Mirrors

- High Power: Weapons and Welders
- Low Power: Instruments

Ultra-high purity single or semi-single [polycrystalline] silicon blanks, up to 22" diameter in single crystal form and 24" diameter in semi-single crystal form, reflecting or transmitting grade.

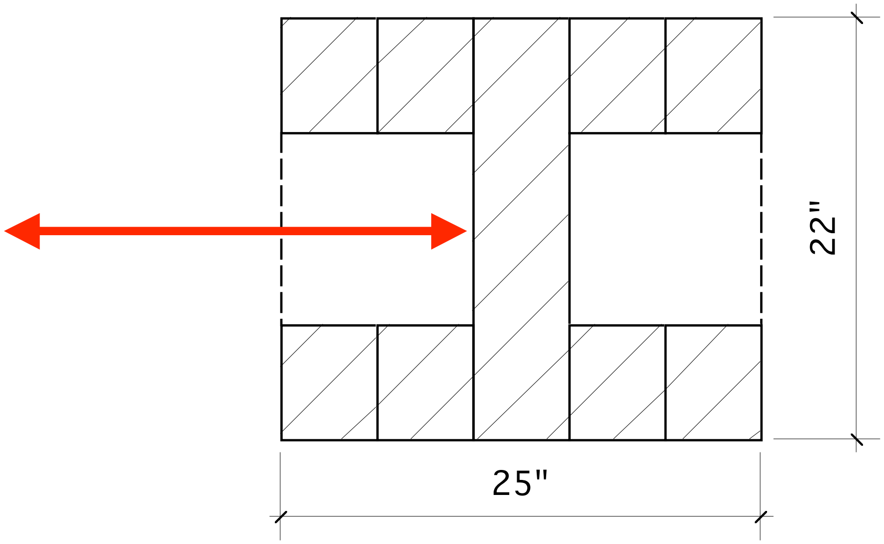
These blanks are capable of being polished into mirrors with surface finishes free of work damage and having an extremely high resistance to high power pulses. When polished with the "semiconductor" silica sol process, it is possible to achieve RMS of less than 3 angstroms combined with extremely low BRDF and BTDF scattering figures.

Composite mass is possible

- Several techniques could be used to “weld” together ~300 kg silicon crystals for bigger mass
  - Metal film deposition, then vacuum furnace fusion
  - Stanford “silica bonding” technique
- One possible configuration:

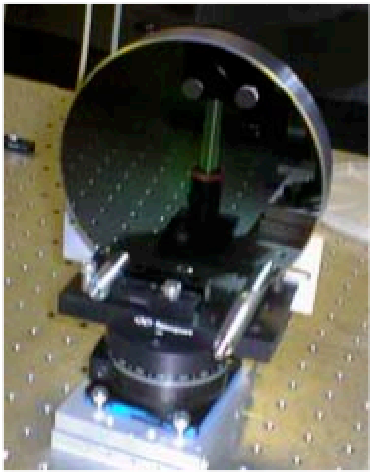
a disk bonded to annuli

(bonding polished flats)



Sheila Rowan and colleagues have emphasized possibilities of silicon. Two viewgraphs from a talk ~2 years ago.

- **Thermal noise** from test masses and suspensions important below few 100 Hz
- **Silicon** has various desirable material properties (optical and thermal noise)
-
  - High thermal conductivity, κ
  - Available in large pieces (~100kg)
  - Can be polished and coated to form high quality dielectric mirrors
  - Measurements suggest intrinsic mechanical loss (and **thermo-elastic loss***) comparable to sapphire at room temperature
  - Can be silicate bonded to silica (and by extension to itself)



Coated silicon mirror

- At room temperature, thermo-elastically driven displacement noise forms hard limit to detector sensitivity
- **By cooling test masses, expect significant gains in thermal/thermo-elastic noise performance**

*** Braginsky et al**

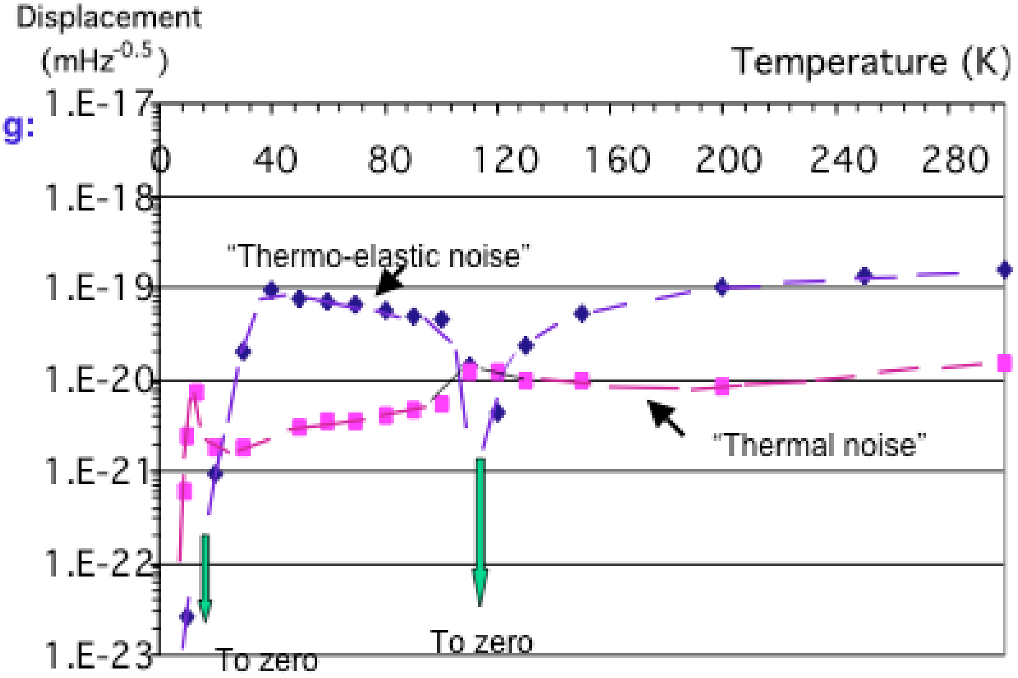
Gone at Low-temp: substrate thermoelastic noise, *and* thermal deformation

- Silicon: unique material properties on **cooling:**
  - Intrinsic mechanical loss decreases
  - Two zero's in coefficient thermal expansion, α, at ~130K and ~20K

Dual benefits:

- thermal deformation proportional to α/κ
- thermo-elastic noise proportional to α

- **both should vanish as α tends to zero**



"Thermo-elastic" displacement noise and "thermal" noise in a silicon test mass as a function of temperature

- **silicon substrates opens avenues for significant thermal noise improvements at low temperatures but material properties need further study**

Proposal: Transparent (conventional) interferometer

- Crucial ideas from Stan Whitcomb (my paraphrase)
  - ‘Silicon is nominally transparent above the band edge, ($\lambda > 1.2$ microns), so regular (transmissive) optics can be used’, <u>just like LIGO</u>
  - ‘There exist high power laser systems, at ~1.5 microns’, (under development for “telecom” use).
  - ‘There are reasonably efficient photodiodes at this wavelength.’

Silicon has been proposed before for use in "unconventional" IFOs

- Previous proposals for silicon mirrors have been part of proposals for "unconventional" interferometers, e.g., ones that use diffractive mirrors for crucial components.
- Seems fair to say, at this time, it is <u>unknown</u> whether "unconventional" designs will be <u>more, or less,</u> susceptible to major *technical* problems (which have taken a long time to 'solve' with the conventional design.)

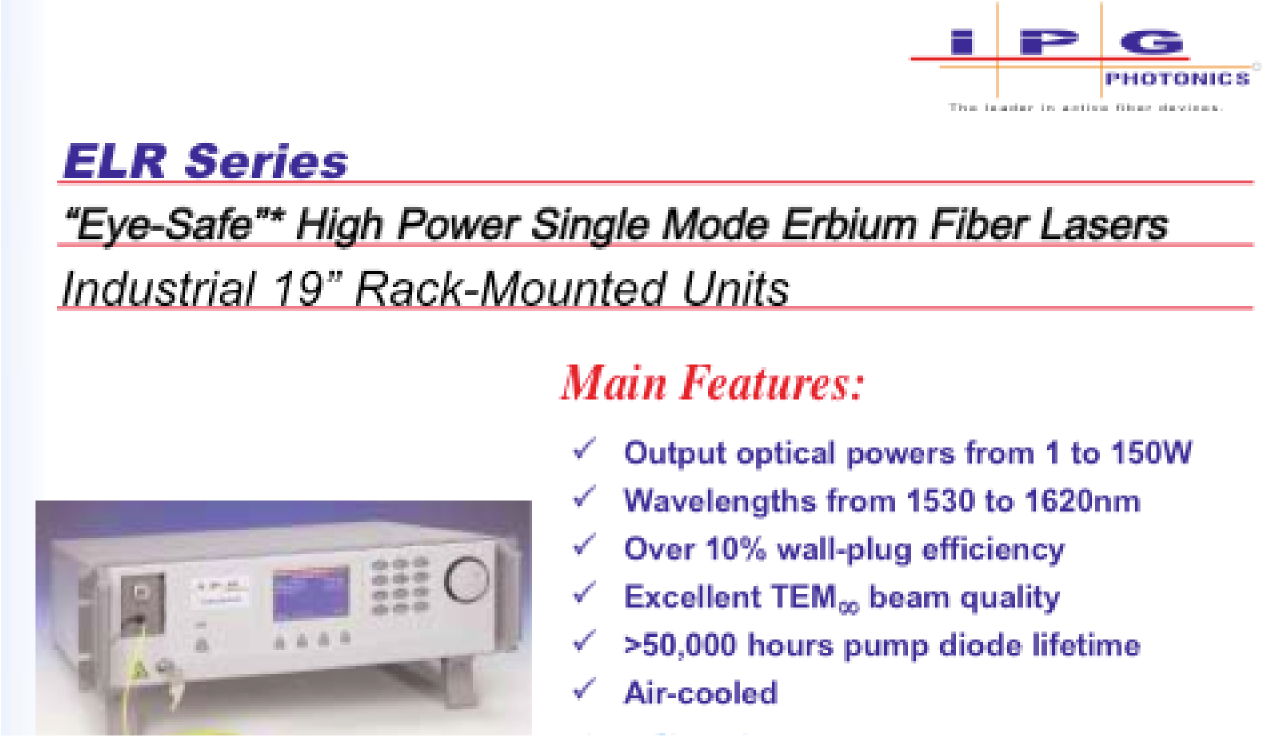
Silicon transparency at 1.5 microns

- There has been preliminary measurements, verbally communicated, of upper limit of 5ppm/cm at room temperature, (much better than sapphire).

- But it remains to be seen whether such results can be replicated, and whether required conditions on purity, temperature, power density, etc are practical for large crystals.

High power lasers

- IPG Photonics makes an <u>erbium fiber laser</u> with power =100 Watts at 1.55 microns.
- Power likely to increase.



IPG PHOTONICS

The leader in active fiber devices.

ELR Series

"Eye-Safe" High Power Single Mode Erbium Fiber Lasers*

Industrial 19" Rack-Mounted Units

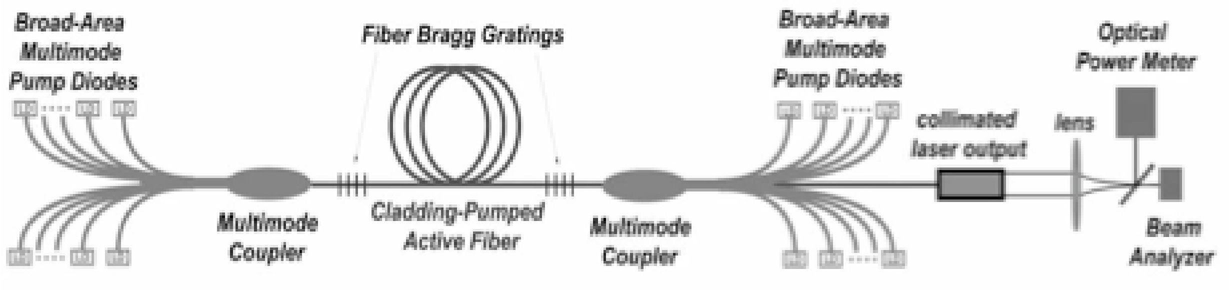
Main Features:

- ✓ Output optical powers from 1 to 150W
- ✓ Wavelengths from 1530 to 1620nm
- ✓ Over 10% wall-plug efficiency
- ✓ Excellent TEM_{00} beam quality
- ✓ >50,000 hours pump diode lifetime
- ✓ Air-cooled

High power lasers (cont)

- BUT, it remains to be seen if this type of laser can have the high amplitude and frequency stability required.

IPG High Power Fiber Laser



Active Fiber :	**Pump Diodes :**
Double-Clad, Circular Cladding	Multimode
9.1µm Core Diameter	100µm stripe
60m Total Length	Up to 5.5W Output Power
3000ppm Yb^{3+} Concentration	

Photodiodes

366 IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 14, NO. 3, MARCH 2002

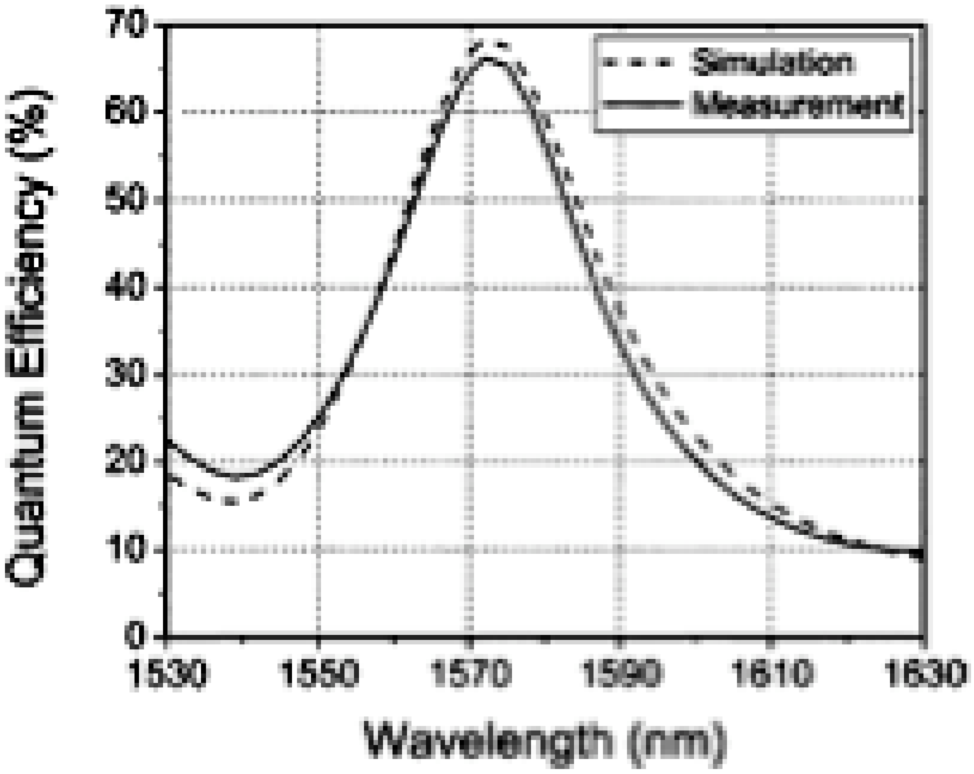
InGaAs-Based High-Performance p-i-n Photodiodes

Ibrahim Kimukin, *Student Member, IEEE*, Necmi Biyikli, *Student Member, IEEE*,
Bayram Butun, *Student Member, IEEE*, Orhan Aytur, *Member, IEEE*, Selim M. Ünlü, *Senior Member, IEEE*, and
Ekmel Ozbay, *Member, IEEE*

Photodiodes - (cont)

- BUT, it remains to be seen if such diodes can handle the required optical power, and etc.

(a)



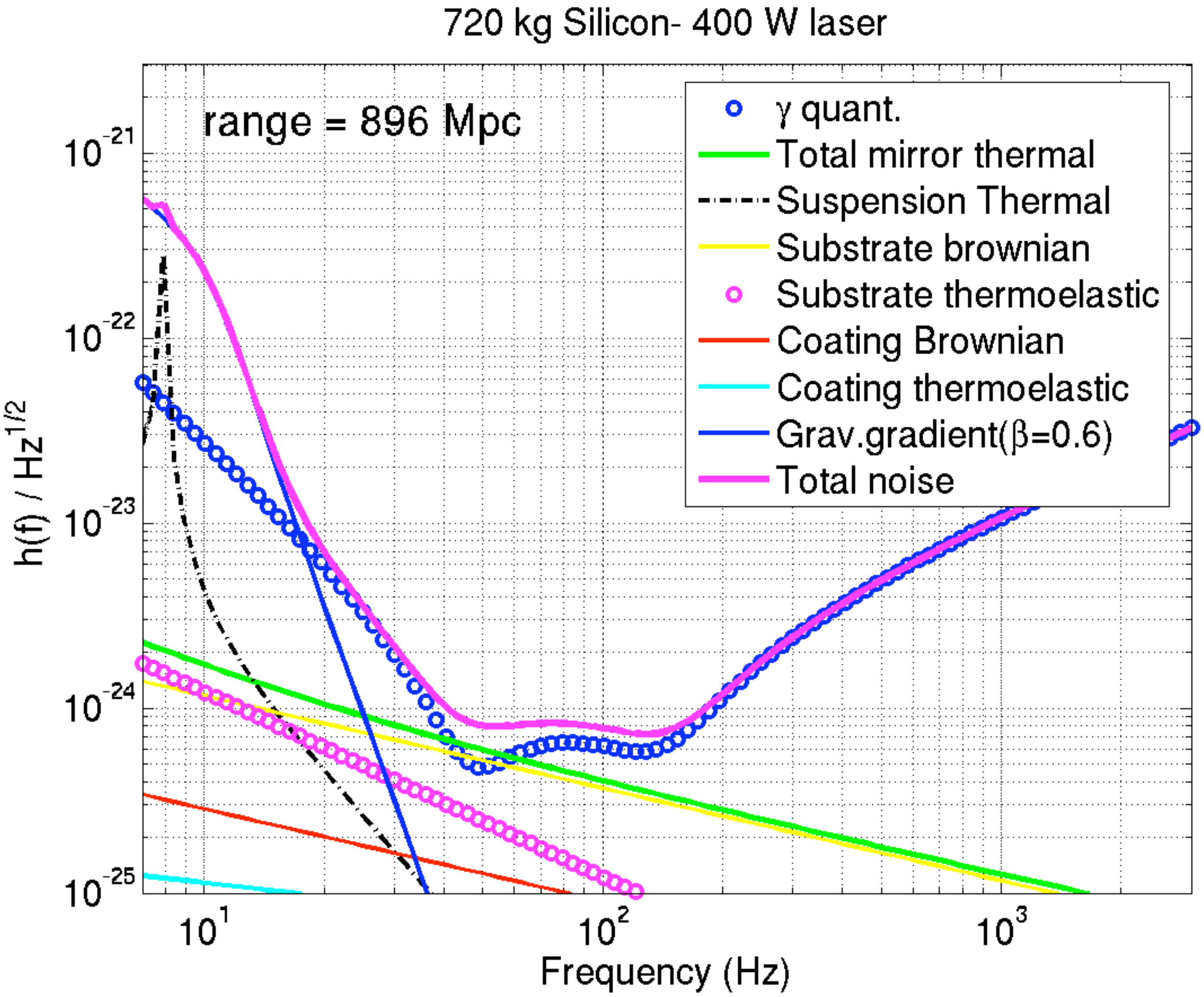
(b)

Fig. 1. (a) Spectral quantum efficiency measurements of the fabricated detectors after consecutive recess etches. (b) The theoretical calculation and experimental quantum efficiency measurement of a detector whose resonance had been tuned to 1572 nm.

“Dream” BLITS

- Increase mass to ~700 kilograms
- Increase power to ~ 400 Watts
- Assume a miracle, so that coating losses become smaller than currently,
  - either because of new materials, or
  - because of low temperature.

result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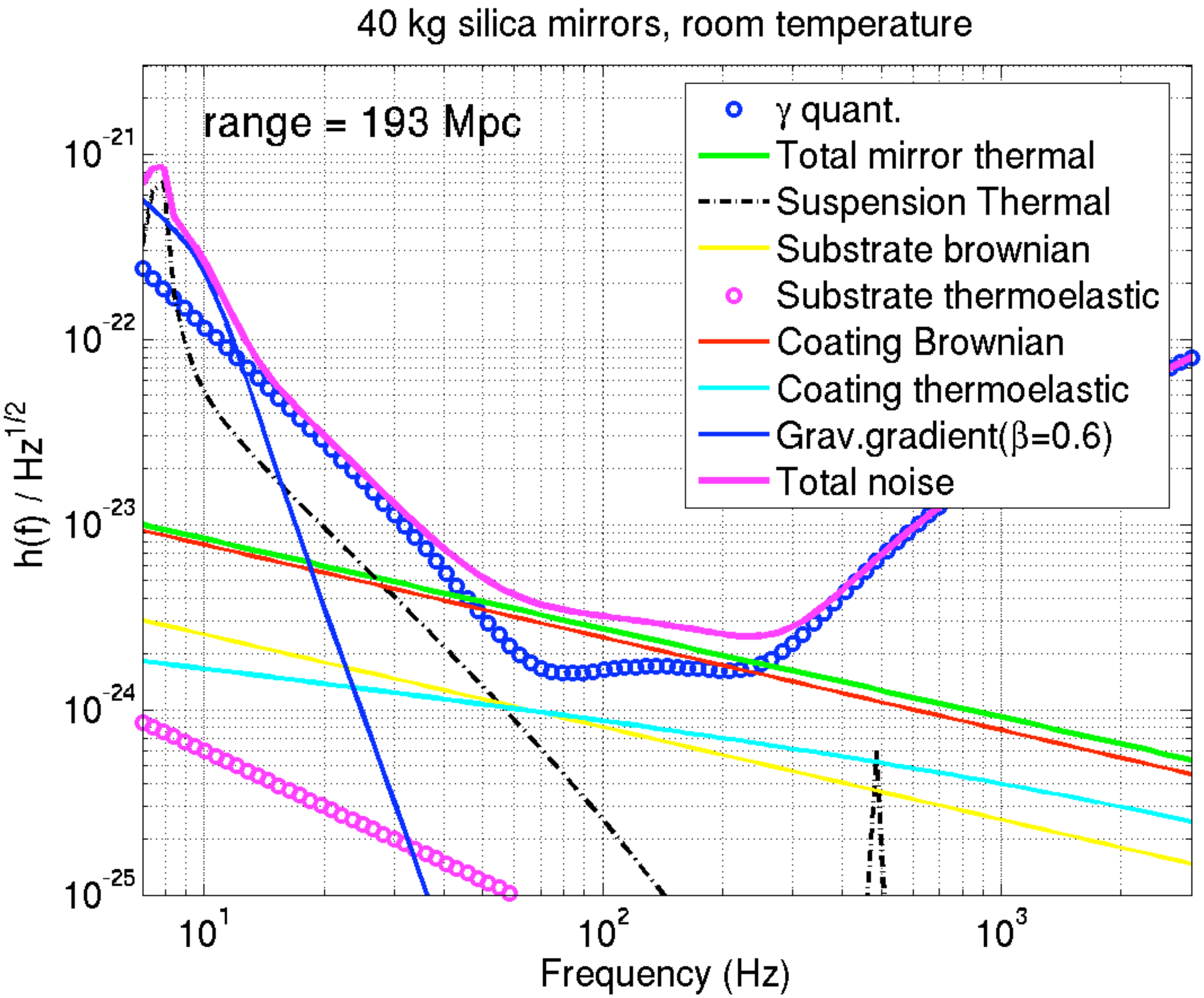
Silica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result (cont)

- Range increases by factor of 896/186 ~ 5
- Volume of space sampled increases by ~125

What are some of the problems which must be solved?

- Can coating noise be made small enough?
- Test that bonding (to make larger pieces) does not greatly increase the dissipation.
- Can a cryogenic suspension be good enough?
  - ‘Rumors’ about the LCGT project suggest their initial design is not adequate.
  - Our experience with cryogenic bar suspension suggests it is possible.
    - There are *some* suspension problems that become easier at low temperature.