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GEO 600

OPTICAL PROPERTIES OF SILICON FOR CRYOGENIC GW DETECTORS

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11/07/2017 - HILTON HOTEL, PASADENA, CA, U.S.A.

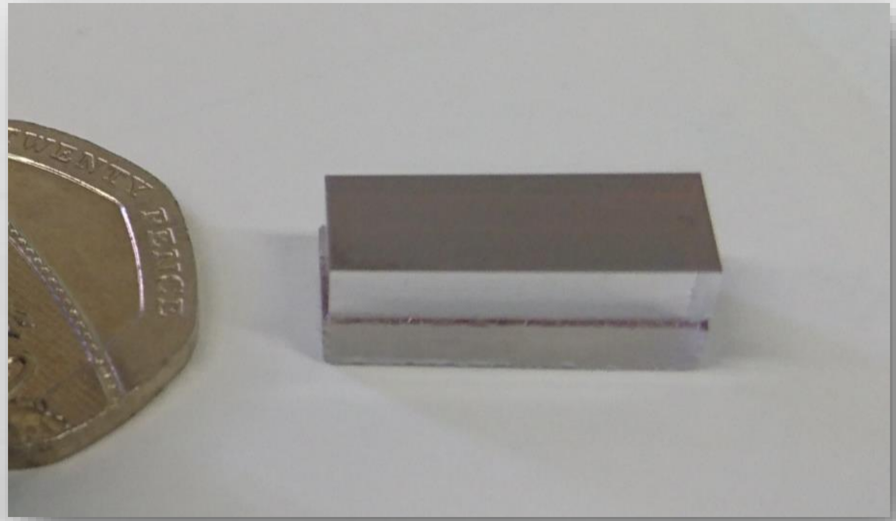
GraWIToN GW Initial Training Network

MARIE CURIE ACTIONS

LIGO-G1700998

Crystalline silicon

Optical scattering



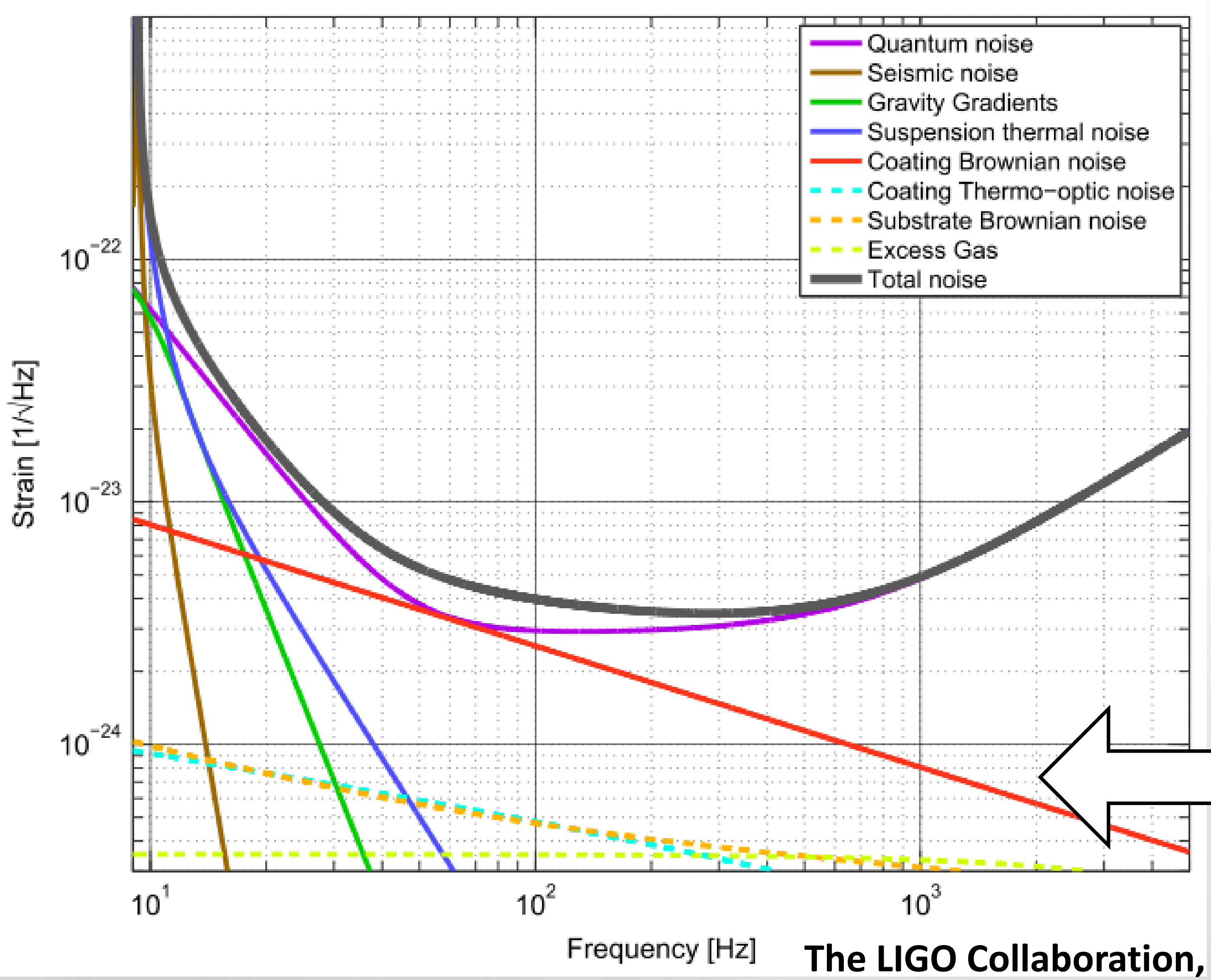
Amorphous silicon coatings

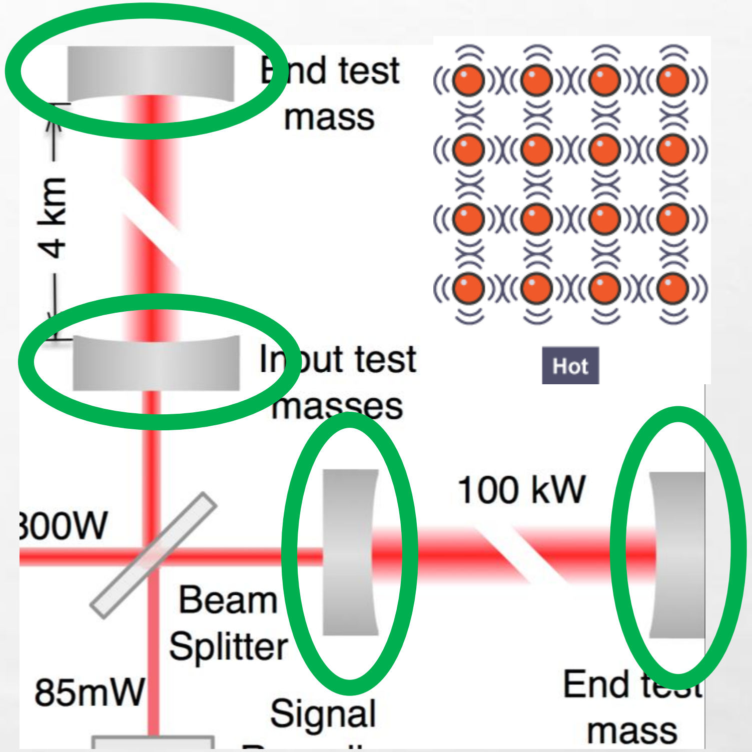
Optical absorption

Topics

Why silicon?

Introduction



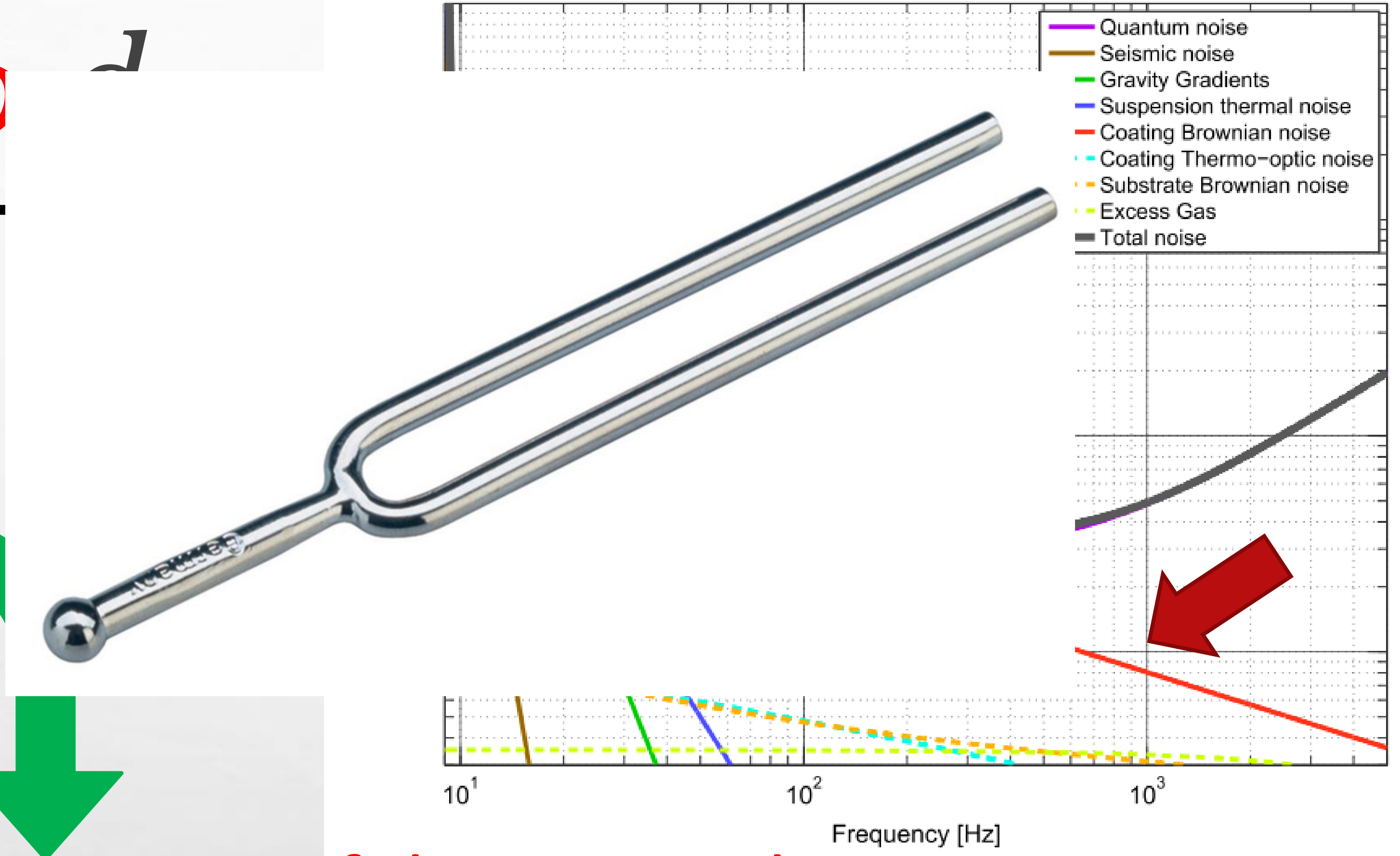


Coating Brownian noise

The LIGO Collaboration, Class. Quantum Grav. 32 (2015) 074001

Noise in a gravitational wave detector

$$S_x(f) \propto \frac{T\ \phi\ d}{f\ Y}$$



Temperature

Mechanical loss

Coating thickness

Young's modulus

Beam width

Property of the material

Current detectors operate at room T

Can vary by orders of magnitude

Can we just go cryogenic then? Not yet…

Can be engineered to some extent

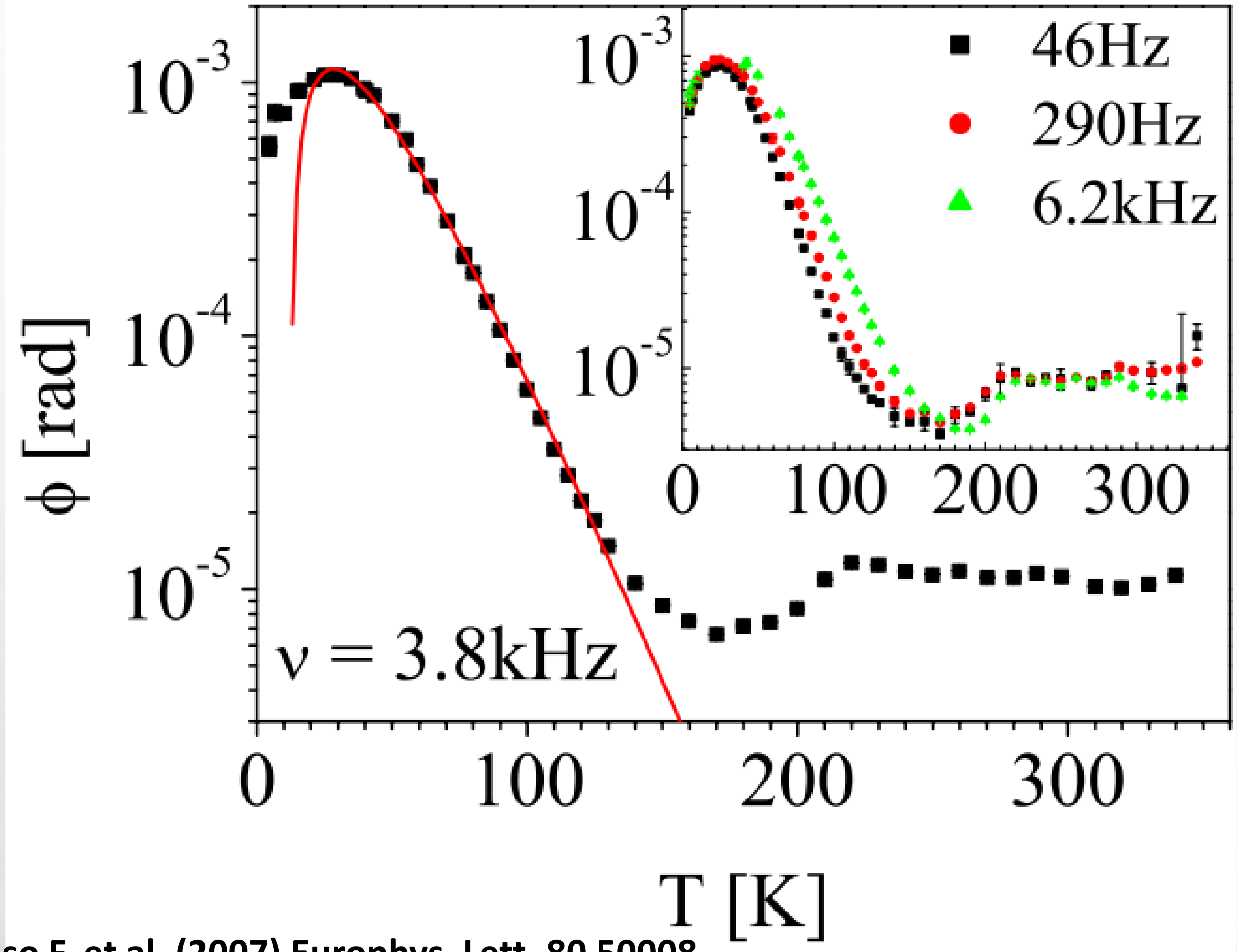
Coating Brownian noise (similar idea for substrates)

- In general

$$S_x(f) \propto \frac{T\,\phi(T)\,d}{f\,Y\,w^2}$$

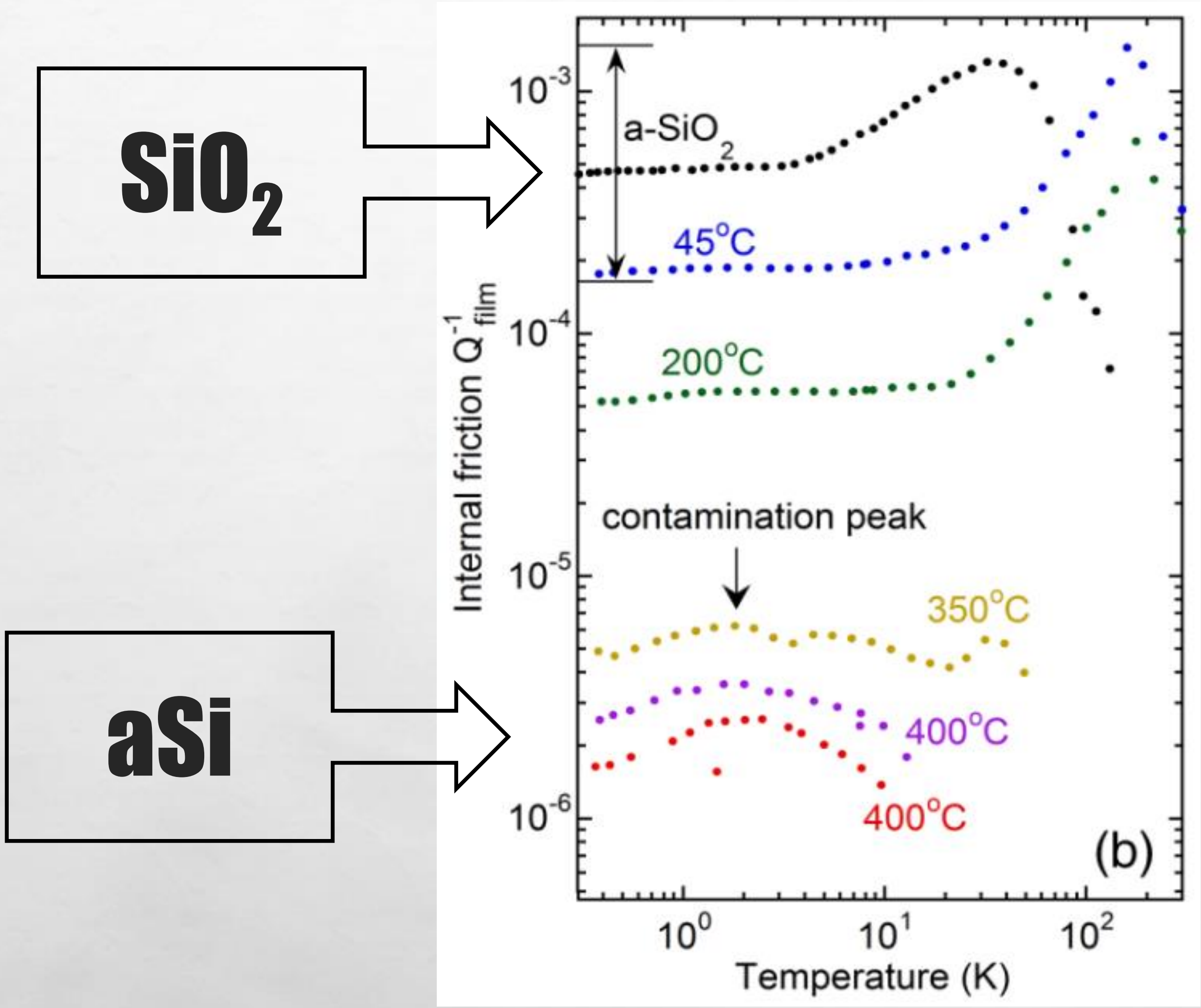
- Currently LIGO optics are made of fused SiO_2

- How does the mechanical loss change with T in SiO_2?



Travasso F. et al. (2007) Europhys. Lett. 80 50008

Fused silica has a high mechanical loss at low T



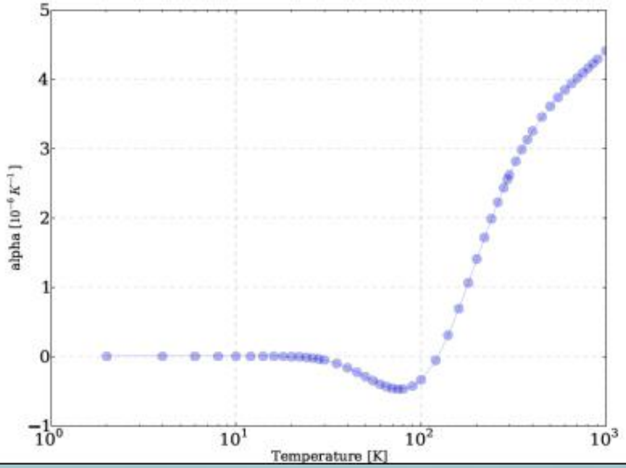
For coatings, a high refractive index helps (Silicon: 3.47)

Amorphous silicon looks promising

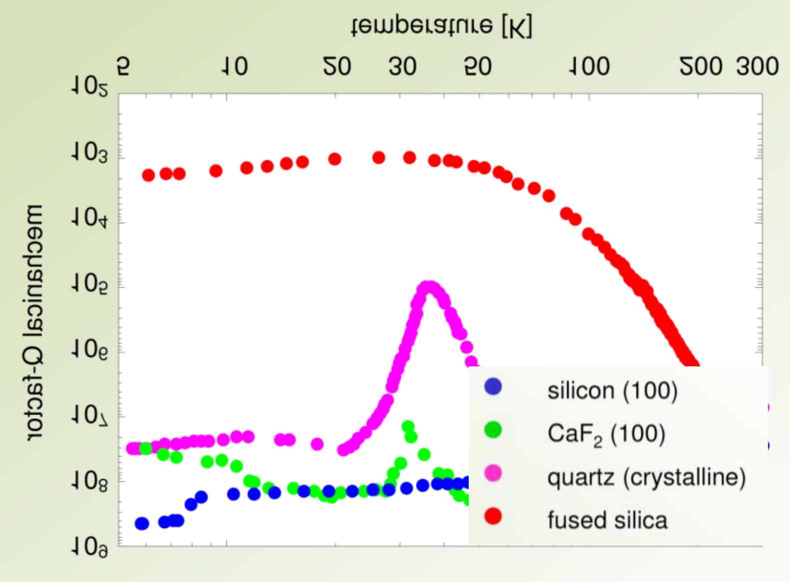
Christopher Wipf / LIGO-G1700602

SEDUCTION OF SILICON

- Analogous to sapphire
  - (and various other crystalline materials)
  - No cryogenic loss peak
  - High thermal conductivity (and TE noise)
- But thermal expansion coeff $\alpha \to 0$ for $T \sim 120$ K, $T \lesssim 20$ K
- Thermal deformation and TE noise vanish at those temperatures
- Also, cryogenics at 120 K can cope with heat load from **high circulating power**



Low mechanical loss at low temperature.



Credits: Ronny Nawrodt

Crystalline silicon looks great too

Both cSi and aSi have low mechanical loss at low temperature

But what about optical properties?

	cSi (bulk)	cSi (surface)	aSi
Absorption	A. Bell, A. Markosyan	Ongoing (A. Bell)	This work
Scattering	This work	Future work?	Future work

Recap

Stanford

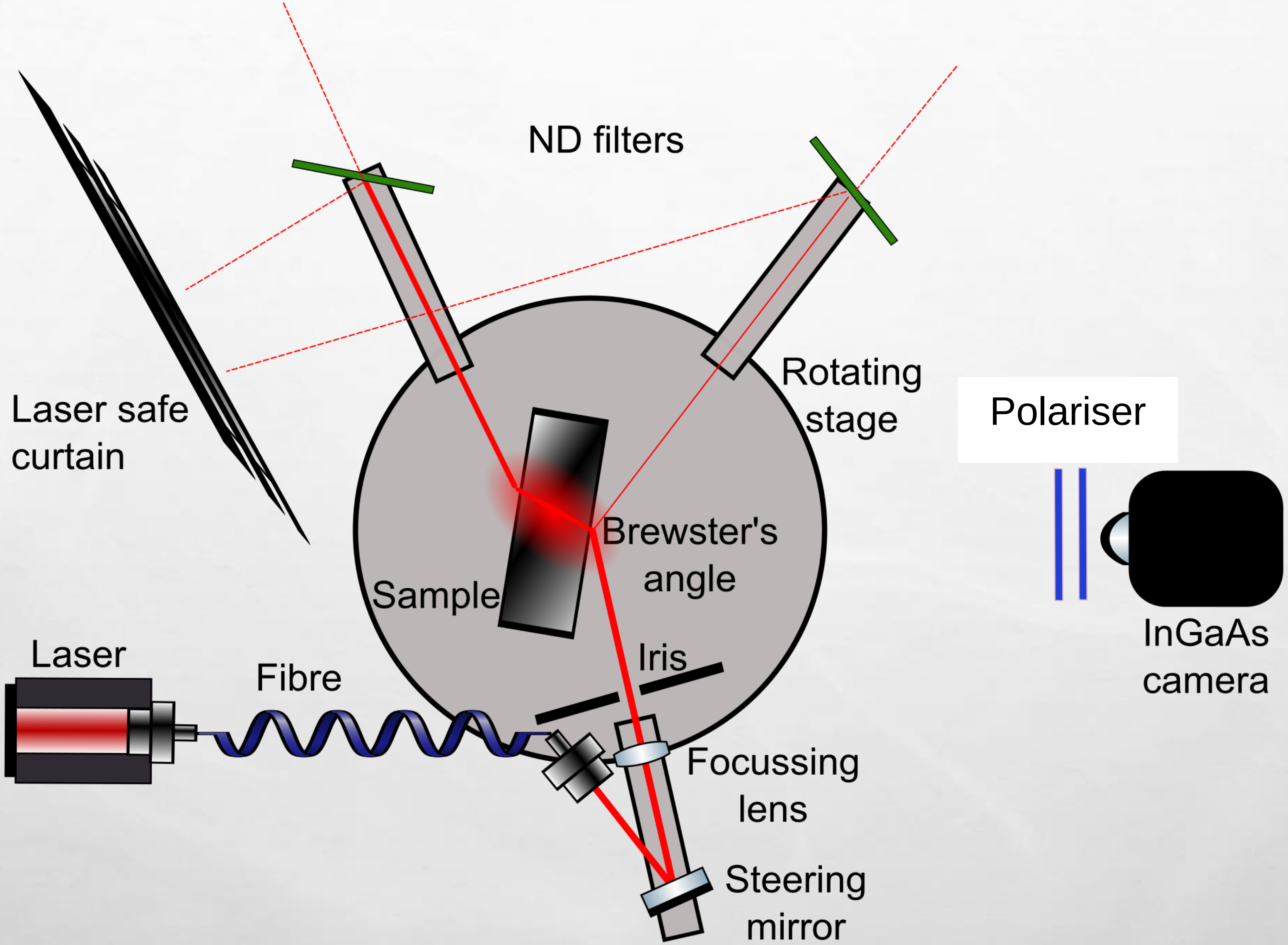
University of Glasgow

A. Markosyan, A. Bell / LIGO-G1700480

1. **Standard Czochralski grown silicon (Cz Si)**
   Too impure for application in GW detectors because of high optical absorption ✗
2. **Float-zone silicon (FZ Si)**
   Very pure and low absorbing: 2 ppm/cm @ 1550 nm ✓
   Available in crystals of maximum diameter 20 cm ✗
3. **Magnetic field-grown Czochralski silicon (MCz Si)**
   Available up to 45 cm in diameter ✓
   Bulk absorption can be as low as 5 ppm/cm @ 1550 nm, albeit inhomogeneous ✓
   Occasional surface absorption still under investigation

A. Bell / LIGO-P1700134

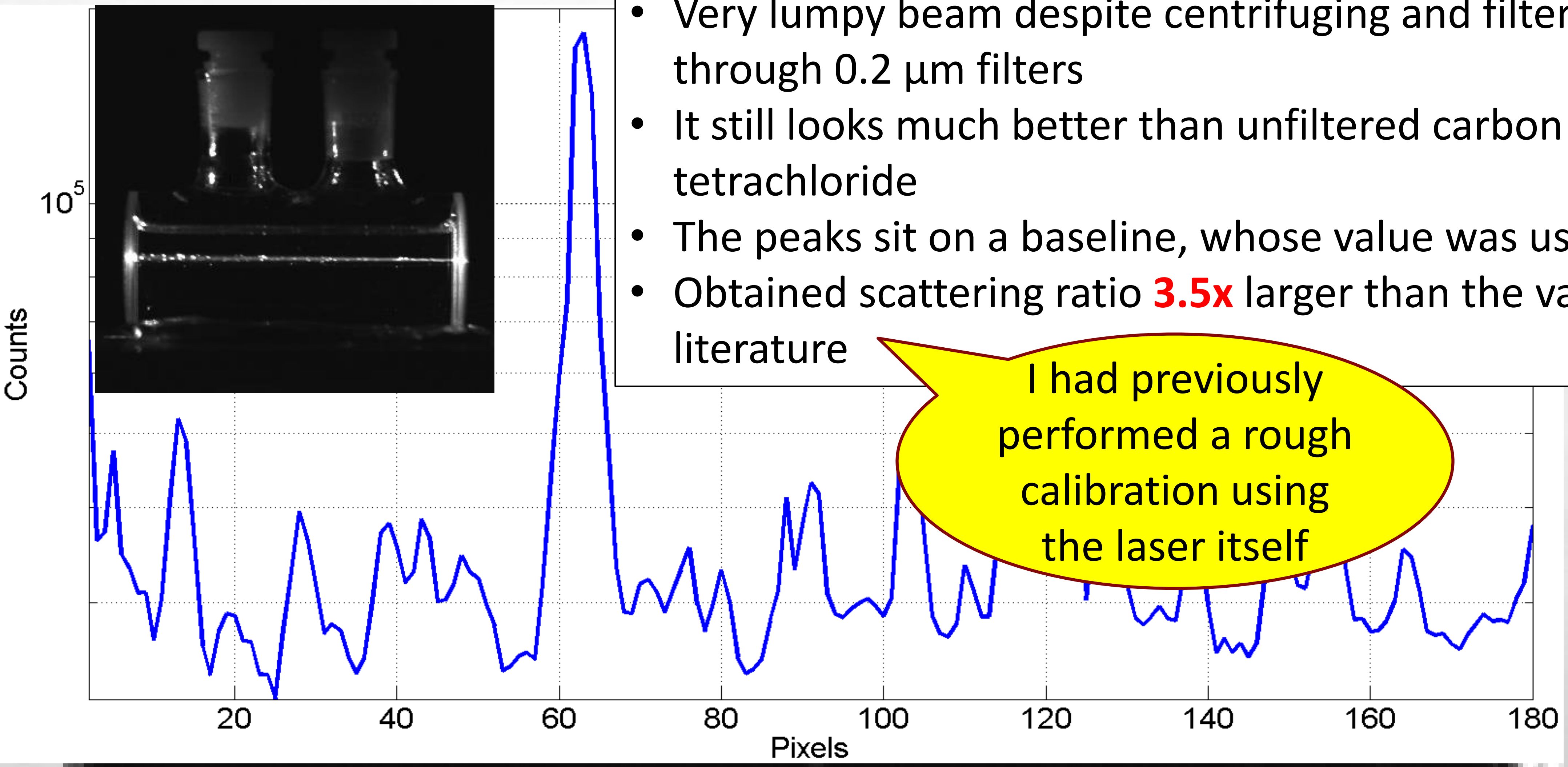
Crystalline silicon absorption



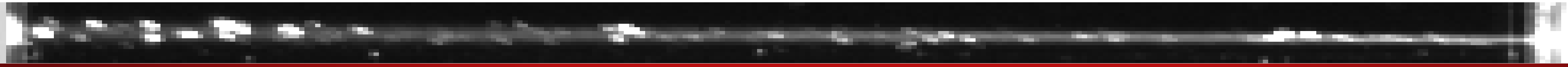
The Glasgow scatterometer

“Engineering run 1”: looking at CCl_4

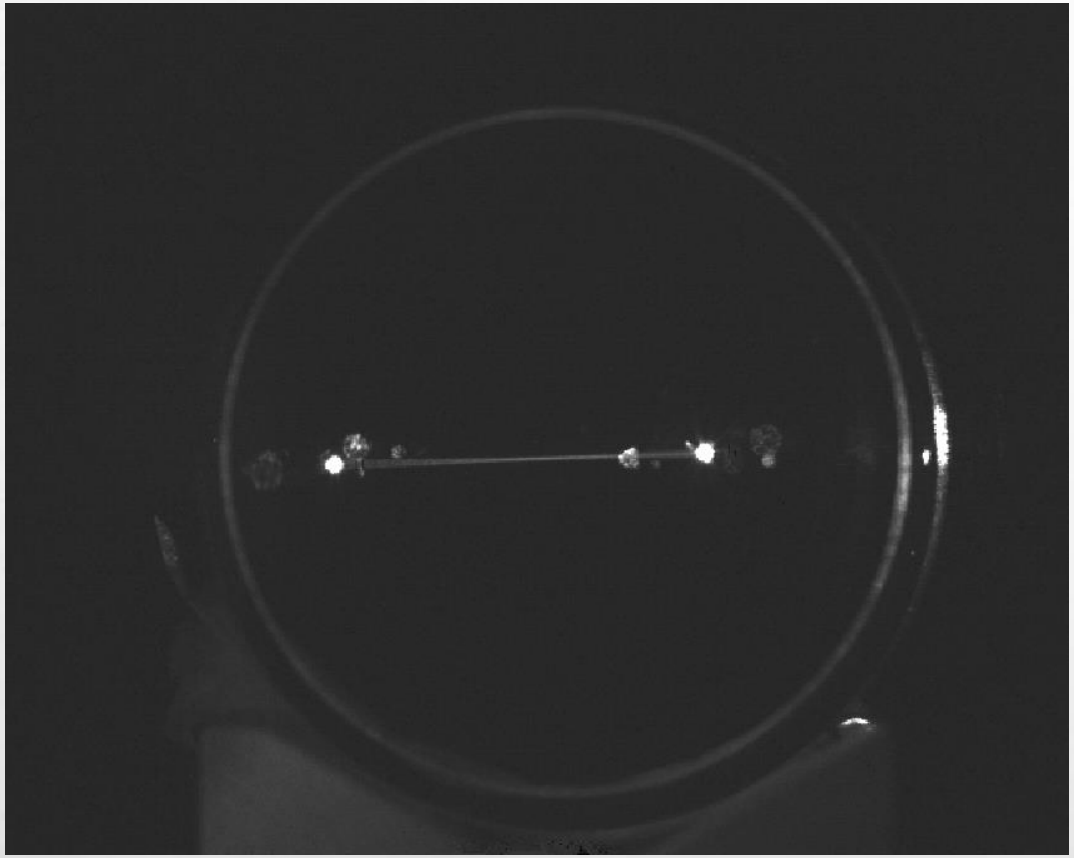
- Very lumpy beam despite centrifuging and filtering through 0.2 µm filters
- It still looks much better than unfiltered carbon tetrachloride
- The peaks sit on a baseline, whose value was used
- Obtained scattering ratio **3.5x** larger than the value in literature



I had previously performed a rough calibration using the laser itself



"Engineering run 2": fused silica



Heraeus Suprasil 3001 fused silica cylinder (same silica used in LIGO)

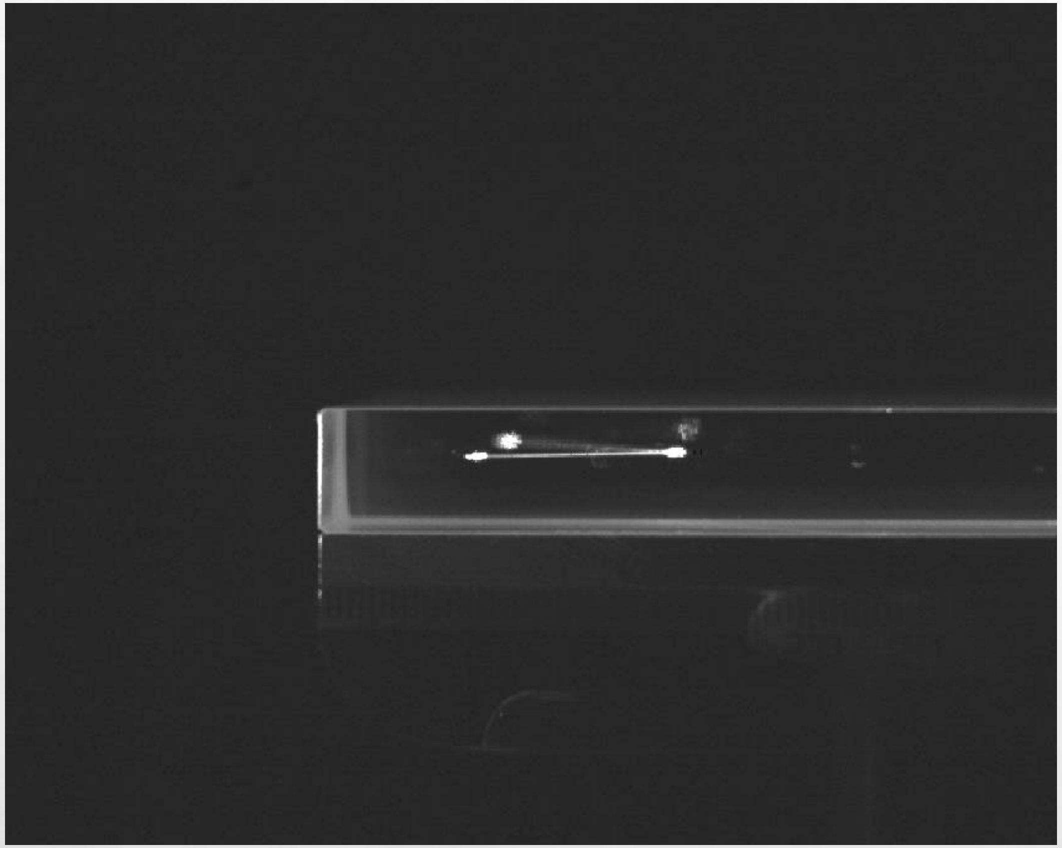
- Smooth beam
- Scattering ratio obtained is **2.16x** larger than literature, according to my rough calibration
- Or it's **0.6x** literature, taking CCl_4 as a reference

TAKE AWAY MESSAGES

1. Still "commissioning" the scatterometer, plenty of things to understand better

BUT

2. It's **NOT** off by orders of magnitude!



Magnetic Czochralski silicon slab

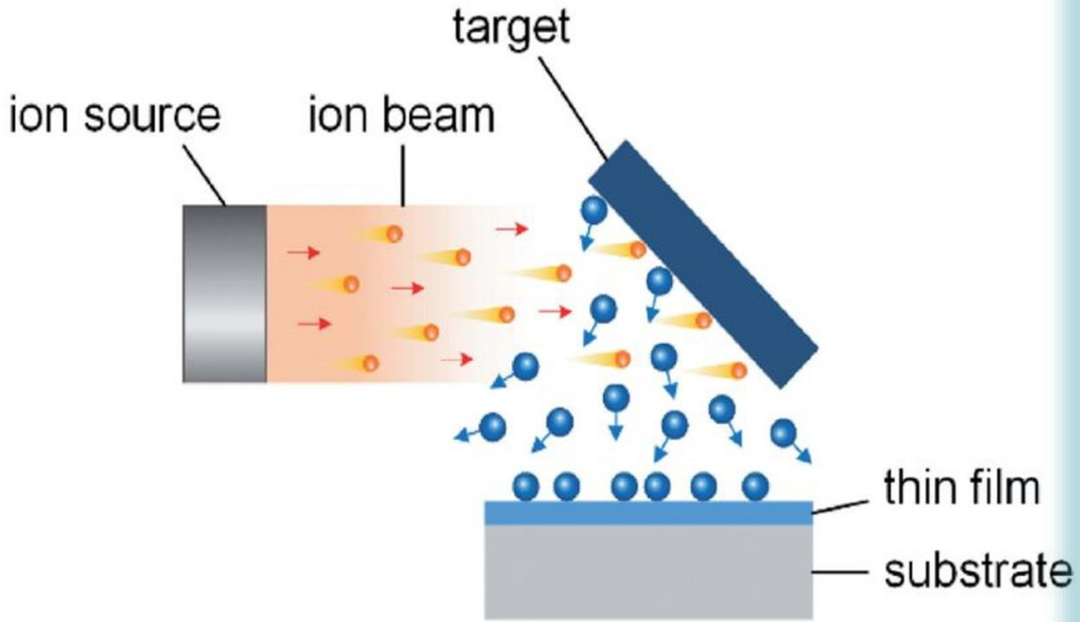
- Smooth beam
- Difficult to isolate the main beam from the many strong reflections (high refr. index, small polished sample)
- Images **10** times brighter than fused silica under similar conditions.

With the current understanding of the instrument, MCz Si scatters at 1550 nm, at 16° observation angle:

0.11 - 0.17	ppm cm^{-1} sr^{-1}
0.99 - 1.6	ppm cm^{-1}

"O1": magnetic Czochralski silicon

Ion beam deposition (IBD)



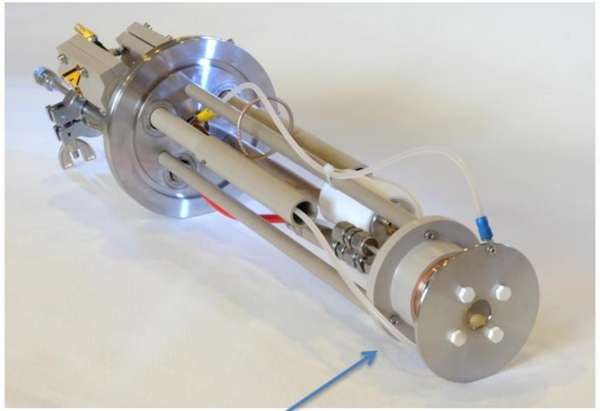
ECR Ion Source

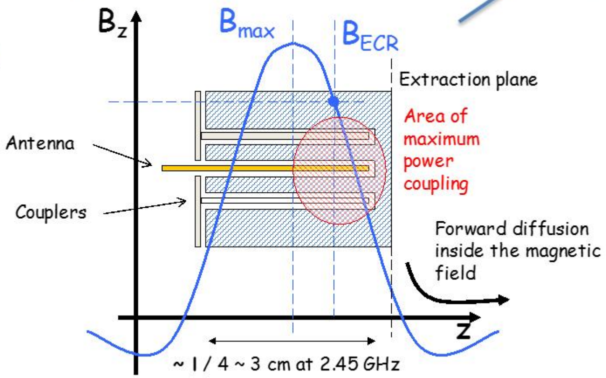
2.4GHz ECR ion source

Compact λ/4 microwave resonant cavity

Advantages:

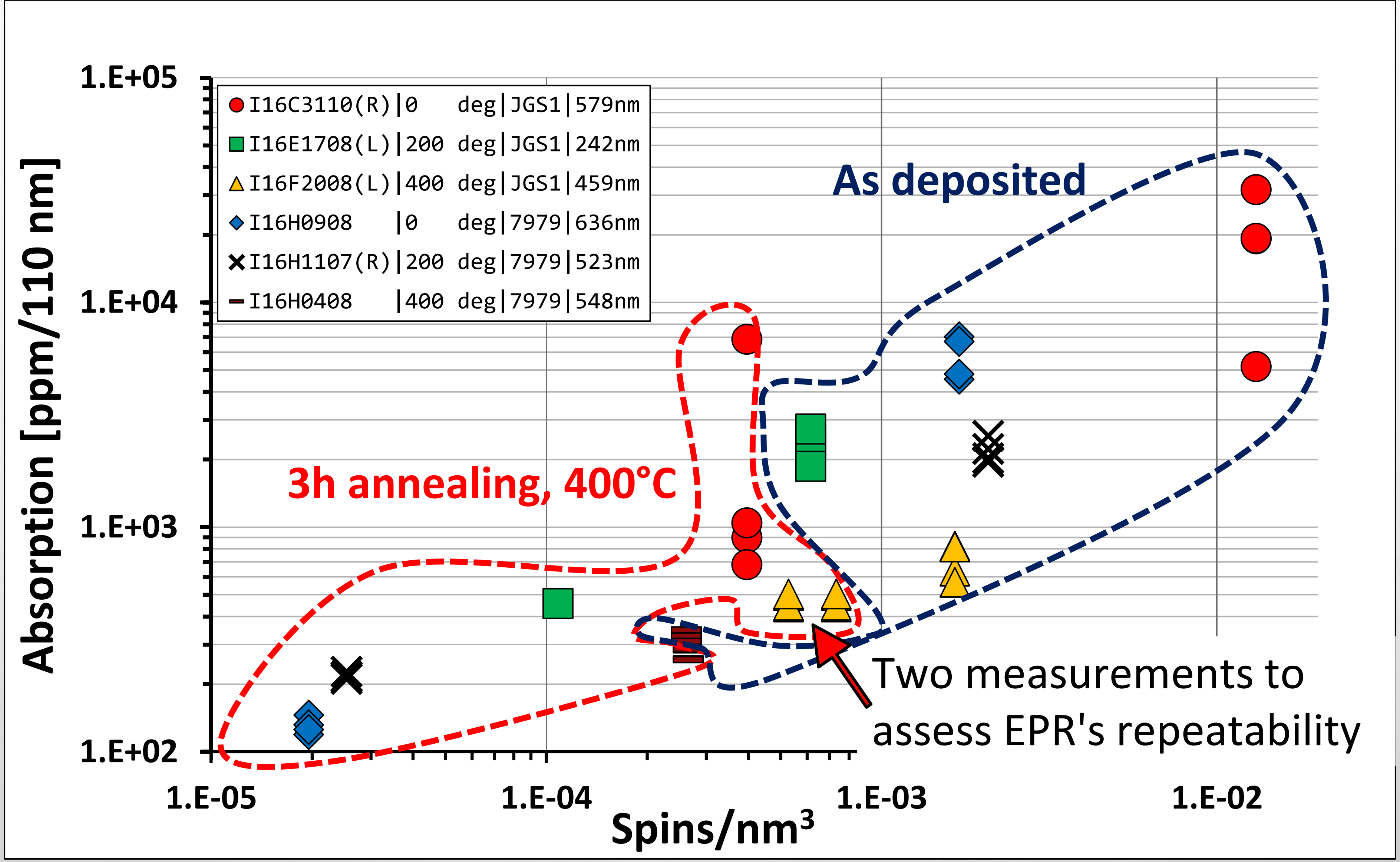
- Filament-free
- Gridless
- Maintenance free
- Low current
- 0-20kV extraction potential



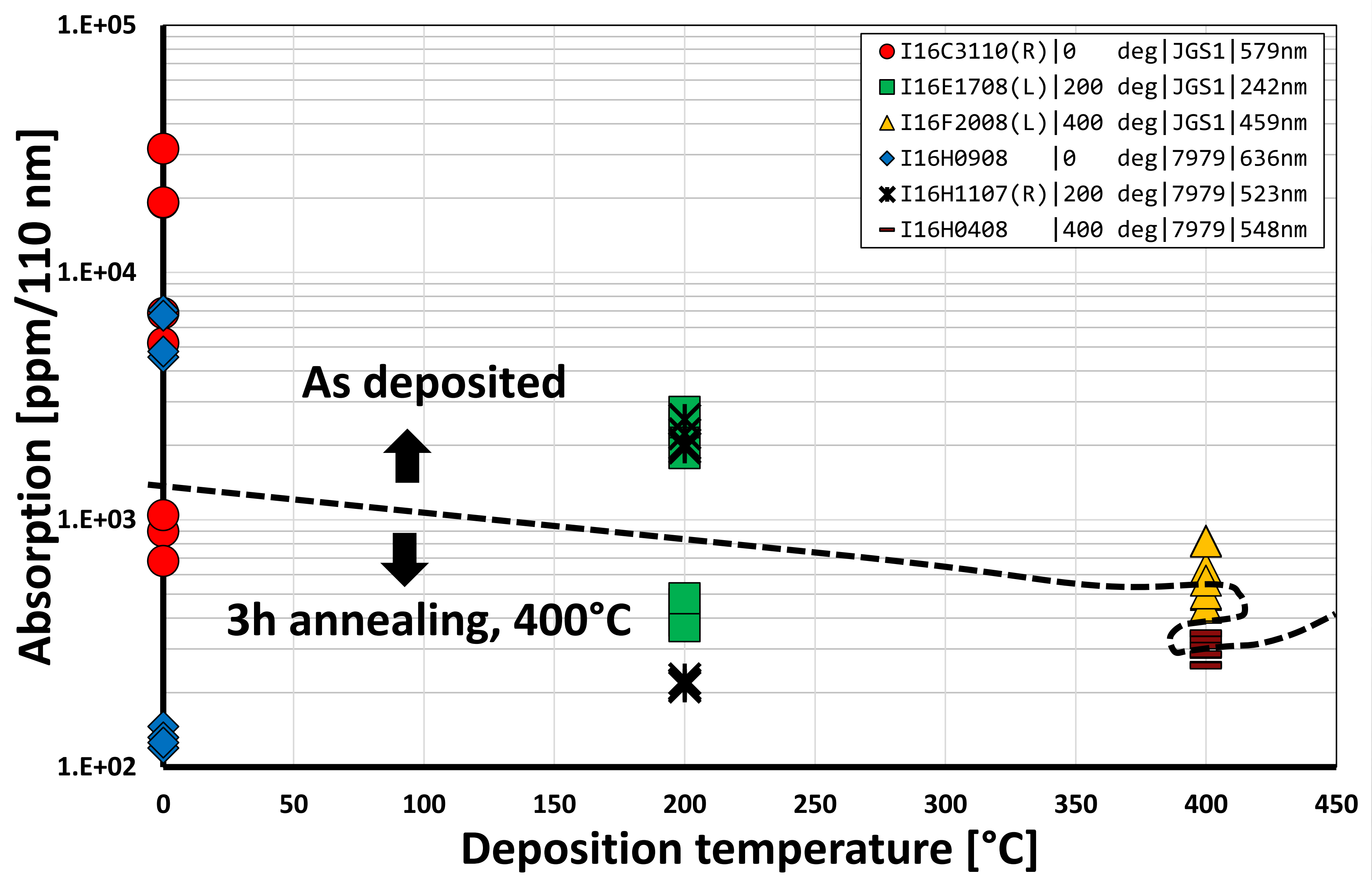


Slides coutesy of prof. Stuart Reid

aSi films were made at UWS



Dangling bonds - absorption correlation



Deposition temperature - absorption correlation

1. Silicon is a promising material for cryogenic GW core optics.
2. It has low mechanical loss at low temperature, zeros of expansion coefficient, high refractive index

3. In Glasgow a scatterometer is active
4. It is able to take measurements to better than order of magnitude level but we're working hard towards a fully reliable instrument

5. Preliminary measurement of MCz Si suggest values compatible with use in ET.
6. 45-74 ppm bulk scatter for a 46 cm thick test mass would likely be dominated by coating scattering

7. Heat deposited aSi coatings show absorption comparable with annealed ones.
8. A clear link has been established between absorption and dangling bonds, and absorption and deposition temperature.

Conclusions

1. Optimise the scatterometer, understand its noise sources and discrepancies with literature
2. Carry out systematic angle-dependent measurements to verify to which extent the scattering observed is really only Rayleigh
3. Find a way to reliably calibrate the system

4. Work towards understanding surface absorption (not discussed here)

5. Integrate the aSi coatings study with other analyses such as Raman spectroscopy

Future

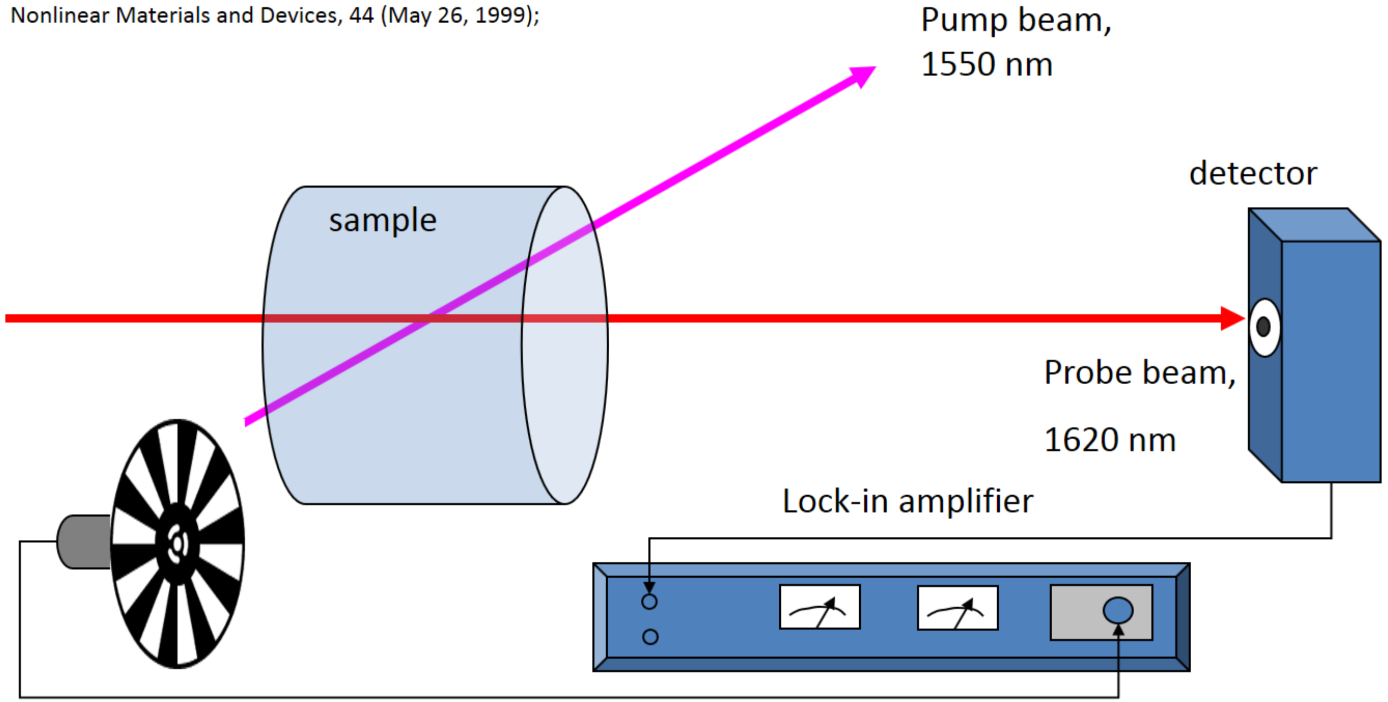
Thank you!

Absorption measurements - IGR

UWS UNIVERSITY OF THE WEST of SCOTLAND
University of Glasgow

Photo-thermal commonpath interferometry (PCI)

A. Alexandrovski et al. *Proc. SPIE* 3610, Laser Material Crystal Growth and Nonlinear Materials and Devices, 44 (May 26, 1999);



Slide courtesy of J. Steinlechner (IGR, Glasgow)

Photothermal common-path interferometry (PCI)