University of Glasgow | School of Physics & Astronomy

IGR

SUPA

LSC

ET EINSTEIN TELESCOPE

GEO 600

OPTICAL PROPERTIES OF SILICON FOR CRYOGENIC GW DETECTORS

ZENO TORNASI

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

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J. Steinlechner[2,5], S. Reid[3], S. Rowan[2], S. Sproules[2]

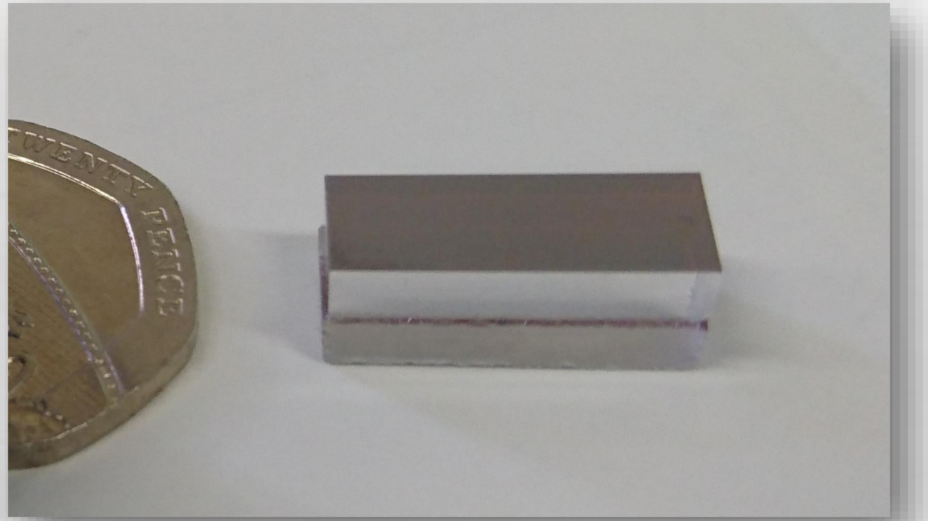
[1]CALTECH, [2]UofG, [3]UWS, [4]STANFORD, [5]HAMBURG

GraWIToN
GW Initial Training Network
MARIE CURIE ACTIONS

Topics

Crystalline silicon

Optical scattering

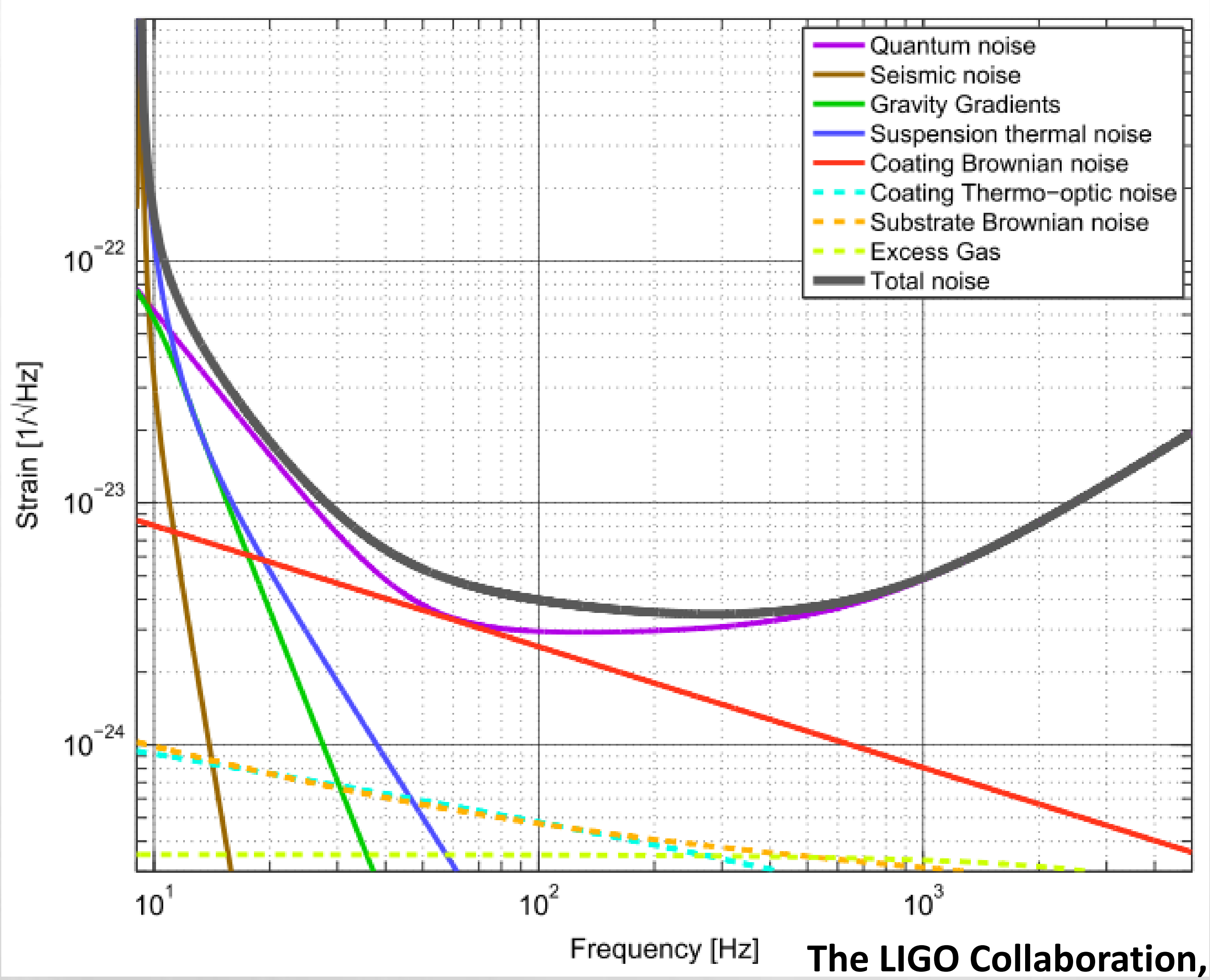


Amorphous silicon coatings

Optical absorption

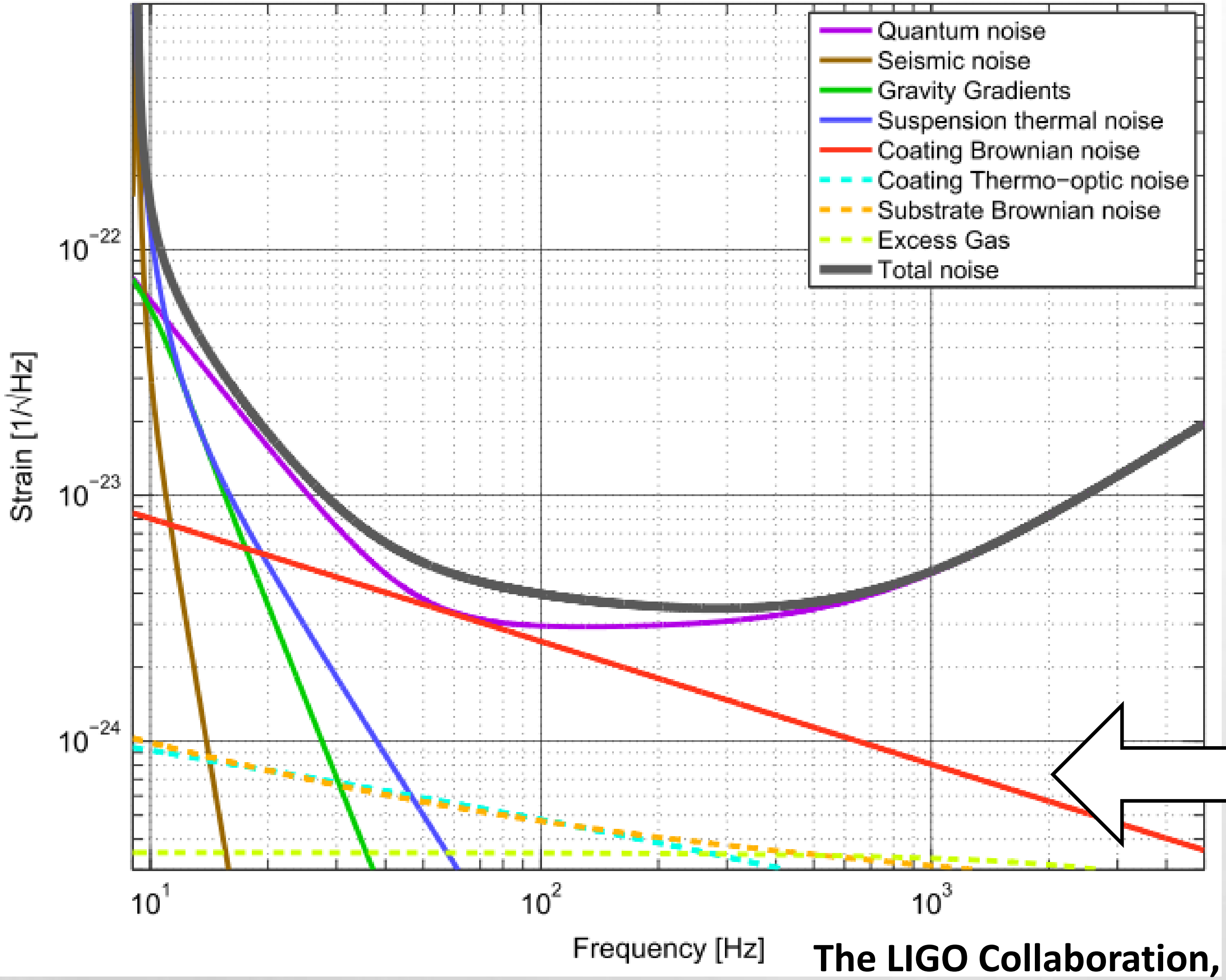
Why silicon?

Introduction



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

Noise in a gravitational wave detector



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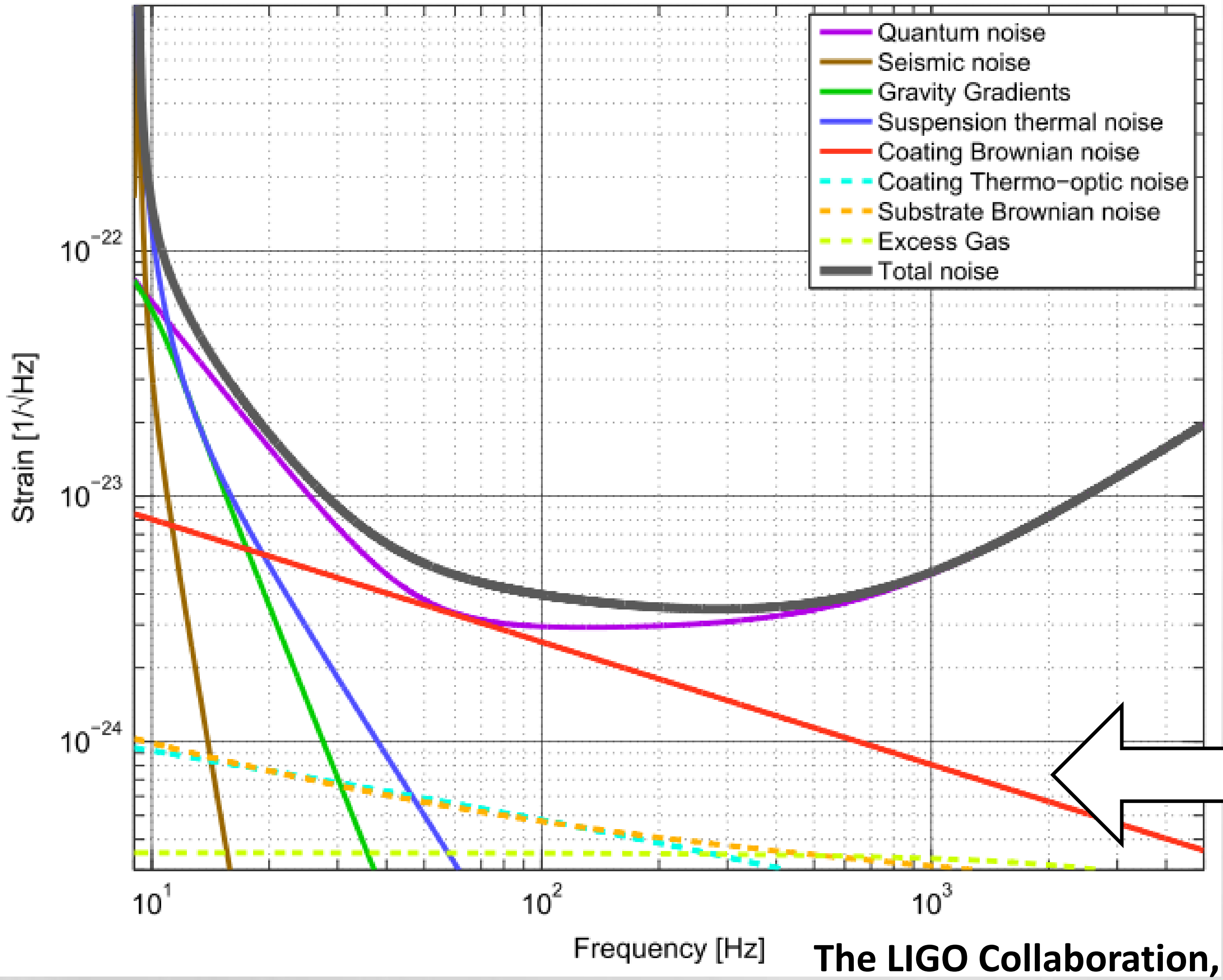
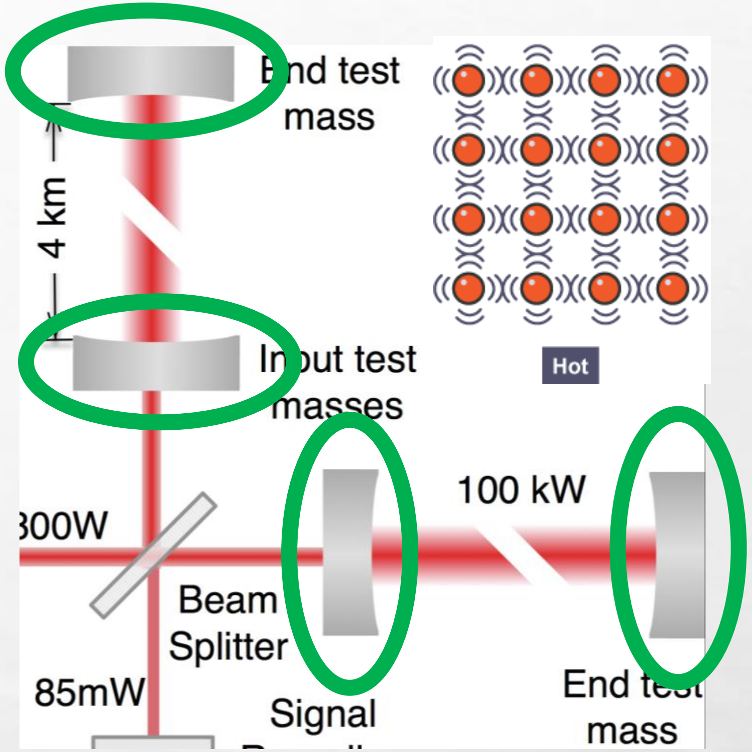




Coating Brownian noise

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

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

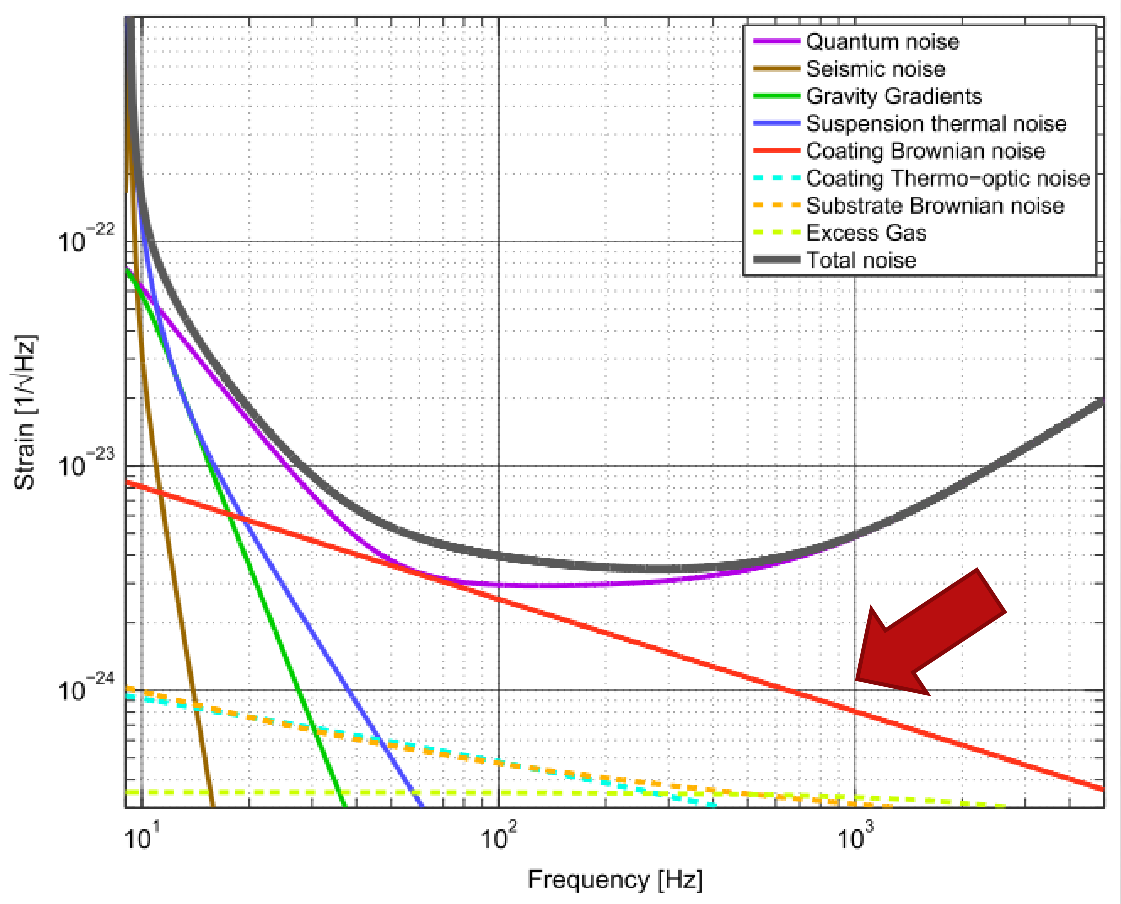
Temperature

Mechanical loss

Coating thickness

Young’s modulus

Beam width



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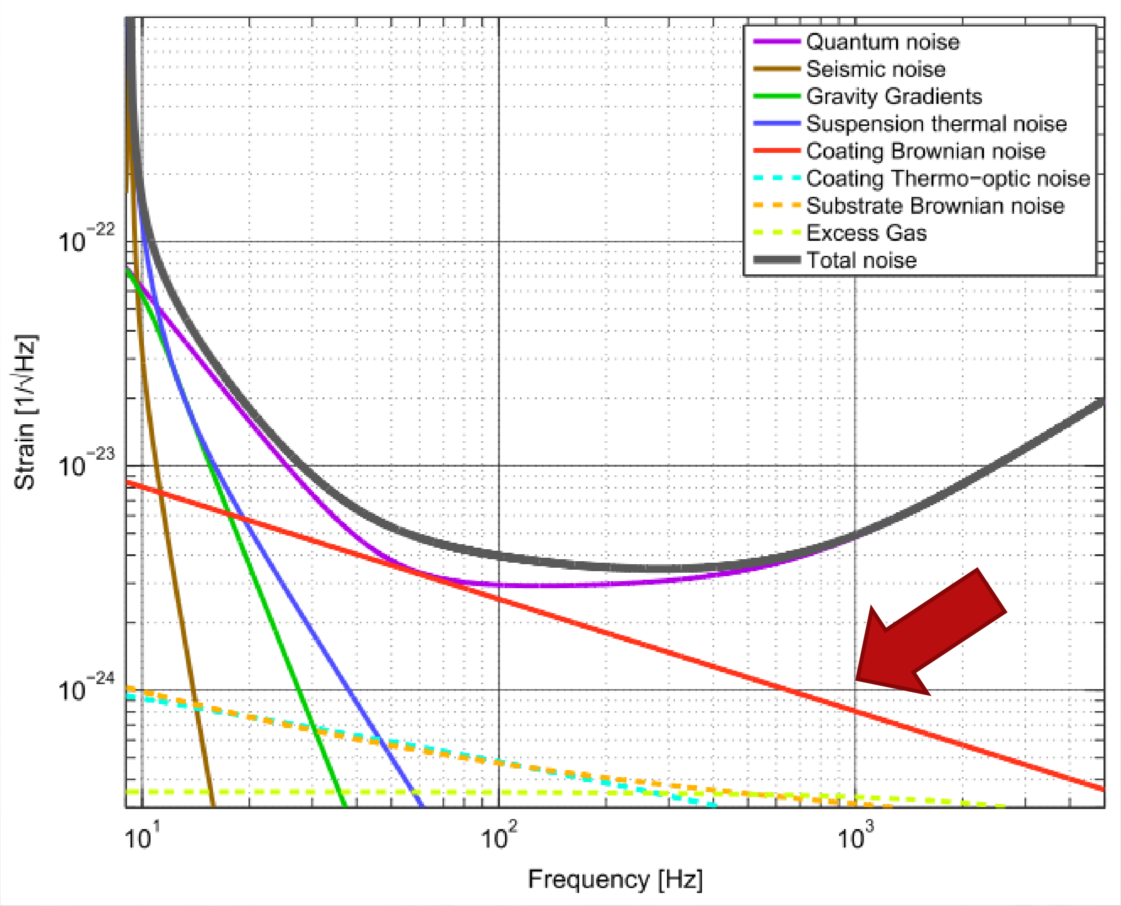
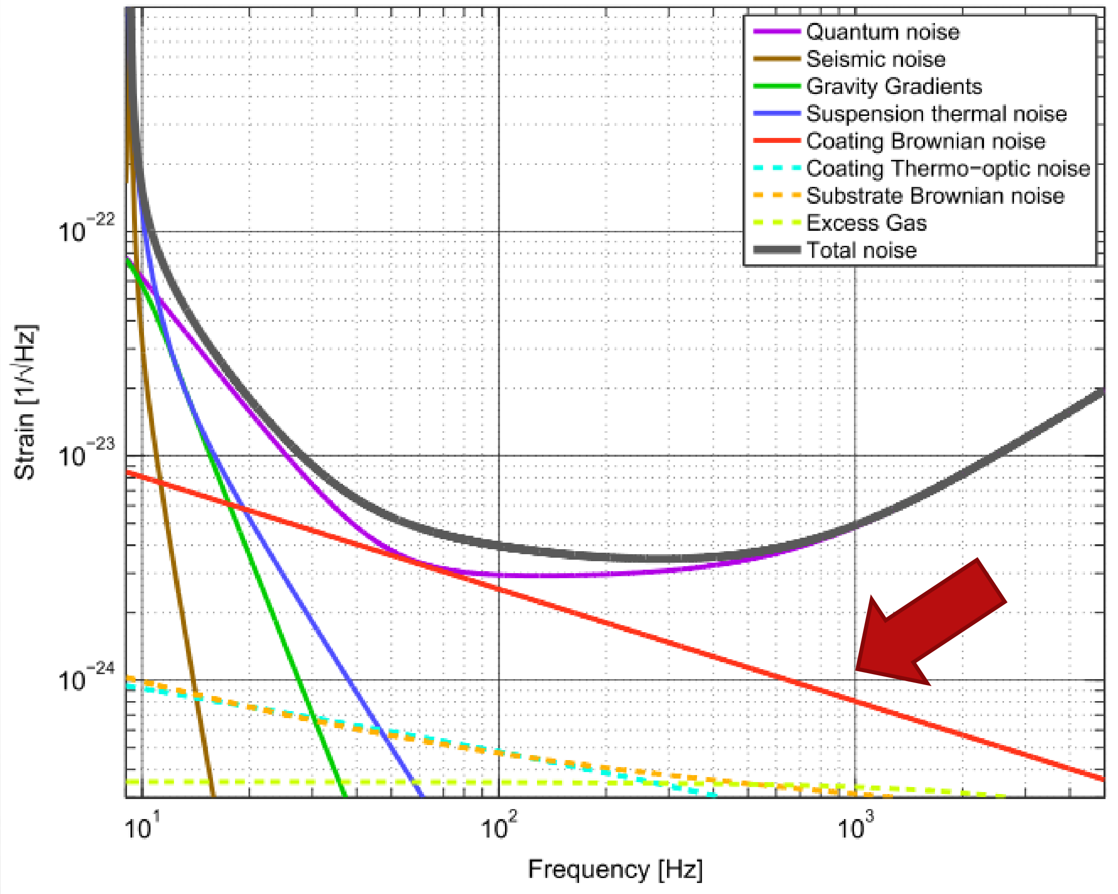


→ Limited room for improvement

Substrate engineering constraints

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



Temperature

Mechanical loss

Coating thickness

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Beam width

Property of the coating material

Not much to do about it

Coating Brownian noise (similar idea for substrates)

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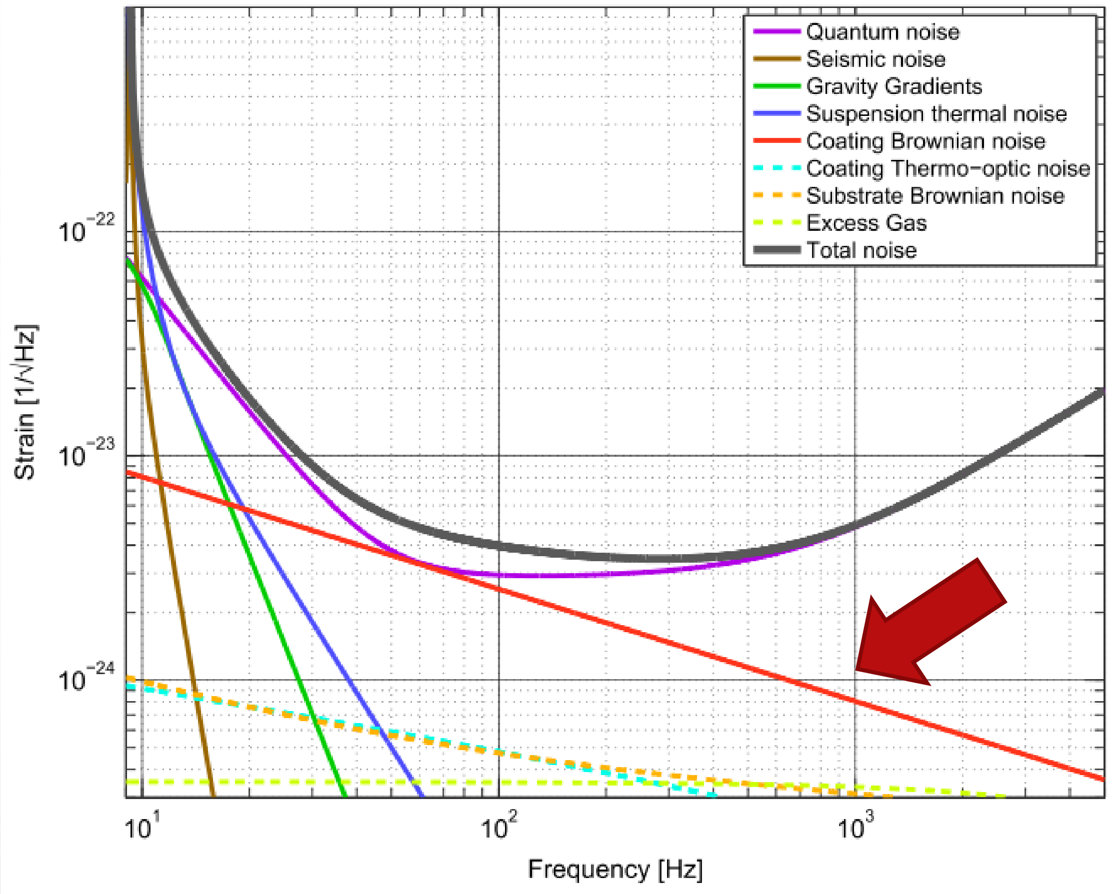
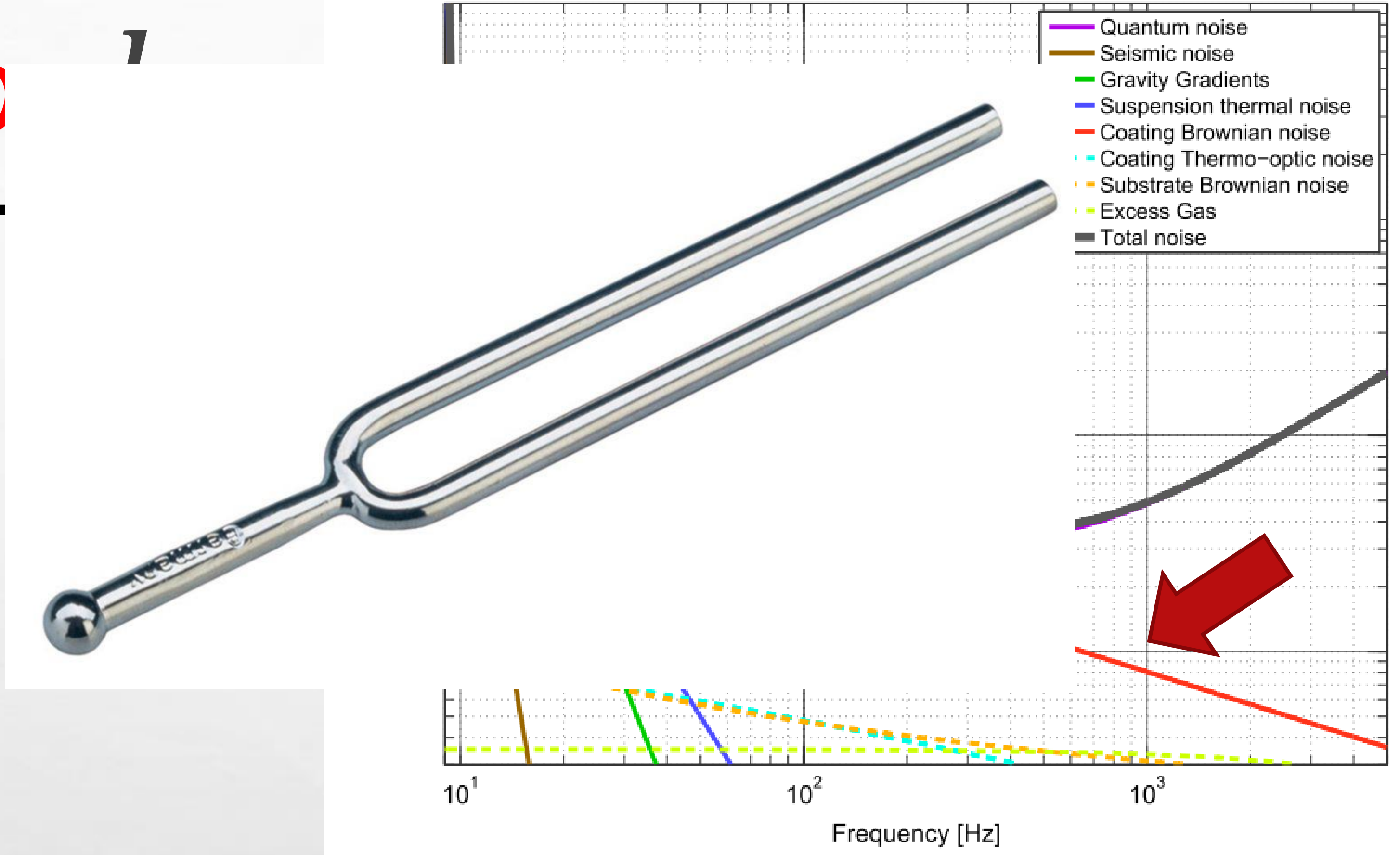


High refractive index materials

Coating Brownian noise (similar idea for substrates)

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



Temperature

Mechanical loss

Coating thickness

Young’s modulus

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Property of the material

Can vary by orders of magnitude

Can be engineered to some extent

Coating Brownian noise (similar idea for substrates)

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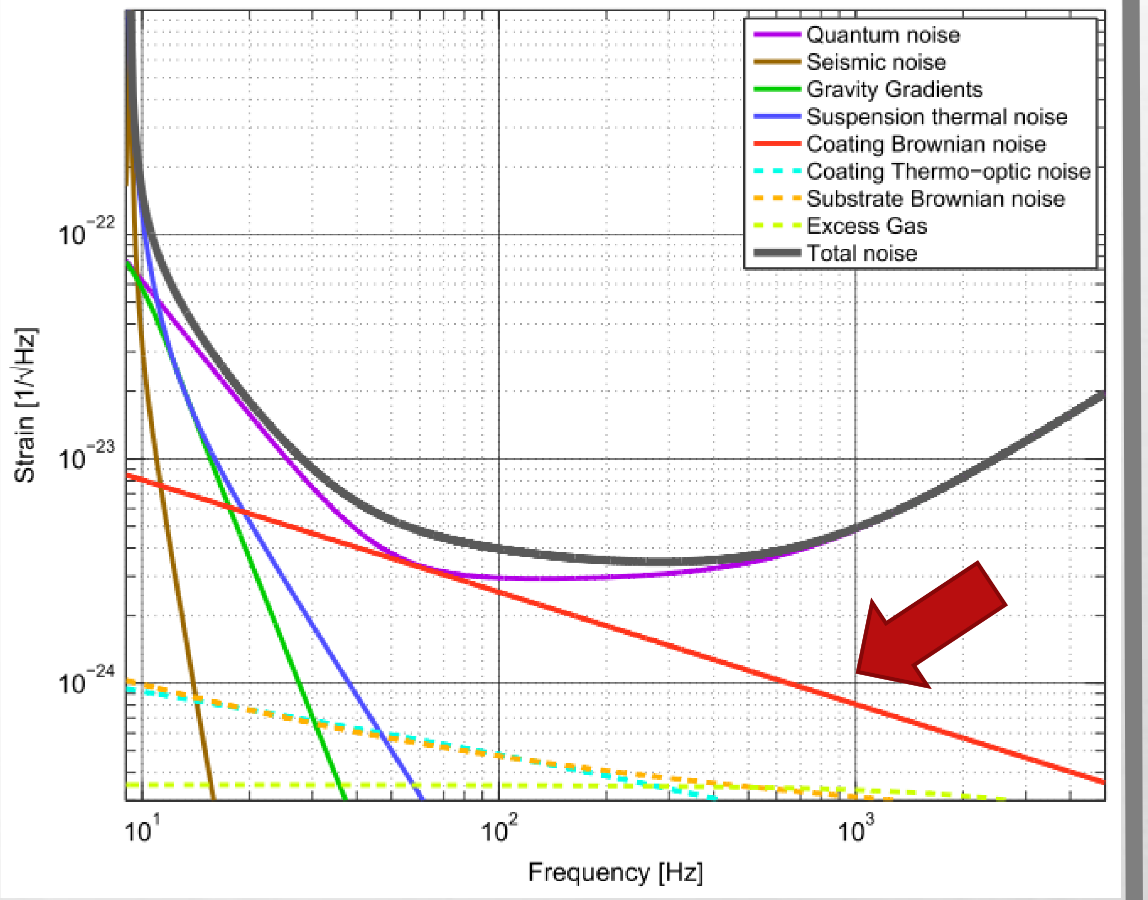

Current detectors operate at room T

Can we just go cryogenic then? Not yet…

- In general

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

Fused silica has a high mechanical loss at low T

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- Currently LIGO optics are made of fused SiO_2

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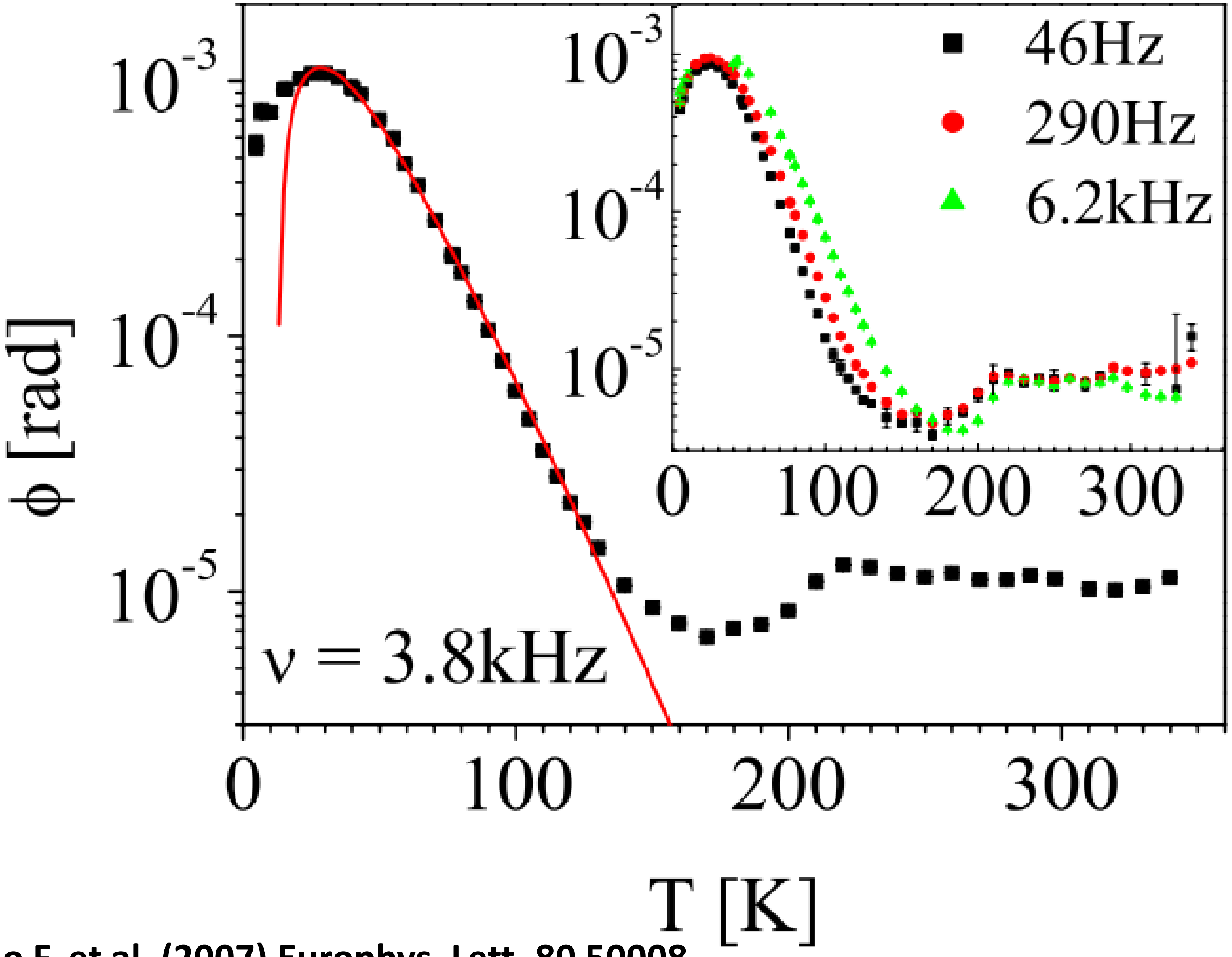
$$S_x(f) \propto \frac{T\ \phi(T)\ d}{f\ Y\ w^2}$$

- Currently LIGO optics are made of fused SiO_2

- Since the ’50s we know that mechanical loss in SiO_2 goes like →→



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

Fused silica has a high mechanical loss at low T

THE PROBLEM

Fused silica is used

As a substrate

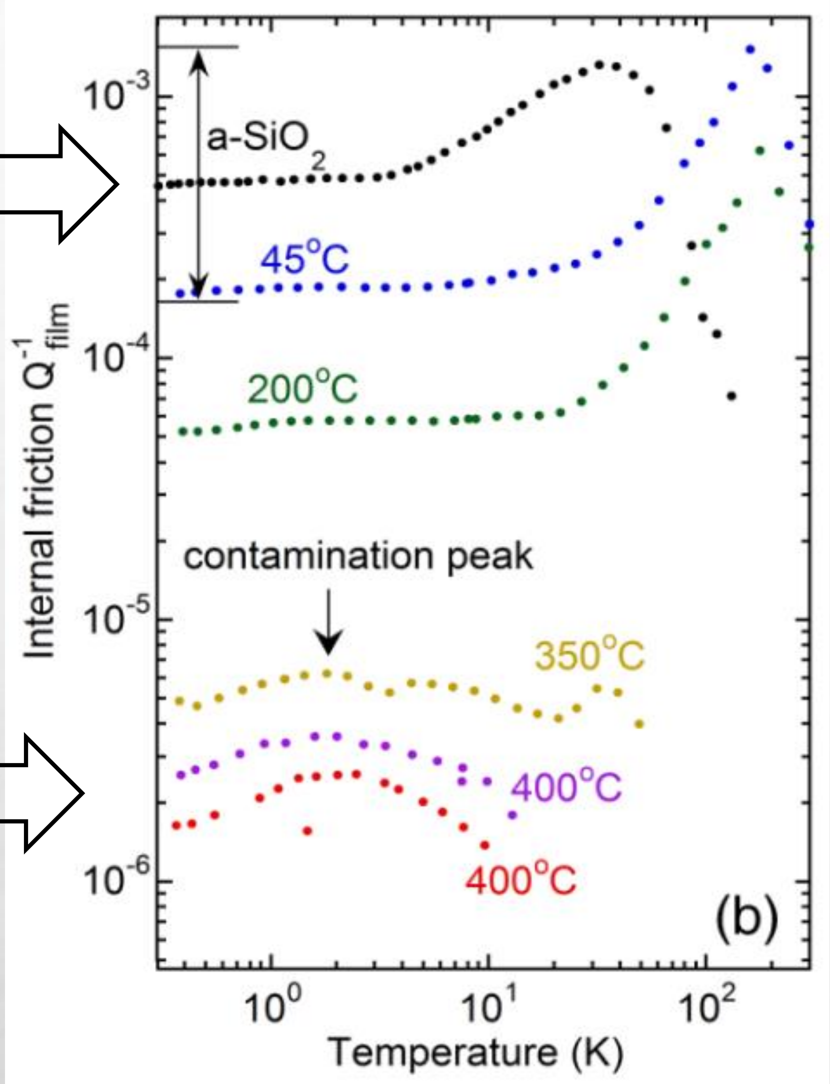
As a coating

With tantala (also lossy at low T)

WHAT DO WE USE INSTEAD?

SiO_2

aSi



X. Liu, F. Hellman, et al, *PRL* 113, 025503 (2014)

Coatings: Amorphous silicon looks promising

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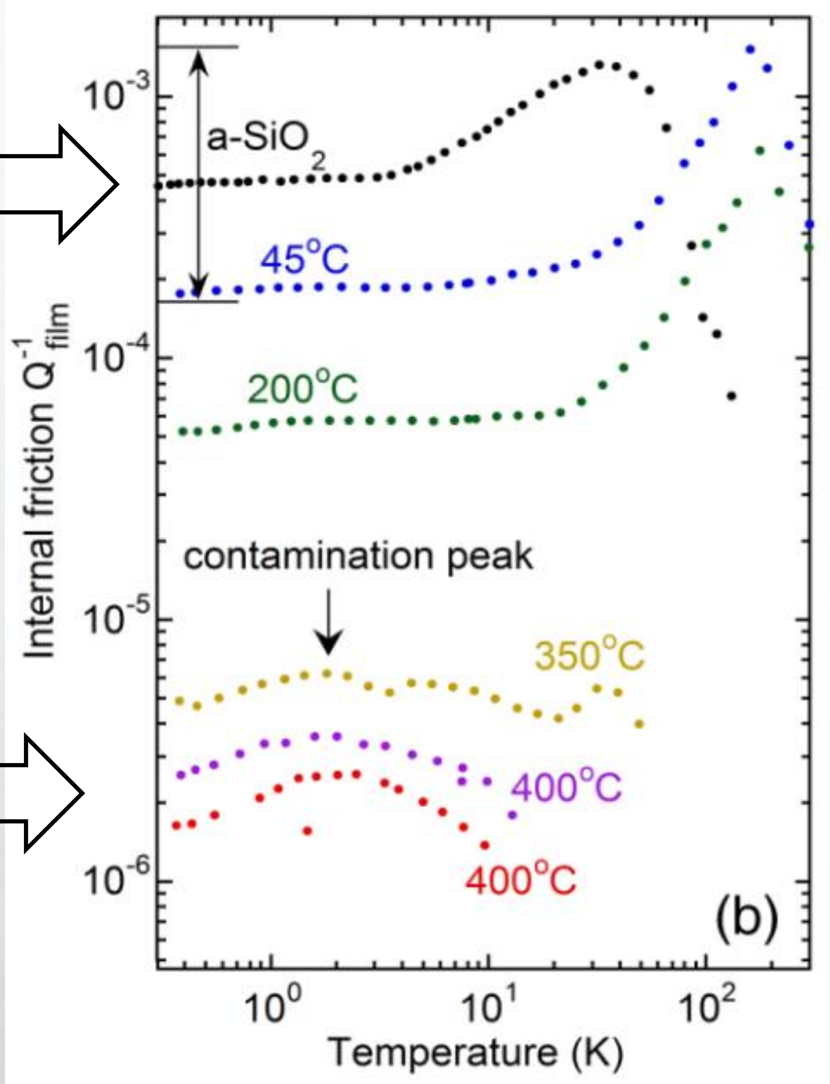

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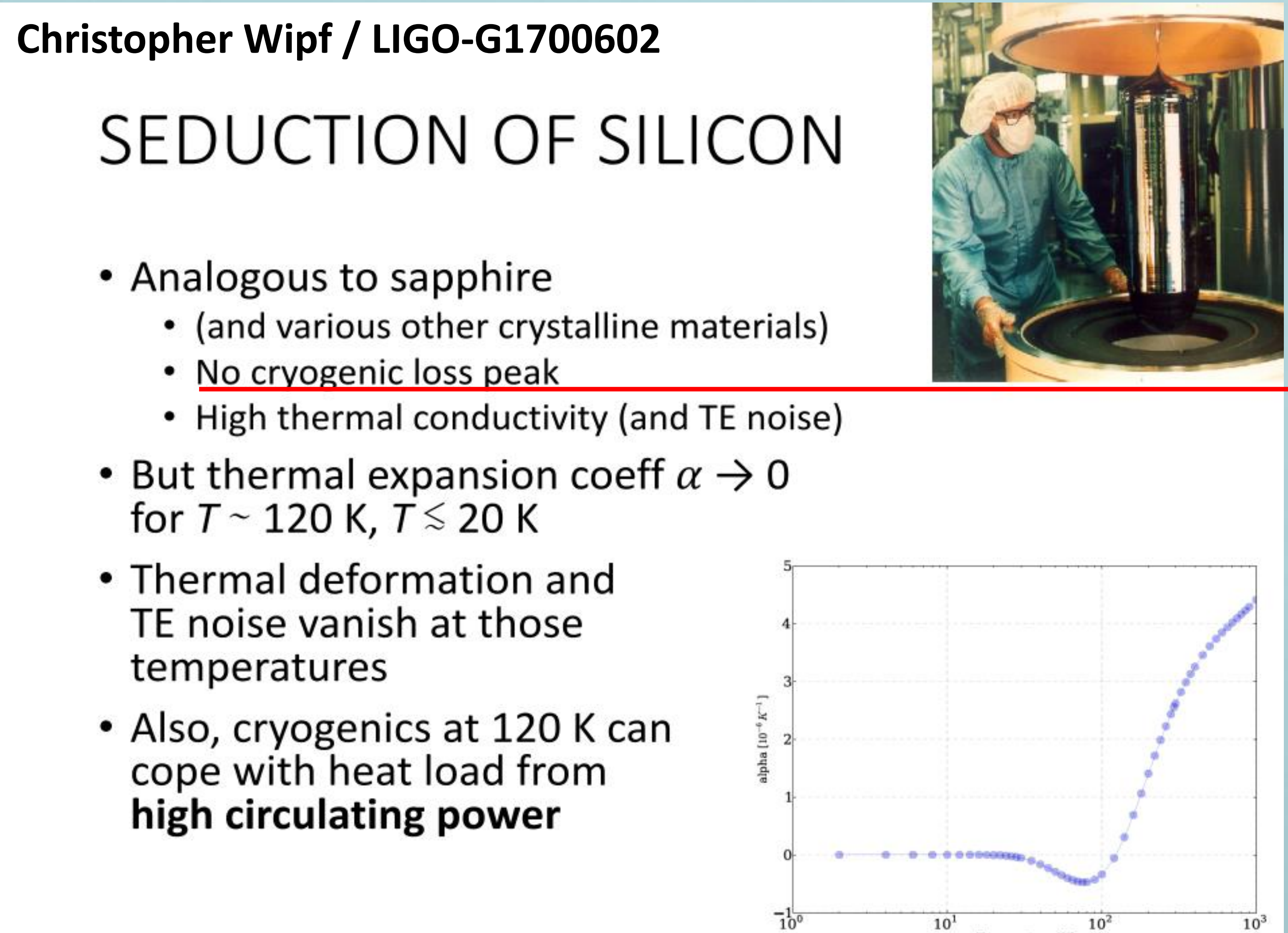
Bonus

High refractive index

n = 3.47 @ 1550 nm

helps reducing thickness

Substrates: Crystalline silicon looks great too

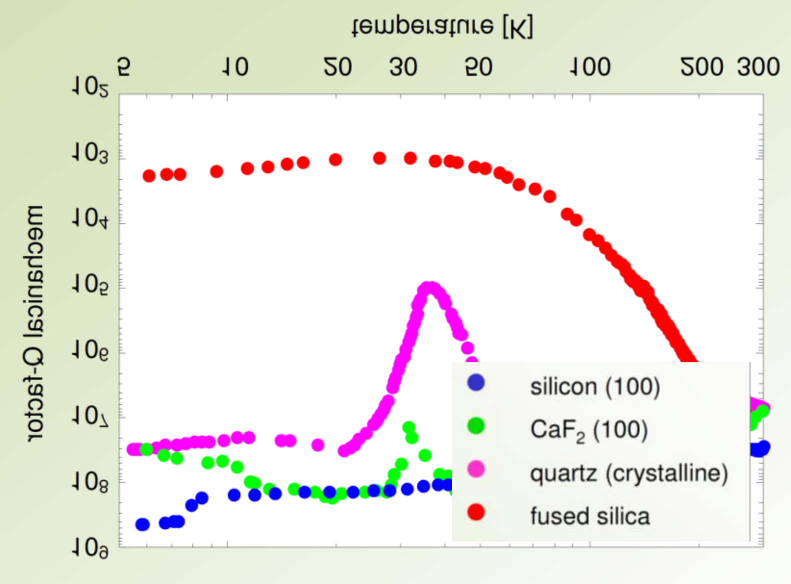


Christopher Wipf / LIGO-G1700602

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**

We know since the '70s that cSi has very low mechanical loss at low temperature.



Credits: Ronny Nawrodt

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

Crystalline silicon

Crystalline silicon bulk absorption

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 ✓

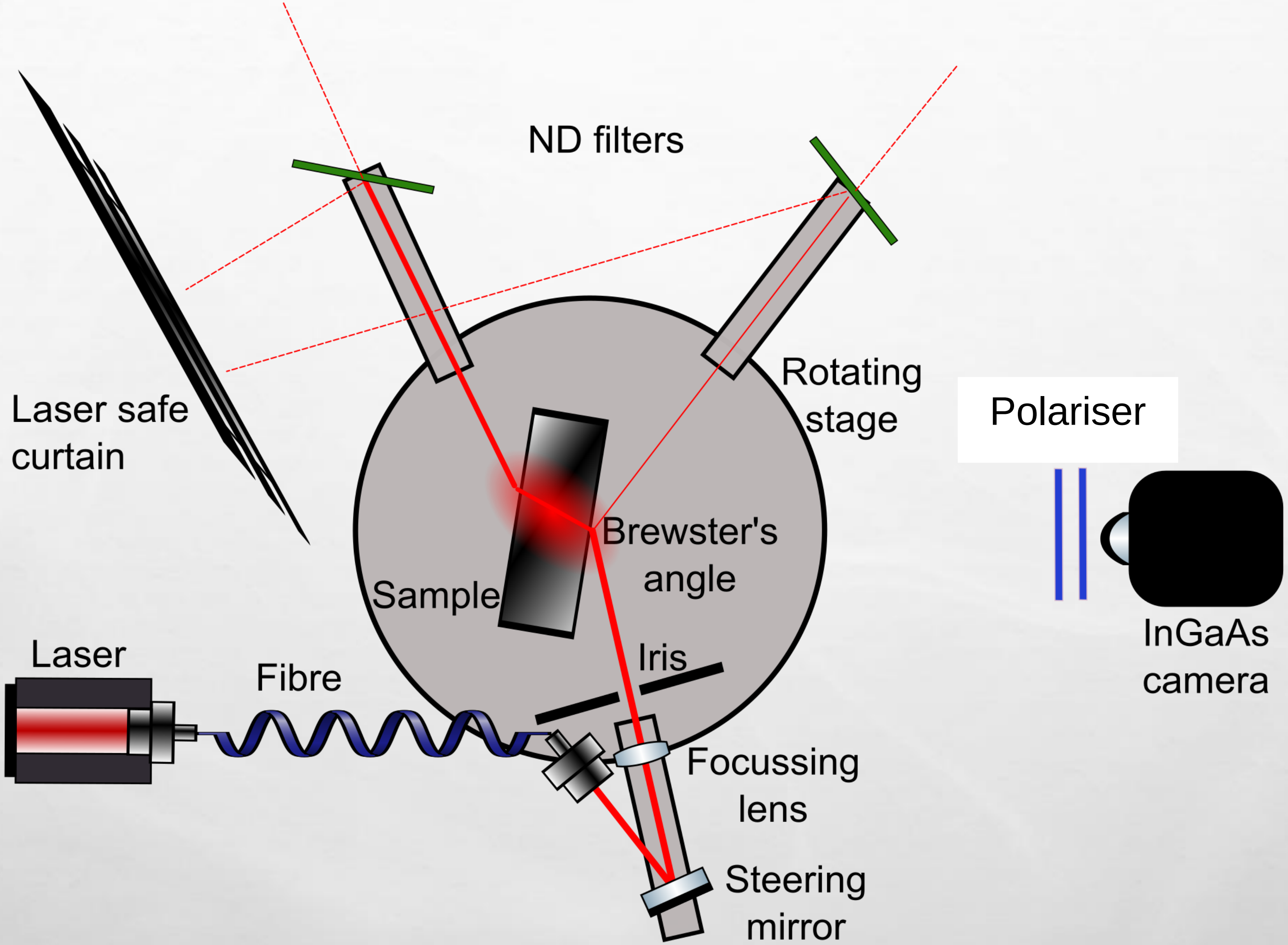
A. Markosyan, A. Bell / LIGO-G1700480

Surface absorption
is a different beast
A. Bell / LIGO-P1700134

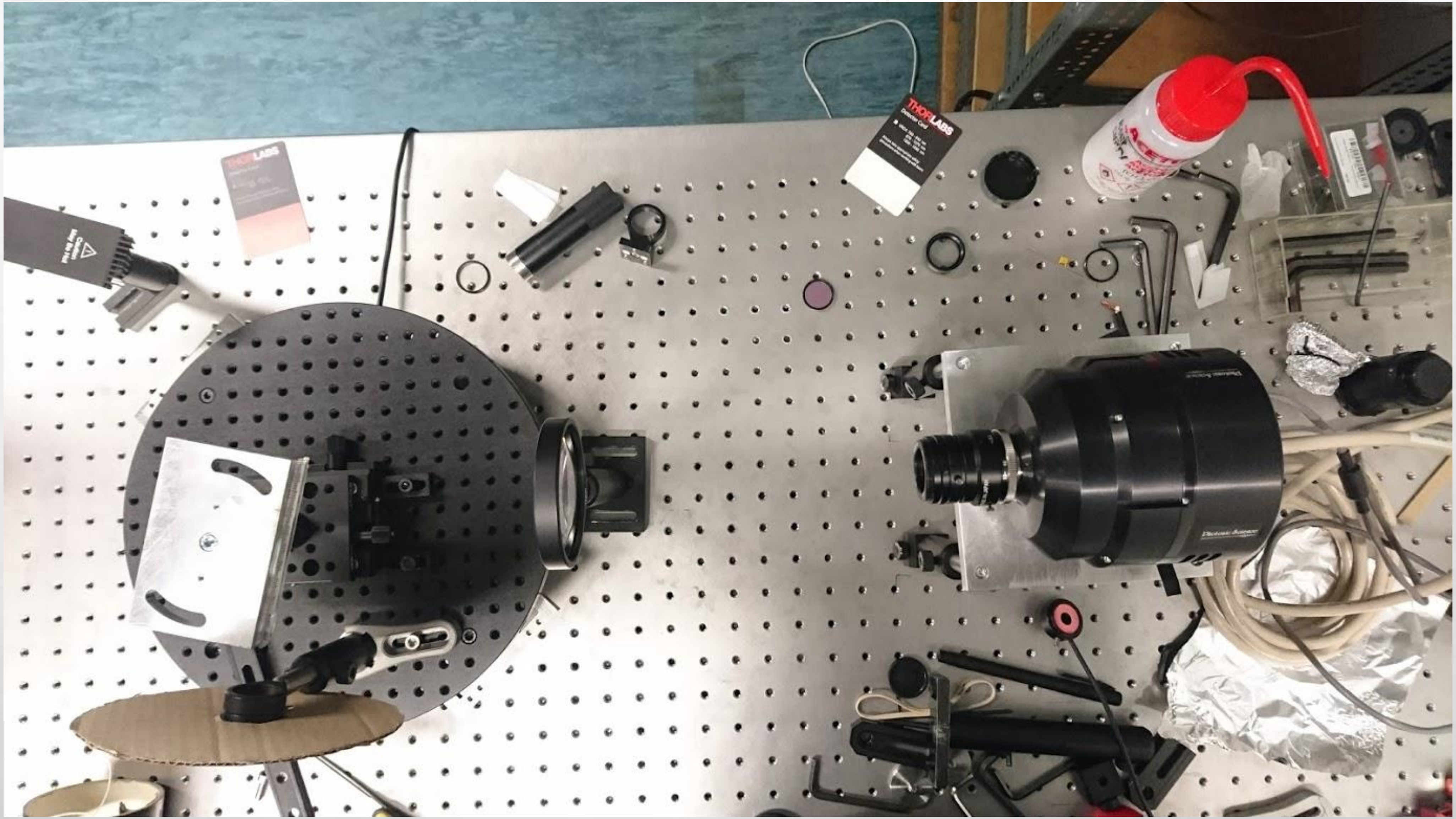
Photons scattered off axis

- Add phase noise if they are reflected back in the system by the environment
- Contribute to cavity round trip loss
- Easily disrupt squeezed states

Why scattering matters



The Glasgow scatterometer



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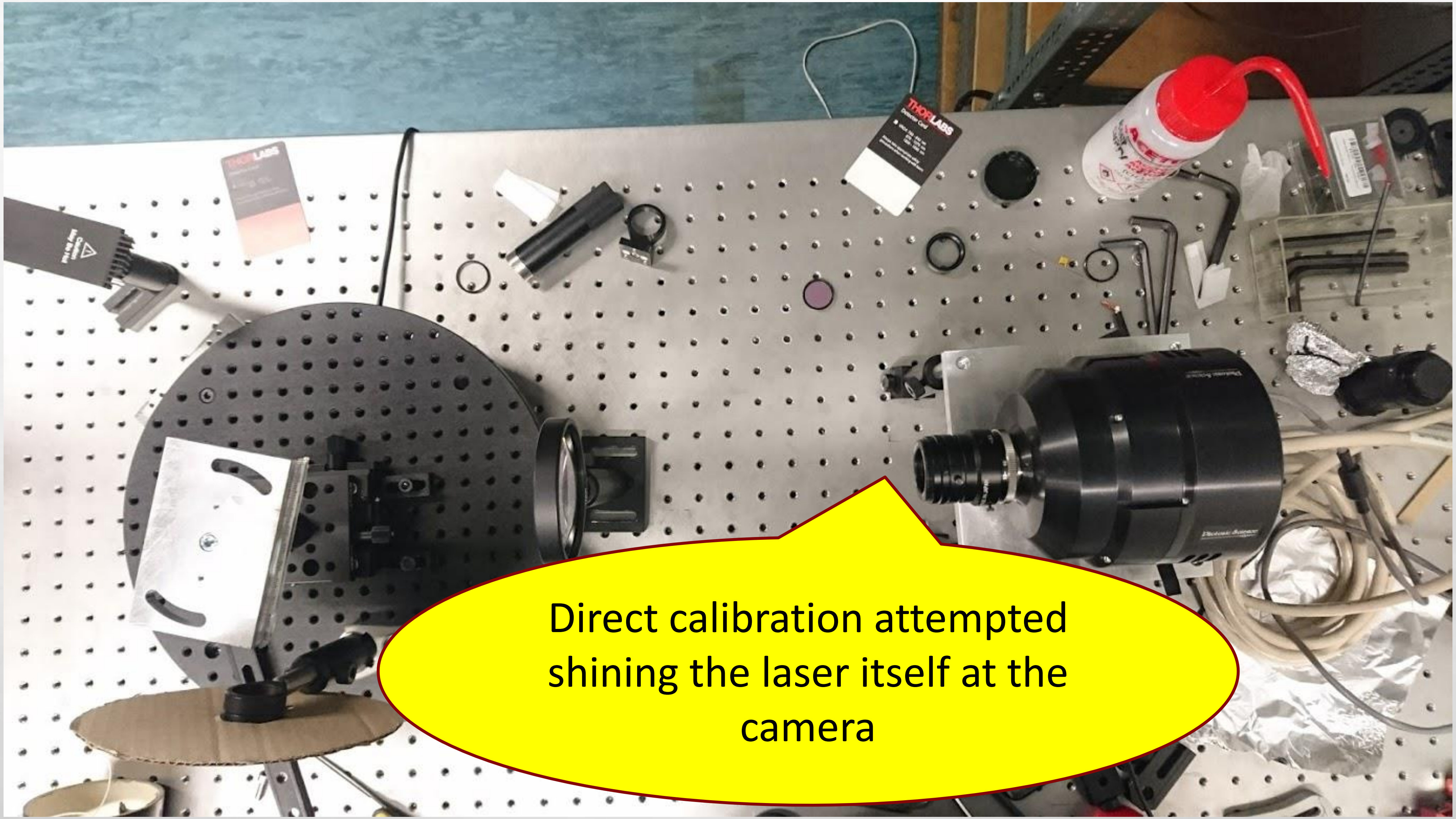
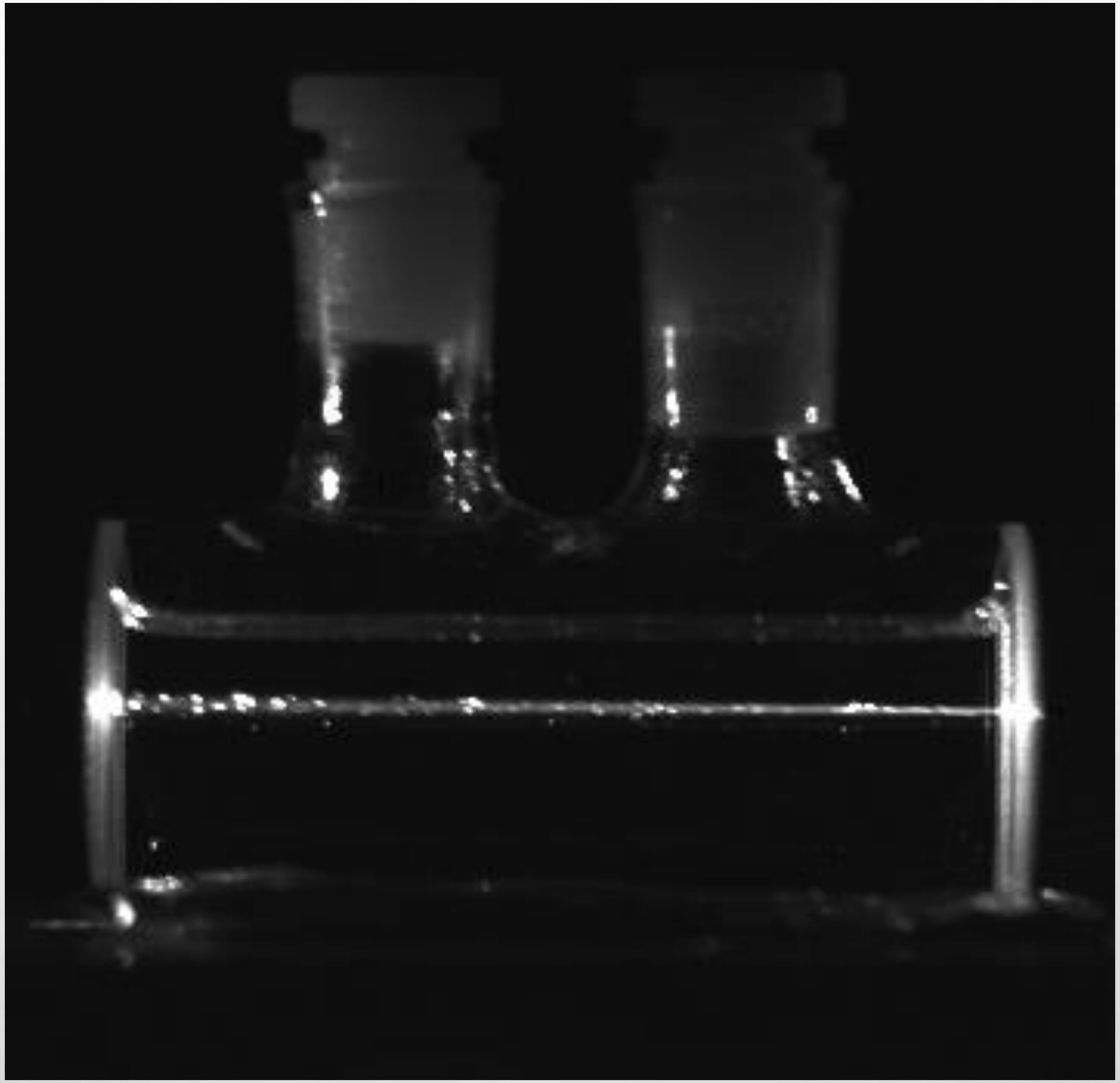
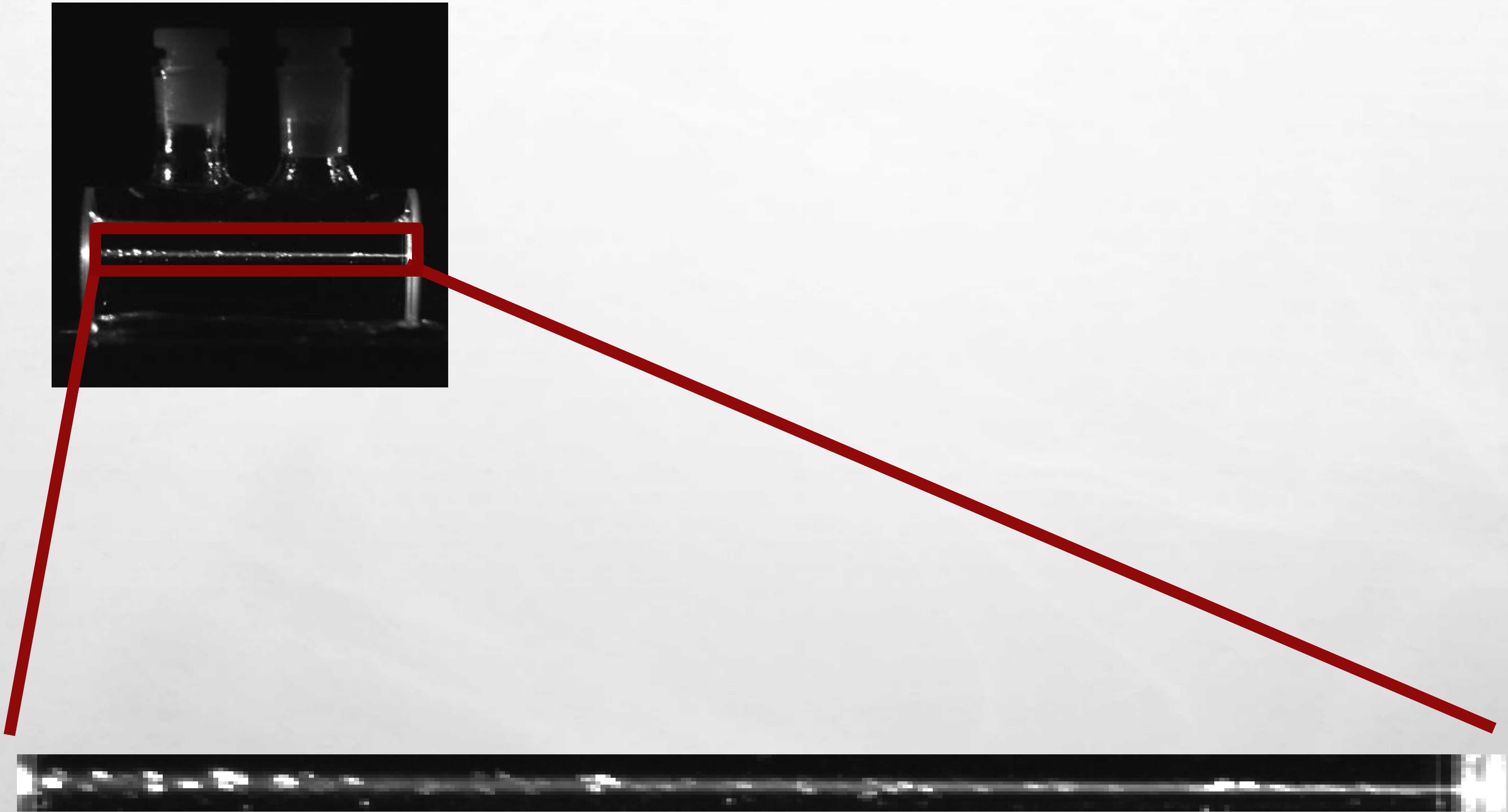


Direct calibration attempted shining the laser itself at the camera

The Glasgow scatterometer



“Engineering run 1”: looking at CCl_4



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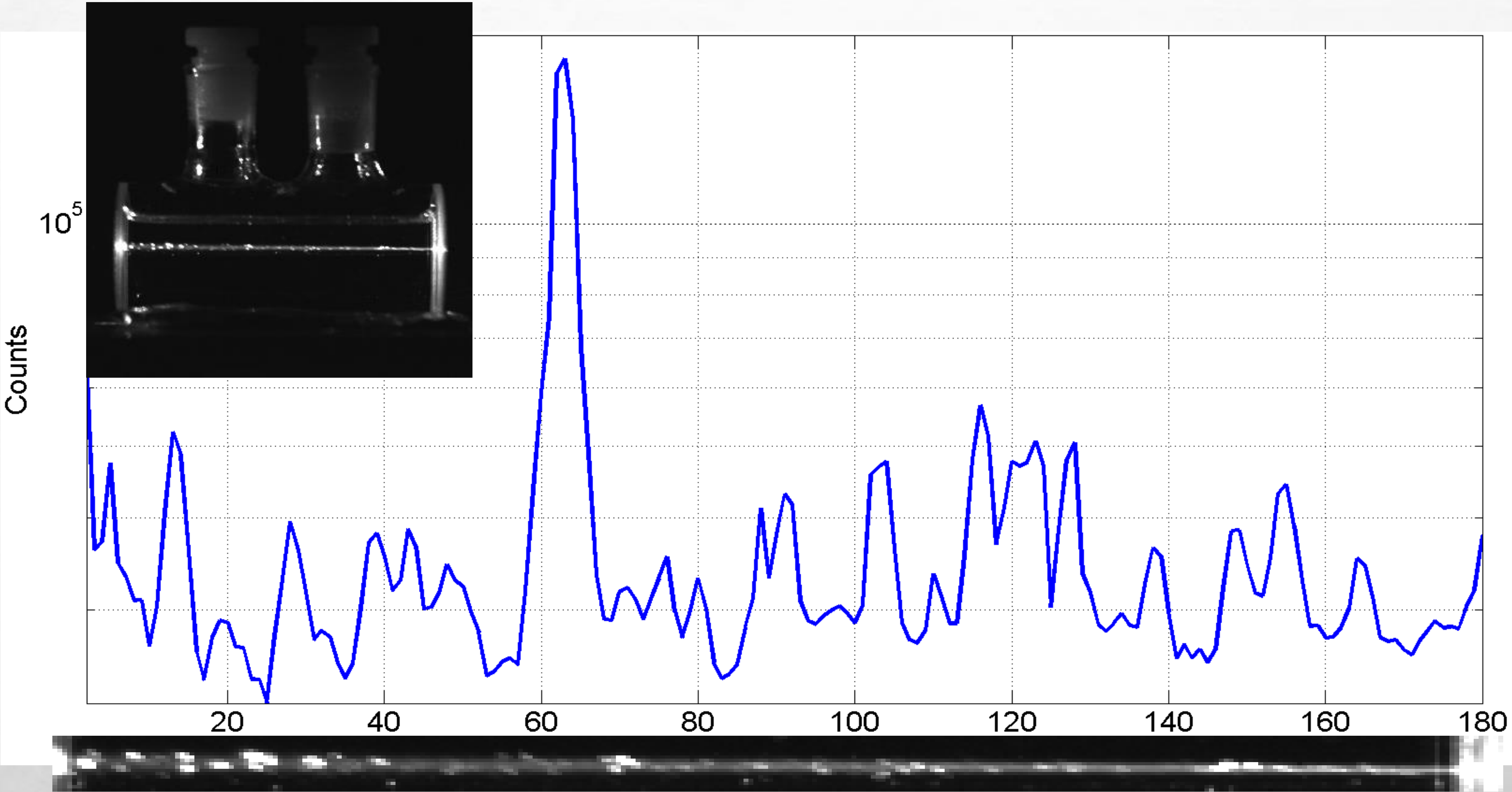

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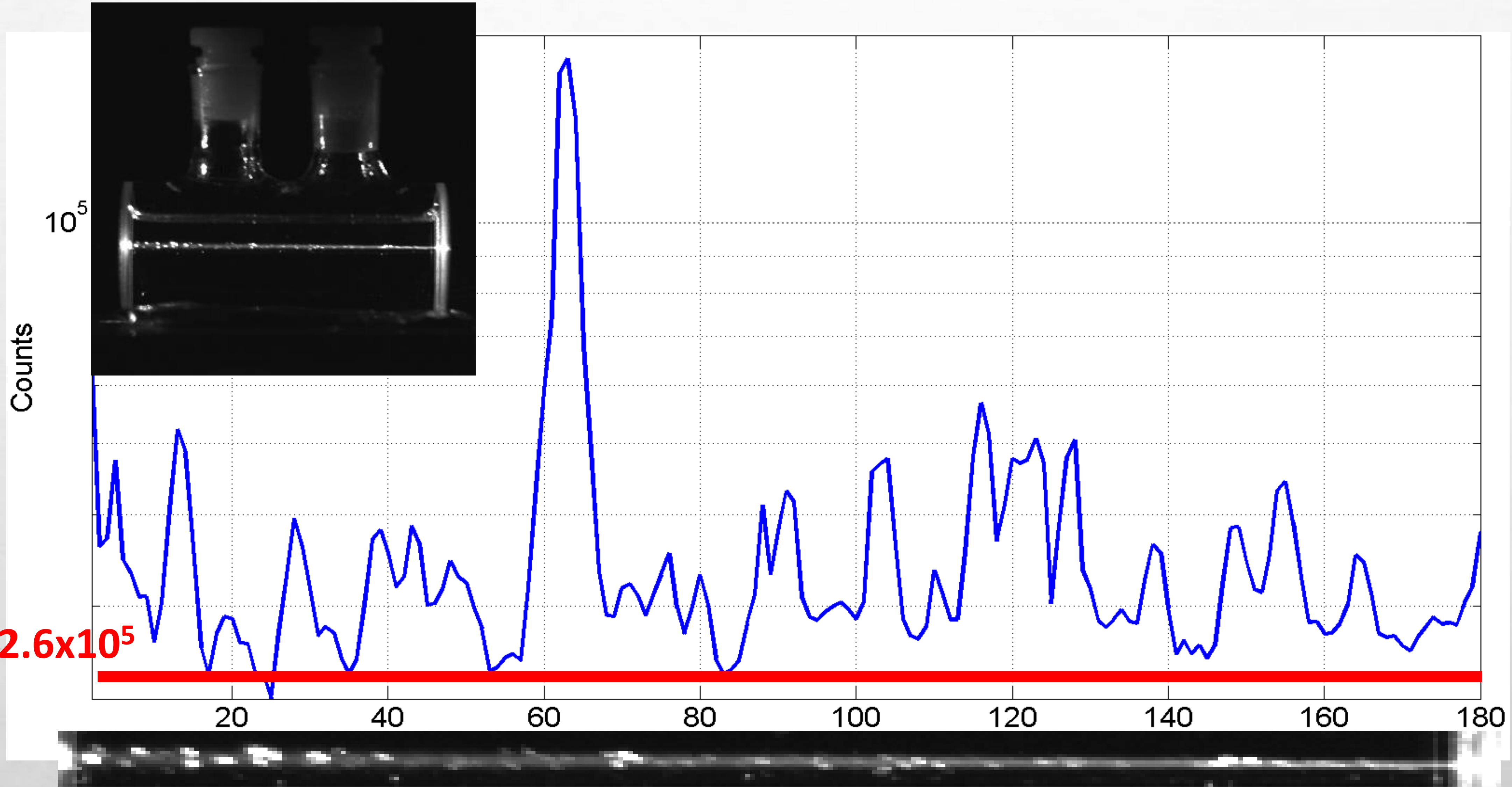

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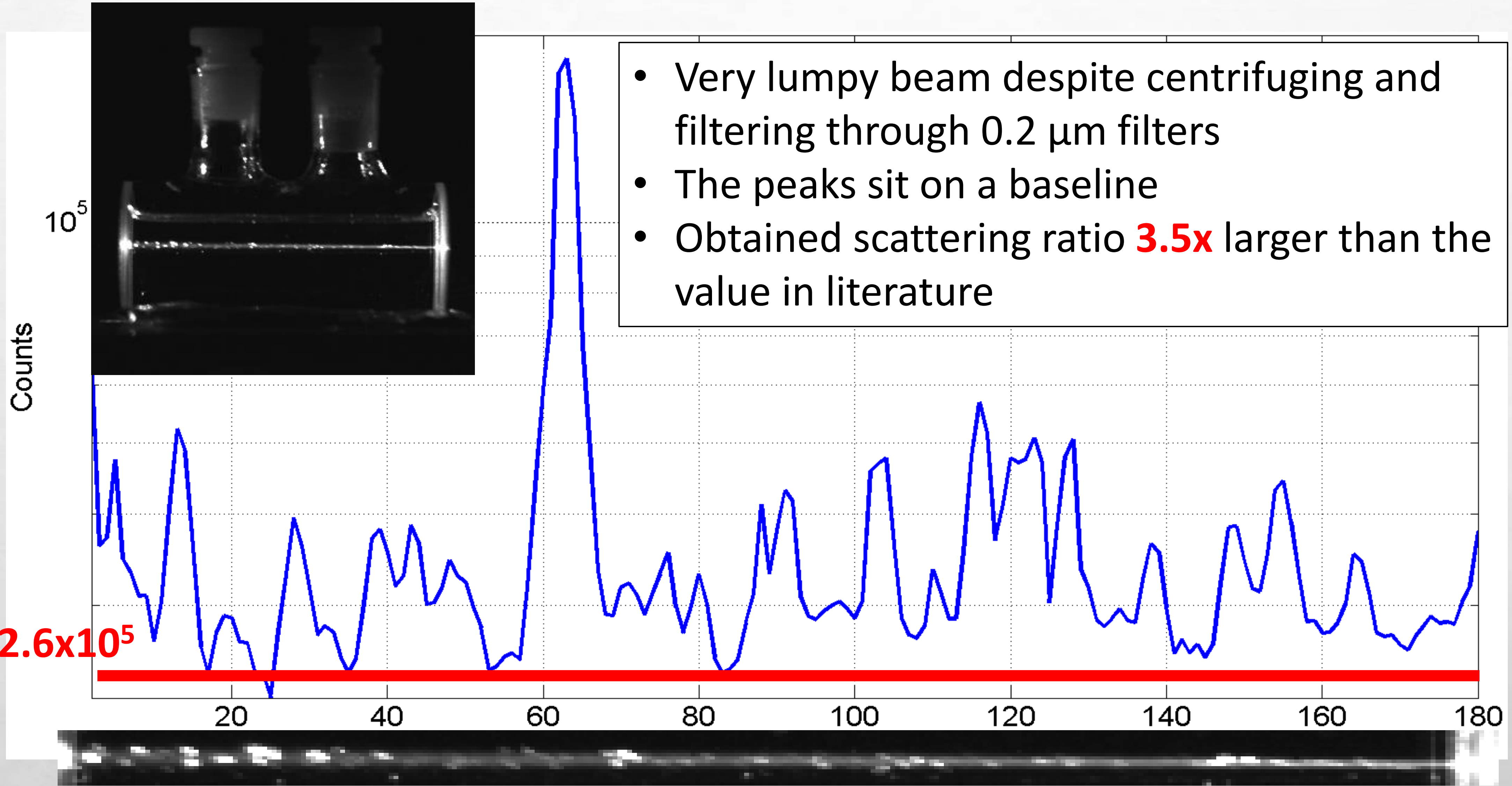
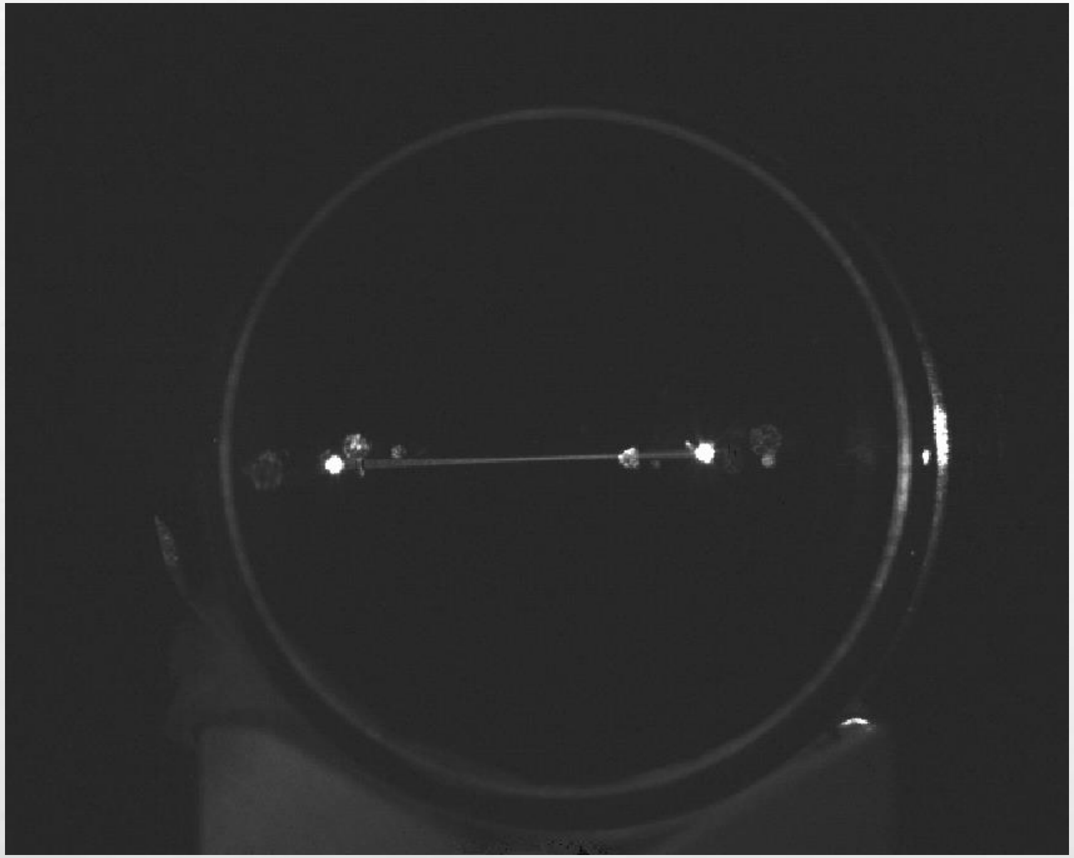
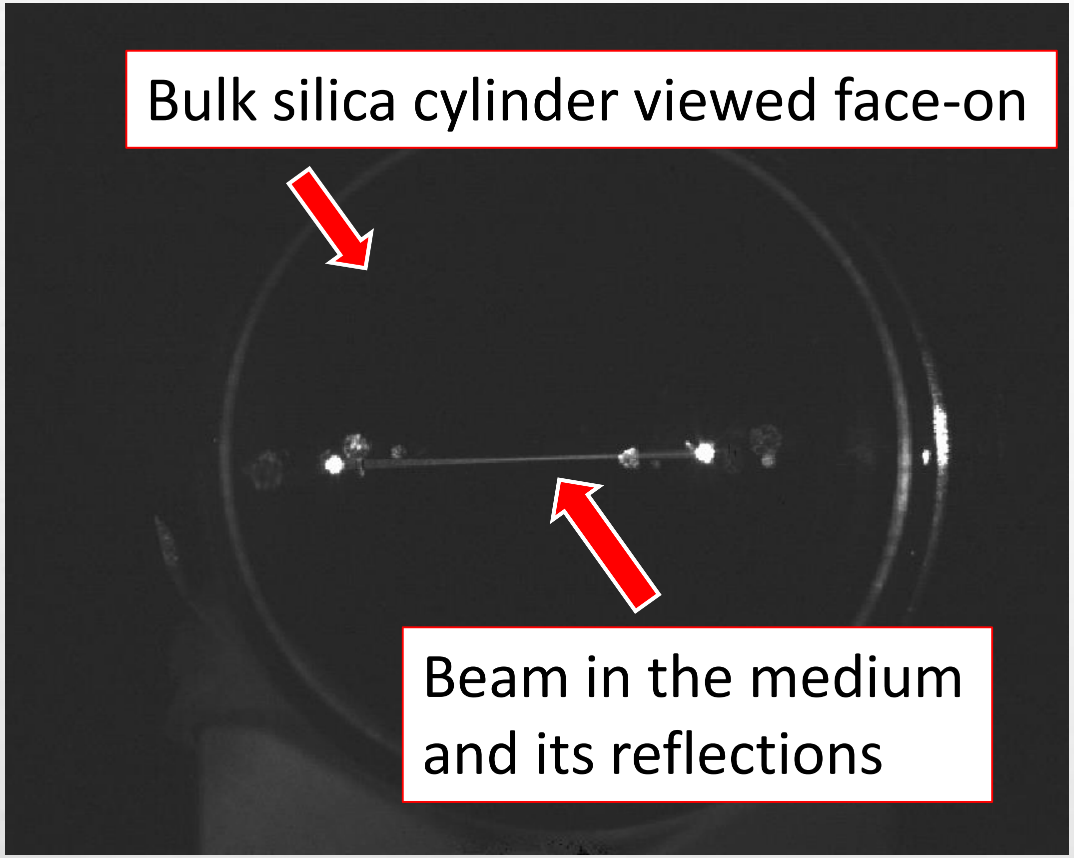


- Very lumpy beam despite centrifuging and filtering through 0.2 µm filters
- The peaks sit on a baseline
- Obtained scattering ratio **3.5x** larger than the value in literature



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

“Engineering run 2”: fused silica



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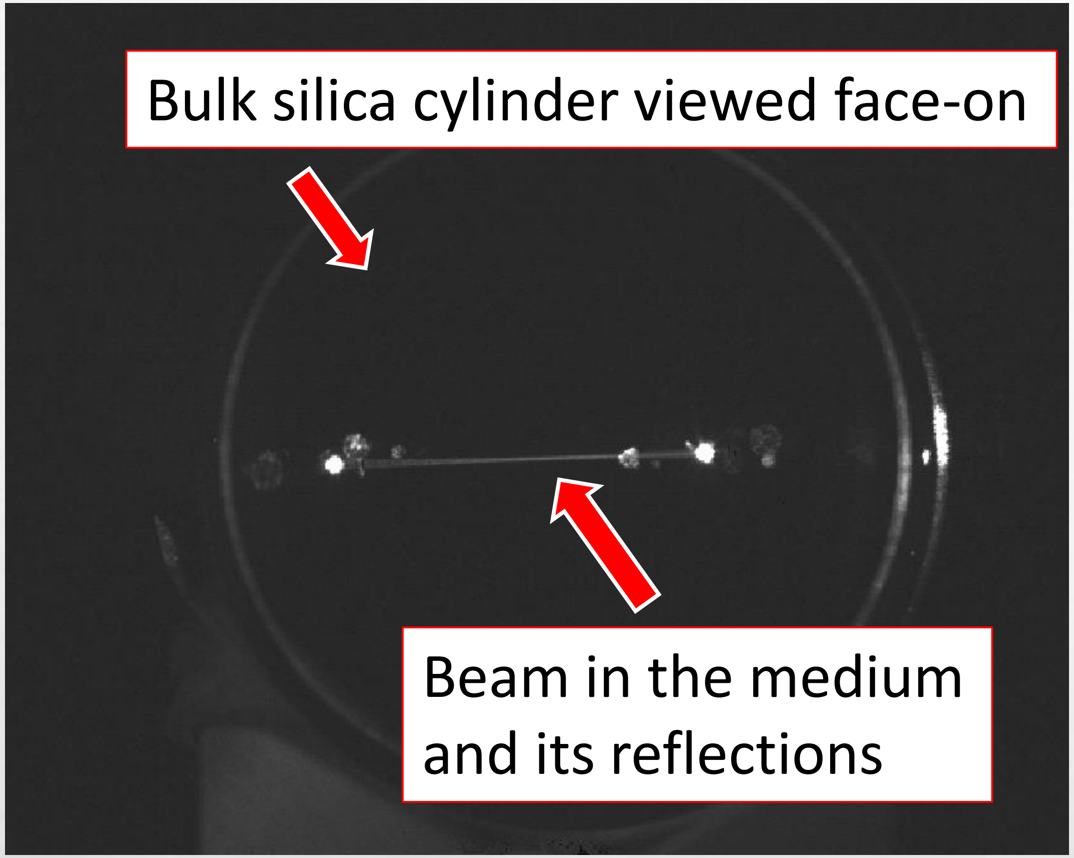

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Difference between direct calibration and CCl4

- Scattering ratio obtained is **2.16x** larger than literature, according to my direct calibration
- Or it's **0.6x** literature, taking CCl4 as a reference

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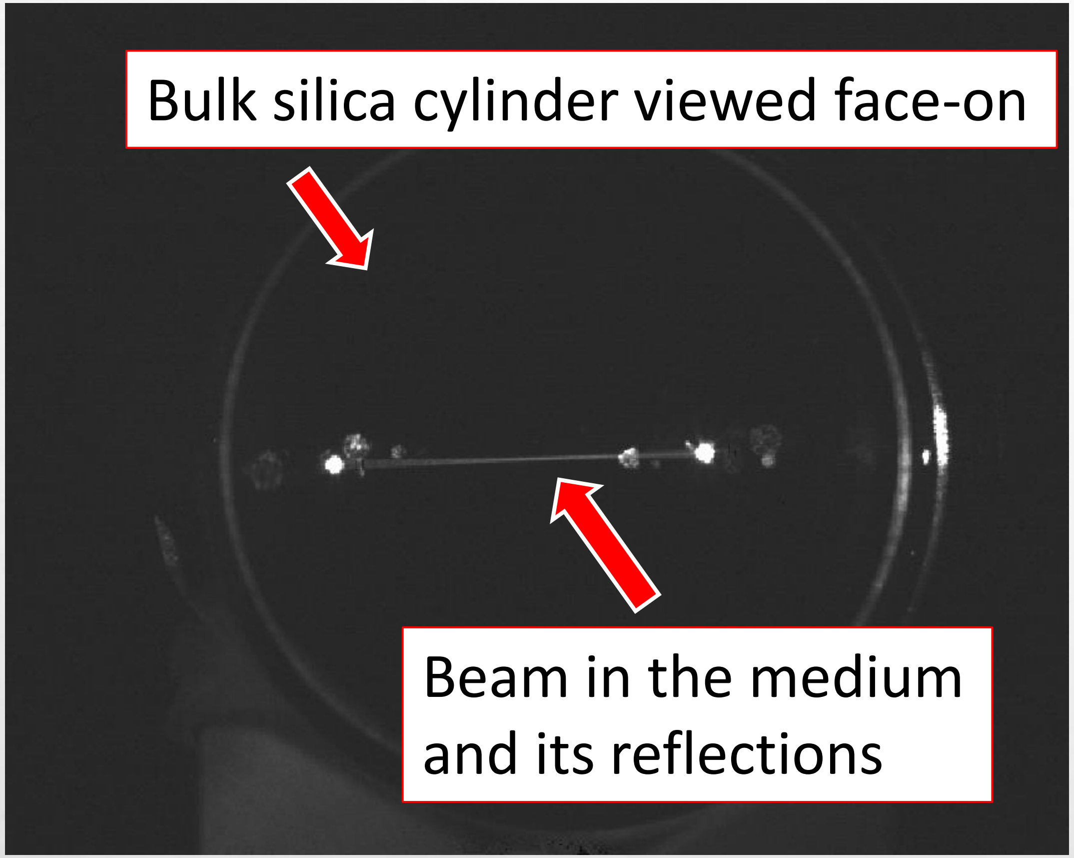

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Take away message

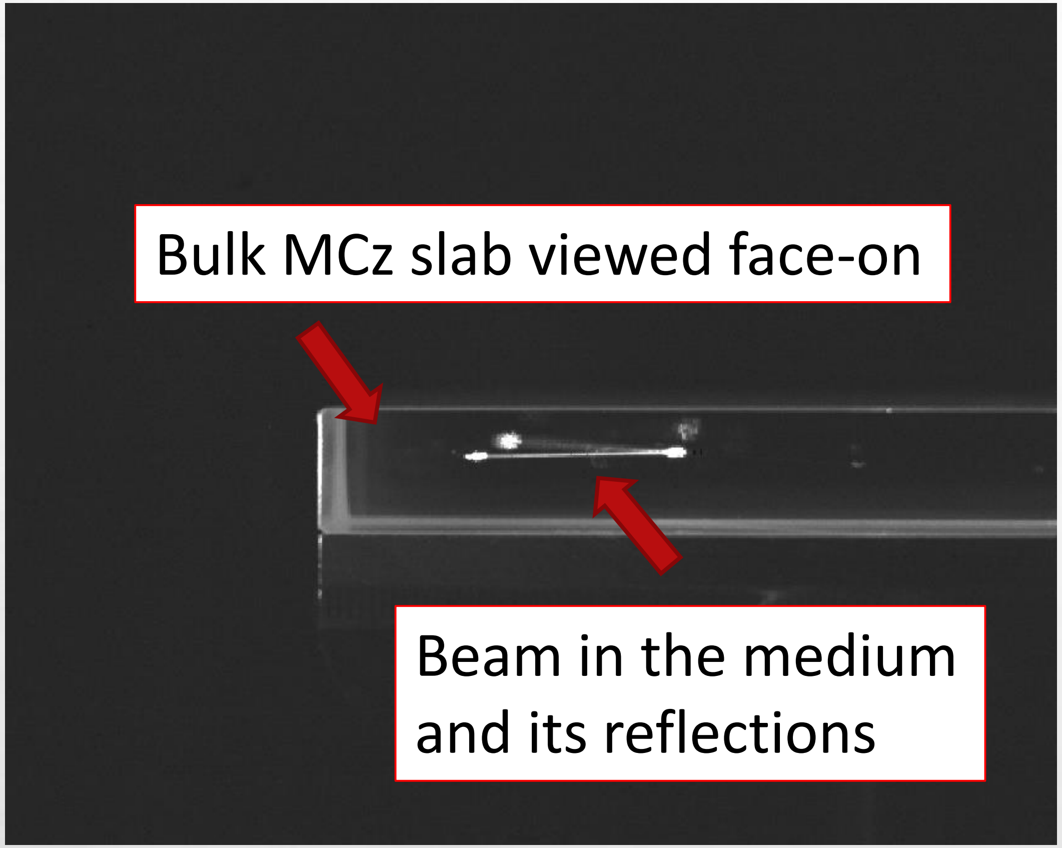
1. Still "commissioning" the scatterometer, plenty of things to understand better

BUT

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

"Engineering run 2": fused silica

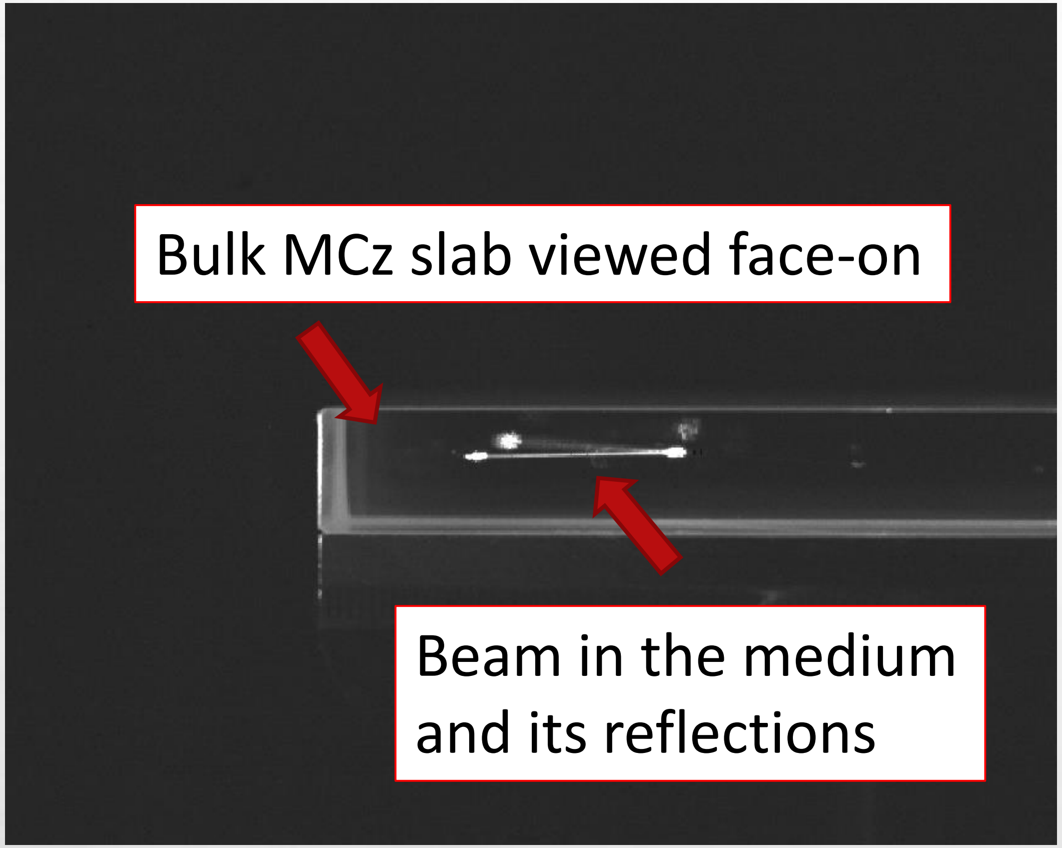
“O1”: magnetic Czochralski silicon



Bulk MCz slab viewed face-on

Beam in the medium and its reflections

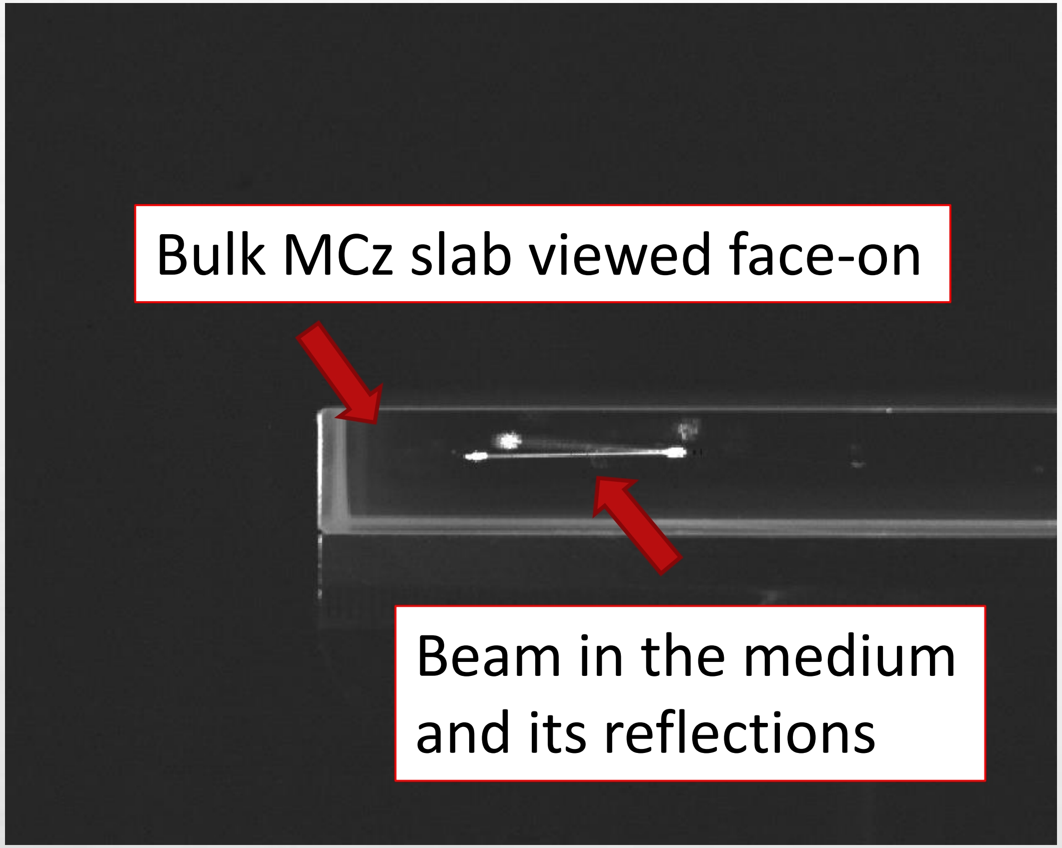
Magnetic Czochralski silicon slab



Magnetic Czochralski silicon slab

- 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.

"O1": magnetic Czochralski silicon



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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}

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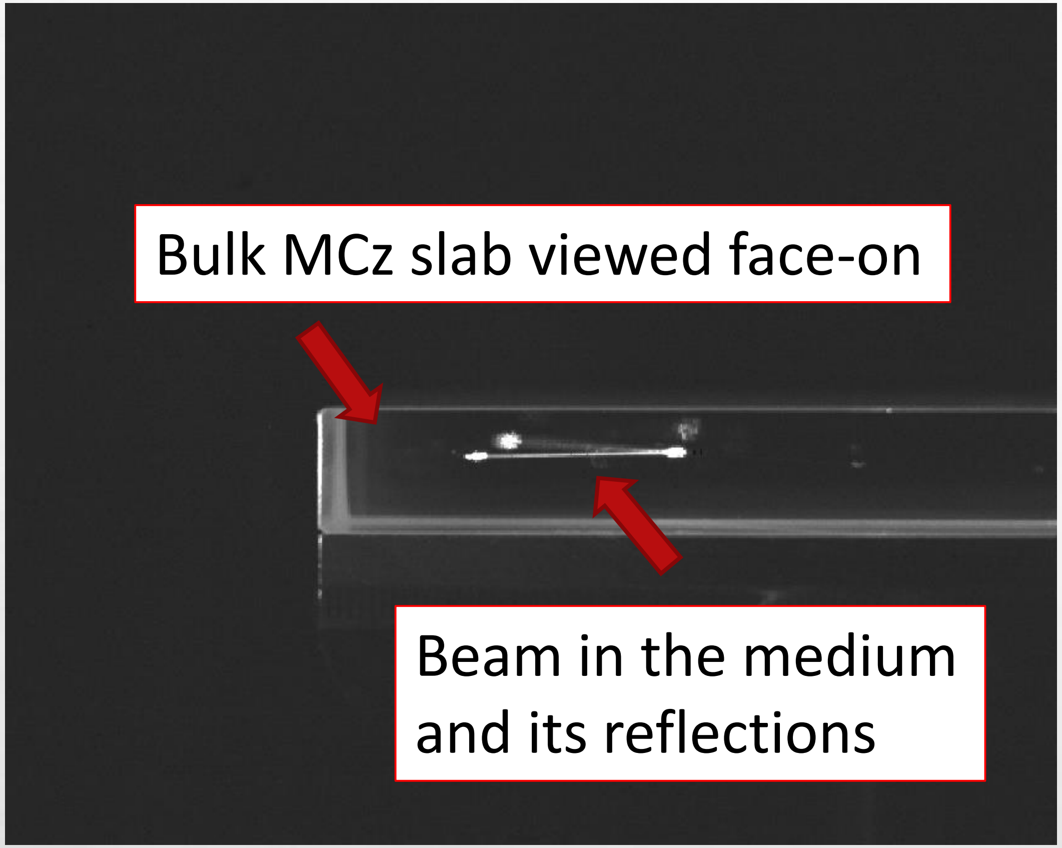
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45-74 ppm bulk scatter for a 46 cm thick test mass
No requirement in ET design document
Could be dominated by coating scattering*finesse

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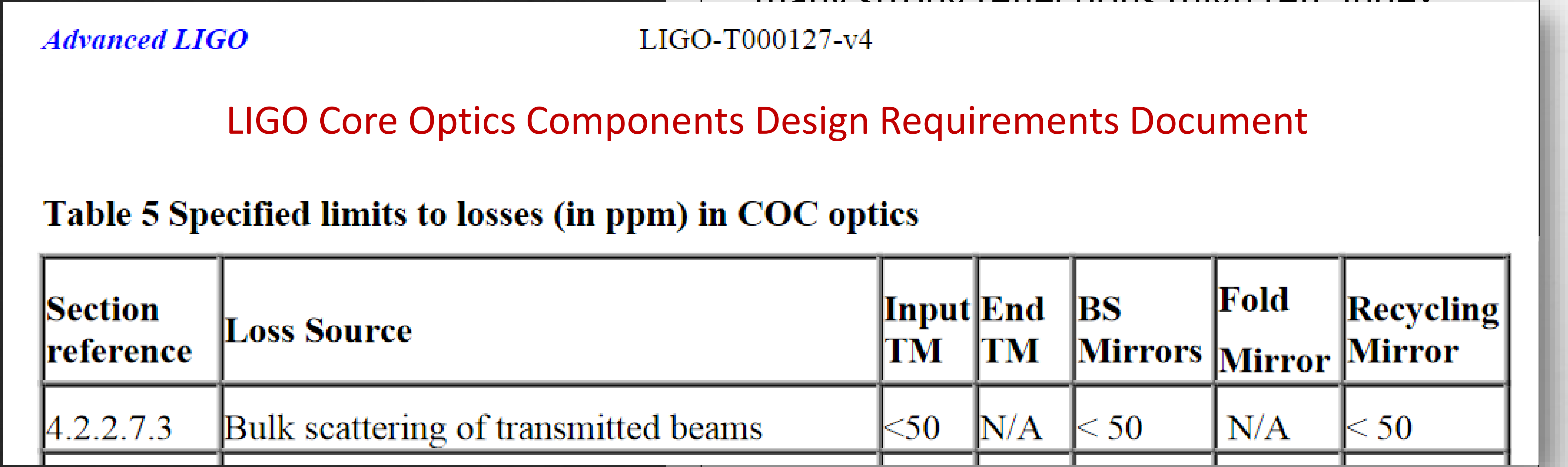

Advanced LIGO LIGO-T000127-v4

LIGO Core Optics Components Design Requirements Document

Table 5 Specified limits to losses (in ppm) in COC optics

Section reference	**Loss Source**	**Input TM**	**End TM**	**BS Mirrors**	**Fold Mirror**	**Recycling Mirror**
4.2.2.7.3	Bulk scattering of transmitted beams	<50	N/A	< 50	N/A	< 50

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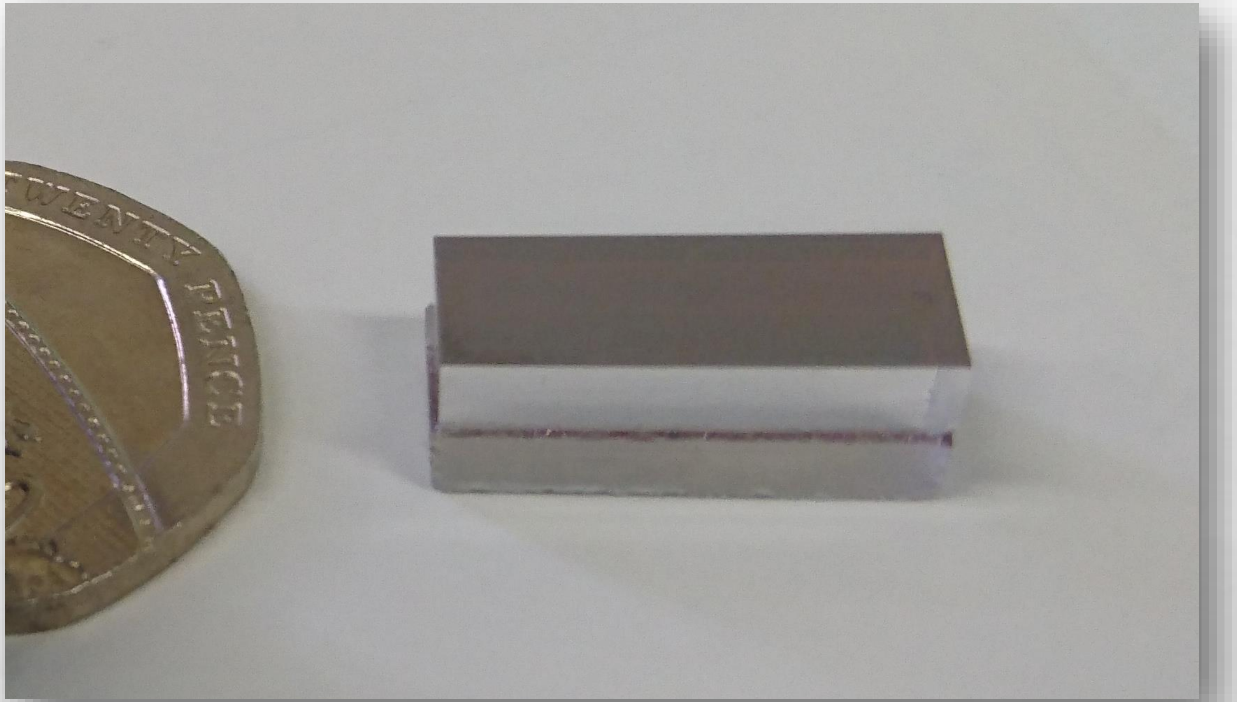
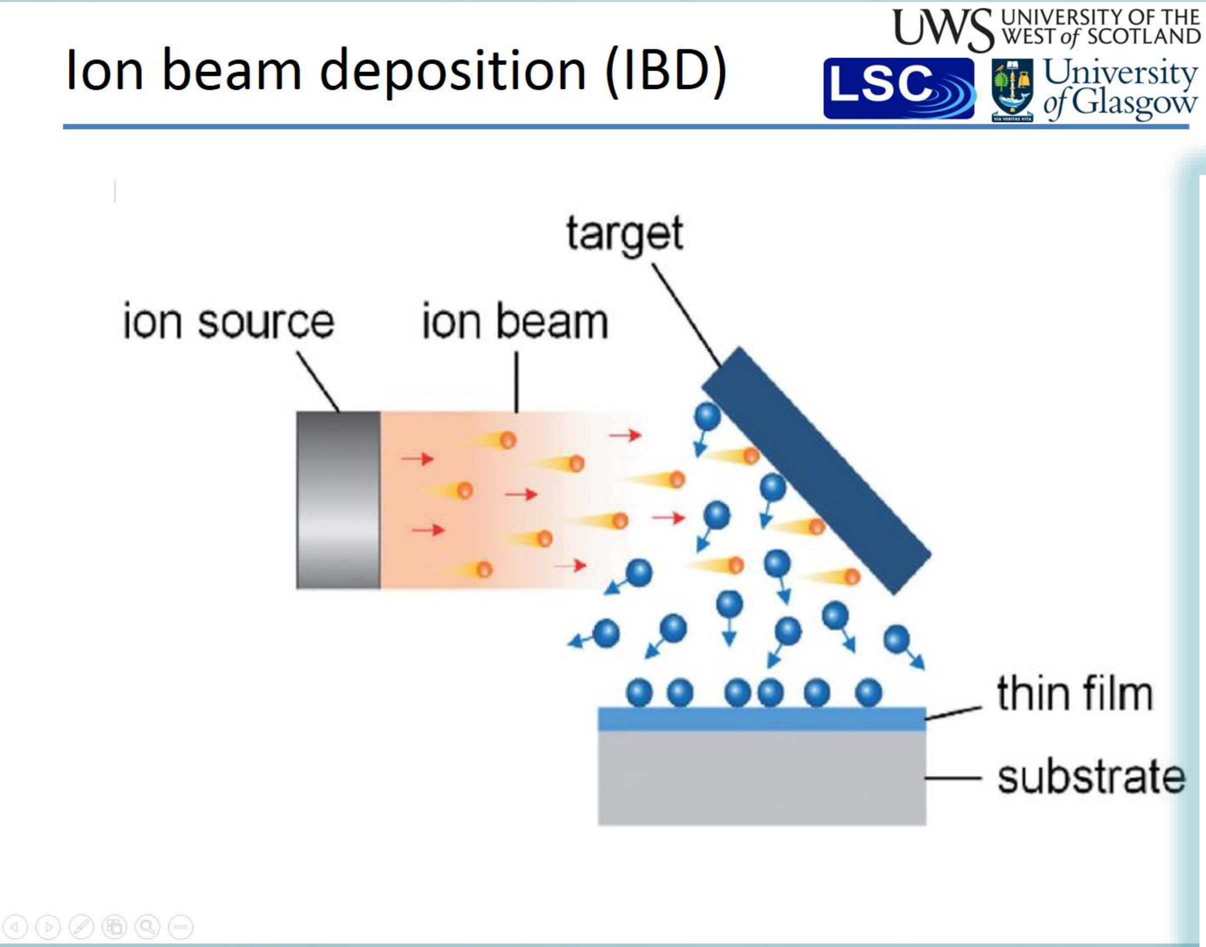
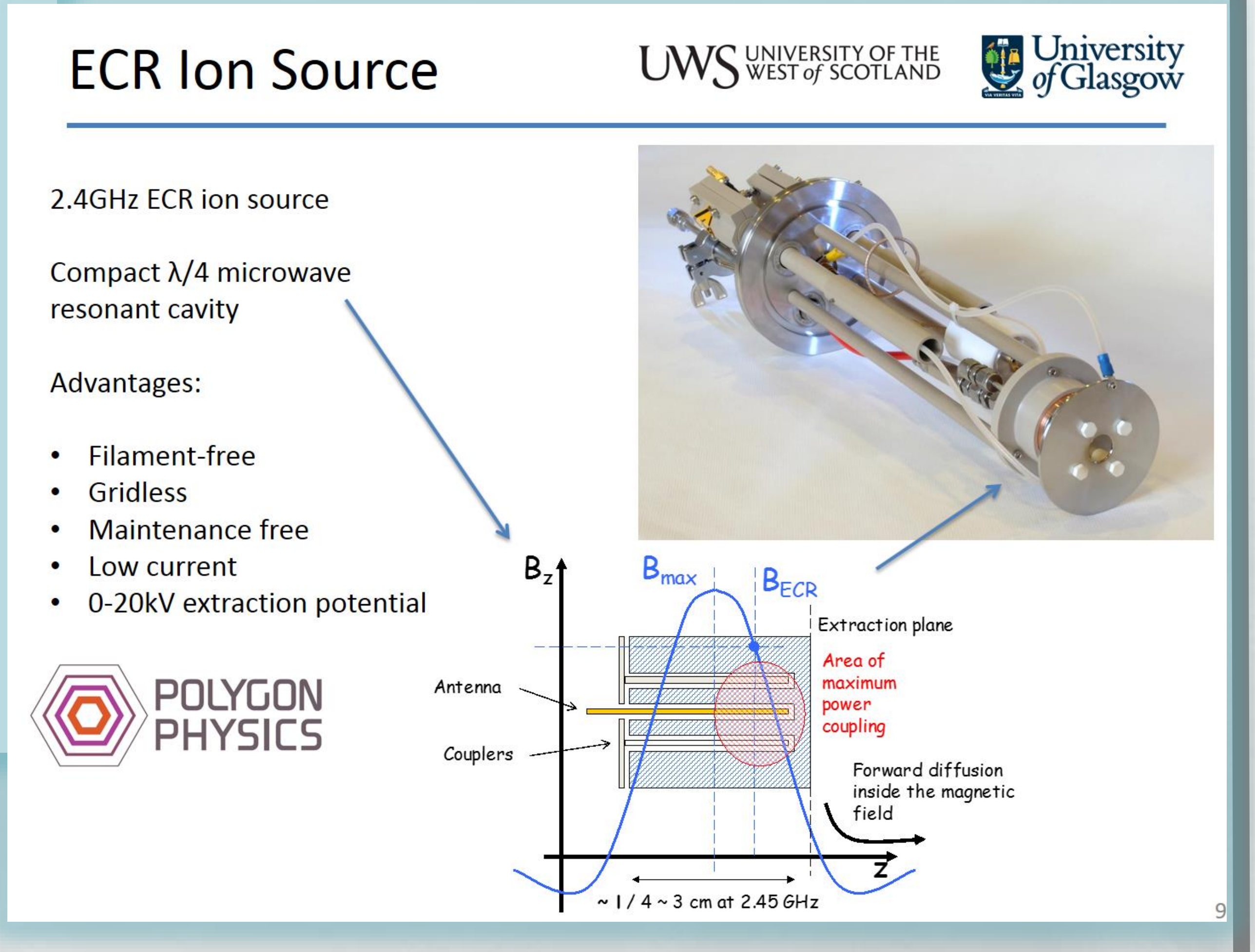


Amorphous silicon

Heat deposited aSi films made at UWS



Ion beam deposition (IBD)



ECR Ion Source

2.4GHz ECR ion source

Compact λ/4 microwave resonant cavity

Advantages:

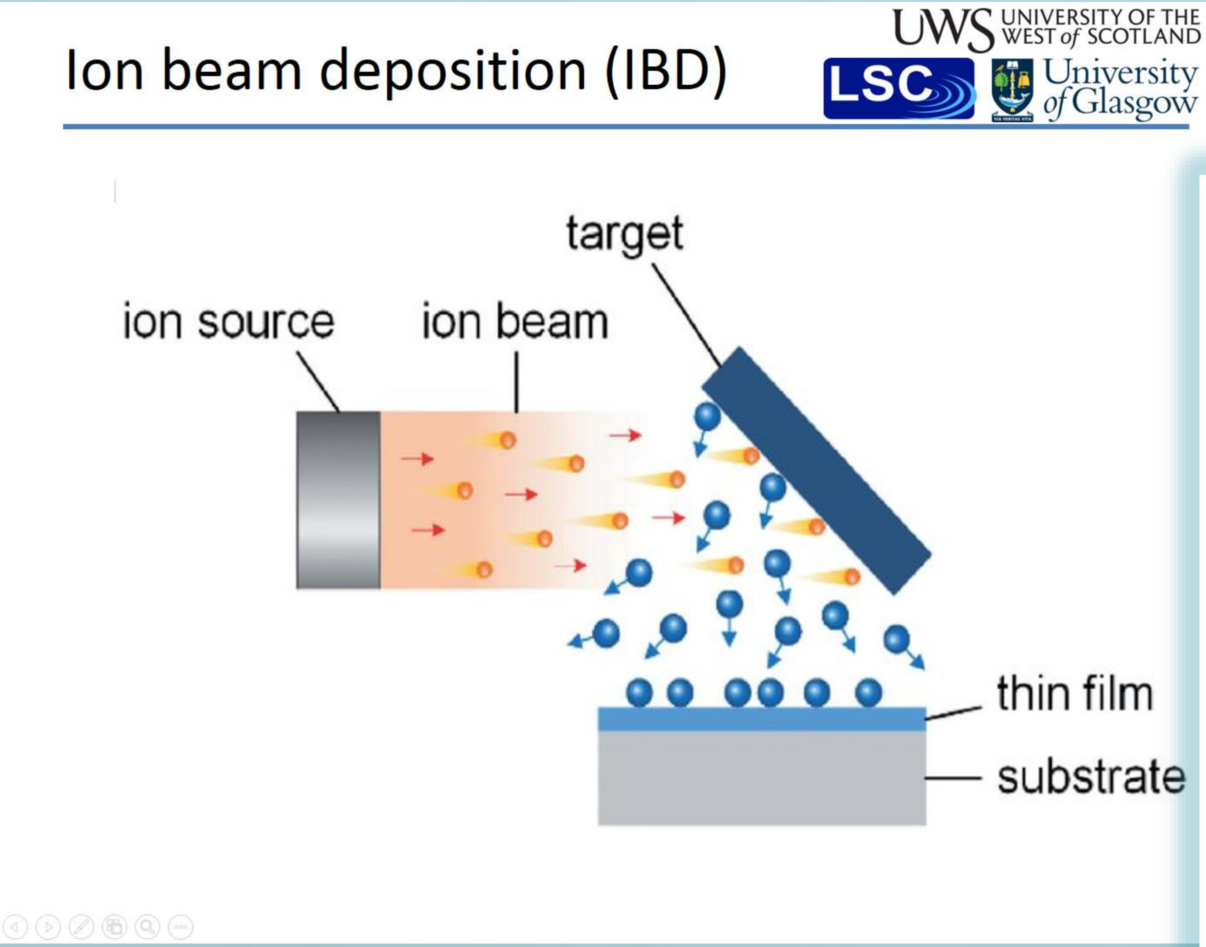
- Filament-free
- Gridless
- Maintenance free
- Low current
- 0-20kV extraction potential

POLYGON PHYSICS

Slides courtesy of prof. Stuart Reid

Heat deposited aSi films made at UWS

First coatings: 20 ppm/QWL
Very hard to reproduce!



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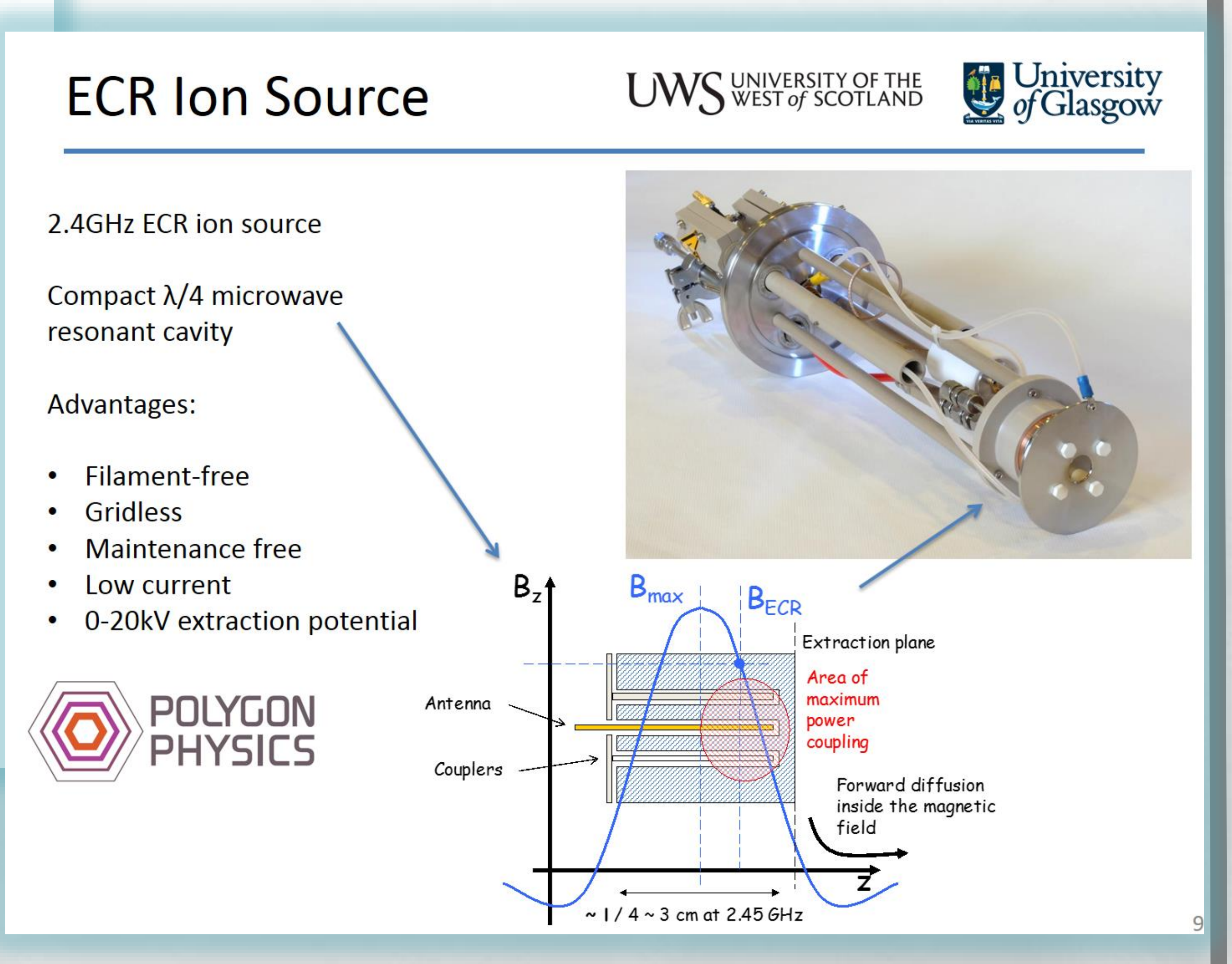

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Compact λ/4 microwave resonant cavity

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Slides courtesy of prof. Stuart Reid

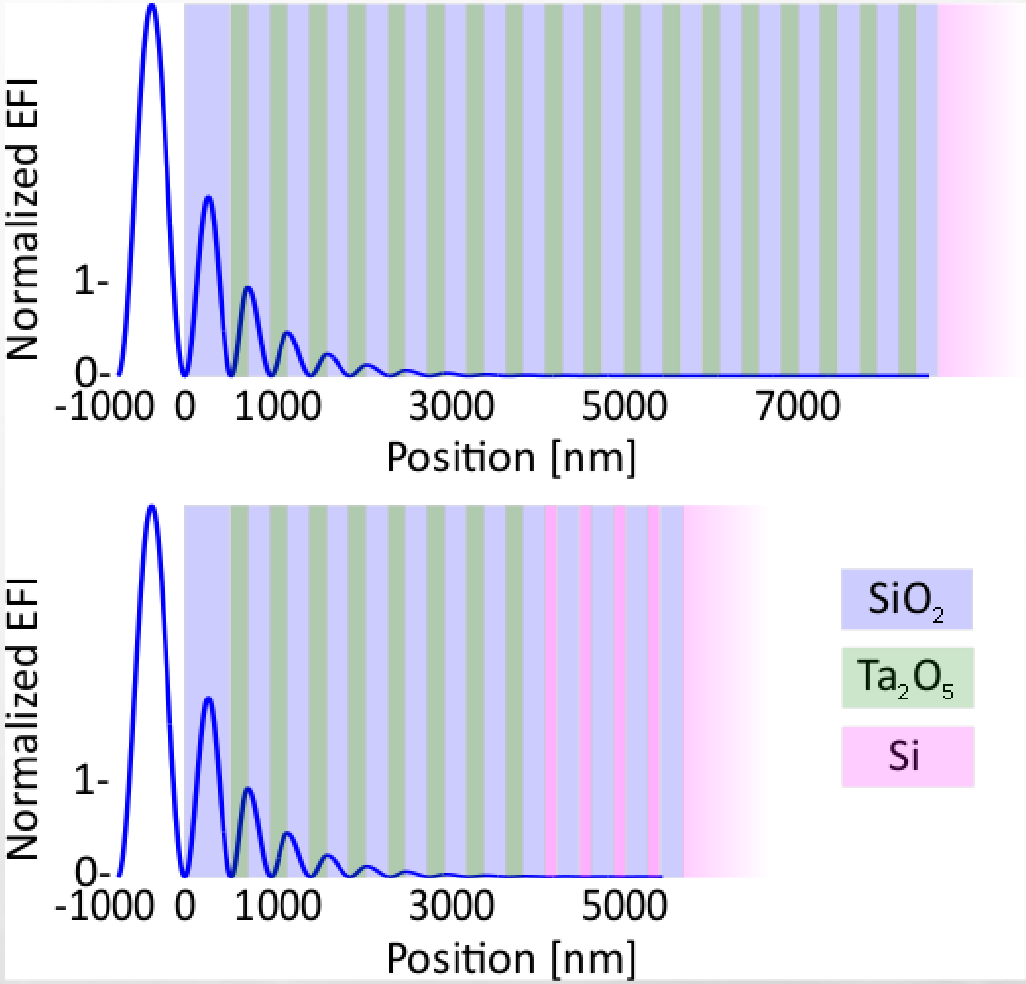
Multimaterial coating with aSi

Assuming aSi absorption 20 ppm/QWL at 1550nm

- We need 5 bilayers of SiO_2 and Ta_2O_5 to reduce the laser power
- For an ITM with T= 6000 ppm we need 2 bilayers of SiO_2 and aSi
- For an ETM with T = 6 ppm we need 5 bilayers of SiO_2 and aSi

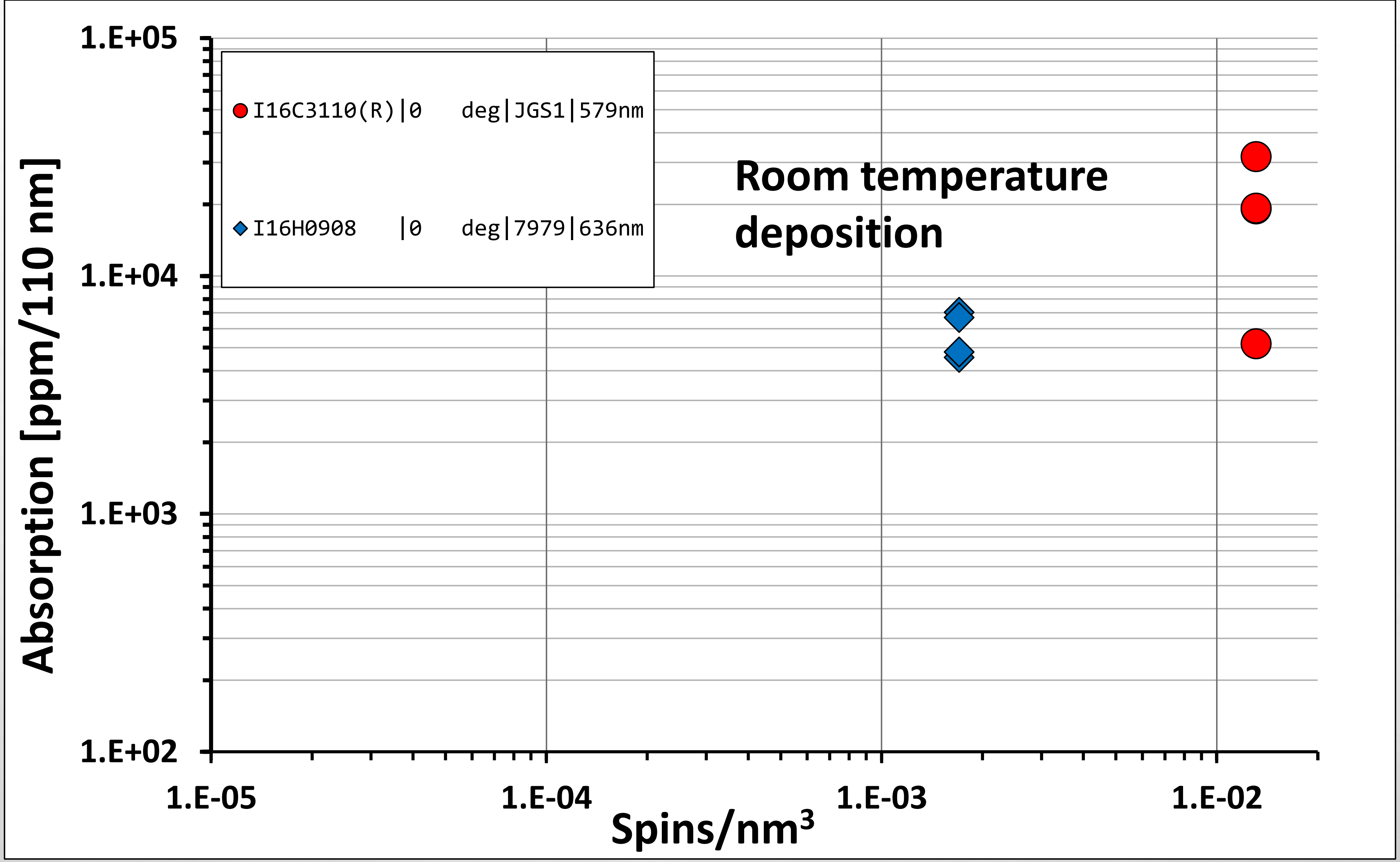
- Thermal noise improvement* compared to a pure SiO_2 and Ta_2O_5 coating:

120 K	**20 K**
ITM: -21%	-20%
ETM: -38%	-36%
total: -32%	-31%

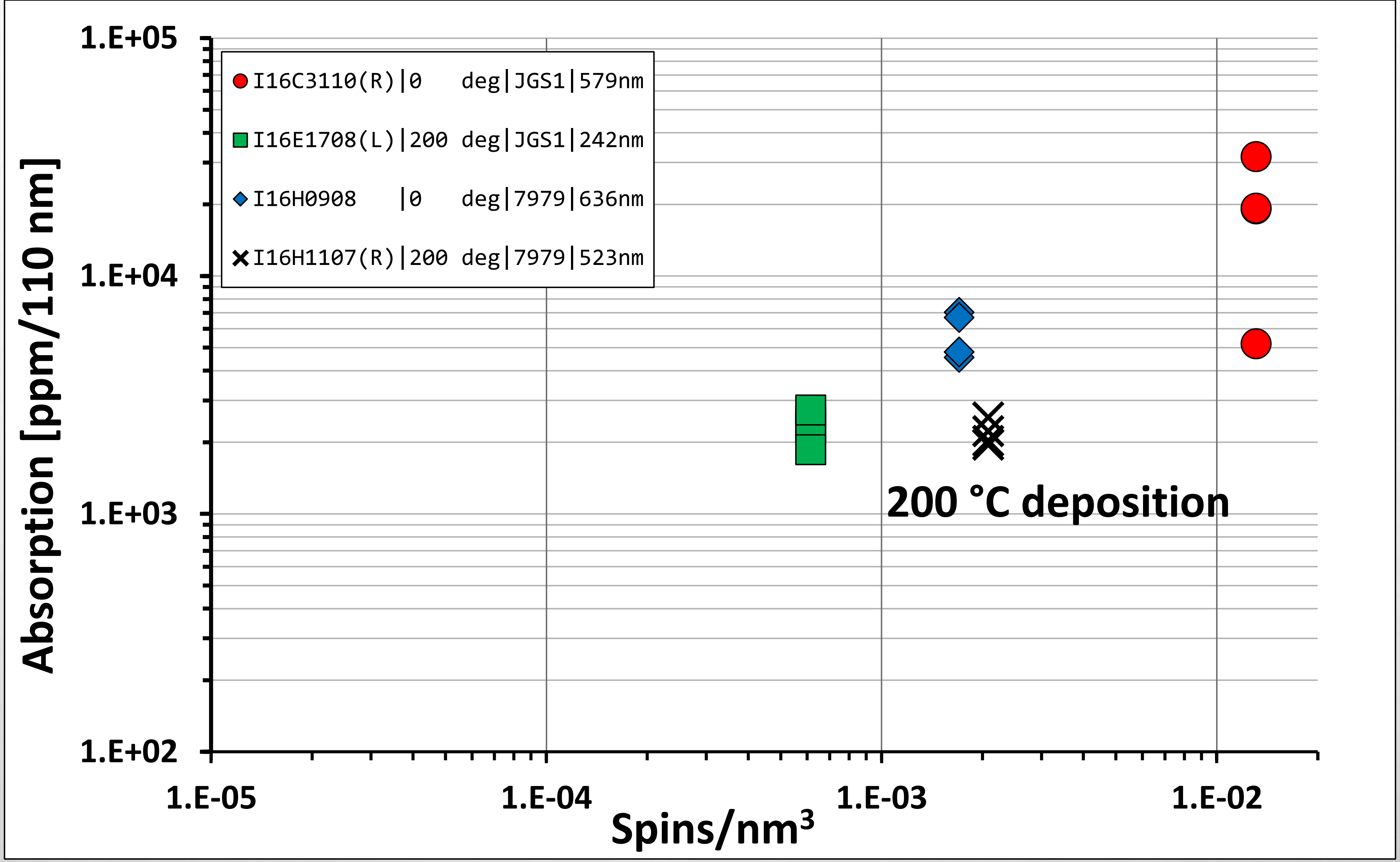


*Loss for aSi: values from commercial coatings; no cryogenic measurements on UWS coatings

Simulations: J. Steinlechner



Dangling bonds - absorption correlation



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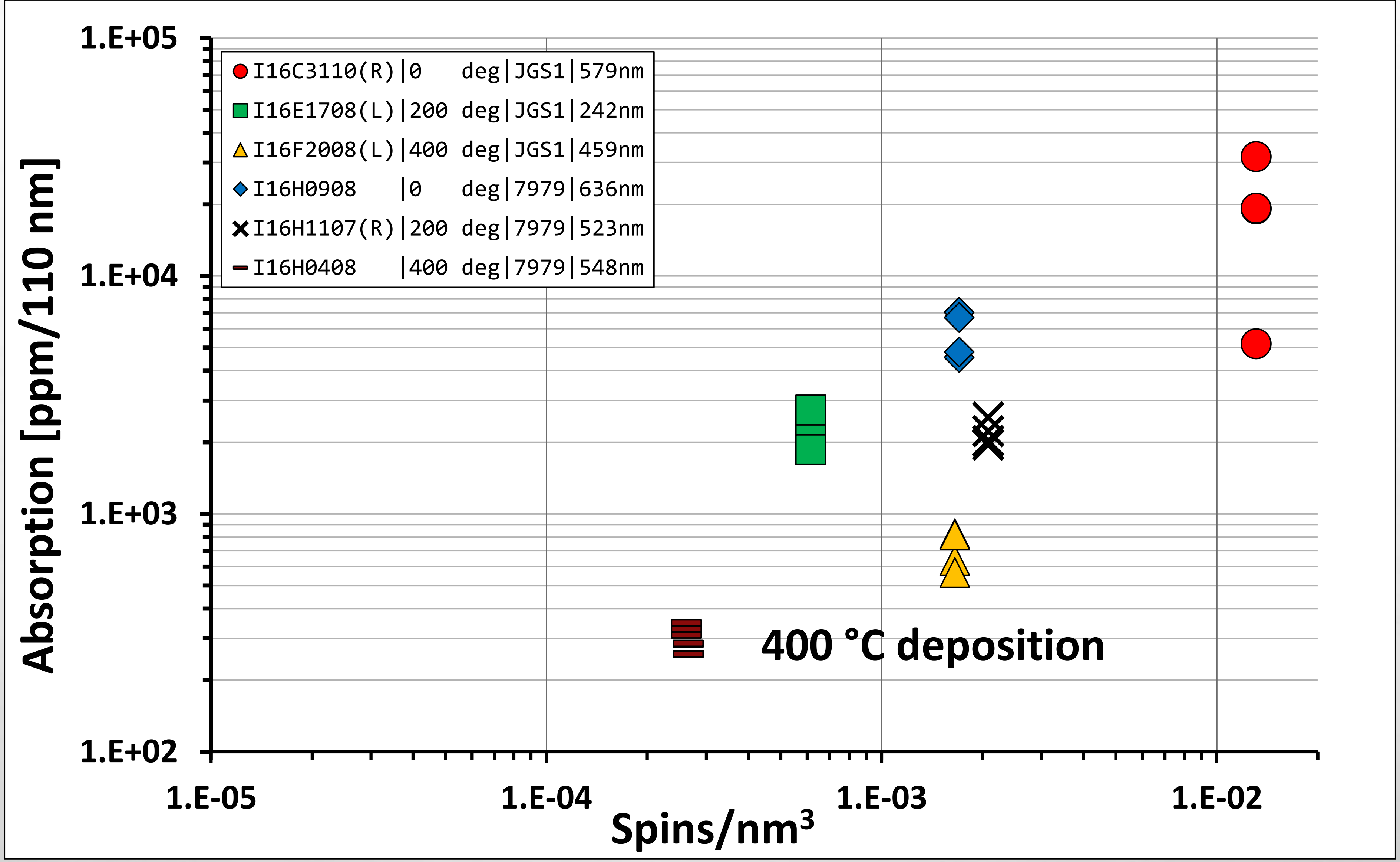
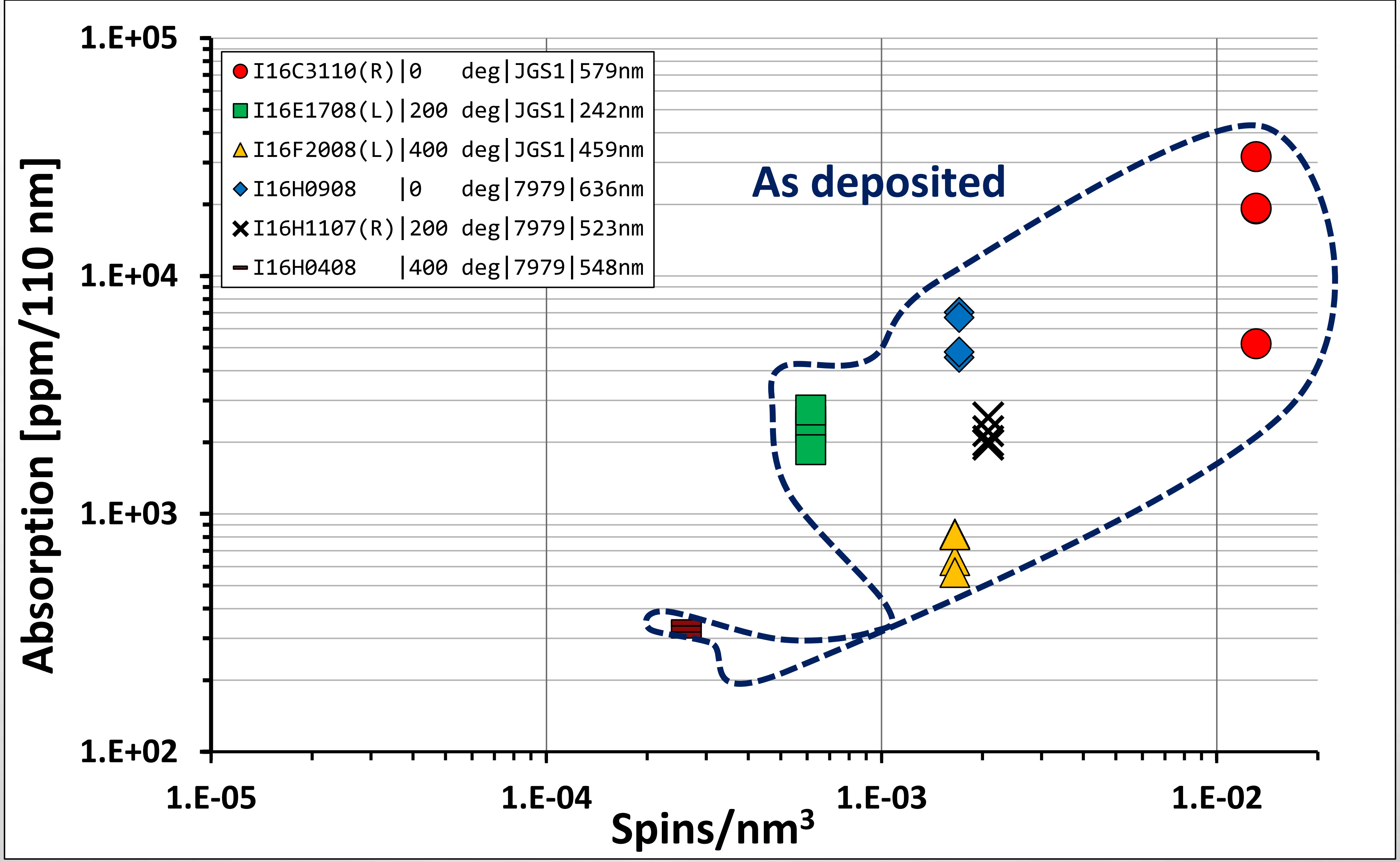


400 °C deposition



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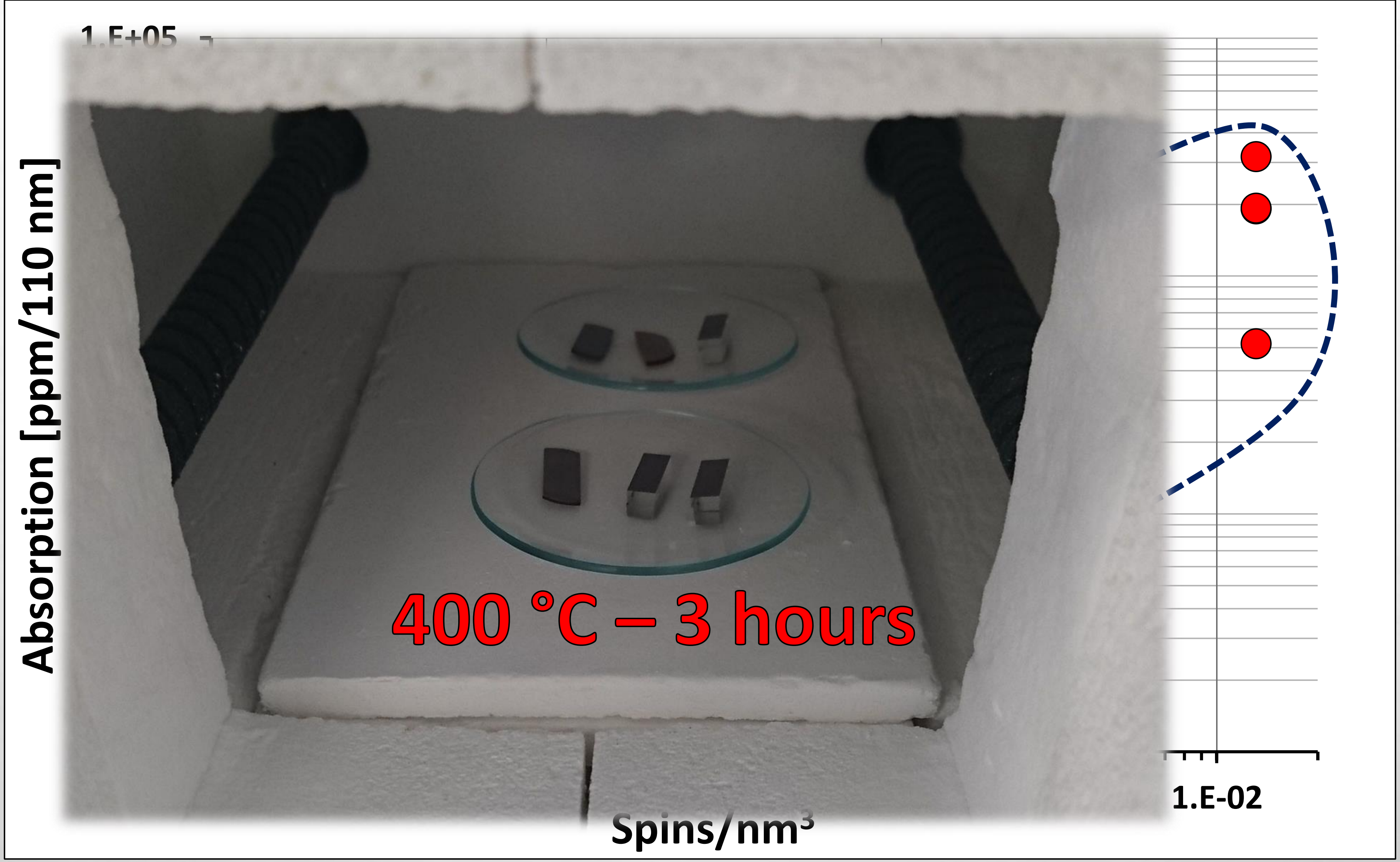
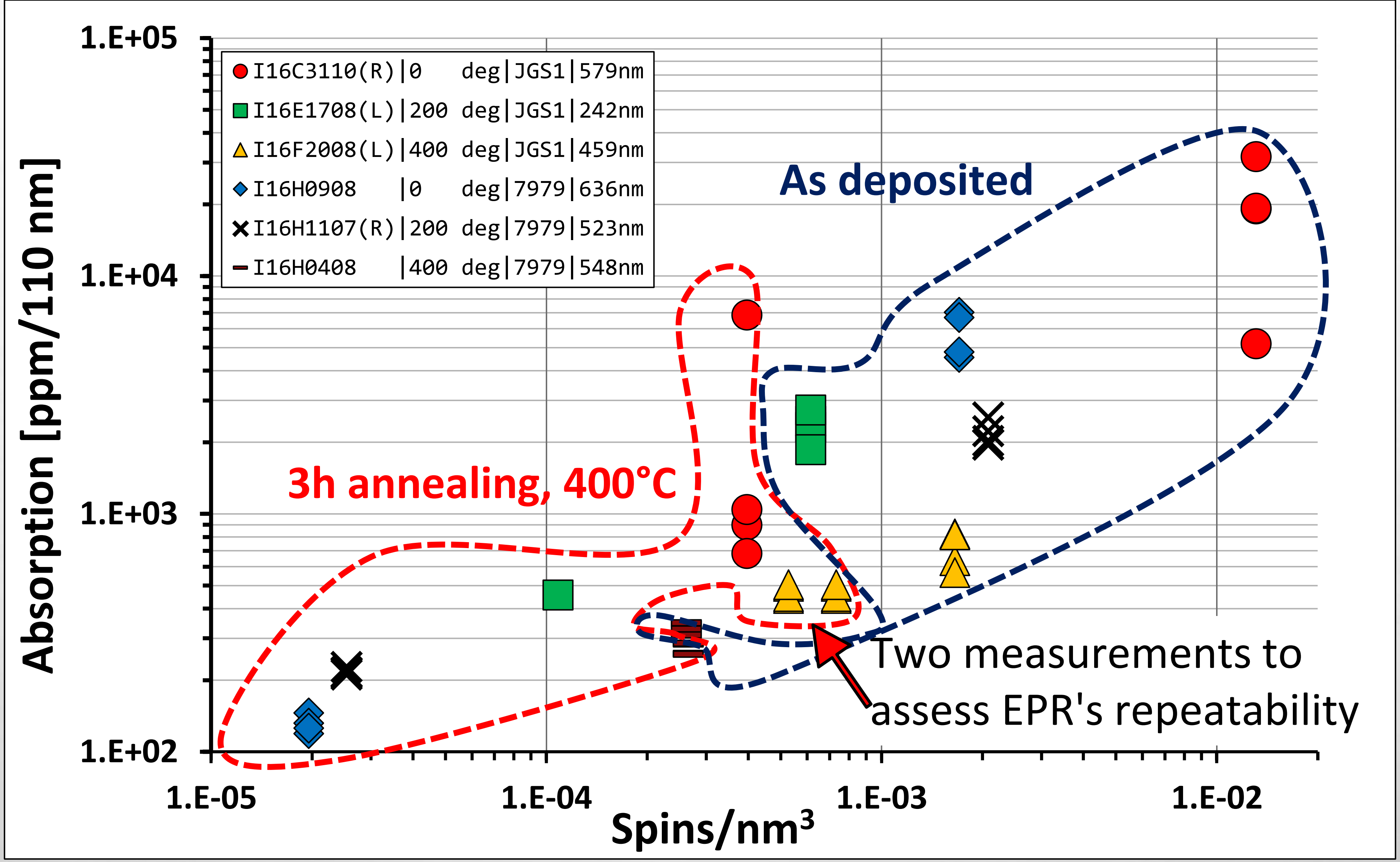


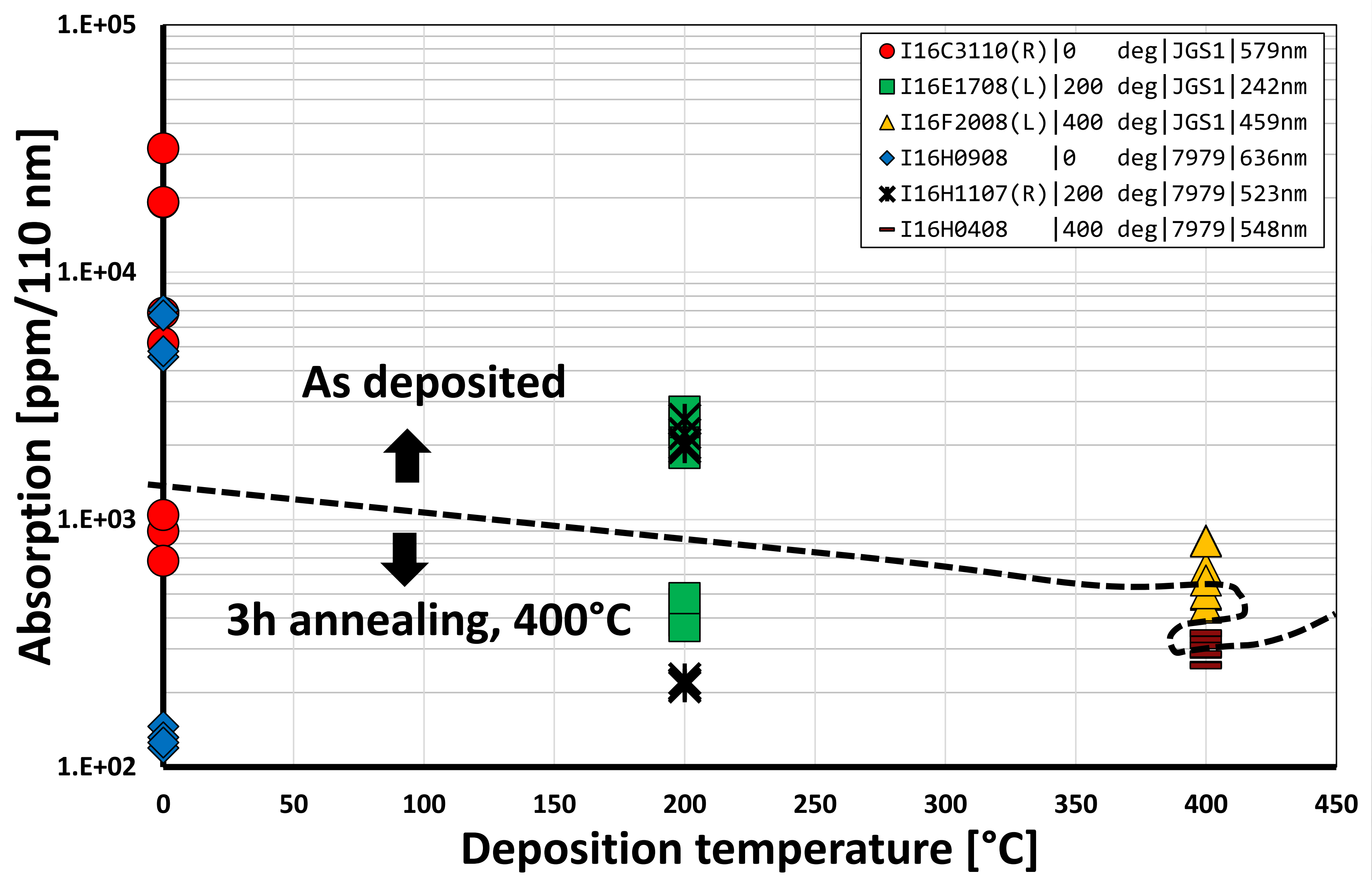
400 °C – 3 hours

Dangling bonds - absorption correlation



Two measurements to assess EPR's repeatability

Dangling bonds - absorption correlation



Deposition temperature - absorption correlation

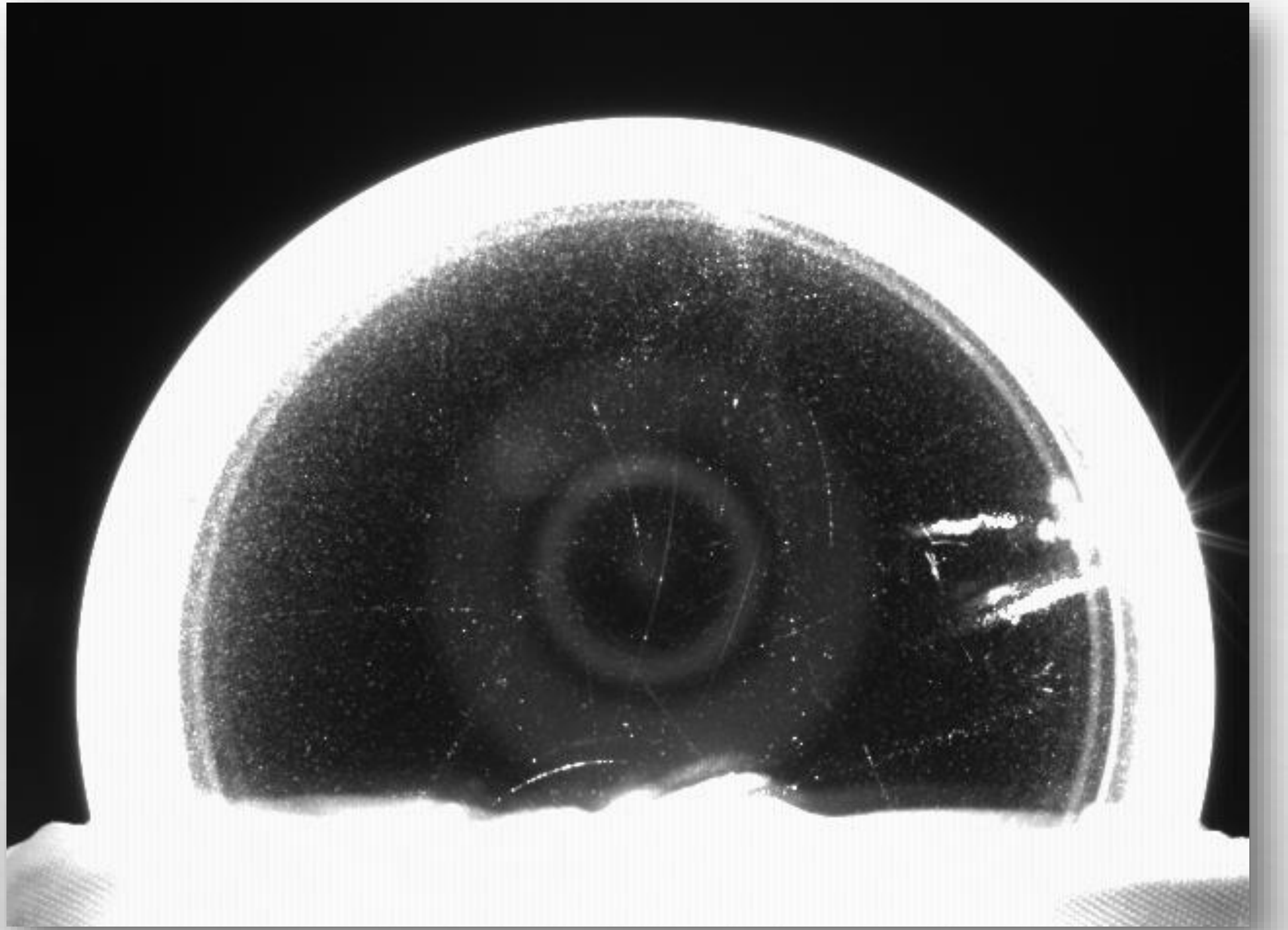
1. Silicon is a promising material for cryogenic GW core optics.
2. It has low mechanical loss at low temperature, zeros of expansion coefficient, high refractive index

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 bulk scattering suggests that might be compatible with use in ET -- 45-74 ppm bulk scatter for a 46 cm thick test mass could be just as high as we can afford**

6. Heat deposited aSi coatings show absorption comparable with annealed ones (but better mechanical loss).
7. A clear link has been established between absorption and dangling bonds, and absorption and deposition temperature.

Conclusions



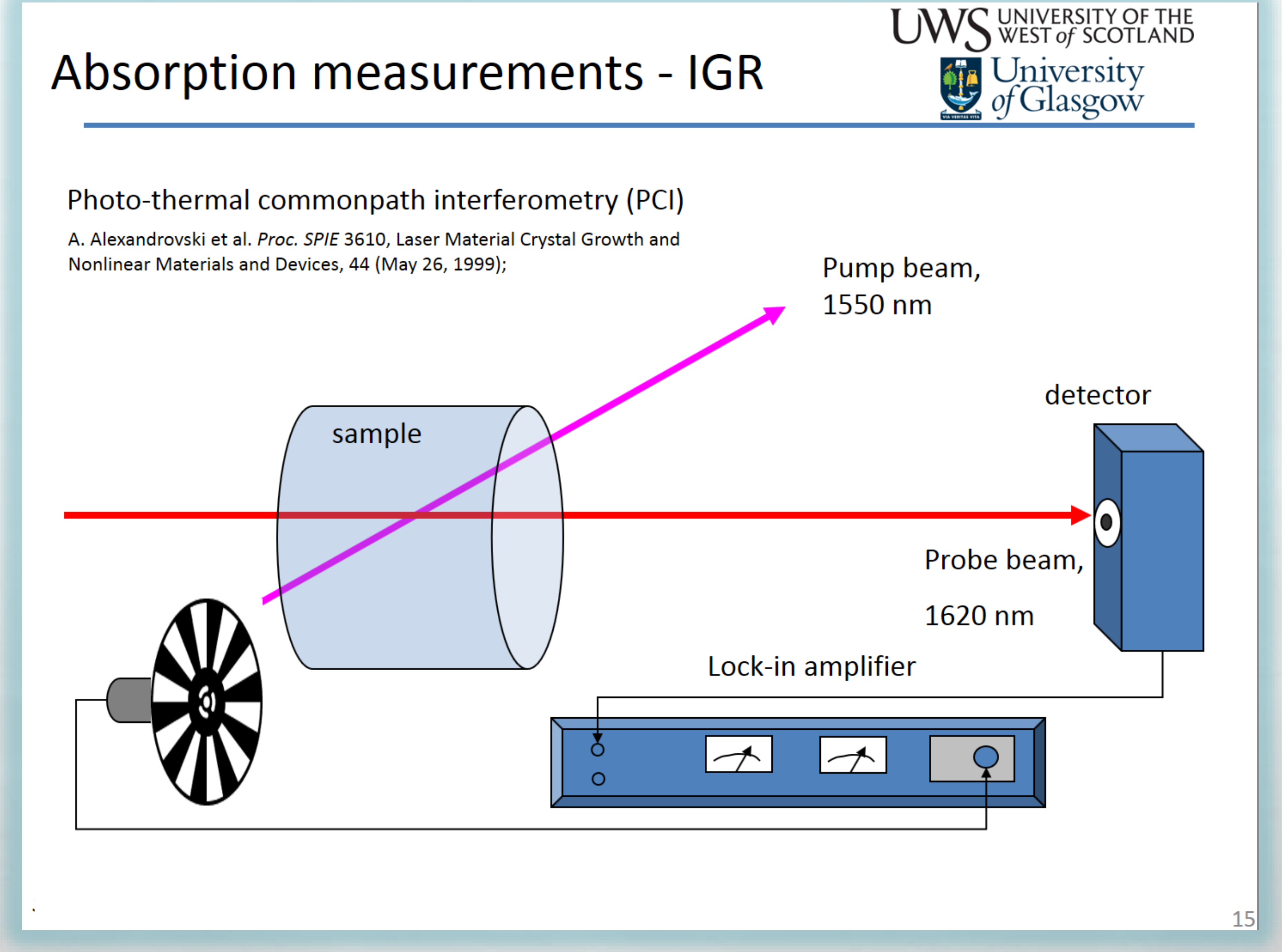
Thank you!

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



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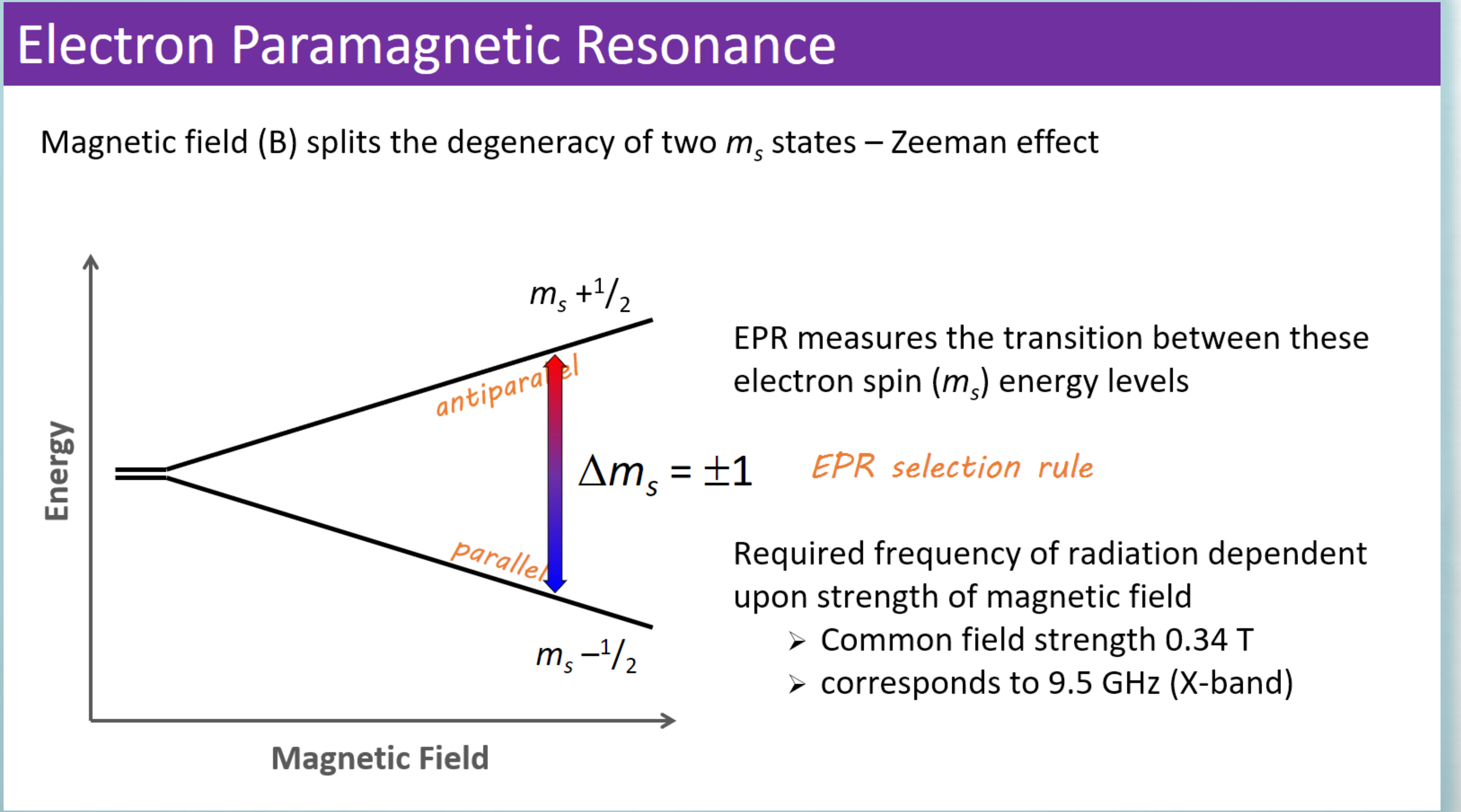
Absorption measurements - IGR

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);

Photothermal common-path interferometry (PCI)

EPR – Courtesy of Stephen Sproules



Electron Paramagnetic Resonance

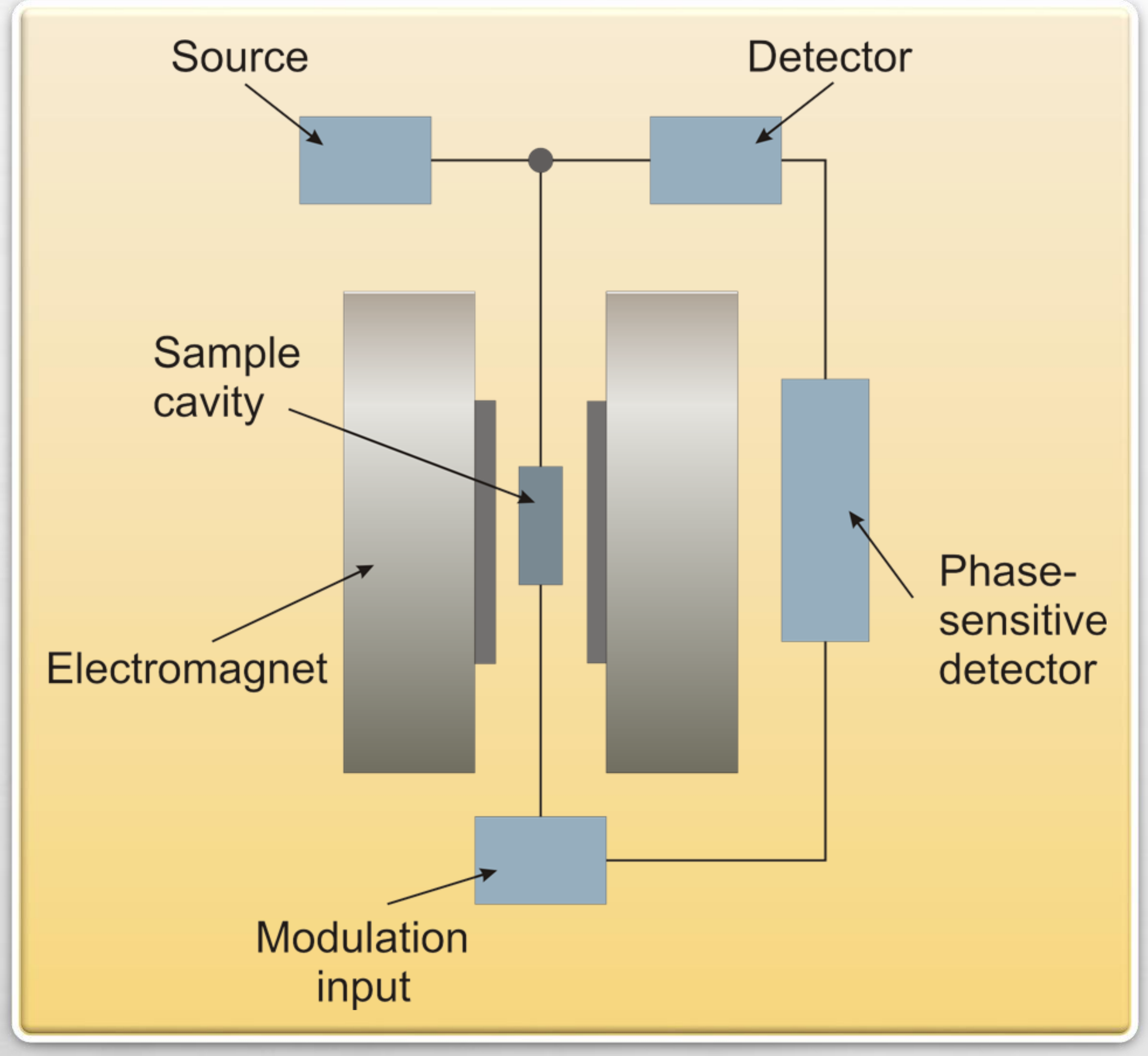
Magnetic field (B) splits the degeneracy of two m_s states – Zeeman effect

EPR measures the transition between these electron spin (m_s) energy levels

$\Delta m_s = \pm 1$ *EPR selection rule*

Required frequency of radiation dependent upon strength of magnetic field

- Common field strength 0.34 T
- corresponds to 9.5 GHz (X-band)



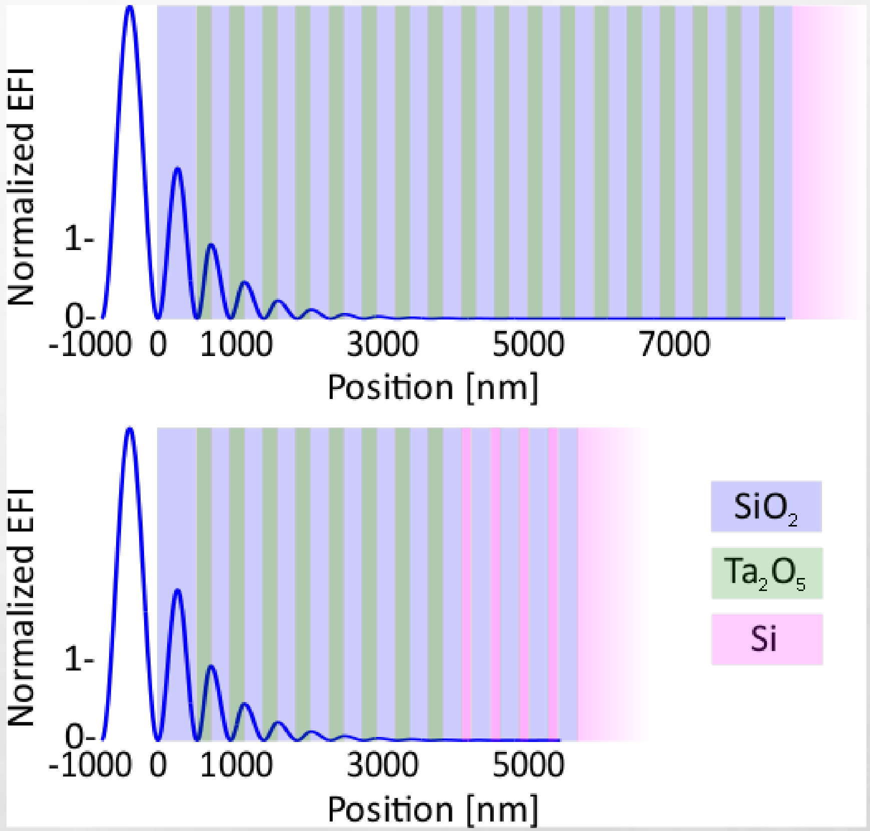
EPR – Courtesy of Stephen Sproules

At 1064 nm RT:

- We need 8 bilayers of SiO_2 and Ta_2O_5 to reduce the laser power
- For an ITM with T= 1.4% we can't improve the coating using aSi in lower layers
- For an ETM with T = 6 ppm we need
  4 bilayers of SiO_2 and aSi

- Thermal noise improvement* compared to a pure SiO_2/Ta_2O_5 coating:

  Room temperature:
  ITM: - 0%
  ETM: - 28%
  total: -22%



Almost no improvement by reducing mechanical loss further (limited by silica loss and ITM thermal noise)

Simulations: J. Steinlechner

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*Loss for aSi: values from commercial coatings; no cryogenic measurements on UWS coatings

EPR – Courtesy of Stephen Sproules