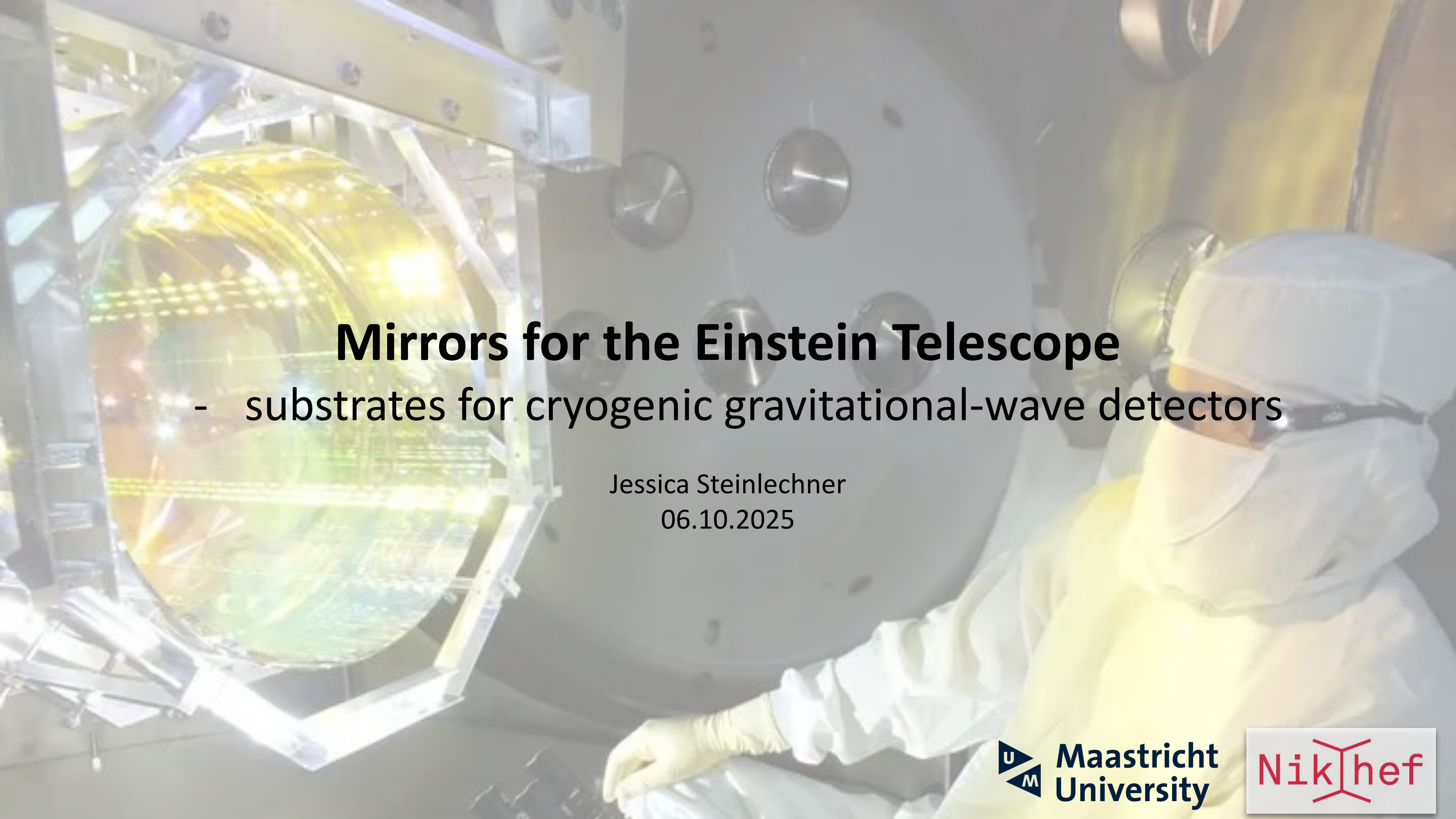

Mirrors for the Einstein Telescope

- substrates for cryogenic gravitational-wave detectors

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06.10.2025

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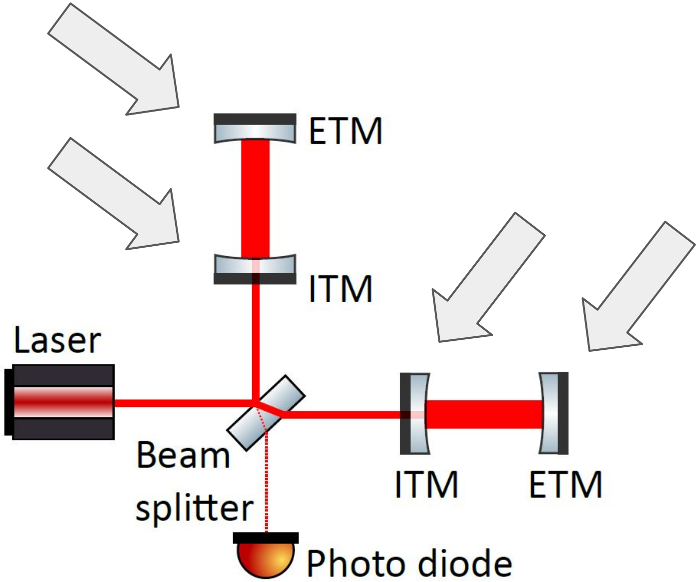
Gravitational Wave Detectors

- Michelson interferometer - using many ‘tricks’ to increase the sensitivity
  - Several kilometer long arms
  - Suspended mirrors
  - High laser power
  - Squeezed light
  - Arm cavities formed by input test masses (ITMs) and end test masses (ETMs)
  - …

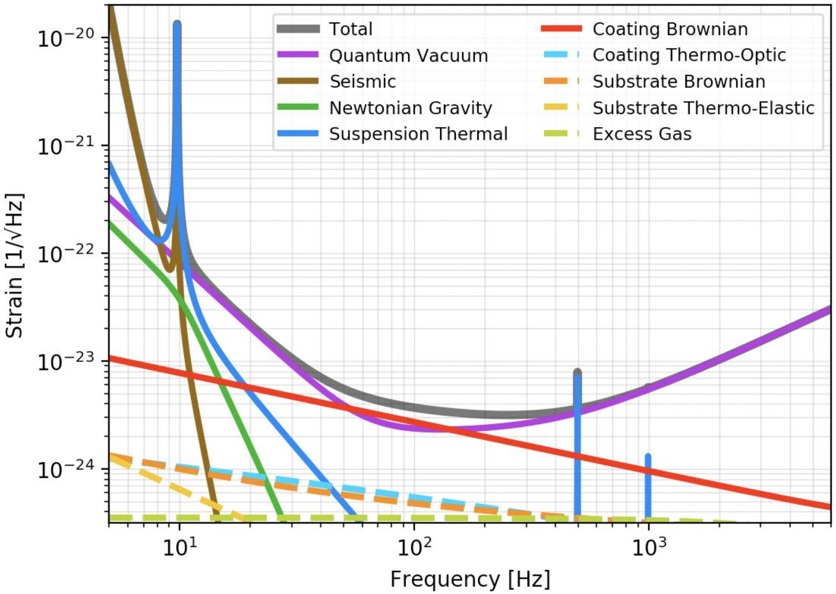
- Currently: 5 active detectors:
  - LIGO in Livingston and Hanford, US
  - Virgo in Cascina (near Pisa), Italy
  - GEO600 in Ruthe (near Hannover), Germany
  - KAGRA in Kamioka mine, Japan



Limitations of Current Gravitational Wave Detectors

- < 50Hz
  - Seismic / environmental noise, coupling either directly or via gravity gradient forces
  - Radiation pressure noise, photons pushing on suspended mirrors
- around 100Hz
  - Coating thermal noise, Brownian motion of mirror surface
- > 1 kHz
  - Shot noise, counting statistics of photons

Advanced LIGO design sensitivity
(example of a current generation detector)

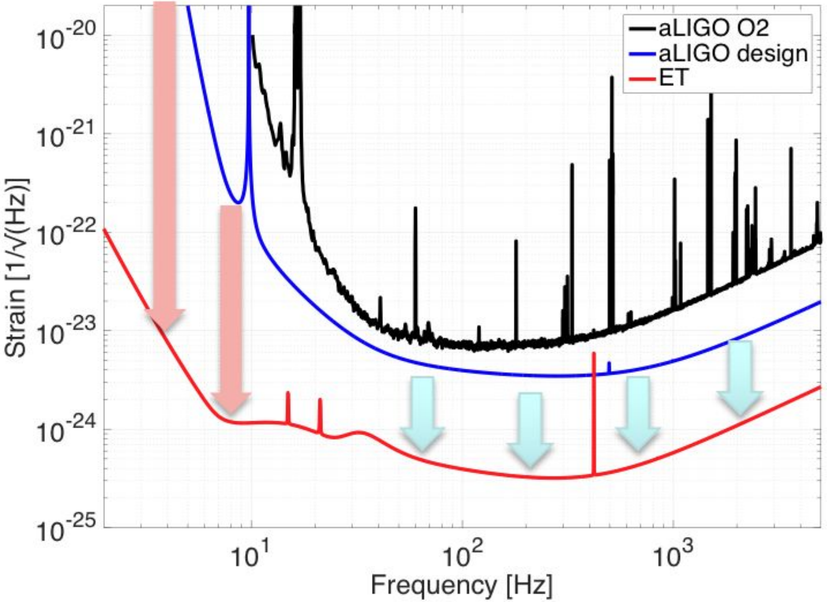


Plans and Challenges of Future Detectors

- Aim for ***a factor 10 improvement*** at mid and high frequencies
  "within reach of continuous improvements"
- Low frequencies: improvement more ***a factor of 100 to 1000***
  → only possible with new approaches *"disruptive technologies"* (e.g. cryogenics)

- Plan for the Einstein Telescope: Split detector into
  - Room temperature and high laser power at high frequencies
  - Low temperature (see next slide) and low laser power at low frequencies

Einstein Telescope design sensitivity
(example of a next generation detector)



Coating Thermal Noise (simplified model)

Coating thermal noise (CTN)

- Lower for larger beams
- Determined by material properties of coating and substrate
- Frequency dependent: more prominent at low frequencies
- Temperature dependent → motivation for cryogenic mirrors (at low frequencies)
- Thin coating

mirror temperature

coating thickness (depends on reflectivity and refractive indices)

$$\mathrm{CTN} = \sqrt{\frac{4k_\mathrm{B}T}{\pi^2 f w^2 Y_\mathrm{sub}} d\phi \left[\frac{Y_\mathrm{coat}}{Y_\mathrm{sub}} + \frac{Y_\mathrm{sub}}{Y_\mathrm{coat}}\right]}$$

beam radius (on mirror)

coating mechanical loss

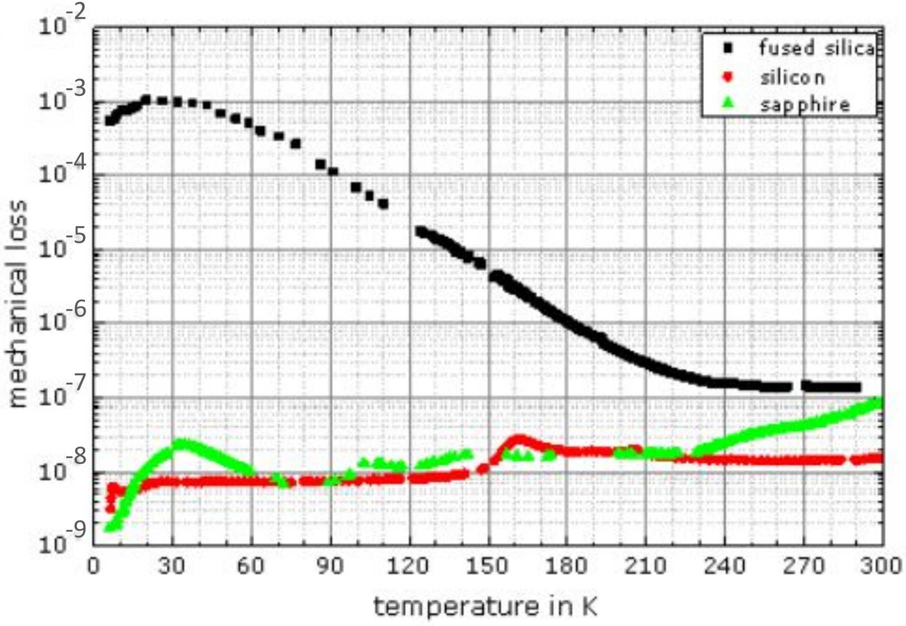
→ Motivation for low temperature

Mechanical loss of (currently used) fused silica increases at low T

Mechanical loss can be strongly temperature dependent

- Increases significantly on cooling for fused silica.
- Slightly decreases for silicon.
- Similar for Sapphire

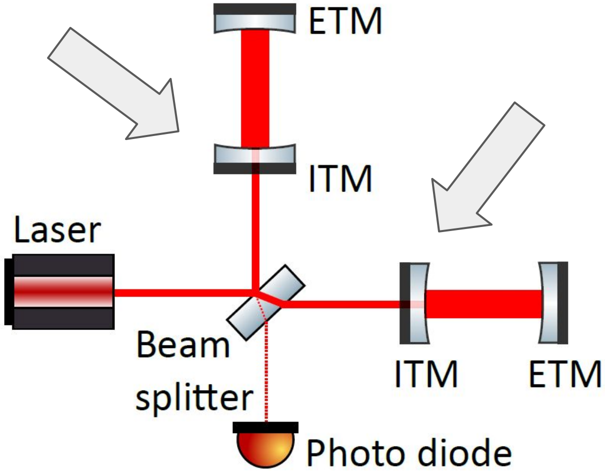
→ Motivation for investigating silicon



[R. Nawrodt et al.: *Cryogenic Setup for Q-factor measurements on bulk materials for future gravitational wave detectors*, in Proceedings of ICEC22-ICMC2008 (2009)]

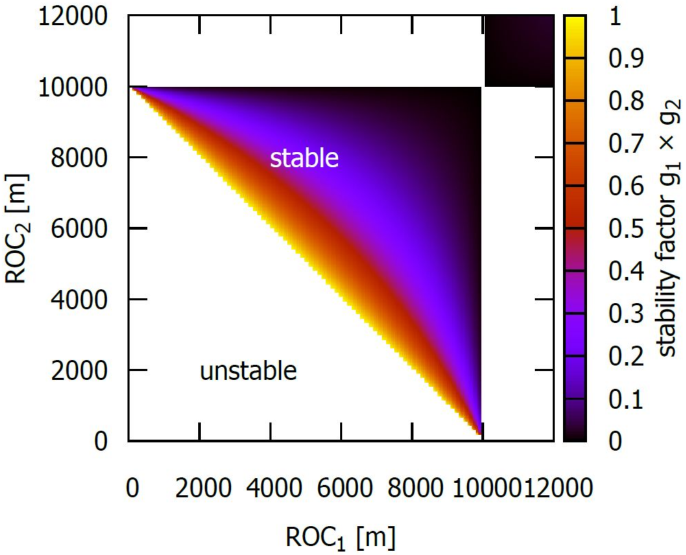
Challenges

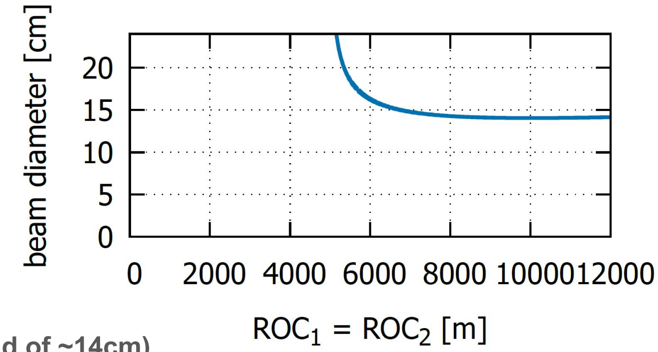
- Our mirrors require low optical absorption as
    - Some of our mirrors have to be transmissive
    - Absorption would heat the cryogenic mirrors
    - Tolerable absorption: order of a few 10 ppm/cm



Challenges

- Our mirrors require low optical absorption as
  - Some of our mirrors have to be transmissive
  - Absorption would heat the cryogenic mirrors
  - Tolerable absorption: order of a few 10 ppm/cm
- Mirror diameter has to be approximately 45cm (or larger) with a mass of ~200kg
  - To reduce coating thermal noise
  - To reduce radiation pressure noise
  - Due to laser beam propagation in 10km long detector arms
    - Mirror diameter has to be about 2.5 x beam diameter or more





(this is for 1550nm; at 1064nm, the beam is slightly smaller, i.e. min. ~12cm instead of ~14cm)

Silicon, Sapphire, (Germanium)

- Silicon requires to move from 1064nm to e.g. 1550nm
  - Possibly 2um as beneficial for some coating materials
- Low optical absorption requires very pure material, i.e. float zone silicon or possibly magnetically purified Czochalski silicon

→ High-purity material not available in such large sizes

Two options:

(a) make large material purer: optimize process; (what impurities matter most?)

(b) make pure material larger: optimize process; composite testmasses;

- Sapphire can be used at 1064nm
  - Used in KAGRA
    - Has not yet achieved envisioned low temperature
    - Issues with inhomogeneigites, absorption, birefringence, bubbles
    - KAGRA mirrors are smaller than ET mirrors due to shorter arms; (2.5 x minimum beam diameter = ~20cm)
- (Germanium: Shares many of the silicon issues, but has a higher density, allowing for smaller mirrors from a radiation pressure noise point of view.)

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