High-Quality Mirrors for Future Gravitational-Wave Detectors

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on behalf of the GWFP group of Maastricht University

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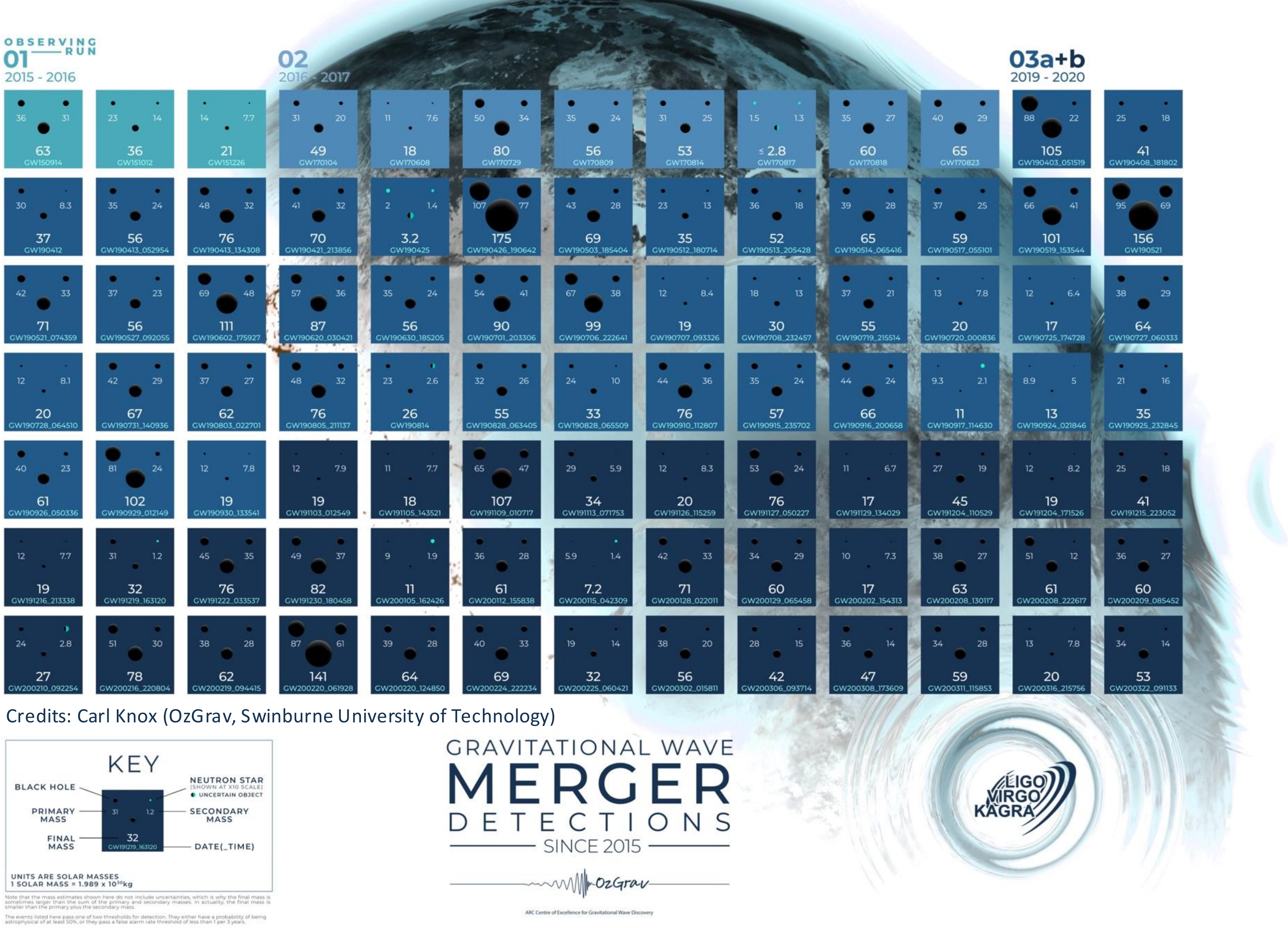
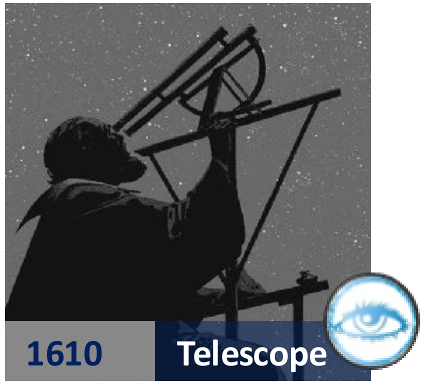
GRAvitational-waves Science&technology Symposium
GRASS 2024

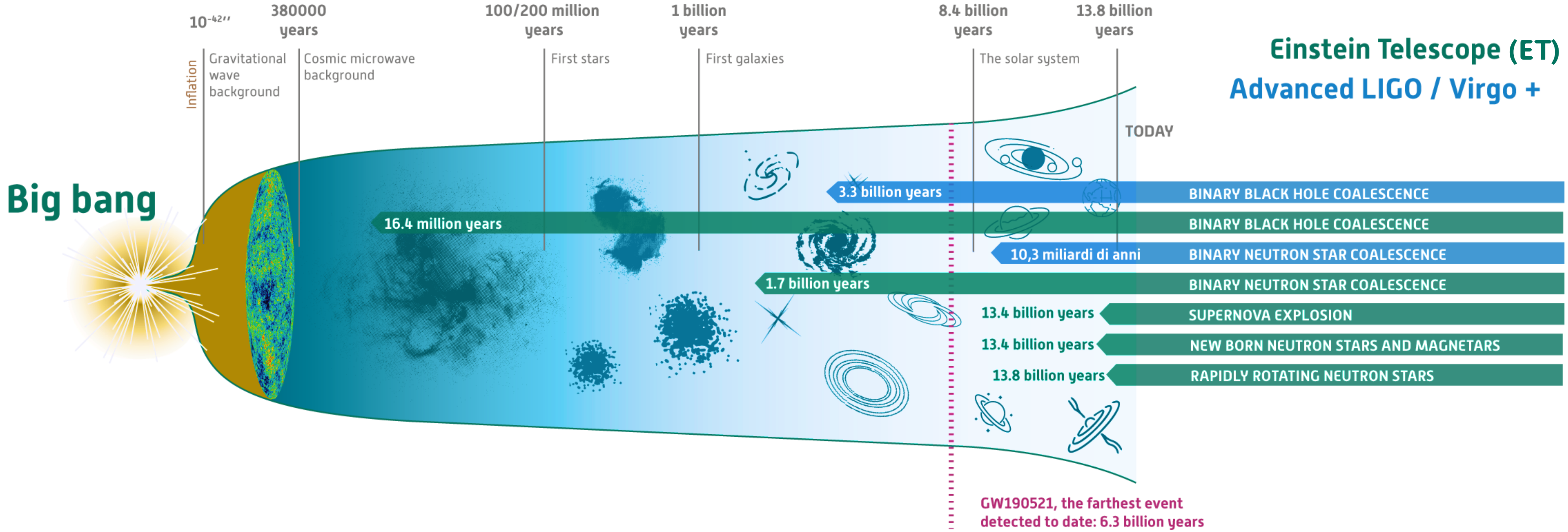
Gravitational-Waves Detectors



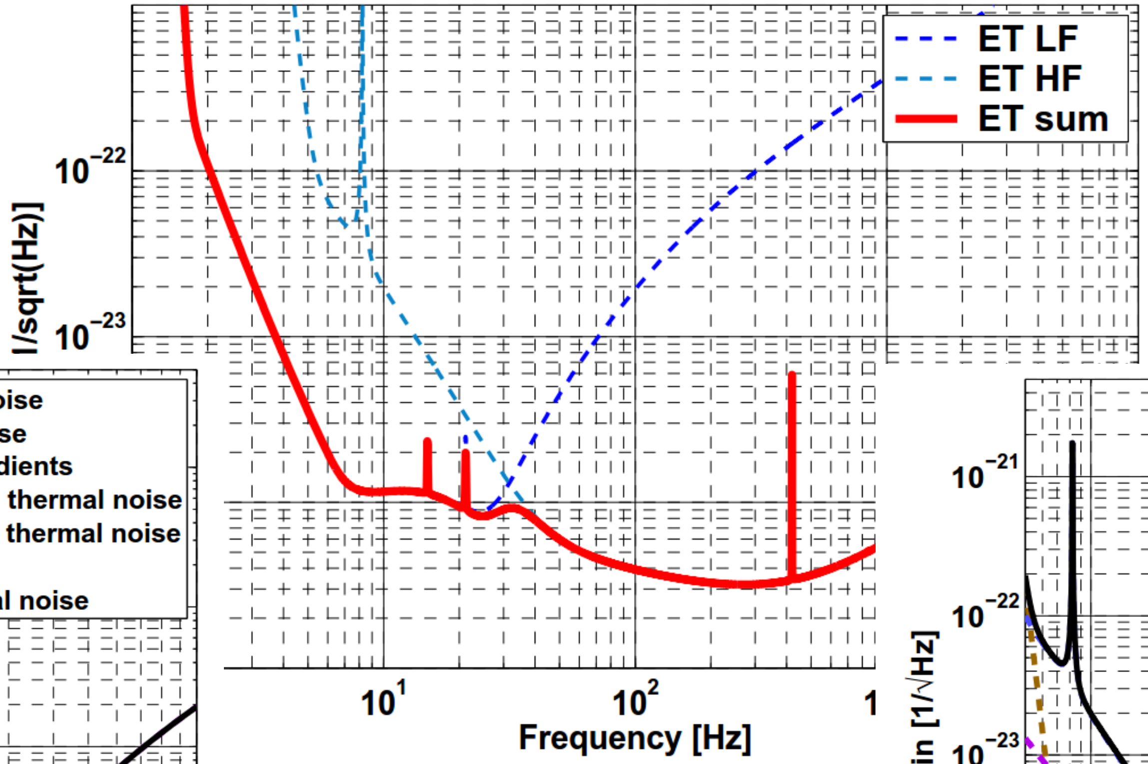
Credits: Carl Knox (OzGrav, Swinburne University of Technology)



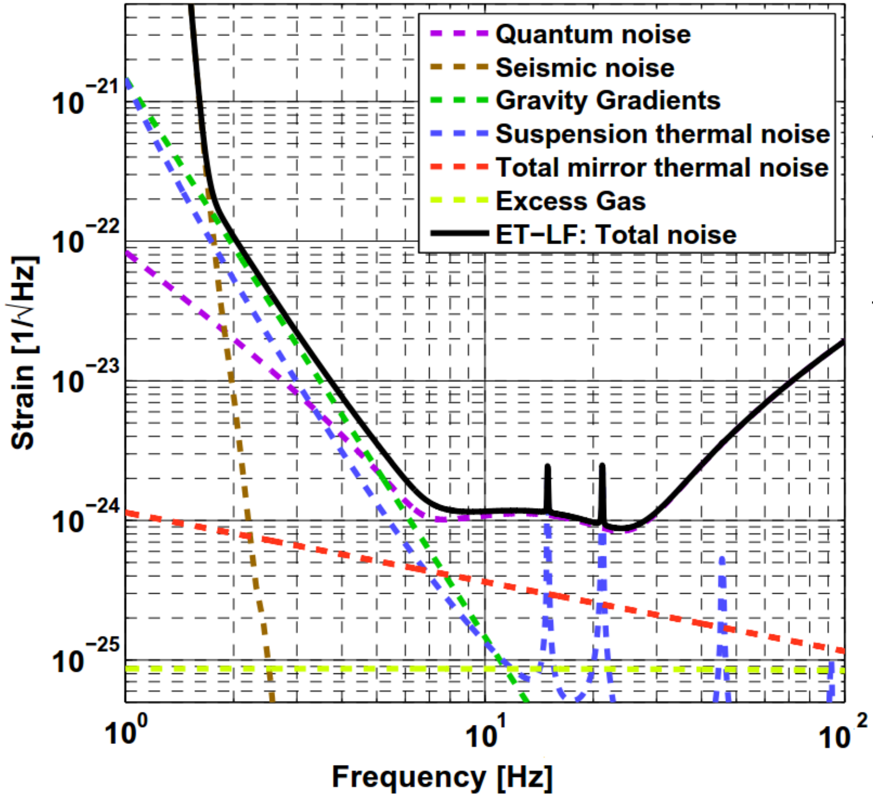
Future Gravitational-Waves Detectors



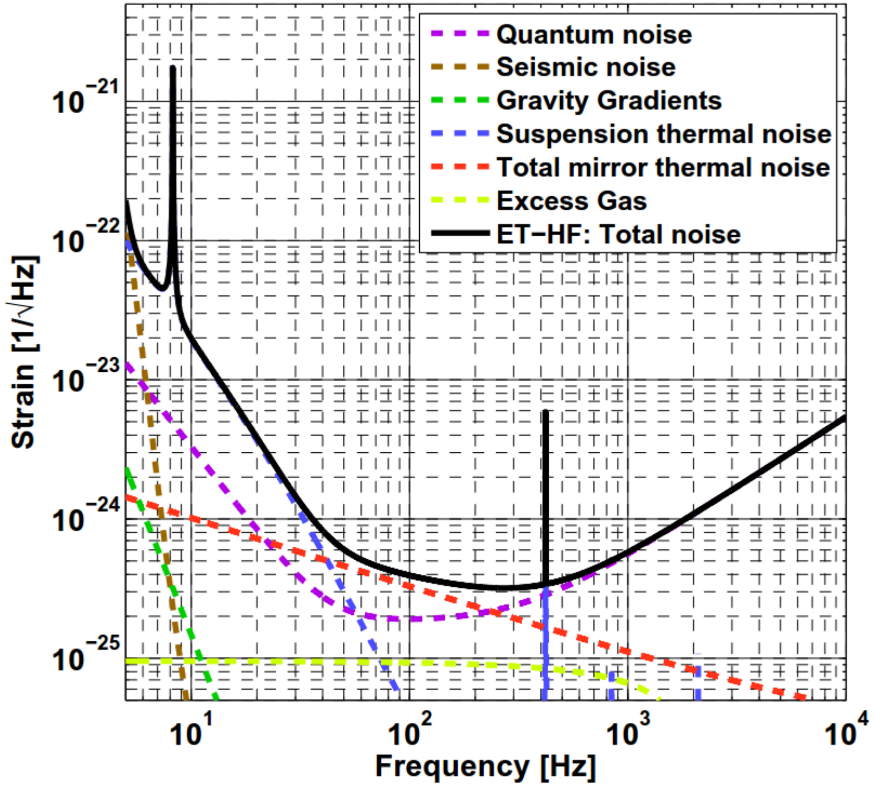
Future Gravitational-Waves Detectors



Cryo T

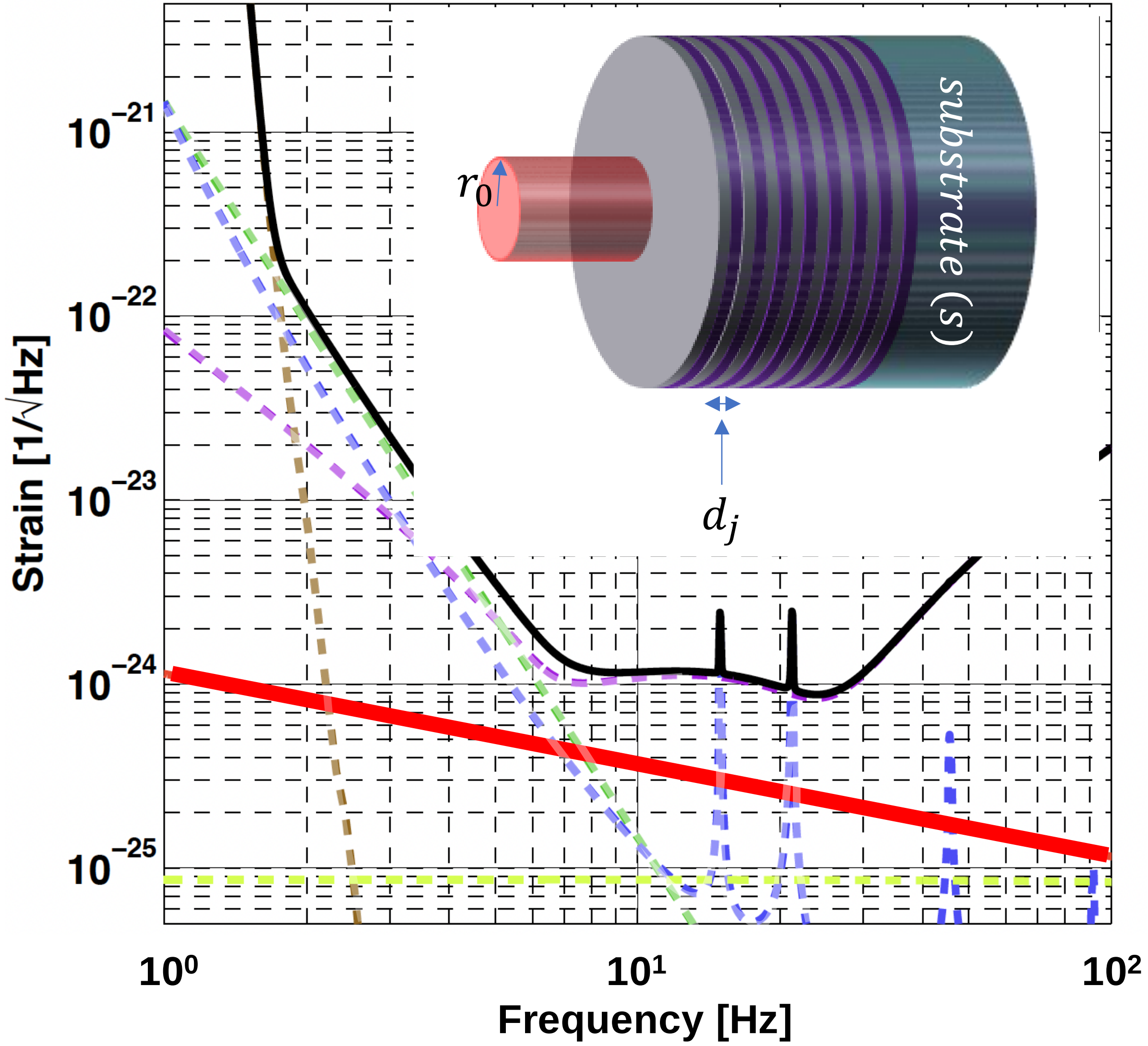


Room T



Coating Thermal Noise

https://apps.et-gw.eu/tds/?content=3&r=17196



Power Spectral Density:

$$S_{CTN} = \frac{4k_BT}{\omega}\left(\frac{1}{\pi r_0^2}\right)\frac{1-\sigma_s-2\sigma_s^2}{Y_s}\sum_j b_j d_j \phi_j$$

$$b_j = \frac{1}{1-\sigma_j}\left[\left(1-n_j\frac{\partial\gamma_c}{\partial\gamma_j}\right)^2\frac{Y_s}{Y_j}+\frac{(1-\sigma_s-2\sigma_s^2)^2}{(1+\sigma_j)^2(1-2\sigma_j)}\frac{Y_j}{Y_s}\right]$$

W. Yam, S. Gras, and M. Evans
Phys. Rev. D 91, 042002 (2015)

Approximation from:
T. Hong et al.
Phys. Rev. D 87, 082001 (2013)

Coating Thermal Noise (CTN) reduction comes from:

- Temperature
- Coating Thickness
- Laser beam size
- Mechanical Parameters
  (Young modulus of Substrate Y' and Coating Y')
- Coating loss angle

The Einstein Telescope Low Frequency (ET-LF) detectors will use cryogenic temperatures and large mirrors

Coating Thermal Noise

Steinlechner J. et al., *Phys. Rev. Lett.*, **120**, 263602 (2018).

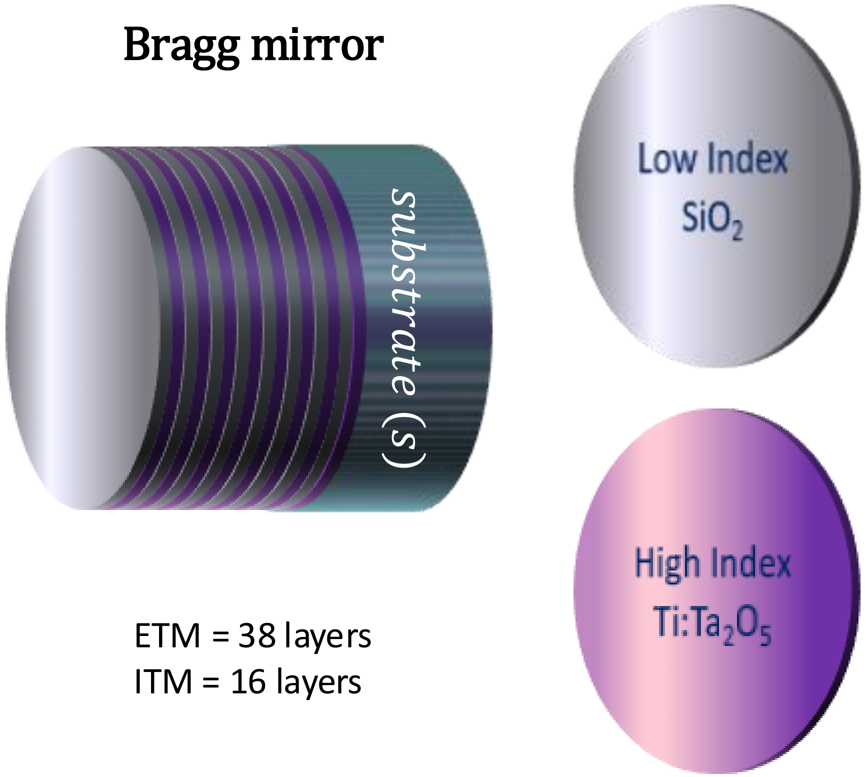
TABLE I. Mechanical loss ϕ and refractive index n used for all wavelengths considered.

	Mechanical loss $\phi \times 10^{-4}$	
Temperature [K]	SiO_2	$Ti:Ta_2O_5$
290	0.4 [16]	2.4 [16]
120	1.7 [17]	3.3 [34]
20	7.8 [17]	8.6 [34]
n (refr. Index)	1.5	2.05
κ (ext. Coeff.)	$< 10^{-6}$	$< 10^{-6}$

[a]Our measurements.
[b]Upper limit from sample without heat treatment.

Materials used in current detectors

Bragg mirror



ETM = 38 layers
ITM = 16 layers

CTN problem at cryogenic temperatures

Coating Thermal Noise

Steinlechner J. et al., *Phys. Rev. Lett.*, **120**, 263602 (2018).

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	Mechanical loss $\phi \times 10^{-4}$			
Temperature [K]	SiO_2	$Ti:Ta_2O_5$	a-Si [a]	SiN
290	0.4 [16]	2.4 [16]	0.2	0.8 [32,33]
120	1.7 [17]	3.3 [34]	≤ 0.5 [b]	0.2 [32,33]
20	7.8 [17]	8.6 [34]	≤ 0.2 [b]	0.1 [32,33]
n (refr. Index)	1.5	2.05	3.65	2.17 [35]
κ (ext. Coeff.)	$< 10^{-6}$	$< 10^{-6}$	3.5×10^{-5}	1.2×10^{-5}

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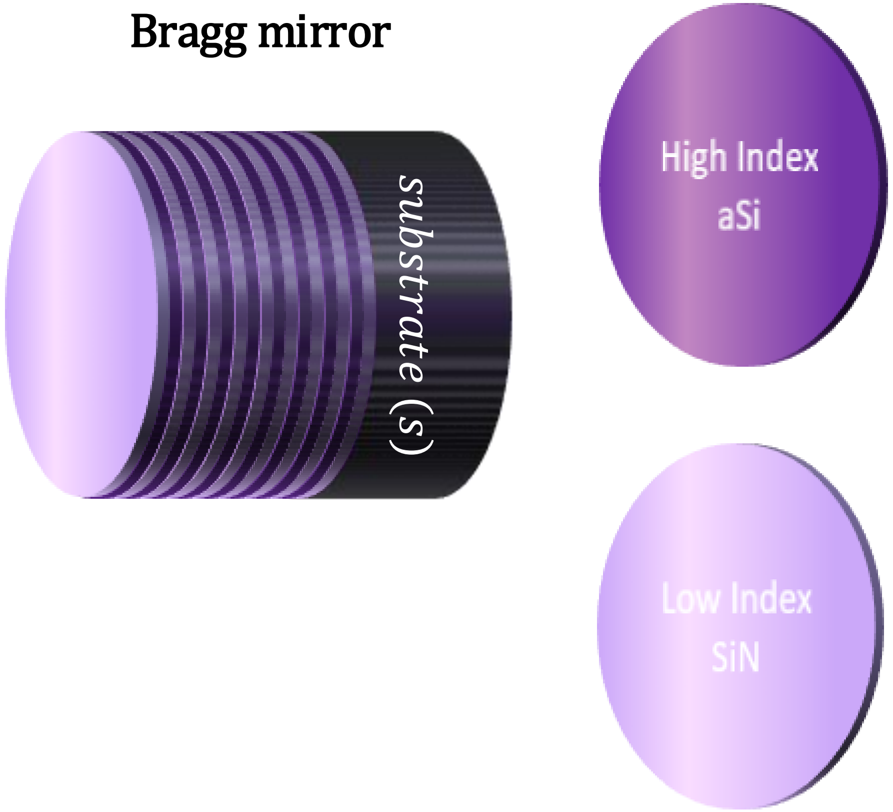
Bragg mirror



Absorption problem

Crystalline-silicon Top-layer Design

Problem: The main problem in using aSi and SiN is the relatively high optical absorption.

Solution: Use a top layer of crystalline silicon to reflect ≈70% of laser power before it reaches the amorphous layers and reduce the absorption.

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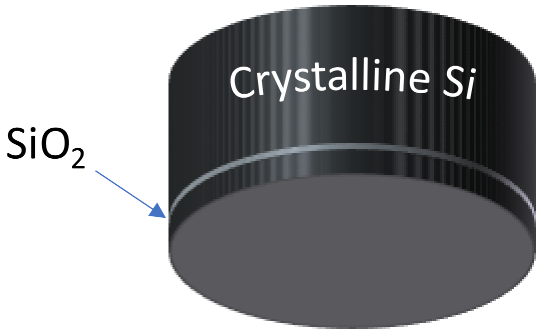
a)



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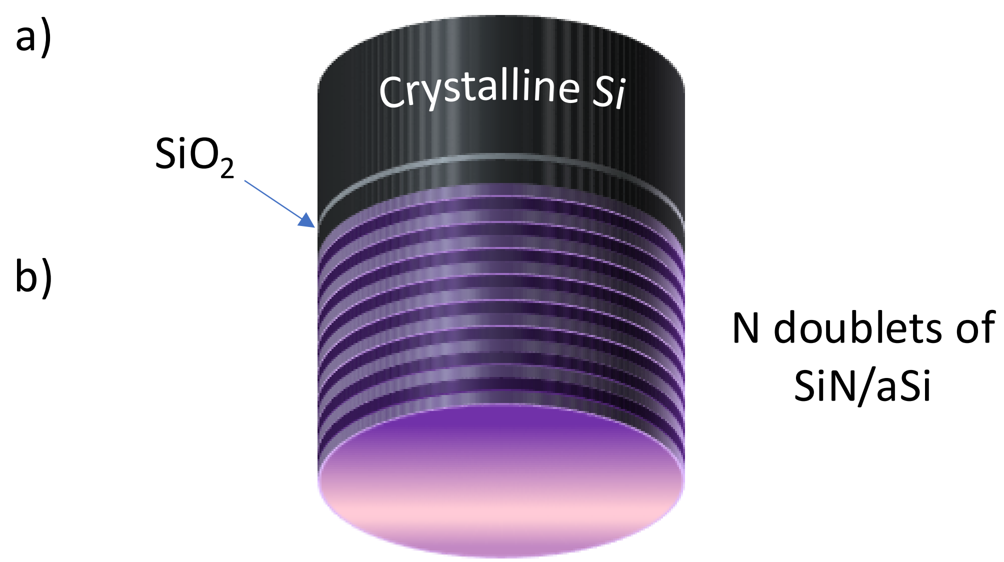
b) An amorphous aSi/SiN HR coating, which displays a CTN of 2.56 x 10^{-22} $\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 20 K and at 100 Hz, is deposited on the SOI.



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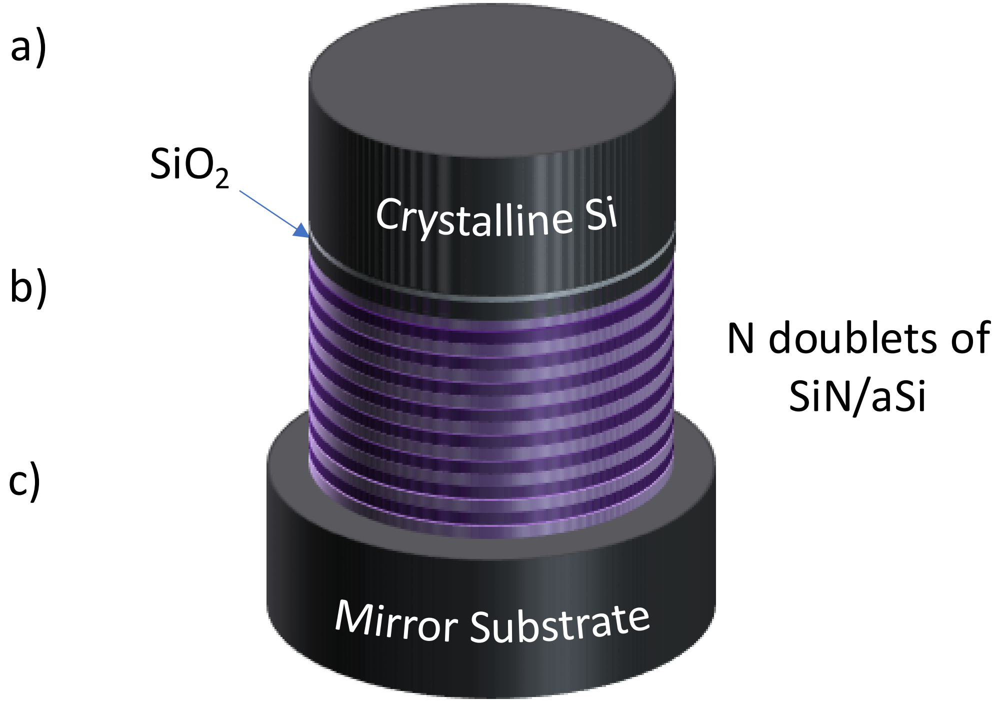
c) The SOI with the multilayer is bonded to the mirror substrate on the side of the stack.



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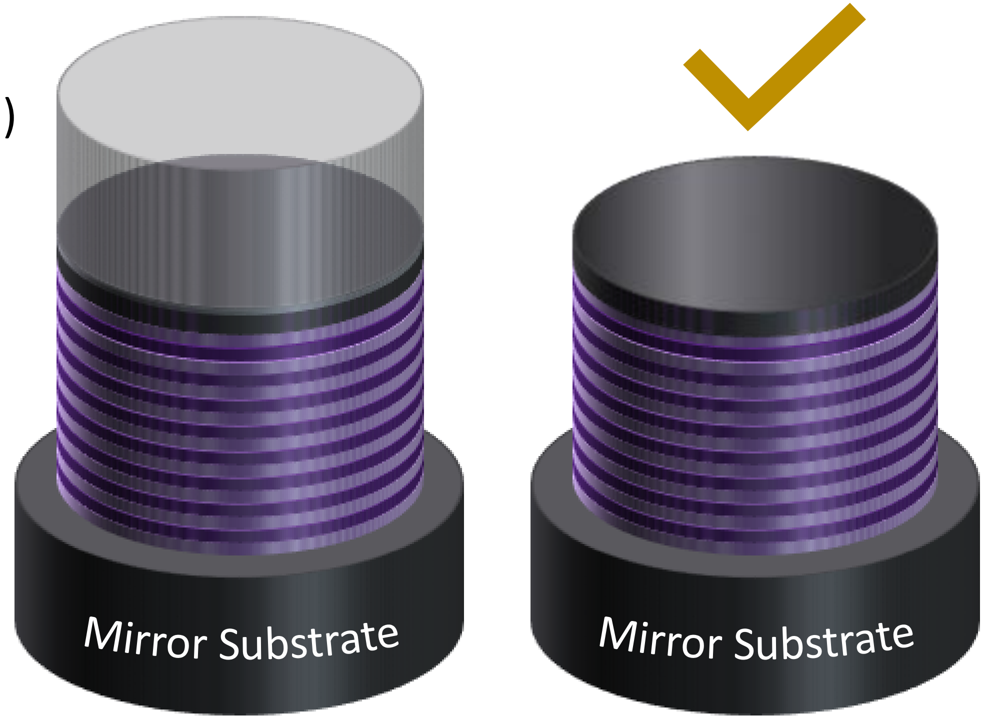
d) The thick base crystalline silicon wafer and the SiO_2 layers are etched so to leave the thin crystalline silicon layer on top of the mirror.

Etching of cSi and SiO_2

d)



aSi Single Layer Characterization

Materials

Single layers of aSi, deposited by *magnetron sputtering* on silica substrates at Padova University. Two different gases during production:

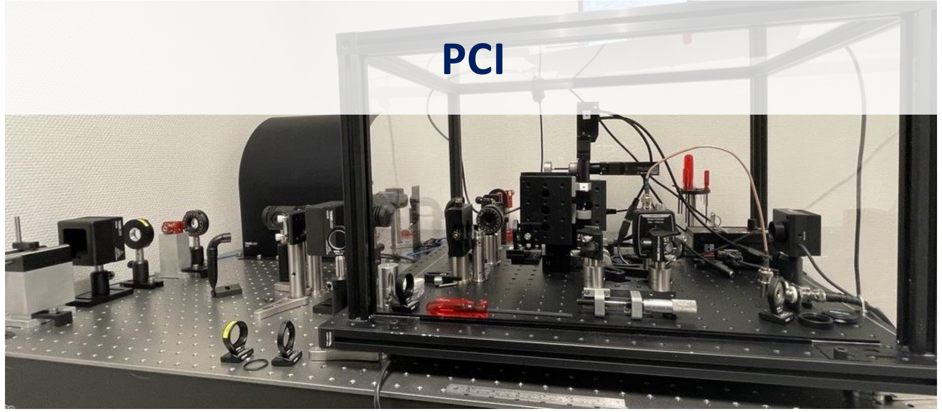
- ❑ 100% Ar
- ❑ 95% Ar and 5% Hydrogen

Treatments

Samples annealed in air for 4h at temperatures up to 600°C, with a step of 100°C.

Tools

- ❑ Cary 5000 spectrophotometer for n.
- ❑ Photothermal Common-path Interferometry (PCI) for k @1550nm.



Why Hydrogen?

- Studies related the absorption in the NIR region of aSi to the dangling bonds (unpaired electron-spin density)

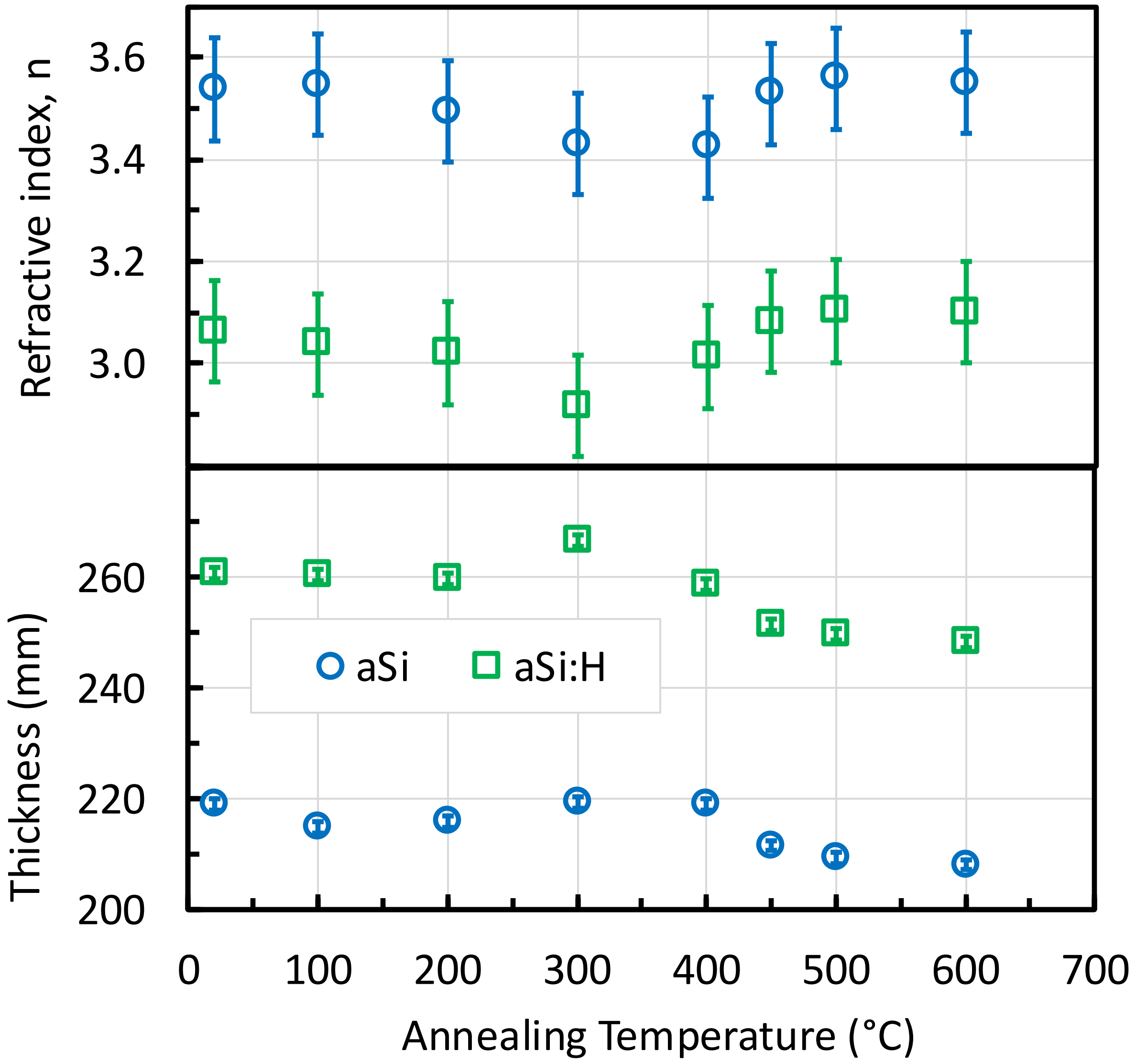
(Phys. Rev. Lett. 131, 256902)

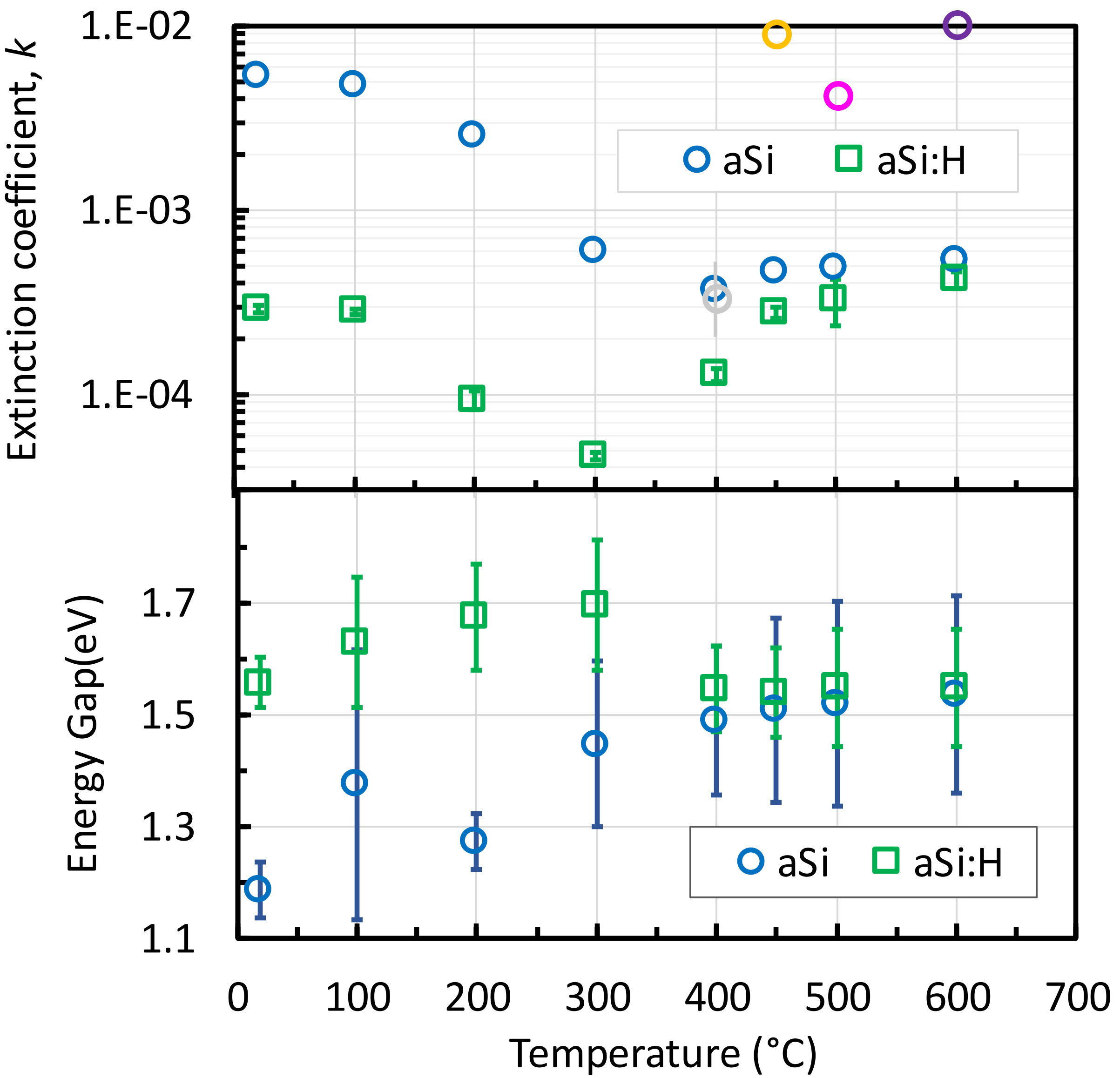
- Hydrogenation can help reducing dangling bond and hence absorption

(Phys. Rev. Lett. 121, 191101)

Optical Properties of aSi

IP: *Phys. Rev. D* 103.4 (2021): 042001.
ECR-IBS: *Phys. Rev. Lett.* 121 (2018): 191101.
IBS: *Phys. Rev. D* 103.4 (2021): 042001.
IBS: *Phys. Rev. D* 93 (2016): 062005.





SiN Single Layer Characterization

Materials

Single layers of SiN, deposited by *Ion Beam Sputtering* by LMA on silica substrate. (Sample S17033)
Film composition (RBS in Padova University):
$SiN_{1.35}Ar_{0.015}$

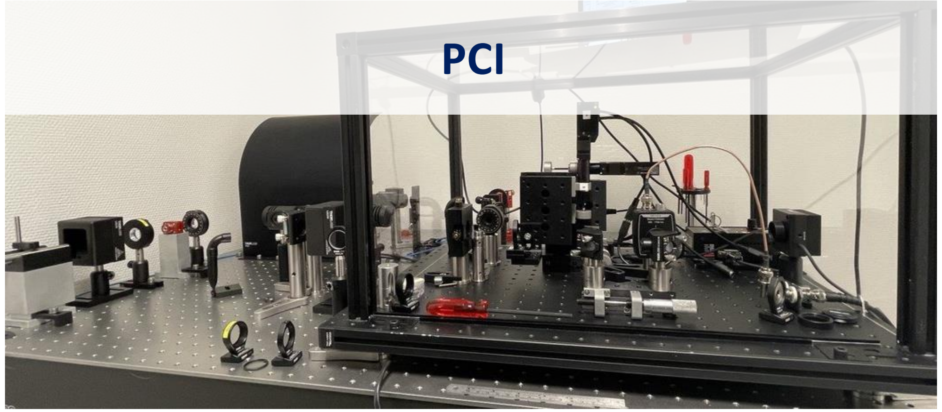
New samples: arXiv:2409.07147 (2024)

Treatments

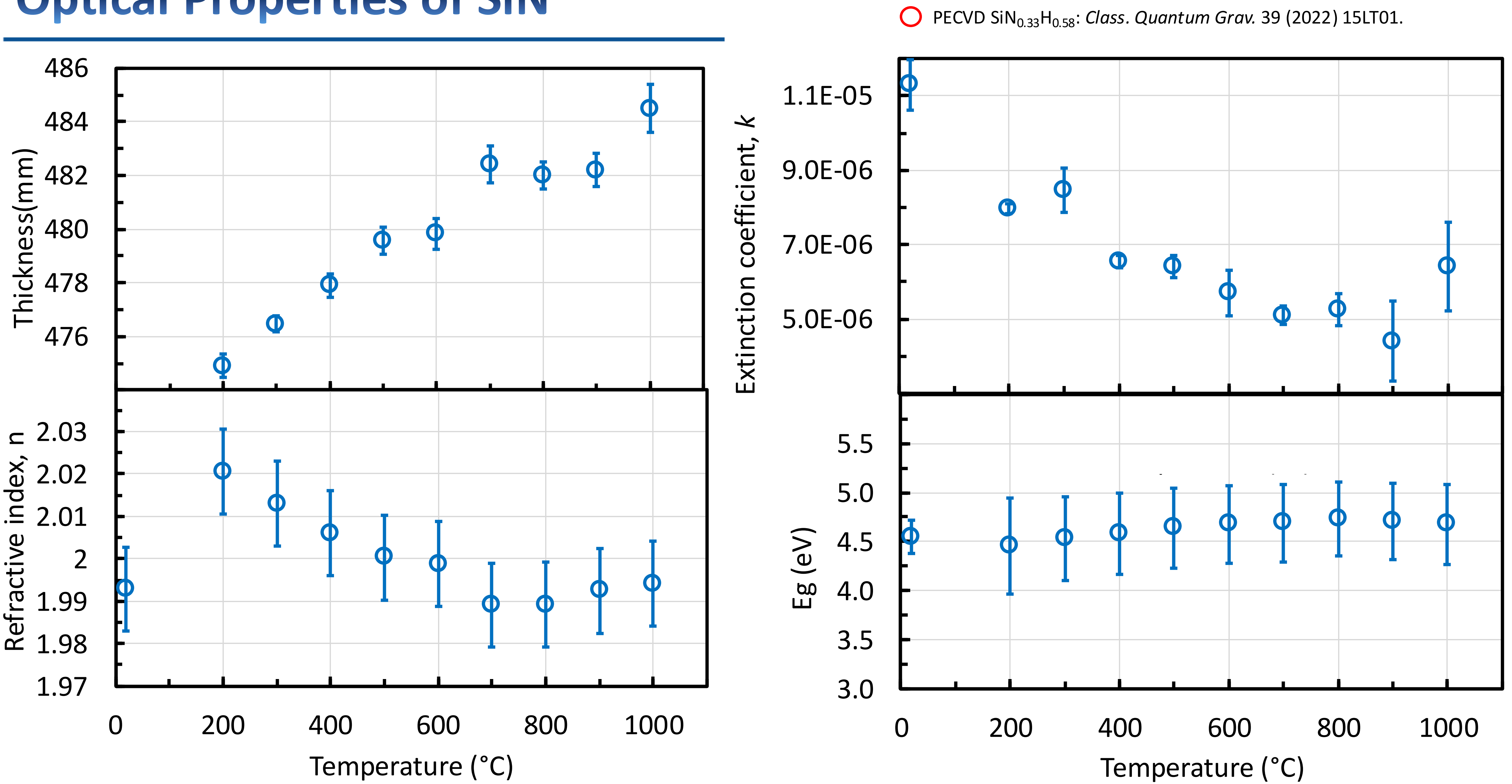
Coatings annealed in air, 4h at 200°C, 300°C, 400°C, 500°C and 600°C, consecutively.

Tools

- Cary 5000 spectrophotometer for n.
- Photothermal Common-path Interferometry (PCI) for k @1550nm.



Optical Properties of SiN



Future Perspectives

Coating Deposition and Characterization

- ❑ Further reduction of optical absorption for aSi is needed.
  - ➢ We need to prevent desorption of H content (?)
  - ➢ We need to use higher deposition temperature (?)
- ❑ We have problems of bubble formation after 450-500 °C heat treatment.
  - ➢ Stress (?)
  - ➢ Argon (?)
  - ➢ Water (?)
- ❑ SiN single layer investigation just started at 1550 nm on an old sample and further investigation is needed on new samples.
- ❑ aSi/SiN multilayer investigation is missing.

Bonding and Etching

- ❑ Bonding procedure → some tests already done before this project but need further investigation.
- ❑ Etching procedure → ongoing (some tests already done).

Acknowledgments

This project is funded by NWO – VI.Vidi.203.062.

Thank you for your attention!