Overview of coating thermal noise

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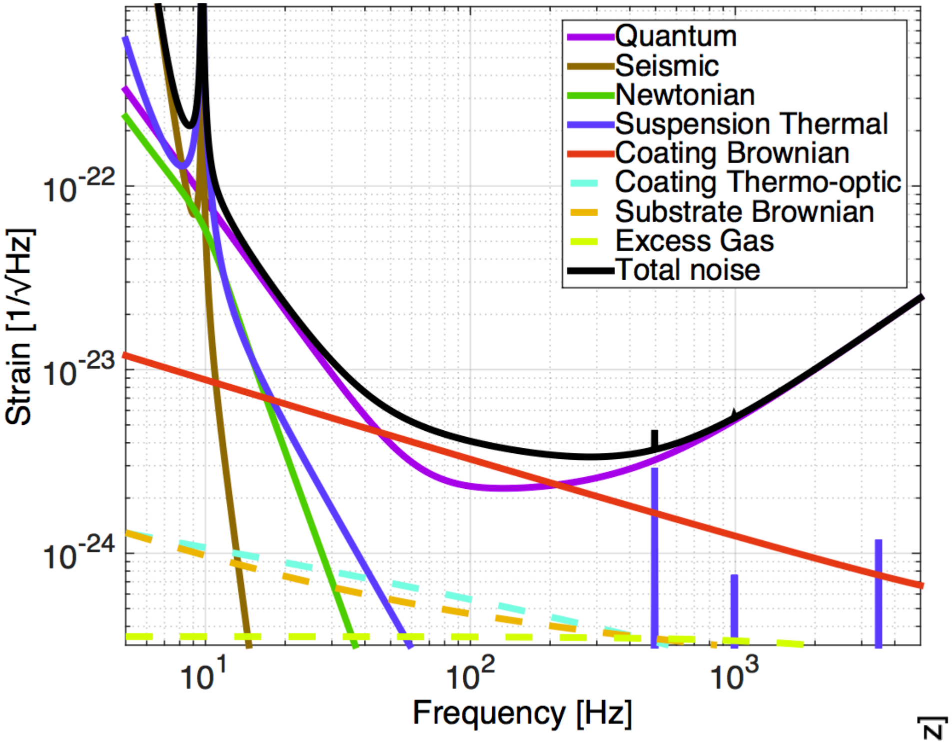
GWADW 18

15th May 2018, Girdwood, Alaska

LIGO-G1800920-v4

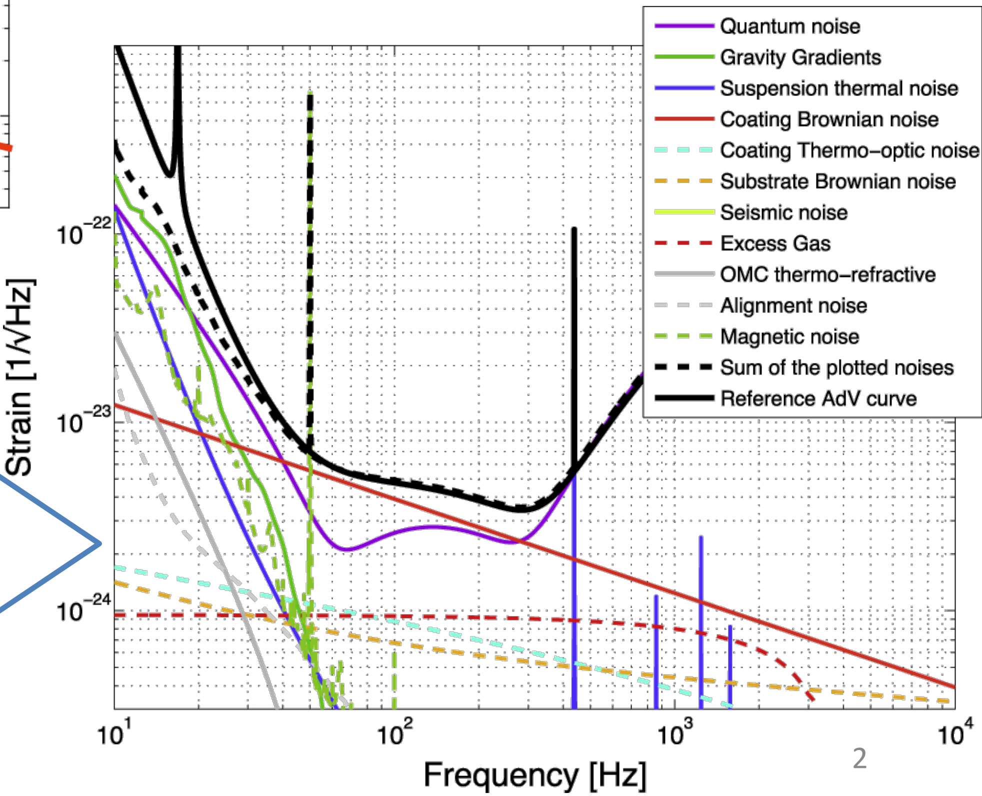
Image credits: LIG

Advanced Detector Sensitivities



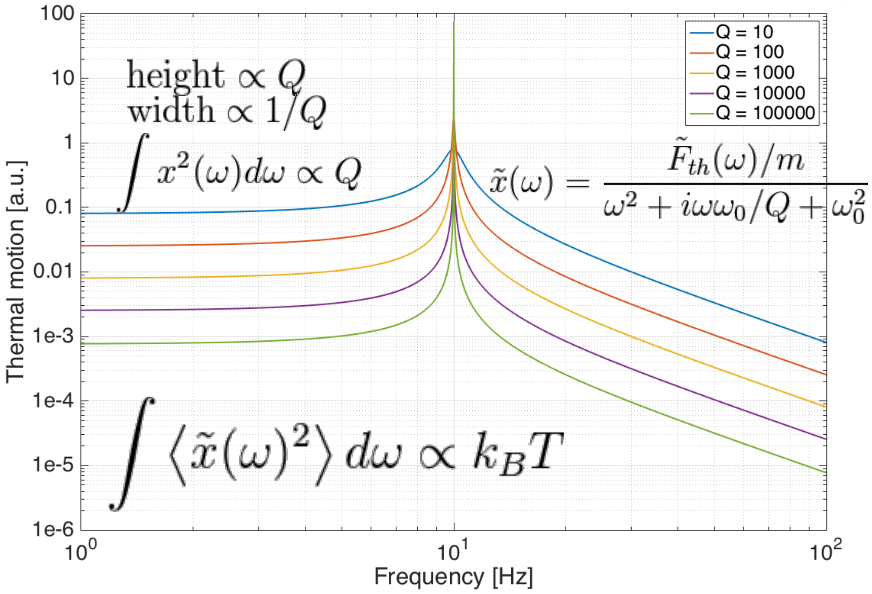
New aLIGO design curve
from LIGO-T1800044-v5
Thermal noise measurement
Gras et al. arxiv:1802.05372

AdVirgo design curve
From Acernese et al. CQG 32,
024001 (2015)



Coating Thermal Noise: a primer

- Thermal (Brownian) noise:
  - system in thermal equilibrium, couples energy to thermal bath through mechanical dissipations
  - The reverse is true: energy couplec to the system (k_BT per each mode), random over all frequencies
  - The higher the dissipations, the more energy is spread out of resonance
- Other sources of thermal noise: thermo-elastic, thermo-refractive



Imaginary part of the system transfer function (linked to dissipations)

Power spectral density of fluctuations in the (mechanical) variable x

$$\boxed{S_x(\omega)} = \frac{4k_BT}{\omega} \boxed{\mathrm{Im}\tilde{\chi}(\omega)}$$

Fluctuation dissipation theorem

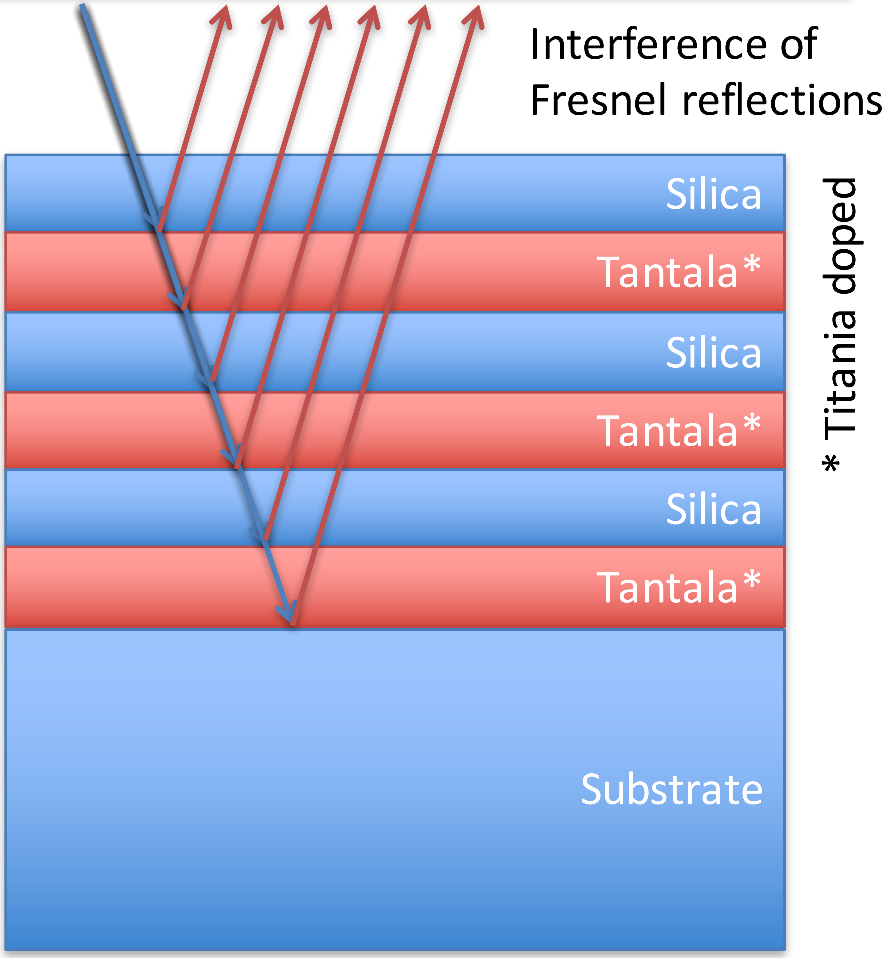
H. B. Callen, T. A. Welton (1951). "Irreversibility and Generalized Noise". *Physical Review*. **83**: 34

How we make high reflection coatings

- Alternate layers of high and low refractive index materials

Material	Refractive index	Loss angle (100 Hz)
Silica SiO_2	1.45	0.5 x 10^{-4}
Tantala Ta_2O_5	2.03	3.4 x 10^{-4}
Titania-doped tantala Ta_2O_5-TiO_2	2.07	(original design*) **2.4 x 10^{-4}** **(MIT direct CTN*)** **3.6 x 10^{-4}**

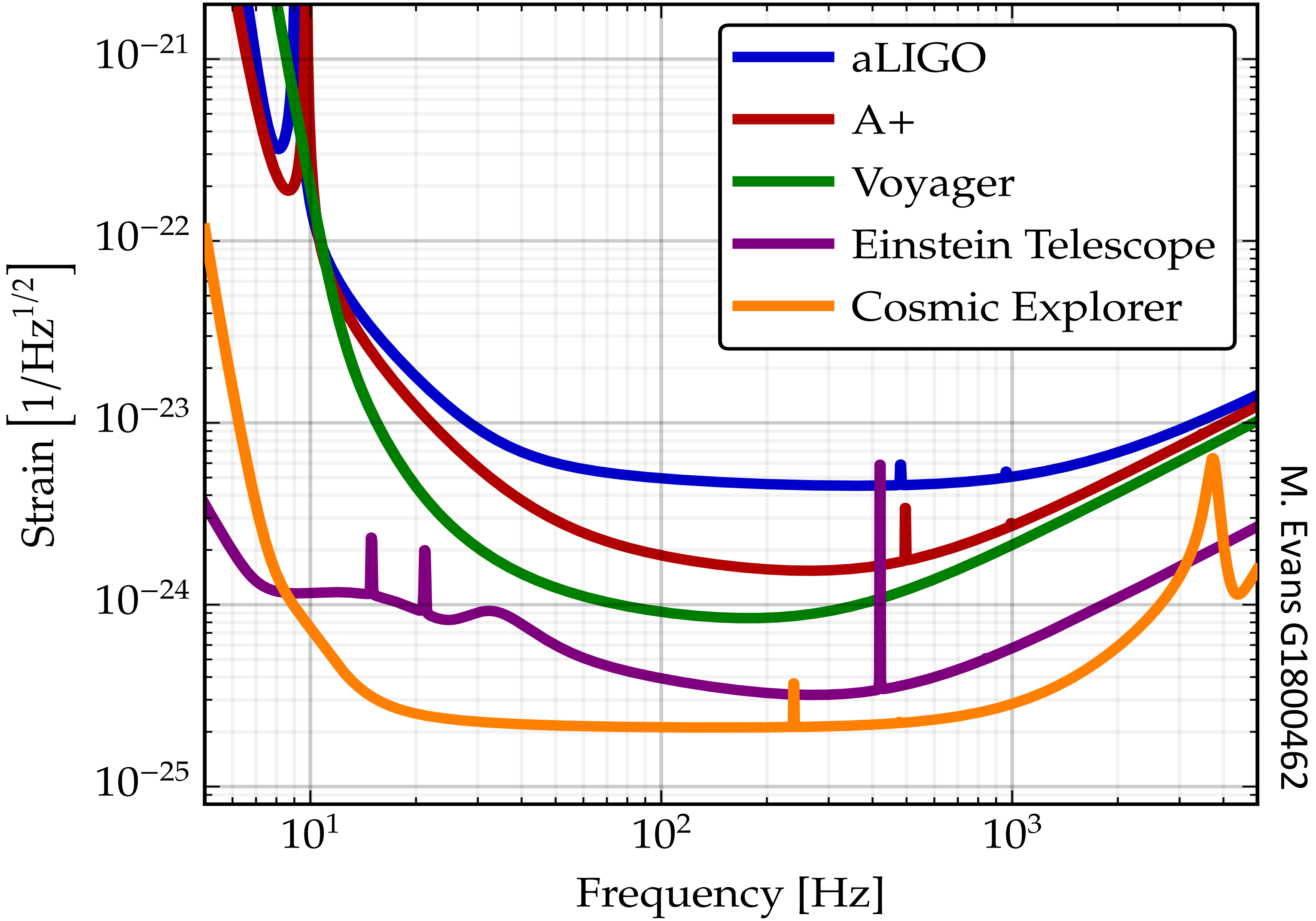
The effective loss angle is a combination of those of the two materials: dominated by the high index material



$$S_x^{\text{coating}}(f,T) = 2k_{\text{B}}T\frac{1-\nu}{\pi^{3/2} f Y w}\phi_{\text{eff}}$$

*Class. Quantum Grav. **24** (2007) 405–415
Phys. Rev. D **95, 022001

The future



Exploring the sensitivity of next generation gravitational wave detectors
CQG 34, 044001 (2017)

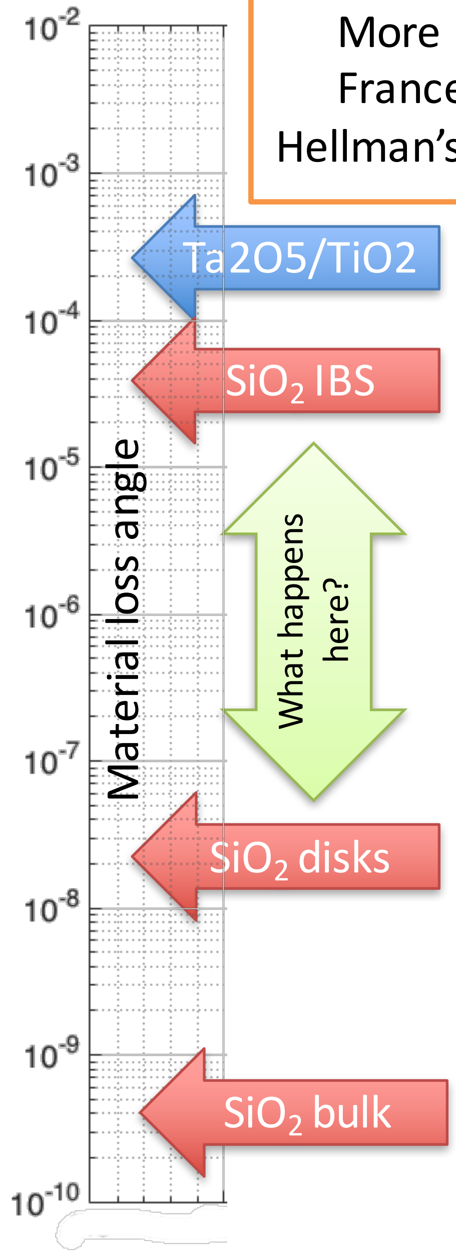
Future coatings: different requirements

	aLIGO	aLIGO+	AdVirgo+	Voyager	C.E.	E.T.
Temperature	300 K	300 K	300 K	123 K	123 K	10 K
Wavelength	1064 nm	1064 nm	1064 nm	1.5 - 2 μm	1.5 - 2 μm	HF 1064 nm LF 1.5-2 μm
Substrate	Silica	Silica	Silica	Silicon	Silicon	HF Silica LF Sapphire
Beam radius (approx.) [cm]	6	6	9	6.5	14	HF 9 LF 7 (LG)
Coating thermal noise at 100 Hz [m/√Hz]	$1.3\mathrm{x}10^{-20}$	$6.5\mathrm{x}10^{-21}$ ($5.0\mathrm{x}10^{-21}$)	$9\mathrm{x}10^{-21}$ ($5\mathrm{x}10^{-21}$)	$2.3\mathrm{x}10^{-21}$	Optimistic $1.3\mathrm{x}10^{-21}$ Pessimistic $5\mathrm{x}10^{-21}$	HF $3\mathrm{x}10^{-21}$ LF $1.1\mathrm{x}10^{-21}$
Coating loss [rad]	$3.6\mathrm{x}10^{-4}$ ($2.4\mathrm{x}10^{-4}$)	$0.9\mathrm{x}10^{-4}$ ($0.6\mathrm{x}10^{-4}$)	$2.4\mathrm{x}10^{-4}$ ($0.8\mathrm{x}10^{-4}$)	$6.5\mathrm{x}10^{-5}$	Optimistic $5\mathrm{x}10^{-5}$ Pessimistic $1.2\mathrm{x}10^{-4}$	HF $1.2\mathrm{x}10^{-4}$ LF $1.3\mathrm{x}10^{-4}$
Coating materials	SiO_2 TiO_2-Ta_2O_5	SiO_2 ?-Ta_2O_5	SiO_2 ?-Ta_2O_5	SiO_2/Al_2O_3 a-Si	SiO_2/Al_2O_3 a-Si	SiO2/Al_2O_3/SiN ?-Ta_2O_5 a-Si ?

CE: Class. Quantum Grav. **34** (2017) 044001
ET: Class. Quantum Grav. **28** (2011) 094013 / Conceptual Design Doc.

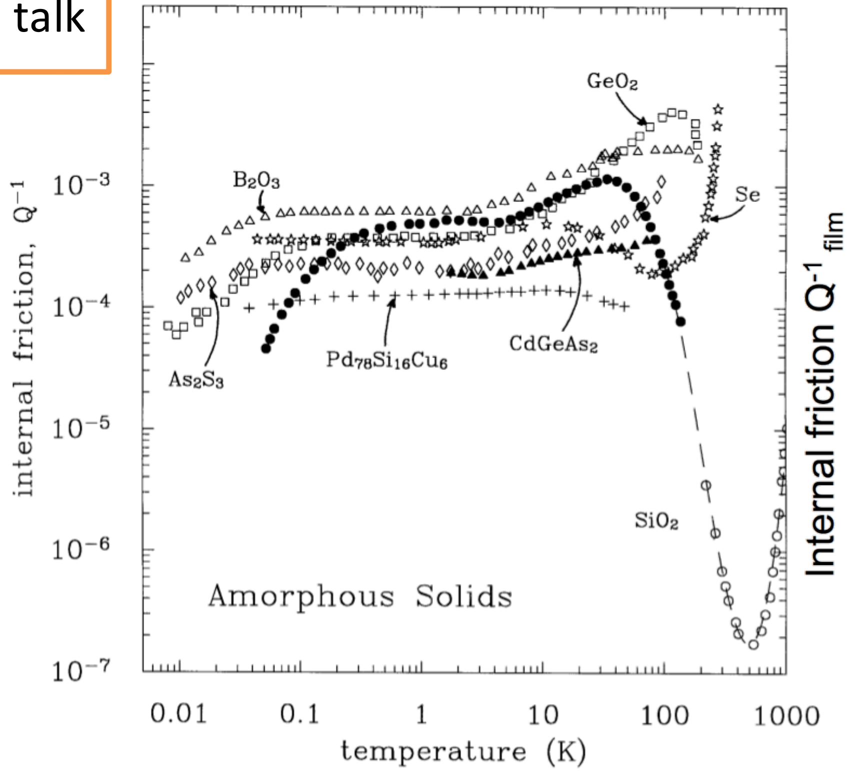
aLIGO+: Phys. Rev. D **91** (2015) 062005 / LIGO-G1800514
Voyager: LIGO-T1400226-v9 / LIGO-G1801004
AdVirgo+ LIGO-G1800999

Why do we think we can improve?

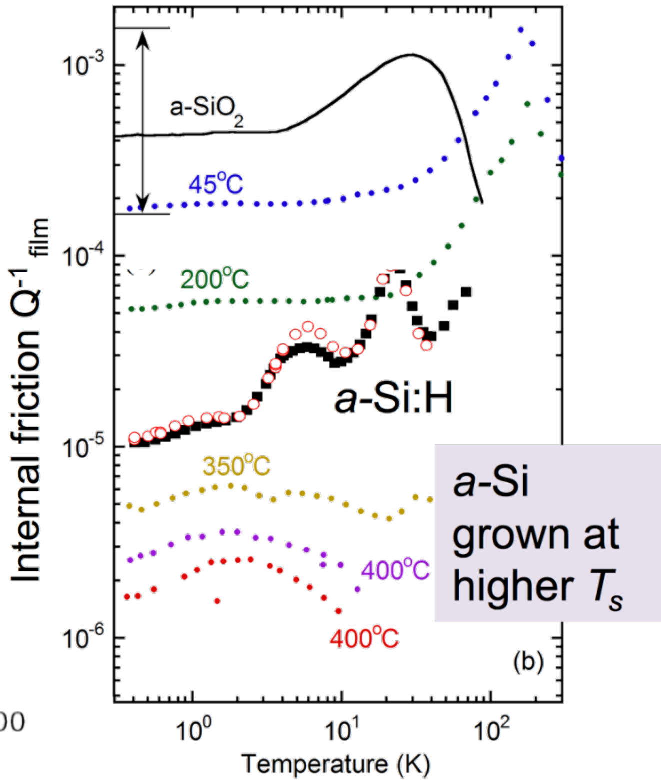


More in Frances Hellman's talk

Zeitschrift für Physik B Condensed Matter. 101. 235-245



Phys. Rev. Lett. **113**, 025503 (2014)



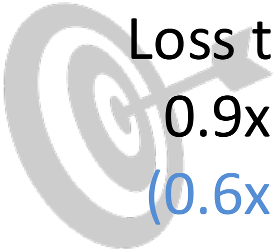
- Most amorphous solids have loss angles in a limited range
- (At least) two exception (in glasses):
  - bulk silica at room temperature (low mechanical loss measured at room temperature)
  - amorphous silicon grown at high temperature (low mechanical loss measured at low temperature)

Room temperature coatings (A+)

- High temperature deposition of tantala did not show enough improvement

  Class. Quantum Grav. **35** (2018) 075001

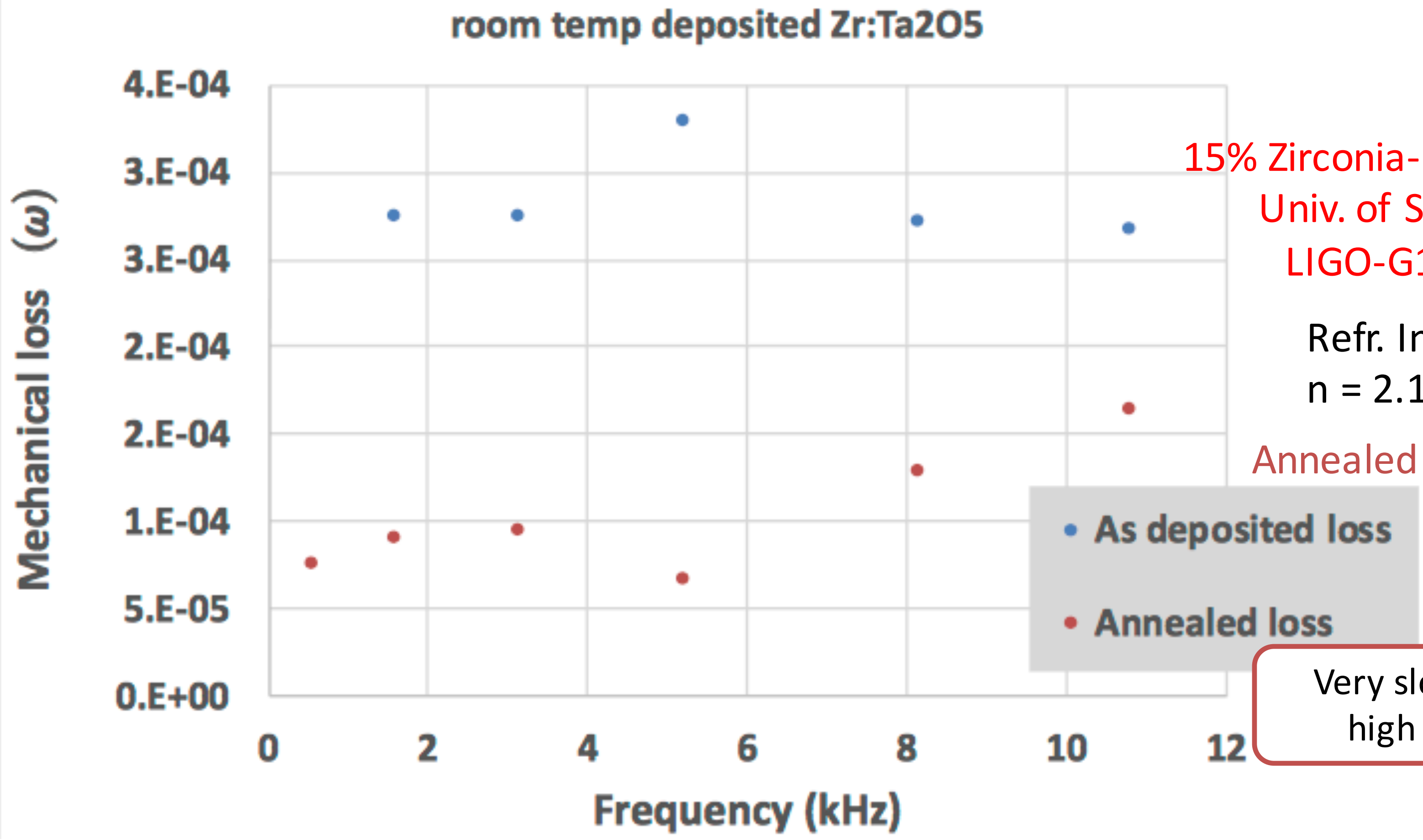
- Two promising candidates: doping of tantala



Loss target

0.9×10^{-4}

(0.6×10^{-4})



15% Zirconia-doped-Tantala
Univ. of Strathclyde
LIGO-G1800585

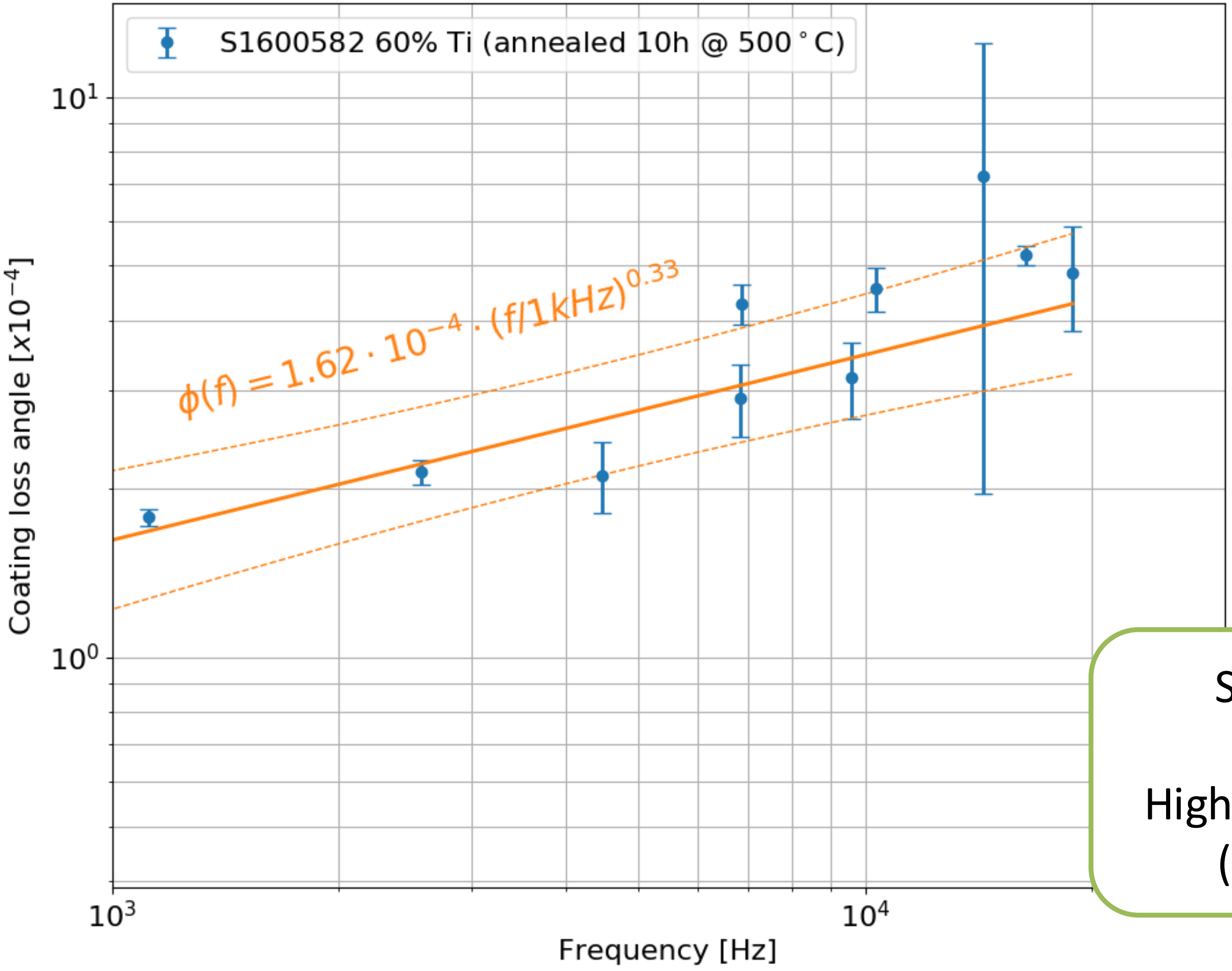
Refr. Index
n = 2.12

Annealed 750C

Very slow deposition
high energy ions

Room temperature coatings (A+)

- Two promising candidates: doping of tantala



Loss target
0.9×10^{-4}
(0.6×10^{-4})

60% Titania-doped-Tantala
Univ. Colorado
Fort Collins
and Caltech
LIGO-G1800360

Refr. Index
n = 2.36

Steep frequency dependence
High optical absorption (contamination)

What's next?

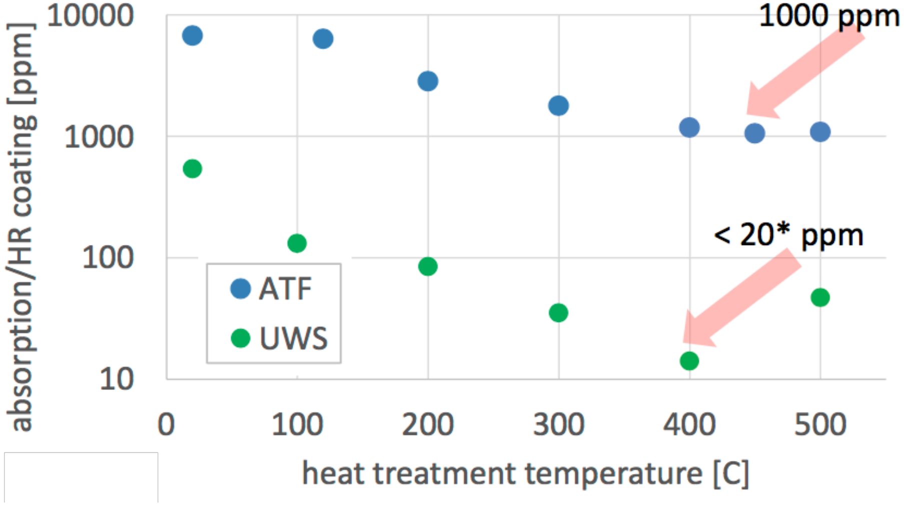
- Zr-doped-Ta:
  - check dependency on concentration / deposition rate / method
  - structural and modeling studies
  - produce a multi-stack and do a direct measurement of thermal noise
- Ti-doped-Ta:
  - fix contamination and high optical absorption
  - repeat measurements probing low frequencies, to confirm the slope

More in Kiran Prasai's talk

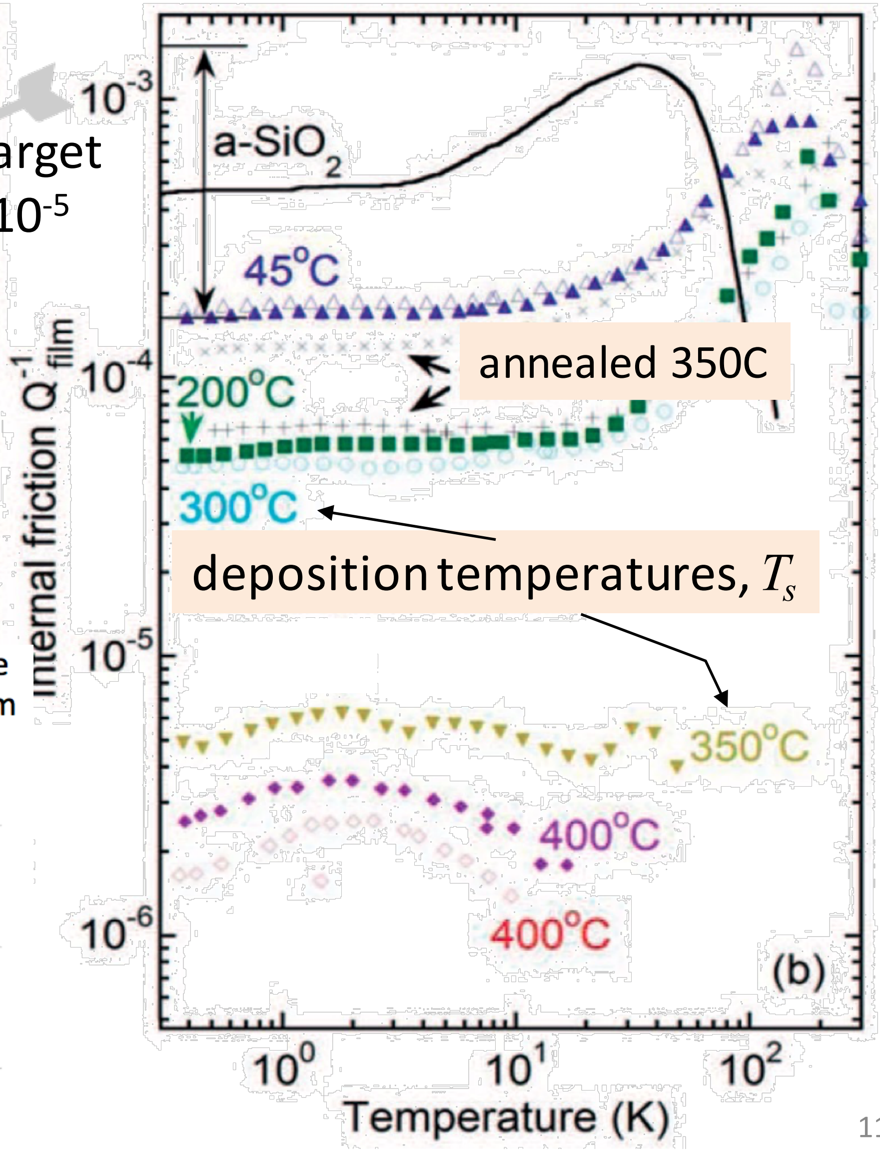
123 K coatings (Voyager – C.E.)

- **Amorphous silicon** deposited at high temperature is the best candidate
  - High refractive index ~3.4
- Low mechanical loss at low temperature. **But at 123K?**
  - Measurements of loss at room temperature shows $\phi < 1\times10^{-4}$ depending on deposition method
- Optical absorptions still high, but improving

Loss target 5.5×10^{-5}



* Measurements limited by absorption of substrate



annealed 350C

deposition temperatures, T_s

High-T deposited a-Si, loss at low temperature (Berkeley)

123 K coatings (Voyager – C.E.)

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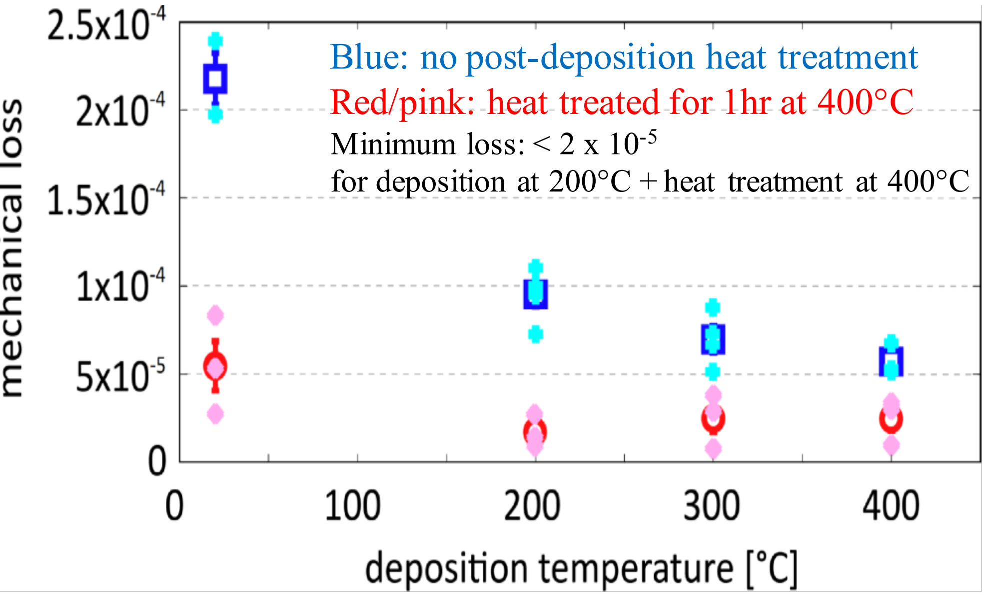
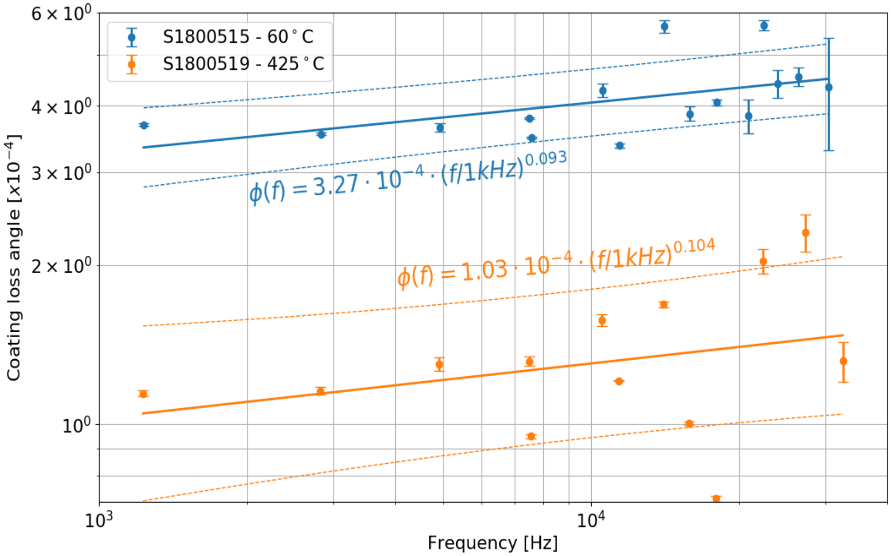
High-T IBS deposited a-Si, Loss at room temperature (Strathclyde)



High-T e-beam deposited a-Si (Berkeley) Loss at room temperature (Caltech)

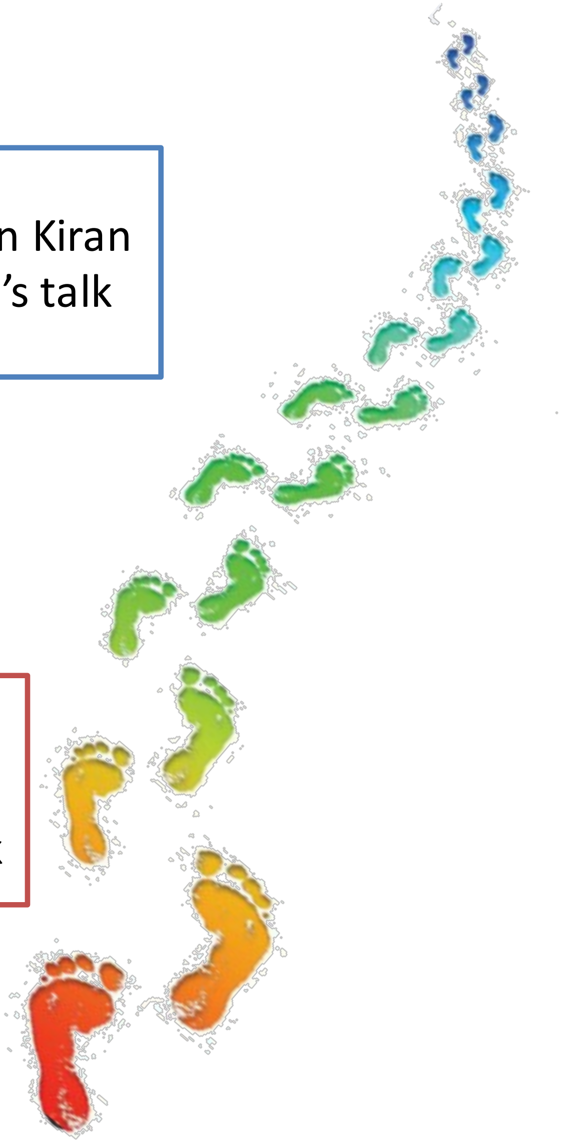


What's next?

- Measure mechanical loss angle of a-Si at 123 K
- Improve optical absorptions
- Structural measurements and modeling
- Why the different behavior of mechanical loss with growth temperature?
- Understand differences due to deposition method

More in Kiran Prasai's talk

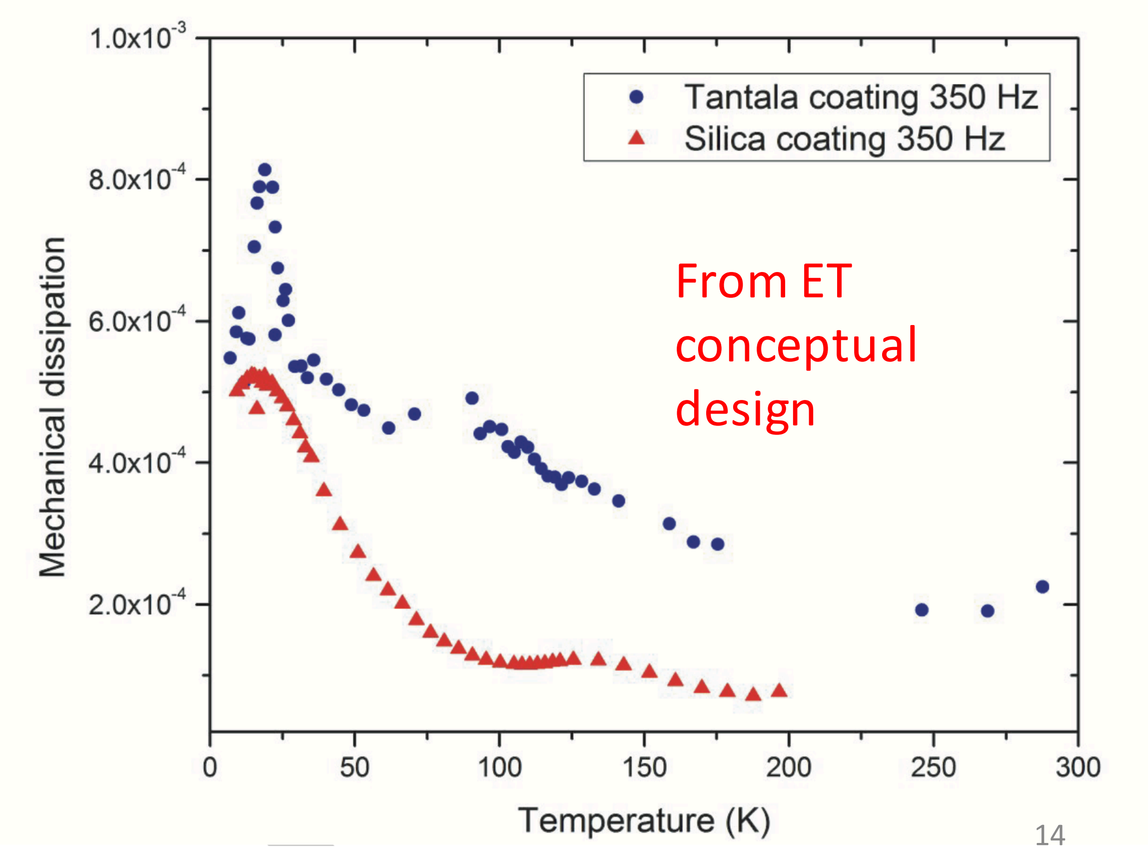
More in Frances Hellman's talk



Low temperature coatings (E.T.)

- Amorphous silicon is a promising high index material
- What about the low index material?
  Silica ≈ 5×10^{-4} at 10 K
- Dependent on heat treatment
  - In many cases annealing improves high temperature loss, but worsen low temperature loss
- Al_2O_3 and SiN good low index candidates

Loss target
HF 1.2×10^{-4}
LF 1.3×10^{-4}



From ET conceptual design

Class. Quantum Grav. **31** (2014) 035019

Low temperature coatings (E.T.)

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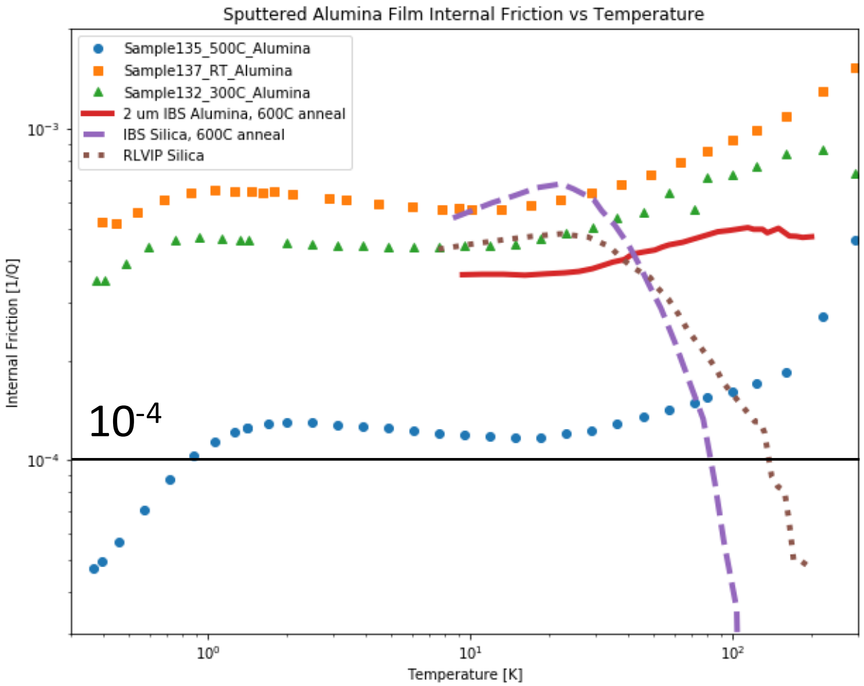
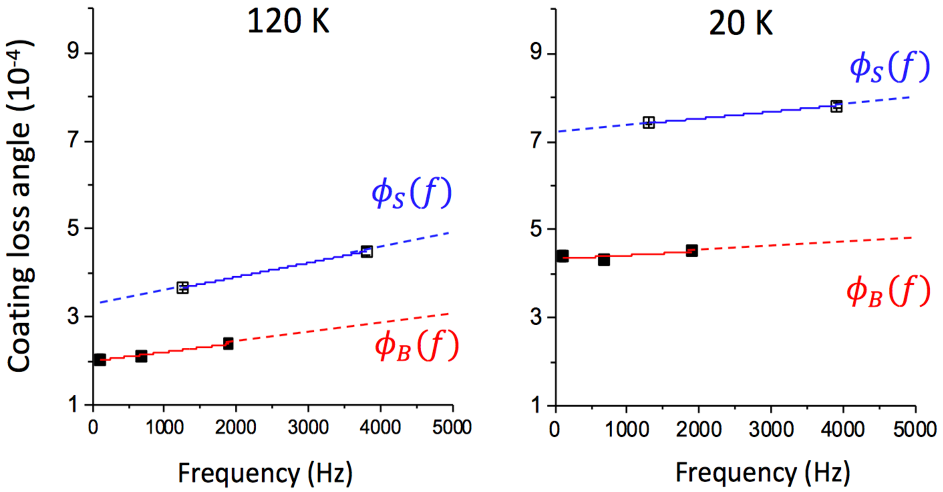
Magnetron sputtered
Al_2O_3 (NRL) LIGO-G1800418



SiN CVD deposition
LIGO-G1800350

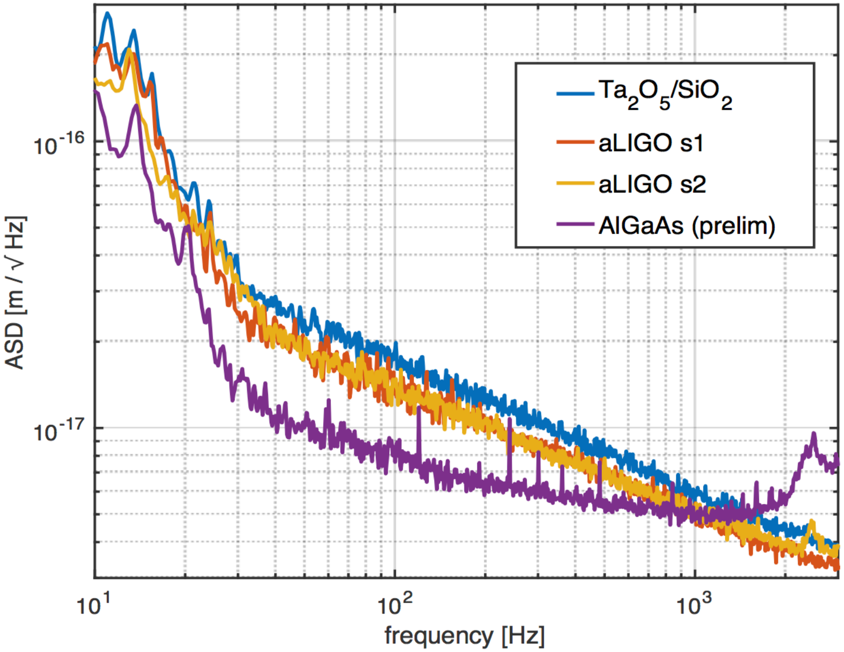


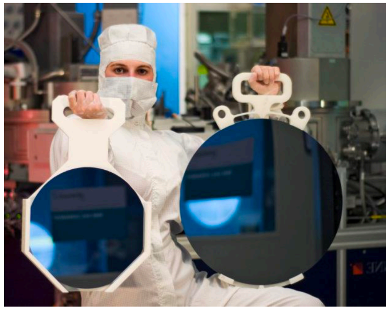
What's next?

- Further characterize Al_2O_3 and SiN mechanical loss
- Improve optical absorption
- Alumina shows improvement with growth temperature, similar to a-Si, dissimilar to Ta_2O_5

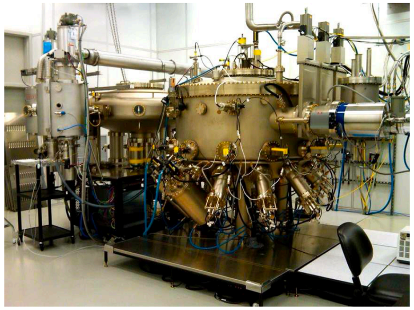
Crystalline coatings

- Promising candidate for 3rd generation
- Low mechanical loss at room temperature ($2x10^{-5}$)
- Good optical absorption and good figure
- Need to develop technology to scale up to large mirror size

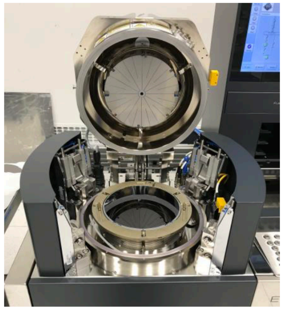




GaAs wafers: 20 → 40 cm



Epitaxy: 30 → 40 cm



Bonding: 45 cm

- AlGaAs room temperature:

  $\varphi_{RT} < 4\times10^{-5}$
- AlGaAs cryogenic :

  •$\varphi_{cryo} < 5\times10^{-6}$

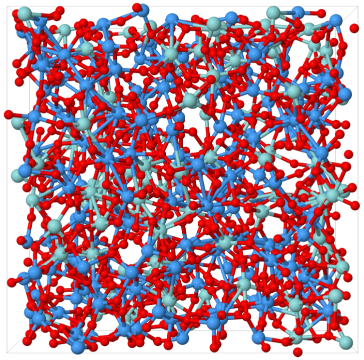
More in Garret Cole's
and Manuel Marchio's talks

Class. Quantum Grav. **32** 035002 (2015)

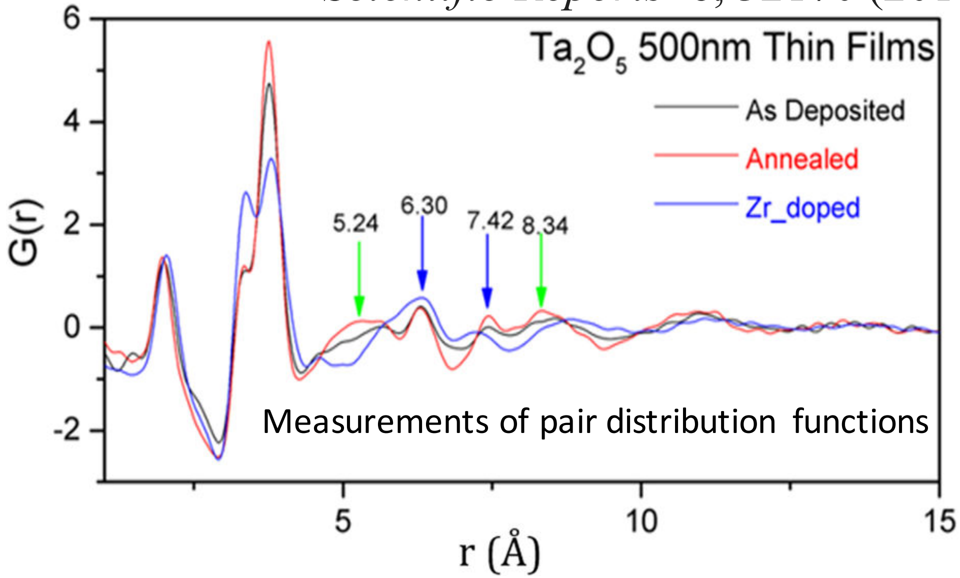
G. Cole LIGO-G1800645 G. D. Cole, et al., Nature Photonics (2013)

Structure and Modeling

- Important to bridge mechanical loss, structural studies and modeling efforts
- Use measured distributions to tune simulations and extract structural information
- Reverse Monte Carlo + Energy minimization
- Crucial: simulate the deposition process

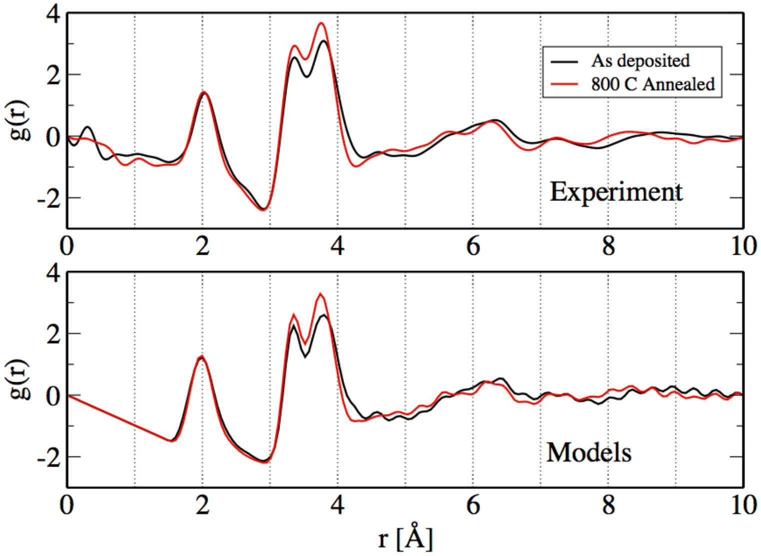


Scientific Reports **6**, 32170 (2016)



Measurements of pair distribution functions

Models track the changes in experimental PDF very well.



K.Prasai LIGO-G1800872

Outlook

- Rate of progress significantly increased in the last few years
- Promising candidates for A+ detector coatings (but we need a recipe very soon)
- Amorphous silicon a promising candidate at mid and low T, but some more characterization are needed (and on-going)
- Low temperature low index material? Some candidates (Al_2O_3, SiN)
- Not one material good for all configurations

Other complementary directions:
Crystalline coatings *Class. Quantum Grav.* **32** 035002 (2015)
Nano-layers LIGO-G1800300