Meeting the Advanced LIGO+ coating requirements by using multimaterial designs

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GWADW, 17.5.2021, online

Overview

- Introduction
- Experimental demonstration
- Calculating a MM coating design for interesting materials
- Implications for room temperature detectors
- Ternary coating optimisation (I. Pinto, V. Pierro)
- Conclusions

Multimaterial coatings

- Proposed to enable the use of aSi layers – high absorption, very low mechanical loss
  - Principle: Use aSi in the lower part of coating stack, where electric field intensity is low
  - Enable loss reduction without large absorption increase

Thermal noise

$$x(f) = \sqrt{\frac{2k_B T}{\pi^2 f} \frac{1}{w^2} \frac{1-\sigma_{\rm sub}-2\sigma_{\rm sub}^2}{Y_{\rm sub}} \sum_j b_j d_j \phi_j}$$

thickness d
loss ϕ

$$b_j = \frac{(1-2\sigma_j)(1+\sigma_j)}{(1-2\sigma_{\rm sub})(1+\sigma_{\rm sub})} \frac{1}{1-\sigma_j} \times \left[\left(1-n_j\frac{\partial\theta_{\rm coat}}{\partial\theta_j}\right)^2 \frac{Y_{\rm sub}}{Y_j} + \frac{(1-\sigma_{\rm sub}-2\sigma_{\rm sub}^2)^2}{(1+\sigma_j)^2(1-2\sigma_j)} \frac{Y_j}{Y_{\rm sub}}\right]$$

Reflectivity

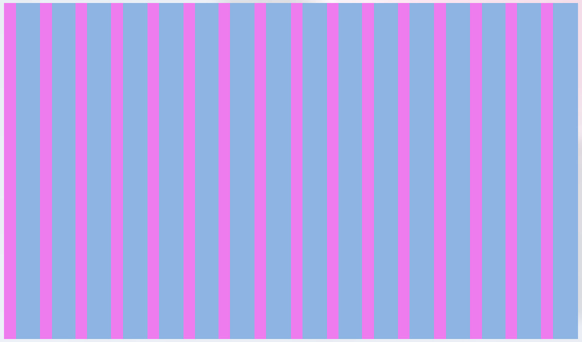
$$R_{\rm 2N+1} = \left(\frac{n_{\rm H}^2 (n_{\rm H}/n_{\rm L})^{2N} - n_{\rm S}}{n_{\rm H}^2 (n_{\rm H}/n_{\rm L})^{2N} + n_{\rm S}}\right)^2$$

layers N required for reflectivity R depend on index contrast

Steinlechner et al., PRD 91 (2015) 042001
Yam et al., PRD 91 (2015) 042002

Multimaterial coatings

- Use of more than two materials in coating stack
- Allows trade-off between thermal noise and absorption
- Possible motivations:
    - Reduce coating thermal noise



Coating with high TN

MM design using higher absorbing, lower loss layers to reduce TN while retaining absorption performance

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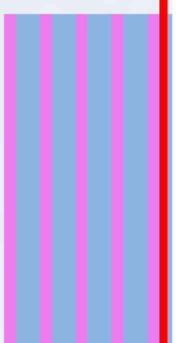

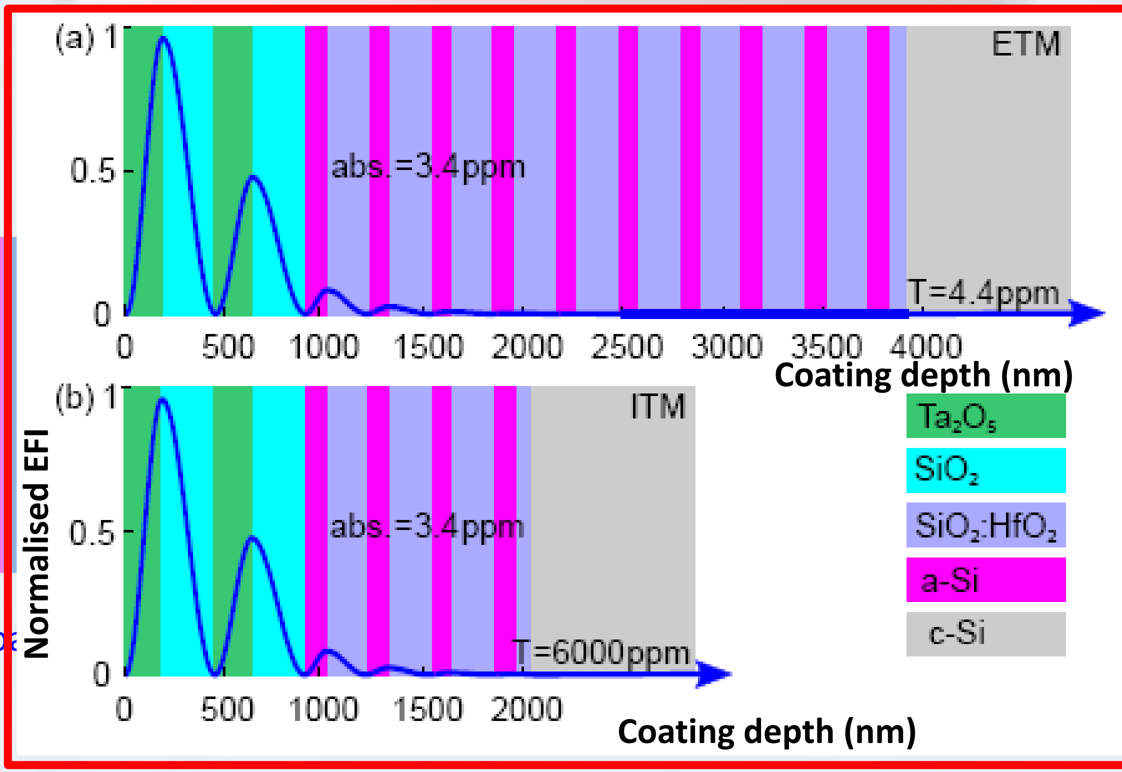

Example design, showing light field reduction in low absorbing upper layers

Co

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performance

Multimaterial coatings

- Use of more than two materials in coating stack
- Allows trade-off between thermal noise and absorption
- Possible motivations:
  - Reduce coating thermal noise
  - Reduce coating absorption

Coating with high absorption

MM design to reduce EFI in lower layers, reducing absorption

Multimaterial coatings

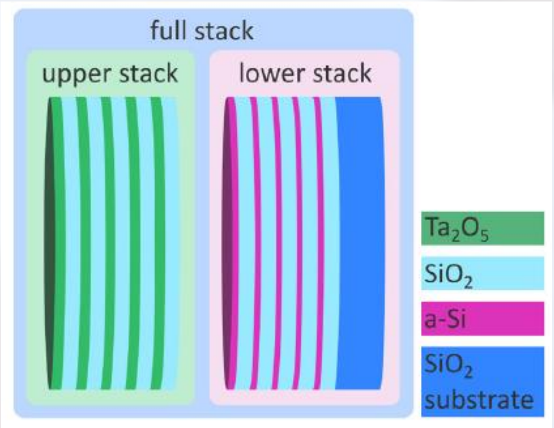
- Use of more than two materials in coating stack
- Allows trade-off between thermal noise and absorption
- Possible motivations:
  - Reduce coating thermal noise
  - Reduce coating absorption
  - Reduce coating thickness - directly reducing thermal noise, possible mitigation of possible defects during deposition, stress / annealing effects

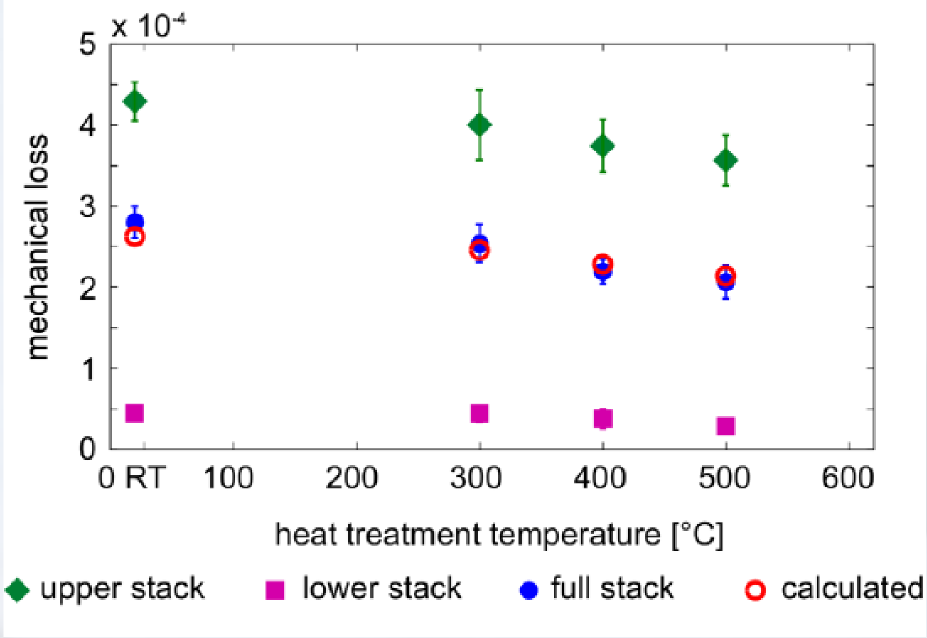
Thick coating with low index contrast

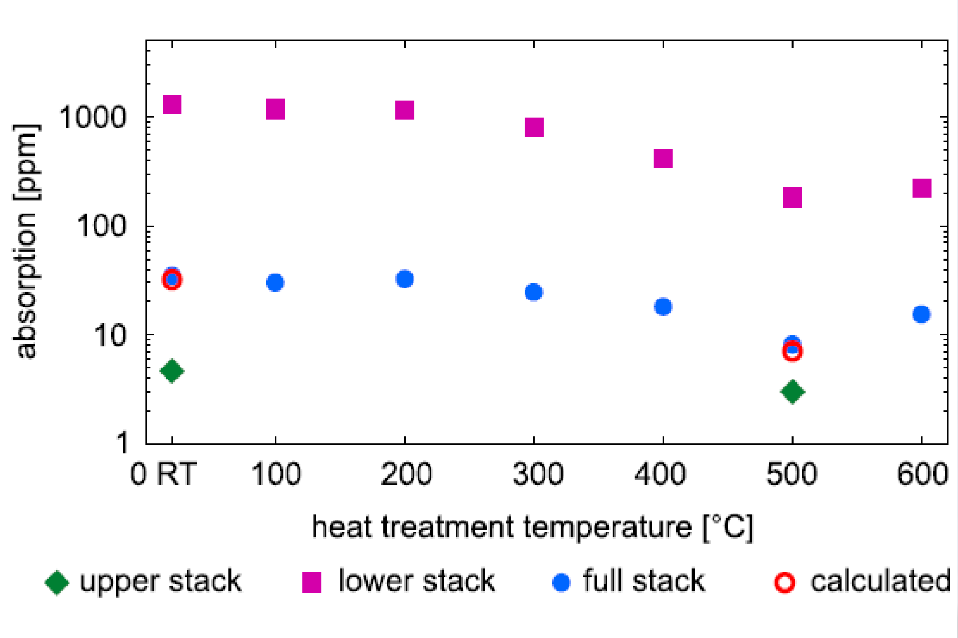
MM design to achieve same reflectivity with fewer layers

Multimaterial coatings

- Experimental demonstration of Ta_2O_5/SiO_2/a-Si/SiO_2 design
- Multimaterial loss and absorption behave as expected with annealing



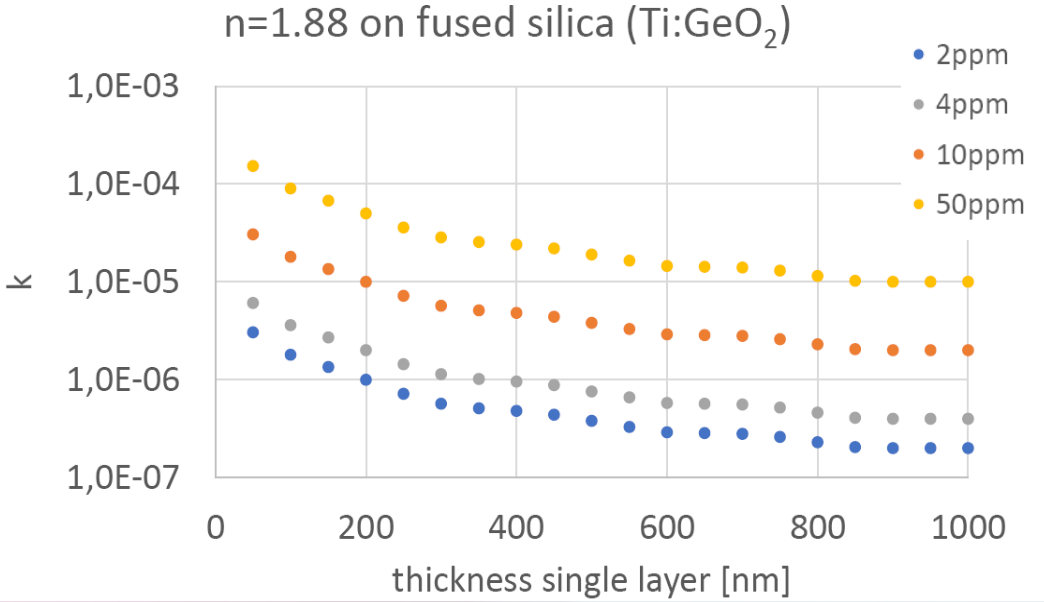


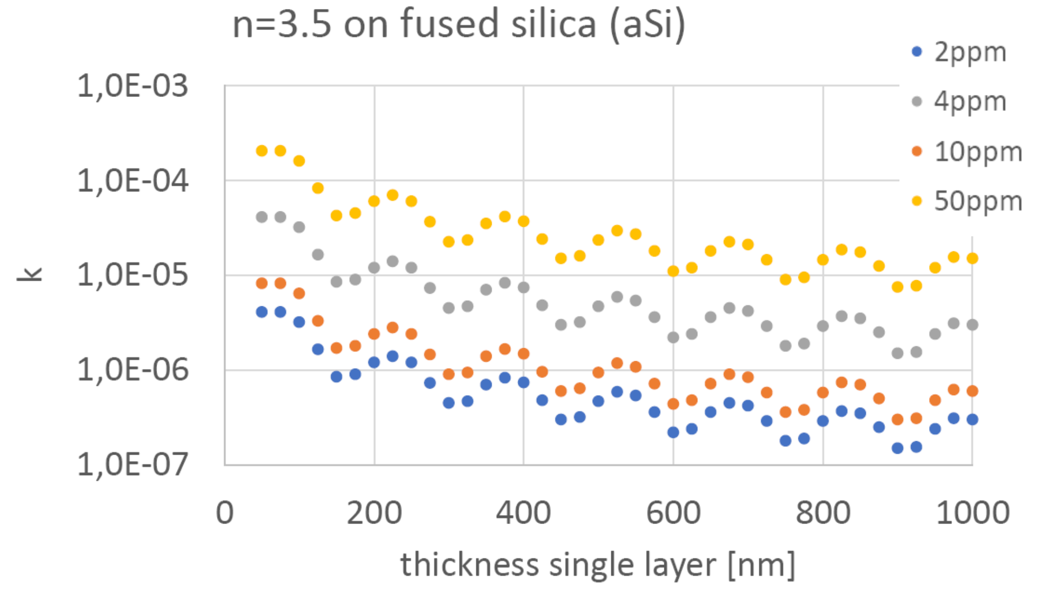


Tait et al., PRL 125 011102 (2020)

Multi-material designs to reduce coating absorption

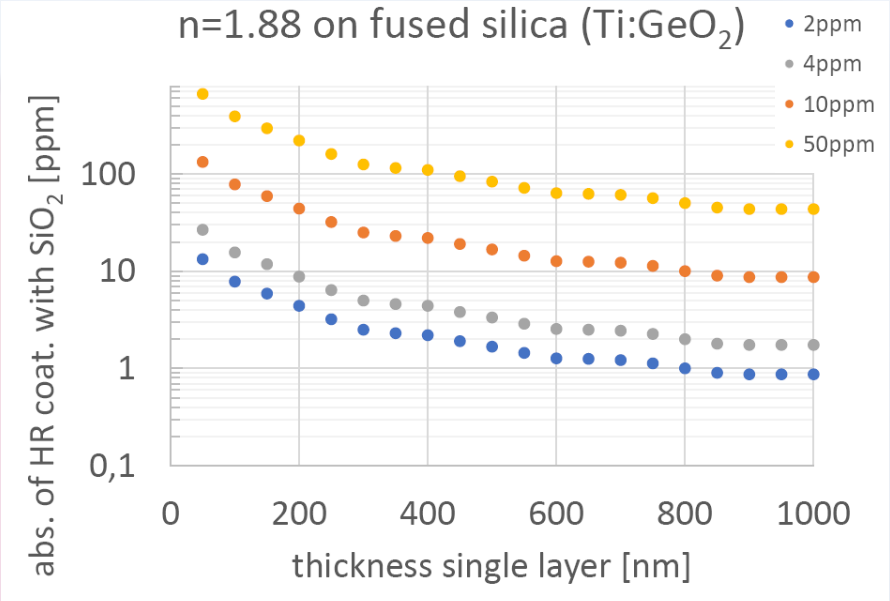
- Step 1: calculate *k*
- For measured absorption, convert to extinction coefficient *k* using thickness of measured layer
- *k* is independent of thickness and can easily be compared between different coatings
- Prominent oscillation in aSi case due to high index (maxima at minimum electric field intensity

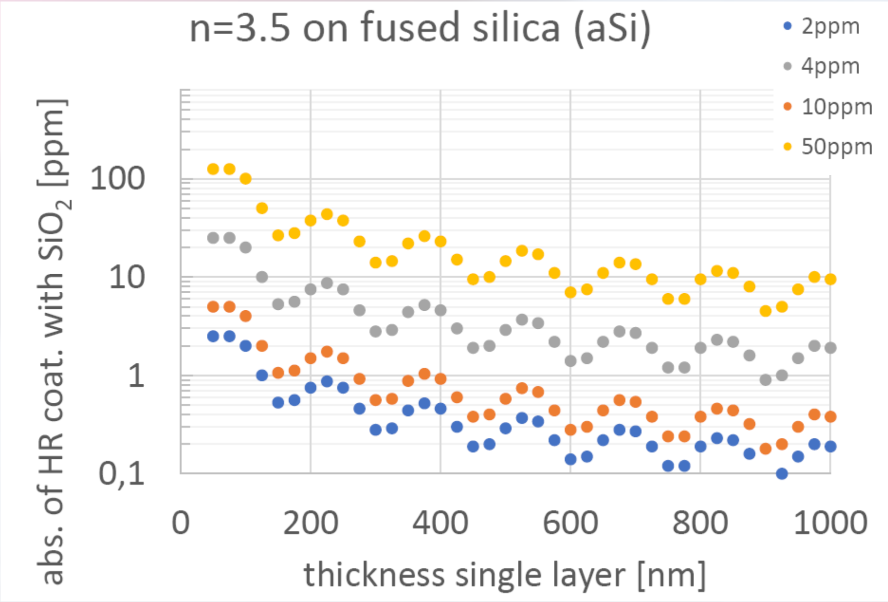




Multi-material designs to reduce coating absorption

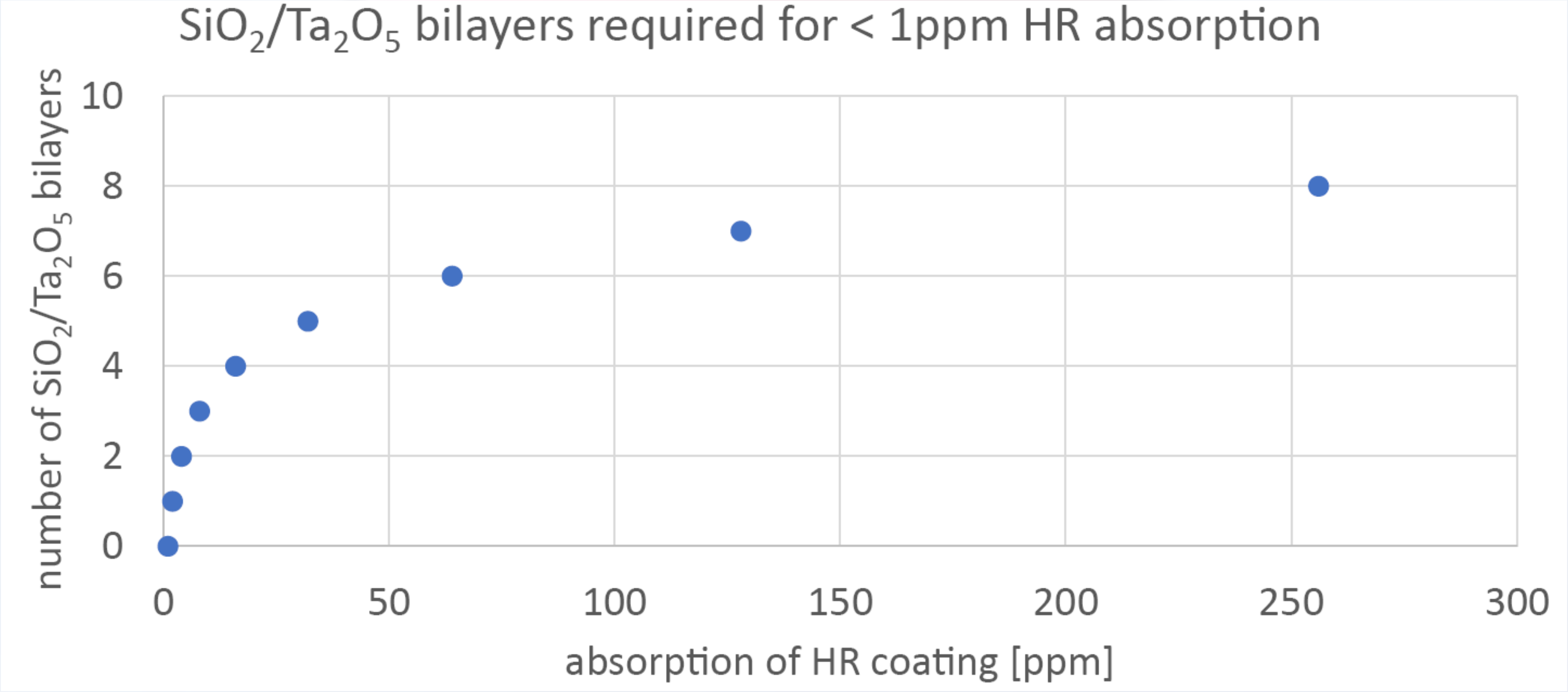
- Step 2: calculate absorption of an HR stack with your material and (e.g.) SiO_2





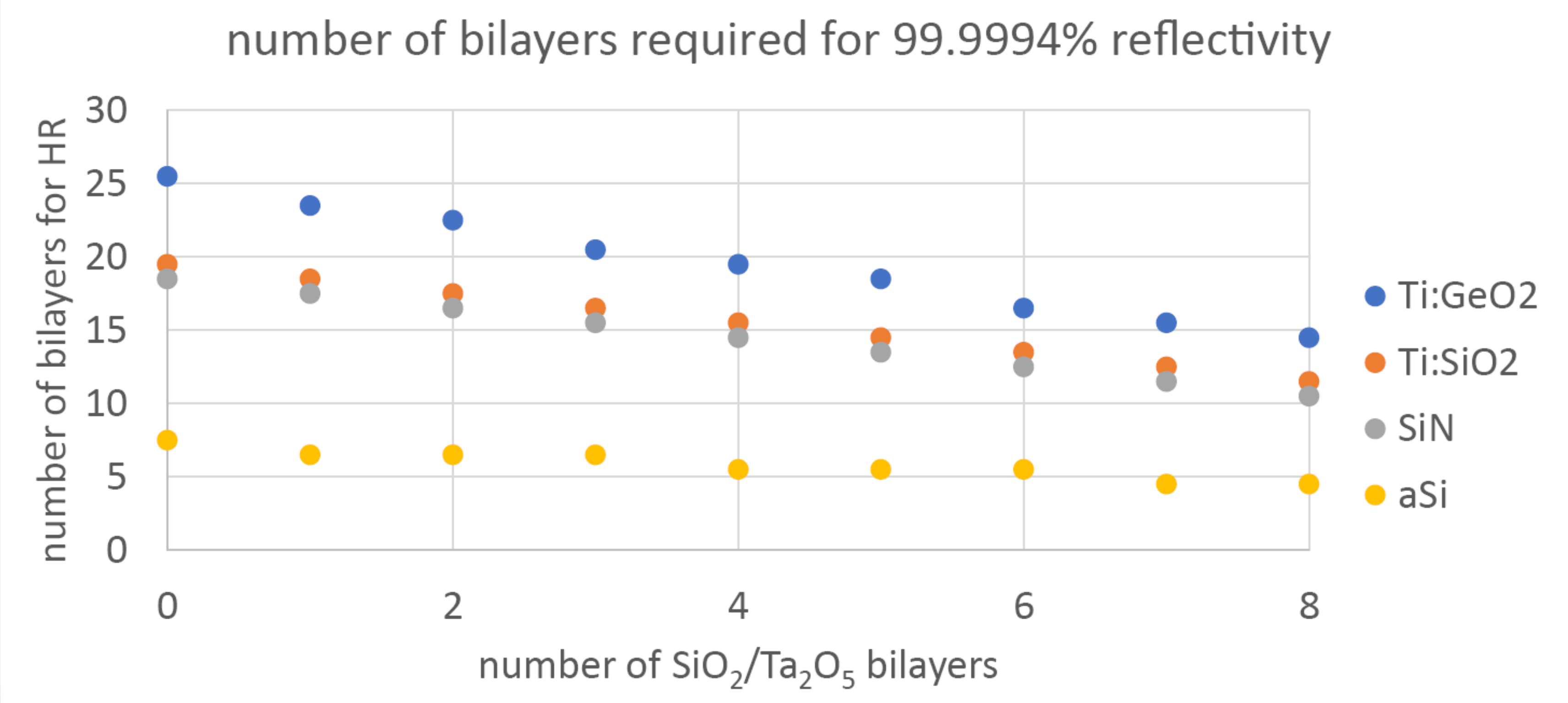
Multi-material designs to reduce coating absorption

- Step 3: based on your HR absorption, find how many top layers (here of SiO_2/Ta_2O_5) are required to reduce the lower stack absorption to <1ppm



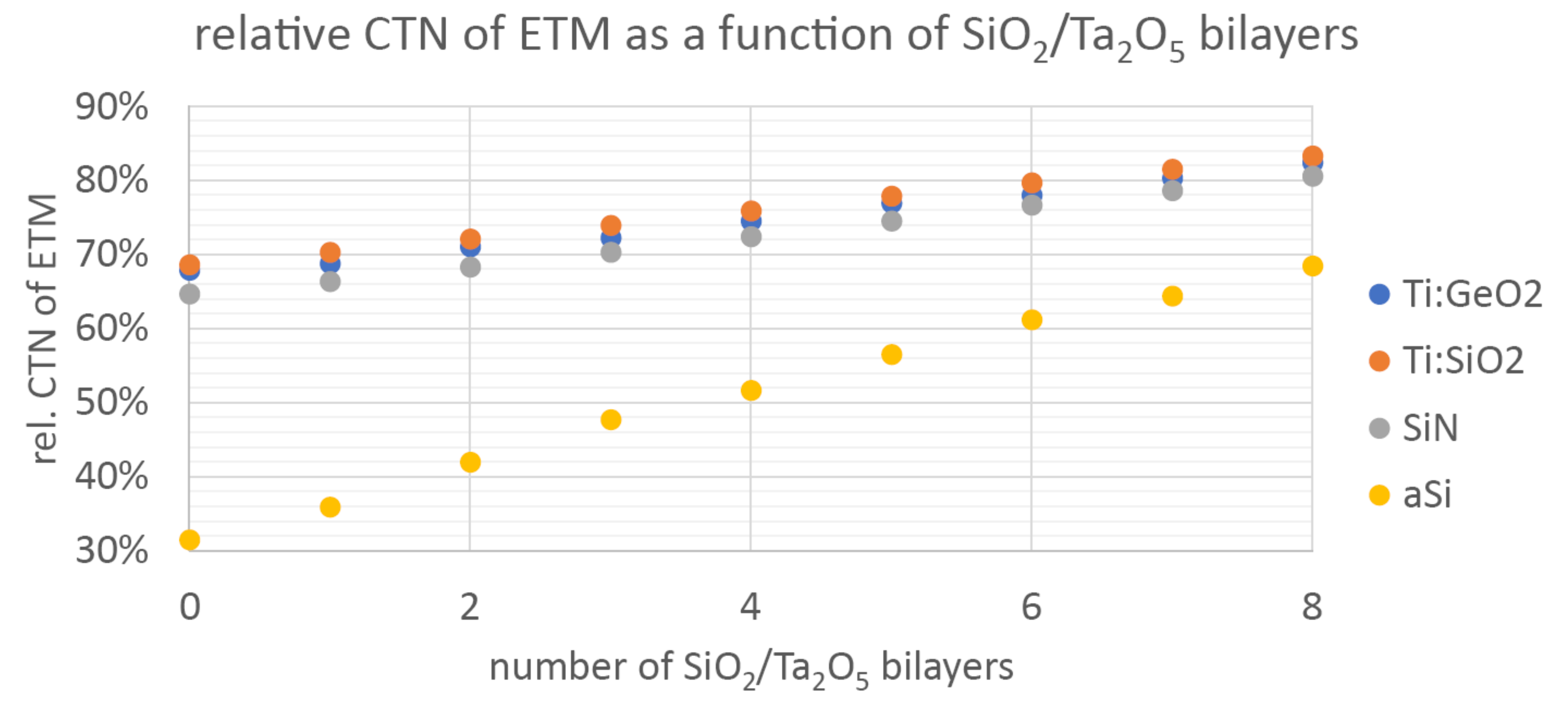
Multi-material designs to reduce coating absorption

- Step 4: based on your number of top layers, calculate how many lower layers to get the required absorption



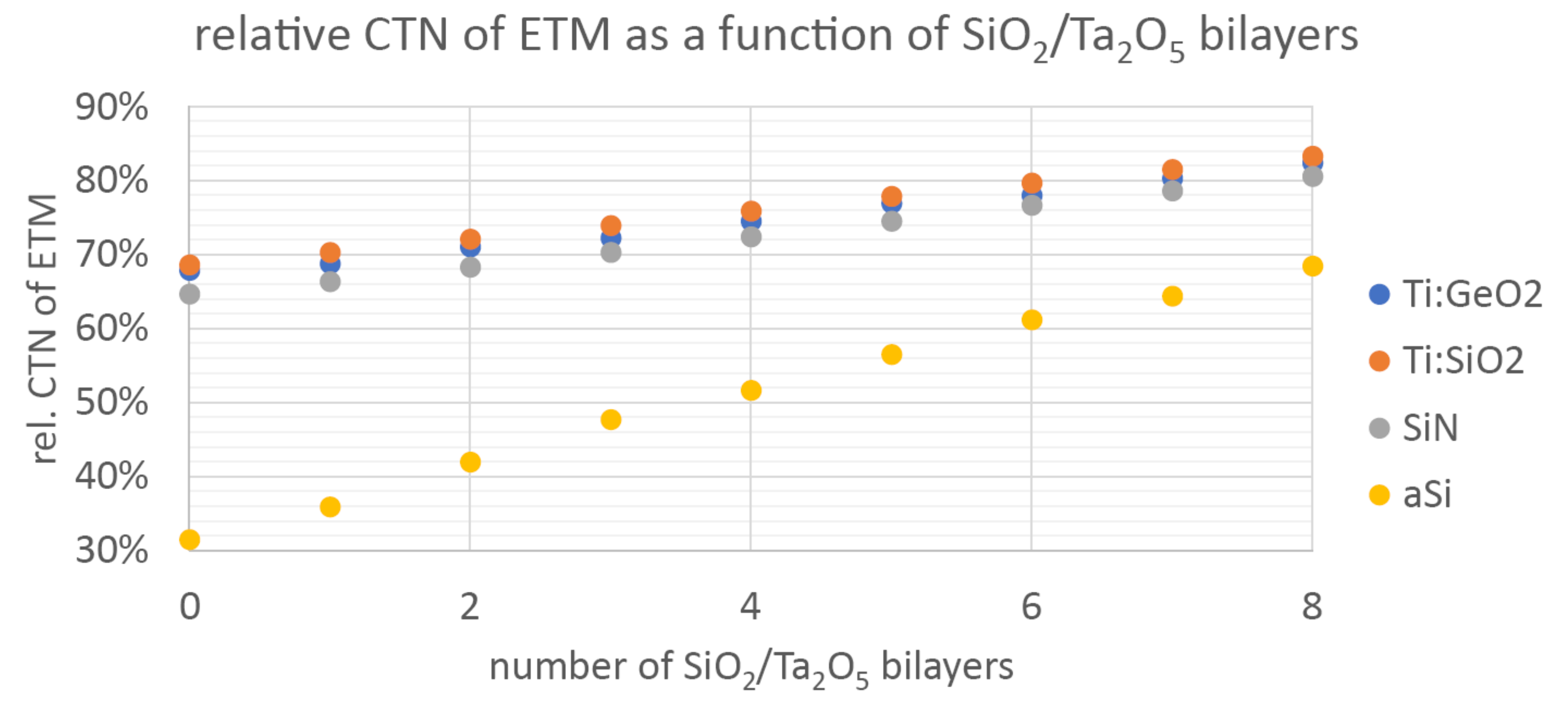
Multi-material designs to reduce coating absorption

- Step 5: calculate the thermal noise of your coating design



Implications for room temperature detectors

- Using $Ti:GeO_2$ /SiO_2 might reach ~67% of aLIGO CTN
- If we had an HR absorption of 2ppm, we could reduce this to <1ppm using 2 SiO_2/Ta_2O_5 bilayers, at the expense of increasing CTN to 72% of aLIGO
  - For ETM, could reduce CTN with aSi layers at bottom of stack



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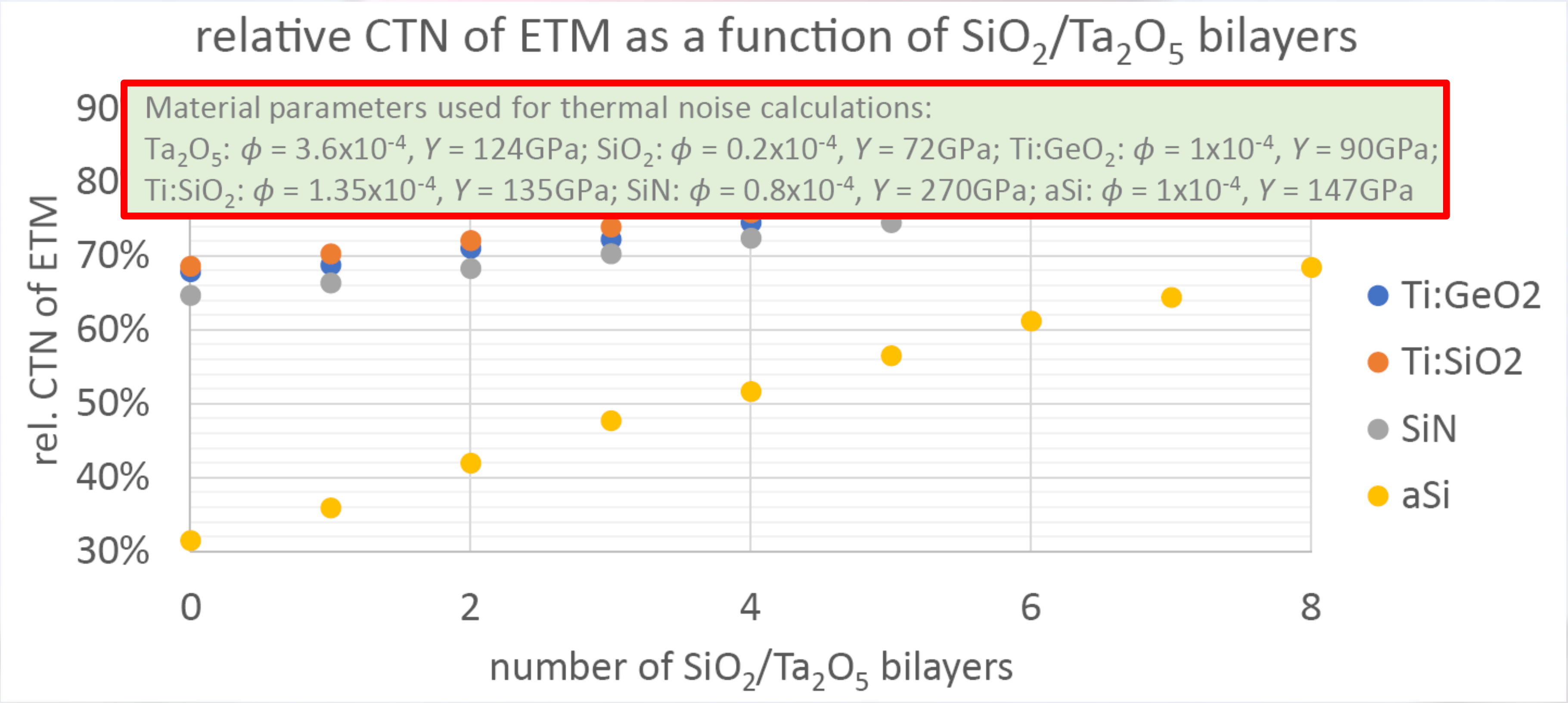


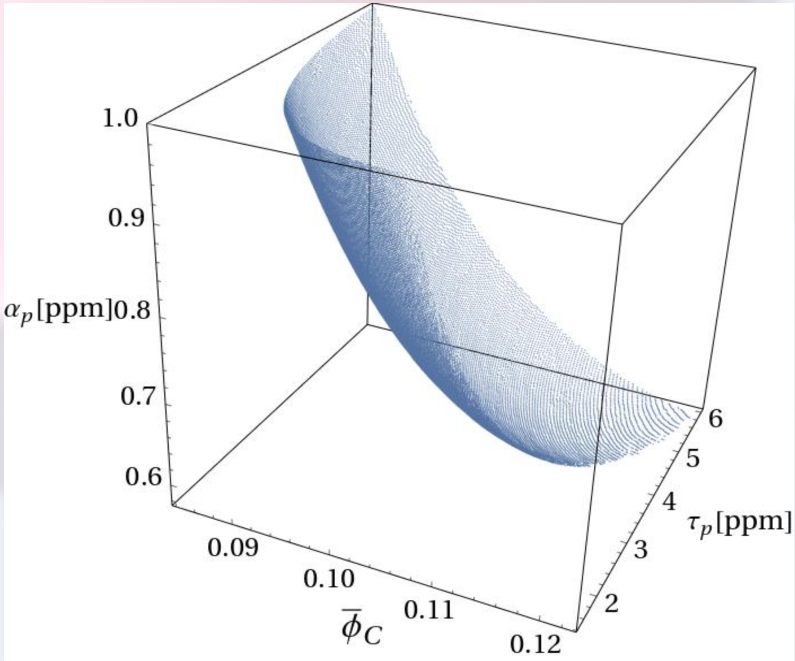
J. Yang, G Vajente et al. https://arxiv.org/abs/2102.08526

Ternary coating optimisation (I. M. Pinto, V. Pierro)

- Work on computational methods to optimise three-material (ternary) coating designs ongoing by Sannio group
- Recent work looking to exploit amorphous silicon and silicon nitride

aSi @ 20 K
cSi substrate

Pareto manifold

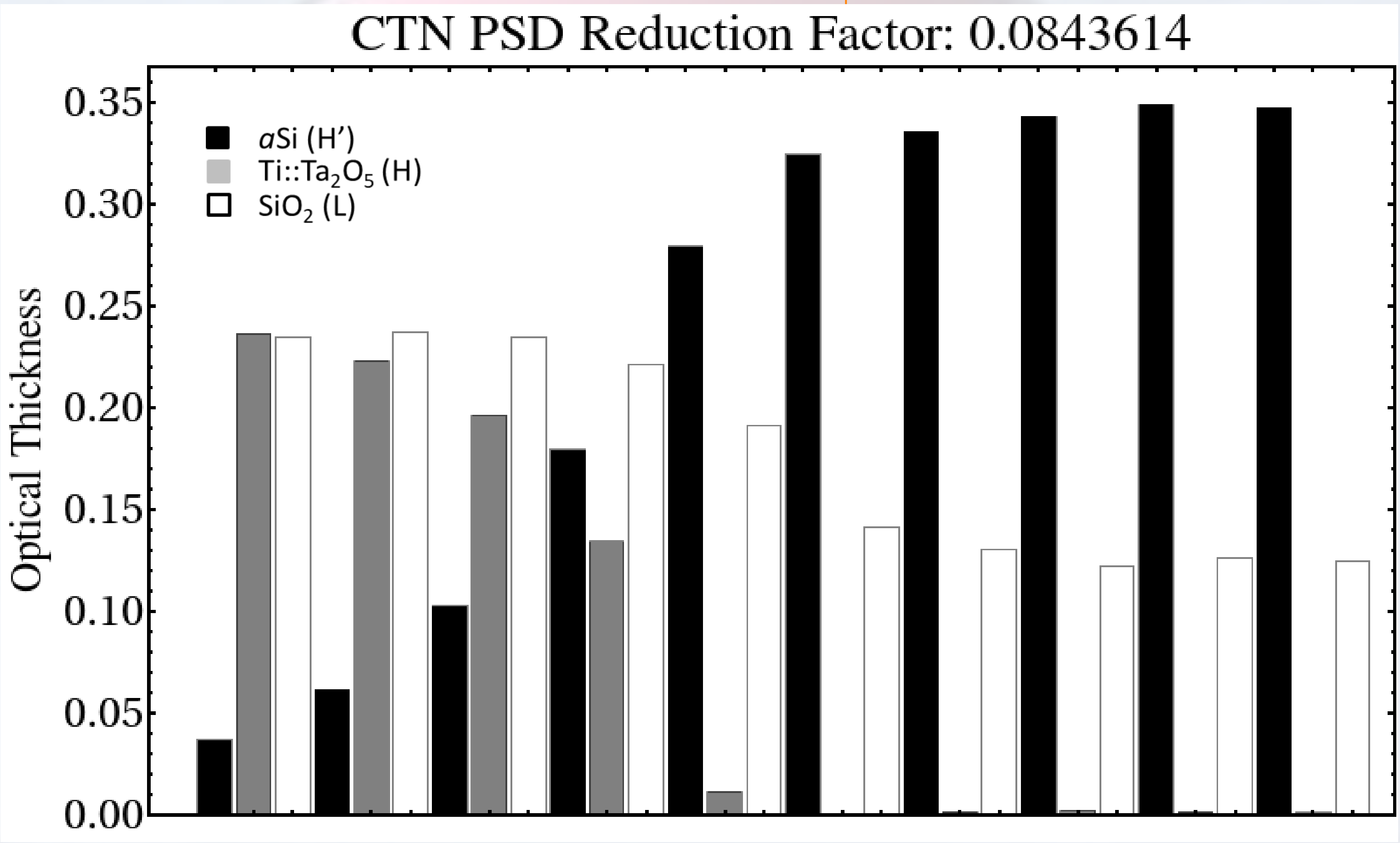


From LIGO-G2101040

See also Pierro et al., https://arxiv.org/abs/2012.02146 DCC: P2000519
Steinlechner and Martin, Phys. Rev. D 103 (2021)

Ternary coating optimisation (I. M. Pinto, V. Pierro)

- aSi @ 20 K, cSi substrate, optimized
- Optimised design of 5 tapered triplets [H‘, H, L] on top of 5 doublets [H‘, L]



Summary

- Use of multimaterial designs allows some optimisation of thermal noise / absorption / thickness
- Room temperature – possible application to candidate coatings for A+, V+, ET-HF, CE to reduce optical absorption / reduce coating thickness
- Cryogenic temperature – application in allowing the use of materials such as aSi and silicon nitride for thermal noise reduction
- Further optimised designs are possible - optimisation code developed by Pinto, Pierro et al.
- Poster with further details in the poster session on Thursday
- See also G Vajente talk on TiO_2:GeO_2 in this meeting