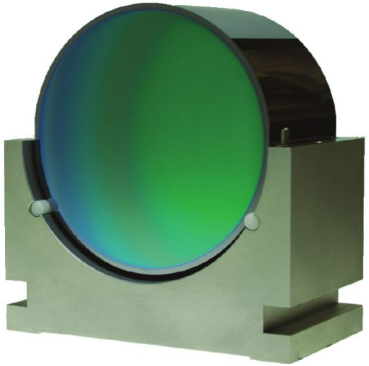
Coatings for the Einstein Telescope

J. Steinlechner

ET Symposium - 3 Dec 2020



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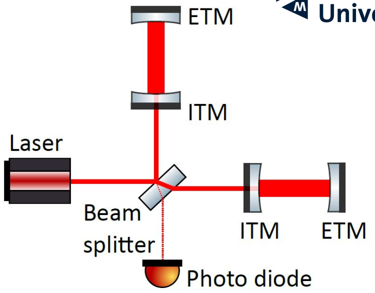
Coating Basics

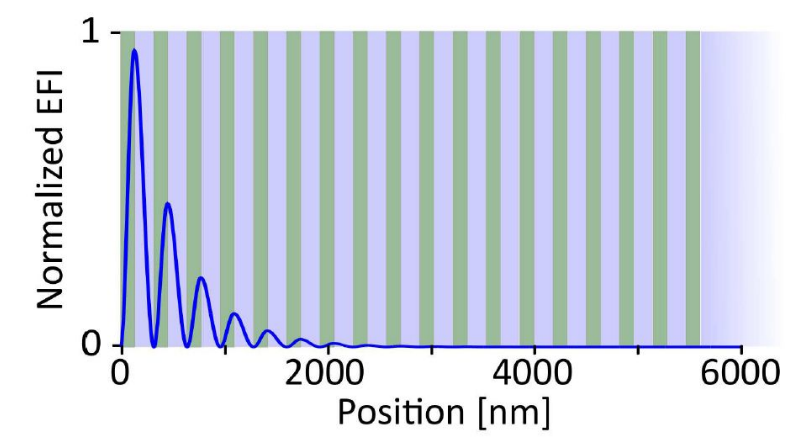


Highly-reflective coatings

- stack of many layers; usually two materials with different refractive index *n*
- optical layer thickness: quarter of a wavelength (= higher *n* → thinner layer)

Example: SiO_2 (blue, *n*=1.45) and Ta_2O_5 (green, *n*=2.05)

- ~38 layers needed for highly reflective ETMs of *R* = 99.9995%
- light intensity reduces with every layer pair
- ITMs, lower reflectivity → fewer layers (about half of ETM



Requirements:

- Low coating thermal noise (CTN):
  - limiting noise source → needs to get reduced
- Low optical absorption: few parts per million (10^{-6})
  - to avoid heating
  - to avoid thermal deformations
- Low scattering (from e.g. defects or micro crystals)
  - only purely amorphous or single-crystalline materials suitable

Coating thermal noise

- Coating thermal noise
    - frequency dependent
    - lower for larger beams
    - temperature dependent
    - determined by material properties (coating and substrate)

  → Cooling at low *f* where CTN is high!

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

mirror temperature (T)

mirror temperature (depends on reflectivity and refractive indices) (d)

beam radius (on mirror) (w)

coating mechanical loss (ϕ)

1. ET low-frequency (LF) detector
    a. low temperature (10K, 20K or 120K?))
    b. low laser power (to minimize heating from absorption)
    c. fused silica unsuitable at low temp. due to high thermal noise: change to crystalline silicon (or sapphire)
    d. silicon requires longer wavelength (1550nm or ~2000nm?)

2. ET high-frequency (HF) detector
    a. same substrate material, temperature and laser wavelength as LIGO and Virgo detectors
    b. can tolerate high laser power to reduce quantum noise

→ both LF and HF require new coating solutions!

ET HF (same wavelength, substrate material and temperature as LIGO and Virgo detectors)

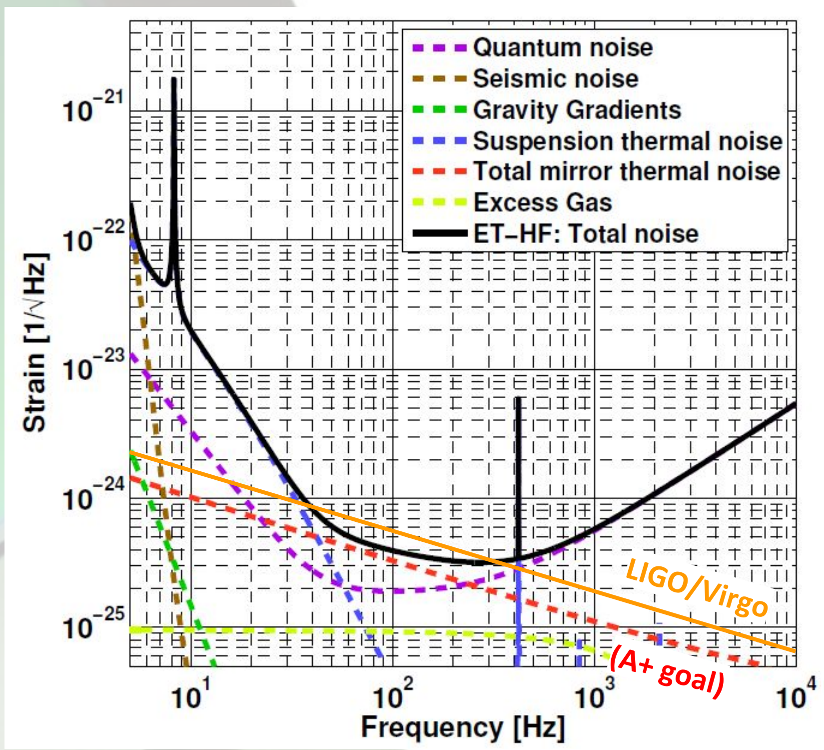
- Orange line: Using aLIGO/AdvVirgo coatings in ET-HF
  - Reduction from longer arms and larger beams
- Red dashed line: ET-HF design

- Planned A+ coatings will meet ET-HF design
  - Likely candidates to achieve this goal: TiO_2: GeO_2 or TiO_2:SiO_2 to replace TiO_2:Ta_2O_5 as high-n material, (currently ~20% above ET-HF goal)
  - Still to be confirmed: low absorption and mechanical loss of multilayers
- AdV+ looking into SiN as a high-n material
  - Similar mechanical loss to TiO_2: GeO_2, but thinner coatings from higher n → meets ET-HF goal
  - SiN R&D in Taiwan, Virgo groups working on absorption reduction of IBS SiN

- R&D and implementation for A+/AdvV+: Best test!

Remaining challenges: Upscaling coating diameter by almost a factor of two (bubble- and defect-free)

ET-HF design (2020 update)



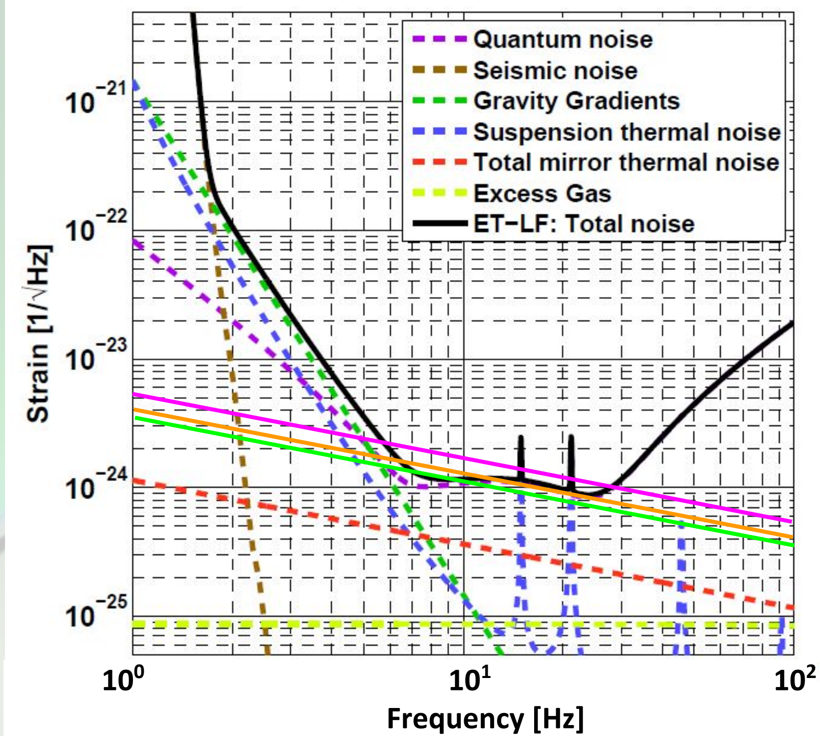
ET-LF (using 1550nm and 20K for calculations)

- Orange line: Current LIGO/Virgo coatings cooled: mechanical loss of SiO_2 and TiO_2:Ta_2O_5 increases → less improvement than expected from low temp. (note different x range)

- Pink line: (undoped) GeO_2 and SiO_2: increasing loss → CTN increase
- Green line: SiN and SiO_2
  - limited by SiO_2 loss

  → less CTN improvement than at room temp.

ET-LF design (2020 update)



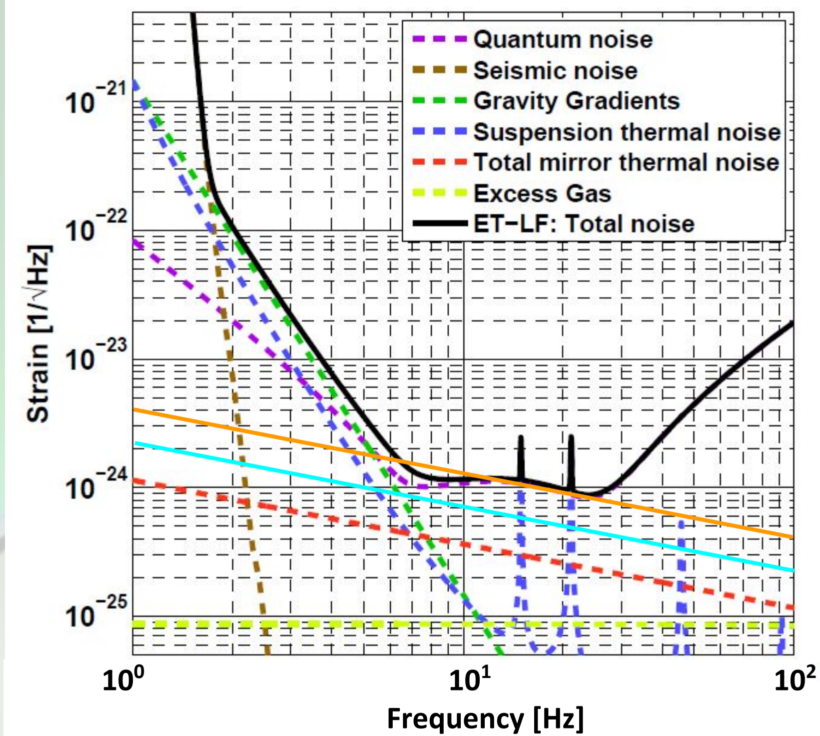
Low temperatures: We need a factor of two CTN reduction.
Different low-n material needed (or fewer SiO_2 layers)!

ET-LF (using 1550nm and 20K for calculations)

- Orange line: Current LIGO/Virgo coatings cooled (for comparison)

- Blue: SiO_2/aSi coatings - few layers due to high n of aSi
  ~8ppm coating absorption → too high + further R&D needed for reproducibility
  absorption lower at 2um (slight CTN increase from thicker layers)

ET-LF design (2020 update)



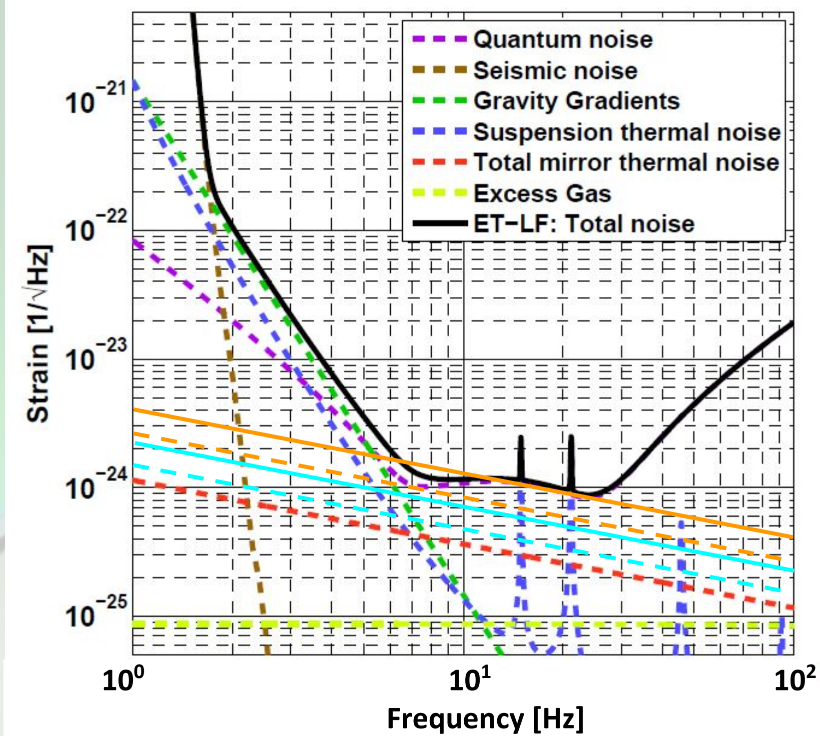
ET-LF (using 1550nm and 20K for calculations)

- Orange line: Current LIGO/Virgo coatings cooled (for comparison)
- Blue: SiO_2/aSi coatings - few layers due to high n of aSi
  ~8ppm coating absorption → too high + further R&D needed for reproducibility
  absorption lower at 2um (slight CTN increase from thicker layers)
- 10K: CTN reduces further, but we can tolerate even less absorption

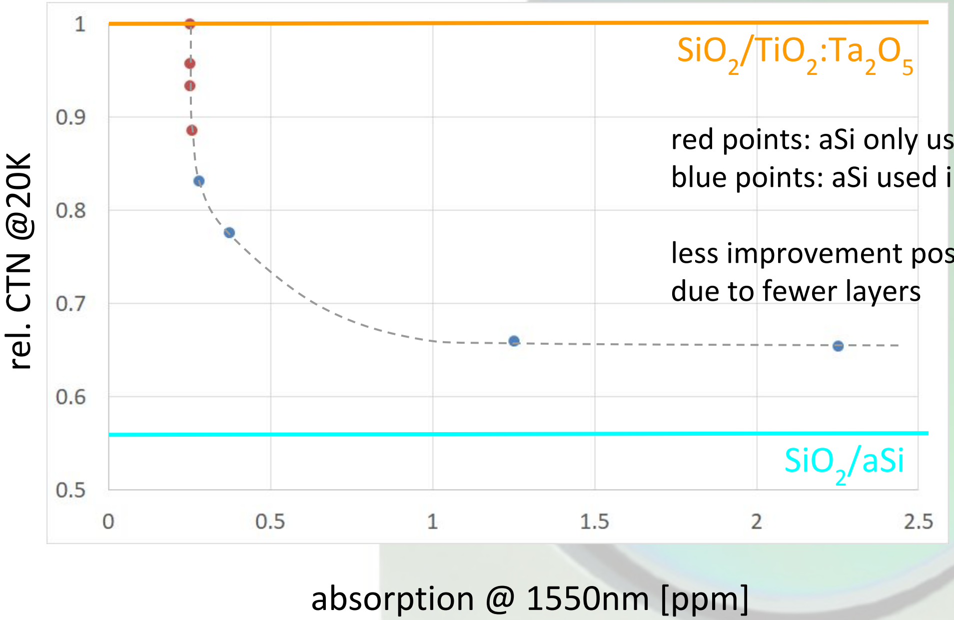
Other options:

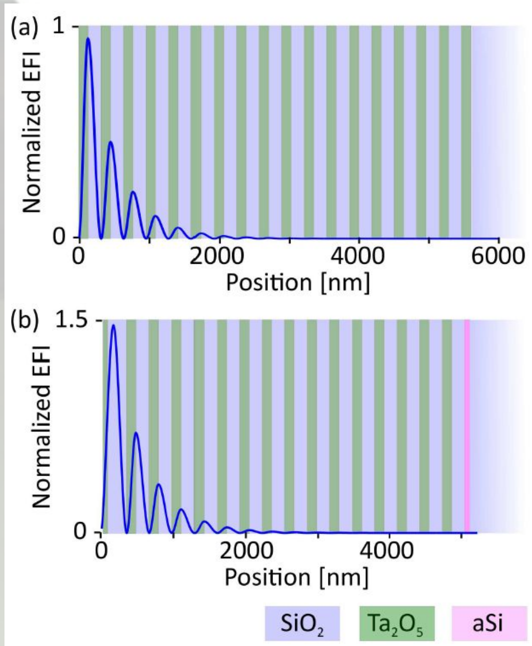
- Nanolayers: Can suppress cryogenic loss peaks (suppressing structural changes with annealing? Layers thinner than structural units responsible for loss?)
- Other materials: Structural predictions
- Multimaterial coatings

ET-LF design (2020 update)



Multimaterial Coatings - a trade-off of absorption and CTN



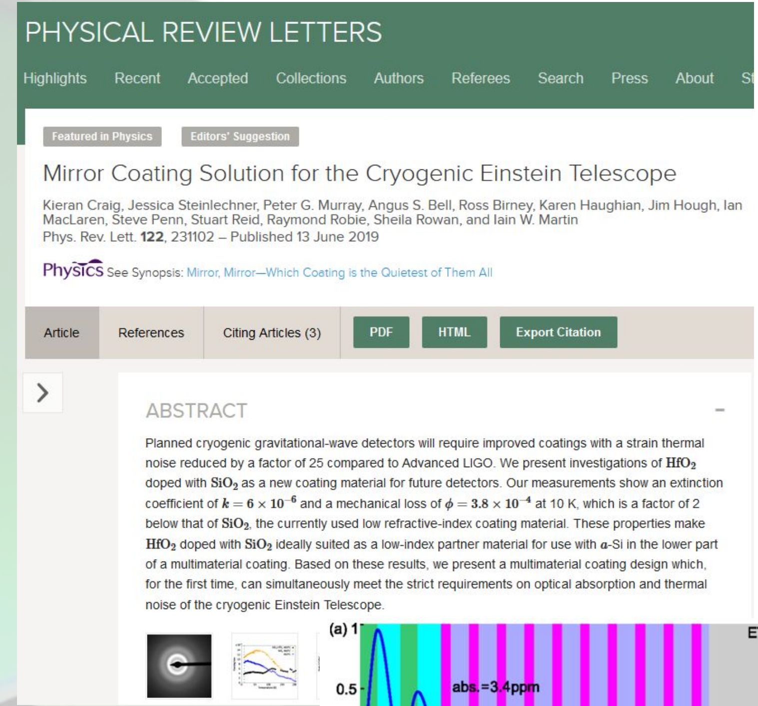


Due to high *n*, replacing one Ta_2O_5 layer by aSi, allows to remove additional SiO_2/Ta_2O_5 for *R* = const.

- Use some low-absorbing $SiO_2/TiO_2:Ta_2O_5$ at the top to reduce laser power, high-absorbing aSi only used further down
- each point represents one aSi layer added
- trade-off between CTN decrease and absorption increase

Coating Solution for ET-LF

You might have seen this picture in some talks this week...



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Mirror Coating Solution for the Cryogenic Einstein Telescope

Kieran Craig, Jessica Steinlechner, Peter G. Murray, Angus S. Bell, Ross Birney, Karen Haughian, Jim Hough, Ian MacLaren, Steve Penn, Stuart Reid, Raymond Robie, Sheila Rowan, and Iain W. Martin

Phys. Rev. Lett. **122**, 231102 – Published 13 June 2019

Physics See Synopsis: Mirror, Mirror—Which Coating is the Quietest of Them All

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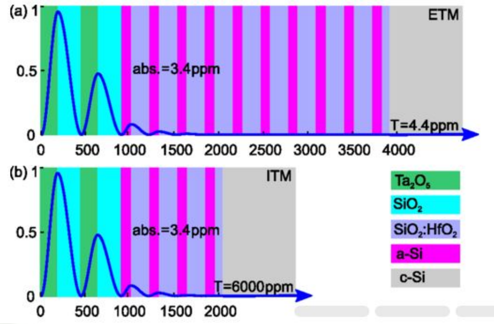
ABSTRACT

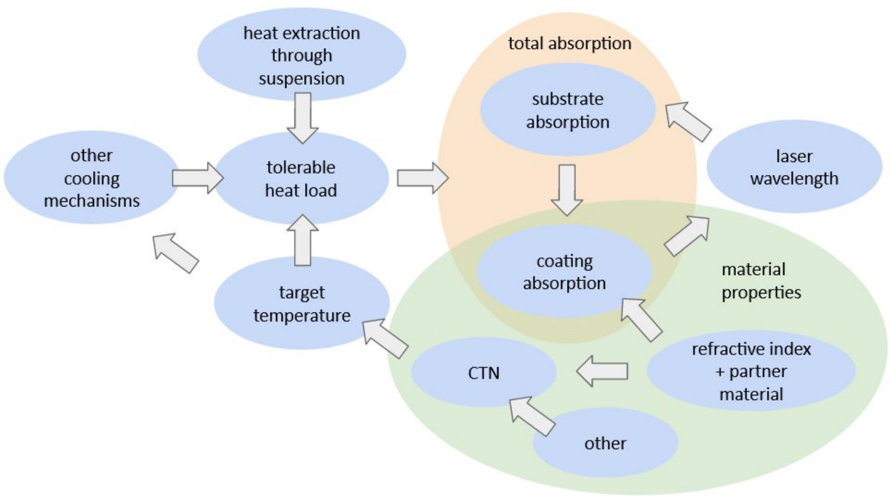
Planned cryogenic gravitational-wave detectors will require improved coatings with a strain thermal noise reduced by a factor of 25 compared to Advanced LIGO. We present investigations of HfO_2 doped with SiO_2 as a new coating material for future detectors. Our measurements show an extinction coefficient of $k = 6 \times 10^{-6}$ and a mechanical loss of $\phi = 3.8 \times 10^{-4}$ at 10 K, which is a factor of 2 below that of SiO_2, the currently used low refractive-index coating material. These properties make HfO_2 doped with SiO_2 ideally suited as a low-index partner material for use with a-Si in the lower part of a multimaterial coating. Based on these results, we present a multimaterial coating design which, for the first time, can simultaneously meet the strict requirements on optical absorption and thermal noise of the cryogenic Einstein Telescope.

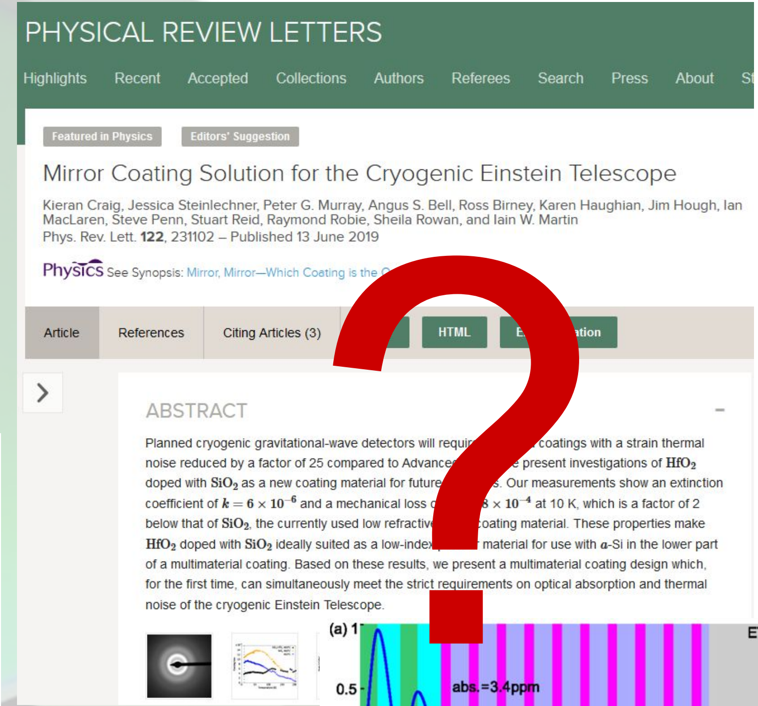


Coating Solution for ET-LF?

- meets CTN design of ET-LF at 10K
- uses 2 x $SiO_2/TiO_2:Ta_2O_5$ on top of aSi and $SiO_2:HfO_2$
- absorption = 3.4 ppm per mirror
  - < 5ppm: target in initial (2011) ET design study
  - more recently: absorption ideally lower

- but how low?

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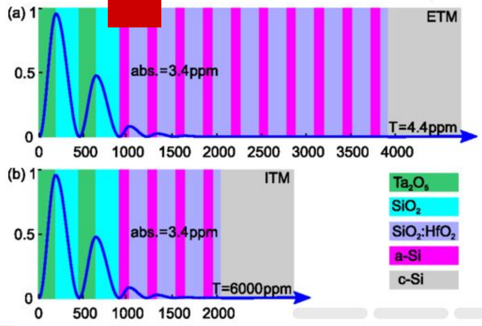
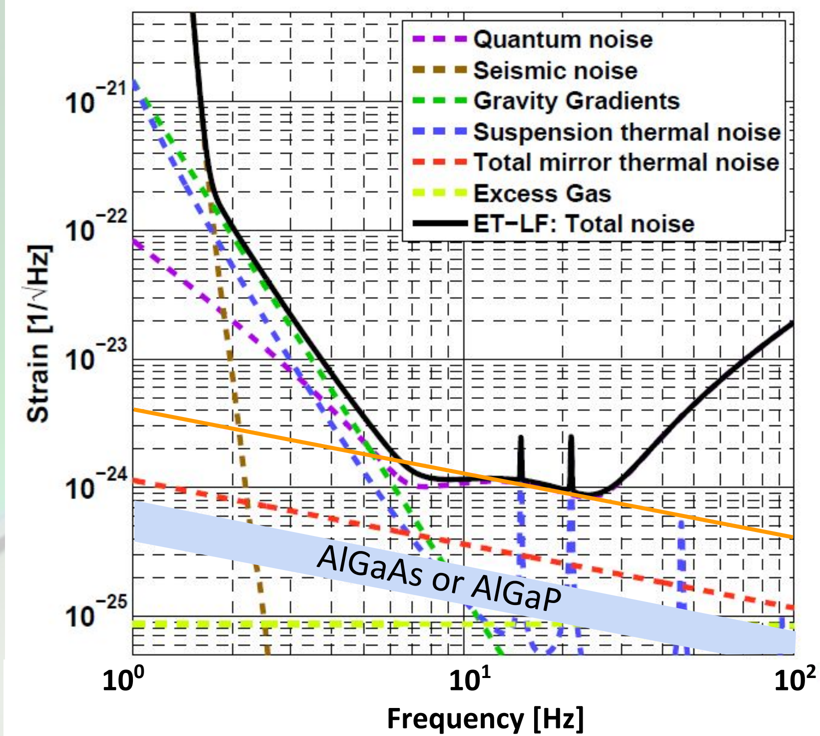


Crystalline Coatings an alternative concept

- Orange line: Current LIGO/Virgo coatings cooled (for comparison)
- Blue area: Crystalline coatings show low CTN
  - upper boundary: AlGaP/GaP
    → can be grown directly on silicon
    (matching lattice structure required for growth),
    absorption needs reduced
  - lower boundary GaAs/AlGaAs
    → low absorption,
    needs to be grown on GaAs wafers: too small

- Crystalline coatings: Promising
  - variety of materials can be grown on silicon
    (or also on other materials + transfer)
  - Within ETPF: J.P. Locquet, Uni Leuven

ET-LF design (2020 update)



Other ideas: amorphous and crystalline hybrids
- Hamburg: amorphous coatings with crystalline toplayer

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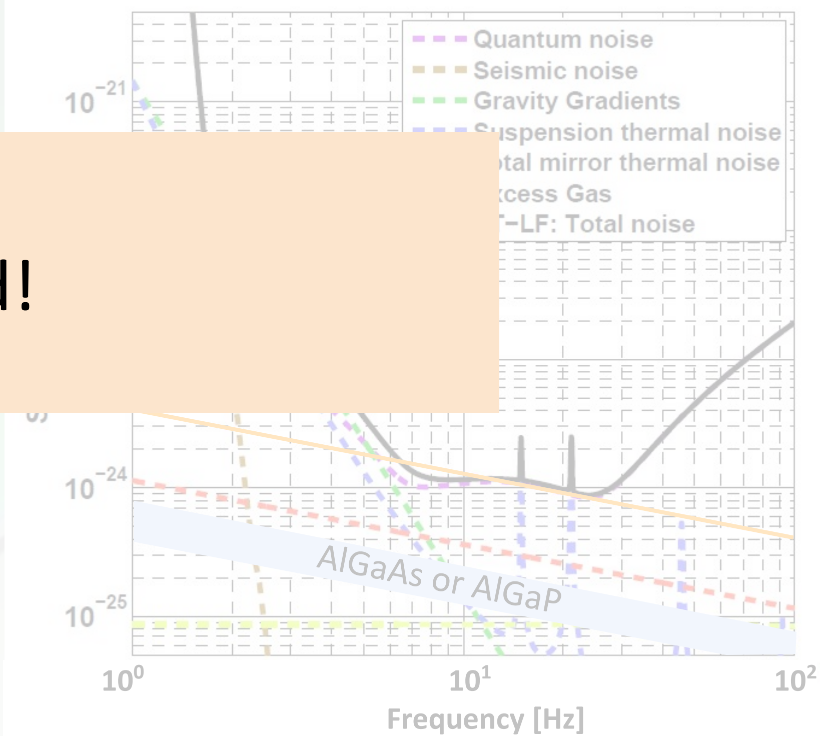

The End!

- Crystalline coatings: Promising
  - variety of materials can be grown on silicon (or also on other materials + transfer)
  - Within ETPF: J.P. Loquet, Uni Leuwen

Other ideas: amorphous and crystalline hybrids
- Hamburg: amorphous coatings with crystalline top layer
- Glasgow: SiO_2 implantation into silicon substrate