Journée de rencontre des jeunes chercheurs

26/11/19

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Introduction

- Thesis title: AlGaAs crystalline mirrors for the space-time metrology and their application to gravitational wave detectors

- Idea : Searching for methods to reduce thermal noises on the mirrors of Virgo

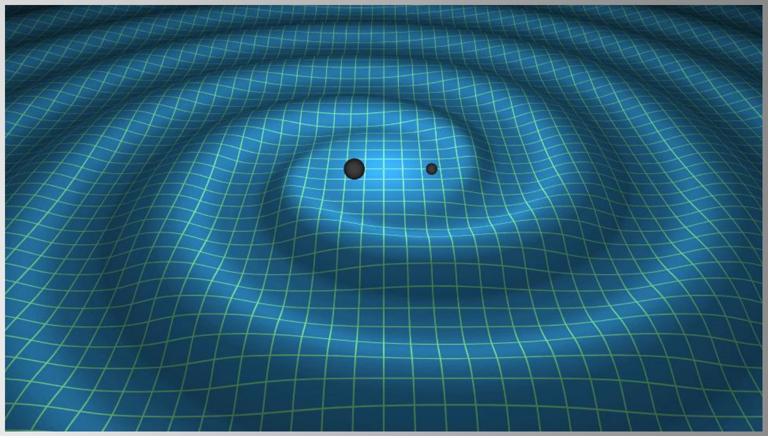
- A good solution to reduce thermal noises : Crystalline coatings

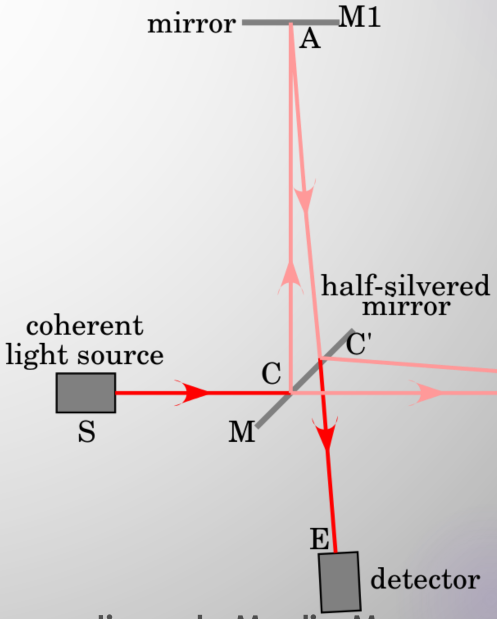
Outline

- Introduction
- The interferometer Virgo
- Thermal noises
- Thermal noise models
  - Thermal noise model for small beams
  - Thermal noise model for Higher Order Modes
- Development of crystalline coatings

Introduction

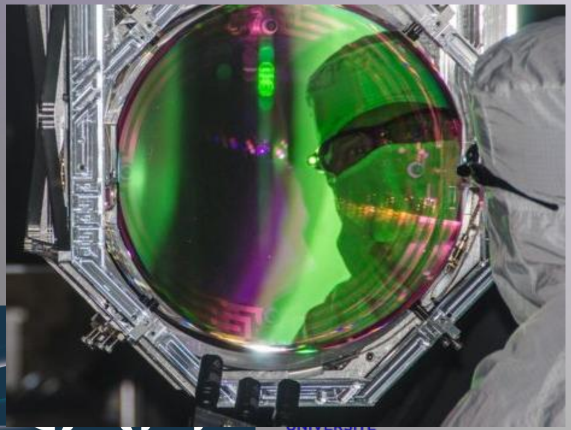
- VIRGO interferometer: Detection of Gravitationnal Waves

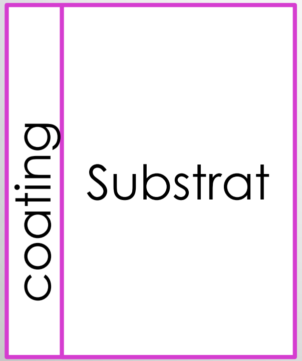


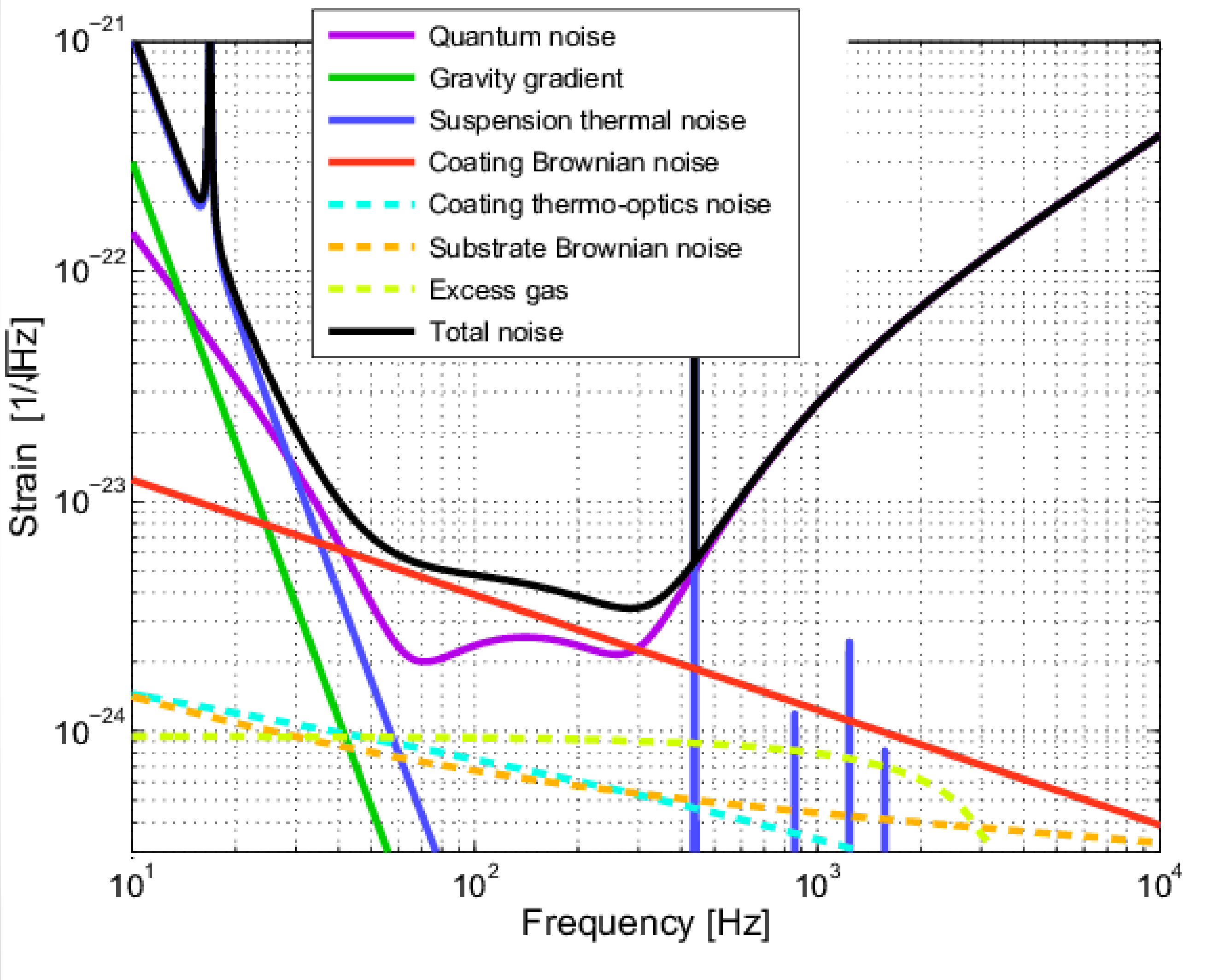


Motivation

- One of the main limitation of the sensitivity is the thermal noises on the mirrors of the interferometer
- Two main thermal noises in the coating:
  - Brownian noise
  - Thermo-optic noise







Brownian noise

- Caused by Brownian motion of mirror surface
- Largest contribution to the overall detector noise by the optics

$$S_x(f,T) \approx \frac{2k_B T}{\pi^2 f}\frac{d}{{r_0}^2 Y}\phi\left(\frac{Y'}{Y}+\frac{Y}{Y'}\right)$$

Temperature

Coating thickness

Substrate Young Modulus

frequency

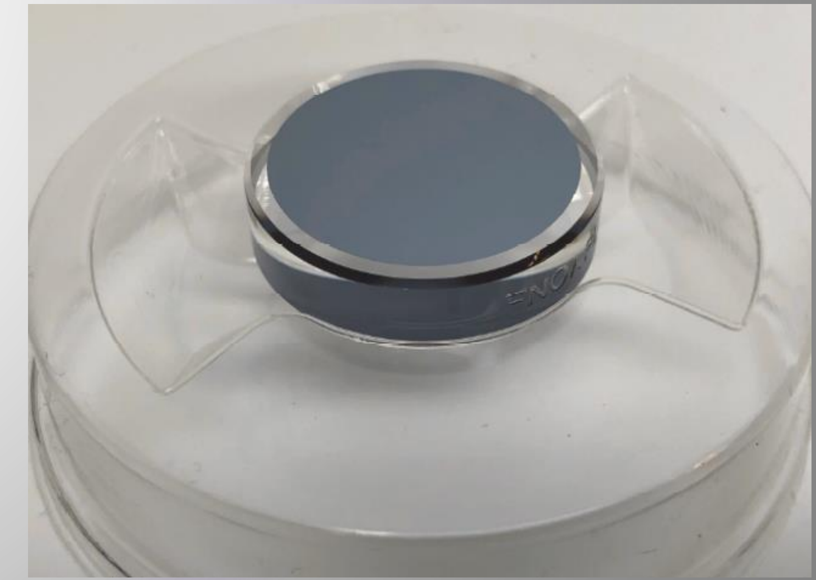
Laser beam radius

Coating mechnical loss

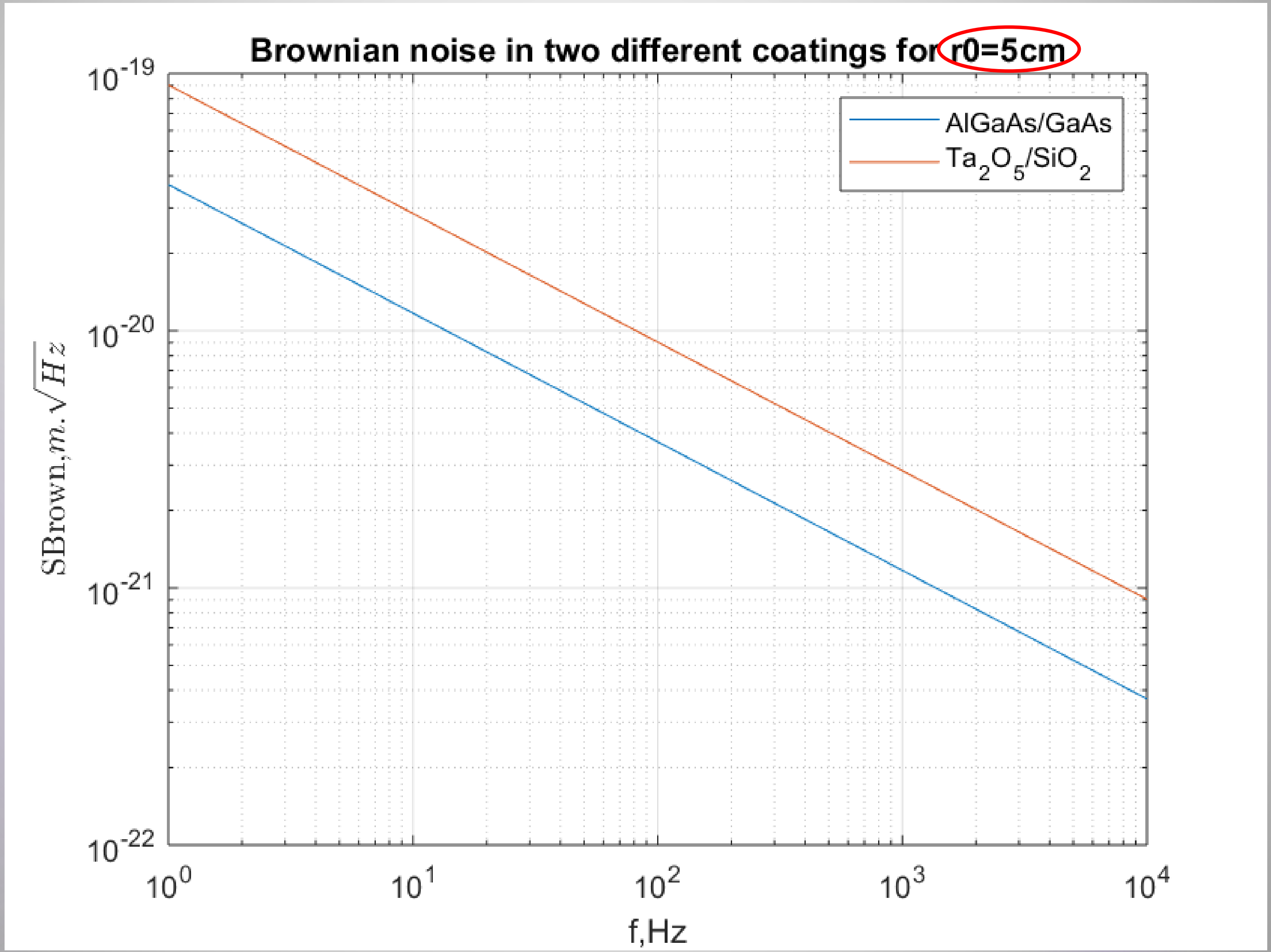
Coating Young Modulus

Reduction of thermal noise

- Coatings used for now : amorphous coatings
  - Ta_2O_5/SiO_2
  - Made at LMA (Laboratoire des Matériaux Avancés)
- How to reduce thermal noise?
  - Operating the interferometer at cryogenic temperature
  - Manufacturing new coatings
- Reduction of thermal noise with crystalline coatings (G. Cole et al. 2013)
  - Better mechanical properties



Brownian noise



Thermo-optic noise

- Two noises that compose coating thermo-optic noise : Thermoelastic noise and Thermorefractive noise

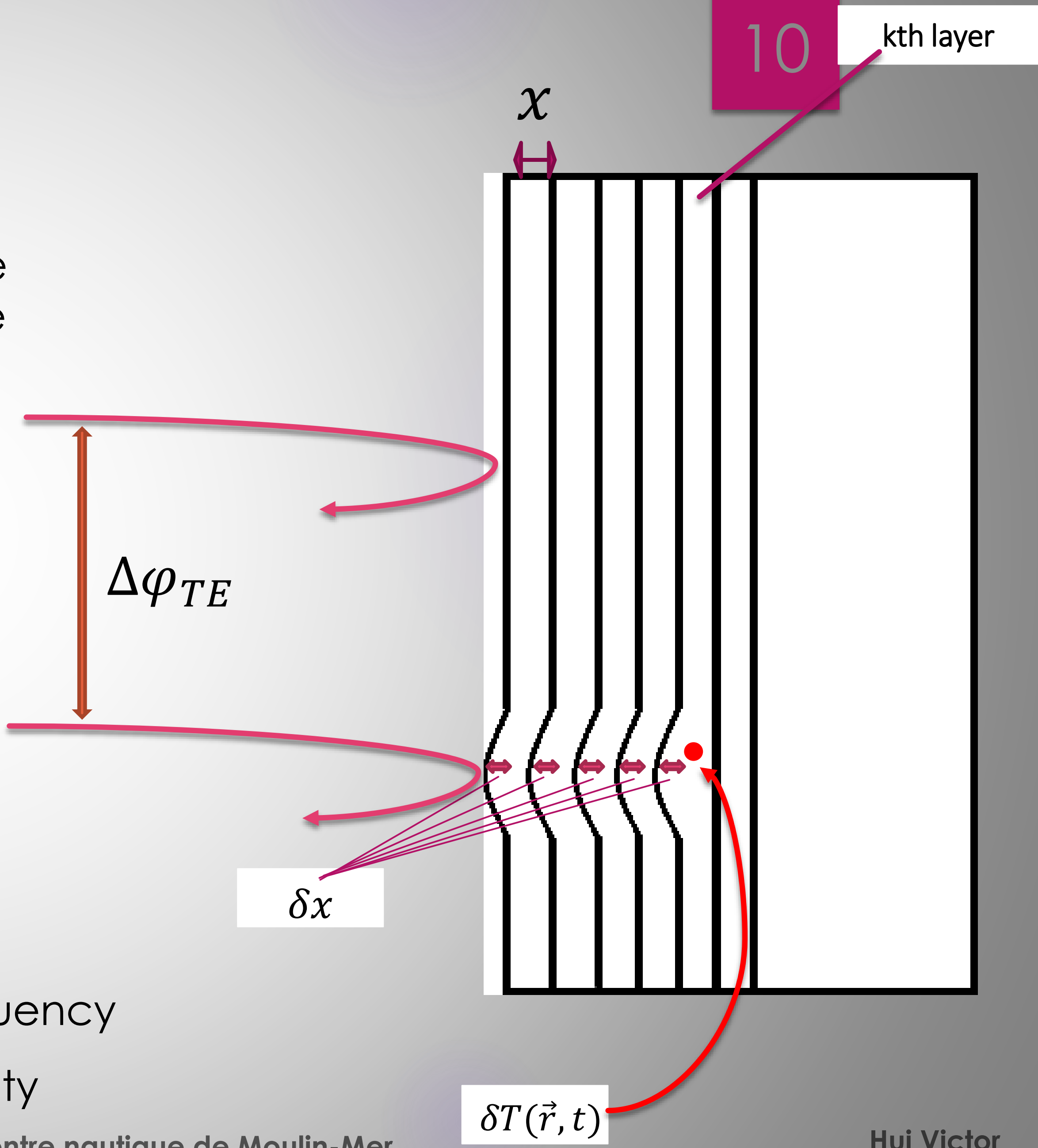
- Induced by the fluctuations of the temperature in the coating

Thermoelastic noise

Thermoelastic noise is the apparent expansion of the mirror coating into the probe beam causing change in phase

$$\Delta\varphi_{TE} = \frac{4\pi}{\lambda}\alpha_c x \delta T$$

α_c : coating coefficient of thermal expansion



Coating thickness

$$S_{TE}(\omega, T) \approx \frac{2\sqrt{2}k_B T^2}{\pi {r_0}^2\sqrt{\kappa_S C_S \omega}}(\alpha_c d)^2$$

Angular frequency

Substrate thermal conductivity

Substrate heat capacity

Thermorefractive noise

Thermorefractive noise comes from both the physical change in size of coating layers and the change in refractive index with temperature in the coating

$$\Delta\varphi_{TR} = \frac{4\pi}{\lambda}\beta\lambda\delta T$$

β: coefficient of thermorefraction ($\beta = \frac{dn}{dT}$)

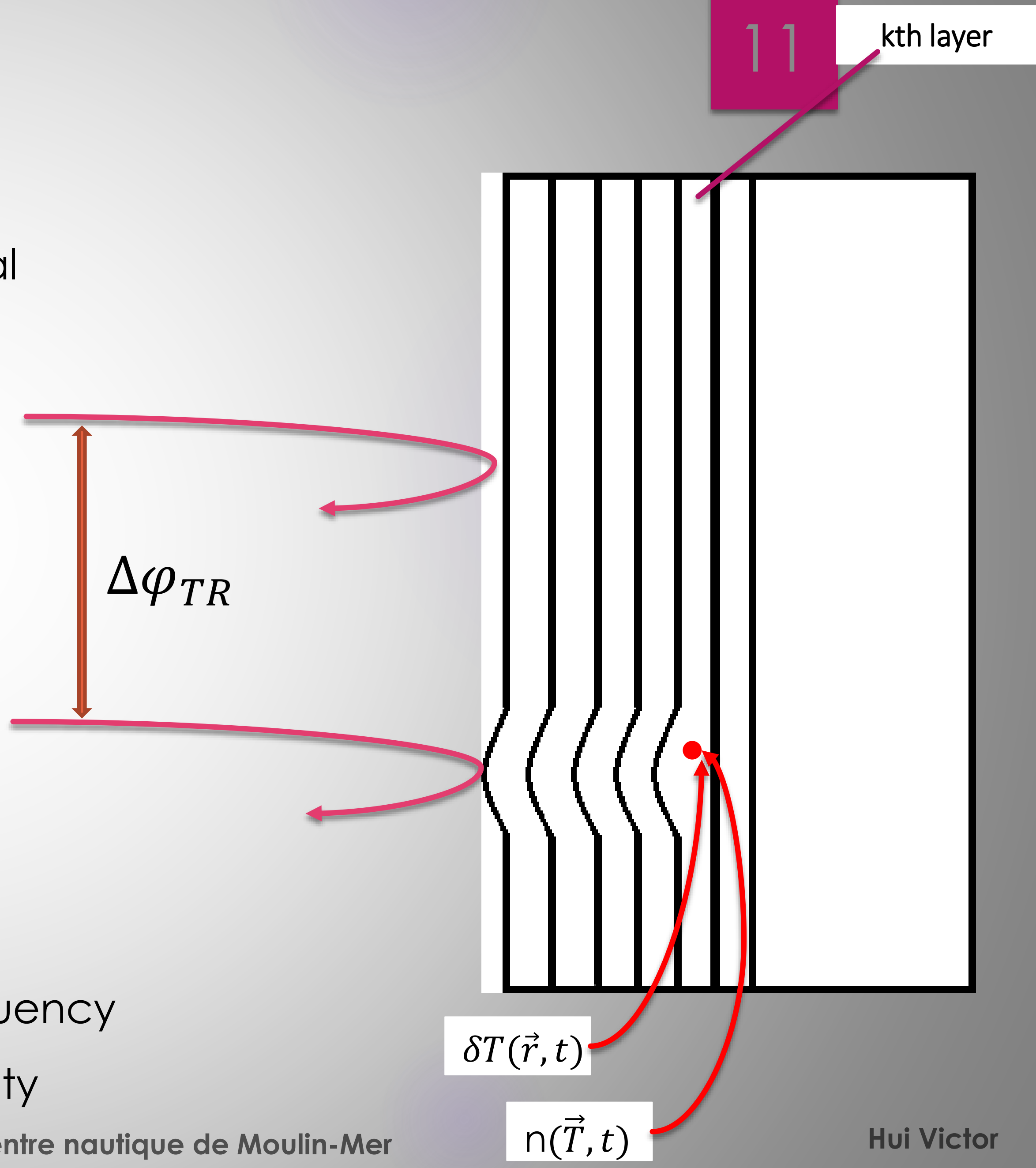
λ : wavelength of the laser

$$S_{TR}(\omega, T) \approx \frac{2\sqrt{2}k_B T^2}{\pi {r_0}^2\sqrt{\kappa_S C_S \omega}}(\beta\lambda)^2$$

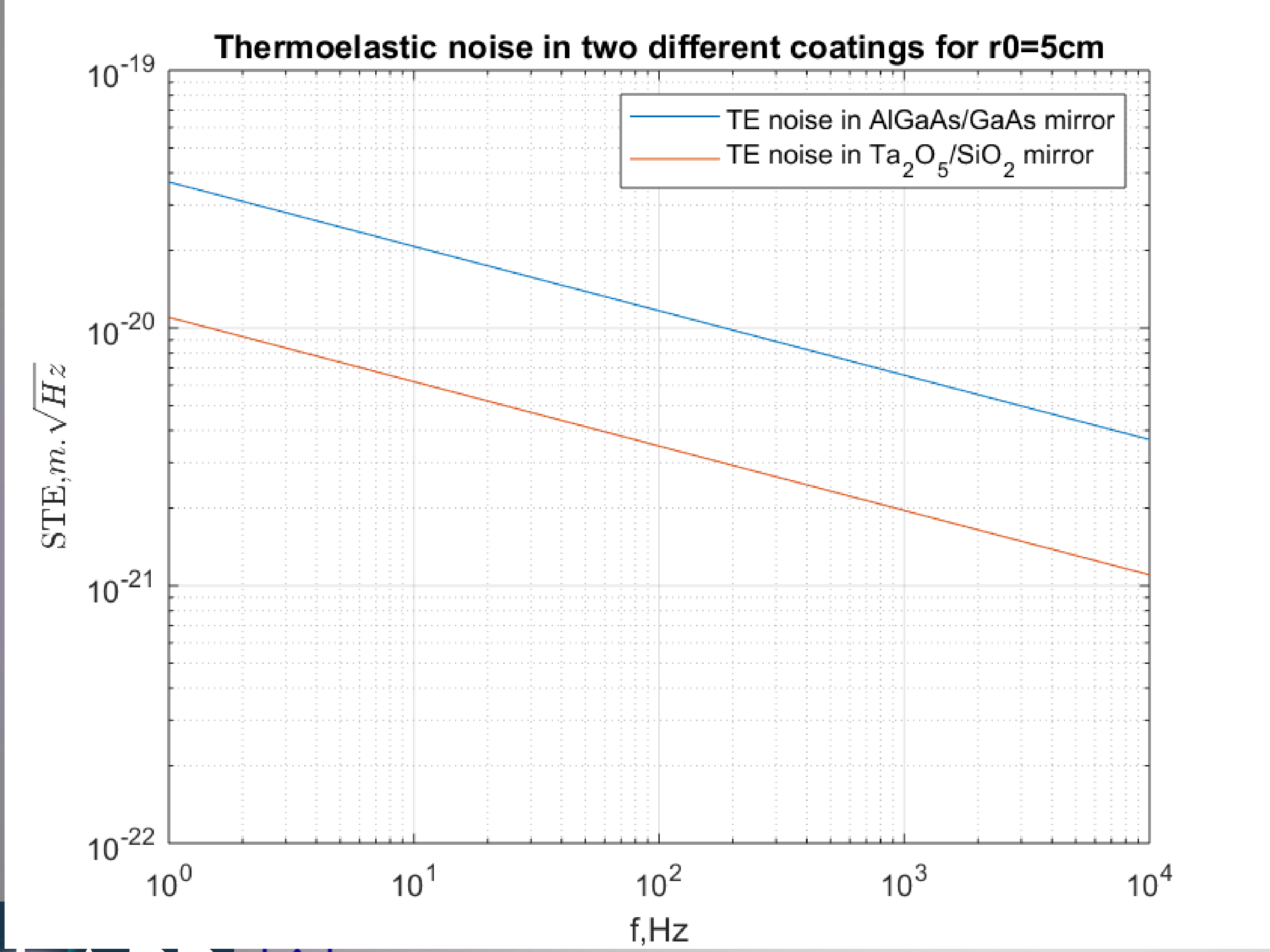
Substrate thermal conductivity

Substrate heat capacity

Angular frequency

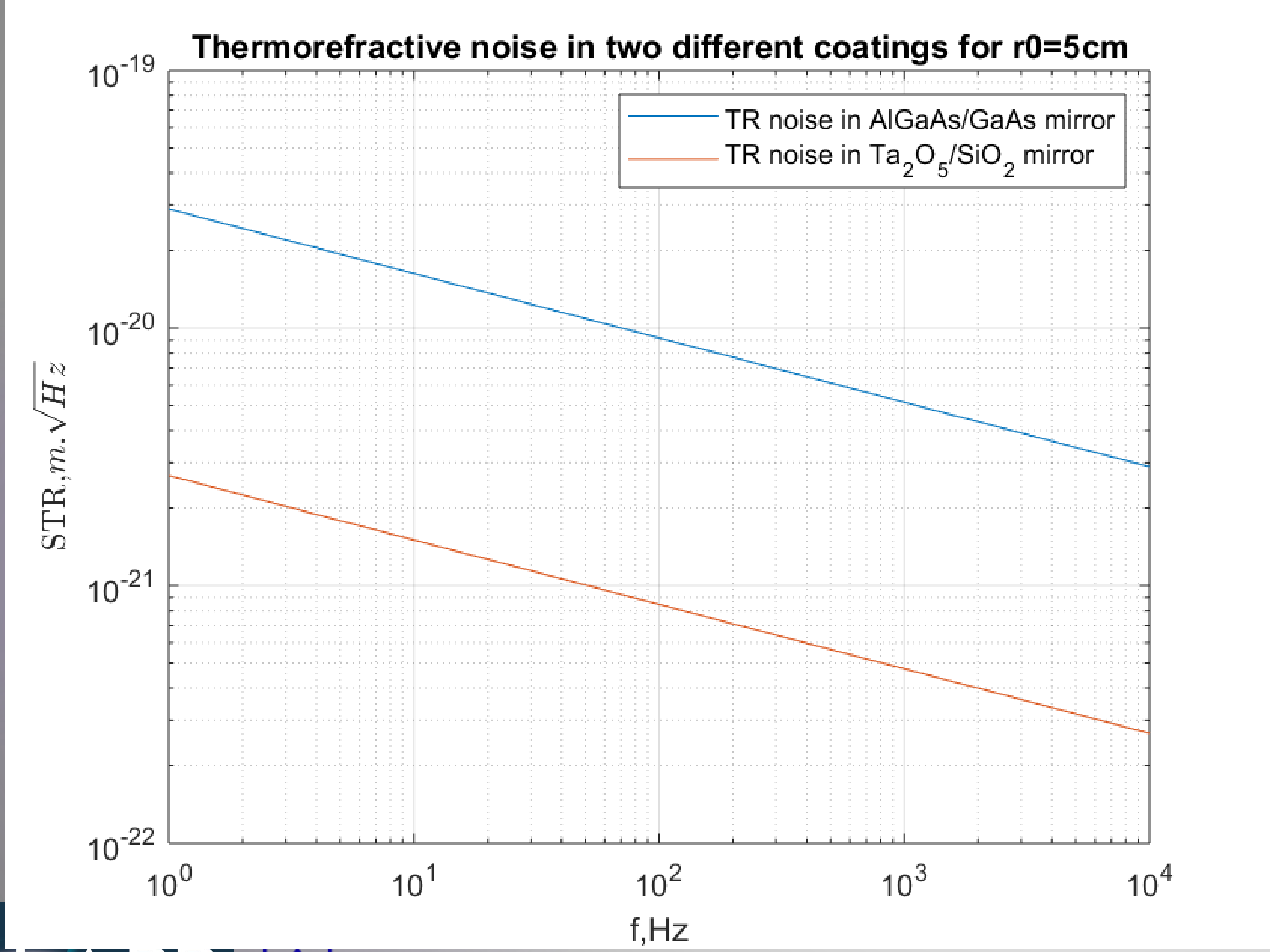


Thermoelastic noise



α_c(Ta2O5/SiO2)	6e-6 K^{-1}
d(Ta2O5/SiO2)	6 µm
α_c(AlGaAs/GaAs)	2e-5 K^{-1}
d(AlGaAs/GaAs)	4.7 µm

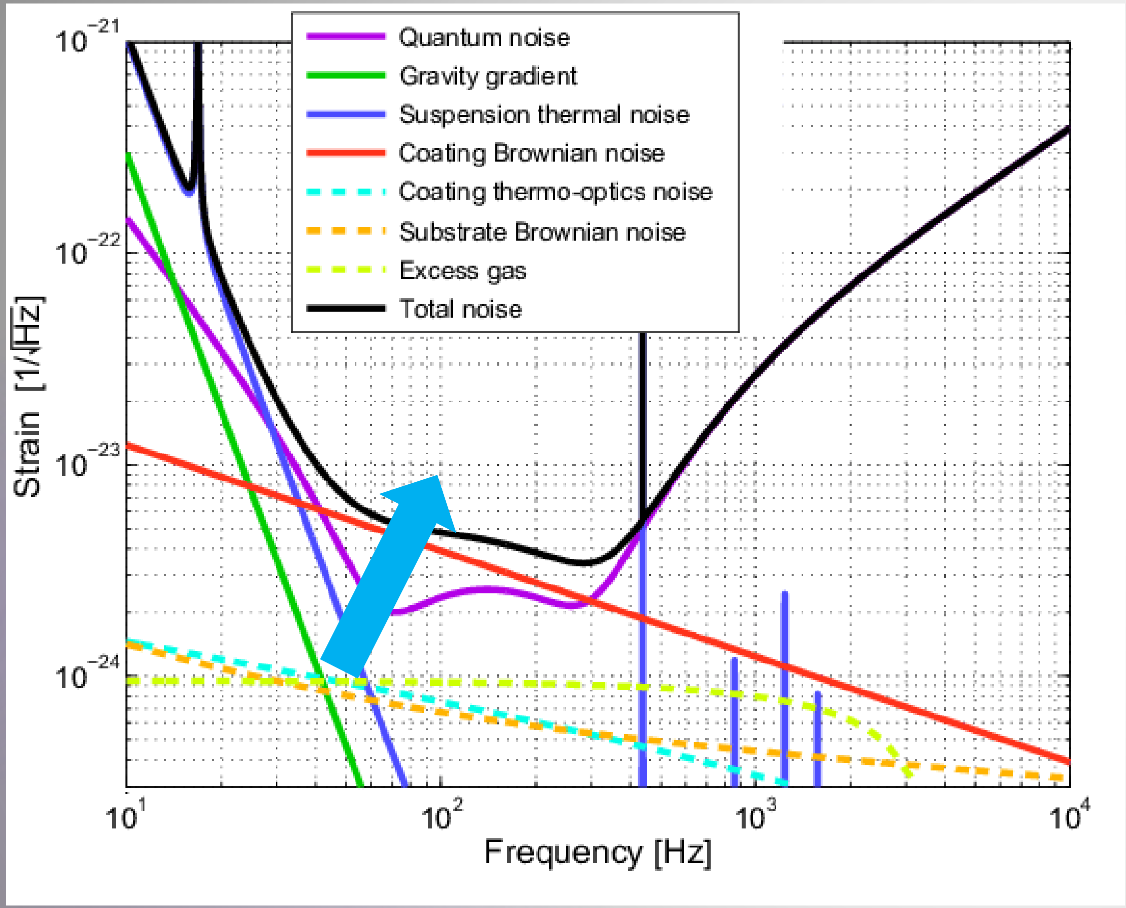
Thermorefractive noise



β (Ta2O5/SiO2)	7e-6 K^{-1}
β (AlGaAs/GaAs)	8e-5 K^{-1}
λ	1064 µm

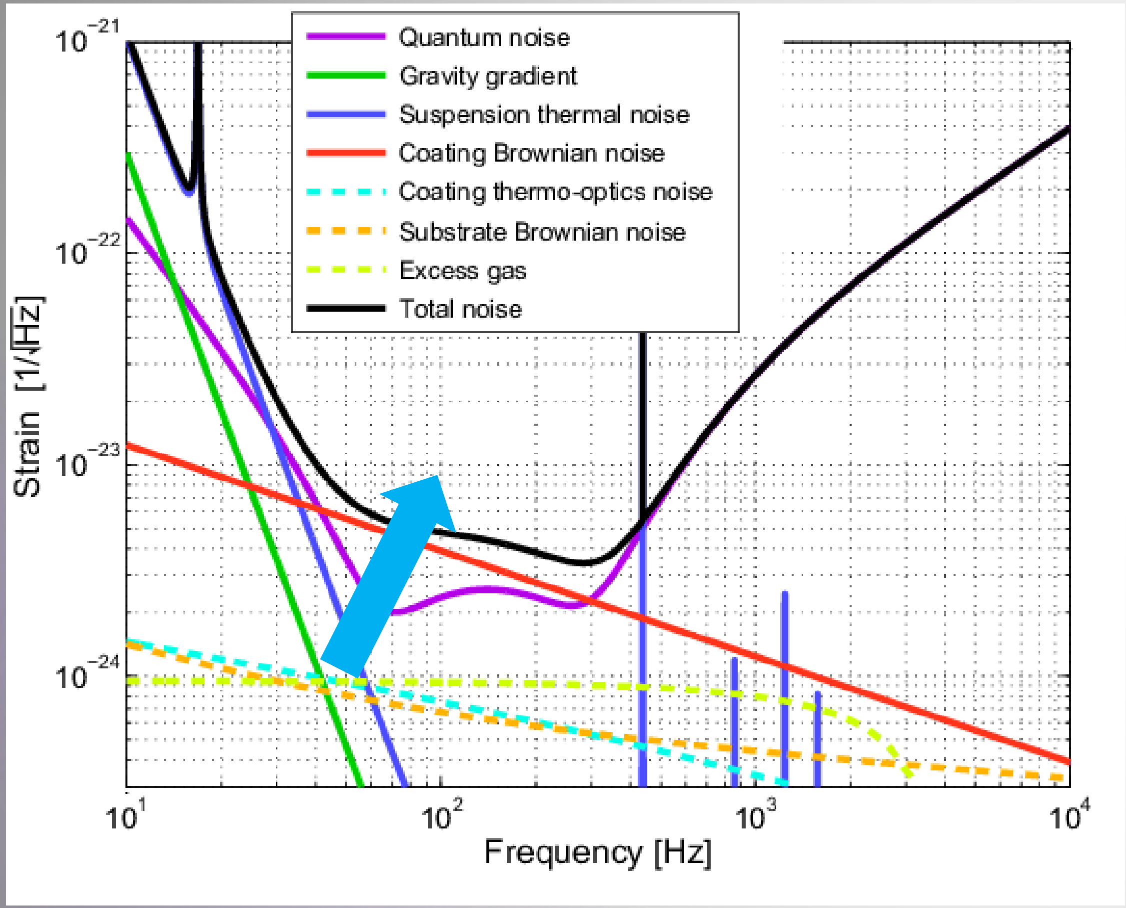
- TE and TR noise higher in crystalline coatings???

Thermo-optic noise



TO higher in crystalline coatings???

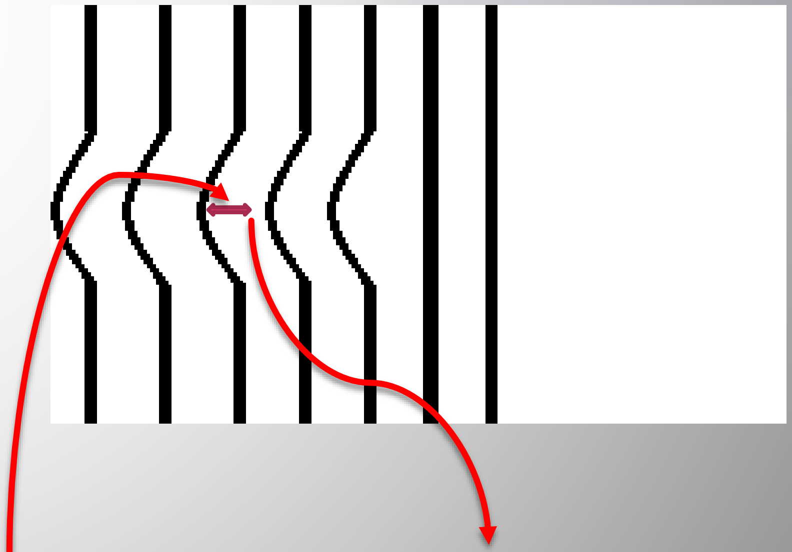
Thermo-optic noise



TO higher in crystalline coatings???

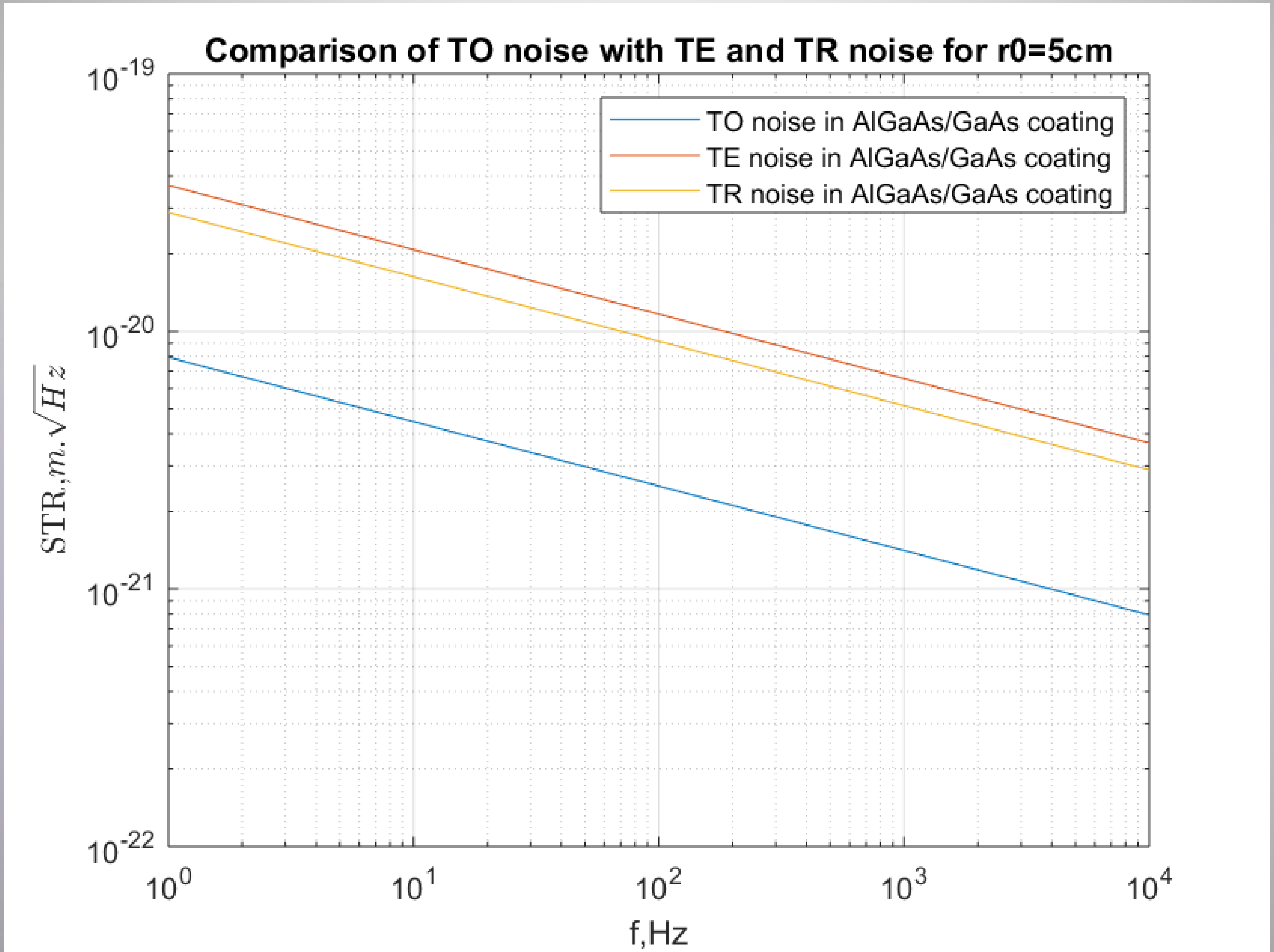
TO noise is not a sum of TE and TR noise

TR and TE noise are correlated and they tend to « compensate » each other



Expansion => Refraction Index decreasing

Thermo-optic noise



Thermal noise model for small beams

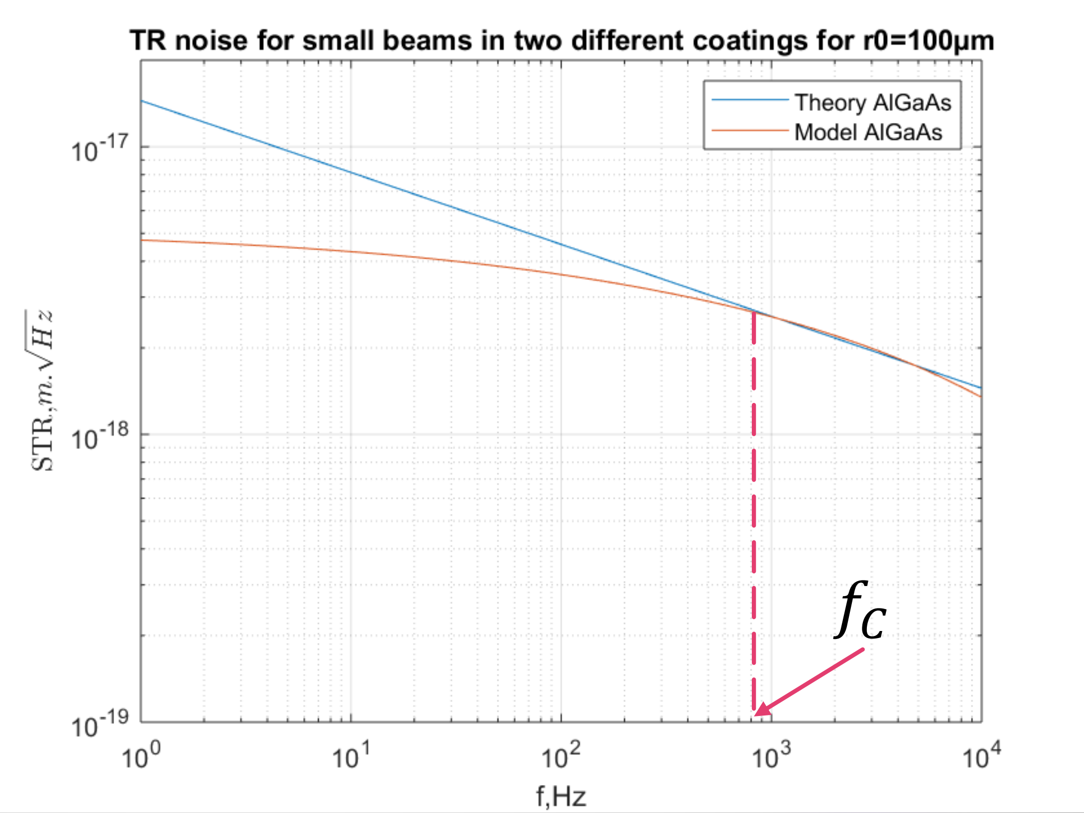
- We cannot test coatings directly in Virgo
- Need to do the measurements in Lab : short cavities => small beams
- Thermal noise increases when r0 decreases (Thermal noise $\propto \frac{1}{{r_0}^2}$)=> easier to measure
- Until now: coating thermal noises measured for $r_0 \sim cm - mm$
  - Approximations can be applied => thermal diffusion negligible
- For small radius (~100µm)
  - Approximation not valid anymore at low frequencies
  - Need to build a new model

Thermal noise model for small beams

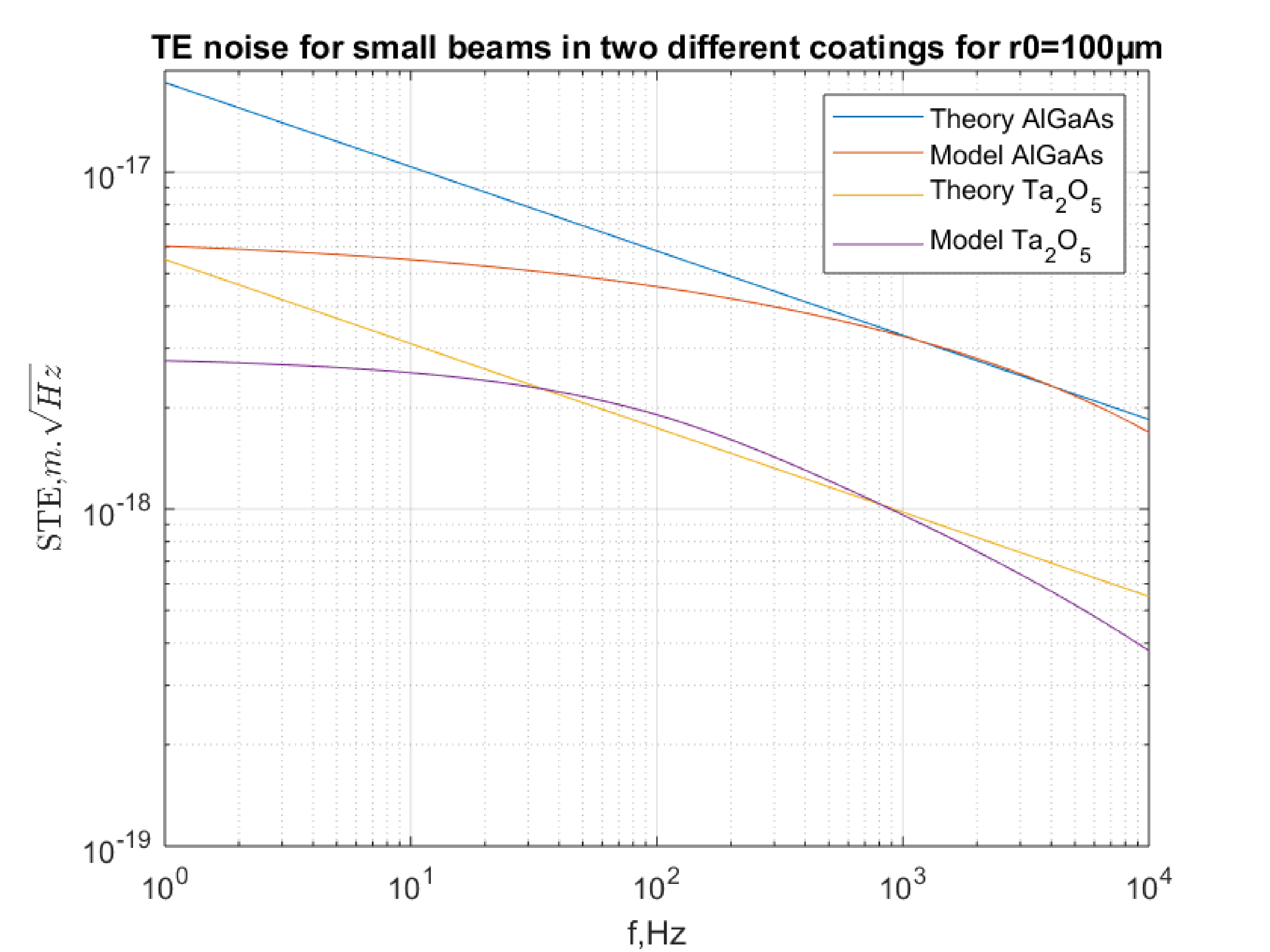
$$l_t = \sqrt{\frac{\kappa}{\rho C f}}$$ *to be compared to* r_0 $\quad l_t \gg r_0 \Rightarrow$ *thermal diffusion significant*

f ↘↘ => l_t ↗↗

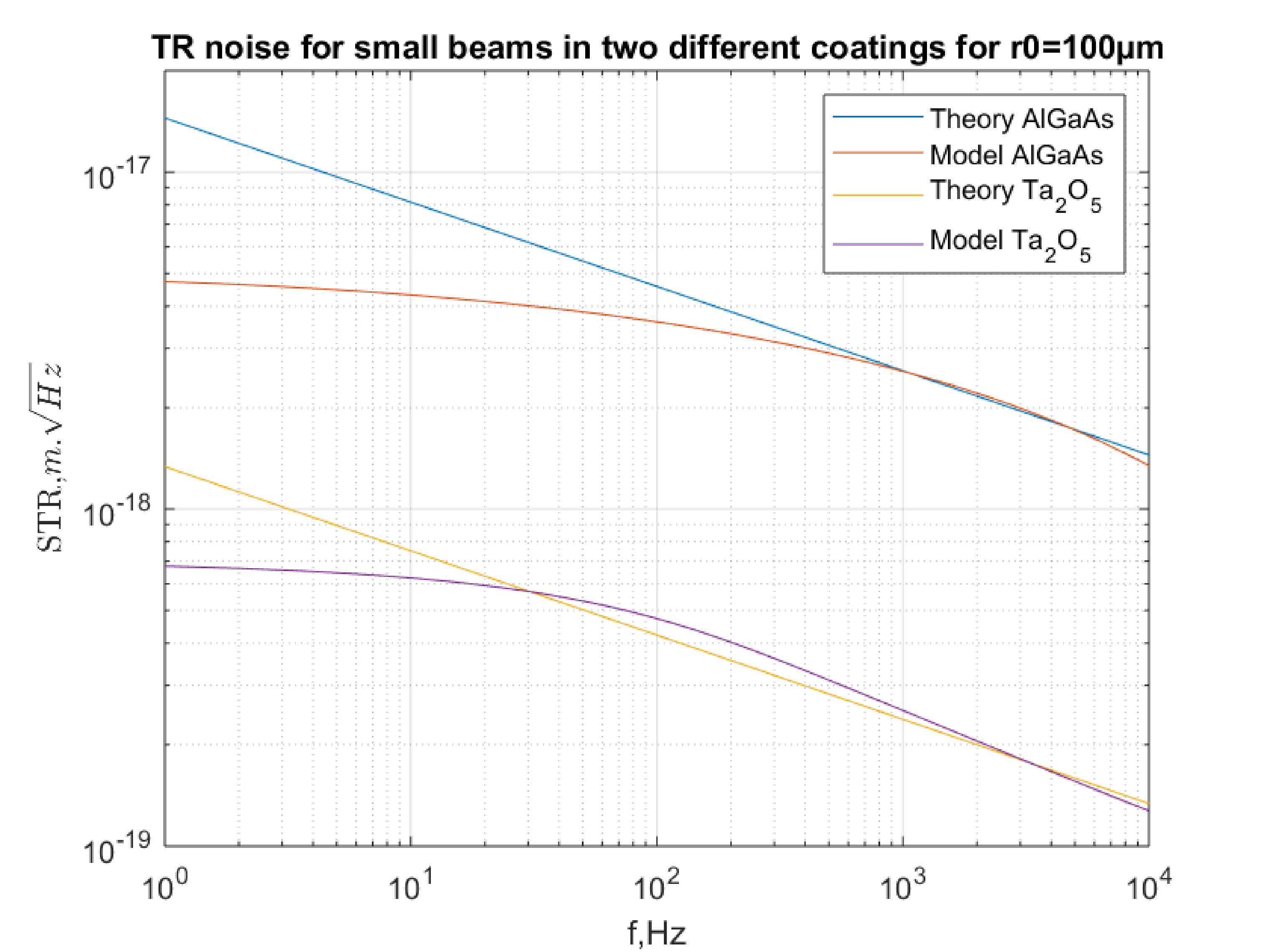
l_t : *Thermal diffusion length*
κ : *Thermal conductivity*
ρ : *Volumic mass*
C : *Heat capacity*
f : *frequency*



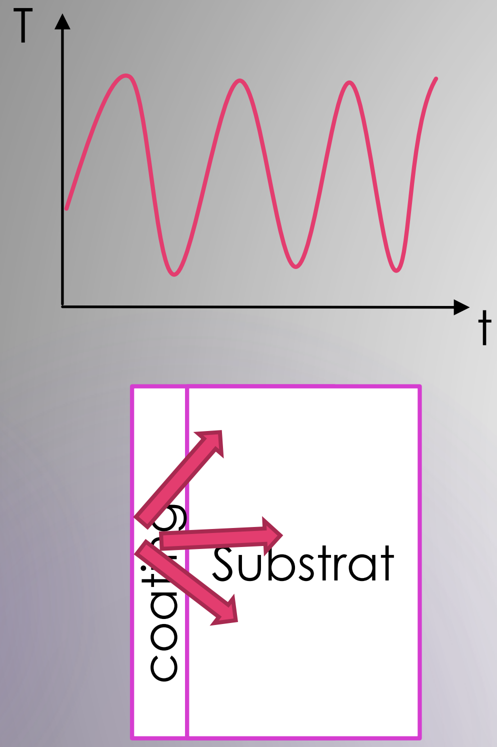
Thermal noise model for small beams



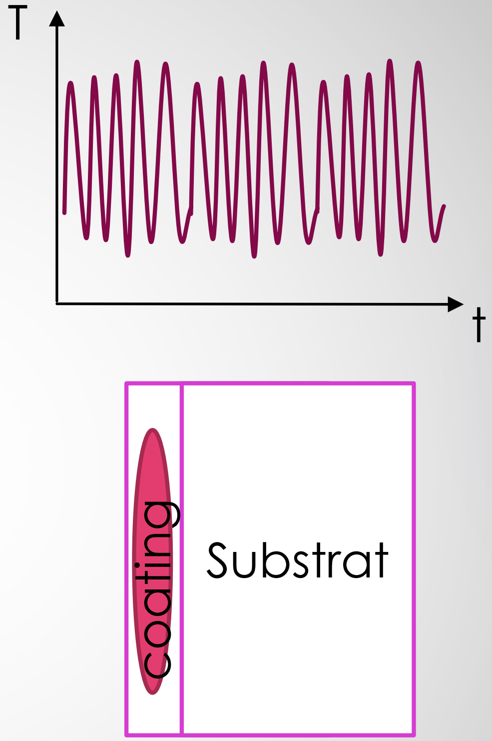
Thermal noise model for small beams



Thermal noise model for small beams

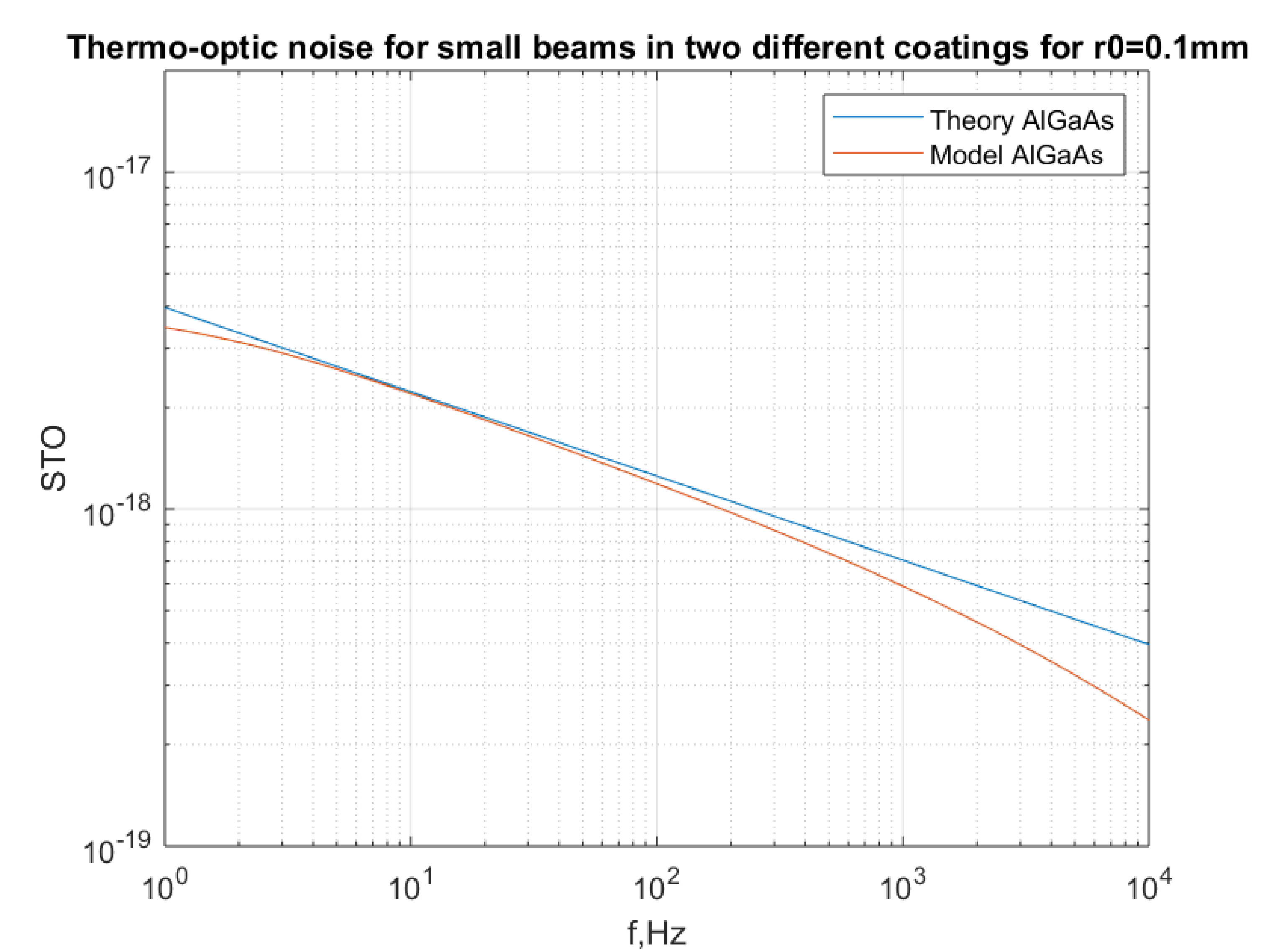


Low frequency
-> bigger heat volume
-> grad(T)

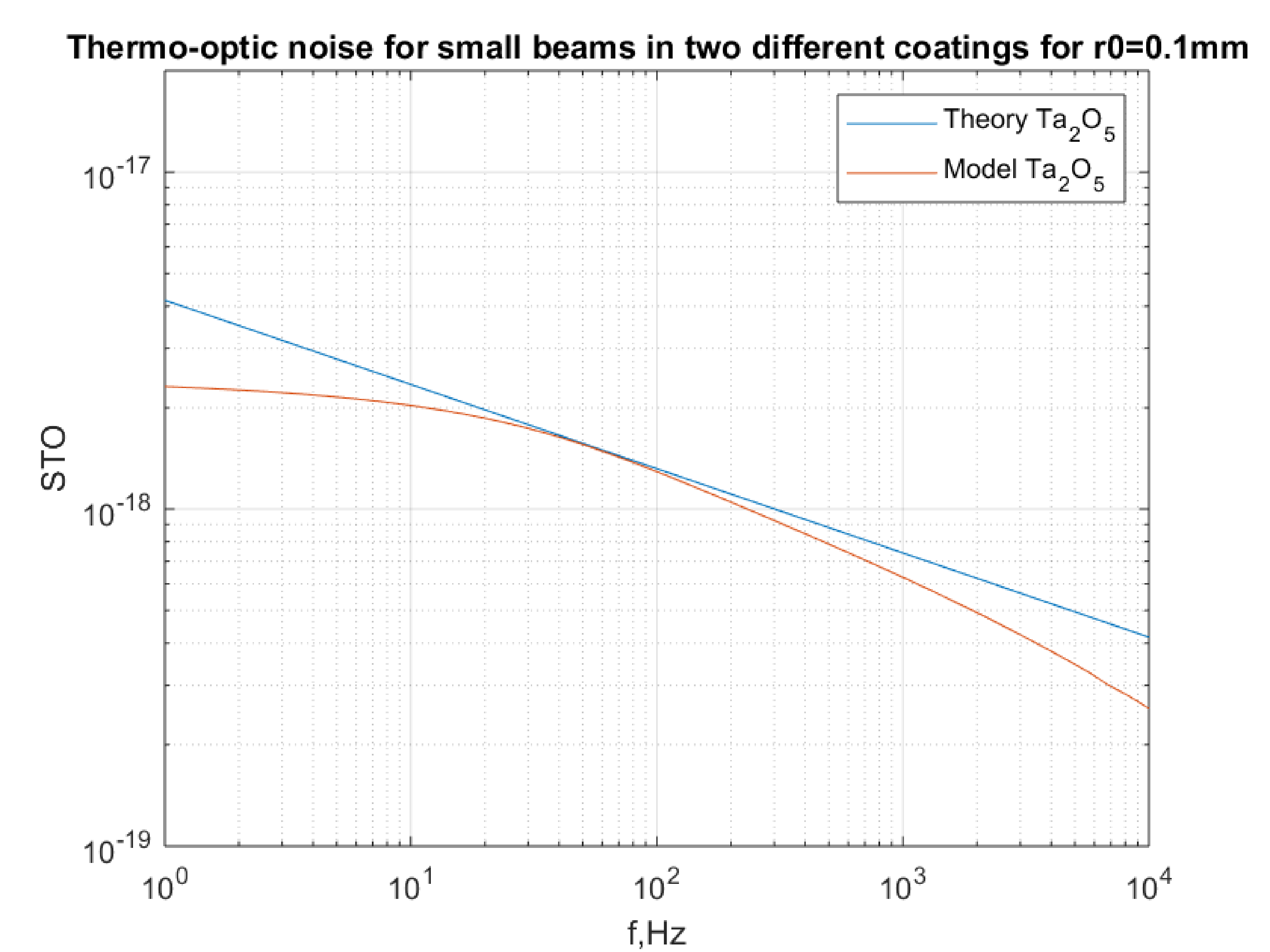


High frequency
-> Thermal diffusion negligeable
-> Heat essentially in the coating

Thermal noise model for small beams

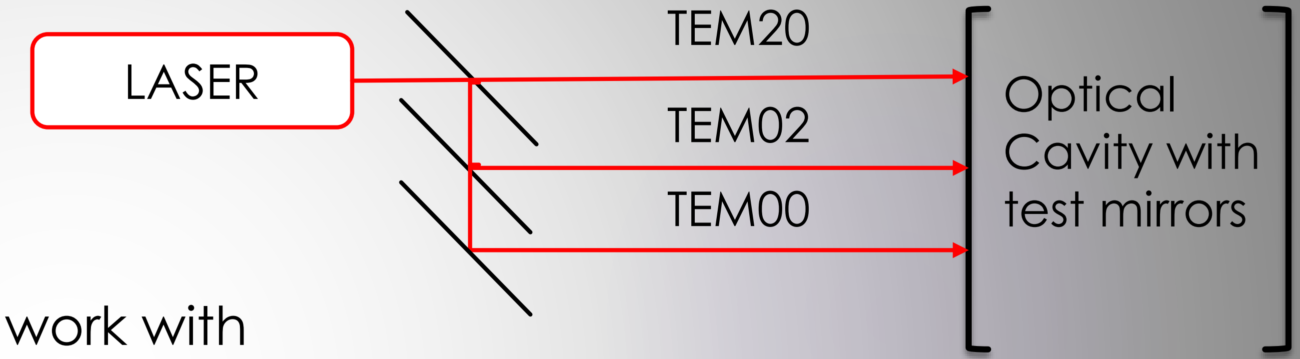


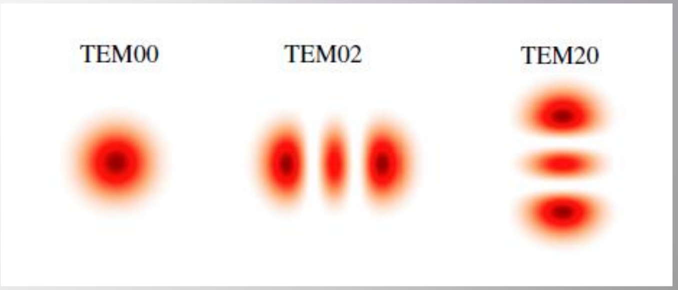
Thermal noise model for small beams



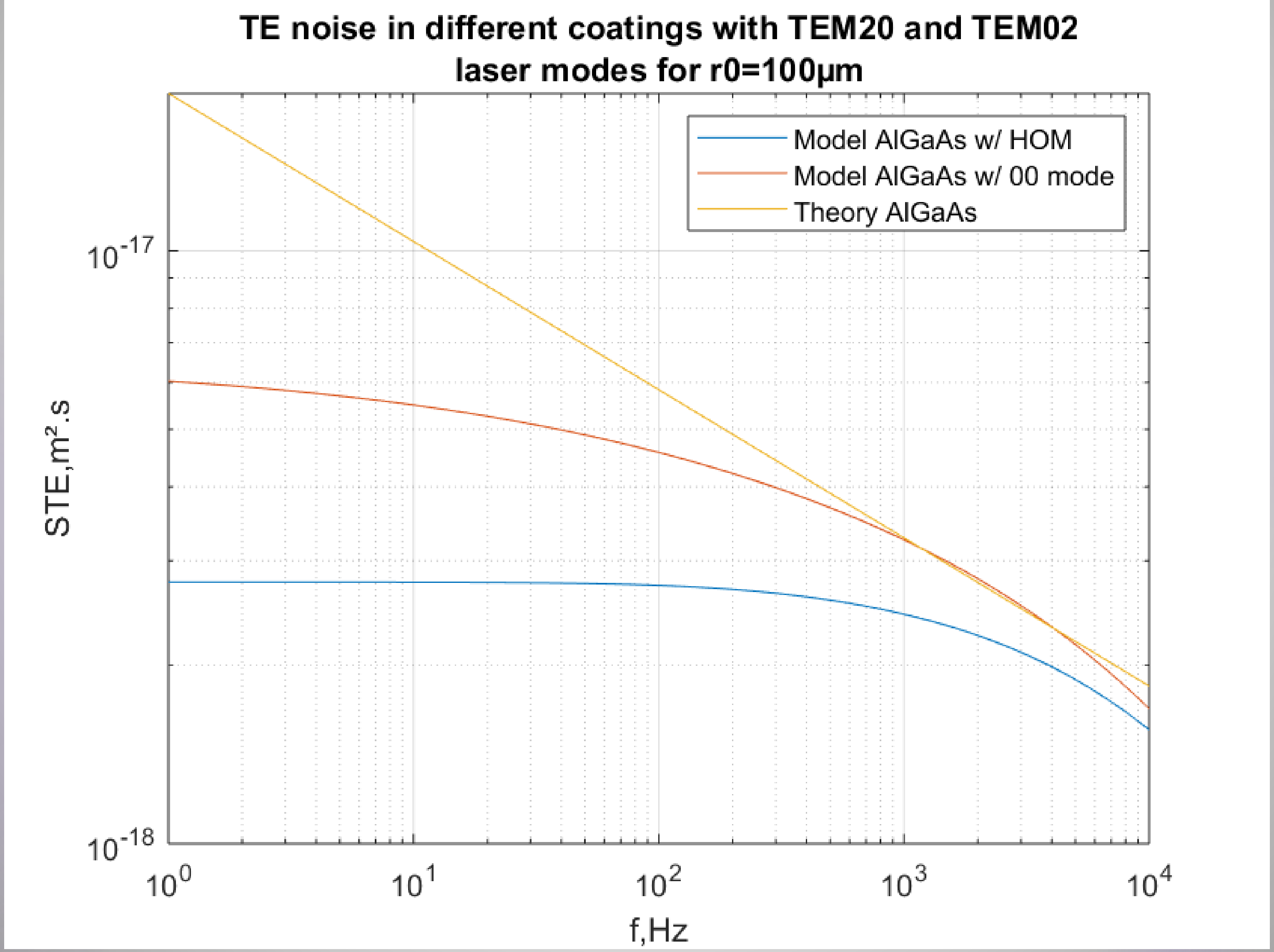
Thermal noise models with higher order modes

- We cannot only use small r0
- To reduce laser noises we need to work with higher order modes
- MIT experiment
  - Reducing laser noise
  - Measurements of thermal noise
- The model to describe thermal noise will be different

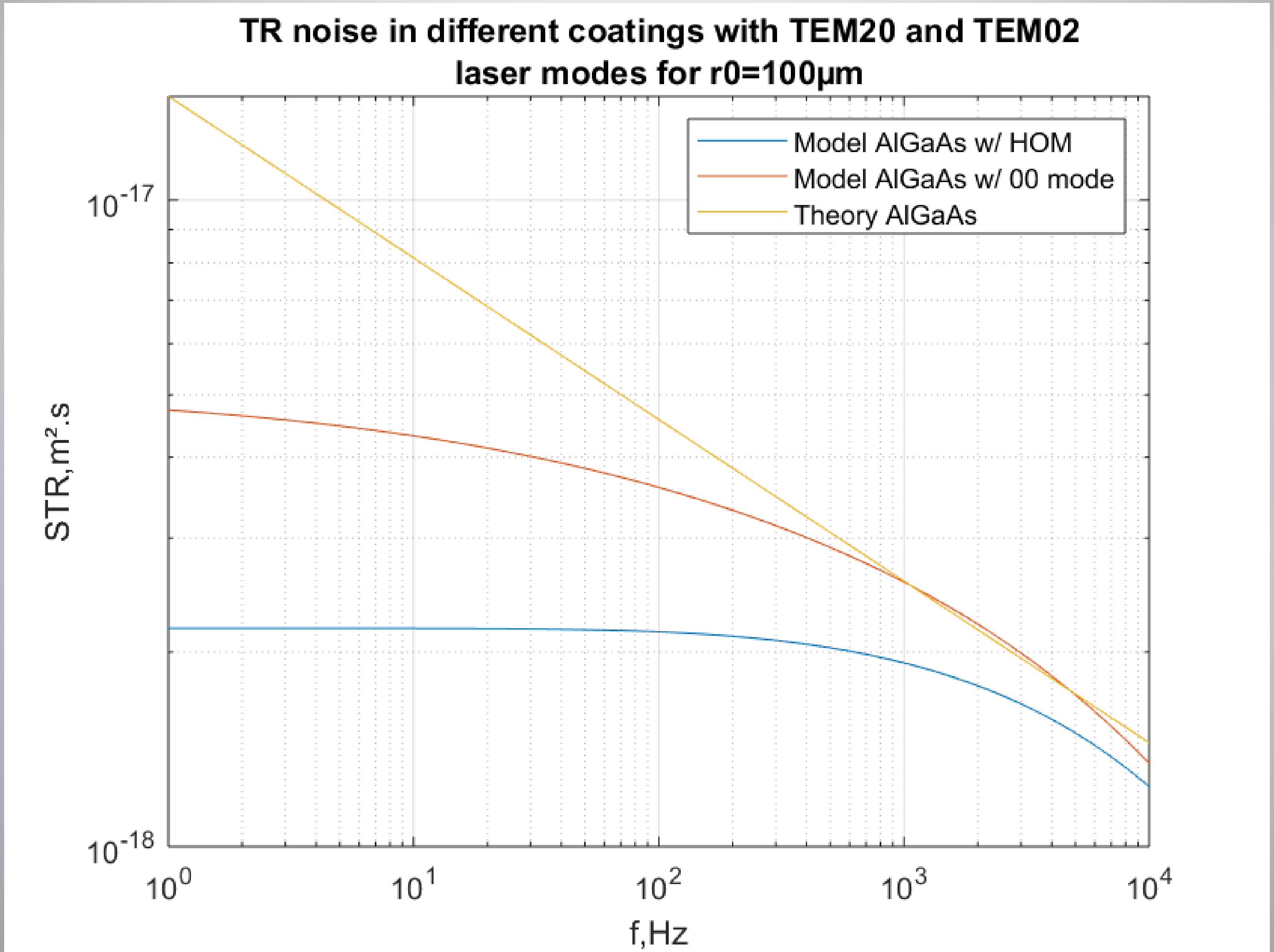




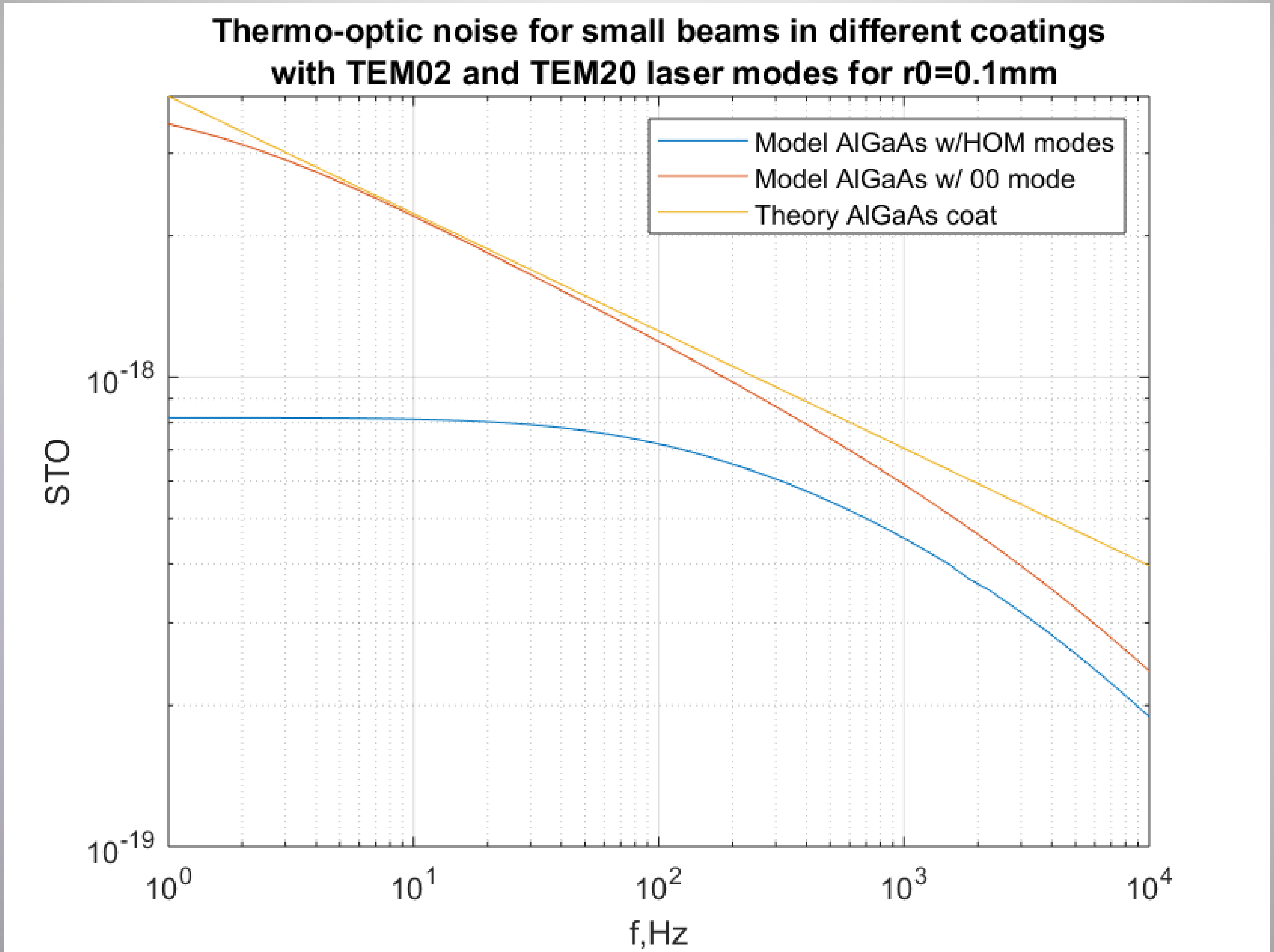
Thermoelastic noise model with HOM laser



Thermorefractive noise model with HOM laser

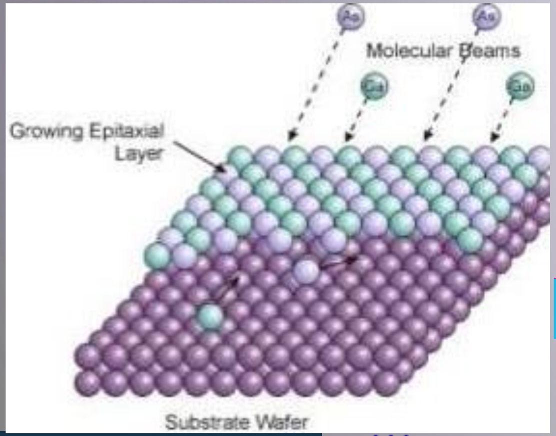


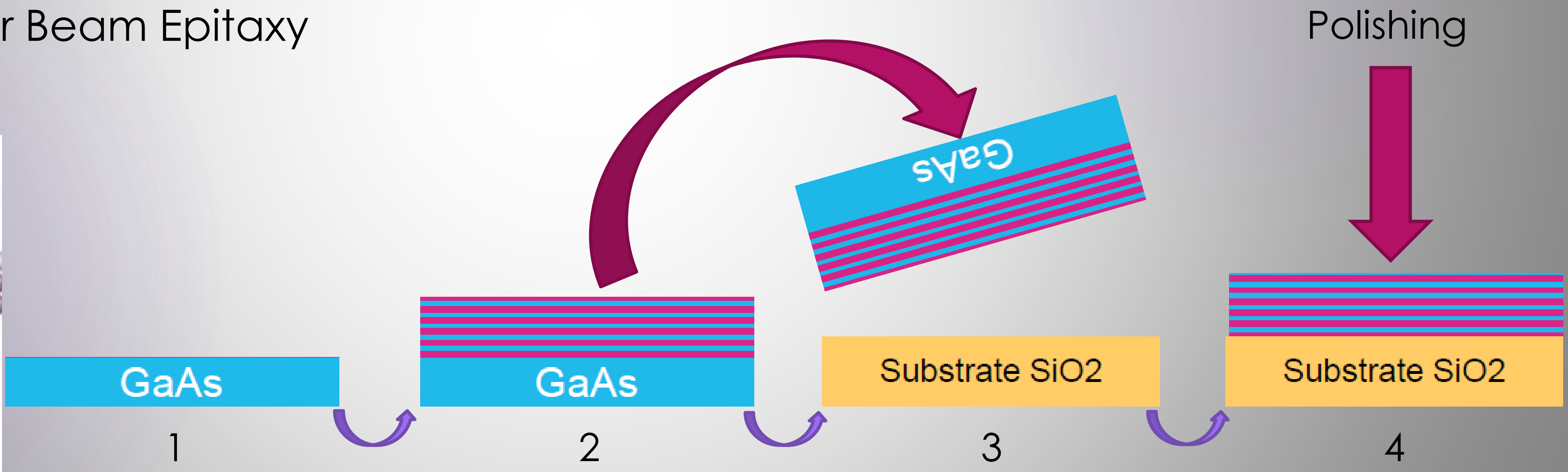
Thermo-optic noise model with HOM laser



Development of crystalline mirrors

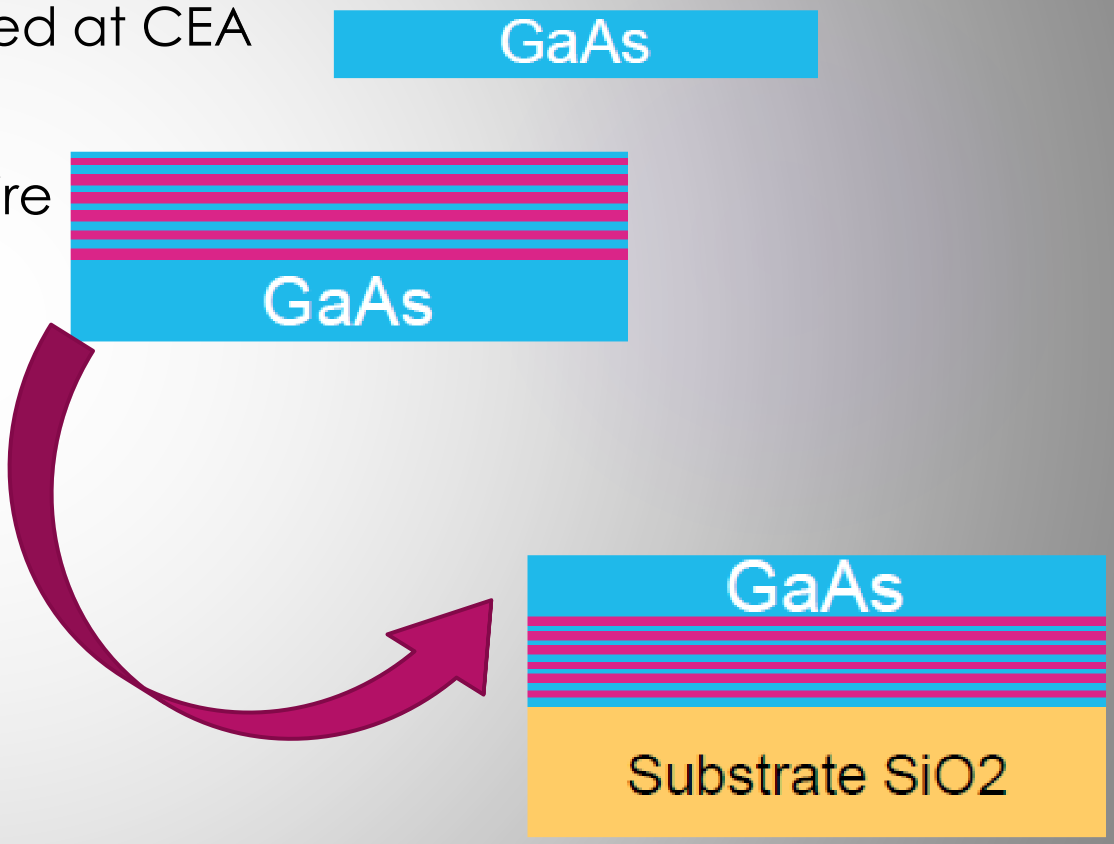
- Until now, measurements of thermal noise on small coatings ($\sim cm$)
- For Virgo => bigger mirrors (30+cm)
- Goal : to make bigger coatings at CEA Leti
- Molecular Beam Epitaxy



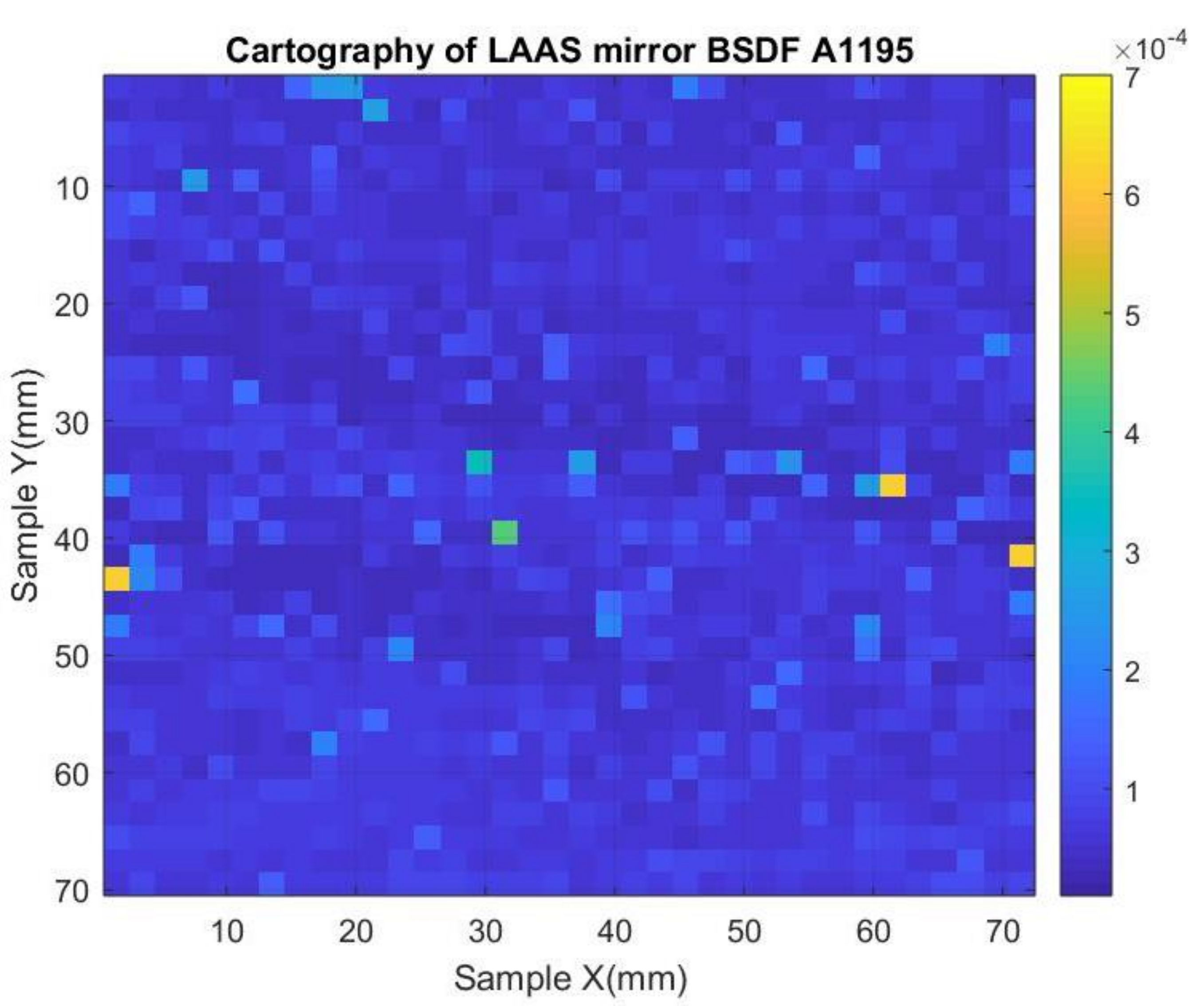


Development of crystalline mirrors

- GaAs and Silica Substrates characterized at CEA
- GaAs substrate sent to LAAS (Laboratoire Analyse et Architecture Systèmes)
  - MBE to grow crystalline coatings
- Characterization at LMA
  - Scattering map
  - Defaults map
- Transfert on silica substrate at CEA



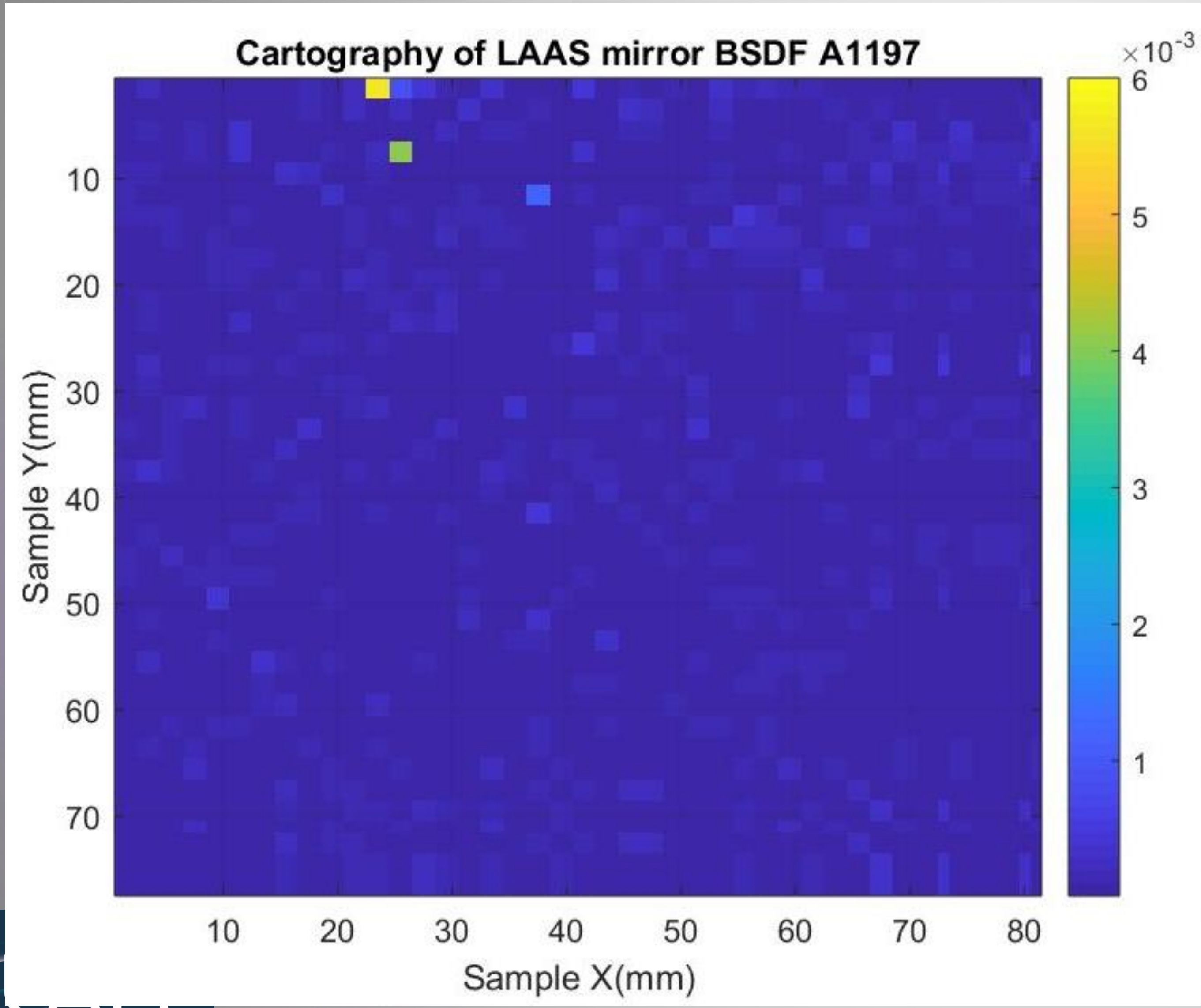
Characterization at LMA



Mean : 45 ppm

Virgo : 5-10 ppm

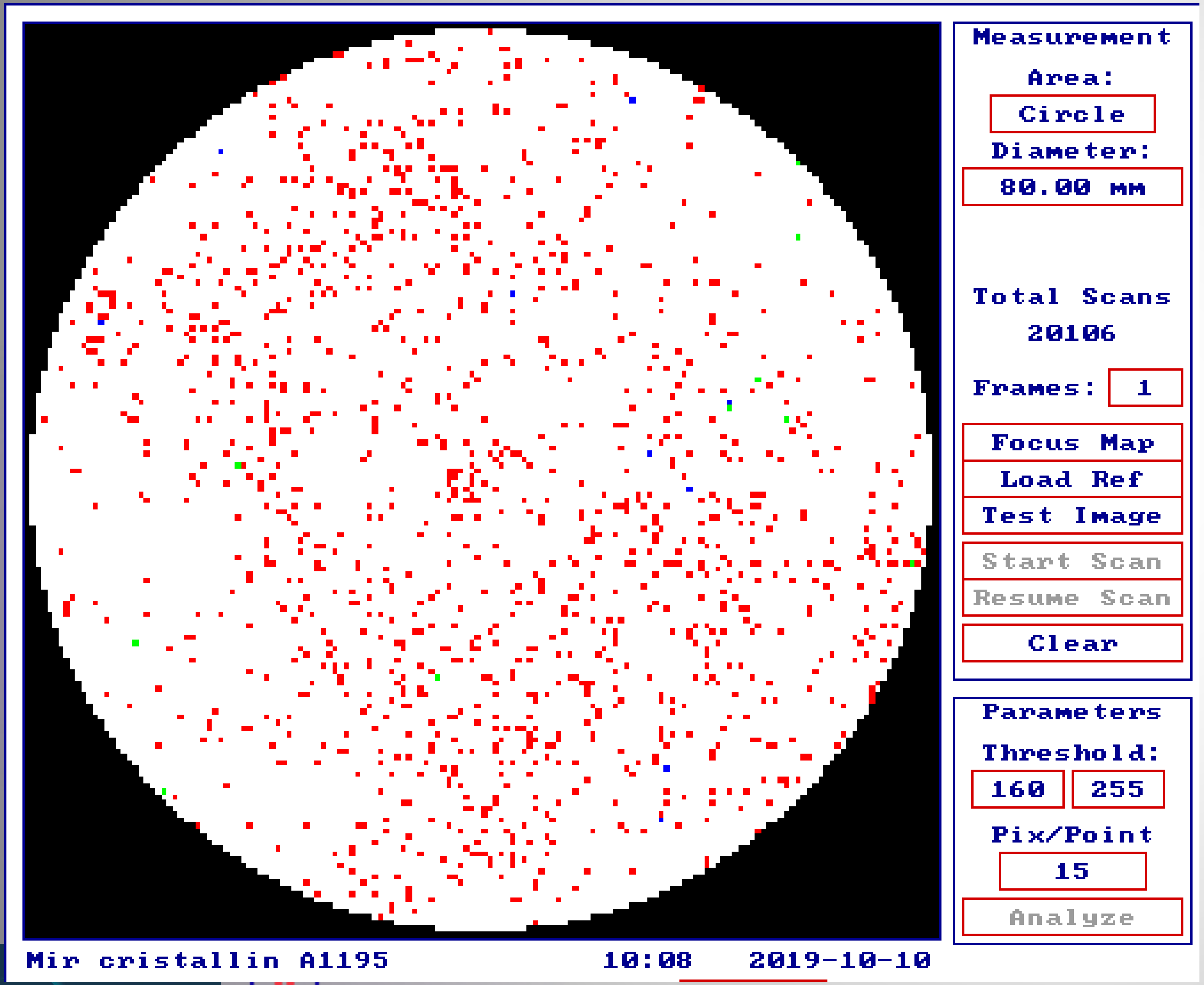
Characterization at LMA



Mean : 60 ppm

Virgo : 5-10 ppm

Characterization at LMA



800 defects/cm²

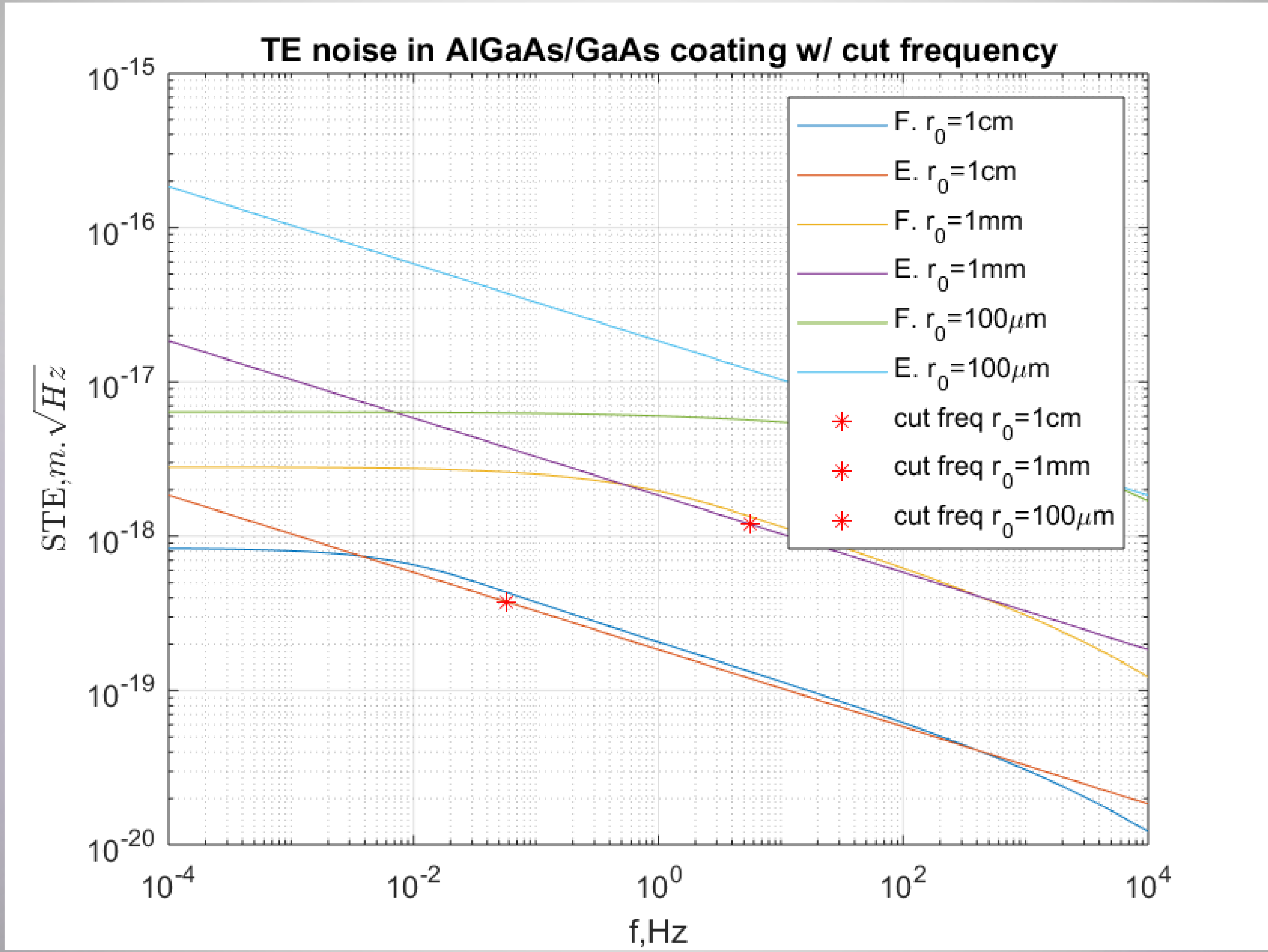
Development of crystalline mirrors

- Collaboration between three laboratories
  - CNRS/LAPP
    - Thermal noise measurements on optical bench
  - CEA/LETI
    - Epitaxy for growth of cristalline coatings, wafer transfer, wafer bondings
  - CNRS/LMA
    - Optical characterizations on cristalline mirrors

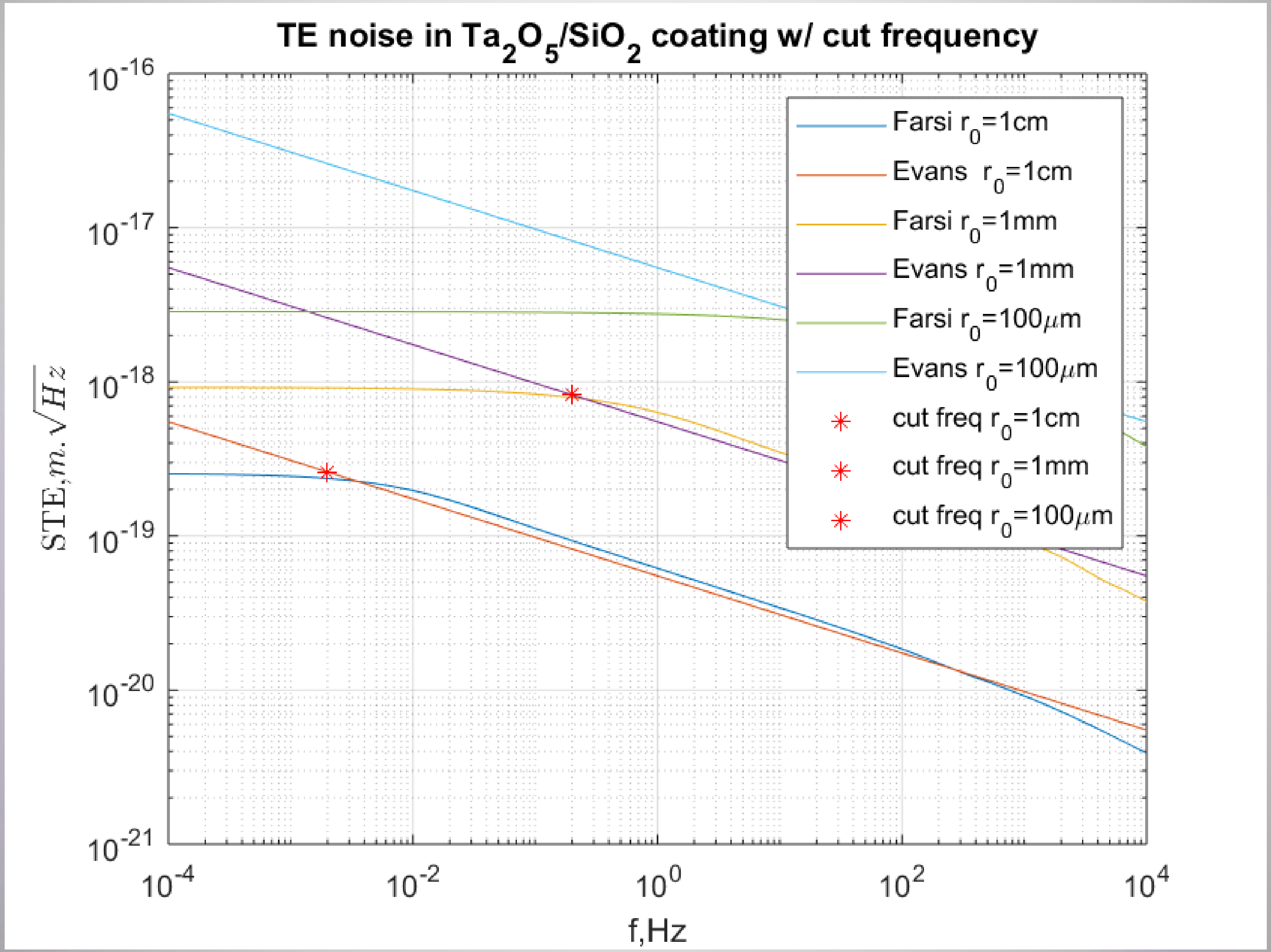
Thank you for your attention!

Back-up slides

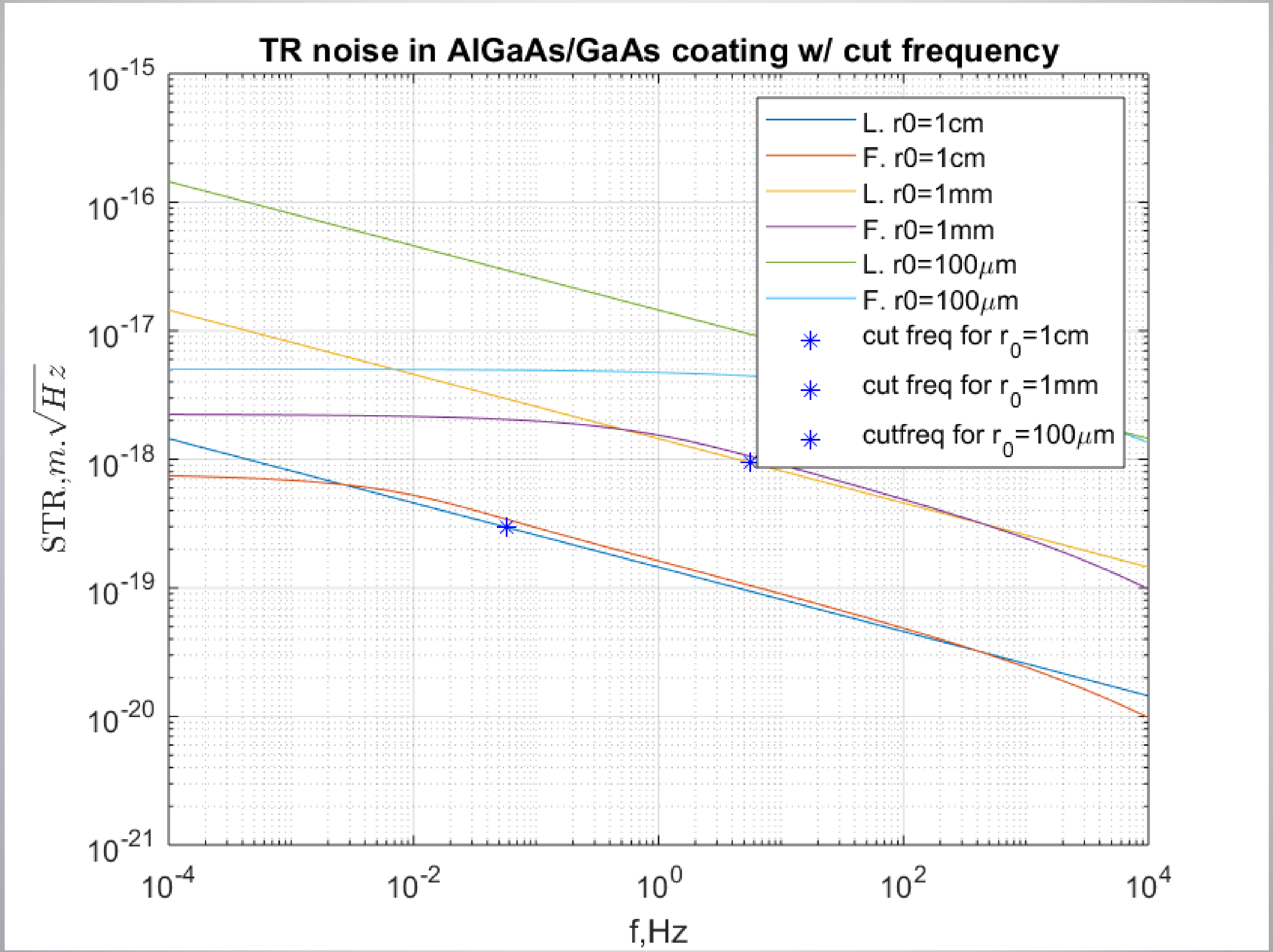
Thermal noise model for small beams



Thermal noise model for small beams



Thermal noise model for small beams

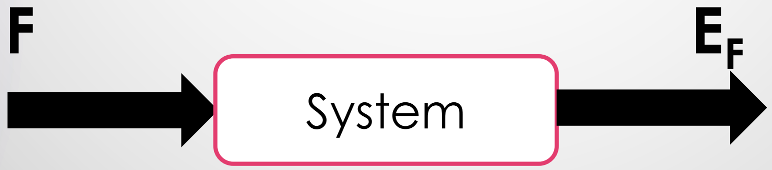


Modelizing thermal noise

- Fluctuation dissipation theorem $S_{\Delta T}(\omega) \propto Re(Z(\omega))$

- In a linear system, fluctuation of a observable is linked to the amplitude of its dissipation

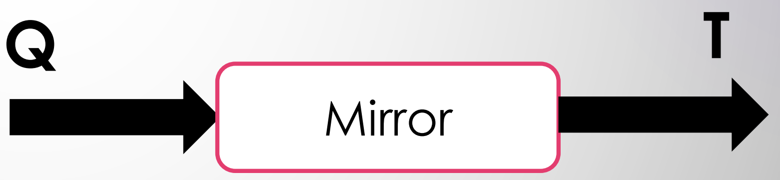
- Injecting a force F and we study the energy dissipated by this force



Modelizing thermal noise

- Application to the thermal noise
- Injection of Entropy and study of the temperature dissipation

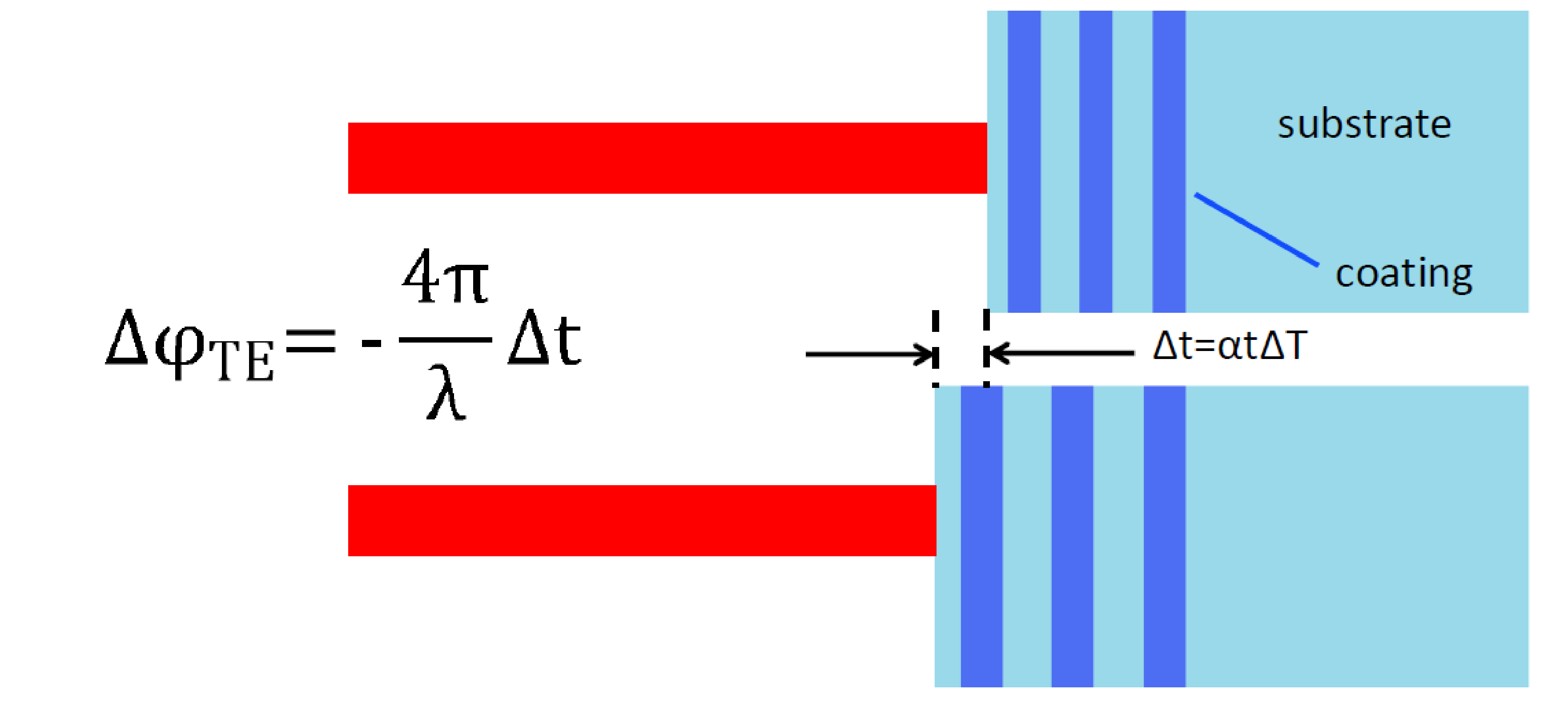
$$S_{\Delta T}(\omega) \propto P_{diss}(T(z,t))$$



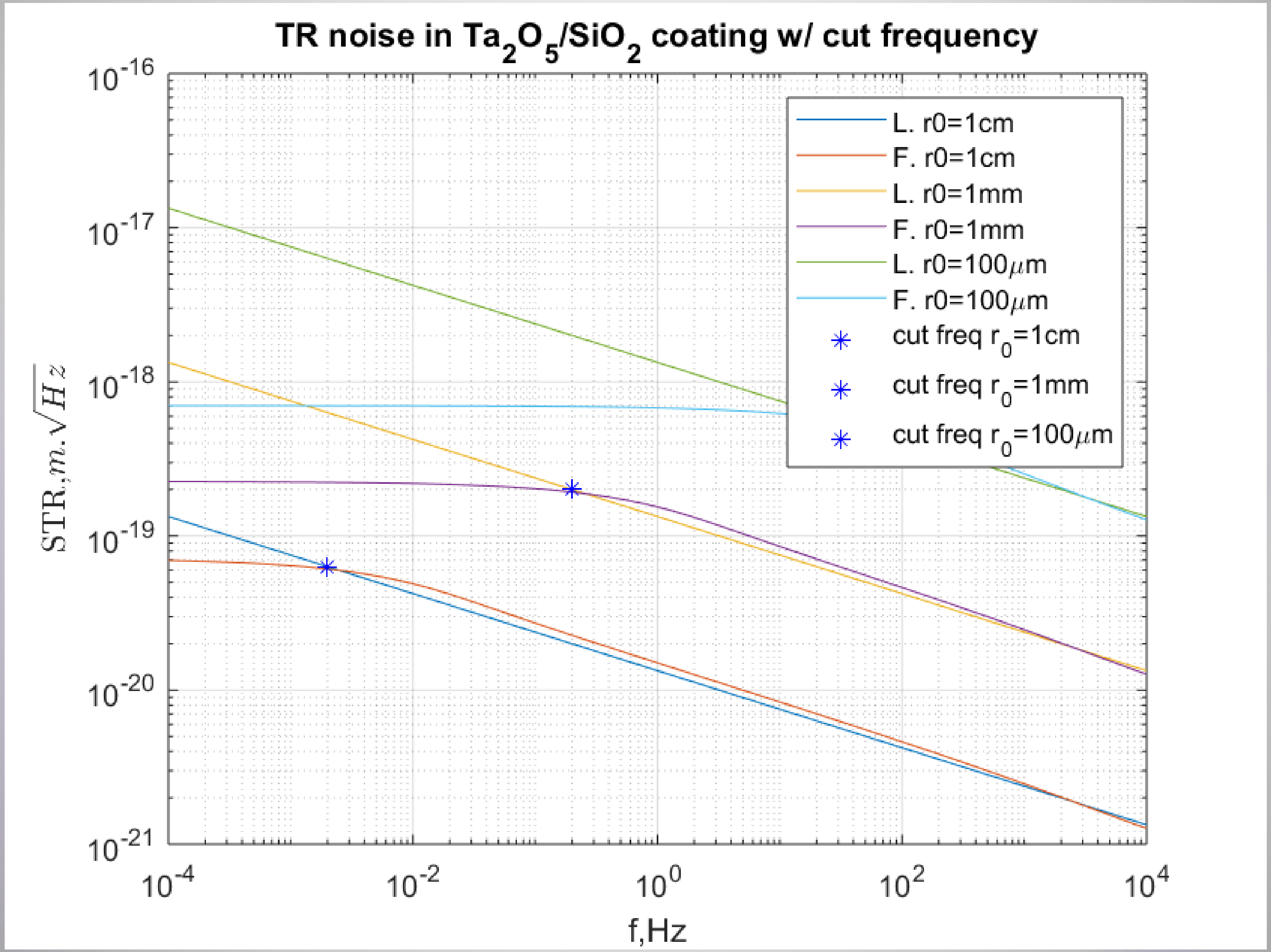
- Temperature dissipation given by the diffusion equation
- Boundary conditions given by the study of how the light is reflected

Back up

- Thermoelastic noise is the apparent expansion of the mirror coating into the probe beam causing change in phase



Thermal noise model for small beams



Research areas

- Collaboration with CEA Leti
  - Design of crystalline coatings
  - Evaluation of substrate surface state
  - Epitaxy (crystalline growth from crystalline substrate GaAs)
  - Transfer techniques to separate the coating from the substrate and then bonding with silica substrate
- Collaboration with LMA
  - Optical measurements (diffusivity, reflectivity, defects…)