BARCELONA 2015

Thermal and mechanical noise in gravitational wave detectors

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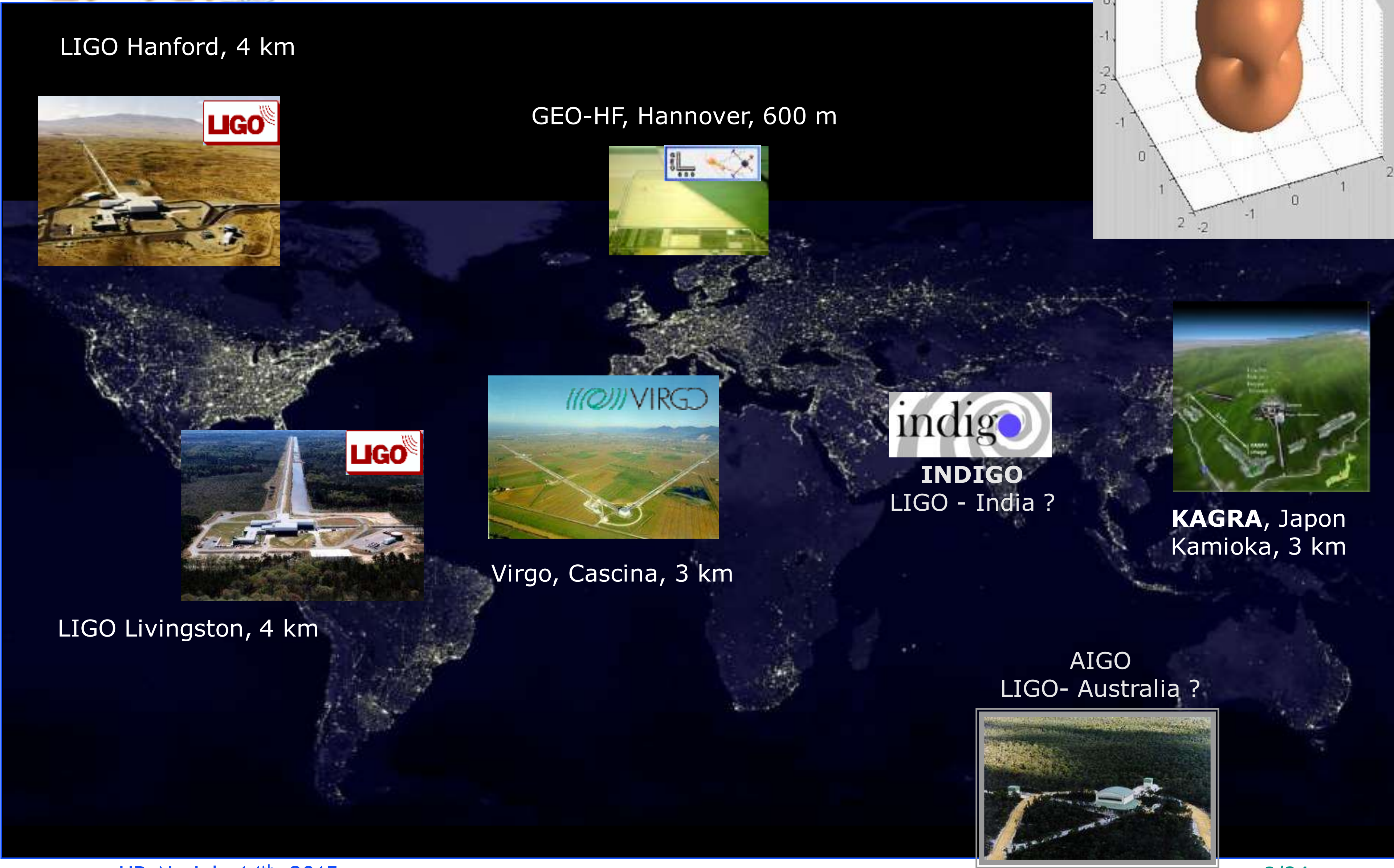
Virgo, a GW detector

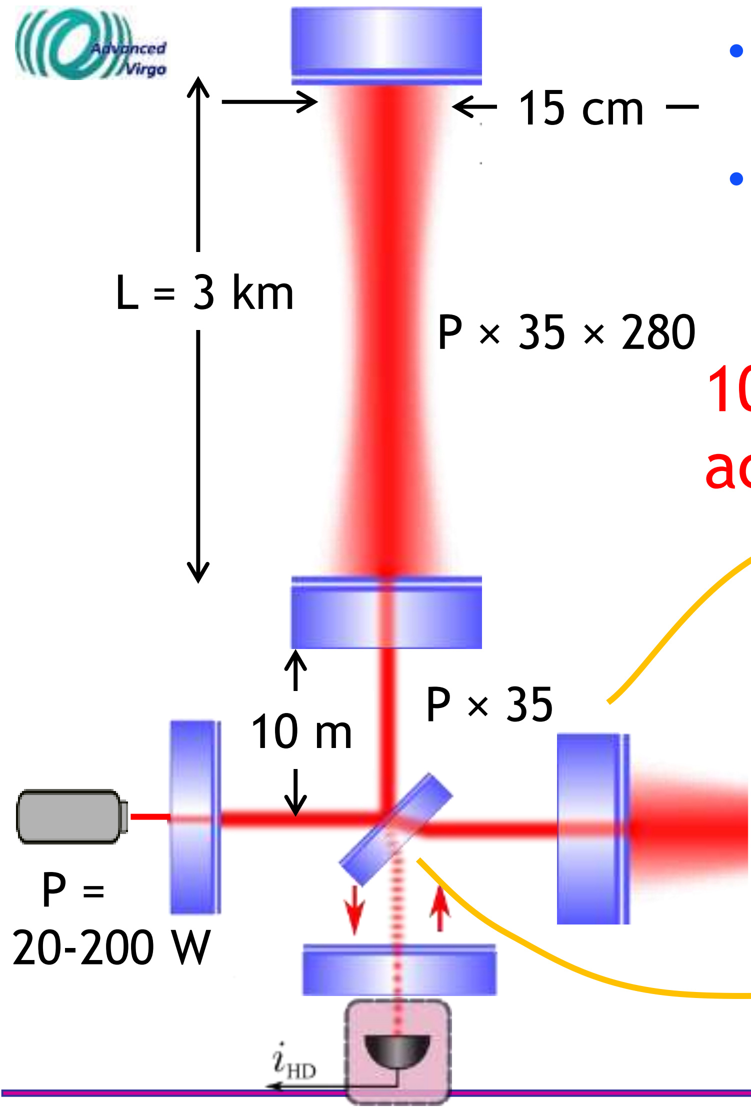
THE VIRGO COLLABORATION
5 European countries
19 laboratories - ~200 authors

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

The GW Interf. network

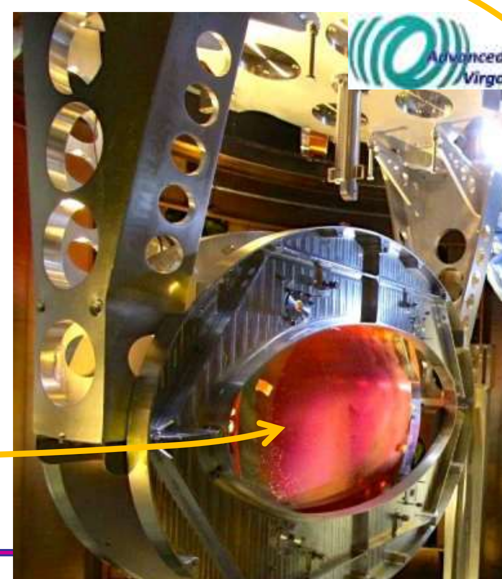


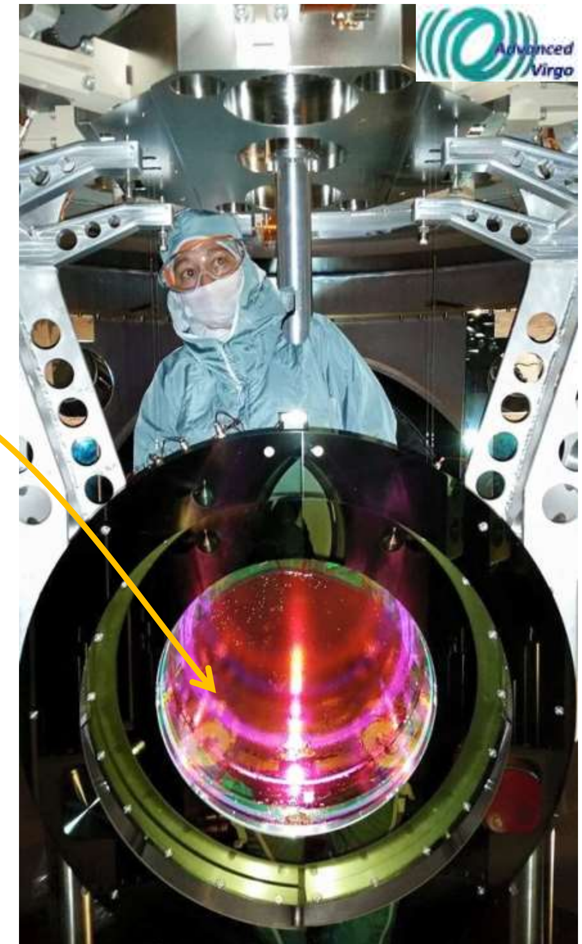
The Virgo optical system



- Mechanical noises: seismic, newtonian, thermal
- Optical quantum noise:
  - radiation pressure
  - shot noise

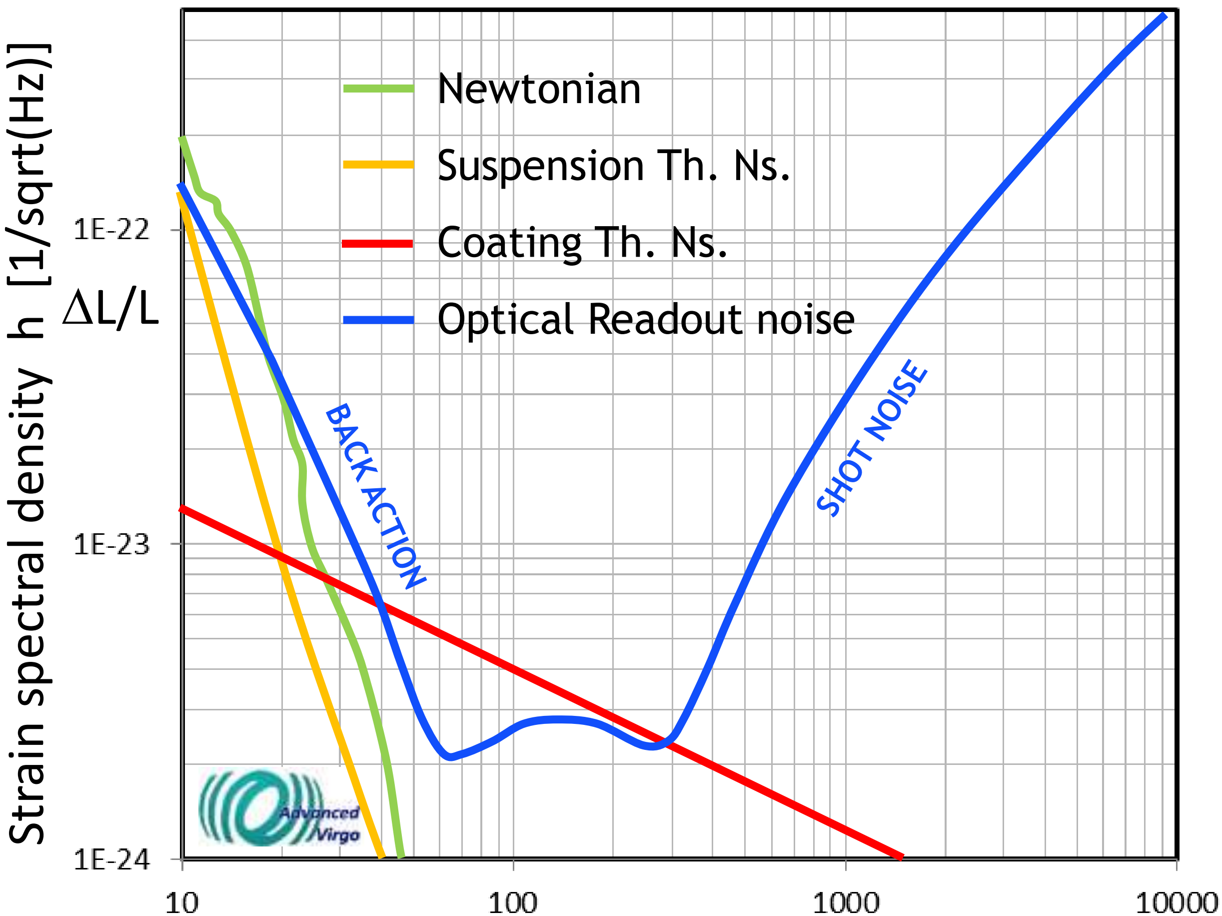
10^{-40} m²/Hz @100 Hz achievable !


Beam splitter


West Input Mirror

A typical noise spectrum

Classical Quantum Grav. 32 (2015) 024001

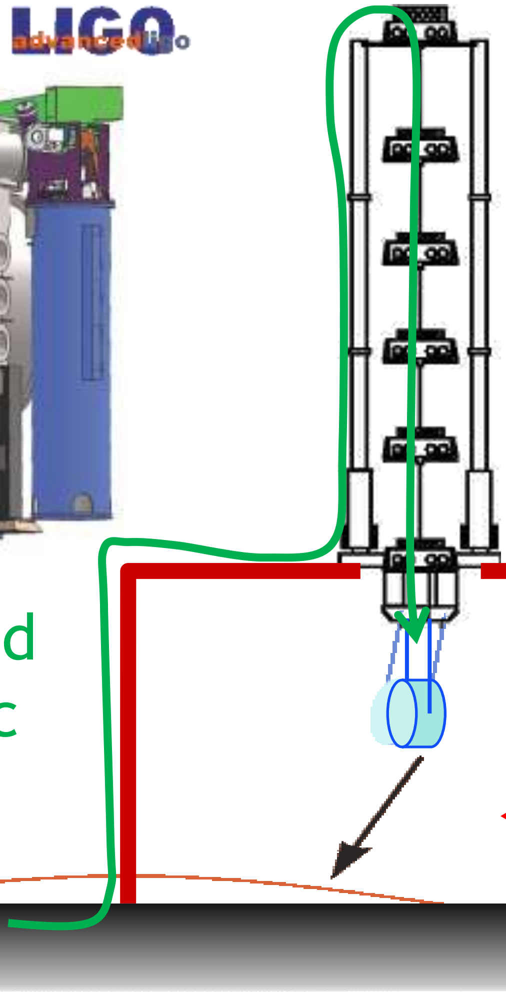


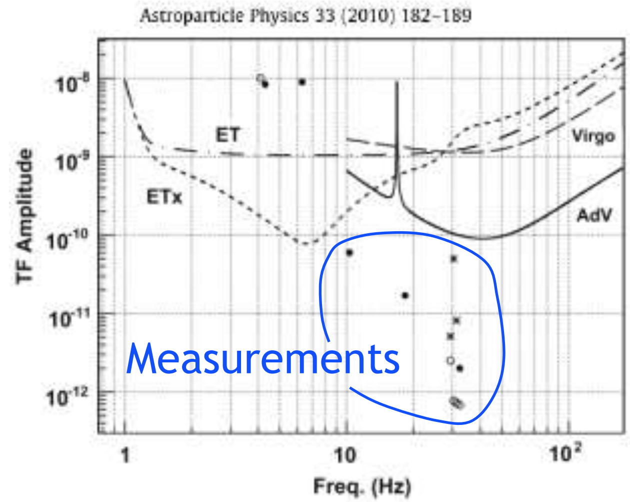
Seismic noise is below 1e-24 m/sqrt(Hz)

Noises covered by my presentation:

- Newtonian
- Creep
- Thermal on mechanics
  - Coatings

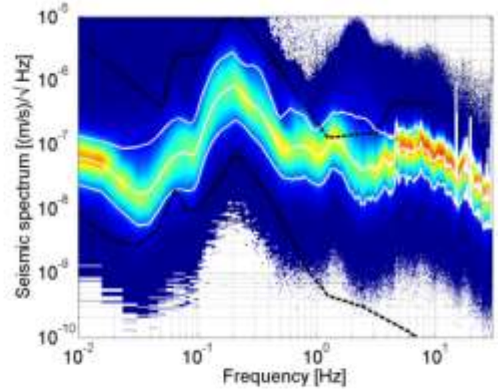
Seismic and Newtonian noises

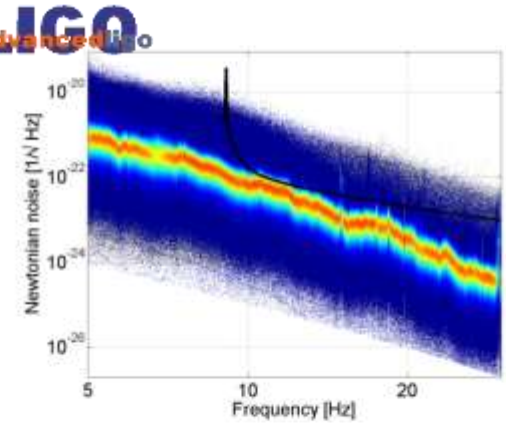




Fluctuation of local gravity

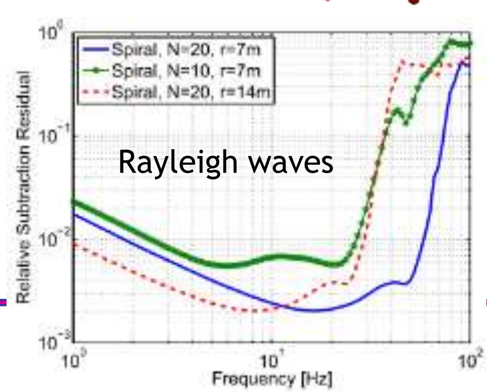
- **Origins**
  - Seismic fields
  - Seismic point sources
  - Atmosphere

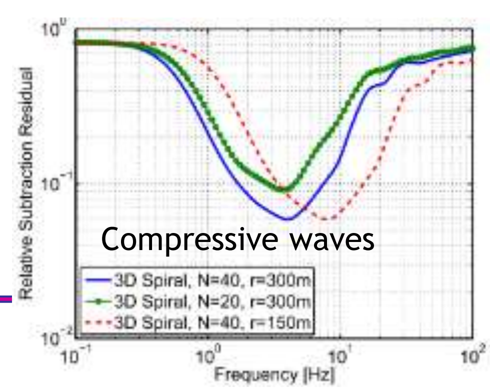




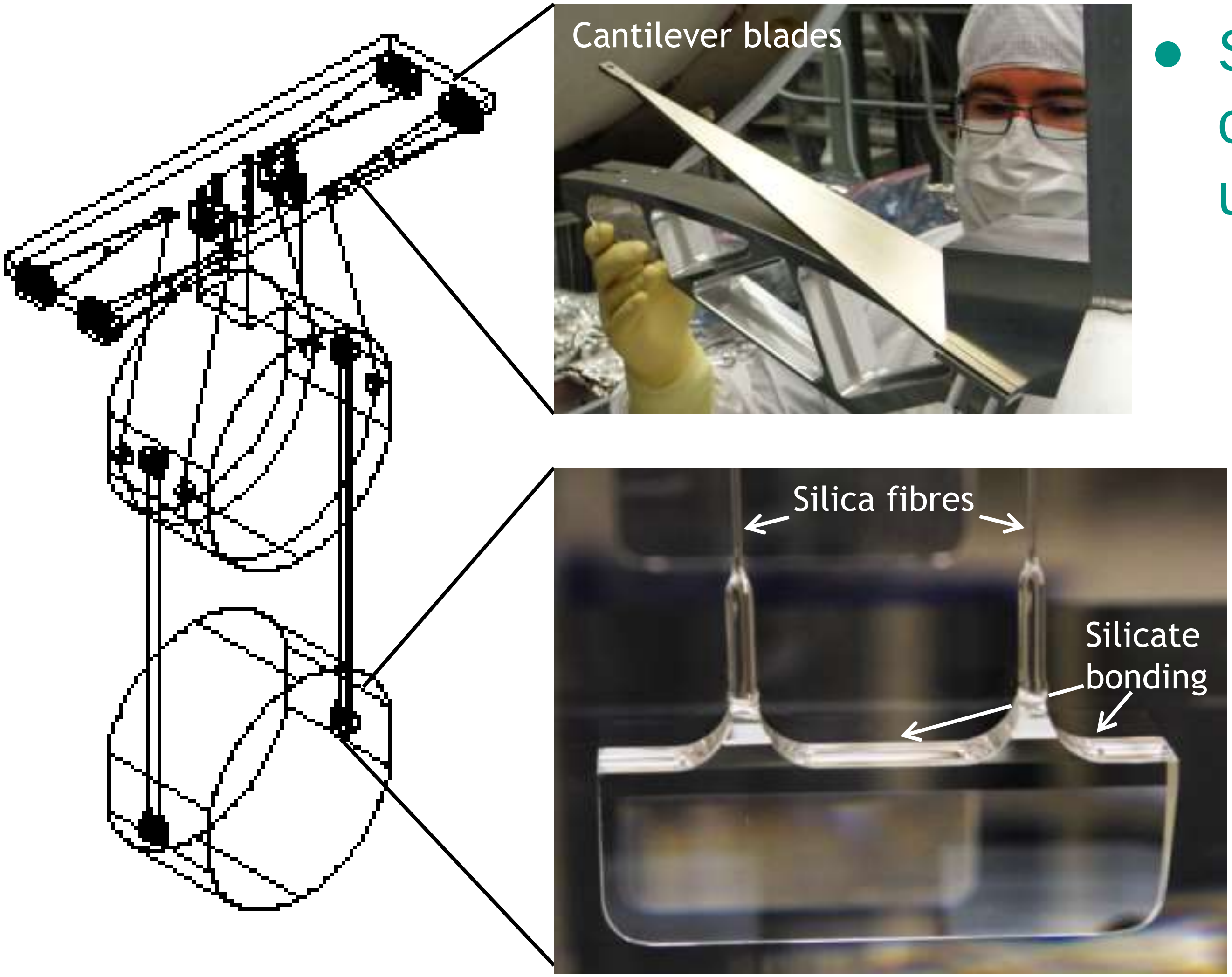
- **Characteristics**
  - Rayleigh waves are strongly attenuated with depth
  - Atmospheric noise important below 10Hz. More investigations needed
- **Cancellation of Newtonian Noise**
  - 2D array of seismometers
  - Wiener filters

IN PREPARATION
Time-Varying Terrestrial Gravity
Jan Harms





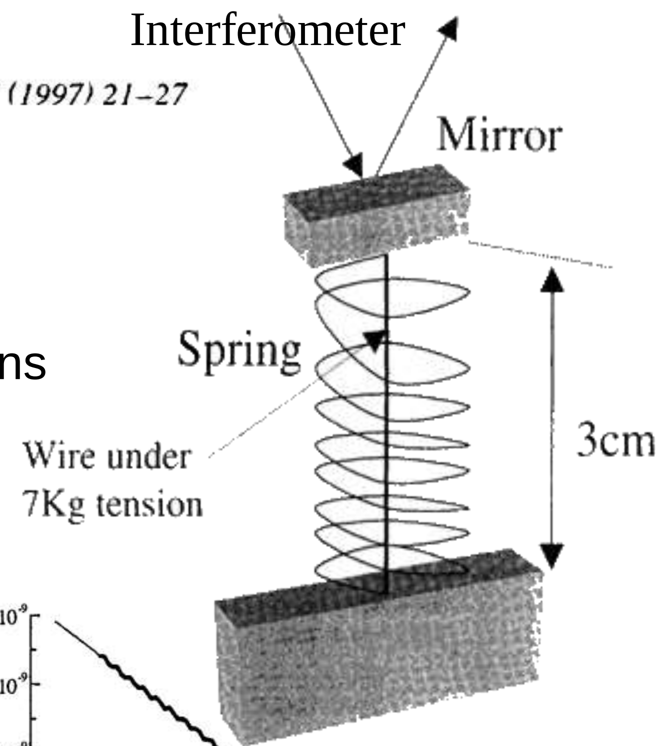
Creep noise



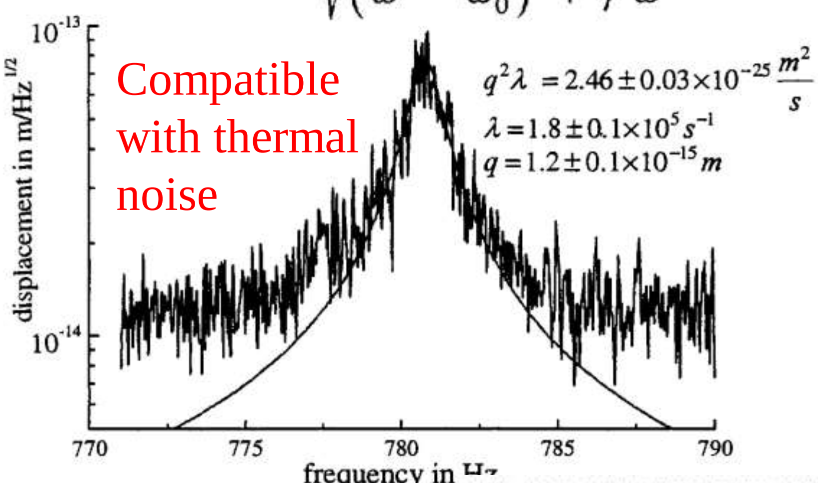
- Several components are under high stress
  - Creep is possible
  - Is it continuous or has it a shot noise like behavior?

Creep noise in wires and fibres

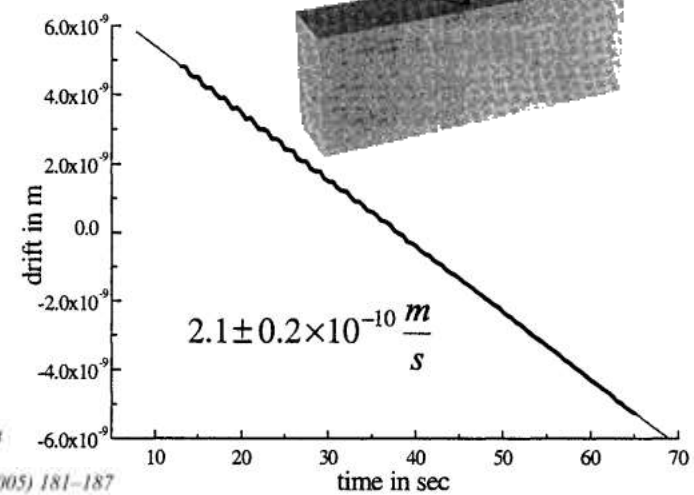
- A simple model *G. Cagnoli et al. / Physics Letters A 237 (1997) 21–27*
  - ♦ Poissonian sequence of wire length steps of magnitude q_S and average rate λ
  - ♦ Vertical to horizontal coupling done through Earth curvature and mechanical imperfections



$$|z(\omega))| \simeq \frac{\omega_0^2}{\sqrt{(\omega^2-\omega_0^2)^2+\gamma^2\omega^2}} \frac{q_S\sqrt{\lambda}}{\omega}$$

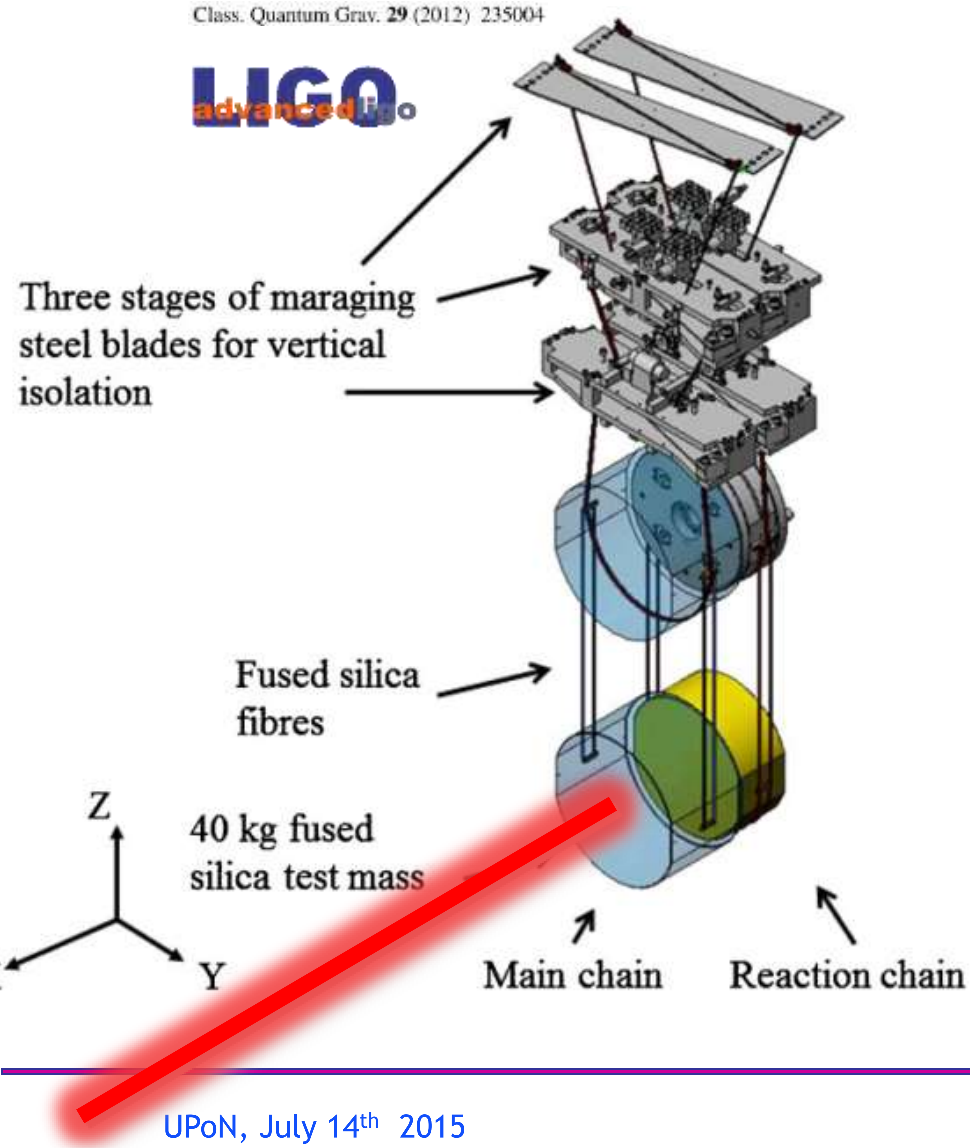


A.Yu. Ageev et al. / Physics Letters A 227 (1997) 159–164



Other works from Moscow U. *I.A. Bilenko, N.Yu. Lyaskovskaya / Physics Letters A 339 (2005) 181–187*

Thermal noise level in GW detectors



- The observable: the position along the laser beam of a portion of the mirror front face

- Reduction of the problem: modal expansion
  - Pendulum thermal noise separated from Mirror thermal noise: OK !
  - Mode expansion not used on mirrors

The FDT

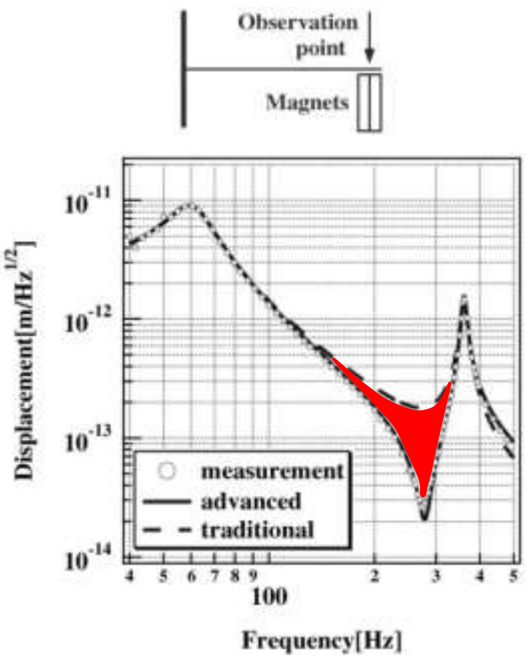
$$G_X(f) = -\frac{4k_B T}{\omega}\,\mathrm{Im}[H_X(\omega)] \qquad H_X(\omega) = \frac{\tilde{X}(\omega)}{\tilde{F}(\omega)}$$

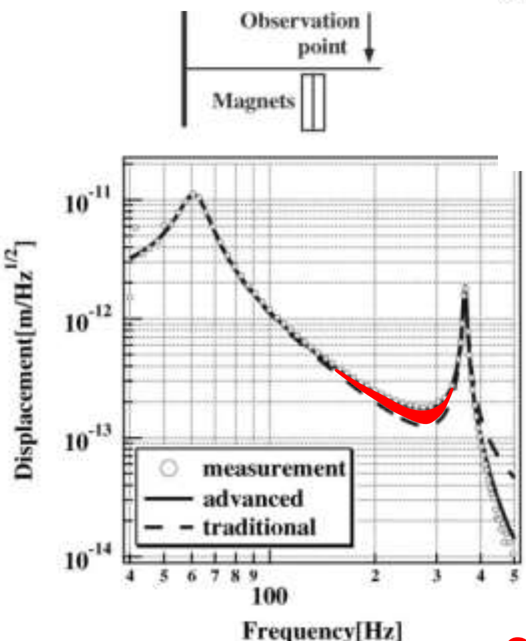
The advanced modal expansion

YAMAMOTO, ANDO, KAWABE, AND TSUBONO PHYSICAL REVIEW D **75**, 082002 (2007)

K. Yamamoto, S. Otsuka, M. Ando, K. Kawabe, and K. Tsubono, Phys. Lett. A **280**, 289 (2001)

$$G_X(f) = \sum_n \frac{4k_B T}{m_n \omega} \frac{{\omega_n}^2 \phi_n(\omega)}{(\omega^2 - {\omega_n}^2)^2} + \sum_{k \neq n} \frac{4k_B T}{m_n m_k \omega} \frac{\alpha_{nk}}{(\omega^2 - {\omega_n}^2)(\omega^2 - {\omega_k}^2)}$$





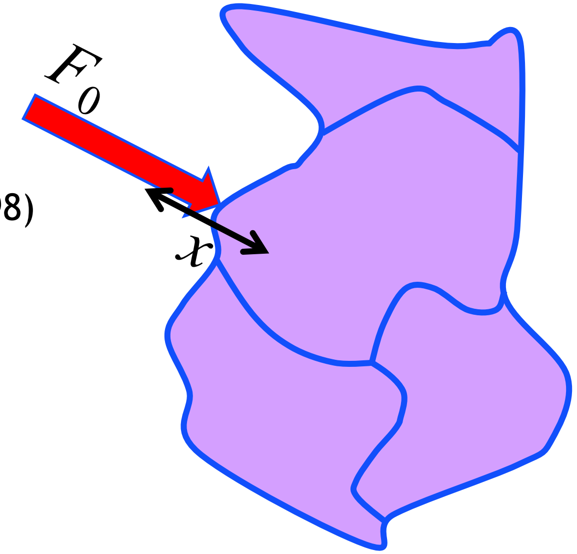
On mirrors the modal expansion is not convenient because of coatings

The Levin's direct approach

Structural loss angle φ:

- E → E·(1 + *i* φ)
  1/f noise
- 0.1 Hz < Freq. <100 kHz
- No viscous elastic model used

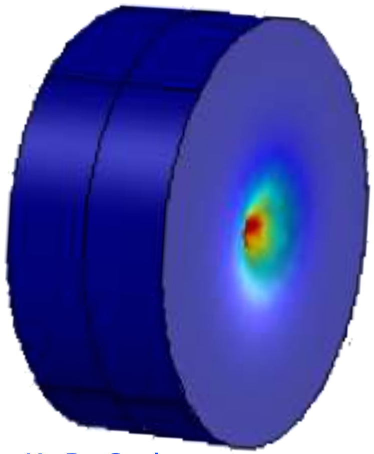
Levin Y., PRD 57, 2, 659 (1998)



$$S_x(f) = \frac{2k_B T}{\pi^2 f^2} \frac{W_{\rm diss}}{F_0^2}$$

$$W_{\rm diss} = \sum_i U_i \cdot \phi_i$$

$U_{\rm i}$ is the static strain energy of part i
$\varphi_{\rm i}$ is the loss angle associated to the material of part i



Applied to the mirror thermal noise immediately:

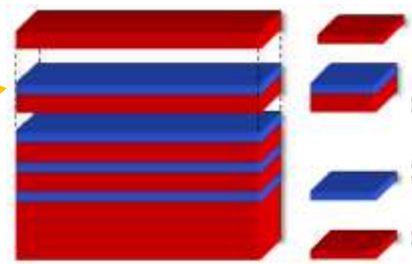
F. Bondu, P. Hello, and J-Y. Vinet, Phys. Lett. A **246**, 227 (1998)

K. R. Corley, NAOJ

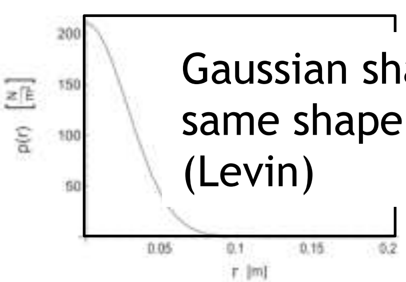
IMPORTANCE OF LEVIN'S FORMULA COMES IN COATED MIRRORS

The coating thermal noise

- Optical Interference Coatings are used to reflect light with sub ppm absorption of light
- Transparent materials with different refractive indexes:
  - Silica SiO_2: n ~ 1.4
  - Tantala Ta_2O_5: n ~ 2.1
  - 18 pairs for 99.999% reflection (~6µm total)

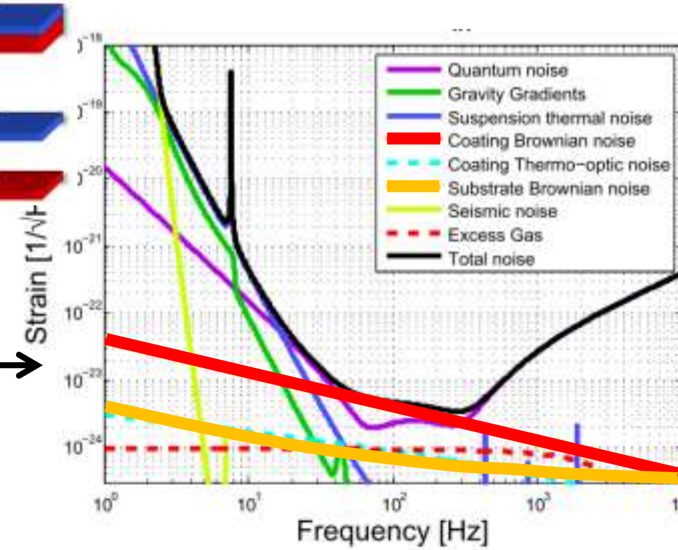


G. Harry *et al.*, Classical Quantum Gravity **19**, 897 (2002)



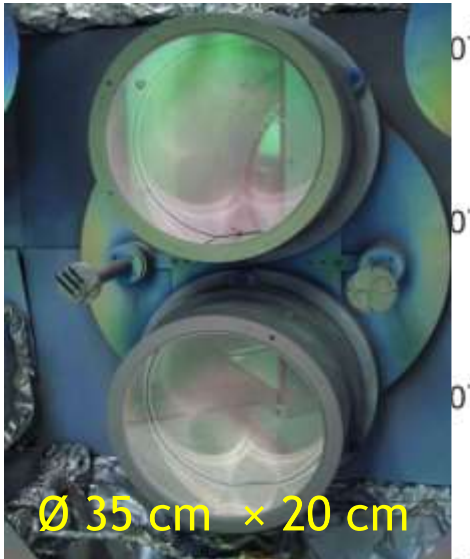
Gaussian shaped pressure same shape as beam intensity (Levin)

(Poisson ratio = 0)



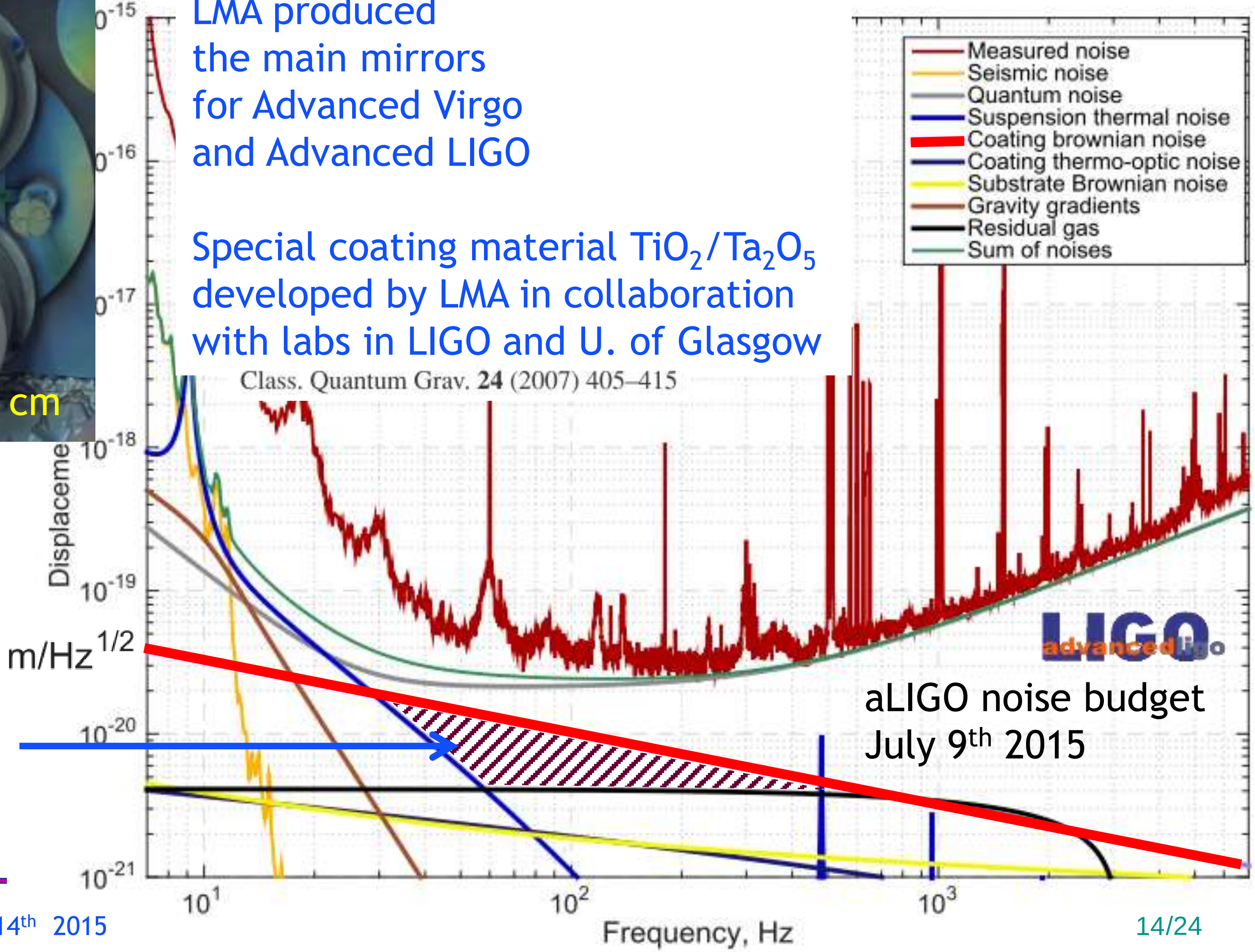
$$S_x(f) = \frac{2k_BT}{\pi^{3/2}f}\frac{1}{wY}\left\{\phi_{\text{substrate}} + \frac{1}{\sqrt{\pi}}\frac{d}{w}\left(\frac{Y'}{Y}\phi_\parallel + \frac{Y}{Y'}\phi_\perp\right)\right\}$$

The Advanced detectors start taking data



LMA produced
the main mirrors
for Advanced Virgo
and Advanced LIGO

Special coating material TiO_2/Ta_2O_5
developed by LMA in collaboration
with labs in LIGO and U. of Glasgow

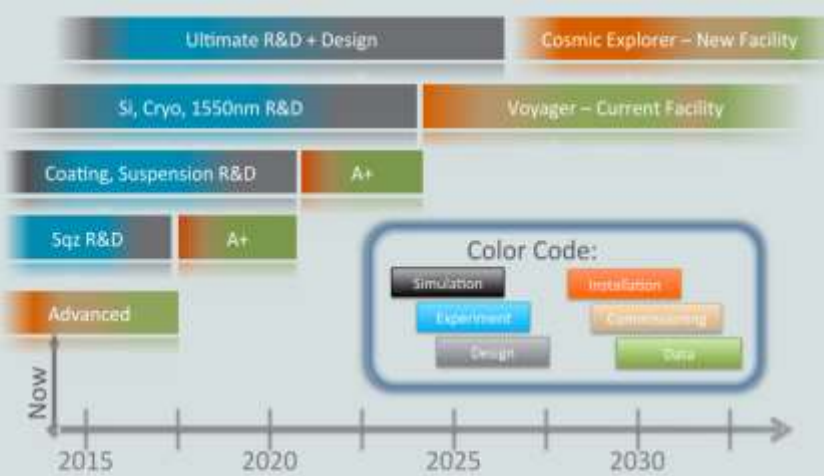


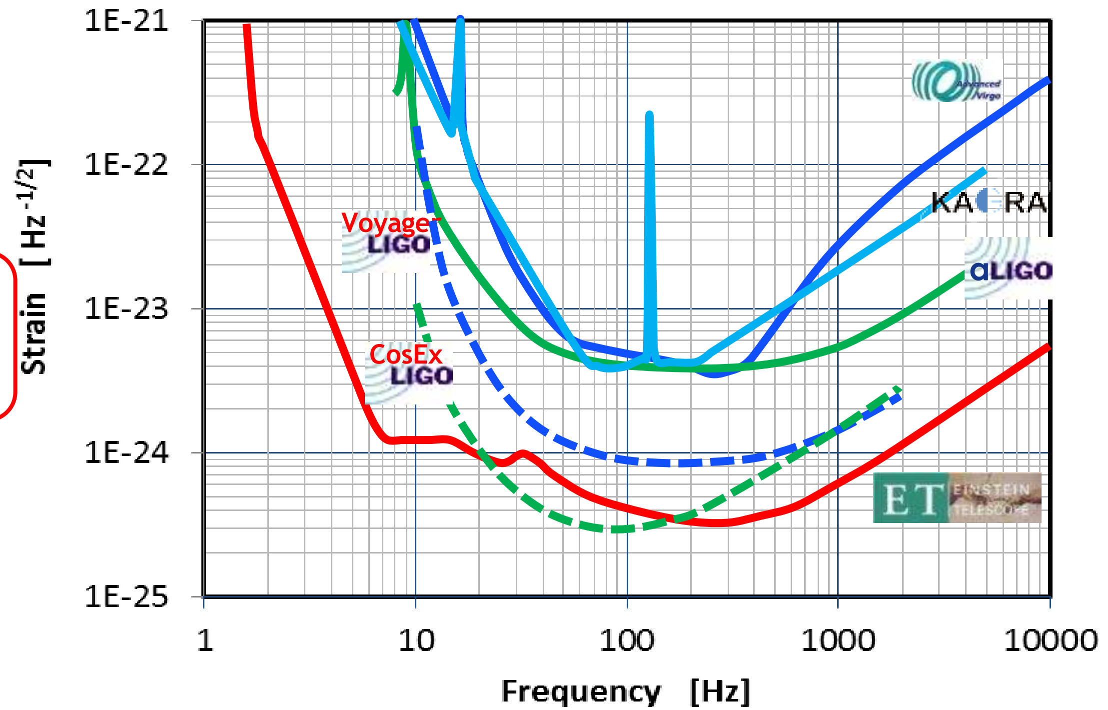
The future of GW detectors

- LIGO
  - Voyager: 4km, **larger mirrors cryogenic**
  - Cosmic Explorer: 40km, **larger mirrors**
- Einstein Telescope
  - 10 km long
  - **200 kg mirrors**
  - 2 types of detectors
    - **Room T**, HF
    - **Cryogenic T**, LF
- Lower mechanical losses
  - Factor 3 at least

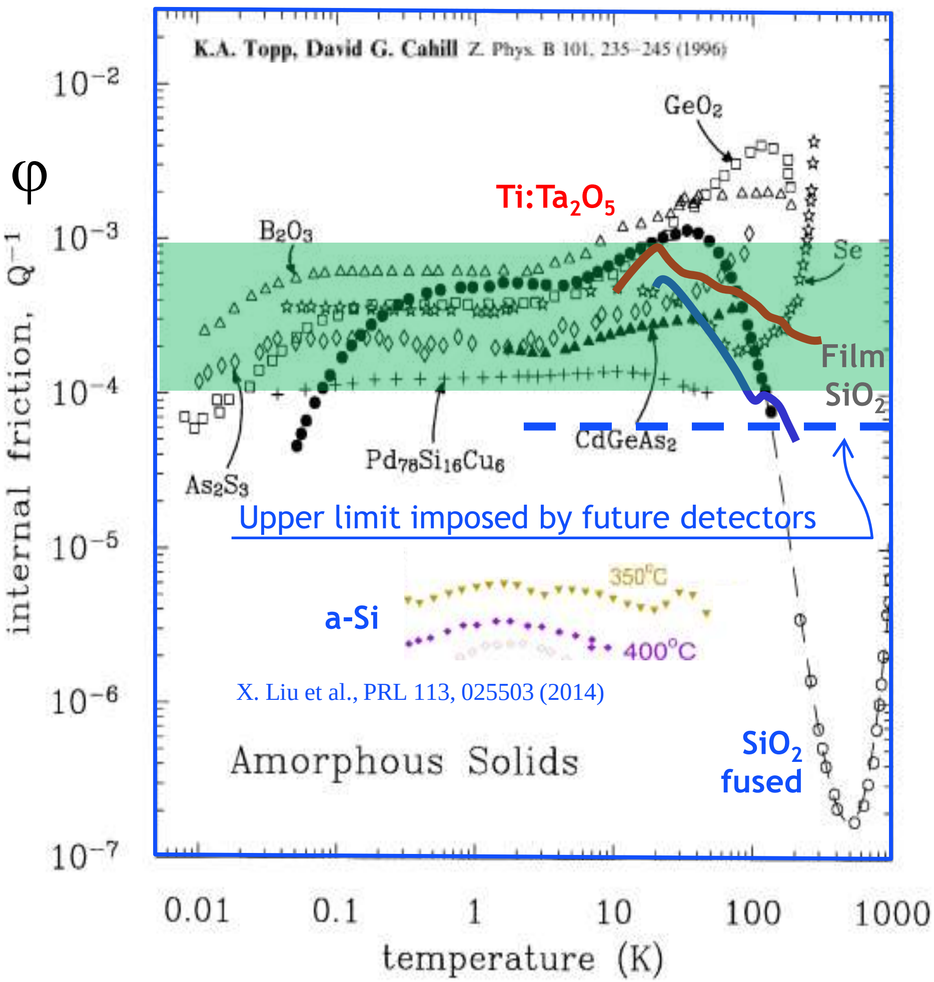
FOR ALL

Maximum distance of detection
NS-NS Binaries ~ z = 2
BH-BH Binaries ~ z = 17

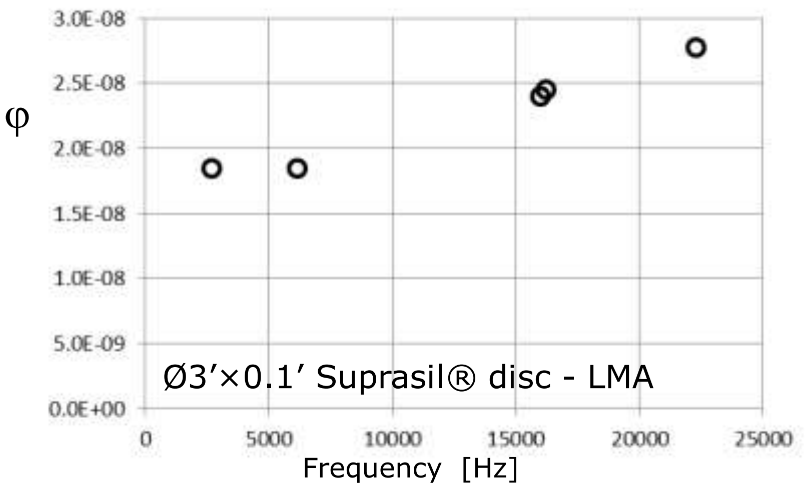




The amorphous materials wall

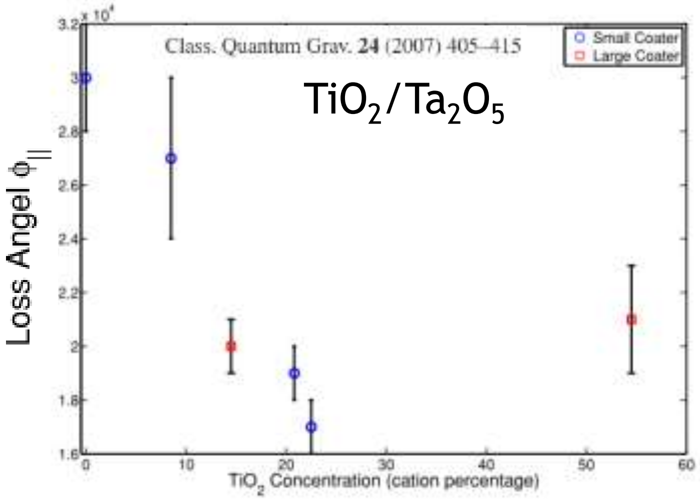


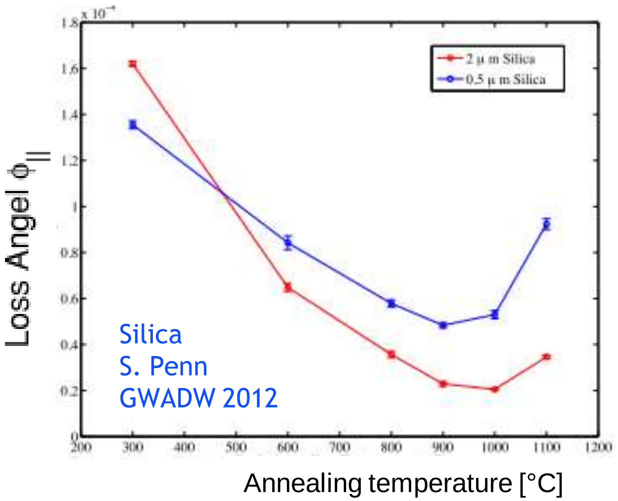
- Almost all the amorphous materials have a loss angle between 10^{-4} and 10^{-3}
- “Anomalies” are found in fused silica at room T and in amorphous Si low T



Open problems in coatings noise

- Bulk losses
  - Are losses in films anisotropic?
  - Shear and bulk ?
- Interface losses
  - If any they are not dominant
- Mixing oxides
  - Why the internal friction is reduced for some particular combination of oxides?
- Annealing
  - Annealing reduces mechanical losses
  - How to avoid crystallization?
- Origin of thermal noise in amorphous materials
  - Universal law?

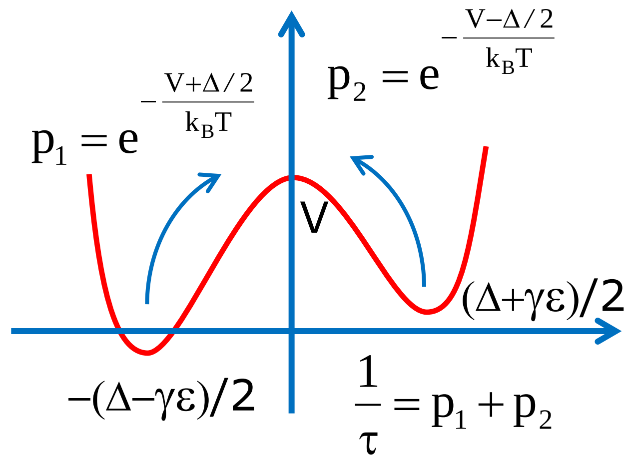




A phenomenological model

K. S. Gilroy and W. A. Phillips Philosophical Magazine B, 1981, Vol. 43, No. 5, 735–746

- Asymmetric Double Well Potential (ADWP)
  - 2 energy levels at +Δ/2 and -Δ/2, divided by a barrier of height V
  - The strain ε changes Δ, τ is the typical relaxation time between the two equilibrium populations
  - The modulus defect ΔY and the time τ are:



$$\Delta Y(\Delta) = \frac{N\gamma^2}{4k_B T} \cdot \mathrm{sech}^2\left(\frac{\Delta}{2k_B T}\right) \qquad \tau = \tau_0 \,\mathrm{sech}\left(\frac{\Delta}{2k_B T}\right) \exp\left(\frac{V}{k_B T}\right),$$

  - There are two distributions: f(Δ) and g(V)

Agreement with data

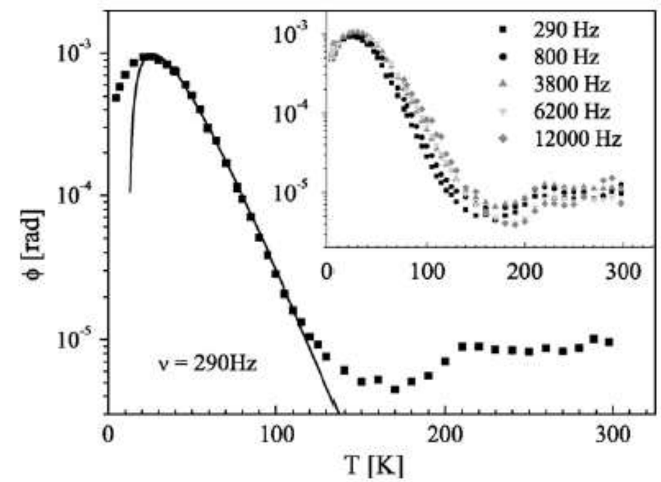
- $\Delta Y \neq 0$ for $\Delta \sim 0$:
  f(Δ) is assumed cnst.

$$\varphi(\omega)=\iint \frac{\Delta Y(\Delta)}{Y_R}\cdot\frac{\omega\tau_{V,\Delta}}{1+\left(\omega\tau_{V,\Delta}\right)^2}\cdot f(\Delta)\cdot g(V)\; d\Delta\, dV$$

- g(V) exponential:
  - It seems the right choice for fused silica

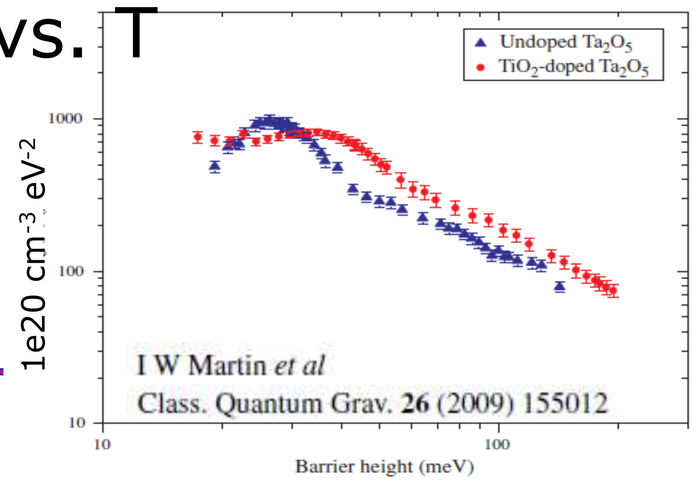
$$\varphi(\omega)=\frac{\pi}{4}\frac{\gamma^2}{Y_R}\cdot\frac{1}{\Delta_0}\cdot\frac{n}{V_0}\cdot k_B T\cdot(\omega\tau_0)^{\frac{k_B T}{V_0}}$$

- For Ta_2O_5 or SiO_2 film g(V) comes from the curve loss angle vs. T



Materials Science and Engineering A 521–522 (2009) 268–271
F. Travasso et al.

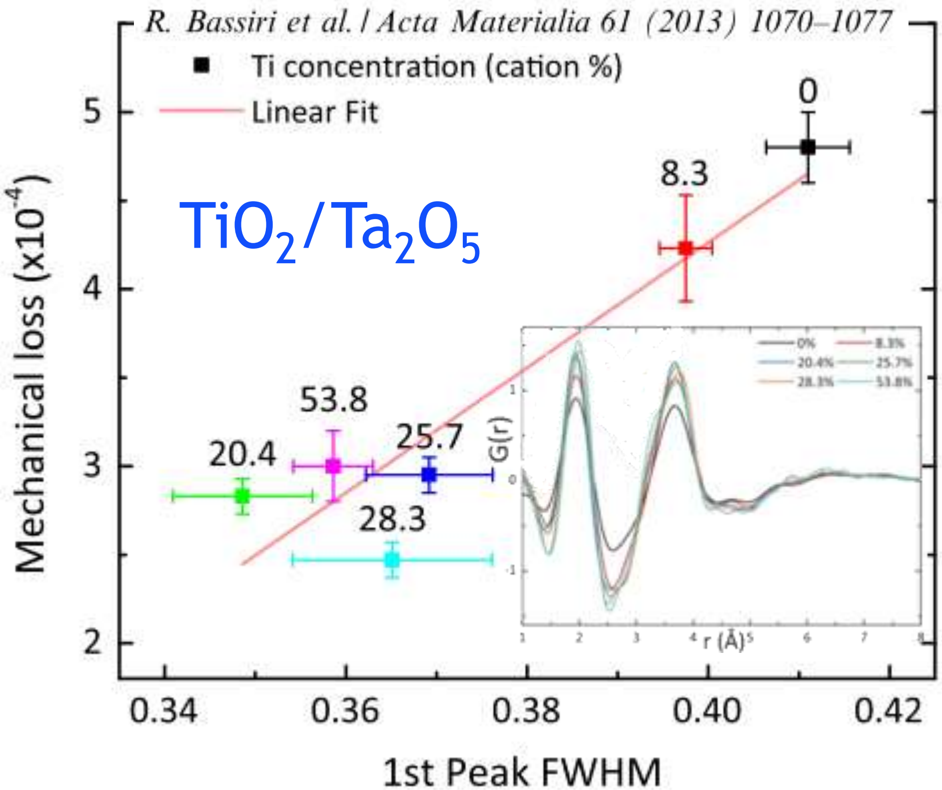
What are these relaxation mechanisms?

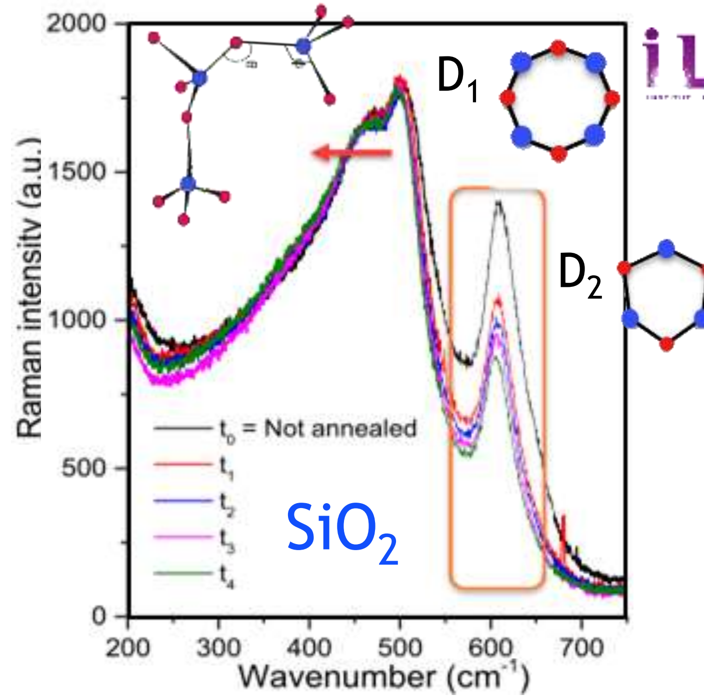


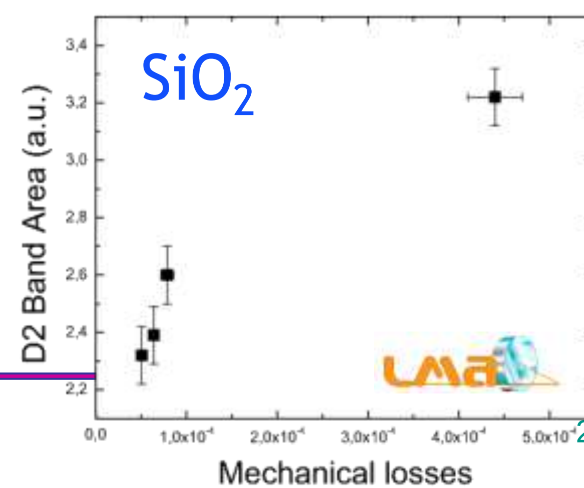
Structure investigations

- Correlation studies
  - RDF, varying fraction of TiO2
  - Raman, varying annealing time

AND YET, WHAT ARE THE RELAXATIONS ?

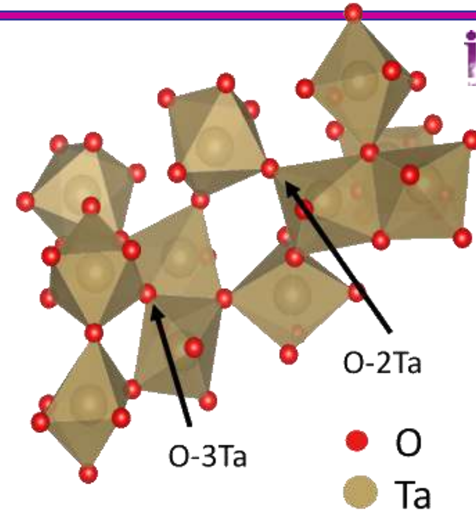


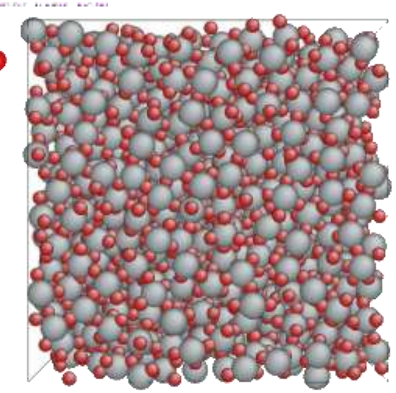


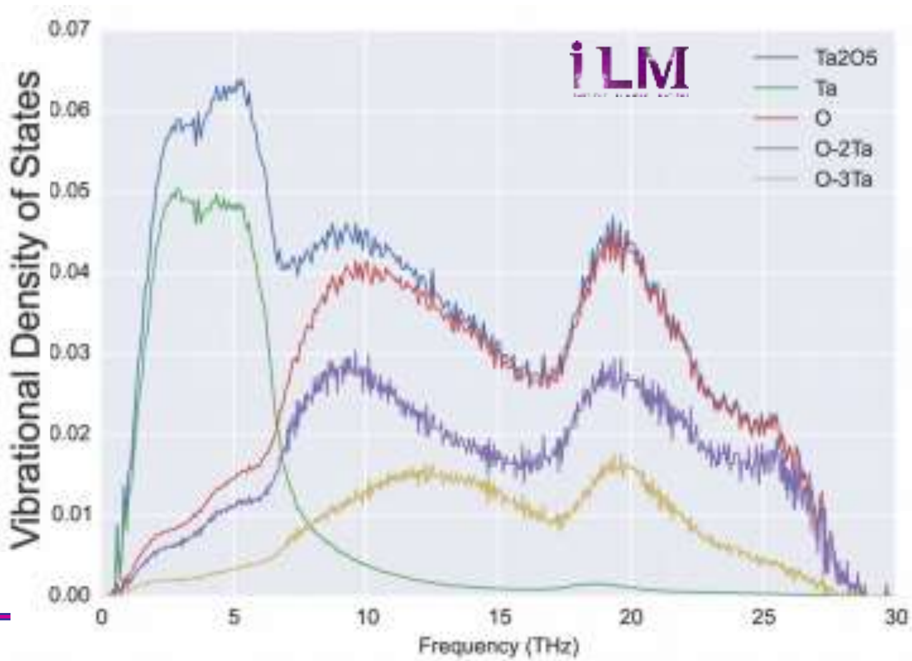


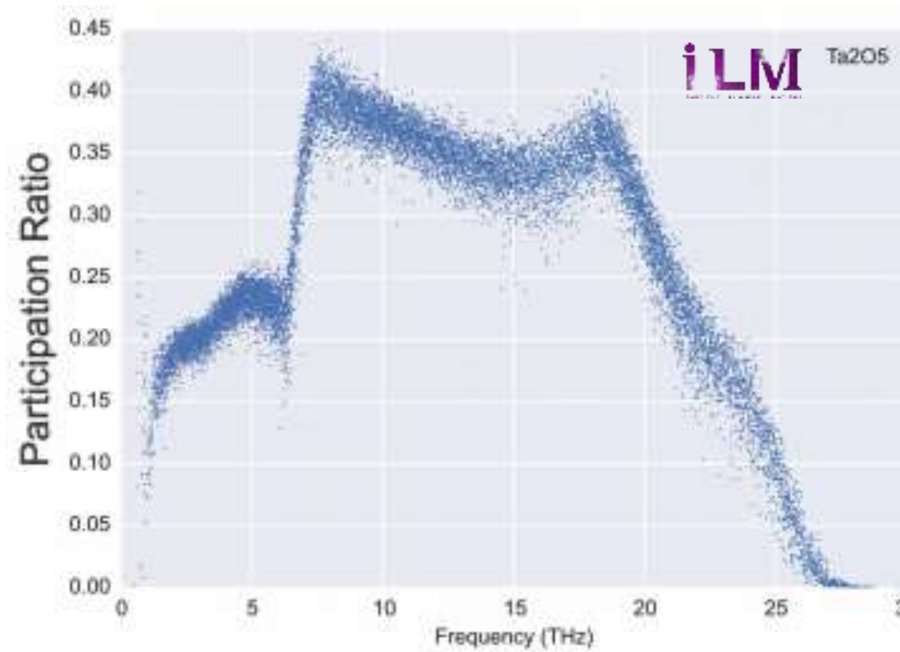
Structure modeling

- Molecular dynamics
  - Structure
  - Density and elastic constants
  - Vibrational properties
  - Relaxations ?





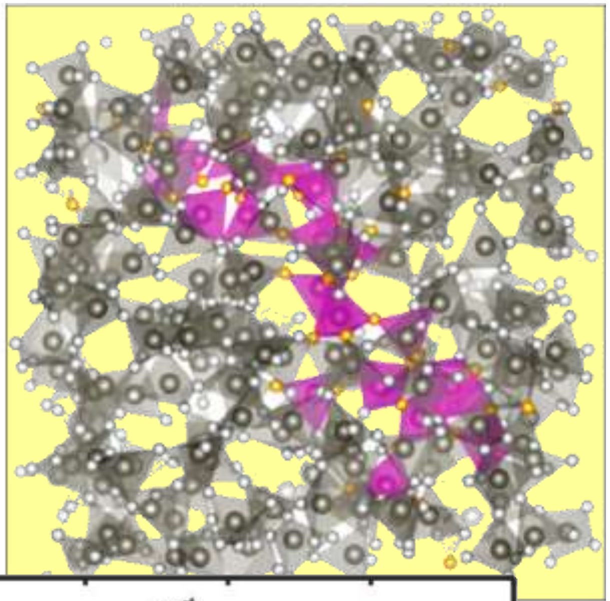


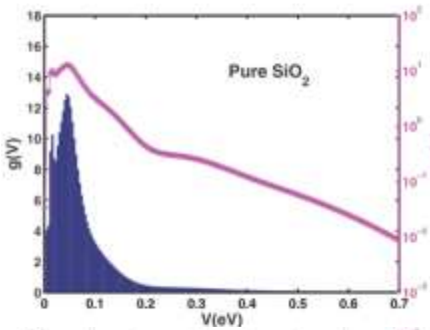


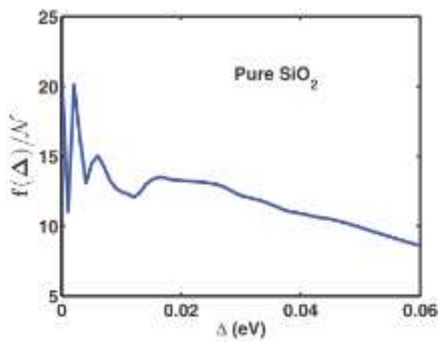
Calculation of losses by MD

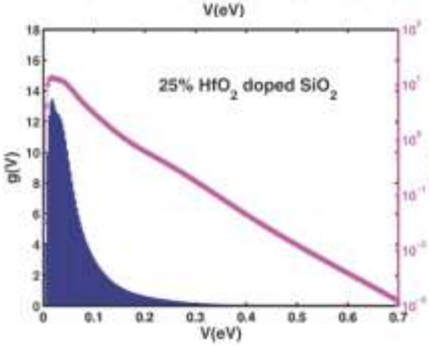
Hamdan, Trinastic, and Cheng J. Chem. Phys. **141**, 054501 (2014)

- Calculation partially based on the ADWP
  - Identification of the relaxation mechanisms
  - Estimation of f(Δ) and g(V)
  - Estimation of the deformation potential γ
  - Finally, calculation of loss angle φ

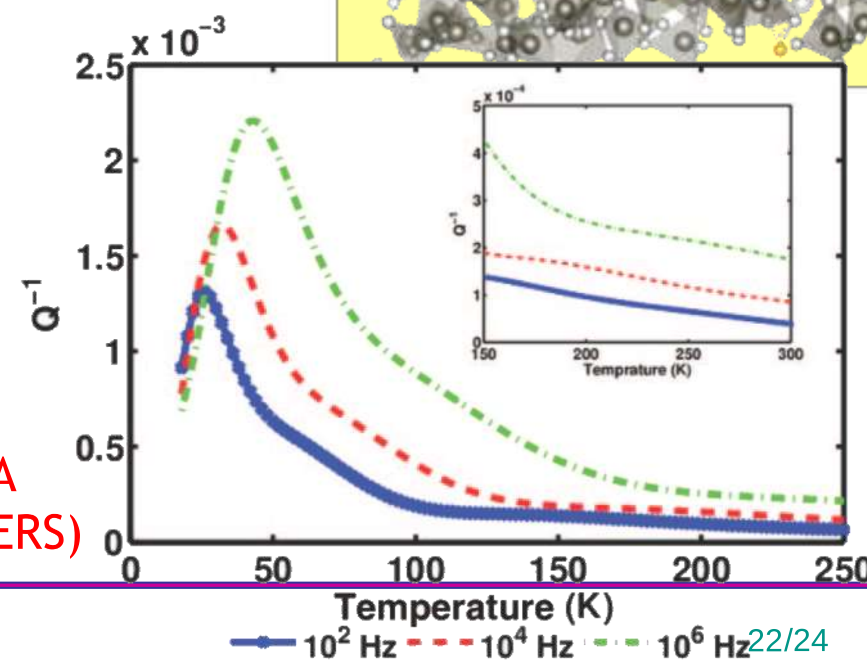






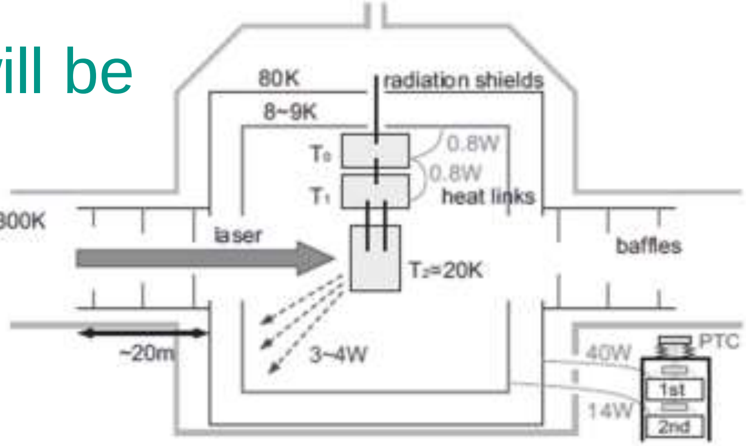


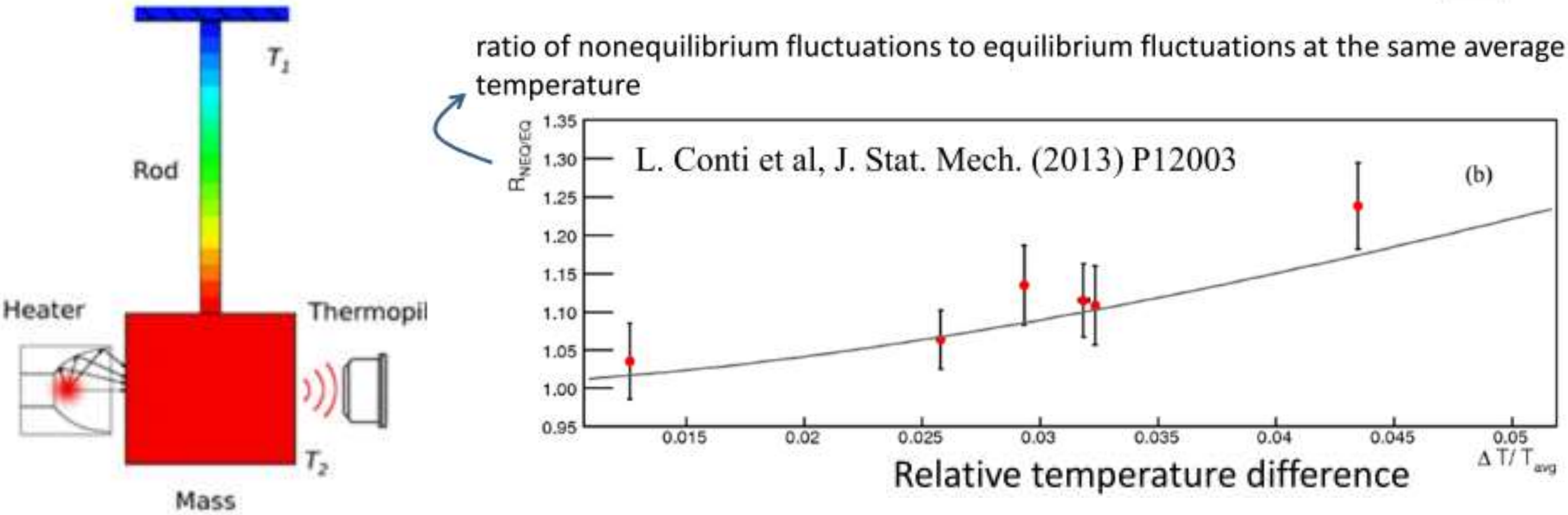
ENCOURAGING AGREEMENT WITH EXPERIMANTAL DATA (SLIDE 19 AND OTHERS)



The known unknown

- In GW future detectors there will be thermal gradients
  - www.rarenoise.lnl.infn.it
  - How to control it? Th.Ns reduction
  - What is the role of the materials?





Last comments

- Among other topics I have not talked about:
  - ♦ Suspension Th. Noise
  - ♦ Crystalline coatings
  - ♦ Thermorefractive noise in semiconductors

- Unsolved problems presented here
  - ♦ Newtonian noise cancellation
  - ♦ Existence of creep noise
  - ♦ Origin of relaxations in amorphous materials
  - ♦ Thermal noise out of thermal equilibrium

Thank you for your attention