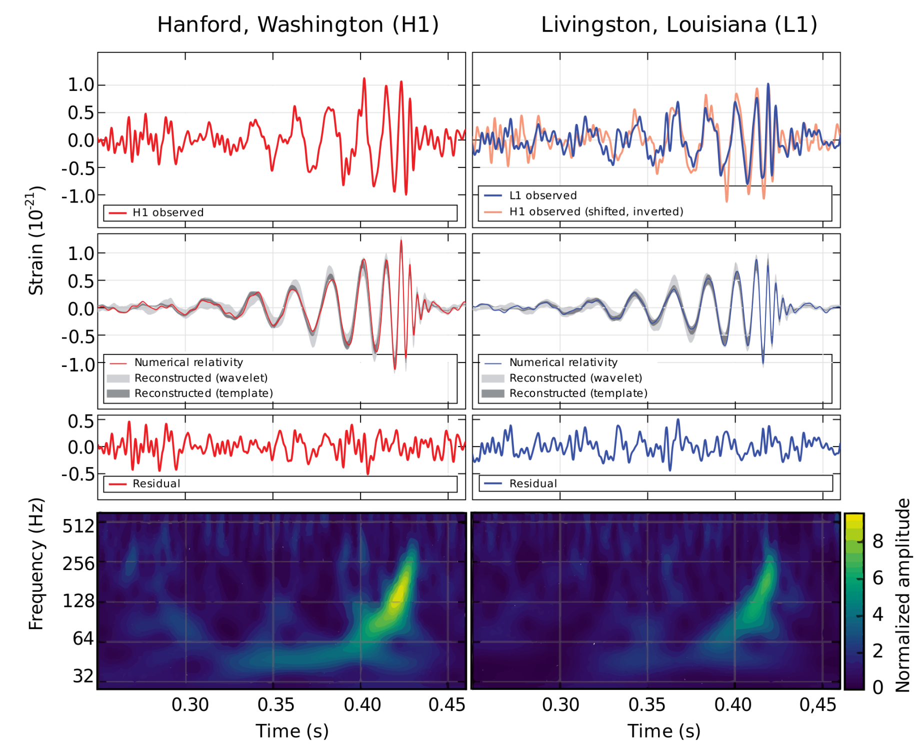
Coatings research for current and future Gravitational Wave detectors

F. Puosi

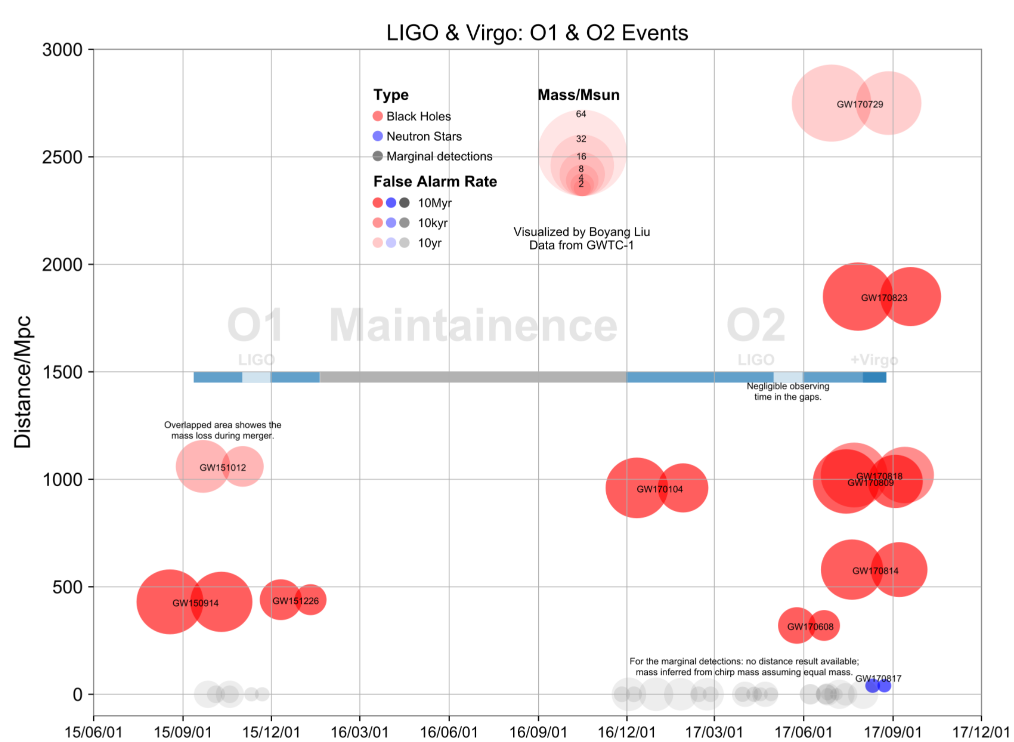
INFN Pisa

A storm of waves

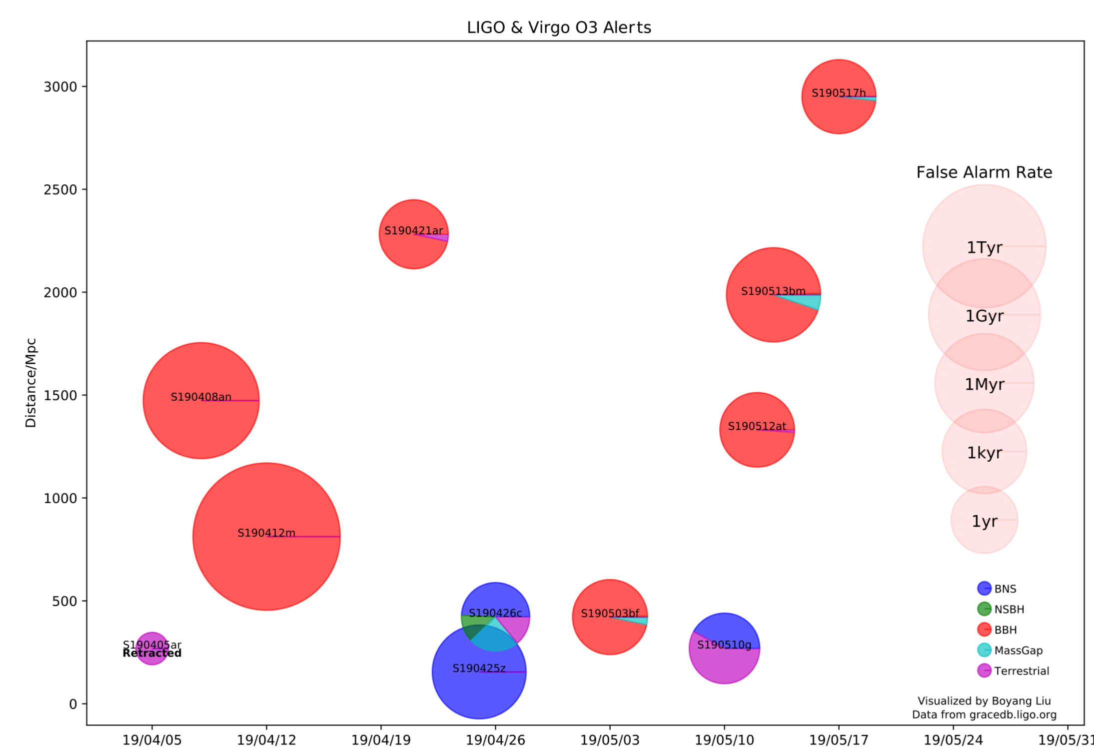
On 15th September 2015, LIGO interferometers directly sensed the distortions in spacetime caused by passing GWs generated by two colliding black holes nearly 1.3 billion light years away.



Phys. Rev. Lett. **116** 061102 (2016)

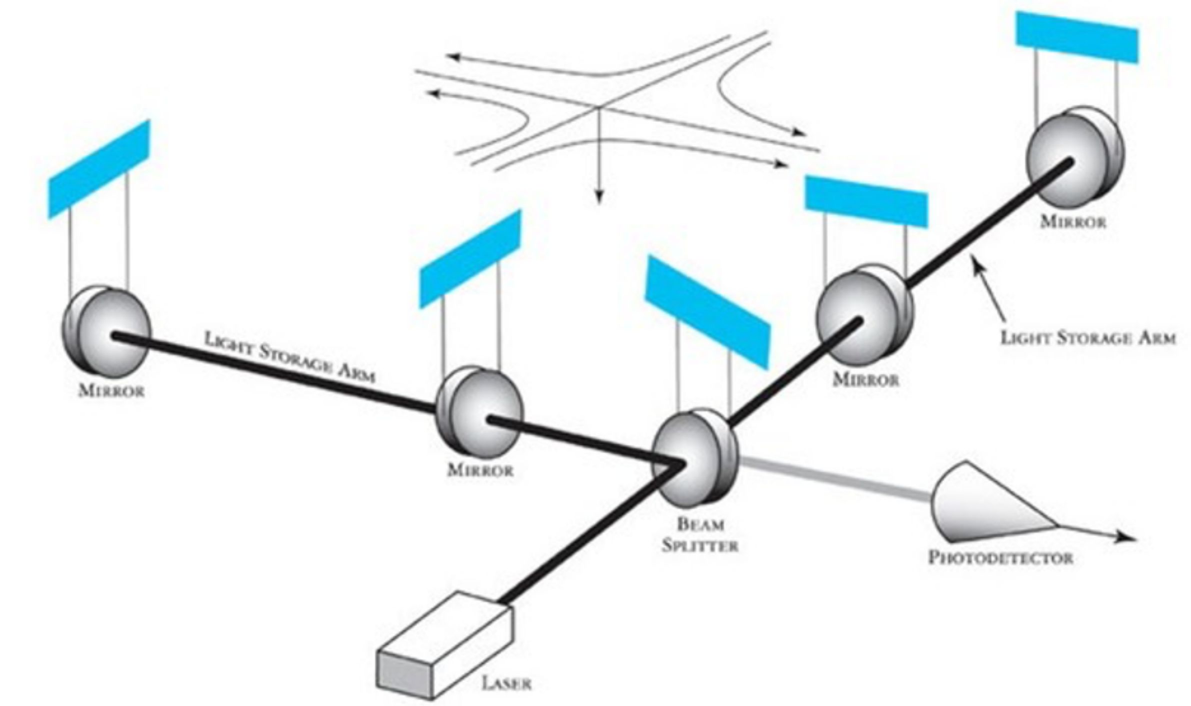


O1 & O2/2015-2017 events



O3/2019 alerts

The right instrument: GW interferometer



Inherently differential

“Easy” to scale up

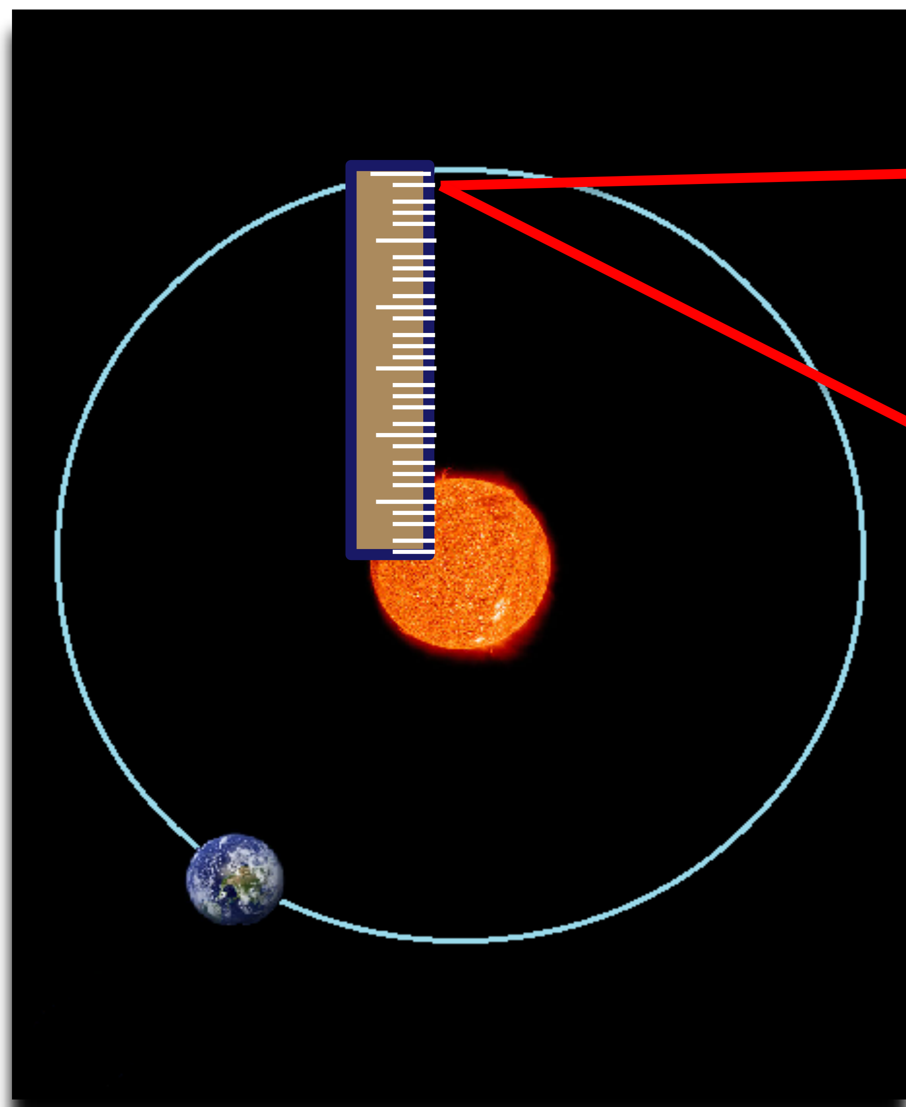
Broadband

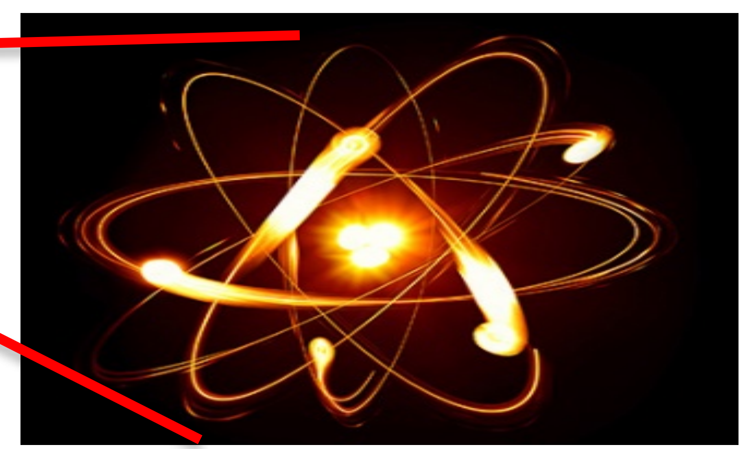
The winning team:

A small displacement... really small

$$\frac{\textbf{Length variation}}{\textbf{Length}} \approx 10^{-21}$$

Equivalent to measure a displacement of the size of one atom compared to the Earth – Sun distance!

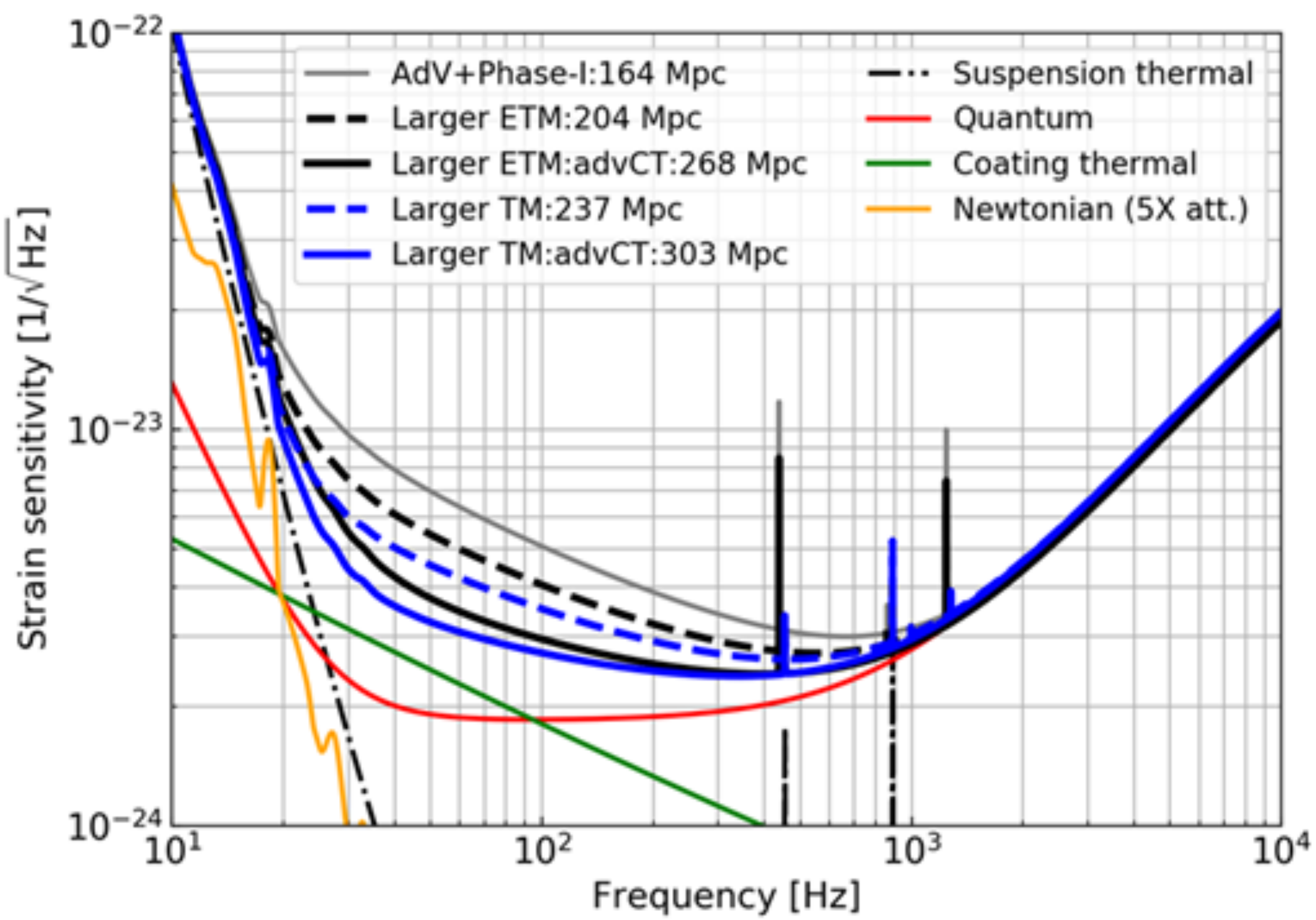




Need to be sure that nothing else is moving the mirrors by this tiny amount: ground vibrations, for example, are billions of times too big!

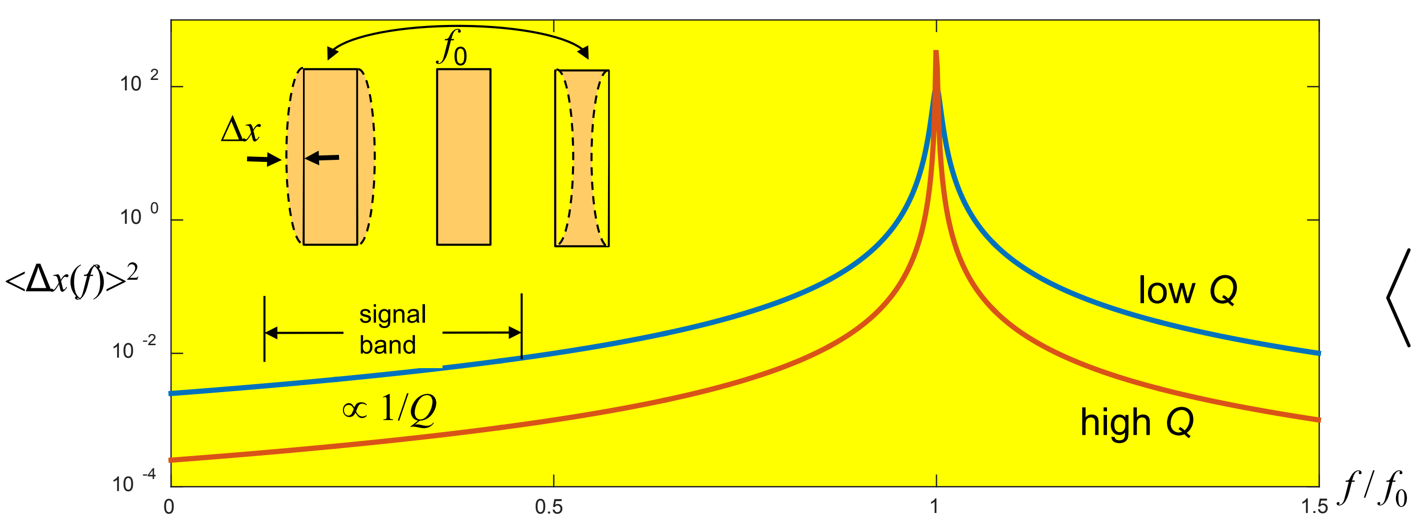
The Coating Thermal Noise issue

VIRGO sensitivity (from the AdV+ roadmap)



Coating Thermal Noise (CTN) limits the detection band in the “bucket“ (middle frequencies) which is the most sensitive region of the GW detectors.

Oversimple picture: KT of energy per mechanical mode, viscous damping - moves front of the mirror with respect the center of mass



CTN power spectrum:

$$\langle \Delta x(f,T)^2 \rangle \approx \frac{2k_B T}{\pi^2 f} \frac{d}{w^2 Y} \phi(f)$$

temperature

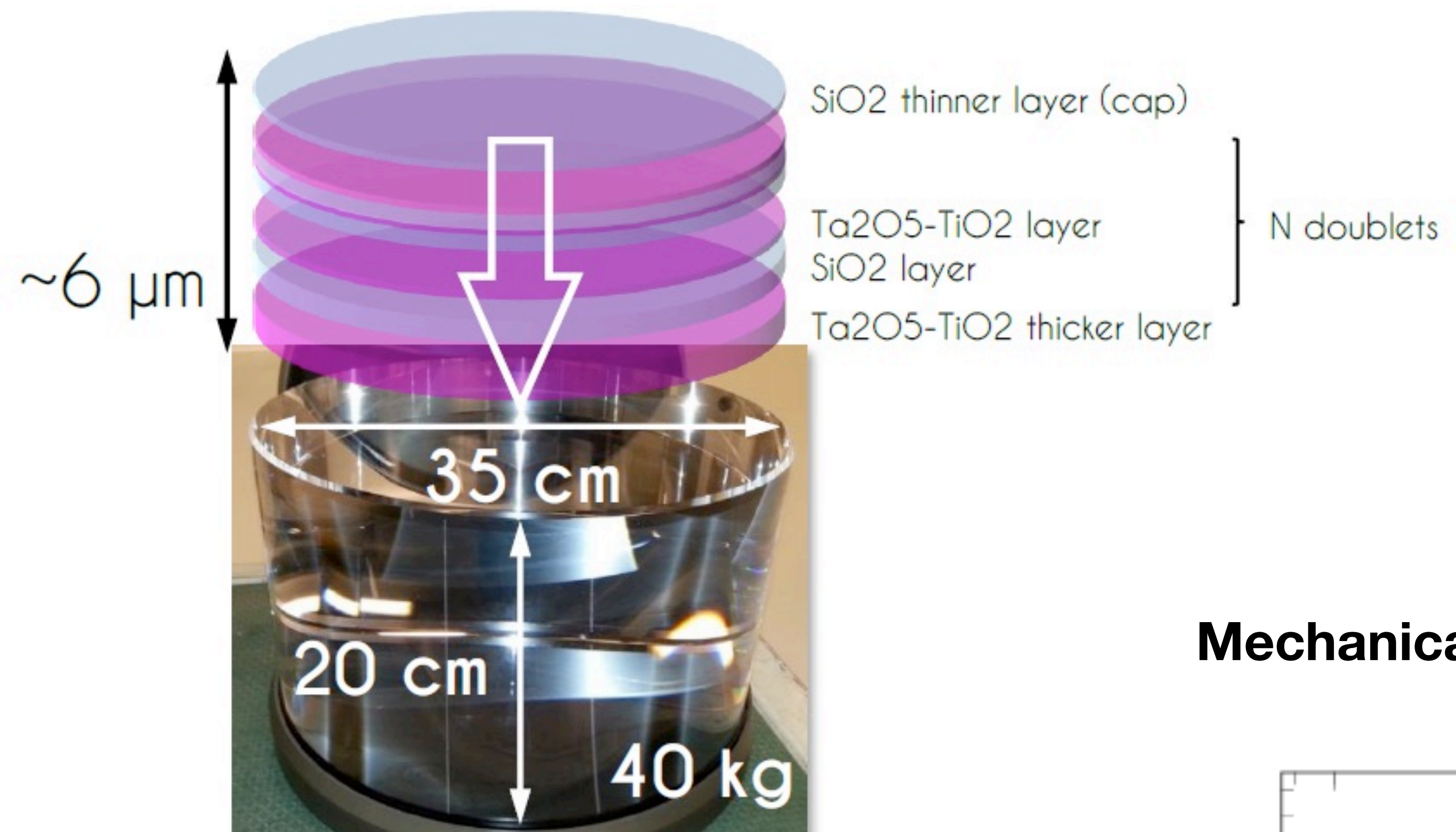
coating thickness

beam radius

Young modulus

elastic loss

State of the art

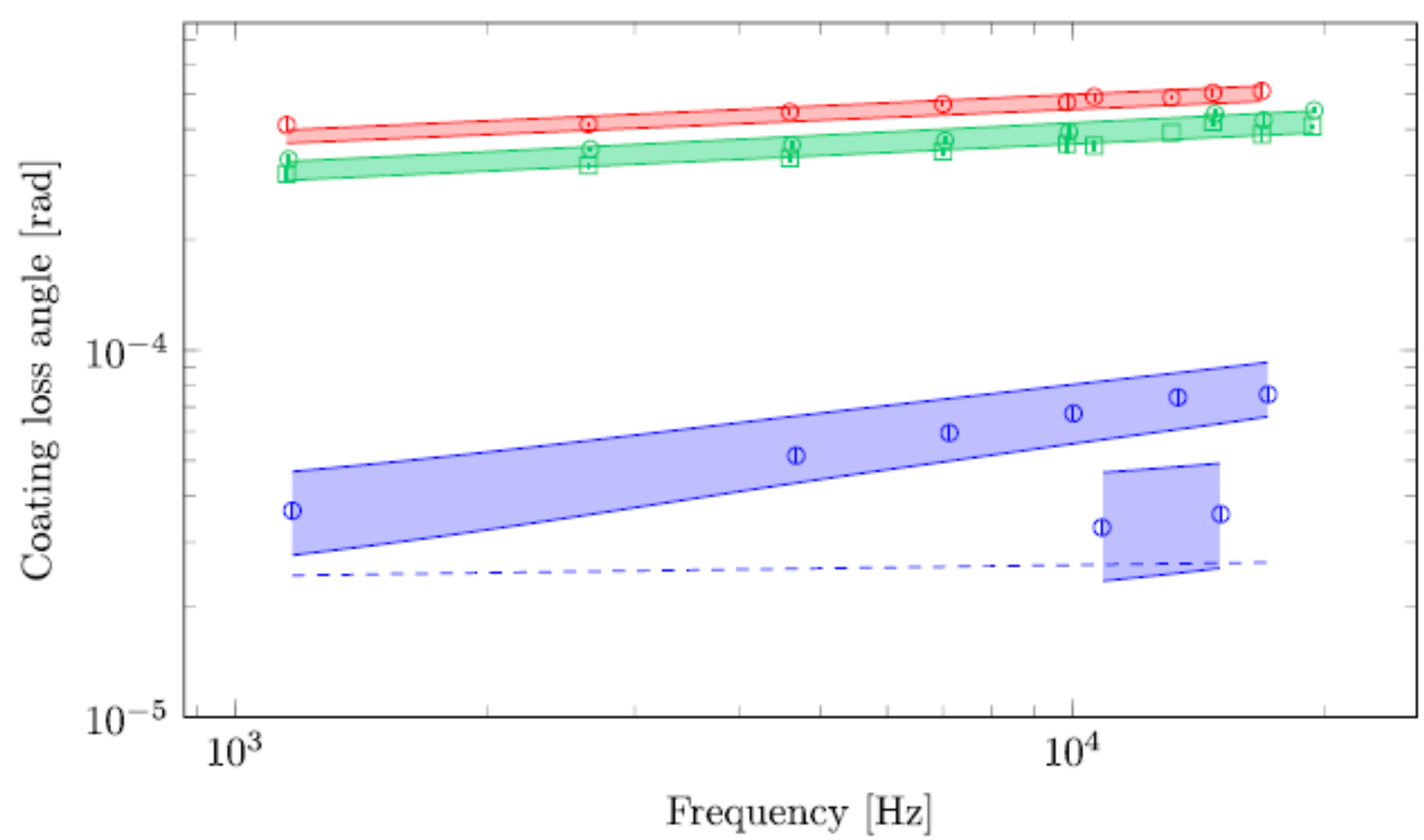


Amorphous coatings deposited by Ion Beam Sputtering (IBS)

Ti:Ta_2O_5	High Index (n=2.05-2.09)
SiO_2	Low Index (n=1.44-1.47)

10 mm of coating produces more thermal noise than 10 cm of substrate.

Mechanical loss angle after deposition and thermal treatment



Granata et al, Class. Quantum Grav. 37 (2020)

How can we do better?

Developing new coating materials for AdV+

- Factor 3 reduction of coating losses is targeted
- Same absorption and scattering

A recipe

- A material
- A deposition method
- A post-deposition treatment

Oxides

- Oxides
- Mixing
- High Index Silica Glasses

New materials

- Nitrides
- Fluorides
- High Coordination Number Glasses SiN, GaN, SiC, etc

Materials

Deposition

- High Temperature
- Nano-layering
  - High index
  - Low index
  - HR stack

Absorption and Metrology

- Origin of absorption
- Loss measurement protocol
- Thermo-elastic effect

Post-deposition treatments

- Annealing
- Outgassing and chemical status
- Controlled crystallization

The different activities

Synthesis

- Coating deposition
- Heat treatments

Modeling

- Structure
- TLS relaxations

Macroscopic characterization

- Q measurements
- Absorption measurements
- Dielectric response
- Elastic constants
- Density

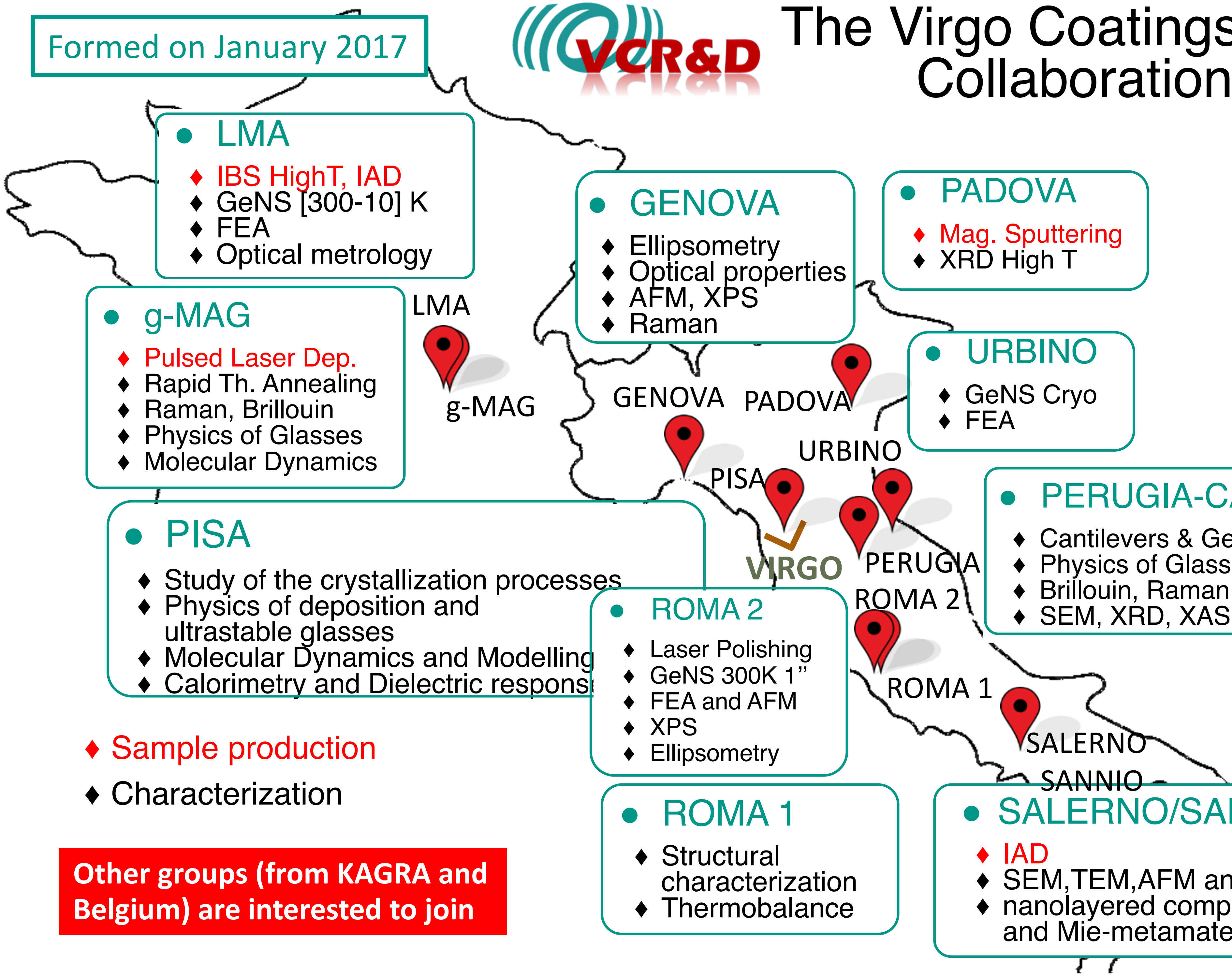
Microscopic characterization

- TEM, SEM
- Raman, Brillouin
- XRD, XPS, XAS
- AFM

The Virgo Coatings R&D collaboration

The Virgo Coatings R&D Collaboration

Formed on January 2017



- **LMA**
  - ♦ IBS HighT, IAD
  - ♦ GeNS [300-10] K
  - ♦ FEA
  - ♦ Optical metrology

- **g-MAG**
  - ♦ Pulsed Laser Dep.
  - ♦ Rapid Th. Annealing
  - ♦ Raman, Brillouin
  - ♦ Physics of Glasses
  - ♦ Molecular Dynamics

- **GENOVA**
  - ♦ Ellipsometry
  - ♦ Optical properties
  - ♦ AFM, XPS
  - ♦ Raman

- **PADOVA**
  - ♦ Mag. Sputtering
  - ♦ XRD High T

- **URBINO**
  - ♦ GeNS Cryo
  - ♦ FEA

- **PISA**
  - ♦ Study of the crystallization processes
  - ♦ Physics of deposition and ultrastable glasses
  - ♦ Molecular Dynamics and Modelling
  - ♦ Calorimetry and Dielectric response

- **PERUGIA-CAMERINO**
  - ♦ Cantilevers & GeNS Cryo
  - ♦ Physics of Glasses
  - ♦ Brillouin, Raman
  - ♦ SEM, XRD, XAS

- **ROMA 2**
  - ♦ Laser Polishing
  - ♦ GeNS 300K 1”
  - ♦ FEA and AFM
  - ♦ XPS
  - ♦ Ellipsometry

- **ROMA 1**
  - ♦ Structural characterization
  - ♦ Thermobalance

- **SALERNO/SANNIO**
  - ♦ IAD
  - ♦ SEM,TEM,AFM and XRD
  - ♦ nanolayered composites and Mie-metamaterials

♦ Sample production

♦ Characterization

Other groups (from KAGRA and Belgium) are interested to join

Credits: G. Cagnoli

Molecular Dynamics, a theoretical guidance

Simulations and **modeling** are standard tools for studying glasses and can be of help in the material selection:

- computation of losses (quality factor)

- microscopic characterization of loss mechanisms

- modeling of deposition methods

- estimate of crystallization and glass transition temperature

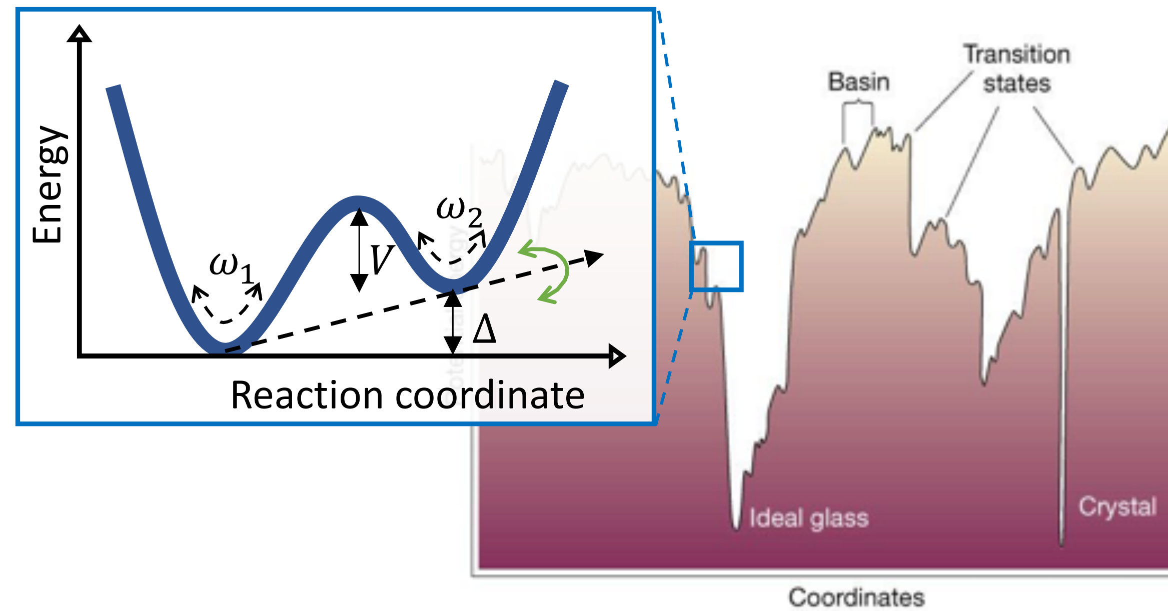
…

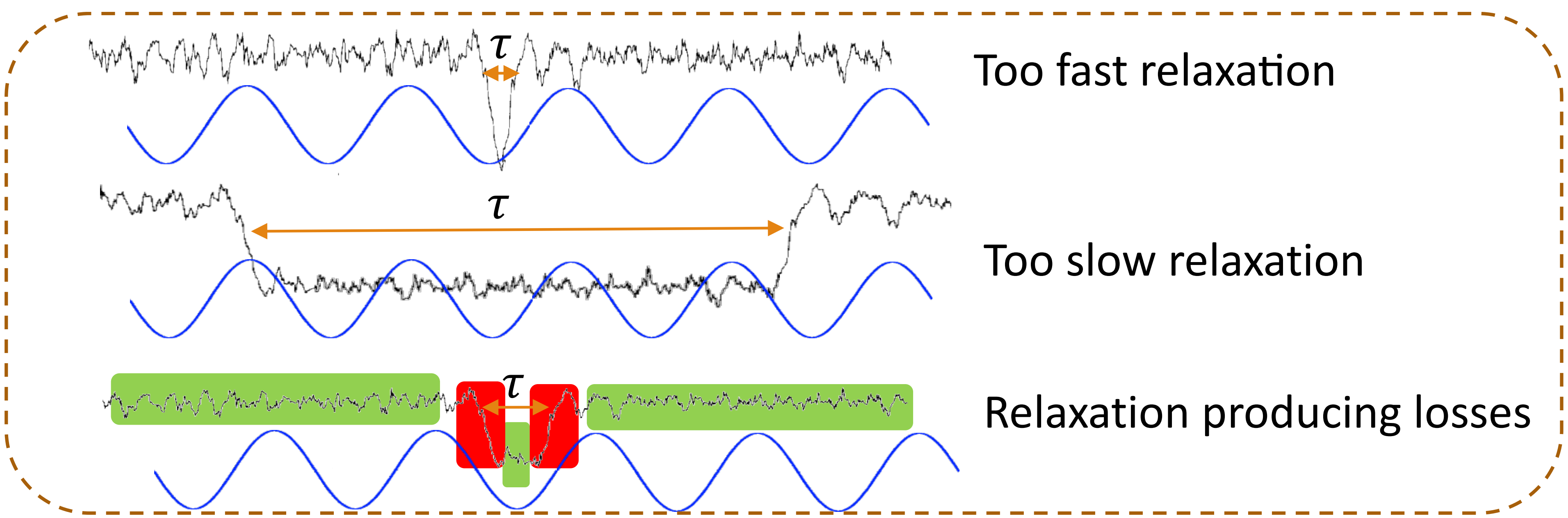
Microscopic picture of dissipation in glasses

At low frequencies (kHz range), dissipation dominated by anharmonic effects:
Interactions of mechanical waves with thermally-activated relaxations (TAR)

Two-Level System (TLS) model: dissipation dues to atomic motion during transitions from one well to another, which are possible via coupling between external strain and thermal motion.

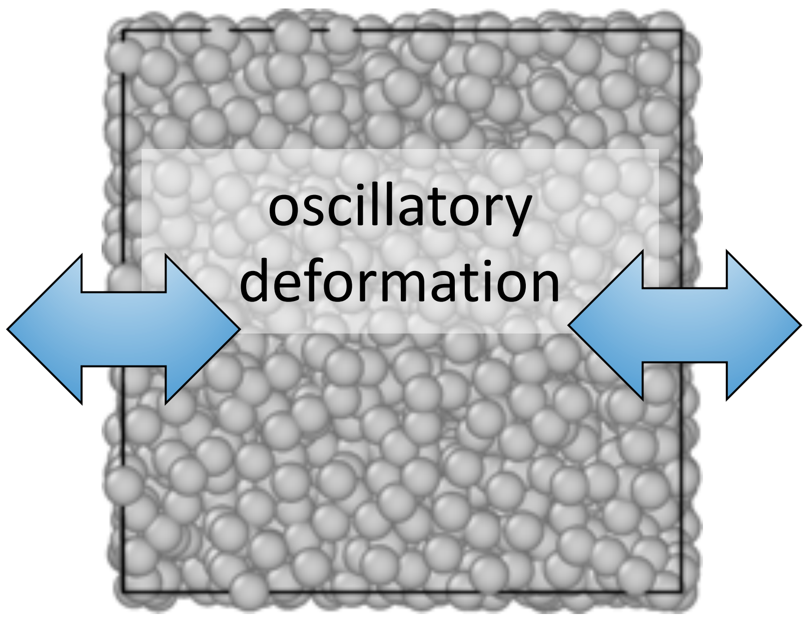
Only transitions with a relaxation time of the same order of the period of the strain wave propagating in the material produce mechanical losses





A new modeling approach

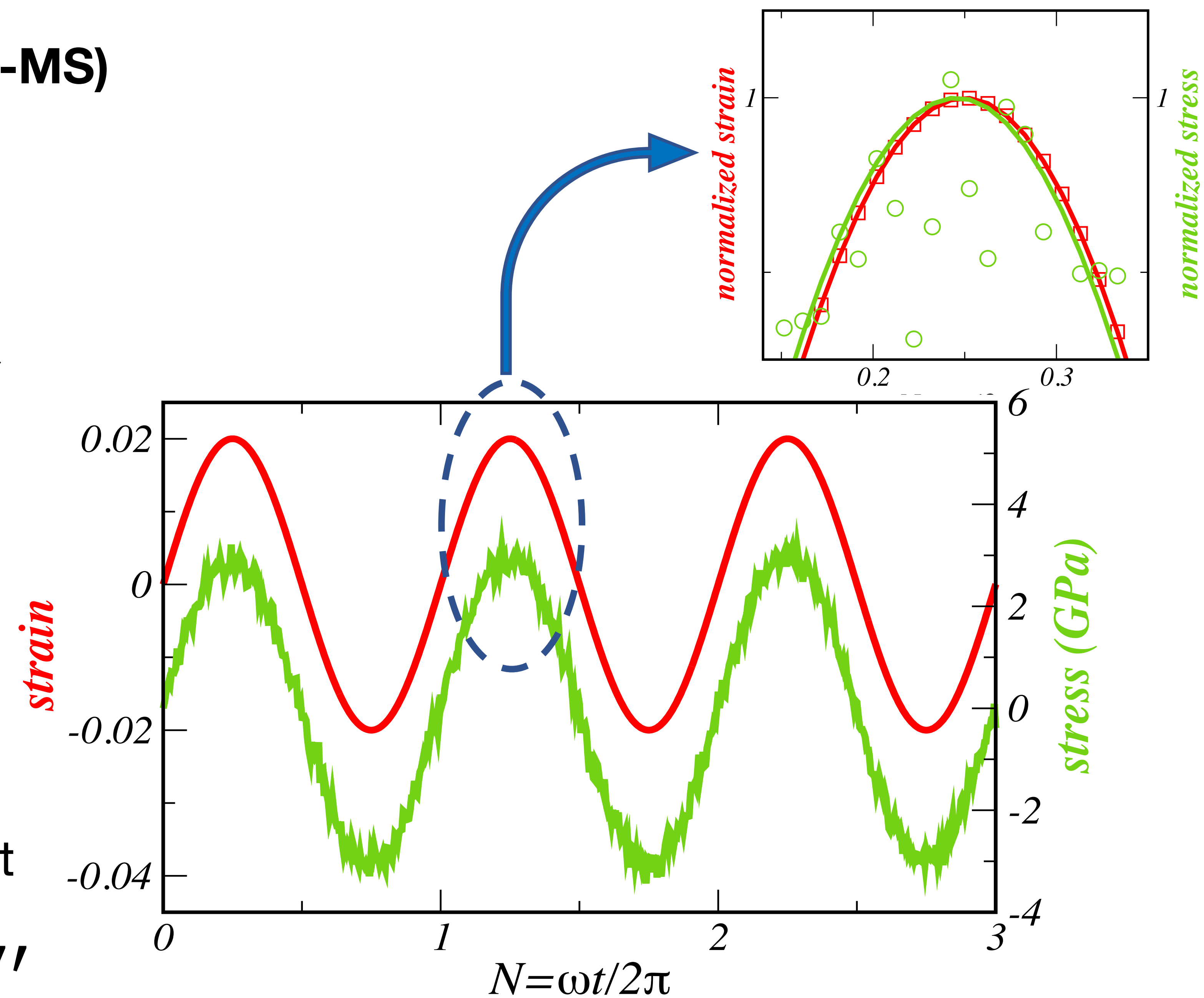
Molecular Dynamics
Mechanical Spectroscopy (MD-MS)



Apply numerical strain and compute the stress

Losses computed from phase shift

$$Q^{-1} = \tan\delta = \frac{E''}{E'}$$

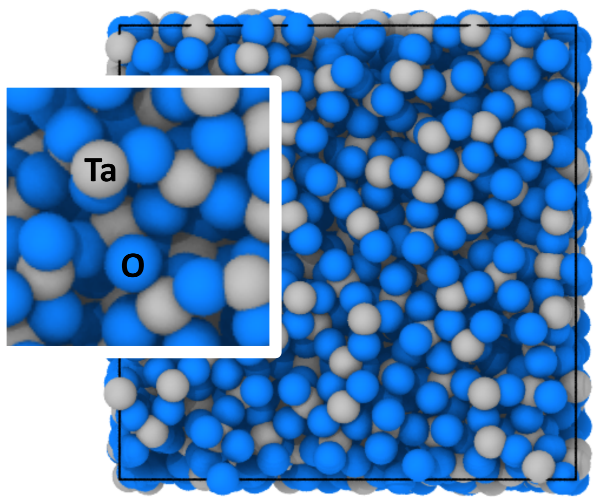


Theory-independent approach

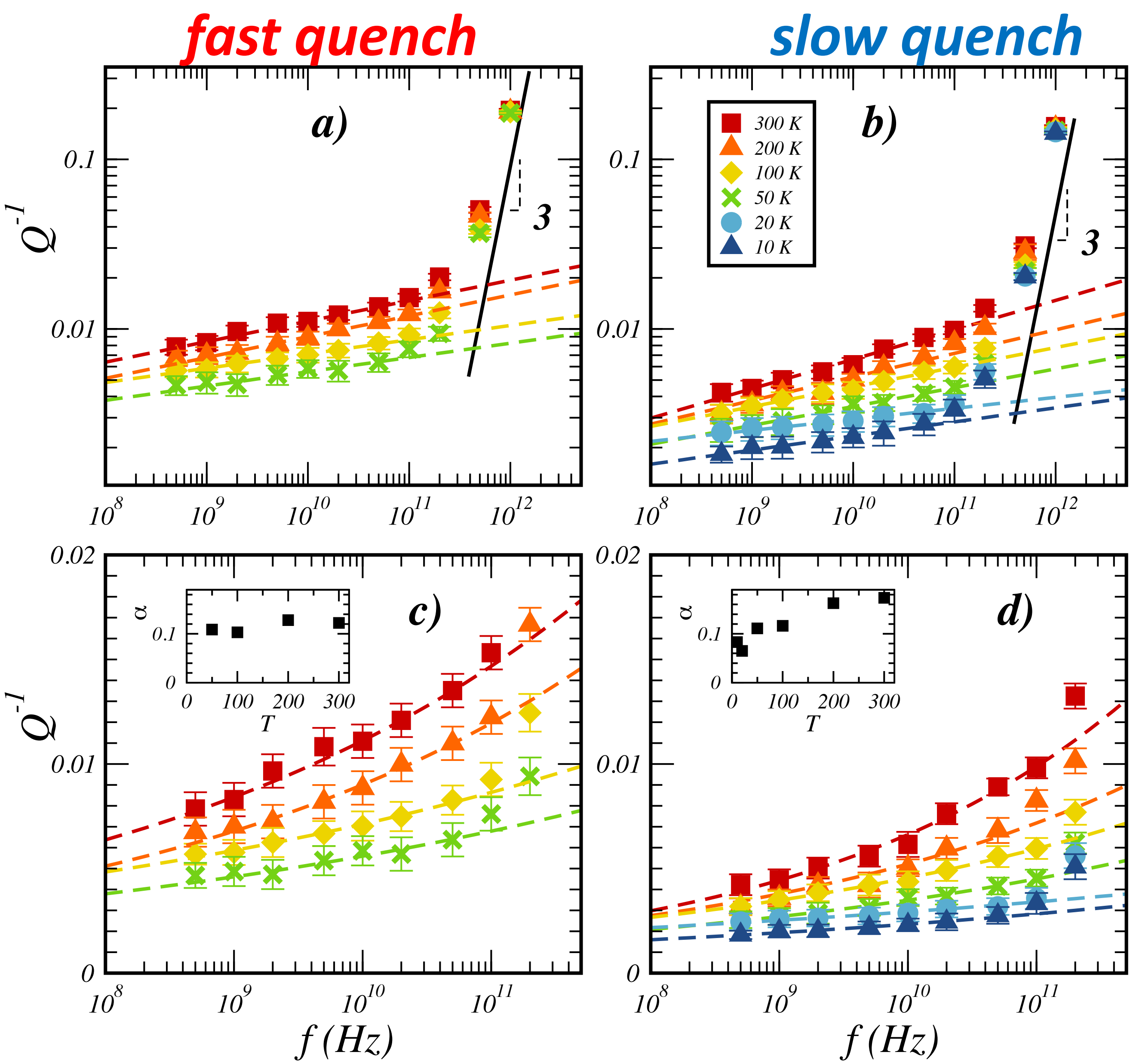
Mechanical losses in simulated amorphous Ta_2O_5

Glasses by cooling the liquid

Slowing down the cooling rate to replicate experimental annealing

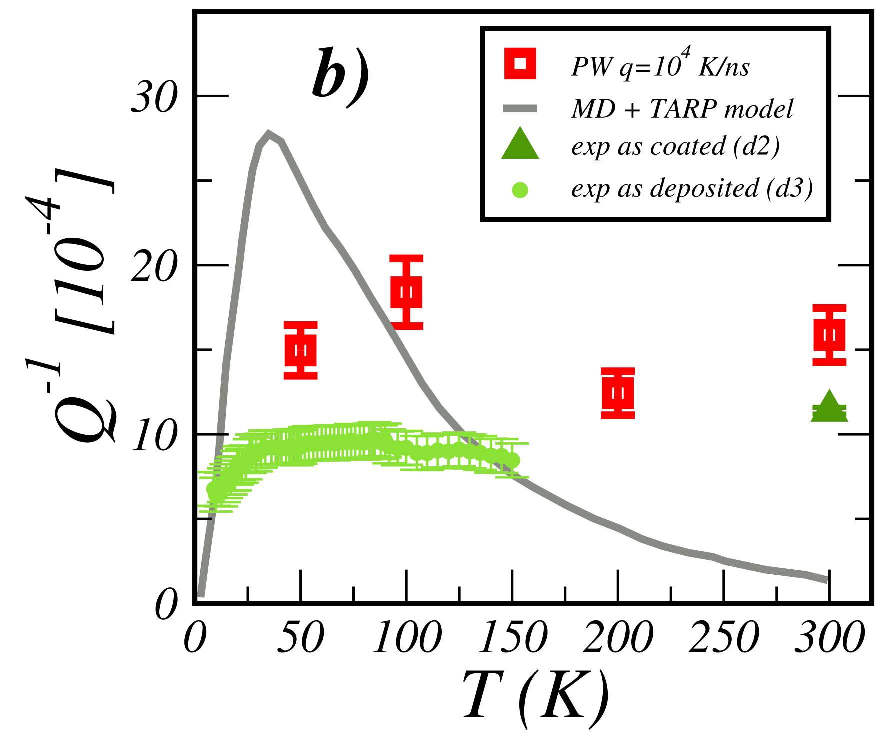


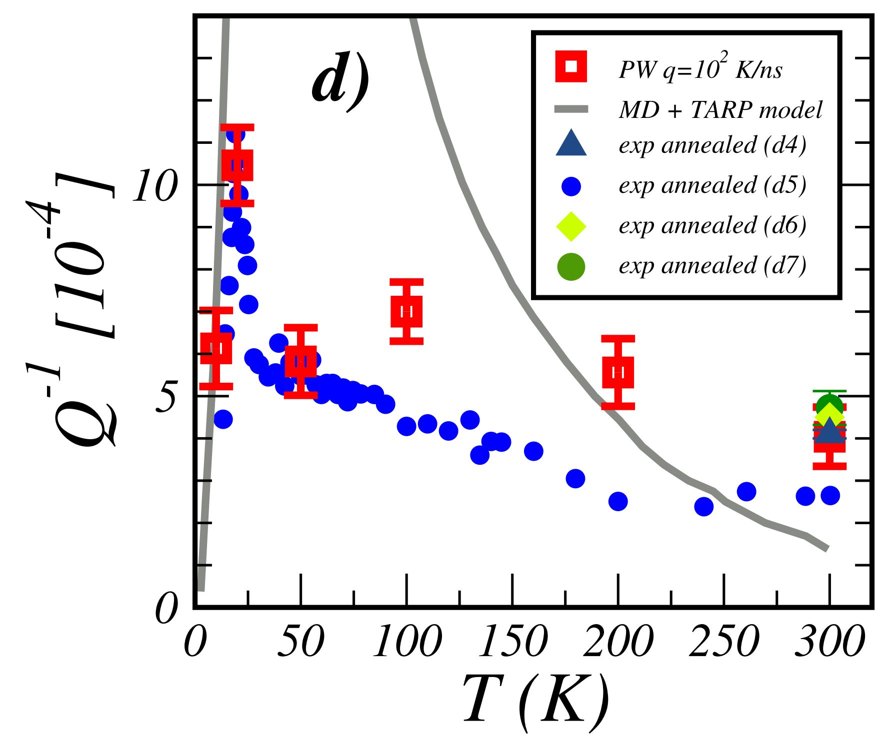
Puosi, Fidecaro, Capaccioli, Pisignano and Leporini
Phys. Rev. Res. **1** 033121 (2019)



We extrapolate from GHz to the acoustic frequencies
(range of interest for applications in GW detectors)

Comparing with experimental data





d1: M. Granata et al., in preparation
d2: M. Granata et al., PRD 93, 012007 (2016)
d3: R. Robie, Ph.D. thesis, Univ. of Glasgow (2018).
d4: M. Granata et al., PRD 93, 012007 (2016).
d5 I.W. Martin et al. Class. Quantum Grav. 27 225020 (2010).
d6: G. Vajente et al. Class. Quantum Grav. 35 075001 (2018).
d7: M. Principe et al., PRD 91, 022005 (2015).

A microscopic perspective on dissipation

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

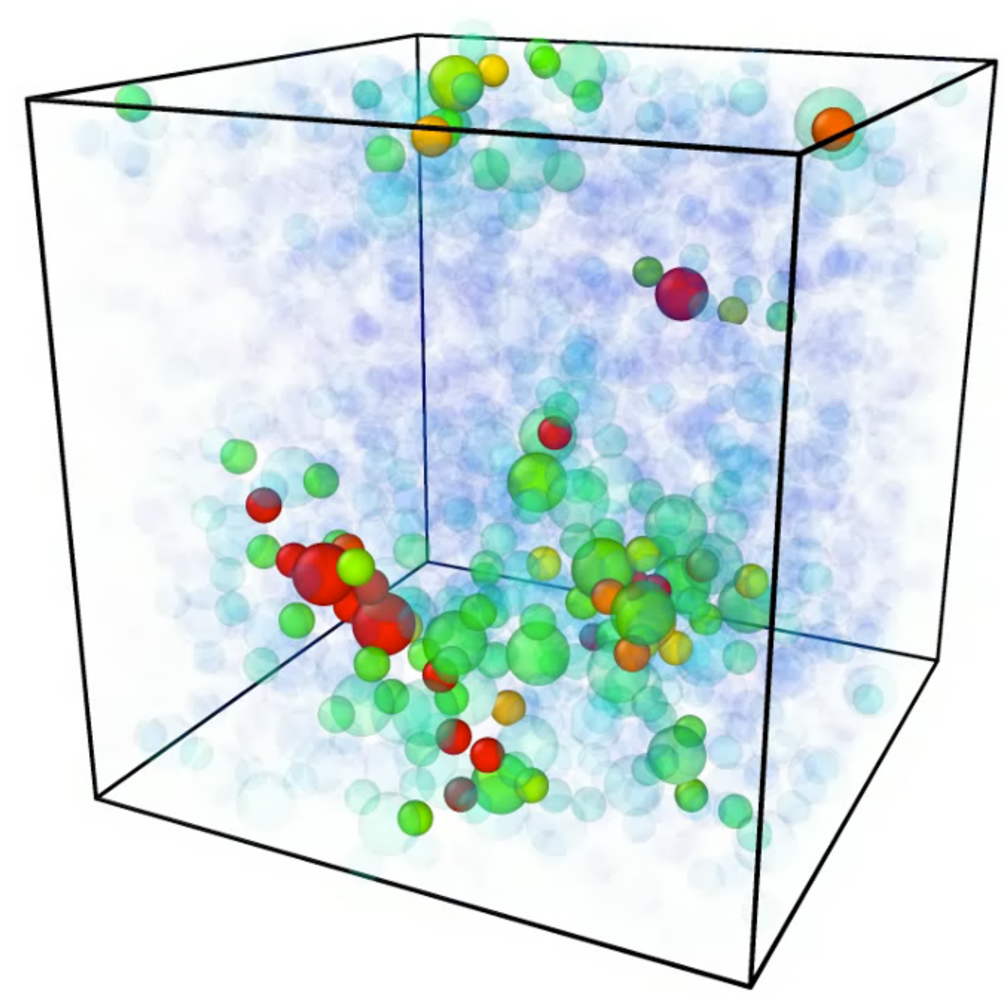
ELSEVIER

Full length article

Non-local cooperative atomic motions that govern dissipation in amorphous tantala unveiled by dynamical mechanical spectroscopy

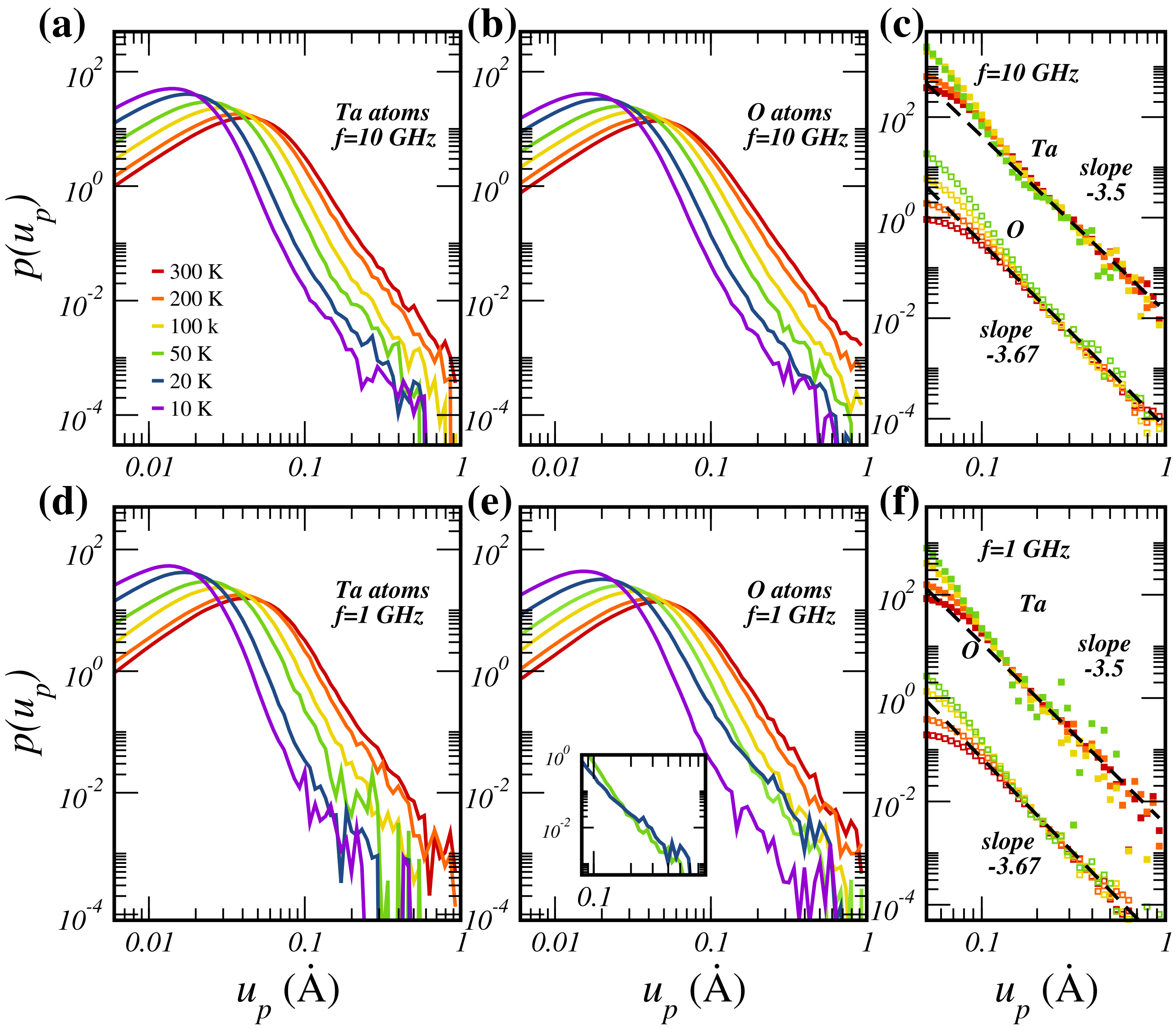
F. Puosi[a,b,*], F. Fidecaro[a,b], S. Capaccioli[a,b], D. Pisignano[a,b], D. Leporini[a,b]

Slowly quenched glass
T=300 K
$f=10^9$ Hz



Color code: magnitude of non-affine displacement

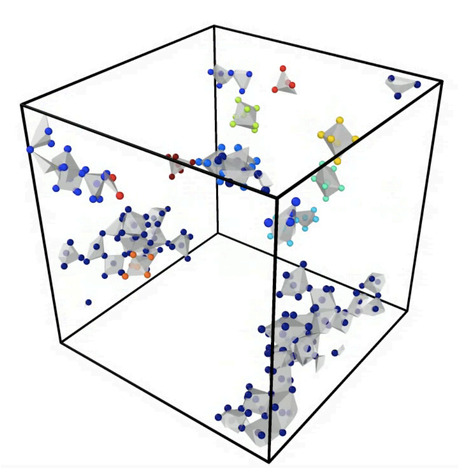
A microscopic perspective on dissipation

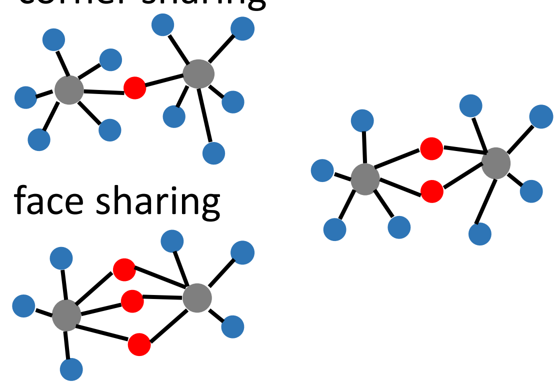


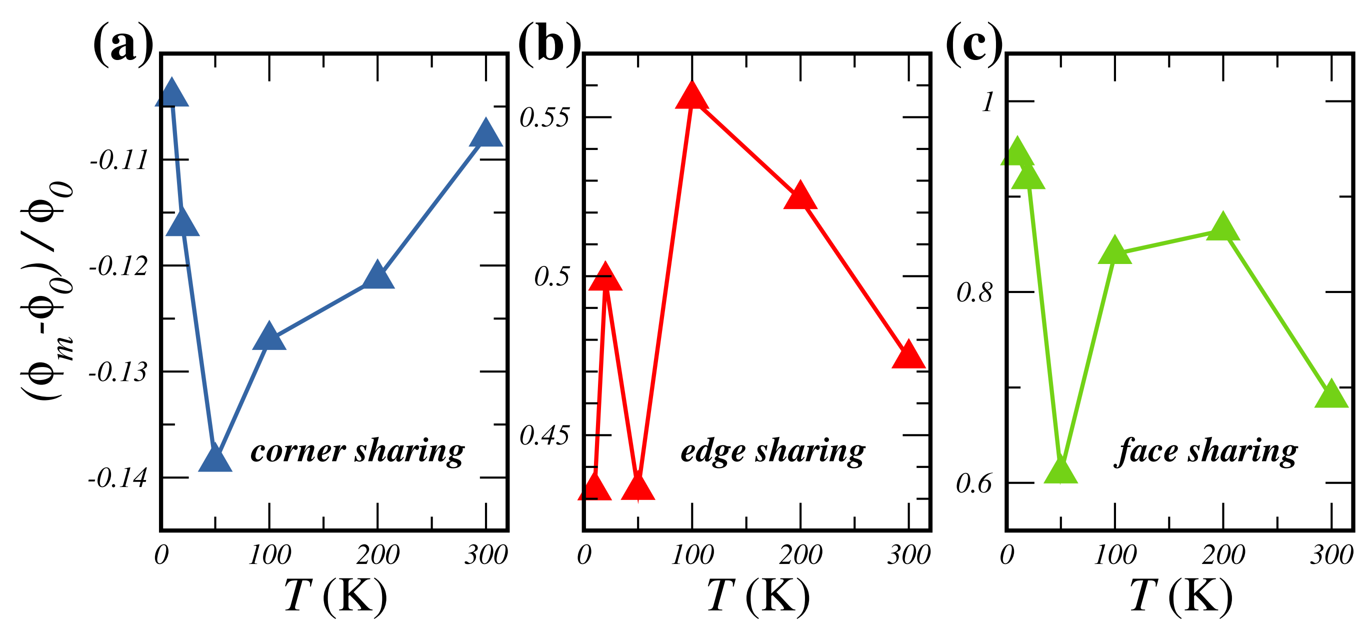
Dissipation as due to irreversible events leading to change of basin in the PEL

u_p: atom displacement over one strain cycle

Excess of high mobility oxygen atoms at 20 K which correlates with the cryogenic peak in mechanical losses







Next steps: new materials

Silicon nitride Si_3N_4: candidate as coating material for AdV+ ALigo+

Experiments

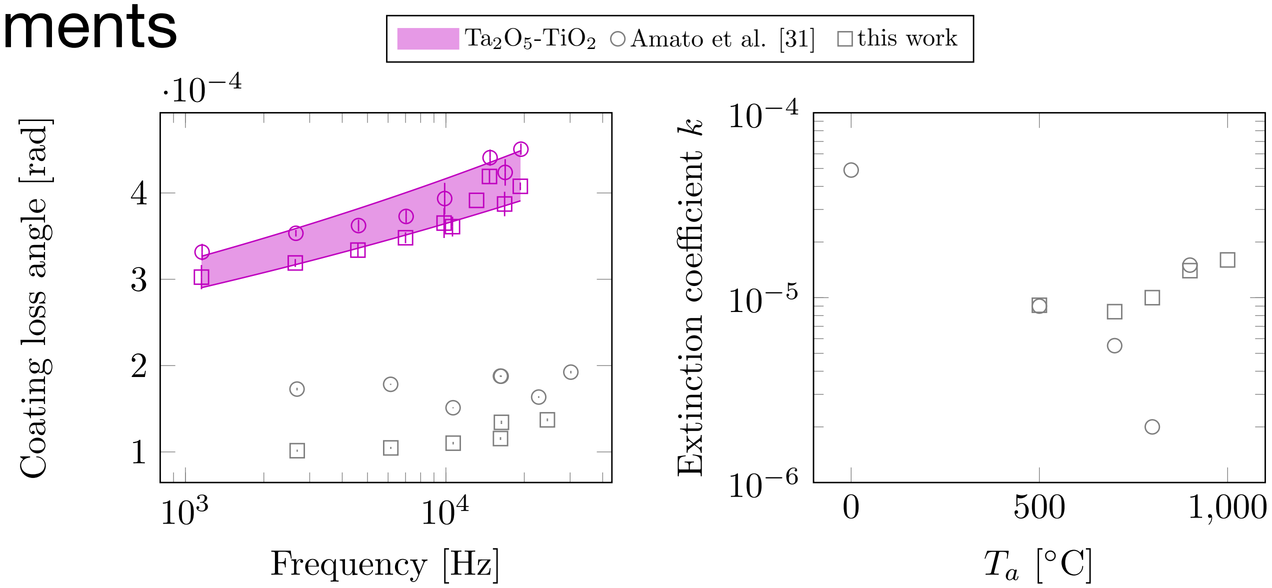
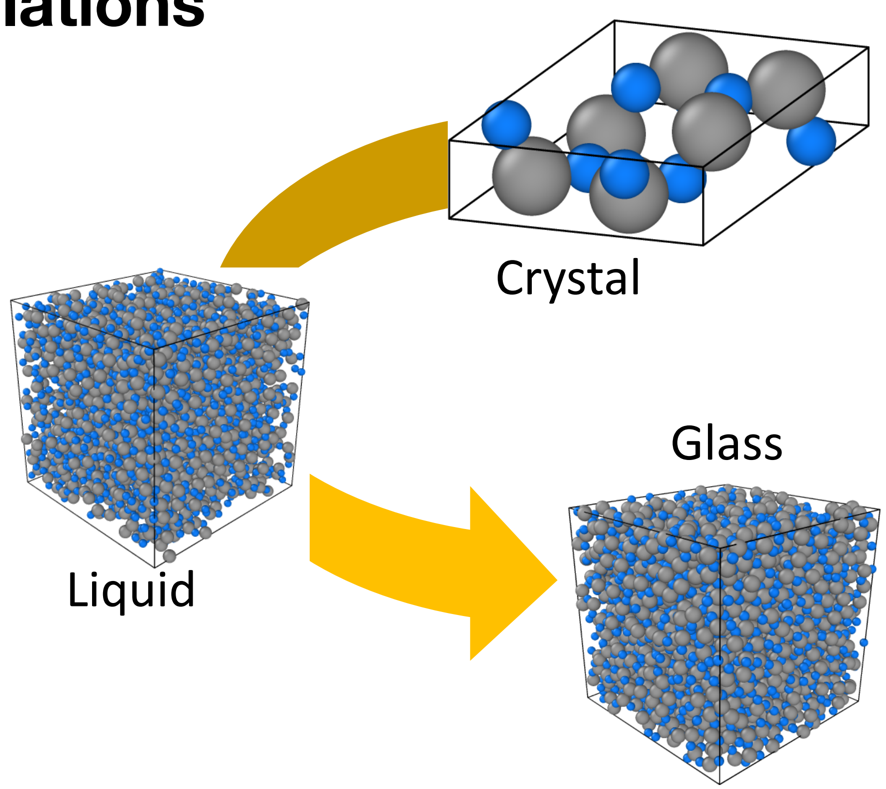
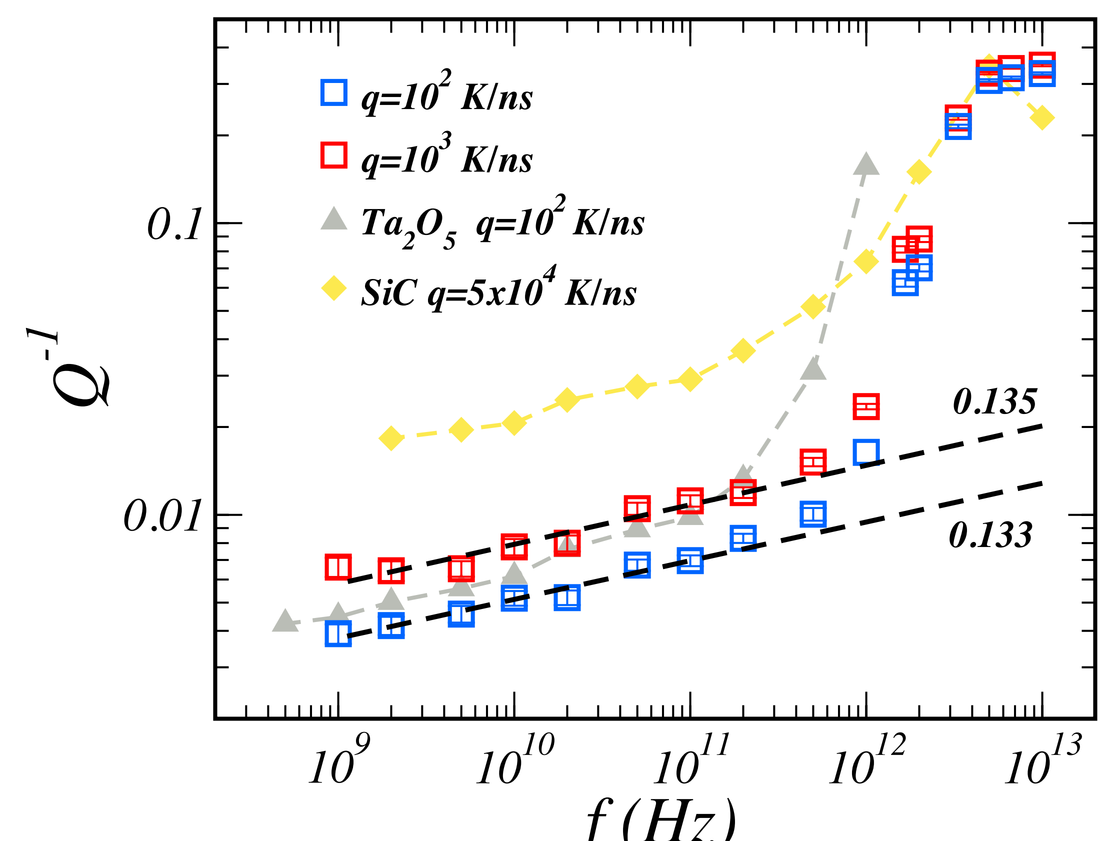


Fig. 7. Characterization of IBS SiN_x coatings. Left: internal friction of our first [31] and latest coating samples annealed in air at 900 °C for 10 hours, compared to current values of Ta_2O_5-TiO_2 coatings annealed in air at 500 °C for 10 hours (from Fig. 2). Right: extinction coefficient of our first [31] and latest coating samples as a function of the annealing temperature T_a (in-air annealing time is 10 hours, T_a = 0 °C corresponds to as-deposited coatings).

M. Granata et al., Appl. Opt. 59, A229-A235 (2020)

Simulations



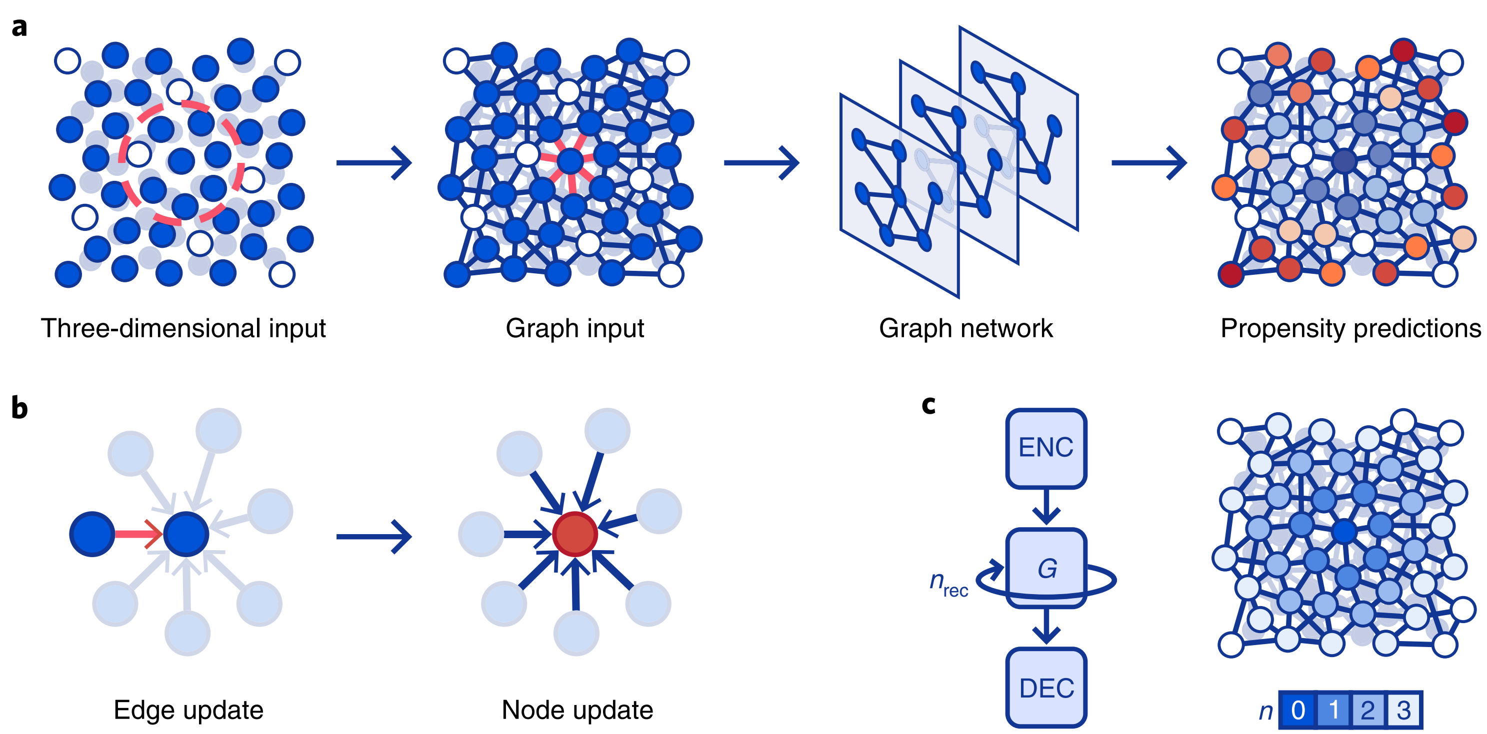


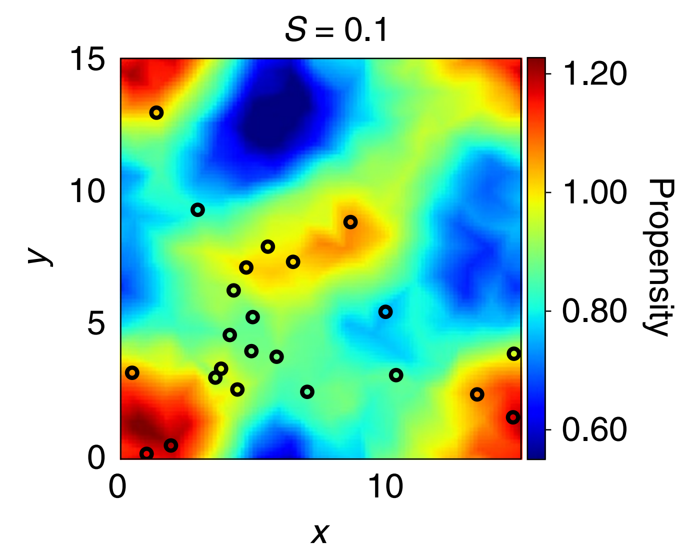
Next steps: Machine Learning methods

Unveiling the predictive power of static structure in glassy systems

V. Bapst[1,3], T. Keck[1,3], A. Grabska-Barwińska[1], C. Donner[1], E. D. Cubuk[2], S. S. Schoenholz[2], A. Obika[1], A. W. R. Nelson[1], T. Back[1], D. Hassabis[1] and P. Kohli[1]

NATURE PHYSICS | VOL 16 | APRIL 2020 | 448–454 |





Comparison between predicted and true mobility

Where we are:

- Setting up a collaboration with DeepMind (Google)
- Preliminary stage: approach design and coding