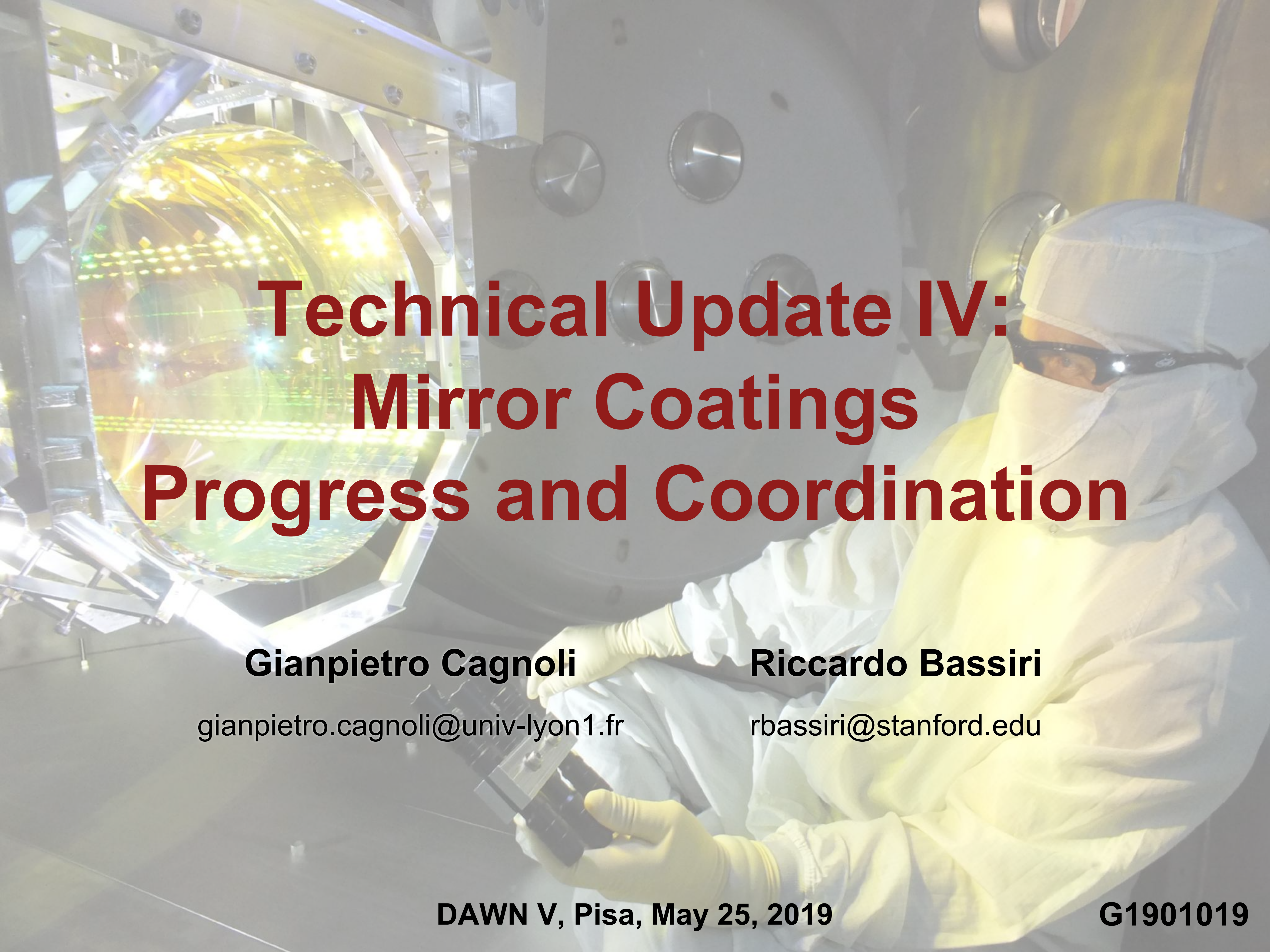

Technical Update IV: Mirror Coatings Progress and Coordination

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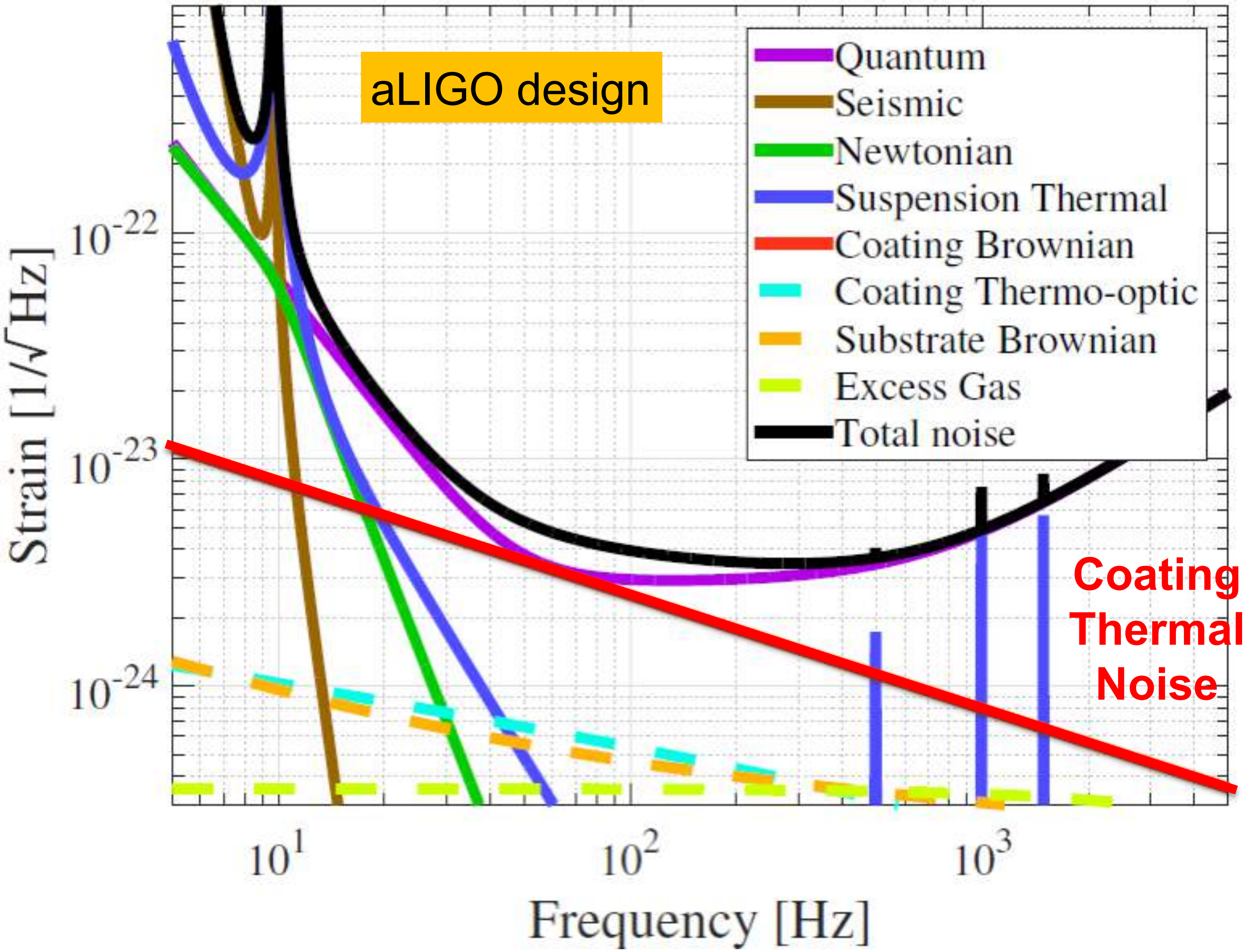
Riccardo Bassiri

rbassiri@stanford.edu

DAWN V, Pisa, May 25, 2019

G1901019

GW Detector Noise Sources



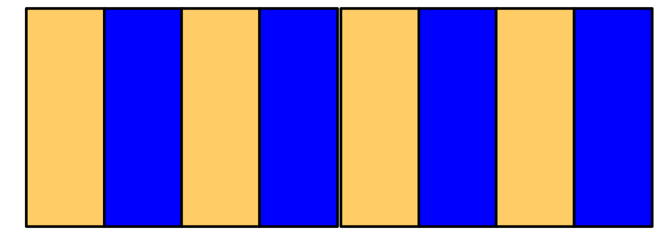
- Coating thermal noise (CTN) dominates mid-band frequency sensitivity
- All planned future detectors require reduction of CTN

Basic Coating Concepts

- Dielectric mirror
  - alternating high/low index ¼ wavelength-thick layers
  - large index contrast ⇒ fewer required layers:

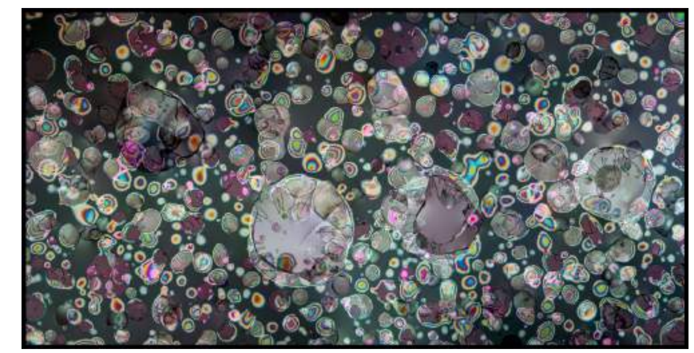
$$d \sim 1/(n_H - n_L)$$

$\lambda/4n_H$ - $\lambda/4n_L$



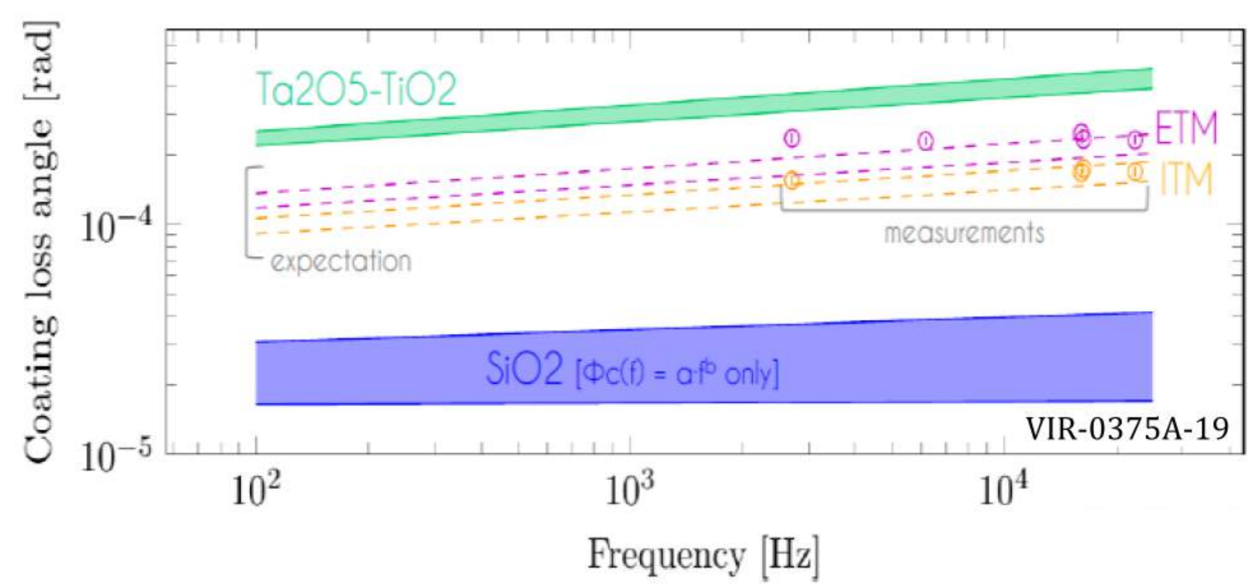
n_H n_L

- Key optical properties
  - absorption < 0.5 ppm, scatter – ppm's
  - industry standard: ion-beam sputtering
    R.T. deposition followed by 300 C – 500 C annealing
  - scaling to >30 cm nontrivial
    with ~1 nm RMS figure: LMA, Lyon

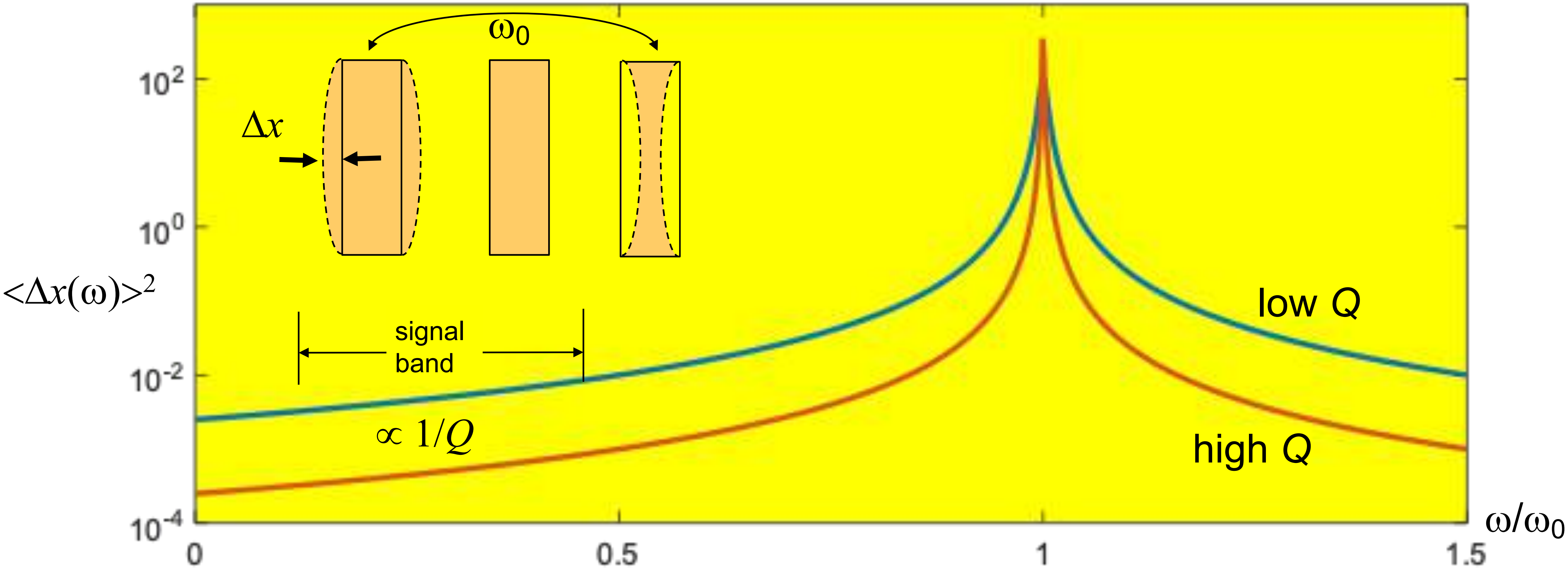


S. Gras, *et al.* GWADW 2019

- Current LIGO mirrors:
  - Ti(20%):Ta_2O_5 : n = 2.07, $\phi \sim 2.4 \times 10^{-4}$
    SiO_2: n = 1.45, $\phi = 2.3 \times 10^{-5}$



Thermal Noise



- Oversimple: kT of energy per mechanical mode, viscous damping
  - moves front of mirror w.r.t. center of mass
  - can obscure gravitational wave signal

- Coating thermal noise key variables:

Temperature

Mechanical loss

$$\mathrm{CTN} \propto \frac{\sqrt{\frac{T}{f}\,\frac{1}{w^2}\,\varphi\, d}}{L}$$

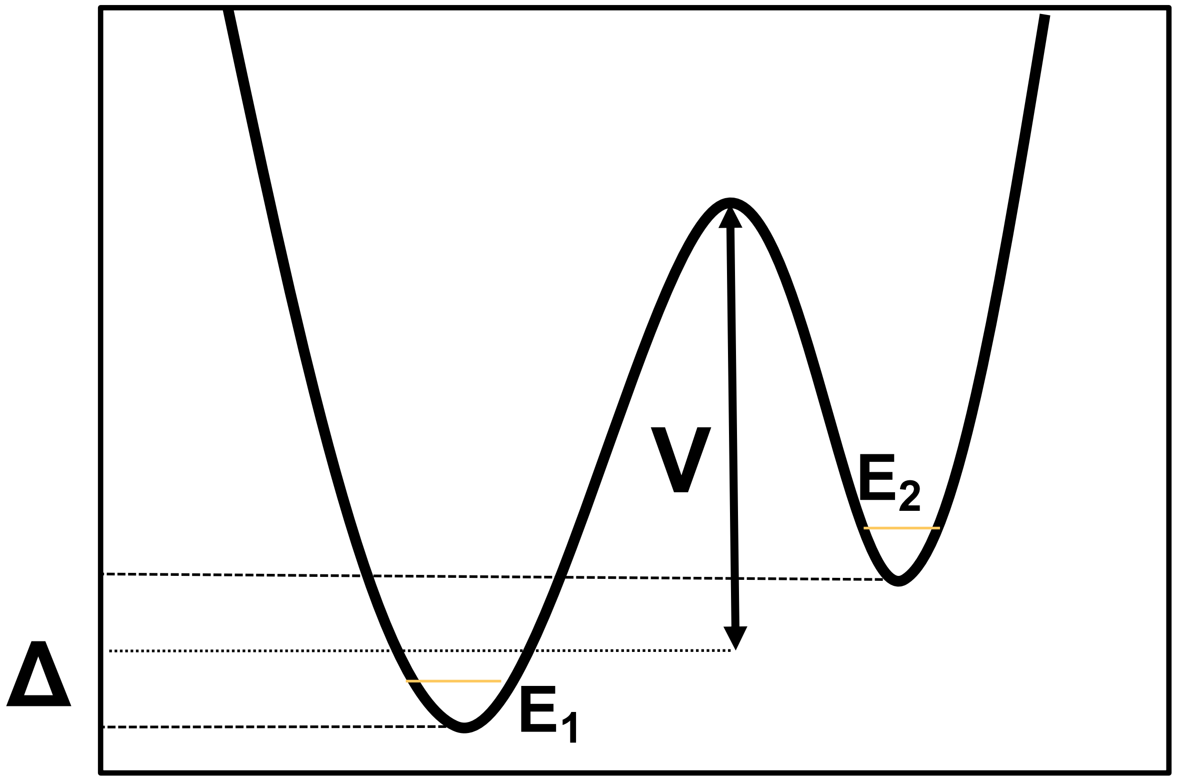
Coating thickness

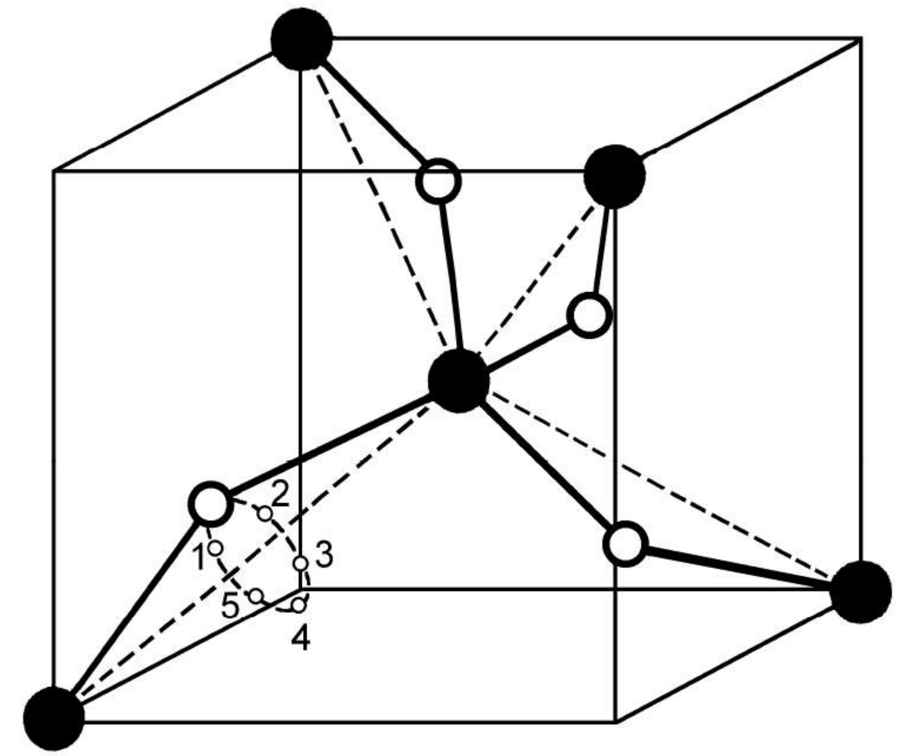
Beam-size

Arm length

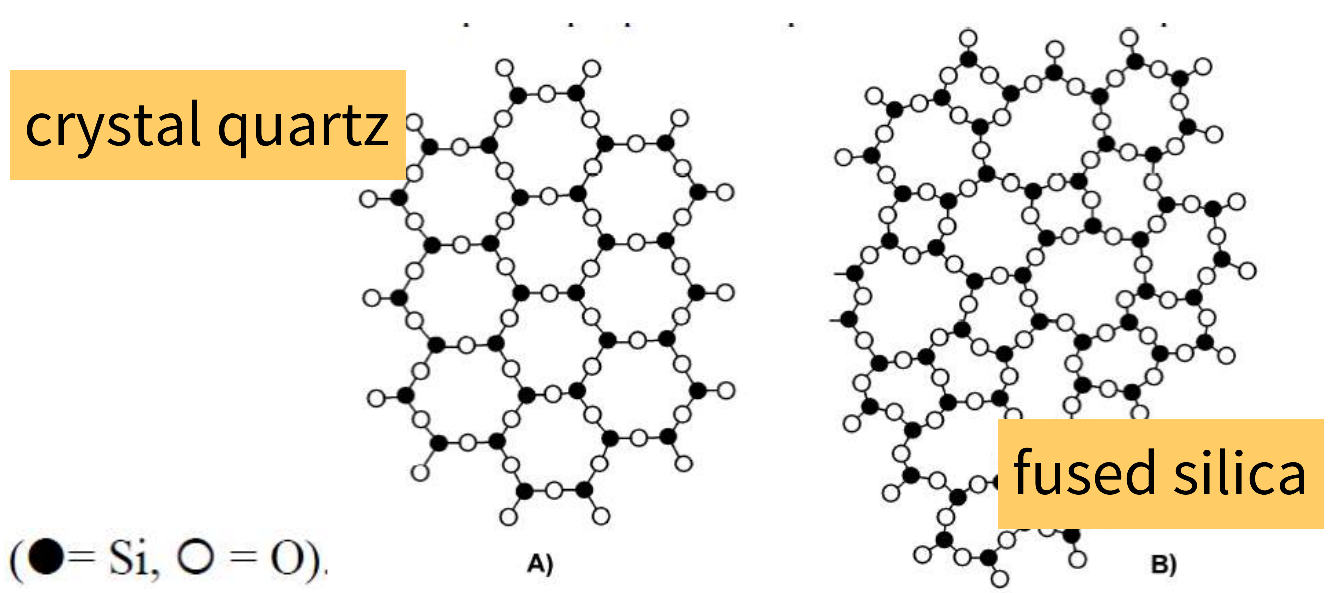
Two Level Systems and Mechanical Loss

- Conventionally associated with low energy excitations
  - conceptualized as two-level systems (TLS)





Oversimple picture: bond flopping

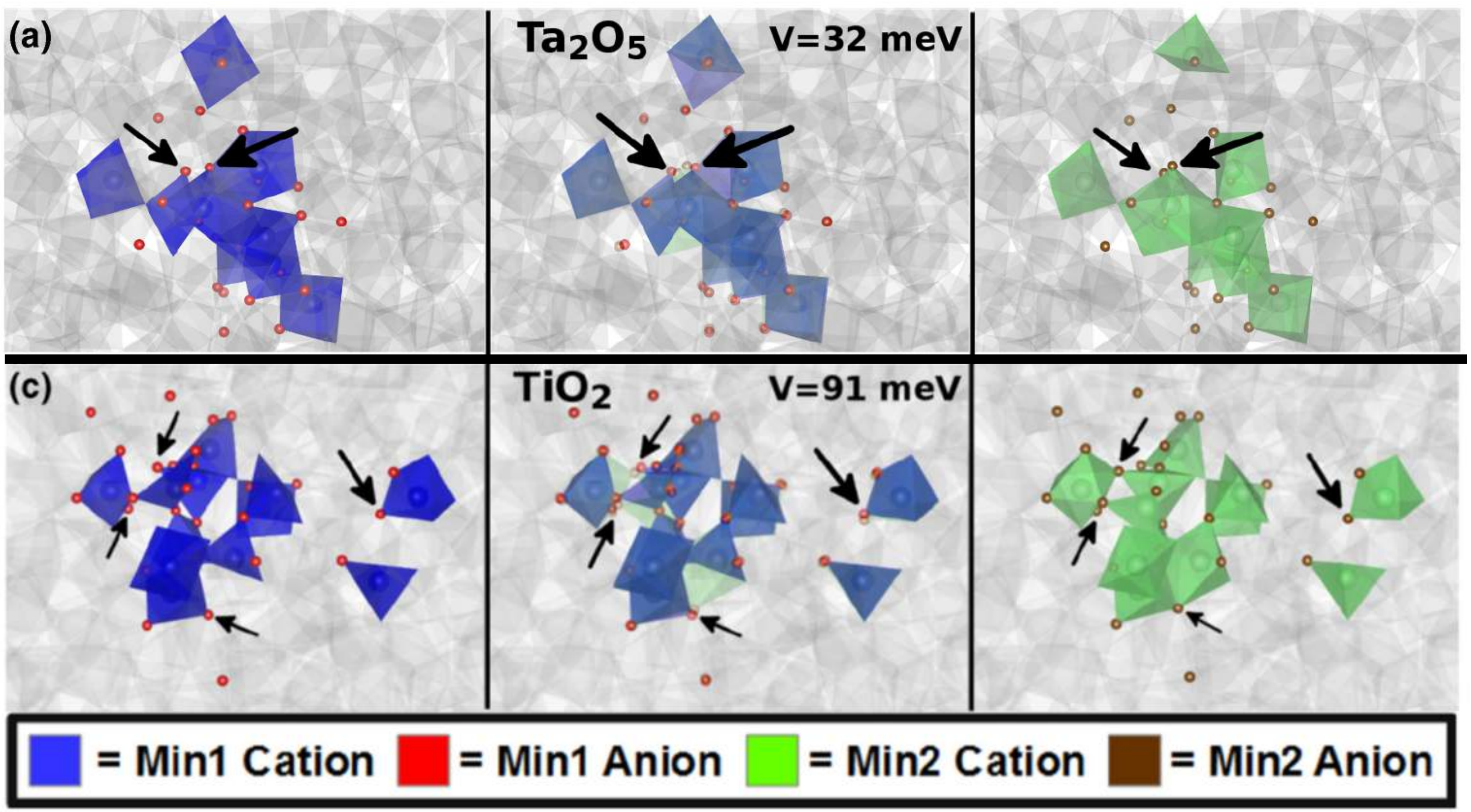


Distribution of TLS in silica
due to disordered structure

Figures: B.S. Lunin, monograph

Two Level Systems and Mechanical Loss

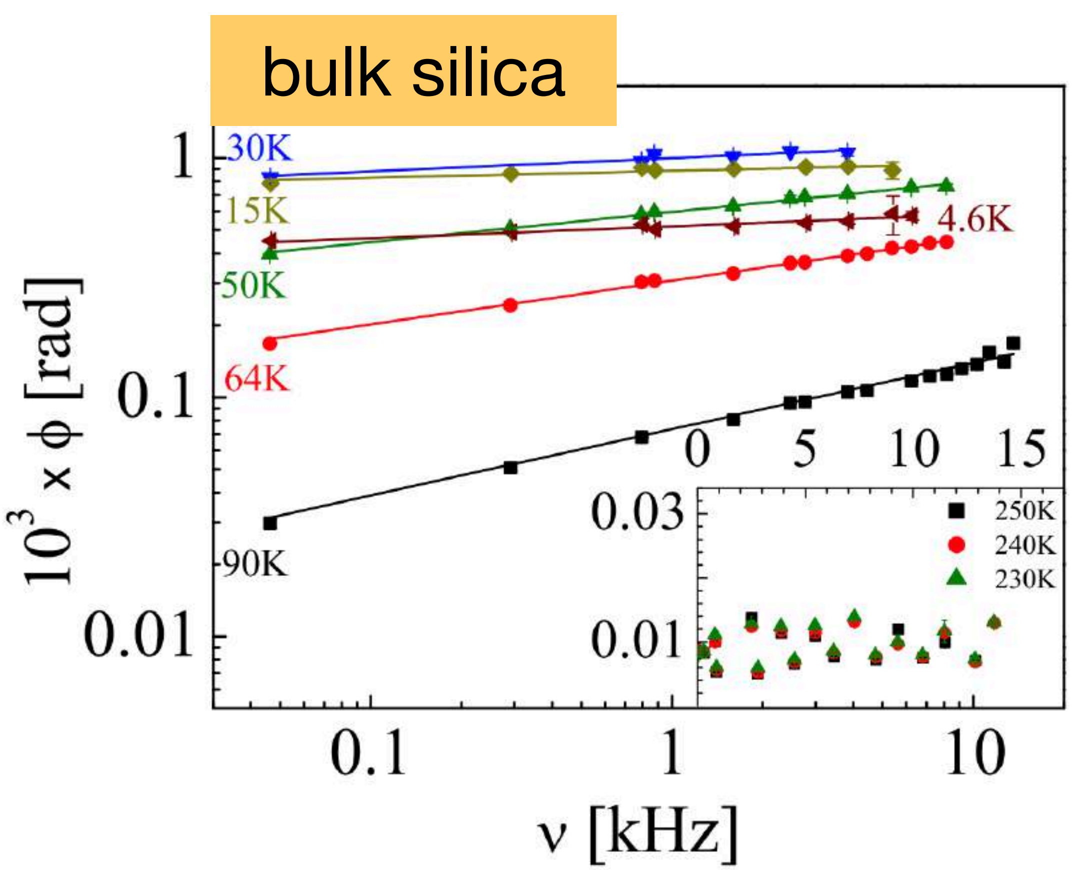
- Molecular dynamics calculations for amorphous materials
  - simple bond-flopping inadequate picture
  - TLS involves dozens of atoms in nm-scale configurations



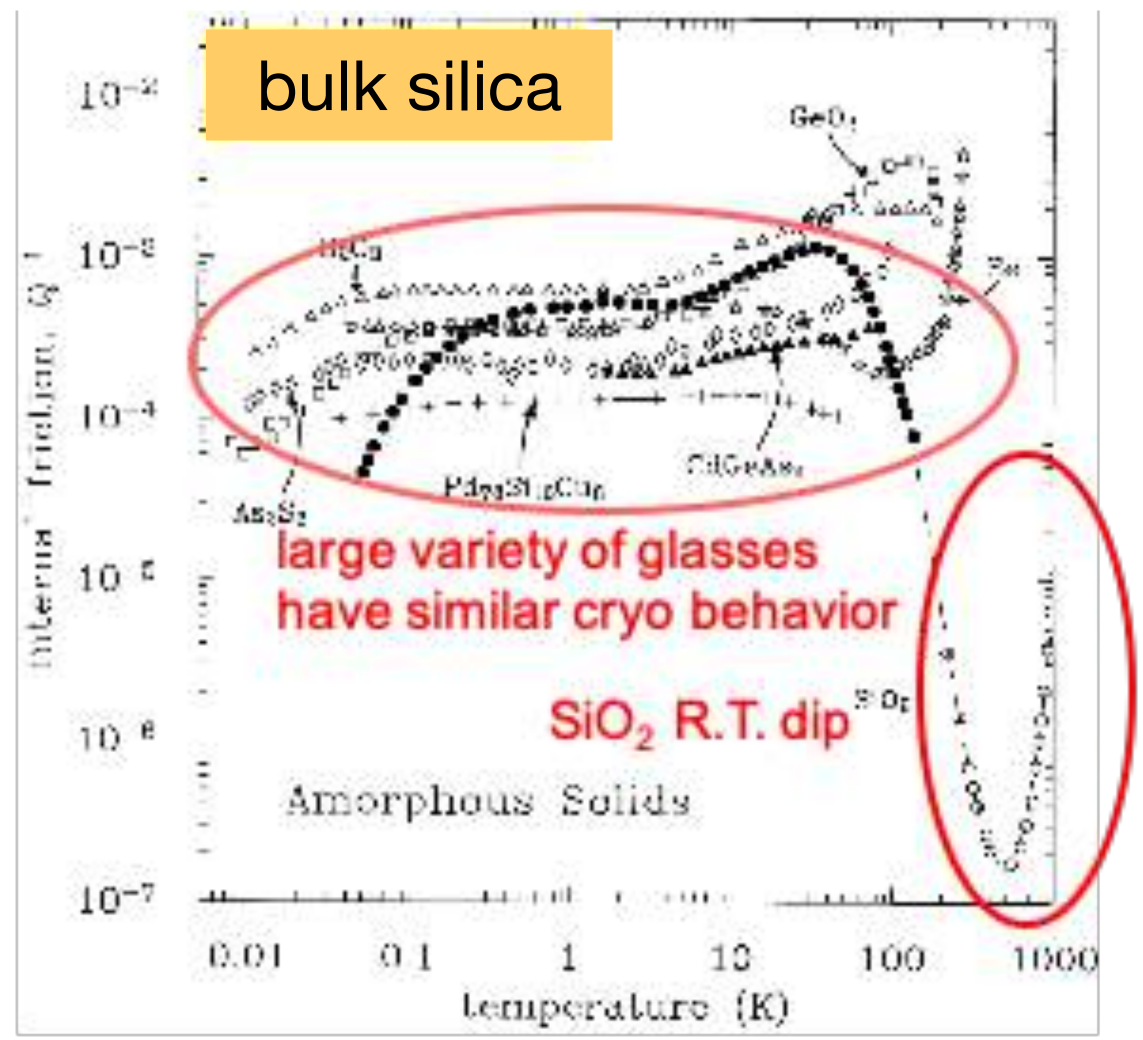
J. Trinastic, R. Hamdan, C. Billman, H. Cheng, Phys. Rev. B 93 014105 (2016)

Mechanical loss

- Mechanical loss result of distribution/quantity of TLSs
- Volume rather than interface losses dominate in tantala/silica mirror
  - current values: titania doped tantala ~ 10 x lossier than silica
- Typical behavior vs temperature and frequency
  - amorphous materials have loss peak at low temperatures



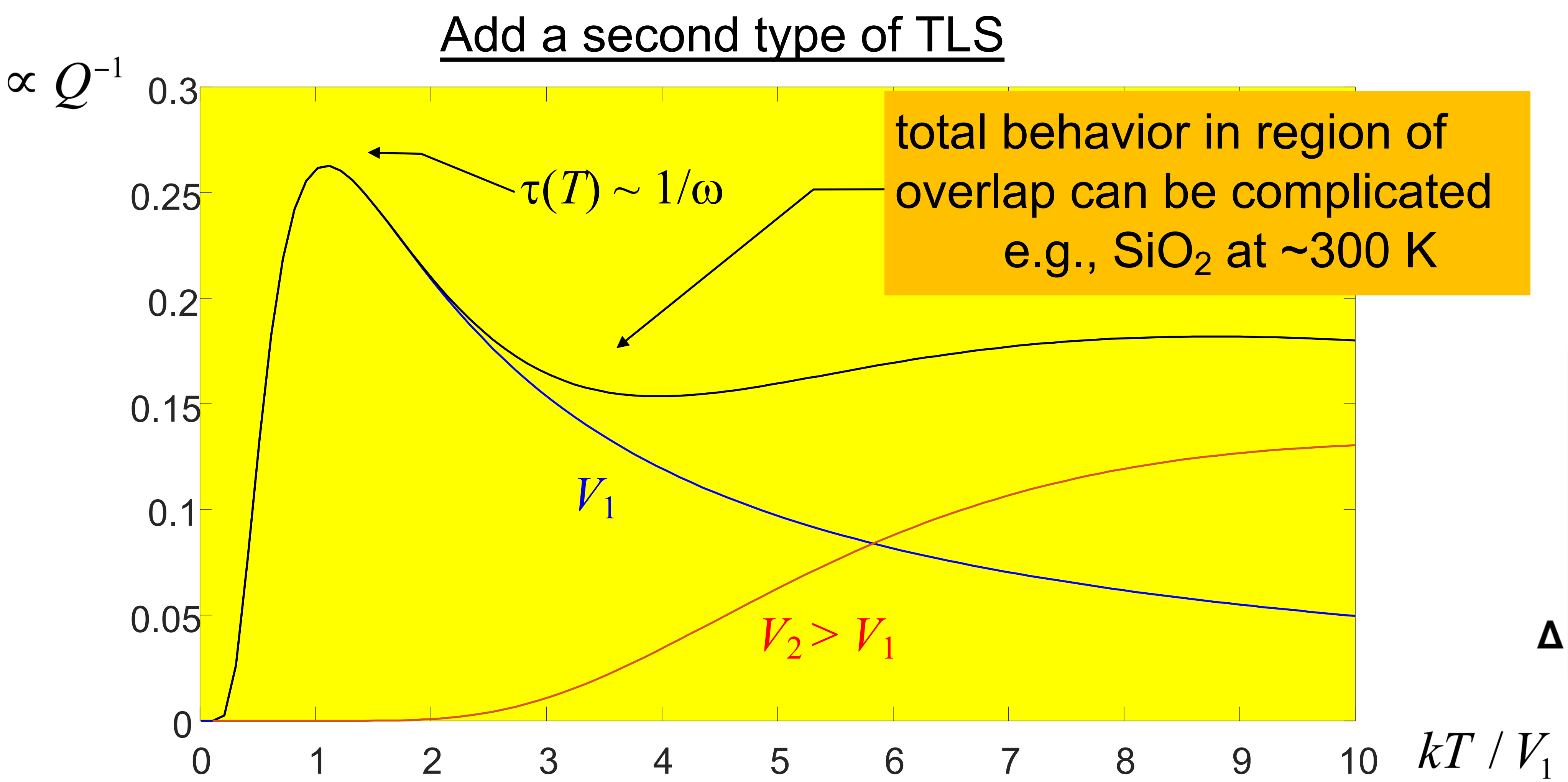
*F. Travasso et al., EPL **80** 50008 (2007)*

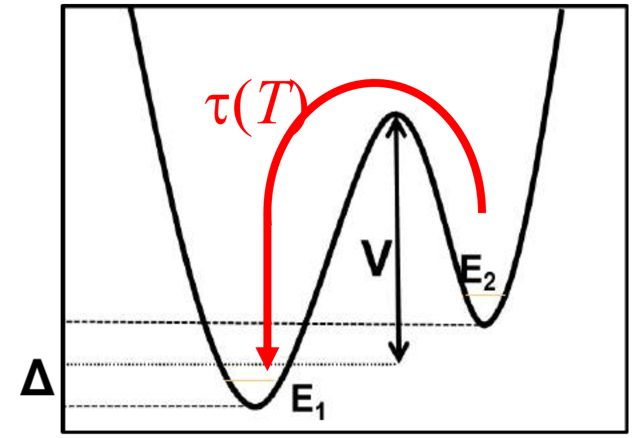


*K.A. Topp, Z. Physik B Condensed Matter **101** 235–45 (1996)*

7

Reduce Mechanical Loss





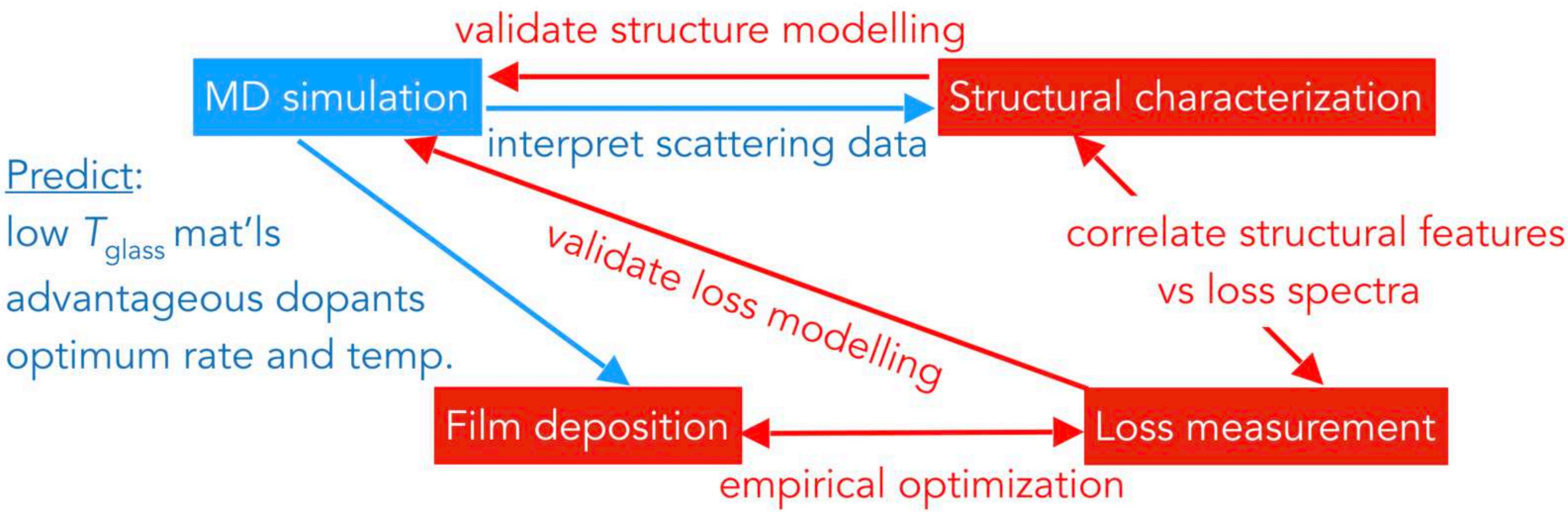
- Guidelines for reducing coating mechanical loss
  - Reduce total number of TLS
  - Redistribute TLS

MATERIALS

DEPOSITION

ABSORPTION
& DEFECTS

TREATMENTS


validate structure modelling
MD simulation
Structural characterization
interpret scattering data
Predict:
low T_{glass} mat'ls
advantageous dopants
optimum rate and temp.
validate loss modelling
correlate structural features
vs loss spectra
Film deposition
Loss measurement
empirical optimization

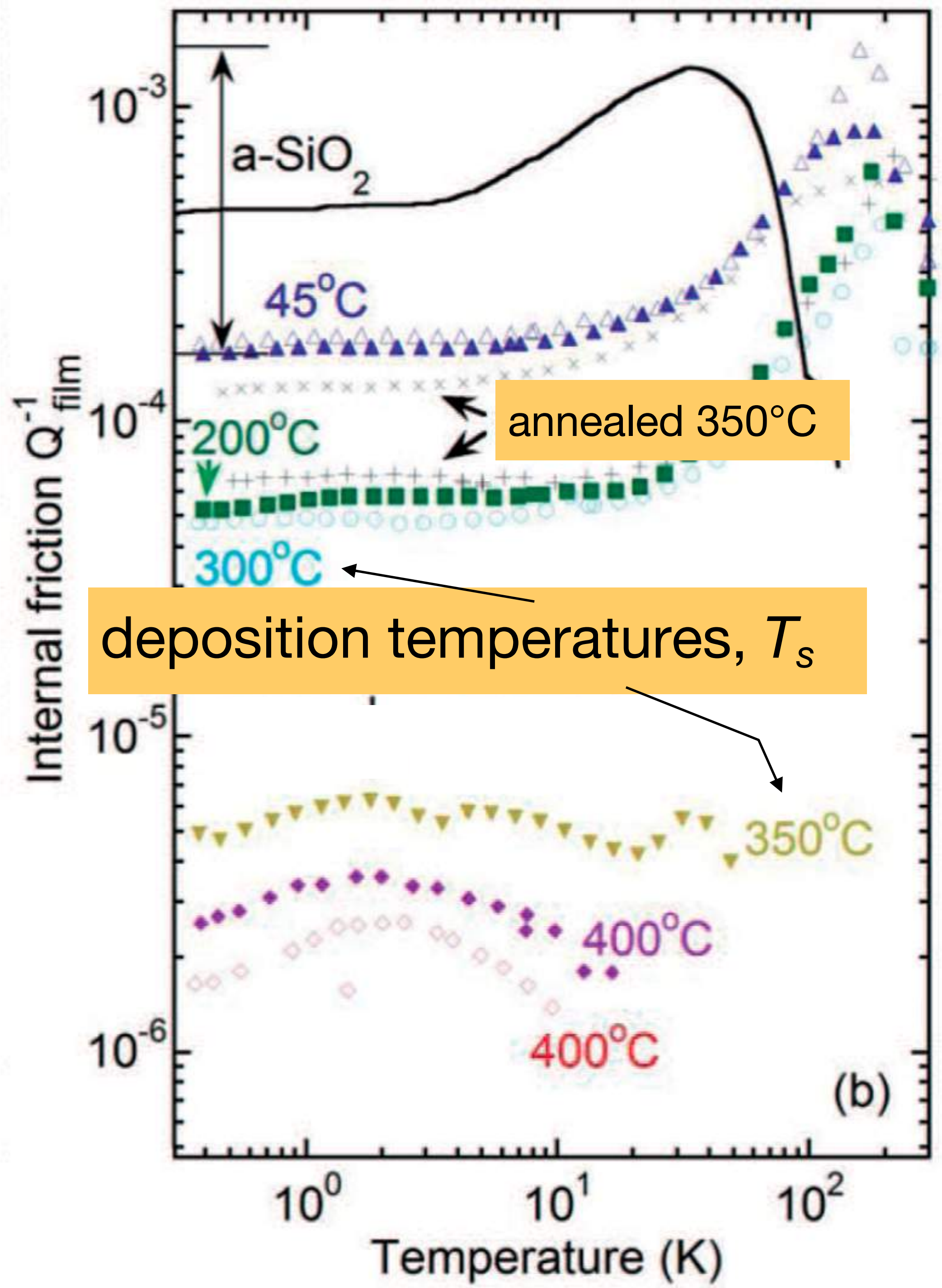
Ultra-stable Glasses

- a-Si experiment: steep improvement for deposition at T_s ~ 400 C: $\phi \sim 10^{-6}$ (!)
  - much lower loss compared to deposit at 300 C and anneal at 400 C
  - theoretical* T_{glass} ~ 900 K :
    critical T_s / T_{glass} ~ 0.75 vs predicted $T_s \sim 0.8\ T_{glass}$

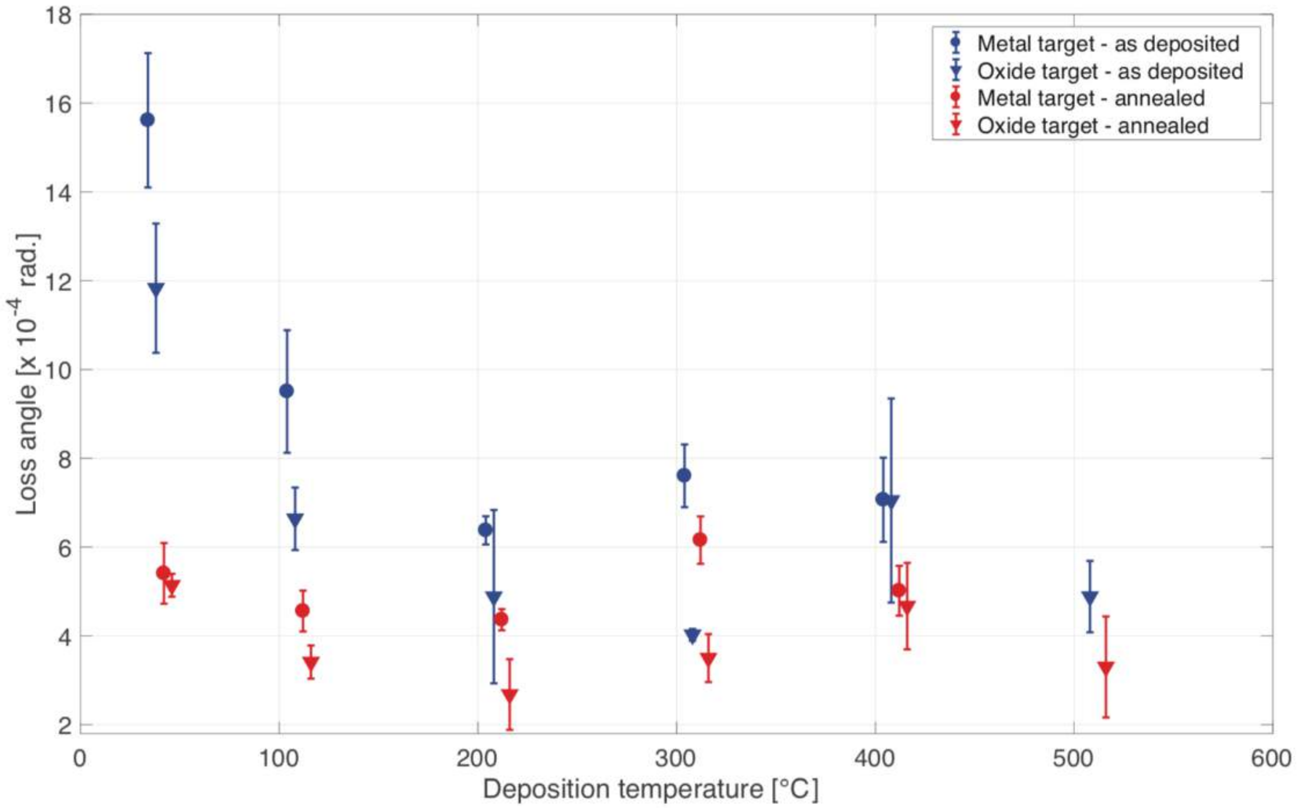
** C.R. Miranda and A. Antonelli, J. Chem. Phys. 120, 11672 (2004)*

- Formation of ultrastable glass favored by:
  - Deposition at $T_s \sim 0.8\ T_{glass}$
  - Low deposition rates

X. Liu, F. Hellman, et al, PRL 113, 025503 (2014)



Ultra-stable Glasses: Oxides

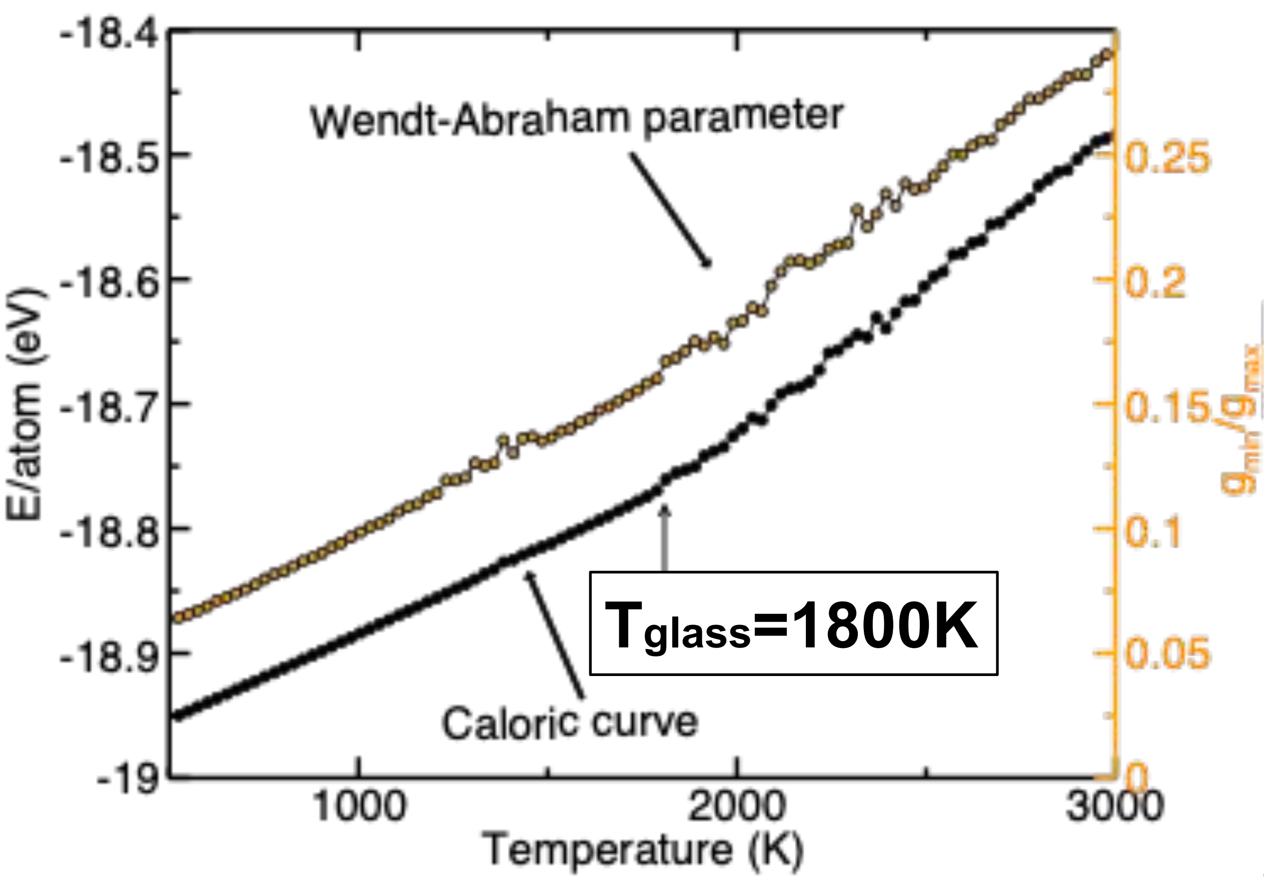


- **Ta_2O_5** high T_s deposition
  - Room temperature loss: lower than with R.T. dep but similar after annealing
  - cryogenic loss: under investigation

G Vajente, (2018) Class. Quantum Grav. ***35*** *075001*

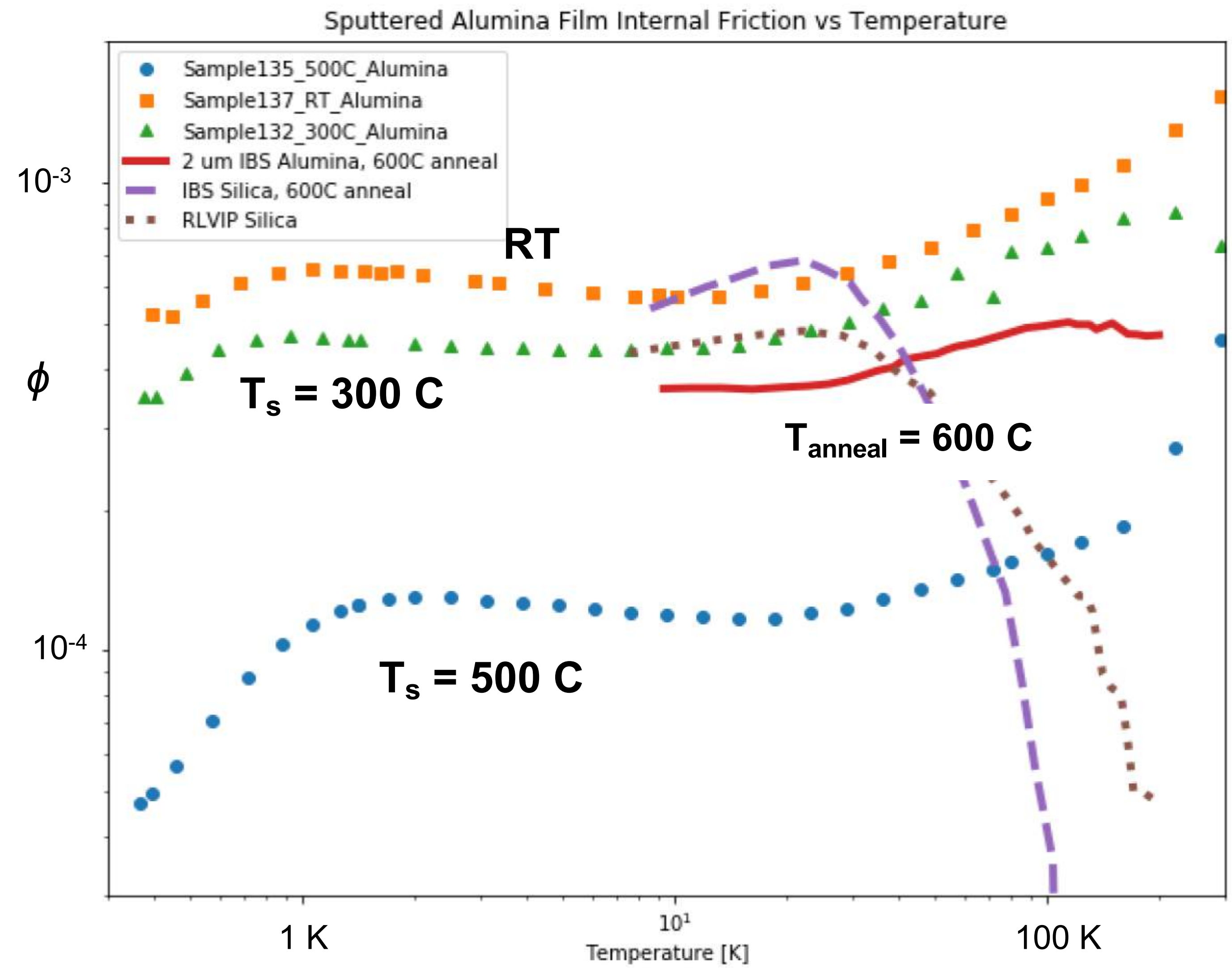
- Why?
  - simulated $T_{glass} >> T_{crystallization}$
  - not able to reach 0.8 T_{glass}

A year in the lab can save you a week of computation!



Ultrastable Oxides?

- **Possible ultrastable oxide — Al_2O_3**



M. Abernathy, G1800418

- Cryogenic mechanical loss lower when deposited with hot substrate
  - cannot be reached by annealing alone
- Further investigations required
- Paves way for further studies in oxides

- Search for $T_{glass} \lesssim T_{crystallization}$ in order to reach 0.8 T_{glass} underway
  - using MD simulations

Crystallization Suppression

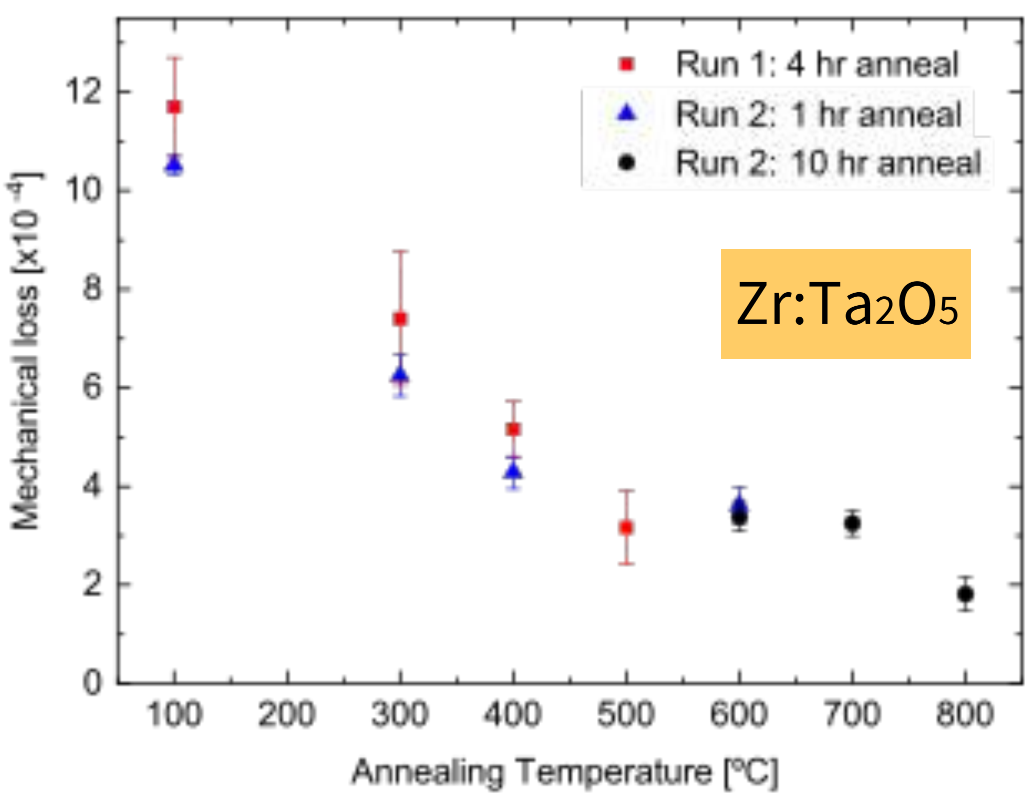
- Higher annealing temperatures for oxide glasses
  - push toward more uniform glass, even if not ultra-stable
- Frustrate crystallization *with suitable dopant*
  - $Zr:Ta_2O_5$

    Zirconia (34%)-Tantala: T_{anneal} = 800 C

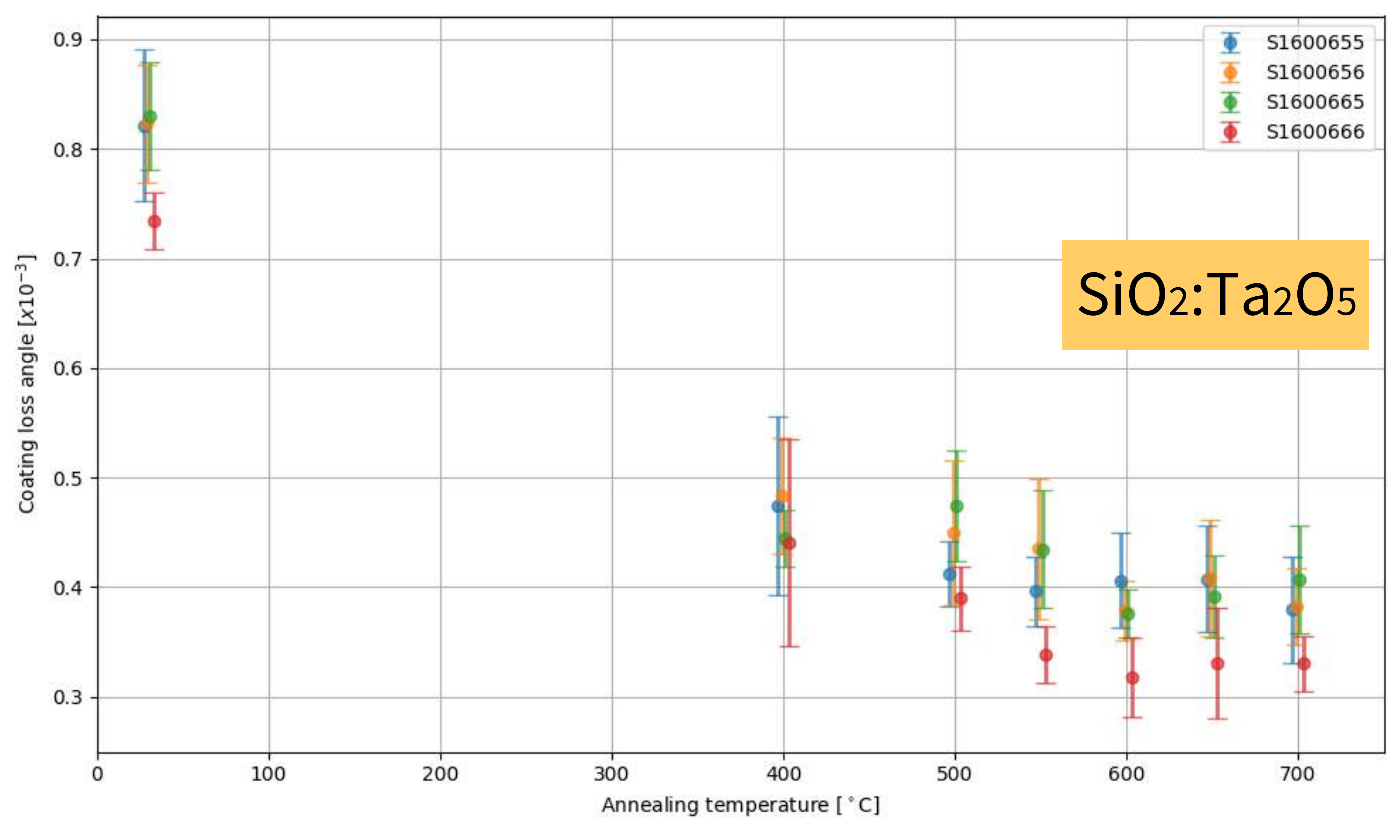
    ϕ = 1.4 x 10^{-4} at 300 K (~15% Zr, S. Reid et al), potentially useful
  - $SiO_2:Ta_2O_5$

    Silica (10%)-Tantala: T_{anneal} = 750 C

G. Cagnoli et al. G1801753



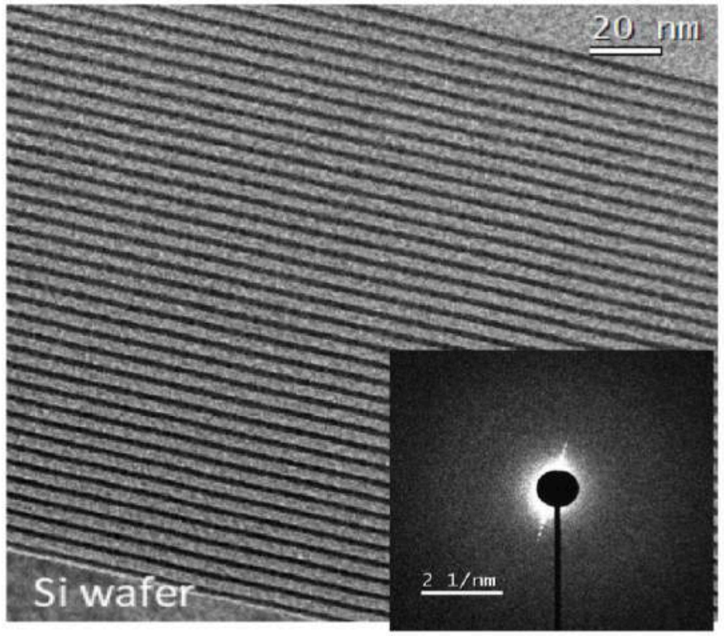
R Robin's thesis (U of Glasgow),
G Vajente (Caltech), G1800783

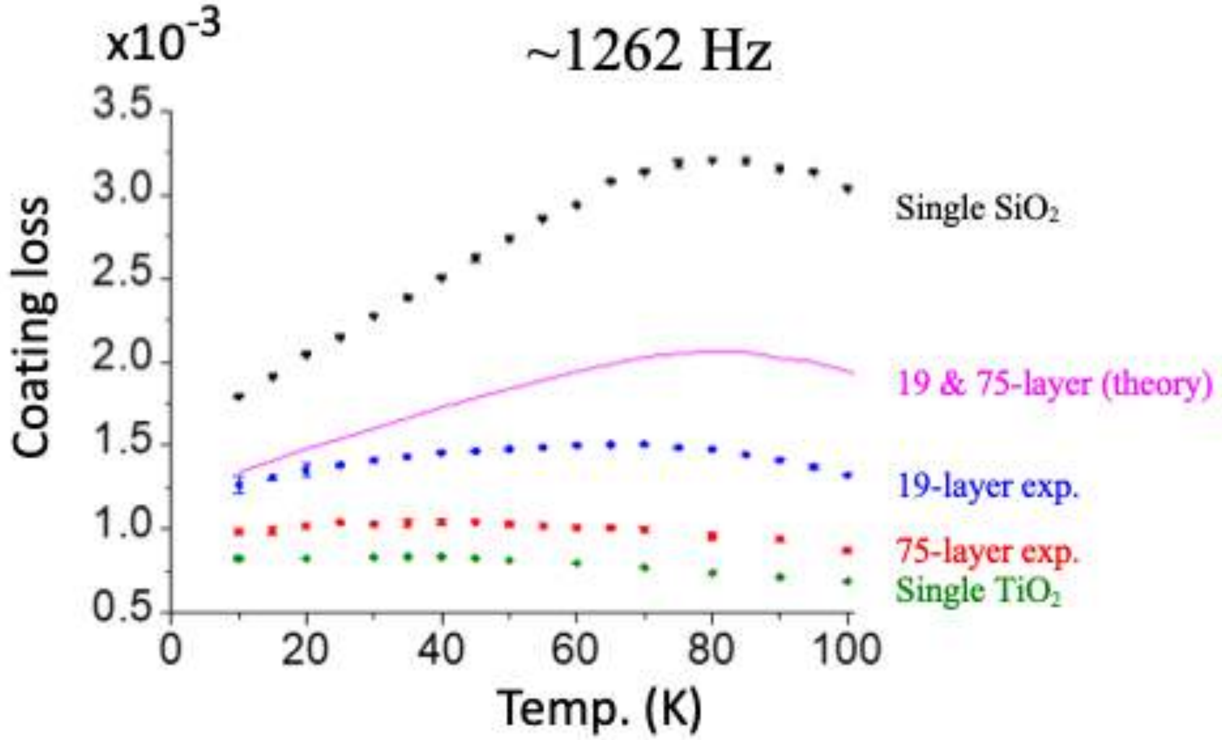


Le Yang, G1900528

Crystallization Suppression + Nanolayers

- Frustrate crystallization using “nanolayers” [S. Chao, LIGO-G1900289]
  [Chao, Pinto, DeSalvo]
  – intersperse thin stable (SiO_2) layers in high index material
  – TiO_2/SiO_2 nanolayers: 75 sublayers
    T_{anneal} < 800 C, crystallization suppressed
    $\phi \approx 10^{-4}$
  – volume/interface scatter an issue?



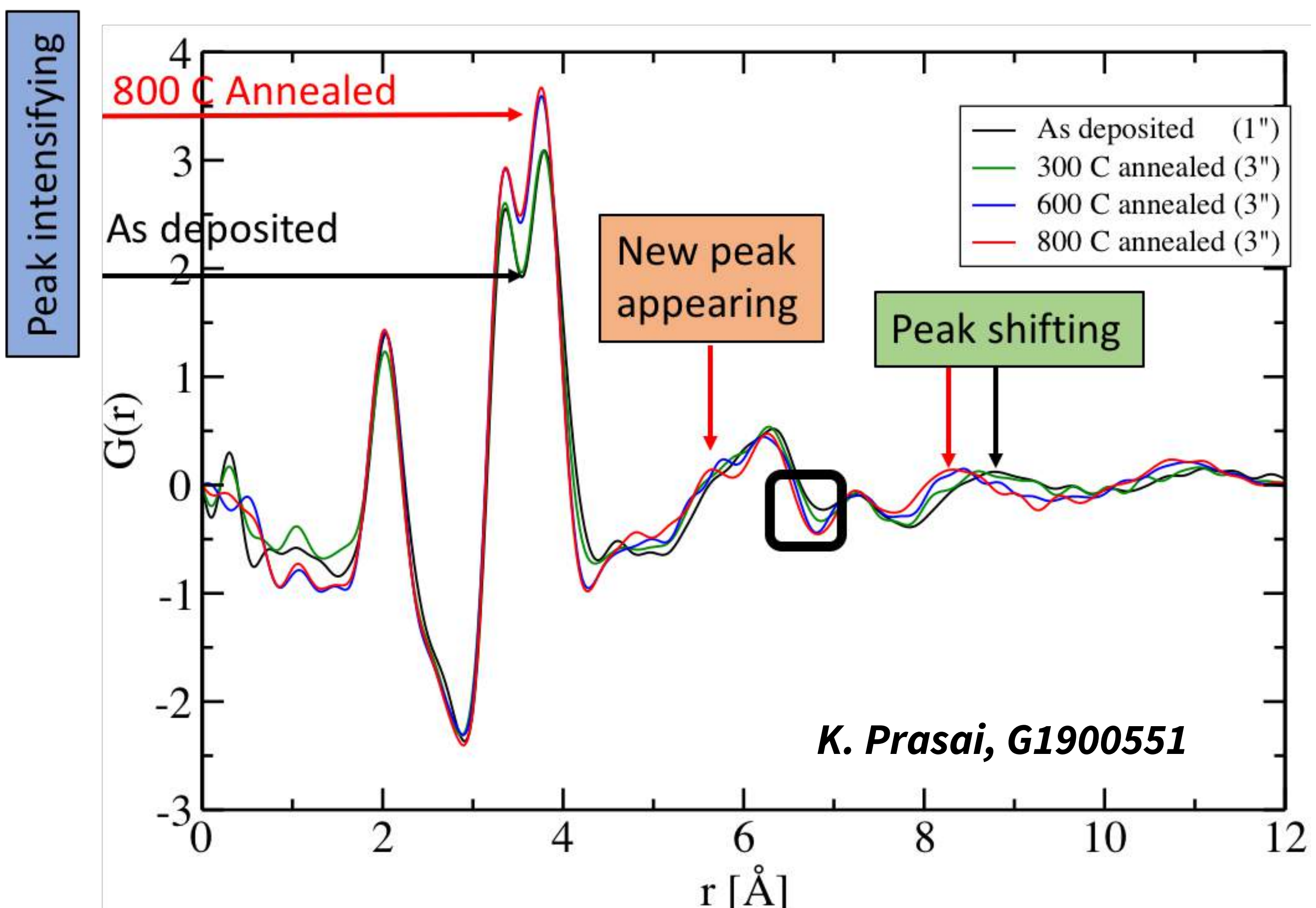


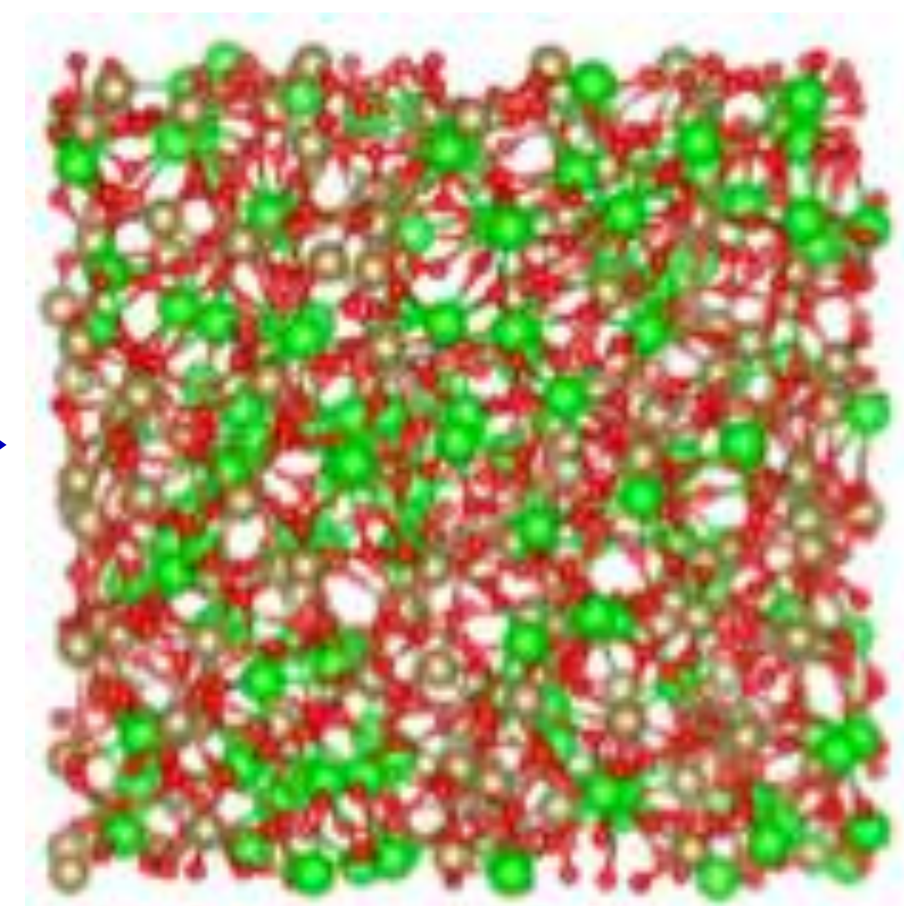
Suppresses low-T loss peak of silica – reducing low-energy TLS

S Chao *et al.*, P1900090

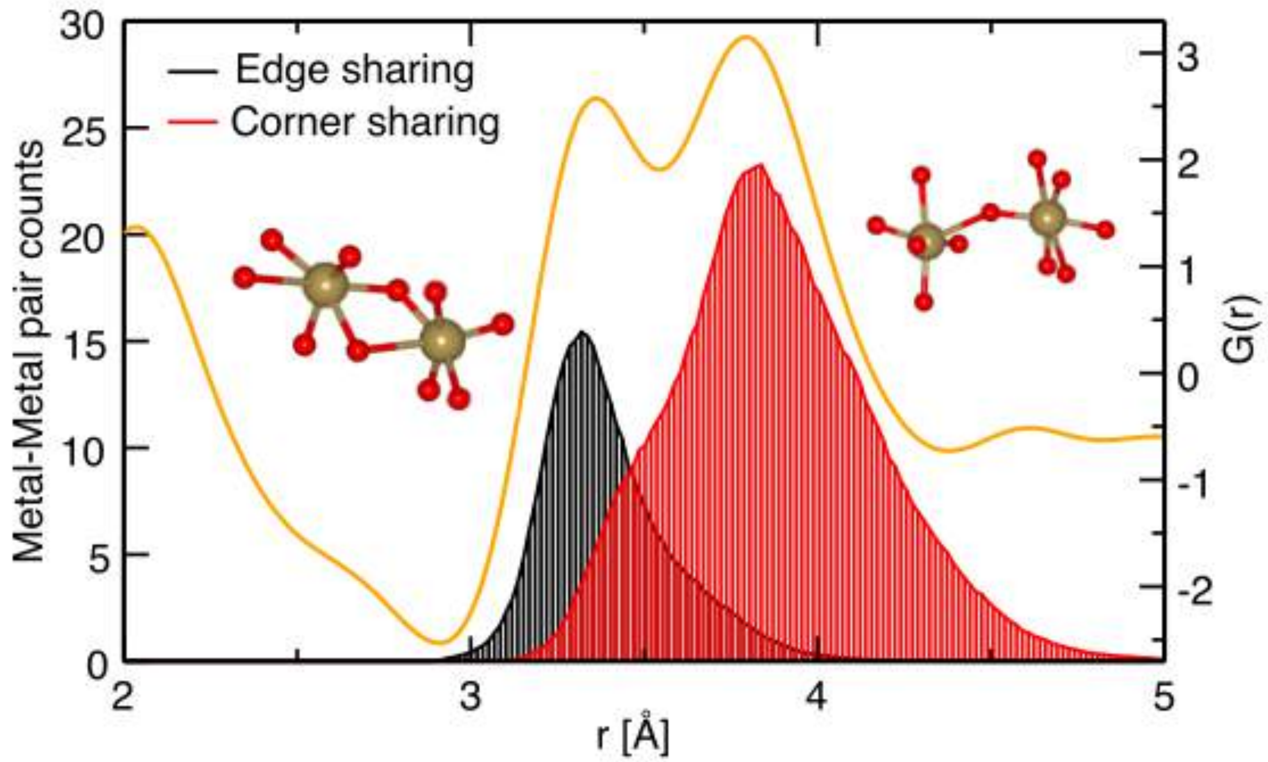
Structural Characterization ($Zr:Ta_2O_5$)

- $Zr:Ta_2O_5$ model system
  - strong candidate material
  - strong annealing dependence
  - MD potentials already developed (UF)
- GIPDF - X-ray Grazing-incidence Pair Distribution Functions
  - MD potentials
- atomic modeling (RMC + DFT)

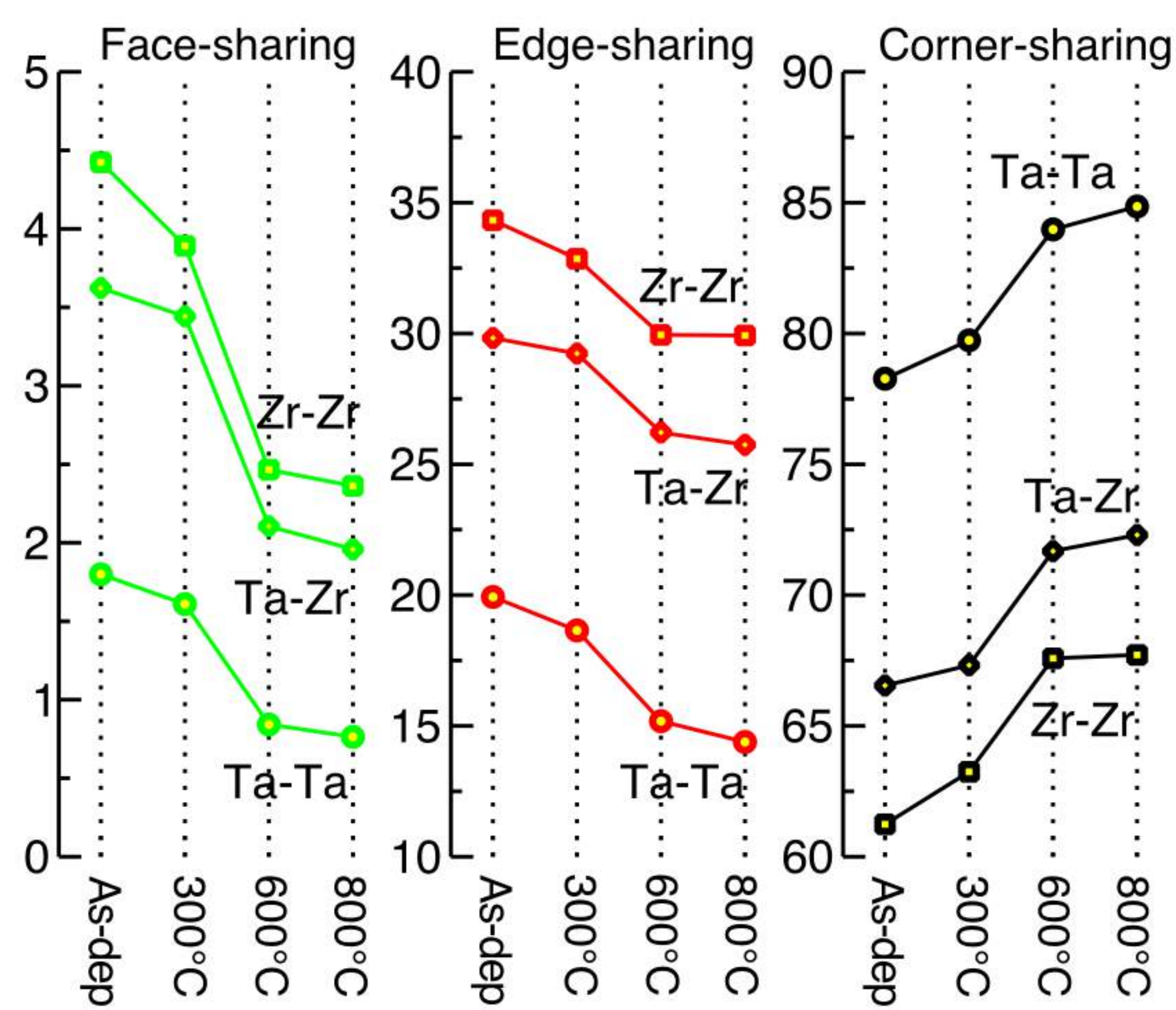




Structural Characterization ($Zr:Ta_2O_5$)



- Intermediate range structure
  - Mostly formed of edge-shared (ES) and corner-shared (CS) polyhedra
  - Changes with annealing: ES decreases, CS increases
- Know that RT loss goes down with increasing annealing temperature

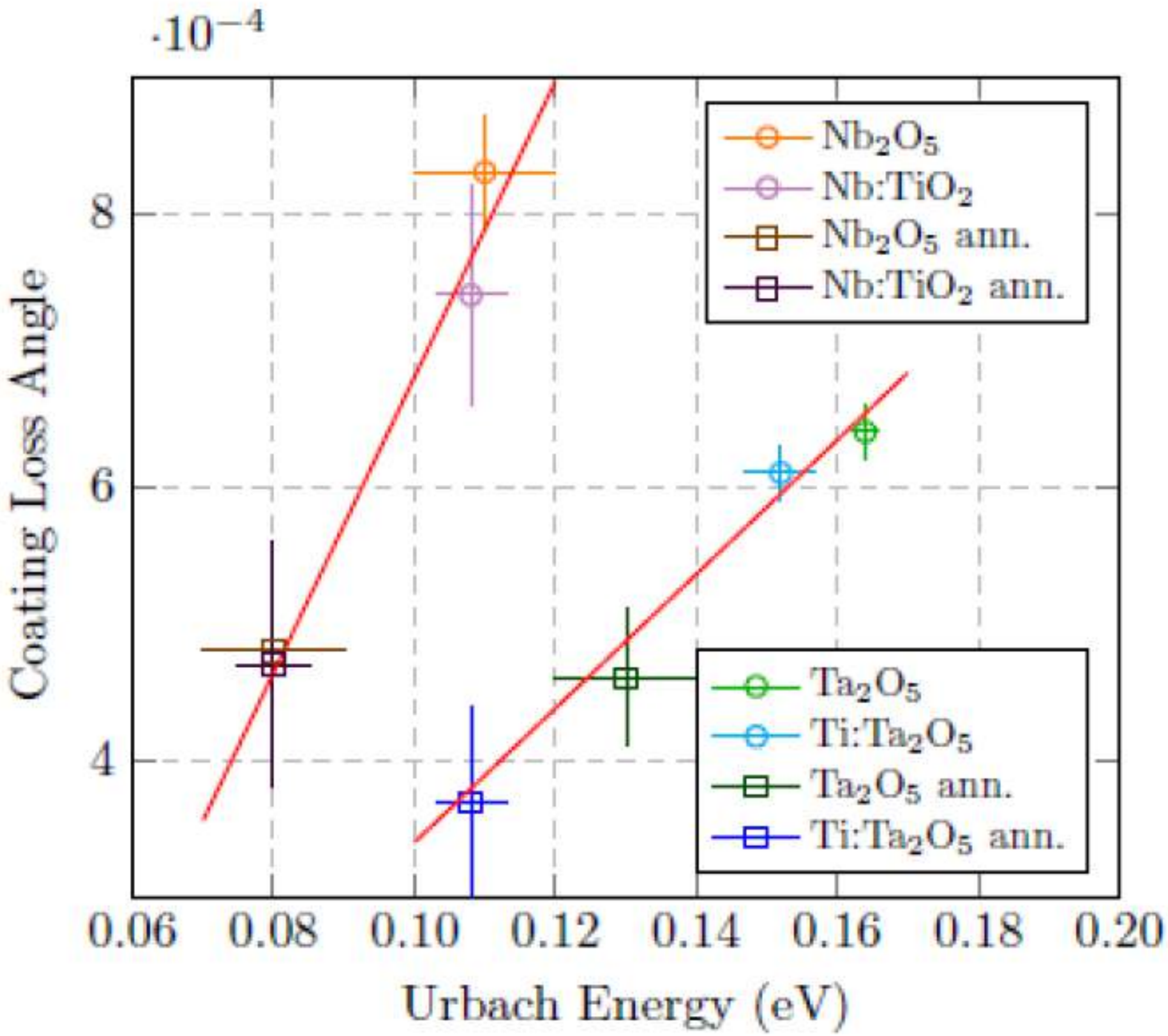


- Predictions for mechanical loss
  - TLS and mechanical loss
    - RT loss involves ES and FS polyhedra
    - Cryo-loss involve more CS polyhedra
  - Reducing ES polyhedra likely lower RT loss
    - Lower Zr doping concentration is beneficial
  - Tetrahedral oxide dopants, with high CS could be beneficial lower RT loss.
- TLS modeling underway to test conjectures

K. Prasai, G1900551

Structural Characterization (Urbach Tails)

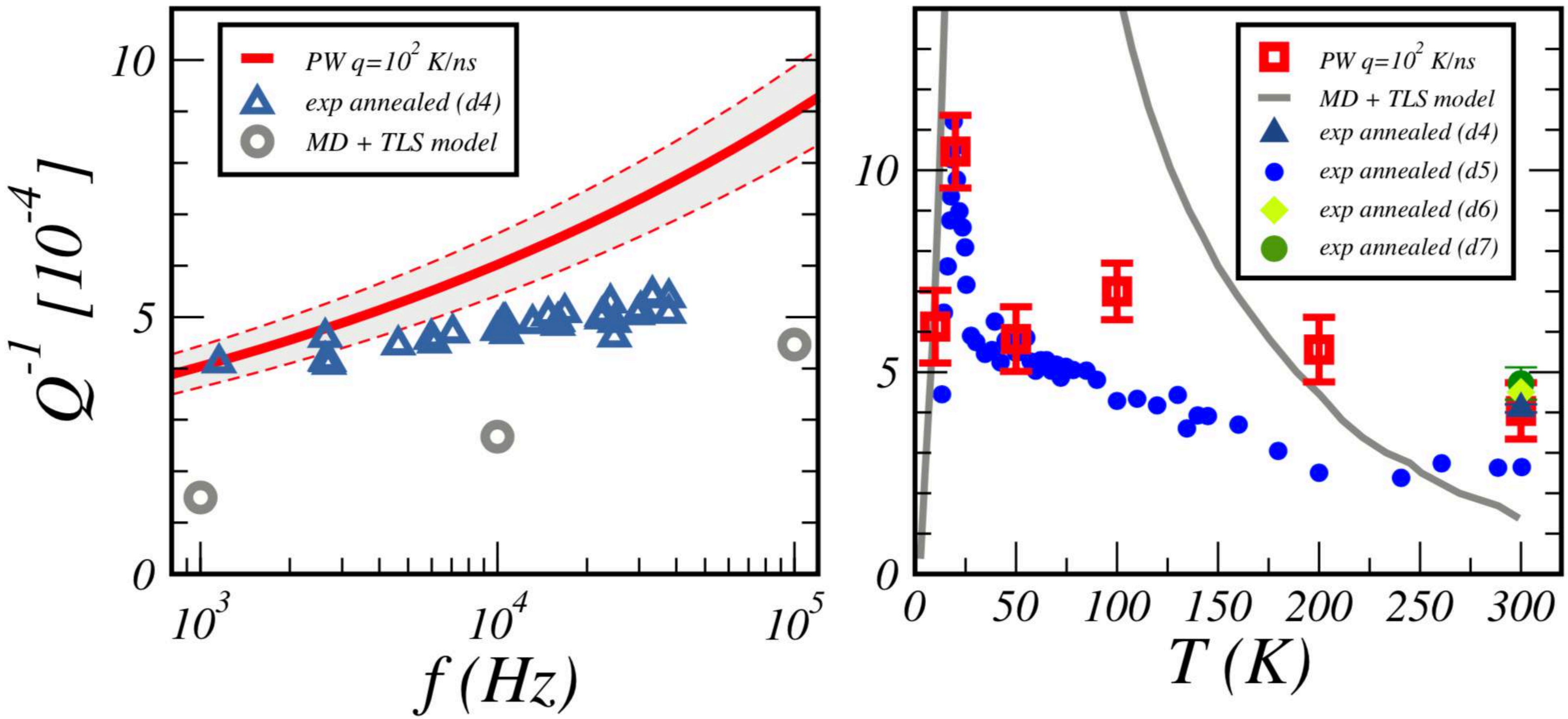
The **Urbach energy** is a parameter which quantifies the homogeneity of the structure by absorption investigation, probing a multi-range structural organization. **Annealing and doping** modify the structure leading to a more organized/ homogeneous atomic dispositions, reducing the mechanical loss angle.



Amato et al 2019
arXiv:1903.06094

Mechanical Loss Calculations

- Mechanical Spectroscopy modelling to calculate losses in numerical simulations of Ta_2O_5



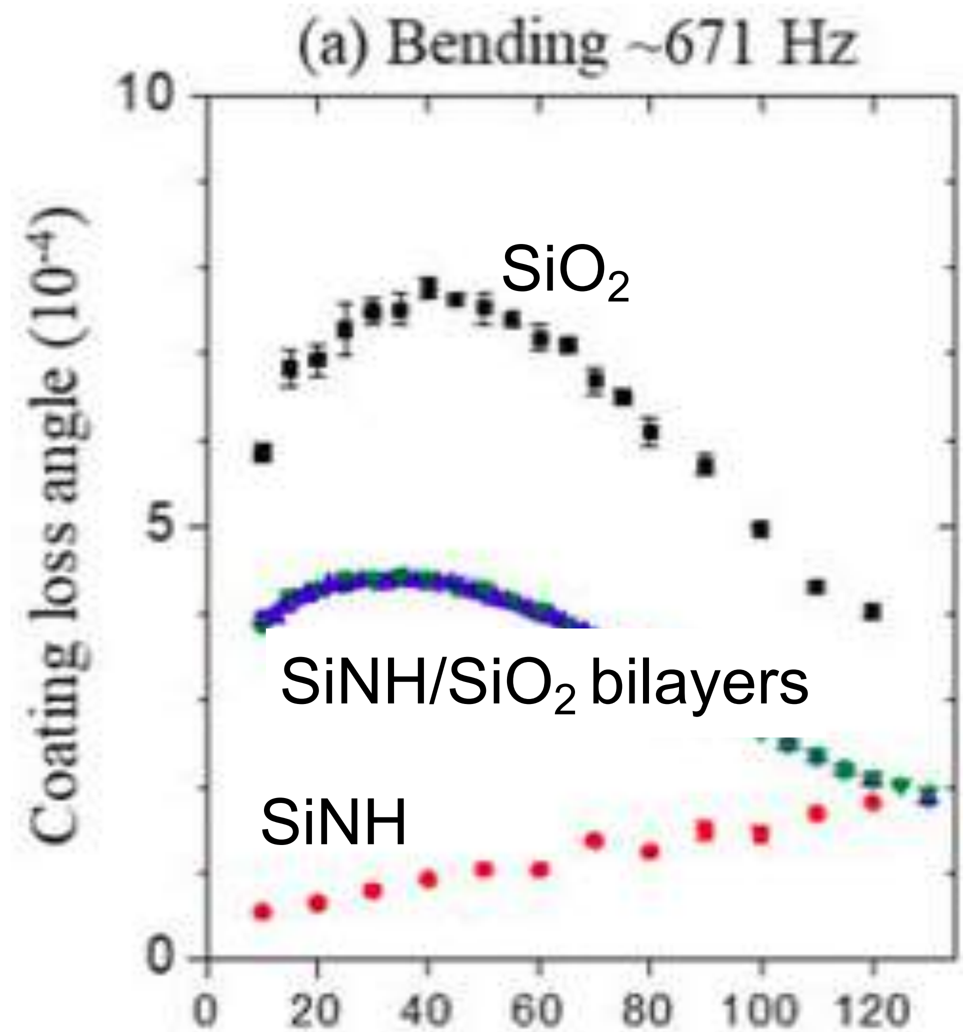
F Puosi et al. U. Pisa, GWADW 2019

- Qualitative and quantitative agreement between MD results and experimental data

- Further study on SiO2 and other mixtures ongoing

Non-oxide Materials: Silicon Nitride

- LPCVD deposition of $SiN_{0.40}H_{0.79}$
  - R.T.: ϕ ~1 x 10^{-4}
  - no low temperature loss peak
- 1/4-wave $SiN_{0.40}H_{0.79}/SiO_2$ bilayers
  - within ~2 of ET-LF and Voyager CTN specs
- Optical absorption of SiN/SiO_2 HR: ~50 ppm
  multi-material with Ta_2O_5/SiO_2
  - could bring absorption to ~2 ppm
- Recent post-deposition annealing
  - Releases H2
  - Bond reconfiguring in PECVD SiN film leads to thickness reduction and change of refractive index.
  - Further study on implications for coating design



Pan et al NTHU, P1800164

S Chao, NTHU, G1900305

Non-oxide Materials: a-Si and Multimaterial Coatings

- a-Si — absorption from dangling bonds too high for use at 1 μm
  - ~10x worse at 1 vs 1.5 μm
  - reduced by high T_s

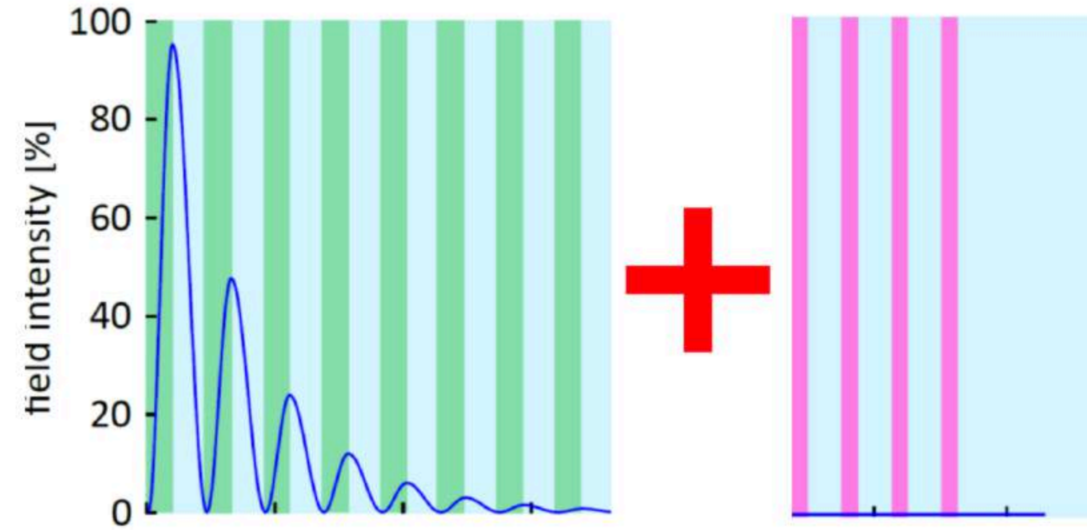
    but ~2x, not 10^3x
- Recent depositions promising
  - hot substrate, low-rate ECR

    20 ppm @ 1.5 μm with a-Si/SiO_2

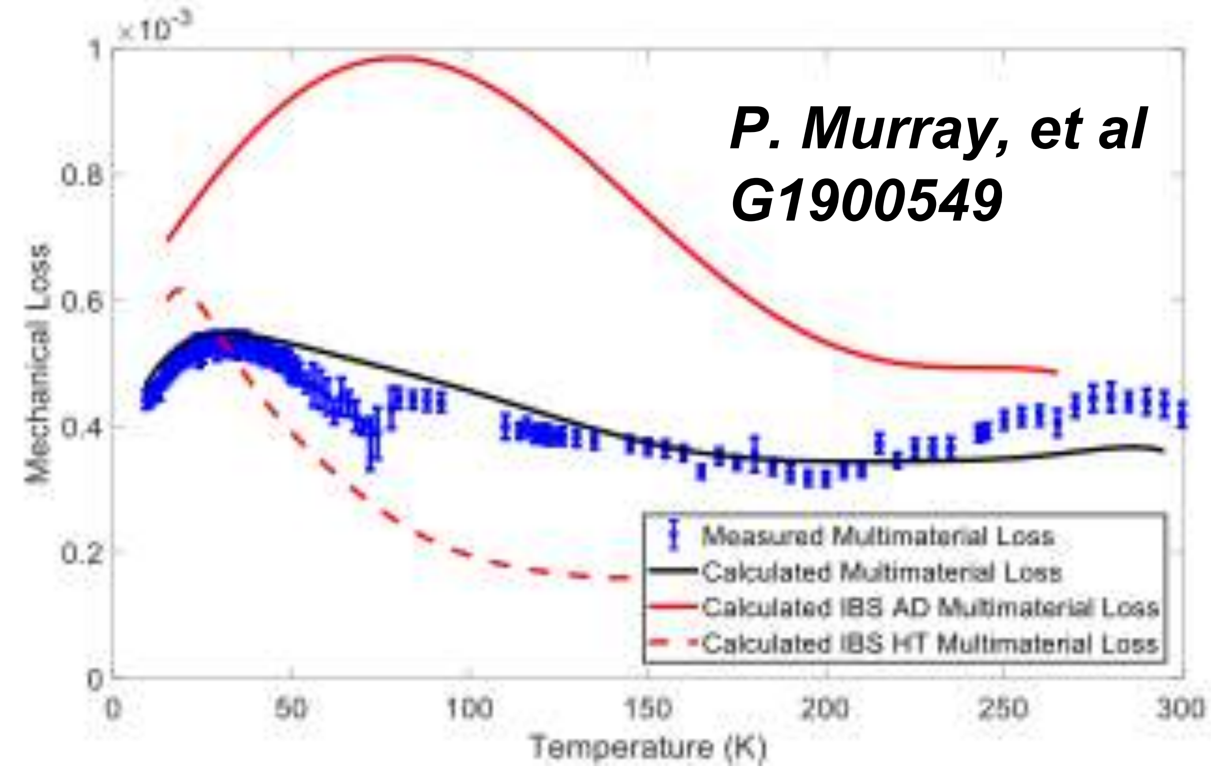
    S. Reid, Strathclyde
  - H^+ annealing ***A. Markosyan, G1900548***

    promising initial results

    <10 ppm @ 2 μm *F. Hellman, UCB*
- Multi-material coatings could help mitigate absorption
  - recent deposition shows loss = expected values
- SiOx – aSi (MIT/Lincoln Labs/Evans *et al.*)
  - thermal noise slightly below aLIGO, with low absorption (0.7 ppm)



J. Steinlechner, et al , Phys. Rev. D ***91*** *042001 (2015)*
W. Yam et al, Phys. Rev. D ***91****, 042002 (2015)*

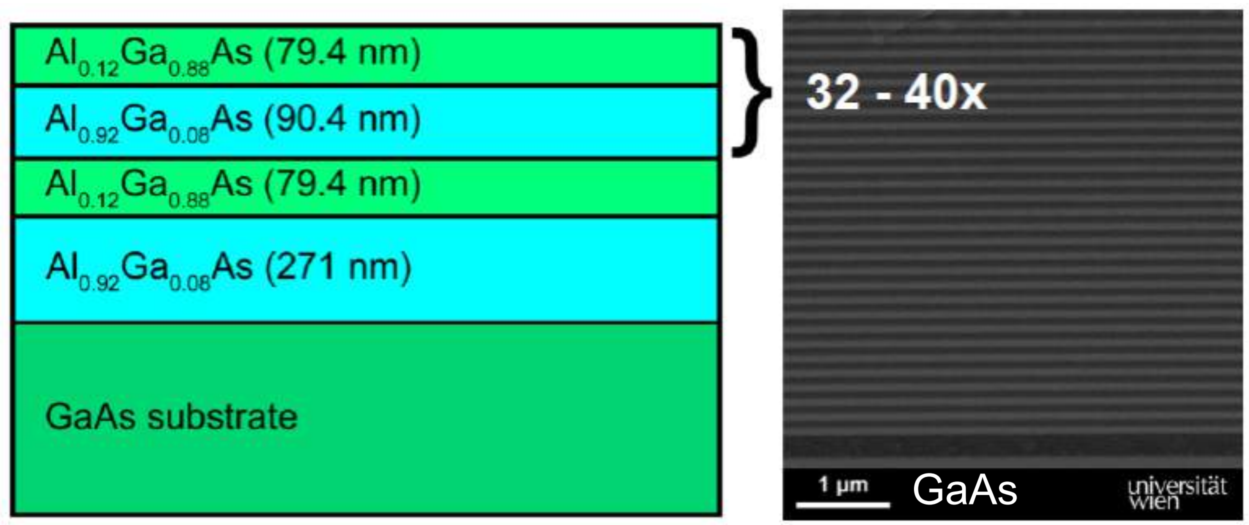


P. Murray, et al G1900549

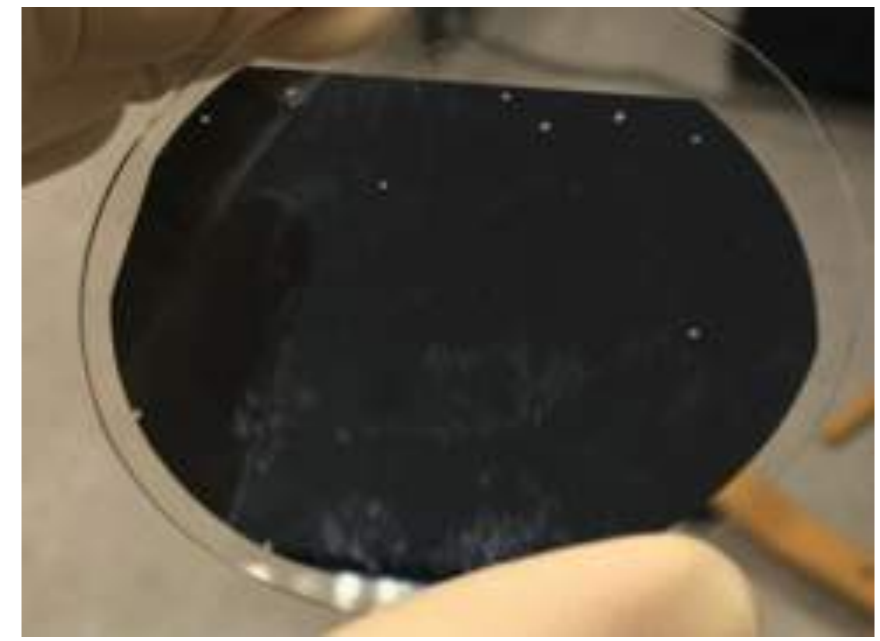
Crystalline Coatings

- GaAs/AlGaAs epitaxy on GaAs, transferred to mirror substrate

  $\phi \sim 2 \times 10^{-5}$, $\alpha < 1$ ppm *G. D. Cole et al., Nature Photonics **7**, 644–650 (2013)*



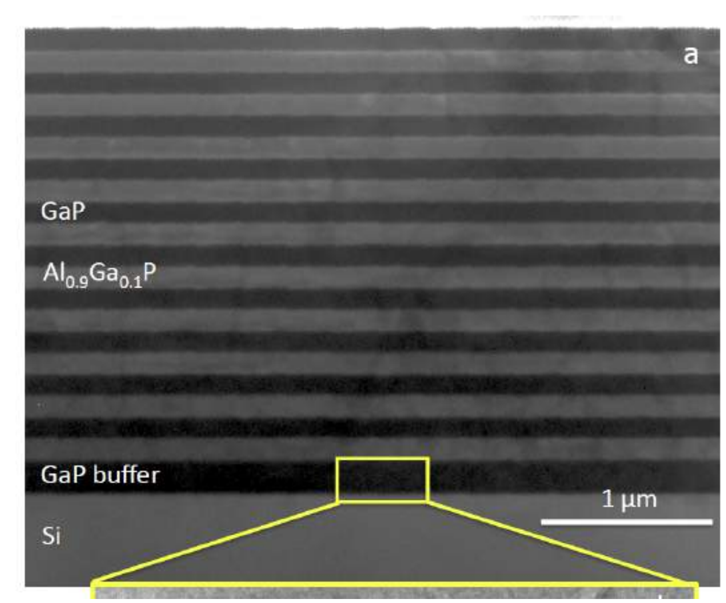
G. Cole, Crystalline Mirror Solutions



- GaP/AlGaP epitaxy on Si mirror substrate

  A. Lin, SU: $\phi < 1 \times 10^{-4}$, $\alpha = ??$ *A. C. Lin et al., Opt. Mater. Express **5** 1890-1897 (2015)*

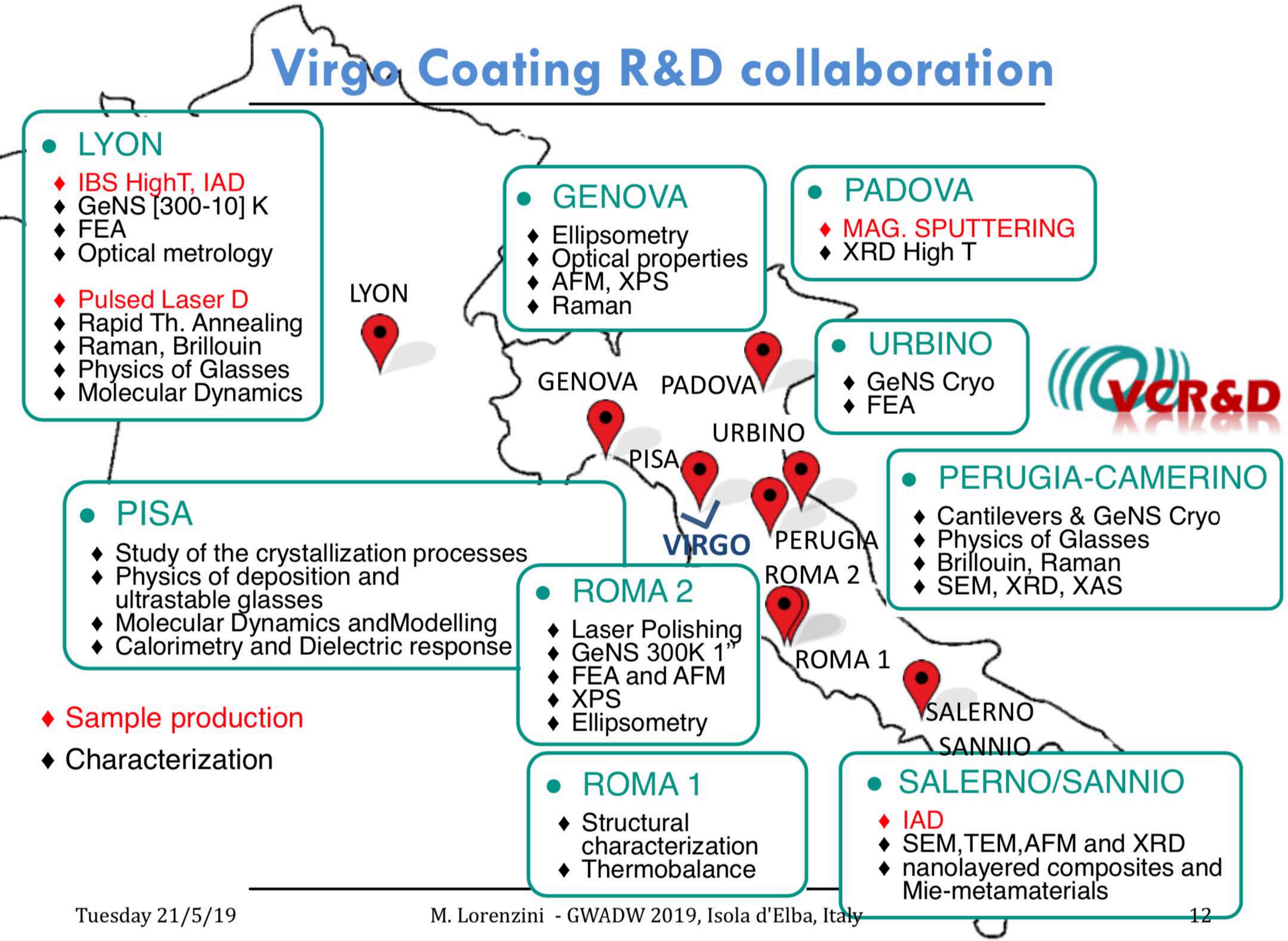
- Key challenges for any crystalline coating:
  - scatter loss over large areas?
  - shear vs. bulk loss loss — further study needed
  - MBE tool maintaining nm uniformity over 34 cm: $$$
  - AlGaAs: GaAs substrates, bonding over large area
  - AlGaP: investigation of absorption mechanisms, development of large area process



LSC Optics Working Group

	CCR	U.S.	GEO	INT'L
Deposition	Berkeley Col. State	NRL LL/MIT CSLA/Sannio	Strathclyde Hamburg	Montreal Tsinghua ANU
Mechanical Loss	Syracuse HWS SU	Caltech NRL MIT	Glasgow	Tsinghua
Atomic Structure Model	Florida SU			
Atomic Char.	SU		Glasgow	
Optical Char.	Fullerton Col State Whitman	CSLA/Sannio	Glasgow Strathclyde	Tsinghua
Macroscopic Model	Fullerton American SU	MIT	Strathclyde Hamburg Glasgow	

Virgo Coating R&D collaboration



- LYON
  - ♦ IBS HighT, IAD
  - ♦ GeNS [300-10] K
  - ♦ FEA
  - ♦ Optical metrology
  - ♦ Pulsed Laser D
  - ♦ 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

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

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

- 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


Winding road,
with promising
directions

Co-ordination Efforts

- Why is collaboration needed?
  - Why scientists should gather in OWG to work together?
  - What is Virgo gaining from VCR&D?
  - Answer:
    - collaboration is needed when the task is too complicated for one single group
    - when time is short, a parallelization of tasks is fundamentally important
    - “if you find all this trivial, at the moment this is not happening” *G. Cagnoli*

- How collaboration between OWG and VCR&D is progressing:
  - Started combined LIGO-Virgo telecons (every two weeks)
  - LSC working to generate research lines similar to Virgo
  - Continue with dedicated cross-collaboration F2F workshops
  - OWG needs to show that money is well spent, VCR&D needs to show that funding is required
  - Ongoing efforts to develop closer ties – expand to include expertise outwith LSC and VCR&D