

LIGO Highlights

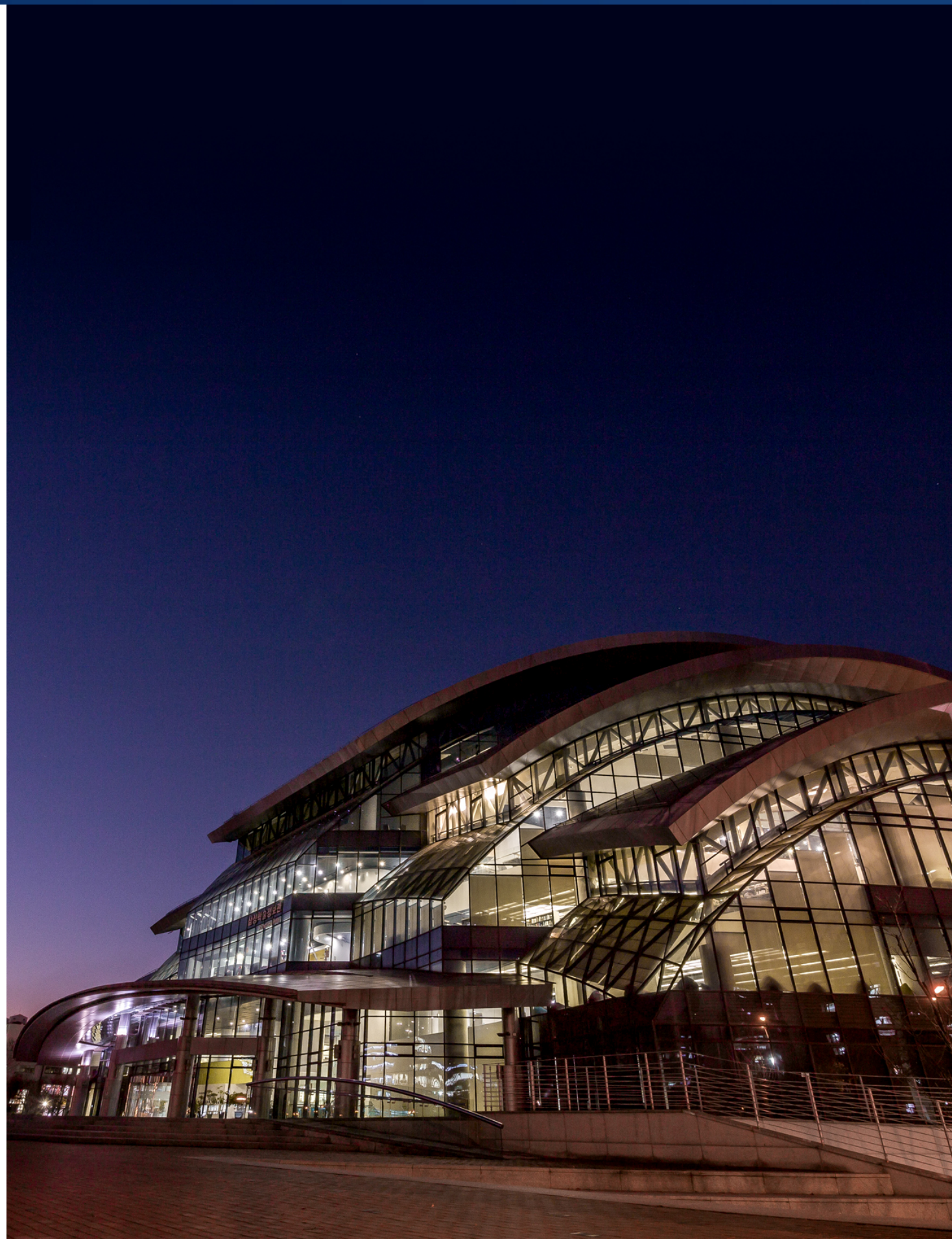
On behalf of Korean LIGO members

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2025 Particle/Nuclear/Astro
Workshop

November 19, 2025





GW Talks

- 1. LIGO Highlight (NOW): Kyung-ha Lee**
- 2. GW Universe (5pm Today): Hyung Mok Lee**
- 3. KGWG Highlight (5pm Friday): Hyung Won Lee**
- 4. YEMIGO (12pm Saturday): John Oh**

Overview

1. LIGO Introduction

- ▶ Observing Plans
- ▶ Structure of LSC
- ▶ Korean LIGO Group Summary

2. LIGO Experimental Work in Korea

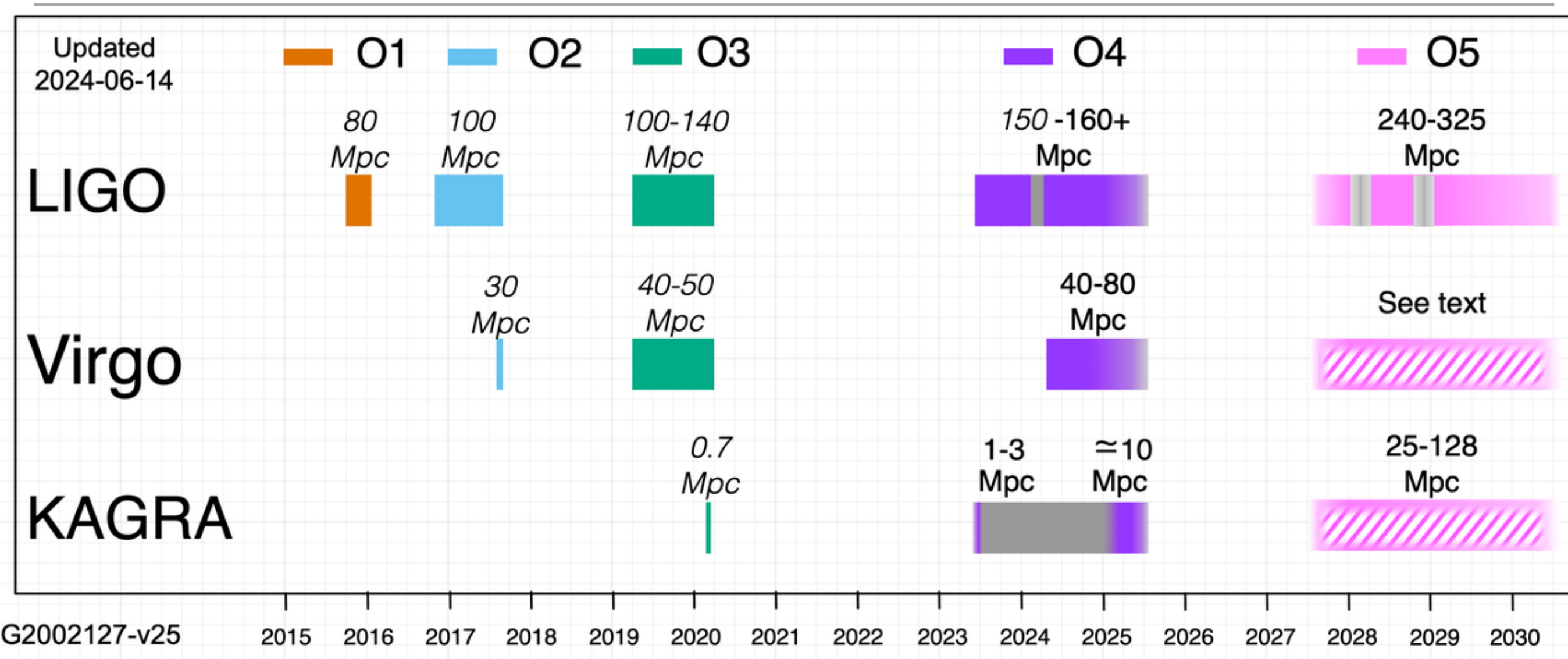
- ▶ Coating Brownian Noise

3. LIGO Data Analysis Work in Korea

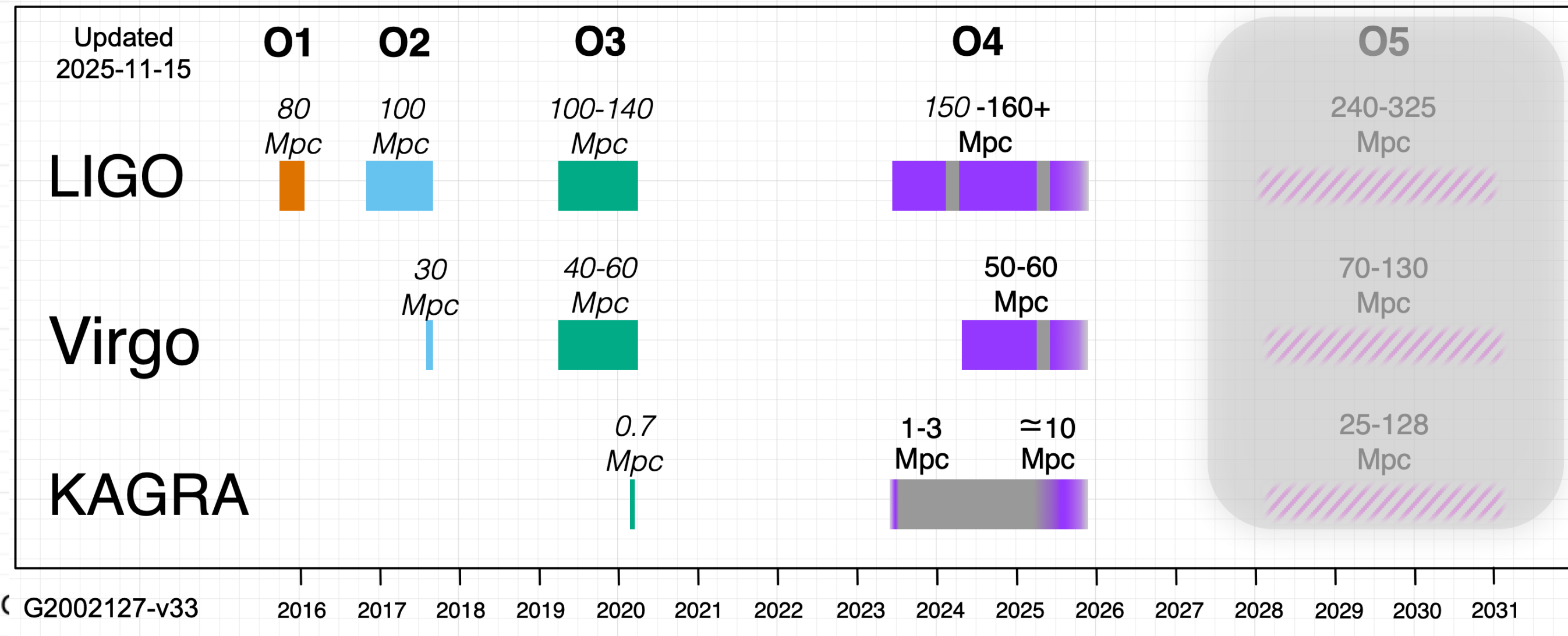
- ▶ CBC & DetChar & etc

4. Summary & Future Work

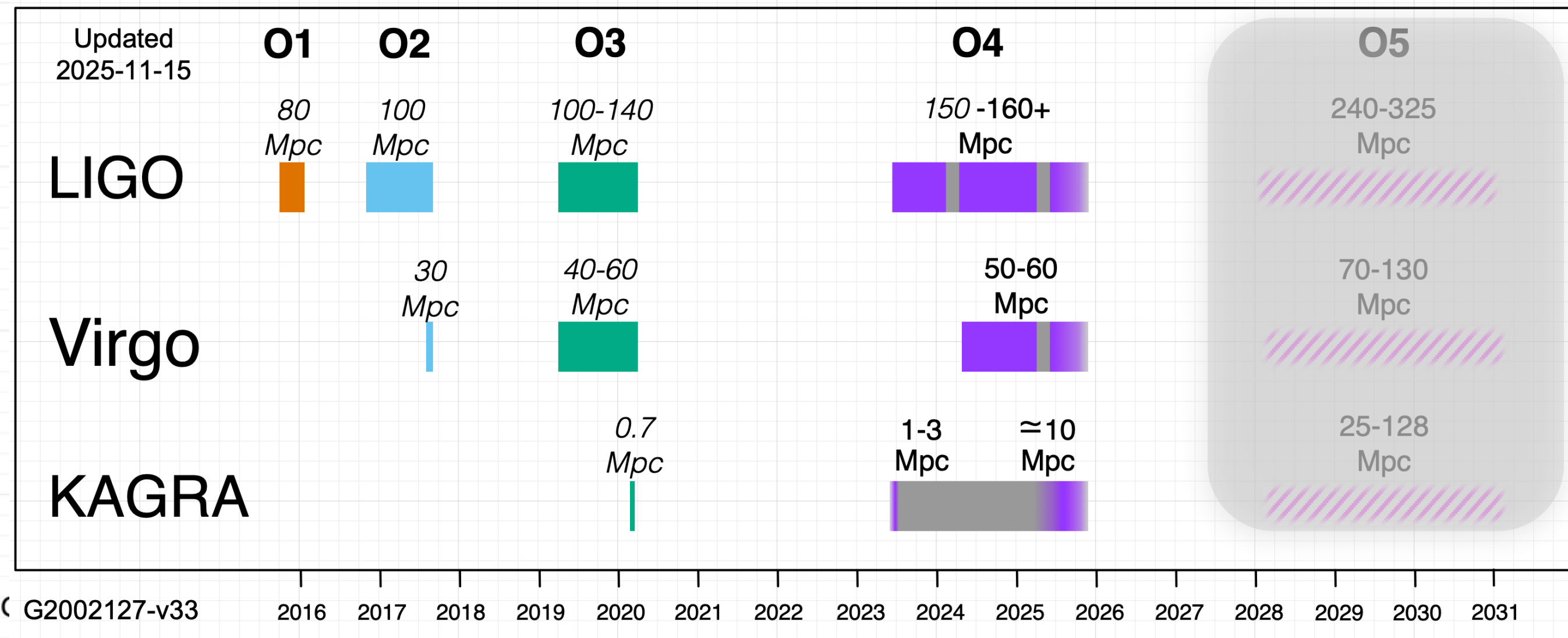
LIGO Observing Plan



LIGO Observing Plan



LIGO Observing Plan



- Observing Plans are constantly changing.
- O4 was just concluded last night!
- Upgrading & Commissioning period started now!
- Partners: IceCube, CHIME, IPN, Swift, Fermi, etc

LIGO Scientific Collaboration (LSC)

◆ Experimental

- Optics Working Group
 - KGWG
- Advanced Interferometer Configurations Group
- Newtonian Noise Group
- Seismic Isolation & Suspension Working Group
- Controls Group
- Lasers and Auxiliary Optics Group
- Quantum Noise Group

◆ Data Analysis & Theory

- Burst Search Group
 - KGWG
- Compact Binary Coalescence Search Group
 - KGWG
- Continuous Wave Search Group
- Stochastic Search Group
- Detector Characterization Working Group
 - KGWG
- Data Analysis Council

LIGO/KGWG

- Members 16 [2024 Jan.] (→ 19 [current, three students were added])
 - 8: Permanent Members (1 SNU, 1 Ewha, 2 NIMS, 1 Inje, 1 KISTI, 1 Chungang, 1 SKKU)
 - 4 Researchers (1 SNU, 1 Ewha, 1 UNIST, 1 KASI)
 - 7 Students (1 NIMS, 1 Ewha, 1 ChungAng, 4 SKKU)
 - Authors: 13

Recent Activities of KGWG in LSC (2024-2025)

- Software
 - Investigation of the effects of limited number of bins on the parameter estimation, for further development of parameter estimation code,
 - Development of fast templates for microlensed events using surrogate modelling
 - Review of the results from tidal parameter estimation and EoS inference pipelines for LVK publications based upon nuclear physics perspectives, i.e. the effect of nuclear symmetry energy.
 - Optimization of parameter estimation for Compact Binary Coalescences with low-eccentricity
- Waveforms
 - Support for precession in gw_eccentricity, review the code and add to PE post processing.
 - Provide NR waveforms for Black Hole Capture Events

Recent Activities of KGWG in LSC (2024-2025)

- Data Analysis
 - Search for BH capture events with Coherent Wave Burst (cWB) + Gaussian Mixture Model (GMM) pipelines
 - Simulation-based study for finding multi-messenger signals of strong lensing utilizing EM catalogs
 - Offline PE activities including PE rota for O4
 - Analysis of low-mass CBCs from O4 and/or O3 using TaylorF2Ecc, as contribution for O4 full-author paper
- Review
 - Chairing analysis review for the S230814ah paper (GW230814, the loudest event so far)
- Detector Characterization
 - Maintain and update the codes of machine learning model (MSNN, explainable AI) to classify and trace the responsible or witnessing channels of known noiseCoating
 - Monitoring known or new Data Quality issues in the LIGO interferometers

Recent Activities of KGWG in LSC (2024-2025)

- Shifts
 - DQ Shifts
 - Rapid Response Team (RRT) Shift
- Computing Resources
 - Managing Condor on KISTI Cluster for IGWN
 - Maintaining KISTI Cluster (Tier 2 Center of LIGO Data Grid) H/W for IGWN
- Public Outreach
 - Maintain and refine of the portable GW detection simulator for exhibitions at educational and outreach events.
- Experiments
 - Coating candidate material search

Potential Collaborations with us!

◆ Data analysis

- Multi-messenger astrophysics
- Simulations between LIGO & nuclear physics / high energy physics
- Theory?

◆ Experimental

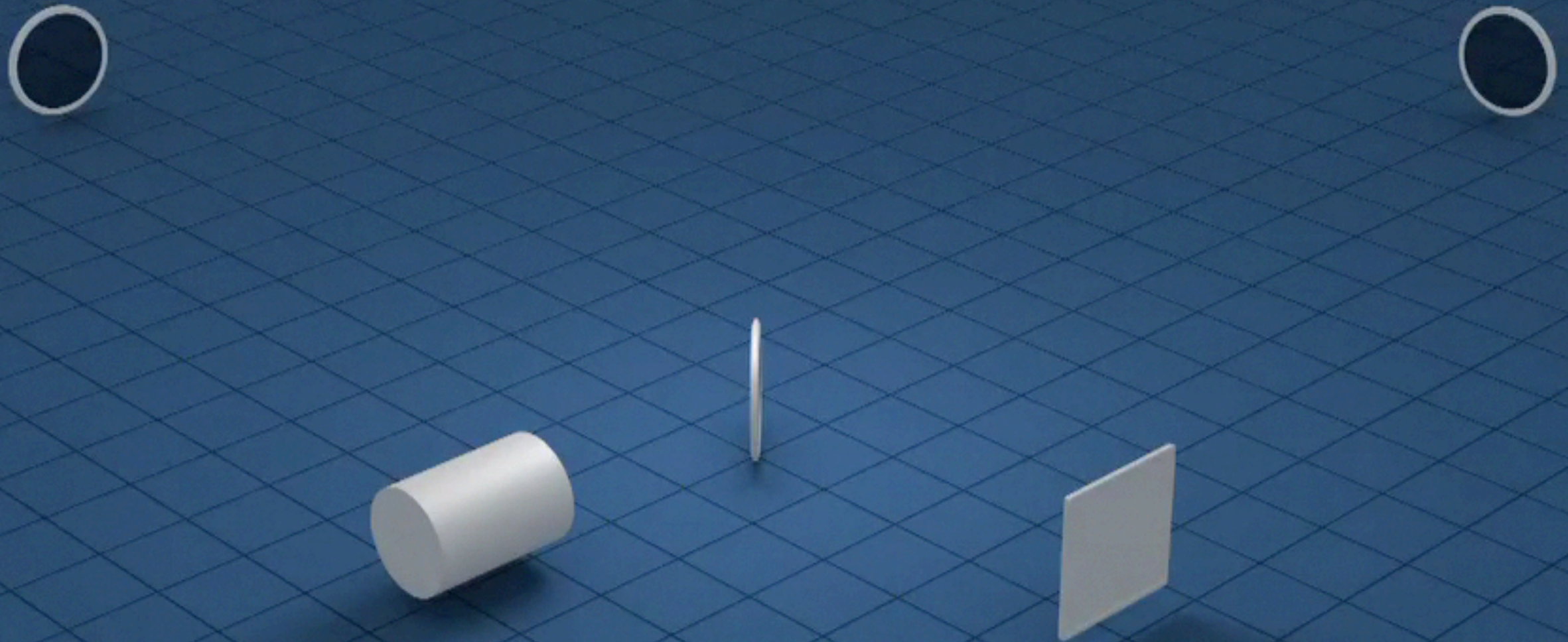
- Each noise needs various research expertise.
 - Coatings —> Optics & Material science
 - Quantum —> Optics & Quantum
- Hardware contribution is essential for LIGO.

◆ Becoming LIGO member might not be very straightforward, but LSC is definitely welcoming all multi-messenger collaborators & experimental expertise who can contribute to upgrade plans!

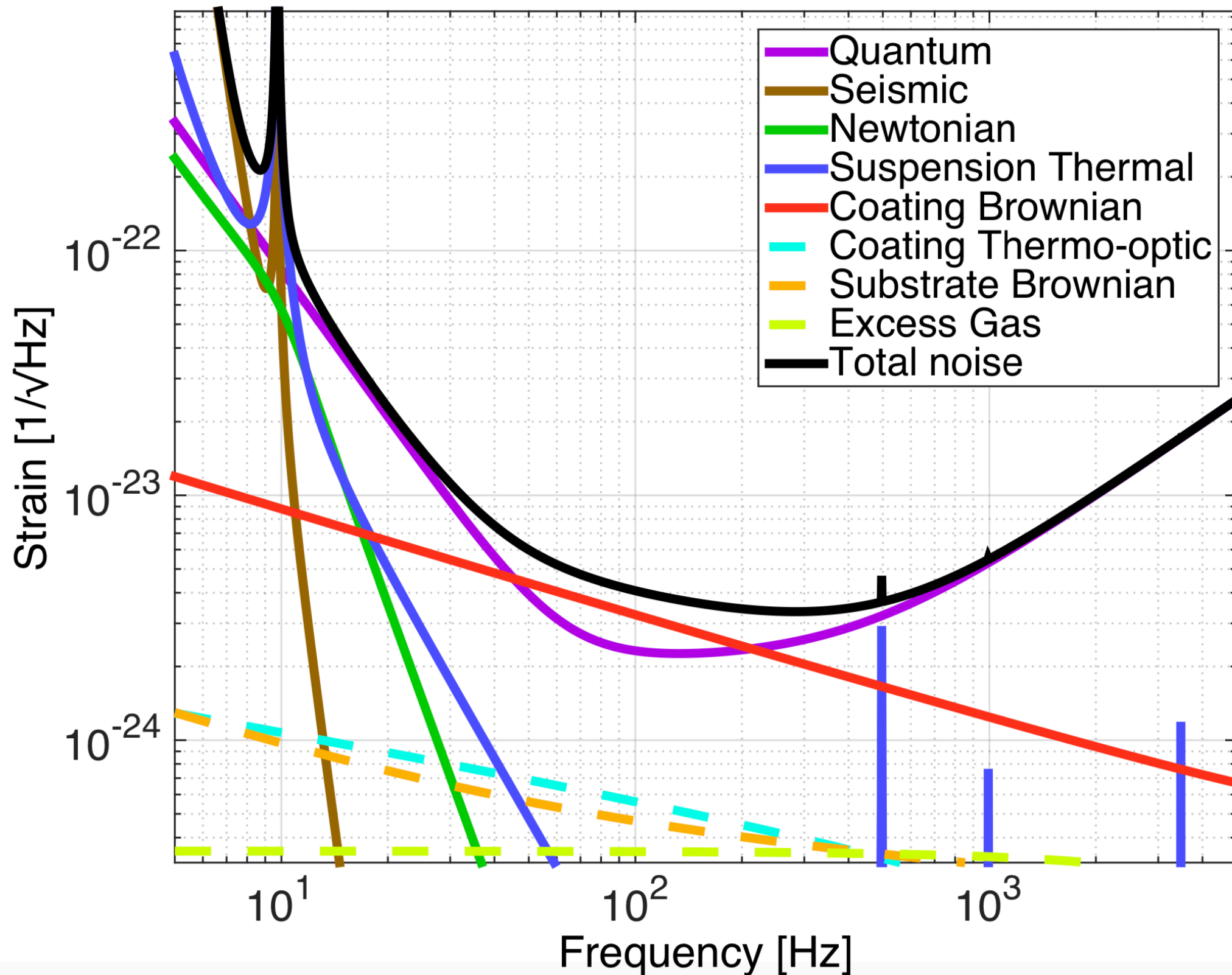


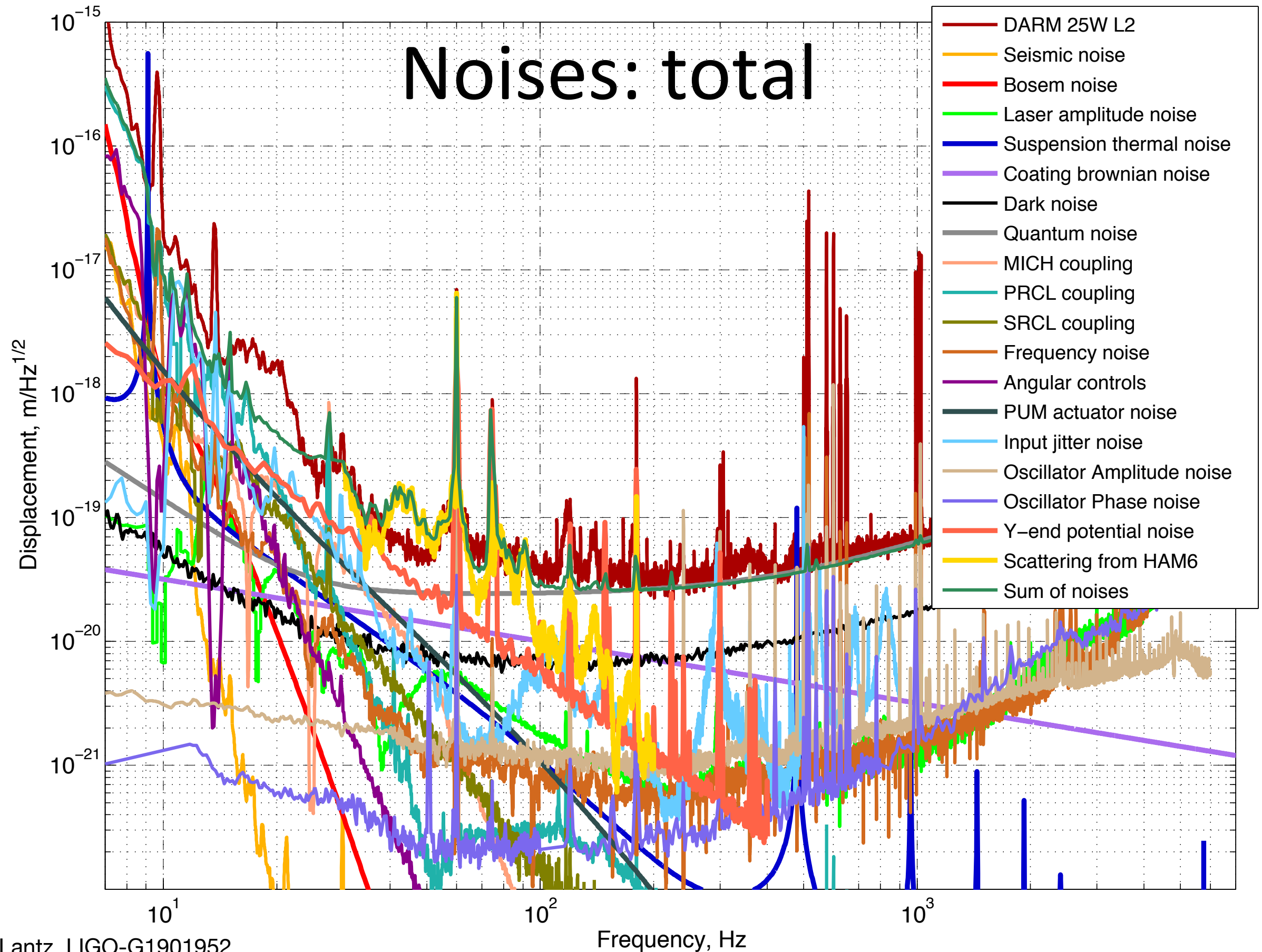
LIGO Detector Introduction

LIGO Detector Introduction: Interferometer 101



LIGO Detector Introduction: Noise Curve

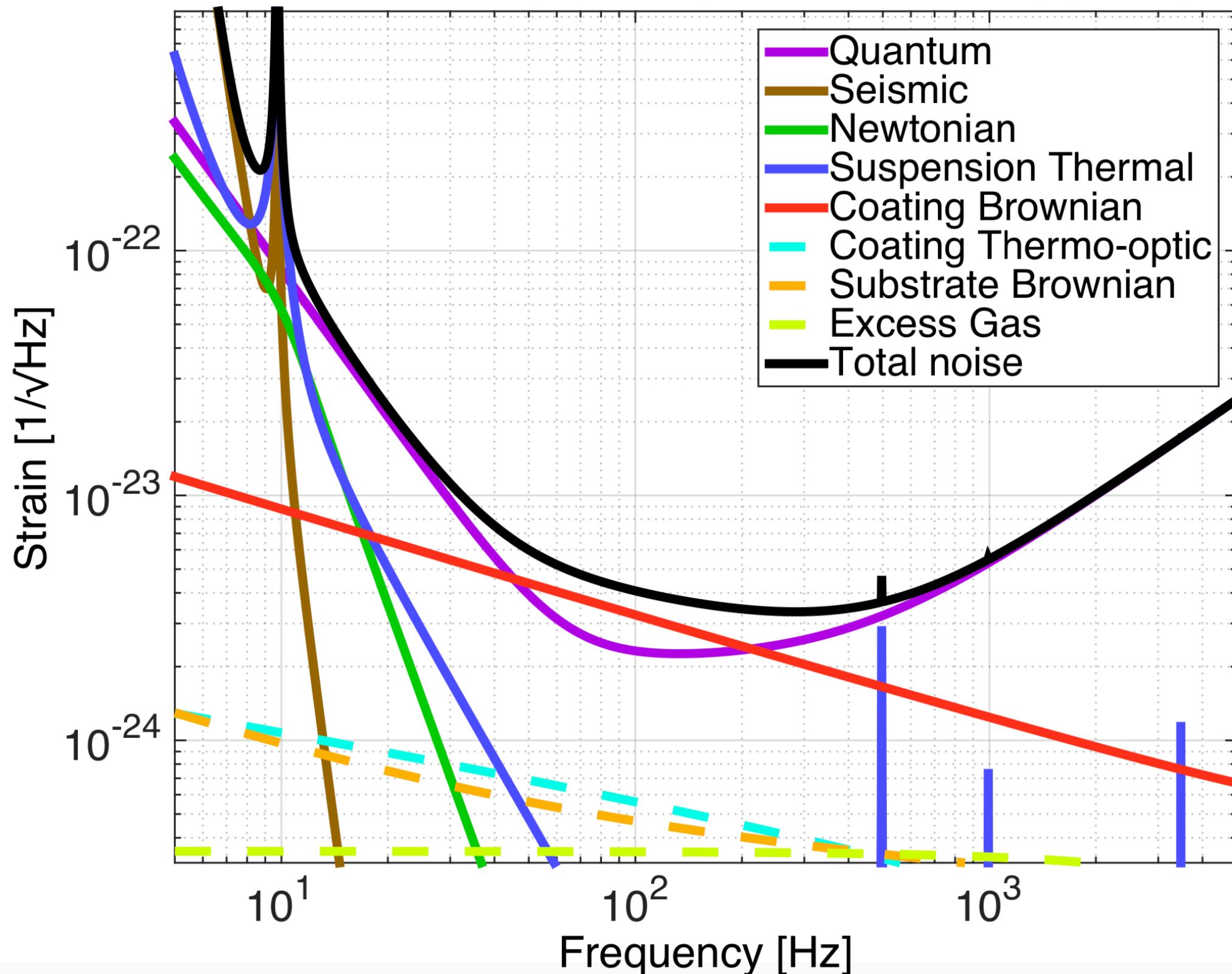




Brian Lantz, LIGO-G1901952

Den M. G1500281

LIGO Detector Introduction: Noise Curve

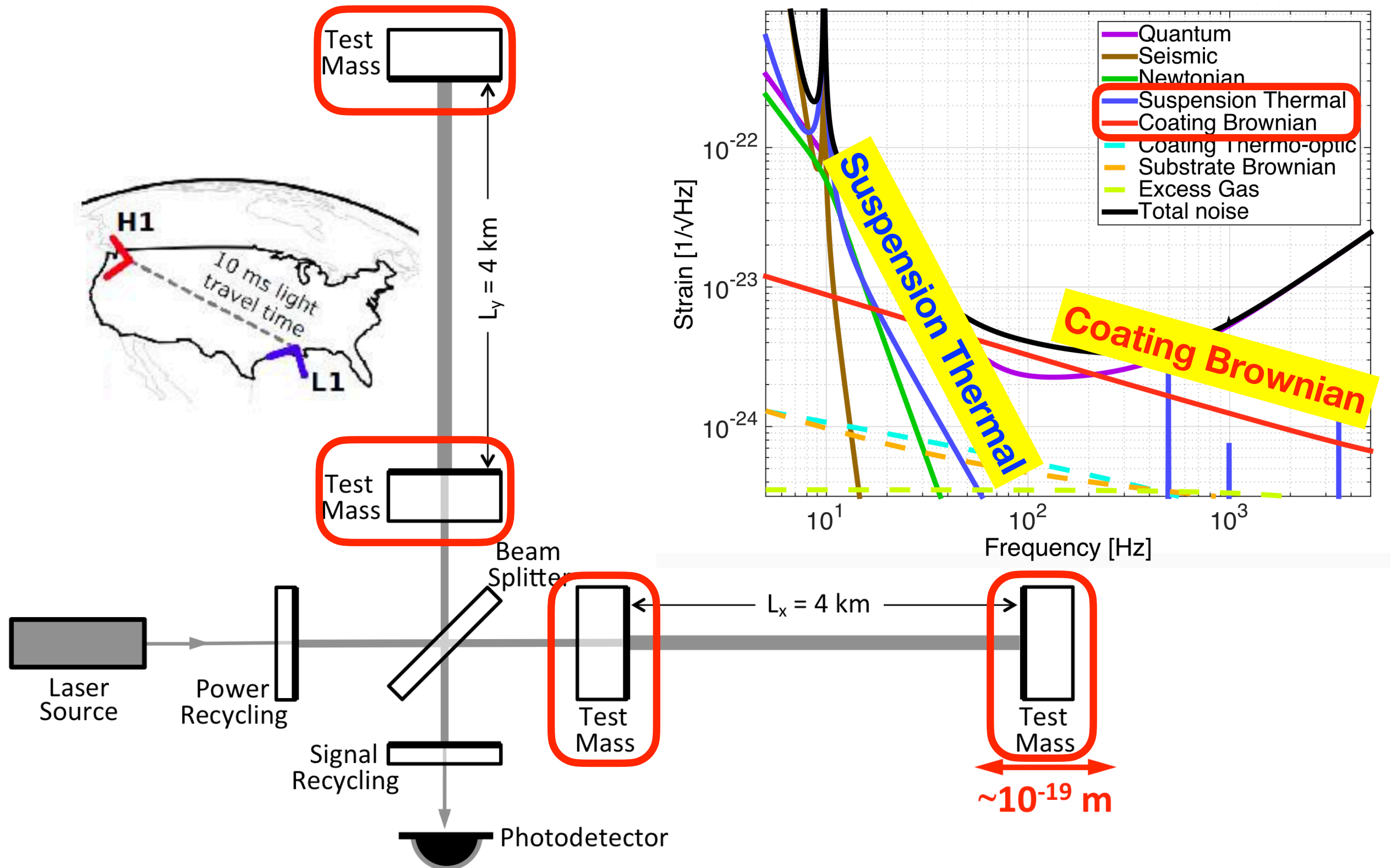




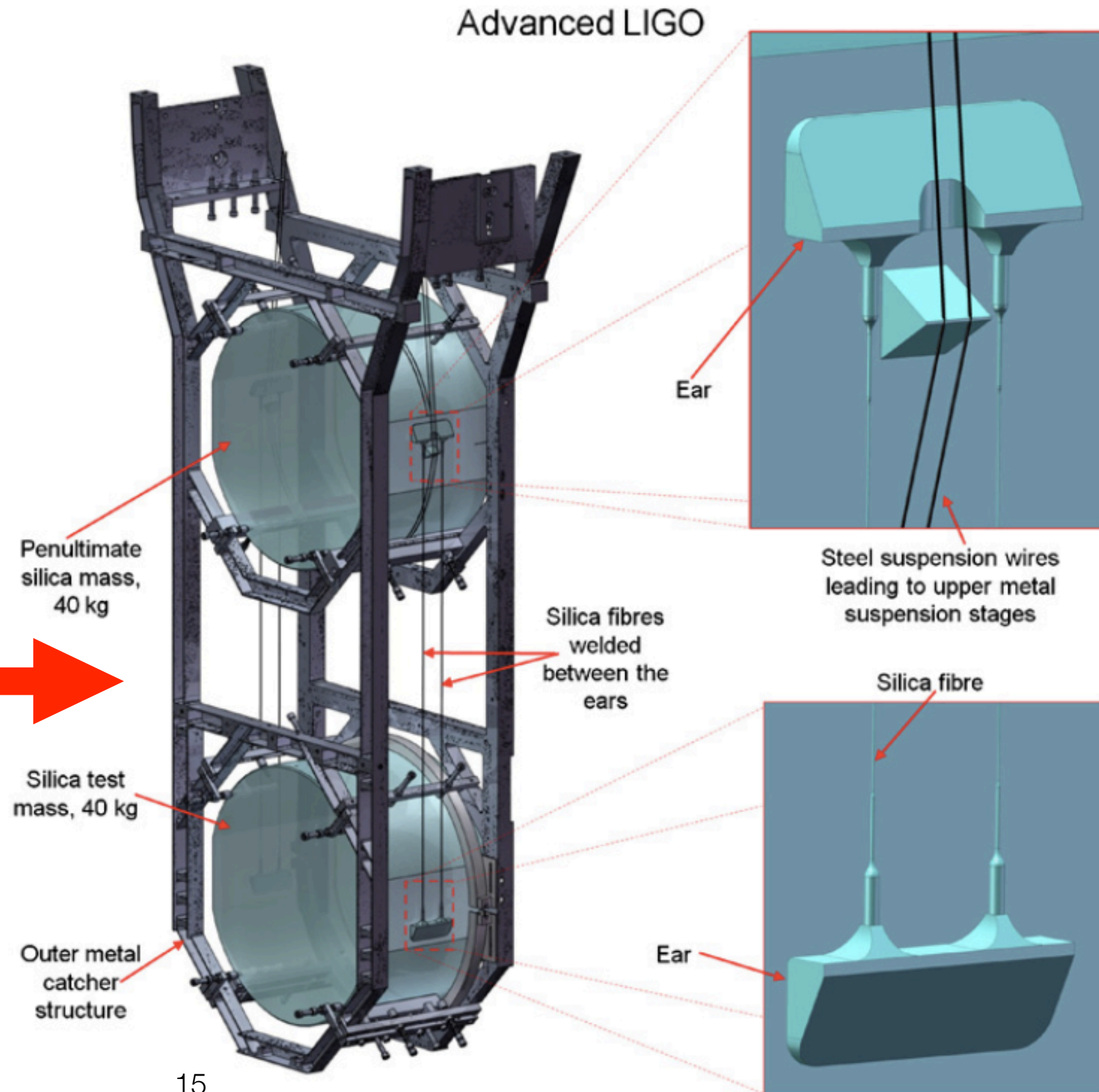
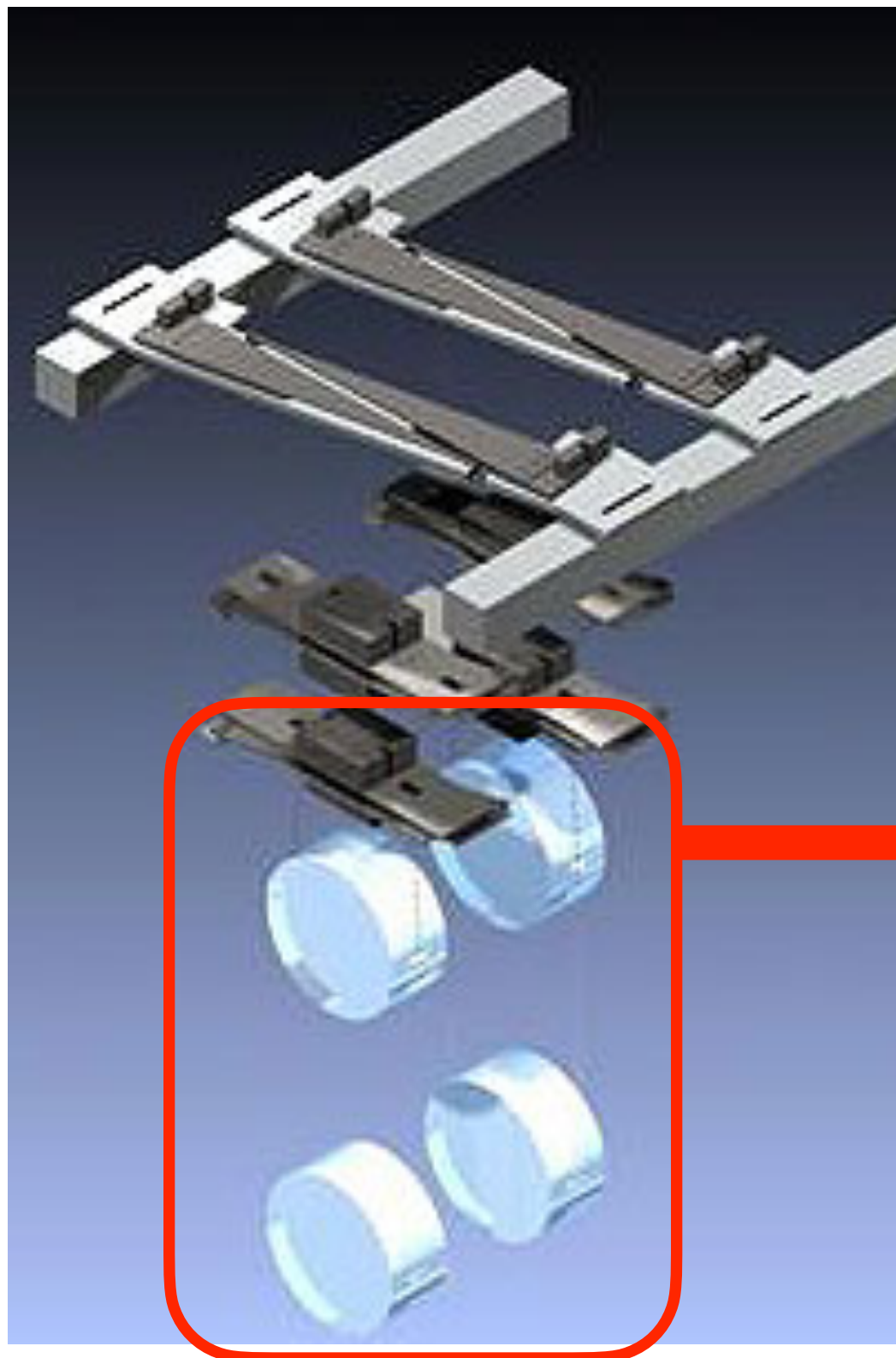
LIGO Experimental Work in Korea

LIGO Experimental Work in Korea

Suspension Thermal & Coating Thermal

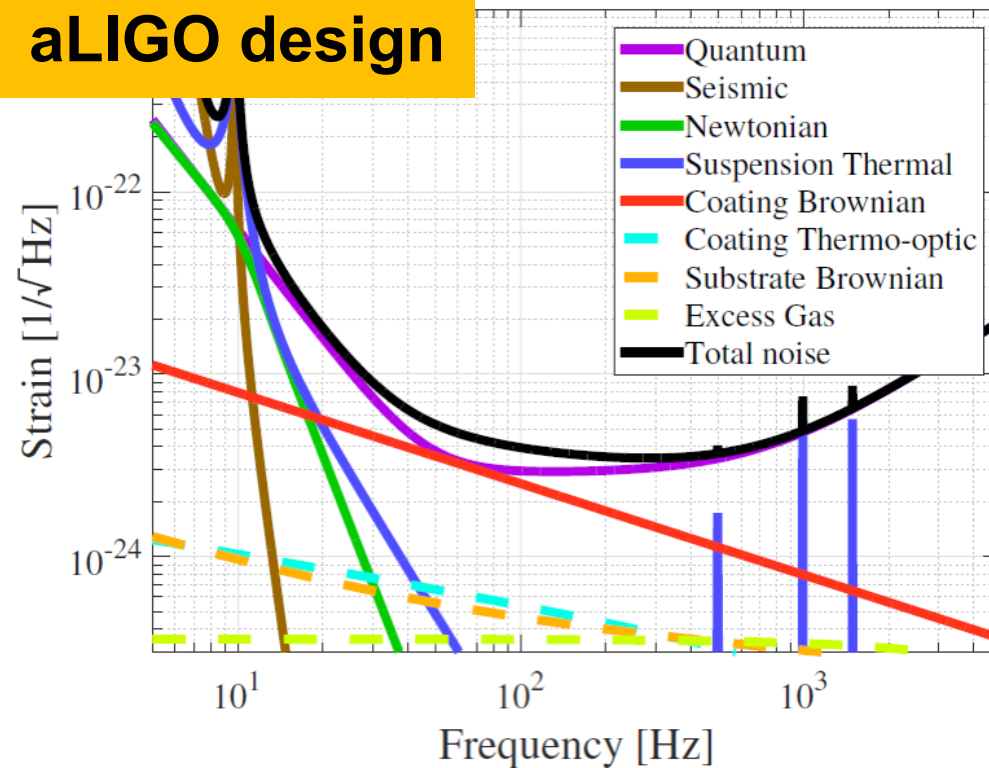


Suspension Thermal Noise: Quadruple Monolithic Suspension

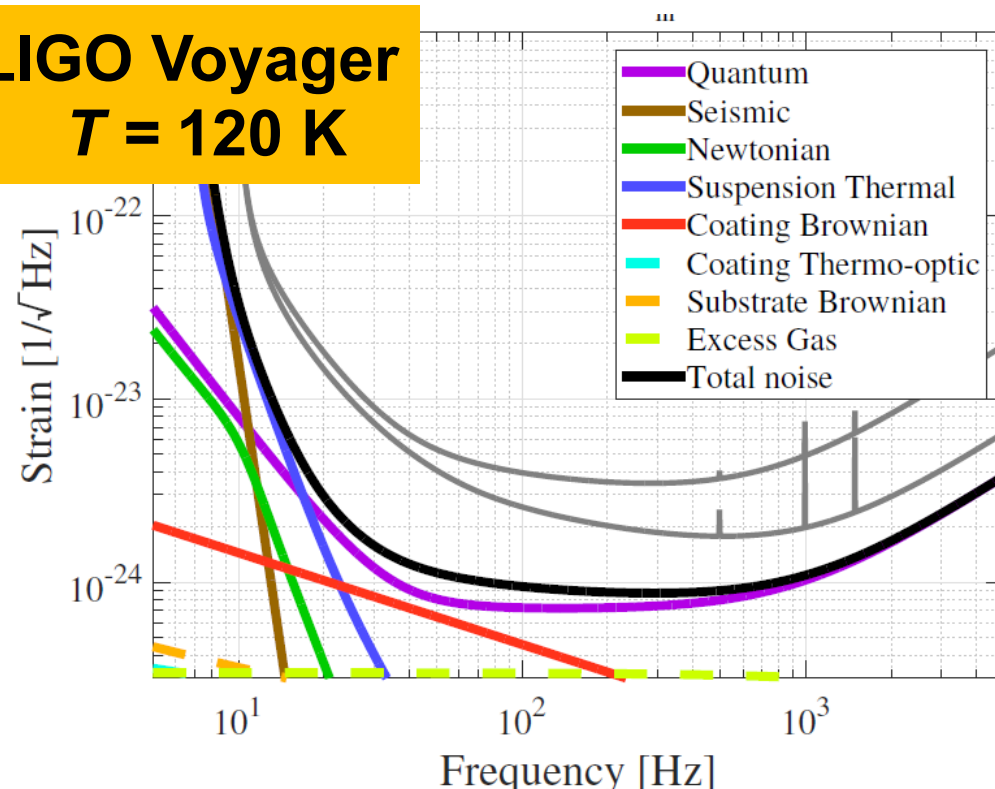


Coating Brownian Noise: Why Important?

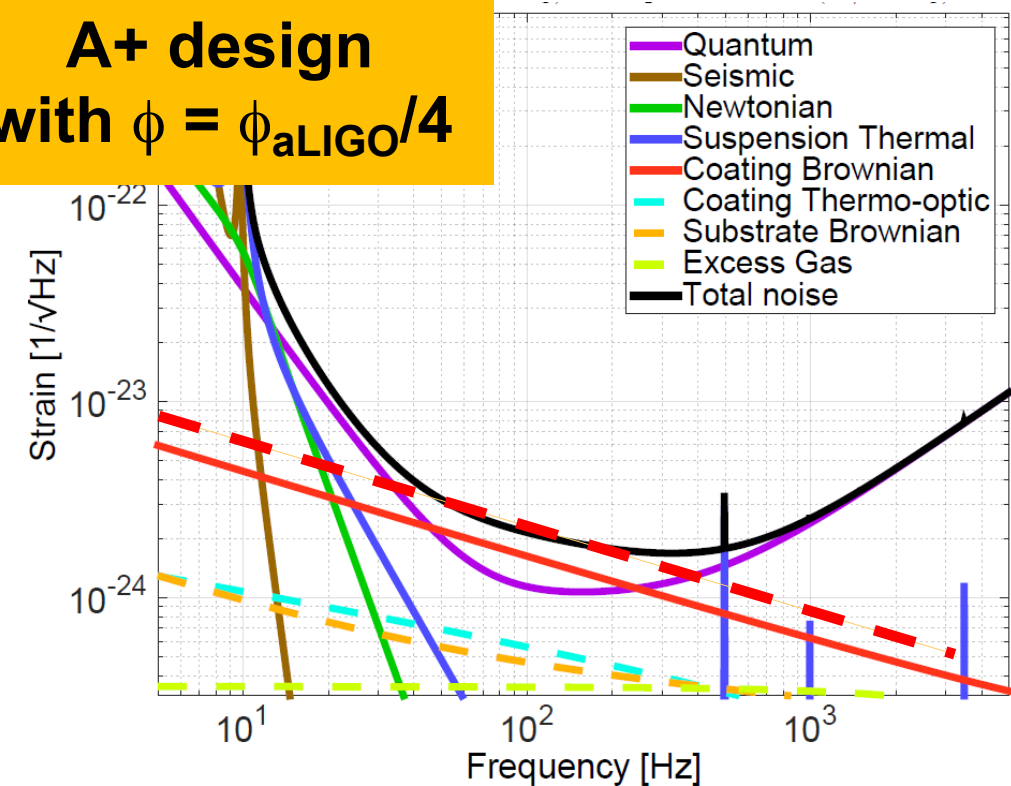
aLIGO design



LIGO Voyager $T = 120$ K



A+ design with $\phi = \phi_{\text{aLIGO}}/4$

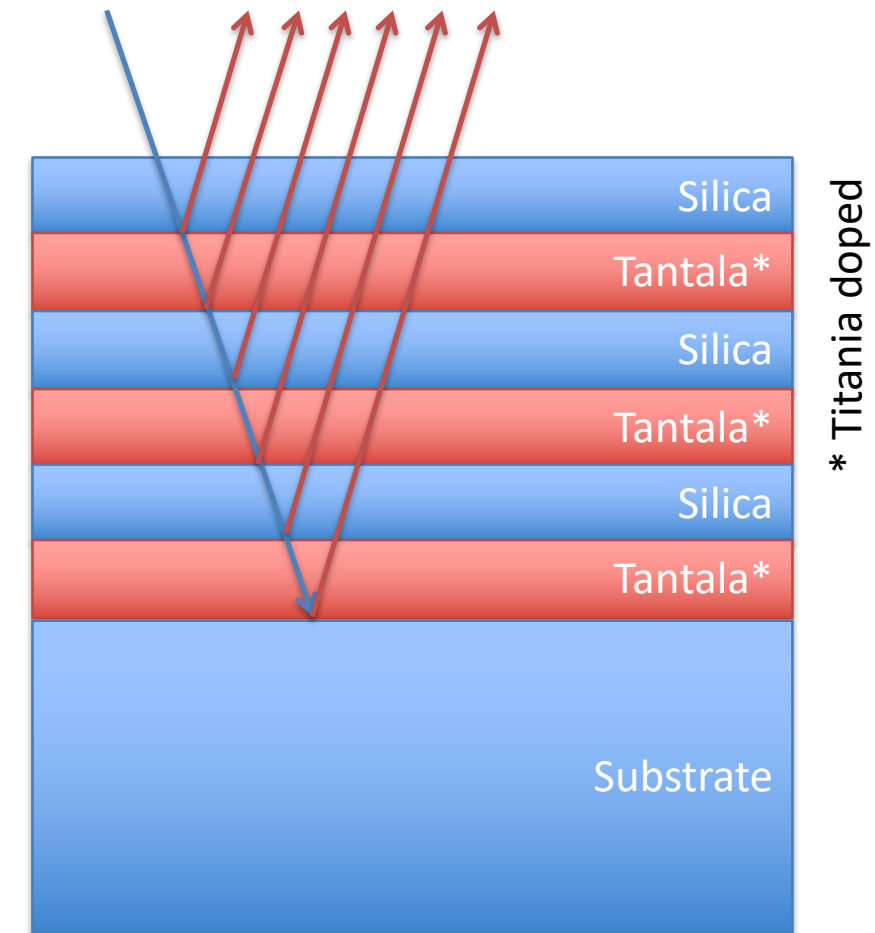


--- $\phi = \phi_{\text{aLIGO}}/2$

Plots from LIGO-T15TBI-v1, I.S. White Paper
LIGO-T1800042-v5 A+ Design Curve

Coating Brownian Noise: Current aLIGO Coating

- Ion-beam sputtered (IBS) dielectric multi-layer amorphous coatings
- Materials: SiO₂ (low index) + Ti:Ta₂O₅ (high index)



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

temperature → T

coating thickness → d

laser beam radius → w

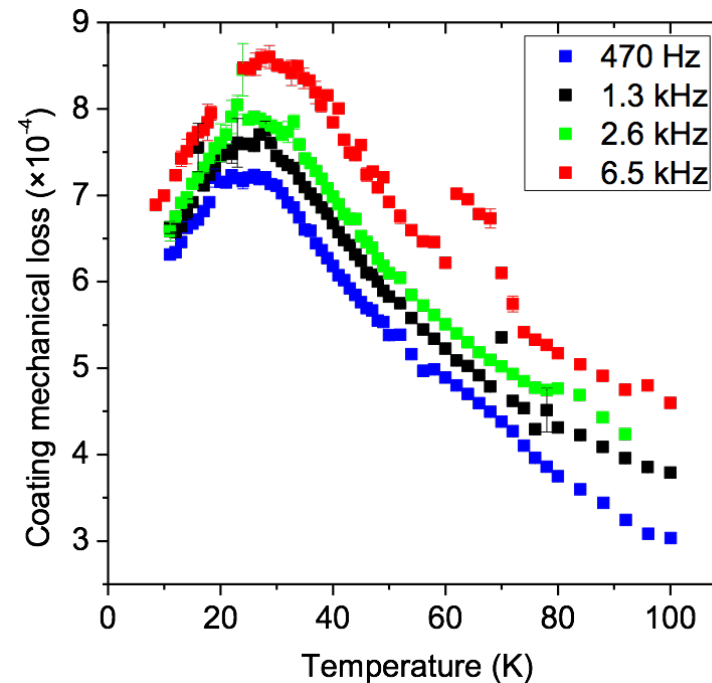
coating mechanical loss → ϕ

- Optical specs:
 - Diameter: 34 cm
 - Optical Absorption: ~0.5 ppm
 - Micro-roughness scatter: ~5 ppm
 - Uniformity: ~0.5 nm

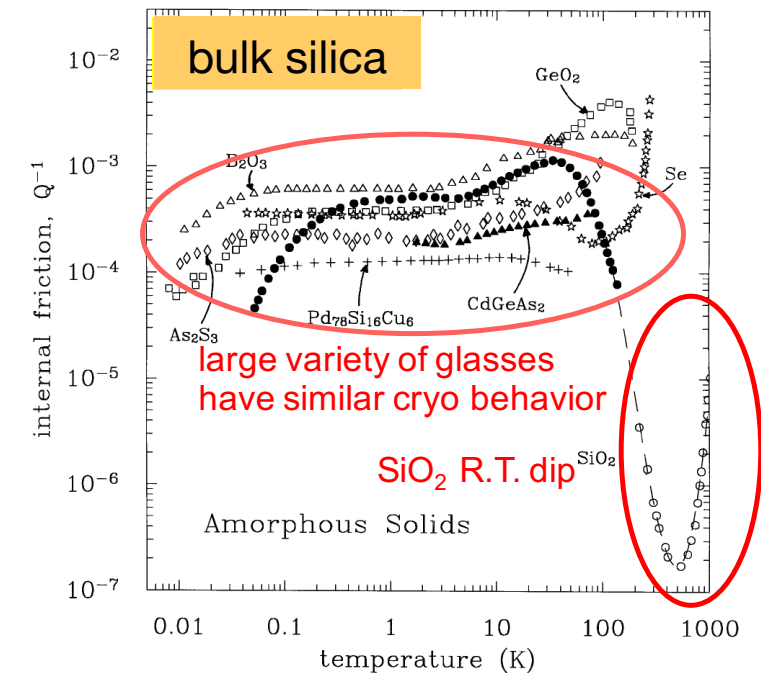
Material	Refractive index	Loss
Silica SiO ₂	1.45	0.4 x 10 ⁻⁴
Tantara Ta ₂ O ₅	2.03	3.4 x 10 ⁻⁴
Titania-doped tantala Ta ₂ O ₅ -TiO ₂	2.07	2.3 x 10⁻⁴

Coating Brownian Noise: Amorphous + Dopant + Annealing

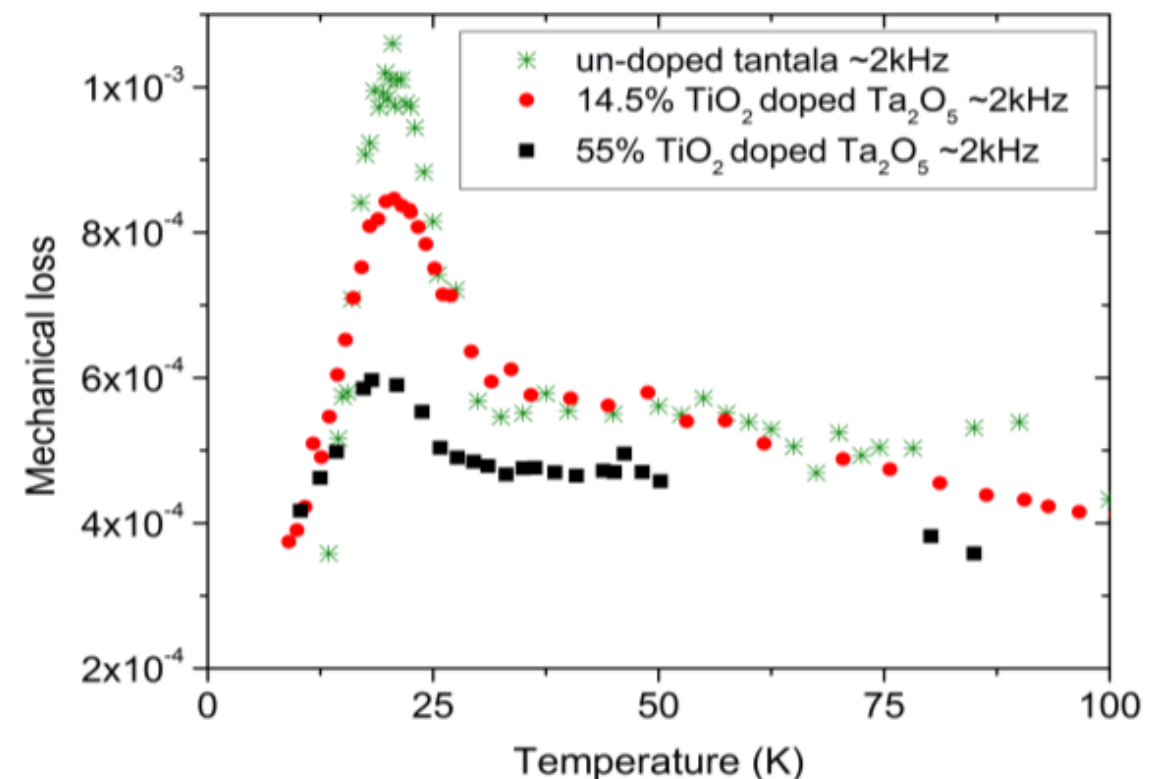
- Why amorphous?
 - Loss peak at low temperature low RT loss
 - Less scattering
- Why dopants?
 - Can reduce RT mechanical loss
 - Can increase crystallization temperature
- Why annealing?
 - Can reduce RT mechanical loss



I W Martin et al, Class. Quant. Grav. **27** 225020, (2010)



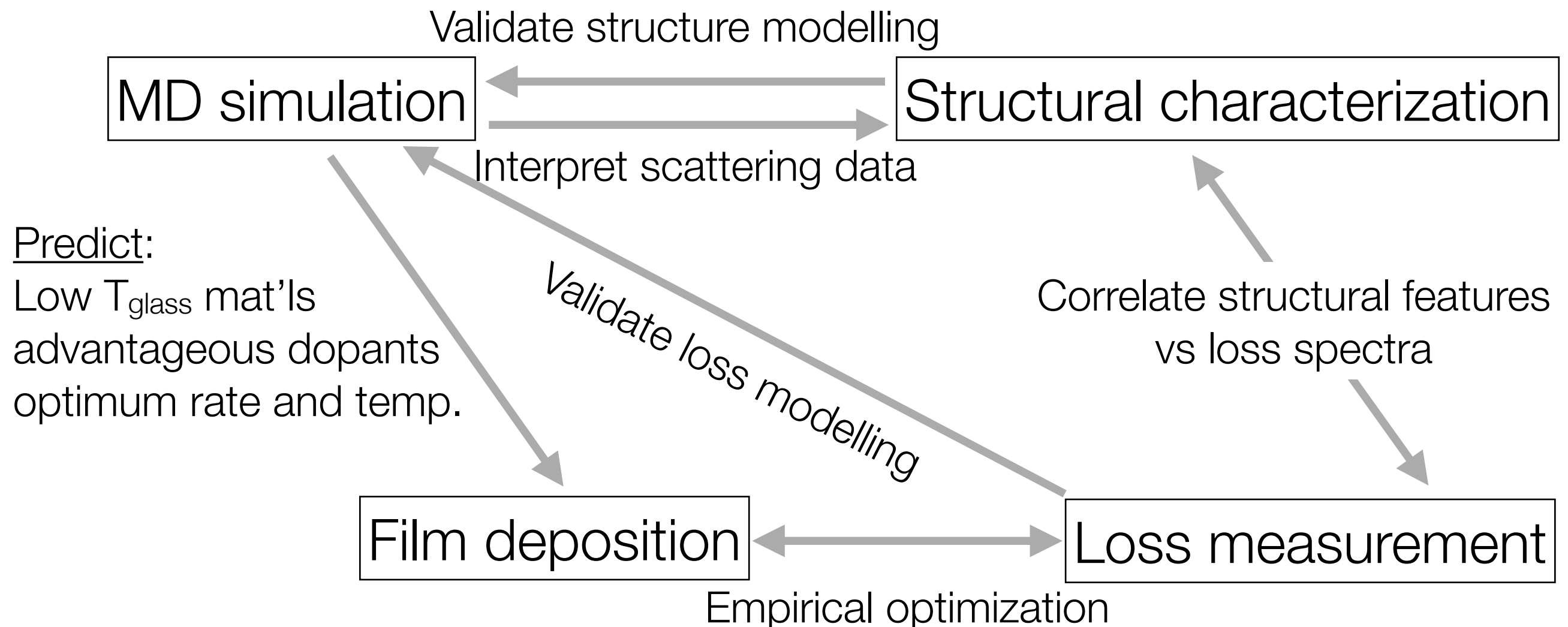
K.A. Topp, Z. Physik B Condensed Matter **101** 235-45 (1996)



P. Murray et al, U. Glasgow, unpublished

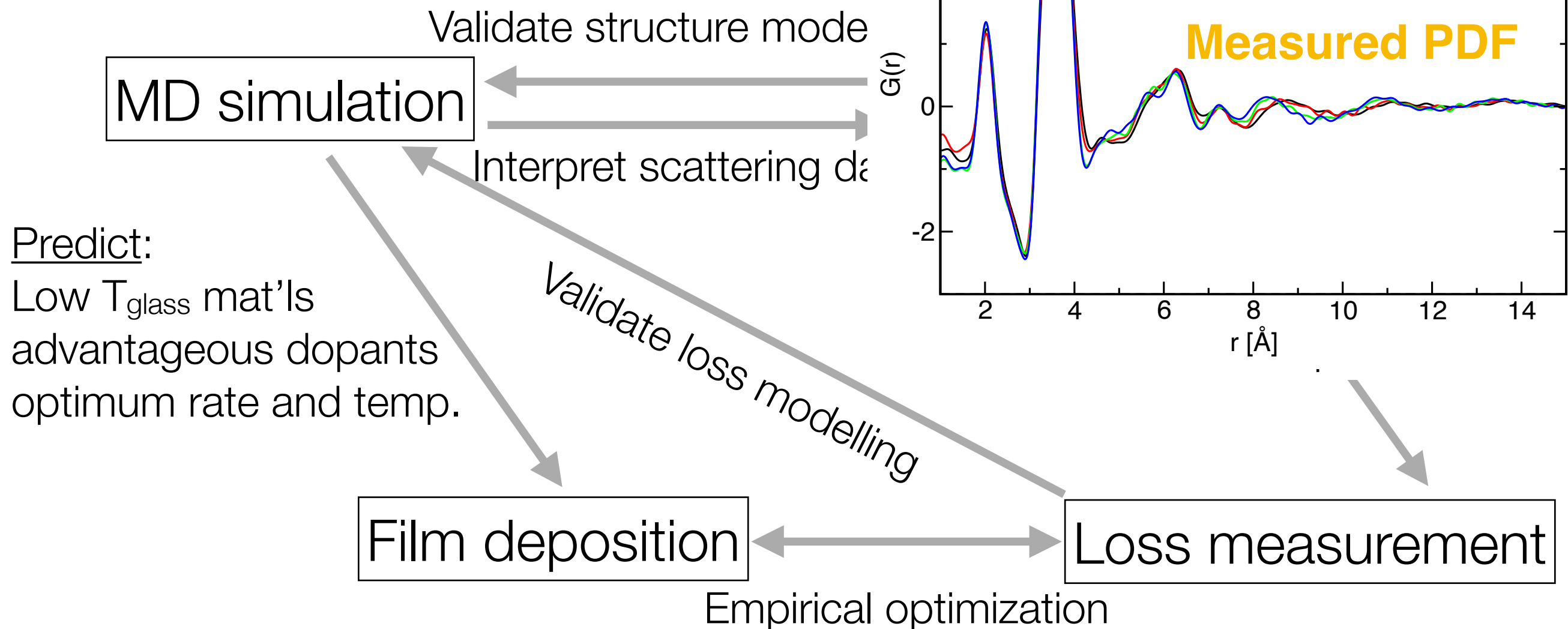
Coating Brownian Noise: A+LIGO Coatings Research Model

- How to find a new coating material?

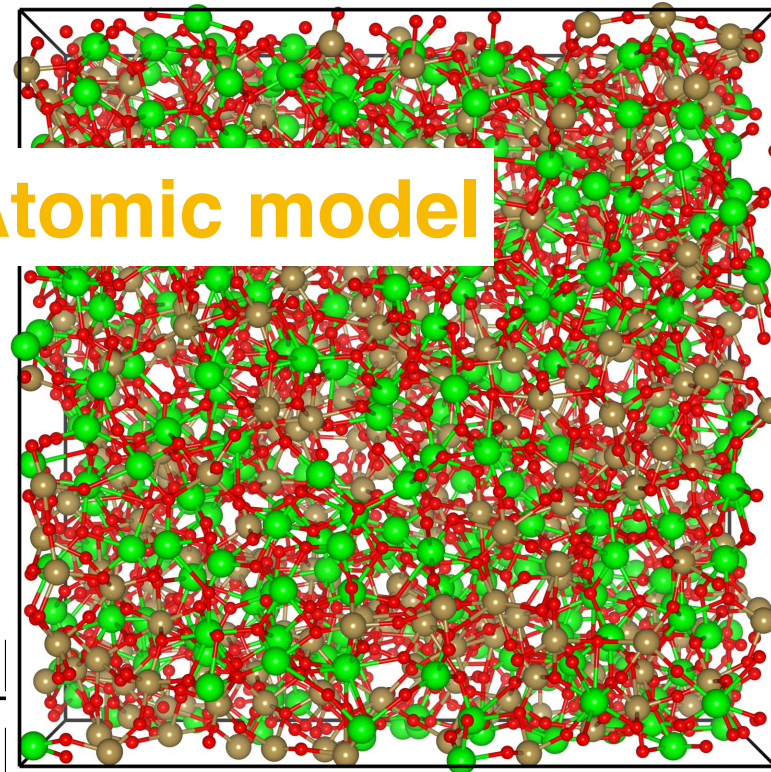


Coating Brownian Noise: A+LIGO Coatings Research Model

- How to find a new coating material



Coating Brownian Noise: A+LIGO Coatings Research Model

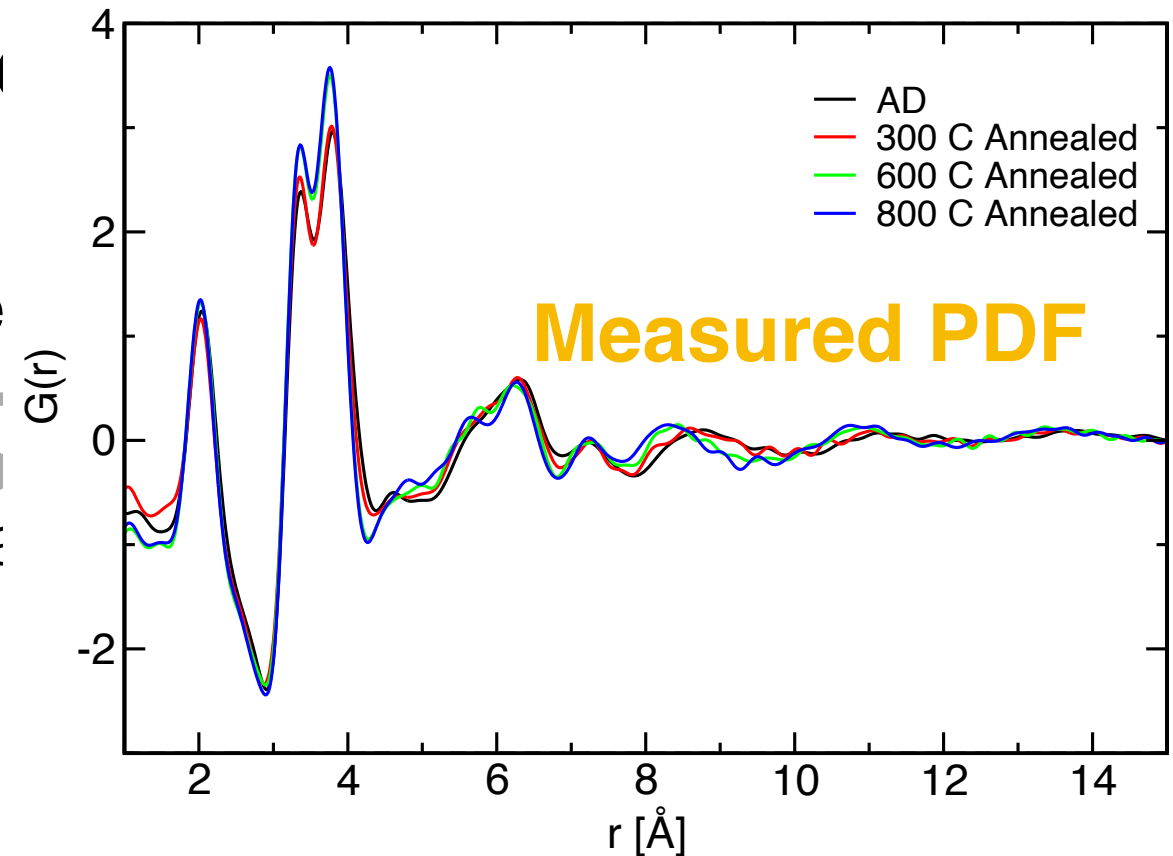


new coating materials

validate structure model

interpret scattering data

advantageous dopants
optimum rate and temp.



Validate loss modelling

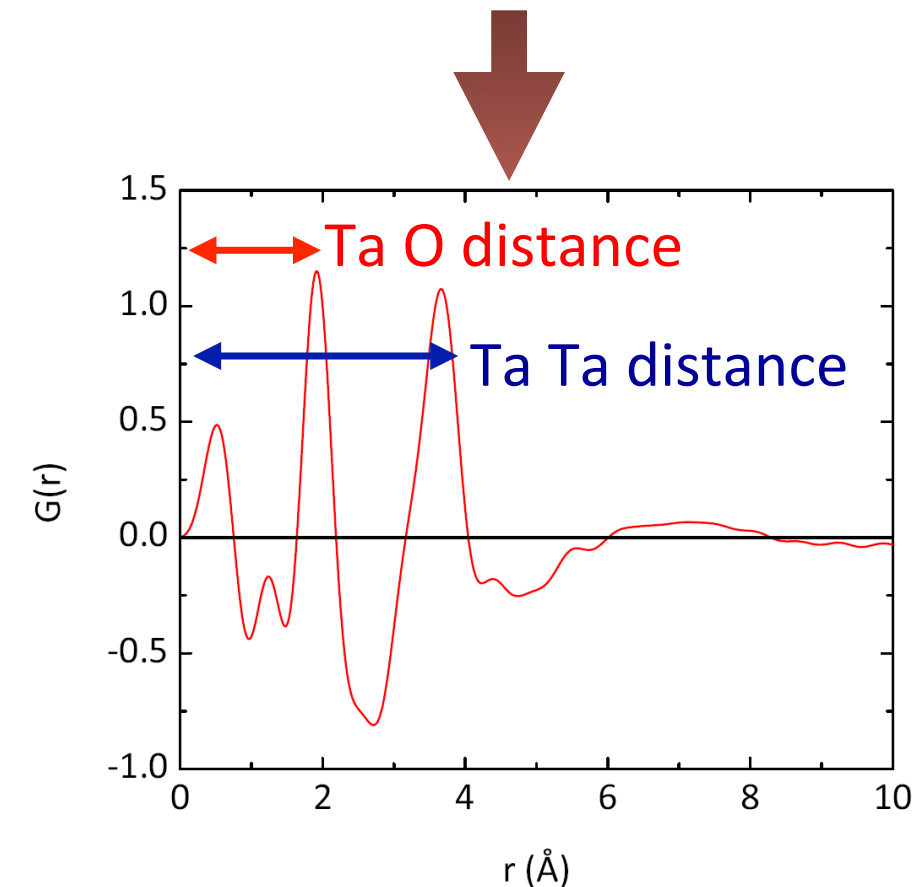
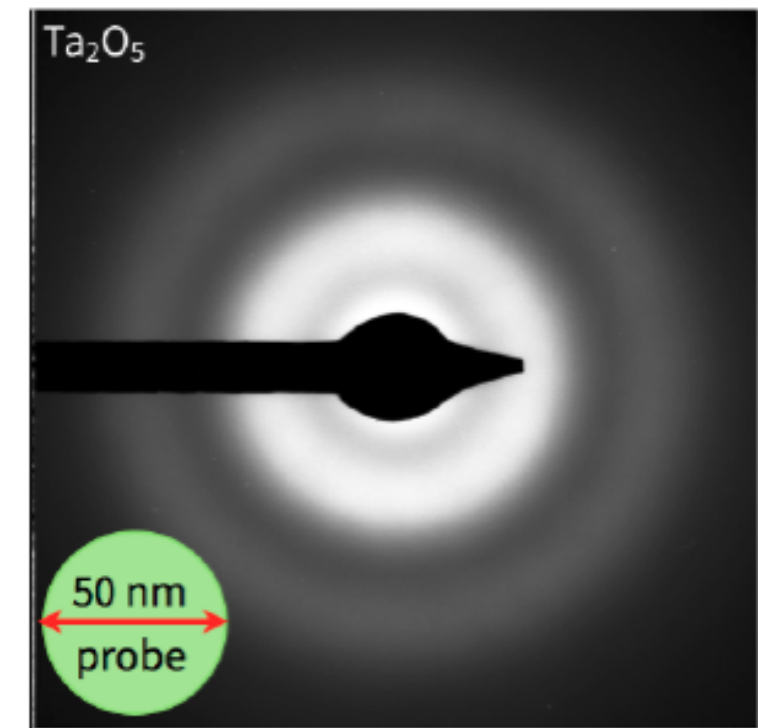
Film deposition

Loss measurement

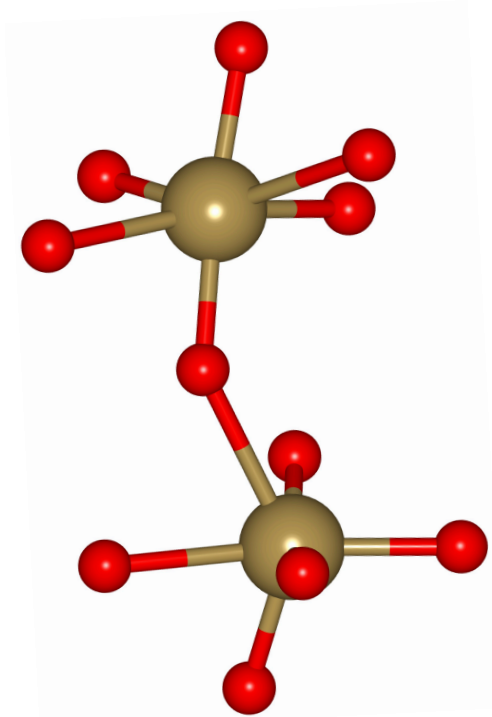
Empirical optimization

Coating Brownian Noise: Atomic Structure Characterization

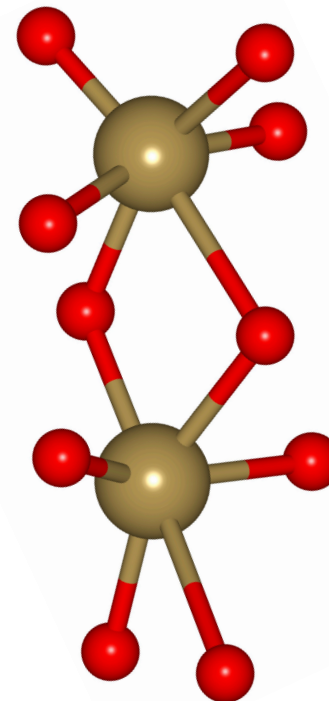
- Characterization of structure of amorphous materials more difficult than crystalline
 - **PDF** (Pair Distribution Function) Analysis:
 - Most efficient to get SRO & Intermediate SRO information
 - **GIPDF** (Grazing Incidence PDF) from SLAC SSRL (Stanford Linear Accelerator Center, Stanford Synchrotron Radiation Lightsource)
 - **ePDF** (electron PDF) via TEM (Transmission Electron Microscope)
 - **FEM** (Fluctuation Electron Microscopy) Analysis:
 - Conducted @ Lawrence Berkeley National Lab, USA
 - Most efficient to get MRO information



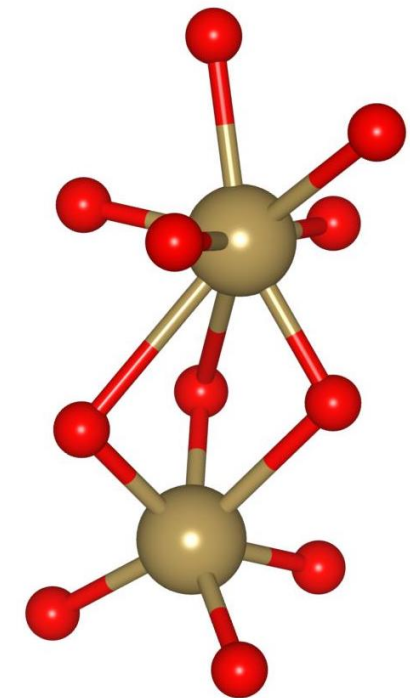
Coating Brownian Noise: What kind of atomic structure?



Corner-sharing



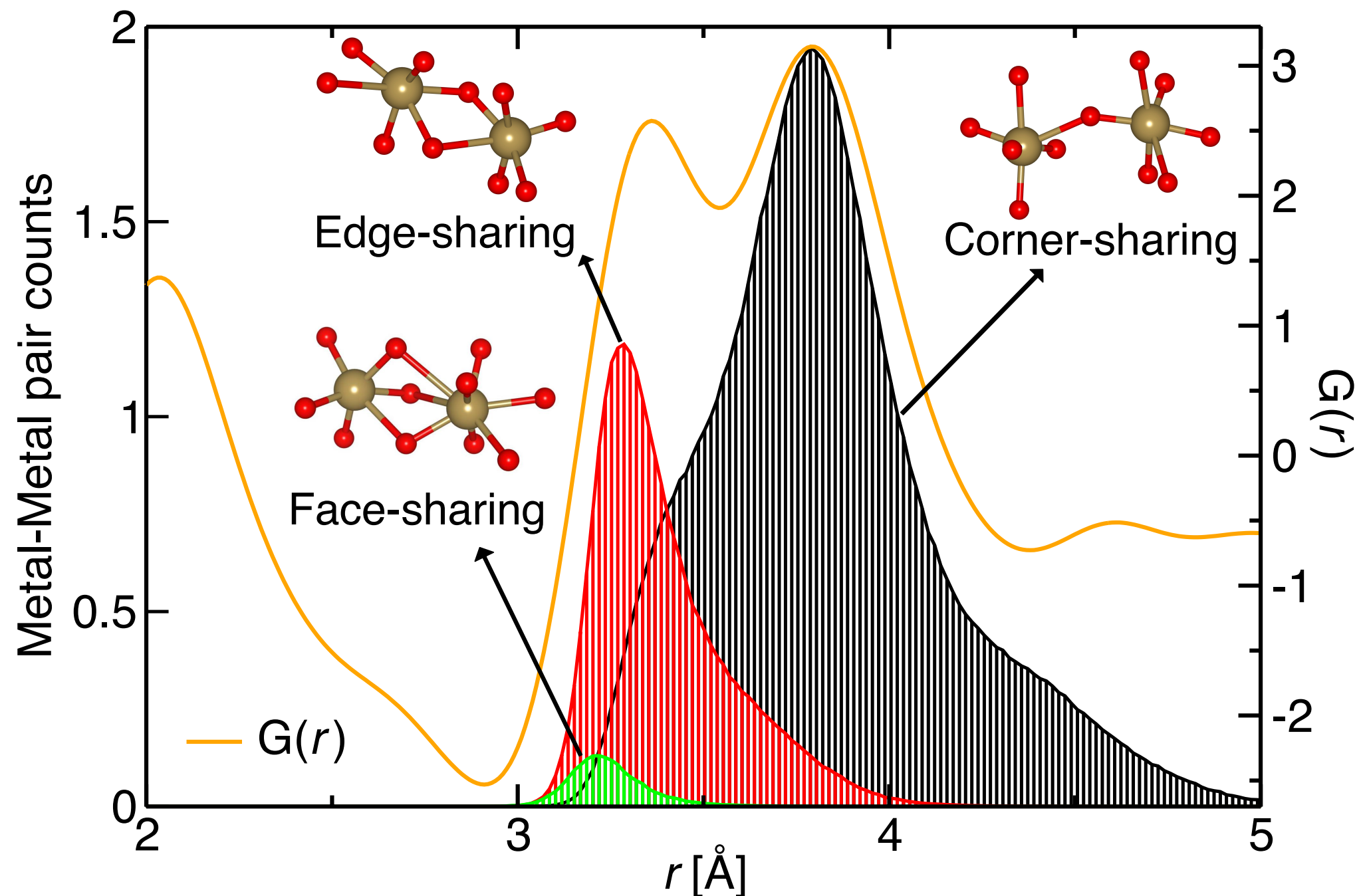
Edge-sharing



Face-sharing

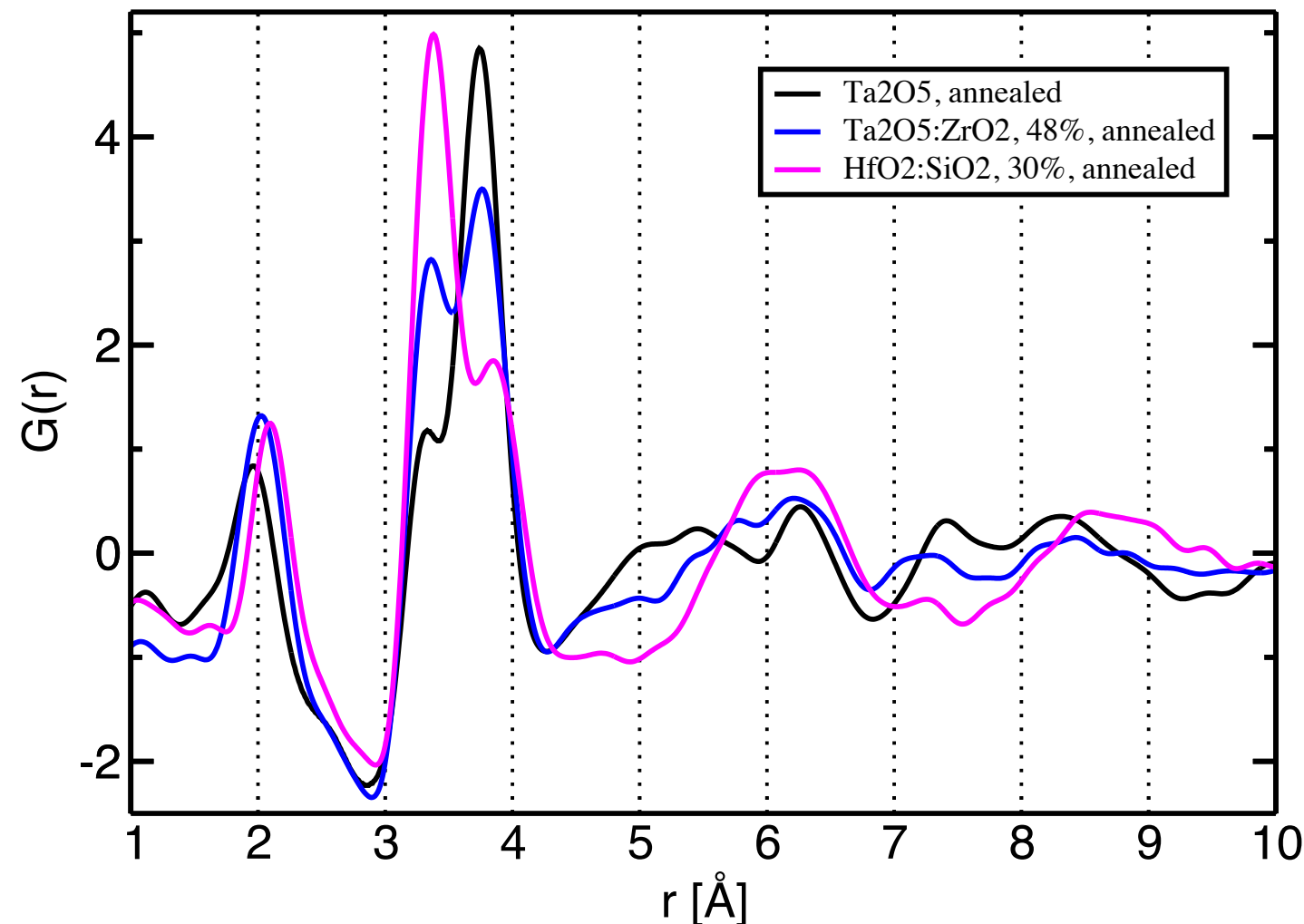
Three types of polyhedral connections exist.

Coating Brownian Noise: What kind of atomic structure?



Corner-, edge- and face- sharing polyhedra register distinct peaks in measured PDFs.

Coating Brownian Noise: PDF Results: Material Comparison



Corner-shared polyhedra:

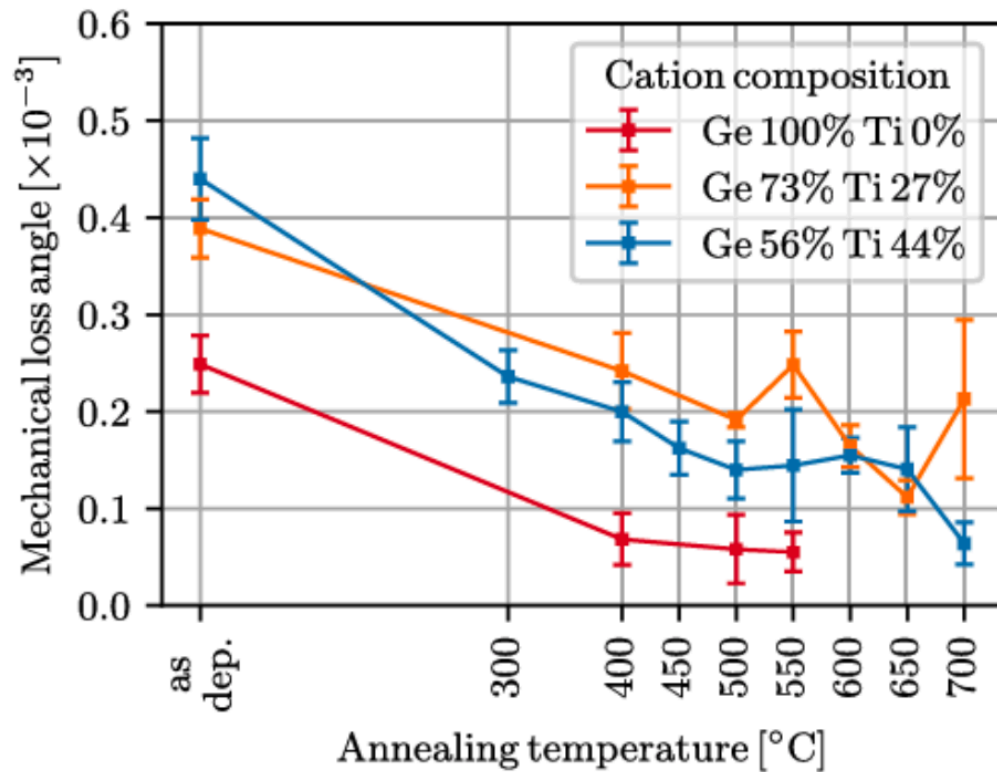
Silica* > Tantalum > Zirconia-doped tantalum > Silica-doped hafnia
(*silica is not in the plot but is known to be corner-shared)

Room temperature mechanical loss:

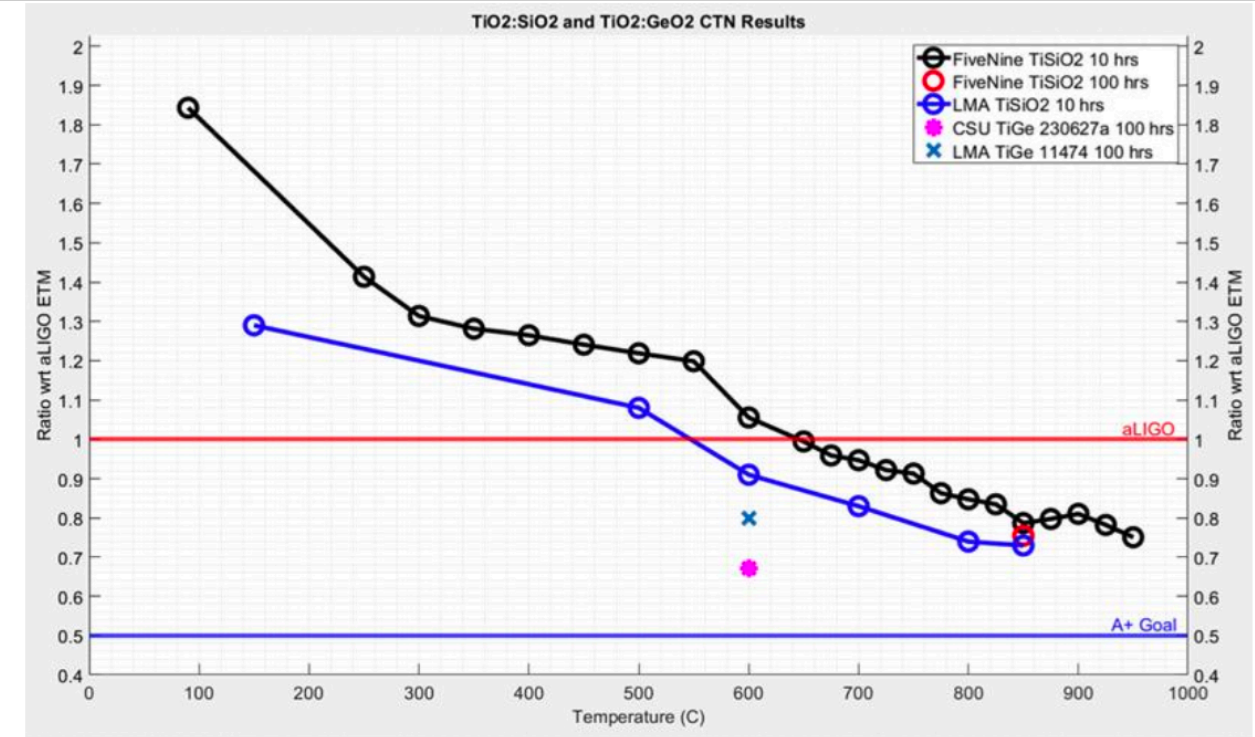
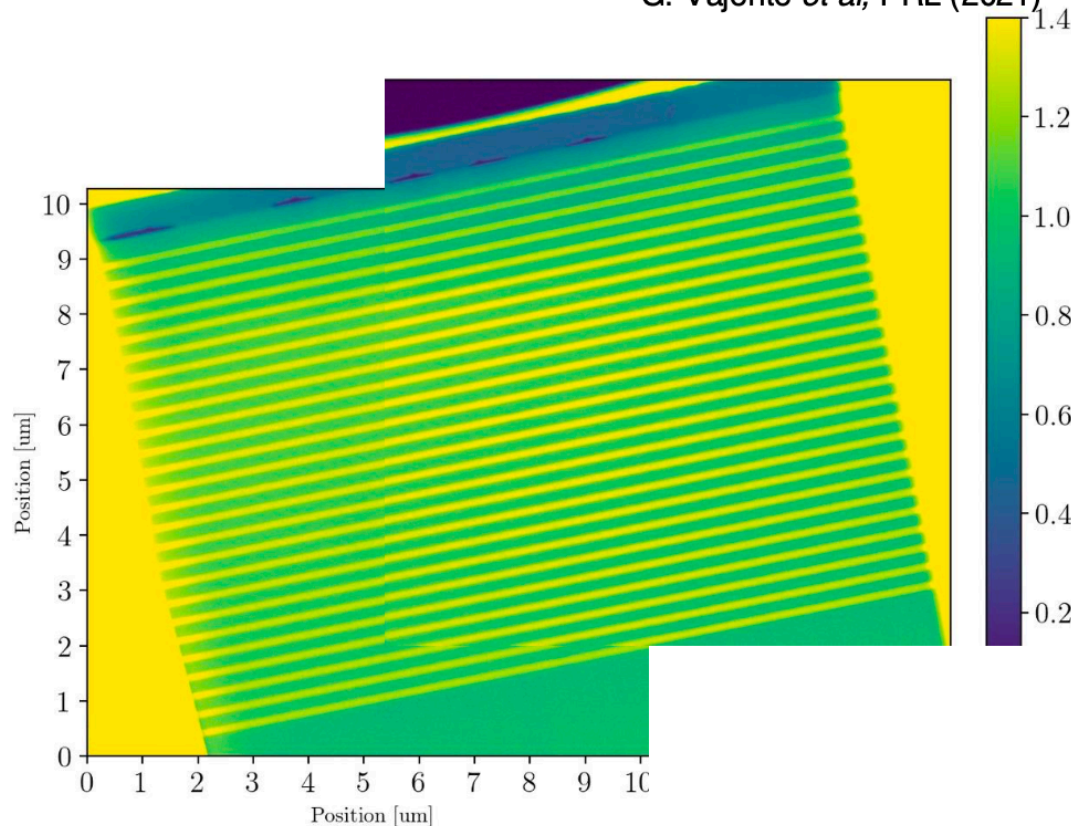
Trends in corner-shared polyhedra and loss are flipped*.

*RT loss for silica-doped hafnia is not measured.

Coating Brownian Noise: Energy Dispersive Spectroscopy (EDS)



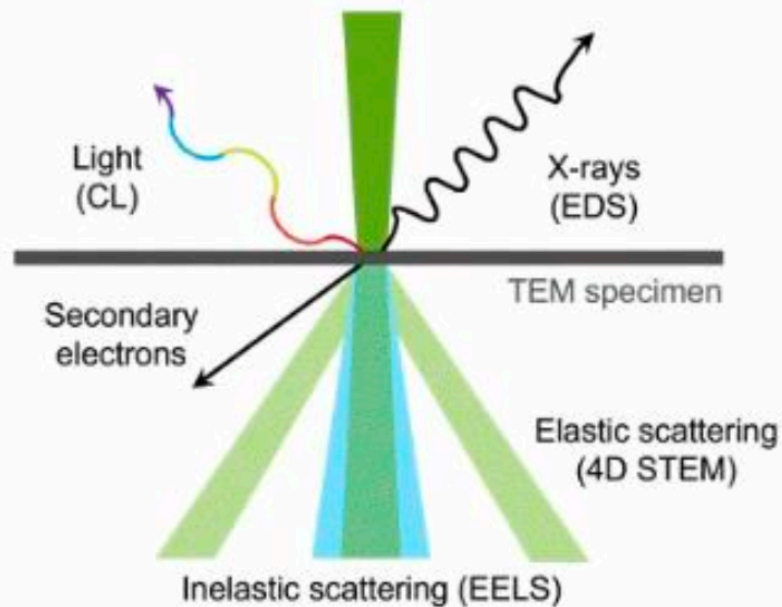
G. Vajente *et al*, PRL (2021)



[G2301954](#)

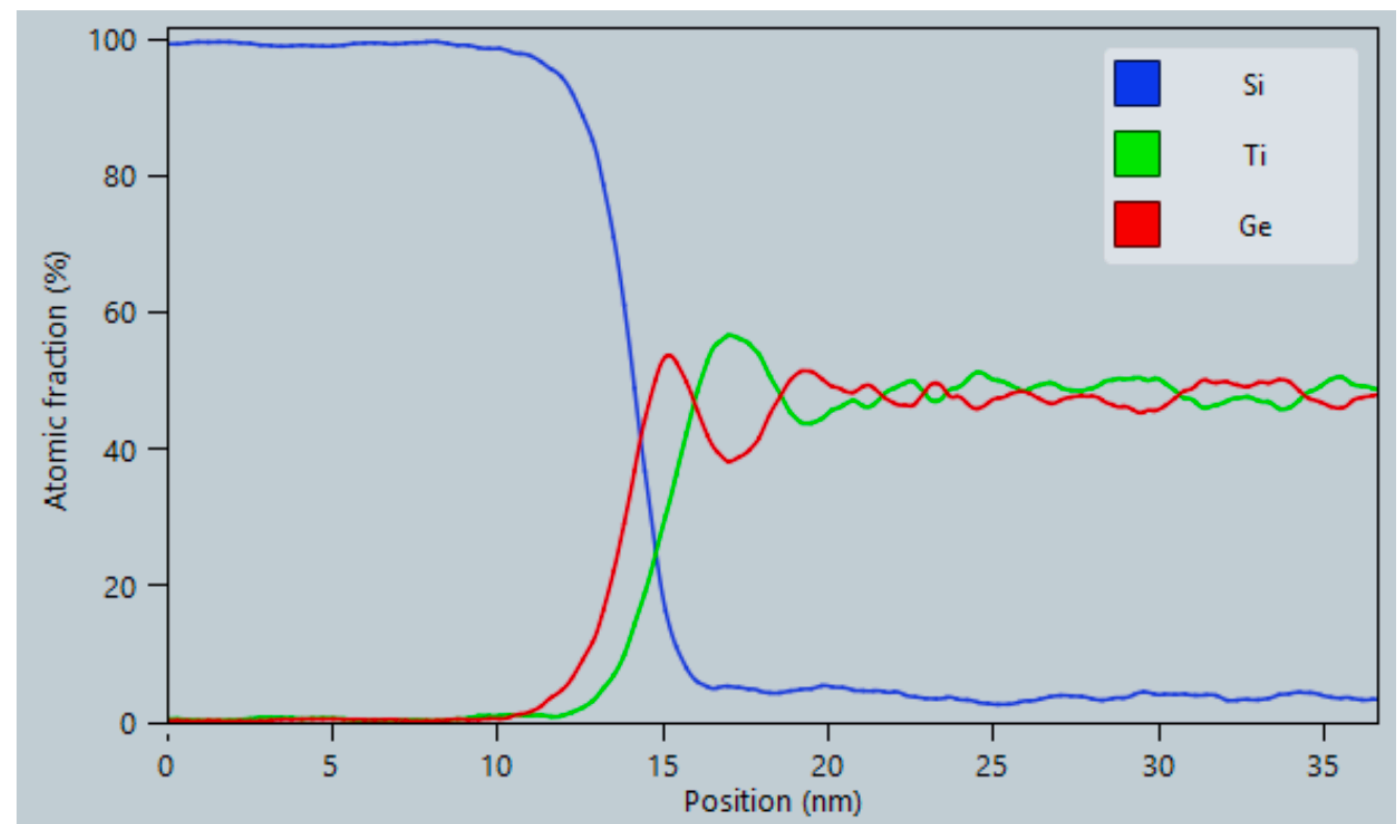
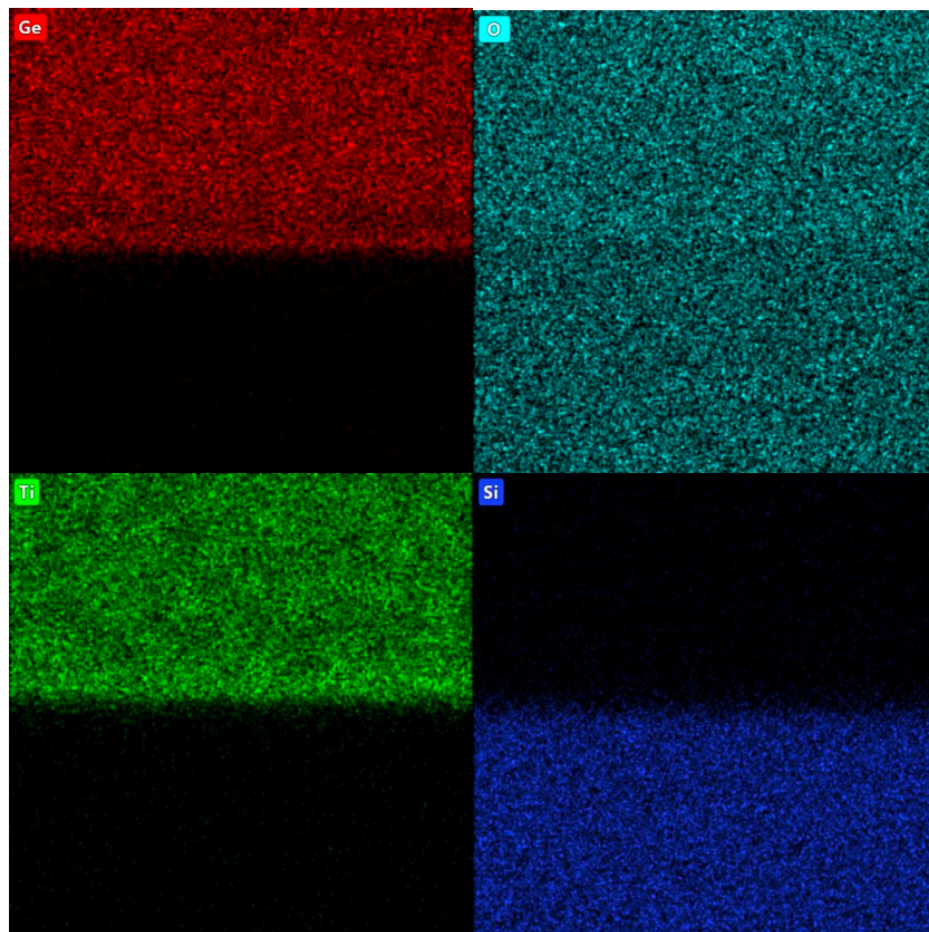
- Optimal coating for A+LIGO upgrade:
52 layer of dielectric HR coating
- 44% TiO₂-doped GeO₂ / SiO₂
- 600°C, 100hr annealing
- Discrepancy between expected CTN from single-layer vs actual multi-layer coating.
➔ Expected: 0.5CTN @ aLIGO
- Possible source: interfaces between TiGe/SiO₂ layers

Coating Brownian Noise: Energy Dispersive Spectroscopy (EDS)



- EDS: Captures x-rays from excited atoms inside of material
- EDS can show atomic composition mapping at the interface.
➔ Relative, qualitative comparison

<https://www.gatan.com/techniques/eds>





LIGO Data Analysis Work in Korea

Korean LIGO Group Summary

- ◆ 13 authors (up to 2024-2025 MOU), 16 members total
 - Hyungmok Lee (SNU): Management, election administration, RRT shifts
 - Gungwon Kang (CAU): Burst pipeline, outreach, RRT shifts
 - Jiyeon Sun (CAU): Burst pipeline, offline search of burst signals
 - Young-min Kim (KASI): DetChar Code development, Nuclear & High Energy collaboration
 - Kyungmin Kim (KASI): O4 lensing paper, multi-messenger signals of lensing
 - Jeongcho Kim (KASI): Parameter estimations, evaluation and development of codes
 - Chunglee Kim (EWU): Parameter estimations, evaluation of methods, RRT shifts
 - Kyung-ha Lee (SKKU): Structural studies of coatings, material evaluation & assessments
 - Minhyo Kim (SKKU): Structural studies of coatings, material evaluation & assessments
 - Jeonghyeon Ju (SKKU): Structural studies of coatings, material evaluation & assessments
 - Sunjae Lee (SKKU): Structural studies of coatings, material evaluation & assessments
 - Sangwook Bae (KISTI): Maintaining & managing KISTI cluster
 - Md Shaikh (SNU): Eccentric waveform models for CBC systems
 - Whansun Kim (NIMS) (Not LIGO author): Developing new ML tool for DetChar
 - Byeol Kim (NIMS) (Not LIGO author): Monitoring DQ issues
 - Hyungwon Lee (IJU) (Not LIGO author): Parameter estimations, evaluation&development of codes

Korean LIGO Group Summary

Strong lensing of dark sirens and galaxies as a probe of the Hubble constant [in preparation]

• Motivation

- Simultaneous observations of GW170817 & GRB170817 → GWs can be a probe of the Hubble constant, H_0 !
- GW events without identified EM counterparts, a.k.a. dark sirens, can also be such a probe.
- Accurate sky localization and precise estimation of luminosity distance to the source of dark sirens can be achieved if the events are strongly lensed.

• Methods

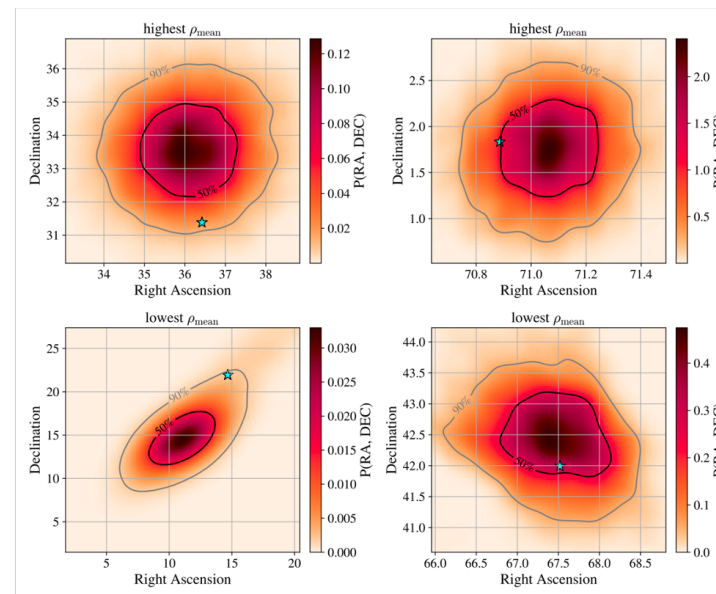
- Simulated dark sirens and simulated galaxy catalog
- Single lensed dark sirens w/ the Hubble-Lemaître law
- Multiple lensed dark sirens w/ combining individual inferences of H_0

• Result (preliminary)

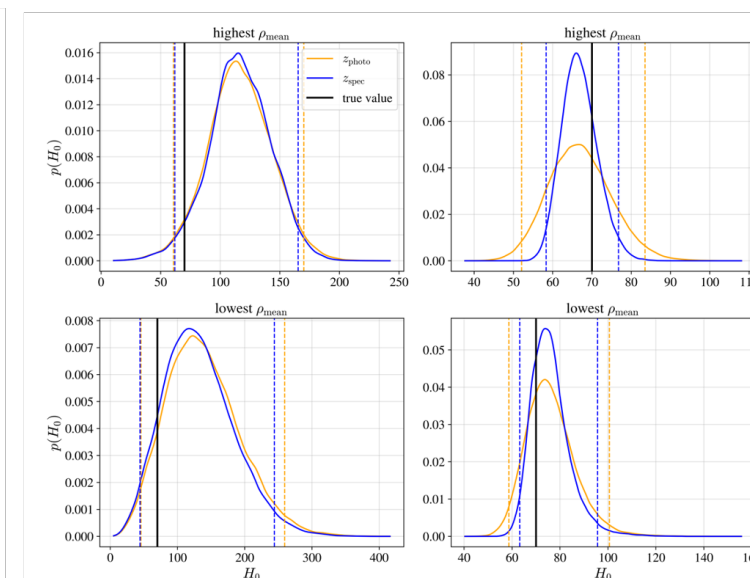
- Using quadruple lensed images is better than double images in
 - accurately localizing the host galaxy of a dark siren.
 - well constraining and precisely inferring H_0 .

- Contact: Kyungmin Kim (KASI; kkim@kasi.re.kr)

“sky localization”
[double images (left) vs quadruple images (right)]

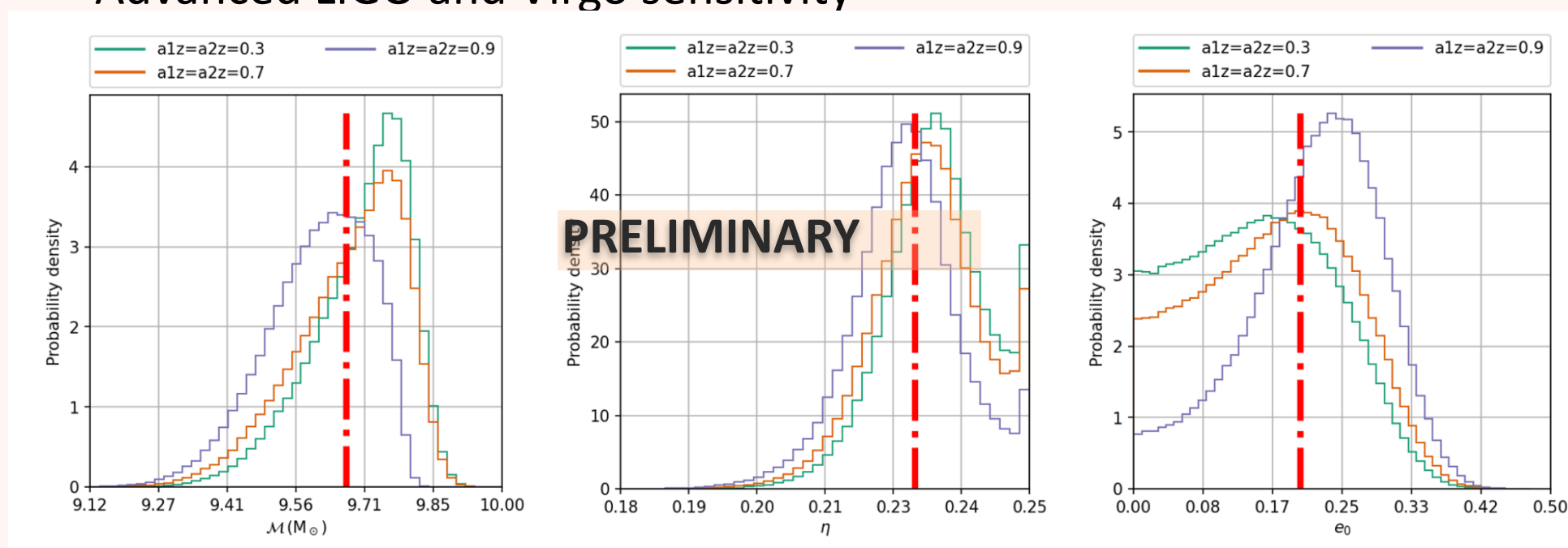


“ H_0 inference”
[double images (left) vs quadruple images (right)]



Parameter Estimation Group (1/2)

- Simulation of parameter estimation for binary inspiral with aligned spin and eccentricity
- Waveforms: TaylorF2Ecc-Inspiral
- Advanced LIGO and Virgo sensitivity



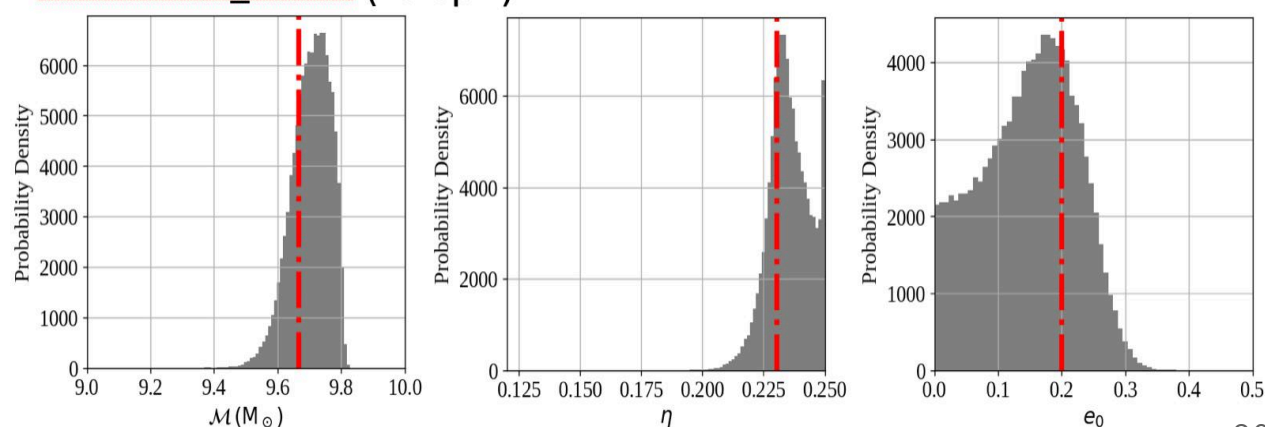
Assuming GW20015 parameters for mass and distance (NS-BH) with $e_0=0.2$, eccentricity is more precisely constrained for higher aligned spin magnitude

Parameter Estimation Group (2/2)

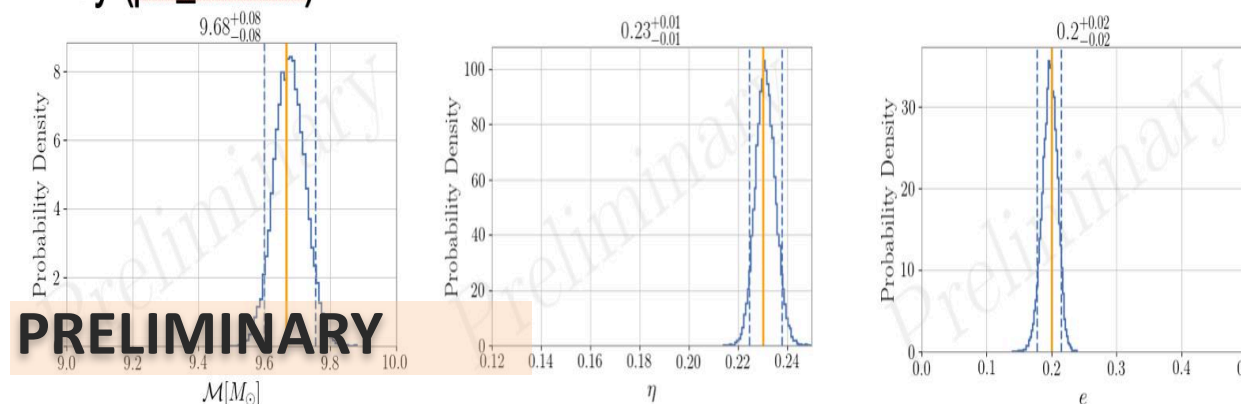
- Comparison of two pipelines: lalinference_mcmc vs Bilby
- Purpose: to investigate the accuracy improvements for important parameters such as distance and mass of the sources with external constraints on viewing angle through EM observations (BNS or NSBH)
- There are some differences in estimated parameters for different pipelines: We need more thorough tests

GW151226

lalinference_mcmc (no-spin)



Bilby (pn_order0)



PRELIMINARY

30

Gaussian Mixture Modelling(GMM)

슬라이드 제공: 선지윤

- Describes a non-Gaussian distribution of data as a superposition of multivariate

$$p(\vec{x}_i) = \sum_{j=1}^K w_j \mathcal{N}(\vec{x}_i | \mu_j, \Sigma_j)$$

- Model parameters:

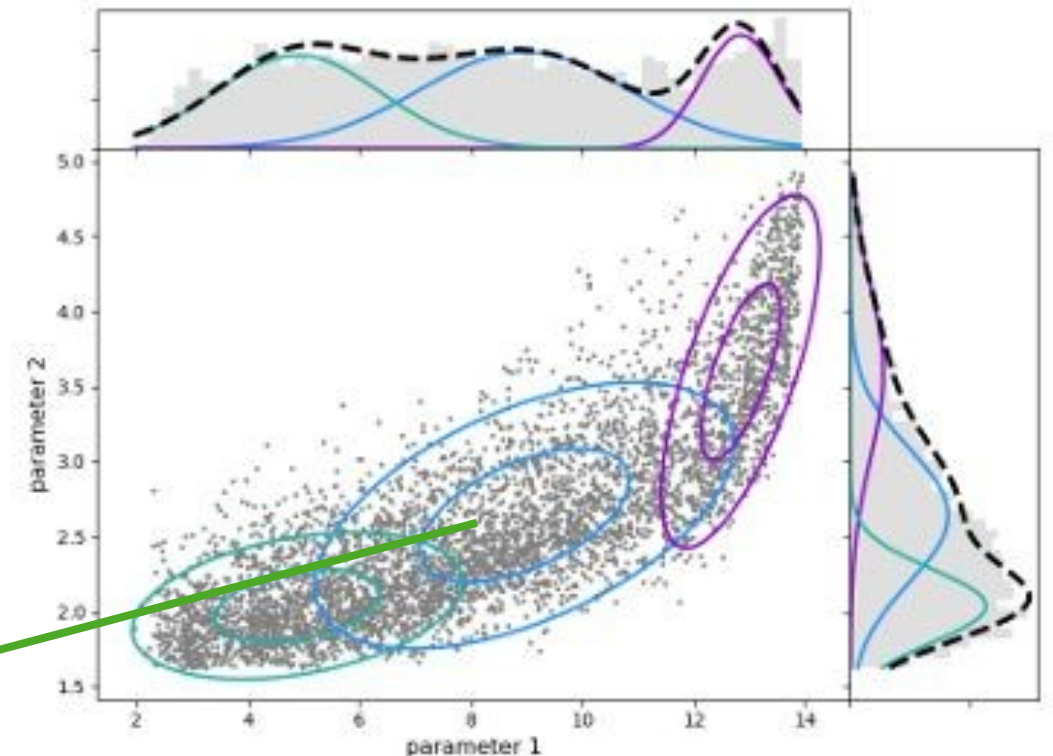
$$\hat{\mu}_k = \frac{\sum_{i=1}^n r_{ik} \mathbf{x}_i}{N_k}$$

$$\hat{\Sigma}_k = \frac{1}{N_k} \sum_{i=1}^n r_{ik} (\mathbf{x}_i - \mu_k) (\mathbf{x}_i - \mu_k)^T$$

$$\hat{w}_k = \frac{\sum_{i=1}^n r_{ik}}{n} = \frac{N_k}{n}$$

For k^{th}
Gaussian
component

Maximisation



$$\ln \mathcal{L} = \sum_{i=1}^n \ln p(\vec{x}_i | \Theta) = \sum_{i=1}^n \ln \left\{ \sum_{j=1}^K w_j \mathcal{N}(\vec{x}_i | \mu_j, \Sigma_j) \right\}$$

GW detections: Application to O3 data

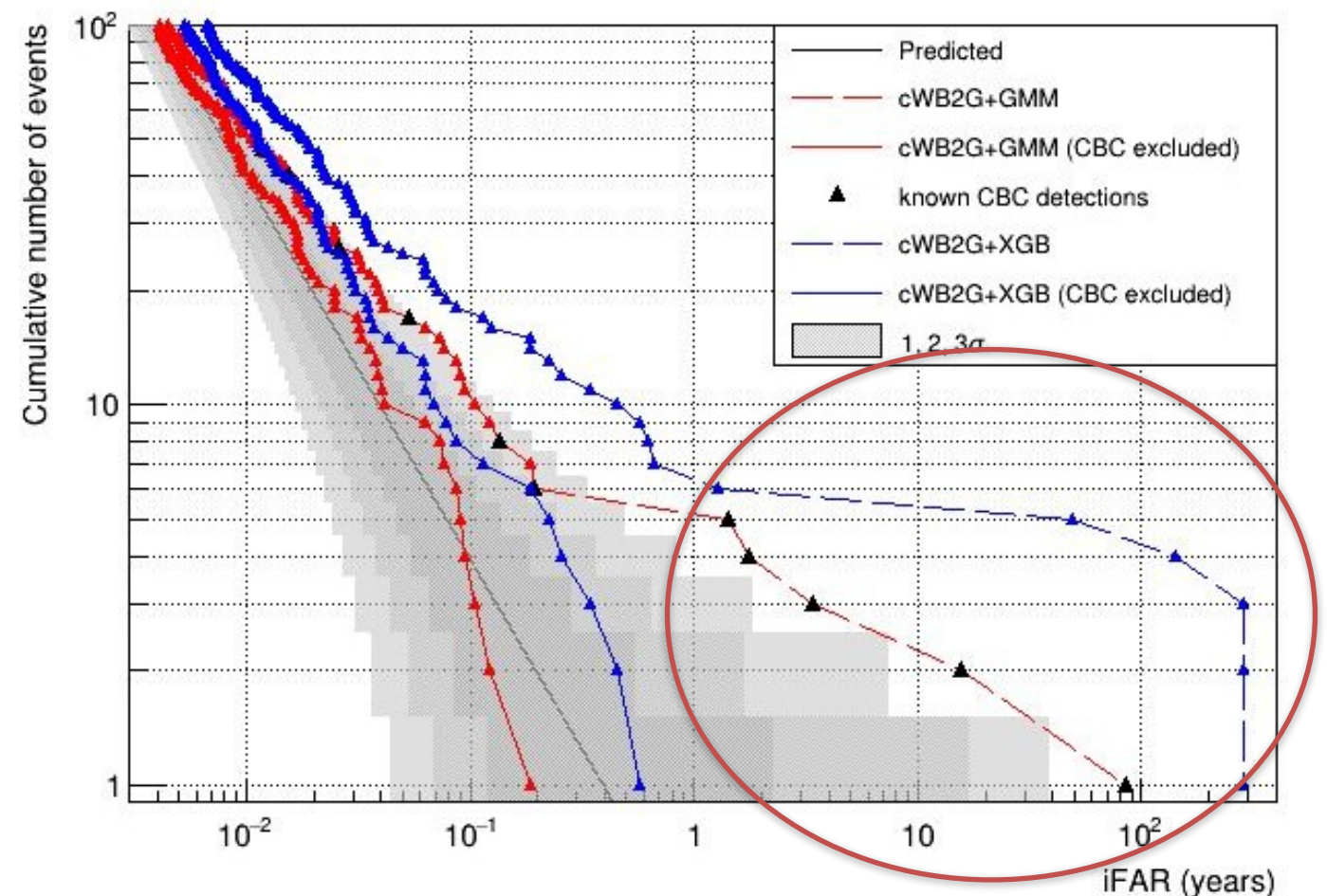
슬라이드 제공: 선지윤

- List of detected events:

Event Name	T	GMM+ iFAR (yr)
GW190412	18.46	85.93
GW190519_153544 ²	7.94	19.09
GW190828_063405	5.79	15.62
GW200224_222234	10.74	3.39
GW190706_222641	-0.14	1.75
GW190521_074359	-0.5	1.43

- No non-CBC events were found during the O3 run

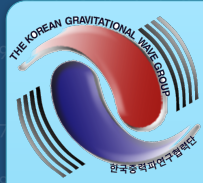
- [PhysRevD.110.083032](https://arxiv.org/abs/PhysRevD.110.083032) (L. Smith, S. Ghosh, J. Sun et al.)



Main Results so far

슬라이드 제공: 선지윤

- GMM brings sensitivity improvements for many of the tested waveforms.
 - Especially, GMM has noticeable sensitivity for GAs and CSs, and it proves that GMM can **effectively mitigate blip glitches**
- First case of cWB flavours to have better sensitivity on H1L1V1 network than on H1L1 network
- Further investigations ...
 - Search for optimal setting of GMM configuration
 - Test on released regulators



LIGO/KAGRA DECHAR Group

1. CAGMon and EEMD – 김별 (NIMS), 오정근(NIMS), 김영민 (KASI)
2. MSNN and Occlusion sensitivity – 김환선(NIMS), 김영민(KASI)
3. t-SNE & PCA analysis (unsupervised learning) for classification – 이우진, 곽규진, 정기현 (UNIST)
4. KAGRA O4a hveto analysis – 정기현, Nursyifa Ruhama, 곽규진 (UNIST)
5. Bayesian Analysis for NS EoS – 김영민 (KASI)

Summary & Future Work

- ✓ **LIGO has successfully running to detect gravitational waves but noise sources has been the main constraint for the sensitivity.**
- ✓ **Instrumental R&D is the core research to overcome that challenge.**
- ✓ **Collaborations established working groups assigned for each noise source for high-level expertise.**
- ✓ **Korean groups are expanding their research field from data analysis to experimental R&D.**

Summary & Future Work

- ✓ LIGO has successfully running to detect gravitational waves but noise sources has been the main constraint for the sensitivity.
- ✓ Instrumental R&D is the core research to overcome that challenge.
- ✓ Collaborations established working groups assigned for each noise source for high-level expertise.
- ✓ Korean groups are expanding their research field from data analysis to experimental R&D.

**Gravitational wave field has JUST started
its first baby step,
and more exciting things are to come! :)**



Thank you for your attention.

Kyung-ha Lee
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SUNG KYUN KWAN
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