FACULTY
OF SCIENCES

DEPARTMENT OF SOLID STATE SCIENCES
CONFORMAL COATING OF NANOMATERIALS

Atomic precision mirror coatings for gravitational wave detectors

Jorden De Bolle, Christophe Detavernier

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fwo Research Foundation Flanders
Opening new horizons

CoCooN
Conformal Coating of Nanomaterials

Overview

- Who are we?
  - The CoCooN research group
  - Atomic layer deposition (ALD)
  - Thin film characterisation
- Mirror coatings in GW detectors
  - Making mirrors reflective
  - Mirror coatings and noise
- ALD as alternative deposition technique
  - Current state of the art
  - Why ALD?
  - Growth of Ta_2O_5
  - Growth of SiO_2
- Structural characterisation of mirror coatings
  - Why structure is important
  - Total scattering experiments
  - PDF of Ta_2O_5

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Who are we?

The CoCooN research group

- Jorden De Bolle
- PhD student
- Physicist (MSc Physics, Ghent University)
- jorden.debolle@ugent.be

- CoCooN research group (Conformal Coating of Nanomaterials)
- Thin film and material research
- Application driven (batteries, proton conductors…) and fundamental research

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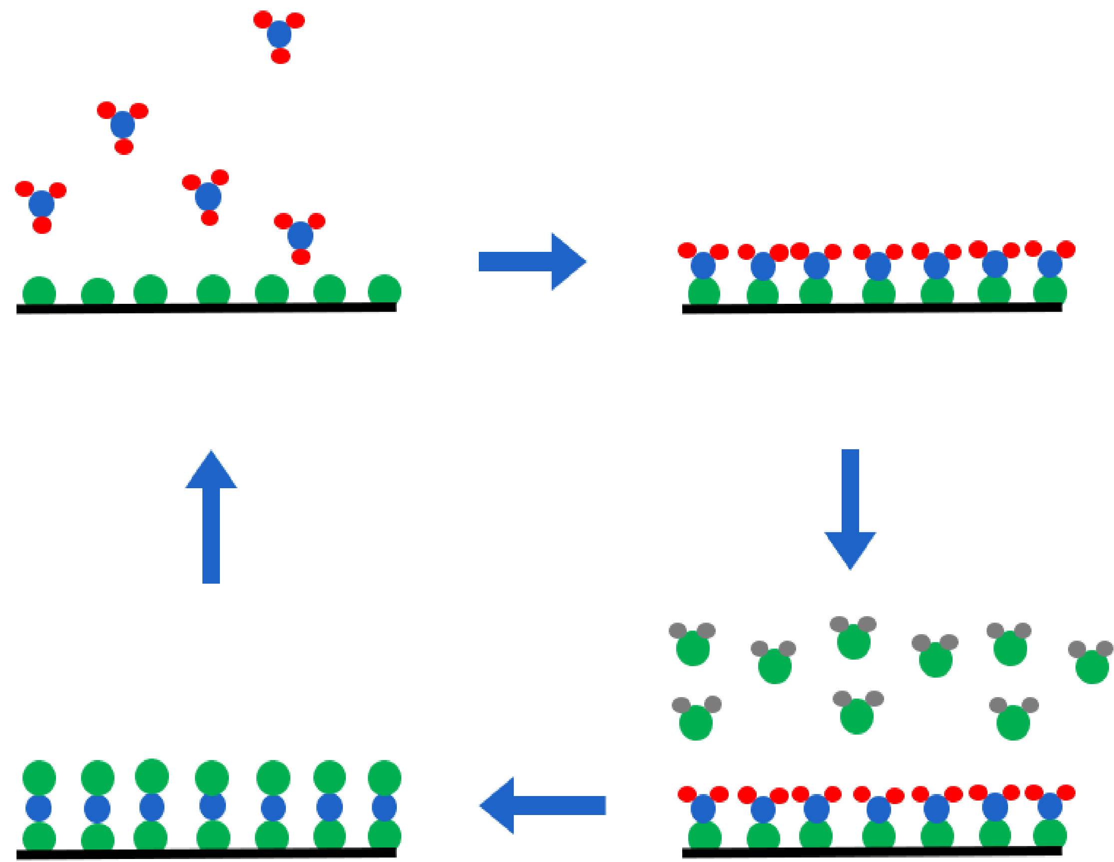
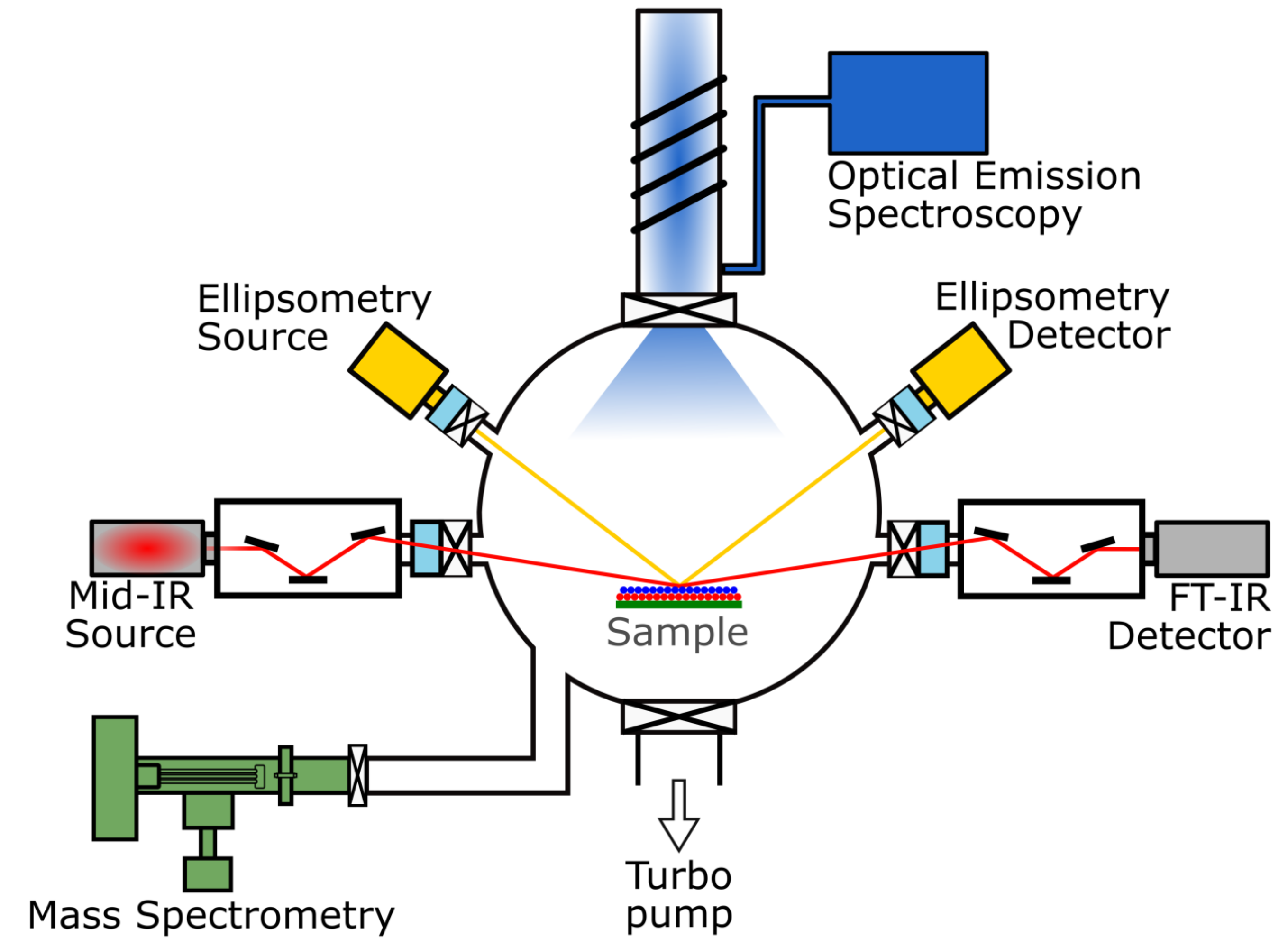
Atomic layer deposition (ALD)





Self-limiting reactions between substrate and precursor gases!

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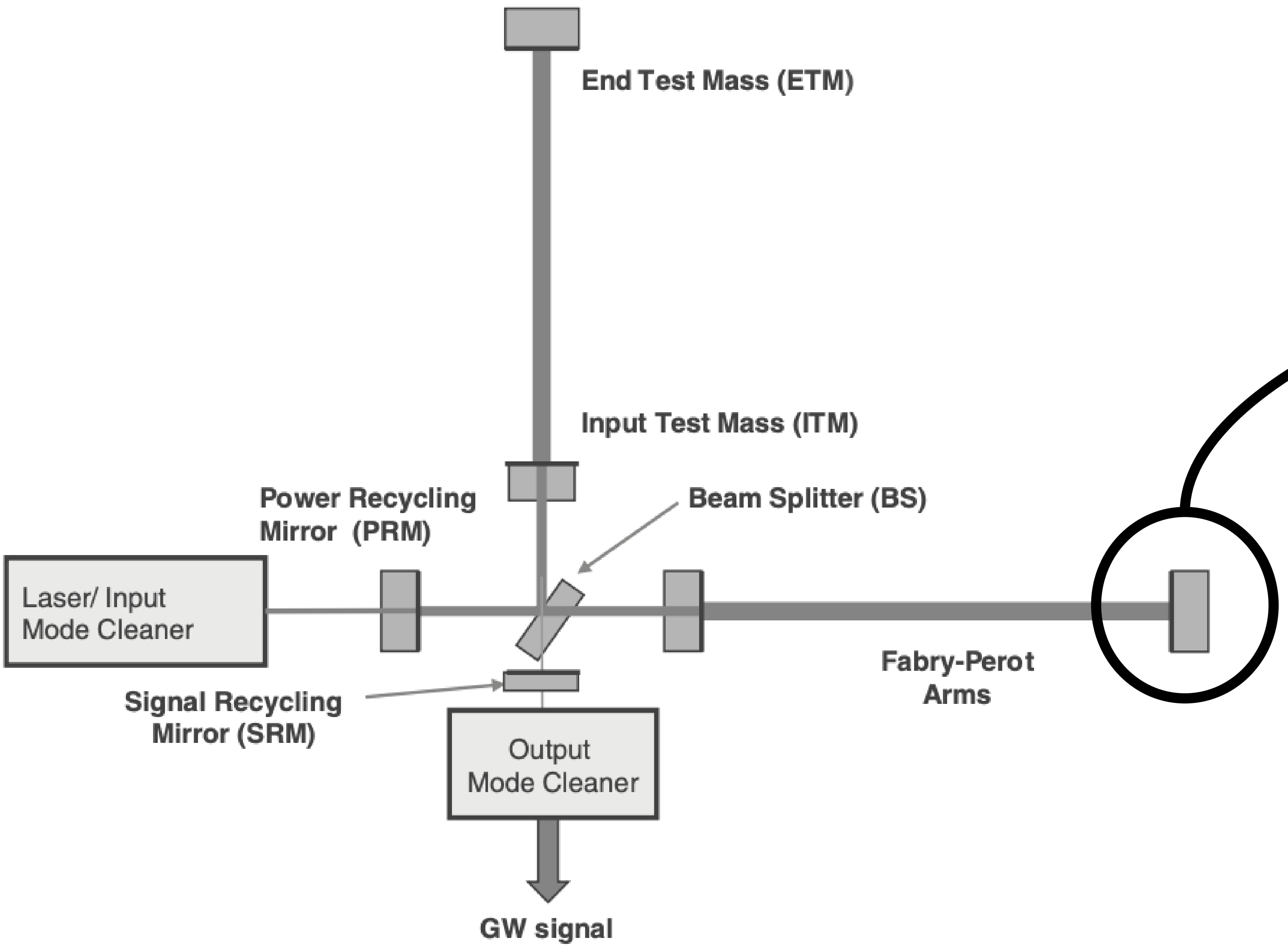
CoCooN

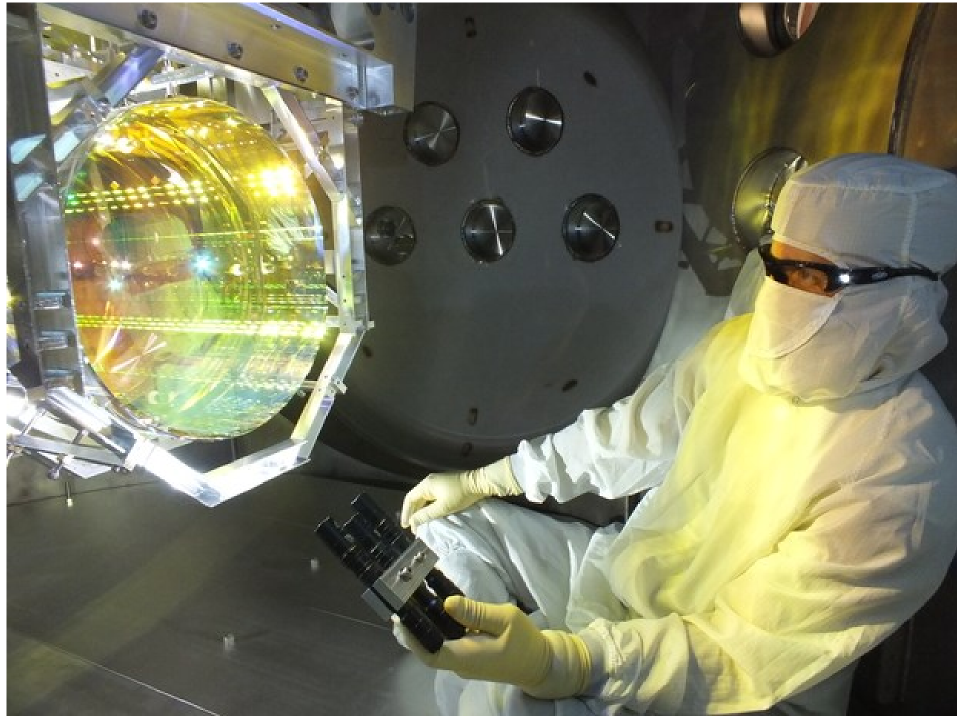
→ https://www.ugent.be/we/solidstatesciences/cocoon/en

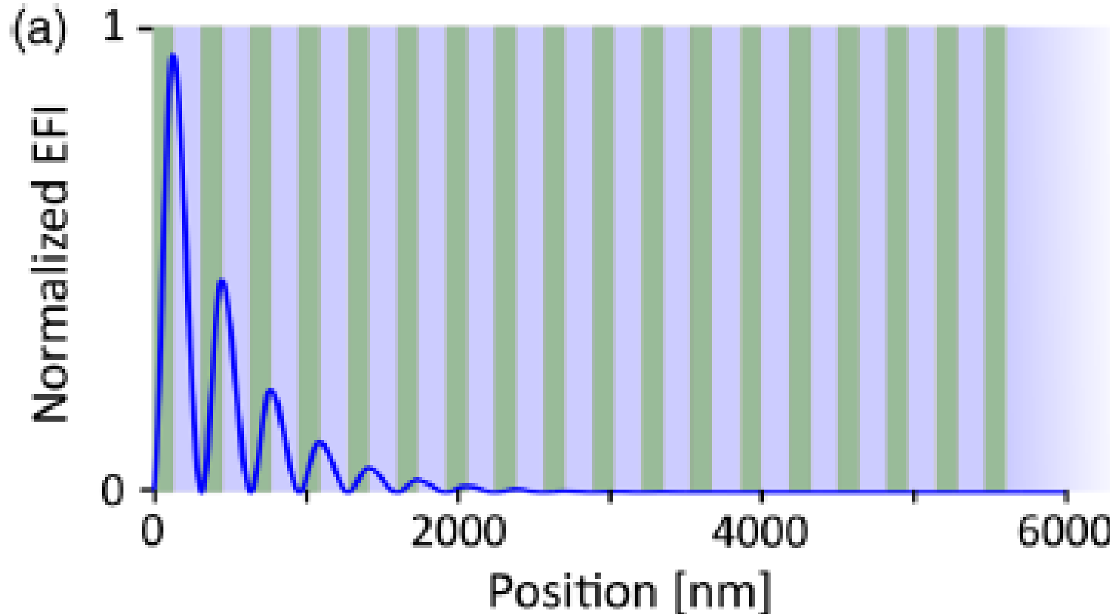
- 8 ALD reactors, 3 MLD reactors
- 1 mobile ALD reactor to take to a synchrotron facility
- PVD reactors
- Characterization:
  - Ellipsometry (in situ during ALD and anneal, ex situ)
  - FTIR (in situ during ALD, ex situ)
  - XRR (ex situ)
  - XRD (in situ during anneal, ex situ)
  - Stress measurements (in situ during anneal, ex situ)
  - Mass spectrometry (in situ during ALD)
  - XPS (in vacuo during ALD, ex situ)
  - SEM (ex situ)
  - …
- Characterization at synchrotron facilities (GISAXS (in situ during ALD and anneal and ex situ), PDF…)

Mirror coatings in GW detectors

Making mirrors reflective







- Mirrors operate as Bragg reflectors
- Key components of the detectors

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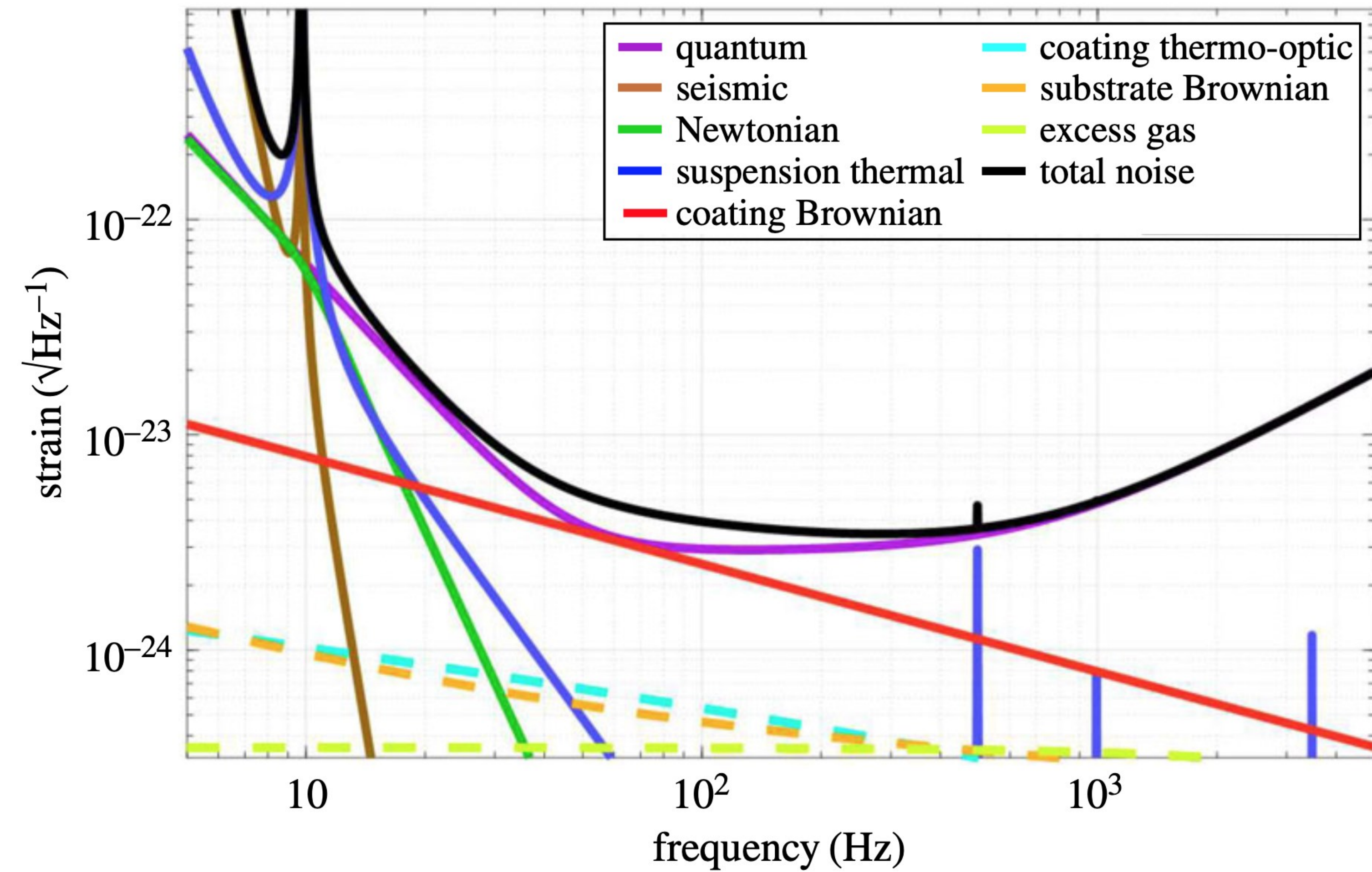
The LIGO website. www.ligo.caltech.edu/page/optics
G. Harry et al. *Optical Coatings and Thermal Noise in Precision Measurement*, Cambridge University Press, 2012
J. Steinlechner et al. *Phys. Rev. D*, no. 103, p. 042001, 2021

I. W. Martin et al. *Class. Quantum Grav.*, no. 26, 2009
J. Steinlechner. *Phil. Trans. R. Soc. Lond. A*, no. 376, 2018

Mirror coatings and noise



- Mirror coatings contributre large fraction to total detector noise

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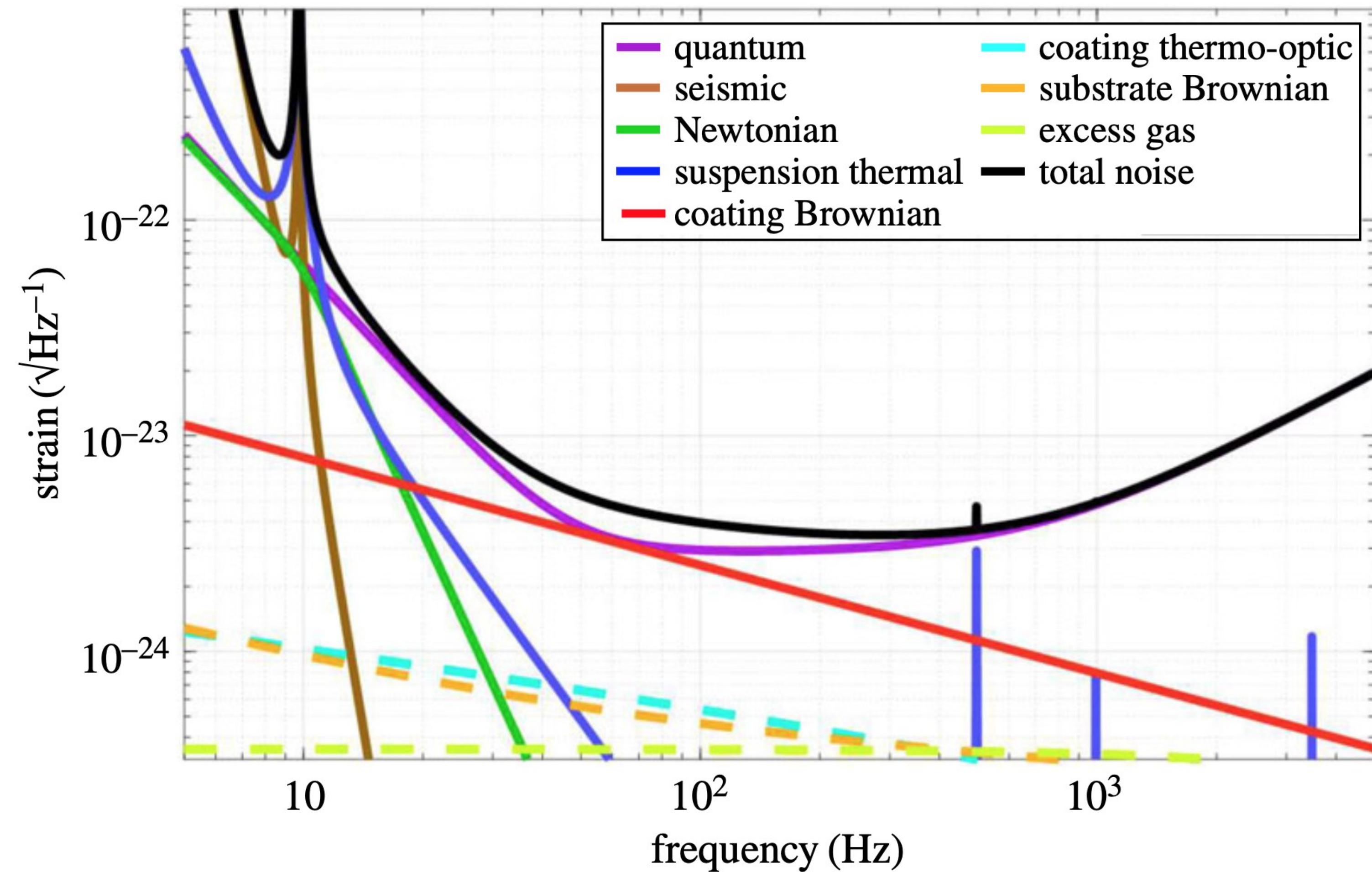
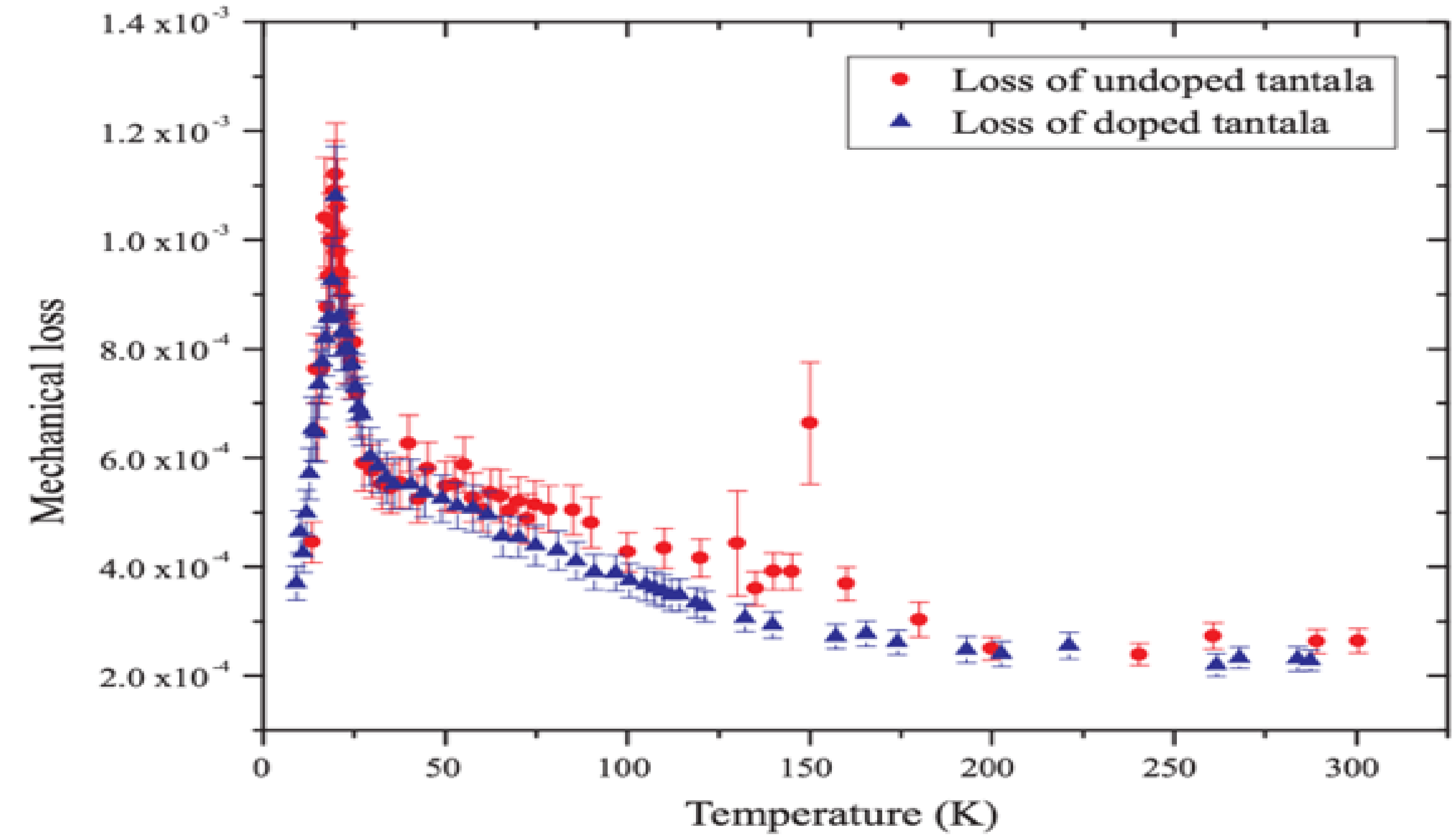
Mirror coatings and noise





- Mirror coatings contributre large fraction to total detector noise
- Current state of the art coatings not suited for operation in future detectors

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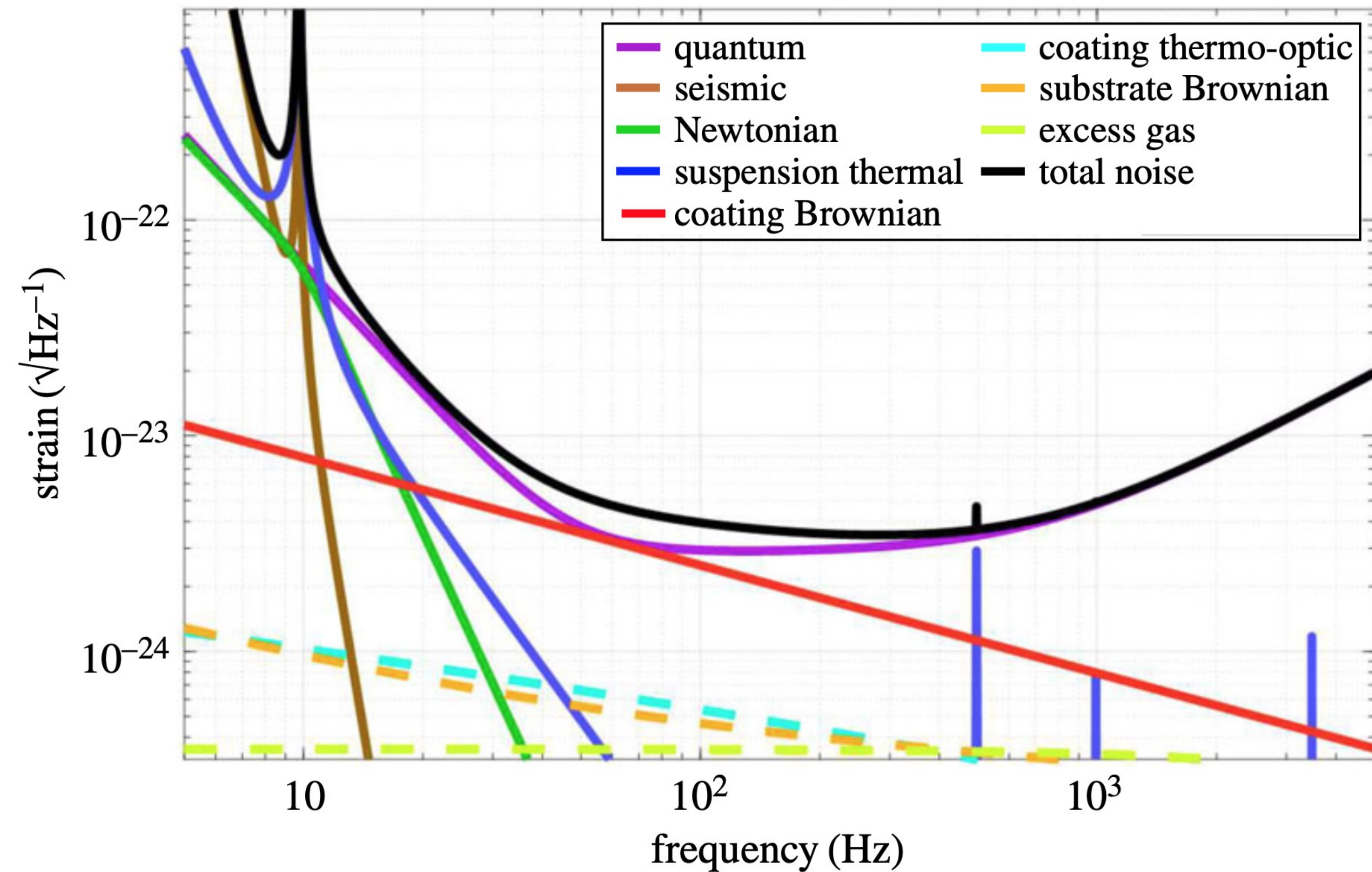
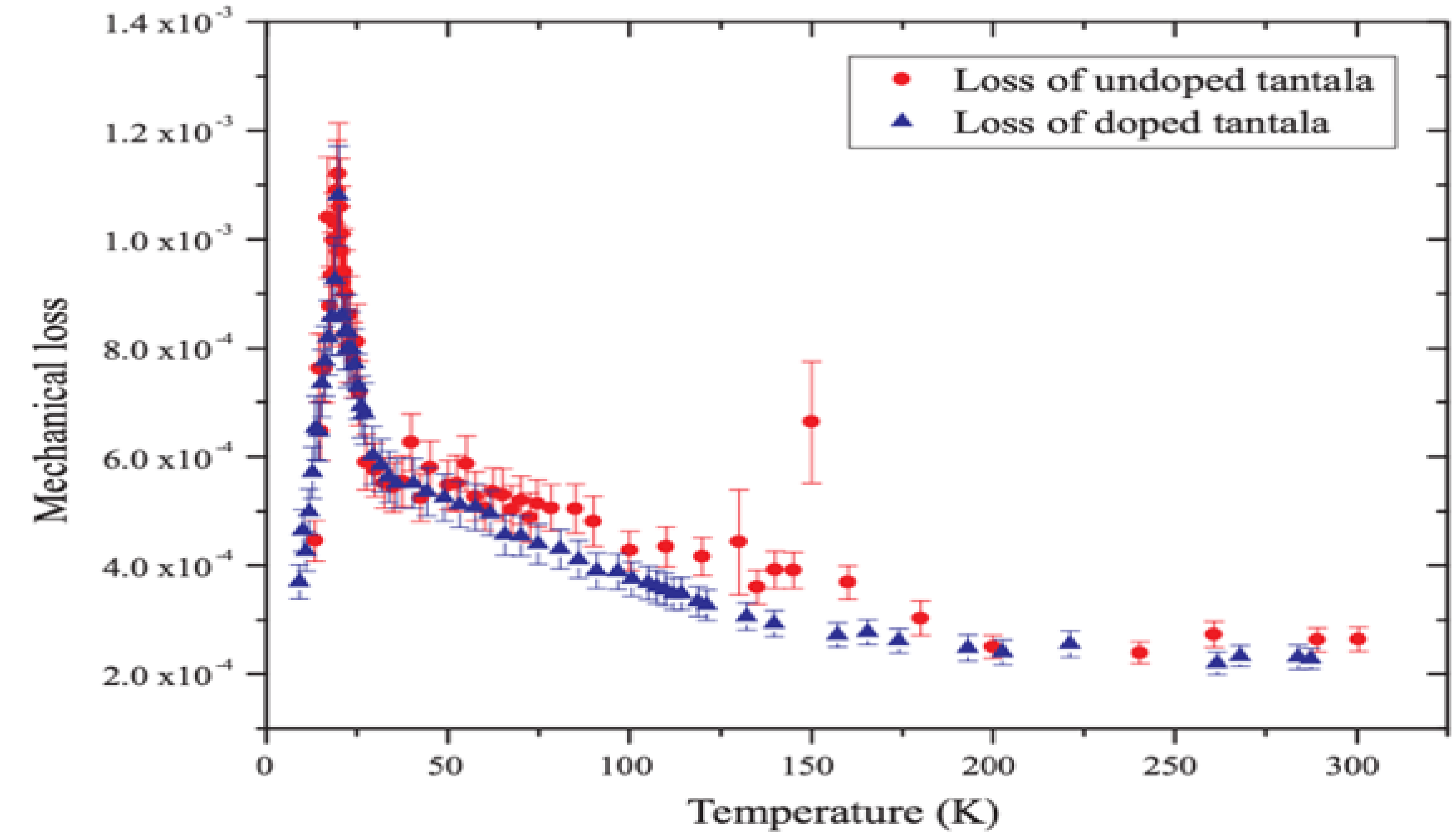
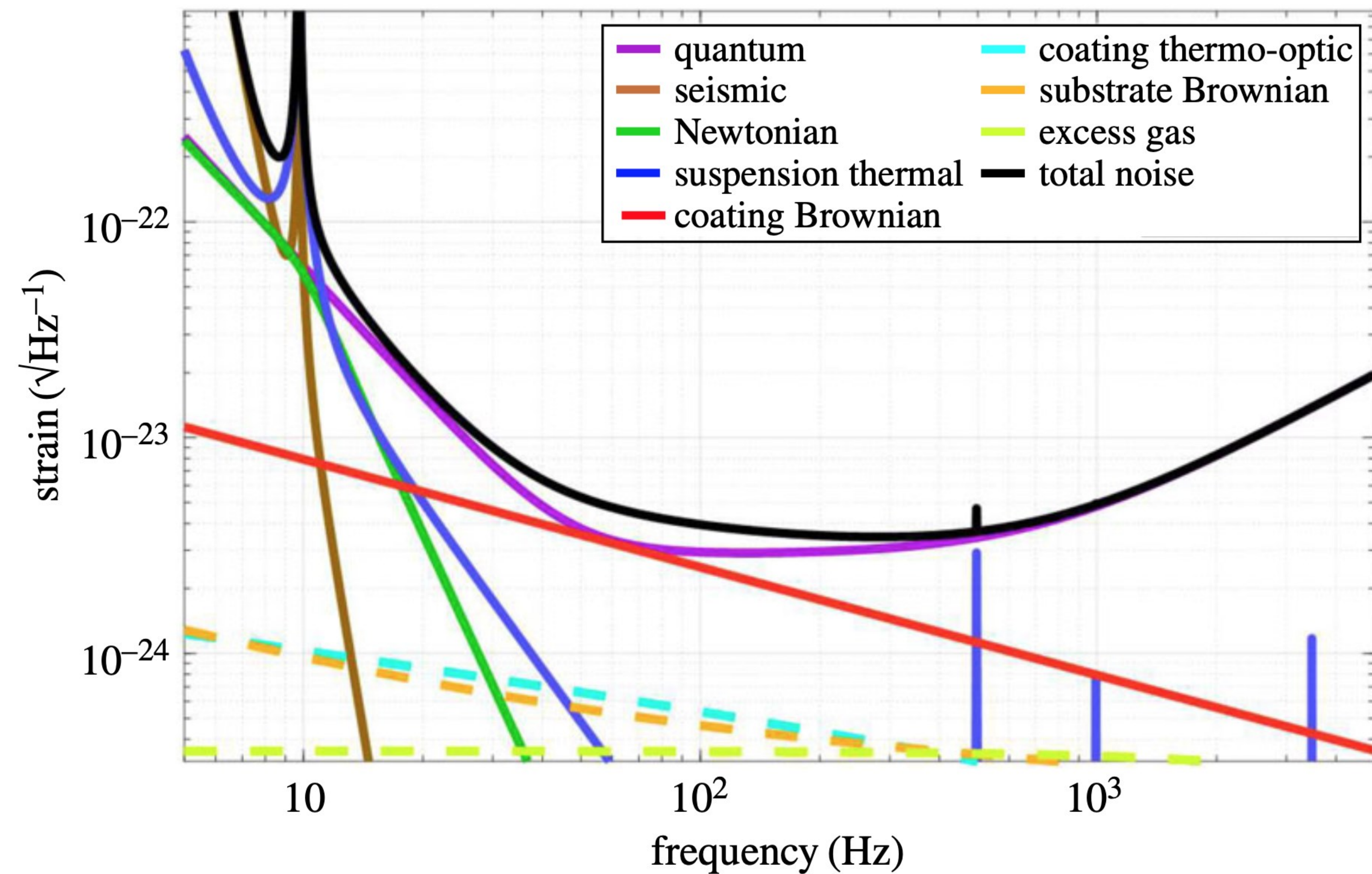
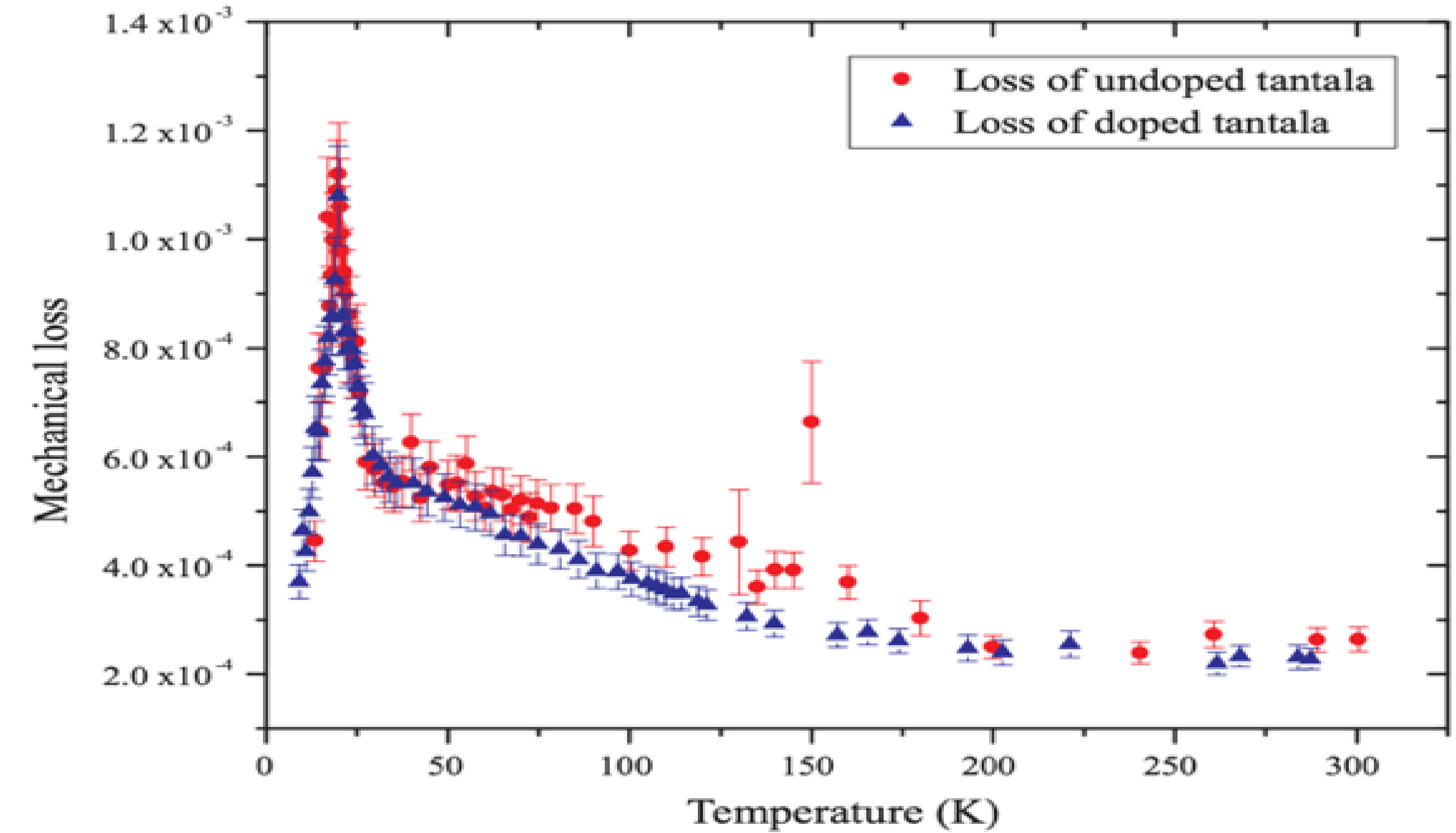




- Mirror coatings contributre large fraction to total detector noise
- Current state of the art coatings not suited for operation in future detectors
- Need for new coating materials and coating designs

Mirror coatings and noise





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- Need for more knowledge on how atomic structure influences performance and how this can be controlled

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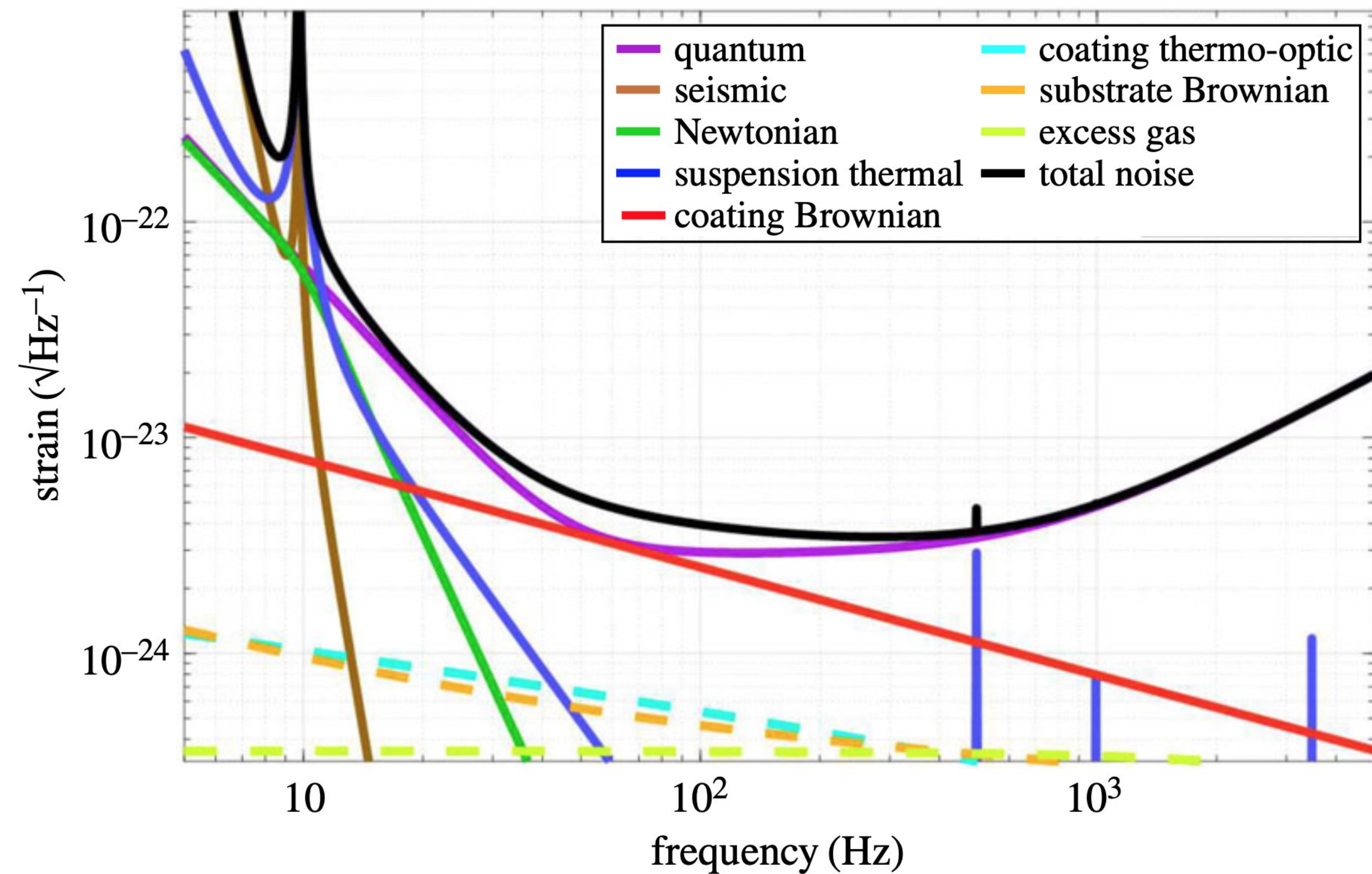

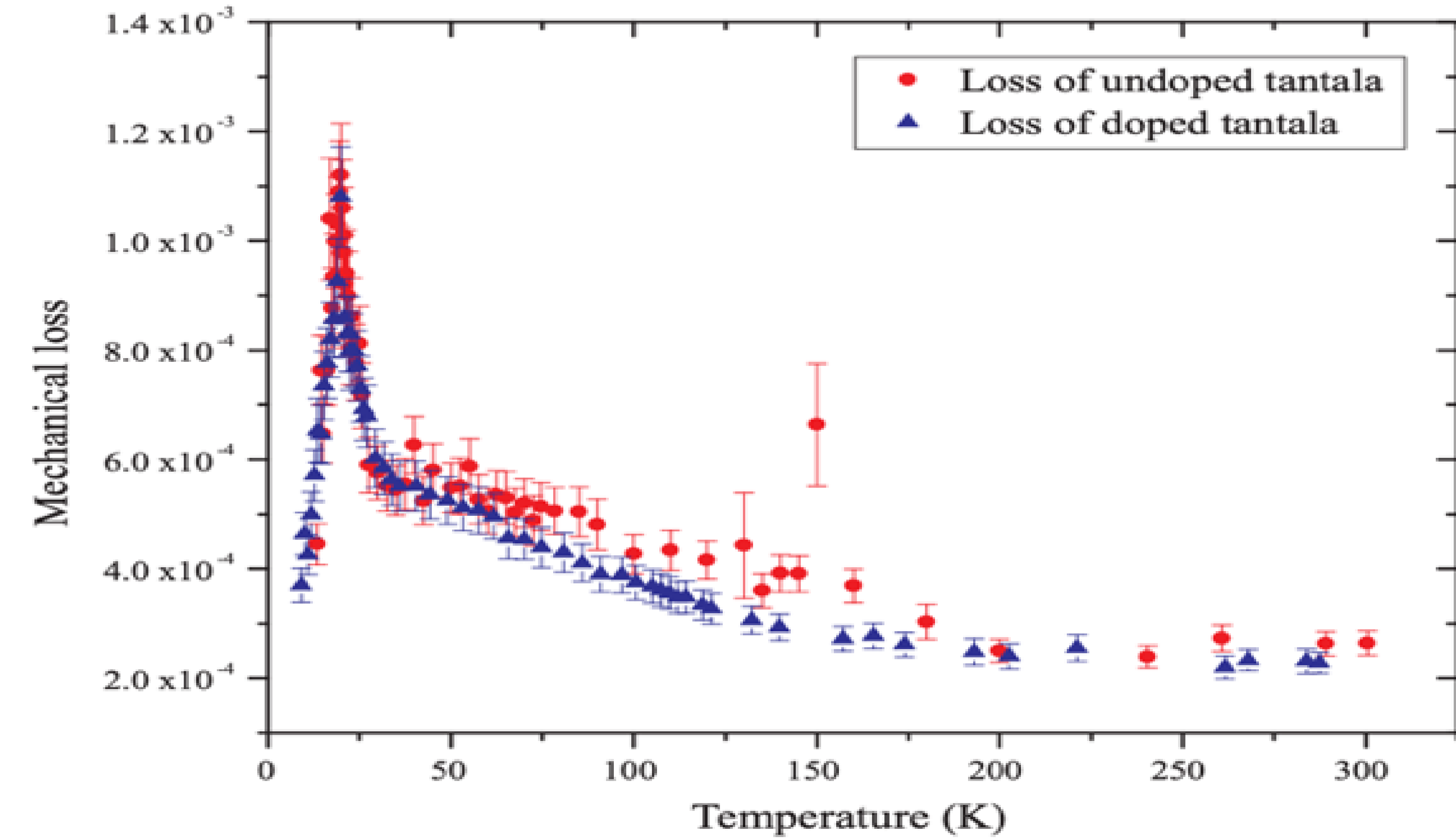

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- Current state of the art coatings not suited for operation in future detectors
- Need for new coating materials and coating designs **← ALD as alternative deposition technique**
- Need for more knowledge on how atomic structure influences performance and how this can be controlled

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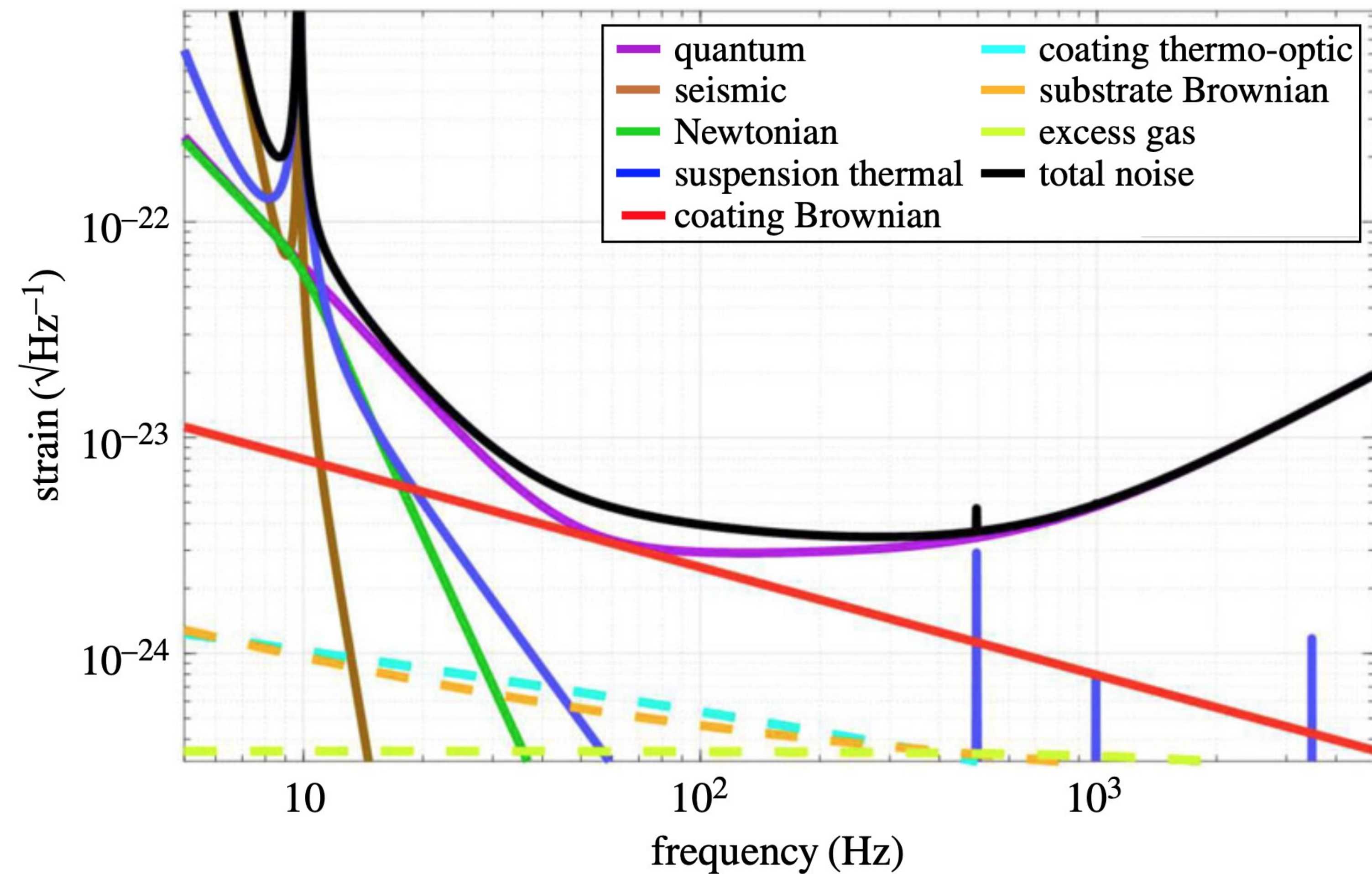
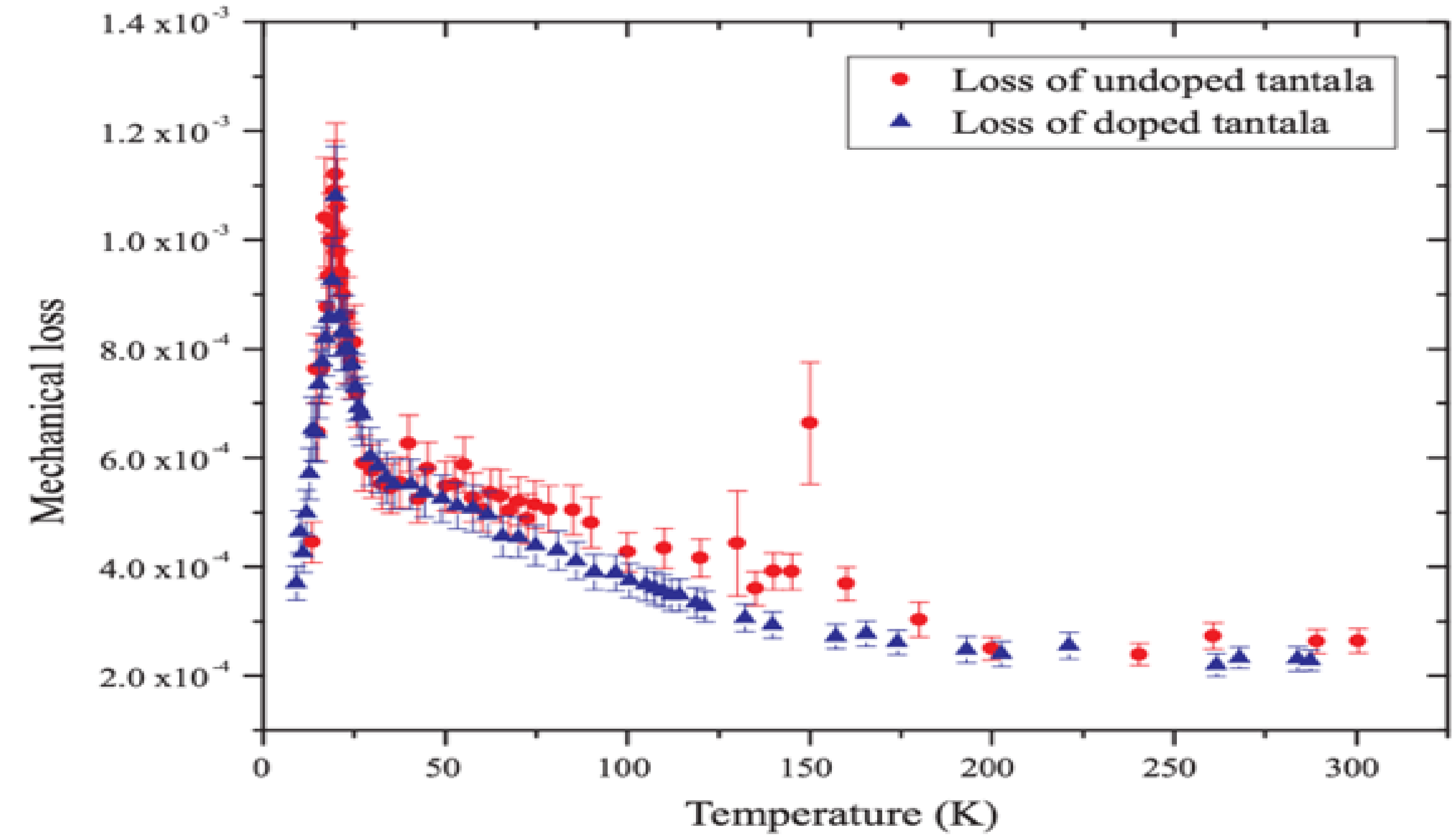


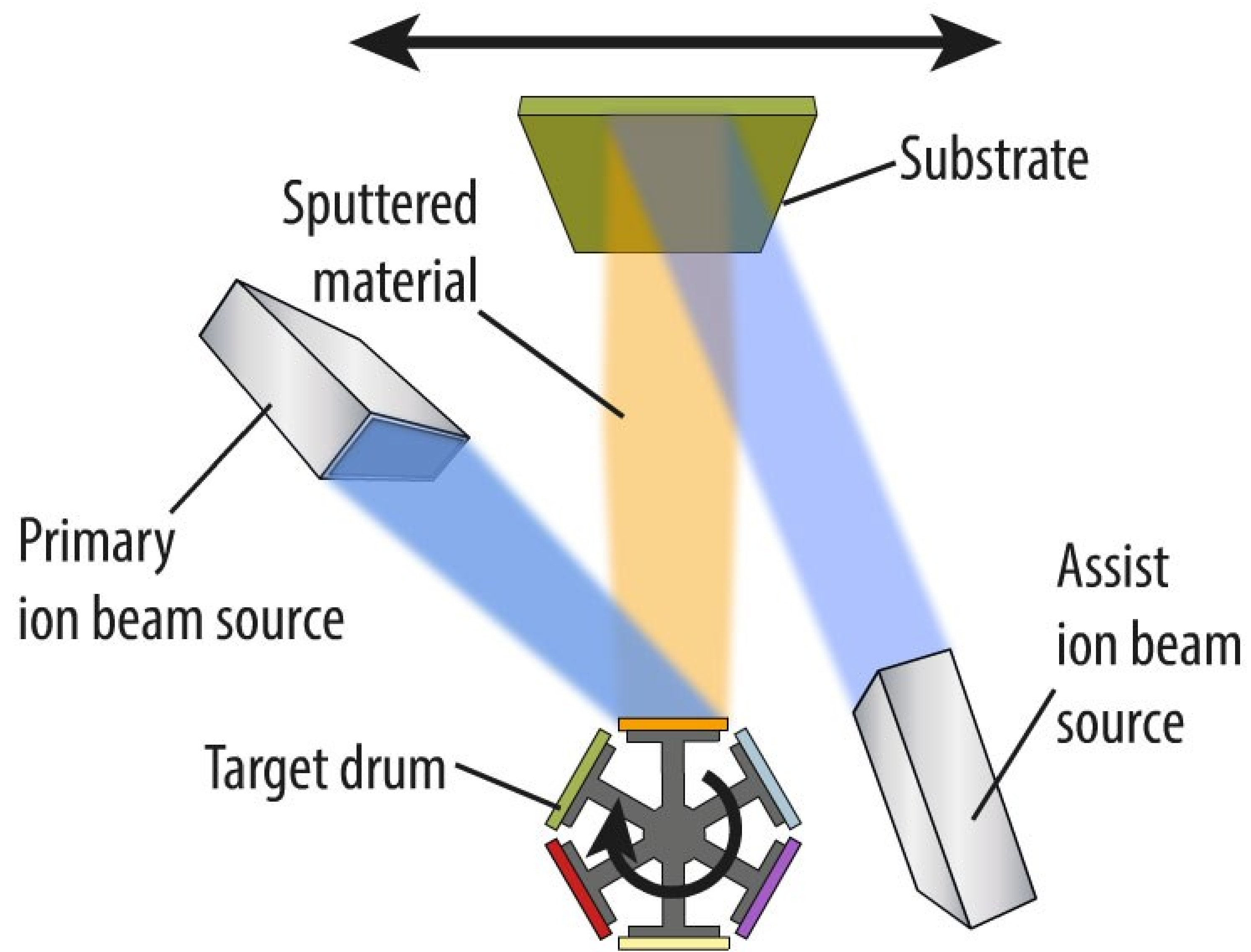


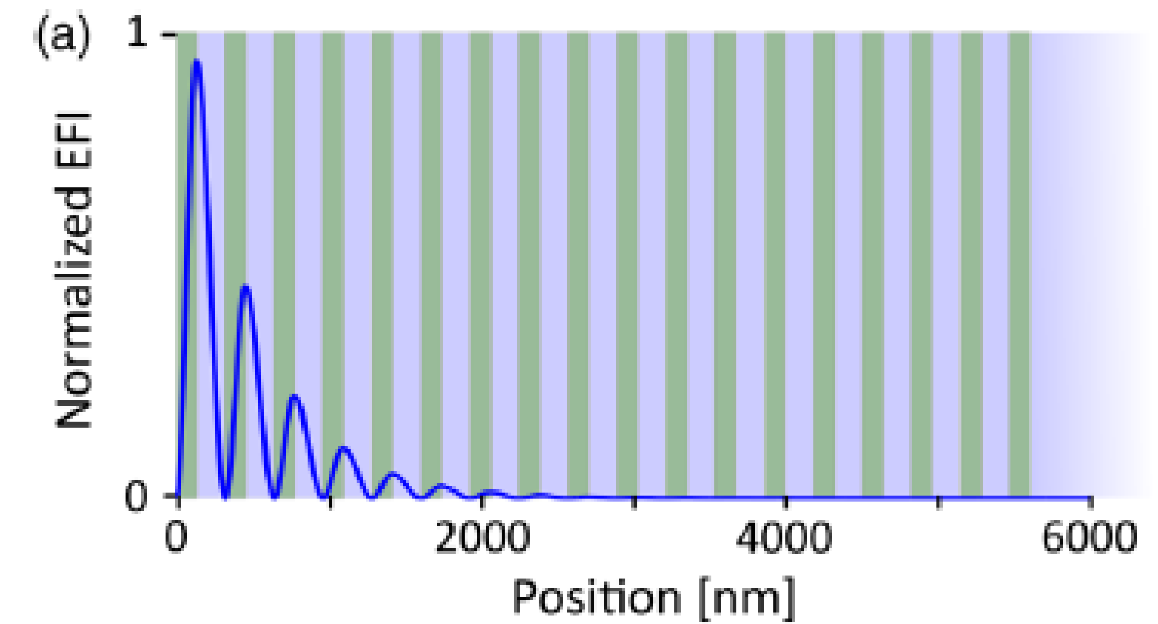
- Mirror coatings contributre large fraction to total detector noise
- Current state of the art coatings not suited for operation in future detectors
- Need for new coating materials and coating designs ← **ALD as alternative deposition technique**
- Need for more knowledge on how atomic structure influences performance and how this can be controlled ← **structural characterisation with total scattering measurements**

ALD as alternative deposition technique

Current state of the art

Ion beam sputtering is used to deposit coatings of Ti:Ta2O5 and SiO2





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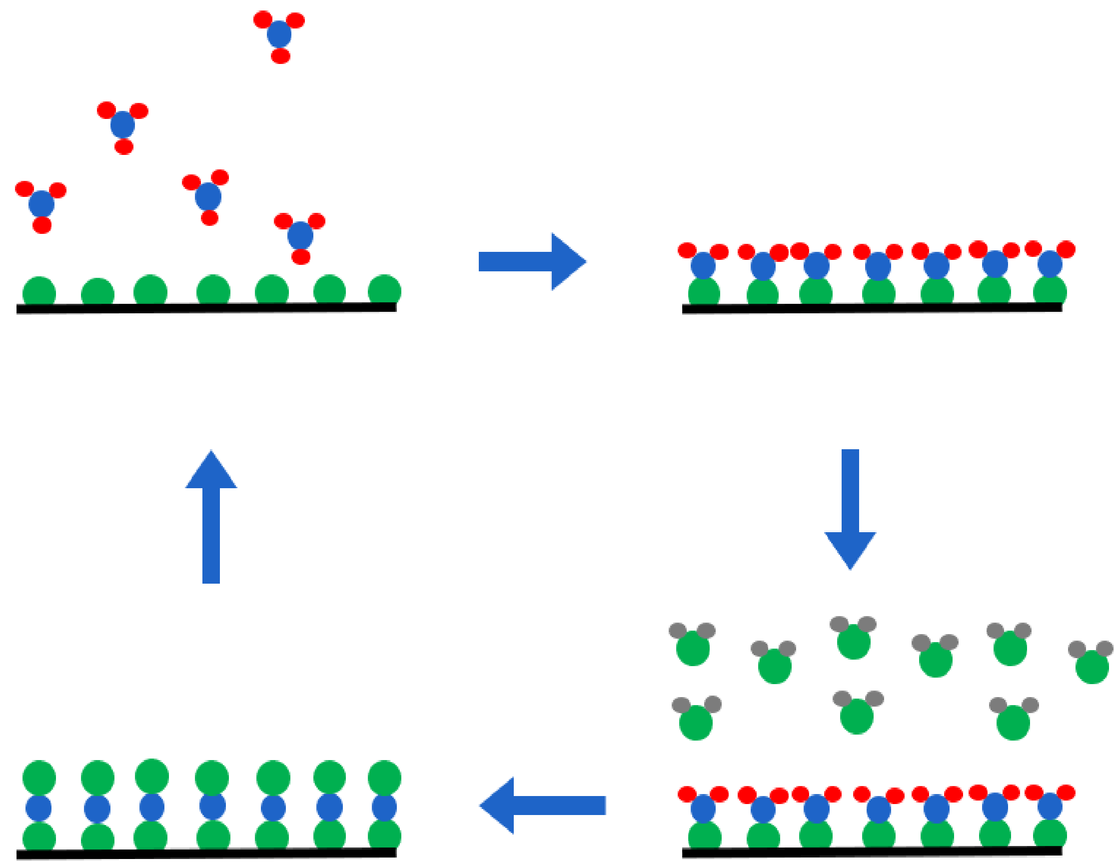
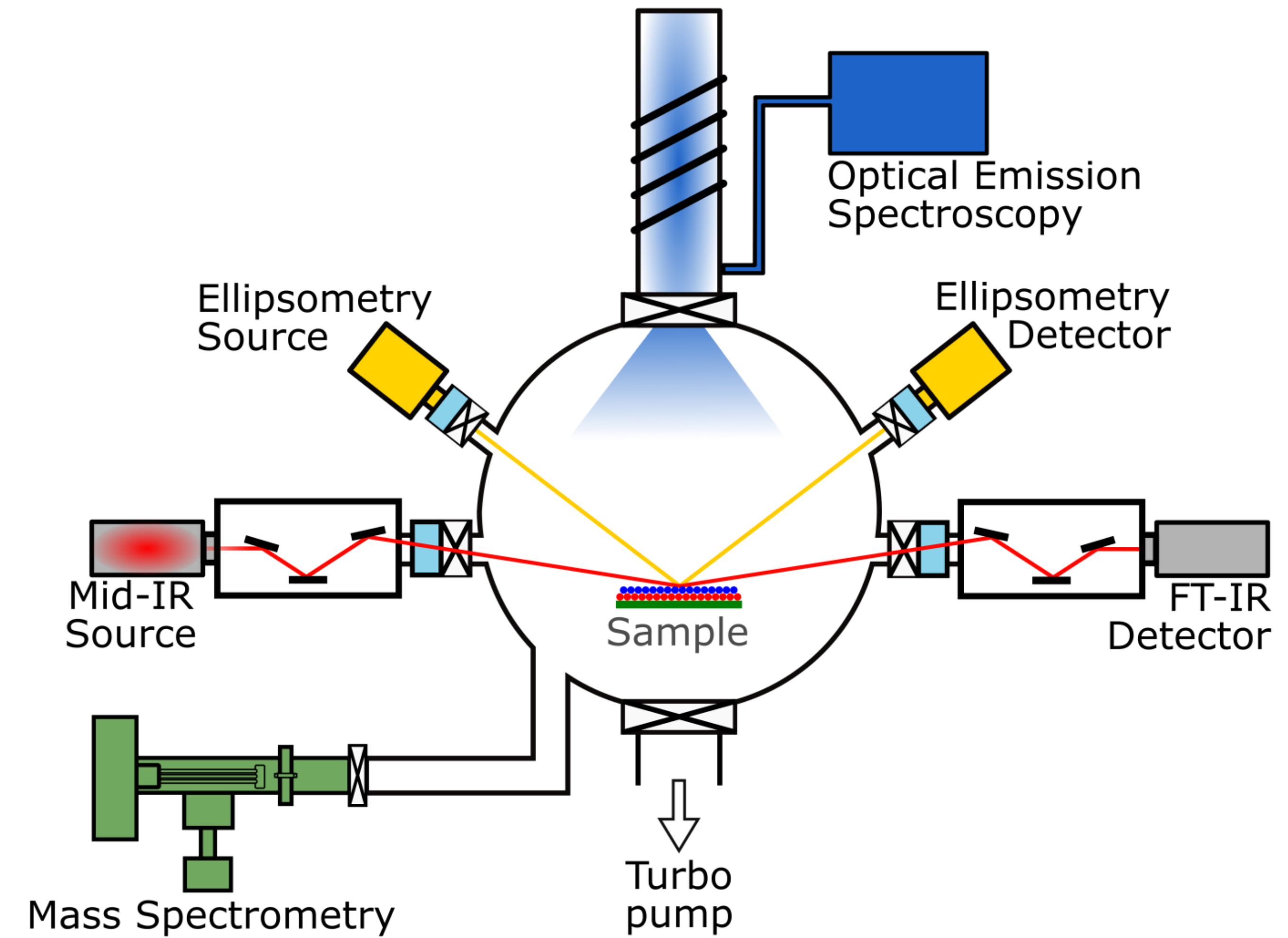
J. Steinlechner et al. *Phys. Rev. D*, no. 103, p. 042001, 2021
The LMA website. http://lma.in2p3.fr/Images/coater2.jpg
Scia Systems. *Ion beam sputtering: Dense and high-precision coatings for advanced applicationshe*. Accessed on February 20, 2024 from https://www.scia-systems.com/products/ion-beam-sputtering

Atomic layer deposition (ALD)





Self-limiting reactions between substrate and precursor gases!

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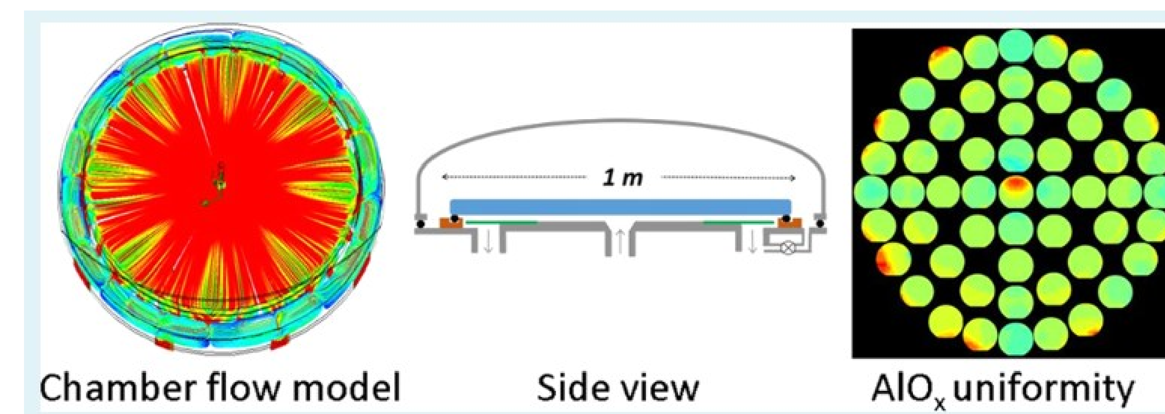
Why ALD?

ACS APPLIED MATERIALS & INTERFACES
Research Article
Cite This: *ACS Appl. Mater. Interfaces* 2018, 10, 41678–41689
www.acsami.org

Scaling Atomic Layer Deposition to Astronomical Optic Sizes: Low-Temperature Aluminum Oxide in a Meter-Sized Chamber

David M. Fryauf,*,† Andrew C. Phillips,‡ Michael J. Bolte,§ Aaron Feldman,∥ Gary S. Tompa,∥ and Nobuhiko P. Kobayashi†



Available ALD processes at CoCooN

(Click for selection and/or link to paper)

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

- Sulfate
- Silicate
- Phosphate
- Oxide
- Nitride
- MLD
- Metal

✔ Atomic thickness control

D. M. Fryauf et al. *ACS Appl. Mater. Interfaces*, no. 10, p. 41678–41689, 2018

The CoCooN website. https://www.ugent.be/we/solidstatesciences/cocoon

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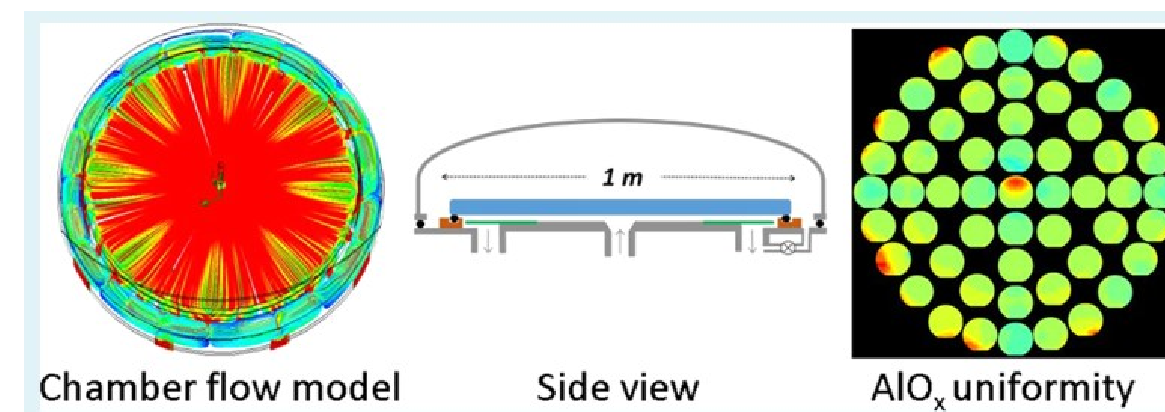

- ✔ Atomic thickness control
- ✔ Superior uniformity

Available ALD processes at CoCooN

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H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
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Chamber flow model | Side view | AlO_x uniformity

1 m

Available ALD processes at CoCooN

(Click for selection and/or link to paper)

H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo

Sulfate
Silicate
Phosphate
Oxide
Nitride
MLD
Metal

- ✓ Atomic thickness control
- ✓ Superior uniformity
- ✓ Easily scaleable

D. M. Fryauf et al. *ACS Appl. Mater. Interfaces*, no. 10, p. 41678–41689, 2018

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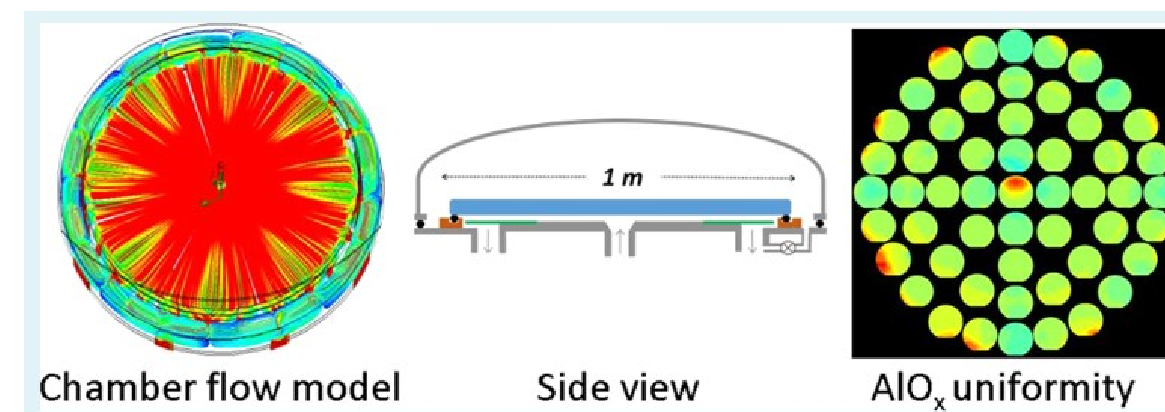

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Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

- Sulfate
- Silicate
- Phosphate
- Oxide
- Nitride
- MLD
- Metal

- ✓ Atomic thickness control
- ✓ Superior uniformity
- ✓ Easily scaleable
- ✓ Wide variety of materials

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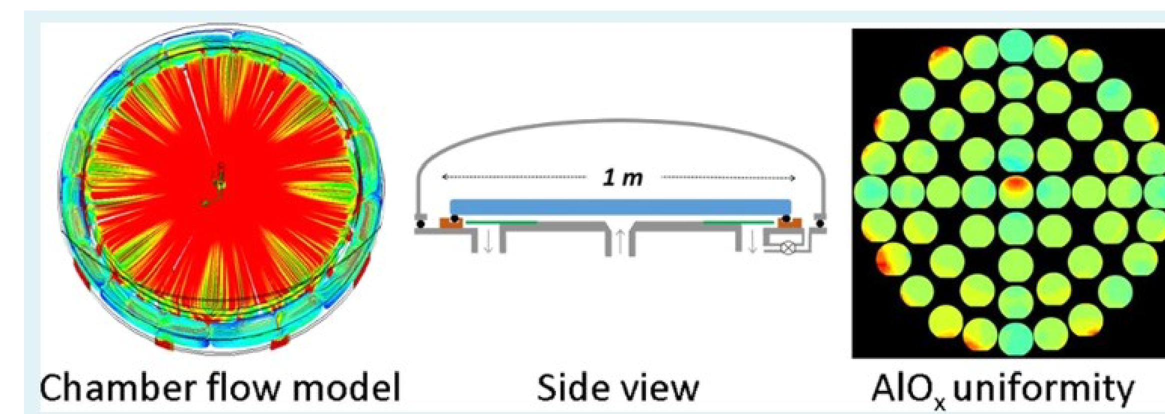

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- ✓ Atomic thickness control
- ✓ Superior uniformity
- ✓ Easily scaleable
- ✓ Wide variety of materials
- ✗ Slow

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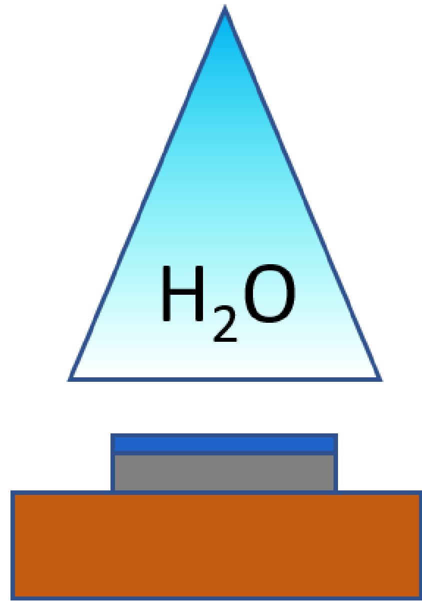
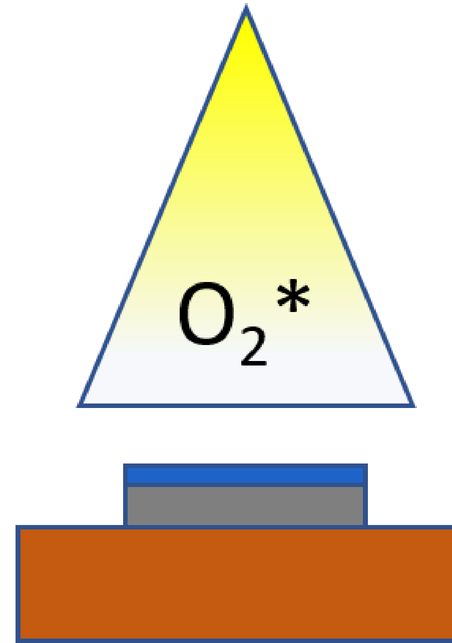
Growth of Ta_2O_5

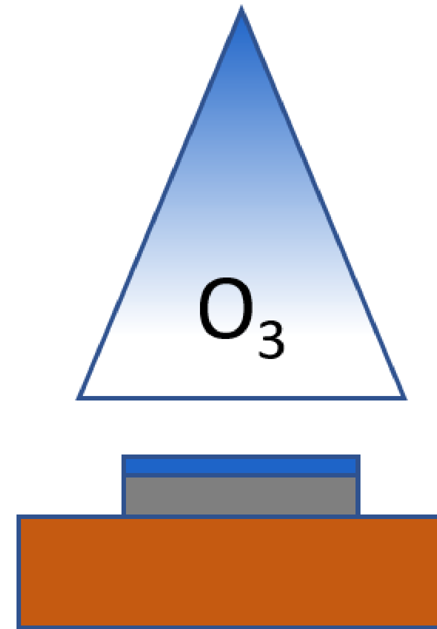
PDMAT/H_2O



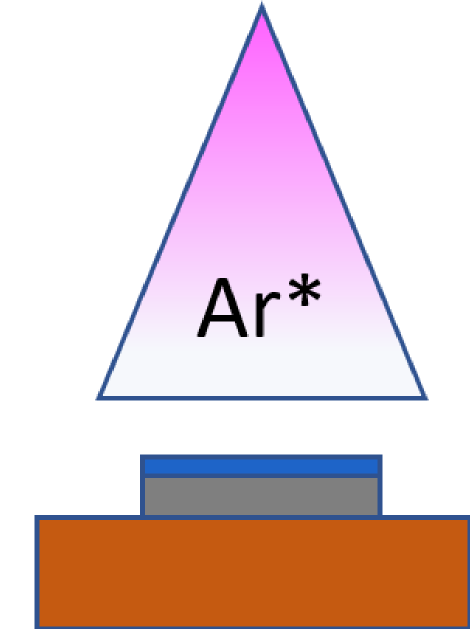
PDMAT/O_2*



PDMAT/O_3



Additional Ar* step



Influence of coreactant on:

- Growth speed
- Density
- Purity
- Optical absorption
- Mechanical losses

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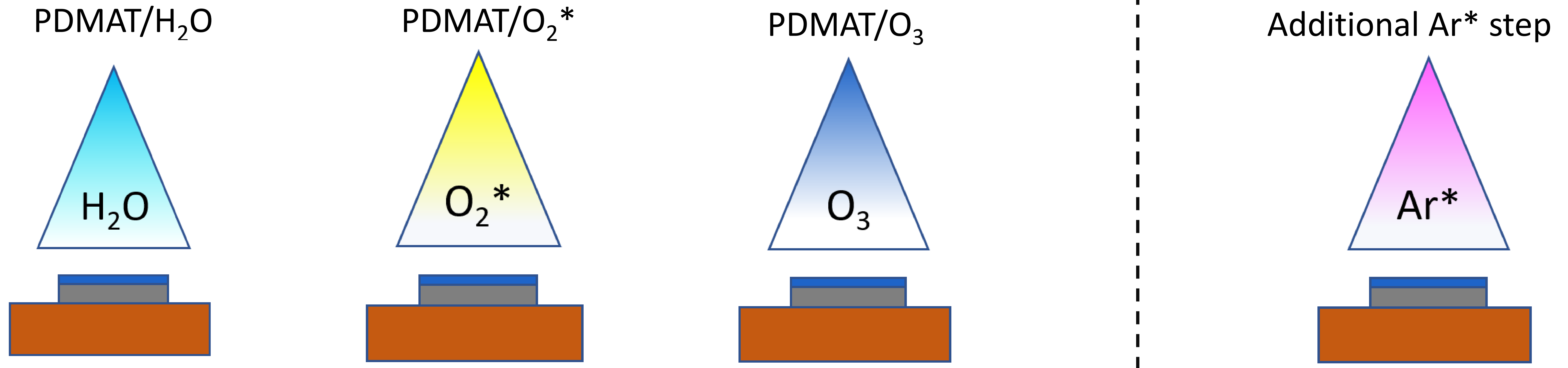
Growth of Ta_2O_5



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- Growth speed
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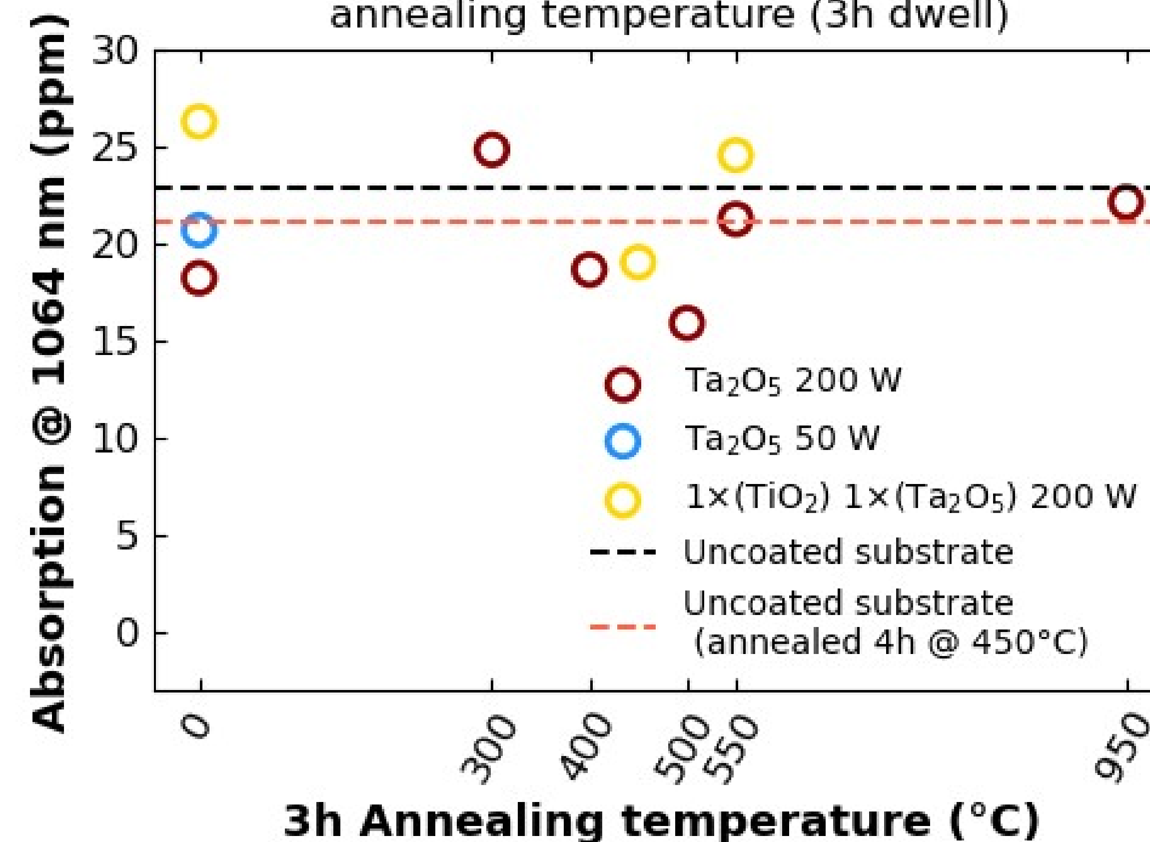
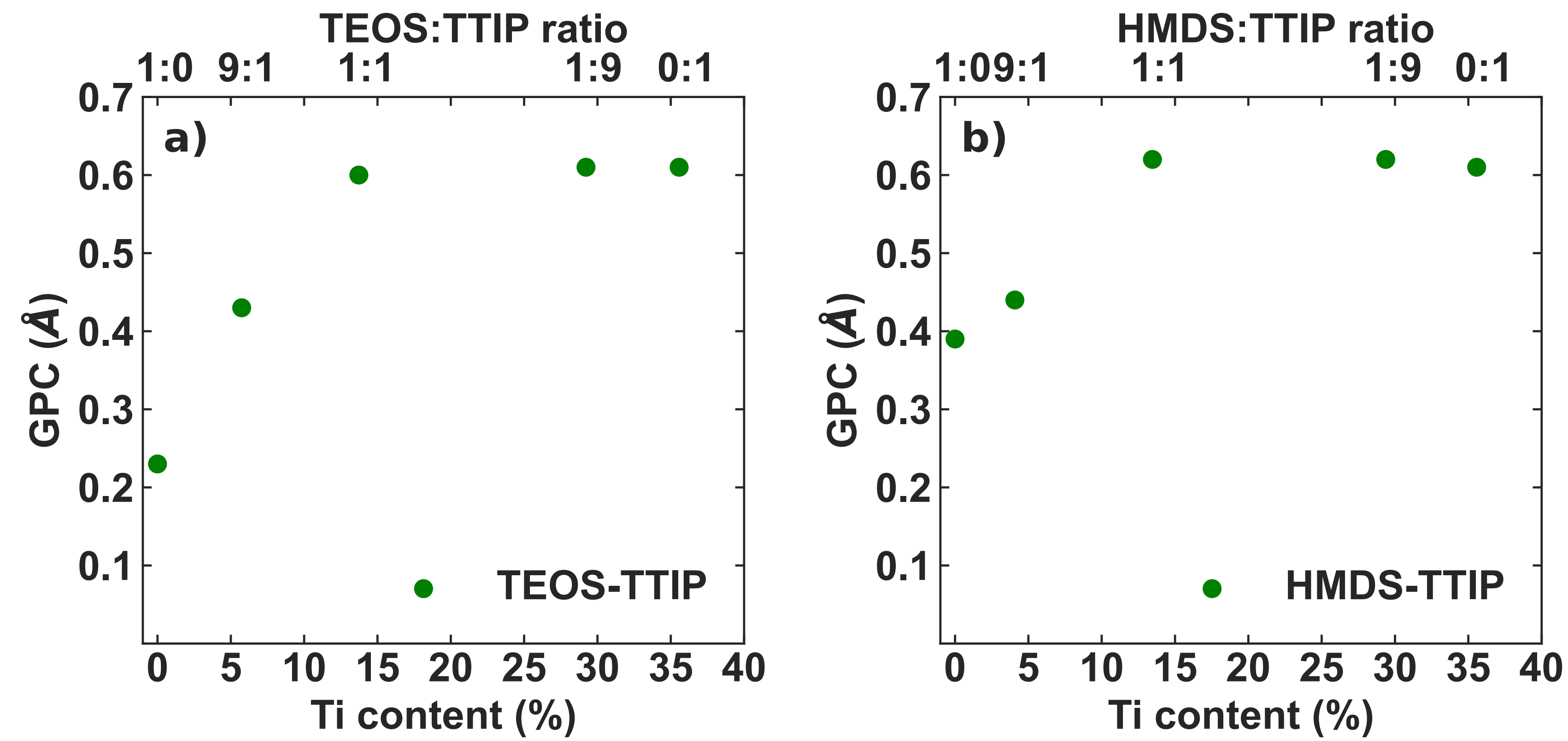
- Purity
- **Optical absorption**
- Mechanical losses



Upper boundary for extinction coefficient: 2E-5 (not bad)

Growth of SiO_2

SiO_2 grows faster when TiO_2 is added



Titania Mixed with Silica: A Low Thermal-Noise Coating Material for Gravitational-Wave Detectors

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G. I. McGhee et al. *Phys. Rev. Lett., no.* **131**, p. 171401, 2023

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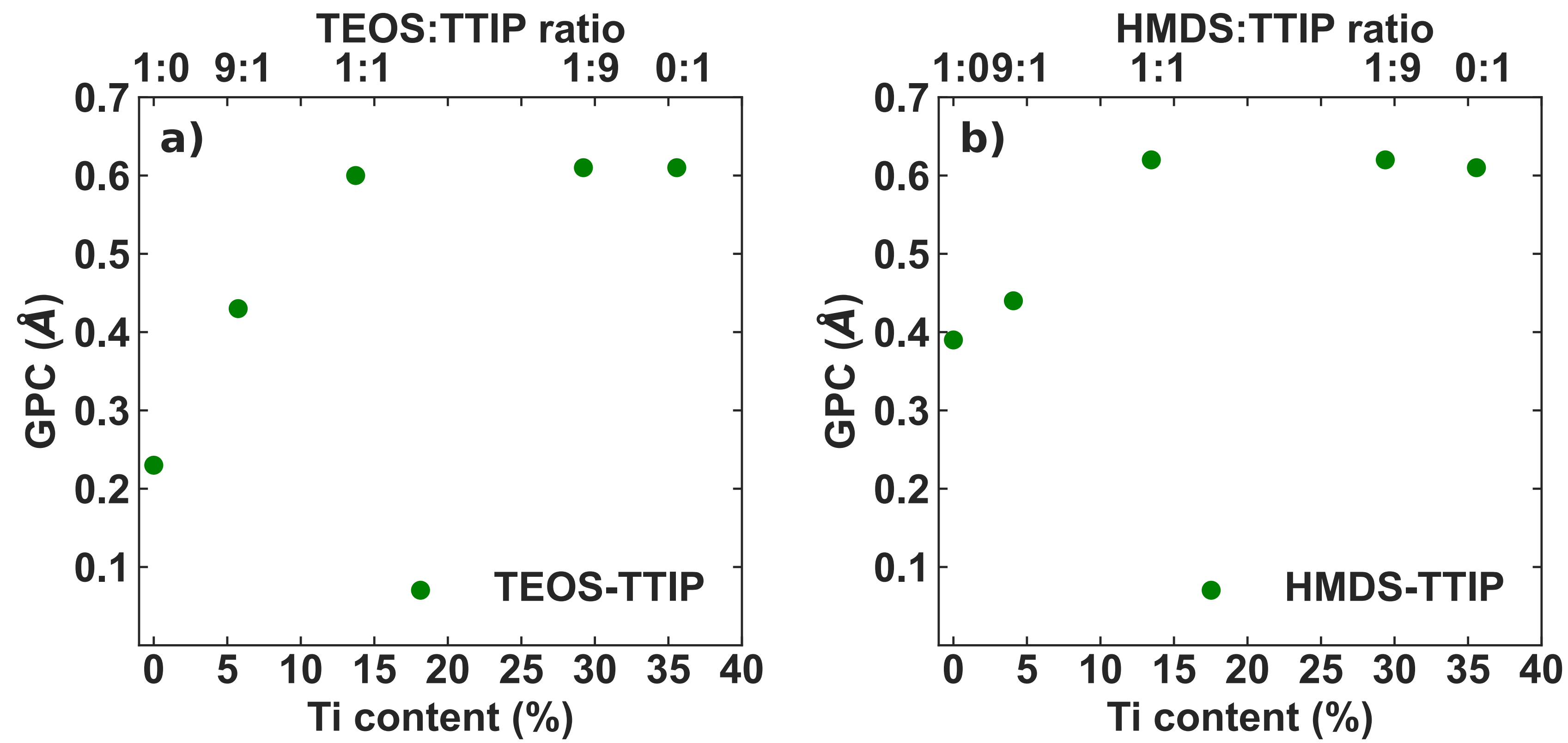

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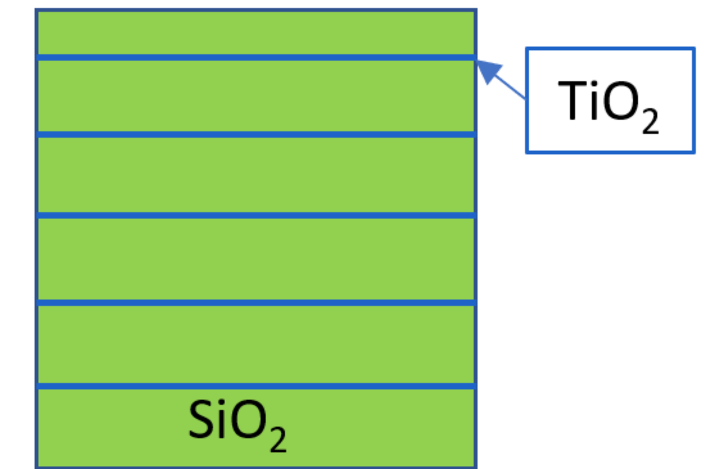
ALD allows for "delta doping", where delta layers of the doping material are inserted



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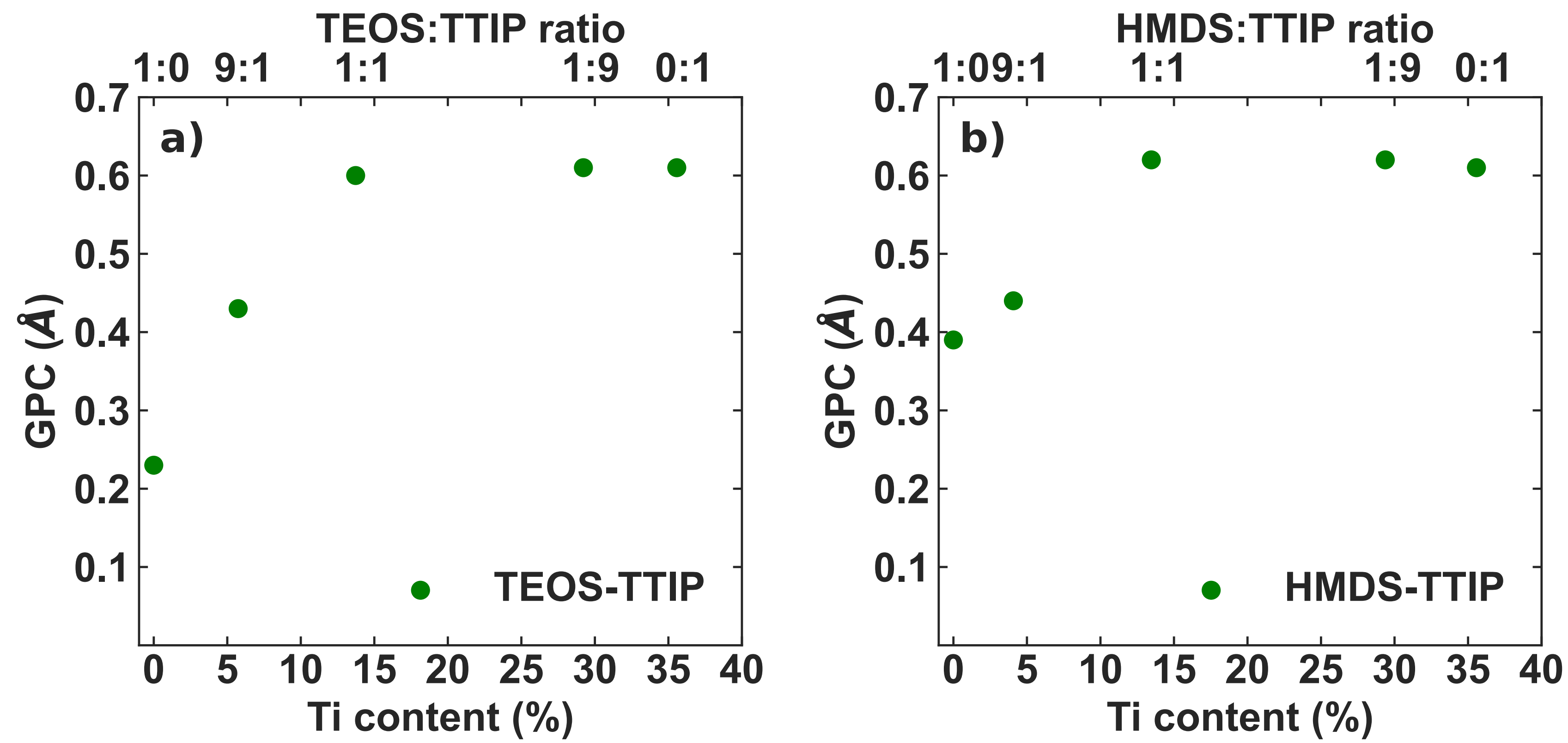
Growth of SiO_2

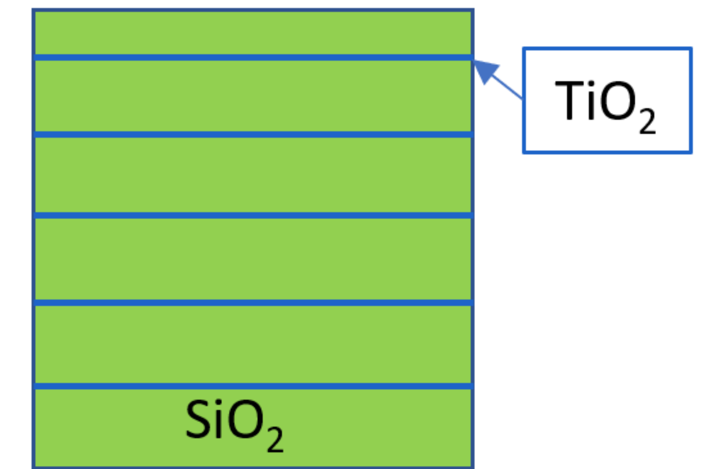
SiO_2 grows faster when TiO_2 is added

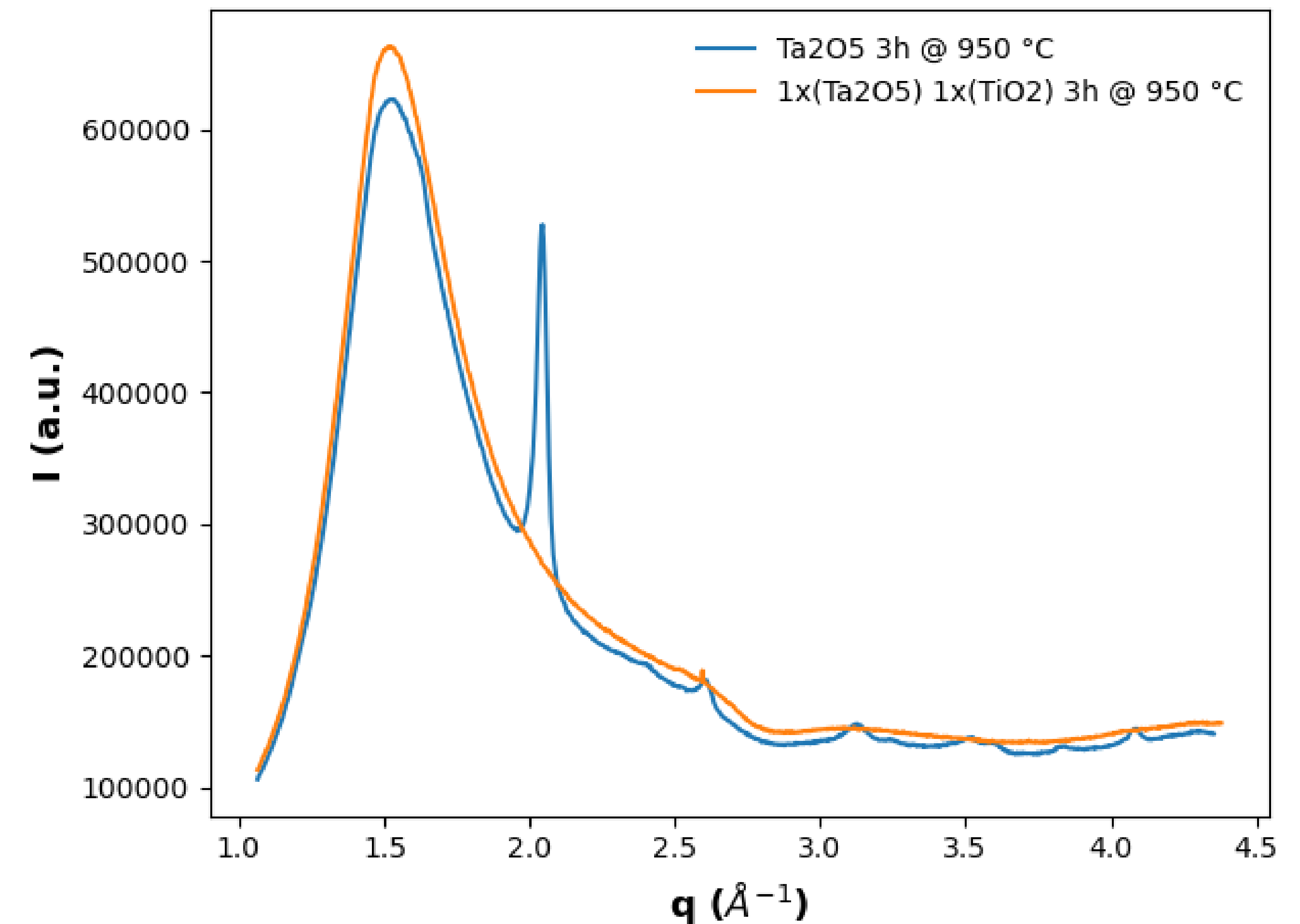


Titania Mixed with Silica: A Low Thermal-Noise Coating Material for Gravitational-Wave Detectors

Graeme I. McGhee,[1] Viola Spagnuolo,[2,3] Nicholas Demos,[4] Simon C. Tait,[1] Peter G. Murray,[1] Martin Chicoine,[5] Paul Dabadie,[6] Slawek Gras,[4] Jim Hough,[1] Guido Alex Iandolo,[2,3] Ross Johnston,[1] Valérie Martinez,[6] Oli Patane,[7] Sheila Rowan,[1] François Schiettekatte,[5] Joshua R. Smith,[8] Lukas Terkowski,[9] Liyuan Zhang,[10] Matthew Evans,[4] Iain W. Martin,[1] and Jessica Steinlechner[1,2,3,*]

ALD allows for “delta doping”, where delta layers of the doping material are inserted





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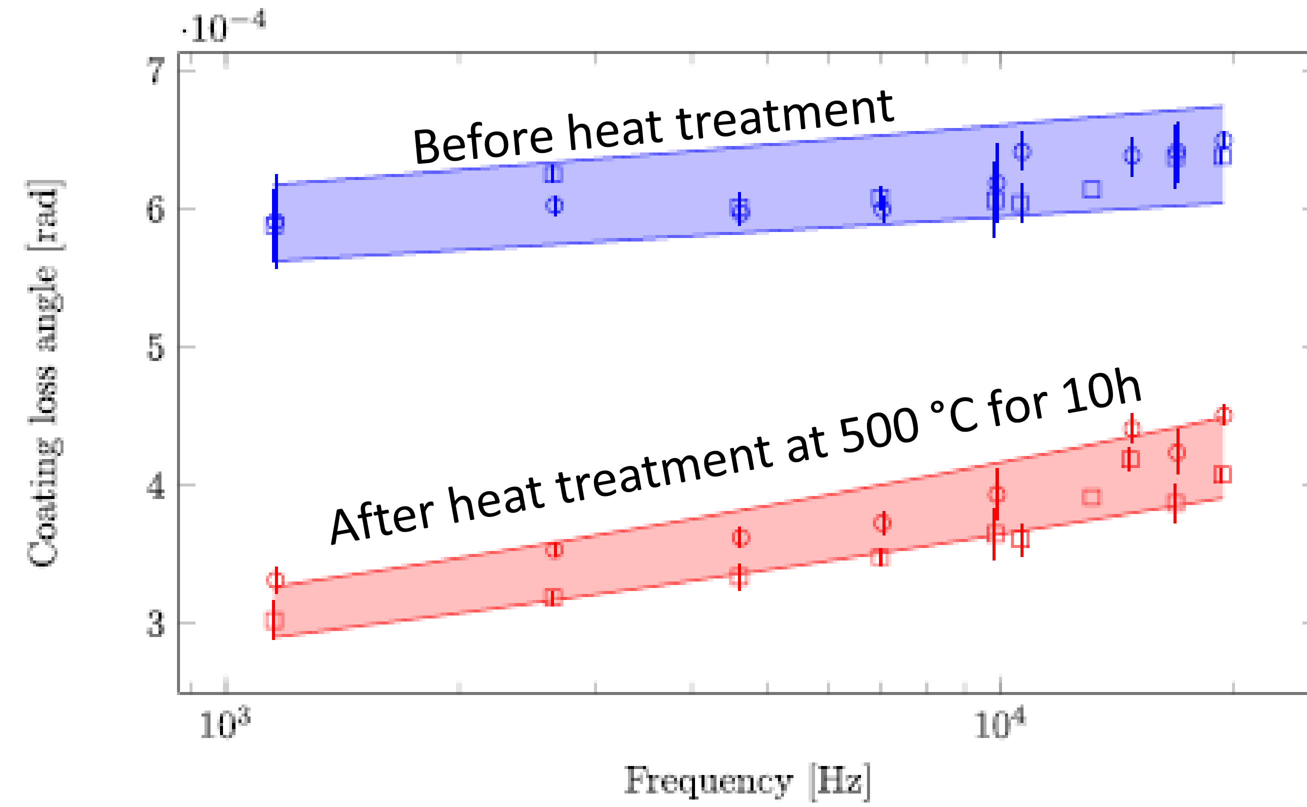
G. I. McGhee et al. *Phys. Rev. Lett., no.* **131**, p. 171401, 2023

Structural characterisation

Why structure is important



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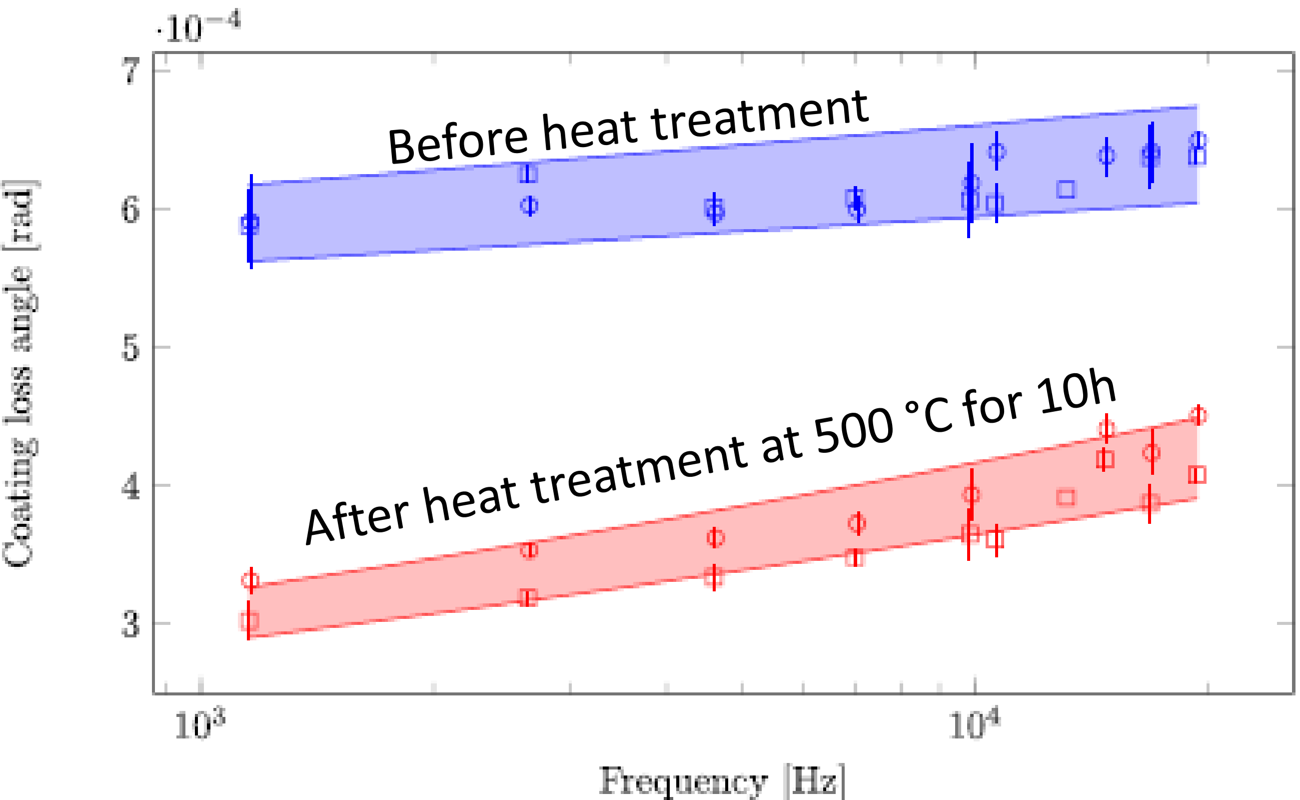
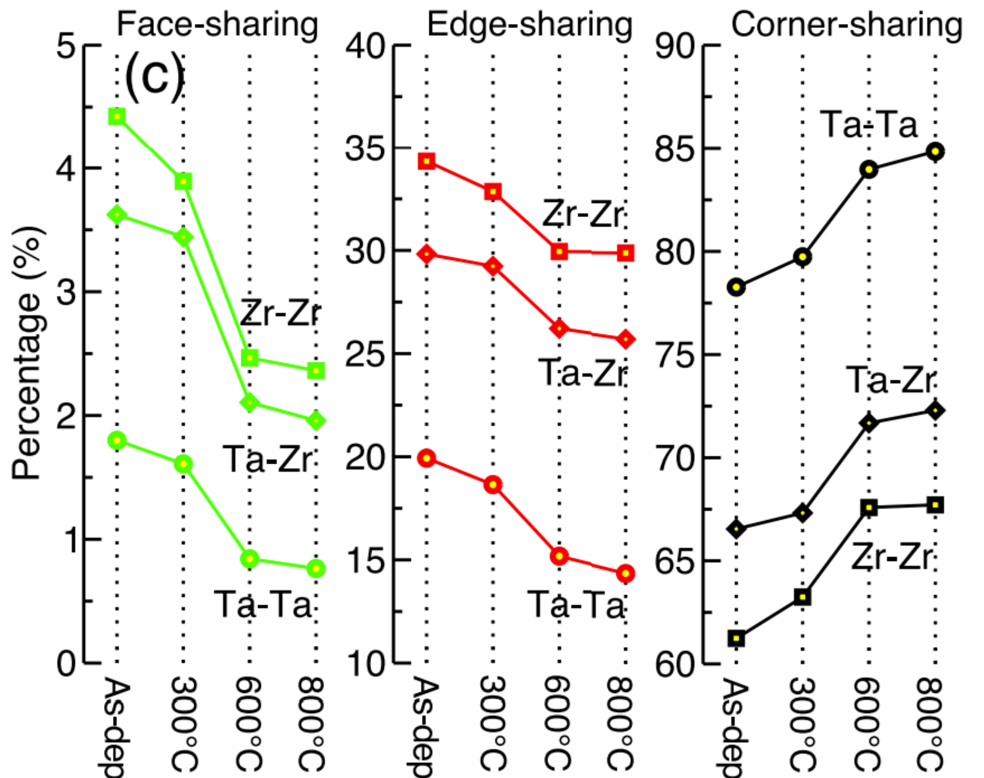
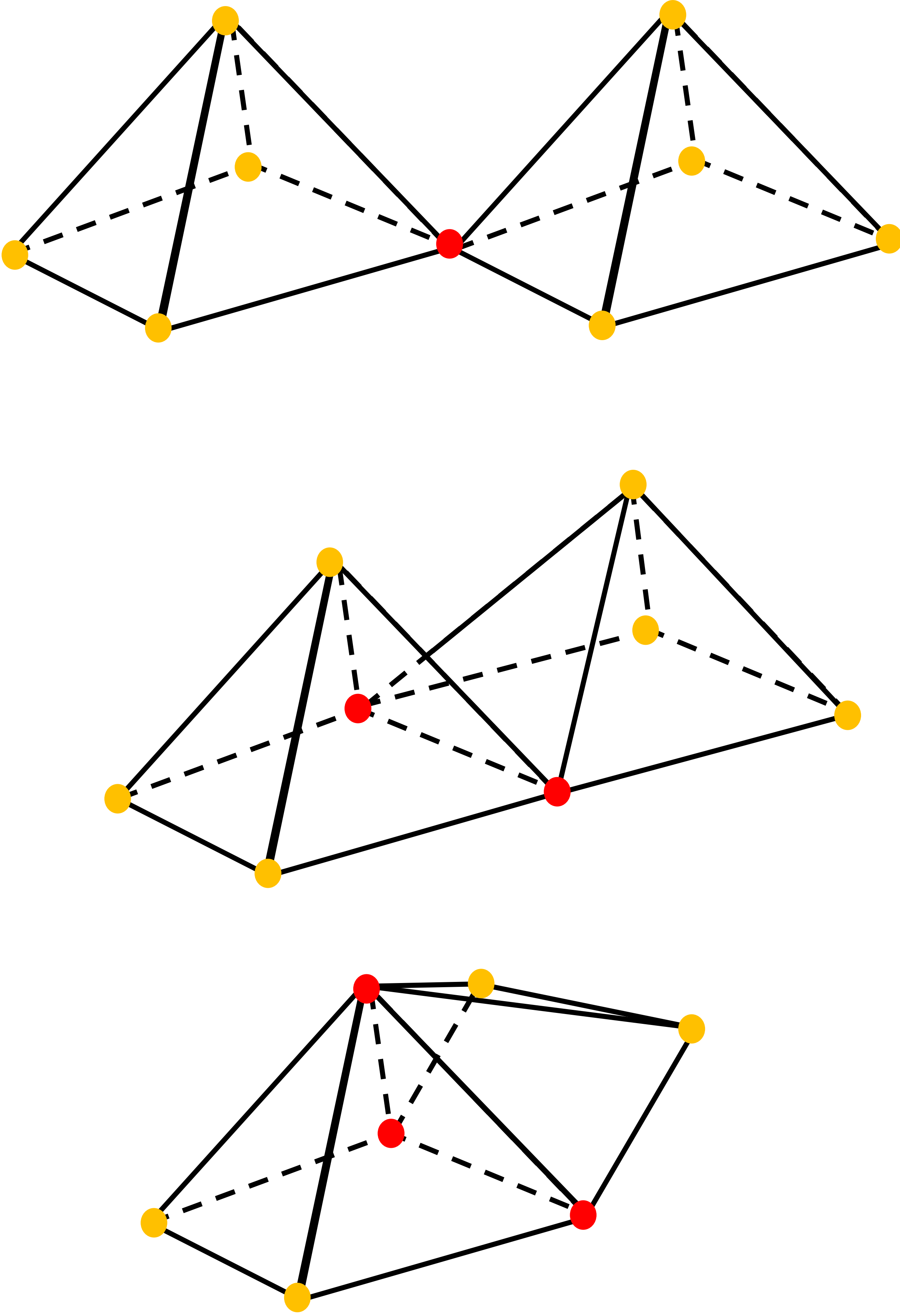
M. Granata et al. Class. Quantum Grav. 37 095004, 2020
K. Prasai et al. *Phys. Rev. Lett*. 123, 045501, 2019

Why structure is important







Corner sharing

Edge sharing

Face sharing

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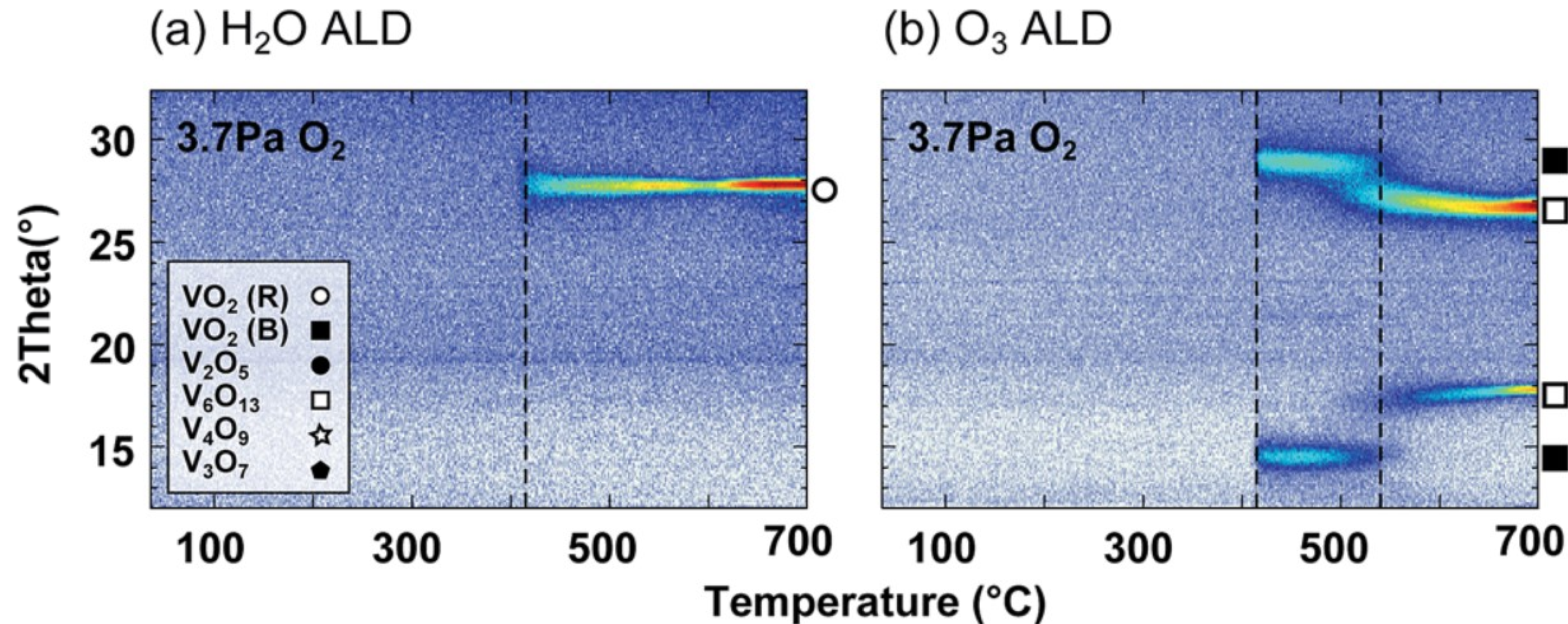
M. Granata et al. Class. Quantum Grav. 37 095004, 2020
K. Prasai et al. *Phys. Rev. Lett*. 123, 045501, 2019

Why structure is important

ALD of VO_2 (TEMAV + H_2O/O_3)



- Amorphous VO_2 shows different crystallisation behaviour when deposited with different ALD processes
- Hints at differences in amorphous phase

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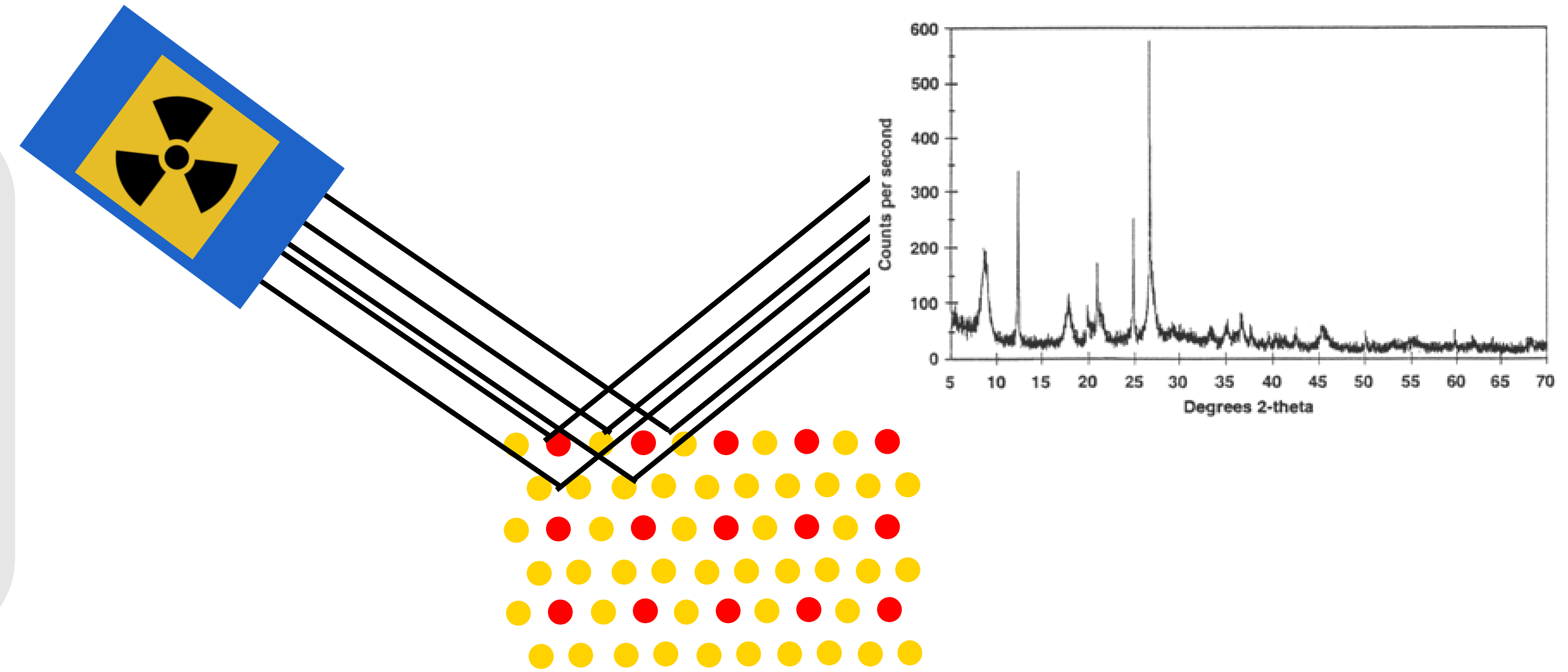
F. Mattelaer et al. *RSC Adv.*, 6, 114658-114665, 2016

Measuring structure

- For crystalline materials: XRD
  - Measure Bragg scattering
  - Determine lattice parameters very accurately
  - Measures coherence lengths
  - → Probes the average structure



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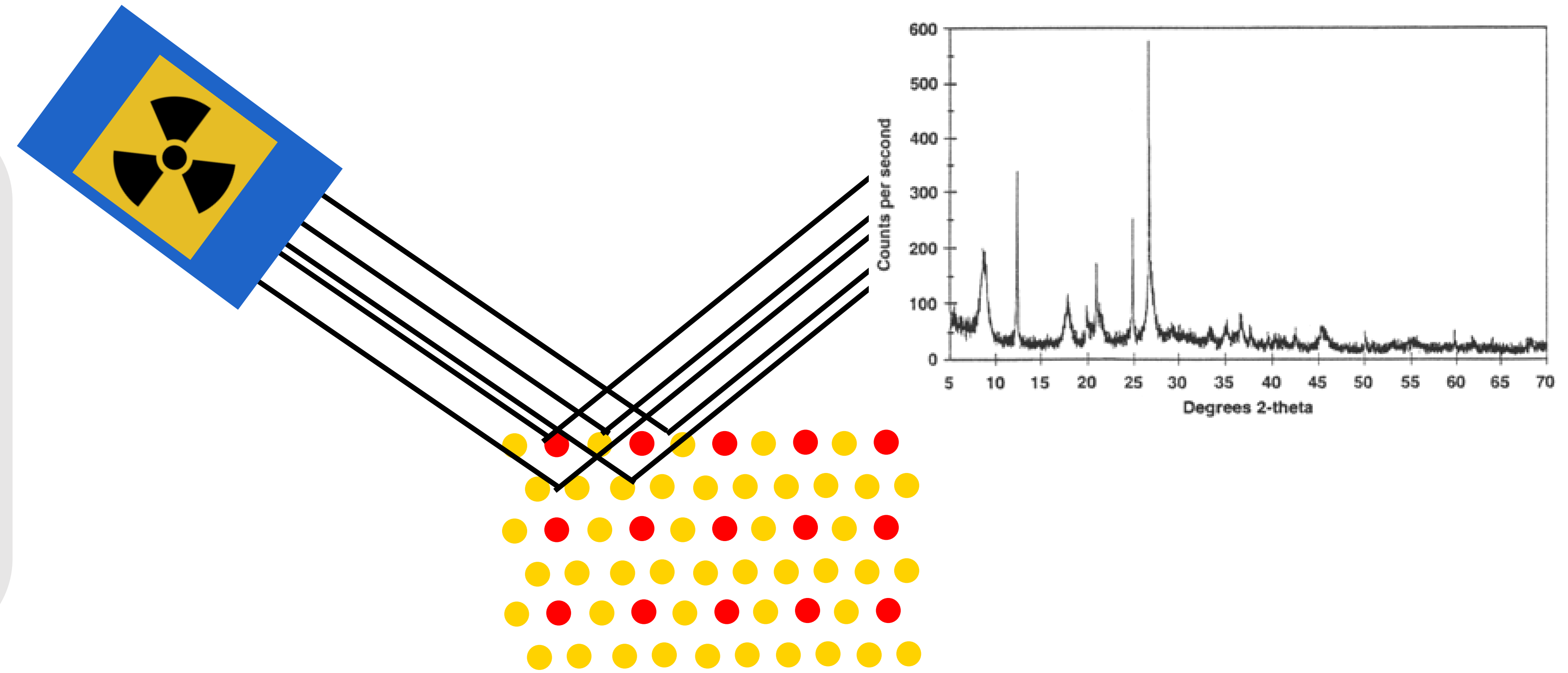

Measuring structure

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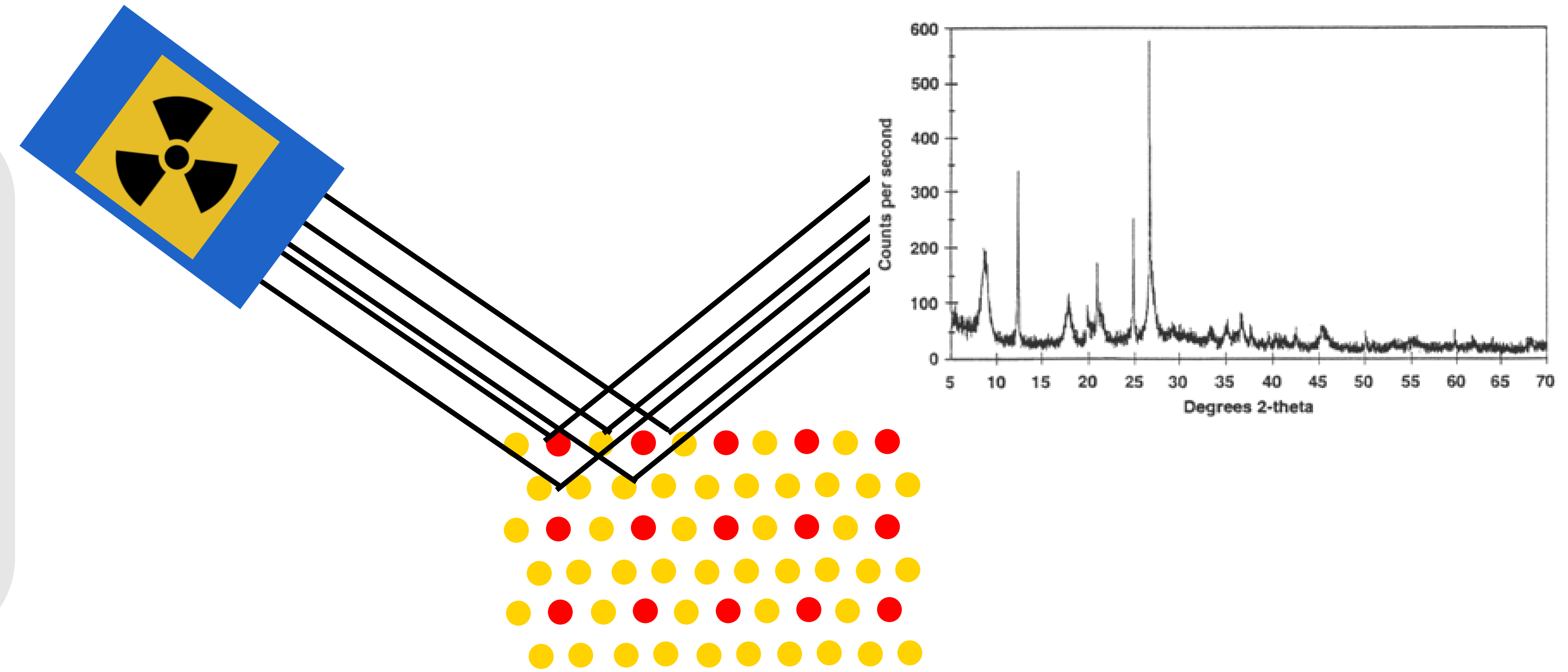

- For amorphous materials:
  - No long range coherence

  → Need to probe local structure

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Measuring structure

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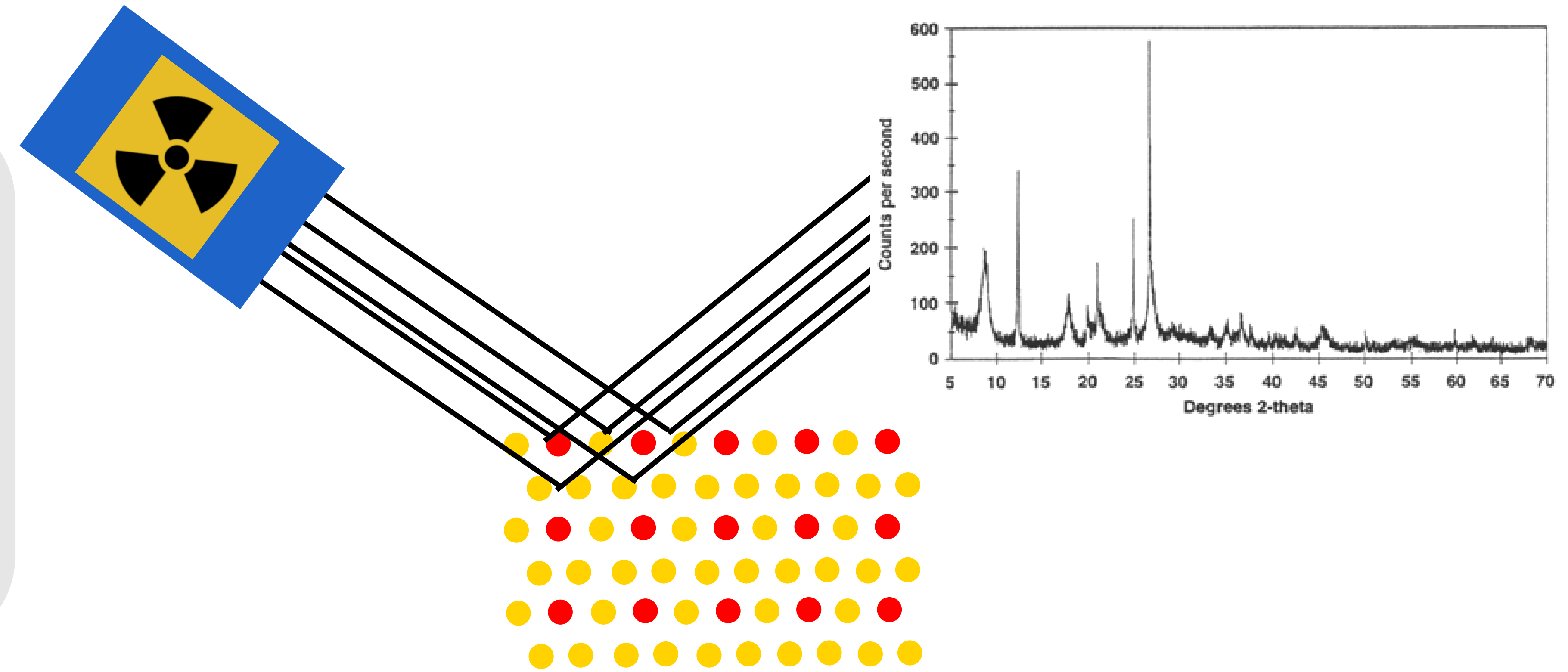
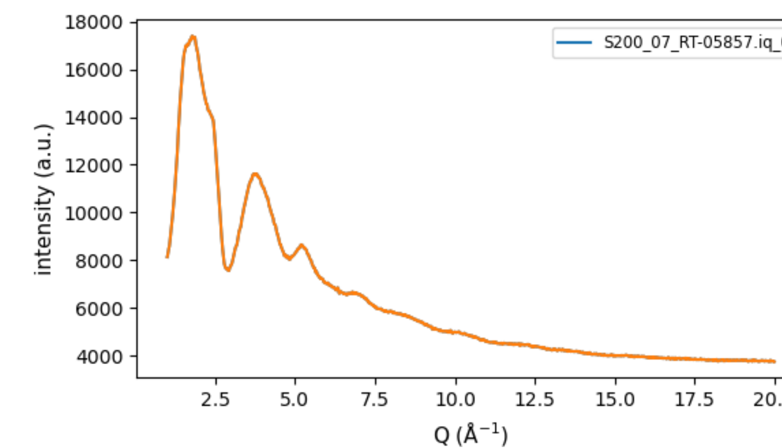
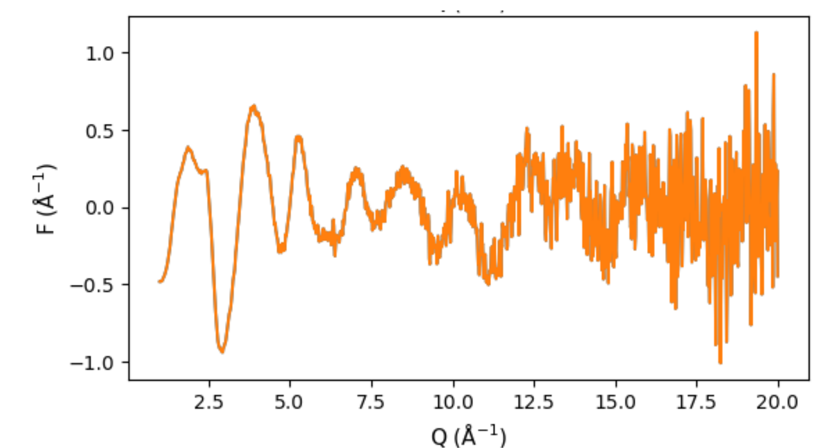


- For amorphous materials:
  - No long range coherence
  - → Need to probe local structure
  - Measure all scattering (also diffuse scattering)
  - Measure high Q-region with good statistics
  - → Synchrotron based experiments





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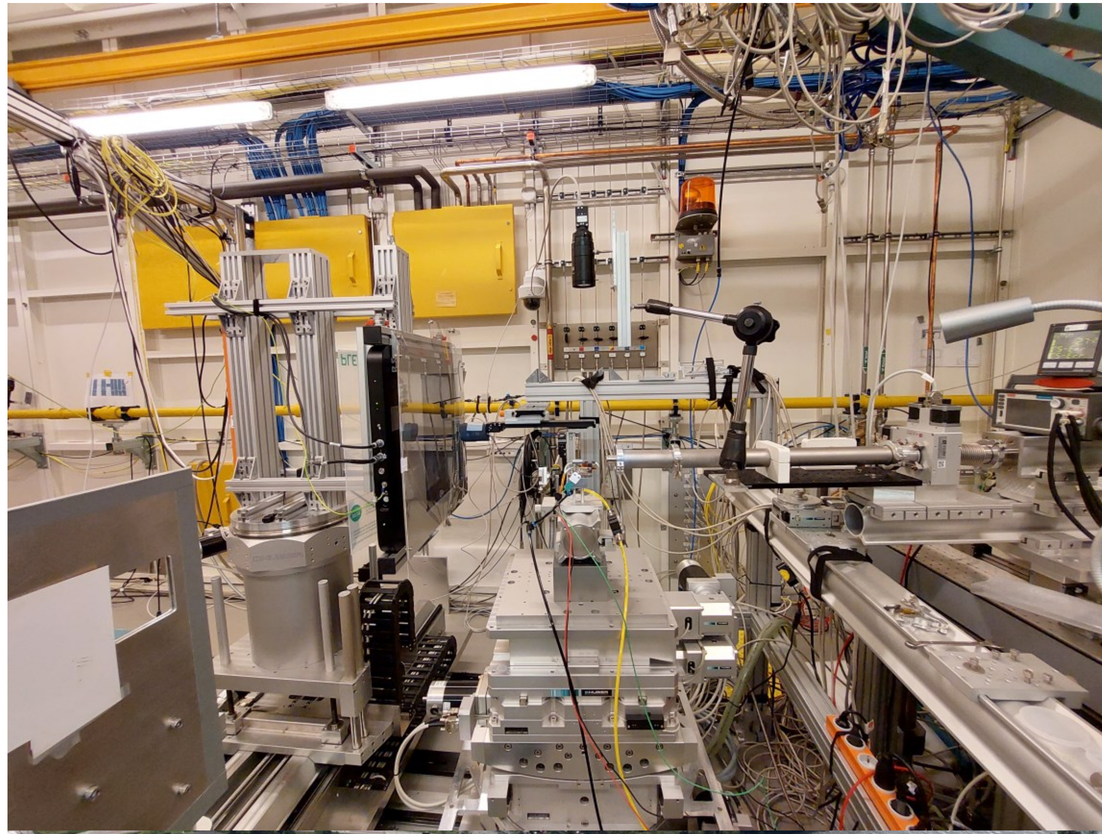
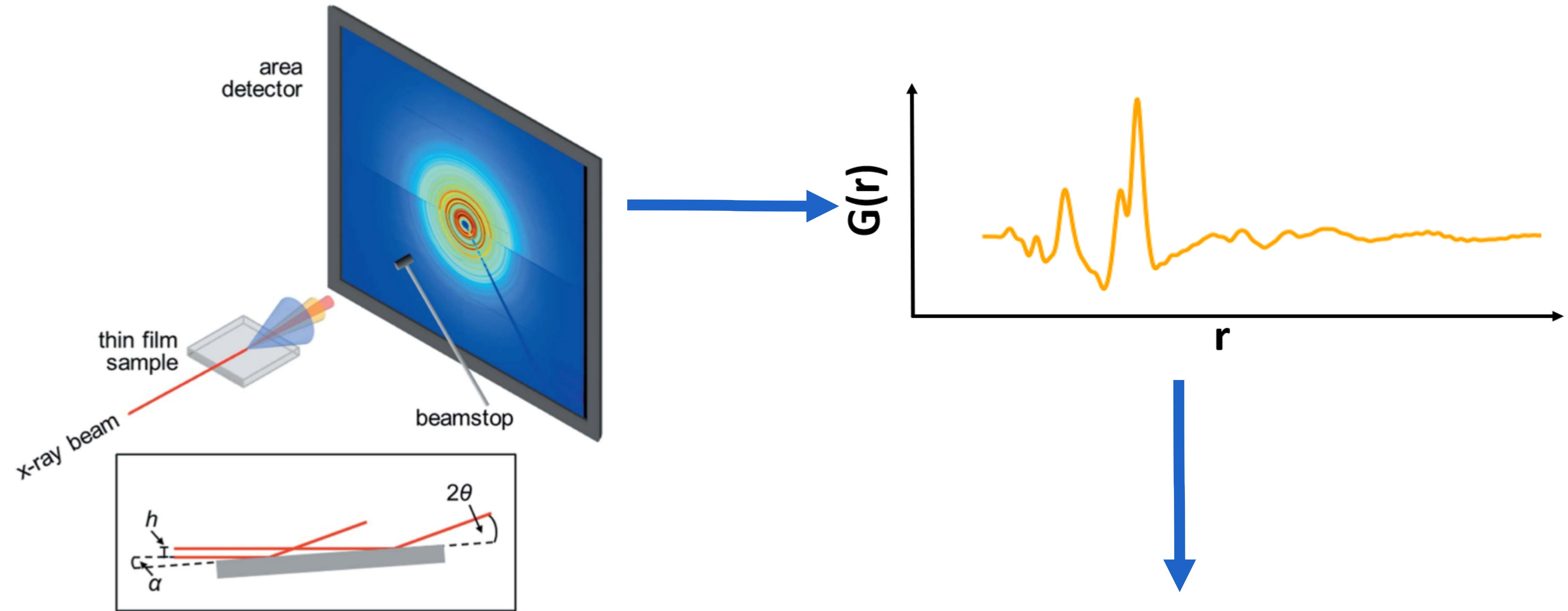
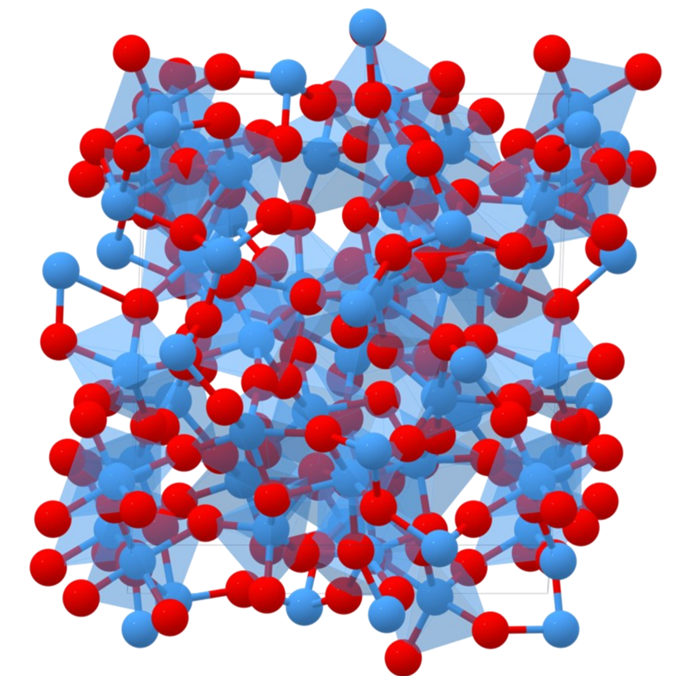
Total scattering experiments



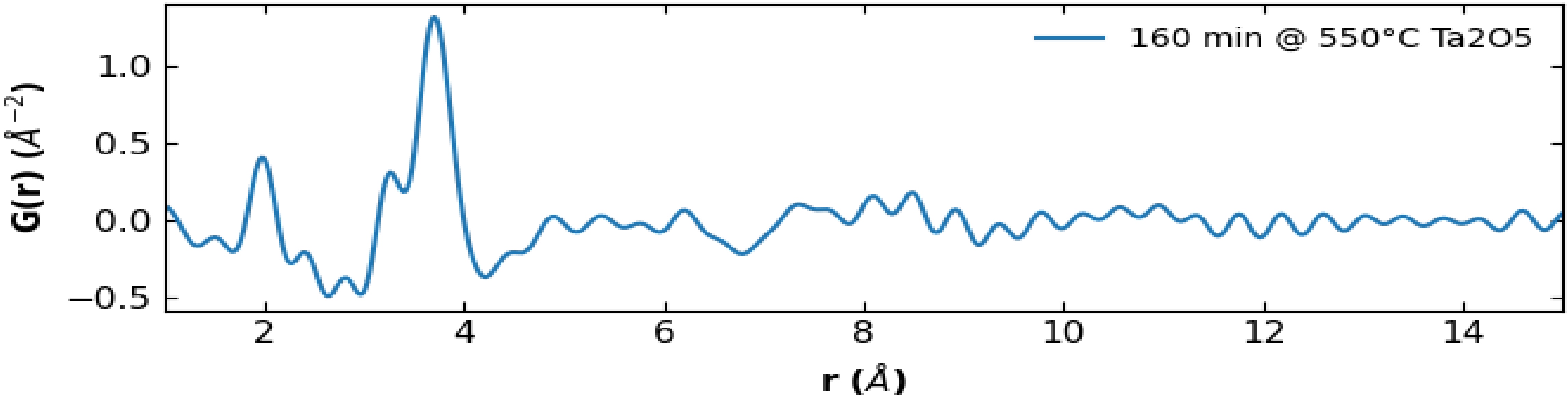




Goal: identifying the fundamental link between deposition conditions, atomic structure and performance of the coatings

A.-C. Dippel et al. IUCrJ, no. 6.2, 2019
The Materials Project website. https://next-gen.materialsproject.org/materials/mp-1245285
The ESRF website. https://www.esrf.fr

PDF of Ta_2O_5



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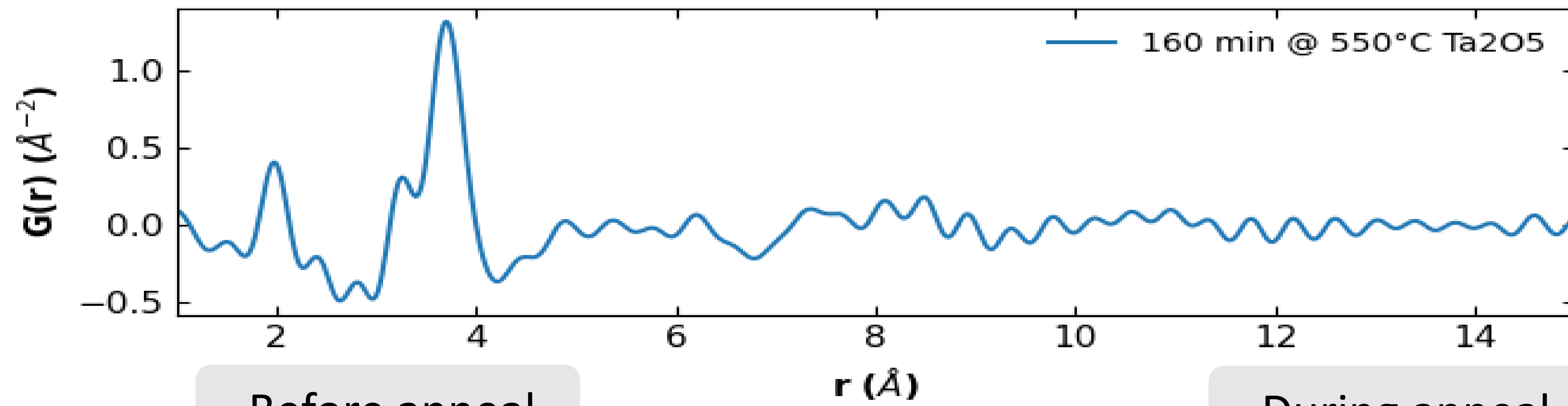
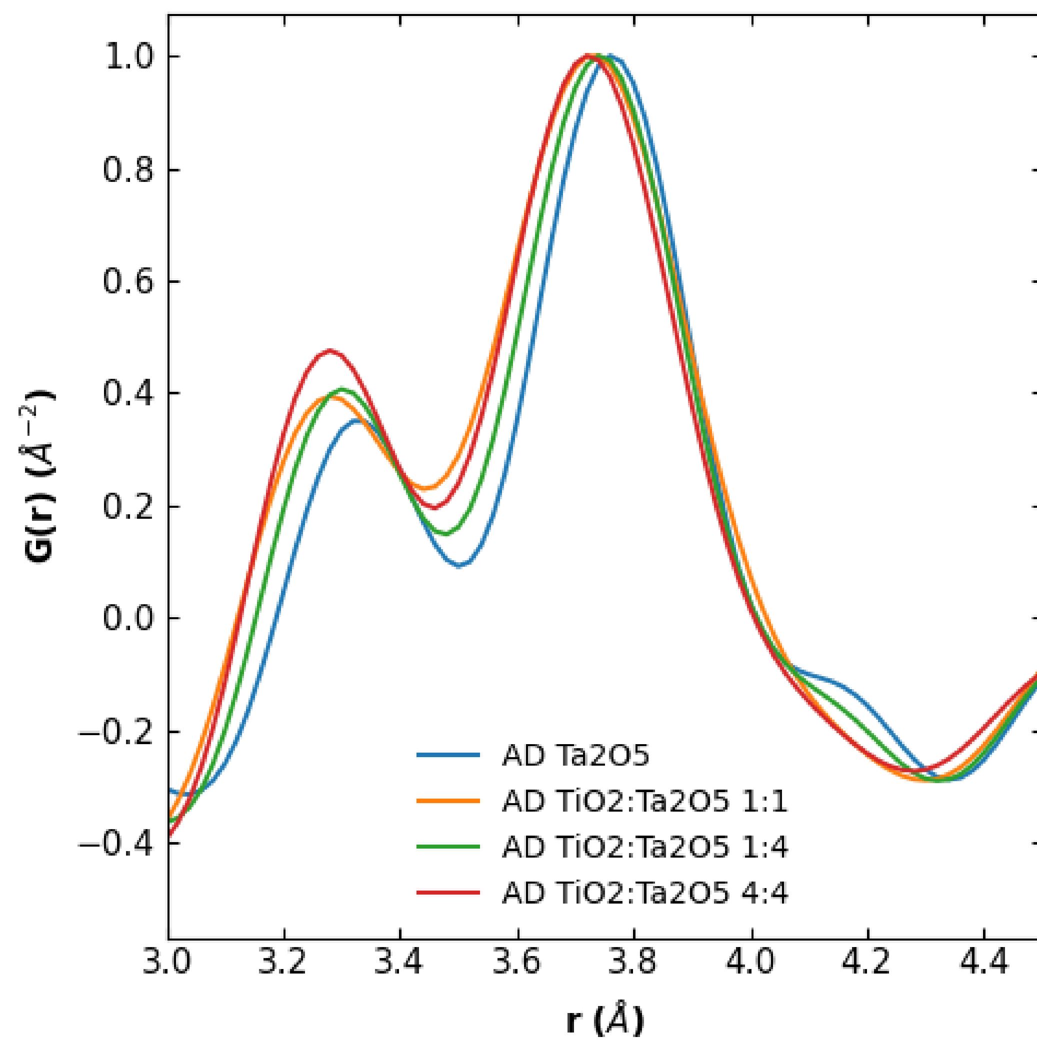
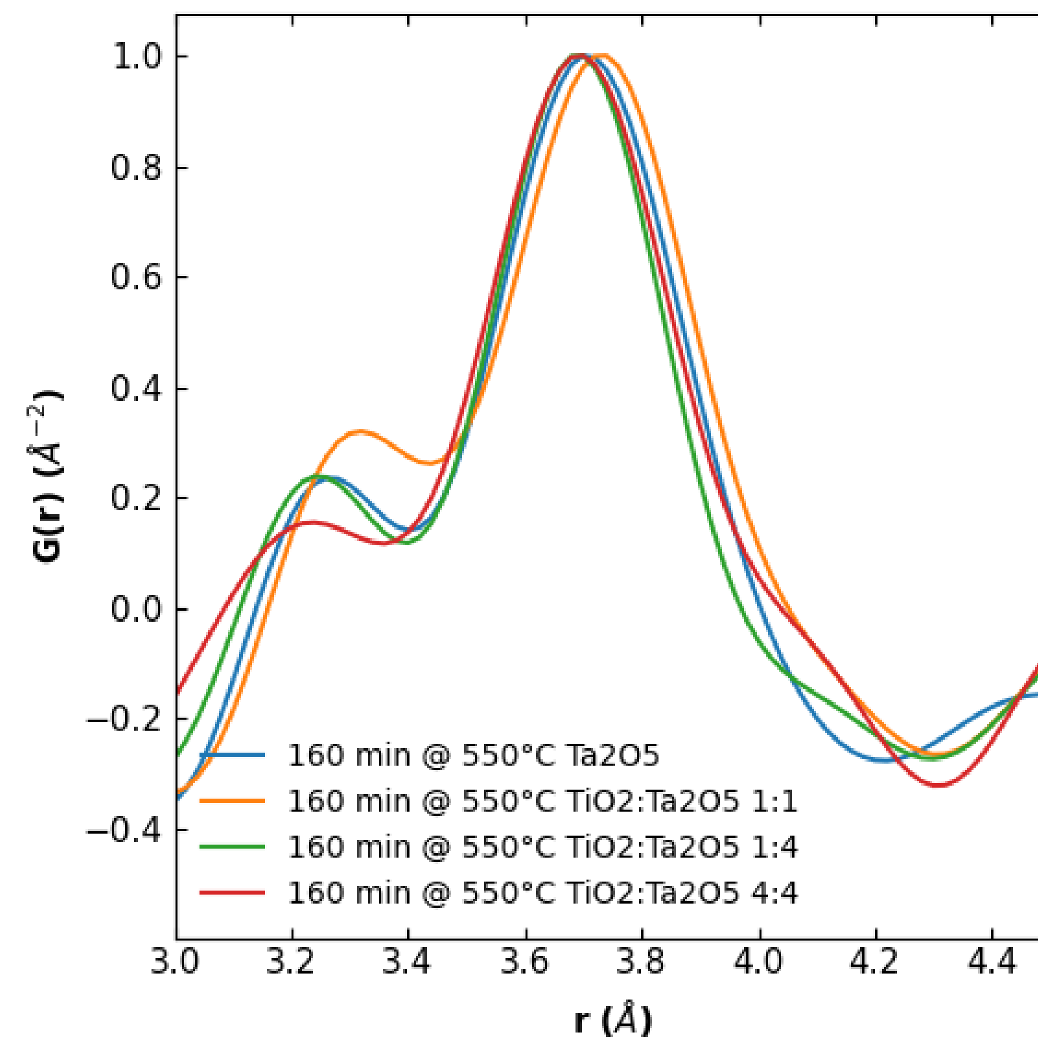


Before anneal

During anneal





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Thank you for your attention

Any questions?

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