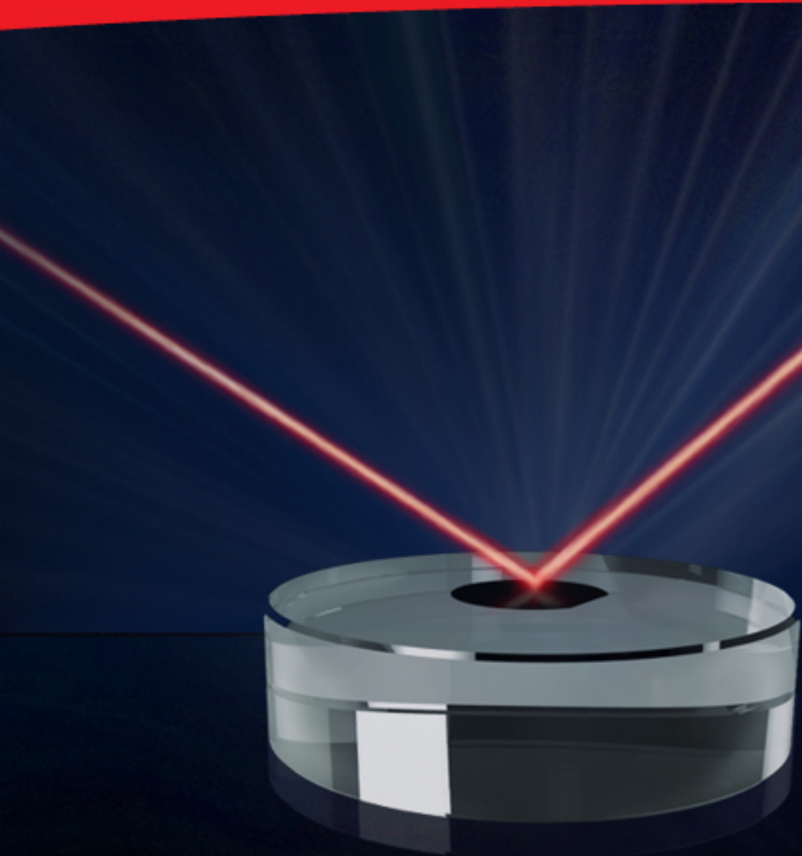

Crystalline Coatings

a new paradigm in optical coating technology

Markus Aspelmeyer
Vienna Center for Quantum Science (VCQ)
Faculty of Physics, University of Vienna, Austria
Crystalline Mirror Solutions GmbH & LLC

CMS
Redefining precision laser optics

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Outline

- Introduction to CMS
- NIR noise- and optical performance
  - demonstration of sub-ppm absorption and <5 ppm scatter
  - demonstration of ultra-low coating thermal noise
- MIR optical performance (> 2μm)
  - demonstration of sub-100ppm absorption losses @ 4mm
  - potential for significantly lower optical loss-levels
- Application Examples

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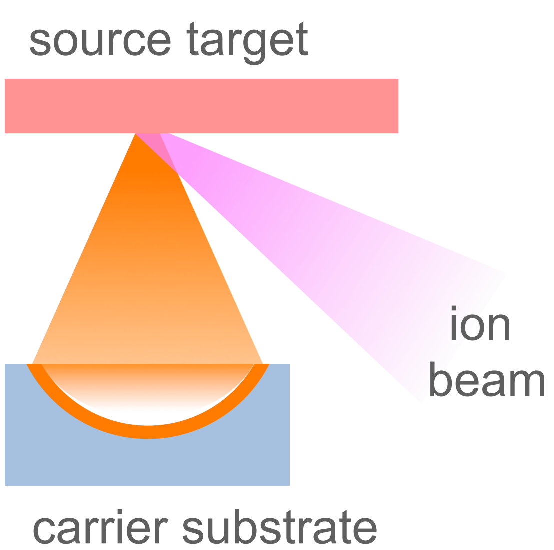
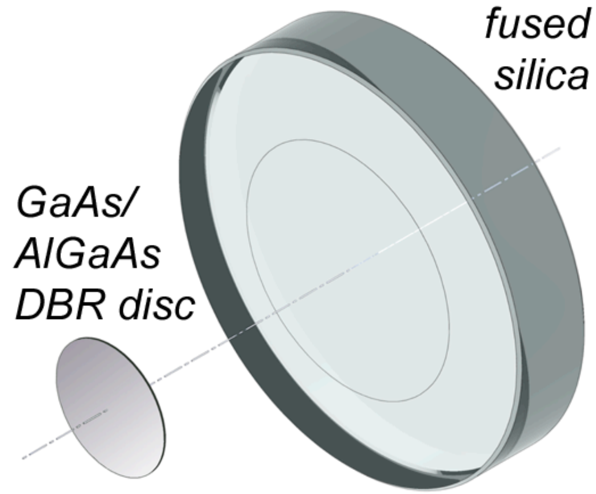
In a nutshell…

State-of-the-art technology –
sputtered dielectric mirrors



-30 years of in-market experience

New technology – substrate transferred crystalline coatings

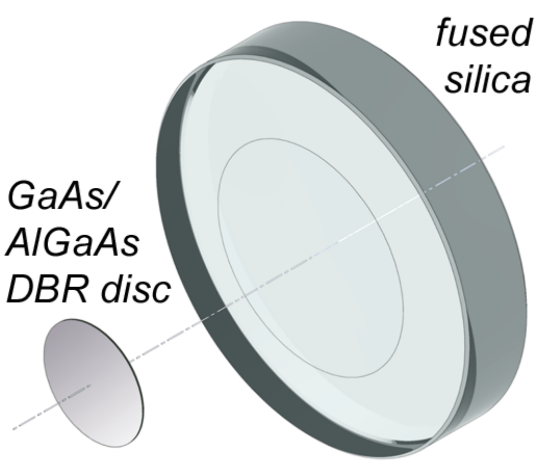


<3 years of in-market experience

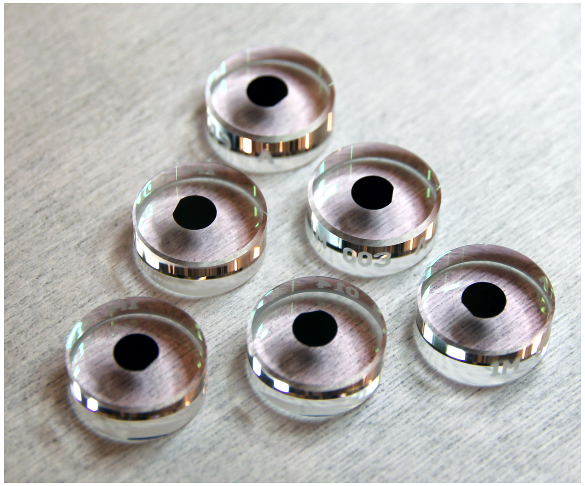
Crystalline Mirror Solutions…

… a spin-off of fundamental research from the University of Vienna

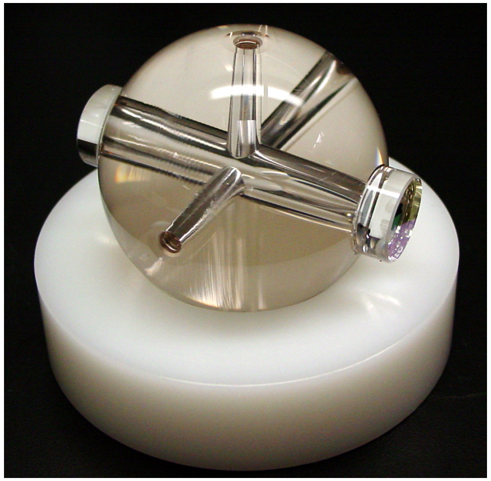
- We offer an entirely unique technology for precision laser optics
  - Applications span fundamental R&D + emerging industrial uses
    - cutting-edge research efforts in spectroscopy and metrology
    - advanced industrial applications in manufacturing and sensing



substrate-transferred single-crystal coatings



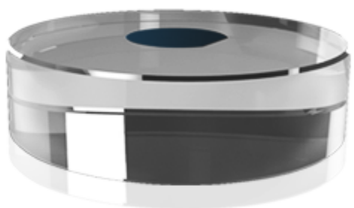
end mirrors for ultrastable cavities



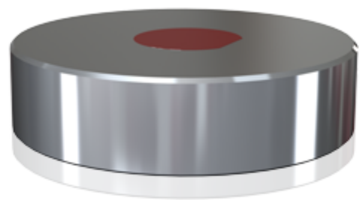
cavity employed for laser stabilization

Current Product Lines

CMS



xtal stable



xtal mir

xtal therm

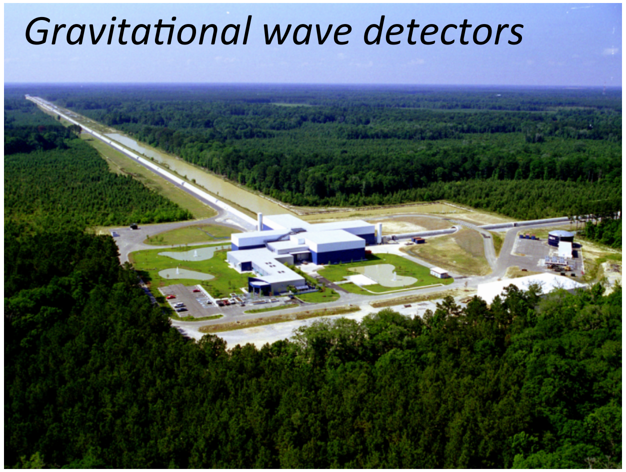
- We are offering **three distinct product lines** based on the <u>unique performance advantages of semiconductor crystalline coatings</u>

xtal stable: Ultralow Brownian noise for cavity-stabilized lasers used in optical metrology, laser ranging, and inertial navigation systems

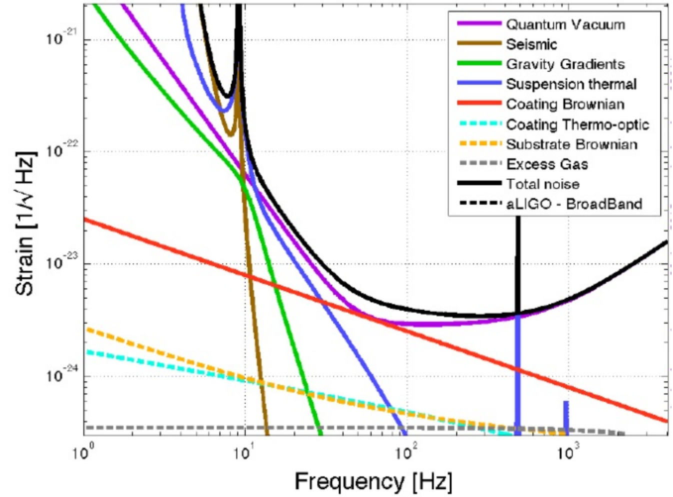
xtal mir: Low optical losses in the mid-IR (projected loss <100 ppm to ~5 µm and beyond) for spectroscopy / trace gas analysis

xtal therm: High thermal conductivity (50-100× greater than amorphous films) reflectors for high power (i.e. thin disk) lasers

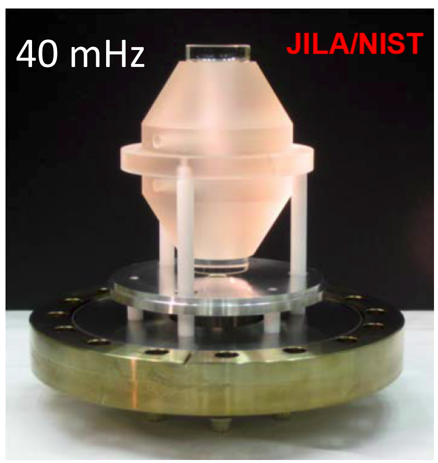

BREAKING NEWS – Jan 11 2016, 5pm CET
„We have detected a gravitational wave. It is from two black holes with masses in the 30 solar mass range and is a picture perfect fit to what Einstein predicts. „
CONGRATULATIONS LIGO!!
LIGO – Laser Interferometer Gravitational Wave Observatory

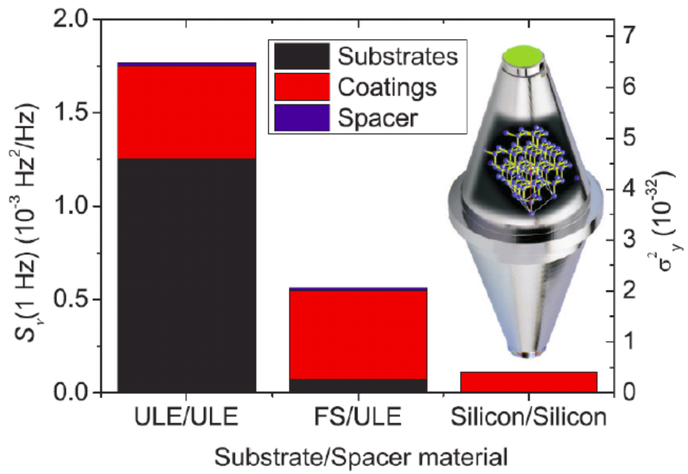


Advanced LIGO



Ultrastable lasers





Coating thermal noise

Optomechanics of optical coatings

Thermal noise of optical coatings: fundamental limit for laser frequency stabilization with cavities (atomic clocks, precision spectroscopy, gravitational wave detectors, …)

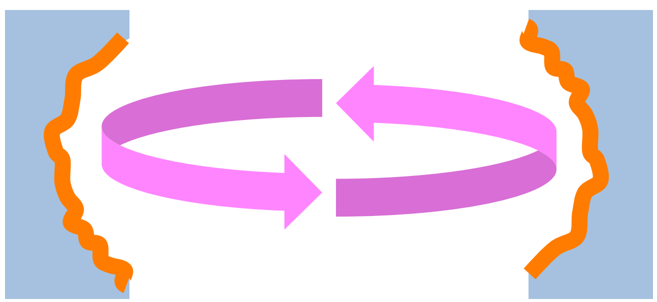
Penn et al., Class. Quant. Grav. 20, 2917 (2003)
Numata et al., PRL 93, 250602 (2004)
Notcutt et al., PRA 73, 31804 (2006)
Kessler et al., JOSA B 29, 117 (2012)
…

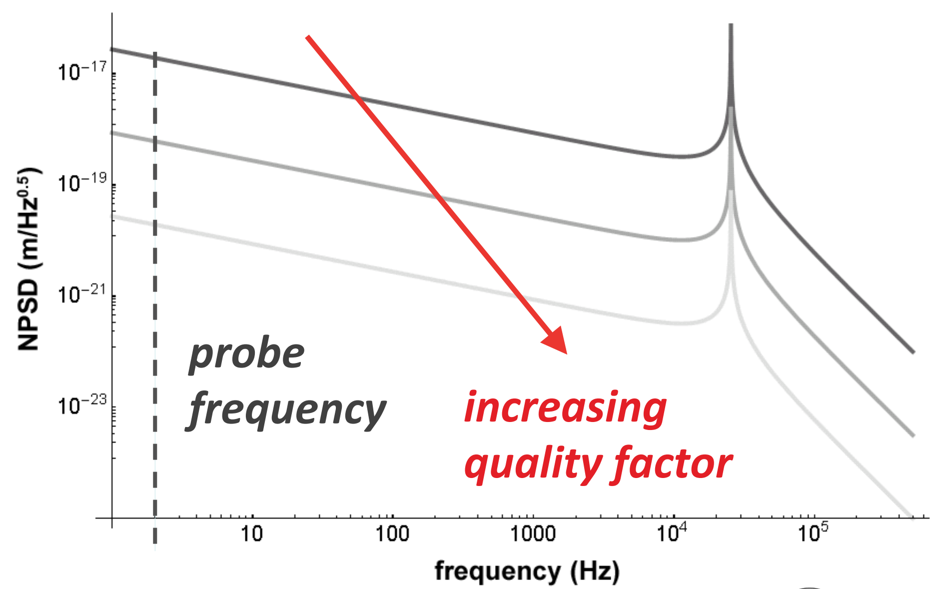
Fluctuation–Dissipation Theorem:

$$\left[\delta x(\omega) = \left(\frac{2 k_B T}{\pi m}\gamma\right)^{1/2} |\chi_{mech}|\right] \propto \sqrt{\gamma} = \sqrt{\frac{1}{Q}} =: \sqrt{\phi}$$

δx: Thermally driven displacement fluctuations → cavity phase noise

Φ: Loss angle





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CMS

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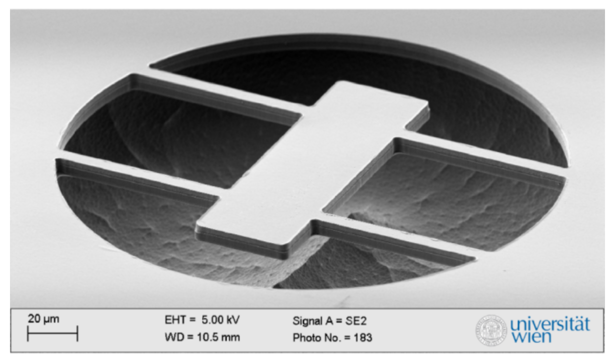
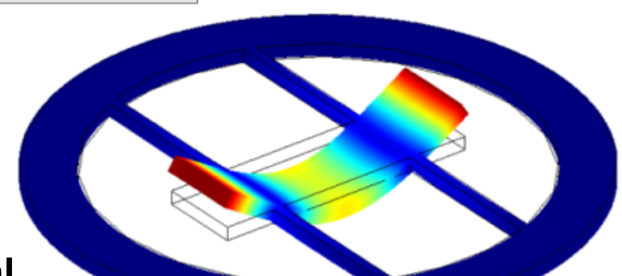
Monocrystalline optomechanics:
high optical AND mechanical quality
→ low coating thermal noise

AlGaAs crystalline coatings
Φ_{coat} ~ **2×10^{-5}** @ 300K
Φ_{coat} ~ **5×10^{-6} – 1×10^{-5}** @ 4K

vs.

SiO_2/Ta_2O_5 coatings
Φ_{coat} > 4×10^{-4} @ 300K





Cole et al., APL 92, 261108 (2008)
Cole, Wilson-Rae et al., Nature Comm. 2, 231 (2011)

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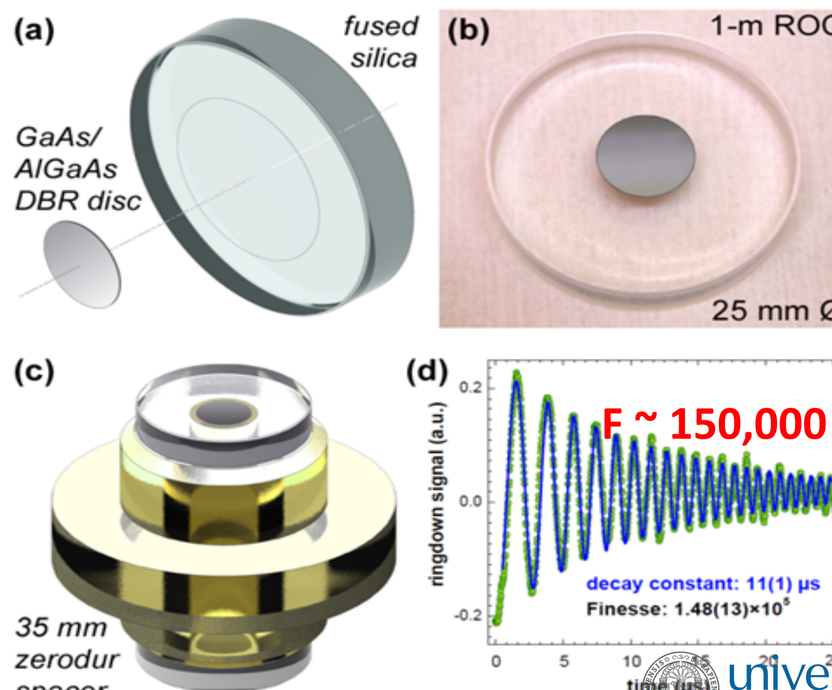

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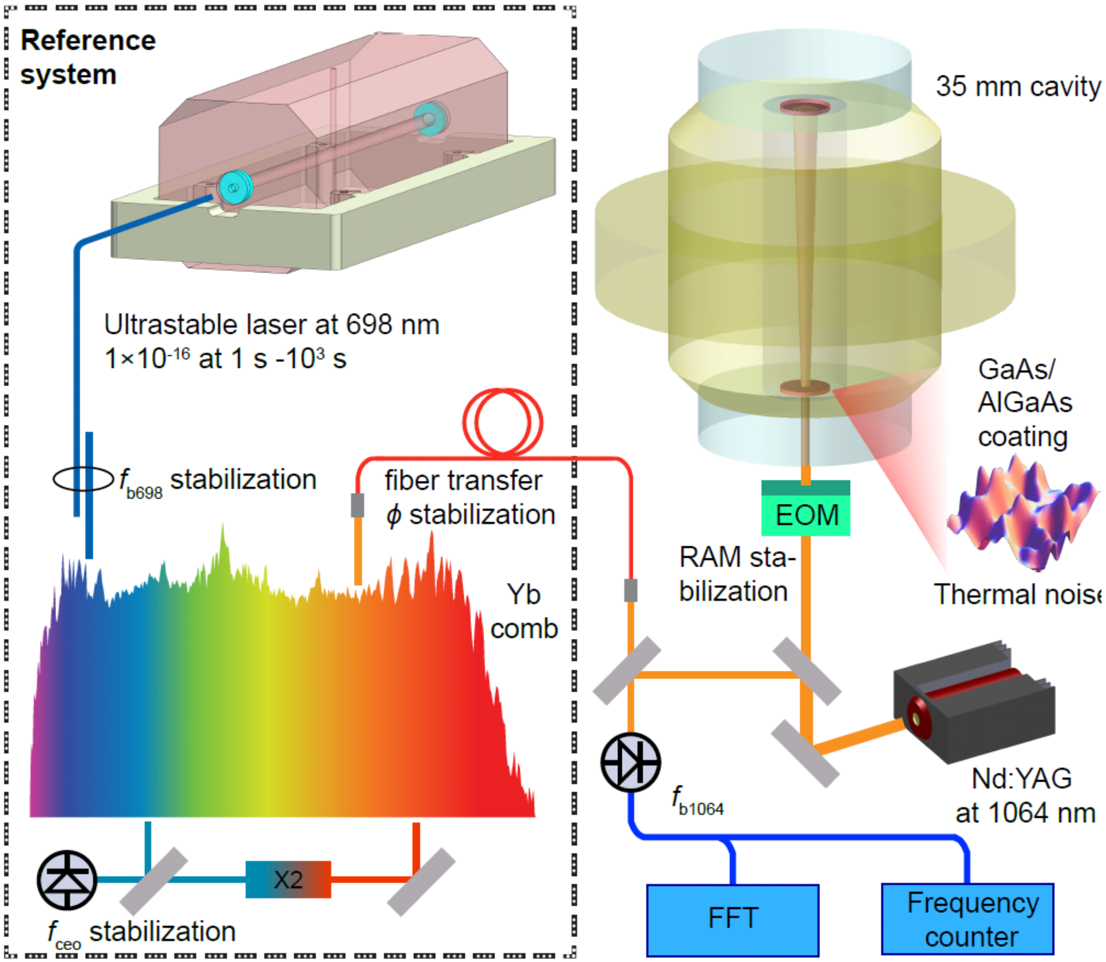
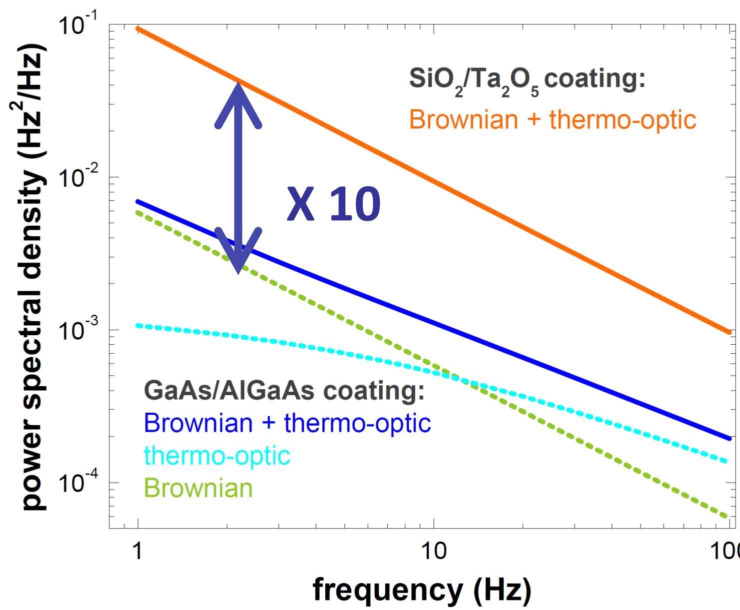
Optomechanics of optical coatings

aLIGO

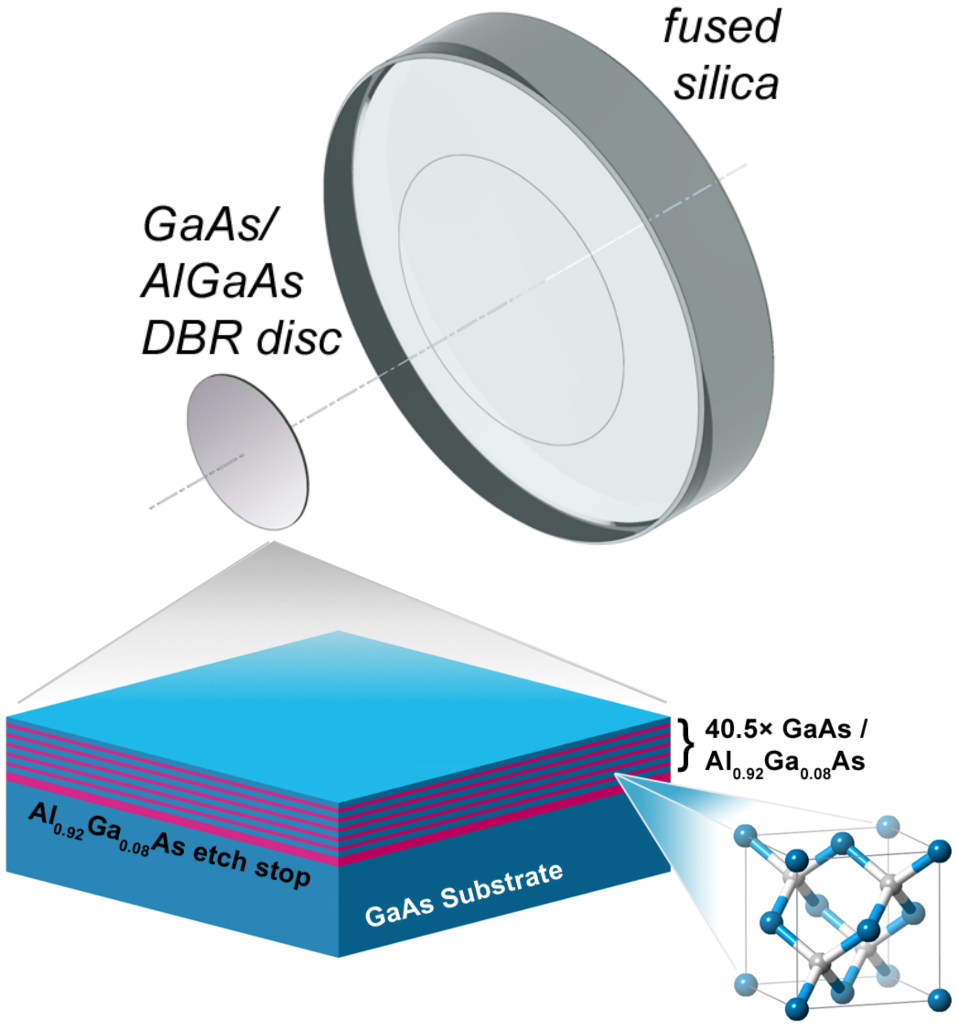




G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, *Nature Photonics* **7**, 644–650 (2013)

Epitaxial Coating Details

- AlGaAs multilayer with varying Al content for index contrast
  - high index layers consist of binary GaAs thin films
  - 8% Ga incorporated in low index AlGaAs layers to slow oxidation in ambient
- Potential for high reflectivity from ~900 nm → 5+ μm
  - peak performance in NIR
- High quality epitaxy requires a lattice matched substrate
  - same crystalline symmetry
  - minimal deviation of lattice parameter (atomic spacing)



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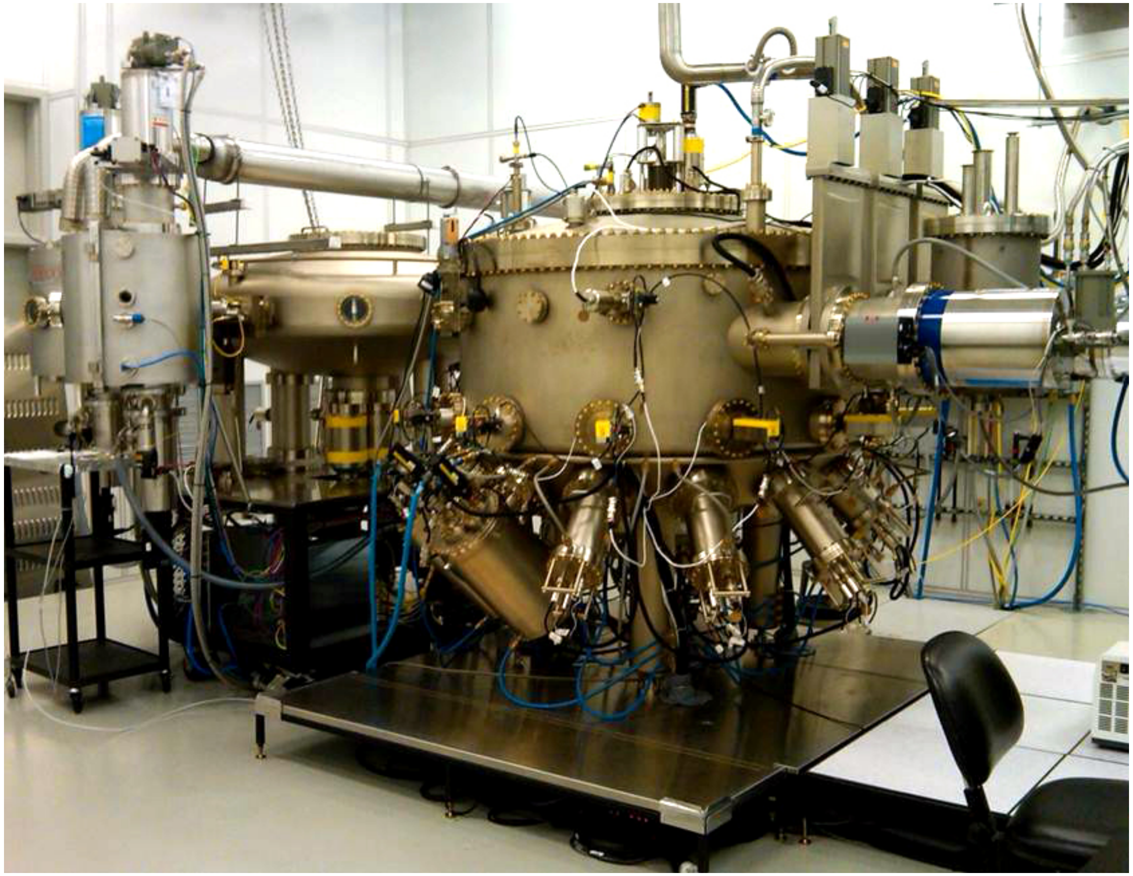
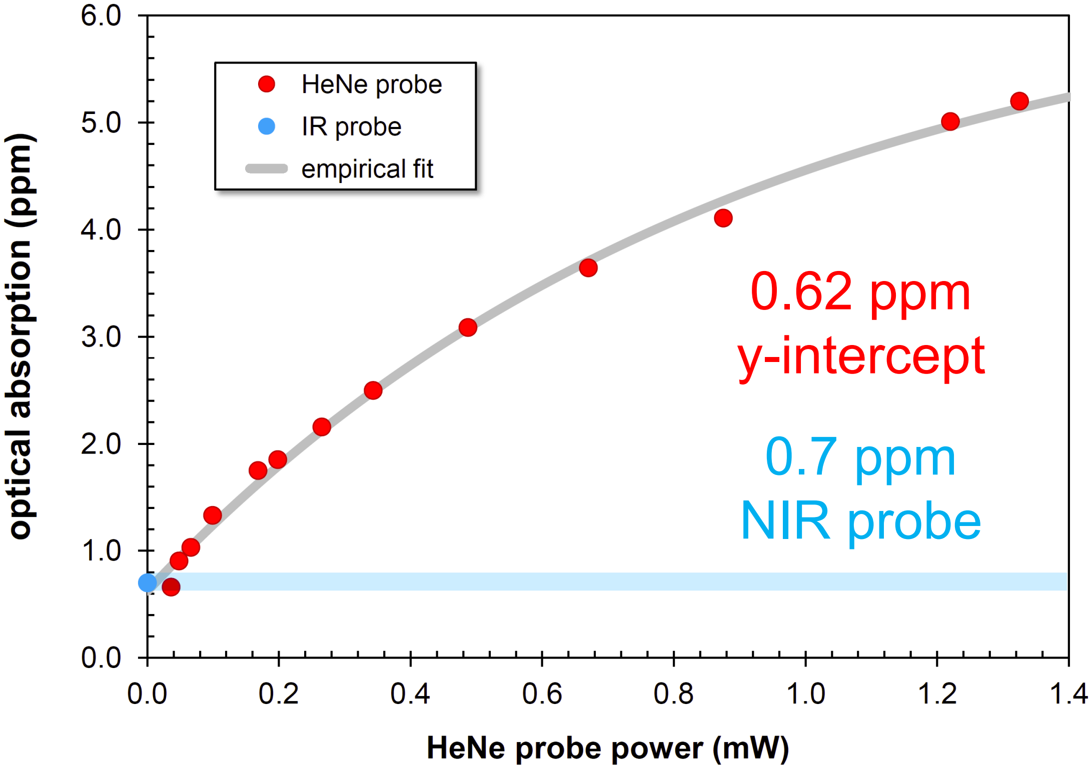
MBE Process Optimization



Since June 2016:
in-house MBE growth (tool operated on IBM Research campus in Zurich)

- Absorption study run with our epitaxial growth foundry
- Samples sent to SPTS, Pahoa, HI for absorption measurements

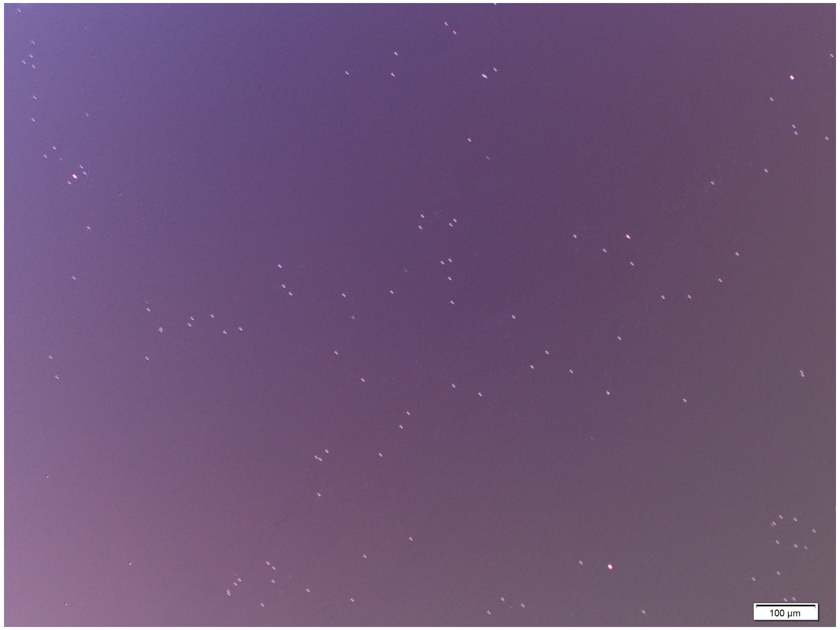
Sub-ppm NIR Absorption

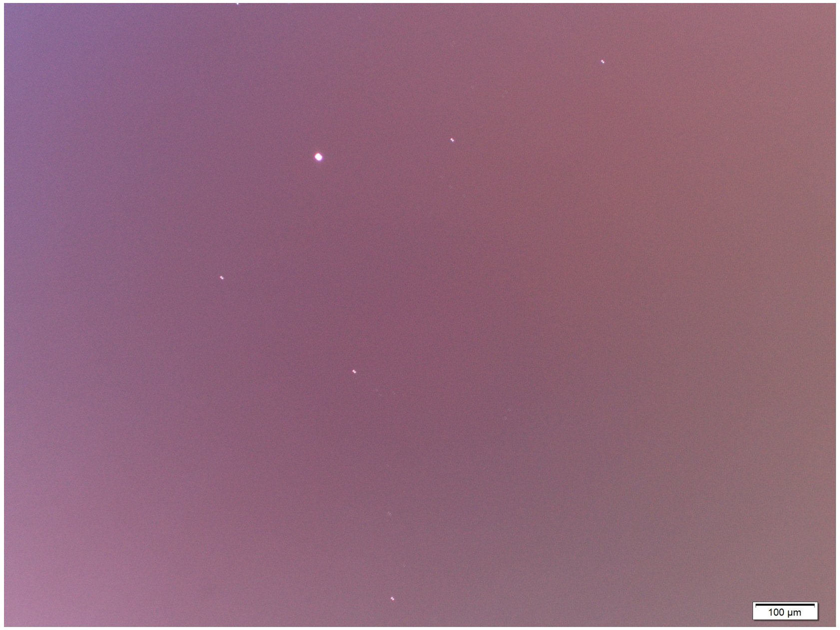


- Red HeNe probe in PCI system limits minimum absorption value
  - the use of a transparent near-IR probe is now being investigated
- Probe-power dependent measurements yield sub-ppm absorption

Measurements by Dr. Alexei Alexandrovski, SPTS Pahoa, HI

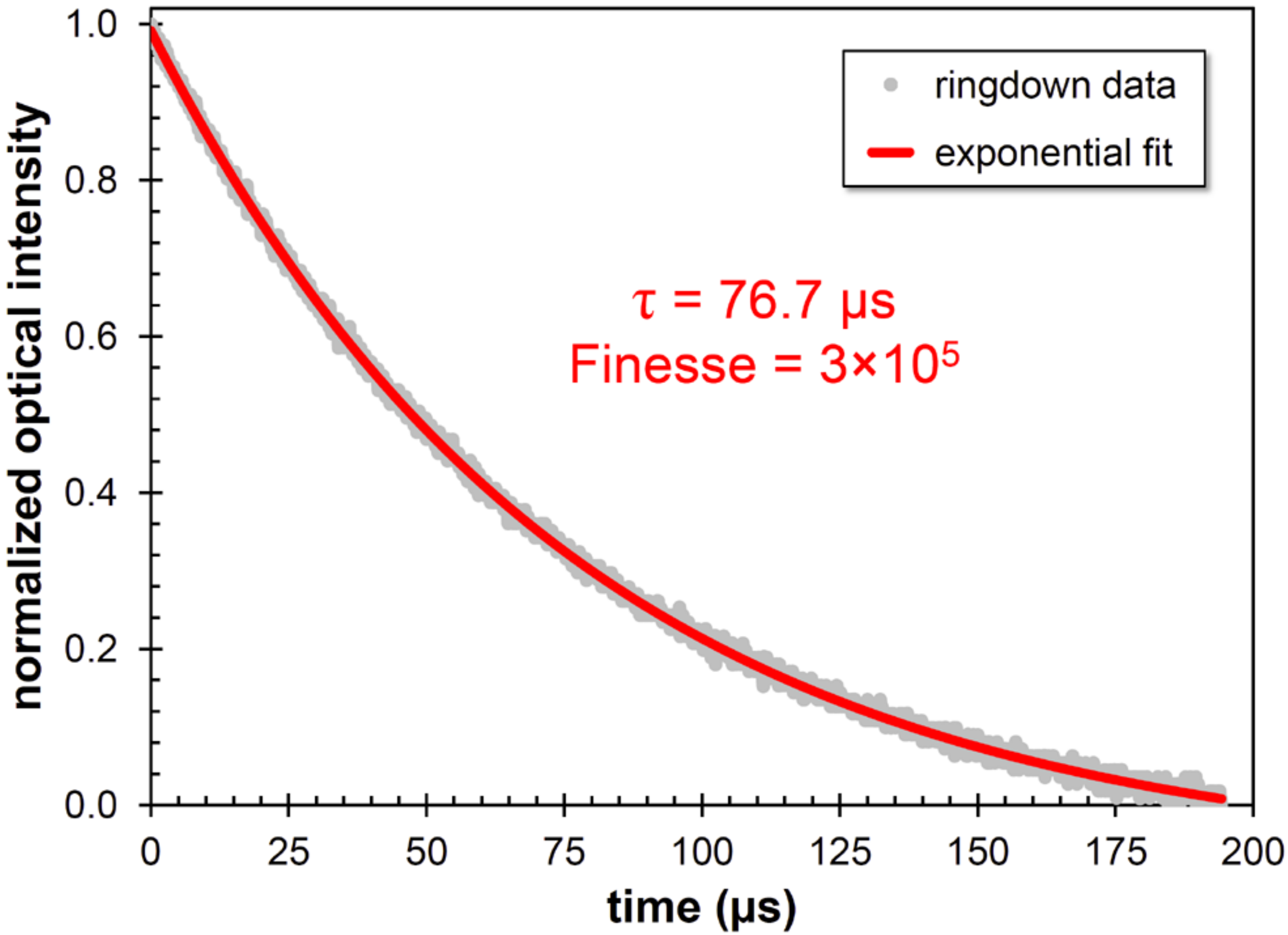
Scatter Limits Optical Quality





- Embedded “oval defects” incorporated during MBE growth process
  - leads to strong position dependence in optical loss of coatings
- Defect free regions have shown micro-roughness-limited losses
  - excess losses (scatter + absorption) verified at the <5 ppm level

High-Finesse Optical Cavity



G. D. Cole, et al., Optica 3, 647 (2016)

Summary of NIR properties

Substrate-transferred crystalline coatings simultaneously exhibit **excellent optical and mechanical quality**

- Damping reduction of 10-100× compared with IBS films
  - IBS-deposited Ta_2O_5/SiO_2: typical Q ~3000 ($\varphi_{IBS} \approx 2\text{-}4\times10^{-4}$)
  - AlGaAs room temperature Q-value of 4×10^4 ($\varphi_{RT} \approx 2\times10^{-5}$)
  - AlGaAs cryogenic performance: Q > 1×10^5 ($\varphi_{min} \approx 4.5\times10^{-6}$)
- Minimal scattering loss and optical absorption
  - absorption verified at < 1 ppm (< 0.01 cm^{-1} at 1064 nm)
  - RMS micro-roughness of 1.3 Å RMS (< 3 ppm at 1064 nm)
- Excess losses (S+A) down to levels < 5 ppm
  - measured finesse of $>3\times10^5$ at 1064, 1397 and 1550 nm

Multiple order-of-magnitude improvements

xtal stable

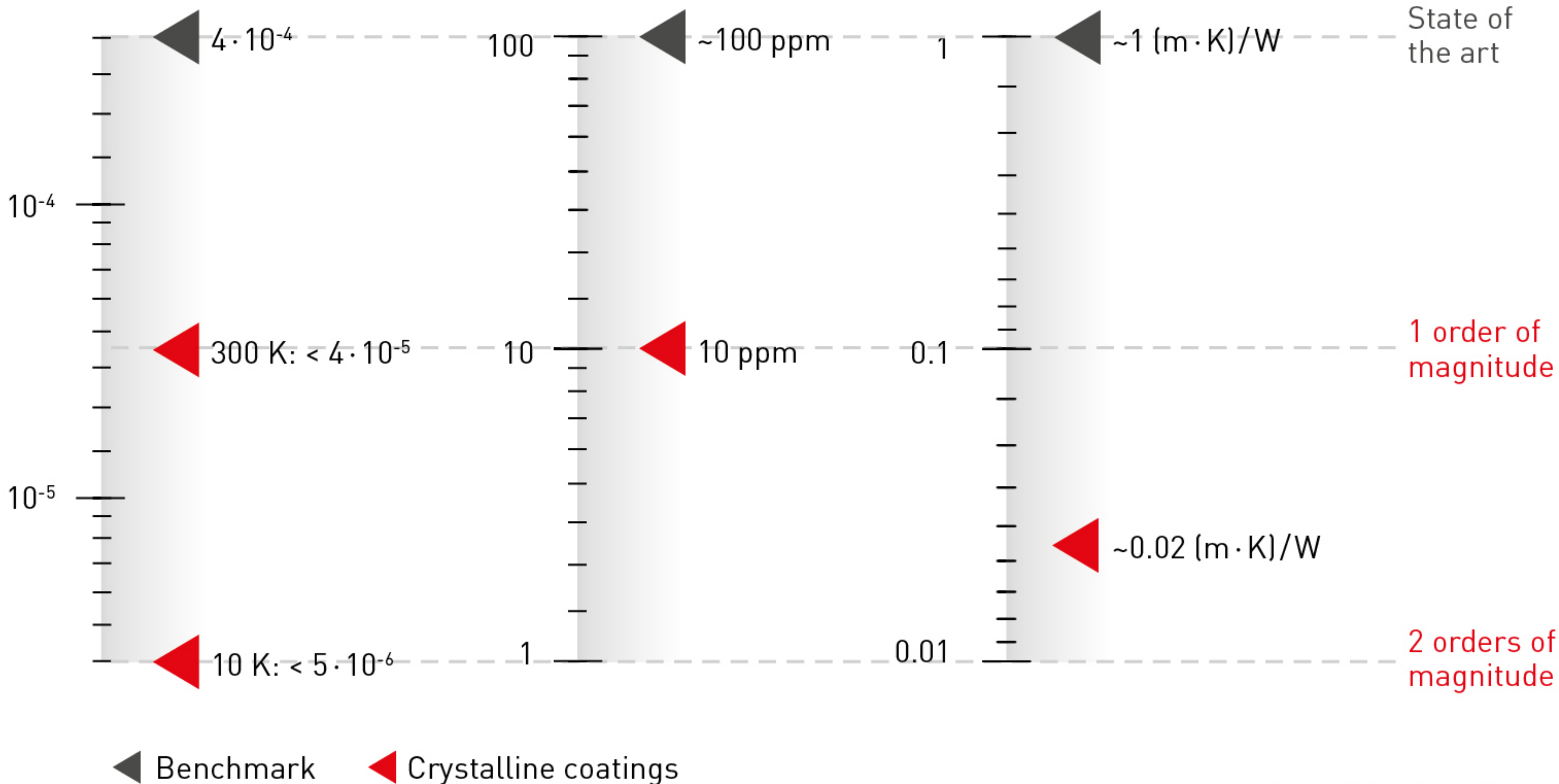
Reduced Brownian noise **(mechanical loss angle)**

xtal mir

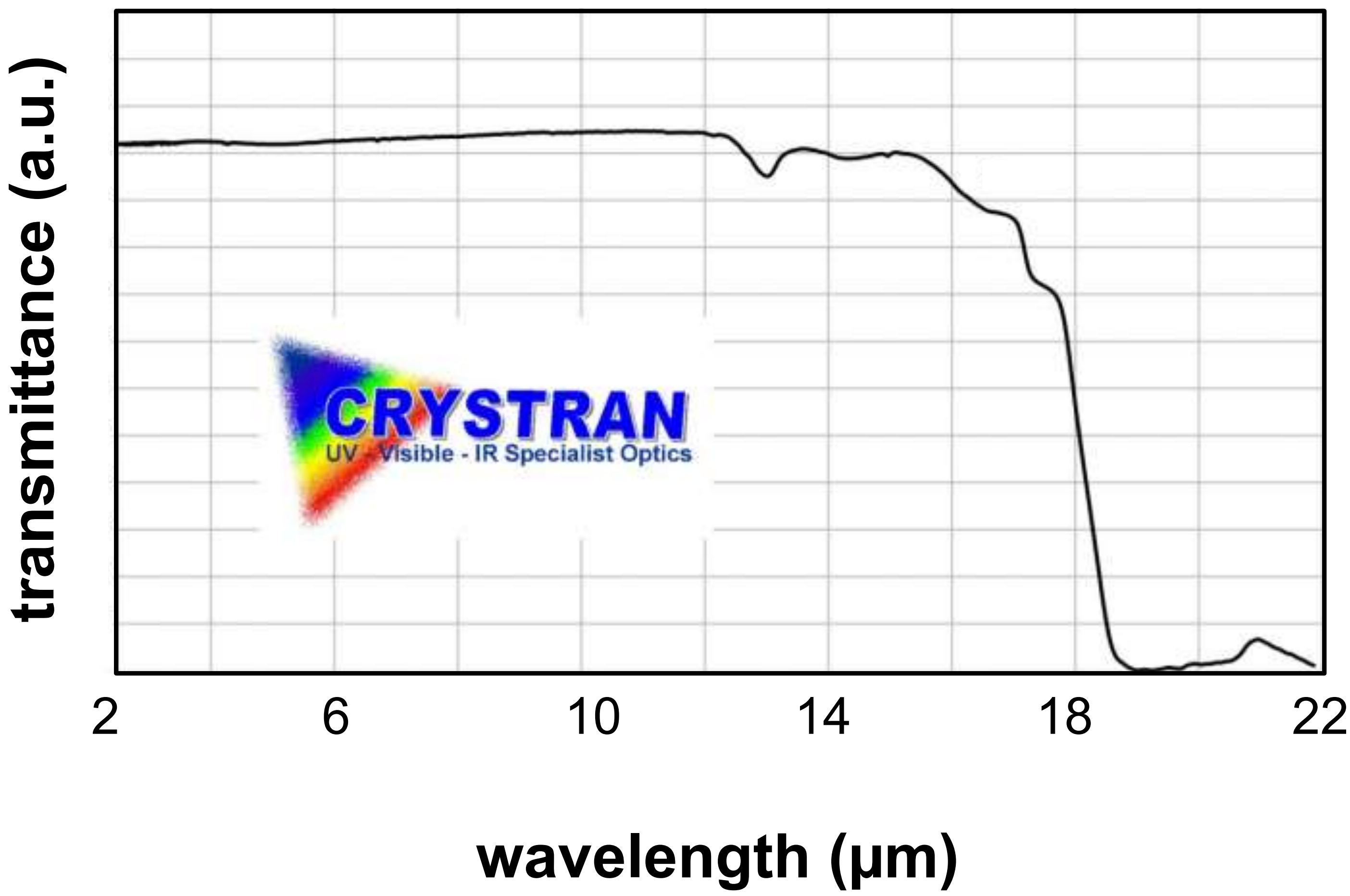
Reduced **mid-IR optical absorption**

xtal therm

Reduced **thermal resistivity**

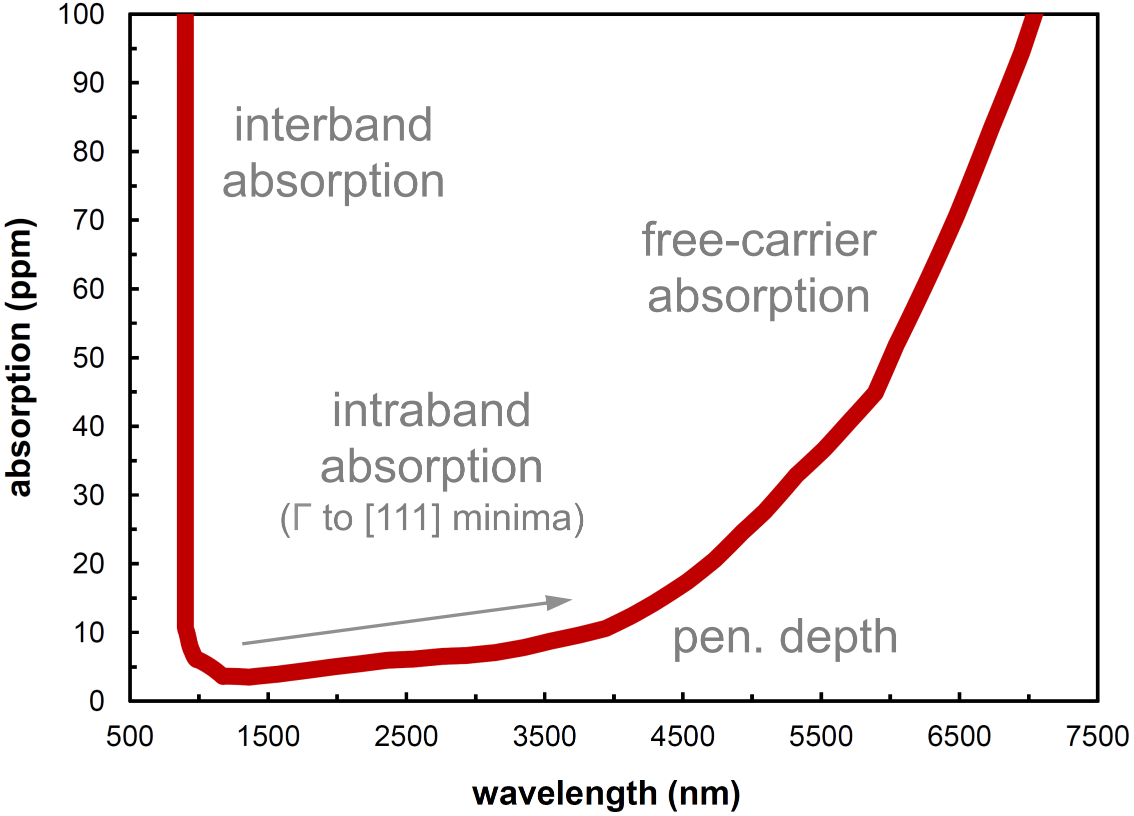


Transparency Window for GaAs



GaAs is a commonly used material for mid and long-wave optics
What losses can be expected from GaAs/AlGaAs multilayers?

Expanding the Wavelength Window



- Plot incorporates
  - material dispersion
  - absorption coefficient
  - penetration depth
- Assumes n-type background doping
- GaAs band-edge limits operation to >900 nm
  - short-wave cutoff
- Long-wavelength cutoff beyond 5 µm
  - free-carrier absorption
  - proportional to λ^3

For abs. coefficient see: W. G. Spitzer and J. M. Whelan, Physical Review 114, April 1959

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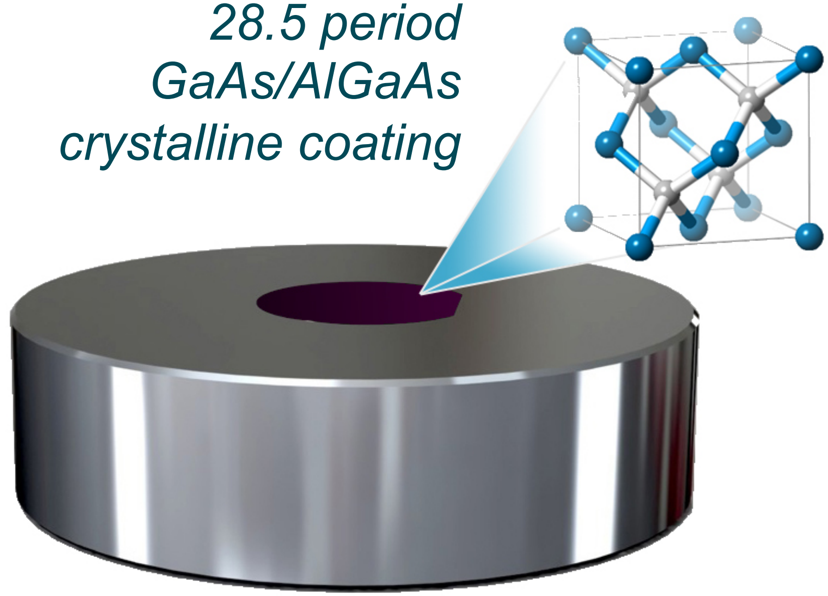
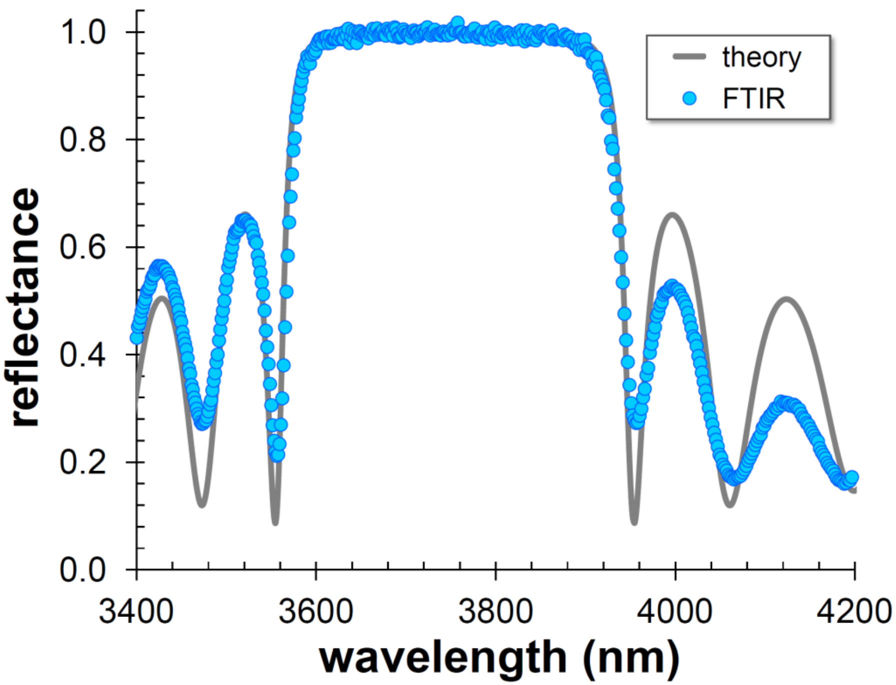
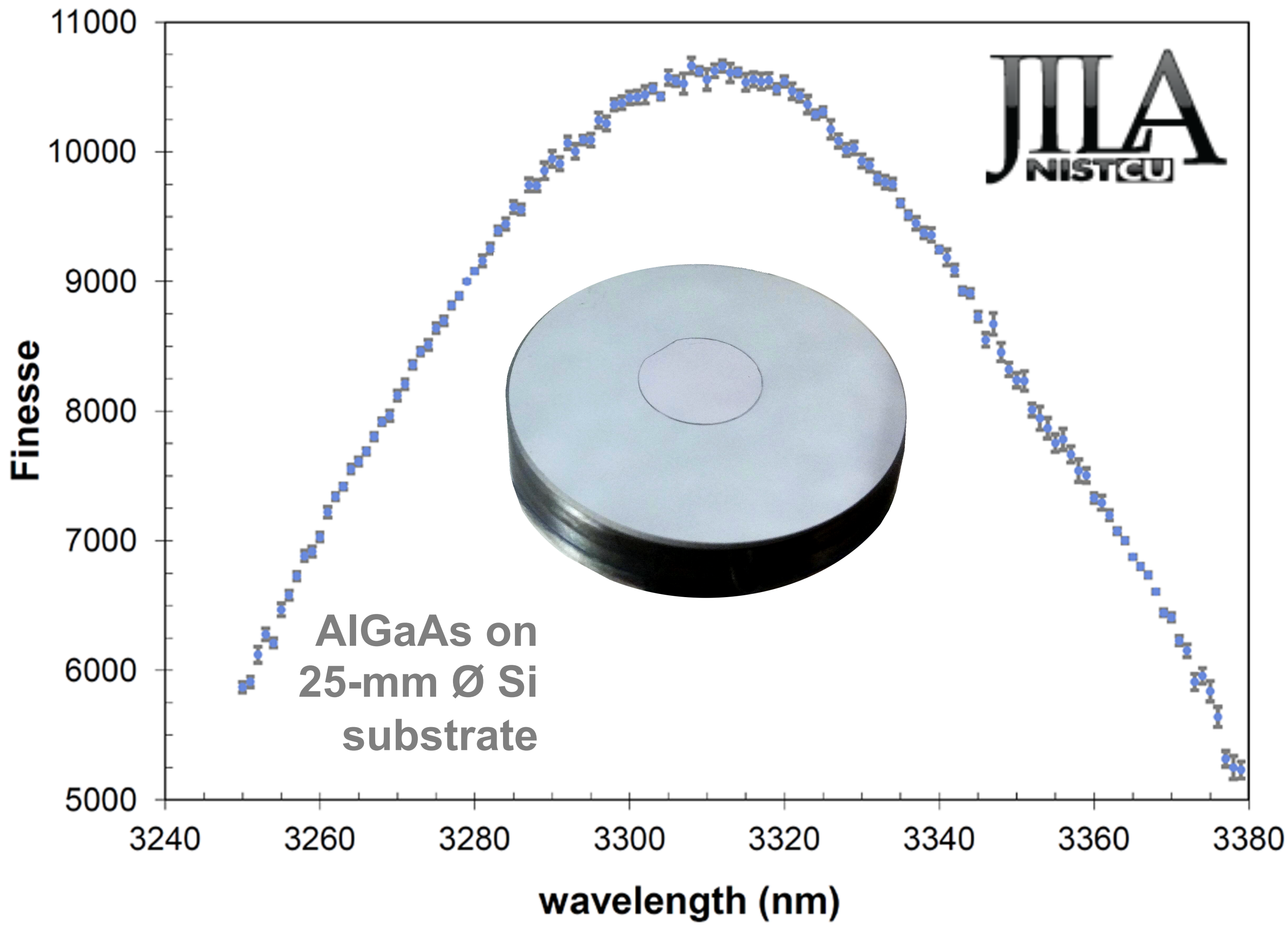
MIR crystalline coatings





- Monocrystalline mirror discs transferred to curved SCS substrates
  - 28.5 period GaAs/$Al_{0.92}Ga_{0.08}As$ DBR, 600 ppm trans. @ 3725 nm
  - potential for optical losses below 100 ppm up to ~5 µm

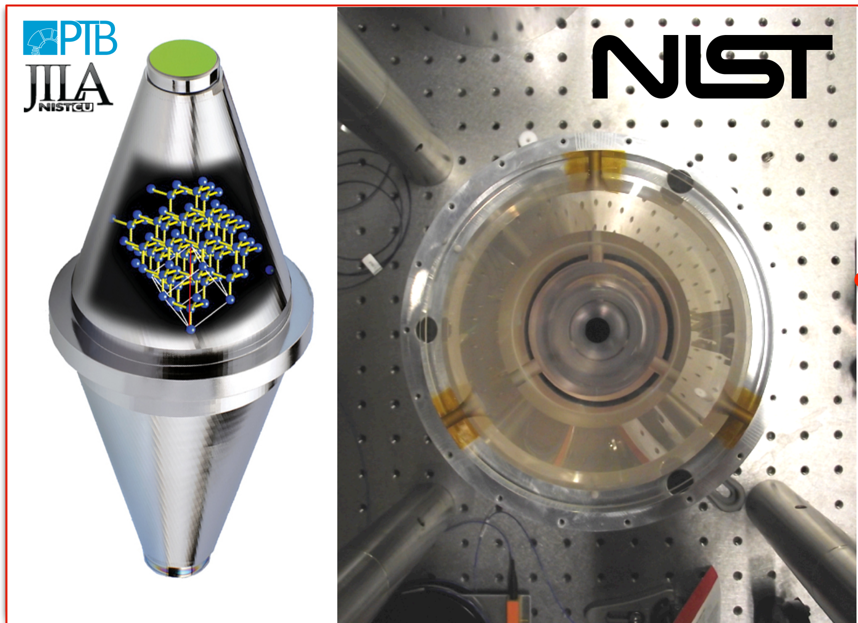
Preliminary MIR Mirror Results



Collaboration with B. Bjork, O. Heckl, B. Spaun, B. Changala, J. Ye, JILA, Boulder, CO

Application Examples

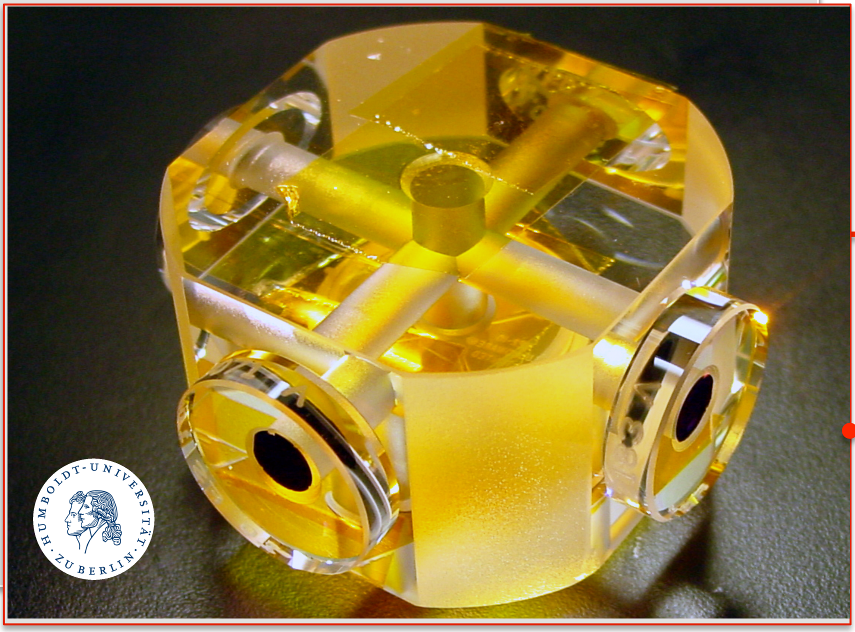
towards frequency stability Δf/f of $1x10^{-17}$ and beyond



optical atomic clocks

Zhang et al., Opt. Lett. 39, 1980 (2014)
Cole et al., Optica 3, 647 (2016)

Application Examples



- optical atomic clocks
- test of fundamental symmetries

Application Examples

optical atomic clocks

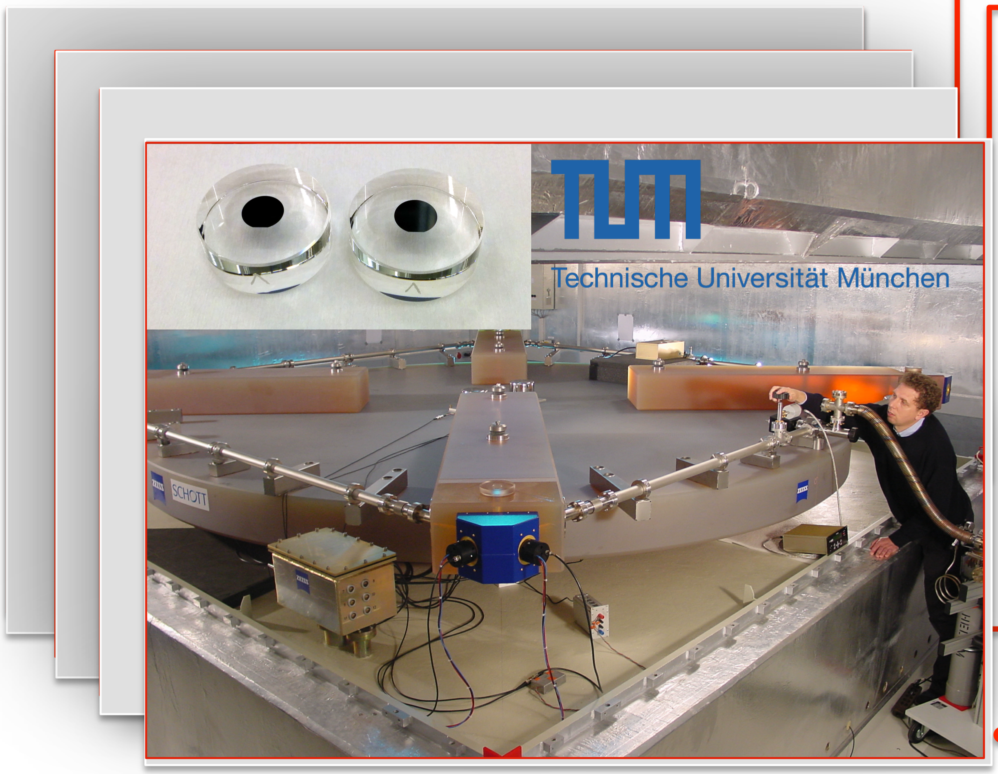
test of fundamental symmetries

gravitational wave detector optics

Chalermsongsak et al., Metrologia 53, 860 (2016)
J. Steinlechner et al., CQG 32, 105008 (2015)

Application Examples

2.56 m2 helium–neon based ring laser interferometer at a wavelength of 1.152 µm



- optical atomic clocks
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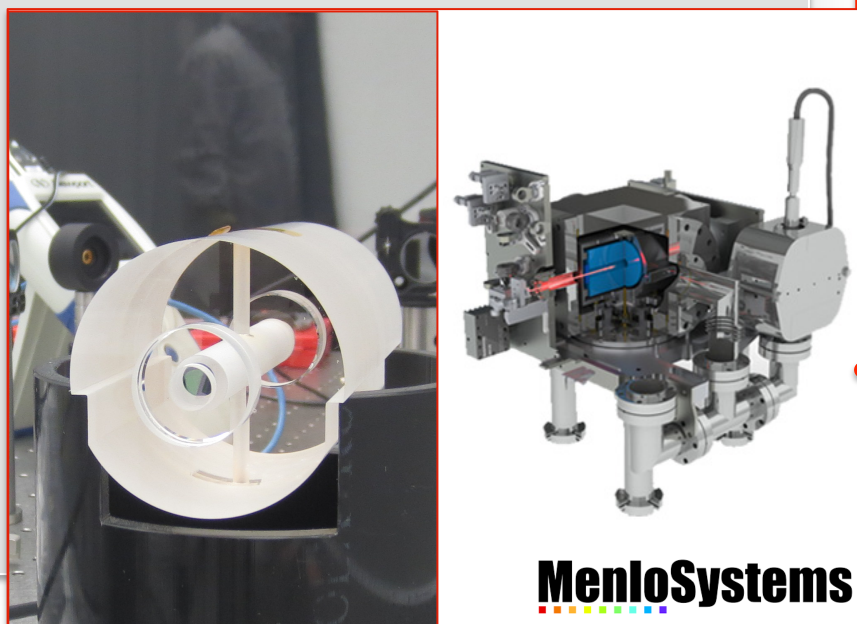
- ring-laser gyroscopes

Schreiber et al., Opt. Lett. 40, 1705 (2015)

Application Examples



- optical atomic clocks
- test of fundamental symmetries
- gravitational wave detector optics
- ring-laser gyroscopes
- commercial ultrastable laser systems

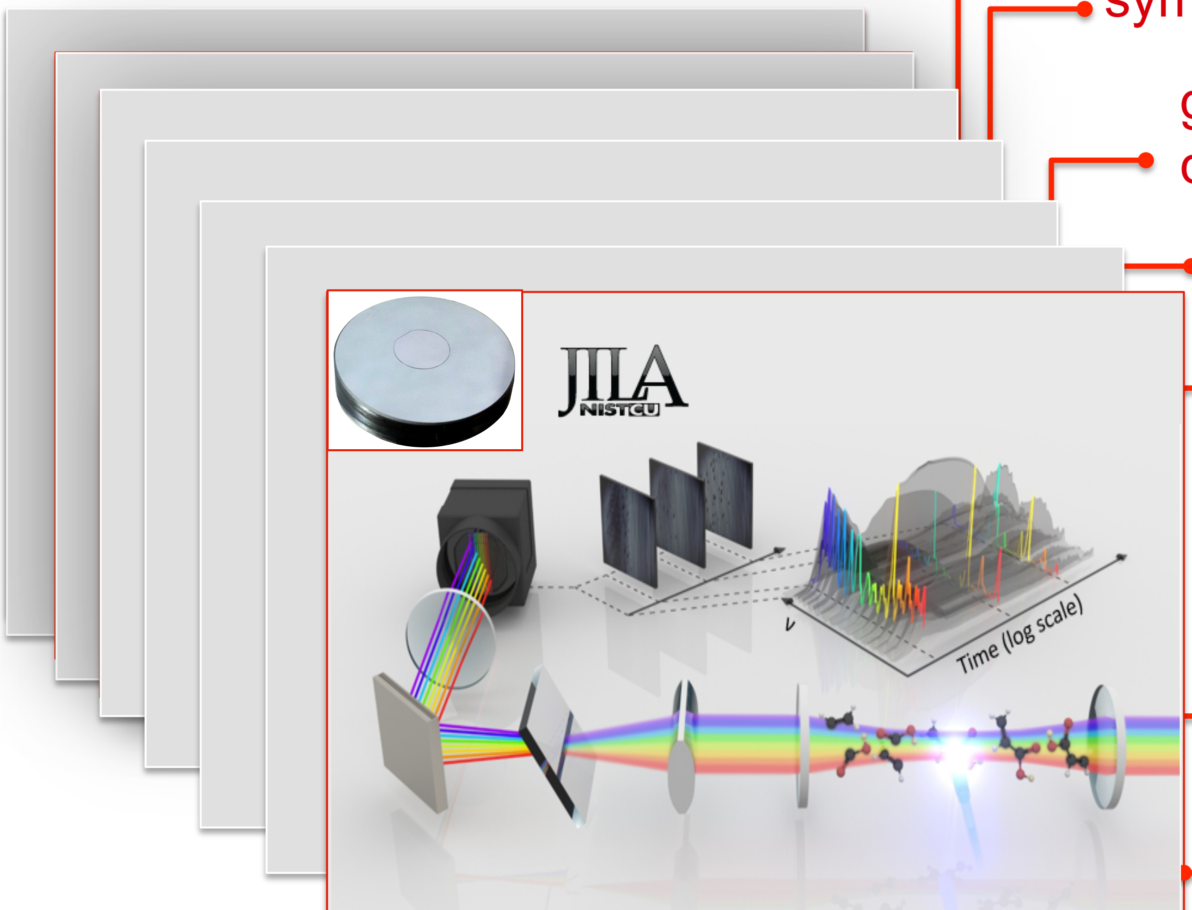
Application Examples

- GaAs-based SESAMs transferred to SiC
- superior flatness to competing technologies

- optical atomic clocks
- test of fundamental symmetries
- gravitational wave detector optics
- ring-laser gyroscopes
- commercial ultrastable laser systems
- high-power / ultra-fast laser systems

Diebold et al., Optics Express 24, 10512 (2016)

Application Examples

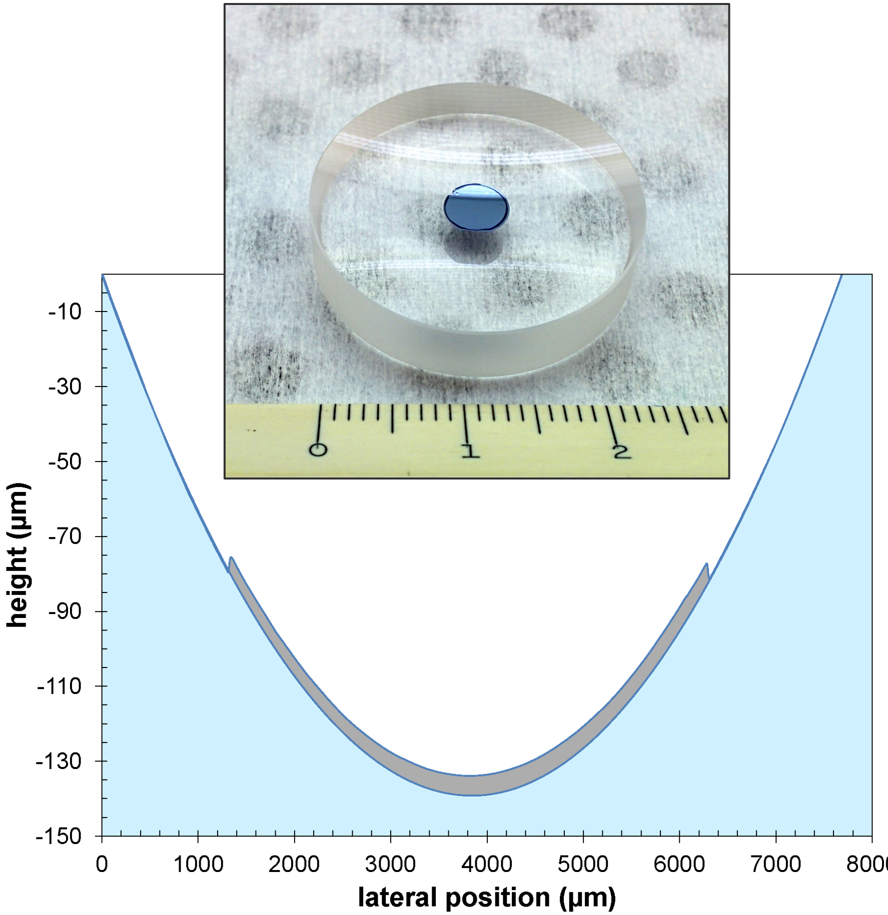


- optical atomic clocks
- test of fundamental symmetries
- gravitational wave detector optics
- ring-laser gyroscopes
- commercial ultrastable laser systems
- high-power / ultra-fast laser systems
- MIR trace gas sensing

B. Bjork, J. Ye et al., submitted (2016)

Additional Capabilities

- High optical quality in the mid-infrared (2-5 µm)
  - initial tests with Jun Ye's group reveal scatter + absorption losses at the ~100 ppm level (3725 nm)
- High thermal conductivity
  - ~70 W/m*K (IBS: ~1)
- Variety of substrate options
  - Si, SiC, diamond, sapphire
- Transfer to curved surfaces
  - minimum ROC: 100 mm
  - larger ROC is easier
- 100+ mm Ø direct bonding
  - void free over entire area
  - bond strengths of ~1 J/m^2



Transfer to curved surfaces:
minimum achievable ROC of 10 cm

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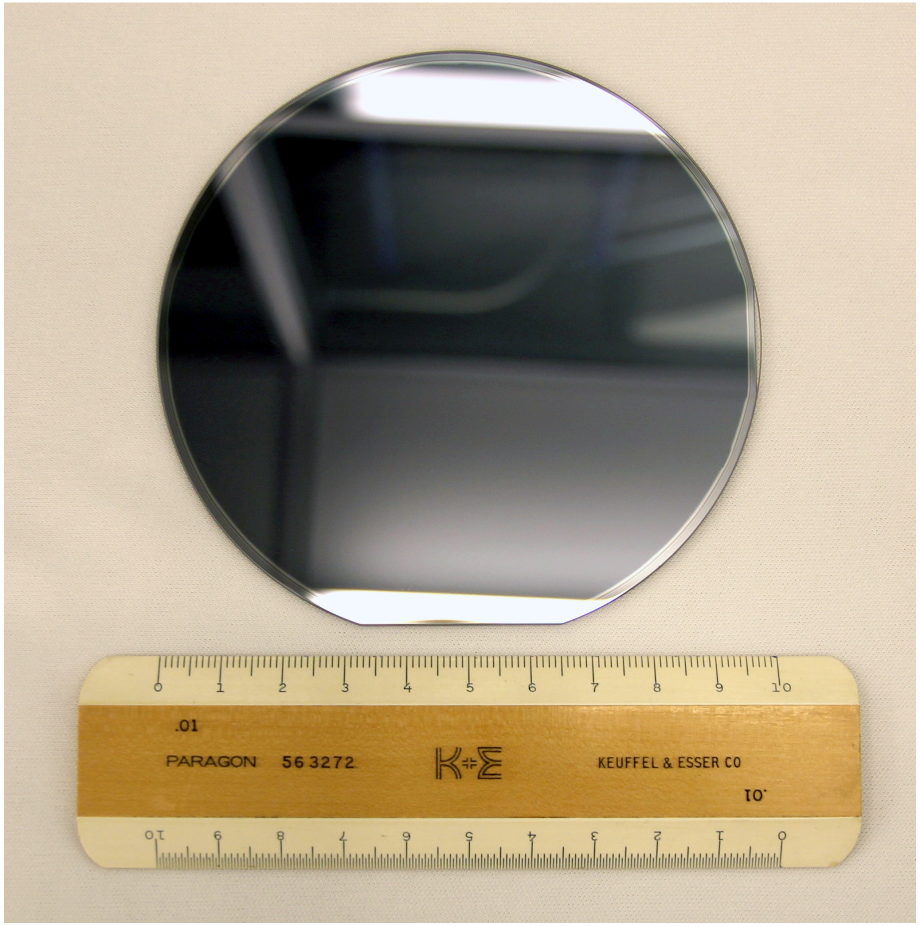
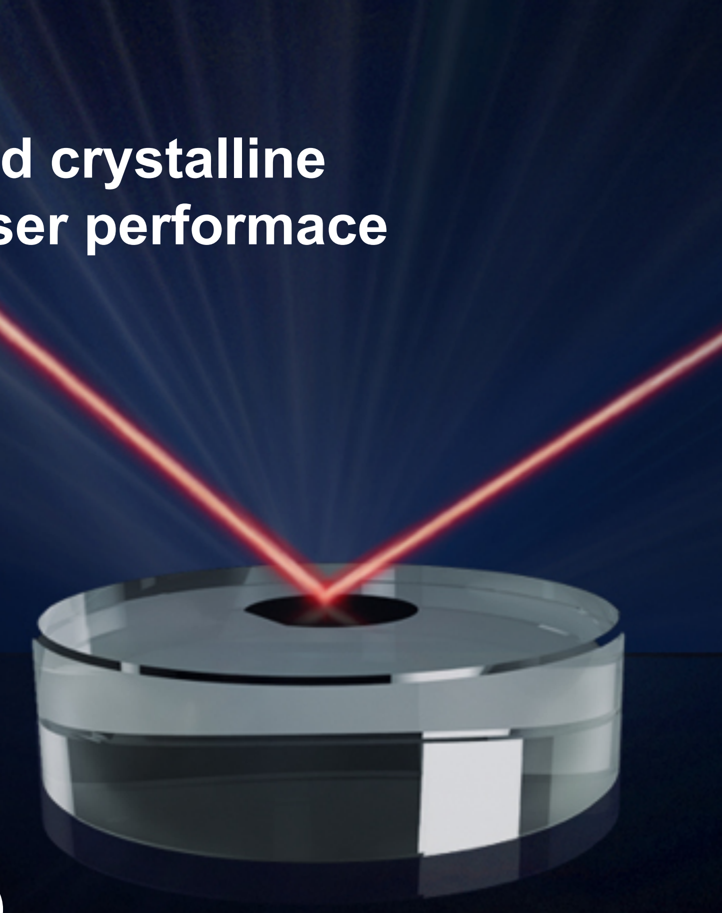


Large area direct bonding:
100-mm diameter GaAs on silica

Semiconductor-based substrate-transferred crystalline coatings - pushing the limits of ultimate laser performace



> 10-fold improvement in...

...Brownian noise (for optical clocks, gravitational wave detectors, ...)

Cole et al., Nature Phot. 7, 664 (2013)

Zhang et al., Opt. Lett. 39, 1980 (2014)

Schreiber et al., Opt. Lett. 40, 1705 (2015)

Chalermsongsak et al., Metrologia 53, 860 (2016)

...MIR absorption (for cavity ringdown, trace-gas sensing, ...)

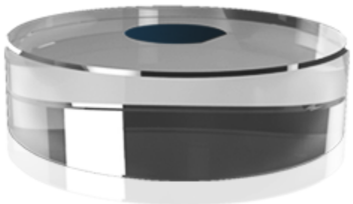
Cole et al., Optica 3, 647 (2016)

...thermal conductivity (for high-power lasers, SESAMs, etc.)

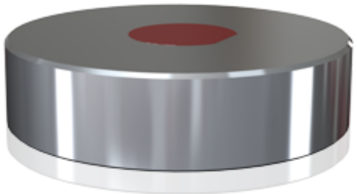
Diebold et al., Opt. Expr. 24, 10512 (2016)

Current Product Lines

CMS



xtal stable



xtal mir

xtal therm

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Thanks to the CMS team












Thank You For Your Attention!

CMS

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