Coating Landscape for CE:
Status and Research Directions

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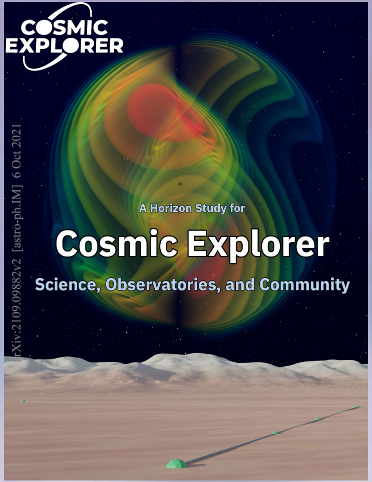
American University/LIGO Scientific Collaboration

Cosmic Explorer Symposium
April 23, 2024

CE-G2400027
LIGO-G2400974

Cosmic Explorer Overview


COSMIC EXPLORER

arXiv:2109.09882v2 [astro-ph.IM] 6 Oct 2021

A Horizon Study for

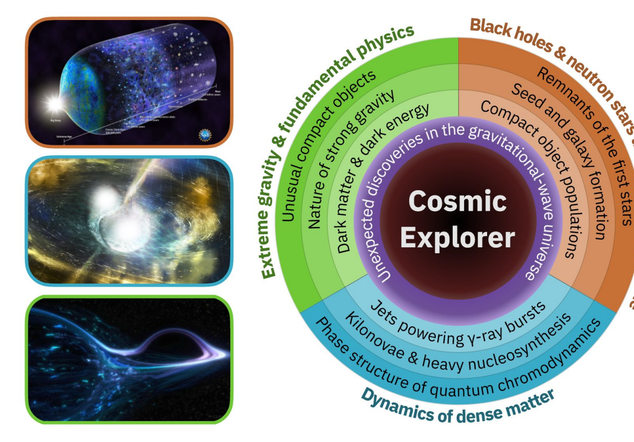
Cosmic Explorer

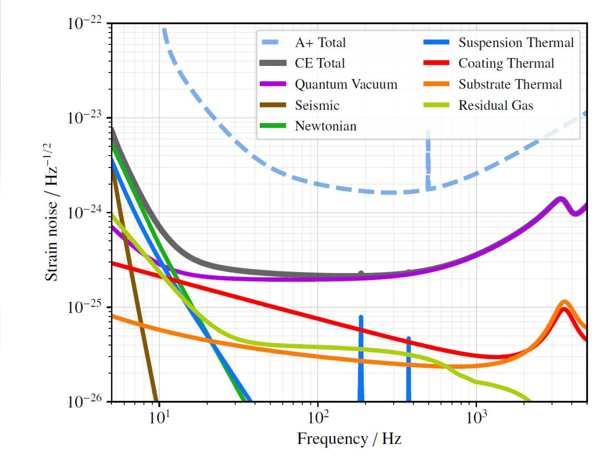
Science, Observatories, and Community

Recommended as next generation detector by NSF MPSAC Next-Generation Gravitational Wave Detector Concept Subcommittee

Goals

- 10X sensitivity of LIGO A+ detectors
  - Part of network with ET, LISA, etc.
- Observe BHs & NSs through cosmic time, study nuclear matter, measure extreme gravity

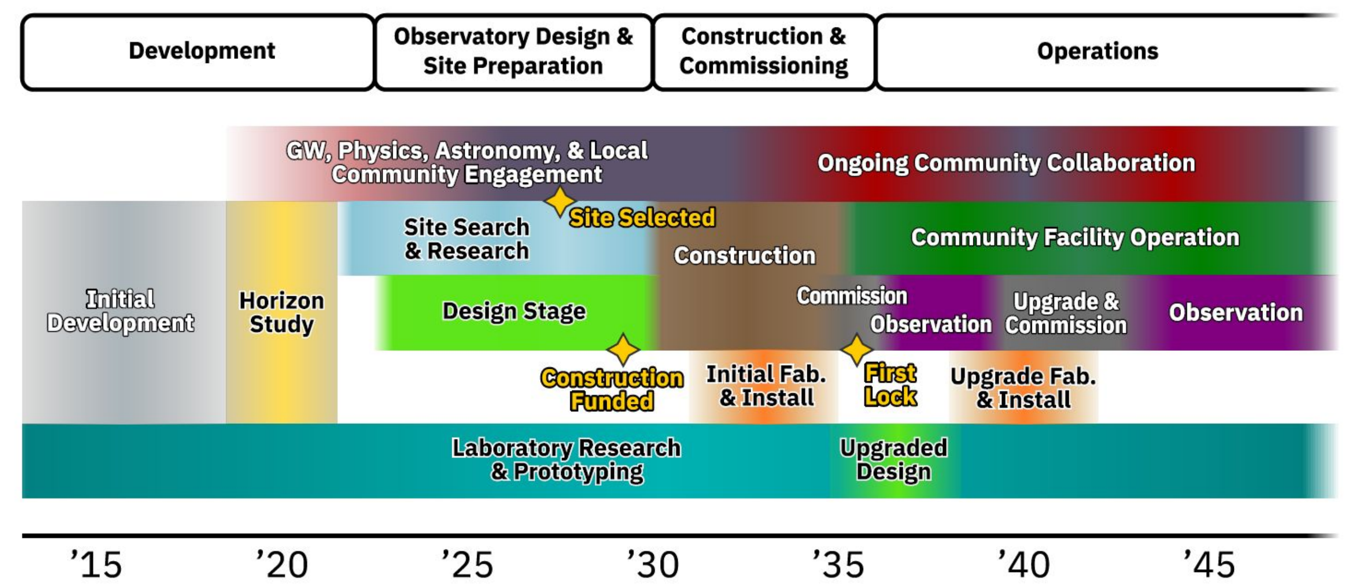




Design

- Two detectors, 40 km and 20 km long
- Peak sensitivity $3\times10^{-25}/\sqrt{\text{Hz}}$ @ 30-200 Hz, 40 km, broadband
- Two phases: A+/# technology, advanced upgrades
- Optical parameters: >1 MW power, 1 (2?) µm, 10 dB squeezing
- Test masses: 320 kg, silica (silicon?), 293 K, > 50 cm diameter
  - LMA cleaning facility maximum 55 cm diameter
- Coating: 8.2-8.5 cm beam size (20 km), 40 ppm round trip optical loss, Brownian noise: $8\times10^{-26}/\sqrt{\text{Hz}}$ @ 100 Hz, below quantum noise

Cosmic Explorer Schedule



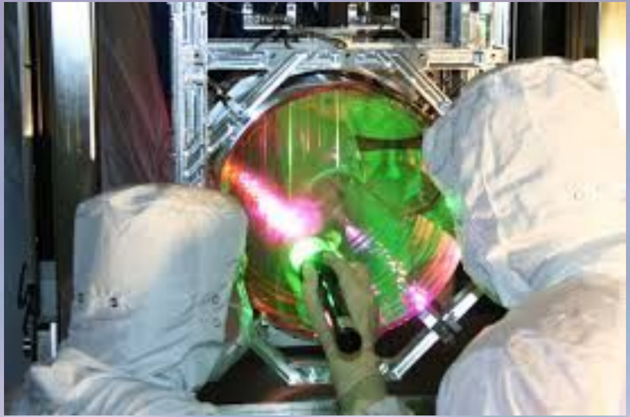
Dates ± 1 year

- 2021 Horizon study compete
- 2024 Entering design stage
    - Laboratory research and prototyping
- Late 2025 Construction proposal
    - Initial coating preliminary choice
    - Site selection
- 2027 Site Selection
    - Bonder decision if appropriate
- 2029 Construction funded

Red initial CE coating, Yellow adv CE coating

- 2031 Pathfinder optic
    - Initial coating decision finalized
- 2032 Begin fabrication
    - Optics typically longest lead item
- 2034 Coat optics for installation
- 2035 Upgrade design
    - Begin taking science data with initial CE
    - Upgrade coating preliminary choice
- 2038 Upgrade fabrication
    - Shutdown for installation

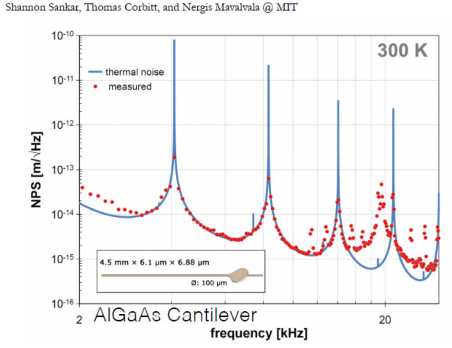
Coating Possibilities



Amorphous oxides, ion beam deposited

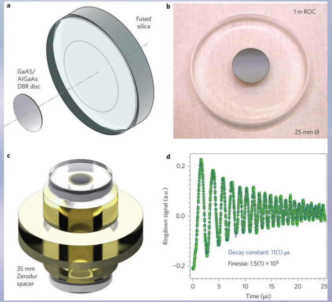
- High n: Titania, tantala, germania, hafnia
- Low n: Silica, alumina
- Significant experience in field and industry

See Wed morning session
Martynov and Ballmer talks


Shannon Sankar, Thomas Corbitt, and Nergis Mavalvala @ MIT

Amorphous silicon

- High n, low n silica
- Silicon optics/cryogenics



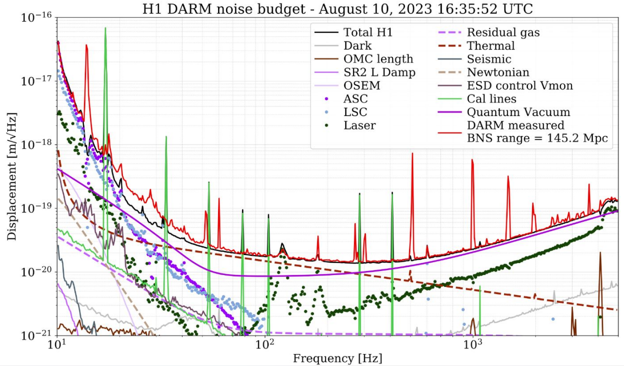
Crystalline

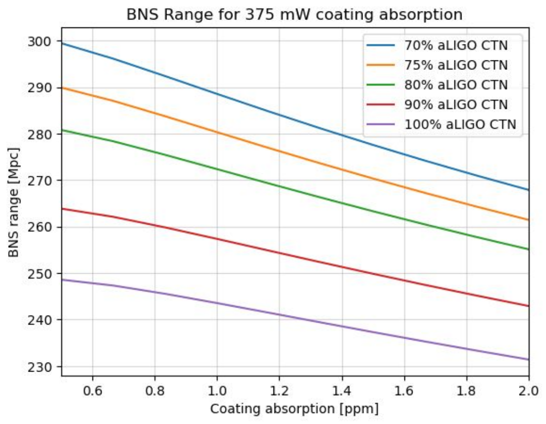
- Aluminum gallium arsenide/gallium arsenide (AlGaAs)
- Substrate transfer technique
- In use in precision timing experiments

Amorphous Oxides

- aLIGO coating 3 times CE ref design at 100 Hz
  - High, and variable, thermal noise in aLIGO ~30% over expected
- A+ coating 2 times CE Spec at 100 Hz
  - Unlikely to meet A+ thermal noise spec, ~40% high
  - Discrepancy in φ between single layer and stack
  - 1-2 ppm absorption

- Elevated coating thermal noise by 30% (1.45e-20 m/rtHz@100Hz)
- Remaining unknown noise between 20-70 Hz



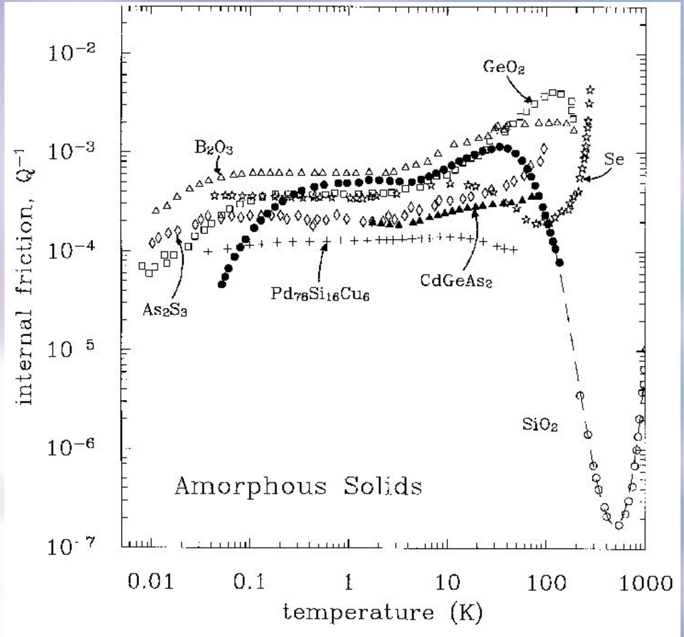


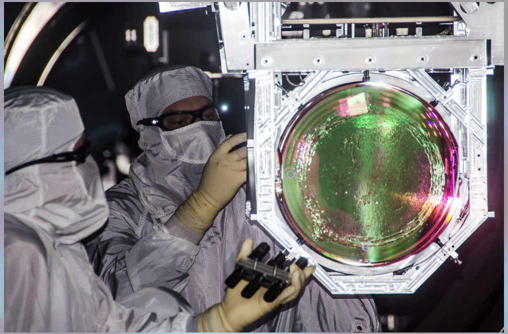
- Timeline difficult to estimate, possibly 3-5 years?
  - A+ coating for initial CE
  - Realistic for CE upgrade
  - New coating materials for upgrade CE

Amorphous Oxides

Advantages

- Decades of GW experience, more in optics industry
- Deposition over > 30 cm diameter
- Good optical properties; scatter, absorption, etc.
- Likely experience from Ti-Ge use in A+ upgrade



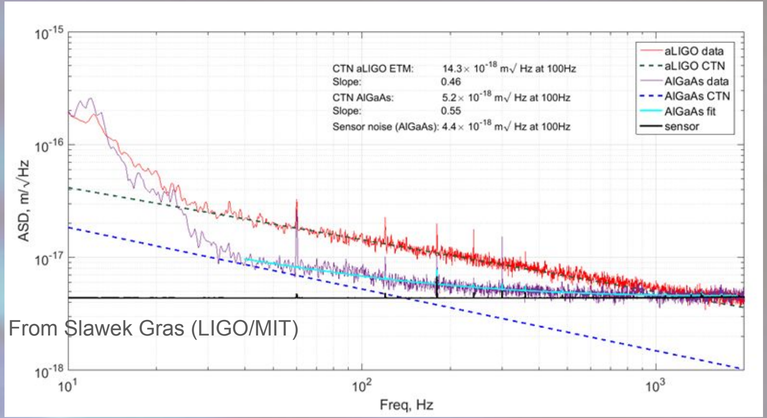


Challenges

- Minimal improvement over two decades
  - Many ideas pursued to no result
  - Needs research, not just development
- Possible mechanical loss limitations
- Cost and schedule difficult to estimate
- Significant & hard to predict annealing impact

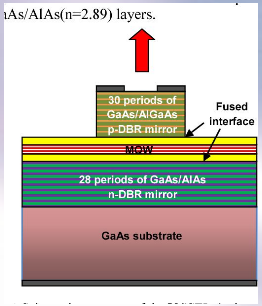
Crystals: AlGaAs

- Upper limit 65% X CE ref design at 100 Hz
  - From MIT measurement, contaminated with coupler noise



From Slawek Gras (LIGO/MIT)

Clear up misinformation and misunderstanding



- **No reason to expect excess noise at room temperature**
  - Birefringence noise only at cryogenic temperature
  - Mystery noise inconclusive whether from coatings and only cryogenic
  - Many groups have room temperature experience with no problems

- Start in 2025, pathfinder by 2029 construction funding
  - Decide on bonder size 2027

Crystals: AlGaAs

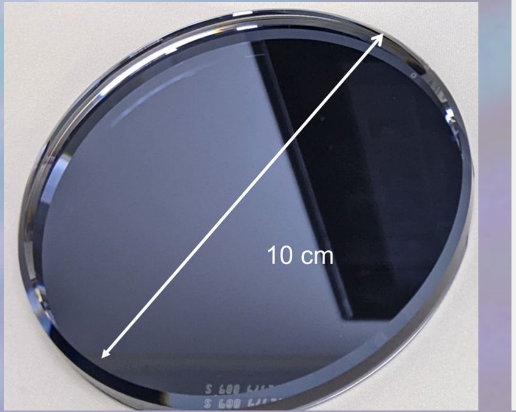
Timeline	Activity	Cost
First Year	1. Design and order of GaAs crystal wafer (Freiberger) 2. Order AlGaAs mirrors for prototype detector (Hannover) 3. Continuing noise studies (Syracuse, American, MIT)	$1.6 M
Second Year	1. Growth and measurement of gallium arsenide crystal (Freiberger) 2. Begin AlGaAs coating bonder construction (EVG) 3. Install AlGaAs mirrors in prototype (Hannover) 4. Continuing noise studies (Syracuse, American, MIT, Caltech, CSU Fullerton)	$6.6M
Third Year	1. Gallium arsenide substrate etching and metrology (Freiberger) 2. Bonder delivery (EVG) 3. Prototype detector operation (Hannover) 4. Continuing noise studies (Syracuse, American, Stanford)	$5.2M
Fourth Year	1. Single gallium arsenide wafer deliver (Freiberger) 2. AlGaAs epitaxy on GaAs wafer (ThorLabs) 3. Continuing noise studies (Syracuse, American, Caltech)	$4.8M

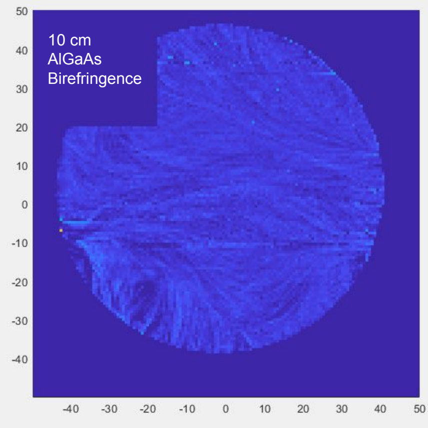
Advantages

- 10X better thermal noise than aLIGO at room temperature
- Good optical properties
- Repeatable properties, no annealing surprises
- Extensive experience in small mirror (< 5 cm diameter) from precision optical measurements
- Works at 1-2+ microns and all temperatures
- Development with realistic budget and schedule

Challenges

- Scale up to ≧40 cm diameter
  - Possible improvement with Ge wafer
- Limited experience above 10 cm diameter
  - 20 cm sample in process
- Birefringent, possible issues
  - Eliminate with nitrogen alloying
- Not transparent at 532 nm
  - Alternative lock acquisition design



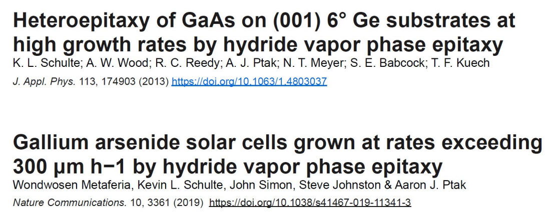


GaAs Wafer Production

- GaAs boule growth and waferization: 3.5 years and over $3M
- “New” technique for rapid GaAs growth of Ge wafers
    - Ge lattice constant (5.646 Å) close to GaAs (5.653 Å)
    - Ge (Diamond structure, 90° symmetry) while GaAs (zinc-blende, 180° symmetry). Depositing GaAs on Ge flat crystal face form region of different polarization.
    - GE wafers: 6° cut exposes crystal steps that establish polarization.
    - Single polarization after 100 nm.
    - HVPE (Hydride Vapor Phase Epitaxy) is a gas-based (GaCl & AsH_3) epitaxy that can grow GaAs at rates of 300 µm/hr. A GaAs wafer could be grown in a few hours!
    - 30-cm Ge wafer are commercially available. Requesting quotes from vendor for HVPE produced GaAs wafers.
    - IQE exploring using MBE on 6° cut Ge wafers to deposit GaAs and then directly grow GaAs/AlGaAs coatings.

30 cm Ge Wafers

Produced by Umicore and American Elements



Heteroepitaxy of GaAs on (001) 6° Ge substrates at high growth rates by hydride vapor phase epitaxy

K. L. Schulte; A. W. Wood; R. C. Reedy; A. J. Ptak; N. T. Meyer; S. E. Babcock; T. F. Kuech

J. Appl. Phys. 113, 174903 (2013) https://doi.org/10.1063/1.4803037

Gallium arsenide solar cells grown at rates exceeding 300 µm h−1 by hydride vapor phase epitaxy

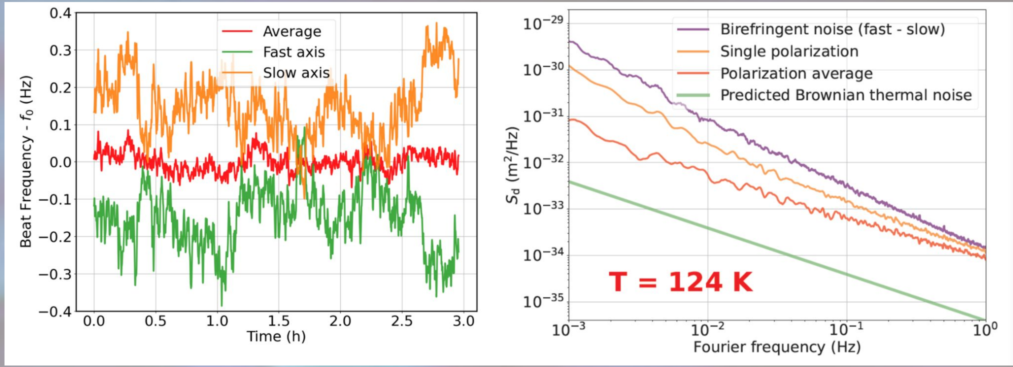
Wondwosen Metaferia, Kevin L. Schulte, John Simon, Steve Johnston & Aaron J. Ptak

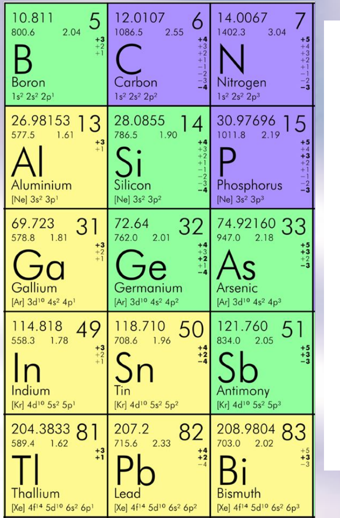
Nature Communications. 10, 3361 (2019) https://doi.org/10.1038/s41467-019-11341-3

Birefringence

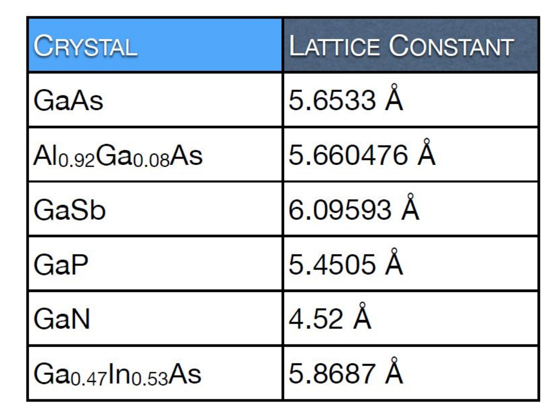
Birefringence noise

- Excess noise, above Brownian & TE, at 124 K on Silicon
- **No room temperature birefringence noise seen**
- Room temperature cavity experiments in progress (JILA/PTB, Thorlabs, MIT).
  - Results anticipated this year.





3	4	5
10.811 5 800.6 2.04 +3 +2 +1 B Boron $1s^2 2s^2 2p^1$	12.0107 6 1086.5 2.55 +4 +3 +2 +1 −1 −2 −3 −4 C Carbon $1s^2 2s^2 2p^2$	14.0067 7 1402.3 3.04 +5 +4 +3 +2 +1 −1 −2 −3 N Nitrogen $1s^2 2s^2 2p^3$
26.98153 13 577.5 1.61 +3 +1 Al Aluminium $[Ne] 3s^2 3p^1$	28.0855 14 786.5 1.90 +4 +3 +2 +1 −1 −2 −3 −4 Si Silicon $[Ne] 3s^2 3p^2$	30.97696 15 1011.8 2.19 +5 +4 +3 +2 +1 −1 −2 −3 P Phosphorus $[Ne] 3s^2 3p^3$
69.723 31 578.8 1.81 +3 +2 +1 Ga Gallium $[Ar] 3d^{10} 4s^2 4p^1$	72.64 32 762.0 2.01 +4 +3 +2 +1 −4 Ge Germanium $[Ar] 3d^{10} 4s^2 4p^2$	74.92160 33 947.0 2.18 +5 +3 +2 −3 As Arsenic $[Ar] 3d^{10} 4s^2 4p^3$
114.818 49 558.3 1.78 +3 +2 +1 In Indium $[Kr] 4d^{10} 5s^2 5p^1$	118.710 50 708.6 1.96 +4 +2 −4 Sn Tin $[Kr] 4d^{10} 5s^2 5p^2$	121.760 51 834.0 2.05 +5 +3 −3 Sb Antimony $[Kr] 4d^{10} 5s^2 5p^3$
204.3833 81 589.4 1.62 +3 +1 Tl Thallium $[Xe] 4f^{14} 5d^{10} 6s^2 6p^1$	207.2 82 715.6 2.33 +4 +2 −4 Pb Lead $[Xe] 4f^{14} 5d^{10} 6s^2 6p^2$	208.9804 83 703.0 2.02 +5 +3 −3 Bi Bismuth $[Xe] 4f^{14} 5d^{10} 6s^2 6p^3$



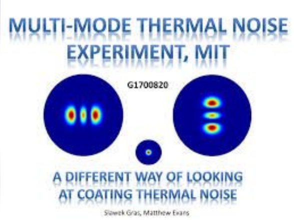
CRYSTAL	LATTICE CONSTANT
GaAs	5.6533 Å
$Al_{0.92}Ga_{0.08}As$	5.660476 Å
GaSb	6.09593 Å
GaP	5.4505 Å
GaN	4.52 Å
$Ga_{0.47}In_{0.53}As$	5.8687 Å

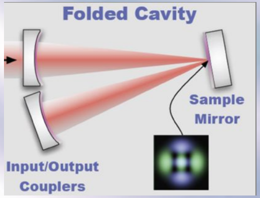
Zeroing birefringence

- 1 mrad of phase difference for HR coating
- Birefringence arises from stress of lattice mismatch
- 2 Alloys match GaAs lattice constant:
  - $Al_{0.92}Ga_{0.08}As_{0.994}N_{0.006}$
  - $Al_{0.92}Ga_{0.08}As_{0.964}P_{0.036}$.
- AlGaAsN cantilever samples show **no bowing. No stress**.
- No Stress = No Birefringence ?
- Samples will be tested at Thorlabs then produced for LIGO

AlGaAs Research Questions and Directions

- Nitrogen alloying to eliminate strain
  - Greatly reduce birefringence
  - Industry and VCSEL laser experience
  - Research impact on optical properties, mechanical loss, etc.
- Germanium wafers for large area deposition
  - Industry experience
  - Research impact on optical properties, mechanical loss, etc.

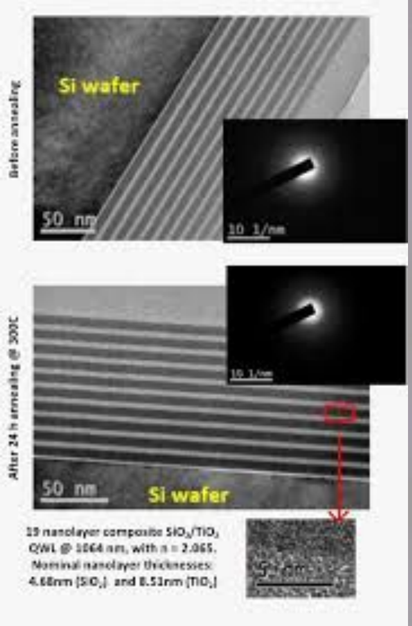




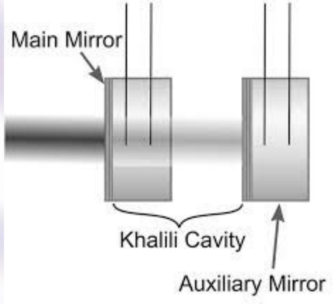
- Further direct thermal noise measurements
  - MIT plans summer 2024, AlGaAs couplers to reduce instrument noise
  - Cavity experiments at ThorLabs for birefringence related noise
- Model thermo-optic noise cancellation, determine limits
  - MIT TNI measurements to set limits
- Prototype 2048 nm lock acquisition system
  - In progress at Syracuse
- Refine and upgrade schedule and budget
  - Germanium wafers may reduce time and cost noticeably; 1+ year, $2M

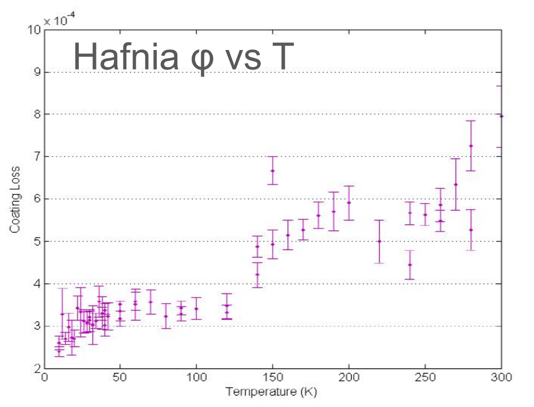
Other Coating Research Directions

- Amorphous silicon coatings and cryogenics
- Nitride coatings: absorption challenges, multimaterials
- Prototyping on multimaterial and nanolayer coatings
- Cryogenic hafnia
- Other amorphous oxides; Ti:SiO_2, TeO_2, ZrO_2
- Khalili cavities



19 nanolayer composite SiO_2/TiO_2 QWL @ 1064 nm, with n = 2.065. Nominal nanolayer thicknesses: 4.68nm (SiO_2) and 8.51nm (TiO_2)



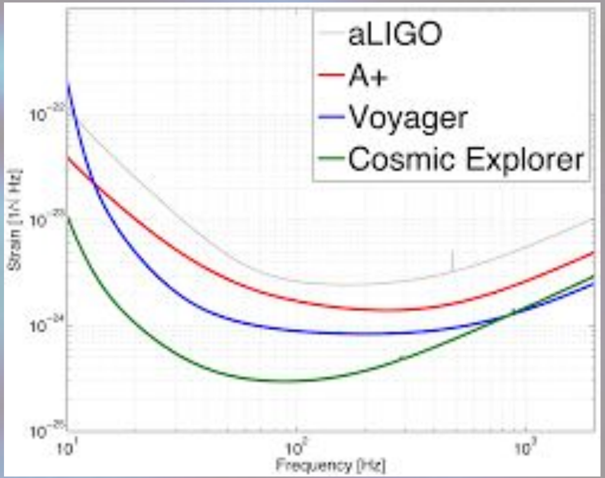


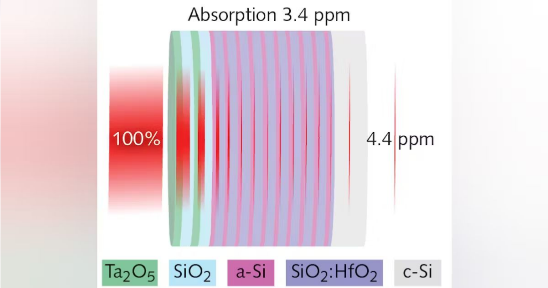
General Research Questions and Directions

- Include annealing and prototyping earlier in research plans
  - When amorphous materials are trouble generally during annealing
- More to thermal noise than just mechanical loss
  - Study of real part of elastic constants, Y and σ
  - Also 2+ loss angles per material
- Spatial dependence of optical properties
  - Caltech full optic TNI might help
- Large area substrate fabrication and polishing
  - Plus coating and handling technology

IBS Amorphous Oxide Research Questions and Directions

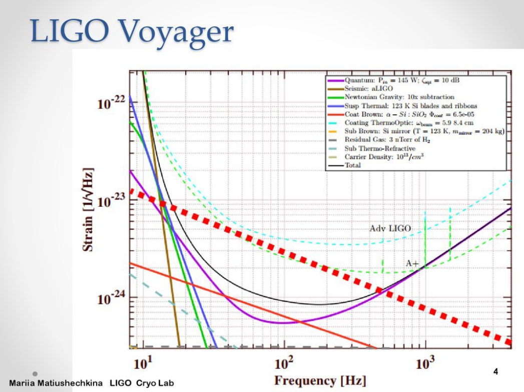
- Learn from Advanced LIGO and A+
  - Both research directions and performance
- Explore new materials in lab and modeling
  - Limited promising options based on structure
- Include annealing in research phase
  - Avoid surprises, demonstrate through prototypes





- Properties other than mechanical loss
  - Real part of elastic moduli, multiple loss angles, thermo-optic parameters
- Nanocoatings and multimaterial options
  - Need prototyping and direct measurements

Amorphous Silicon


LIGO Voyager

Mariia Matiushechkina LIGO Cryo Lab 4

- Voyager spec with α-Si:SiO$_2$ right at CE ref design at 100 Hz
- Estimated 3 years for Voyager from downselect to procurement
    - Fits CE schedule if ready by late 2025

Pro

- Promise of improved thermal noise over IBS oxides, possible to get $\Phi < 10^{-4}$
- Industry experience
- Can benefit from multimaterial designs
- Possible experience with Voyager
    - Now planning on silicon nitride

Con

- Generally cryogenic, difficult and expensive
- High absorption, 10-1000s of ppm
- Need to change laser wavelength from 1064 nm
- Properties including mechanical loss and absorption dependent on deposition parameters
- No detailed development budget or schedule
- Limited GW field experience including no prototyping nor direct TN measurement
    - Plans at Caltech and ANU

Amorphous Silicon Research Questions and Directions

- Broad cryogenics research, including cost and schedule estimates
- Continuing studies of hydrogenation, especially as related to absorption. Is hydrogenation stable and permanent?
- Explore multimaterial options to minimize impact of absorption
    - Carry through to prototyping beyond modeling
- Operate prototype with α-Si coated mirrors
    - 40 m Mariner at Caltech
- Research silicon substrate properties