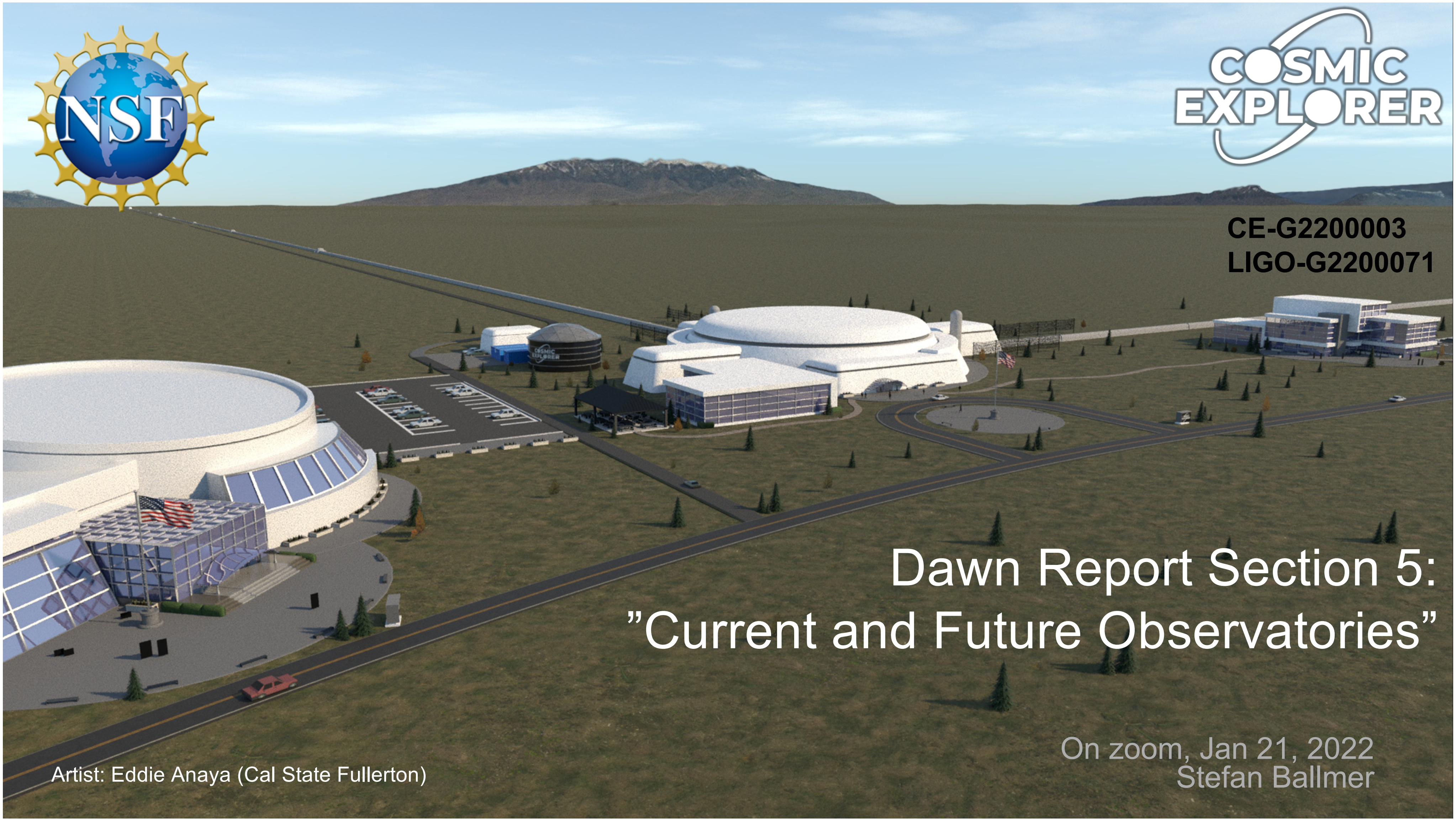

CE-G2200003
LIGO-G2200071

Dawn Report Section 5: ”Current and Future Observatories”

On zoom, Jan 21, 2022
Stefan Ballmer

Artist: Eddie Anaya (Cal State Fullerton)

Dawn report on “Current and Future Observatories”

COSMIC EXPLORER

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Key quotes from the report

On the post-O5, pre-3G period:

- "Beyond 2028, the LIGO Laboratory is firmly committed to continued observations of the gravitational-wave sky."
- "The durations of downtime and the post-O5 run should be such that the observational science goals of the greater community are best satisfied."
- "The current detectors have significant excess technical noise at low frequencies, impacting current and future observational science goals. How can the designs for post-O5 detectors best address this excess (or at least facilitate the effort to identify and mitigate the excess)?"

Key quotes from the report

On 3G detectors in general:

- "The best path for upgrades of the detectors in the current 3- and 4 km observatories will evolve most significantly with the time scales for realizing CE and ET."

- "ET was included on the ESFRI roadmap in June 2021, which is equivalent to a quality label at the European level."

- "…the observational science value to having a network node in the southern hemisphere is significant. The community should continue to explore means to realize a next-generation observatory there."

Key quotes from the report

On Cosmic Explorer specifically:

- "Guided by the experience with the LIGO and Virgo detector commissioning, the CE team came to the conclusion that while making the detector longer evidently increased the cost, it appeared to be the lowest risk path to better sensitivity."
- "The cost for construction of the two sites and the detectors for them is roughly estimated at a cost of $1.6B 2021 USD. Operations then follows, with a yearly cost estimated to be $60M 2021 USD."

Dawn VI Meeting on Next Generation Observatories

October 5-7, 2021

Virtual event

Next Generation Observatories
Report from the Dawn VI workshop; October 5-7 2021

Dawn VI SOC and Presenters

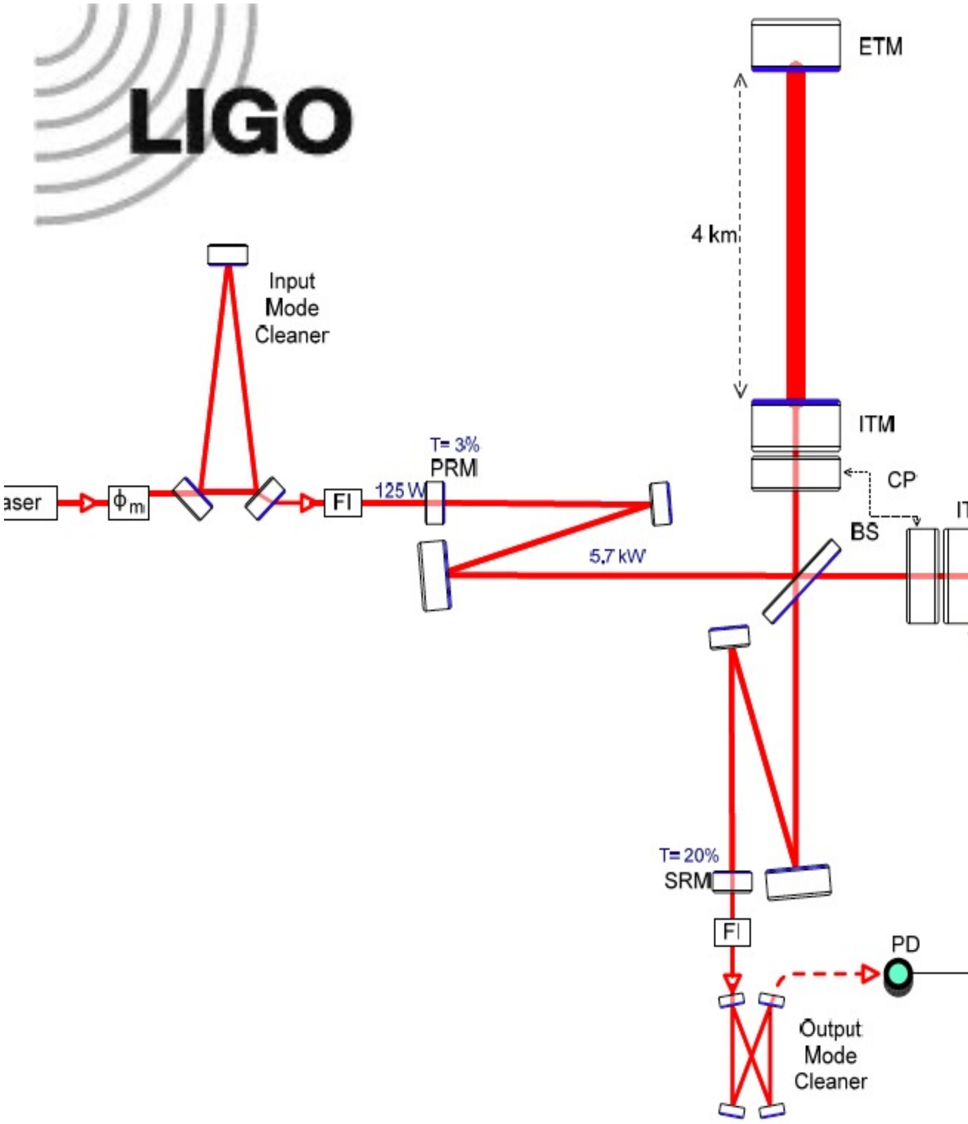
December 9, 2021

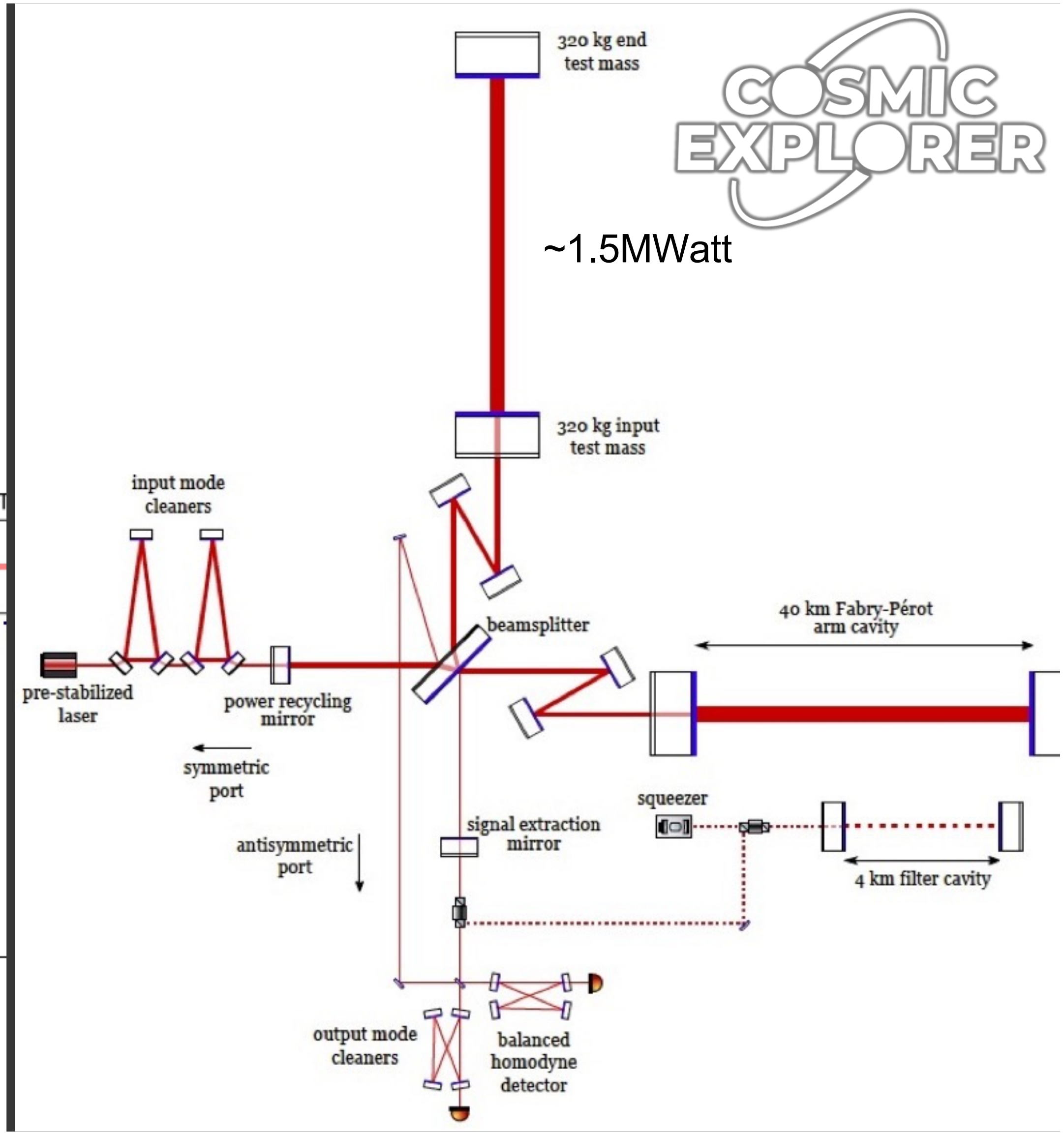
- "The science opportunities afforded by CE and ET are broad and compelling, impacting a wide range of disciplines in physics and high energy astrophysics. There was a consensus that CE is a concept that can deliver the promised science".
- Design phase cost of order $100M 2021 USD over 7-9yrs
  - Conceptual Design 3 years
  - Preliminary Design 2 years
  - Final Design 2-4 years
- https://gwic-documents.s3.us-west-2.amazonaws.com/dawn/Dawn-VI-report.pdf

Cosmic Explorer Reference Design

- A next-generation US-led gravitational-wave observatory
  - 40 km and 20 km L-shaped surface observatories
  - 10x sensitivity of today's observatories (Advanced LIGO+)

- Guiding principles:
  - "Build on what works"
    Basic configuration, silica technology, 1um laser
  - "Let observational science drive the design"
    Match antenna to known sources, wave front control, squeezing, etc.
  - "But keep it flexible" to take advantage of technology development
    Possible upgrade path to cryogenic, 2um, or Crystalline Coatings


LIGO
ETM
4 km
Input
Mode
Cleaner
ITM
T= 3%
PRM
CP
aser
ϕ_m
FI
125 W
BS
5.7 kW
T= 20%
SRM
FI
PD
Output
Mode
Cleaner


320 kg end
test mass
COSMIC
EXPLORER
~1.5MWatt
320 kg input
test mass
input mode
cleaners
beamsplitter
40 km Fabry-Pérot
arm cavity
pre-stabilized
laser
power recycling
mirror
symmetric
port
squeezer
signal extraction
mirror
antisymmetric
port
4 km filter cavity
output mode
cleaners
balanced
homodyne
detector

Configuration changes compared to Advanced LIGO

- Longer arm cavities (4km→40km)
- Larger test masses (m=40kg, ø=34cm →m=320kg, ø=70cm)
  - Minimal possible spot size for 40km (@ 1um) is 12cm, double of Advanced LIGO (Phys. Rev. D 103, 122004 (2001))
  - Reduction in radiation pressure noise
- 2^{nd} input mode cleaner for frequency stabilization (arXiv:2107.14349)
- Beam reduction telescopes on arm-side of beam splitter
- Lower-loss signal recycling cavity (e.g. BS orientation)
- Scaled filter cavity (compared to A+)
- Homodyne readout (same as A+)
- Larger vacuum system (cost-critical)

Cosmic Explorer Challenges

- Large Optics
- Coatings
- Squeezing (application)
- Suspensions and seismic isolation systems
- Vacuum system
- Site identification and Civil Engineering

Research & Development

- Cosmic Explorer-specific R&D document (white paper) available at tinyurl.com/P2100005
  (dcc.cosmicexplorer.org/public/0163/P2100005/001/ce-design-rnd.pdf)

- Will evolve as the CE design matures

The Message

- Endorsing the Dawn VI report is very much in the long-term interest of the LSC.
  - Read: arXiv:2112.12718
  - Endorse: https://bit.ly/3t8XMDz
  - Separate from Cosmic Explorer Horizon Study, please endorse that at cosmicexplorer.org
- R&D is needed for LIGO post-O5 and Cosmic Explorer
  - Lots of overlap
  - Numerous research topics
  - Corresponding proposals to NSF welcome
- Cosmic Explorer project established to
  - Develop execution plan
  - Coordinate high-priority Research and Development

End

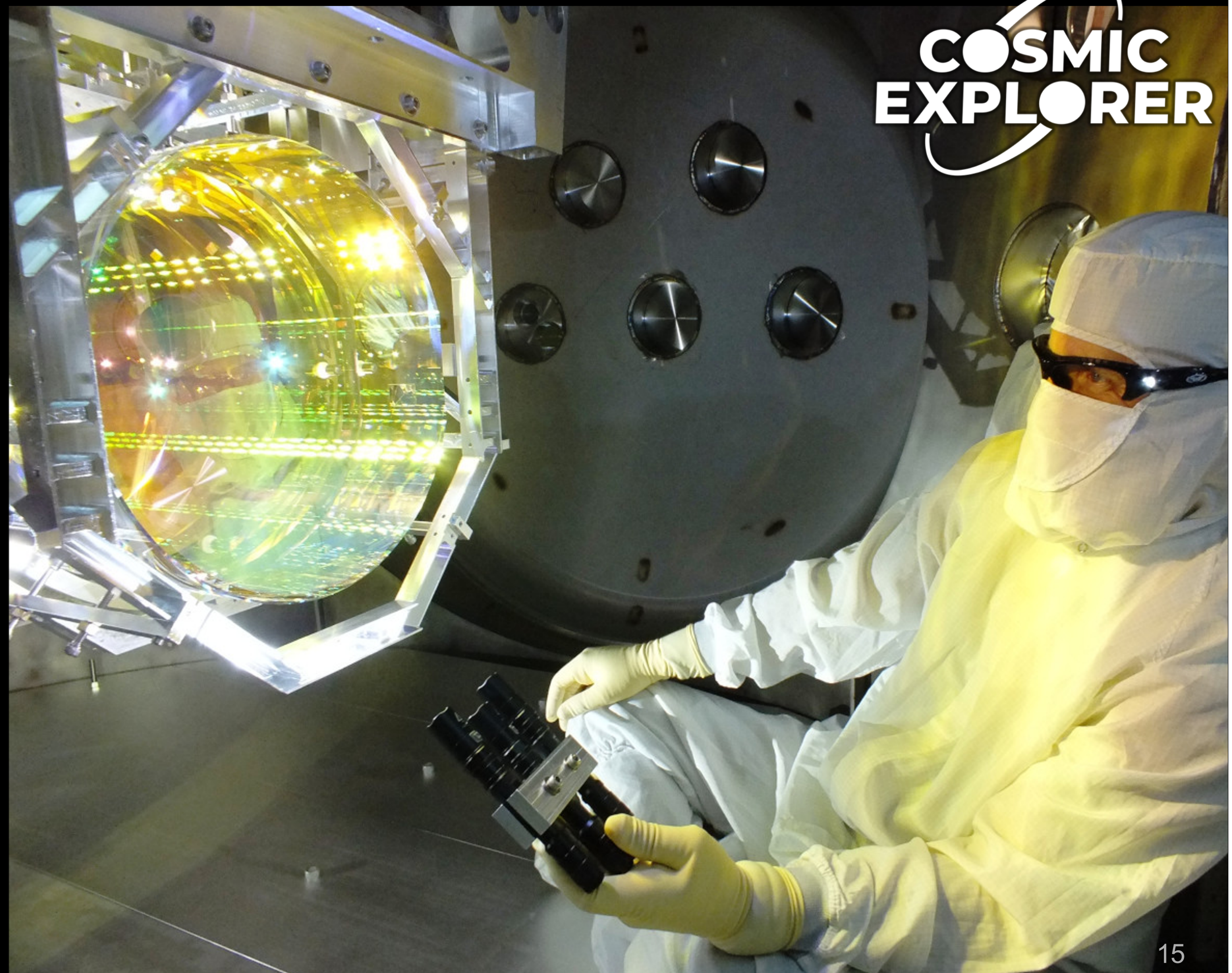
Extra slides

Large Test masses

320 kg ultra-pure glass:
Reduce thermodynamic fluctuations and heat-induced deformation

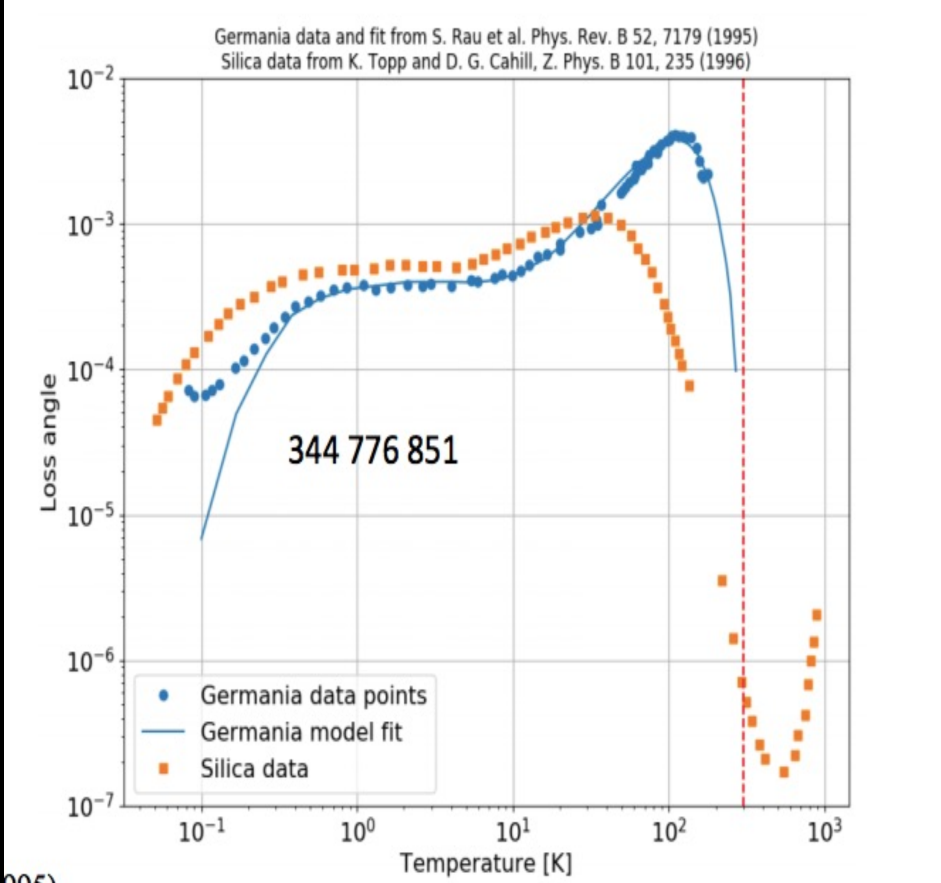
Research into fabrication techniques & metrology

Metal-oxide thin-film coatings:
Turn test mass into a mirror with reflectivity >99.995%



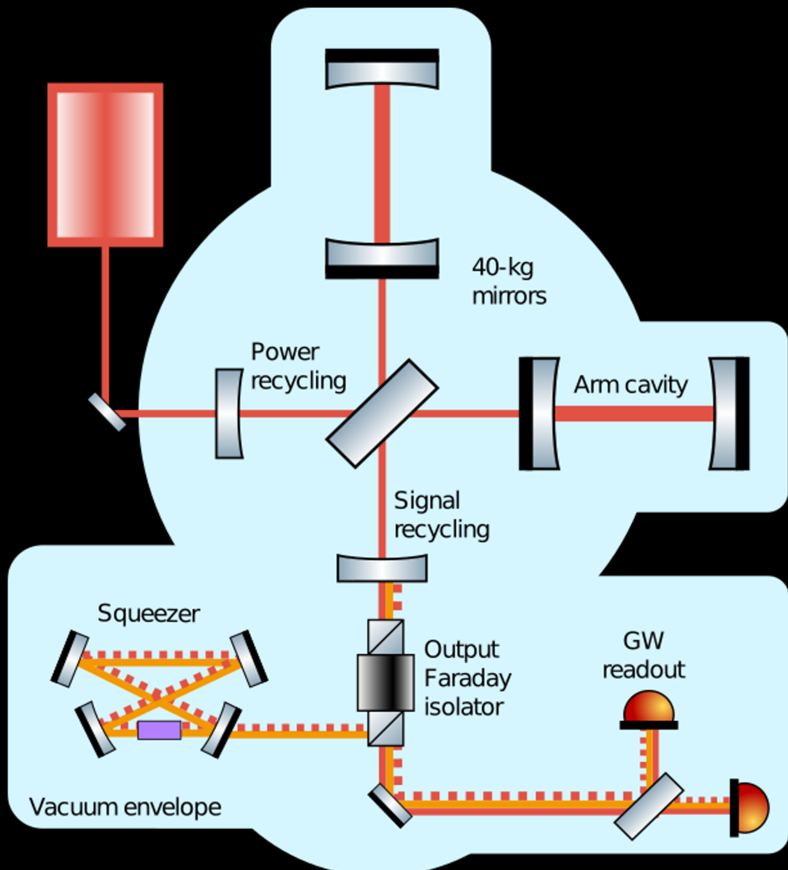
$TiO_2:GeO_2$ / SiO_2 coatings

- Germania (GeO_2) has loss angle ~4e-5
  - similar to Silica (SiO_2)
  - much lower than Tantala (Ta_2O_5)
- But:
  - Refractive index of Germania 1.6
  - 2.1 for Tantala
  - 1.45 for Silica
- Can achieve ~30% thermal noise amplitude reduction
- Candidate for A+ upgrade

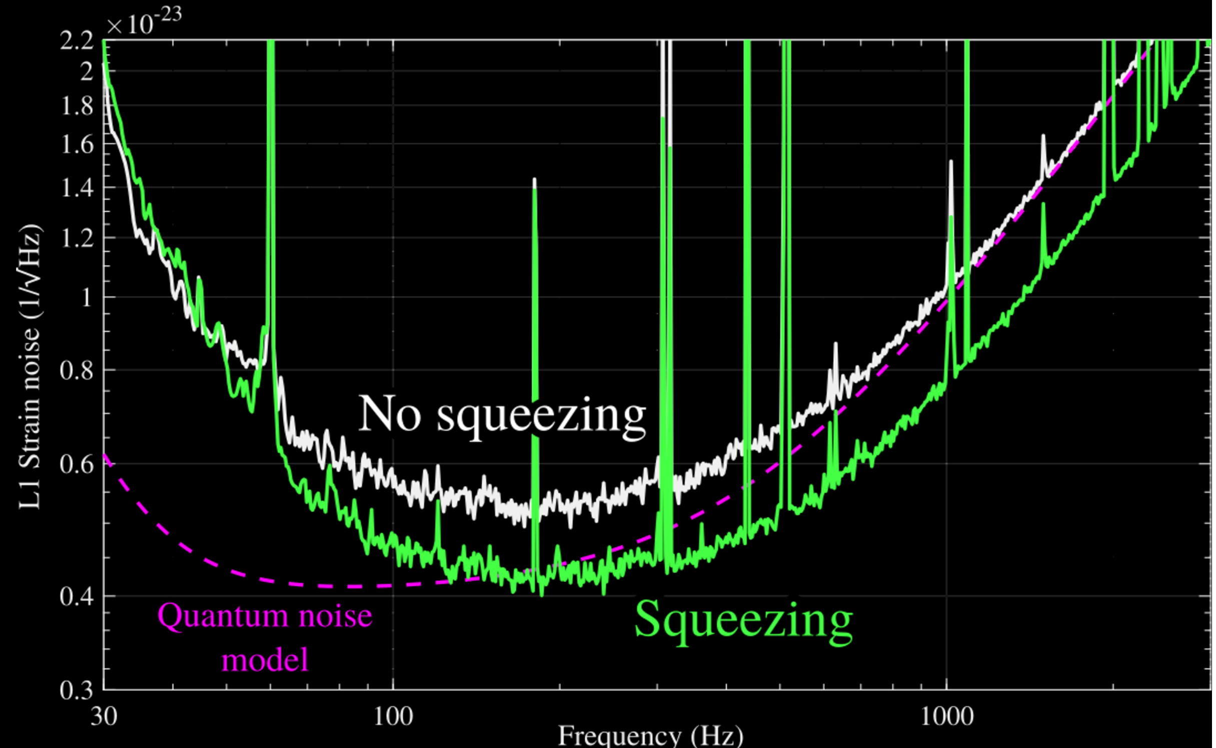


995)

Squeezed light



Yu et al. (2020), *Nature* **583** 43



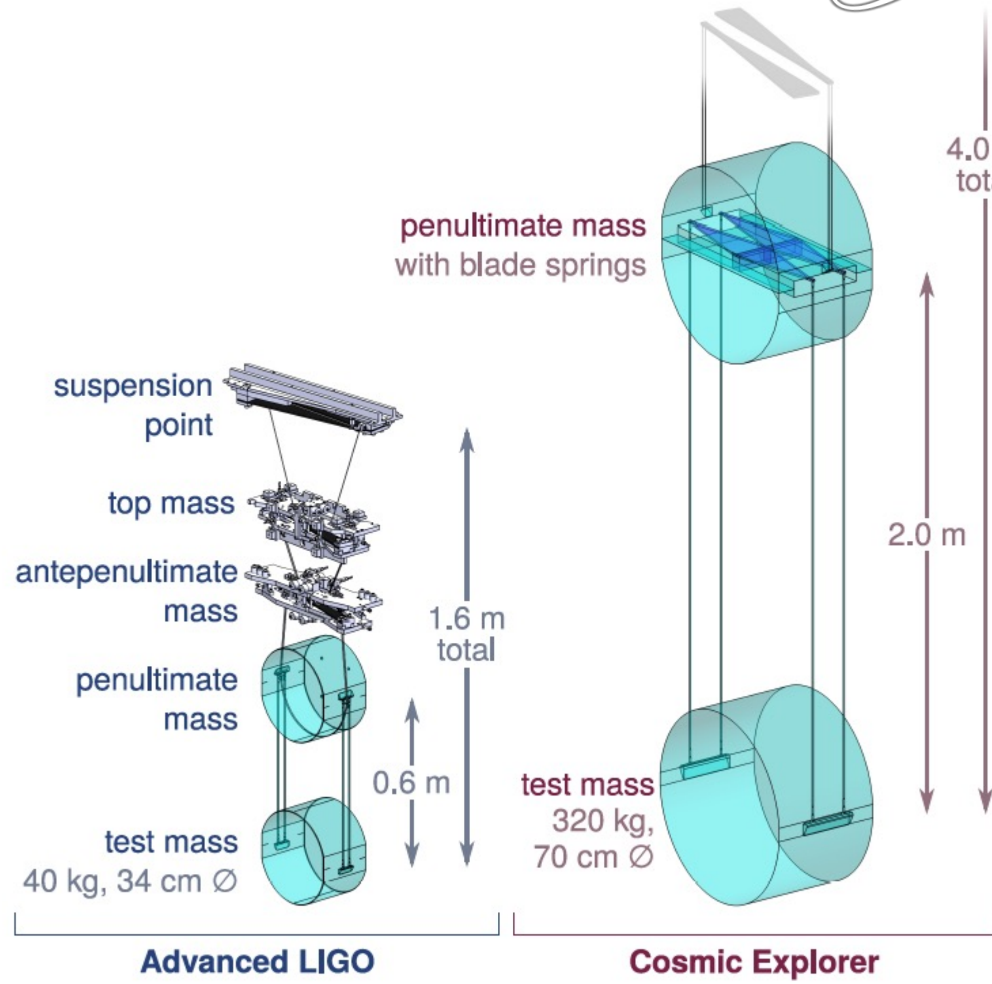
Tse et al. (2019), *PRL* **123** 231107

10dB squeezing in reference design

requirement on interferometer…

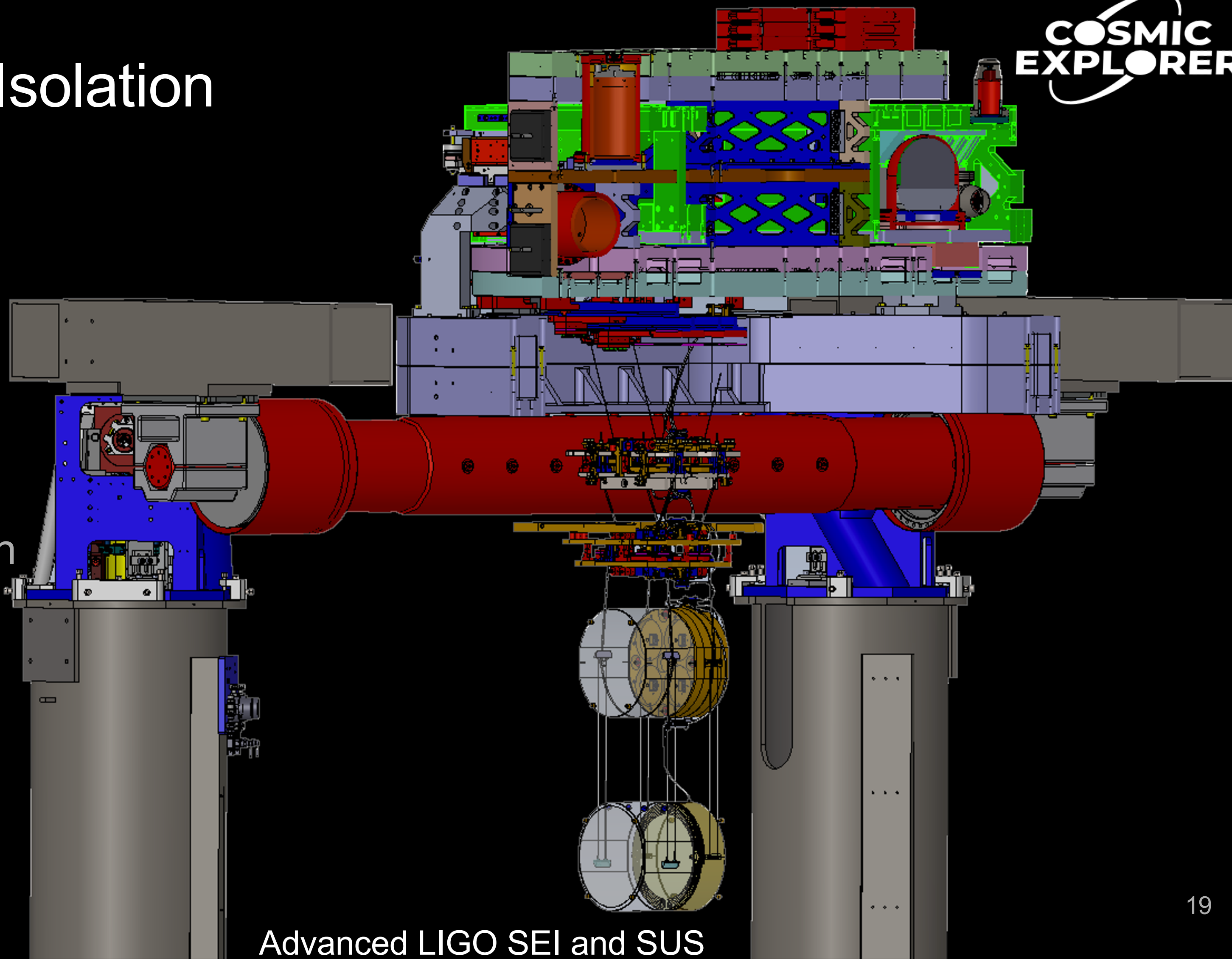
Suspension

- Built on Advanced LIGO design
- Scaled up to handle 320kg
- Scaled up to extend sensitivity to lower frequencies
- Add penultimate mass blade springs to reduce vertical suspension thermal and seismic noise.
- Phys. Rev. D 103, 122004 (2001)



Seismic Isolation

- Based on Advanced LIGO
- Support heavier mass, Longer suspension
- Improved inertial and position sensors



Advanced LIGO SEI and SUS

Vacuum system

World's largest ultrahigh vacuum volume

Two 40 km tubes,
1 m diameter

Total pressure ~ 1e-9 torr

Active research into:

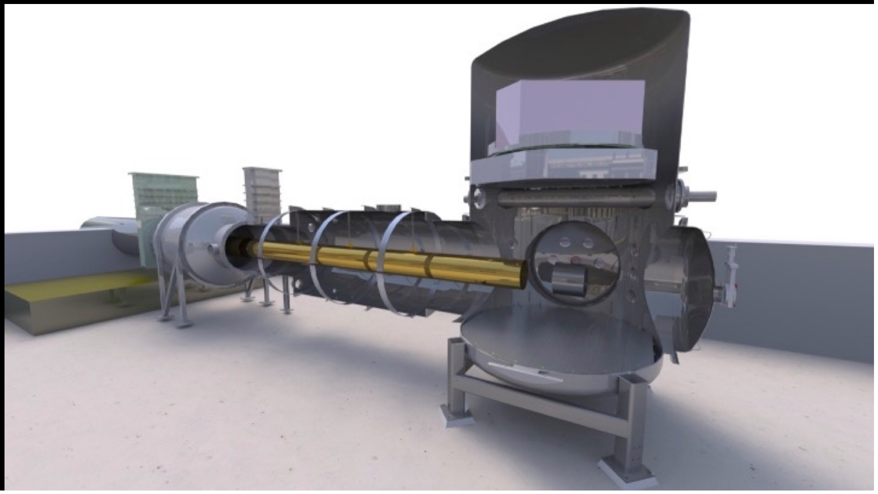
- Less costly, more durable materials
- Fabrication techniques
- Bakeout technologies
- Leak detection and mitigation systems

(NSF PHY-2110001)

Backup Technology Options

- Crystalline AlGaAs Coatings

- Cryogenic 2um interferometer

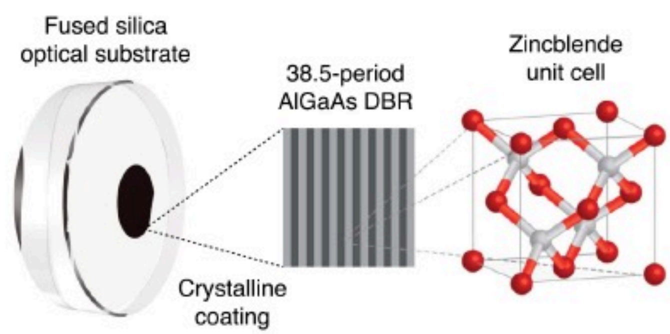


AlGaAs

- Meet the technical requirements
- Size limitation due to production process

Crystalline GaAs/AlGaAs Coatings • Overview

- The crystal is grown via Molecular Beam Epitaxy (MBE) on a single-crystal GaAs wafer.
- Alternating the Al alloy composition forms a Bragg reflector from layers of $Al_{0.92}Ga_{0.08}As$ ($n = 2.89$) and GaAs ($n = 3.30$)
- Wafer is etched away. Coating is transferred and bonded to substrate.
- Material is bandgap limited to $\lambda > 870$ nm
- Bragg reflectors can be made for $\lambda \approx 0.9 - 12$ µm. Specific mirrors produced at 1, 1.5, 2, 3.3, 3.8, 4, 4.5 µm



S. Penn, LIGO-G2101494

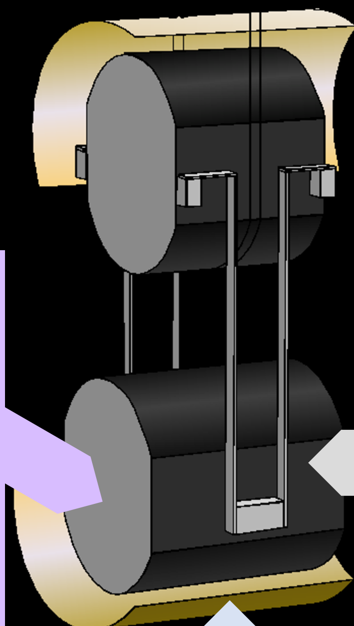
AlGaAs

- Very promising if large-diameter production is possible

Cryogenic interferometry at 2um

CORE IDEAS

(Voyager concept)



① Amorphous silicon coating
- Reduces thermal noise. Prospect of a **4-7x** reduction from aLIGO level
- Favors **2 μm** wavelength

② Crystalline silicon substrate
- Improves quantum noise. **200 kg** mass, **3 MW** power
- High thermal conductivity, ultra-low expansion at **123 K**

③ Radiative cooling
- Still efficient at **123 K**
- Suspension design not constrained by cryogenics

Adhikari et al. CQG 37 165003 (2020)

Cosmic Explorer Horizon Study

- 3-year NSF award (2018-2021) to "develop and document the international community's vision for third-generation science".
- PIs & Co-PIs on current NSF award
  - Caltech (PI: Yanbei, Adhikari)
  - Fullerton (PI: Lovelace, Smith, Read)
  - MIT (PI: Evans, Vitale)
  - Penn State (PI: Sathyaprakash)
  - Syracuse University (PI: Ballmer, Brown)
- Several postdocs and graduate students
- Input from the LIGO lab

Cosmic Explorer Meeting MIT, 2019

Horizon Study Document

- High-impact science in context of 2030-era astronomical observatories (Athena, Lynx, LISA, etc.)
- Connect science goals to design choices
  - Number of detectors and location
  - Detector length and configuration
- Delivered to the NSF this Fall:
  - https://arxiv.org/abs/2109.09882
  - https://cosmicexplorer.org