

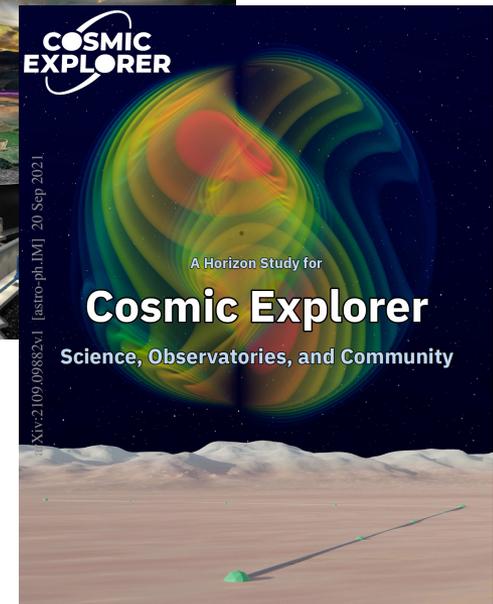
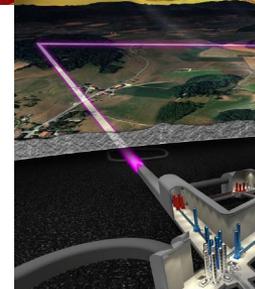
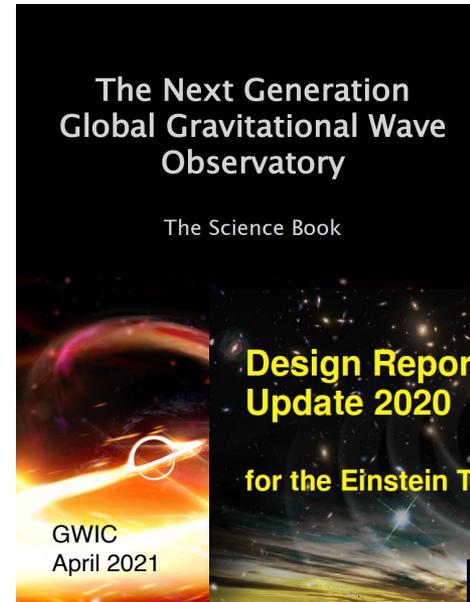
Next Generation US Gravitational-wave Observatories: LIGO Laboratory Roles and Perspectives

*Dave Reitze
Executive Director
LIGO Laboratory*

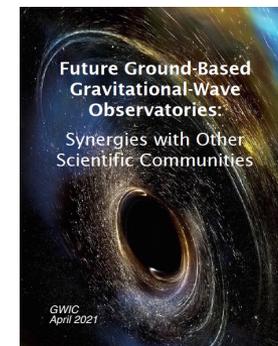
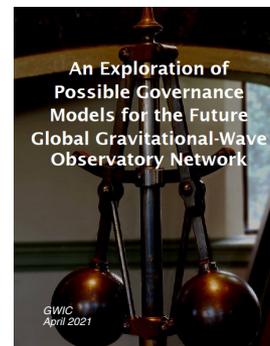
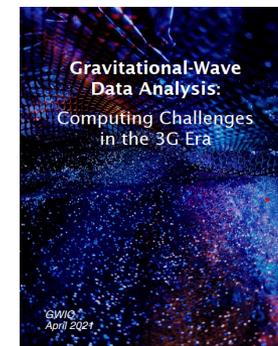
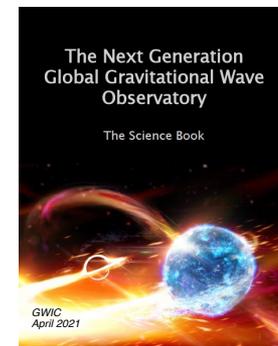
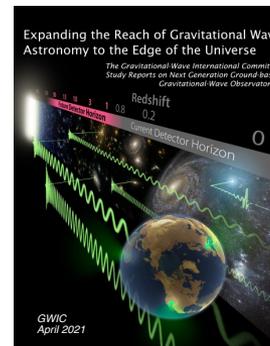
(with input from Albert Lazzarini, Fred Raab, Peter Fritschel)

- CE (and ET) Science: Awesome!
- LIGO Laboratory & CE: Retrospective and Perspective
- Challenges and Opportunities
- Moving into the Future

- The science case for future gravitational observatories – Cosmic Explorer and Einstein Telescope – is breathtaking.
 - » The GWIC Next Generation Global Gravitational Wave Observatory Science Book
 - » The Science Case for the Einstein Telescope
 - » The Cosmic Explorer Horizon Study
- Science themes (an incredibly abridged list):
 - » Survey stellar mass binary black hole systems throughout the Universe
 - » Understand the states and dynamics of the densest matter in the Universe
 - » Probe gravity on unprecedented scales
 - » Shed a new perspective on Dark Energy and Dark Matter
- Potential for new discoveries abound!
- Multi-messenger observations: synergies with other messengers/observatories
 - » GW: LISA
 - » OIR: Vera Rubin, ELT, TMT, GMT, ...
 - » Radio: SKA, ngVLA, ...
 - » Particle: IceCube Gen2, KM3NeT, AugerPrime, DUNE, HyperK
 - » Space: Nancy Grace Roman, Athena, Einstein Probe, NASA MidEx missions, ... (JWST?)



- Recognizing the scientific potential afforded by ‘3rd generation’ ground-based GW observatories, in 2016 [GWIC](#) charged a [3G Subcommittee](#) “with examining the path to a future network of observatories/facilities”
- Five reports have been issued (+ Introduction)
 - » Science Drivers for 3G Detectors: “The Science Book”
 - » R&D Coordination of the Global Ground-based GW Community
 - » Investigation of Governance Structures
 - » Computing Challenges
 - » Synergies w/ other Communities
- Each report was led by two or three co-chairs, and authored by experts in the specific subject matter
- Prior to release, reports were extensively reviewed by reviewers appointed by the [Gravitational Wave Agencies Correspondents](#)
 - » 30 reviewers with broad experience, including agency officers, discipline experts and generalist scientists.
 - » Lots of good feedback, with the verdict: “the great majority of the reviewers commend the authors for this exemplary work”
- These reports make lots of good recommendations and have been influential in the development of the updated Einstein Telescope Design Study and the Cosmic Explorer Horizon Study.
- So they are worth reading!



- The LIGO Laboratory is not currently a formal member of the CE consortium.
 - However, we are already involved in CE!
 - » Several LIGO Lab members are key members of the CE team or serve in advisory roles.
 - Current LIGO Lab involvement in Cosmic Explorer:
 - » The Horizon Study PI Matt Evans (MIT) and co-Is Rana Adhikari (Caltech) and Salvo Vitale (MIT) are Lab-affiliated faculty; many Lab members have joined the CE Consortium.
 - » Significant LIGO Lab Involvement in the writing of the Astro2020 Decadal Survey White Paper [*Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO*](#)
 - » David Shoemaker (chair), Bob Eisenstein, and Dave Reitze serve on the Cosmic Explorer Advisory Panel.
 - » The LIGO Laboratory was awarded an NSF PHY grant in 2021 to explore novel value-engineered concepts for Cosmic Explorer vacuum system. PI: Albert Lazzarini (LIGO Laboratory Deputy Director), Rai Weiss & Jon Feicht (LIGO Laboratory lead vacuum engineer) are participating investigators.
 - Partnerships with CERN and FermiLab vacuum groups!
- *The LIGO Laboratory brings expertise in research and development, design, and construction of km-scale gravitational wave observatories.*
 - » It functions as the US national laboratory for gravitational wave detector development!

- 1984 LIGO founded as a Caltech/MIT project
- 1990: LIGO Construction Project approved by NSF
- 1992: LIGO Construction Project funded by NSF
- 1992 --1995: Site selection, vacuum prototyping
- 1995 – 1999: LIGO facilities construction at Hanford and Livingston
- 1998 – 2002: Installation/integration of initial LIGO interferometers
- 2002 - 2005: Interferometer commissioning interleaved with science runs (S1-S4)
- Nov 4, 2005 – Sept 31, 2007: S5 science run
 - » Design sensitivity reached
 - » 15 Mpc range; > 1 year of triple coincidence data
- 2007 – 2009: Enhanced LIGO instrument upgrade
 - » Tests key Advanced LIGO technologies
- July 7, 2009 – Oct 20, 2010: S6 science run
 - » 18 Mpc range to merging binary neutron stars
- April 2008: Advanced LIGO Construction begins
- Dec 2011 – Advanced LIGO detector installation begins
- Mar 2015 - Advanced LIGO Construction complete
- Sept 2015 – First Advanced LIGO Observing Run 'O1'
- Sept 14, 2015 – First binary black hole detection
- Oct 2018 – Advanced LIGO Plus 'A+' Midscale

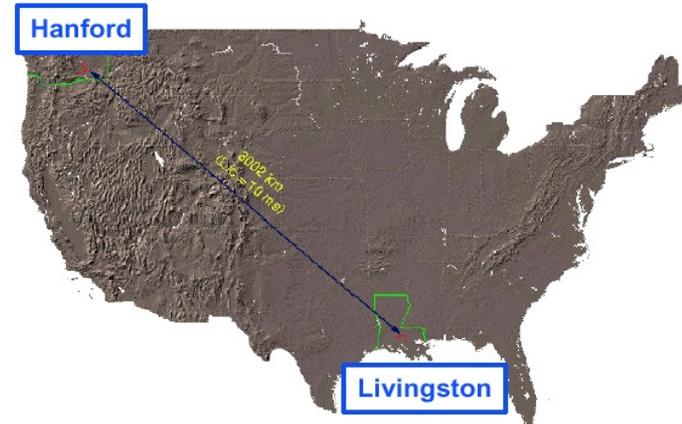
**Initial LIGO:
Design**

**Initial LIGO:
Construction**

**Initial LIGO:
Operations
Advanced LIGO:
Design**

**Advanced LIGO:
Construction
& Operations**

A+ Midscale Construction

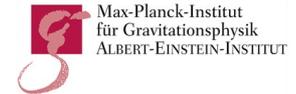


**LIGO Laboratory:
190 staff located at Caltech,
MIT, Hanford, Livingston**

**LIGO Scientific
Collaboration: 1400 people
from 100+ institutions and 20
countries**



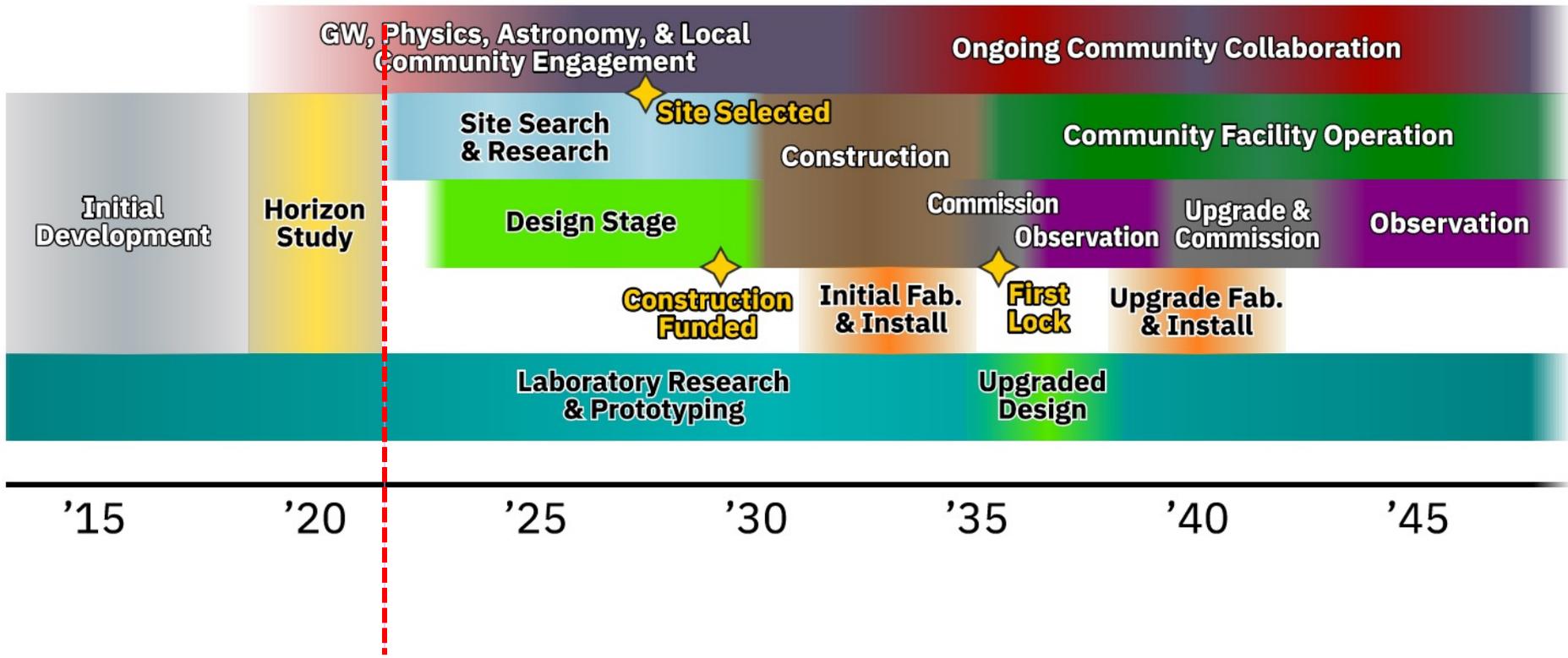
- Many of the core Advanced LIGO technologies were contributed by international collaborators:
 - » The 'pre-stabilized' high power laser (by Max Planck Albert Einstein Institute, Germany)
 - » The 4-stage test mass suspensions (by Univ. Glasgow and Rutherford Labs, UK)
 - » The output optics, arm length stabilization (by Australian National Univ., Australia)
 - » Test mass mirrors coatings (by Laboratoire d'Optique Appliquée, France)
 - » High power handling Faraday isolators (by Institute of Applied Physics, Russia)
- The GEO600 interferometer tested many concepts used in Advanced LIGO (Max Planck Albert Einstein Institute, Germany)
- Many detector research & development efforts leading to the Advanced LIGO design were carried out by international partners
- ~ 30% of computational resources come from overseas
- The future: we are awaiting for LIGO India to come online!
 - » A partnership between Raja Ramanna Centre for Advanced Technology, Institute of Plasma Physics, InterUniversity Centre for Astronomy and Astrophysics, and Departments of Atomic Energy and Science and Technology (India) and LIGO Laboratory and NSF (USA)

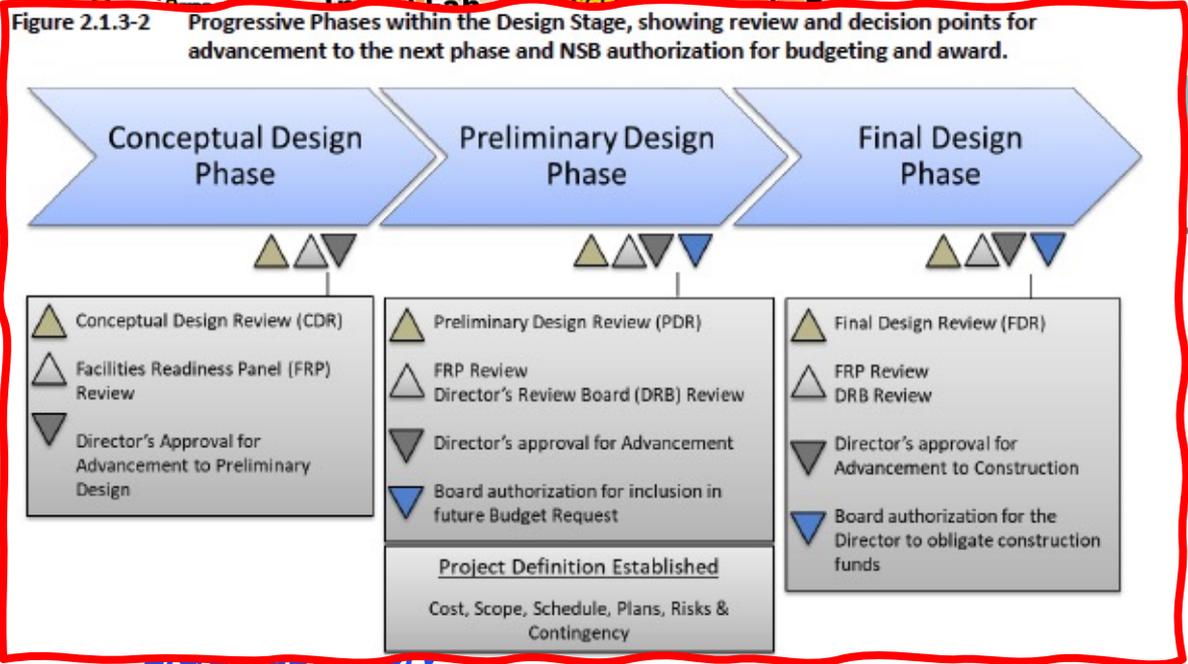
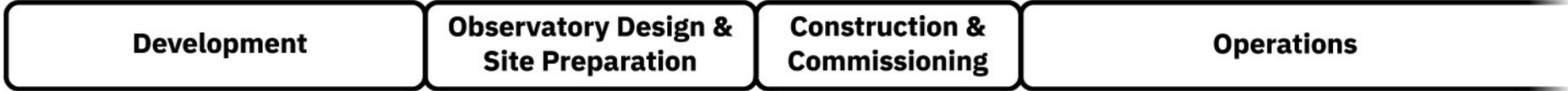


Key Recommendation from the GWIC R&D Report: International consortia should be formed to work on key R&D challenges and opportunities with industrial partners, establish a governance and organizational structure with authority and seek funding through joint proposals submitted across funding agencies.

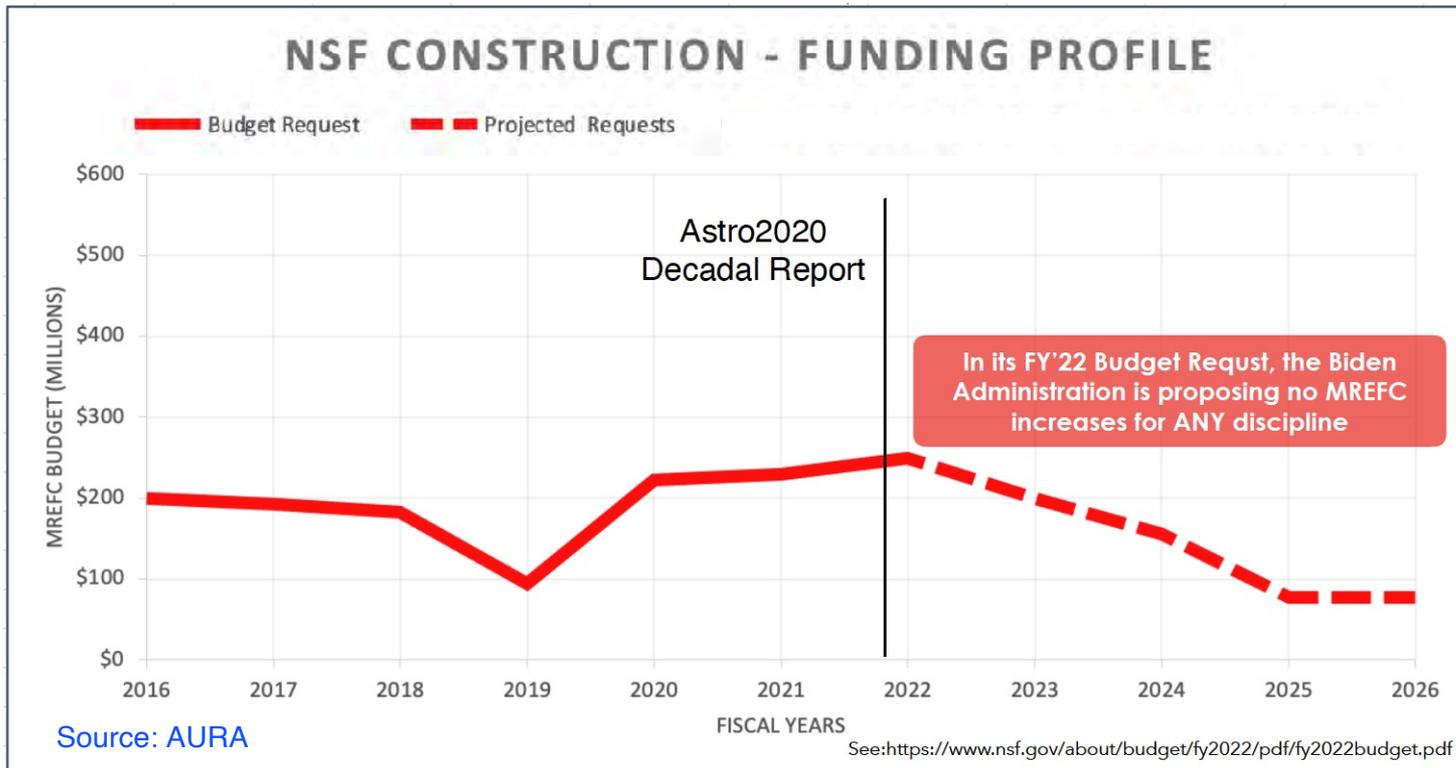


- By virtue of its expertise and experience, the LIGO Lab is planning to take on specific roles in the Cosmic Explorer Project.
 - » LIGO Laboratory personnel working on specific aspects of CE
 - » LIGO Laboratory infrastructure available as needed for CE R&D and prototyping
 - » ...
 - Per discussions with NSF, CE will not be built into the current or future core LIGO Maintenance and Operations awards.
 - » LIGO Laboratory primary focus over the next ten years will be to i) keep the existing LIGO Hanford and Livingston Observatories producing data and ii) carry out upgrade programs to improve the reach of the Advanced LIGO detectors.
 - LIGO Lab involvement in CE support will come through targeted proposal (Design Phase Proposals)
- My perspectives:
 - » The LIGO Laboratory will need to play a foundational role in CE over the coming years.
 - » Cosmic Explorer is an order of magnitude larger than LIGO.
 - Almost any way one looks at it: arm length, construction budget, site size ...
 - » → There must be significant participation by the US and international GW community well beyond the LIGO Laboratory.
 - » The scale of CE necessitates developing/cultivating a strong central laboratory structure (project management, system engineering, business functions, ...) beyond the scale that exists today.





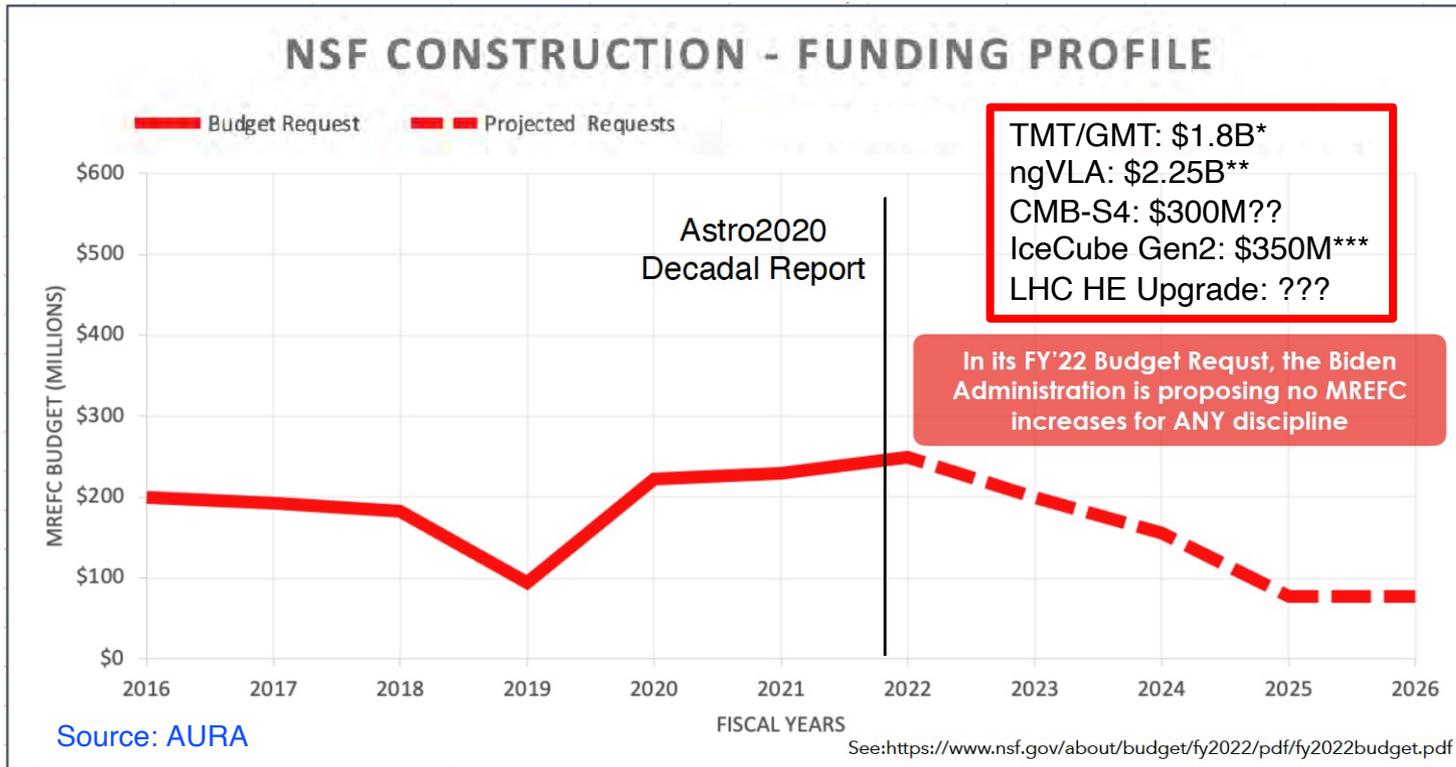
- Funding profiles for NSF MREFC budget line



Cosmic Explorer
MREFC Start
(\$1.65B,
2021\$)

2030

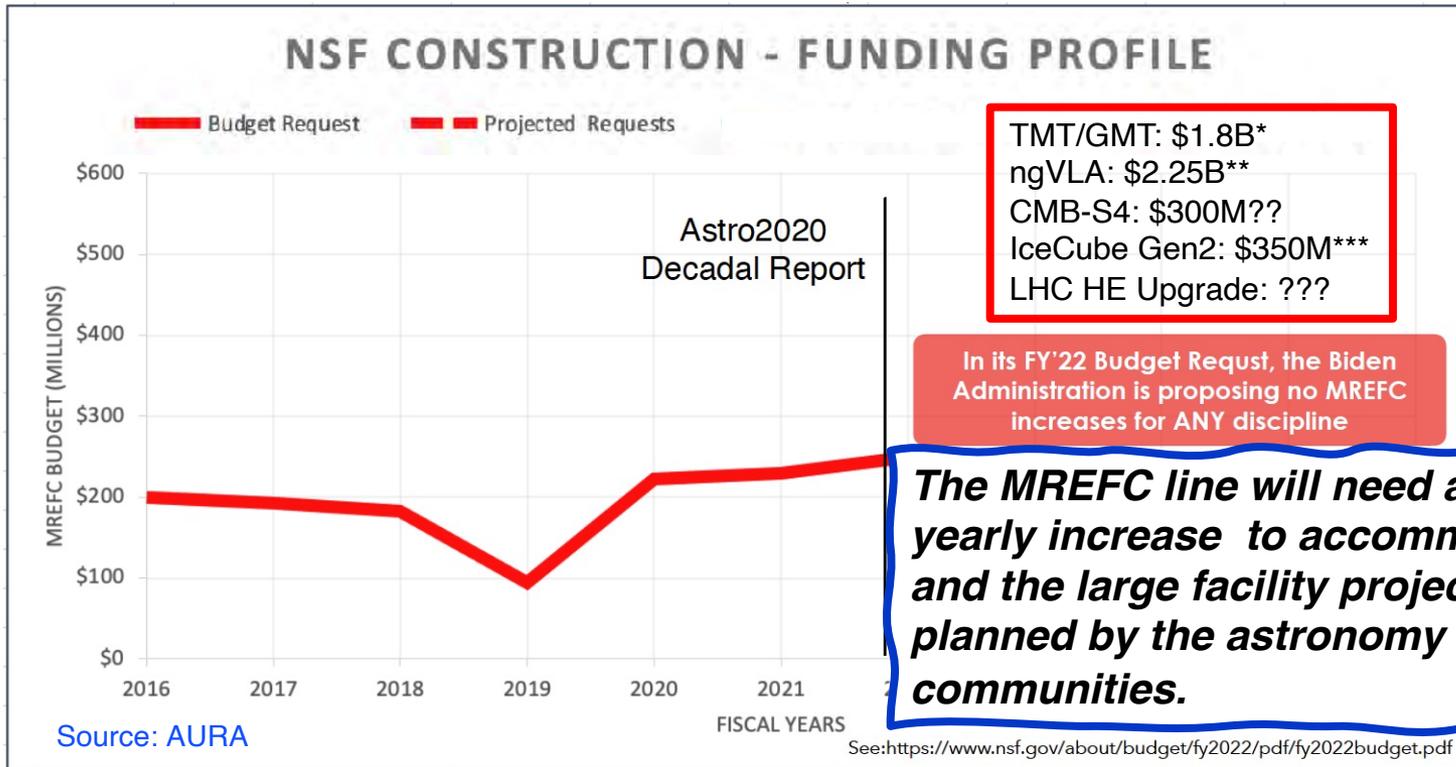
● Funding profiles for NSF MREFC budget line



* [Science Mag, 1 Sept 2021](#)
 ** [ngVLA Web Site](#)
 *** [IceCube Web Site](#)

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2030

- Design Stage funding is critical to move CE forward on the proposed time scale
 - » This will enable many critical activities to begin (all of which are needed to get through the Final Design Review gate):
 - Establishment of a CE Project Office
 - WBS Structure Development and Refinement
 - System Engineering
 - Schedule & Milestones
 - Realistic Budget
 - Risks and Mitigations
 - ...
 - Refinement of the site selection criteria and process for final selection
 - Site permitting (NEPA, NHPA, local, ...) and partnerships w/ local/indigenous communities, ...
 - Science Requirements and flowdown to Detector Requirements
 - R&D prototyping of critical CE subsystems
 - ...
 - The science case is compelling, but that doesn't mean it will be easy to get a CE construction project funded!
 - » NSF will need a large increase in the MREFC budget and/or DOE Laboratory involvement will be needed. Good news: There is an existence proof for joint NSF/DOE construction funding model! The Vera Rubin Observatory
- Whatever the pathway forward, the LIGO Lab is planning to contribute in a major way to make CE a reality.

Thanks!

- O4 will (hopefully) begin in late summer early fall 2022; (less certainly) O5 will begin in early 2025.
- O5 duration: schedule still under development, perhaps 3 years long
- This morning's panel "Roadmap for the current observatories until CE/ET observe" provided some perspectives for Post O5 evolution of current GW detectors.

- LIGO Voyager offers significant gains in sensitivity over current Advanced LIGO detectors: $z > 7$ for $\sim 100 M_{\odot}$ mergers (source frame)
- There are some considerations to work through:
 - › Needed technology development: (mild) cryogenics, pure silicon test masses, 2 μm lasers
 - › Time scale for implementation and project cost?
 - If more than \$70M (MREFC), does it compete with Cosmic Explorer?
 - › *Down time for existing Advanced LIGO Detectors: how long a down time would the community be willing to tolerate?*