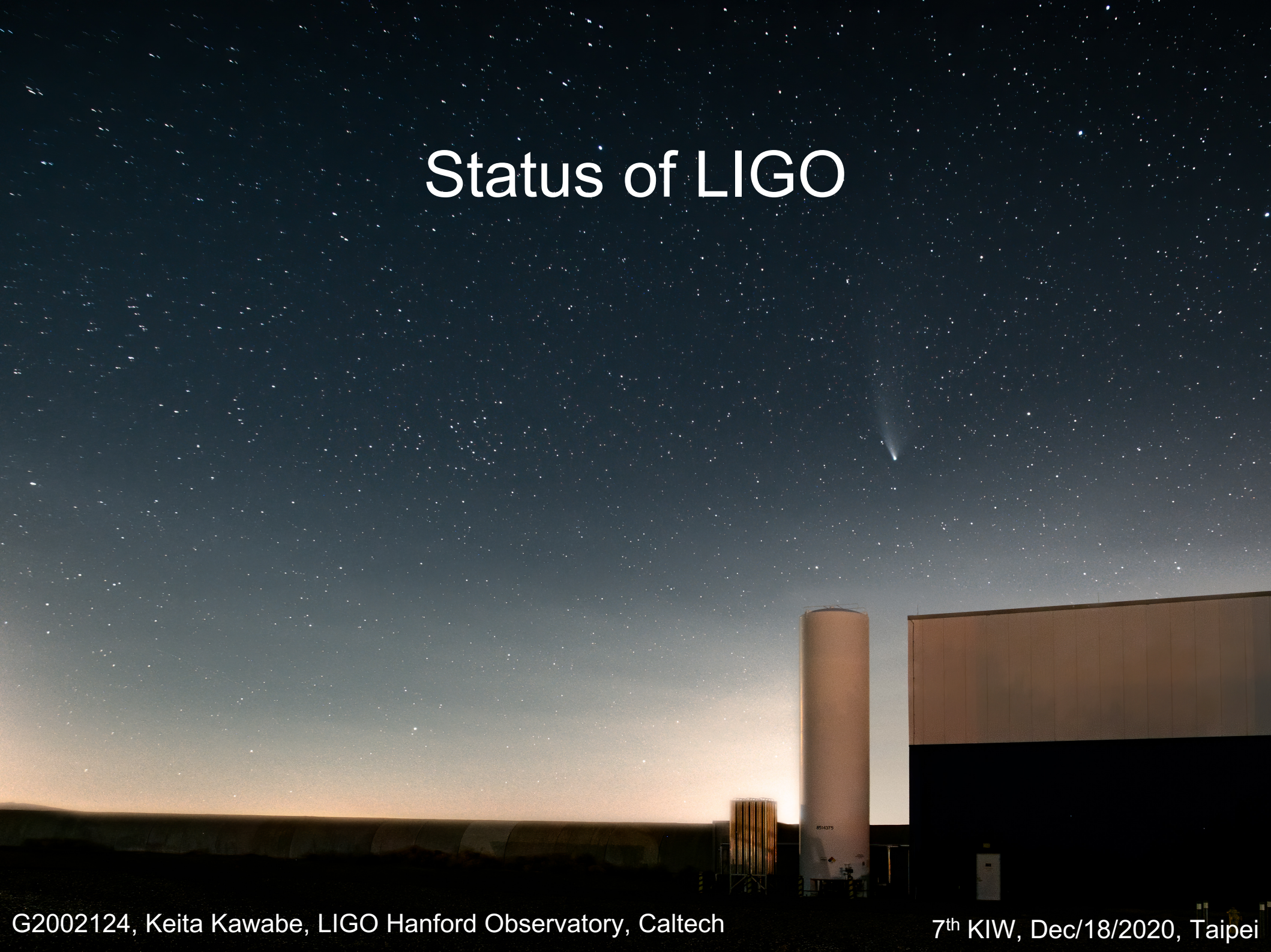
Status of LIGO

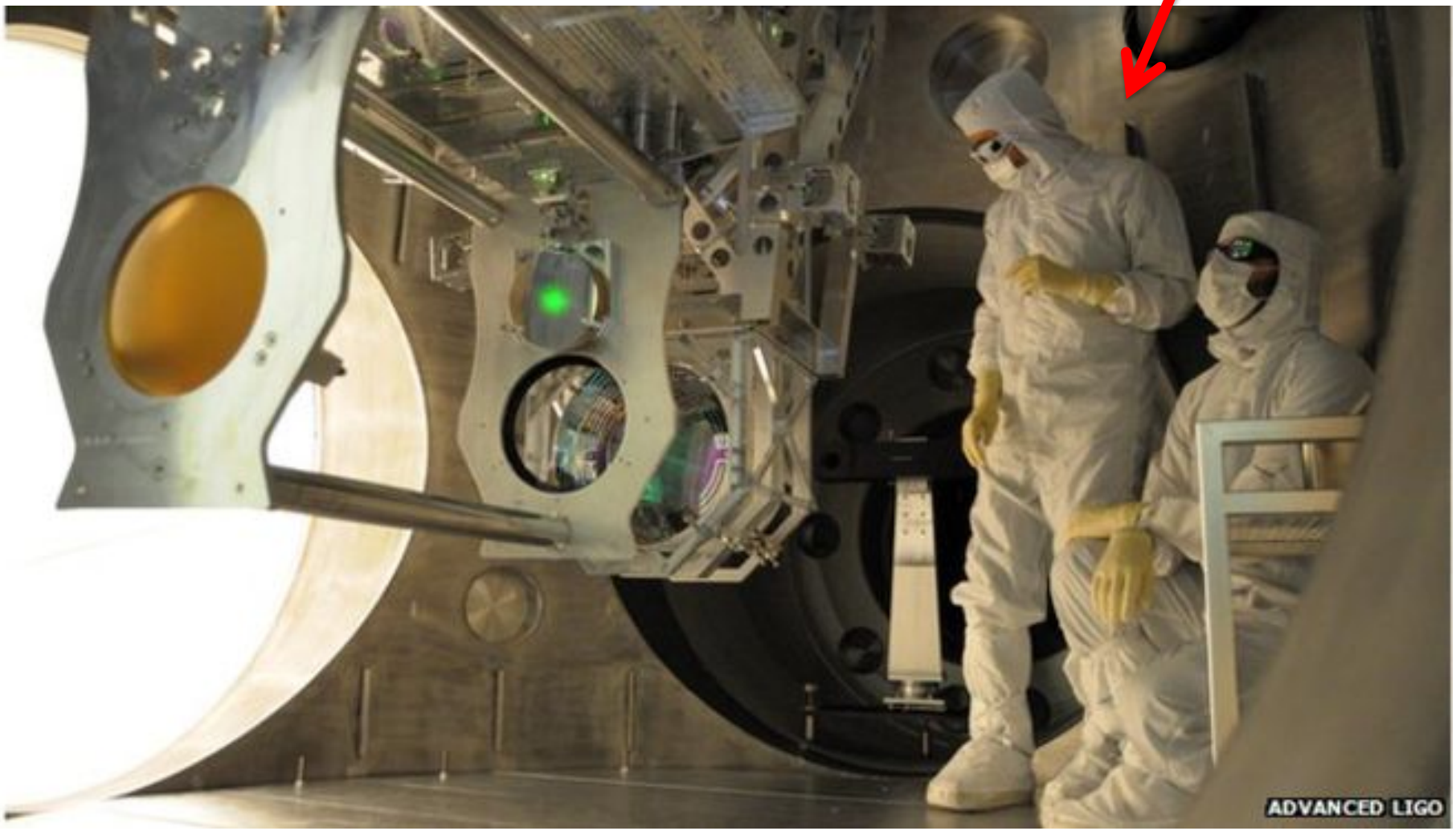


G2002124, Keita Kawabe, LIGO Hanford Observatory, Caltech

7th KIW, Dec/18/2020, Taipei

About the speaker

河邊径太 (Kawabe, Keita) PhD

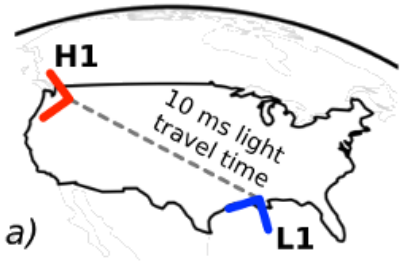


LIGO

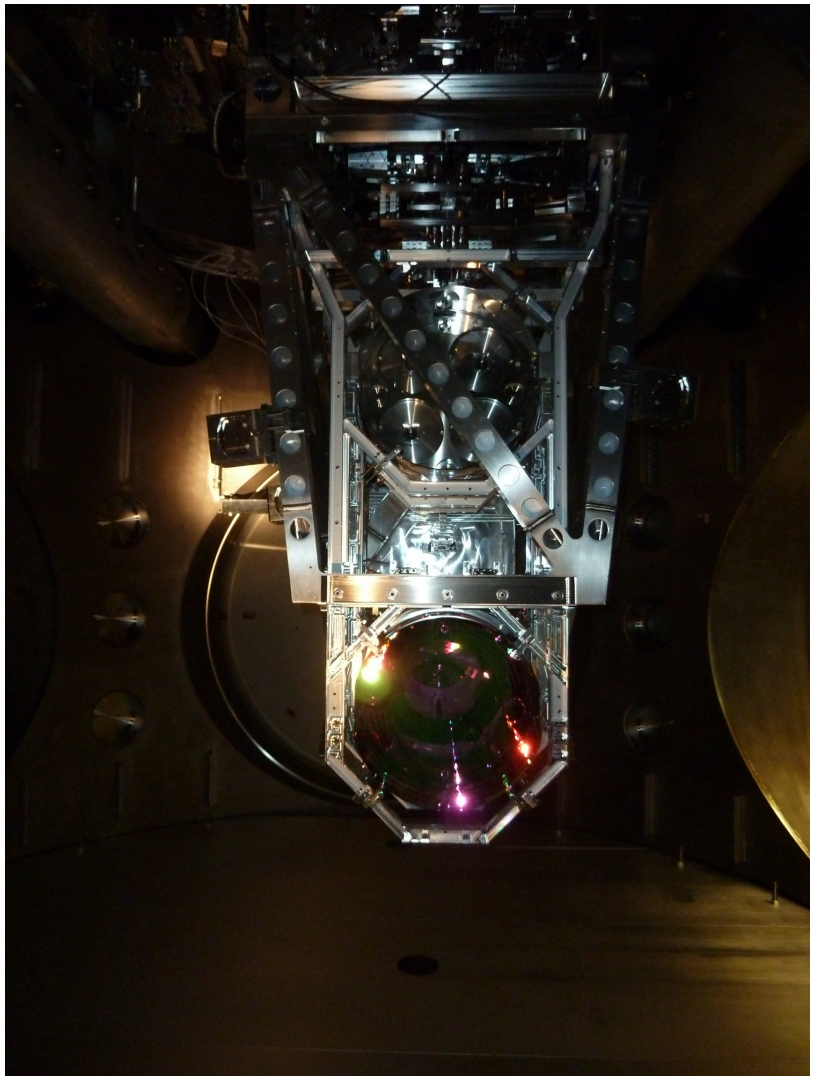
TOC

- (Brief) LIGO in the past, Observing Runs
- LIGO under COVID
- O4 preparation and enhancements
- (Brief) A+
- (Brief) India

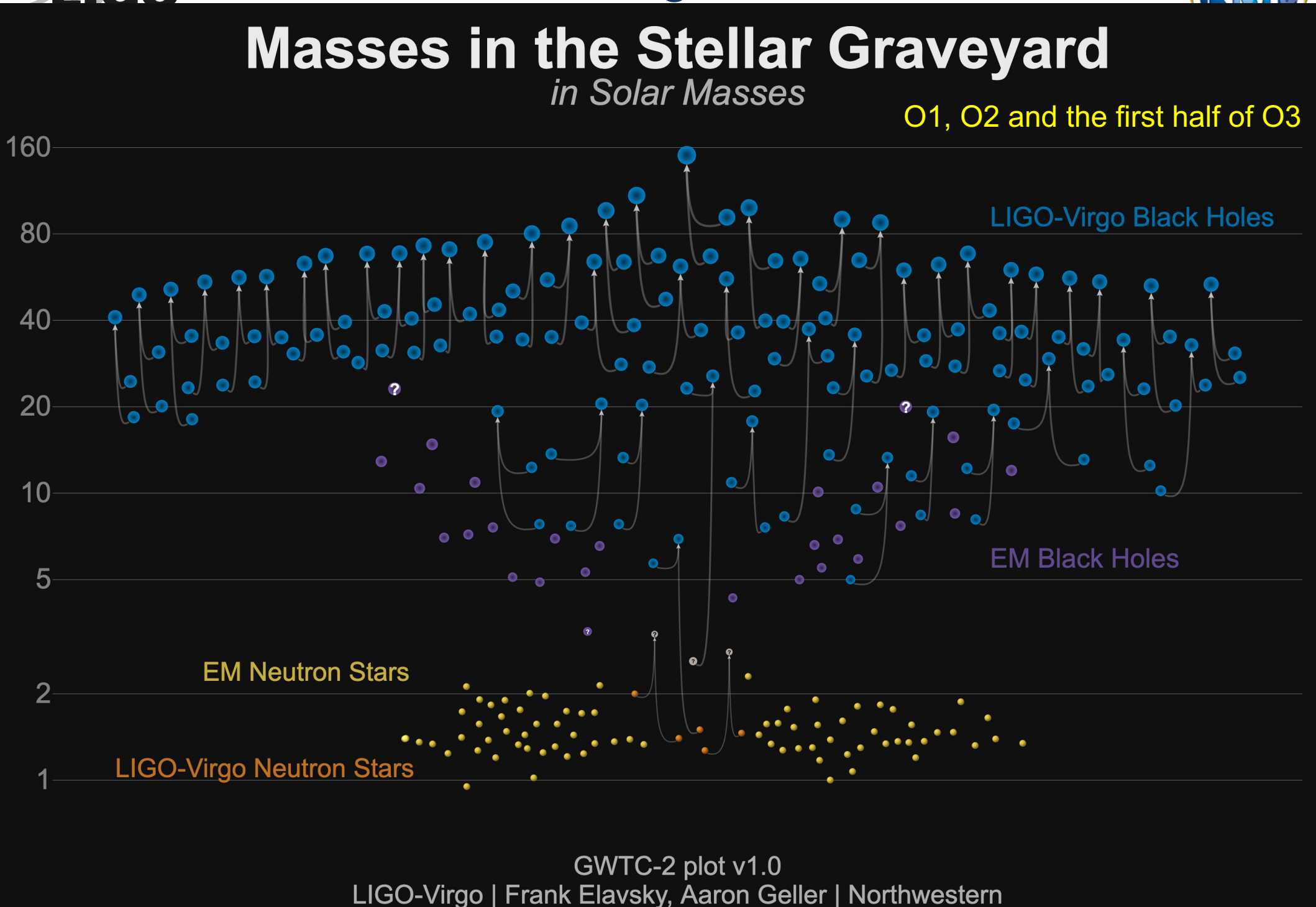
LIGO: Twin instruments in USA (But LIGO India is coming!)



Just to give you the sense of the scale of things



Three Observing Runs So Far:



Three Observing Runs So Far: O1, O2 and O3 (=O3a+O3b)

- O1 (Sep/2015-Jan/2016): 3 BBH by LIGO.
  - GW150914: First detection. Beginning of GW astronomy era.
- O2 (Nov/2016-Aug/2017): 7 BBH and 1 BNS.
  - Virgo joined in Summer!!
  - GW170817: BNS with EM. Beginning of MMA.
- O3 (Apr/2019-Mar/2020, one-month break in Oct.)
  - Full Virgo participation.
  - Terminated in Mar/2020 due to COVID before KAGRA joined.
  - O3a, 1st half of O3 (Stas' talk.)
    - Detection results in GWTC-2 catalog (https://arxiv.org/abs/2010.14527). 39 event candidates, one BNS, one NSBH and one BH-"mystery" small object.
    - Papers about notable events.
  - No O3b paper yet. Expect more O3 publications in the future.
  - Started distributing low-latency public alerts!

Low latency public alerts with localization, source classification etc.

Visit OpenLVEM Forum for details.
(https://wiki.gw-astronomy.org/OpenLVEM/)

https://gracedb.ligo.org/superevents/S190924h/view/

GraceDB — Gravitational-Wave Candidate Event Database

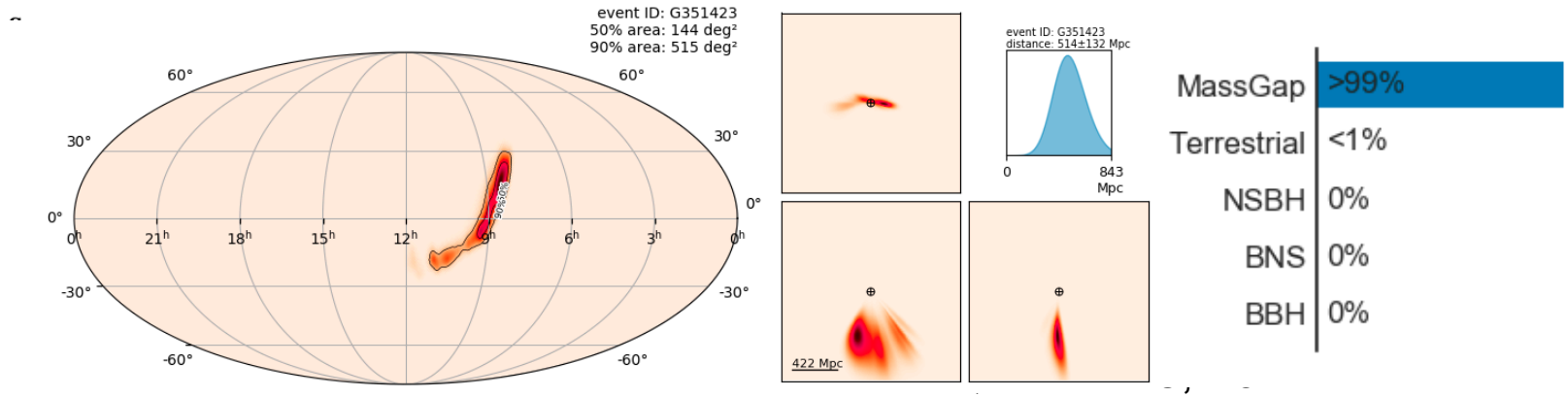
HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION | LOGIN

Superevent Info

Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S190924h	Production	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	8.928e-19	1 per 3.5493e+10 years	1253326743.785645	1253326744.846654	1253326745.876674	2019-09-24 02:19:25 UTC	Data

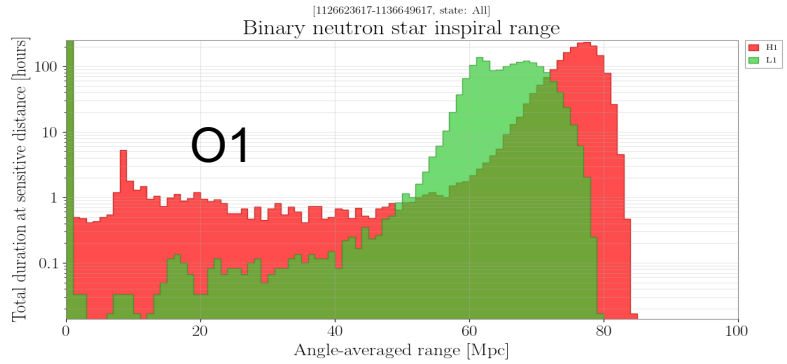
Preferred Event Info

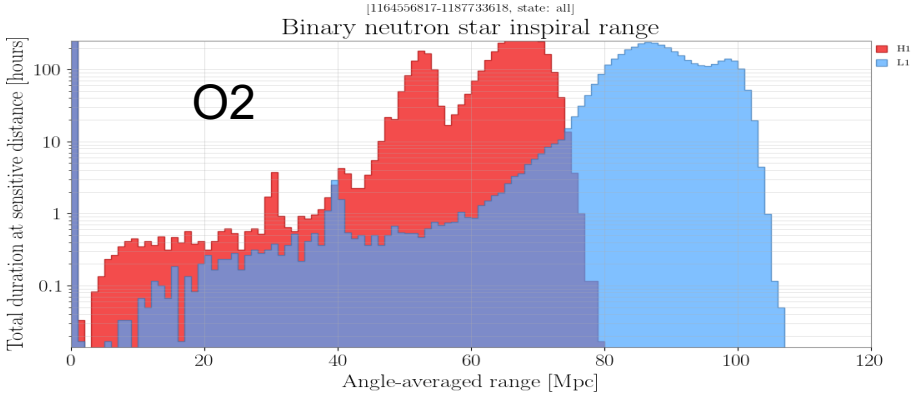
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	H1,L1,V1	1253326744.8467	2019-09-24 02:19:15 UTC

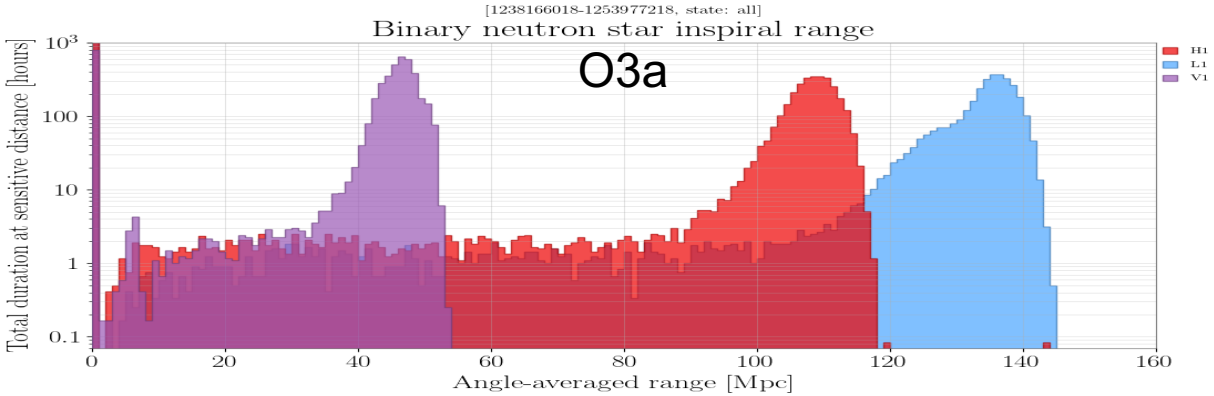


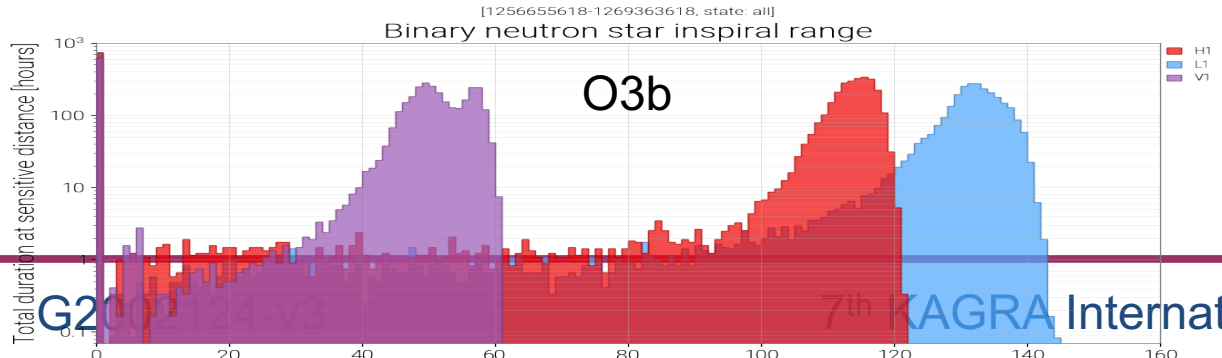
October 2019

We take observation-upgrade cycles approach.









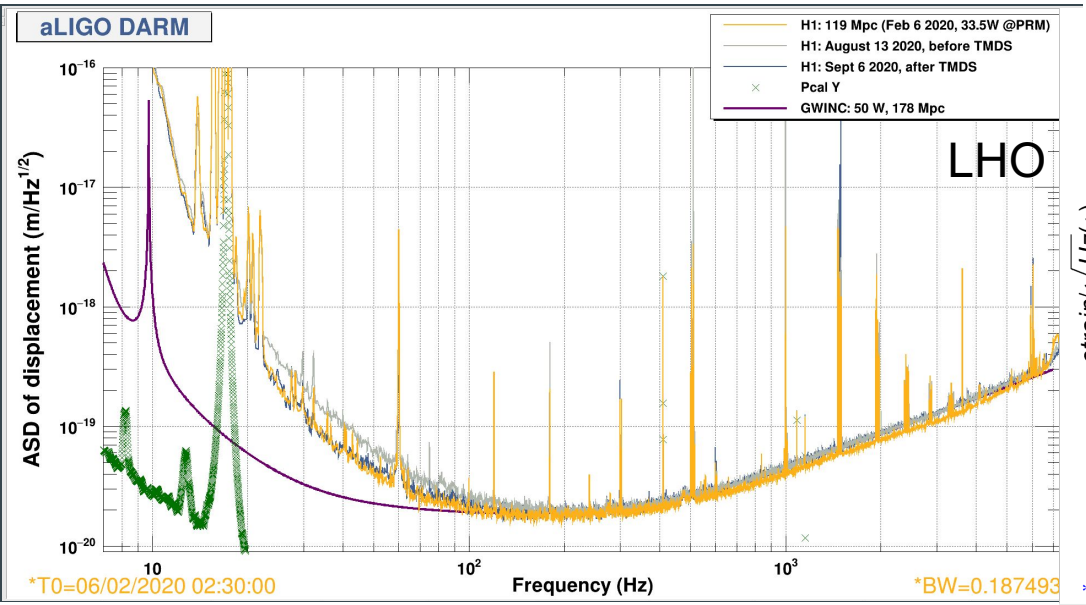
- Detectors don't perform as initially envisioned from get-go.
- Learn from observing.
- Make upgrades incorporating the lessons learned.
- Repeat this cycle.
- We're in the middle of the upgrade phase for O4.

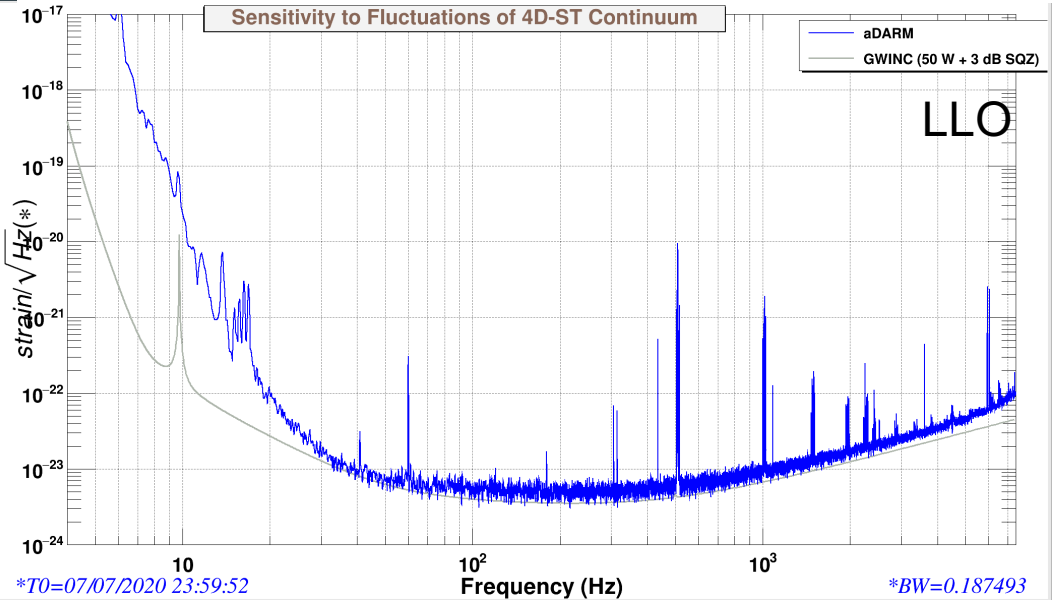
O4 will be our first 4-detector run with LHO, LLO, Virgo and KAGRA!

- Will continue for 1 calendar year.
- Originally projected to start late 2021 – early 2022, but it's delayed as far as LIGO is concerned due to something not related to COVID. More on this later.

LIGO timeline since the end of O3

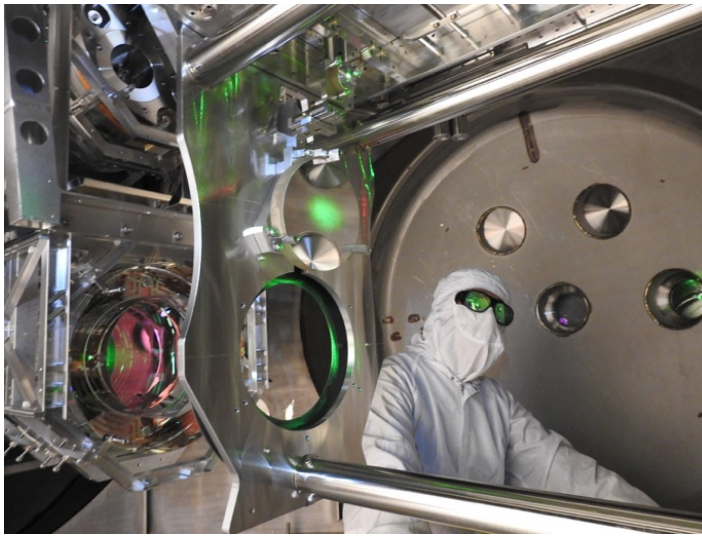
- Mar. 27 2020: O3 ends 1 Month earlier than planned.
- Mar 30-Jul 5(LLO), Jul 26 (LHO): Phase 3, only to maintain the integrity of the detector and the facilities.
- Jul- ongoing: Phase 2. Limited person power at the site under strict safety guidelines. O4-prep ongoing.
- Before doing big surgery, we first recovered IFO's sensitivity to O3-level successfully.

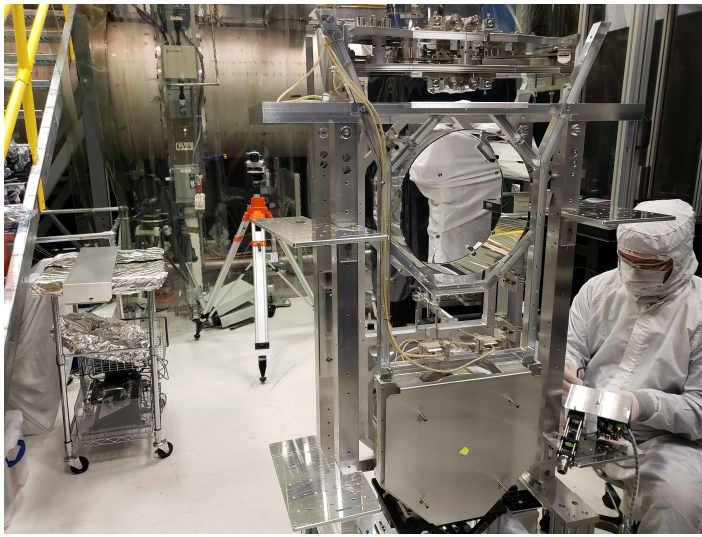




LIGO sites today

- Sites under Phase 2 (mission triage).
  - Focus on the most important tasks. Emphasis on human safety and stewardship of the detectors/sites.
  - 20+ to 50% of site staff are at the Observatories on any given day.
- Travel restrictions are in place.
- These have impacts on efficiency etc., nevertheless we've been making good progress on installation/upgrades for the next observation run. (More on this later.)



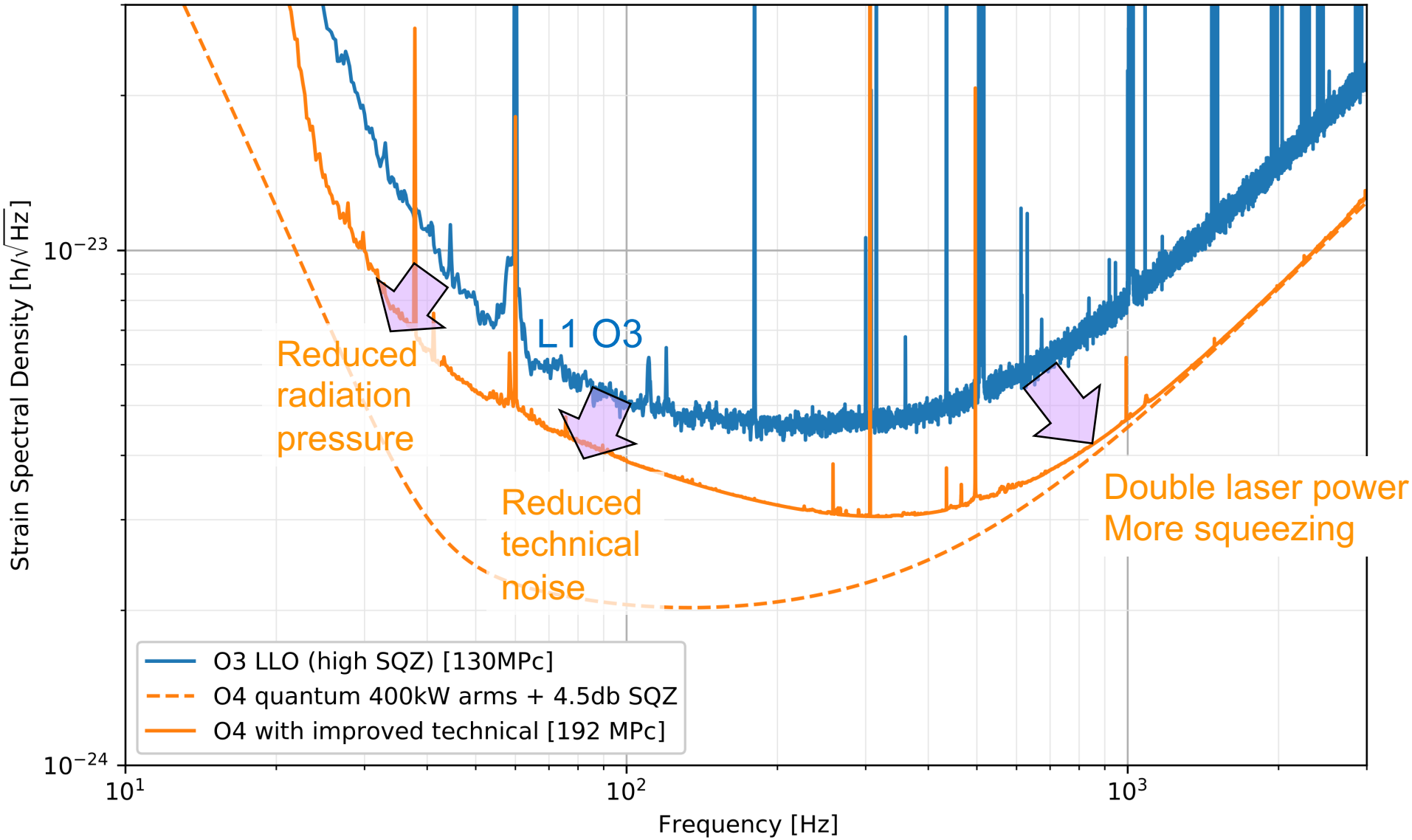


(What have we been doing other than performance upgrades?)

- Fixing/upgrading vacuum system for long term functionality.
  - Fixing/replacing pumps.
  - Decommission pumps from old iLIGO days at LHO.
  - Fixing leaks at LLO.
- Construction of LIGO Exploration Center (LExC, a new outreach facility at LHO, expected opening in 2022).

LExC Mostly-Virtual Groundbreaking, Oct 23, 2020

O4 Upgrade Motivations: This is what we want to do.

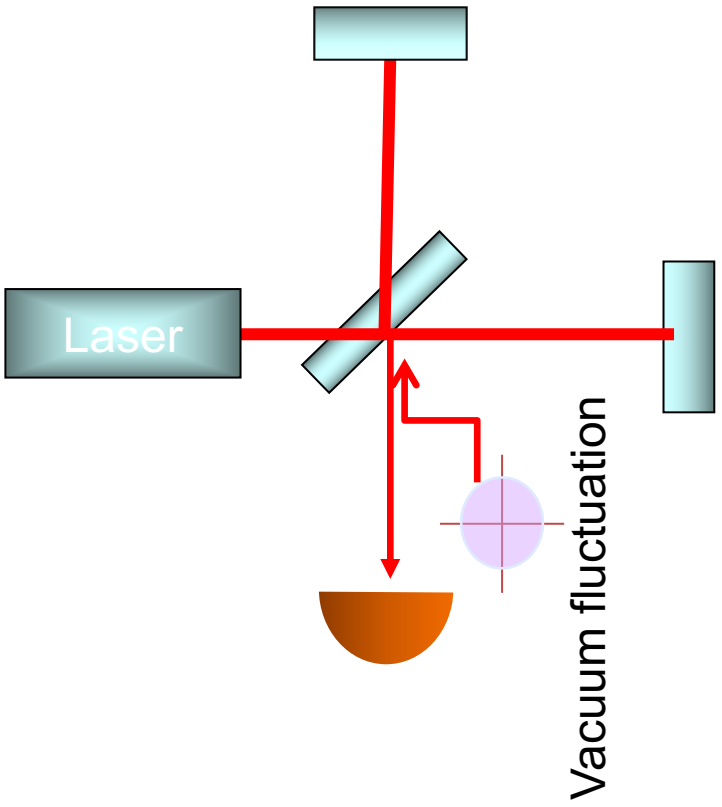


Selected topics for O4 Upgrades

- Squeezing enhancements (High and Low frequency)
- More power (High frequency) -> Bonus slides
- New Mirrors are necessary for enhanced SQZ and higher power: Point absorbers observed in O2/O3.
  - ITMY at LHO (swapping right now)
  - Re-polished and re-coated ETMs (procurement delay)
- More stray light baffles (Low to Low-Mid frequency) -> Bonus slides

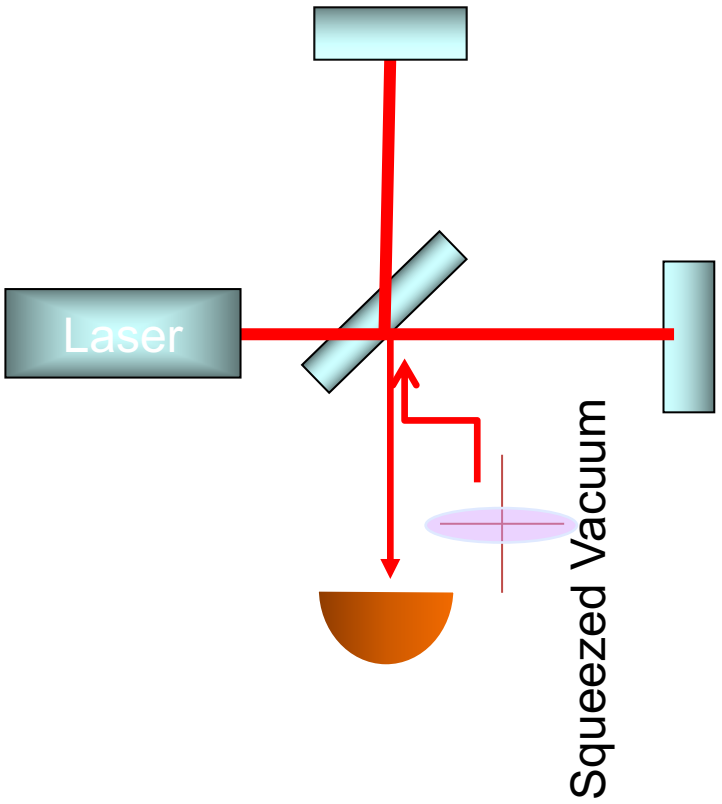
Squeezing?
Quantum noise in Michelson-type IFOs.

- Traditional picture: Shot noise (randomly timed photons) & radiation pressure noise (fluctuation in light power pushing the mirrors)
- Quantum: Both arise from vacuum fluctuation injected from the detection port, interfering with the laser field.



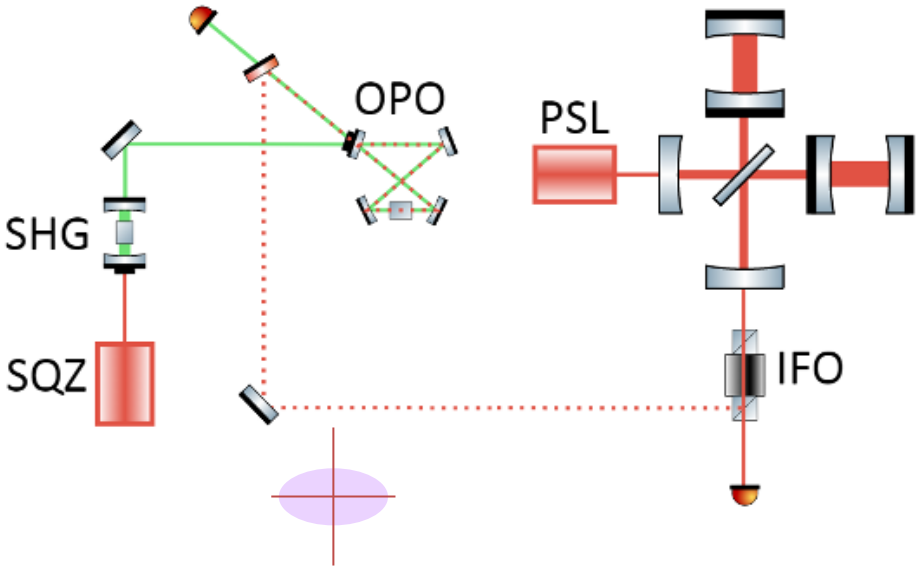
Squeezing?
Quantum noise in Michelson-type IFOs.

- We can inject manipulated vacuum fluctuation (“squeezed vacuum”) to reduce noise in certain frequency band (e.g. shot noise in high frequency).

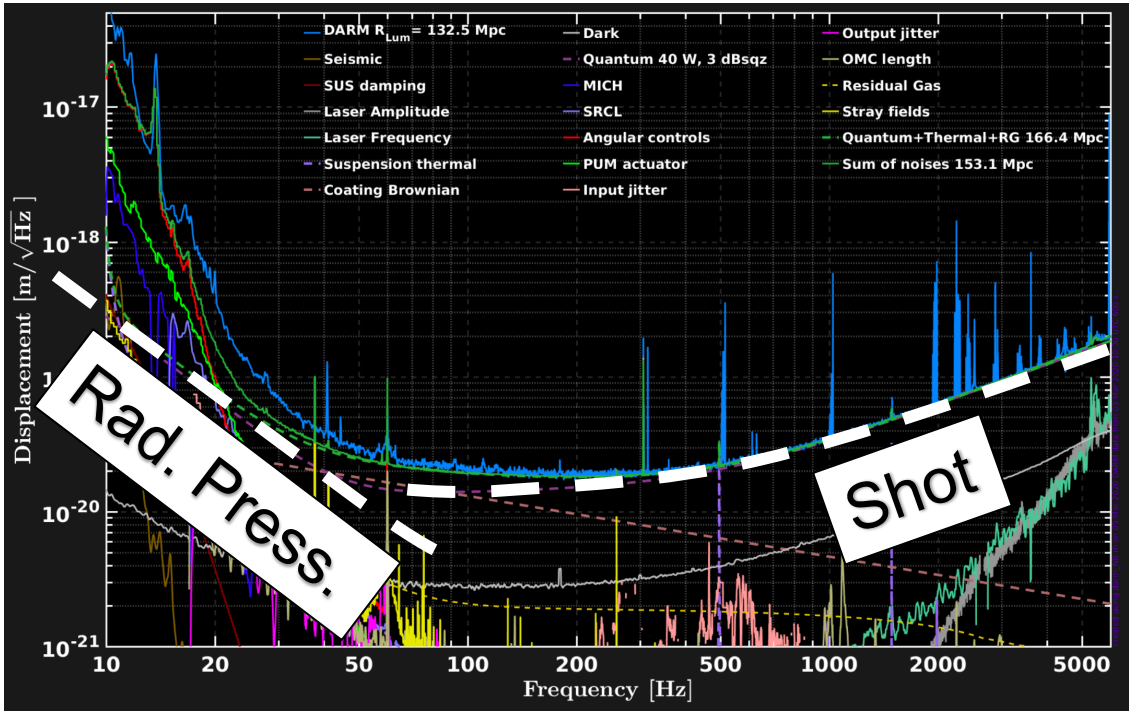


We've been doing this in O3

- LIGO (and Virgo and GEO) ran with frequency-independent squeezing in O3.
- 2~3 dB reduction of shot noise.

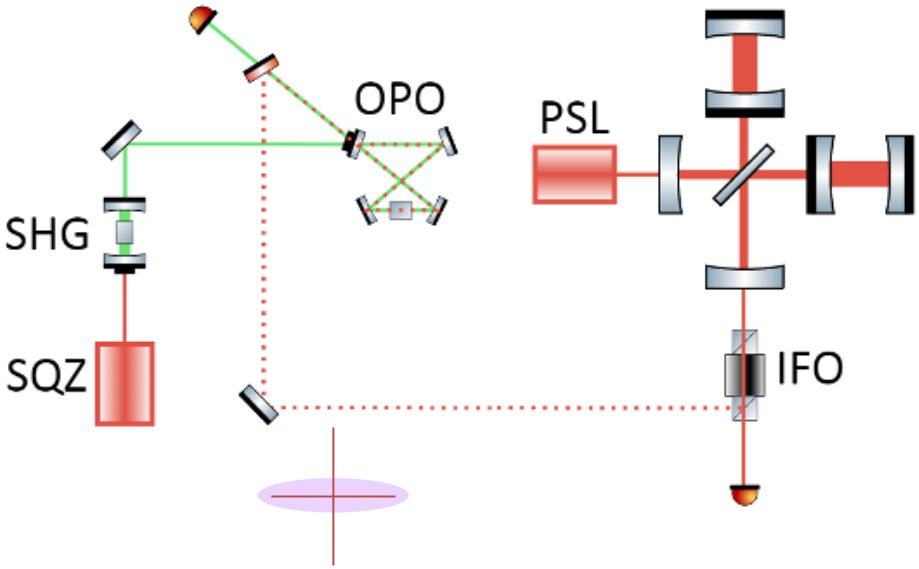


L1 Noise Budget 2020 Mar
(alog 51967)

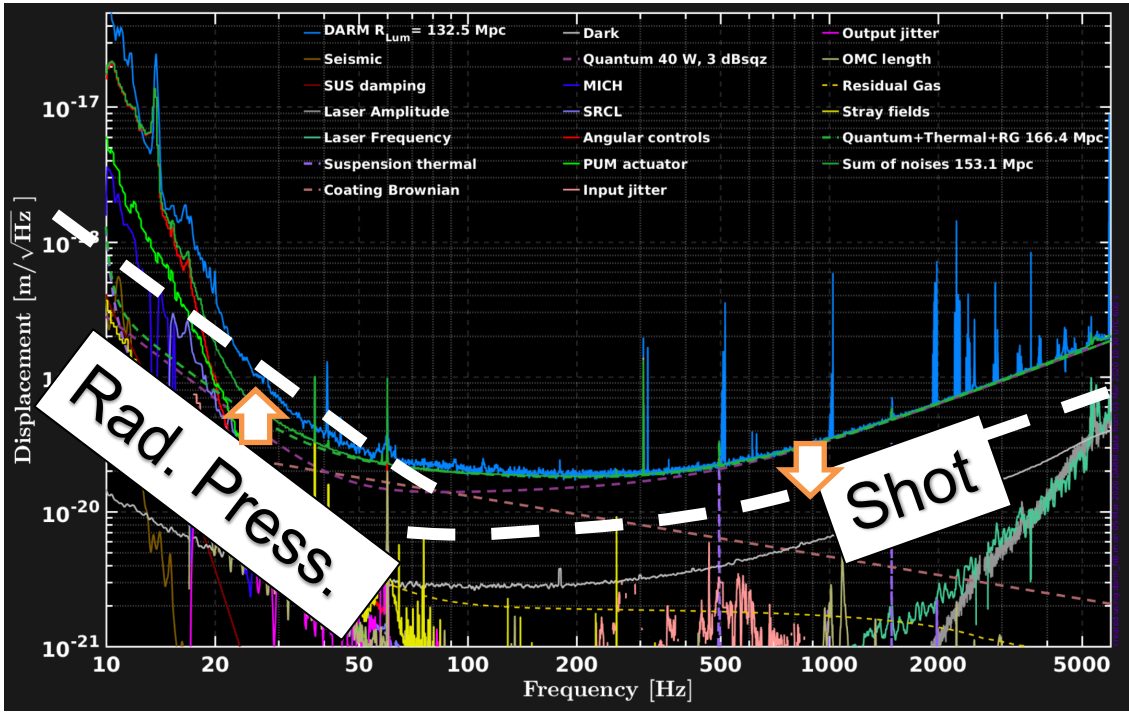


Frequency-independent Squeezing goes only so far

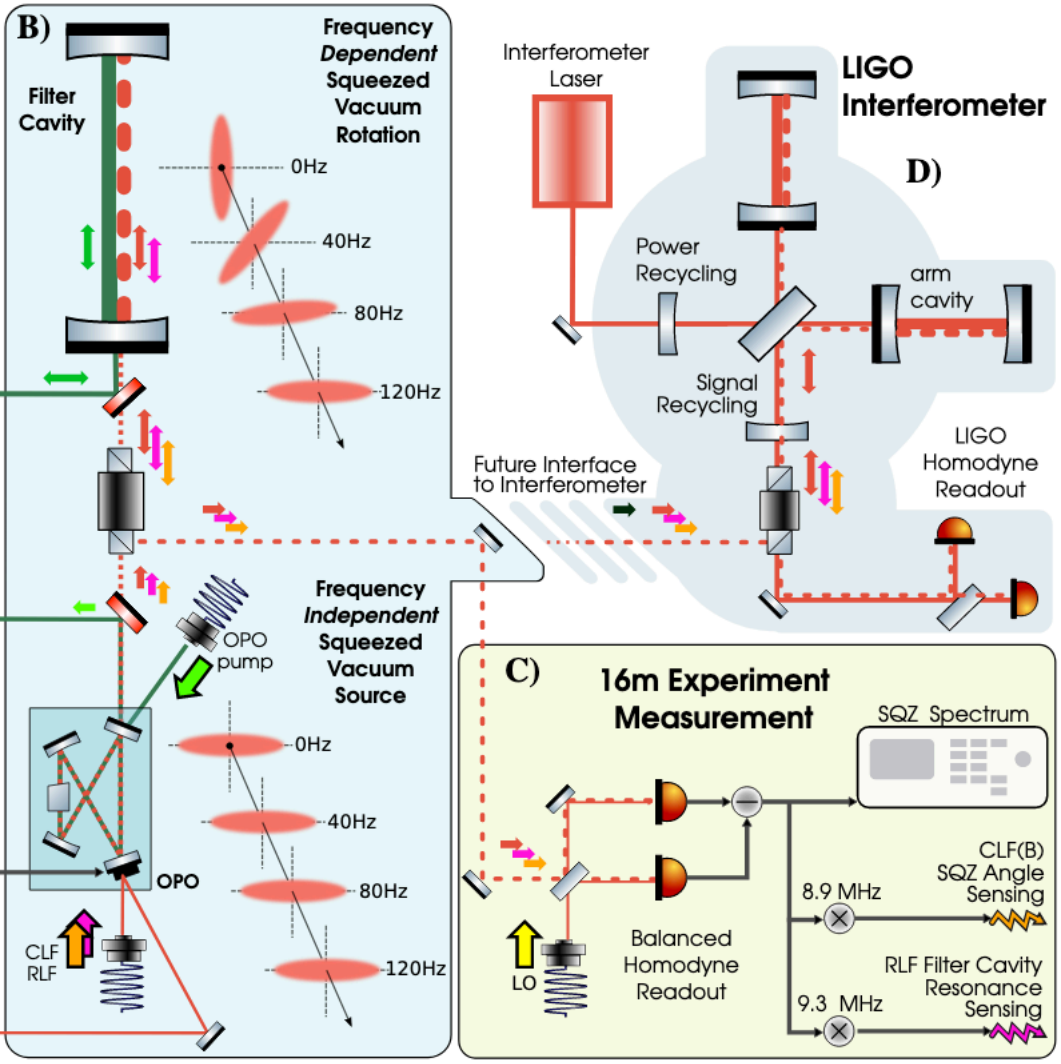
- More SQZ-> smaller shot noise, larger radiation pressure noise.



L1 Noise Budget 2020 Mar
(alog 51967)



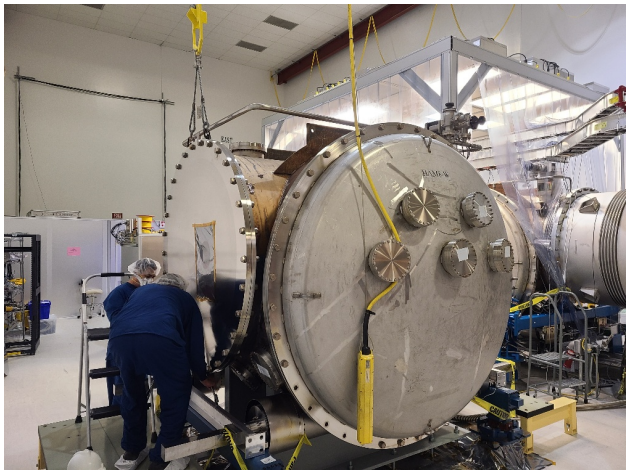
Frequency-Dependent Squeezing (FDS, A+ tech in O4)



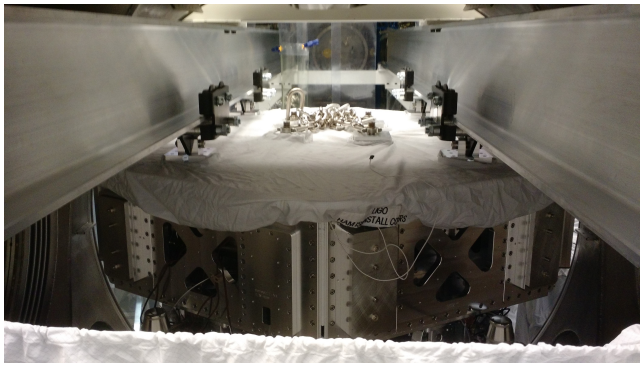
- Rotate the squeezed vacuum angle as the function of frequency with a long (300m) “filter cavity”.
- (This is cool, but note that optical losses are the enemy.)
- New vacuum chambers, one in the corner and the other between the corner and EY. Reuse H2.

New vacuum chambers

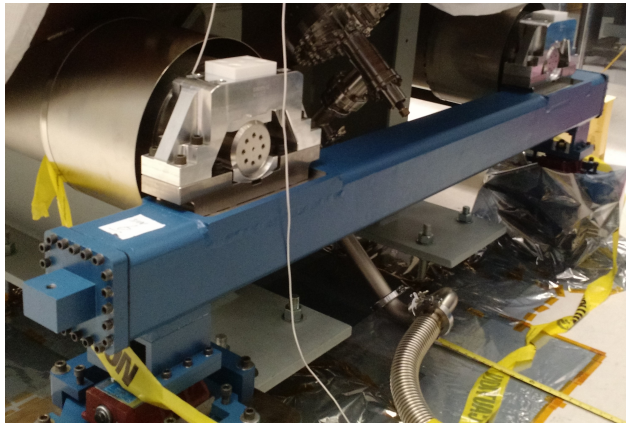
WHAM7 put in place



ISI was moved into WHAM7



WHAM7 ext. seismic structure

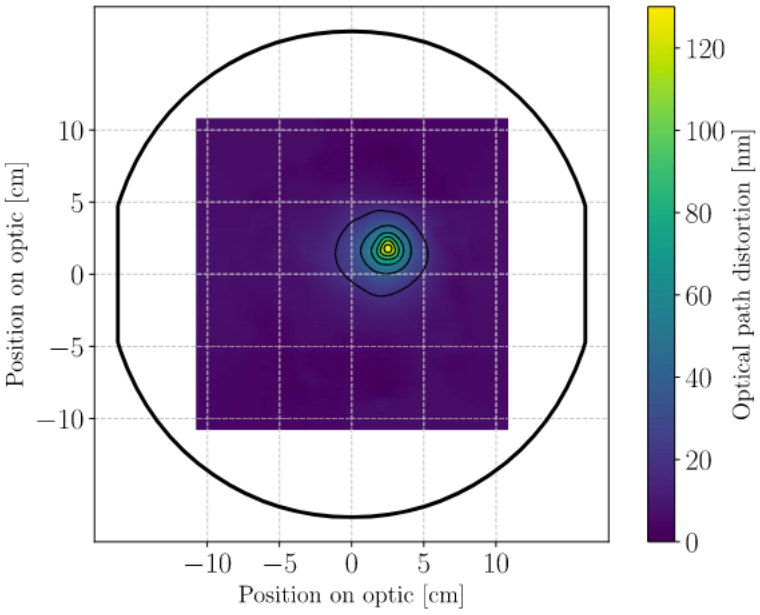


LHAM7 core drilling

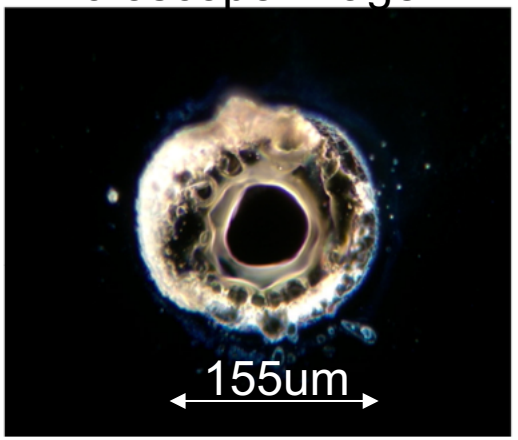
Why new mirrors: Spot absorbers

- O2: For H1, increasing power didn't necessarily come with expected benefits.
- Bad spot absorber was identified in situ on H1 ITMX.
- ITMX Removed after O2: Microscope inspection revealed a structure.
- Spot heating -> thermal deformation.

HWS in-situ image



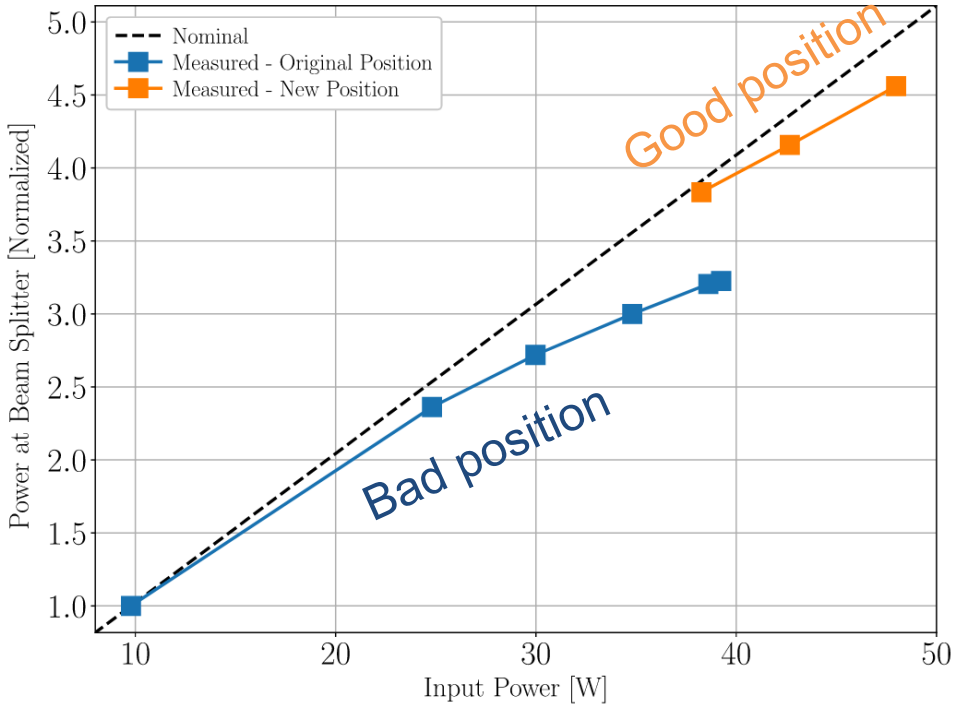
Microscope image



Why new mirrors: Spot absorbers

- O3: New H1 ITMX.
- Smaller absorbers found on H1 ITMY, H1 ETMX, L1 ETMX and L1 EMTY.
- In-situ cleaning didn't help.

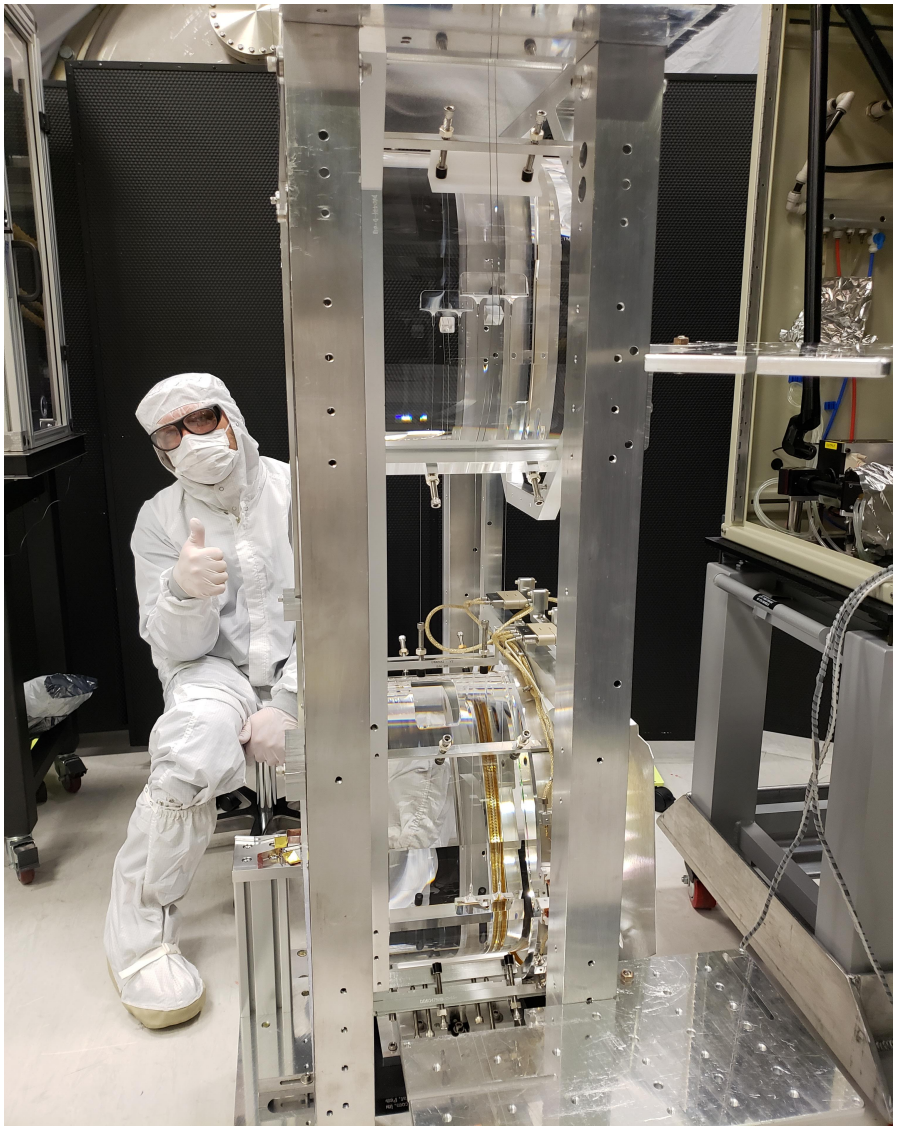
L1: Avoiding bad spots on ETMs



New mirrors are coming.

- New H1 ITMY has just been installed in the chamber!
  - Weeks of adjustments etc. ahead.
- ETMs: Change profile to mitigate the spot absorber effect.
  - This means that we'll replace all ETMs.
  - Procurement delay.

Hanging the new ITMY with monolithic suspension outside of the chamber.

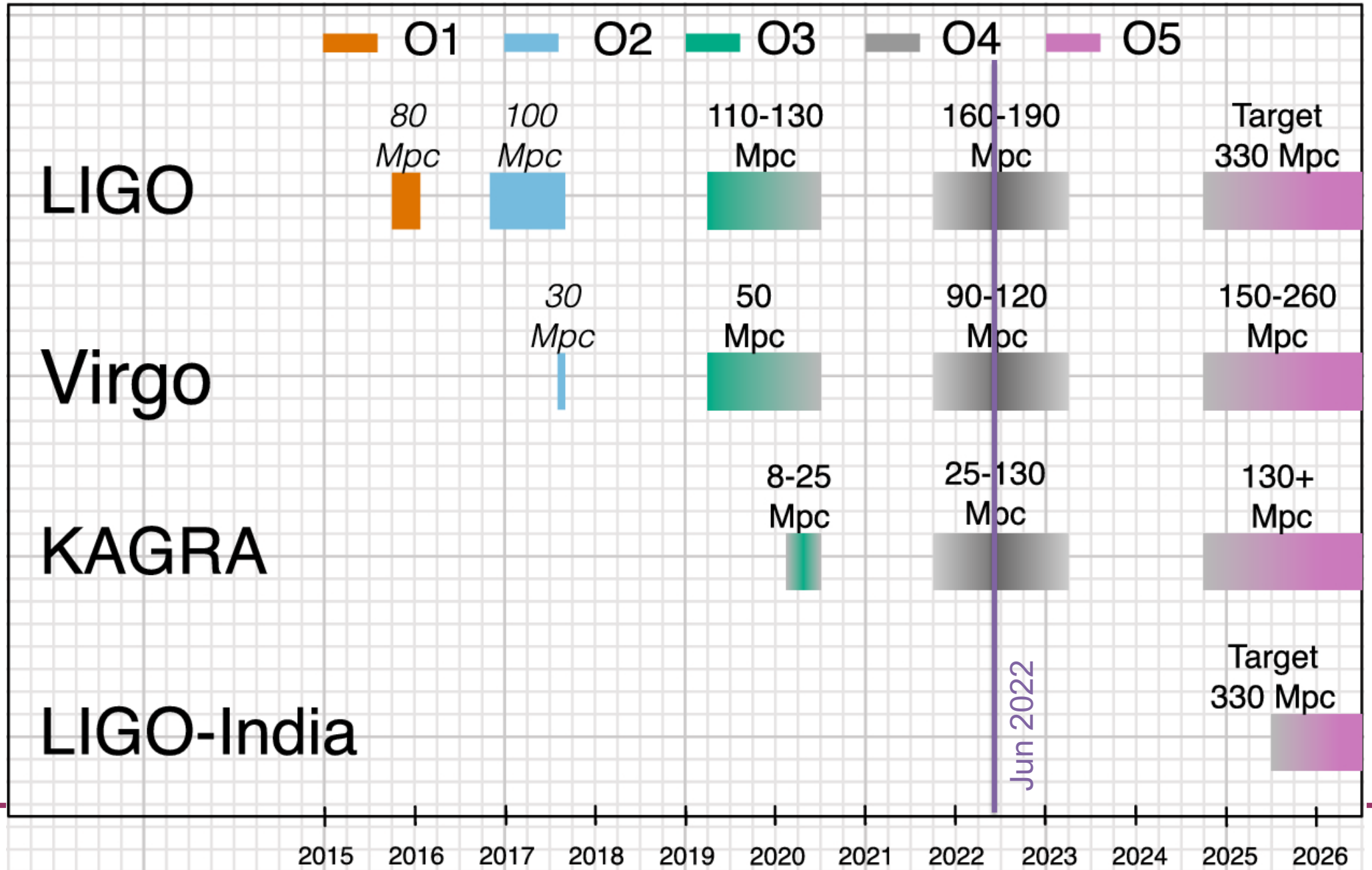


O4 start projection update

- O4 observing run projected NOT to begin before June 2022: LIGO-L2000281
  - Previously, the projection was to start late 2021 – early 2020, see e.g. "Prospects of Observing" paper.
  - Mainly due to procurement delays (ETM) unrelated to COVID.
  - Stay tuned: Revised projection will be available in March 2021.

“Prospects of Observing…” and the new projection.

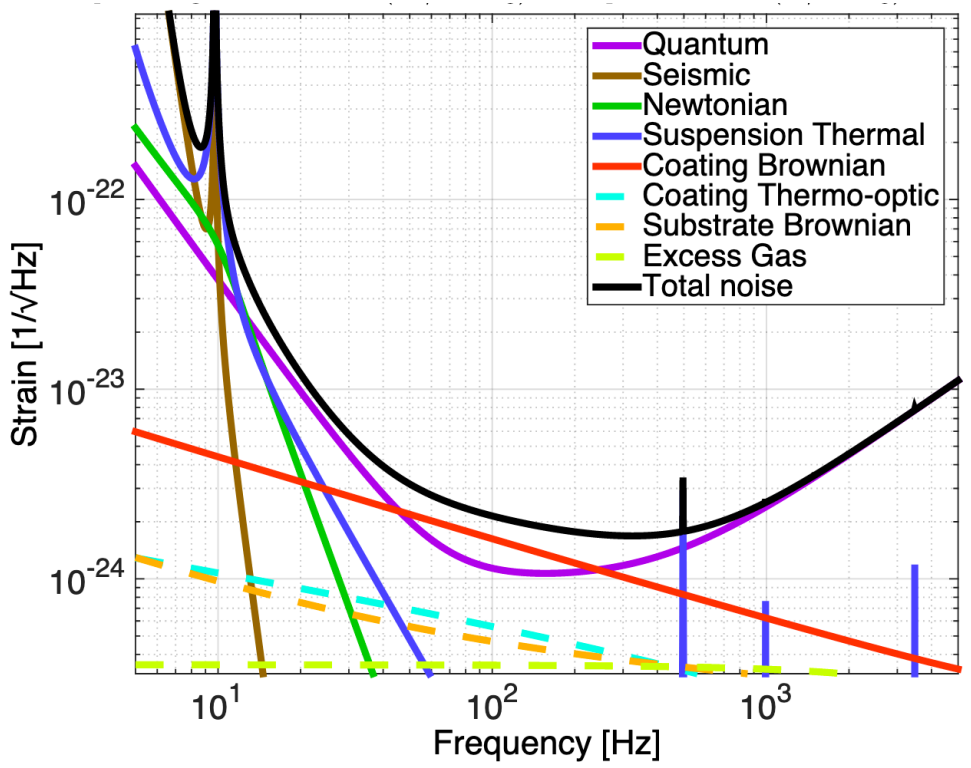
https://link.springer.com/article/10.1007/s41114-020-00026-9



A+ upgrade and O5

- Incremental (but ambitious) upgrade using the existing facility.
  - Larger BS
  - Lower thermal noise test mass coating
  - New readout scheme (balanced homodyne)
  - Pre-O4 A+ Scope includes
    - FDS with filter cavity
    - Lower-loss Faraday
    - Adaptive mode matching
- No update on schedule at this point (but note the new O4 projection).

- A+ design: ~1.6x BBH (30-30M_{sun}) reach over aLIGO baseline design (~2.5Gpc vs ~1.6Gpc)
- ~1.9x BNS (1.4-1.4M_{sun}) reach (~320Mpc vs ~170Mpc)



LIGO India: A big deal.

- A third LIGO observatory under common LIGO technical management and with comparable sensitivity.
- LHO, LLO and LIGO India will continue to integrate operations with Virgo and KAGRA.
- 5th IFO in the global network: Think about improvements!
  - Sharp localization, polarization resolution, sensitivity, 4-detector uptime!

- "In-principle" funding (~$23M) was provided.
  - Used to purchase the land for the observatory site and for staff and visitor quarters, create a Testing & Training Facility, and manufacture prototypes for vacuum chambers and beam tube. -> Bonus slides
- Site is at Aundha
  - Latitude 19° 36' 50" N, Longitude 77° 01'54" E

If you're an LVK collaborator, you might want to check Milind Gowardhan's LVK talk for details:
https://dcc.ligo.org/LIGO-G2001647

LIGO-India

http://www.ligo-india.in

http://www.gw-indigo.org/

- Partner Agencies
  - Department of Atomic Energy
  - Department of Science & Technology
  - US National Science Foundation
- LIGO-India Institutes:
  - Institute for Plasma Research(IPR), Gandhinagar
  - Inter-University Centre for Astronomy & Astrophysics (IUCAA), Pune
  - Raja Ramanna Centre for Advanced Technology (RRCAT), Indore
  - Directorate of Construction, Services and Estate Management (DCSEM), Mumbai
- LIGO Laboratory, Caltech & MIT
- R&D at institutes across India

LIGO

Summary

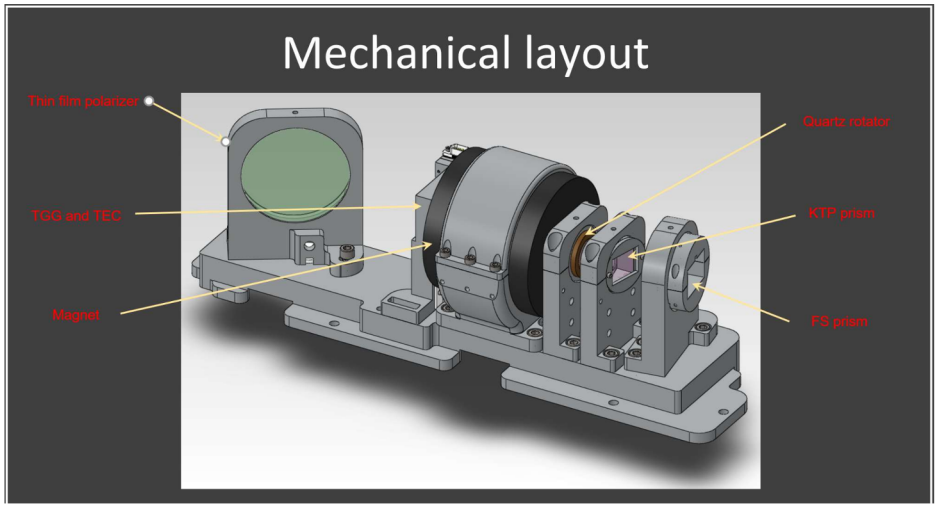
- Awesomeness in O1, O2, O3a and O3b.
- Better performance expected in O4 from various upgrades. Further awesomeness.
  - Making progress for LIGO O4 upgrades (incl. A+ Pre-O4 scope) despite COVID restrictions.
  - O4 won't start before June 2022.
    - We'll update again next March as we learn things.
- A+ and LIGO India: Both will be the next big things for O5.

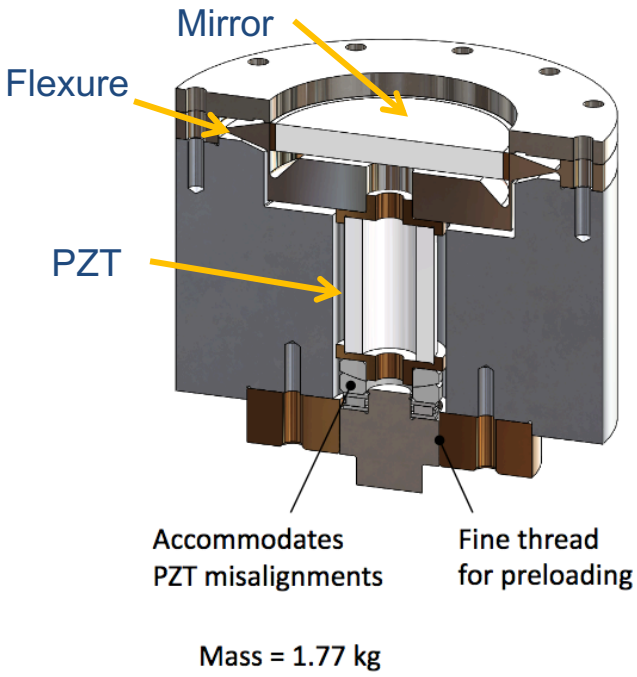
LIGO

Bonus Slides

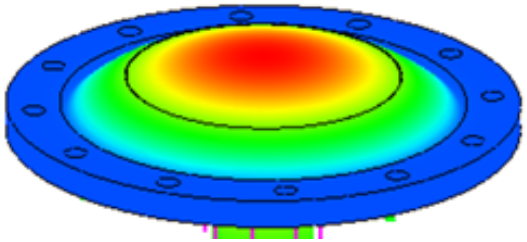
Toward Smaller Losses

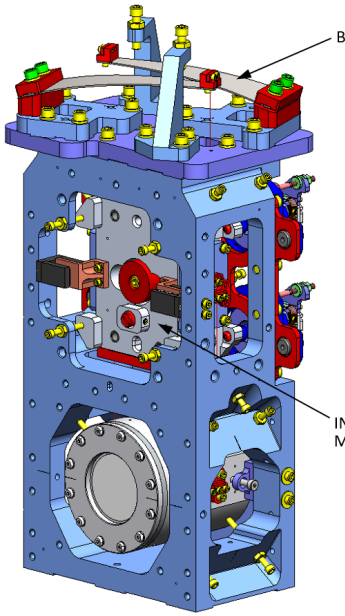
- New Faraday (A+)
- Suspended adaptive mode matching optics (PZT- or thermally-driven) (A+)
- (New test masses)



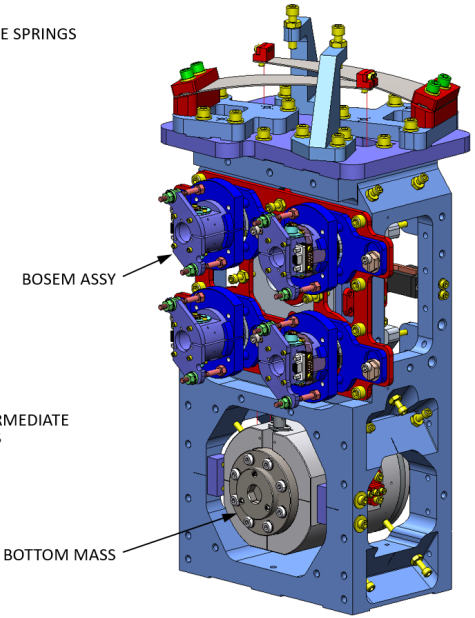


PZT pushes on flexure, which bends mirror





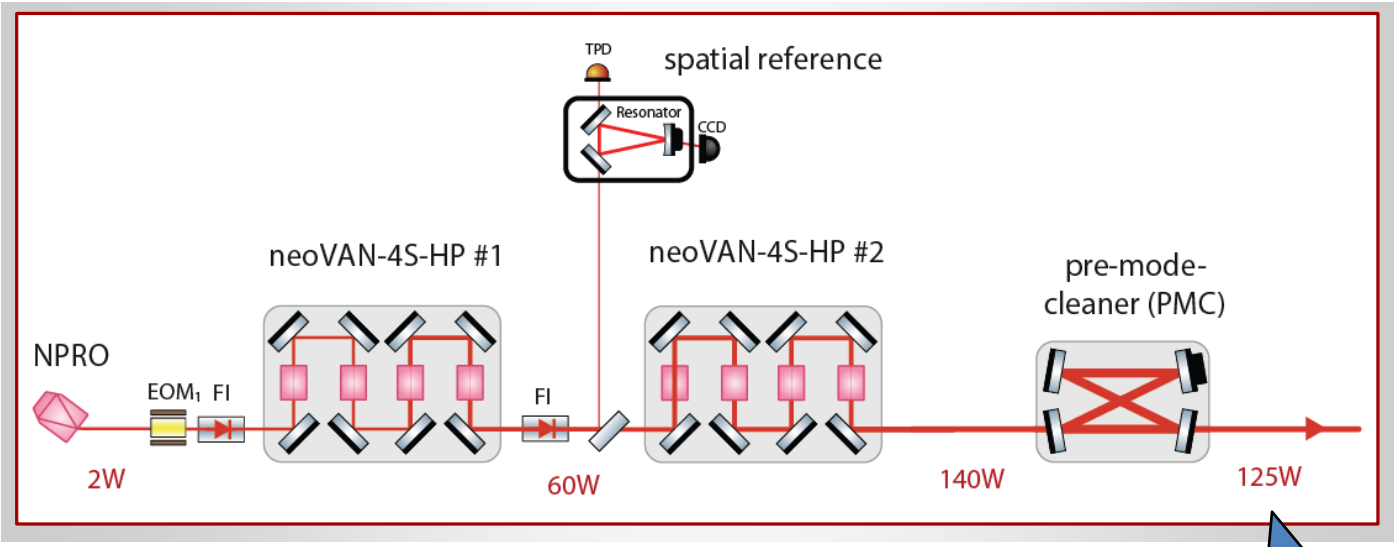
FRONT 3D VIEW



REAR 3D VIEW

Higher laser power

- Double the laser power (400kW in the arms)
- Two stages of neoVAN-4S-HP (only 1 in O3)
- Test ongoing at LLO

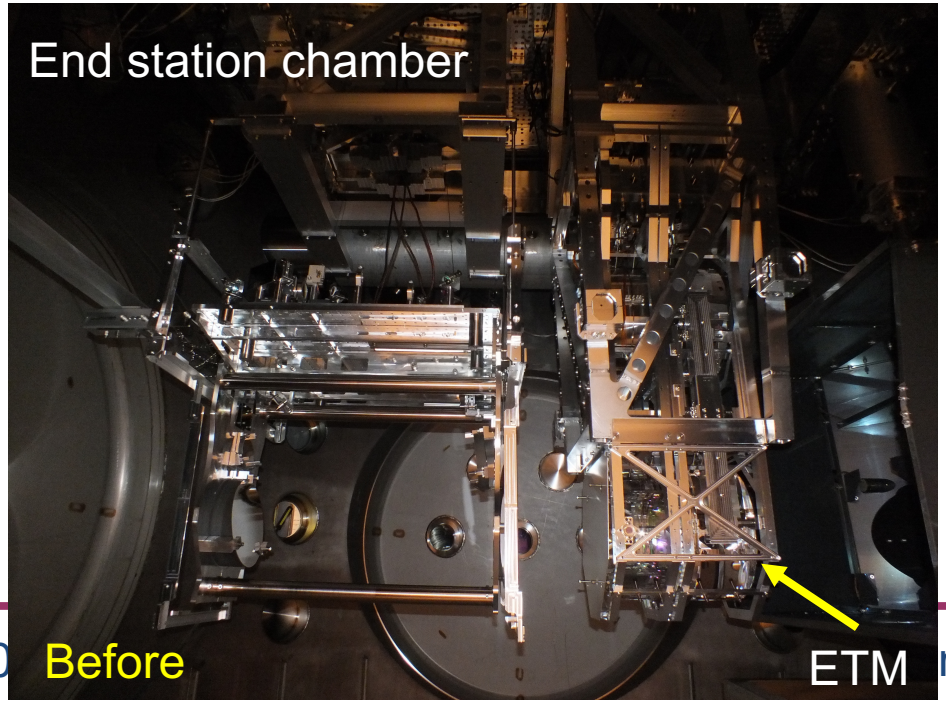


112 W actual

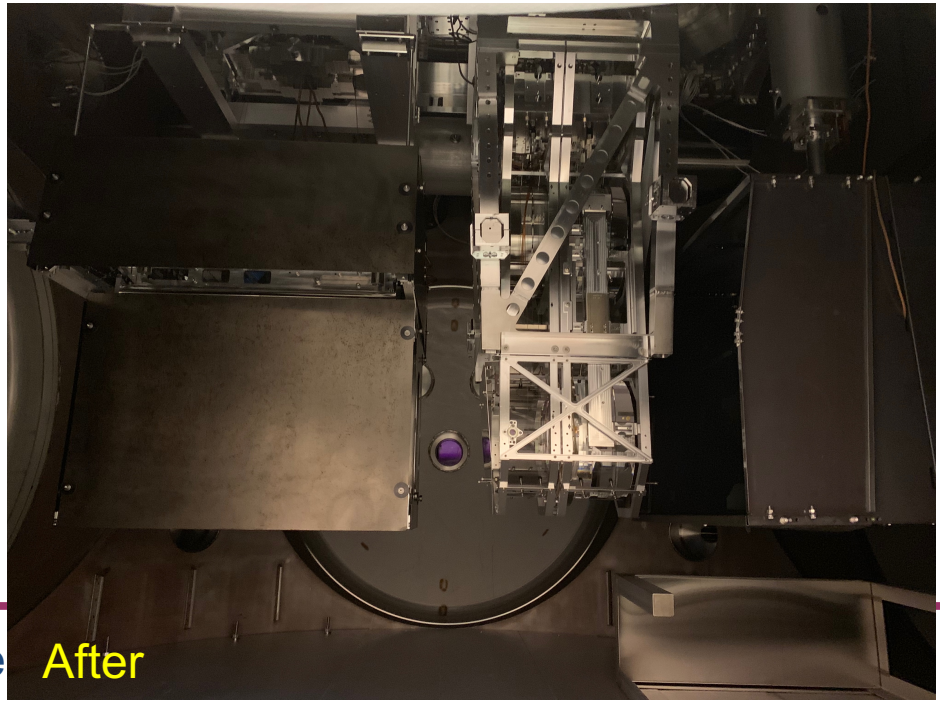
LIGO Mitigating Excess Low Frequency Noise

- Unexplained noise between 20-80Hz.
- Difference between H1 and L1. H1 MAY be due to ITM point absorbers.
- Non-stationary noise due to scattering -> installing many baffles everywhere.

Shroud around ETM Transmission Monitor



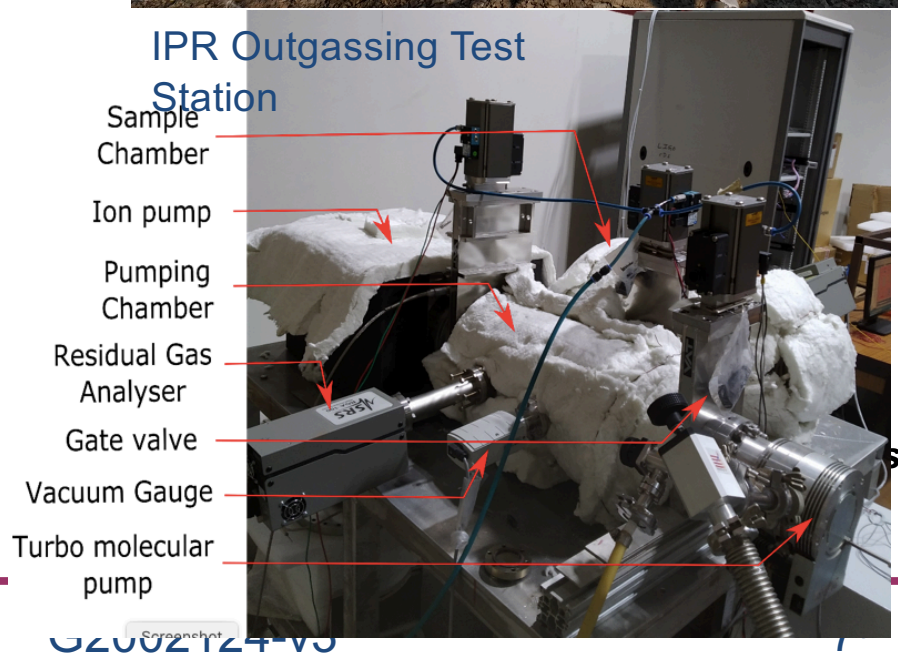
1 installed, 3 more to go

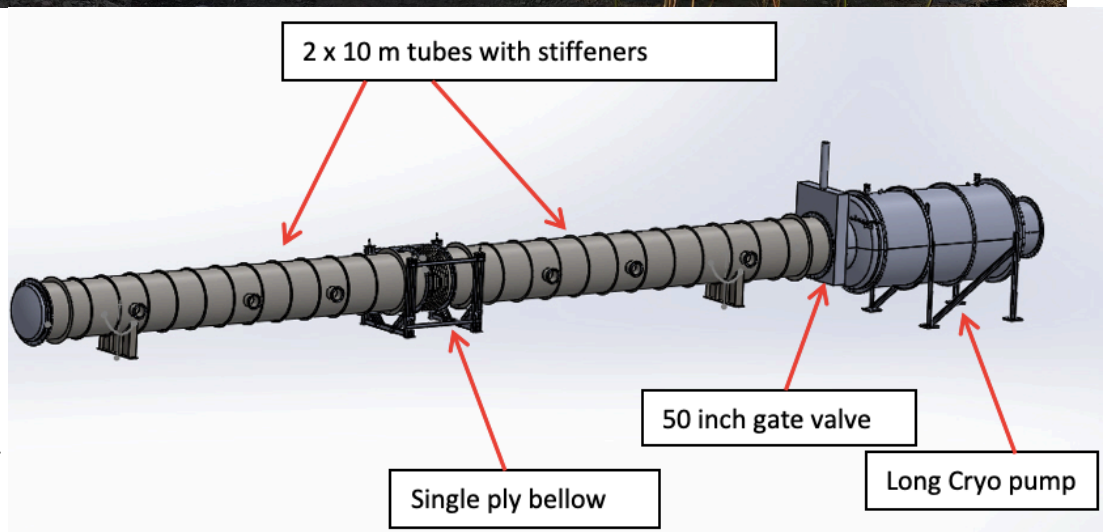


Just one example of additional baffles for O4

LIGO Building capacity and experience in India

IPR Outgassing Test Station

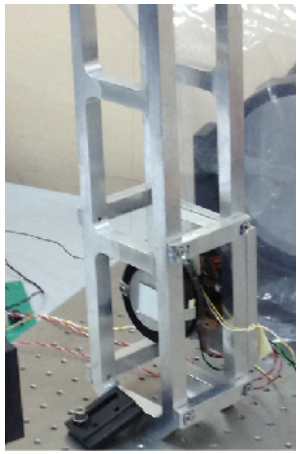




Proposed IPR Beam-Tube Protoype

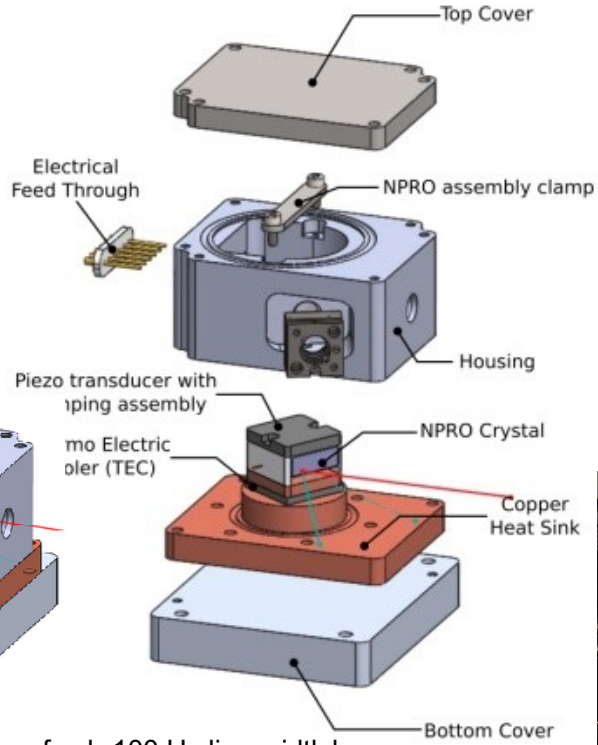
10 meter prototype Interferometer

(Capacity Building Activities)

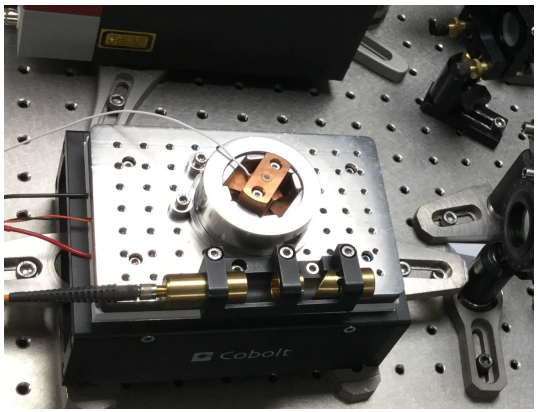


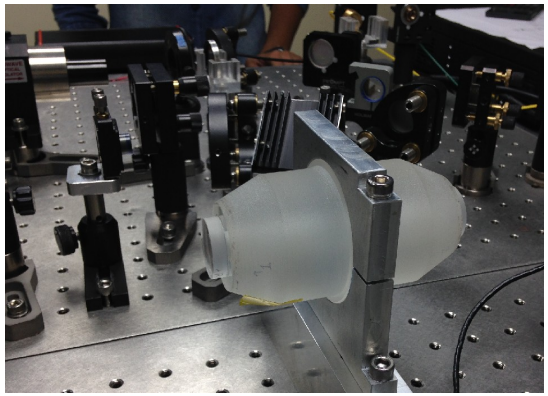
Optics suspension testing for the 10 m Prototype

Vacuum system for 10 m prototype



Engineering prototype of sub-100 Hz line-width laser





An ultra-narrow line-width NPRO Laser has been developed (1064 nm) with sub-100 Hz line-width.

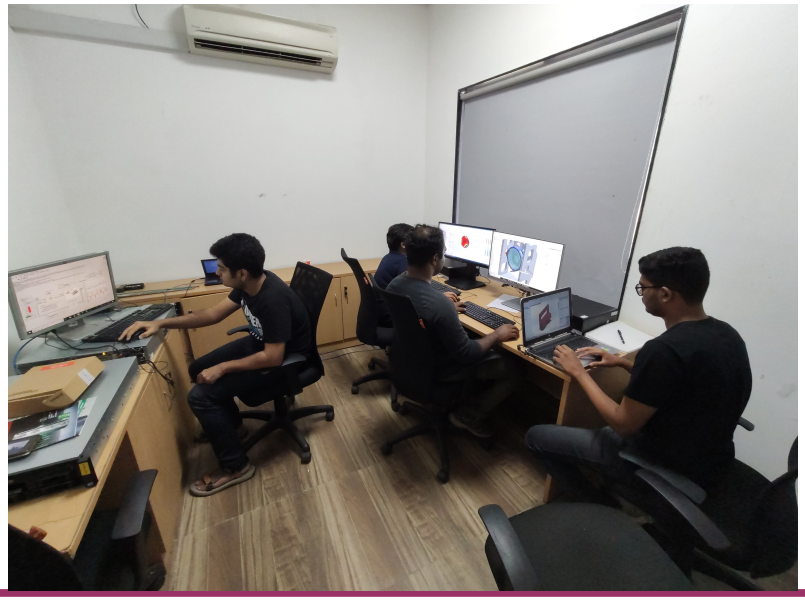
A 10 m arm length prototype interferometer is being setup to serve as a training facility for Gravitational Wave Detectors. A sub-100 Hz line-width laser has been developed for the 10 m prototype, the testing of the suspension design for the interferometer optics is under progress. The design for the vacuum system to house the 10 m interferometer has been completed and fabrication of the same has been taken up. The setting of the 10 m prototype interferometer is scheduled for completion by Dec 2021.

Slide from Milind Govardhan LVK talk

Training in CGPA (IUCAA & IISER-Pune)

- Suspension Control and Damping
  - Design and Fabrication of a single stage suspension
  - Active and Passive feedback hardware
  - Design of local damping loops using LabView
- Seismic Isolation
  - Development of seismometers
  - Fabrication of Single seismic isolation stage
  - Active control at Low frequencies
  - Design of compact low frequency isolation systems
- Modern Control Systems
  - System identification using MCMC and Bayesian methods
  - Modern Control using Machine learning and Neural Networks

Trainees in CGPA



Trainees in IUCAA's Design Cell