Australian Government

Australian Research Council

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

High Power Cryogenic Silicon
Gingin High Optical Power Facility

In this presentation the progress and experimental plan for high power cryogenic silicon experiments at Gingin will be described.

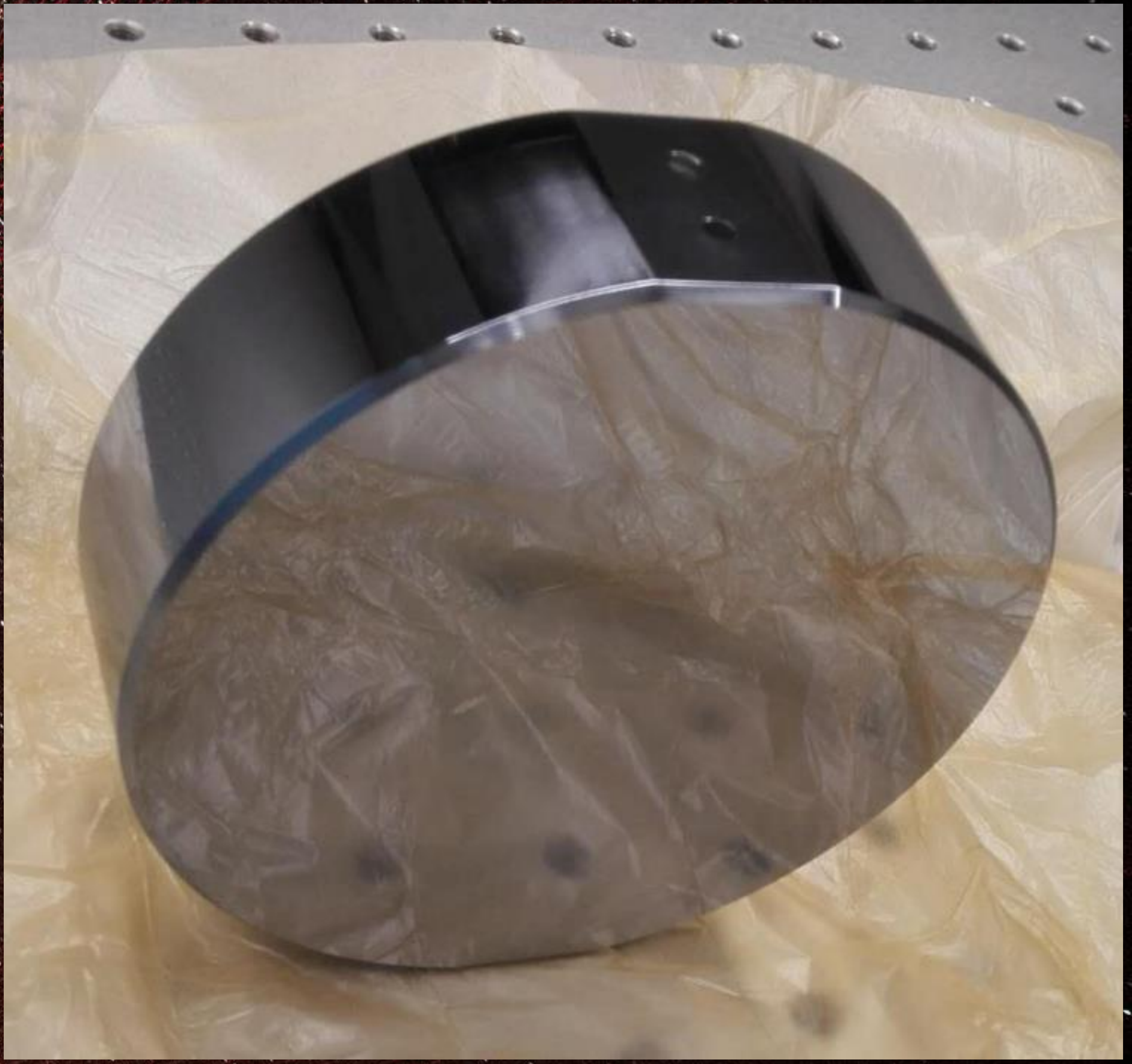
KAGRA Future Working Group

7 Dec 2023

Swinburne University of Technology · Australian National University · Monash University · The University of Adelaide · The University of Melbourne · The University of Western Australia · AAO · CSIRO

Overview

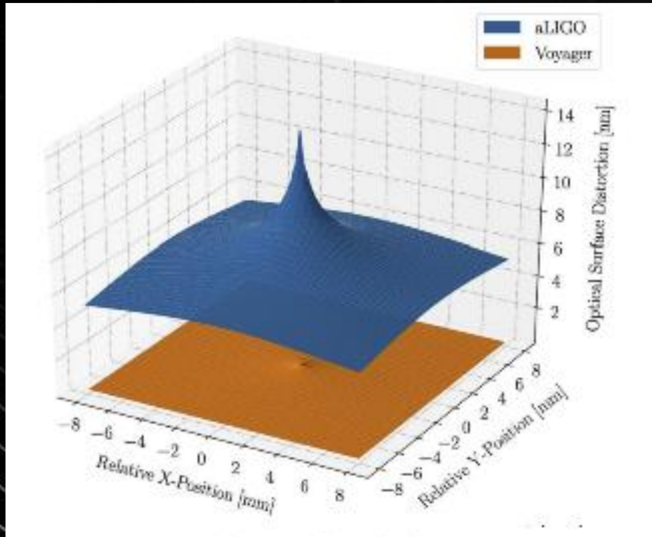
- Motivation
- Proposed experiment plan
- Progress
- Future Direction

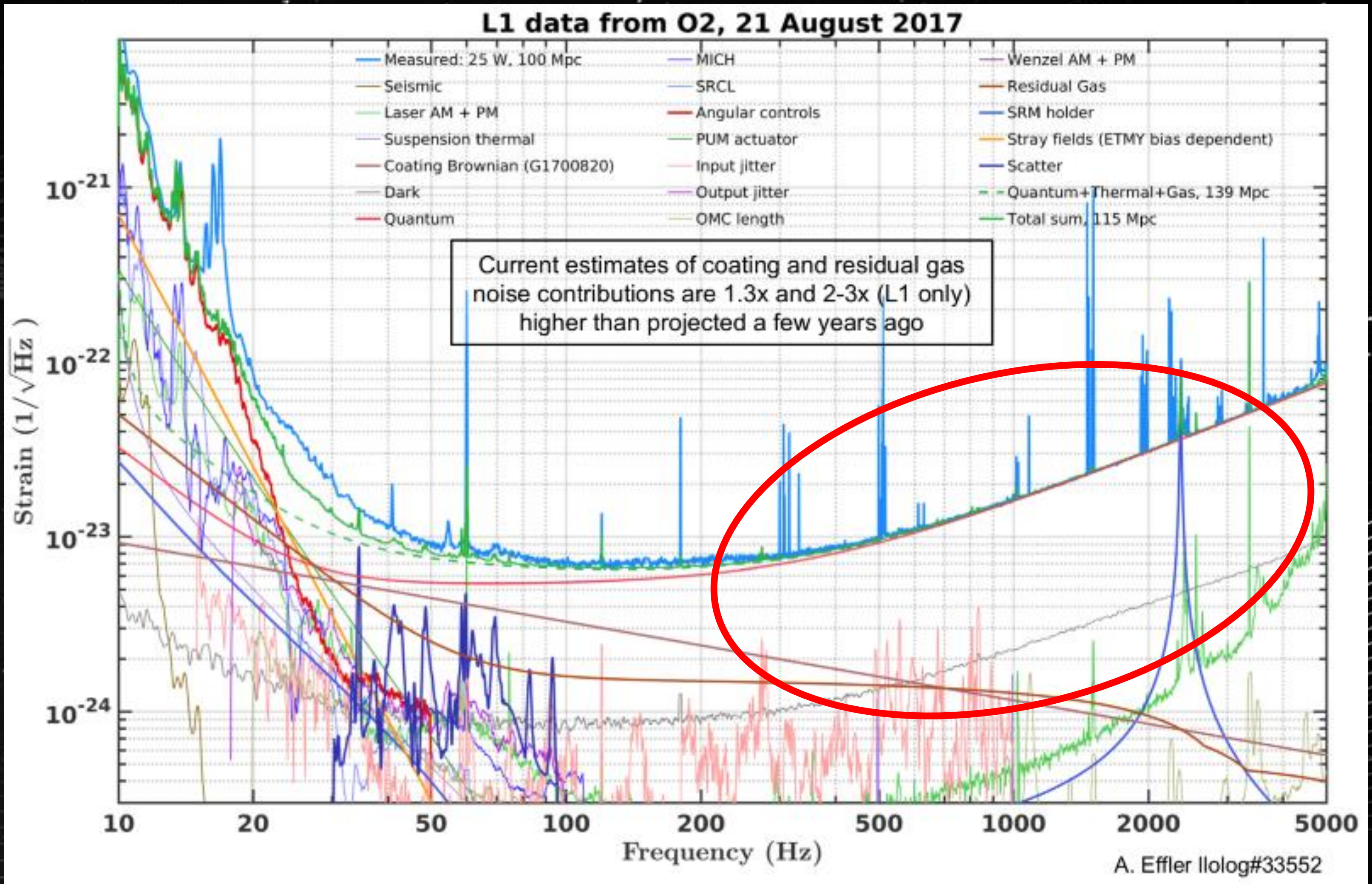


Motivation

High Optical Power

- Less technical noise at HF
- Thermal problems
- FS – low thermal conductivity
- - high thermal expansion
- Silicon - high thermal conductivity
- - 0 thermal expansion (18,123K)

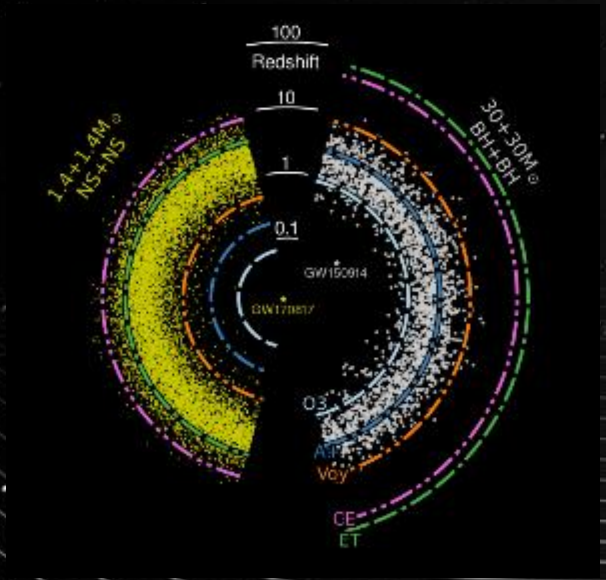


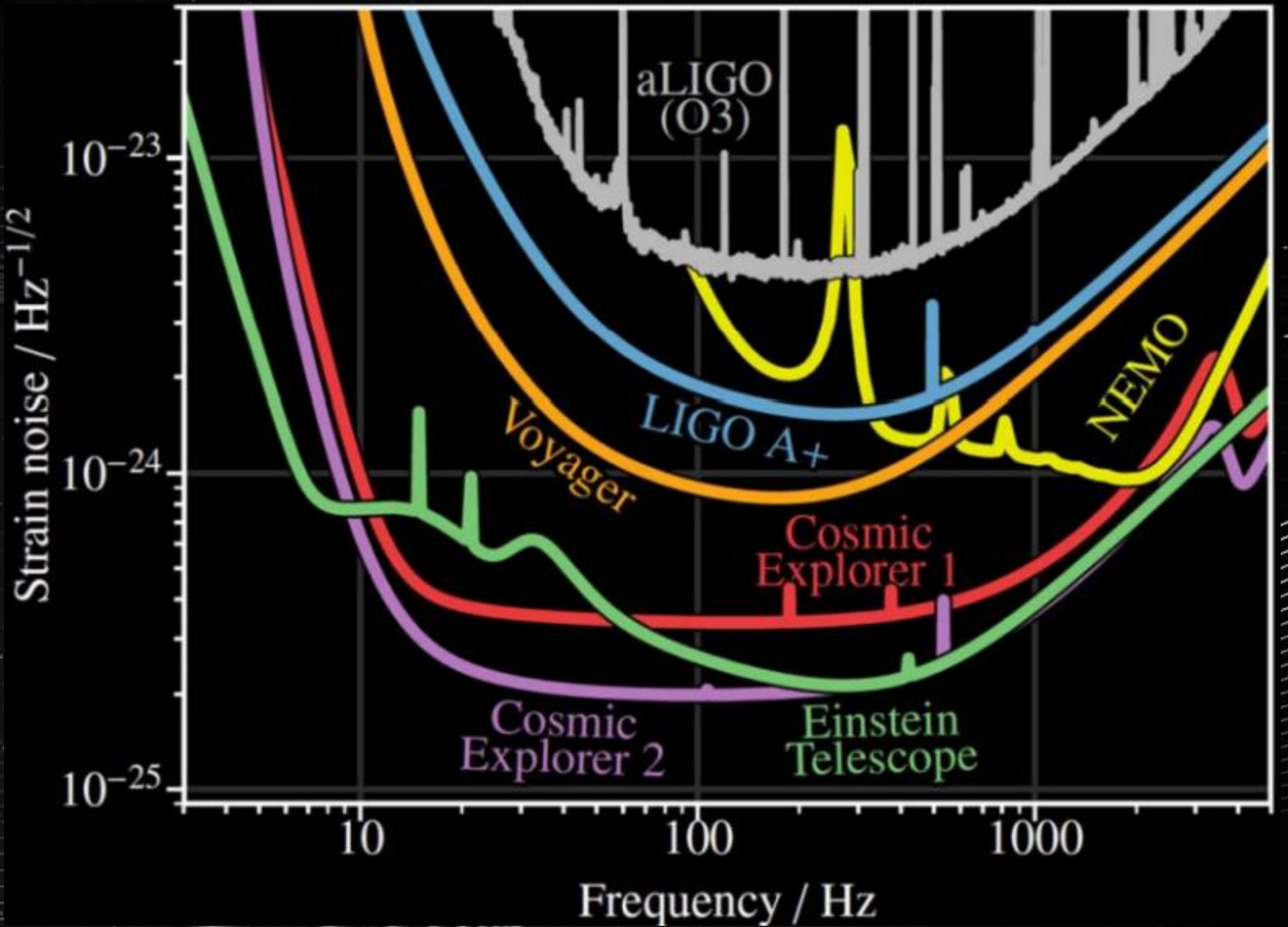


Motivation

Maximise Range

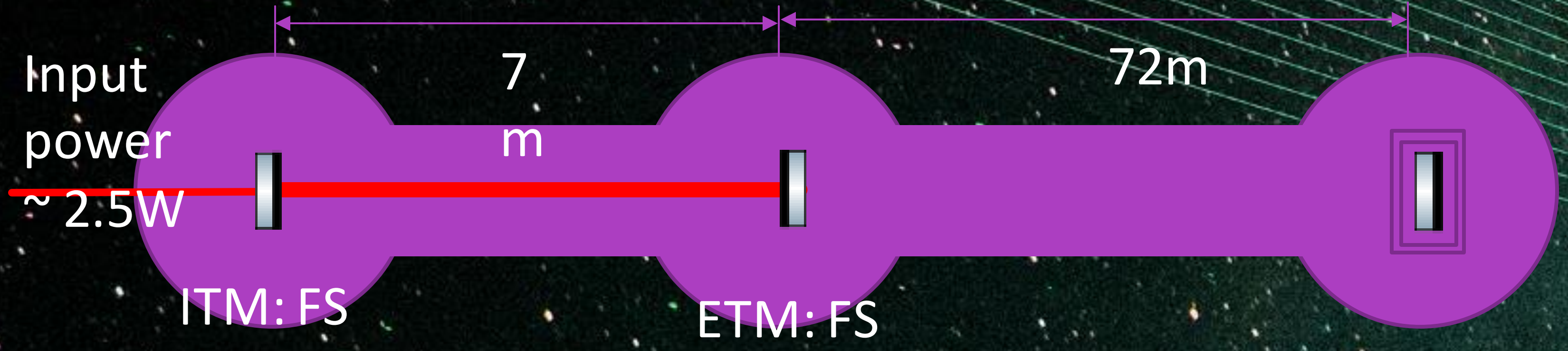
- NEMO Proposal
- Voyager Proposal
- Cosmic Explorer 2
- 123K – easy cryogenics
- Lower noise coatings



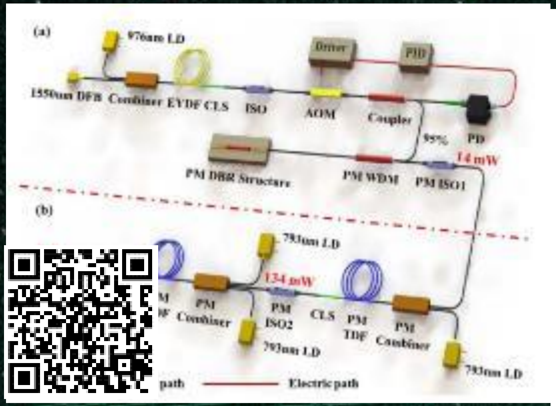


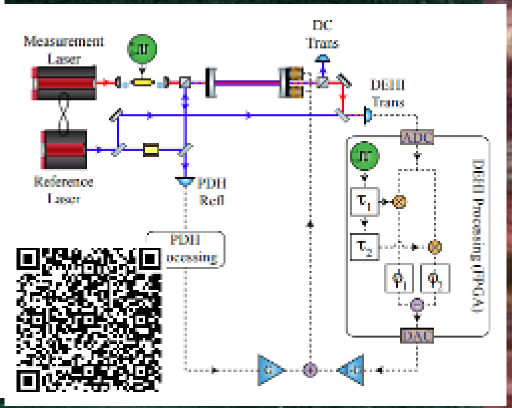
Experiment Plan

Seven Meter cavity and cryogenic test (23-24)



- Phase 0
  - 2um laser stability + suitability
  - Narrow linewidth suspended 2um cavity
  - Auxiliary optic piezo tables
  - Suspended Platform Digital Interferometry
  - Isolated Cryogenic Test



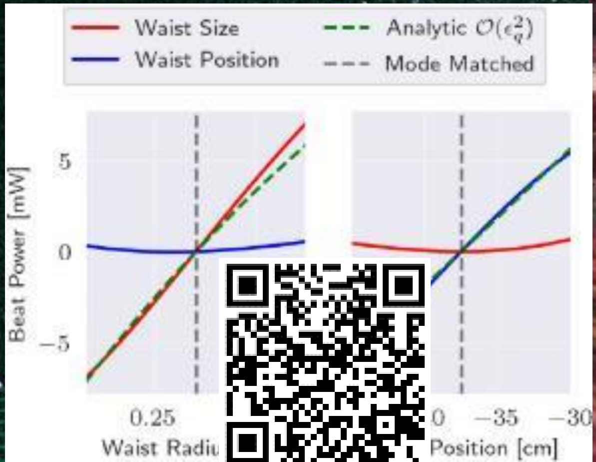


Experiment Plan

72m Silicon cavity

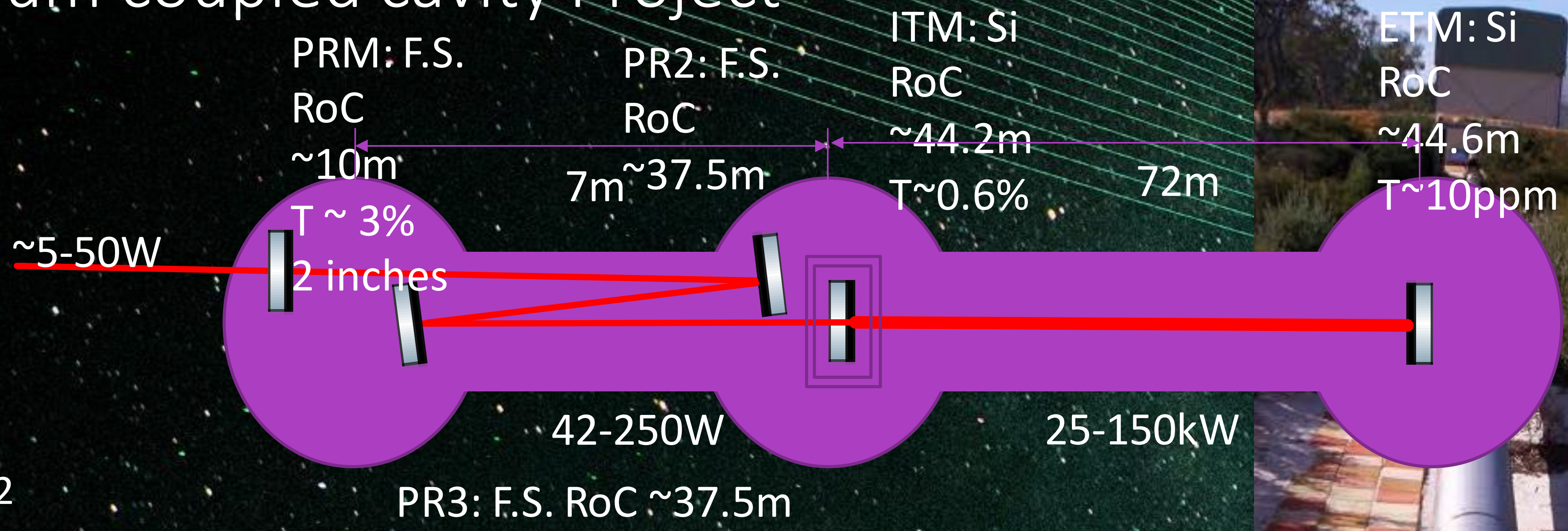
Finesse ~ 1000
Circulating power ~ 1.5kW

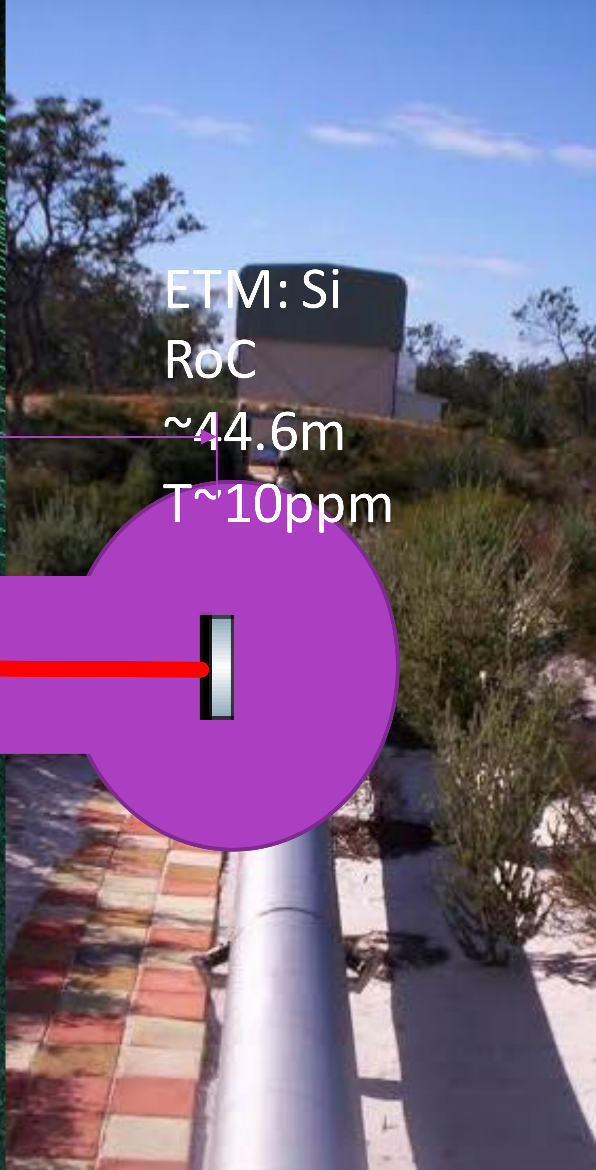
- Phase 1
  - 2um laser stability + suitability
  - Scattering investigation
  - Absorption / uniformity
  - Simple mode matching sensing and control
  - Thermal actuation – substrate lens and RoC
  - Possible cryogenic ITM



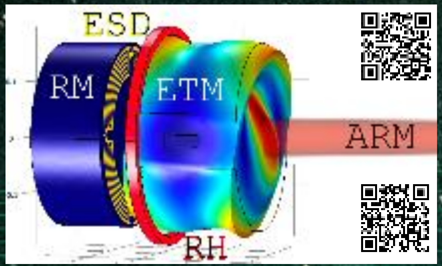
Future Detectors

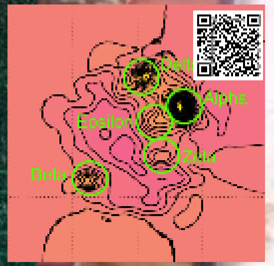
The 2um coupled cavity Project

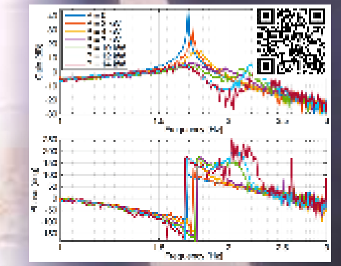




- Phase 2
  - Mode matching sensing and control in coupled cavities
  - Parametric instability in Silicon cavities
  - Coating absorption uniformity at ~ 3G power density
  - Angular control at ~ 3G power / weight
- Phase 3
  - High power and Cryogenic ITM



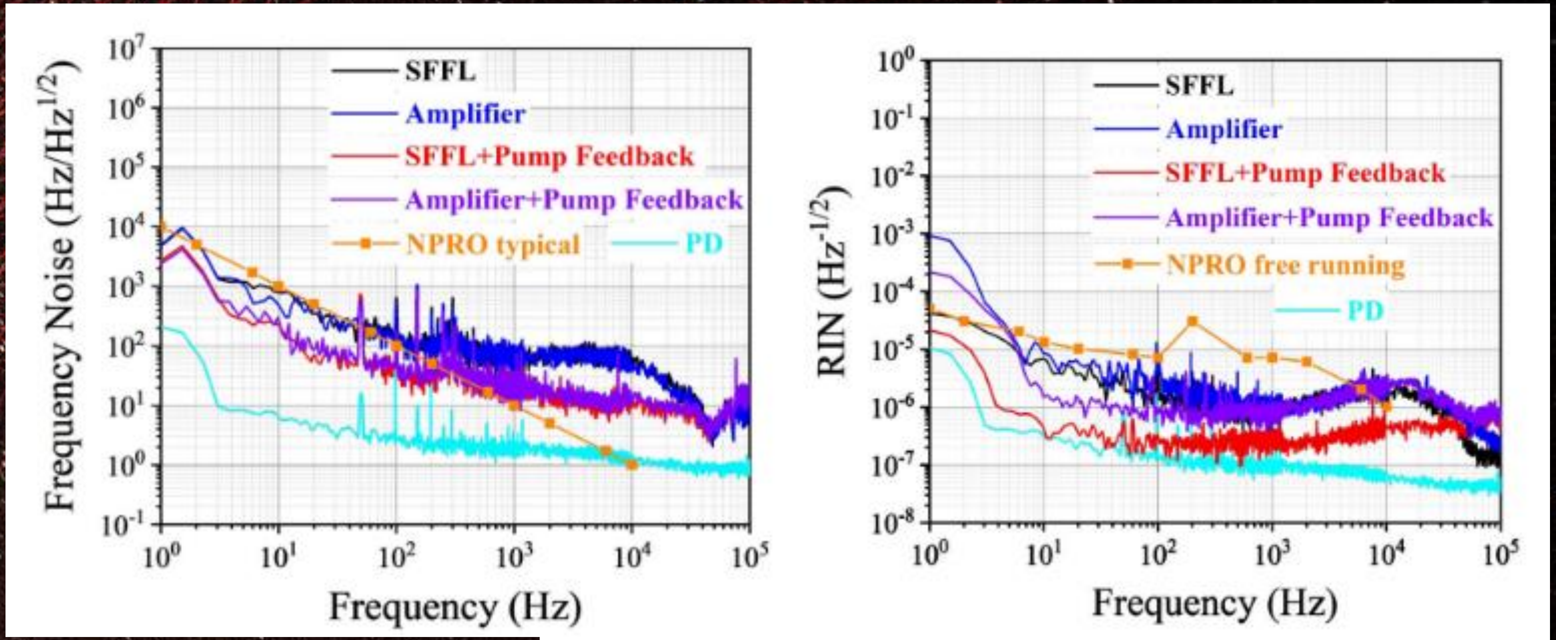


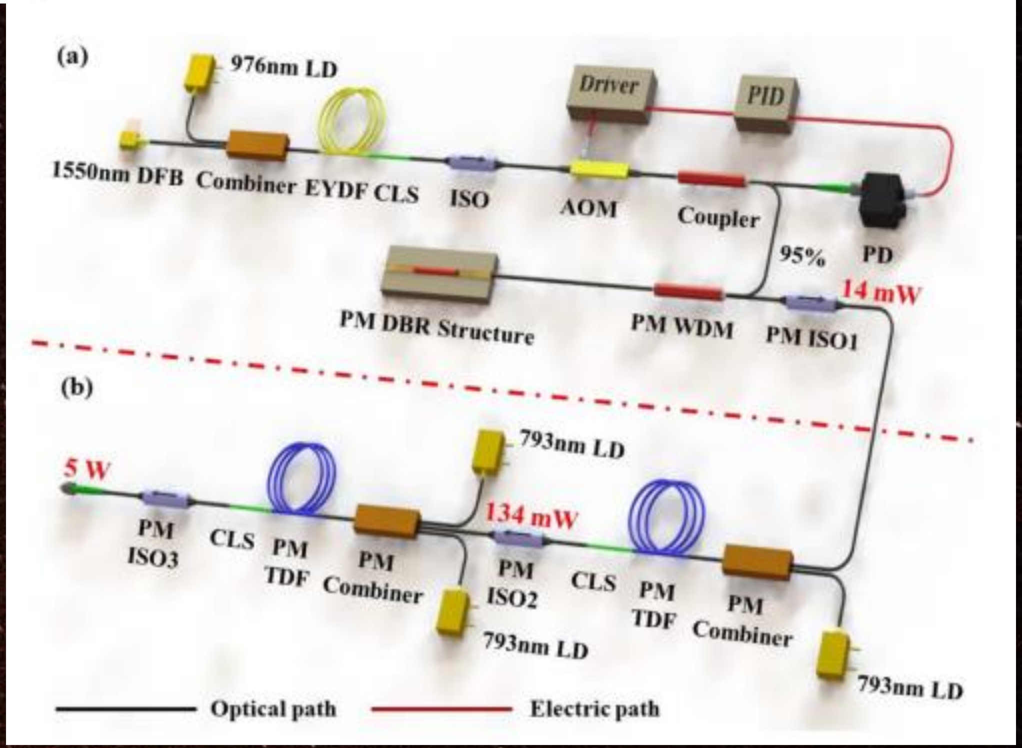


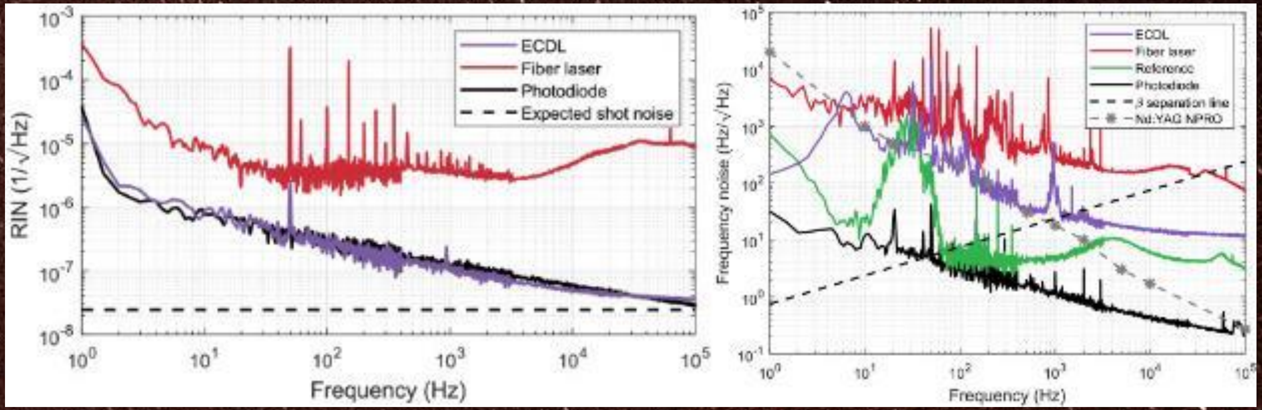
Progress

3G 2um Lasers

- Fiber laser developed in collaboration between UWA and BUT China
- Demonstrated low frequency and intensity noise (comparable to existing LIGO laser)
- UA and ANU developing 2um external cavity diode laser. – also demonstrated low noise.



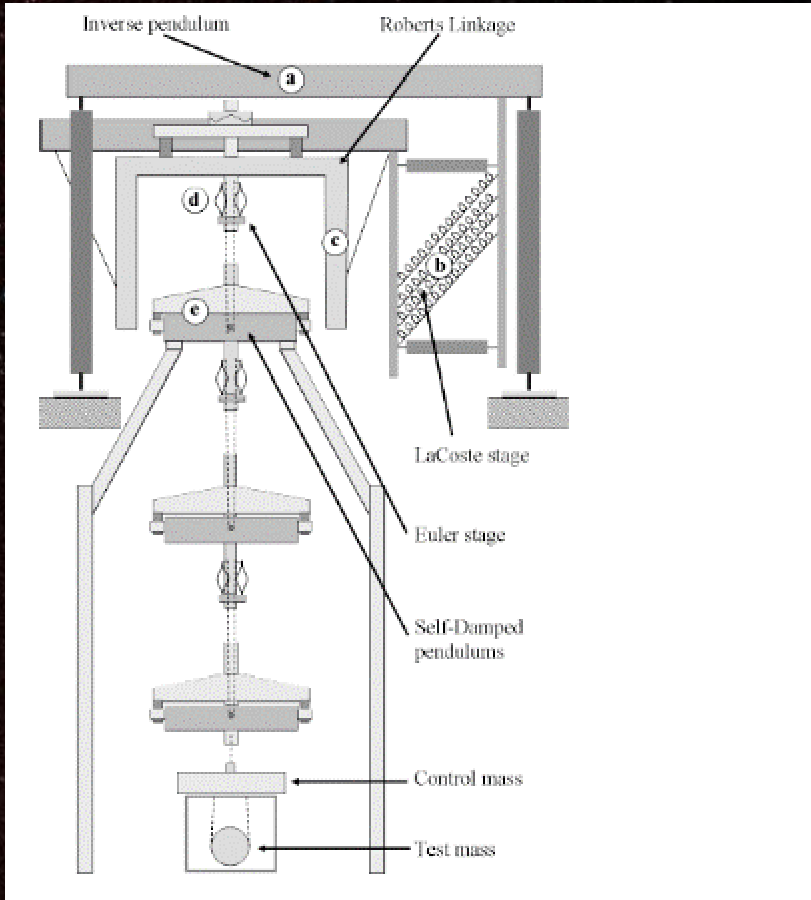


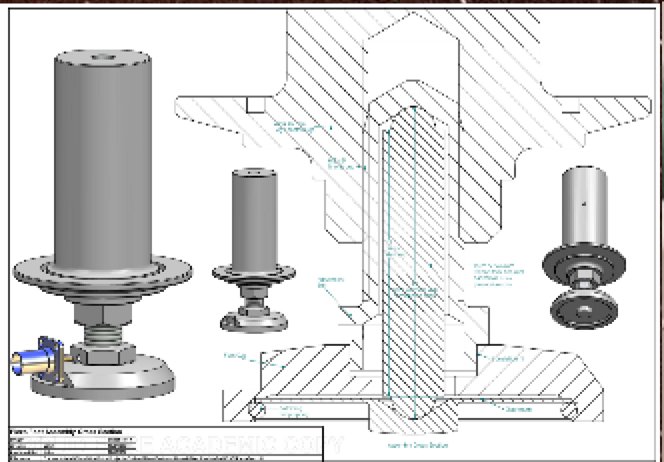


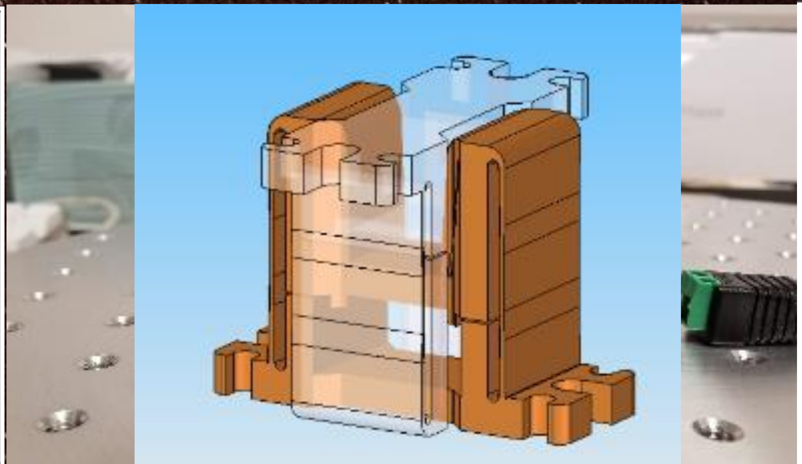
Progress

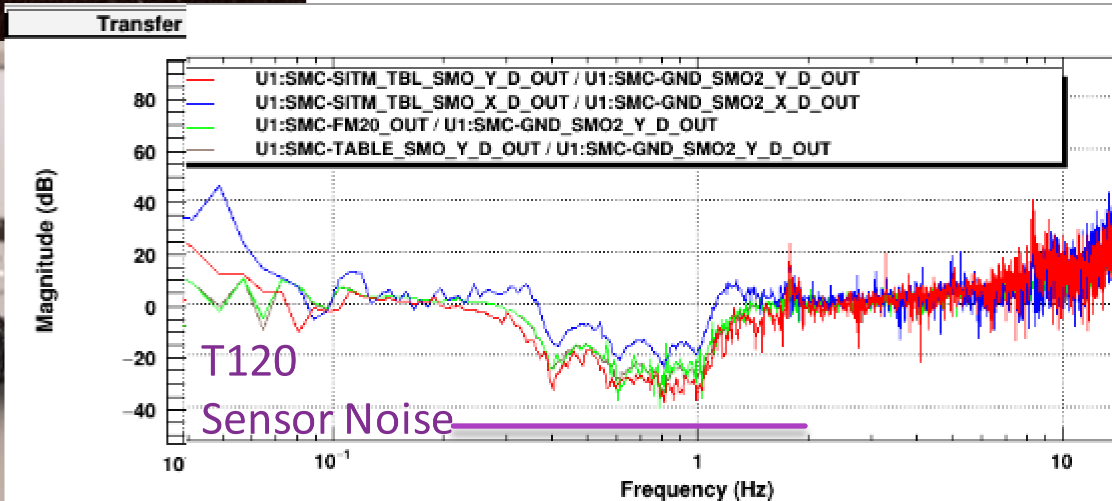
Vibration Isolation and Suspensions

- Science cavity – UWA compact vibration isolator
- Recycling cavity – piezo tables and single stage suspension.
- UA and ANU developing 2um external cavity diode laser. – also demonstrated low noise.





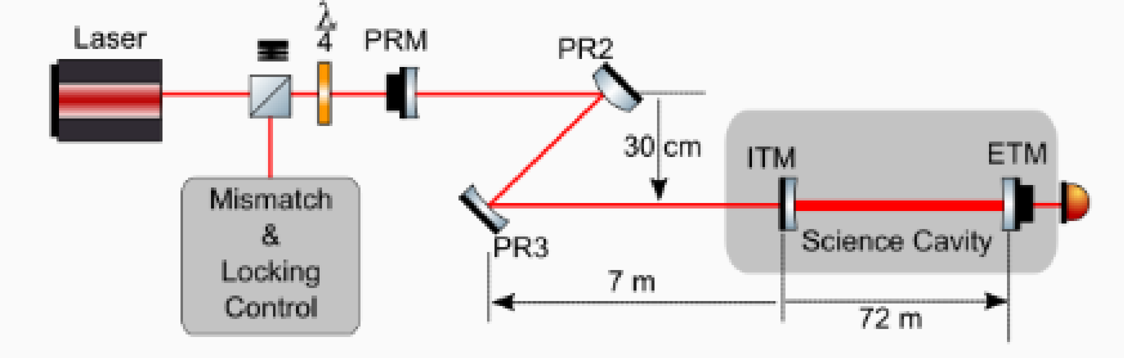


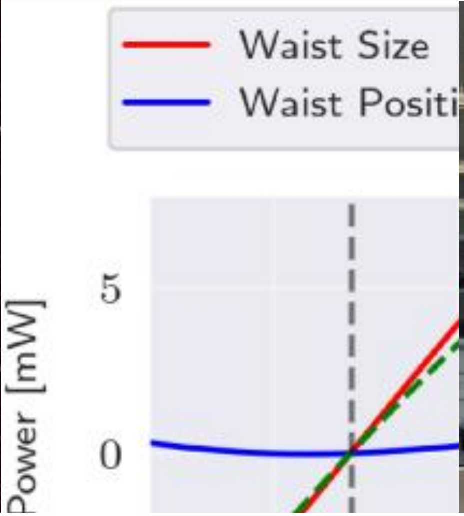


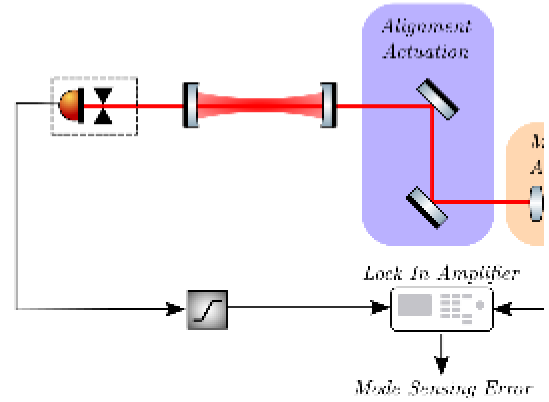
Progress

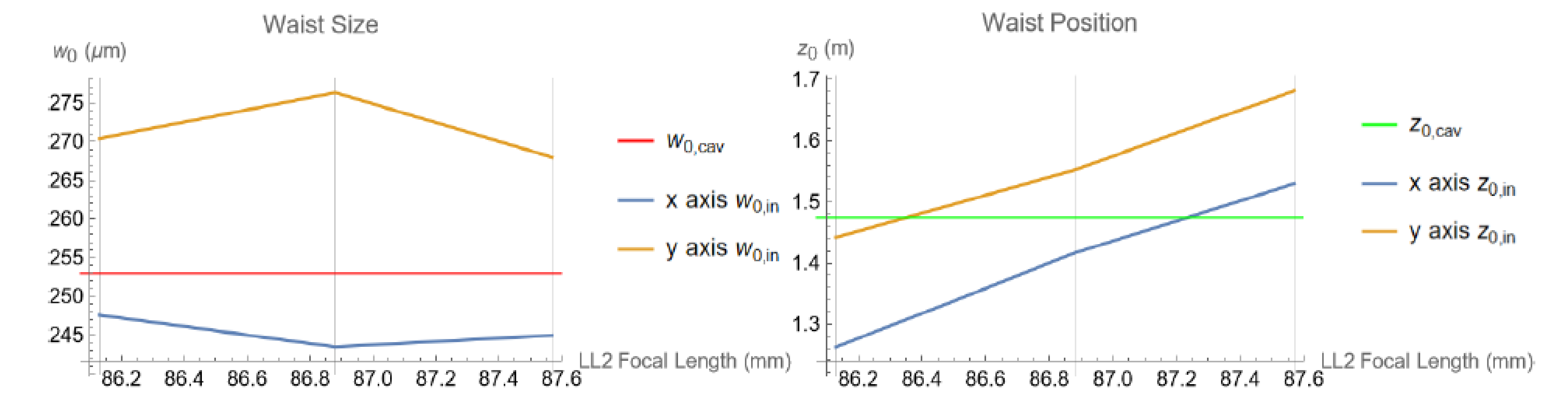
Coupled Cavity Mode Sensing

- Anderson scheme – drive LG10 mode
- Finesse simulation for Gingin
- Table top demonstration
- https://doi.org/10.1364/OE.502911



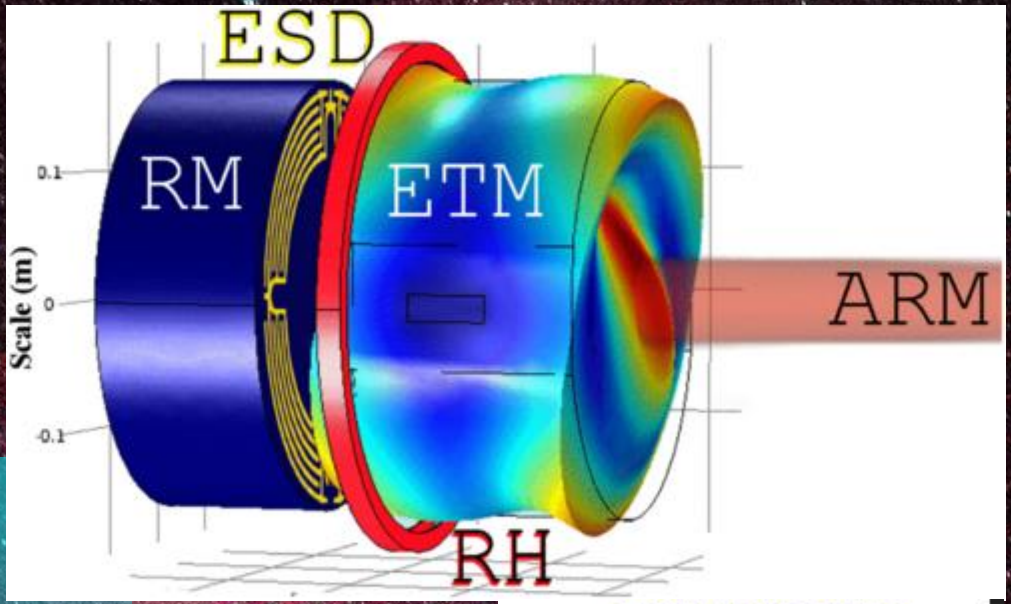






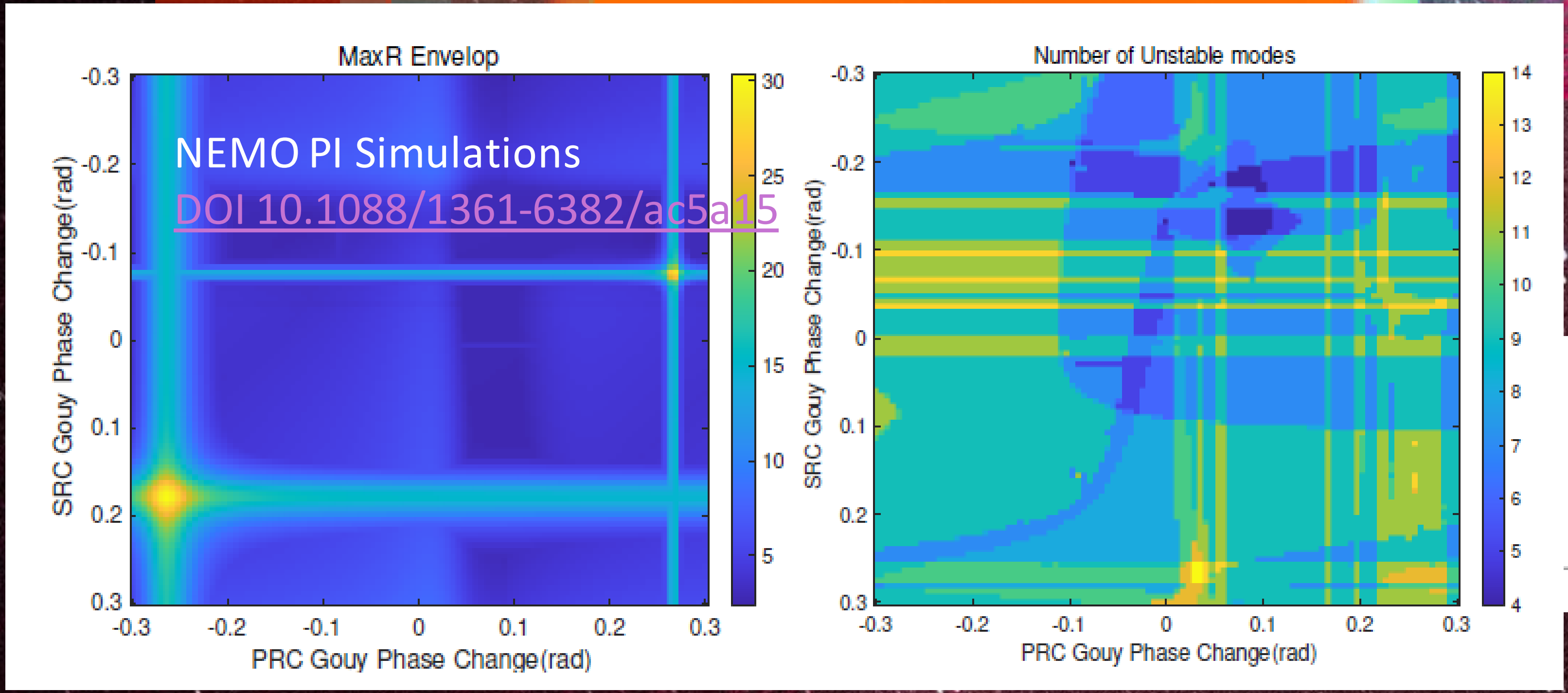
Progress

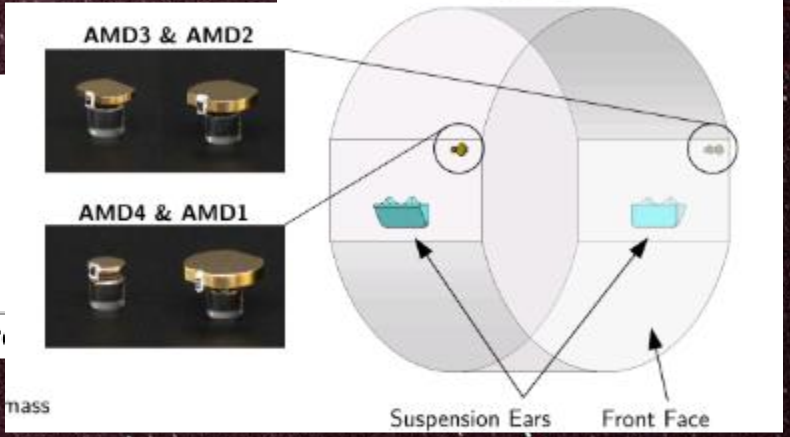
Parametric Instability



NEMO PI Simulations

DOI 10.1088/1361-6382/ac5a15

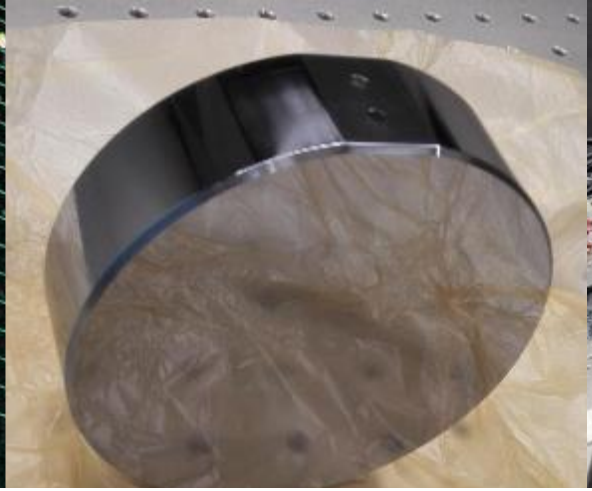


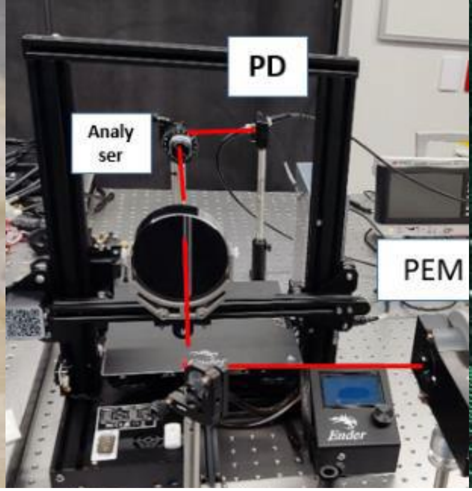


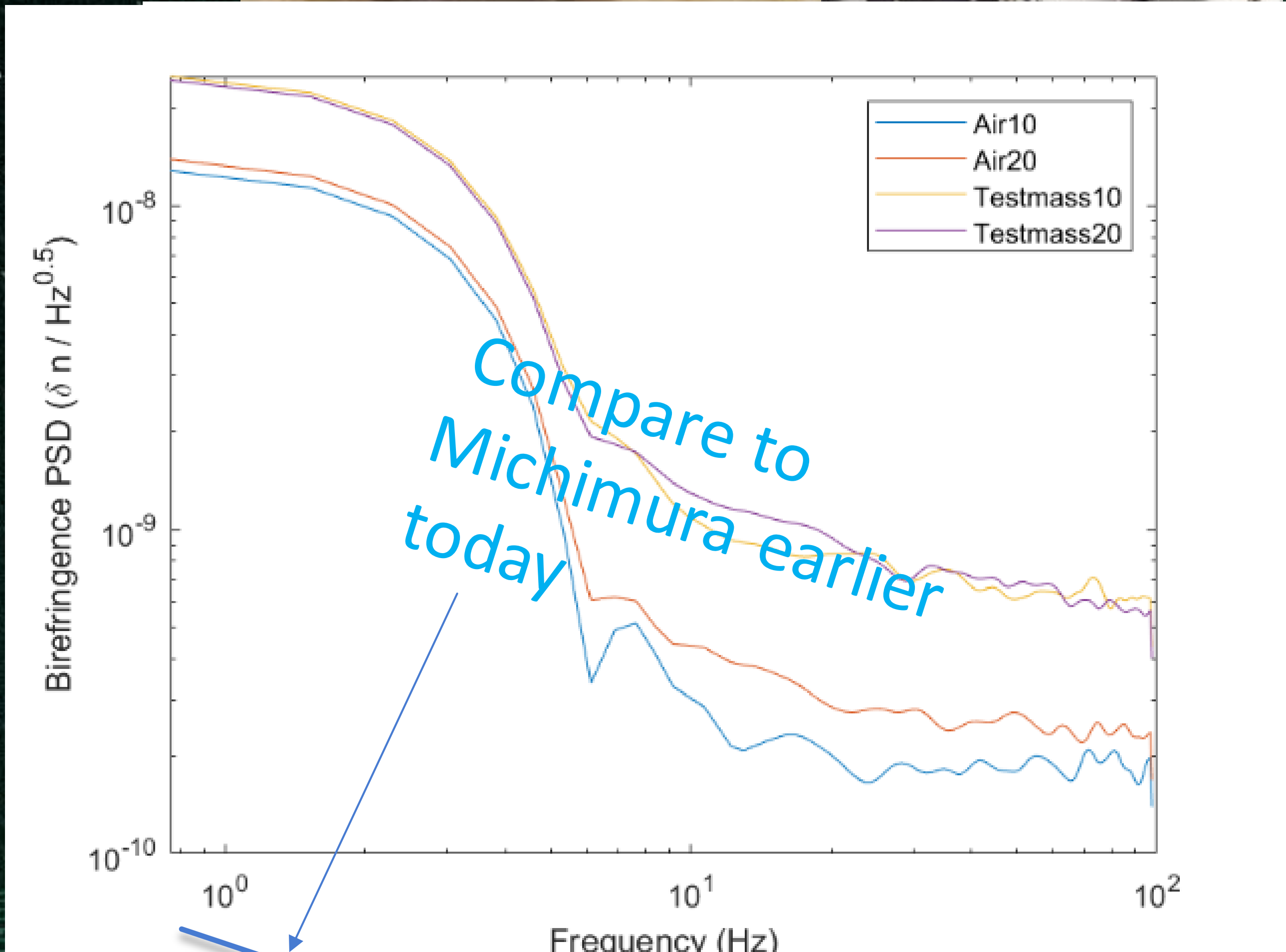
Progress

Float Zone Silicon Birefringence

- Crystalline -> Birefringent?
- Photoelastic modulator -> 1E-9
- Good except defects - https://doi.org/10.1063/5.0136869
- AlGaAs crystalline coatings ?
- Amorphous silicon and silica layers - future
- Silicon beam splitters – measurement ~2E-7, expect intrinsic to dominate (in prep.)
- Birefringence noise – noise non-stationary–noise hunting (first test)
- Thermal induced birefringence (planned)

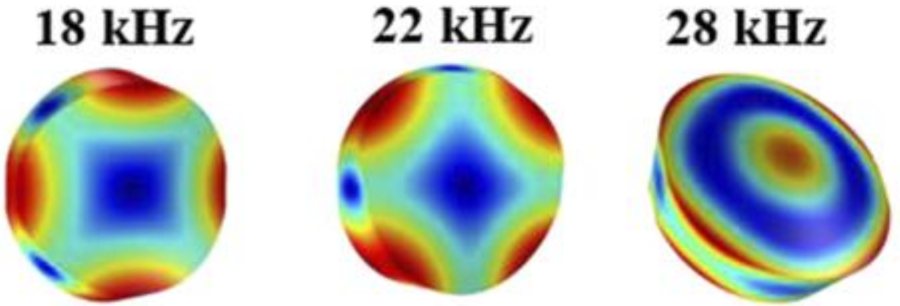


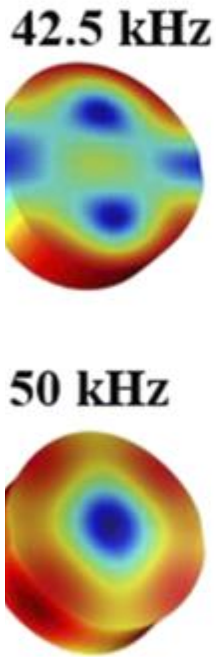


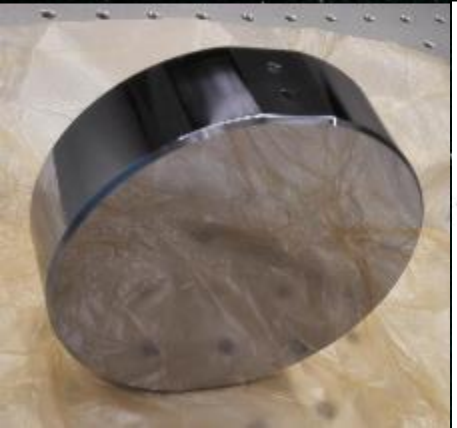


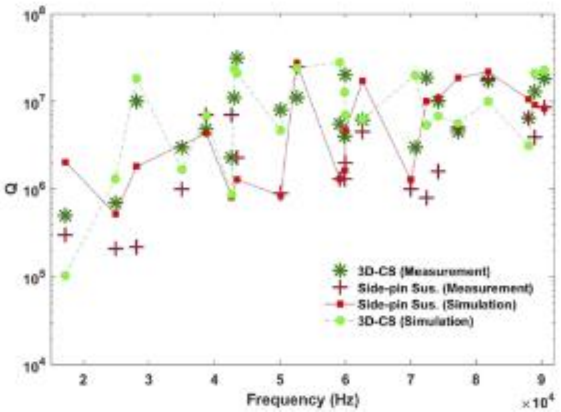
FZS and AlGaAs Mechanical loss

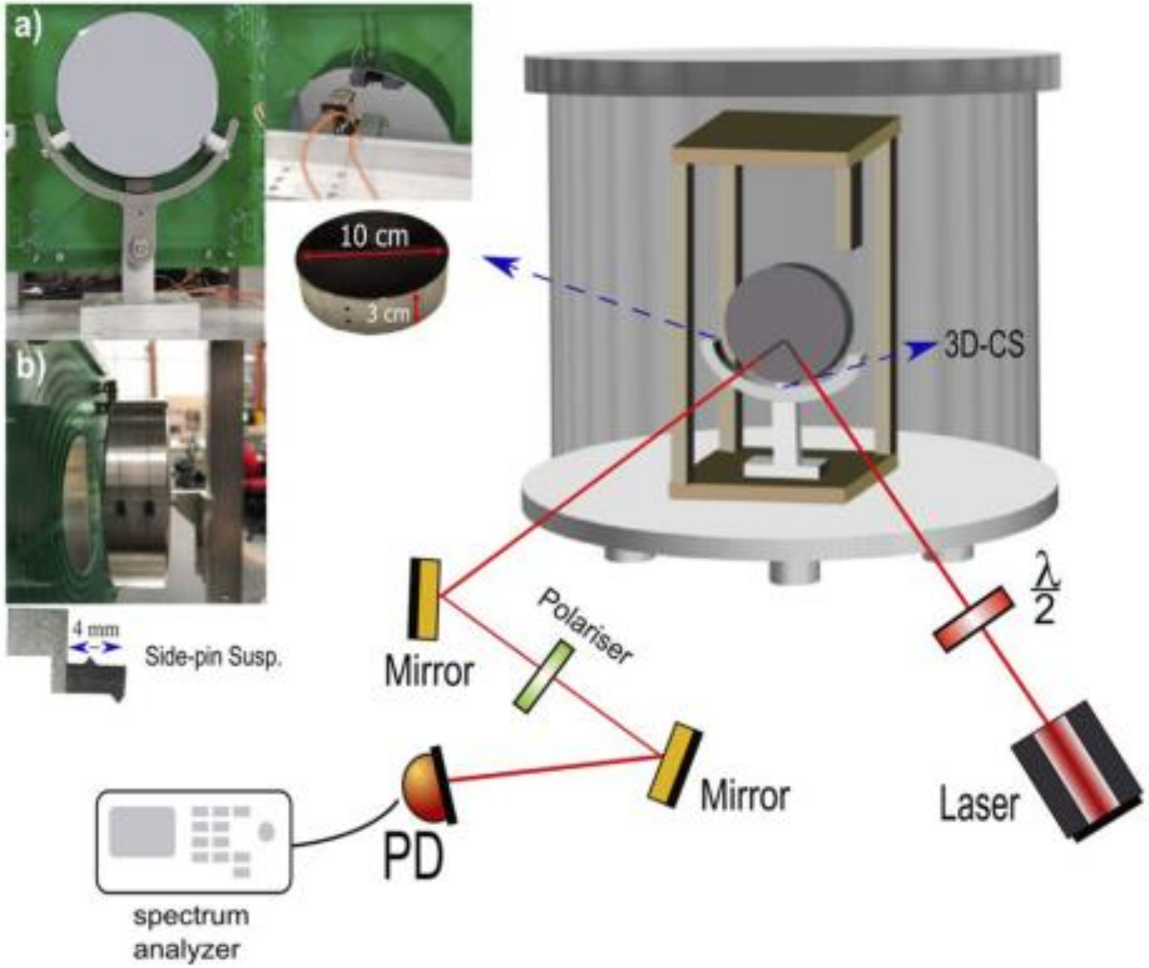
- Mechanical loss measurements system developed - https://doi.org/10.1063/5.0106565
- Estimate coating loss (to 10%) from change in Q factor of many modes
- 10cm diameter coating of ITM complete (not received yet)
- ETM coating thickness is a problem for coating transfer (10ppm ~20um)







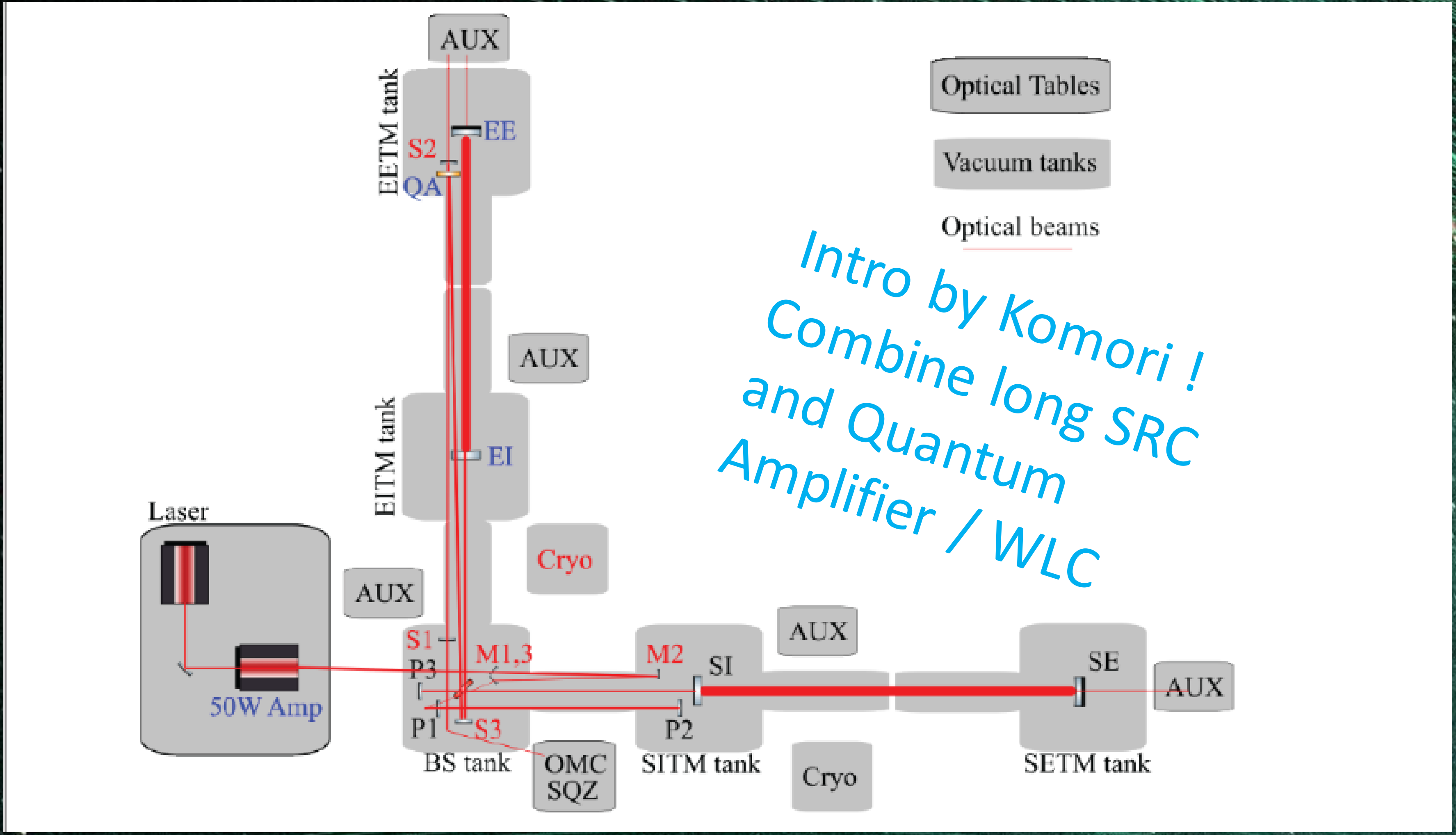




Future Direction

Gingin High Frequency Prototype Design

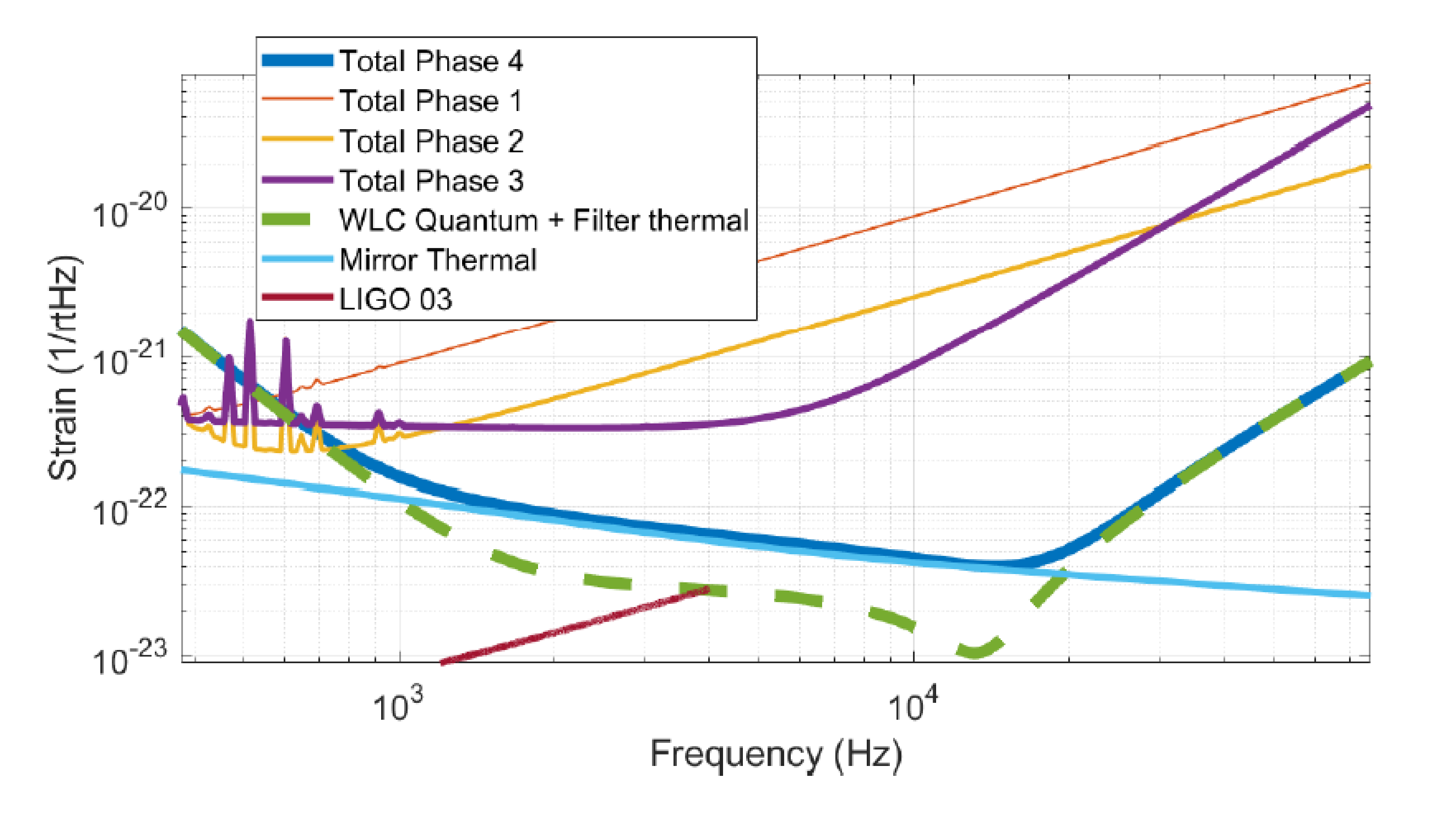
1. Technology Demonstrator
2. Operate Prototype in Science mode
3. Science Goal ?



Future Direction

Gingin Prototype Expected Sensitivity Progression

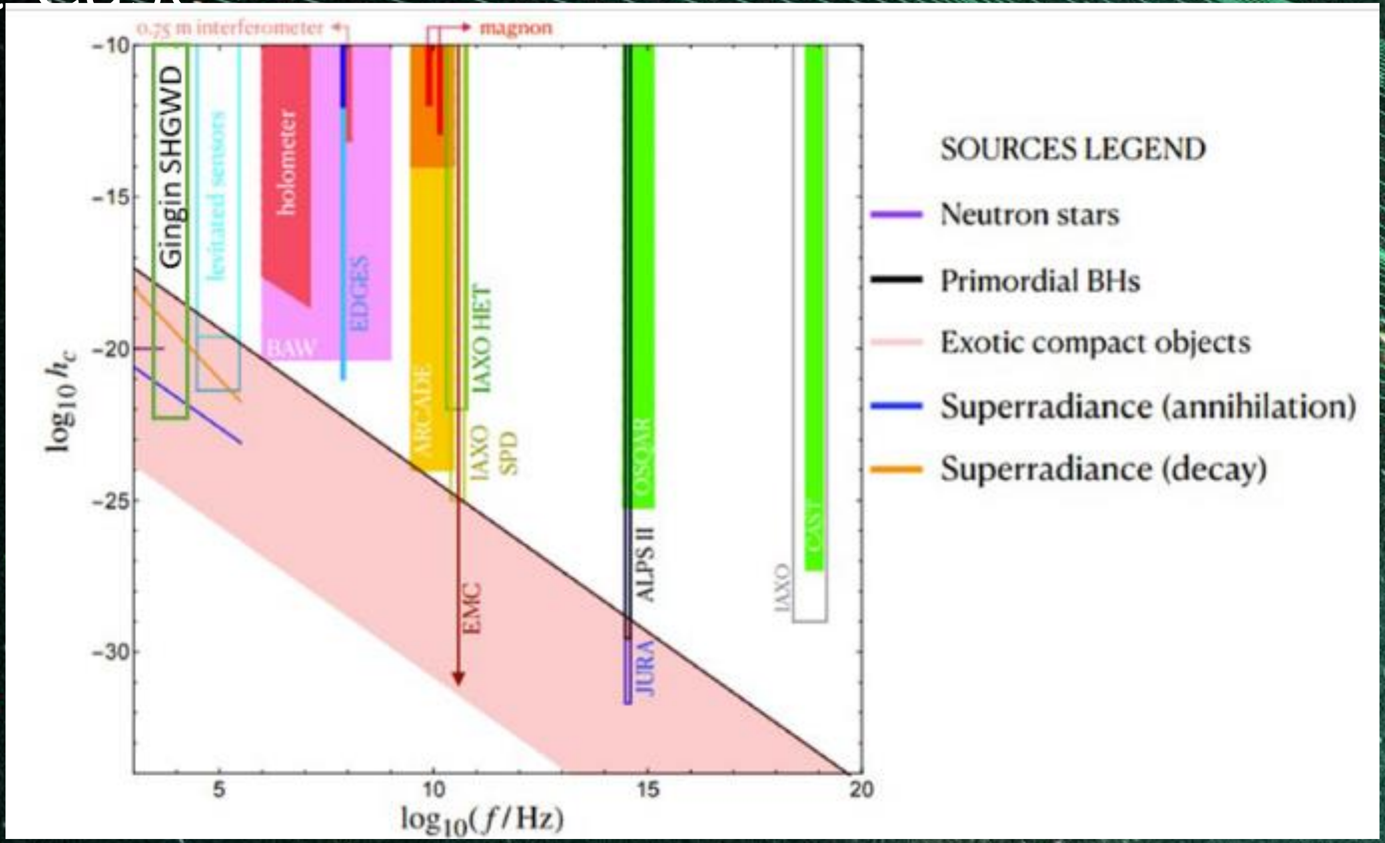
1. PR Michelson
2. 50W input
3. 10dB squeezing SRC in RSE
4. WLC



Future Direction

Gingin Prototype Science Case

- Many speculative targets
- Achieve best sensitivity in frequency band – set upper limits on targets
- (This is 10kPc sensitivity limit)



Summary

- Gingin is being used for a NEMO, Voyager, CE technology demonstrator .
- 2um, Float Zone Silicon, Cryogenic, Coupled Cavity
- 5W 2um laser installed and in use – noise demonstrated
- Vibration Isolation for test masses 1/2 built, recycling cavity tables – built optimising control.
- AlGaAs mirror coating (ITM complete not yet received)
- Coupled cavity mode sensing scheme designed, simple test complete, coupled cavity in progress
- Parametric instability investigations – confirm simulations for NEMO
- Float Zone Silicon Birefringence Measurements – beams splitters, noise, AlGaAs and plan for thermally induced.
- Float Zone Silicon and AlGaAs coating loss angle
- Plan for a future prototype facility at Gingin

Other progress and plan not reported

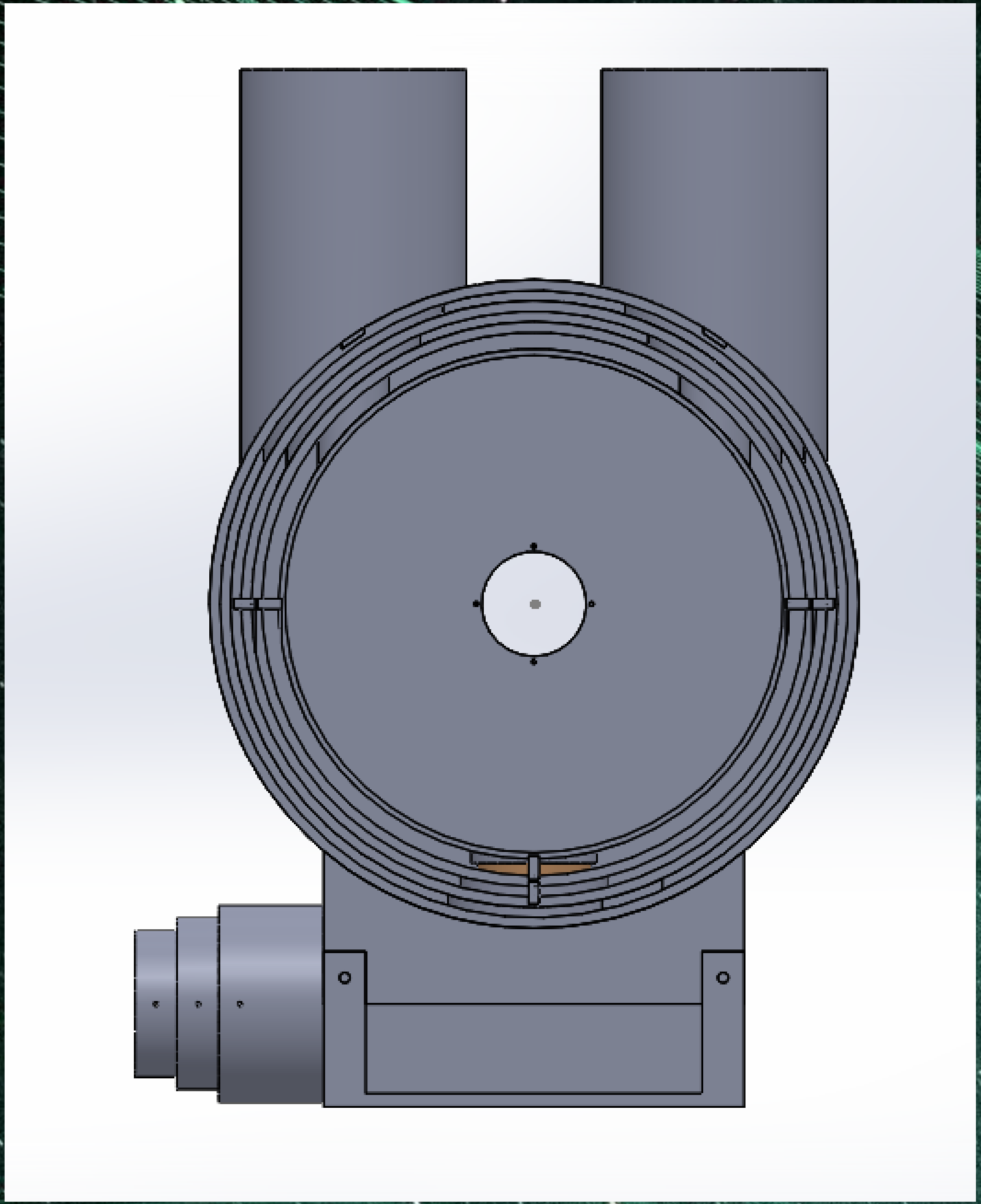
- Vacuum system (7m Cavity complete, fixing 72m)
- Optical design complete
- Locking scheme design complete
- Cryogenic Design – complete
- Thermal actuated power recycling mirrors built and characterising
- AlGaAs mirror coating (ITM complete not yet received)
- Isolator upgrade

Questions?


Power Recycling Mirror Tank
ITM Tank
Injection Room
72 m
ETM Tank
ITM Seismic Isolator

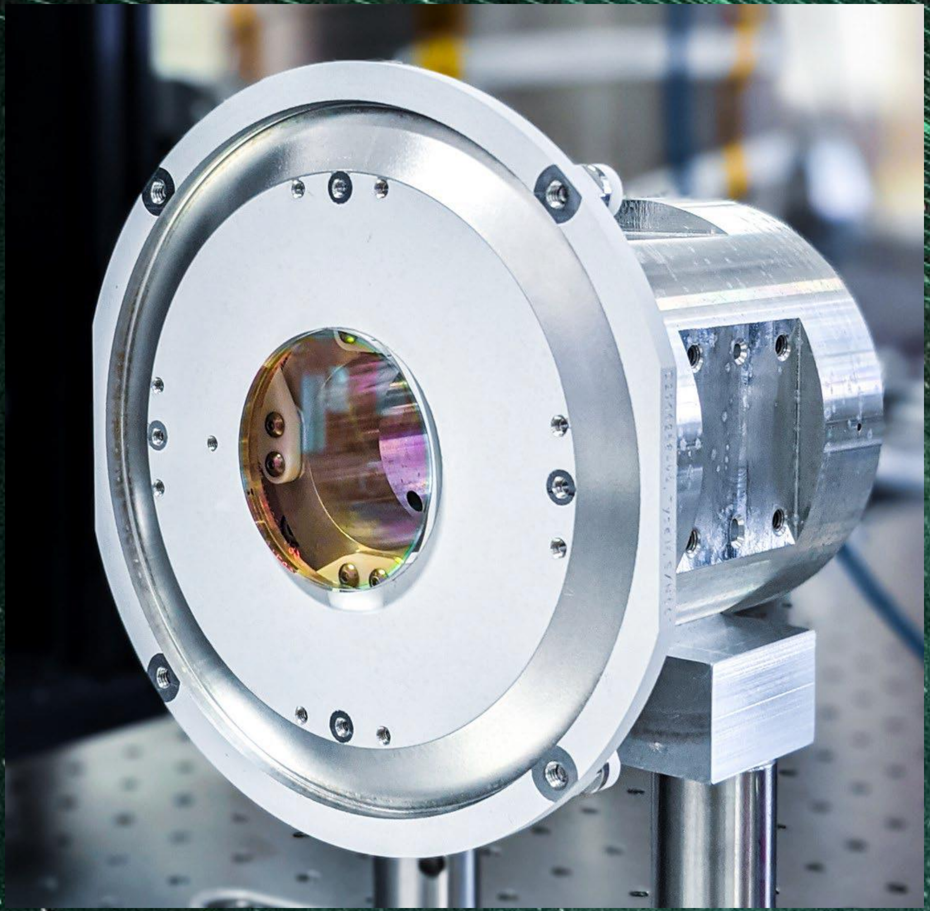
Cryogenics design

- Requirement 123K ITM
- Cryo pump



Thermally Actuated Recycling Mirrors

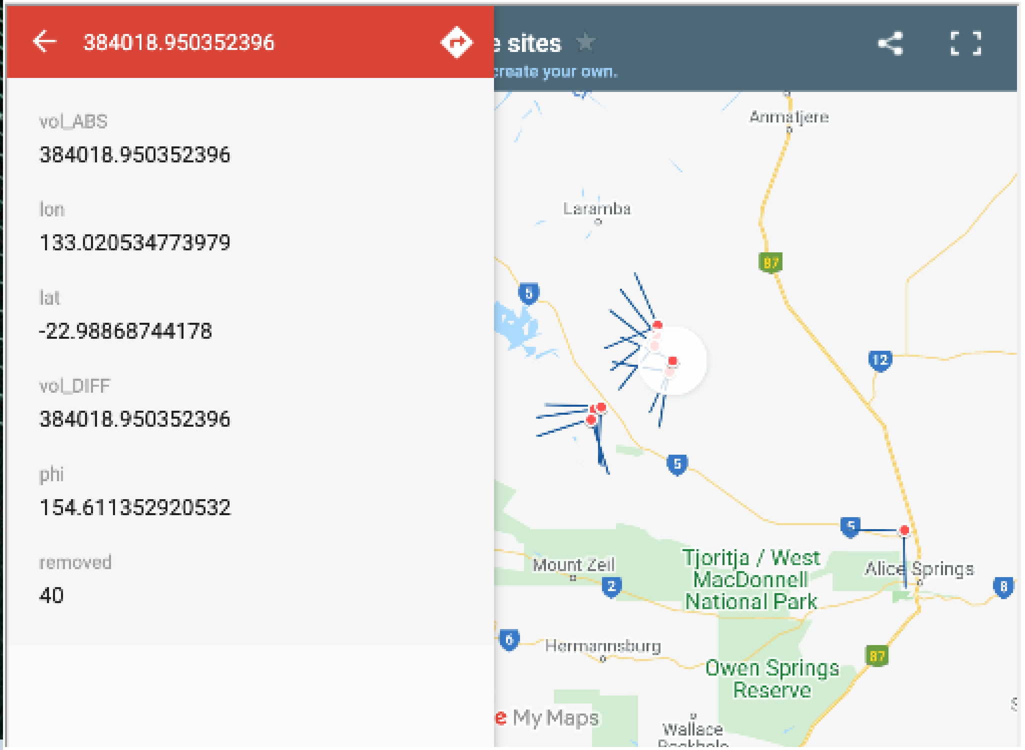
- Use the LIGO TSAMs design
- Scale up to 75mm diameter mirror (PR3)
- Built
- Characterising

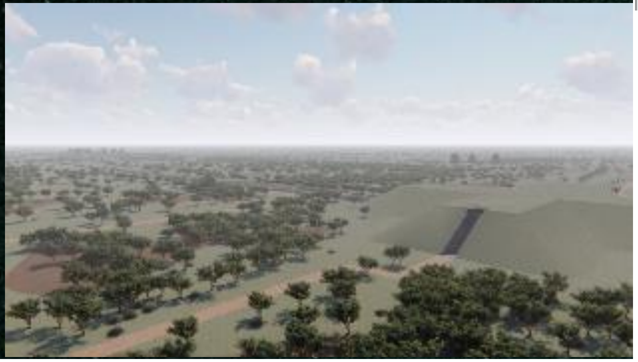


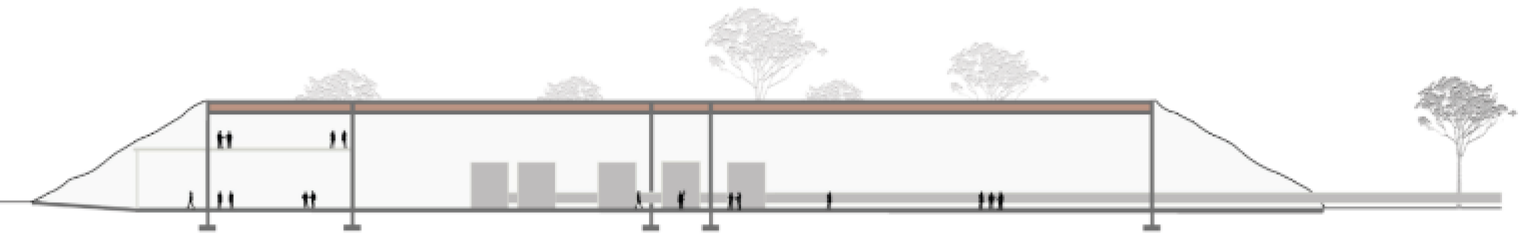
Future Detectors

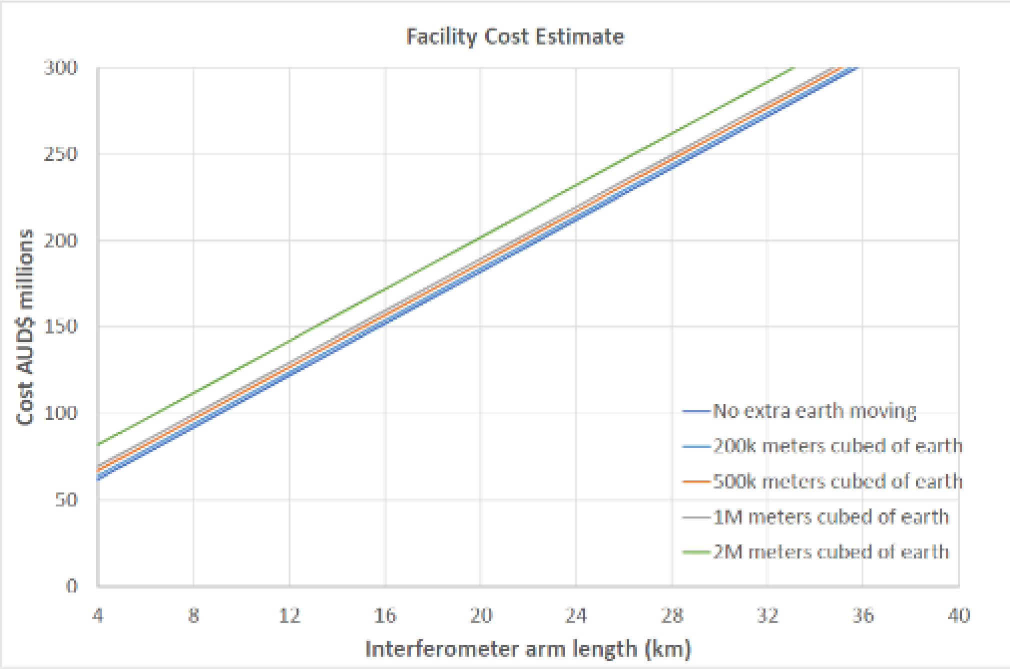
3G An Australian Detector

- NEMO proposal
- Cosmic Explorer South proposal
- Scoping study to estimate the cost
- Site selection study
- Initiated a Project Office with executive structure and oversight to manage an Australian GW observatory project



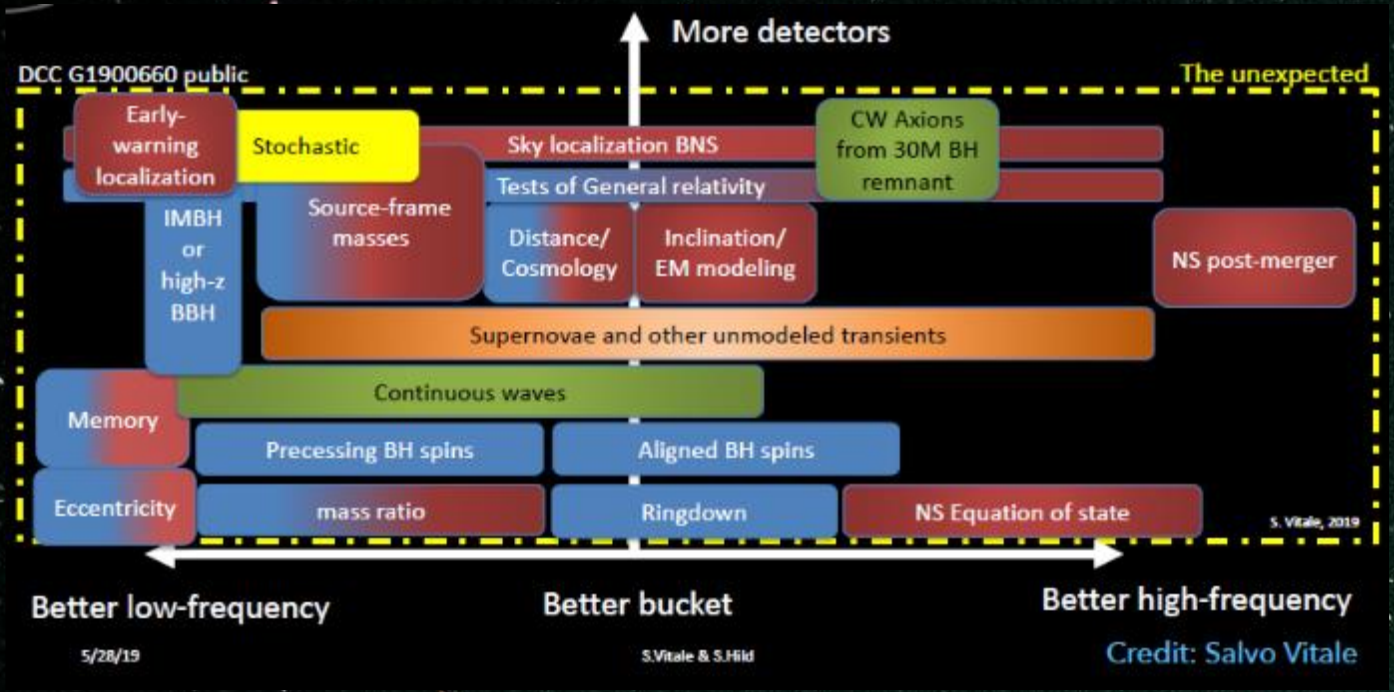


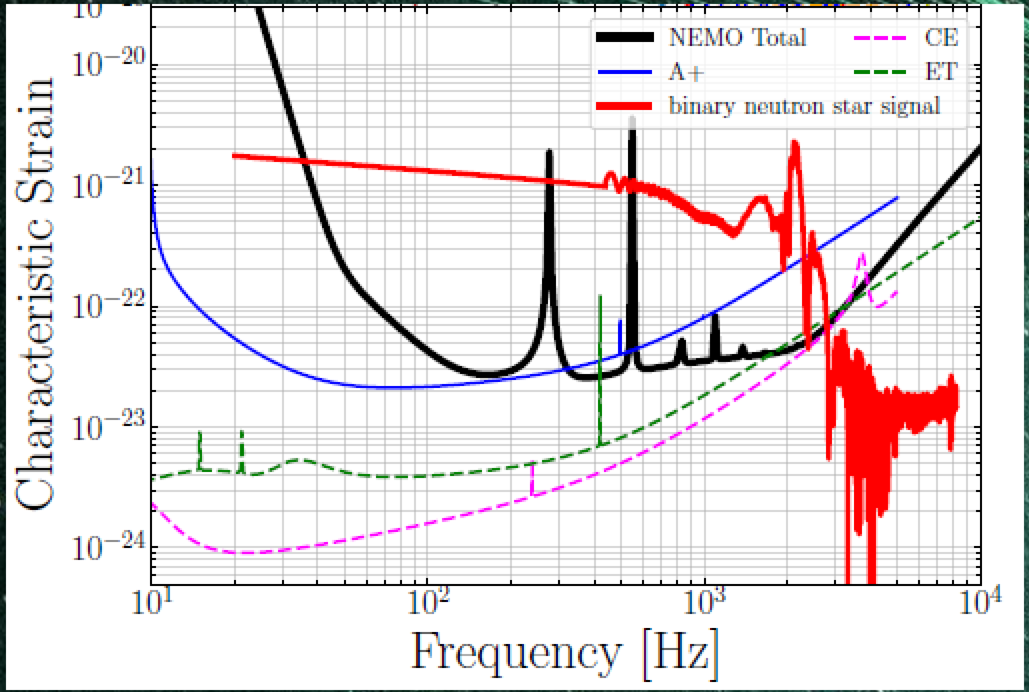




3G An Australian Detector – NEMO Proposal

- 4km detector cryogenic, high power, silicon
- Study the BNS post merger signal

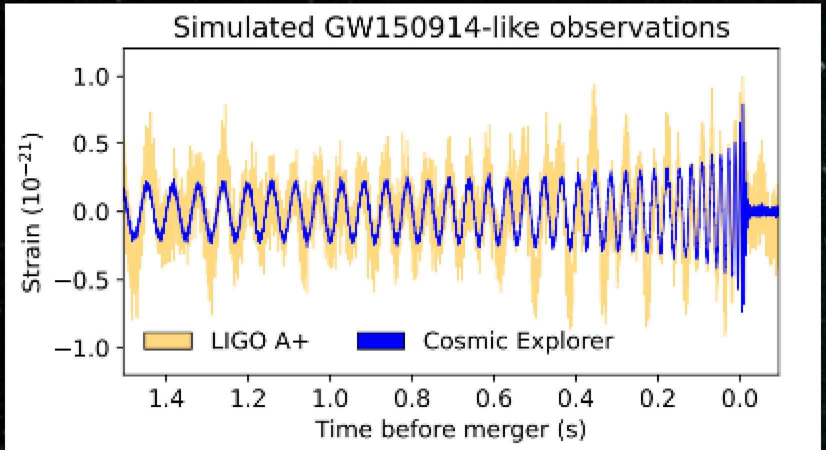


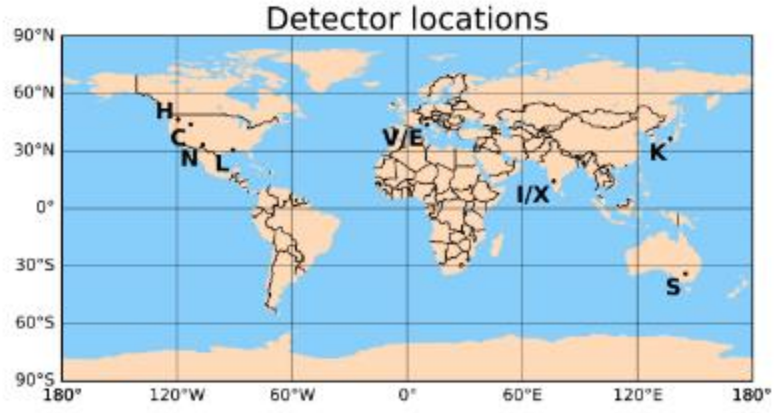


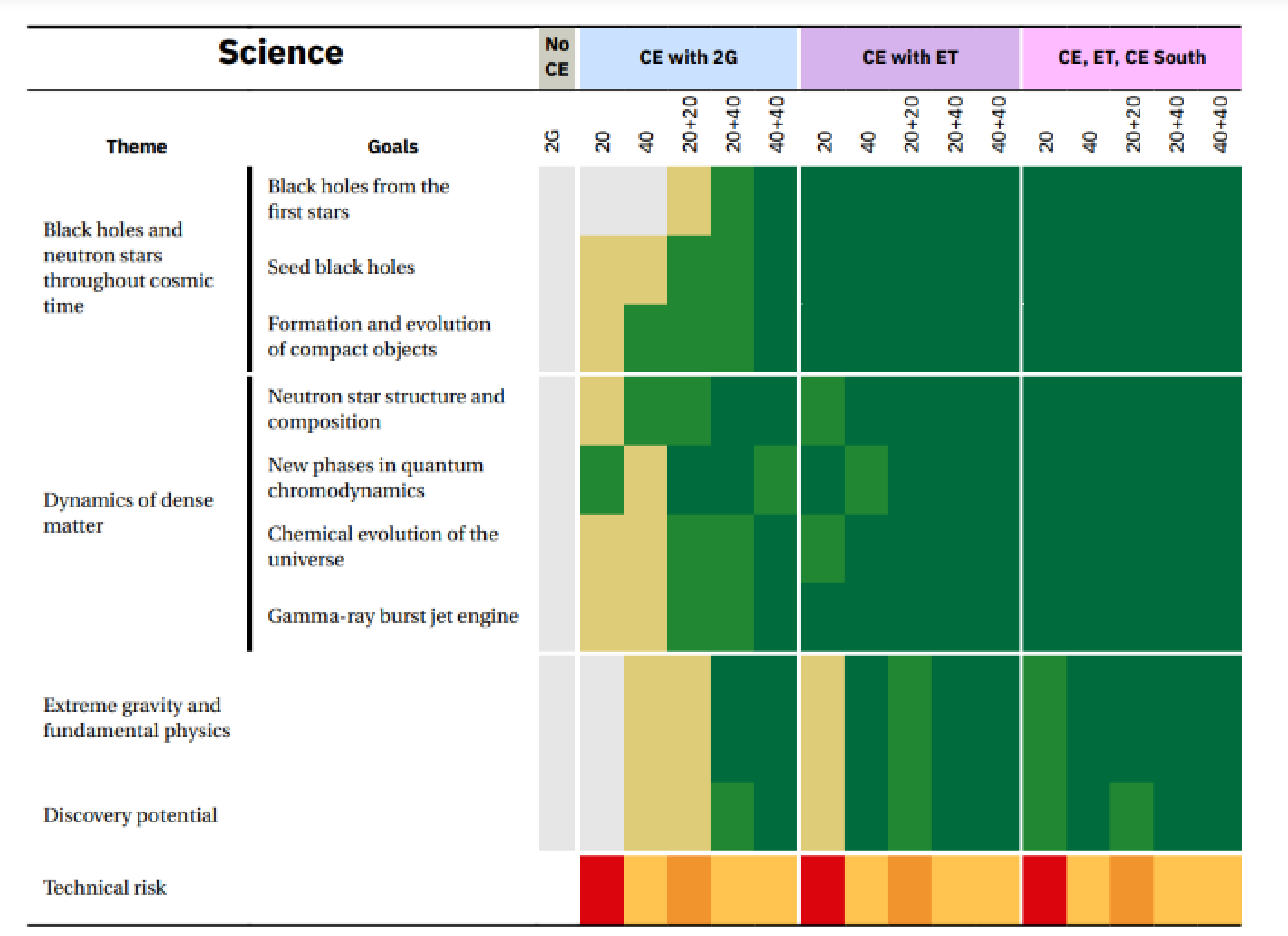
Future Detectors

3G An Australian Detector – Cosmic Explorer South

- 20km detector – known technologies

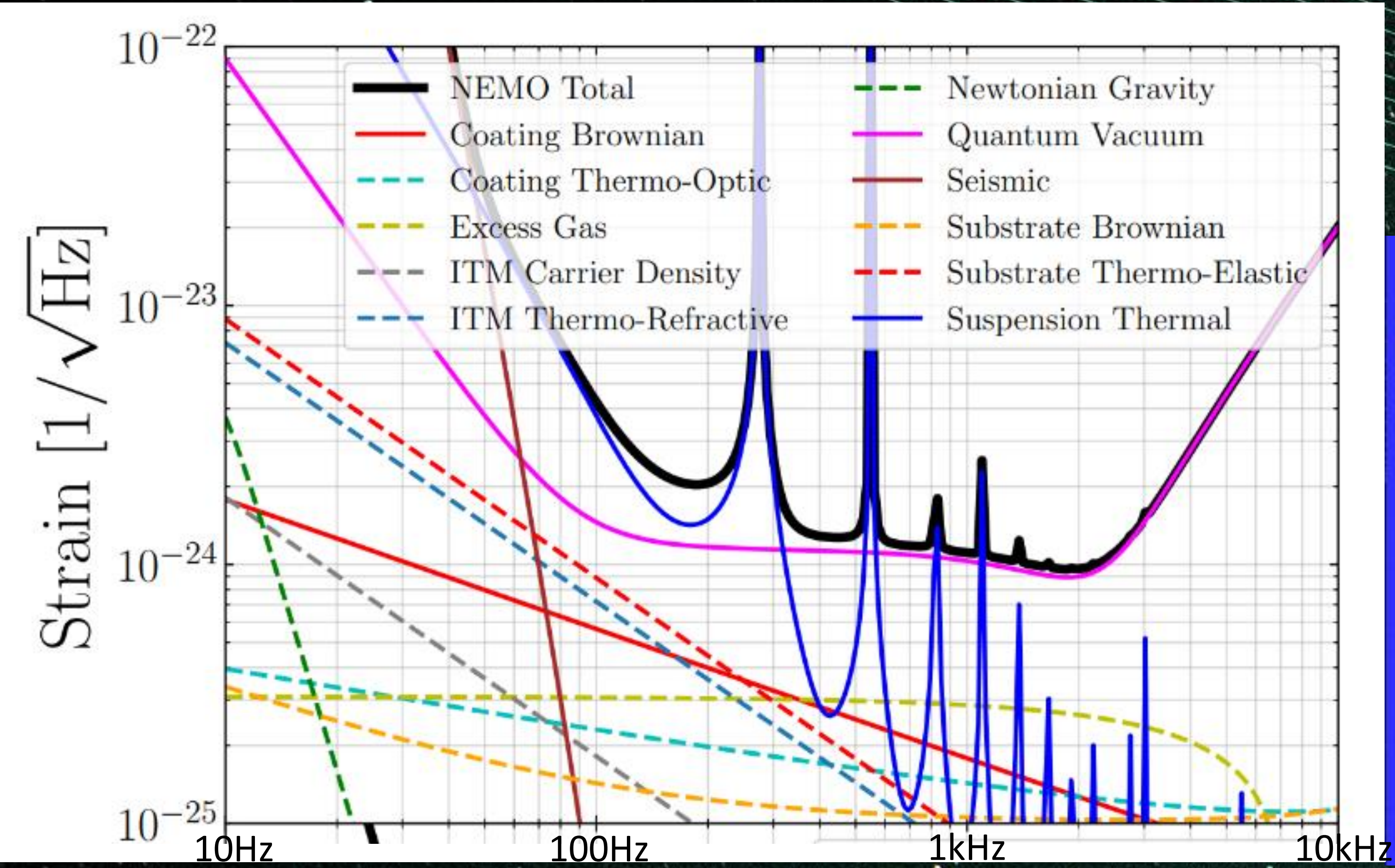


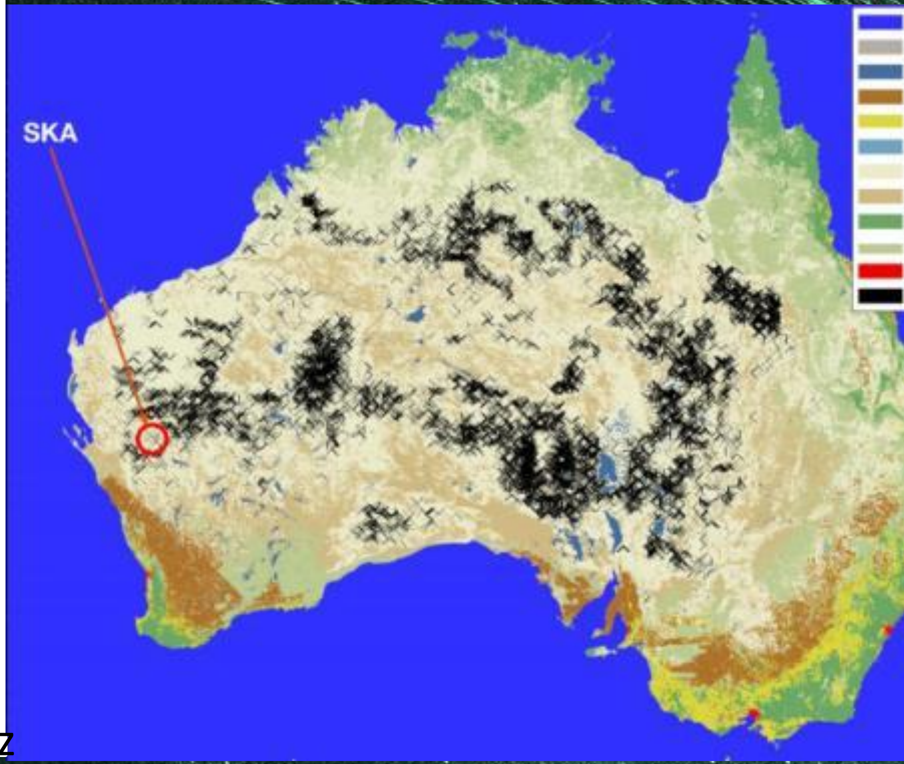




Future Detectors

Australia, NEMO and High Frequency Detectors



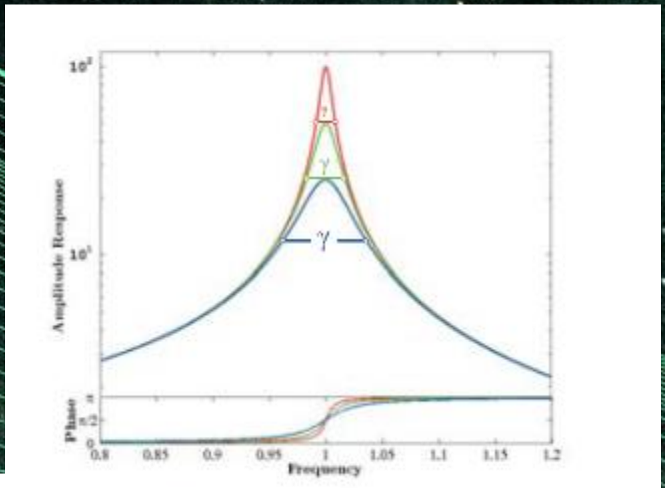


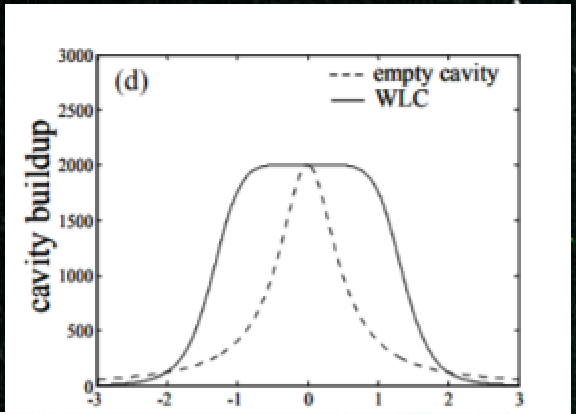
Can we do Better???

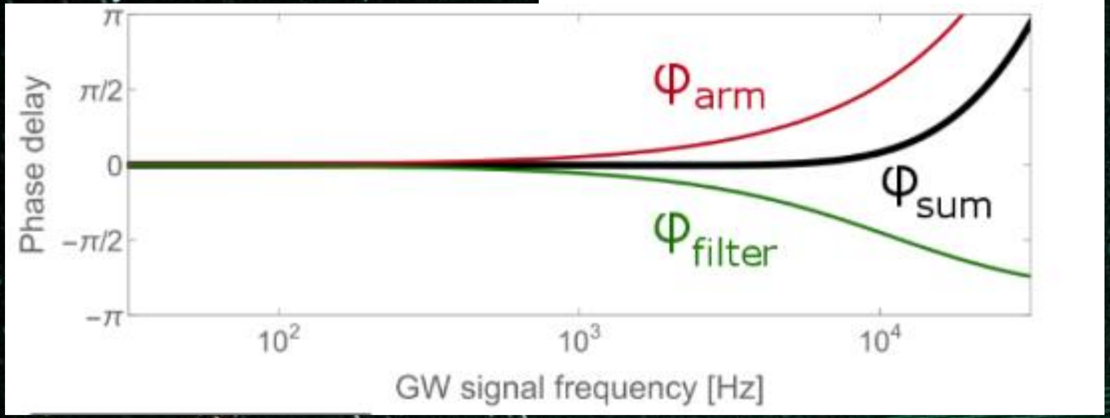
Future Detectors

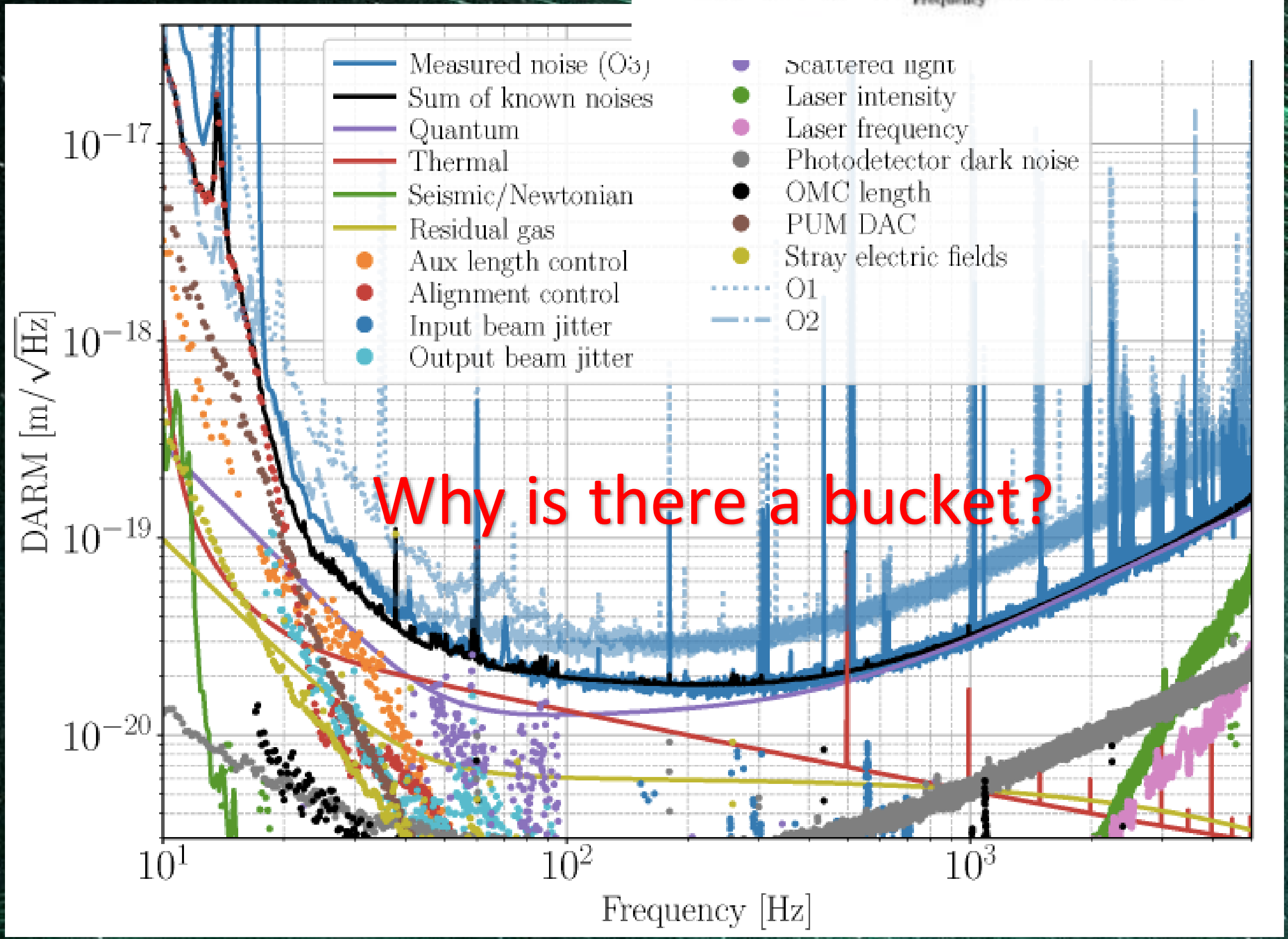
White Light Cavities and Quantum Amplifiers

- Gain bandwidth product
- Negative dispersion
- White light cavity



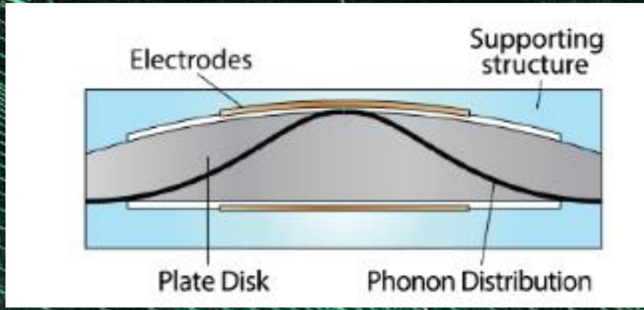




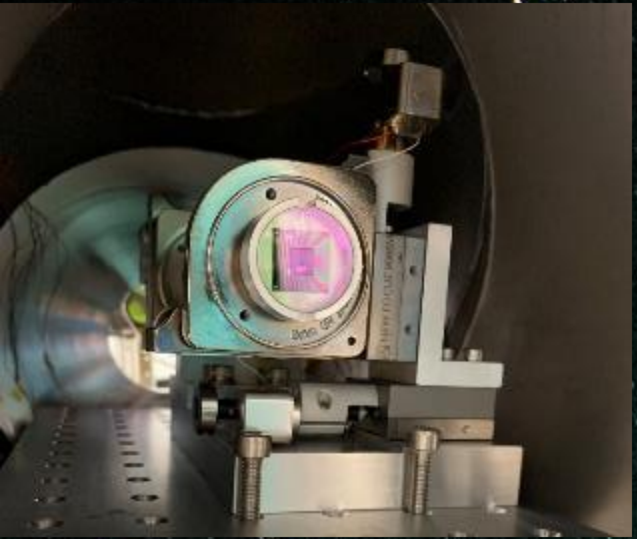


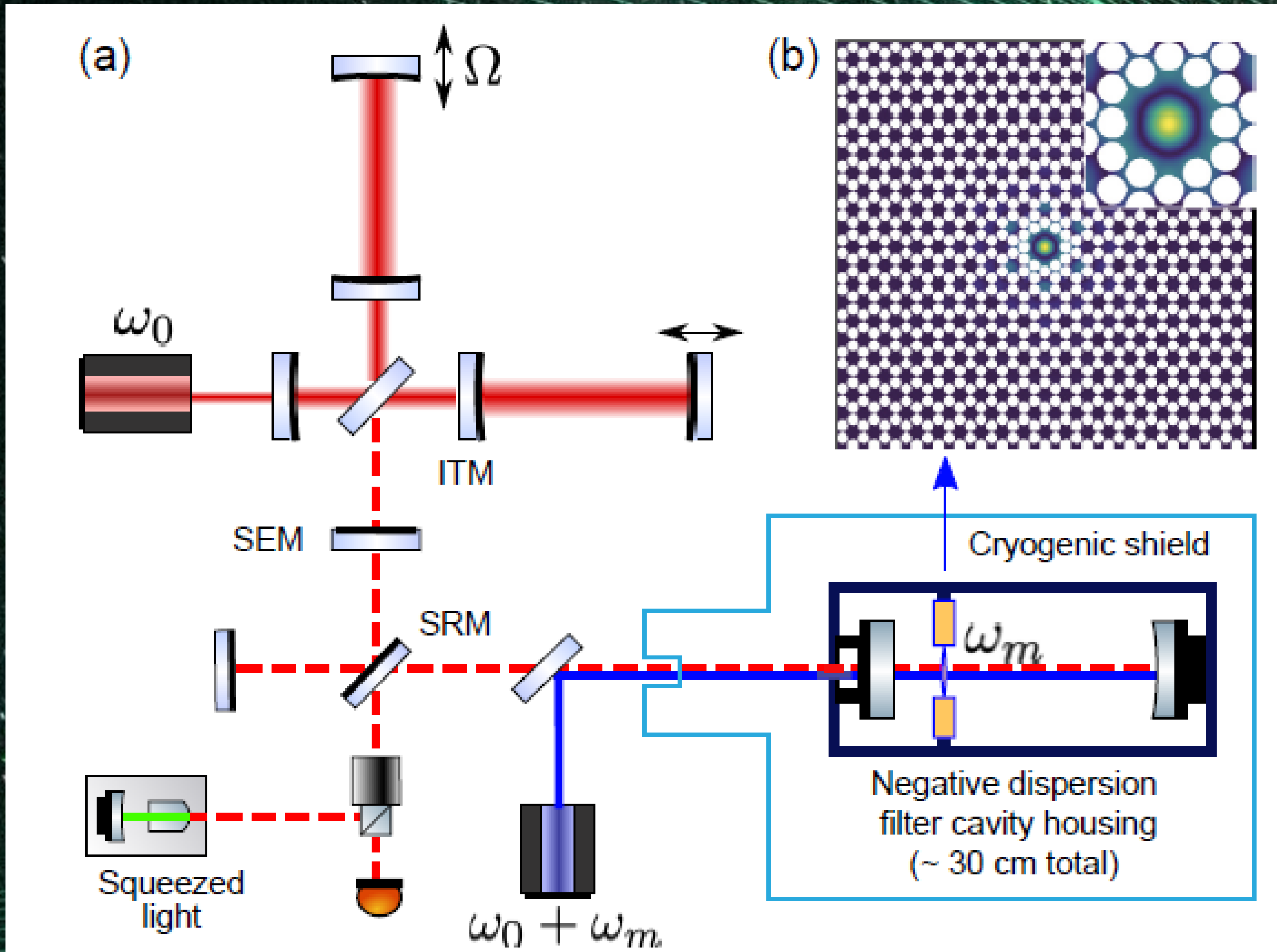
Future Detectors

Opto-mechanical negative dispersion at UWA



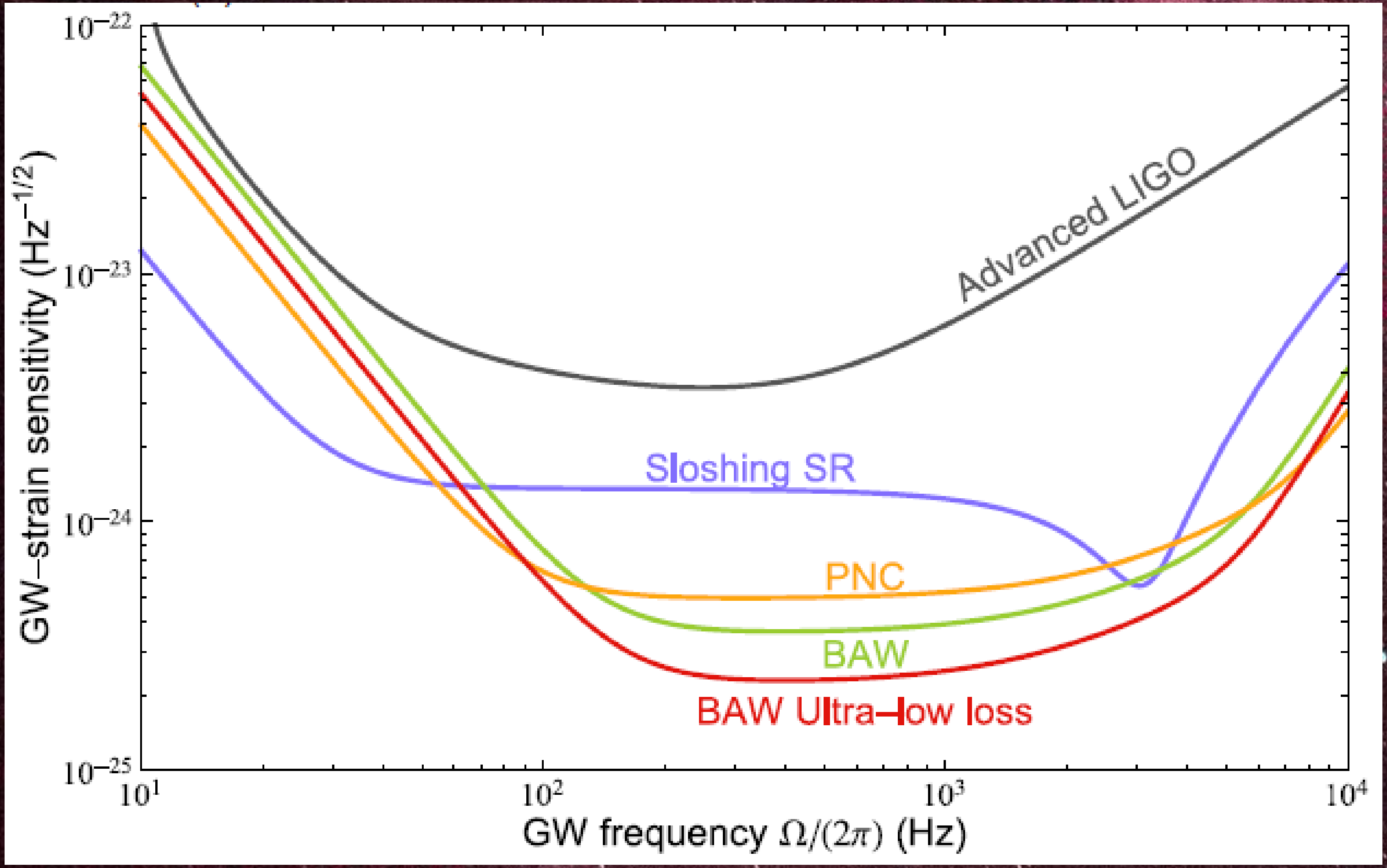
- Q/T ~ 10^9 -> low thermal noise
- High opto-mechanical coupling
- Bulk Acoustic Wave resonator
- Phononic Crystal
- Optically diluted cat flap





Future Detectors

White light cavity simulations



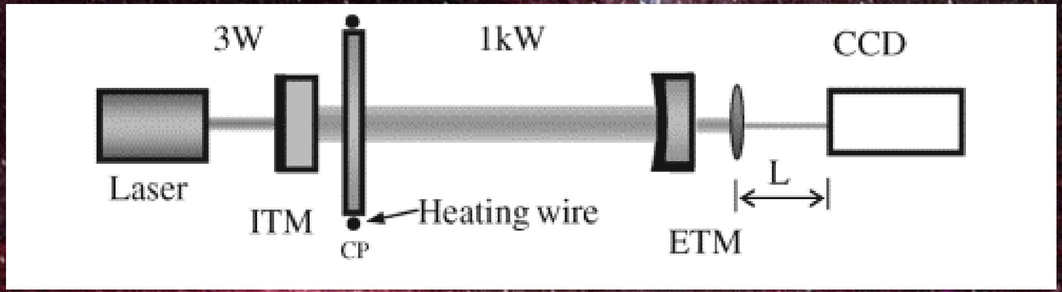
Future Detectors

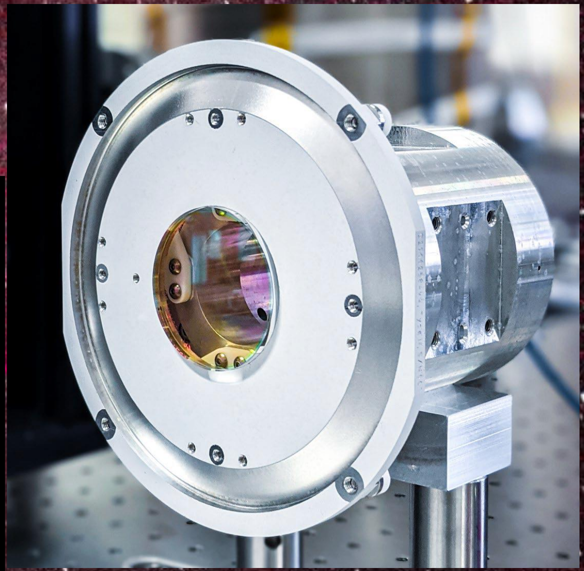
Gingin Prototype

The aim of this project is to demonstrate the new technology of silicon optics for high optical power gravitational wave detectors. It will be assembled and tested in our existing 80m arm length interferometer facility. Besides being a pathfinder for a future Australian interferometer, the detector will achieve astrophysical interesting sensitivity in the unexplored frequency band between 2-30kHz.

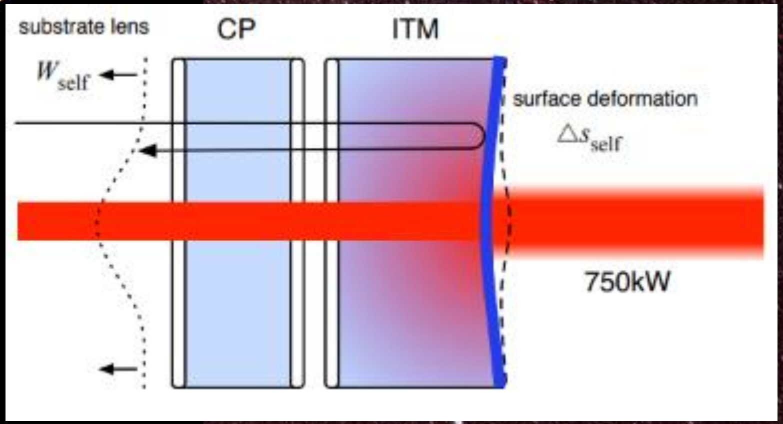
Australian Contributions

High Power - Thermal Issues





- Thermal compensation proposed in 2006 UWA – still in use
- Adaptive optics supplied to LIGO for O4, also being supplied to VIRGO
- Investigating material and coatings
- Large effort across many nodes to understand the thermal problem
- New Grant to build a Thermal Test Stand to have a full scale model to work on



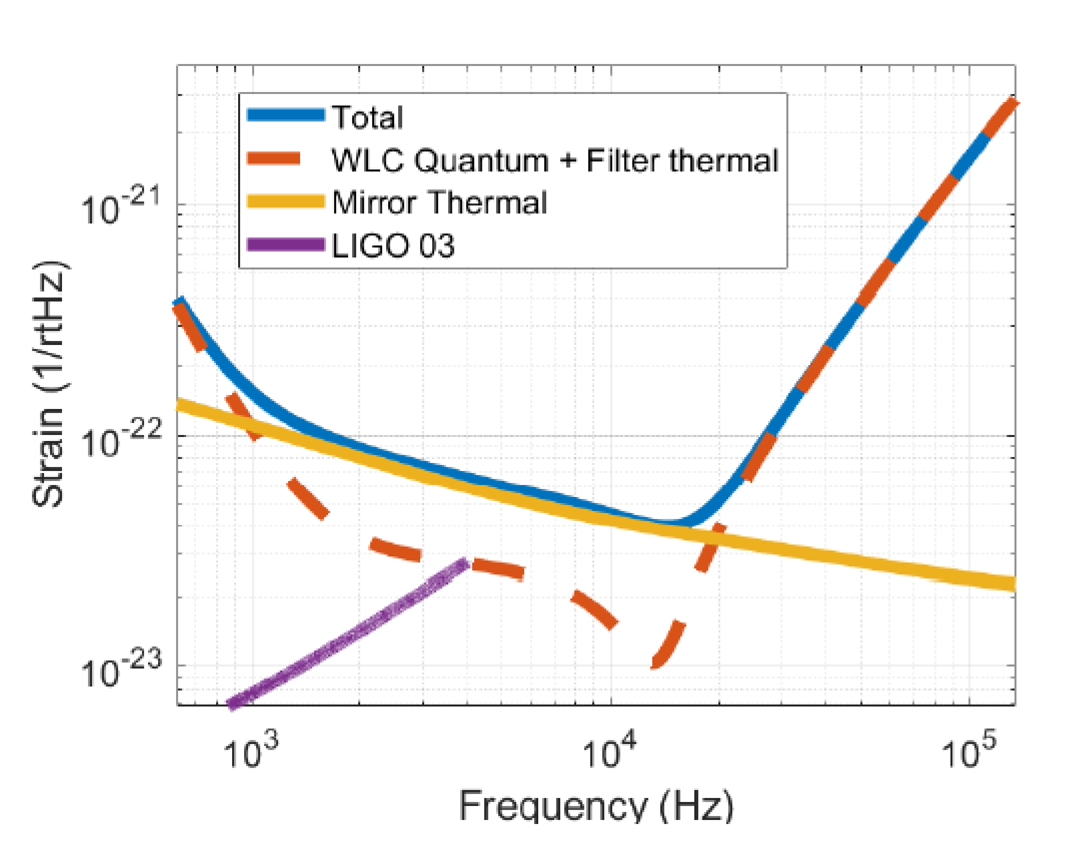
The Gingin Prototype – What should we build?

- Something with interesting instrument science
- Something we are killed at
- Something practical / possible
- Something with a science case

- Use quantum engineering to push the sensitivity of an 80m facility to its limits
- White light cavities
- Existing suspensions, vacuum
- Can we beam any limits?

What sensitivity could we achieve?

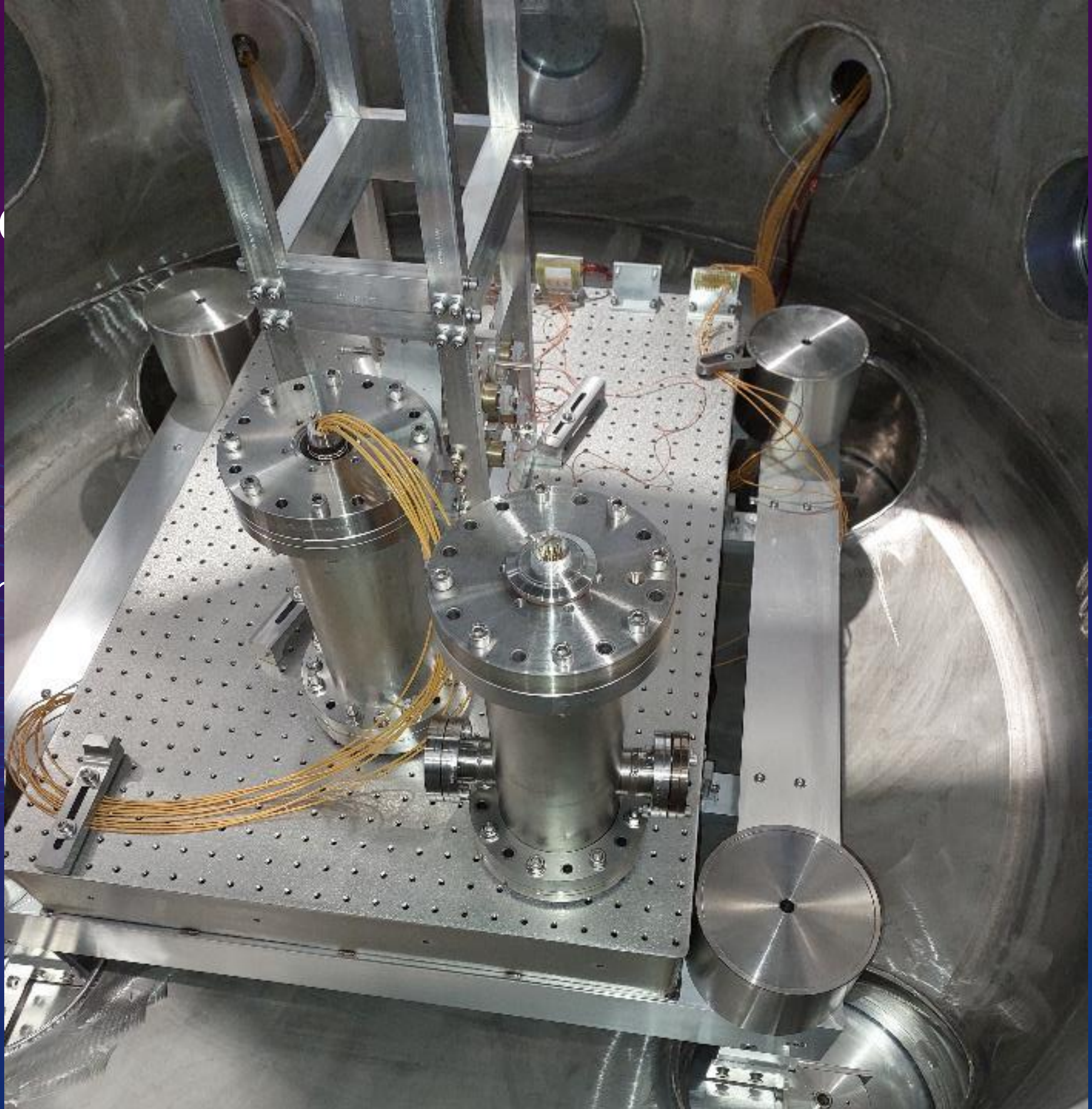
- White light cavity
- AlGaAs Coatings
- Long signal recycling cavity
- Fine tuned parameters by hand



Parametric Instability Control Strategies

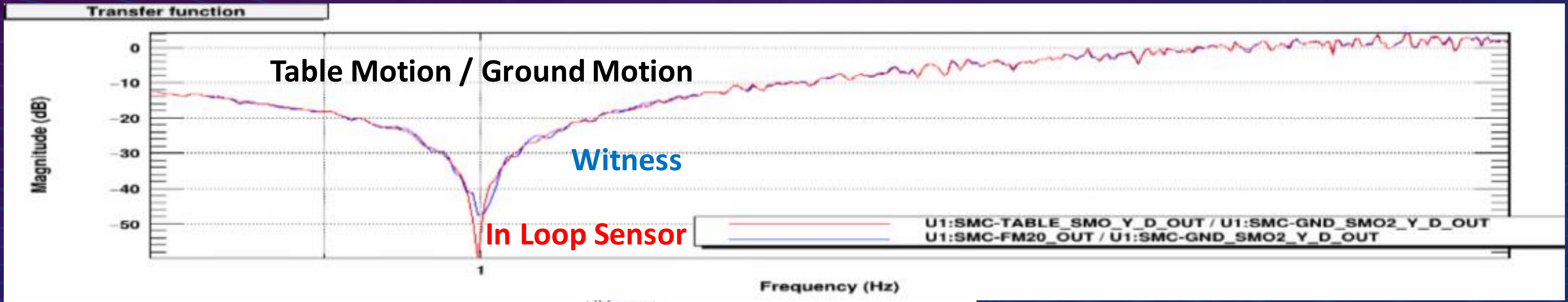
- Break the optical resonance
  - Optical feedback dx.doi.org/10.1103/PhysRevA.81.013822
  - Cavity non-resonance for HOOM (discussion with Slawec Gras)
  - HOOM modulation dx.doi.org/10.1103/PhysRevD.91.092001
- Break the acoustic resonance
  - Sapphire test masses (or other material with lower acoustic mode density) dx.doi.org/10.1103/PhysRevLett.94.121102
  - Passive damping dx.doi.org/10.1016/j.physleta.2007.10.079
  - ESD feedback control doi.org/10.1103/PhysRevLett.118.151102
- Break the overlap
  - Use a minimally interacting cavity mode doi.org/10.1088/1361-6382/ab7716

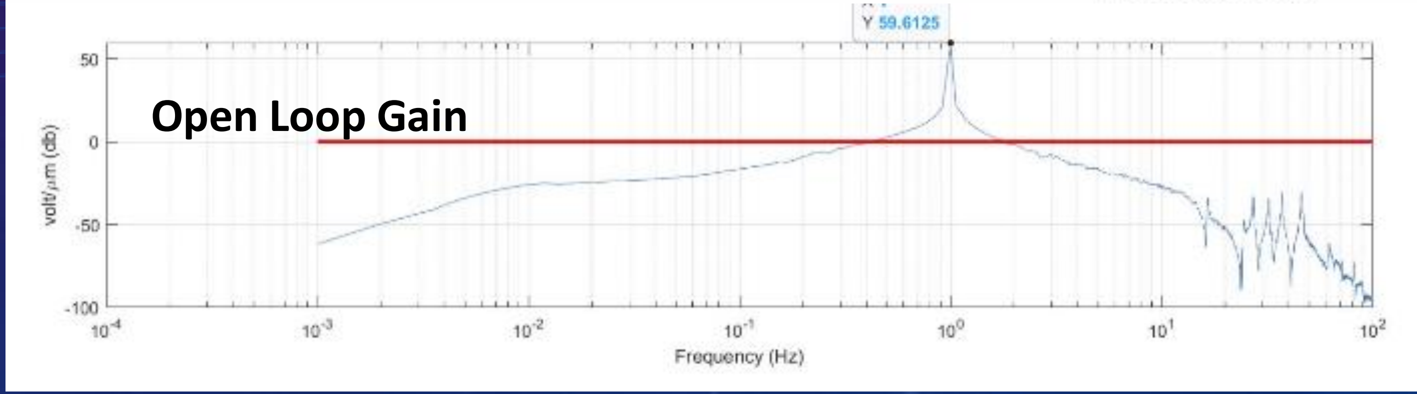
Seismom



- One in loop ar

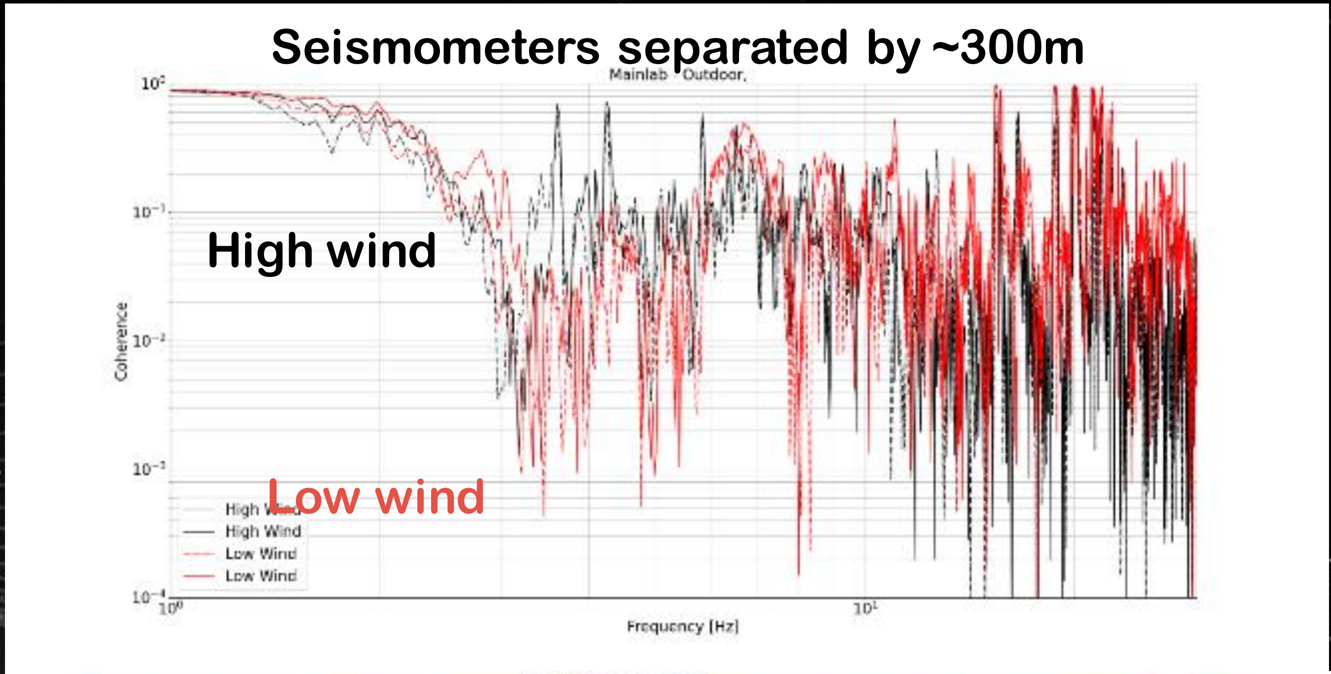
Table, Sensor noise measurement

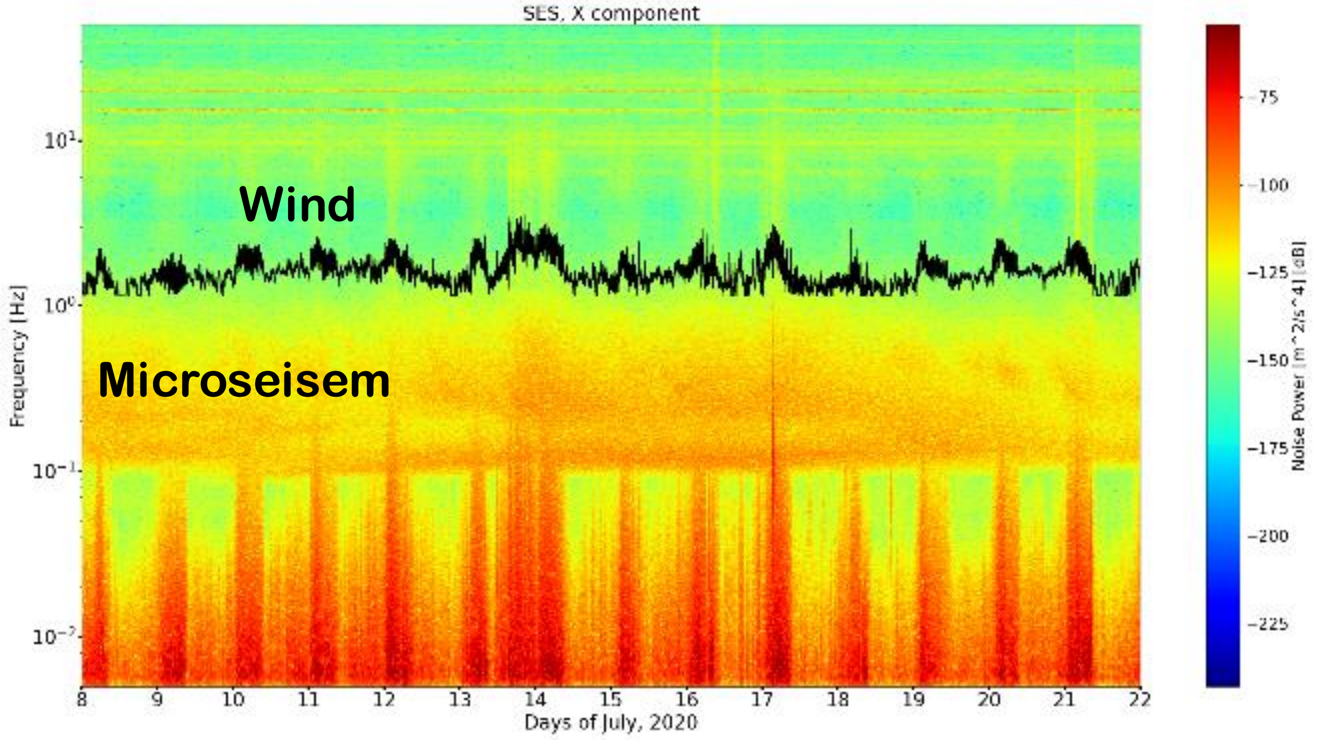




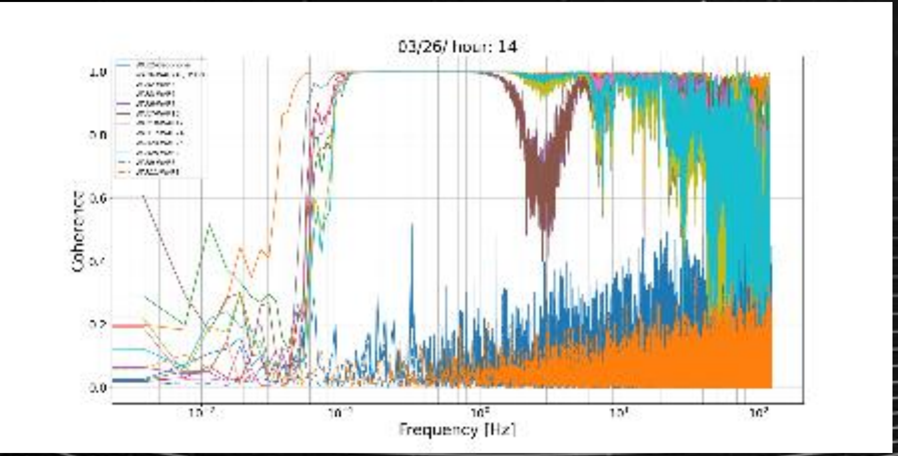
Gingin Real Time Seismic Array Progress

- Identified most of the frequency band of interest is dominated my incoherent wind driven noise on windy days inside and outside the building
- Serious issue for Newtonian noise projection and Seismic super-sensors for improving suspension systems
- Commenced initial Study to understand noise source - coherence length and amplitude maps





Huddle Test

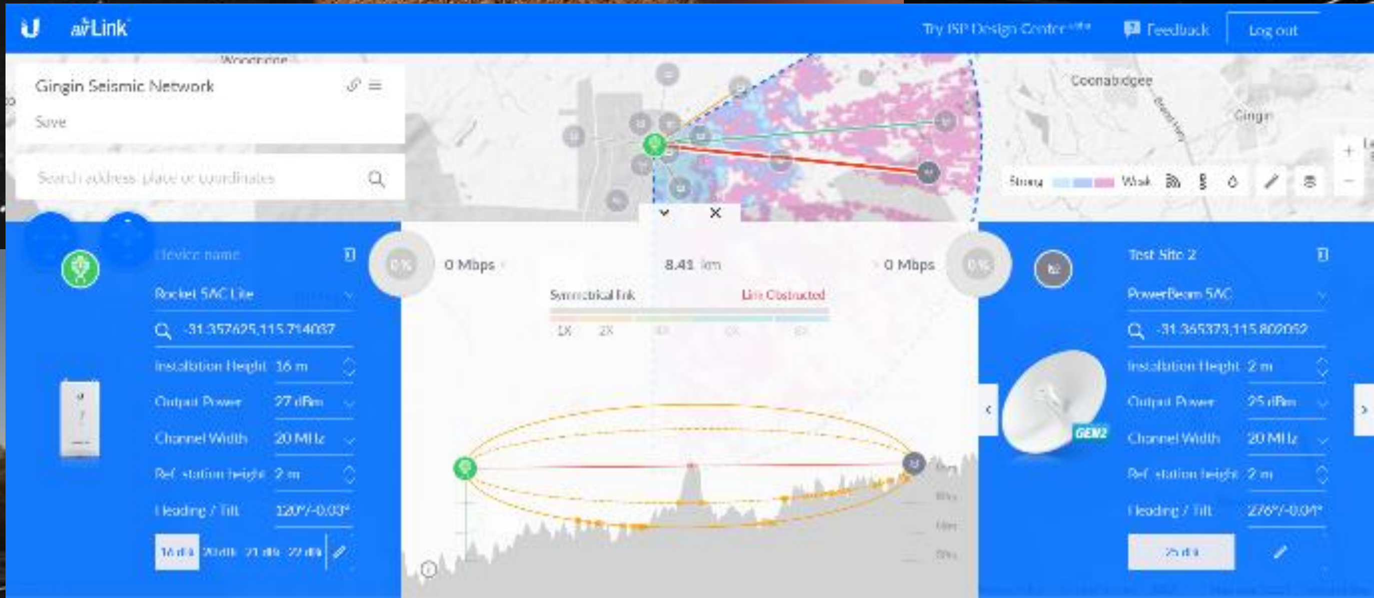


Wifi connected Array Progress

- Wifi array aims to give 10km of coverage with antenna on lab roof and 5m station antenna height
- Tested 3 sites, significantly lower signal strength than projected
- Difficulty with
  - Site access and navigation
  - Trees. Not in ubiquiti www.link.ui.com
  - Seeing where to point the antenna
- Propose use of drone to aid in station positioning





Conclusion

- *This fellowship application is designed to demonstrate the full suite of key technologies at the appropriate scale.* It builds on substantial developments of silicon optics at OzGrav's Gingin high optical power facility over the past few years
- This project de-risks NEMO, that focusses on a specific science goal of detecting gravitational waves from the final moments when coalescing neutron stars collapse to form a black hole.
- NEMO is likely to be designed to be extendable in the 2040sto a larger detector known currently as Cosmic Explorer South (CES) [13]. It will be pivotal in improving source localisation to achieve science goals in a global network of detectors that will observe almost all the stellar mass black hole mergers in the observable universe.
- As detailed in the CE horizon study it is shown that a 20km CES along with a US 40km CE and ET will provide a generation of GW detectors that achieve all science goals currently envisaged with least technical risk.
- To achieve the above ambitious goals over the next two decades, it is essential that the Australian Gravitational Wave Instrumentation community demonstrate its ability to build, manage and run a gravitational wave detector.
- This project will help fulfill these requirements while allowing a new part of the gravitational wave spectrum to be explored. This work is aligned with the recently approved OzGrav 2 Centre of Excellence in Gravitational Wave Discovery (2024-2031) of which I am an Associate Investigator. The project is bold and ambitious, and is likely to extend through the lifetime of OzGrav 2.