

#### Next animation



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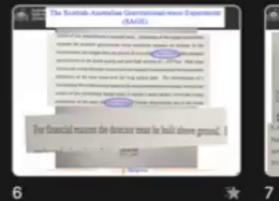


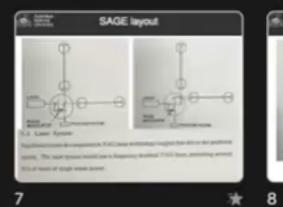


Slide 1 of 29









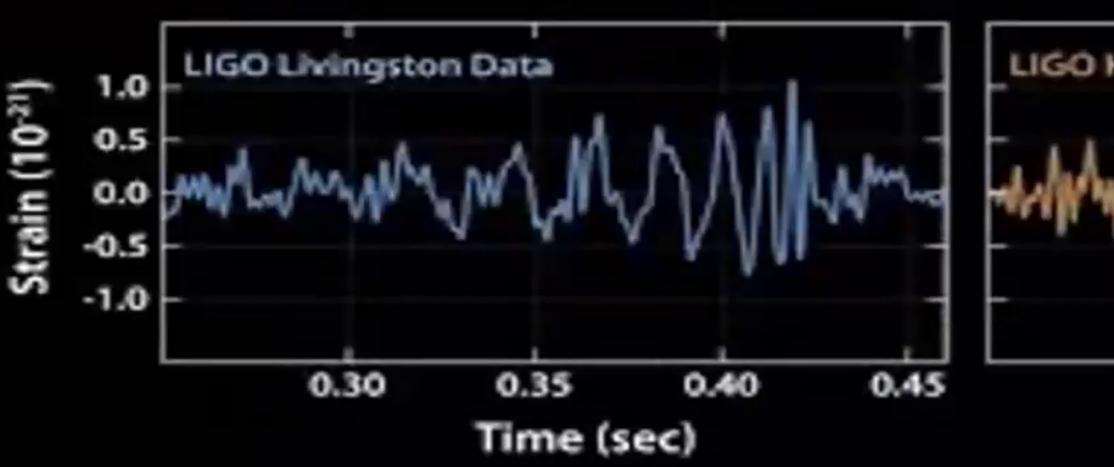


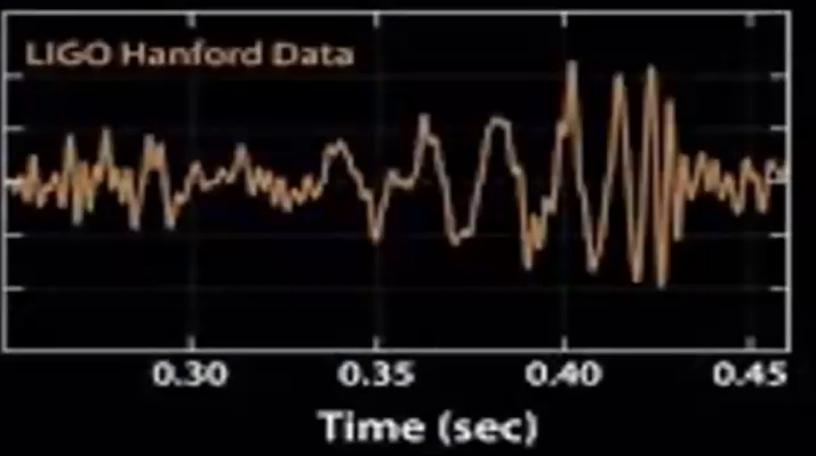




# Australia's partnership in the first detection of gravitational waves









1980: Caves proposes 'squeezing' light to enhance LIGWD





### 1980: Caves proposes 'squeezing' light to enhance LIGWD

Late 1980's ANU squeezes light - SO lets get into the GWD business!



McClelland, Manson, Hope, Bachor





Disclaimer: DEM and UWA



#### Pre 1988:

- Blair, Veitch (UWA) and resonant bars
- McClelland, Bachor, Sandeman (ANU) Quantum optics
- Hough (Glasgow): 10m Glasgow prototype interferometer and the US\$60M Glasgow 3km detector proposal.





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- MG8 Perth: Hough converts Blair
- Independently, McClelland contacts Blair/Veitch with proposal to collaborate on LIGWD





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1988: why not a Scottish Australian LIGWD!

UK has the heritage; Australia has the land



Preliminary Design Study for a Laser
Interferometer Gravitational Wave Observatory
in Western Australia

A proposed collaboration between
University of Glasgow
University of Western Australia
and
Australian National University

Prepared on behalf of the University of Western Australia and the State Government of Western Australia

(28/10/88)





# The Scottish-Australian Gravitational-wave Experiment (SAGE)

Preliminary Design Study for a Laser

Interferometer Gravitational Wave Observatory
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A proposed collaboration between
University of Glasgow
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> (<del>28/10/88)</del> (4 | 11 | 88)



# The Scottish-Australian Gravitational-wave Experiment (SAGE)

consist of two perpendicular evacuated tubes. Attainment of the higher sensitivities required for practical gravitational wave astronomy requires an increase in the interferometer arm lengths from the present 30 m to about 3 km to 5 km, with stringent specifications on the mirror quality and ultra high vacuum of ~ 10-8 Torr. Both large mirrors and a large diameter vacuum tube are required to accommodate the unavoidable diffraction of the laser beam over the long optical path. The development of a Gravitational Wave Observatory based on the laser interferometer technique, which is the subject of this preliminary design study, is clearly a major project involving a large expenditure of the order of \$20-25 million. Similar observatories are in the initial

Prepared on behalf of the University of Western Australia and the State Government of Western Australia

> (<del>28/10/88)</del> (4 | 11 | 88)



# The Scottish-Australian Gravitational-wave Experiment (SAGE)

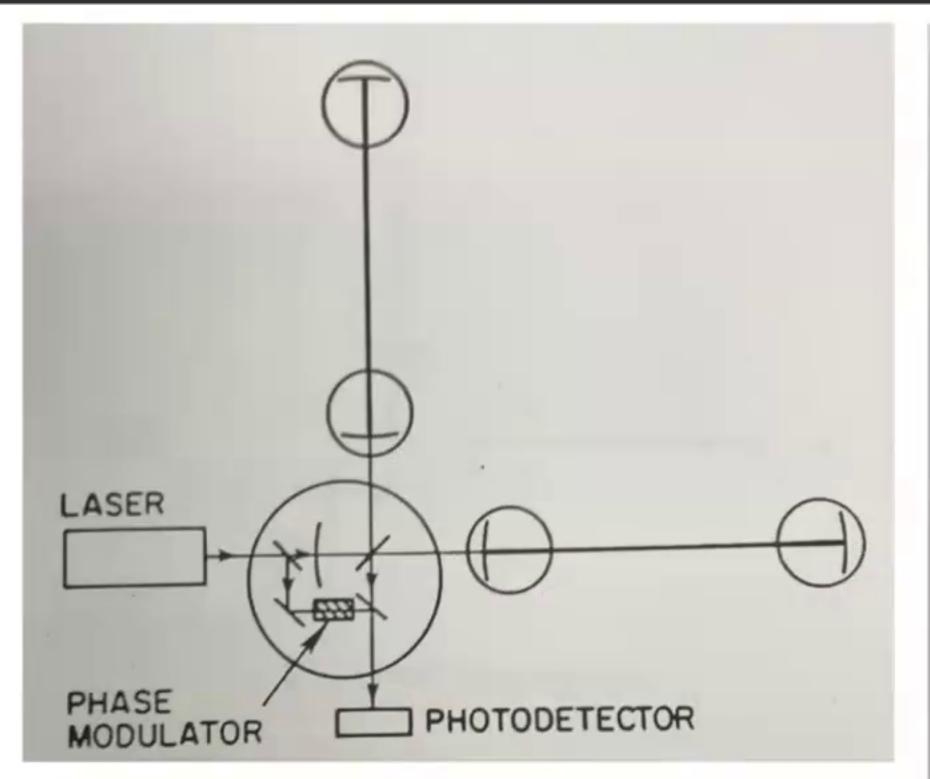
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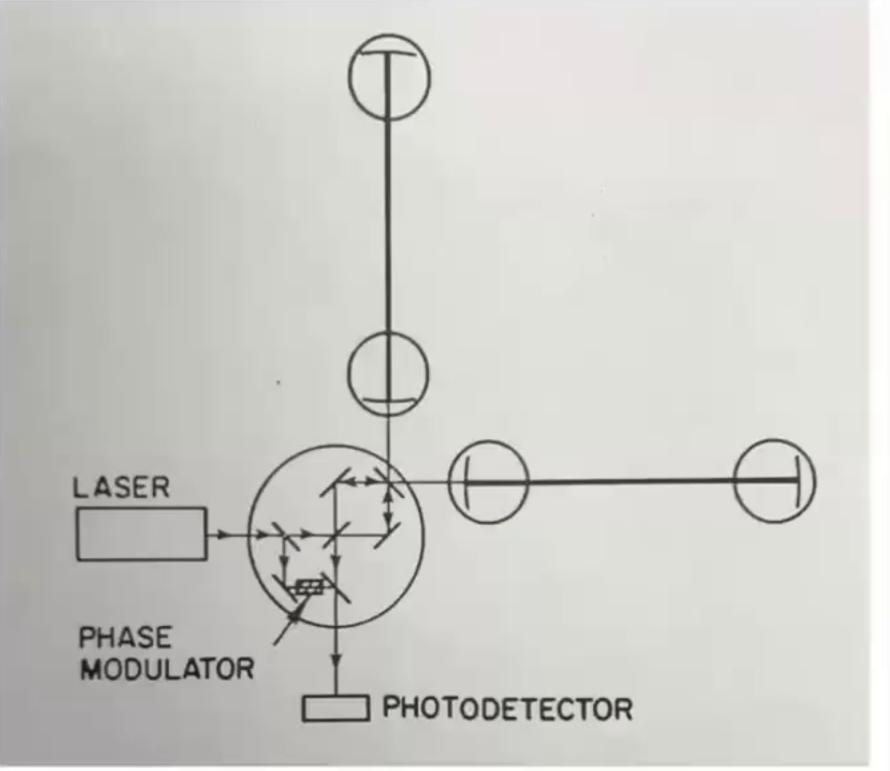
For financial reasons the detector must be built above ground. I

(<del>28/10/88)</del> (<del>14</del> | 11 | 88)



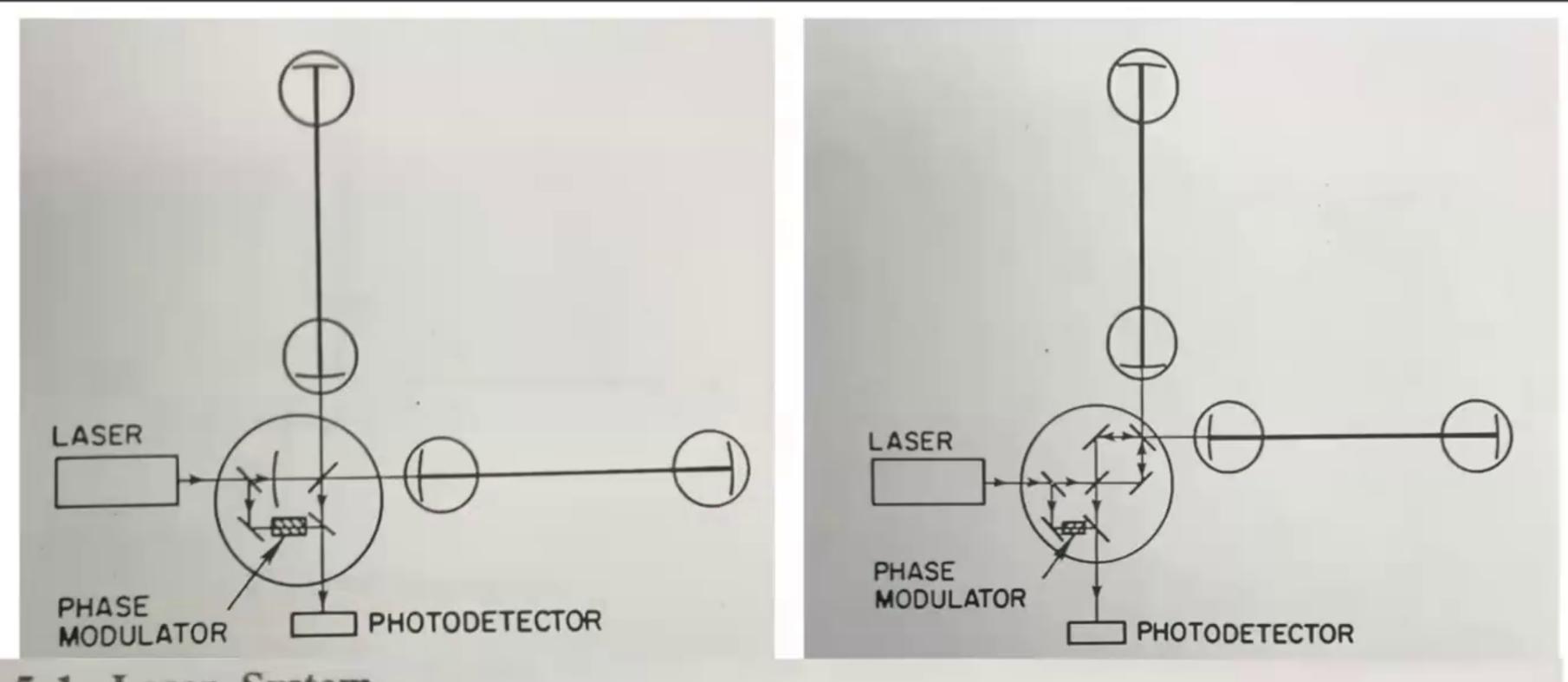
# SAGE layout







# SAGE layout

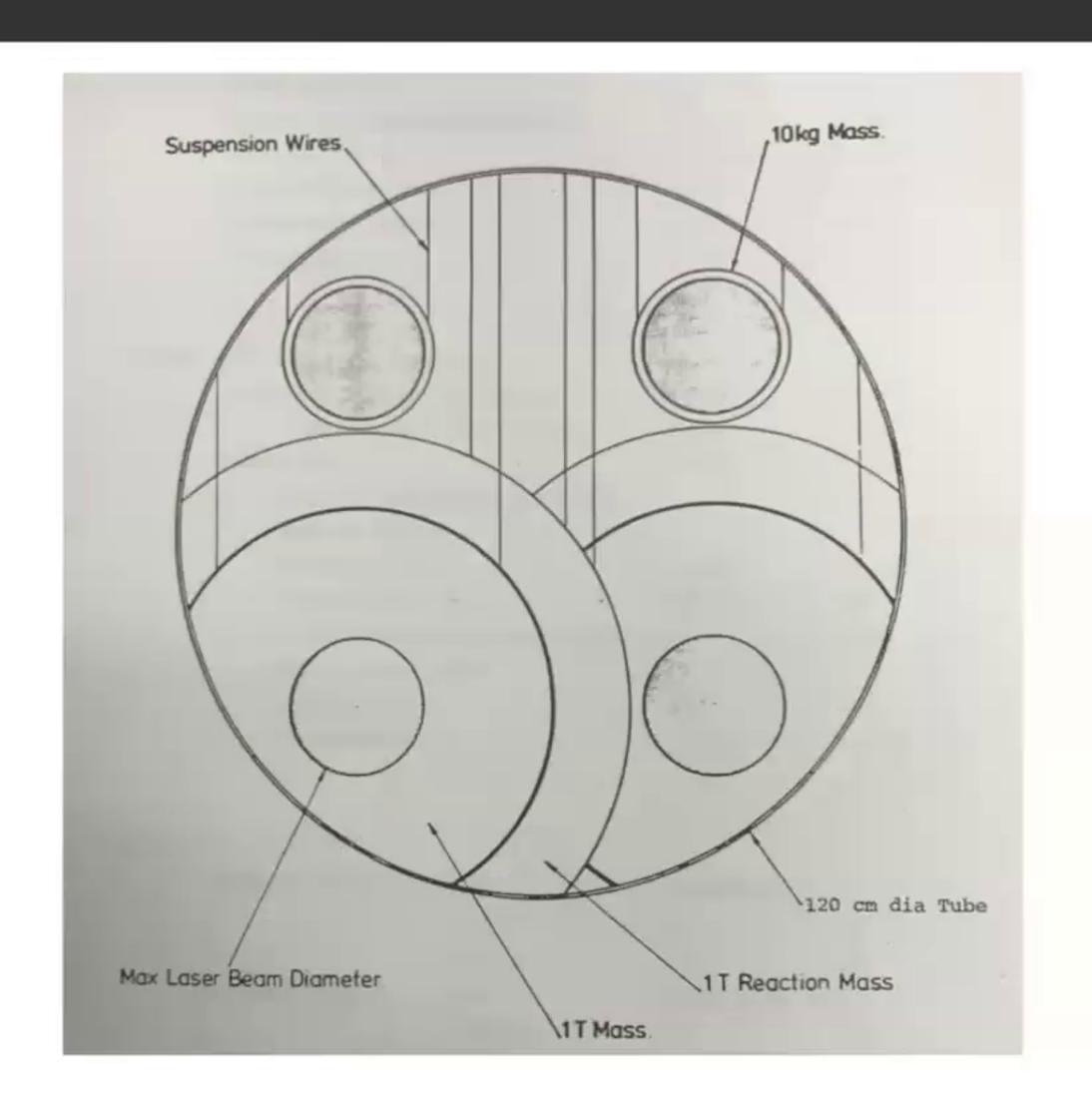


#### 5.1 Laser System

Significant recent developments in YAG laser technology suggest that this is the preferred option. The laser system would use a frequency doubled YAG laser, providing several 10's of watts of single mode power.



# SAGE – 2 interferometers







# Then the world changed....

1989: Berlin wall came down

UK dumps Australia in favour of Europe!

So we go it alone:

The Australian International Gravitational-wave Observatory (AIGO) is borne

We increase the price and descope throughout the 1990s, \$30M ... \$40M



#### Exploring black holes an issue of some gravity

A WORLDWIDE care is under they to be flow to poor make the experiences beauty of our of they want black beauty and between to be as the rea-less cover of present a sur-



Heavy duty ... Dr Daud McClelland with a pretotype of a grant gravity wave telescope — Picture: PALIL 2047cs

THE AGE, Saturday 15 April 1989

#### Joint bid to bring the universe a little closer

TWO universities held synchronised press conferences in Perth and Canber-

The University of WA and the Australian National University want the telescope to probe the distant reaches of the universe.

If the bid is successful the telescope will be set on

By ALEX HARRIS

ra yesterday in a bid for a than the second-generation \$30 million Australian niob.um bar gravitation Research Grant to build a wave detector already bas-

> It would be able to observe black holes forming among the nearest million

It would also be able to constantly monitor black hole processes among 1000

It is expected to be a mil- " It will be the forerunner monitoring and olter high

be built in the Northern Hemisphere in the next few

co-operation of nearly 20 major scientific institutions round the world.

Australia as a leader in astronomy well into the

It will also give a power-Gingin, 60km april of million billion stars follows to advanced techniques, 60km april of million billion stars to both and export opposition of the project is besided by uniting a for Australian And it could be operating the Dri David (Blast) of the developments; in later by 1994. ful boost to advanced tech-



Bid for \$31M gravity wave telescope

A nation-wide bid by scientists and industry for a \$31M telescope, if successful, will give Australia the world's first giant telescope for the observation of the most mystifying phenomenon in the universe - gravity

John Sandeman. Dr David black holes which existing op-McClelland and Dr Hans tical and radio telescopes Bachor, along wath colleagues can not 'tee' from the University of Western Linttein's theory says that

Australia, the Western Assirp- these catastrophic events in the an Government and BHP En- universe radiate energy in the intering have proposed a fea- form of gravity waves. follow study for the project. The telescope would use m-The Australian Research, tense laser beams and high-pm

founcil has maximal a funding. Onion mirrory to measure the thursman and a doctains will barely detectable gravitations waves that pass through the Earth. Professor Sandensus

stove that if a gravity ware laced the mirrors by mir tion-million-millionth part a metry, or less than the size a single anom, the removement add be desected.

The telescope would be a silico times more semme han the second generation survey wave desector at the coversoy of Western Assa.

ANU's role would be to develop the interferometer and to develop systems to much ner technology developed at ANU white investigating the o-called 'squeezed some of the light.

Scientists and engineer ross more than 16 autumns and academic research organiamons in Abstralia and New Cestand would be 'swotyed a leveloping the necessary as mord technology for the triv cope, if it goes abest

Professor Sandenna and hat although the triescope was fundamental seumor promo-

#### Gravity wave project quashed

THE Federal Government has given a proposal to build Australia's first \$50 million gravity wave observatory in WA the financial thumbs down for now.

The proposal, by the University of WA and the Australian National University in Canberra. would have seen a facility built near Gingin by 1996 in the hope of proving physicist Albert Einstein's gravity wave theory.

International physicists and industry groups, including BHP Engineering and British Aerospace. endorsed the proposal.

A detailed review of the project's impact on science and technology was requested by Science and Technology Minister Simon Crean and carried out by the Australian Science and Technology Council.

#### funding policy jeopardises ravity waves project

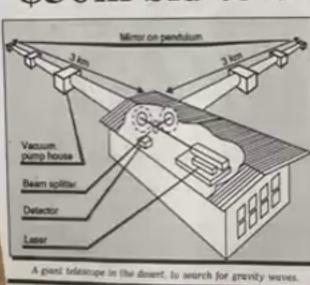


Quarter Opice, Related hading origin of present more.

process of the field and is part of a none of Comment than is roing to Smild a land amount in Sometime with it made opposite space

Community of Stand Standard and the same of th

## \$30m bid to build gravity wave telescope



science and technology reporter

A hid was insuched yesterday to construct a \$30 million high-technology observatory near Perts to study the most elusive phenomenon in the universe -

such as amoin cralin and New Zealand, the Western Australian Government and BHP hope that most of the money will come from the Australian Research Council.

The gravity telescope would require construction of the world's largest vacuum chamber, a right-angled structure six kilometres long. It would search among 1000 million billion stars for an invisible form of energy predicted decades ago by Albert limiteis, but still not observed.

Einstein said violent events in the somerie such as supernevas

form of gravity waves. The gravity telescope, which

would be be built on the sand plain about 100 kilometres north of Perth, would have a laserased device capable of detecting rors suspended at the end of two three-kilometre tunnels set at right angles to each other.

Before the telescope became years to pump its tunnels down to their final hard vacuum. The laser beams are split from

a single beam and, after bouncing off the mirrors at the ends of each tunnel, return to the point of origin in phase, cancelling each other out. If a gravity wave disturbs the mirrors, the beams go out of phase, producing a detectable signal.
Dr David McClelland, an Aus-

so sensitive that if a gravity wave passed through the Earth and displaced the mirrors by no more than the diameter of an atom the movement would be detected. "The Europeans and Americans are building two such tele-

cist, says the instrument would be

we build one in Australia so that we can verify each other's observations," he said. There would be a delay of 30 to

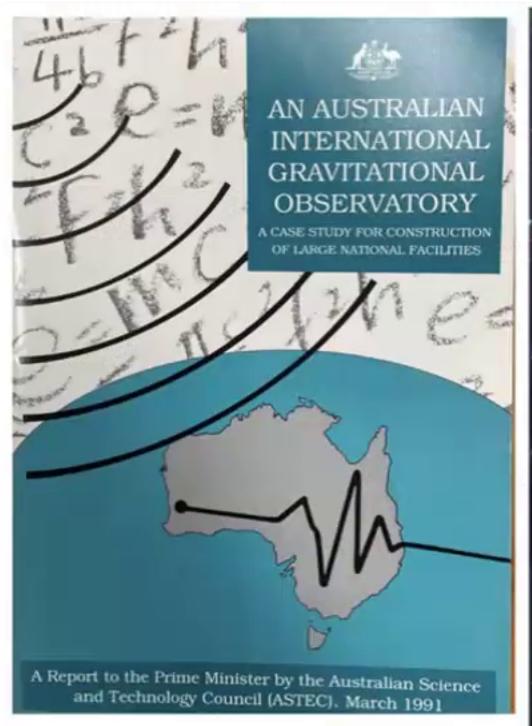
50 milliseconds between the registering of a gravity wave at two widely separated telescopes as it passed through the Earth.

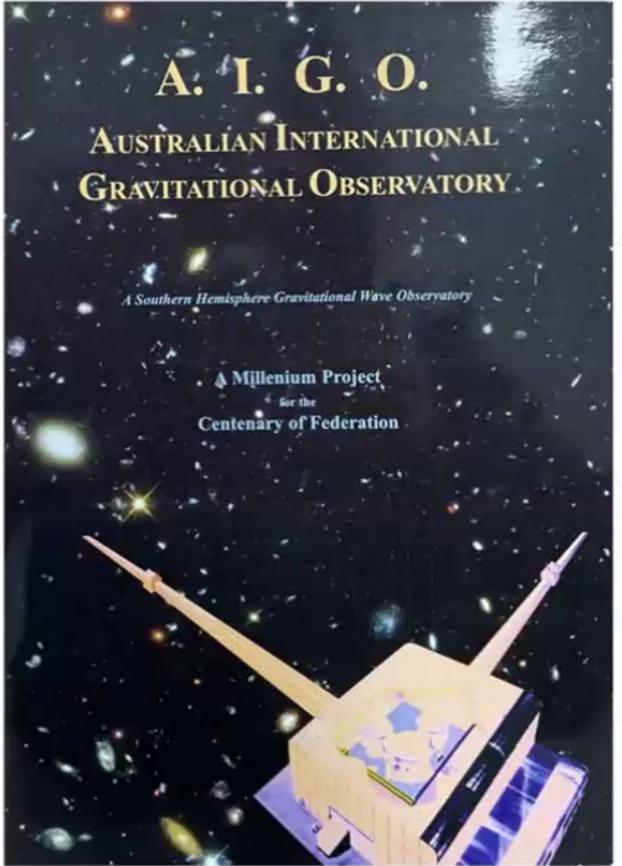
Dr McClelland said the telescope network could look through the expanding gas shell of an object such as the 1987a supernova and observe the core. He said that although gravity waves have never been observed, they

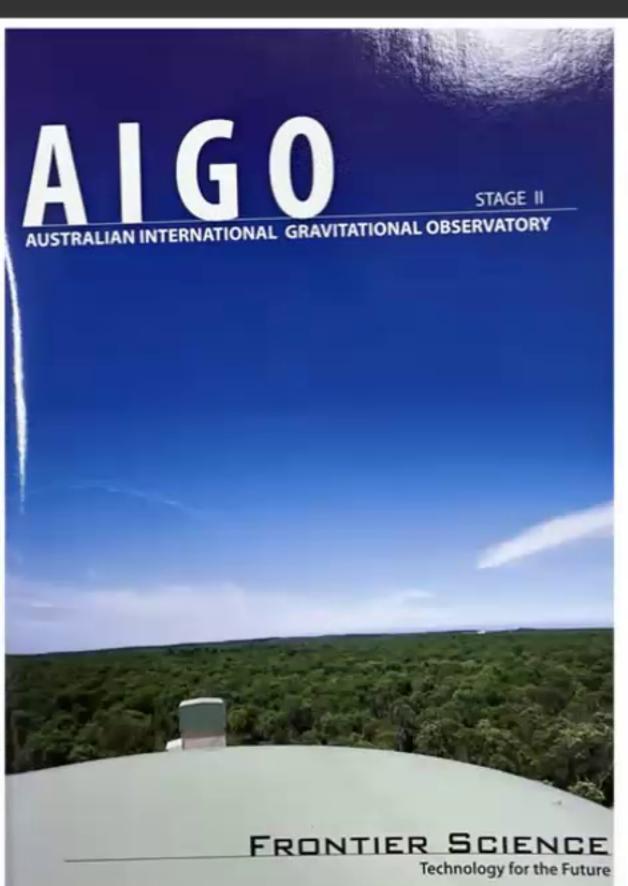
then has been consistent in these would be many corectly may as business years, each spin-offs. These could be and mental his street to desire clade the development of manand the same of the same of

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Numerous AIGO bids throughout the 1990s
AIGO-400 put up as a Millenium Project
Deaf ears and empty pockets



#### 1990

#### E&F White International Conference on GWA; Canberra



Instrument Design and Astrophysical Prospects



Bob Byer, Ginzton Lab, Stanford

Thibault Damour\* Institute Des Hautes Etudes Scientifiques

Karsten Danzmann Max-Planck-Institute Für Quantenoptik,

Paul Davies, U Adelaide

M Fujimoto, NAOJ

Alberto Giazotto, INFN, Pisa

Patrice Hello, Laboratoire d'Optique Appliquee, Palaiseau,

Ju Li, University of Western Australia

Dick Manchester, CSIRO

Brian Meers, University of Glasgow

Gerard Milburn, U Queensland

**Peter Michelson,** Dept of Physics, Stanford University, Stanford,

Guido Pizzella, European Centre for Nuclear Physics, Geneva,

Valentin Rudenko, Sternberg Astronomical Institute, Moscow Peter Saulson, JILA, Boulder, Colorado,

Dan Walls, Dept of Physics, University of Auckland, Auckland, New Zealand

12 (of 65) from Industry/CSIRO

Following year, Robbie Vogt and Fred Raab visited Australia







1992: Susan Scott (ANU) brings the theory dimension

1993: Jesper Munch joins UA; recruits Peter Veitch



1994: ASGRG formed



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1994: ASGRG formed

1995: Formation of Australian Consortium for Interferometric Gravitational-wave Astronomy (ACIGA) Inaugural Chair: John Sandeman

- ANU control systems and quantum noise
- UA lasers, stabilization, distortions
- UWA isolation & suspension systems; instabilities
- joint (successful) bid to ARC for coordinated Large (ie DP) Grants successful \*

ACIGA grows to include UoM, Monash and CSU

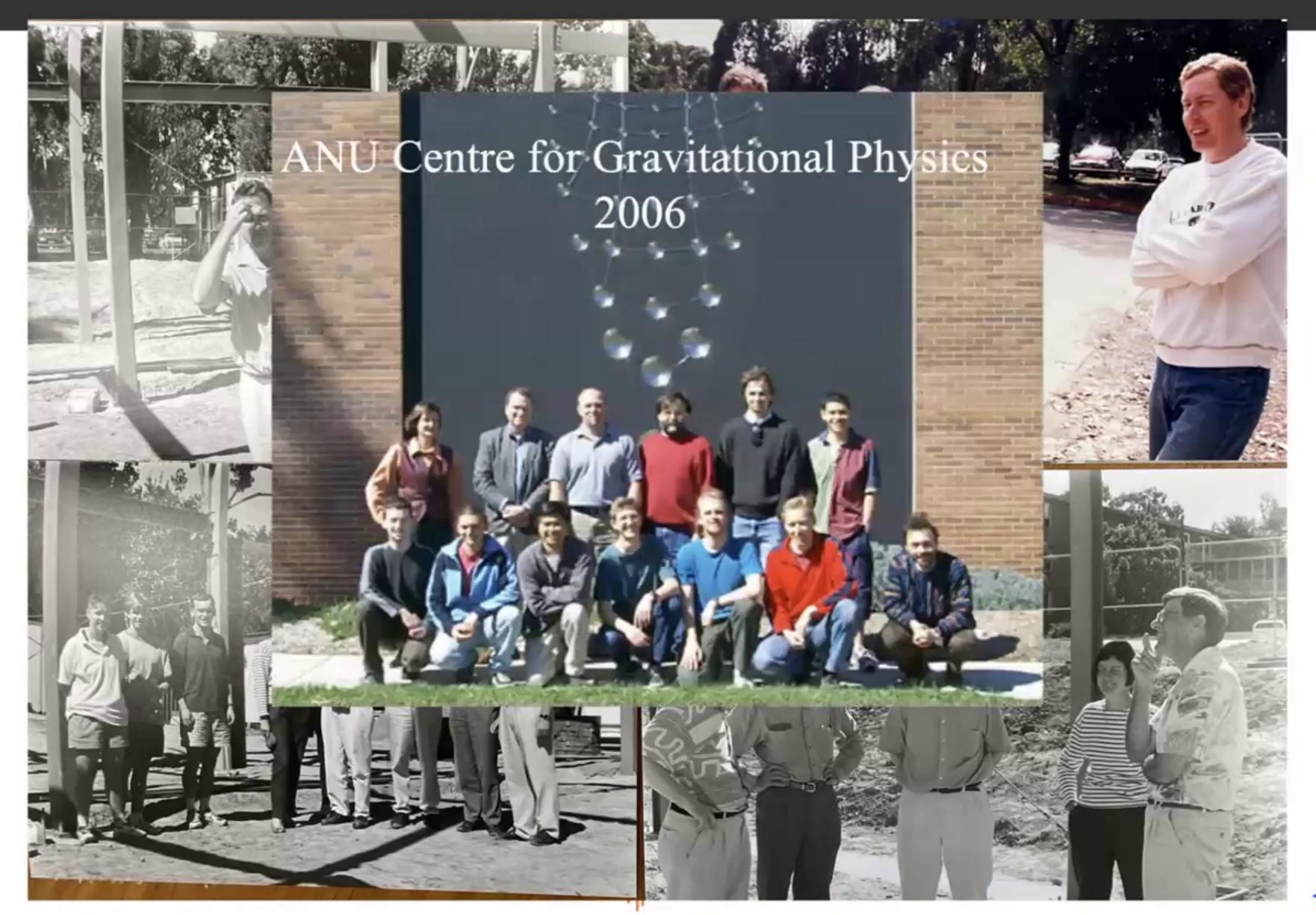


# ANU high-bay GW lab completed 2000





## ANU high-bay GW lab completed 2000





1998: LIGO Scientific Collaboration formed ACIGA founding member

2003: Gingin High Power, suspended mass, test facility commences

2004: Initial LIGO scientifical and technical contributions from ACIGA

2004: McKenzie et al reports squeezing in the LIGO band

2008: Advanced LIGO project (aLIGO) partnership USA, UK, Germany and Australia

2009: LE09/13/17/21: Australian Partnership in Advanced LIGO





Interlude: 2010-2012 \* LIGO-Australia: An opportunity lost but lessons learned

# LIGO-AUSTRALIA - ON THE CREST OF THE WAVE LIGO-Australia Virgo **GEO** LCGT LIGO OPPORTUNITY AND CHALLENGE The next decades will see a revolution in physics and astrophysics as a global network of ultra-sensitive gravitational wave detectors begin to harness the new spectrum of gravitational waves to probe the dark side of







the universe. Australia can become a pivotal partner in this most challenging quest. The US LIGO Laboratory will transfer to Australia an advanced gravitational wave detector, valued at \$140M, provided Australia funds the construction of a national facility to house the detector (estimated to cost \$140M) and commits to funding operations for at least 10 years (operating costs estimated at \$6M p.a.). This offer has the approval and support of the National Science Foundation, the primary funding agency for Advanced LIGO, and the approval of the President's National Science Board, provided Australia makes a commitment by October 1, 2011.

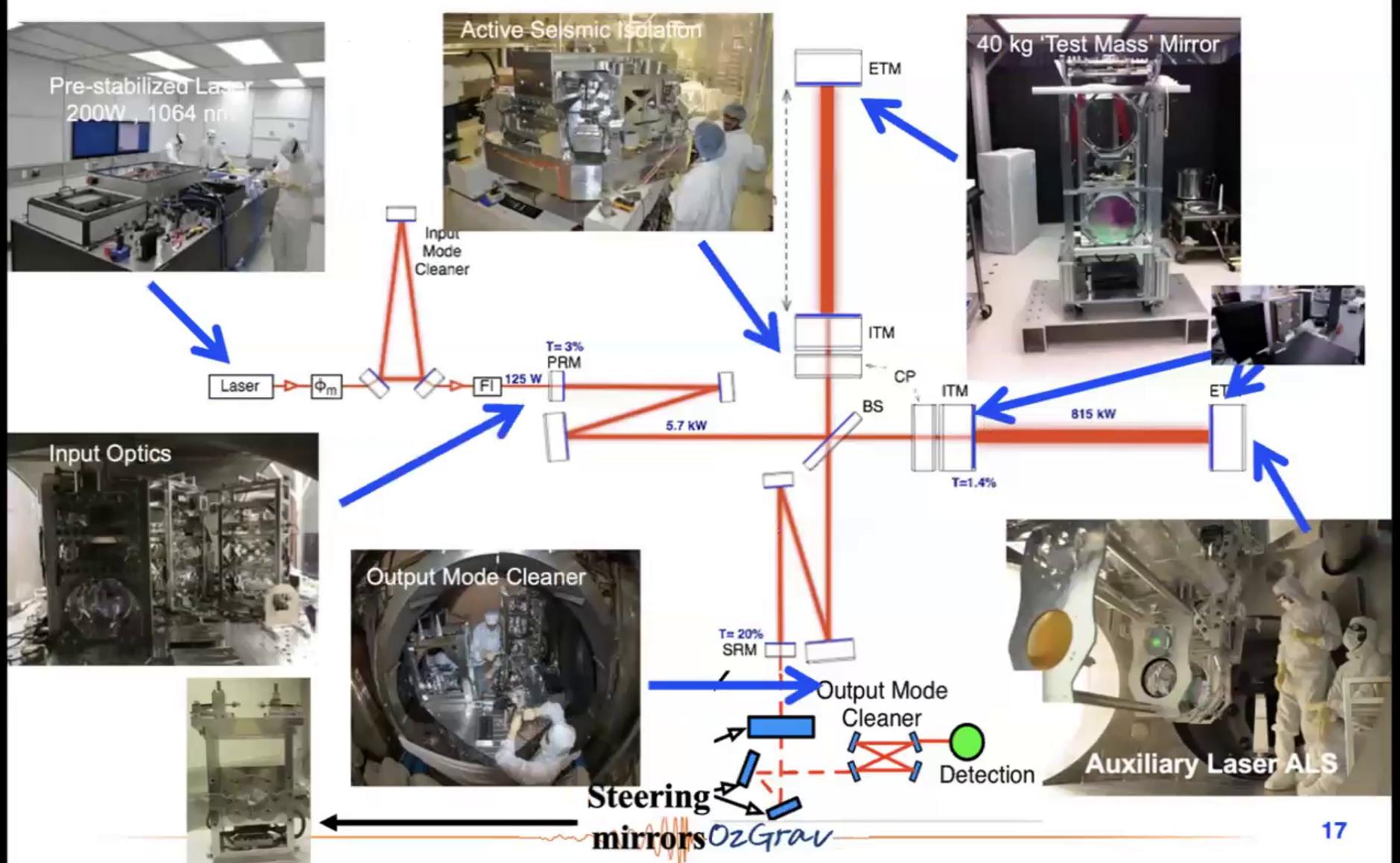






# Advanced LIGO Interferometer





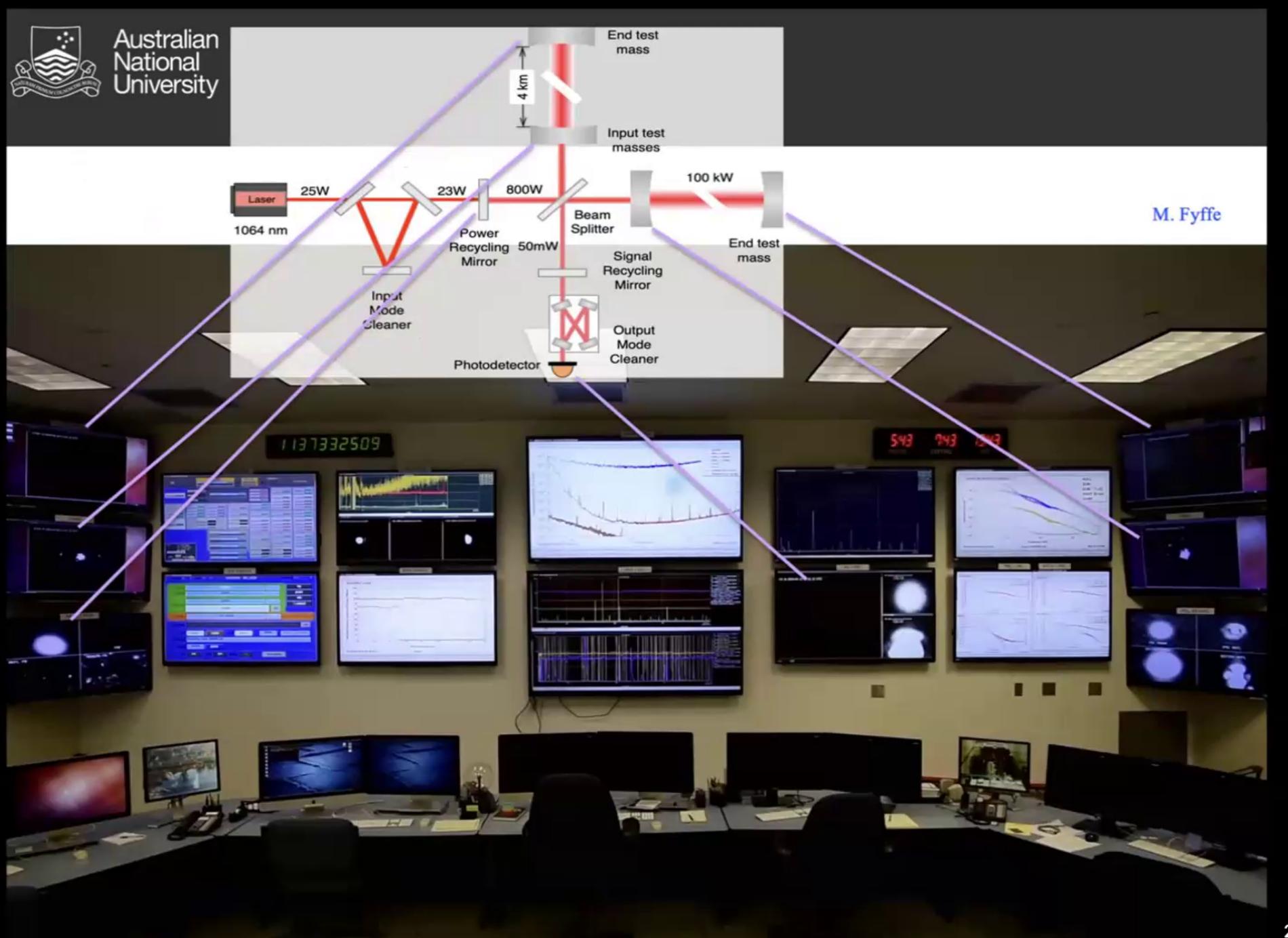


## Australian Partnership in aLIGO

#### funded by ARC LIEF

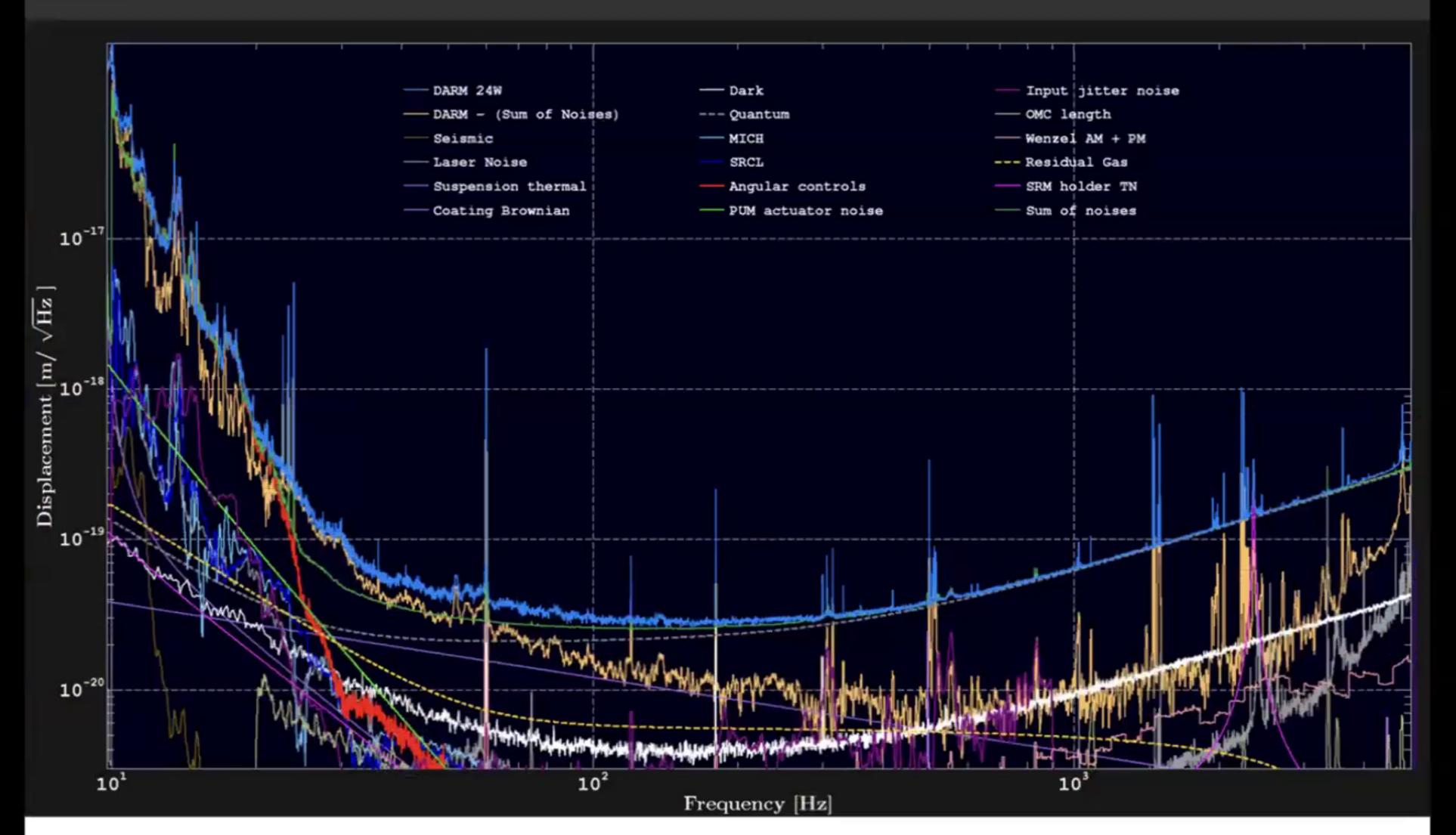
- Suspended Steering Mirror (ANU)
  - » Directing interferometer sensing beam.
- Lock Acquisition System (ANU)
  - » Arm Length Stabilisation
  - » Guiding the interferometer gently into science mode.
- Hartmann Cameras (UA)
  - Monitoring the shape of the test masses under thermal load.
- Optical and Gold coatings (CSIRO)
  - » Providing high quality coatings on the input optics and beamsplitter.
- Parametric Instability Control (UWA)
  - » Mitigation techniques to avoid interferometer instabilities with high optical powers.
- Hardware injection (Monash)
- Data Quality and detector characterization (All)
- Coalescing binary and CW searches (UWA, ANU, U Melbourne)
- EM Follow-up (Swinburne, ANU, UWA, CSIRO)



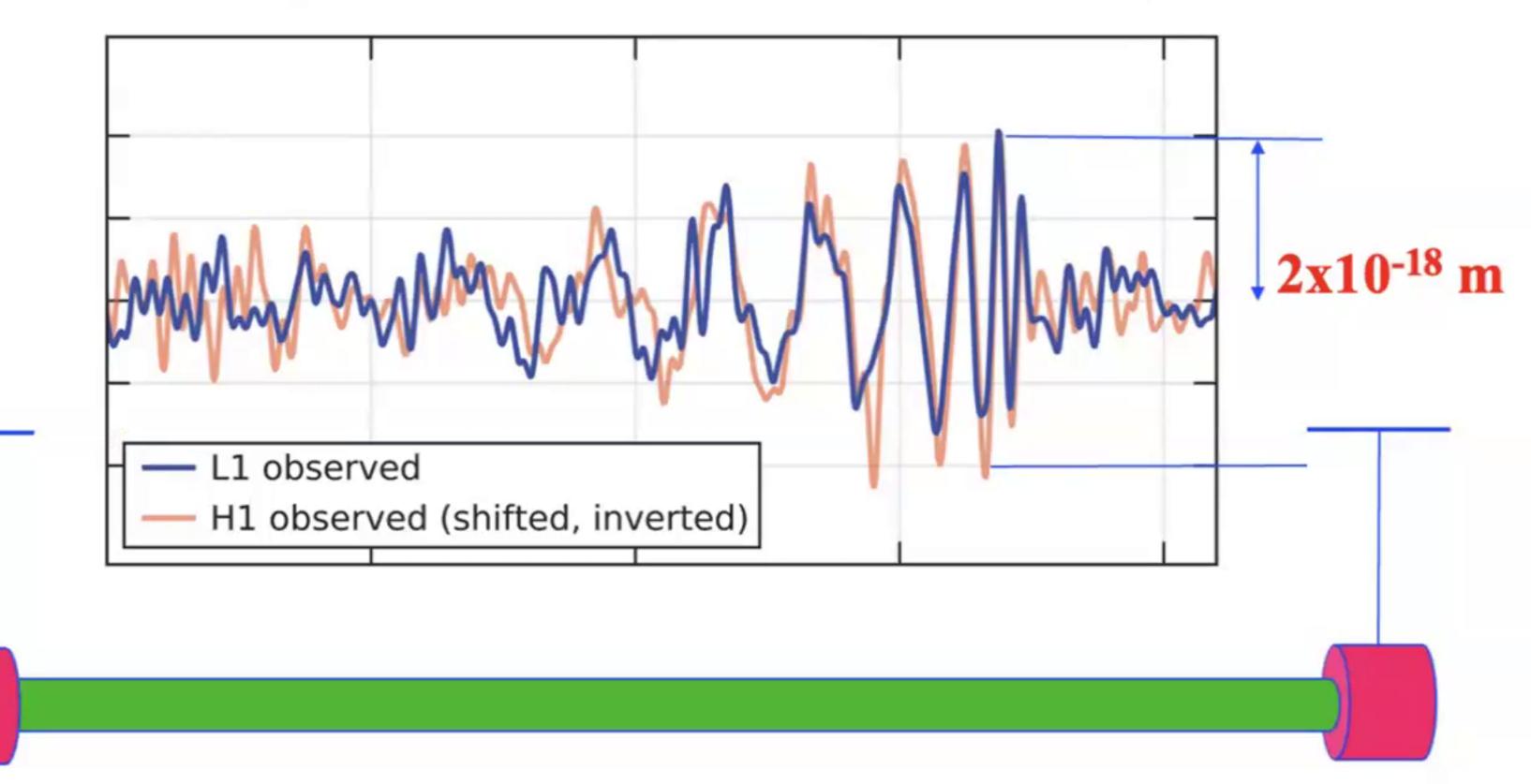




## aLIGO in Observing run 2



## Pinup for precision measurement and engineering!

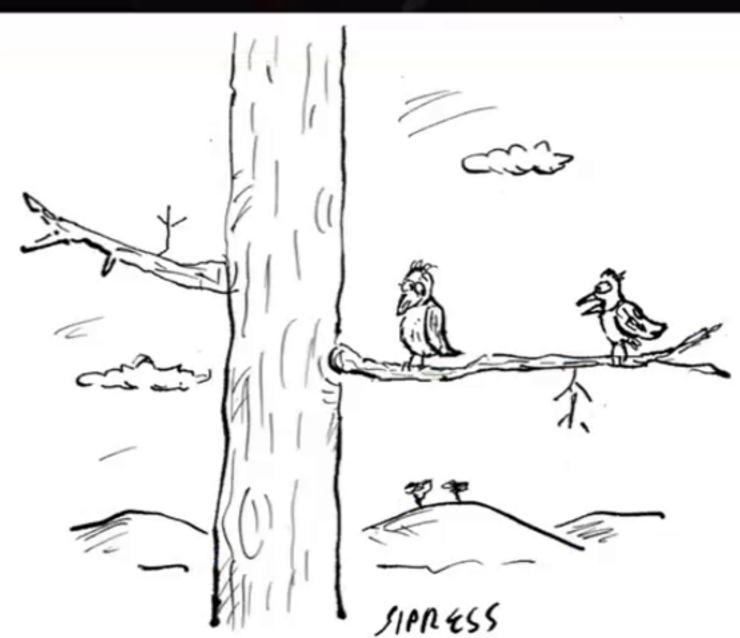


Effectively we have observed the separation between the centres of mass of 40kg objects oscillate from 30Hz up to 240Hz with a peak amplitude of

 $\sim 2 \times 10^{-18} \text{ m}!$ 



February 11, 2016



"Was that you I heard just now, or was it two black holes colliding?"





### February 11, 2016



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## Nobel Prize 2017 – Barish, Thorne, Weiss



And 4 recipients of the PM Prize for Science 2020

But on the order of 50 Australian authors on the detection paper.



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Dan Shaddock, Bram

Slagmolen, Rob Ward

And

non authors

Mal Gray, Terry McRae, Kirk

McKenzie.

And of course

UWA: Blair, Ju, Zhao +

UA: Munch, Veitch, Ottaway +

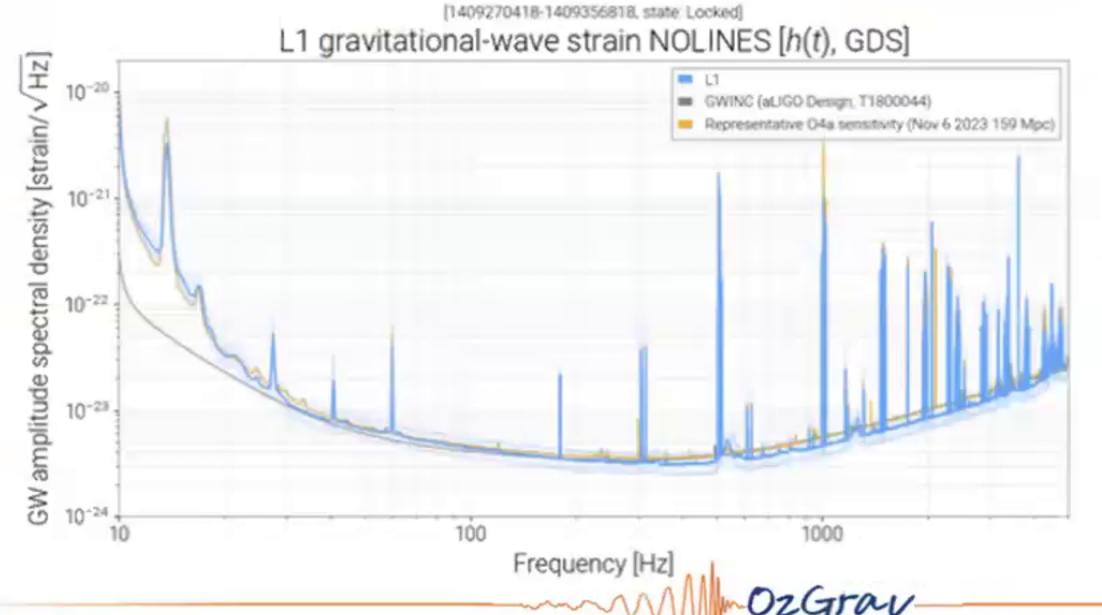


### Since 2015

- Final subsystem was installed on LIGO from 2019
- a frequency dependent squeezer to reduce quantum noise
- key contributions from Australia
- 30 years after the possibility drew me in

For the next few years the design will not change in any significant way.....







#### Contributions to LISA + GRACE FO+

 Australia and Australian scientists have contributed to development of LISA and GRACE Follow-On (Earth Science) over the last 25 years.

#### Scientific input since 2003

• Invention laser stabilization technique "arm locking" (ANU/NASA-JPL)

- Advancement of LISA's measurement scheme: time delay interferometry (Shaddock + JPL coauthors)
- LRI technology architecture design (JPL,ANU, Germany)
- Contribution to digital locking system of LRI Cavity
- Prototype Triple Mirror Assembly (ANU, CSIRO)
  - Flight units were developed and delivered by Germany.
- Laser-Link Acquisition joint development (JPL, Germany, ANU)
- Low Power Limits of Phasemeter
- Implementation Team on GRACE FO (2018 launch)
  - McKenzie US LRI Manager ('16-'19), Shaddock Adviso
  - Team members: Sheard, de Vine, Wuchenich, Sutton, Francis
- Technology development for GRACE C (2028 launch)
  - Long term laser stabilization, system engineering



