Australian Gravitational Wave Research

Focus on Gravitational Wave Detectors and Technology

David Blair

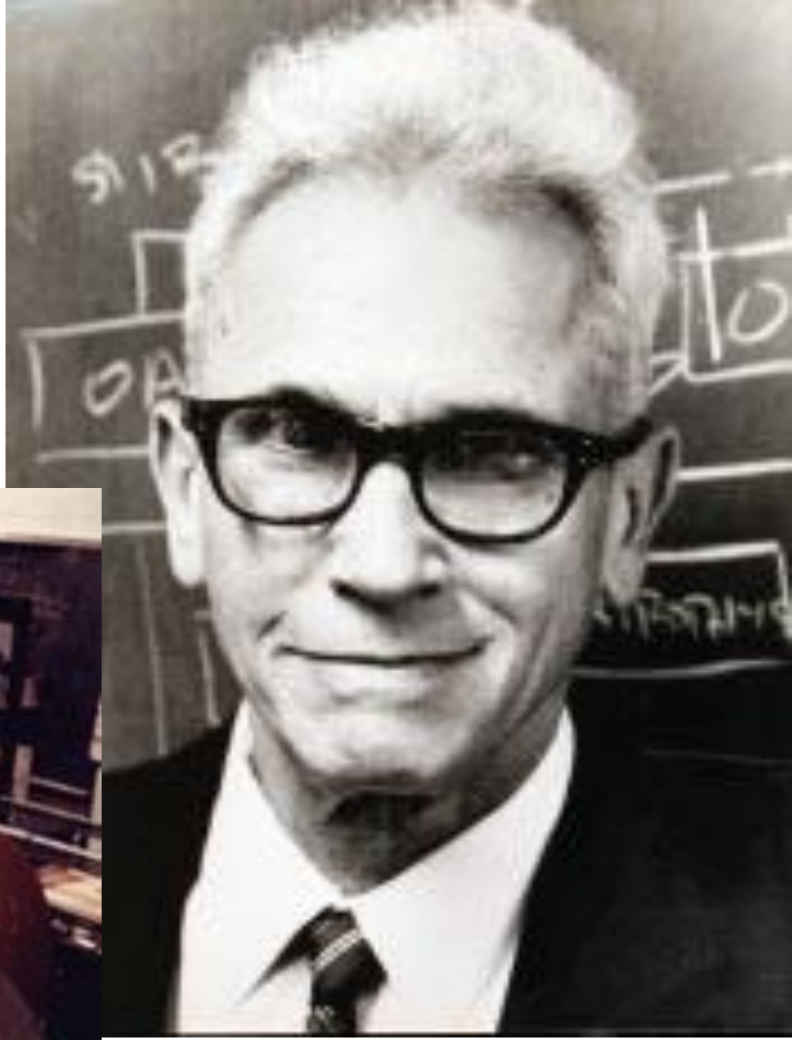
Topics

- International background and context
- Choosing Niobium and Parametric Readout
- Technologies: symbiosis between Niobe and Interferometers
- Australia's Role in the IGEC
- Vision of AIGO: ACIGA formed, bush meetings and Gingin site selection
- 8m power recycling interferometer at UWA, squeezing and laser stabilization at ANU, isolation and diagnostics at UWA
- Contributions to Virgo and LIGO
- Discovery of gravitational waves and creation of OzGrav
- Technology Development for Improving Detectors and Future Detectors.
- The dream continues: a future Australian detector

60 years ago

Joseph Weber, bold and flawed pioneer

- 1960: Weber proposed GW detectors
- 1965: bars with piezo transducers
- 1969: Weber announces detection

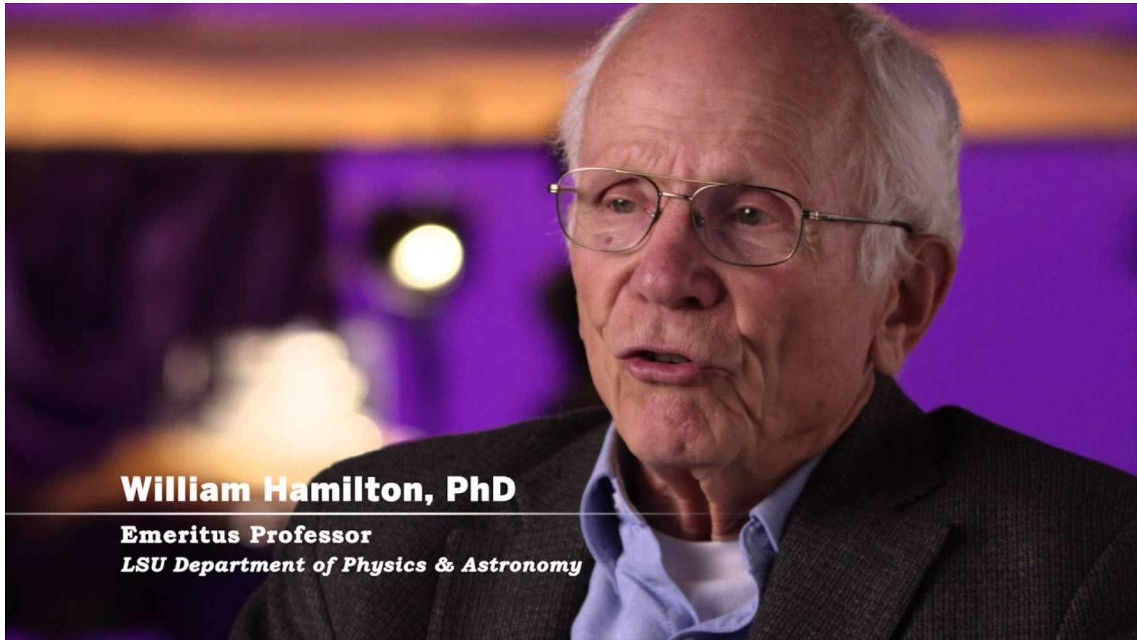


50 years ago

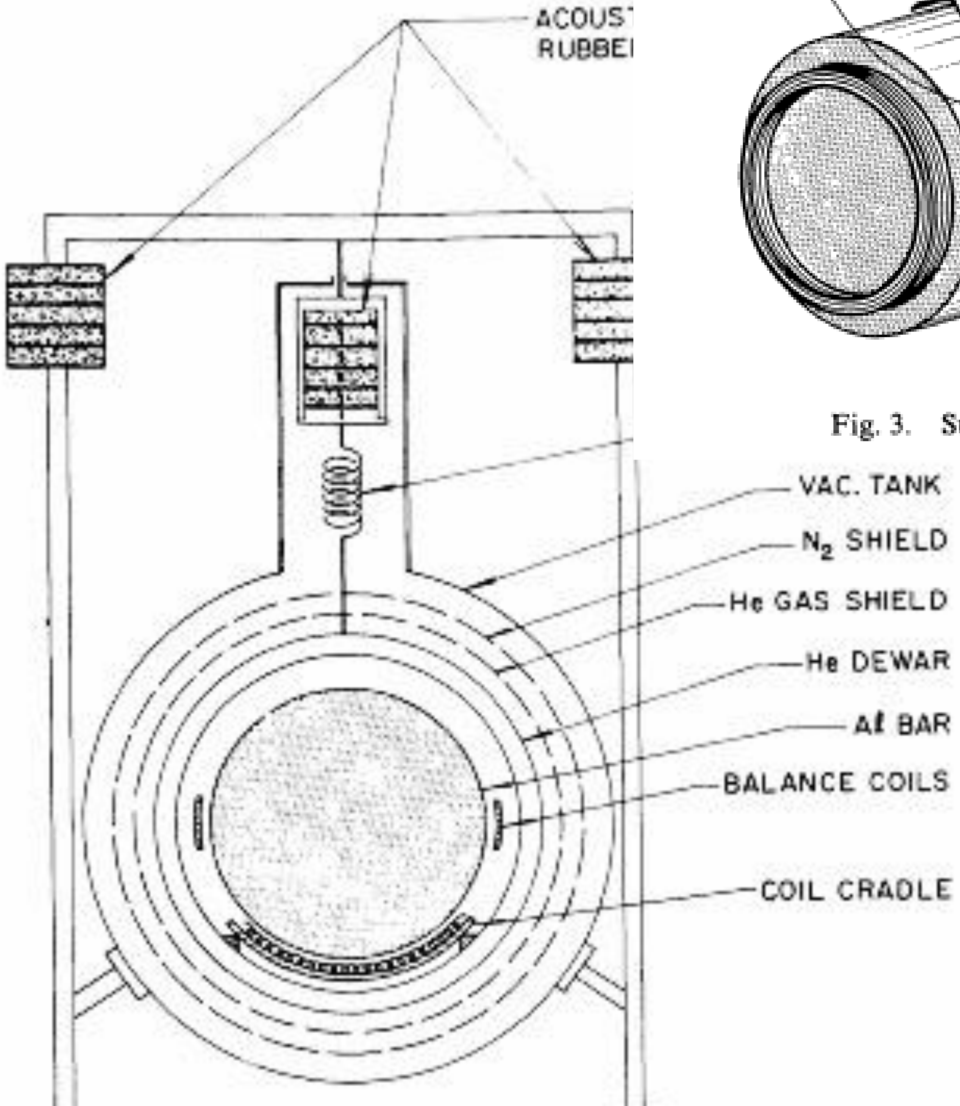
- 3mK cryogenics
- Superconductivity
- Magnetic levitation

THE USE OF CRYOGENIC TECHNIQUES TO ACHIEVE HIGH SENSITIVITY IN GRAVITATIONAL WAVE DETECTORS

S. P. BOUGHN, W. M. FAIRBANK, M. S. McASHAN, H. J. PAIK, and R. C. TABER
Dept. of Physics, Stanford University, Stanford, Calif. 94305, U.S.A.
and
T. P. BERNAT, D. G. BLAIR, and W. O. HAMILTON
pt. of Physics and Astronomy, Louisiana State University, Baton Rouge, La. 70803, U.S.A.



Magnetic Levitation
5ton bars of Al



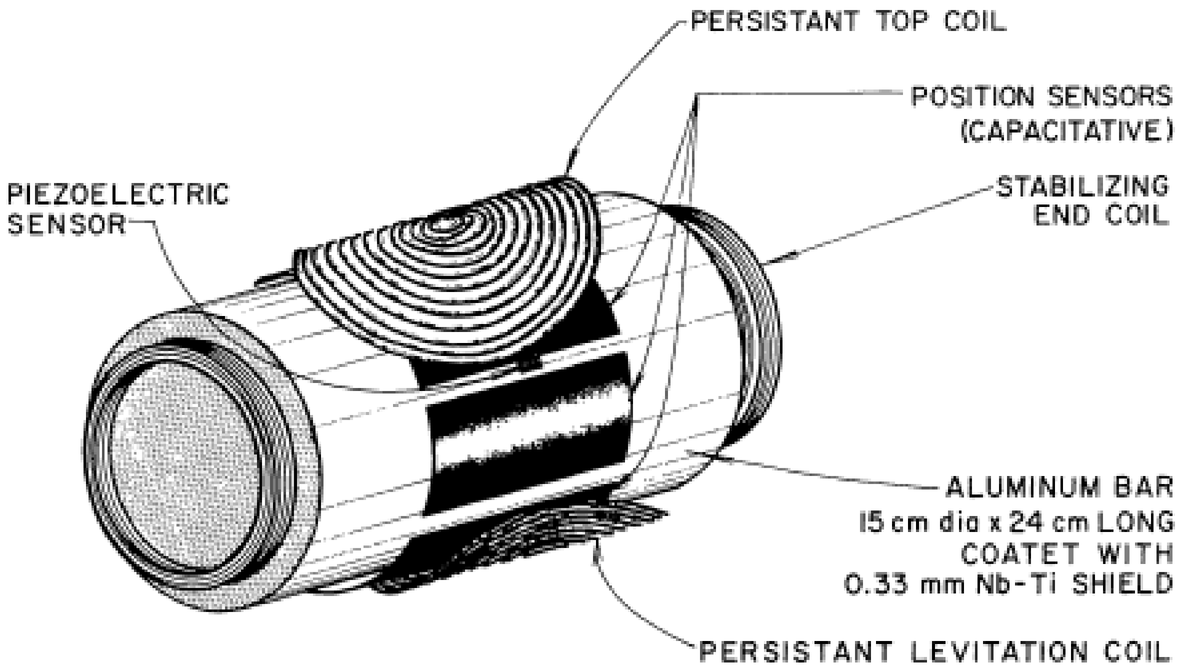
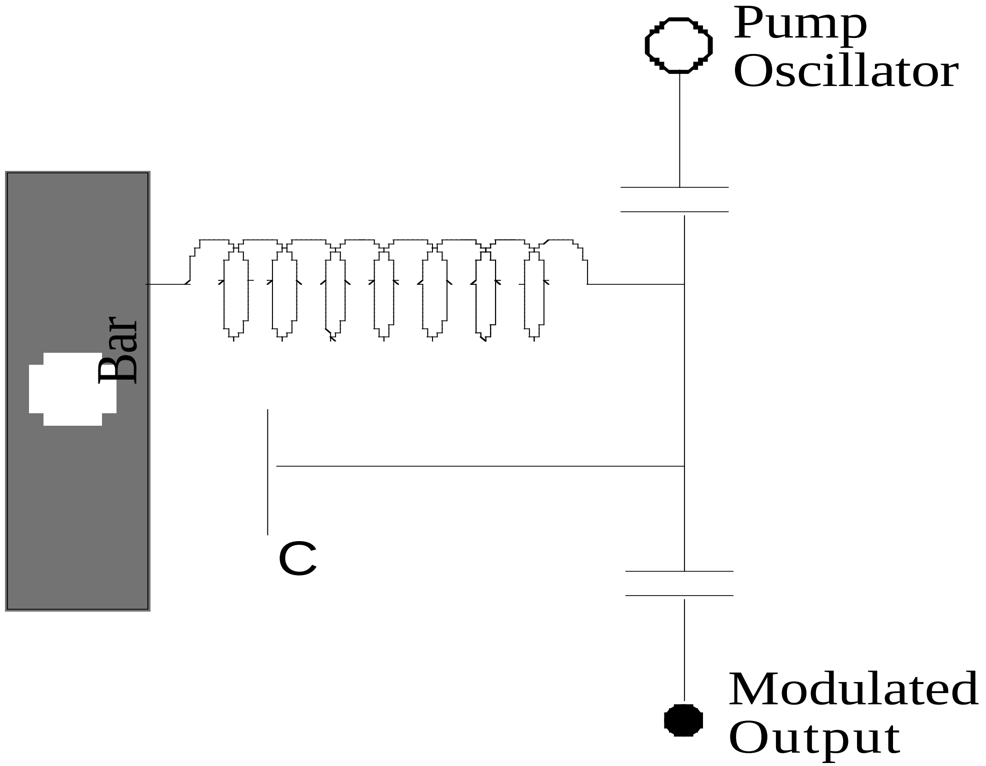


Fig. 3. Superconducting magnetic levitation system for test bar.

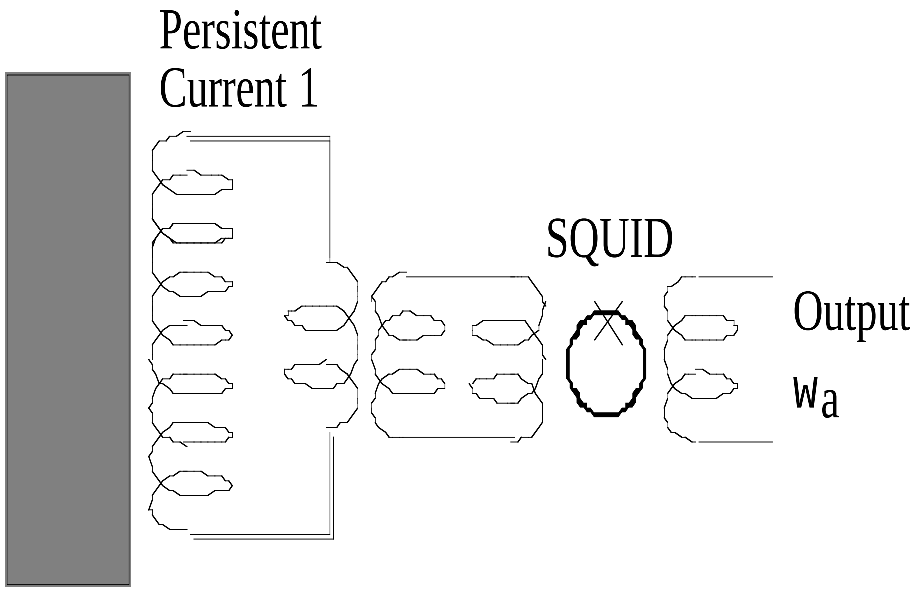
Superconducting Transducer Concepts

Parametric readout



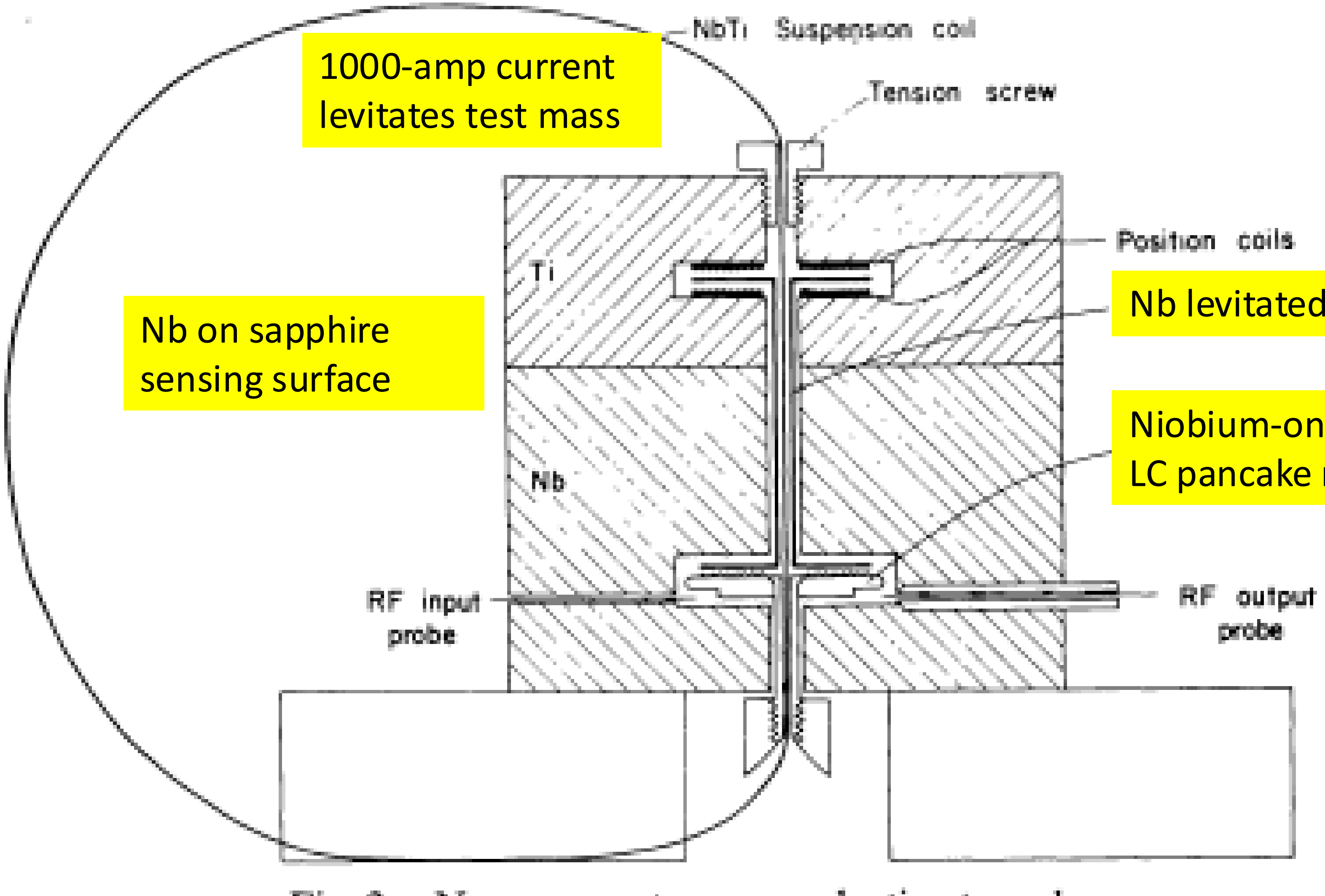
Signal detected as *modulation sidebands of oscillator frequency*

SQUID amplifier readout



Signal at antenna frequency

First Superconducting Parametric Transducer 1973



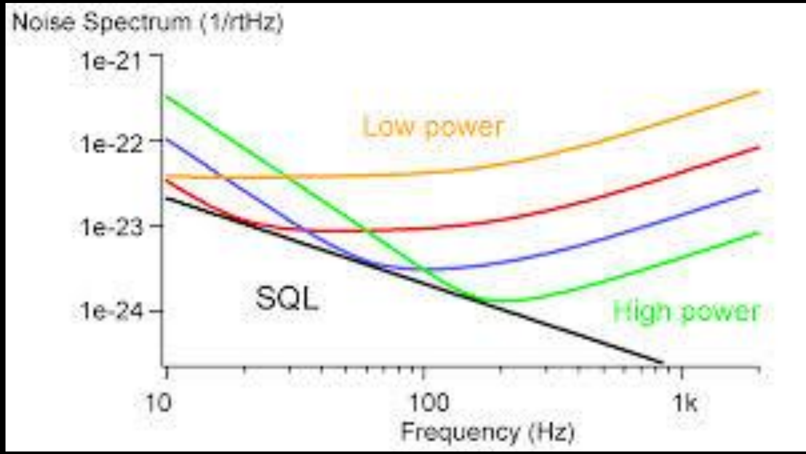
1973: What we expected to detect

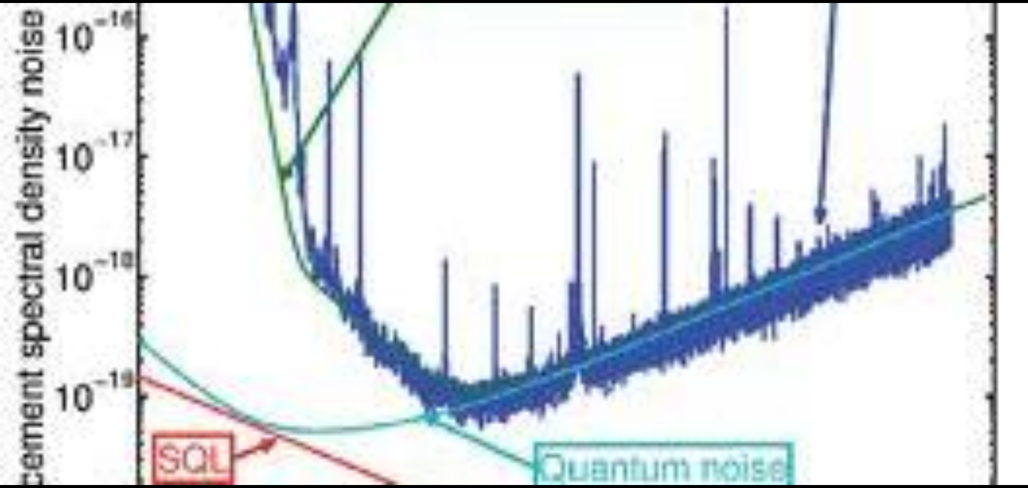
Ref: Gravitational Radiation and Gravitational Collapse 1974
Ed C. DeWitt-Morette

"The most likely theoretical source of high intensity gravitational radiation is gravitational collapse to a neutron star or black hole (Hewish et al 1968)"

"Supernovae…..one every 30 years"
"Many collapses without supernovae"
"10^{49} -10^{53} ergs"
Gamma ray bursts "could be associated with gravitational collapse in our galaxy"

Recognising Quantum Limits
Vladimir Braginsky 1975



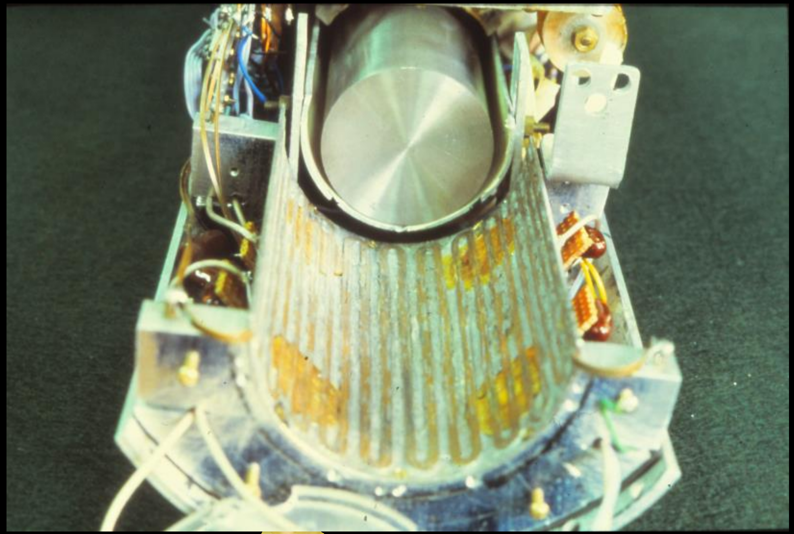


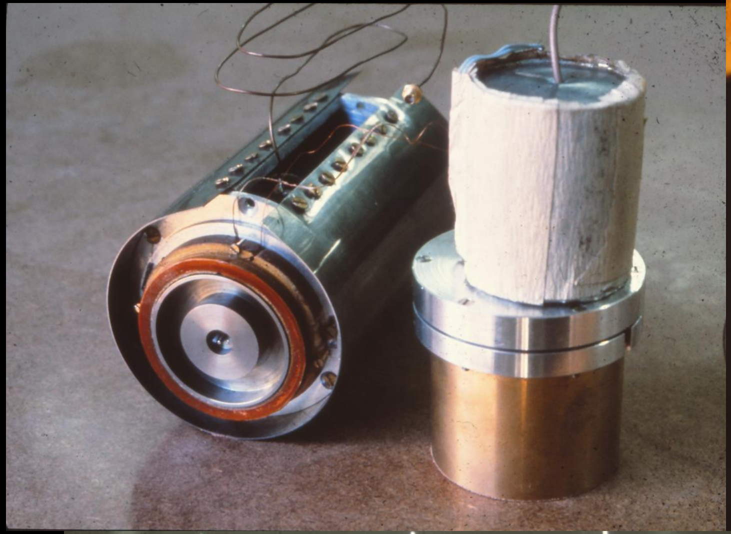
- Standard quantum limit
  - Linear amplifier measurement limit
- Quantum non-demolition
  - Achievable using phase sensitive amplifiers

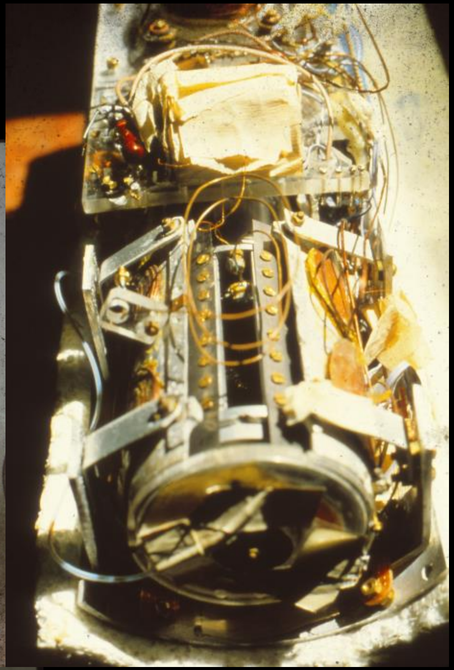
Planning a southern hemisphere bar detector

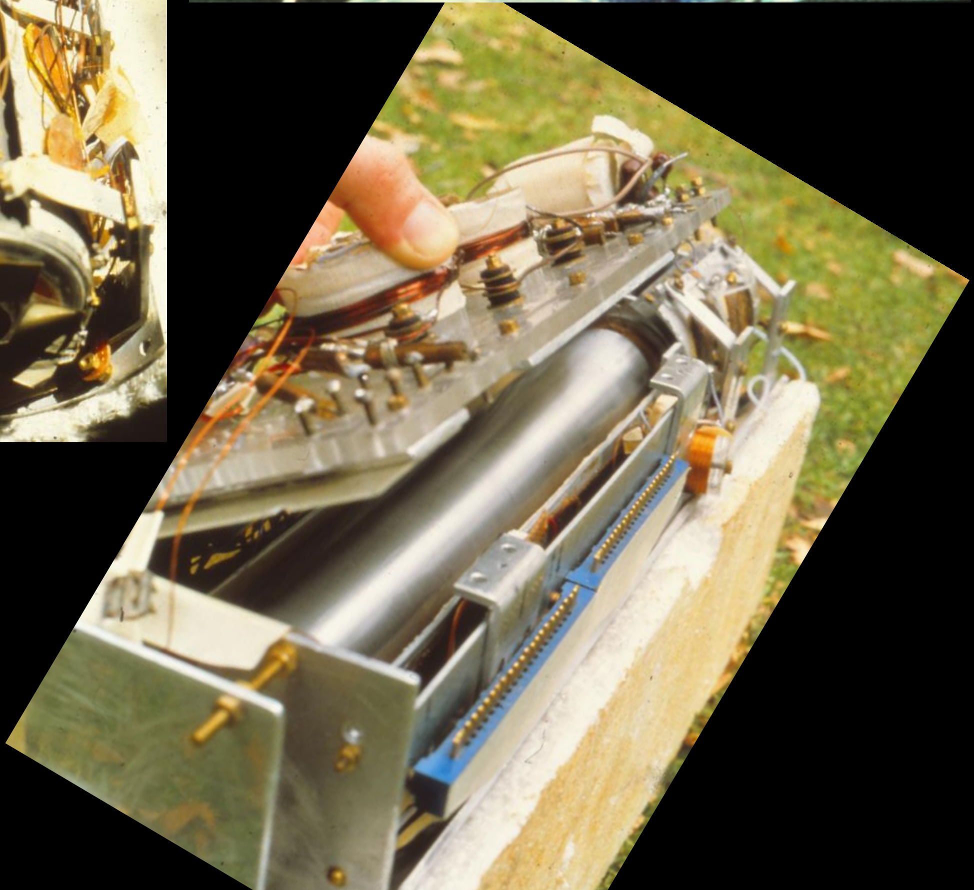
- Community-wide discussions
- Much influence from Braginsky
- Huge support from Stanford
- ARC funding 1976

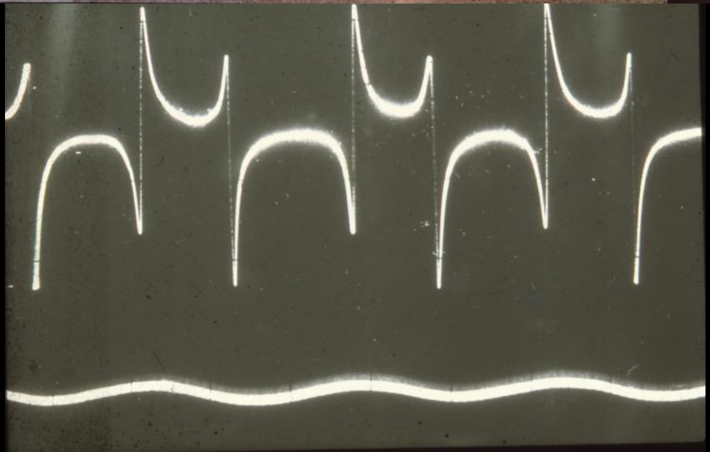
Levitated Antenna with Superconducting Transducer



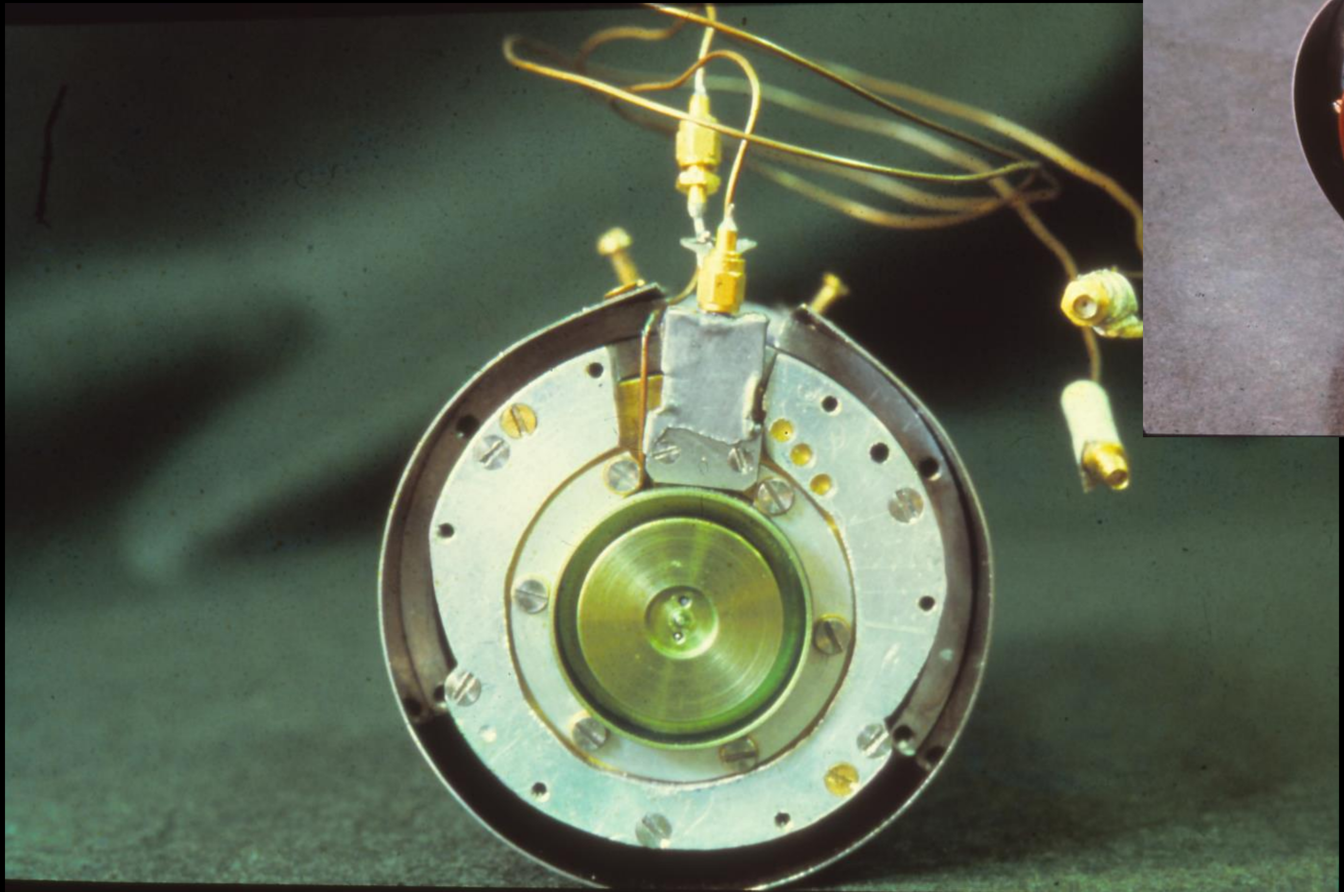


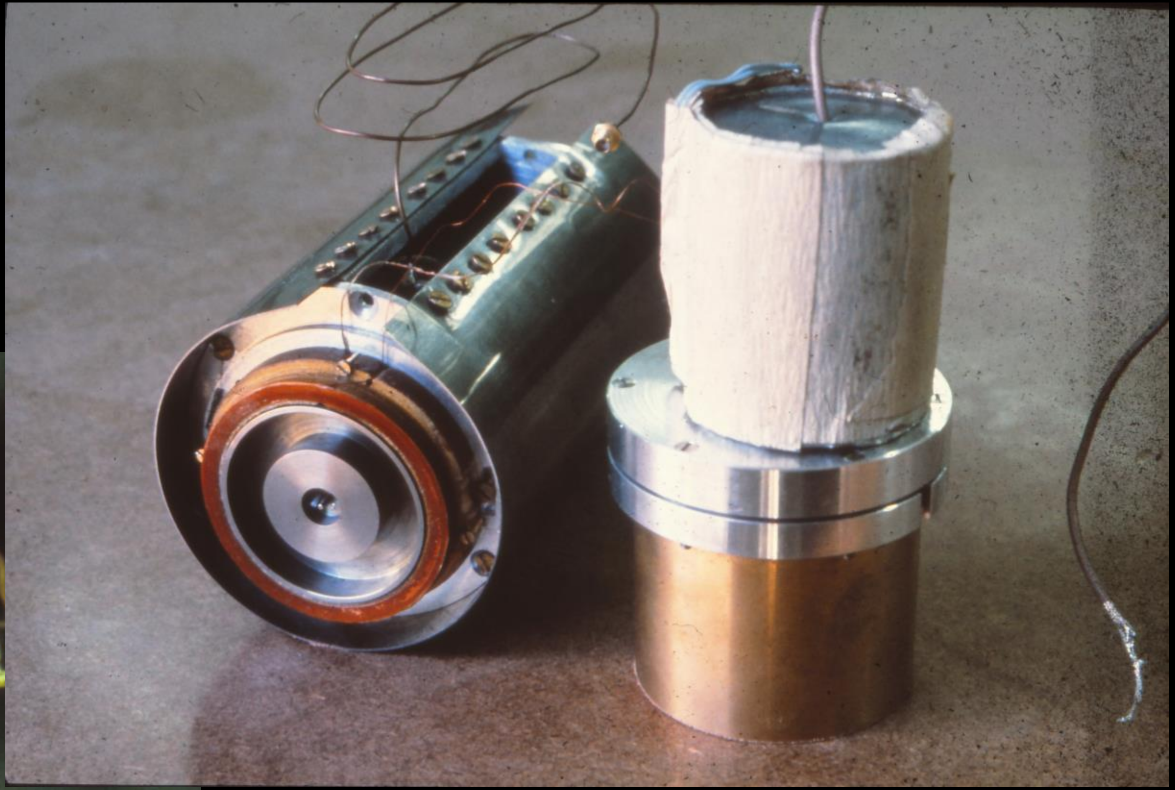






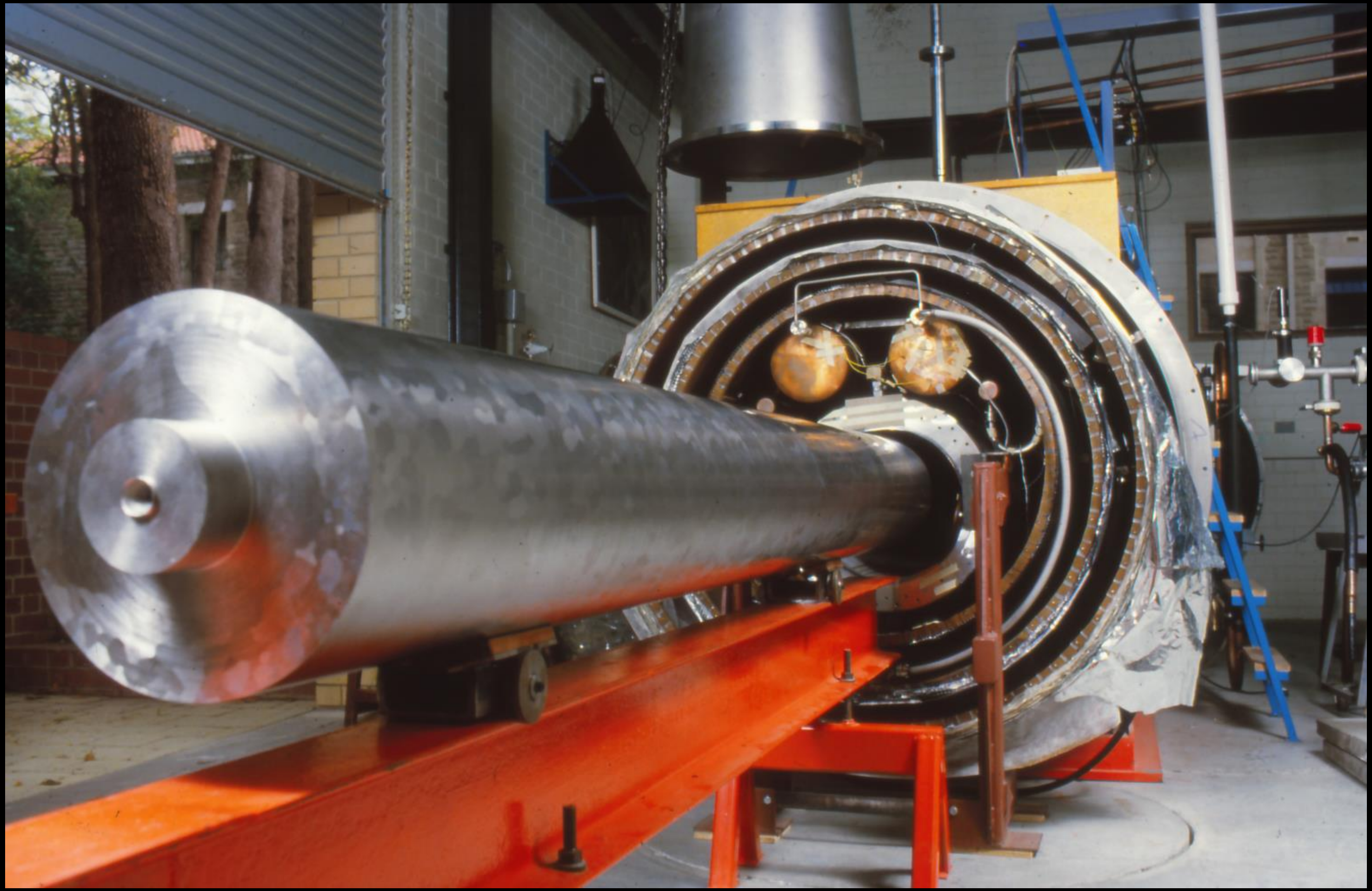
Levitated Re-Entrant Cavities

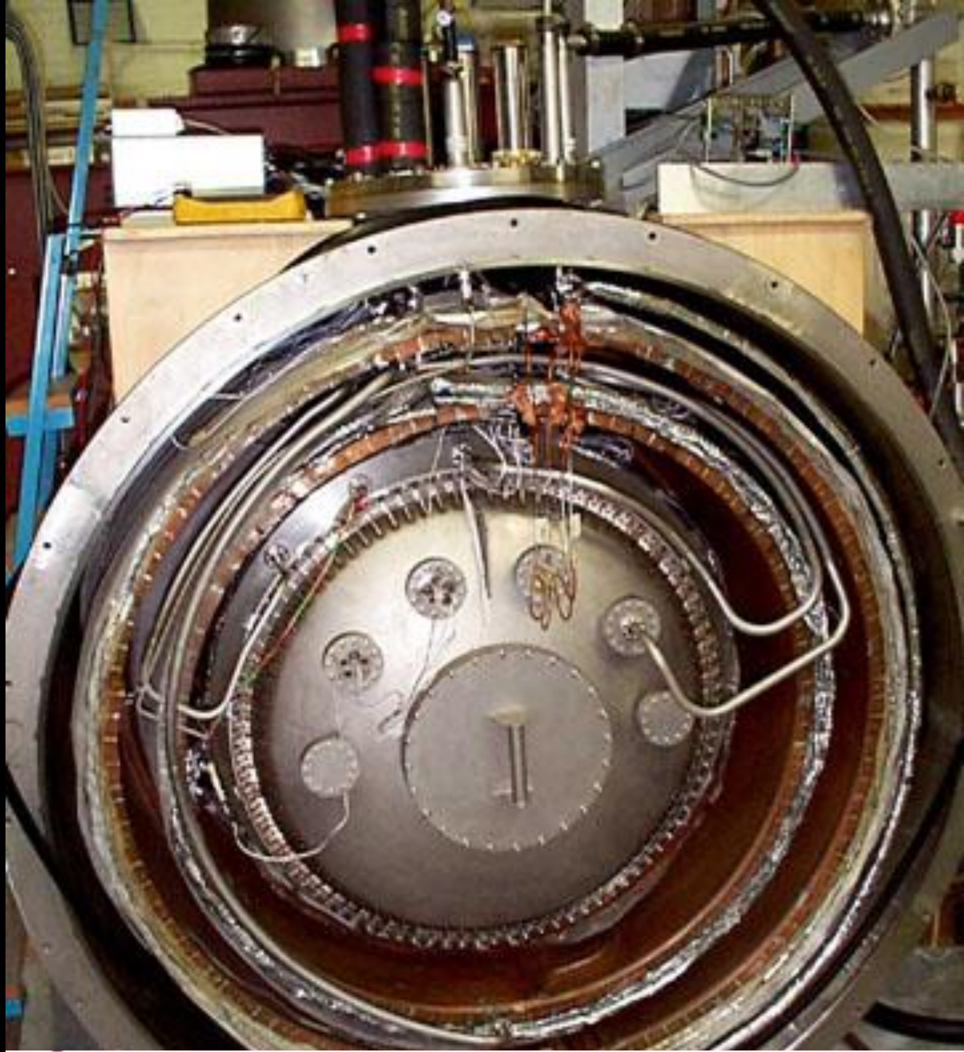


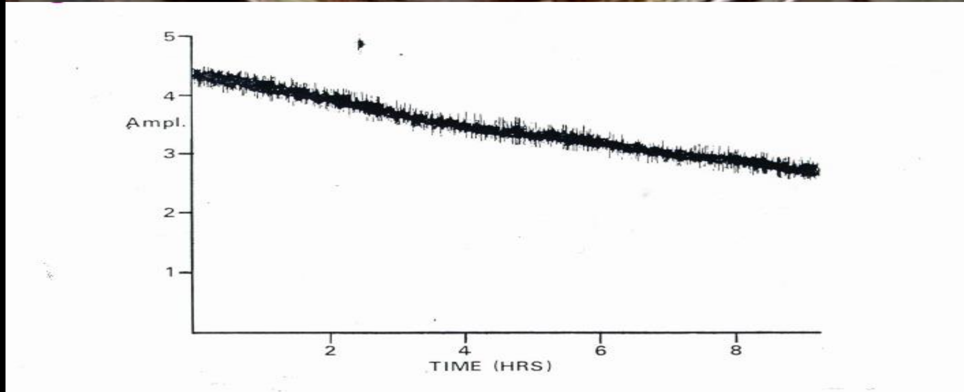


Constructing Niobe

Niobe: 1.5 tonnes, 3m x 30cm

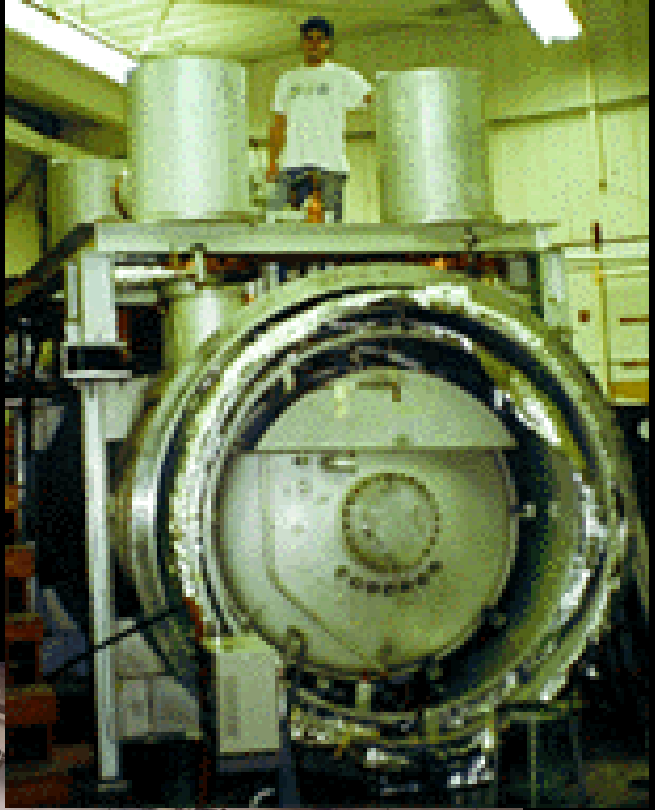






- Parametric readout
- Cryogenic vibration isolation
- Q= 2.3×10^8

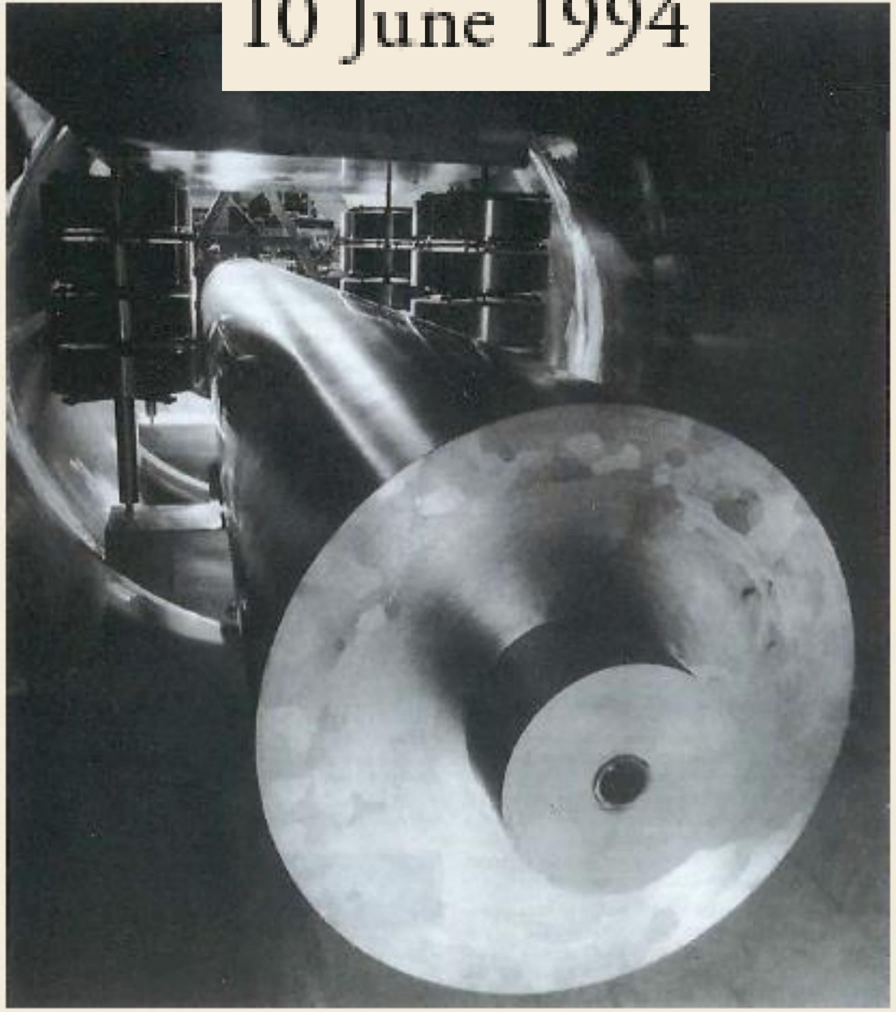
Resonant
Mass
Detectors



The Australian Physicist

Niobé: Monitoring the Milky Way

10 June 1994



The Perth antenna is quite different from any other antennas in the world. It is the only niobium bar, the only successfully operated antenna with a parametric transducer and the only antenna with a non-contacting readout.

Now our perseverance has been vindicated. We have achieved the lowest noise temperature ever recorded in a gravity wave antenna. We are continuously monitoring the Milky Way, and hoping for a gravitational collapse!

Late in this decade large scale laser interferometer gravitational wave observatories will probably supersede resonant bars. With broad bandwidth and greater sensitivity they should make gravitational wave astronomy a reality. In the meantime the bars have a modest chance of making the first detection of a gravity wave.

2001
No detections with 5 detectors!

Pia Astone representing the International Gravitational Events Collaboration

New Life for the Old Bar?

Graviton detection

Photo - electron detection
proved photons

↕

gravito-phonon detection
can prove gravitons

nature communications

Detecting single gravitons with quantum sensing

Germain Tobar [1,2,5], Sreenath K. Manikandan [3,5], Thomas Beitel[4] & Igor Pikovski [1,4]

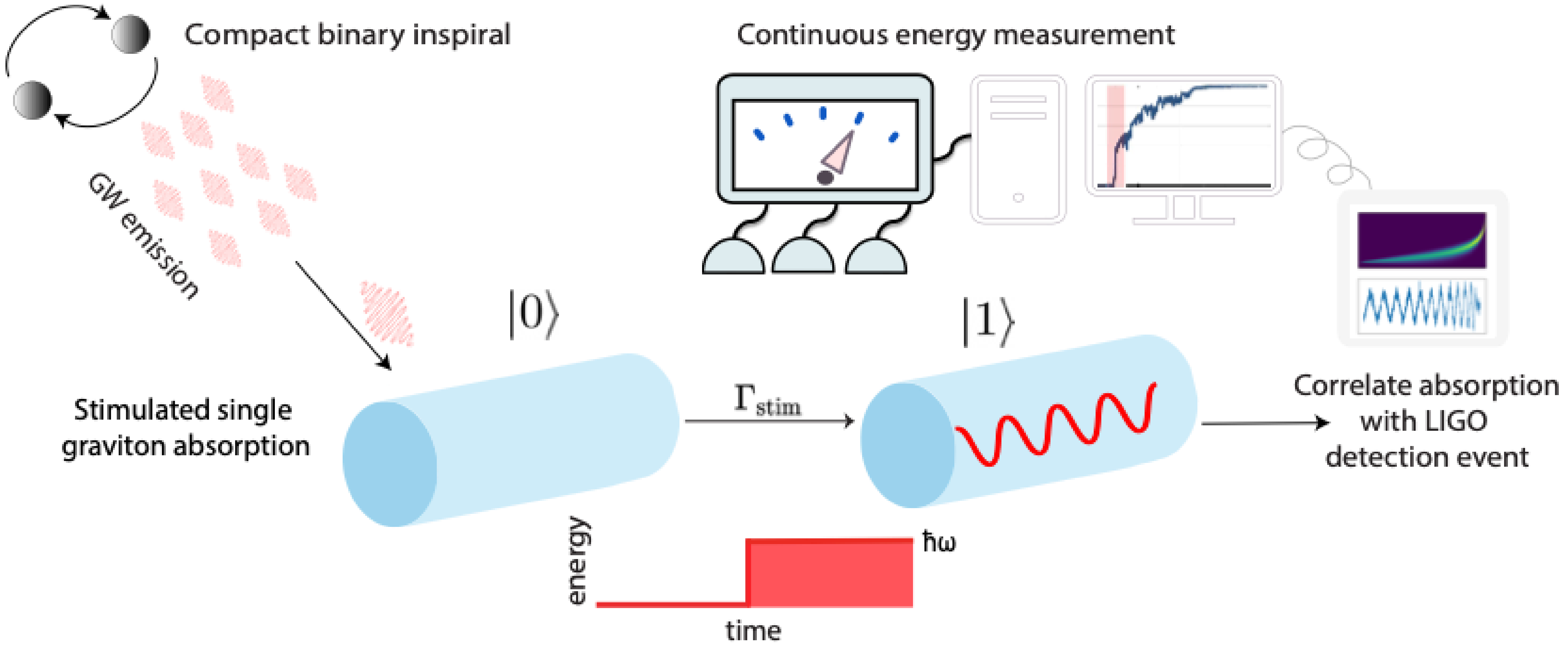
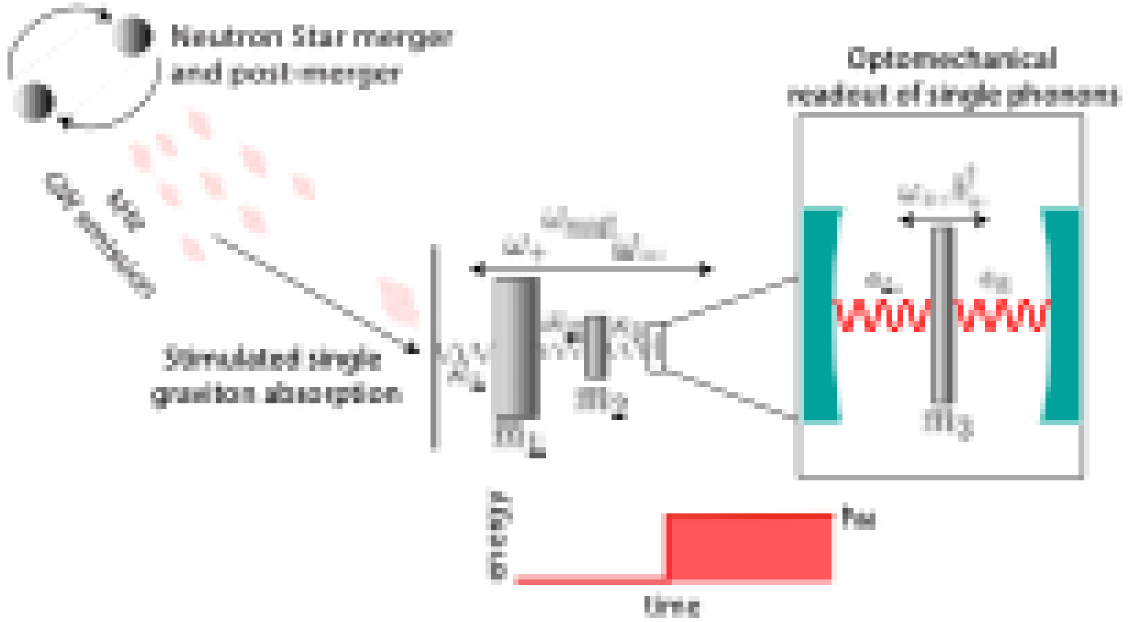


Photo-electric analogue with a multi-mode resonant bar

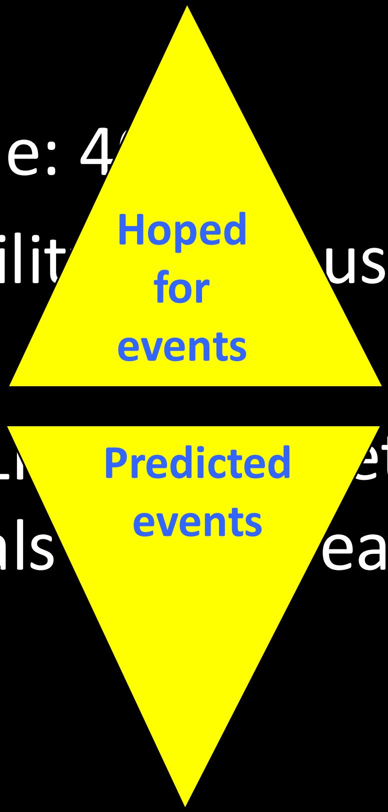
The most practical way to do the experiment would be to use a multi-mode resonant bar



Get graviton to phonon conversion in the normal mode of the coupled oscillator system, which can be read-out directly from the smallest end mass.
Outlined in *'Detecting kHz gravitons with a multi-mode resonant bar'*, *Germain Tobar, Igor Pikovski, Michael E. Tobar (to appear).*

Brief history of Laser Interferometer Gravitational Wave Detectors

- 1990: Large Interferometers designed to detect known sources at reasonable rate.
- Three stages
  - 1990s: Proof of principle: 4
  - 2000s: LIGO 1: 4km facilit … us design, expected signals: 2 events per 100 years.
  - 2015-2020: Advanced Li … etter sensitivity, 1000 x larger volume, expected signals … ear



Split Bar with Laser Interferometer Readout

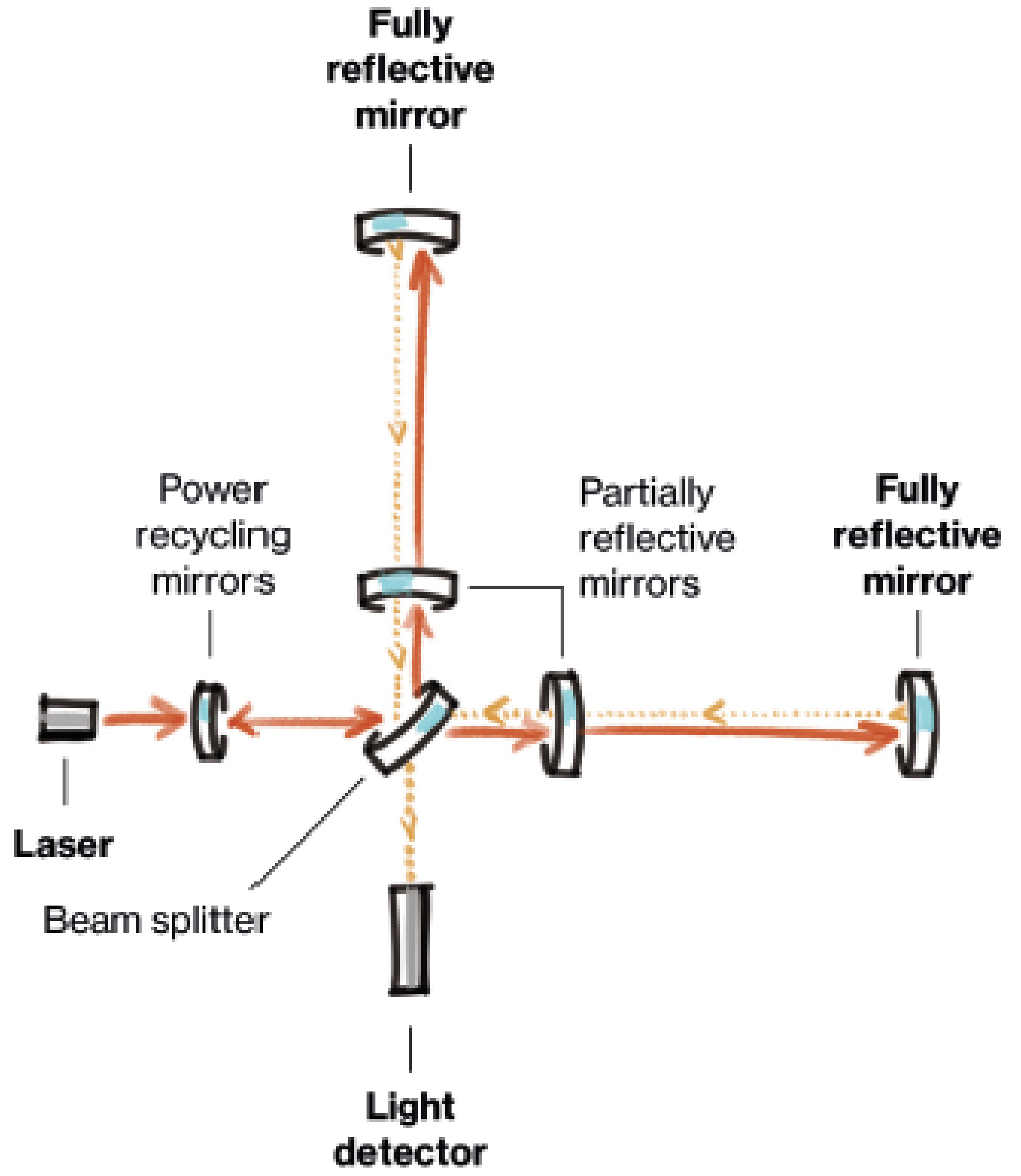
Jim Hough and Ron Drever with split aluminium bar

Ron Drever introduces power recycling

Les Houches, France 1981

Suddenly optical power build-up becomes possible

But can the photon counting noise be reduced?



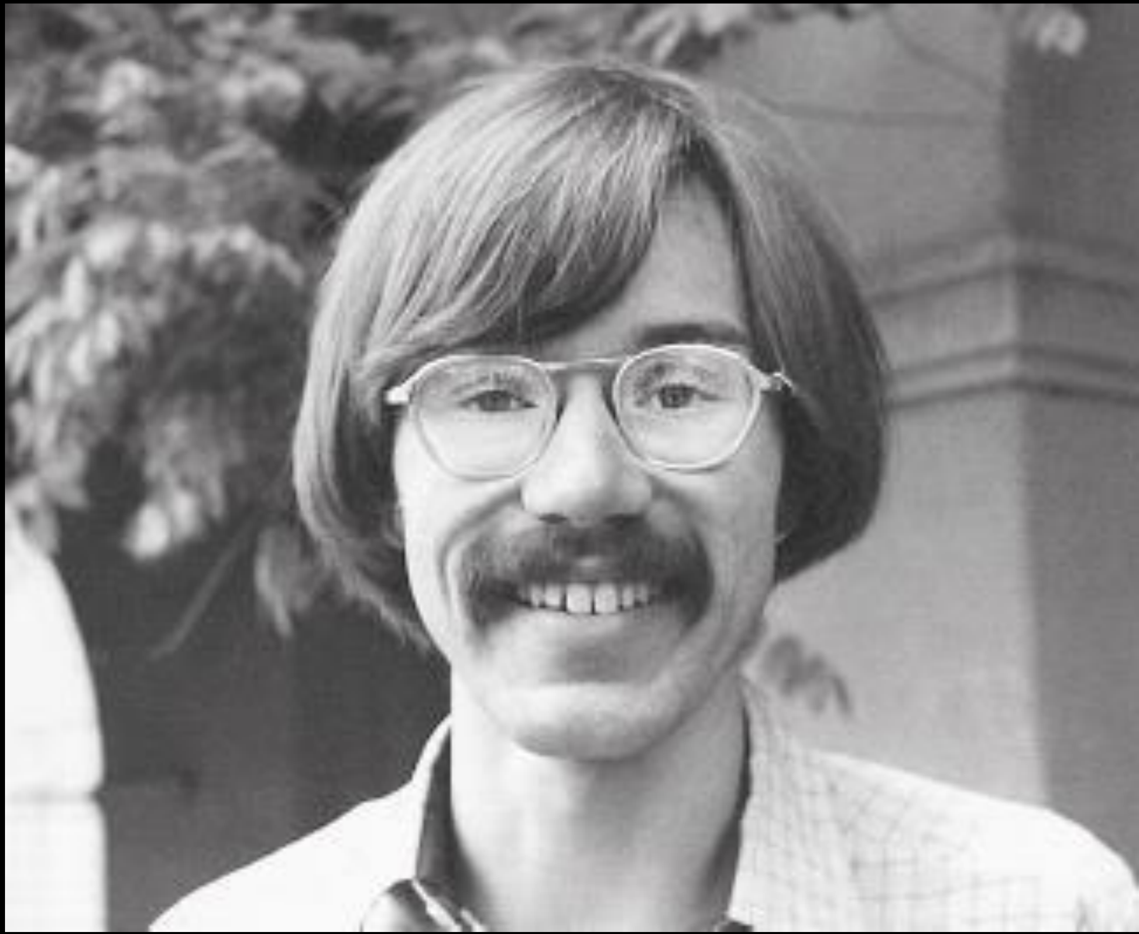
Carlton Caves introduces quantum squeezing 1981

‘The squeezed-state technique outlined in this paper will not be easy to implement…..[but].. the entire task of detecting gravitational radiation is exceedingly difficult.

‘Difficult or not, the squeezed state technique might turn out at some stage to be the only way to improve the sensitivity.

…improvements in sensitivity… [will] await an increase in laser power or implementation of the squeezed-state technique.

Experimenters might then be forced to learn how to very gently squeeze the vacuum before it can contaminate the light in their interferometers.’

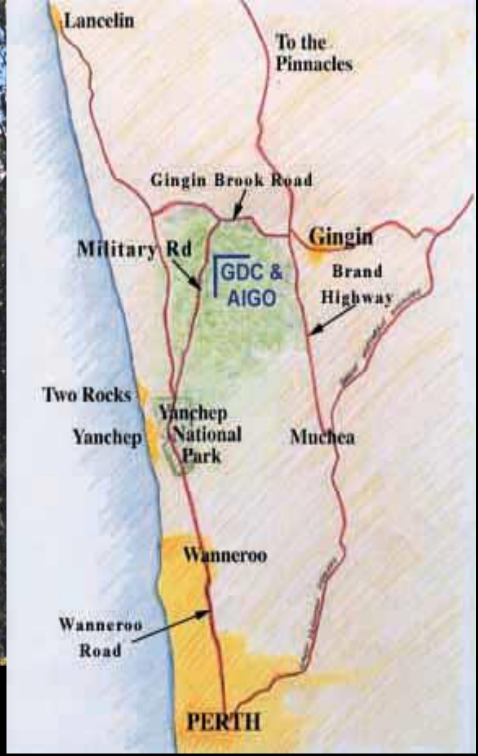


Vision of an Australian Detector 1990s

- UWA builds an 8m prototype and begins to develop isolators
- Gingin site identified and approved including indigenous approval
- Adelaide proposes lasers and high optical power experiments
- ANU develops squeezing and laser stabilization
- UWA supports fundraising for development of the Gravity Discovery Centre

Gravity Discovery Centre

Australian International Gravitational Observatory



AIGO 80 meter high optical power facility


$T = \frac{c^4}{8\pi G} G$

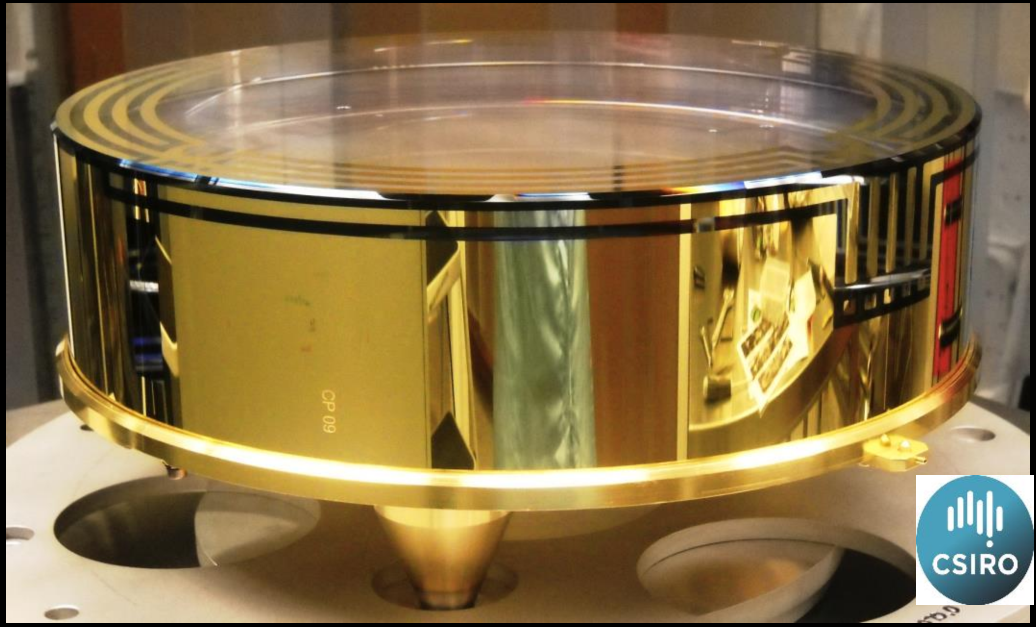

Central Station

Contributing to International projects

- Vibration Isolation: UWA Team works closely with VIRGO project
- High optical power: Adelaide develops high power lasers
- Quantum Squeezing: ANU demonstrates squeezing for low sideband frequencies…works closely with LIGO
- UWA team begins to investigate parametric instability
- CSIRO ACPO contracted for LIGO mirror polishing

Mirrors and Coatings

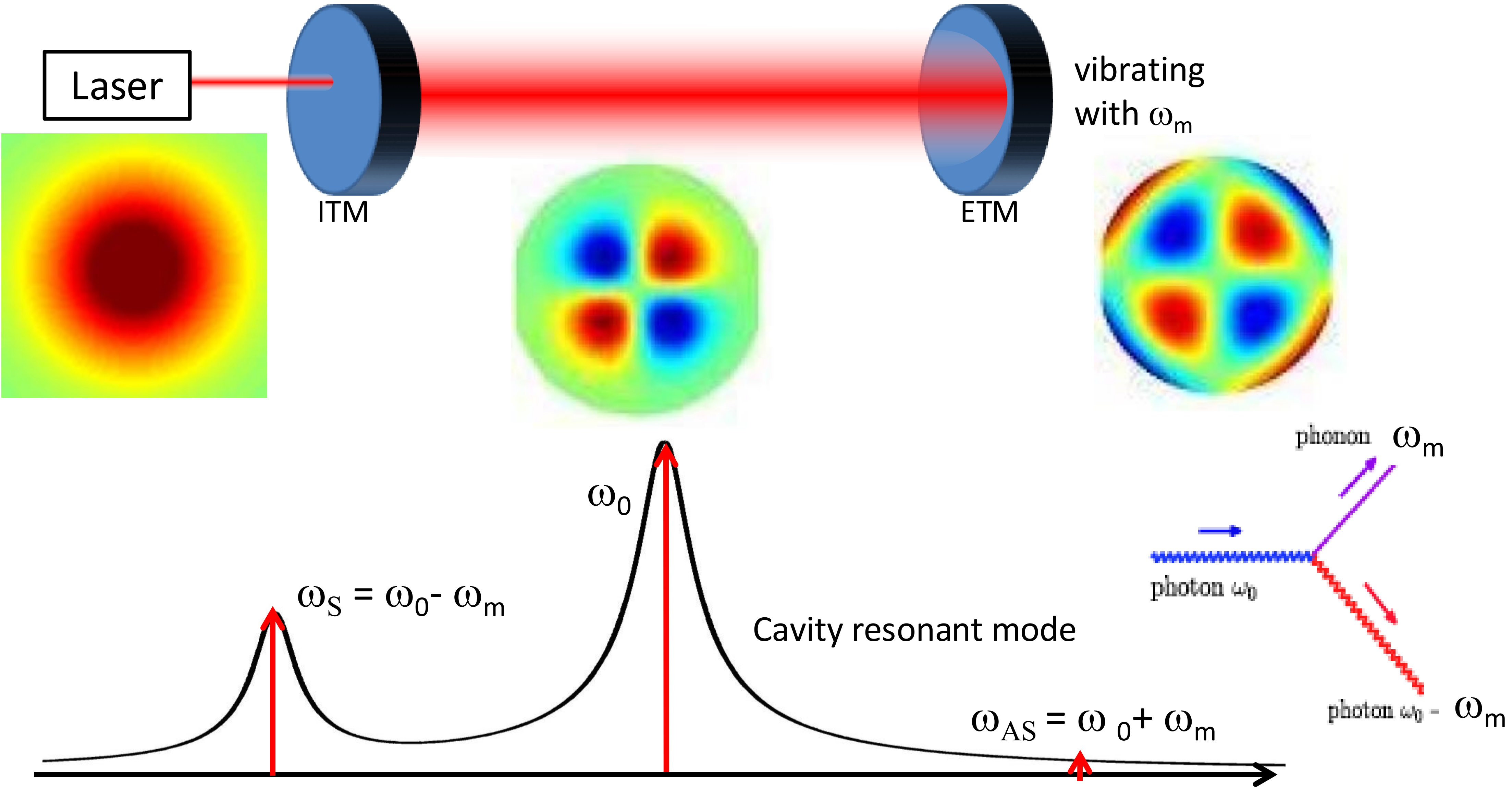
- Best mirrors ever made
- AR on one surface
- Gold on barrel for thermal control
- Reflecting: ~ 40 layers amorphous coatings.



Prediction of Parametric Instability 2005

- 2005 UWA team predicts Advanced LIGO will experience three-mode parametric instability at 5%-10% of full input power
- Partial methods of control proposed
- Demonstrated at UWA (small scale) in 2012, Gingin 2013 at high power with suspended test masses
- 2014 Instability observed in Advanced LIGO (PRL Evans et al 2015)
- Still working with LIGO to find solutions since all high power interferometers suffer parametric instability
- Developing techniques for using PI as a tool for monitoring and control
- Design techniques developed for interferometers with minimum instability

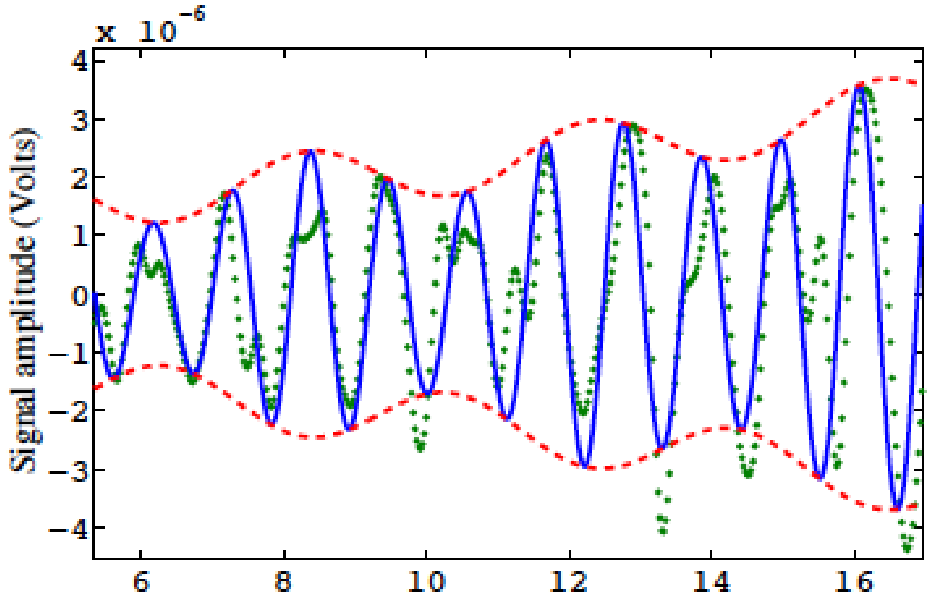
Three-mode scattering in GW optical cavity

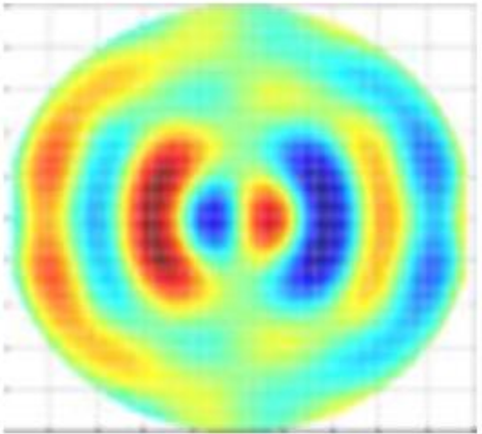


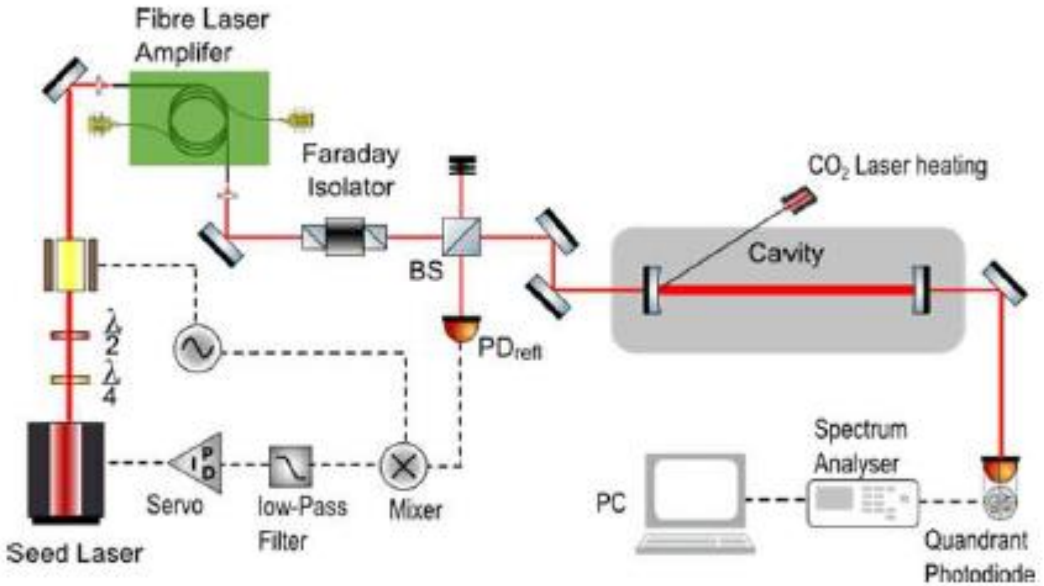
First observation of parametric instability in high power suspended interferometer cavity

Finesse: 15,000
Optical Power 20kW
Parametric Gain = 6

Exponential growth modulated by suspension mode due to figure 1nm errors



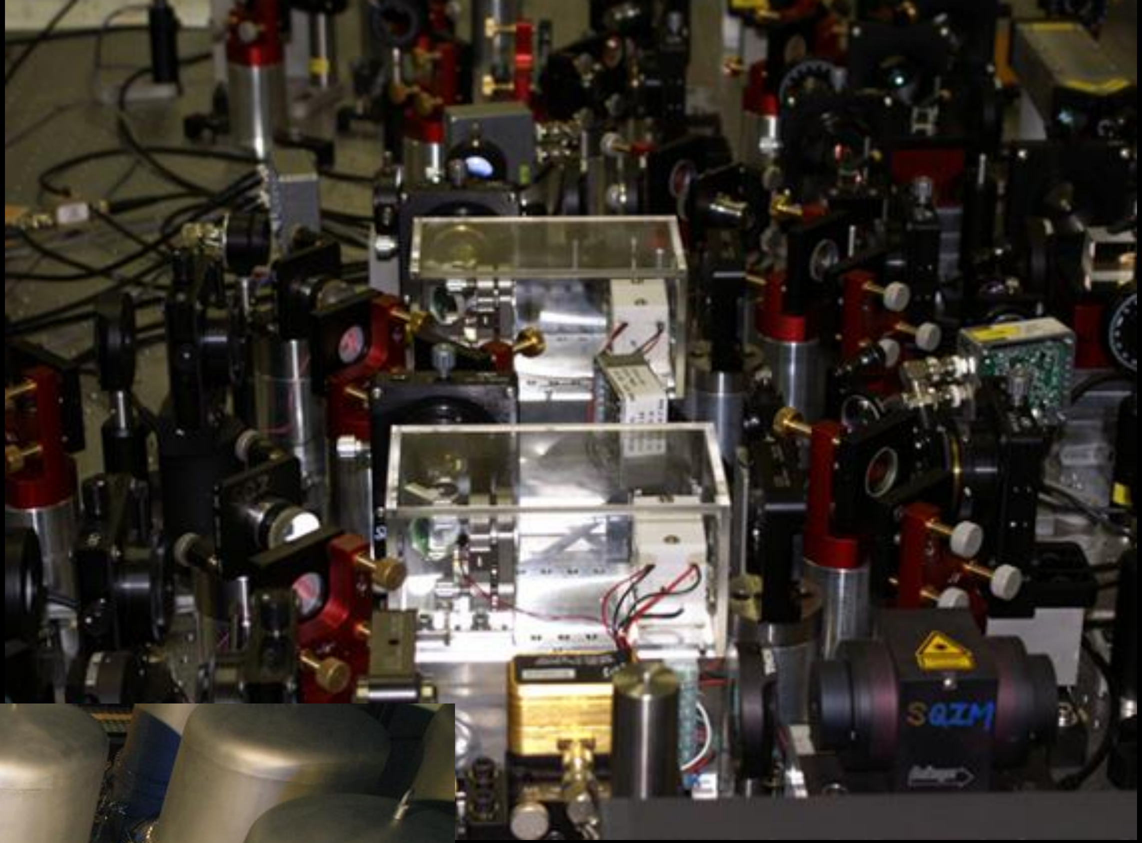


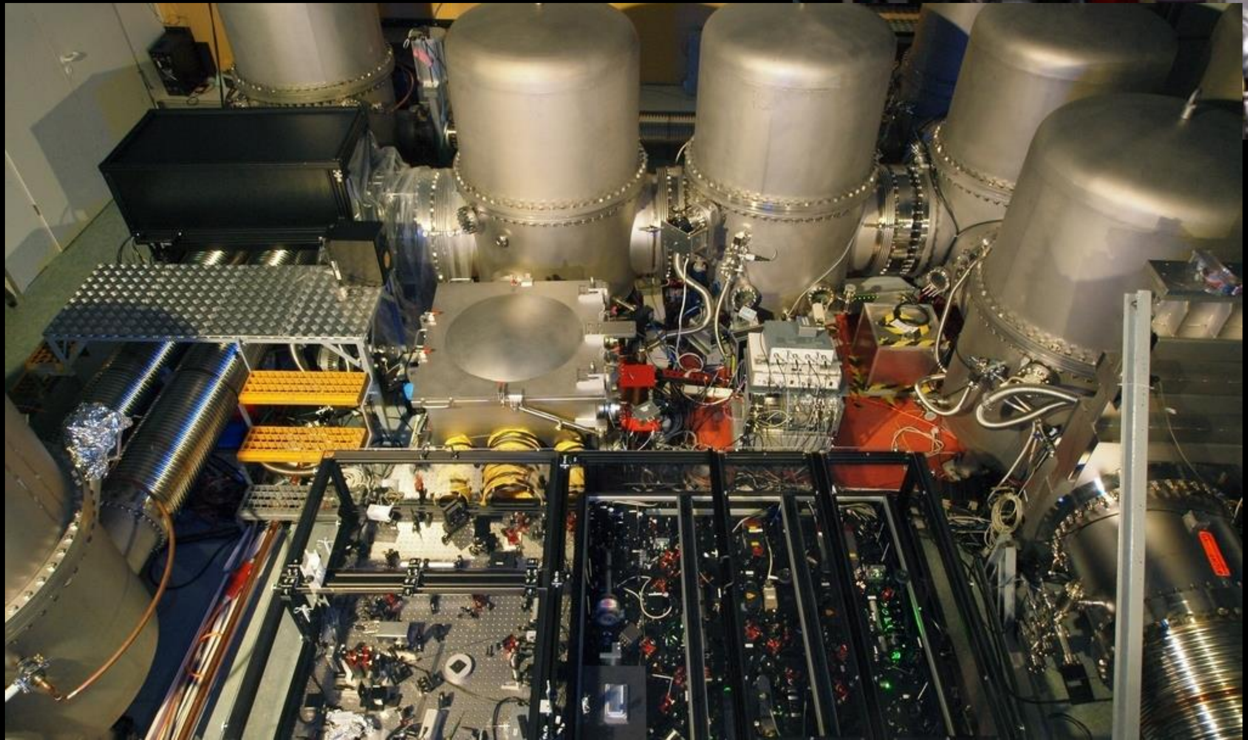


Quantum squeezers ~2002

ANU and AEI

Phase sensitive amplifier squeezes vacuum fluctuations





Squeezed light has been used to suppress vacuum fluctuations and reduce interferometer shot noise below the SQL limit.

Next generation detector technology

- Optomechanical techniques for future detectors
- Silicon optics using 2-micron laser light
- Crystalline coatings
- Precision mode matching for improved squeezing

The ideas are the easy part!

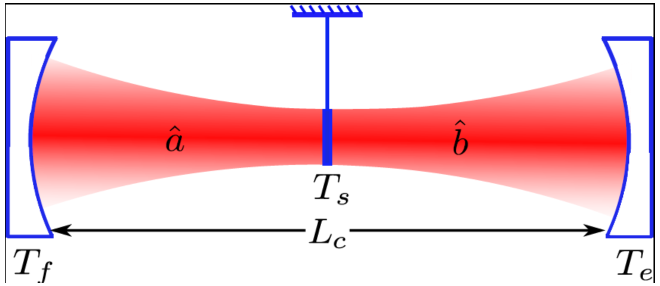
Slow and painstaking research

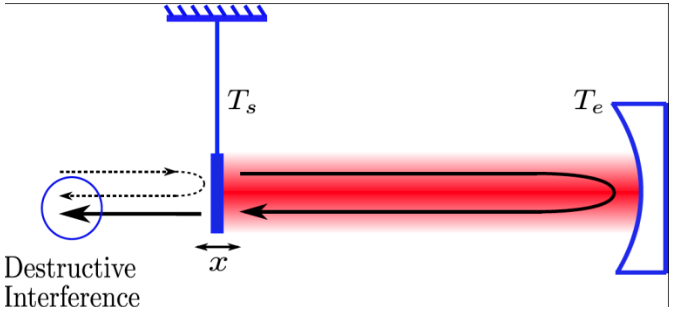
Optical dilution

PRL 113, 151102 (2014) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2014

Narrowing the Filter-Cavity Bandwidth in Gravitational-Wave Detectors via Optomechanical Interaction

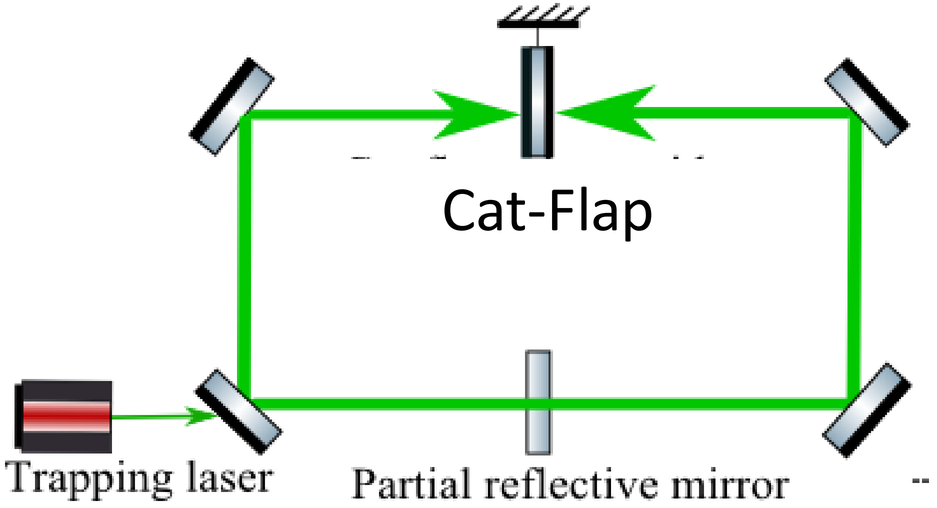
Yiqiu Ma,[1,*] Shtefan L. Danilishin,[1] Chunnong Zhao,[1,†] Haixing Miao,[2,‡] W. Zach Korth,[3]
Yanbei Chen,[2] Robert L. Ward,[4] and D. G. Blair[1]

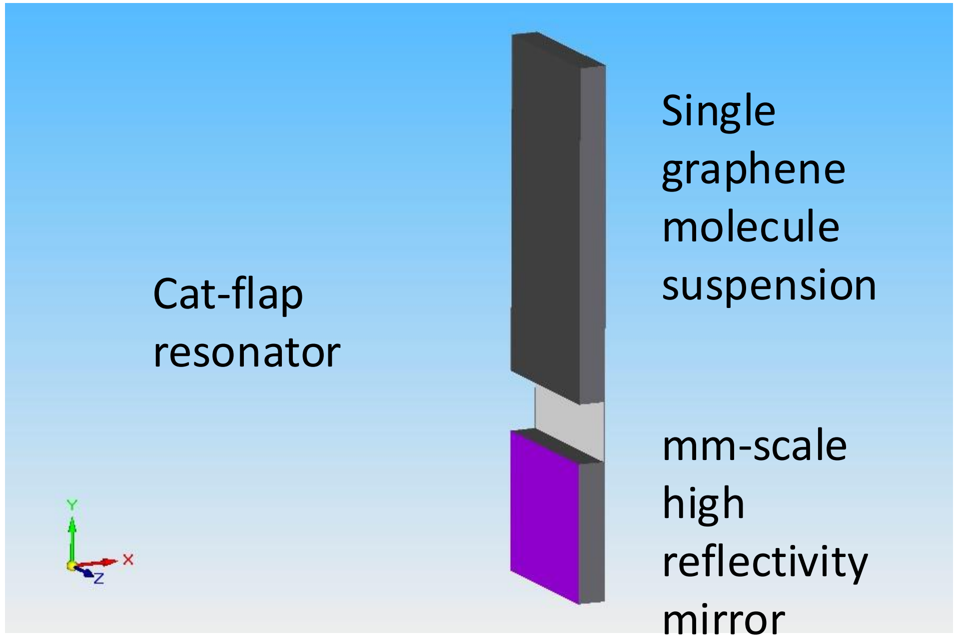




Quantum destructive interference cancels quantum noise and cancels optical damping

Noise-free Optomechanics: Optical Dilution and Cat-flap resonators



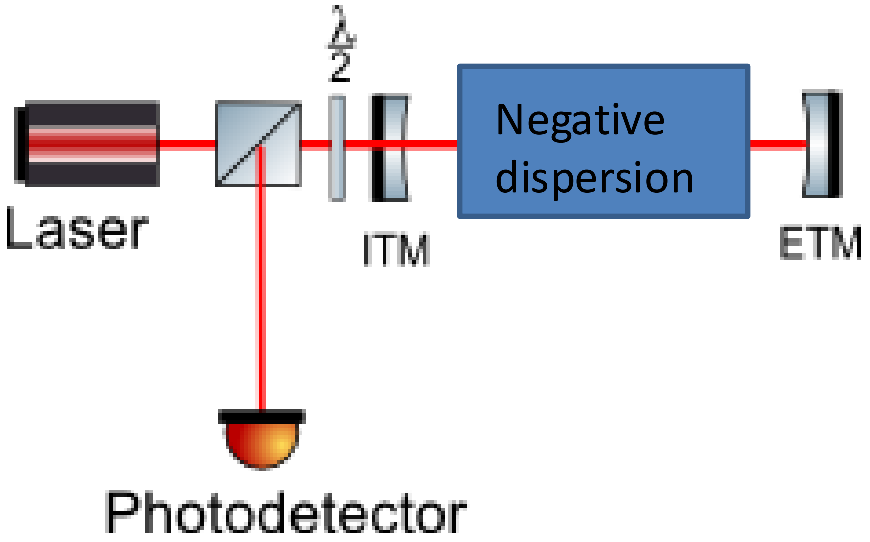


Optics for quantum-noise-free optical dilution.

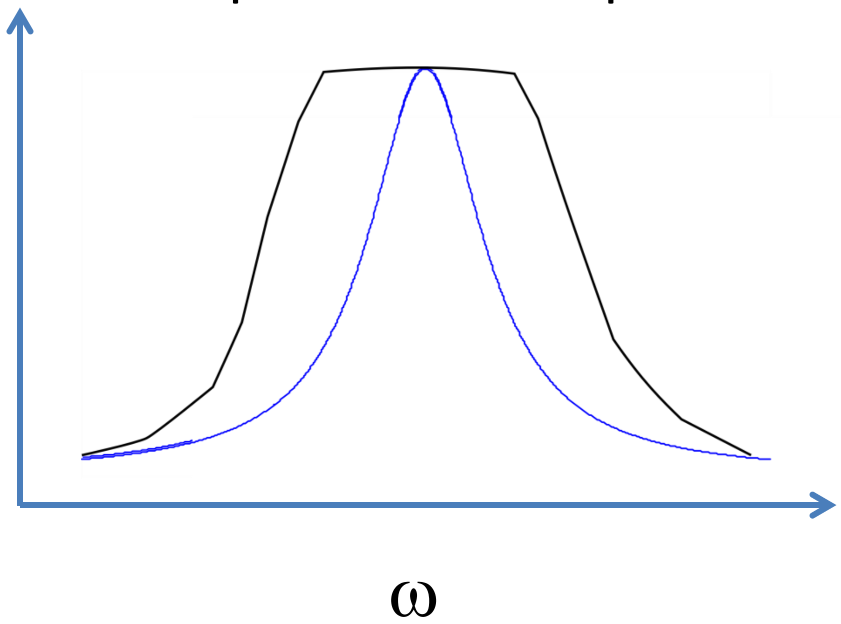
Dilution of mechanical losses: predicted Q ~ 10^{16}

Effectively noise-free.

White-light cavity

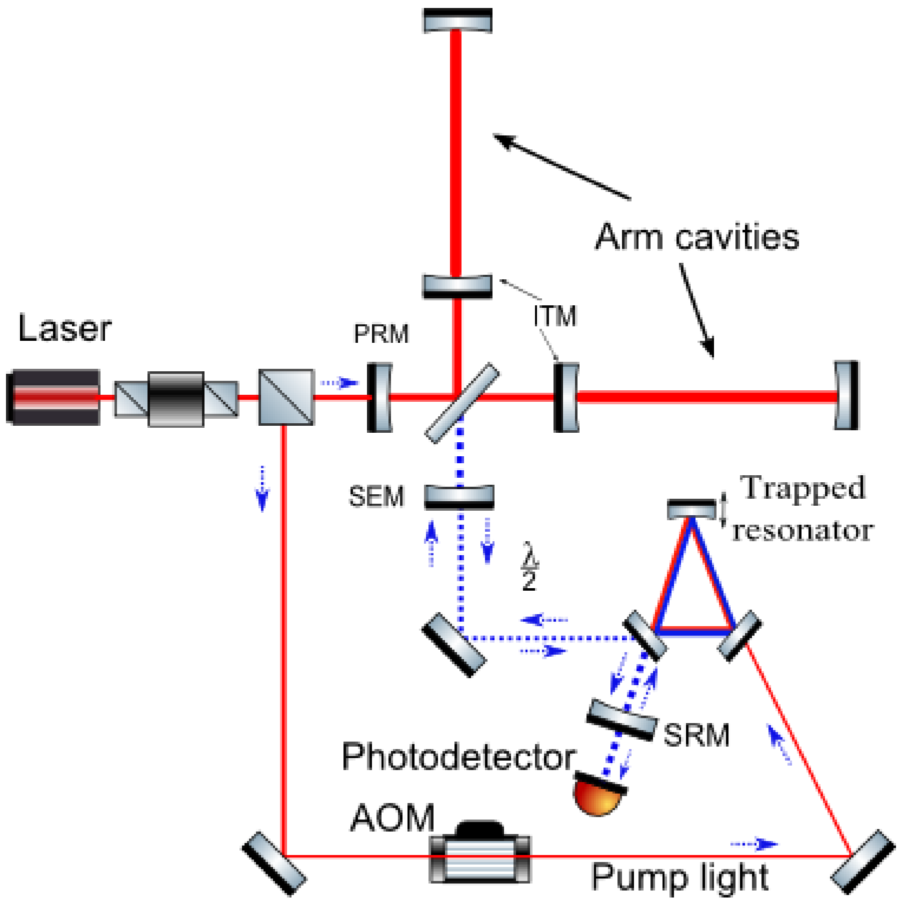


WLC breaks the nexus between bandwidth and amplitude build up.



Negative dispersion makes the cavity "longer" for longer wavelengths so all frequencies are simultaneously resonant

White-light cavity enhanced GW detector



- Signal extraction mirror resonates the signal sidebands
- Optomechanical cavity provide negative dispersion
- Broad range of frequencies enhanced
- Hence broadband sensitivity enhancement

Next Detectors for Gravitational Astronomy KITPC, Beijing 2015

Crystalline Coatings

minimizing Brownian noise in precision interferometry

Garrett D. Cole
Crystalline Mirror Solutions GmbH & LLC
Faculty of Physics, University of Vienna

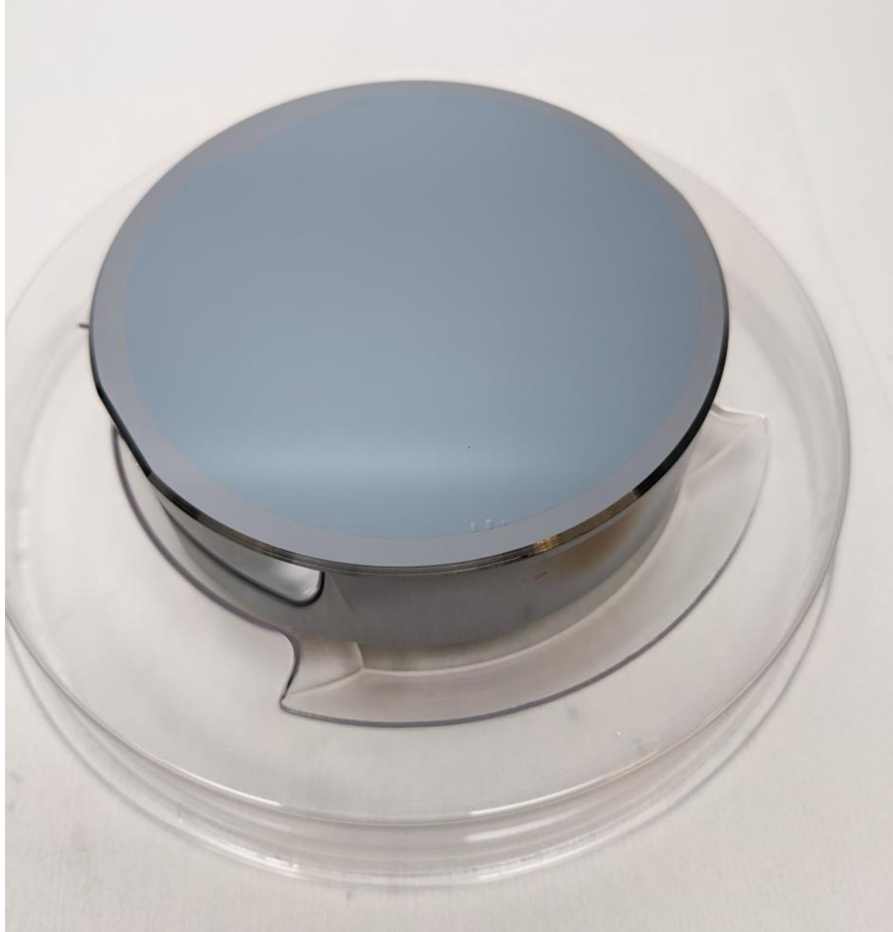
Ten-fold reduction in thermal noise

Challenges!

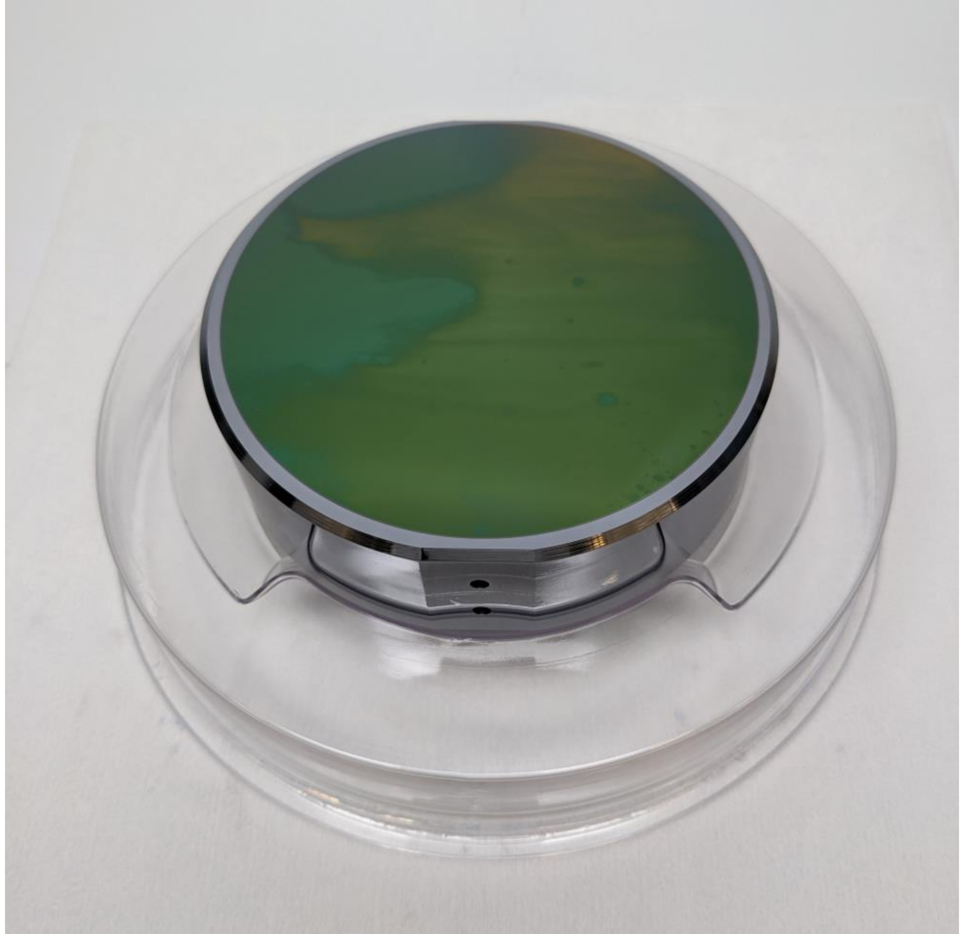
Crystalline AlGaAs/GaAs coatings on silicon test masses

Silicon test mass: diameter: 100mm, thickness 30mm

Completed ITM crystalline 99.6% HR coating
3 small edge defects.



Damaged AR coating
The polymer film applied to protect the AR coating on the mirror backside failed and the AR coating was damaged (etched by HF acid)



Southern Hemisphere Detector

BENEFITS

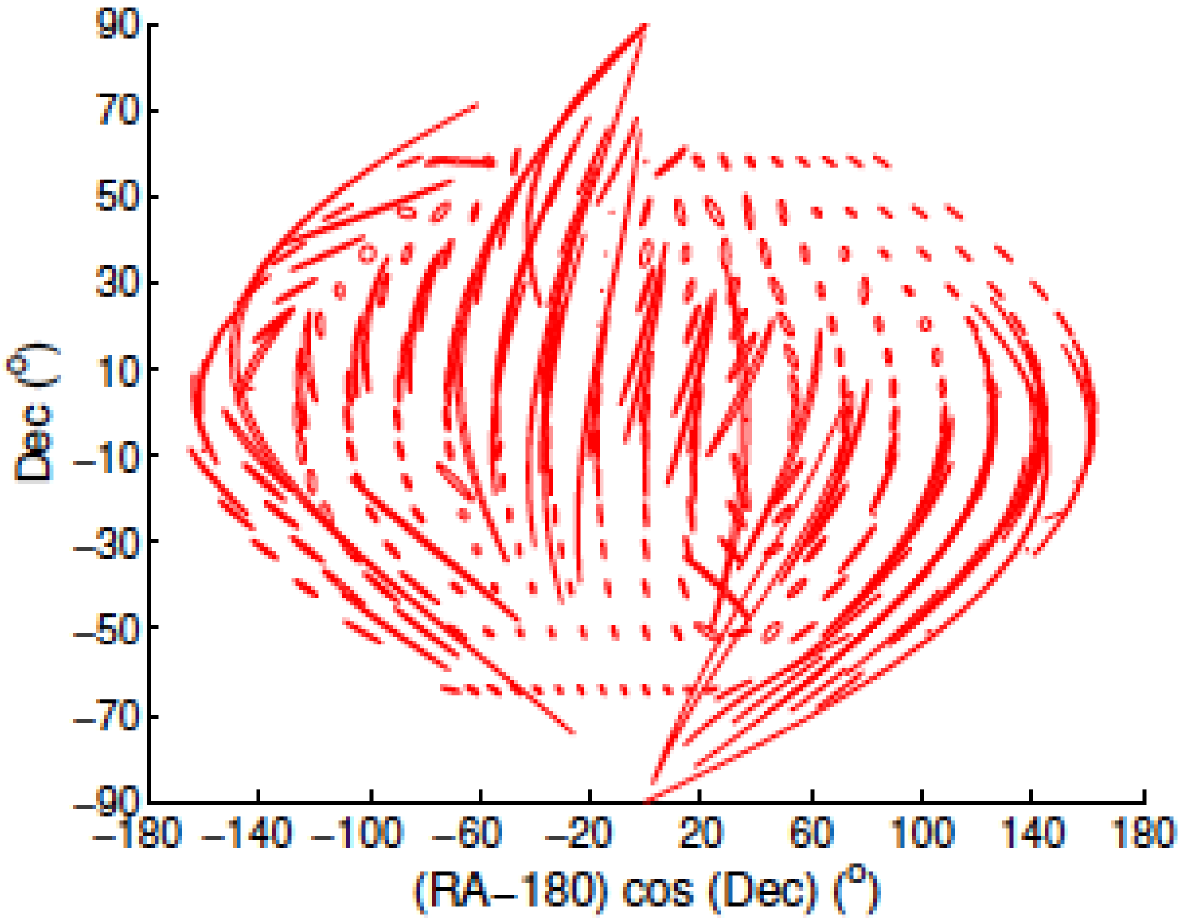
Source localization   Source parameters   Source distance

EM identification   Noise reduction

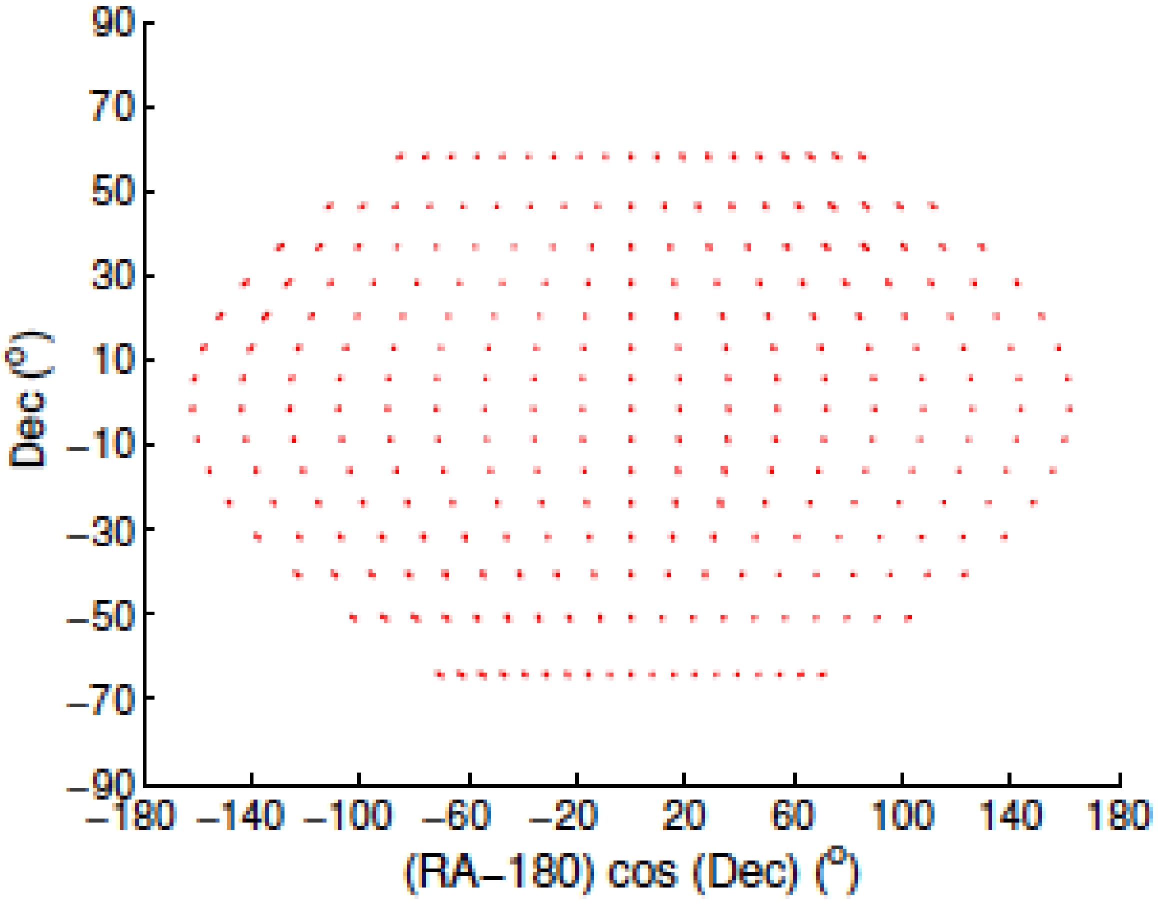
- Multiple attempts including partnerships: UK, Japan, India, China, USA
- Full LIGO-Australia proposal 2010
- NEMO concept, scoping study
- Needs a systematic, concerted and long-term effort
- OzGrav 2 leading the way

2008

Existing Array: Can’t tell source direction, much worse interference



Expanded array: pinpoint sources, reduce interference



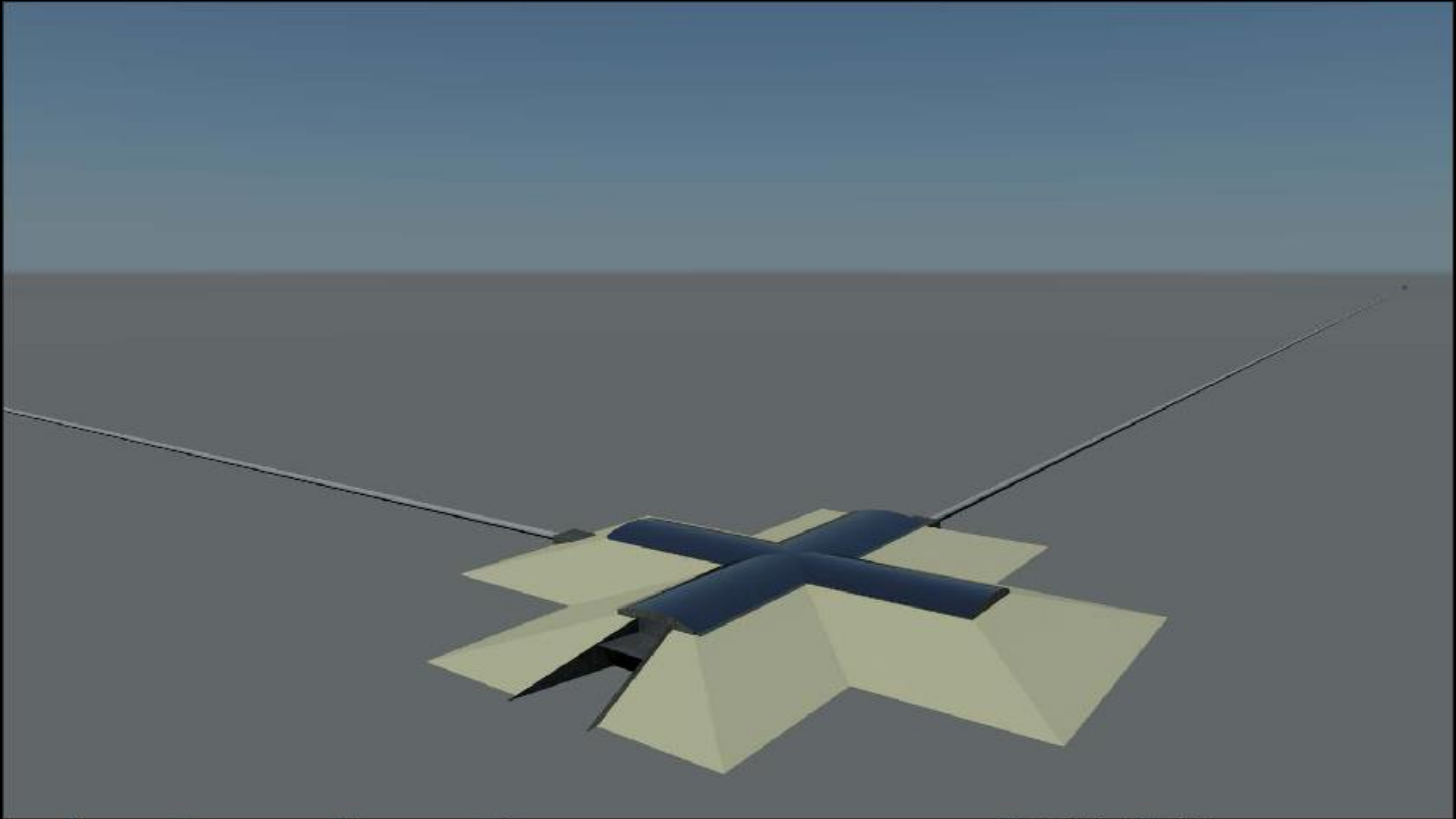
LIGO-Australia

Jesper Munch

For ACIGA and LIGO Laboratory

LSC-VIRGO Meeting
Arcadia, 14-17 March 2011

LIGO-G1100235 – x0



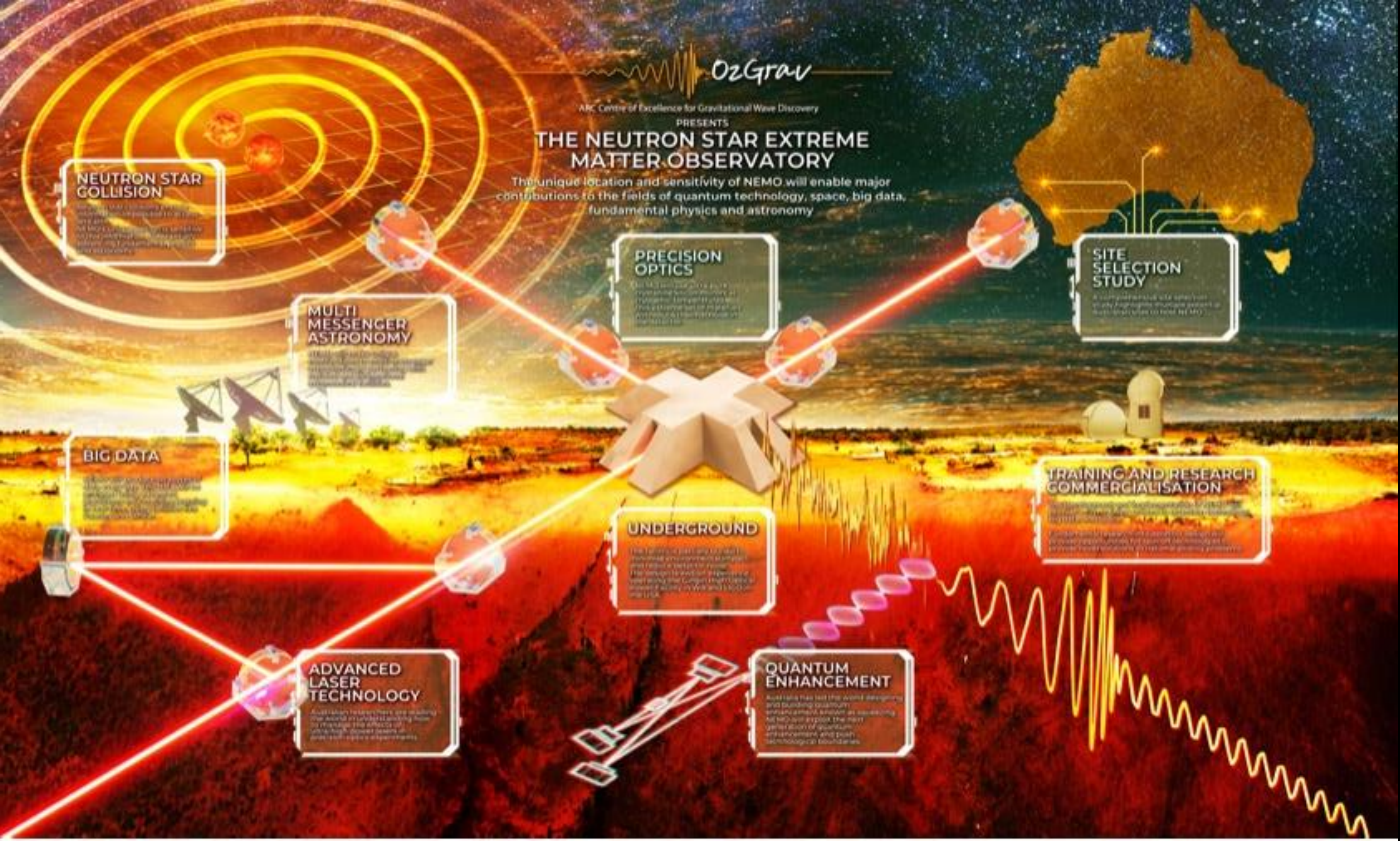
AUSTRALIAN INTERNATIONAL GRAVITATIONAL OBSERVATORY

CONCEPT MODEL **AERIAL VIEW** SIMON ANDERSON

Construction Funding Profile

Funding requirement in (2010$)

FY2011-2012	$7M
FY2012-2013	$37M
FY2013-2014	$49M
FY2014-2015	$33M
FY2015-2016	$9M
FY2016-2017	$4M
Total	**$140M**



OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery
PRESENTS
THE NEUTRON STAR EXTREME MATTER OBSERVATORY
The unique location and sensitivity of NEMO will enable major contributions to the fields of quantum technology, space, big data, fundamental physics and astronomy
NEUTRON STAR COLLISION
PRECISION OPTICS
SITE SELECTION STUDY
MULTI MESSENGER ASTRONOMY
BIG DATA
TRAINING AND RESEARCH COMMERCIALISATION
UNDERGROUND
ADVANCED LASER TECHNOLOGY
QUANTUM ENHANCEMENT

Gingin Gravity Precinct: testing predictions, public education

Opening the Gravity Discovery Centre

2003

Cosmology Gallery, Pendulum Tower and Leaning Tower

Sunset at the Gravity Discovery Centre

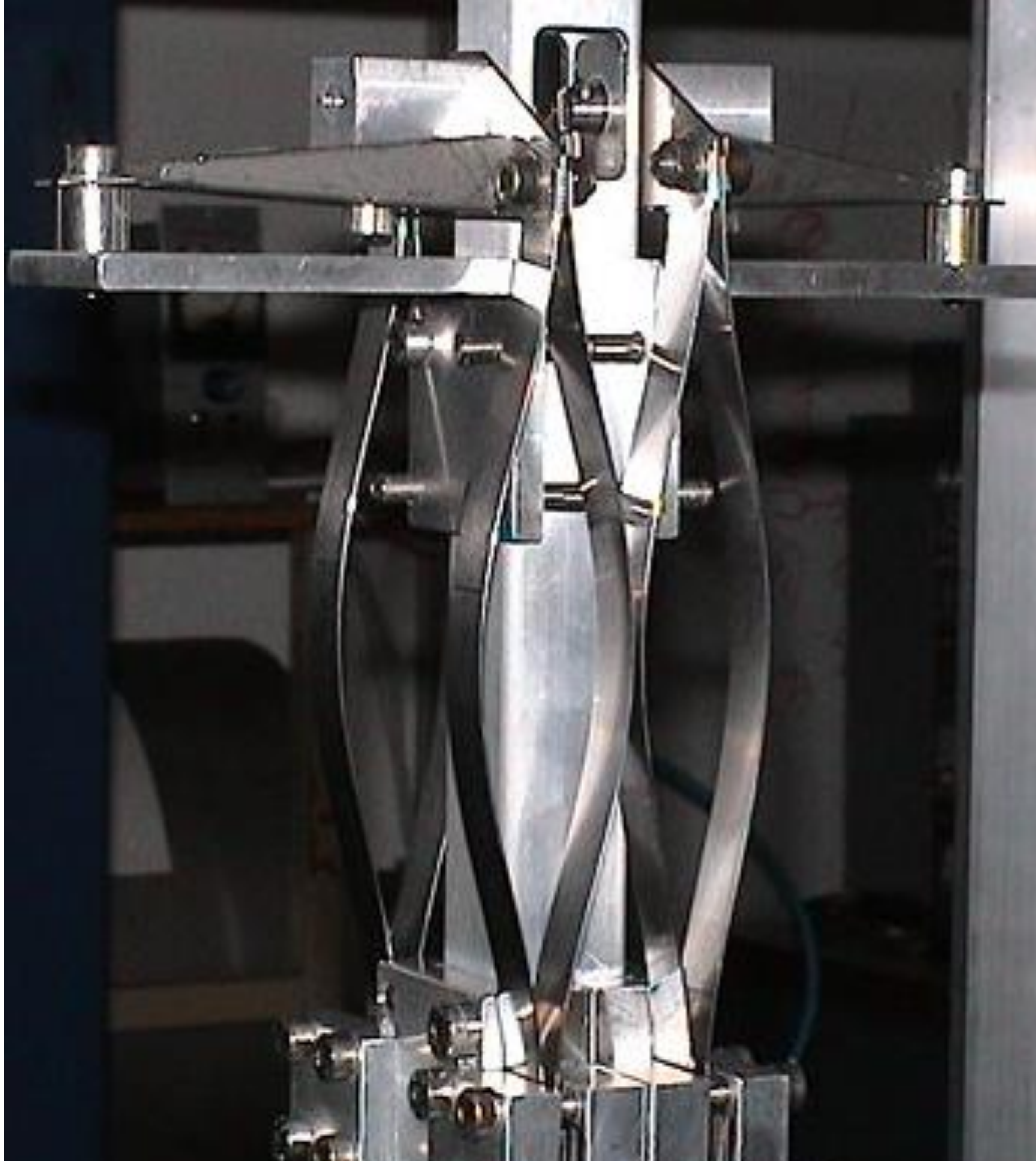
Thank You

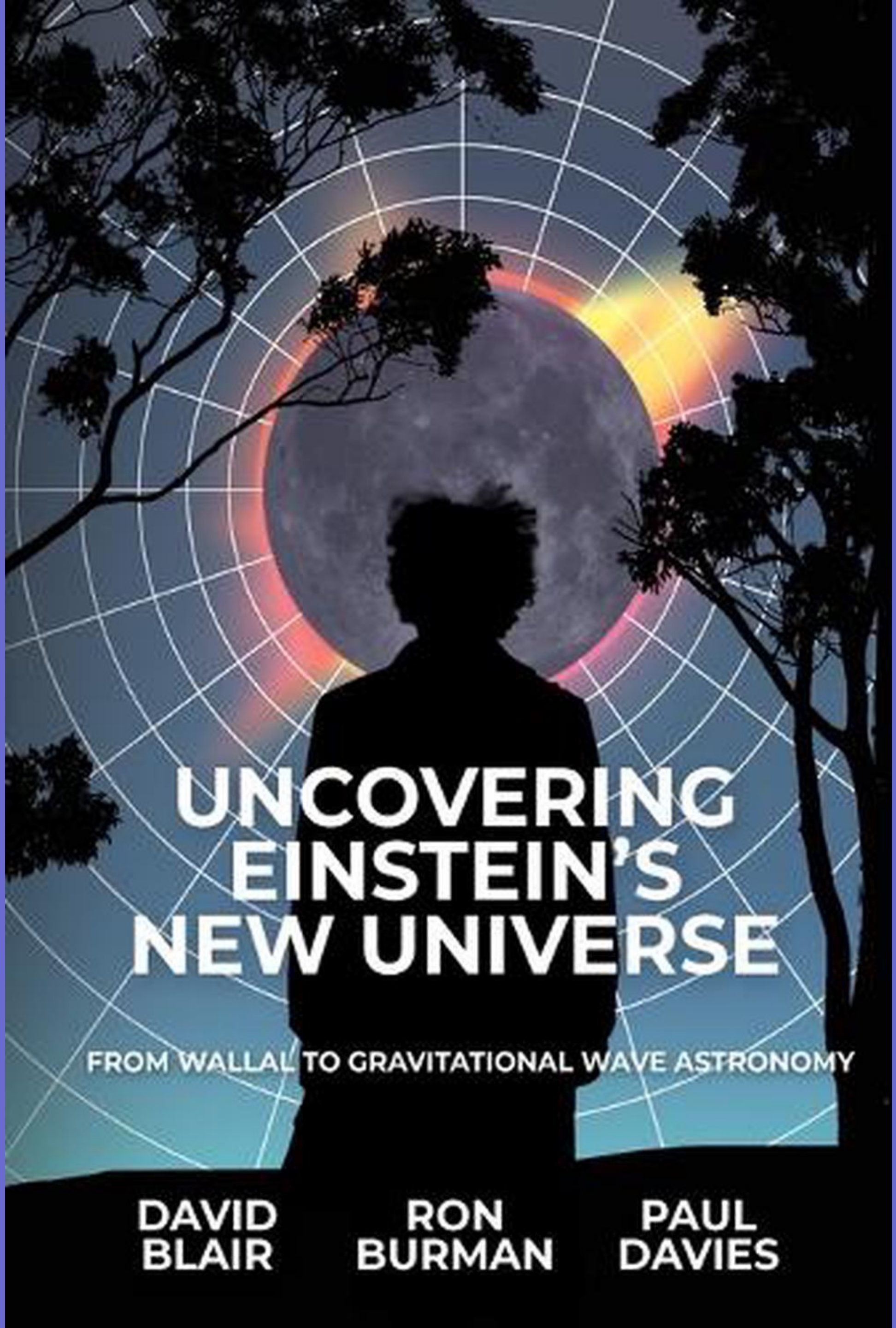
PS OzGrav was a partner in the discovery of GW in 2015

PPS OzGrav was a partnes in the discovery of the first BNS event in 2017

PPPS: Australia is actively involved with analysis of GW data and commissioning of improvements

PPPPS: There are now more than 250 active members of OzGrav and GW Astronomy has become mainstream astronomy




UNCOVERING
EINSTEIN'S
NEW UNIVERSE
FROM WALLAL TO GRAVITATIONAL WAVE ASTRONOMY
DAVID
BLAIR
RON
BURMAN
PAUL
DAVIES


BENDING
Light
SUPER
CHANNEL
Entertainment Network

Chirping gravitational waves

Zooming into the second Column, for the response of the BAR to GW170817 ($h_0 = 10^{-22}$):

$$\begin{aligned} \text{BAR detector resonance frequency}: \ f &= 150\ \text{Hz} \\ \text{Required enivironmental temperature}: &\ 1\ \text{mK} \\ \text{Required Q} - \ \text{factor}: &\ 10^{10} \\ \text{Optimal detector mass}: &\ 250\ \text{kg} \end{aligned} \tag{19}$$

What parameters have been achieved?

High Sensitivity Gravitational Wave Antenna with Parametric Transducer Readout

D. G. Blair, E. N. Ivanov, M. E. Tobar, P. J. Turner, F. van Kann, and I. S. Heng

Physics Department, University of Western Australia, Nedlands, Western Australia, 6009

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The ultracryogenic gravitational-wave detector AURIGA

M Cerdonio[1], M Bonaldi[2], D Carlesso[1], E Cavallini[3], S Caruso[1], A Colombo[1], P Falferi[2], G Fontana[4], P L Fortini[3], R Mezzena[4] + Show full author list

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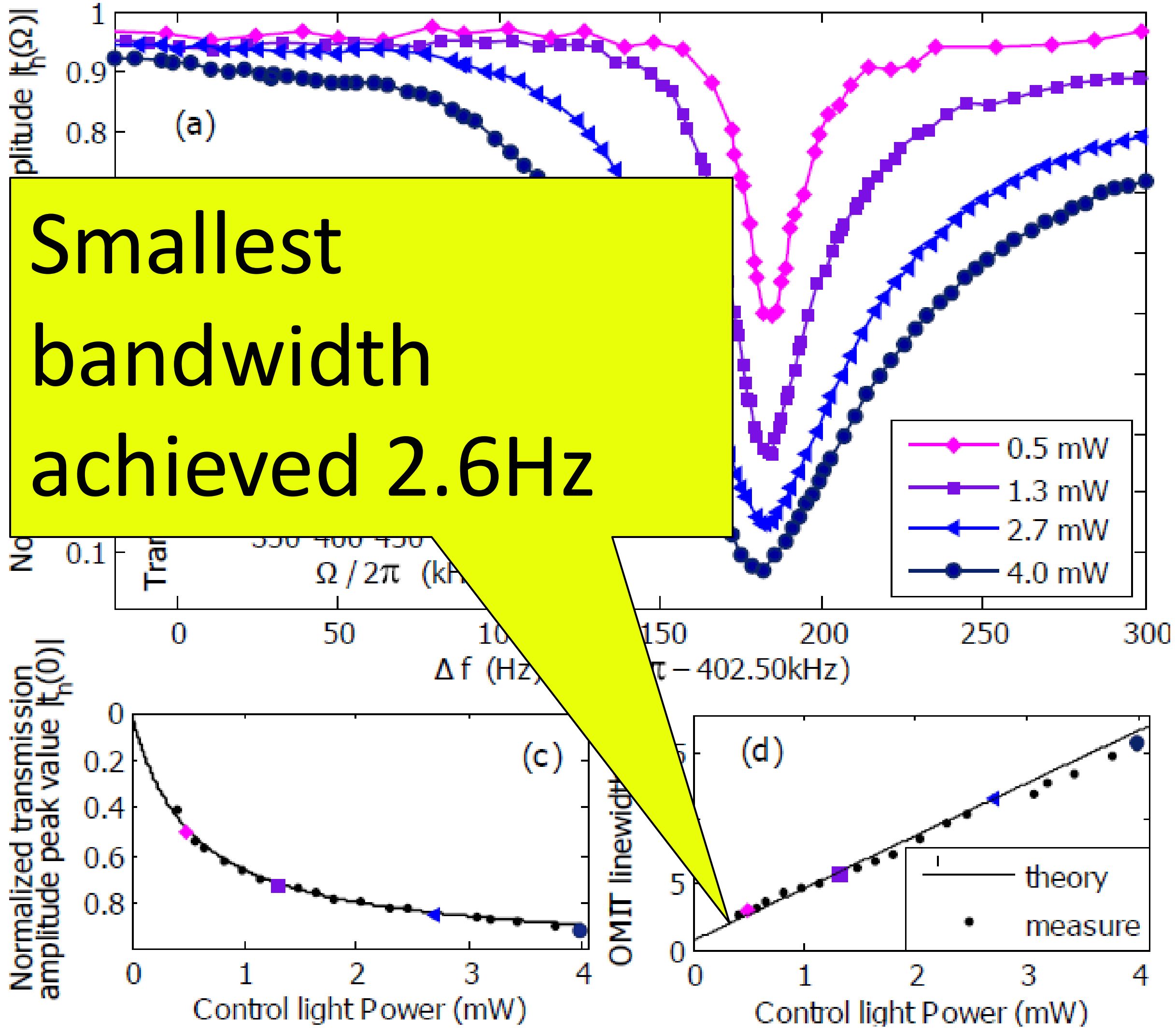
Progress towards ground state cooling of a 1.5 tonne Niobium BAR, with $Q \leftarrow 10^8$ and $f = 700$ Hz

Opto-mechanically induced transparency creates ultra-narrow band cavity

- Q-factor ~ 2 x 10^{14}



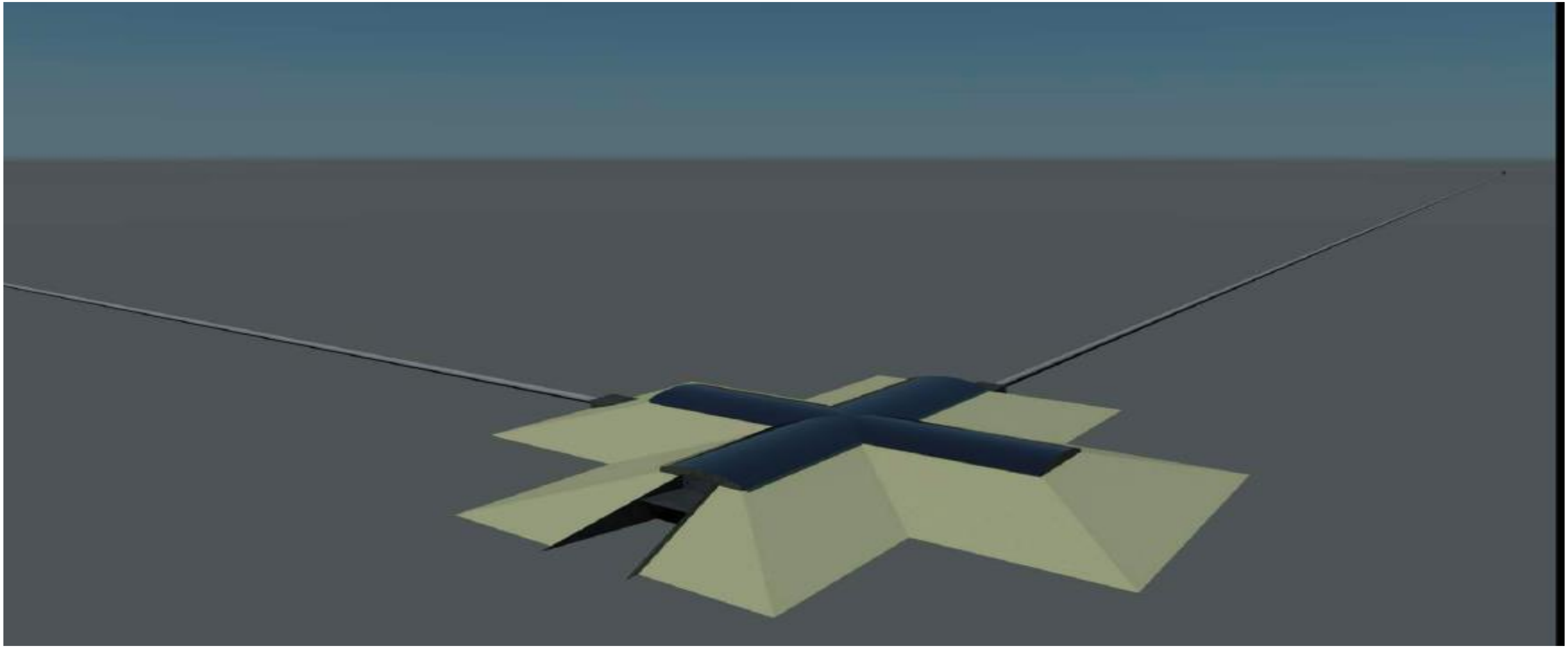
Conclusion

- GW detection has entered a new paradigm: detecting predicted sources.
- Parametric instability will limit sensitivity but already we are at the one event per year sensitivity level.
- Opto-mechanics offers exciting new solutions if we can achieve the optical dilution predicted.
- Many interesting sensor applications of 3-mode interactions

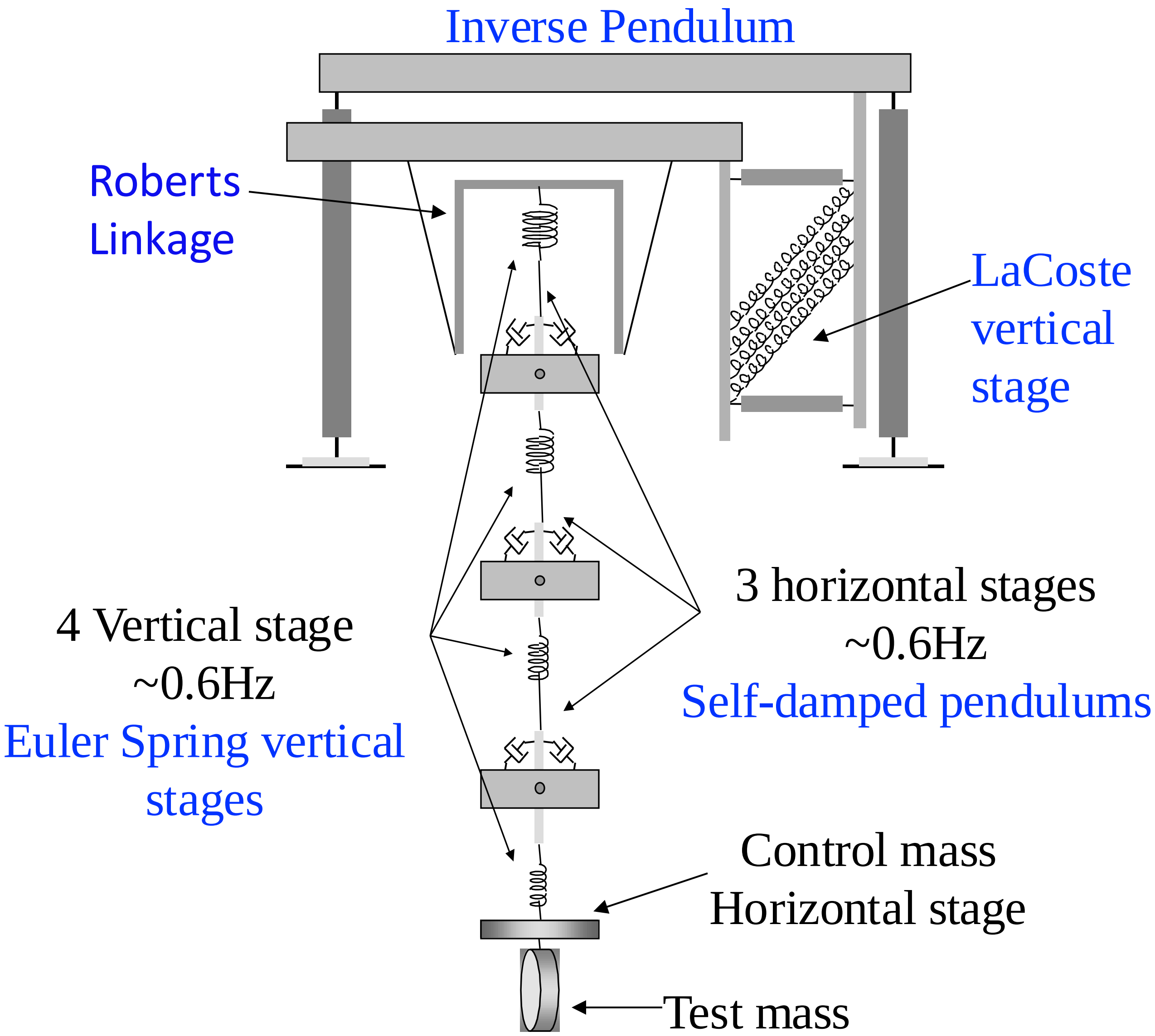
AIGO Development

- 1998: 50 Km^2 AIGO site provided by West Australian Government
- 2001-2008: Independent Foundation builds the Gravity Discovery Centre.
- 2001-2005: Australian Consortium ACIGA develops infrastructure, site studies, 80m research interferometer, site protection.
- 2010: International community sets AIGO as first priority for the field. (GWIC 30-year Roadmap)
- 2009 -2012: International planning meetings in China (3), Europe, Australia (2)

AIGO

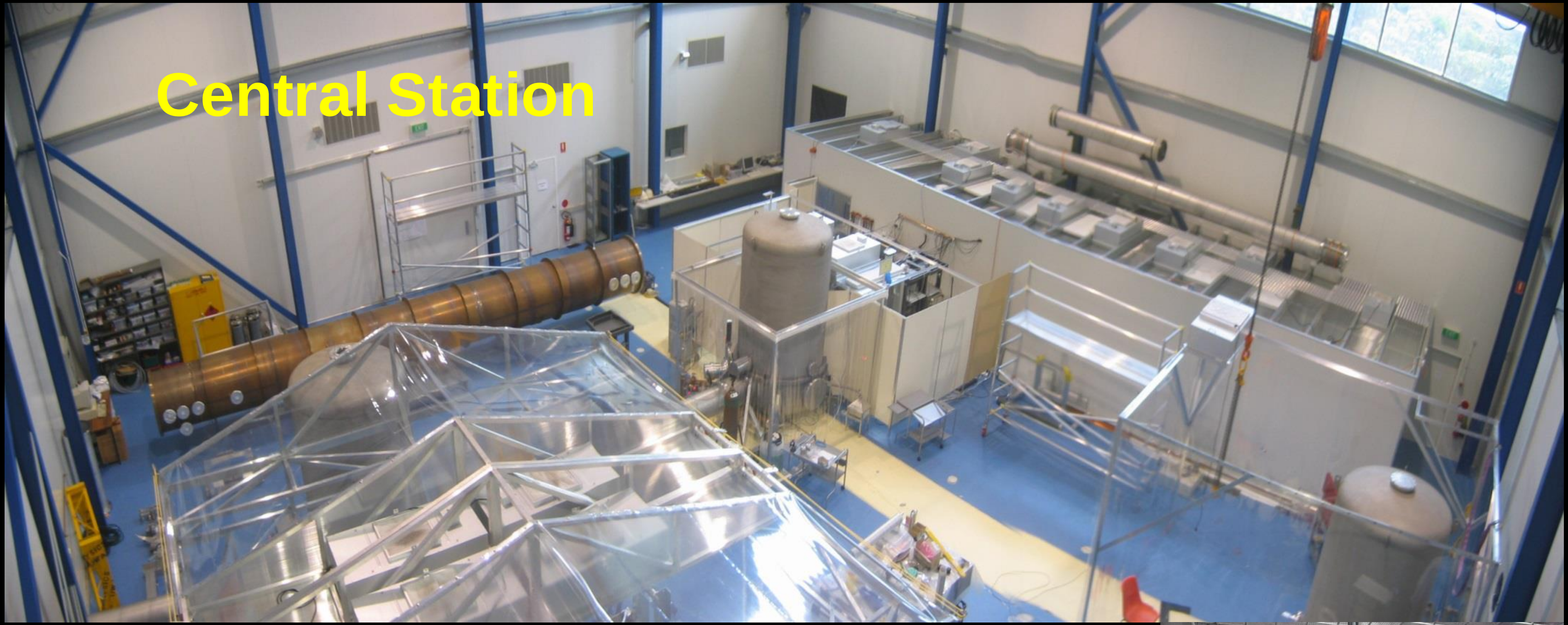


UWA Vibration isolation System

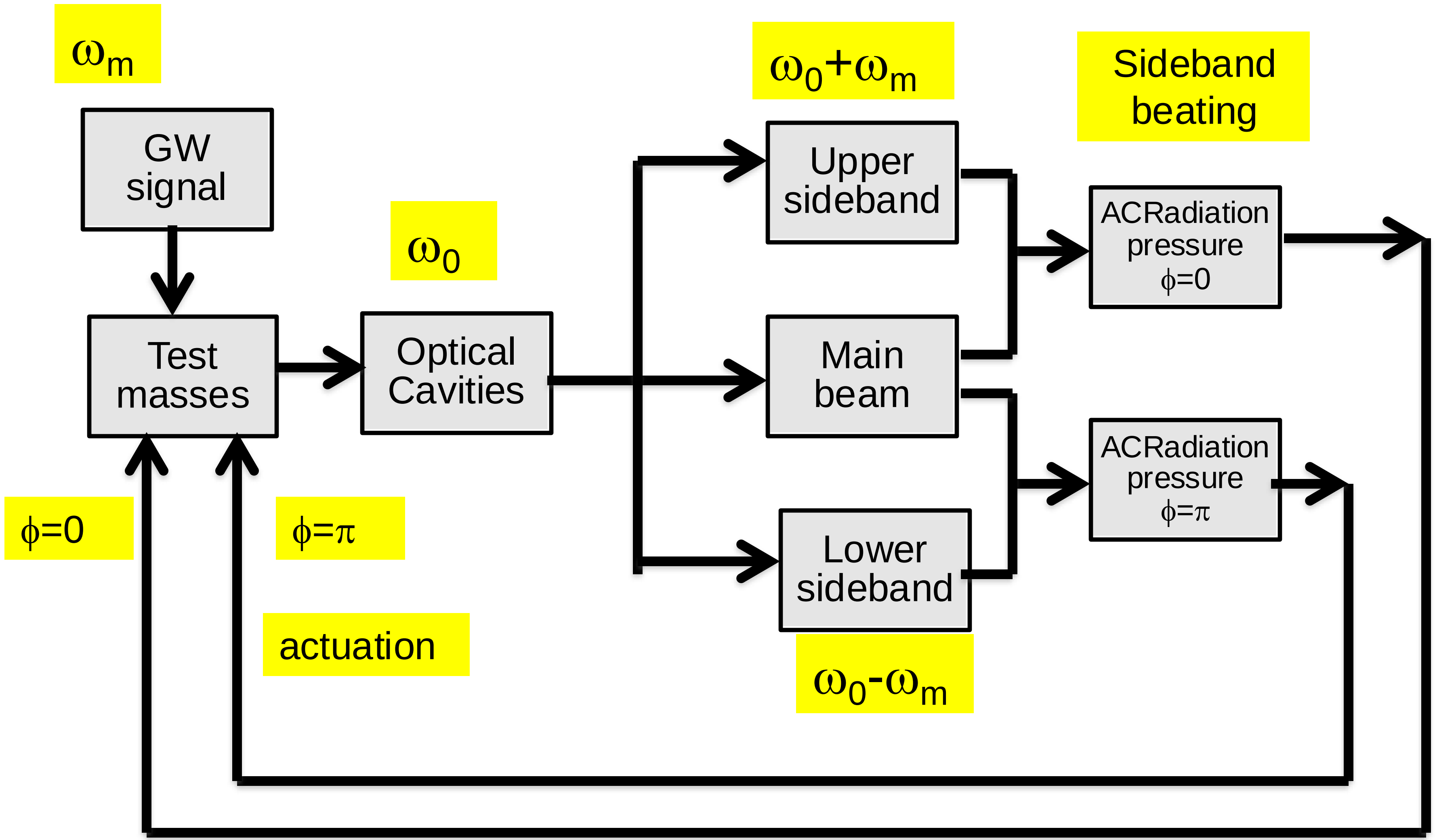


Site in Wallingup Sand plain

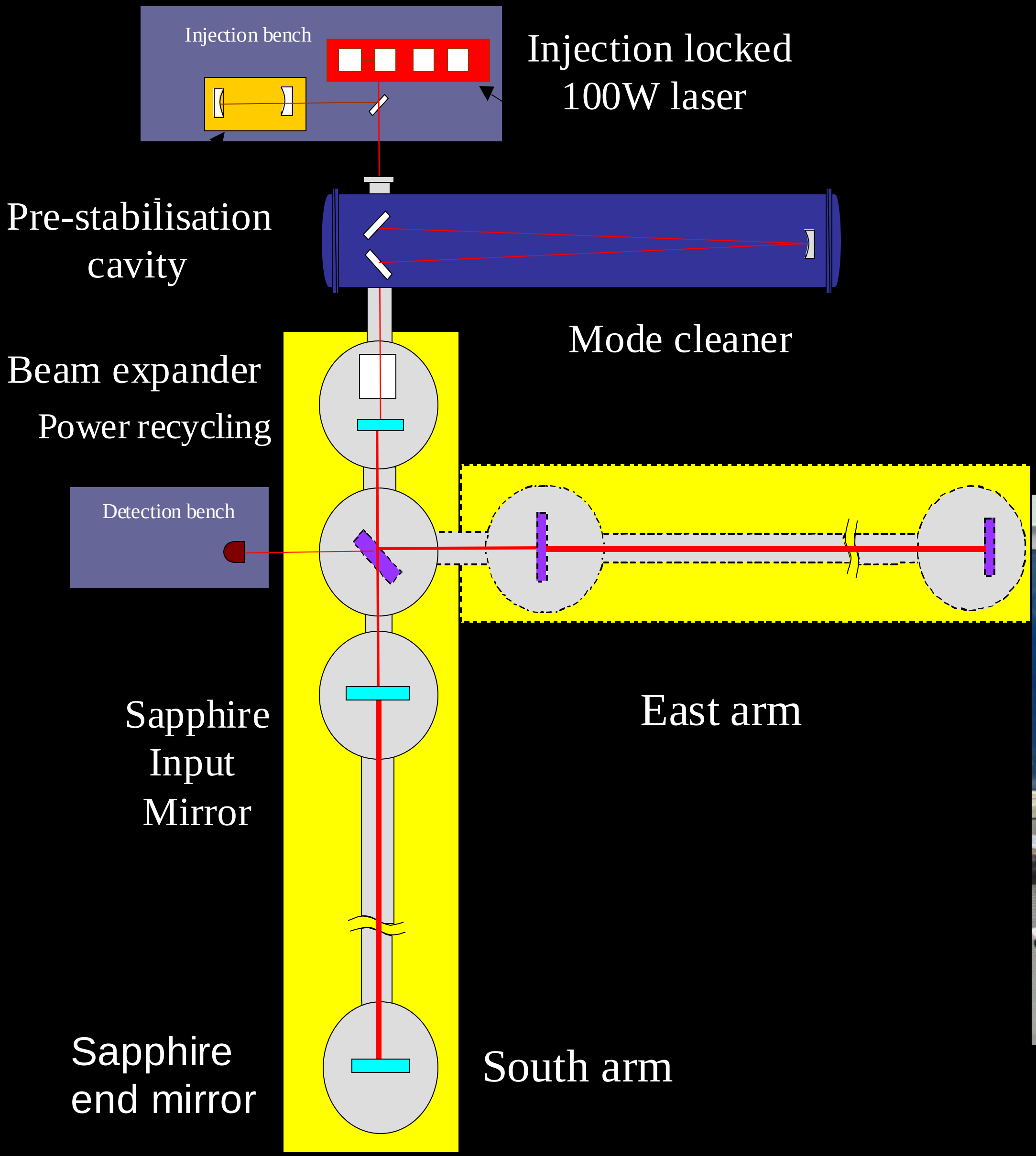
Central Station



GW Transducer Feedback



AIGO High Optical Power Test Facility



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