Laser Interferometer Gravitational-wave Detectors: Advancing toward a Global Network

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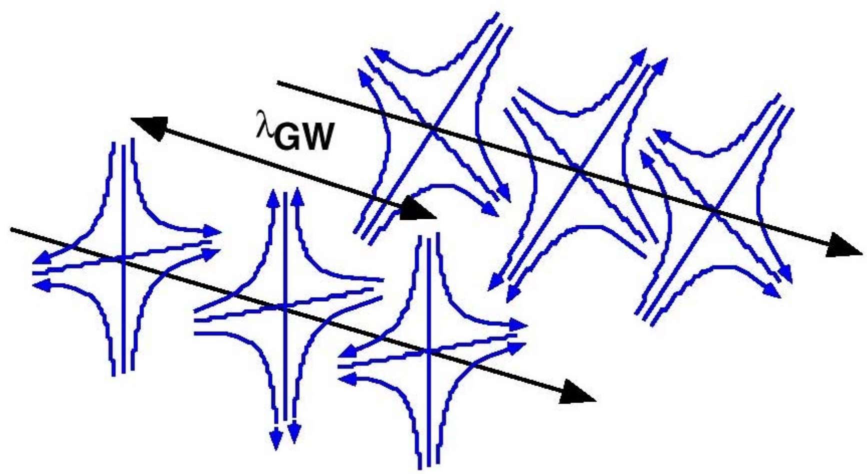
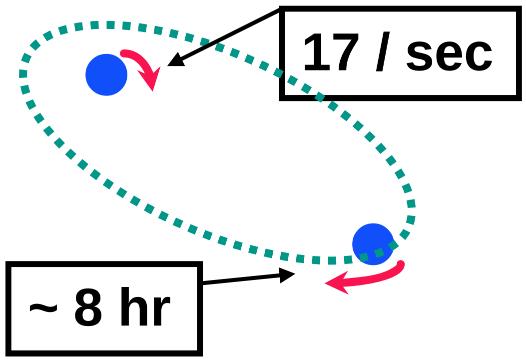
Gravitational Wave Physics

- Einstein (in 1916) recognized gravitational waves in his theory of General Relativity
  - » Necessary consequence of Special Relativity with its finite speed for information transfer
  - » Most distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by the acceleration of masses
  - » Propagate away from the sources at the speed of light
  - » Pure transverse waves
  - » Two orthogonal polarizations

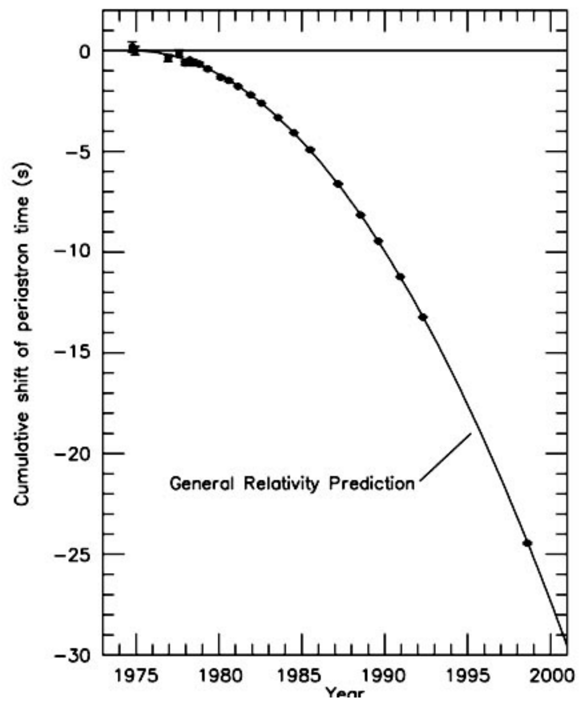


$$h = \Delta L / L$$

Evidence for Gravitational Waves:
Binary Pulsar PSR1913+16



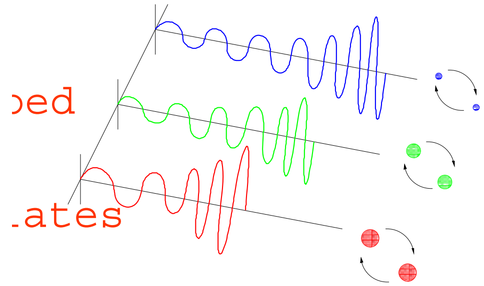
- Discovered by Hulse and Taylor in 1975
- Unprecedented laboratory for studying gravity
  - » Extremely stable spin rate
- Possible to repeat classical tests of relativity (bending of "starlight", advance of "perihelion", etc.



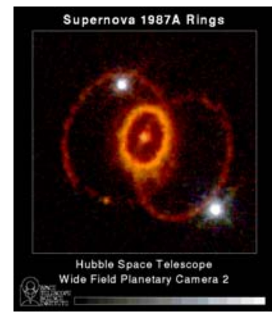
- After correcting for all known relativistic effects, observe loss of orbital energy
=> Emission of GWs

Astrophysical Sources for Terrestrial GW Detectors

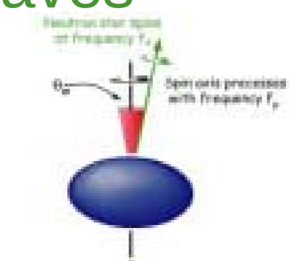
- Compact binary inspiral: "chirps"
  - » **NS-NS, NS-BH, BH-BH**



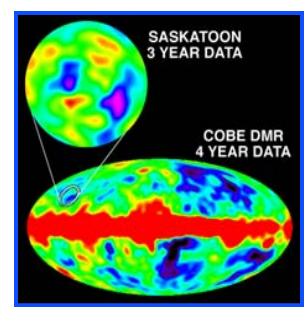
- Supernovas or long GRBs: "bursts"
  - » **GW signals observed in coincidence with EM or neutrino detectors**



- Pulsars in our galaxy: "periodic waves"
  - » **Rapidly rotating neutron stars**
  - » **Modes of NS vibration**



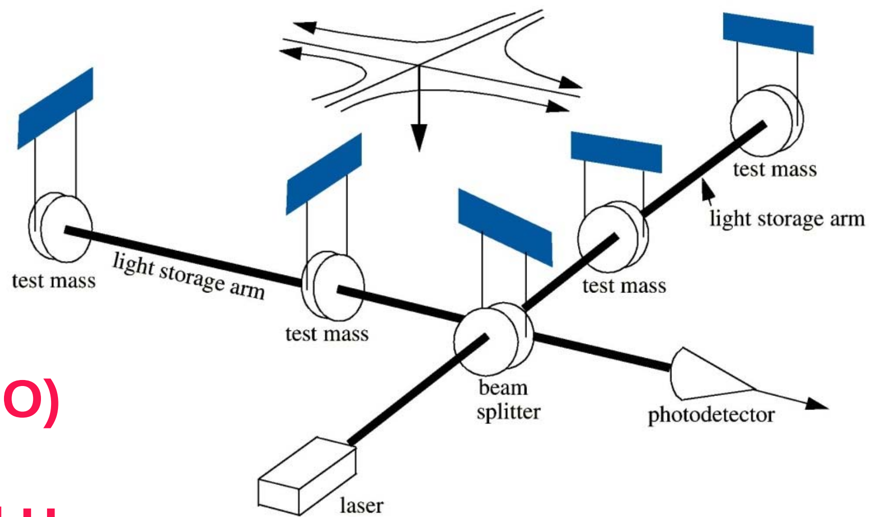
- Cosmological: "stochastic background"
  - » **Probe back to the Planck time (10^{-43} s)**



Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies f >> f_{pend}

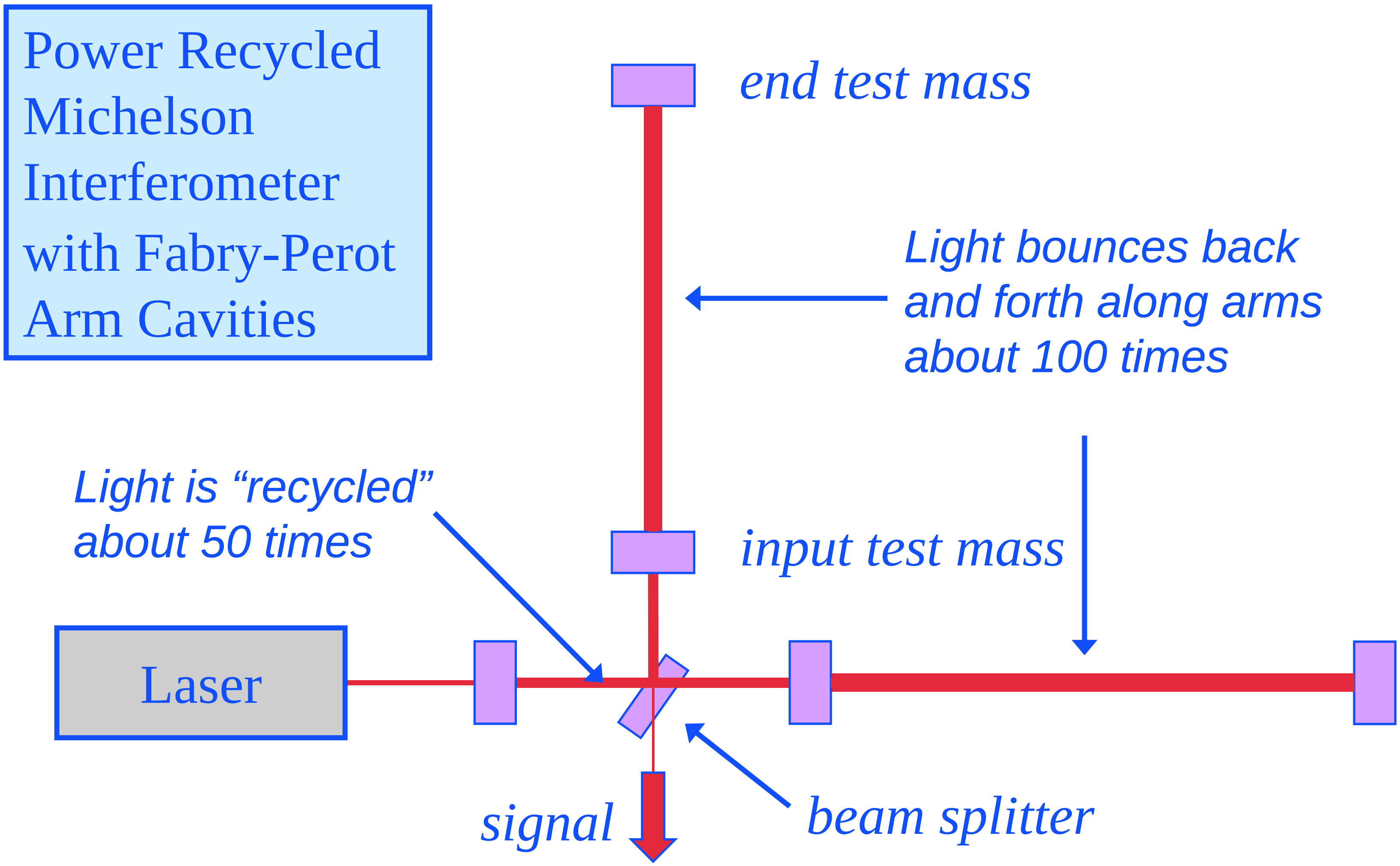
$$h = \Delta L / L$$



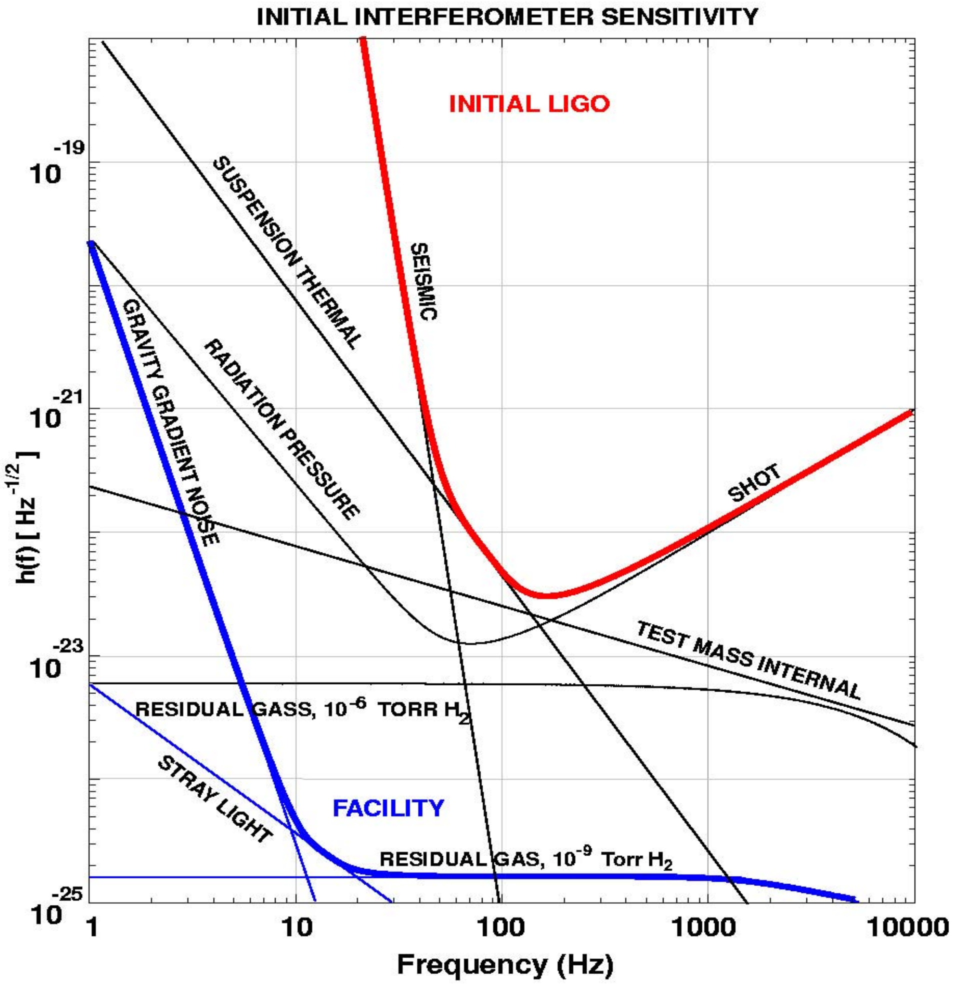
Terrestrial detector,
L ~ 4 km
For h ~ 10^{-22} – 10^{-21} (Initial LIGO)
ΔL ~ 10^{-18} m
Useful bandwidth 10 Hz to 10 kHz, determined by "unavoidable" noise (at low frequencies) and expected maximum source frequencies (high frequencies)

Laser Interferometer Gravitational-wave Observatory (LIGO)

LIGO Optical Configuration

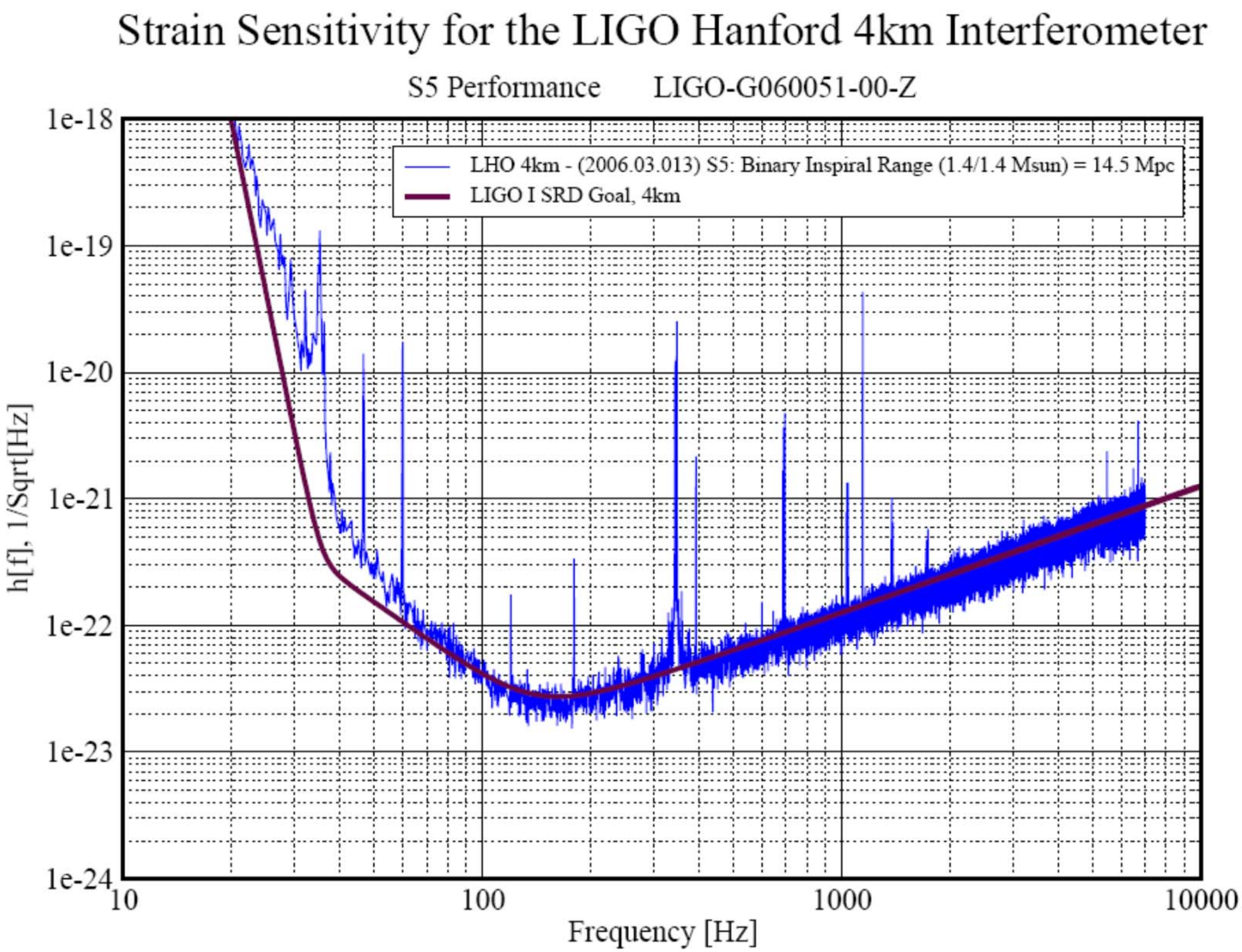


Initial LIGO Sensitivity Goal



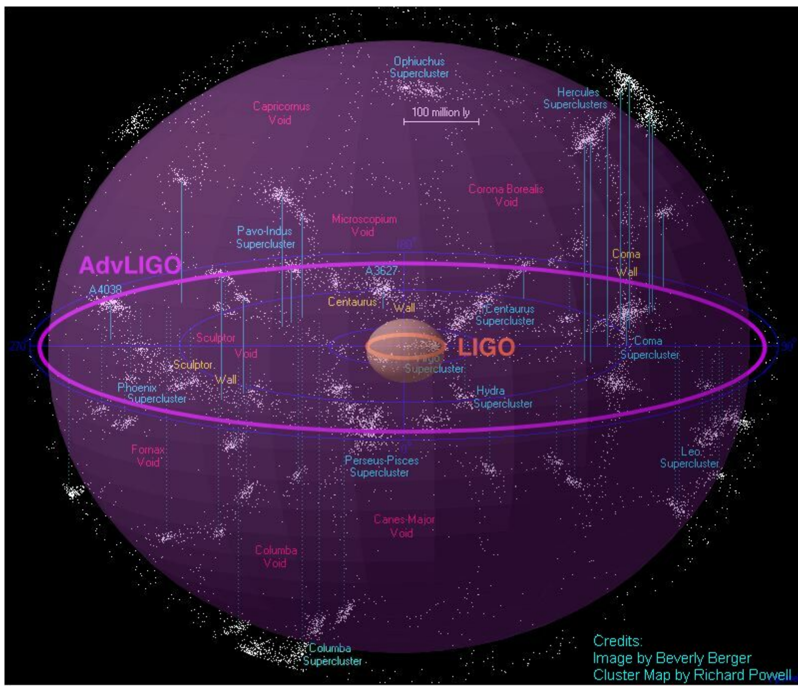
- Strain sensitivity $<3\times10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

LIGO Sensitivity



What's next for LIGO? Advanced LIGO

- Take advantage of new technologies and on-going R&D
  - » Active anti-seismic system operating to lower frequencies
  - » Lower thermal noise suspensions and optics
  - » Higher laser power
  - » More sensitive and more flexible optical configuration



x10 better amplitude sensitivity

$\Rightarrow$ x1000 rate=(reach)^3

$\Rightarrow$ 1 day of Advanced LIGO

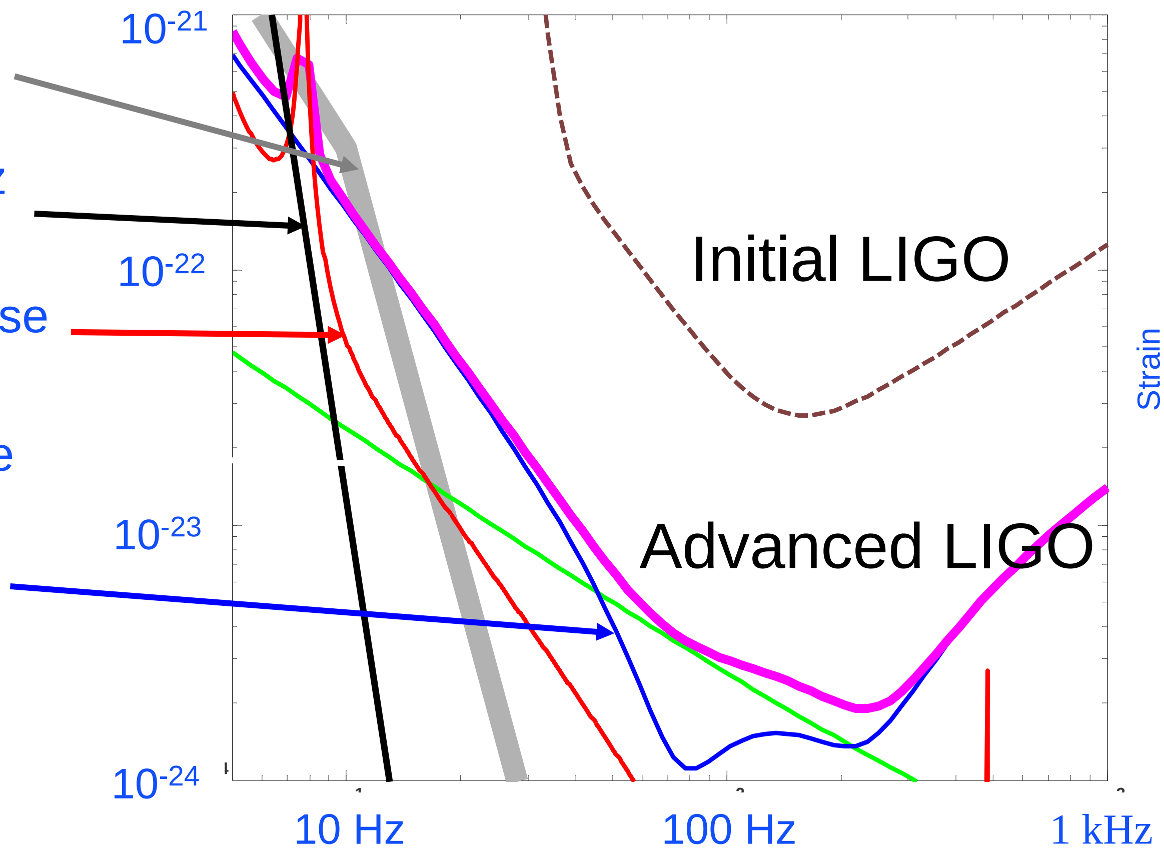
» 1 year of Initial LIGO !

Advanced LIGO: Big Picture

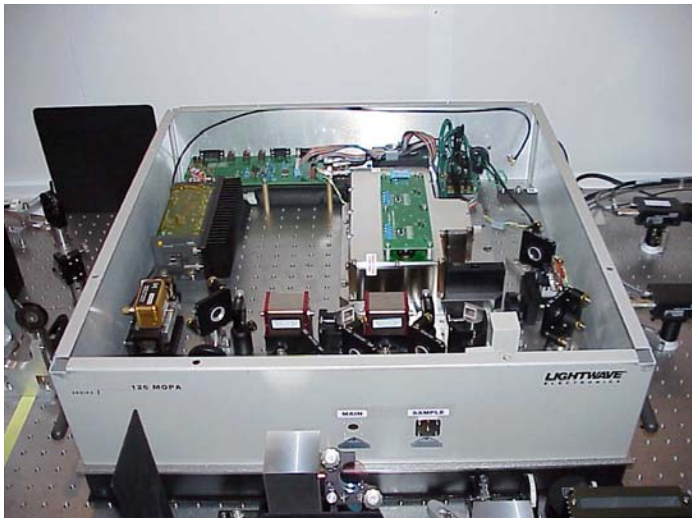
- Advanced LIGO design begins ~1999, just about finished
- Construction project started April 2008, completes in 2015
- Enthusiastically supported by the National Science Foundation
- Costs: $205 million from the NSF,
  plus contributions from UK, Germany, Australia
- Complete replacement of detectors at Livingston and Hanford
  - » Improved technology for increased sensitivity

Advanced LIGO Performance

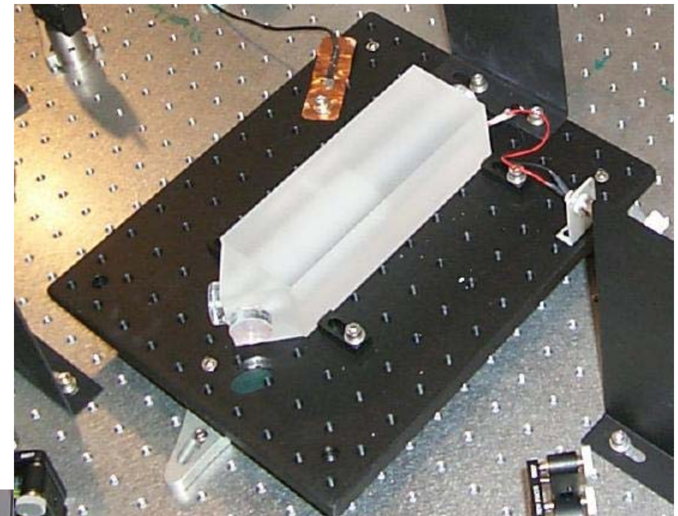
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Quantum noise dominates at most frequencies



Initial LIGO Laser



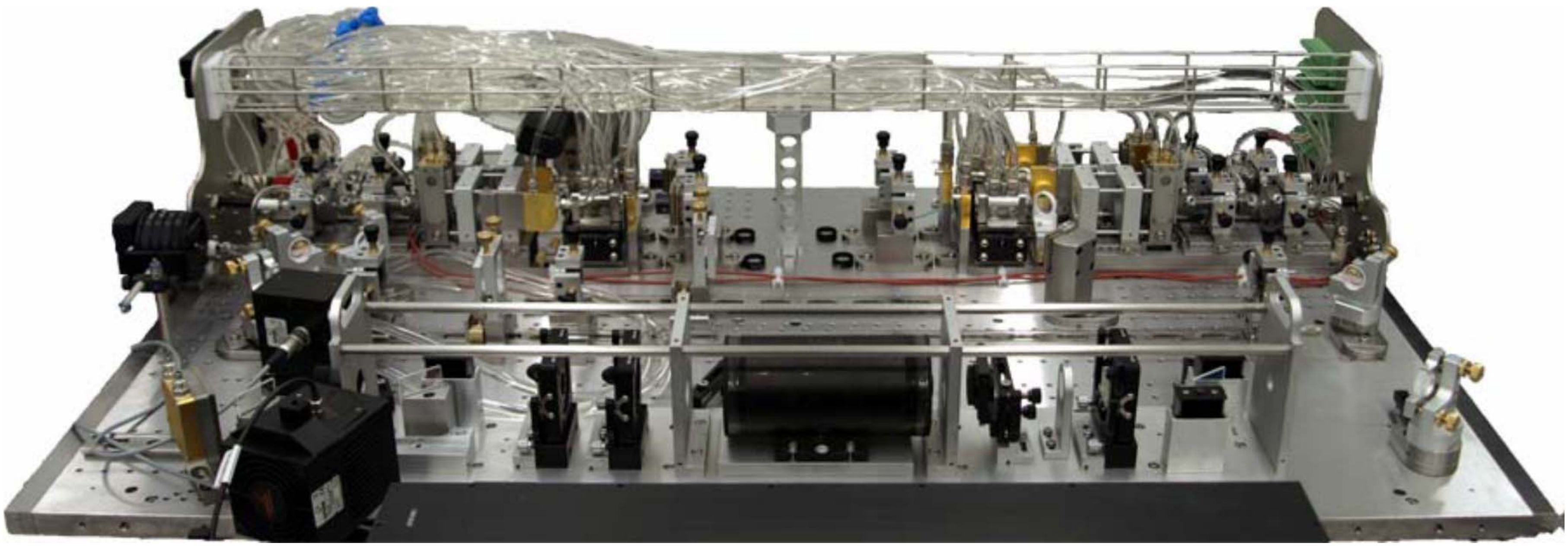
Custom-built
10 W
Nd:YAG
Laser



Stabilization
cavities
for frequency
and beam shape

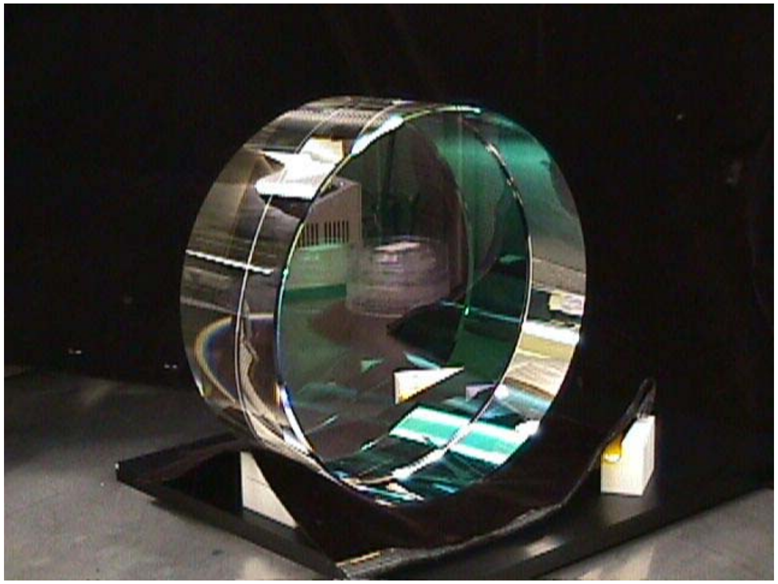
Advanced LIGO Laser

- Designed and contributed by Albert Einstein Institute
- Higher power
  - » 10W -> 180W
- Better stability
  - » 10x improvement in intensity and frequency stability

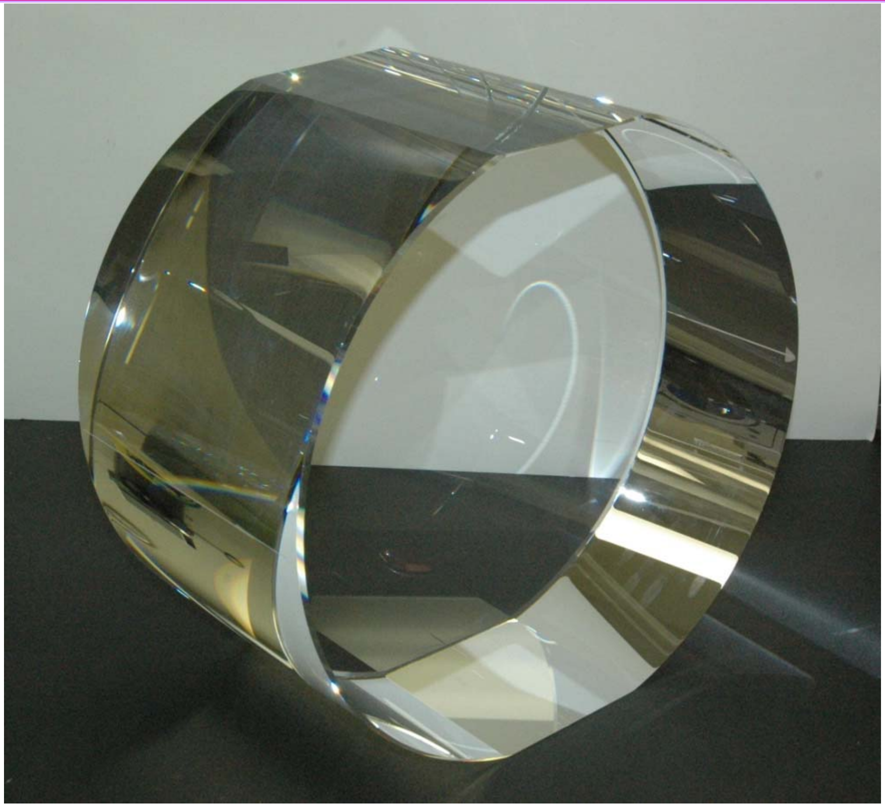


Initial LIGO Mirrors

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms (λ / 1000)
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}
- Production involved 5 companies, CSIRO, NIST, and LIGO



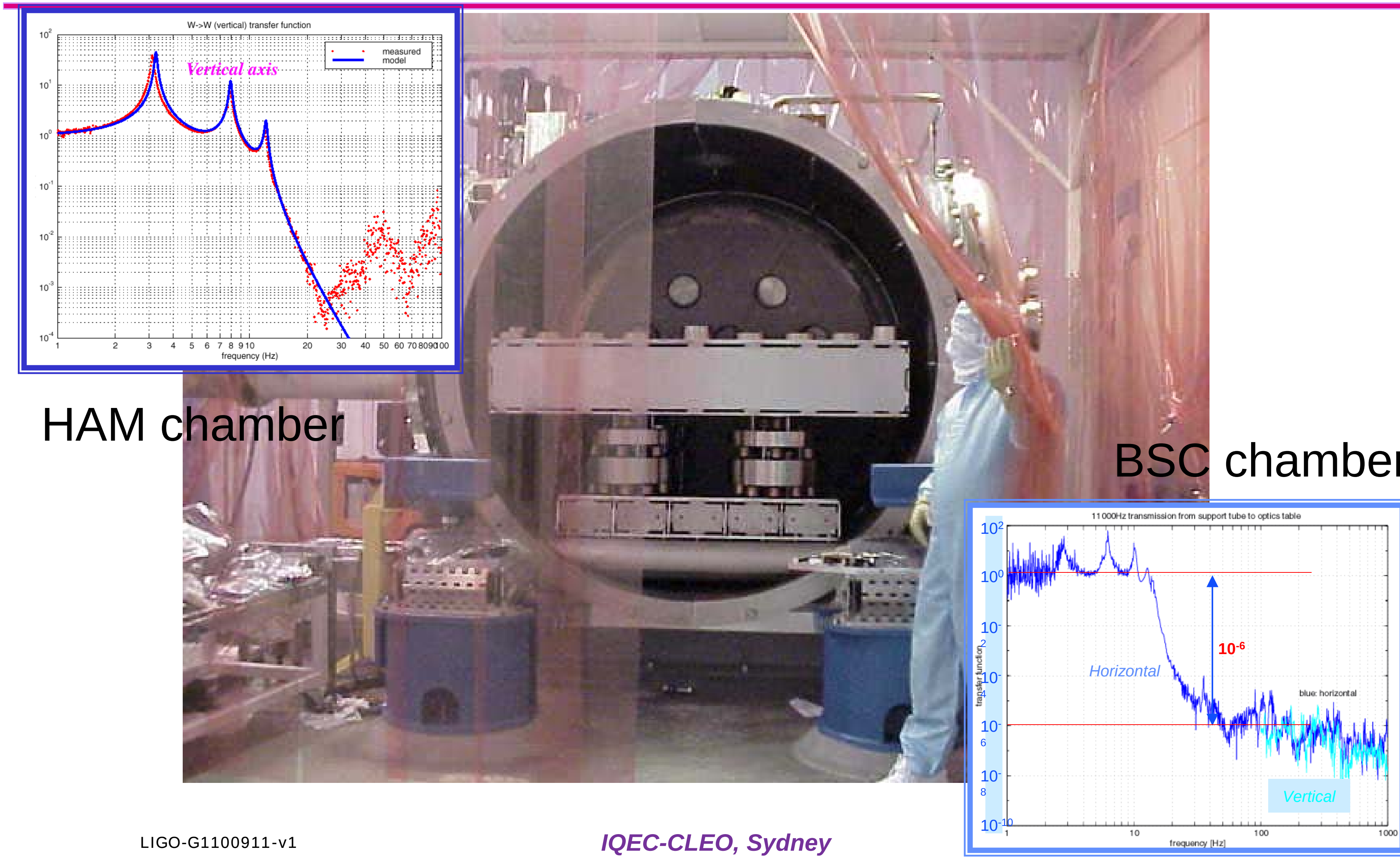
Advanced LIGO Mirrors



- Larger size
  - » 11 kg -> 40 kg
- Smaller figure error
  - » 0.7 nm -> 0.35 nm
- Lower absorption
  - » 2 ppm -> 0.5 ppm
- Lower coating thermal noise

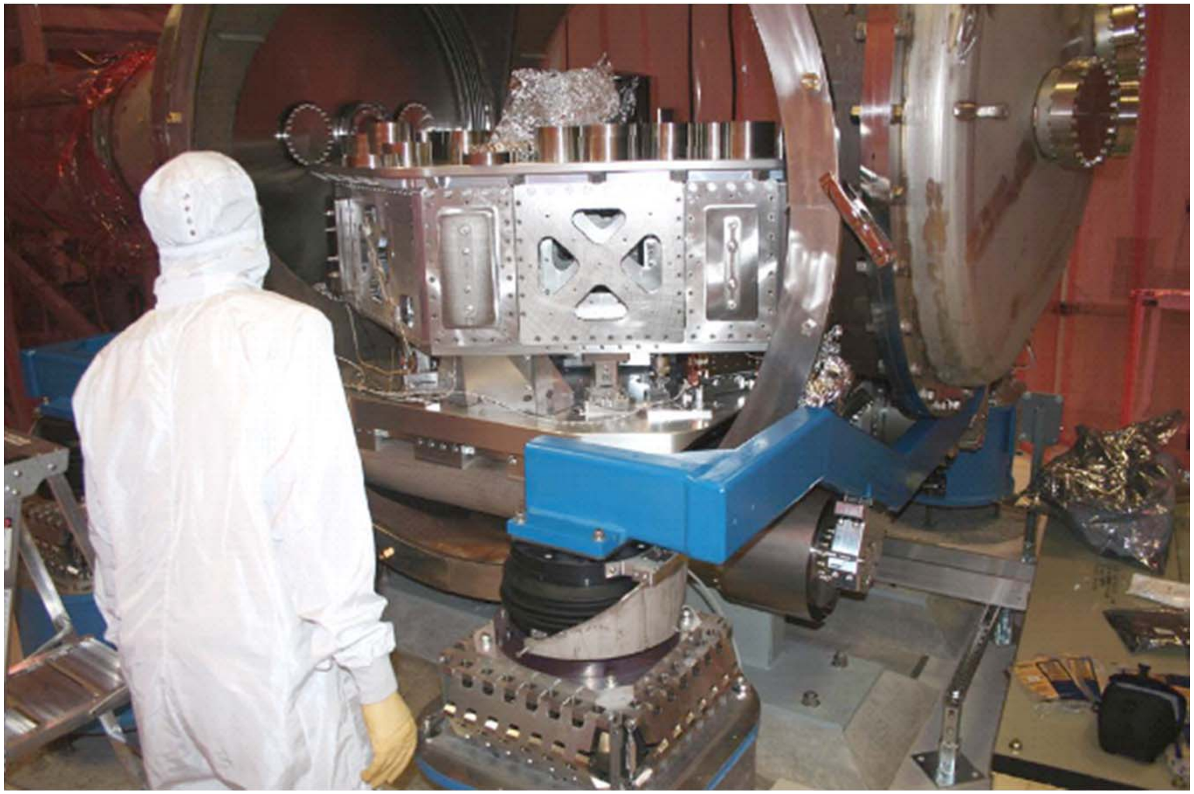
- All substrates delivered
- Polishing underway
- Reflective Coating process starting up

Initial LIGO Vibration Isolation



Advanced LIGO Seismic Isolation

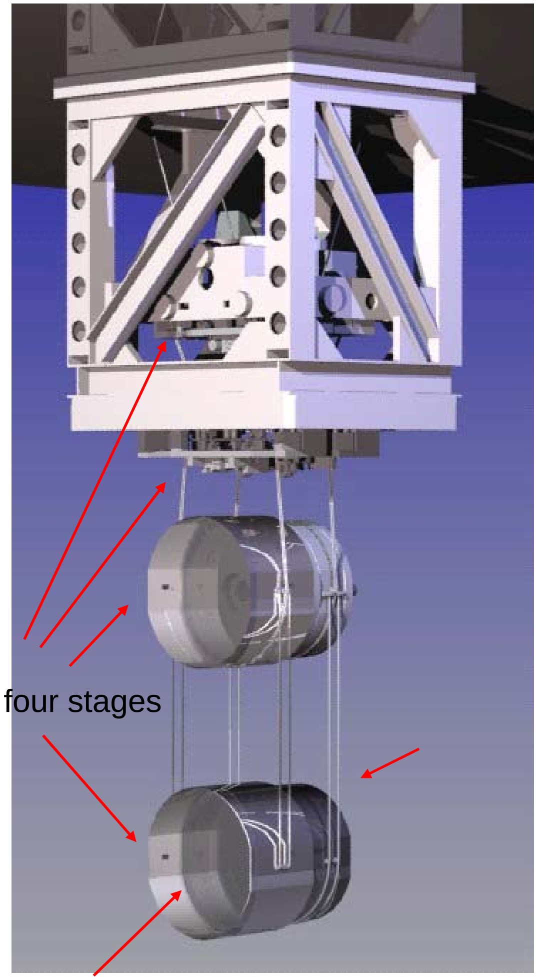
- Two-stage six-degree-of-freedom active isolation
  - » Low noise sensors, Low noise actuators
  - » Digital control system to blend outputs of multiple sensors, tailor loop for maximum performance
  - » Low frequency cut-off: 40 Hz -> 10 Hz



Initial LIGO Test Mass Suspension

- Simple single-loop pendulum suspension
- Low loss steel wire
  - » Adequate thermal noise performance, but little margin
- Magnetic actuators for control

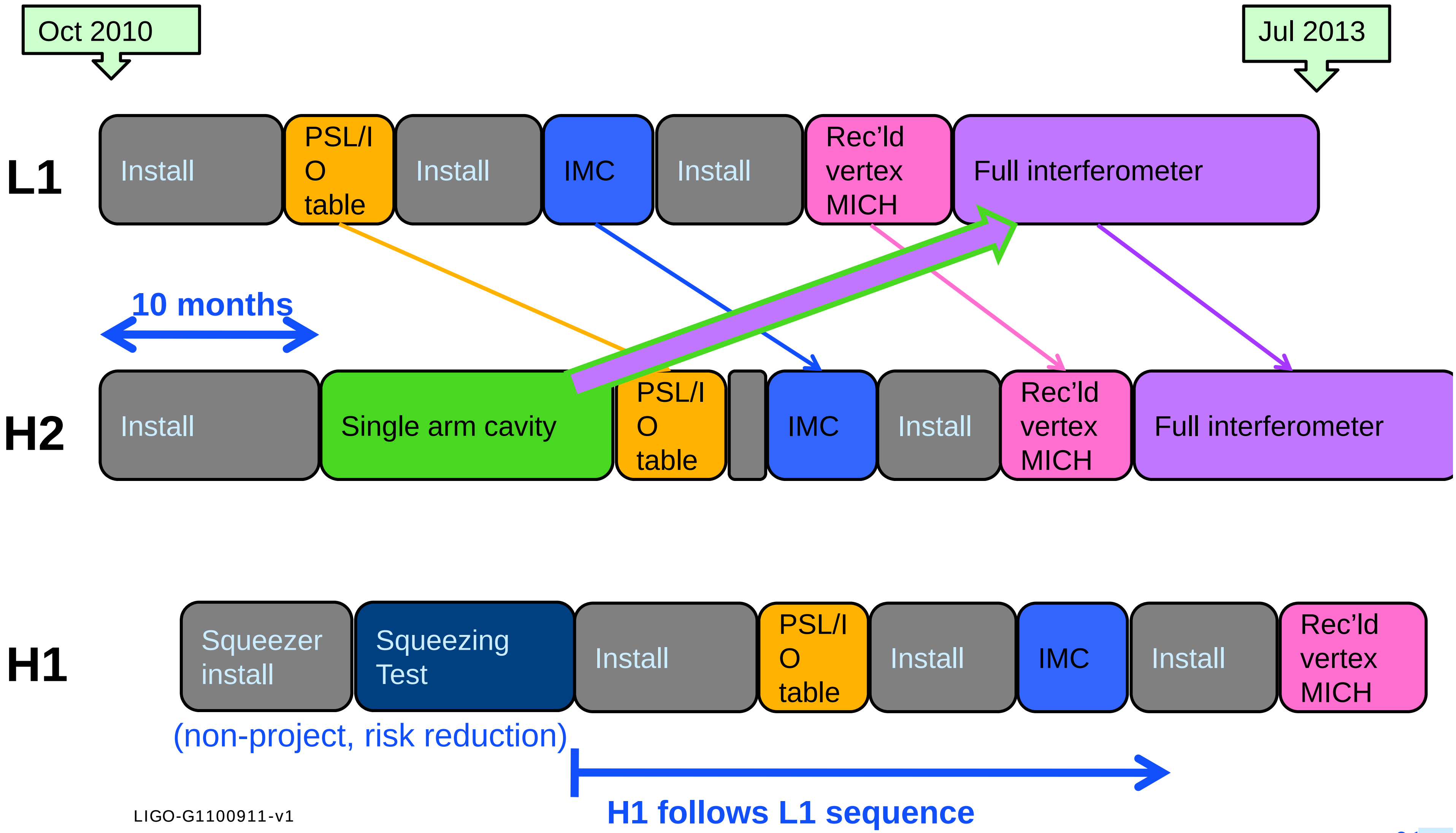
Advanced LIGO Suspensions



40 kg silica
test mass

- UK designed and contributed test mass suspensions
- Silicate bonds create quasi-monolithic pendulums using ultra-low loss fused silica fibers to suspend interferometer optics
  - » Pendulum Q ~10^5 -> ~10^8
- Electrostatic actuators for alignment and length control

Install and Integration sequence



Beyond Advanced LIGO

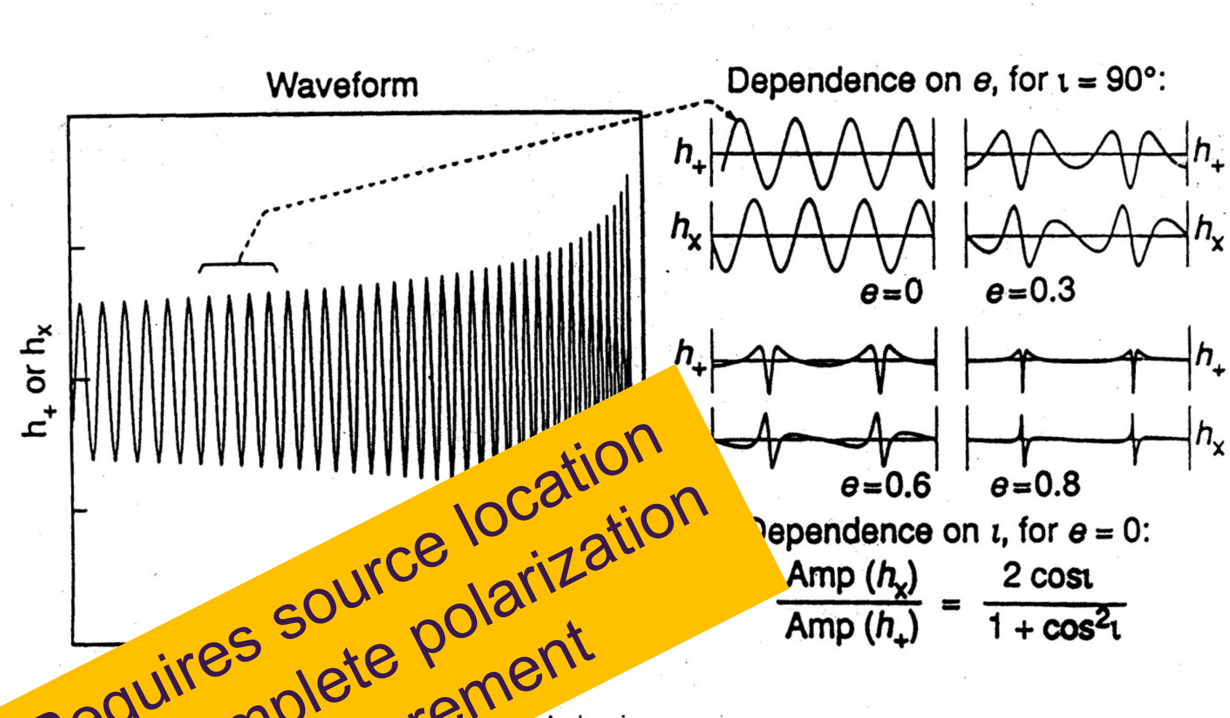
Future detectors will require much further development

- Squeezed light, entanglement, macroscopic quantum mechanical techniques
- Unconventional optics: gratings, cryogenic optics, new shapes
- New materials for substrates and coatings
- New interferometer configurations
- Lasers: higher power, greater stability, new wavelengths

Using GWs to Learn about the Sources: an Example

Chirp Signal

binary inspiral

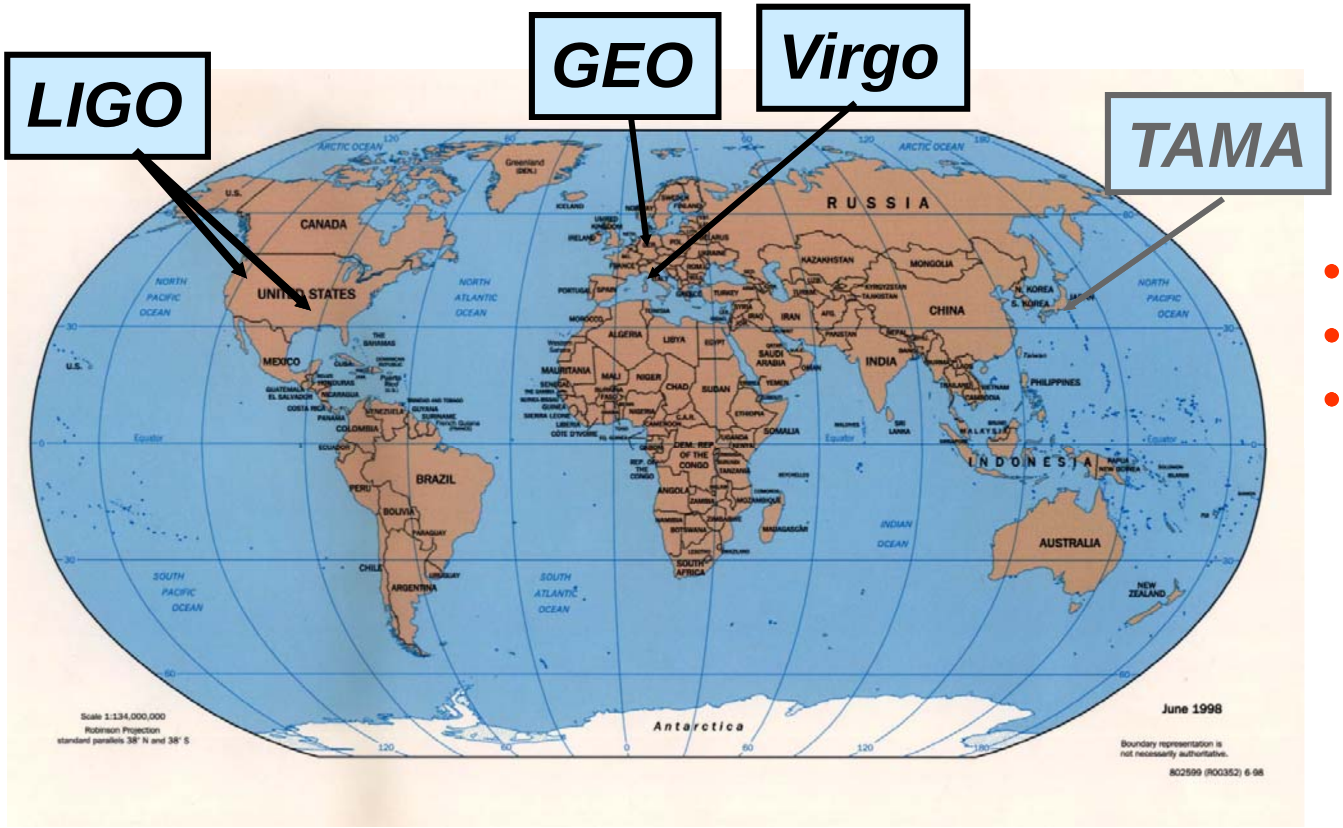


Requires source location and complete polarization measurement

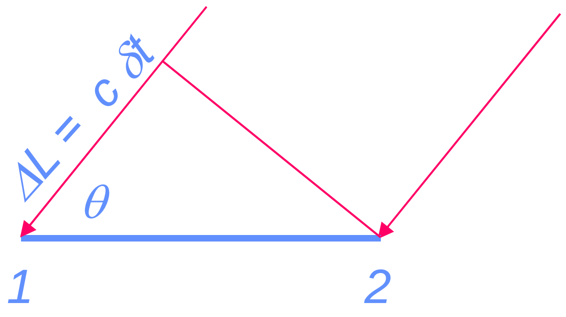
ermine

- **Dist... om the earth r**
- **Mass... of the two bodies**
- **Orbital eccentricity e and orbital inclination *i***

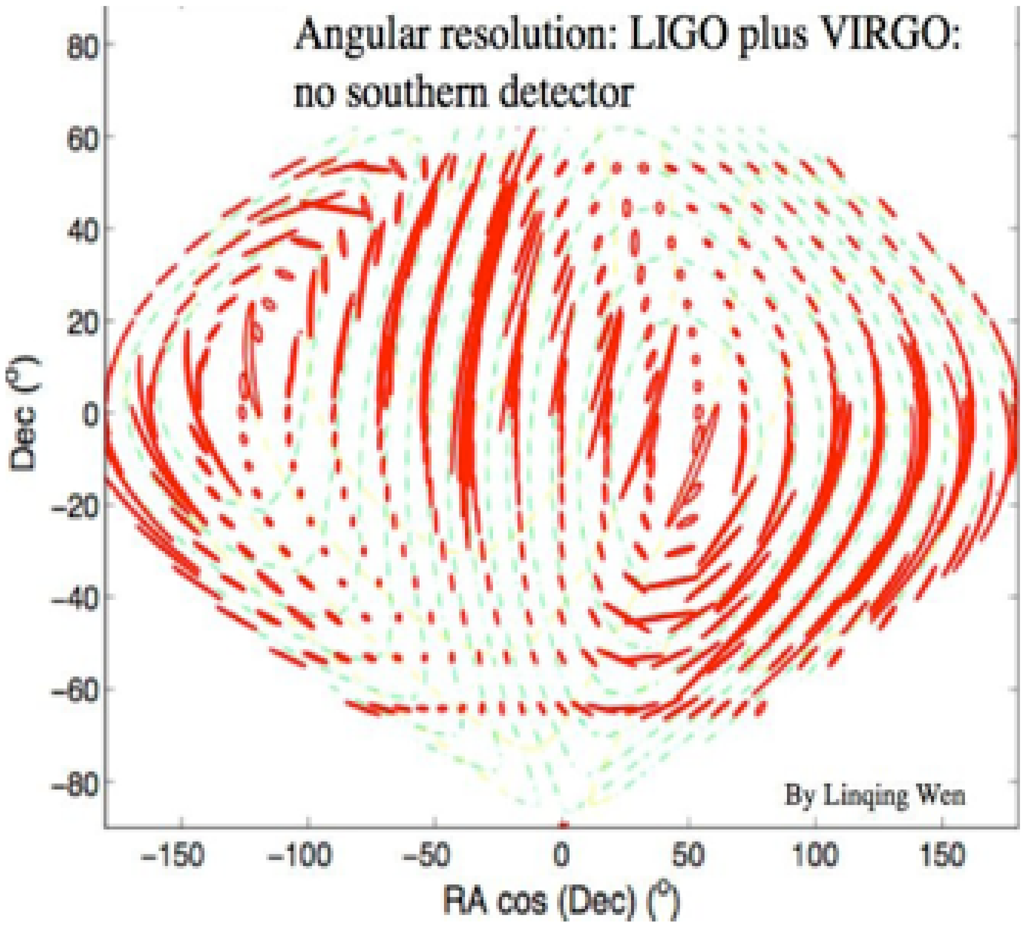
A Global Network of GW Detectors 2009



- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves

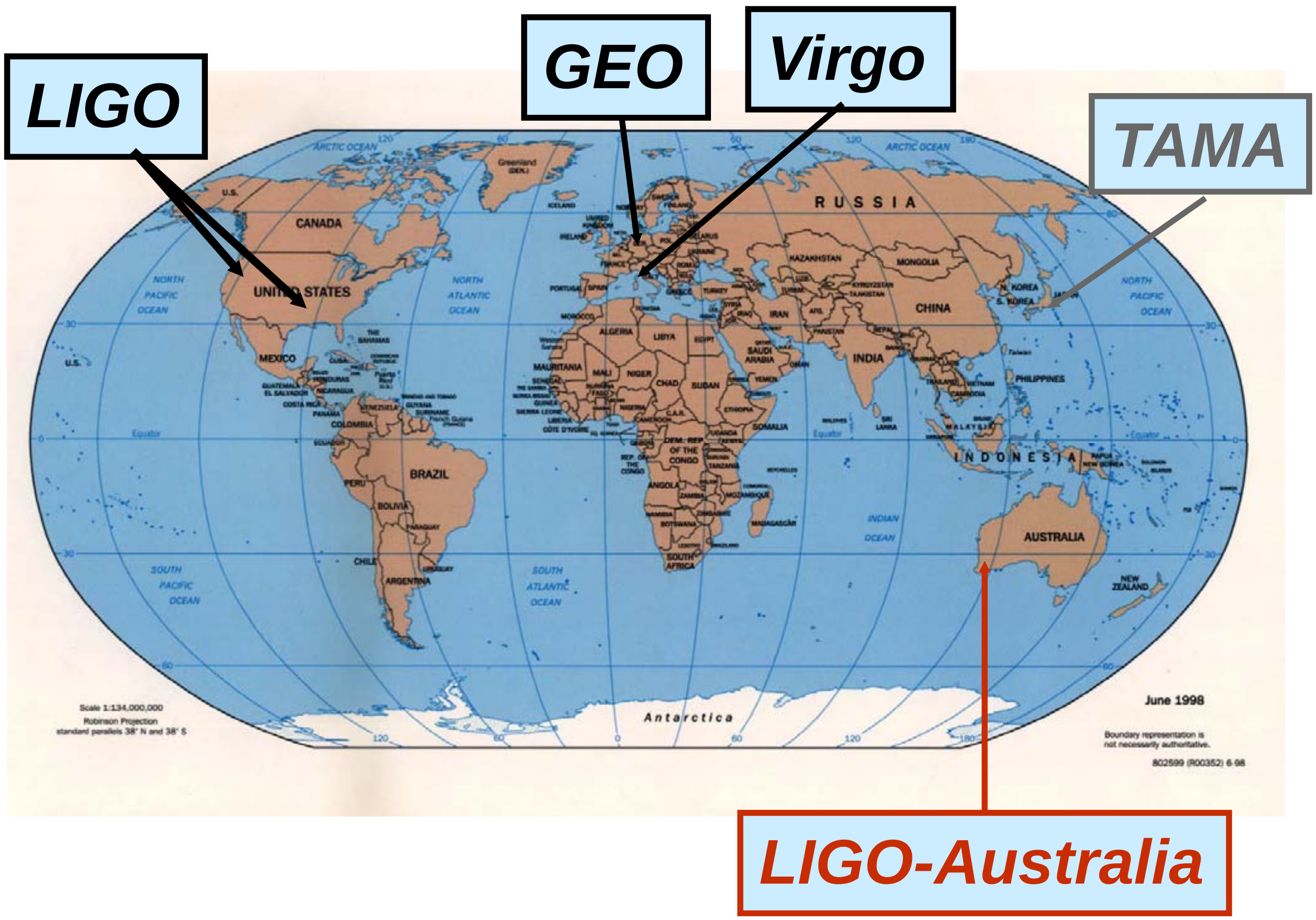


LIGO and Virgo Alone



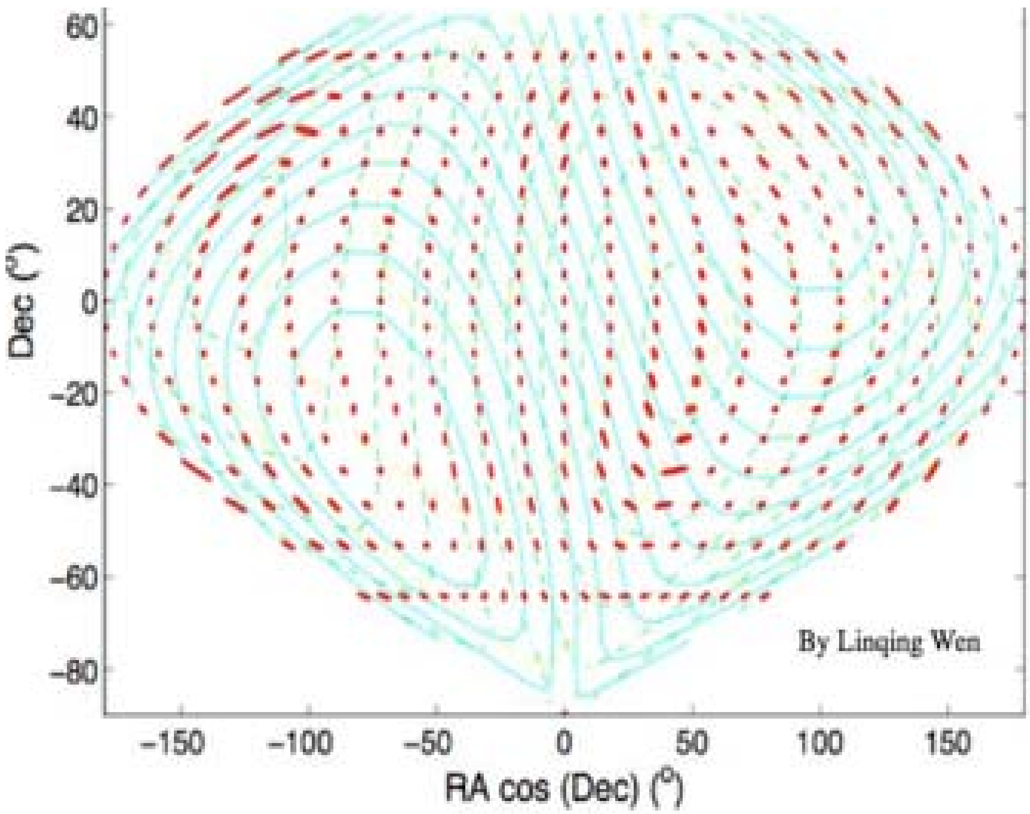
Northern hemisphere detectors have limited ability to locate sources particularly near the celestial equator

Completing the Global Network



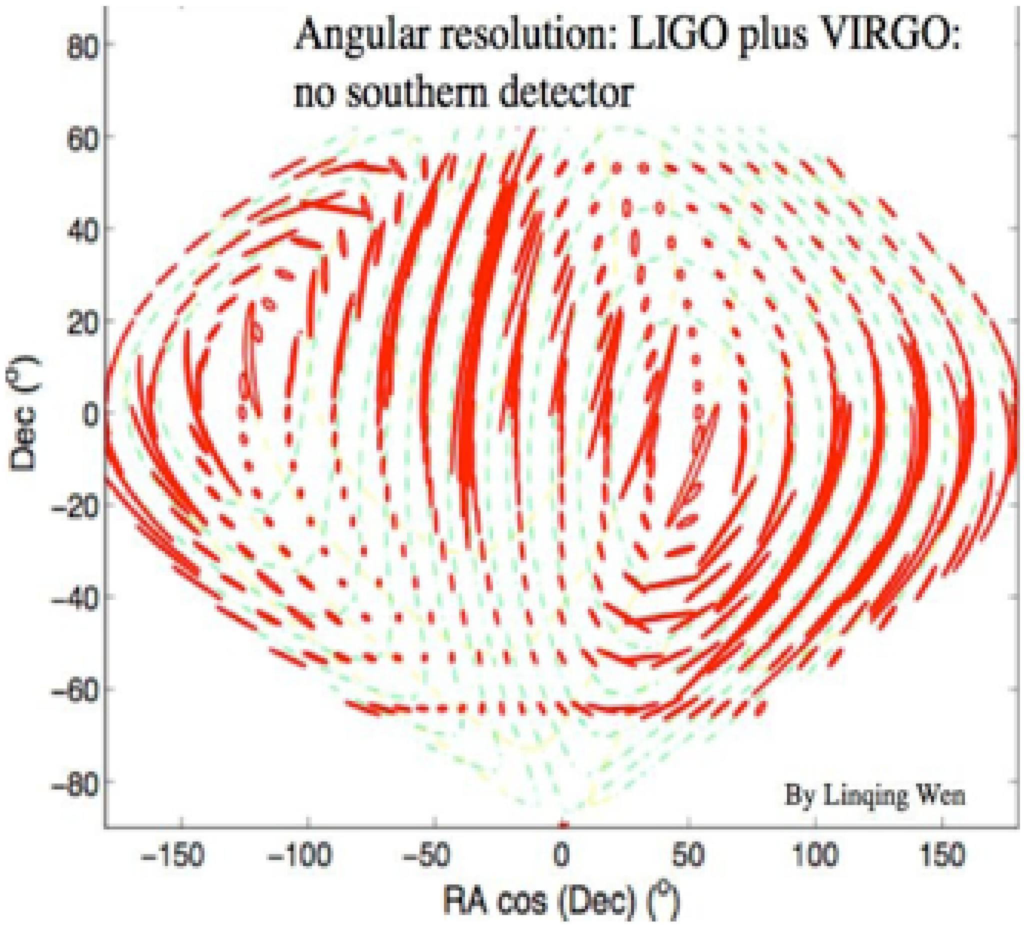
Southern Hemisphere detector

LIGO and Virgo Plus LIGO-Australia



Adding LIGO-Australia to existing network gives nearly all-sky coverage

LIGO and Virgo Alone



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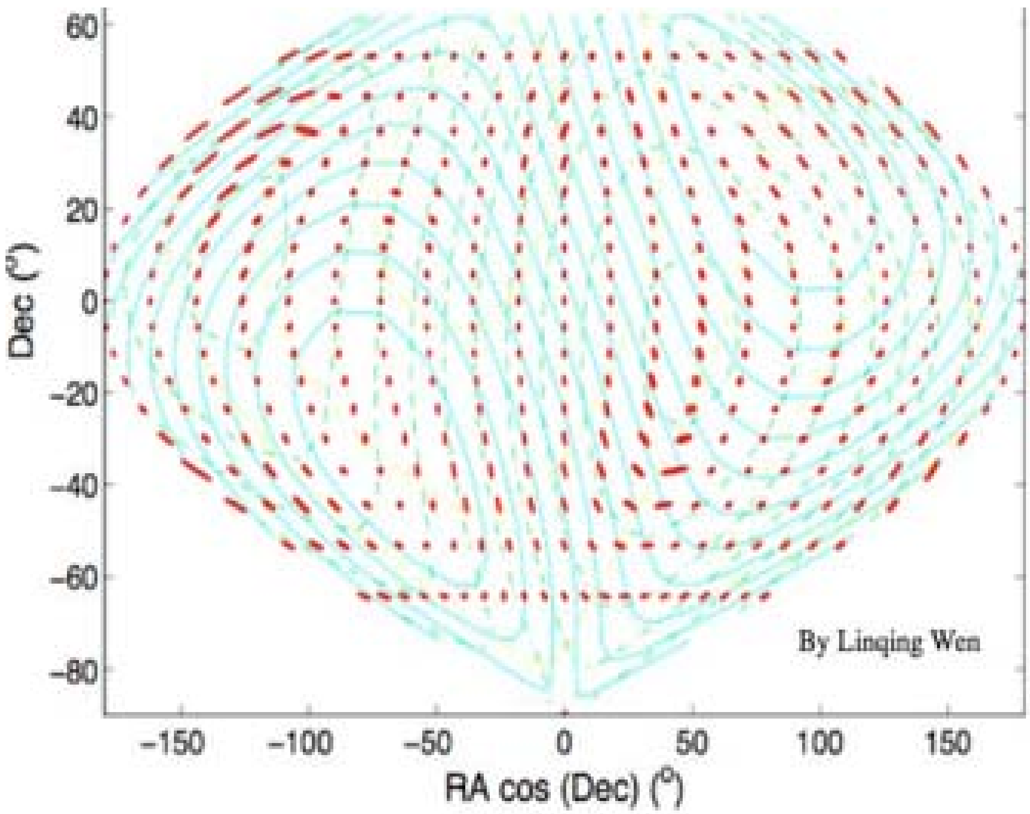
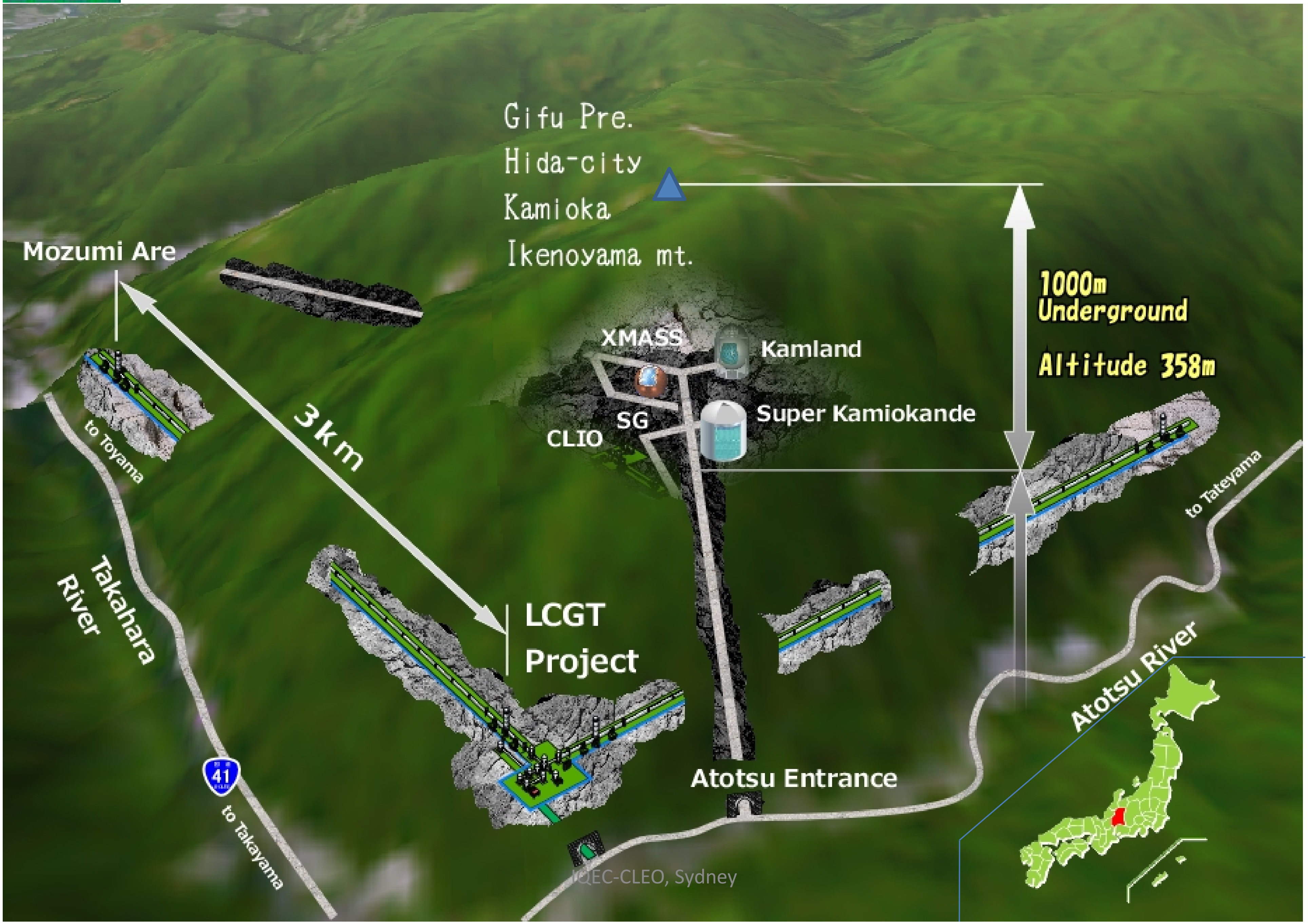
LIGO and Virgo Plus LIGO-Australia



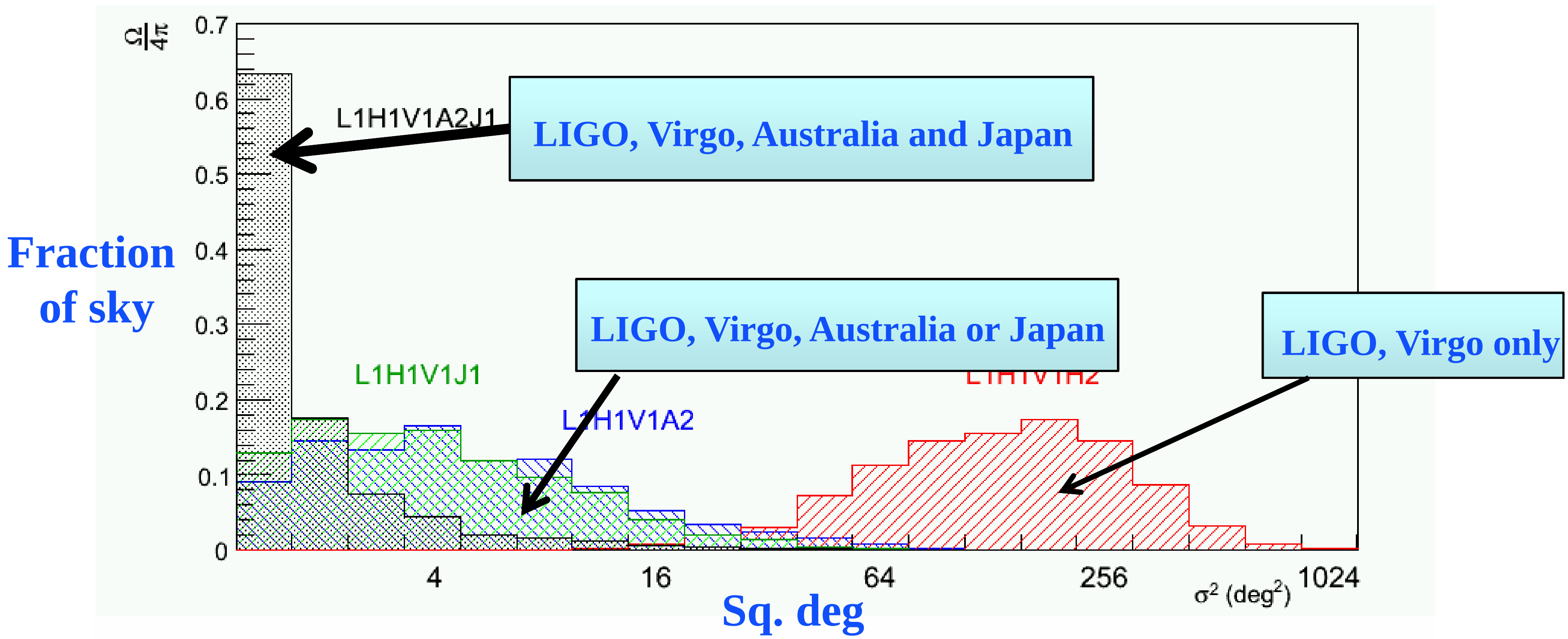
Adding LIGO-Australia to existing network gives nearly all-sky coverage

Large Cryogenic Gravitational-wave Telescope



Is Importance of LIGO-Australia Reduced Because of LCGT?

- Improvement in localization is ~independent of LCGT
- To first order, LIGO-Australia improves N-S localization, while LCGT improved E-W localization



LIGO-Australia Concept

- A direct partnership between LIGO Laboratory and Australian collaborators to build an Australian interferometer
  - » LIGO Lab (with its UK, German and Australian partners) provides components for one Advanced LIGO interferometer, unit #3, from the Advanced LIGO project
  - » Australia provides the infrastructure (site, roads, building, vacuum system), “shipping & handling,” staff, installation & commissioning, operating costs
- The interferometer, the third Advanced LIGO instrument, would be operated as part of LIGO to maximize the scientific impact of LIGO-Australia
- Key deadline: LIGO needs a commitment from Australia by October 2011—otherwise, LIGO must pursue other options (e.g., installation at US site)

LIGO-Australia Site

- Australian Consortium for Interferometric Gravitational Astronomy (Australian National University, University of Western Australia, University of Adelaide, University of Melbourne, Monash University)
- 80 m facility located at Gingin (about 100 km from Perth)
- Operated as a high power test bed for LIGO
- Site expandable to 4 km
- Site also contains 1m robotic optical telescope and an award-winning science education centre

Final Thoughts

- We are on the threshold of a new era in GW detection
- First generation detectors have broken new ground in optical sensitivity
  - » Initial LIGO reached design sensitivity and proved technique
- Second generation detectors are starting installation
  - » Will expand the "Science" (astrophysics) by factor of 1000
- Will continue to drive developments in optical technology and optical physics for decades to come
- A worldwide network is starting to come on line
  - » Groundwork has been laid for operation as a integrated system
  - » Australia could play a key role