Advanced LIGO, LIGO-Australia and the International Network

Stan Whitcomb

LIGO/Caltech

IndIGO - ACIGA meeting on LIGO-Australia

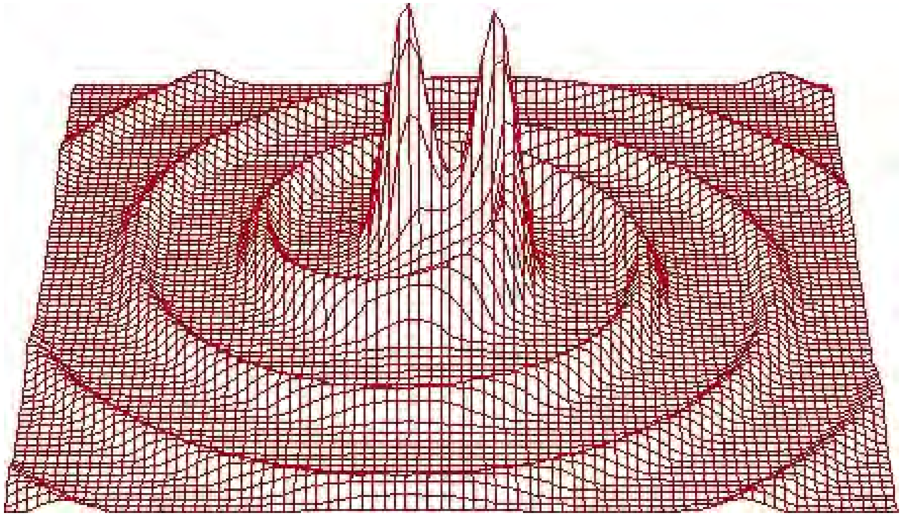
8 February 2011

LIGO-G1100109-v1

Gravitational Waves

- Einstein in 1916 and 1918 recognized gravitational waves in his theory of General Relativity

- Necessary consequence of Special Relativity with its finite speed for information transfer

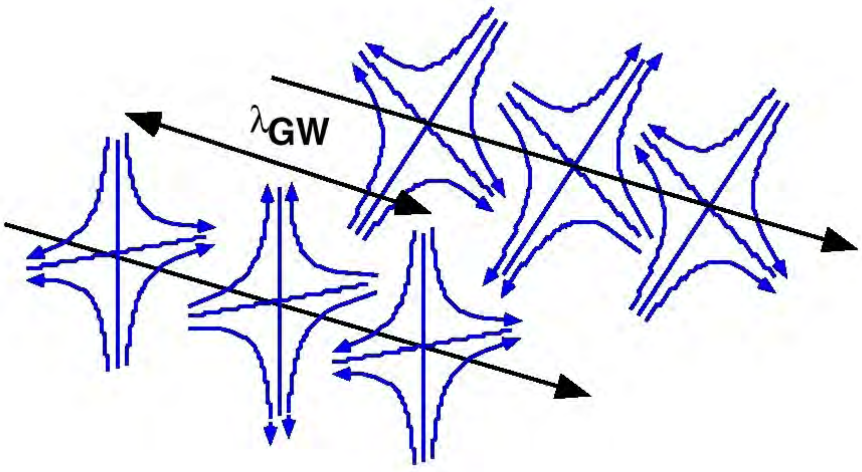


gravitational radiation
binary inspiral of compact objects
(blackholes or neutron stars)

Gravitational Wave Physics

- **Time-dependent distortion of space-time created by the acceleration of masses**
  - » **Most distinctive departure from Newtonian theory**
- **Analogous to electro-magnetic waves**
  - » **Propagate away from the sources at the speed of light**
  - » **Pure transverse waves**
  - » **Two orthogonal polarizations**

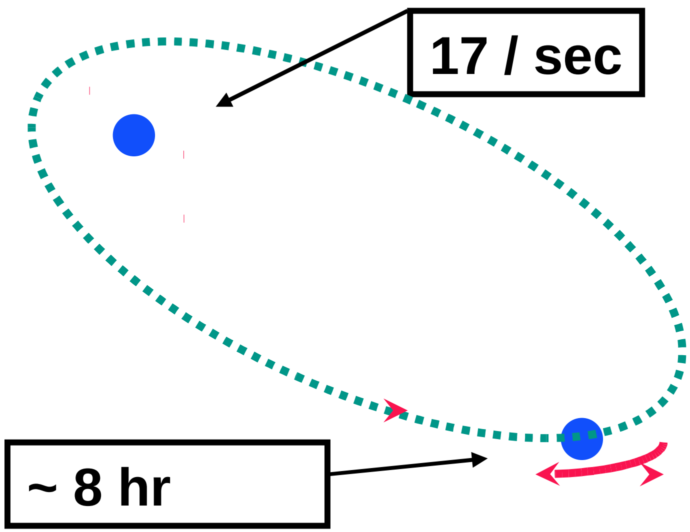
$$h = \Delta L / L$$



Evidence for Gravitational Waves

Binary Neutron Star System

PSR 1913 + 16

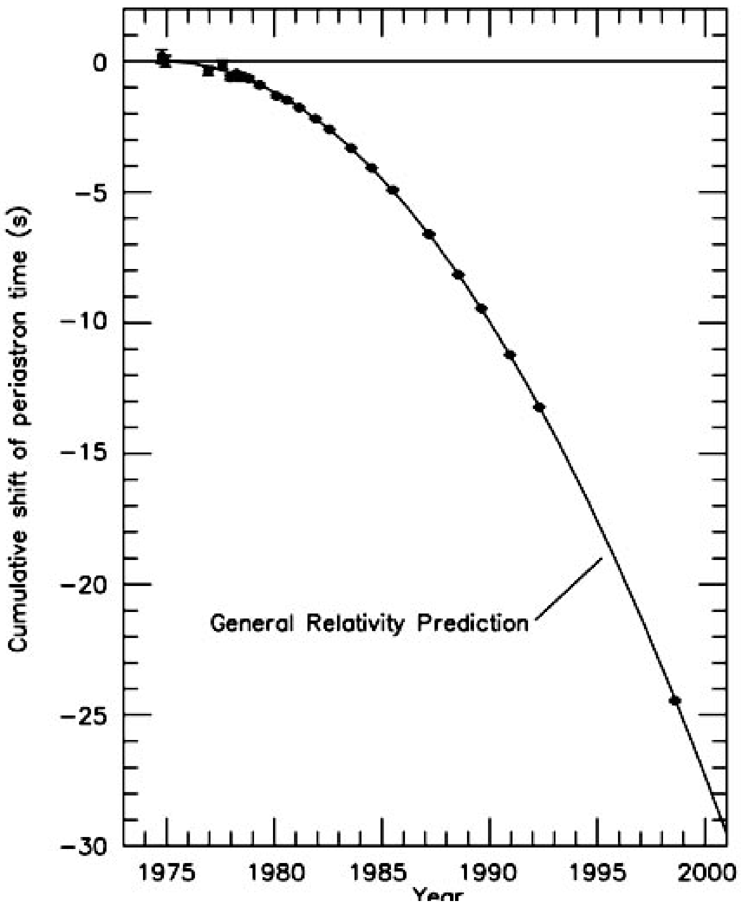


- Discovered by Hulse and Taylor in 1975
- Unprecedented laboratory for studying gravity
  - » Extremely stable spin rate
- Possible to repeat classical tests of relativity (bending of “starlight”, advance of “perihelion”, etc.

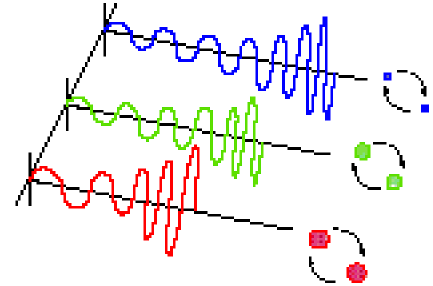
Binary Pulsar Timing Results

- After correcting for all known relativistic effects, observe loss of orbital energy
- Advance of periastron by an extra 25 sec from 1975-98
- Measured to ~50 msec accuracy
- Deviation grows quadratically with time

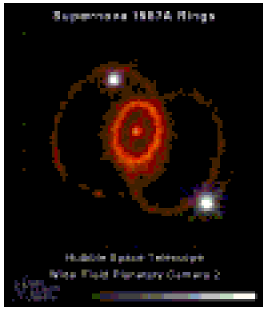
=> <u>emission of gravitational waves</u>



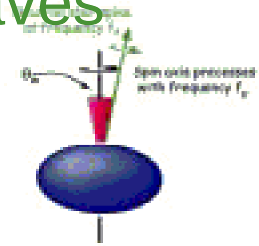
Astrophysical Sources for Terrestrial GW Detectors

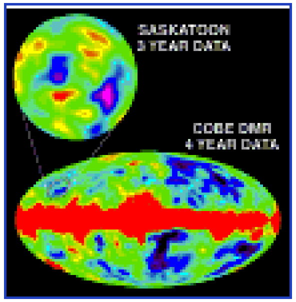


- Compact binary inspiral: “chirps”
  - » **NS-NS, NS-BH, BH-BH**



- 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**



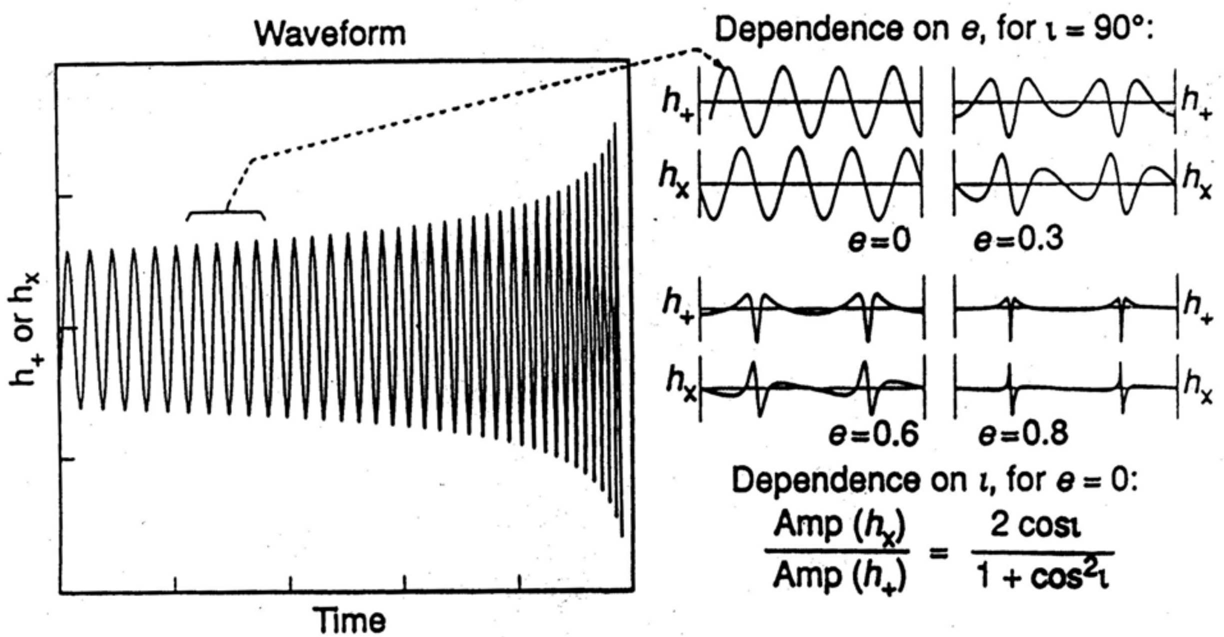


- Cosmological: “stochastic background”
  - » **Probe back to the Planck time (10^{-43} s)**

Using GWs to Learn about the Sources: an Example

Chirp Signal

binary inspiral



Can determine

- Distance from the earth r
- Masses of the two bodies
- Orbital eccentricity e and orbital inclination *i*

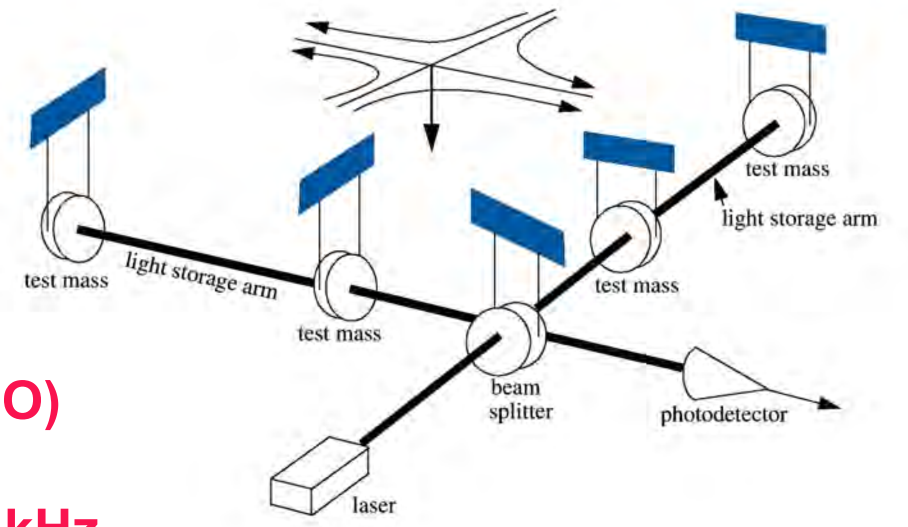
Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses

in horizontal plane for frequencies $f \gg f_{pend}$

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

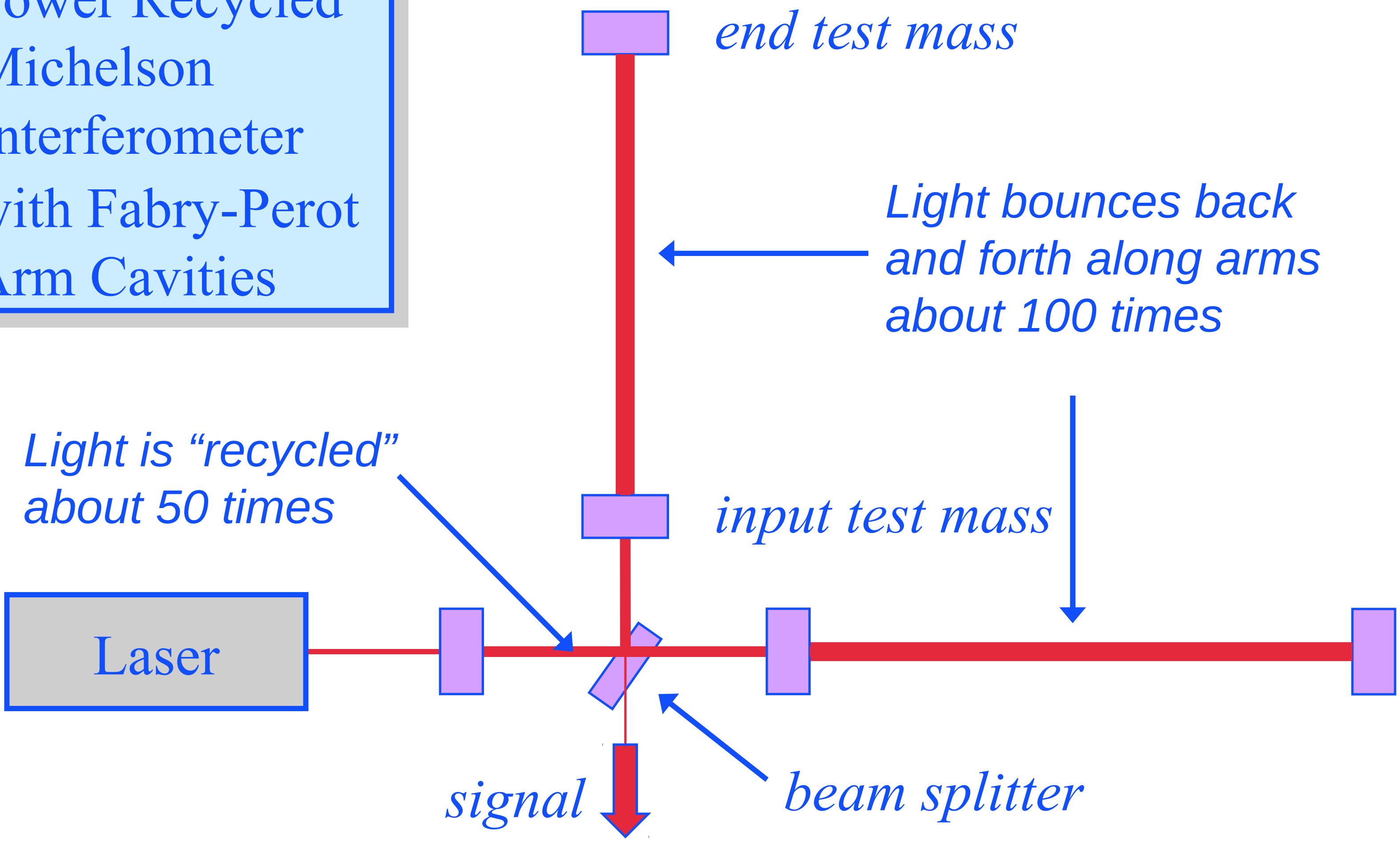
$$h = \Delta L / L$$



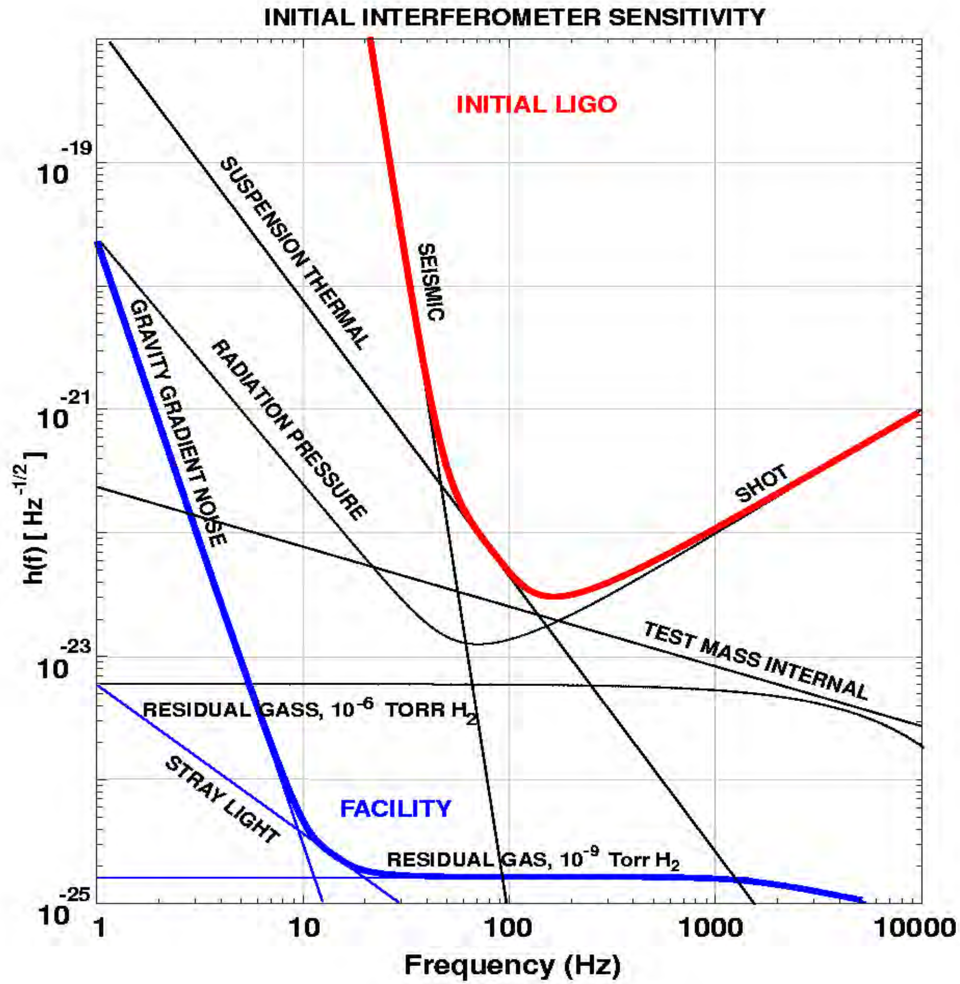
Laser Interferometer Gravitational-wave Observatory (LIGO)

LIGO Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities

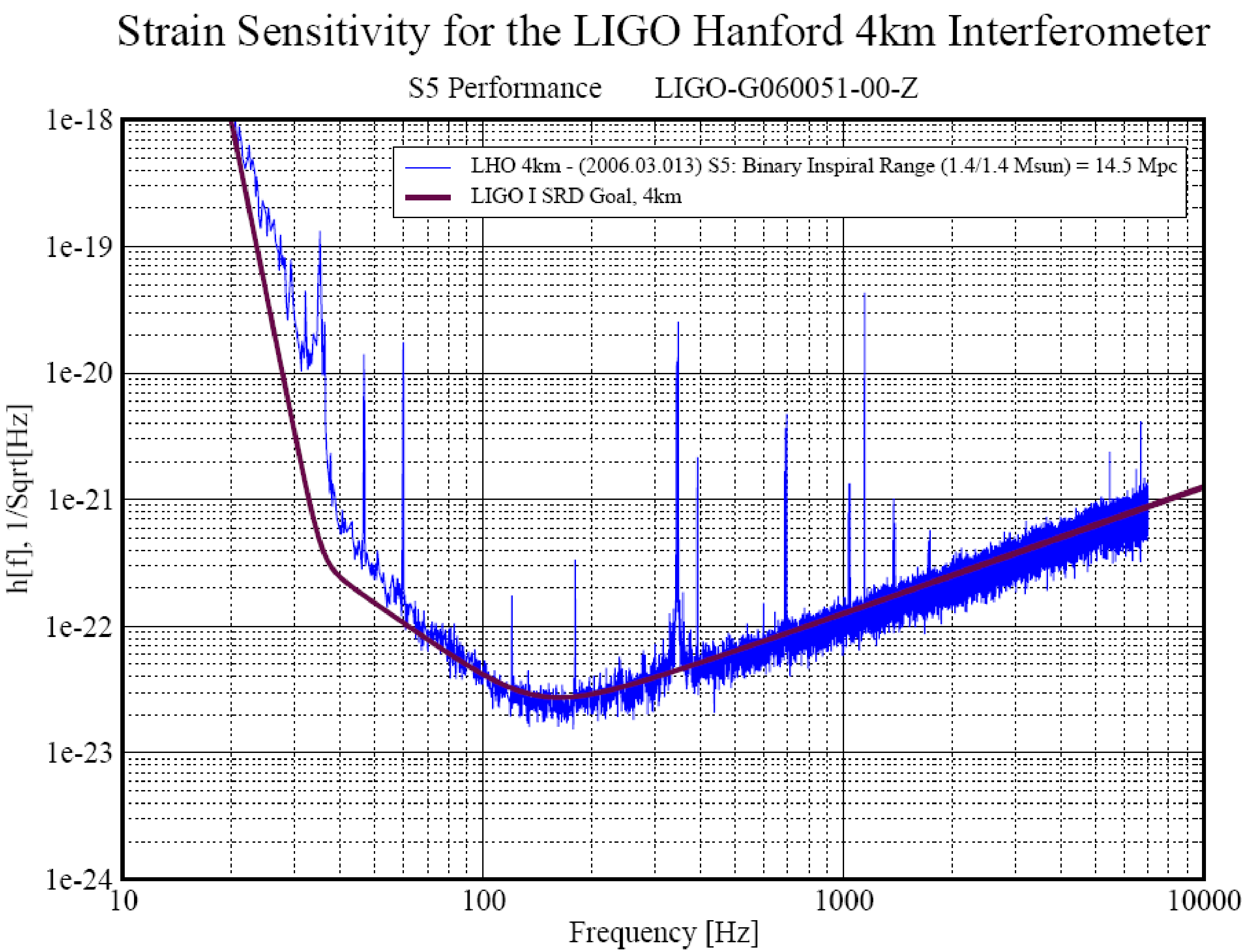


Initial LIGO Sensitivity Goal

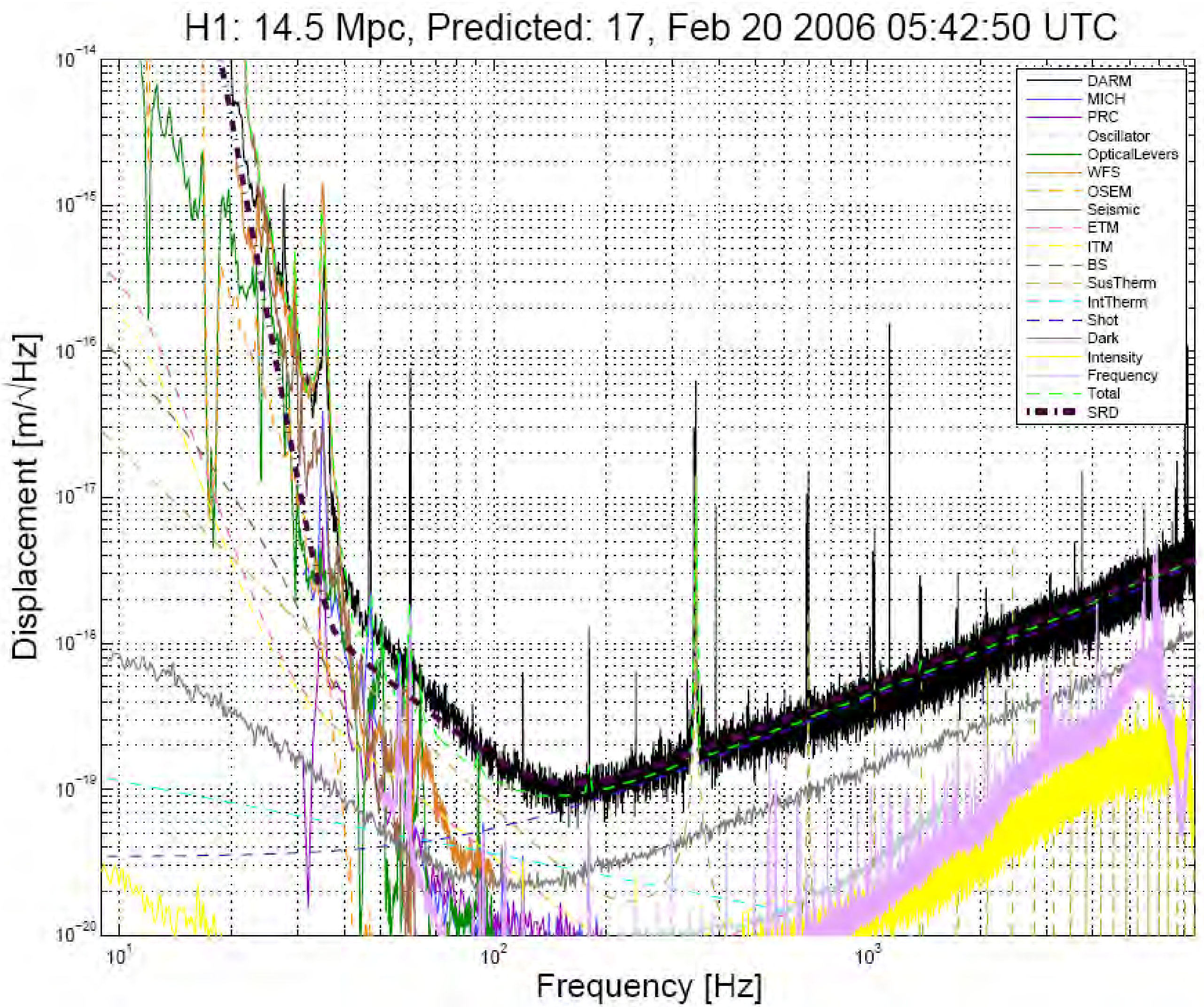


- Strain sensitivity $<3x10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

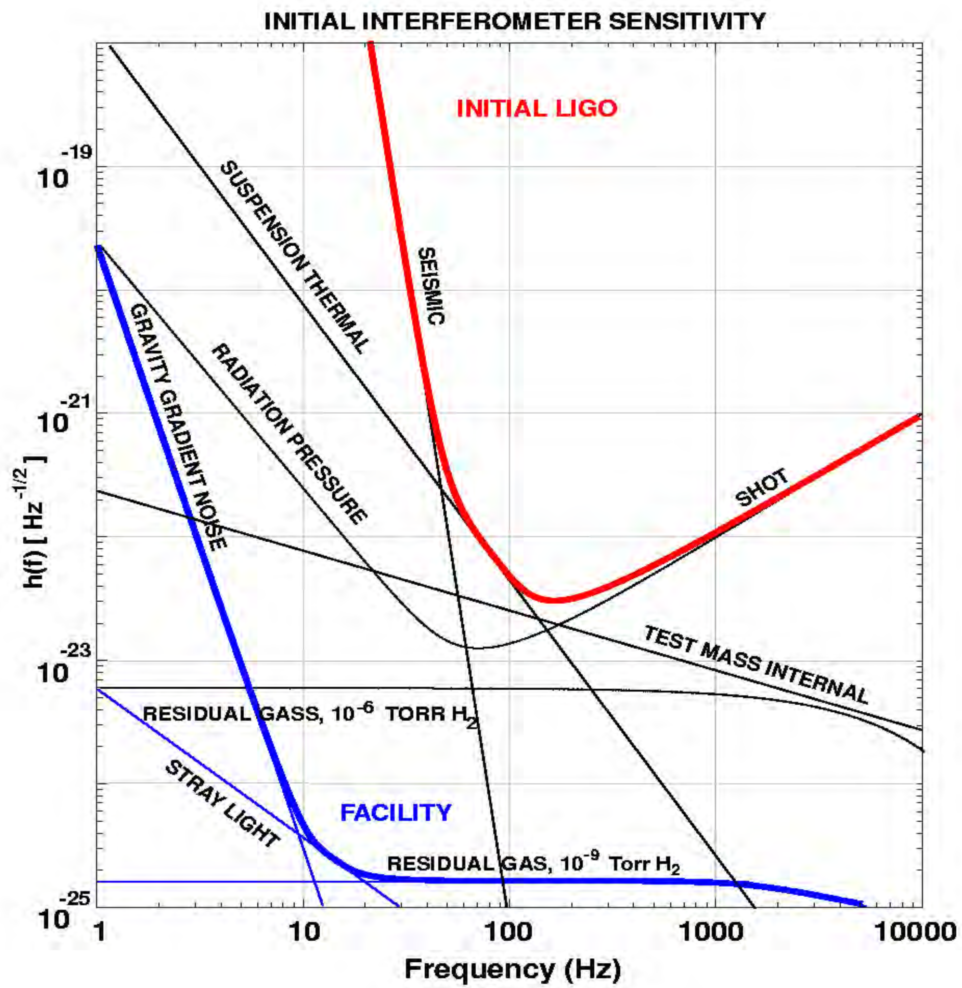
LIGO Sensitivity



Anatomy of a Noise Curve



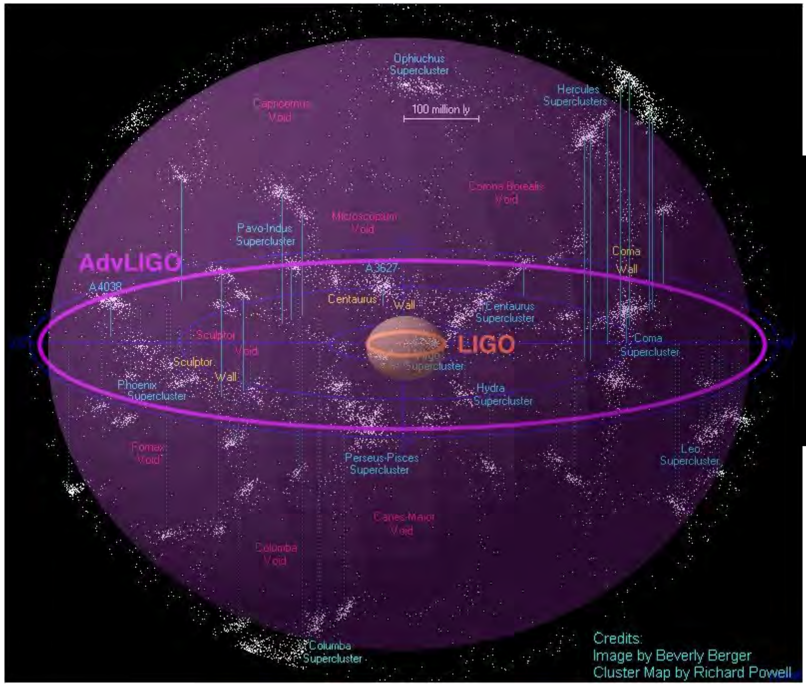
Facility Limits to Sensitivity



- Facility limits leave lots of room for future improvements

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

⇒ x1000 rate=(reach)³

⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

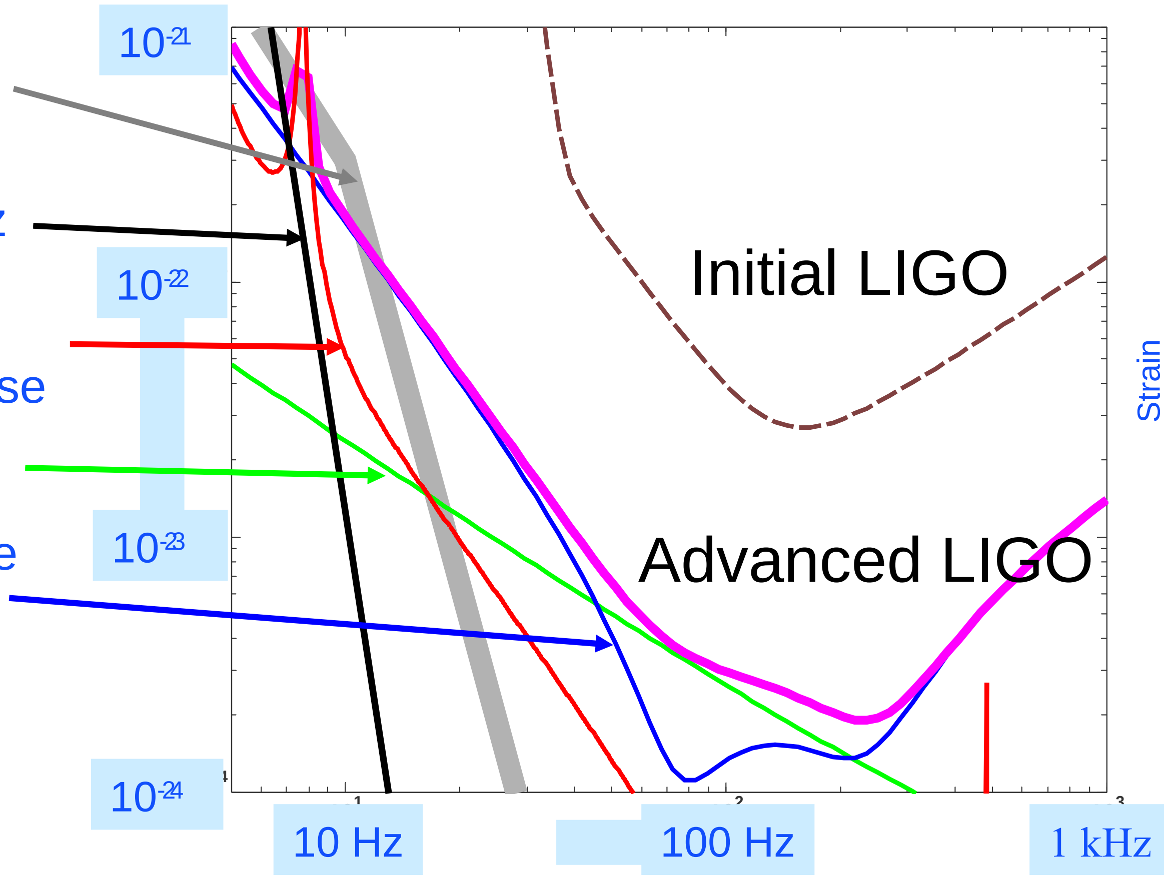
2008 start,
installation beginning 2011

Advanced LIGO: Big Picture

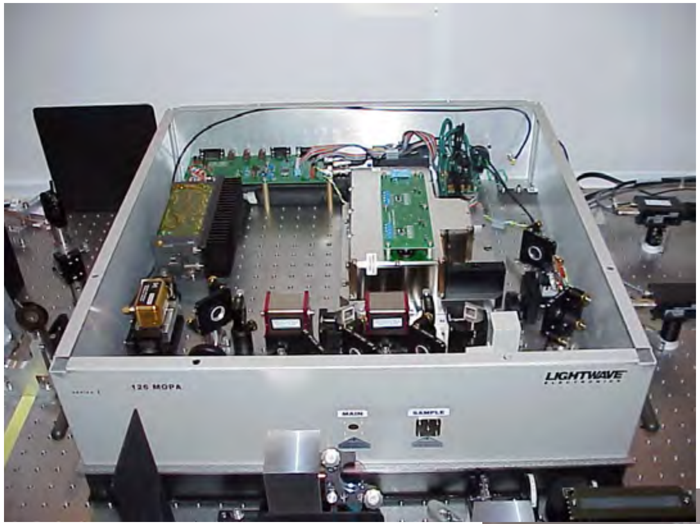
- Advanced LIGO design begins ~1999, just about finished
- Construction project started April 2008, completes in 2015
  - » Will observe with Advanced LIGO for quite some time after that
- Enthusiastically supported by the National Science Foundation
- Costs: $205 million from the NSF,
  plus contributions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

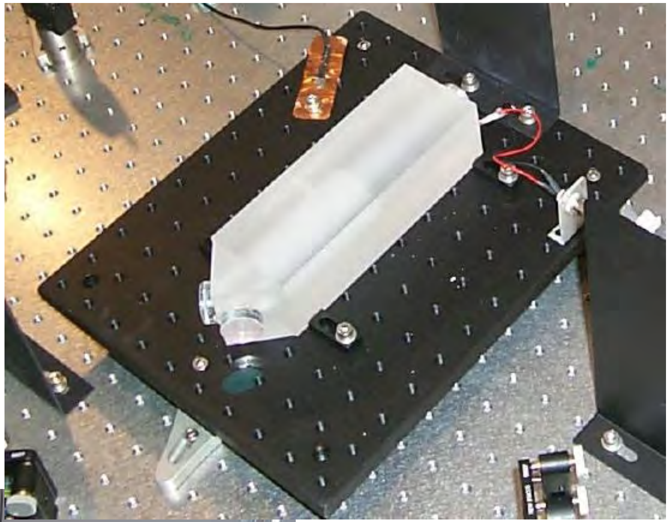
Advanced LIGO Performance

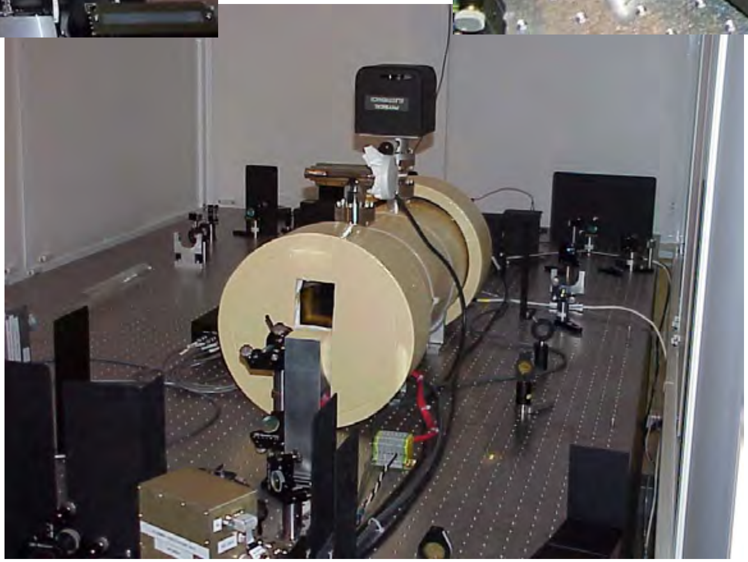
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Quantum noise dominates at most frequencies



Initial LIGO Laser





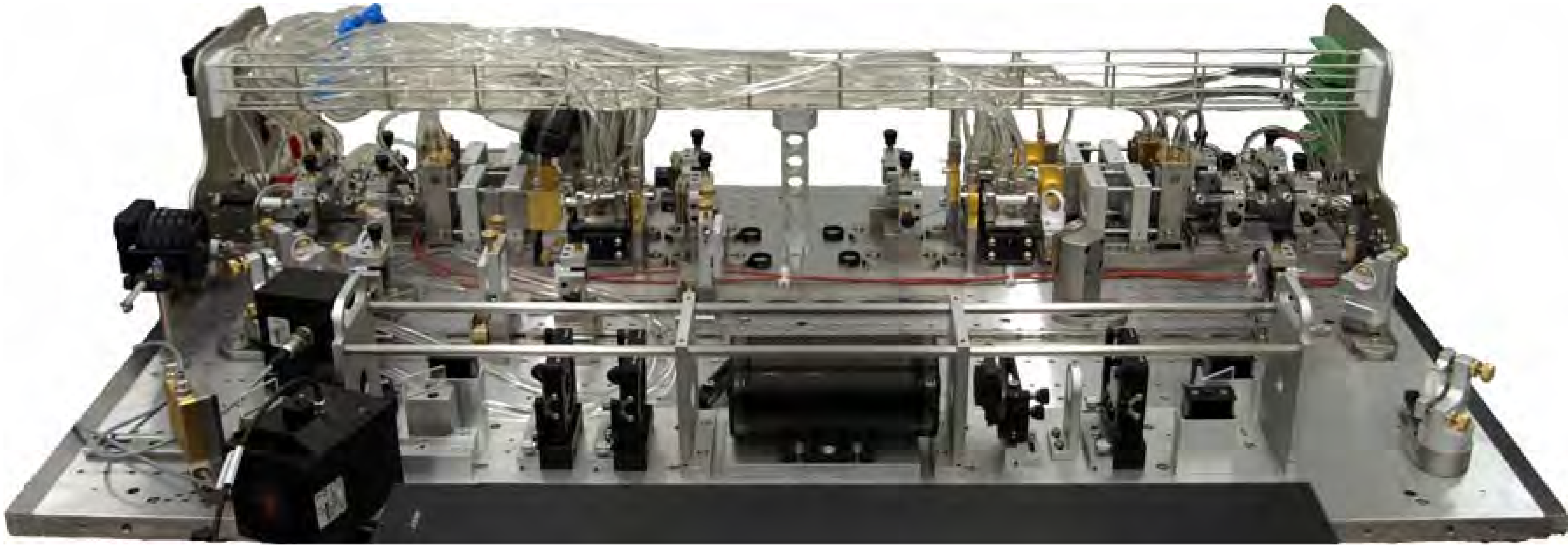


Custom-built
10 W
Nd:YAG
Laser

Stabilization
cavities
for frequency
and beam shape

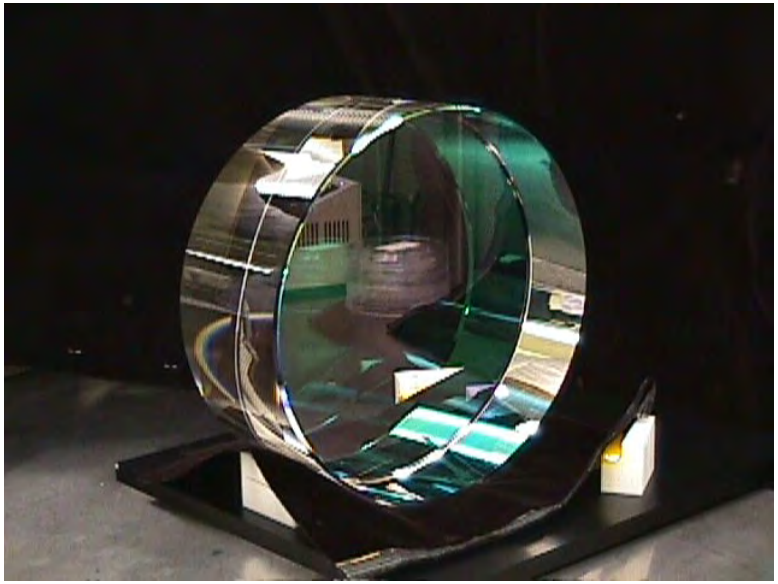
Advanced LIGO Laser

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

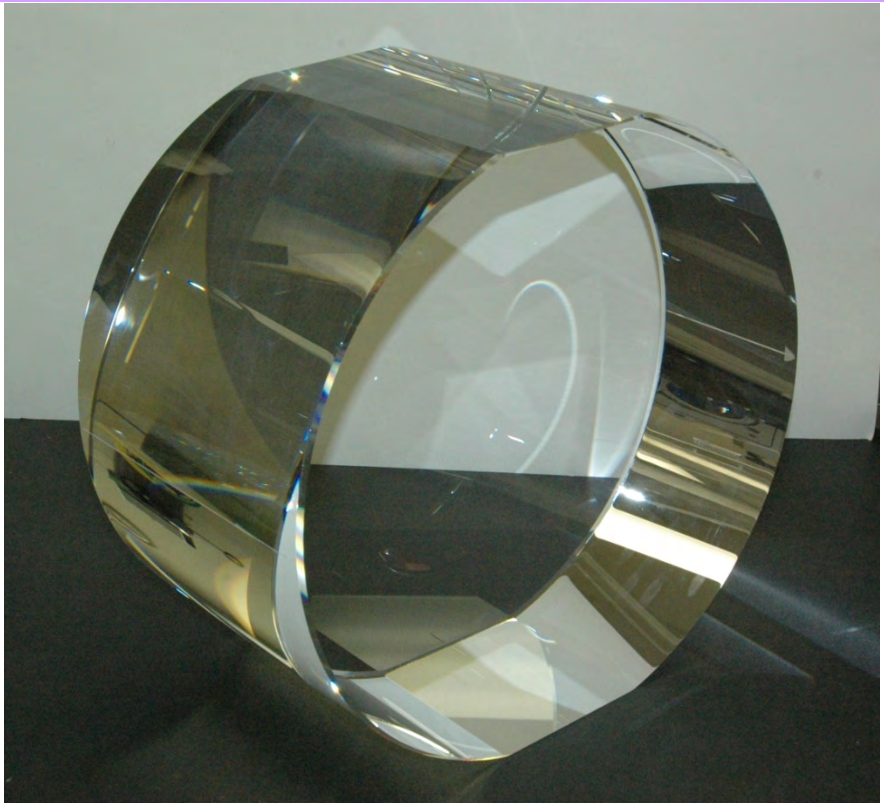


Initial LIGO Mirrors

- 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



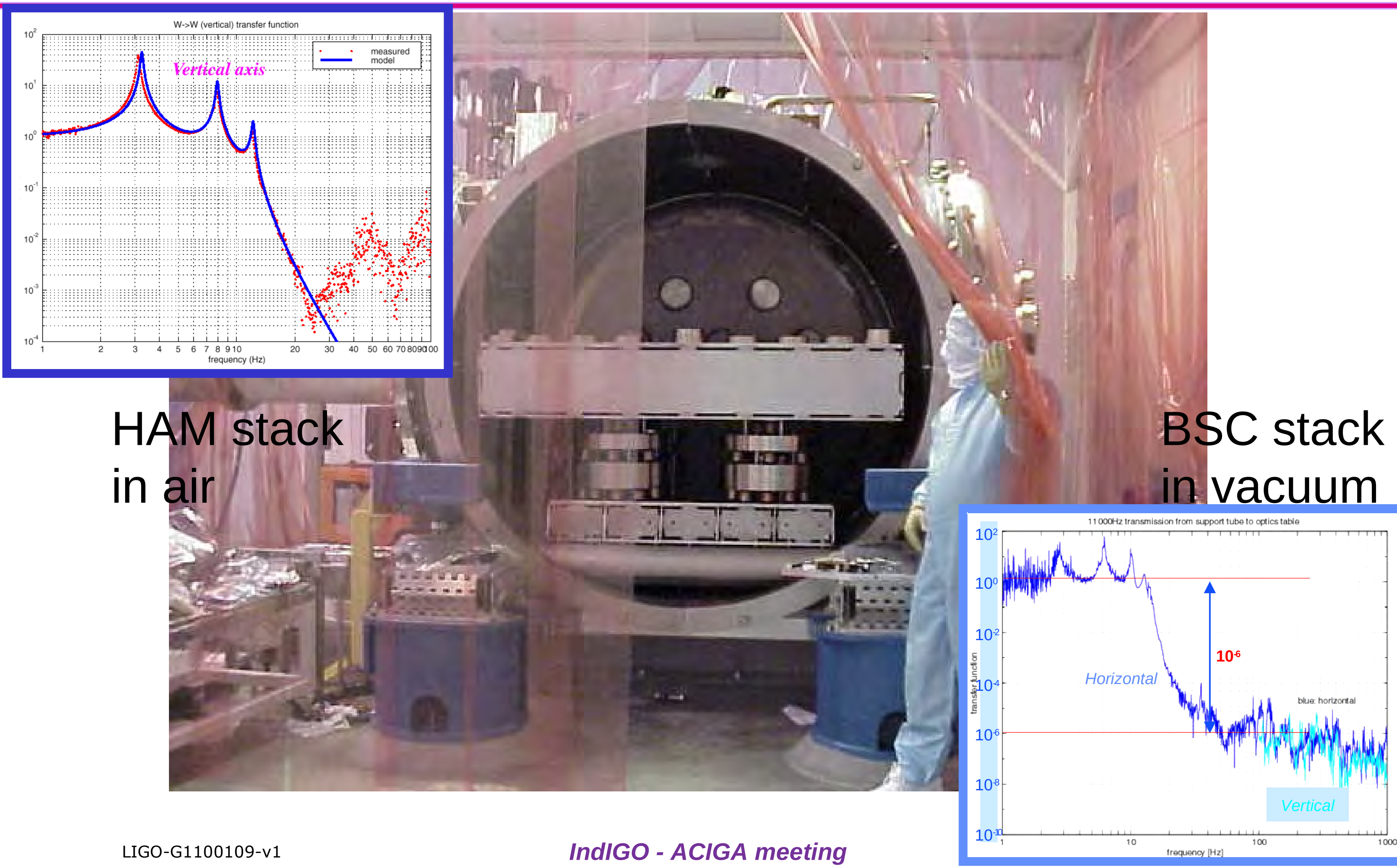
Advanced LIGO Mirrors



- 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



HAM stack
in air

BSC stack
in vacuum

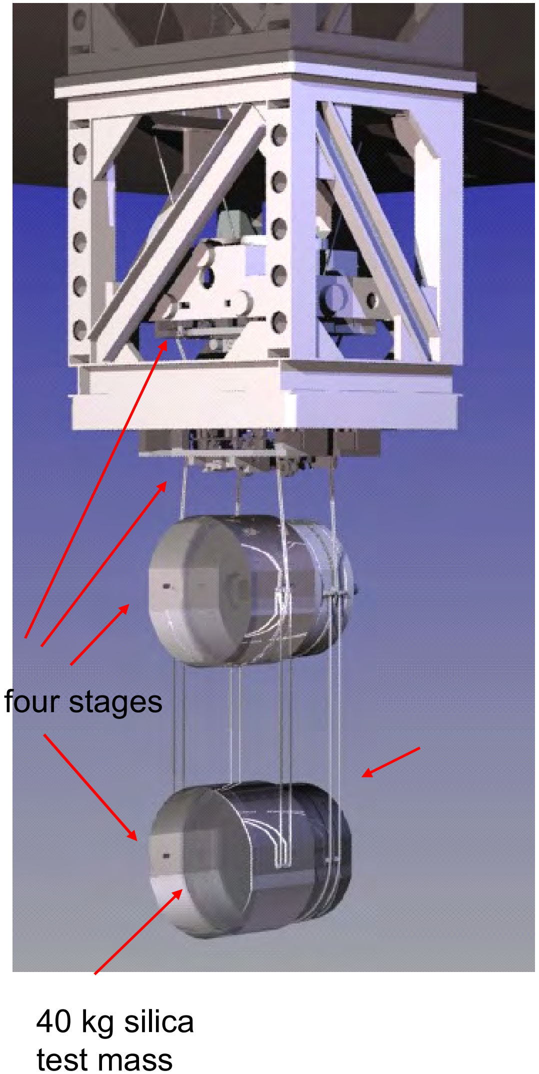
Advanced LIGO Seismic Isolation

- 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

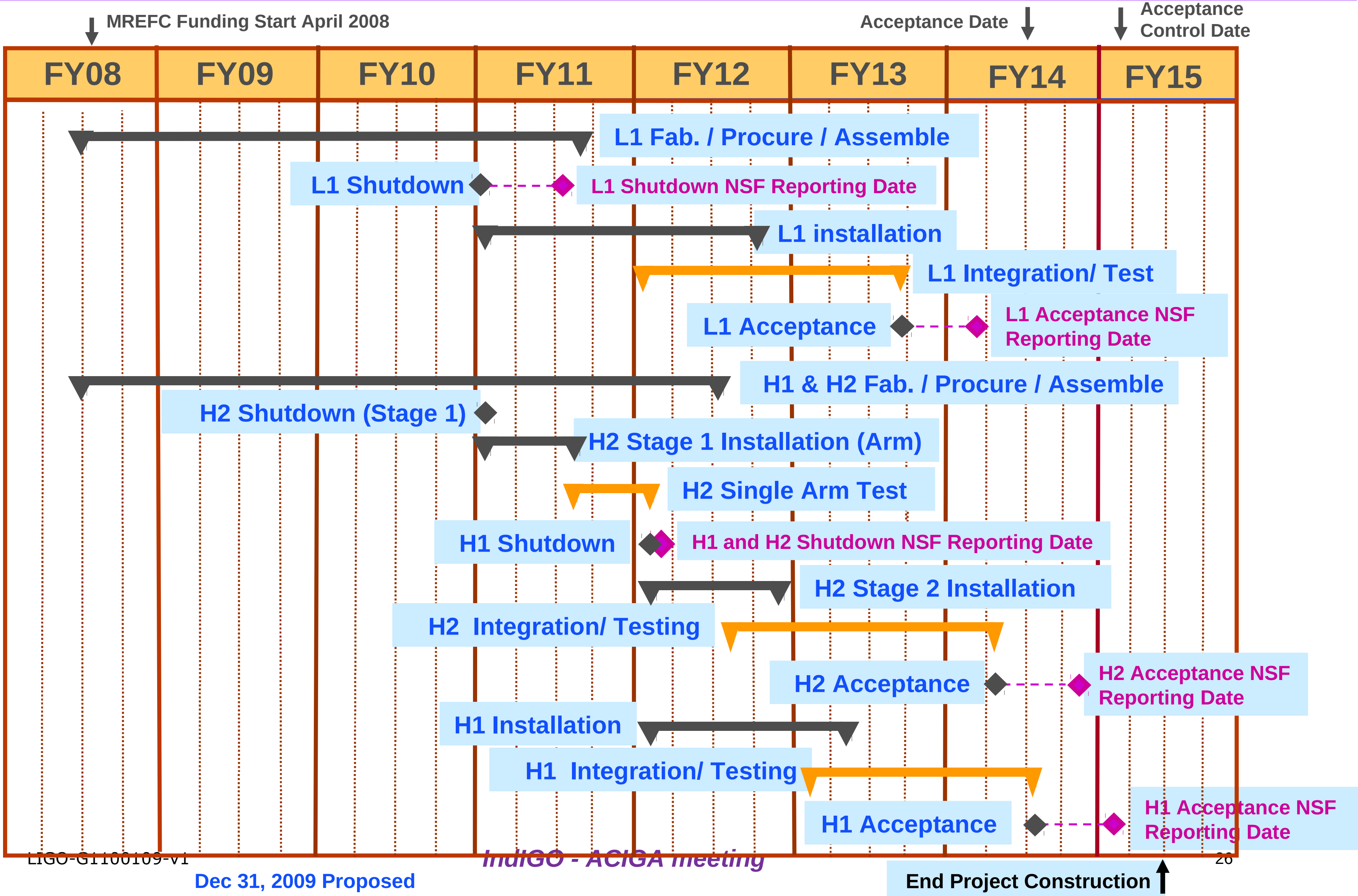
- Simple single-loop pendulum suspension
- Low loss steel wire
  - » Adequate thermal noise performance, but little margin
- Magnetic actuators for control

Advanced LIGO Suspensions

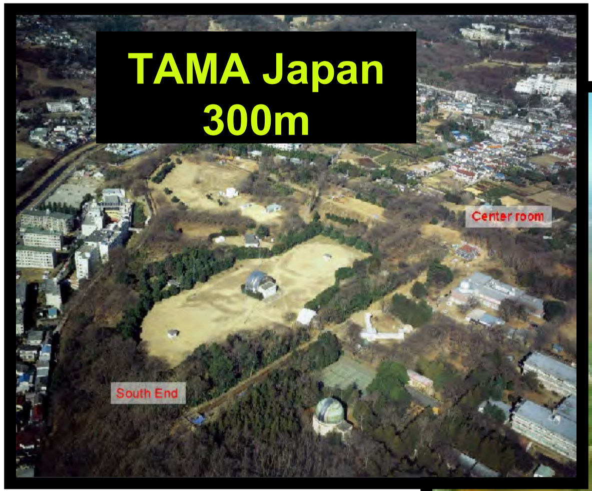


- UK designed and contributed test mass suspensions
- Silicate bonds create quasi-monolithic pendulums using ultra-low loss fused silica fibers to suspend interferometer optics
  - » Pendulum Q ~10^5 -> ~10^8

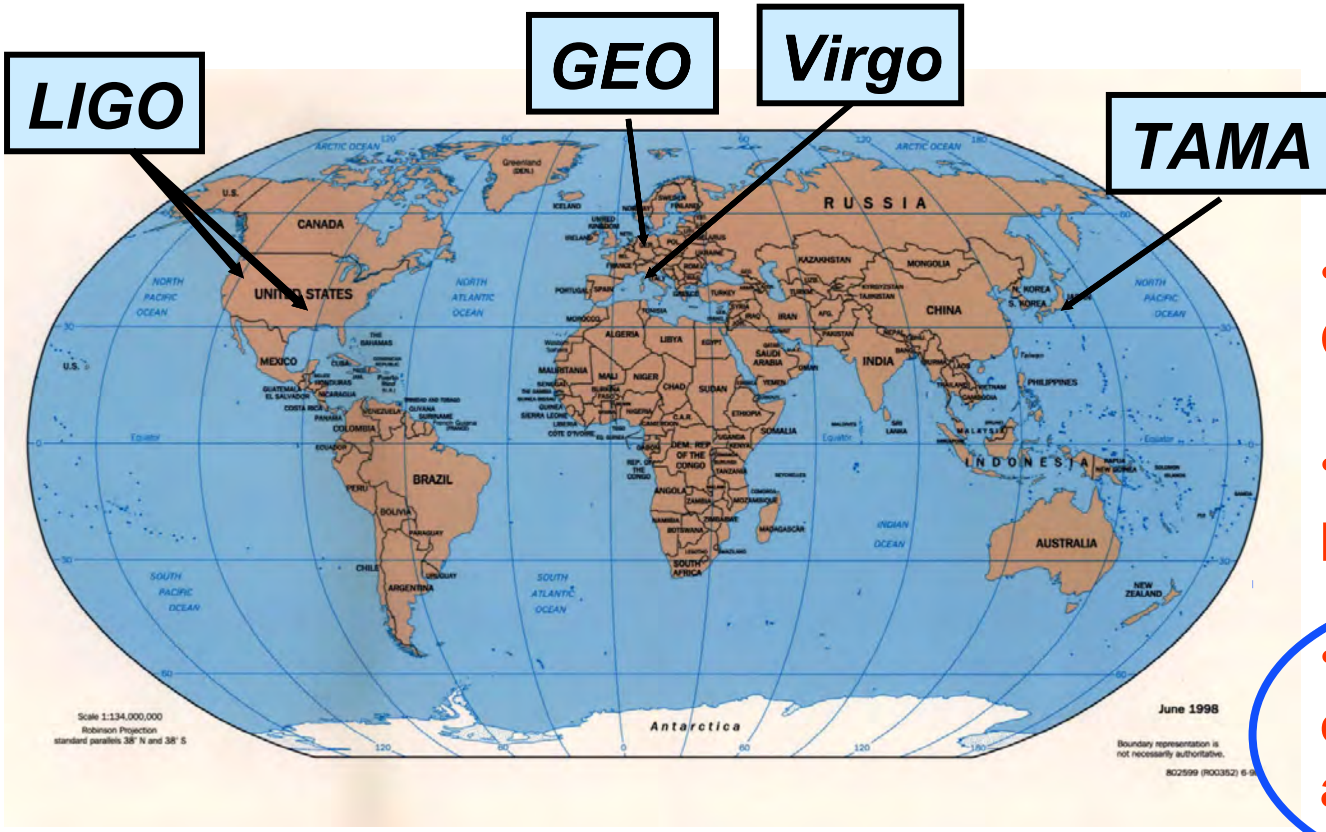
Installation and Integration



Gravitational Wave Interferometers Around the World



A Global Network of GW Detectors 2009



- Global interest in GW science
- Multiple large projects
- How do we coordinate their activities

What is GWIC?

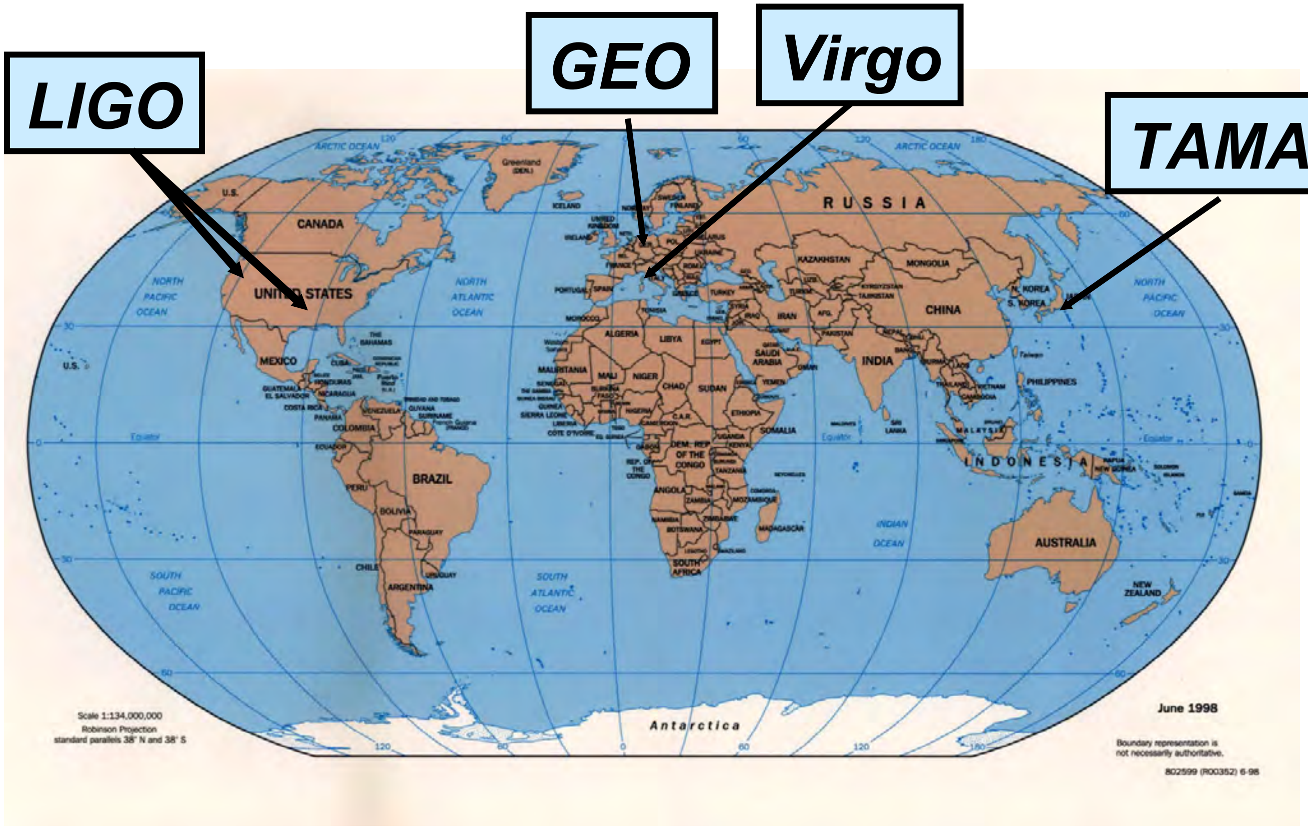
Gravitational Wave International Committee

- Formed in 1997 to facilitate international collaboration in the construction and use of gravitational wave detectors world-wide
  - Affiliated with the International Union of Pure and Applied Physics (IUPAP)
  - Promotes international cooperation for the benefit of science
- GWIC Roadmap Committee:
  - Develop roadmap to optimize the global science in the field with 30-year horizon
  - Identify relevant science opportunities and the facilities needed to address them

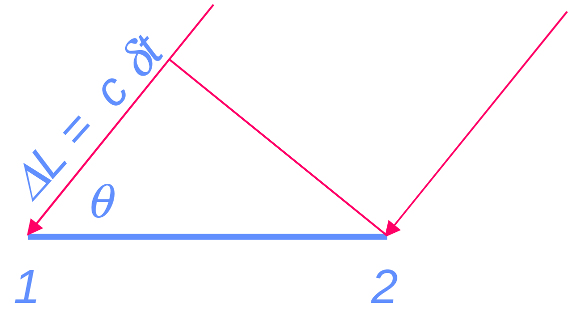
From the GWIC Roadmap:

- … the first priority for ground-based gravitational wave detector development is to expand the network, adding further detectors with appropriately chosen intercontinental baselines and orientations to maximize the ability to extract source information.

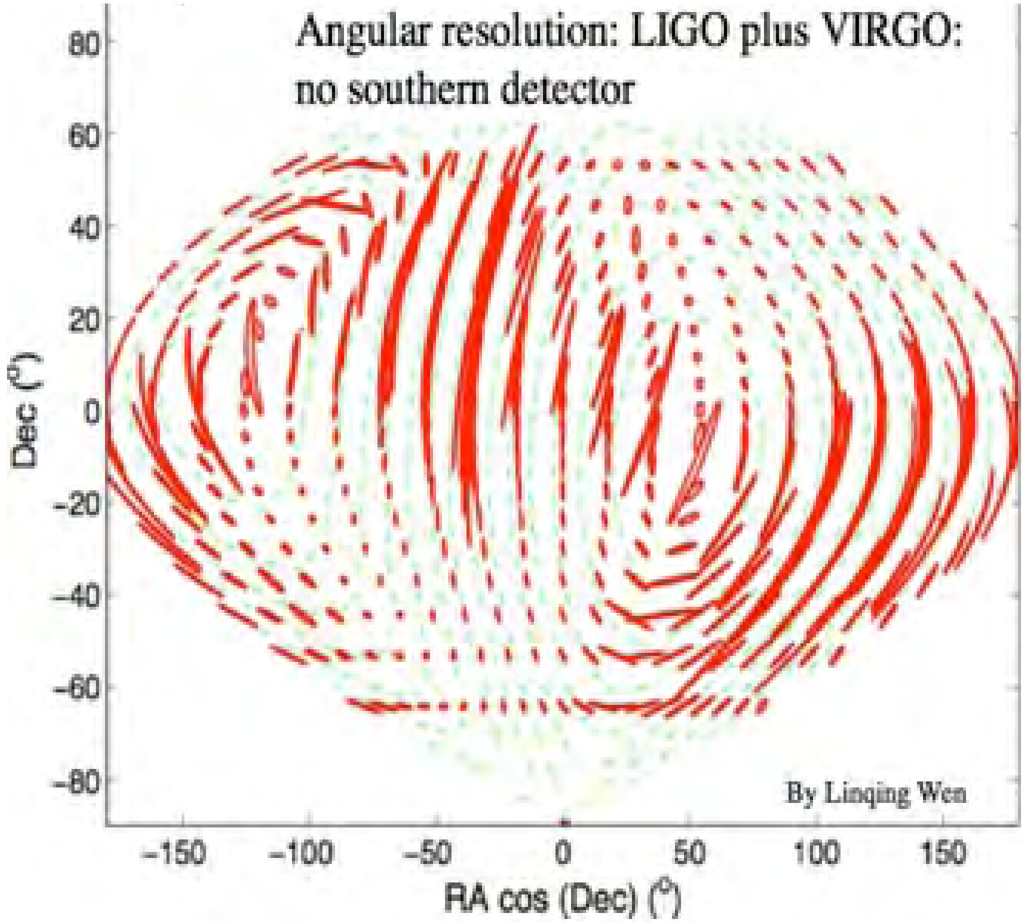
A Global Network of GW Detectors 2009



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

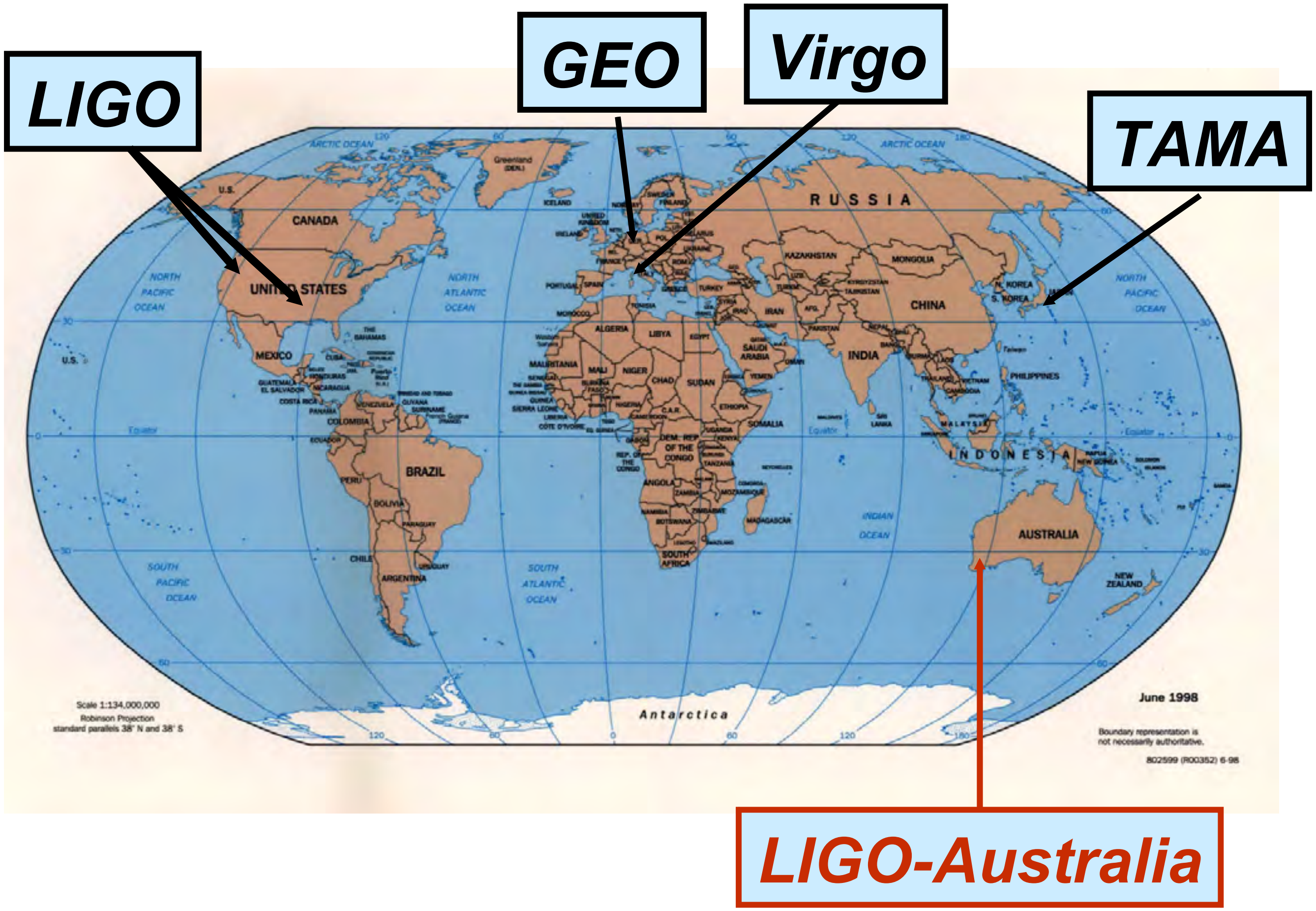


LIGO and Virgo Alone



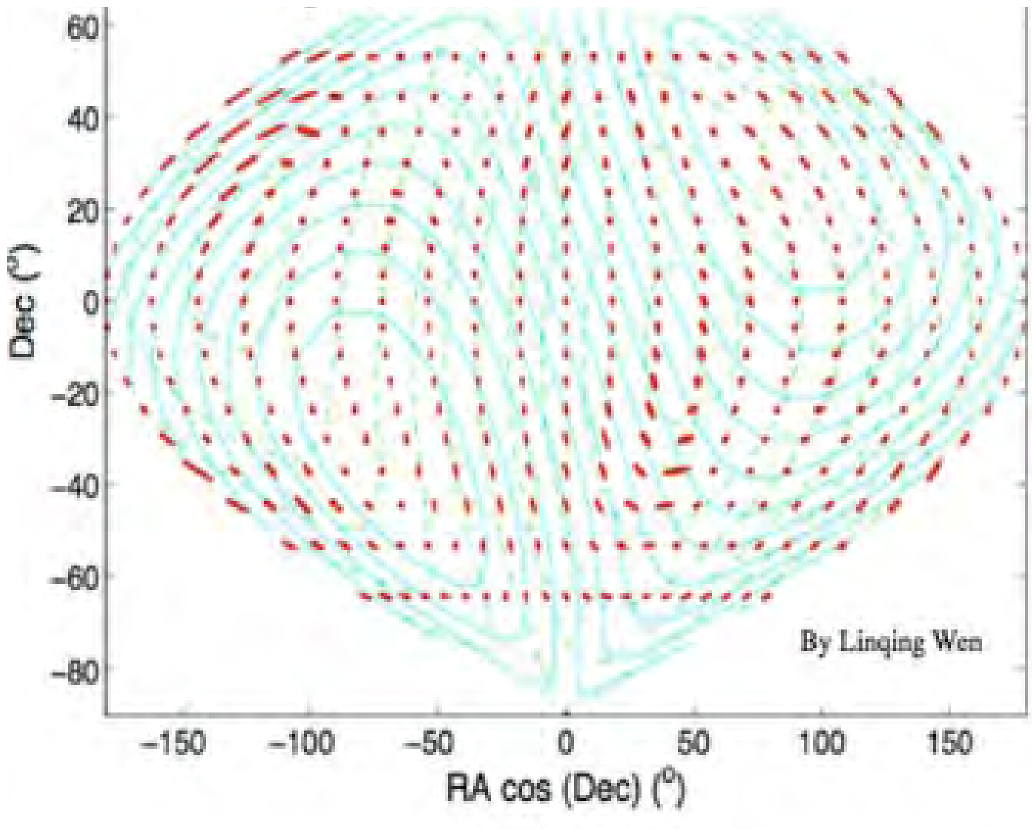
Northern hemisphere detectors have limited ability to locate sources particularly near the celestial equator

Completing the Global Network



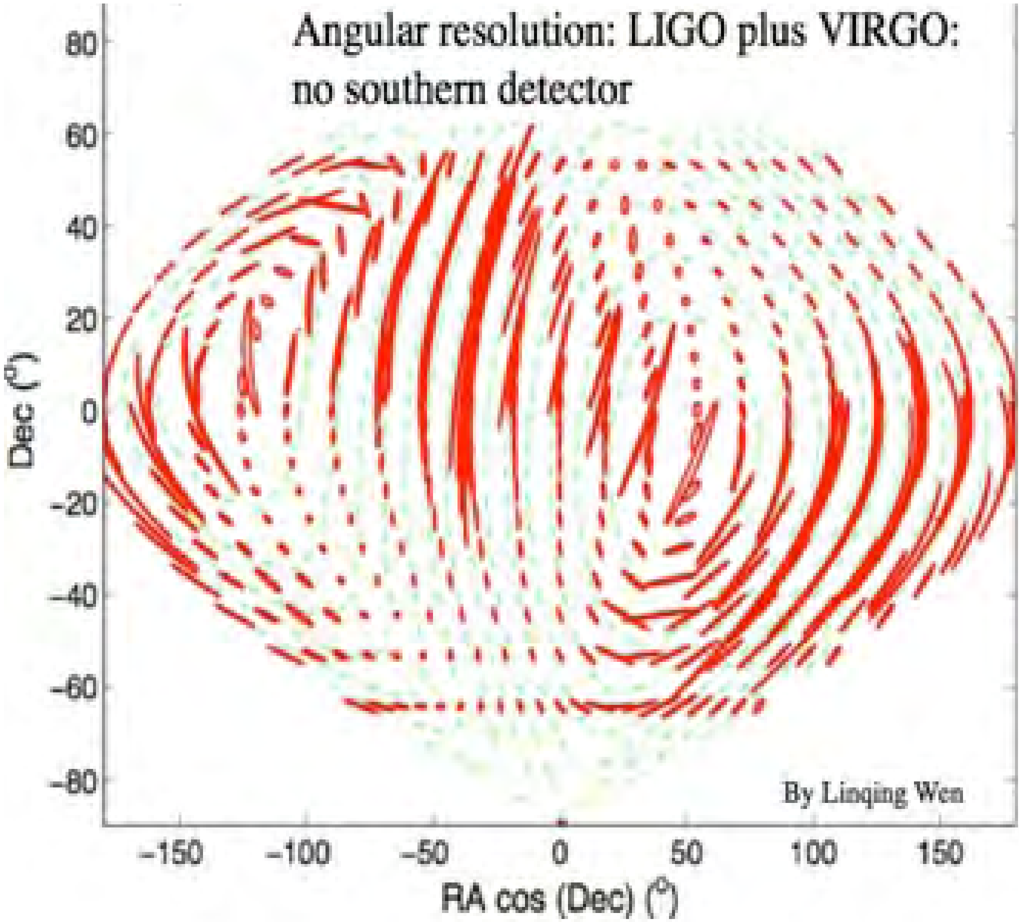
Southern Hemisphere detector

LIGO and Virgo Plus LIGO-Australia



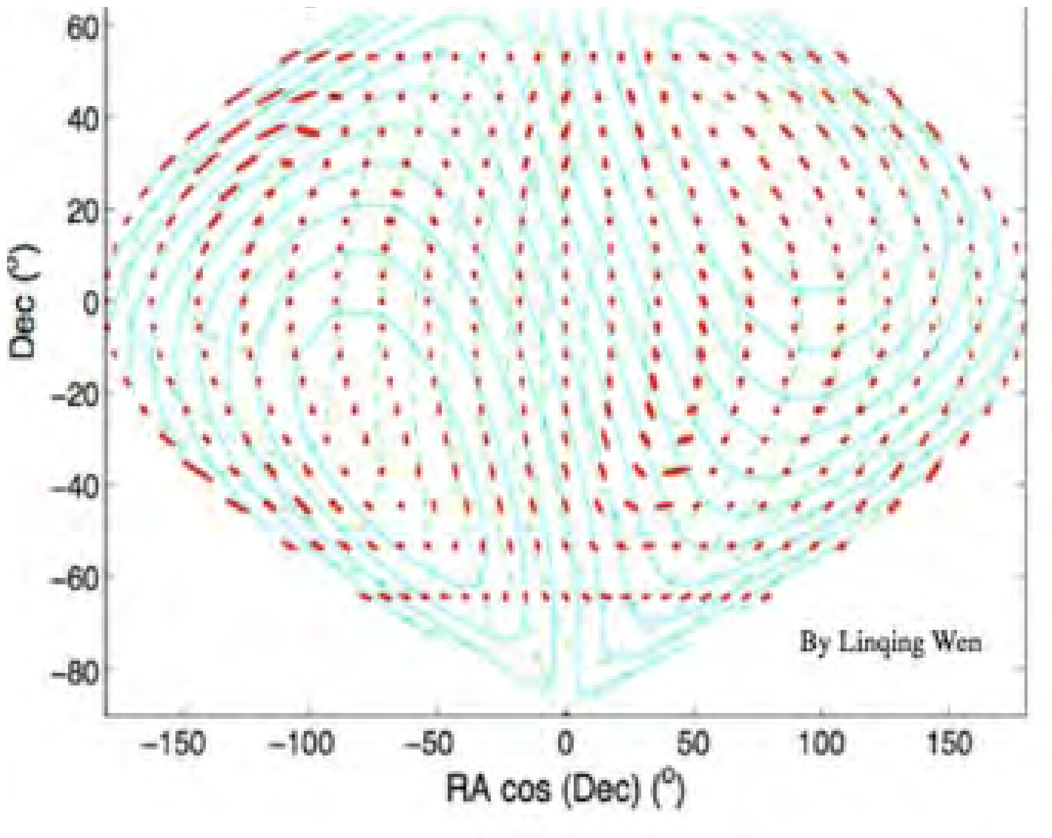
Adding LIGO-Australia to existing network gives nearly all-sky coverage

LIGO and Virgo Alone



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

LIGO and Virgo Plus LIGO-Australia

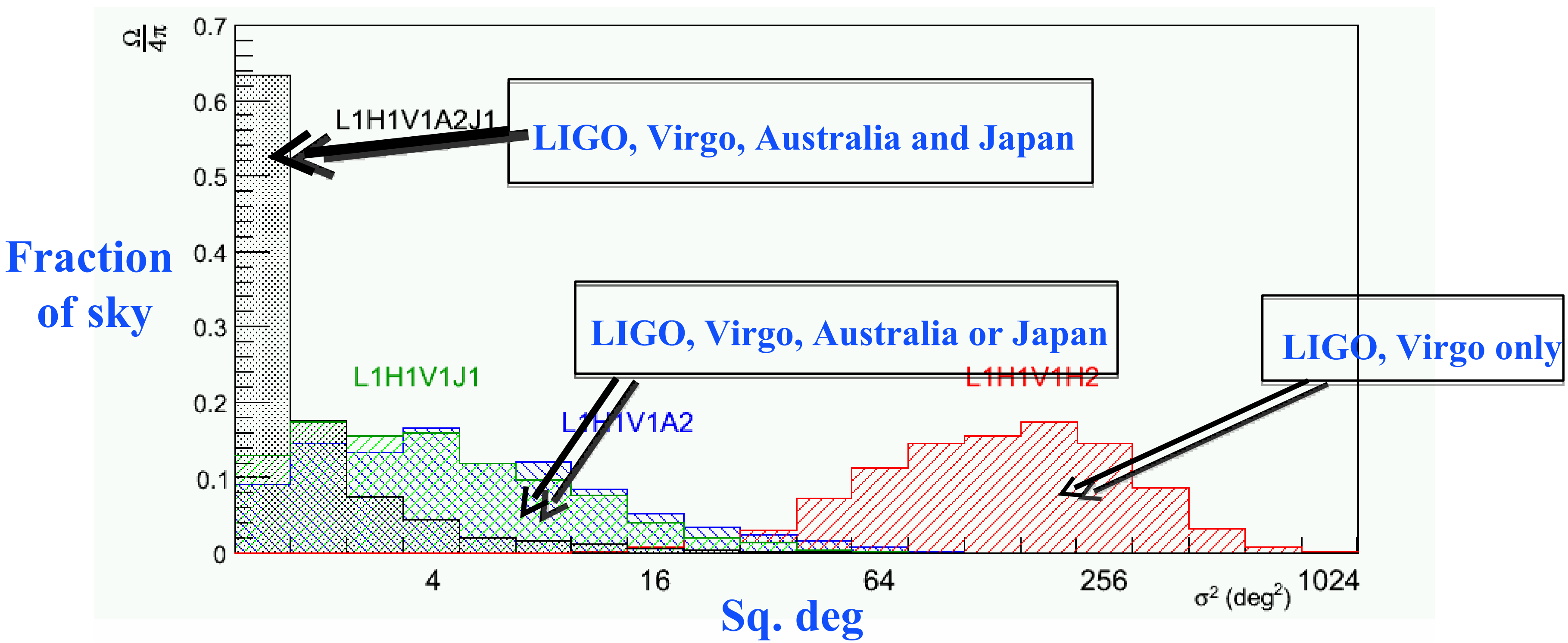


Adding LIGO-Australia to existing network gives nearly all-sky coverage

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, must begin installation of the LIGO-Australia detector at LHO

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

Progress toward LIGO-Australia

- Australian population and economy ~7% of US => Project >$100M is a BIG project
  - One year isn't a lot of time to react
- LIGO Laboratory proposed it to NSF
  - Reviewed by NSF panel—strong endorsement
  - NSF informed National Science Board and received approved
- Five ACIGA universities have signed MOU for project
  - Five of the "Group of Eight" major research universities
  - "Acting" Project Director (SW) appointed
- Indian Collaboration (IndIGO) exploring opportunities for participation

What Needs to be Done?

- Scale of Australian investment ("Landmark" scale) will require partnership among Universities, State Government, Federal Government
- Formal proposal in final stages
- Will almost certainly require Australian Government Cabinet action to create funding line
  - » Political considerations will be as important as scientific ones
  - » International partners could play a crucial role!
- Prospects still very uncertain

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
- A worldwide network is starting to come on line
  - » Groundwork has been laid for operation as a integrated system
  - » Australia and India could play a key role