Building a Global Gravitational Wave Telescope

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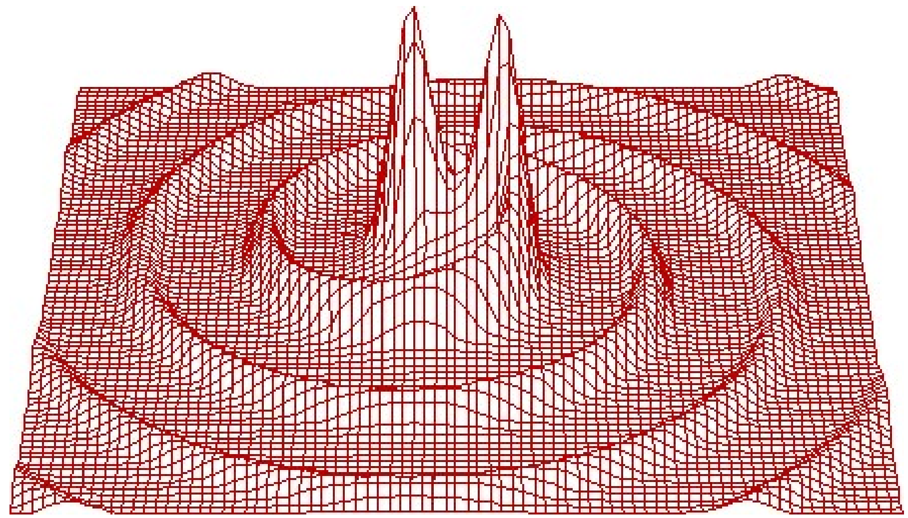
Gravitational Waves

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

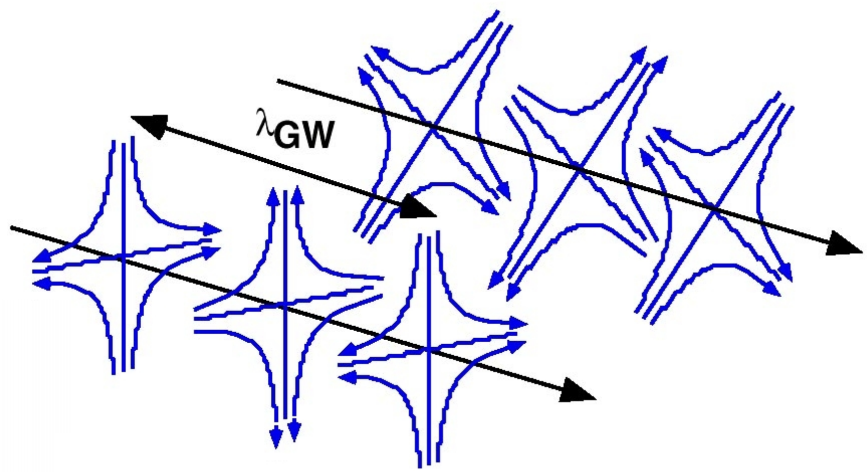
- **Necessary consequence of Special Relativity with its finite speed for information transfer**



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**

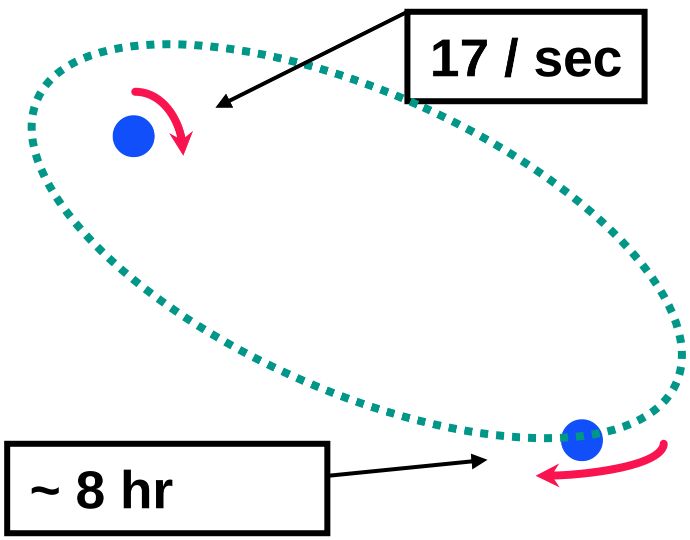


$$h = \Delta L / L$$

Evidence for Gravitational Waves

Binary Neutron Star System

PSR 1913 + 16

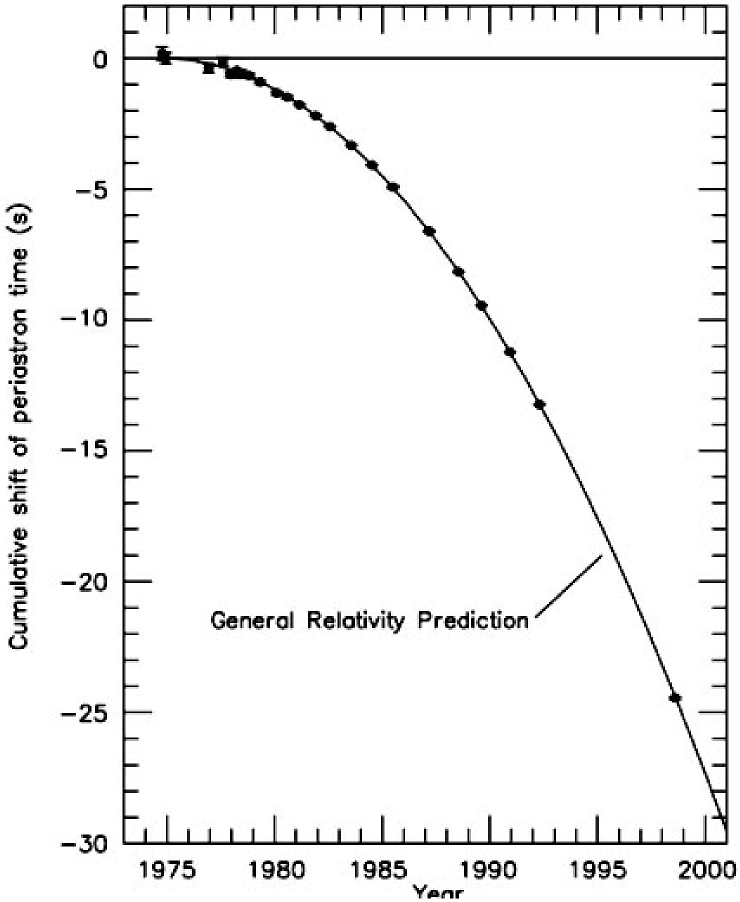


- **Discovered by Hulse and Taylor in 1975**
- **Unprecedented laboratory for studying gravity**
  - » **Extremely stable spin rate**
- **Possible to repeat classical tests of relativity (Shapiro delay, advance of "perihelion", etc.**

Binary Pulsar Timing Results

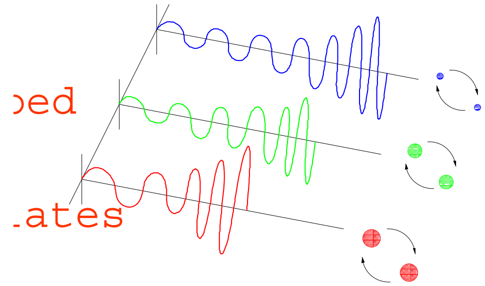
- After correcting for all known relativistic effects, observe steady loss of orbital energy
- Advance of periastron by an extra 25 sec from 1975-98
- Measured to ~50 msec accuracy
- Deviation grows quadratically with time

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

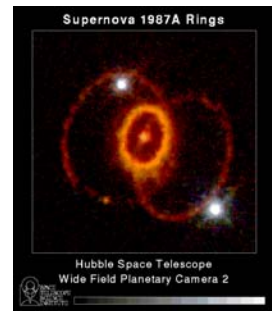


Astrophysical Sources for Terrestrial GW Detectors

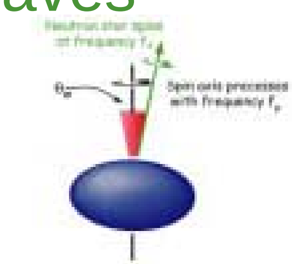
- Compact binary inspiral: "chirps"
  - » **NS-NS, NS-BH, BH-BH**



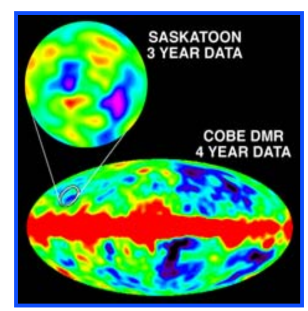
- Supernovas or long GRBs: "bursts"
  - » **GW signals observed in coincidence with EM or neutrino detectors**



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

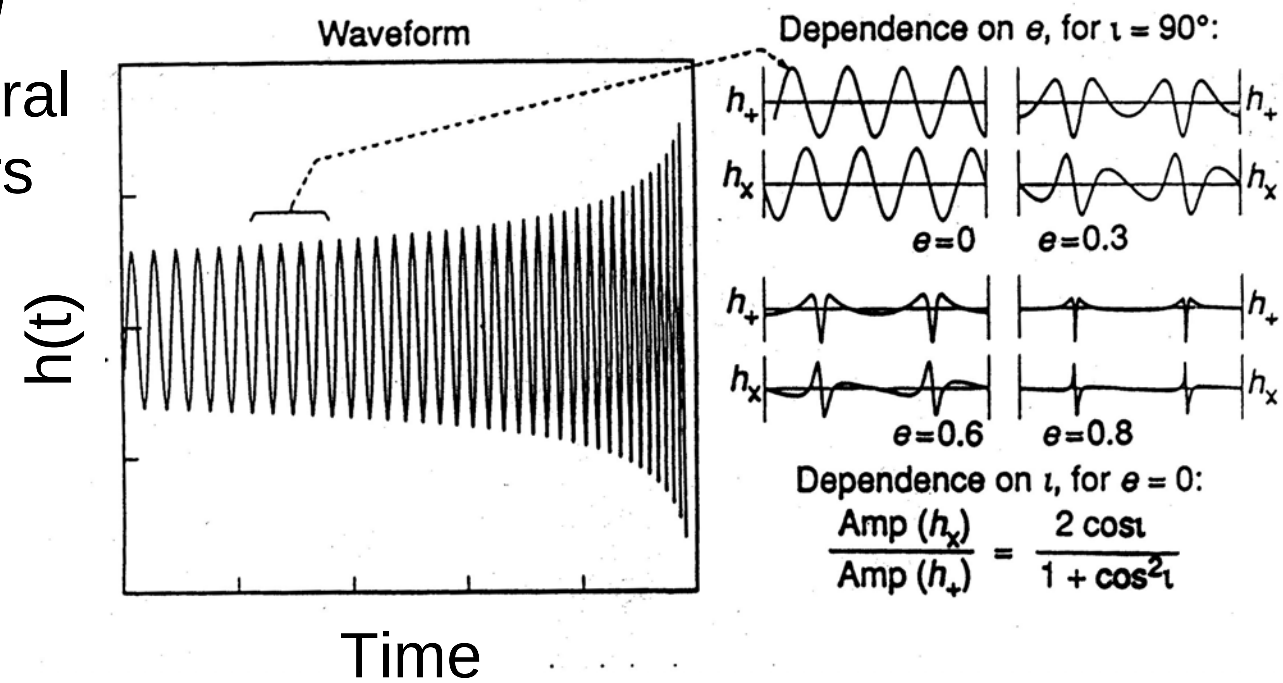


- Cosmological: "stochastic background"
  - » **Probe back to the Planck time (10^{-43} s)**



Using GWs to Learn about the Sources: an Example

Chirp Signal
from binary inspiral as system nears merger



<u>Can determine</u>

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

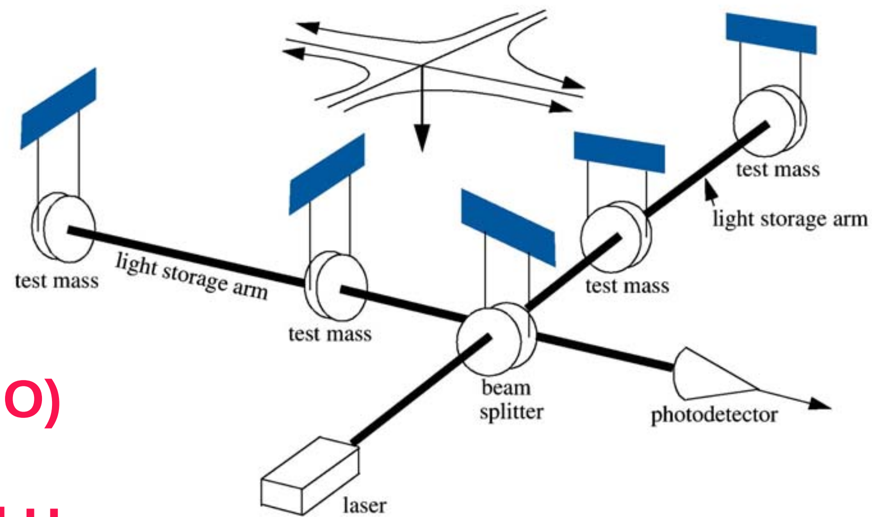
Breadth of Science with Compact Binary Inspirals

- Fundamental Physics
  - » Waveforms from black hole – black hole mergers are a pure test of General Relativity in its most non-linear regime
  - » Mass-radius relationship for neutron star tests equation of state of nuclear matter
- Astronomy
  - » Neutron star – neutron star mergers likely source of short hard gamma ray bursts
    - – Masses of GRB progenitors
    - – Geometry of jets: opening angle, opening angle versus mass, …
  - » Population census of double black hole binaries
- Cosmology
  - » Independent luminosity distance scale for confirming redshift-distance relationship

Detecting GWs with Interferometry

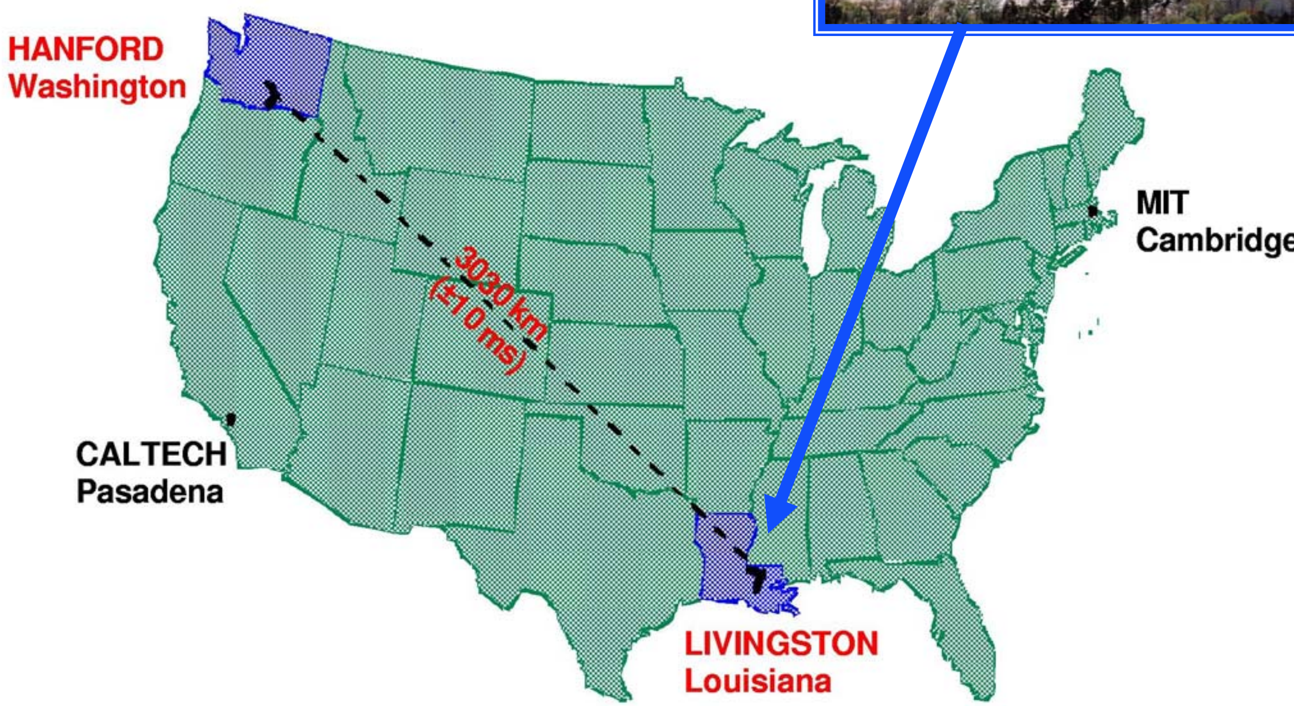
Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies $f >> f_{pend}$

$$h = \Delta L / L$$

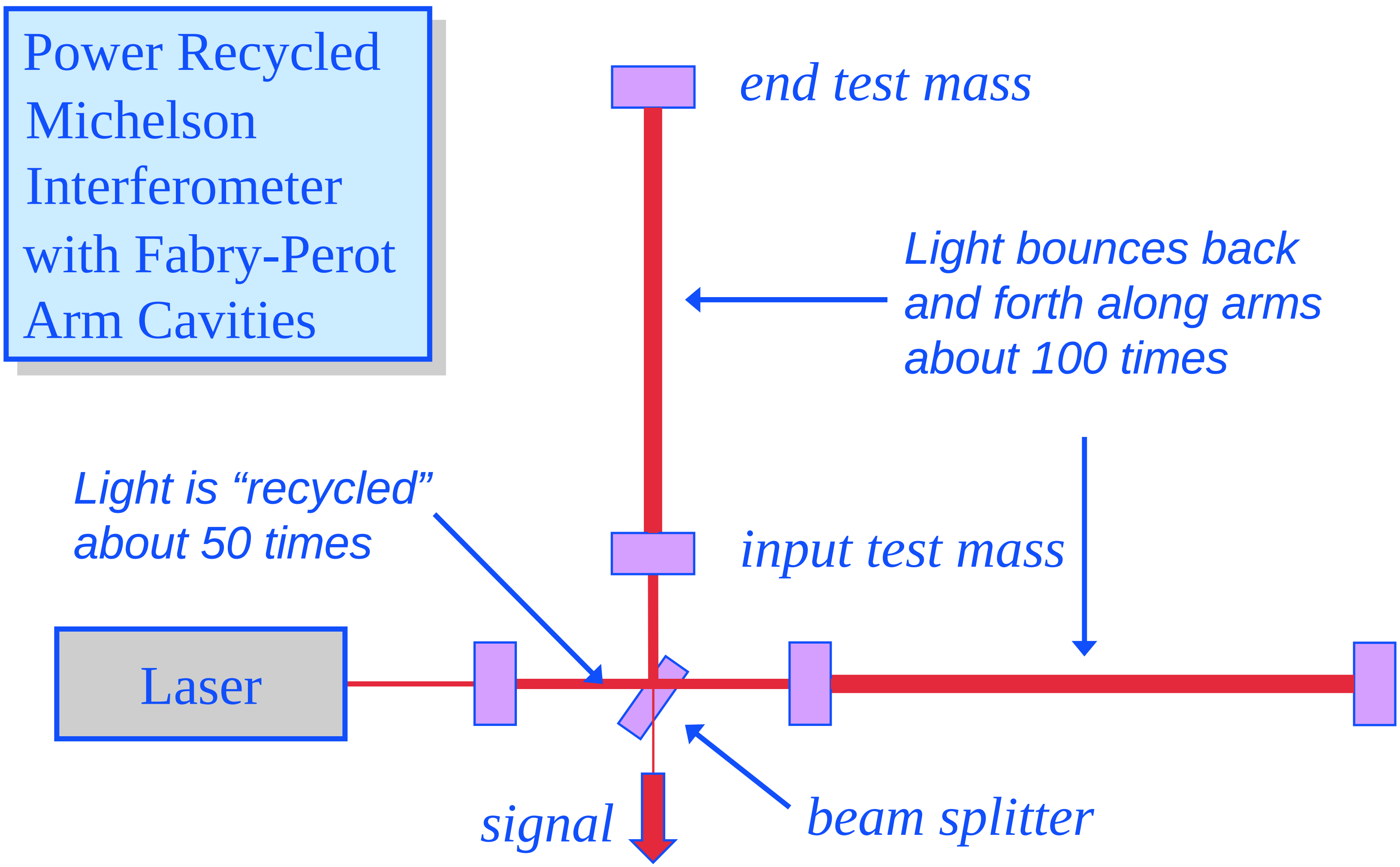


Terrestrial detector,
L ~ 4 km
For $h \sim 10^{-22} - 10^{-21}$ (Initial LIGO)
$\Delta L \sim 10^{-18}$ m
Useful bandwidth 10 Hz to 10 kHz, determined by "unavoidable" noise (at low frequencies) and expected maximum source frequencies (high frequencies)

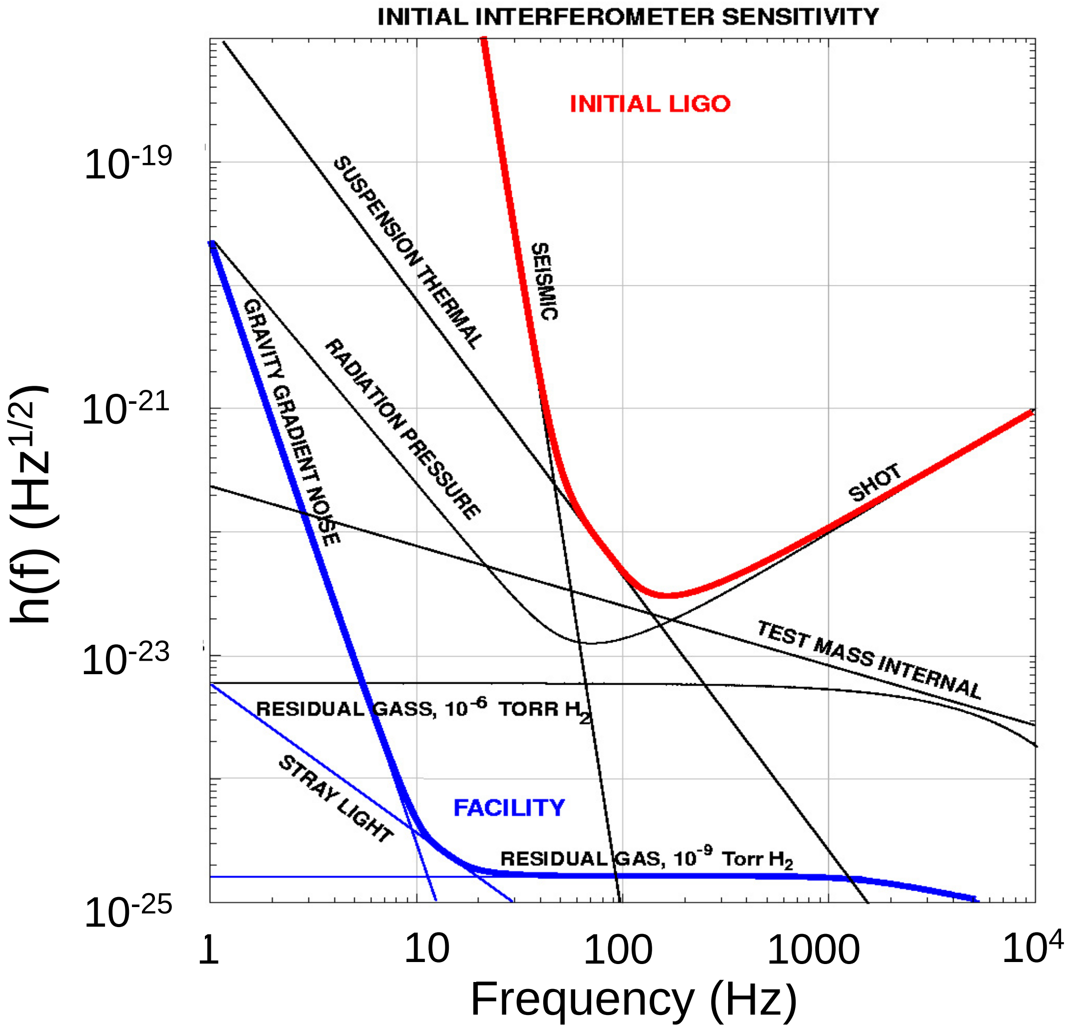
Laser Interferometer Gravitational-wave Observatory (LIGO)



LIGO Optical Configuration

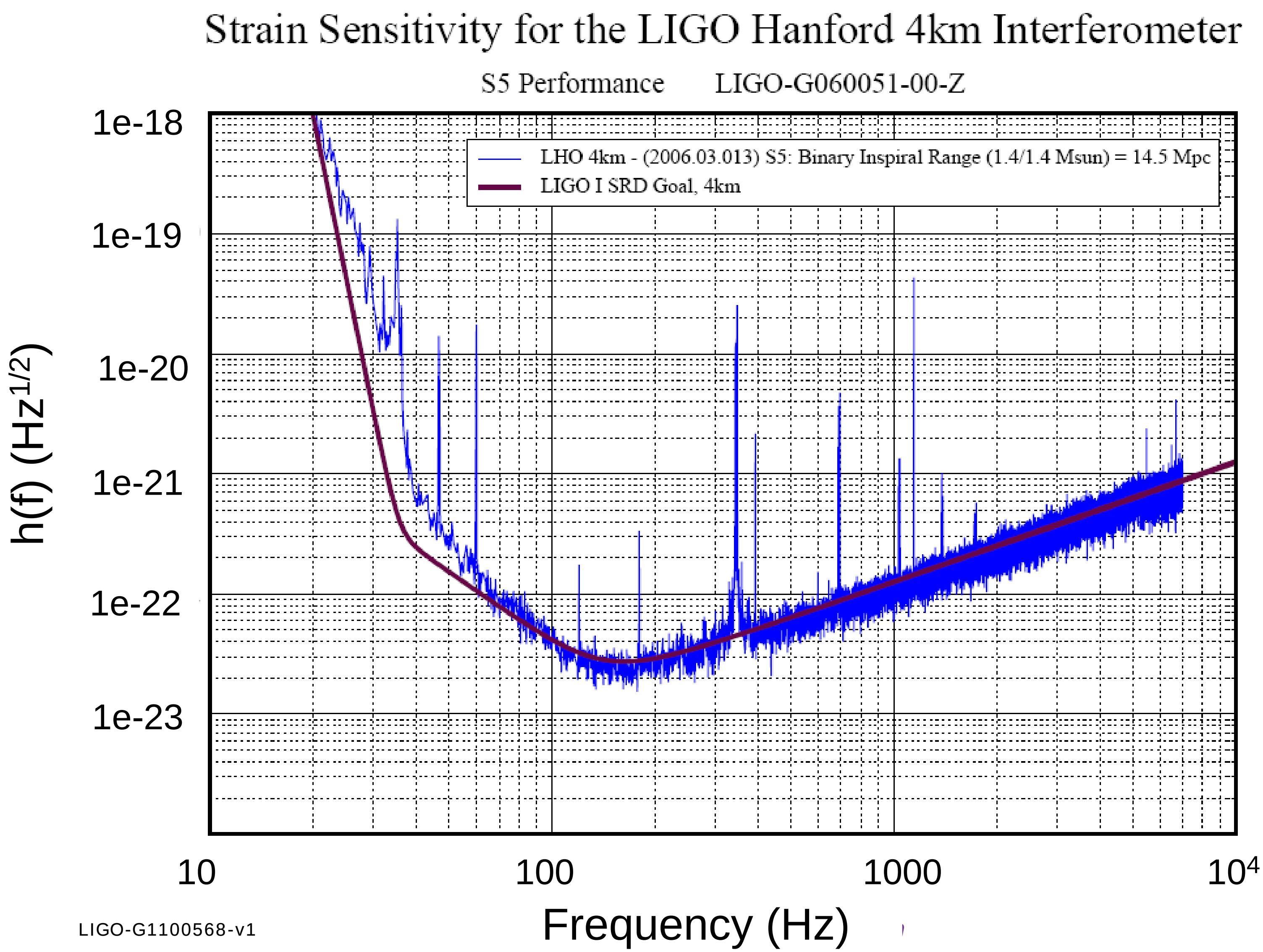


Initial LIGO Sensitivity Goal

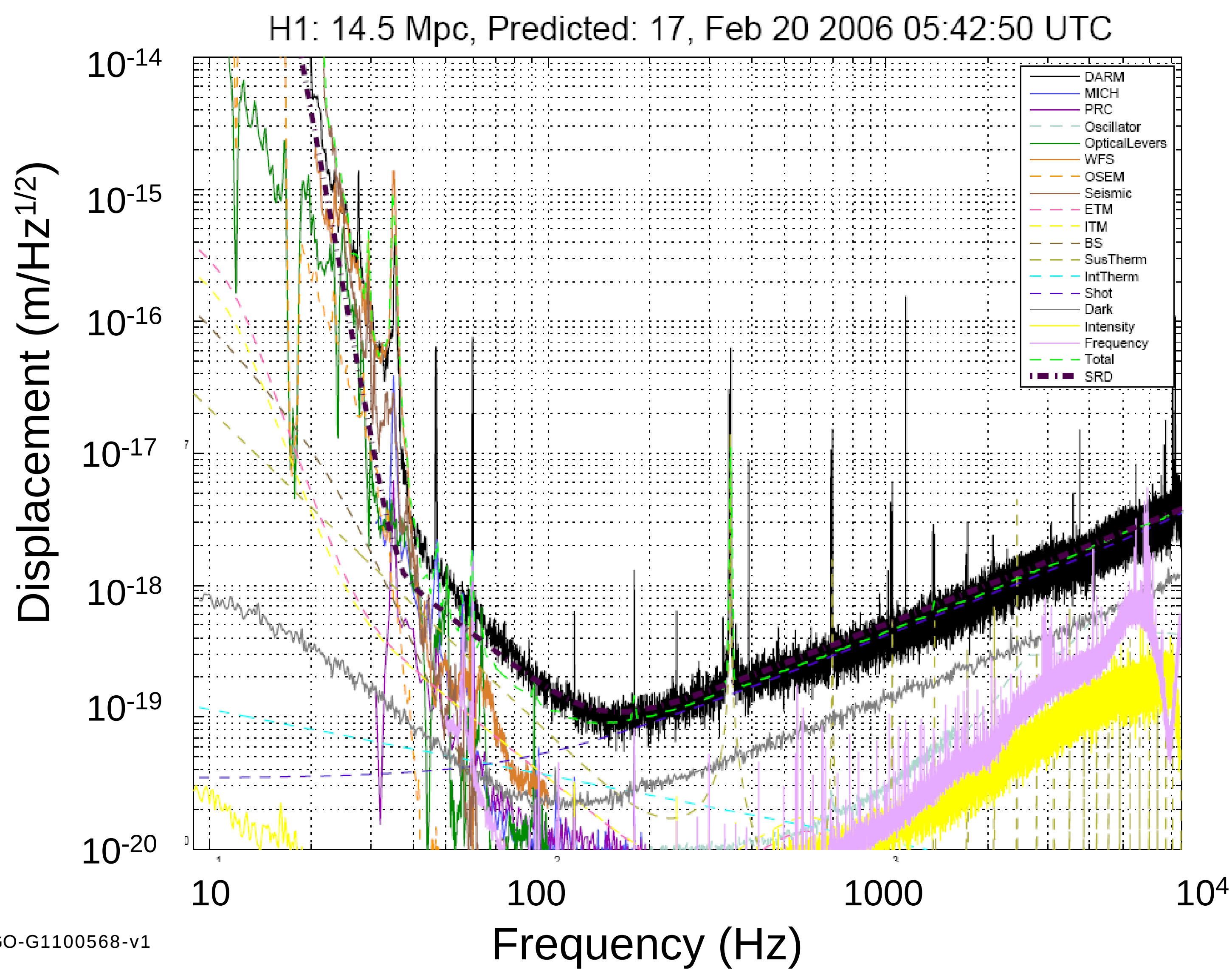


- Strain sensitivity $<3 \times 10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

LIGO Sensitivity



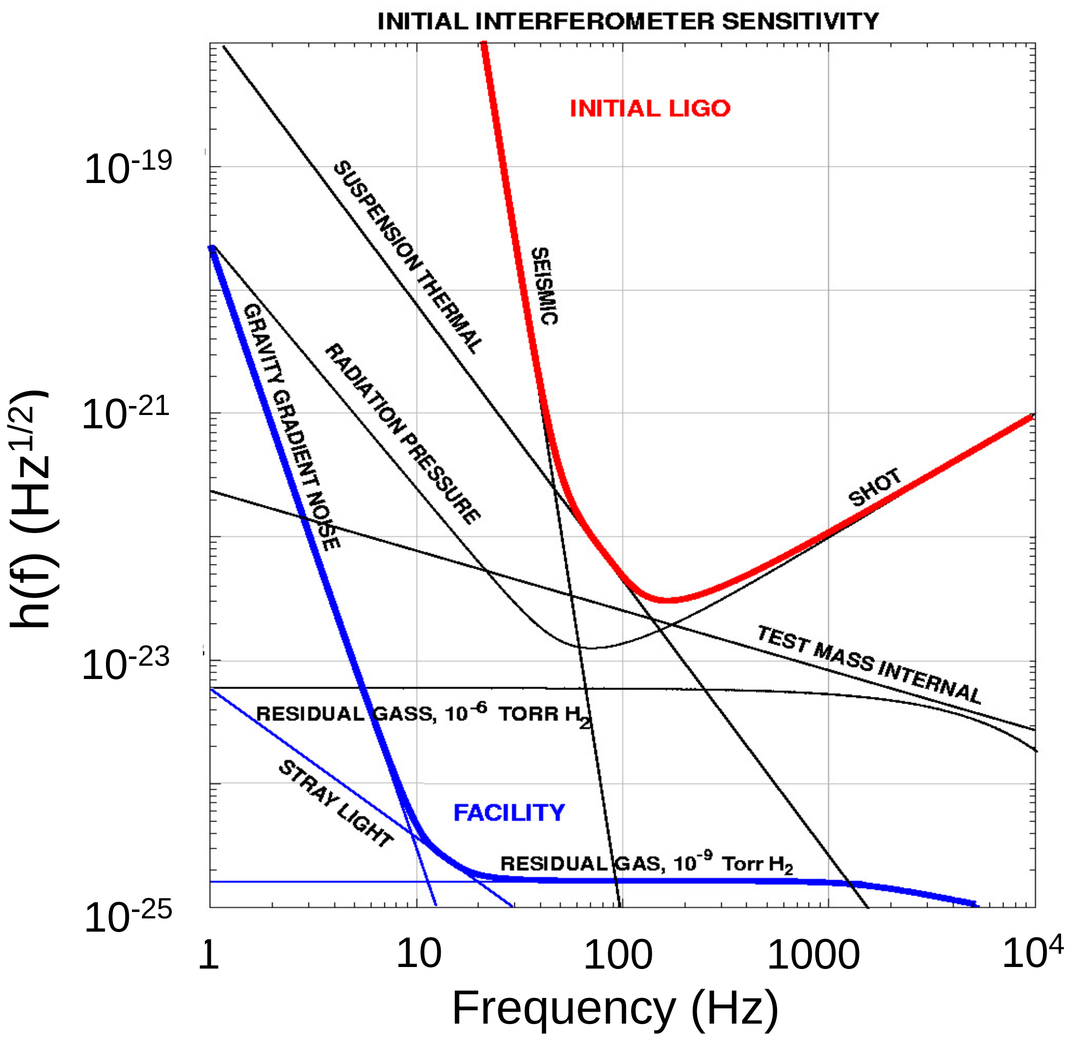
Anatomy of a Noise Curve



Initial LIGO Observations

- 25+ years of R&D, design, construction and commissioning led to Initial LIGO design sensitivity in 2005
- Two extended science data-taking runs
- S5 (2005-2007)
  - » Two years calendar time for one year of coincidence data
- S6 (2009-2010)
  - » 15 months calendar time for ~6 months coincidence data
- No gravitational waves found (so far)
- Some useful upper limits on gravitational wave strengths and rates

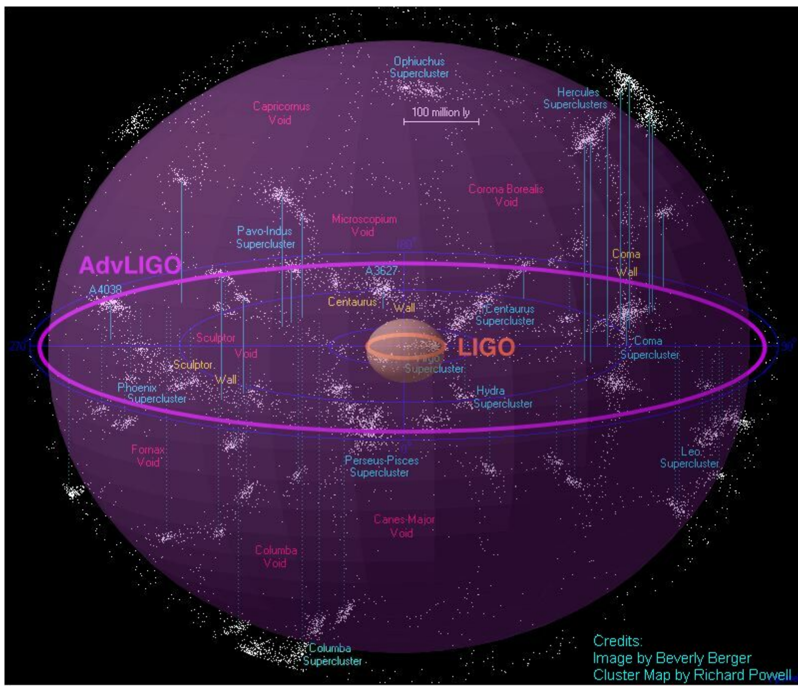
Facility Limits to Sensitivity



- Designed with second phase in mind
- Facility limits leave lots of room for future improvements

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

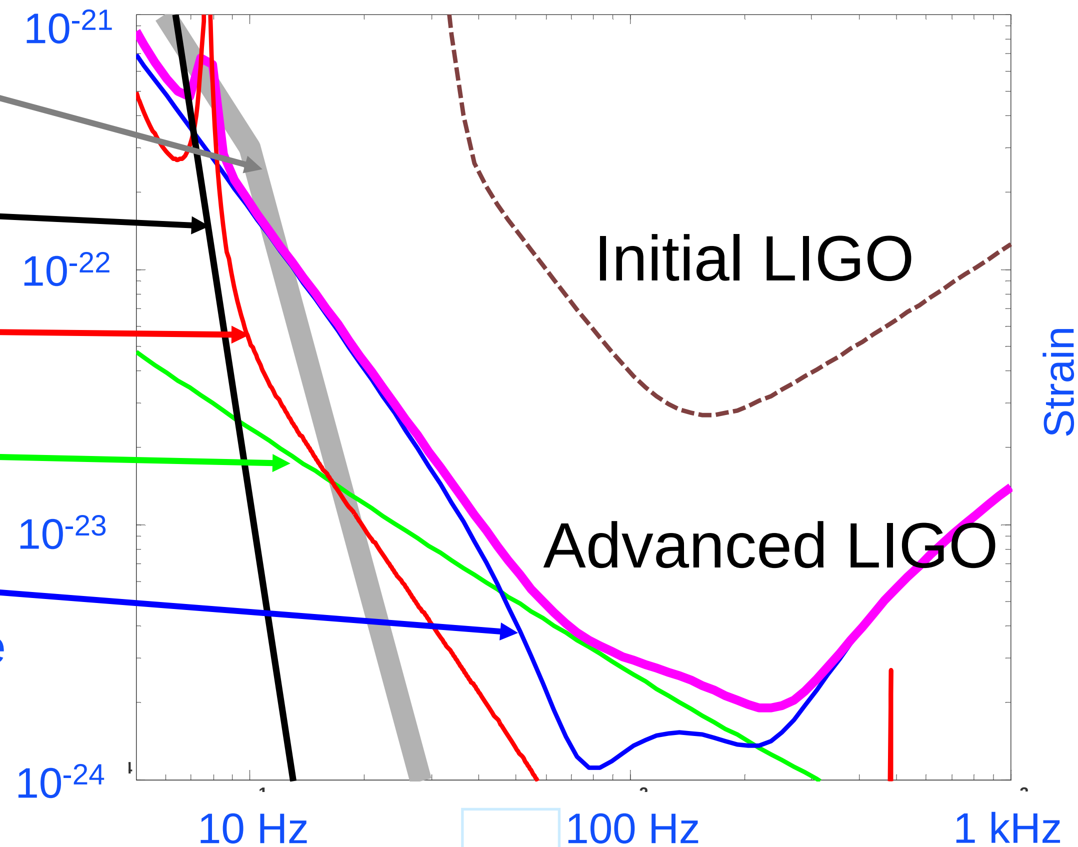
$\Rightarrow$ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

Project start 2008,
installation beginning 2011

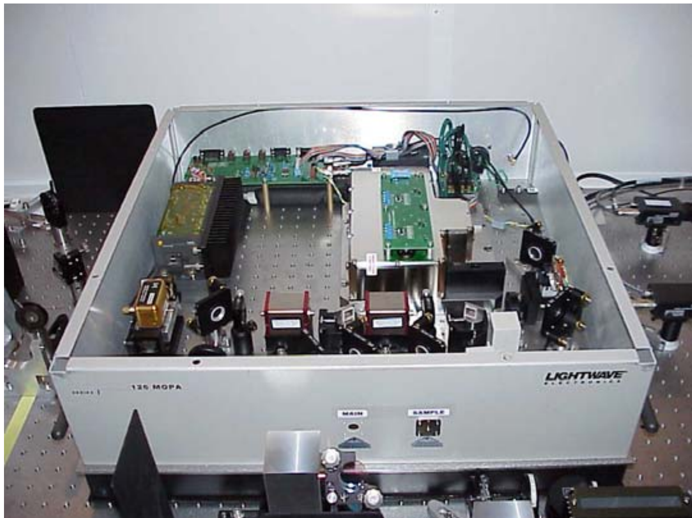
Advanced LIGO Performance

- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Quantum noise (shot noise and radiation pressure noise) dominates at most frequencies

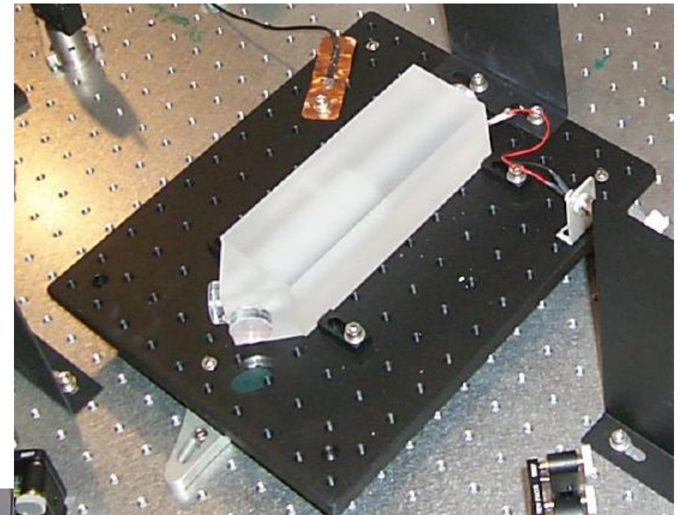


What makes Advanced LIGO so "Advanced"

Initial LIGO Laser



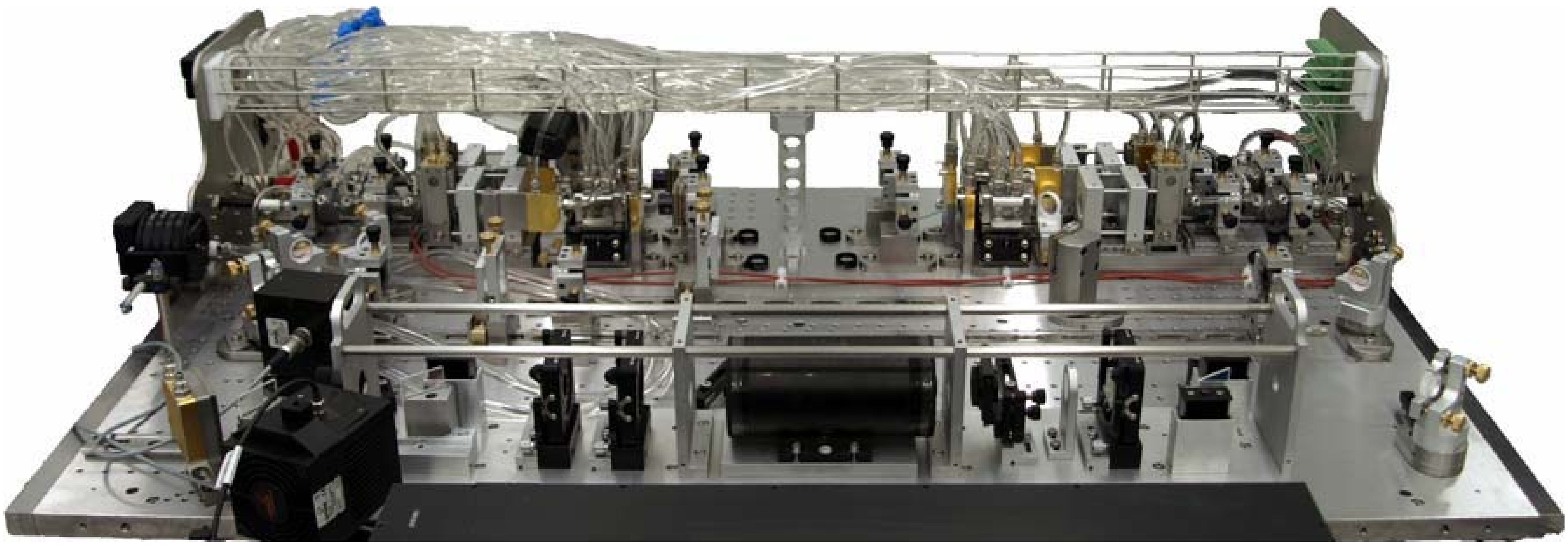
Custom-built
10 W
Nd:YAG
Laser



Stabilization
cavities
for frequency
and beam shape

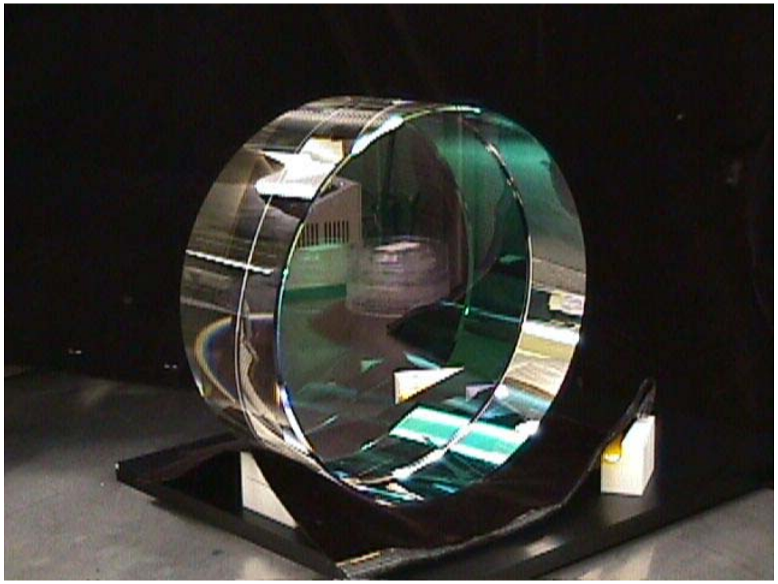
Advanced LIGO Laser

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

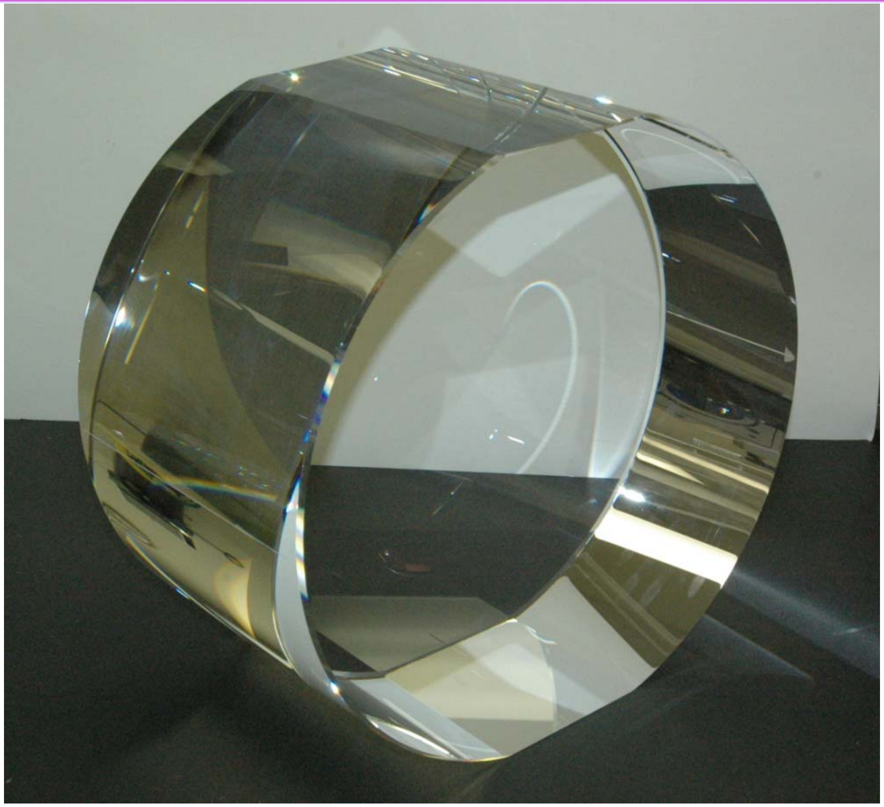


Initial LIGO Mirrors

- 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}



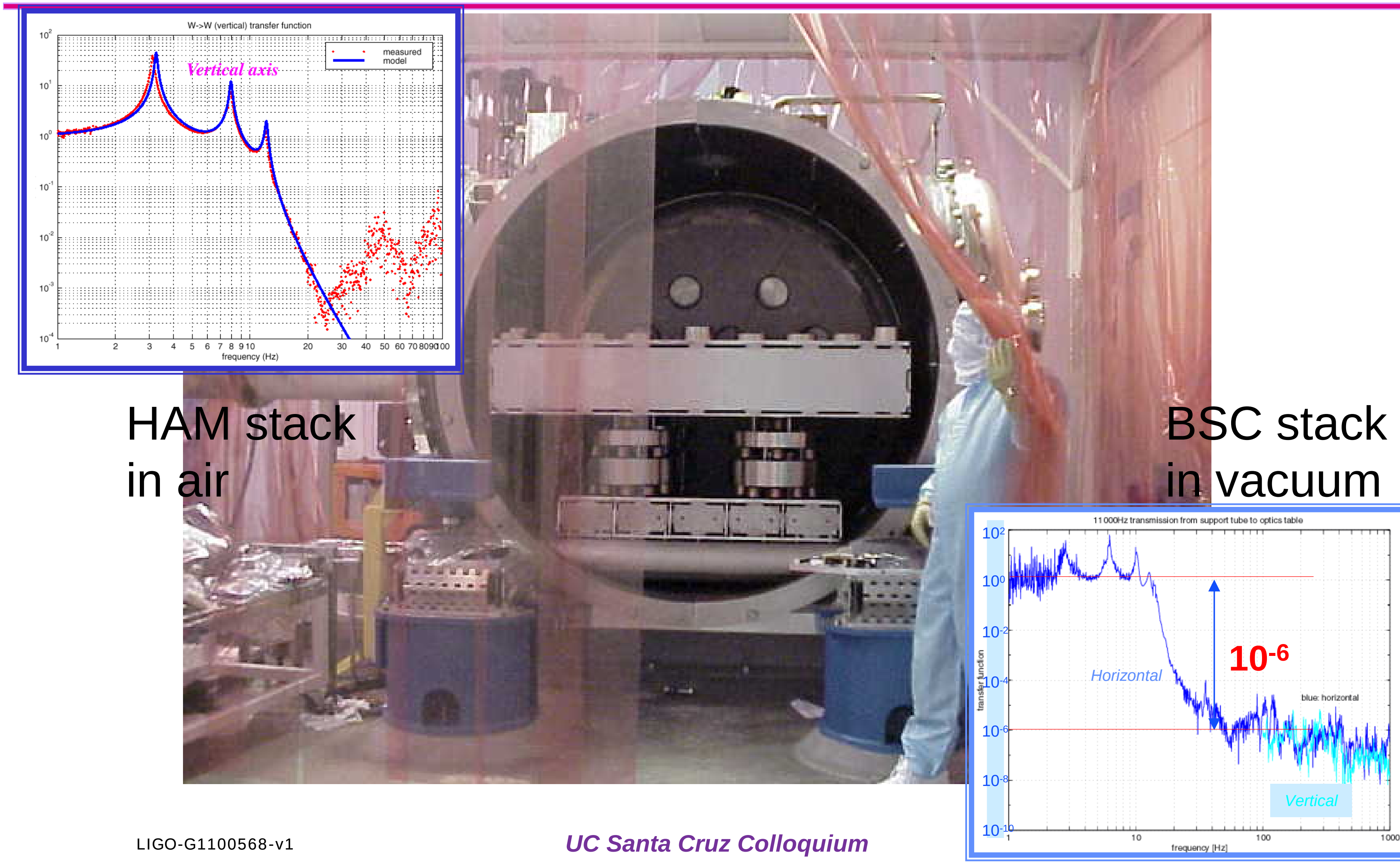
Advanced LIGO Mirrors



- Larger size
  - » 11 kg -> 40 kg
- Smaller figure error
  - » 1 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



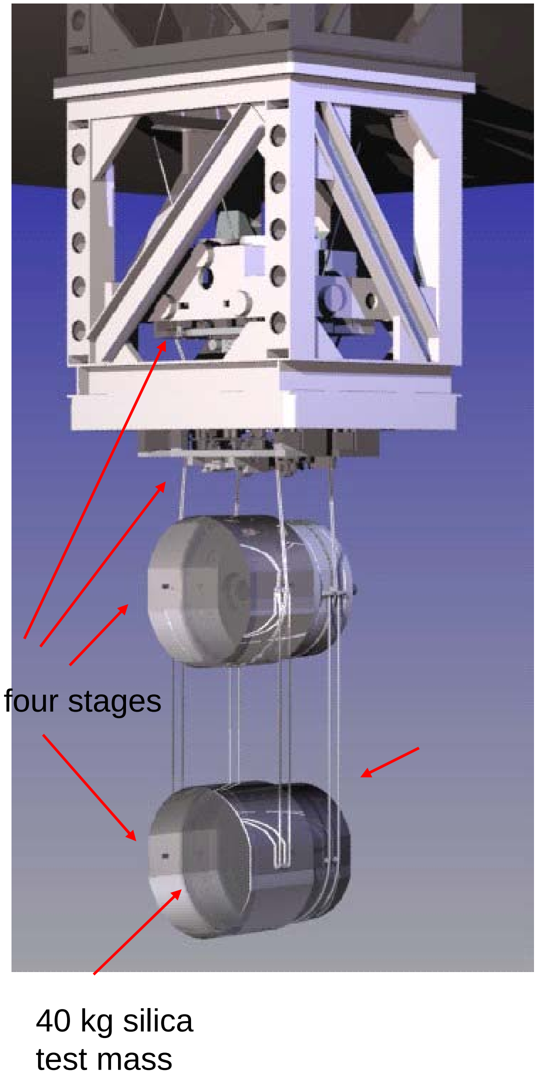
Advanced LIGO Seismic Isolation

- 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



- 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

Advanced LIGO Status

- Construction of components started 2008
- Installation began October 2010

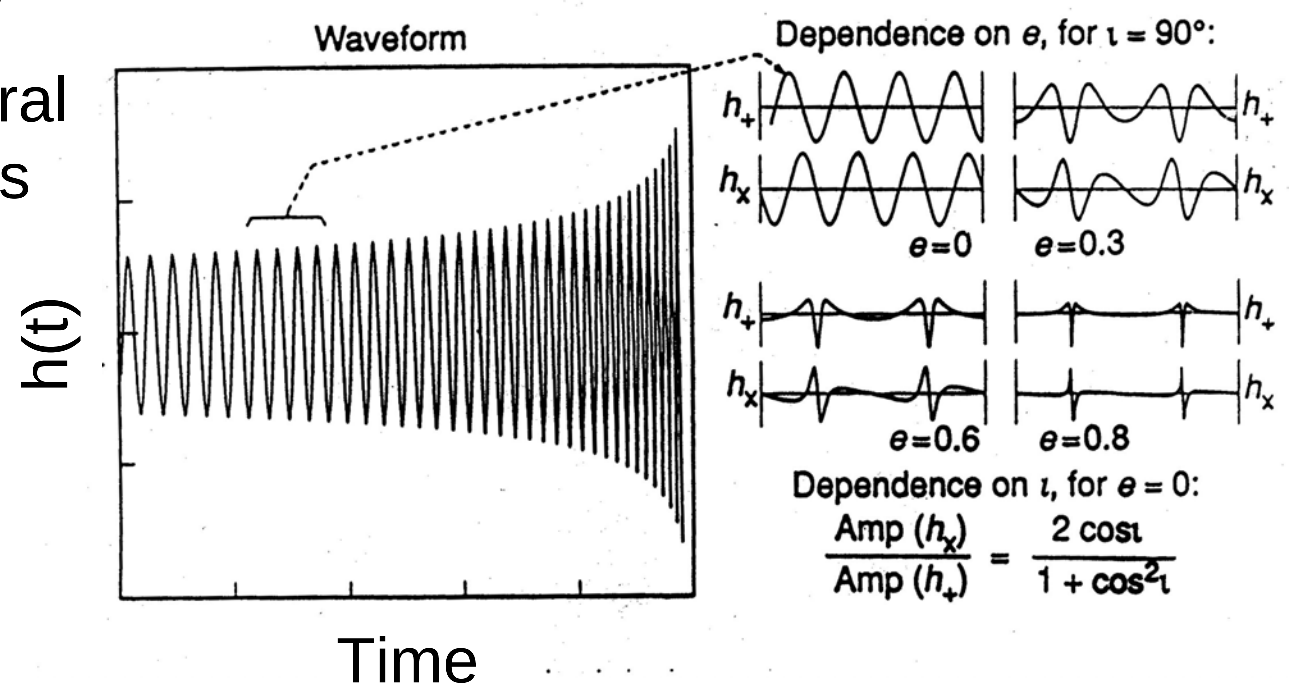
UC Santa Cruz

2015

Using GWs to Learn about the Sources: an Example

Chirp Signal

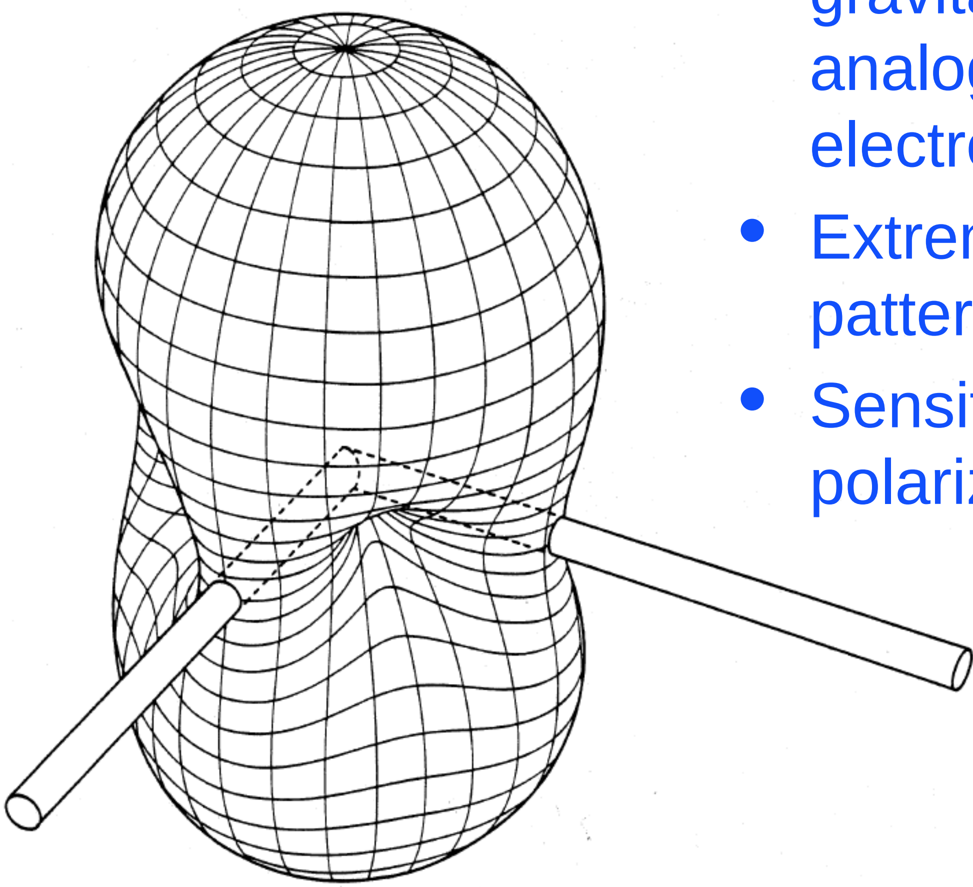
from binary inspiral as system nears merger



<u>Can determine</u>

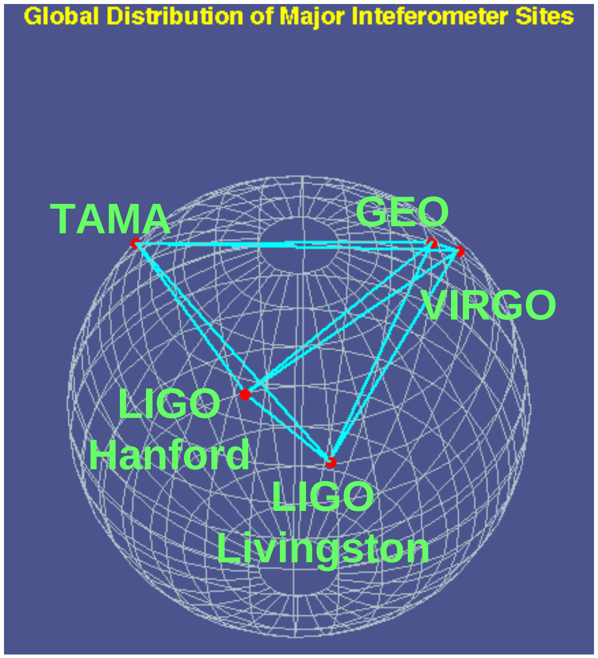
- **Masses of the two bodies**
- **Orbital eccentricity e and orbital inclination *i***
- **Distance from the earth r**

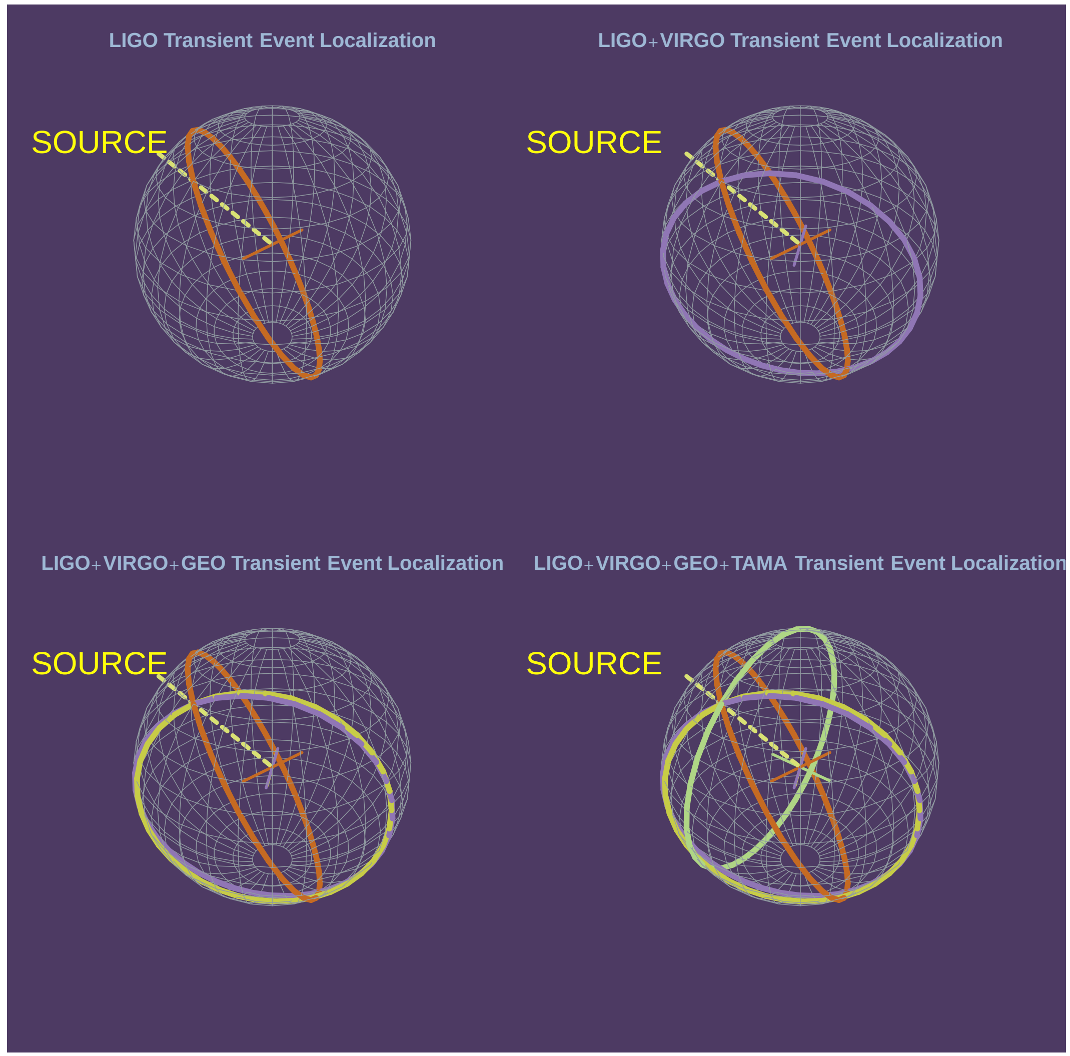
Directionality and Polarization Sensitivity



- Michelson interferometer for gravitational wave detection is analogous to an electromagnetic dipole antenna
- Extremely broad antenna pattern
- Sensitive to a single (linear) polarization

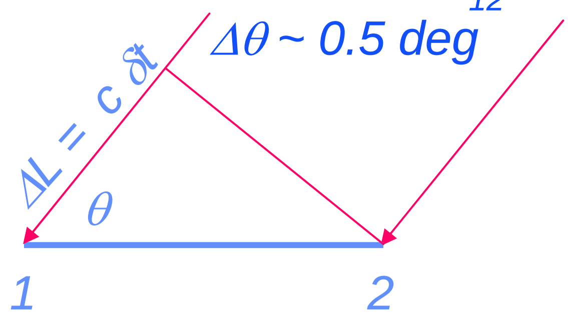
Event Localization with Array of Detectors ("Aperture Synthesis")



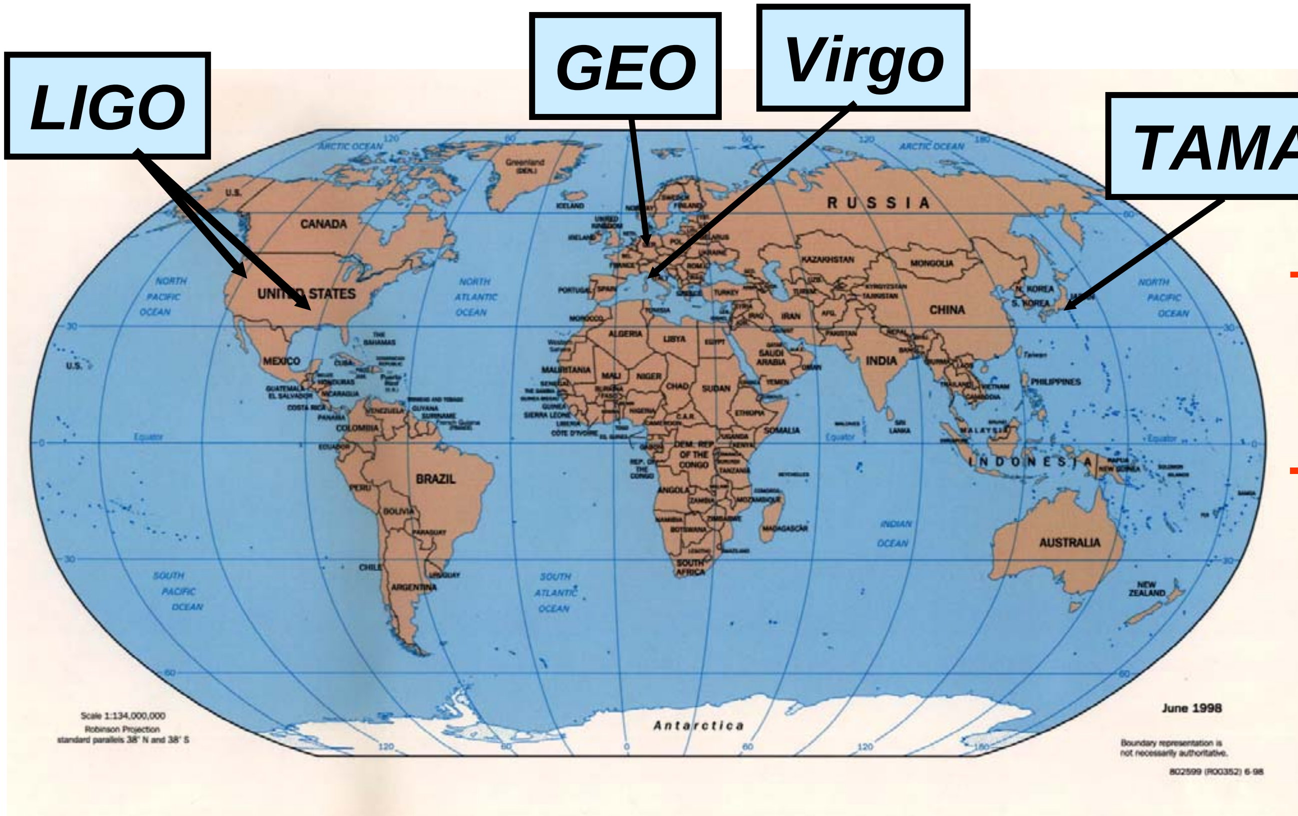


$\Delta\theta \sim c\ \delta t\ / D_{12}$

$\Delta\theta \sim 0.5$ deg



A Global Network of GW Detectors (2009)



++ Global interest in GW science

-- Multiple independent projects

Gravitational Wave Interferometers Around the World

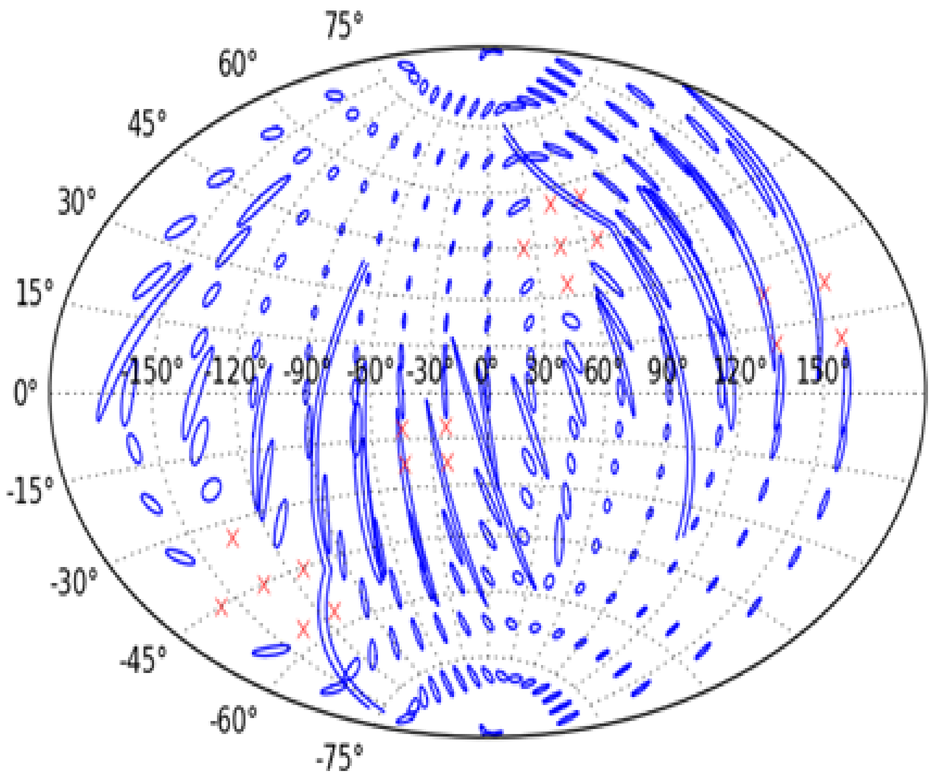
Virgo

- Virgo
  - » Italian, French, Dutch collaboration, located near Pisa
  - » Single 3 km interferometer, similar to LIGO in design and specification
  - » Advanced seismic isolation system (“Super-attenuator”)
  - » Operation in coincidence with LIGO since May 2007
- Future Improvements
  - » Advanced Virgo (similar in scope and time to Advanced LIGO)

LIGO-Virgo Agreement

- LIGO-Virgo signed data-sharing MOU in May 2007
  - » Not a merging of the two collaborations, but….
  - » All analyses, all observational publications to be joint after signing
  - » Joint run planning
  - » Hardware collaborations encouraged but not mandated
  - » Joint collaboration meetings
  - » LIGO-Virgo MOU explicitly invites other detectors to join when they reach a “useful” sensitivity

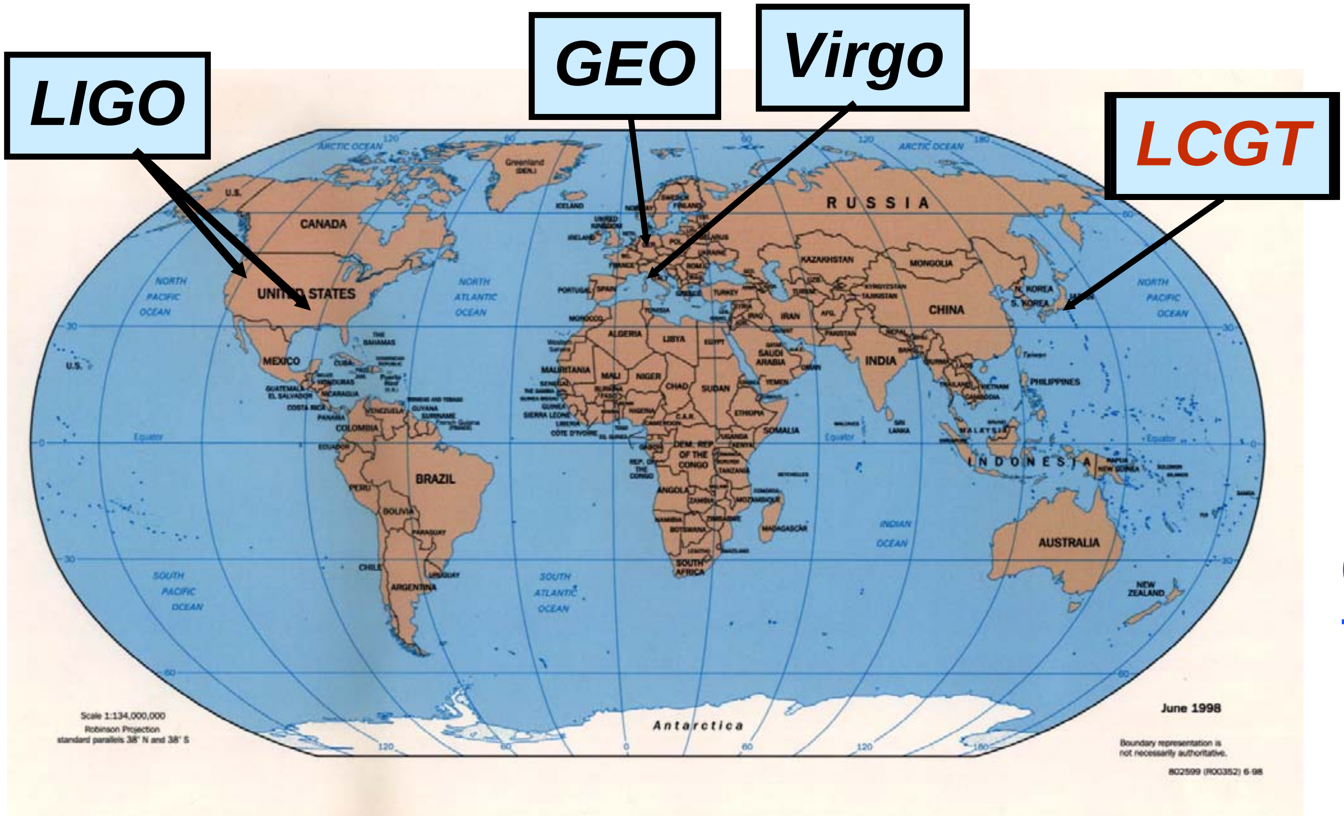
LIGO and Virgo Alone



Three detector "network" has good directional sensitivity perpendicular to plane of the detectors,

but limited ability to locate sources near the plane

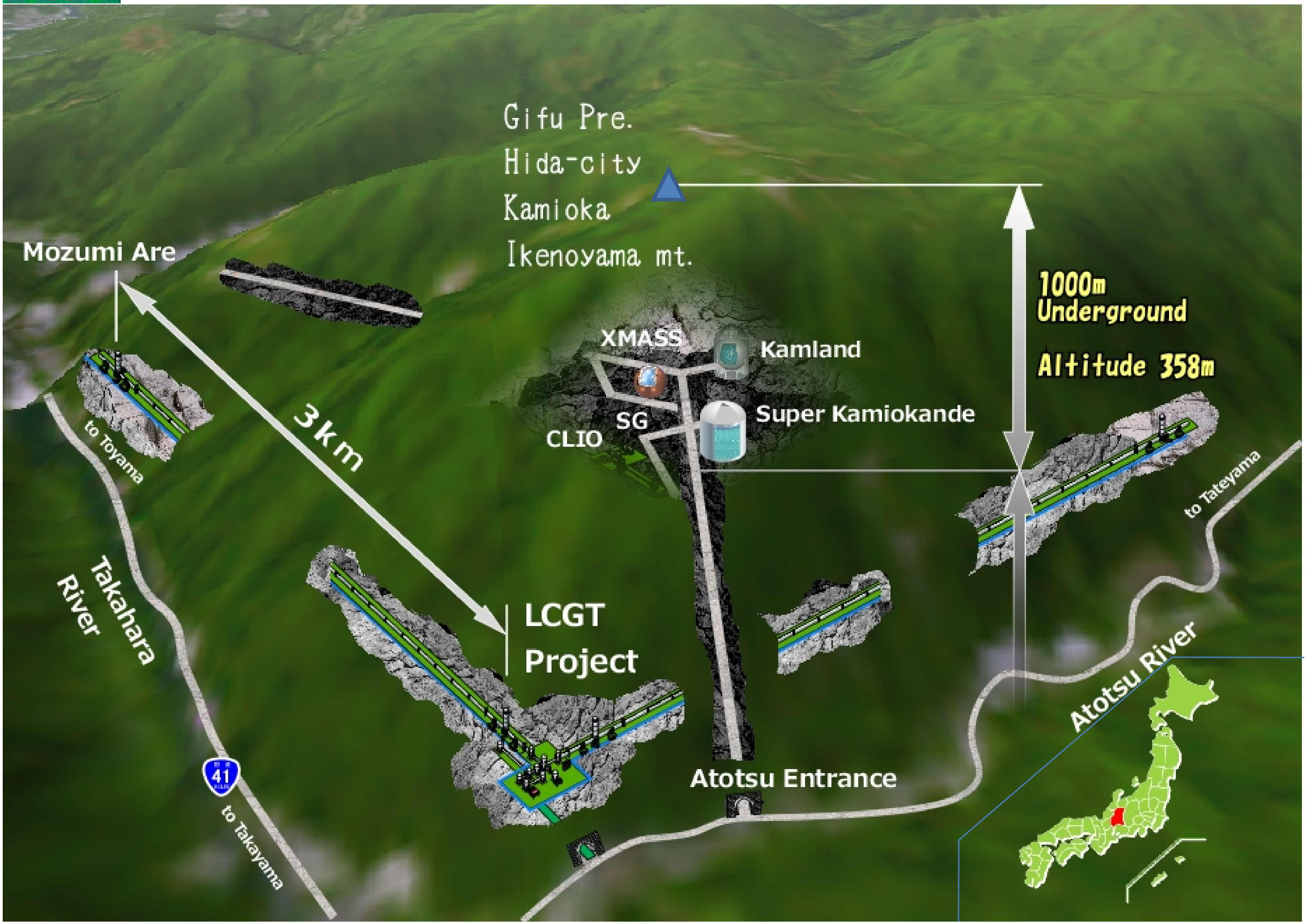
Completing the Global Network (Step 1)



New development in Japan:

Large Cryogenic gravitational Telescope (LCGT)

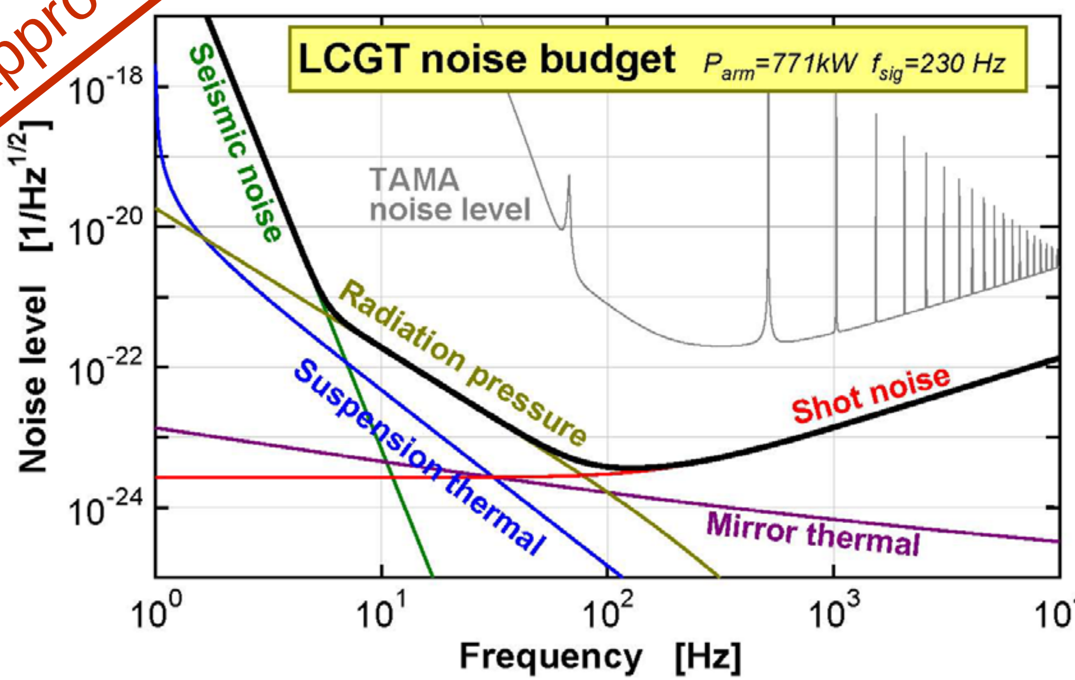
Large Cryogenic Gravitational-wave Telescope



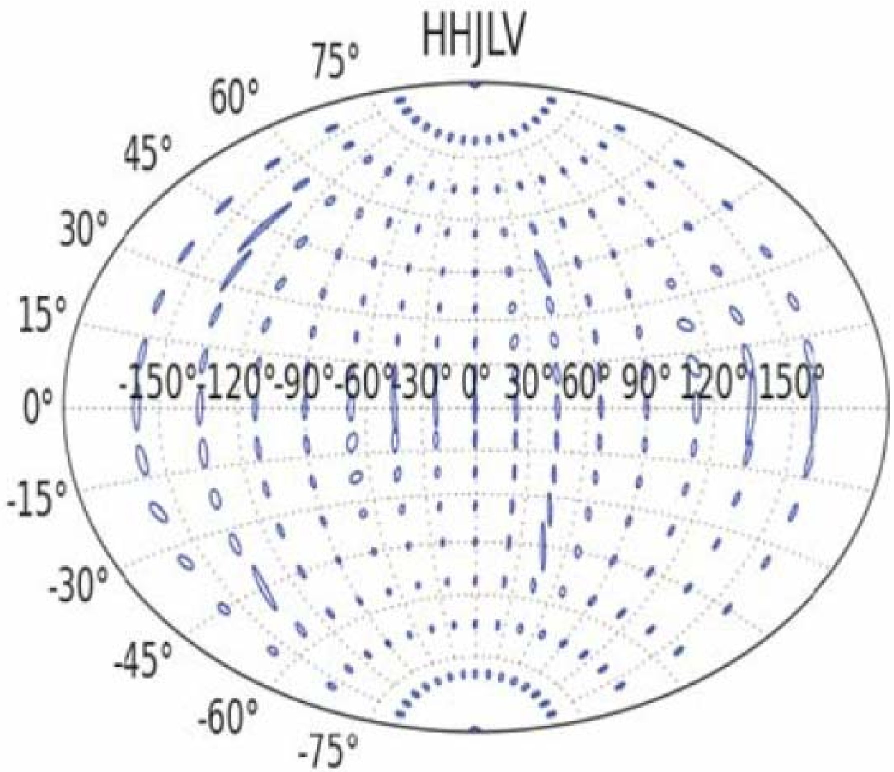
Large Cryogenic Gravitational-wave Telescope (LCGT)

- LCGT Project
  - » Institute for Cosmic Ray Research lead ins titution
  - » Other participants include University of , National Astronomical Observatory of Japan ...
- Key Design Parameters
  - » Underground (Kamioka m
  - » Sapphire test masses cooled to <20K
  - » 150W Nd:YAG
  - » Five stage frequency (s) suspension
  - » Promised initial sensitivity similar to Advanced LIGO

Funding Approved mid-2010



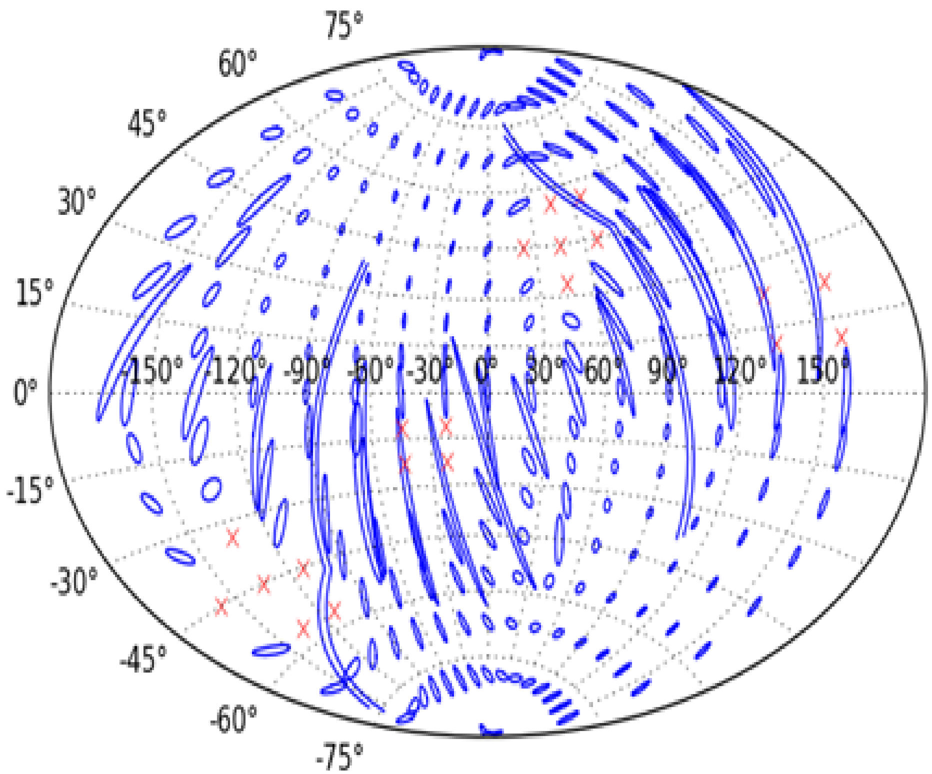
LIGO, Virgo, LCGT



Dramatic Improvement in source localization

Still a troublesome band of poorer localization near the equator

LIGO and Virgo Alone



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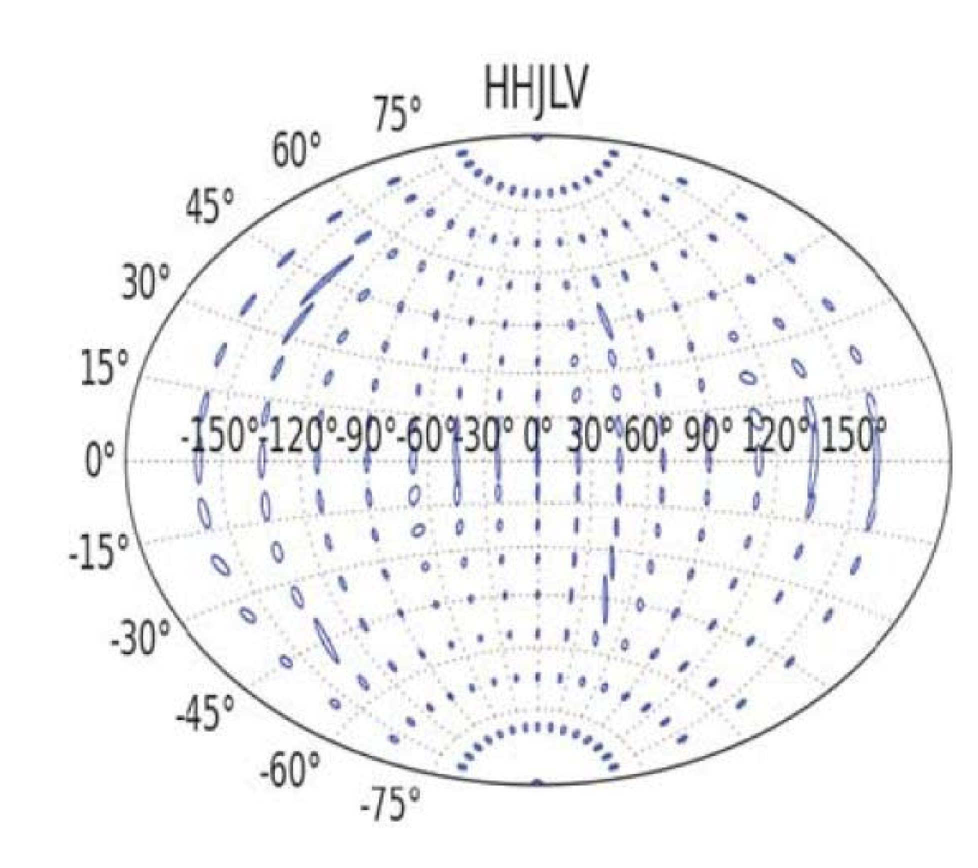
LIGO, Virgo, LCGT



Dramatic Improvement in source localization

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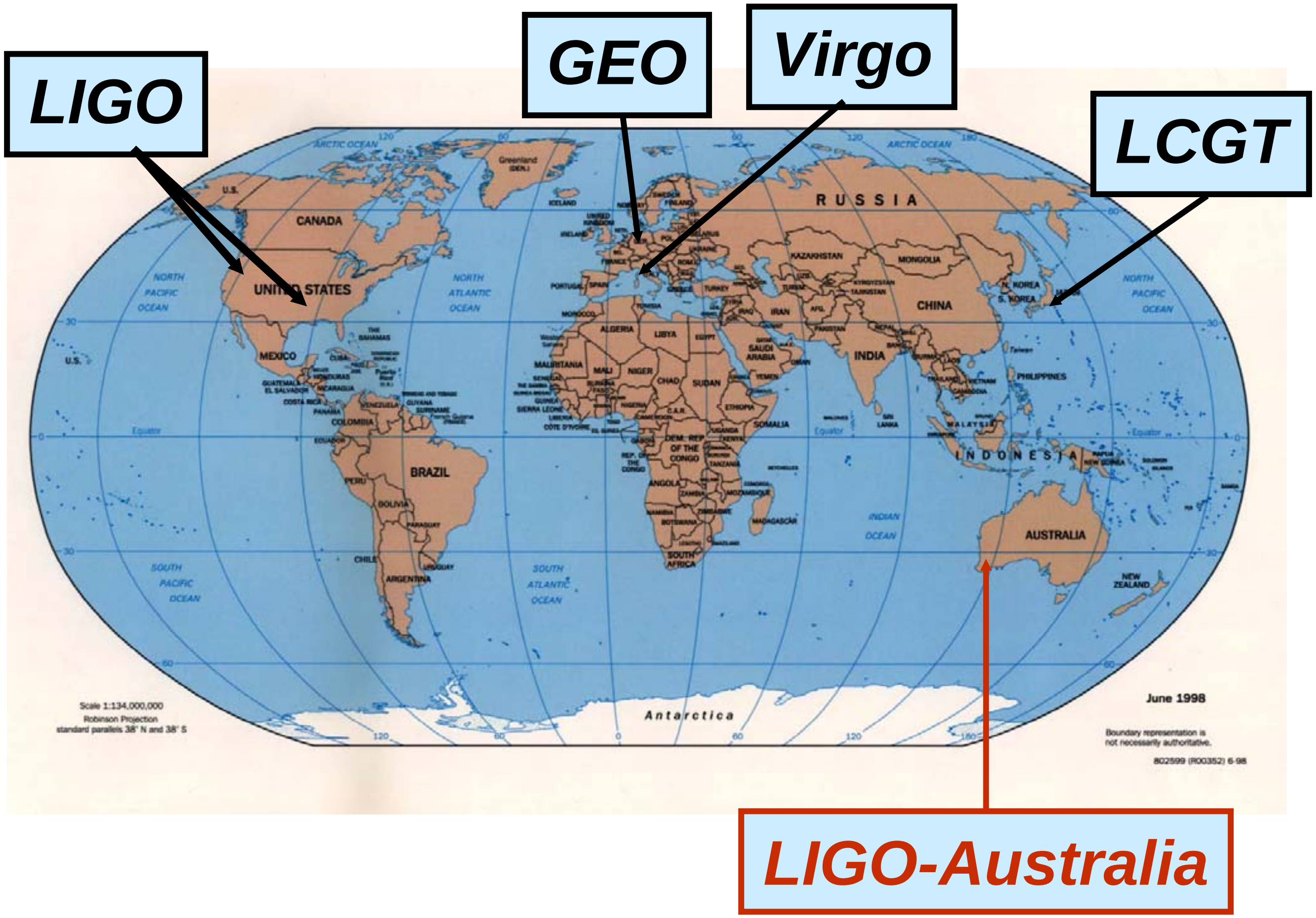
Completing the Global Network (Step 2)

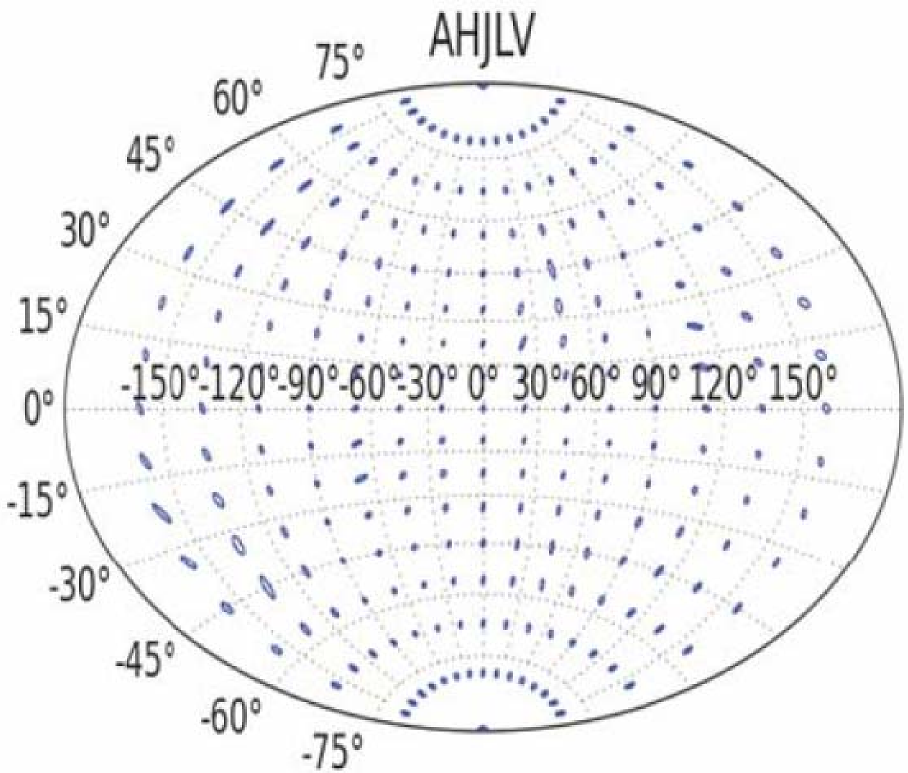


Add a Southern Hemisphere detector

LIGO-Australia

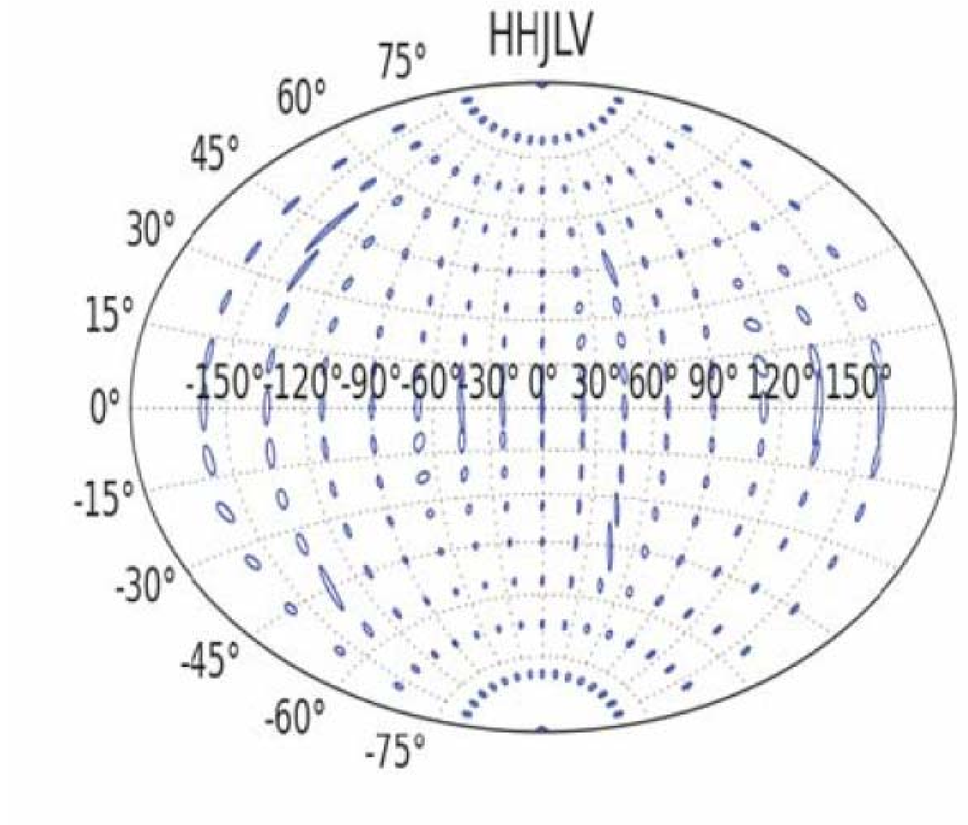
- Proposed as a direct partnership between LIGO Laboratory and our Australian collaborators
  - » LIGO Lab provides components for one Advanced LIGO interferometer
  - » Australia provides the infrastructure (site, roads, building, vacuum system), installation & commissioning, operating costs
- The interferometer, 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

LIGO, Virgo, LCGT Plus LIGO-Australia



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

LIGO, Virgo, LCGT



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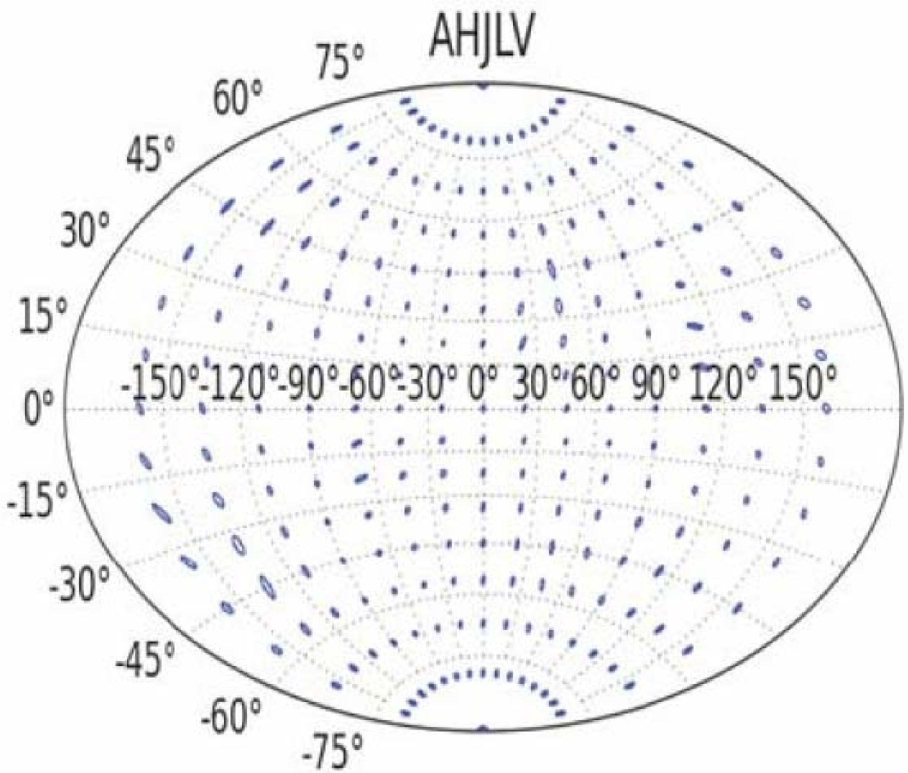
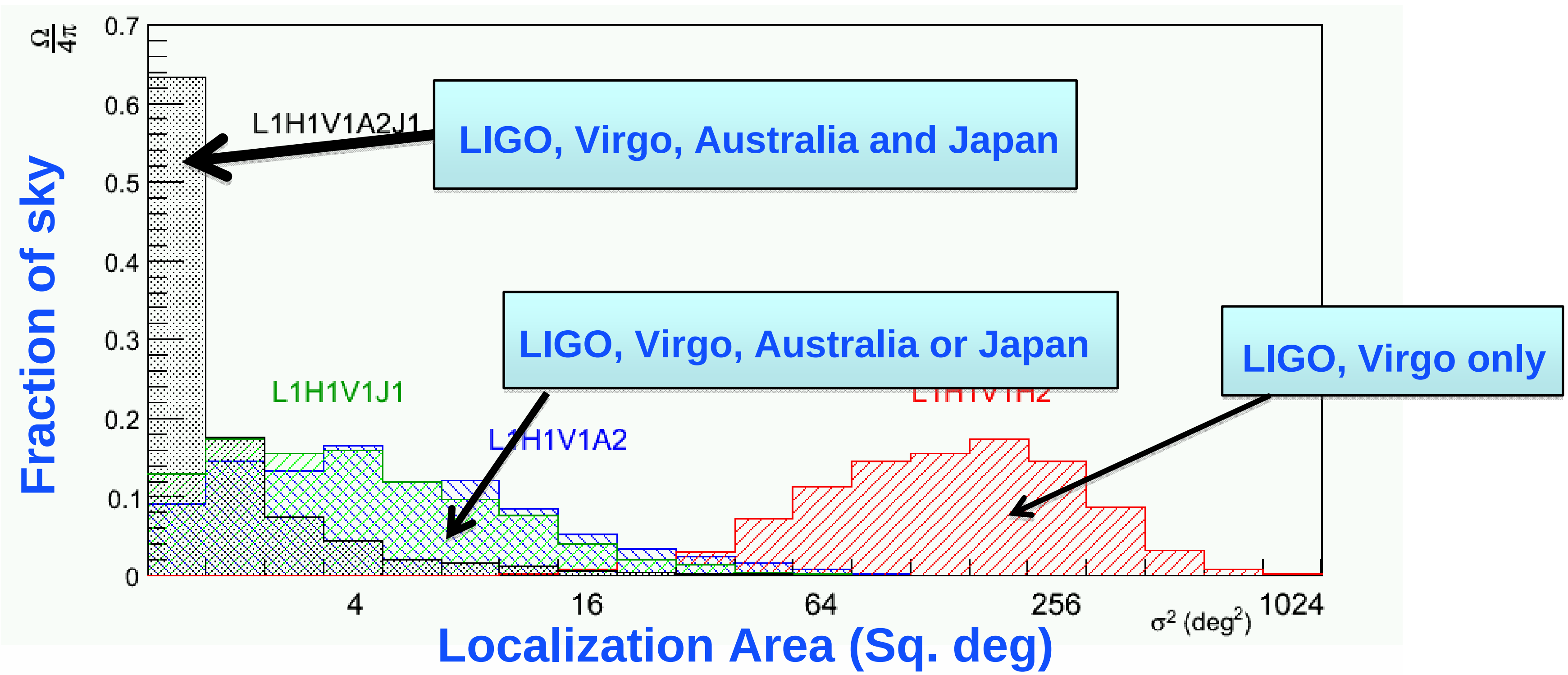
LIGO, Virgo, LCGT
Plus LIGO-Australia



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

Cumulative Improvement due to LCGT and LIGO-Australia

- To first order, LIGO-Australia improves N-S localization, while LCGT improved E-W localization



Progress toward LIGO-Australia

- Australian population and economy ~7% of US => Project >$100M is a REALLY BIG project
- LIGO Laboratory proposed it to NSF
  - » Reviewed by NSF panel—strong endorsement
  - » NSF informed National Science Board and received approved
- Five Australian universities have signed MOU for project
  - » Five of the “Group of Eight” major research universities
- Indian Collaboration (IndIGO) proposed for ~$20M from Indian government to participate

Indications from Australian government not encouraging

Building a Global Collaboration is More than Building a Network of Detectors

- LIGO-scale projects involve hundreds of scientists with different backgrounds, different goals, different scientific traditions, and different personalities
  - » Sense of competition is strong among scientists
  - » Scientists like to invent their own ways of doing things

- Governments and funding agencies can have their own goals and needs, not always parallel to those of the scientists

Looking to the Future

- Five years from now
  Expect to see first observations with Advanced Detectors

- Ten years
  Expect to see a rudimentary gravitational wave telescope spanning the globe