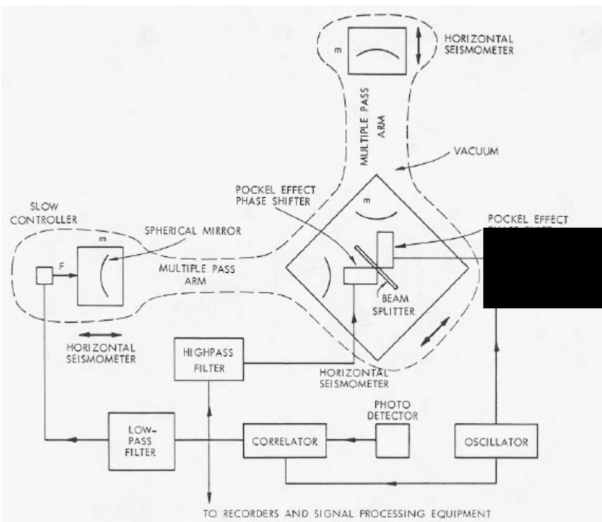
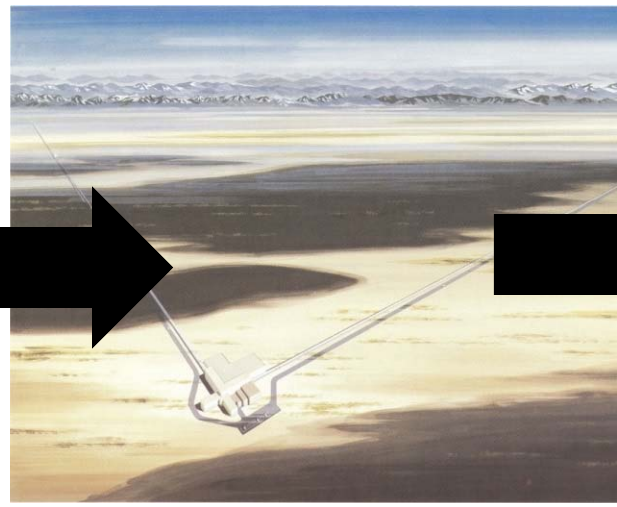
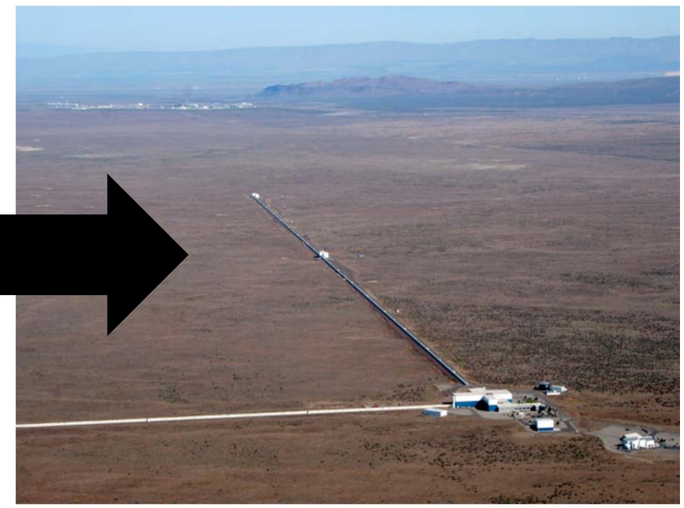
Historical Context for LIGO's Detection of Gravitational Waves







Stan Whitcomb

National Academy of Sciences Annual Meeting

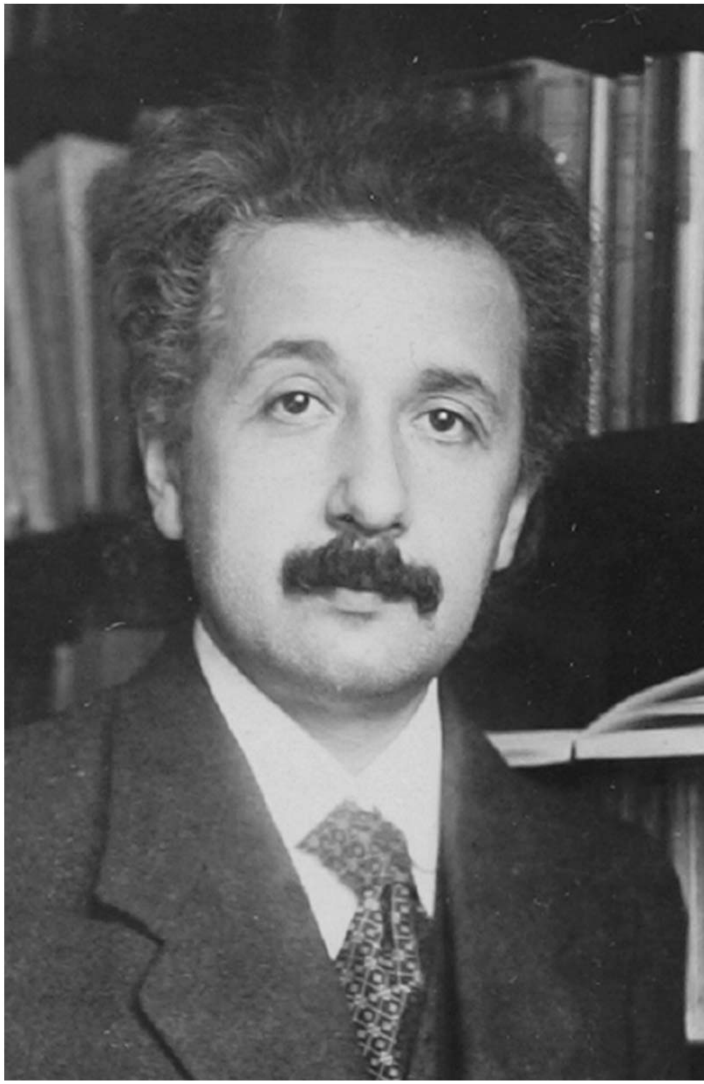
1 May 2016

LIGO-G1600910-v2

Einstein and Gravitational Waves

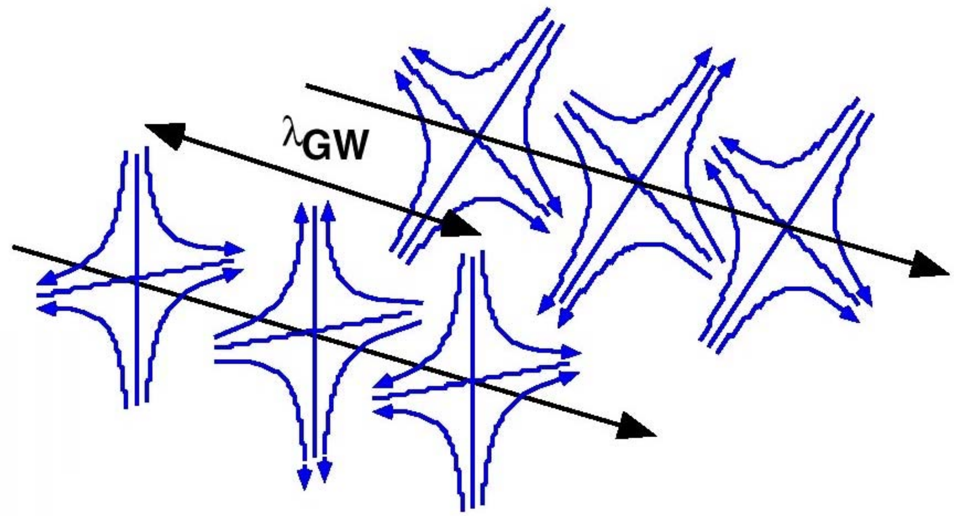
- In 1915, Einstein published the field equations of General Relativity
- 1st publication indicating the existence of gravitational waves by Einstein in 1916
  - » Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors, and contains quadrupole formula for radiating source
- 1936 submission to Physical Review (with Rosen) used a ‘bad’ coordinate system to “prove” that gravitational waves do not exist
  - » PhysRev’s use of a referee angered Einstein and he withdrew paper
- Corrected version published elsewhere in 1937, and Einstein never used PhysRev again

(For more details see article by Kennefick, *Physics Today*, Sept 2005)

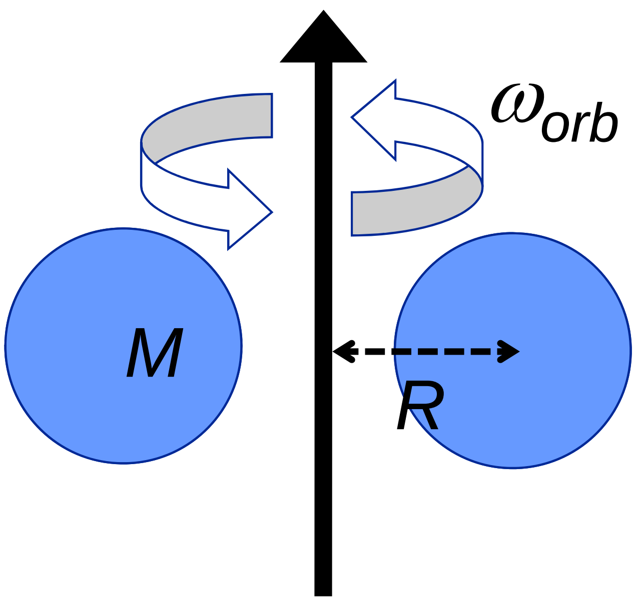


Gravitational Wave Basics

- 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



$$h(t) = 2\Delta L(t)/L$$



- Emitted from rapidly accelerating mass distributions

$$h_{\mu\nu} \approx \frac{G}{c^4}\frac{\ddot{I}_{\mu\nu}}{r}$$

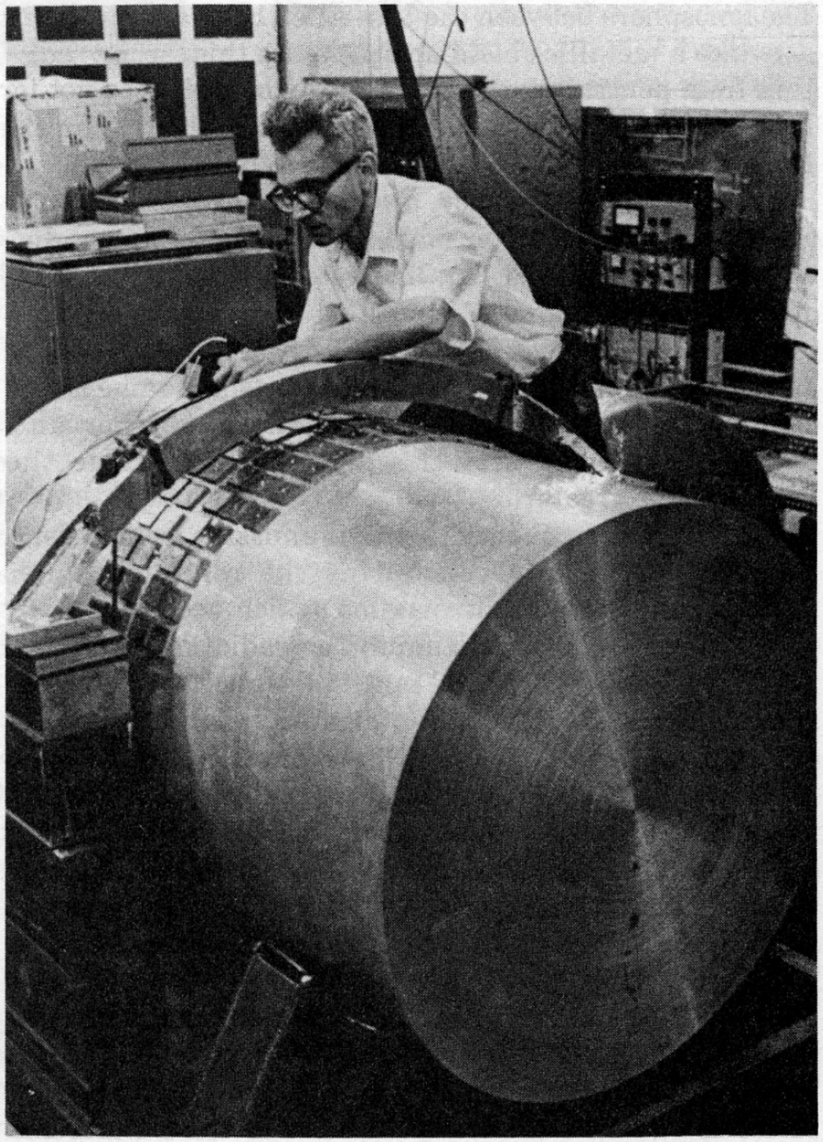
- GWs carry direct information about the coherent bulk motion of matter in the highly relativistic regime

The “Gravitational Wave Problem”

- An unresolved question for GR’s first 50 years:
Are gravitational waves real, or are they “pure gauge”?
- GWs were one focus of the “Chapel Hill Conference” (Jan 1957), attended by 44 of the world’s leading relativists
- One approach was to (attempt to) solve the equations of motion of a binary star, and show that they generated waves that couldn’t be transformed away.
- Felix Pirani’s presented a breakthrough by analyzing the reception of gravitational waves, not their generation.
- He showed that in the presence of a gravitational wave a set of freely-falling particles would experience genuine motions with respect to one another, and thus, they must be real.
- This line was sharpened through discussions with Bondi and Feynman, resulting in the “sticky bead argument”

The First Detectors: Resonant Bars

- Joseph Weber attended Chapel Hill meeting and soon after began to look for practical detector concepts
- Conceived and built the first bar detectors
  - » Used longitudinal resonant mode of bar to increase sensitivity
  - » Narrowband sensitivity (~1 Hz) around resonant frequency (~1 kHz)
- Announced in 1969 that he had seen evidence for gravitational waves in coincident pulses observed in three widely separated bars
- Triggered wide interest in gravitational waves



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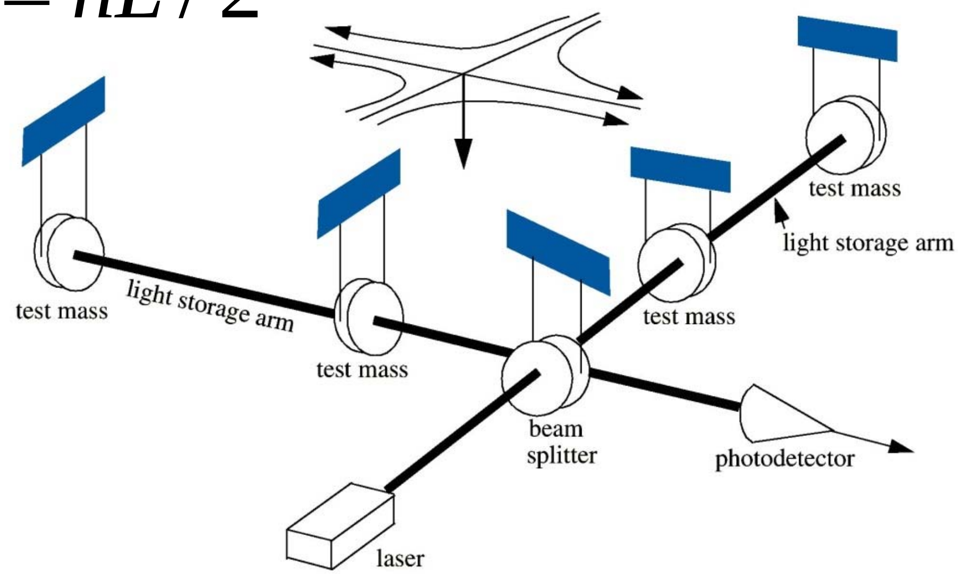
Subsequent Developments in Resonant Bars

- In the next 2 decades, at least 19 different bar detectors (in 8 countries) were built and used in searches
- *None were able to confirm Weber's result*
- Important contributions:
  - » Thermal noise
  - » Back action/Quantum noise
  - » Seismic/acoustic noise
  - » Need for multiple detectors
- Some progress toward wider bandwidth, but few got beyond 10's of Hz.
- Major impetus for theoretical studies of sources

Detecting GWs with Interferometry

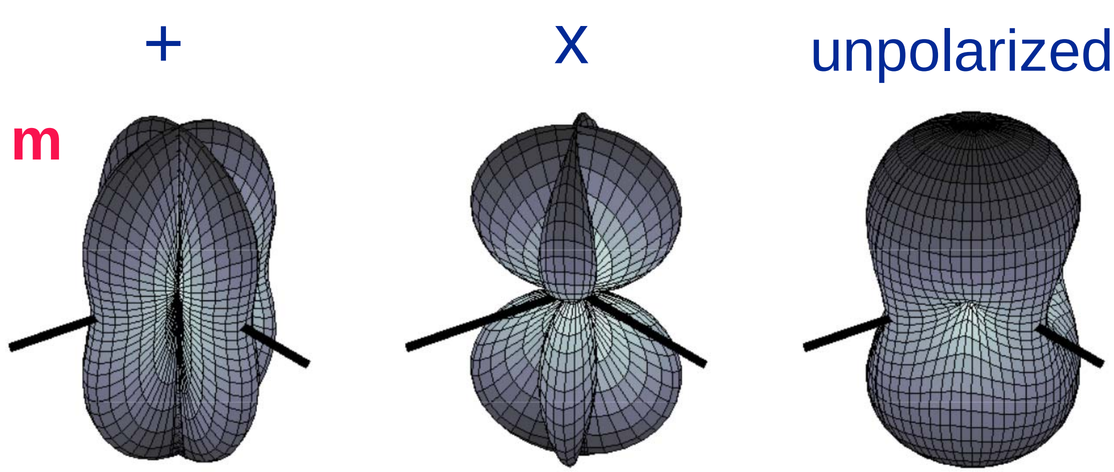
Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies f >> f_{pend}

$$\Delta L = hL/2$$



Bandwidth 10 Hz - 10 kHz, determined by "unavoidable" noise (at low frequencies) and expected maximum source frequencies

For a LIGO L = 4 km
For *h* ~ 10^{-22} – 10^{-21}, ΔL ~ 10^{-18} m
(~1/1000 diameter of proton)



Interferometric Detectors: Multiple Independent Inventions

- Gedanken experiment using interferometry to detect GWs:
  - » F.A.E. Pirani, *Acta Phys. Polon*. **15**, 389 (1956)
  - » (predates invention of laser by 4 years)
- Often cited as first suggestion:
  - » M.E.Gertsenshtein and V.I. Pustovoit, Zh. Eksp. Teor. Fiz. **43**,605 (1962); Sov. Phys JETP,**16**, 433 (1063).
  - » Not recognized in West, but was noted by Braginsky in 1966
- R.L. Forward started at Hughes Research Labs in 1966
  - » Described in G.E. Moss, R.L. Miller and R.L. Forward, *Applied Optics* **10**, 2495 (1971).
  - » Credits a phone conversation with Weber
- Rai Weiss's "RLE paper" represented an independent invention ("several years" before 1972)
  - » Cites Pirani paper above
- Rai's RLE paper cites Philip Chapman (NASA) as having independently proposed technique

The Seeds of LIGO Are Laid Out in 3 Key Documents

- “Rai’s RLE paper”
  - » “Electromagnetically Coupled Broadband ... Antenna”
  - » R. ... of ... , p. ... (1973).
  - » Paper “… grew out of an undergraduate seminar that I ran at M.I.T. several years ago…”

Led to Prototype Experimental Program

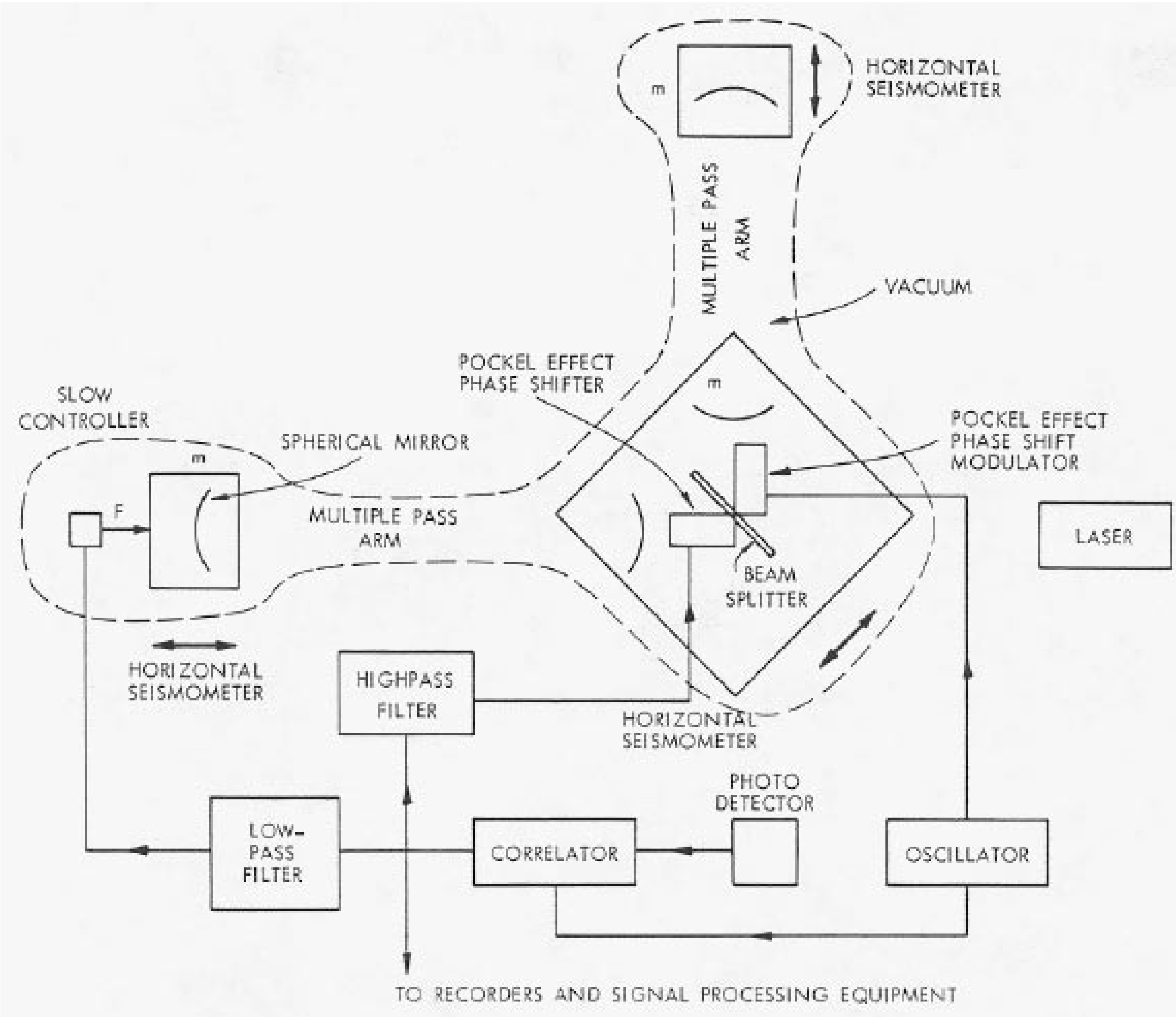
- The “Blue Book”
  - » “A Study of a Long Baseline ... System”
  - » ... Weiss
  - » ... 1983, but not really published

Led to LIGO Construction Proposal

- NSF Proposal for LIGO Construction (’89 proposal)
  - » Proposal team: Robbie Vogt, Ron ... Thorne, ...

Led to LIGO Project

The RLE Paper (1972)

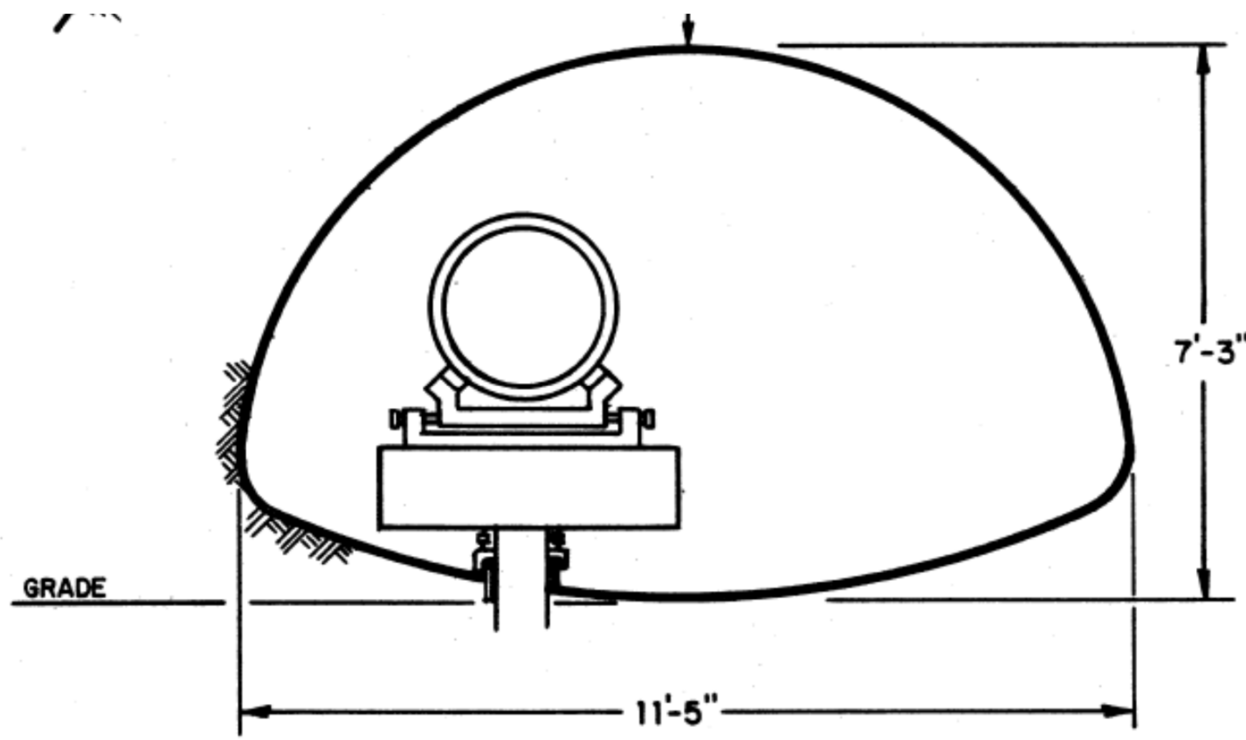


Not first suggestion of a laser interferometer to measure GWs, but first detailed noise/ sensitivity analysis

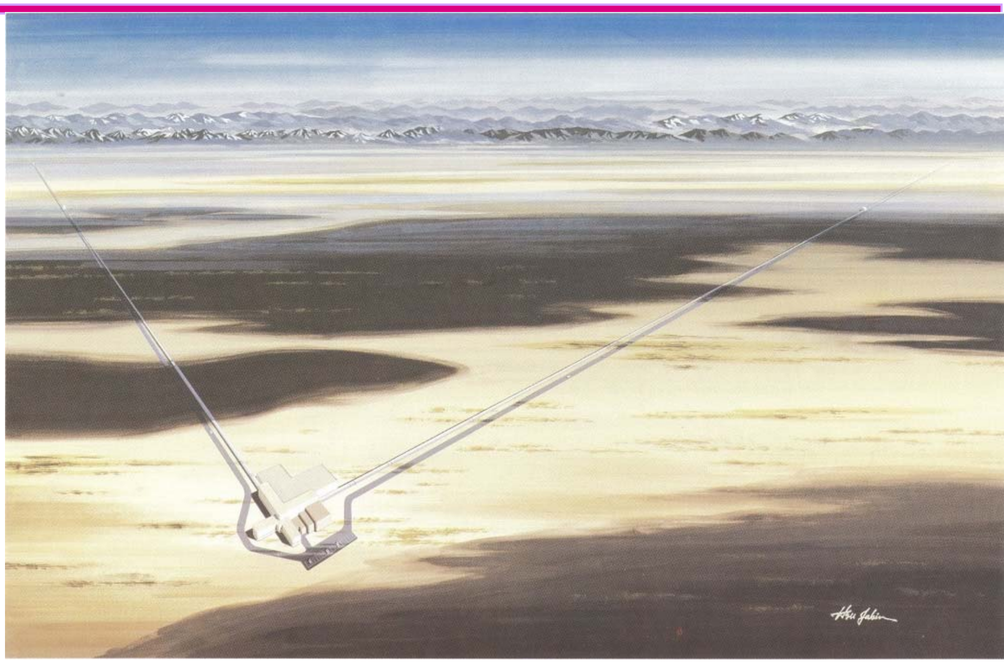
- » Shot noise/ radiation pressure
- » Thermal noise
- » Seismic noise
- » Gravity gradient
- » …

The Blue Book (1983)

- Science and Engineering feasibility study
- Comprehensive scope—Chapter titles include:
  - » Sources of Gravitational Radiation
  - » Physics and Detection
  - » Prototypes and Optical Concepts
  - » Noise sources
  - » Vacuum System
  - » Site survey
  - » Construction
  - » Proposed Design
- Important because of first engagement of engineers



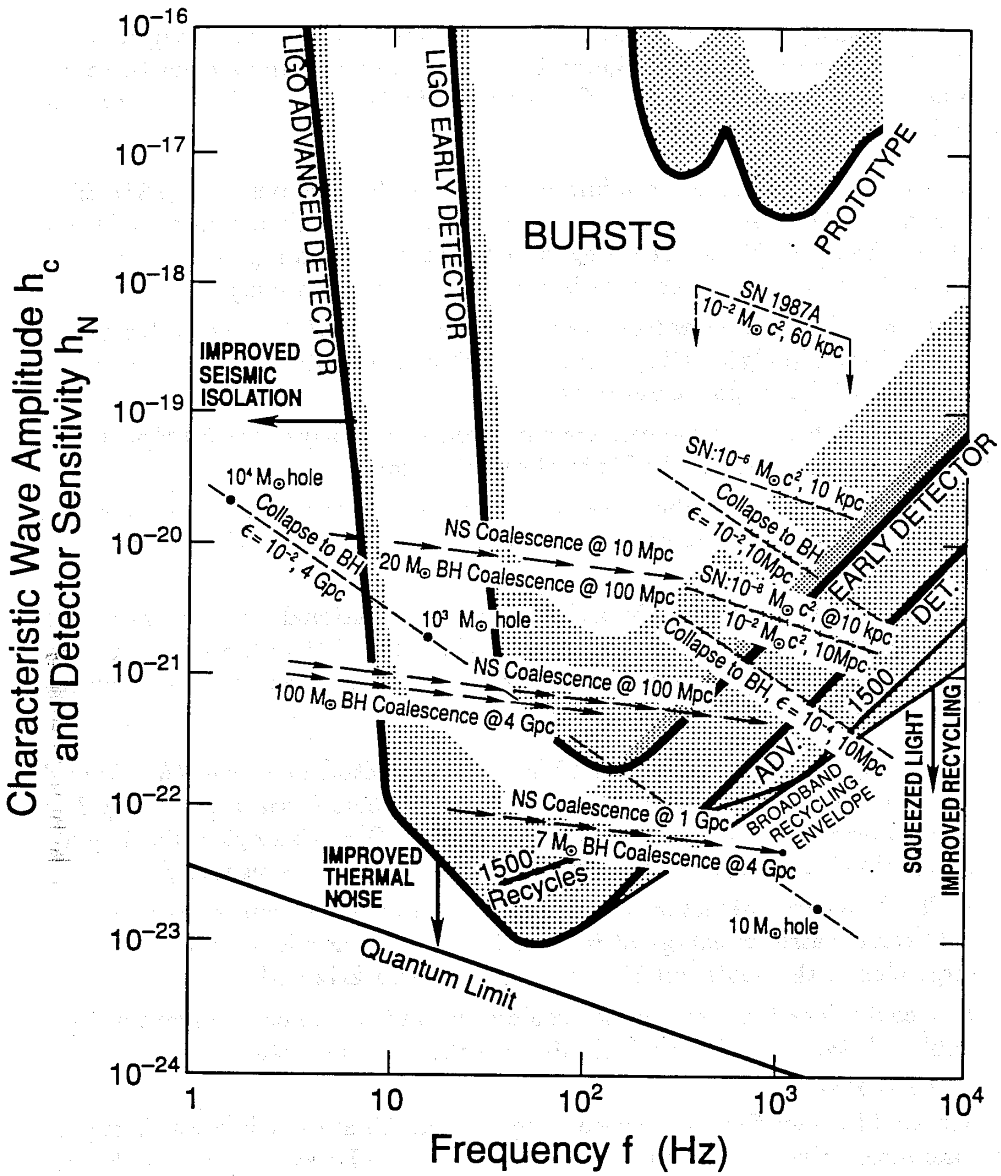
The '89 Proposal



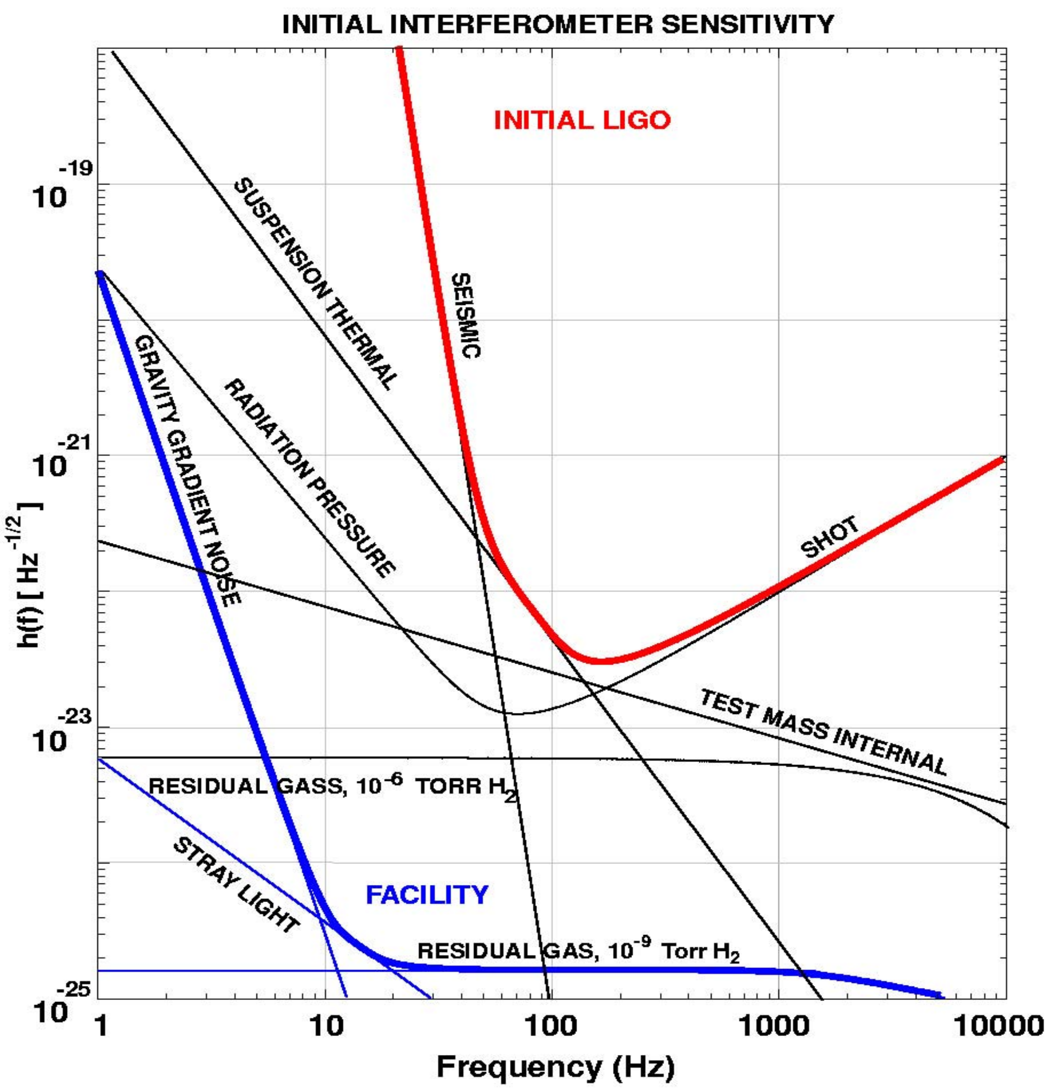
- Defined sensitivity goals, phased approach, scope
- Two main thrusts
  - » Science case, detector physics, noise analysis, prototype experience
  - » Engineering design and cost basis
- Key project concepts
  - » Immediate jump to an astronomically interesting sensitivity
  - » Parallel construction and detector development
  - » Continued usage of facility for future generations of detectors

The Leap to Kilometer-Scale Detectors

- Improving knowledge of sources showed that multi-km arm lengths required for plausible detections
- Arguments against construction of intermediate length detector (e.g. 400m):
  - » Cost a lot,
  - » Not give significant scientific return,
  - » Would stretch the project timescale too long to attract scientifically capable team



Separation of Detector Noise Sources and Facility Noise Sources

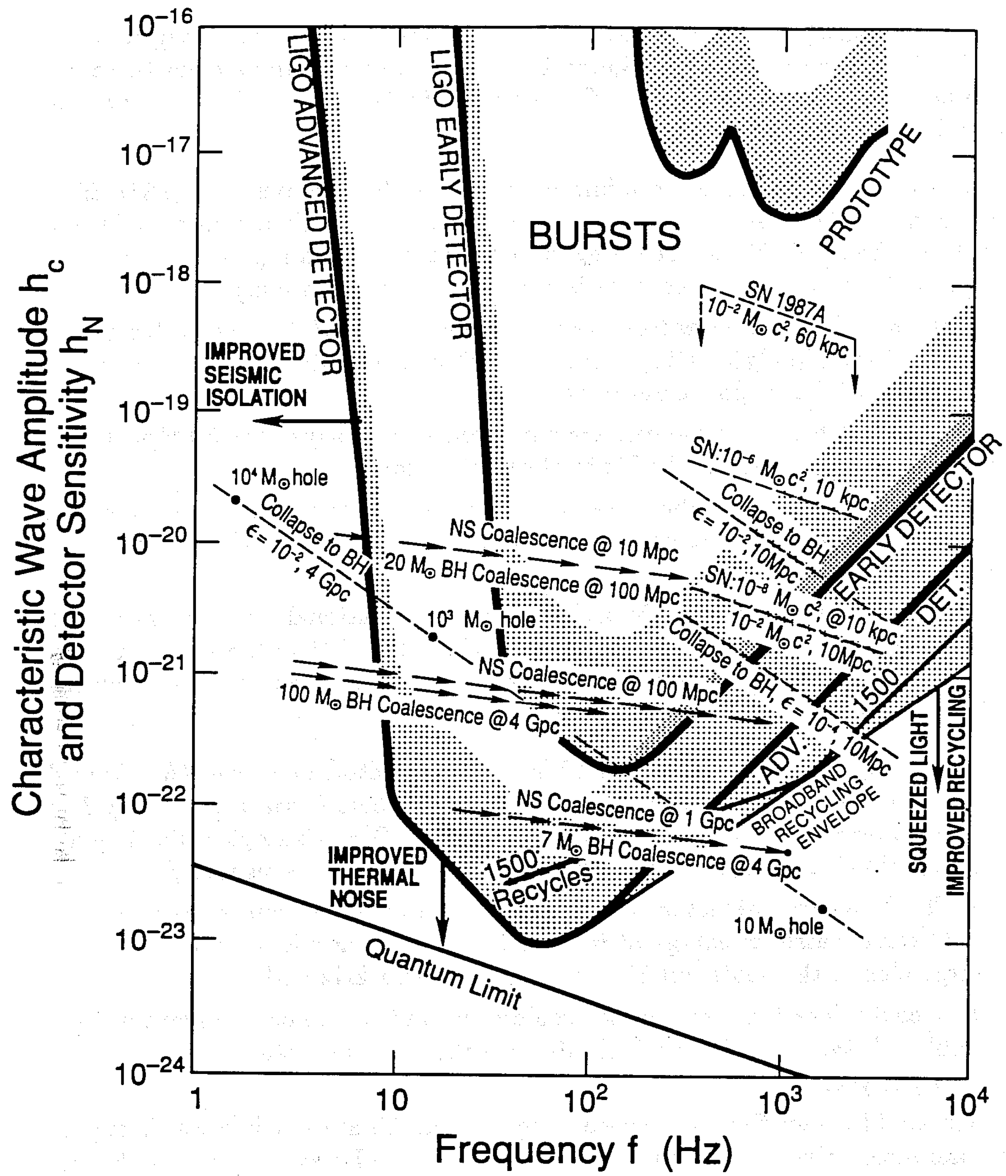


- Initial construction cost dominated by facility and vacuum system (~80%)
- Sensitivity limits from facility design/construction clearly separate from detector sensitivity limits
  - » Possible to design facility and vacuum system to accommodate future detectors
  - » Allows the construction of the facilities without the design of the detectors being finalized

(Rai's talk will give further details)

Phased Approach to LIGO

- **Initial LIGO**
  - » Gain experience with long baseline interferometry
  - » *Might* have a chance to detect gravitational waves, but might not
- **Advanced LIGO**
  - » 10 times more sensitive
  - » High probability of detection
  - » Required significant R&D
  - » Would not require any significant facility upgrades
- Required vigorous R&D program, both inside LIGO Lab and in broader community



LIGO Chronology

- Funded in 1993, facilities constructed from 1994 – 1999
- Initial LIGO installation and commissioning 1998-2002
  - » 3 Interferometers: 4 km & 2 km at Hanford; 4 km at Livingston
- 2002 – 2007: interleaving observations and sensitivity improvements
  - » Reached design sensitivity (Key milestone for second phase), though no gravitational waves were detected
- Advanced LIGO project funding began in 2008
  - » Totally new detector, in existing buildings & vacuum system
- International partners in Advanced LIGO
  - » Max Planck Institute (Germany): Laser
  - » Science & Technology Facilities Council (UK): Suspensions
  - » Australian Research Council: Sensors & controls
- Advanced LIGO installation began 2010

LIGO Scientific Collaboration (LSC)

- 1996: NSF Convenes Panel on the Usage of LIGO
  - » Recommended expanding beyond Caltech and MIT
- 1997: Barry Barish (LIGO Director) formed LIGO Scientific Collaboration

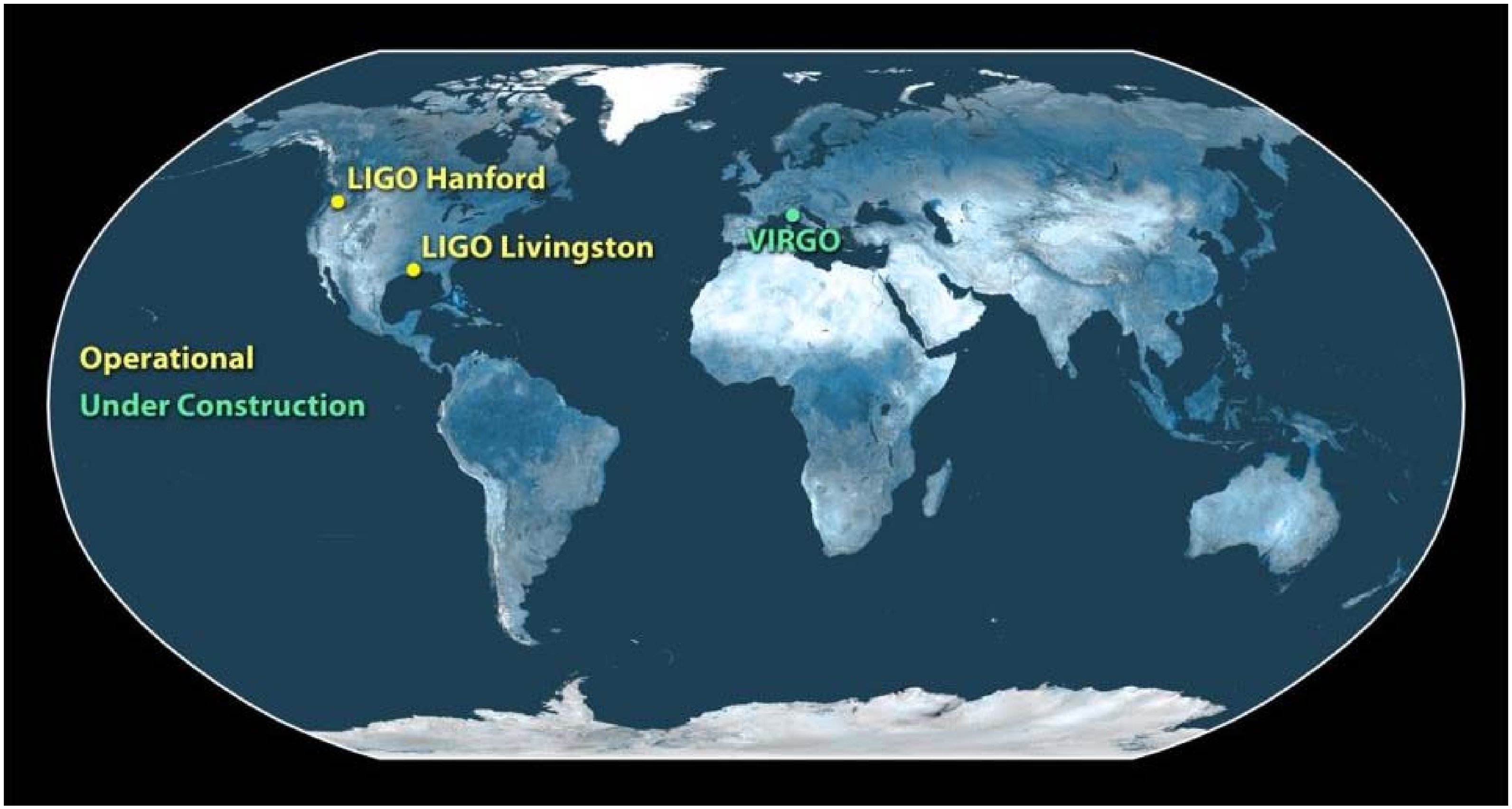
- » Broaden the impact of gravitational wave science
- » Develop robust community of gravitational wave researchers
- » Engage outside experts to ensure success of Advanced LIGO

(Some Other)
Elements Behind LIGO's Success

- Consistent support and oversight from NSF
  - » Funding was defined and sustained
  - » Frequent, high caliber external reviews of progress and plans
- Robust R&D program carried out
  - » Significant portion of the LIGO Lab and LSC budget devoted to R&D for Advanced LIGO
  - » New ideas could be deployed whenever they were ready and needed—excellent coordination between LSC and LIGO Lab
- Growth of international collaboration
  - » Throughout 80's and early 90's, projects pursued independent paths hoping for funding of large detectors (many exchanges of technical, but few real collaborations)
  - » Birth of the LSC gave groups in UK, Germany and Australia the opportunity to contribute as full collaboration members

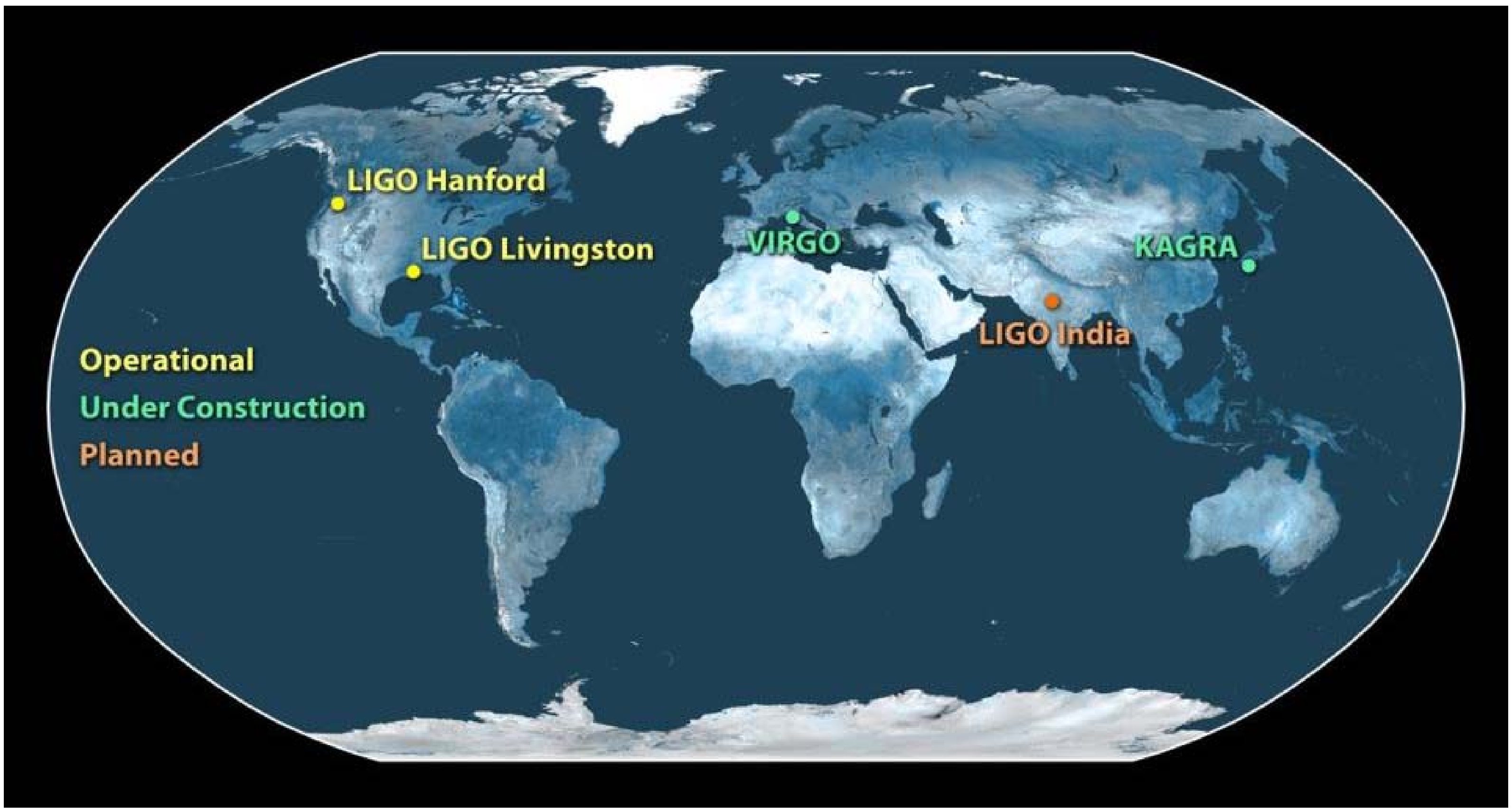
International Collaboration

- 2005, LIGO proposed data sharing agreement with Virgo, a 3 km detector nearing completion near Pisa
- Since then, all data analysis carried out jointly, with joint publication of searches and discoveries



The Global Network

- All existing and planned projects have a strong commitment to jointly managed observations and shared data



LIGO Laboratory

ligo.caltech.edu

LSC

www.ligo.org

Support: National Science Foundation

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