Searching for Gravitational Waves with LIGO

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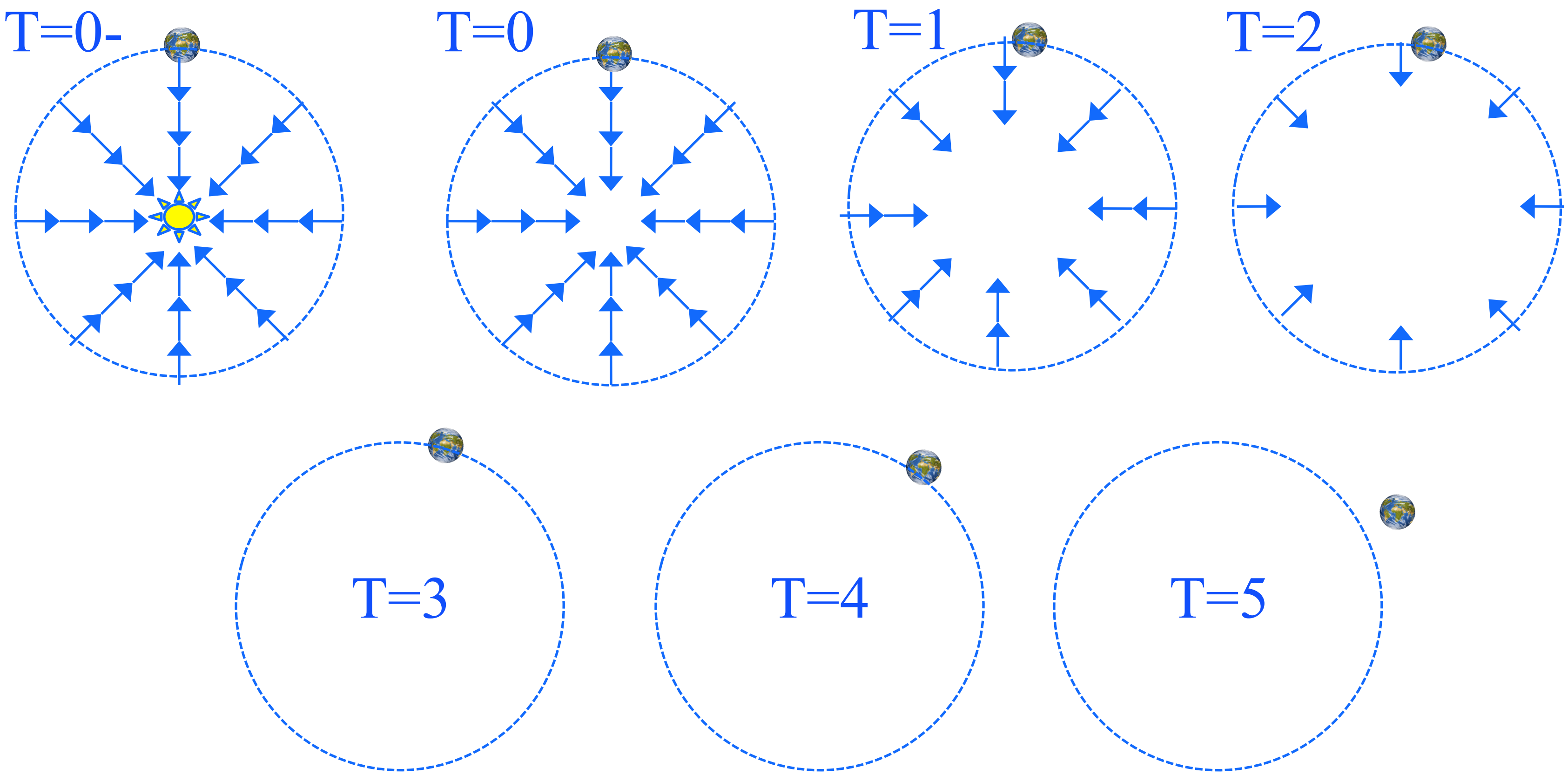
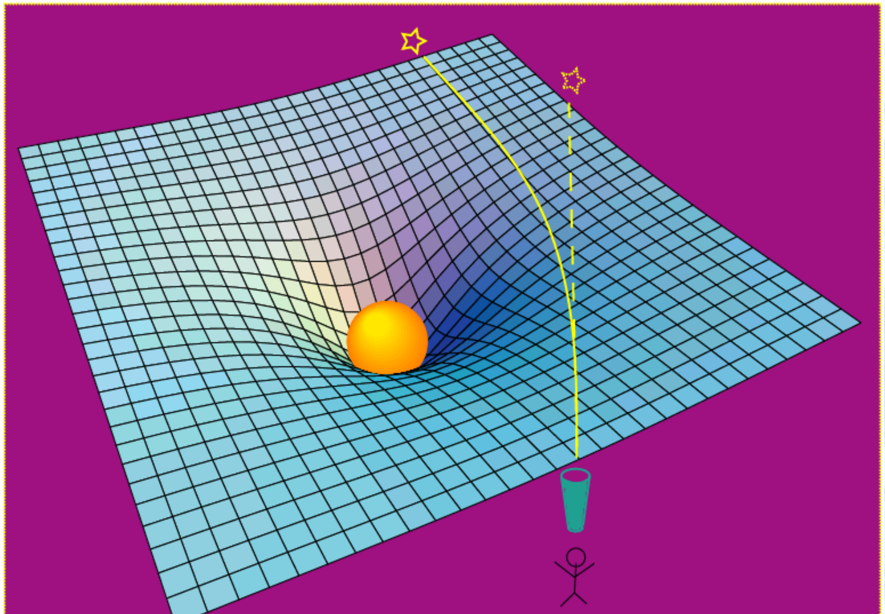
Outline

- Basic ideas:
  - » Special relativity requires gravitational waves
  - » General relativity gives prediction of strength, confirmed by binary neutron star orbital mechanics
- Some numbers
- What do generic detectors look like and how do they work?
- Kilometer-scale terrestrial detectors:
  - » First generation: Initial LIGO detectors and the worldwide network
  - » Second generation: Advanced LIGO

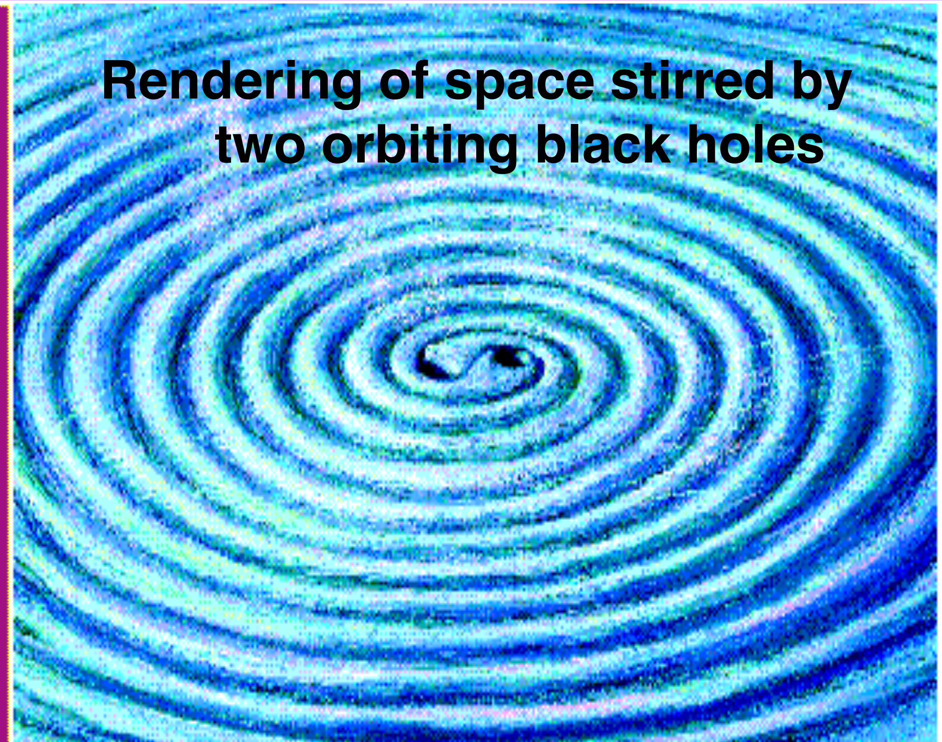
Special Relativity and the Case of the Missing Sun



Einstein's General Relativity re-wrote the rules of space and time

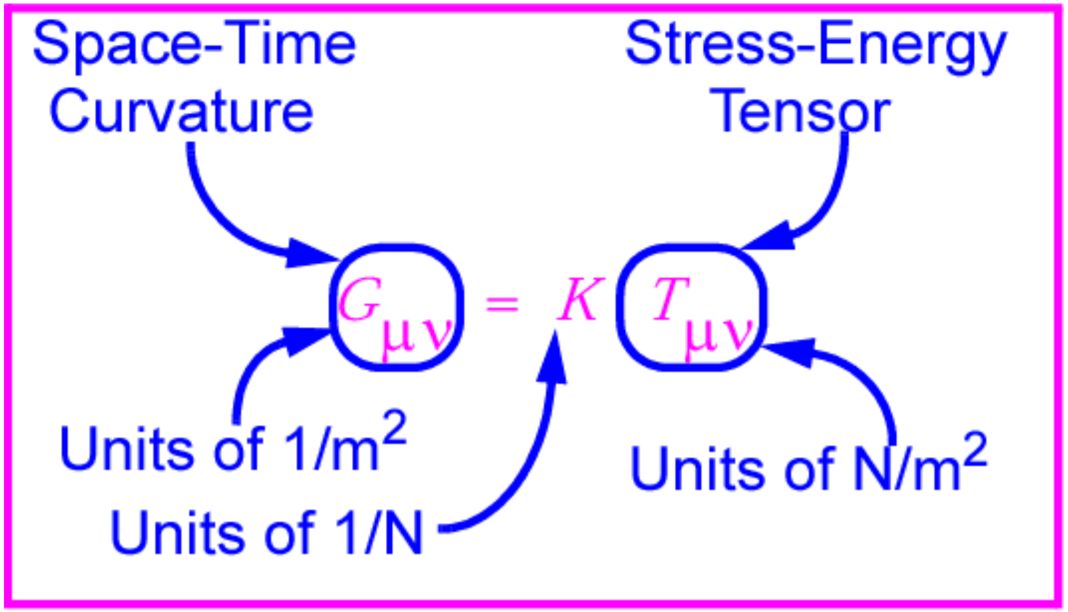


A massive object shifts apparent position of a star



Empty space and time are things, with real physical properties. Space has a shape, a stiffness and a maximum speed for information transfer.

Gravitational waves: hard to find because space-time is stiff!



- K~[G/c^4] is lowest order combination of G, c with units of 1/N

$$K \sim 10^{-44}\ N^{-1}$$

⇒ Wave can carry huge energy with miniscule amplitude!

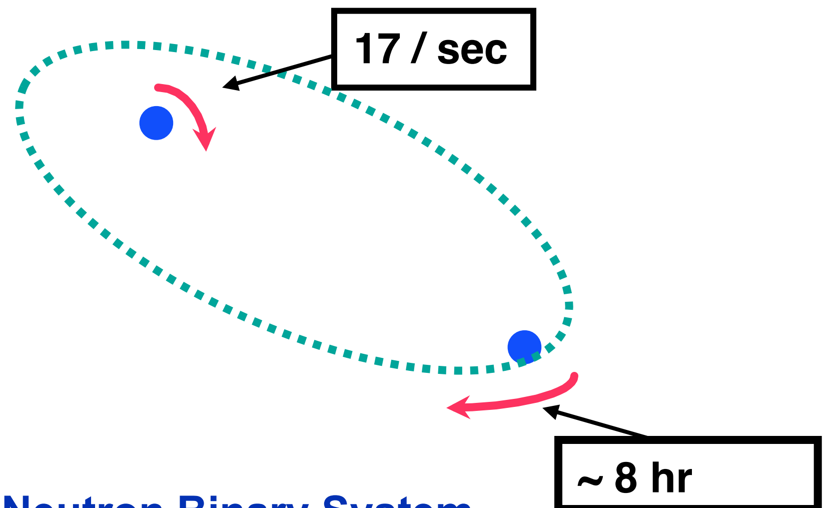
Gravitational Waves

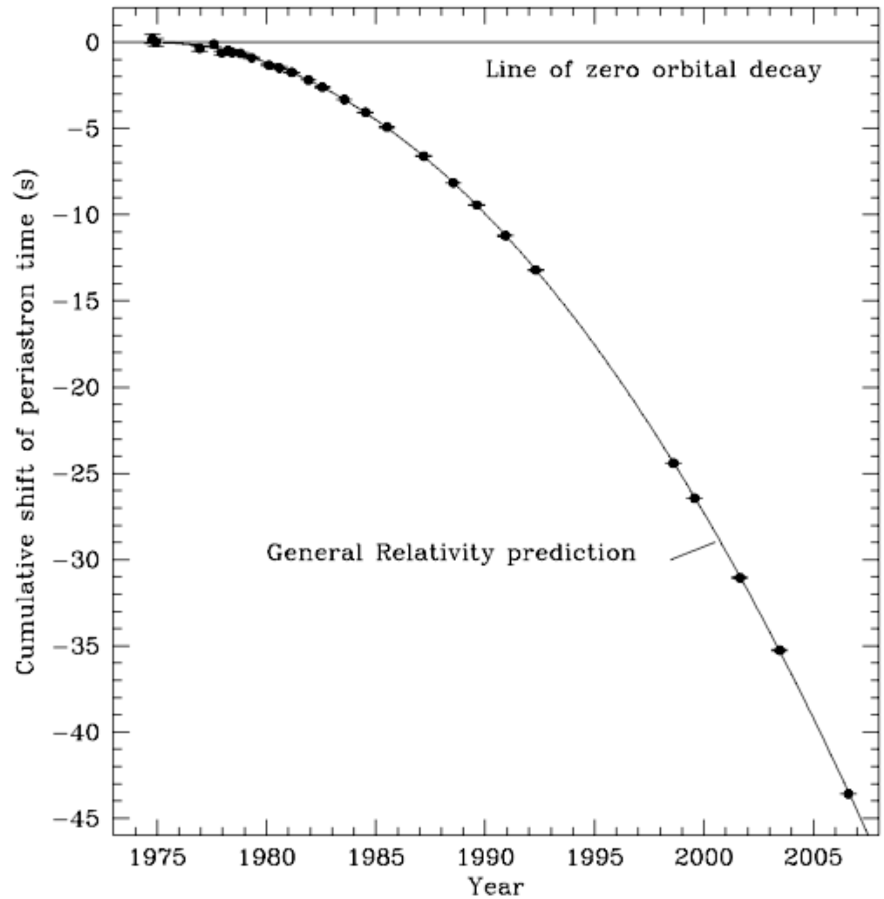
known to exist, just hard to find

Emission of gravitational waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

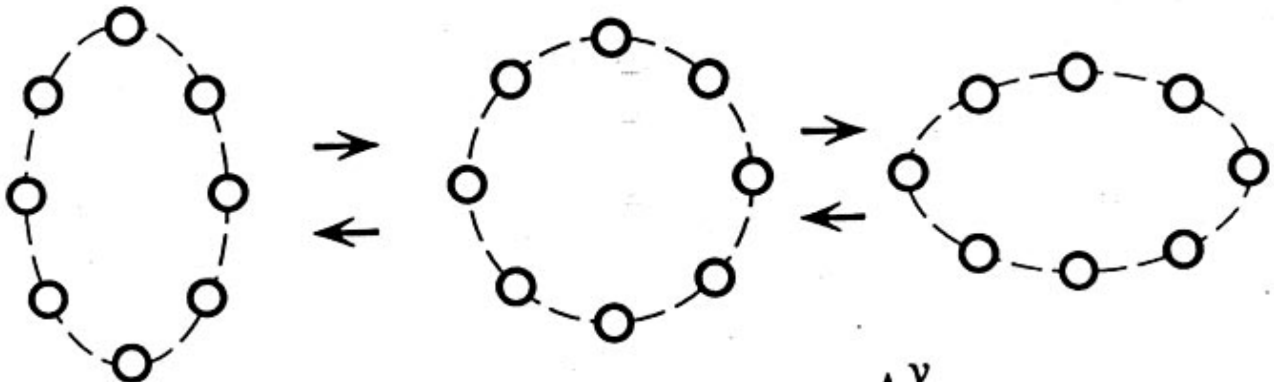




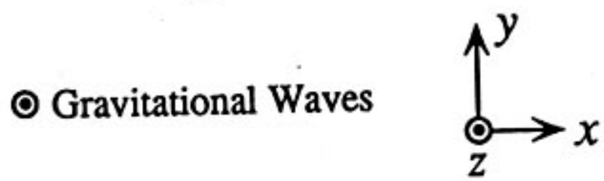
Neutron Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

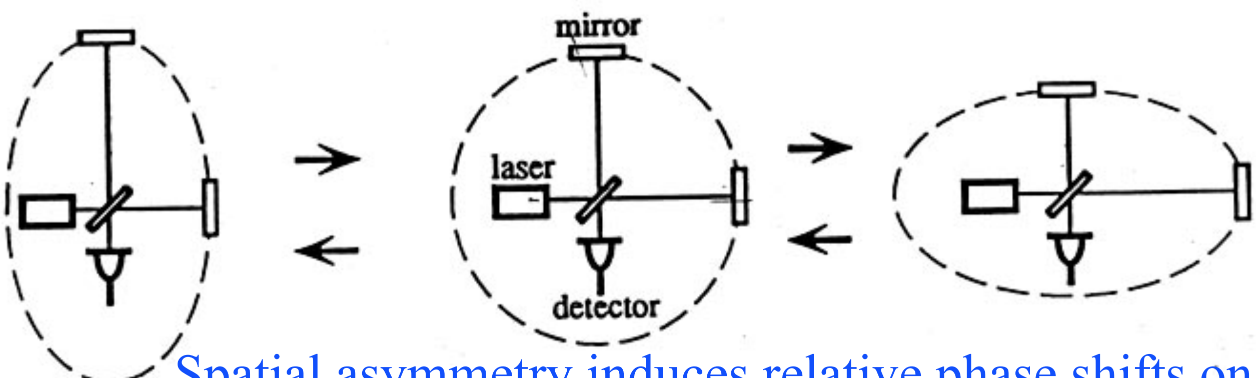
Basic idea for a laser interferometer GW detector



For R=4km, expect
R_x-$R_y \approx 10^{-19}$ m



GW amplitude h
= (R_x-R_y)/R



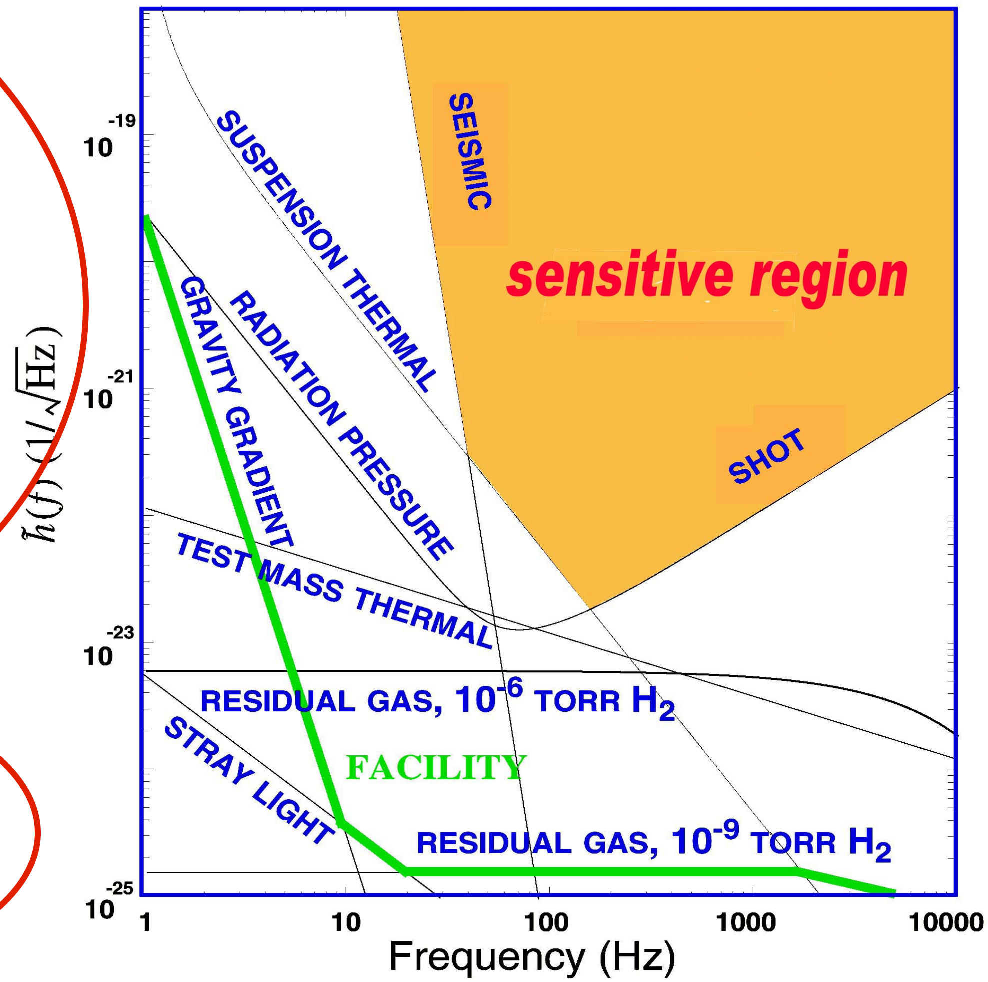
Spatial asymmetry induces relative phase shifts on light in arms

What Limits Sensitivity of Interferometers?

DESIGN

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

COMMISSIONING

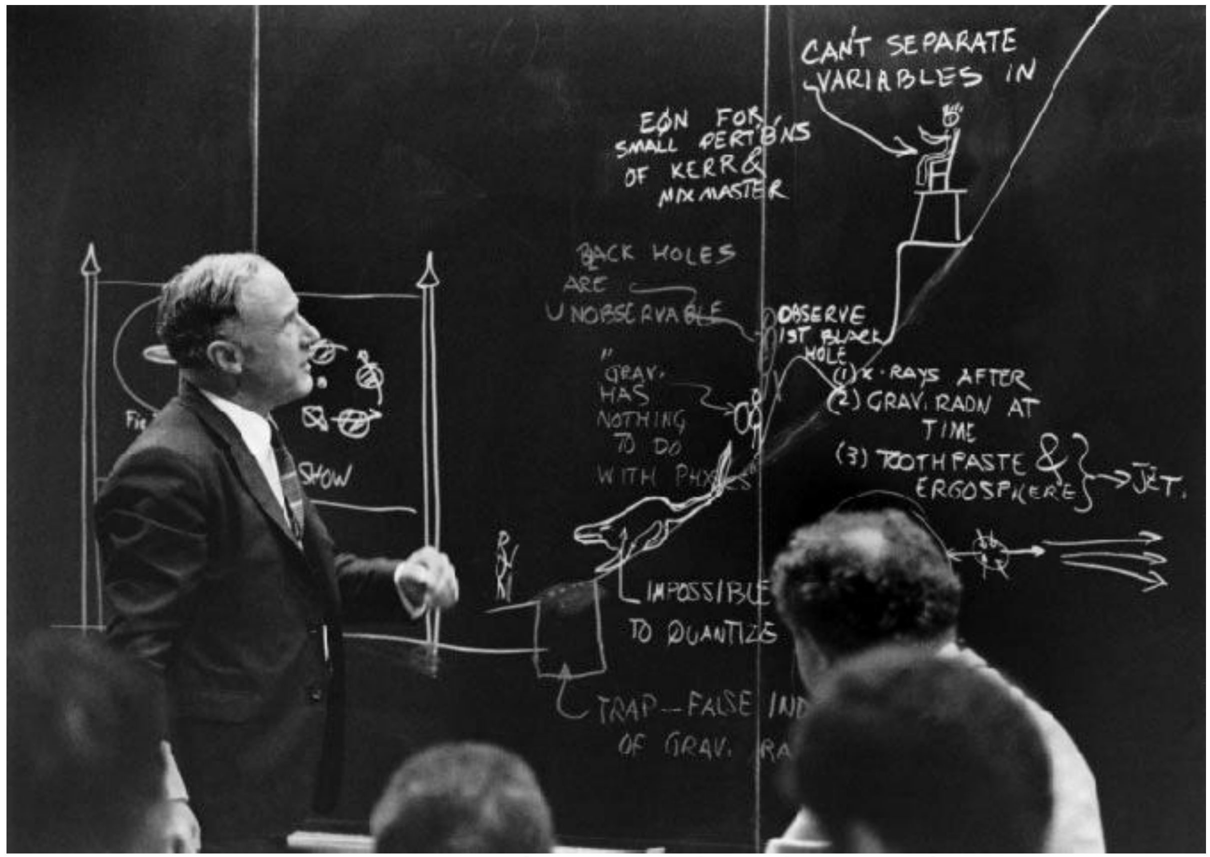


What Phenomena Do We Expect to Study With LIGO?

Gravitational Collapse and Its Outcomes Present LIGO Opportunities

f_{GW} > few Hz accessible from earth

f_{GW} < several kHz interesting for compact objects



Photograph by Robert Matthews, Courtesy of Princeton University (1971)

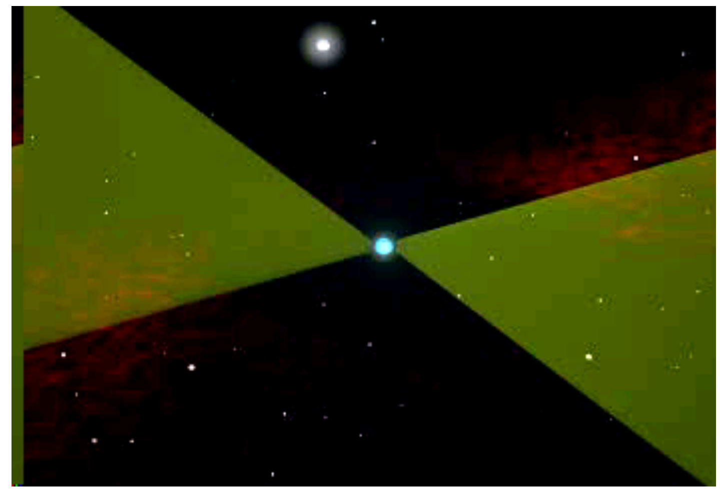
Supernova: Death of a Massive Star

- Spacequake should preceed optical display by ½ day
- Leaves behind compact stellar core, e.g., neutron star, black hole
- Strength of waves depends on asymmetry in collapse
- Observed neutron star motions indicate some asymmetry present
- Simulations do not succeed from initiation to explosions

Credit: Dana Berry, NASA

Neutron Stars and Black Holes

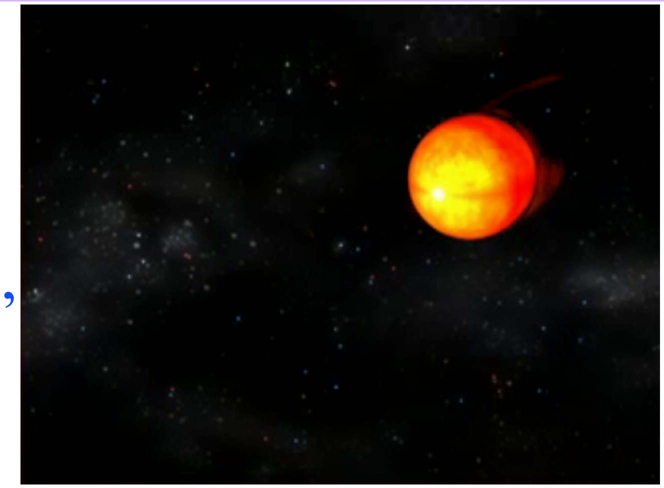
- Neutron stars have a mass equivalent to 1.4 suns packed into a ball 10 miles in diameter, enormous magnetic fields and high spin rates
- Black holes are the extreme edges of the space-time fabric



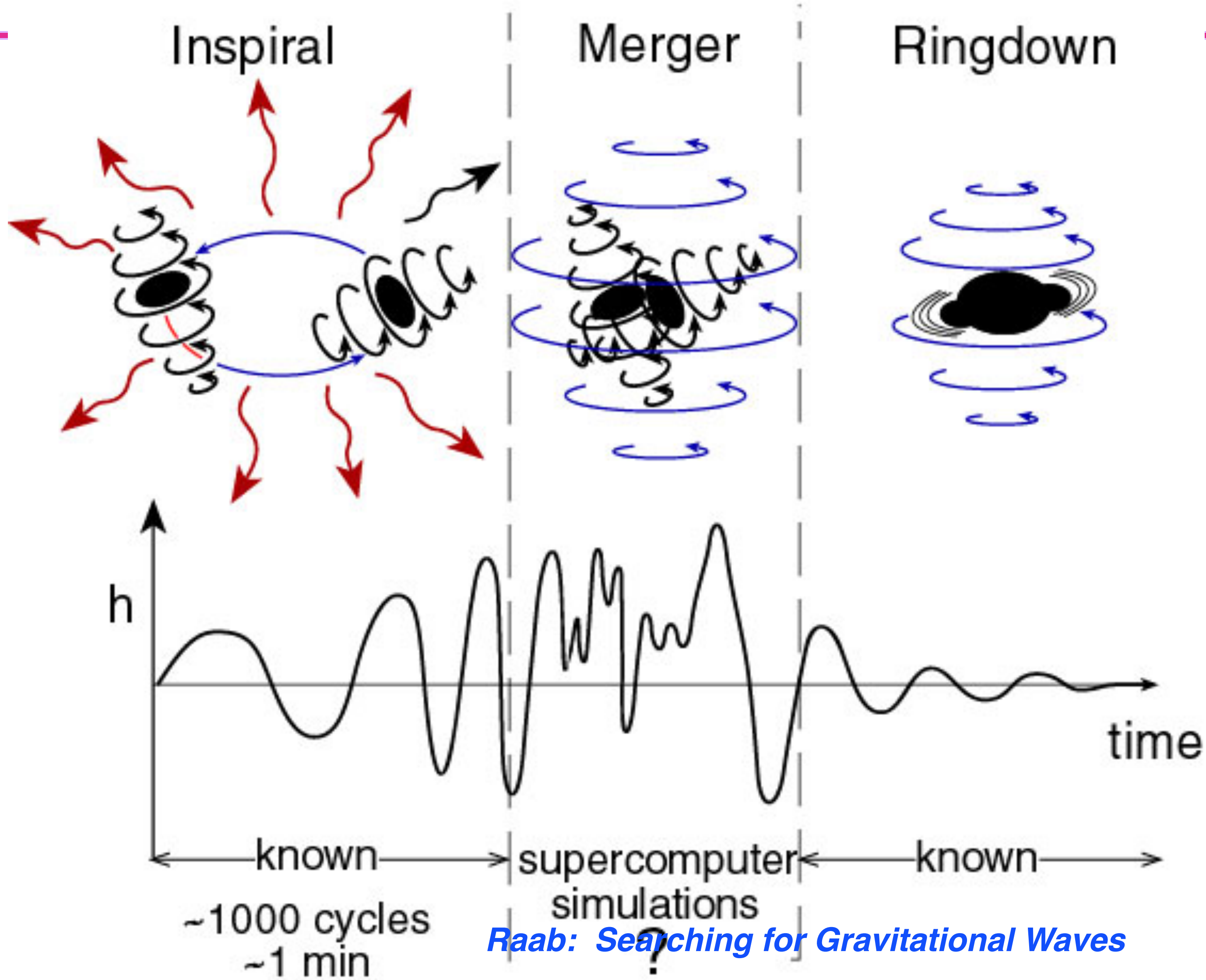
Artist: Walt Feimer, Space Telescope Science Institute

Gravitational-Wave Emission May be the "Regulator" for Accreting Neutron Stars

- Neutron stars spin up when they accrete matter from a companion
- Observed neutron star spins "max out" at ~700 Hz
- Gravitational waves are suspected to balance angular momentum from accreting matter

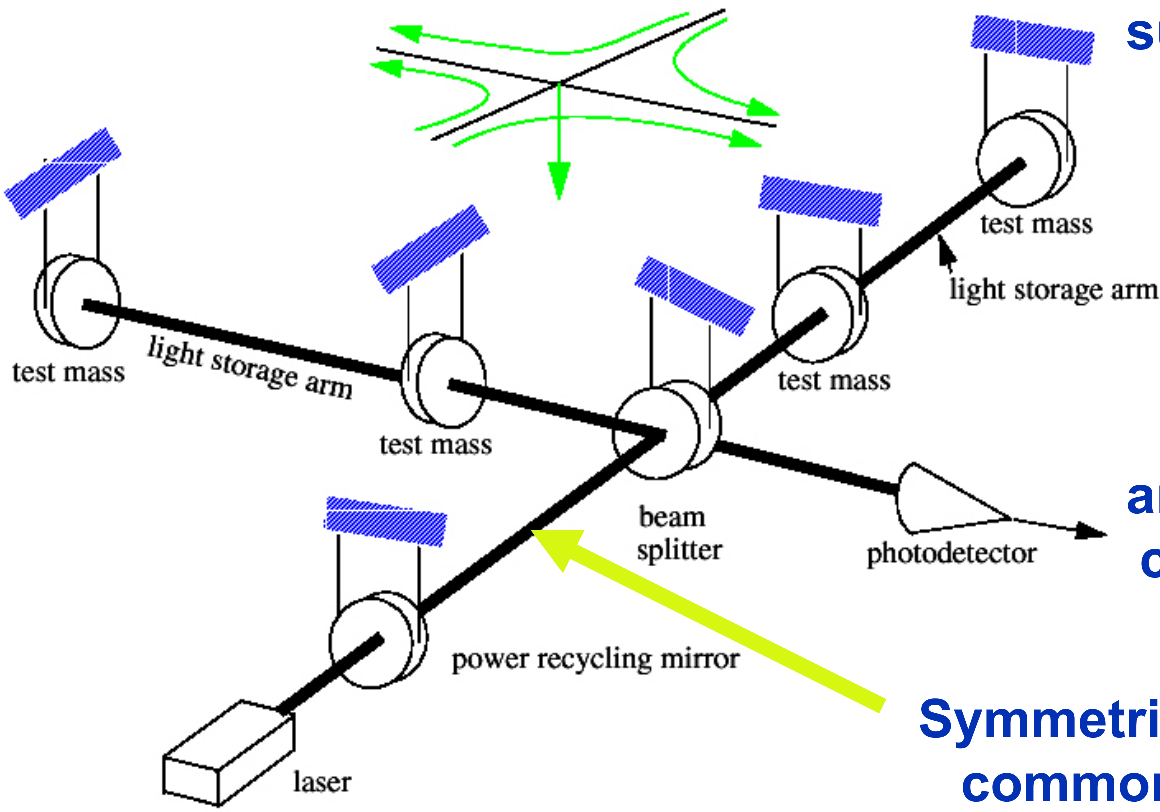

Credit: Dana Berry, NASA

Catching Waves From Black Holes



Sketches courtesy of Kip Thorne

Initial LIGO: Power-recycled Fabry-Perot-Michelson



suspended mirrors mark inertial frames

Once the world's most sensitive machine

antisymmetric port carries GW signal

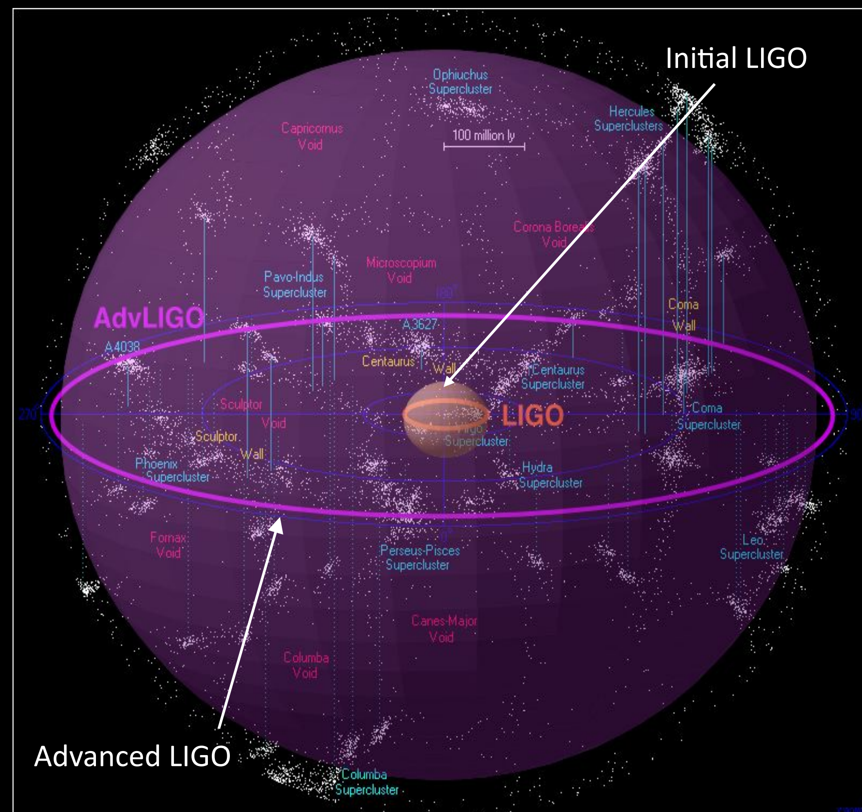
Symmetric port carries common-mode info

Intrinsically broad band and size-limited by speed of light.

2-Step Approach, From Discovery to Astronomy

1st generation: iLIGO, pathfinder that pays the billion-fold cost of admission; no guarantee of a home run

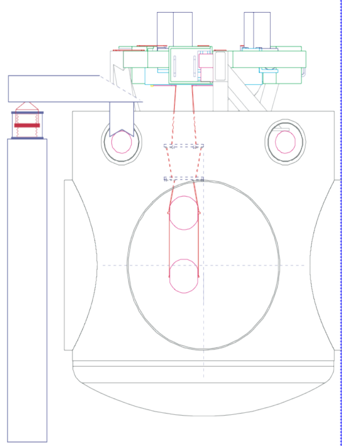
2nd generation: aLIGO, the trillion-fold home-run king



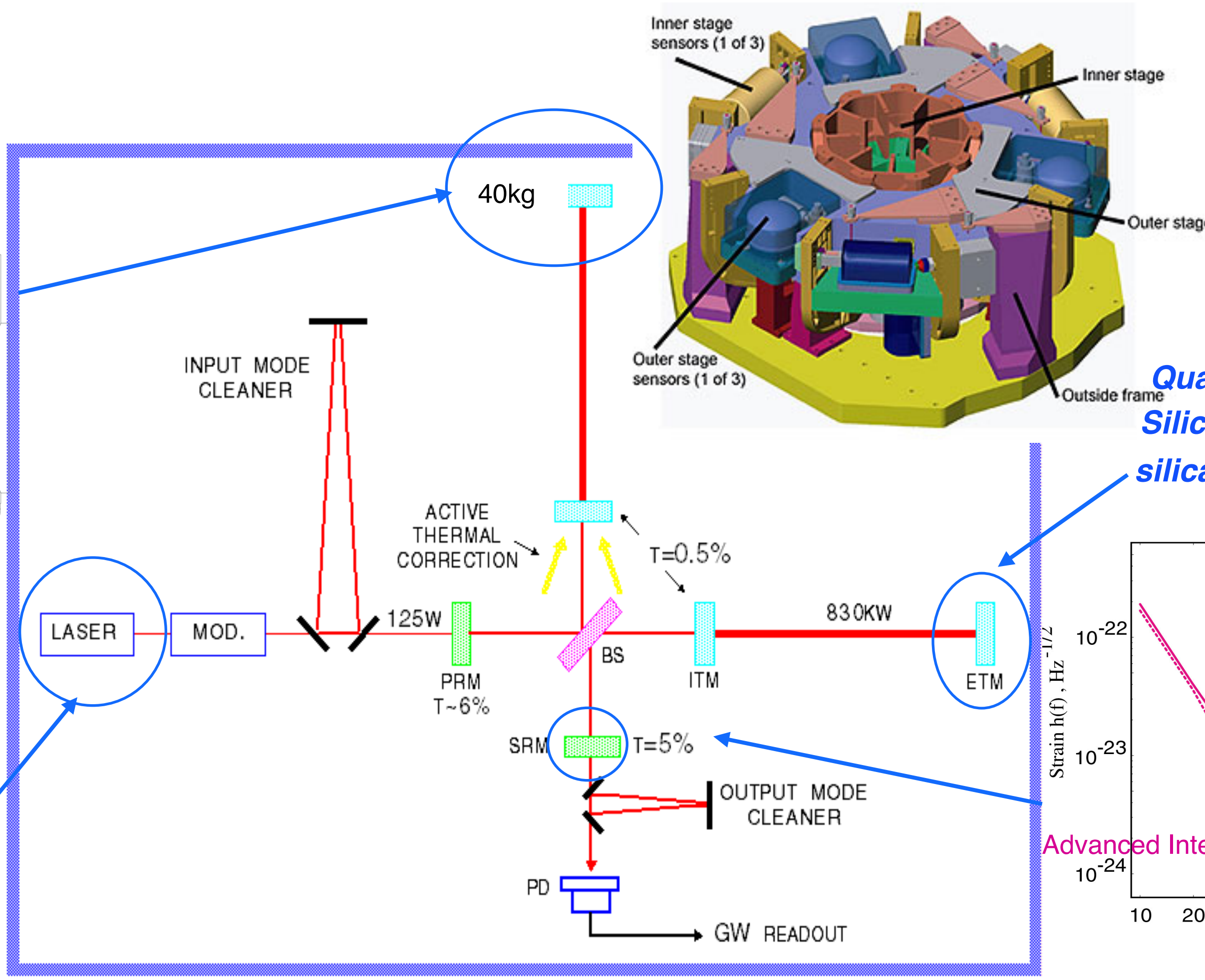
Credit: R.Powell, B.Berger

Advanced LIGO construction (aLIGO) started 1Apr2008

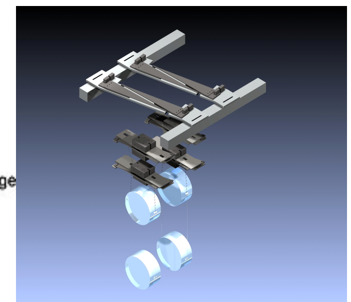
Major technological differences between LIGO and Advanced LIGO



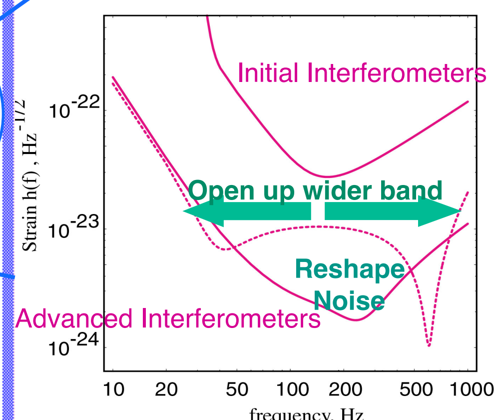
Active vibration isolation systems



High power laser (180W)

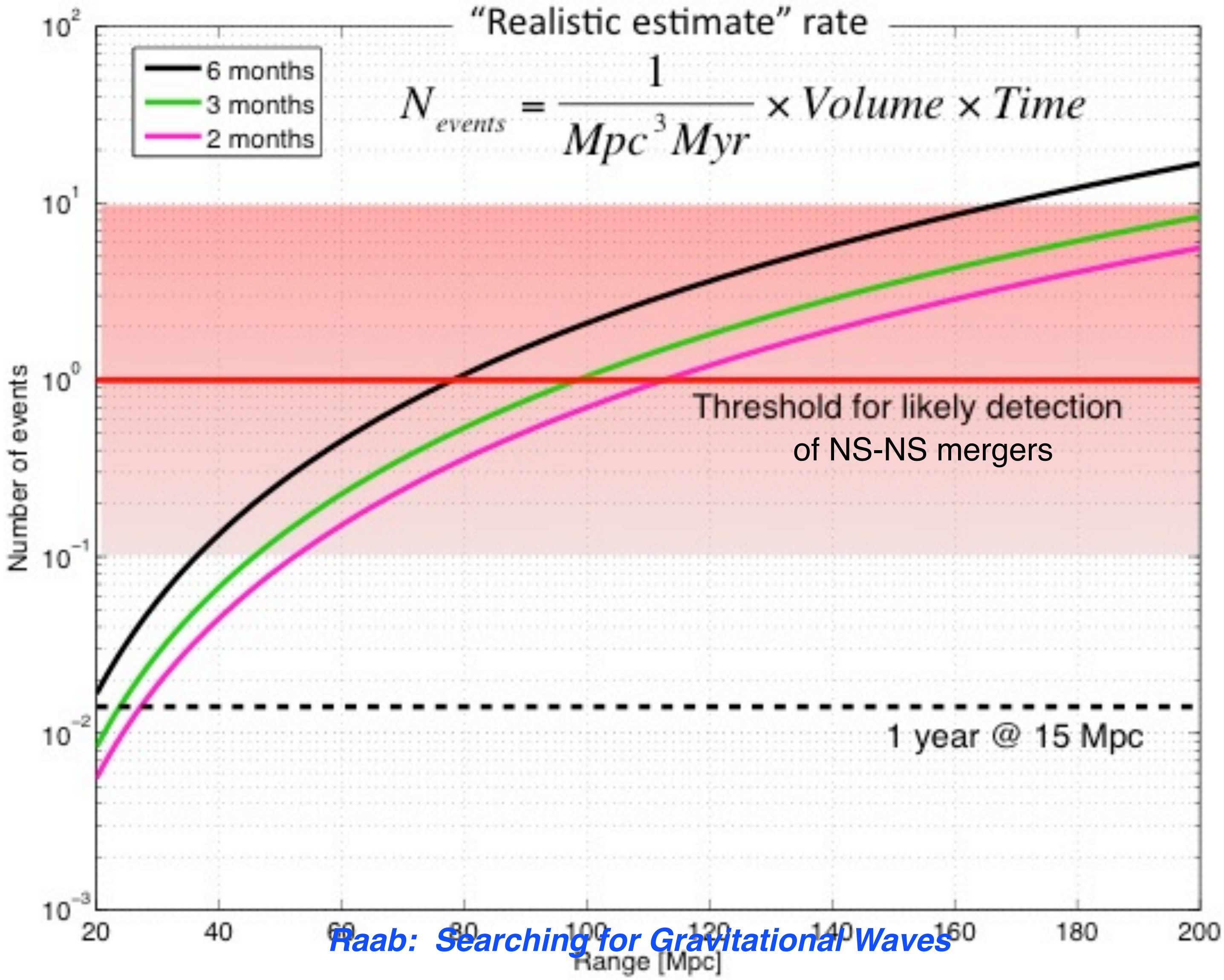


Quadruple pendulum: Silica optics, welded to silica suspension fibers

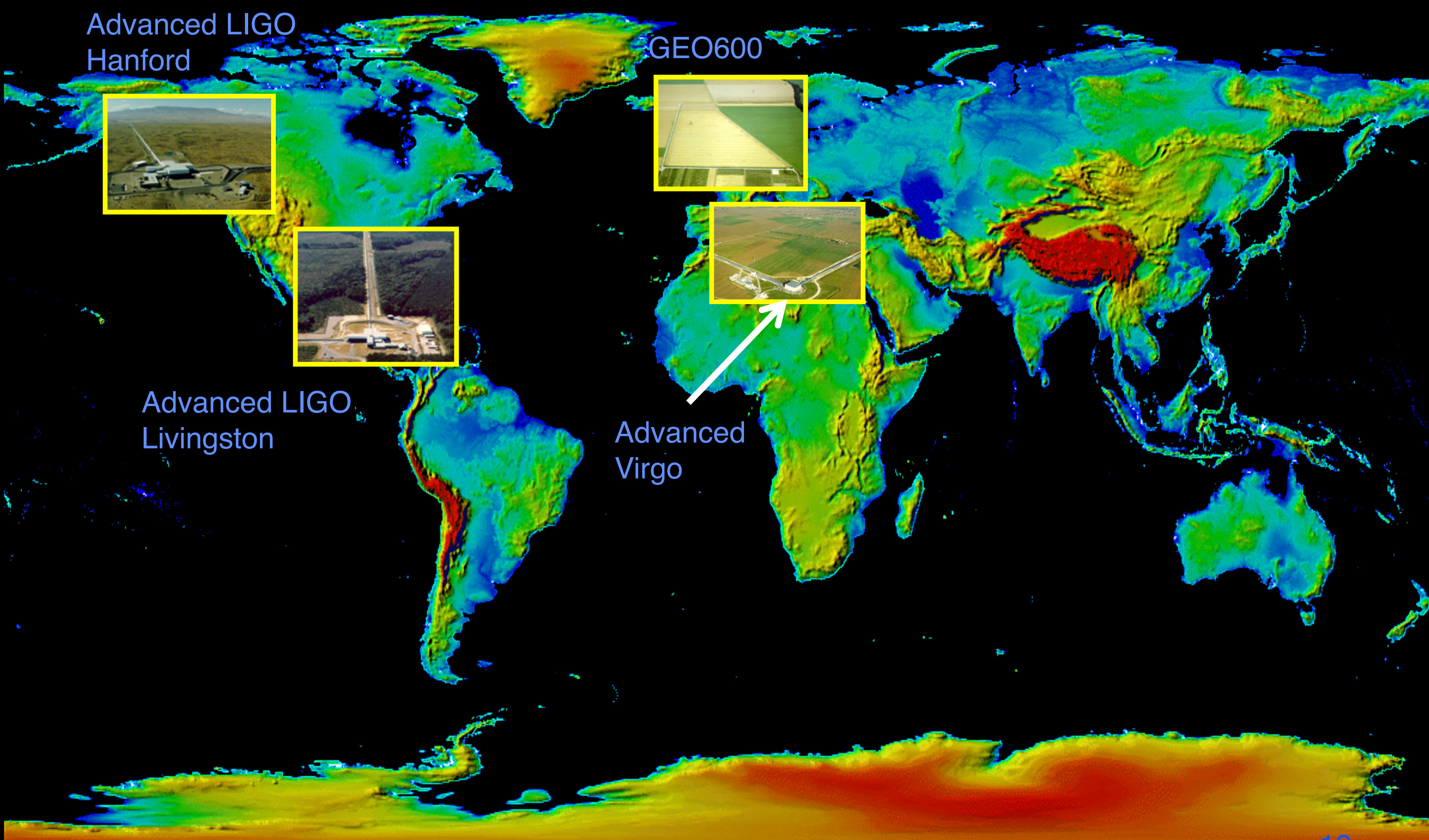


Advanced interferometry Signal recycling

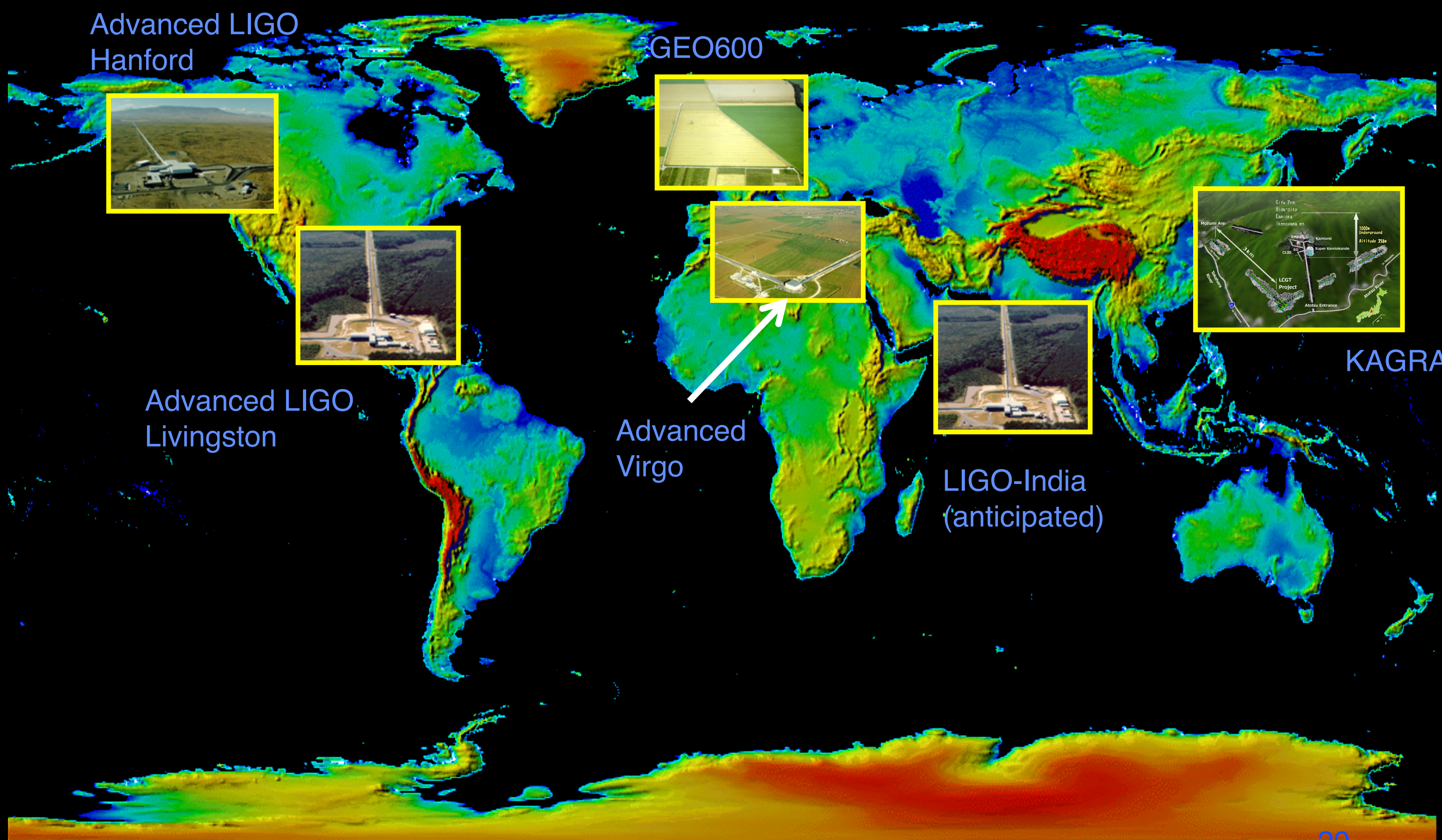
Criteria for early science runs



The Advanced Ground-based GW Detector Network in 2015



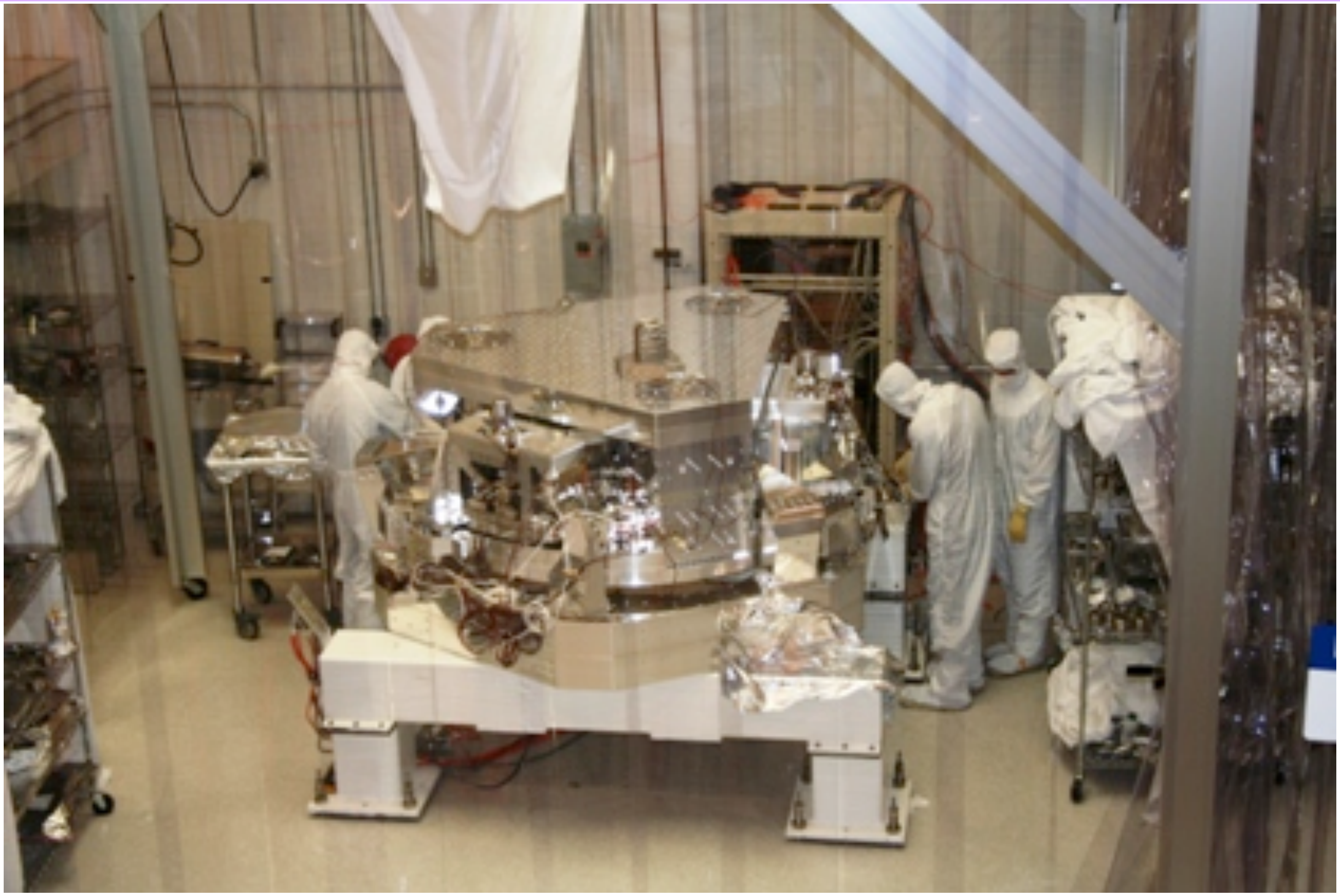
The Advanced Ground-based GW Detector Network in 2020



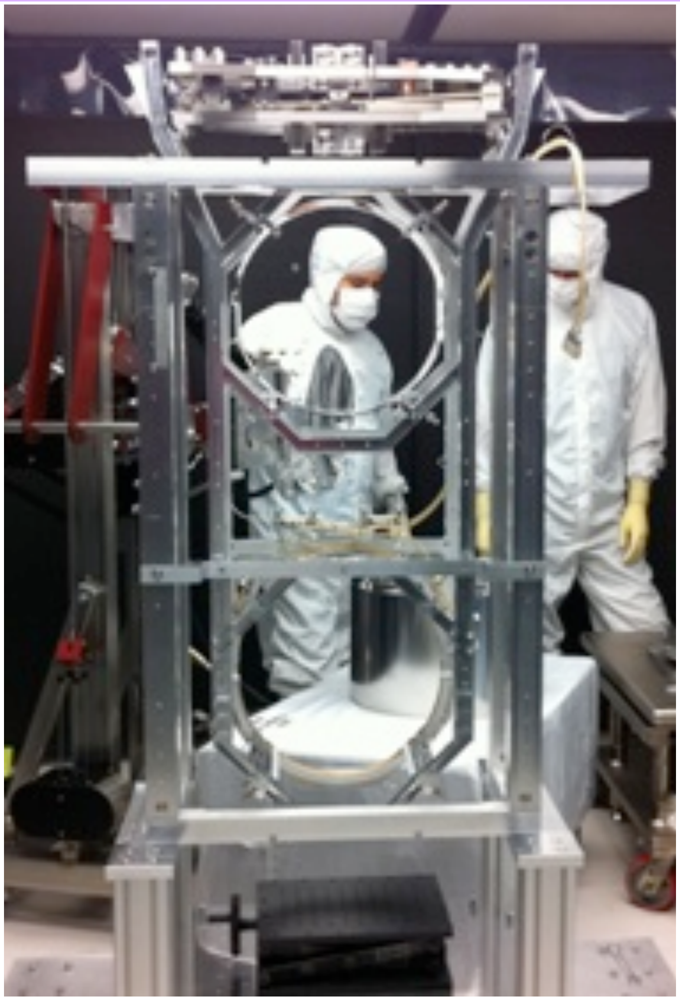
PHOTOS

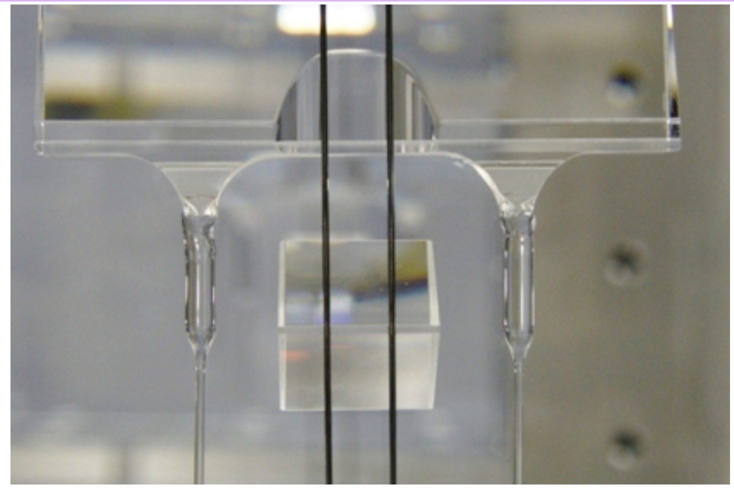
OMC Seismic Isolation platform

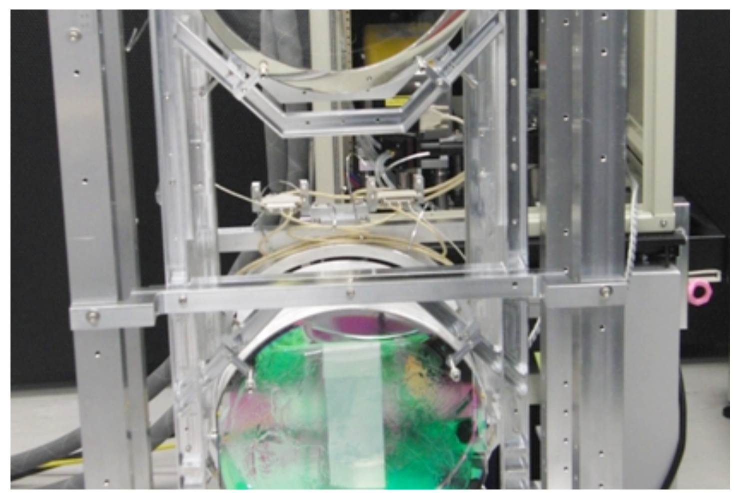
BSC Internal Seismic Isolator



Adv. LIGO Monolithic Suspension







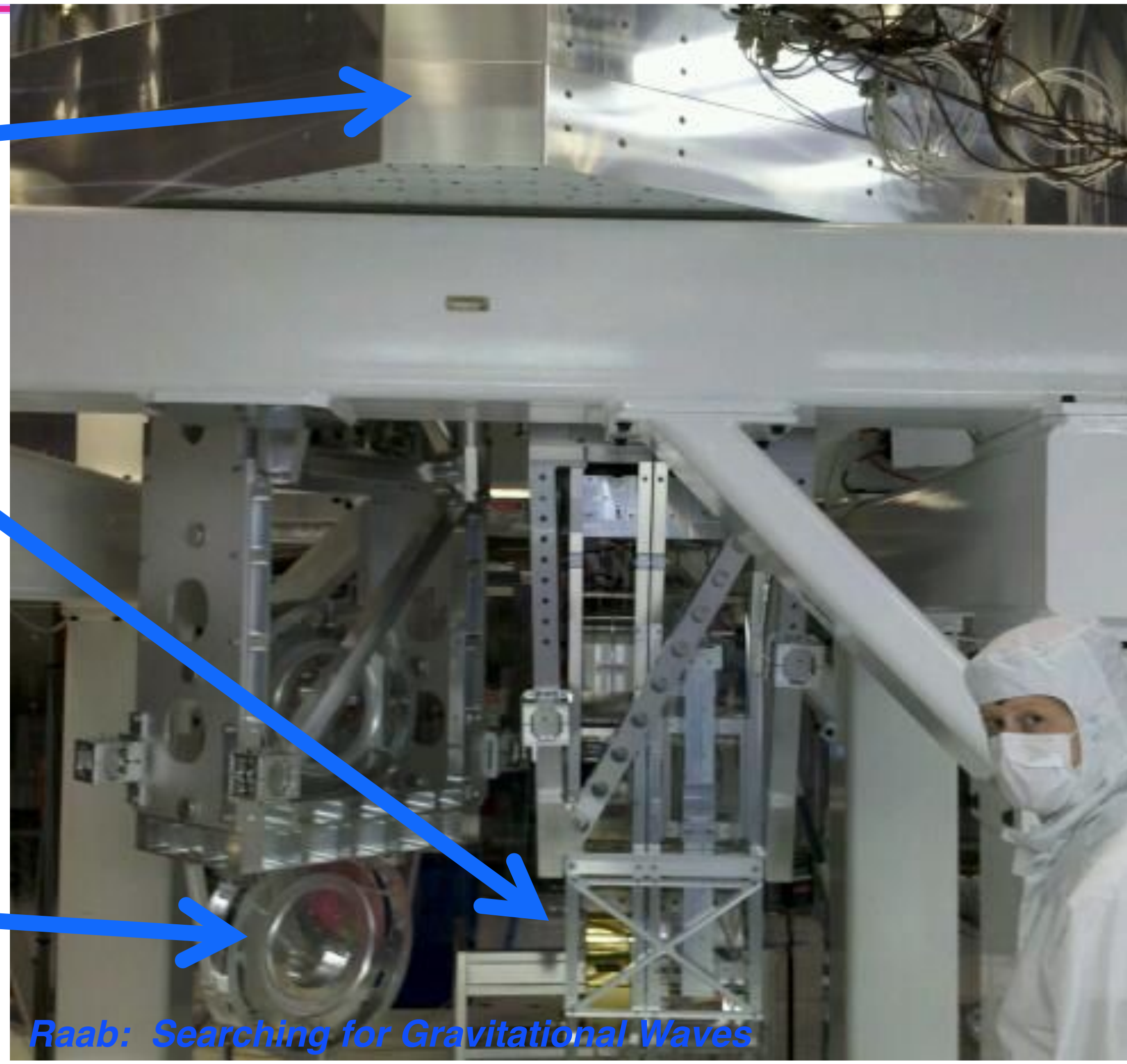
aLIGO installation in progress

Putting it together: Seismic & Suspension & Optics

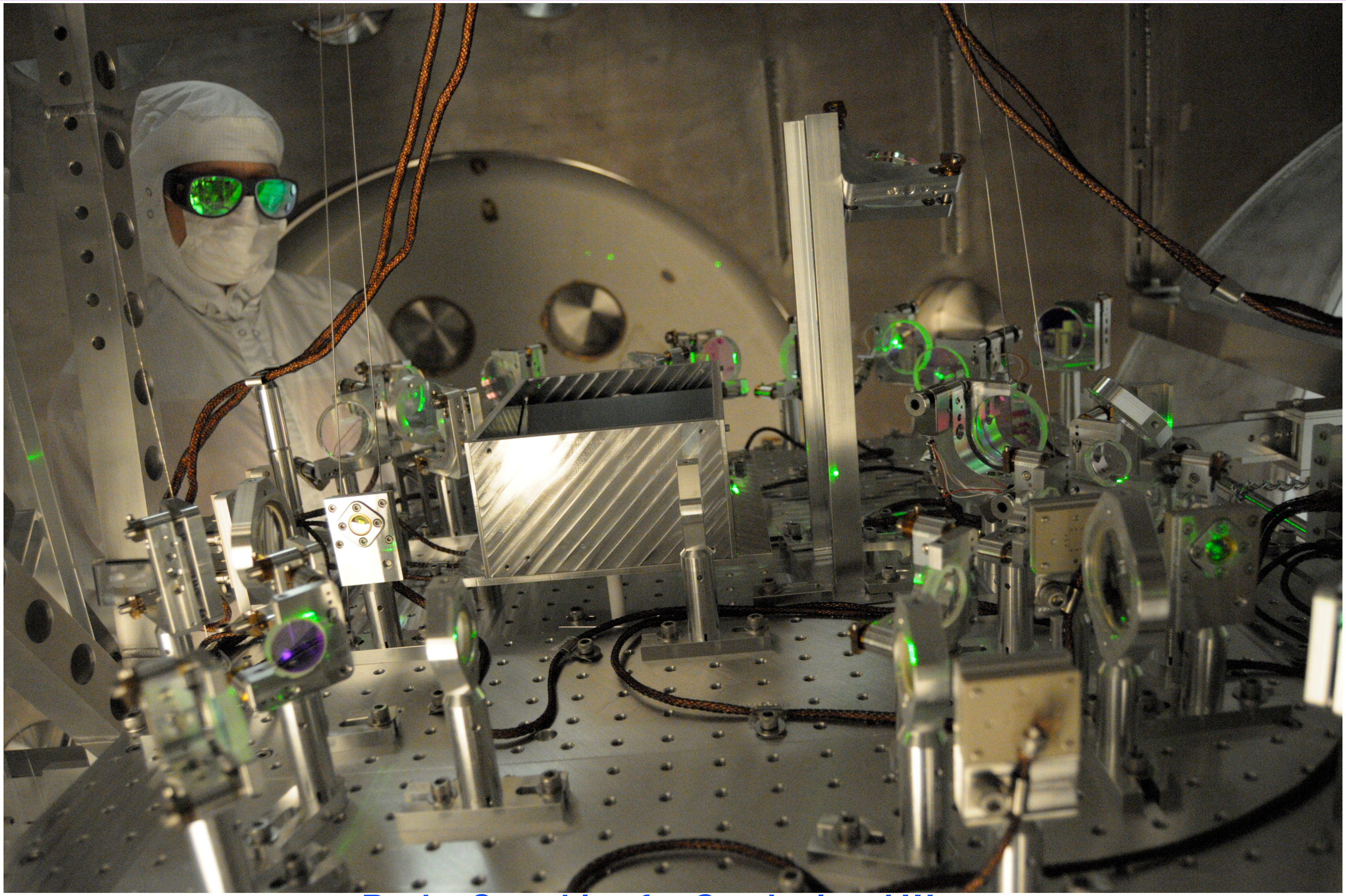
Seismic isolation

Test mass suspension

Folding mirror suspension



Lock Acquisition: Arm Locking Subsystem



aLIGO Pre-stabilized laser

What will be the legacy of LIGO discoveries?

- Attempts in the 19th century to explain why the sky is blue, sunsets red and clouds white led to the 20th century economy:
  - » Atomic and nuclear physics and modern materials
  - » Modern chemical and pharmaceutical industries
  - » Modern electronics and computer industries
  - » Unraveling the structure of DNA and other bio-molecules, leading to modern biochemistry and gene therapy
  - » Development of almost all medical diagnostic machines
  - » Also a new phrase, "Blue-sky research"
- LIGO discoveries likely will revolutionize our understanding of space, time, matter and energy, as well as redefine what people can imagine and build