LIGO

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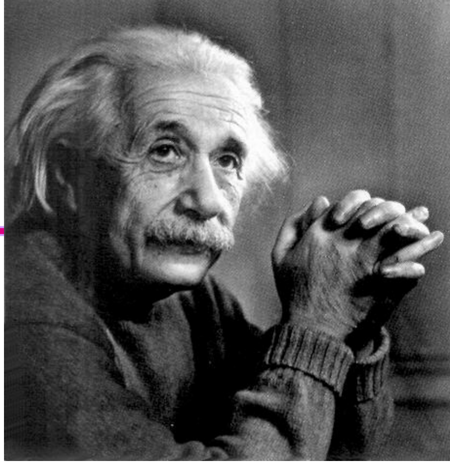
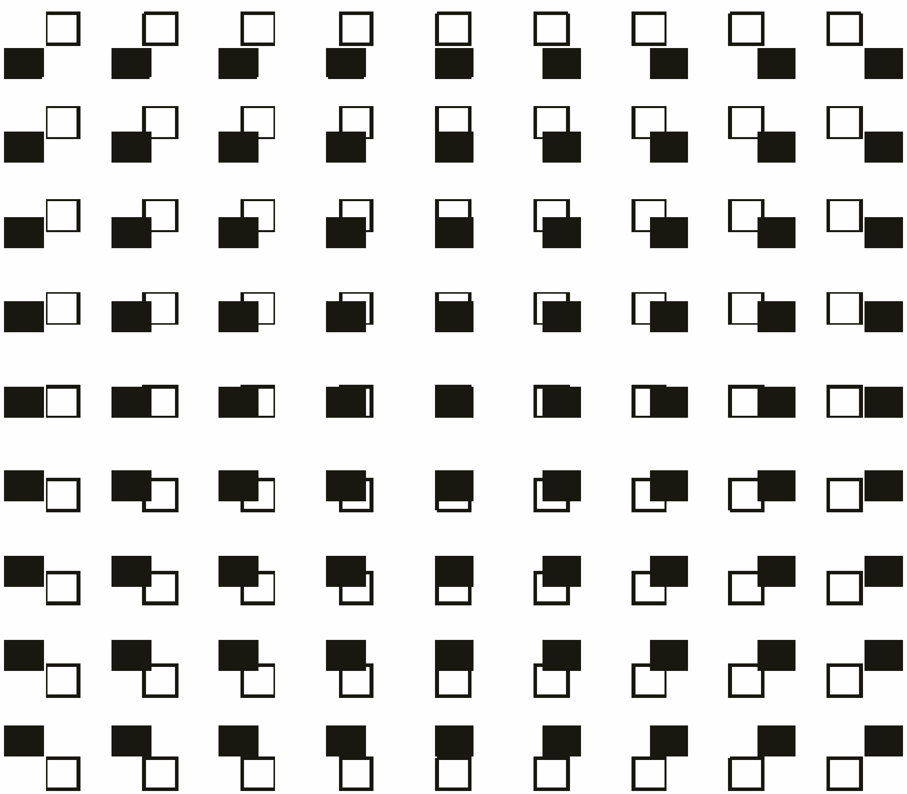
What is LIGO?

- **L**aser **I**nterferometer **G**ravitational-wave **O**bservatory
  - » Thank you, NSF and taxpayers!
- LIGO's mission is to use Gravitational Waves as a completely new window on to the universe
  - » Analogous the change in perspective made when going from optical observation to cosmic radio waves, or x-rays – an entirely new view
- GWs are produced by accelerating mass: e.g., supernovae
  - » The biggest signals made by the most violent, extreme events in the universe
  - » GWs are not attenuated by matter – can see through dust, intervening galaxies, dark matter
- GWs are ripples in space-time – to be observed as variations in the apparent distance between objects as the wave passes
  - » Effect is tiny….

Gravitational Waves

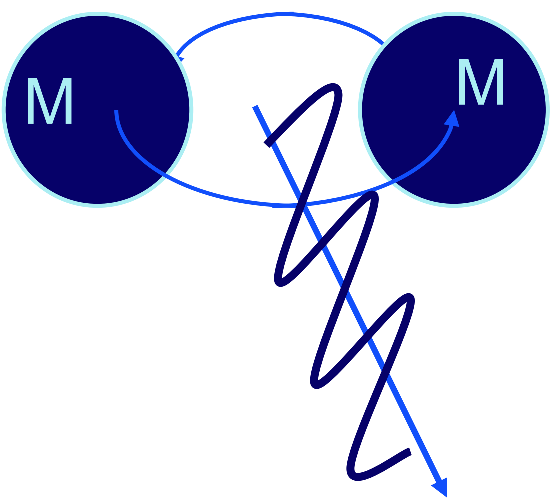


- Einstein's General Theory of Relativity predicts gravitational radiation
  - » Analogous to electromagnetic radiation – transverse waves, carrying energy, speed of light, due to accelerations of 'charge'
  - » Amplitude measured as the dimensionless strain in space, $h = (\Delta L)/L$
- Quadrupolar – *x* axis shrinks while *y* axis grows, then vice versa, as wave passes



Gravitational Waves

- A very weak effect: only astrophysical events make conceivably measurable effects
- A ‘binary inspiral’ of two solar-mass stars at the Virgo cluster (18 Mpc away) will cause a change in apparent length of a meter stick of ~10^{-21} meters
- …a 10m stick would see a change of 10^{-20} m, 100m → 10^{-19} m…



$$M \approx 10^{30}\ \mathrm{kg}$$

$$R \approx 20\ \mathrm{km}$$

$$f \approx 400\ \mathrm{Hz}$$

$$r \approx 10^{23}\ \mathrm{m}$$

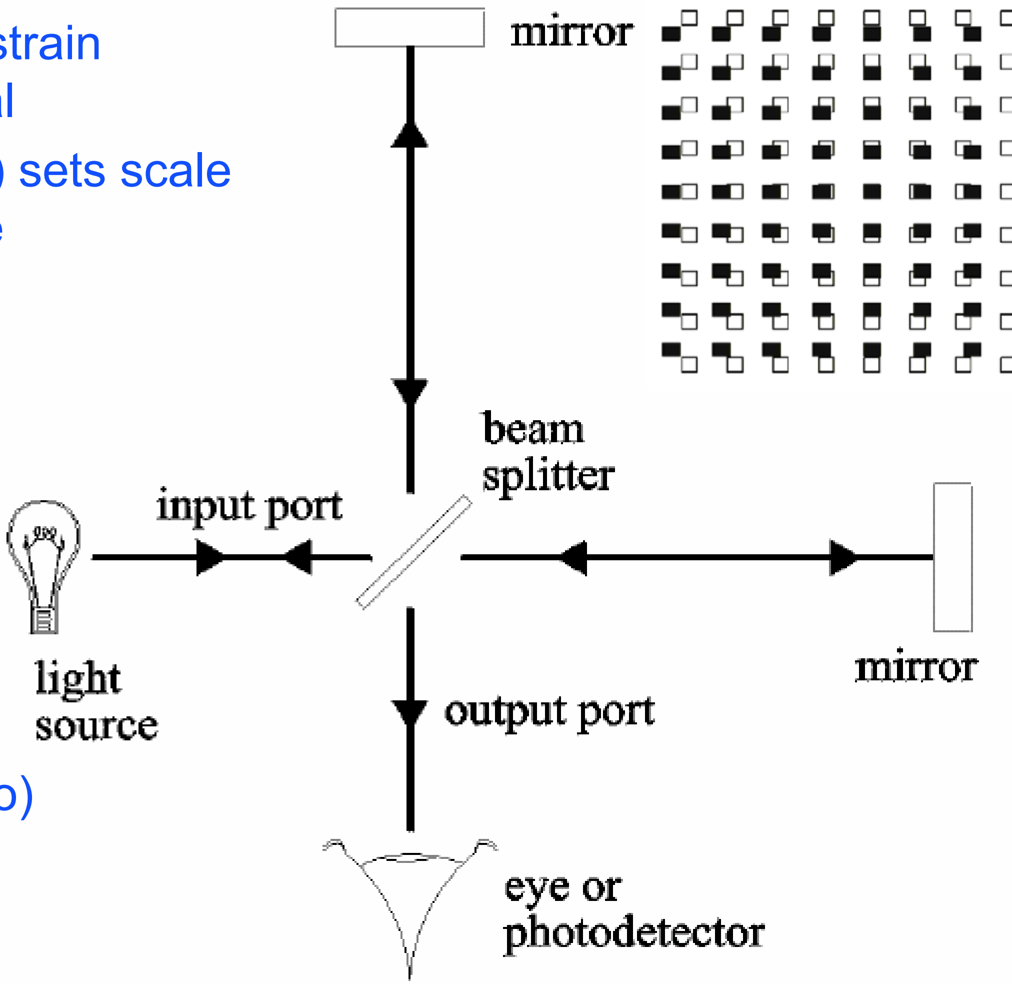
⇨ $h \sim 10^{-21}$

Interferometry

- Rainer Weiss in 1972:
- Use laser interferometry to sense the strain due to the expected quadrupolar signal
- Wavelength of light (typically 1 micron) sets scale for measurement 'ruler'; split the fringe

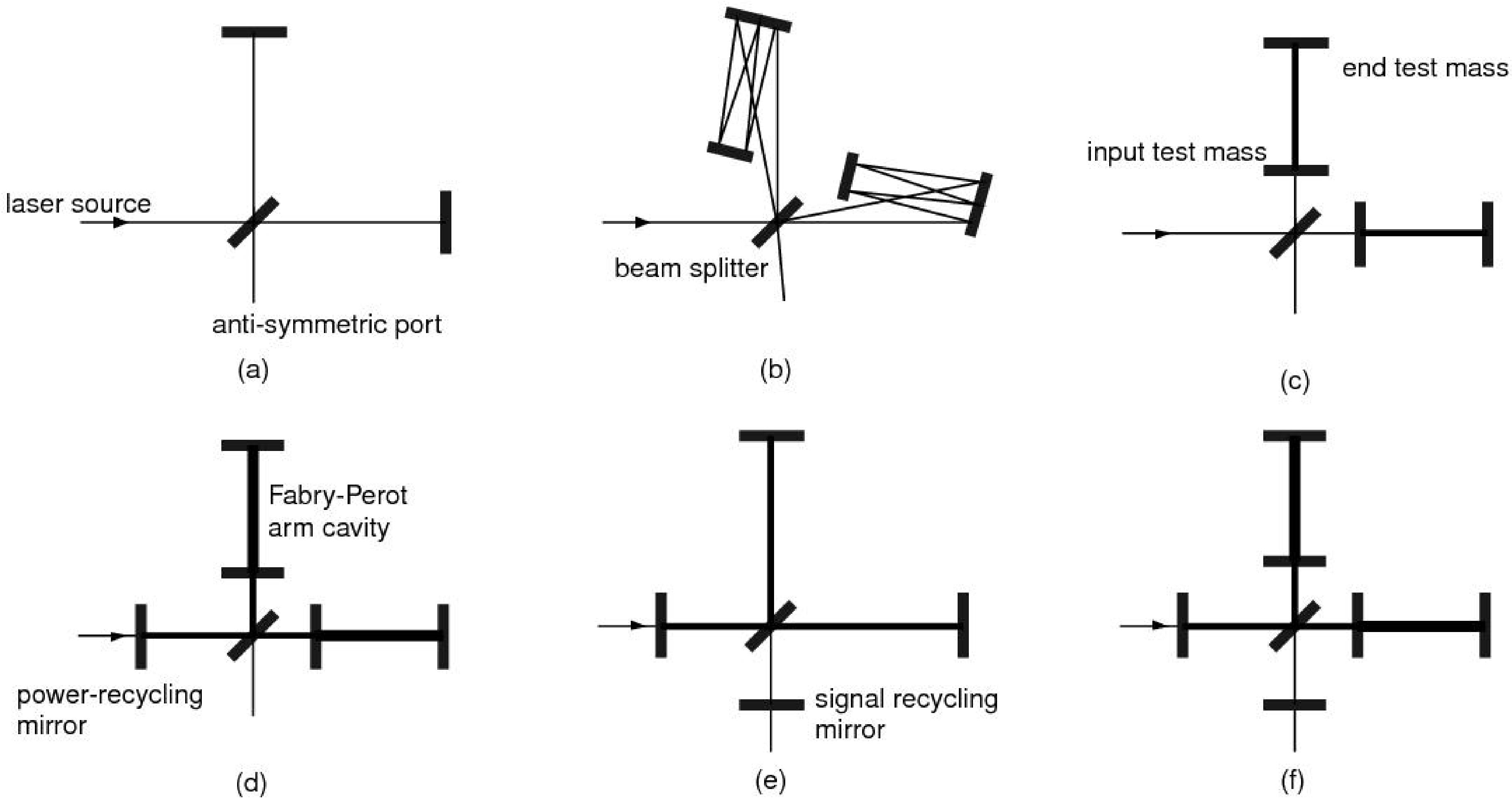
- However, an instrument of ~4km is needed to have an astrophysically interesting sensitivity
- Light must travel in a good vacuum to avoid scintillation
- Need two instruments, separated, to claim detection (and get directional info)

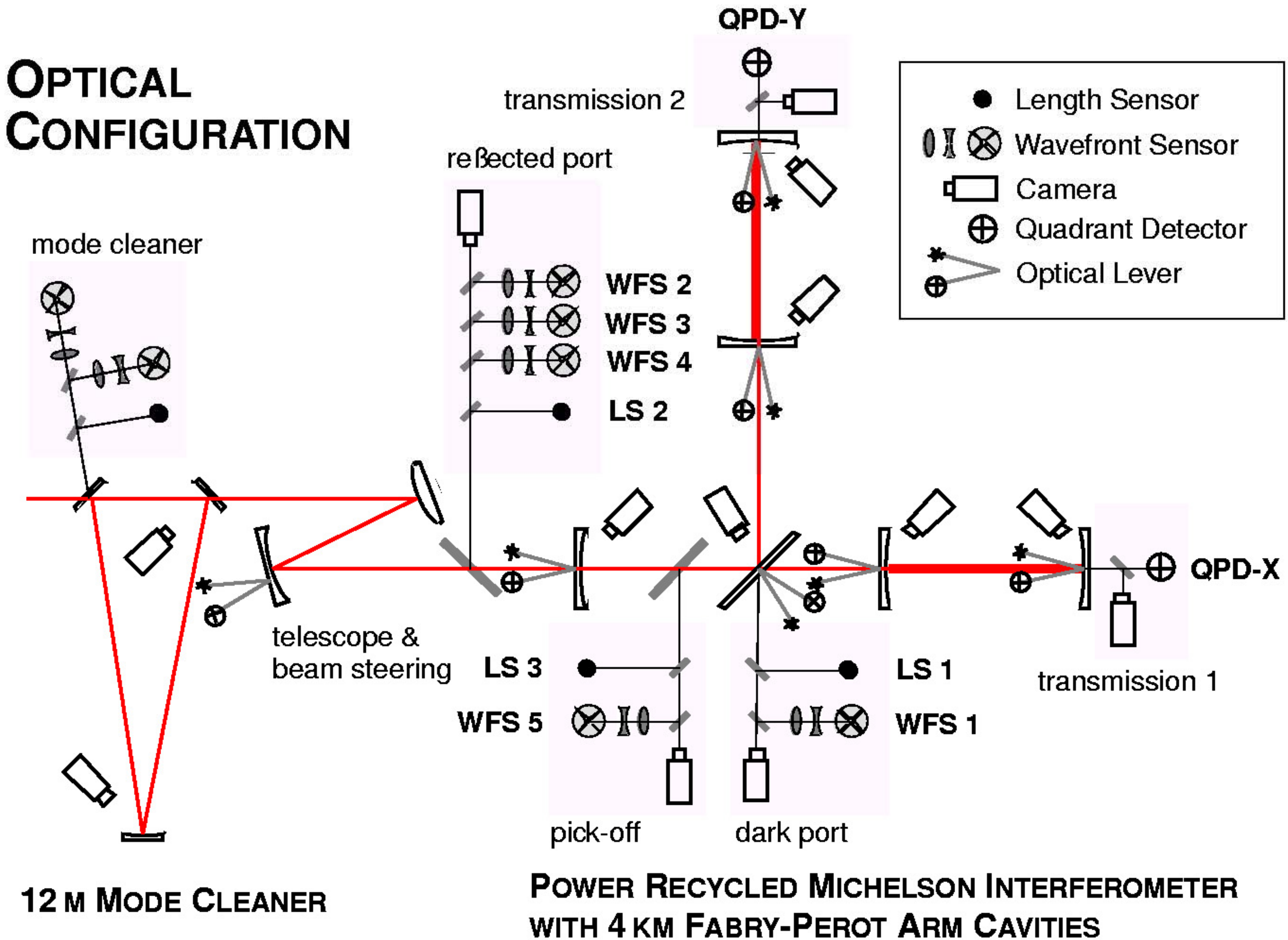
→ Detector must be big!



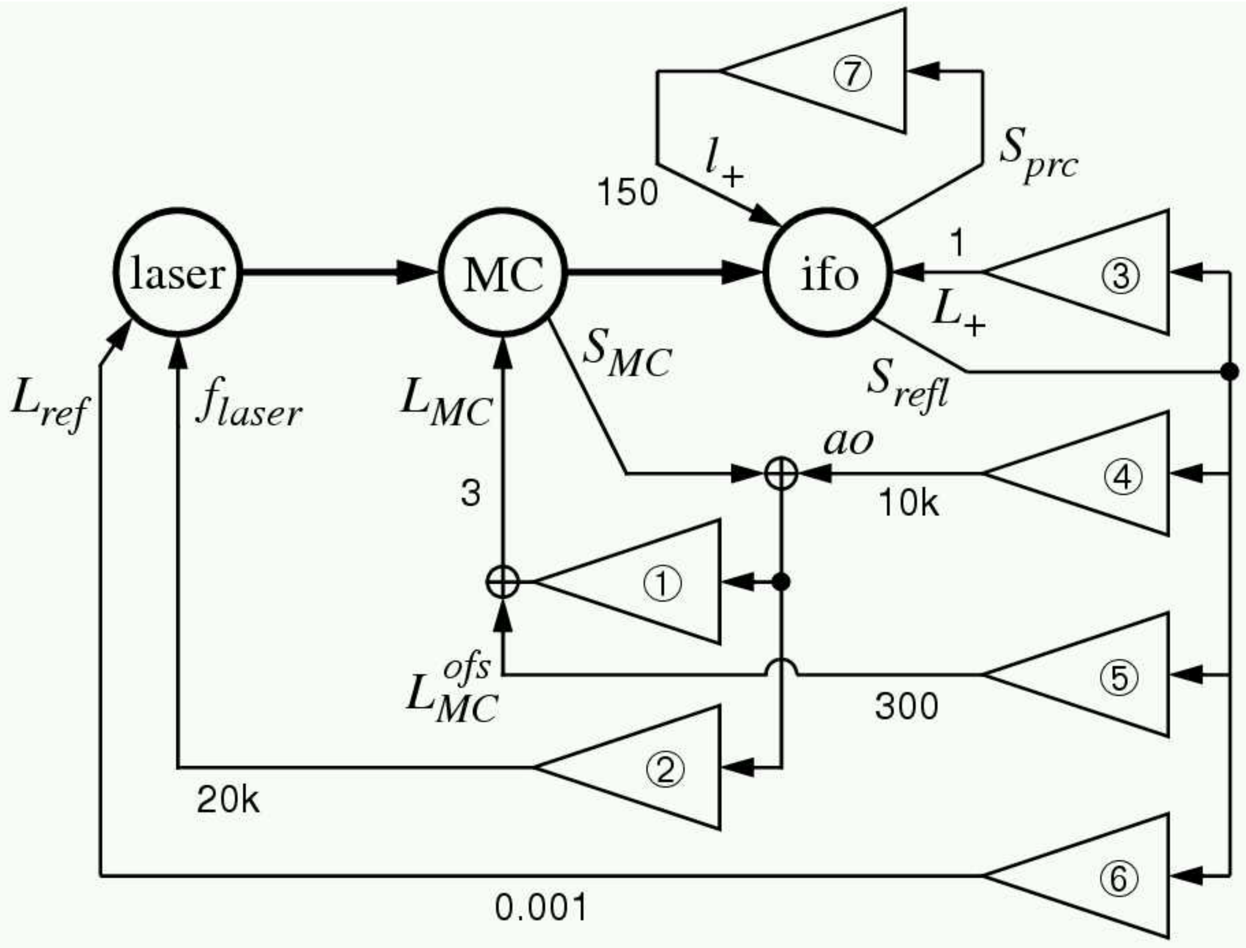
LIGO

Interferometer Configurations




OPTICAL CONFIGURATION
QPD-Y
transmission 2
reflected port
Length Sensor
Wavefront Sensor
Camera
Quadrant Detector
Optical Lever
mode cleaner
WFS 2
WFS 3
WFS 4
LS 2
QPD-X
telescope &
beam steering
LS 3
WFS 5
LS 1
WFS 1
transmission 1
pick-off
dark port
12 M MODE CLEANER
POWER RECYCLED MICHELSON INTERFEROMETER
WITH 4 KM FABRY-PEROT ARM CAVITIES

Length Sensing and Control

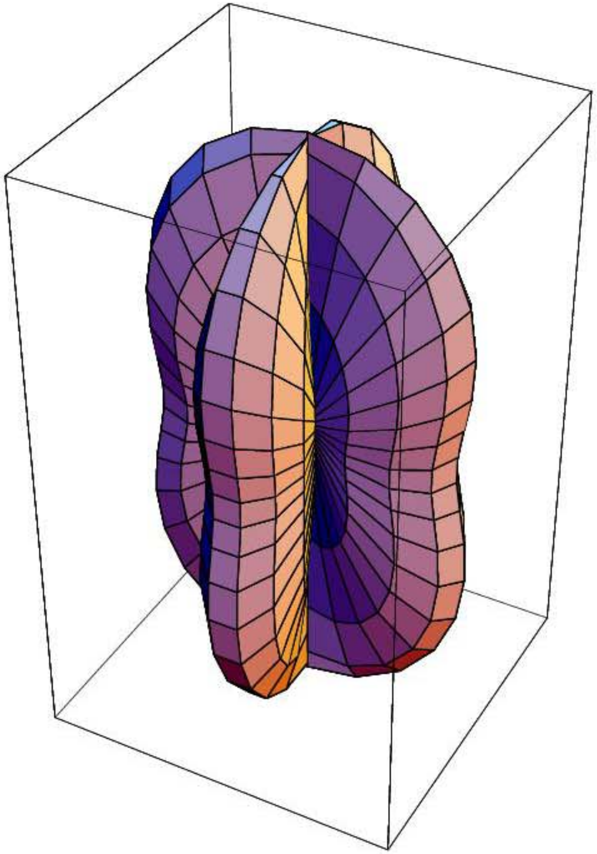


- Separate common and differential mode
  - » Diff. arm
  - » Michelson
  - » Common arm
  - » PR cavity
- Sensors
  - » Anti-symmetric port
  - » In reflection
  - » PR cavity sample

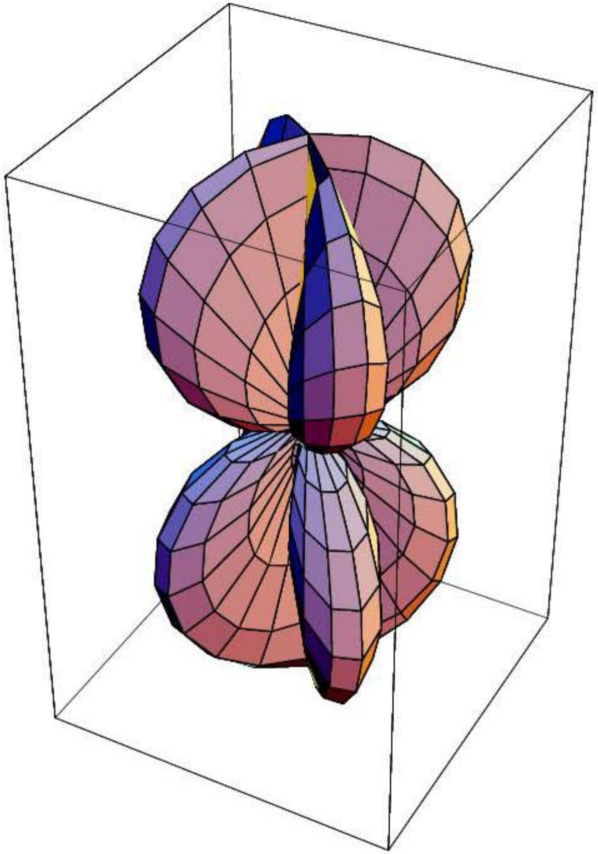
Some Requirements

- Sensitivity: ~10^{-19} m/√Hz at 150 Hz
- Controller range: ~100 μm (tides)
- Control of diff. arm length: ≤10^{-13} m rms
- Laser intensity noise: ≤10^{-7} /√Hz at 150 Hz
- Frequency noise: ≤3×10^{-7} Hz/√Hz at 150 Hz
- Angular Control: ≤10^{-8} rad rms
- Input beam jitter: ≤4×10^{-9} rad/√Hz at 150 Hz

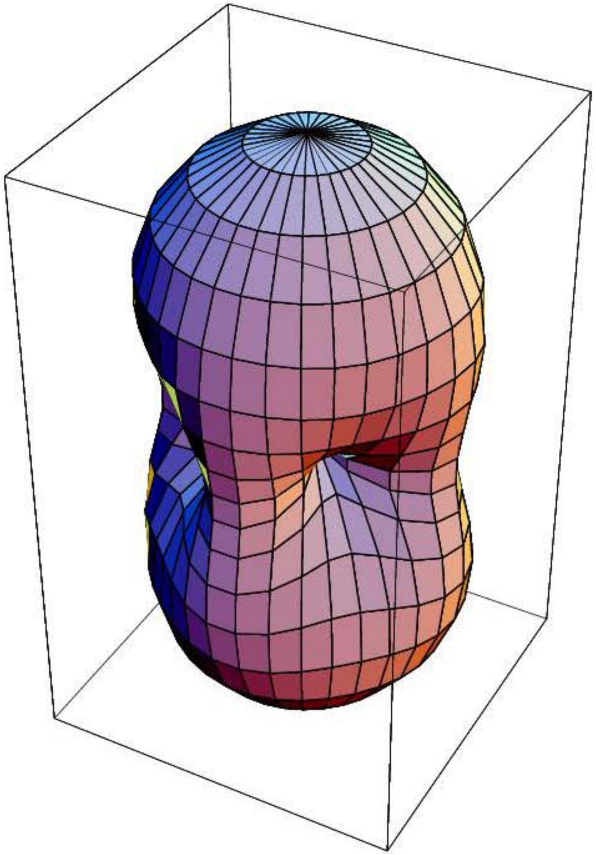
Antenna Pattern



+ polarization



× polarization

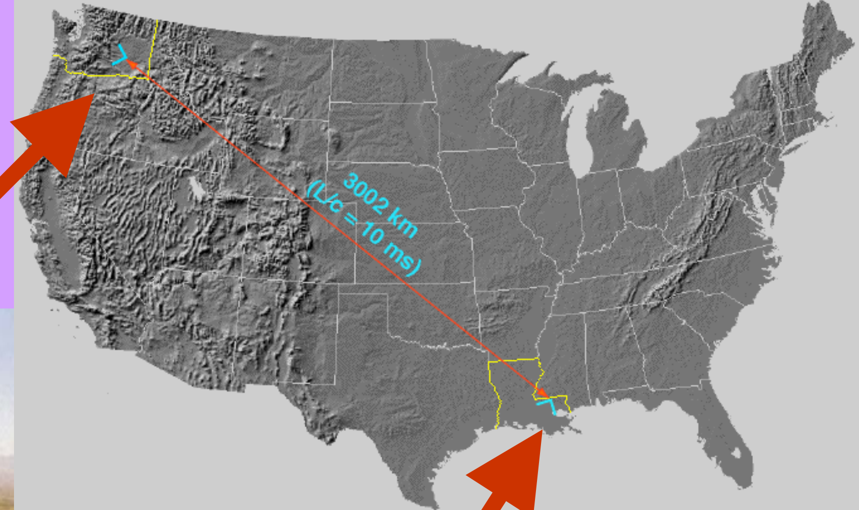


averaged

LIGO

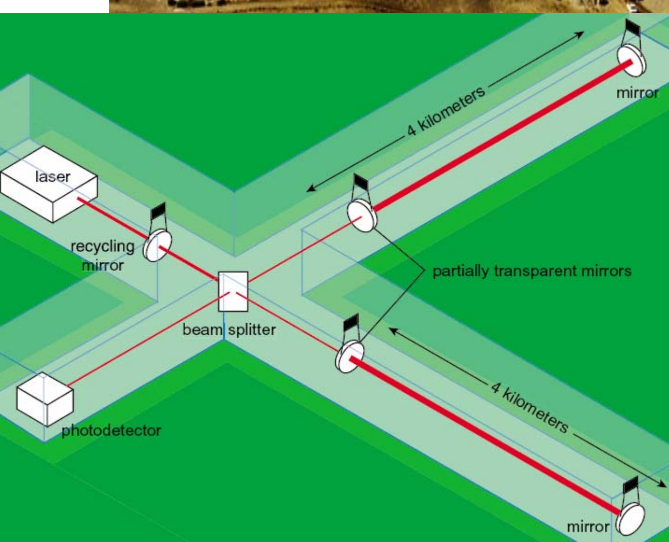
LIGO Hanford Observatory [LHO]

2 km + 4 km interferometers in same vacuum envelope



LIGO Livingston Observatory [LLO]

Single 4 km interferometer



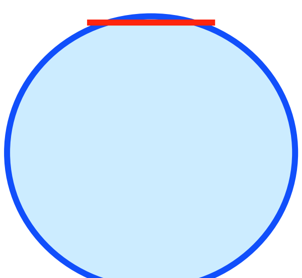
- Two separated observatories for detection confidence, directional information
- Initial planned sensitivity just enough to plausibly see signals; evolution to greater sensitivity in the mission
- Proposed in ’89, construction starting ’95, construction finished on time and on budget

LIGO
beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

- Concrete slab flat to 3mm precision over 4km length
- Nice, thick, concrete cover

1.2 m diameter - 3mm stainless
50 km of weld….and not one leak



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vacuum equipment

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Seismic Isolation

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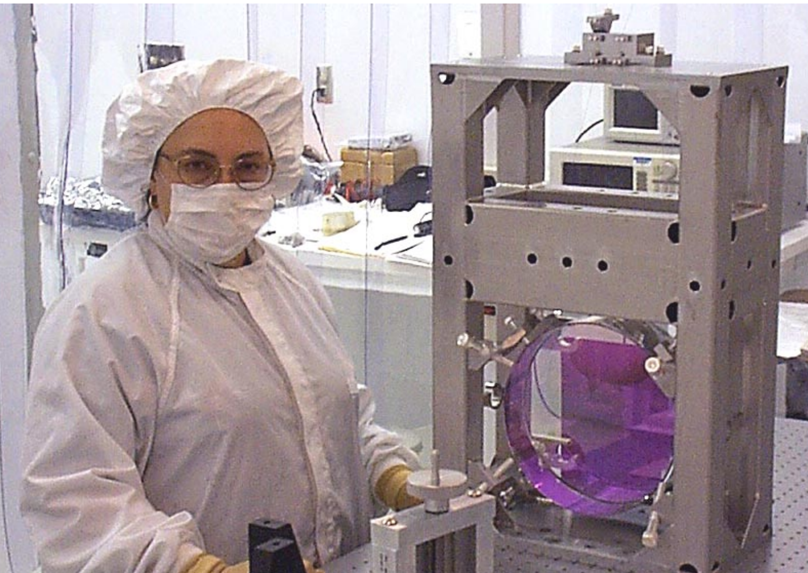
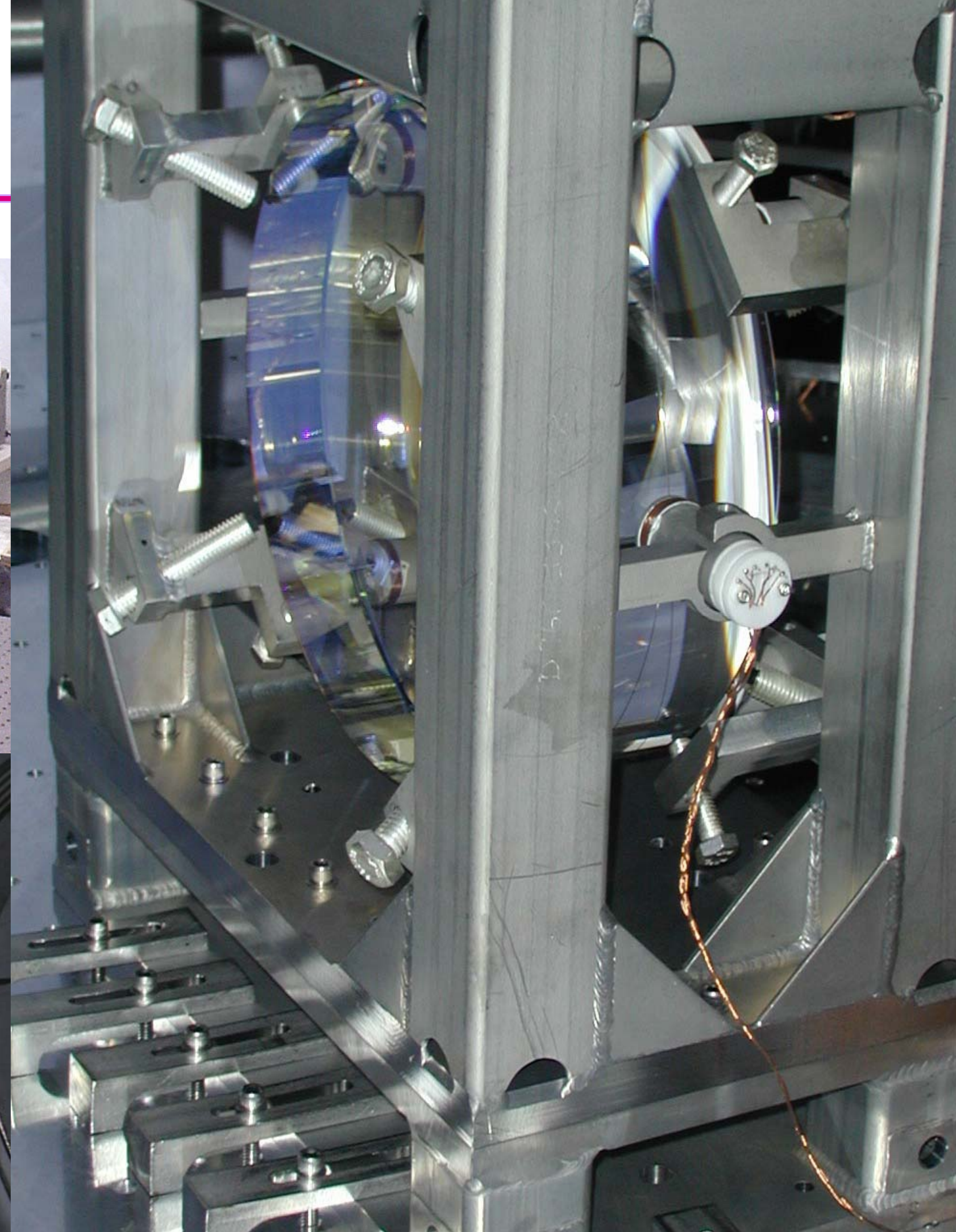
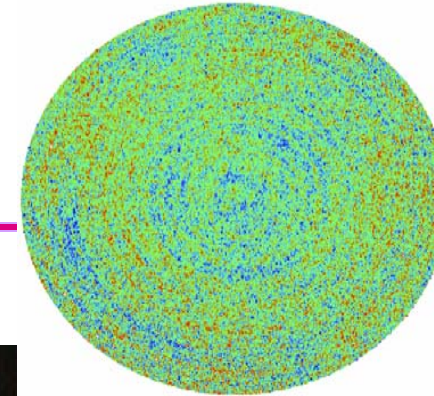
Suspensions





LIGO Optic



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

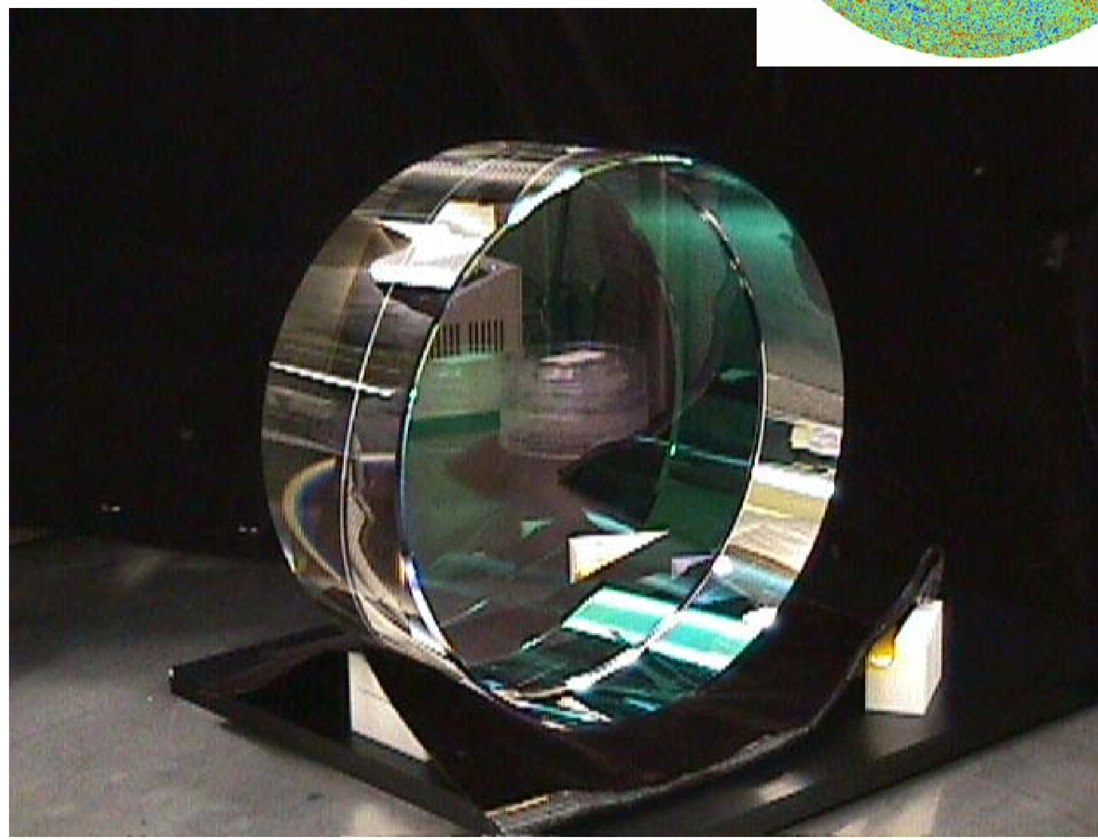
Radii of curvature matched < 3%

Coating

Scatter < 50 ppm

Absorption < 2 ppm

Uniformity <10^{-3}

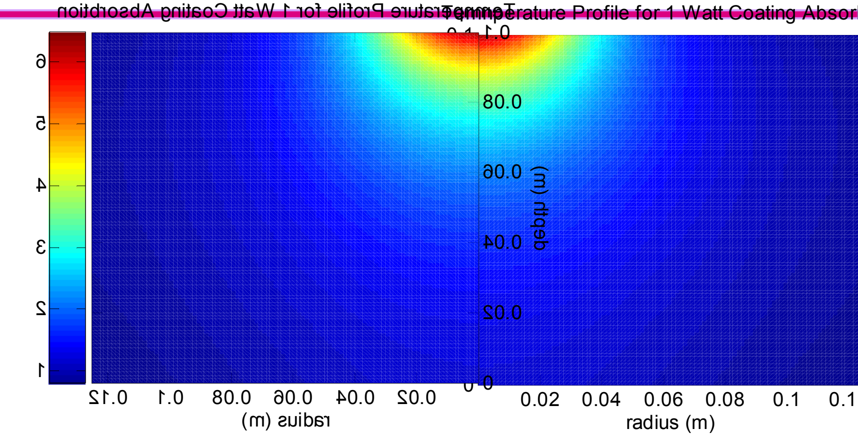


Absorption in LIGO Optics

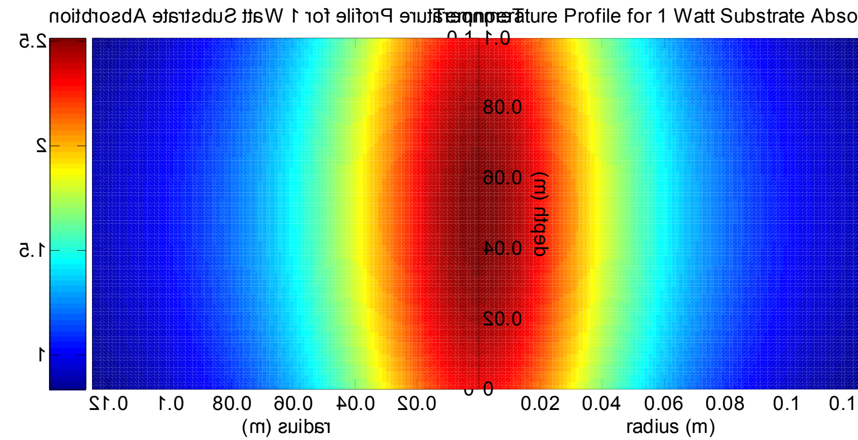
Laser light reflecting off coatings and traversing silica substrates will be absorbed.

Largest effect in input mirrors because of the transmission

Heating and lensing cause reduction in interference pattern and power buildup



Coating absorption



Substrate absorption

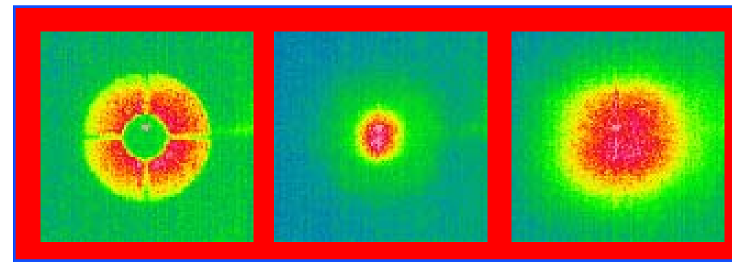
Thermal Compensation

Heating and lensing controlled by adding additional heat with a CO_2 laser

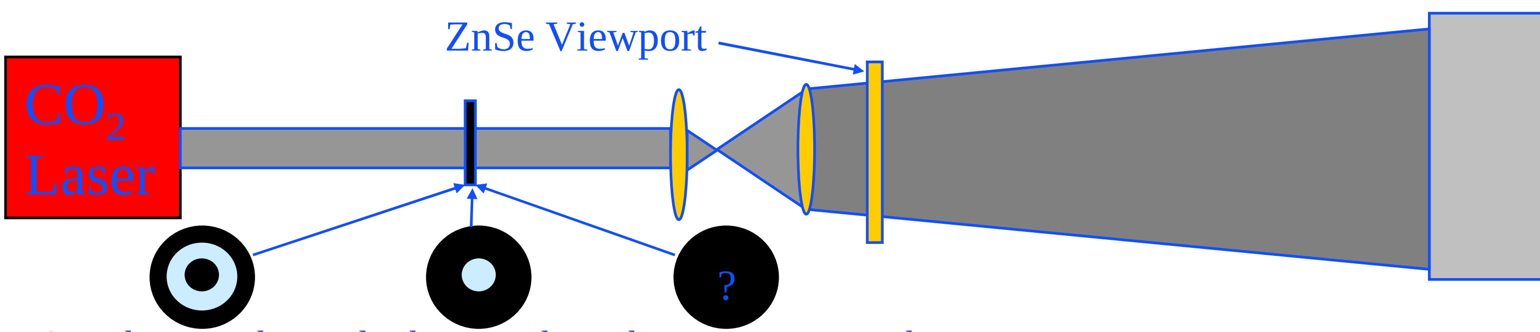
Too much heating can be corrected by adding CO2 light to optic edge

Too little heating can be corrected by adding CO2 light to center

May have to correct for inhomogeneous heating in advanced LIGO

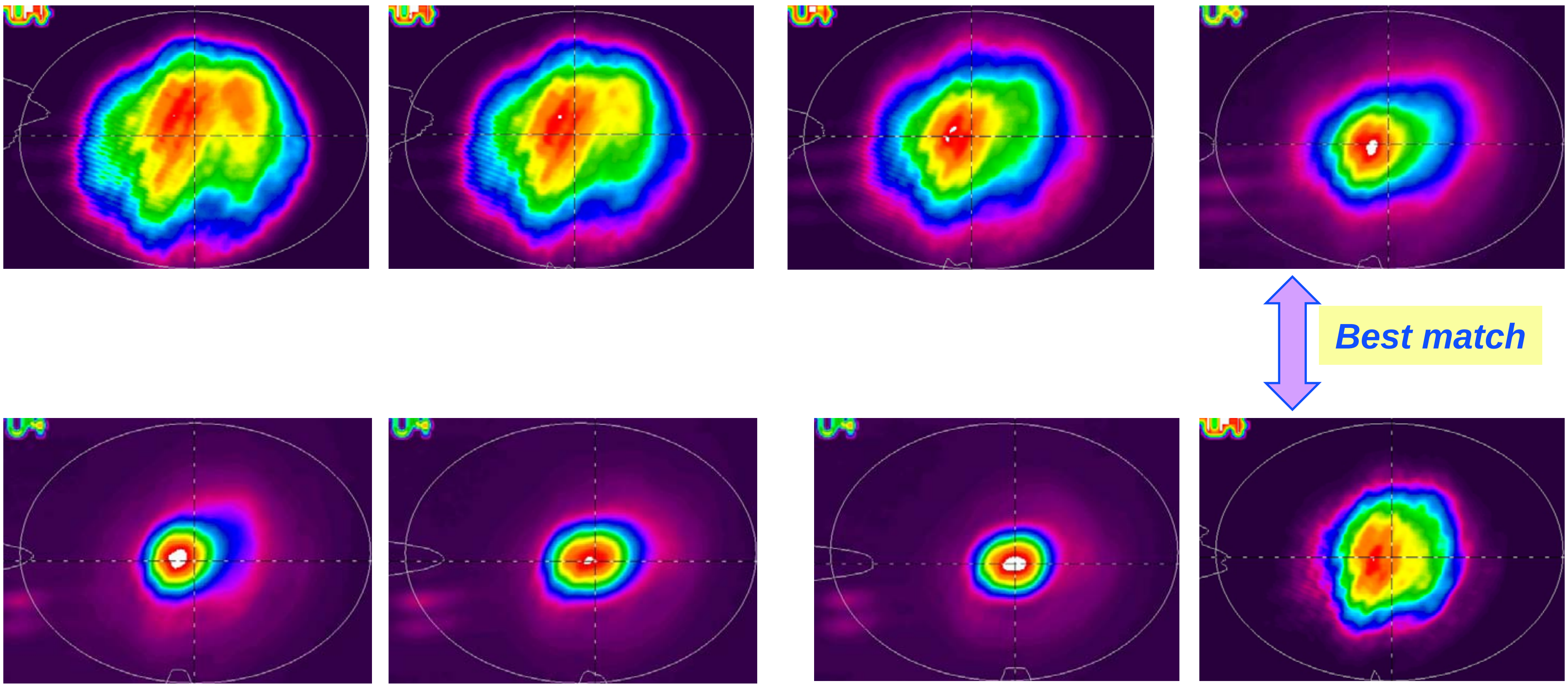


Over-heat pattern | Under-heat pattern | Raw Heating pattern



Sideband Images as Function of Thermal Heating

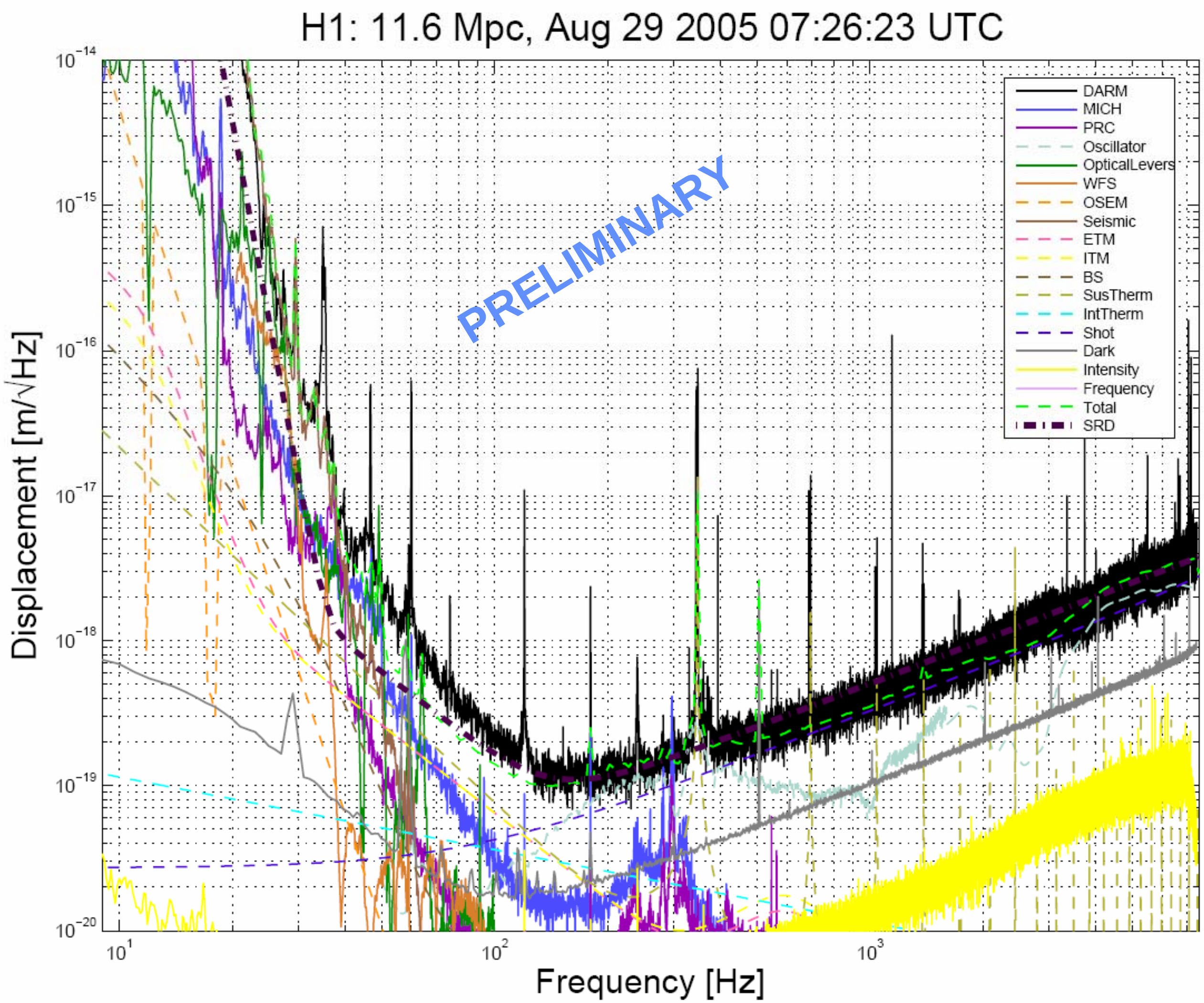
No Heating | 30 mW | 60 mW | 90 mW



120 mW | 150 mW | 180 mW | Input carrier

Overall LIGO Status

- Commissioning drawing to a close
- Have run, collected data, analyzed, published – no detections to date
- Significant new ‘upper limits’ established
- Initial instruments ready to observe at design sensitivity
- Will start long runs in November 2005

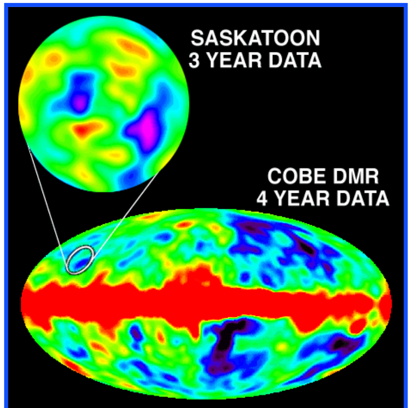


Sources of gravitational waves

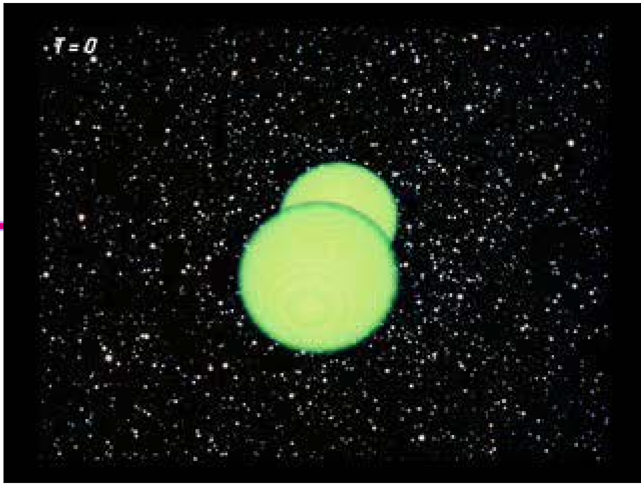
- Supernovae / GRBs / Strings:
  “bursts”
  - » burst signals in coincidence, maybe with signals in electromagnetic radiation, neutrinos
  - » prompt alarm (~ one hour) with neutrino detectors

- Pulsars in our galaxy: *“periodic”*
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)

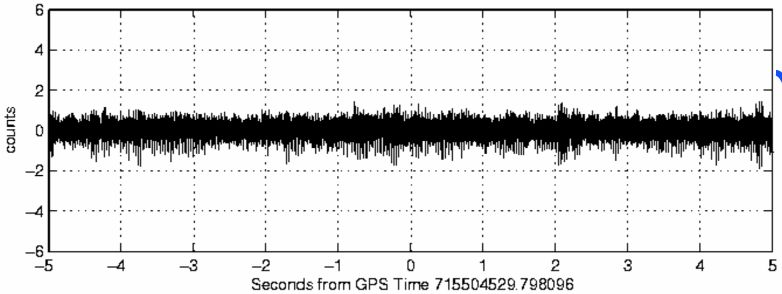
- Cosmological Signals *“stochastic background”*

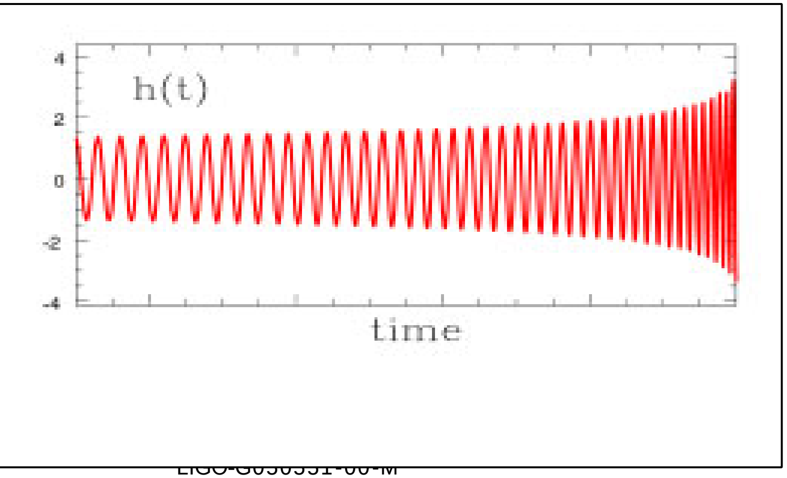


Compact binary inspiral: *"chirps"*

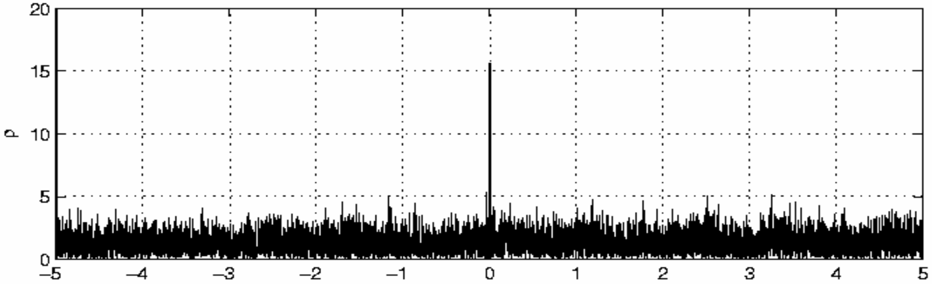


GW Channel
+ simulated inspiral





SNR

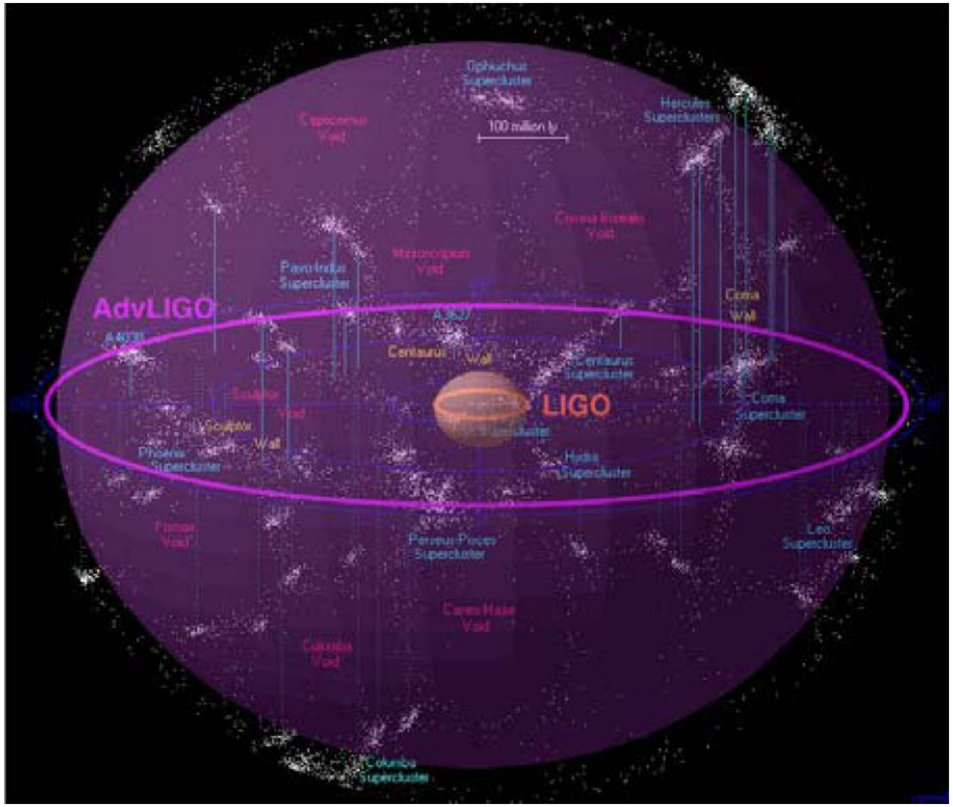


Coalescence Time

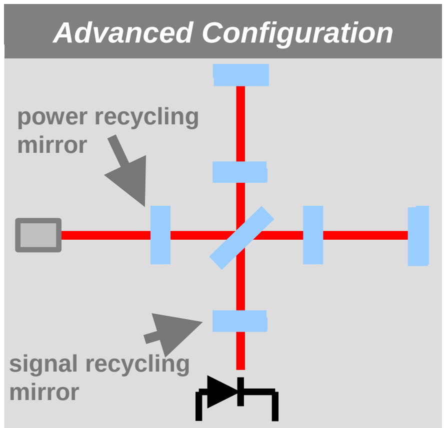
NS-NS waveforms -- good predictions
BH-BH (<10 Ms) – would like better models
search technique: matched templates
…also triggers to/from Gamma Ray Bursts

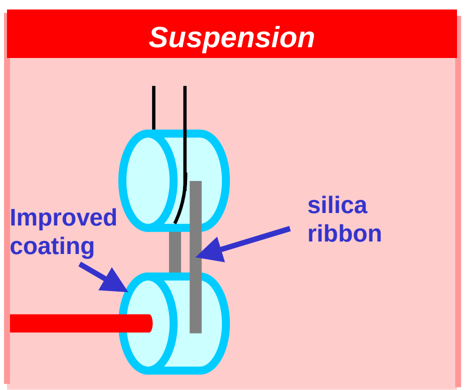
LIGO Future

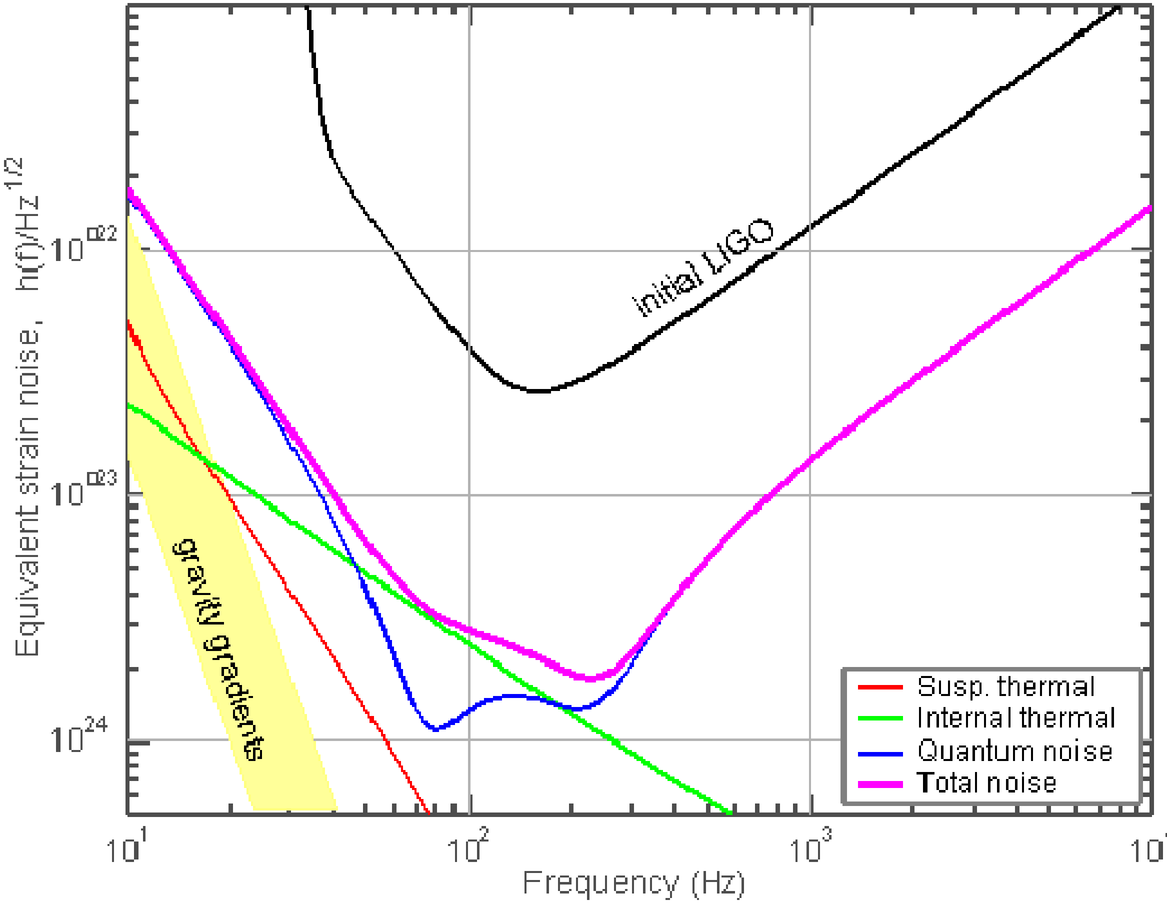
- LIGO proposed and designed to house several generations of detectors
- Advanced LIGO proposed to follow initial LIGO observation run
- Factor of 10 more sensitive → 1000x greater volume, many more sources
- Anticipate several GW events per day



Advanced LIGO



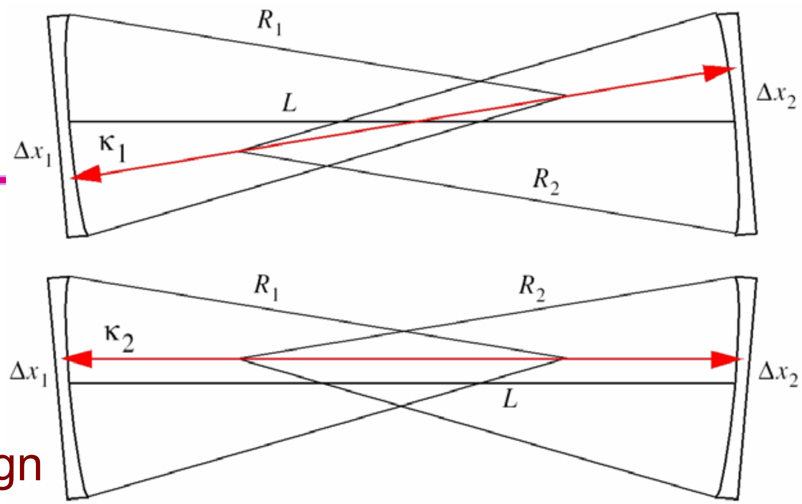




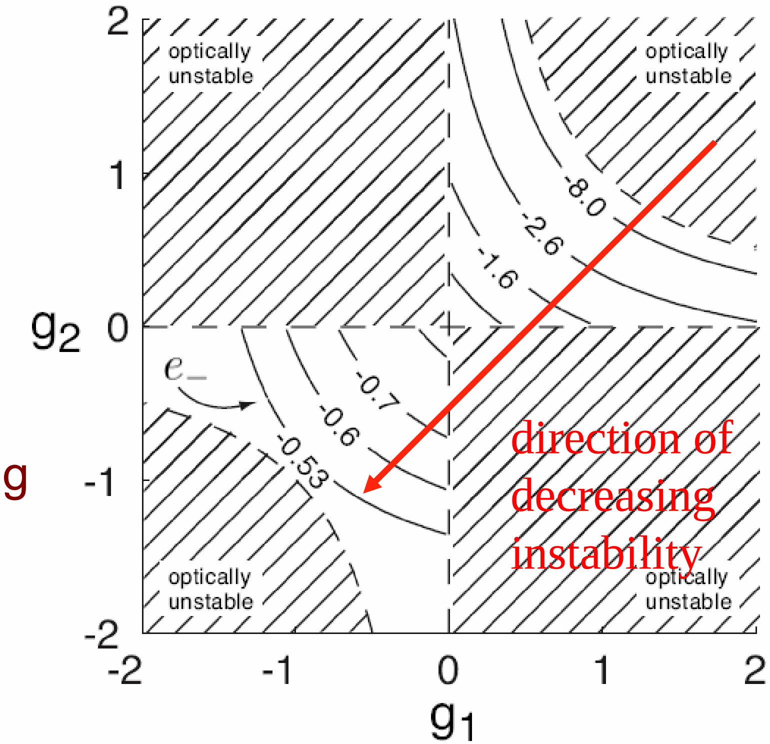
- **Factor of 15 in strain improvement**
- **Seismic isolation down to 10 Hz**
- **Multiple pendulum suspension**
- **180 W of laser power**
- **Larger optics with improved coating**
- **Additional mirror for signal recycling**
- **Some nice new technical challenges!**

Cavity stability

- Sidles-Sigg Instability
- Significant torques from light pressure (1 Mw) if beams are not centered on optics
- In a spherical mirror cavity, mirror tilts misalign the mode off axis, creating radiation pressure torque.
- This torque can restore equilibrium (**a**) or further misalign the mirrors (**b**).
- Countered by choosing appropriate sign of cavity ‘g’ factor (nearly concentric cavity), reducing seismic input to stay close to equilibrium point, and (reluctantly) increasing actuator authority.



(b) negative eigenvalues of the normalized torsional stiffness matrix



Acoustic Parametric Instability

- Radiation force on a mirror from a light beam of power P

$$F = \frac{2P}{c}$$

- For two coincident beams the (ponderomotive) force is

$$F \propto \frac{2}{c}\left[E_1^2 + E_2^2 + E_1 E_2 \cos(\omega_1 - \omega_2)t\right]$$

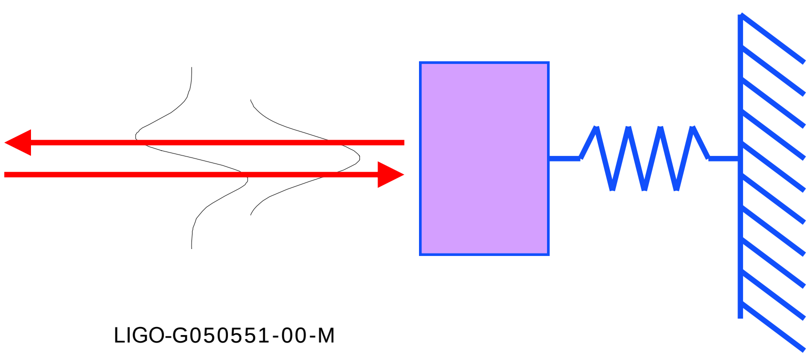
- The E_1 E_2 term drives the mirror oscillation x

$$x \propto \frac{E_1 E_2 e^{i(\omega_1 - \omega_2)t}}{Mc\left(\omega_m^2 - (\omega_1 - \omega_2)^2\right)} = x_0 e^{i\delta\omega t}$$

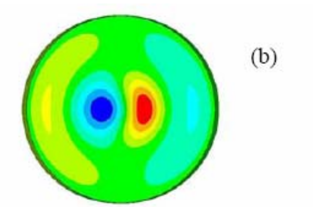
- The mirror oscillation modulates the carrier E_1 to produce sideband E_2

$$E_1 e^{i\omega_1 t} \rightarrow E_1 e^{i(\omega_1 t + 2x_0/\lambda \cos(\delta\omega t))}$$

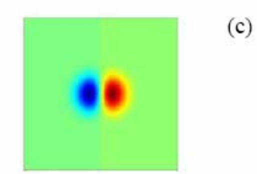
$$\approx E_1 e^{i\omega_1 t} + i\frac{x_0}{\lambda} E_1 e^{i\omega_2 t} + \cdots$$



acoustic mode



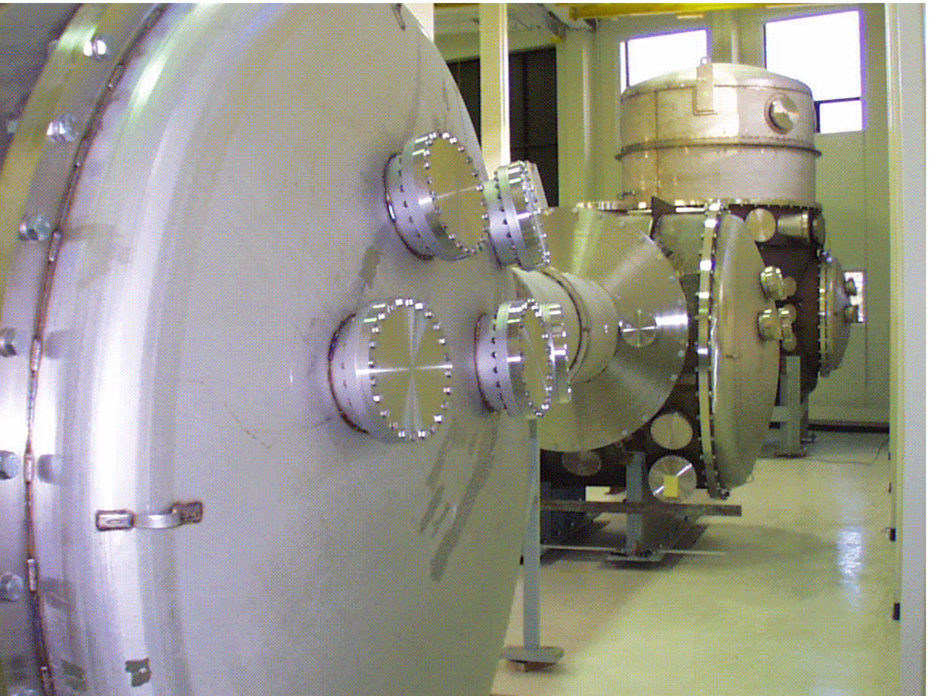
optical mode



Prototype testing

- Testbeds at MIT, Caltech – also collaborator installations at Stanford, Glasgow, Perth, Hannover….
- Full scale mechanical systems at MIT: exact LIGO vacuum system
- Scaled optical systems at Caltech: 40m interferometer, right topology

- Bottom line: we model and then prototype everything we can!

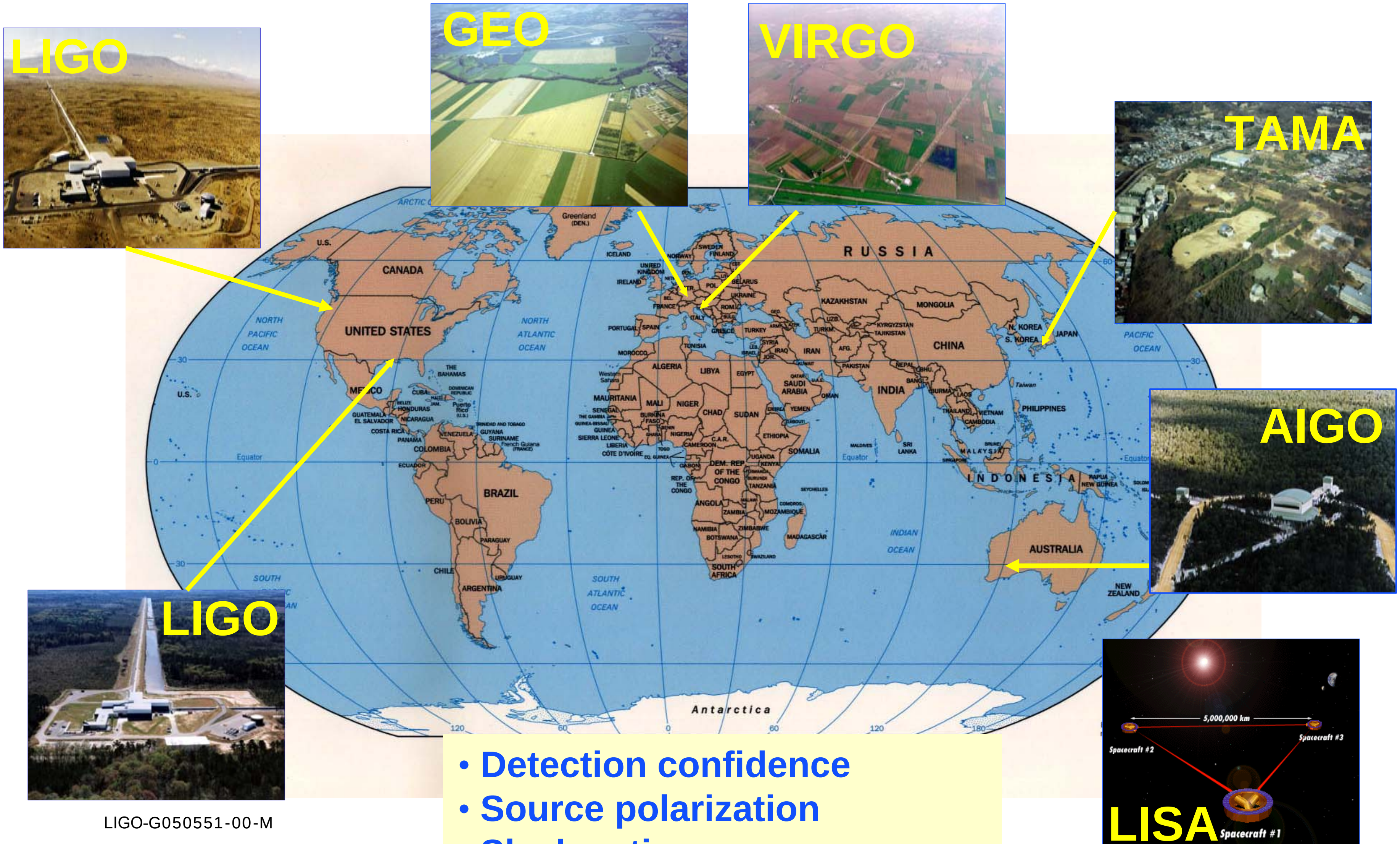


LIGO Community

- LIGO MIT: Nice mix of faculty, professional scientists, students, engineering/technical; ~25 persons
- LIGO Laboratory: Caltech and MIT, and the staff at the observatories - ~180 people
- LIGO Scientific Collaboration: ~400 people, ~40 institutions, US + international collaborators
  - » UK, Germany significant capital partners in Advanced LIGO
  - » Very strong and tight collaboration, with shared responsibilities
- World-wide field: perhaps 1000 persons

- US LIGO instruments the most sensitive to date, and by design
  - » After initial observation, will join with others for joint observation
- Second generation instruments proposed around the world

Global network of detectors



- Detection confidence
- Source polarization
- Sky location

LIGO

- An instrument builder's dream: mechanical, optical, controls challenges
- A relativist's dream: tests of relativity for multi-solar-mass objects moving almost at the speed of light
- An astrophysicist's dream: a view of the universe of a completely different kind, unobscured by dust; a new telescope

- Poised to observe, with a fighting chance for a first detection in the coming year

- Advanced LIGO upgrade in the wings, with a promise of daily detections at very high signal-to-noise ratios – should get project start in 2008

- Stay tuned!
  - » www.ligo.mit.edu
  - » Einstein@home (einstein.phys.uwm.edu)