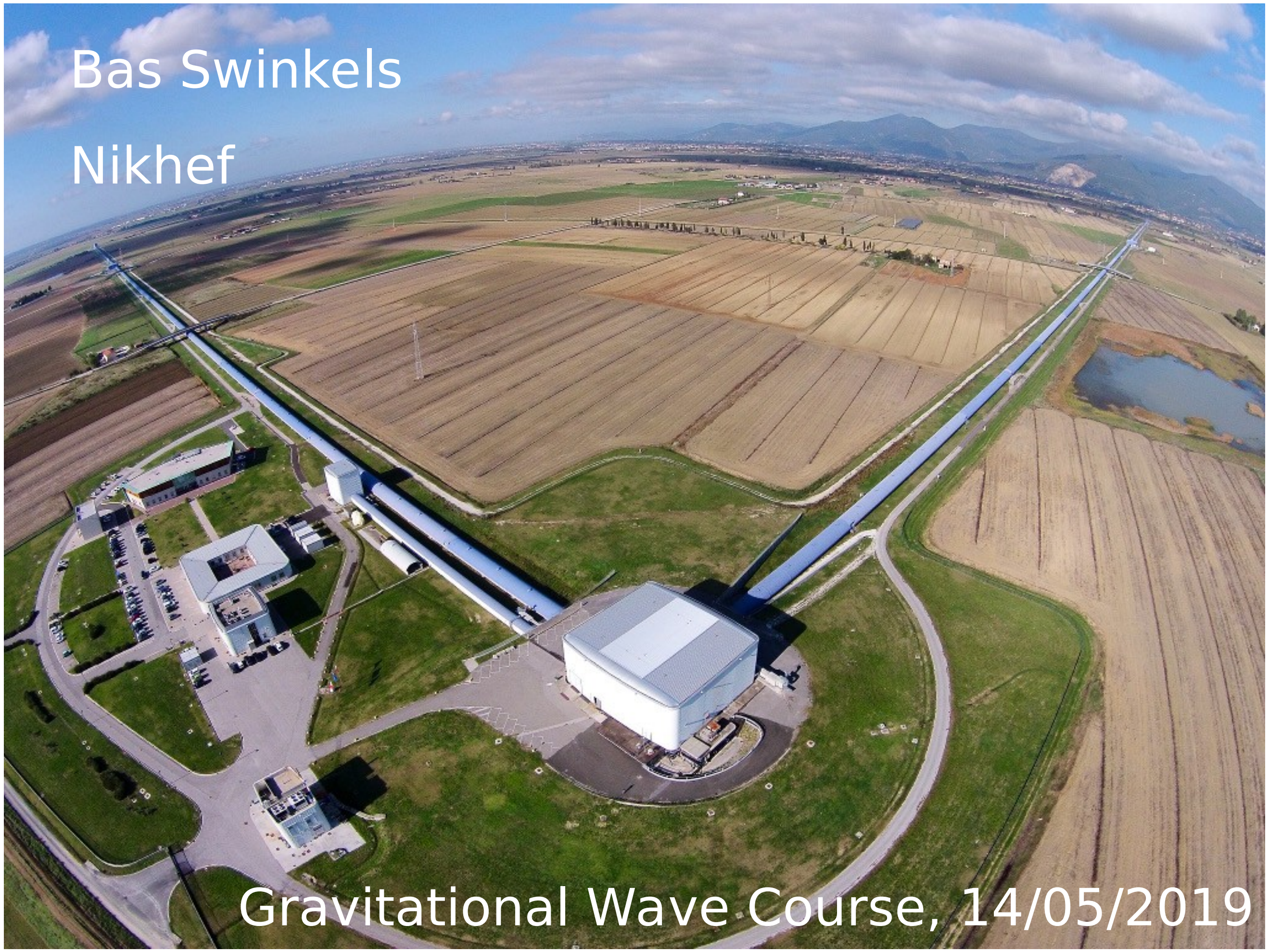
Experimental detection of gravitational waves



Advanced Virgo

Nikhef

Announcements from Sarah

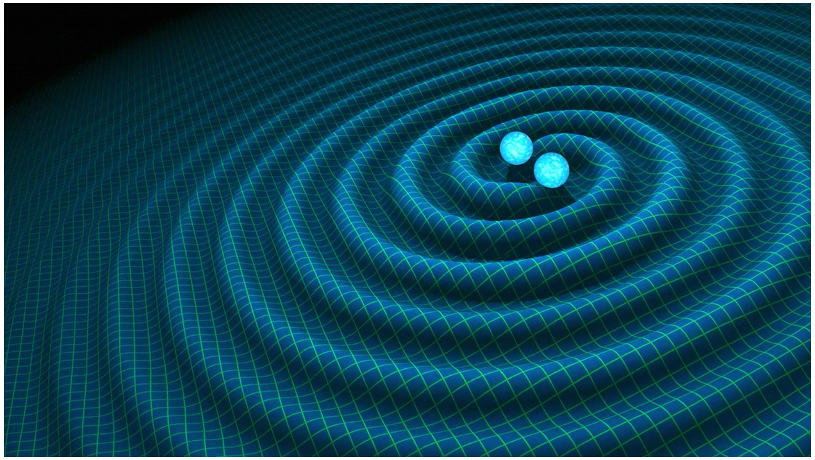
- Please pick up Assignment 5 on GW instrumentation.
- Please make sure to email any code you wrote for your HW assignments to our TA Pawan (p.gupta@nikhef.nl). The code counts for part of your HW grade.
- We will have our final lecture on May 21. We will also have a final exam review. Note: we did not have a class previously scheduled for this day. If this is a problem for anybody, please email Sarah.
- To give you a bit more time to work on your visualisation project, the new due date for the project will be May 28.

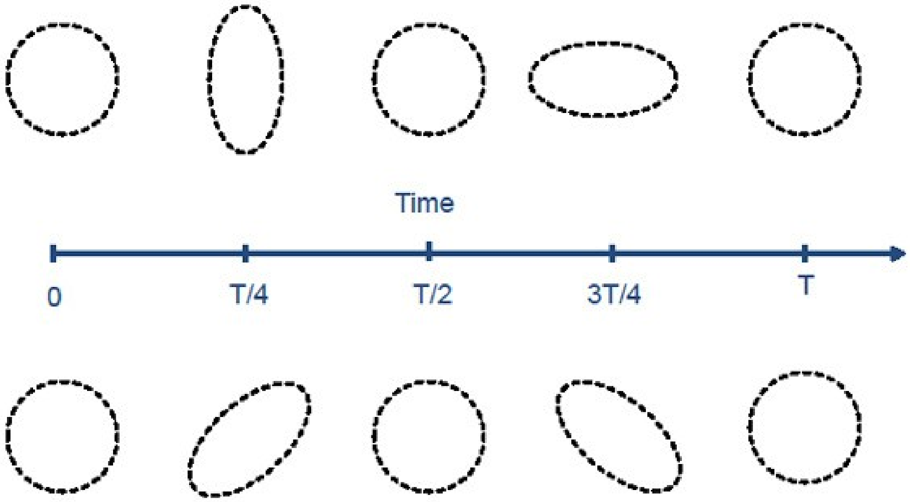
Outline

- Historic attempts to measure GW
- Detecting GW with interferometry
- Future instruments

- Disclaimer: I am an experimental physicist with a background in optics, I don’t know a lot about GR or astronomy

What are Gravitational Waves?

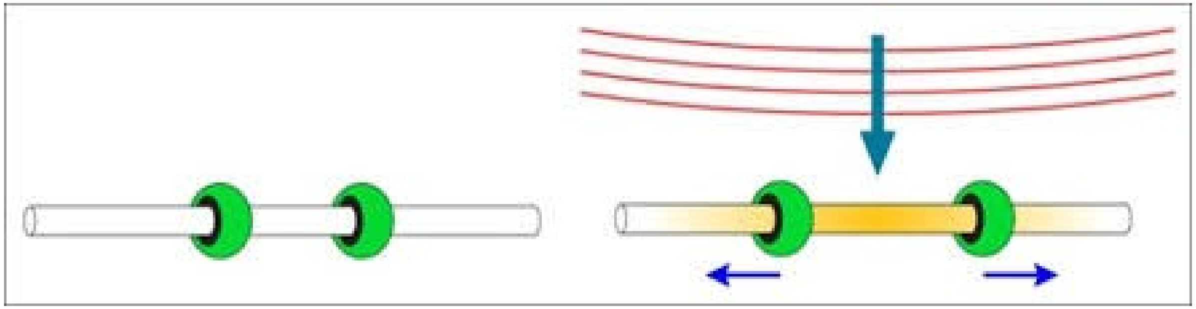




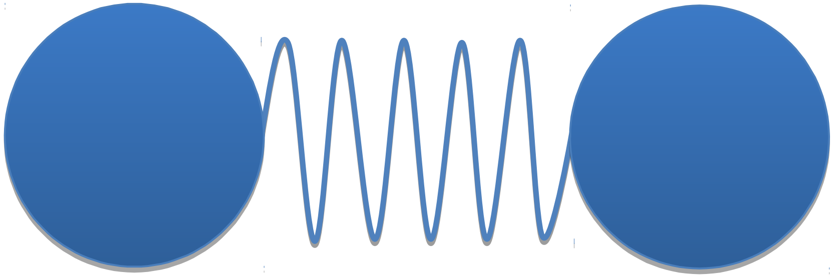
- 'Ripples in the fabric of space-time' that propagate with the speed of light
- Natural wave solution of General Relativity (Einstein, 1916/1918/1936)
- A GW stretches and squeezes space-time in transverse direction, 2 possible polarizations
- Gravitational wave strain: $h = \frac{\delta L}{L}$
- Generated when masses are accelerated non-symmetrically (change of quadrupole moment)
- Extremely weak, h = 10^{-21} for typical astronomical sources

Are GW detectable?

- Einstein: GW are so small that they can be ignored, too hard to detect
- Not a surprising idea at the time:
  - missing technology: lasers, modern electronics, ...
  - missing observational evidence for astronomical sources of GW (black holes, neutron stars, pulsars, ...)
  - theory was not yet mature, not immediately clear if GW are observable at all, if they carry energy
- **Sticky Bead Argument** (Feynman, 1957): Beads sliding with friction on a stick would generate heat due to a passing GW, so GW carries energy



Weber bars

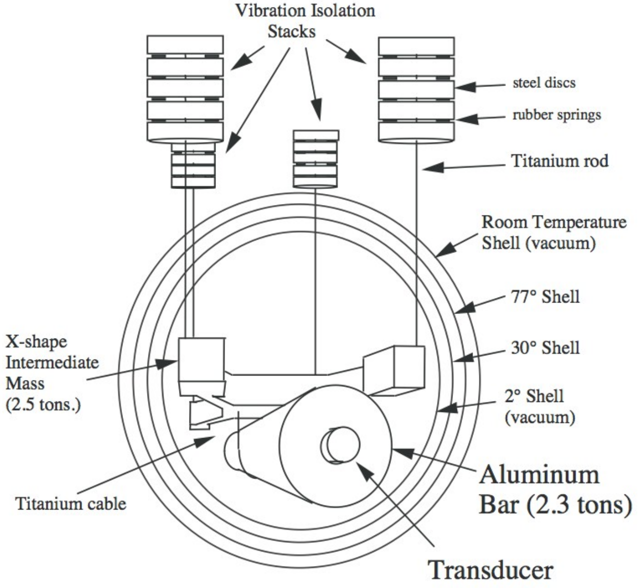


- Passing GW will excite a mechanical resonator like a tuning fork
- First experiments around 1968 by J. Weber: resonant aluminum bar at room temperature
- Resonance frequency 1660 Hz, capacitive readout, sensitivity around 10^{-16} m
- Did claim detection: excess correlation of signals between 2 separated instruments
- Results could not be reproduced by others
- Weber was discredited for not retracting his claims, but is widely considered as the pioneer of experimental GW detection

Modern resonant detectors

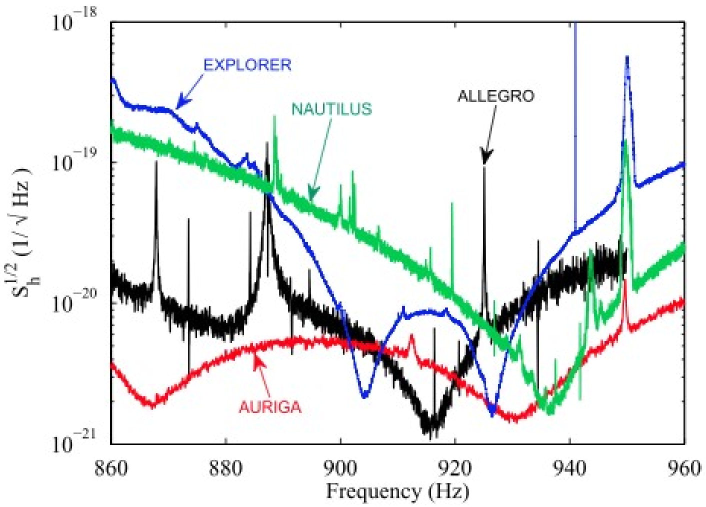
NAUTILUS

ALLEGRO

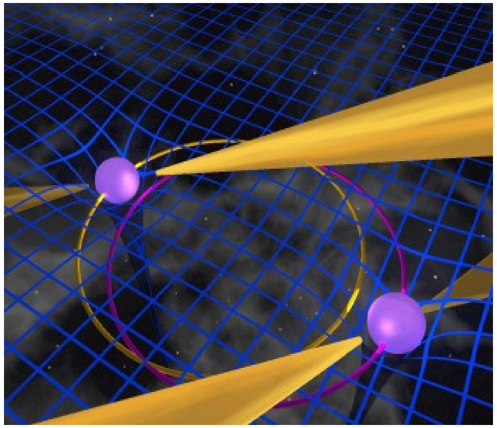


mini-GRAIL

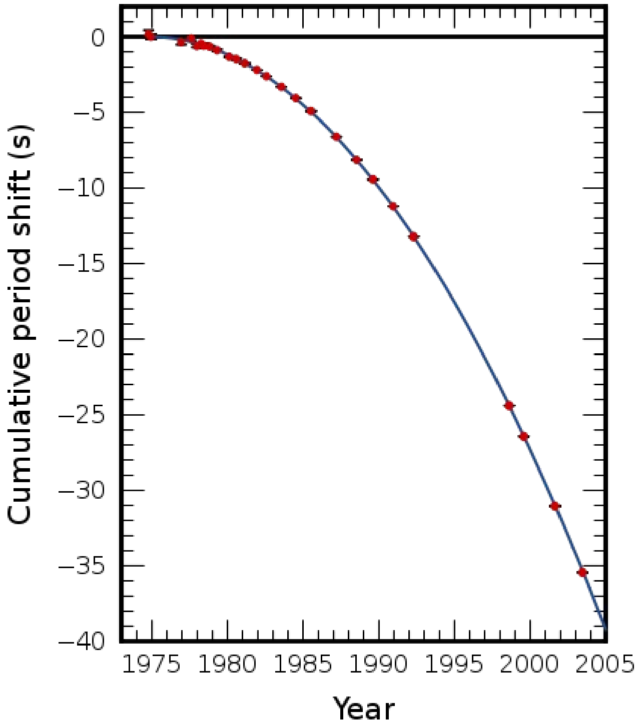
- Cryogenic (few mK) version of Weber bars
- Resonant bars or spheres, seismically isolated
- Position readout with capacitive or super-conducting transducers (SQUIDs), using amplification by a small mechanical resonator
- Never detected anything (one claim due to bad statistics)
- Mostly decommissioned around 2007, since they are narrow-band, and even at resonance have lower sensitivity than interferometers



Indirect evidence for GW



- Binary system of neutron star and pulsar observed by radio telescopes (1974)
- Orbital period of 8 hours, but accurate timing over years showed that orbits get shorter
- Decay perfectly predicted by loss of energy due to gravitational waves
- Nobel prize in physics for Hulse and Taylor (1993)
- System will collide in 300 million years



Primordial GW in CMB?


theguardian

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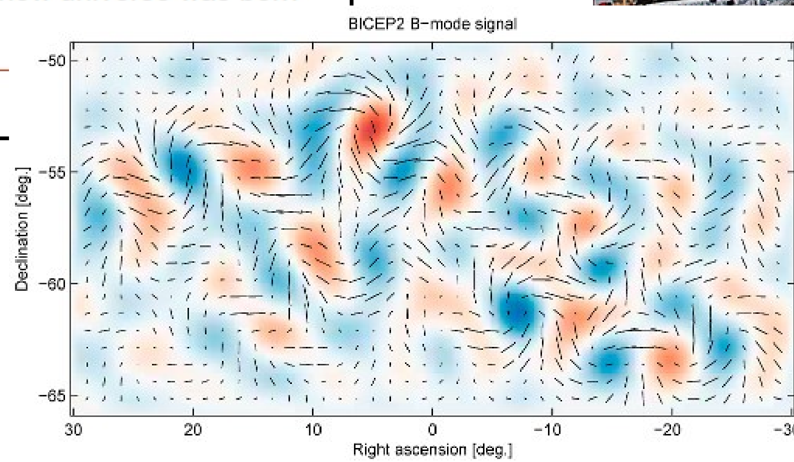
Gravitational waves: have US scientists heard echoes of the big bang?

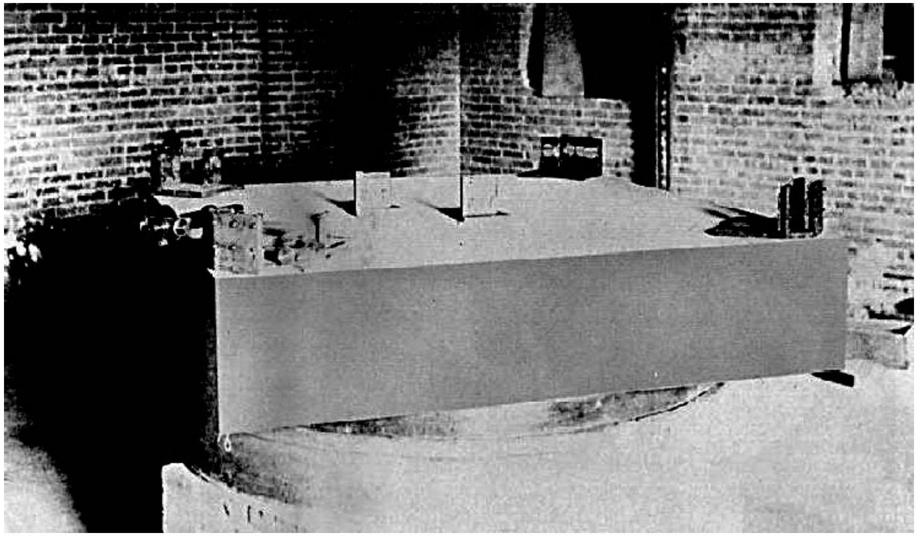
Discovery of gravitational waves by Bicep telescope at south pole could give scientists insights into how universe was born

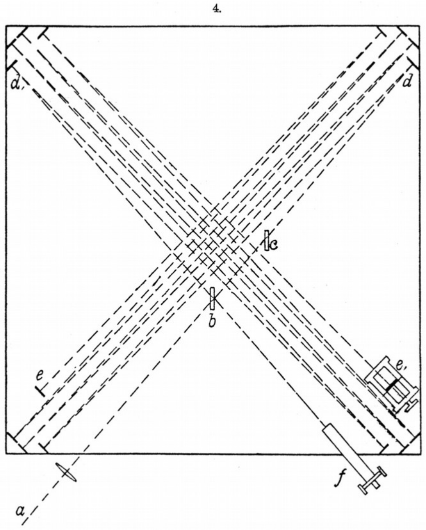
Stuart Clark
The Guardian, Friday 14 March 2014 15.33 GMT

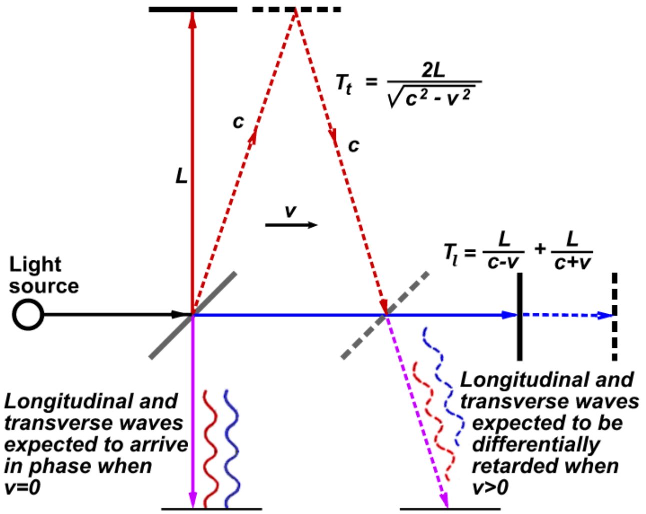


- BICEP2 (2014): possible imprint of gravitational waves found in polarization of Cosmic Microwave Background
- Claim later retracted: forgot to account for effect of dust in our galaxy

Michelson-Morley experiment





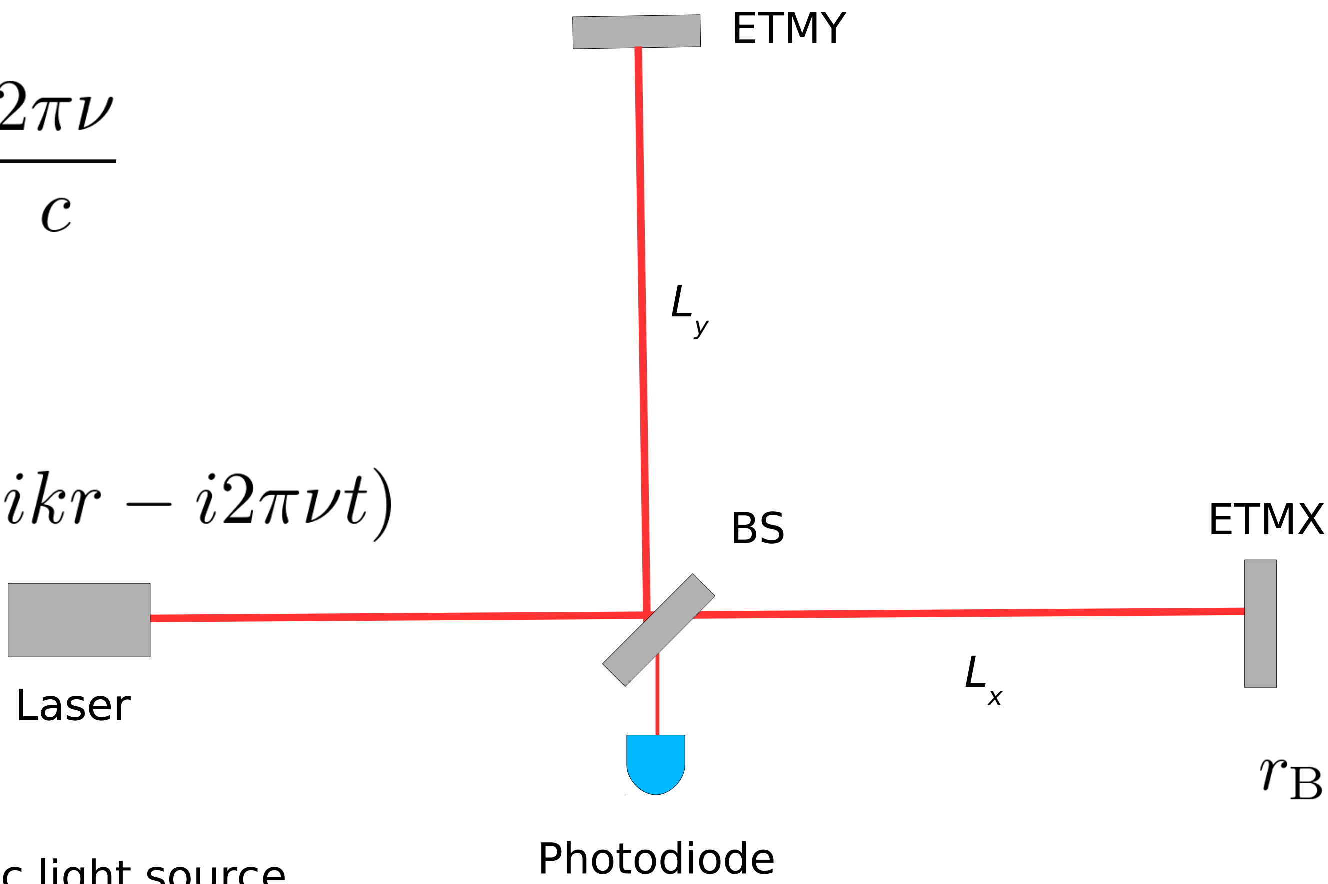


- Old idea: if light is an oscillation in some medium (luminiferous aether), it should be possible to measure difference in the speed of light based on the direction of travel (movement of Earth around Sun)
- MM experiment (1887): white light interferometer, folded path length of 11 meter, setup could be rotated in bath of mercury
- Expected a shift of 0.4 fringe when rotating setup, observed < 0.02 fringe: one of the most famous null-results, which was at basis of Lorentz transformations, Special Relativity
- Could MM have detected GW: no, too insensitive by about 10 orders of magnitude!

Michelson interferometer

$$k = \frac{2\pi}{\lambda} = \frac{2\pi\nu}{c}$$

$$E = E_0 \exp(ikr - i2\pi\nu t)$$



$$r_{\mathrm{BS}} = \pm\frac{1}{\sqrt{2}}$$

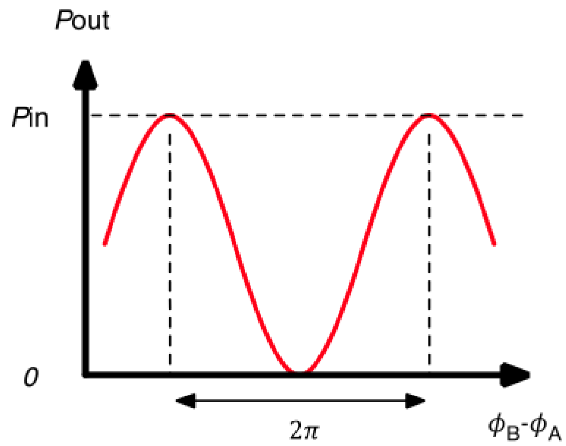
$$t_{\mathrm{BS}} = \frac{1}{\sqrt{2}}$$

$$r_{\mathrm{ETM}} = 1$$

$$P = |E|^2$$

- Monochromatic light source
- 50/50 beam-splitter, note sign flip in reflection coefficient to conserve energy (see Stokes relations)
- Perfectly reflecting end-mirrors (End Test Mass):
- Light of arms interferes on photodiode, which measures power

Interferometry basics

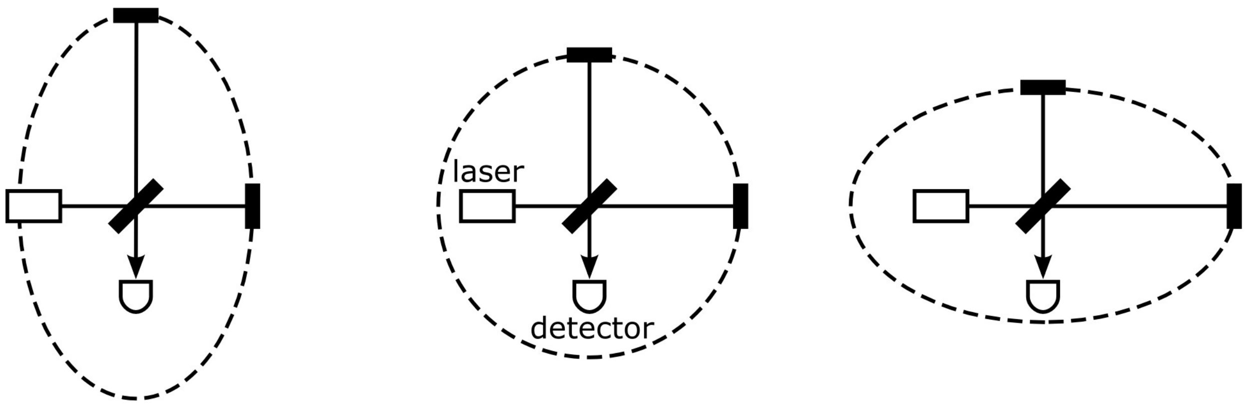


- For a perfect interferometer:

$$P = \left| E_0/2(\mathrm{e}^{ik2L_x} - \mathrm{e}^{ik2L_y}) \right|^2 = P_0/2\,(1 - \cos(\Delta\phi))$$

- Sensitive to differential path length differences $\Delta\phi = 2k(L_x - L_y)$
- Maximum sensitivity (in W/m) at 'half fringe'
- Detected power also fluctuates due to laser intensity noise (~10^{-8}) and shot noise. To achieve the best SNR, you therefore want to be close to 'dark fringe'
- Also sensitive to laser frequency noise if arms are not equal!

Interferometric GW detection



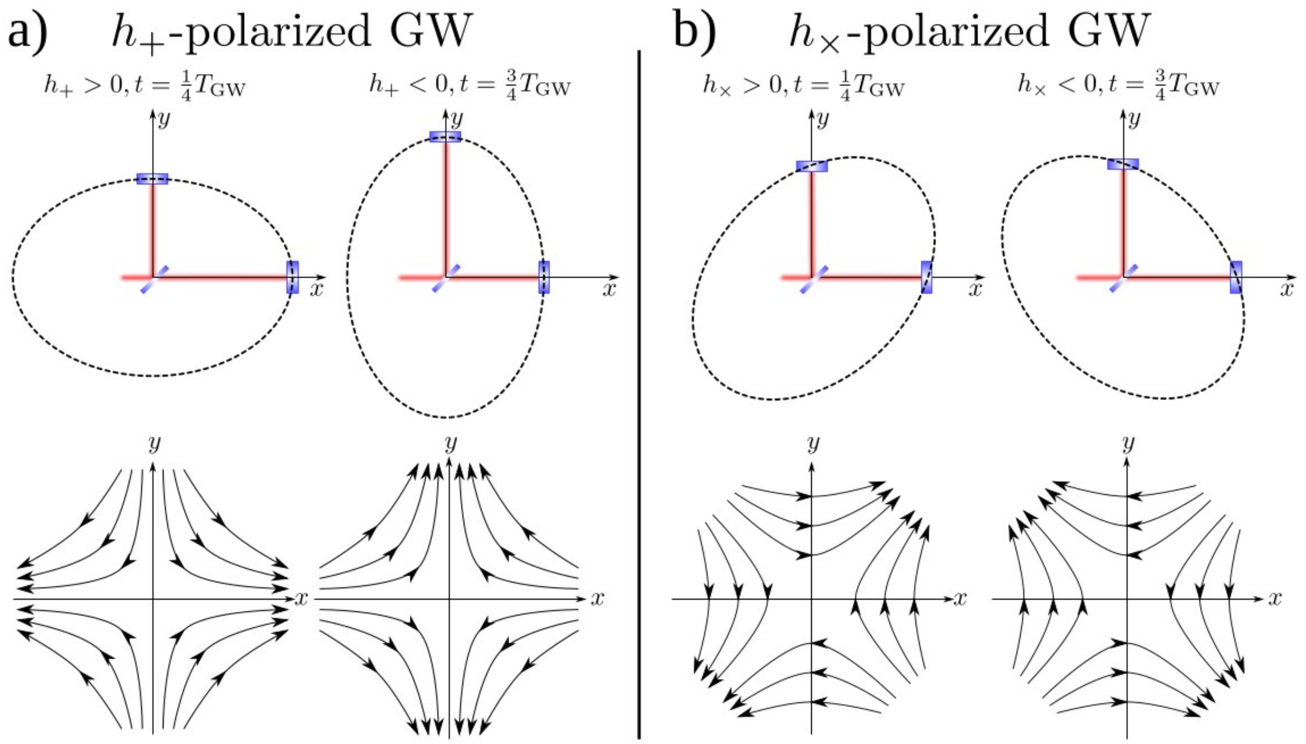
- Michelson interferometer is a natural fit for measuring gravitational waves: GW cause a differential change of arm length:

$$L_x = (1 + h/2)L$$
$$L_y = (1 - h/2)L$$
$$\Delta\phi = 2k(L_x - L_y) = 2khL$$

- Idea first proposed by Braginsky, first technical feasibility study by R. Weiss (1972)
- Note: interferometers measure the **amplitude** of the GW and not the power, so dependency on source distance is 1/R instead of 1/R^2
- A simple Michelson is not sensitive enough to detect GW, need several extra tricks ...

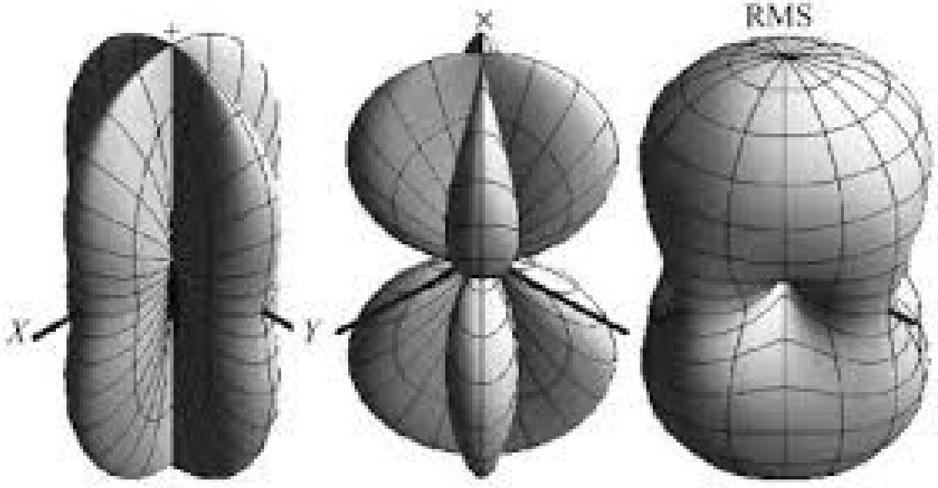
GW polarization

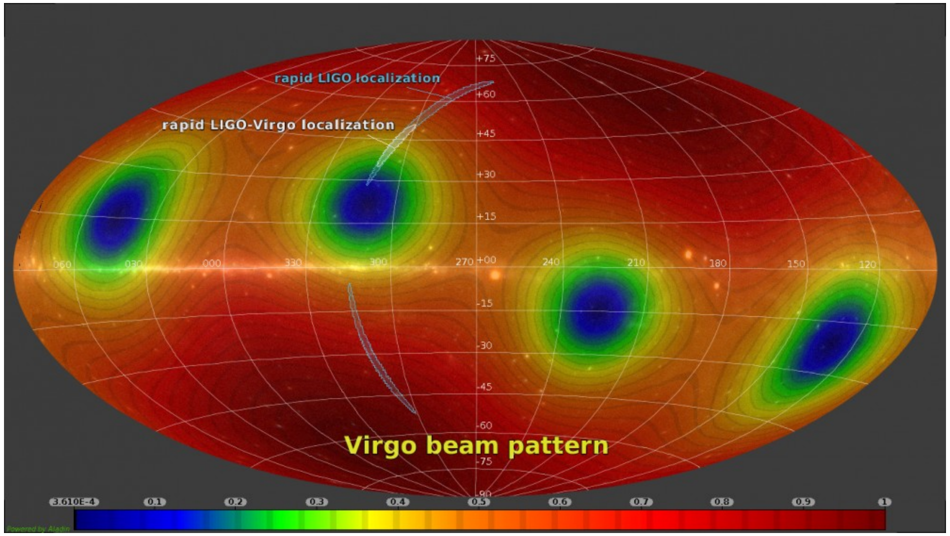
$$\delta x = \frac{1}{2} h_+ x \quad \delta y = -\frac{1}{2} h_+ y$$
$$\delta x = \frac{1}{2} h_\times y \quad \delta y = \frac{1}{2} h_\times x$$



- + polarization: $d\vec{r}_{\mathtt{ETMX}} = (h_+ L/2, 0), d\vec{r}_{\mathtt{ETMY}} = (0, -h_+ L/2)$
- x polarization: $d\vec{r}_{\mathtt{ETMX}} = (0, h_X L/2), d\vec{r}_{\mathtt{ETMY}} = (h_X L/2, 0)$
- An interferometer is only sensitive to differential changes of arm lengths, which depends on mirror movements along the optical axis
- **Perfect for detecting + polarized GW, but insensitive to X polarized GW**

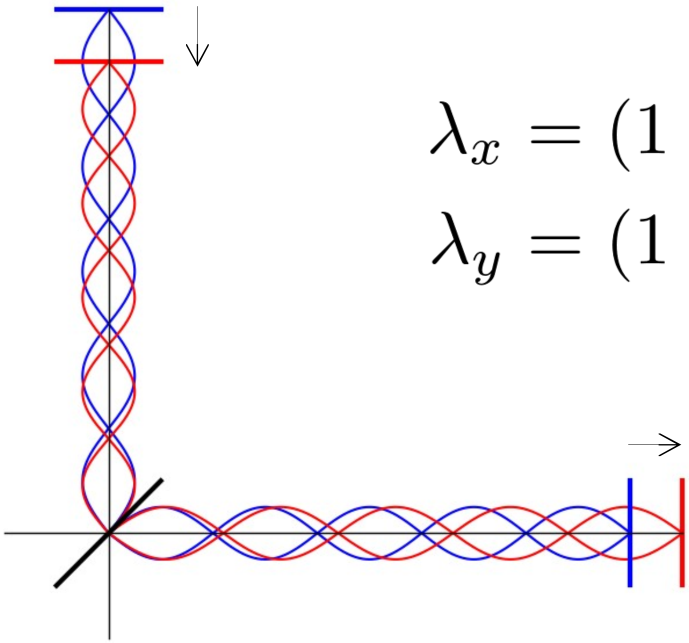
Antenna pattern





- In addition to GW polarization, the sensitivity depends also on the propagation direction of the GW: sensitive to GW traveling perpendicular to the plane, insensitive to the some directions in the plane. Leads to ‘blind spots’ (see GW170817 for Virgo)
- Argument for having multiple interferometers spread around the Earth with different orientations, if you want to observe the whole sky in both polarizations all the time (other arguments are redundancy, coincident detection and sky localization)

Why can interferometers measure GW?



$$\lambda_x = (1 + \delta h/2)\lambda_0$$
$$\lambda_y = (1 - \delta h/2)\lambda_0$$

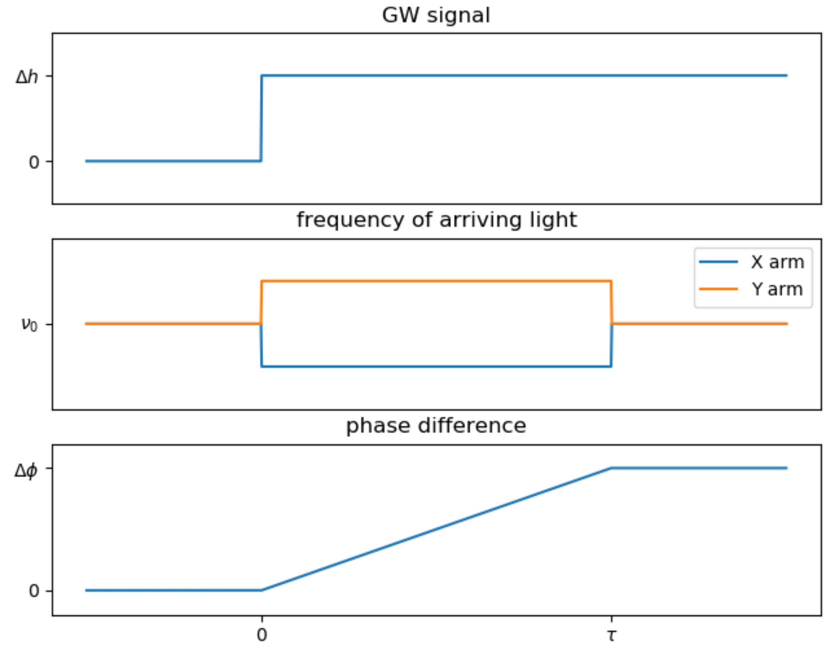
- Valid question: we use an optical wavelength as our ruler to measure distances, but doesn't the wavelength itself change by a passing GW? It does ...
- Assume a GW with a sudden step at t=0: $h(t)$ = dh * step(t). Not a realistic waveform, but imagine some slowly oscillating signal as composed of several steps.
- The passing GW changes the wavelength (and thus frequency) of the light inside interferometer, but interference condition does initially stays the same
- After the step, the arm lengths have changed, but speed of light is still c

Why can interferometers measure GW?

$$\tau = 2L/c$$

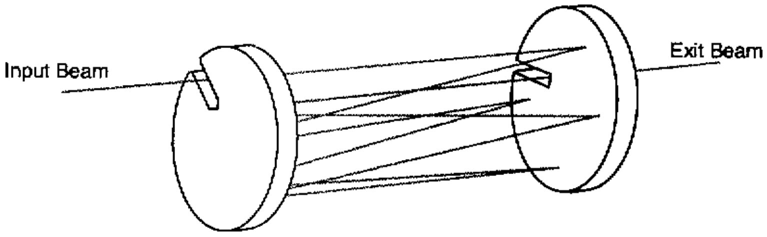
$$\phi(t) = 2\pi \int_0^t \nu(t)\, dt$$

$$\Delta\phi(t) = \phi_x(t) - \phi_y(t)$$



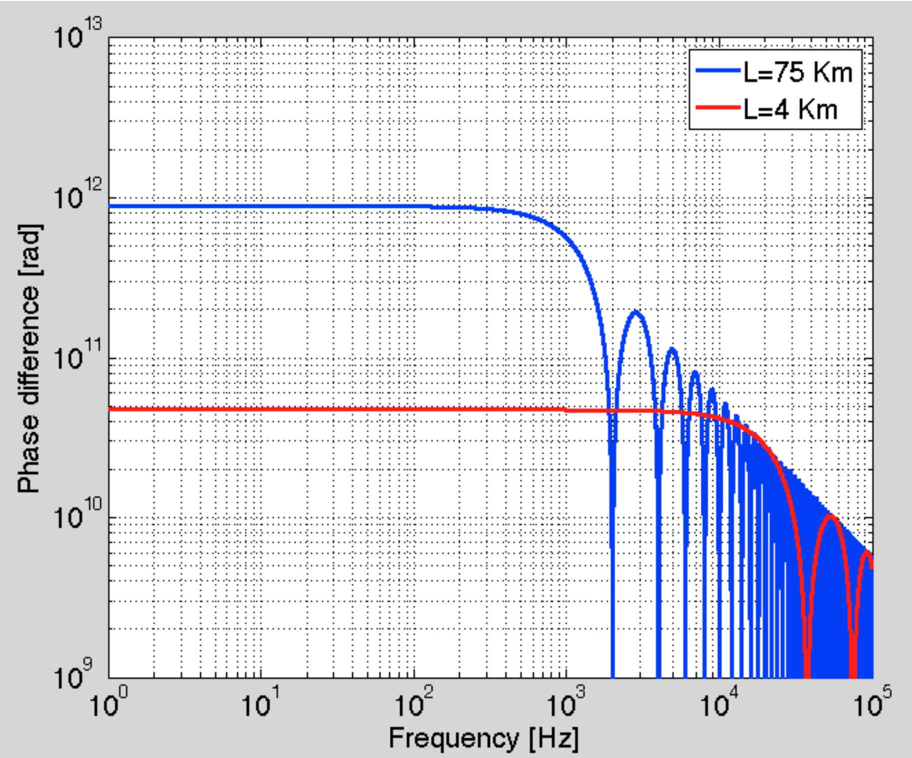
- It takes a period tau for the modified light to stream out of the interferometer, which meanwhile fills with light of the original frequency
- A phase difference will gradually accumulate due to the change in frequencies
- Measured phase is ‘moving average’ of GW signal over a period *tau*
- See Saulson, American Journal of Physics 65, 501 (1997) for complete argument
- Alternative view: you don’t measure GW using the wavelength itself, but using difference of arrival time of wavefronts

Increasing the arm length



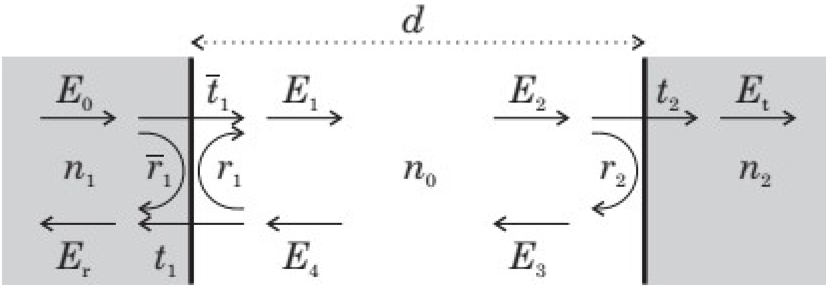
$$\phi = 2kLh$$

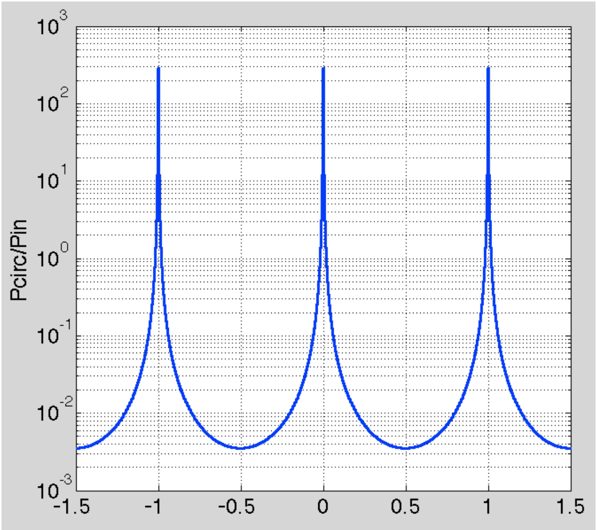
$$\phi(t) = 2kL\frac{1}{\tau}\int_{t-\tau}^{t} h(t')dt'$$



- Sensitivity of Michelson can be increased by making the arms longer
- Ideally few 100 km long, but money/terrain limit this to few km
- Could use a delay line (Herriot cell), but this has practical issues
- Note that longer interferometers have a smaller bandwidth, since GW signal gets ‘averaged’ over the round-trip time, leads to Sinc-function in frequency response

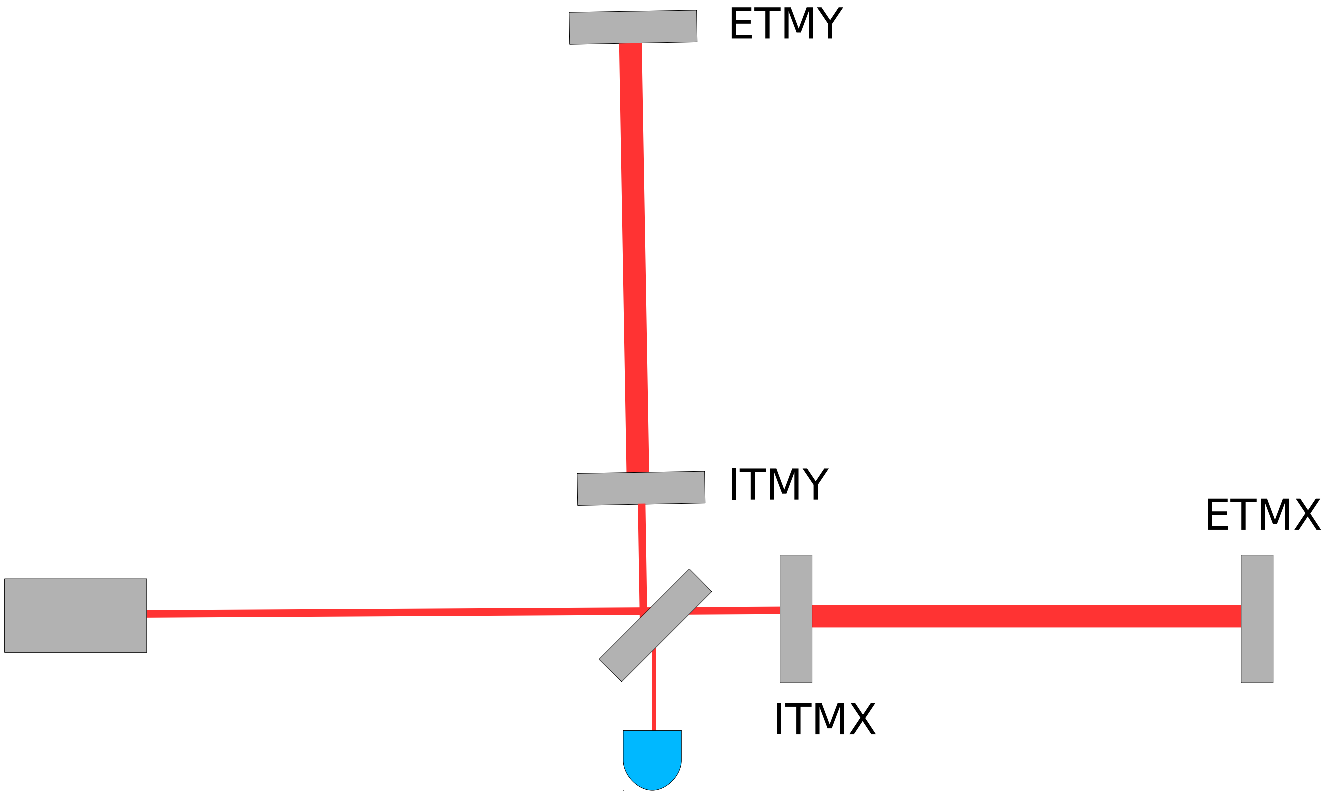
Fabry-Perot cavity





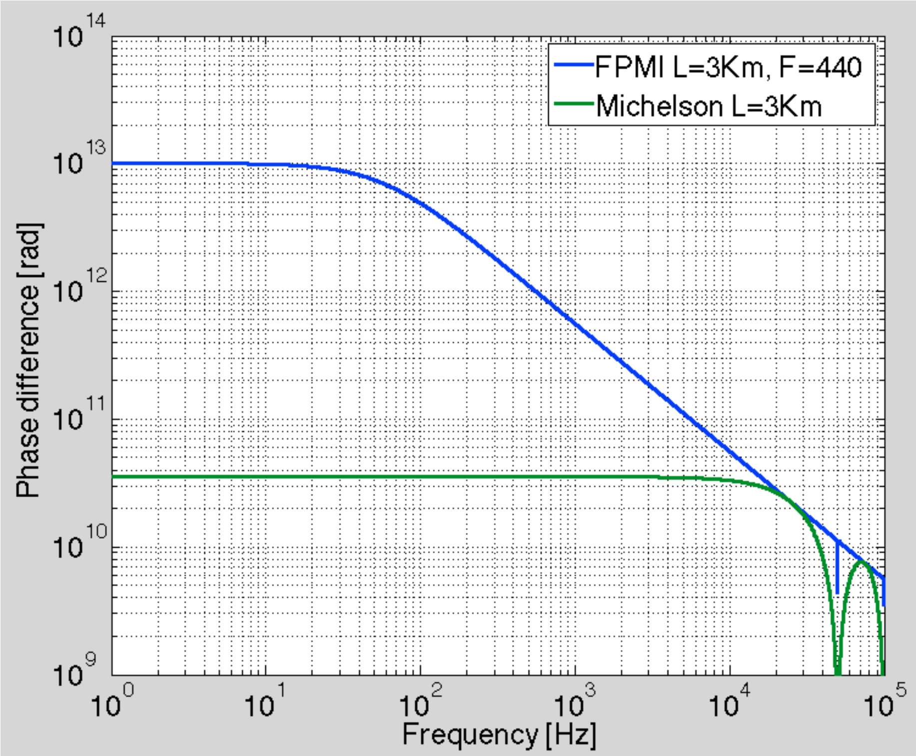
- Resonant optical cavity formed by two highly reflecting mirrors
- Reflection: $$\frac{E_r}{E_0} = -r_1 + \frac{t_1^2 r_2 \mathrm{e}^{i\phi}}{1 - r_1 r_2 \mathrm{e}^{i\phi}} \qquad \phi = 2kL$$
- Resonances spaced by Free-Spectral Range: $$\delta L_{\mathrm{FSR}} = \frac{\lambda}{2} \qquad \delta\nu_{\mathrm{FSR}} = \frac{c}{2L}$$
- Finesse: $$\mathcal{F} = \frac{\delta L_{\mathrm{FWHM}}}{\delta L_{\mathrm{FSR}}} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$
- Effective number of round-trips: $$N_{\mathrm{eff}} = \frac{2}{\pi}\mathcal{F}$$

Fabry-Perot Michelson



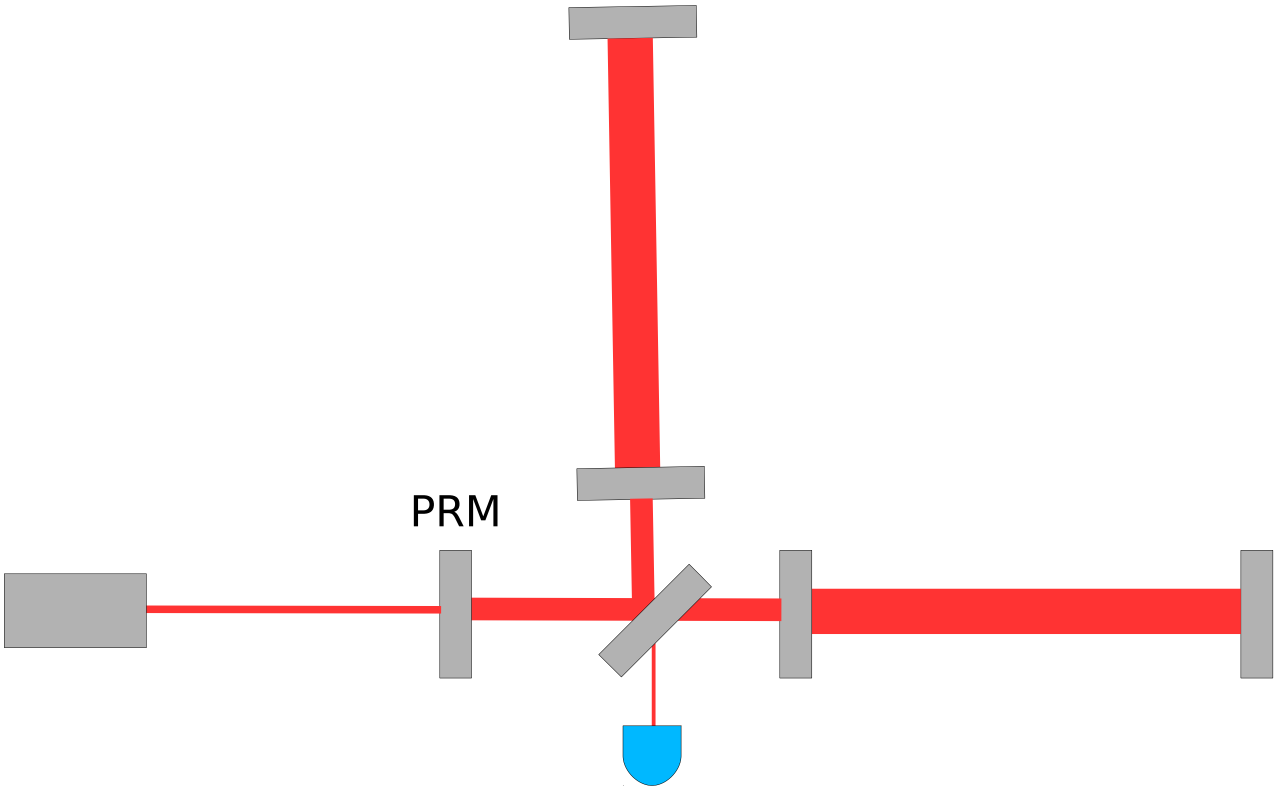
- Add extra ‘Input Test Masses’ at the beginning of the long arms, so that light will bounce many times up and down arm cavities. Only works when arms are kept on resonance!
- For Virgo: F = 440, L = 3 km, L_{eff} = 840 km!

Fabry-Perot Michelson



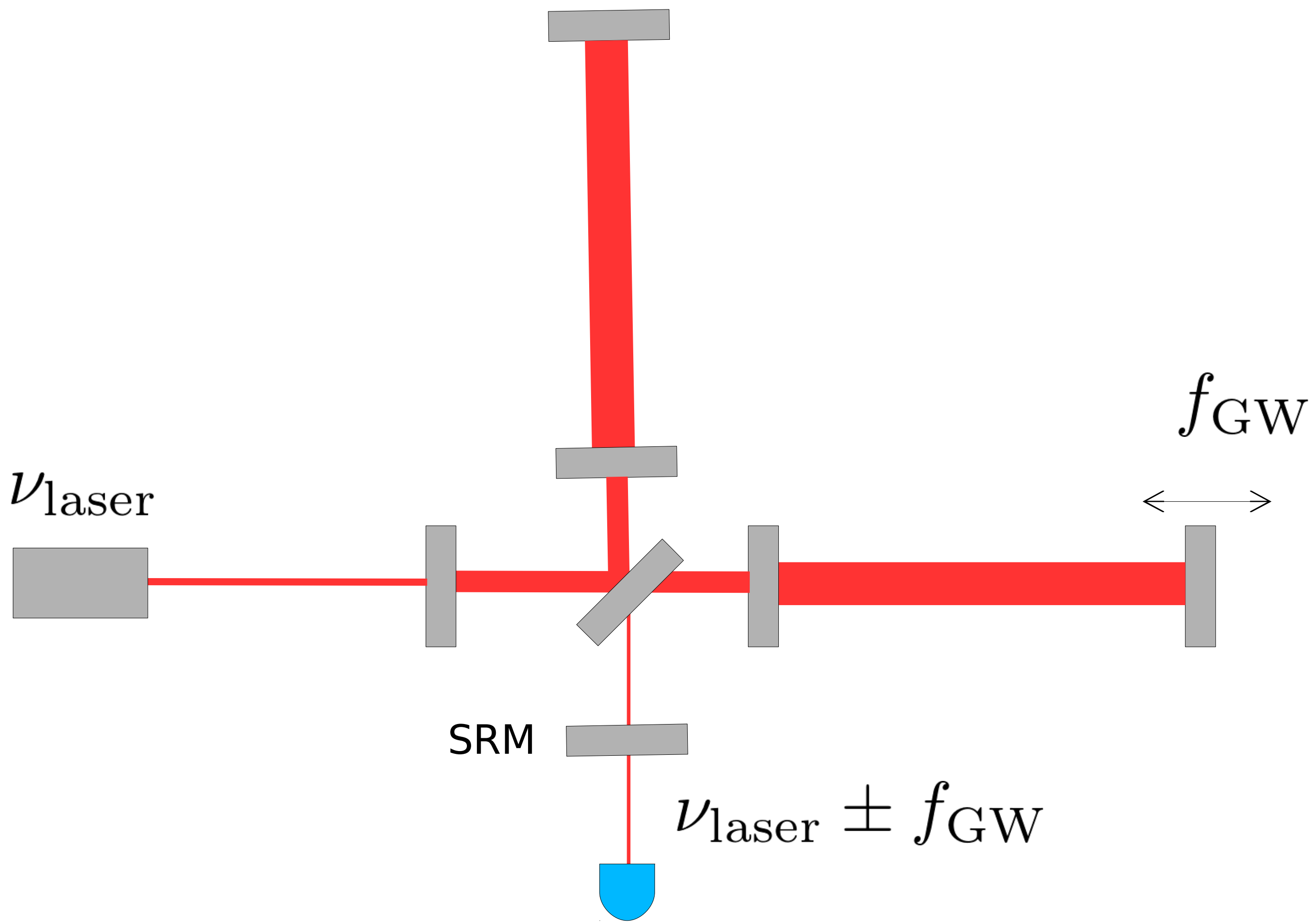
- Effect on sensitivity of adding a FP to the arms is similar to increasing the arm lengths by a factor N_{eff}, but without the extra zeros in frequency domain
- Cavity behaves like a low-pass filter with $f_{\mathrm{cut-off}} = \delta L_{\mathrm{FWHM}}/2$
- For Virgo: $f_{\text{cut-off}}$ = 57 Hz

Power recycling



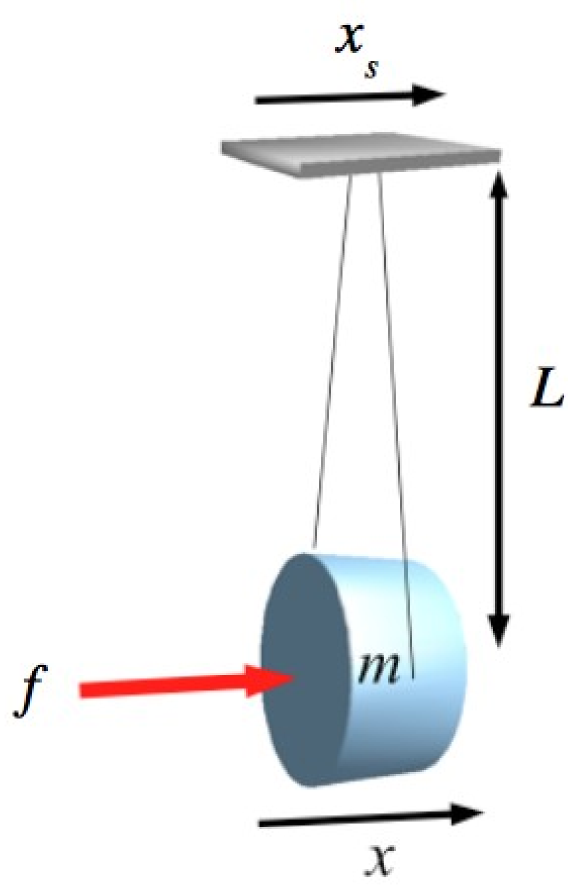
- Michelson is tuned to dark-fringe, light is reflected back to the source
- For shot-noise reasons, you want to have a high laser power
- Add a 'Power Recycling Mirror', to form another resonant cavity, effectively increasing the laser power by a factor ~37
- Power in central cavities ~500 W, power in long arm cavities ~100 kW

Signal recycling

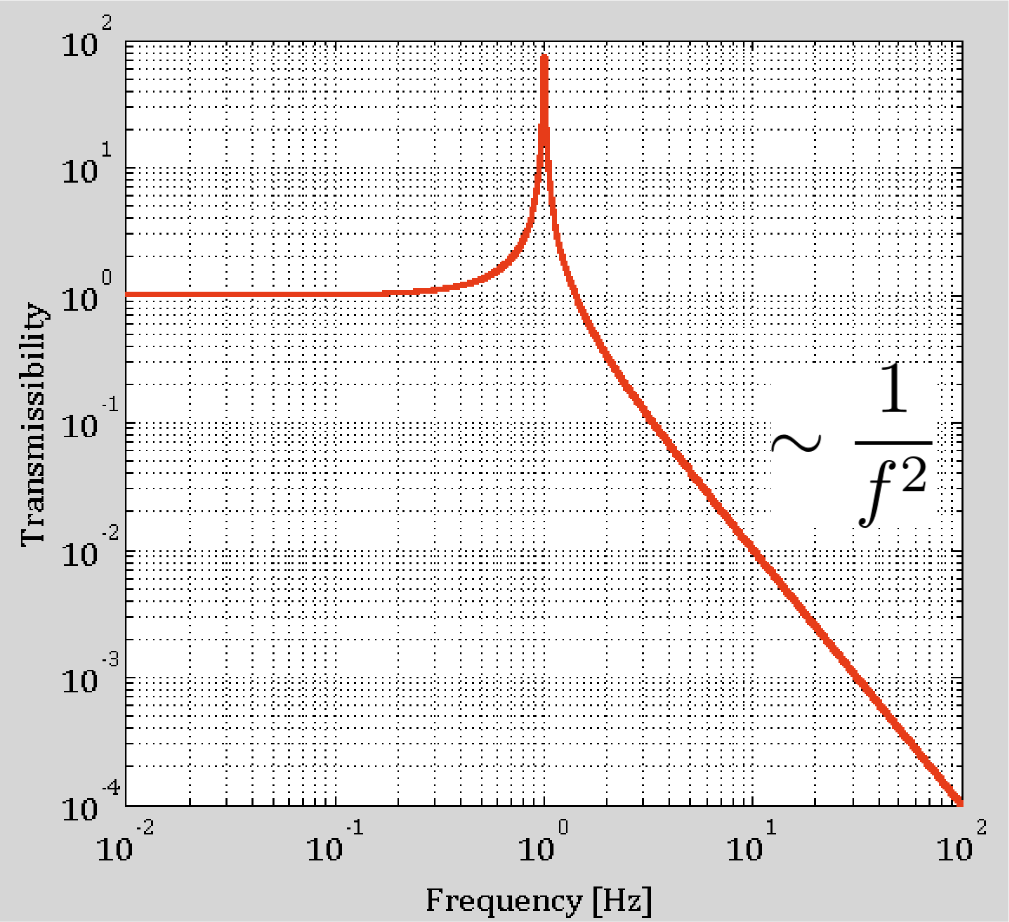


- Passing GW causes ‘sidebands’ around laser frequency. By adding an extra Signal Recycling Mirror, these signal sidebands can be sent back into the interferometer
- Already used at LIGO, will be installed at Virgo in one year

Seismic isolation: pendulum

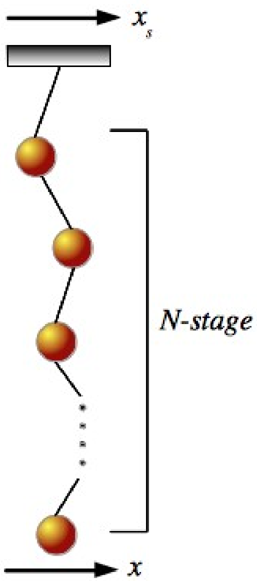


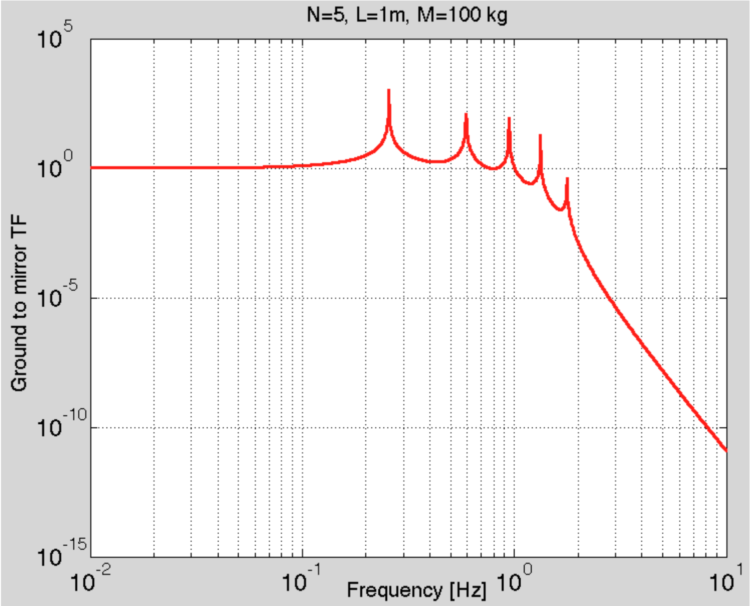
$$f = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$



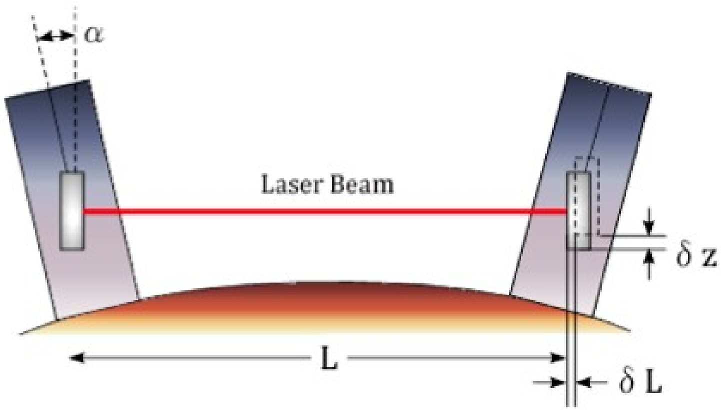
- Mirrors on Earth would vibrate to much, needs seismic isolation
- Suspend them by wires to form a pendulum, you win above resonance

Multi-stage pendulum



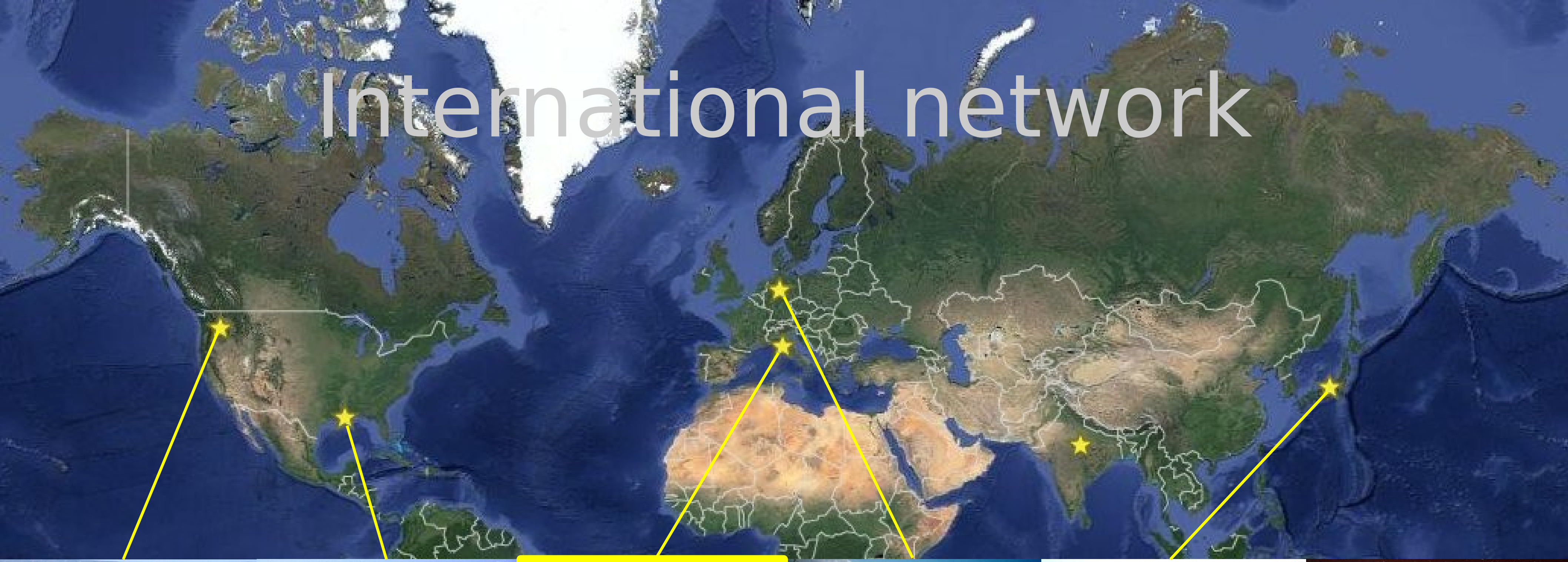


$$\sim \frac{1}{f^{2N}}$$



- In reality, a single pendulum is not enough: use multiple stages
- Also need to isolate vertically due to curvature of the earth

International network

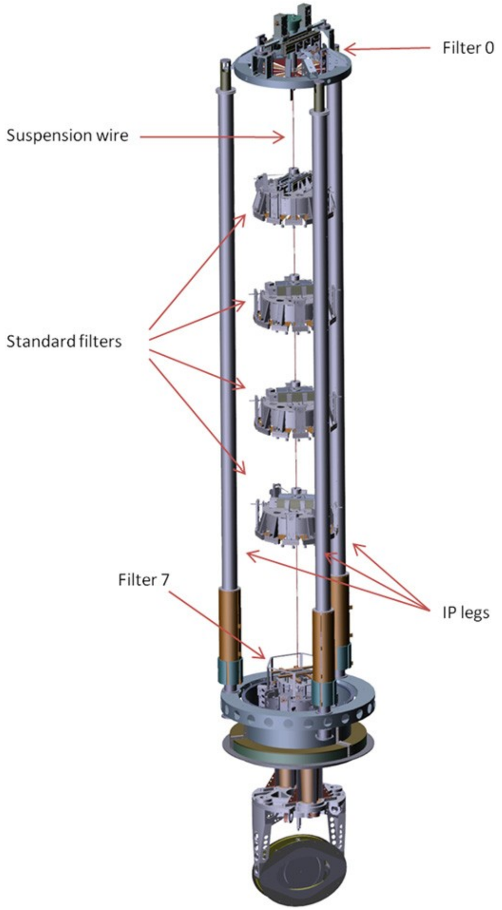


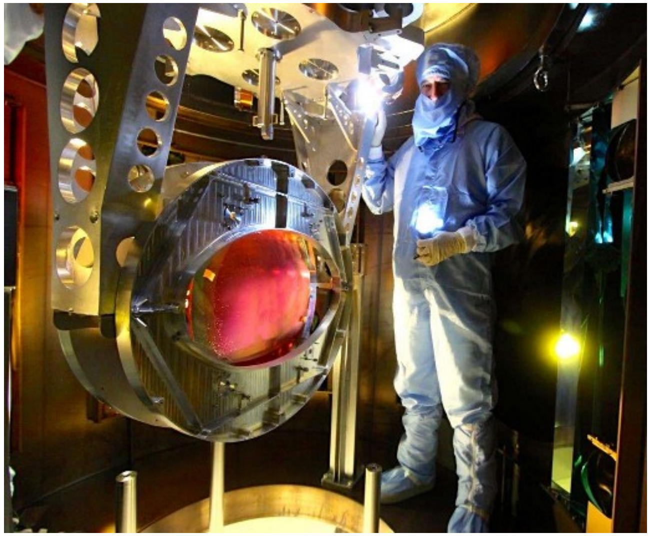
2x LIGO USA	INDIGO India	Virgo, Italy	GEO, Germany	KAGRA, Japan	LISA, space
4 km	4 km	3 km	600 m	3 km, cryog., underground	10^6 km
Operational 2015	Planned 2022	Operational 2017	Operational	Planned 2022	Planned 2034

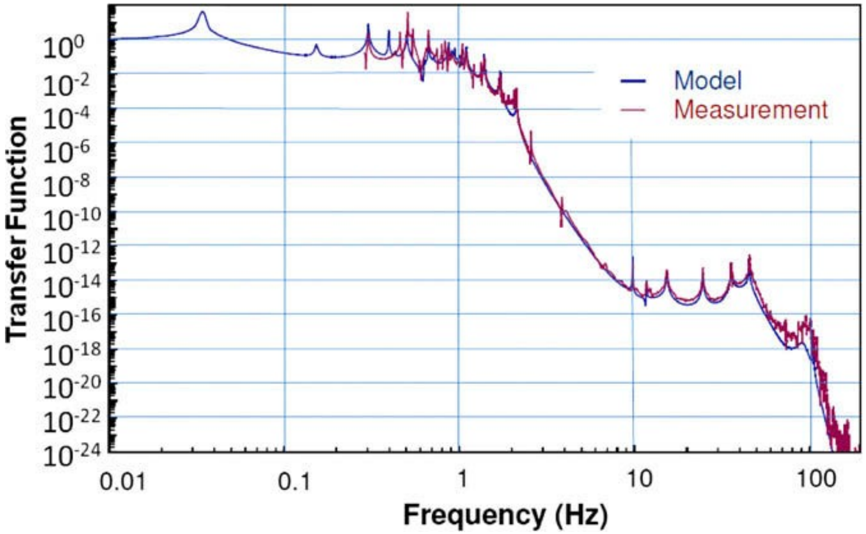
Virgo Interferometer

- 3 x 3 km interferometer, located near Pisa, Italy
- Originally a French-Italian collaboration
- Now about 200 scientists from Italy, France, Netherlands (Nikhef, Nijmegen, Maastricht), Poland, Hungary, Spain

Suspensions





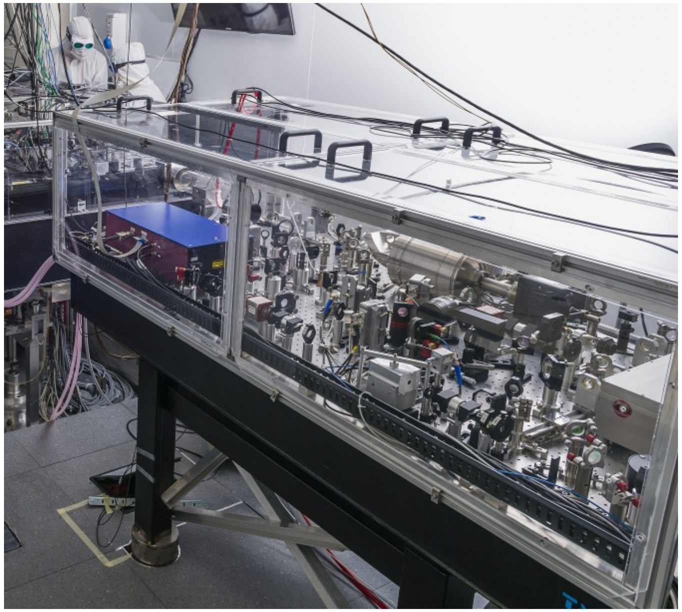


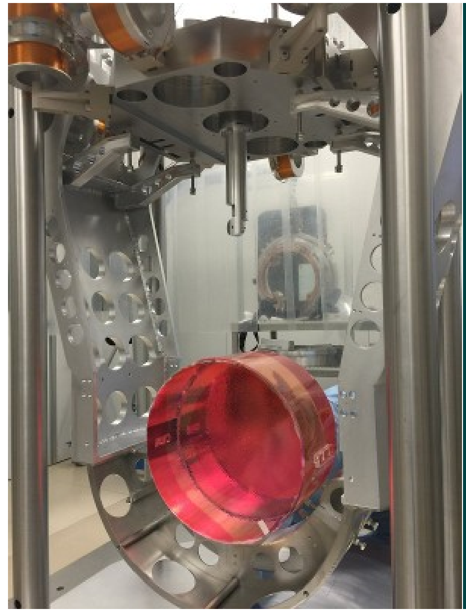
- Need more than a 10 orders of magnitude attenuation above 10 Hz
- Use combination of active pre-isolation stage (inertial free platform balancing on inverted pendulum, using accelerometers and position sensors) and passive multi-stage pendulums and blade springs
- Mirrors are suspended by 4 glass fibers for thermal noise: need materials with low mechanical losses

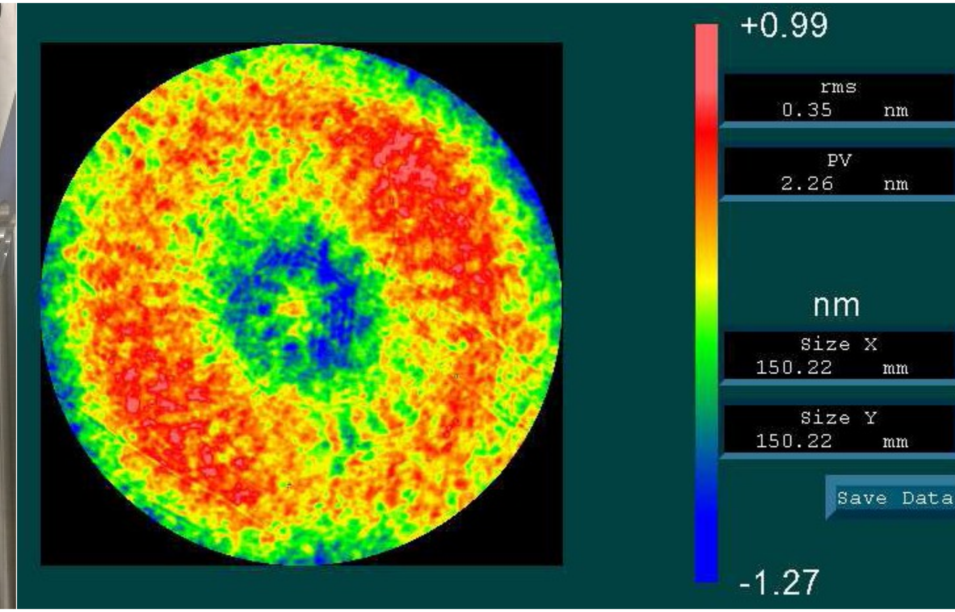
Vacuum system

- Fluctuations of air-pressure obviously not compatible, so GW interferometers are located inside large vacuum tubes
- Virgo interferometer: 7000 m^3 vacuum, long tubes have pressure ~10^{-9} mBar
- Biggest UHV system in Europe, only LIGO is bigger

Optics

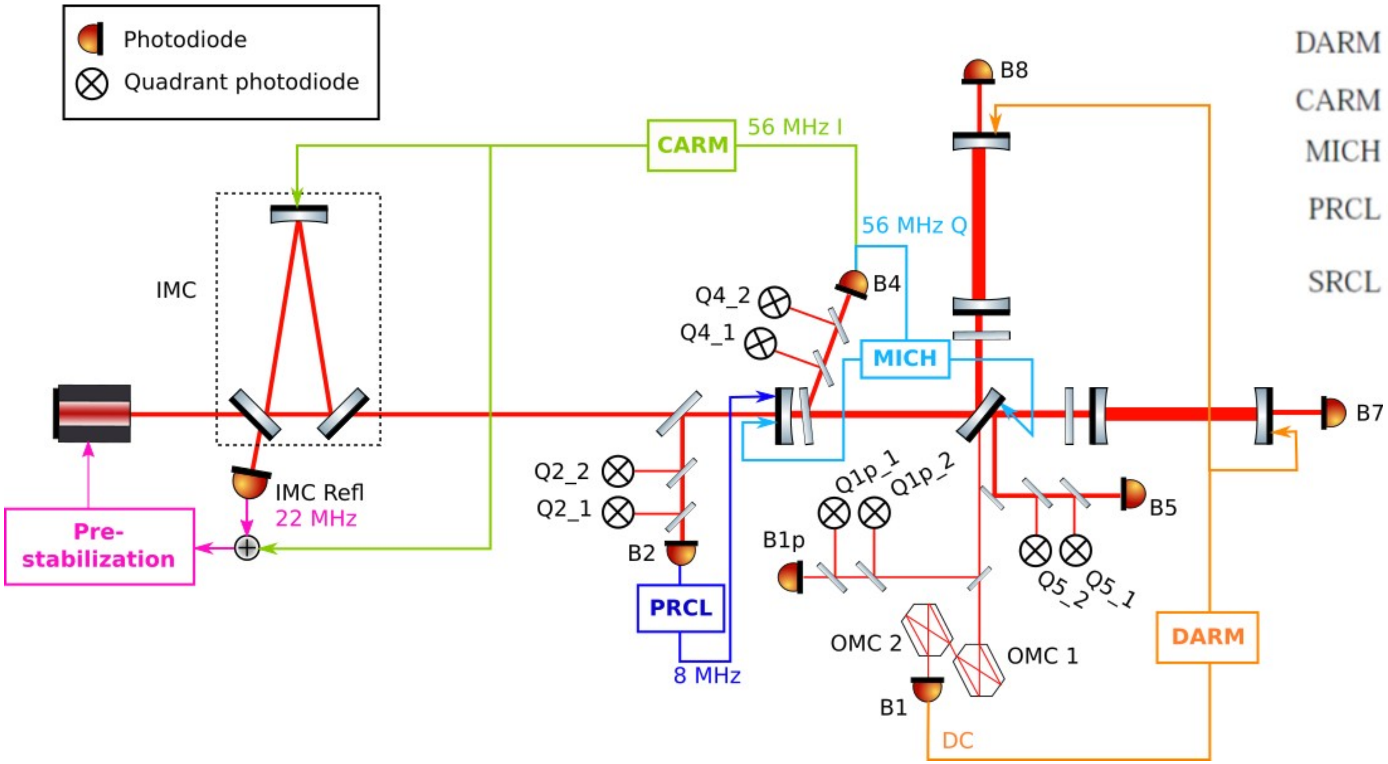






- Main laser: 1064 nm Nd:YAG NPRO, amplified in 2 stages to ~60 Watt
- Main mirrors: 41 kg low absorbing fused silica, polished with RMS < 0.1 nm
- Low loss multi-layer coatings (both optical and mechanical), reflectivity up to 99.996 %
- Beam shape: Gaussian with radius of a few cm, input/output telescopes for matching to laser and photodiodes

Longitudinal control



$$\mathrm{DARM} = L_N - L_W \text{ (differential arm length)}$$

$$\mathrm{CARM} = \frac{L_N + L_W}{2} \text{ (average arm length)}$$

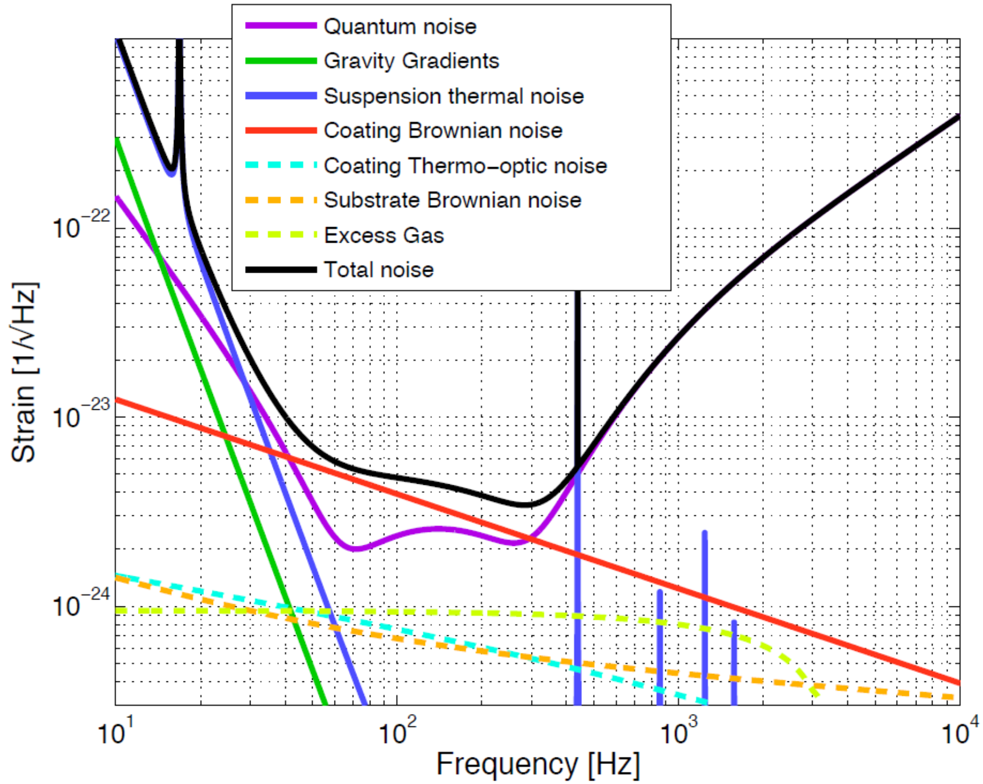
$$\mathrm{MICH} = l_N - l_W \text{ (differential Michelson short arm length)}$$

$$\mathrm{PRCL} = l_P + \frac{l_N + l_W}{2} \text{ (power recycling cavity length)}$$

$$\mathrm{SRCL} = l_S + \frac{l_N + l_W}{2} \text{ (signal recycling cavity length)}$$

- Interferometer is only sensitive when all cavities are on resonance / at dark fringe: use real-time system to control 4 or 5 degrees-of-freedom
- Error signals obtained mostly using Pound-Drever-Hall scheme: modulate laser beam with Electro-Optic Modulater, demodulate photodiode/quadrant signals
- Actuate on mirrors using voice-coil actuators
- Main DARM loop suppresses the GW signal! Effect of control loop compensated in calibration
- Similar control loops for angular degrees of freedom

Fundamental noise sources



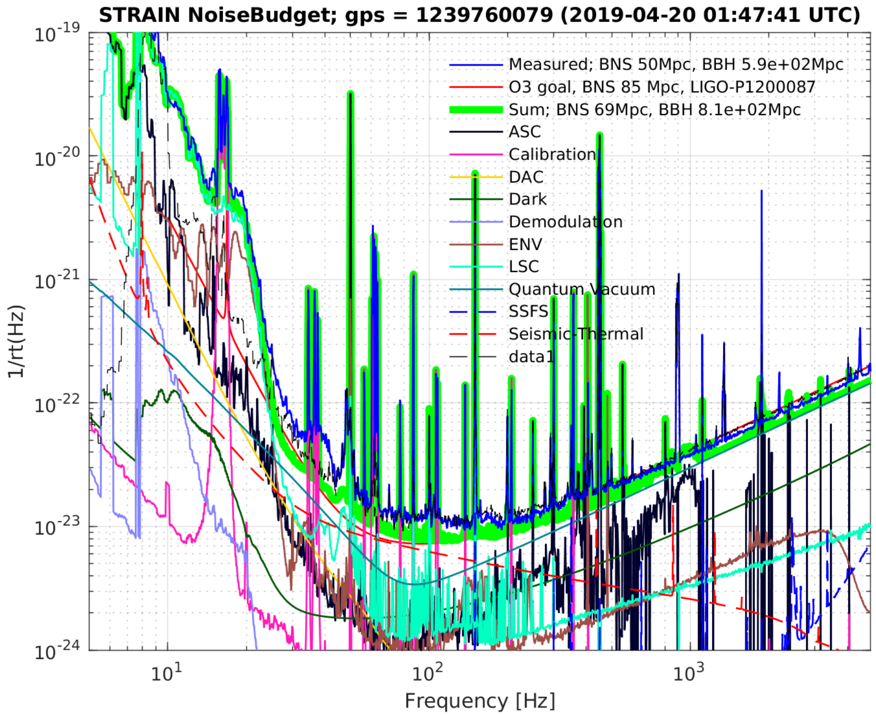
$$P_{\mathrm{sn}}(f) = \sqrt{2h\nu P}$$

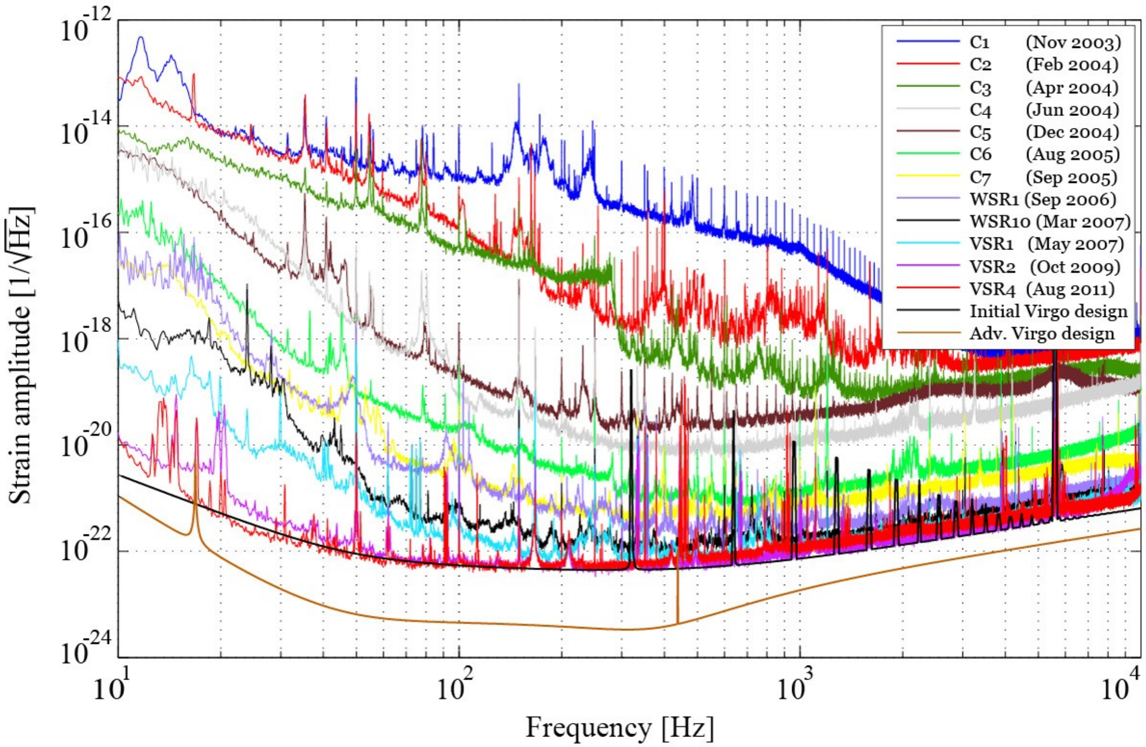
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

$$h_{\mathrm{rp}}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

- Noise budget dominated by 'fundamental noises':
  - quantum noise (shot noise at high frequencies, radiation pressure at low frequencies)
  - thermal noise: suspensions, coatings
  - residual gas pressure
- These noises can only be improved by getting stronger laser, heavier mirrors, better coatings, larger beams, longer arms, better vacuum, cryogenics: $$$/€€€

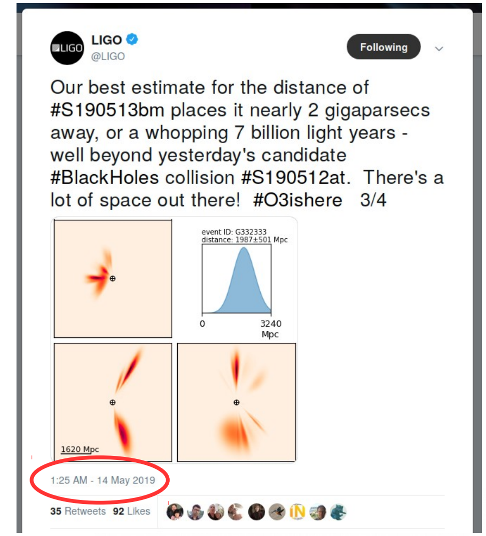
Technical noise sources

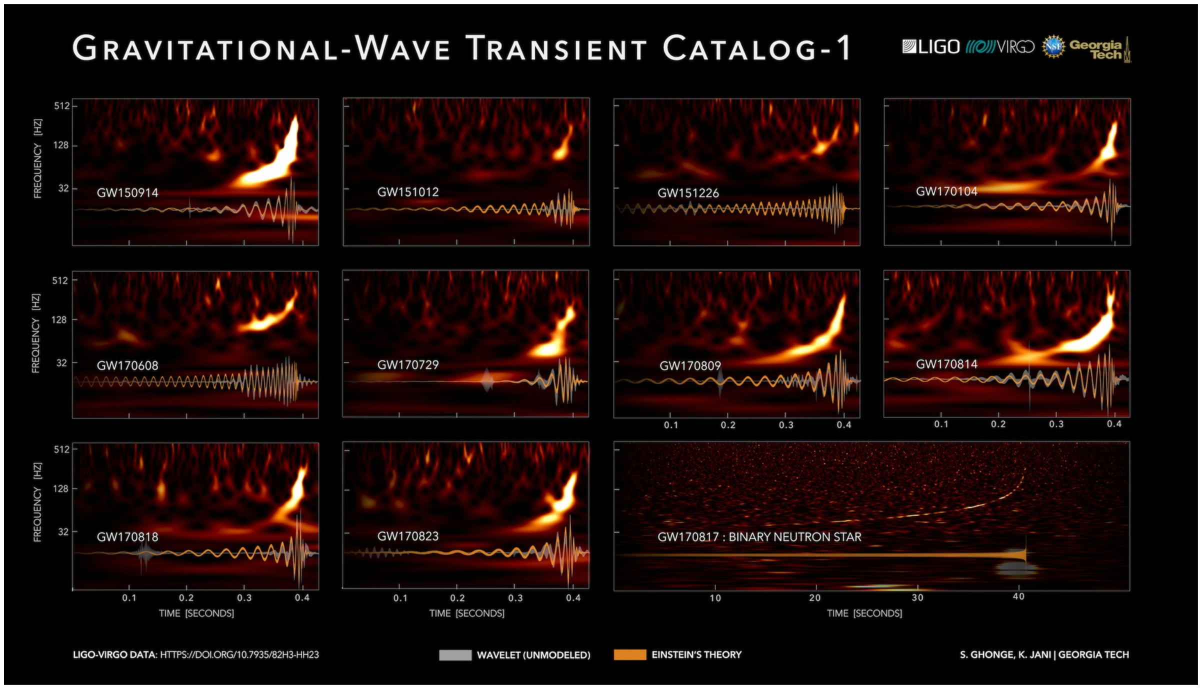


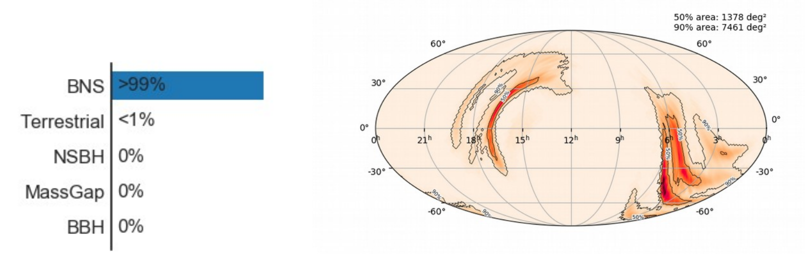


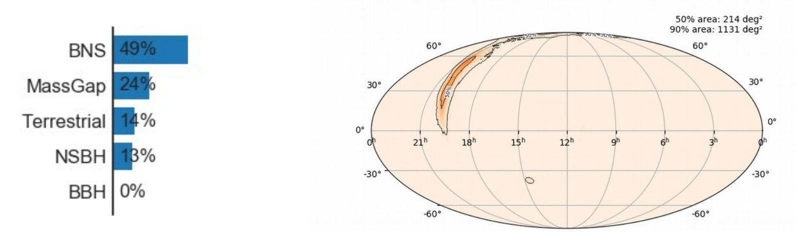
- In practice, the sensitivity is also spoiled by various 'technical noises':
  - coupling to environmental noise: magnetic, acoustic, seismic
  - scattered light: non-linear process!
  - ADC/DAC/electronics noise, ...
- Takes many years of commissioning and ‘noise hunting’ to mitigate all of these

Many detections ...



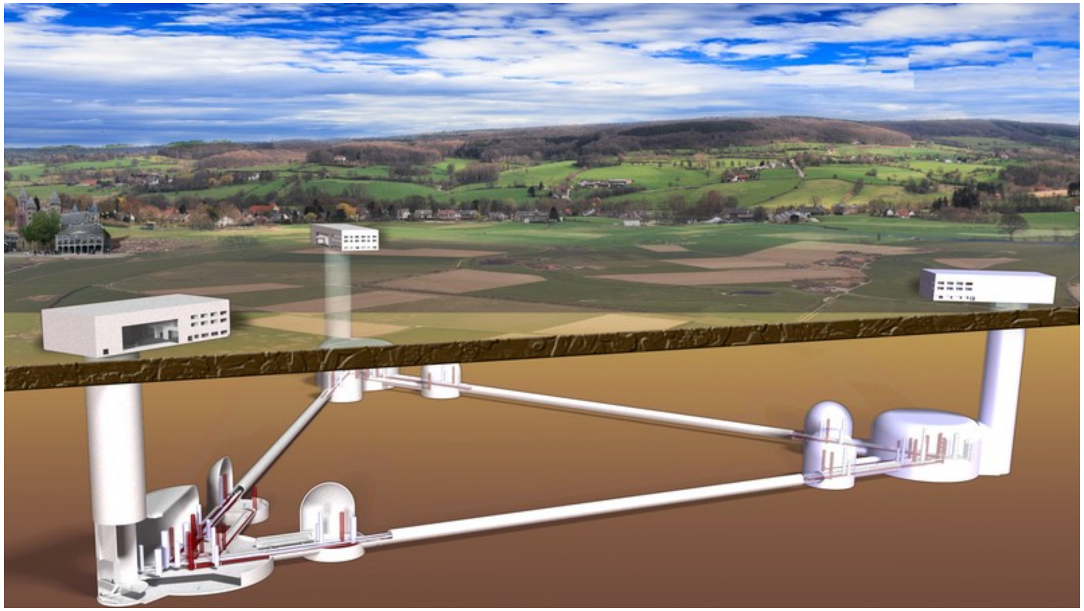


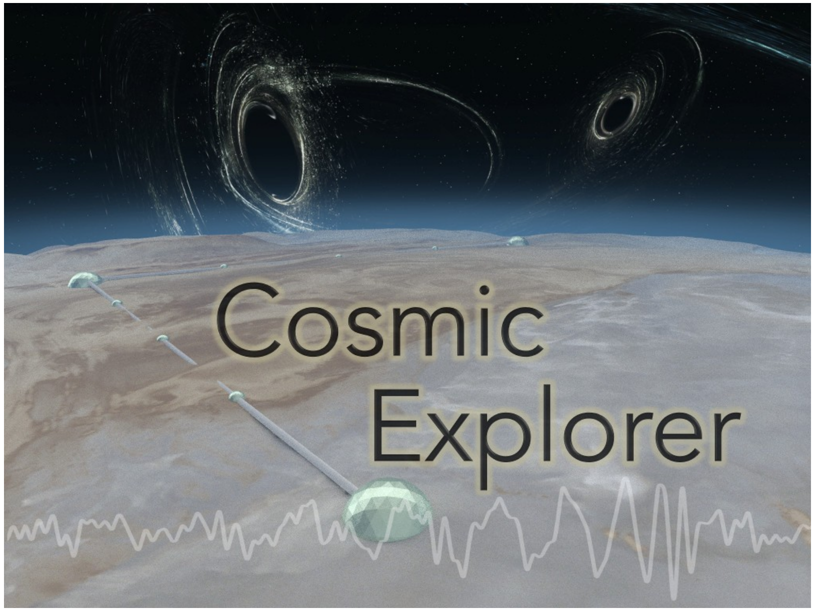




- 11 confirmed GW detections during O1 and O2 science runs (10 BBH, 1 BNS)
- About 1/month in the past, expected about 1/week in O3
- O3 science run started on April 1, already ~6 clear BBH announced publicly (GCN network)
- **2 BNS candidates two weeks ago!** no optical counterparts found yet

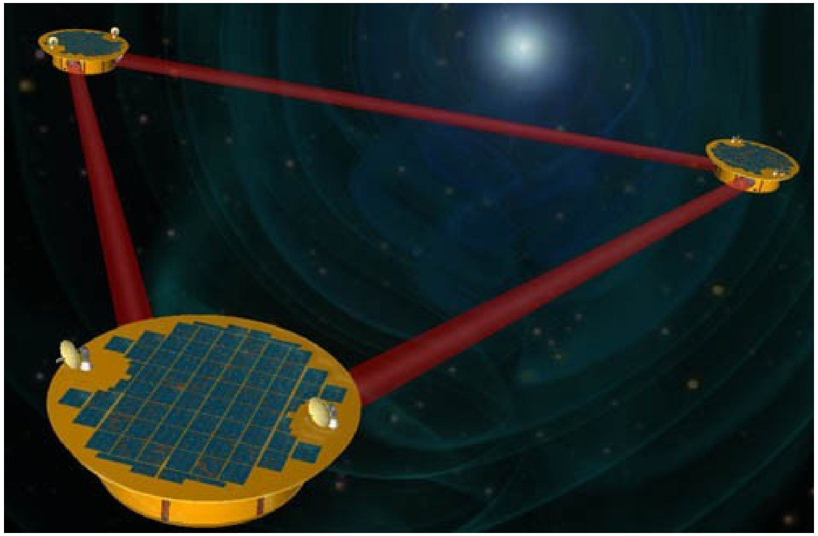
Future Earth-based detectors

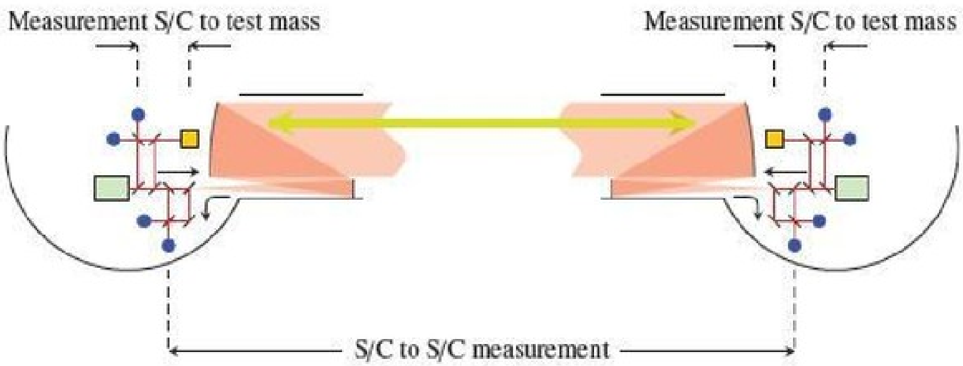




- Further improvement in sensitivity of Advanced LIGO and Advanced Virgo
- LIGO India and KAGRA (Japan) should start in a few years
- New facilities and techniques needed for next big step forward: cryogenic mirrors, underground, longer baseline, bigger beams, squeezing
- Proposal for underground 10 km Einstein Telescope (maybe in NL/BE/DE!) and 40 km Cosmic Explorer, will costs O(1e9 $/Eu)
- Atom interferometers (MIGA)
- Torsion bar (TOBA), would bridge gap between space and ground-based detectors

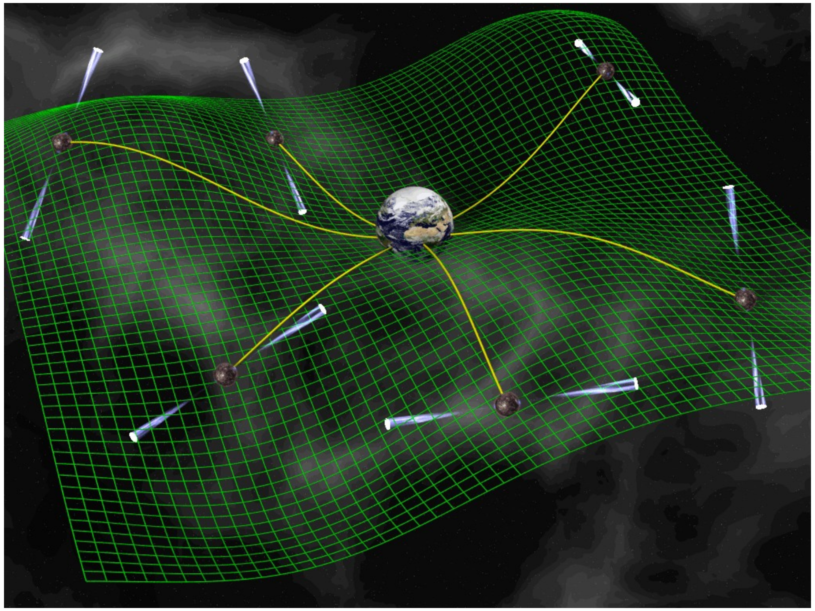
LISA





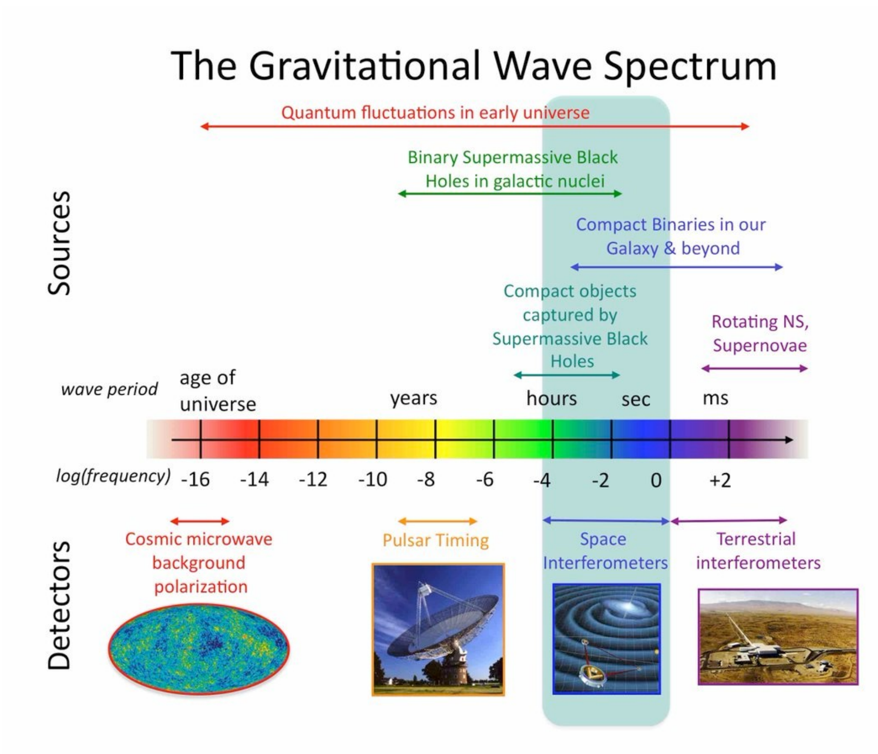
- 3 spacecraft, flying in a triangle with 2.5e6 km sides. Send laser beam to remote spacecraft, amplify it, send it back, measure round-trip phase. GW signal reconstructed in post-processing.
- Spacecraft experiences many disturbances: fly drag-free around test-mass
- Distance resolution 20 pm, observation bandwidth 0.03 mHz to 100 mHz
- LISA pathfinder satellite (2015-2017): technology demonstrator using 2 test-masses at 38 cm distance. Performed better than expected
- LISA mission approved recently, scheduled for launch in 2034

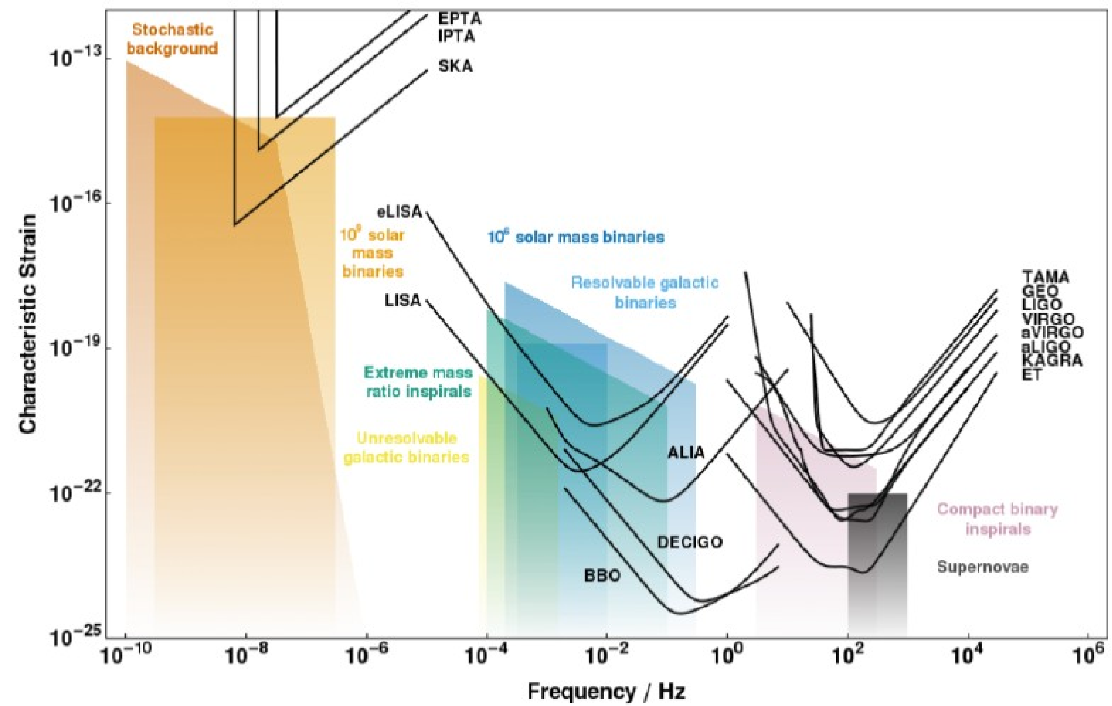
Pulsar timing arrays



- GW at even lower frequency (< μHz) are emitted by super-massive black holes, galaxies
- Pulsars are some of the most stable clocks in the universe
- Idea: take a number of bright and stable pulsars, accurately track pulse arrival times over a long period to look for GW fingerprint
- Challenging to subtract several effects of much higher amplitude
  - rotation of earth, orbit of Earth, movement of Solar system
- Measurements ongoing for several years, no detection so far

GW spectrum





- Interesting science over a huge frequency range
- Science of PTA/space/ground is complementary, similar to IR/VIS/UV astronomy
- In 20 years, we might see sources scanning through LISA band into ET band!

Conclusion

- GW predicted about 100 years ago, serious attempts to measure them since around 50 years
- Indirect evidence of GW from radio astronomy
- After >40 years of work, earth-based interferometers made their first detections of BBH and BNS
- Only the beginning of an era, new instruments are planned that are more sensitive and have different bandwidths. Note: detection rate scales with cube of sensitivity improvements!
- Stay tuned for more expected and unexpected science

- Interested in experimental side of GW detection?
  dedicated course on GW instrumentation, possibility to do thesis in the GW group at Nikhef
- Questions: swinkels@nikhef.nl

End