Experimental detection of gravitational waves



Advanced Virgo



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: $h=rac{\delta L}{L}$
- 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:
 - theory was not yet mature, not immediately clear if GW are observable at all, if they carry energy
 - missing observational evidence for astronomical sources of GW (black holes, neutron stars, pulsars, ...)
 - missing technology: lasers, modern electronics, ...
- **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 (book Gravity's Shadow H. Collins)





Modern resonant detectors







- 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 narrowband, 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 orbit gets shorter
- Decay perfectly predicted by loss of energy radiated away due to gravitational waves
- System will collide in 300 million years
- Nobel prize in physics for Hulse and Taylor (1993)









Primordial GW in CMB?



- 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



Interferometry basics



• For a perfect interferometer:

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

• 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/R²
- A simple Michelson is not sensitive enough to detect GW, need several extra tricks ...





GW polarization



- + polarization: $d\vec{r}_{\text{ETMX}} = (h_+ L/2, 0), d\vec{r}_{\text{ETMY}} = (0, -h_+ L/2)$ • x polarization: $d\vec{r}_{\text{ETMX}} = (0, h_X L/2), d\vec{r}_{\text{ETMY}} = (h_X L/2, 0)$
 - 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

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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 (also helps with redundancy, coincident detection and sky localization)





Why can interferometers measure GW?



- 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



- Sensitivity of Michelson interferometer can be increased by making the arms longer
- Note that longer interferometers have a smaller bandwidth, since GW signal gets 'averaged' over the round-trip time. Transfer function is a Sinc-function in frequency domain, with zeros
- Ideally few 100 km long (for certain interesting astrophysical sources), but money/terrain limits this to few km
- Could use a delay line (Herriott cell), but this has practical issues





Fabry-Perot cavity



- Resonant optical cavity formed by two highly reflecting mirrors
- Reflection: $rac{E_r}{E_0} = -r_1 + rac{t_1^2 r_2 \mathrm{e}^{i\phi}}{1 r_1 r_2 \mathrm{e}^{i\phi}} \qquad \phi = 2kL$
 - Resonances spaced by Free-Spectral Range:
 - Finesse:

$$\delta L_{\rm FSR} = \frac{\lambda}{2} \quad \delta \nu_{\rm FSR} = \frac{c}{2L}$$
$$\mathcal{F} = \frac{\delta L_{\rm FWHM}}{\delta L_{\rm FSR}} = \frac{\pi \sqrt{r_1 r_2}}{1 - r_1 r_2}$$
$$N_{\rm eff} = \frac{2}{\pi} \mathcal{F}$$

• Effective number of round-trips:







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





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 $f_{
 m cut-off}=\delta L_{
 m FWHM}/2$
- For Advanced Virgo: $f_{\text{cut-off}} = 57 \text{ Hz}$





Power recycling PRM

- Michelson is tuned to dark-fringe, light is reflected back to the laser
- For shot-noise reasons, you want to have a very high laser power
- Add a 'Power Recycling Mirror', to form another resonant cavity, effectively increasing the laser power by a factor \sim 37
- Laser power ~25 W, power in central cavities ~500 W, power in long arm cavities ~100 kW!







- Passing GW causes 'audio sidebands' around laser frequency. By adding an extra Signal Recycling Mirror, these signal sidebands can be sent back into the interferometer to gain more phase
- Technique already used at LIGO, will be installed at Virgo this 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



- In reality, a single pendulum is not enough: use multiple stages
- Also need to isolate vertically due to curvature of the earth, vertical to horizontal coupling \sim 1/10000



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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 2024	Operational 2017	Operational	Planned 2020	Planned 2034	
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Virgo Interferometer



- 3 x 3 km interferometer, located near Pisa, Italy
- Originally a French-Italian collaboration
- Now about 400 scientists from Italy, France, Netherlands (Nikhef, Utrecht, Nijmegen, Maastricht), Poland, Hungary, Spain







- 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



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Vacuum system



- Fluctuations of air-pressure changes optical path length, so GW interferometers are located inside large vacuum tubes
- Virgo interferometer: 7000 m³ vacuum, long tubes have pressure $\sim 10^{-9}$ 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



- Interferometer is only sensitive when all cavities are on resonance / at dark fringe: use real-time system to control many 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



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Fundamental noise sources



- 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)
- O3 science run started on April 1 2019, finished one month early due to Covid-19
- 56 alerts sent out during O3, so far only published GW190425 (BNS) and GW190412 (announced this week, very asymmetric), expect more publications soon!
- About 1/month in O1+O2, about 1/week in O3





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Cumulative #

Future Earth-based detectors



- Further improvement in sensitivity of Advanced LIGO and Advanced Virgo
- LIGO India and KAGRA (Japan) should start in the next 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 ~1e9 \$/€
- Atom interferometers (MIGA)
- Torsion bar (TOBA), would bridge gap between space and ground-based detectors





Space: 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 (Time Delay Interferometry).
- Spacecraft experiences many disturbances: fly drag-free around test-mass
- 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
- Distance resolution 20 pm, observation bandwidth 0.03 mHz to 100 mHz: sensitive to heavy black holes





Pulsar timing arrays





- GW at even lower frequency (< μ Hz) 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, orbit of Solar system in Milky Way
- 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 for more than 50 years
- Indirect evidence of GW from radio astronomy
- First direct detection of BBH with Earth-based interferometers in 2015, many more since then, including BNS+GRB
- 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



