Experimental Gravitation and Cosmology

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GW detection! This part is given by Jan Harms.

Marica will talk more about GW science and the multimessenger approach.

The first slide is the north arm of Virgo, Einstein Telescope and the LGWA.

Outline:

1. overview of GW detection;
2. detector responses to GW;
3. noise spectra, filtering, SNR, transfer functions;
4. fluctuation-dissipation, thermal noise;
5. quantum noise & squeezing;
6. passive and active seismic isolation, Newtonian noise;
7. GW detector concepts.

The interferometer is operated at the dark fringe

but not exactly there?

At a frequency scale of $\sim H_0$ we can do measurements thanks to CMB observations.

At the nHz scale (corresponding to lyr wavelengths) we can use Pulsar Timing Arrays, with radio telescopes. Pulsars being the "best clocks in the universe" is not really true. For now, they've discovered red noise, which could potentially be a GW signal.

At the mHz scale we might have space detectors such as LISA: here the GW wavelengths are of the order of 1 AU.

At the 100 Hz scale we have ground-based detectors.

Current infrastructure is expected to reach $z \sim 2$; we expect future infrastructure to reach $z \sim 100$. This goes all the way back to the dark ages in the Universe's history.

This means that ET + CE would see something like 90 % of BNS mergers, and basically all BBH mergers.

It is good to have a long baseline.

Jan disses Cosmic Explorer a bit. 40 km is ambitious because of the cross-couplings due to the fact that the mirrors will not be perpendicular to the suspension system, which will point straight down at both edges. Also, with such lengths there is a loss in sensitivity in the kHz band.

High performance sensing will require cold temperatures, which however also means that we need to redesign basically all the infrastructure.

The dissipation in the system dictates the thermal noise.

We need in-vacuum optical systems; people were extremely worried before the construction of LIGO about this. Now in Livingston they found a hole. The idea to find it is like finding a hole in a bike tire, with liquid helium around the detector and helium sensors inside.

Current detectors have a finite lifetime. Virgo is slowly sinking into the ground, since it is built on soft soil.

There are disturbances caused by powerful lightning strikes. It is crucial to monitor the environment. In the future, there will be online background removal.

Einstein Telescope needs very big underground chambers, with roofs on the order of 25 m. Do we have enough people in Europe to build ET? Not clear.

Kagra taught us some lessons. The spring melt filled up water reservoirs there, so there was a waterfall inside the arms there. That means a lot of humidity. The water stream near the test masses was gravitationally coupled to them; Newtonian noise is bad.

If ET is built in Sardinia it will be really dry; maybe not so for the Netherlands. We need to be careful that the ventilation and cryogenic systems do not create noise.

Ventilation is needed for both humidity and radioactivity management. The experiments in LNGS, say, are much more sensitive.

LISA will be able to locate sources thanks to their amplitude modulation during the year. At these frequencies going underground would not help.

There is a requirement for drag-free navigation, though.

The beam to another satellite is on the order of 25 km in size.

Now we talk about LGWA. Weber invented everything when it comes to GW detection technologies. He invented the resonant bar detectors.

He tried detecting GWs from quadrupolar seismic vibrations on the Earth! We now know that their amplitude is much too small for that. They did, however, put the first upper limits on the amplitude of GWs.

Apollo 17 brought the Lunar Surface Gravimeter. A design flaw limited its sensitivity. The problem of having 14 days of lunar night without solar power is large.

A Russian team is probing microwave beaming for the transmission of power. Nuclear power is possible, but how do we shield from it? They used plutonium there. However, nobody's producing plutonium anymore... But it might be produced again thanks to a decision by the Trump administration.

That gravimeter failed on the Moon because of an arithmetic mistake which failed to account for the decreased gravity there.

One can bring stuff to the Moon at a price of about $\$10^6/\mathrm{kg}$. This might decrease in the future.

LGWA: four seismometers at $\sim$ km separation.

LSGA: interferometers connected to the ground, measuring the deformation of the surface of the Moon. They'd need to be deployed at 10 km distance, but the Moon curves: maybe put them at the rims of a crater? this is very difficult.

GLOC: basically Cosmic Explorer on the Moon. By Jani and Loeb, two theorists. These detectors do require a lot of maintenance.

The spectrum of noise on the Moon is on the order of $10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ between 0.1 Hz and 1 Hz.

This is much lower than what is observed on the Earth, and which is mostly due to the ocean.

Micro-meteoroid impacts have a small impact.

The Moon might be the quietest place in the Solar System: it being tidally locked helps a lot. It is also near the coldest: there are permanently shadowed regions at the poles. These have never seen sunlight, neither direct nor indirect, for a billion years or more.

It might even be colder than Uranus or Neptune: the absence of radioactivity helps a lot.

We can use superconductors for free there.

How do we get power there? An option is beaming from solar panels at the rim. Another option is beaming from satellites in orbit.

Nuclear power? Europe will not do it, since ESA does not launch for Europe (as opposed to NASA and the Chinese space agency): therefore, any issues would be dumped onto a South American country, a huge political issue.

The presence of gravitational waves from inflation, at the tensor-to-scalar ratio given by simple, single-field inflationary models, would be incredibly important.

A direct observation for this kind of thing would be the Big Bang Observer. This would be a proof of quantum gravity!

This would be a 12-satellite configuration, two triangles and a hexagon, smaller than LISA, sensitive to the deciHertz regime. Why not the milliHertz band? LISA is also limited by GW foregrounds!

Foreground removal is computationally difficult.

1 GW detectors

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The basic design of a GW detector is that found in LIGO Scientific Collaboration and Virgo Collaboration et al. [LIG+16, fig. 3].

It is roughly a Michelson-Morley interferometer, with 10 kW coming in from a power-recycling mirror plus a Fabry-Perot cavity amplifying that power to 100 kW.

These cavities are roughly 3 km long.

The frequency of the laser is on the order of $f \sim 10^{15}$ Hz, and it has a small dispersion in frequency space.

What then happens is that when the length of the cavities is perturbed, some power in each cavity is shifted into the *sidebands* $f_0 \pm \Delta f$ of the carrier frequency f_0, where $\Delta f = f_{\mathrm{GW}} \ll f_0$.

We can fully control the length of the arms, to get our preferred interference condition.

What can happen to laser light? It can be dissipated, it can come back to the mirror, but we need a device to dump the beam and prevent it from coming back to the laser.

A DC offset: we want a small fraction of the light, roughly 0.1 %, to get to the photodetector. We add a bit of the laser light to the sidebands.

This is a homodyne detection scheme, and the laser is called a local oscillator.

Correlated signals go back to the power recycling mirror, while anticorrelated signals go to the detector.

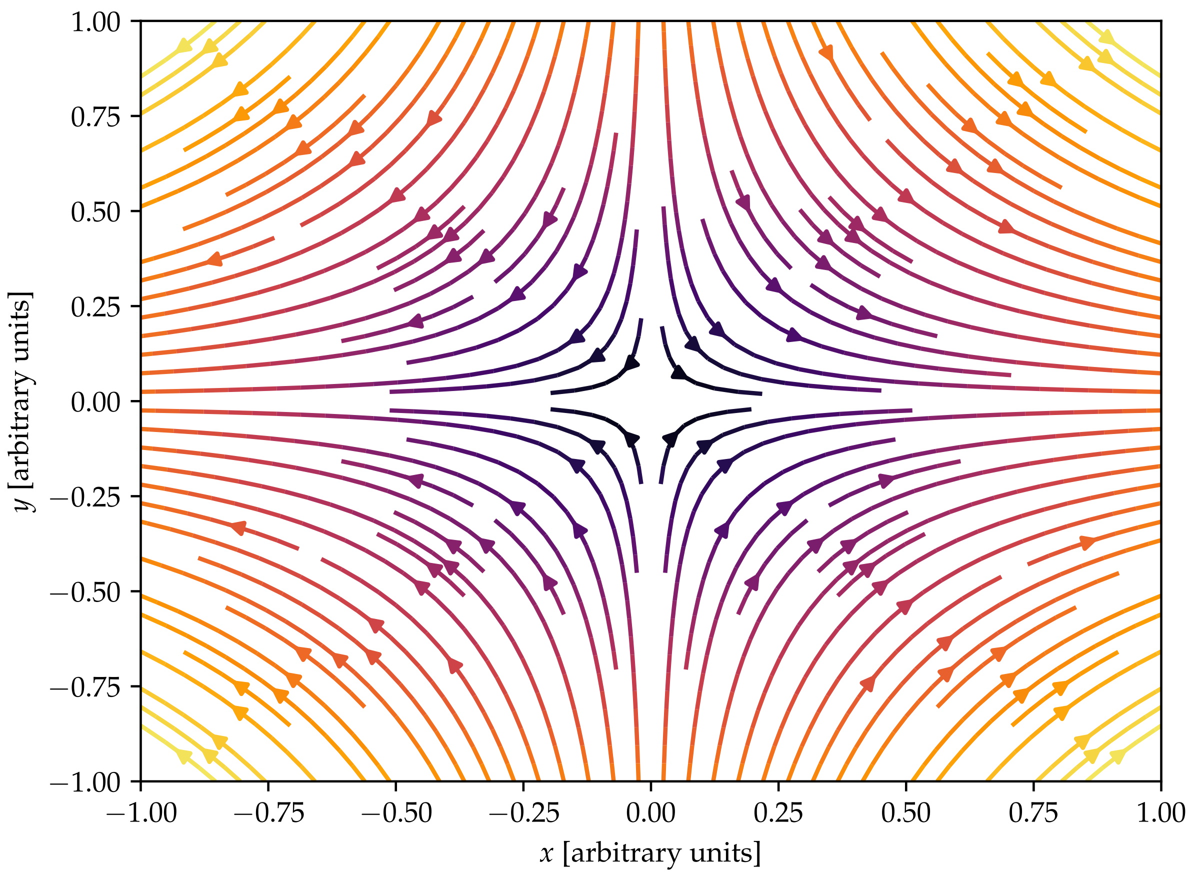

Figure 1: The effect of the h_+ polarization of gravitational waves. Color indicates the magnitude of the field (weaker in the middle).

Noise sources

The main *environmental* noise sources are

1. scattered light;
2. seismic / vibrational noise;
3. Newtonian noise;
4. electromagnetic noise.

Basically all GW detectors have a strain sensitivity curve, which is roughly speaking the noise referred to the quantity "strain": $h = 2\Delta L/L$. The "bucket" is centered around 100 Hz.

The true signal we measure is the current from the photodiode. The noise in the detector could be reported in Ampères, but plotting things in this way allows us to include the response.

A rough way to say this is

$$\text{sensitivity} = \frac{\text{noise}}{\text{response}} . \tag{1.1}$$

The laser is tuned to the resonant frequency of the cavity, but the same does not hold for the sidebands, which are therefore not amplified to the same amount!

However, we can do resonant amplification of the sideband signal as well!

There are around a hundred different relevant noise sources. There are "fundamental" noises and "technical" noises. The former are a limit set by the detector configuration, nothing can be done about them. The technical noises can be gradually reduced by the crew working on the detector.

At high frequencies, the problem is quantum noise; at mid-low frequencies we have thermal noise, while at low frequencies the dominant contribution is environmental noise.

Isolation from the environment means:

1. seismic isolation;
2. reducing susceptibility to EM fields;
3. picking a quiet environment;
4. dealing with scattered light;
5. vacuum system.

Building underground helps! The seismic fields are quieter there, and there is more insulation.

Why do we need to build an interferometer in Europe? We (Europeans) have optical telescopes in Chile, for example.

Telescopes only need a small amount of people to man them, while GW interferometers need tens of people, and not that many people want to work in an extremely remote location.

We only want the zeroth-order, Gaussian mode in the spatial cross-section of the decomposition of the beam.

However, since the mirrors are not perfectly spherical higher modes are also excited, with magnitudes of the order of 20 ppm. Out of the fraction, then, a tiny fraction scatters on the edge of the vacuum tube (10 ppm) and re-enters the beam. The vacuum tube is not seismically isolated! This means that that light picks up a huge amount of noise.

We therefore need to insert a *baffle*, which absorbs any light which hits it. What people now do is make detailed models of the system, use raytracers to figure out where the light is going and block it. People have also though about just coating the whole interior — then, the issue becomes maintenance and coating lifetime.

Thermal noise: it is mainly about thermal vibrations of our suspensions, our mirrors (coating and substrate), and the electronics.

Changing the mirror's thermal noise is hard, electronics could be made superconductive...

Quantum noise is quite simple: it has only two components,

1. shot noise;

2. radiation pressure noise.

Once we know how the fluctuations enter our system, we can control them! What defines the quantum state of the detector?

The scaling of the high-frequency part is mostly shot noise, RP noise has a lower frequency, and we can currently manage to make it negligible.

There are methods to manipulate quantum states in order to reduce quantum noise. The broad topic here is "quantum nondemolition techniques".

There are all kinds of other noises which enter our system, but the most important ones are the ones we mentioned.

How do we cool our experiment? We have roughly 0.5 ppm absorption, which means about a Watt of power going to the optics! A thermal link is dangerous, since it can introduce vibrations. Voyager wants to do radiative cooling, since it introduces no extra vibrations. However, getting to very low temperatures is basically impossible because of the $\sim T^4$ temperature.

So, ET needs a thermal link to get to 10 K to 20 K. Maybe superfluid helium could work for this purpose...

Timeseries analysis

The basic tenet of timeseries analysis is to work with the spectral representation of the data.

This timeseries will typically be uniformly sampled.

We define the autocorrelation as

$$C(y; t, t') = \left\langle y(t) y(t') \right\rangle \,, \tag{1.2}$$

where the brackets denote an ensemble average. If the noise is stationary, this will just be a function of $\tau = t' - t$, so we get $C(y; \tau) = \left\langle y(t) y(t+\tau) \right\rangle$.

Even things like thermal and quantum noise are not really stationary, while environmental noise is *definitely* not stationary.

Fourier transforms diverge for infinitely-extending timeseries, but we can take an alternative approach, which is consistent with the fact that our signals are finite in time.

We can only transform a section of length T; its transform will be $\widetilde{y}_T(f)$. In the case of stationary noise, we can define the single-sided Power Spectral Density as

$$\mathrm{PSD}(f) = S(f) = \lim_{T \to \infty} \frac{1}{T} \left| \widetilde{y}_T(f) \right| . \tag{1.3}$$

This converges for stationary noise. We can also include a 2 in the definition, it is a matter of convention. This is the standard way to represent timeseries in the frequency domain.

In terms of units, $[\tilde{y}] = [y]/\text{frequency}$; therefore, $[S] = [y]^2/\text{frequency}$.

If we plot $\sqrt{S}$, this will have units of $[\sqrt{S}] = [y]/\sqrt{\text{Hz}}$.

The integral of the PSD over all frequencies yields

$$\int_{-\infty}^{\infty} \mathrm{d}f\, S(f) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} \mathrm{d}t\, y_T(t) \int_{-T/2}^{T/2} \mathrm{d}t'\, y_T(t') \underbrace{\int_{-\infty}^{\infty} \mathrm{d}f\, e^{2\pi i (t-t') f}}_{\delta(t-t')} \tag{1.4}$$

$$= \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} \mathrm{d}t\, y_T^2(t) = \left\langle y^2 \right\rangle = \sigma_y^2\,. \tag{1.5}$$

We can also compute a *bandlimited* variance:

$$\sigma^2_{\text{bandlimited}} = \int_{f_1}^{f_2} \mathrm{d}f\, S(f)\,. \tag{1.6}$$

References

[LIG+16] LIGO Scientific Collaboration and Virgo Collaboration et al. "Observation of Gravitational Waves from a Binary Black Hole Merger". In: *Physical Review Letters* 116.6 (Feb. 11, 2016), p. 061102. DOI: 10.1103/PhysRevLett.116.061102. URL: https://link.aps.org/doi/10.1103/PhysRevLett.116.061102 (visited on 2020-03-23).