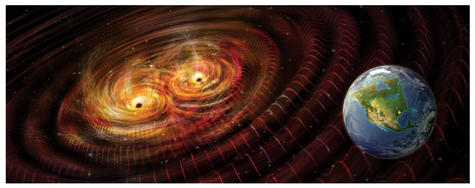
The G-spot of Gravitational Wave Astronomy



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1. What is a G-wave (GW)?

Gravitational waves (G-waves, GW for short) are:

- A prediction of General Relativity
- A radiation emitted by any accelerating mass (cf. electromagnetic waves are radiation emitted by charged bodies)
- Waves travelling at the speed of light, or is light a wave that moves at the speed of GW?
- A fundamental property of spacetime
- Made of quanta called gravitons

2. The strain & experiments

The ***strain*** (or deformation), h, is the main observable in GW astronomy and experiments. What is the strain h? Easy! The strain is the *relative change of length*, i.e.,

$$\boxed{h = \frac{\Delta L}{L}} \tag{1}$$

Remark: the strain can also be understood as the amplitude of the metric perturbation of the spacetime.
Remark (II): Typical strains for GW detection and experiments are about 10^{-21}

3. Spectrum & Detection

There are 4 magnificent main GW bands:

- **Cosmological band**, $\sim 10^{-16}$ Hz.
  Sources are frozen relic waves from the big bang at ultralow frequency.
  Detection method is B-mode polarisation of the CMB (Cosmic Microwave Background)
- **Nanohertz band**, $\sim 10^{-9}$–10^{-7} Hz.
  Sources are waves from supermassive black holes at a frequency 1 cycle per 3 years.
  Detection method is the correlated pulse arrival time variations of millisecond pulsar signals (Pulsar Timing Arrays, PTAs)
- **Millihertz band**, $\sim 10^{-4}$–10^{-3} Hz.
  Sources are waves from massive black hole binaries at ~ 1 cycle per minute partially masked by galactic binary star systems.
  Detection method is drag free space interferometers of $\sim 10^6$ km baselines
- **Audio band**, ~ 10–10^4 Hz.
  Sources are mergers of stellar mass neutron stars and black holes.
  Detection method is high power ground based multi-km baseline interferometers

Question: Is *Quantum Gravity* beyond the edges of ultralow and ultralight GW bands or everywhere?

4. The GW Matrix

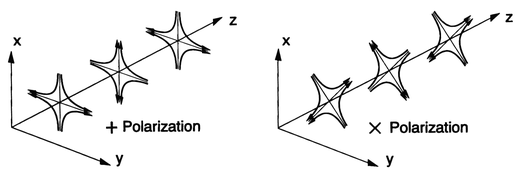
GW arise naturally from the Einstein equation

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}} \tag{2}$$

If we assume a weak gravitational field exciting the flat Minkovski spacetime $\eta_{\mu\nu} \to \eta_{\mu\nu} + h_{\mu\nu}$, then we arrive in the linear approximation to the wave-like equation (in vacuum): $\Box^2 \overline{h}_{\mu\nu} = 0$. *Metric* or *spacetime perturbations* propagate as a wave. In the so called transverse-traceless gauge, one can further write down the explicit form of $h_{\mu\nu}$ for a wave propagating in the z direction, which is

$$h_{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \mathrm{e}^{\mathrm{i}(\omega t - kz)}, \tag{3}$$

where h_+ and $h_\times$ are two real numbers indicating the amplitudes of the two polarizations of the GW.



Ground based GW observatories/*Gravitational Telescopes*

Interferometers (2th generation like aLIGO or aVIRGO, 3rd generation like KAGRA and the ET-Einstein Telescope), *PTA* (Parkes PTA, EPTA, NanoGrav, IPTA, SKA) and ultra-high energy *resonators* for very high and ultra-high frequency GW detection.

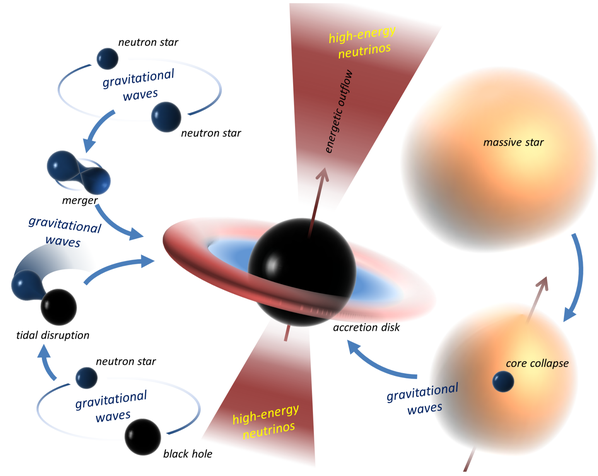
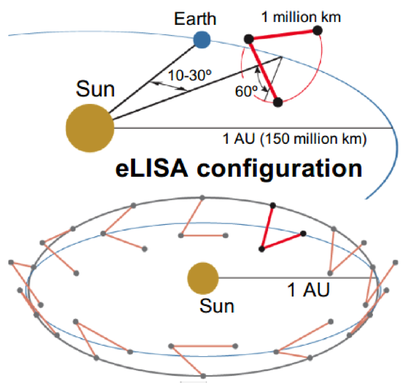


Figure 1: Future Astronomy. New telescopes plus classical photon telescopes to test fundamental physics, (classical & quantum) field theories and gravity in the strong regime. New messengers are neutrinos and gravitons.

Space based GW observatories/*Gravitational Telescopes*

(e)LISA, DECIGO, ASTROD-GW, BBO, TAIJI, TIANQIN, future CMB/inflation probes.



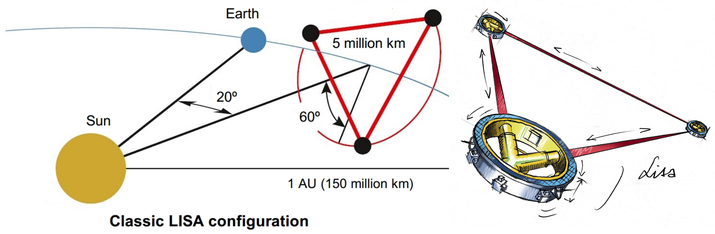


Figure 2: eLISA vs. LISA. The first man-made GW space telescope. Recently, ESA scheduled eLISA launch in 2034. eLISA technology is currently being paved and tested with the LISA Pathfinder mission.

References

[1] *Gravitational wave astronomy: the current status.* Blair, D., Ju, L., Zhao, C., et al. 2016, *arXiv:1602.02872*

[2] *Gravitational wave physics and astronomy: an introduction to theory, experiment and data analysis.* Wiley. 2011.

The discovery of GW: confirmed events

Advanced LIGO and LIGO-VIRGO collaboration have observed 2 GW events (circa 2016, June):

- **GW150914.** Details here https://losc.ligo.org/events/GW150914/
- **GW151226.** Details here https://losc.ligo.org/events/GW151226/

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Motto *Mobilis in mobili!*
GW equation with sources $\Box^2 \overline{h}_{\mu\nu} = -16\pi G T_{\mu\nu}/c^4$