Gravitational wave observations and the memory effect

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Gravitational waves

The existence of gravitational waves (GW) is predicted by Einstein's general theory of relativity (GR). They are described as ripples of space-time caused by accelerated masses. The detection and analysis of GW signals tell us more about the physics of black holes, neutron stars, supernovae or the early universe and provide new means to test GR.

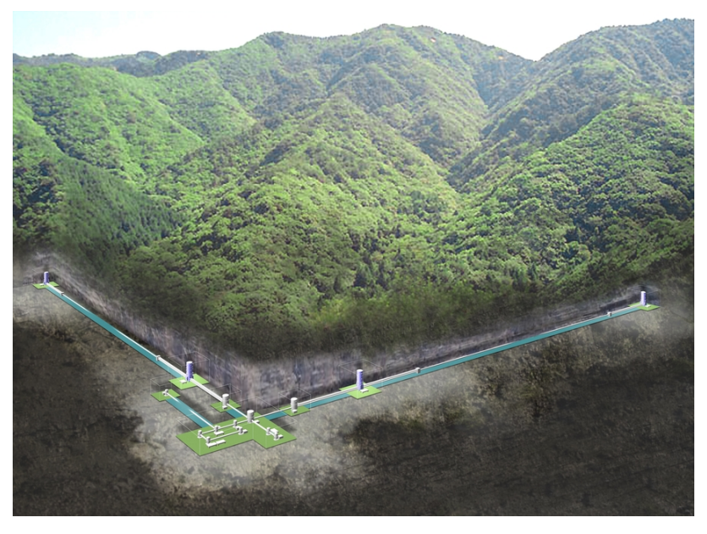
Global GW detector network

- Currently four operational GW detectors:

LIGO Livingston, USA

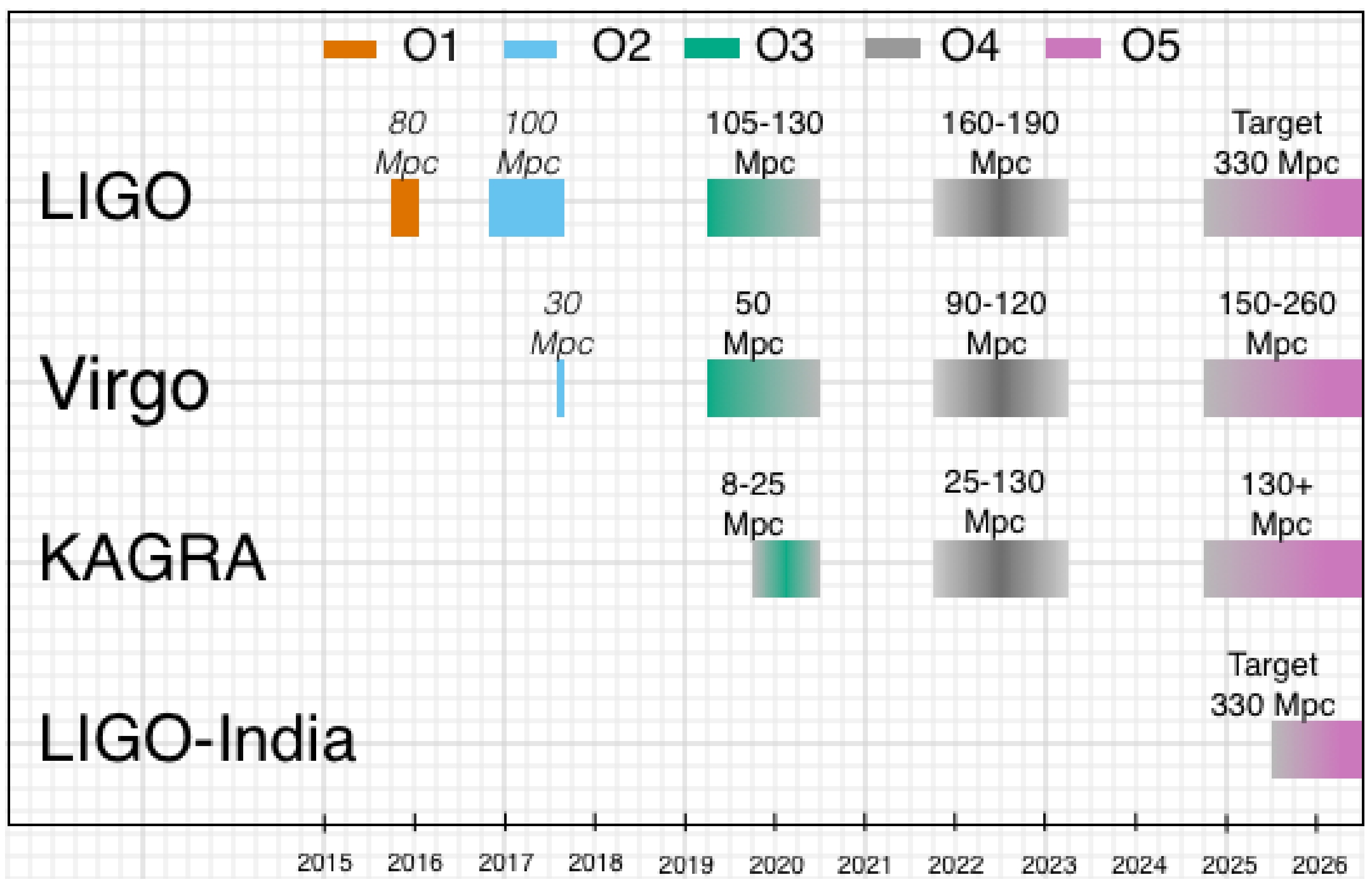
LIGO Hanford, USA

Virgo, Italy



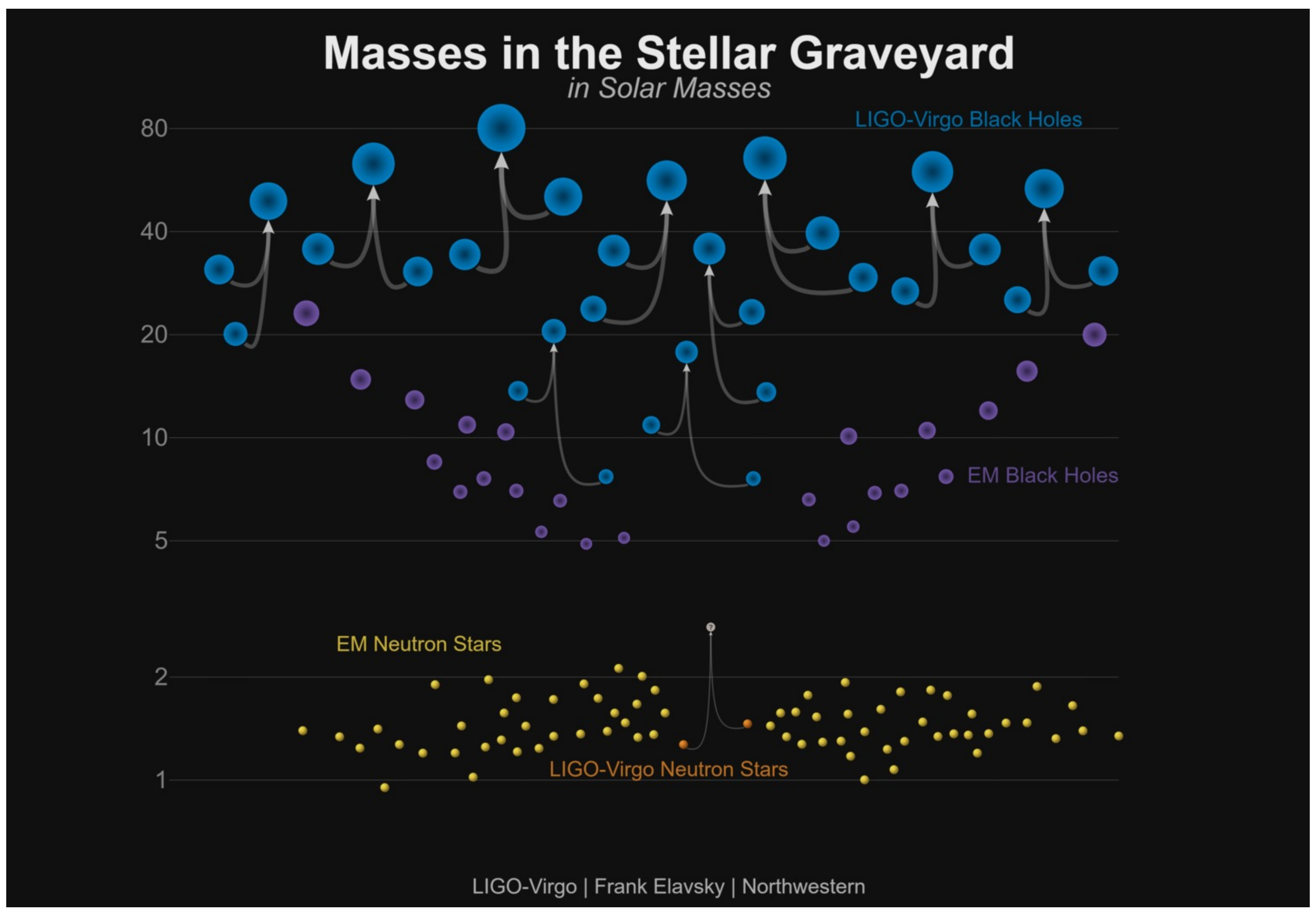
KAGRA, Japan

- 2-arm interferometers, each arm 3-4 km long
- Sensitive to GW frequencies from decahertz to kilohertz
- More detectors improve source localization and parameter estimation
- Observing runs with expected binary neutron star range:



GW Detections

- First detection in 2015 (GW150914): A $36M_\odot$ and a $29M_\odot$ black hole merged into a $62M_\odot$ black hole
- 11 confident GW detections in observing runs O1 and O2:
  - 10 binary black hole mergers
  - 1 binary neutron star merger with electromagnetic counterpart
    → Sets a tight constraint on the speed of gravity: $-3 \times 10^{-15} \leq \frac{v_{\mathrm{GW}} - c}{c} \leq 7 \times 10^{-16}$
- New insights on the astrophysical population of black holes and neutron stars



- Observing run O3 is underway: Already more than 30 GW event candidates and still counting...!

Non-linear memory effect

- One usually thinks of GWs as purely oscillatory phenomena
  → But they can also contain a non-oscillatory (DC) component
- An "ideal" GW detector would experience a permanent displacement after the GW has passed, leaving a memory of the signal:

$$\Delta h_{\mathrm{mem}} = \lim_{t \to +\infty} h(t) - \lim_{t \to -\infty} h(t)\,. \tag{1}$$

- The memory arises from GWs produced by GWs:

$$\Box \bar{h}^{jk} = -16\pi G(-g)\left(T^{jk} + T^{jk}_{\mathrm{GW}}[\bar{h}, \bar{h}]\right) + \mathcal{O}(\bar{h}^2)\,. \tag{2}$$

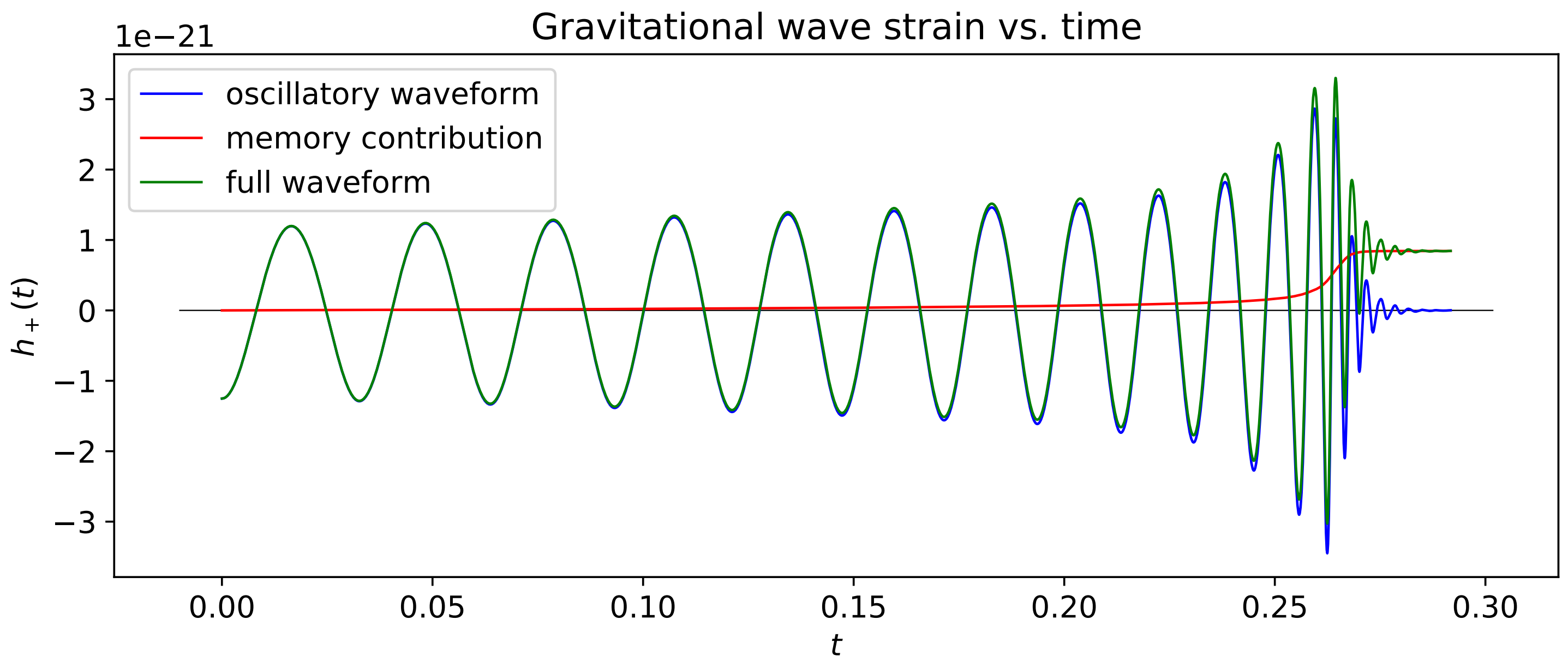
- It is present in all GW sources and scales like the radiated energy
- The memory is hereditary, it depends on the entire dynamical past of the source
- Allows us to probe a peculiar non-linear feature of GR

Memory in compact binary coalescences

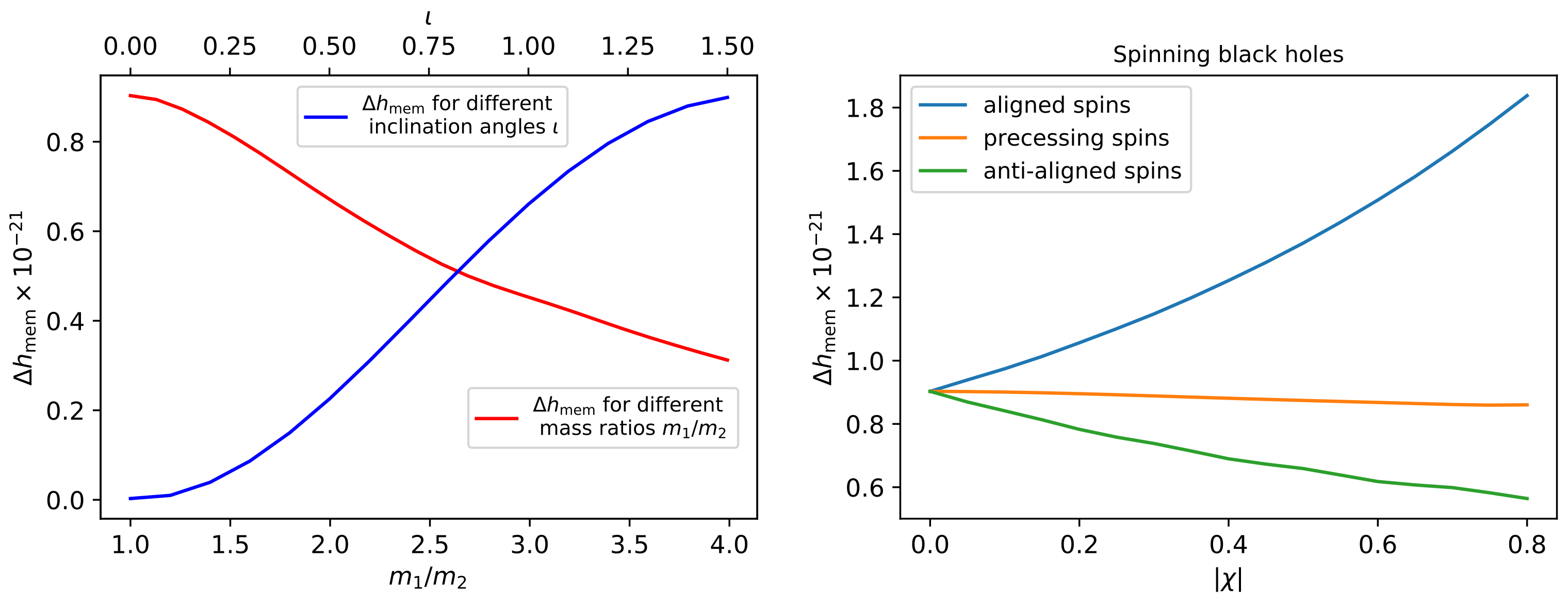
- If we know the oscillatory GW signal $h(t)$ of a compact binary coalescence, we can compute the memory contribution via

$$h^{\ell m}_{\mathrm{mem}} \sim \int_{-\infty}^{T_R} dt \sum_{\ell_1 \ell_2 m_1 m_2} G^{\ell \ell_1 \ell_2}_{m m_1 m_2}\, \dot{h}^{\ell_1 m_1}(t)\, \dot{h}^{\ell_2 m_2 *}(t)\,. \tag{3}$$

- The GW memory slowly builds up during the inspiral and grows rapidly during the merger before it saturates to its final value:

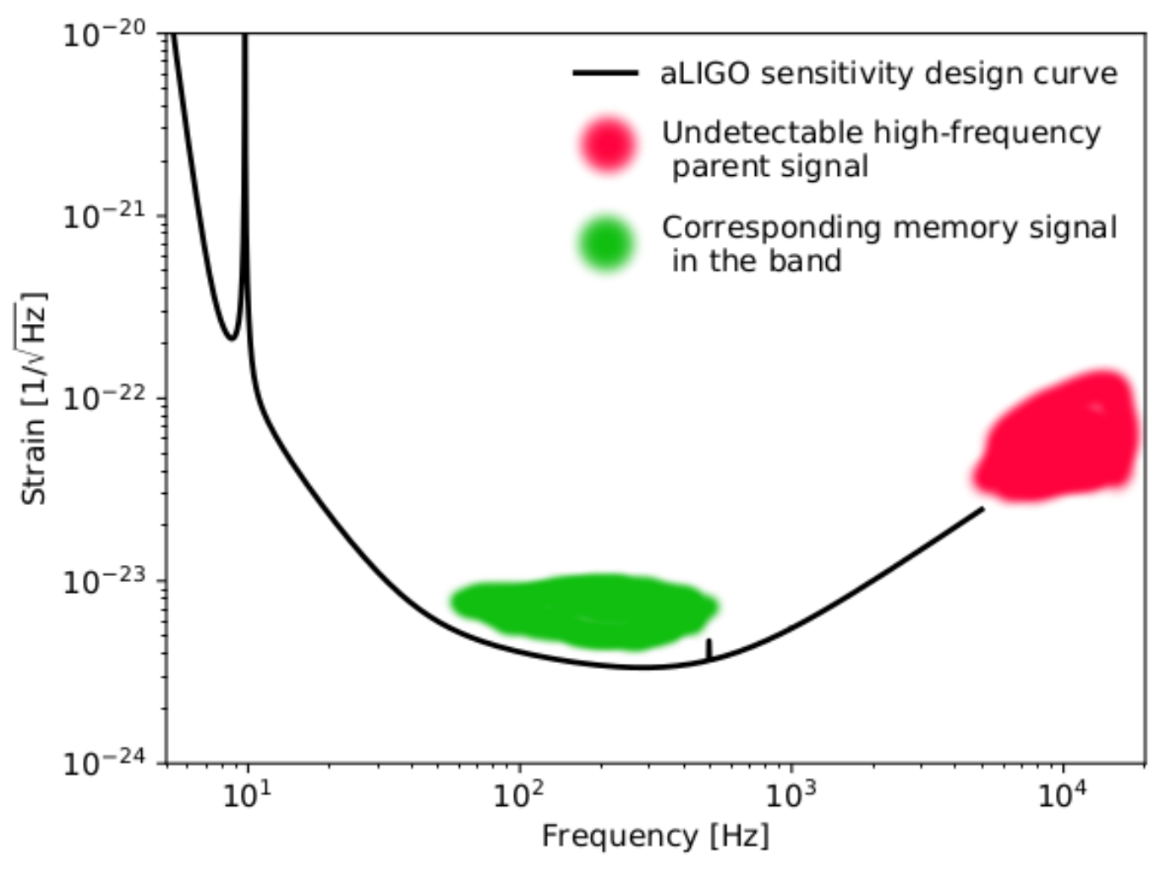


- The memory contribution depends on the configuration of the binary. Comparison to an edge-on, equal mass and non-spinning reference system:



Subsolar mass memory

- The merger of subsolar mass black holes produces GWs with frequencies beyond LIGO's sensitivity band ($\gtrsim$ kHz)
  → But its memory could be detectable as a burst signal in LIGO
- We are searching for such memory signals in LIGO data
- Detection of such black holes will provide insights into the composition of dark matter



References

[1] LIGO Lab Caltech Website, `https://www.ligo.caltech.edu/`.

[2] LIGO/Virgo Public Alerts User Guide, `https://emfollow.docs.ligo.org/userguide/`.

[3] LIGO/Virgo Scientific Collaboration, Phys. Rev. X 9, 031040 (2019), arXiv:1811.12907.

[4] LIGO/Virgo Scientific Collaboration, ApJL 848, L13 (2017), arXiv:1710.05834.

[5] M. Favata, Phys. Rev. D 80, 024002 (2009), arXiv:0812.0069.

[6] M. Ebersold et al., Phys. Rev. D 100, 084043 (2019), arXiv:1906.06263.

[7] LIGO/Virgo Scientific Collaboration, Phys. Rev. Lett. 123, 161102 (2019), arXiv:1904.08976.