Excitation of GW modes by motion: detecting the peculiar velocity of galaxies using EMRIs

Based on: **arXiv:2010.15856** & **arXiv:2010.15842**

by

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Moving sources

Velocity dispersion of clusters
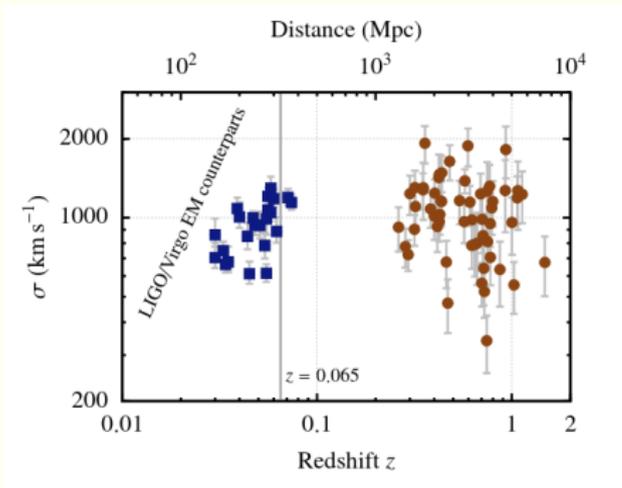
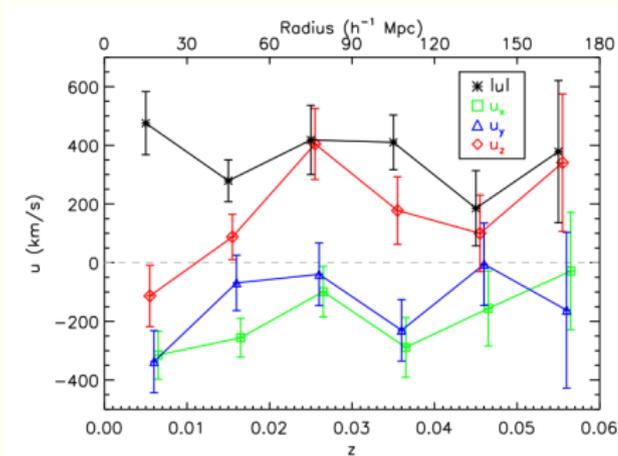Velocity dispersion of galaxy clusters
[Amaro-Seoane+2020]

- GWs located inside host systems!
- galaxies in clusters with deep potential
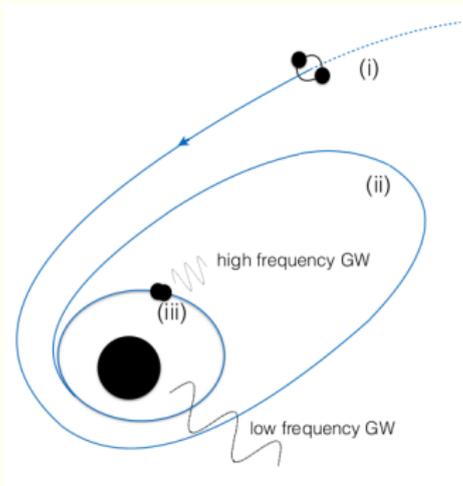- average velocity dispersion $\approx$ 1000 km/s

Bulk flow

Bulk flow: motion of the Milky Way
relative to the background
[Scrimgeour+2016]

- Milky Way moves relative to background ($\approx$ 400 km/s)

- motion relative to particular clusters can be higher

Interaction with third body

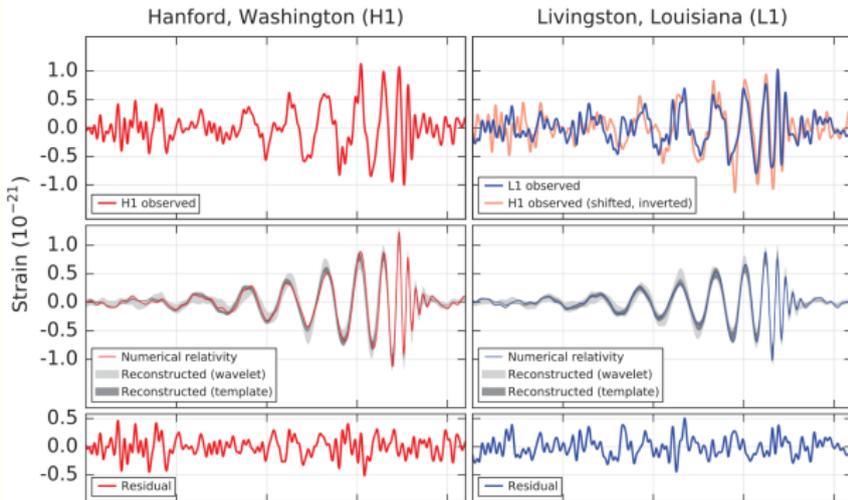BBH orbiting SMBH
[Chen+2018]

- interaction of GWs source with third body induces motion
- more relevant for BBHs, but up to highly relativistic velocities [Chen+2018, ArcaSedda2020, Tagawa+2019]

Templates & motion

GWs templates

First GW detection [LIGO2016]

- templates are essential for the detection and interpretation of GWs sources

Formalisms & motion

Forma.	NR	Post-Newt.	Self-Force	EOB	Phenom
CoM motion	yes, but restricted	usually not	usually not	restricted by NR, PN & SF	restricted by NR, PN & SF

▸ no formalism describes general motion of CoM
   [SXS2019, Blanchet2006, Barack+2019, Buonanno+1999, Santamaria+2010]

Mass-redshift degeneracy
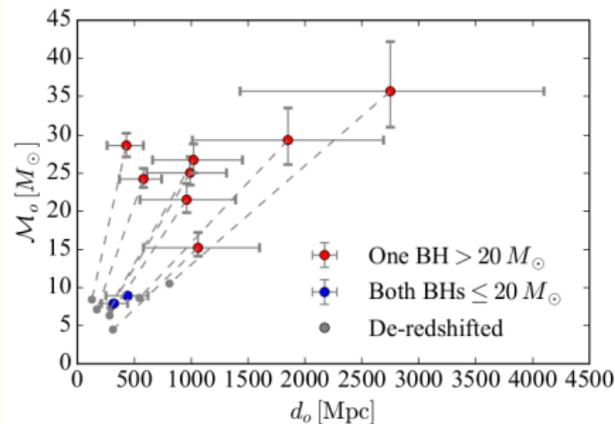
Mass & distance of LIGO detections
(GWTC-1) [Chen+2019]

- **mass-redshift degeneracy** of GWs [Chen+2019]:
$$\mathcal{M}_o = (1 + v)\mathcal{M}$$
$$d_o = (1 + v)d$$

- detections could be distorted by motion... but we do not know

Motion & GW detections

- motion can distort results from GW detection
- detecting motion allows extraction of more information about the source and its environment
- Can we break the mass-redshift degeneracy and detect the motion of GW sources?

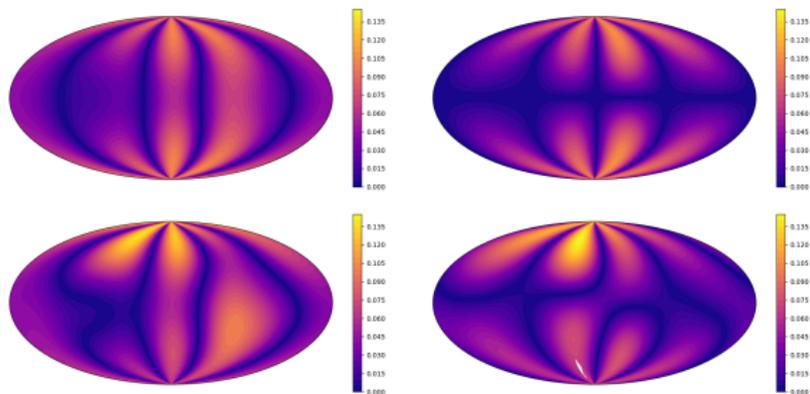# The effect of motion on gravitational radiation

Source shape vs. wave modes
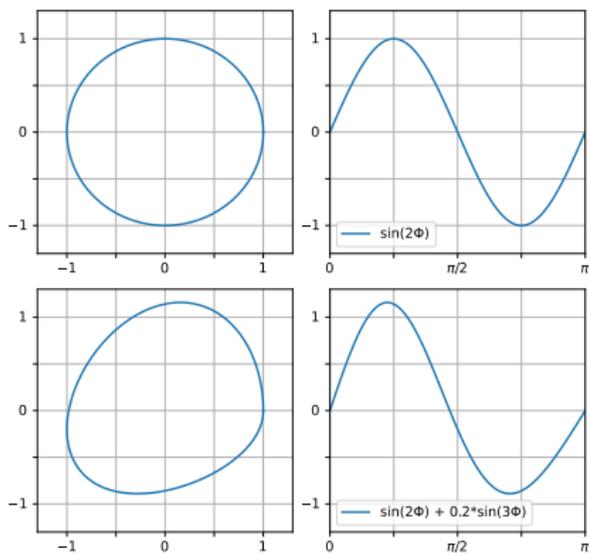
Sketches of a regular and a deformed orbit and their associated waveforms

- shape of the source affects form of the wave
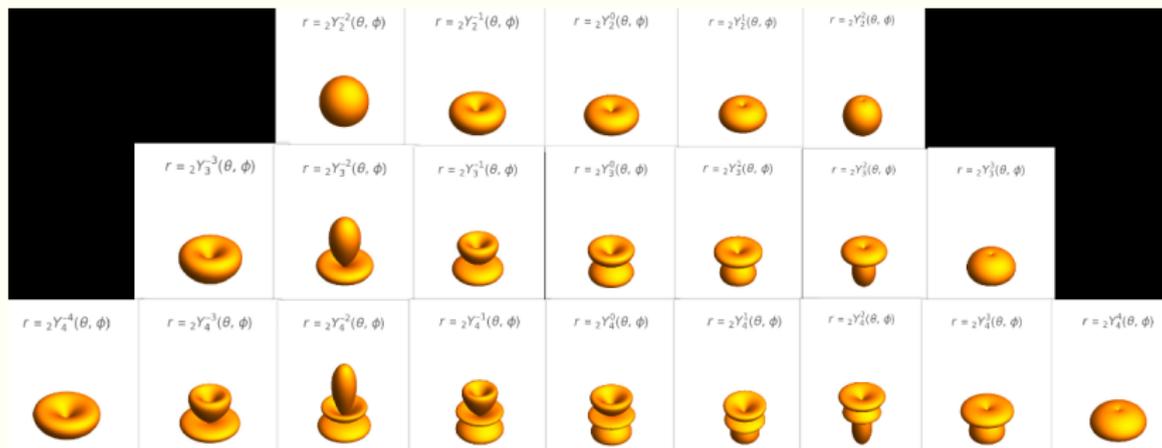- change in wave expresses as change in modes

Deformed radiation patterns

Radiation patterns for $+$- & $\times$-polarization of a source at rest and a moving one [Torre-Orjuela+2020]

- CoM motion → aberration of rays, rotation of polarization & Doppler shift of frequency [Torres-Orjuela+2019]
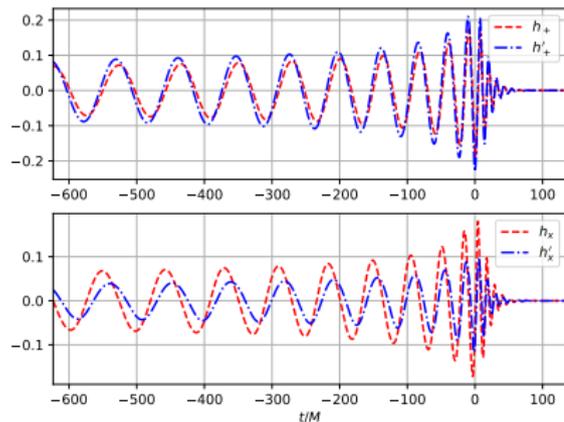
Spin-2 spherical harmonics

Spin-2 spherical harmonics (S2SH) [Wolfram Demonstration]

- decompose GWs in modes using S2SH:

$$H^{\ell,m} := \int [h_+(\theta,\phi) - i h_\times(\theta,\phi)]_{-2}\bar{Y}^{\ell,m}(\theta,\phi)\mathrm{d}\Omega$$

Excitation of modes

Waveforms for $+$- & $\times$-polarization of a source at rest and a moving one
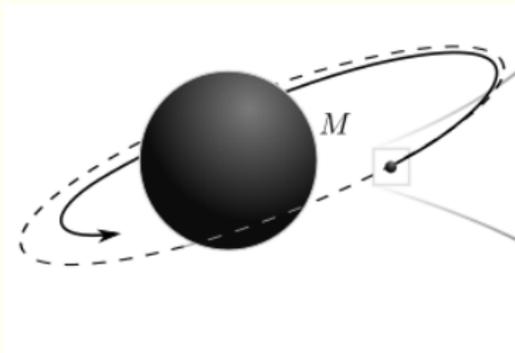[Torre-Orjuela+2020]

- motion 'deforms' radiation pattern $\rightarrow$ modes are excited:
  $$H'^{\ell,m} = H^{\ell,m} + v \sum C^{\ell',m'} H^{\ell',m'}$$

- amplitude and phase change in time dependent manner!

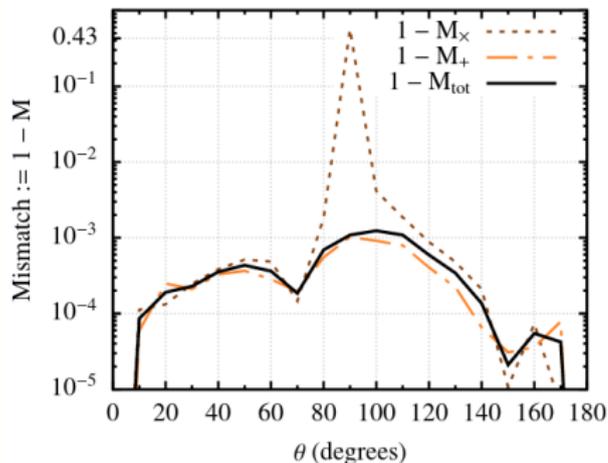# Detecting the motion of EMRIs

What we consider

Extreme mass ratio inspiral (EMRI) [Barack+2019]

- stellar BH (10 $M_\odot$) on non-eccentric orbit around SMBH (10^6 $M_\odot$)
- observation time of 5 yr
- compare moving EMRI (1000 km/s) to one at rest

Mismatch between the waveforms

Mismatch between waveforms from a moving EMRI and one at rest
[Amaro-Seoane+2020]

- mismatch quantifies difference between waveforms
- for EMRIs mismatch $\gtrsim 10^{-4}$ can be resolved
- peculiar velocity of galaxies is detectable

To cut a long story short

Summary

- peculiar velocity of host galaxy $\rightarrow$ GWs sources move with velocity $\approx 1400\,\text{km/s}$ (+ e.g. orbital motion)

- CoM motion excites GWs modes $\rightarrow$ mass-redshift degeneracy is broken

- velocity of GWs sources and their hosts(!) detectable up to high redshifts

Many thanks for your attention!

References

- Scrimgeour+2016: M. I. Scrimgeour et al., MNRAS 455 (2016)
- Chen+2018: X. Chen & W.-B. Han, Communications Physics 1 (2018)
- Arca-Sedda2020: M. Arca Sedda, ApJ 891 (2020)
- Tagawa+2019: H. Tagawa et al., ApJ 898 (2020)
- LIGO2016: B. P. Abbott et al., Phys. Rev. L 116 (2016)
- SXS2019: M. Boyle et al., Class. Quant. Grav. 36 (2019)
- Blanchet2006: L. Blanchet, Living Rev. Relativ. 9 (2006)
- Barack+2019: L. Barack & A. Pound, Rep. Prog. Phys. 82 (2019)

References

- Buonanno+1999: A. Buonanno and T. Damour, Phys. Rev. D 59 (1999)
- Santamaria+2010: L. Santamaria et al., Phys. Rev. D 82 (2010)
- Chen+2019: X. Chen et al., MNRAS Letters 1 (2019)
- Torres-Orjuela+2019: A. Torres-Orjuela et al., Phy. Rev. D 100 (2019)
- Amaro-Seoane+2020: P. Amaro-Seoane et al., arXiv:2010.15842
- Torres-Orjuela+2020: A. Torres-Orjuela et al., arXiv:2010.15856 (2020)