Gravitational Waves

Sources near and far

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LIGO++!

- Unexpected population of merging 30 $M_\odot$ BHs.
- Nobel prize 2017 to Weiss, Barish, Thorne
- Exciting possibility: Primordial BH=DM
- Many discrepant papers on (non-) constraints

PBH

- Observational evidence for dark matter for over 80 years (Zwicky)
- no confirmed candidate
- Primordial black holes allowed in sparse windows, including 30 $M_\odot$ (Bird et al 2016).
- Cosmic scaling: formation when cosmic horizon=r_G, $t = 10^{-4}$s
- $1/\epsilon = 10\sigma$ rare (well separated) peaks collapse into PBH
- gravitational wave background from formation is redshifted to $f = (1+z)c/r_s \sim 30$nHz.
- amplitude $\epsilon^4(1+z)$, $h \sim 10^{-15}$ (Turok & Pen 2016, PRL, 117, 1301)

Movie

nanoHz window

- supermassive BH binaries in galaxy centres
- binary versions of EHT picture

Pulsar Timing Arrays

- GWs change the ToA of pulsars
- Three analysis scenarios: 1-D vs 2-D vs 3-D array (Boyle+UP 2012)
- To-date, most analyses are 1-D (Helling-Downs 1983)
- 2-D is sensitive to source position, polarization
- 3-D analysis requires (precise) pulsar distances

3-D

- if distances to pulsars are known to better than a few wavelengths (∼pc), source positions are known to $\delta\theta \sim \frac{\lambda}{D}$.
- arc minute localization: much more precise than LIGO++
- small added complexity if chirp changes over the 3-D extent of PTA (kpc)

Distance measurement

- VLBI Scintillometry: demonstrated 50 pico arcsecond astrometry (Pen++2014)
- ongoing test in known systems
- promising for binary systems
- low frequency VLBI monitoring: LWA, LOFAR, GMRT, MWA, etc
- promising initial results (Reardon+ 2019)
- interstellar holography

Redshift maps

- overcoming 'confusion limit'
- redshift maps: Roebber+Holder 2017
- Densely sampled limit
- ToA map: angle+time data cube
- FFT into complex 2-D map at each frequency

Redshift Image

- $\delta t = \sin(2\phi)[1 + \cos(\theta)]$

Play/Pause Face-on

singular spatial structure near GW source, no residual in anti-direction (TT).

Two sources

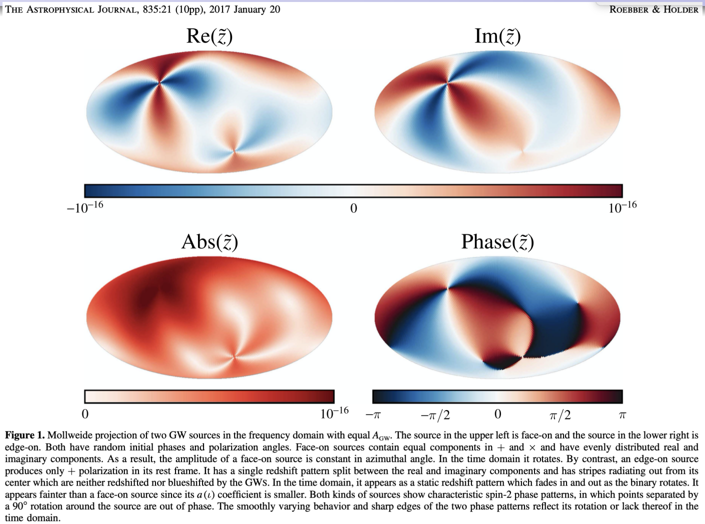

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Figure 1. Mollweide projection of two GW sources in the frequency domain with equal A_{GW}. The source in the upper left is face-on and the source in the lower right is edge-on. Both have random initial phases and polarization angles. Face-on sources contain equal components in $+$ and $\times$ and have evenly distributed real and imaginary components. As a result, the amplitude of a face-on source is constant in azimuthal angle. In the time domain it rotates. By contrast, an edge-on source produces only $+$ polarization in its rest frame. It has a single redshift pattern split between the real and imaginary components and has stripes radiating out from its center which are neither redshifted nor blueshifted by the GWs. In the time domain, it appears as a static redshift pattern which fades in and out as the binary rotates. It appears fainter than a face-on source since its $a(\iota)$ coefficient is smaller. Both kinds of sources show characteristic spin-2 phase patterns, in which points separated by a 90° rotation around the source are out of phase. The smoothly varying behavior and sharp edges of the two phase patterns reflect its rotation or lack thereof in the time domain.

- Well resolved by dense PTA

Background

- traditional technique: measure 2 point correlation function of residuals (Hellings-Downs, Jenet, etc).
- equivalent to power spectrum
- results in unintended source confusion, 'stochastic background'
- sell as 'pulsar GW imaging array'

Formulation

TT gauge line element:

$$ds^2 = -dt^2 + [\delta_{ij} + 2h_{ij}]dx^i dx^j. \tag{1}$$

In this gauge, the $\vec{x} = \mathrm{constant}$ worldlines are timelike geodesics; along such a worldline, the proper time τ is just the coordinate time t. Single gravitational plane wave travelling in the $\hat{n}$ direction

$$\delta\tilde{t}_\alpha(\omega) = \frac{i}{\omega}\frac{\tilde{h}_{ij}(\omega)\hat{r}^i_\alpha\hat{r}^j_\alpha[1-\mathcal{P}_\alpha(\omega)]}{(1+\hat{n}\cdot\hat{r}_\alpha)} \tag{2}$$

with phase

$$\mathcal{P}_\alpha(\omega) \equiv \mathrm{e}^{i\omega r_\alpha(1+\hat{n}\cdot\hat{r}_\alpha)}. \tag{3}$$

reduces to $\delta t = \sin(2\phi)[1+\cos(\theta)]$ when averaging over all pulsar distances. Well known result.

Distance

- At angles $\theta < \sqrt{\frac{\lambda_{\rm GW}}{r}}$ the intrinsic pulsar delay cancels the earth delay
- Typical distances $r \sim$ kpc, $\lambda_{\rm GW} \sim 3$ pc, $\theta \sim 5^o$
- Confused if more than 100's of sources, or more sources than pulsars.

Conclusions

- Gravitional wave era has just begun
- new probes into BH, dark matter
- PTA has potential to be high resolution GW telescope
- 3-D: $\sim \frac{10'}{\mathrm{SNR}}$. Potential for optical redshifts of BBH.
- Changes physical interpretation of PTA GW signals: unlikely to be in stochastic regime.
- motivation for precision pulsar VLBI scintillometry distances
- potential use of FRB scintillometry for GW detection