Abbott et al. (2016)
There are ten thousand other tiny things, and I really mean ten thousand. And every single one needs to be working correctly so that nothing interferes with the signal.” - Rainer Weiss

- minuscule seismic tremors
- the wind in Hanford
- the water near Livingston
- fluctuations in the power grid
- distant lightning storms
- passing cars
- airplanes
- wolves
...
Distortions in spacetime alter pulsar phase
Gravitational Wave Detection

• Sazhin (1978) and Detweiler (1979)
  – single pulsar-Earth baseline
  – single SMBH binary system

• Hellings & Downs (1983)
  – quadrupolar correlations between pulsars
  – stochastic background of gravitational waves
Pulsar Timing Array

Hellings & Downs (1983)
Gravitational Wave Background

• Cosmological
  – energetic processes in early Universe
    (e.g. inflation)

• Astrophysical
  – population of SMBH binaries
  – Sesana, Vecchio & Colacino (2008)
Pulsar Timing Arrays

- **PPTA**: Parkes Pulsar Timing Array
- **NANOGrav**: North American Nanohertz Observatory
- **EPTA**: European Pulsar Timing Array
- **IPTA**: International Pulsar Timing Array
  - consortium of consortia (2008)
Gravitational Wave Detection is Challenging

- **Pulsar intrinsic**
  - Stochastic impulsive emission (white noise)
  - Spin irregularity (red noise)

- **Interstellar medium**
  - Variations in electron density along line of sight (red)
  - Multipath propagation (scattering)

- **Within solar system**
  - Errors in the solar system ephemeris (dipolar)
  - Errors in the definition of time on Earth (monopolar)
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Habibi et al. (2011)
Macquart et al. (2013)
Lazio et al. (2004)
Lorimer & Kramer (2004)
Hemberger & Stinebring (2008)
Stinebring et al. (2001)
Delay - Doppler

\[ F_v = \frac{D_s \theta^2}{2c \beta} \]

\[ F_t = \frac{1}{\lambda \beta} \theta \cdot u_\perp \]

Walker et al. (2004)
Conventional (Pulsar) Spectroscopy

- Dynamic spectrum on-pulse less off-pulse
- Time span = $P/2$
- $\Delta v_{\text{min}} = 2/P$
Cyclic Spectroscopy

\[ S_x(\nu; \alpha) = E \{ X(\nu + \alpha/2)X^*(\nu - \alpha/2) \} \]

- \( \alpha = k/P \) = harmonics of spin frequency
- \( \nu = \) radio frequency
- \( X(\nu+\alpha/2) = \) RF spectrum “mixed” with harmonic of spin frequency
- upper and lower “sidebands” cross-multiplied
Demorest (2011)
Transfer

\[ y(t) = h(t) \ast x(t) \]

\[ Y(\nu) = H(\nu)X(\nu) \]

\[ S_y(\nu; \alpha) = H(\nu + \alpha/2)H^*(\nu - \alpha/2)S_x(\nu; \alpha) \]
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Hemberger & Stinebring (2008)
Degeneracy

\[ Q(\nu) = \exp[i(\tau \nu + \phi) + \rho] \]

\[ S_x(\alpha) \rightarrow S_x(\alpha) \exp[-i\tau \alpha - 2\rho] \]

- \( \exp(\rho) = \) overall scale
- \( \phi = \) absolute phase
- \( \tau = \) delay (phase gradient in Fourier domain)
Brisken et al. (2010)
Delay - Doppler

\[ F_v = \frac{D_s \theta^2}{2c \beta} \]

\[ F_t = \frac{1}{\lambda \beta} \theta \cdot v_\perp \]

Walker et al. (2004)
The scintillation velocity was determined using the following equation:

\[ V = \frac{f}{f_{\text{ISS}}} \cos i \]

where \( f \) is the scintillation bandwidth in megahertz, \( f_{\text{ISS}} \) is the scintillation timescale in seconds, and \( i \) is the inclination angle of the system. Therefore, we require estimates of the pulsar's velocity as a function of five free parameters: orbit, pulsar, and neutron star. We require estimates of the pulsar's velocity as a function of five free parameters: orbit, pulsar, and neutron star. The structure of the binary indicates an unreasonably low neutron star mass. The latter is accurately determined by pulse timing and allows us to construct a model that describes the observed scintillation velocity into a scaling parameter within the model.
Future Work

• Break geometric degeneracies
  – pulsar orbital phase
  – Earth’s orbital phase (day of year)

• Holographic image of scattering screen
  – test / modify theories of physical origin

• Predict absolute propagation delays
  – increase PTA sensitivity to GWB!