Stochastic Gravitational Wave Detection: a year after

Pierre Auclair

Be.HEP meeting 2024

Cosmology, Universe and Relativity at Louvain (CURL)
Institute of Mathematics and Physics
Louvain University, Louvain-la-Neuve, Belgium

Outline

Introduction to GW astronomy

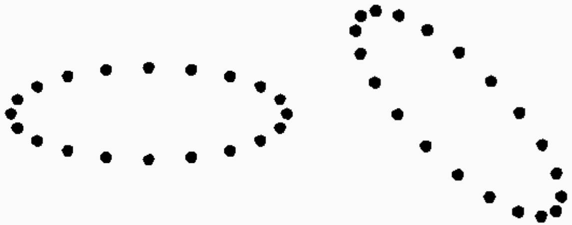
What are gravitational waves?

Gravitational waves are tensorial perturbations of the metric

$$\mathrm{d}s^2 = -\,\mathrm{d}t^2 + a^2(t)\left[(\delta_{ij} + 2h_{ij})\,\mathrm{d}x^i\,\mathrm{d}x^j\right].$$

At linear order in vacuum, they satisfy a wave equation, i.e. they are ripples of space-time curvature propagating unimpeded at the speed of light.

Two polarizations h_+ and $h_\times$

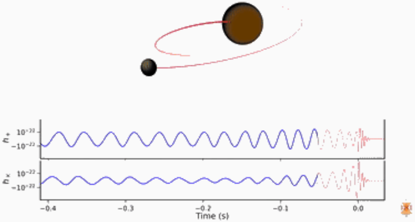


- Network of ground based detectors LIGO Hanford, LIGO Livingston and Virgo

The LIGO/Virgo interferometers. Credits: LIGO/Virgo

First direct detections of Gravitational Waves (GWs)

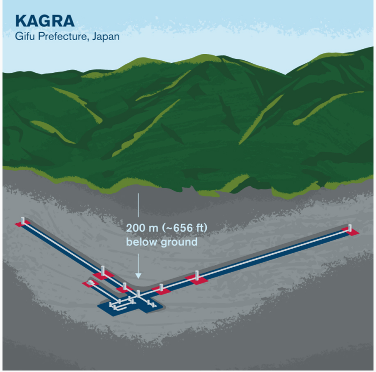
- Network of ground based detectors LIGO Hanford, LIGO Livingston and Virgo
- 2016: LIGO/Virgo collaboration announced the first direct detection of gravitational waves



Credits: SXS Collaboration

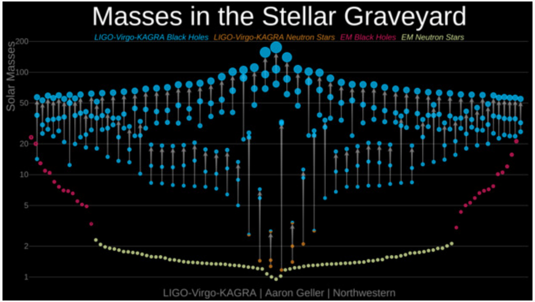
First direct detections of Gravitational Waves (GWs)

- Network of ground based detectors LIGO Hanford, LIGO Livingston and Virgo
- 2016: LIGO/Virgo collaboration announced the first direct detection of gravitational waves
- 2019: KAGRA joins the LVK collaboration



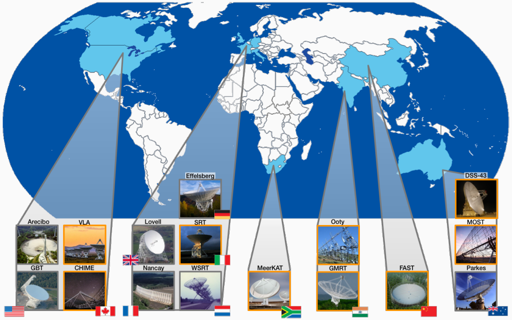
First direct detections of Gravitational Waves (GWs)

- Network of ground based detectors LIGO Hanford, LIGO Livingston and Virgo
- 2016: LIGO/Virgo collaboration announced the first direct detection of gravitational waves
- 2019: KAGRA joins the LVK collaboration
- 2021: Latest catalogue of gravitational-wave detections listed 90 events



First direct detections of Gravitational Waves (GWs)

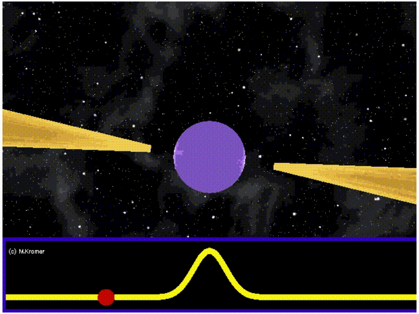
- Network of ground based detectors LIGO Hanford, LIGO Livingston and Virgo
- 2016: LIGO/Virgo collaboration announced the first direct detection of gravitational waves
- 2019: KAGRA joins the LVK collaboration
- 2021: Latest catalogue of gravitational-wave detections listed 90 events
- 2023: Evidence for a Stochastic Background of GWs by Pulsar Timing Arrays



Pulsar Timing Arrays and GWs

Introduction to pulsars

- Neutron stars are **compact stars** with very **short rotational period** and extreme **magnetic fields**
- Magnetic axis not aligned with spin axis
  $\Longrightarrow$ radiation is swept through space (lighthouse)
- They appear to the observer as pulses, separated by a fixed period (spin)

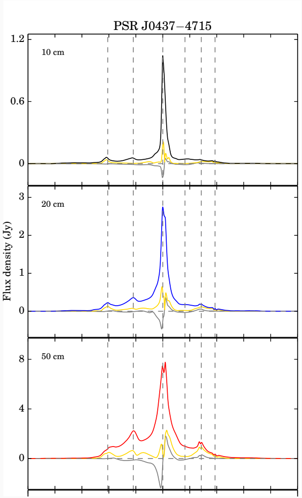


Pulse profiles

Pulse profiles vary across observing frequencies

- Pulse profiles tend to get sharper at higher frequencies...
- but the noise level increases due to the pulsar's steep spectrum

Most pulsar timing are carried around 1.4 GHz



Pulsars studied in Parkes Pulsar Timing Array Dai et al. 2015

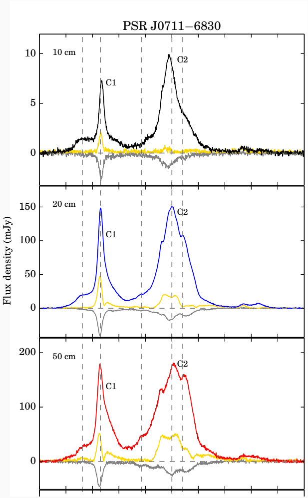
Pulse profiles

Pulse profiles vary across observing frequencies

- Pulse profiles tend to get sharper at higher frequencies...
- but the noise level increases due to the pulsar's steep spectrum

Most pulsar timing are carried around 1.4 GHz

Pulse profiles also vary across pulsars!



Pulsars studied in Parkes Pulsar Timing Array Dai et al. 2015

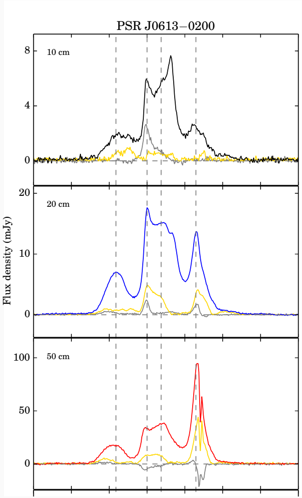
Pulse profiles

Pulse profiles vary across observing frequencies

- Pulse profiles tend to get sharper at higher frequencies...
- but the noise level increases due to the pulsar's steep spectrum

Most pulsar timing are carried around 1.4 GHz

Pulse profiles also vary across pulsars!



Pulsars studied in Parkes Pulsar Timing Array Dai et al. 2015

Template profile

How do we time a pulse?

- Time the peaks?
- Intensity-average arrival time of the pulse?

Template profile

How do we time a pulse?

- Time the peaks?
- Intensity-average arrival time of the pulse?

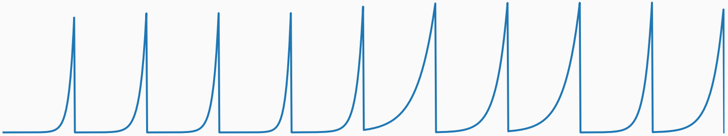
To achieve the precision needed in PTA, the pulsar-arrival times are determined using template profiles

- standardized pulse shape, obtained after averaging over many rotations (noise-free pulse profile)
- Needs a good knowledge of the pulsar's period
- Take advantage of the frequency dependent shapes of the pulse profiles

Time of Arrivals (ToAs)

One ToA is obtained for each observation period:

- One arbitrary pulse is selected in the observation



Time of Arrivals (ToAs)

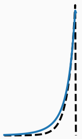
One ToA is obtained for each observation period:

- One arbitrary pulse is selected in the observation
- Folding: average pulses modulo the pulse period to obtain an average pulse

Time of Arrivals (ToAs)

One ToA is obtained for each observation period:

- One arbitrary pulse is selected in the observation
- Folding: average pulses modulo the pulse period to obtain an average pulse
- Template matching: the pulse profile is cross-correlated with the template profile to obtain the phase of the observation

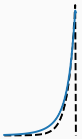


Time of Arrivals (ToAs)

One ToA is obtained for each observation period:

- One arbitrary pulse is selected in the observation
- Folding: average pulses modulo the pulse period to obtain an average pulse
- Template matching: the pulse profile is cross-correlated with the template profile to obtain the phase of the observation

The ToA combines the observation time stamp with the phase measurement



Transferring the observed times to the Pulsar

Accounting for all known propagation and geometric delays

$$t_{\rm PSR} = t_{\rm obs} - \Delta_{\odot} - \Delta_{ISM} - \Delta_{\rm Bin}$$

Transferring the observed times to the Pulsar

Accounting for all known propagation and geometric delays

$$t_{\mathrm{PSR}} = t_{\mathrm{obs}} - \Delta_{\odot} - \Delta_{ISM} - \Delta_{\mathrm{Bin}}$$

- $\Delta_{\odot}$ transferring to the Solar System barycenter:
  Earth's orbital and rotational velocity, mass distribution in the Solar System, Solar winds, parallax... **Needs very precise ephemerides!**

Transferring the observed times to the Pulsar

Accounting for all known propagation and geometric delays

$$t_{\rm PSR} = t_{\rm obs} - \Delta_{\odot} - \Delta_{ISM} - \Delta_{\rm Bin}$$

- $\Delta_{\odot}$ transferring to the Solar System barycenter:
  Earth's orbital and rotational velocity, mass distribution in the Solar System, Solar winds, parallax... **Needs very precise ephemerides!**
- Δ_{ISM} accounts for Interstellar propagation delays. Linked to the Dispersion Measure (DM), or the integrated electron content along the line-of-sight

$$\mathrm{DM} = \int_0^D n_e \, \mathrm{d}\ell$$

Transferring the observed times to the Pulsar

Accounting for all known propagation and geometric delays

$$t_{\rm PSR} = t_{\rm obs} - \Delta_{\odot} - \Delta_{ISM} - \Delta_{\rm Bin}$$

- $\Delta_{\odot}$ transferring to the Solar System barycenter:
  Earth's orbital and rotational velocity, mass distribution in the Solar System, Solar winds, parallax... **Needs very precise ephemerides!**
- Δ_{ISM} accounts for Interstellar propagation delays. Linked to the Dispersion Measure (DM), or the integrated electron content along the line-of-sight

$$\mathrm{DM} = \int_0^D n_e \, \mathrm{d}\ell$$

- $\Delta_{\rm Bin}$, for pulsars that are in binary systems

Building the timing model

Once the time of emission is determined, it can be converted to a rotational phase

$$\phi(t_{\mathrm{PSR}}) = \nu(t_{\mathrm{PSR}} - t_0) + \frac{1}{2}\dot{\nu}(t_{\mathrm{PSR}} - t_0)^2 + ...$$

- ν is the pulsar's frequency
- $\dot{\nu}$ is the derivative of the pulsar frequency
- $\ddot{\nu}$ is usually too small in the case of MSPs

Building the timing model

Once the time of emission is determined, it can be converted to a rotational phase

$$\phi(t_{\mathrm{PSR}}) = \nu(t_{\mathrm{PSR}} - t_0) + \frac{1}{2}\dot{\nu}(t_{\mathrm{PSR}} - t_0)^2 + \dots$$

- ν is the pulsar's frequency
- $\dot{\nu}$ is the derivative of the pulsar frequency
- $\ddot{\nu}$ is usually too small in the case of MSPs

In practice, there is an interplay between the construction of the template profile, the timing model and the propagation/geometric delays.

Timing residuals

Difference between observed and predicted time of arrivals of the pulsars' radio pulses

$$\delta t_i = t_i^{\mathrm{obs}} - t_i^{\mathrm{TM}}$$

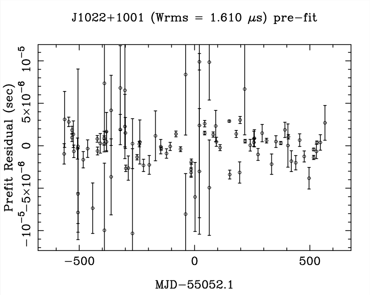
Timing residuals

Difference between observed and predicted time of arrivals of the pulsars' radio pulses

$$\delta t_i = t_i^{\mathrm{obs}} - t_i^{\mathrm{TM}}$$

Some errors may be found by visual inspection of timing residuals

From Verbiest, Oslowski, and Burke-Spolaor 2022



Typical PTA dataset

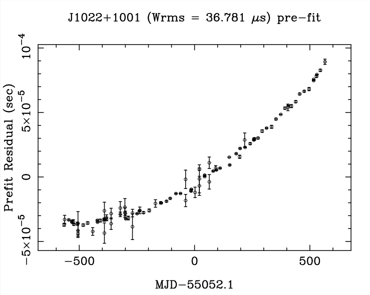
Timing residuals

From Verbiest, Oslowski, and Burke-Spolaor 2022

Difference between observed and predicted time of arrivals of the pulsars' radio pulses

$$\delta t_i = t_i^{\mathrm{obs}} - t_i^{\mathrm{TM}}$$

Some errors may be found by visual inspection of timing residuals



1% error on the spindown

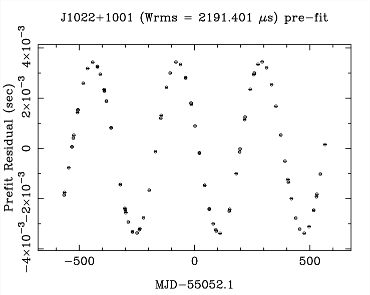
Timing residuals

Difference between observed and predicted time of arrivals of the pulsars' radio pulses

$$\delta t_i = t_i^{\mathrm{obs}} - t_i^{\mathrm{TM}}$$

Some errors may be found by visual inspection of timing residuals

From Verbiest, Oslowski, and Burke-Spolaor 2022



Positional offset of 0.1 arcsec in right ascension and declination

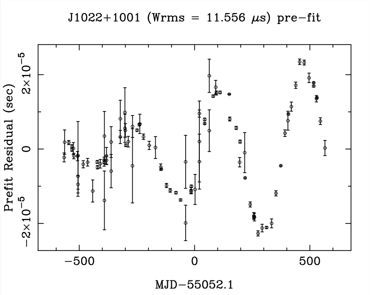
Timing residuals

Difference between observed and predicted time of arrivals of the pulsars' radio pulses

$$\delta t_i = t_i^{\mathrm{obs}} - t_i^{\mathrm{TM}}$$

Some errors may be found by visual inspection of timing residuals

From Verbiest, Oslowski, and Burke-Spolaor 2022



Proper motion is 10% incorrect

Hellings and Downs correlations

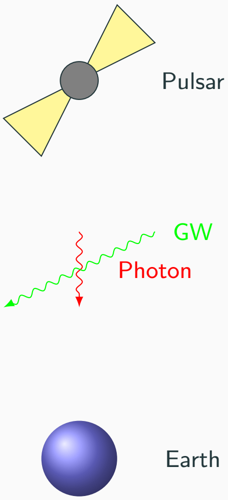
Good reviews:

Jenet and Romano 2015; Romano and Allen 2023

Time delay due to a GW (1/2)

- Time delay due to the passing of a GW

$$\Delta T(t) = \frac{1}{2c} u^i u^j \int_0^L \mathrm{d}s\, h_{ij}[\tau(s), \vec{\mathbf{x}}(s)]$$



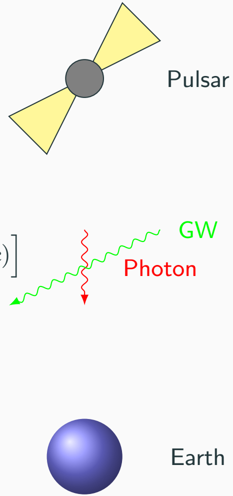
Time delay due to a GW (1/2)

- Time delay due to the passing of a GW

$$\Delta T(t) = \frac{1}{2c} u^i u^j \int_0^L \mathrm{d}s \, h_{ij}[\tau(s), \vec{\mathbf{x}}(s)]$$

- Plane-wave decomposition of the GW

$$h_{ij}(t, \vec{\mathbf{x}}) = \int_{-\infty}^{+\infty} \mathrm{d}f \int \mathrm{d}\hat{\mathbf{k}} \sum_{A=+,\times} h_A(f, \hat{\mathbf{k}}) e_{ij}^A(\hat{\mathbf{k}}) \exp\left[i2\pi f(t - \hat{\mathbf{k}} \cdot \vec{\mathbf{x}}/c)\right]$$



Time delay due to a GW (1/2)

- Time delay due to the passing of a GW

$$\Delta T(t) = \frac{1}{2c} u^i u^j \int_0^L \mathrm{d}s\, h_{ij}[\tau(s), \vec{\mathbf{x}}(s)]$$

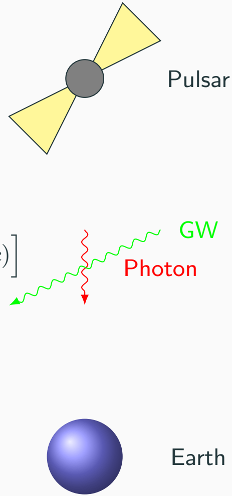
- Plane-wave decomposition of the GW

$$h_{ij}(t, \vec{\mathbf{x}}) = \int_{-\infty}^{+\infty} \mathrm{d}f \int \mathrm{d}\hat{\mathbf{k}} \sum_{A=+,\times} h_A(f, \hat{\mathbf{k}}) e_{ij}^A(\hat{\mathbf{k}}) \exp\left[i2\pi f(t - \hat{\mathbf{k}} \cdot \vec{\mathbf{x}}/c)\right]$$

- At zeroth order, the photon propagates on a straight line

$$\vec{\mathbf{x}}(s) = \vec{\mathbf{r}}_1 + s\hat{\mathbf{u}}, \quad \tau(s) = t + (s - L)/c \quad \vec{\mathbf{r}}_2 = \vec{\mathbf{r}}_1 + L\hat{\mathbf{u}},$$

pulsar at $\hat{\mathbf{p}} = -\hat{\mathbf{u}}$



Time delay due to a GW (2/2)

$$\Delta T(t) = \int_{-\infty}^{+\infty} \mathrm{d}f \int \mathrm{d}\hat{\mathbf{k}} \sum_{A=+,\times} h_A(f,\hat{\mathbf{k}}) R^A(f,\hat{\mathbf{k}}) \exp\left[i2\pi f(t - \hat{\mathbf{k}}\cdot\vec{\mathbf{r}}_2/c)\right]$$

Response function

$$R^A(f,\hat{\mathbf{k}}) \equiv \frac{1}{2} u^i u^j e^A_{ij}(\hat{\mathbf{k}}) \frac{1}{i2\pi f} \frac{1}{1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}}} \left[1 - \exp\left(-\frac{i2\pi f L}{c}(1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}}) \right) \right]$$

- Earth term

Time delay due to a GW (2/2)

$$\Delta T(t) = \int_{-\infty}^{+\infty} \mathrm{d}f \int \mathrm{d}\hat{\mathbf{k}} \sum_{A=+,\times} h_A(f,\hat{\mathbf{k}}) R^A(f,\hat{\mathbf{k}}) \exp\left[i2\pi f(t - \hat{\mathbf{k}}\cdot\vec{\mathbf{r}}_2/c)\right]$$

Response function

$$R^A(f,\hat{\mathbf{k}}) \equiv \frac{1}{2} u^i u^j e^A_{ij}(\hat{\mathbf{k}}) \frac{1}{i2\pi f} \frac{1}{1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}}} \left[1 - \exp\left(-\frac{i2\pi f L}{c}(1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}})\right)\right]$$

- Earth term
- Pulsar term

Time delay due to a GW (2/2)

$$\Delta T(t) = \int_{-\infty}^{+\infty} \mathrm{d}f \int \mathrm{d}\hat{\mathbf{k}} \sum_{A=+,\times} h_A(f,\hat{\mathbf{k}}) R^A(f,\hat{\mathbf{k}}) \exp\left[i2\pi f(t - \hat{\mathbf{k}}\cdot\vec{\mathbf{r}}_2/c)\right]$$

Response function

$$R^A(f,\hat{\mathbf{k}}) \equiv \frac{1}{2} u^i u^j e^A_{ij}(\hat{\mathbf{k}}) \frac{1}{i2\pi f} \boxed{\frac{1}{1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}}}} \left[1 \; - \; \exp\left(-\frac{i2\pi f L}{c}(1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}})\right) \right]$$

- Earth term
- Pulsar term
- Breaks the $\hat{\mathbf{u}} \to -\hat{\mathbf{u}}$ symmetry, there is a difference if the photon is *surfing* the GW or *fight upstream*

Time delay due to a GW (2/2)

$$\Delta T(t) = \int_{-\infty}^{+\infty} \mathrm{d}f \int \mathrm{d}\hat{\mathbf{k}} \sum_{A=+,\times} h_A(f,\hat{\mathbf{k}}) R^A(f,\hat{\mathbf{k}}) \exp\left[i2\pi f(t - \hat{\mathbf{k}}\cdot\vec{\mathbf{r}}_2/c)\right]$$

Response function

$$R^A(f,\hat{\mathbf{k}}) \equiv \boxed{\frac{1}{2}u^i u^j e_{ij}^A(\hat{\mathbf{k}})} \frac{1}{i2\pi f} \frac{1}{1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}}} \left[1 - \exp\left(-\frac{i2\pi f L}{c}(1-\hat{\mathbf{k}}\cdot\hat{\mathbf{u}})\right)\right]$$

- Earth term
- Pulsar term
- Breaks the $\hat{\mathbf{u}} \to -\hat{\mathbf{u}}$ symmetry, there is a difference if the photon is *surfing* the GW or *fight upstream*
- Interaction between the photon and the GW polarizations

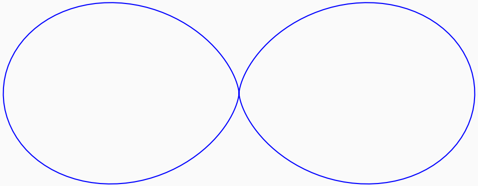
Short-arm limit $fL/c \ll 1$ (LVK)

- The response function reduces to

$$R^A(f, \hat{\mathbf{k}}) = u^i u^j e^A_{ij}(\hat{\mathbf{k}}) \frac{L}{2c}$$

- Take a pulsar in the $\hat{\mathbf{z}}$ direction and $\cos(\theta) = \hat{\mathbf{k}} \cdot \hat{\mathbf{u}}$, then

$$\left|R^+(f, \hat{\mathbf{k}})\right| = \frac{L}{2c} \sin^2(\theta), \quad \left|R^\times(f, \hat{\mathbf{k}})\right| = 0$$



Reponse function $\left|R^+\right|$ for a pulsar located in the $+\hat{\mathbf{z}}$ direction.

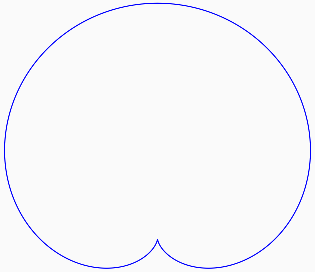
Long-arm limit $fL/c \gg 1$ (PTA)

- We neglect the oscillatory pulsar term, provided $\hat{\mathbf{k}} \cdot \hat{\mathbf{u}} \neq 1$

$$R^A(f, \hat{\mathbf{k}}) = \frac{1}{2} u^i u^j e^A_{ij}(\hat{\mathbf{k}}) \frac{1}{i2\pi f} \frac{1}{1 - \hat{\mathbf{k}} \cdot \hat{\mathbf{u}}}$$

- Take a pulsar in the $\hat{\mathbf{z}}$ direction and $\cos(\theta) = \hat{\mathbf{k}} \cdot \hat{\mathbf{u}}$, then

$$\left|R^+(f, \hat{\mathbf{k}})\right| = \frac{1}{4\pi f}(1+\cos\theta), \quad \left|R^\times(f, \hat{\mathbf{k}})\right| = 0$$



Reponse function $\left|R^+\right|$ for a pulsar located in the $+\hat{\mathbf{z}}$ direction.

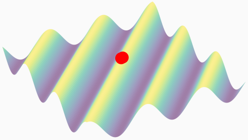
Long-arm limit $fL/c \gg 1$ (PTA)

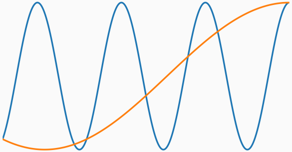
- We neglect the oscillatory pulsar term, provided $\hat{\mathbf{k}} \cdot \hat{\mathbf{u}} \neq 1$

$$R^A(f, \hat{\mathbf{k}}) = \frac{1}{2} u^i u^j e^A_{ij}(\hat{\mathbf{k}}) \frac{1}{i2\pi f} \frac{1}{1 - \hat{\mathbf{k}} \cdot \hat{\mathbf{u}}}$$

- Take a pulsar in the $\hat{\mathbf{z}}$ direction and $\cos(\theta) = \hat{\mathbf{k}} \cdot \hat{\mathbf{u}}$, then

$$\left|R^+(f, \hat{\mathbf{k}})\right| = \frac{1}{4\pi f}(1+\cos\theta), \quad \left|R^\times(f, \hat{\mathbf{k}})\right| = 0$$





Hellings and Downs correlation (1/2)

Stochastic background of GW

$$\left\langle h_A(f,\hat{\mathbf{k}})\right\rangle = 0, \quad \left\langle h_A(f,\hat{\mathbf{k}}) h_{A'}(f',\hat{\mathbf{k}}')\right\rangle = \frac{1}{8\pi} H(f)\,\delta(f'-f)\;\delta_{AA'}\,\boxed{\delta^2(\hat{\mathbf{k}},\hat{\mathbf{k}}')}$$

- Statistically isotropic and homogeneous
- Stationary
- Unpolarized

Hellings and Downs correlation (1/2)

Stochastic background of GW

$$\left\langle h_A(f,\hat{\mathbf{k}})\right\rangle = 0, \quad \left\langle h_A(f,\hat{\mathbf{k}})h_{A'}(f',\hat{\mathbf{k}}')\right\rangle = \frac{1}{8\pi}H(f)\,\delta(f'-f)\;\delta_{AA'}\;\;\delta^2(\hat{\mathbf{k}},\hat{\mathbf{k}}')$$

- Statistically isotropic and homogeneous
- Stationary
- Unpolarized

Hellings and Downs correlation (1/2)

Stochastic background of GW

$$\left\langle h_A(f,\hat{\mathbf{k}})\right\rangle = 0, \quad \left\langle h_A(f,\hat{\mathbf{k}}) h_{A'}(f',\hat{\mathbf{k}}')\right\rangle = \frac{1}{8\pi} H(f)\, \delta(f'-f)\, \boxed{\delta_{AA'}}\, \delta^2(\hat{\mathbf{k}},\hat{\mathbf{k}}')$$

- Statistically isotropic and homogeneous
- Stationary
- Unpolarized

Hellings and Downs correlation (1/2)

Stochastic background of GW

$$\left\langle h_A(f,\hat{\mathbf{k}})\right\rangle = 0, \quad \left\langle h_A(f,\hat{\mathbf{k}}) h_{A'}(f',\hat{\mathbf{k}}')\right\rangle = \frac{1}{8\pi} H(f)\,\delta(f'-f)\ \ \delta_{AA'}\ \ \delta^2(\hat{\mathbf{k}},\hat{\mathbf{k}}')$$

- Statistically isotropic and homogeneous
- Stationary
- Unpolarized

- Photons coming from pulsars a and b have correlated time-delays

$$\langle \Delta T_a(t) \Delta T_b(t')\rangle = \int_{-\infty}^{\infty} \mathrm{d}f\, \mathrm{e}^{i2\pi f(t-t')}\,\Gamma_{ab}(f) H(f)$$

Hellings and Downs correlation (1/2)

Stochastic background of GW

$$\left\langle h_A(f,\hat{\mathbf{k}})\right\rangle = 0, \quad \left\langle h_A(f,\hat{\mathbf{k}}) h_{A'}(f',\hat{\mathbf{k}}')\right\rangle = \frac{1}{8\pi} H(f)\ \delta(f'-f)\ \ \delta_{AA'}\ \ \delta^2(\hat{\mathbf{k}},\hat{\mathbf{k}}')$$

- Statistically isotropic and homogeneous
- Stationary
- Unpolarized

- Photons coming from pulsars a and b have correlated time-delays

$$\left\langle \Delta T_a(t) \Delta T_b(t')\right\rangle = \int_{-\infty}^{\infty} \mathrm{d}f\, \mathrm{e}^{i2\pi f(t-t')}\, \Gamma_{ab}(f) H(f)$$

- The correlation between two pulsars in encoded in

$$\Gamma_{ab}(f) \equiv \frac{1}{8\pi} \int \mathrm{d}\hat{\mathbf{k}} \sum_A R_a^A(f,\hat{\mathbf{k}}) R_b^A(f,\hat{\mathbf{k}}) \exp\left[-i2\pi f\, \hat{\mathbf{k}} \cdot (\vec{\mathbf{r}}_a - \vec{\mathbf{r}}_b)/c\right]$$

Hellings and Downs correlation (1/2)

Stochastic background of GW

$$\left\langle h_A(f,\hat{\mathbf{k}})\right\rangle = 0, \quad \left\langle h_A(f,\hat{\mathbf{k}})h_{A'}(f',\hat{\mathbf{k}}')\right\rangle = \frac{1}{8\pi}H(f)\ \delta(f'-f)\ \ \delta_{AA'}\ \ \delta^2(\hat{\mathbf{k}},\hat{\mathbf{k}}')$$

- Statistically isotropic and homogeneous
- Stationary
- Unpolarized

- Photons coming from pulsars a and b have correlated time-delays

$$\left\langle \Delta T_a(t)\Delta T_b(t')\right\rangle = \int_{-\infty}^{\infty} \mathrm{d}f\ \mathrm{e}^{i2\pi f(t-t')}\ \Gamma_{ab}(f)H(f)$$

- The correlation between two pulsars in encoded in

$$\Gamma_{ab}(f) \equiv \frac{1}{8\pi}\int \mathrm{d}\hat{\mathbf{k}}\sum_A R_a^A(f,\hat{\mathbf{k}})R_b^A(f,\hat{\mathbf{k}})\exp\left[-i2\pi f\,\hat{\mathbf{k}}\cdot(\vec{\mathbf{r}}_a-\vec{\mathbf{r}}_b)/c\right]$$

Hellings and Downs correlation (2/2)

- Isolate the frequency-dependence

$$\Gamma_{ab}(f) = \frac{1}{12\pi^2 f^2}\Gamma_{ab}$$

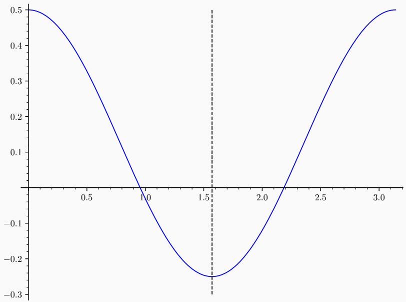
Hellings and Downs correlation (2/2)

- Isolate the frequency-dependence

$$\Gamma_{ab}(f) = \frac{1}{12\pi^2 f^2}\Gamma_{ab}$$

- In the short-arm limit

$$\Gamma_{ab} = \frac{1}{2}P_2(\cos\gamma_{ab}) + \frac{\delta_{ab}}{2}$$



Hellings and Downs correlation (2/2)

- Isolate the frequency-dependence

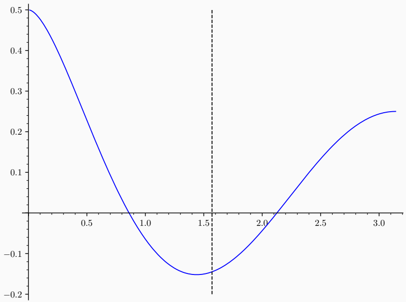
$$\Gamma_{ab}(f) = \frac{1}{12\pi^2 f^2}\Gamma_{ab}$$

- In the short-arm limit

$$\Gamma_{ab} = \frac{1}{2}P_2(\cos\gamma_{ab}) + \frac{\delta_{ab}}{2}$$

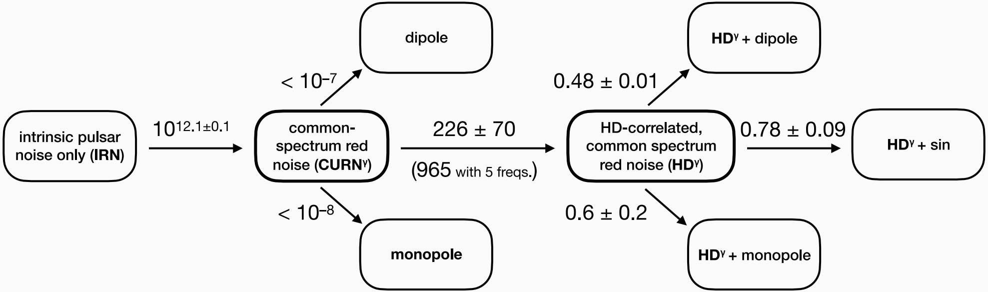
- In the long-arm limit

$$\Gamma_{ab} = \frac{1}{2}+\frac{3}{2}\left(\frac{1-\cos\gamma_{ab}}{2}\right)\left[\ln\left(\frac{1-\cos\gamma_{ab}}{2}\right)-\frac{1}{6}\right]+\frac{\delta_{ab}}{2}$$



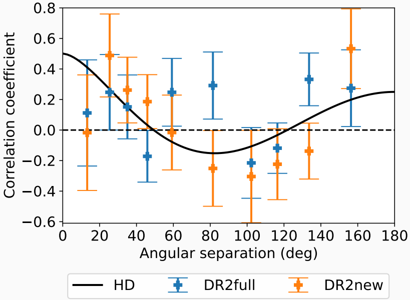
Results and interpretations

- NANOGrav claims $3.5-4\sigma$ with 67 pulsars Gabriella Agazie et al. 2023a



Bayes factors between models of correlated red noise in the NANOGrav 15-year data set Gabriella Agazie et al. 2023a

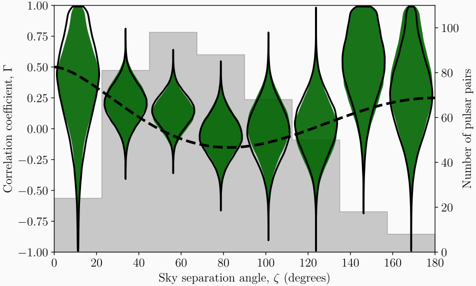
- NANOGrav claims $3.5 - 4\sigma$ with 67 pulsars Gabriella Agazie et al. 2023a
- EPTA claims $\geq 3\sigma$ with 25 pulsars Antoniadis et al. 2023



Constraints on the overlap reduction function from the optimal statistic Antoniadis et al. 2023

Increasing evidence for GWs

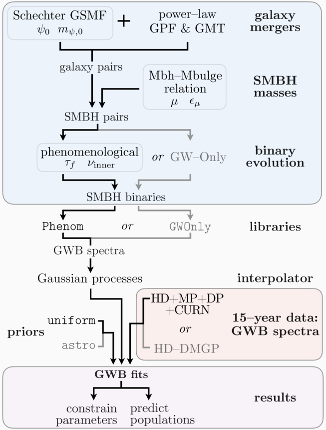
- NANOGrav claims $3.5 - 4\sigma$ with 67 pulsars Gabriella Agazie et al. 2023a
- EPTA claims $\geq 3\sigma$ with 25 pulsars Antoniadis et al. 2023
- PPTA claims 2σ with 30 pulsars Reardon et al. 2023



Measured spatial correlations as a function of the angular separation angle Reardon et al. 2023

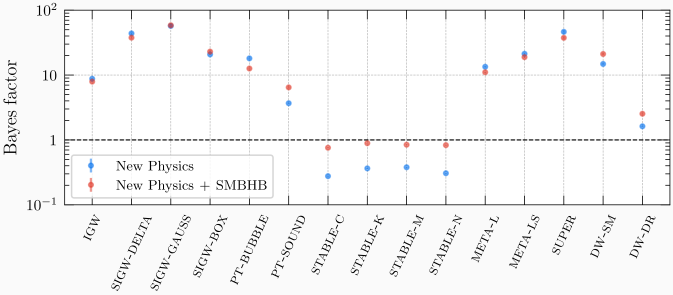
- SMBH Binary Population Synthesis
  - Galaxy masses and merger rates
  - SMBH masses based on a galaxy–host relationship
  - a binary evolution prescription
- Interpolation of Population Synthesis Models with Gaussian Processes
- Fitting Simulated GWB Spectra to PTA Observations

The GWB is Consistent with Expectations from Populations of SMBH Binaries

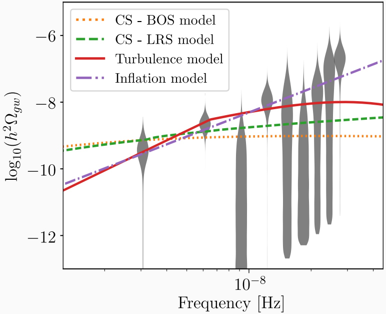


NANOGRAV's pipeline Credits: Gabriella Agazie et al. 2023b

Cosmological interpretations



Bayes factors for NANOGRAV 15 years Credits: Afzal et al. 2023



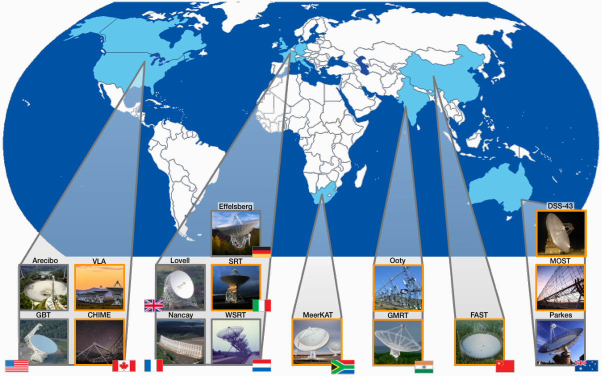
EPTA Credits: Antoniadis et al. 2024

- First-order phase transitions (PT)
- Cosmic strings (STABLE/META/SUPER)
- Domain walls (DW)
- Inspiraling supermassive black hole binaries (SMBHBs)
- Scalar-induced GWs (SIGW)

What’s next

International Pulsar Timing Array (nHz)

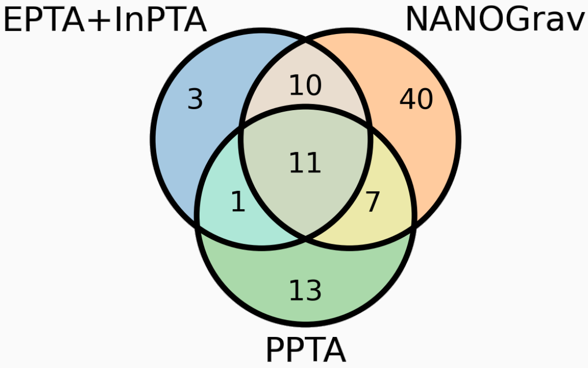
- 2015: IPTA Data Release 1
- 2019: IPTA Data Release 2



Credits: NANOGRAV's website

International Pulsar Timing Array (nHz)

- 2015: IPTA Data Release 1
- 2019: IPTA Data Release 2
- Data Release 3 under way



Credits: G. Agazie et al. 2024

Ground based detectors (10Hz - 1000Hz)

Latest results

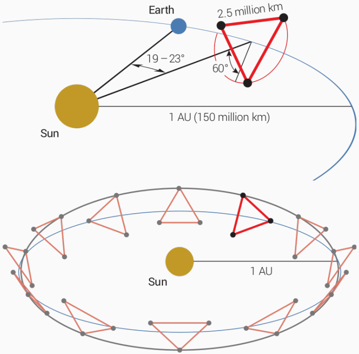
- Cross-correlation between detectors
- Upper-limits on $\Omega_{\mathrm{GW}}(f = 25\mathrm{Hz})$ after O3 (2021)[a]
- Expected sources
  - compact binary coalescences
  - core collapse supernovae
  - rotating neutron stars
  - stellar core collapses
  - cosmic strings
  - primordial black holes
  - superradiance of axion clouds around black holes
  - phase transitions in the early universe
  - GWs produced during inflation

[a] Abbott et al. 2021.

	Uniform prior			Log-uniform prior		
α	O3	O2	Improvement	O3	O2	Improvement
0	1.7×10^{-8}	6.0×10^{-8}	3.6	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	1.2×10^{-8}	4.8×10^{-8}	4.0	3.4×10^{-9}	3.0×10^{-8}	8.8
3	1.3×10^{-9}	7.9×10^{-9}	5.9	3.9×10^{-10}	5.1×10^{-9}	13.1
Marg.	2.7×10^{-8}	1.1×10^{-7}	4.1	6.6×10^{-9}	3.4×10^{-8}	5.1

LISA (mHz)

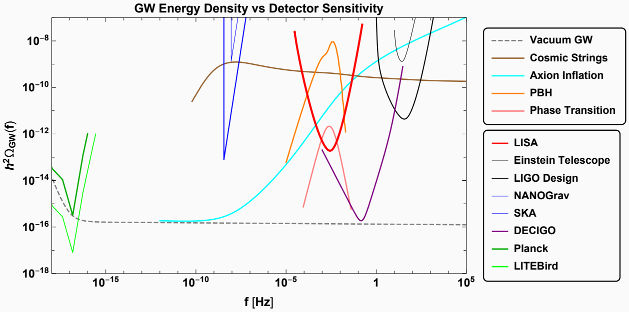
- 1997: Initial design, collaboration ESA/NASA
- 2015: LISA Pathfinder, technology demonstrator
- 2024: LISA adoption
- 2035: Planned launch on Ariane 6



Credits: Amaro-Seoane et al. 2017

LISA (mHz)

- 1997: Initial design, collaboration ESA/NASA
- 2015: LISA Pathfinder, technology demonstrator
- 2024: LISA adoption
- 2035: Planned launch on Ariane 6



Auclair et al. 2023

Conclusion

Take-home messages

- Advent of GW astronomy, new window into the darkest corners of the Universe
- Access to a new population of BH and NS binaries
- Increasing evidence for the detection of a Stochastic Background of GW

Take-home messages

- Advent of GW astronomy, new window into the darkest corners of the Universe
- Access to a new population of BH and NS binaries
- Increasing evidence for the detection of a Stochastic Background of GW
- Either of astrophysical origin
    - Clues for the formation of SMBHs
    - Connexion with latest JWST detections of early galaxy formation

Take-home messages

- Advent of GW astronomy, new window into the darkest corners of the Universe
- Access to a new population of BH and NS binaries
- Increasing evidence for the detection of a Stochastic Background of GW
- Either of astrophysical origin
  - Clues for the formation of SMBHs
  - Connexion with latest JWST detections of early galaxy formation
- Either of cosmological origin
  - Tracer of very HEP, currently inaccessible in colliders
  - Hints of violent **phase transitions** in the Early Universe (GUT, EW)
  - Hints of cosmic inflation

Take-home messages

- Advent of GW astronomy, new window into the darkest corners of the Universe
- Access to a new population of BH and NS binaries
- Increasing evidence for the detection of a Stochastic Background of GW
- Either of astrophysical origin
  - Clues for the formation of SMBHs
  - Connexion with latest JWST detections of early galaxy formation
- Either of cosmological origin
  - Tracer of very HEP, currently inaccessible in colliders
  - Hints of violent **phase transitions** in the Early Universe (GUT, EW)
  - Hints of cosmic inflation
- Massive effort to narrow down the origin of the signal around the globe and at different frequencies

Thank you