Beyond Einstein phenomenology in the nanohertz gravitational wave sky

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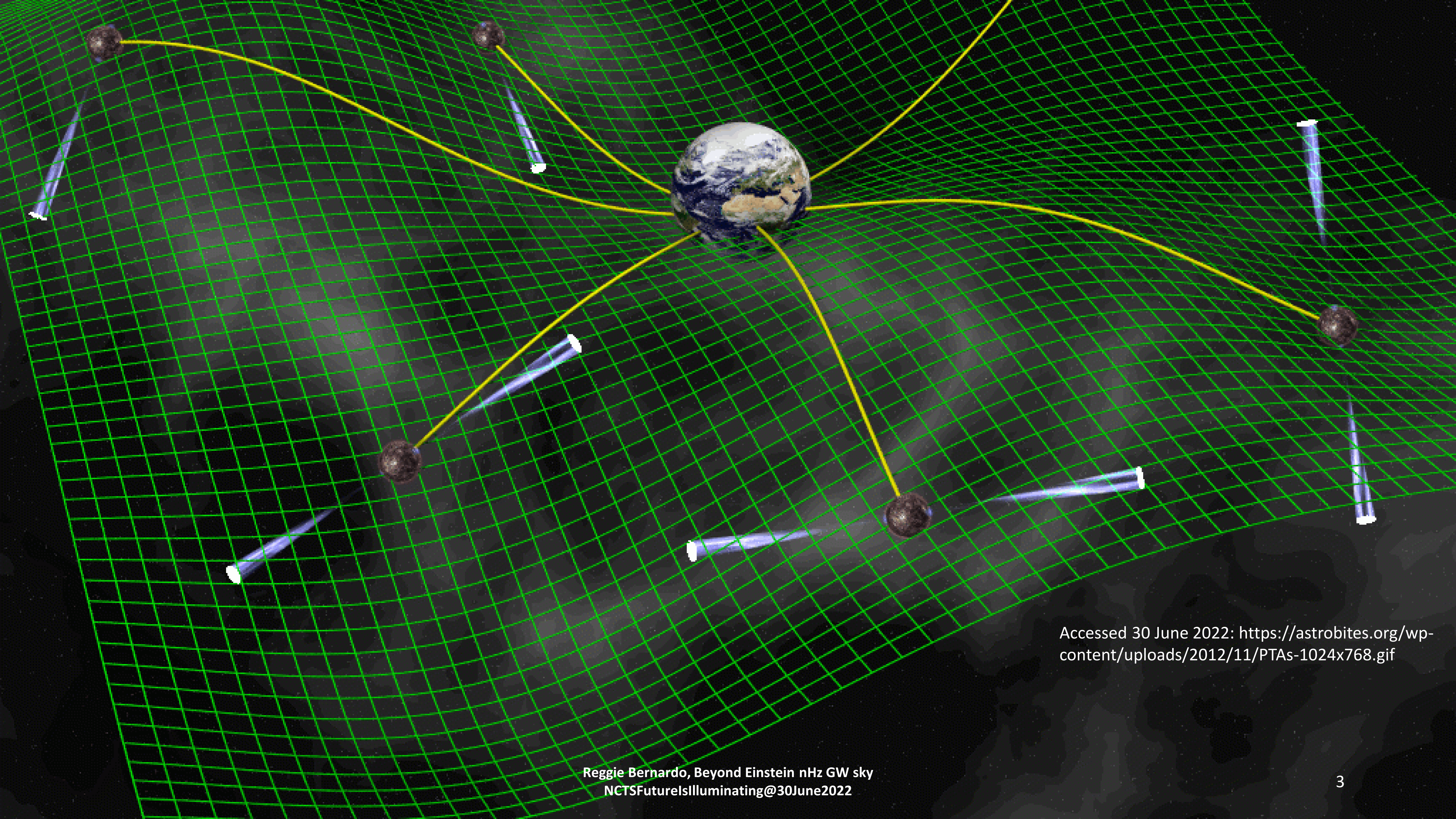
Outline

1. Gravitational waves and pulsar timing
2. Beyond Einstein phenomenology in the nHz GW sky
3. Looking out for the Galileon
4. Outlook



Accessed 30 June 2022: https://astrobites.org/wp-content/uploads/2012/11/PTAs-1024x768.gif

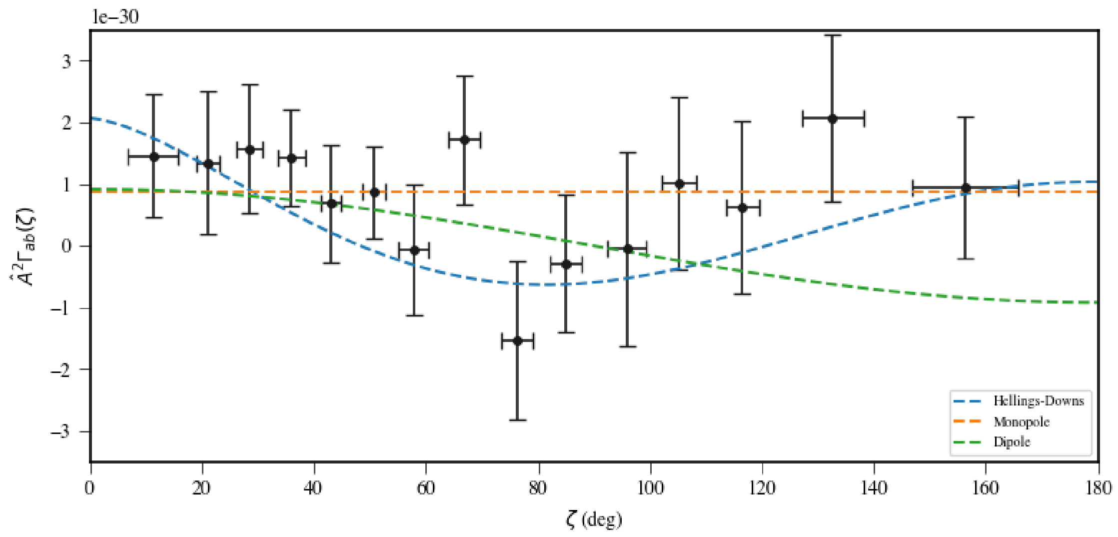
Pulsar Timing Array: The NANOGrav 12.5-year data set

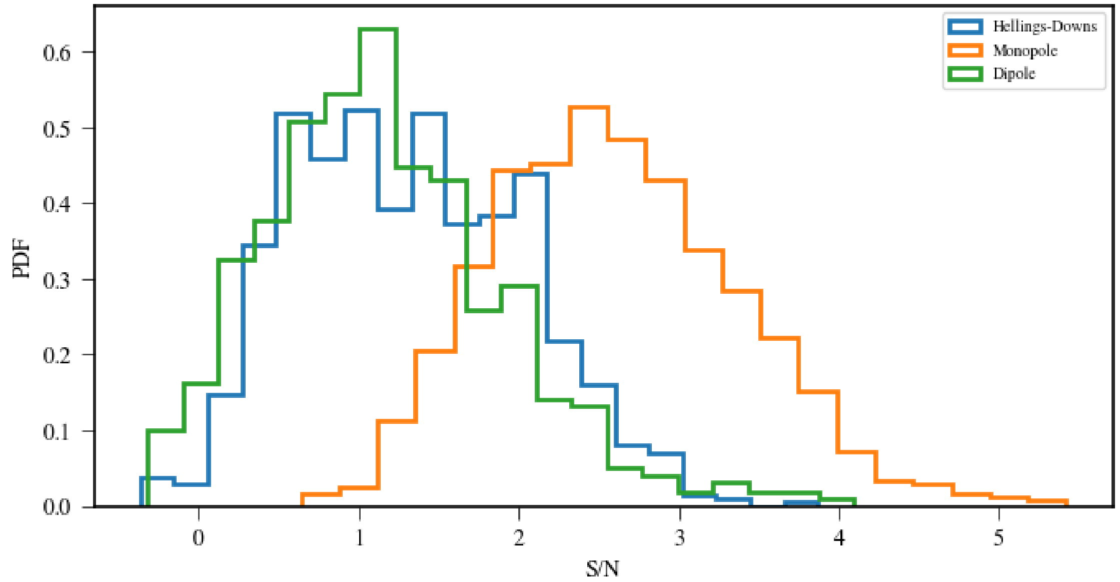
arXiv:2009.04496

- Evidence of stochastic process
- Not exactly “Hellings-Downs”
- S/N ratio of monopole > HD

arXiv:2109.14706

- Non-Einstein polarizations
- ST > TT correlations
- Caveats:
  - Modes on light cone
  - Pulsars at infinitely far





Pulsar Timing

- The **timing residual** – observable

$$r(t) = \int dt'\, z(t')$$

- Redshift fluctuation from GW $h_{ij}(t)$:

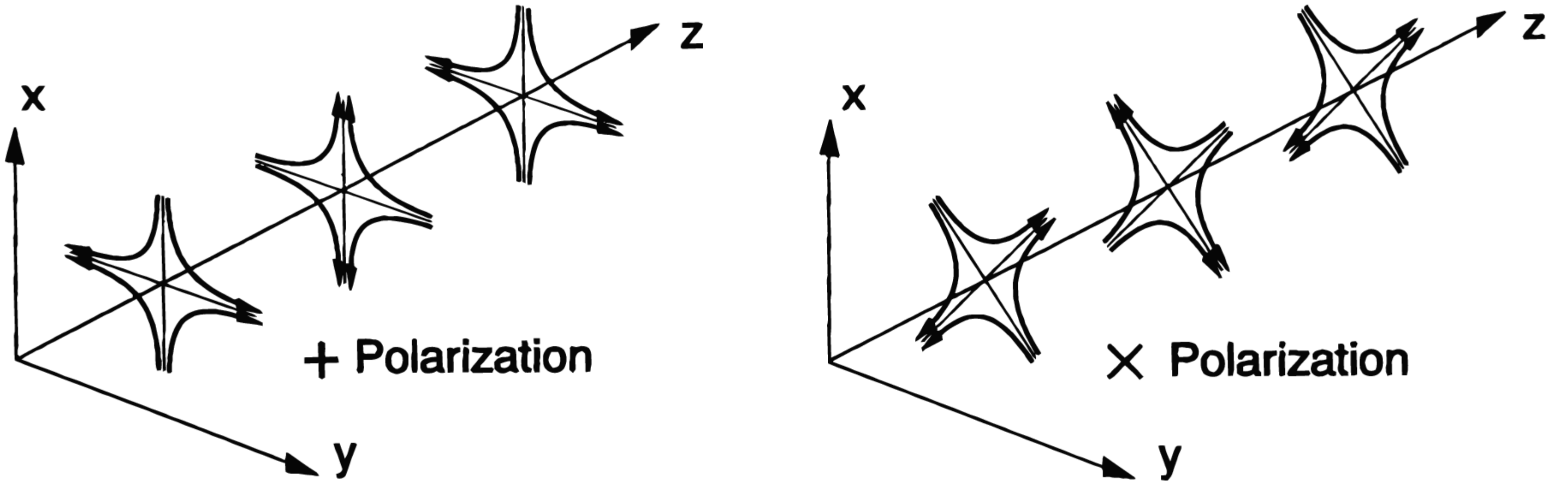
$$z(t) = \frac{\left(\hat{e}^i \otimes \hat{e}^j\right)}{2\left(1 + v\hat{k}\cdot\hat{e}\right)}\left(h_{ij}^e - h_{ij}^p\right)$$

$$\boxed{z(t) = -\frac{1}{2}\int d\eta\, \hat{e}^i \otimes \hat{e}^j\, \partial_\eta h_{ij}(\eta)}$$

- **Two point function**

$$\langle r_a(t) r_b(t)\rangle = \sum a_{lm} Y_{lm}(\hat{e}_a \cdot \hat{e}_b)$$

Gravitational Wave Polarizations



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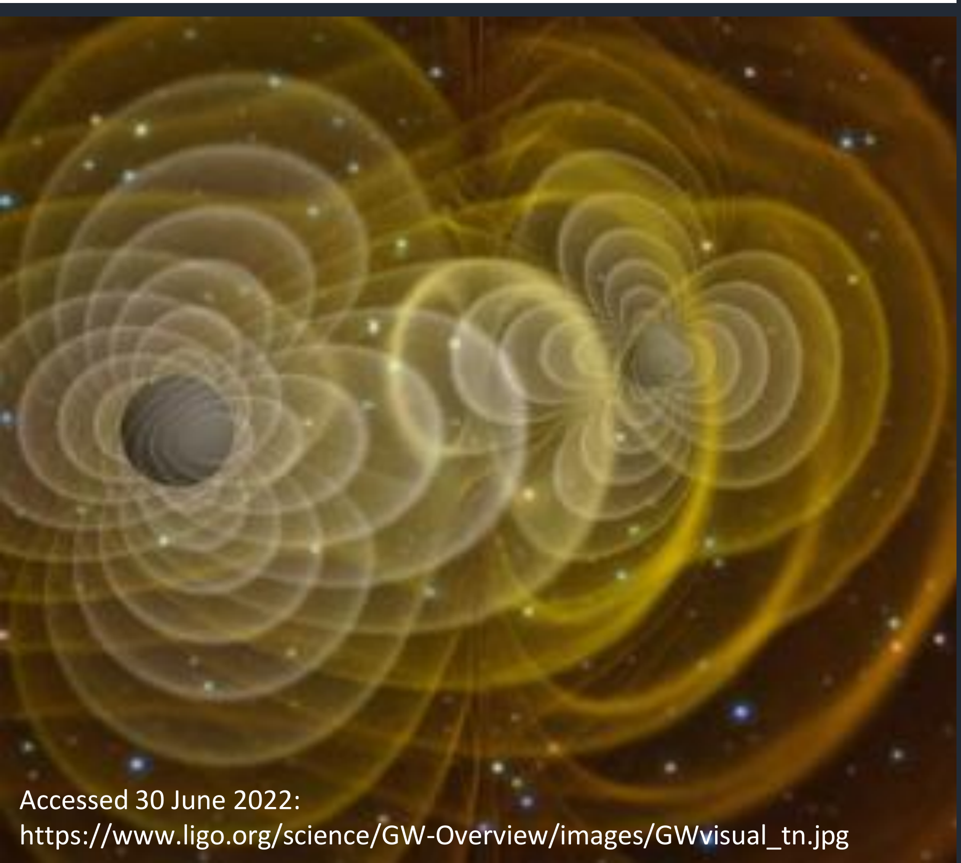


Accessed 30 June 2022: https://www.ligo.org/science/GW-Overview/images/GWvisual_tn.jpg

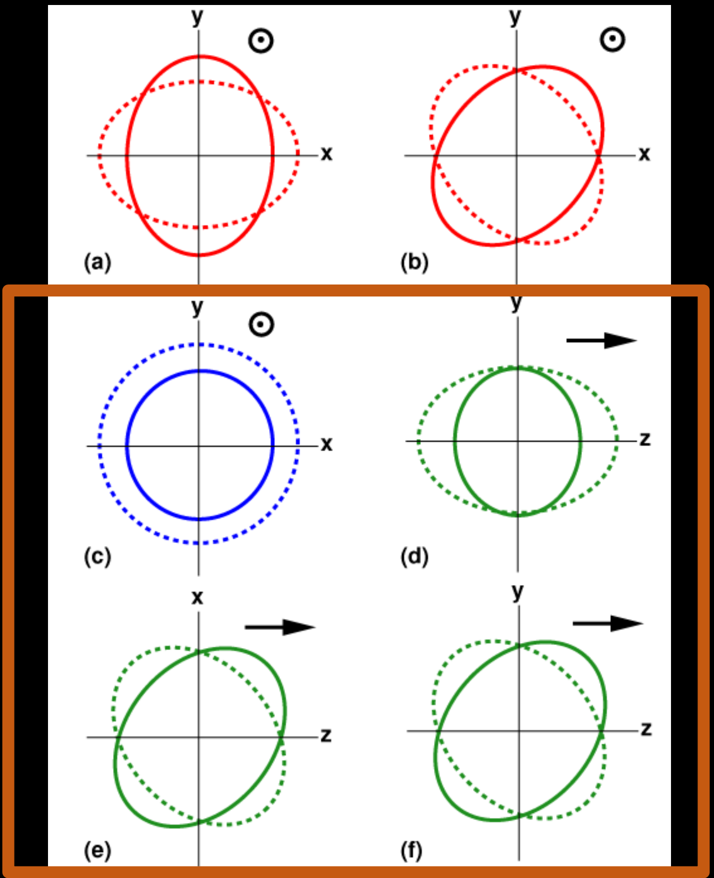
$$h_{ij}(\eta,\vec{x}) = \sum_A \int df \int d\hat{k}\ \tilde{h}_A\left(f,\hat{k}\right) \boldsymbol{\varepsilon}^{\boldsymbol{A}}_{\boldsymbol{ij}}\, e^{-2\pi i f\left(\eta - v\hat{k}\cdot\vec{x}\right)}$$

GW amplitude

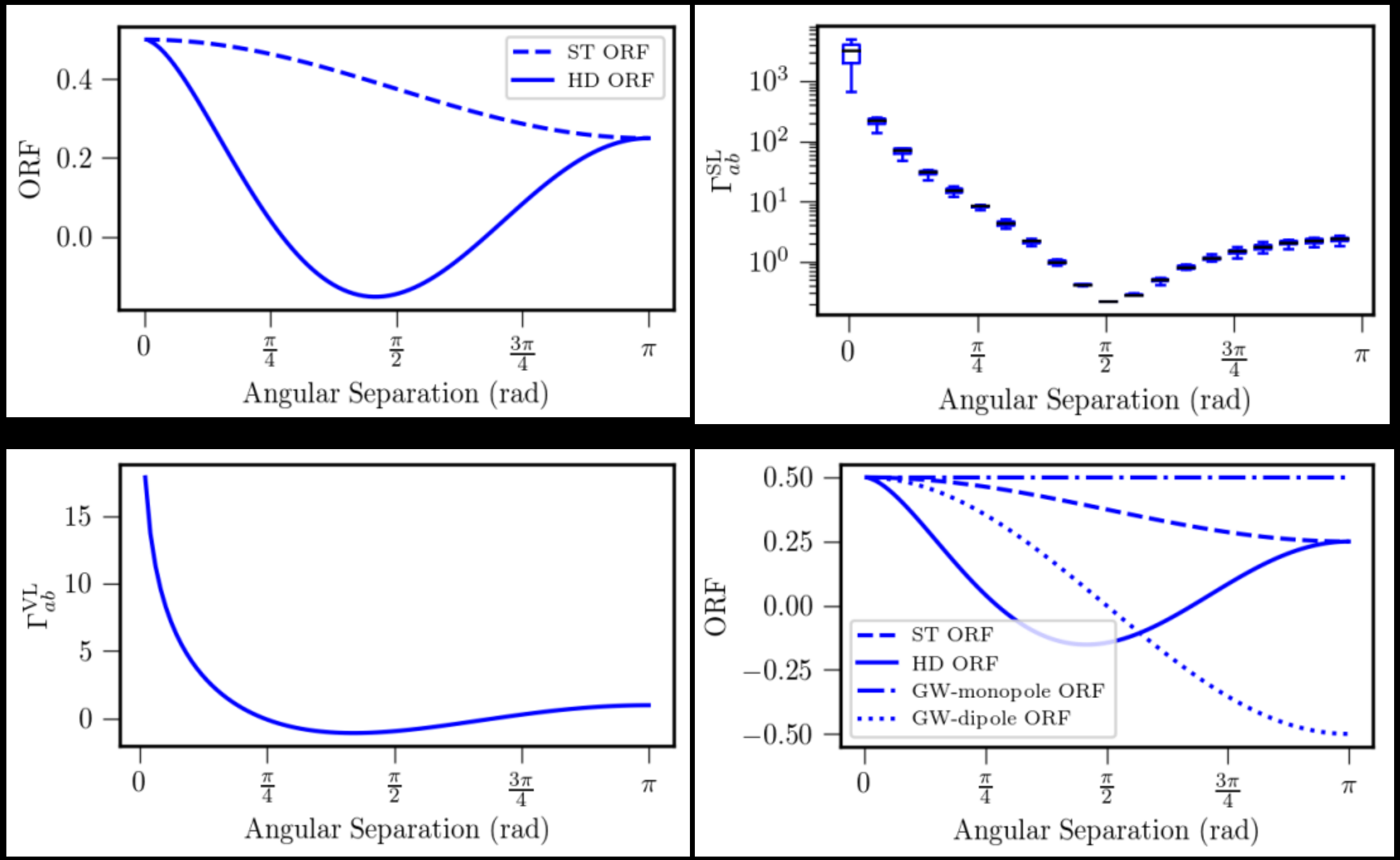
polarization basis tensor

velocity

GW Polarizations: Beyond Einstein



Accessed 30 June 2022:
https://www.ligo.org/science/Publication-GW170814/images/figure5.png



NANOGrav: arXiv:2109.14706

The ORF of Isotropic SGWB: technical

- ORF γ_{ab} is given by:

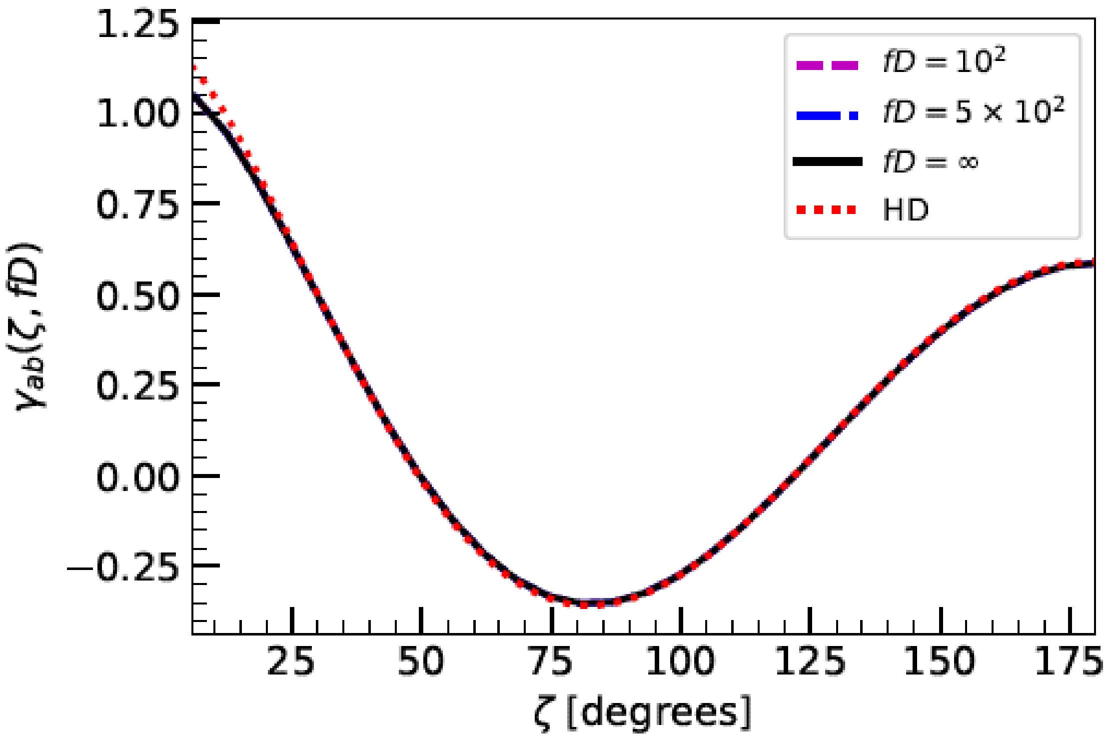
$$\gamma_{ab}(\zeta) = \sum_{l} \frac{2l+1}{4\pi} C_l P_l(\cos\zeta)$$

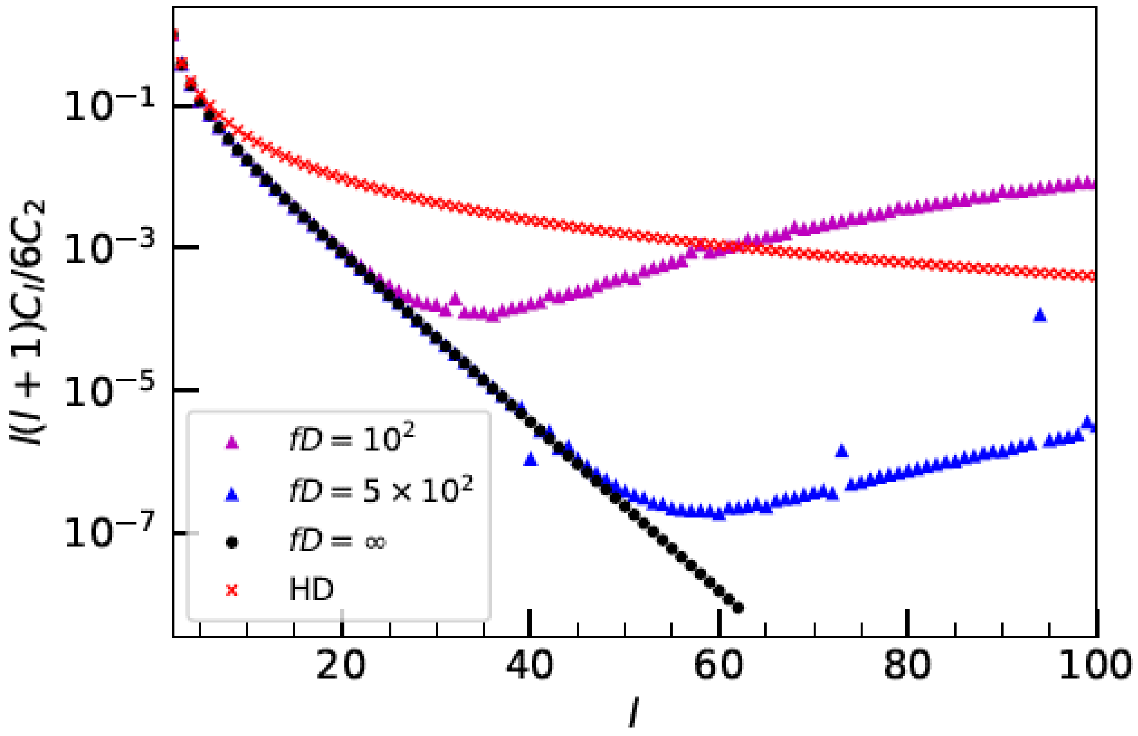
$$C_l^A = \frac{J_l^A(fD_a) J_l^{A*}(fD_b)}{\sqrt{\pi}}$$

- For polarization A (**tensor, vector, scalar transverse/longitudinal**)

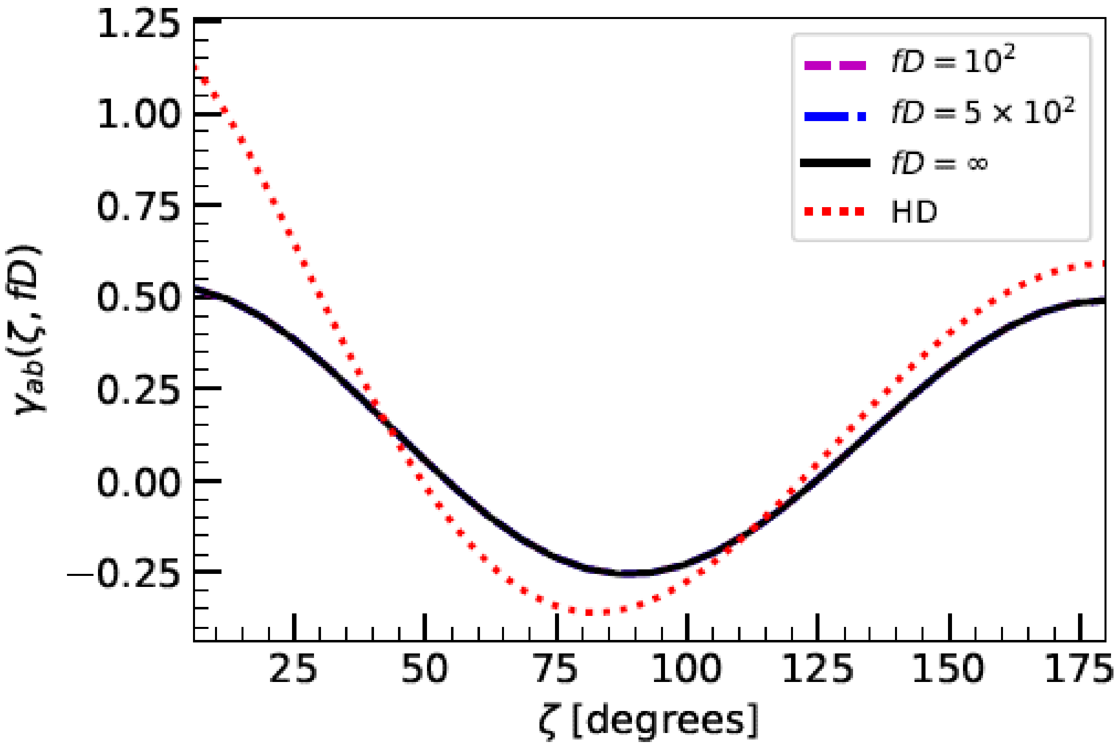
$$J_l^A = N_l \int_0^{2\pi \boldsymbol{fDv}} \frac{dx}{\boldsymbol{v}} \boldsymbol{e^{ix/v}} \partial_x^{\boldsymbol{p=0,1}} \left(\frac{\boldsymbol{j_l(x)}}{x^{\boldsymbol{q=0,1,2}}} \right)$$

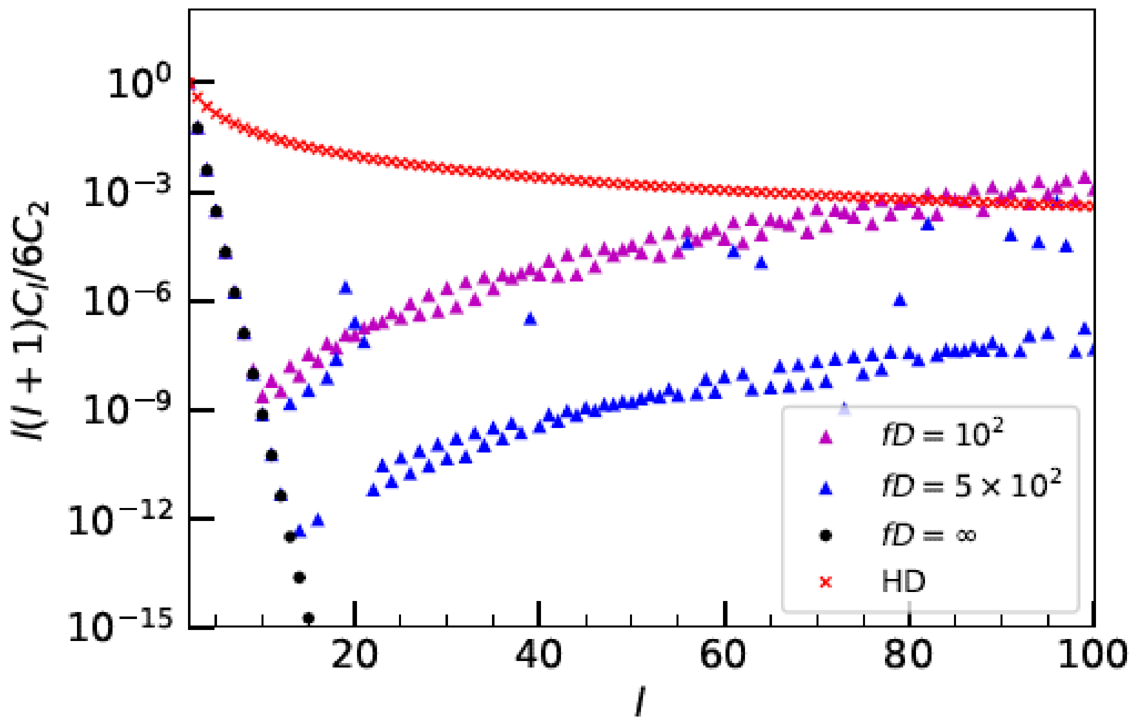
Tensor PS and ORF ($v \sim 1$, near luminal)



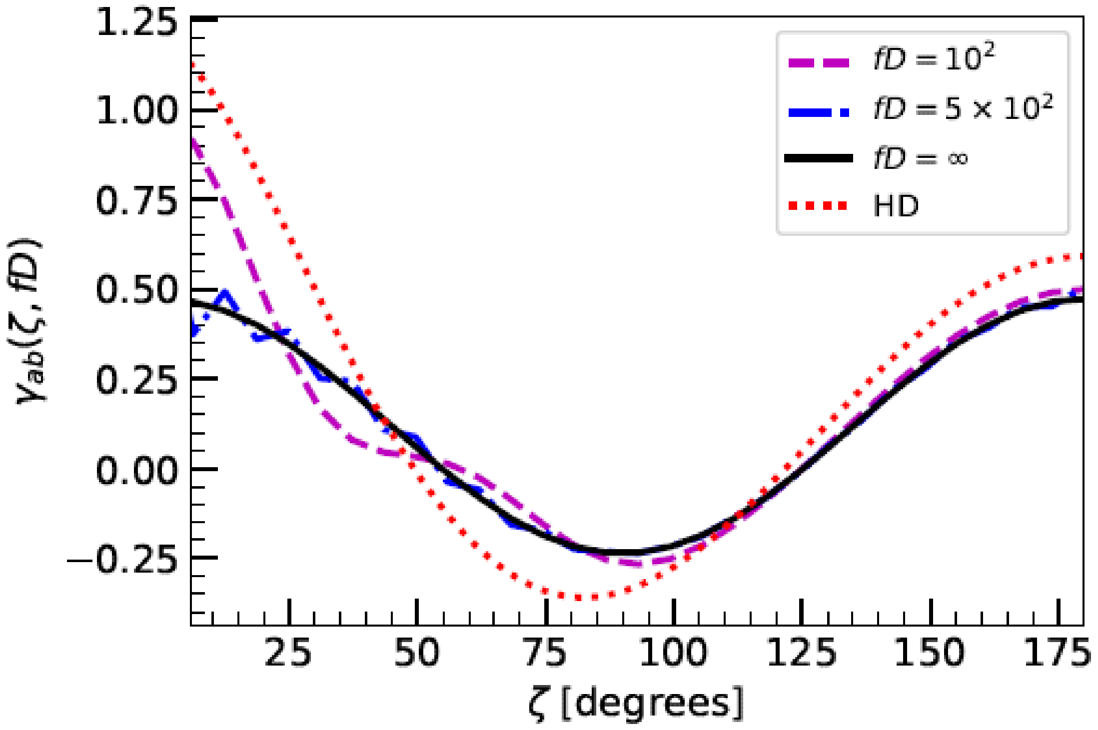


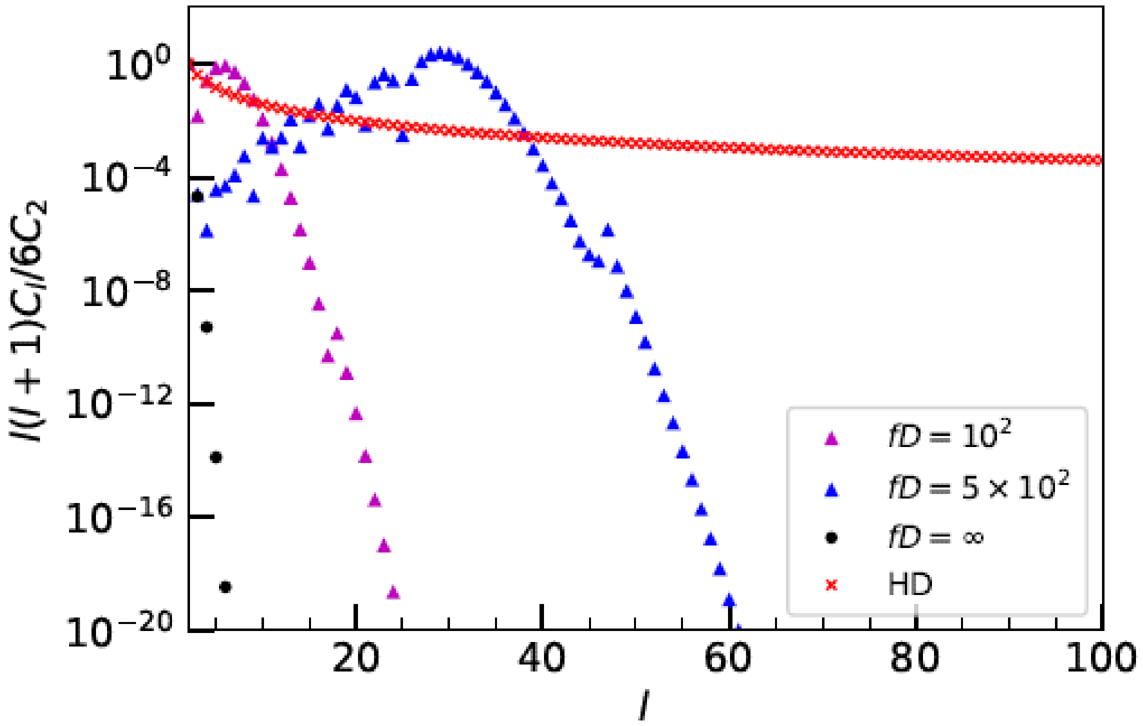
Tensor PS and ORF ($v = 1/2$, half luminal)

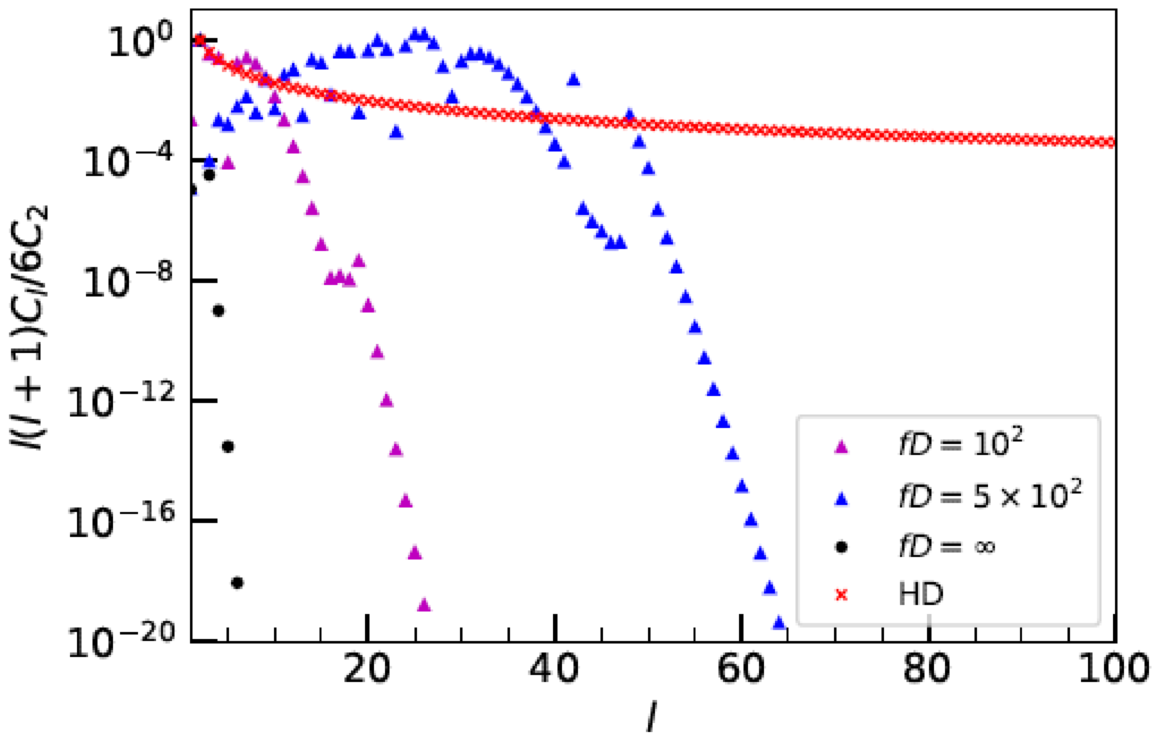


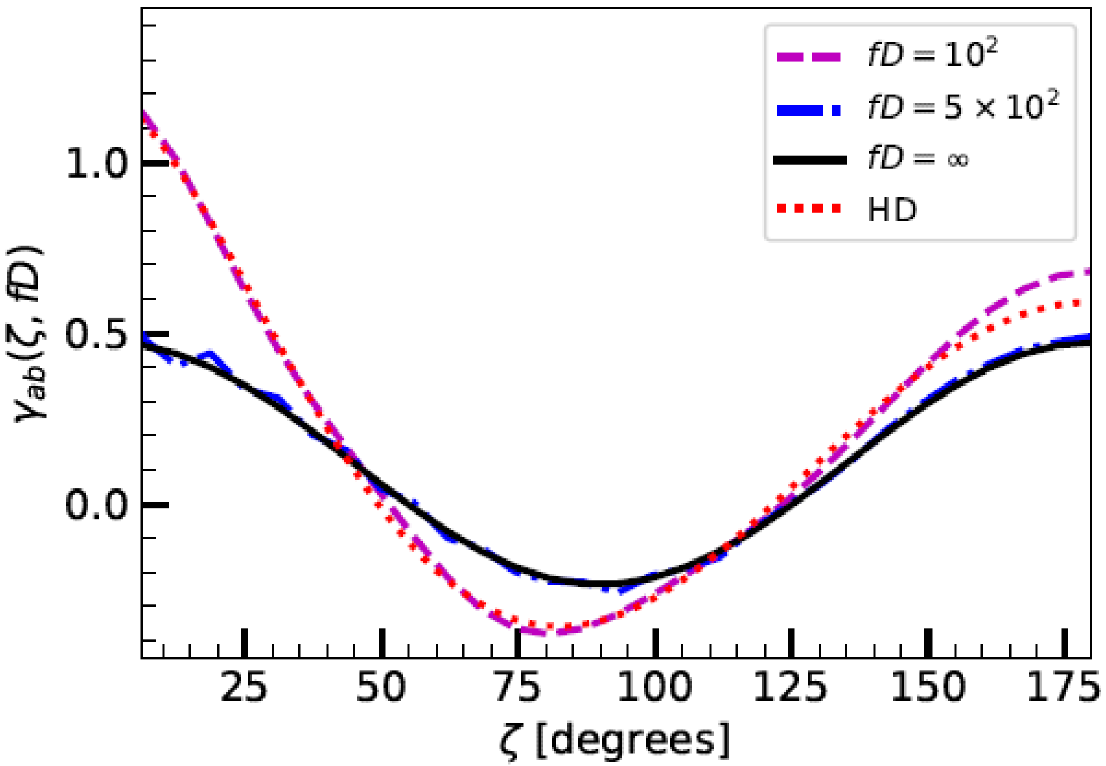


Tensor PS and ORF ($v \ll 1$, near static)









Vector PS and ORF ($v \ll 1$, near static)

Galileon in the nHz GW sky

The covariant Galileon

$$S_G[g_{ab}, \phi] = \int d^4x\sqrt{-g}\left(\left(1+\frac{\alpha\phi}{M_{\rm P}}\right)\mathrm{EH} - \Lambda - \lambda^3\phi + X + \frac{X}{\kappa^3}\partial^2\phi + \frac{\mu^2\phi^2}{2}\right)$$

- **EH** = Einstein-Hilbert term
- Λ = cosmological constant
- κ = braiding -> Vainshtein mechanism/ϕ suppression at $R \ll L$
- μ = *bare* mass -> chameleon screening/ϕ suppression at dense environments
- α = conformal coupling -> mixes the tensor and scalar modes
- λ = tadpole -> self tuning mechanism (2202.08672, Appleby, **RCB**)

Galileon polarizations

- ***Tensor*** perturbations -> **+, x polarizations**
- ***Scalar*** perturbations satisfy the **massive KG eq**.

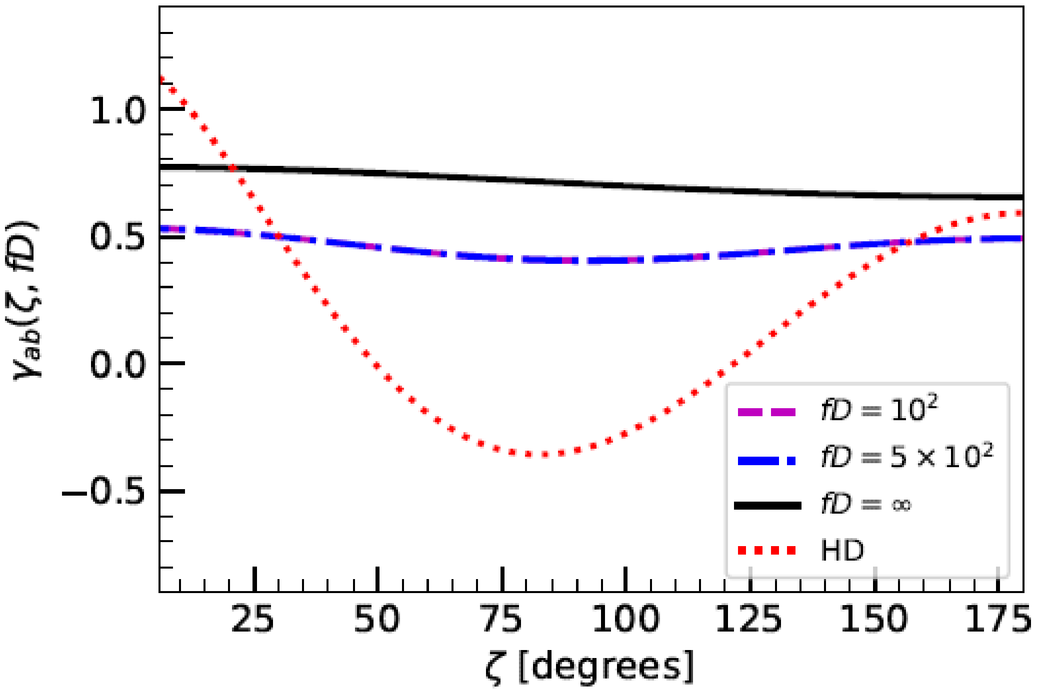
$$D^2\psi - \ddot{\psi} - m_{\text{eff}}^2(\mu, \alpha, \lambda)\psi = 0$$

- Brings in scalar transverse (**ST**) and longitudinal (**SL**) **pols**:

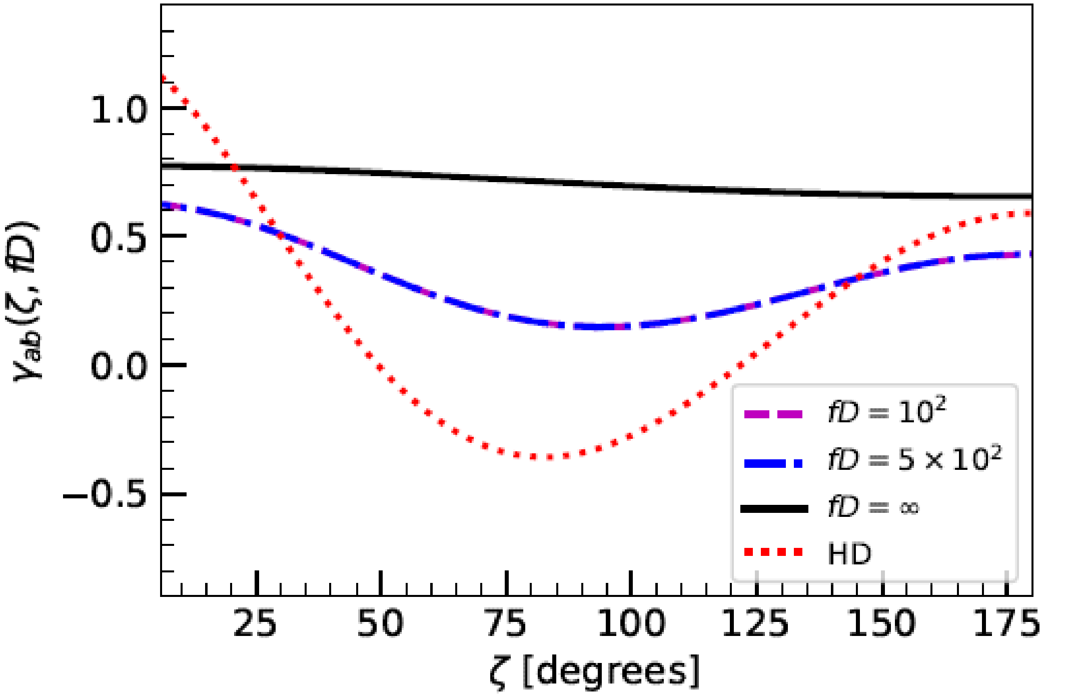
$$h_{AB} \propto \left(\boldsymbol{\varepsilon}_{AB}^{\mathbf{ST}} + \frac{1 - v(m_{\text{eff}})^2}{\sqrt{2}} \boldsymbol{\varepsilon}_{AB}^{\mathbf{SL}} \right) \times \text{plane wave}$$

Scalar ORFs ($v = 1/2$, half luminal)

ST



SL

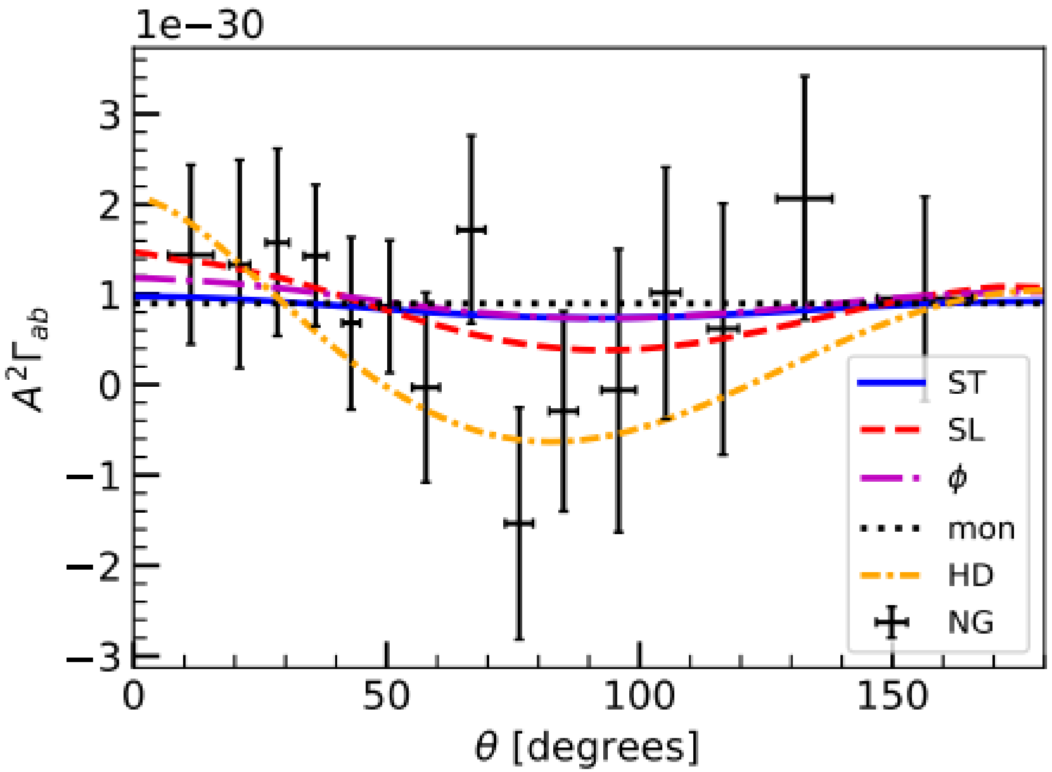


Best fit in NG12.5

$$v = 0.47 \pm 0.22\, c \ \rightarrow m_{\mathrm{eff}} \sim 10^{-22}\ \mathrm{eV\ (Galileon)}$$

Marginalized statistics for the ST, SL, and the Galileon (**φ**) constrained by NG12.5. The performance statistics (chi-squared, AIC, and BIC) are relative to the systematic monopole, or that a positive value means statistical preference over the systematic monopole.

mode	v	$A^2\ [\times 10^{-30}]$	$\Delta\chi^2$	ΔAIC	ΔBIC
ST	< 0.609	$0.53^{+0.16}_{-0.20}$	0.90	-1.10	-1.80
SL	0.42 ± 0.19	$0.78^{+0.26}_{-0.42}$	2.73	0.73	0.02
ϕ	0.47 ± 0.22	$0.47^{+0.12}_{-0.15}$	1.46	-0.54	-1.25
HD	$v = 1$	4.2 ± 1.7	-2.96	-2.96	-2.96
syst. mon.	$---$	0.90 ± 0.25	0	0	0



Outlook

In this work, we:

- presented an efficient **PS formalism** for calculating the overlap reduction function;
- studied the **pulsar timing array phenomenology** of a generic **subluminal metric polarizations** for **finite pulsar distances**.

- analysis of tensor polarizations off the light cone;
- alternative gravity constraints;
- anisotropies.

Extra Slides

Metric Perturbations

Synchronous gauge:

$$ds^2 = -dt^2 + \left(\delta_{AB} - 2\psi\delta_{AB} + 2D_A D_B E + 2D_{(A}E_{B)} + 2E_{AB}\right)dx^A dx^B$$

$$\phi = \varphi + \delta\phi$$

Effective mass $\left(\omega^2 = k^2 + m_{\text{eff}}^2\right)$:

$$m_{\text{eff}}^2 = \mu^2 \left(\frac{1 - \frac{\alpha\lambda^3}{M_{\text{P}}\mu^2}}{1 + \frac{3\alpha^2}{2} - \frac{\alpha\lambda^3}{M_{\text{P}}\mu^2}} \right)$$