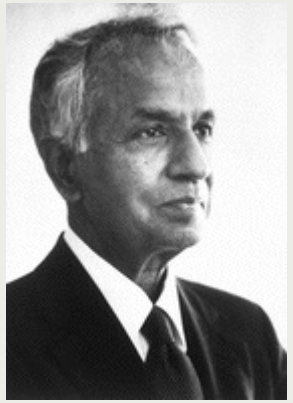
GRAVITATIONAL PHYSICS FRONTIERS IN THE PTA ~~AND SKA~~ ERA

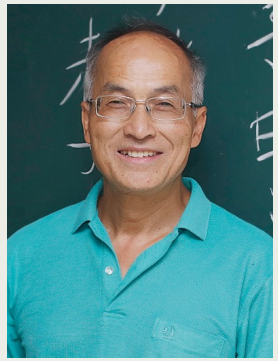
ascl:2211.001, arXiv:2312.03383, in prep, in prep





Reggie Bernardo

and **Kin-Wang Ng**



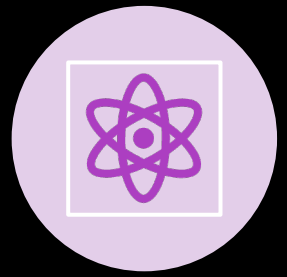
with **Guo-Chin Liu** (TKU)

with **Gopakumar Achamveedu** (InPTA)

nHzGravCosmo @ GC2024/YITP @ 19 Feb 2024

OUTLINE

NANOHERTZ GWS SGWB AND PTA



ANISOTROPIC POLARIZED SGWB

FUZZY DM IN PTA

OUTLOOK

Reggie Bernardo

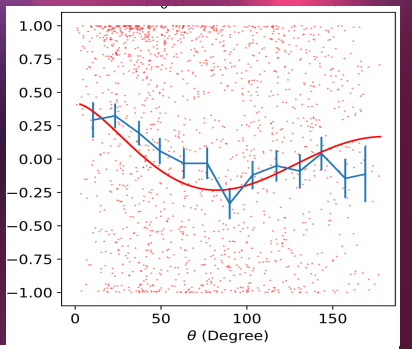
Accessed 031022
https://www.mpifr-bonn.mpg.de/6794804/original-1641977112.jpg?t=eyJ3aWR0aCI6ODQ4LCJmaWxlX2V4dGVuc2lvbiI6ImpwZyIsIm9ial9pZCI6Njc5NDgwNH0%3D--053bbbcc9675fa5b671035699dcd54a75f636fe9

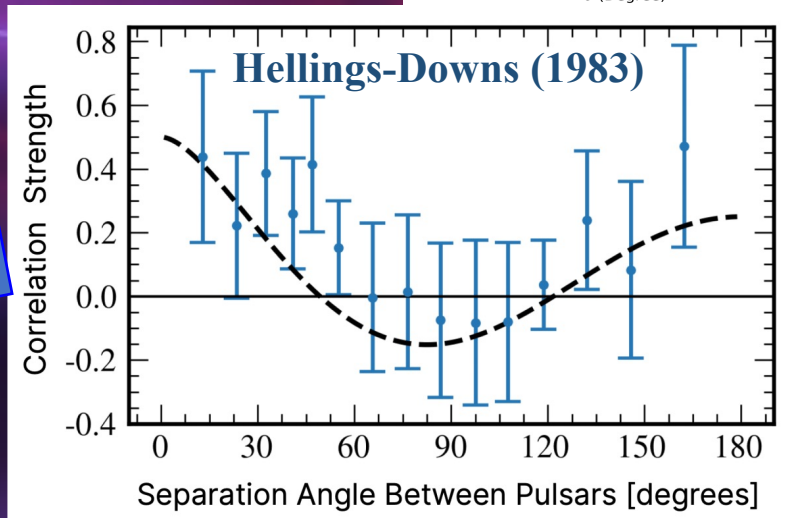
EARTH

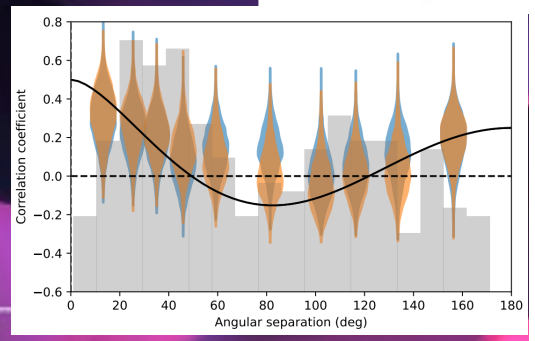
PULSAR TIMING ARRAY

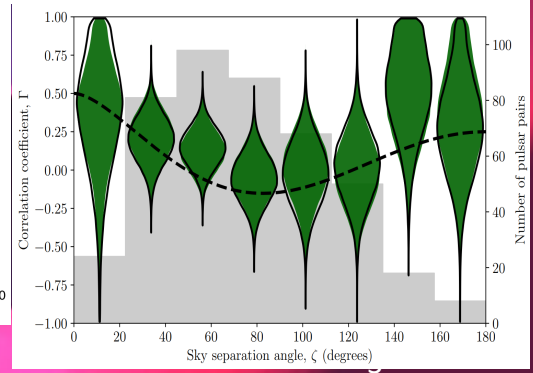
GRAVITATIONAL WAVES

SUPERMASSIVE BLACK HOLE BINARY









Reggie Bernardo
nHzGravCosmo @ GC2024/YITP @ 19Feb2024

Pulsar Timing

- The **timing residual** = observation - timing model

$$r(t) = \int dt'\, z(t') = \textbf{Earth Term} - \textbf{Pulsar Term}$$

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

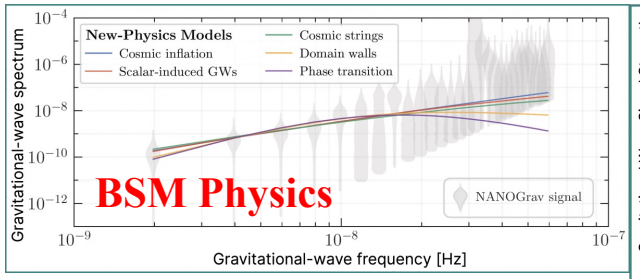
$$z(t) = -\frac{1}{2}\int d\eta\, \hat{e}^i \otimes \hat{e}^j\, \partial_\eta\, h_{ij}(\eta)$$

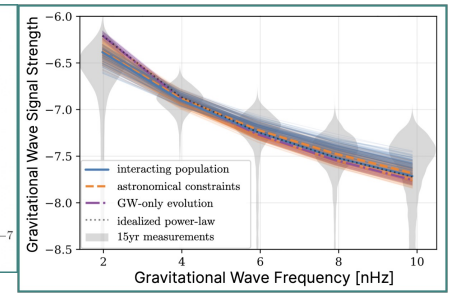
- **Two-point function**

Frequency Spectrum
~SMBHBs, SIGWs, FOPT, etc.

$$\langle r_a(t) r_b(t)\rangle = \sum \langle a_{l_1 m_1} a_{l_2 m_2}\rangle Y^*_{l_1 m_1}(\hat{e}_a) Y^*_{l_2 m_2}(\hat{e}_b)$$

$$\sim \sum_A \int df \left(1 - e^{-2\pi i f t}\right)\left(1 - e^{2\pi i f t}\right) \times \frac{P_{AA}(f)}{f^2} \times \gamma^A_{ab}(\hat{e}_a \cdot \hat{e}_b)$$





Pulsar Timing

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

- **Two-point function**

Correlation/ORF

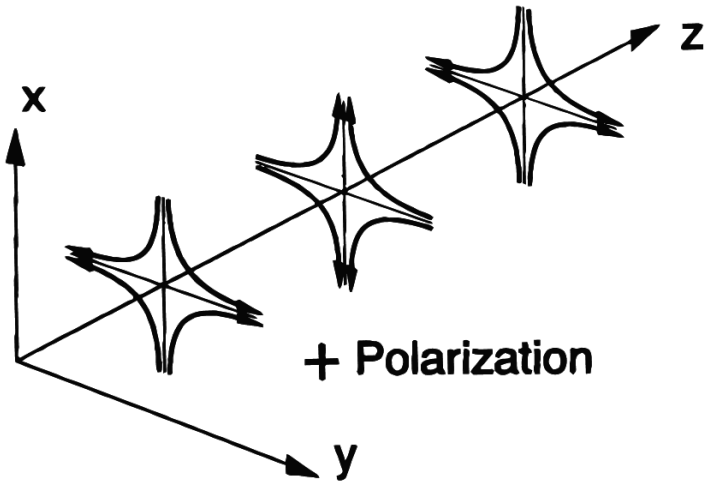
~GW, Fuzzy Dark Matter, etc.

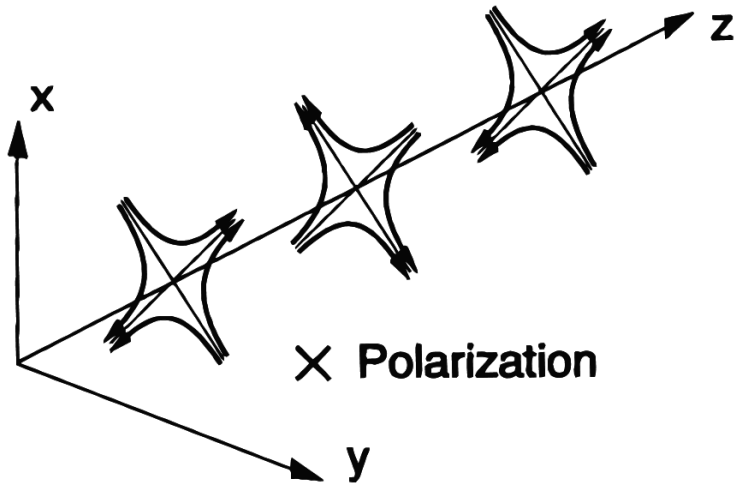
$$\langle r_a(t) r_b(t)\rangle = \sum \langle a_{l_1 m_1} a_{l_2 m_2}\rangle Y^*_{l_1 m_1}(\hat{e}_a) Y^*_{l_2 m_2}(\hat{e}_b)$$

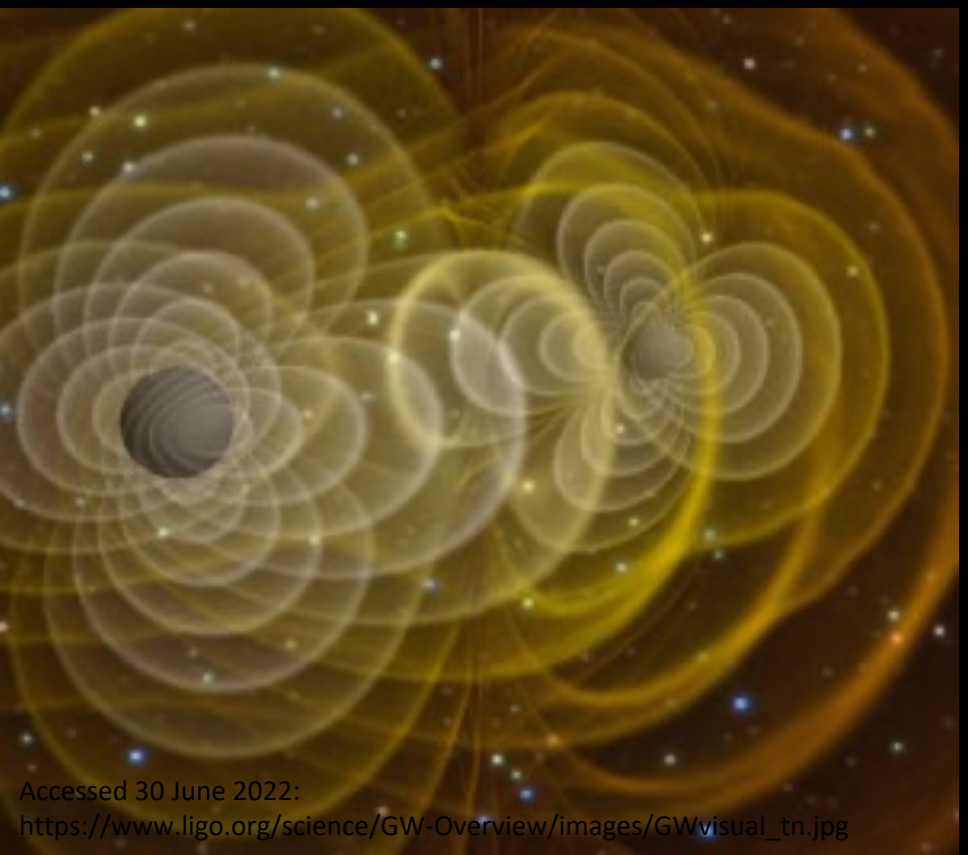
$$\sim \sum_A \int df \left(1 - e^{-2\pi i f t}\right)\left(1 - e^{2\pi i f t}\right) \times \frac{P_{AA}(f)}{f^2} \times \boxed{\gamma^A_{ab}(\hat{e}_a \cdot \hat{e}_b)}$$

- **Quantifies SGWB induced correlation between pulsars *a* and *b*;**
- **A function of the frequency and the angle between pulsars across PTA.**

Gravitational Wave Polarizations







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

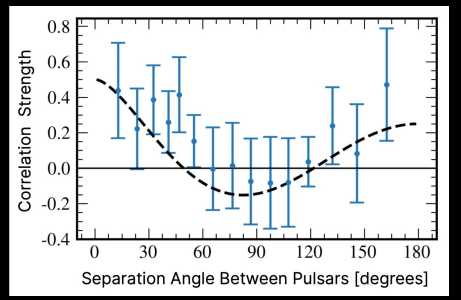
GW amplitude -> Omega

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

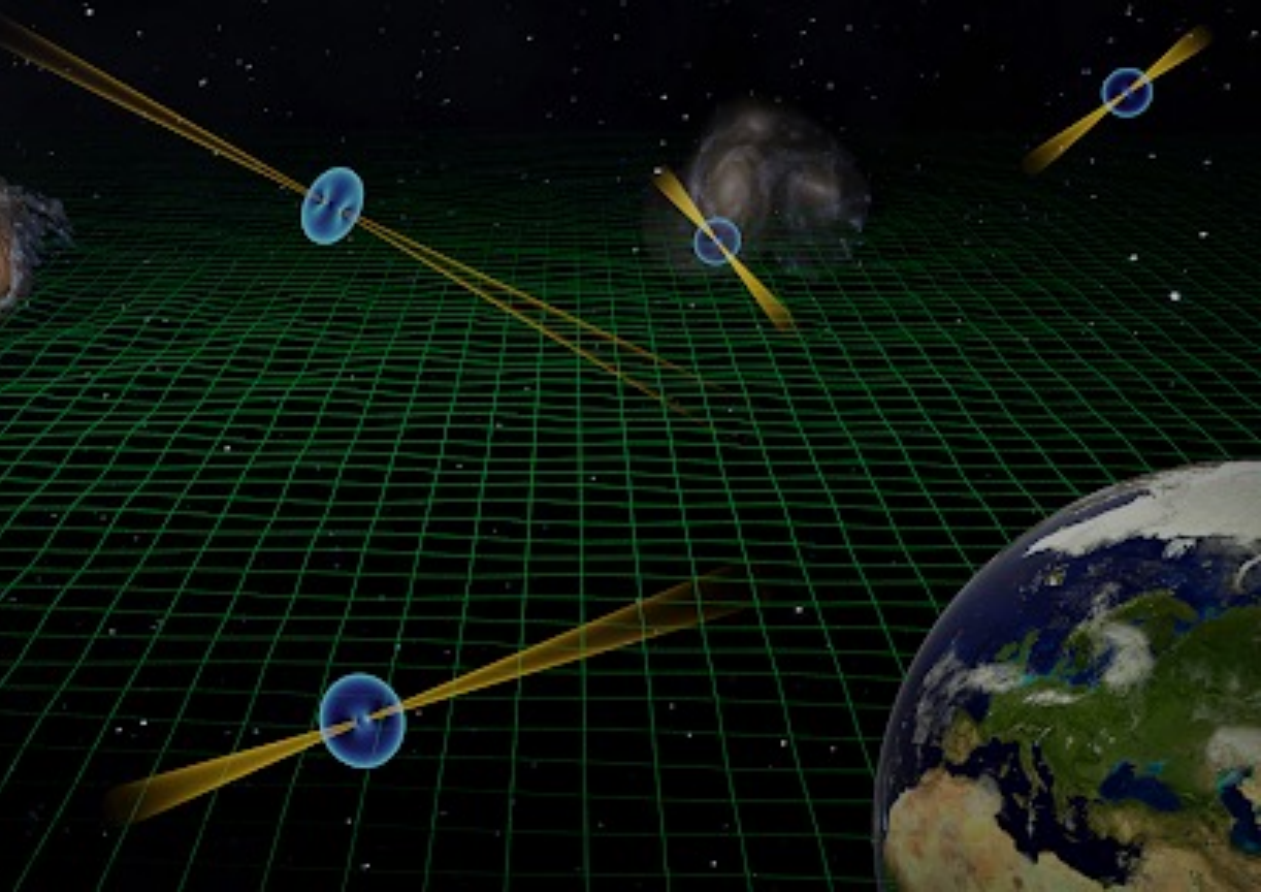
velocity

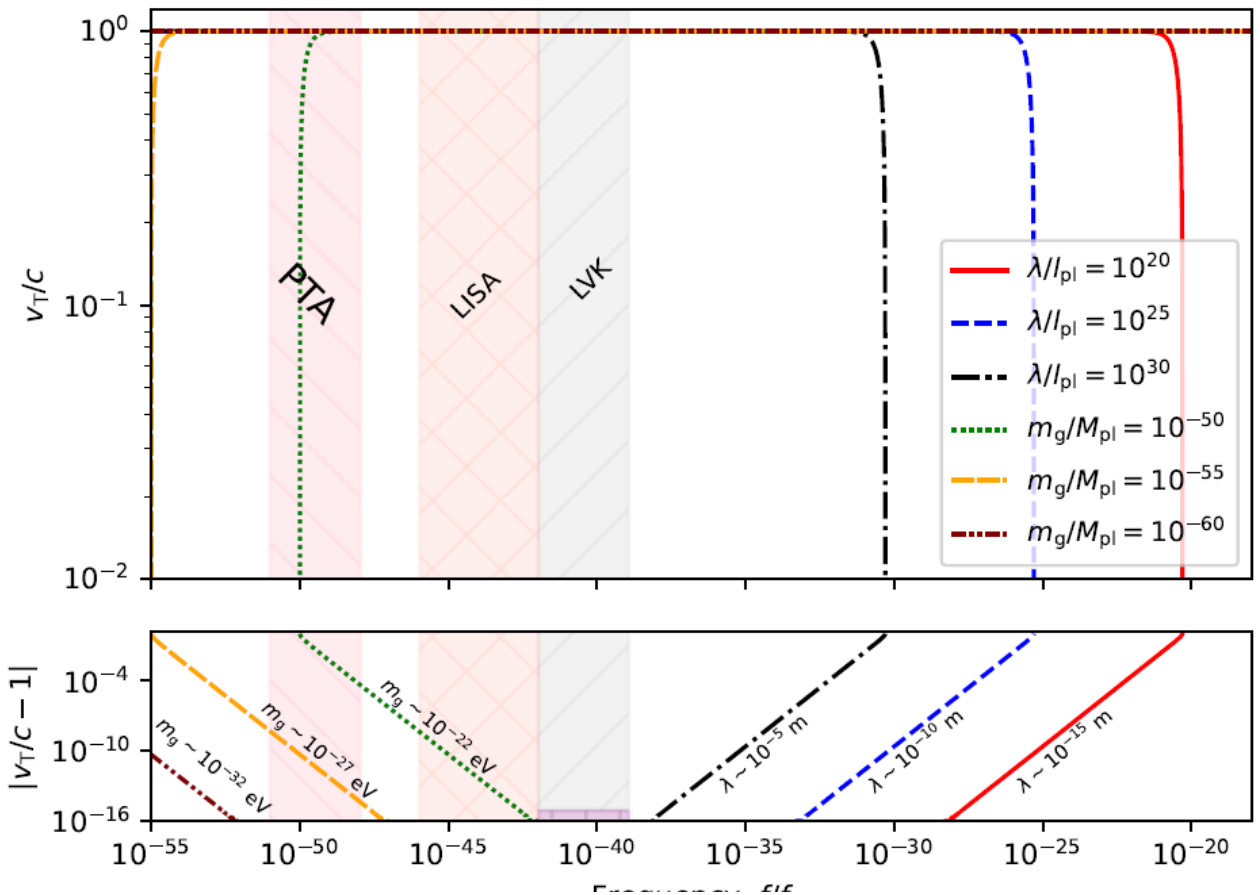
Polarization Tensor -> ORF

TT tensor + $\underline{v = 1}$ **+** $\underline{D \to \infty}$ **+ Isotropic =**



What’s next?

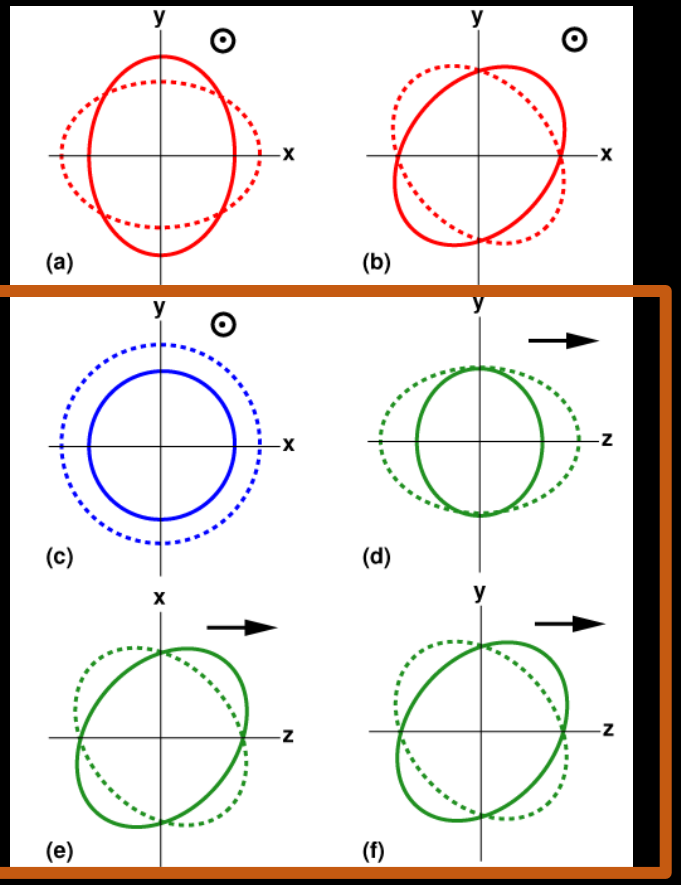




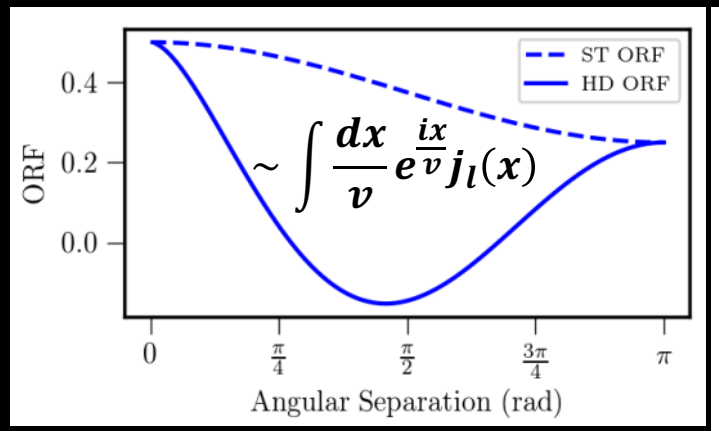
PTA Playbook: Testing Gravity

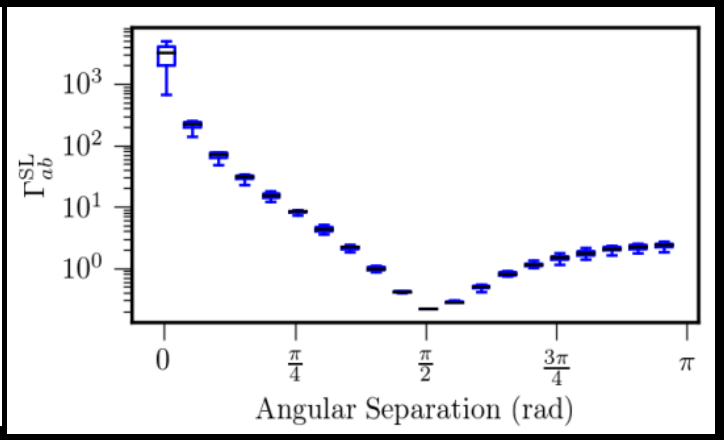
$$S[g,\phi] = \int d^4x \sqrt{-g}\left(\frac{M_p^2}{2}R - \frac{1}{2}(\partial\phi)^2 + \text{Horndeski} - \text{GB terms} + \cdots\right)$$

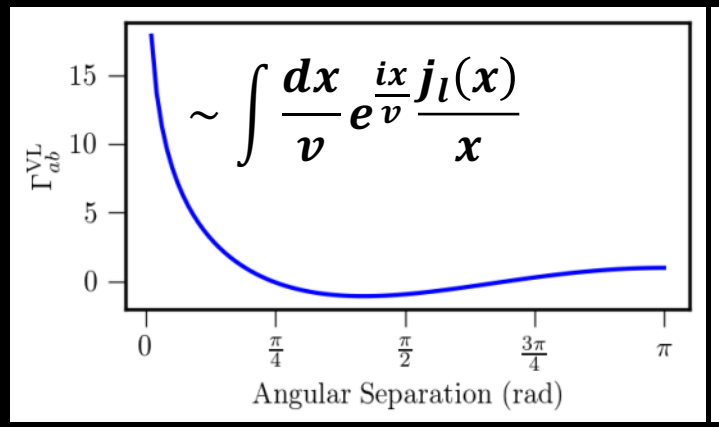
GW Polarizations: Beyond Einstein

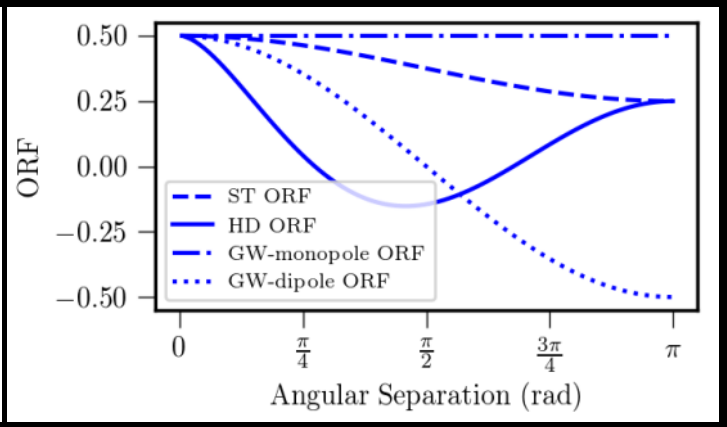


Accessed 30 June 2022:
https://www.ligo.org/science/Publication-GW170814/images/figure5.png



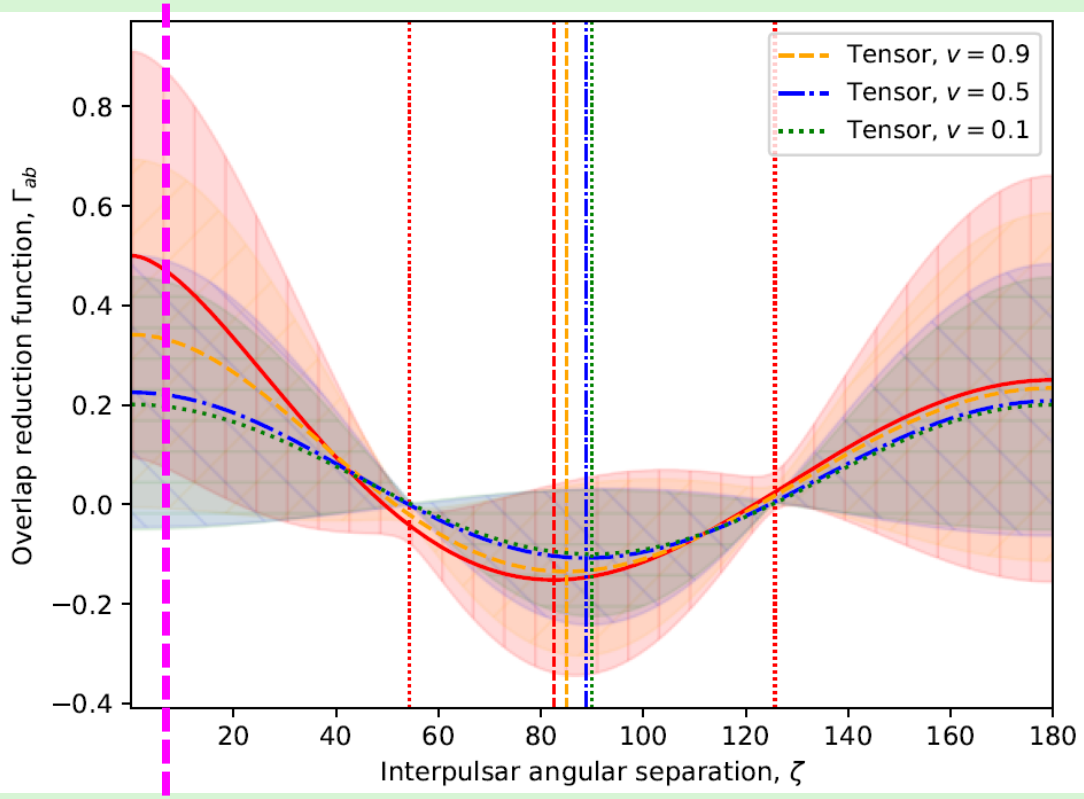






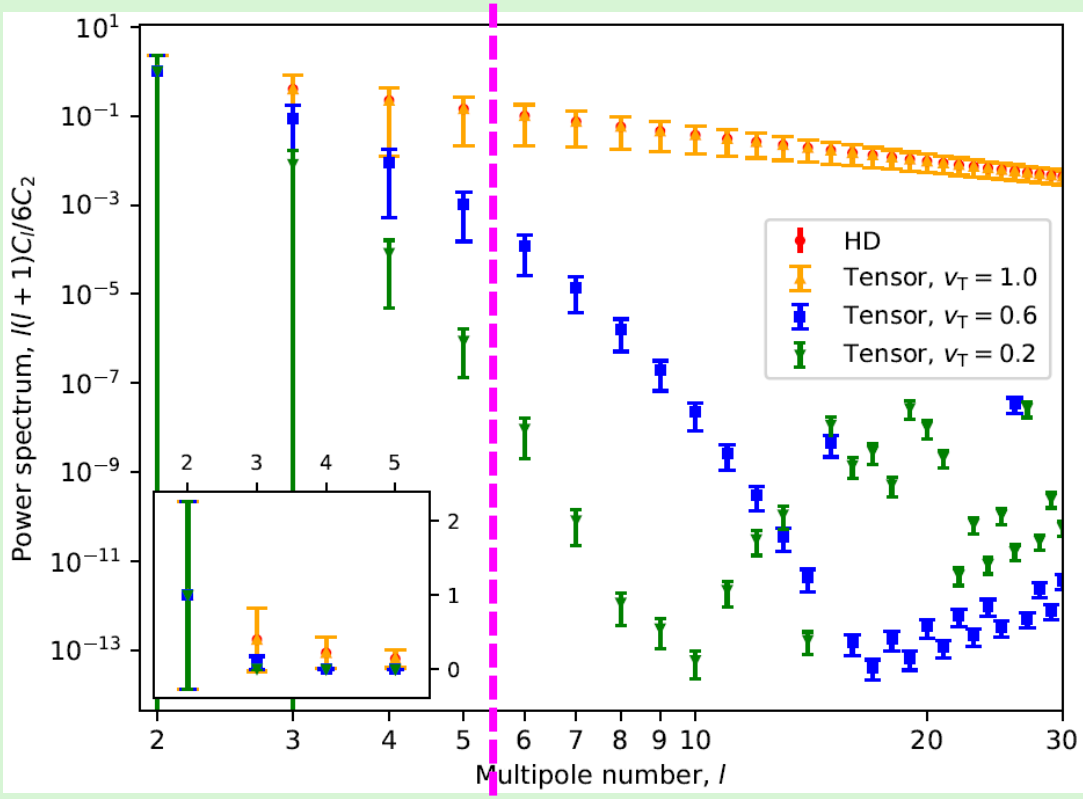
NANOGrav: arXiv:2109.14706

CORRELATION



NG15 →

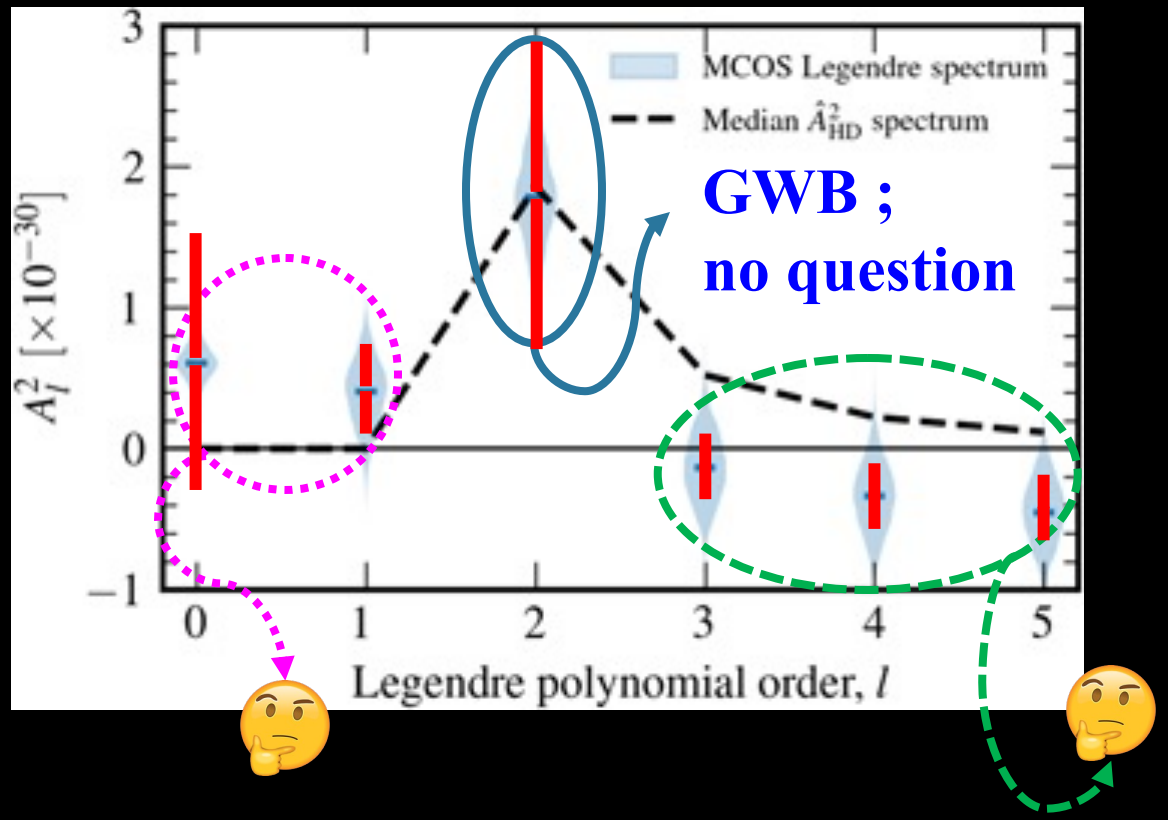
POWER SPECTRUM



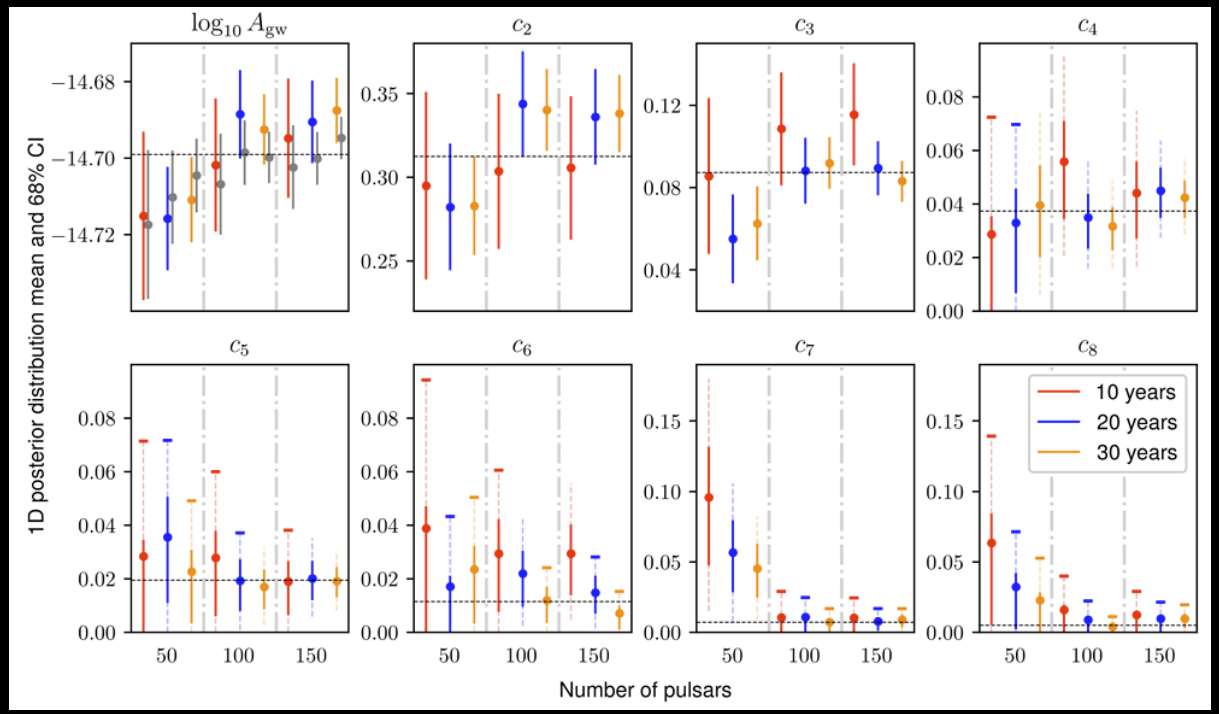
← NG15

NG15 + future projections ~ CV-precise

NANOGrav 15 years detection paper



2306.06168 (Nay, Boddy, Smith, Mingarelli)



Forecast ~ 150 MSPs + 30 yrs PTA ~ $l \leq 8$

Anisotropy and Polarization

Anisotropy
and
Polarization

- Cosmological source ~ Isotropic
- Individual SMBHBs ~ Anisotropy
- Finite N_{sources} ~ Anisotropy
- Linear/Circular GW Polarization

What if?

Correlation = Hellings-Downs

+ Anisotropy + Polarization

Some Highlights

Mingarelli et al., Characterising SGWB **anisotropy** with **Pulsar Timing Arrays**, **1306.5394**---Anisotropy in SGWB using RSF

Liu & Ng, Timing-residual power spectrum of a **polarized** SGWB in **pulsar-timing-array** observation, **2201.06767**---Keep Pulsar Terms

2013

2019

2022

2023

Hotinli, Kamionkowski, Jaffe, The search for **anisotropy** in the GWB with **PTA**s, **1904.05348**---Harmonic Analysis

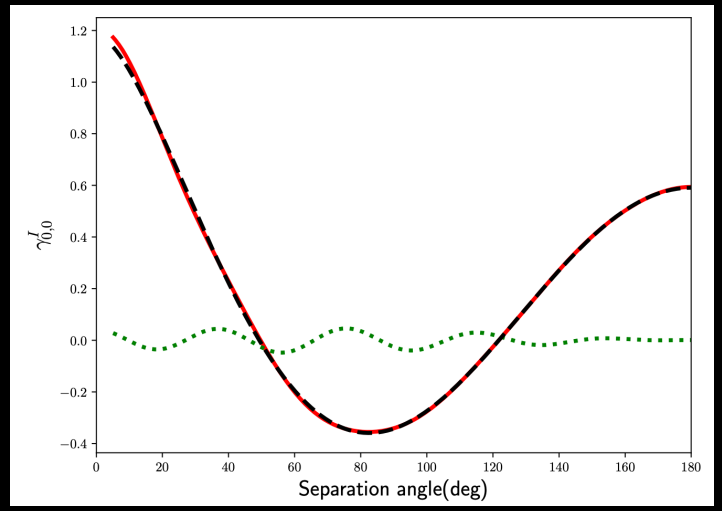
RCB, Liu, & Ng, **2312.03383**

Anil Kumar & Kamionkowski, 2311.14159

Anil Kumar et al. 2312.03056

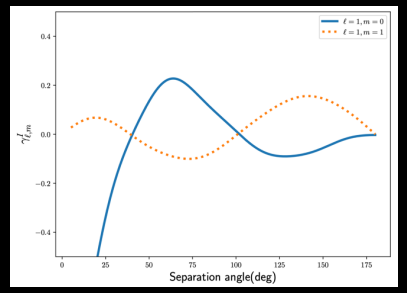
Standard GR-Tensor Case

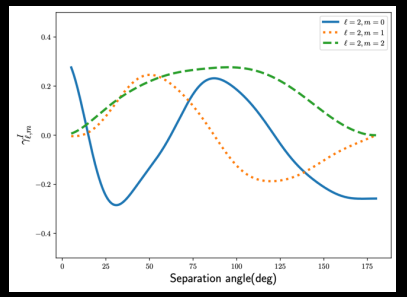
Chu, Liu, & Ng, 2107.00536



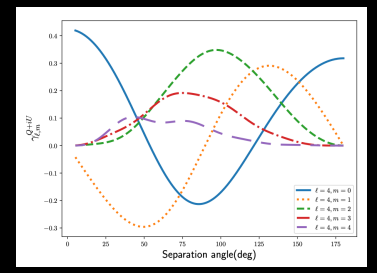
HD/Isotropic

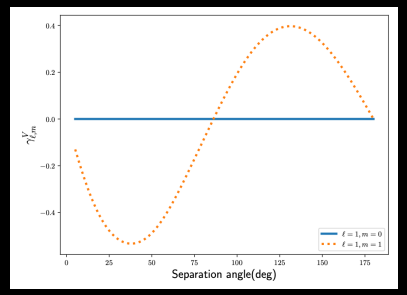
Leading Anisotropy

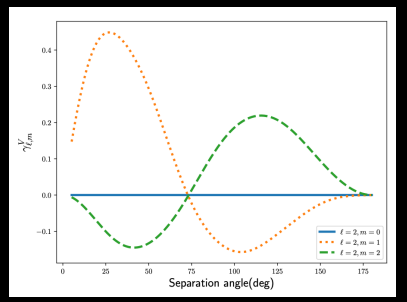


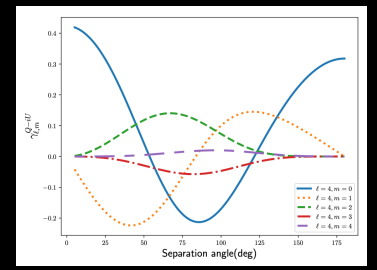


Leading Polarization









NG15/CPTA

Correlations for anisotropic polarized SGWB

$$\gamma_{lm}^{I,V}(fD_a, fD_b, \zeta) = \sum_{l_1 l_2} (-1)^m \left(\frac{2l_1+1}{4\pi}\right) \left[1 \pm (-1)^{l+l_1+l_2}\right] C_l^{\mathbf{T}}(fD_a, fD_b) Y_{l_2 m}(\zeta, 0)$$

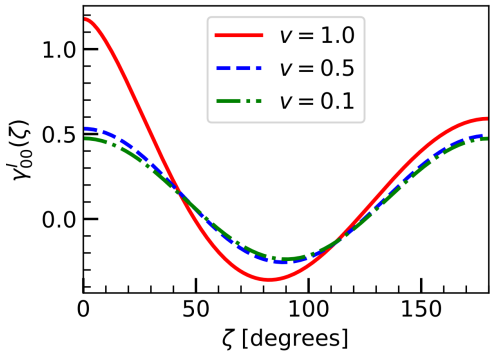
$$\times \sqrt{(2l+1)(2l_2+1)} \begin{pmatrix} l & l_1 & l_2 \\ 0 & -2 & 2 \end{pmatrix} \begin{pmatrix} l & l_1 & l_2 \\ m & 0 & -m \end{pmatrix}$$

3j-symbols
spin-2 field

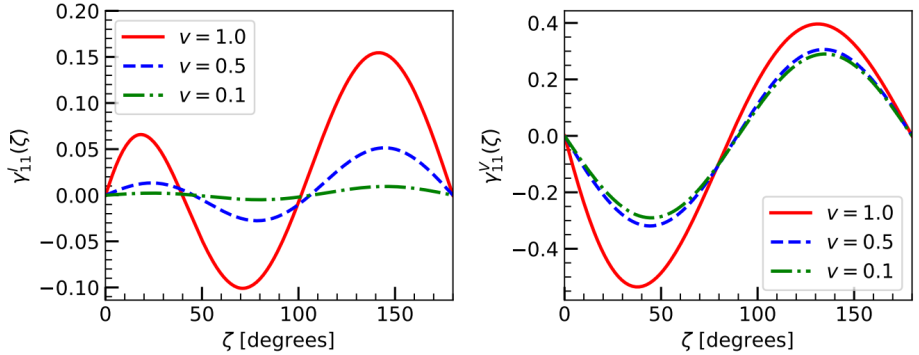
$$\gamma_{lm}^{Q \pm iU}(fD_a, fD_b, \zeta) = \sum_{l_1 l_2} (-1)^m \left(\frac{2l_1+1}{4\pi}\right) C_l^{\mathbf{T}}(fD_a, fD_b) Y_{l_2 m}(\zeta, 0)$$

$$\times \sqrt{(2l+1)(2l_2+1)} \begin{pmatrix} l & l_1 & l_2 \\ \mp 4 & \pm 2 & \pm 2 \end{pmatrix} \begin{pmatrix} l & l_1 & l_2 \\ m & 0 & -m \end{pmatrix}$$

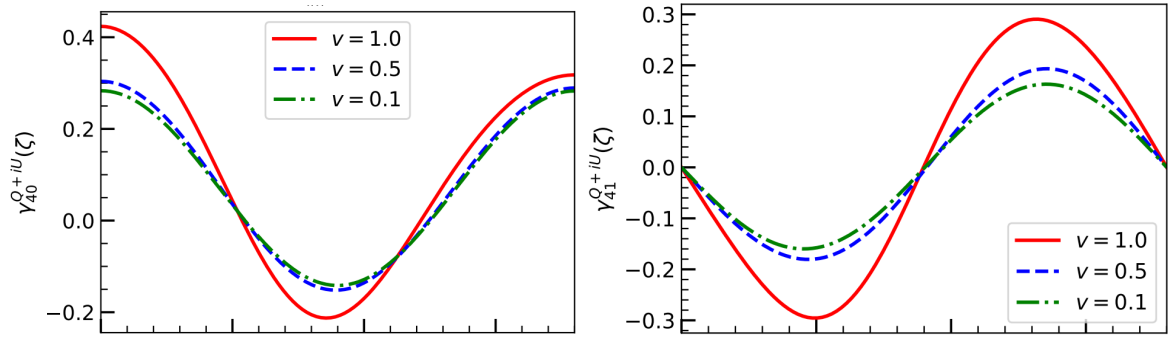
Isotropic SGWB—$l = m = 0$



Anisotropic SGWB—$l = 1$, $m = 1$



Anisotropic Polarized SGWB—$l = 4$, $m = 0, 1$

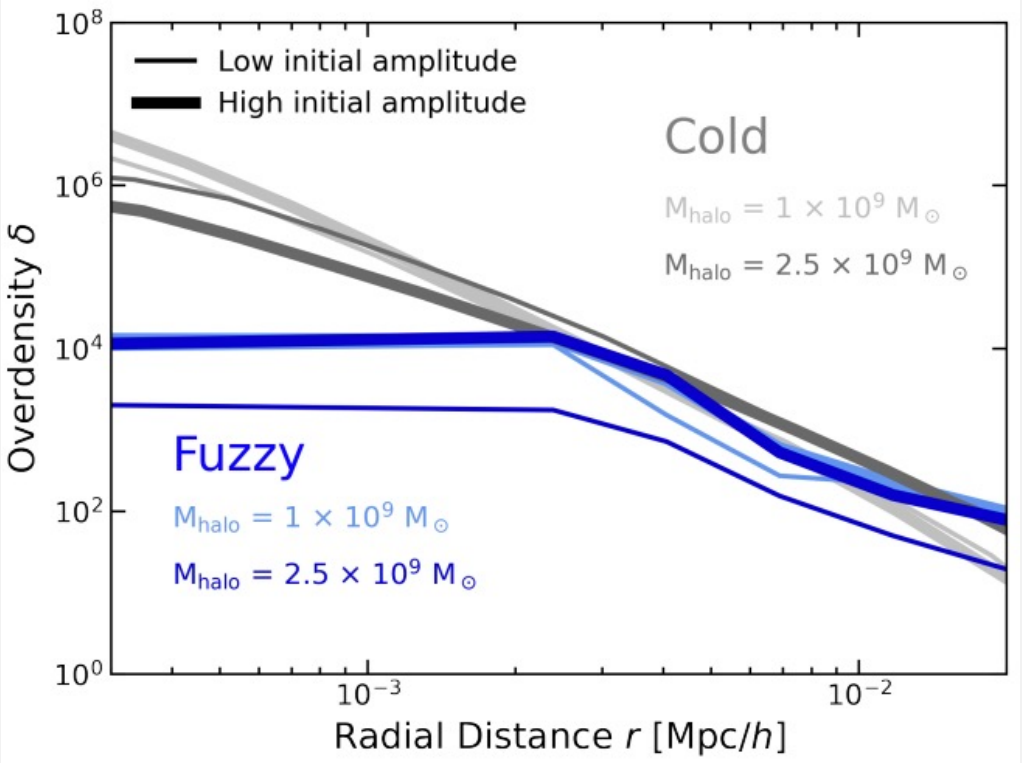


Fuzzy Dark Matter

Accessed 22 Jan 2024—https://scx2.b-cdn.net/gfx/news/2019/1-newfuzzydark.jpg

Fuzzy Dark Matter

- CDM~good enough for cosmology
- Fuzzy Dark Matter
  - $m \sim 10^{-22}$ eV
  - Core-cusp problem
  - Satellites problem
  - Central Black Holes



Accessed 22 Jan 2024—https://curj.files.wordpress.com/2022/05/screen-shot-2022-05-30-at-3.26.29-pm.png

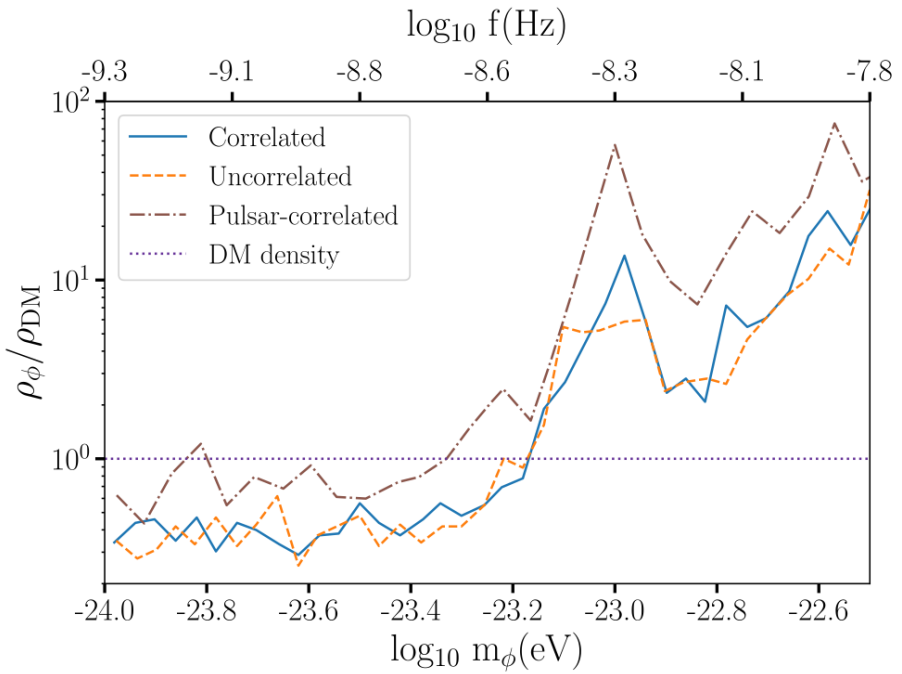
Pulsar Timing Array Searches

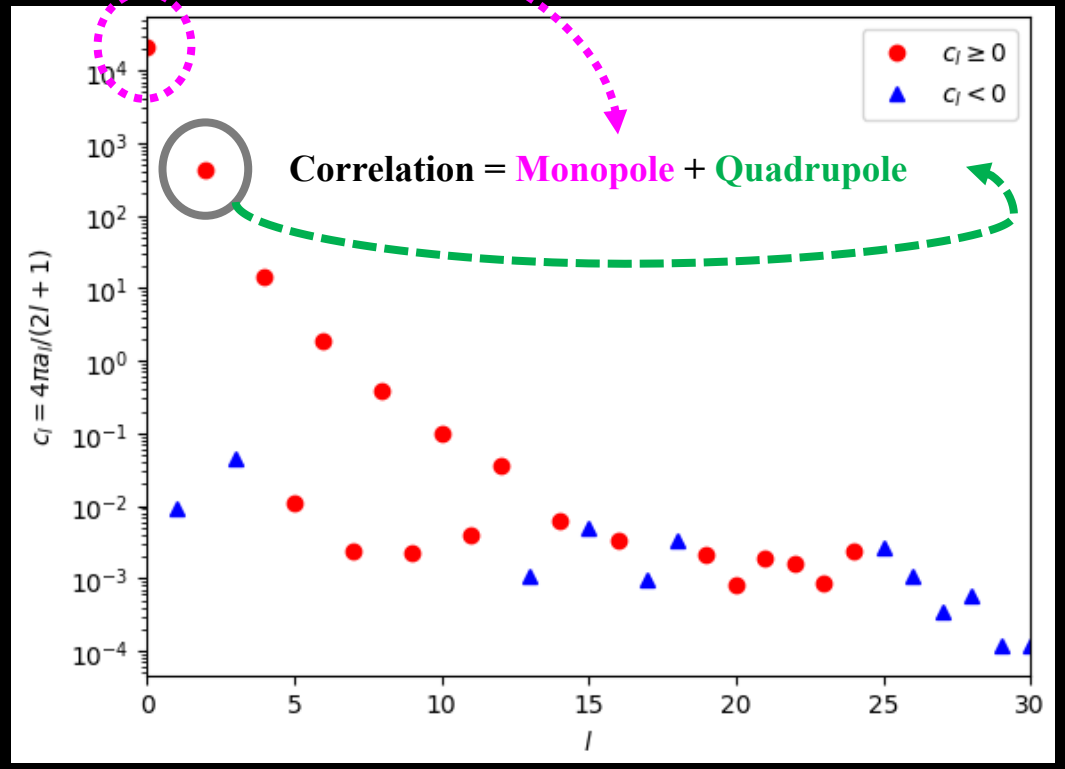
- Khmelnitsky & Rubakov, Pulsar timing signal from ultralight scalar dark matter, 1309.5888
- N.K. Porayko, K.A. Postnov, Constraints on ultralight scalar dark matter from pulsar timing, 1408.4670
- Inter-pulsar correlation~Monopole

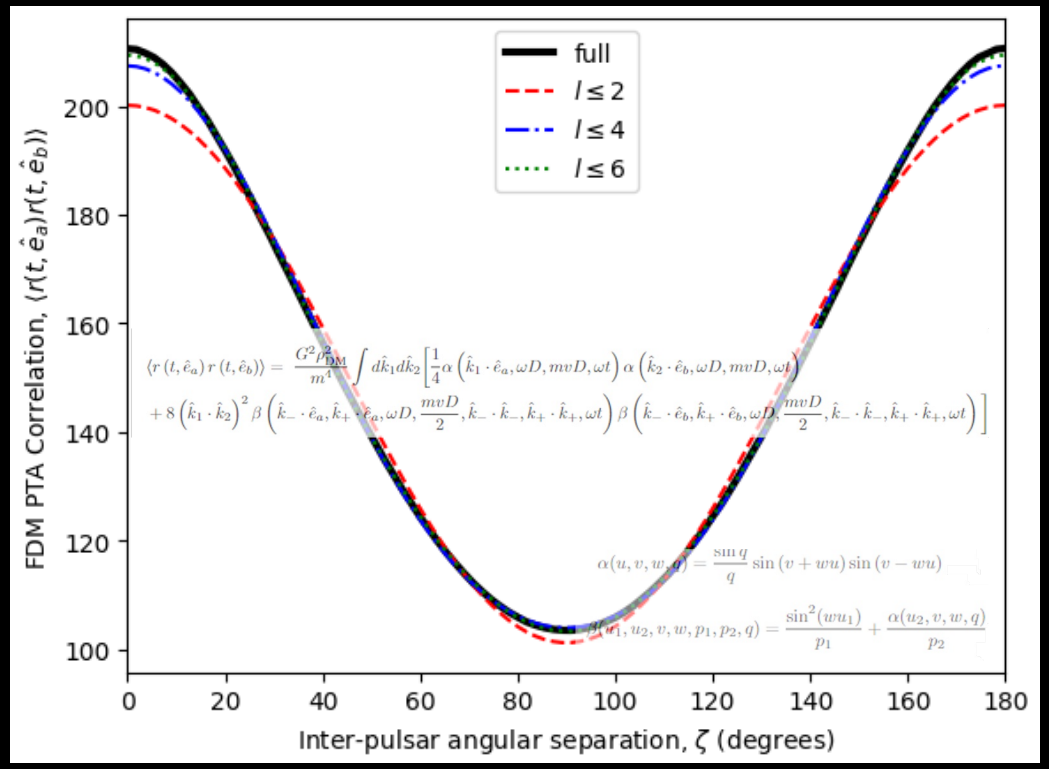
$$r(t) = \mathrm{FDM}$$

$$\zeta_{\alpha\beta} = 1/2(1 + \delta_{\alpha\beta})$$

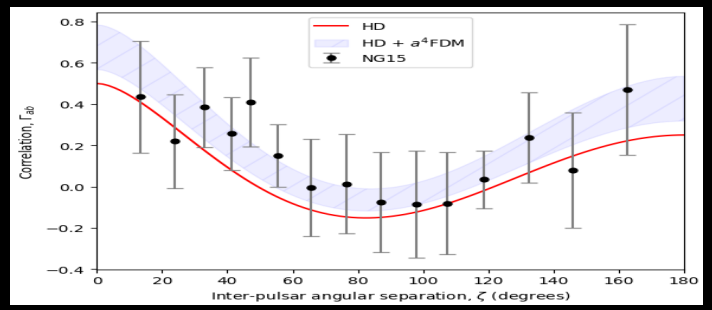
EPTA PRL 2023



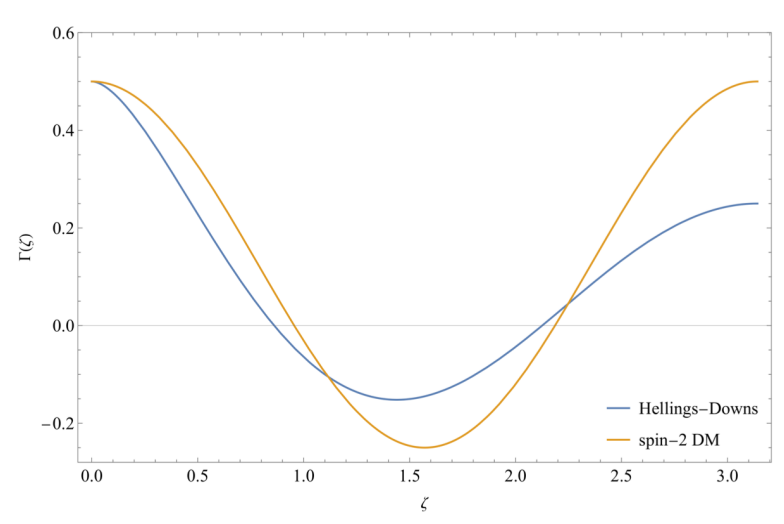




Fuzzy Dark Matter (*in prep*)



$$\sigma^2_{\substack{\text{cosmic}\\\text{pol}}} = \sigma^2_{\substack{\text{cosmic}\\\text{unpol}}} + \frac{103}{6300}\mu^2_{\text{u}}(\gamma)\sum_j A_j^4$$

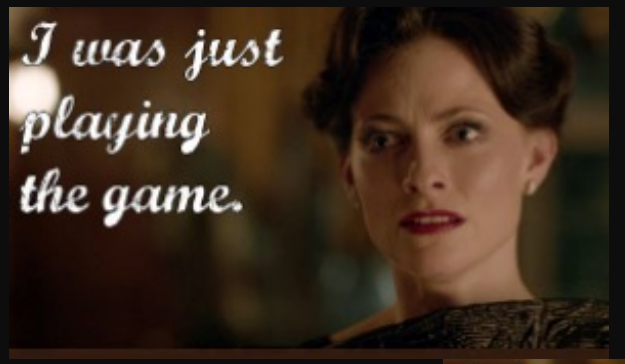


Recent highlights by others (zero credits to me!)

- Allen & Valtolina, 2401.14329—finite sources
- Cai, Zhang, & Zhang, 2402.03984—spin-2 ULDM
- Kehagias & Riotto, 2401.10680—HD unmasked

$$\Gamma_{ab} = \alpha\,\sigma_{ab}\ln\sigma_{ab} + \beta\,\sigma_{ab} + \Gamma_v$$

Outlook



Accessed 24 Nov. 2023
https://i.pinimg.com/736x/60/5d/0f/60
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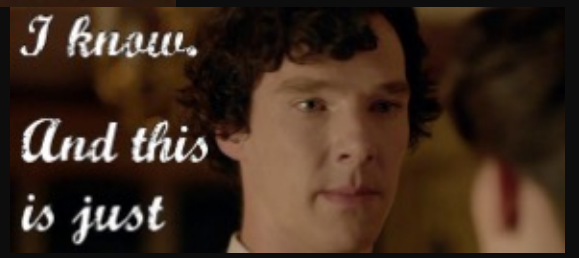

PTAfast: PTA correlations from SGWB [ascl:2211.001]

RCB & KWN

- ✓ **PS formalism** for **mean** and **variance** of **SGWB correlations**;
- ✓ **Phenomenology** of **subluminal GW polarizations** for **finite pulsar distances**;
- ✓ Analysis of **tensor & vector polarizations** off the light cone;
- ✓ **Scalar/Vector** constraints;
- ✓ **Playbook** for **Testing Nanohertz Gravity**.

- ❑ **Anisotropy; Fuzzy DM correlations; Coding; Coding; Coding**