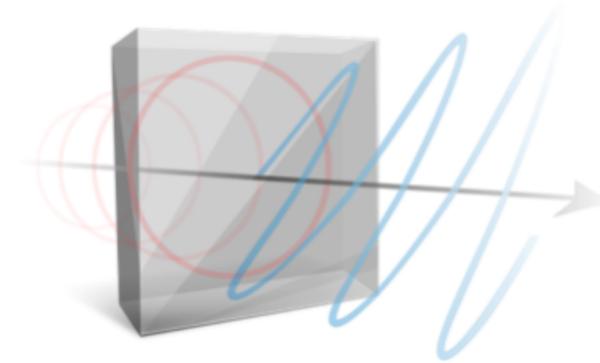


*Cross-Strait 2026*  
*Guangzhou, Jan 2026*



# **Unveiling Ultralight Axion-like Dark Matter — A PPA-PTA Method**

**Tao LIU**

**(The Hong Kong Univ. of Science & Technology)**

# Some Basics of Pulsars



Jocelyn Bell photographed in 1968 outside the Mullard Radio Astronomy Observatory at the University of Cambridge.  
Credit: National Media Museum / Science & Society Picture Library



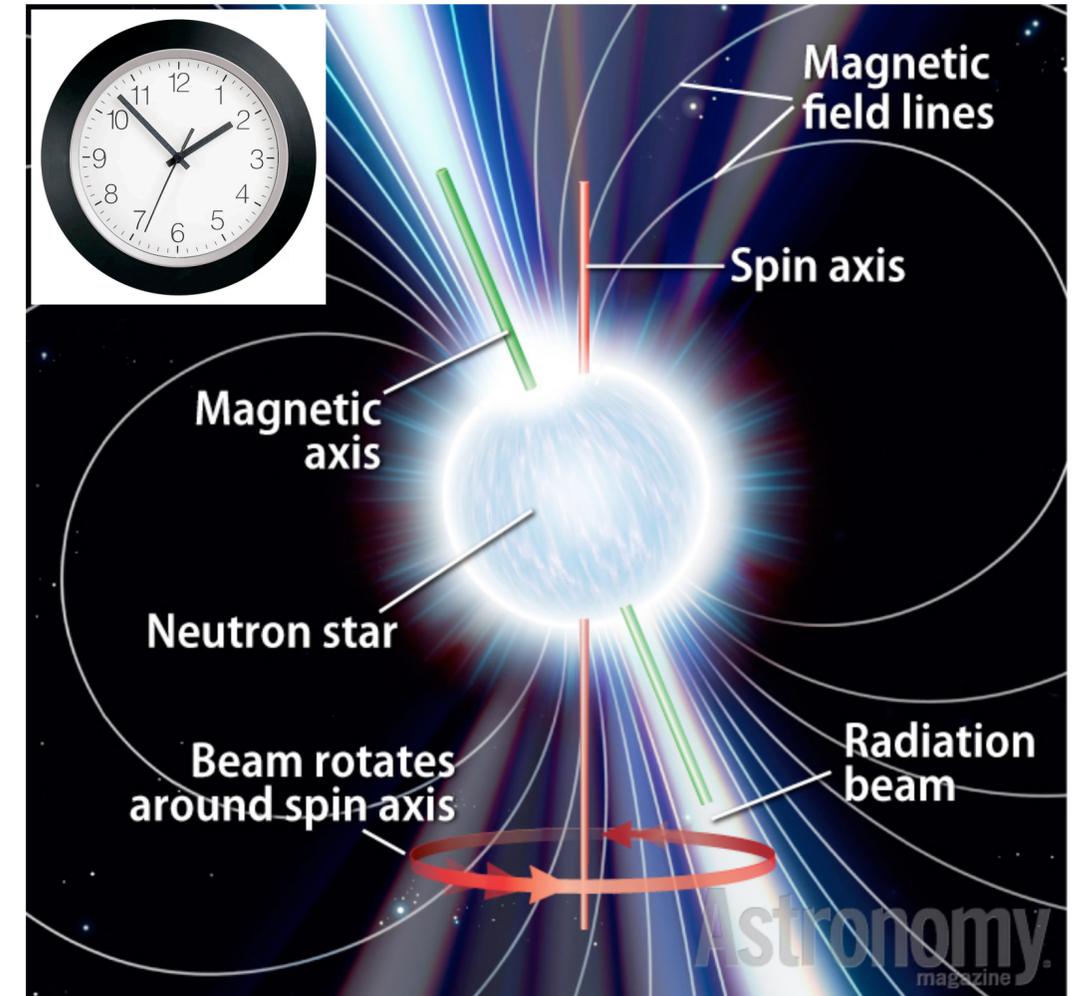
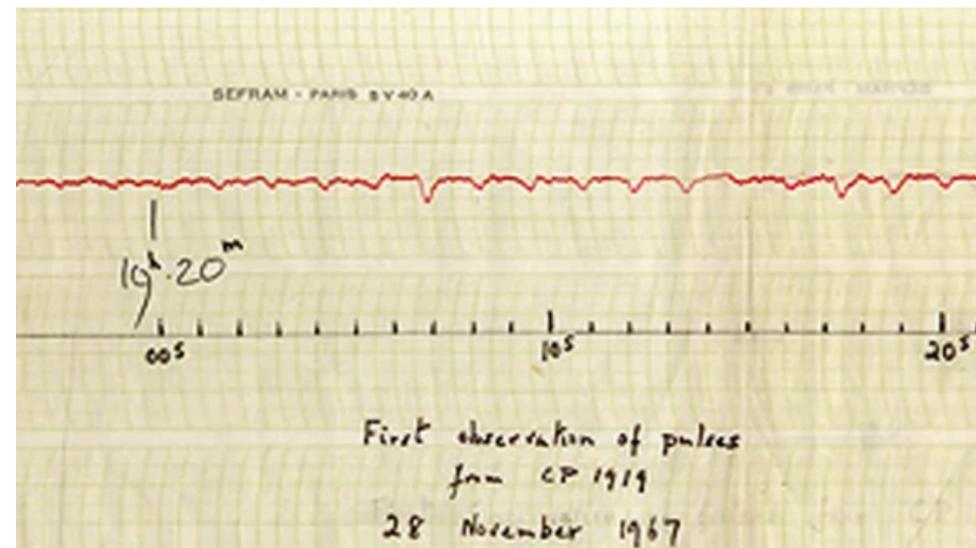
**Antony Hewish**



(Physics, 1974, shared with Ryle)

“... .. for his decisive role in the discovery of pulsars”

— [www.nobelprize.org](http://www.nobelprize.org)



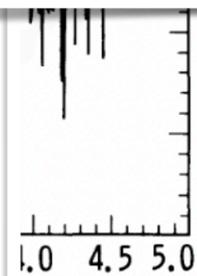
- Pulsating radio stars - remnants of stellar evolution (e.g., neutron stars, white dwarfs)
- Misaligned spin and magnetic axes => Send pulses with extremely high regularity

# Pulsar Timing Array (PTA)

THE ASTROPHYSICAL JOURNAL, 265:L39–L42, 1983 February 15  
 © 1983. The American Astronomical Society. All rights reserved. Printed in U.S.A.

## UPPER LIMITS ON THE ISOTROPIC GRAVITATIONAL RADIATION BACKGROUND FROM PULSAR TIMING ANALYSIS<sup>1</sup>

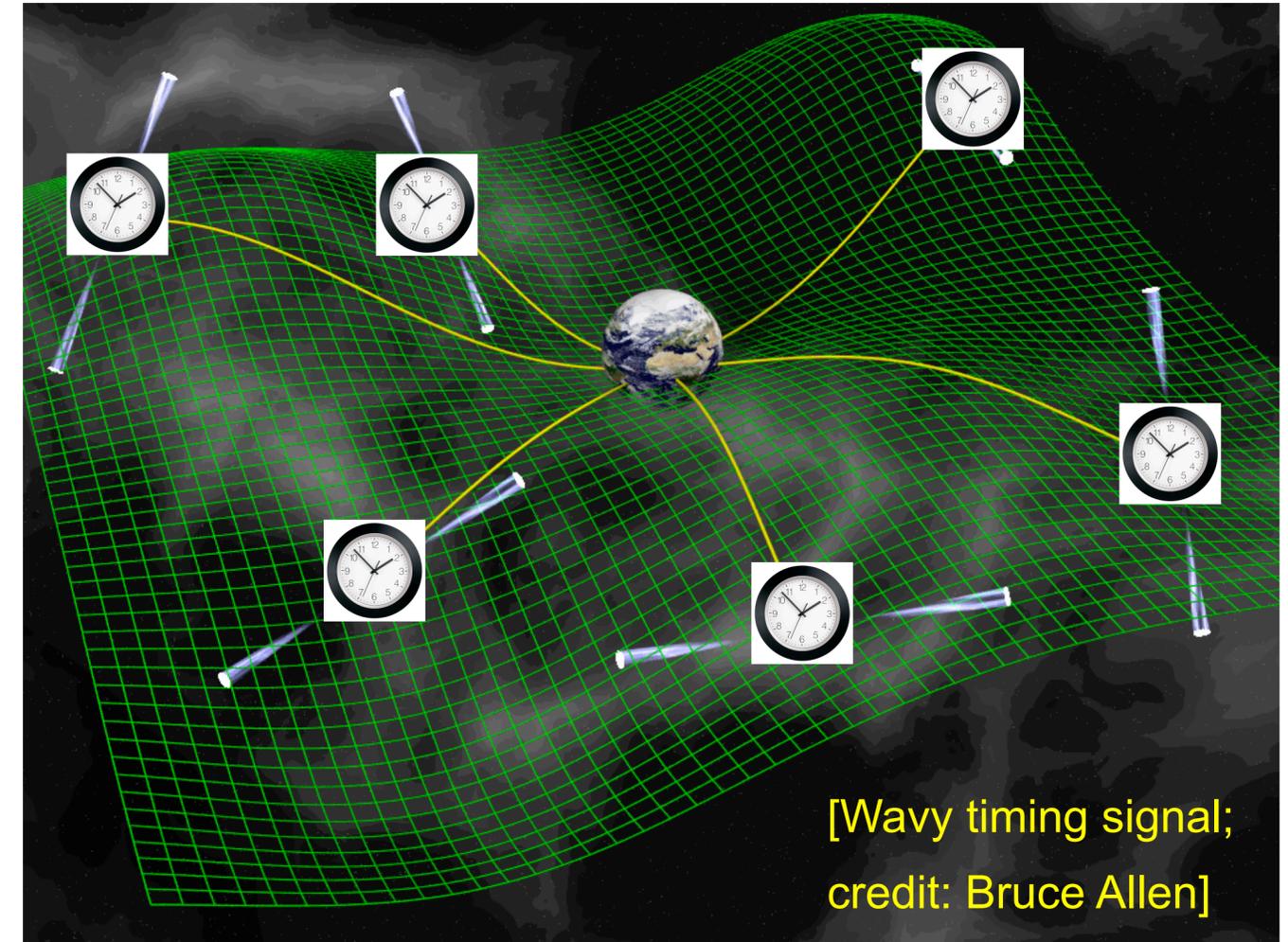
R. W. HELTINGS AND G. S. DOWNS  
 Jet Propulsion Laboratory, California Institute of Technology  
 Received 1982 October 1; accepted 1982 October 20



is an upper limit of about  $10^{-5}$  for the periods to which the data are sensitive. It should also be noted from equation (1) that data from any pulsar contain information about  $h(t)$  at the time and place of reception (i.e., at Earth) and about the value  $h(t)$  had at the pulsar at the time of emission of the signal. Thus, data from any pulsar will have a gravitational wave signal in common with all other pulsars (though with an amplitude scaled by  $1 - \cos \theta$ ) as well as a component of the signal which will be independent of the others due to the long light times between pulsars compared with the 12 yr data span. When data from several pulsars are cross-correlated, this common signal will allow one to dig into the pulsar noise to detect a possible common gravitational wave signal.

### b) Cross-Correlation

The fractional frequency shift observed in the data on pulsar number  $i$  may be written



[Wavy timing signal; credit: Bruce Allen]

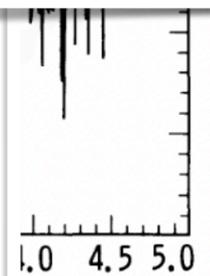
- A network of widely distributed and well-timed MSPs, proposed to detect nanoHz gravitational waves (GWs) [Hellings and Downs, *Astrophys. J.* 265 (1983)]

# Pulsar Timing Array (PTA)

THE ASTROPHYSICAL JOURNAL, 265:L39-L42, 1983 February 15  
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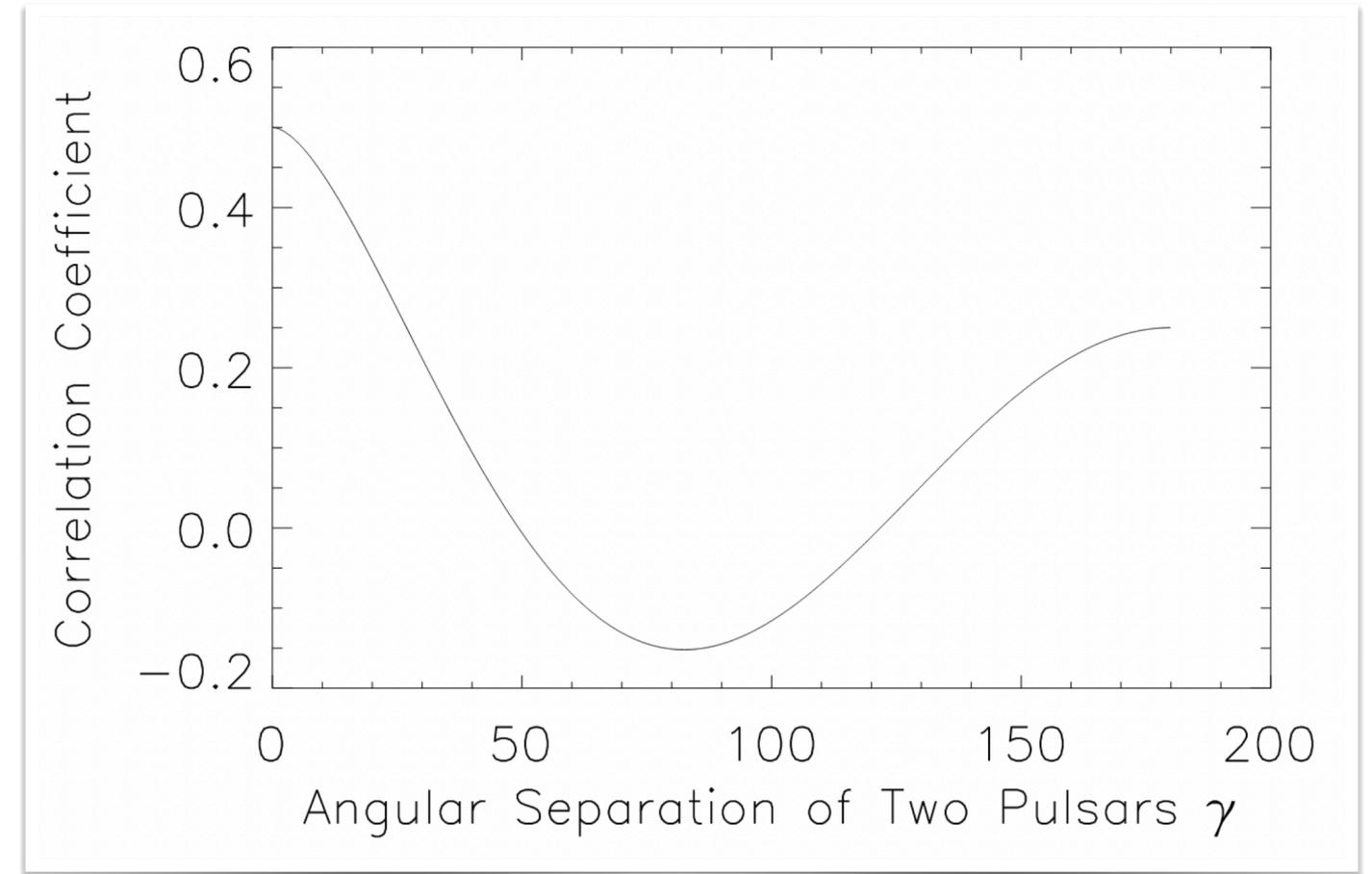
R. W. HELTINGS AND G. S. DOWNS  
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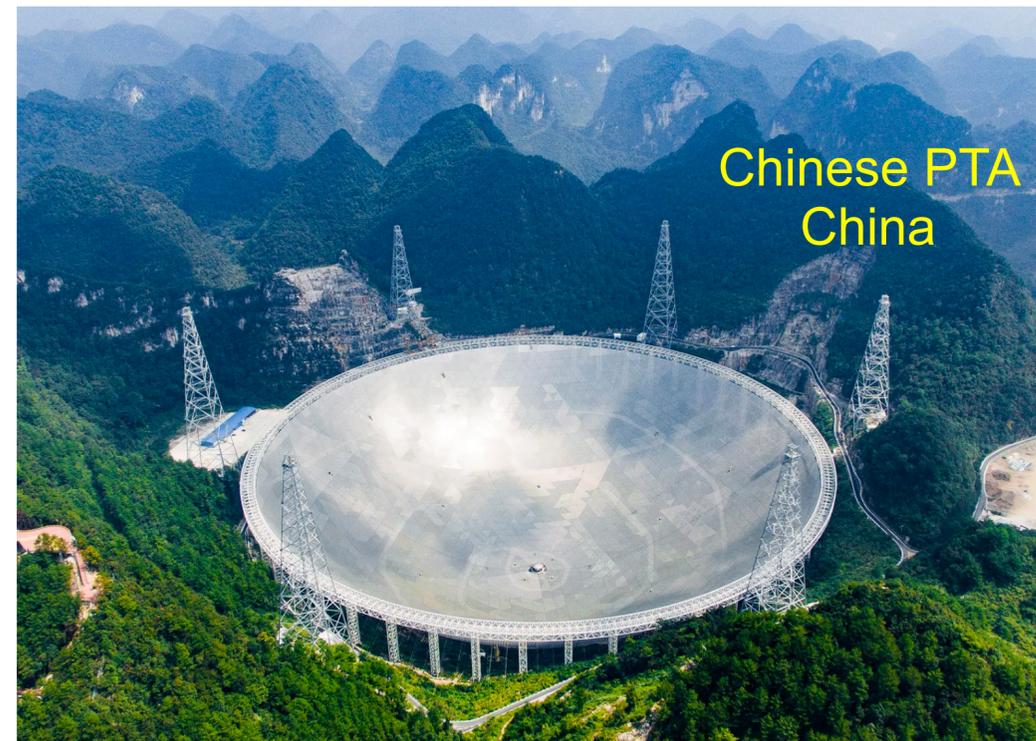
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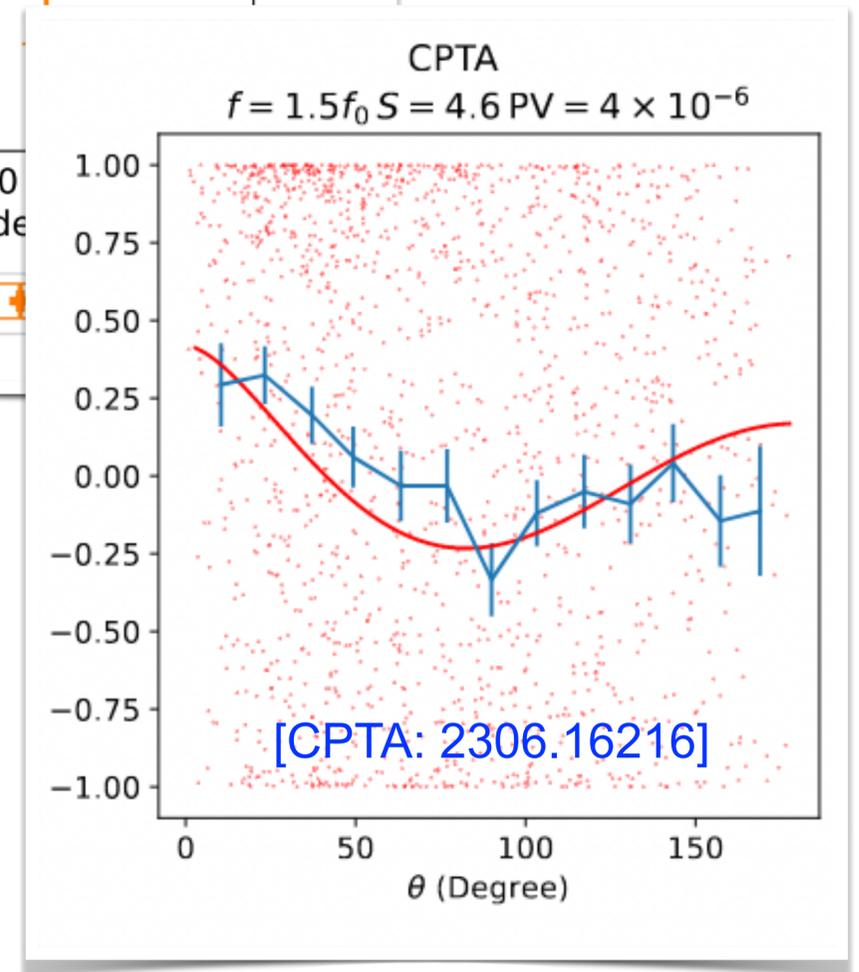
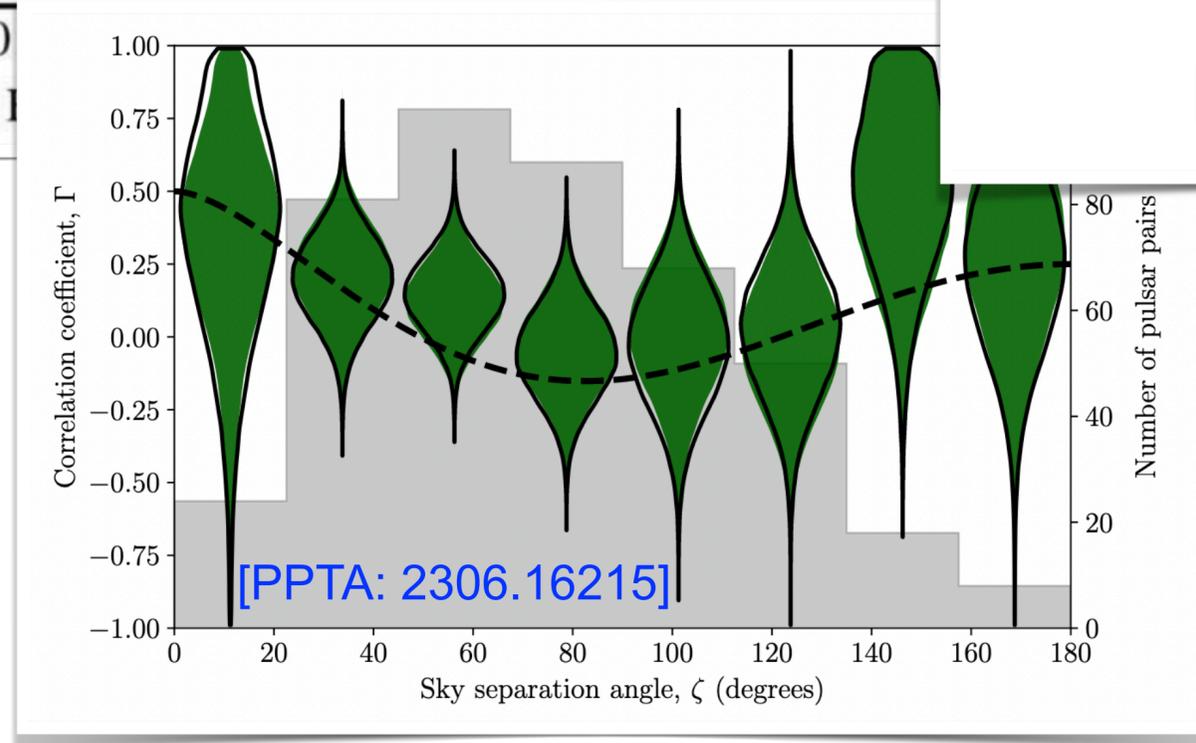
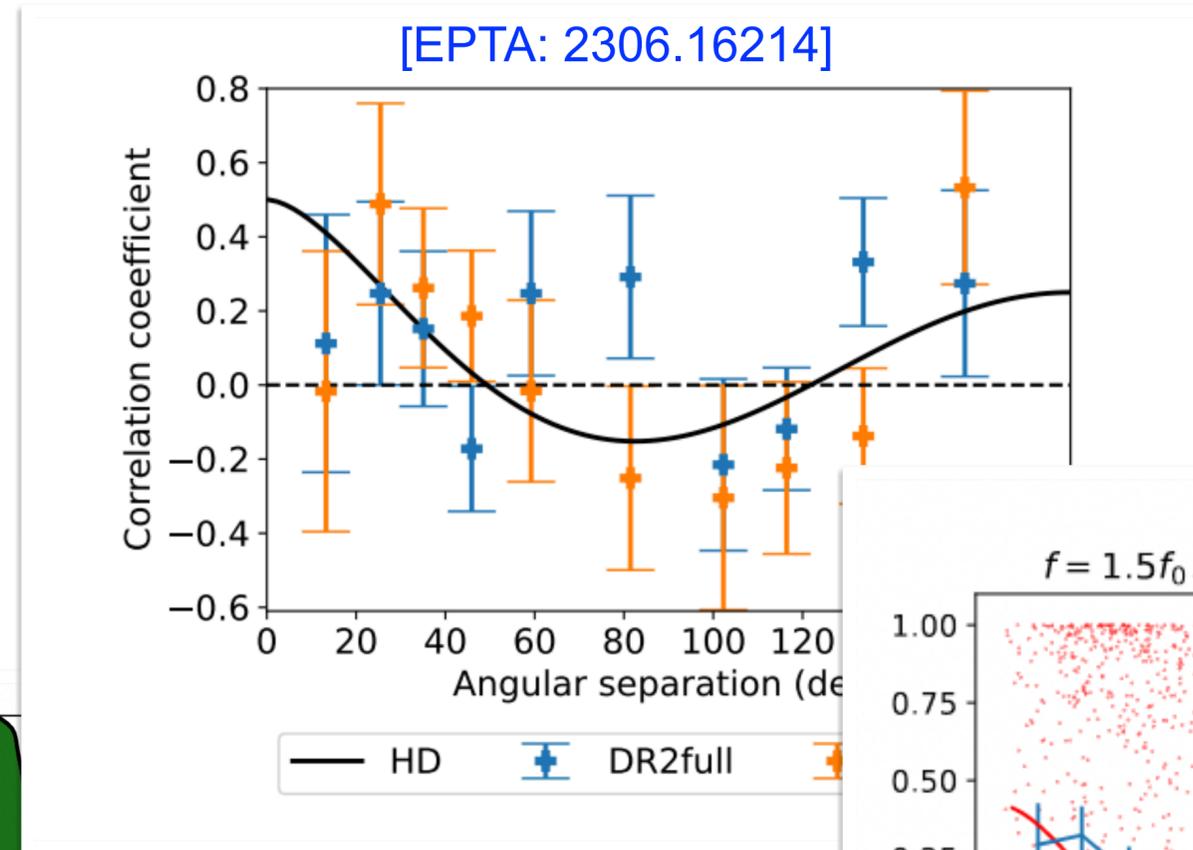
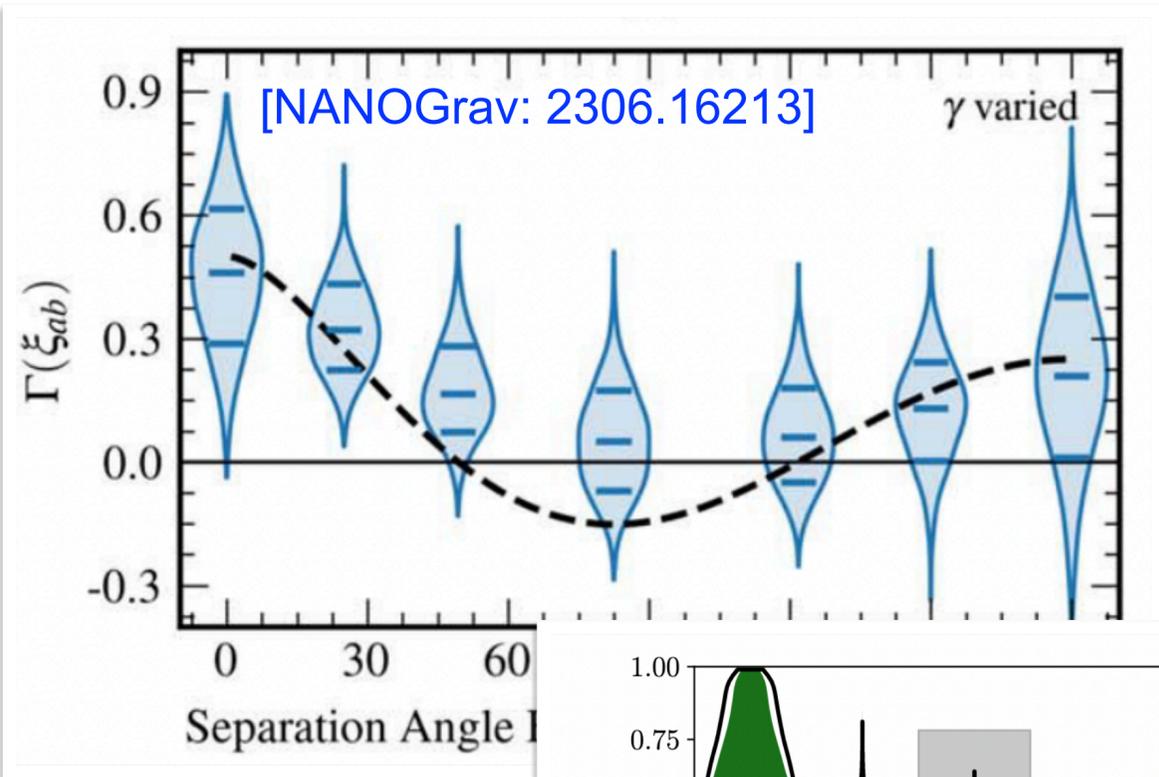
### Hellings-Downs Curve

Encodes exactly the cross-correlation of pulsar timing data that would indicate a common origin of GWs.

# Leading PTA Programs in the World

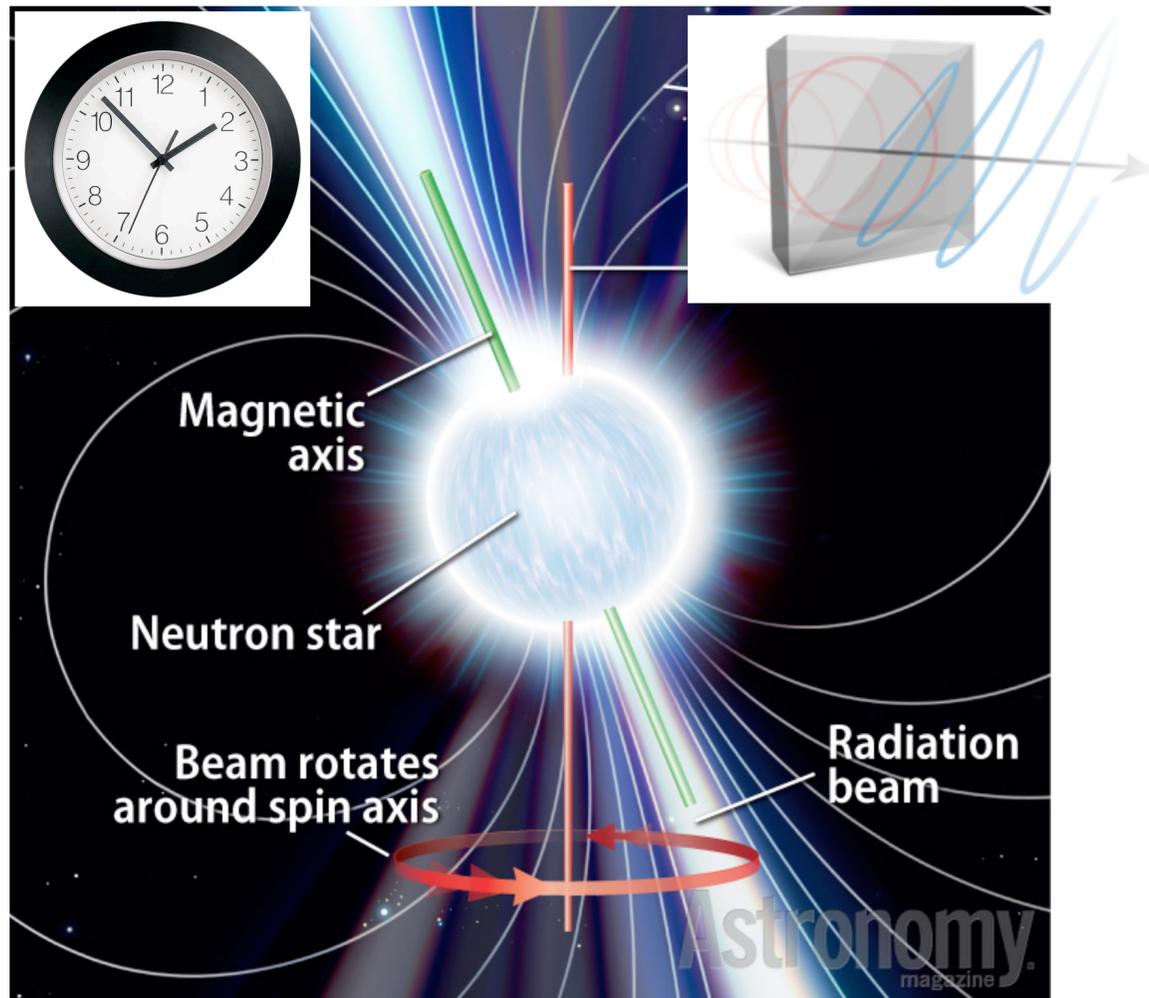


# A Milestone for GW Astronomy



Milestone for GW astronomy and roaring success for PTA programs

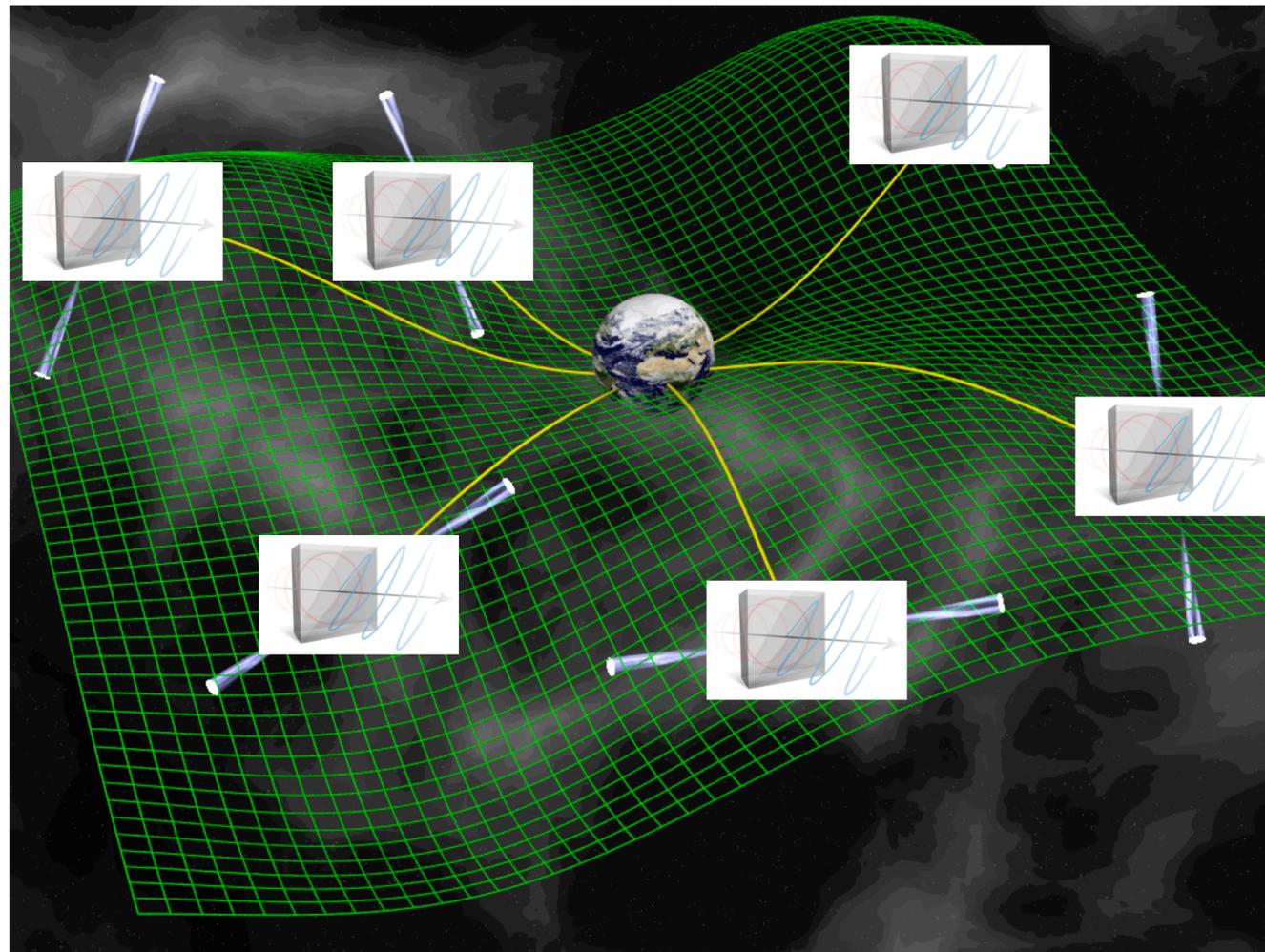
# Astronomical Source for Linearly Polarized Light



$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

- Polarization of pulsars has been monitored for decades for calibrating pulsar observation
- Timing residuals can be determined by phase profile of Stokes parameters

# Pulsar Polarization Array (PPA)



PHYSICAL REVIEW LETTERS **130**, 121401 (2023)

## Pulsar Polarization Arrays

Tao Liu,<sup>1,\*</sup> Xuzixiang Lou<sup>1,†</sup> and Jing Ren<sup>2,‡</sup>

<sup>1</sup>*Department of Physics, The Hong Kong University of Science and Technology, Hong Kong S.A.R., People's Republic of China*

<sup>2</sup>*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China*

(Received 21 February 2022; revised 31 December 2022; accepted 27 February 2023; published 23 March 2023)

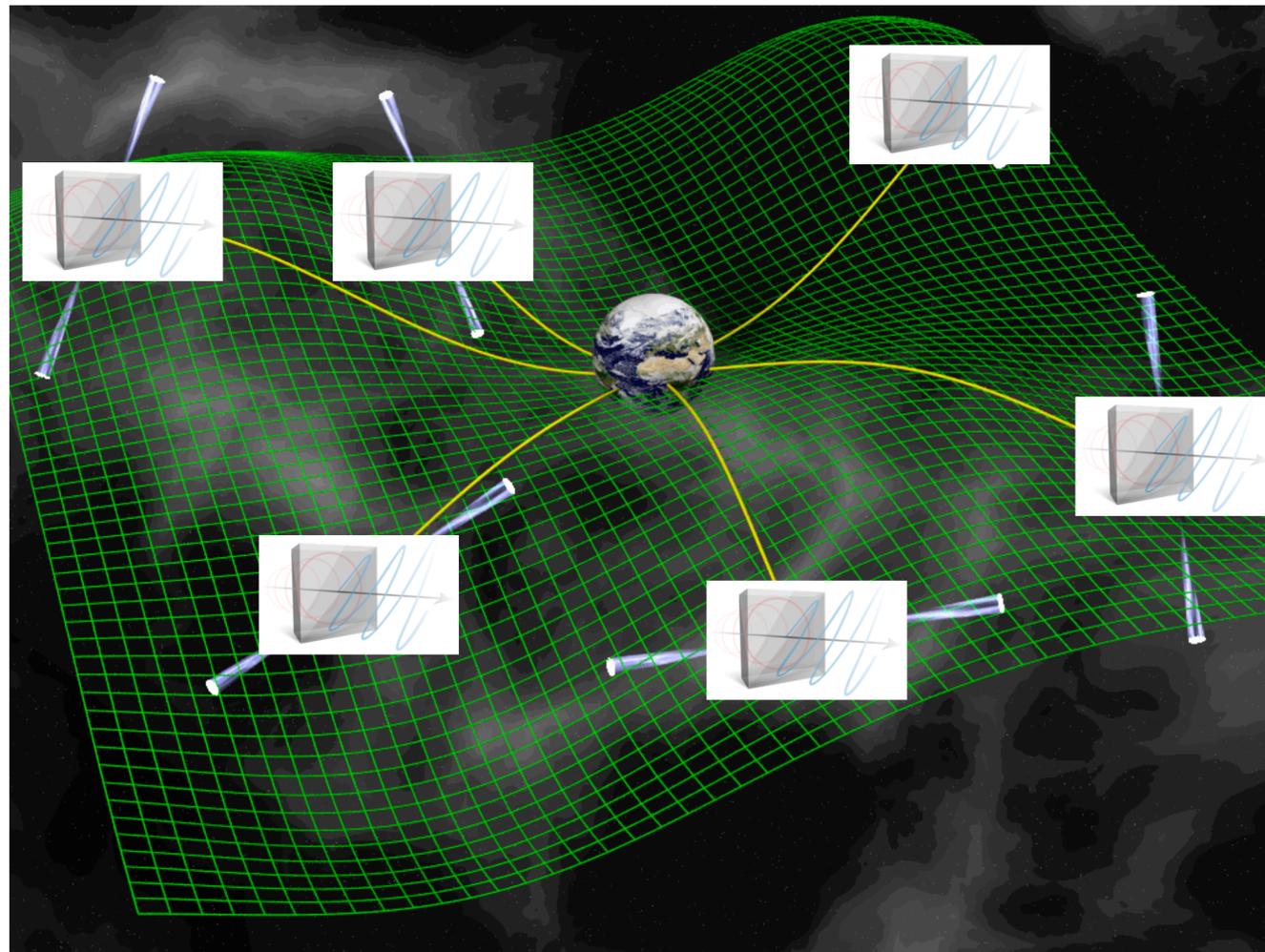
Pulsar timing arrays (PTAs) consisting of widely distributed and well-timed millisecond pulsars can serve as a galactic interferometer to measure gravitational waves. With the same data acquired for PTAs, we propose to develop pulsar polarization arrays (PPAs), to explore astrophysics and fundamental physics. As in the case of PTAs, PPAs are best suited to reveal temporal and spatial correlations at large scales that are hard to mimic by local noise. To demonstrate the physical potential of PPAs, we consider detection of ultralight axionlike dark matter (ALDM), through cosmic birefringence induced by its Chern-Simons coupling. Because of its tiny mass, the ultralight ALDM can be generated as a Bose-Einstein condensate, characterized by a strong wave nature. Incorporating both temporal and spatial correlations of the signal, we show that PPAs have a potential to probe the Chern-Simons coupling up to  $\sim 10^{-14} - 10^{-17} \text{ GeV}^{-1}$ , with a mass range  $\sim 10^{-27} - 10^{-21} \text{ eV}$ .

DOI: [10.1103/PhysRevLett.130.121401](https://doi.org/10.1103/PhysRevLett.130.121401)

Can we correlate (existing and expected) polarization data of different pulsars, as done for timing data, to explore astrophysics and fundamental physics?

**PTA:** suited for revealing physics with a common correlated **timing** signal  
**PPA:** suited for revealing physics with a common correlated **polarization** signal

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PHYSICAL REVIEW LETTERS **130**, 121401 (2023)

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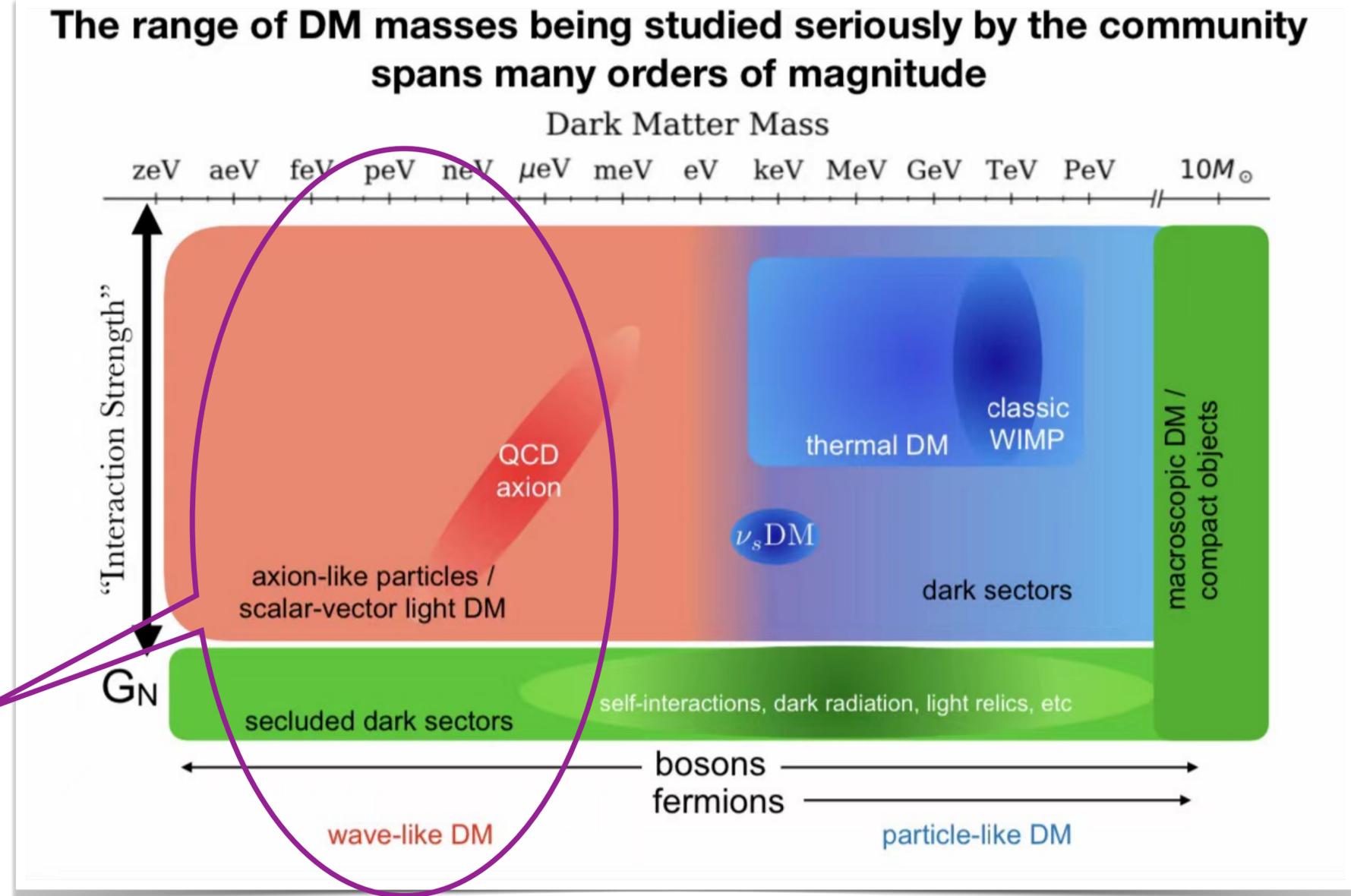
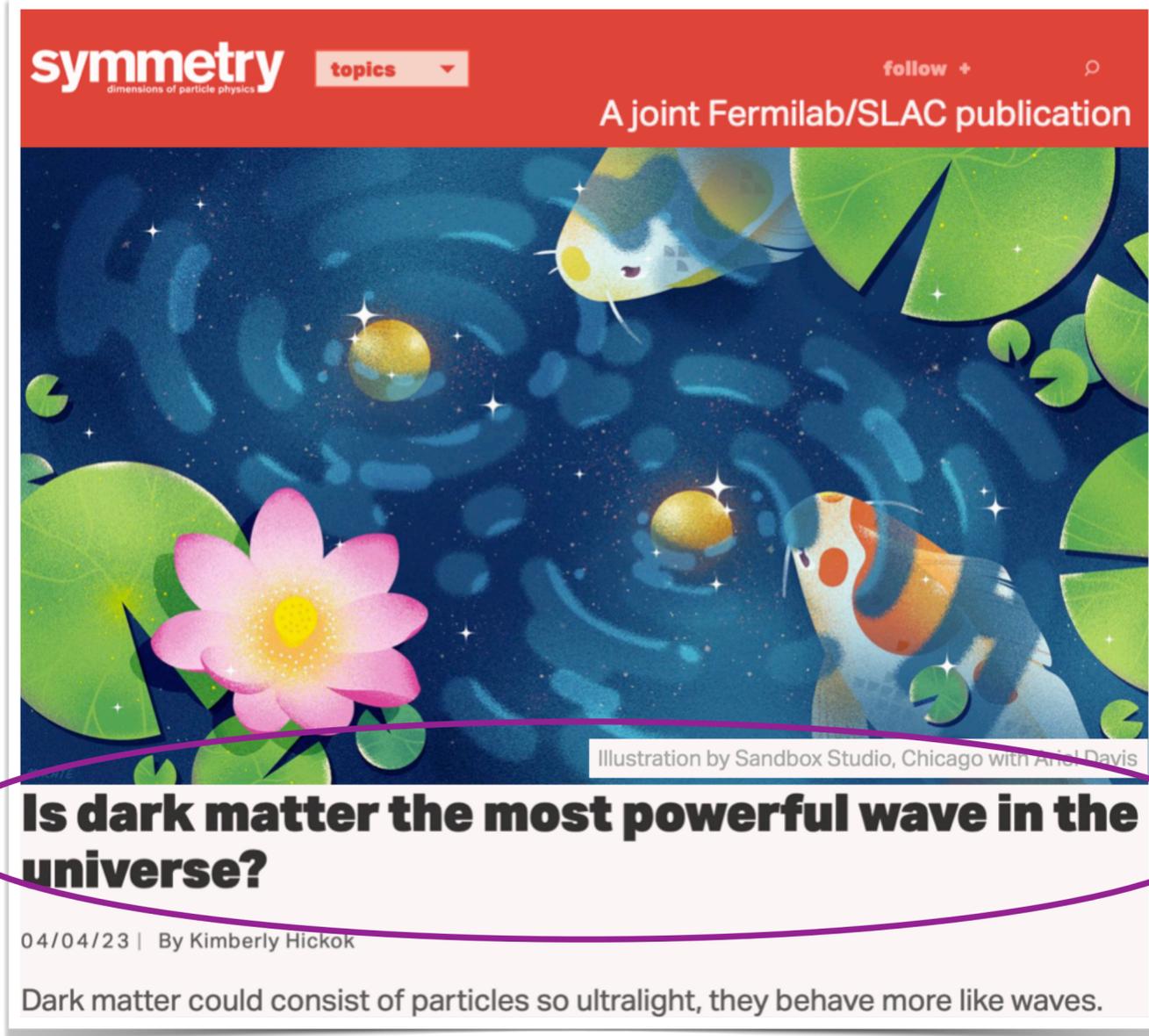
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DOI: [10.1103/PhysRevLett.130.121401](https://doi.org/10.1103/PhysRevLett.130.121401)

One scientific task for both PPA and PTA  
— **Detection of ultralight axion-like dark matter (ALDM)**

# Wave Dark Matter

[Aaron Chou, Snowmass 2021]



**Wave Dark Matter (WDM):** Bosonic and  $m \ll 30 \text{ eV}$   
 $\Rightarrow$  Large occupation number per de Broglie volume ( $N_{dB} \gg 1$ ) in a Milky-Way-like environment  
 $\Rightarrow$  Galactic halo  $\sim$  uncorrelated superposition of **particle waves**

# Ultralight Axion-like Dark Matter (ALDM)

[Aaron Chou, Snowmass 2021]

APS physics

APS Response to the Russian Invasion

PHYSICAL REVIEW D  
covering particles, fields, gravitation, and cosmology

Ultralight scalars as cosmological

Lam Hui, Jeremiah P. Ostriker, Scott Tremaine  
Phys. Rev. D **95**, 043541 – Published 28 February 2017

78

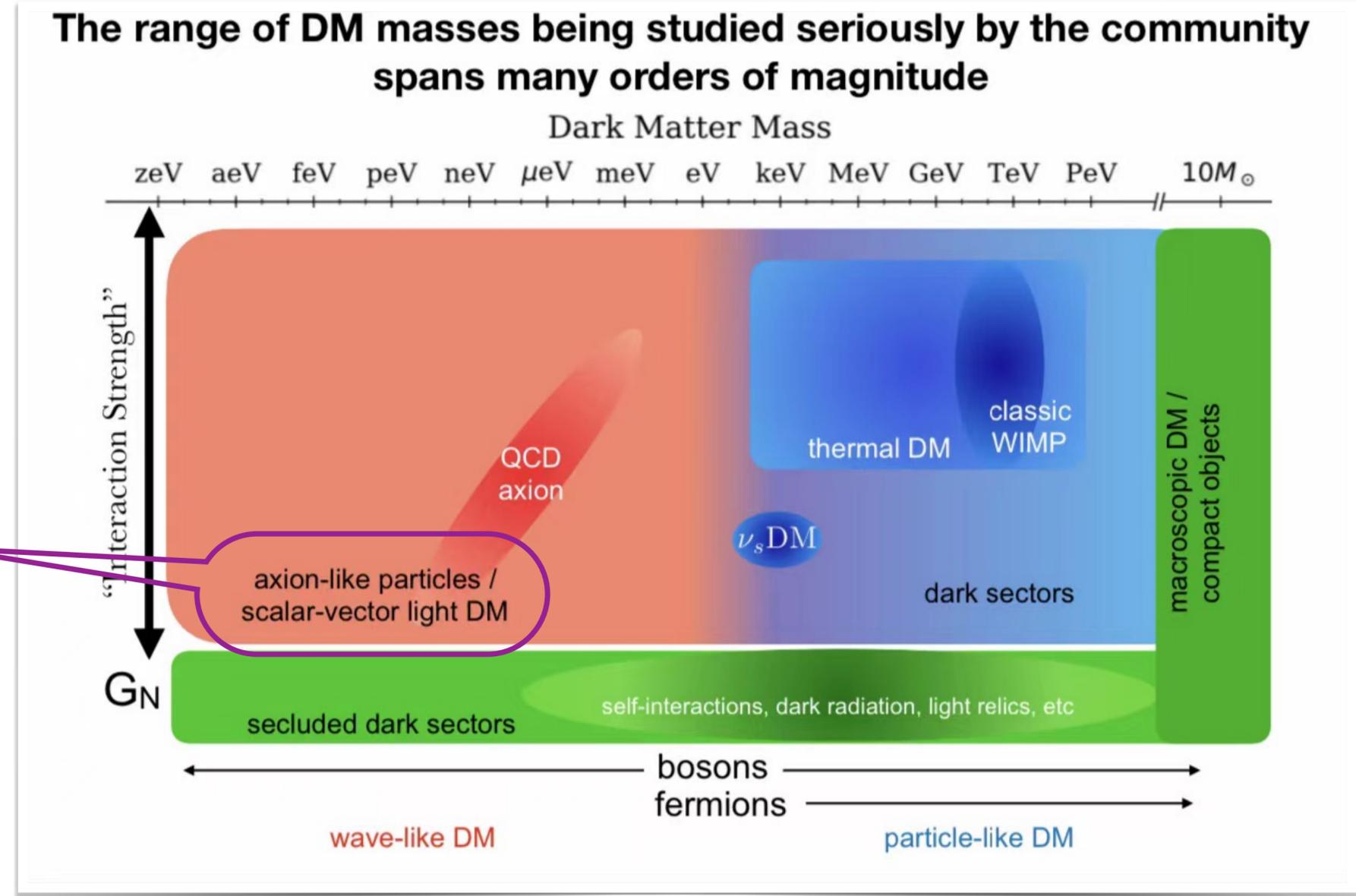
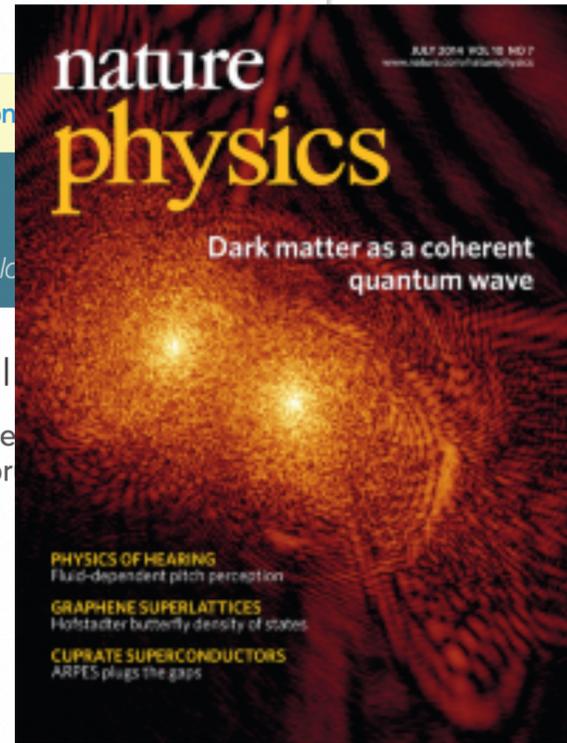
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ABSTRACT

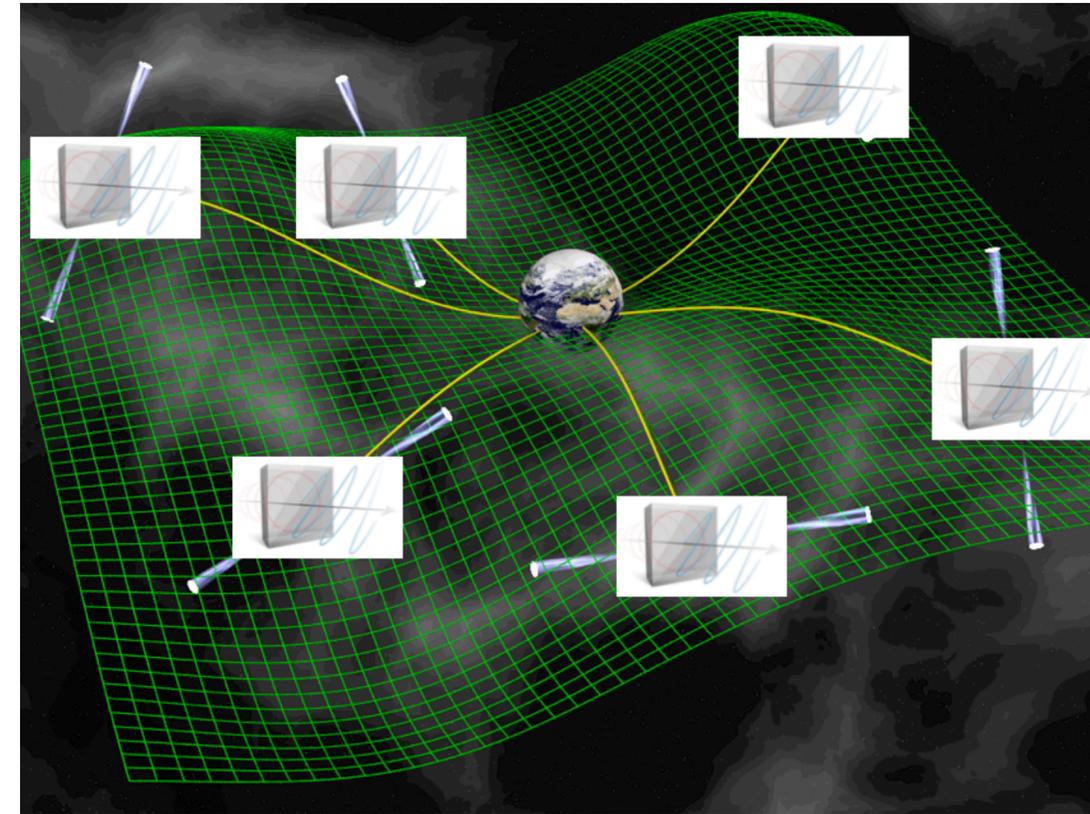
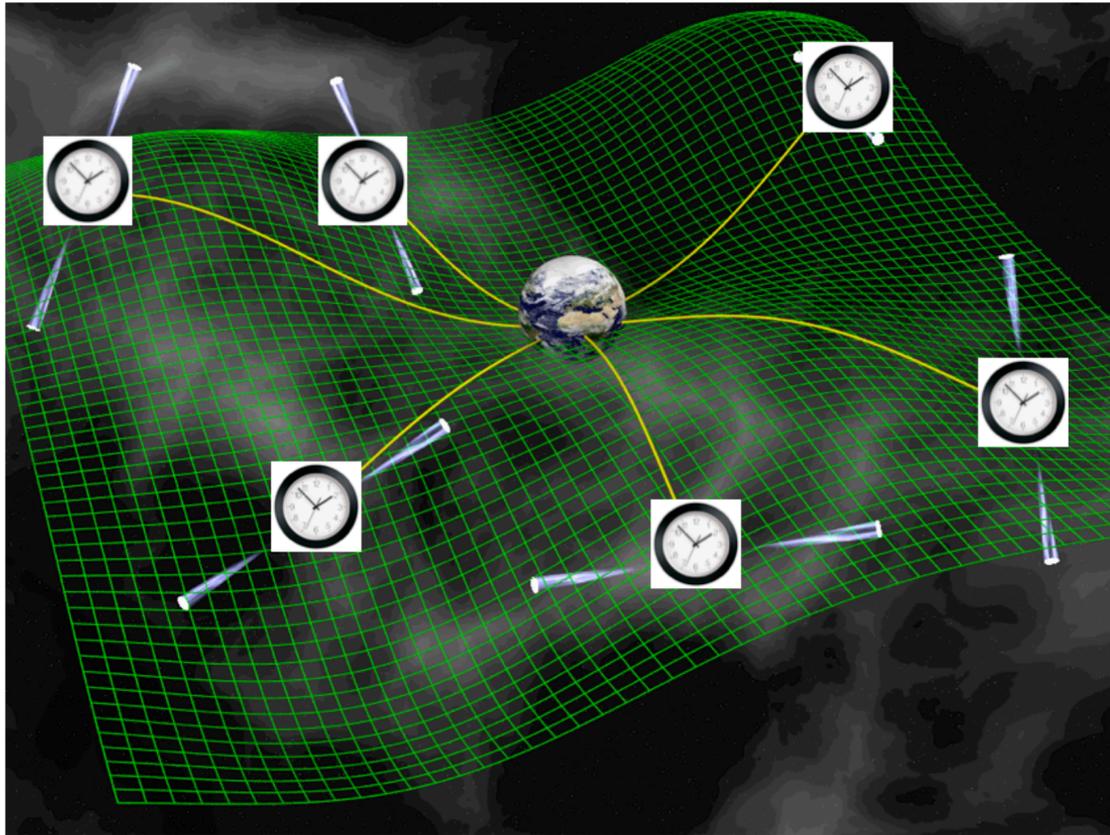
Many aspects of the large-scale structure of the Universe can be described successfully using cosmological models in which  $27 \pm 1\%$



## Ultralight ALDM (Fuzzy DM) [Hu, et. al., Phys.Rev.Lett. 85 (2000)]

$m_a \sim O(10^{-21} - 10^{-22})$  eV  $\Rightarrow$  Strong wave properties on galactic scales:  
Oscillation period  $\sim 2\pi/m_a \sim O(1)$  yr and de Broglie wavelength  $2\pi/m_a v \sim O(100)$  pc

# Ultralight ALDM — PTA-PPA Detection



The ALDM halo as an astronomical background can:

- Perturb Galactic gravitational potential => Yield oscillating timing residuals to pulsar light [Khmel'nitsky and Rubakov, 1309.5888]
- Couple to pulsar light through Chern-Simons coupling => Yield oscillating position angle residuals to its linearly polarized component [TL, Smoot and Zhao, 1901.10981]

Because of the wavy nature of ultralight ALDM, the generated residuals in both cases are correlated among pulsars!  
=> Particularly suited for the PPA and PTA detections! [TL, Lou and Ren, Phys.Rev.Lett. 130 (2023) 12]

# Two-point Correlation Functions

- ◆ Two-point correlation function of **ALDM-induced PA residuals** (pulsars:  $p, q$ ; epochs:  $n, m$ ) [TL, Lou and Ren, Phys.Rev.Lett. 130 (2023) 12]

$$\begin{aligned}\hat{C}_{p,n;q,m}^a &= \langle \Delta\theta_{p,n}\theta_{q,m} \rangle / S_a^2 \\ &= \cos[m_a(t_{p,n} - t_{q,m})] + \cos[m_a(t'_{p,n} - t'_{q,m})]\text{sinc}(y_{pq}) \\ &\quad - \cos[m_a(t'_{p,n} - t_{q,m})]\text{sinc}(y_{ep}) - \cos[m_a(t_{p,n} - t'_{q,m})]\text{sinc}(y_{eq})\end{aligned}$$

- ◆ Two-point correlation function of **ALDM-induced timing residuals** [Luu, TL, et. al., Astrophys. J. Lett. 963, no.2, L46 (2024)]

$$\begin{aligned}\langle A_c^{(p)} A_c^{(q)} \rangle &= \langle A_s^{(p)} A_s^{(q)} \rangle \\ &\approx \left( \frac{\pi G}{2m_a^3} \right)^2 \left[ \rho_e^2 + \rho_p \rho_q \cos[2m_a L_{pq}] \frac{\sin^2 y_{pq}}{y_{pq}^2} \right. \\ &\quad \left. - \rho_e \rho_p \cos[2m_a L_p] \frac{\sin^2 y_{ep}}{y_{ep}^2} - (p \rightarrow q) \right], \\ \Delta t_p &= A_c^{(p)} \cos(2m_a t) + A_s^{(p)} \sin(2m_a t) \\ \langle A_s^{(p)} A_c^{(q)} \rangle &\approx \left( \frac{\pi G}{2m_a^3} \right)^2 \left[ \rho_p \rho_q \sin[2m_a L_{pq}] \frac{\sin^2 y_{pq}}{y_{pq}^2} \right. \\ &\quad \left. + \rho_e \rho_p \sin[2m_a L_p] \frac{\sin^2 y_{ep}}{y_{ep}^2} - (p \rightarrow q) \right],\end{aligned}$$

# First PPA Detection (In Collaboration with PPTA Team)

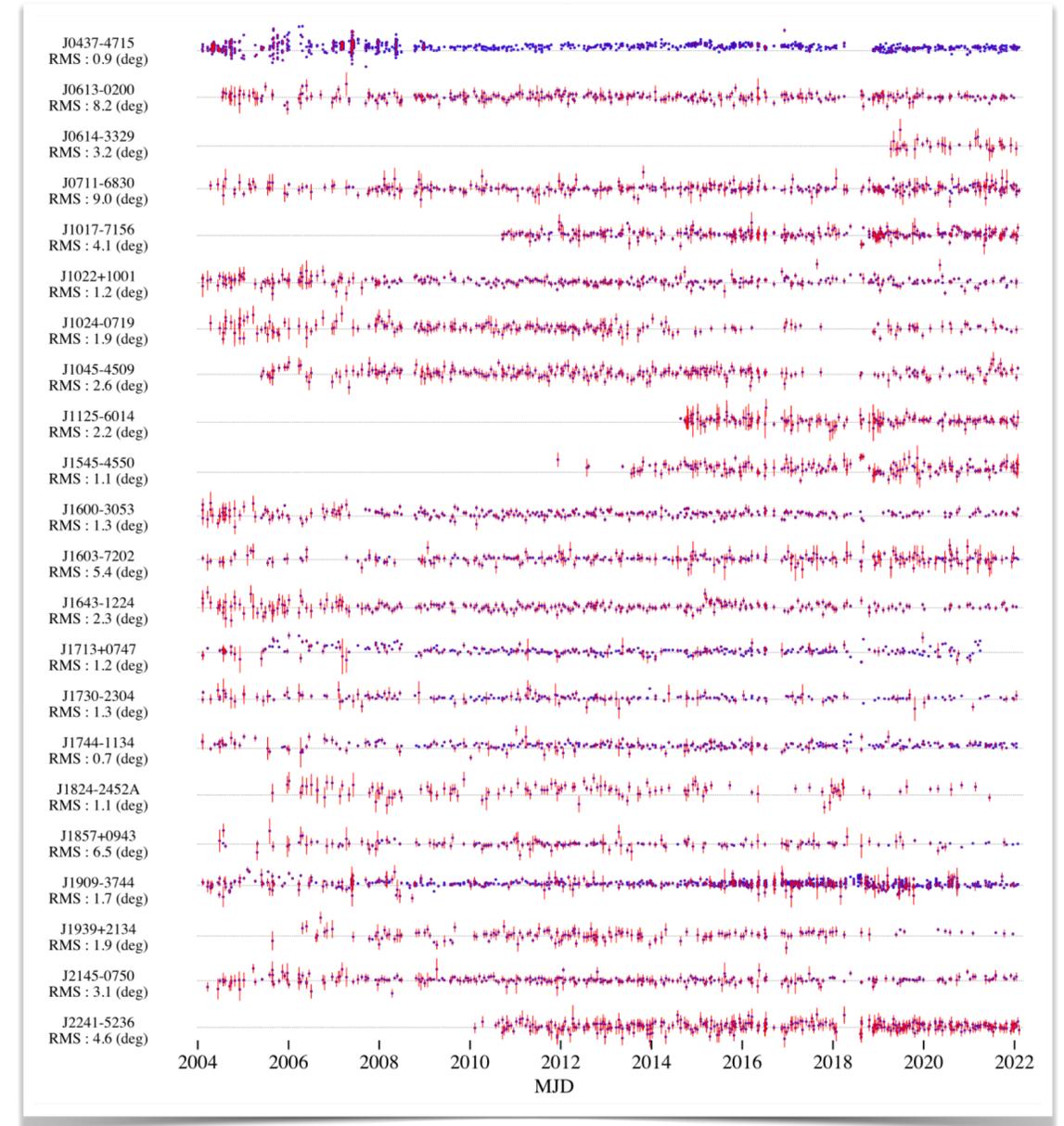
- ◆ Construct PA residual time series
  - Polarization data of 22 MSPs from PPTA data release 3 (2023)
  - Maximal observation time span: 18 years from 2004 to 2022
- ◆ Build noise model for the observed PA residual time series

$$\Delta PA^{\text{obs}} = \underbrace{\Delta PA^a}_{\text{ALDM induced signal}} + \underbrace{\Delta PA^{\text{ion}}}_{\text{Ionosphere FR}} + \underbrace{\Delta PA^w}_{\text{White noise}} + \underbrace{\Delta PA^r}_{\text{Red noise}} + \underbrace{\Delta PA^{\text{det}}}_{\text{Deterministic residual}}$$

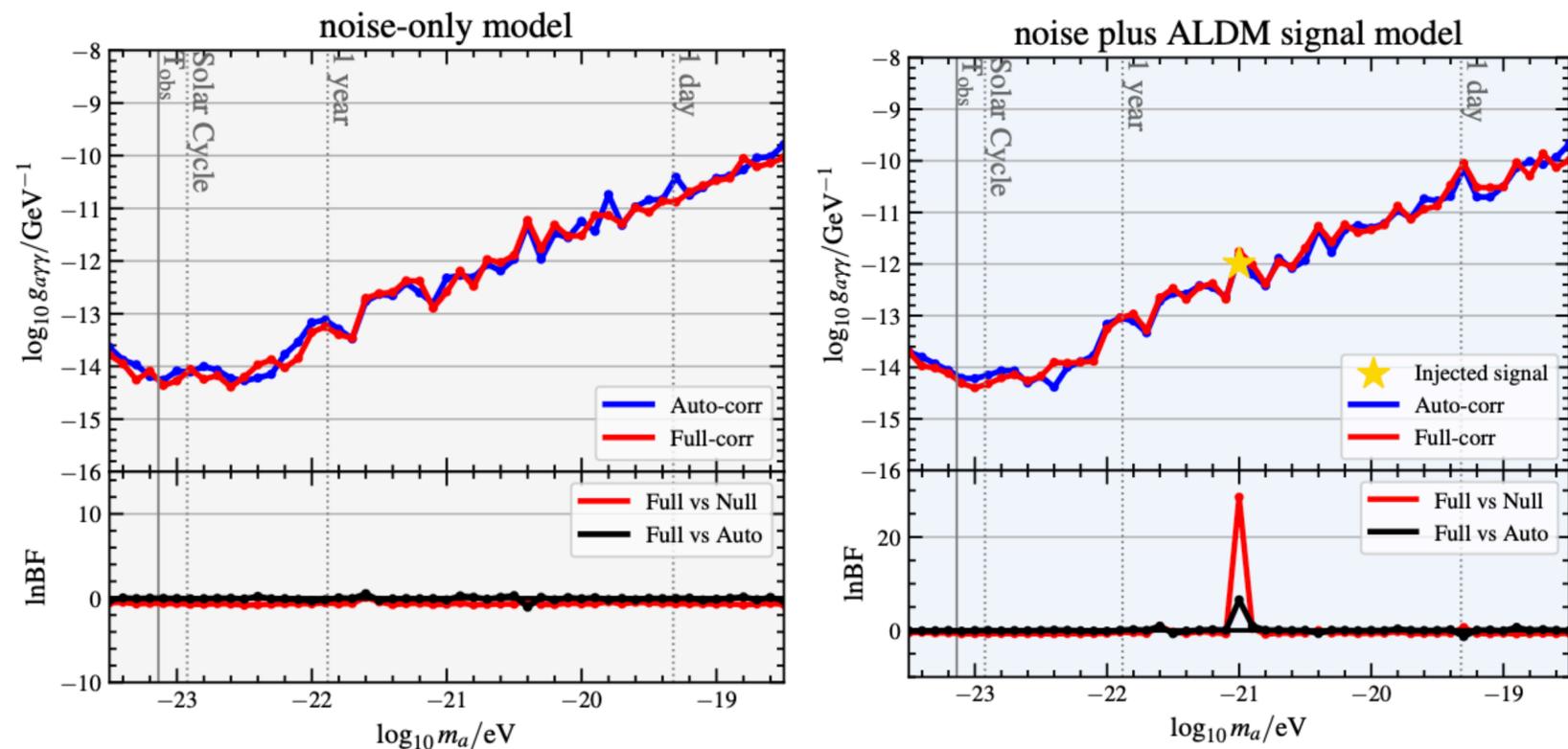
- ◆ Search for pulsar cross correlation

$$\ln \mathcal{L} = -\frac{1}{2} \left( \Delta PA^{\text{obs}} - \Delta PA^{\text{ion}} - \Delta PA^{\text{det}} \right)^T C^{-1} \left( \Delta PA^{\text{obs}} - \Delta PA^{\text{ion}} - \Delta PA^{\text{det}} \right) - \frac{1}{2} \ln |2\pi C|$$

$$C = C^w + C^r + S_a^2 \hat{C}^a$$



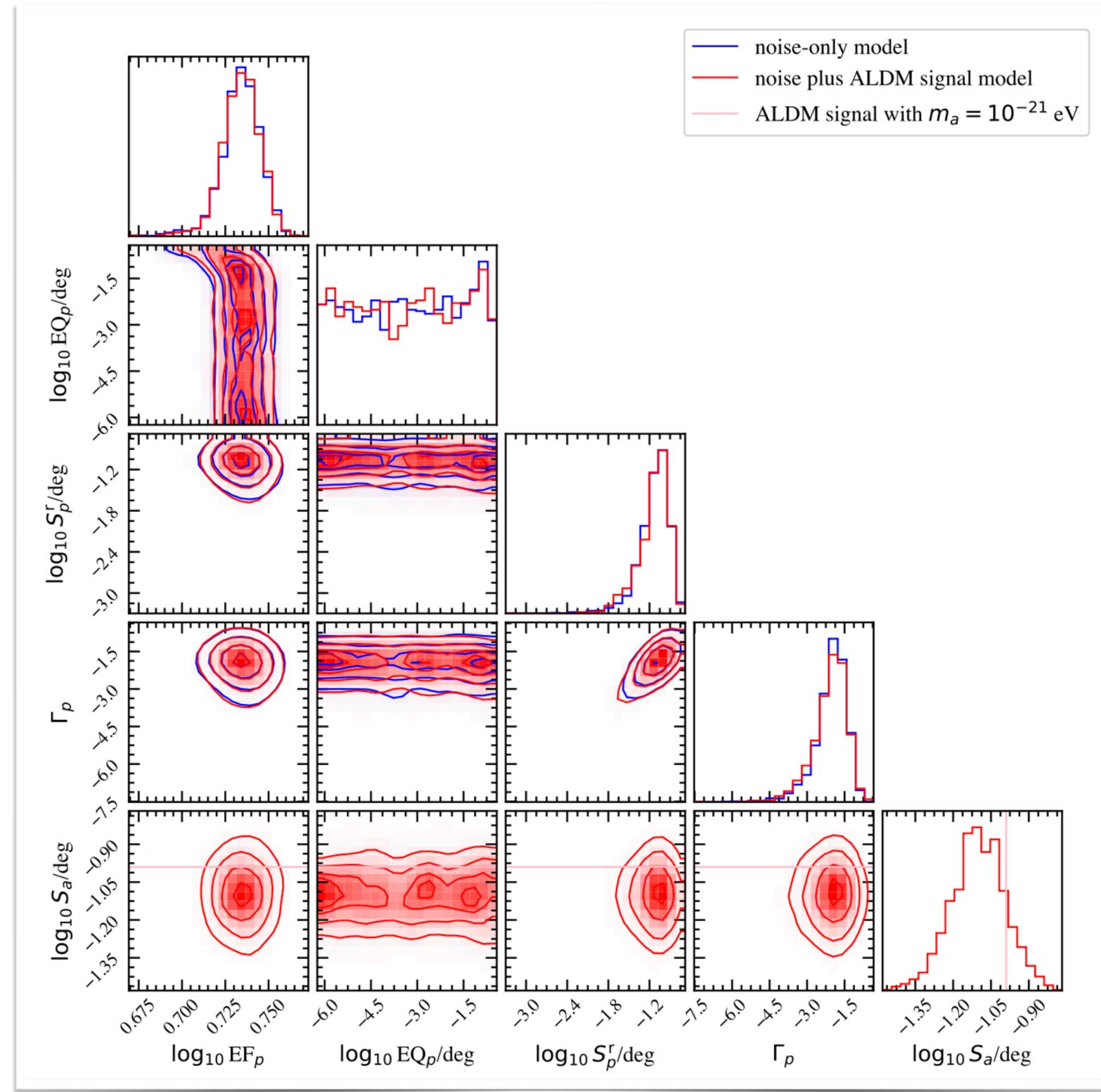
# Mock Response of PPA to ALDM Signals



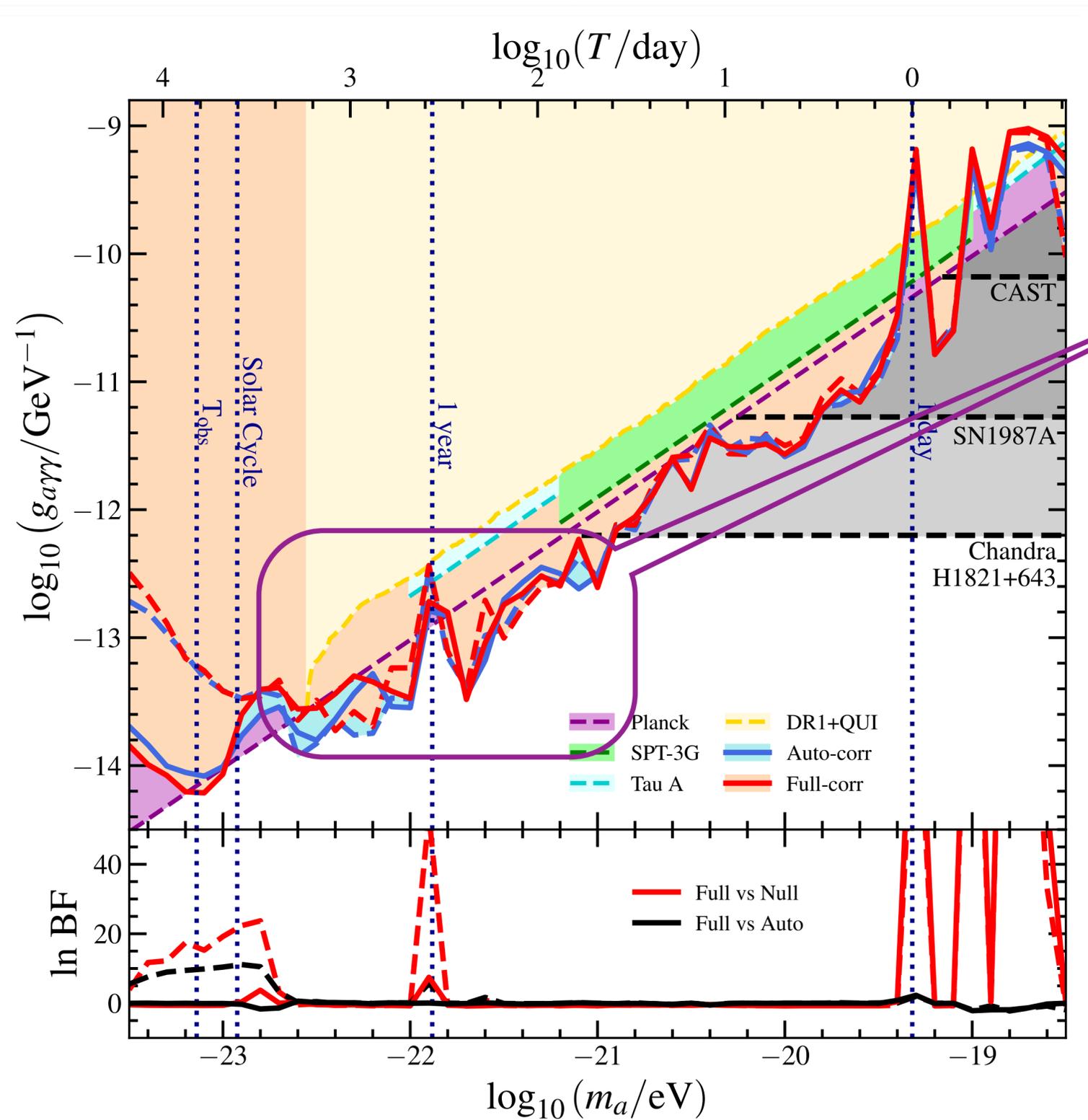
BF1: Full-correlation vs. Null

BF2: Full-correlation vs. Auto-correlation only

The strength of injected signals, together with pulsar noise parameters, can be recovered with a precision  $\sim O(10\%)$ .

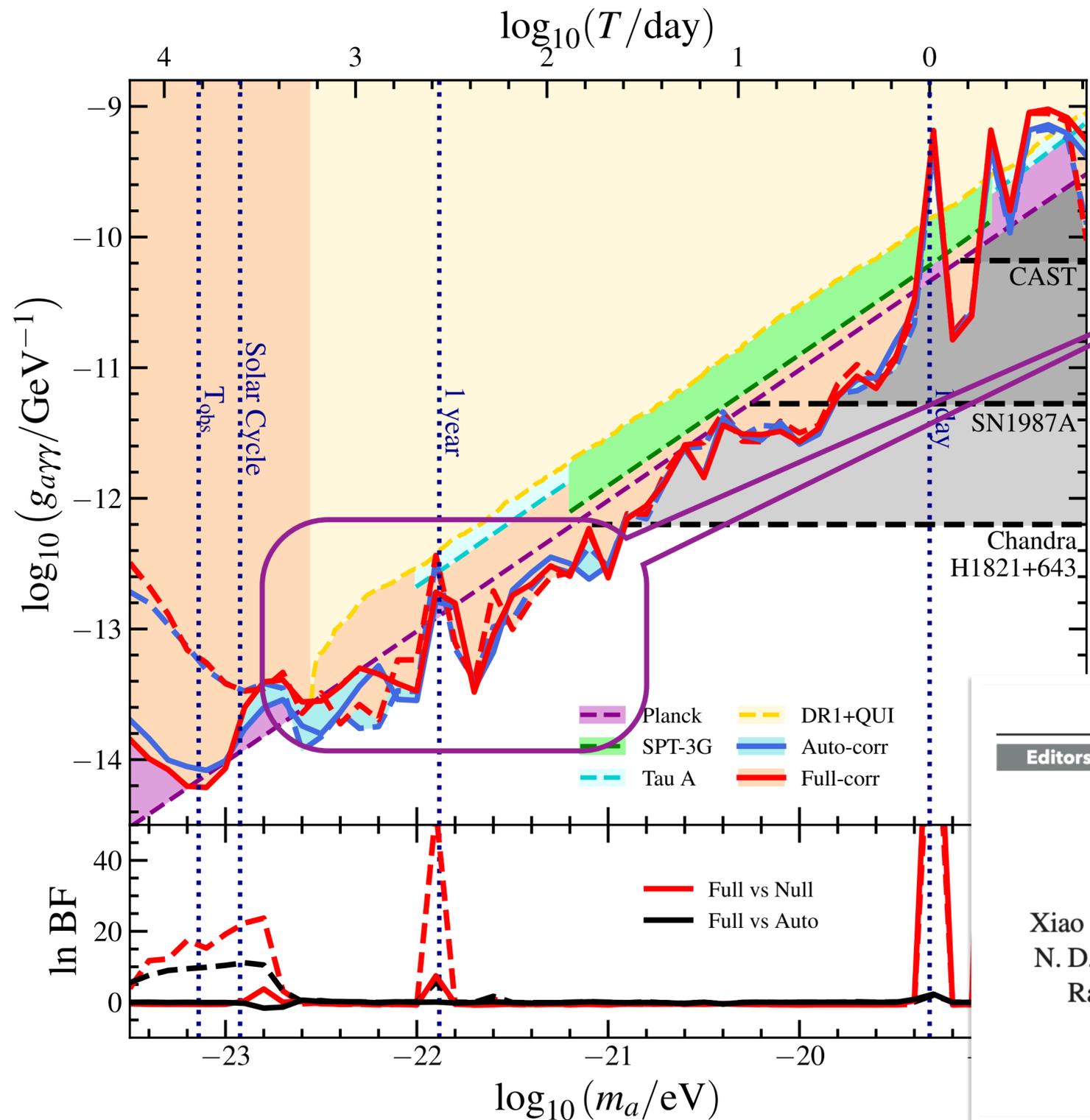


# Parkes PPA Limits on Ultralight ALDM



- For the mass range of Fuzzy DM - **The world-leading limits on the ALDM Chern-Simons coupling!**
- Sharp peaks on several time scales
- The cross-correlation of ALDM signals is not favored by Bayes factor
- Highlights the value of pulsar cross-correlation in recognizing the nature of anomalous signals

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PHYSICAL REVIEW LETTERS **136**, 011001 (2026)

Editors' Suggestion

## Pulsar Polarization Array Limits on Ultralight Axionlike Dark Matter

Xiao Xue,<sup>1,2,3,\*</sup> Shi Dai,<sup>4,\*</sup> Hoang Nhan Luu,<sup>5</sup> Tao Liu,<sup>6,†</sup> Jing Ren<sup>7,8,‡</sup>, Jing Shu,<sup>9,8,10</sup> Yue Zhao,<sup>6</sup> Andrew Zic,<sup>4</sup> N. D. Ramesh Bhat,<sup>11</sup> Zu-Cheng Chen,<sup>12,13</sup> Yi Feng,<sup>14</sup> George Hobbs,<sup>4</sup> Agastya Kapur,<sup>4</sup> Richard N. Manchester,<sup>4</sup> Rami Mandow,<sup>15,4</sup> Saurav Mishra,<sup>16</sup> Daniel J. Reardon,<sup>16,17</sup> Christopher J. Russell,<sup>18</sup> Ryan M. Shannon,<sup>16,17</sup> Shuangqiang Wang,<sup>19,20</sup> Lei Zhang,<sup>21,16</sup> Songbo Zhang,<sup>22,4</sup> and Xingjiang Zhu<sup>23,24,25</sup>

(PPTA Collaboration)

# Existing PTA Detections

PHYSICAL REVIEW D **98**, 102002 (2018)

Editors' Suggestion

## Parkes Pulsar Timing Array constraints on ultralight scalar-field dark matter

Nataliya K. Porayko,<sup>1,\*</sup> Xingjiang Zhu,<sup>2,3,4,†</sup> Yuri Levin,<sup>5,6,2</sup> Lam Hui,<sup>5</sup> George Hobbs,<sup>7</sup> Aleksandra Grudskaya,<sup>8</sup> Konstantin Postnov,<sup>8,9</sup> Matthew Bailes,<sup>10,4</sup> N. D. Ramesh Bhat,<sup>11</sup> William Coles,<sup>12</sup> Shi Dai,<sup>7</sup> James Dempsey,<sup>13</sup> Michael J. Keith,<sup>14</sup> Matthew Kerr,<sup>15</sup> Michael Kramer,<sup>1,14</sup> Paul D. Lasky,<sup>2,4</sup> Richard N. Manchester,<sup>7</sup> Stefan Osłowski,<sup>10</sup> Aditya Parthasarathy,<sup>10</sup> Vikram Ravi,<sup>16</sup> Daniel J. Reardon,<sup>10,4</sup> Pablo A. Rosado,<sup>10</sup> Christopher J. Russell,<sup>17</sup> Ryan M. Shannon,<sup>10,4</sup> Renée Spiewak,<sup>10</sup> Willem van Straten,<sup>18</sup> Lawrence Toomey,<sup>7</sup> Jingbo Wang,<sup>19</sup> Linqing Wen,<sup>3,4</sup> and Xiaopeng You<sup>20</sup>

(PPTA Collaboration)

PHYSICAL REVIEW LETTERS **131**, 171001 (2023)

Editors' Suggestion

Featured in Physics

## Second Data Release from the European Pulsar Timing Array: Challenging the Ultralight Dark Matter Paradigm

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(European Pulsar Timing Array)

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## The NANOGrav 15 yr Data Set: Search for Signals from New Physics

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Pulsar cross-correlations have been overlooked in all of these efforts!

# PTA Detection with Pulsar Cross-Correlation

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## Stochastic Wave Dark Matter with Fermi-LAT $\gamma$ -Ray Pulsar Timing Array

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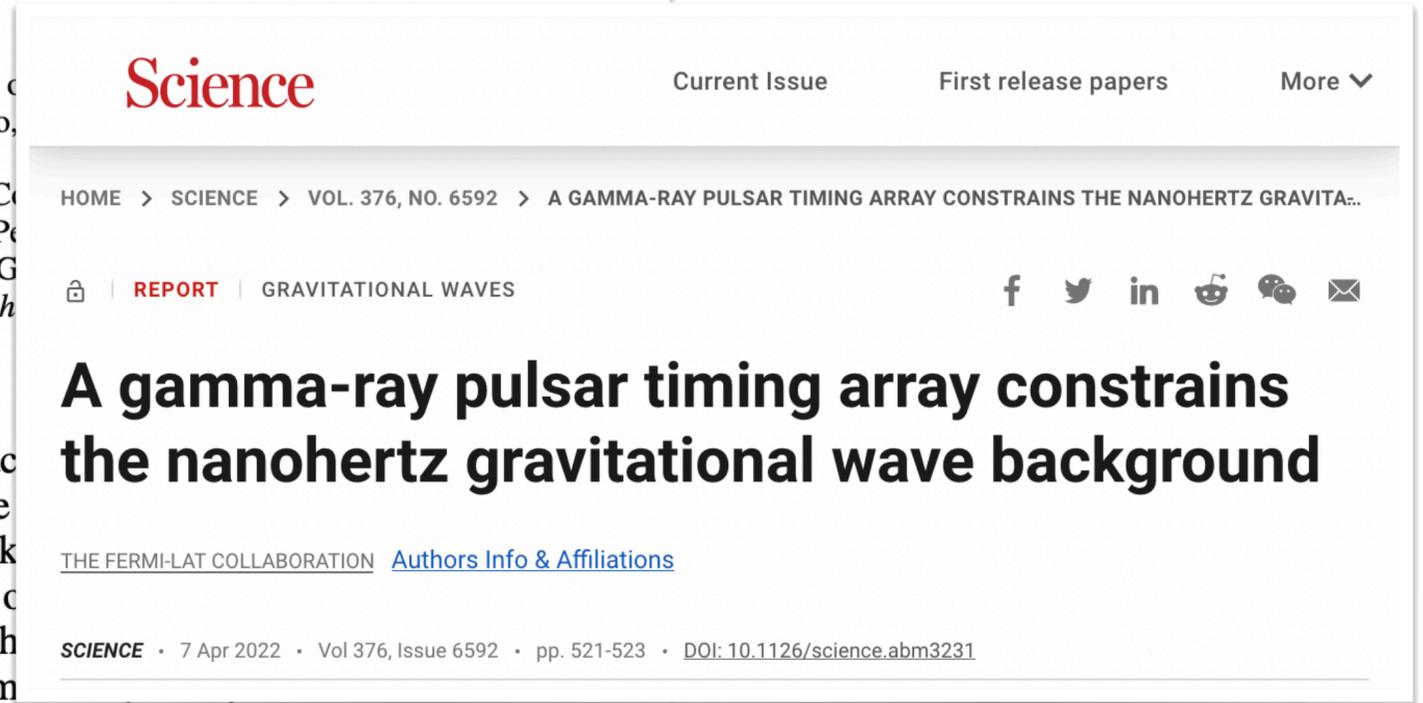
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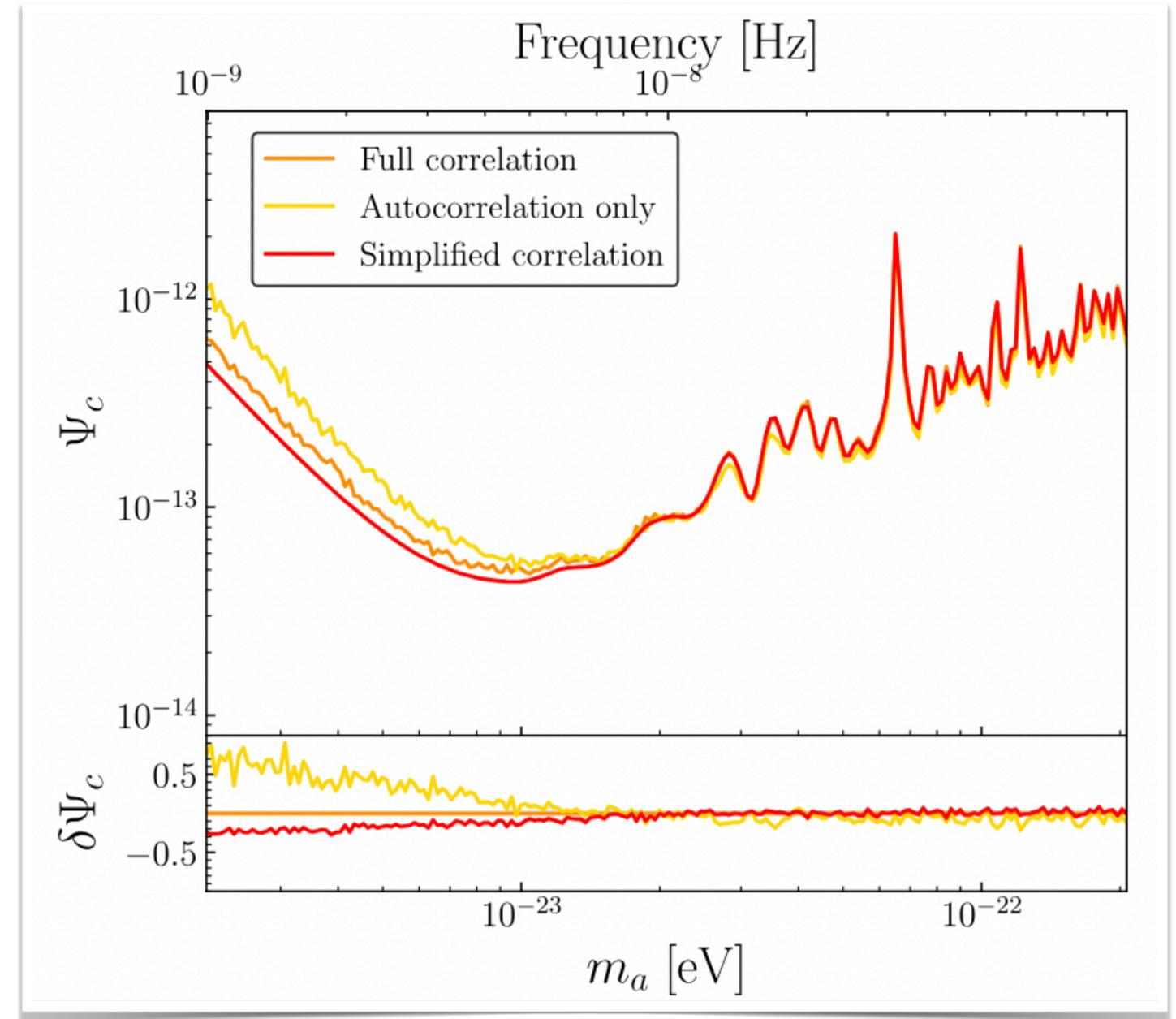
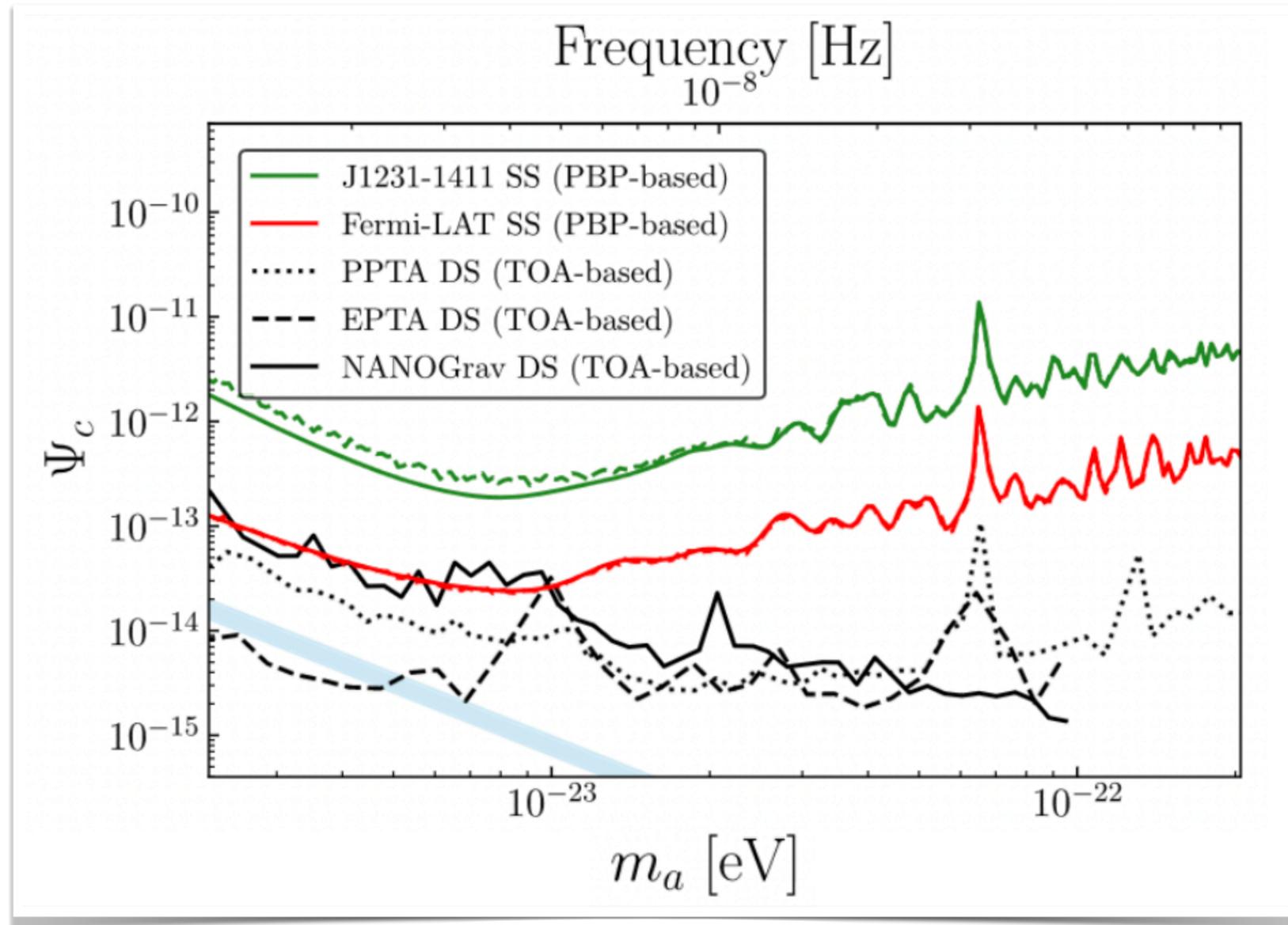
### Abstract

Pulsar timing arrays (PTAs) can detect disturbances in the fabric of spacetime on a galactic scale by measuring the arrival time of pulses from millisecond pulsars (MSPs). Recent advancements have shown that high-energy radiation emitted by MSPs, in addition to radio waves, for PTA experiments. Wave dark matter (DM) candidates, can be detected with PTAs due to its periodic perturbations on the timing. In response to this development, we perform in this Letter a first analysis of applying the data of Fermi Large Area Telescope (Fermi-LAT)  $\gamma$ -ray PTA to detect wave DM. With a smaller collecting area, the Fermi-LAT  $\gamma$ -ray PTA demonstrates a promising sensitivity potential. We show that the upper limits not far from those of the dedicated radio-PTA projects can be achieved. Moreover, we initiate a cross-correlation analysis using the data of two Fermi-LAT pulsars. The cross-correlation of phases, while carrying key information on the source of the spacetime perturbations, has been ignored in the existing data analyses for the wave DM detection with PTAs. Our analysis indicates that taking this information into account can improve the sensitivity to wave DM by  $\gtrsim 50\%$  at masses below  $10^{-23}$  eV.

*Unified Astronomy Thesaurus concepts:* [Pulsar timing method \(1305\)](#); [Gamma-ray astronomy \(628\)](#); [Dark matter \(353\)](#)



# PTA Detection with Pulsar Cross-Correlation



Pipeline for the PTA analysis including pulsar cross correlation was built, and applied to two Fermi-LAT pulsars with the “best” quality

# More Progress and Summary

- PPA detection of ultralight ALDM
  - PPTA collaboration published its first results in 2026 Jan [[Xue, Dai, Luu, TL, Ren, et al. \(PPTA collaboration\); Phys.Rev.Lett. 136 \(2026\) 1, Editors' Suggestion](#)]
  - NANOGrav and CPTA collaborations are preparing their first results
  - One team in South Africa is extending the PPA construction from millisecond pulsars to regular pulsars, using the data of MeerKAT Thousand-Pulsar Program
- PTA detection of ultralight ALDM
  - We published first analysis with pulsar cross-correlation in 2024, using the Fermi-LAT gamma-ray data [[Luu, TL, et. al., Astrophys. J. Lett. 963, no.2, L46 \(2024\)](#)]
  - PPTA and NANOGrav collaborations are preparing their new analyses by cross-correlating pulsar data
- Timing and polarization data could be further correlated to enhance the pulsar-array's capability of recognizing signal nature (2024) [[Li,... ..., TL, Ren and Wu, \[arXiv:2506.04871 \[astro-ph.CO\]\]](#)]
  - Signals: gravitational (timing) VS. non-gravitational (polarization)
  - Timing and polarization noises: uncorrelated or correlated but with a different pattern
- Stay tuned ... ..



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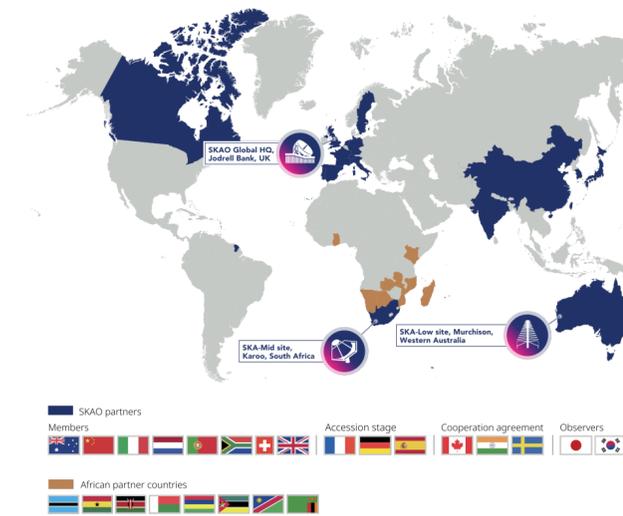
CRF under Grant No. C6017-20G



*Thank you!*

# Square Kilometer Array (SKA)-PTA

SKA radio telescope - international radio telescope project (to be launched ~ 2027)



Over 80 MSPs have been monitored by the global PTA network over a timespan of years. Future observations (SKA/FAST) can increase this number to  $O(100 - 1000)$ , with higher timing precision

# Timing Signals

Oscillating halo density => Oscillating gravitational potential  
=> Oscillating timing residuals

$$\begin{aligned}\rho_{\text{DM}}(\mathbf{x}, t) &= \rho_{\text{k}} + \rho_{\text{p}} + \rho_{\text{g}} \\ &= \frac{1}{2}(\partial_t a)^2 + \frac{1}{2}m^2 a^2 + \frac{1}{2}(\nabla a)^2\end{aligned}$$

$$\Psi(\mathbf{x}, t) \simeq \Psi_0(\mathbf{x}) + \Psi_c(\mathbf{x}) \cos(\omega t + 2\alpha(\mathbf{x}))$$

$$\Delta t^a(t) = - \int_{t_0}^t \frac{\nu(t') - \nu_0}{\nu_0} dt' \approx - \int_{t_0}^t [\Psi_c(\mathbf{x}_p, t') - \Psi_c(\mathbf{x}_e, t')] dt'$$

○ Pulsar term    ○ Earth term

arXiv

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[Submitted on 23 Sep 2013]

**Pulsar timing signal from ultralight scalar dark matter**

Andrei Khmelnitsky, Valery Rubakov

# Polarization Signals



$$L \sim -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial^\mu a\partial_\mu a - \frac{1}{2}m_a^2 a^2 + \frac{g}{2}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\omega_\pm \simeq k \pm g \left( \frac{\partial a}{\partial t} + \nabla a \cdot \frac{\mathbf{k}}{k} \right) \xrightarrow[\text{relativistic}]{\text{non-}} k \pm g \frac{\partial a}{\partial t}$$

- ◆ Cosmological birefringence (parity-violating effect) [Carroll, Field and Jackiw, Phys. Rev. D41 (1990) 1231]
- ◆ Position Angle (PA) residual caused by the ALDM - determined by boundary terms of light path

$$\Delta\theta_p(t) = \frac{g}{m_a} \int \alpha_{\mathbf{v}} \left\{ \sqrt{\rho_p f_p(\mathbf{v})} \cos[m_a(t - L_p - \mathbf{v} \cdot \mathbf{x}_p) + \phi_{\mathbf{v}}] - \sqrt{\rho_e f_e(\mathbf{v})} \cos(m_a t + \phi_{\mathbf{v}}) \right\} d^3\mathbf{v}$$

○ Pulsar term    ○ Earth term

arXiv > astro-ph > arXiv:1901.10981
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**Astrophysics > Cosmology and Nongalactic Astrophysics**

[Submitted on 30 Jan 2019 (v1), last revised 25 Feb 2019 (this version, v2)]

## Detecting Axion-like Dark Matter with Linearly Polarized Pulsar Light

Tao Liu, George Smoot, Yue Zhao

# Comparison with the SGWB PTA Detection

Timing residuals caused by stochastic GW background

○ Pulsar term    ○ Earth term

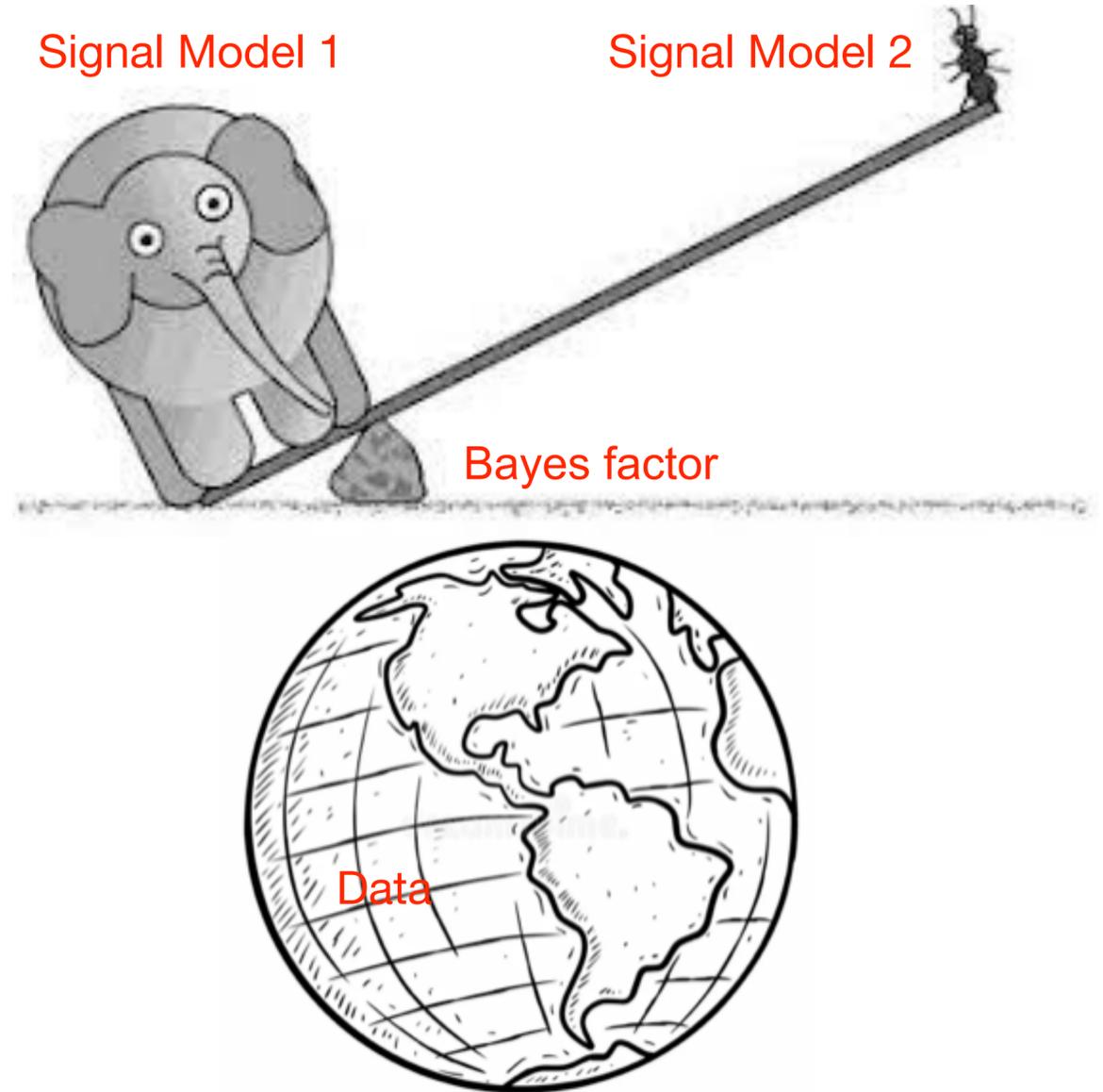
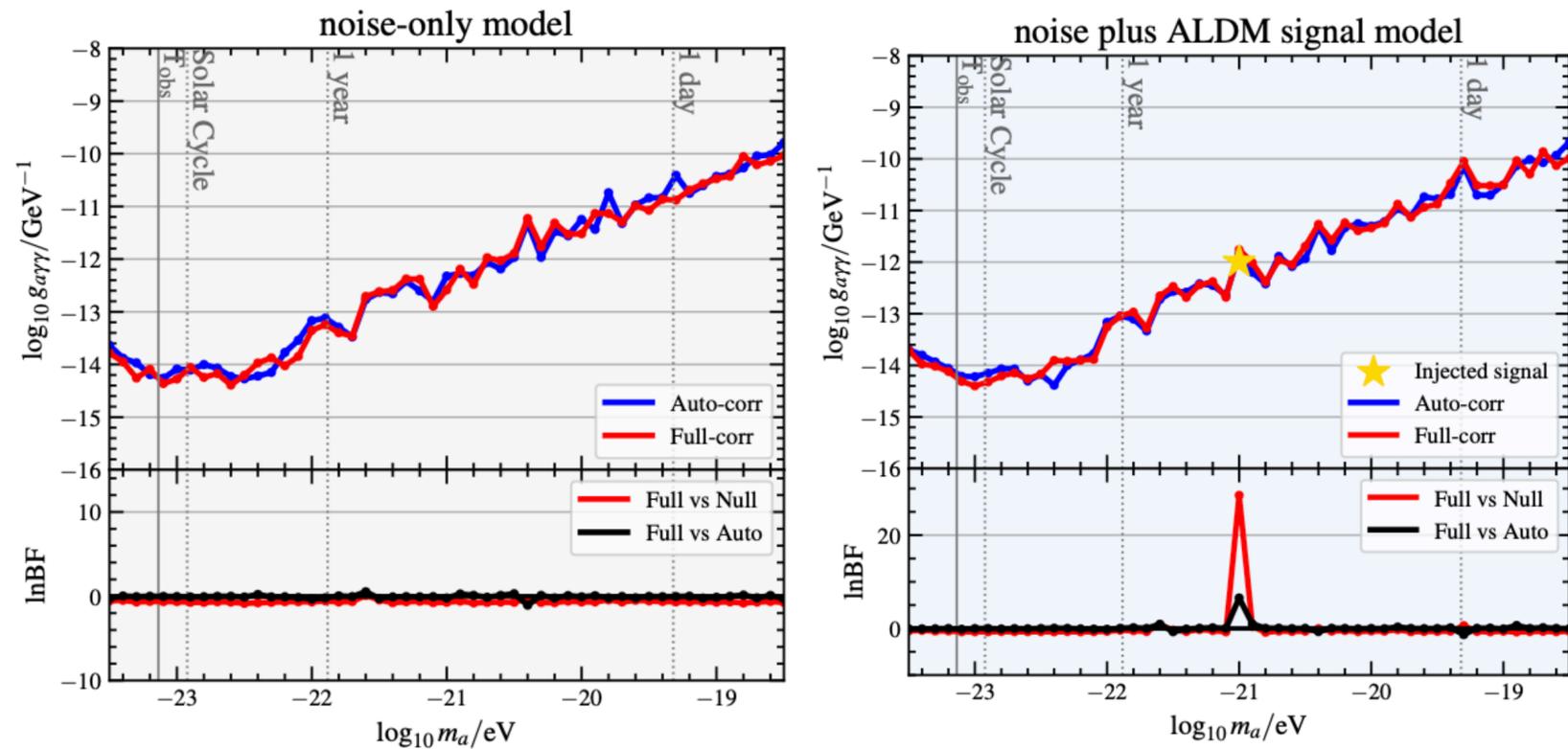
$$\Delta T_p(t) = \int_{-\infty}^{\infty} df \frac{1}{2} u^a u^b h_{ab}(f, \hat{n}) \frac{1}{i2\pi f} \frac{1}{1 + \hat{n} \cdot \hat{u}} \left[ e^{i2\pi f t} e^{i2\pi f (t - L_p + \hat{n} \cdot \mathbf{x}_p)} \right]$$

Signal covariant matrix:  $\langle \Delta T_p \Delta T_q \rangle$   $\langle \Delta T_p \Delta T_q \rangle$   $\langle \Delta \theta_p \Delta \theta_q \rangle$

	SGWB (PTA)	ALDM (PTA+PPA)
Earth-Earth Term	quadrupolar correlation (Hellings-Downs curve)	monopolar correlation
Pulsar-Pulsar Term	spatial correlation greatly suppressed (dB wave length $\sim 1/w$ )	spatial correlation degrades much slower (dB wavelength $\gg 1/w$ )

For the nanoHz SGWB PTA detection, Earth-Earth term plays a leading role.  
 For the ultralight ALDM PTA/PPA detections, all terms could be relevant at leading order.

# Mock Response of PPA to ALDM Signals



BF1: Full-correlation vs. Null  
 BF2: Full-correlation vs. Auto-correlation only