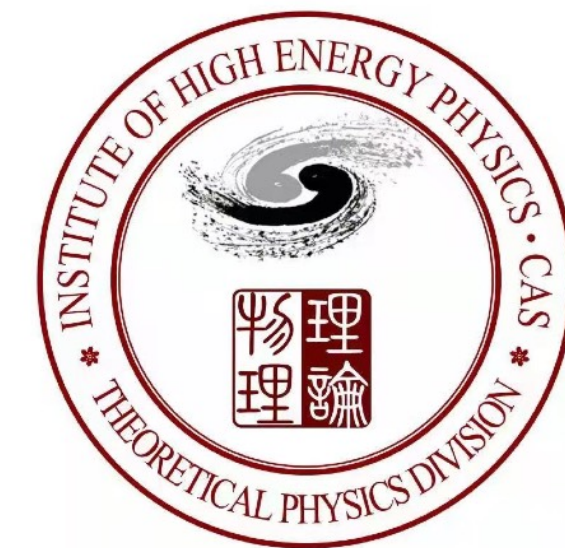




Institute of High Energy Physics
Chinese Academy of Sciences



Probing ultralight axion-like dark matter with pulsar arrays

Jing Ren (任婧)

IHEP, CAS

2026年新物理前沿与交叉科学研讨会 (NPhiS 2026)

May 16th, 2026

Based on works with Tao Liu and others, arXiv: 2111.10615, 2304.04735, 2412.02229, 2506.04871, 2605.*****

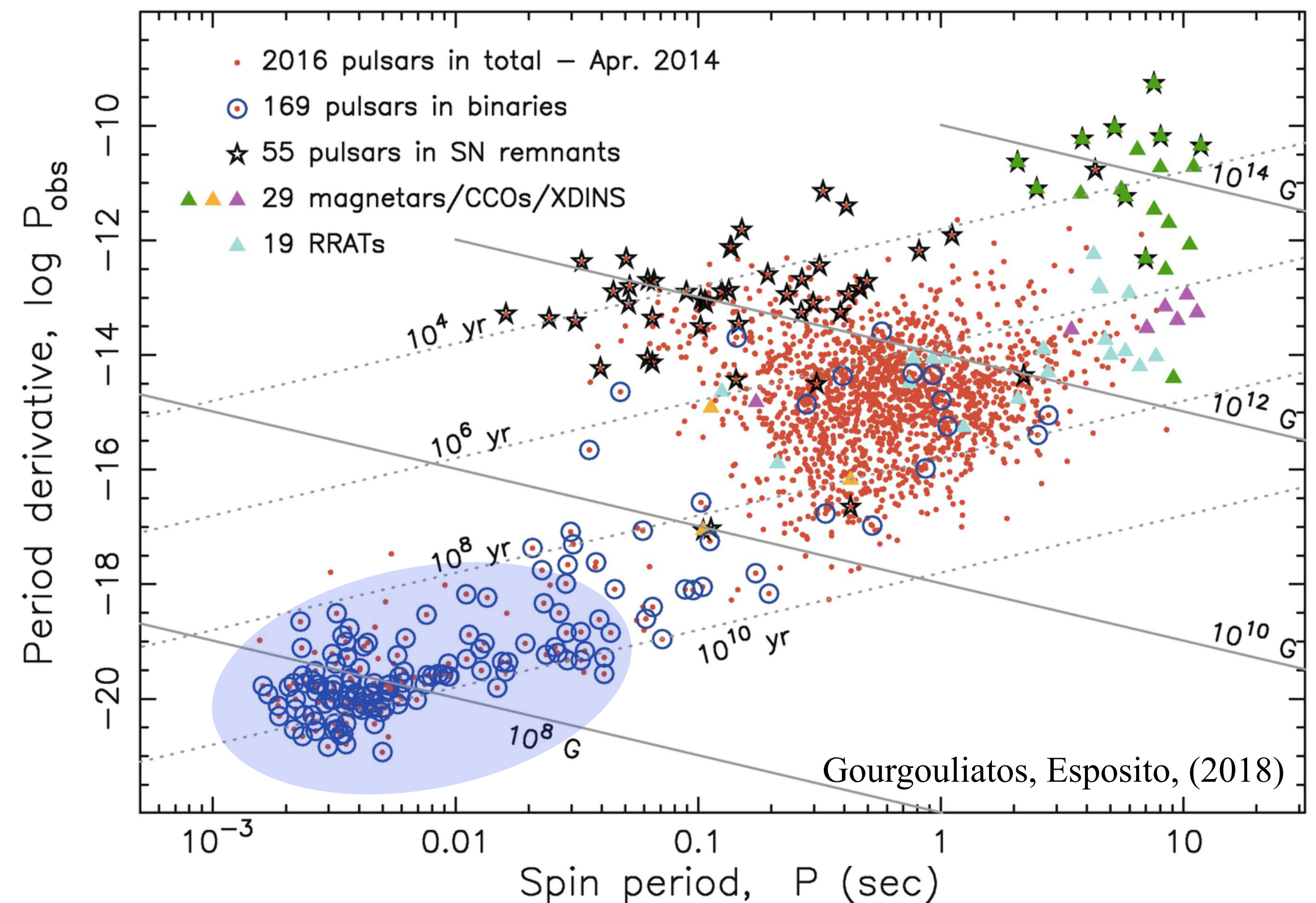
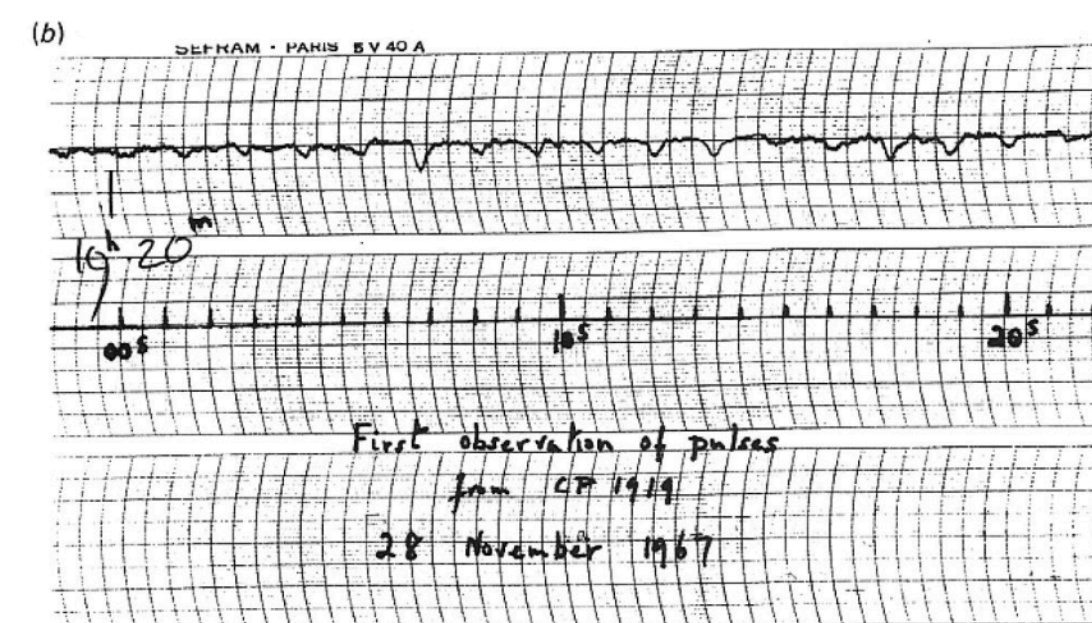
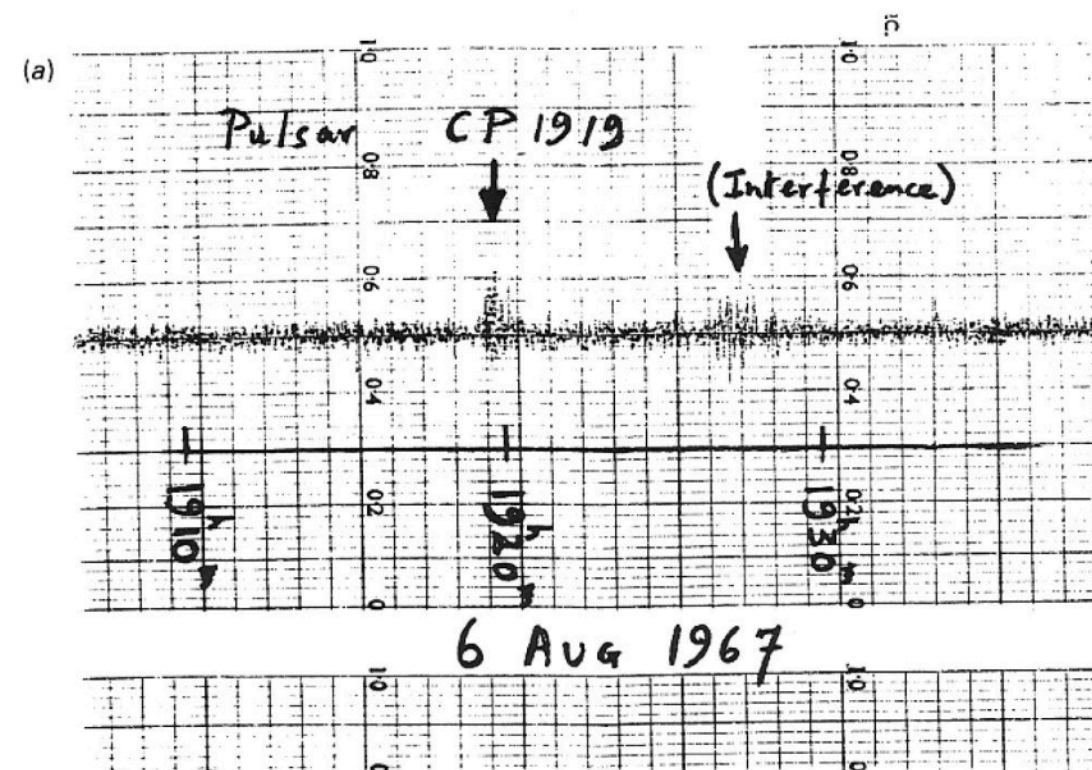
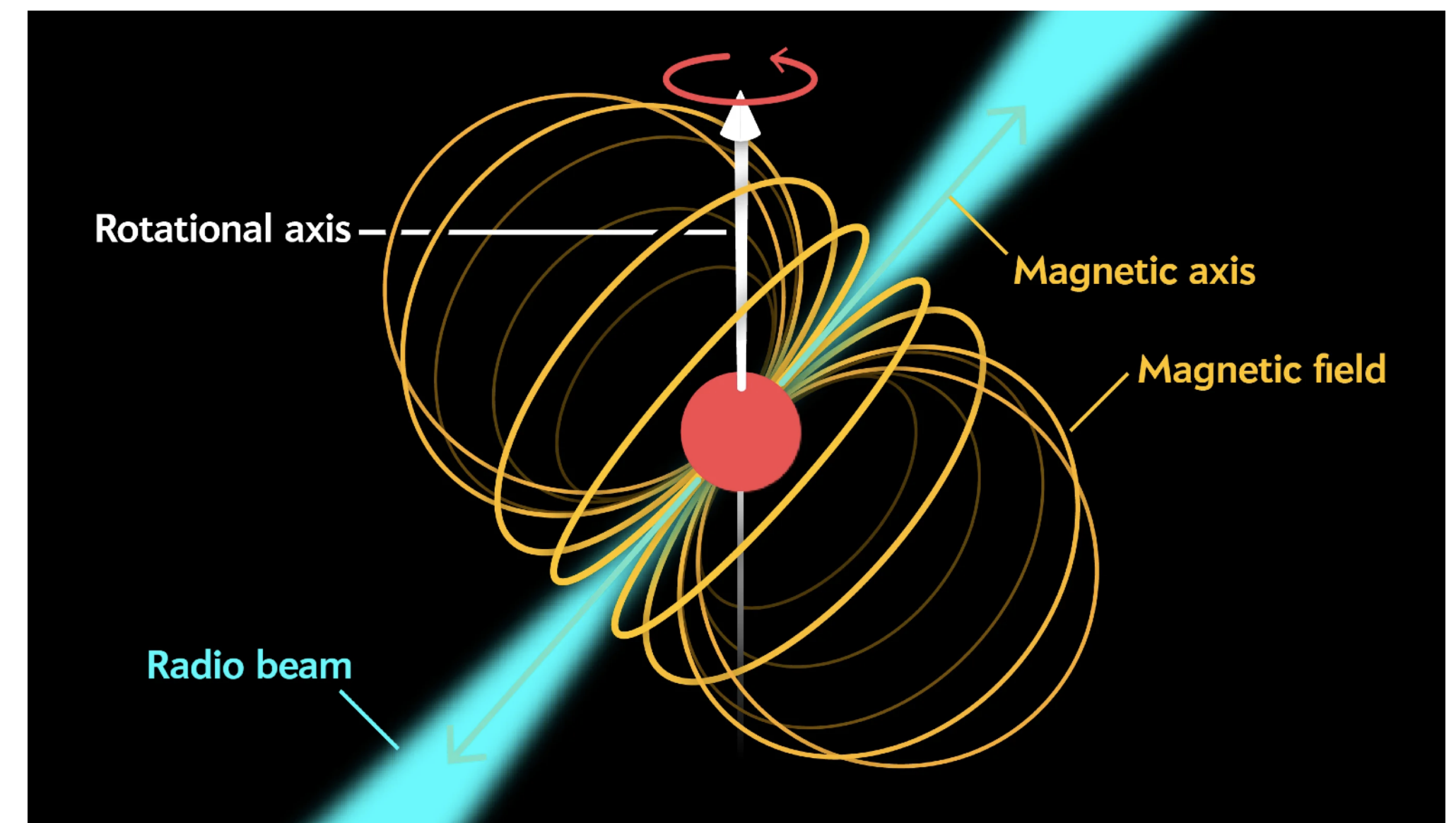
Content

- ✦ Pulsar timing arrays (PTAs) and pulsar polarization arrays (PPAs)
- ✦ Ultralight axion-like dark matter searches with PTAs and PPAs
- ✦ Summary and outlook

Pulsar timing arrays & pulsar polarization arrays

Pulsars

- ♦ Pulsars emit electromagnetic pulses with extraordinary regularity
- ♦ Till now ~3000 pulsars observed in our galaxy
- ♦ Millisecond pulsars (MSPs) especially stable; can play roles as *astronomical clocks* [Backer *et al.* Nature 300 (1982)]



Pulsar timing arrays (PTAs)

- ✦ Given precise timing model of the expected time of arrival of the pulse, the measured **time difference** can be directly related to **gravitational waves (GWs)**

$$\Delta t(t) = \int_{-\infty}^{\infty} df \frac{1}{2} u^a u^b \underbrace{h_{ab}(f, \hat{n})}_{\text{metric perturbation}} e^{i2\pi f(t + \hat{n} \cdot \vec{r}_2/c)} \frac{1}{i2\pi f} \frac{1}{1 + \hat{n} \cdot \hat{u}} \left[1 - e^{-\frac{i2\pi f L}{c}(1 + \hat{n} \cdot \hat{u})} \right]$$

“Earth” “pulsar”

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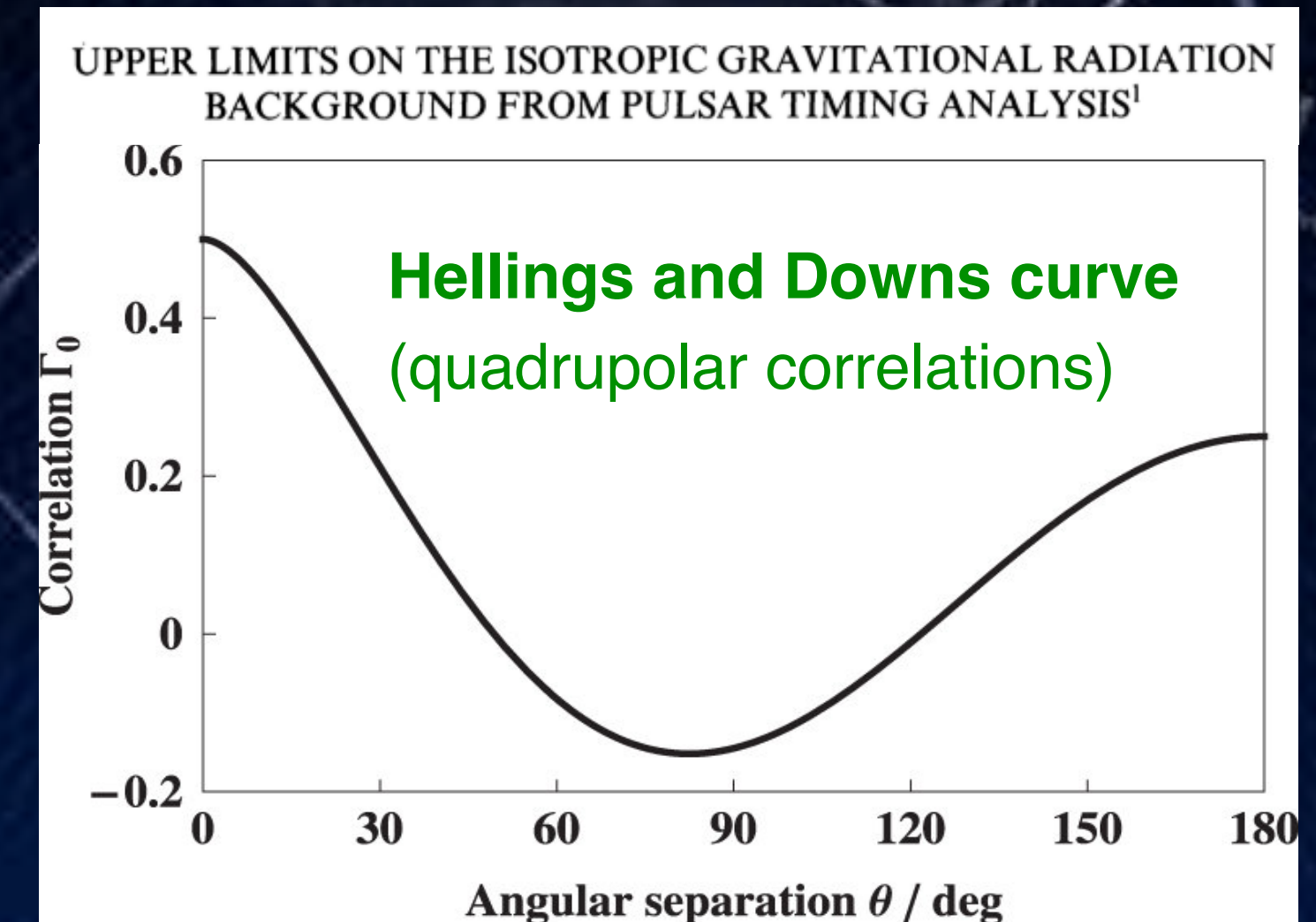
“Earth” “pulsar”

- Stochastic GW backgrounds (SGWBs) can be identified by the **quadrupolar spatial correlations among pulsars**

$$\Delta t_p = \mathbf{F}_p \mathbf{c}_p, \quad \langle c_{pi} c_{qj} \rangle = \Gamma_0(\theta_{pq}) \Phi_i \delta_{ij}$$

- Constructing PTAs with MSPs as **galactic-scale GW detectors** [Foster and Backer, ApJ 361 (1990)]

- Till now, global PTA network monitors over 80 MSPs for 10+ years. FAST/SKA may increase number to O(100)

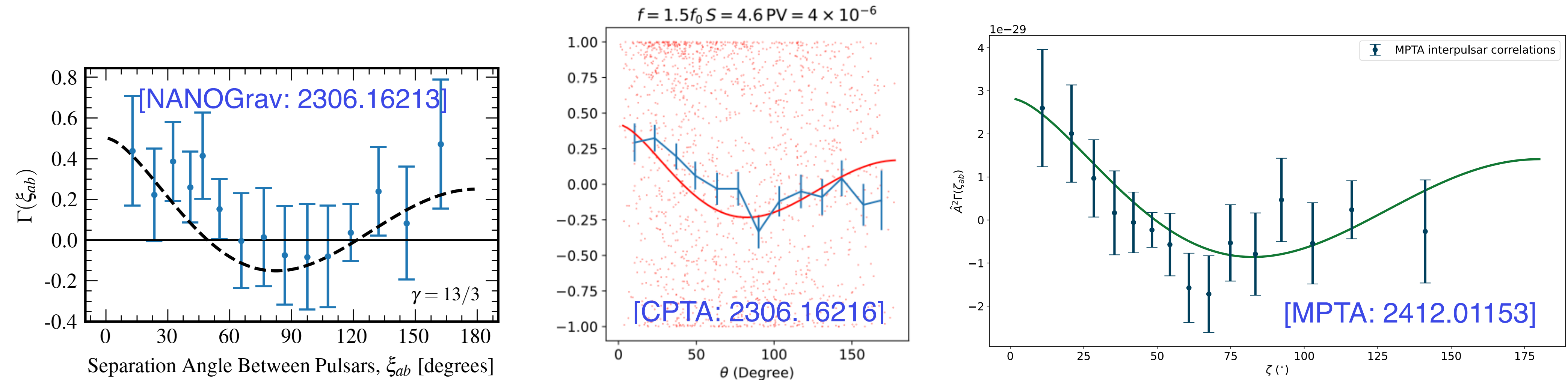


[Hellings and Downs, ApJL 265 (1983)]



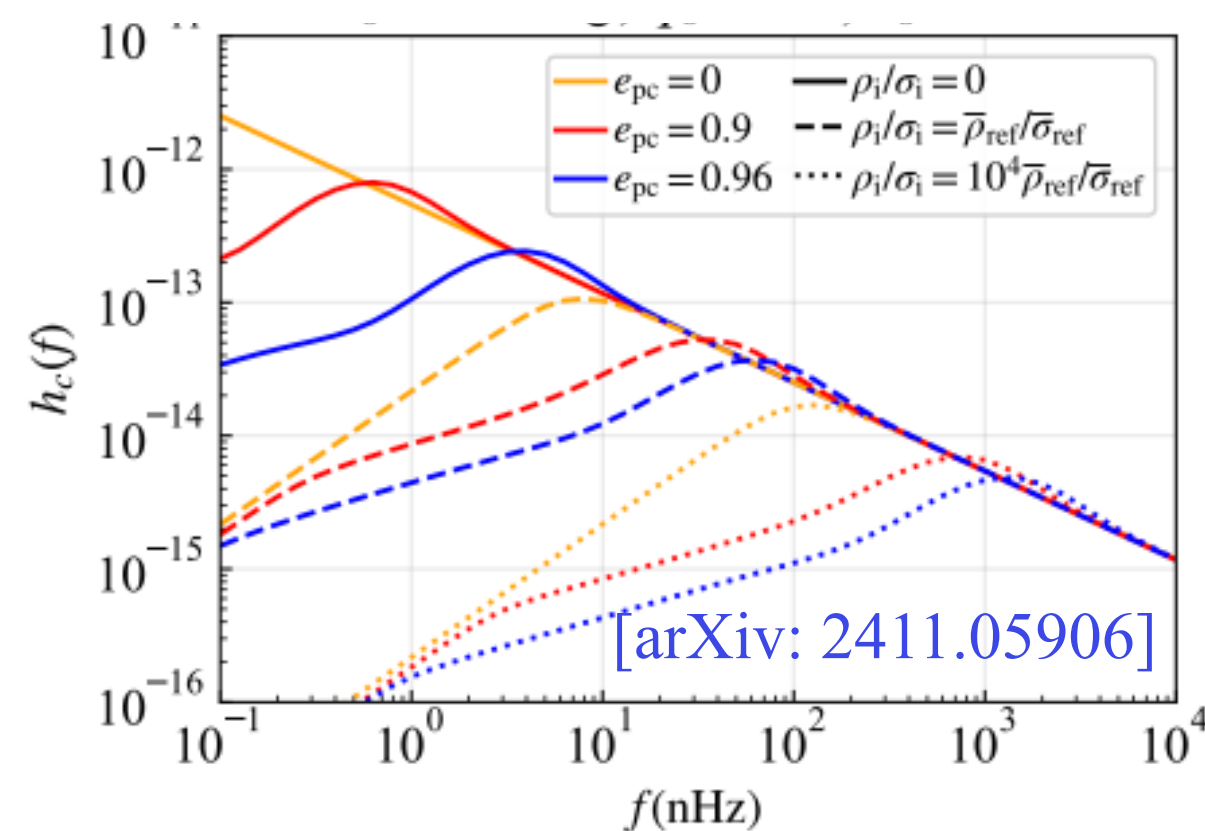
Key evidence for nHz SGWBs

- ◆ Compelling evidence for a *HD-correlated*, common-spectrum red noise

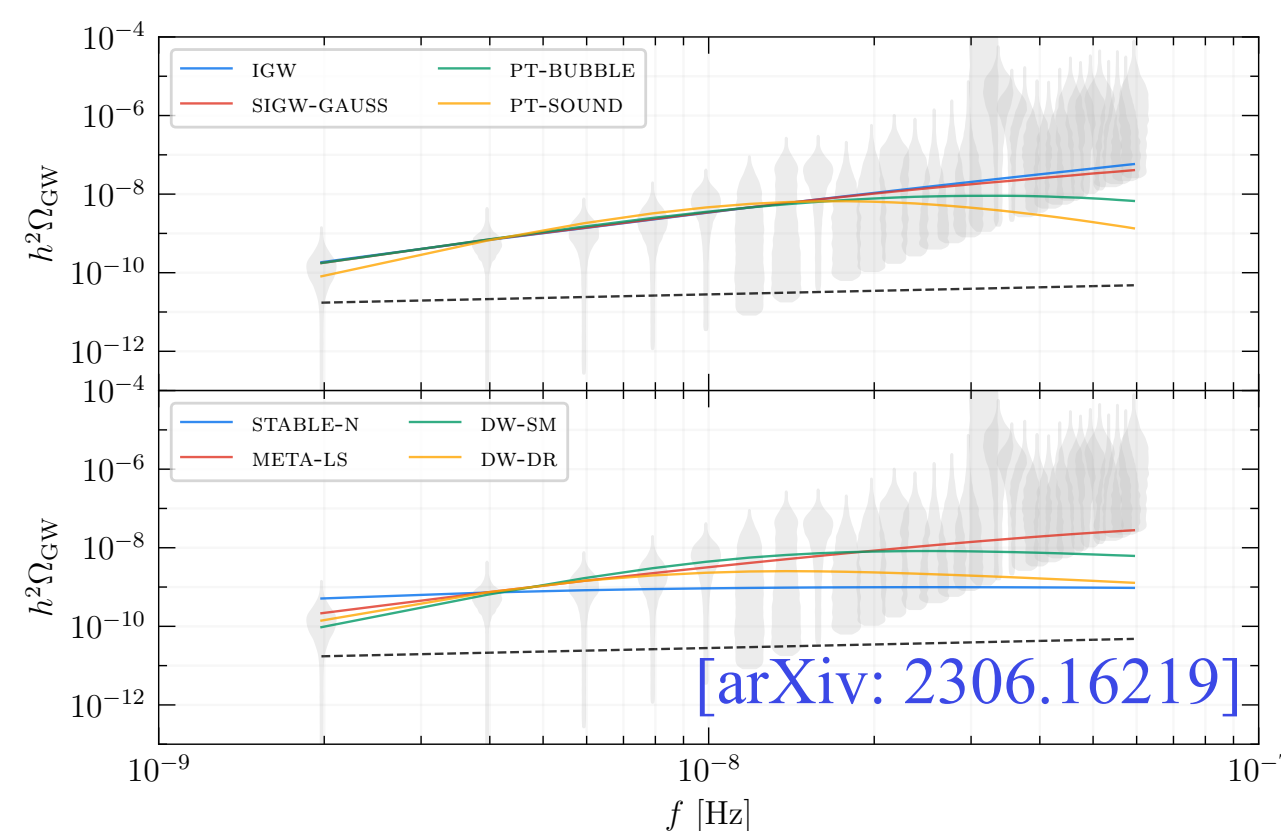


- ◆ Enormous physical implications: GW sources, Test of gravity

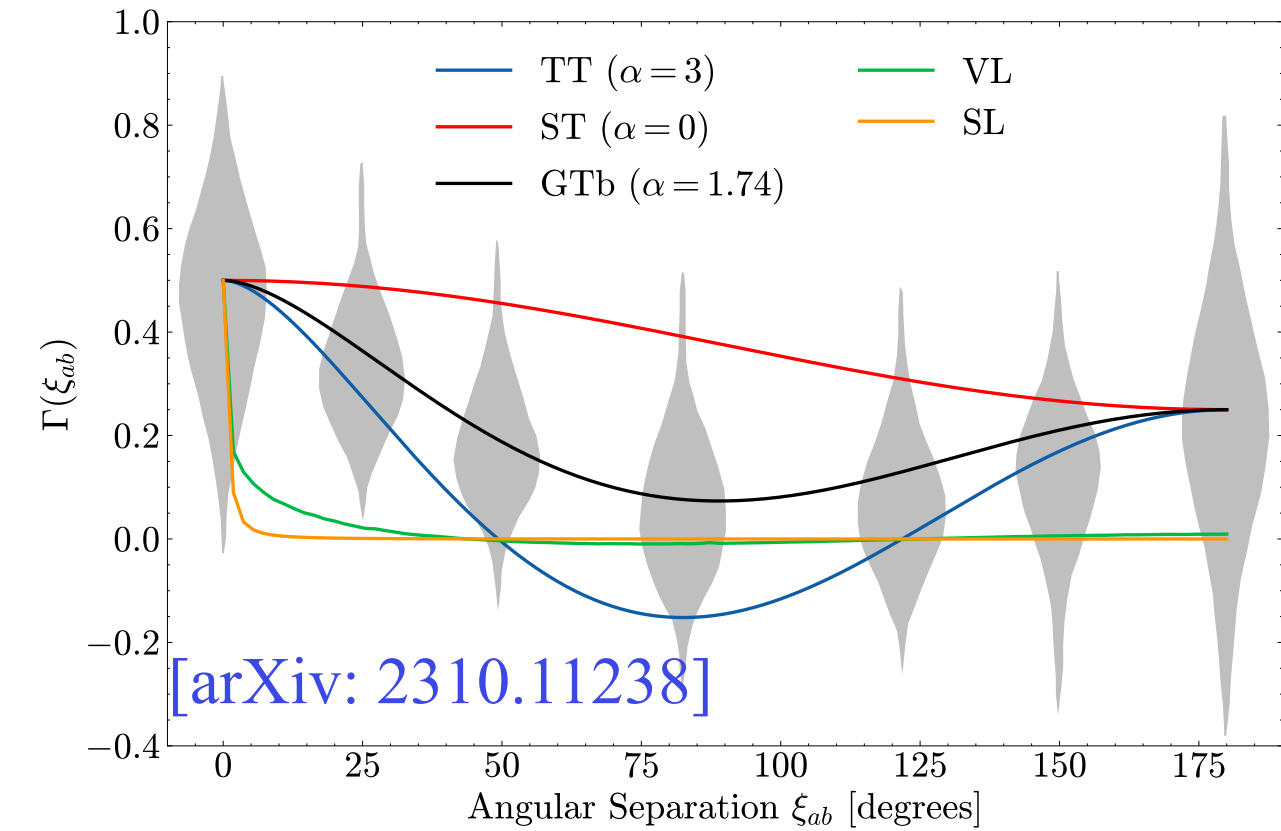
SMBHB environment



various cosmological origin



new GW polarizations



Pulsars as linear polarizers

- ♦ Pulsar radio emissions typically have **strong linear polarization**

Stokes parameters: $\{I, U, Q, V\}$

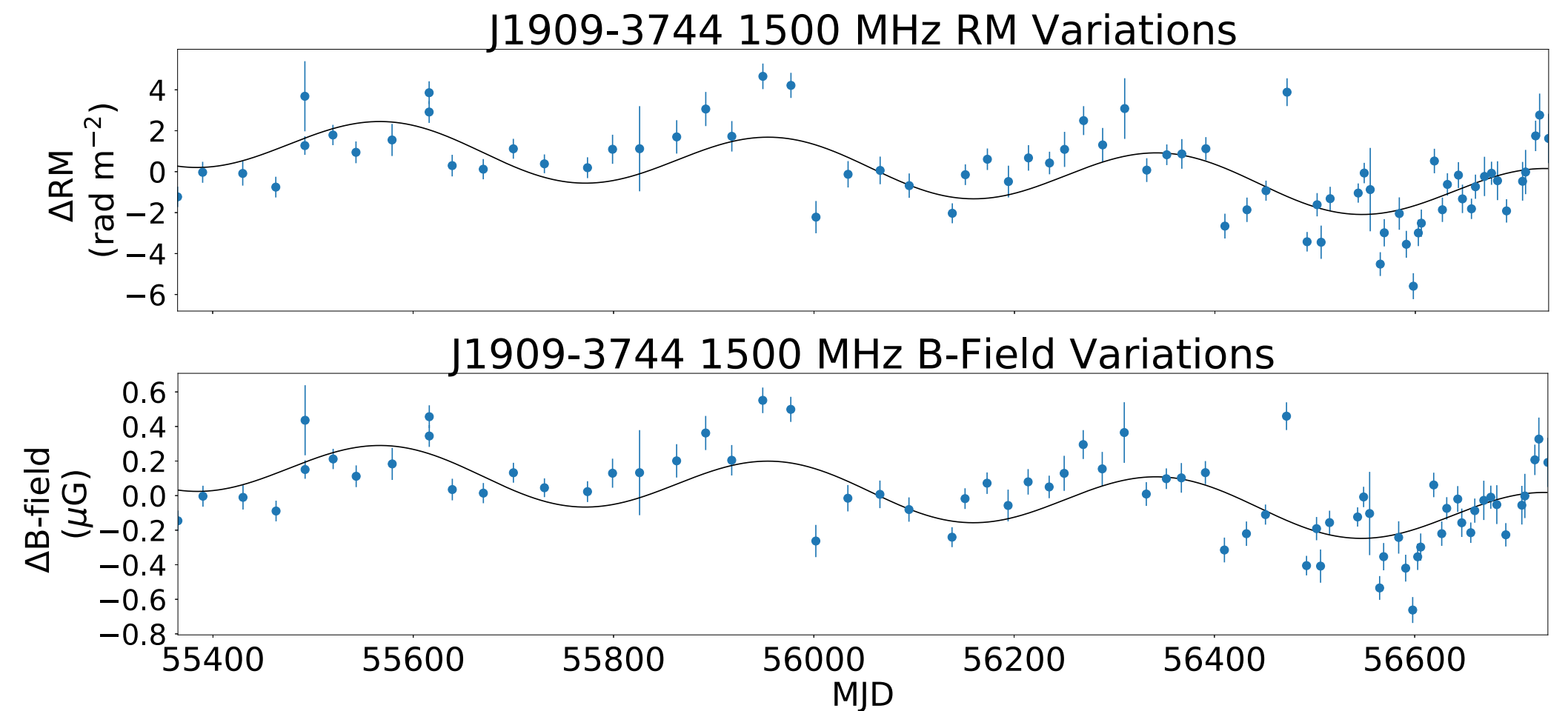
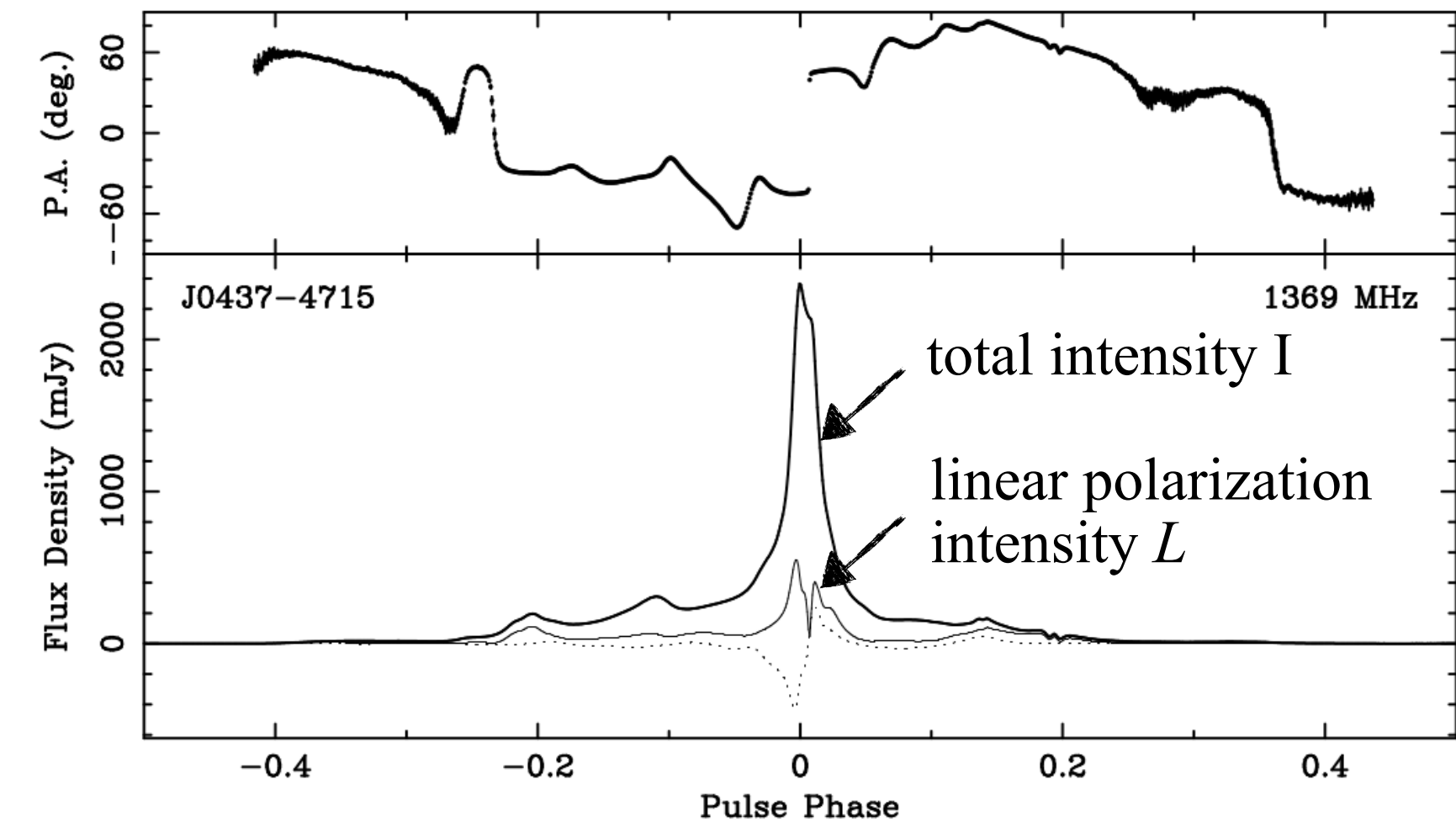
Polarization angle (PA): $PA = \frac{1}{2} \arctan \left(\frac{U}{Q} \right)$

- ♦ Polarization profiles obtained as a *by-product of PTAs* for the purpose of calibration

Faraday rotation (FR) of PA by galactic magnetic field

$$\Delta PA = \frac{e^3 \lambda^2}{2\pi m_e^2 c^4} \int_0^d n_e(l) B_{\parallel}(l) dl, \quad \Delta RM = \frac{\Delta PA}{\lambda^2}$$

[Yan et al. (PPTA collaboration), MNRAS (2011)]



[Wahl et al. [NANOGrav], ApJ 926 (2022)]

Pulsar Polarization Arrays

Tao Liu, Xuzixiang Lou, and Jing Ren
Phys. Rev. Lett. **130**, 121401 – Published 23 March 2023

Article	References	No Citing Articles	Supplemental Material	PDF	HTML
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Abstract

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 $\sim 10^{-27} - 10^{-21} \text{ eV}$.

Measured polarization angle

$$PA = PA_{\text{source}} + PA_{\text{instru}} + PA_{\text{propa}}$$

- **Source:** change of pulsar physics; single pulse stochastic variation (jitter noise)
- **Instrument:** PA calibration; radiometer noise
- **Propagation:** Faraday rotation from interstellar magnetic field/Earth’s ionosphere

TOPICAL REVIEW • OPEN ACCESS
Pulsar timing arrays-challenges, and current status

G M Shaifullah
Published 16 December 2025 • © 2025 The Author(s). Published by IOP Publishing Ltd
[Classical and Quantum Gravity](#), [Volume 42](#), [Number 24](#)

14.3. Pulsar polarisation arrays

Pulsar polarisation arrays (PPAs) are a recently proposed observational approach that parallels PTAs, but focuses on polarisation signals rather than pulse arrival times [261]. While PTAs detect GWs through correlations in the timing residuals of multiple MSPs, PPAs search for correlated variations in pulsar polarisation, potentially revealing novel astrophysics or fundamental physics.

[261] Liu T, Lou X and Ren J 2023 Pulsar polarization arrays *Phys. Rev. Lett.* **130** 121401

Cosmology of axion dark matter (Topical review)

(Contribution to 1st Training School of the COST Action COSMICWISPers)
PoS COSMICWISPers, 040 (2024)

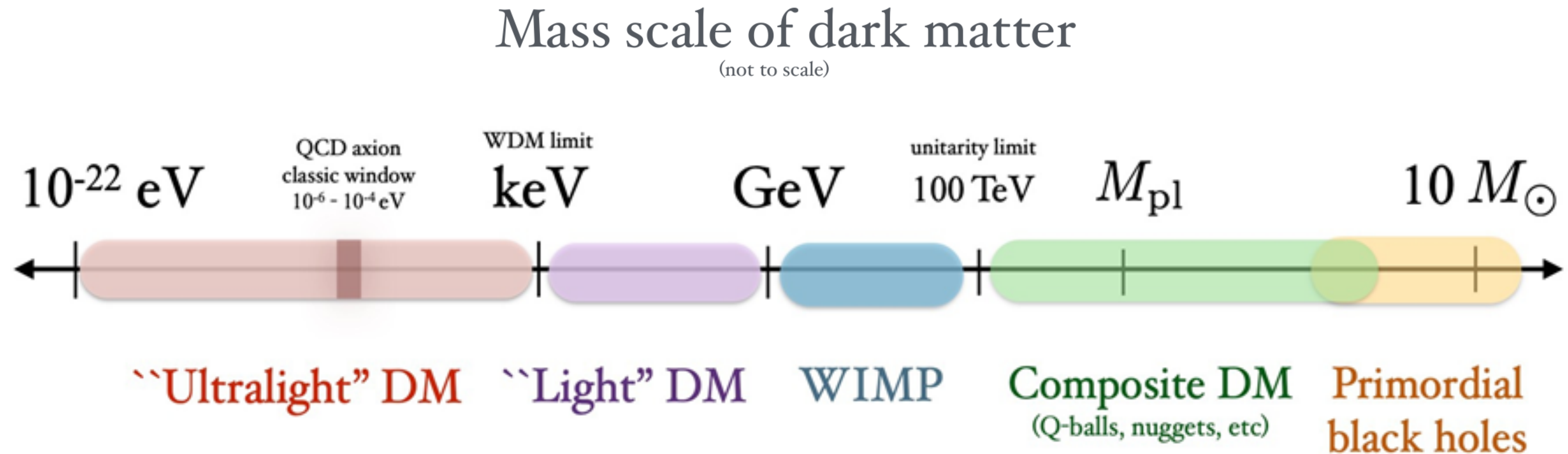
Ciaran A. J. O’Hare*
ARC Centre of Excellence for Dark Matter Particle Physics, The University of Sydney, School of Physics, NSW 2006, Australia
E-mail: ciaran.ohare@sydney.edu.au

Several groups have considered pulsar timing arrays (PTAs) for this purpose. PTAs are large networks of continuously monitored nearby pulsars in the Milky Way. The plane of linear polarisation of the radio emission from these objects is observed to be essentially constant, meaning a bound can be placed on any extra oscillations in the angle caused by the changing axion field value between us and the various pulsars in the network [712, 713]. The bound from Ref.[714] is labelled PPTA—they used twenty pulsars from the Parkes Pulsar Timing Array of the Murriyang radio telescope in Australia, in conjunction with data on the Crab pulsar from QUIJOTE, a CMB experiment on the Canary Islands. The ultimate reach of the PTA approach is to think about pulsar polarisation arrays, in which the polarisation information on different pulsars in the network is spatially and temporally correlated rather than considered separately as a measure of Faraday rotation [715].

[715] T. Liu, X. Lou and J. Ren, *Pulsar Polarization Arrays*, *Phys. Rev. Lett.* **130** (2023) 121401 [2111.10615]. 105

Ultralight axion-like dark matter searches with PTAs and PPAs

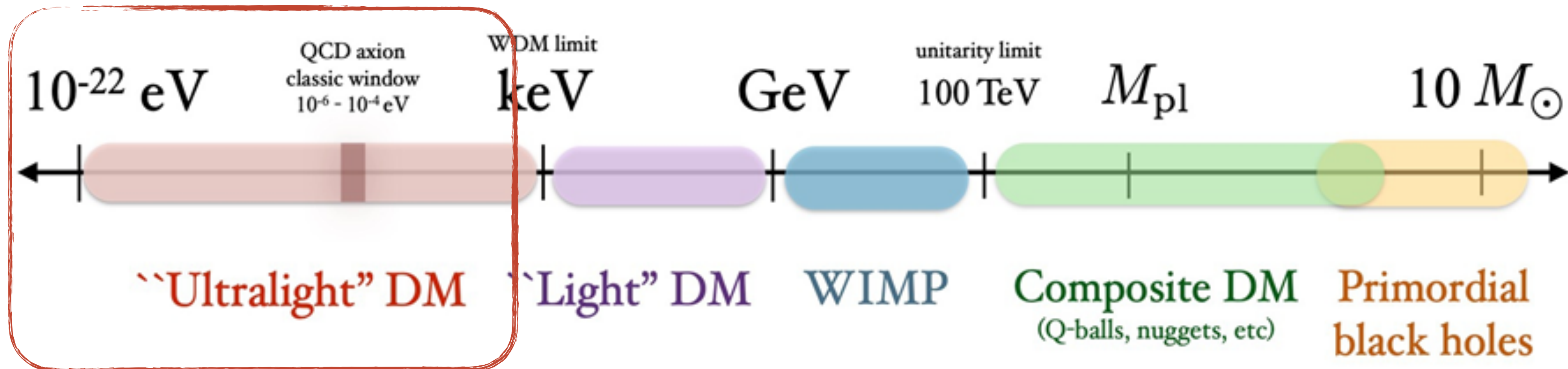
A variety of theoretical candidates of DM



- ◆ Different types of candidates: distinct characteristics + different detection methods

A variety of theoretical candidates of DM

Mass scale of dark matter
(not to scale)



- ✦ Different types of candidates: distinct characteristics + different detection methods
- ✦ **Ultralight DM: wavelike + Pulsar Timing/Polarization Arrays**

$$N_{\text{dB}} = \rho_{\text{DM}} \lambda_{\text{dB}}^3 \sim \left(\frac{34 \text{ eV}}{m_a} \right)^4 \left(\frac{250 \text{ km/s}}{v} \right)^3$$

occupation number per de Broglie volume $\gg 1$ when $m_a \ll 30 \text{ eV}$

Ultralight axion-like dark matter (ALDM)

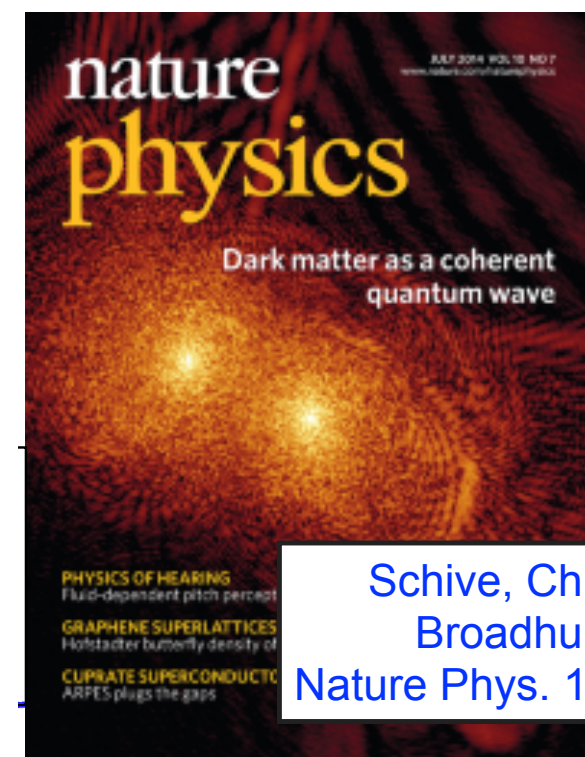
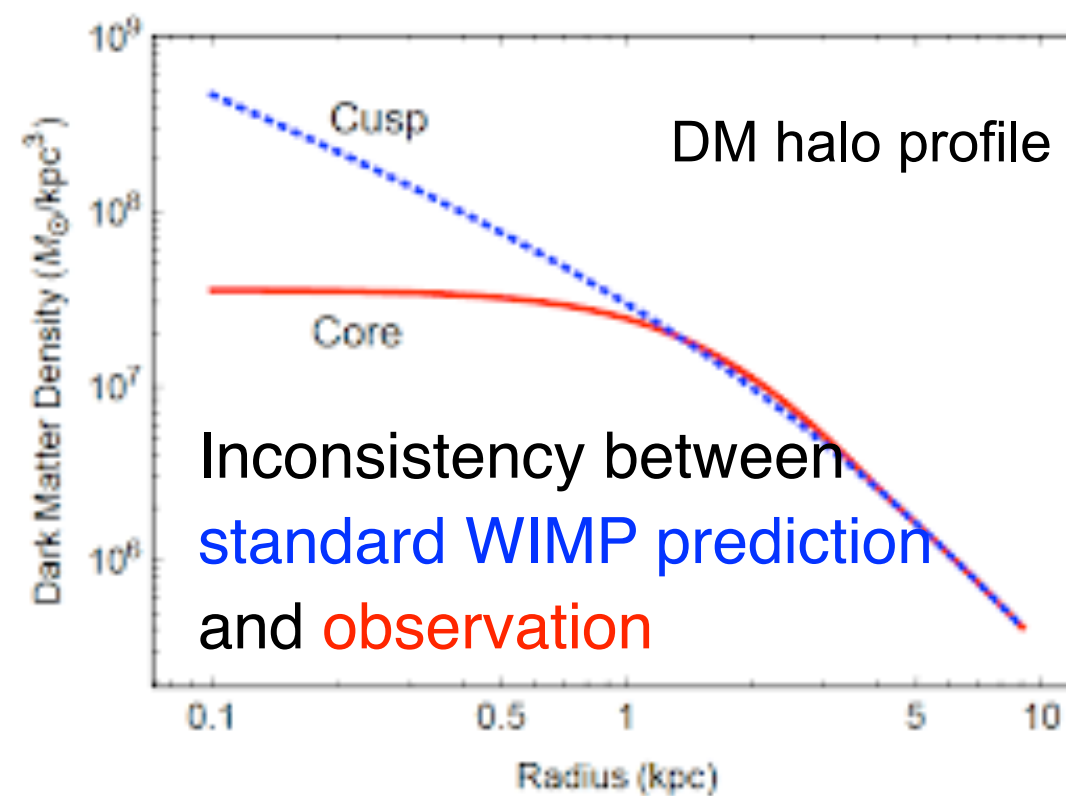
- ♦ Axion-like particles (ALP): light and interact feebly
- ♦ Nonthermal wave DM formed as a Bose-Einstein condensate, and behaves as a stochastic classical field

$$a(\mathbf{x}, t) = \frac{\sqrt{\rho(\mathbf{x})}}{m_a} \sum_d \alpha_d \sqrt{f_{\mathbf{x}}(\mathbf{v}_d) (\Delta v)^3} \cos[\omega_a(t - \mathbf{v}_d \cdot \mathbf{x}) + \phi_d]$$

Annotations for the equation:

- $\mathbf{v}$ peak at $v_0 \sim 10^{-3}c$ (points to $\mathbf{v}_d$)
- random phase (points to ϕ_d)
- random amplitude (points to α_d)

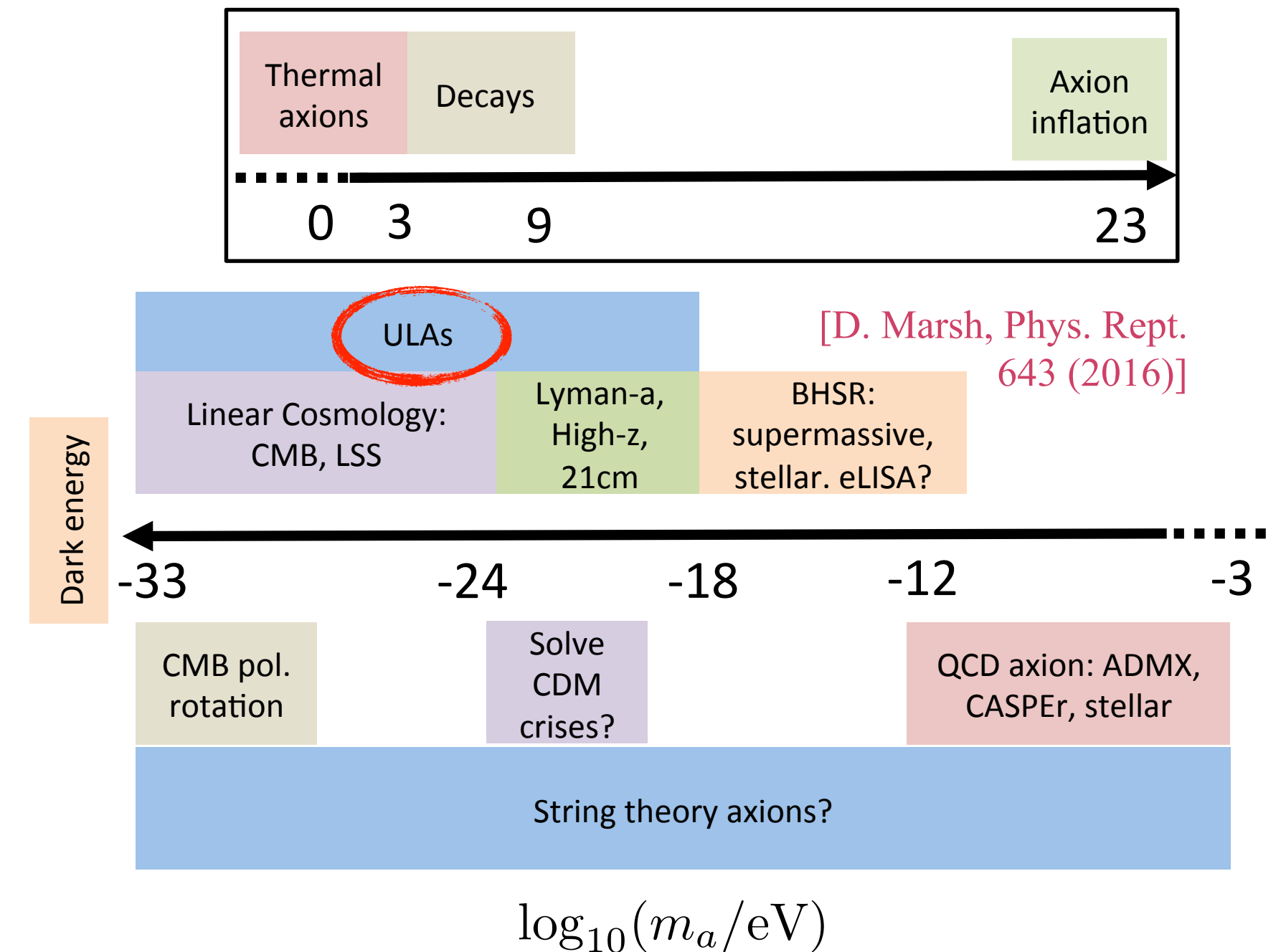
- ♦ Fuzzy DM ($m_a \sim 10^{-22} \text{eV}$) address small-scale problems



A dense soliton core forms at galactic center with radius $\sim$ de-Broglie wavelength $\sim O(100) \text{ pc}$

Schive, Chiueh, Broadhurst
Nature Phys. 10 (2014)

ALPs landscapes



- ♦ Recent constraints on ULDM, i.e. Lyman- α , dwarf galaxies, may suffer from uncertainties — different searches needed!

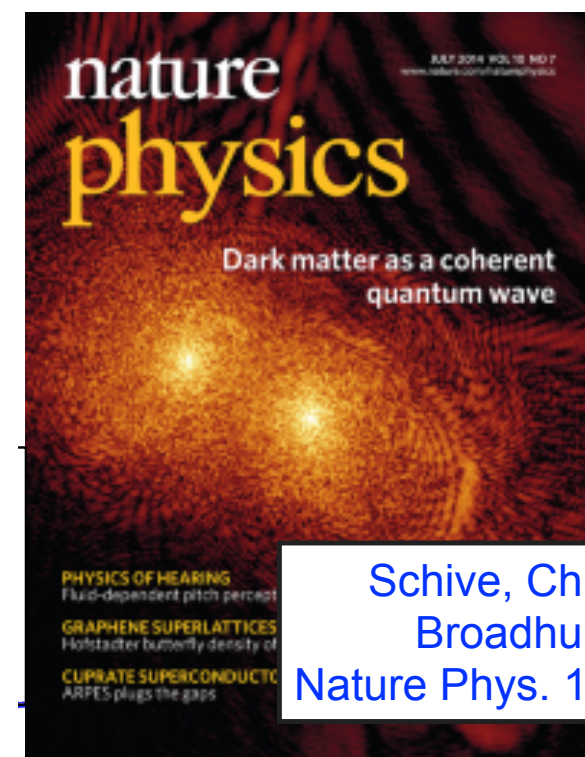
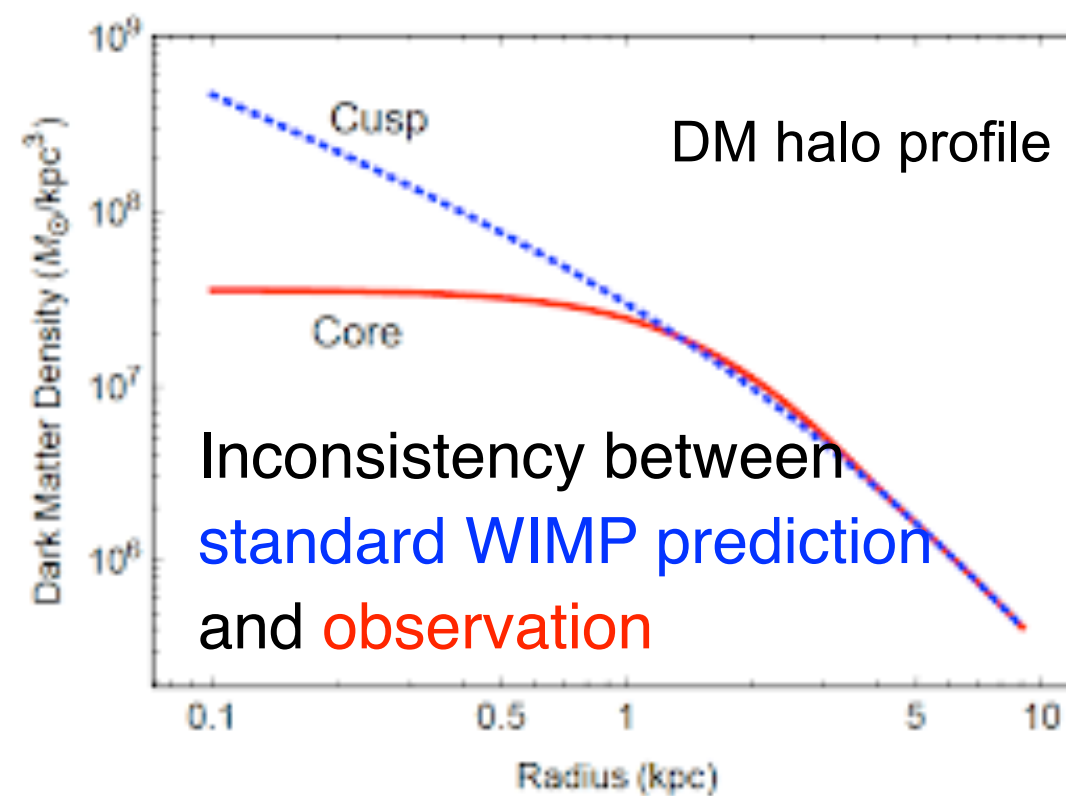
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$\swarrow$ v peak at $v_0 \sim 10^{-3}c$ $\swarrow$ random phase
 $\nwarrow$ random amplitude

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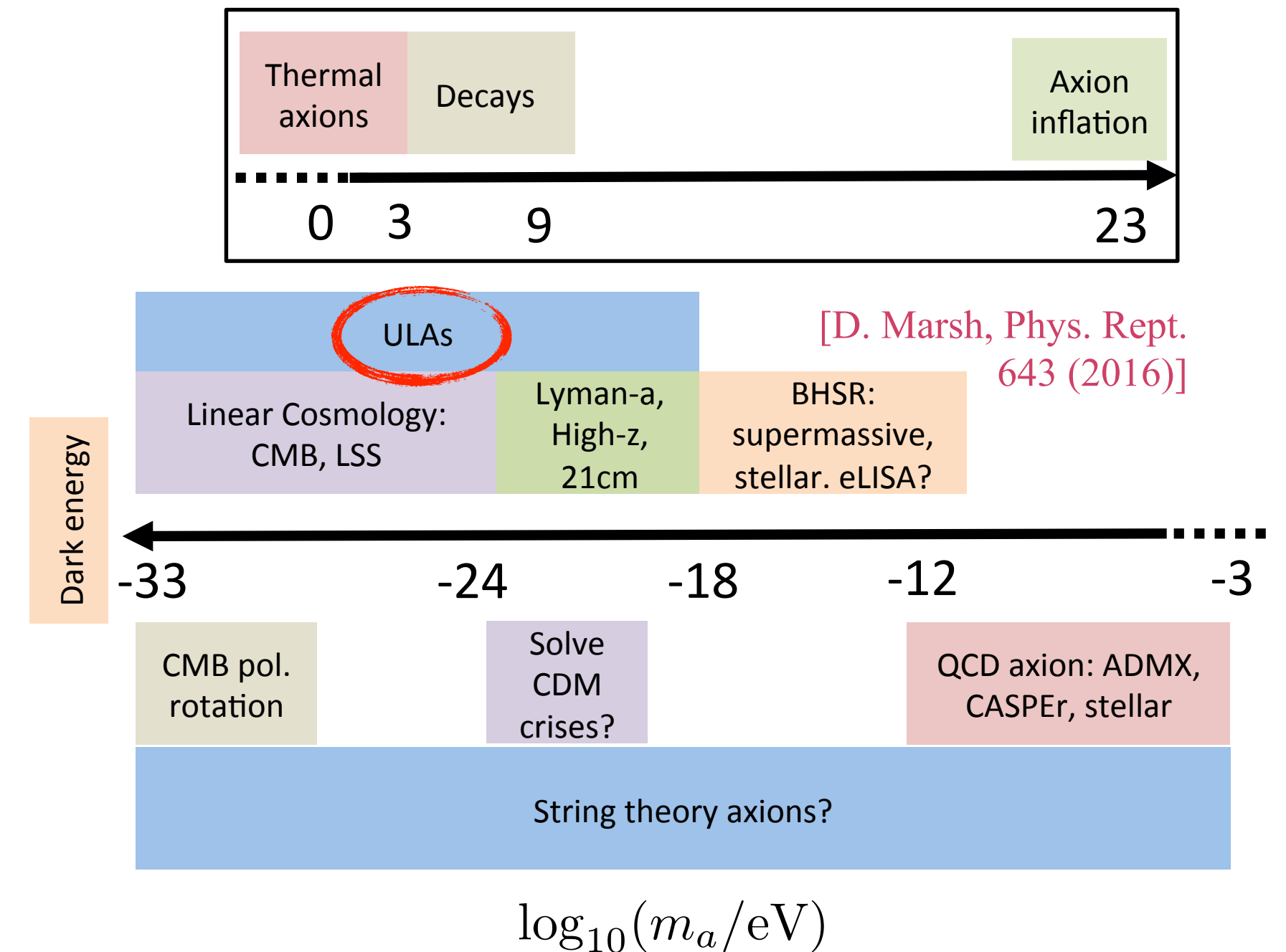


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ALPs landscapes



Gravitational and non-gravitational probe of ALDM by pulsar arrays!

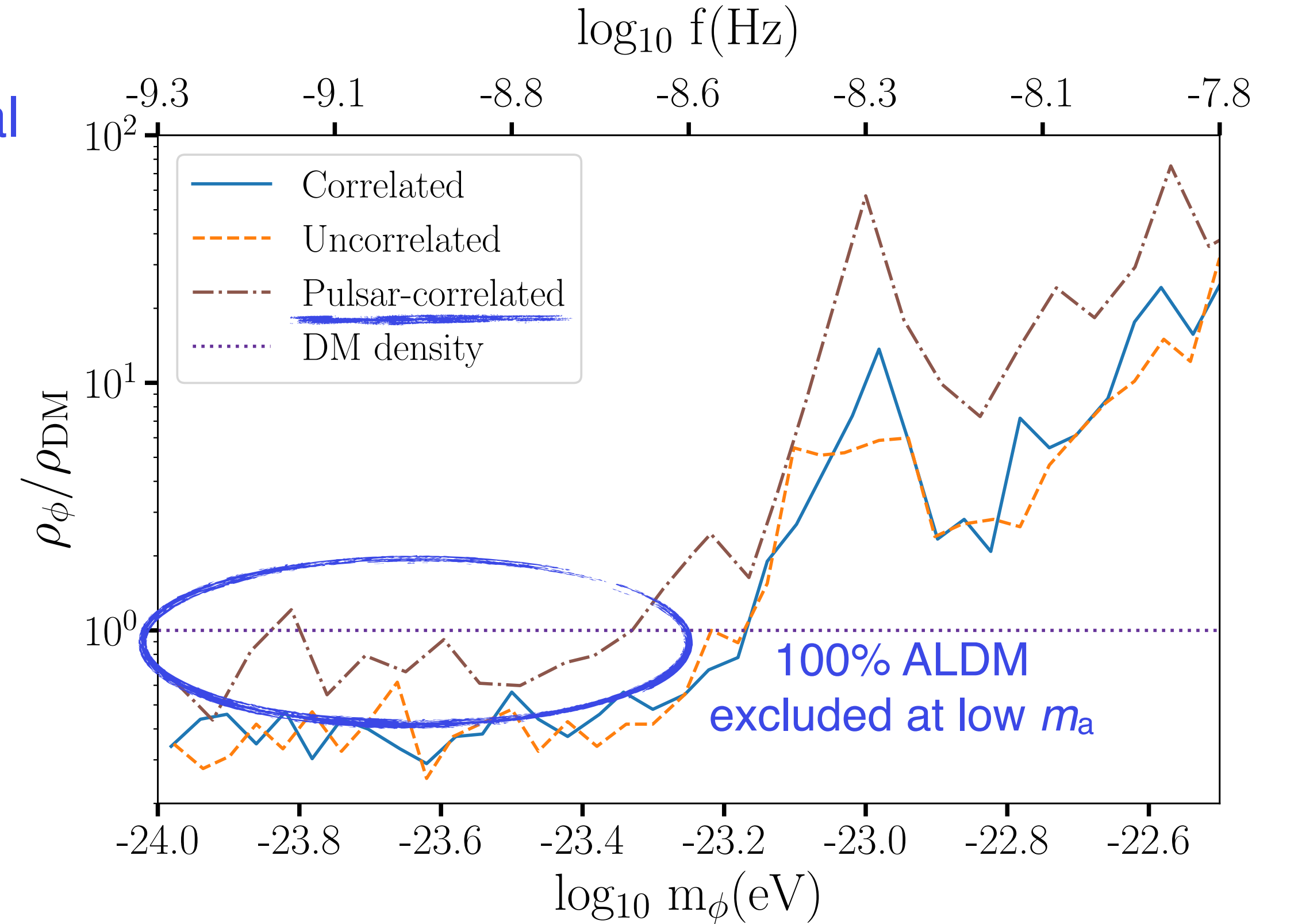
ALDM induced timing signals

ALDM induces **temporal oscillating gravitational potential** through gravity, and then changes the arrival time of the pulses [Khmelnitsky and Rubakov, JCAP 02 (2014)]

$$\Delta t^a(t) \approx - \int^t [\Psi_c(\mathbf{x}_p, t'_p) - \Psi_c(\mathbf{x}_e, t')] dt'$$

$$\approx - \frac{\pi G}{2m_a^2} \left[\underbrace{\dot{a}(\mathbf{x}_p, t_p)a(\mathbf{x}_p, t_p)}_{\text{“Pulsar”}} - \underbrace{\dot{a}(\mathbf{x}_e, t)a(\mathbf{x}_e, t)}_{\text{“Earth”}} \right]$$

The ALDM-induced correction can be > 20 ns for $m < 10^{-23}$ eV



[Smarra *et al.* [EPTA], PRL 131 (2023)]

ALDM induced timing signals

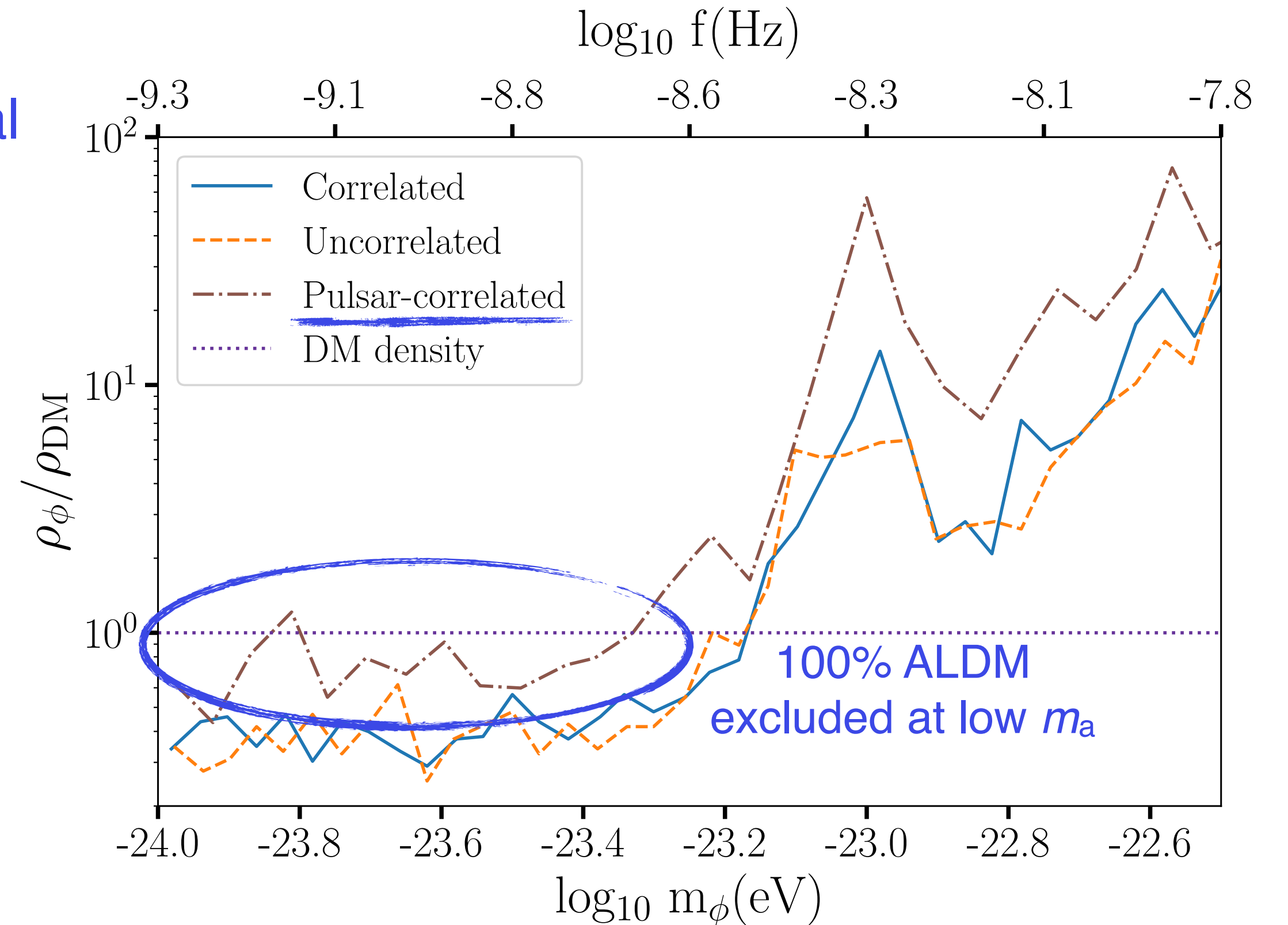
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BUT, the spatial correlation of the signal not fully incorporated in the analysis — which is the key diagnostic for SGWBs detection!



[Smarra *et al.* [EPTA], PRL 131 (2023)]

Characteristic correlations of ALDM timing signals

♦ Two-point correlation functions* [Luu, Liu, JR, *et al.*, ApJL 963 (2024)]

$$\Delta t_p^a = A_c^{(p)} \cos(2m_a t) + A_s^{(p)} \sin(2m_a t). \quad (\text{similar to Fourier transformation})$$

$$\langle A_c^{(p)} A_c^{(q)} \rangle = \langle A_s^{(p)} A_s^{(q)} \rangle \approx \left(\frac{\pi G}{2m_a^3} \right)^2 \left[\rho_e^2 + \rho_p \rho_q \cos[2m_a L_{pq}] \frac{\sin^2 y_{pq}}{y_{pq}^2} - \rho_e \rho_p \cos[2m_a L_p] \frac{\sin^2 y_{ep}}{y_{ep}^2} - (p \rightarrow q) \right]$$

spatial correlation

$$y_{ij} \equiv |\mathbf{x}_i - \mathbf{x}_j| / l_c$$

$$l_c = 1 / (m_a v_0)$$

(coherence length)

* Similar results also highlighted in a recent paper [Boddy, Dror and Lam, PRL 135 (2025)]

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♦ Comparison of spatial correlations

Comparison	SGWB	ALDM
Earth-term correlation	quadrupolar correlation	monopolar correlation (universal)
pulsar-term correlation	pulsar-terms suppressed in $L \gg 1/\omega$ limit; spatial correlations rapidly degrade	spatial correlations degrade slower ($L \gg l_c \gg 1/m_a$); encode DM density dep.; enhanced at galactic center

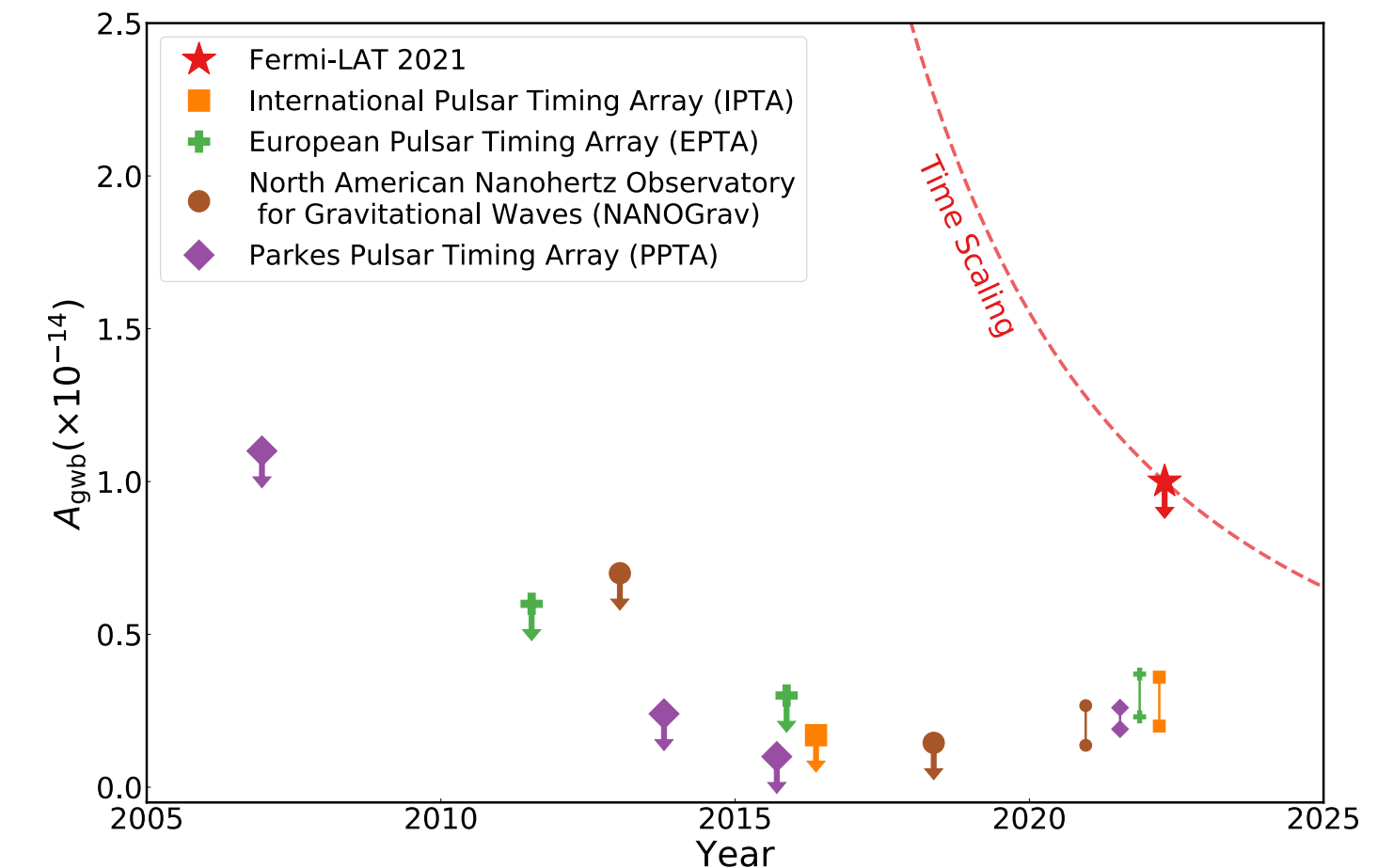
sin y/y term

* Similar results also highlighted in a recent paper [Boddy, Dror and Lam, PRL 135 (2025)]

Gamma-ray PTAs limits

♦ Gamma-ray PTAs

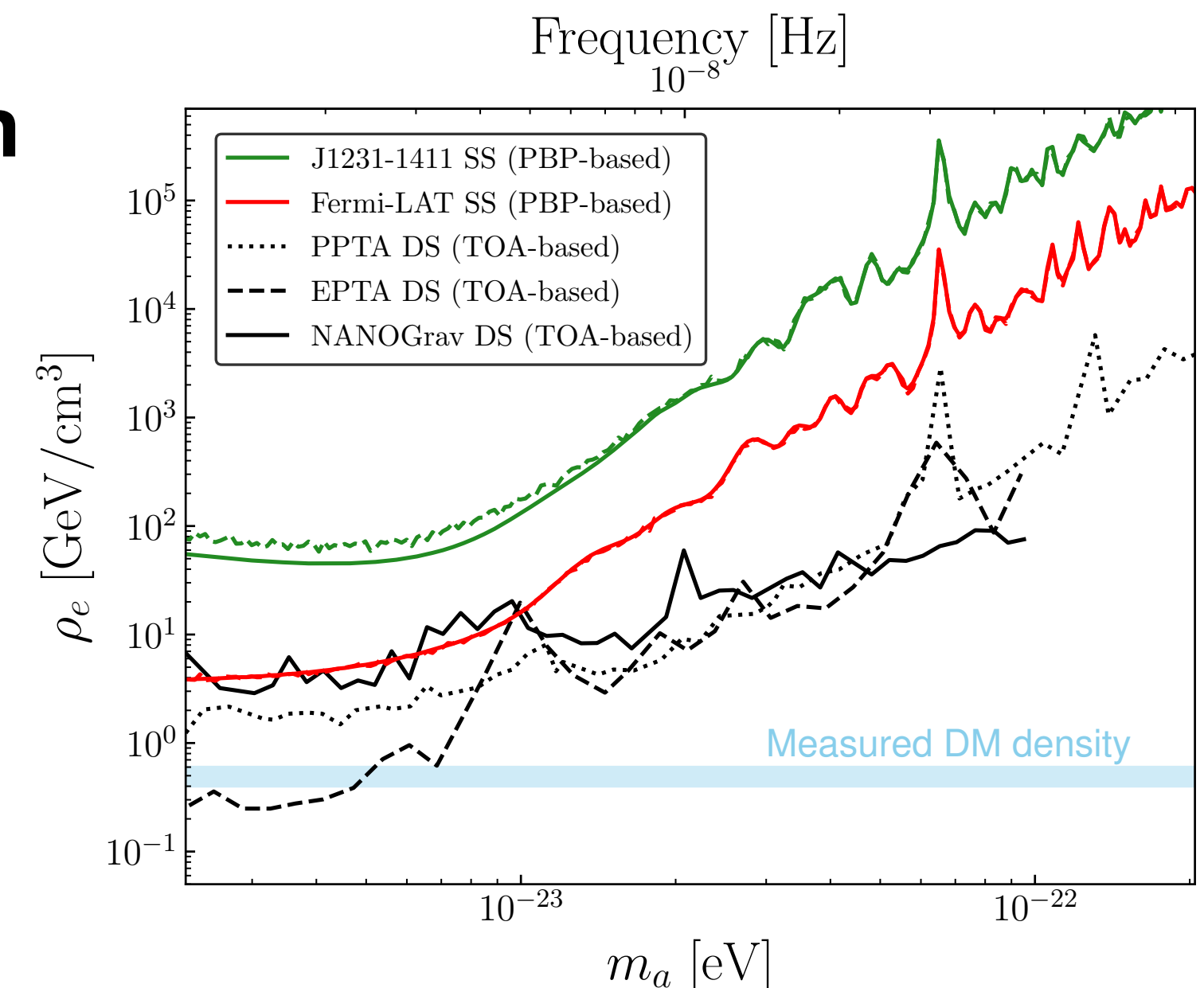
- Fermi-LAT (3rd catalog): ~300 gamma-ray pulsars
- First gamma-ray PTA limits on SGWBs
[Ajello et al. [Fermi-LAT], Science 376 (2022)]
- Intrinsic red noise (FR) suppressed (with statistics limited)
➔ an **independent check** for radio analysis



♦ Gamma-ray PTA limits on ALDM with spatial correlation

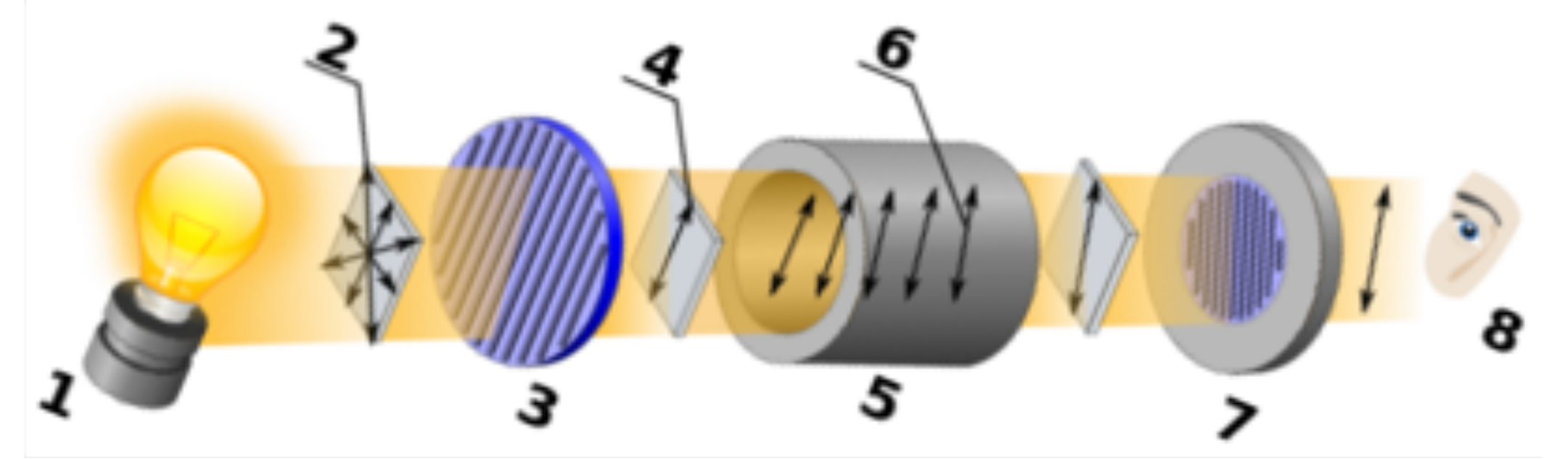
[Luu, Liu, JR, *et al.*, ApJL 963 (2024)]

- Gamma-ray PTA limits not far from those of the dedicated radio-PTA projects at low m_a
- Initial **cross-correlation analysis** using two Fermi-LAT **pulsars**, yielding >50% sensitivity improvement at low m_a



ALDM induced polarization signals

Cosmic Birefringence: the Chern-Simons coupling ($g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) corrects dispersion relations of two circular polarization modes of photons, yielding **position angle (PA) rotation of linearly polarized photons**



$$\omega_{\pm} \simeq k \pm g_{a\gamma\gamma} \left(\frac{\partial a}{\partial t} + \nabla a \cdot \frac{\mathbf{k}}{k} \right) = k \pm g_{a\gamma\gamma} n^{\mu} \nabla_{\mu} a$$

$$\Delta \text{PA}^a \simeq -g_{a\gamma\gamma} \int_C ds n^{\mu} \nabla_{\mu} a(\mathbf{x}, t) \approx g_{a\gamma\gamma} [a(\mathbf{x}_p, t_p) - a(\mathbf{x}_e, t_e)] \quad (C: \text{the photon traveling path, } n^{\mu}: \text{the null tangent vector to } C)$$

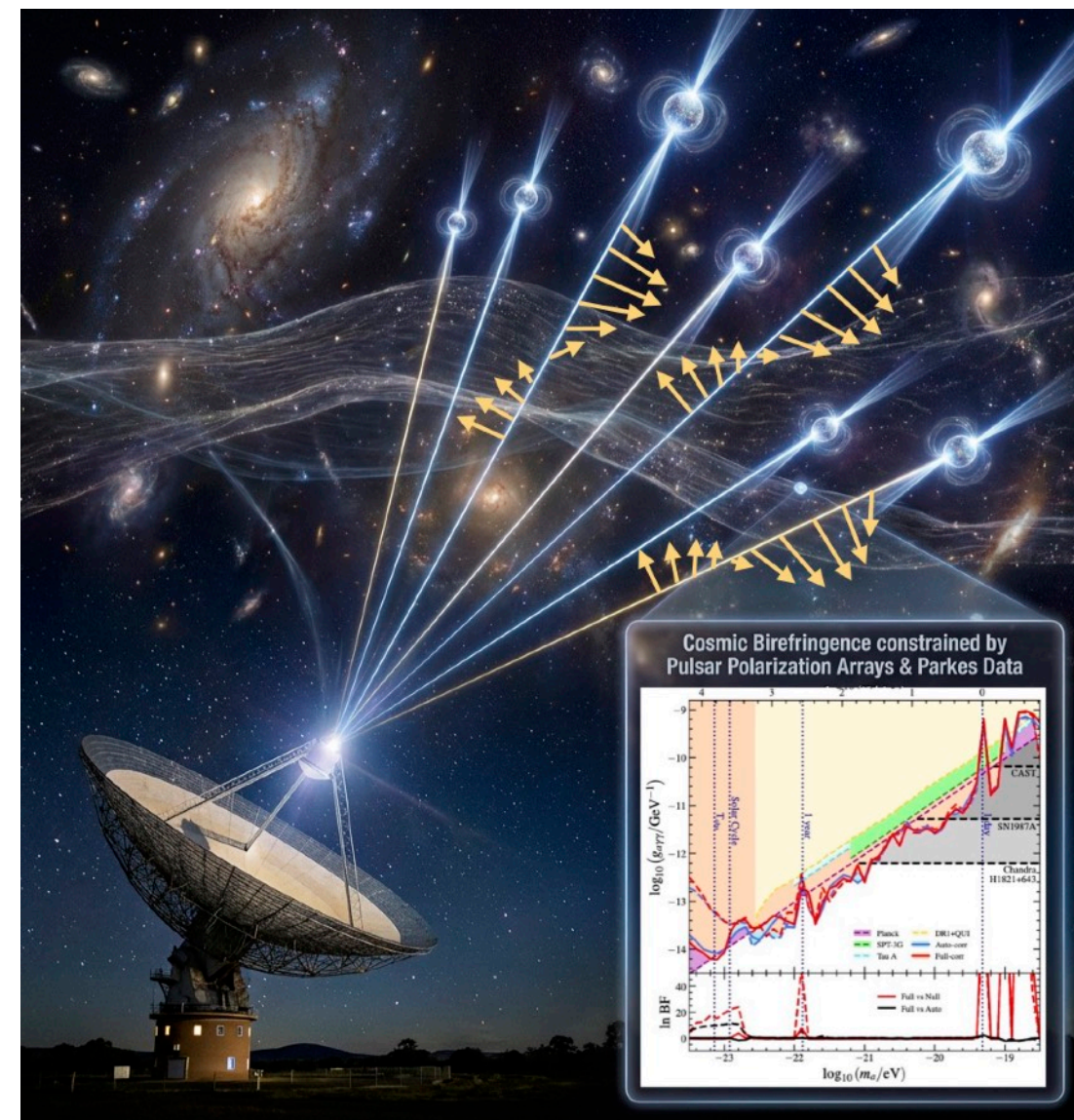
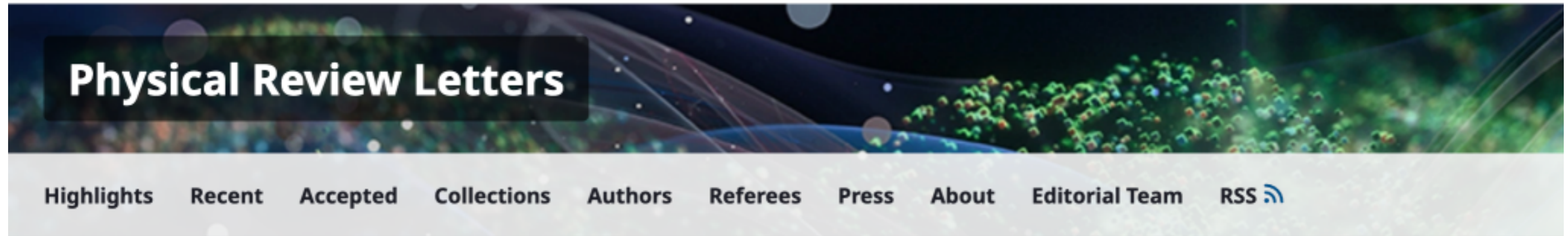
$$\langle \Delta \text{PA}_{p,n}^a \Delta \text{PA}_{q,m}^a \rangle = \frac{g_{a\gamma\gamma}^2}{m_a^2} \sum_{i,j} (-1)^{i+j} \sqrt{\rho(\mathbf{x}_p^{(i)}) \rho(\mathbf{x}_q^{(j)})} \boxed{e^{-\frac{1}{4}(y_{pq}^{ij})^2}} \cos \left[m_a (t_{p,n}^{(i)} - t_{q,m}^{(j)}) + m_a \mathbf{v}_{\odot} \cdot \mathbf{x}_{pq}^{(ij)} \right]$$

spatial correlation

Compared to Faraday Rotation:

- relies only on field profiles at two endpoints of photon traveling
- quasi-monochromatic oscillation at $\omega_a \approx m_a$; no frequency dependence
- Spatial correlated for different pulsars

First PPA limits on ultralight ALDM



EDITORS' SUGGESTION

Pulsar Polarization Array Limits on Ultralight Axionlike Dark Matter

Xiao Xue*, Shi Dai*, Hoang Nhan Luu, Tao Liu[†], Jing Ren[‡], Jing Shu, Yue Zhao, Andrew Zic, N. D. Ramesh Bhat, Zu-Cheng Chen, Yi Feng, George Hobbs, Agastya Kapur, Richard N. Manchester, Rami Mandow, Saurav Mishra, Daniel J. Reardon, Christopher J. Russell, Ryan M. Shannon, Shuangqiang Wang, Lei Zhang, Songbo Zhang, and Xingjiang Zhu (PPTA Collaboration)

Phys. Rev. Lett. **136**, 011001 (2026) - Published 7 January, 2026

By cross-correlating pulsar polarization data within the galaxy, the PPTA collaboration sets the most sensitive limits on how strongly "Fuzzy" axionlike dark matter can interact with Chern-Simons coupling.

*These authors contributed equally to this work.

[†]Contact author: taoliu@ust.hk

[‡]Contact author: renjing@ihep.ac.cn

Bayesian Analysis Framework

♦ Constructing proper PA residual time series

$$\text{PA}_{n,k} \equiv \frac{1}{2} \arctan \left(\frac{U_{n,k}}{Q_{n,k}} \right) \longrightarrow \Delta \text{PA}_n^{\text{obs}} = \frac{1}{2} \arg \sum_k \tilde{L}_k L_{n,k} e^{2i\text{PA}_{n,k} - 2i\overline{\text{PA}}_k} \longrightarrow \langle \Delta \text{PA}_n^{\text{obs}} \rangle = \Delta \text{PA}_n^{\text{t}}$$

(Stokes parameters for each pulsar phase and obs epoch) (subtract standard profile and average over phase) (unbiased estimator)

♦ Establishing a proper noise model

$$\Delta \text{PA}^{\text{obs}} = \Delta \text{PA}^a + \Delta \text{PA}^{\text{ion}} + \Delta \text{PA}^w + \Delta \text{PA}^r + \Delta \text{PA}^{\text{pol}}$$

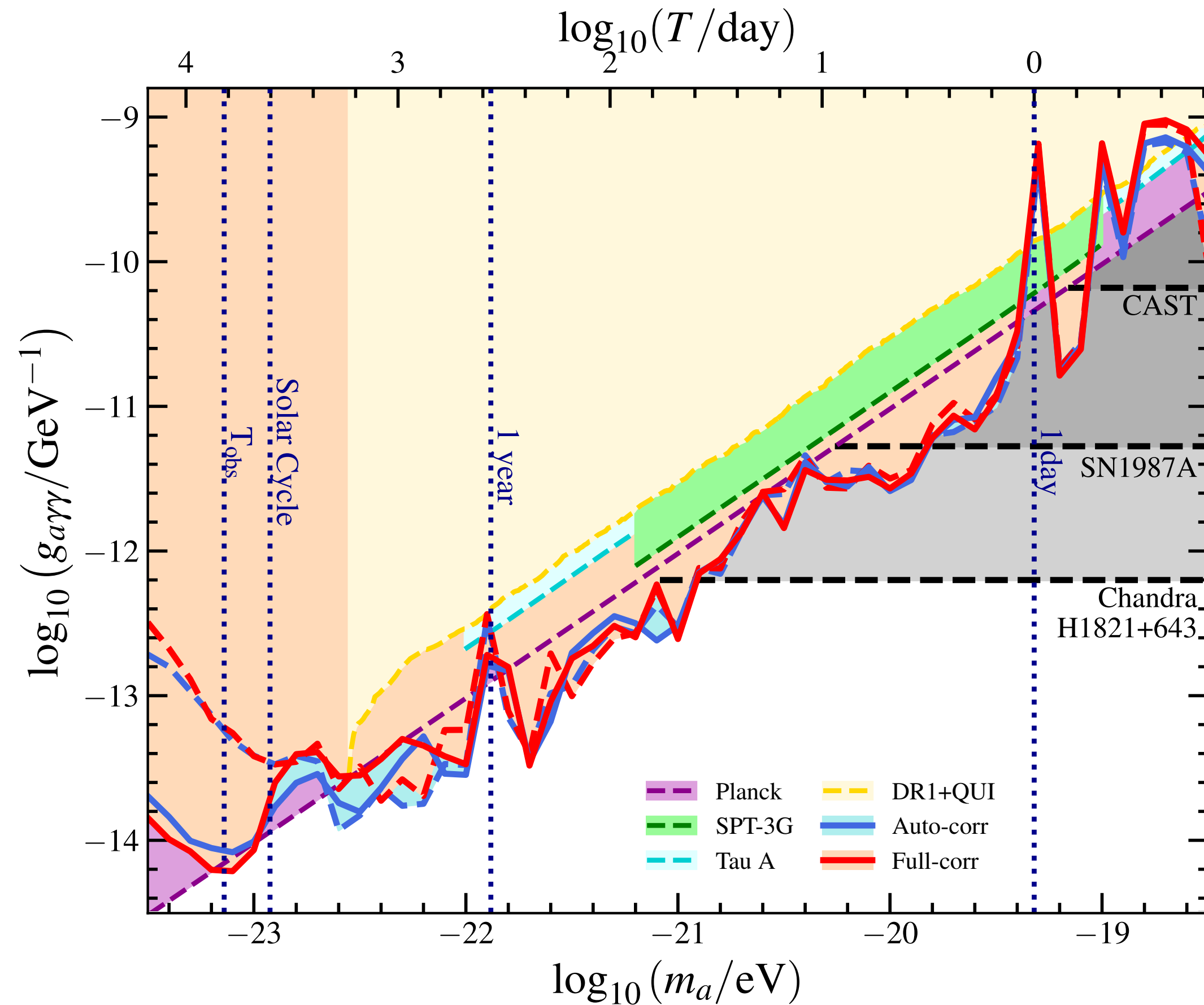
ALDM induced signal ionosphere corrections white noise red noise long-term effects

- Ionospheric corrections vary strongly over time, leading to unmodeled noise
- Additional white noise and red noise remarkably improve the data fitting
- “pol”: linear and quadratic trend

♦ Implementing pulsar cross-correlation: $\ln \mathcal{L} = -\frac{1}{2} \widetilde{\Delta \text{PA}}^T \mathbf{C}^{-1} \widetilde{\Delta \text{PA}} - \frac{1}{2} \ln |2\pi \mathbf{C}|$ $\mathbf{C} = \mathbf{C}^w + \mathbf{C}^r + \mathbf{C}^a$

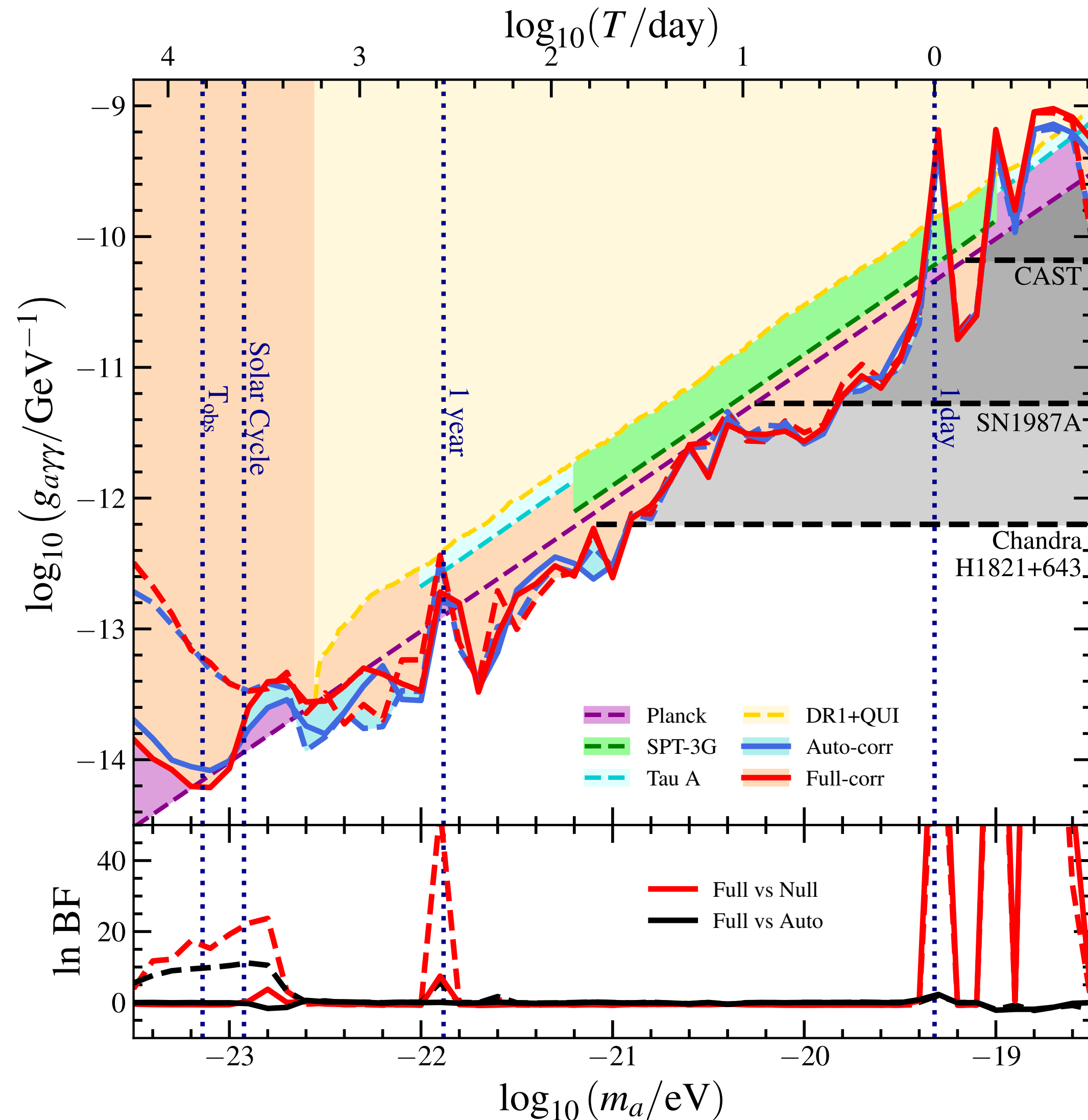
- Maintain phase info: numerically marginalize pulsar distance D_p
- Identify the nature of derived limits: comparing null-signal model and full-correlation and auto-correlation signal models (cross-correlation: full vs auto)

Upper limits on Chern-Simmons coupling



- ♦ Assuming observed local DM density: $\rho_e = 0.4 \text{ GeV}/\text{cm}^3$
- ♦ Characteristic scaling: $g_{a\gamma\gamma} \propto m_a$ for $m_a > 1/T_{\text{obs}}$; $g_{a\gamma\gamma} \propto m_a^{-2}$ for $m_a < 1/T_{\text{obs}}$ ($T_{\text{obs}} \sim 18 \text{ yr}$)
- ♦ Comparison with other limits
 - ALP not DM v.s. ALP being DM: the latter type provides stronger limits at lower frequency
 - Parks PPA limits surpasses all others in $m_a \sim 10^{-22} - 10^{-21} \text{ eV}$; excellent sensitivity extends to $\sim 10^{-23} \text{ eV}$

Upper limits on Chern-Simmons coupling

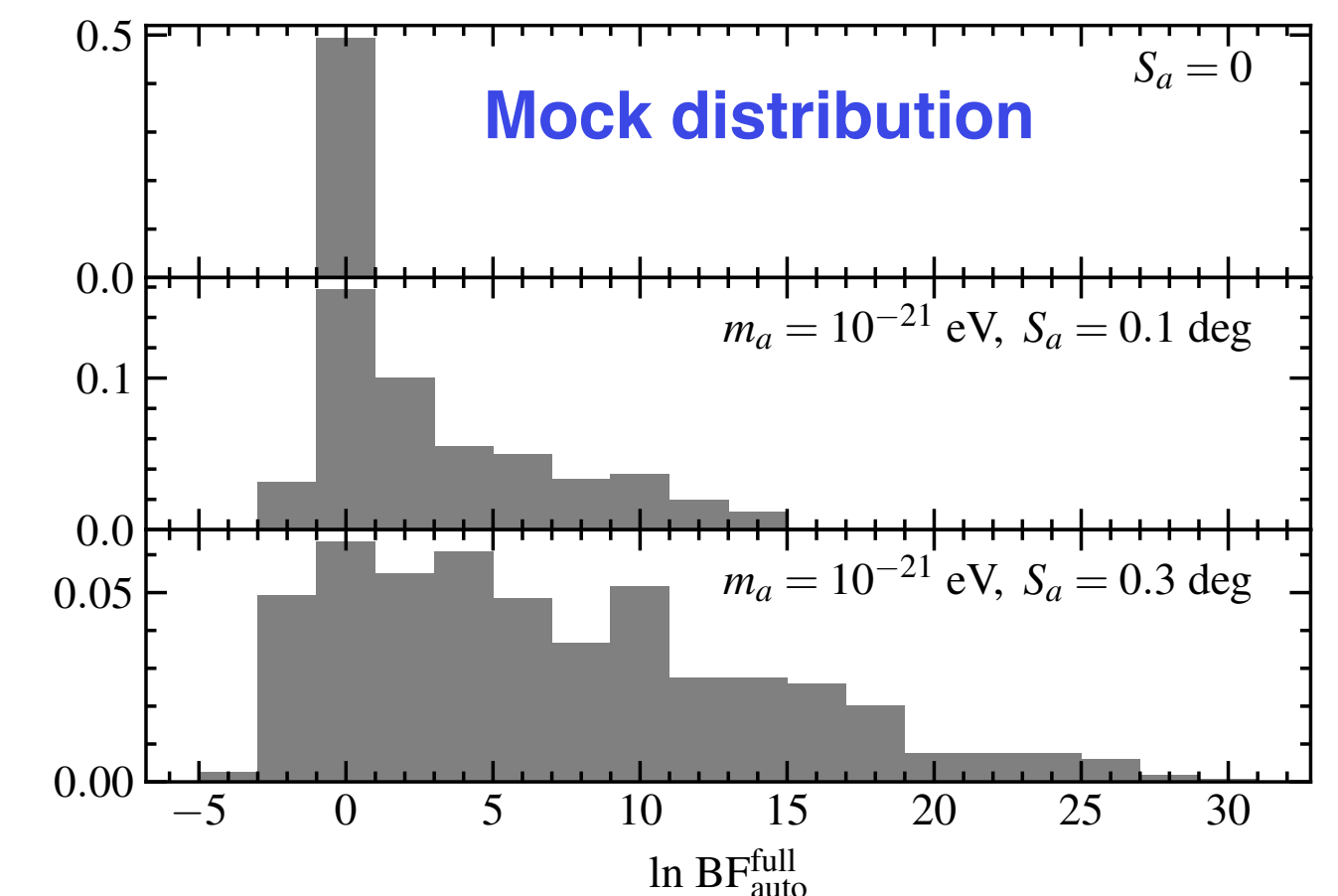


* solid/dash: with/without ionosphere

- ♦ Assuming observed local DM density: $\rho_e = 0.4 \text{ GeV}/\text{cm}^3$
- ♦ Characteristic scaling: $g_{a\gamma\gamma} \propto m_a$ for $m_a > 1/T_{\text{obs}}$; $g_{a\gamma\gamma} \propto m_a^{-2}$ for $m_a < 1/T_{\text{obs}}$ ($T_{\text{obs}} \sim 18 \text{ yr}$)
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Model comparison:

- Full vs Null: sharp peaks appear at $T < 1 \text{ day}$
- **Full vs Auto: no excess at all m_a → shark peaks likely due to imperfect noise modeling**

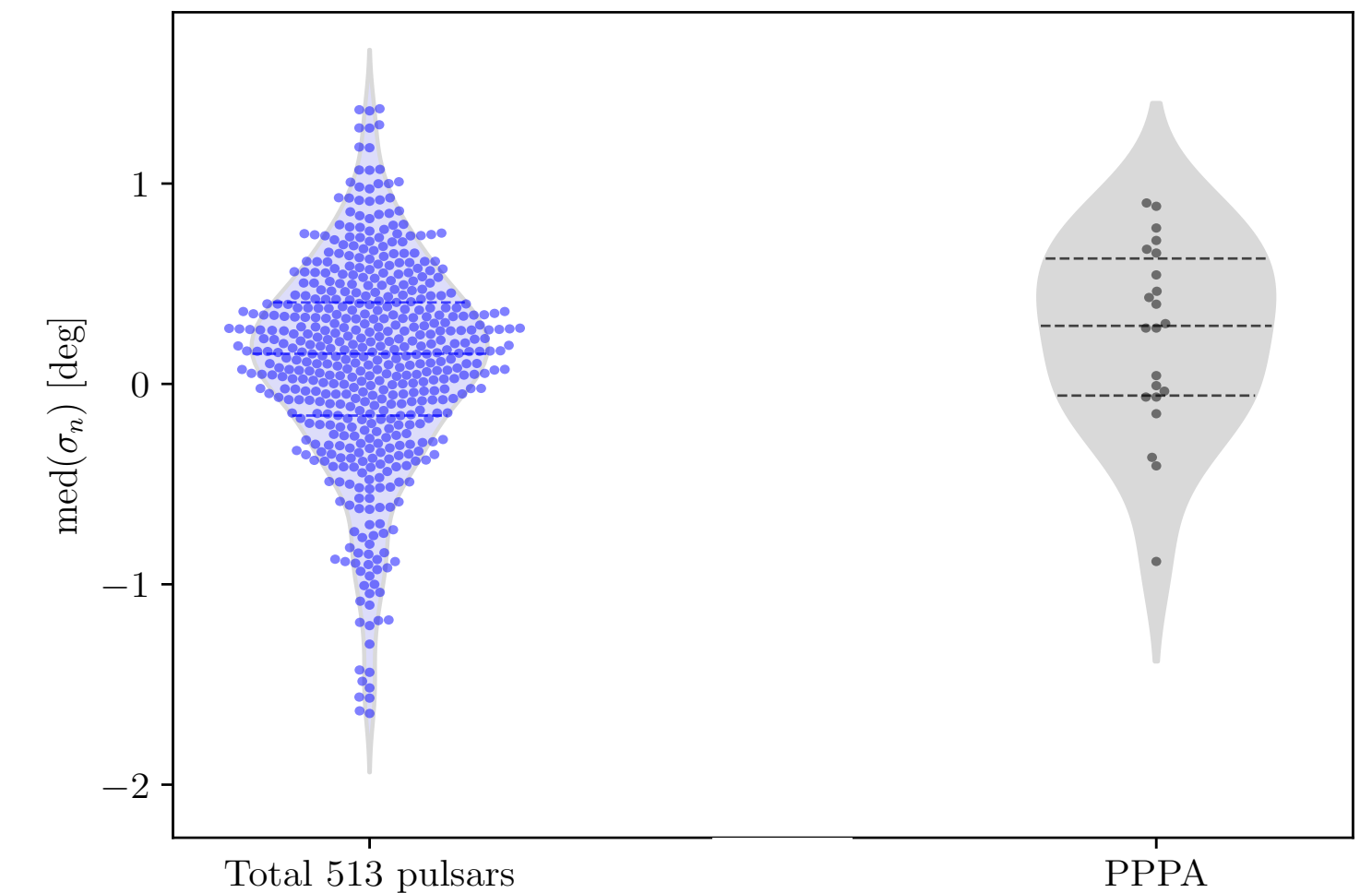


First PPA of regular pulsars

- ♦ **Thousand-Pulsar Polarization Array (TPPA):** first PPA of *regular pulsars*, using data from MeerKAT's Thousand Pulsar Array

[Yuwen, Sarkis, Ma, Liu, **JR**, Weltevrede, Xue, 2605.****]

- Polarization profile stability differs much less with MSPs
- *More population, wider spatial distribution*
- Substantially higher observational precision for MeerKAT



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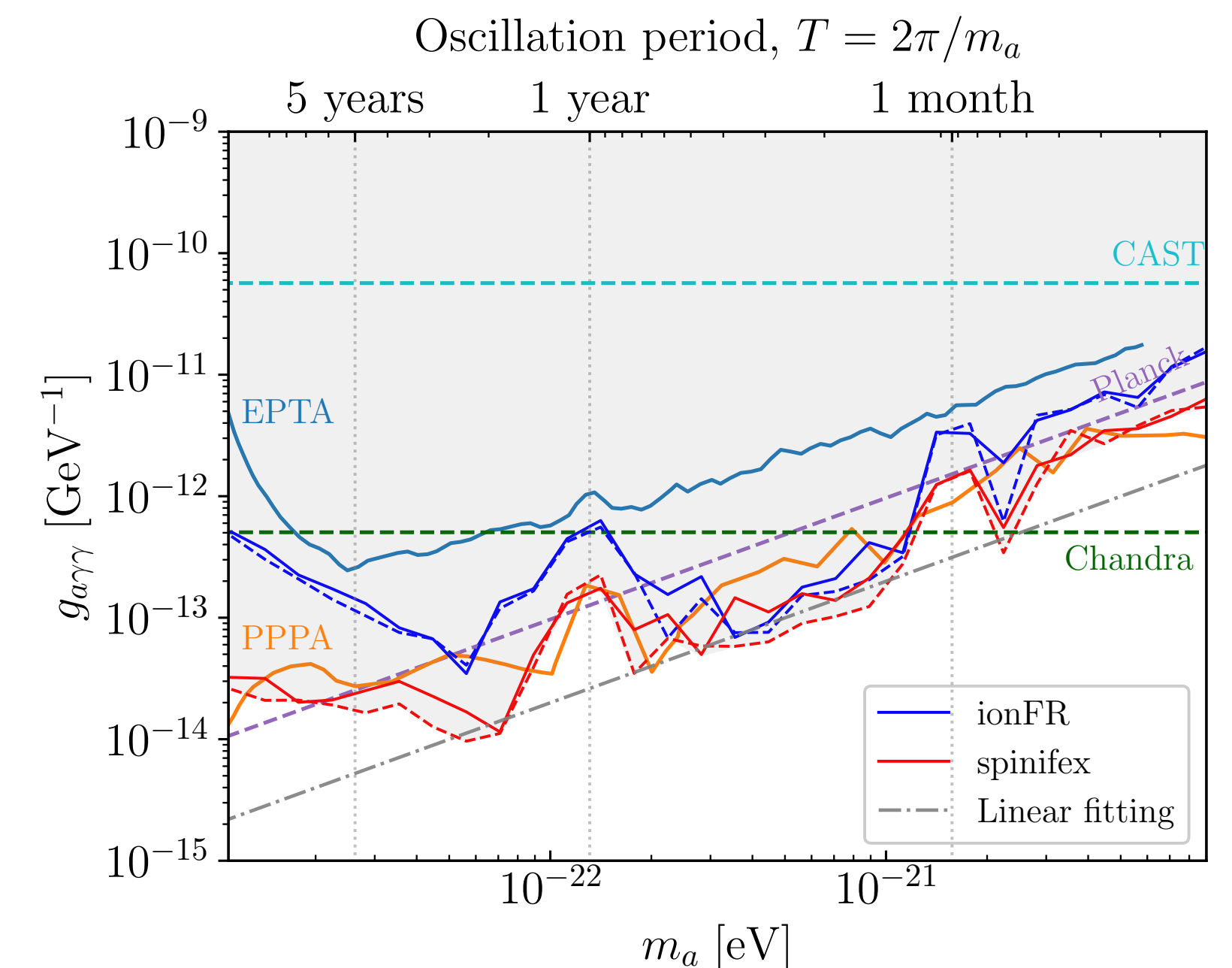
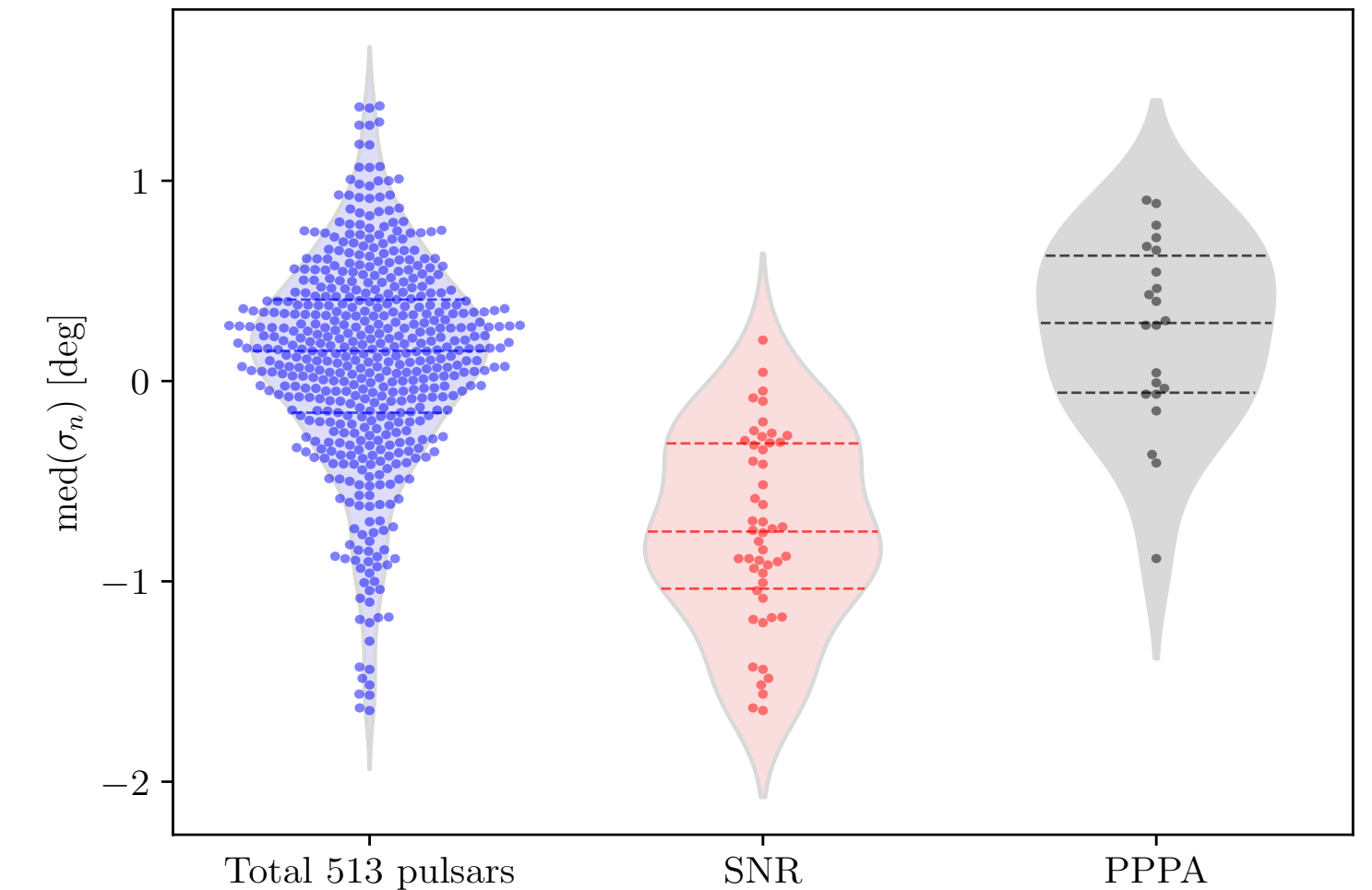
- Polarization profile stability differs much less with MSPs
- **More population, wider spatial distribution**
- Substantially higher observational precision for MeerKAT

♦ Bayesian analysis framework

- **Primary TPPA** constructed from the 50 pulsars with highest SNR
- Two subgroups selected with different spatial distributions
- Two ionospheric models: ionFR and spinifex

♦ Results

- **With only 1/3 observation time, TPPA limits comparable to PPPA!**
- Even better limits with improved ionospheric modeling
- Highlight great potential of constructing regular-pulsar PPAs



ALDM: timing & polarization signals correlations

- ♦ Recall: polarization (**timing**) signal linear (**quadratic**) in ALDM field

$$\Delta \text{PA}_{p,n}^a = \frac{g_{a\gamma\gamma}}{m_a} (\sqrt{\rho_p} X_{p,n}^p - \sqrt{\rho_e} X_{p,n}^e) \quad (\text{Gaussian})$$

($X_{p,n}, Y_{p,n}$: elementary Gaussian variables)

$$\Delta t_{p,n}^a \equiv \frac{\pi G}{2m_a^3} [\rho_e X_{p,n}^e Y_{p,n}^e - \rho_p X_{p,n}^p Y_{p,n}^p] \quad (\text{non-Gaussian})$$

➡ two-point functions vanish: $\langle \Delta t_{p,n}^a \Delta \text{PA}_{q,m}^a \rangle \propto \langle X_{p,n}^{(i)} Y_{p,n}^{(i)} X_{q,m}^{(j)} \rangle = 0$

- ♦ LO correlations appear as the **three-point functions** [Li, Liu, Liu*, JR* *et al.*, PRD 113 (2026)]

$$\begin{aligned} \langle \Delta \text{PA}_{p,n}^a \Delta \text{PA}_{q,m}^a \Delta t_{r,l}^a \rangle &= \frac{\pi G g_{a\gamma\gamma}^2}{2m_a^5} \sum_{i,j,k} (-1)^{i+j+k} \sqrt{\rho(\mathbf{x}_p^{(i)}) \rho(\mathbf{x}_q^{(j)}) \rho(\mathbf{x}_r^{(k)})} \langle X_{p,n}^{(i)} X_{q,m}^{(j)} X_{r,l}^{(k)} Y_{r,l}^{(k)} \rangle \\ &= -\frac{\pi G g_{a\gamma\gamma}^2}{2m_a^5} \sum_{i,j,k} (-1)^{i+j+k} \sqrt{\rho(\mathbf{x}_p^{(i)}) \rho(\mathbf{x}_q^{(j)}) \rho(\mathbf{x}_r^{(k)})} \boxed{e^{-\frac{1}{4}(y_{pr}^{ik})^2} e^{-\frac{1}{4}(y_{qr}^{jk})^2}} \\ &\quad \times \sin \left[m_a (t_{p,n}^{(i)} + t_{q,m}^{(j)} - 2t_{r,l}^{(k)}) + m_a \mathbf{v}_\odot \cdot (\mathbf{x}_{pr}^{(ik)} + \mathbf{x}_{qr}^{(jk)}) \right]. \end{aligned}$$

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QUE: how to incorporate such correlations into Bayesian analysis framework?

ALDM: combined PTA-PPA analysis scheme

- ♦ Assuming independent random noise for timing and polarization data

$$\mathcal{L} = \mathcal{L}_t \mathcal{L}_{\text{PA}} \propto \exp \left[-\frac{1}{2} (\Delta \mathbf{t}_o - \Delta \mathbf{t}^a)^T (\mathbf{C}_t^n)^{-1} (\Delta \mathbf{t}_o - \Delta \mathbf{t}^a) \right] \exp \left[-\frac{1}{2} (\Delta \mathbf{PA}_o - \Delta \mathbf{PA}^a)^T (\mathbf{C}_{\text{PA}}^n)^{-1} (\Delta \mathbf{PA}_o - \Delta \mathbf{PA}^a) \right]$$

- ♦ Marginalizing the elementary Gaussian variables & small-signal limit: [Li, Liu, Liu*, JR* *et al.*, PRD 113 (2026)]

$$\begin{aligned} \mathcal{L}_m \propto & \exp \left[-\frac{1}{2} (\Delta \mathbf{t}_o^T (\mathbf{C}_t^n)^{-1} \Delta \mathbf{t}_o + \Delta \mathbf{PA}_o^T (\mathbf{C}_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o) \right] \exp \left[\frac{1}{2} c_2^2 \Delta \mathbf{PA}_o^T (\mathbf{C}_{\text{PA}}^n)^{-1} \mathbf{C}_X (\mathbf{C}_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o \right] \left[1 + \frac{1}{2} \Delta \mathbf{t}_o^T (\mathbf{C}_t^n)^{-1} \mathbf{C}_t^a (\mathbf{C}_t^n)^{-1} \Delta \mathbf{t}_o \right] \\ & \times \exp \left[\frac{1}{2} c_1 c_2^2 \Delta \mathbf{PA}_o^T (\mathbf{C}_{\text{PA}}^n)^{-1} (\mathbf{C}_X \mathbf{D}_t \mathbf{C}_{XY} - \mathbf{C}_{XY} \mathbf{D}_t \mathbf{C}_X) (\mathbf{C}_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o \right]. \end{aligned}$$

(PPA) (PTA) (PTA-PPA correlation)

- $\Delta \mathbf{PA}_o^T (\mathbf{C}_{\text{PA}}^n)^{-1} (\mathbf{C}_X \mathbf{D}_t \mathbf{C}_{XY} - \mathbf{C}_{XY} \mathbf{D}_t \mathbf{C}_X) (\mathbf{C}_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o = \mathbf{V}_{\text{PA},n} \mathbf{V}_{\text{PA},m} \mathbf{V}_{t,l} \left[(\mathbf{C}_X)_{nl} (\mathbf{C}_{XY})_{ml} + (\mathbf{C}_X)_{ml} (\mathbf{C}_{XY})_{nl} \right],$ $\mathbf{V}_{\text{PA}} = (\mathbf{C}_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o$
 $\mathbf{V}_t = (\mathbf{C}_{\text{PA}}^n)^{-1} \Delta \mathbf{t}_o$
- $\langle \Delta \mathbf{PA}_n^a \Delta \mathbf{PA}_m^a \Delta \mathbf{t}_l^a \rangle = c_1 c_2^2 \langle \mathbf{X}_n \mathbf{X}_m \mathbf{X}_l \mathbf{Y}_l \rangle = c_1 c_2^2 \left[(\mathbf{C}_X)_{nl} (\mathbf{C}_{XY})_{ml} + (\mathbf{C}_X)_{ml} (\mathbf{C}_{XY})_{nl} \right].$

consistency between the LO correction to L_m and the LO three-point correlation function

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$$\mathcal{L} = \mathcal{L}_t \mathcal{L}_{\text{PA}} \propto \exp \left[-\frac{1}{2} (\Delta \mathbf{t}_o - \Delta \mathbf{t}^a)^T (C_t^n)^{-1} (\Delta \mathbf{t}_o - \Delta \mathbf{t}^a) \right] \exp \left[-\frac{1}{2} (\Delta \mathbf{PA}_o - \Delta \mathbf{PA}^a)^T (C_{\text{PA}}^n)^{-1} (\Delta \mathbf{PA}_o - \Delta \mathbf{PA}^a) \right]$$

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$$\begin{aligned} \mathcal{L}_m \propto & \exp \left[-\frac{1}{2} (\Delta \mathbf{t}_o^T (C_t^n)^{-1} \Delta \mathbf{t}_o + \Delta \mathbf{PA}_o^T (C_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o) \right] \exp \left[\frac{1}{2} c_2^2 \Delta \mathbf{PA}_o^T (C_{\text{PA}}^n)^{-1} C_X (C_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o \right] \left[1 + \frac{1}{2} \Delta \mathbf{t}_o^T (C_t^n)^{-1} C_t^a (C_t^n)^{-1} \Delta \mathbf{t}_o \right] \\ & \times \exp \left[\frac{1}{2} c_1 c_2^2 \Delta \mathbf{PA}_o^T (C_{\text{PA}}^n)^{-1} (C_X D_t C_{XY} - C_{XY} D_t C_X) (C_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o \right]. \end{aligned}$$

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- $\Delta \mathbf{PA}_o^T (C_{\text{PA}}^n)^{-1} (C_X D_t C_{XY} - C_{XY} D_t C_X) (C_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o = V_{\text{PA},n} V_{\text{PA},m} V_{t,l} \left[(C_X)_{nl} (C_{XY})_{ml} + (C_X)_{ml} (C_{XY})_{nl} \right],$ $V_{\text{PA}} = (C_{\text{PA}}^n)^{-1} \Delta \mathbf{PA}_o$
 $V_t = (C_t^n)^{-1} \Delta \mathbf{t}_o$
- $\langle \Delta \mathbf{PA}_n^a \Delta \mathbf{PA}_m^a \Delta \mathbf{t}_l^a \rangle = c_1 c_2^2 \langle X_n X_m X_l Y_l \rangle = c_1 c_2^2 \left[(C_X)_{nl} (C_{XY})_{ml} + (C_X)_{ml} (C_{XY})_{nl} \right].$

consistency between the LO correction to L_m and the LO three-point correlation function

- ♦ Next step: find a practical likelihood without relying on the small signal limit??

Summary and Outlook

✦ Pulsar timing/polarization arrays as powerful probes of ultralight ALDM

- **Key ingredient:** characteristic spatial correlations at galactic scale
- Gravitational and non-gravitational probe by PTAs and PPAs; world leading limits from existing data; on-going efforts for combined PTA-PPA searches

✦ Outlook

- Systematic exploration of PTA-PPA synergy
 - ALDM analysis framework: practical likelihood involving non-Gaussianity
 - Data construction: incorporating polarimetry for timing precision
 - Other physical targets: PTA-PPA synergy for parity-violating SGWB
- Synergize PPAs with other observations?
 - CMB-PPA synergy for CB of ALDM



Thank You!



PTA-PPA synergy for parity-violating SGWB

♦ Whether the SGWB violates parity?

- **Theoretical motivation:** astrophysical source (e.g. helical magnetic field); cosmological source (e.g. parity violation in gravity or matter sector)
- **Experimental probe:** PTAs insensitive to parity violation

♦ Detecting parity-violating SGWBs via PTA-PPA synergy [Liang, Nomura and Omiya, PRD 113 (2026)]

Additional effects due to parallel transport of polarization vector

$$z(t_E) = \frac{1}{2} \hat{n}^i \hat{n}^j \int_{t_E-L}^{t_E} dt \partial_0 h_{ij}(t, \mathbf{x}) \Big|_{\mathbf{x}=\bar{\mathbf{x}}(t)} \quad \chi(t_E) = \frac{1}{2} \bar{\epsilon}^i \hat{m}^j \hat{n}^k \int_{t_E-L}^{t_E} dt \partial_{[i} h_{j]k}(t, \mathbf{x}) \Big|_{\mathbf{x}=\bar{\mathbf{x}}(t)} .$$

$$\langle \tilde{z}_A(f) \tilde{z}_B^*(f') \rangle = \delta(f-f') \frac{8\pi}{3} \Gamma_{\text{HD}}(\xi_{AB}) I(f) \quad \langle \tilde{z}_A(f) \tilde{\chi}_B^*(f') \rangle = -i \delta(f-f') \frac{8\pi}{3} \Gamma_{\text{HD}}(\xi_{AB}) V(f) .$$

$$\begin{pmatrix} \langle \tilde{h}_+(f, \hat{\Omega}) \tilde{h}_+^*(f', \hat{\Omega}') \rangle & \langle \tilde{h}_+(f, \hat{\Omega}) \tilde{h}_\times^*(f', \hat{\Omega}') \rangle \\ \langle \tilde{h}_\times(f, \hat{\Omega}) \tilde{h}_+^*(f', \hat{\Omega}') \rangle & \langle \tilde{h}_\times(f, \hat{\Omega}) \tilde{h}_\times^*(f', \hat{\Omega}') \rangle \end{pmatrix} = \delta(f-f') \delta^2(\hat{\Omega} - \hat{\Omega}') \begin{pmatrix} I(f) & -i V(f) \\ i V(f) & I(f) \end{pmatrix} ,$$

Sensitivity forecast: $\text{SNR} \sim 5 \left(\frac{\Omega_{\text{GW}}^V}{0.012} \right) \left(\frac{T_{\text{obs}}}{20 \text{ yr}} \right)^4 \left(\frac{N_p}{200} \right) \left(\frac{\sigma_t}{30 \text{ ns}} \right)^{-1} \left(\frac{\sigma_p}{0.1 \text{ deg}} \right)^{-1} \left(\frac{\delta t}{2 \text{ week}} \right)^{-1}$

In the SKA era, parity-violating SGWB power spectrum $\Omega_{\text{GW}}^V \lesssim 0.012$