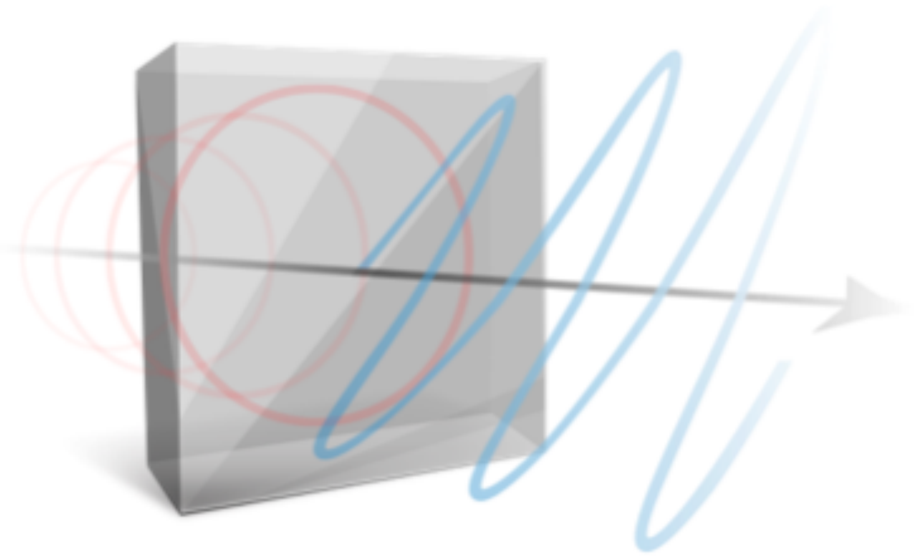
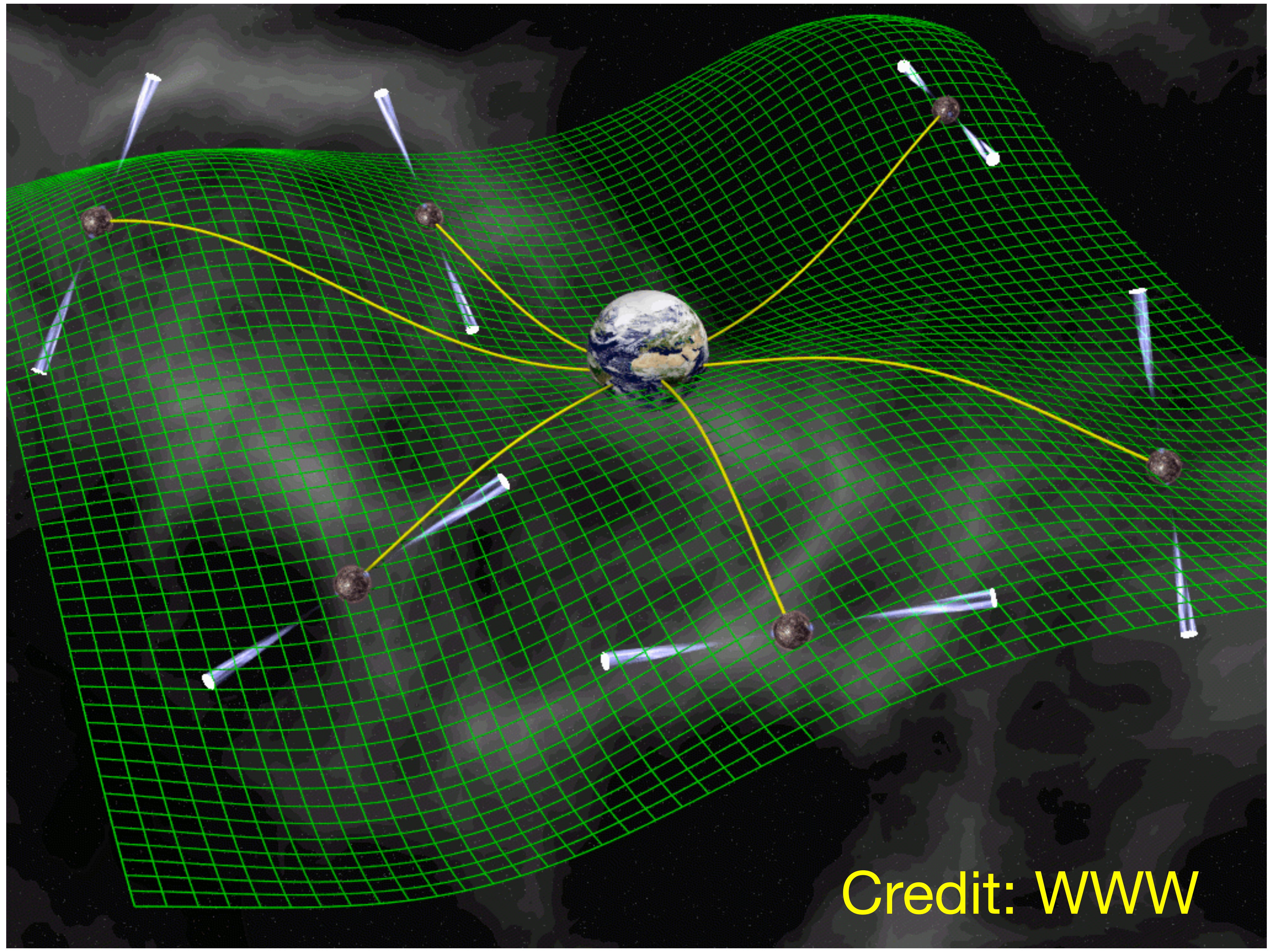
Axion Dark Matter: Theory and Phenomenology
Qingdao, May 2025



Unveiling Ultralight Axion-like Dark Matter — A PTA-PPA Exploration

Tao LIU
(The Hong Kong Univ. of Science & Technology)

Pulsar Timing Array (PTA)



THE ASTROPHYSICAL JOURNAL, **265**:L39–L42, 1983 February 15

UPPER LIMITS ON THE ISOTROPIC GRAVITATIONAL RADIATION BACKGROUND FROM PULSAR TIMING ANALYSIS[1]

R. W. HELLINGS AND G. S. DOWNS
Jet Propulsion Laboratory, California Institute of Technology

Received 1982 October 1; accepted 1982 October 20

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

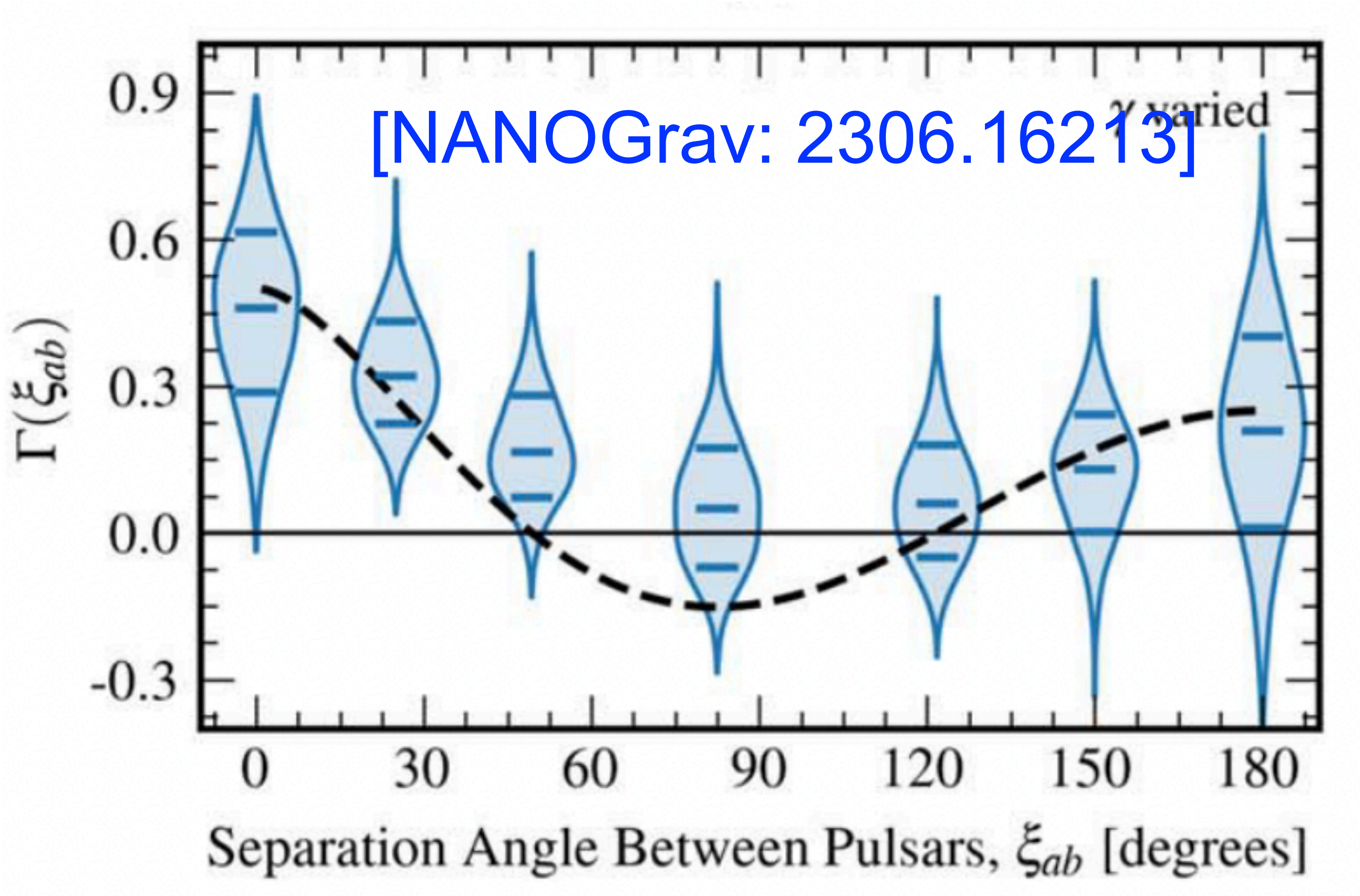
The fractional frequency shift observed in the data on pulsar number i may be written

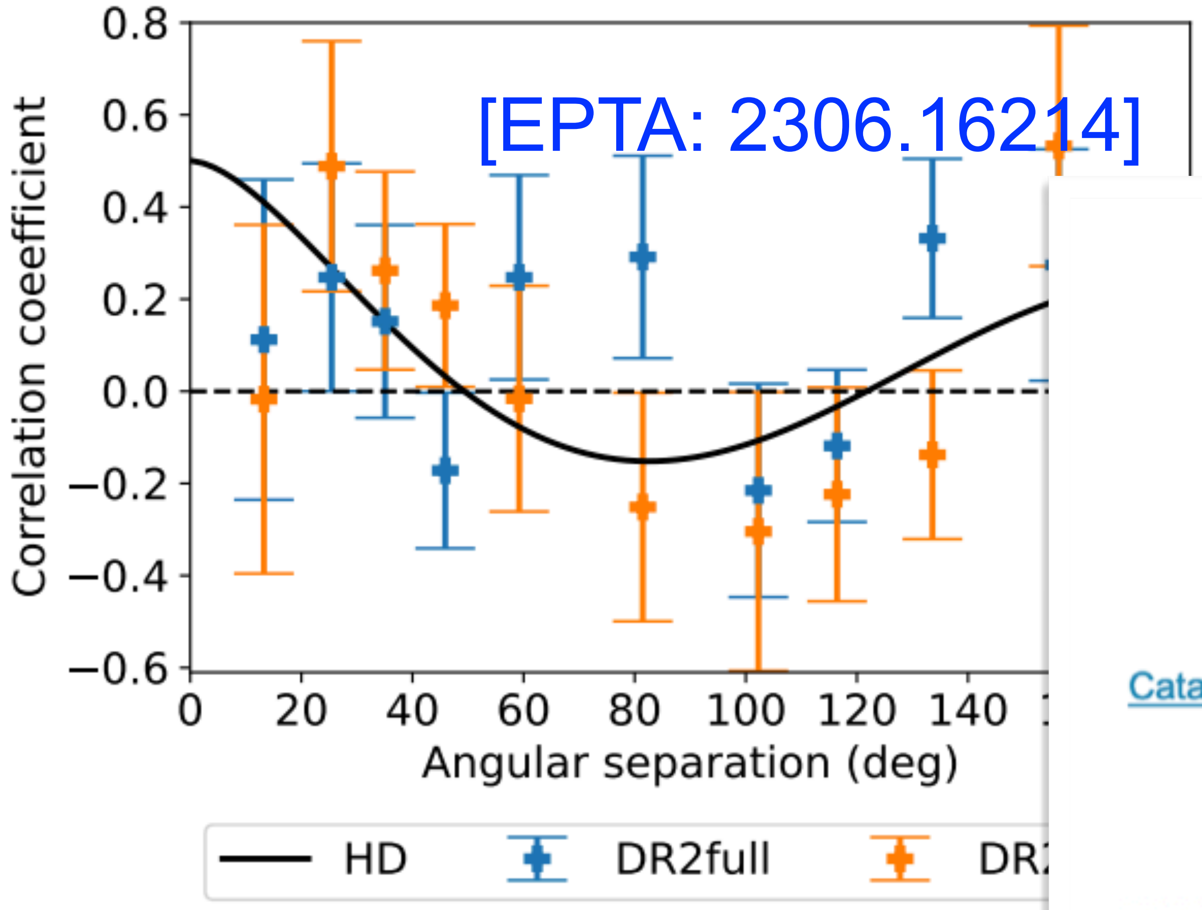
- A network of widely distributed and well-timed MSPs
- A galactic timing interferometer to detect ~nanoHz gravitational waves (GWs) [Sazhin, Sov. Astron., 22, 36 (1978); Detweiler, Atrophy's. J. 234 (1979)]

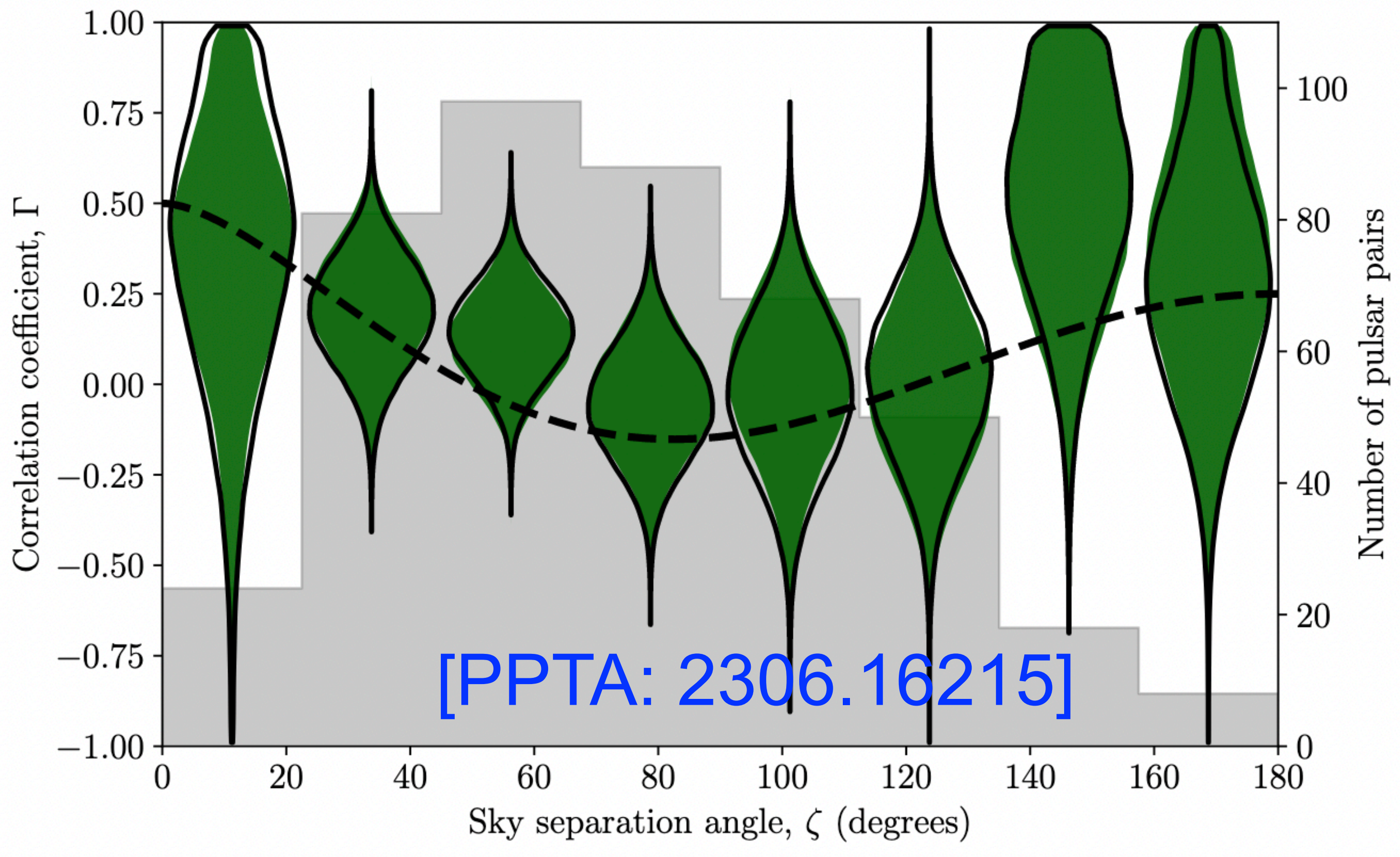
Hellings-Downs Curve

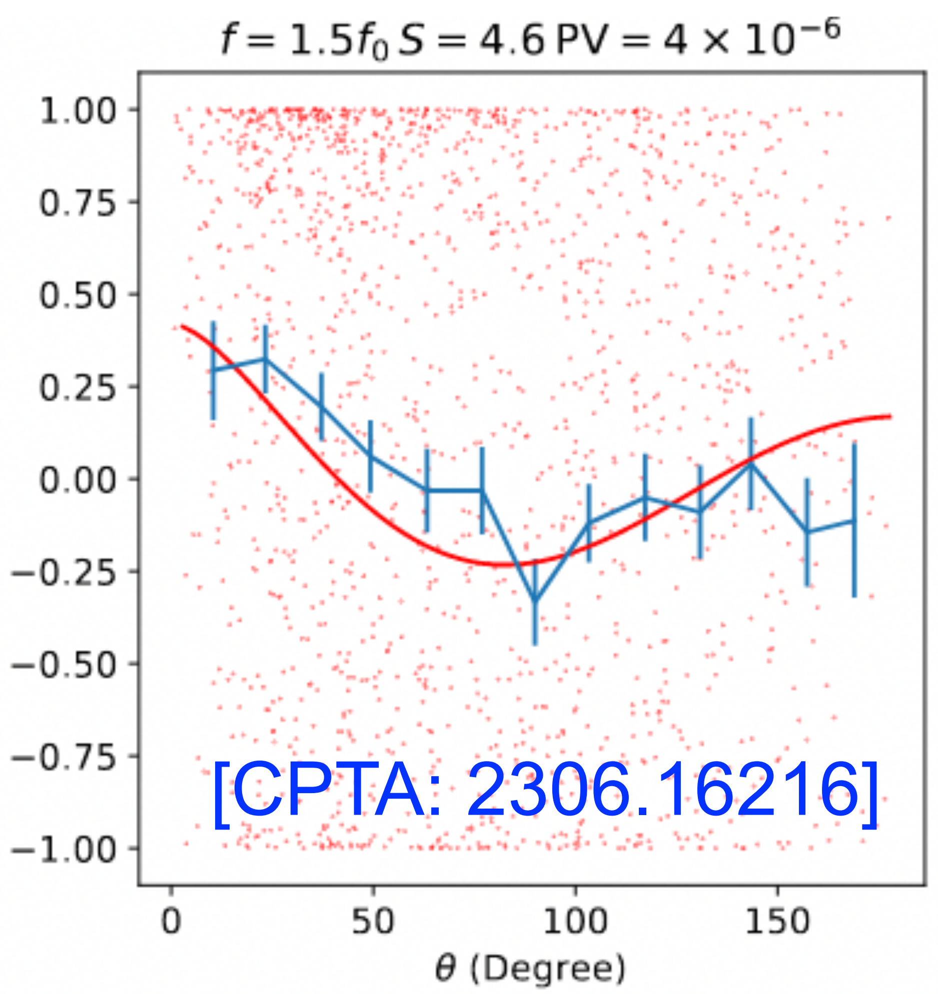
Encodes exactly the cross-correlation of pulsar timing data that would indicate a common origin of GWs.

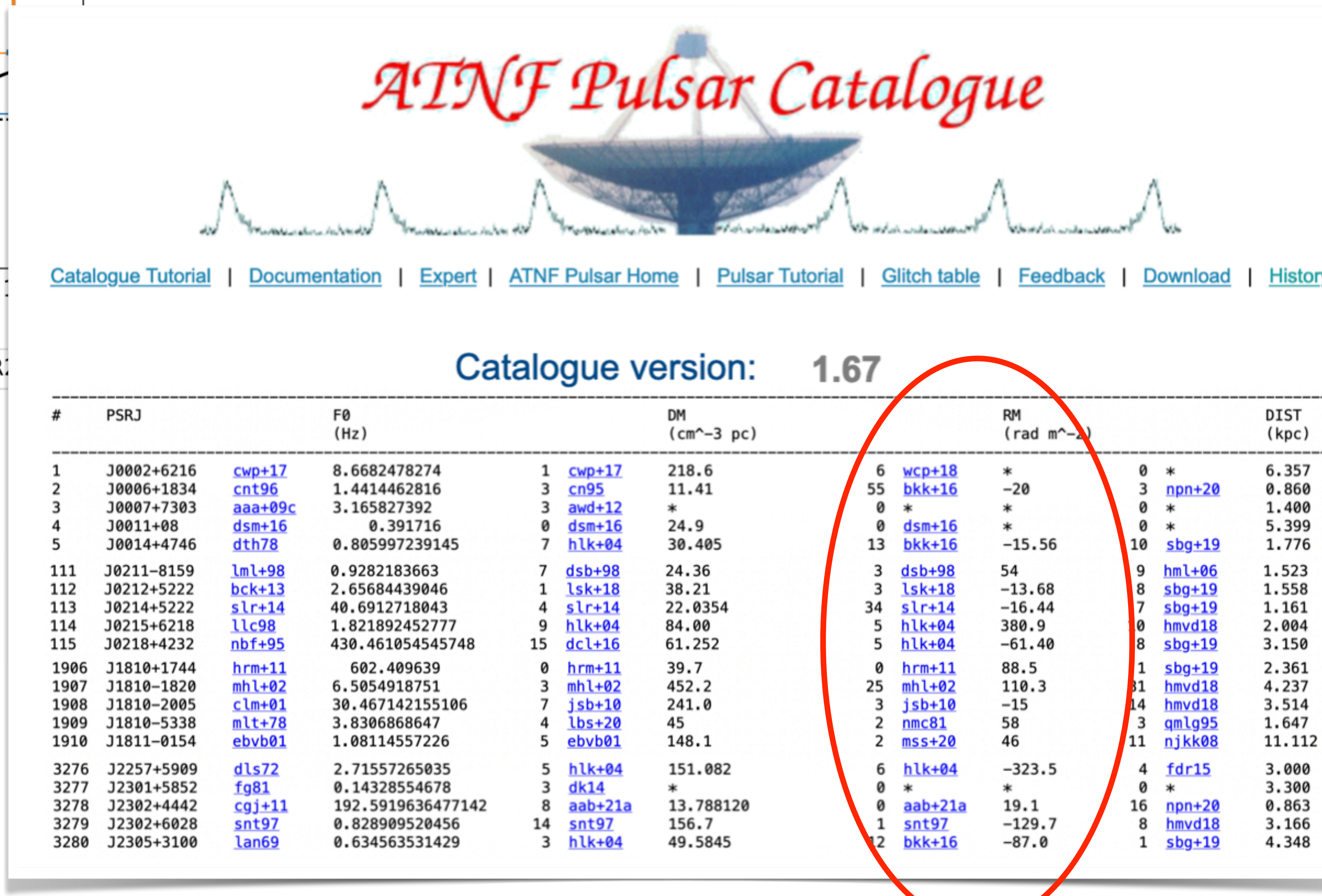
Pulsar Timing Array (PTA)









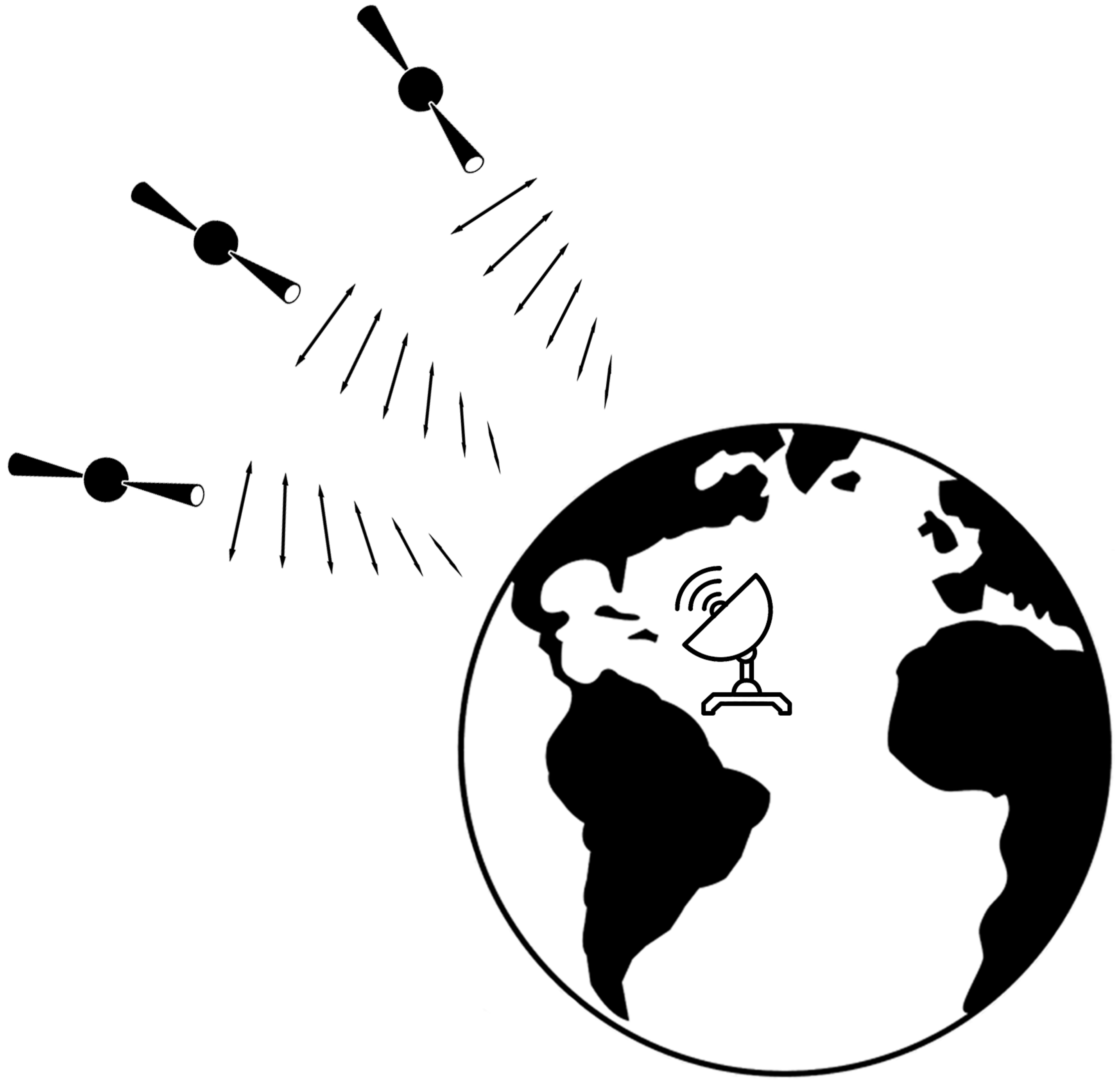


#	PSRJ		F0 (Hz)			DM (cm^-3 pc)			RM (rad m^-2)			DIST (kpc)
1	J0002+6216	cwp+17	8.6682478274	1	cwp+17	218.6	6	wcp+18	*	0	*	6.357
2	J0006+1834	cnt96	1.4414462816	3	cn95	11.41	55	bkk+16	-20	3	npn+20	0.860
3	J0007+7303	aaa+09c	3.165827392	3	awd+12	*	0	*	*	0	*	1.400
4	J0011+08	dsm+16	0.391716	0	dsm+16	24.9	0	dsm+16	*	0	*	5.399
5	J0014+4746	dth78	0.805997239145	7	hlk+04	30.405	13	bkk+16	-15.56	10	sbg+19	1.776
111	J0211-8159	lml+98	0.9282183663	7	dsb+98	24.36	3	dsb+98	54	9	hml+06	1.523
112	J0212+5222	bck+13	2.65684439046	1	lsk+18	38.21	3	lsk+18	-13.68	8	sbg+19	1.558
113	J0214+5222	slr+14	40.6912718043	4	slr+14	22.0354	34	slr+14	-16.44	7	sbg+19	1.161
114	J0215+6218	llc98	1.821892452777	9	hlk+04	84.00	5	hlk+04	380.9	0	hmvd18	2.004
115	J0218+4232	nbf+95	430.461054545748	15	dcl+16	61.252	5	hlk+04	-61.40	8	sbg+19	3.150
1906	J1810+1744	hrm+11	602.409639	0	hrm+11	39.7	0	hrm+11	88.5	1	sbg+19	2.361
1907	J1810-1820	mhl+02	6.5054918751	3	mhl+02	452.2	25	mhl+02	110.3	31	hmvd18	4.237
1908	J1810-2005	clm+01	30.467142155106	7	jsb+10	241.0	3	jsb+10	-15	14	hmvd18	3.514
1909	J1810-5338	mlt+78	3.8306868647	4	lbs+20	45	2	nmc81	58	3	qmlg95	1.647
1910	J1811-0154	ebvb01	1.08114557226	5	ebvb01	148.1	2	mss+20	46	11	njkk08	11.112
3276	J2257+5909	dls72	2.71557265035	5	hlk+04	151.082	6	hlk+04	-323.5	4	fdr15	3.000
3277	J2301+5852	fg81	0.14328554678	3	dk14	*	0	*	*	0	*	3.300
3278	J2302+4442	cgj+11	192.5919636477142	8	aab+21a	13.788120	0	aab+21a	19.1	16	npn+20	0.863
3279	J2302+6028	snt97	0.828909520456	14	snt97	156.7	1	snt97	-129.7	8	hmvd18	3.166
3280	J2305+3100	lan69	0.634563531429	3	hlk+04	49.5845	12	bkk+16	-87.0	1	sbg+19	4.348

Milestone for GW astronomy
and roaring success for PTA programs

Polarization data collected for
calibration of pulsar observation

Pulsar Polarization Array (PPA)



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

Pulsar Polarization Arrays

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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 $\sim 10^{-14} - 10^{-17}$ GeV^{-1}, with a mass range $\sim 10^{-27}$–10^{-21} eV.

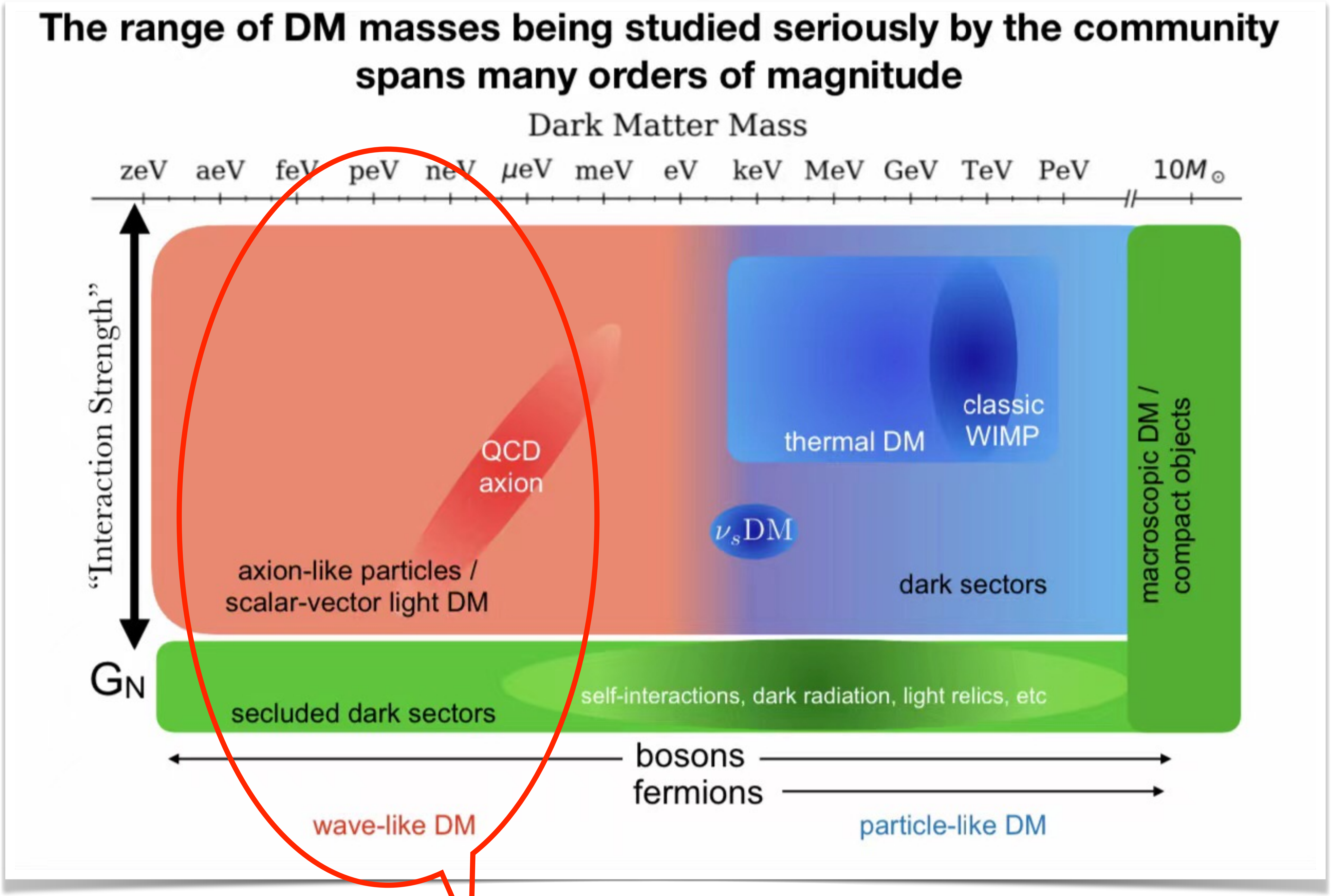
DOI: 10.1103/PhysRevLett.130.121401

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

Ultralight Axion-like Dark Matter (ALDM)

[Aaron Chou, Snowmass 2021]



Most powerful wave in the Universe?

- Galactic halo can be described as uncorrelated superposition of particle waves [Foster, et. al., Phys. Rev. D 97 (2018)]

$$a(\mathbf{x},t) \approx \frac{\sqrt{\rho(\mathbf{x})}}{m_a} \sum_{\mathbf{v}\in\Omega} C_{\mathbf{v}} \cos[m_a(t - \mathbf{v}\cdot\mathbf{x}) + \psi_{\mathbf{v}}],$$

"Fuzzy" DM: $m_a \sim O(10^{-21} - 10^{-22})$ eV
=>
Oscillation period $2\pi/m_a \sim O(0.1 - 1)$ yr,
with a de Broglie wavelength $2\pi/m_a v \sim O(100)$ pc
=>
Strong wave properties on astronomical scales

Ultralight ALDM — PTA-PPA Detection?

Question 1: What imprints can the ultralight ALDM leave on the timing and polarization data of individual pulsars?

Question 2: How can we know the observed anomalous signals are caused by the ultralight ALDM?

Question 1 - Timing Signals

Oscillating halo density => Oscillating gravitational potential

=> Oscillating timing residual

arXiv > astro-ph > arXiv:1309.5888

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 23 Sep 2013]

Pulsar timing signal from ultralight scalar dark matter

Andrei Khmelnitsky, Valery Rubakov

$$\rho_{\mathrm{DM}}(\mathbf{x},t) = \rho_{\mathrm{k}} + \rho_{\mathrm{p}} + \rho_{\mathrm{g}}$$

$$= \frac{1}{2}(\partial_t a)^2 + \frac{1}{2}m^2 a^2 + \frac{1}{2}(\nabla a)^2$$

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

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

Determined by pulsar + Earth terms;
depends on the ALDM field quadratically.

○ Pulsar term ○ Earth term

Question 1 - Polarization Signals

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

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

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

✦ 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

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

Determined by pulsar + Earth terms; depends on the ALDM field linearly.

○ Pulsar term ○ Earth term

Question 2 - Pulsar Cross-Correlation

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

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

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

$$\Delta t_p = A_c^{(p)}\cos(2m_a t) + A_s^{(p)}\sin(2m_a t)$$

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

$$\begin{aligned}\langle A_s^{(p)}A_c^{(q)}\rangle \approx \left(\frac{\pi G}{2m_a^3}\right)^2 &\left[\rho_p\rho_q\sin[2m_aL_{pq}]\frac{\sin^2 y_{pq}}{y_{pq}^2}\right. \\ &\left. +\rho_e\rho_p\sin[2m_aL_p]\frac{\sin^2 y_{ep}}{y_{ep}^2} - (p\to q)\right]\end{aligned}$$

Trigonometric functions describes temporal correlations of the ALDM signals and sinc functions account for their spatial correlations

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~1/w)	spatial correlation degrades much slower (dB wavelength »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.

First PPA Detection (In Collaboration with Parkes PTA Team)

[Xue, Dai, Luu, **TL**, et al. (PPTA collaboration); [arXiv:2412.02229 [astro-ph.HE]]]

✦ 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

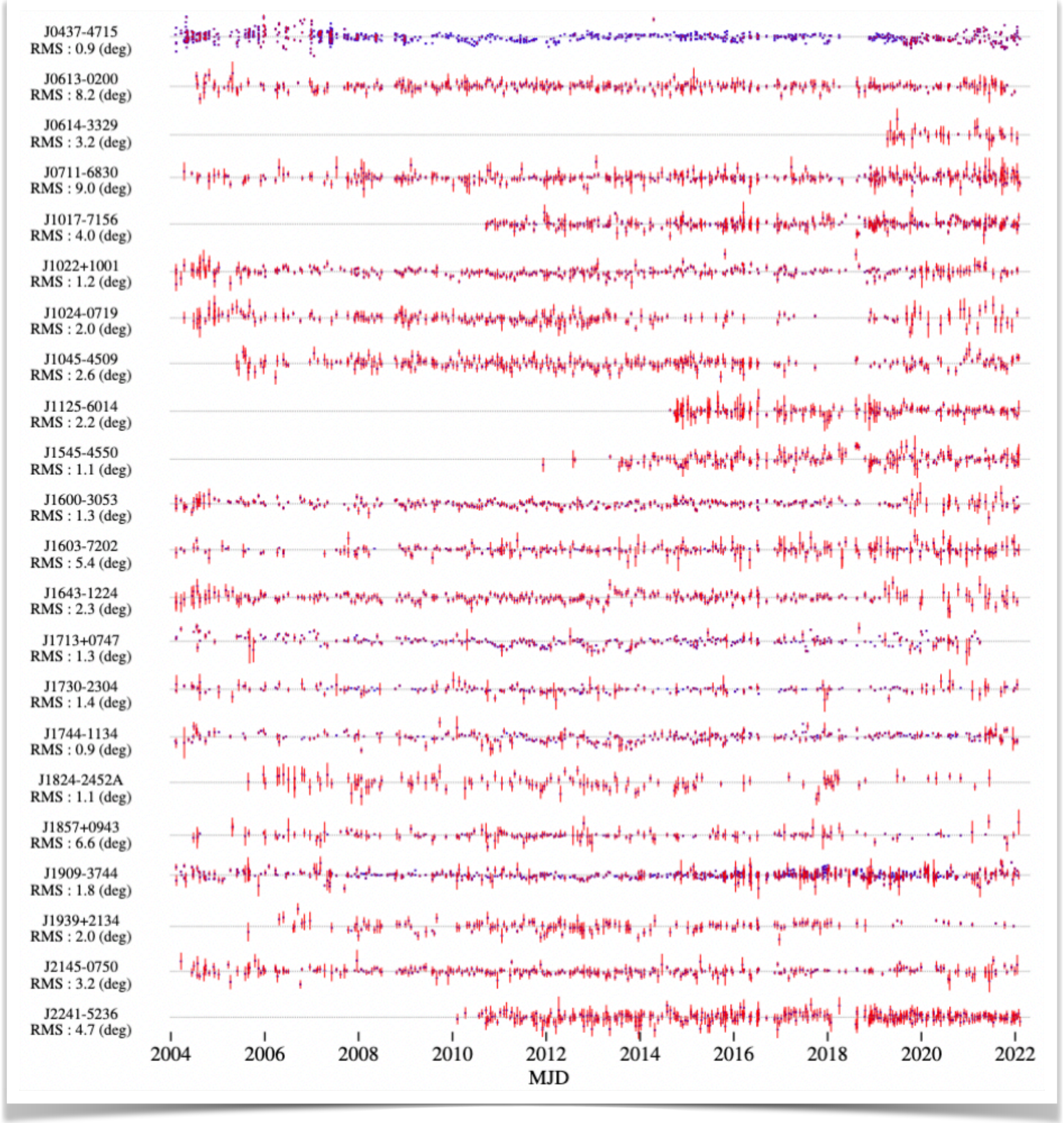
✦ Build noise model for the observed PA residual time series

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

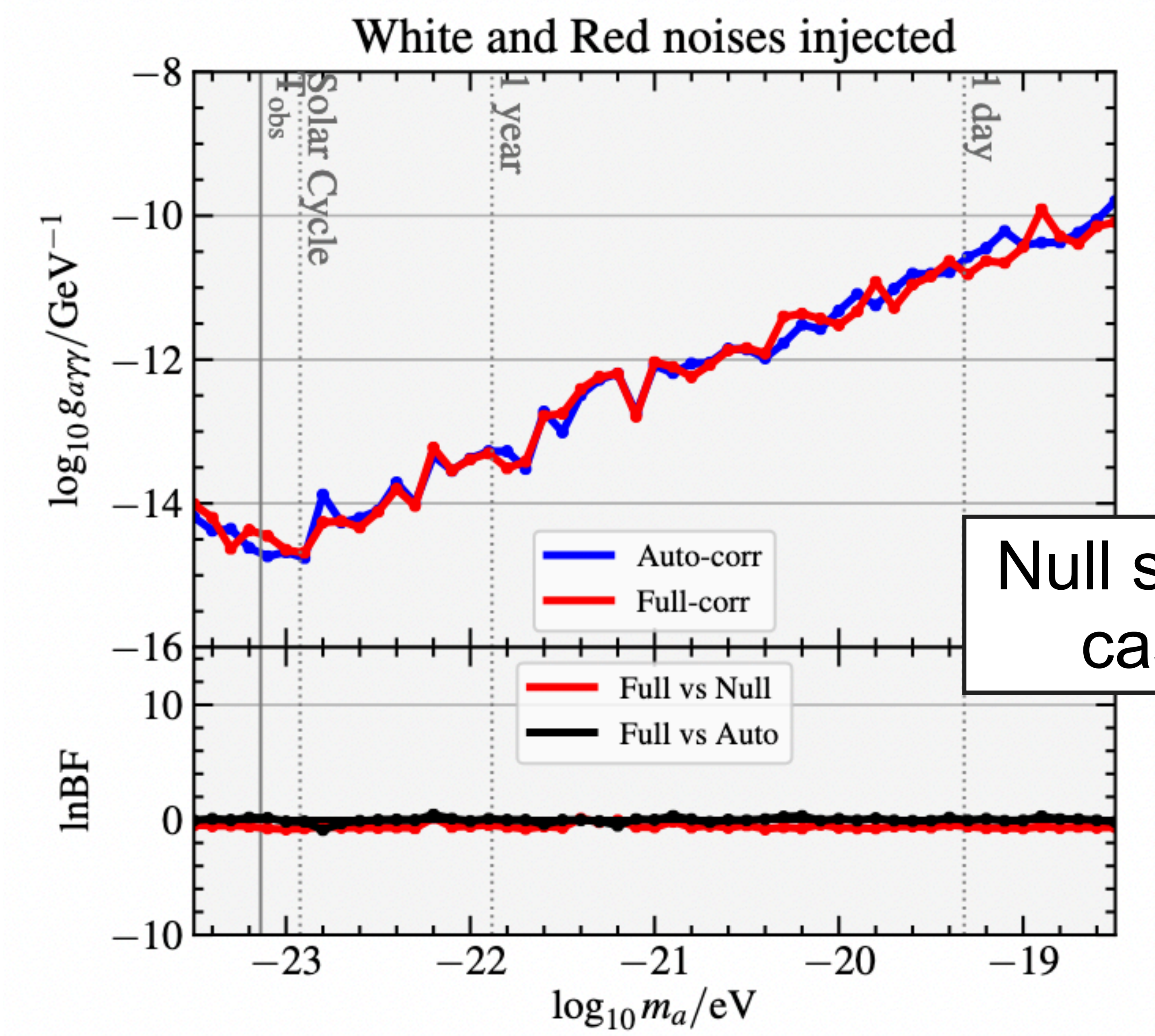
✦ Search for pulsar cross correlation

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

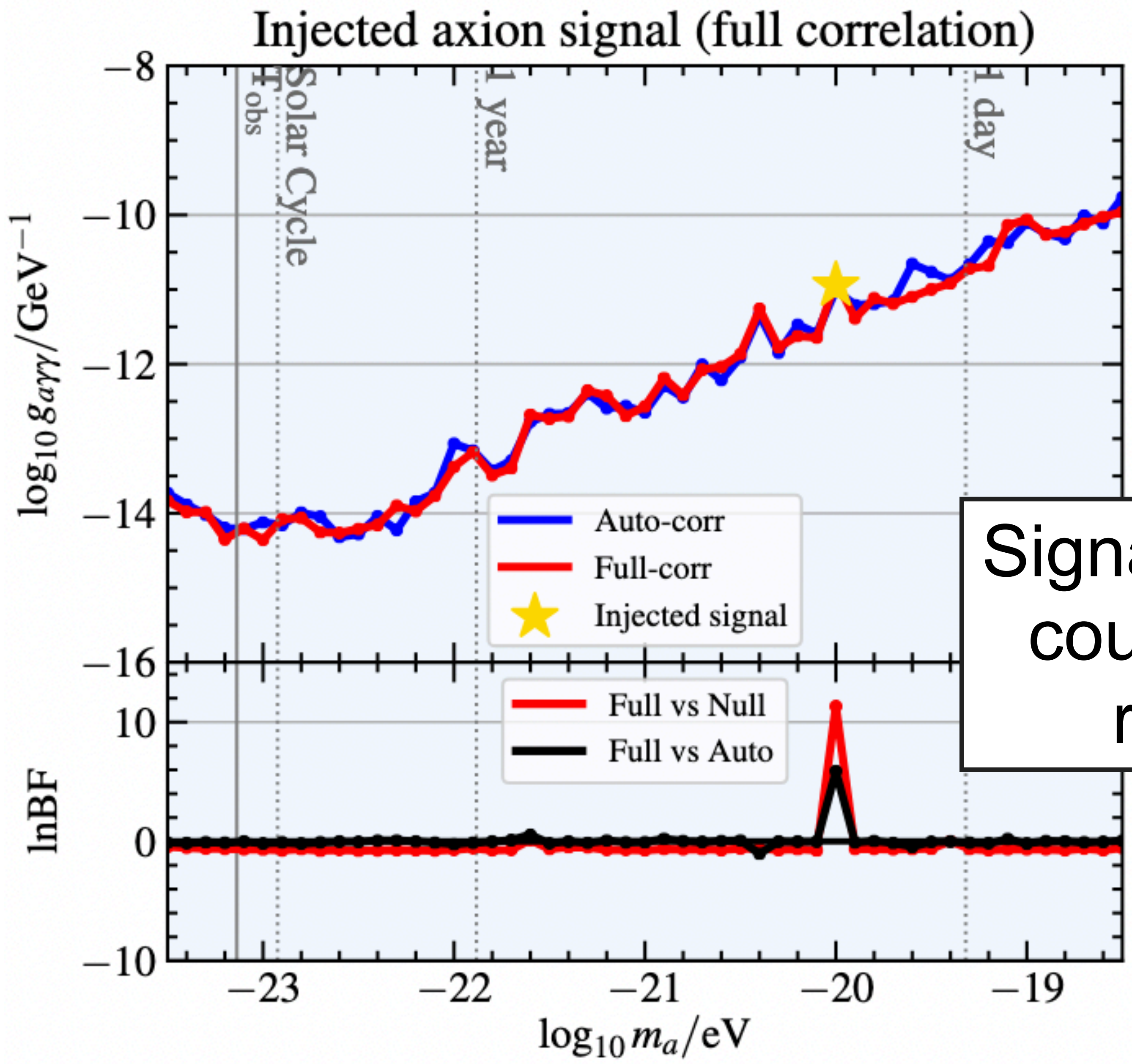
$$C = C^{w} + C^{r} + S_a^2\hat{C}^{a}$$



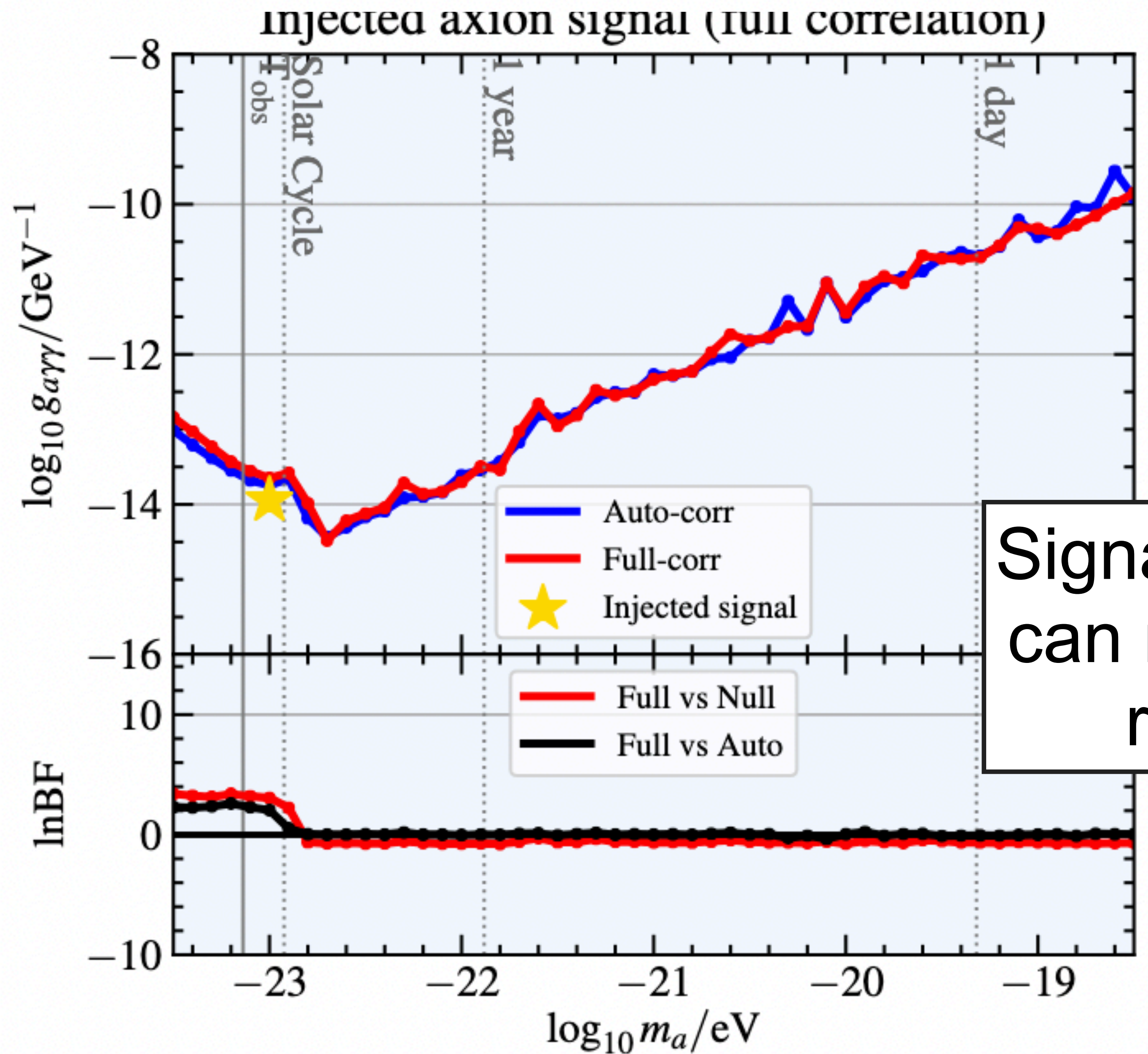
Mock Response of PPA to ALDM Signals



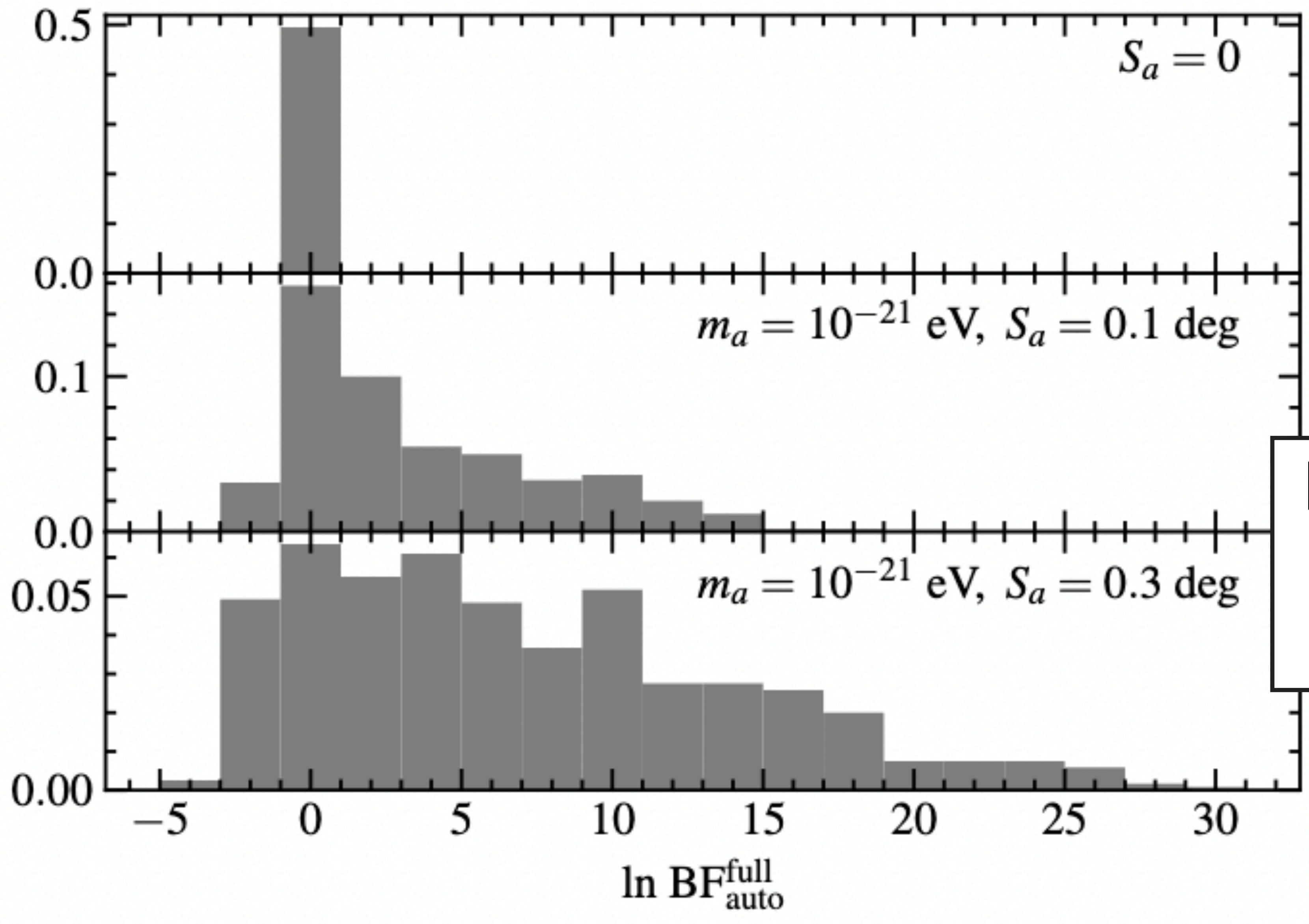
Null signal case



Signal waveform could be well-resolved

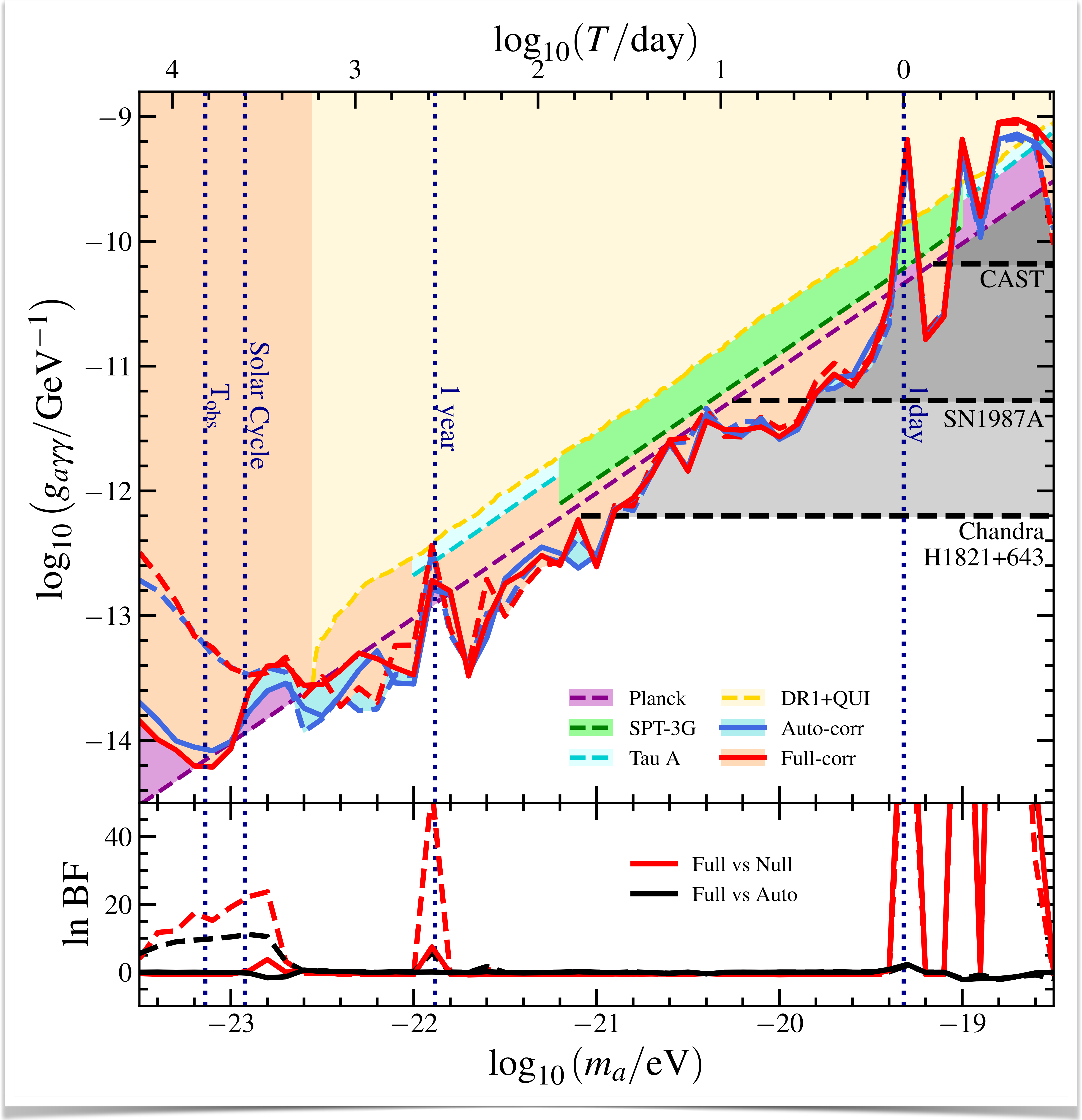


Signal waveform can not be fully-resolved



Enhanced median and variance as the signal strength increases

Parkes PPA Limits on Ultralight ALDM



- Best global limits for the mass range of ``fuzzy'' dark matter ($\rho_0 = 0.4\,\mathrm{GeV/cm^3}$)

  $$\sim 10^{-22} - 10^{-21}\,\mathrm{eV}$$

- Sharp peaks on time scales of one day and below
  - sharp peaks in Bayes curve of full correlation against null signal
  - approximate flatness for Bayes curve of full correlation against auto-correlation-only
  - => no significant ALDM signal signature
- Highlights the value of pulsar cross-correlation in recognizing the nature of anomalous signals

Existing Radio PTA Detections

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

Editors' Suggestion

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

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

(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

Clemente Smarra,[1,2,*] Boris Goncharov,[3,4] Enrico Barausse,[1,2] J. Antoniadis,[5,6] S. Babak,[7] A.-S. Bak Nielsen,[6,8] C. G. Bassa,[9] A. Berthereau,[10,11] M. Bonetti,[12,13,14] E. Bortolas,[12,13,14] P. R. Brook,[15] M. Burgay,[16] R. N. Caballero,[17] A. Chalumeau,[12] D. J. Champion,[6] S. Chanlaridis,[5] S. Chen,[18] I. Cognard,[10,11] G. Desvignes,[6] M. Falxa,[10,7] R. D. Ferdman,[19] A. Franchini,[12,13] J. R. Gair,[20] E. Graikou,[6] J.-M. Grießmeier,[10,11] L. Guillemot,[10,11] Y. J. Guo,[6] H. Hu,[6] F. Iraci,[16,21] D. Izquierdo-Villalba,[12,13] J. Jang,[6] J. Jawor,[6] G. H. Janssen,[9,22] A. Jessner,[6] R. Karuppusamy,[6] E. F. Keane,[23] M. J. Keith,[24] M. Kramer,[6,24] M. A. Krishnakumar,[6,8] K. Lackeos,[6] K. J. Lee,[5,6,11] K. Liu,[6] Y. Liu,[8,25] A. G. Lyne,[24] J. W. McKee,[26,27] R. A. Main,[6] M. B. Mickaliger,[24] I. C. Niţu,[24] A. Parthasarathy,[6] B. B. P. Perera,[28] D. Perrodin,[16] A. Petiteau,[29,7] N. K. Porayko,[6,12] A. Possenti,[16] H. Quelquejay Leclere,[7] A. Samajdar,[30] S. A. Sanidas,[24] A. Sesana,[12,13,14] G. Shaifullah,[12,13,16] L. Speri,[20] R. Spiewak,[24] B. W. Stappers,[24] S. C. Susarla,[31] G. Theureau,[10,11,32] C. Tiburzi,[16] E. van der Wateren,[22,9] A. Vecchio,[15] V. Venkatraman Krishnan,[6] J. Wang,[8,33,34] L. Wang,[24] and Z. Wu[25]

(European Pulsar Timing Array)

The Astrophysical Journal Letters, 951:L11 (56pp), 2023 July 1 https://doi.org/10.3847/2041-8213/acdc91

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

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The NANOGrav Collaboration

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 γ-Ray Pulsar Timing Array

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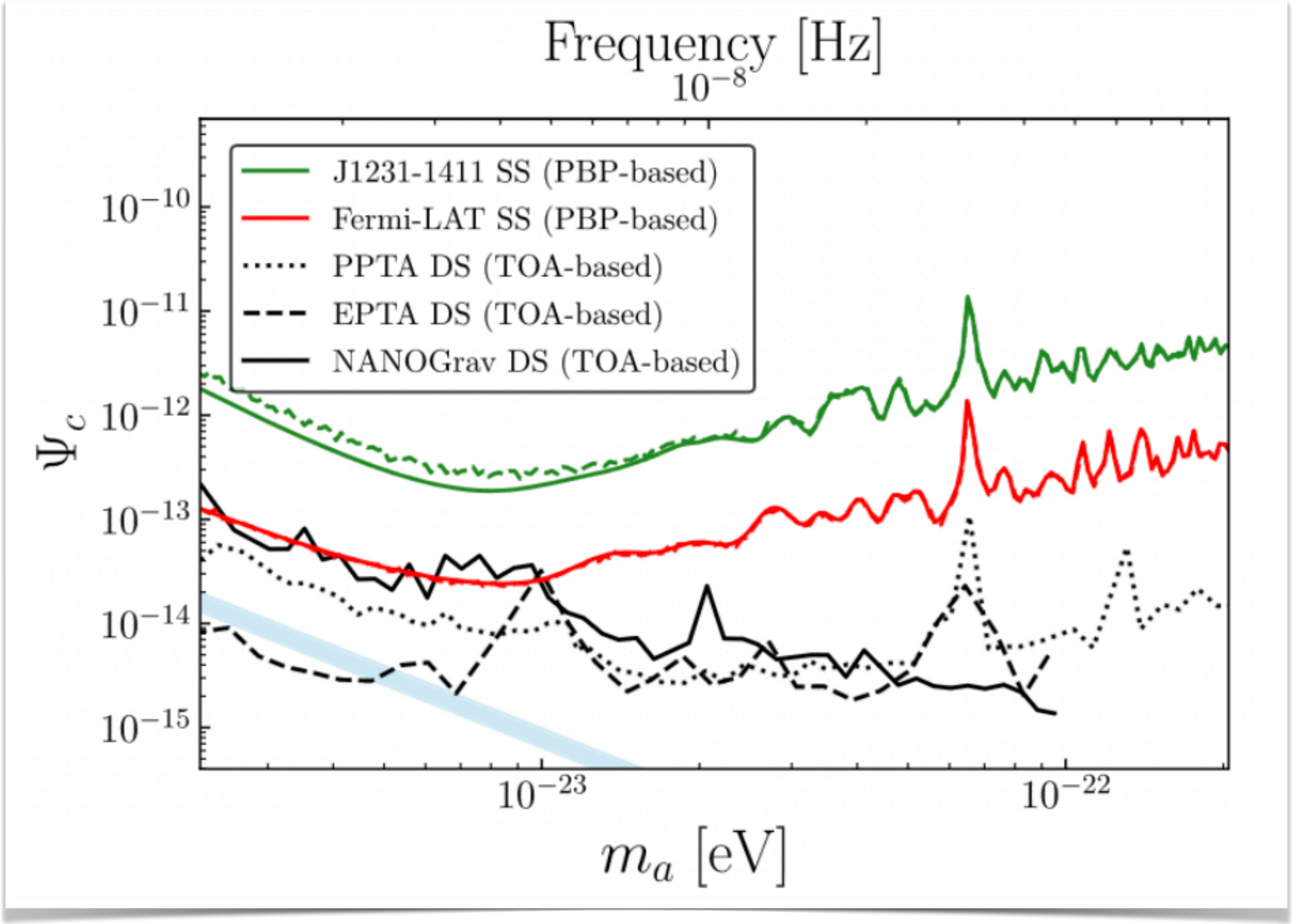
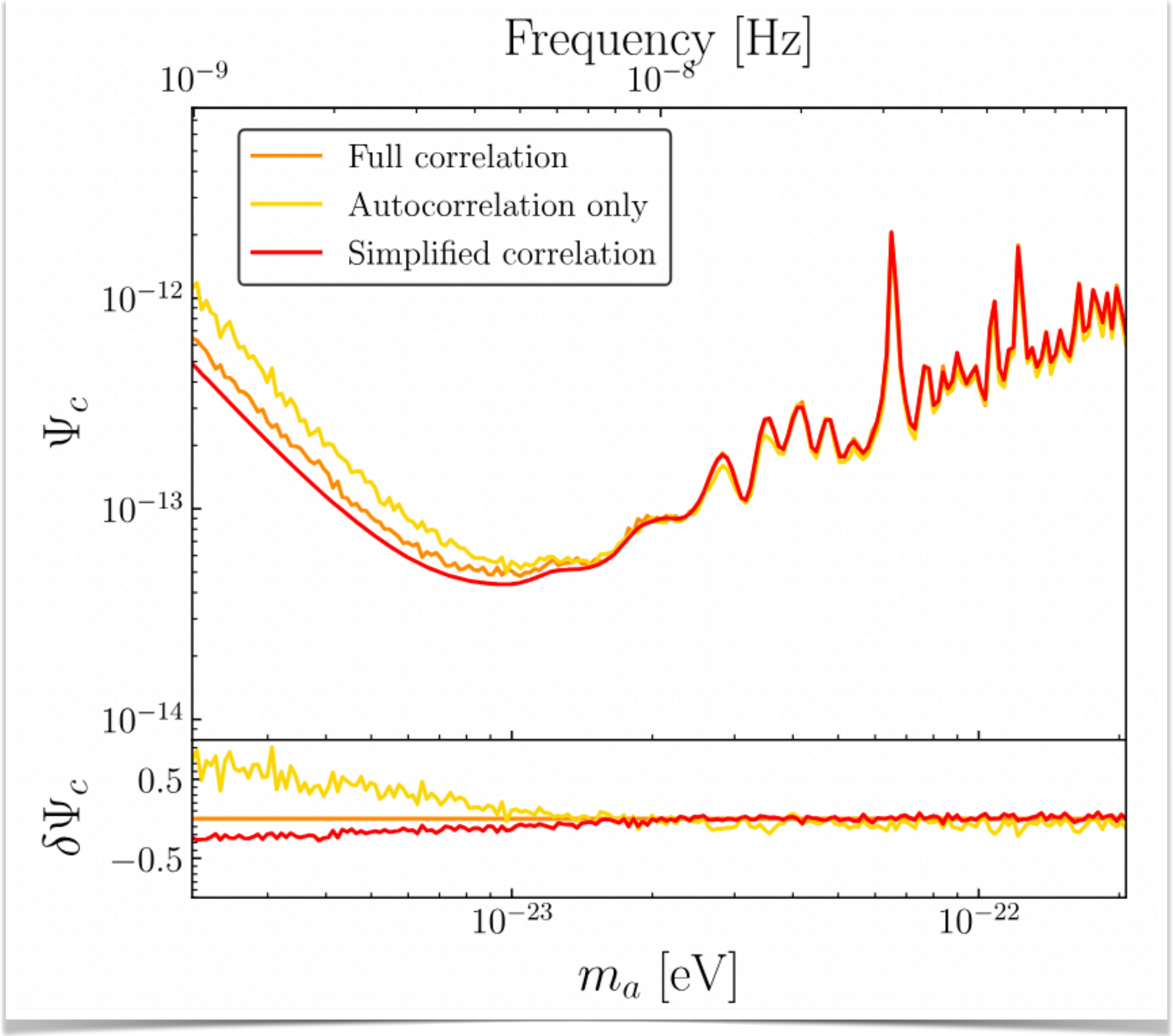
Abstract

Pulsar timing arrays (PTAs) can detect disturbances in the fabric of spacetime on a galactic scale by monitoring the arrival time of pulses from millisecond pulsars (MSPs). Recent advancements have enabled the use of γ-ray radiation emitted by MSPs, in addition to radio waves, for PTA experiments. Wave dark matter (DM), a prominent class of DM candidates, can be detected with PTAs due to its periodic perturbations of the spacetime metric. In response to this development, we perform in this Letter a first analysis of applying the γ-ray PTA to detect the ultralight axion-like wave DM, with the data of Fermi Large Area Telescope (Fermi-LAT). Despite its much smaller collecting area, the Fermi-LAT γ-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

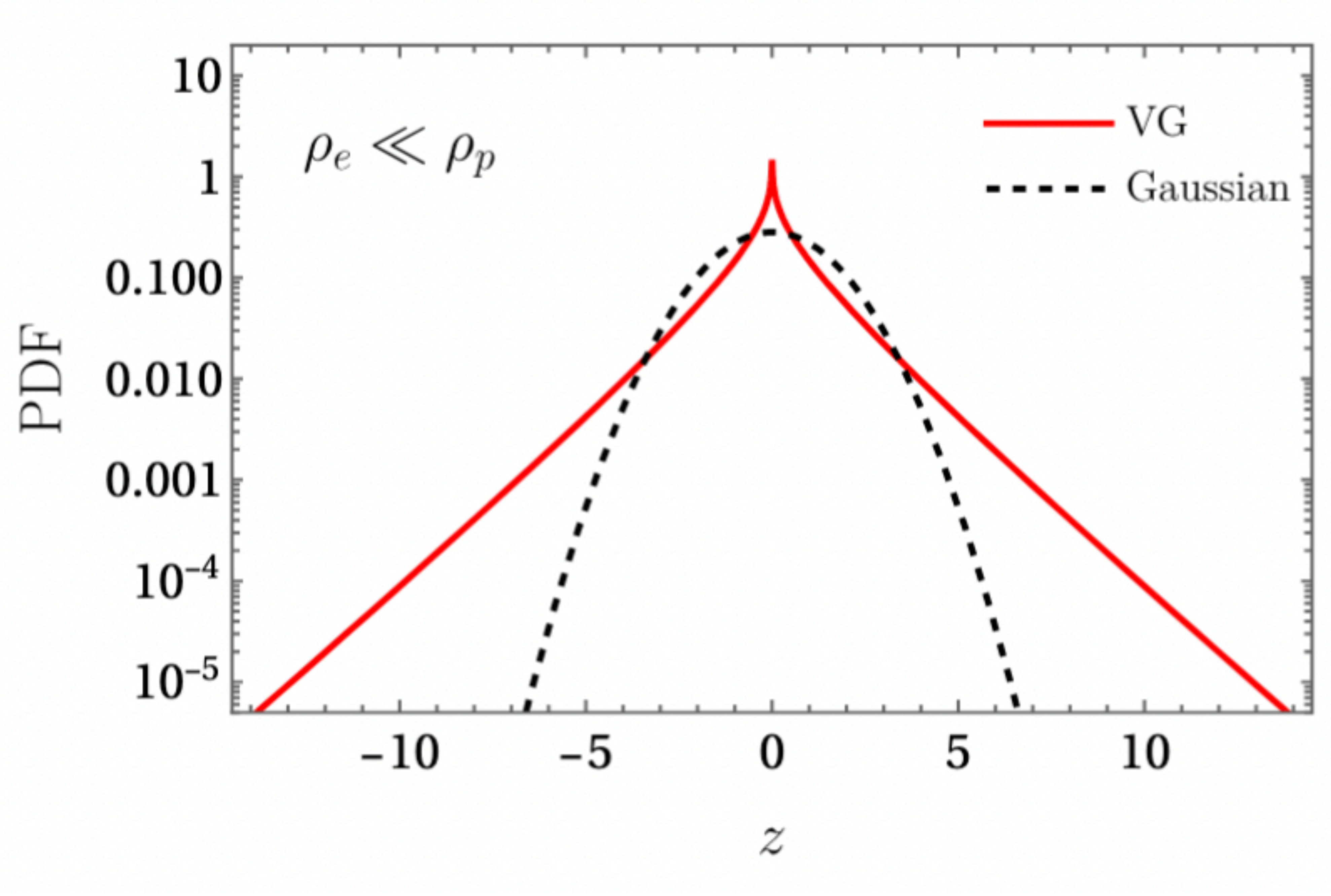




Pipeline for the PTA analysis including pulsar cross correlation was built, and applied to two Fermi-LAT pulsars with the “best” quality

Outlook

- Extend the analysis of Parkes PPA to other active PTA programs, and also from MSPs to normal pulsars
- In addition to Fermi-LAT PTA analysis, apply the pulsar cross-correlation techniques to the timing data of other active PTA programs
- Correlate PTA and PPA to strengthen their capability of recognizing signal nature.
  - Signals: gravitational (timing) VS. non-gravitational (polarization)
  - Timing and polarization noises: uncorrelated or correlated but with a different pattern



Non-Gaussian statistics

$$\Delta t^a(t) \approx -\frac{\pi G}{2m_a^2}\left[\dot{a}(\mathbf{x}_p, t-L_p)a(\mathbf{x}_p, t-L_p) - \dot{a}(\mathbf{x}_e, t)a(\mathbf{x}_e, t)\right]$$

[PTA-PPA work team, in preparation; see Ximeng Li's talk]

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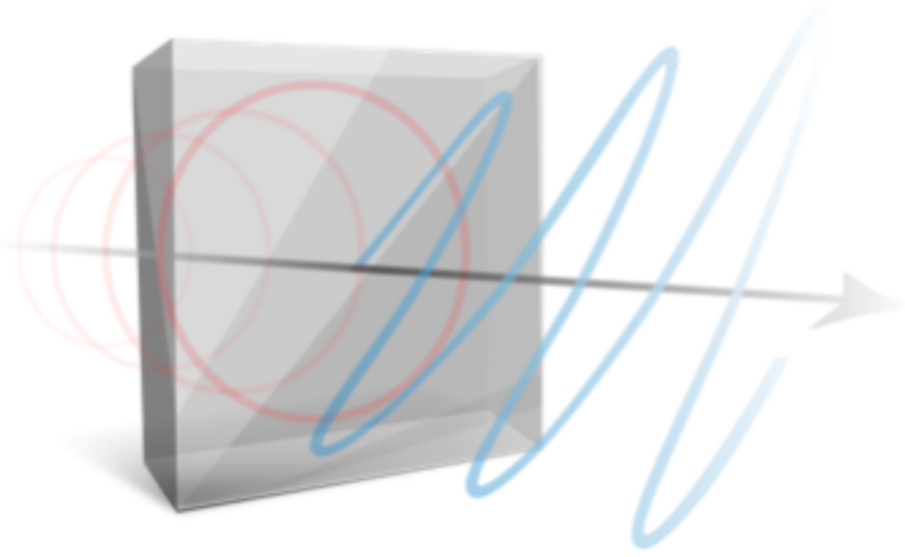

$$\langle \Delta t^a_{p,n} \Delta\theta^a_{q,m} \rangle = 0$$

$$\langle \Delta\theta^a_{p,n} \Delta\theta^a_{q,m} \Delta t^a_{r,l} \rangle =$$
$$-\frac{\pi G g^2_{a\gamma\gamma}}{2m_a^5} \sum_{i,j,k} (-1)^{i+j+k} \sqrt{\rho(\mathbf{x}_p^{(i)})\rho(\mathbf{x}_q^{(j)})\rho(\mathbf{x}_r^{(k)})}$$
$$\times e^{-\frac{1}{4}\left(y^{ik}_{pr}\right)^2} e^{-\frac{1}{4}\left(y^{jk}_{qr}\right)^2} \sin\left[m_a(t^{(i)}_{p,n} + t^{(j)}_{q,m} - 2t^{(k)}_{r,l})\right]$$

[PTA-PPA work team, in preparation; see Ximeng Li's talk]

Take-Home Messages

- To extend physical reach of pulsars as a precision astronomical tool, we have developed the methodology of pulsar polarization array recently
- PTA and PPA offer complementary approaches to detect the ultralight ALDM as a common signal, through gravitational potential perturbation and non-gravitational CB effect, respectively
- Because of its strong wave nature on astronomical scales, the timing and polarization signals of the ultralight ALDM are both correlated across the pulsars
- The first PPA and PTA analyses, with two-point correlation functions implemented, have been performed, using PPTA polarization data and Fermi-LAT gamma-ray data respectively. The crucial role of pulsar cross-correlation in identifying the nature of anomalous signals was recognized
- PPA (polarization data) and PTA (timing data) could be correlated to synergistically enhance their capability in recognizing signal nature
- Anticipate this PTA-PPA methodology to be applied to broad sets of data (PPTA, EPTA, NANOGrav, CPTA, etc.). Stay tuned … …

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