Search for ultralight dark matter and cosmological phase transition using pulsar timing arrays

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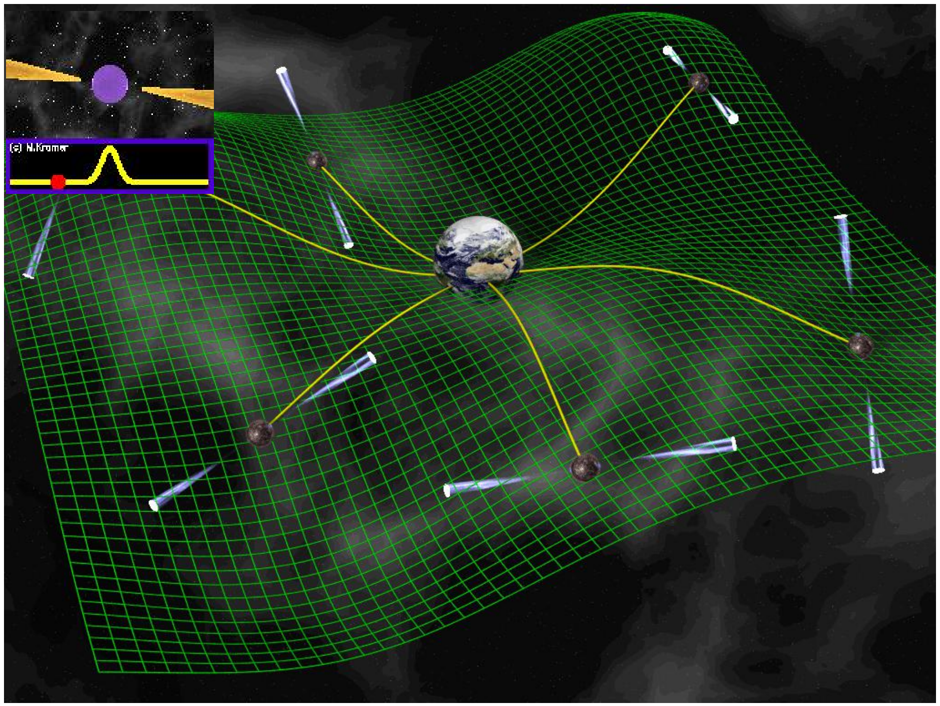
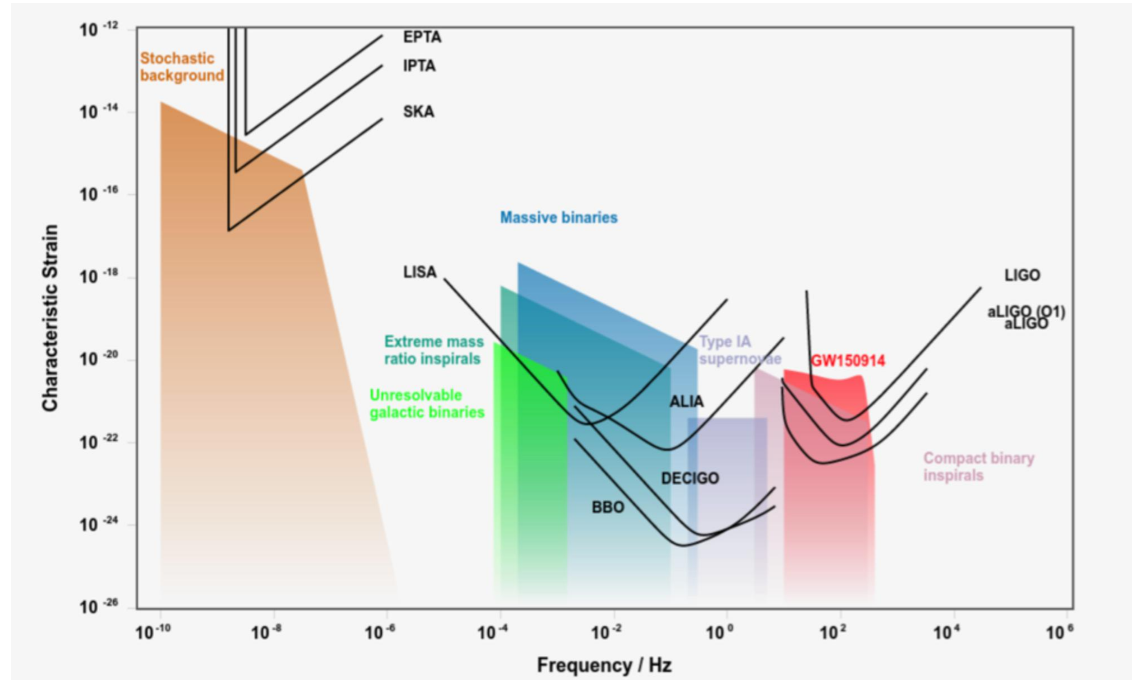
With Ligong Bian, Jing Shu, Ziqing Xia, Xiao Xue, Yue Zhao, Xing-Jiang Zhu and PPTA collaboration

SUSY2021, 2021-08-23, Beijing, China

- Pulsar timing arrays (PTA)
- Ultralight bosonic dark matter searches
- Cosmological first-order phase transition

Pulsar timing array (PTA)





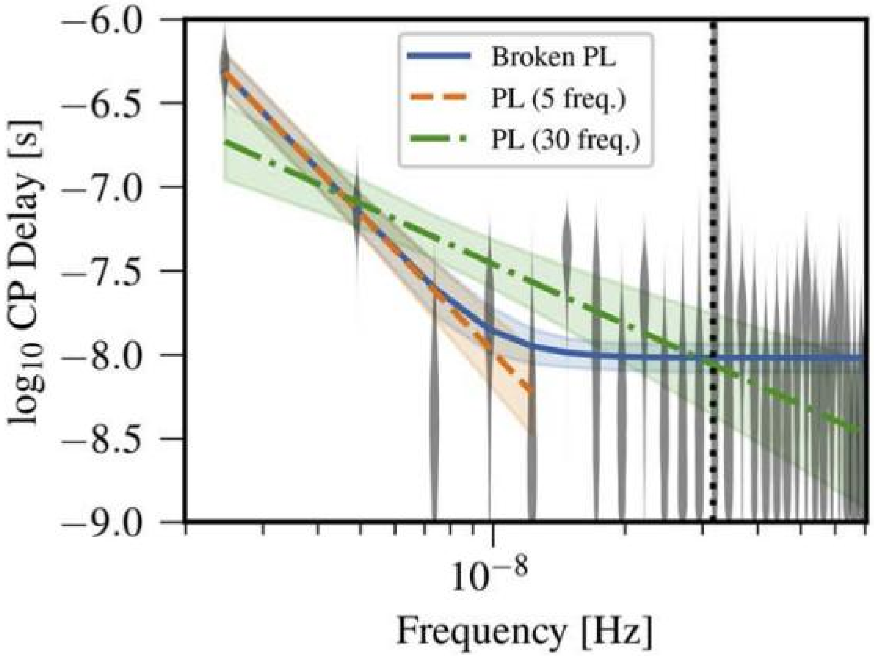
C J Moore et al. Class. Quantum Grav. 32 (2015) 015014.

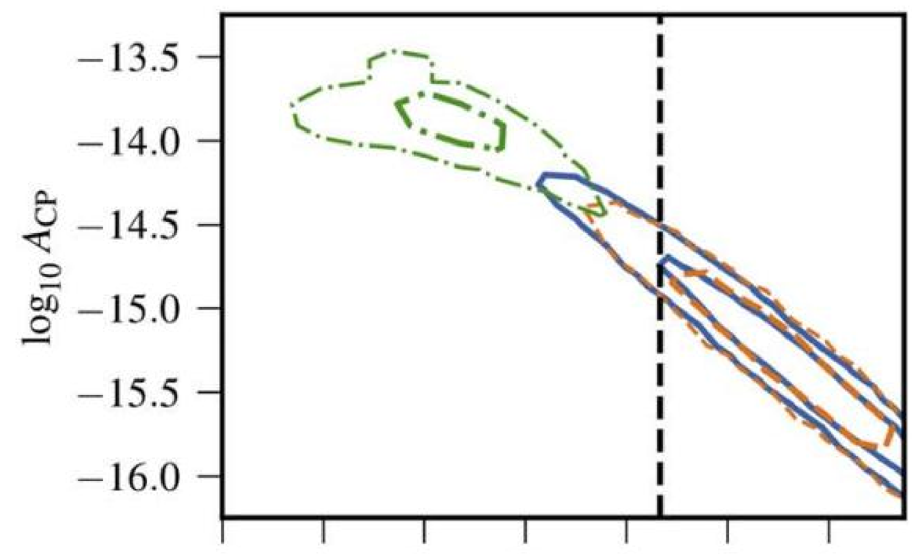
- Proposed for nHz GW detection (binary SMBHs, stochastic bkg)
- PPTA, EPTA, NANOGrav, IPTA, ...
- Can also be used for many other sciences (DM, PBH, small bodies)

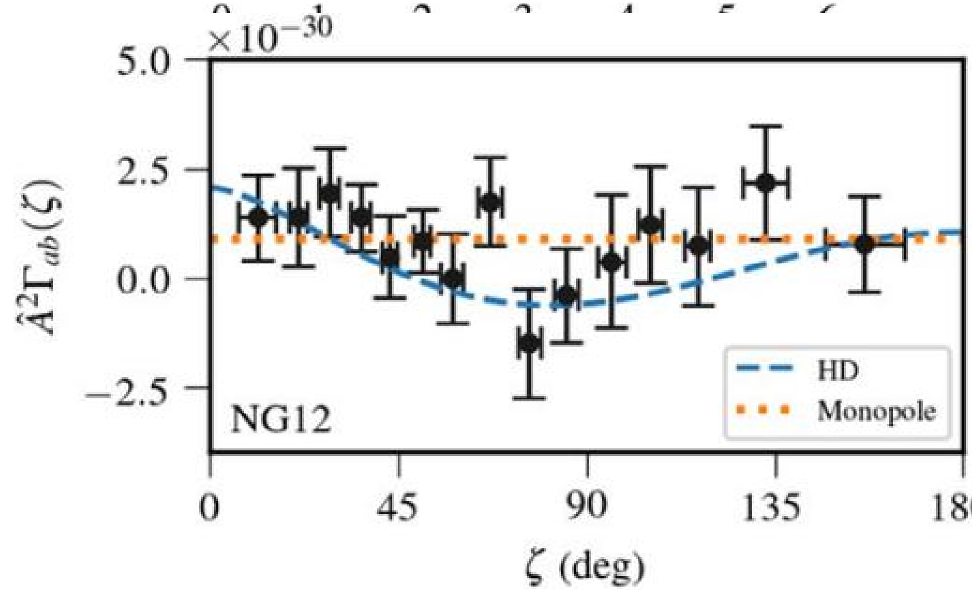
The Astrophysical Journal Letters, 905:L34 (18pp), 2020 December 20
https://doi.org/10.3847/2041-8213/abd401

The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background

Zaven Arzoumanian[1], Paul T. Baker[2], Harsha Blumer[3,4], Bence Bécsy[5], Adam Brazier[6,7], Paul R. Brook[3,4],





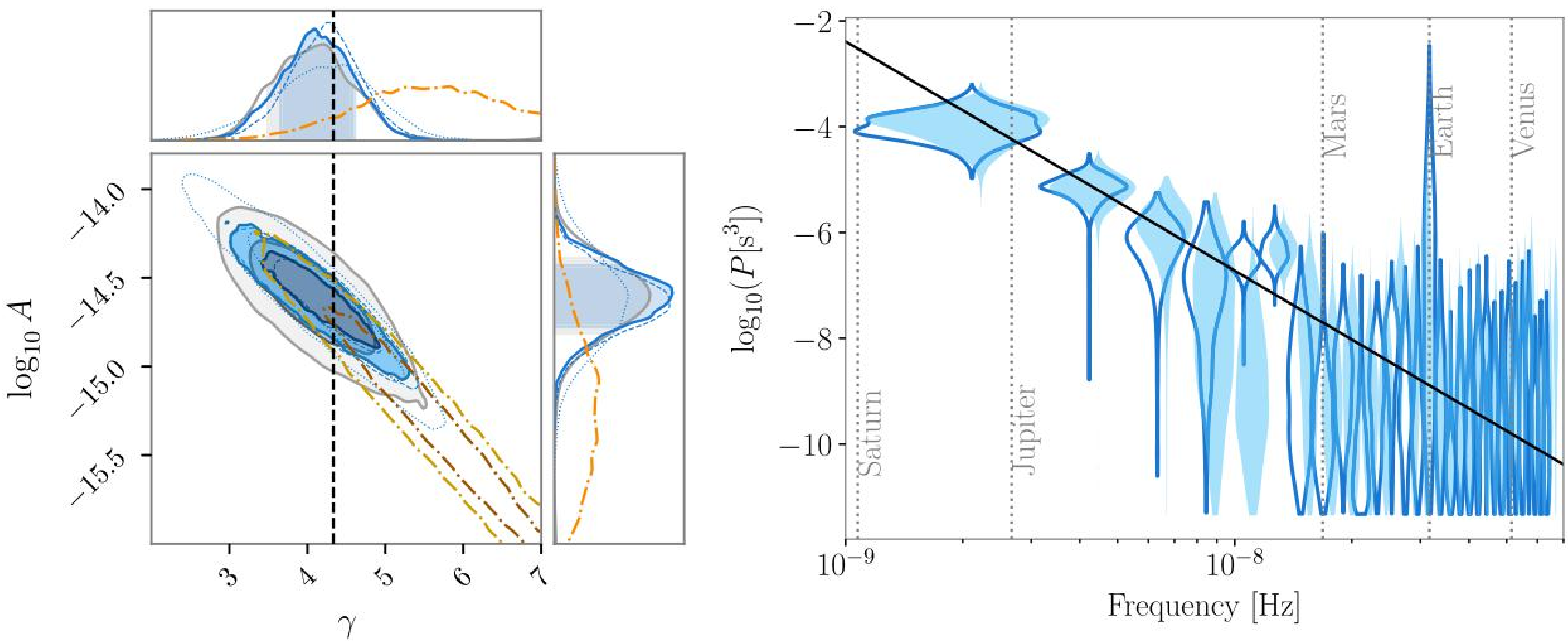


- A common power-law process was revealed by 12.5 yr NANOGrav data
- However, the HD correlation from GW is not significant

THE ASTROPHYSICAL JOURNAL LETTERS, 917:L19 (8pp), 2021 August 20
https://doi.org/10.3847/2041-8213/ac17f4

On the Evidence for a Common-spectrum Process in the Search for the Nanohertz Gravitational-wave Background with the Parkes Pulsar Timing Array

Boris Goncharov[1,2,3], R. M. Shannon[1,2], D. J. Reardon[1,2], G. Hobbs[4], A. Zic[4,5], M. Bailes[1,2], M. Curyło[6], S. Dai[4,7],

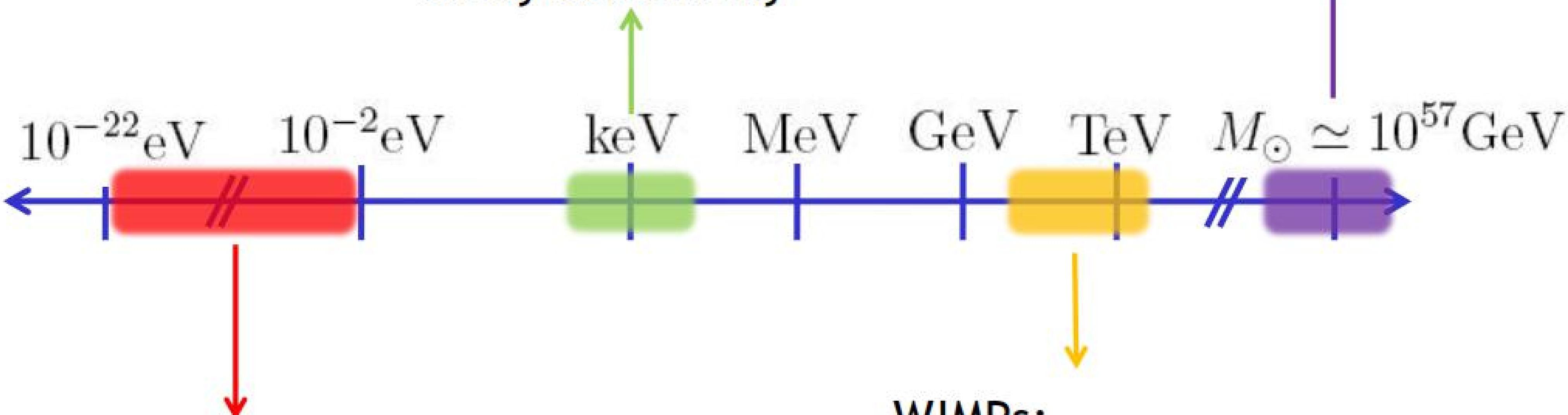


- A similar common power-law excess was shown by PPTA data
- No strong evidence to support or against the HD correlation
- Possible caveat of "common" nature: may not be truly common

Part 1: search for ultralight dark matter

Sterile neutrinos
Neutrino oscillation
X-ray astronomy

Black holes (MACHOs):
Astrophysical detection

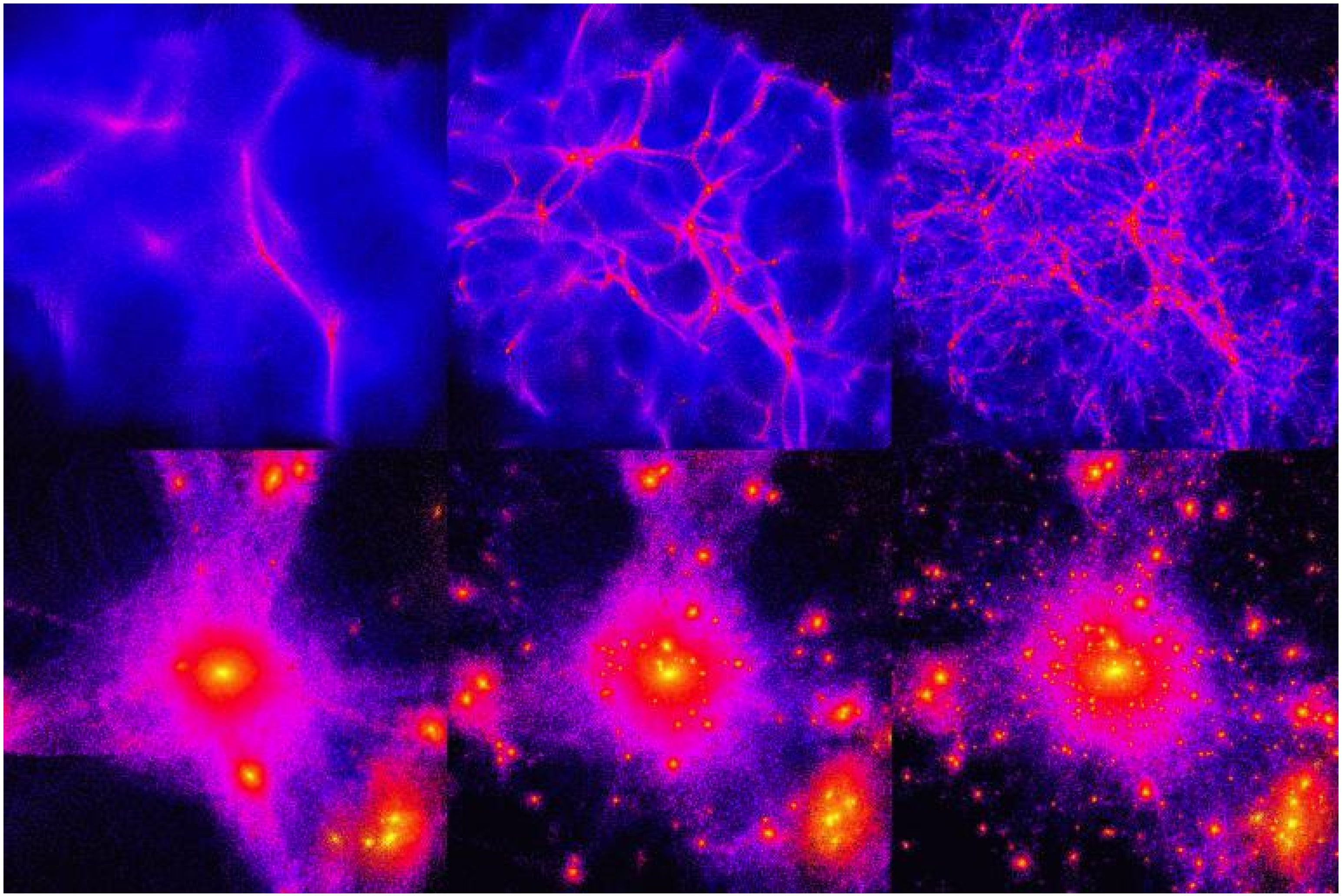


Very light dark matter
Axion, ALP, dark photon ...

WIMPs:
direct detection,
indirect detection,
collider detection

Dark matter should be cold, but not that cold

Courtesy ITC @ University of Zurich



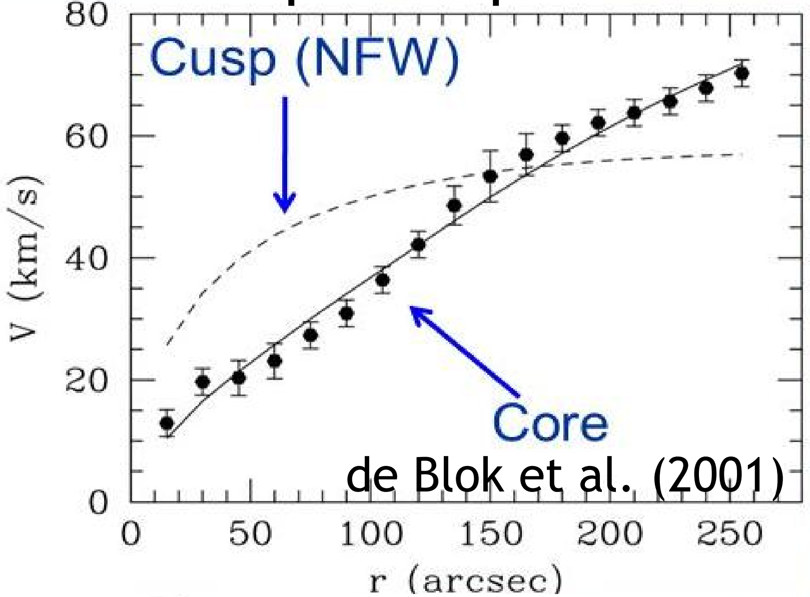
Early

z=0

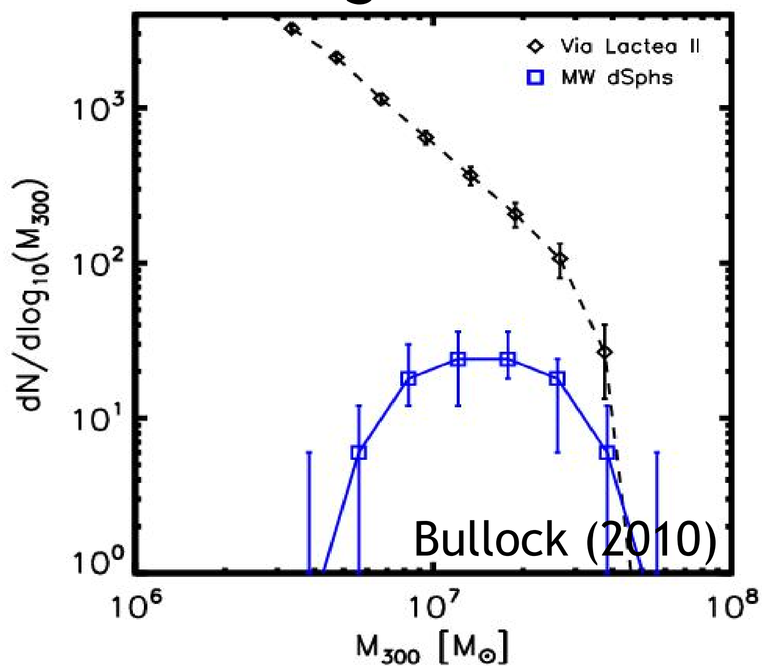
Hot Warm Cold

Small-scale problems of cold dark matter

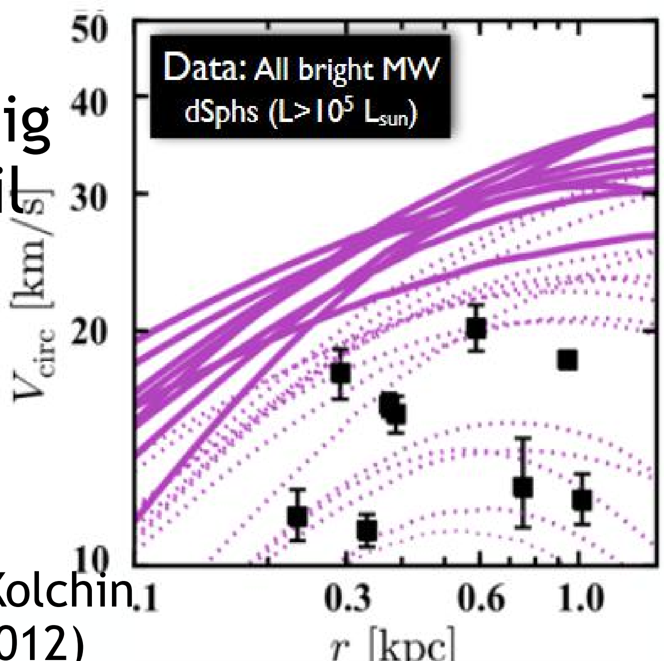
cusp-core problem



missing satellites



too big to fail



Boylan-Kolchin et al. (2012)

- Some may not be real problems
- Baryon effect
- Dark matter properties (warm, self-interaction, ...)

Ultralight (fuzzy) dark matter

- Ultralight, bosonic dark matter can form Bose-Einstein condensation and serve as cold DM

- Ultralight DM (~10^{-22} eV) appear like a coherent wave with wavelength comparable to a dwarf galaxy, which may solve the cusp-core problem of cold DM (Hu et al., 2000)

$$i(\partial_t + \frac{3}{2}\frac{\dot{a}}{a})\psi = (-\frac{1}{2m}\nabla^2 + m\Psi)\psi$$

$$i\partial_t\psi = (-\frac{1}{2m}\nabla^2 + m\Psi)\psi\,, \quad \nabla^2\Psi = 4\pi G\delta\rho$$

$$r_{J\mathrm{h}} \sim 3.4(c_{10}/f_{10})^{1/3} m_{22}^{-2/3} M_{10}^{-1/9} (\Omega_m h^2)^{-2/9}\mathrm{kpc}$$

Jeans scale: below which perturbation is stable and above which behaves like CDM

Detection of ultralight (fuzzy) DM

- Due to its very small mass, it is very difficult to detect them with conventional particle detector

- Astronomical method to try to detect a cumulative effect of such dark matter is a possible way

H. Fukuda, S. Matsumoto, T. Yanagida (2019), solar system body ephemeris

- Astrometry observations (by Gaia) of positions of large number of stars

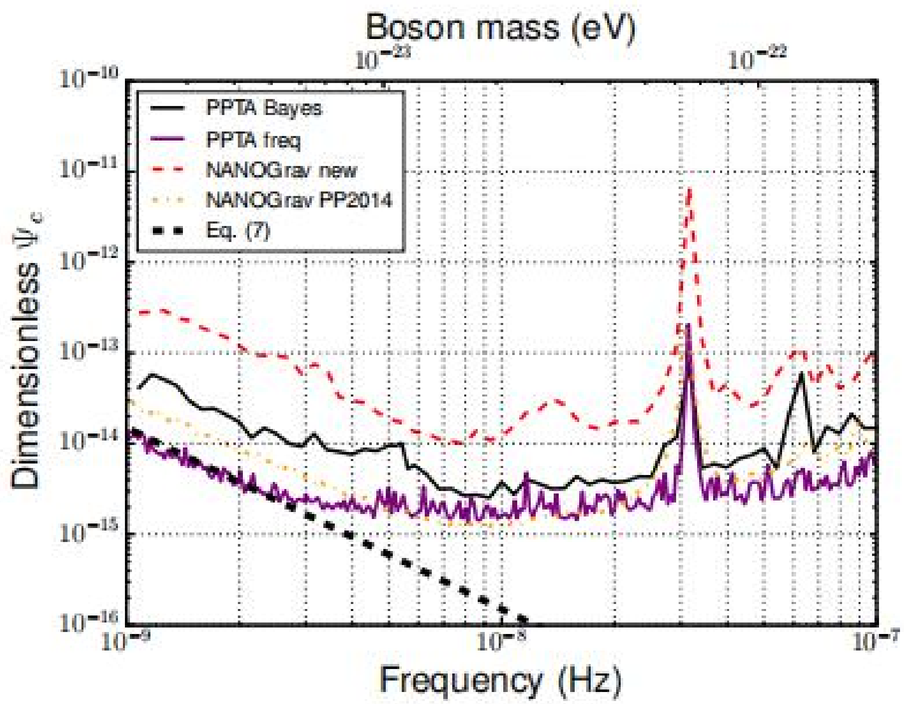
H.-K. Guo, Y. Ma, J. Shu, X. Xue, QY, Y. Zhao (2019), JCAP, arXiv:1902.05962

- Timing measurements (by PTA) of highly stable pulsars

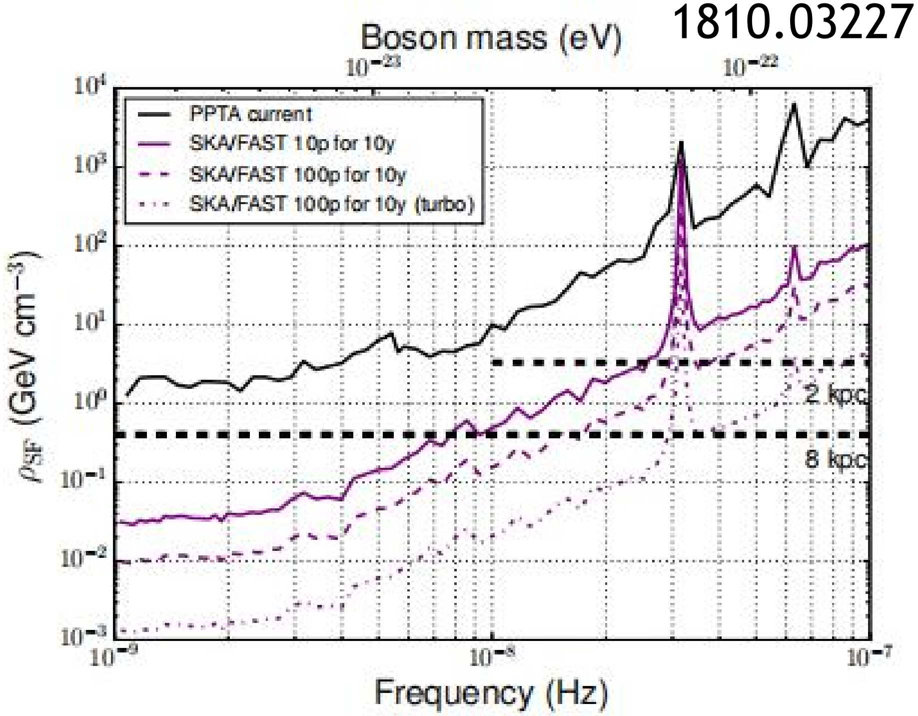
PPTA search for scalar fuzzy DM

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]
(The PPTA Collaboration)



1810.03227



Ultralight dark photon

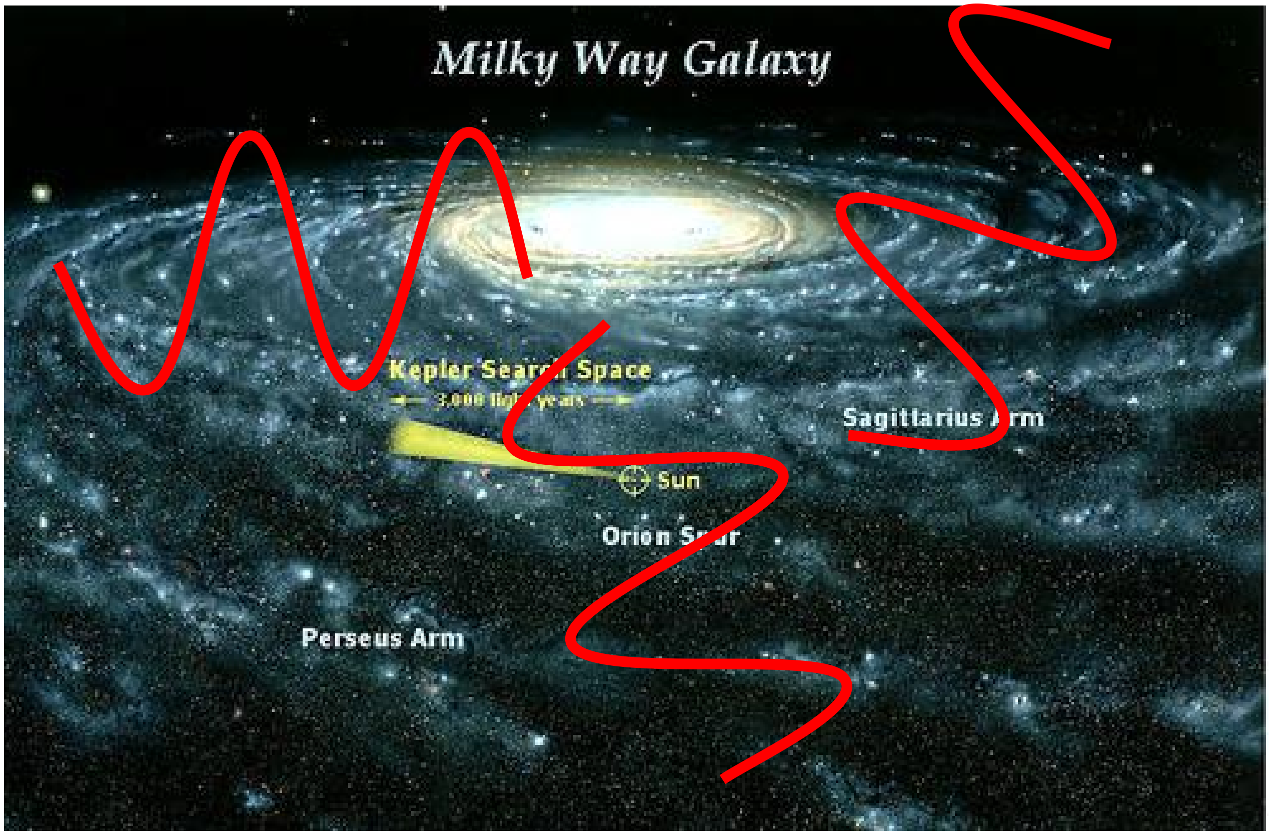
- A hypothetical hiden-sector particle proposed as a force carrier similar to photon

- Considering a special class of dark photon which is the gauge boson of the $U(1)_B$ or $U(1)_{B-L}$ group: it would interact with any object with B or (B-L) number ("dark charge")

- A good candidate of (fuzzy) dark matter (DPDM)

- If its mass is very small (10^{-22} eV), the dark photon behaves like an oscillating background, drives displacements for particles with "dark charge"

Ultralight dark photon



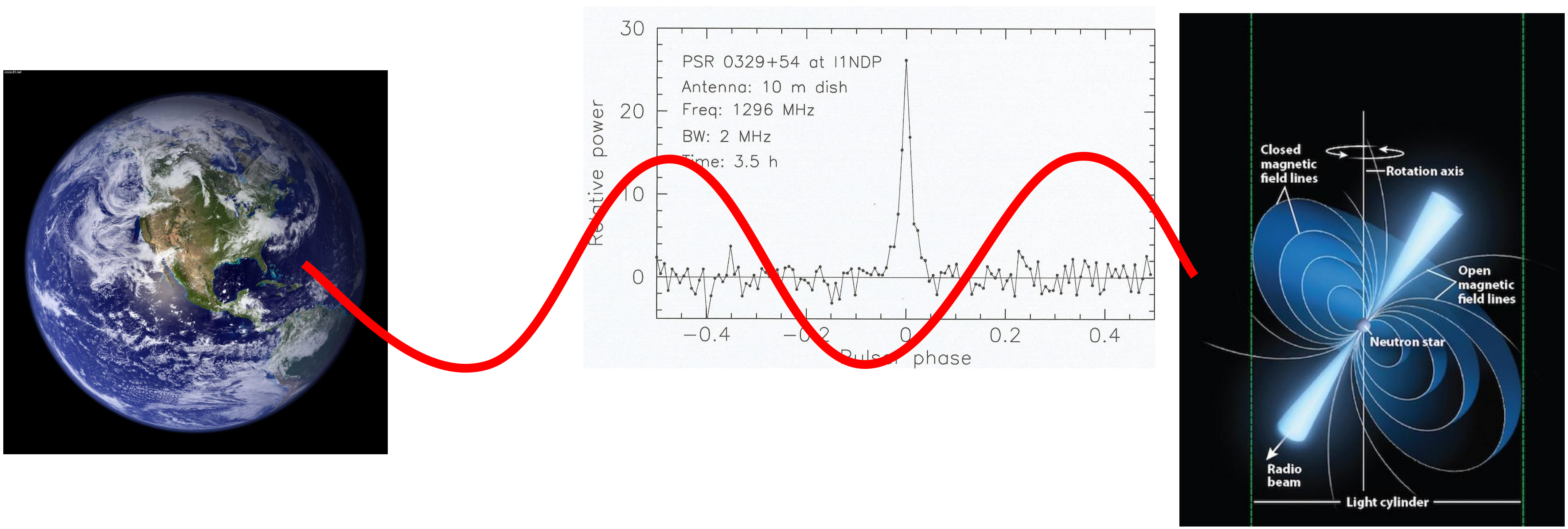
- Coherence length:
  $l \sim 0.4(m_A/10^{-22}\,\mathrm{eV})^{-1}\,\mathrm{kpc}$
- Coherent time: $(m_A/10^{-22}\mathrm{eV})$ Myr
- Frequency: 30 nHz$\times(m_A/10^{-22}\mathrm{eV})$
- Within the reach of PTA: O(10) yrs of observations

PTA search for dark photon dark matter

Both the pulsar and the earth would oscillate in the dark photon background, resulting in time residuals of pulses

$$\delta \boldsymbol{x}_{e,p}(t) \simeq -\frac{\epsilon e q}{m_A m} \boldsymbol{A_0}^{e,p} \cos\left[m_A(t-t_0)+\alpha_{e,p}\right]$$

$$\Delta t_r^d(t) = \frac{\left|\boldsymbol{d} + \delta \boldsymbol{x}_p\left(t - \frac{|\boldsymbol{d}|}{v(t)}\right) - \delta \boldsymbol{x}_e(t)\right| - |\boldsymbol{d}|}{v(t)} \simeq \frac{\boldsymbol{n}_p \cdot \Delta \boldsymbol{x}(t)}{v(t)},$$



Pulsar time of arrival (ToA)

residual

TOA ~ Timing model + White noise + Spin noise + DM noise + SSE noise + Signal

标准模型

噪声项：仪器噪声，pulsar自旋不稳定，DM variations，太阳系内的扰动不确定性等

PBH，dark matter，引力波

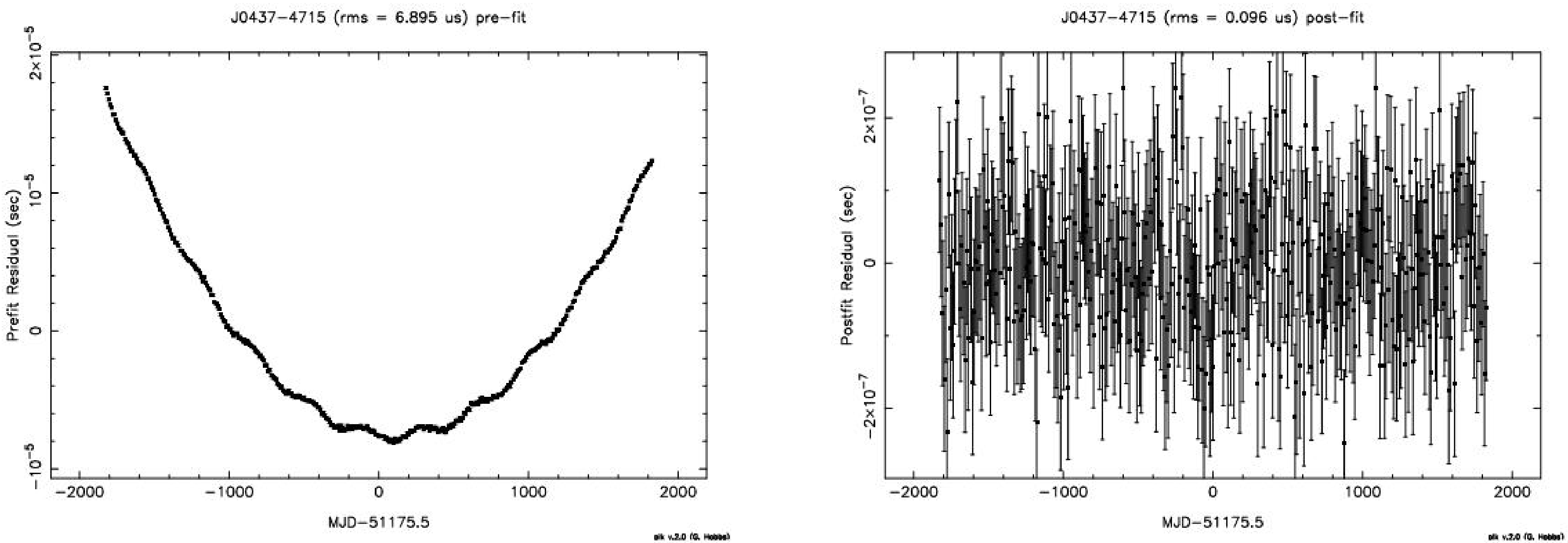


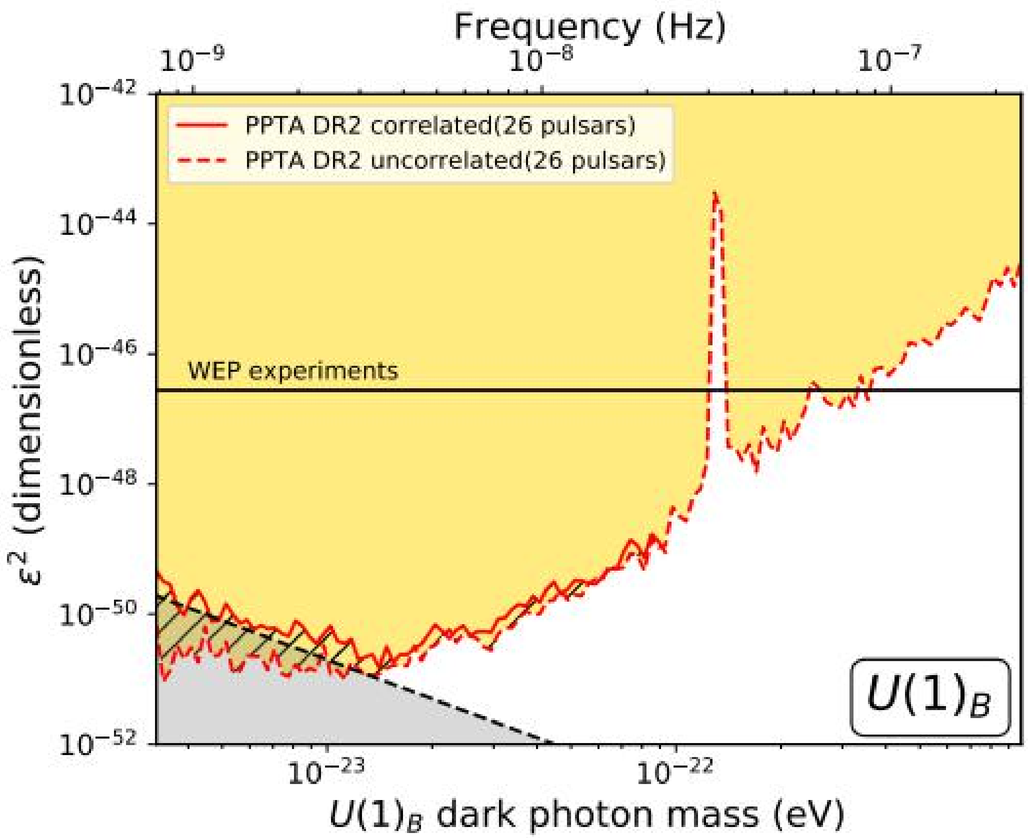
Figure 1: a) pre-fit timing residuals for the test data-set and b) post-fit timing residuals.

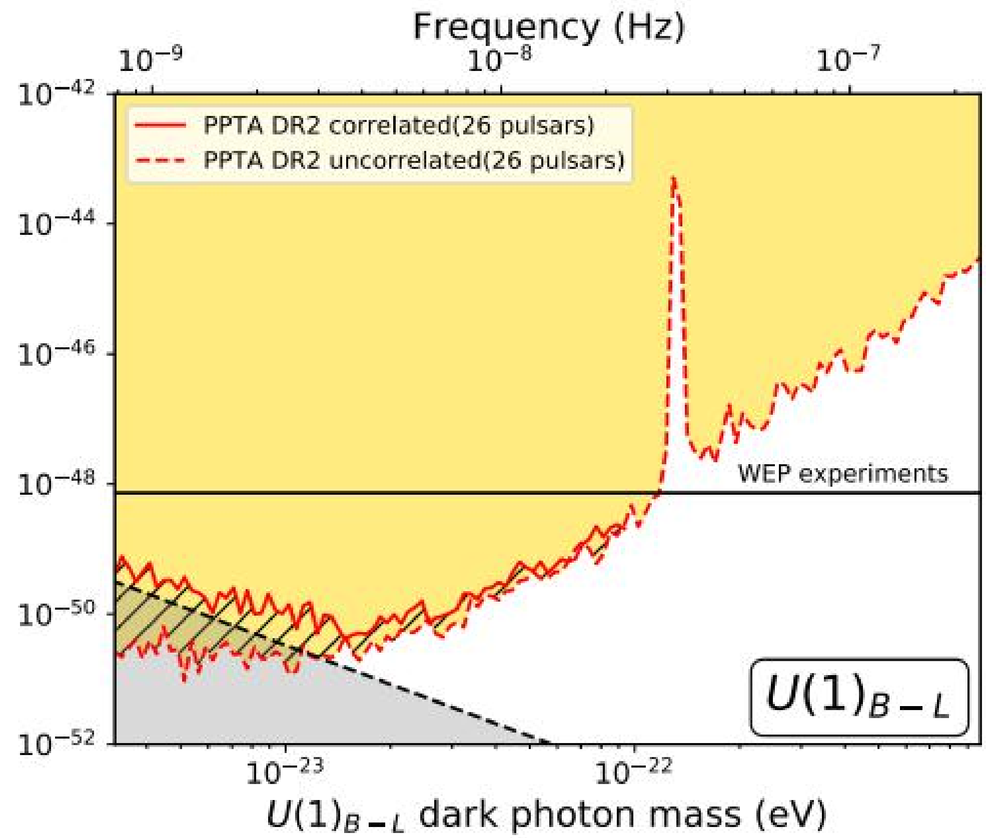
Noise and signal model

	Parameter	Prior	Description
White Noise $\boldsymbol{\vartheta}_{\rm W}$	EFAC	U[0.01,10]	one per backend
	EQUAD	log-U $[10^{-10}, 10^{-4}]$	one per backend
Spin Noise $\boldsymbol{\vartheta}_{SN}$	$\gamma_{\rm SN}$	U[0,7]	one per pulsar
	$A_{\rm SN}$	log-U$[10^{-21}, 10^{-9}]$	one per pulsar
DM Noise $\boldsymbol{\vartheta}_{\rm DM}$	$\gamma_{\rm DM}$	U[0,7]	one per pulsar
	$A_{\rm DM}$	log-U$[10^{-21}, 10^{-9}]$	one per pulsar
Band Noise $\boldsymbol{\vartheta}_{\rm BN}$ for J0437 and J1939	$\gamma_{\rm BN}$	U[0,7]	one per band
	$A_{\rm BN}$	log-U$[10^{-21}, 10^{-9}]$	one per band
Dark photon Parameters $\boldsymbol{\vartheta}_{\rm DPDM}$	α_p	U$[0,2\pi]$	one per pulsar
	α_e^i	U$[0,2\pi]$	three per PTA
	$(\tilde{A}_0^p)^2$	$f(x) = e^{-x}$	one per pulsar*
	$(\tilde{A}_0^{e,i})^2$	$f(x) = e^{-x}$	one per PTA
	ϵ	log-U$[10^{-28}, 10^{-16}]$	one per PTA
	m_A	log-U$[10^{-23.5}, 10^{-21}]$	one per PTA
BayesEphem Parameters $\boldsymbol{\vartheta}_{\rm BE}$	$z_{\rm drift}$	U$[-10^{-9}, 10^{-9}]$	one per PTA
	$\Delta M_{\rm Jupiter}$	N$(0, 1.5 \times 10^{-11})$	one per PTA
	$\Delta M_{\rm Saturn}$	N$(0, 8.2 \times 10^{-12})$	one per PTA
	$\Delta M_{\rm Uranus}$	N$(0, 5.7 \times 10^{-11})$	one per PTA
	$\Delta M_{\rm Neptune}$	N$(0, 7.9 \times 10^{-11})$	one per PTA
	PCA$_i$	U$[-0.05, 0.05]$	six per PTA

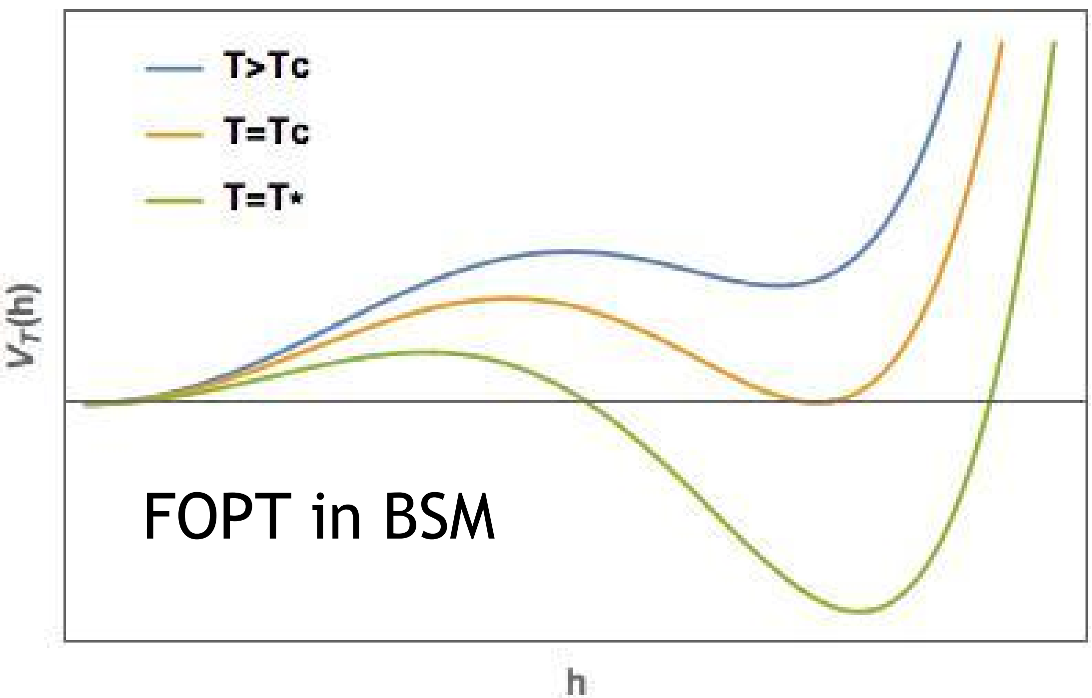
Pulsars	$N_{\rm obs}$	T (years)	$\bar{\sigma} \times 10^{-6}$ (s)	$\log A_{\rm SN}$	$\gamma_{\rm SN}$	$\log A_{\rm DM}$	$\gamma_{\rm DM}$
J0437-4715	29262	15.03	0.296	$-15.76^{+0.17}_{-0.18}$	$6.63^{+0.17}_{-0.13}$	$-13.05^{+0.10}_{-0.08}$	$2.26^{+0.32}_{-0.44}$
J0613-0200	5920	14.20	2.504	$-14.63^{+0.77}_{-0.68}$	$4.93^{+1.33}_{-1.61}$	$-13.02^{+0.08}_{-0.08}$	$0.95^{+0.33}_{-0.31}$
J0711-6830	5547	14.21	6.197	$-12.85^{+0.14}_{-0.16}$	$0.97^{+0.64}_{-0.55}$	$-14.54^{+0.72}_{-0.89}$	$4.43^{+1.68}_{-1.72}$
J1017-7156	4053	7.77	1.577	$-12.89^{+0.07}_{-0.07}$	$0.54^{+0.53}_{-0.37}$	$-12.72^{+0.06}_{-0.06}$	$2.18^{+0.45}_{-0.44}$
J1022+1001	7656	14.20	5.514	$-12.79^{+0.12}_{-0.13}$	$0.54^{+0.55}_{-0.37}$	$-13.04^{+0.10}_{-0.12}$	$0.58^{+0.47}_{-0.36}$
J1024-0719	2643	14.09	4.361	$-14.28^{+0.27}_{-0.20}$	$6.51^{+0.35}_{-0.60}$	$-14.53^{+0.54}_{-0.56}$	$5.22^{+1.14}_{-1.18}$
J1045-4509	5611	14.15	9.186	$-12.75^{+0.24}_{-0.40}$	$1.58^{+1.28}_{-0.93}$	$-12.18^{+0.09}_{-0.08}$	$1.86^{+0.36}_{-0.32}$
J1125-6014	1407	12.34	1.981	$-12.64^{+0.11}_{-0.12}$	$0.51^{+0.55}_{-0.37}$	$-13.14^{+0.19}_{-0.21}$	$3.36^{+0.73}_{-0.66}$
J1446-4701	508	7.36	2.200	$-16.46^{+2.88}_{-3.17}$	$2.74^{+2.49}_{-1.89}$	$-13.49^{+0.32}_{-1.87}$	$2.48^{+1.92}_{-1.45}$
J1545-4550	1634	6.97	2.249	$-17.33^{+2.50}_{-2.55}$	$3.25^{+2.45}_{-2.18}$	$-13.40^{+0.24}_{-0.38}$	$3.90^{+1.61}_{-1.09}$
J1600-3053	7047	14.21	2.216	$-17.63^{+2.10}_{-2.29}$	$3.28^{+2.34}_{-2.15}$	$-13.27^{+0.12}_{-0.13}$	$2.79^{+0.43}_{-0.40}$
J1603-7202	5347	14.21	4.947	$-12.82^{+0.14}_{-0.16}$	$1.01^{+0.67}_{-0.60}$	$-12.66^{+0.10}_{-0.09}$	$1.44^{+0.40}_{-0.38}$
J1643-1224	5941	14.21	4.039	$-12.32^{+0.08}_{-0.09}$	$0.51^{+0.42}_{-0.34}$	$-12.27^{+0.07}_{-0.07}$	$0.55^{+0.32}_{-0.29}$
J1713+0747	7804	14.21	1.601	$-14.09^{+0.25}_{-0.38}$	$2.98^{+1.00}_{-0.64}$	$-13.35^{+0.08}_{-0.08}$	$0.53^{+0.32}_{-0.31}$
J1730-2304	4549	14.21	5.657	$-17.39^{+2.39}_{-2.51}$	$3.05^{+2.59}_{-2.12}$	$-14.11^{+0.40}_{-0.57}$	$4.22^{+1.42}_{-1.04}$
J1732-5049	807	7.23	7.031	$-16.51^{+3.04}_{-2.97}$	$3.29^{+2.37}_{-2.97}$	$-13.38^{+0.54}_{-0.84}$	$4.07^{+1.96}_{-1.93}$
J1744-1134	6717	14.21	2.251	$-13.39^{+0.14}_{-0.15}$	$1.49^{+0.66}_{-0.57}$	$-13.35^{+0.09}_{-0.09}$	$0.86^{+0.40}_{-0.33}$
J1824-2452A	2626	13.80	2.190	$-12.56^{+0.13}_{-0.12}$	$3.61^{+0.41}_{-0.39}$	$-12.18^{+0.11}_{-0.10}$	$1.64^{+0.46}_{-0.59}$
J1832-0836	326	5.40	1.430	$-16.47^{+2.63}_{-3.09}$	$3.66^{+2.33}_{-2.52}$	$-13.07^{+0.24}_{-0.63}$	$3.77^{+2.00}_{-1.05}$
J1857+0943	3840	14.21	5.564	$-14.76^{+0.74}_{-0.50}$	$5.75^{+0.91}_{-1.53}$	$-13.40^{+0.20}_{-0.25}$	$2.66^{+0.83}_{-0.67}$
J1909-3744	14627	14.21	0.672	$-13.60^{+0.13}_{-0.12}$	$1.60^{+0.43}_{-0.46}$	$-13.48^{+0.09}_{-0.08}$	$0.69^{+0.38}_{-0.35}$
J1939+2134	4941	14.09	0.468	$-14.38^{+0.22}_{-0.18}$	$6.24^{+0.49}_{-0.62}$	$-11.59^{+0.07}_{-0.07}$	$0.13^{+0.19}_{-0.10}$
J2124-3358	4941	14.21	8.863	$-14.79^{+0.82}_{-0.67}$	$5.07^{+1.37}_{-1.97}$	$-13.35^{+0.18}_{-0.33}$	$0.95^{+1.11}_{-0.66}$
J2129-5721	2879	13.88	3.496	$-15.48^{+1.92}_{-3.54}$	$2.91^{+2.29}_{-1.83}$	$-13.31^{+0.13}_{-0.14}$	$1.07^{+0.65}_{-0.65}$
J2145-0750	6867	14.09	5.086	$-12.82^{+0.10}_{-0.11}$	$0.62^{+0.50}_{-0.40}$	$-13.33^{+0.14}_{-0.16}$	$1.38^{+0.54}_{-0.55}$
J2241-5236	5224	8.20	0.830	$-13.40^{+0.09}_{-0.08}$	$0.44^{+0.40}_{-0.30}$	$-13.79^{+0.10}_{-0.10}$	$1.42^{+0.61}_{-0.59}$

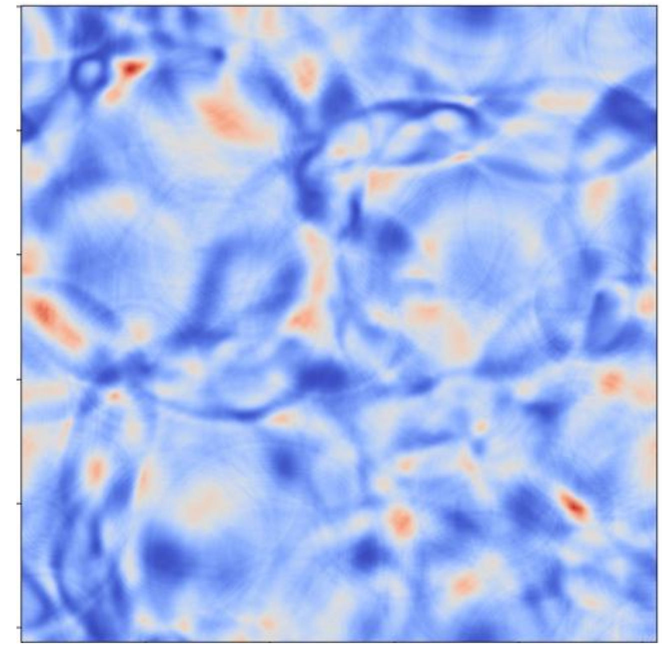
Constraints on DPDM parameters





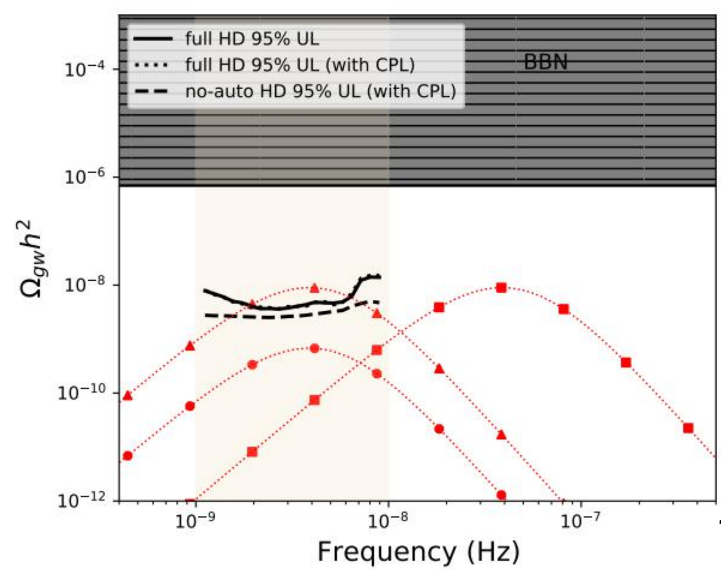
Part 2: search for first-order phase transition



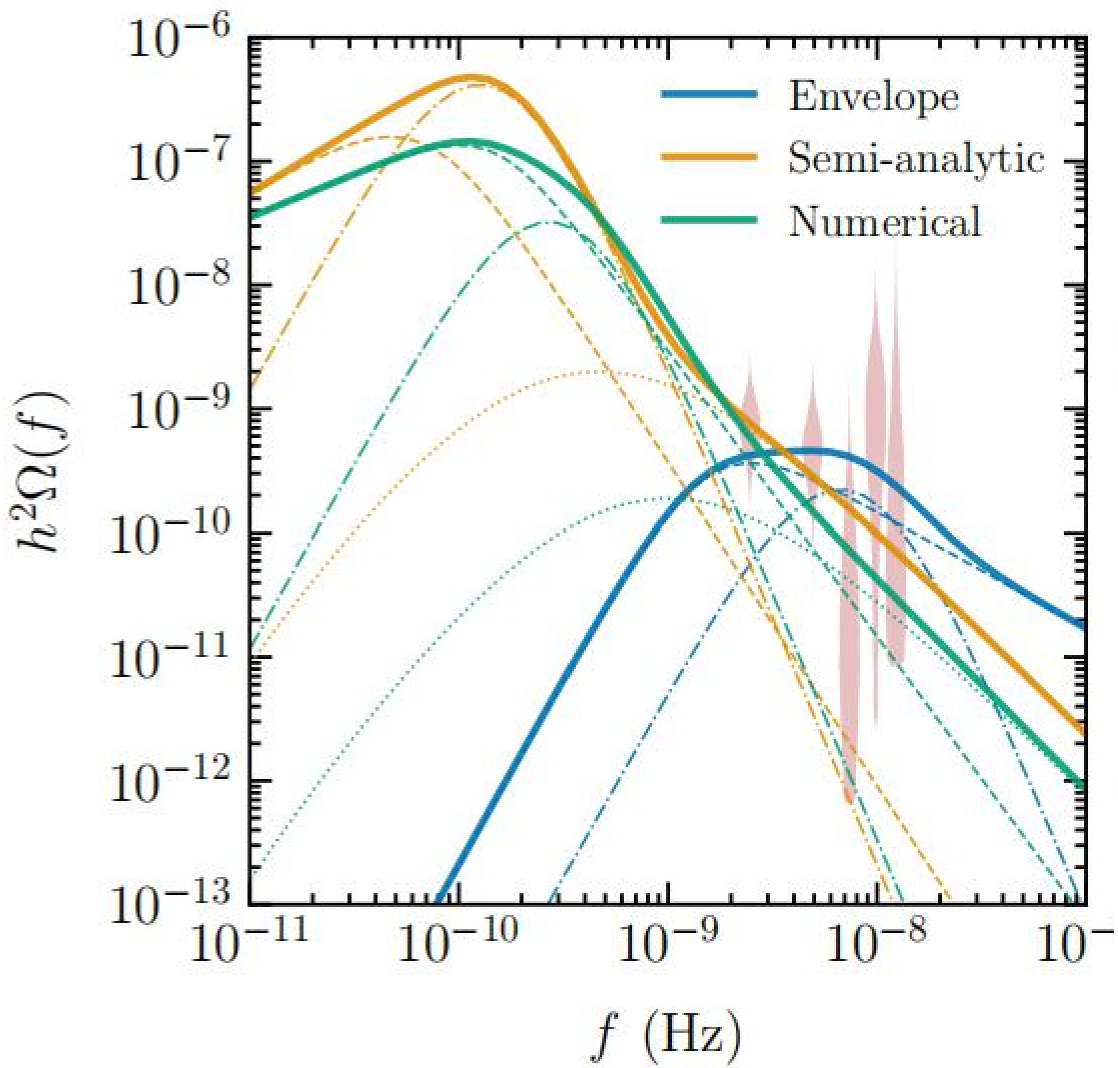


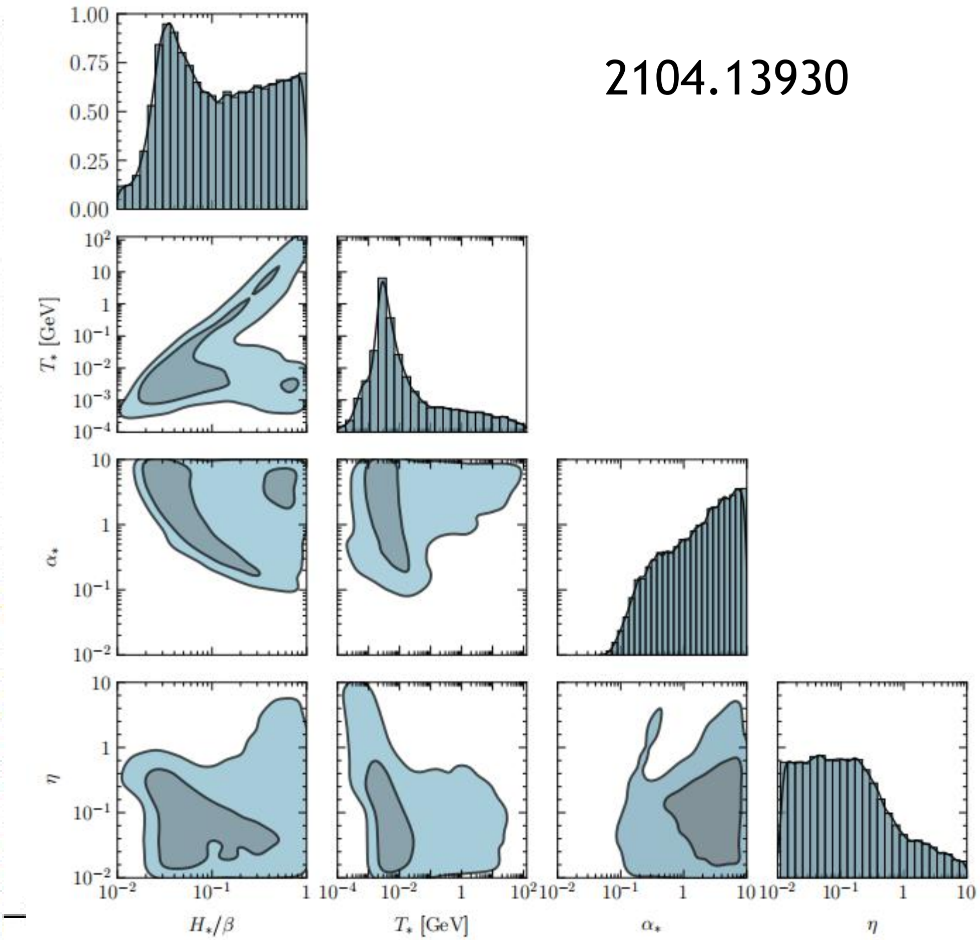
Sources of GW: bubble collisions, sound wave, turbulence

$$\Omega_{sw}(f)h^2 = 2.65\times10^{-6}v_w\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}$$
$$\times\left[(f/f_{sw})^3\left(\frac{7}{4+3(f/f_{sw})^2}\right)^{7/2}\right]$$
$$\times\min\left[1,\ (8\pi)^{1/3}v_w\left(\frac{H_*}{\beta}\right)\left(\frac{3}{4}\frac{\kappa\alpha}{1+\alpha}\right)^{-1/2}\right],$$



NANOGrav search for FOPT



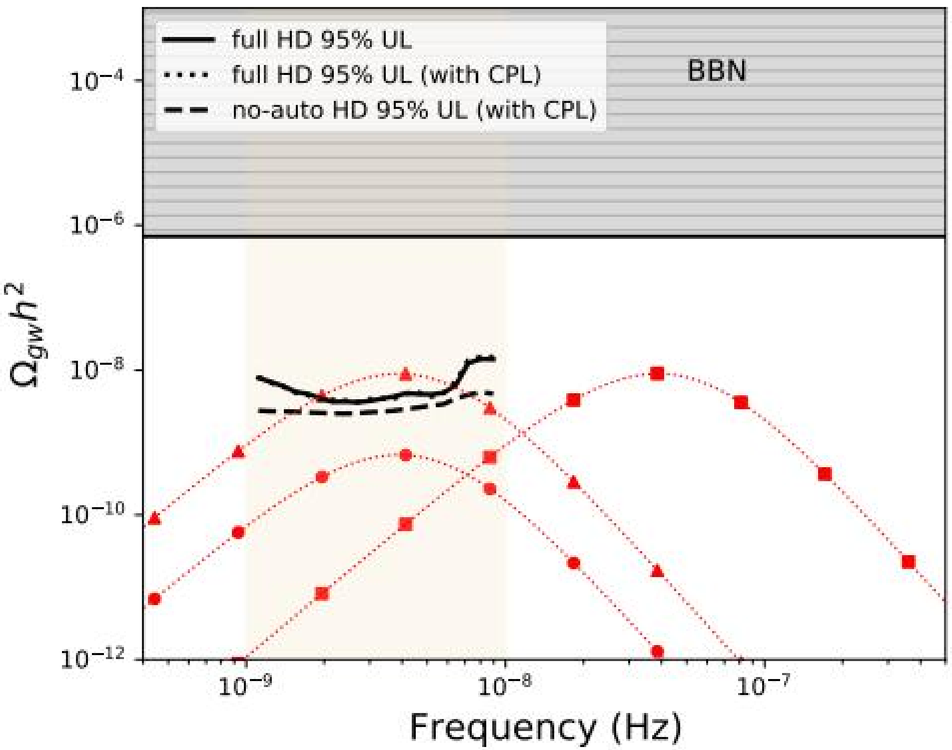


2104.13930

previous NANOGrav analysis found no evidence yet for the inter-pulsar correlation signature of a GWB, the evidence for a common-spectrum process was significant. Here we have interpreted this process as being a GWB of phase-transition origin. We found that the data are well

PPTA search for FOPT

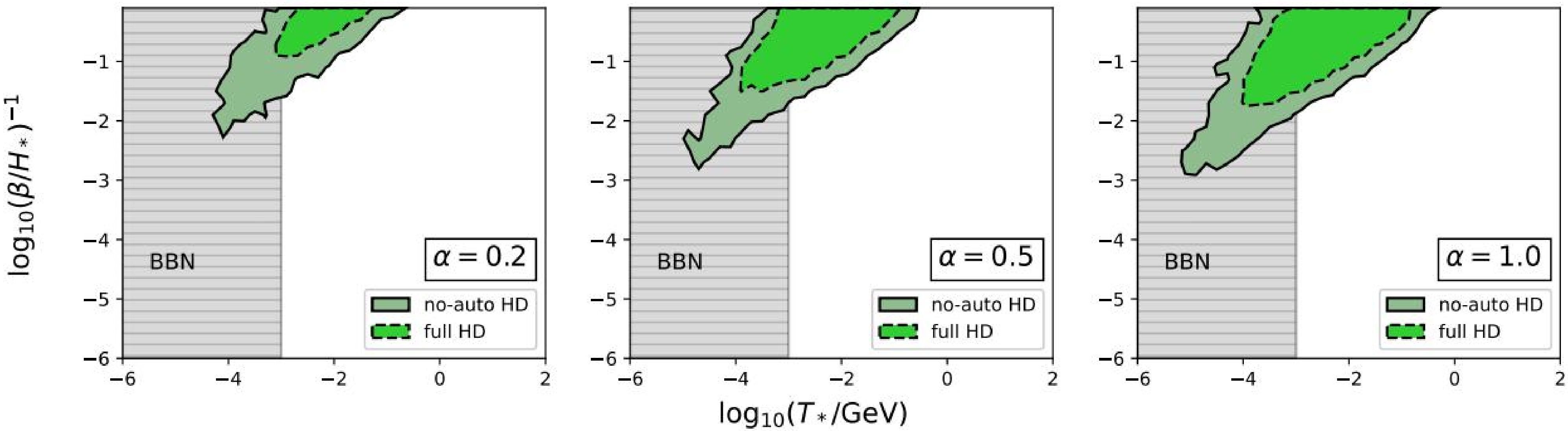
	Parameter	Prior	Description
CPL Process Parameters	$A_{\rm CPL}$	log-U[10^{-18},10^{-11}]	one per PTA
	$\gamma_{\rm CPL}$	U[0,7]	one per PTA
FOPT Parameters	α	log-U[10^{-5},1]	one per PTA
	$(\beta/H_*)^{-1}$	log-U[10^{-6},1]	one per PTA
	T_* (GeV)	log-U[10^{-6},10^{2}]	one per PTA
Free Spectrum Parameters	$\sqrt{\Omega_{gw}(f_i)h^2}$	U[10^{-10},10^{0}]	20 per PTA
BayesEphem [12] Parameters	$z_{\rm drift}$	U[-10^{-9},10^{-9}]	one per PTA
	$\Delta M_{\rm Jupiter}$	N($0, 1.5\times10^{-11}$)	one per PTA
	$\Delta M_{\rm Saturn}$	N($0, 8.2\times10^{-12}$)	one per PTA
	$\Delta M_{\rm Uranus}$	N($0, 5.7\times10^{-11}$)	one per PTA
	$\Delta M_{\rm Neptune}$	N($0, 7.9\times10^{-11}$)	one per PTA
	PCA$_i$	U[-0.05,0.05]	six per PTA



- 95% Bayesian upper limits for free spectrum SGWB power
- Some of the FOPT models (red lines) can be excluded

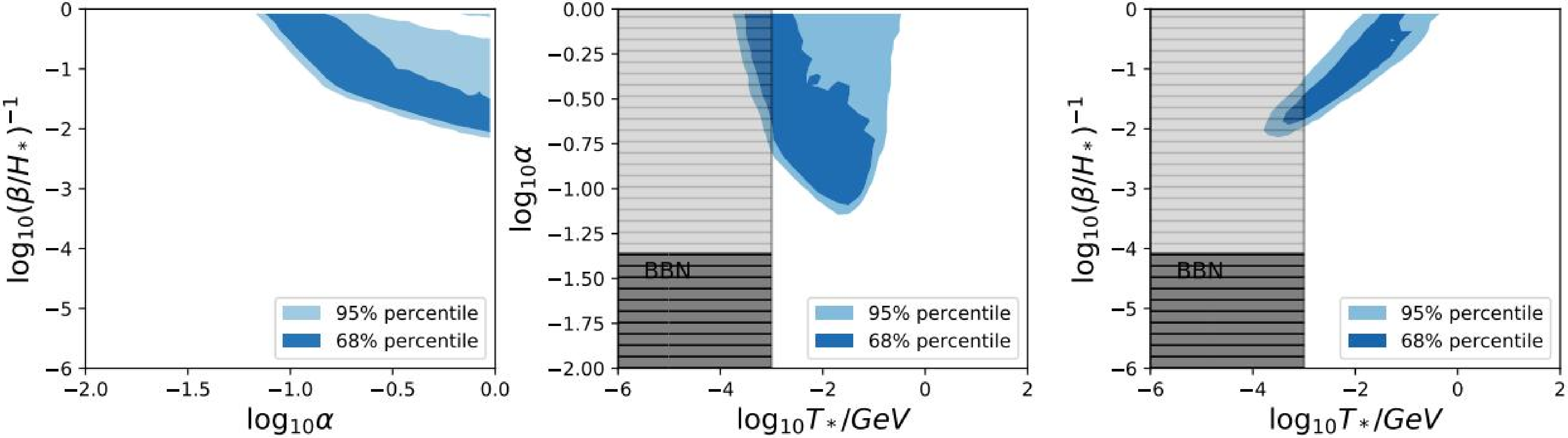
PPTA search for FOPT

Hypothesis	Pulsar noise	CPL process	HD process FOPT spectrum	Bayes Factors	Parameter Estimation (median and 1-σ interval)	
					T_*/MeV, $\alpha \times 10^3$, β/H_*	$A_{\rm CPL}$, $\gamma_{\rm CPL}$
H0:Pulsar Noise	✓					
H1:CPL	✓	✓		$10^{3.5}$ (against H0)		$-14.45^{+0.62}_{-0.64}$, $3.31^{+1.36}_{-1.53}$
H2:FOPT	✓		✓(full HD)	$10^{1.8}$ (against H0)	$7.4^{+11.9}_{-4.7}$, 271^{+165}_{-92}, $9.9^{+11.4}_{-5.4}$	
H3:FOPT1	✓	✓	✓(full HD)	1.04 (against H1)	$9.6^{+232.2}_{-9.2}$, $3.8^{+27.9}_{-3.4}$, 854^{+9622}_{-782}	$-14.51^{+0.64}_{-0.68}$, $3.36^{+1.39}_{-1.54}$
H4:FOPT2	✓	✓	✓(no-auto HD)	0.96 (against H1)	$10.9^{+290.5}_{-10.6}$, $3.2^{+19.9}_{-2.8}$, 1053^{+11256}_{-962}	$-14.45^{+0.62}_{-0.64}$, $3.27^{+1.37}_{-1.54}$

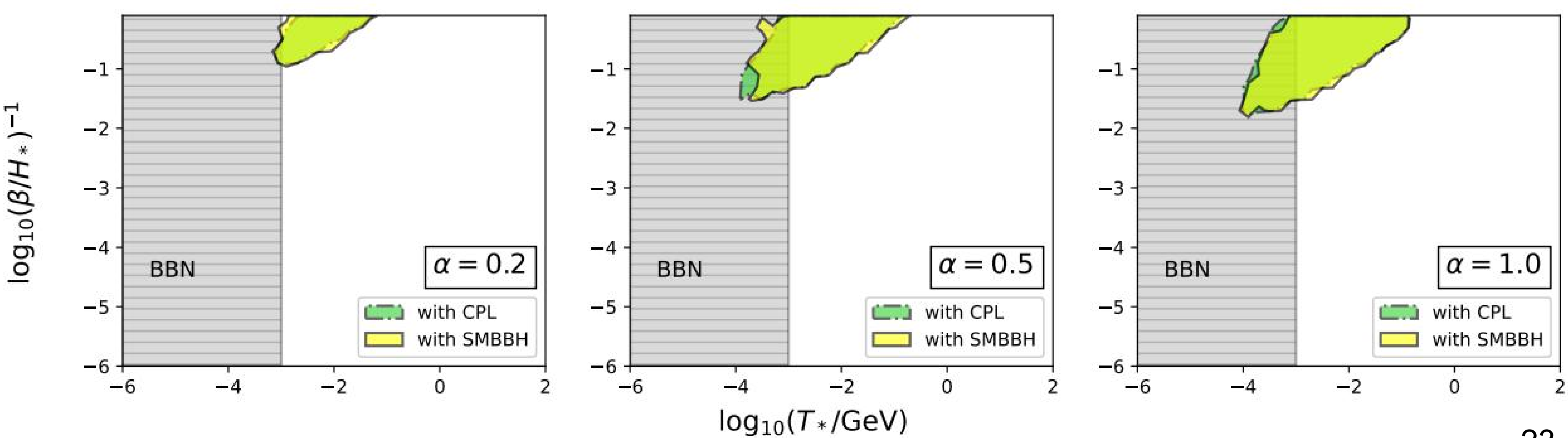


Assuming the common power-law excess is due to unknown noises

Assuming NO common power-law noise



Assuming the common power-law excess is due to binary SMBH



Summary

- Using the long-term (>15 years) high-precision pulsar timing observations by Parkes telescope, we obtain by far the strongest constraints on ultralight dark matter ($<10^{-22}$ eV) coupling with ordinary matter

- The PPTA data place effective constraints on the first-order phase transition parameters with temperature 1-100 MeV and duration $(\beta/H^*)^{-1}$~0.01-0.1

Thanks for your attention!