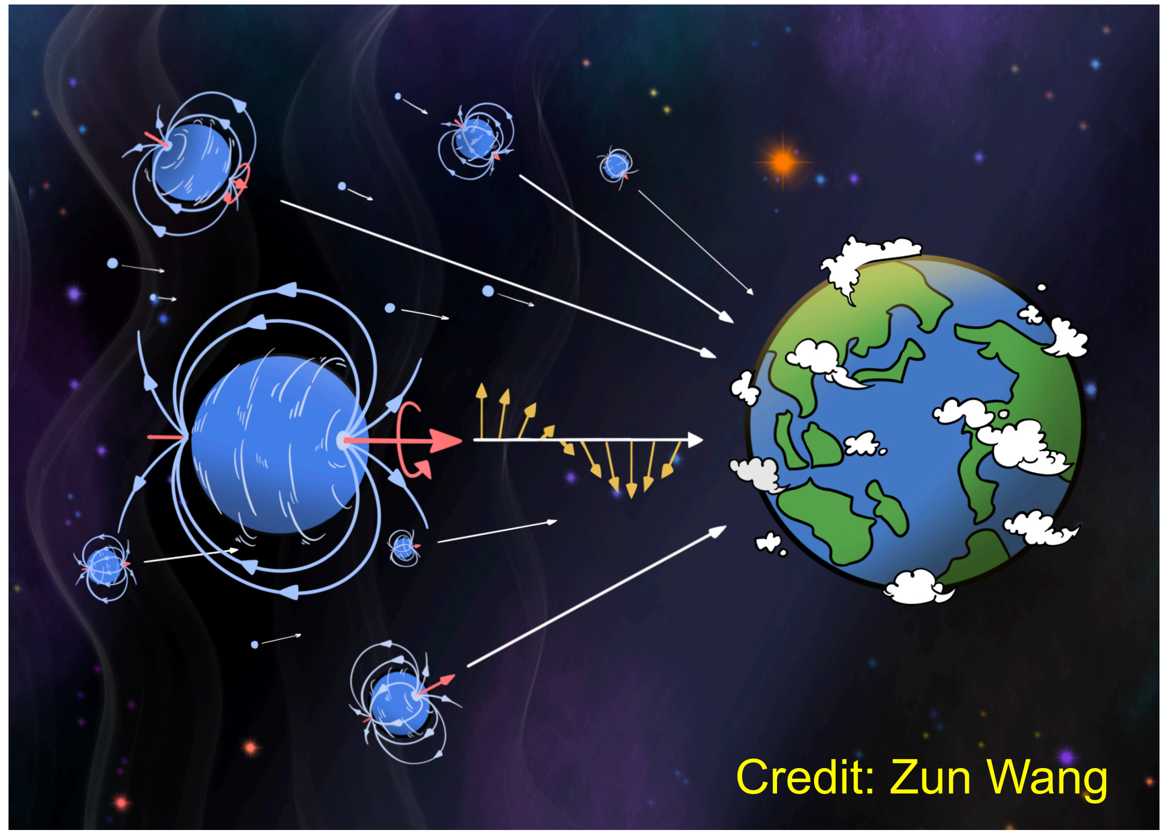
MITP Workshop - ``Pulsar Timing Arrays: A Star Way to New Physics”, 2023

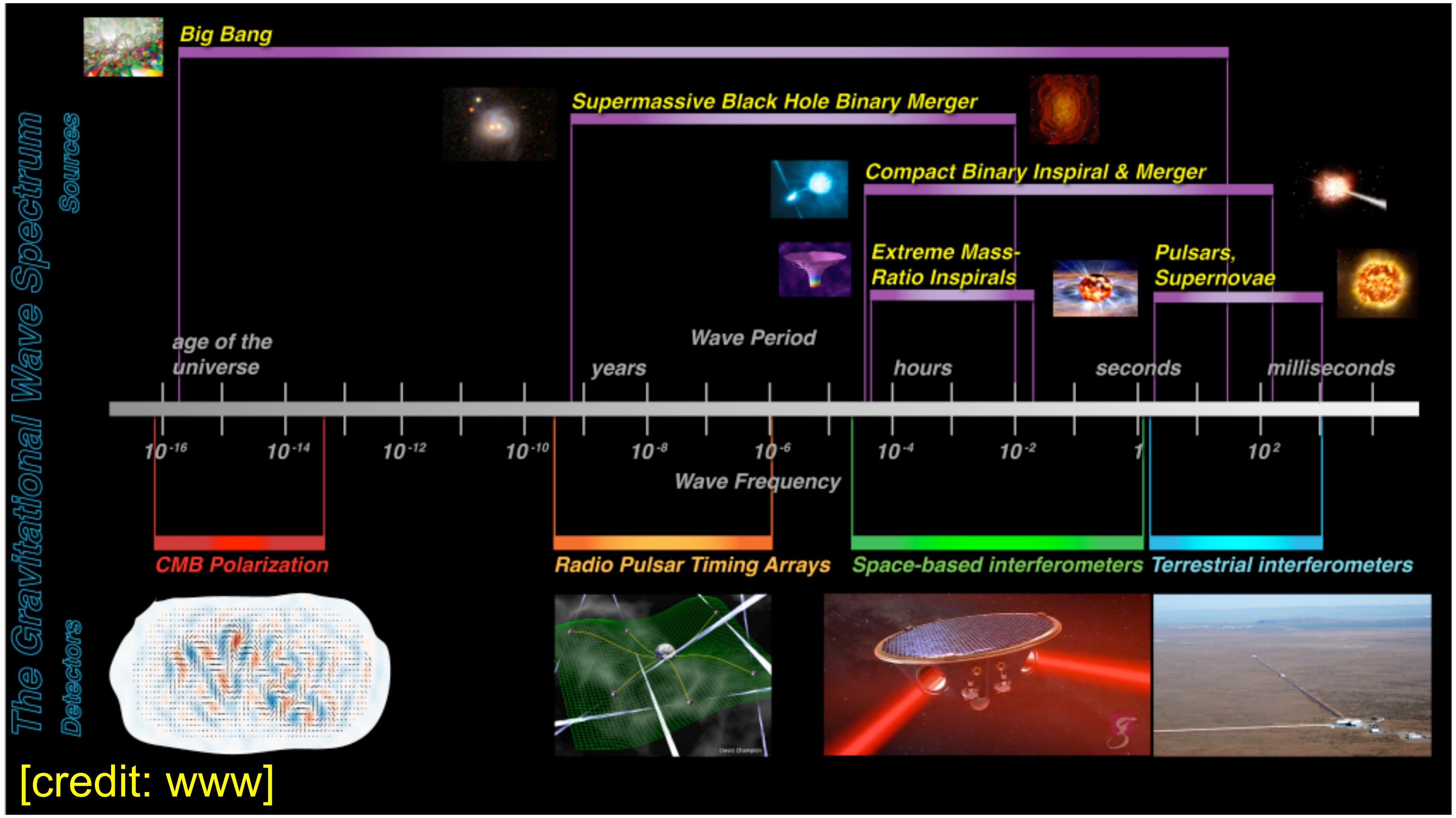


PULSAR POLARIZATION ARRAYS

Tao LIU

Hong Kong Univ. of Science and Technology

Pulsar Timing Arrays (PTAs)



- A network of widely distributed and well-timed millisecond pulsars (MSPs)
- A galactic timing interferometer to detect ~nanoHz gravitational waves (GWs) [S. L. Detweiler, Atrophy's. J. 234 (1979)]

Cross-correlation of Pulsars

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

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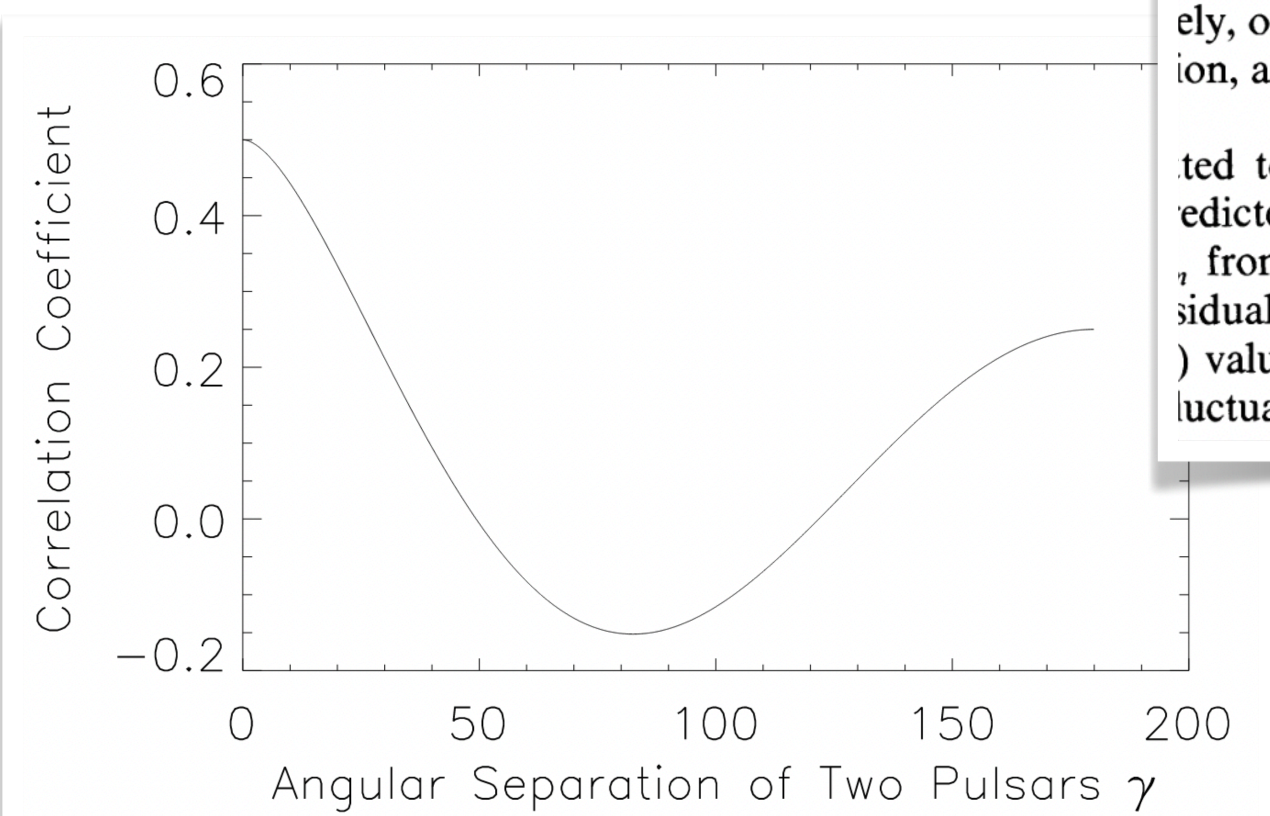
per limit of about 10^- s for the periods to which a are sensitive. It should also be noted from n (1) that data from any pulsar contain informa- out $h(t)$ at the time and place of reception (i.e.,) and about the value $h(t)$ had at the pulsar at of emission of the signal. Thus, data from any vill have a gravitational wave signal in common other pulsars (though with an amplitude scaled cos θ) 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

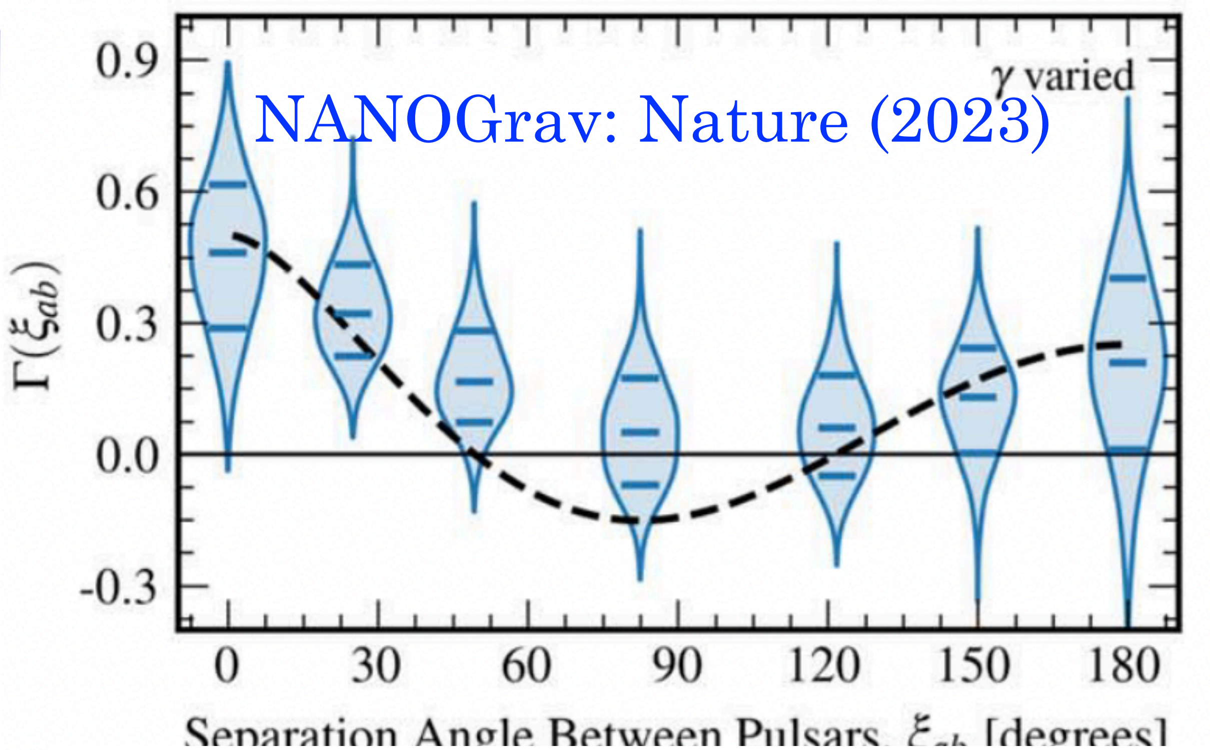
The fractional frequency shift observed in the data on pulsar number i may be written

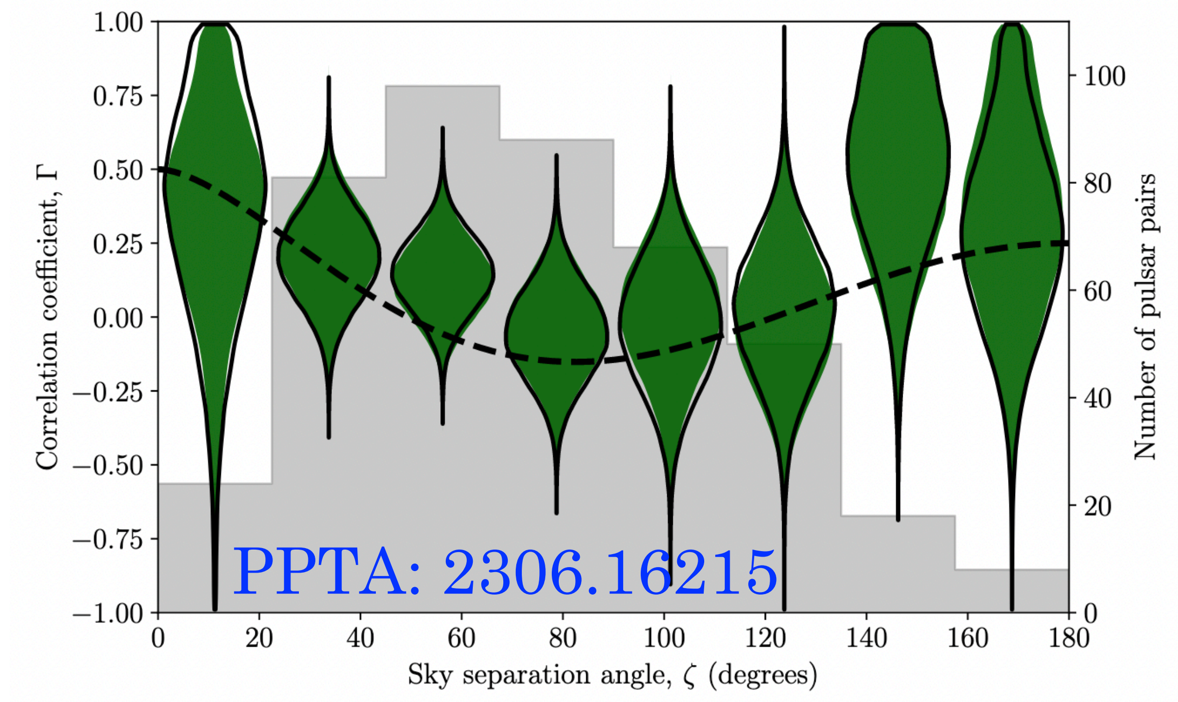


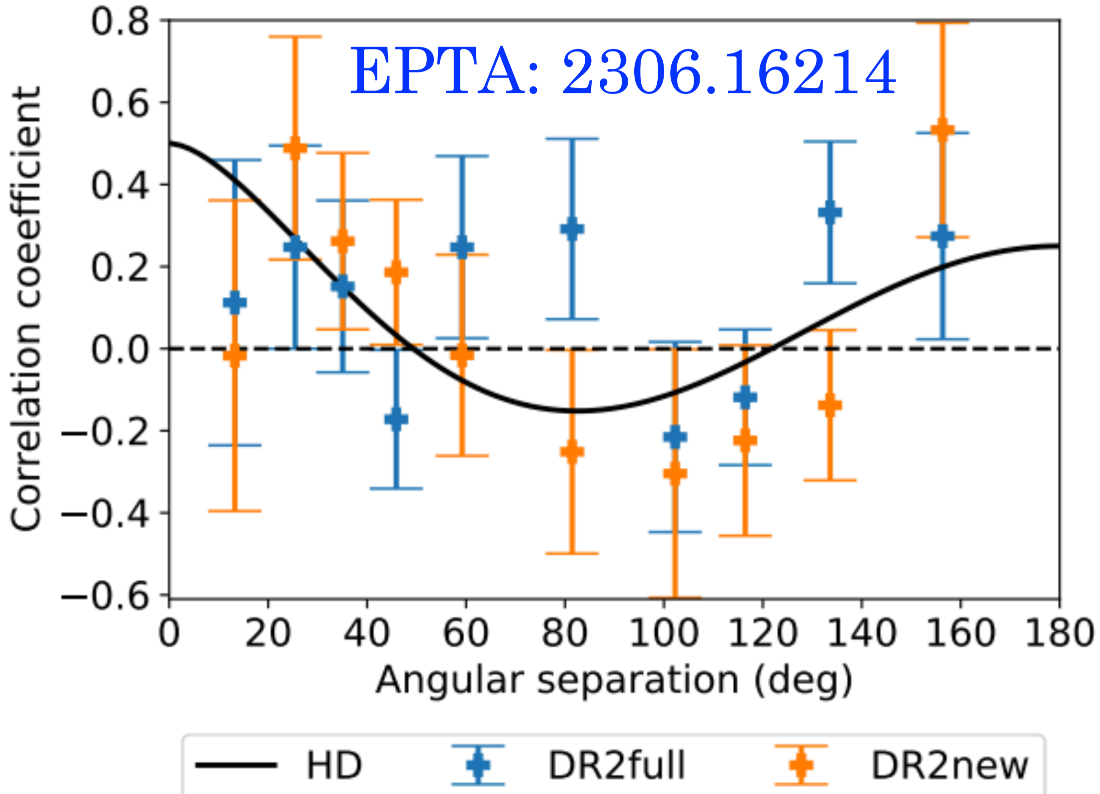
Hellings-Downs Curve

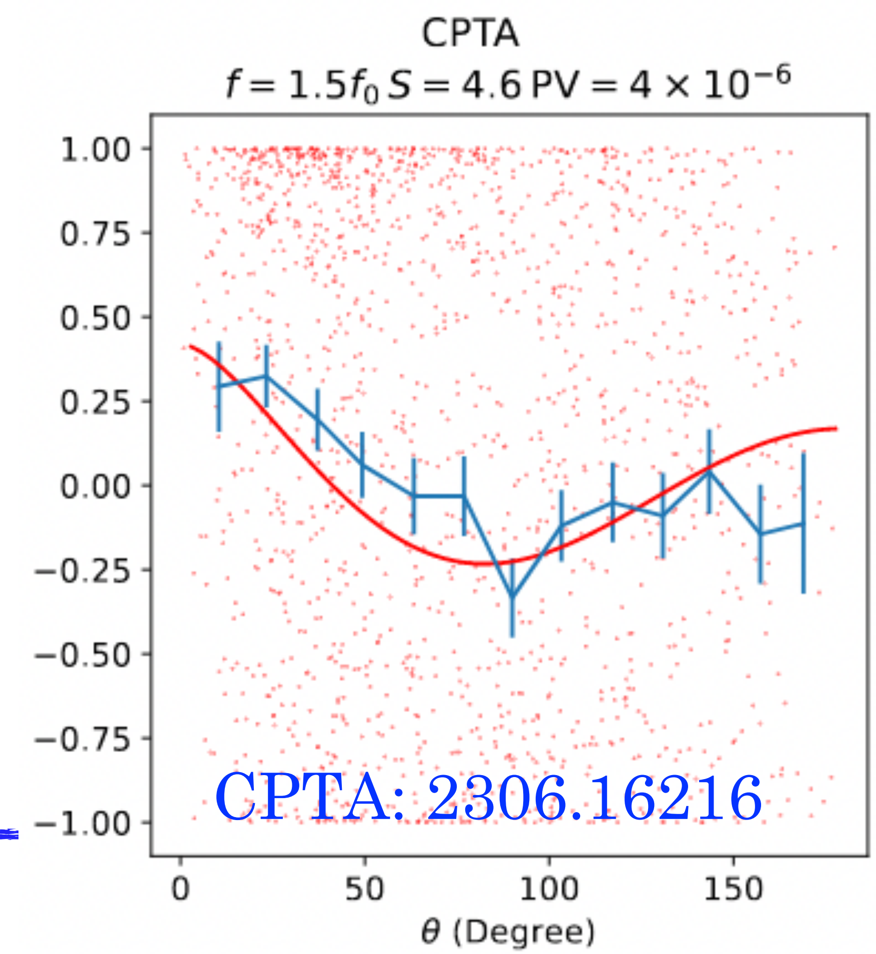
Encodes exactly the cross-correlation of pulsar timing data that would indicate a common GW signal.

A Milestone


NANOGrav: Nature (2023)
γ varied
Γ(ξ_ab)
Separation Angle Between Pulsars, ξ_ab [degrees]


PPTA: 2306.16215
Correlation coefficient, Γ
Number of pulsar pairs
Sky separation angle, ζ (degrees)


EPTA: 2306.16214
Correlation coeefficient
Angular separation (deg)
HD
DR2full
DR2new


CPTA
$f = 1.5 f_0$ $S = 4.6$ PV $= 4 \times 10^{-6}$
CPTA: 2306.16216
θ (Degree)

Pulsars as A Precision Astronomical Laboratory

ATNF Pulsar Catalogue

Catalogue Tutorial | Documentation | Expert | ATNF Pulsar Home | Pulsar Tutorial | Glitch table | Feedback | Download | History

Catalogue version: 1.67

#	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	10	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	81	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

$$\mathrm{RM} = \frac{\mathrm{PA}}{\lambda^2}$$

polarization angle (PA)

rotation measure (RM)

wavelength (λ)

- Timing
- Polarization (linearly-polarized; measured for calibrating pulsar observation)

Can we cross-correlate pulsar polarization data, as done for the timing data, to give full play to its capability in exploring astrophysics and fundamental physics?

Pulsar Polarization Arrays (PPAs)

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

[arXiv:2111.10615]

Pulsar Polarization Arrays

Tao Liu,[1,*] Xuzixiang Lou,[1,†] and Jing Ren[2,‡]
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(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 $\sim 10^{-14} - 10^{-17}$ GeV^{-1}, with a mass range $\sim 10^{-27}$–10^{-21} eV.

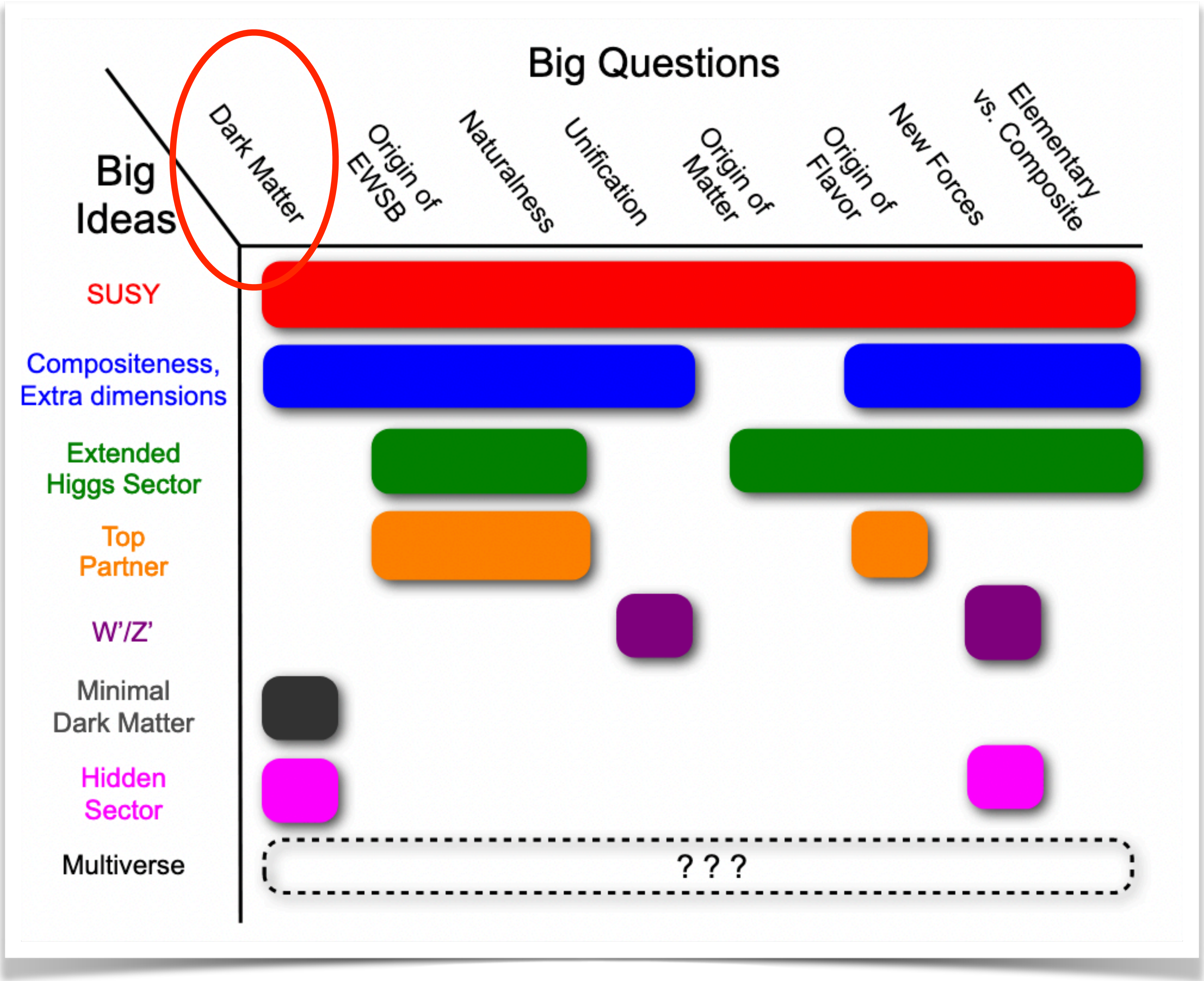
DOI: 10.1103/PhysRevLett.130.121401

PTAs: suited for revealing physics with a common correlated timing signal

PPAs: suited for revealing physics with a common correlated polarization signal

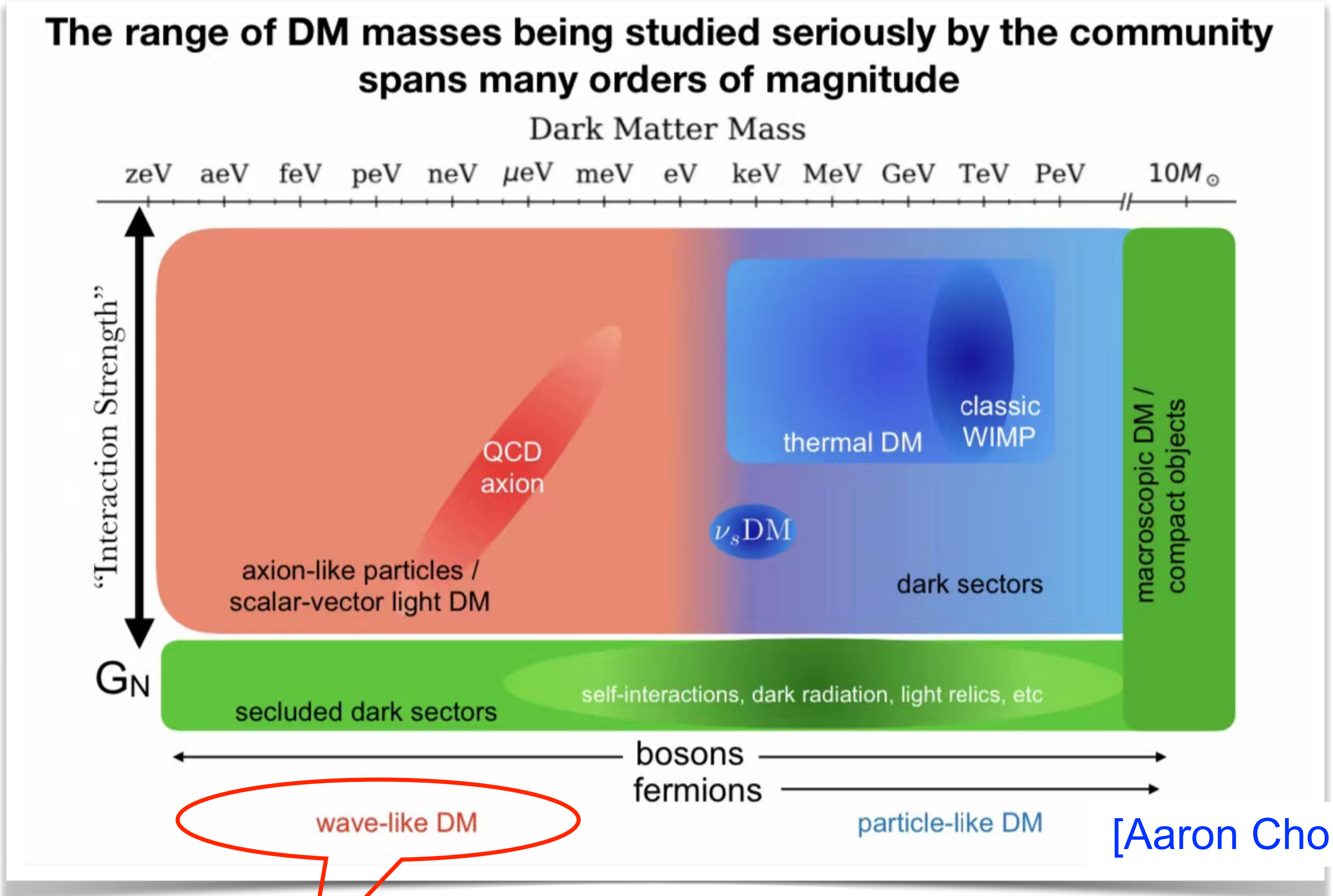
Big Questions for Particle Physicists

[Working group report (particle physics) for Snowmass 2013]



As one scientific case, we consider
the detection of axion-like wave Dark Matter

Wave Dark Matter (WDM)

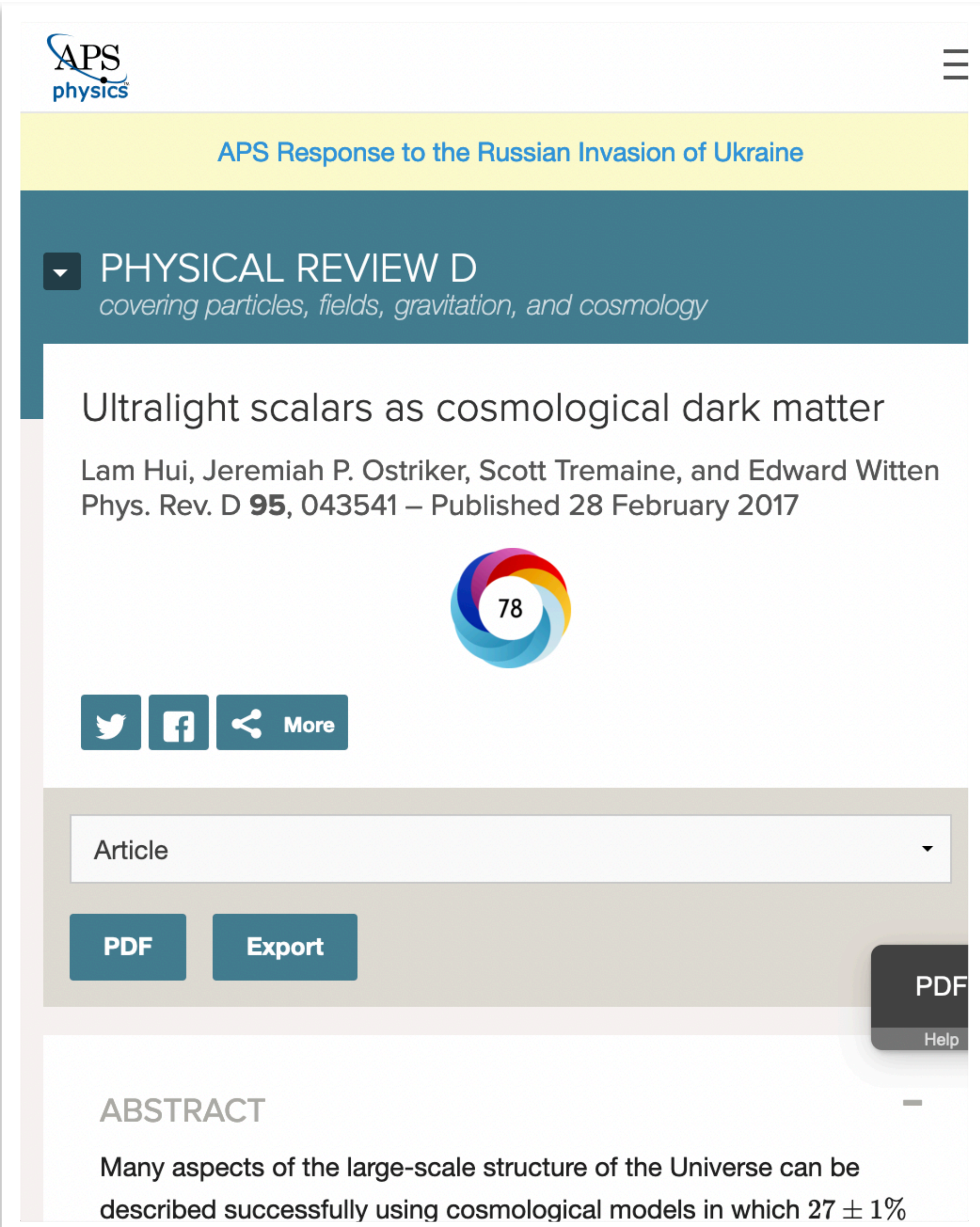


[Aaron Chou, Snowmass2021]

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

Wave Dark Matter: Bosonic and m_a << 30 eV => Large occupation number per de Broglie volume (N_{dB} >> 1) in a Milky-Way-like environment => Formation of a coherent state with strong wave nature

Axion-like WDM


APS physics

APS Response to the Russian Invasion of Ukraine

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

Ultralight scalars as cosmological dark matter

Lam Hui, Jeremiah P. Ostriker, Scott Tremaine, and Edward Witten
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 $27 \pm 1\%$

[Hui, Ostriker, Tremaine, Witten Phys. Rev. D 95 (2017)]

[Also see Geraldine Servant's talk]

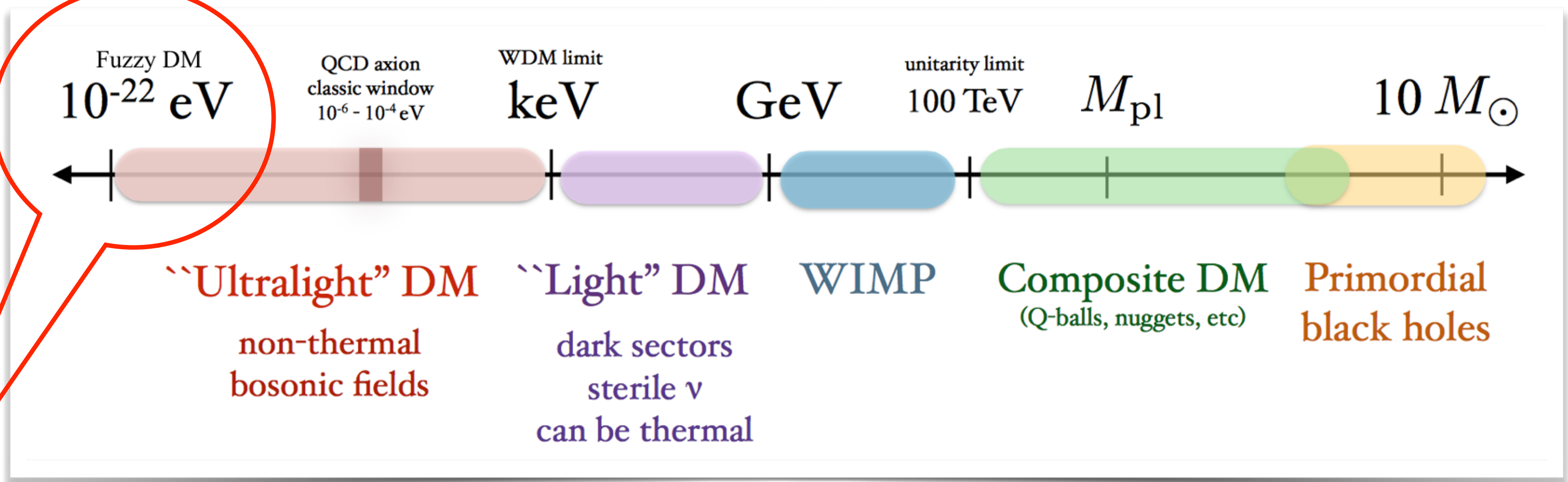
Axion-like particles are probably the most important WDM candidate. Their coherent state usually oscillates as

$$a(\mathbf{x}, t) = a_0(\mathbf{x}, t) \cos(m_a t + m_a \mathbf{v} \cdot \mathbf{x} + \phi)$$

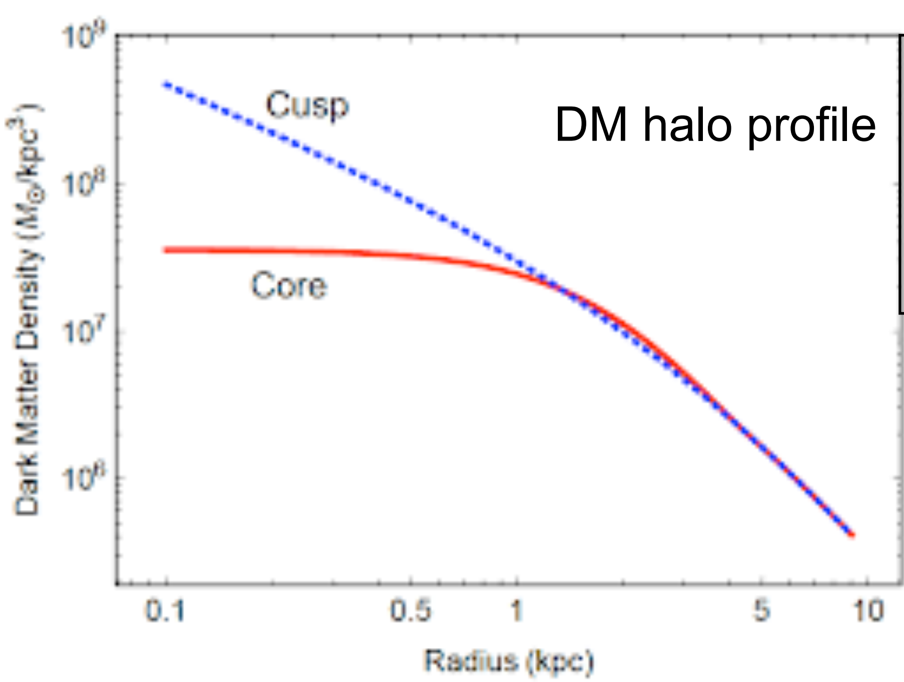
- Period is determined by the axion mass in temporal direction and its momentum in spatial direction;
- Amplitude is determined by energy density of DM halo

$$\rho_{\rm DM}(\mathbf{x}, t) = \frac{1}{2} m_a^2 a_0^2(\mathbf{x}, t) + \mathcal{O}(v^2)$$

Fuzzy Dark Matter

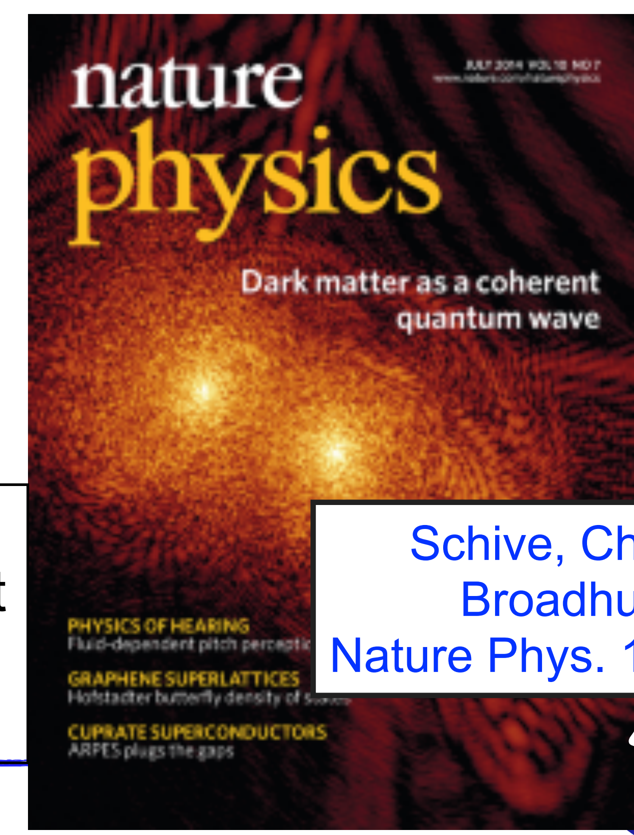


- Fuzzy DM [Hu, et. al., Phys.Rev.Lett. 85 (2000)]: m_a ~ 10^-21 - 10^-22 eV (oscillation period 2*pi/ma ~ 1 yr, with a dB wavelength ~ O(100) pc), where small-scale problems on astronomical structure could be addressed.



Core-cusp problem:
Inconsistency between prediction of standard WIMP and observation

Because of quantum uncertainty, a dense soliton-like core forms at galactic center, with a radius ~ de-Broglie wavelength.



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

symmetry
dimensions of particle physics
topics
follow +
A joint Fermilab/SLAC publication

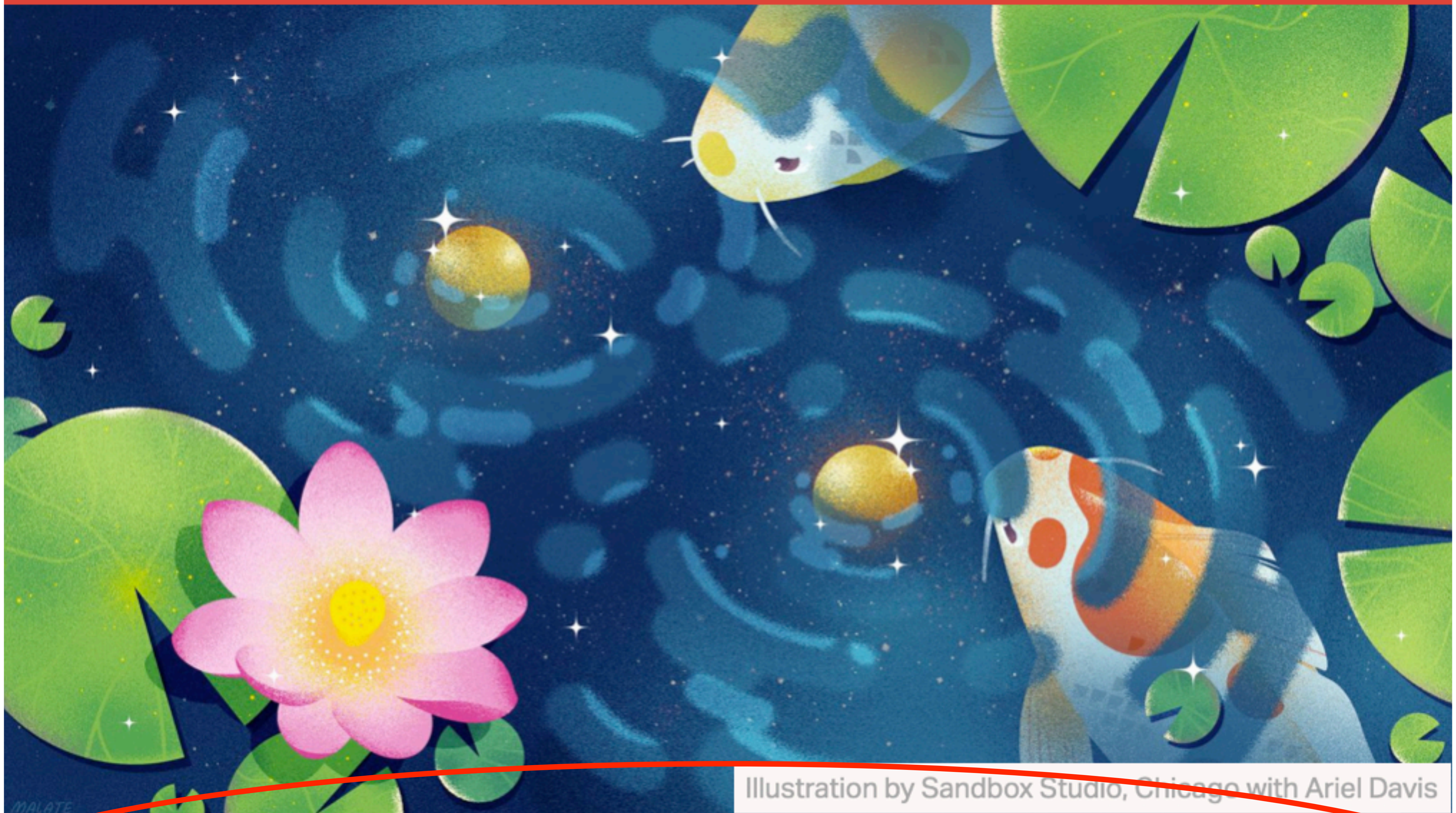


Illustration by Sandbox Studio, Chicago with Ariel Davis

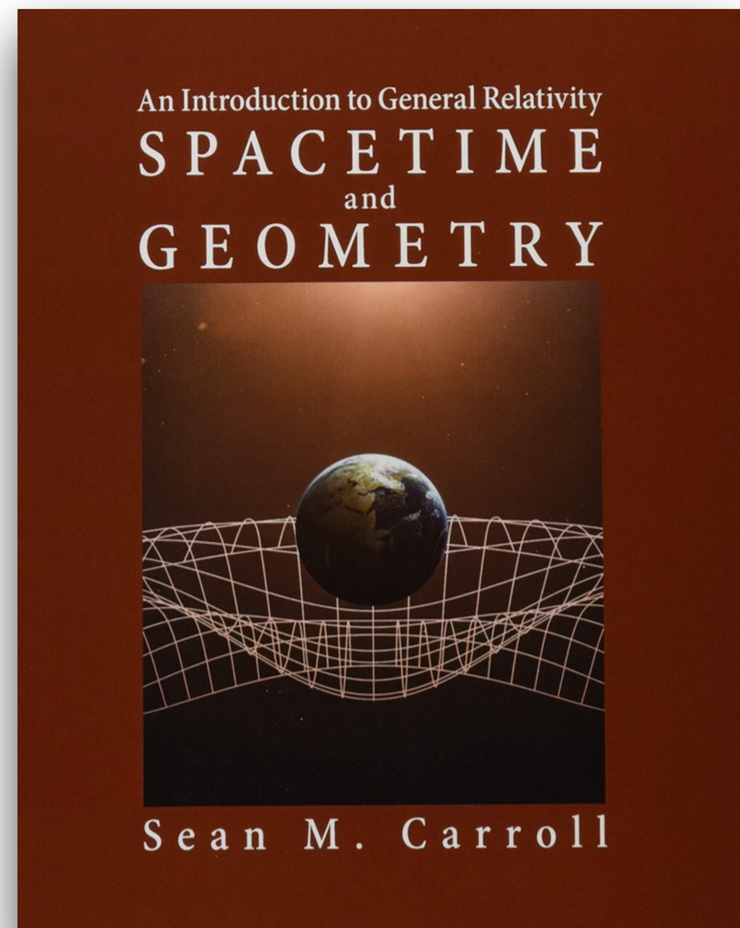
Is dark matter the most powerful wave in the universe?

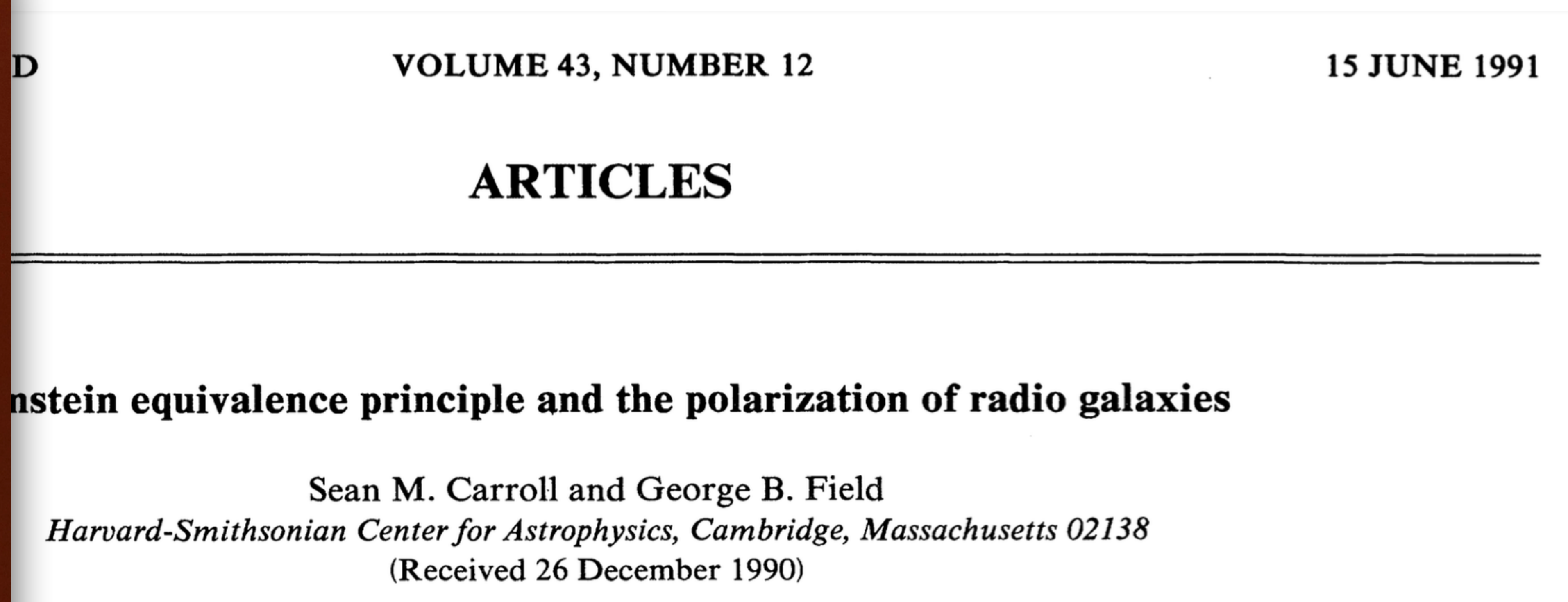
04/04/23 | By Kimberly Hickok

Dark matter could consist of particles so ultralight, they behave more like waves.

Cosmological Birefringence (CB)

Axion-like WDM can affect pulsar polarization via an effect known as ``cosmological birefringence''




D VOLUME 43, NUMBER 12 15 JUNE 1991

ARTICLES

nstein equivalence principle and the polarization of radio galaxies

Sean M. Carroll and George B. Field

Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

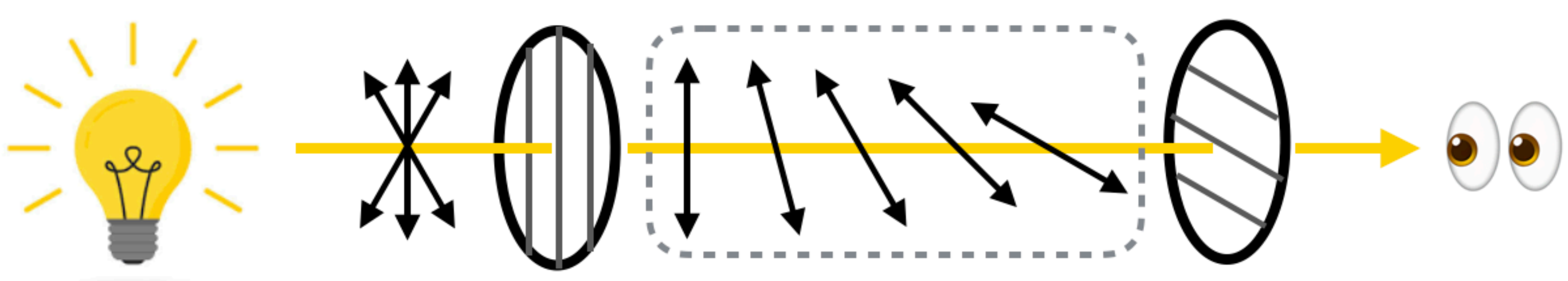
(Received 26 December 1990)

Cosmological Birefringence (CB)

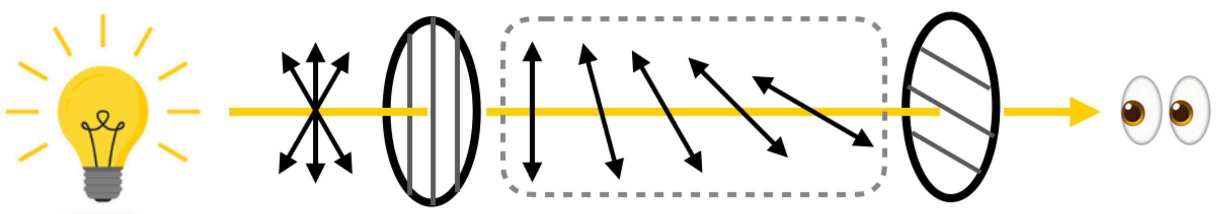
$$L \sim -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial^{\mu}a\partial_{\mu}a - \frac{1}{2}m_a^2a^2 + \frac{g}{2}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

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

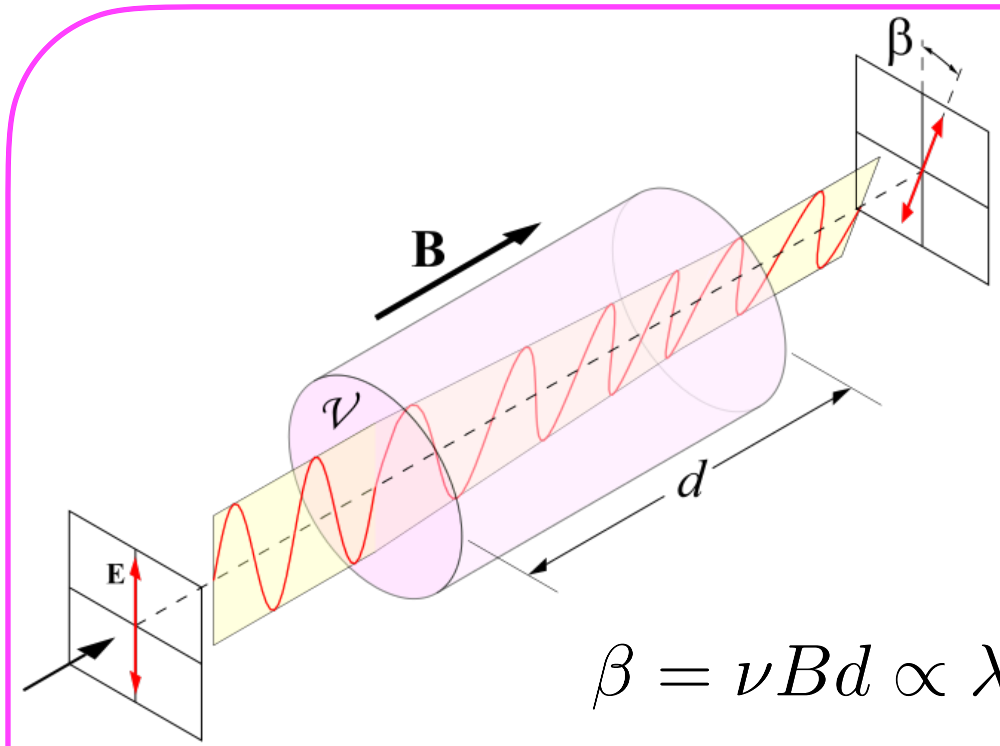
Parity-violating Chern-Simons term => Different dispersion relations for left- and right-circular polarized light => Position angle rotated for the linearly polarized light traveling across an axion field (including axion-like WDM halo)



Comparison with Faraday Rotation (FR)



$$\Delta\theta = -g\int_{t_i}^{t_f} \partial_t a(\mathbf{x},t)\,dt$$
$$= \frac{g}{m_a}\left[\sqrt{\rho_i}\cos(m_a t_i + m_a \mathbf{v}\cdot\mathbf{x_i} + \phi) - \sqrt{\rho_f}\cos(m_a t_f + m_a \mathbf{v}\cdot\mathbf{x_f} + \phi)\right]$$



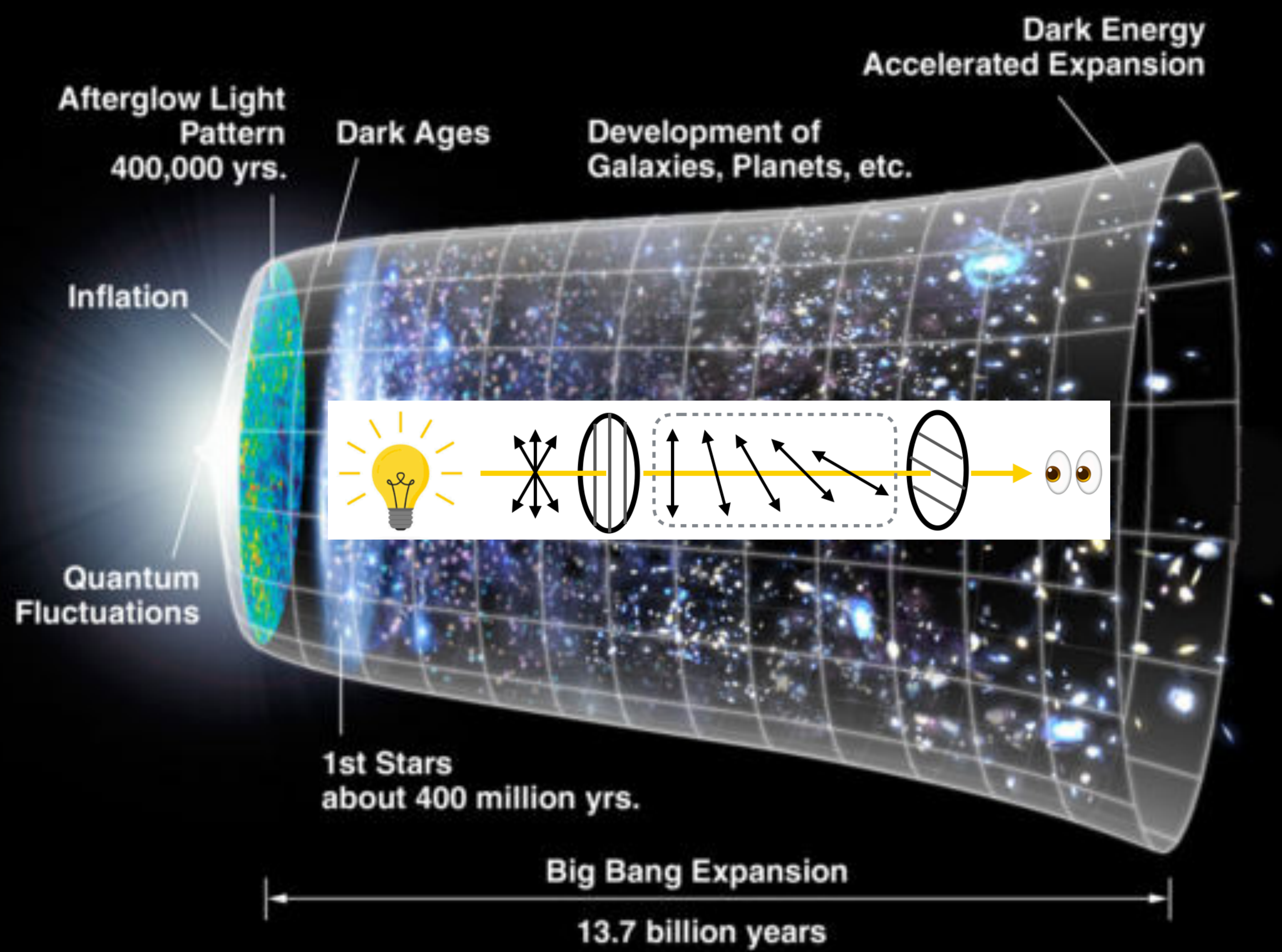
$$\beta = \nu B d \propto \lambda^2$$

- B: magnetic flux density
- d: length of light path
- ν: Verdet constant

- CB: determined by the difference of axion field profile between two endpoints of the light path due to the topological nature of Chern-Simons coupling. VS FR: relies on path length directly.
- CB: no frequency dependence. VS FR: increases with wavelength square.
- CB: features oscillation with a period of 2*pi/ma. VS FR: no characteristic time dependence is expected.

[Lue, Wang, KamionKowski, PRL(1999)]

CMB-Based Detection



PA rotation - Determined by the difference of axion field between at recombination and for the Universe today

CMB-Based Detection

A&A 596, A110 (2016)
DOI: 10.1051/0004-6361/201629018

Astronomy & Astrophysics

Planck intermediate results

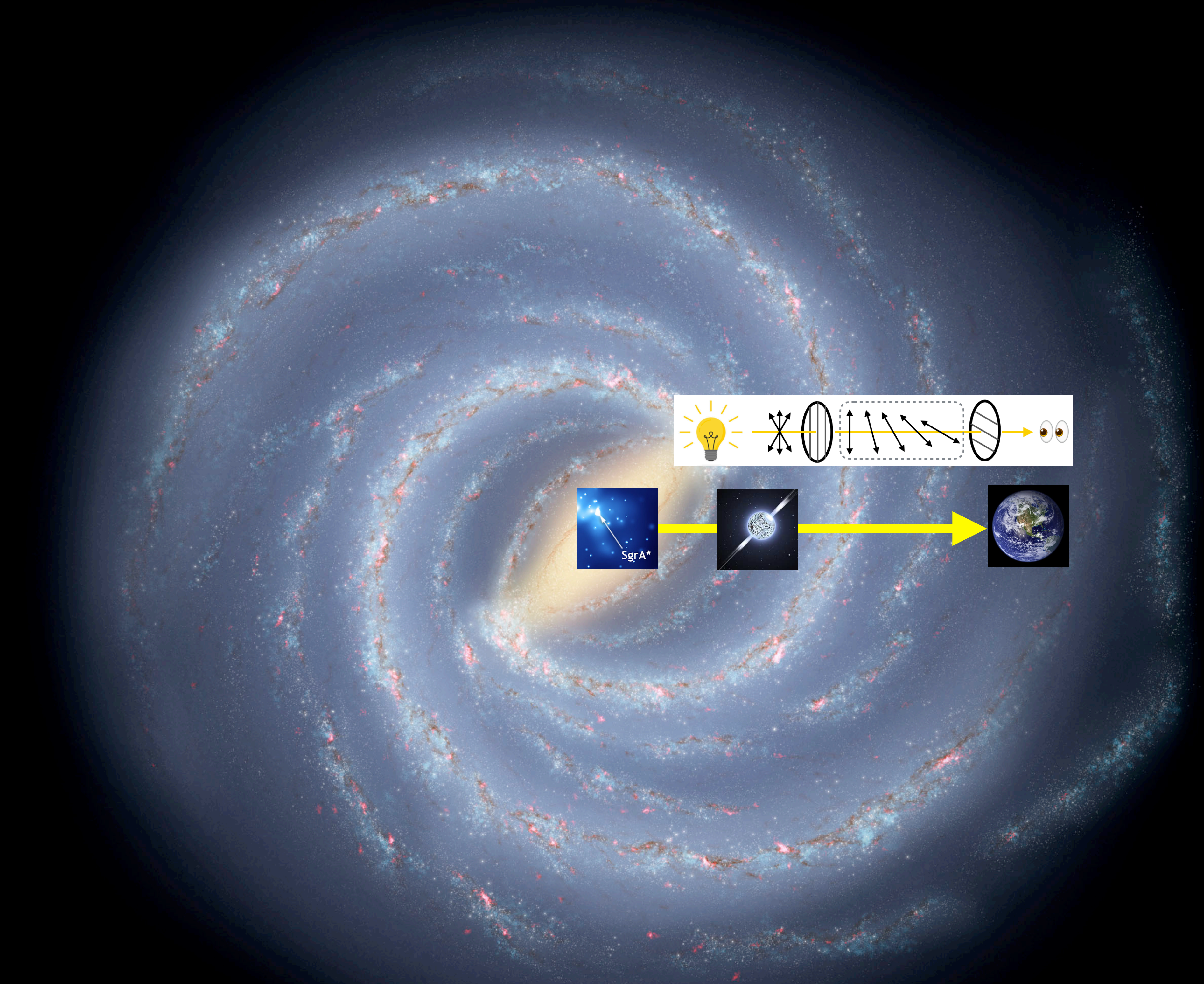
XLIX. Parity-violation constraints from polarization data

Planck Collaboration: N. Aghanim[47], M. Ashdown[57,4], J. Aumont[47], C. Baccigalupi[67], M. Ballardini[23,38,41], A. J. Banday[77,7], R. B. Barreiro[52], N. Bartolo[22,53], S. Basak[67], K. Benabed[48,76], J.-P. Bernard[77,7], M. Bersanelli[26,39], P. Bielewicz[65,7,67], L. Bonavera[12], J. R. Bond[6], J. Borrill[9,73], F. R. Bouchet[48,72], C. Burigana[38,24,41], E. Calabrese[74], J.-F. Cardoso[60,1,48], J. Carron[17], H. C. Chiang[19,5], L. P. L. Colombo[15,54], B. Comis[61], D. Contreras[14], F. Couchot[58], A. Coulais[59], B. P. Crill[54,8], A. Curto[52,4,57], F. Cuttaia[38], P. de Bernardis[25], A. de Rosa[38], G. de Zotti[35,67], J. Delabrouille[1], F.-X. Désert[45], E. Di Valentino[48,72], C. Dickinson[55], J. M. Diego[52], O. Doré[54,8], A. Ducout[48,46], X. Dupac[30], S. Dusini[53], F. Elsner[16,48,76], T. A. Enßlin[63], H. K. Eriksen[50], Y. Fantaye[29], F. Finelli[38,41], F. Forastieri[24,42], M. Frailis[37], E. Franceschi[38], A. Frolov[71], S. Galeotta[37], S. Galli[56], K. Ganga[1], R. T. Génova-Santos[51,11], M. Gerbino[75,66,25], Y. Giraud-Héraud[1], J. González-Nuevo[12,52], K. M. Górski[54,79], A. Gruppuso[38,41,⋆], J. E. Gudmundsson[75,66,19], F. K. Hansen[50], S. Henrot-Versillé[58], D. Herranz[52], E. Hivon[48,76], Z. Huang[6], A. H. Jaffe[46], W. C. Jones[19], E. Keihänen[18], R. Keskitalo[9], K. Kiiveri[18,34], N. Krachmalnicoff[26], M. Kunz[10,47,2], H. Kurki-Suonio[18,34], J.-M. Lamarre[59], M. Langer[47], A. Lasenby[4,57], M. Lattanzi[24,42], C. R. Lawrence[54], M. Le Jeune[1], J. P. Leahy[55], F. Levrier[59], M. Liguori[22,53], P. B. Lilje[50], V. Lindholm[18,34], M. López-Caniego[30], Y.-Z. Ma[55,68], J. F. Macías-Pérez[61], G. Maggio[37], D. Maino[26,39], N. Mandolesi[38,24], M. Maris[37], P. G. Martin[6], E. Martínez-González[52], S. Matarrese[22,53,32], N. Mauri[41], J. D. McEwen[64], P. R. Meinhold[20], A. Melchiorri[25,43], A. Mennella[26,39], M. Migliaccio[49,57], M.-A. Miville-Deschênes[47,6], D. Molinari[24,38,42], A. Moneti[48], G. Morgante[38], A. Moss[70], P. Natoli[24,3,42], L. Pagano[25,43], D. Paoletti[38,41], G. Patanchon[1], L. Patrizii[41], L. Perotto[61], V. Pettorino[33], F. Piacentini[25], L. Polastri[24,42], G. Polenta[3,36], J. P. Rachen[13,63], B. Racine[1], M. Reinecke[63], M. Remazeilles[55,47,1], A. Renzi[29,44], G. Rocha[54,8], C. Rosset[1], M. Rossetti[26,39], G. Roudier[1,59,54], J. A. Rubiño-Martín[51,11], B. Ruiz-Granados[78], M. Sandri[38], M. Savelainen[18,34], D. Scott[14], C. Sirignano[22,53], G. Sirri[41], L. D. Spencer[69], A.-S. Suur-Uski[18,34], J. A. Tauber[31], D. Tavagnacco[37,27], M. Tenti[40], L. Toffolatti[12,52,38], M. Tomasi[26,39], M. Tristram[58], T. Trombetti[38,24], J. Valiviita[18,34], F. Van Tent[62], P. Vielva[52], F. Villa[38], N. Vittorio[28], B. D. Wandelt[48,76,21], I. K. Wehus[54,50], A. Zacchei[37], and A. Zonca[20]

Becomes a standard task for the CMB missions today

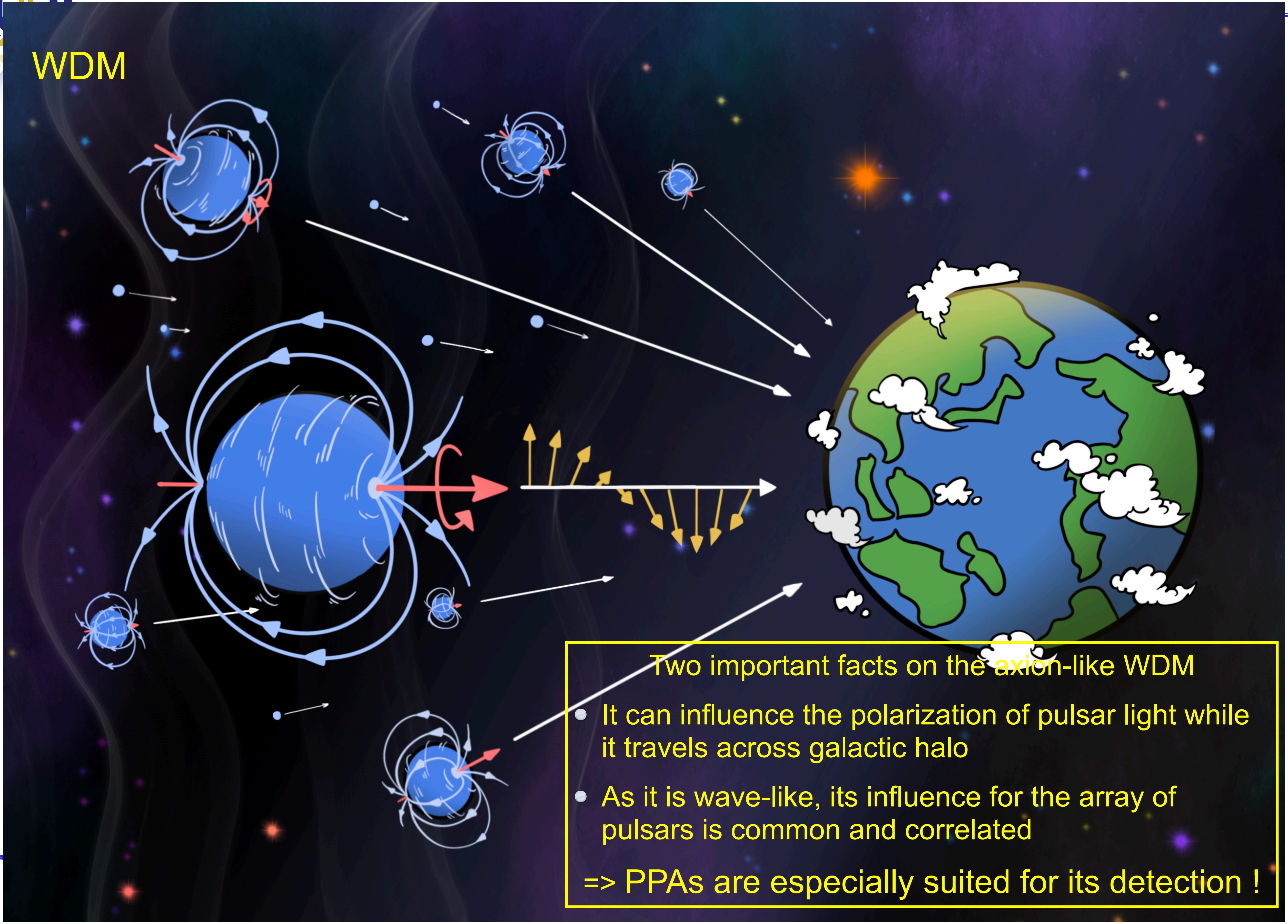
[TL, G. Smoot, Y. Zhao, arXiv:1901.10981]

Pulsar Light-Based Detection



PA rotation - Determined by the difference of axion field between near the PSR at the time of photon emission and around the Earth at the moment of photon receiving.

Detecting Axion-like WDM with PPAs



Two important facts on the axion-like WDM

- It can influence the polarization of pulsar light while it travels across galactic halo
- As it is wave-like, its influence for the array of pulsars is common and correlated

=> PPAs are especially suited for its detection !

Cross-correlation: GWs VS WDM

Earth term　Pulsar term

Timing residue caused by stochastic GWs

$$\Delta T(t) = \int_{-\infty}^{\infty} df \frac{1}{2} u^a u^b h_{ab}(f,\hat{n}) \frac{1}{i2\pi f} \frac{1}{1+\hat{n}\cdot\hat{u}} \left[e^{i2\pi f(t_2+\hat{n}\cdot\vec{r}_2/c)} - e^{i2\pi f(t_1+\hat{n}\cdot\vec{r}_1/c)} \right]$$

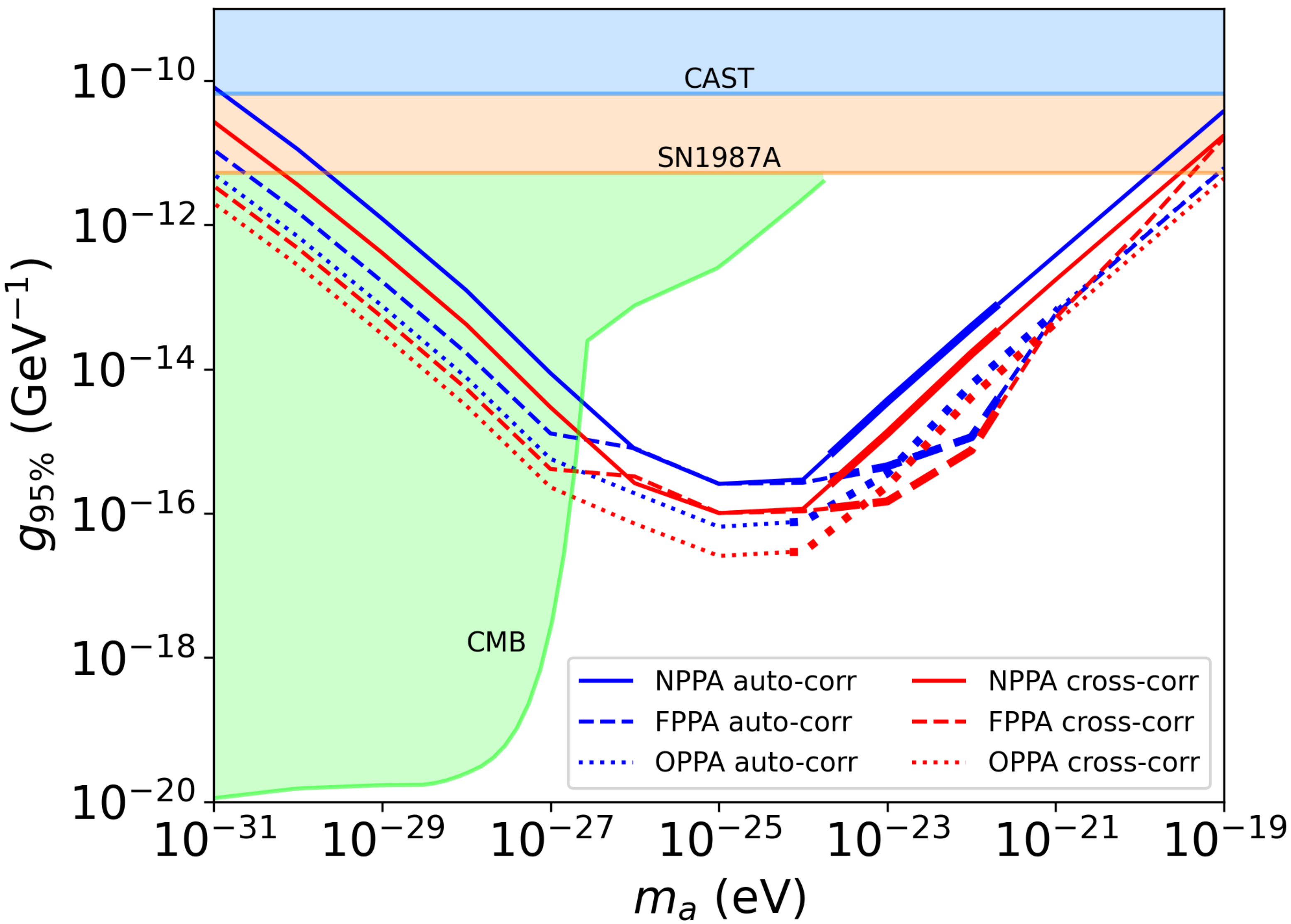
PA rotation caused by axion-like WDM

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

	SGWB (PTAs)	Axion-like WDM (PPAs)
Earth-Earth Term	quadrupolar correlation (Hellings-Downs curve)	monopolar correlation
Pulsar-Pulsar Term	spatial correlation degrades quickly (L»l_{dB}~1/w)	spatial correlation degrades much slower (L»l_{dB}»1/ma), enhanced at galactic center

Sensitivity Projection for Benchmark PPAs

[TL, X. Lou, J. Ren, PRL (2023)]

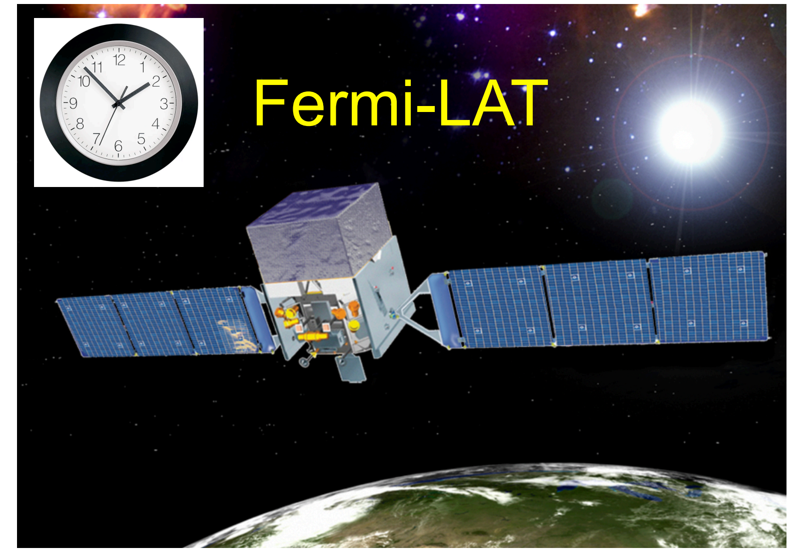


- NPPA: 100 MSPs around the Earth; 10 years' observation with a cadence 10/yr; noise variance - 1deg^2
- FPPA: 100 MSPs near the galactic center; 10 years' observation with a cadence 10/yr; noise variance - 1deg^2
- OPPA: 100 MSPs following the ATNF pulsar distribution; 30 years' observation with a cadence 1/week; noise variance - 1deg^2

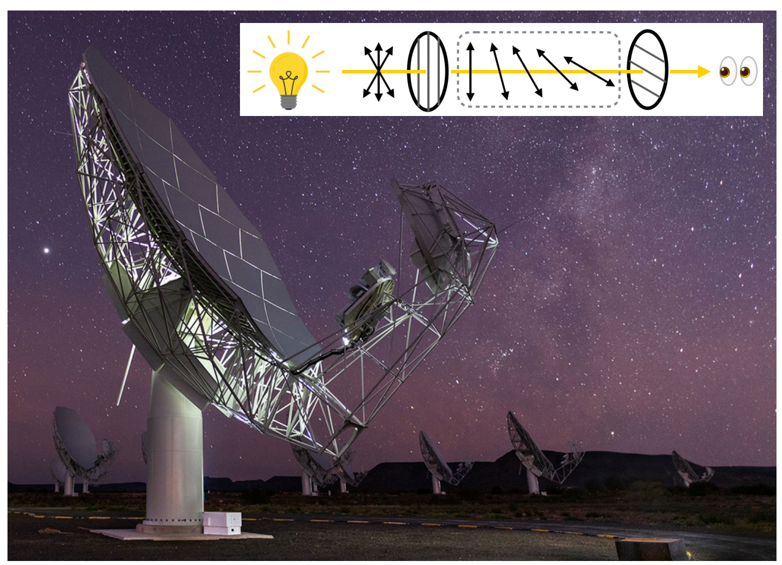
- The projected PPA limits form a complementarity with the existing CMB bounds
- With noise variance ~ (0.1 deg)^2, the limits can be improved by one more order of magnitude
- The analyses with real data (from some PTA programs) are being carried out or planned

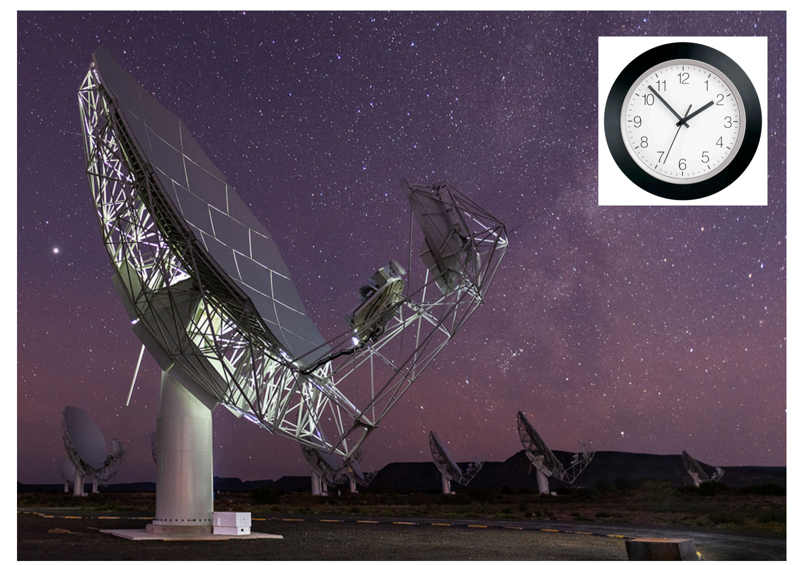
A Wider Landscape

High-F band detection



Radio band detection





PPA detection (non-gravitational)

PTA detection (gravitational)

[Also see Nataliya Porayko's talk]

PTA Detection

arXiv > astro-ph > arXiv:1309.5888

Search...

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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

An ultralight free scalar field with mass around 10^{-23} - 10^{-22} eV is a viable dark mater candidate, which can help to resolve some of the issues of the cold dark matter on sub-galactic scales. We consider the gravitational field of the galactic halo composed out of such dark matter. The scalar field has oscillating in time pressure, which induces oscillations of gravitational potential with amplitude of the order of 10^{-15} and frequency in the nanohertz range. This frequency is in the range of pulsar timing array observations. We estimate the magnitude of the pulse arrival time residuals induced by the oscillating gravitational potential. We find that for a range of dark matter masses, the scalar field dark matter signal is comparable to the stochastic gravitational wave signal and can be detected by the planned SKA pulsar timing array experiment.

PTA Detection

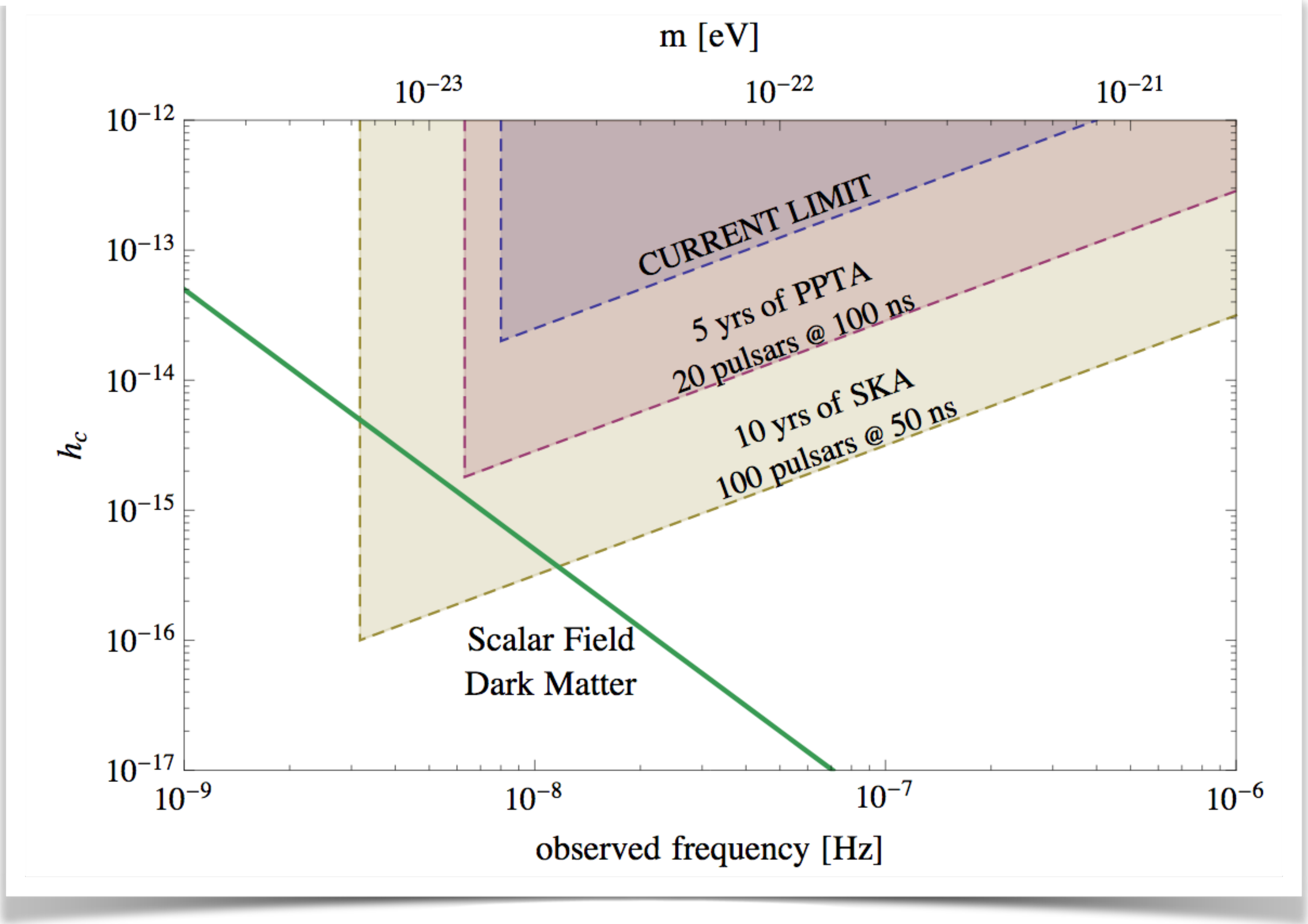
$$ds^2 = \big(1+2\Phi(\mathbf{x},t)\big)dt^2 - \big(1-2\Psi(\mathbf{x},t)\big)\delta_{ij}dx^i dx^j$$

[A. Khmelnitsky, V. Rubakov; arXiv:1309.5888]

$$\rho_{\rm DM}(\mathbf{x},t) = \frac{1}{2}m_a^2 a_0^2(\mathbf{x},t) + \mathcal{O}(v^2)$$

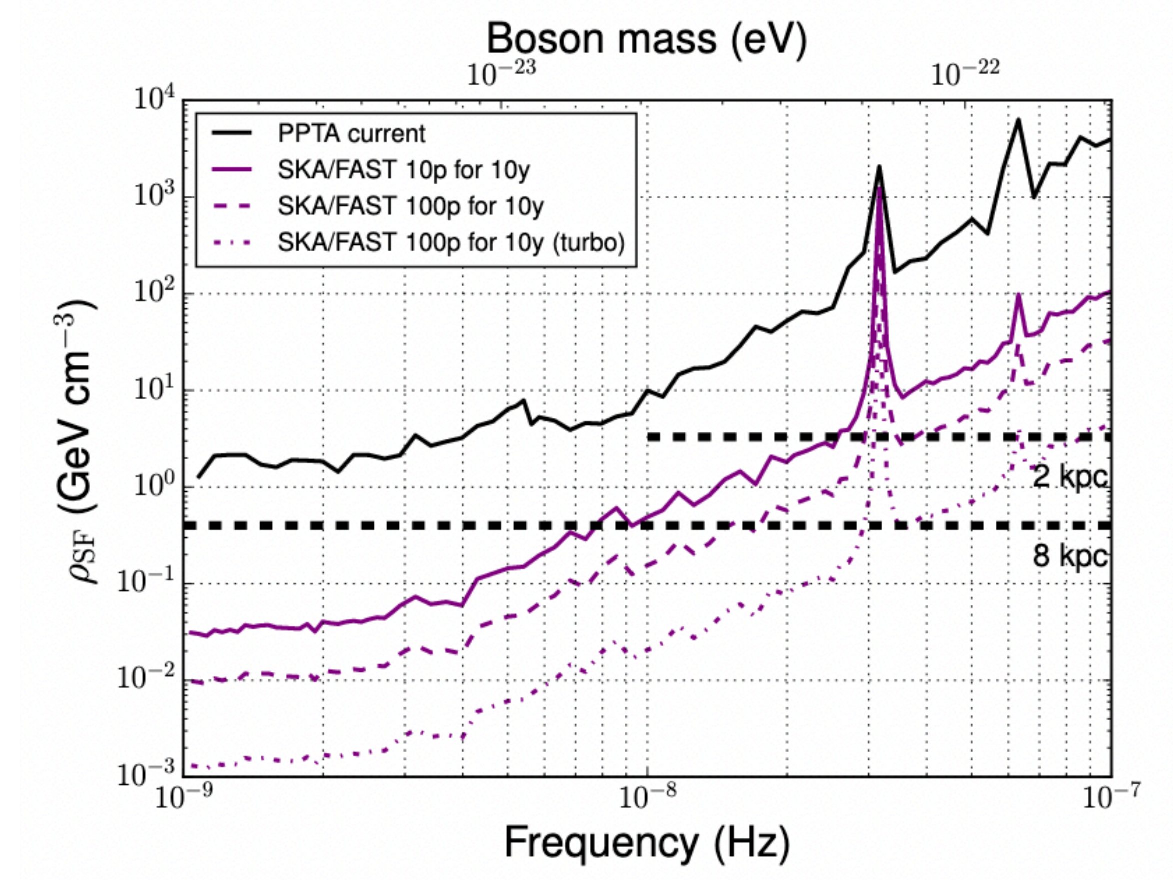
$$\Psi(\mathbf{x},t) \simeq \Psi_0(\mathbf{x}) + \Psi_c(\mathbf{x})\cos\left(\omega t + 2\alpha(\mathbf{x})\right)$$

=> Oscillating timing residual



$$\Delta t(t) = \frac{2\Psi_c}{\omega}\sin\left(\frac{\omega D}{2} + \alpha(\mathbf{x}) - \alpha(\mathbf{x_p})\right)\cos\left(\omega t + \alpha(\mathbf{x}) + \alpha(\mathbf{x_p}) - \frac{\omega D}{2}\right)$$

First Parkes PTA Measurement



PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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Editors' Suggestion

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

Nataliya K. Porayko *et al.* (PPTA Collaboration)

Phys. Rev. D **98**, 102002 – Published 5 November 2018

Gamma-Ray PTA

While being limited by statistics, such a high-frequency PTA can benefit from a suppression of intrinsic red noise of dispersion measure variance

REPORT | GRAVITATIONAL WAVES

A gamma-ray pulsar timing array constrains the nanohertz gravitational wave background

THE FERMI-LAT COLLABORATION Authors Info & Affiliations

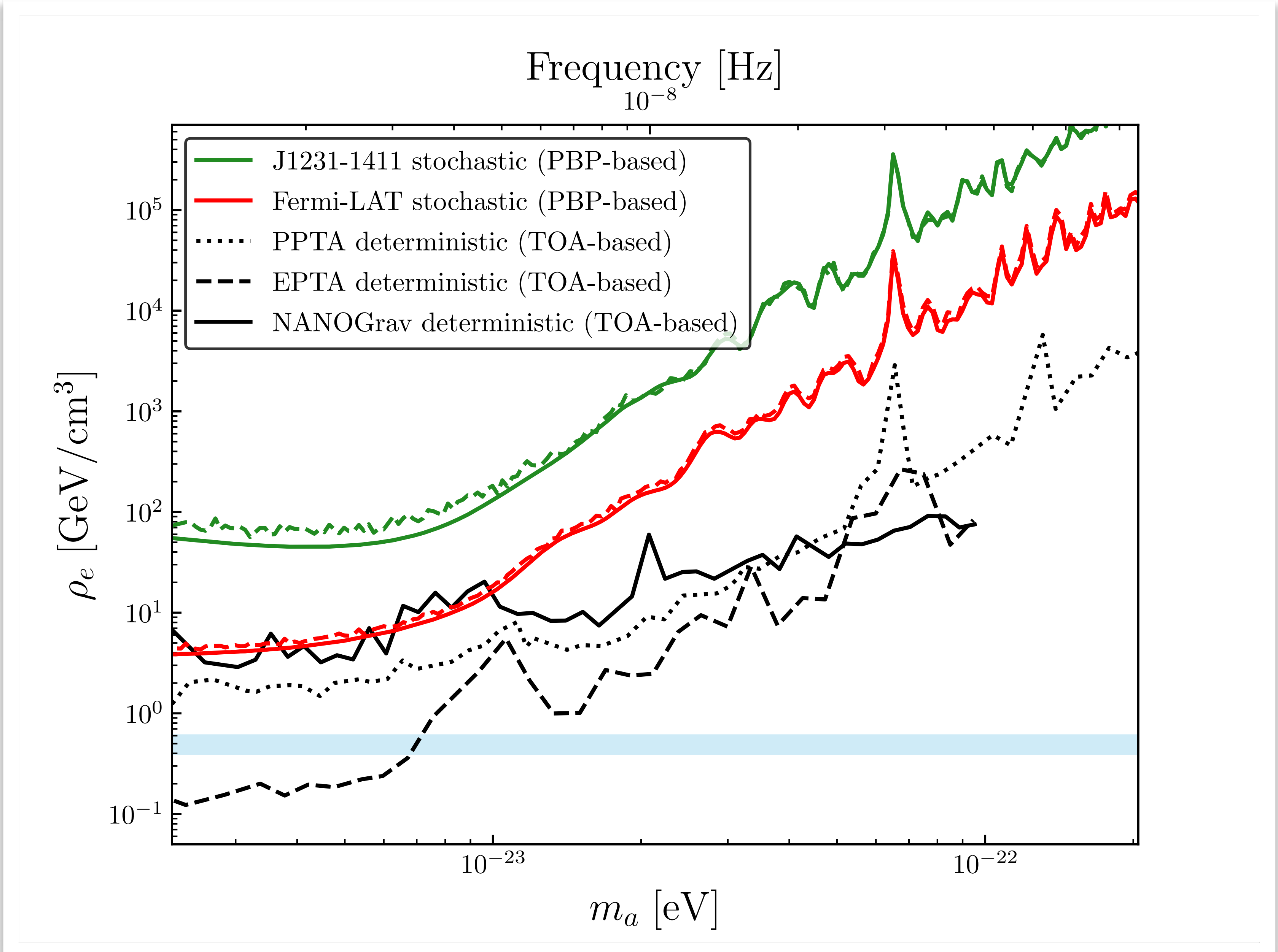
SCIENCE • 7 Apr 2022 • Vol 376, Issue 6592 • pp. 521-523 • DOI: 10.1126/science.abm3231

Detecting Stochastic Wave Dark Matter with Fermi-LAT γ-ray Pulsar Timing Array

Hoang Nhan Luu, Tao Liu, Jing Ren, Tom Broadhurst, Ruizhi Yang, Jie-Shuang Wang, Zhen Xie

Wave dark matter (DM) represents a class of the most representative DM candidates. Due to its periodic perturbation to spacetime, the wave DM can be detected with a galactic interferometer – pulsar timing array (PTA). We perform in this Letter a first analysis of applying the γ-ray PTA to detect the wave DM, with the data of Fermi Large Area Telescope (Fermi-LAT). Despite the limitation in statistics, the γ-PTA demonstrates a promising sensitivity potential for a mass $\sim 10^{-23} - 10^{-22}$ eV. We show that the upper limits not far from those of the dedicated radio-PTA projects can be achieved. Particularly, we have fulfilled an analysis to cross-correlate the pulsar data, which has been essentially missing so far in real data analysis but is known to be crucial for identifying the nature of potential signals, with the Fermi-LAT data of two pulsars.

Gamma-Ray PTA



Based on the current statistics, a sensitivity gap can be clearly seen

Correlating the PPA and PTA Detections

The PPA and PTA detections can be further correlated to strengthen their capability in identifying the nature of signals.

- PTA detection is essentially gravitational (measuring energy density of DM halo), while the PPA detection is non-gravitational (measuring axion Chern-Simons coupling)
- Non-gravitational detection is highly important for exploring the DM properties. Our ignorance on the DM properties to a great extent is due to the limitation of our main knowledge source to gravitational detections
- A combination of PPA and PTA can certainly strengthen our understanding on the nature of DM

Take-home Messages

- To fully extend the physical reach of pulsars as a precision astronomical tool, we have developed the concept of **pulsar polarization arrays**
- As one scientific case, we demonstrated that the PPAs can be applied to detect the axion-like WDM as a common correlated signal. This approach forms a complementarity with the CMB measurement
- In view of its non-gravitational nature, a combination of the PPA with the PTA detections will further benefit our understanding on the nature of DM

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