Evidence of Gravitational Wave Background from Pulsar Timing Array

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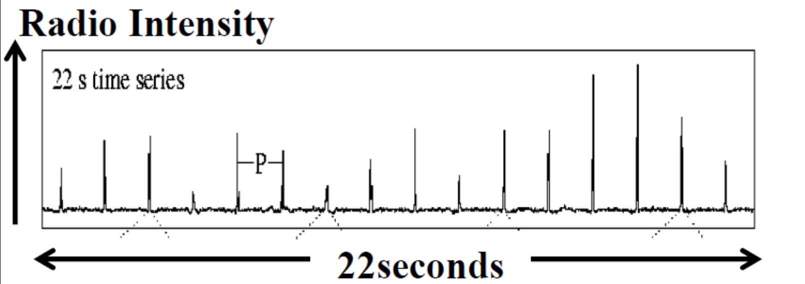
Contents

1. Introduction

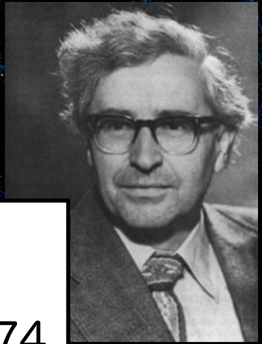
pulsar

- fast-rotating neutron star
- periodic pulse : 1msec - 10sec
- radio ~ optical ~ gamma-rays
- ISM study, gravity test, GW detection
- 3,000 pulsars so far

Pulses from a pulsar(PSR B0301+19)
(in Lorimer and Kramer,“Handbook of Pulsar Astronomy”,2005)

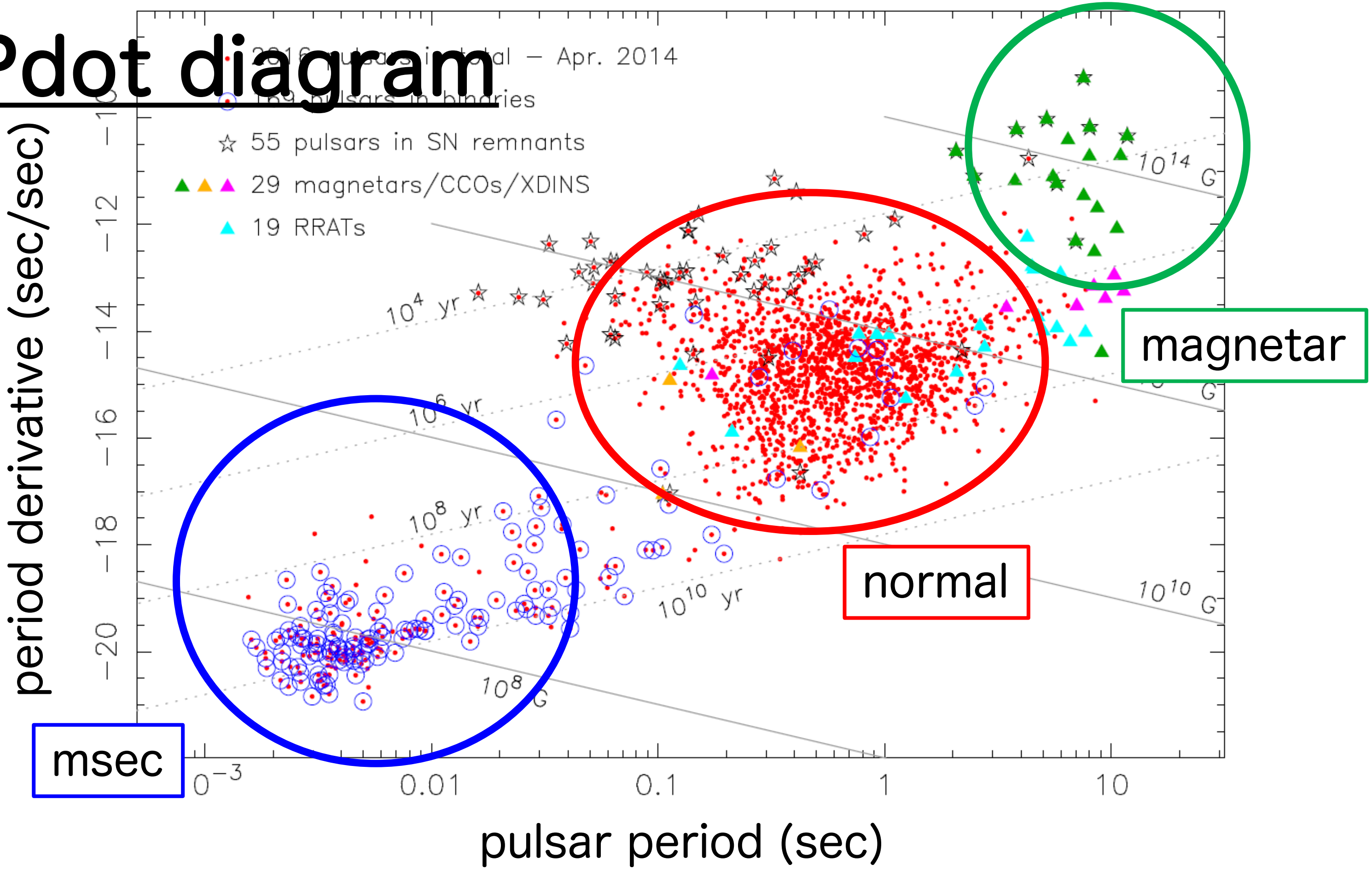


Jocelyn Bell Burnell
(1943-)



Antony Hewish
(1924-2021)
Nobel Prize in 1974

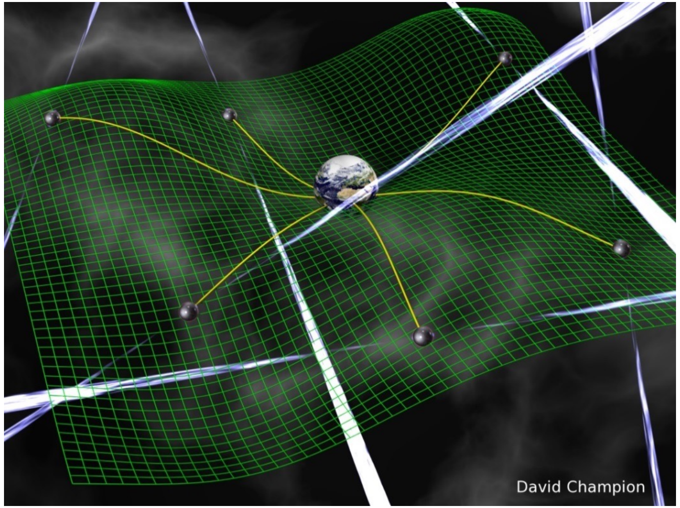
P-Pdot diagram



pulsar timing array

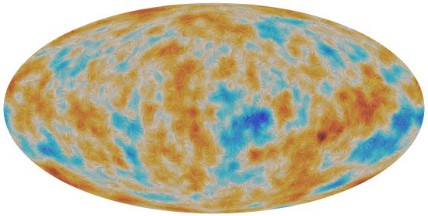
PTA in a nutshell

- direct detection of GWs
- very stable msec pulsars
- precise timing for O(10) years
- GWs affect pulse arrival time O(100) nsec
- GW freqency
  → observation period and cadence
  → $(1\ \text{week})^{-1} \sim (10\ \text{years})^{-1}$
  → $1\,\mu\text{Hz} \sim 1\,\text{nHz}$

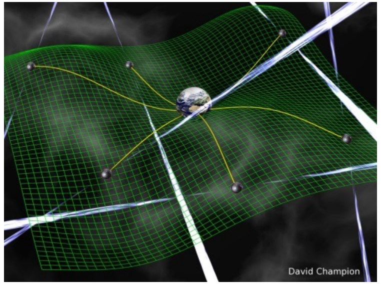


multi-wavelength GW astronomy

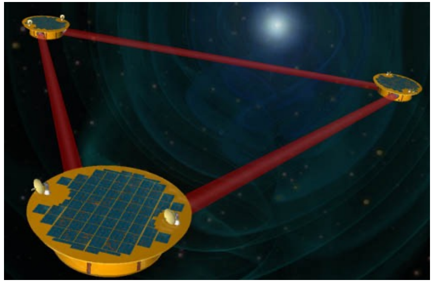
CMB



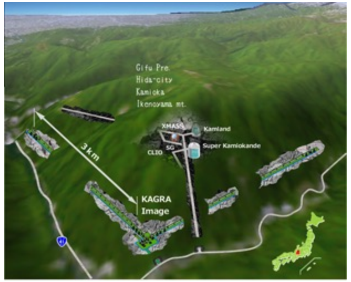
PTA

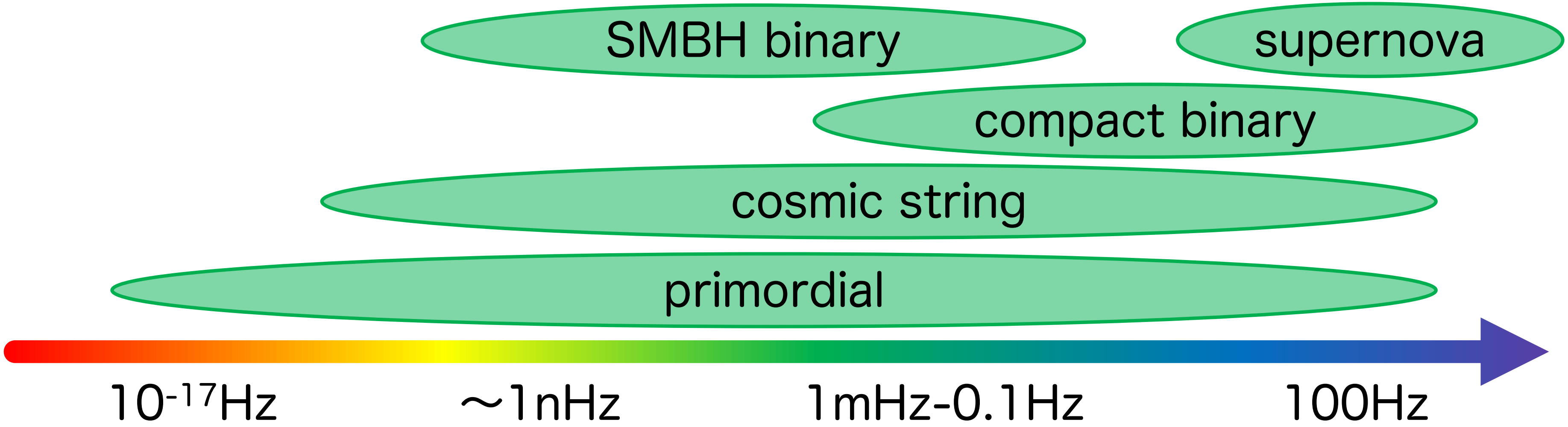


space



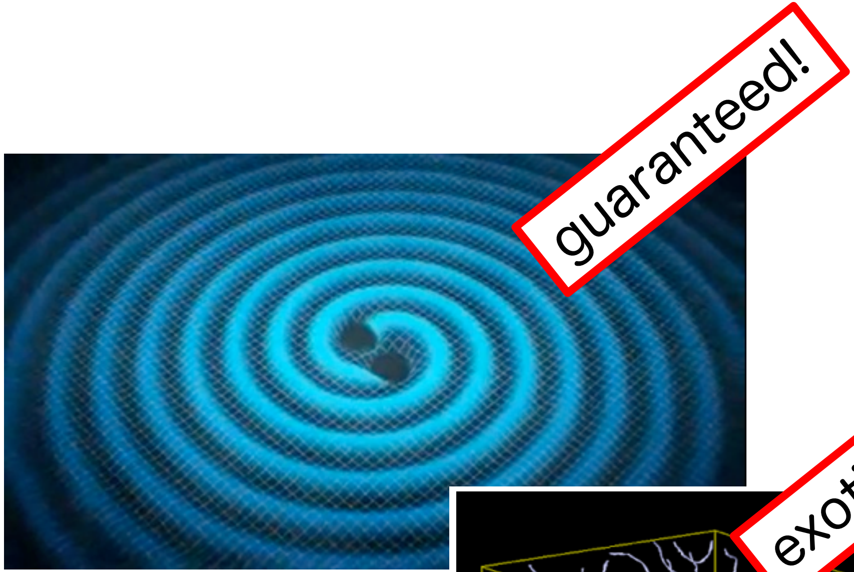
ground

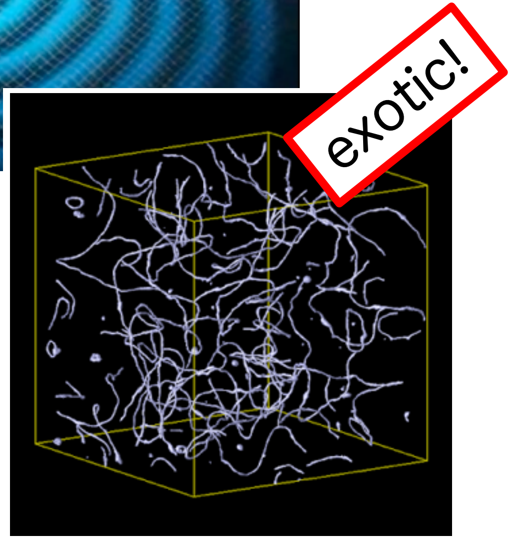




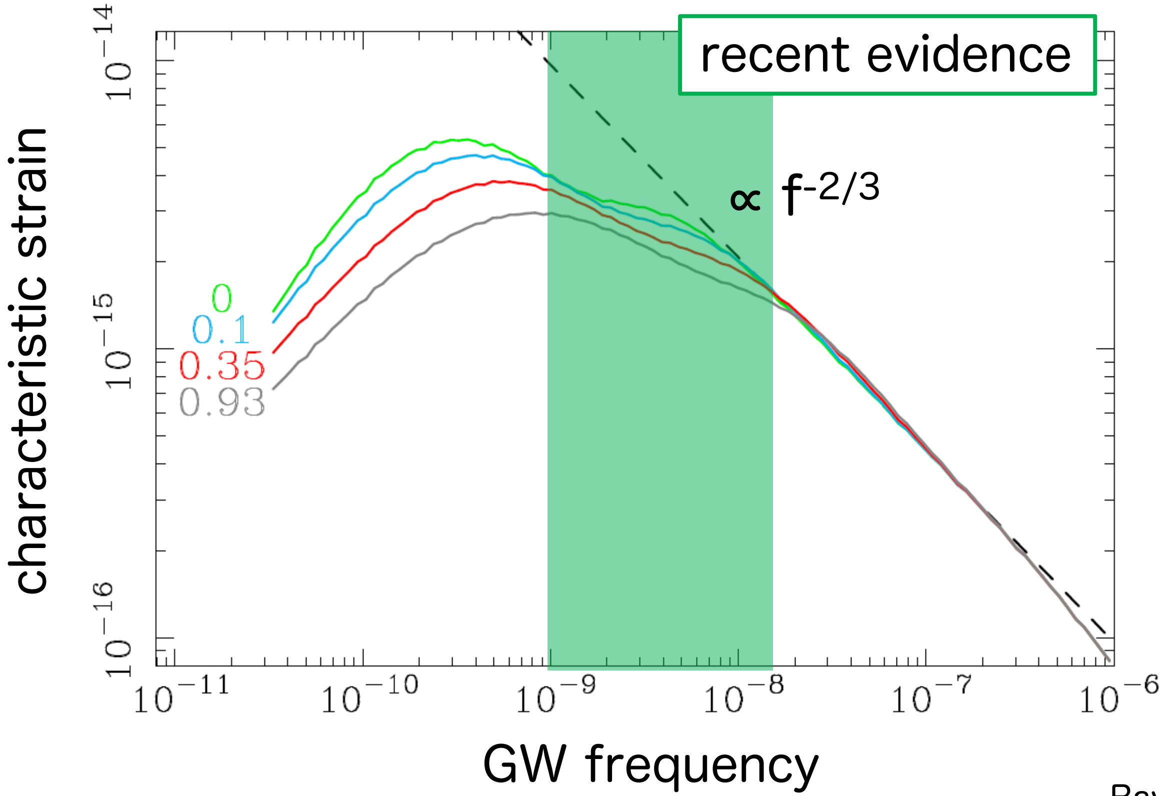
Nano-Hz GWs

- SMBH binary
- cosmic string
- inflation
- phase transition
- 2nd-order scalar fluctuations



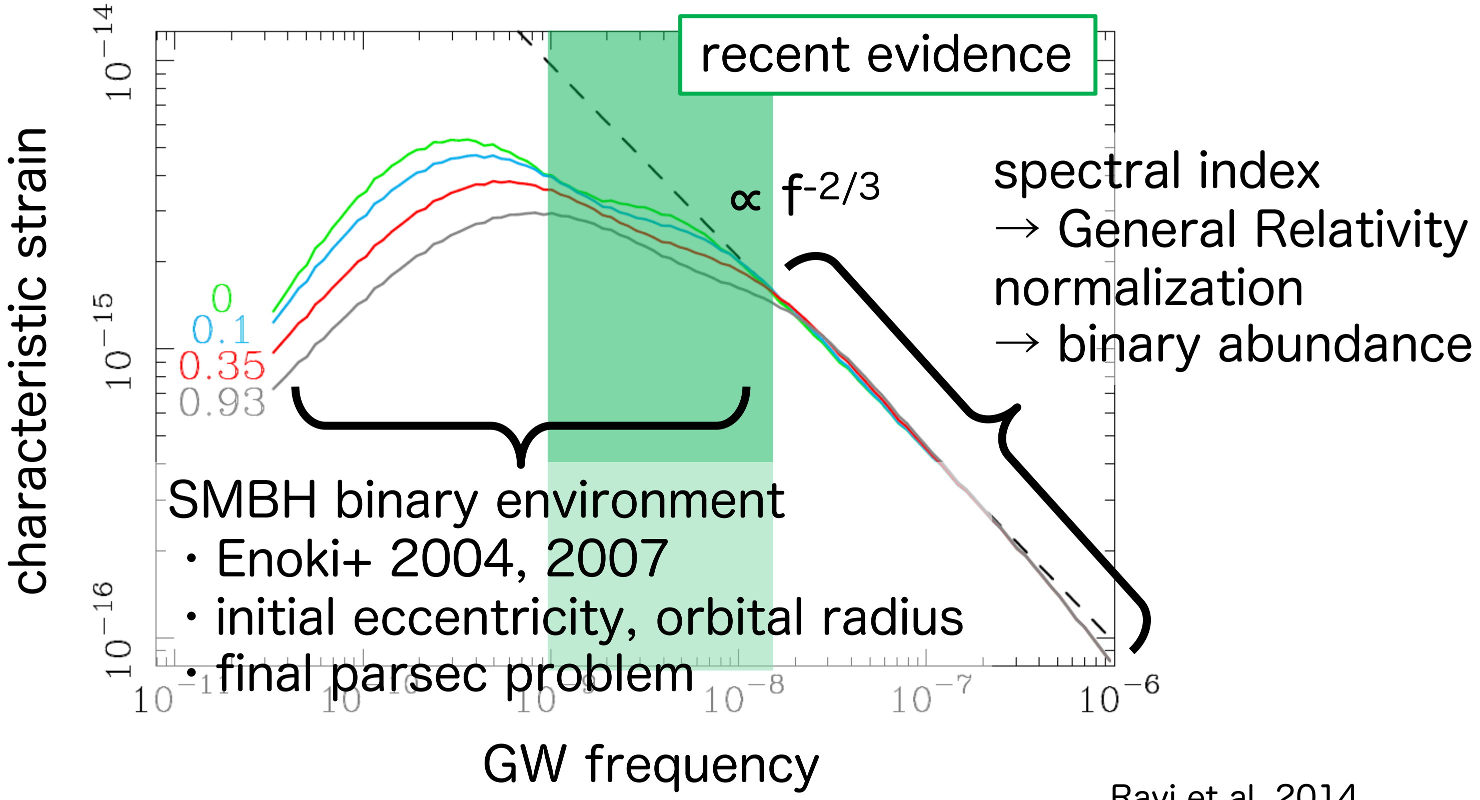


GW background spectrum



Ravi et al. 2014

GW background spectrum



Ravi et al. 2014

PTA projects

IPTA (International PTA consortium)

- EPTA (Europe)
- NANOGrav (North America)
- PPTA (Australia)
- InPTA (India + Japan)

emerging PTAs

- CPTA (China)
- MPTA (South Africa)

These are independent groups but cooperate closely.

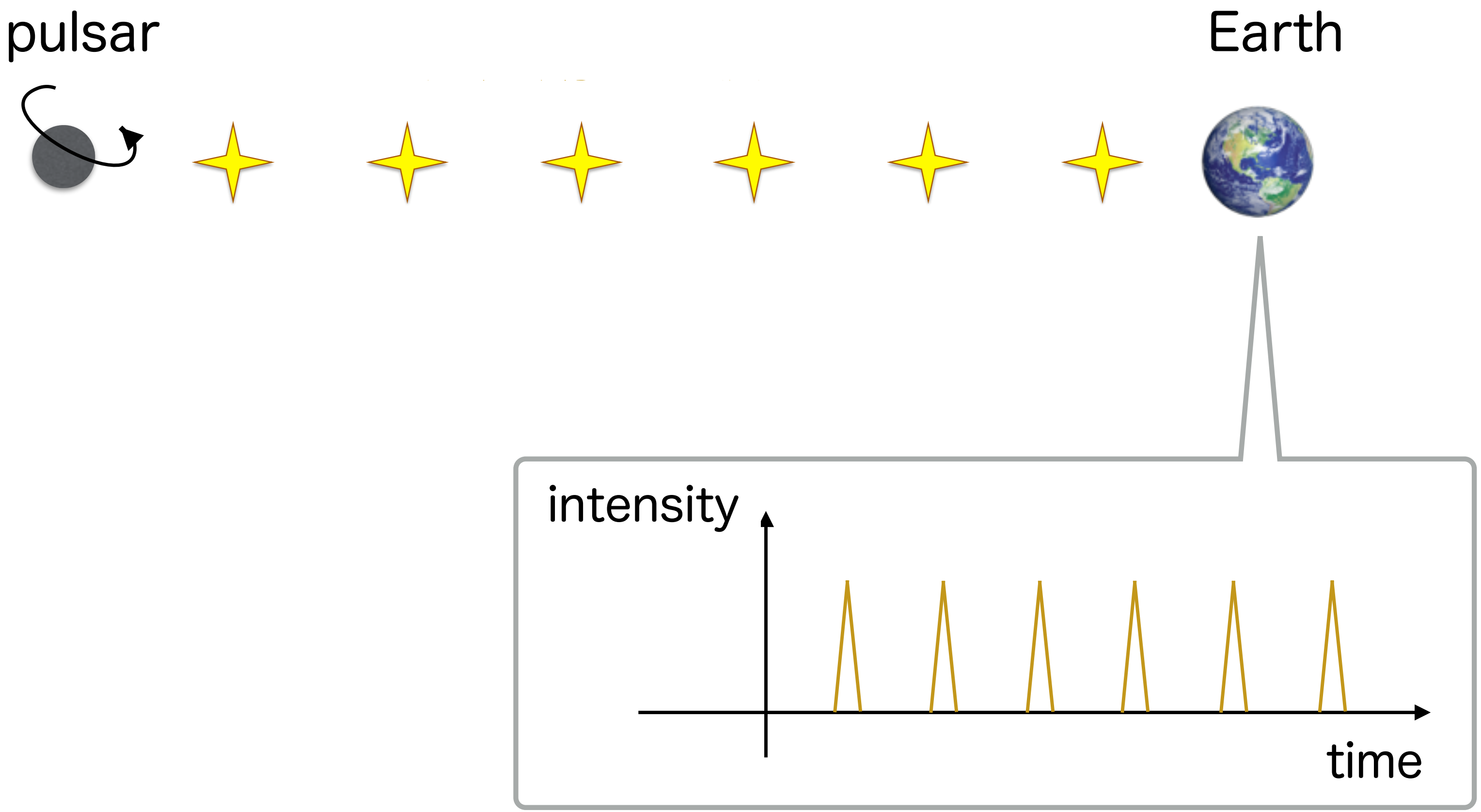
Indian PTA

- India + Japan
- uGMRT (SKA pathfinder)
- low frequency (250-1450MHz)
  - uniqueness of InPTA
  - precise dispersion measure
- 1st data release in 2022

2. Pulsar Timing Array

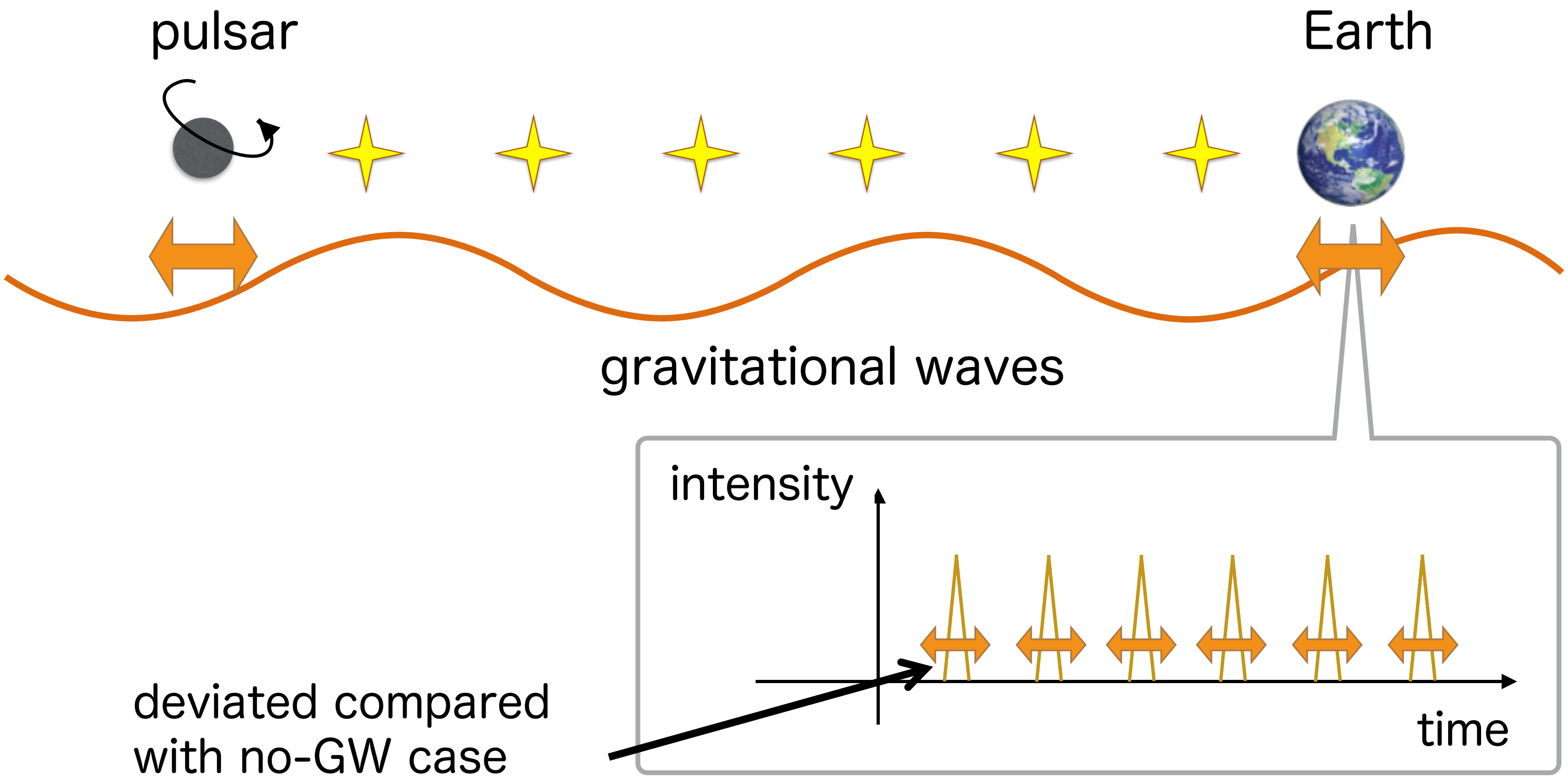
principle of PTA

S. Kuroyanagi



principle of PTA

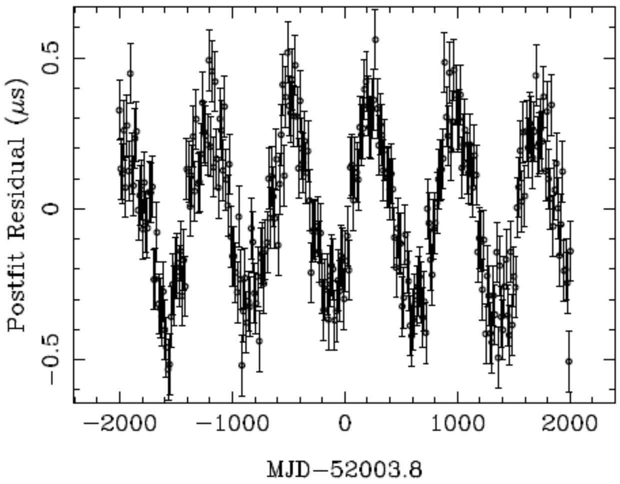
S. Kuroyanagi



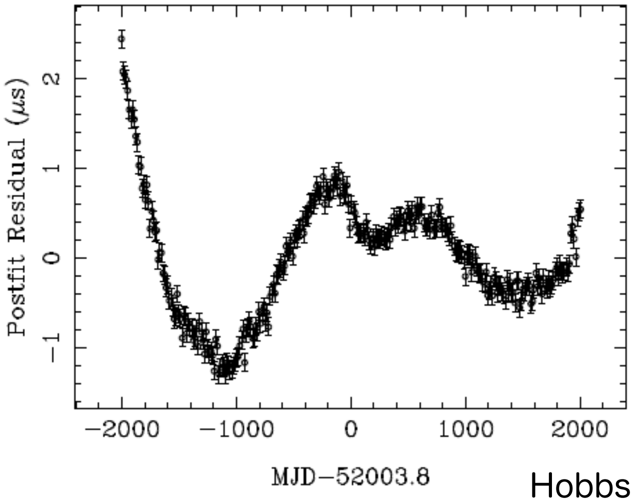
timing residual

timing residual: deviation of pulse arrival time from expectation
GWs are imprinted in timing residual.

single source

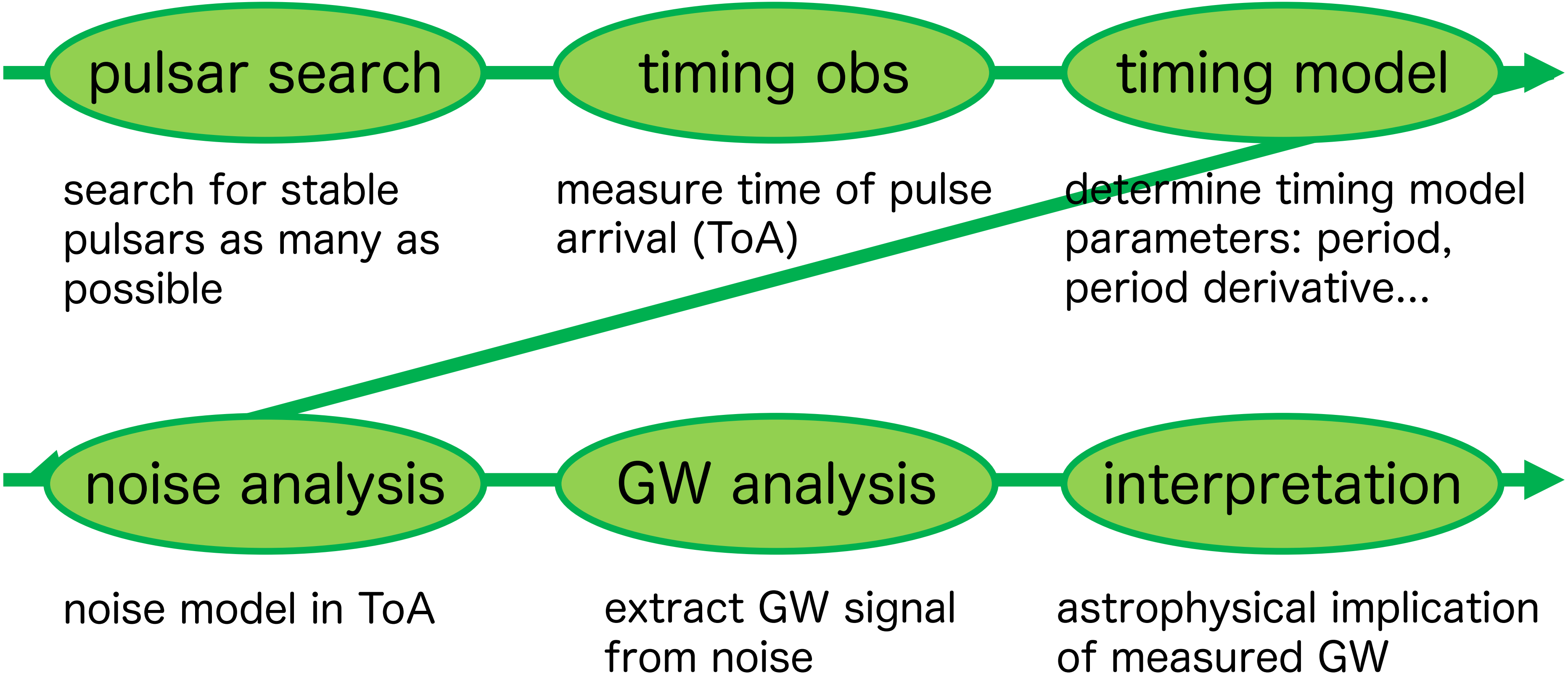


GW background



Hobbs (2011)

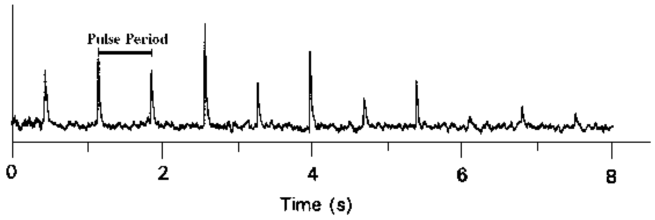
PTA flowchart



folding

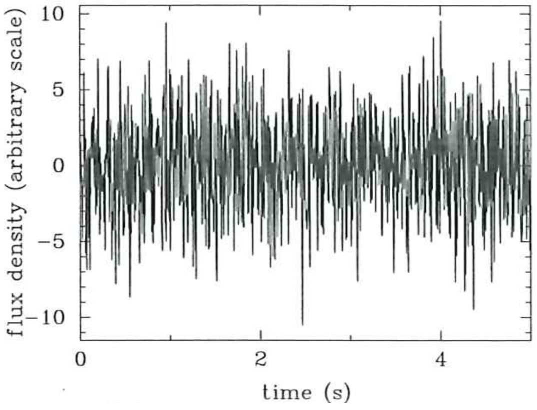
Most of pulsars are so dim that individual pulses cannot be detected and folding is necessary.

high S/N



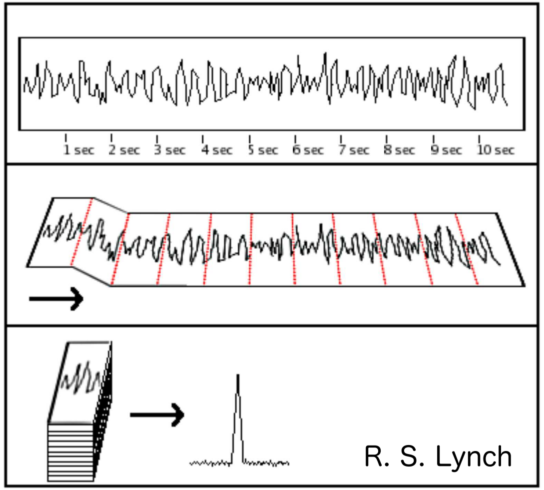
Manchester & Taylor (1977)

low S/N



the handbook of pulsar astronomy

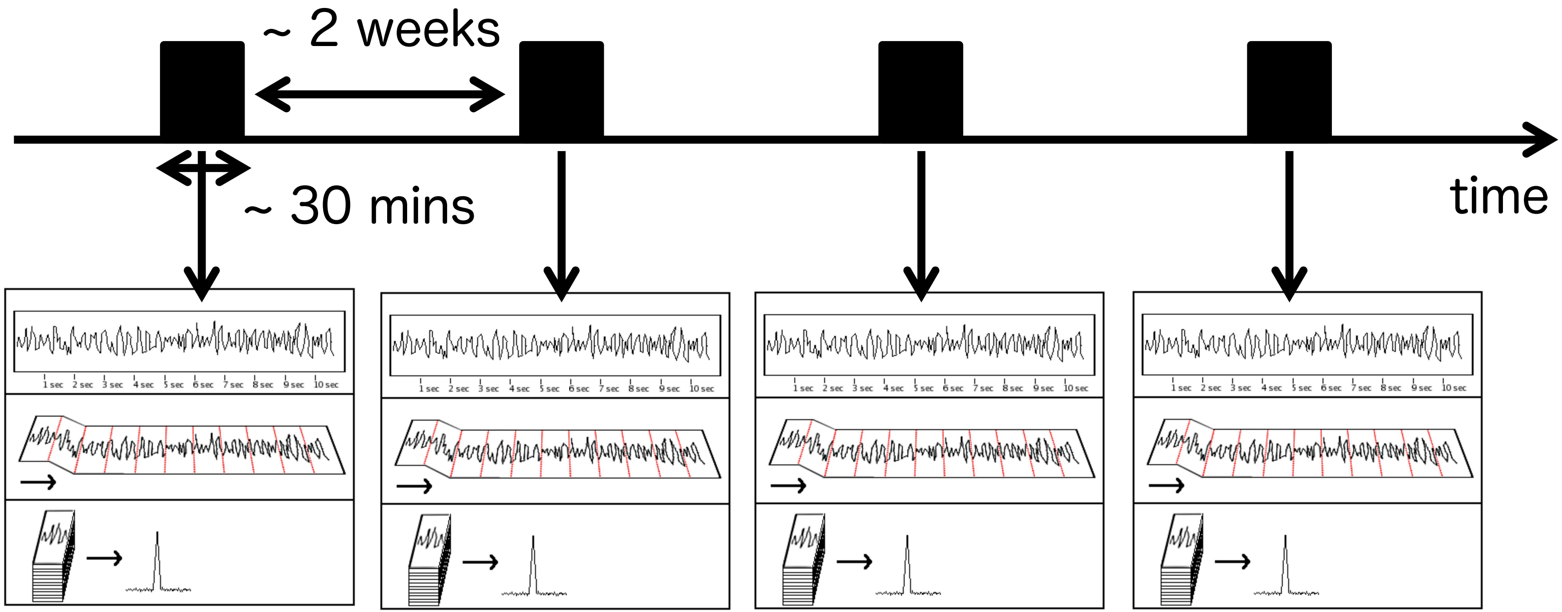
folding



R. S. Lynch

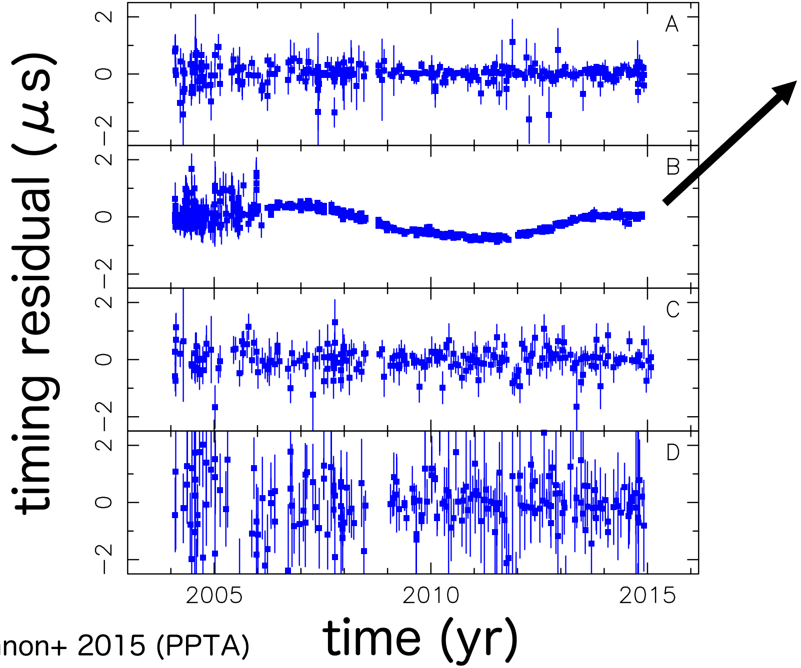
timing observation

observe each pulsar once in a few weeks, and determine the pulse arrival time for each observation (1 ToA for 1 obs)



timing residual

timing residual : deviation of ToA from timing model prediction



Shannon+ 2015 (PPTA)

GW ? → No!
If GW, other pulsars would also be affected.
The residual due to GW depends on the relative position of the GW source and pulsar.
→ (Hellilngs & Downs correlation)

Extract GW signal modeling noise.

noise model

stochastic noise

●white noise

・radiometer noise

・fluctuations intrinsic to pulsar

$$\sigma^2_{\mathrm{scaled}} = \mathrm{EFAC}^2 \times \sigma^2_{\mathrm{original}} + \mathrm{EQUAD}^2$$

●red noise : temporal correlation

・dependent on radio frequency : include GWs

・independent of radio frequency : ISM effects

$$y(t) = \sum_{j=1}^{N_{\mathrm{coef}}} Y_j \Big(a_j \cos(j\omega t) + b_j \sin(j\omega t)\Big)\left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^{-\alpha} \qquad \omega = 2\pi/T_{\mathrm{span}}$$

GW signal

features of GW signal in timing residual

1. temporal correlation of O(1) years

$$f_{\rm GW} = 1.4 \times 10^{-7}\ {\rm Hz} \left(\frac{a}{3\ {\rm mpc}}\right)^{-3/2} \left(\frac{m}{10^9 M_\odot}\right)^{1/2}$$

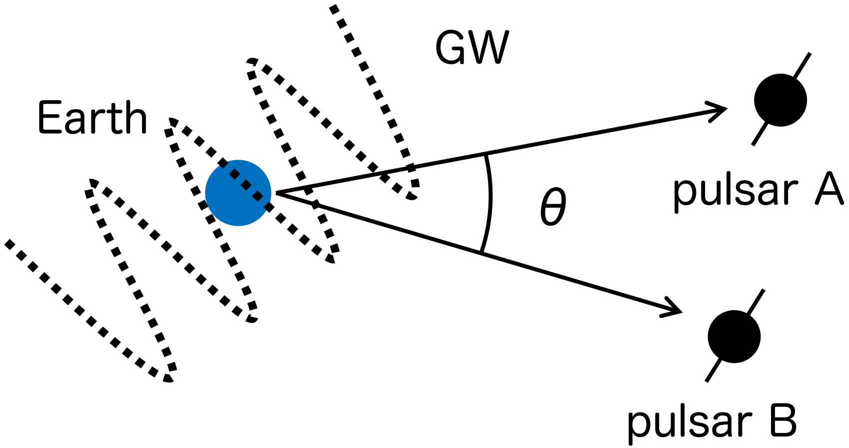
2. common to multiple pulsars
   → Common Red Signal (CRS)

3. inter-pulsar correlation depending on angular separation
   → Hellings & Downs correlation

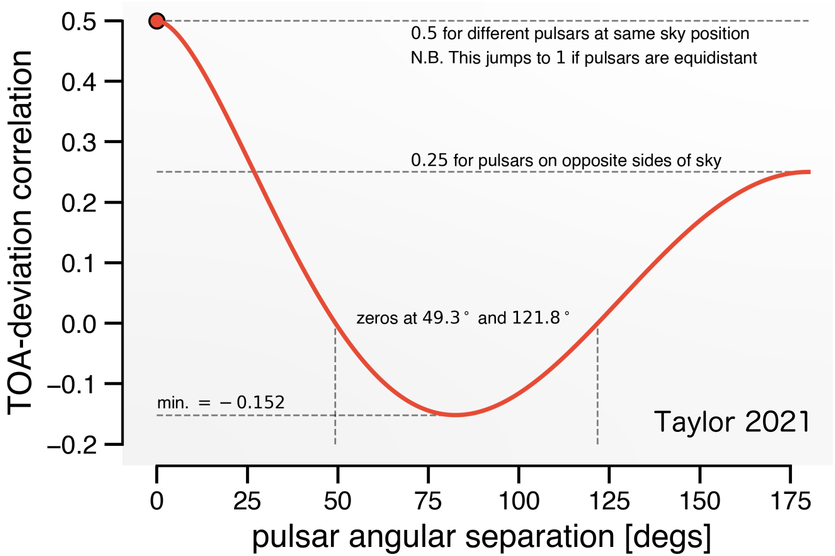
Hellings & Downs correlation

Hellings & Downs 1983

- correlation in timing residuals of 2 pulsars
- depends on angular separation
- ”quadrupole” pattern of GW



$$\Gamma_{mn} = \frac{3}{2} x_{mn} \ln x_{mn} - \frac{1}{4} x_{mn} + \frac{1}{2}(1 + \delta_{mn})$$



3. Evidence for GW Background

worldwide announcement

6/29 UTC 0:00 : papers, arXivs, press release
・EPTA + InPTA
・NANOGrav
・PPTA
・CPTA

conclusion
・GW background signal : 2~4 σ → evidence (~~detection~~)
・results from different PTAs are roughly consistent
・consistent with that from SMBH binaries
・cannot reject other sources

EPTA+InPTA

focus on EPTA+InPTA
similar analysis method for other PTAs
show comparison later

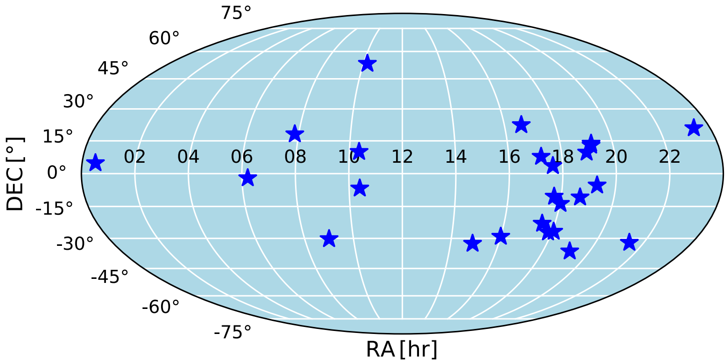
EPTA

- Effelsberg, Lovell, Nançay
  Sardina, WSRT, LEAP
- 25 pulsars, 24.5 years

InPTA

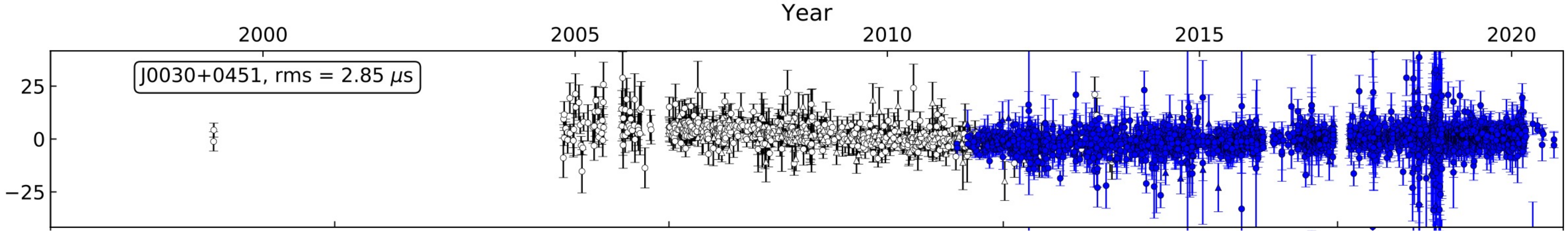
- uGMRT
- 10 pulsars, 3.5 years
- low-frequency observation

pulsar distribution



noise model

timing residual of J0030+0451

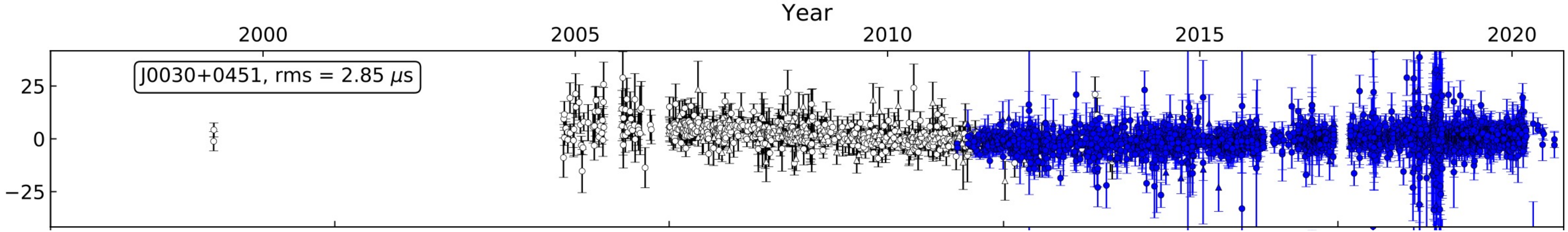


select noise model & estimate parameters from timing residual

・white noise : no time correlation
・red noise (RN) : achromatic time-correlated
・dispersion measure noise (DM) : chromatic time-correlated
・scattering variation (SV) : chromatic time-correlated

noise model

timing residual of J0030+0451



Pulsar	PTA	Favoured	Red noise			DM noise			Time span
		Models	N_{coef}	A	γ	N_{coef}	A	γ	yr
J0030+0451	EPTA	RN	10	$-14.93^{+0.83}_{-1.1}$	$5.49^{+1.93}_{-1.56}$	X	X	X	21.96

noise models for 25 pulsars

RN is identified for 11 pulsars.

Pulsar	PTA	Favoured	Red noise			DM noise			Time span
		Models	$N_{\rm coef}$	A	γ	$N_{\rm coef}$	A	γ	yr
J0030+0451	EPTA	RN	10	$-14.93^{+0.83}_{-1.1}$	$5.49^{+1.93}_{-1.56}$	X	X	X	21.96
J0613−0200	EPTA+InPTA	RN+DM	10	$-14.99^{+0.94}_{-1.24}$	$5.34^{+2.06}_{-1.6}$	129	$-11.58^{+0.06}_{-0.06}$	$1.34^{+0.28}_{-0.26}$	23.83
J0751+1807	EPTA+InPTA	DM	X	X	X	115	$-11.72^{+0.2}_{-0.2}$	$2.69^{+0.51}_{-0.49}$	25.12
J0900−3144	EPTA	RN+DM	135	$-12.76^{+0.09}_{-0.08}$	$1.06^{+0.28}_{-0.27}$	150	$-11.94^{+0.67}_{-0.87}$	$3.89^{+2.12}_{-1.79}$	13.64
J1012+5307	EPTA+InPTA	RN+DM	149	$-13.03^{+0.05}_{-0.04}$	$1.21^{+0.17}_{-0.17}$	47	$-11.95^{+0.11}_{-0.12}$	$1.74^{+0.39}_{-0.37}$	24.61
J1022+1001	EPTA+InPTA	RN+DM	30	$-13.8^{+0.51}_{-0.99}$	$3.01^{+1.55}_{-0.97}$	100	$-11.46^{+0.09}_{-0.08}$	$0.14^{+0.26}_{-0.13}$	25.37
J1024−0719	EPTA	DM	X	X	X	34	$-11.82^{+0.18}_{-0.21}$	$2.46^{+0.87}_{-0.66}$	23.14
J1455−3330	EPTA	RN	49	$-13.26^{+0.28}_{-0.49}$	$2.21^{+1.35}_{-1.04}$	X	X	X	15.72
J1600−3053	EPTA+InPTA	RN+DM	21	$-14.05^{+0.49}_{-0.89}$	$2.86^{+1.99}_{-1.24}$	148	$-11.46^{+0.04}_{-0.04}$	$1.99^{+0.12}_{-0.12}$	15.42
J1640+2224	EPTA	DM	X	X	X	145	$-11.66^{+0.14}_{-0.13}$	$0.48^{+0.49}_{-0.4}$	24.44
J1713+0747	EPTA+InPTA	RN+DM	12	$-14.19^{+0.27}_{-0.29}$	$3.28^{+0.66}_{-0.63}$	148	$-11.86^{+0.05}_{-0.04}$	$1.59^{+0.19}_{-0.19}$	24.5
J1730−2304	EPTA	DM	X	X	X	10	$-11.56^{+0.55}_{-0.57}$	$2.22^{+1.56}_{-1.45}$	16.1
J1738+0333	EPTA	RN	11	$-12.93^{+0.36}_{-0.4}$	$2.14^{+1.31}_{-1.2}$	X	X	X	14.12
J1744−1134	EPTA+InPTA	RN+DM	10	$-14.12^{+0.41}_{-0.72}$	$3.45^{+1.19}_{-0.75}$	150	$-11.82^{+0.1}_{-0.07}$	$0.26^{+0.37}_{-0.23}$	25.14
J1751−2857	EPTA	DM	X	X	X	41	$-11.08^{+0.22}_{-0.33}$	$2.13^{+0.99}_{-0.7}$	14.69
J1801−1417	EPTA	DM	X	X	X	14	$-10.73^{+0.27}_{-0.26}$	$1.68^{+1.16}_{-1.06}$	13.71
J1804−2717	EPTA	DM	X	X	X	38	$-11.19^{+0.18}_{-0.83}$	$0.78^{+2.95}_{-0.71}$	14.73
J1843−1113	EPTA	DM	X	X	X	73	$-11.03^{+0.08}_{-0.08}$	$2.07^{+0.36}_{-0.31}$	16.8
J1857+0943	EPTA+InPTA	DM	X	X	X	11	$-11.86^{+0.27}_{-0.28}$	$2.88^{+0.66}_{-0.62}$	25.11
J1909−3744	EPTA+InPTA	RN+DM	20	$-14.89^{+0.78}_{-0.85}$	$4.77^{+1.96}_{-1.79}$	150	$-11.85^{+0.05}_{-0.05}$	$1.31^{+0.16}_{-0.15}$	17.14
J1910+1256	EPTA	DM	X	X	X	10	$-11.71^{+0.66}_{-0.84}$	$2.98^{+2.38}_{-1.87}$	15.21
J1911+1347	EPTA	DM	X	X	X	10	$-11.98^{+0.39}_{-0.47}$	$3.06^{+1.36}_{-1.06}$	14.2
J1918−0642	EPTA	DM	X	X	X	138	$-12.09^{+0.4}_{-0.44}$	$3.49^{+1.13}_{-1.06}$	19.71
J2124−3358	EPTA+InPTA	DM	X	X	X	18	$-11.77^{+0.34}_{-0.39}$	$2.07^{+1.09}_{-0.98}$	17.15
J2322+2057	EPTA	NONE	X	X	X	X	X	X	14.68

signal models

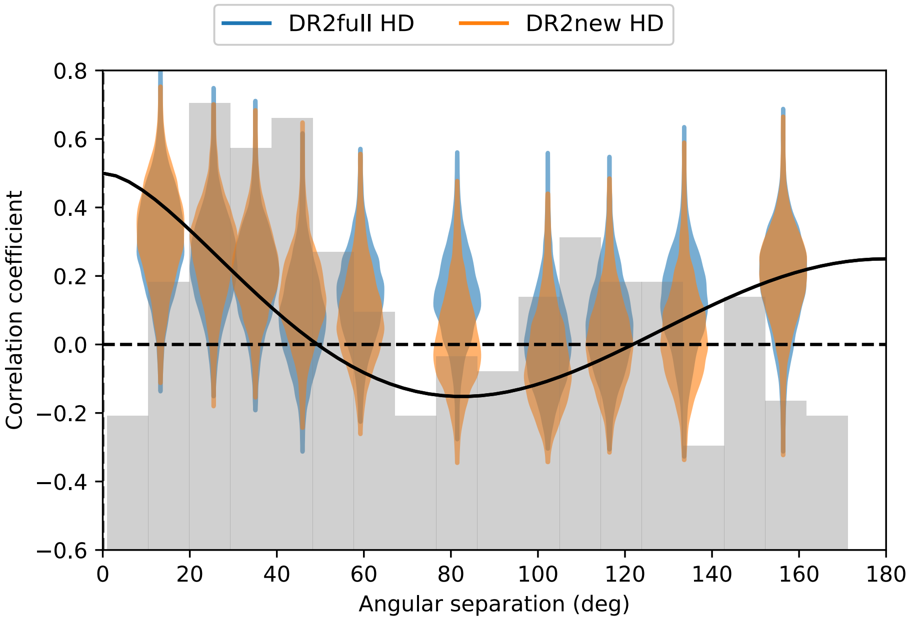
4 types of red noise
・PSRN : pulsar specific red noise
・CURN : common uncorrelated red noise
・GWB : common + quadrupole (GW background)
・CLK : common + monopole (clock error)
・EPH : common + dipole (solar system ephemeris error)

These can be identified by seeing inter-pulsar correlation.

HD correlation

inter-pulsar correlation for Common Red Signal

- 10 angle bins
- at least 30 pairs in each bin
- roughly consistent but slightly larger than HD at around 90 deg



model selection

model selection by comparing Bayes factor of various signal models and "individual red noise & common red noise"

ID	Model	DR2full ENTERPRISE	DR2full FORTYTWO	DR2full+ ENTERPRISE	DR2new ENTERPRISE	DR2new FORTYTWO	DR2new+ ENTERPRISE
1	PSRN + CURN	–	–	–	–	–	–
2	PSRN + GWB	4	5	4	60	62	65
3	PSRN + CLK	< 0.01	< 0.01	< 0.01	0.2	1.2	0.3
4	PSRN + EPH	< 0.01	$\sim 10^{-4}$	< 0.01	0.2	0.2	1.3
5	PSRN + CURN + CLK	2	1	2.7	0.8	2	1.6
6	PSRN + CURN + EPH	1	0.1	1	1	1	1.6
7	PSRN + GWB + CURN	3	3	4	27	13	25
8	PSRN + GWB + CLK	5	12	7	28	35	57
9	PSRN + GWB + EPH	3	3	3.6	33	29	43

"PSRN + GWB" is most favored.

statistical significance

statistical significance of GWB

[1] red noise in individual pulsars

[2] common red noise

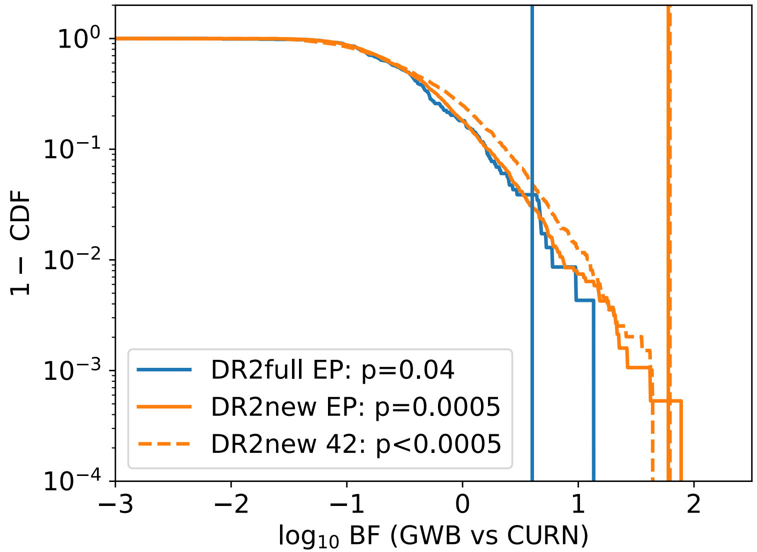
[3] inter-pulse correlation

To evaluate the significance of [3] given [2], mock data are generated from observation data

・change the phase of red noise power spectrum randomly

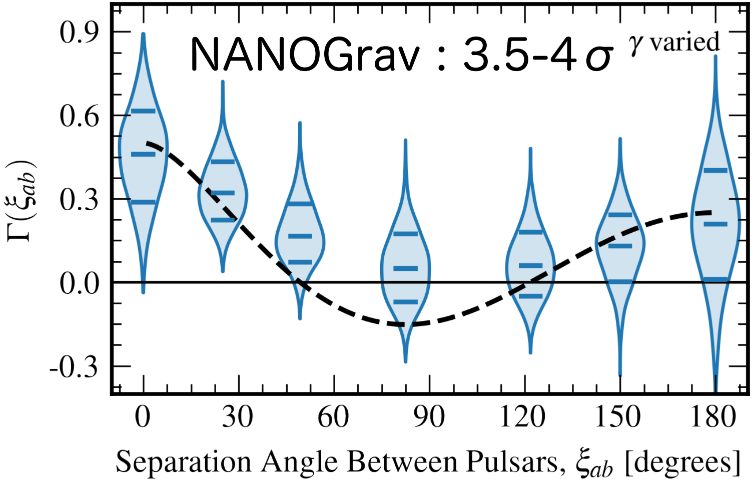
・change the position of pulsars randomly

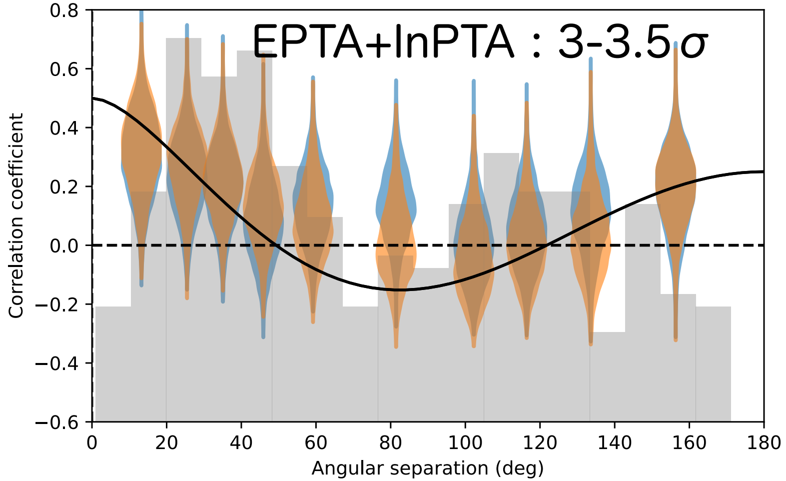
→ 0.05% (~3σ) significance

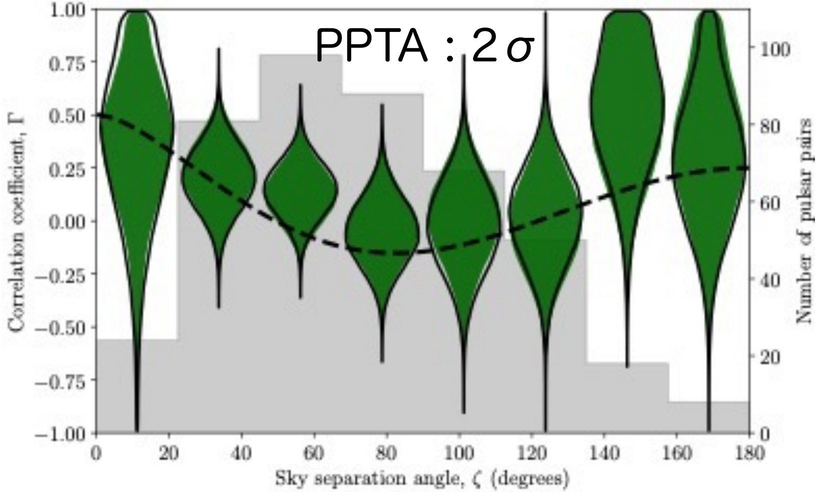


comparison : HD

- comparison of EPTA+InPTA (DR2full+), NANOGrav & PPTA
- roughly consistent
- contaminated by monopole?



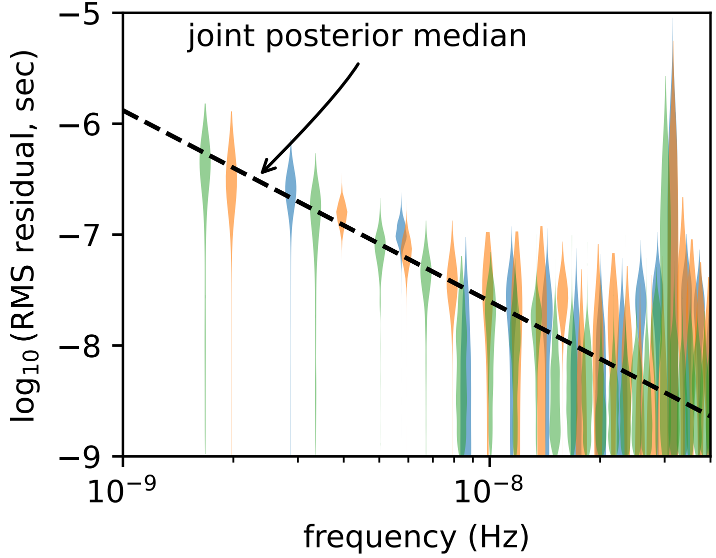




power spectrum

comparison of EPTA+InPTA (DR2full+), NANOGrav & PPTA

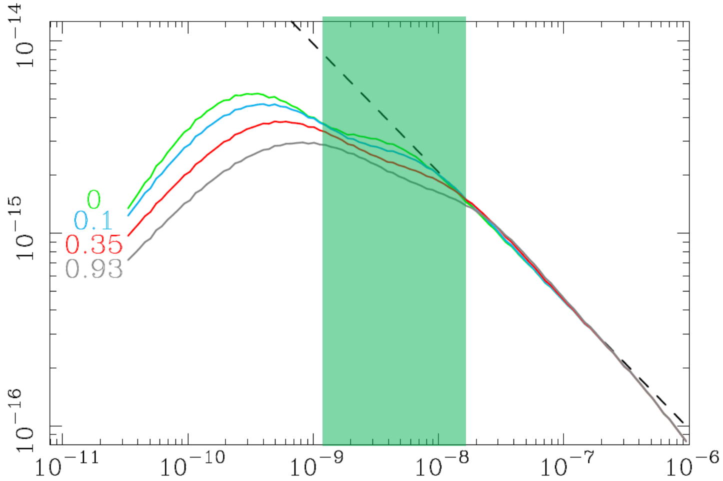
- roughly consistent with each other
- statistically significant power at low frequencies (<10nHz)
- noise floor at high frequencies (>10nHz)

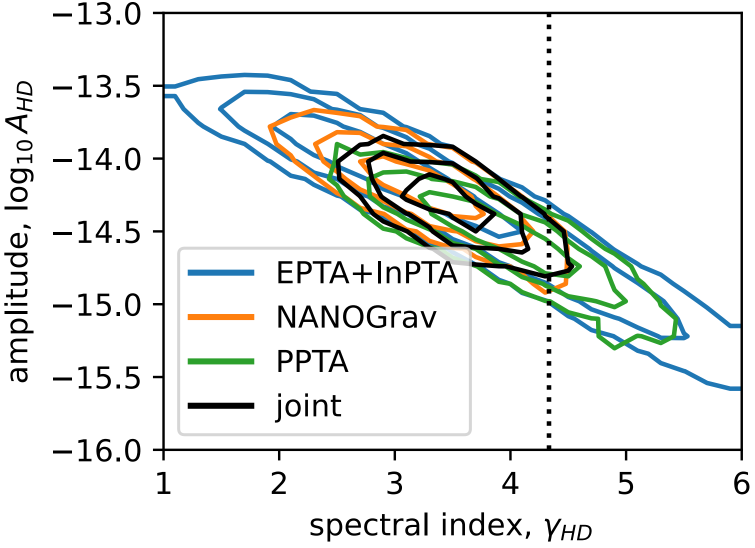


spectral index

comparison of EPTA+InPTA (DR2full+), NANOGrav & PPTA

- roughly consistent with each other
- spectral index is smaller than 13/3 but within 3σ





4. Future Prospects

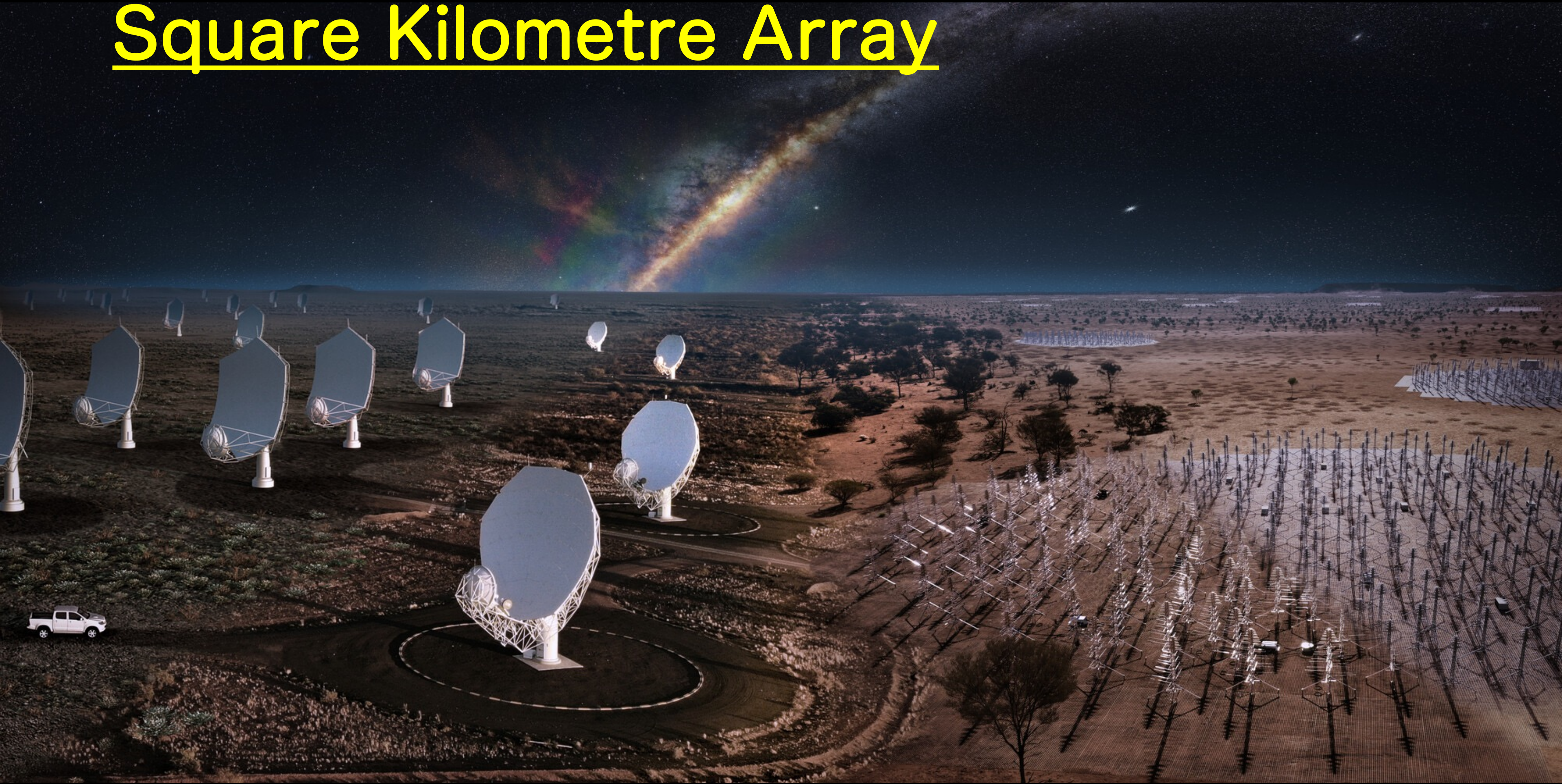
to improve

- understand systematics better
  - monopole in inter-pulsar correlation?
  - pulse jitter : pulsar intrinsic fluctuations
  - RFI, solar system ephemeris

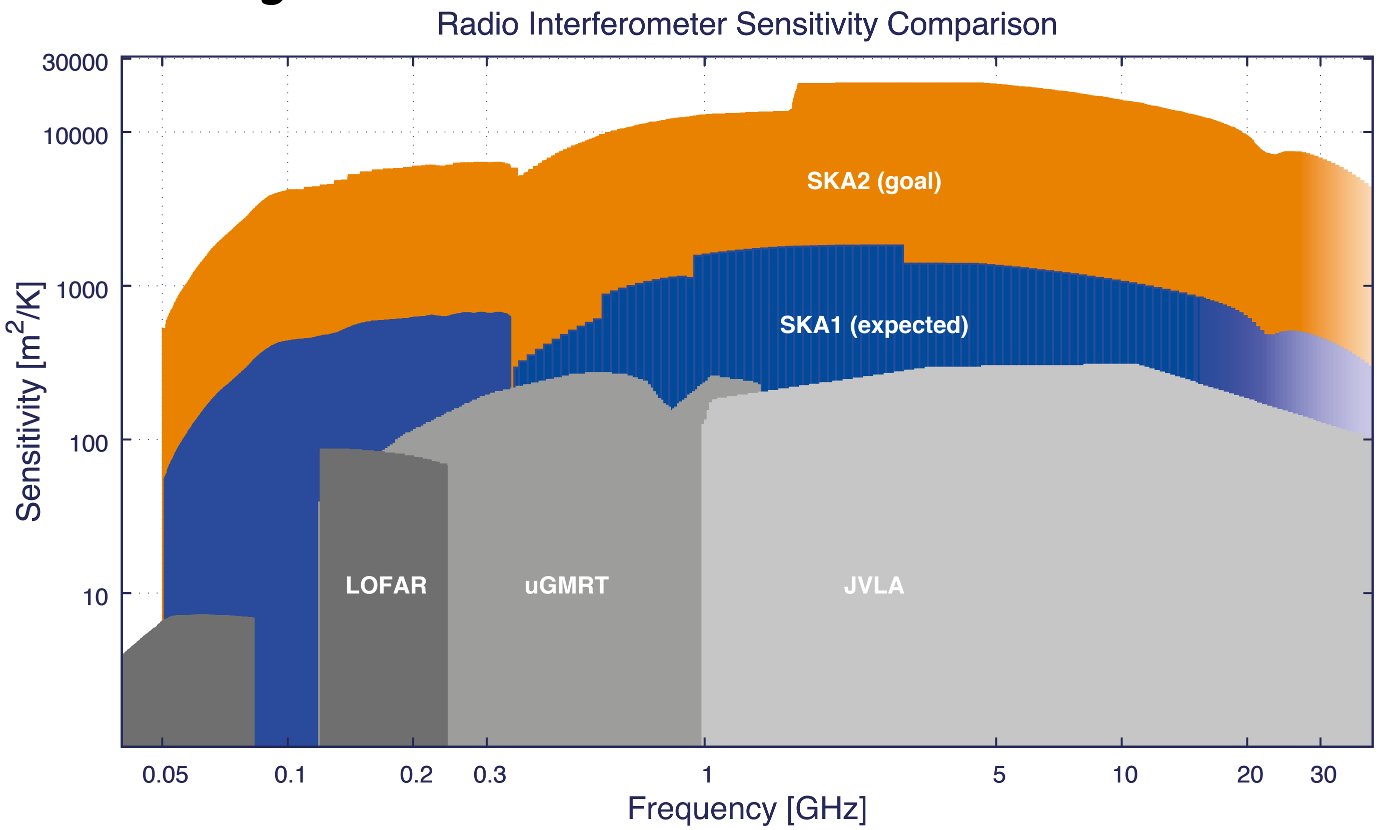
- longer time baseline
  - just continue observations

- more pulsars
  - combine different PTAs
  - more sensitive telescope

Square Kilometre Array



sensitivity



SKA

construction began in 2021
construction complete in 2029

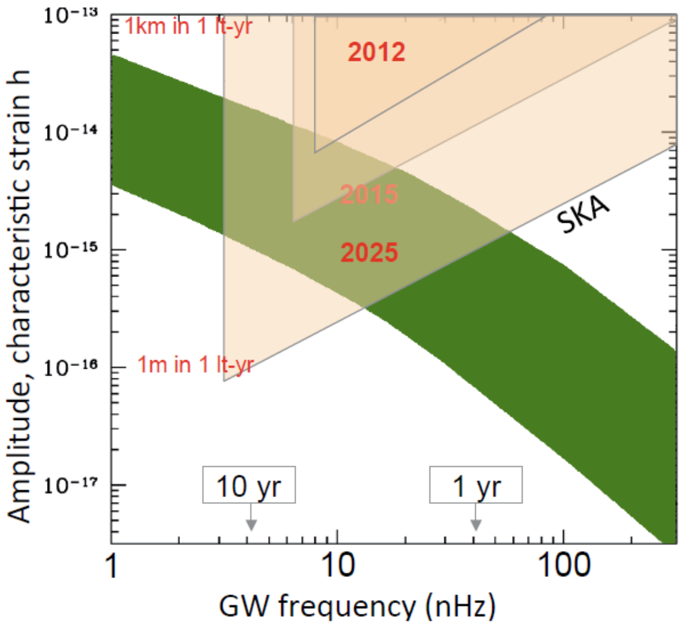
SKA1 pulsar survey
- 9,000 normal pulsars
- 1,400 msec pulsars

x4 !

SKA2 pulsar survey
- 30,000 normal pulsars
- 3,000 msec pulsars

x10 !

SKA1-PTA sensitivity



future prospects

2023 IPTA comparison : arXiv

2024 IPTA combination : ongoing

MeerKAT, FAST join

2029 SKA1

203? SKA2

GWB detection

single source

GWB power spectrum
→ SMBH evolution model

precise GWB power spectrum
→ other sources

GWB anisotropy

SMBH binary catalog

summary

●pulsar timing array

・direct detection of nano-Hz GWs with msec pulsars

●evidence for GW background

・EPTA+InPTA, NANOGrav, PPTA, CPTA

・statistical significance of HD correlation : 2~4σ

・consistent with GW background from SMBH binaries

・cannot reject other sources due to low S/N and limited range of power spectrum measurement

●future prospects

・IPTA : data combination

・SKA1, SKA2

・precise measurement, single sources, astronomy