Opening a new door:

Nano-Hertz Gravitational-Wave Astronomy

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Kumamoto University
2024/9/27

InPTA
Indian Pulsar Timing Array

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

Who am I?

2005 University of Tokyo, Ph.D. (Katsuhiko Sato)
2005-2007 Princeton University, JSPS overseas fellowship
2007-2008 Kyoto University, JSPS fellowship
2009-2011 Nagoya University, GCOE assistant professor
2011- Kumamoto University

my fields : pulsar timing array, epoch of reionization
cosmic magnetism, SETI, history of astronomy
past interests: neutrino astrophysics, brane world,
cosmic strings, etc.

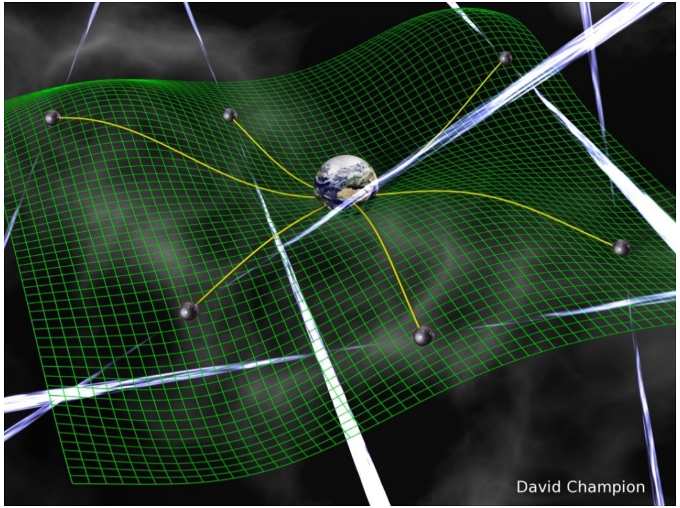
Contents

1. Nano-Hz Gravitational Waves

pulsar timing array

PTA in a nutshell

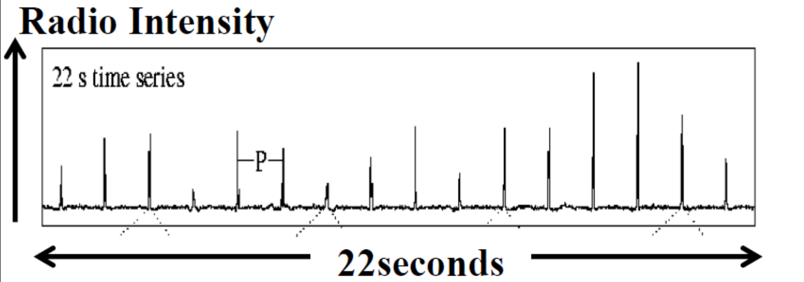
- direct detection of GWs
- very stable msec pulsars
- precise timing for O(10) years
- GWs induce irregularity in pulse arrival time of O(100) nsec
- GW frequency
  → observation period and cadence
  → $(1\ \mathrm{week})^{-1} \sim (10\ \mathrm{years})^{-1}$
  → $1\,\mu\mathrm{Hz} \sim 1\,\mathrm{nHz}$



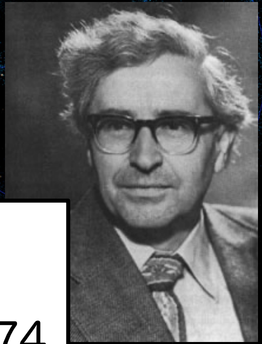
pulsar

- 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)

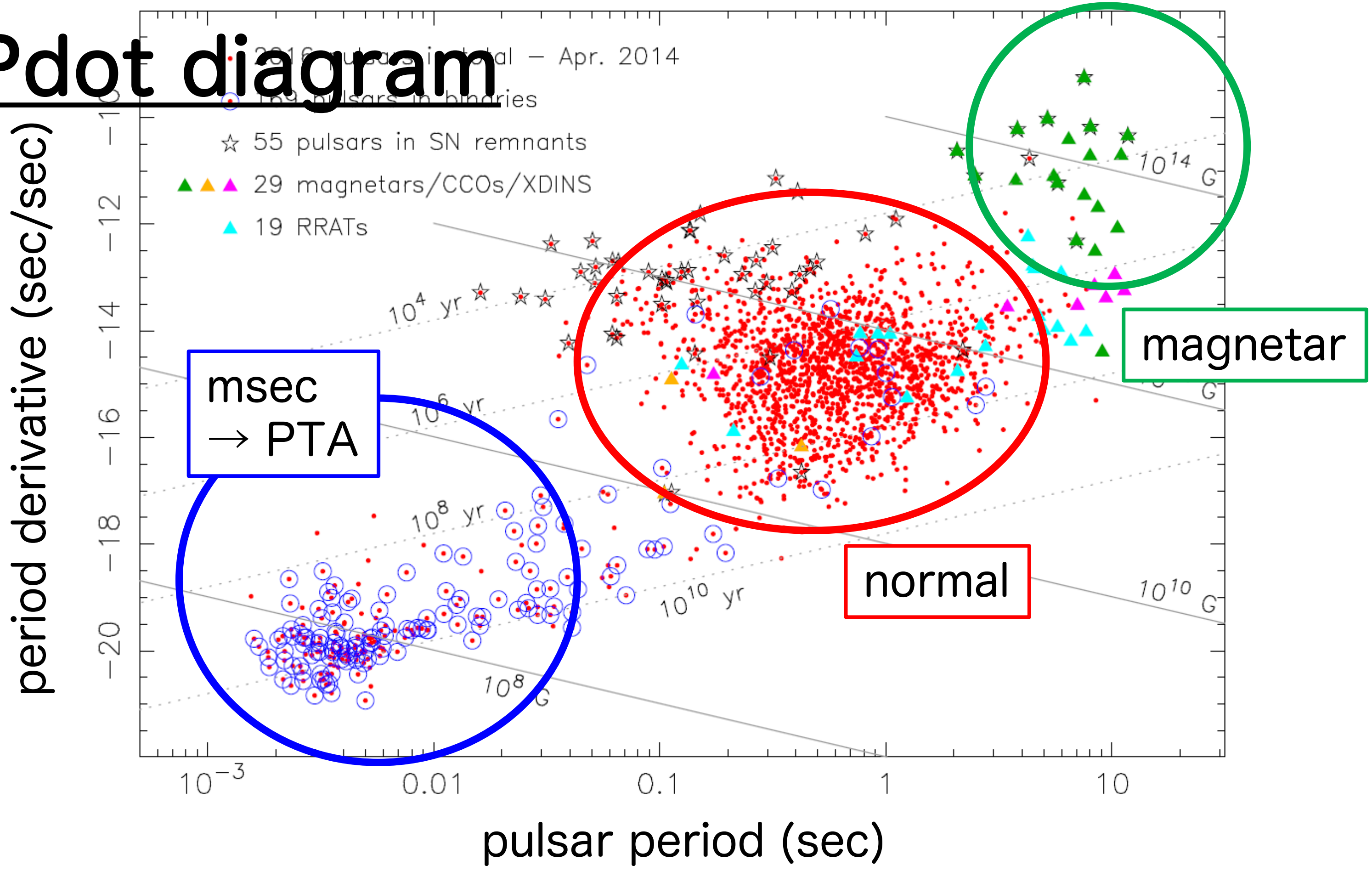


Jocelyn Bell Burnell
(1943-)



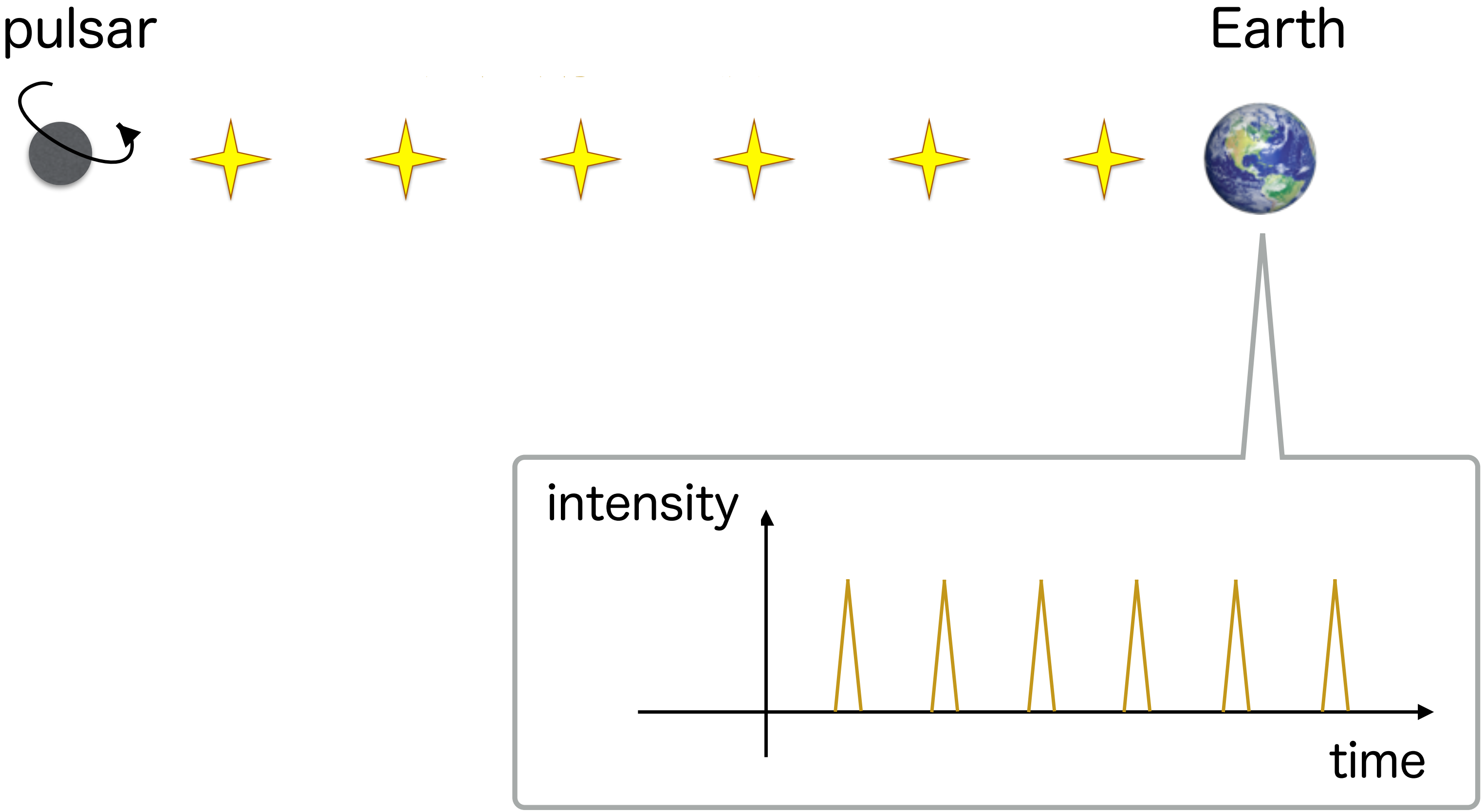
Antony Hewish
(1924-2021)
Nobel Prize in 1974

P-Pdot diagram



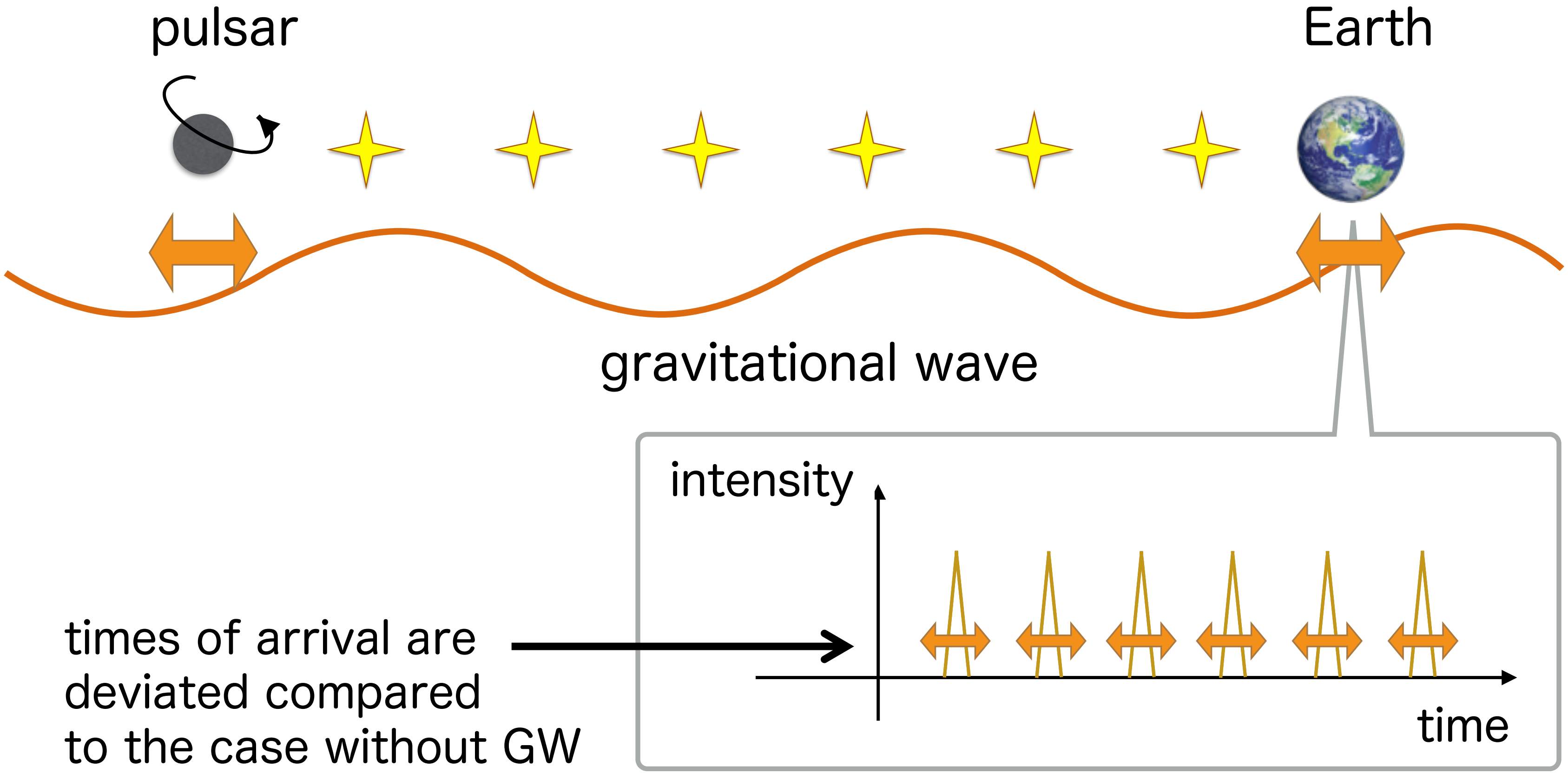
principle of PTA

S. Kuroyanagi



principle of PTA

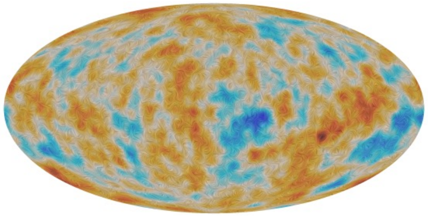
S. Kuroyanagi



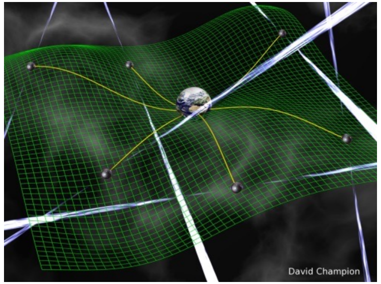
times of arrival are deviated compared to the case without GW

multi-wavelength GW astronomy

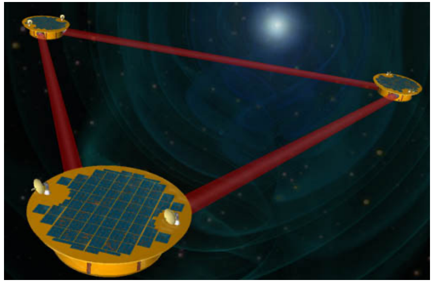
CMB



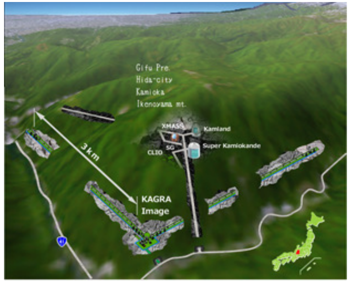
PTA



space



ground



SMBH binary

supernova

compact binary

cosmic string

early universe

10^{-17}Hz　～1nHz　1mHz-0.1Hz　100Hz

Nano-Hz GWs

・SMBH binary

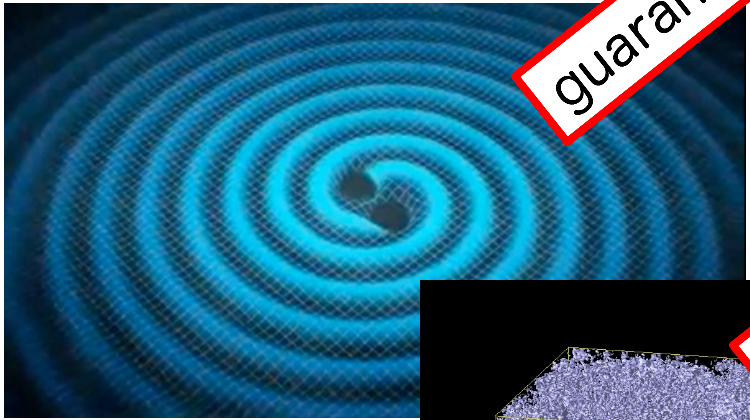
・cosmic string

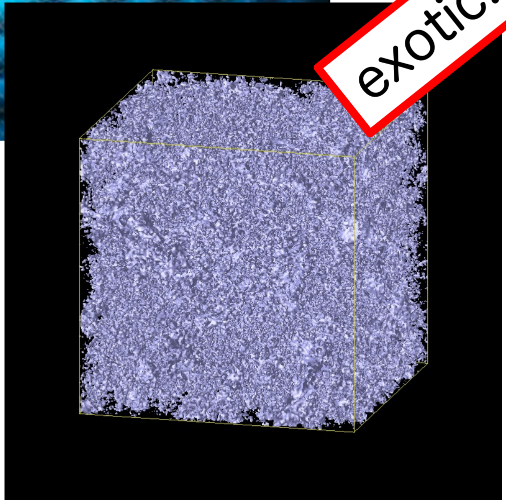
・inflation

・phase transition

・2nd-order scalar perturbation

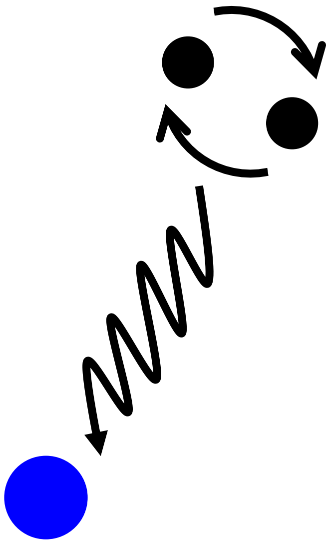
Astrophysics, Cosmology, Particle Physics!



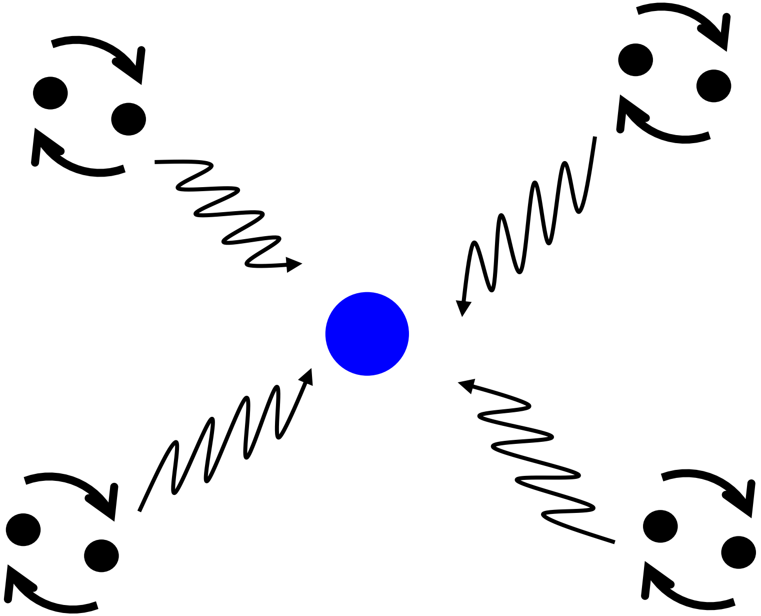


single source & BG

single source



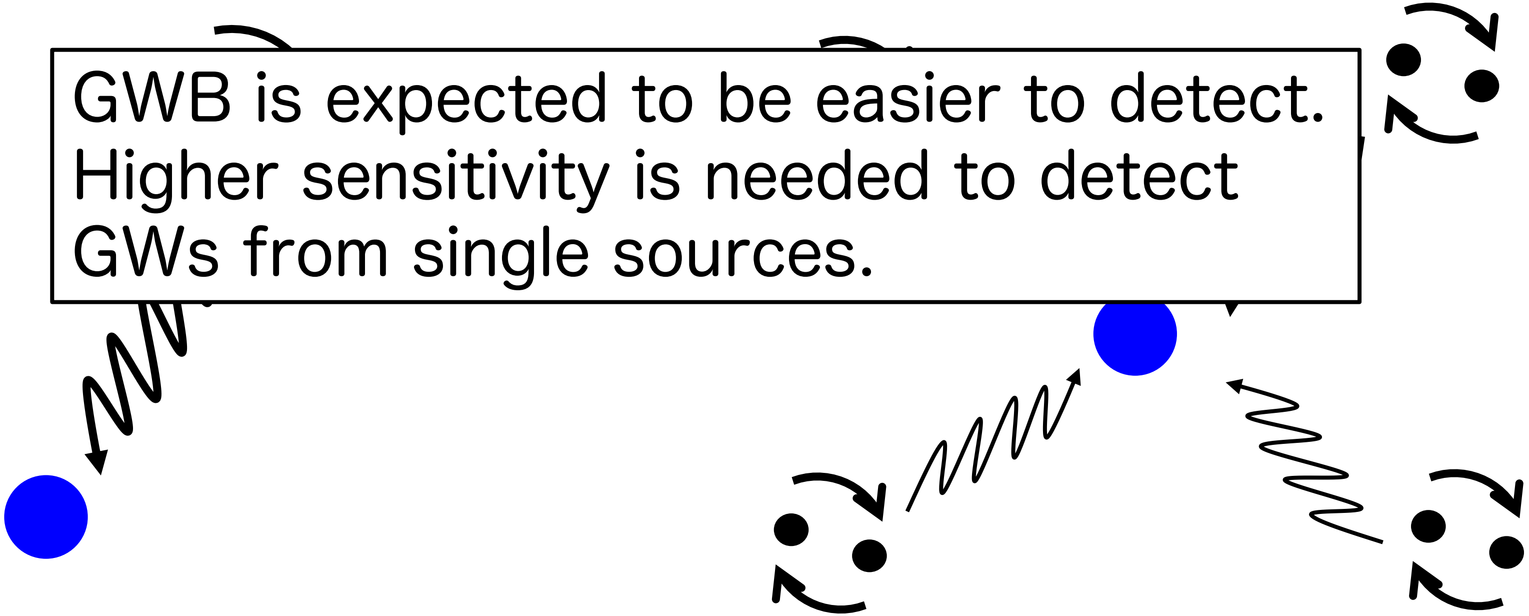
GW background



single source & BG

single source

GW background

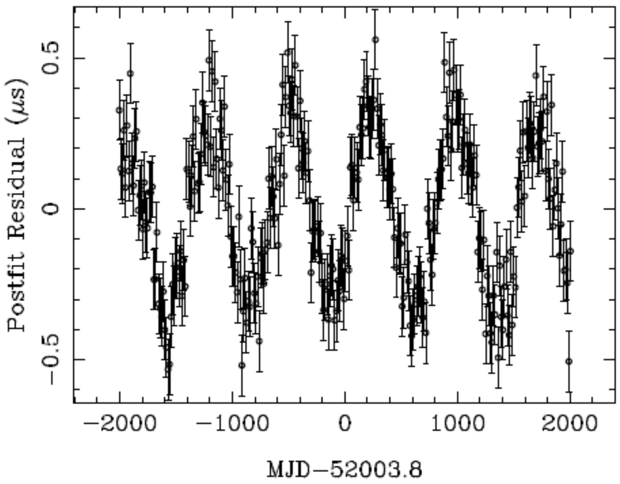


GWB is expected to be easier to detect.
Higher sensitivity is needed to detect
GWs from single sources.

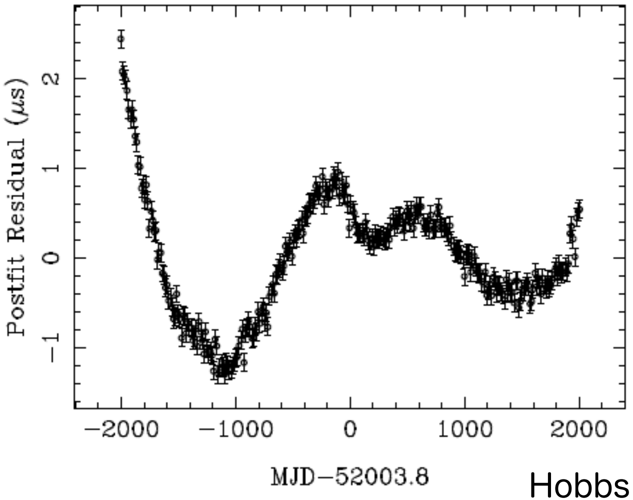
timing residual

GWs → deviation of pulse arrival time from prediction
→ timing residual

single source



GW background

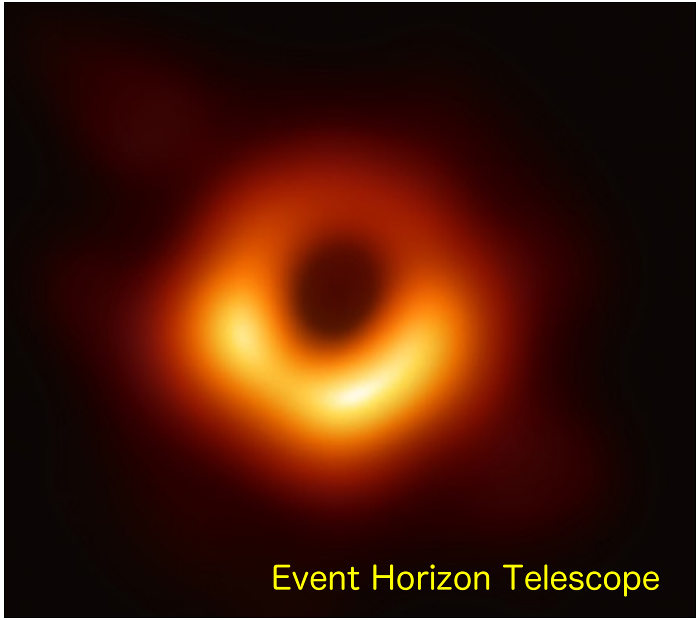


Hobbs (2011)

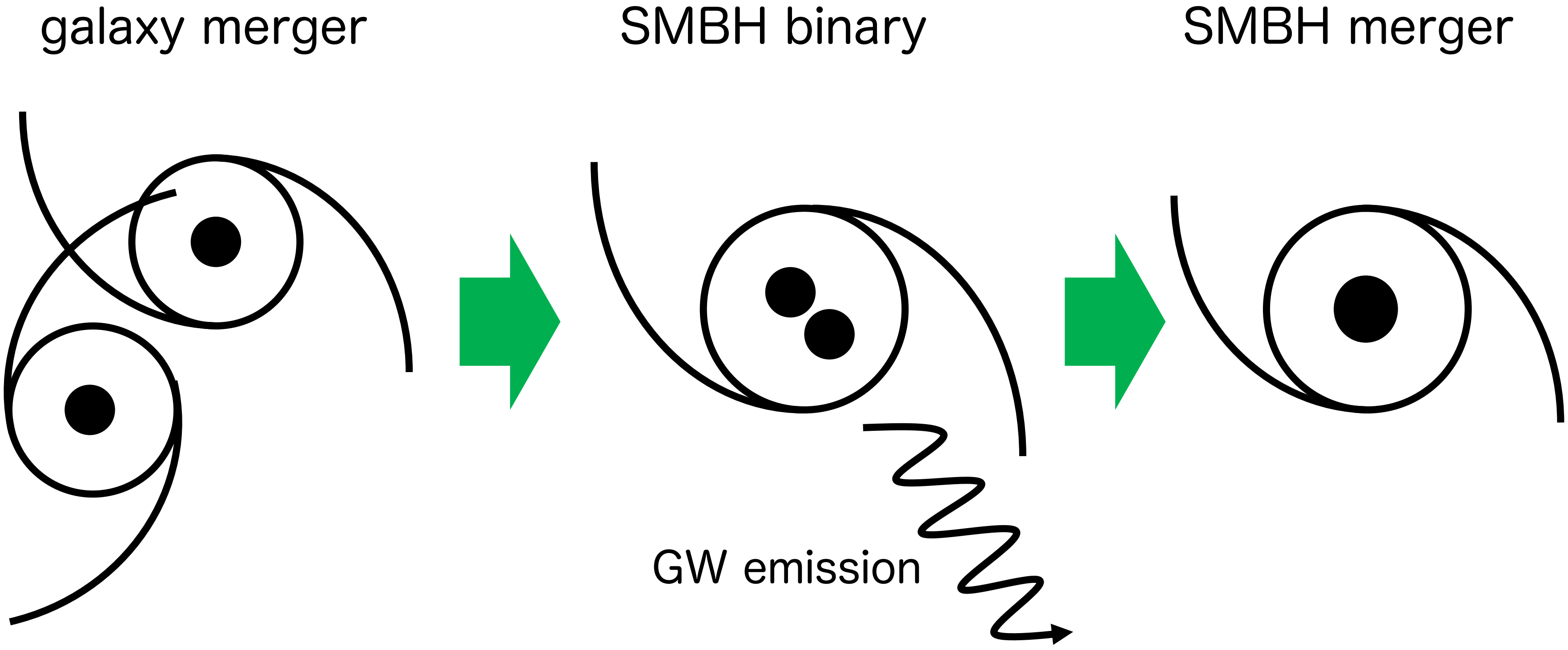
supermassive black hole

SMBHs at galactic center

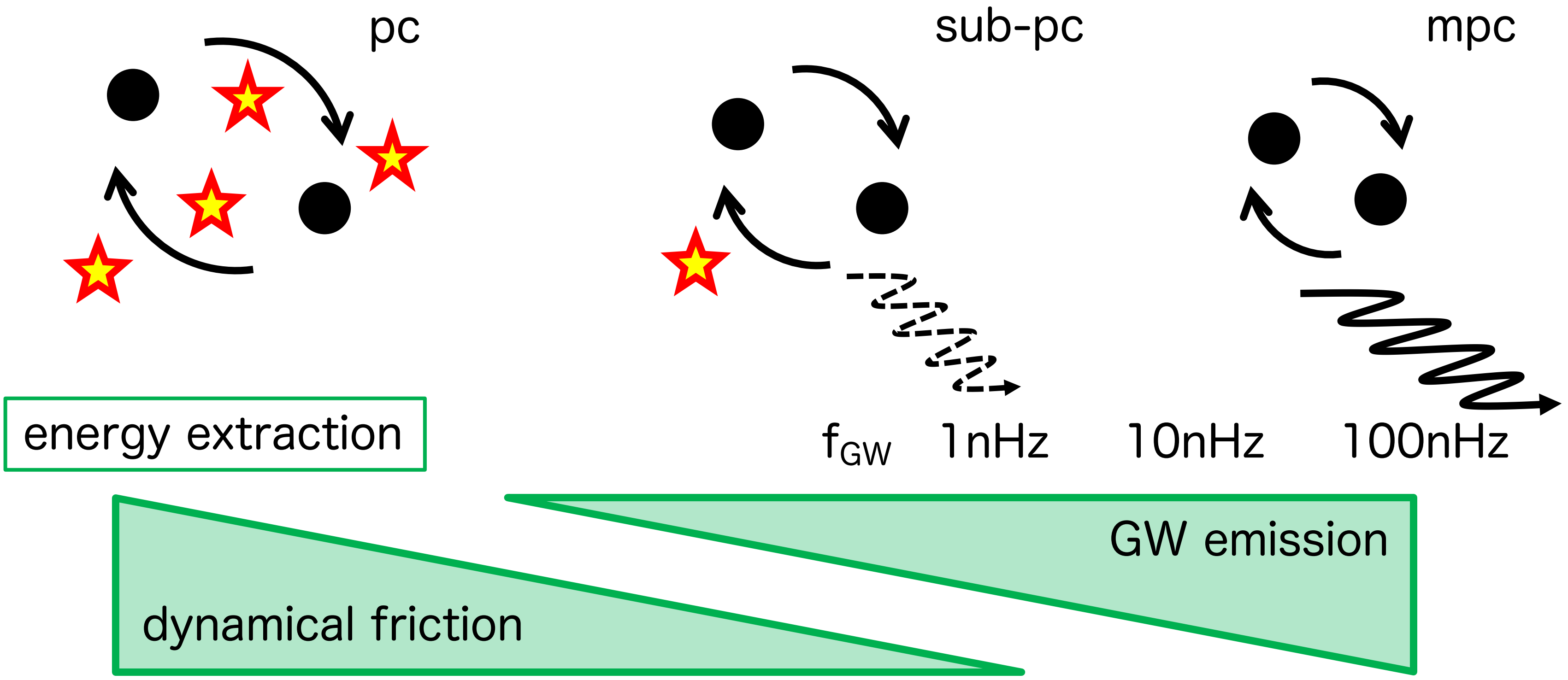
- 10^6 ~10^9 M_{sun}
- discovered by dynamics and energetics
- recently image was obtained
- correlation between SMBH mass and galactic quantities such as bulge mass
- co-evolution with galaxy
- unknown : formation & evolution
  → galaxy merger is a key



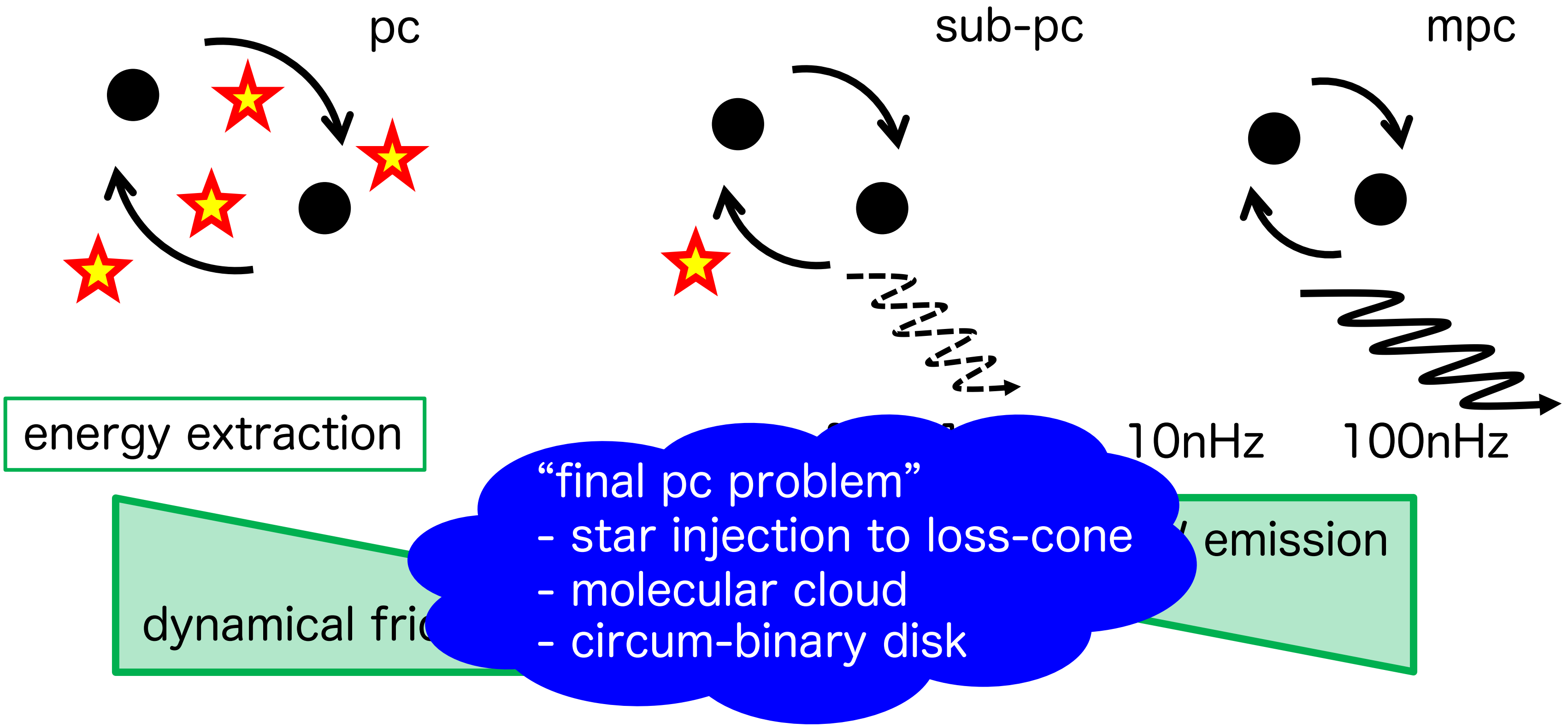
galaxy merger & SMBH binary



SMBH binary evolution



SMBH binary evolution



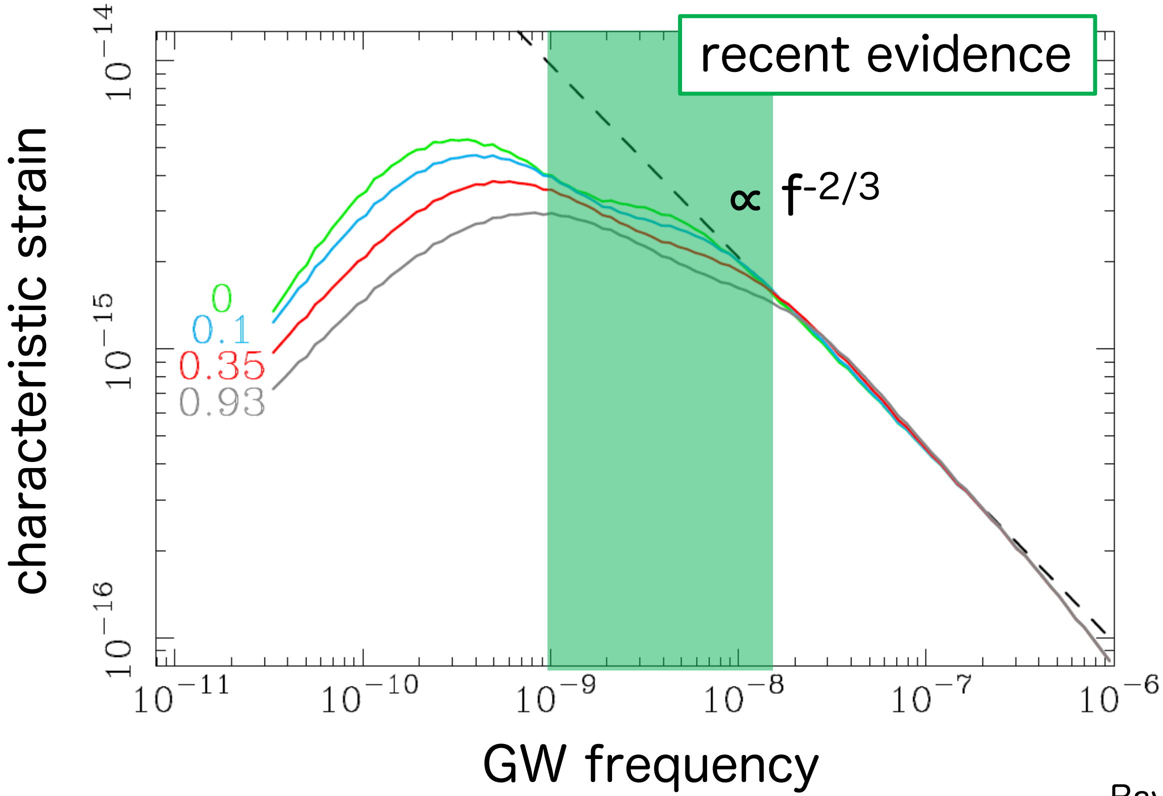
GW frequency

typical GW frequencies

$$f_{\rm GW} = 2.3 \times 10^{-8}\ {\rm Hz} \left(\frac{a}{1\ {\rm mpc}}\right)^{-3/2} \left(\frac{m}{10^6 M_\odot}\right)^{1/2}$$

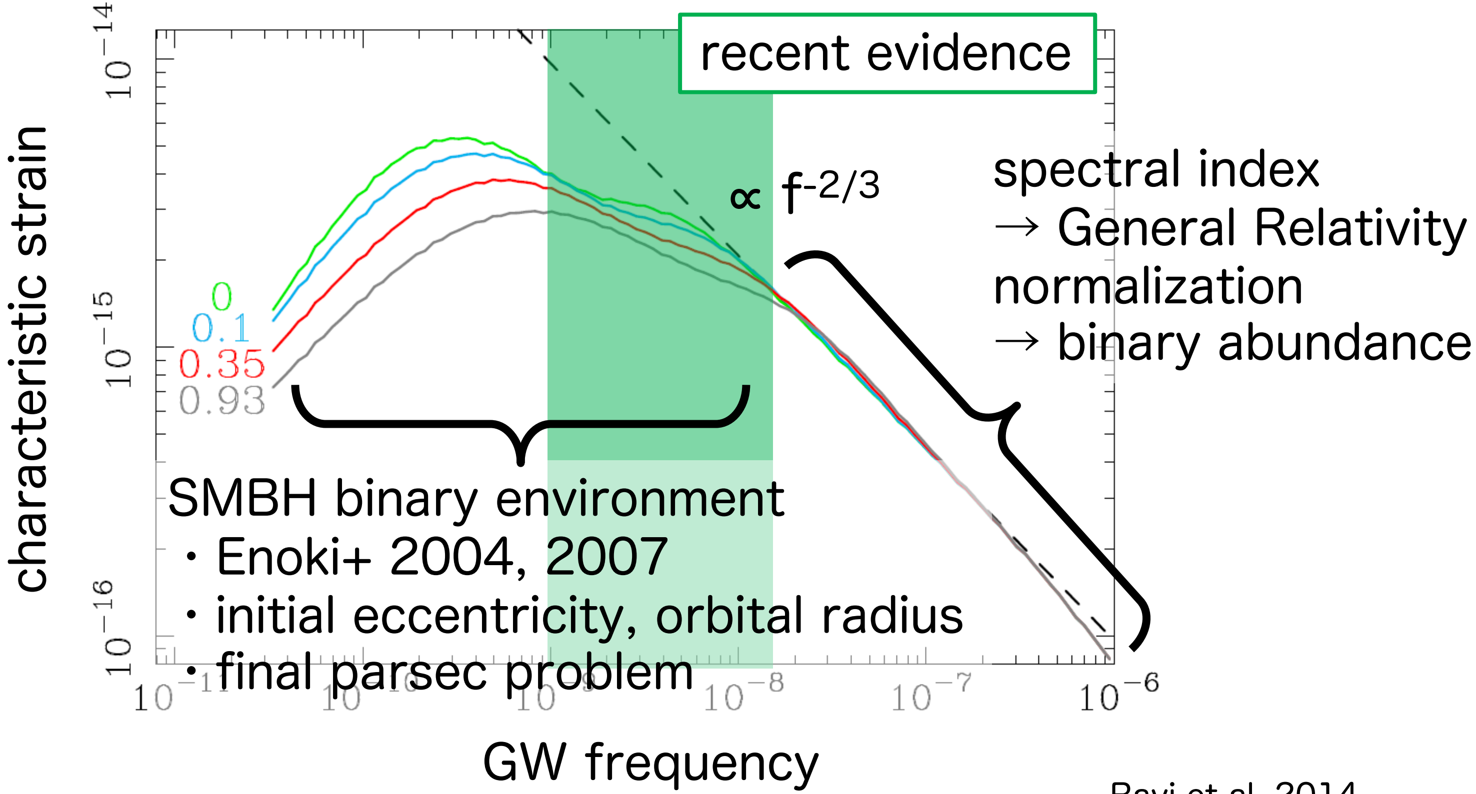
$$= 4.4 \times 10^{-9}\ {\rm Hz} \left(\frac{a}{30\ {\rm mpc}}\right)^{-3/2} \left(\frac{m}{10^9 M_\odot}\right)^{1/2}$$

GW background spectrum



Ravi et al. 2014

GW background spectrum



Ravi et al. 2014

2. Pulsar Timing Array

PTA projects

IPTA (International PTA consortium)

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

emerging PTAs

- CPTA (China)
- MPTA (South Africa)

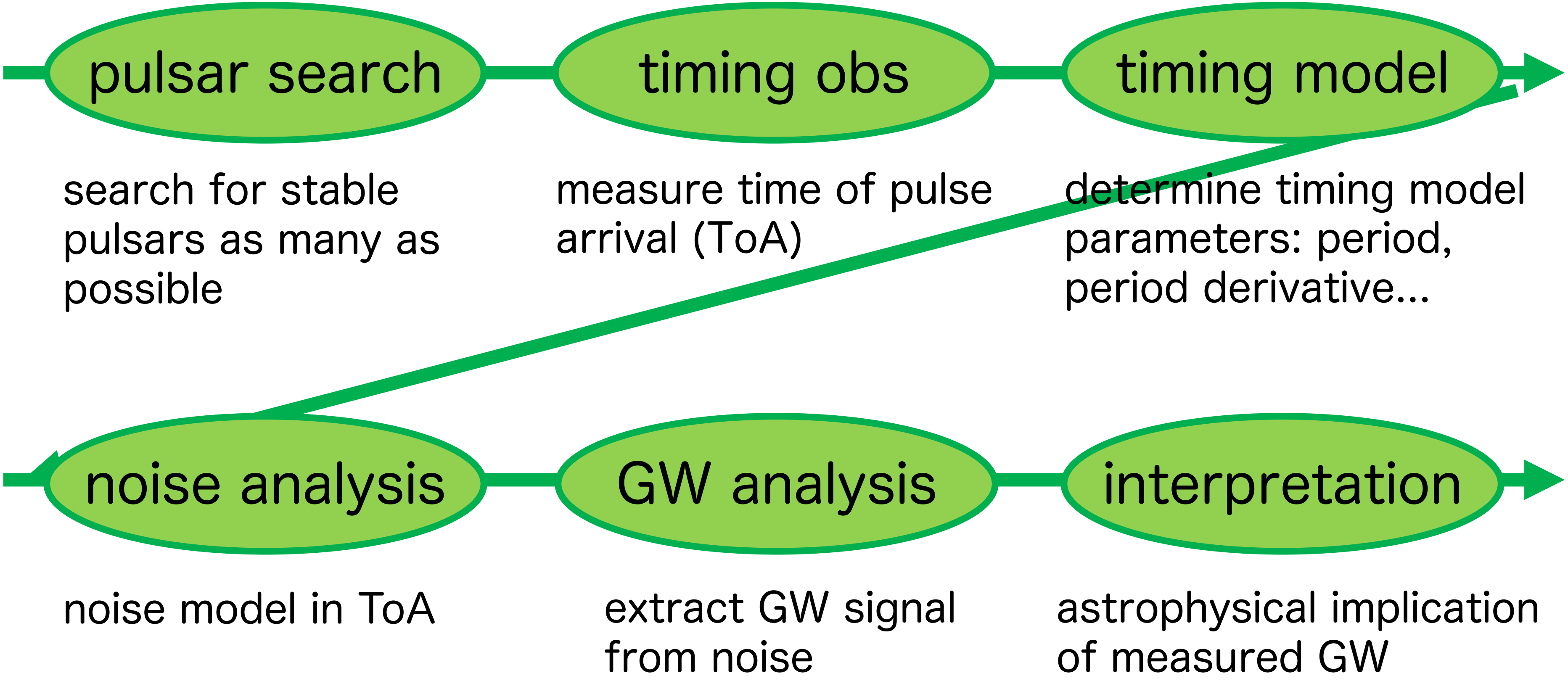
These are independent groups but cooperate closely.

Indian PTA

India-Japan collaboration

- uGMRT (SKA pathfinder)
- low frequency (250-1450MHz)
  → precise dispersion measure
- 1st data release in 2022
- 2nd data release soon

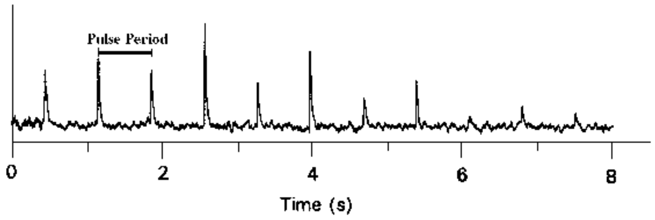
PTA flowchart



folding

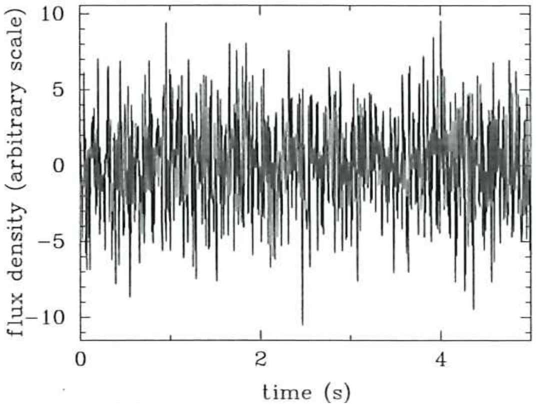
Most of pulsars are so dim that individual pulses cannot be detected and folding is necessary.

high S/N



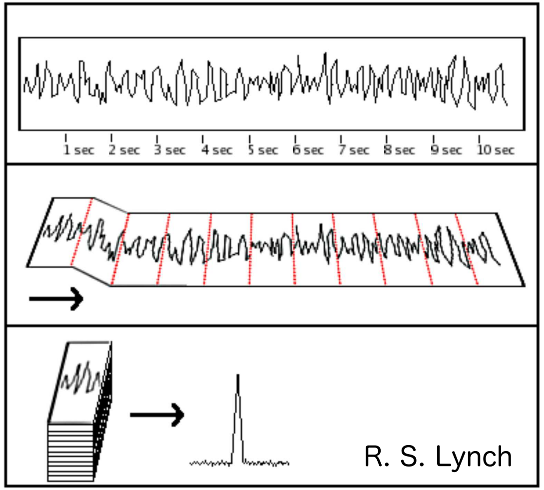
Manchester & Taylor (1977)

low S/N



the handbook of pulsar astronomy

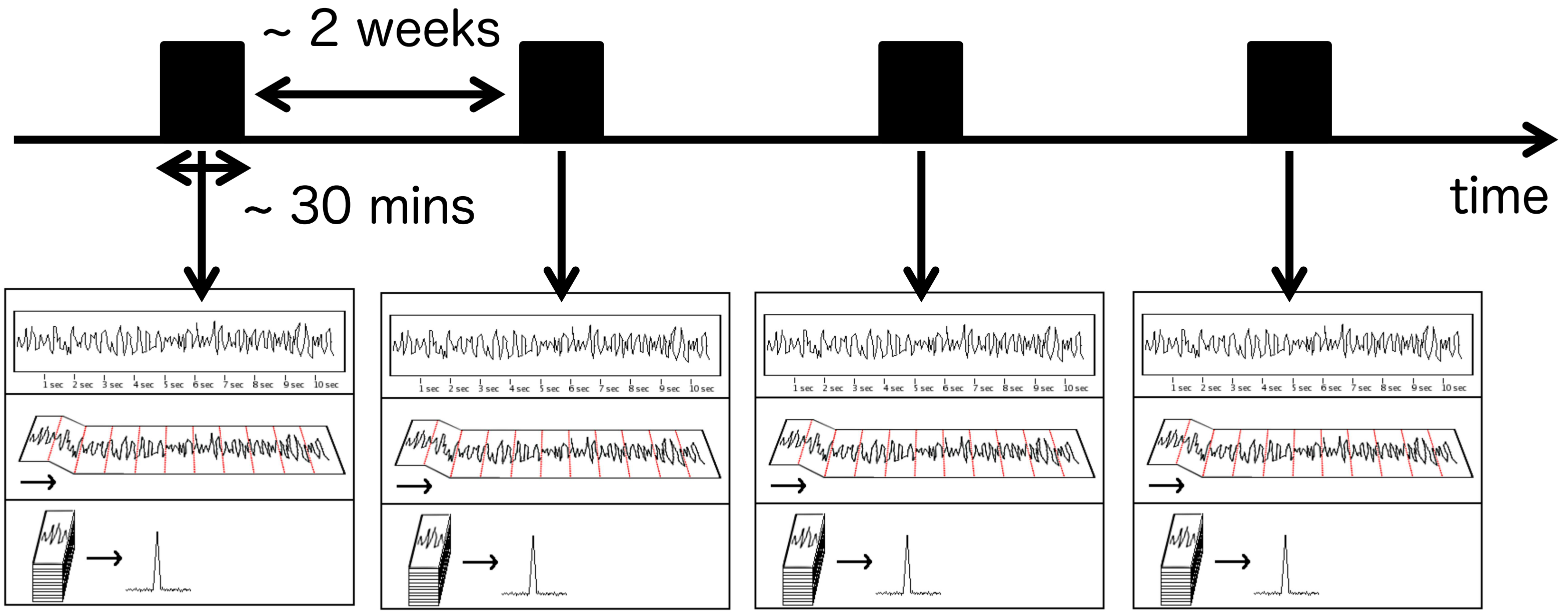
folding



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 model

deterministic model of
pulse arrival time

- pulsar period & its derivative
- dispersion measure
- pulsar position and motion
- Earth motion
- gravitational fields of solar system objects
- pulsar orbital parameters (if binary)

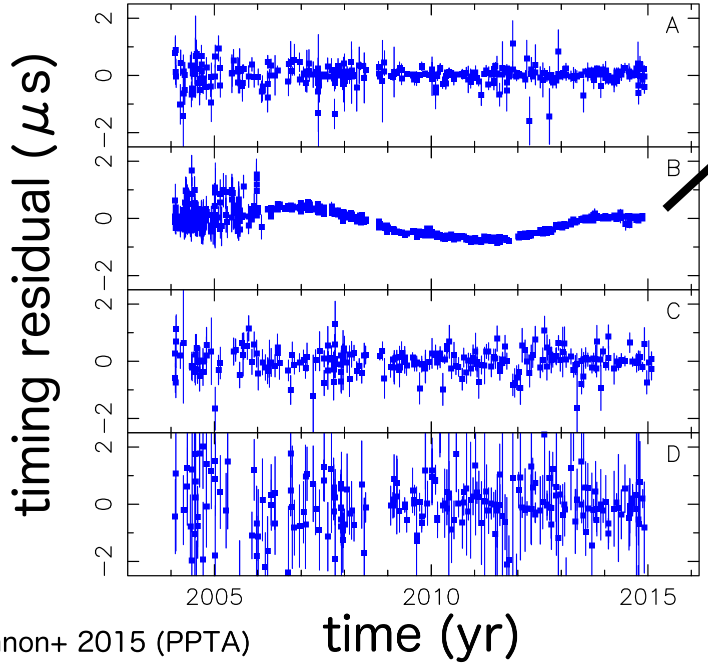
→ we can predict Time of Arrival

Shapiro delay due to solar system objects

Shapiro delay due to Sun	112 μs
Shapiro delay due to Venus	0.5 ns
Shapiro delay due to Jupiter	180 ns
Shapiro delay due to Saturn	58 ns
Shapiro delay due to Uranus	10 ns
Shapiro delay due to Neptune	12 ns
Second order Solar Shapiro delay	9 ns

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.
  → (Hellings & Downs correlation)
- Extract GW signal by modeling noises

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

・independent on radio frequency : include GWs

・dependent of radio frequency : ISM effects

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

GW signal

features of GW signal in timing residual

1. temporal correlation of O(1) years

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

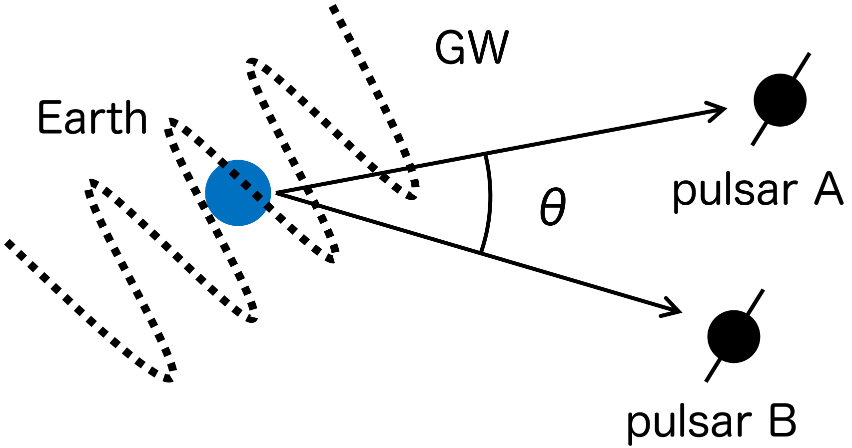
2. common to multiple pulsars
   → Common Red Signal (CRS)

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

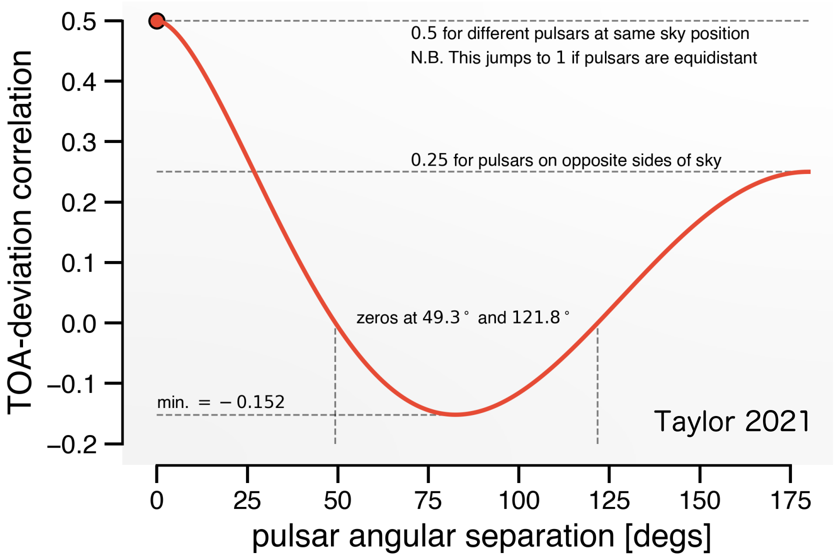
Hellings & Downs correlation

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 ← (Japan)
・NANOGrav
・PPTA
・CPTA

conclusion
・GW background signal : 2~4σ → evidence (~~detection 5σ~~)
・results from different PTAs are roughly consistent
・consistent with that from SMBH binaries
・cannot reject other sources

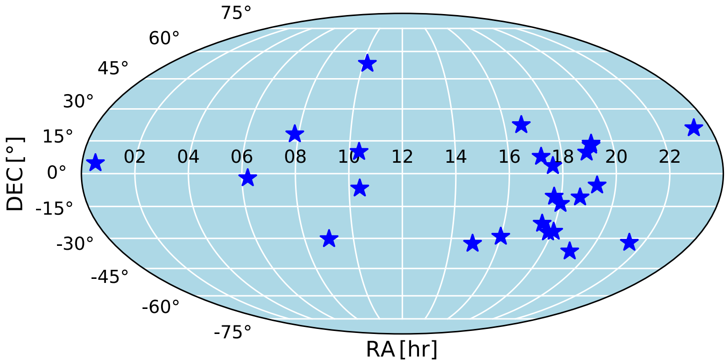
EPTA+InPTA

focus on EPTA+InPTA (2023)
similar analysis method for other PTAs
show comparison later

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

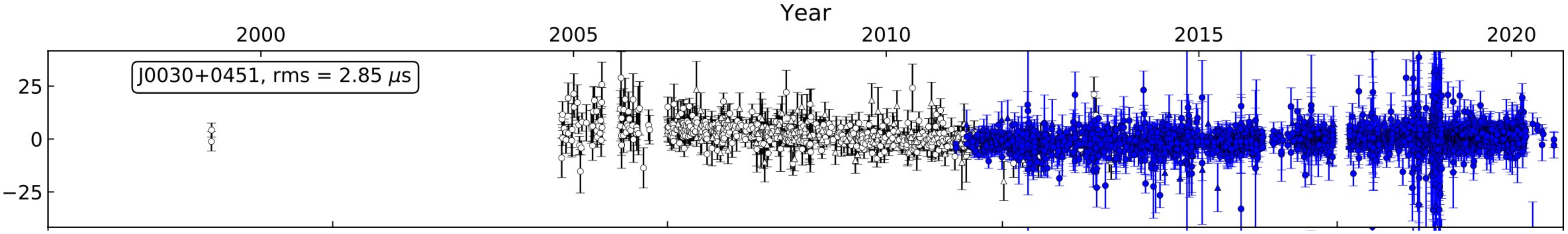
InPTA
- uGMRT
- 10 pulsars, 3.5 years
- low-frequency observation

pulsar distribution



noise model

timing residual of J0030+0451

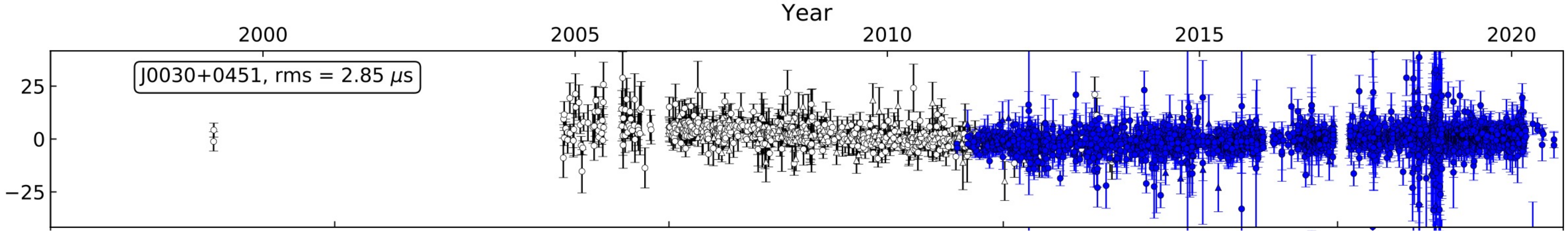


select noise model & estimate parameters from timing residual

・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 Models	Red noise			DM noise			Time span
			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_{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
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

types of red noise

・PSRN : pulsar specific red noise

・CURN : common uncorrelated red noise

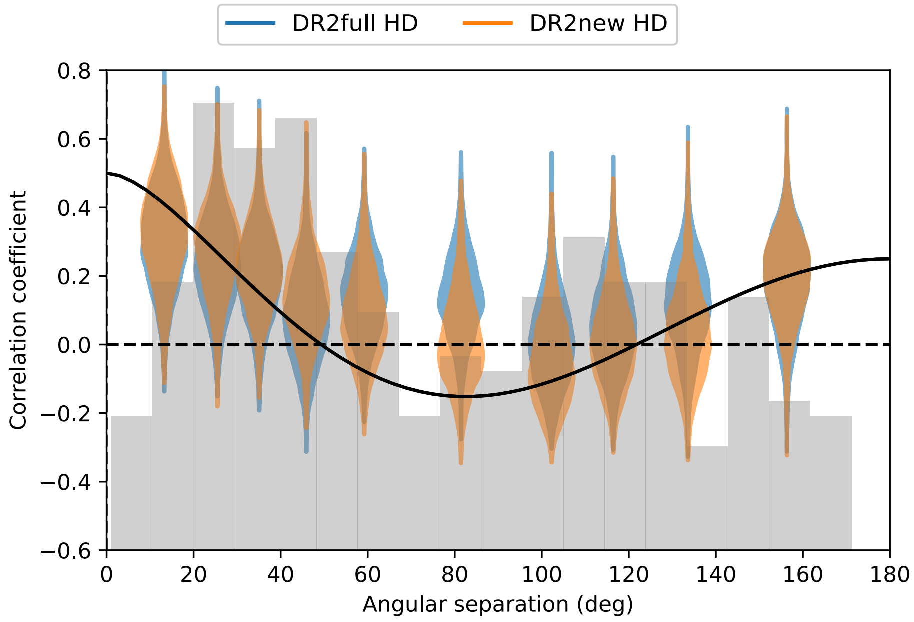
- GWB : common + quadrupole (GW background)
- CLK : common + monopole (clock error)
- EPH : common + dipole (solar system ephemeris error)

These can be identified by studying inter-pulsar correlation.

HD correlation

inter-pulsar correlation for Common Red Signal

- 25 pulsars → 300 pairs
- 10 angle bins
- 30 pairs in each bin
- roughly consistent with HD curve 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"

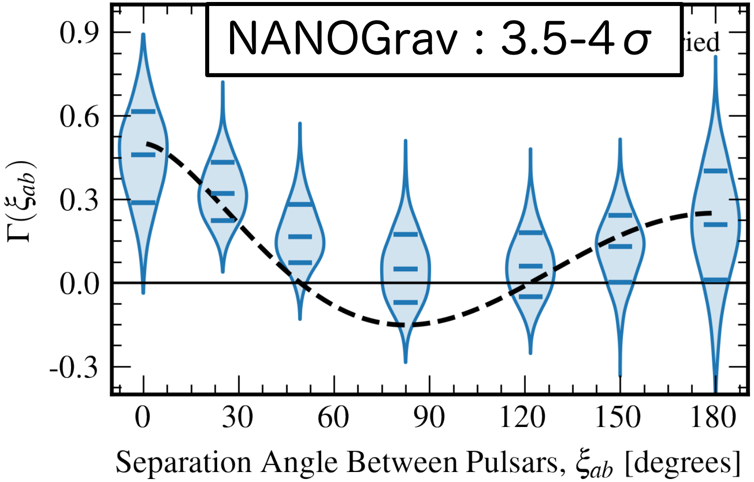
ID	Model	DR2full ENTERPRISE	DR2full FORTYTWO	DR2full+ ENTERPRISE	DR2new ENTERPRISE	DR2new FORTYTWO	DR2new+ ENTERPRISE
1	PSRN + CURN	–	–	–	–	–	–
2	PSRN + GWB	4	5	4	60	62	65
3	PSRN + CLK	< 0.01	< 0.01	< 0.01	0.2	1.2	0.3
4	PSRN + EPH	< 0.01	$\sim 10^{-4}$	< 0.01	0.2	0.2	1.3
5	PSRN + CURN + CLK	2	1	2.7	0.8	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

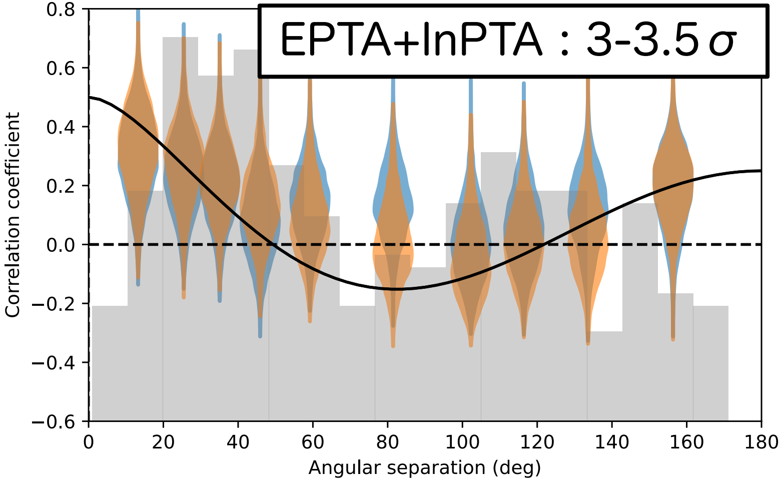
"PSRN + GWB" is most favored with 0.05% (~3σ) significance

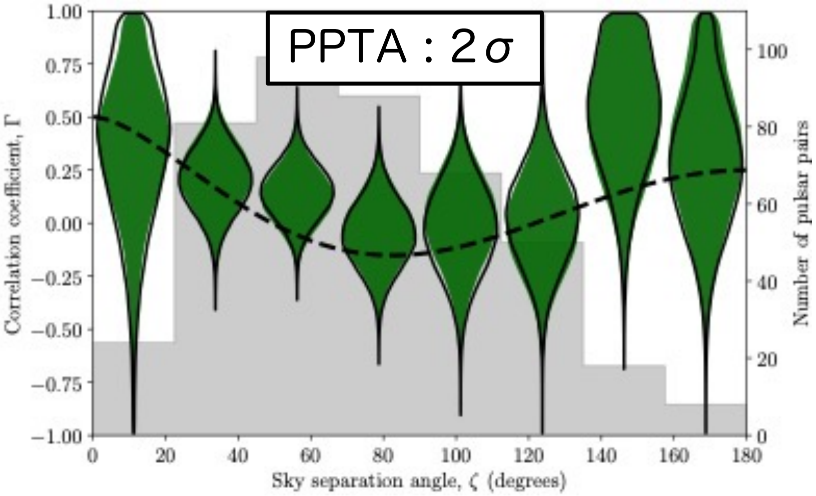
comparison : HD

IPTA collaboration 2024

- comparison of inter-pulsar correlation
- roughly consistent

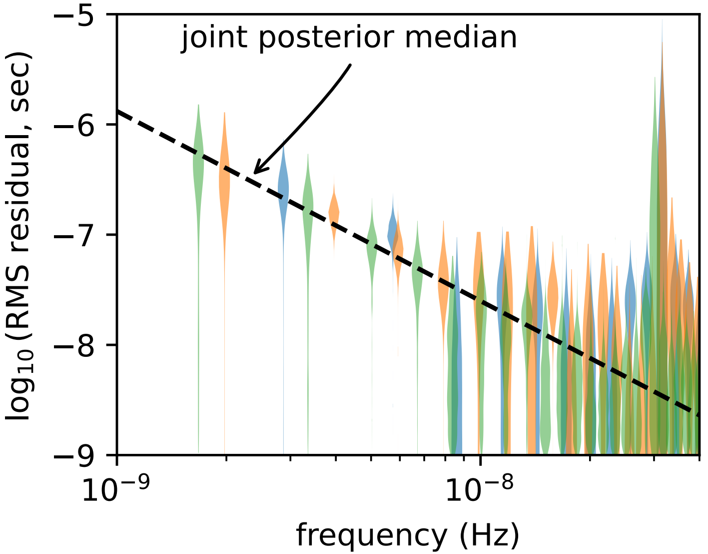


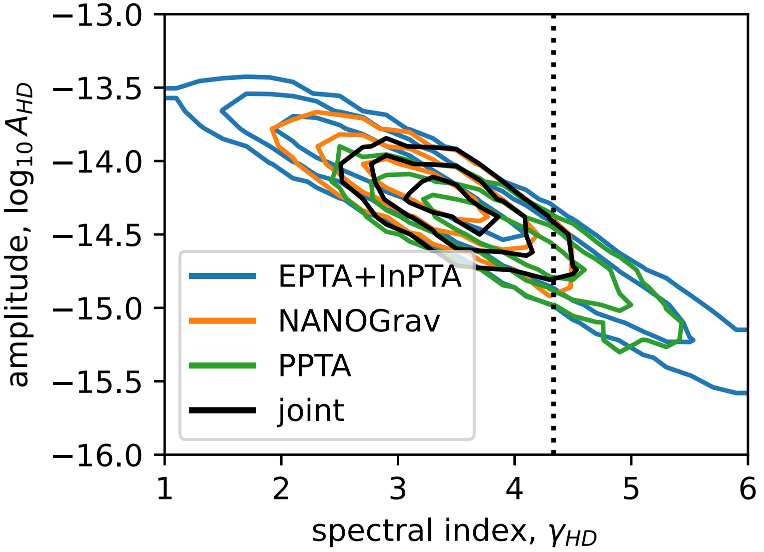




comparison : power spectrum

IPTA collaboration 2024: comparison of EPTA+InPTA, NANOGrav & PPTA, which are roughly consistent.



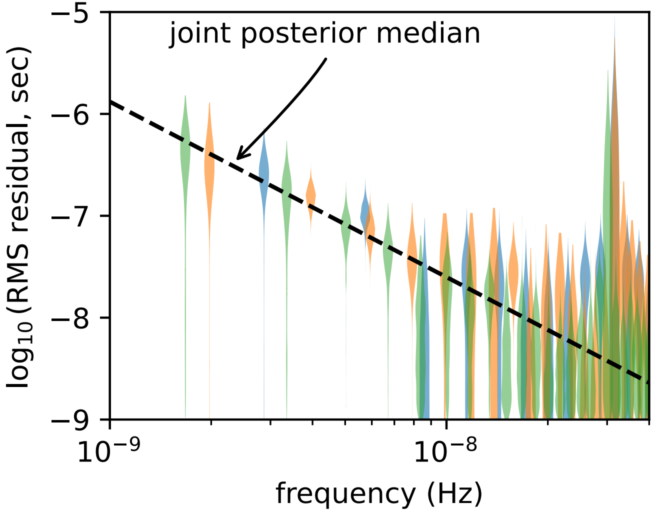


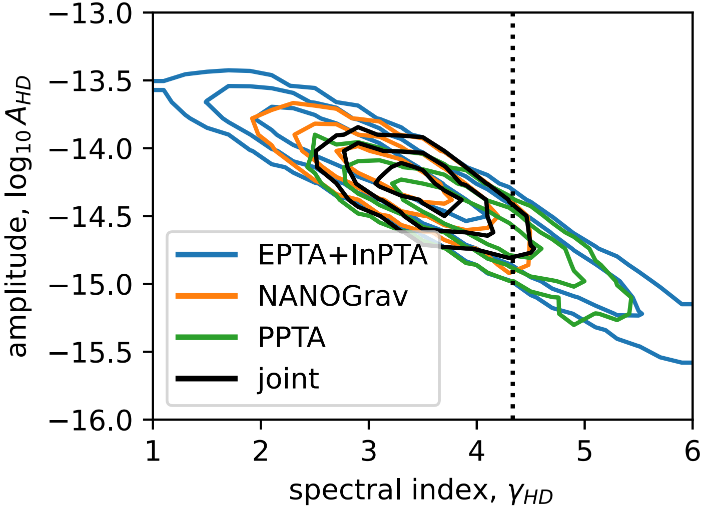
4. Astrophysical Implication

GW background spectrum

Currently, not so precise, but...

- power law index may be deviated from the nominal 13/3?
- deviation from power law?



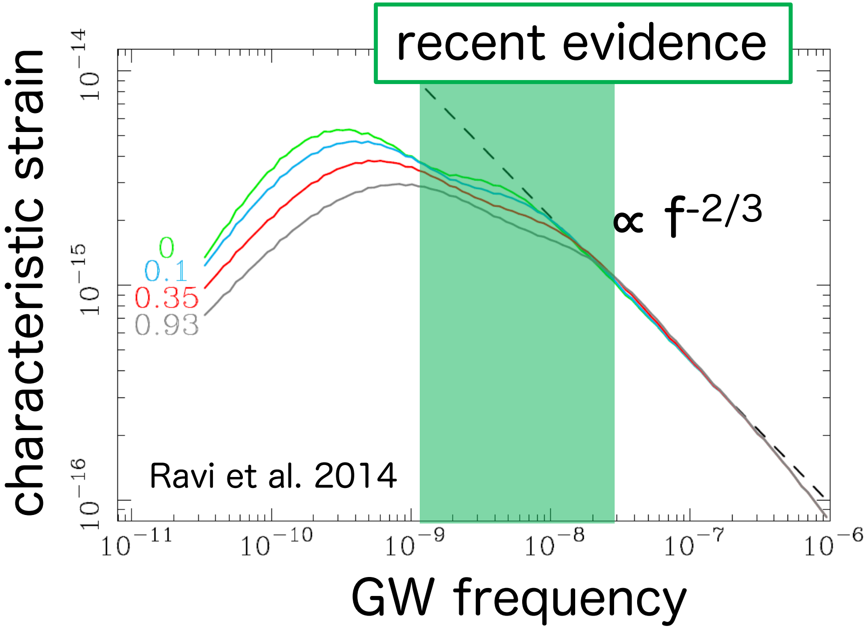


GW background spectrum

frequency range
1×10^{-9} Hz ~ 3×10^{-8} Hz

$$f_{\rm GW} = 4\times10^{-9}\ {\rm Hz}\left(\frac{a}{30\ {\rm mpc}}\right)^{-\frac{3}{2}}\left(\frac{m}{10^9 M_\odot}\right)^{\frac{1}{2}}$$

- a = 10~100mpc ($10^9\ M_{sun}$)
- energy extraction other than GW emission
- not necessarily 13/3
- not necessarily power law
- deviation is useful information!



GW background from SMBH binaries

GWB

population of SMBH binaries

- normalization & shape of spectrum
- galaxy merger history
- evolution from galaxy merger to binary formation
  → time lag between SMBHB formation & galaxy merger

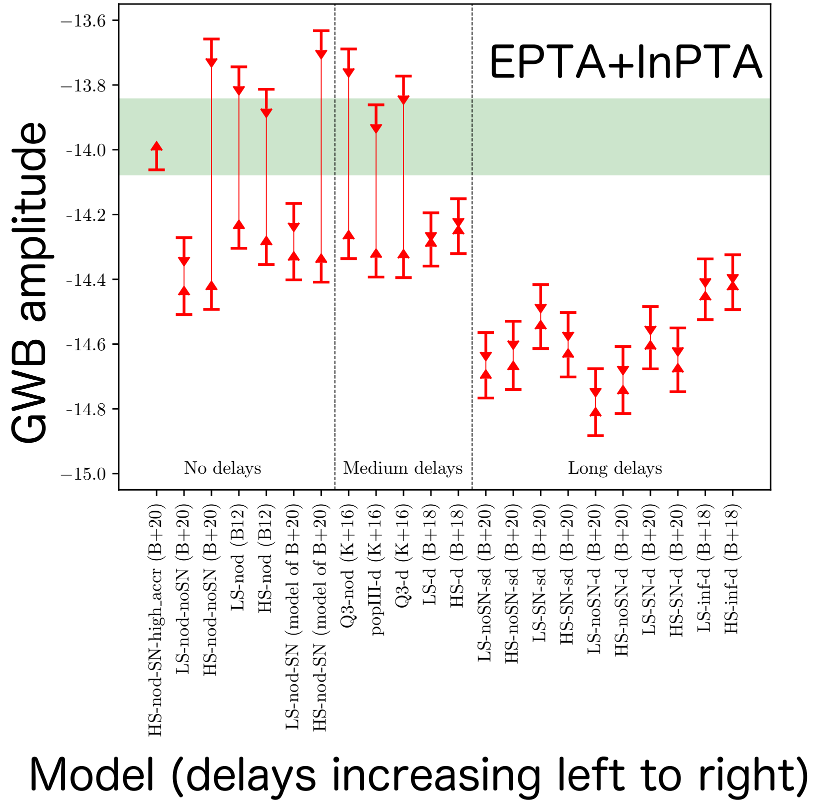
higher harmonics distribution

- shape of spectrum
- initial binary eccentricity

comparison with SMBH models

focus on GWB amplitude

the measured GWB amplitude
is close to the maximum allowed
by galaxy merger history
・rapid SMBH formation
・efficient energy extraction



5. Future Prospects

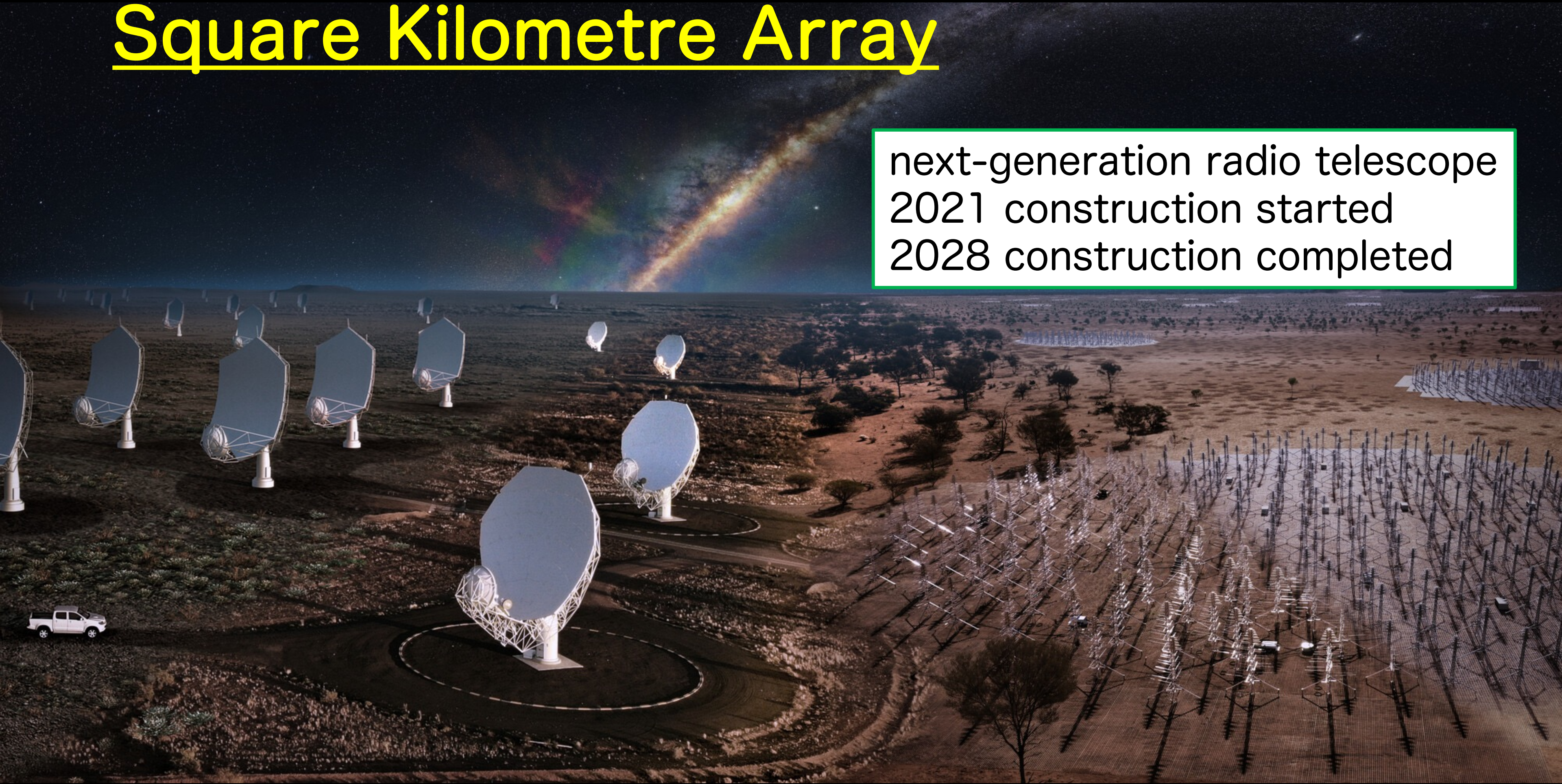
to improve

- 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



next-generation radio telescope
2021 construction started
2028 construction completed

SKA-LOW

THE SKA'S LOW-FREQUENCY TELESCOPE

LOCATION:
AUSTRALIA

FREQUENCY RANGE:
50 MHz–
350 MHz

131,072
ANTENNAS
SPREAD ACROSS **512** STATIONS

MAXIMUM BASELINE:
~65km

SKA-MID

THE SKA'S MID-FREQUENCY TELESCOPE

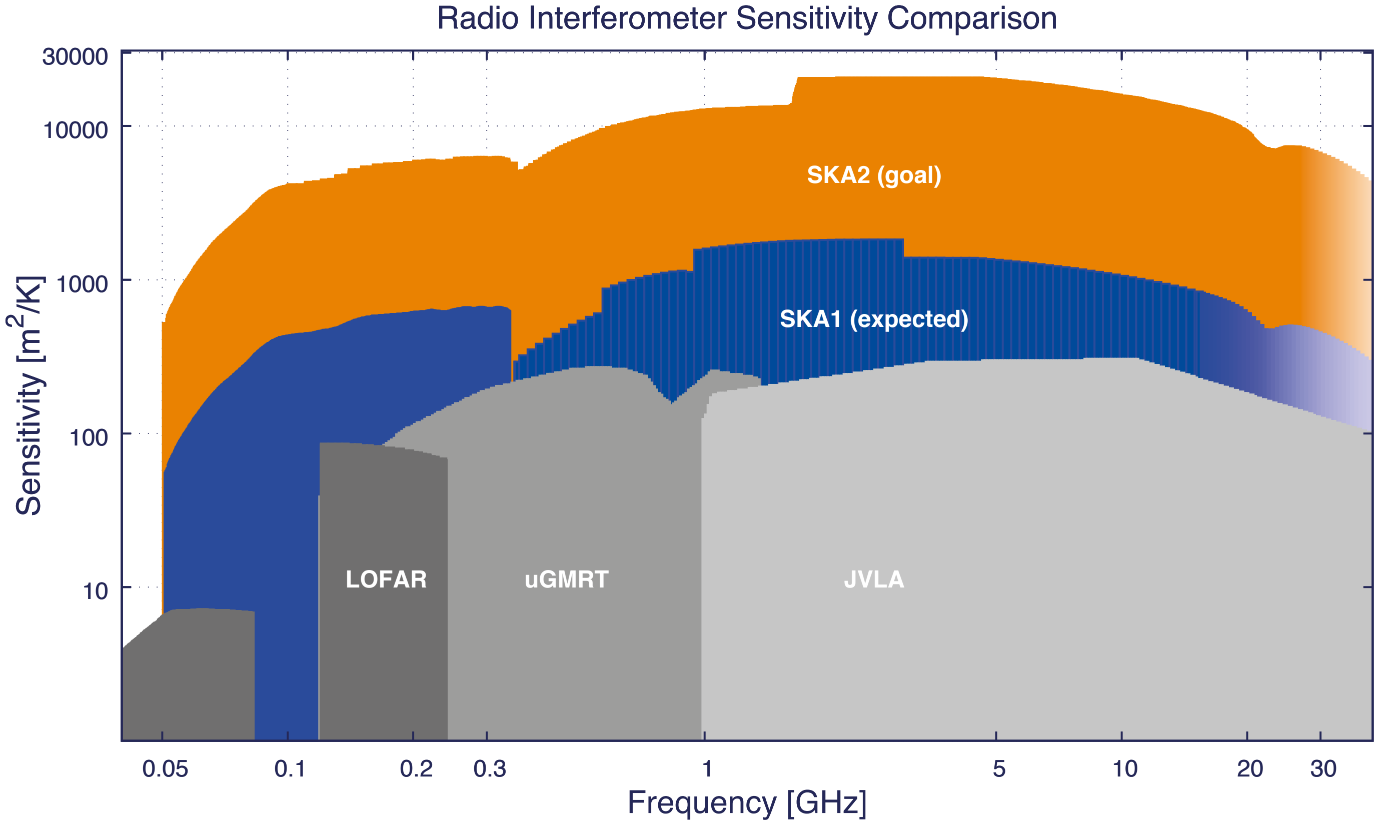
LOCATION:
SOUTH AFRICA

FREQUENCY RANGE:
350 MHz–
15.4 GHz
WITH A GOAL OF 24 GHz

197 DISHES
(INCLUDING 64 MEERKAT DISHES)

MAXIMUM BASELINE:
150km

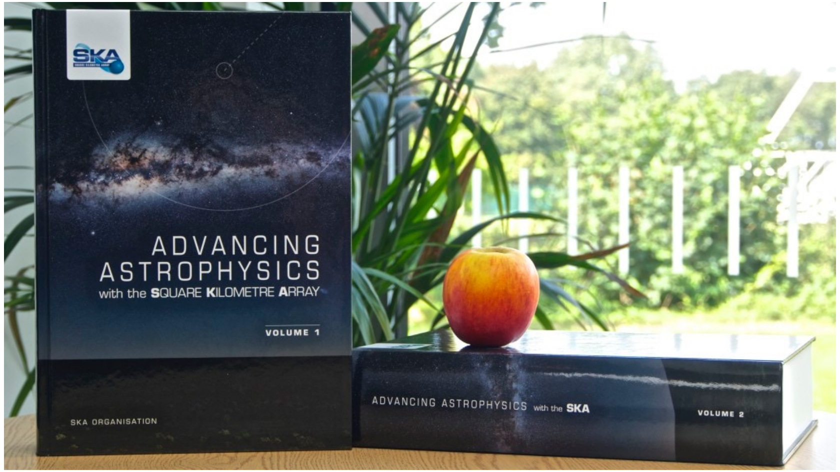
sensitivity



SKA Sciences

- Pulsars
- Cosmic Dawn/Epoch of Reionization
- HI & Continuum Survey
- Galaxy Evolution & Cosmology
- Cosmic Magnetism
- Star & Planet Formation
- Exoplanet & SETI

Science Book
1,000 pages × 2



SKA Japan

SKA Japan

- since 2008
- 250 members
- Chair : N. Sugiyama (Nagoya)
- V. Chair : K. Takahashi (Kumamoto)

Activity

- SWG, EWG
- workshop, webinar
- precursor : MWA, ASKAP

SKA PTA

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

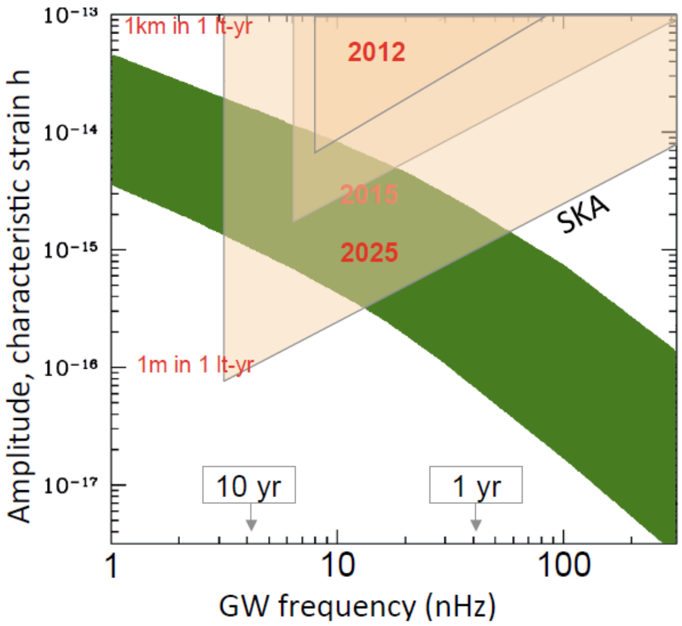
SKA2 survey
- 30,000 normal pulsars
- 3,000 msec pulsars

x3 !

x10 !

SKA-PTA
much more msec pulsars
& much higher sensitivity

SKA1-PTA sensitivity

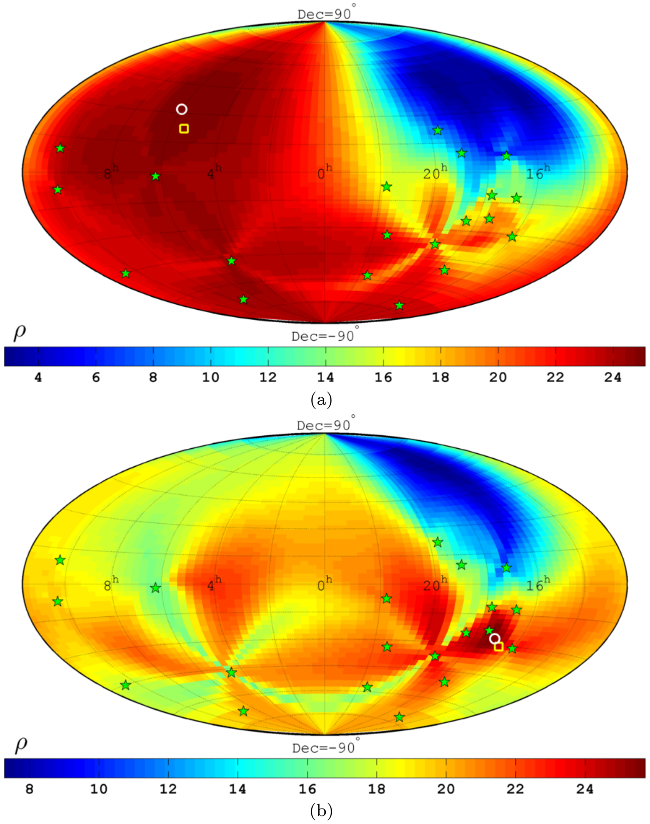


from detection to astronomy

GW source (□)
most likelihood (○)
pulsar (☆)

Zhu+ 2015
- PPTA simulation
- angular resolution of GW source
  → > O(10) deg²
  → GW source cannot be identified

Kato & KT (2023)
- precise pulsar distance from VLBI (< GW wavelength)
- GW angular resolution improves by a few orders



Nano-Hz GW astronomy

$D = 85$ Mpc
$M_1 = 3.2\times10^9\ M_{sun}$
$M_2 = 5.1\times10^7\ M_{sun}$
$a = 0.35$ pc, $e = 0.14$

$D = 156$ Mpc
$M_1 = 9.2\times10^9\ M_{sun}$
$M_2 = 7.5\times10^9\ M_{sun}$
$a = 1.3$ pc, $e = 0.25$

$D = 245$ Mpc
$M_1 = 4.3\times10^9\ M_{sun}$
$M_2 = 5.9\times10^8\ M_{sun}$
$a = 0.12$ pc, $e = 0.02$

future prospects

2023 Evidence of GWB from 4 PTAs
2024 IPTA comparison
2025 IPTA combination : ongoing

MeerKAT, FAST join

GWB detection

single source

GWB power spectrum
→ SMBH evolution model

2029 SKA1

precise GWB power spectrum
→ other sources

203? SKA2

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