Pulsar timing array and the implication

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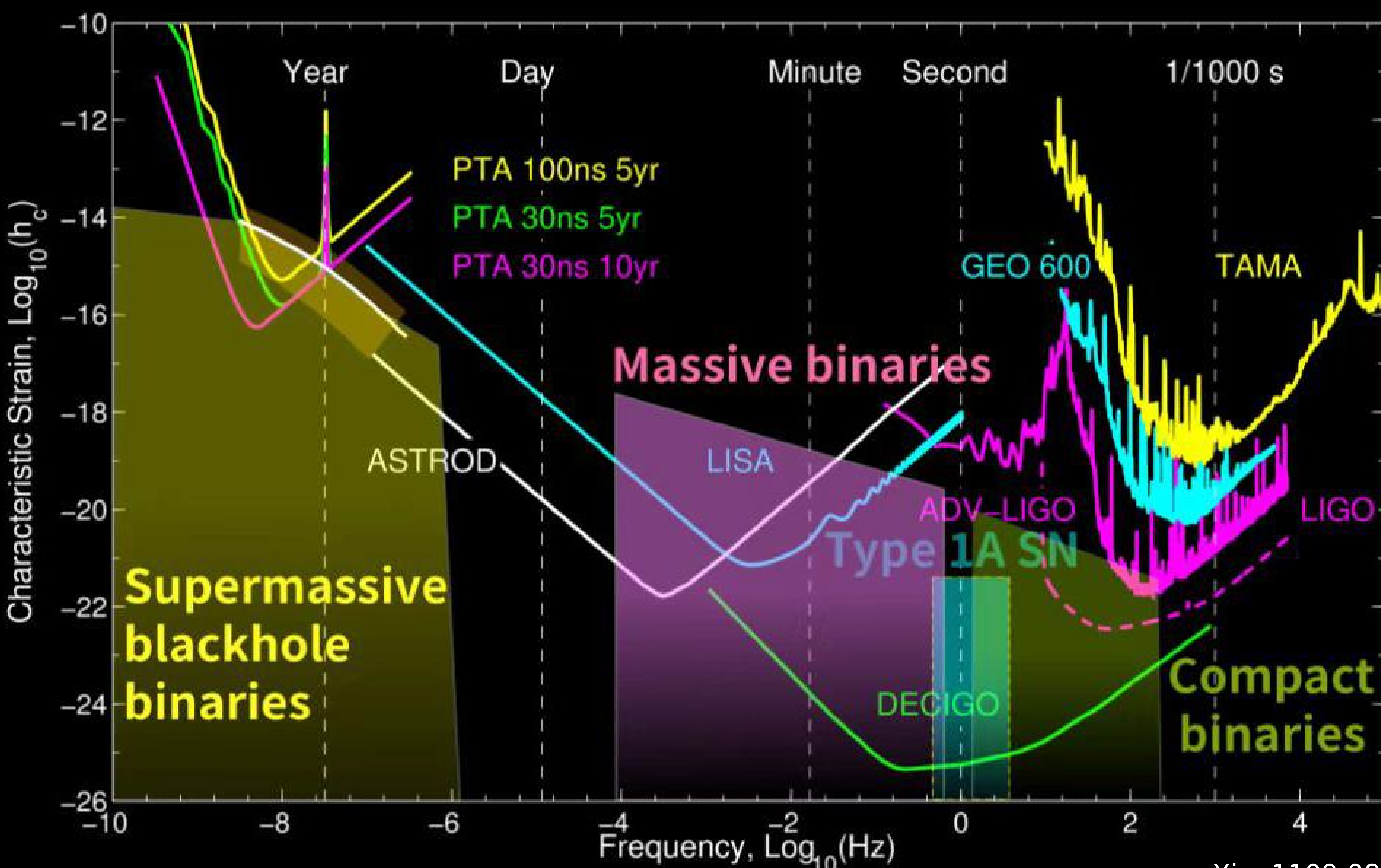
NAOC

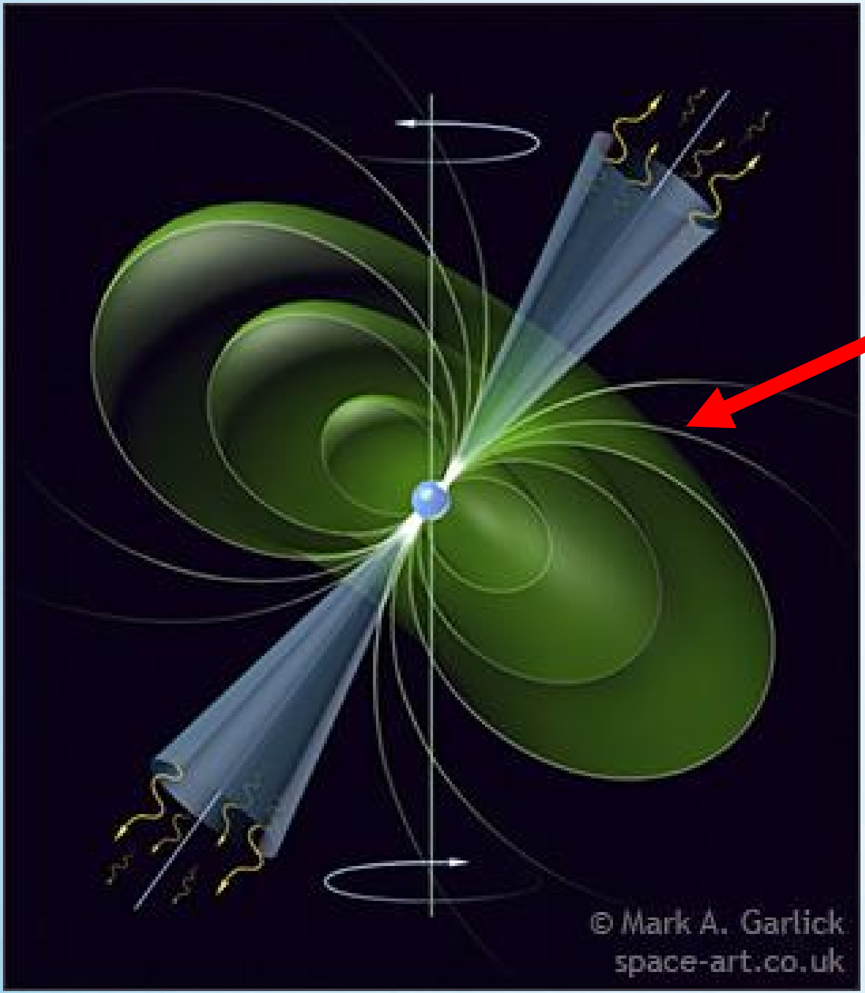
GW ladscape

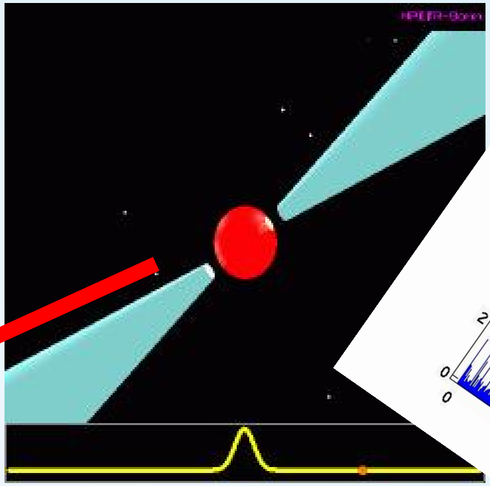


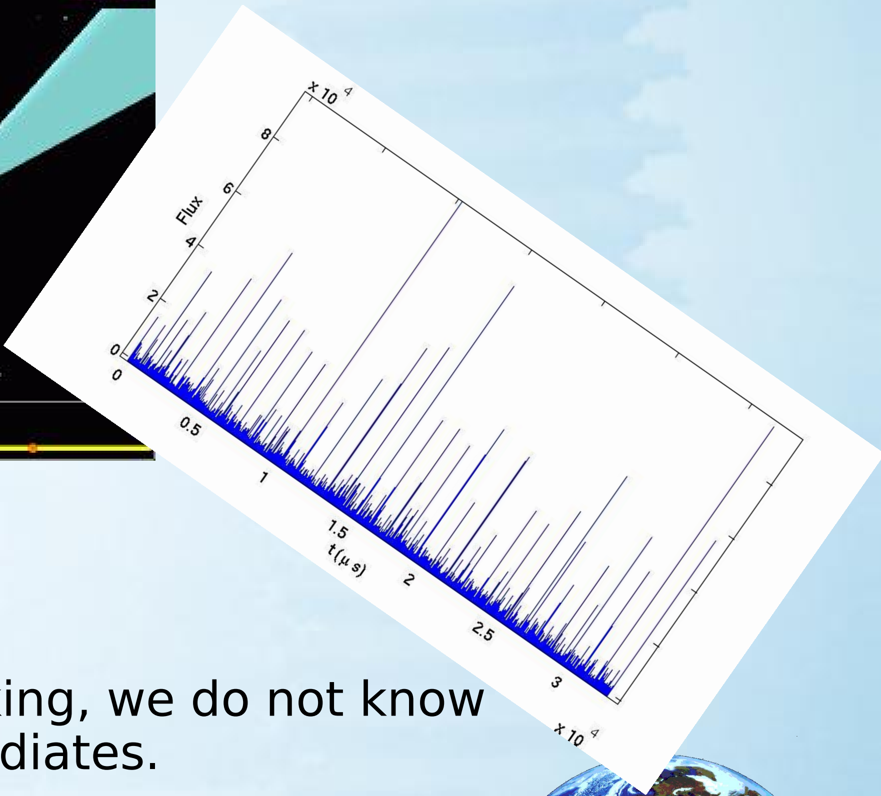
arXiv: 1109.081

Quick guide to the GW detection using pulsar timing array

Phenomenology model of pulsars

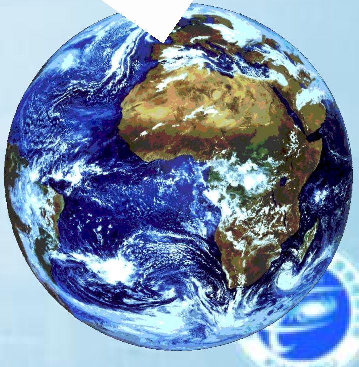






Frankly speaking, we do not know how pulsar radiates.

But the pulse time of arrivals are so accurate.



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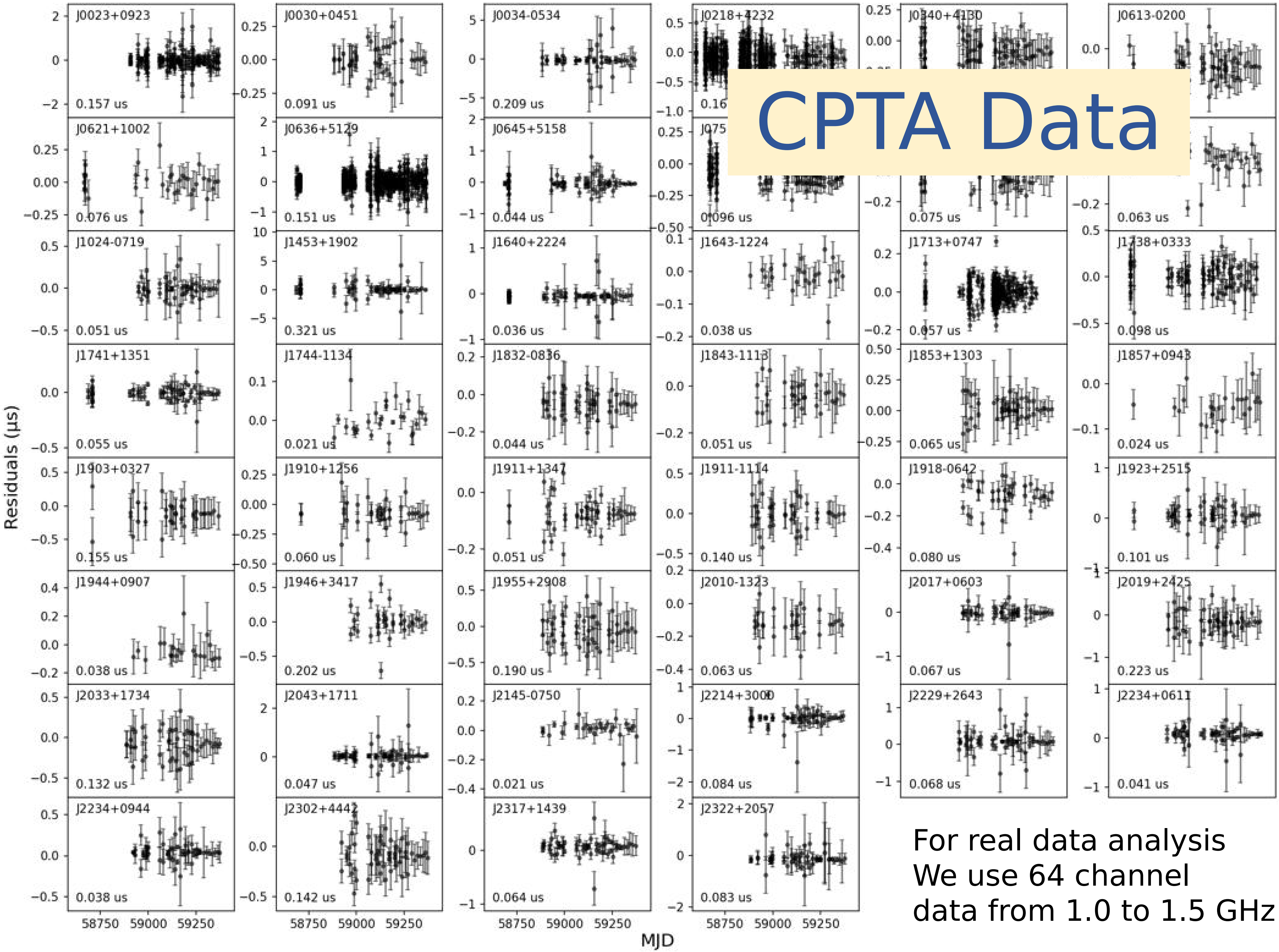
CPTA Data

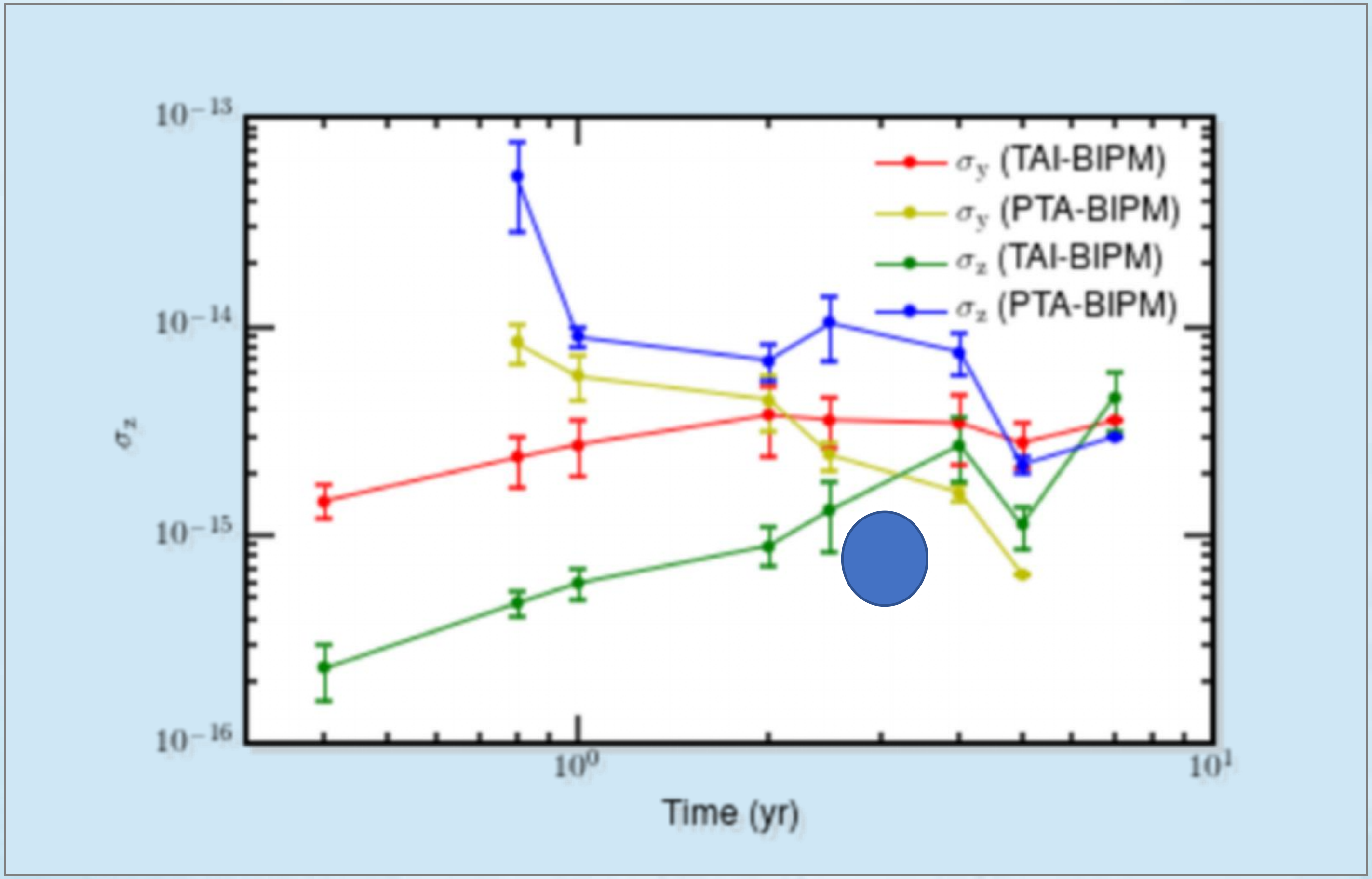


For real data analysis
We use 64 channel
data from 1.0 to 1.5 GHz

What does it means

$$100\text{ns} / 3\text{ yr} = 10^{-7}\text{ s} / 10^{8}\text{ s} \sim 10^{-15}$$

~Measure 1 proton radius over 1 meter and do it over several years



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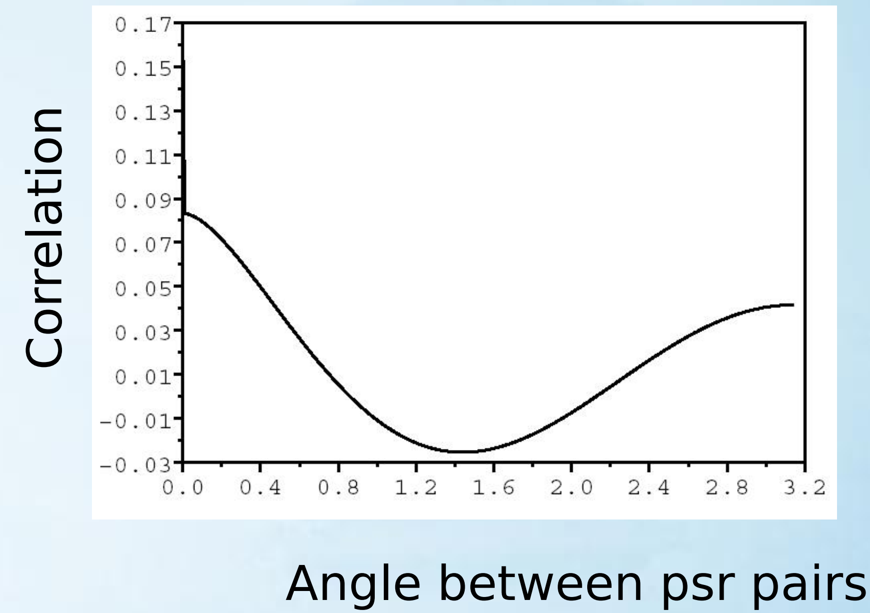
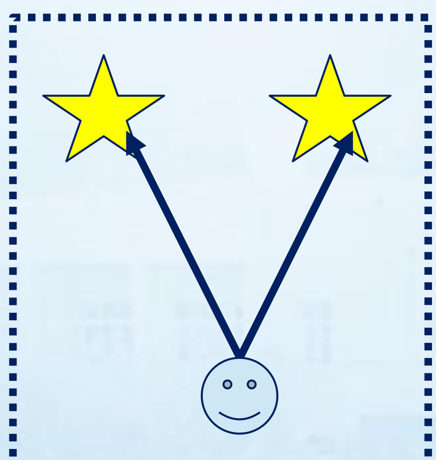
How to identify GW signal?

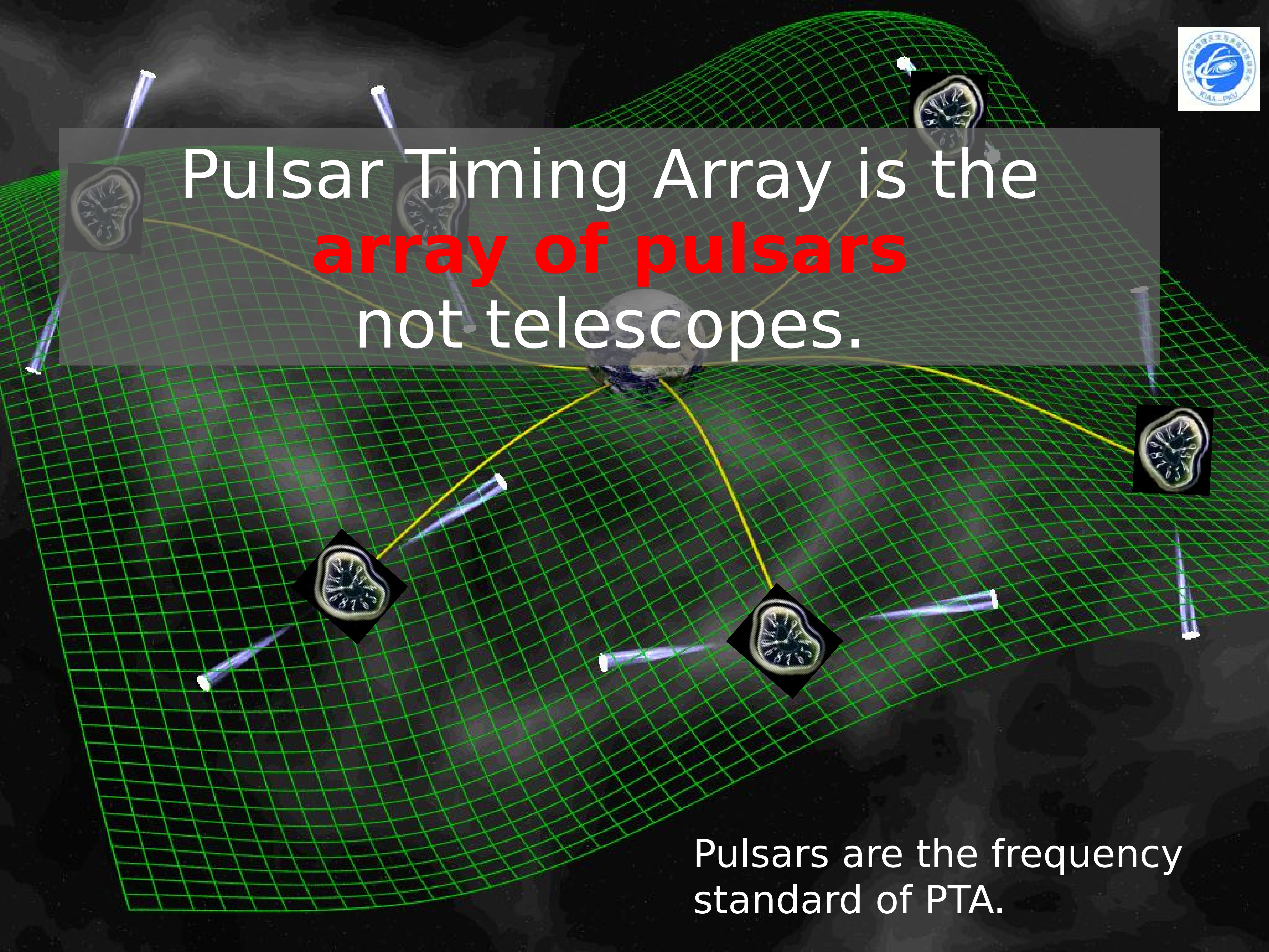
PTA=Multibeam-oneway interferometer





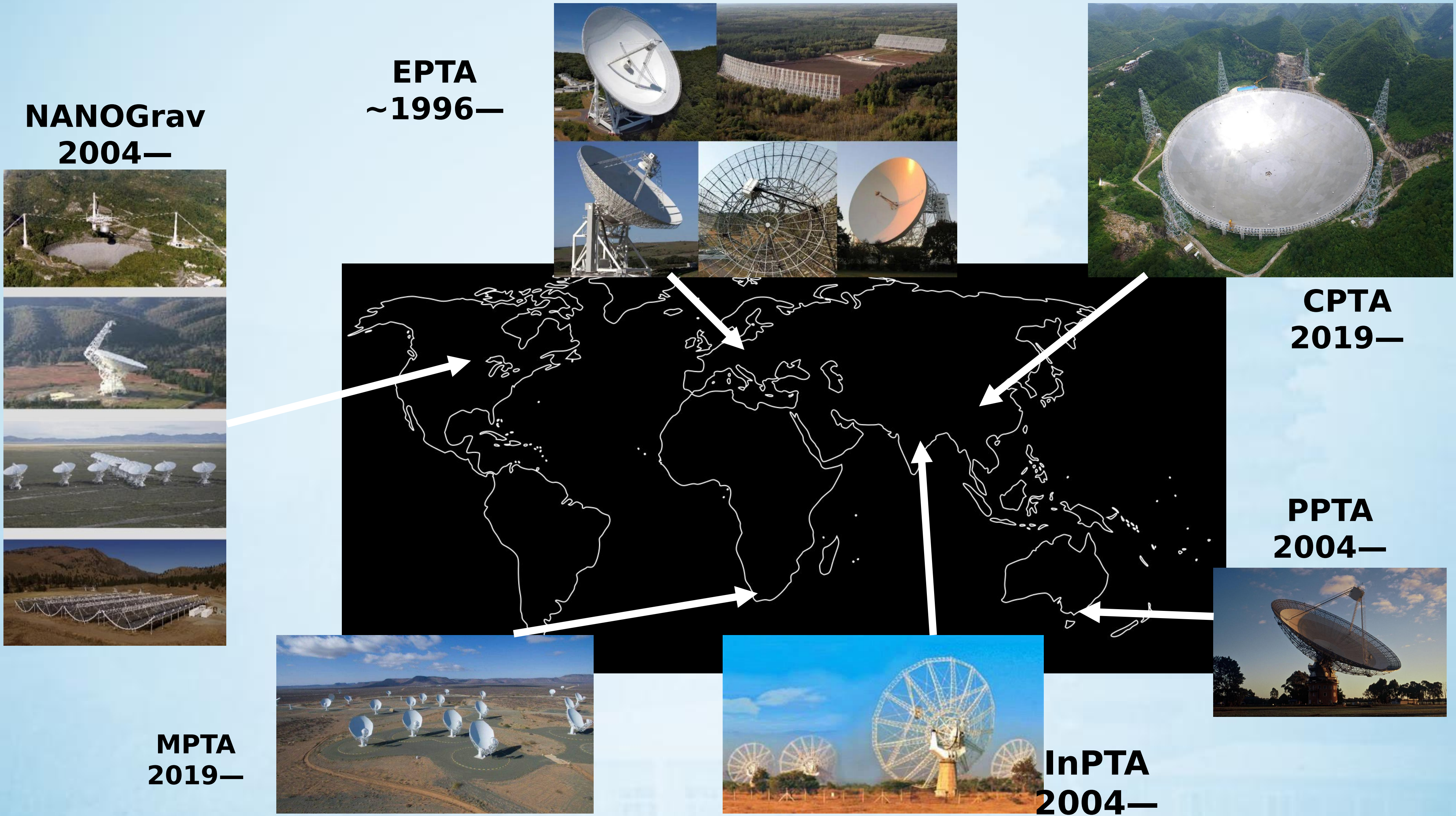
Hellings and Downs 1983

Pulsar Timing Array is the **array of pulsars** not telescopes.



Pulsars are the frequency standard of PTA.

International PTAs



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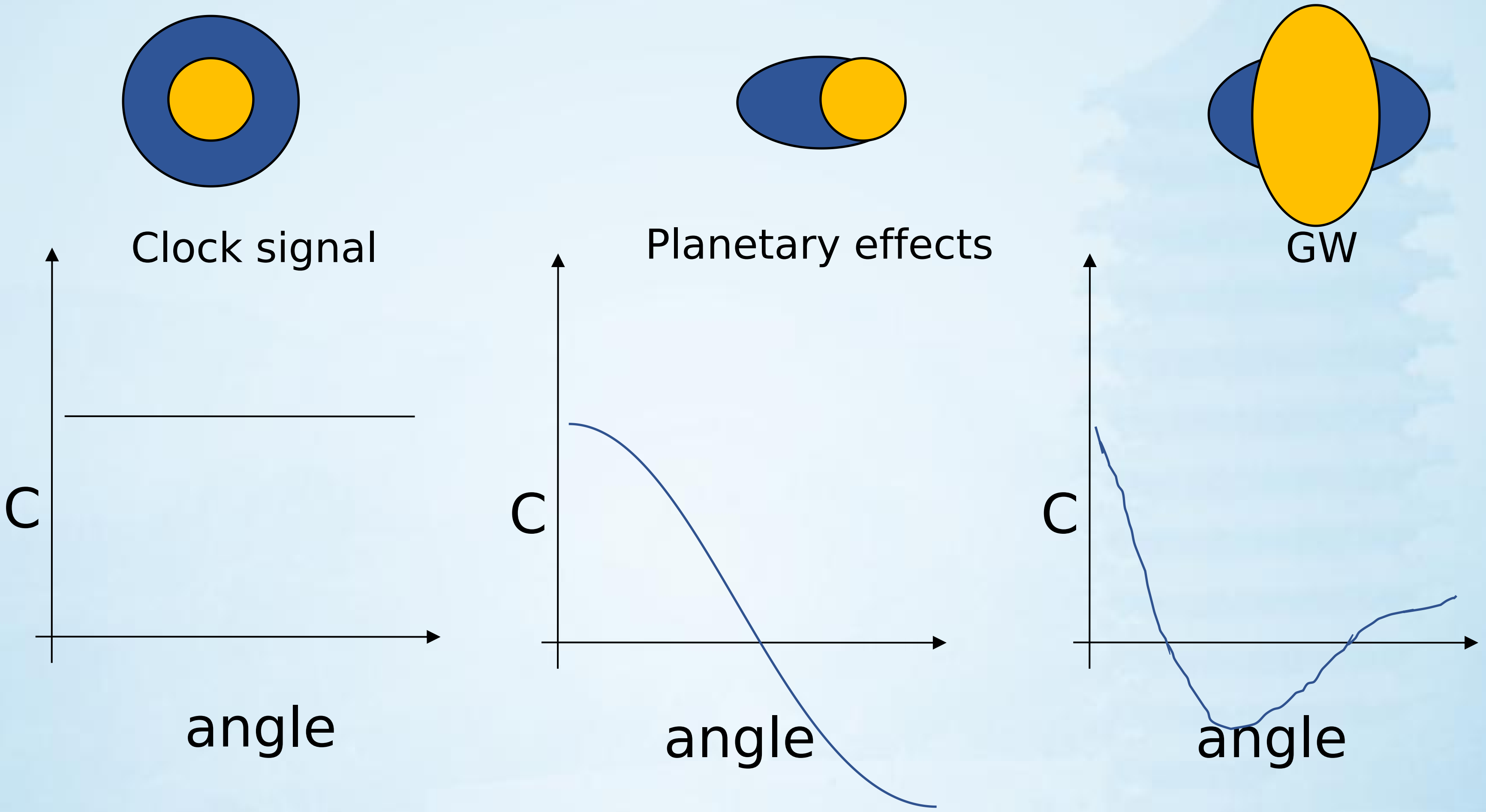
But PTA is not only for GW

Other correlation

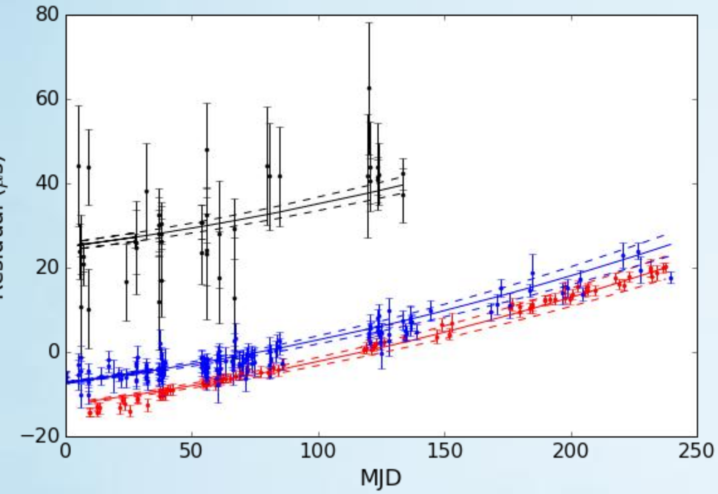


Clock noise

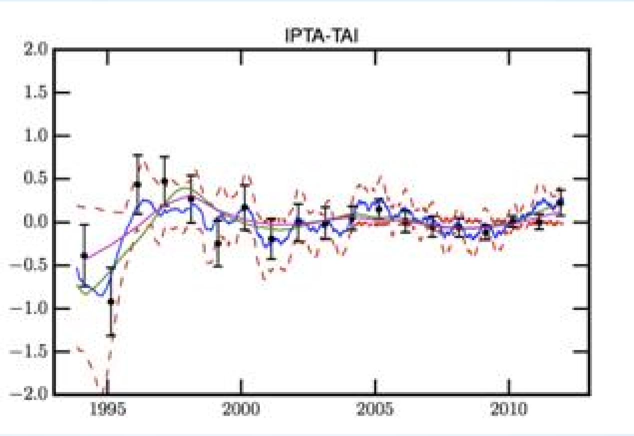
Planet ephemeris

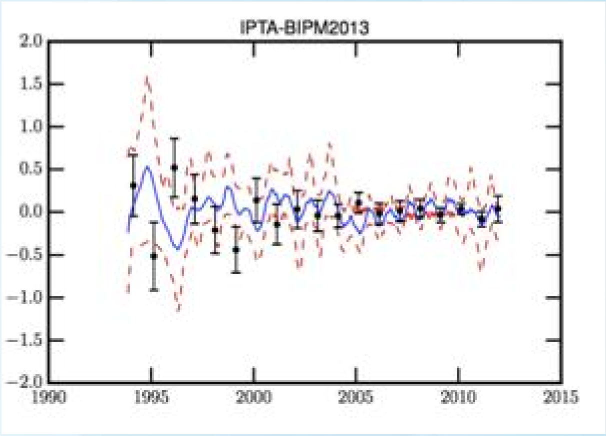
Pulsar to recover local clock

100ns 1yr= 3e-15
100ns 10yr=3e-16



Yunnan 40m, 1e-14 @ 3yr
Unpublished

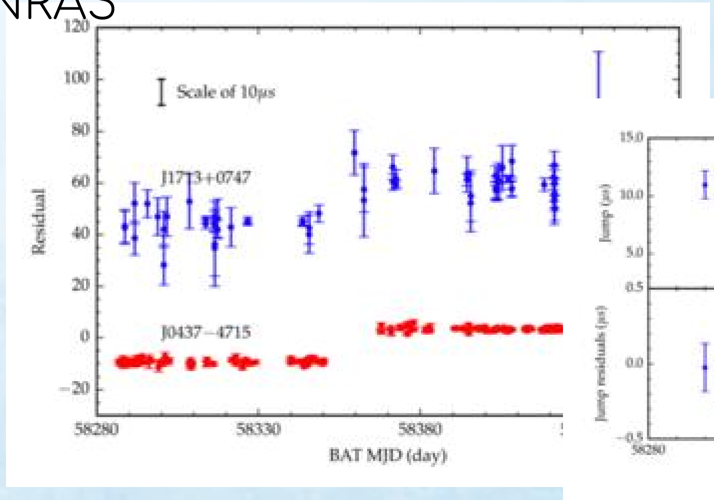


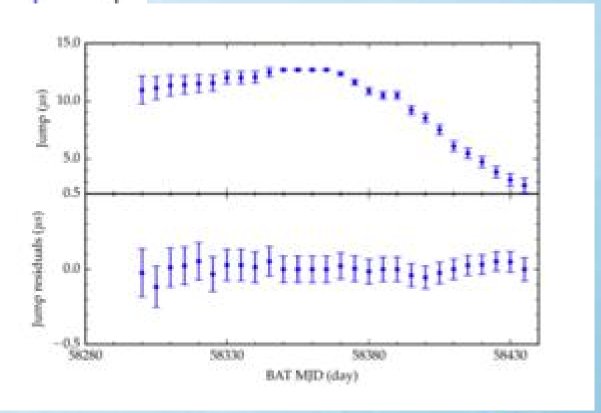


IPTA, 5e-16 @ 20yr

Hobbs, Guo,Caballero, Coles, Lee, et al., 2020, MNRAS

Recover local clock jump at precision level of 80ns.





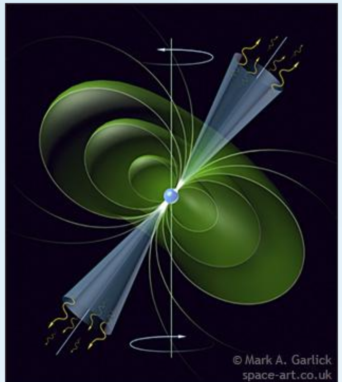
Li et al., 2019,scpma

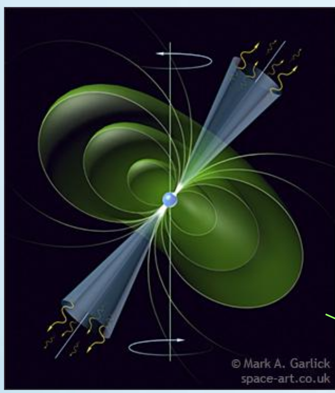
PTA and Solar system dynamics

$$\Delta_{\mathrm{R}\odot} = -\frac{1}{c}\,\vec{r}\cdot\hat{s}$$

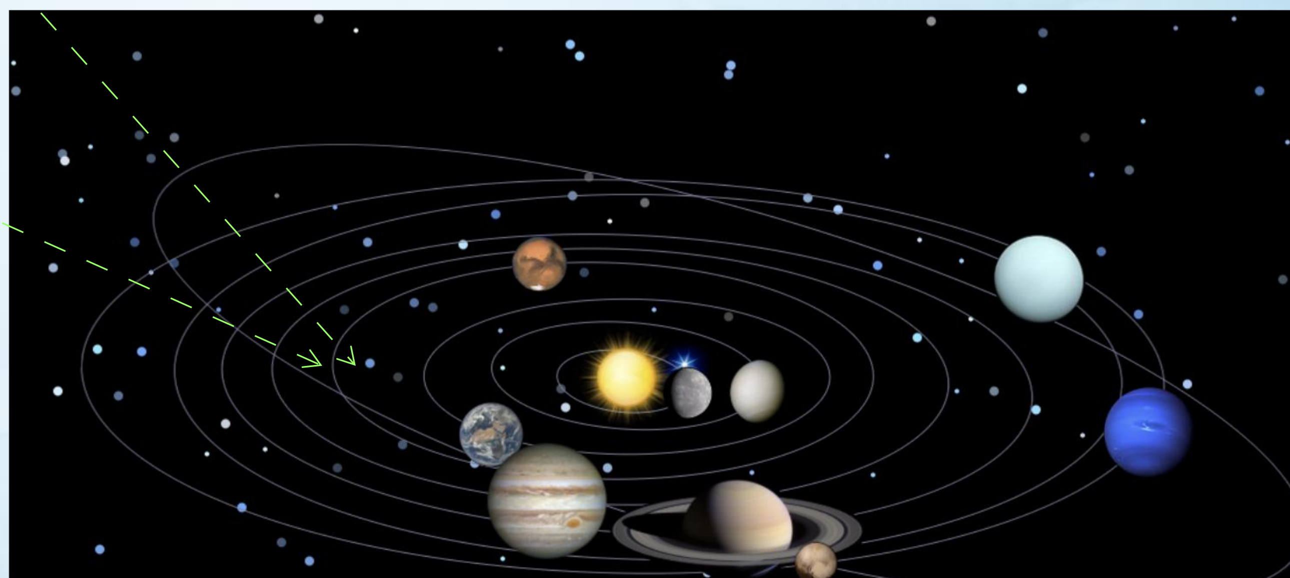
$$\frac{\mathrm{d}\Delta_{\mathrm{E}\odot}}{\mathrm{d}t} = \sum_i \frac{GM_i}{c^2 r_i^{\mathrm{E}}} + \frac{v_{\mathrm{E}}^2}{2c^2} - \mathrm{constant}$$

$$\begin{aligned}\mathbf{a}_{A,pm-pm} = \sum_{B\neq A}\frac{GM_B(\mathbf{r}_B-\mathbf{r}_A)}{r_{AB}^3}\Bigg\{1 &- \frac{2(\beta+\gamma)}{c^2}\sum_{C\neq A}\frac{GM_C}{r_{AC}} - \frac{2\beta-1}{c^2}\sum_{C\neq B}\frac{GM_C}{r_{BC}} \\ &+ \gamma\left(\frac{v_A}{c}\right)^2 + (1+\gamma)\left(\frac{v_B}{c}\right)^2 - \frac{2(1+\gamma)}{c^2}\mathbf{v}_A\cdot\mathbf{v}_B \\ &- \frac{3}{2c^2}\left[\frac{(\mathbf{r}_A-\mathbf{r}_B)\cdot\mathbf{v}_B}{r_{AB}}\right]^2 + \frac{1}{2c^2}(\mathbf{r}_B-\mathbf{r}_A)\cdot\mathbf{a}_B\Bigg\} \\ &+ \frac{1}{c^2}\sum_{B\neq A}\frac{GM_B}{r_{AB}^3}\Big[[\mathbf{r}_A-\mathbf{r}_B]\cdot[(2+2\gamma)\mathbf{v}_A-(1+2\gamma)\mathbf{v}_B]\Big](\mathbf{v}_A-\mathbf{v}_B) \\ &+ \frac{(3+4\gamma)}{2c^2}\sum_{B\neq A}\frac{GM_B\mathbf{a}_B}{r_{AB}}\end{aligned}$$





1PN
1 star, 8 planets, 300+ astroid
Observations: Radar ranging, fly-by, laser ranging, VLBI, optical astrometry



Any error in solar system ephemeris results in timing residual signals

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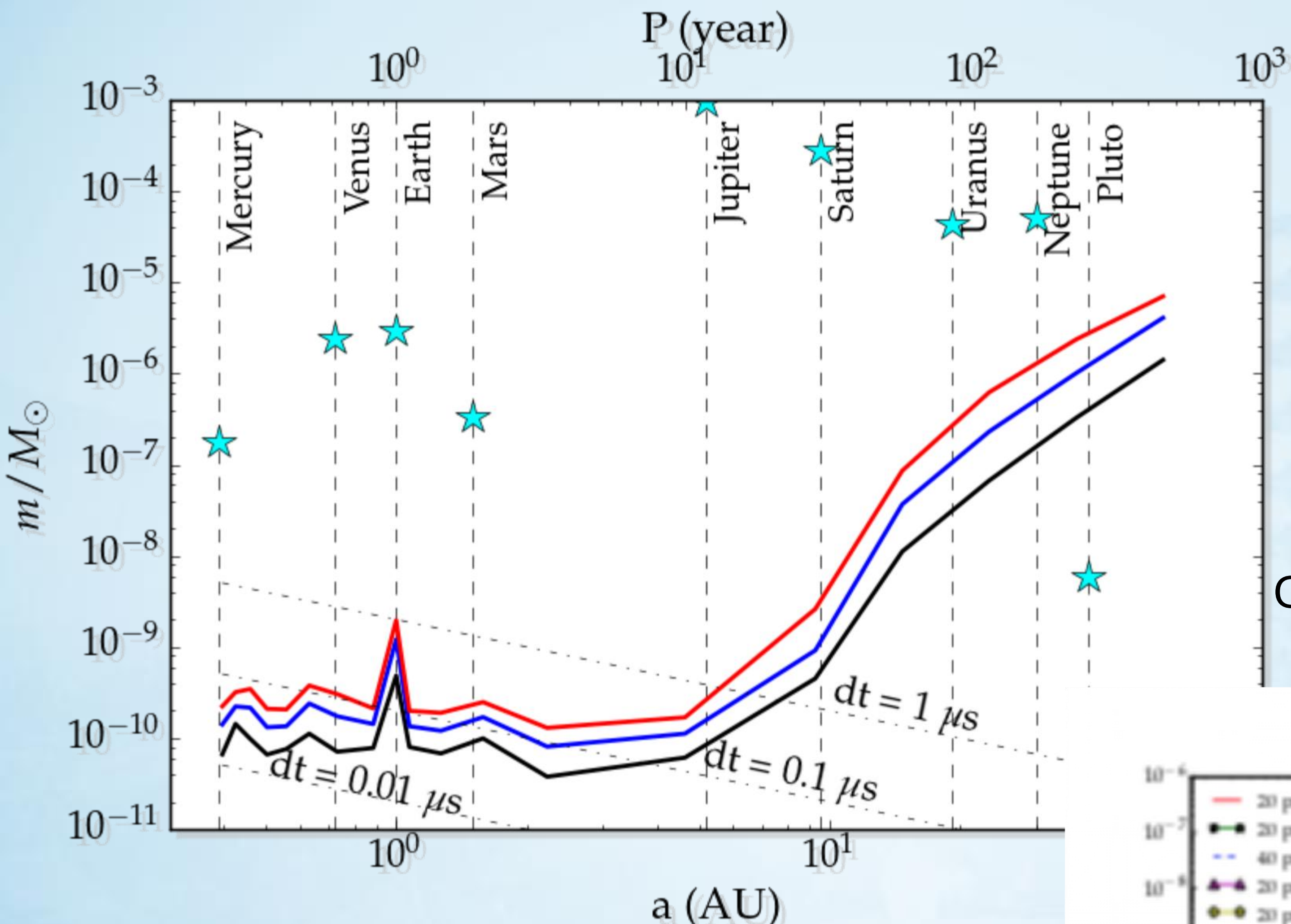
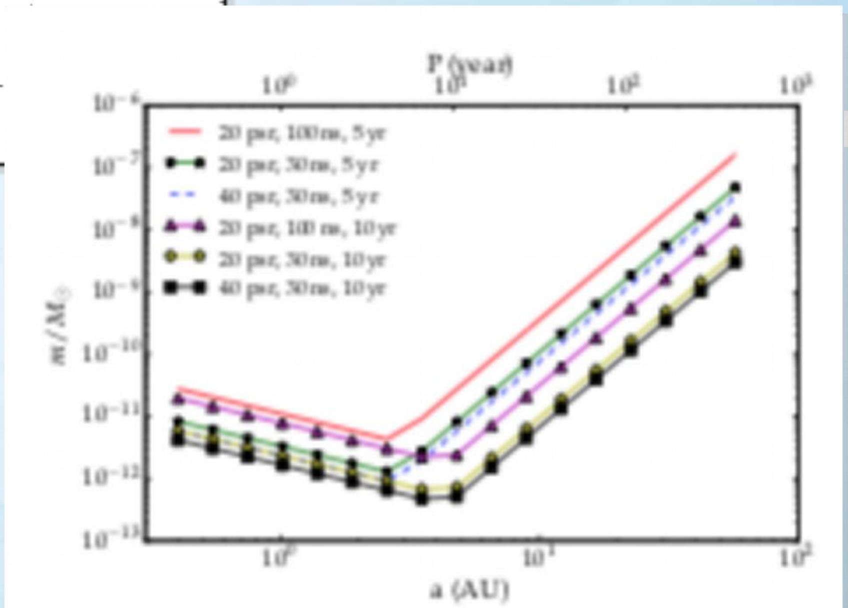
UMO limits



Guo & Lee 2018 MNRAS



There is no planets, dwarf, rock, black hole, cosmic string loop, ASP heavier than 1e20 kg nearby (practically rocks larger than 500km).

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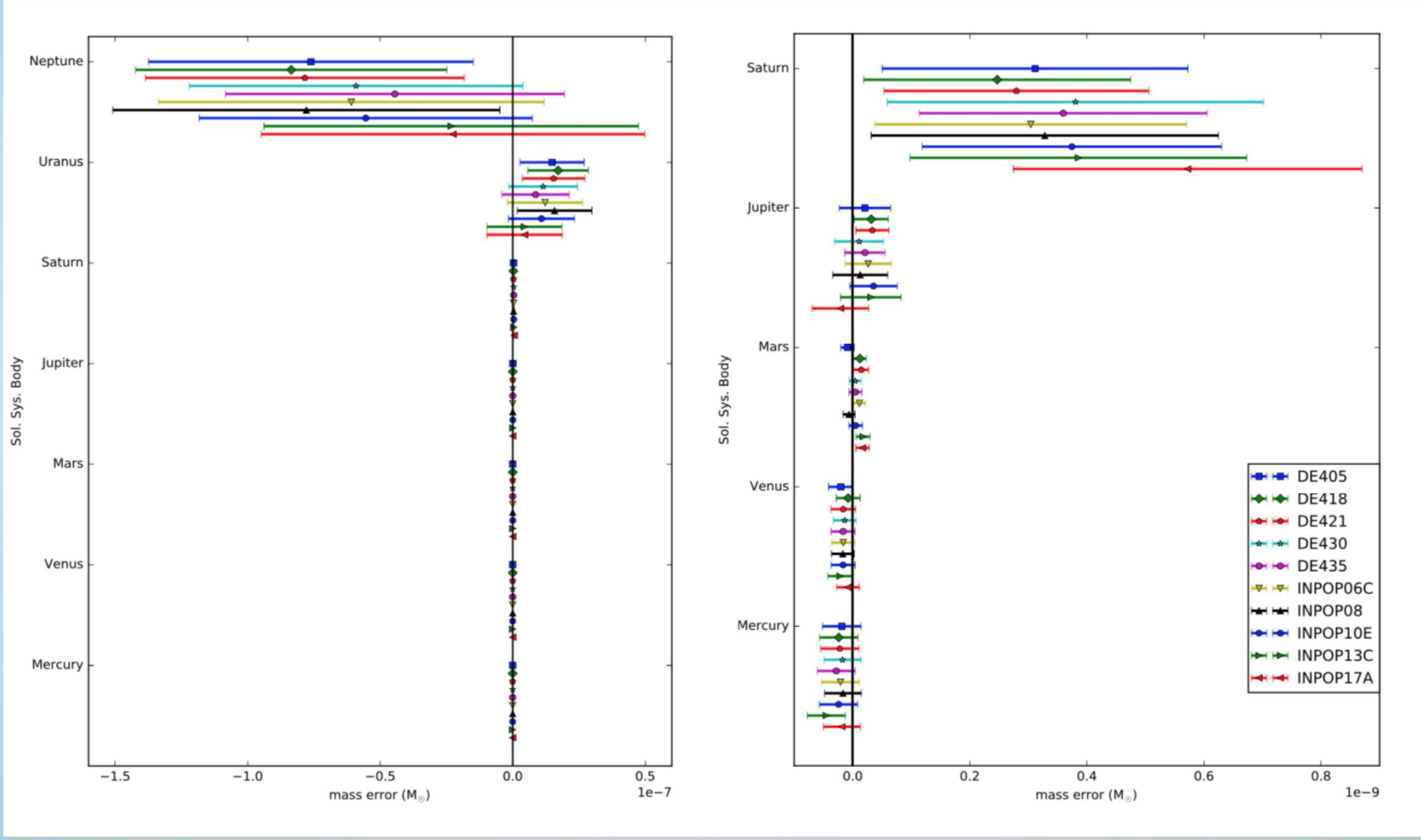
Planet mass measurements



Caballero Guo, Lee et al., 2018

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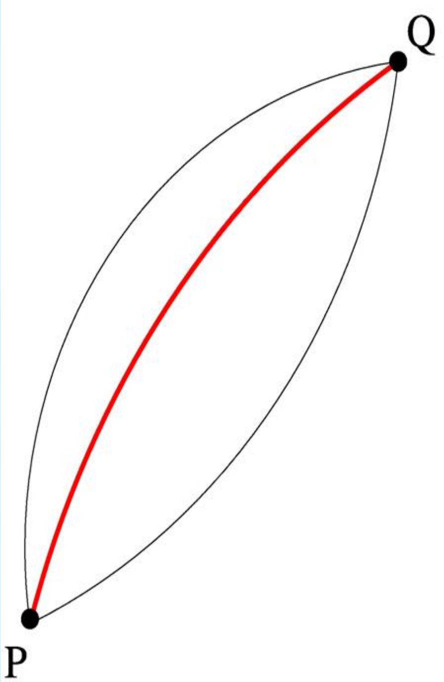
GWs

We have seen that stochastic background is detected by identification of Hellings-Downs correlation.

However,

PTA is not only for stochastic background, but also capable of detecting single sources, if one regard PTA as multi-path interferometer.

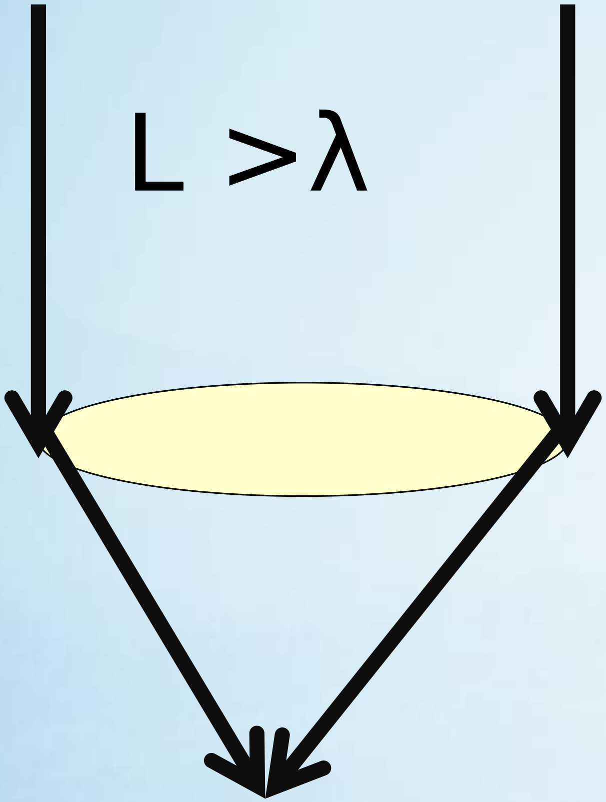


$$\frac{dk}{d\lambda} \sim k k \partial h$$

$$\frac{\Delta\omega}{\omega} \sim g\left(h(t,0) - h(t-r,r)\right)$$

“See” the SMBH

The size make big difference



See

$$h = \Delta p \, \Delta x$$

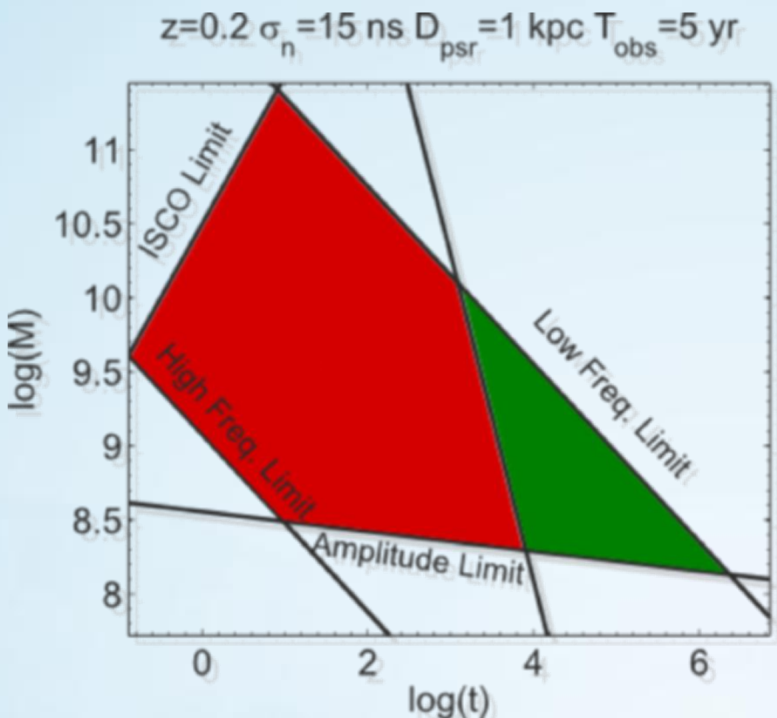
$$h = \Delta\theta \, p \, \Delta x$$

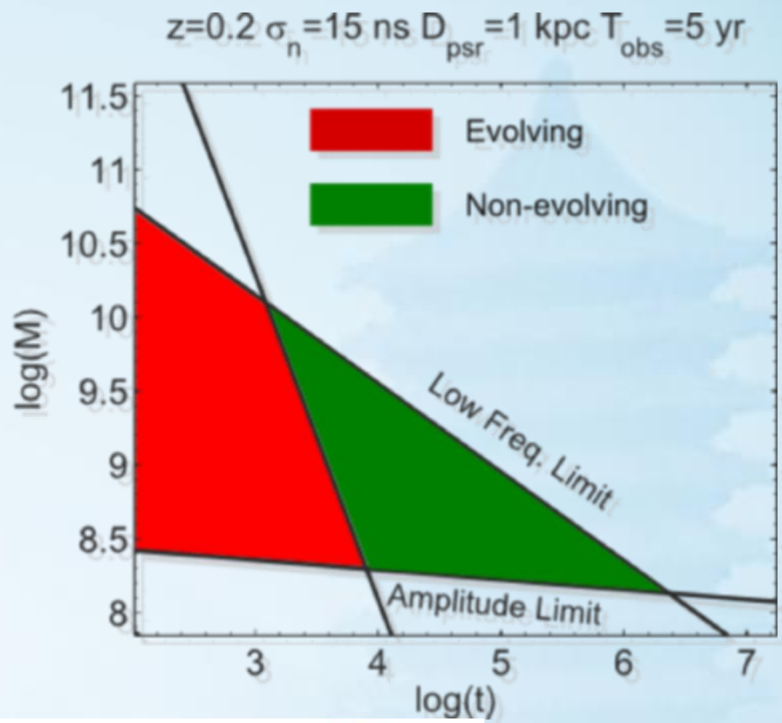
$$\boxed{\Delta\theta} = \frac{h}{p}\,\frac{1}{\Delta x} = \boxed{\frac{\lambda}{\Delta x}}$$

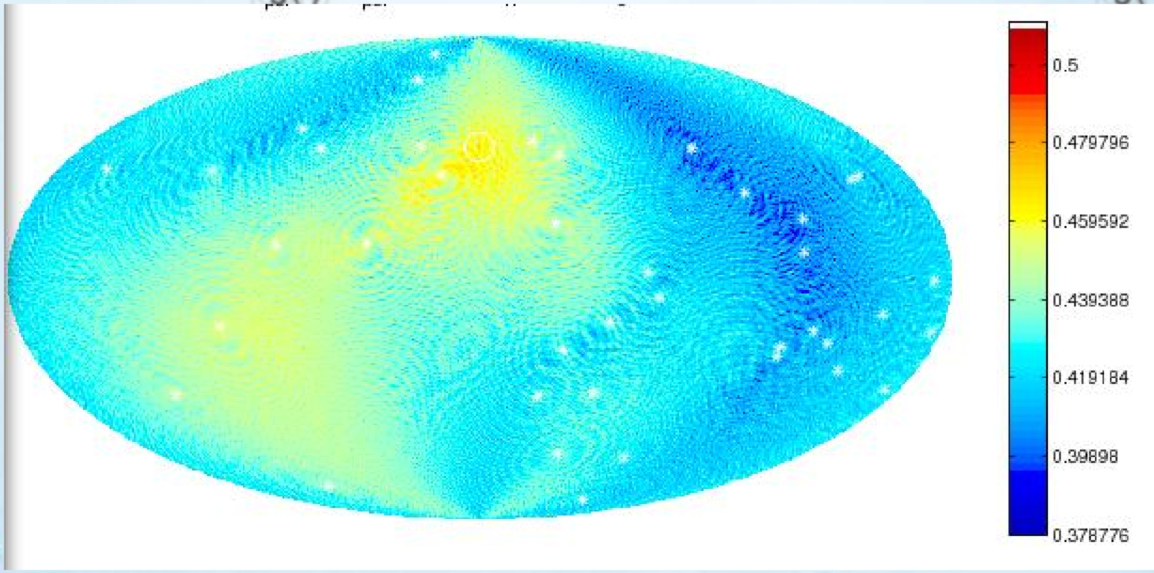
L<λ

Hear

PTA can resolve and localize the single GW source







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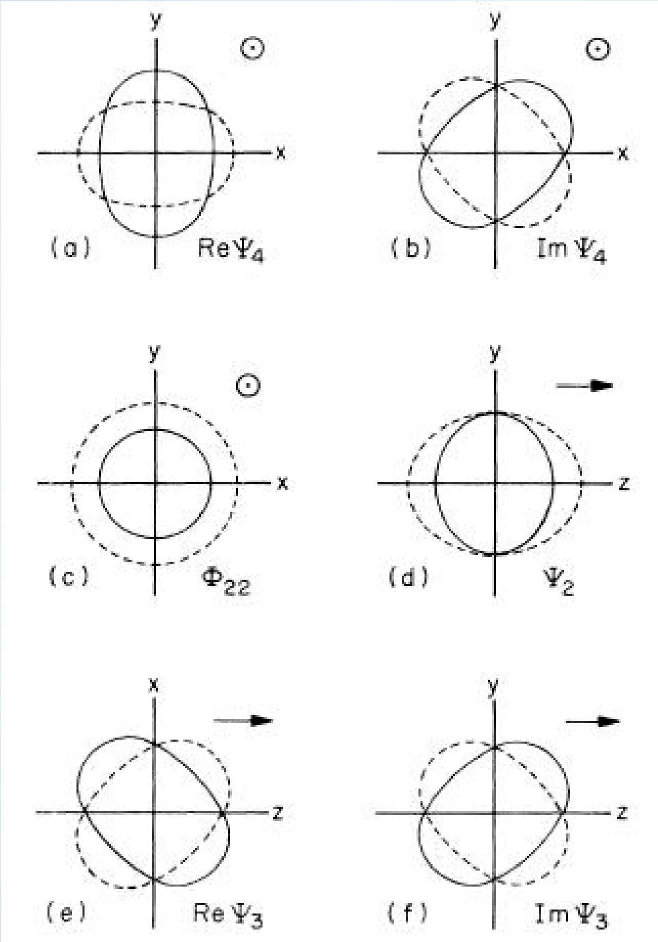
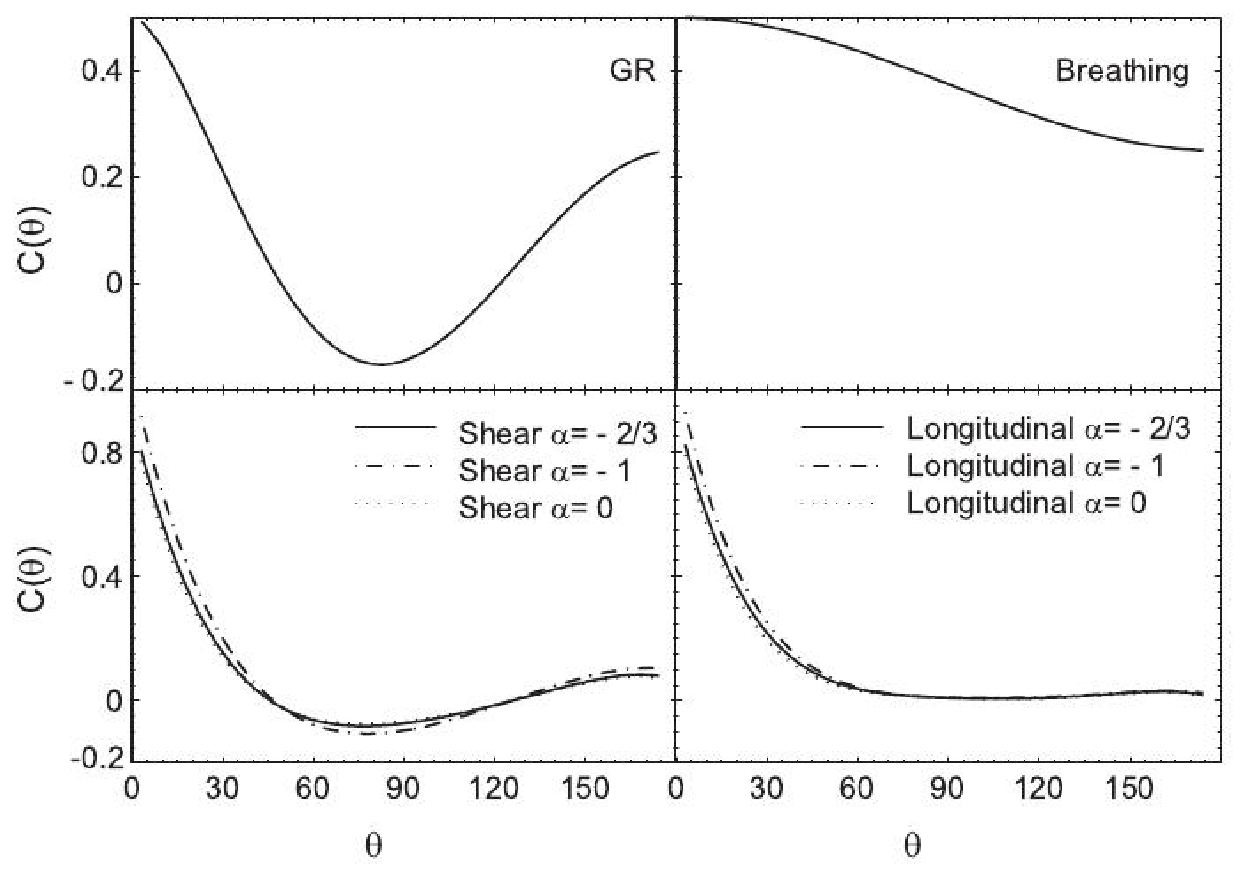
Lee et al. 2012

Polarization of GW and gravity test



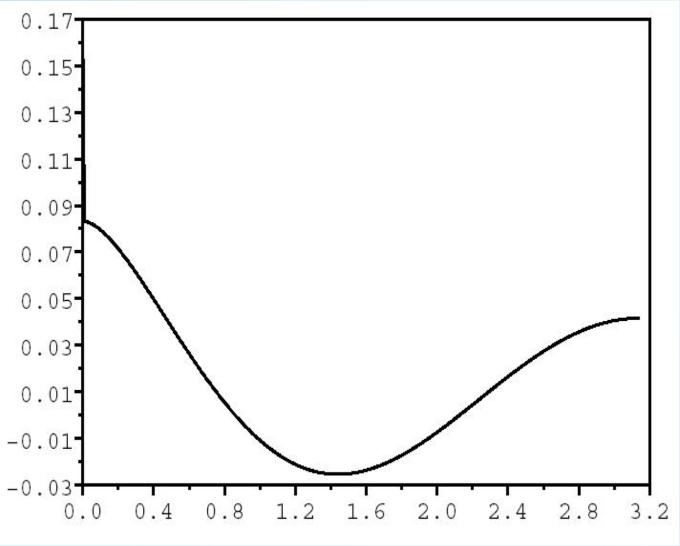


Edward, et al. 73

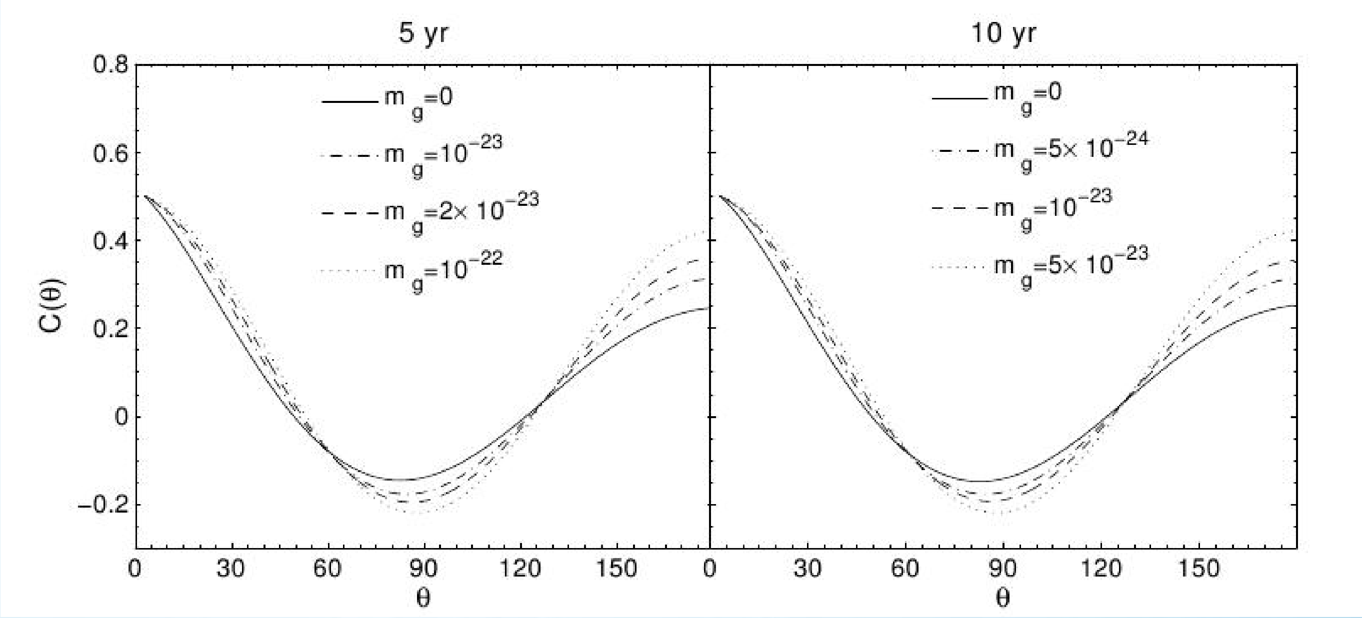
Lee et al. 08

Dispersion / graviton mass

$$\frac{\Delta\omega(t)}{\omega} = -\frac{\hat{\mathbf{n}}^i\hat{\mathbf{n}}^j}{2\left(1+(c/\omega_g)\mathbf{k}_g\cdot\hat{\mathbf{n}}\right)}\left[h_{ij}(t,0) - h_{ij}(t-|\mathbf{D}|/c,\mathbf{D})\right]$$



GR case



Lee et al. 2010

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Recap:

- PTA is array of pulsars
- PTA can
  - Provide long-term stable clock
  - Explore the solar system and searching for hidden objects
  - Detect stochastic GW background
    - Supermassive BH binaries
    - Early universe
  - Resolve single GW sources
    - SMBHBs (1e8-1e12 Msun)
    - Cosmic string loops
  - Test gravity theory via polarization and dispersion relation measurements

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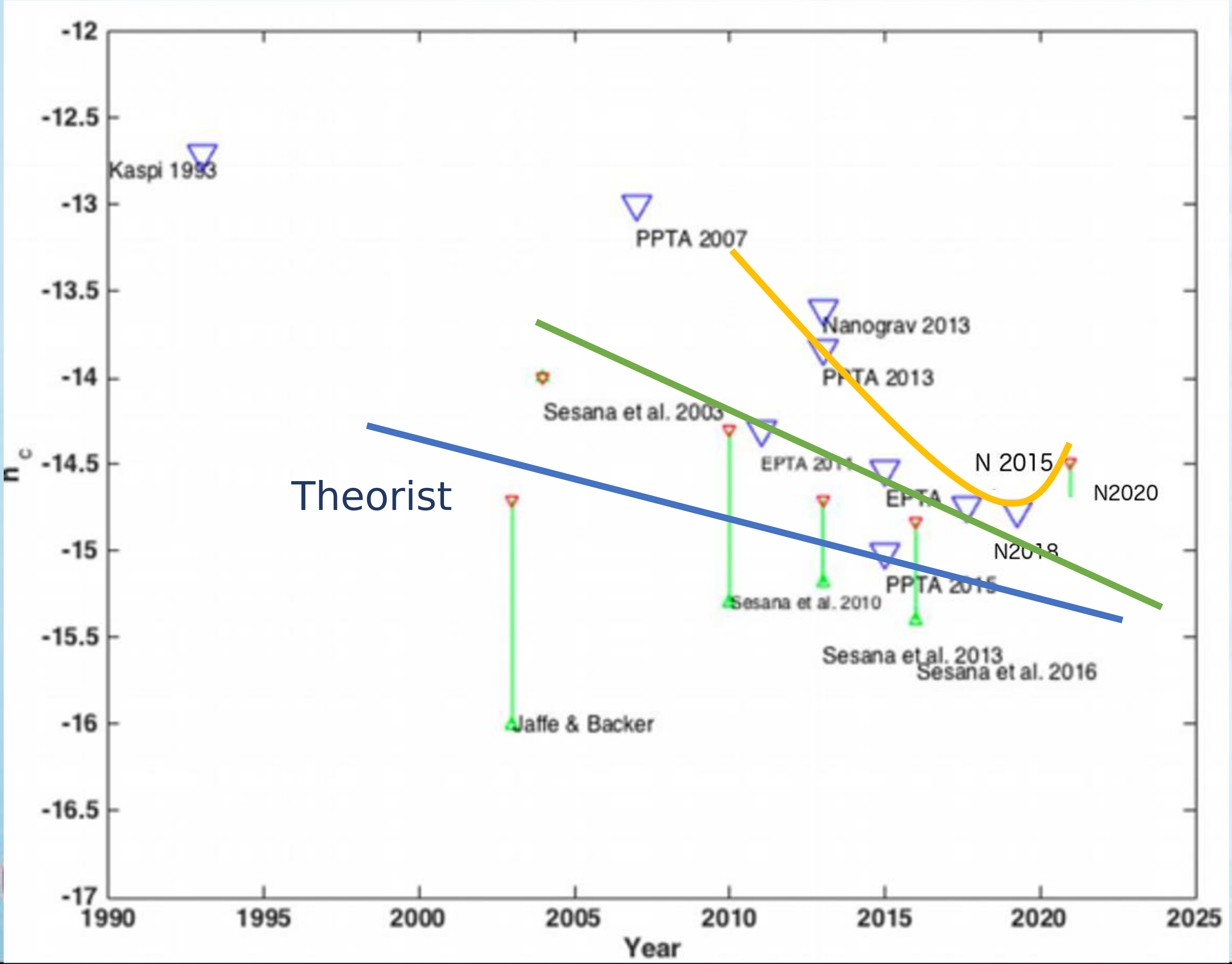
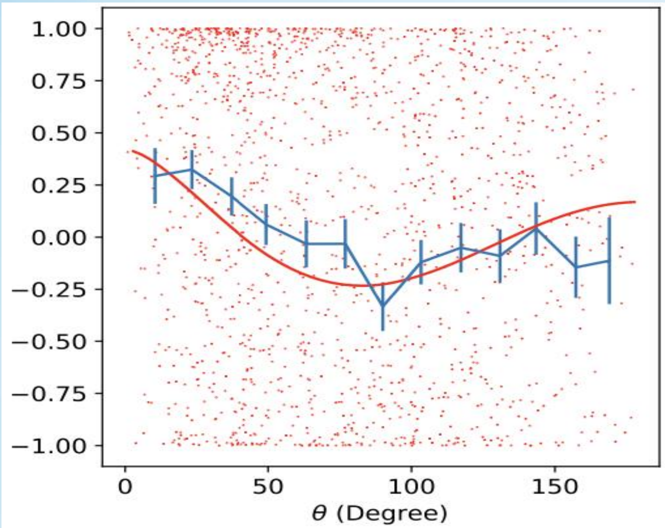
Where we were before 2023?

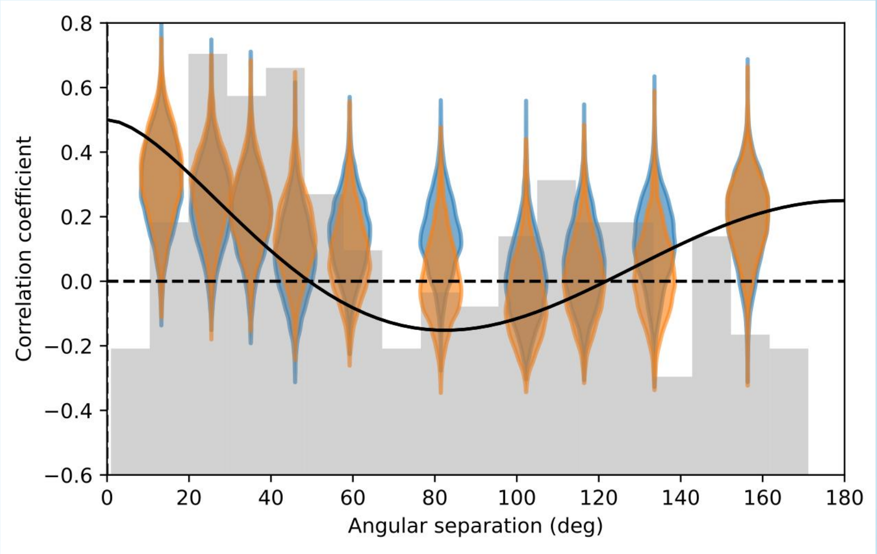
Good news, Theorists low the bar slower than observation.
Bad news, Observer may contradict with eachother.



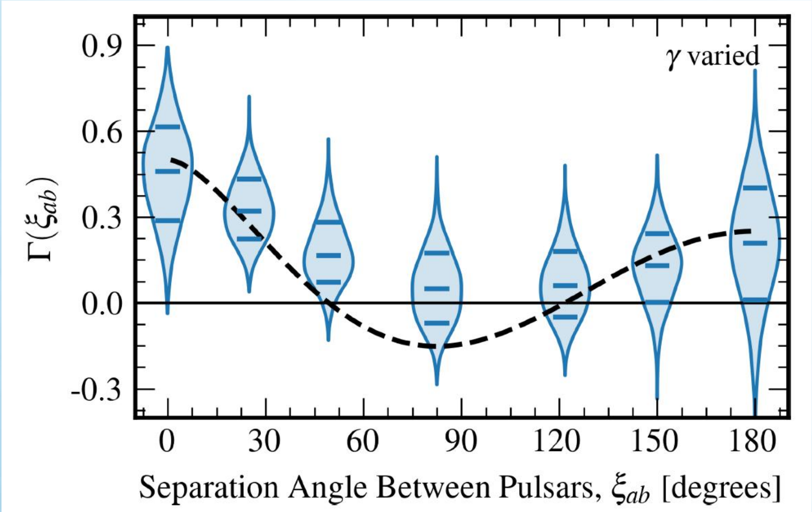
2023 major progress



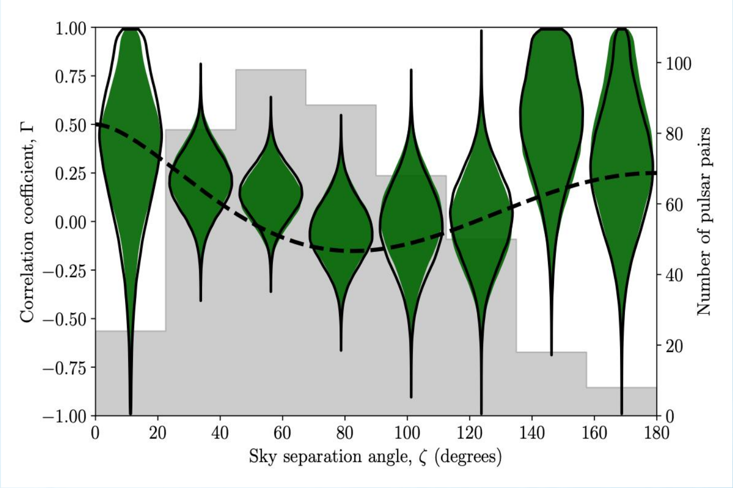
4.6σ; CPTA
Xu et al., 2023, RAA



3σ
EPTA & InPTA, 2023, A&A



3-4σ; NANOGrav
Agazie et al., 2023, ApJL



2σ; PPTA
Reardon et al., 2023 ApJL

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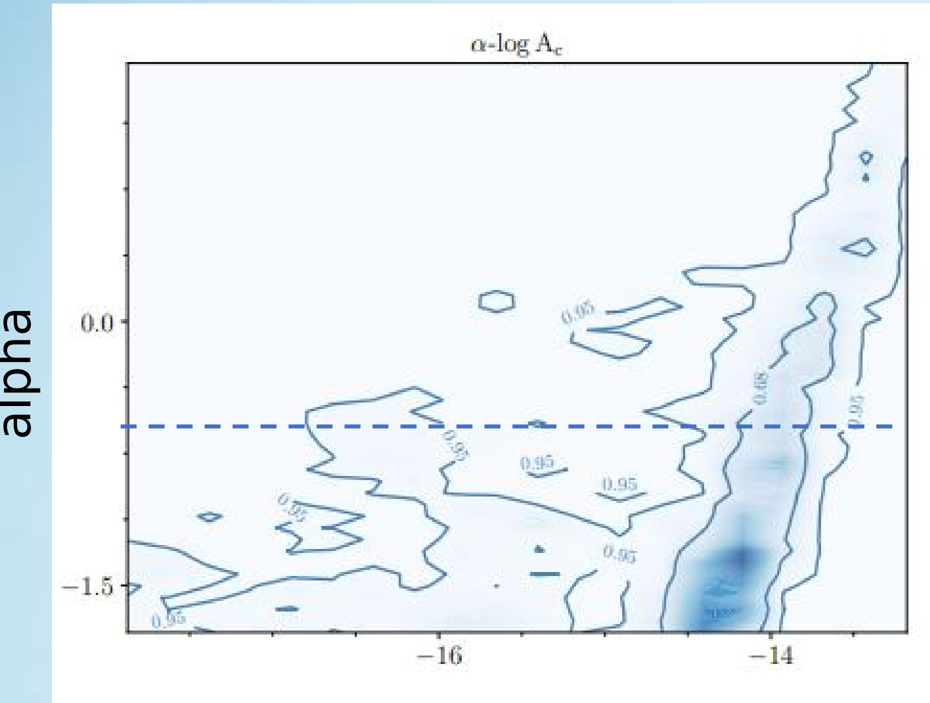
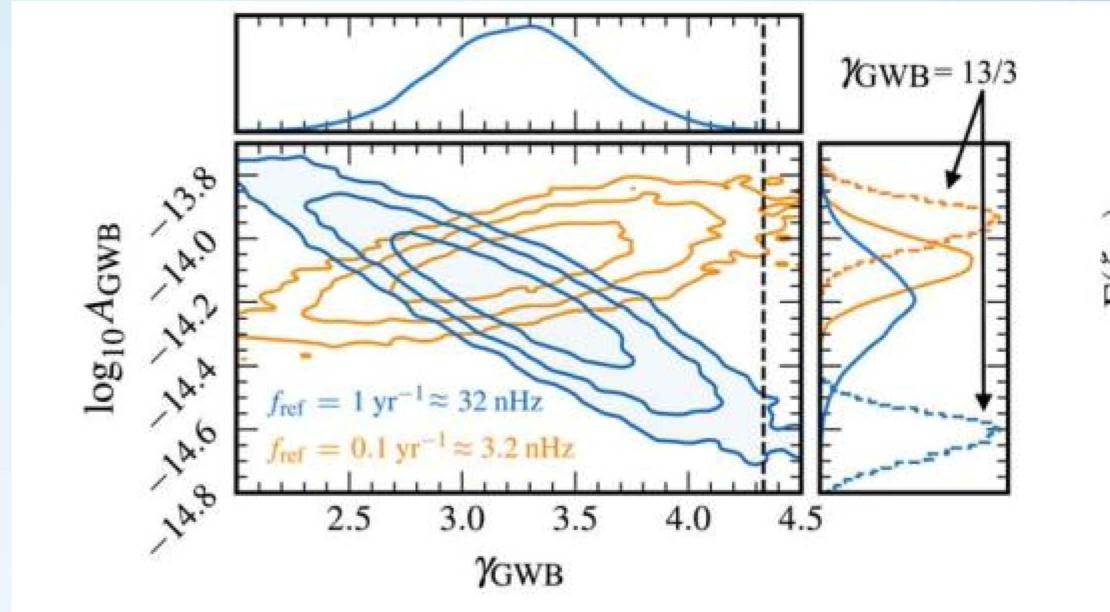
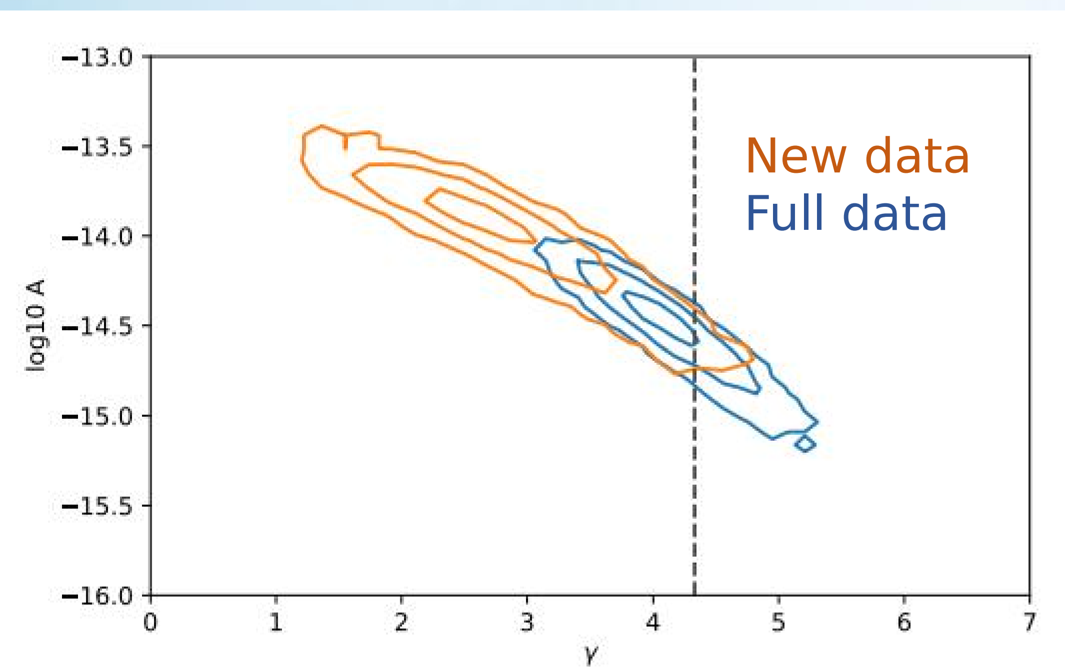
CPTA 2023



Nanograv 2023



EPTA 2023



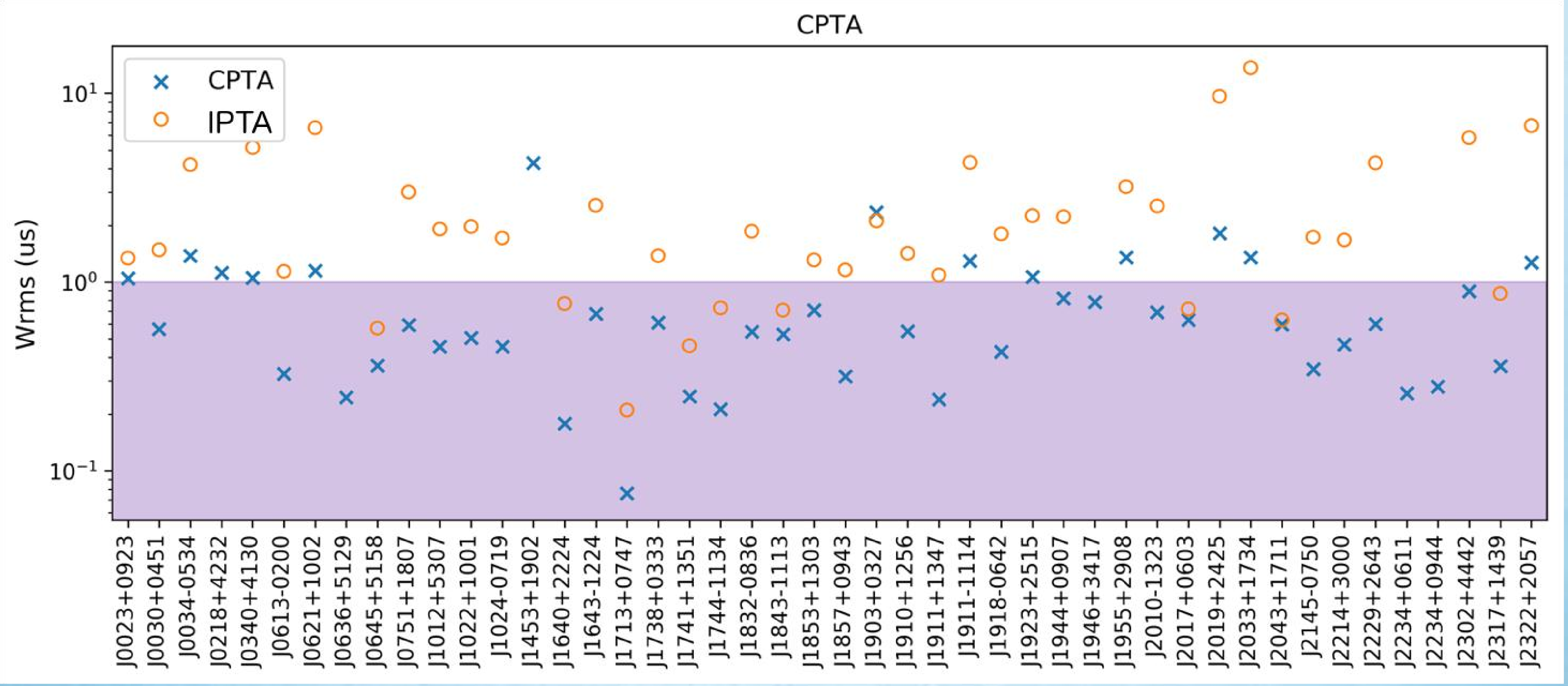
2*alpha-3=gamma

$$A(f) = A_c \left(\frac{f}{1\text{yr}^{-1}} \right)^{\alpha}$$

$$S(f) = \frac{A(f)^2}{12\pi^2 f^3}$$

Data quality

CPTA data precision is improved.



International Efforts

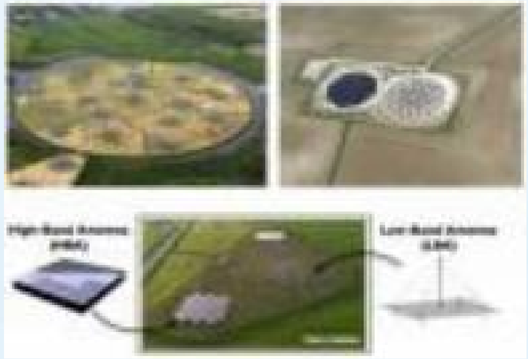
VLA

CHIME

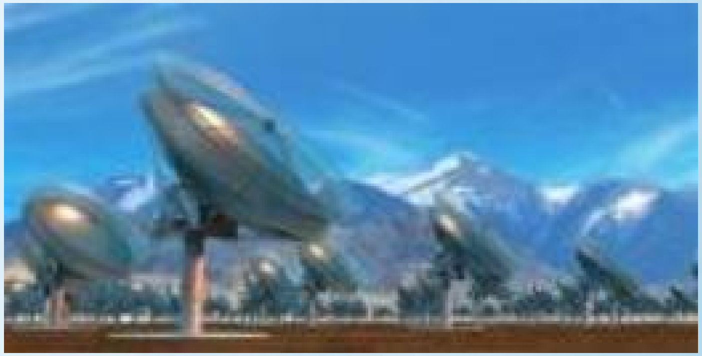
MeerKAT

SKA

ngVLA



LOFAR

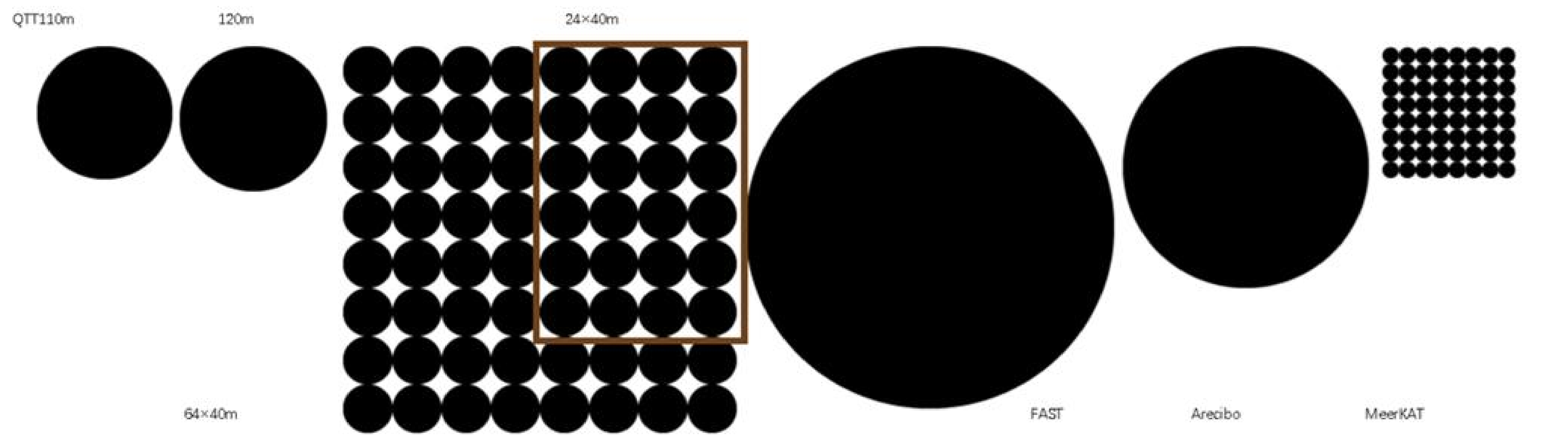


DSA2000

Domestic efforts

- 3 x 100 meter radio telescopes
- 64x 40m telescope array
- 81x 127 antenna low frequency array
- ...

- FAST Array (aims for 64*40m)
  - FAST+24×40m=1.4-1.7 FAST, 50% more precise， sky coverage leads to double the pulsar number
- 3X120m
- low-frequency array (21CMA)



Progress of Chinese **Radio Trinity**

QTT 110m fullband radio teelscope at Xinjiang
In construction, should be ready in 3-5 years.

JRT/RST 120m low frequency (10GHz) radio telescope at Yunnan and Jilin. **Under construction.**

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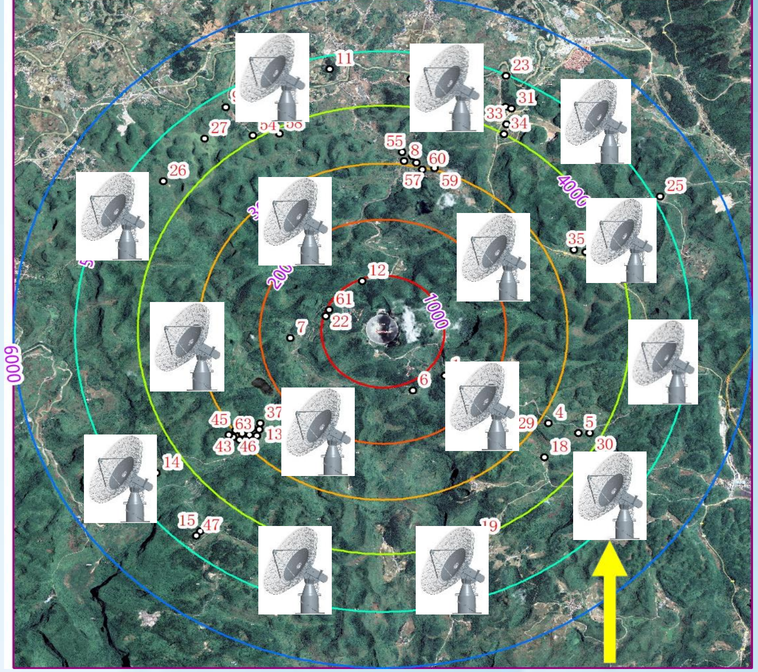
FAST EXT array

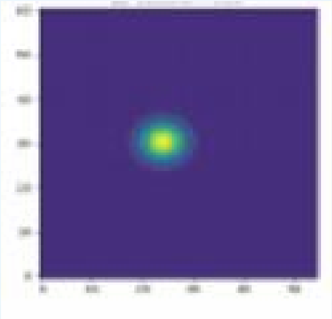
64 x 40m telescope around the FAST.

FAST

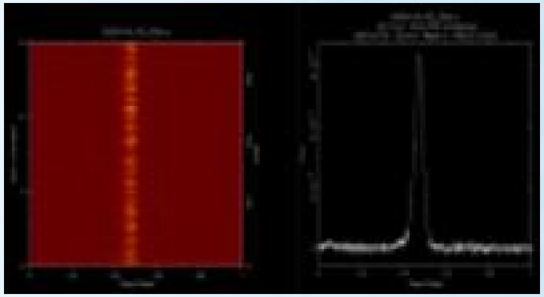
FAST EXTA



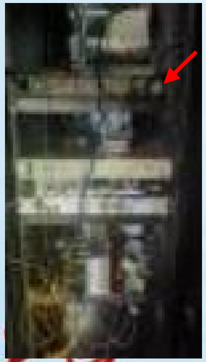
- **Tsys：~20K**
- **Efficiency：54.3%**

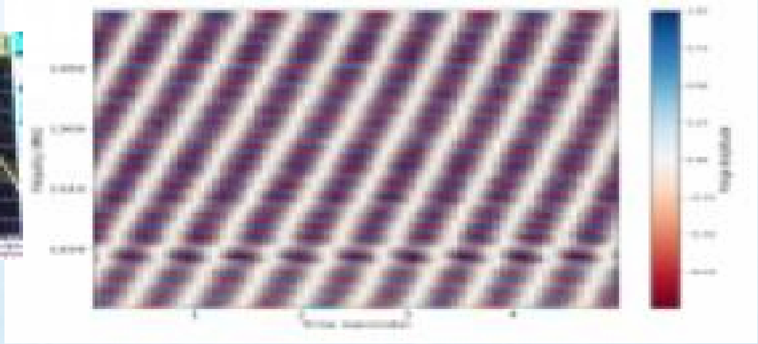


40m station OTF



40m pulsar test obs.

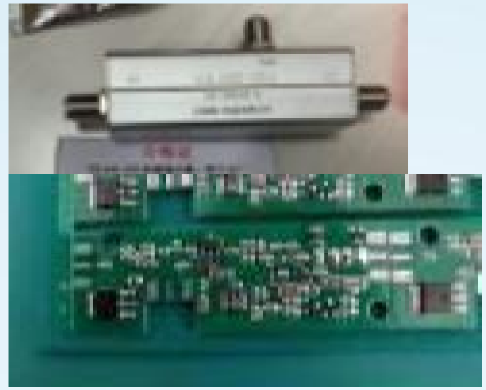




40m-FAST fringe

21CMA upgrade

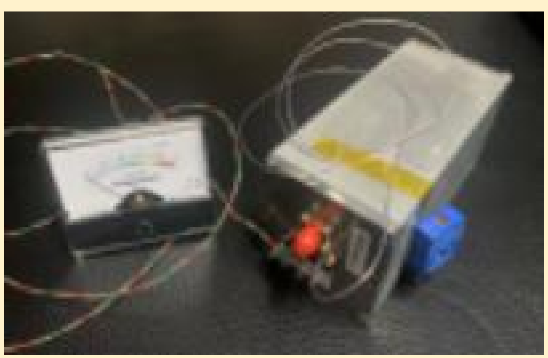
LNA 50-250MHz NF 0.4dB
VSWR < 1.5 δDB<1dB

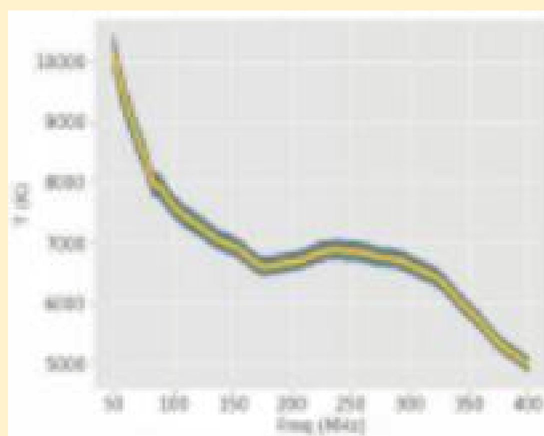


21CMA 127X81 dipoles

SKA-low pilot project

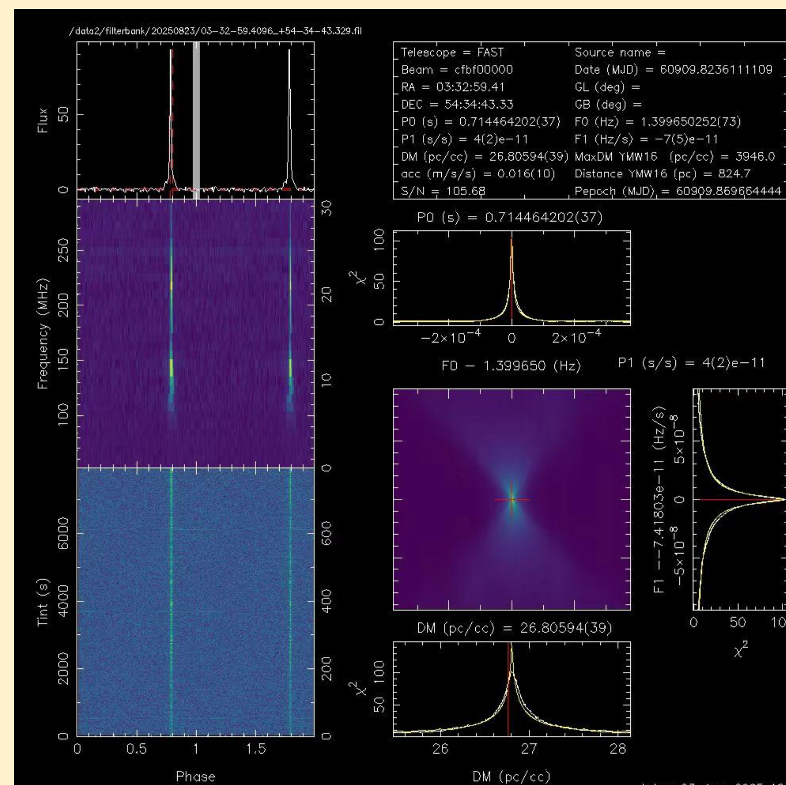
Re-designed all of the RF front-end and backends.

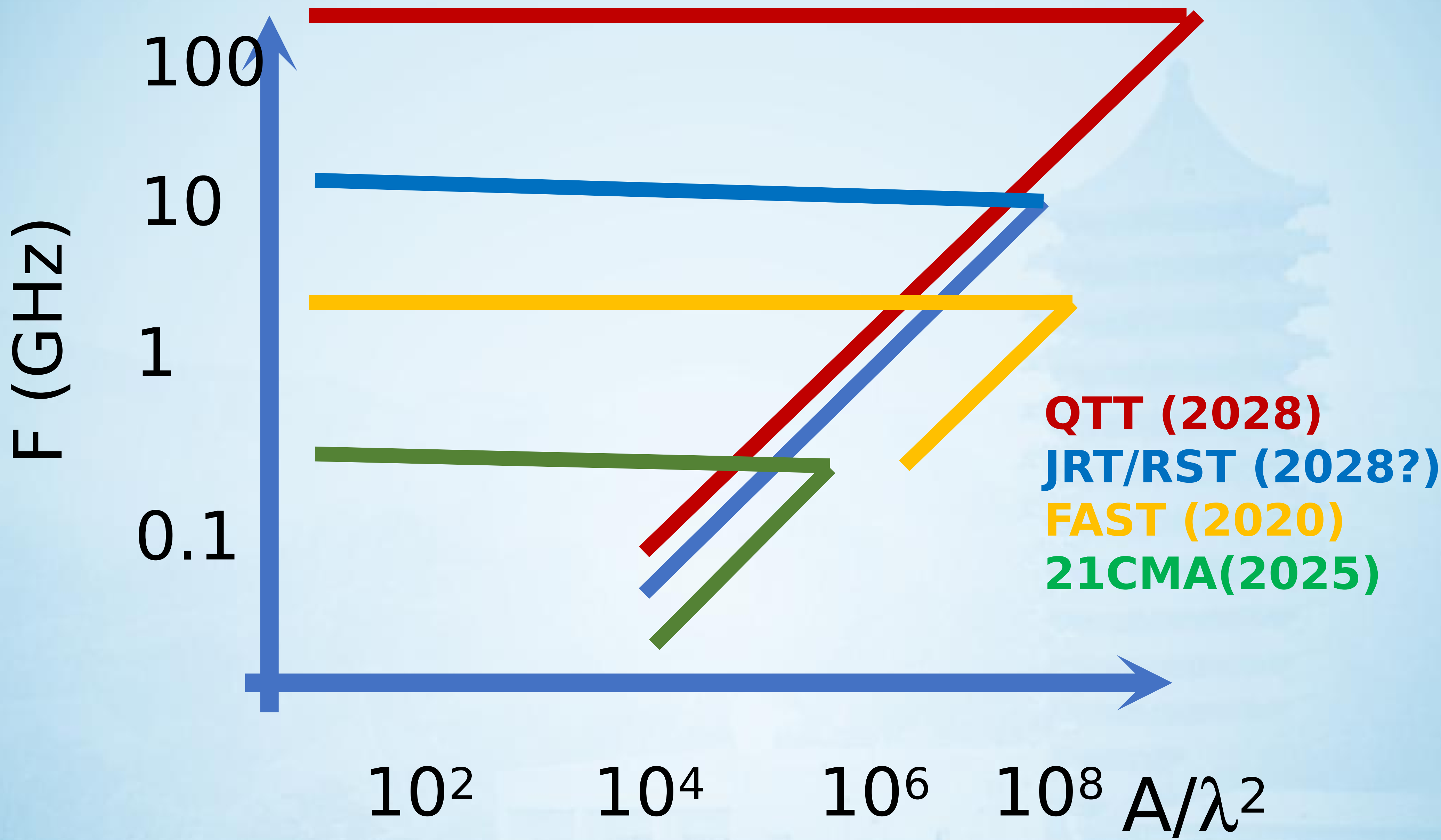




Noise calibrator, 1e-4 variation over 90 hour, Tnoise> 6500 K, VSWR < 1.12

2025 08 21 after first array upgrade





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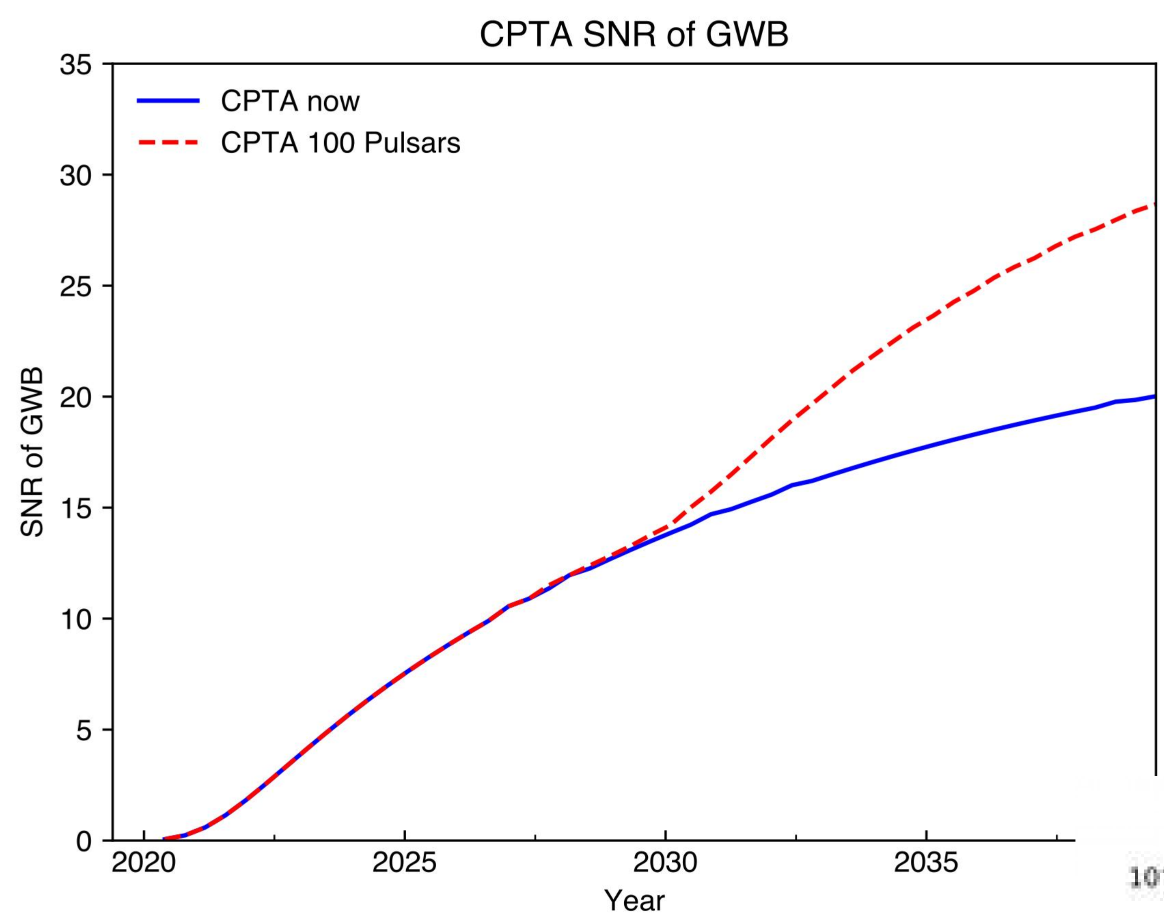

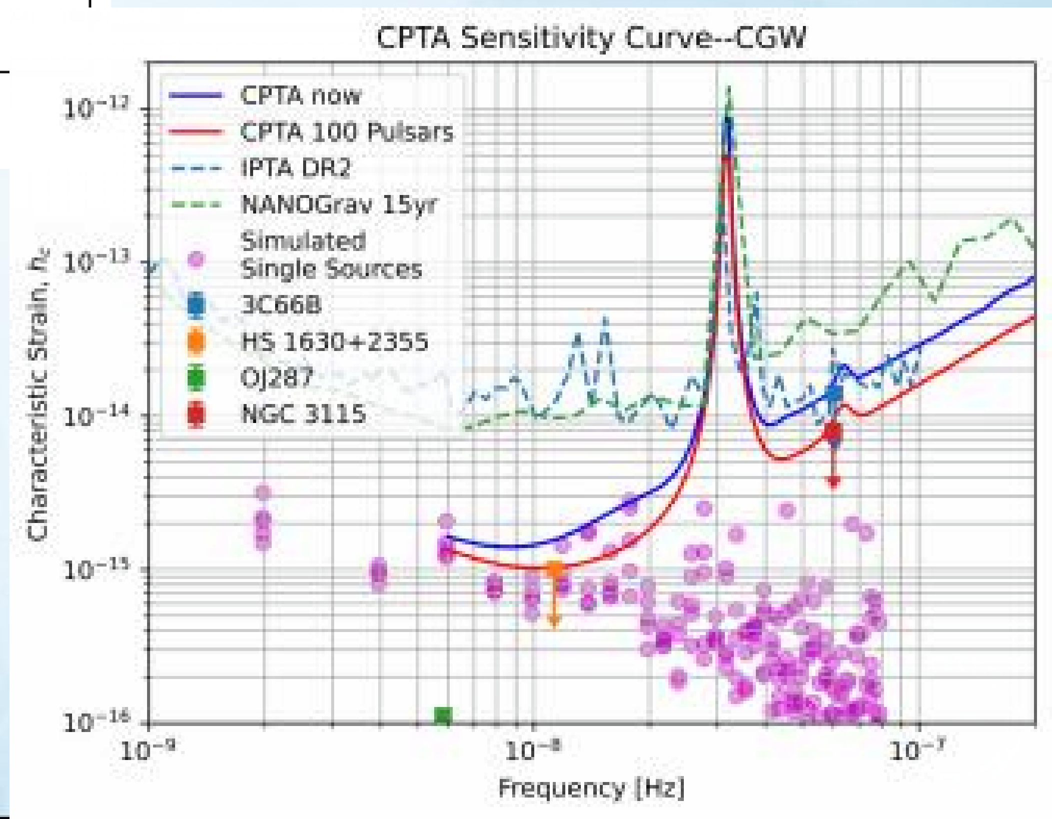

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We are at the dawn of the NanoHz GW astronomy.

Thanks