2019 CCNU-USTC Junior Cosmology Symposium

Prospects for GW astronomy with next generation large-scale PTAs

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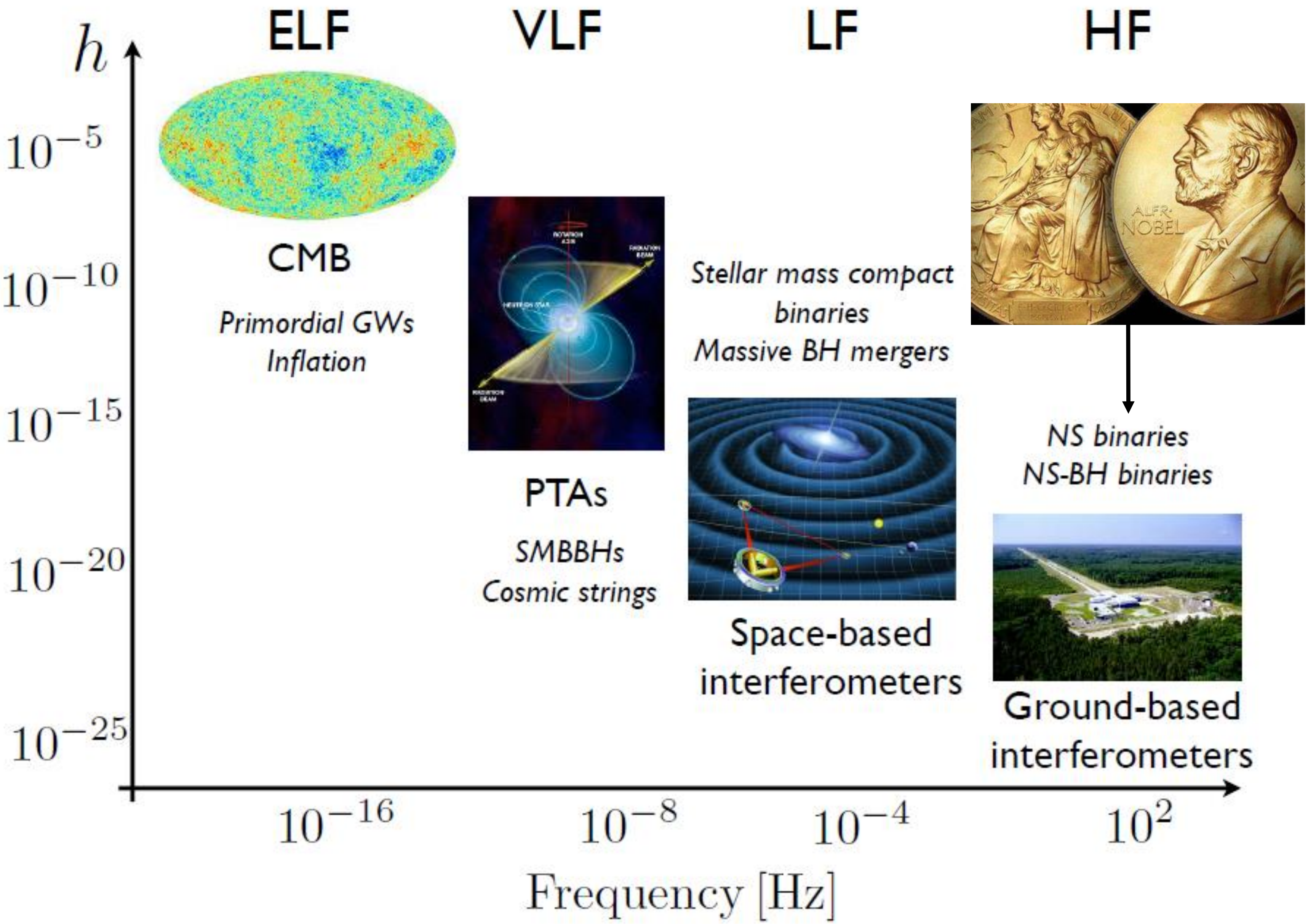
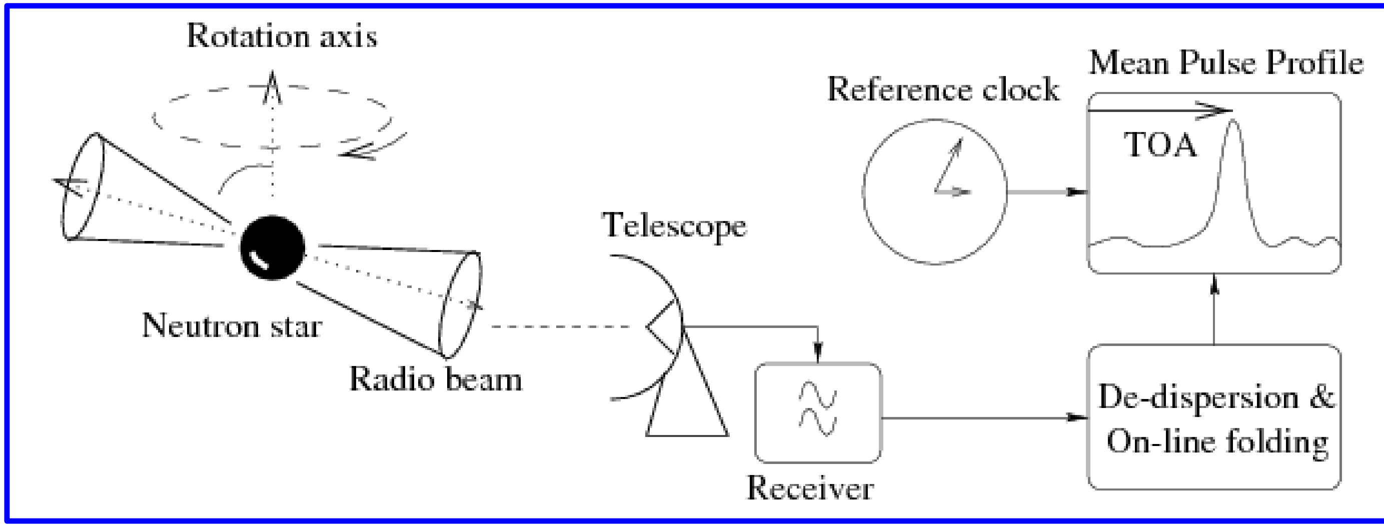
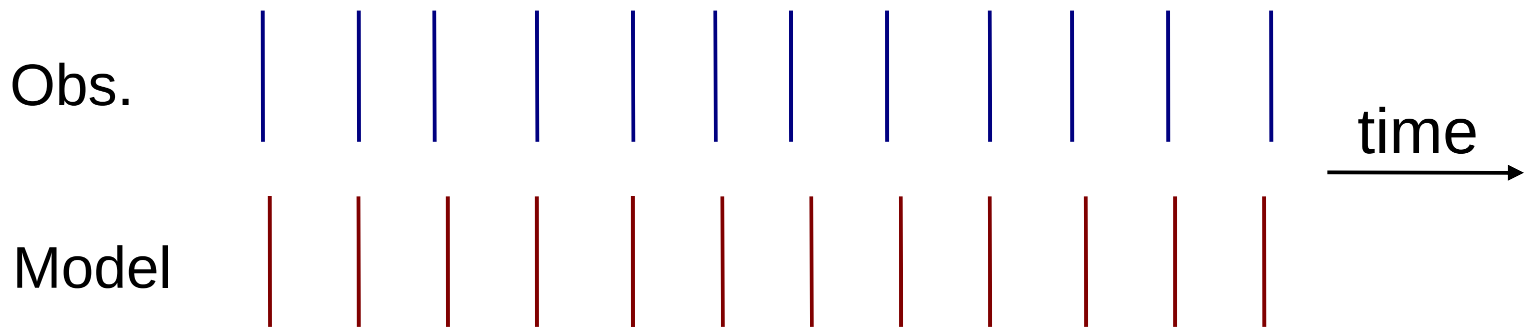
The big picture of gravitational wave astronomy

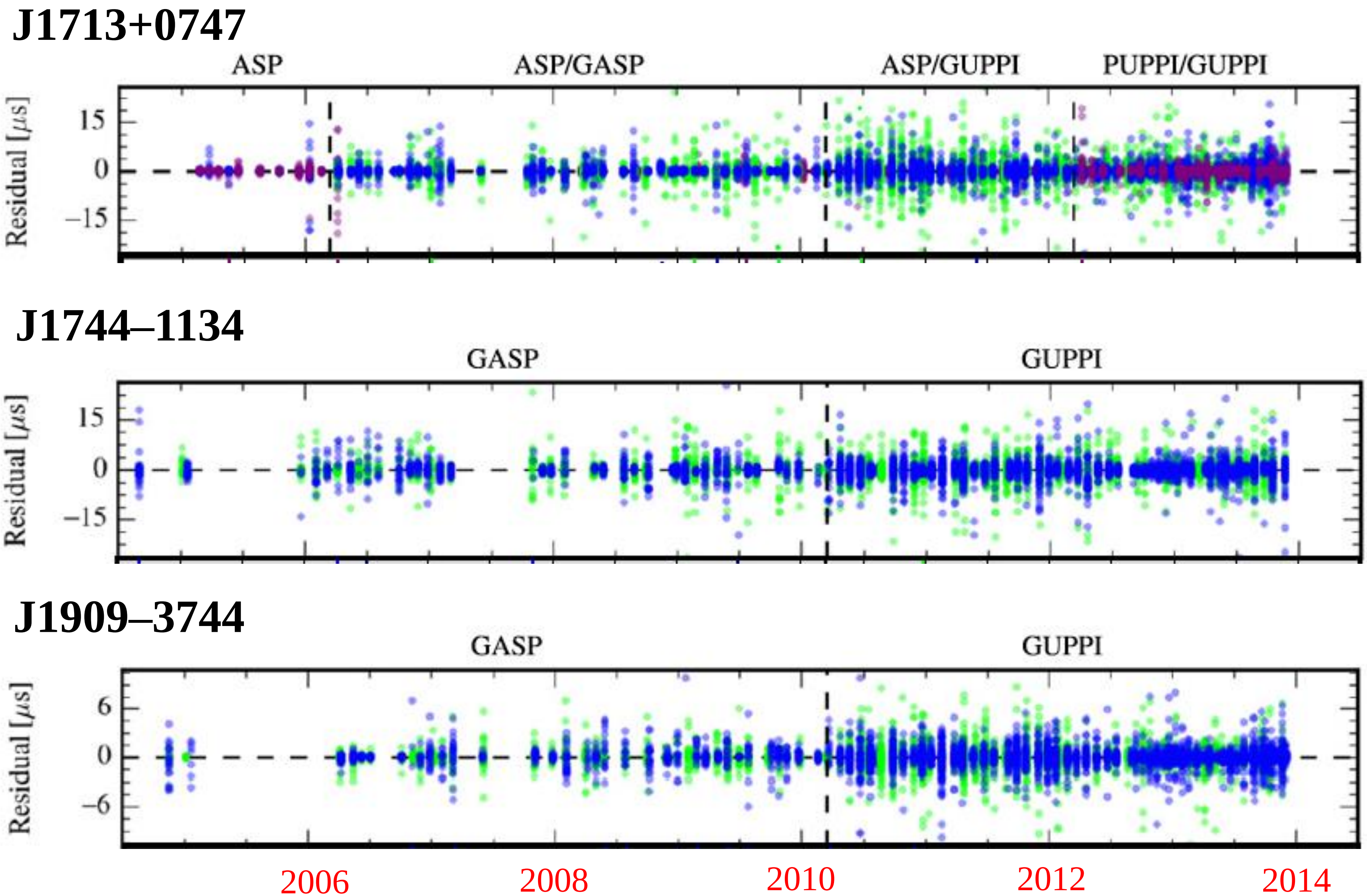


Pulsar timing





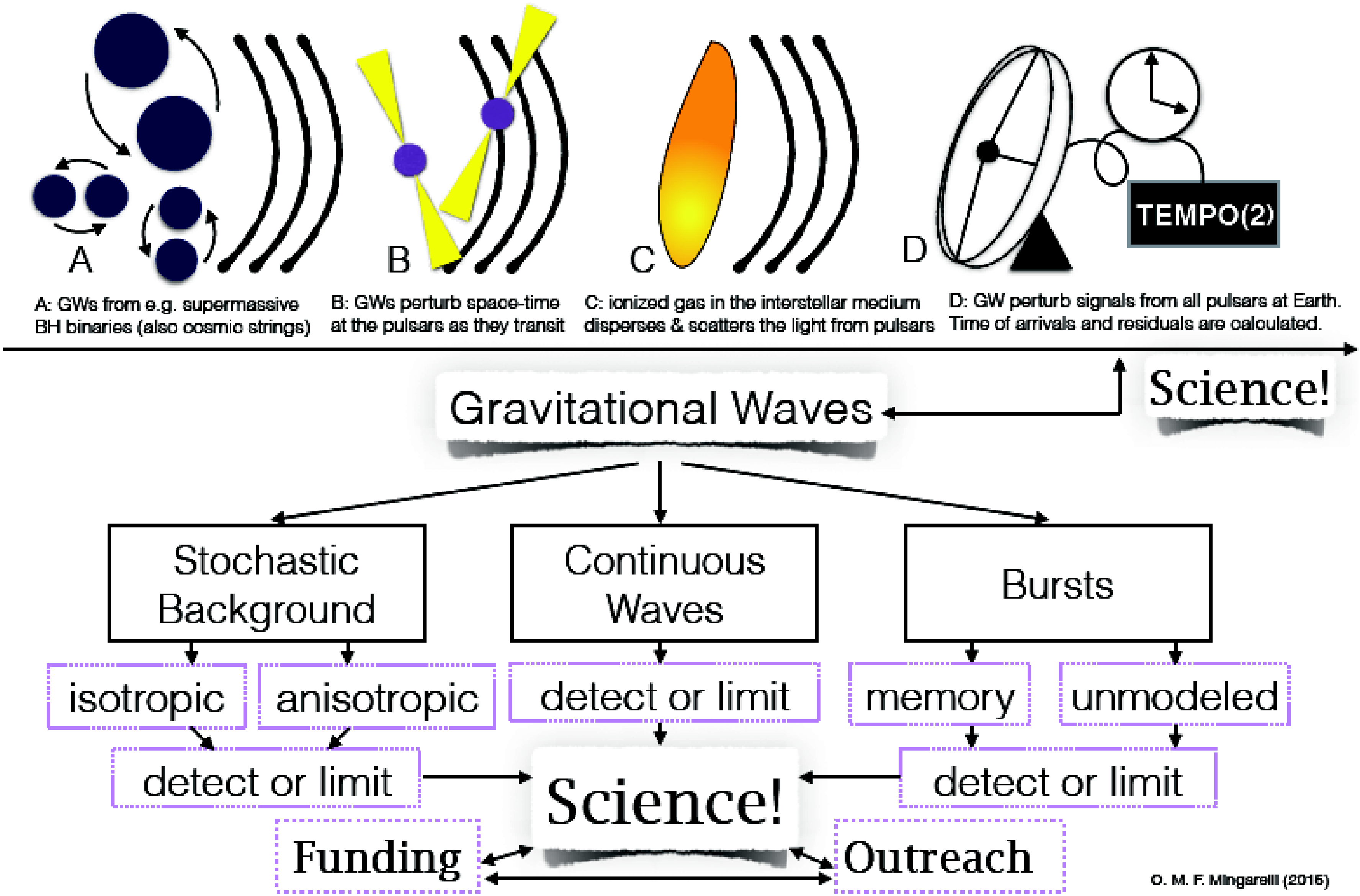
Lorimer & Kramer, “Handbook of Pulsar Astronomy”
Mon. Not. R. Astron. Soc. 369, 655–672 (2006)
Mon. Not. R. Astron. Soc. 372, 1549–1574 (2006)



The NANOGrav Collaboration, ApJ 813, 65 (2015)

Image source, clockwse from upper left: http://www.gb.nrao.edu/; http://www.astron.nl/; http://www.mpifr-bonn.mpg.de/english/index
www.obs-nancay.fr/; http://www.jb.mar

Pulsar Timing Array



GWs from SMBHBs

Frequency of the binary orbit

$$f \approx 1 \text{ nHz} \left(\frac{M}{10^9 M_\odot} \right)^{1/2} \left(\frac{a}{10^4 \text{AU}} \right)^{-3/2}$$

Timing residuals induced by GW

$$\Delta\tau \sim 10 \, \text{ns} \left(\frac{1 \, \text{Gpc}}{\text{d}_\text{L}} \right) \left(\frac{\text{M}}{10^9 \, \text{M}_\odot} \right)^{5/3} \left(\frac{10^{-7} \, \text{Hz}}{f} \right)^{1/3}$$

Time to coalescence

$$a = 10^4 \text{ AU} \qquad M \approx \mu = 10^9 \; M_\odot$$

$$\tau = \frac{5}{256} \frac{c^5}{G^3} \frac{a^4}{M\mu} = \frac{5}{256} \frac{a^3}{r_M^2 r_\mu} \frac{a}{c} \sim 10^5 \text{ yr}$$

Timing effects by GWs

Perturbation of metric tensor:

$$\mathbf{h} = (h_+\mathbf{e}_+ + h_\times\mathbf{e}_\times)e^{i(\omega_{\rm gw}t - \mathbf{k}\cdot\mathbf{x})}$$

GW signals:

$$s_i^I(\lambda) = \boxed{F_+^I(\alpha,\delta)}\Delta h_+(t_i^I;\theta) + \boxed{F_\times^I(\alpha,\delta)}\Delta h_\times(t_i^I;\theta)$$

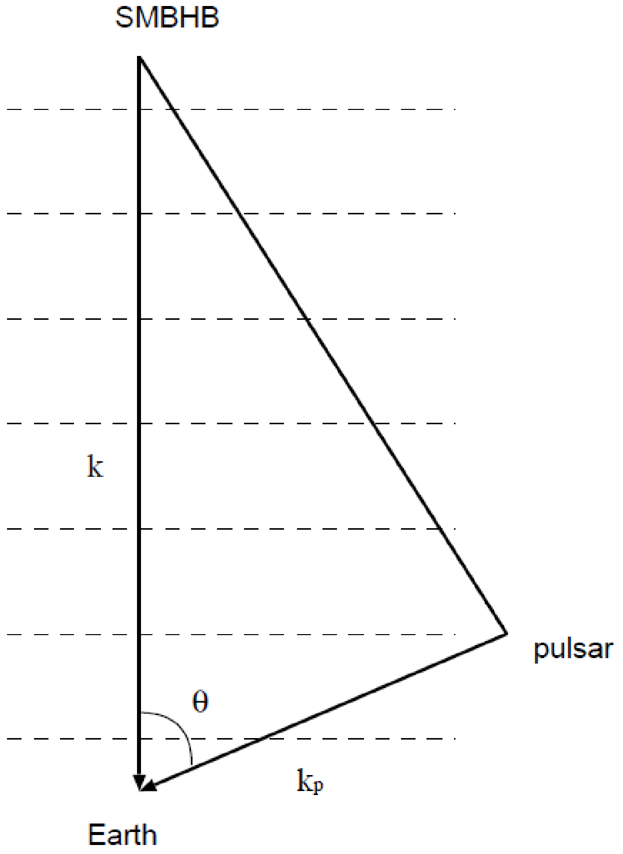
$$\Delta h_{+,\times}(t_i^I;\theta) = \boxed{h_{+,\times}(t_i^I;\theta)} - \boxed{h_{+,\times}(t_i^I - \tau^I;\theta)}$$

Earth term — Pulsar term

$$\tau^I = d^I(1-\cos\theta^I)/c \qquad \lambda = \{\alpha,\delta\}\cup\theta$$

$$\lambda = \{\zeta,\iota,\psi,\alpha,\delta,\omega_{gw},\varphi_0,\varphi_I\}\ (I = 1,2,\ldots,N_p)$$

Pulsar phase: $\varphi_I = \varphi_0 - \frac{1}{2}\omega_{\rm gw}d^I(1-\cos\theta^I)$



Likelihood ratio

$$\mathrm{LR}(\mathbf{r}) = \frac{p(\mathbf{r}|H_\lambda)}{p(\mathbf{r}|H_0)}$$

$$\mathrm{GLRT}(\mathbf{r}) = \max_\lambda \frac{p(\mathbf{r}|H_\lambda)}{p(\mathbf{r}|H_0)}$$

(Log)-Likelihood ratio function:

$$\Lambda(\mathbf{r}) = \ln \frac{p(\mathbf{r}|\mathcal{H}_\lambda)}{p(\mathbf{r}|\mathcal{H}_0)} = \sum_{I=1}^{N_p} \langle r^I | s^I(\lambda) \rangle_I - \sum_{I=1}^{N_p} \frac{1}{2} \langle (s^I(\lambda) | s^I(\lambda) \rangle_I$$

$$\lambda = \{\zeta, \iota, \psi, \alpha, \delta, \omega_{gw}, \varphi_0, \varphi_I\} \; (I = 1, 2, \ldots, N_p)$$

Detection statistics

$$\mathrm{GLRT}(\mathbf{r}) = \max_{\lambda_i} \max_{\lambda_e} \Lambda(\mathbf{r}; \lambda)$$

Option I: Wang, Mohanty, and Jenet. ApJ, 795, 96 (2014)

$$\lambda_e = \{\zeta, \iota, \psi\} + \lambda_i = \{\alpha, \delta, \omega_{gw}, \varphi_0, \varphi_I\}$$

$$s_k^I = \sum_{\mu=1}^{4} a_\mu A_\mu^I(t_k^I)$$

NEC: $a_1 a_2 + a_3 a_4 = 0$

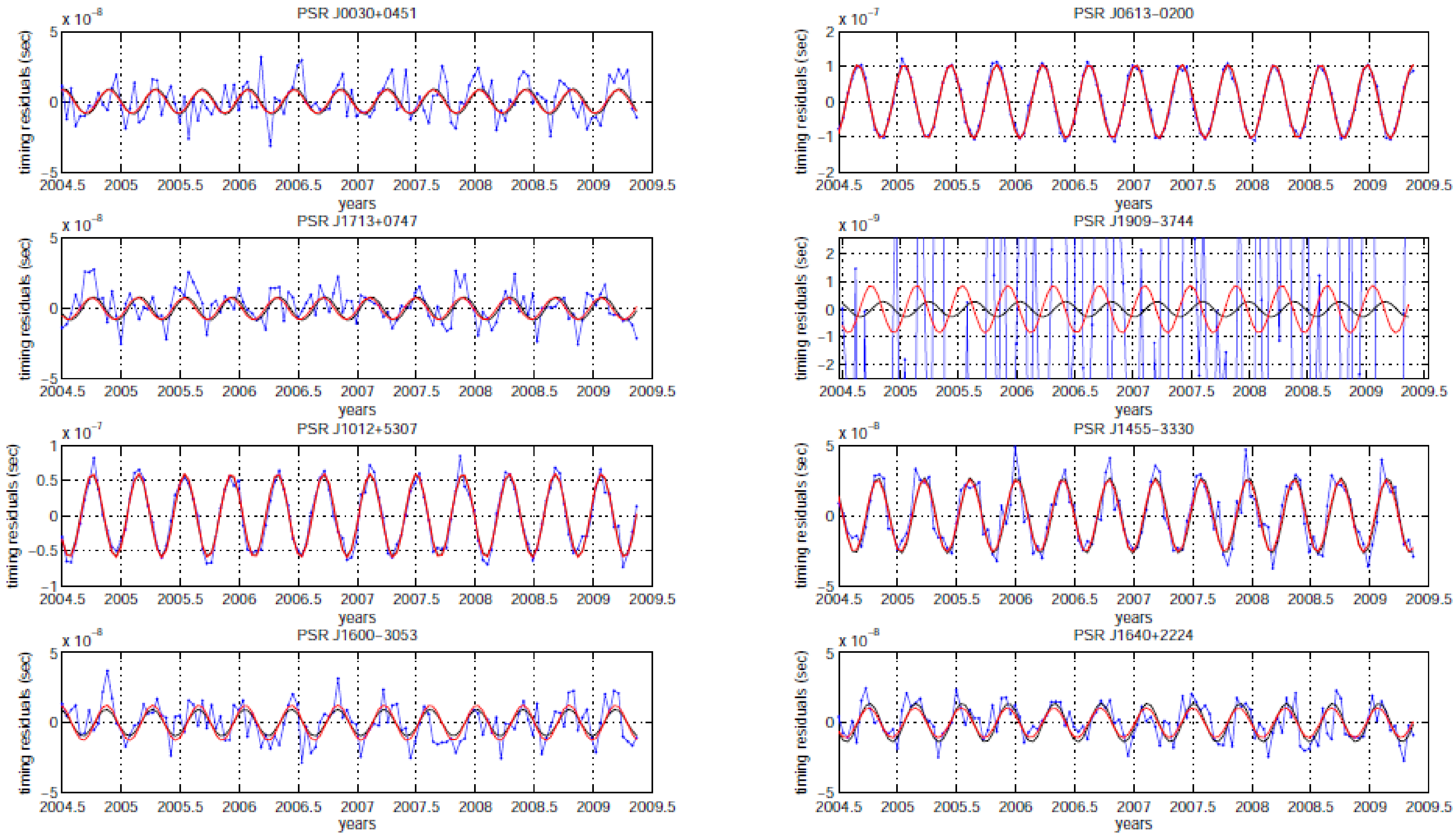
NIEC: $a_1^2 - a_2^2 + a_3^2 - a_4^2 \geq 0$

Option II: Wang, Mohanty, and Jenet. ApJ, 815, 125 (2015)

$$\lambda_e = \{\varphi_I\} + \lambda_i = \{\alpha, \delta, \omega_{gw}, \zeta, \iota, \psi, \varphi_0\}$$

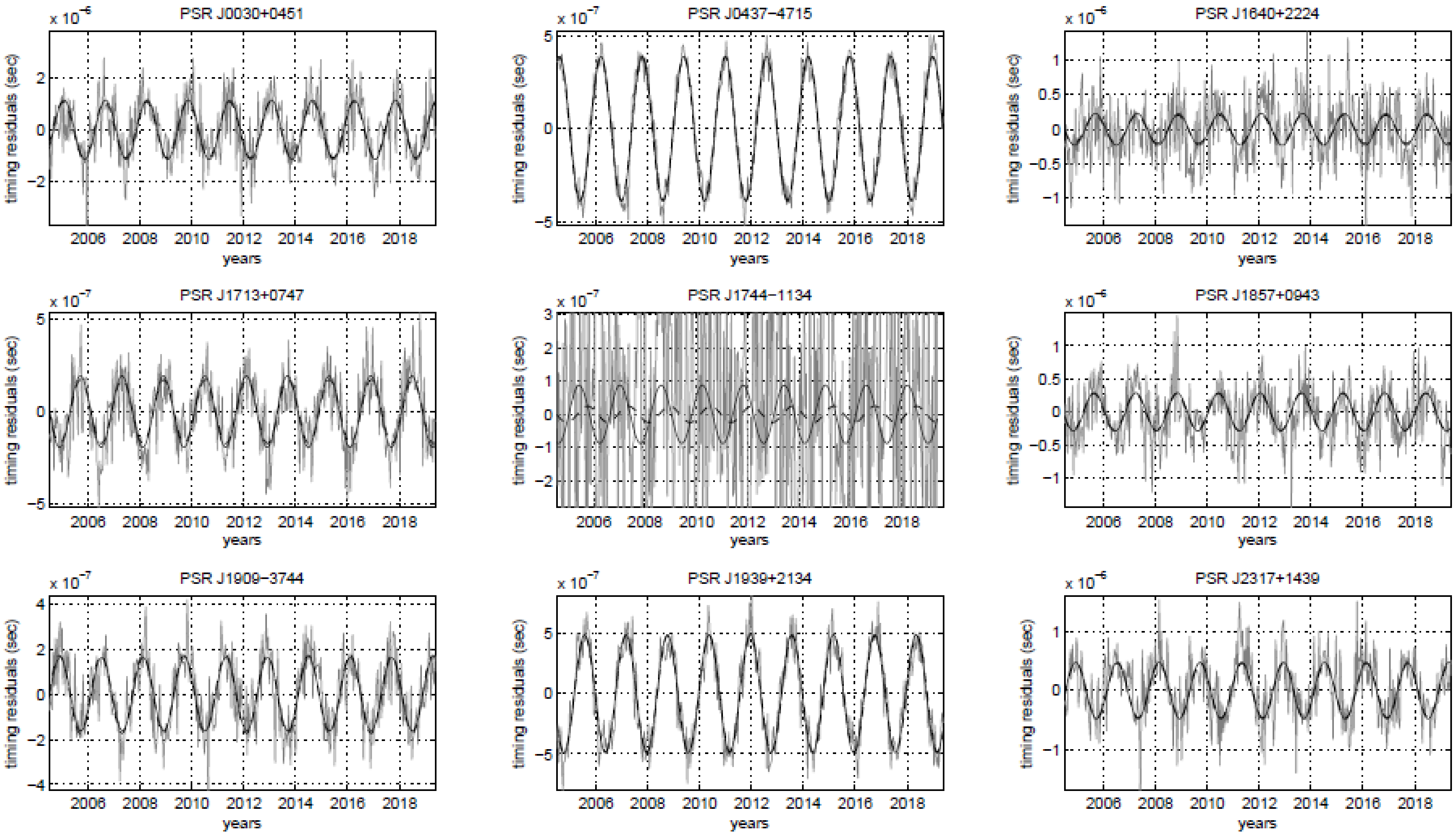
$$s_k^I = X^I \cos 2\varphi_I + Y^I \sin 2\varphi_I + Z^I$$

Opt I: S/N=100, signal recovery



Pulsar catalog from Demorest et al., 2013

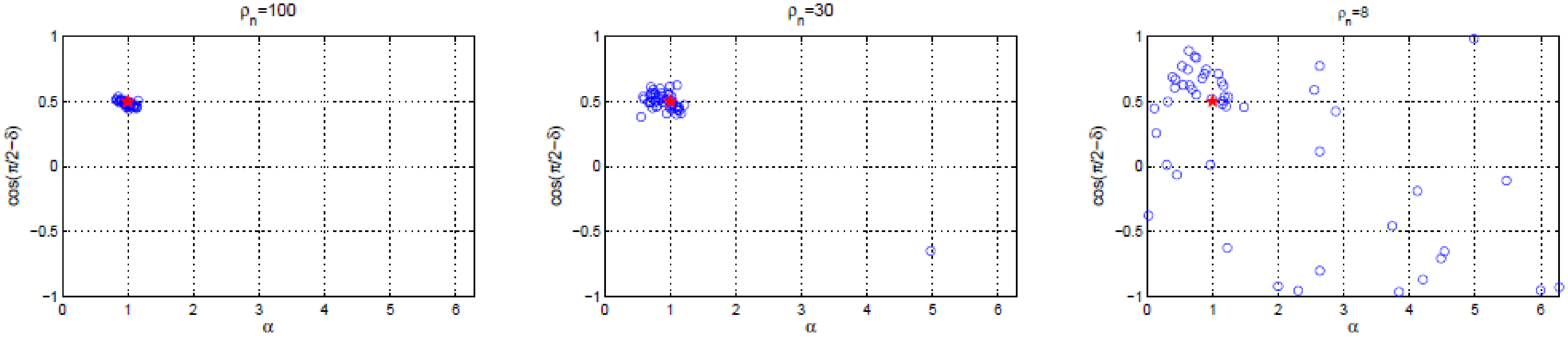
Opt II: network S/N=100, signal recovery



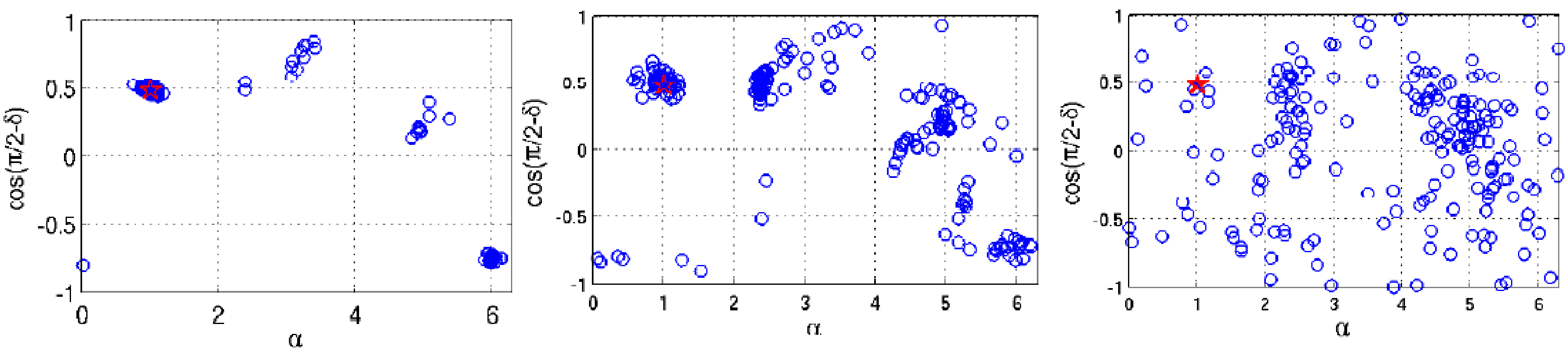
Pulsar catalog from Taylor et. al., 2014

Localization: Opt I v.s. Opt II

Opt I

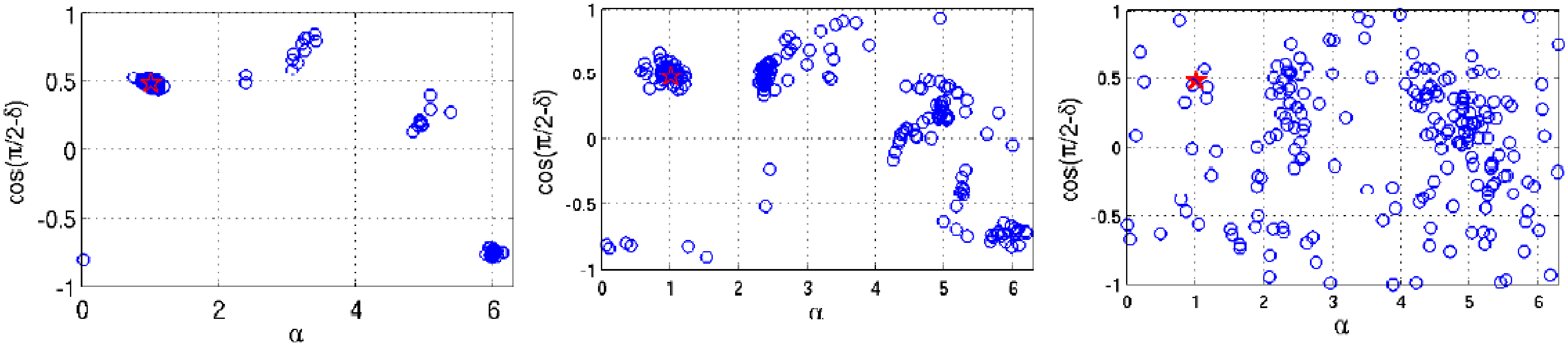


Opt II

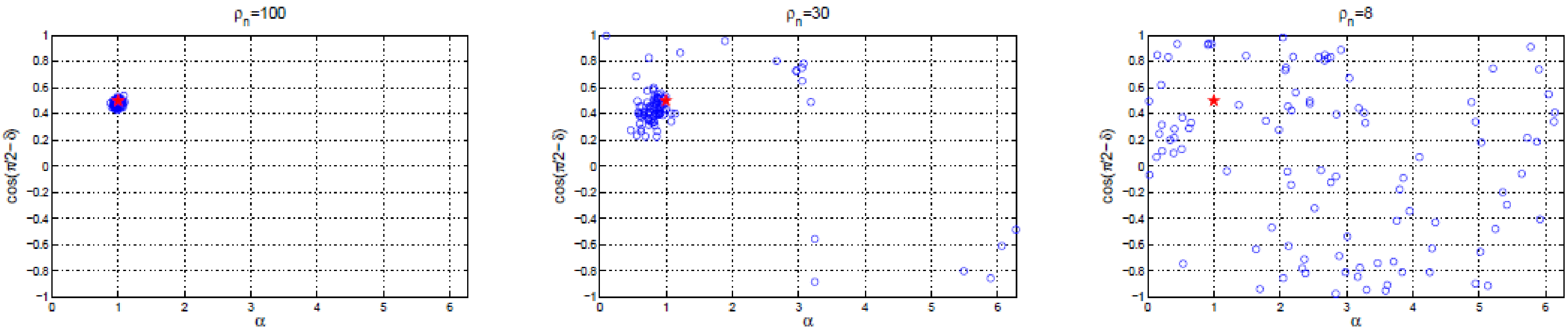


Effect of increasing the PTA size for Opt II

9 pulsars

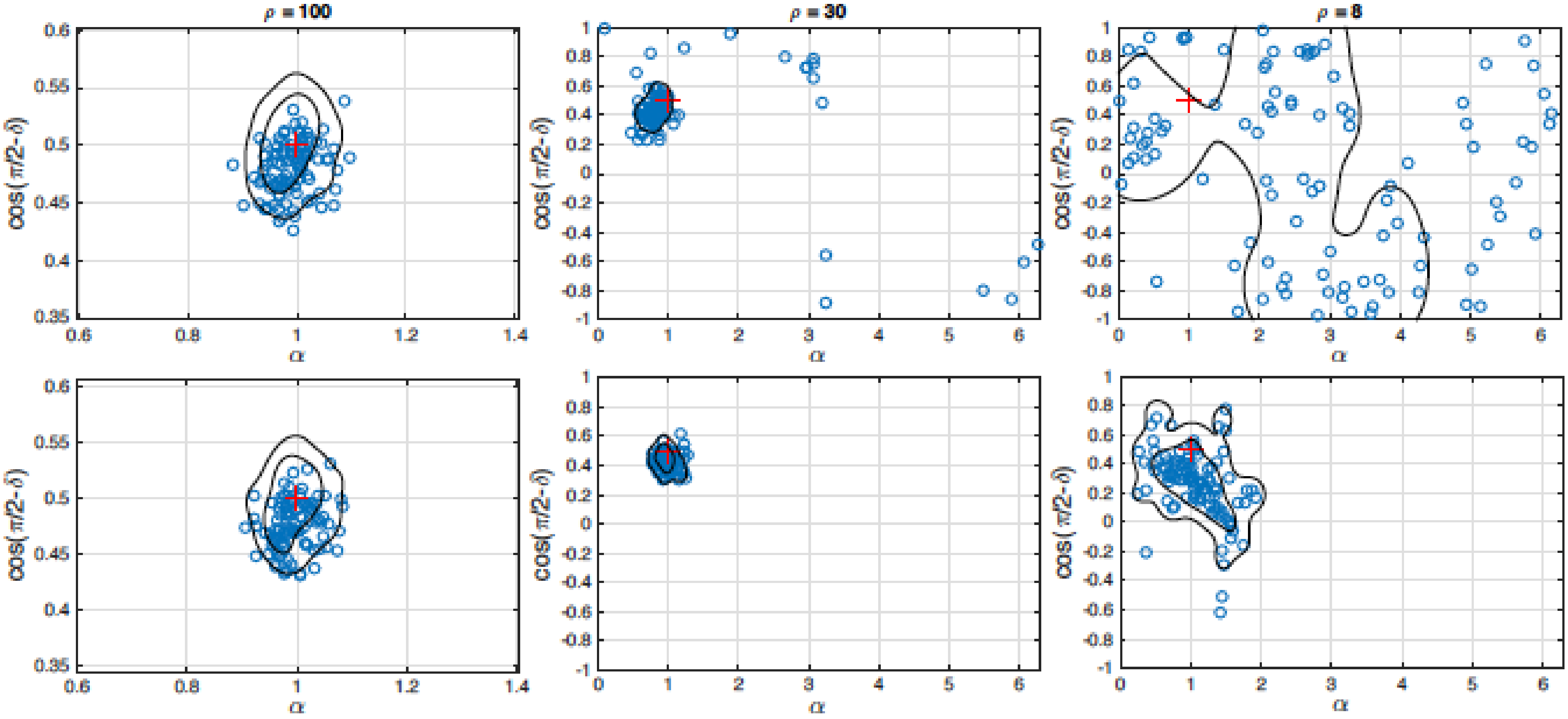


17 pulsars



Klimenko et al. 2005; Mohanty et al. 2006; Rakhmanov 2006

Maximization v.s. marginalization



Wang, Mohanty & Qian, arXiv:1704.05784

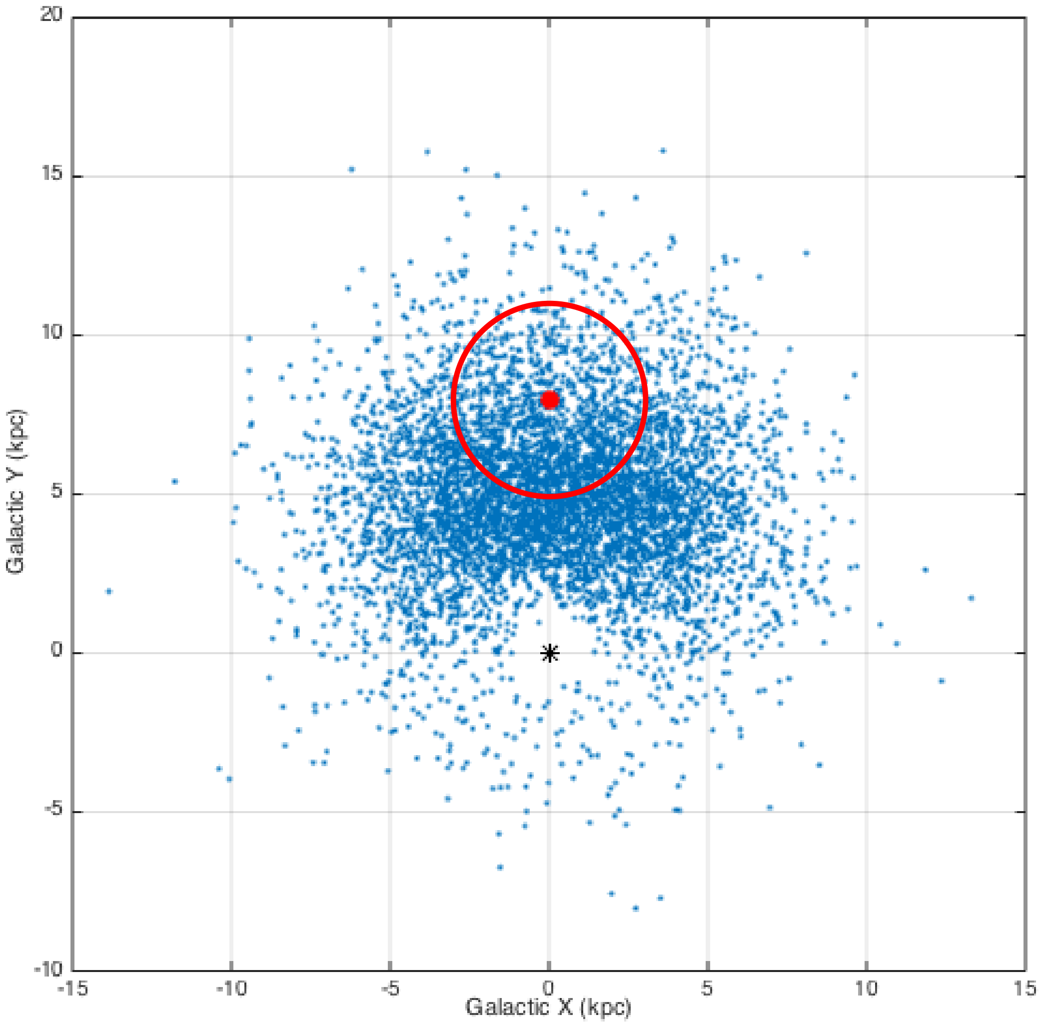
Computational cost

Method	Frequentist /Bayesian	No. of pulsars	Data span	Cost (No. of cores)
Ellis 2013	B	10	~15 yr	~4 hr (4)
Taylor et al. 2014	B	9	~15 yr	~45 min (48)
Wang et al. 2014	F	9	15 yr	89 min (1)
Wang et al. 2015	F	9	15 yr	6.7 min (1)
Zhu et al. 2016	F	12	15 yr	~1.5 min (1)
		30	15 yr	~4 min (1)

Credit: Xing-Jiang Zhu (Monash)

reduced by a factor of 18

PTA in SKA era



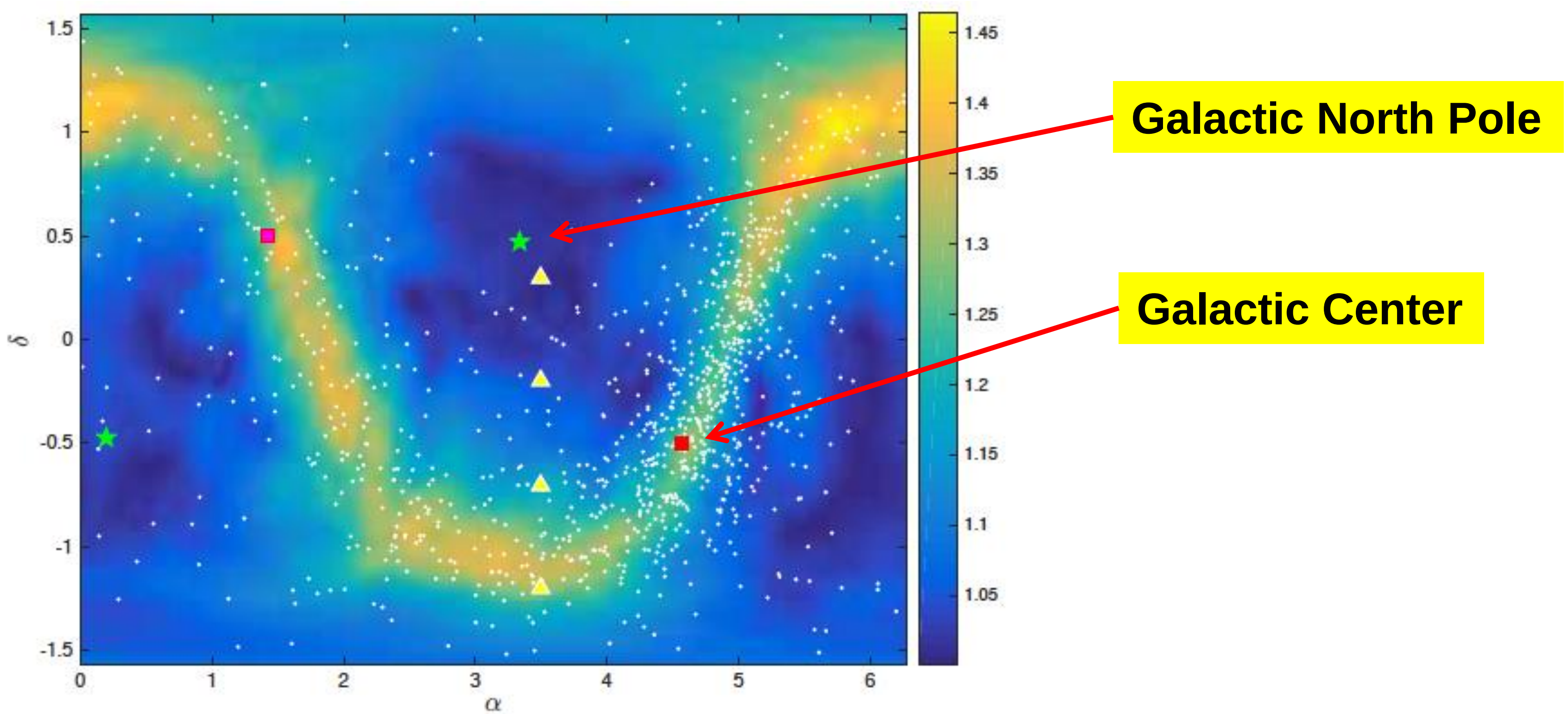
- 14000 canonic PSRs
- 6000 MSPs

- 1000 MSPs < 3 kpc
- 100 ns timing precision

R. Smits et al. A&A (2009)

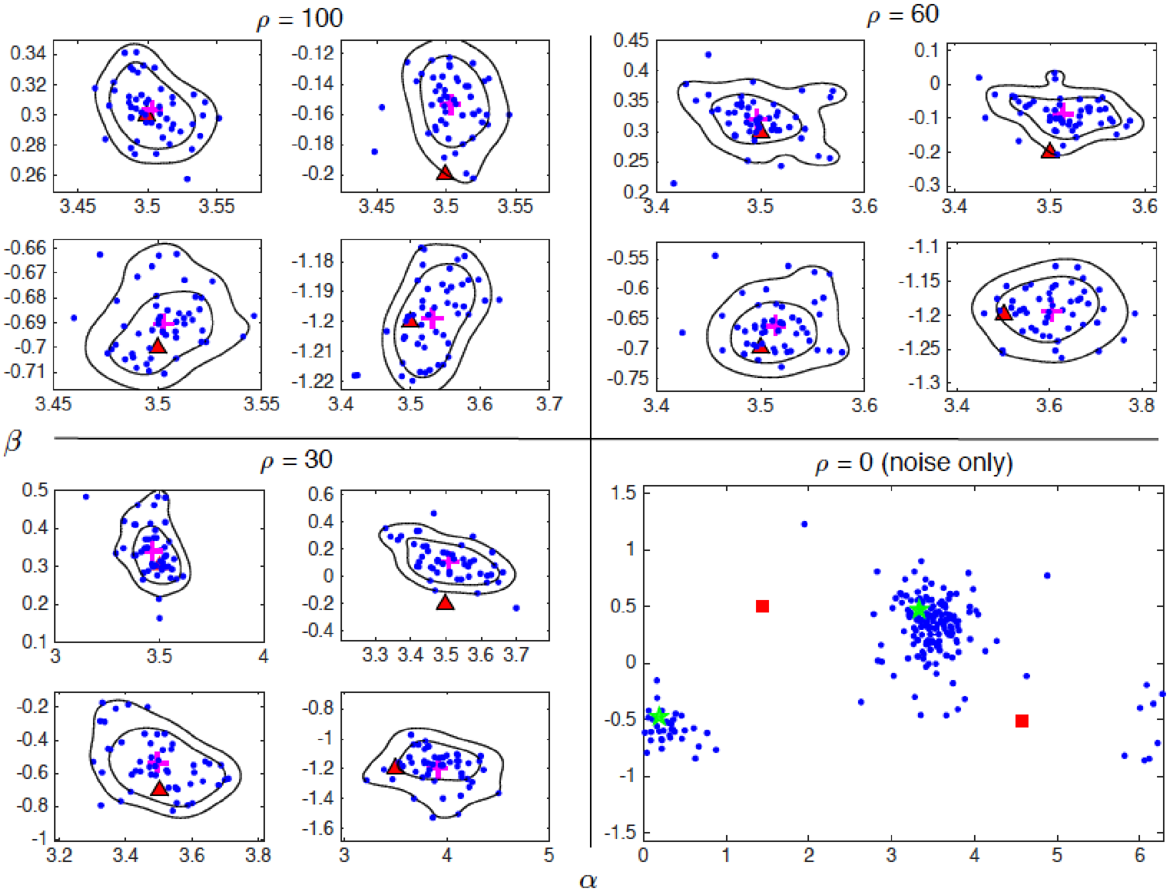
Data model for a network

$$\underbrace{\begin{pmatrix} d_1(t) \\ d_2(t) \\ \vdots \\ d_N(t) \end{pmatrix}}_{\text{Timing Residuals from } N \text{ Pulsars}} = \overbrace{\left[\mathbf{1} - \underbrace{\begin{pmatrix} T[\tau_1] & 0 & \cdots & 0 \\ 0 & T[\tau_2] & \cdots & 0 \\ \cdots & \cdots & \cdots & 0 \\ 0 & 0 & \cdots & T[\tau_N] \end{pmatrix}}_{\text{Time Delay Ops.}} \right] \underbrace{\begin{pmatrix} F_{+,1} & F_{\times,1} \\ F_{+,2} & F_{\times,2} \\ \vdots & \vdots \\ F_{+,N} & F_{\times,N} \end{pmatrix}}_{\text{Antenna Patterns}}}^{\mathbf{A}} \overbrace{\begin{pmatrix} h_+(t) \\ h_\times(t) \end{pmatrix}}^{\mathbf{h}(t)} + \underbrace{\begin{pmatrix} n_1(t) \\ n_2(t) \\ \vdots \\ n_3(t) \end{pmatrix}}_{\text{Noise}}$$



Wang & Mohanty, arXiv: 1611.09440

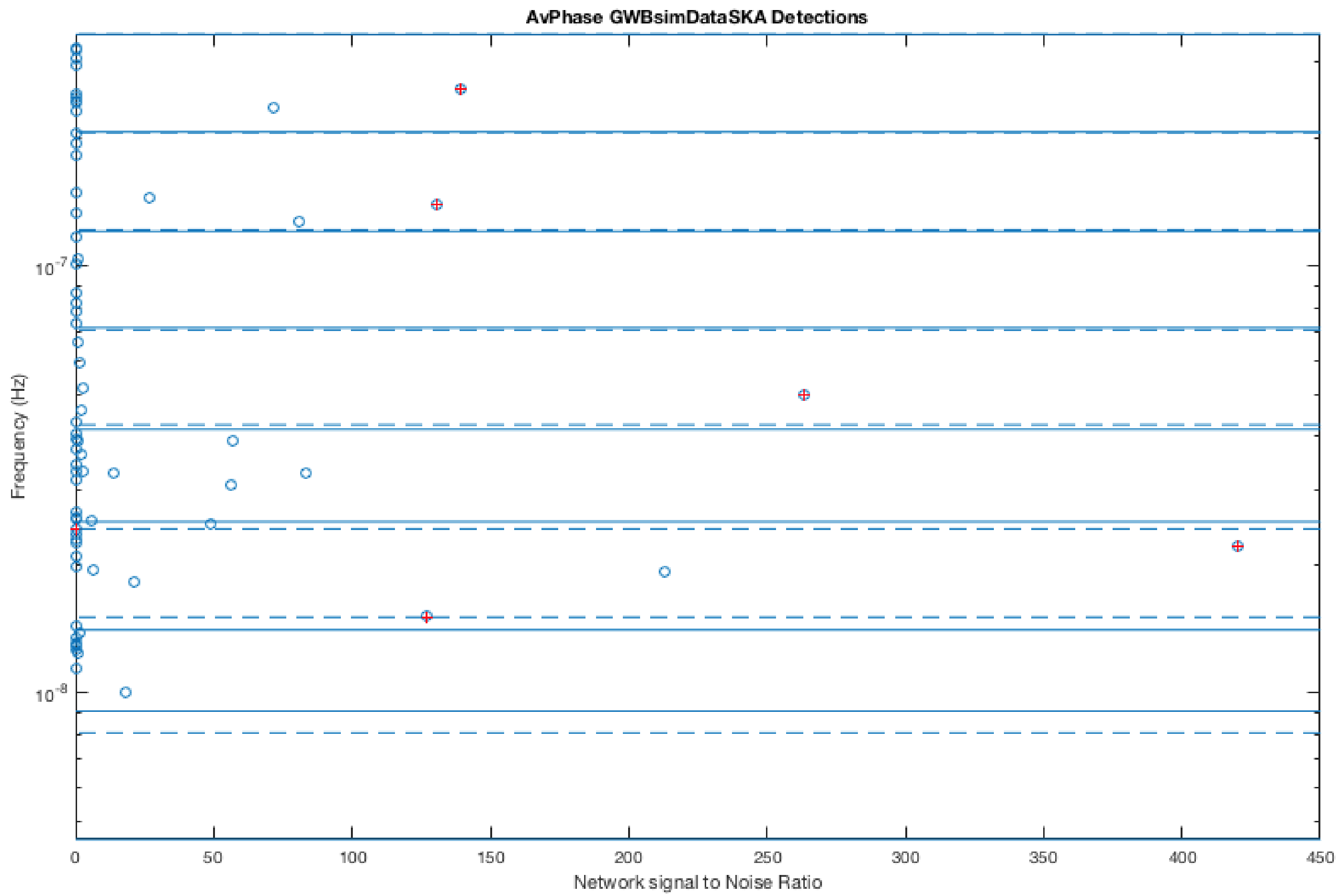
Direction estimation



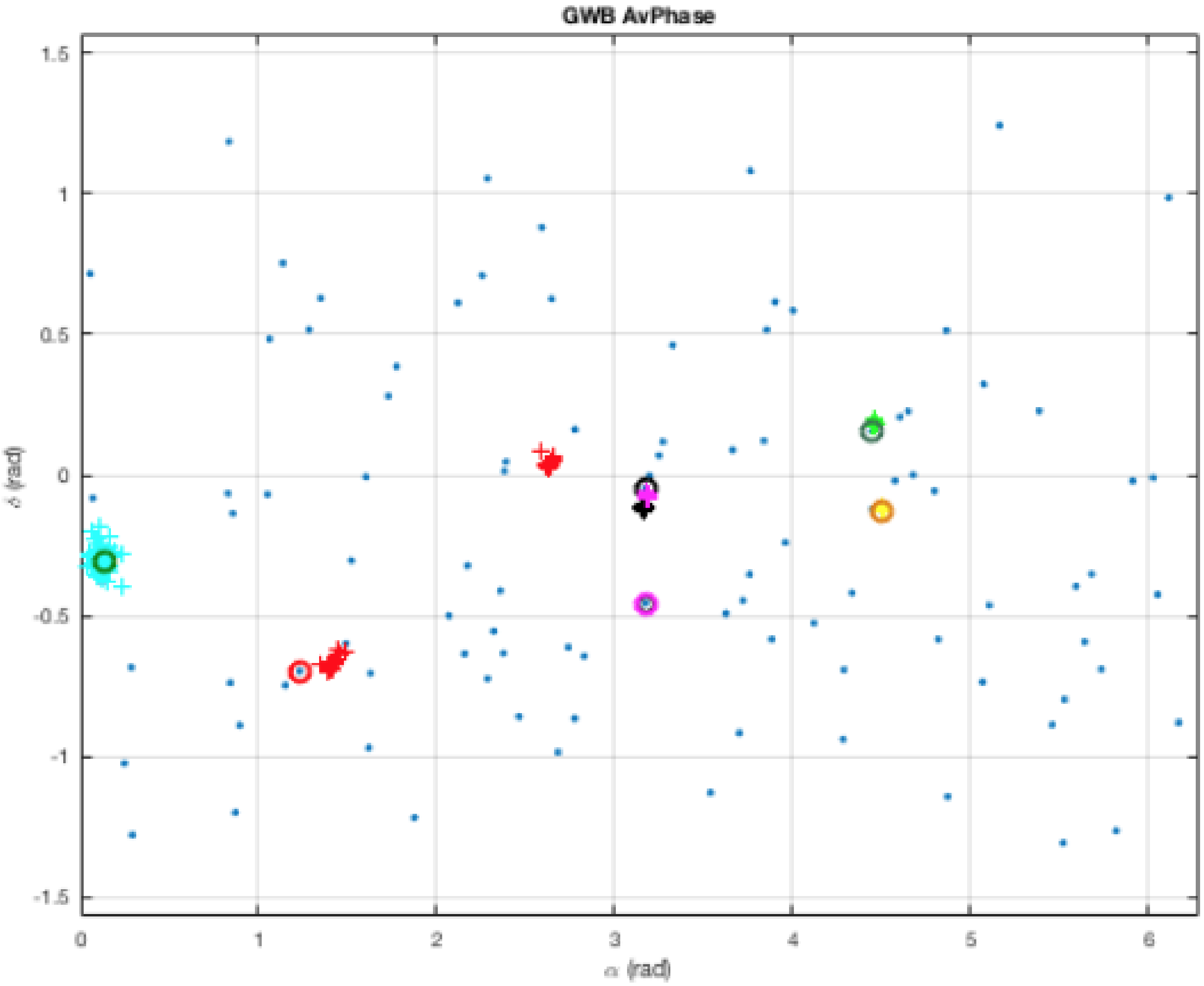
- Conservative error area: $$2\sigma_\alpha \times 2\sigma_\delta \times \cos\delta$$
- Localization to within ~70 to 180 deg^2 at $\rho = 30$
- Search for PSO J334 (Liu et al. ApJL 2015): 80 deg^2 field from Pan-STARRS1 Medium survey
- Optical counterpart searches possible for even the most distant sources (SKA+LSST)

Wang & Mohanty, arXiv: 1611.09440

Multiple source search – Frequency domain

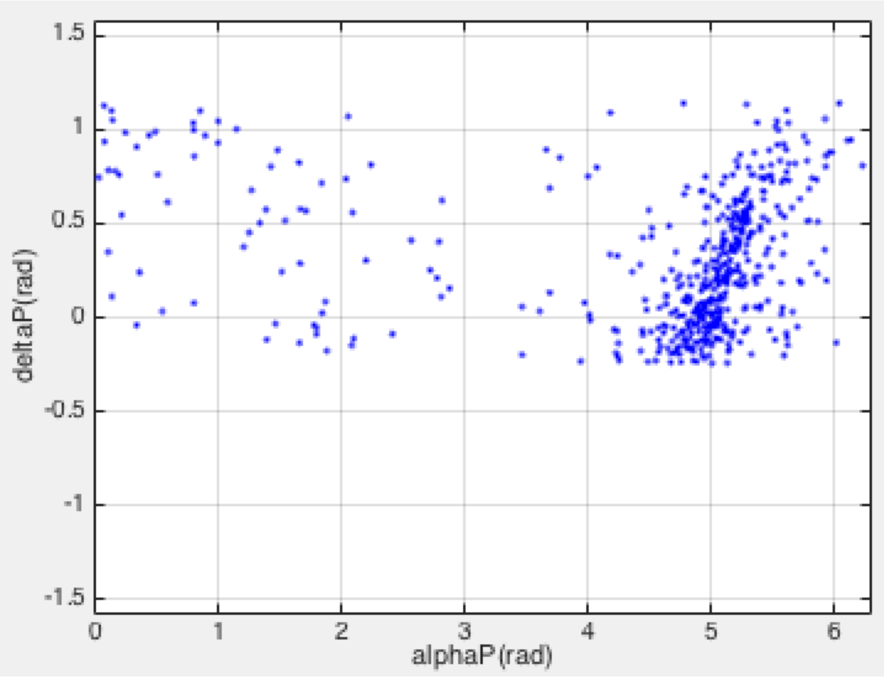


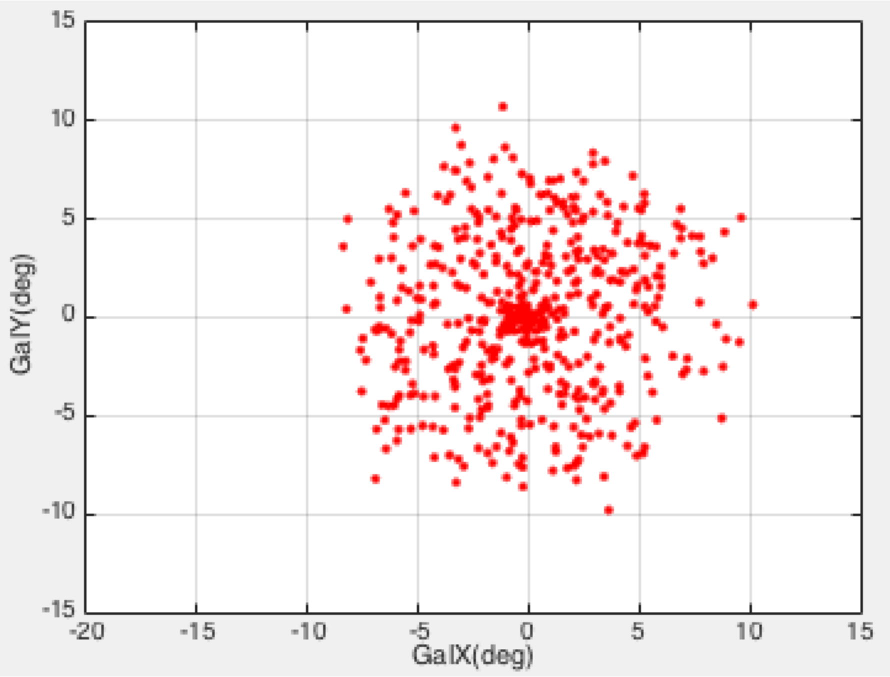
Multiple source search – Sky localization



Wang, Mohanty and Qian. In prep. (2019)

PTA in FAST era



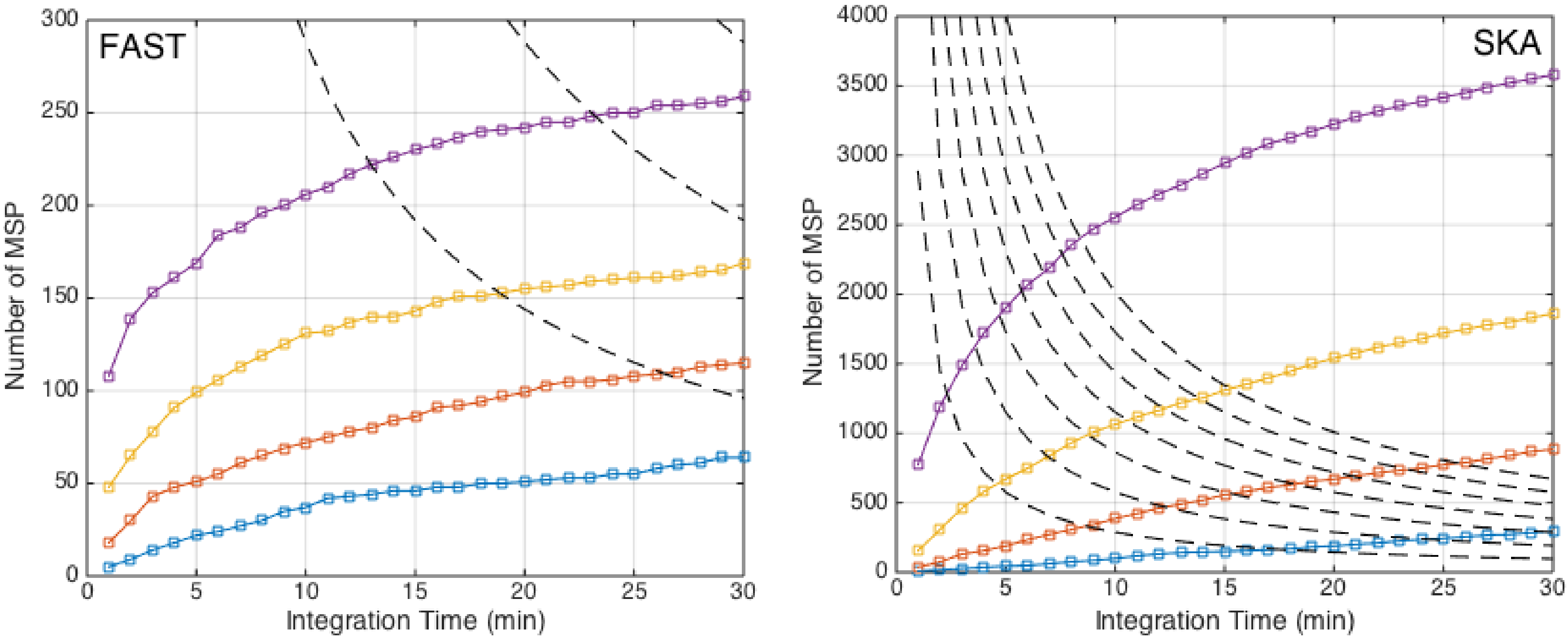


R. Smits et al. A&A (2009)
L. Zhang et al. RAA (2016)

PTA in FAST and SKA era

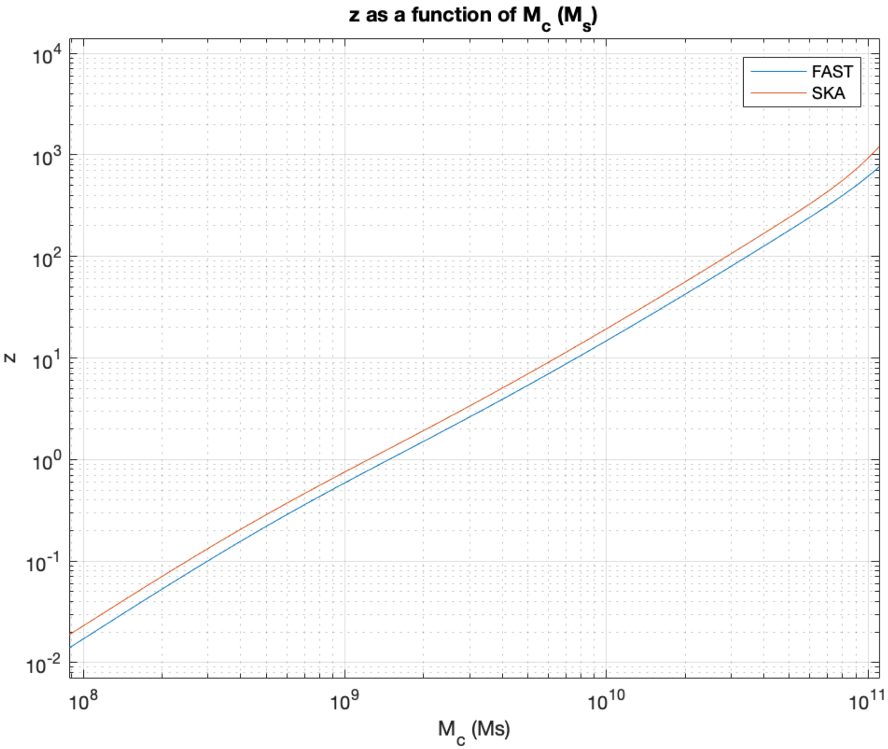
Jitter noise: $$\sigma_{\mathrm{j}} \approx 0.28W\sqrt{\frac{P}{\Delta t}}$$

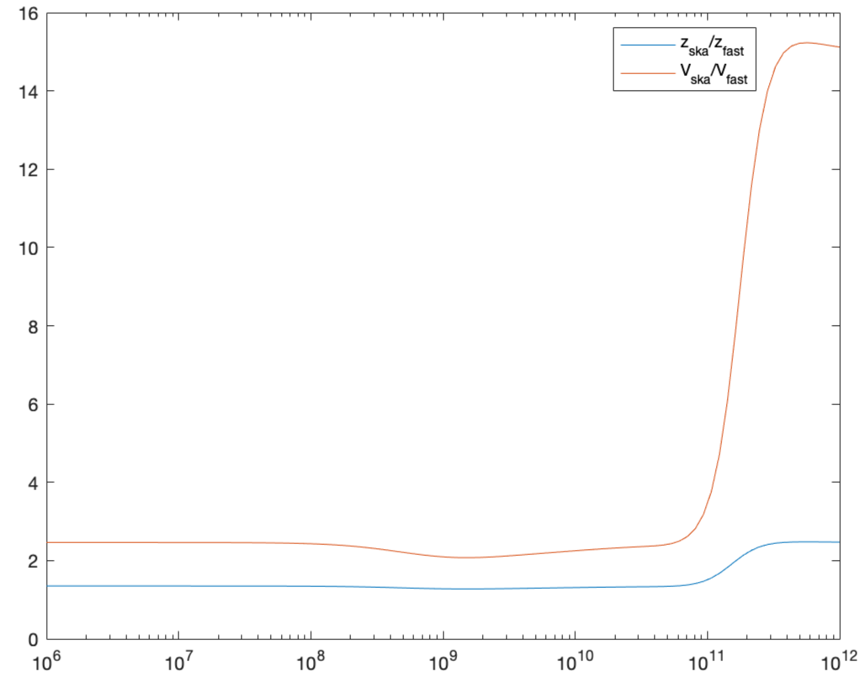
Radiometer noise: $$\sigma_{\mathrm{r}} \approx \frac{WS}{F\sqrt{2\Delta f\Delta t}}\sqrt{\frac{W}{P-W}}$$



Wang & Mohanty, arXiv: 1711.04435

Detection horizon for SKA and FAST





Wang et al., in prep (2019)

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Thank you!

谢谢！