FPS6, HUE, Wuhan

Pulsar timing array based search for supermassive black hole binaries in Square Kilometer Array era

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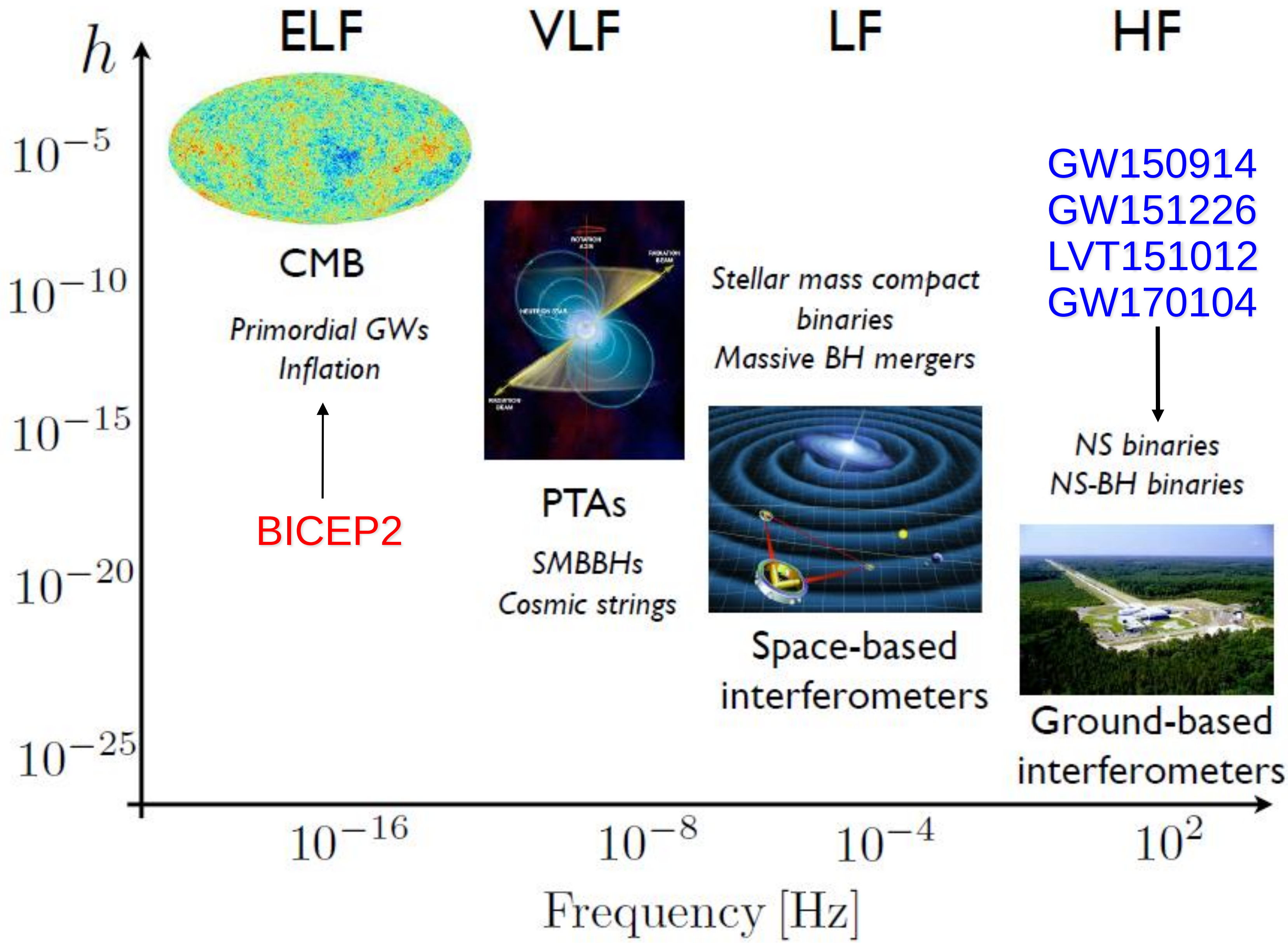
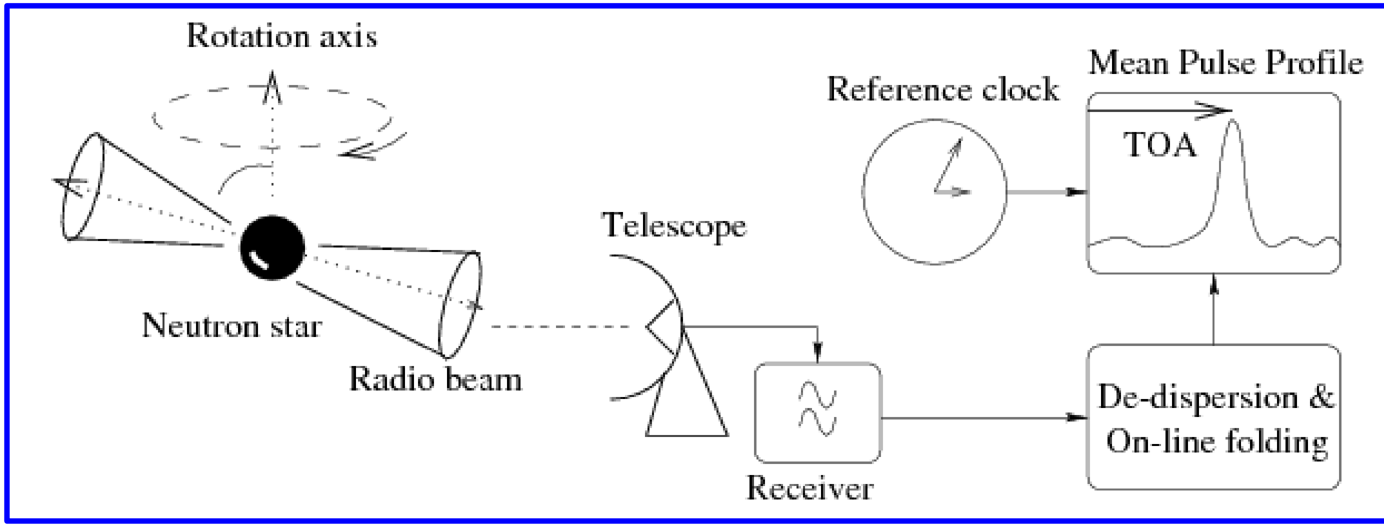
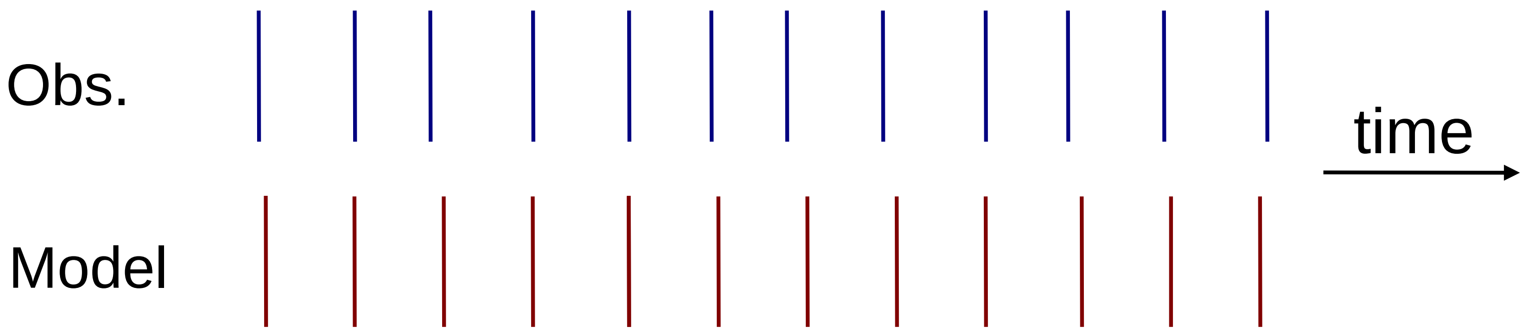
The big picture of gravitational wave astronomy

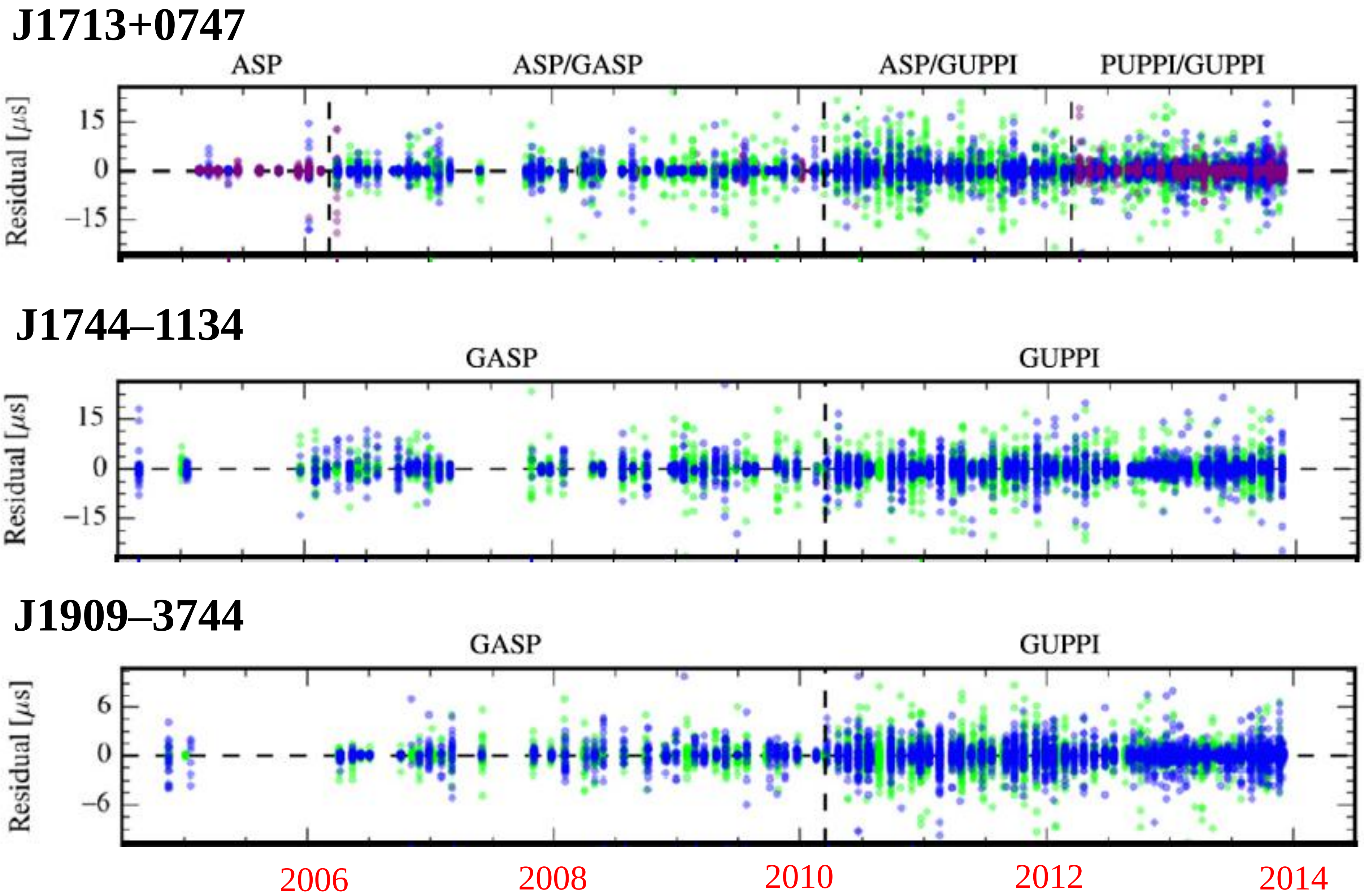


Pulsar timing

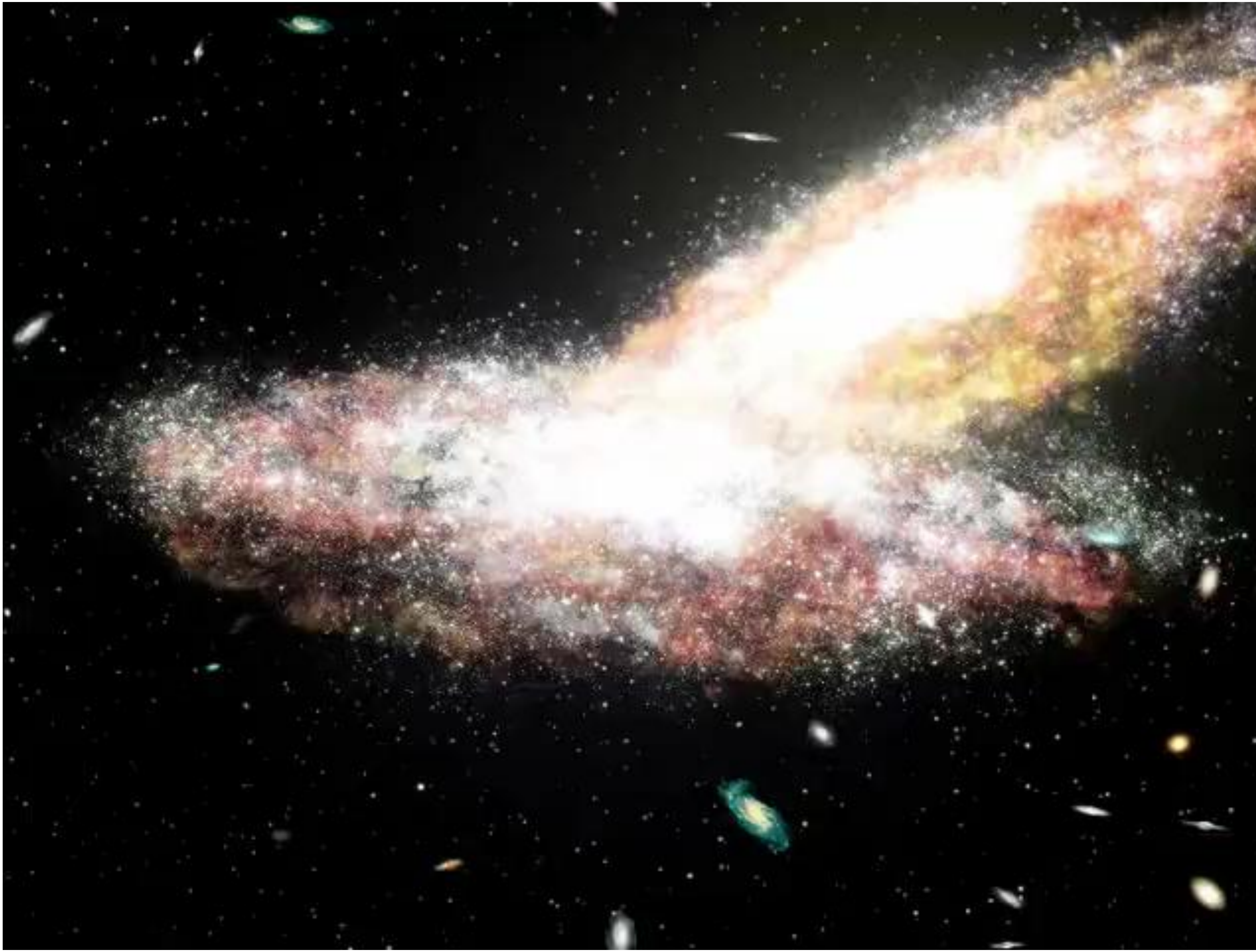




Lorimer & Kramer, “Handbook of Pulsar Astronomy”
Mon. Not. R. Astron. Soc. 369, 655–672 (2006)
Mon. Not. R. Astron. Soc. 372, 1549–1574 (2006)



The NANOGrav Collaboration, ApJ 813, 65 (2015)



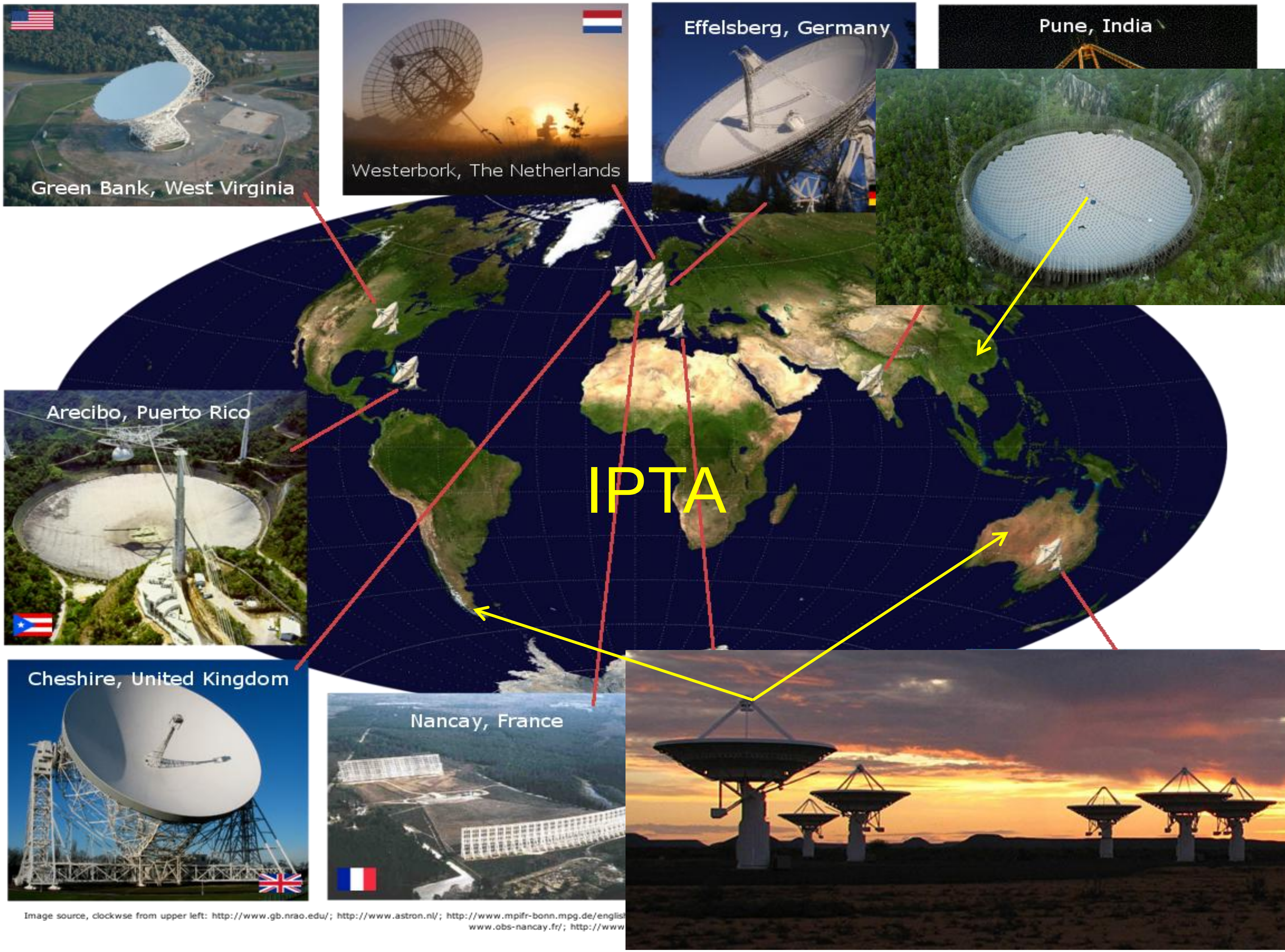
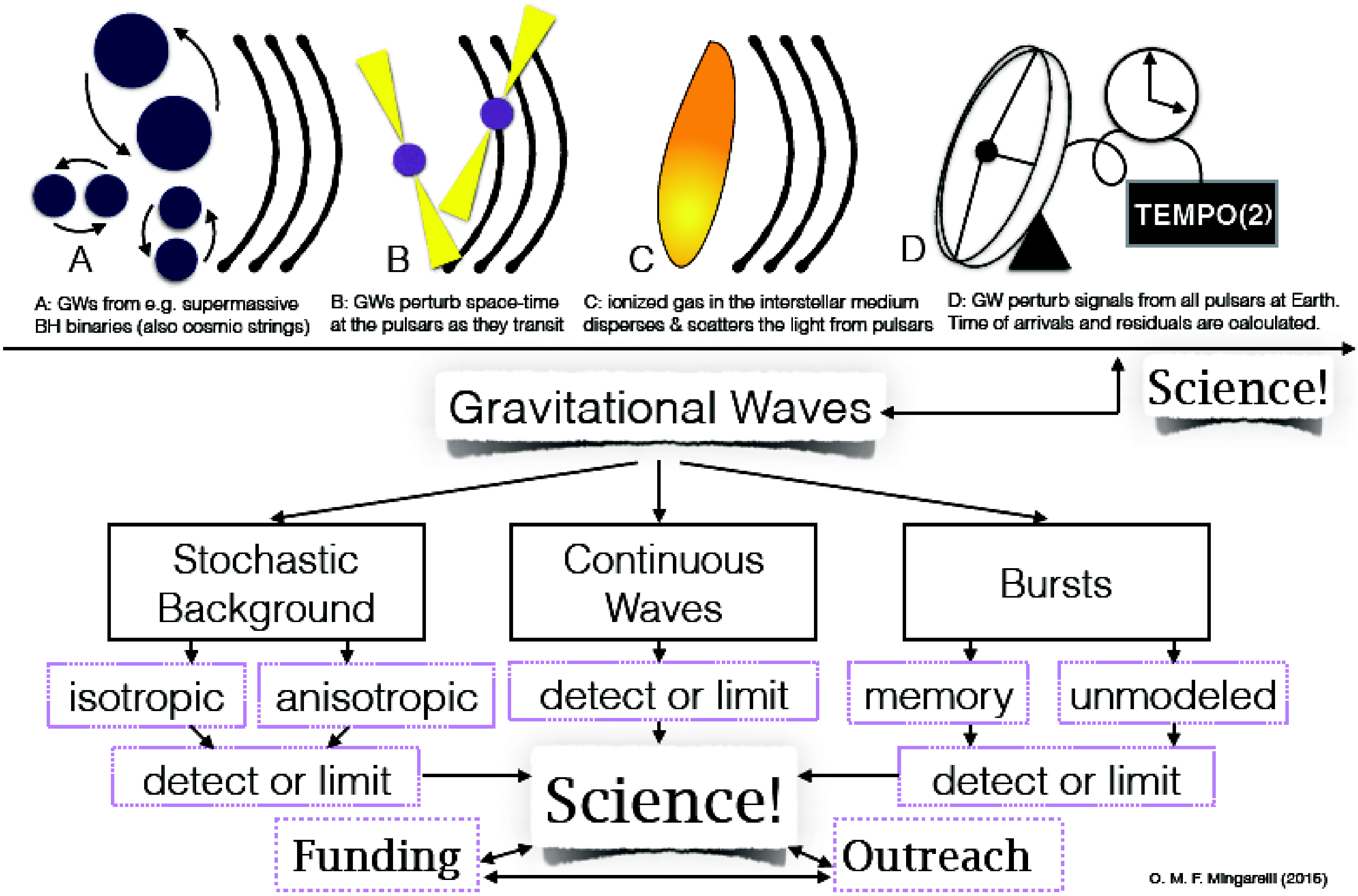


Image source, clockwse from upper left: http://www.gb.nrao.edu/; http://www.astron.nl/; http://www.mpifr-bonn.mpg.de/englis
www.obs-nancay.fr/; http://www

Pulsar Timing Array



Signal model

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

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

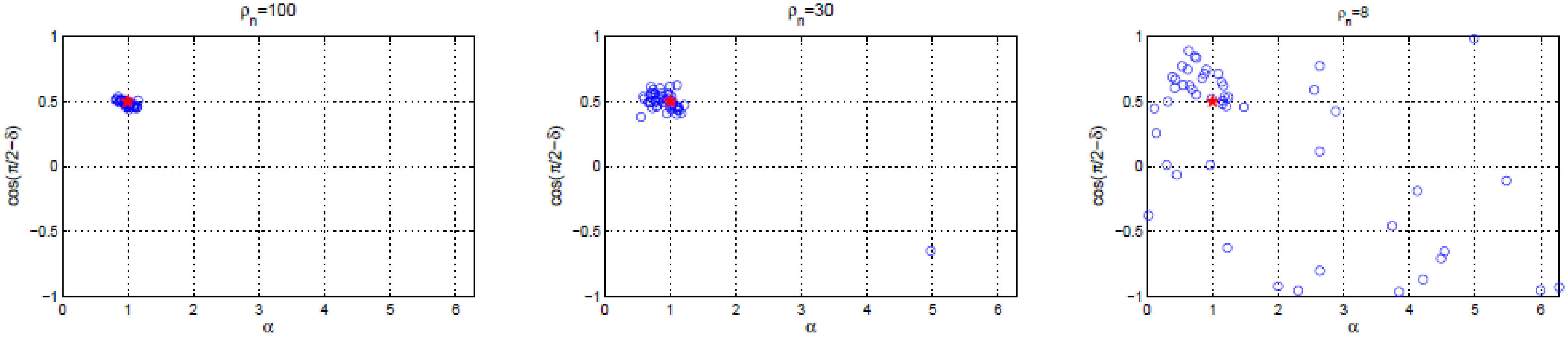
Option II: Wang, Mohanty, and Jenet. ApJ, 815, 125 (2015)

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

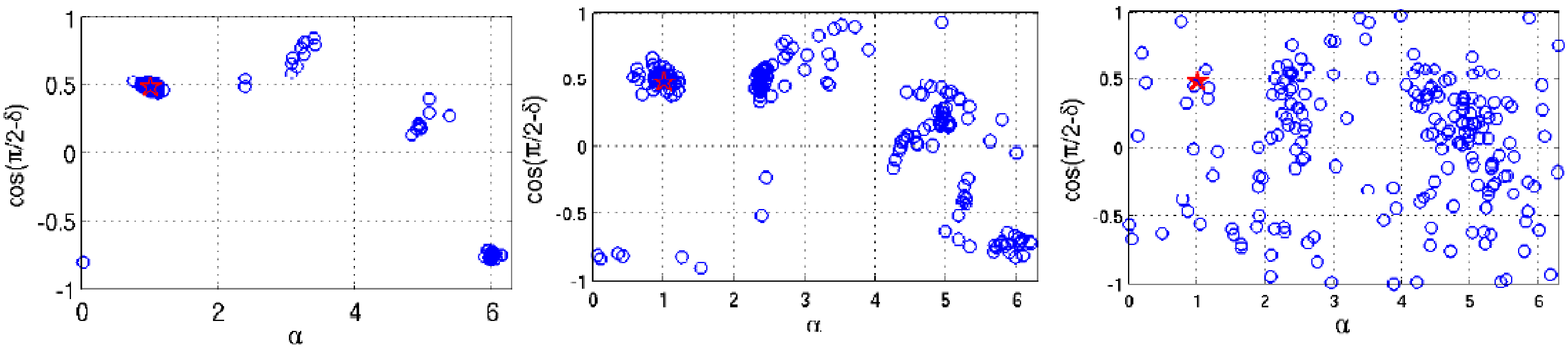
$$s_k^I = X^I \cos 2\varphi_I + Y^I \sin 2\varphi_I + Z^I$$

Localization: Opt I v.s. Opt II

Opt I

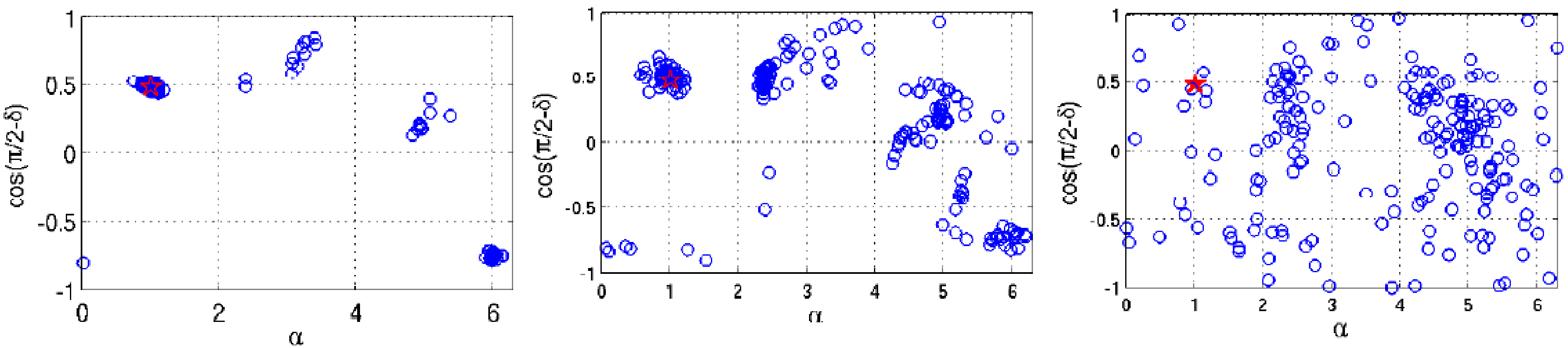


Opt II

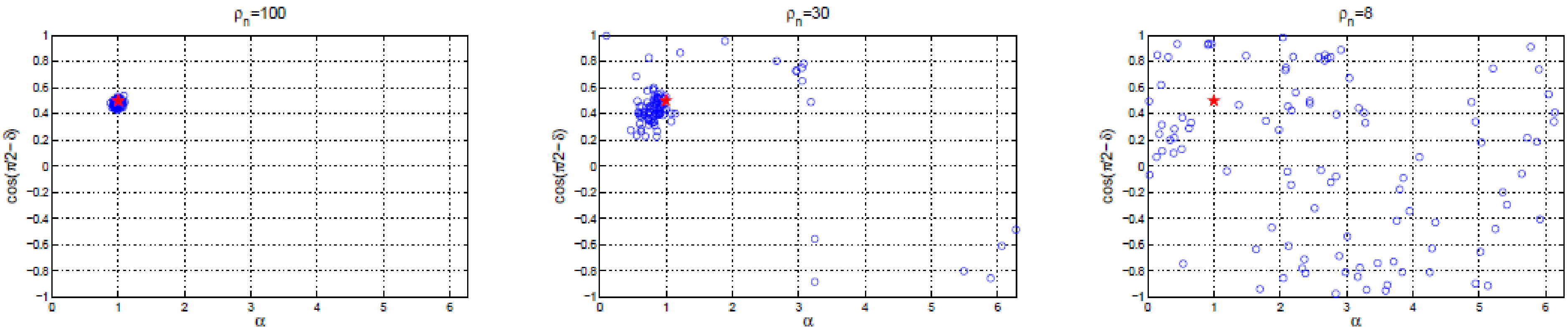


Effect of increasing the PTA size for Opt II

9 pulsars

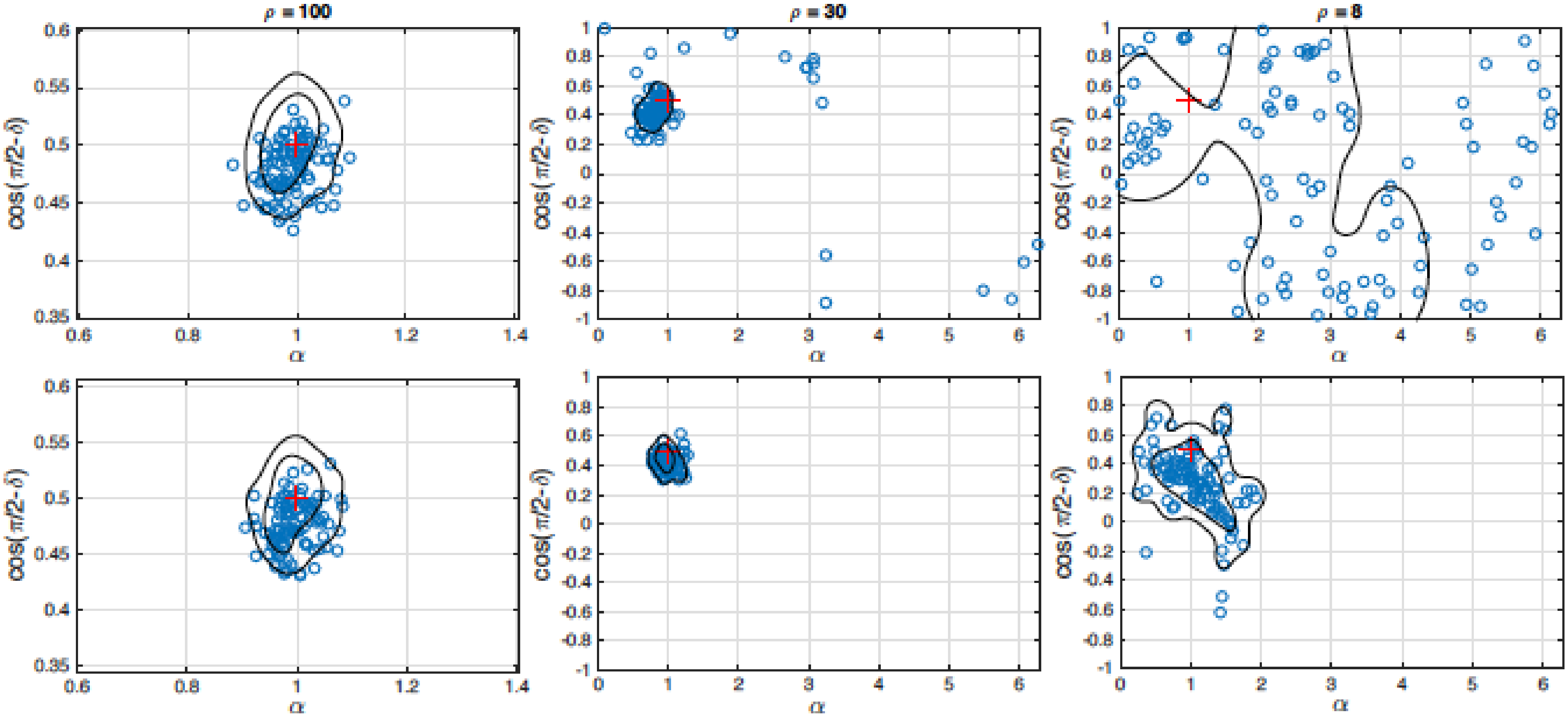


17 pulsars



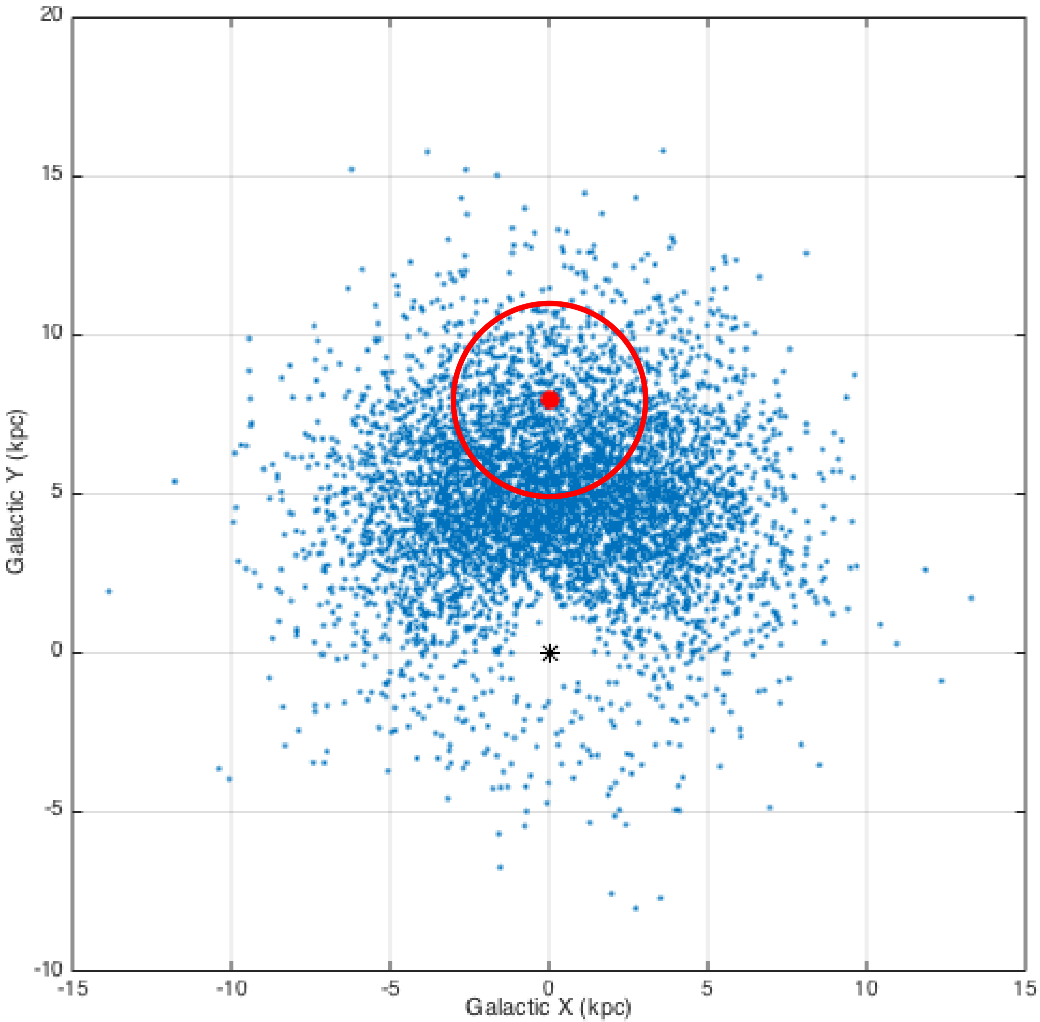
Klimenko et al. 2005; Mohanty et al. 2006; Rakhmanov 2006

Maximization v.s. marginalization



Wang, Mohanty & Qian, arXiv:1704.05784

PTA in SKA era



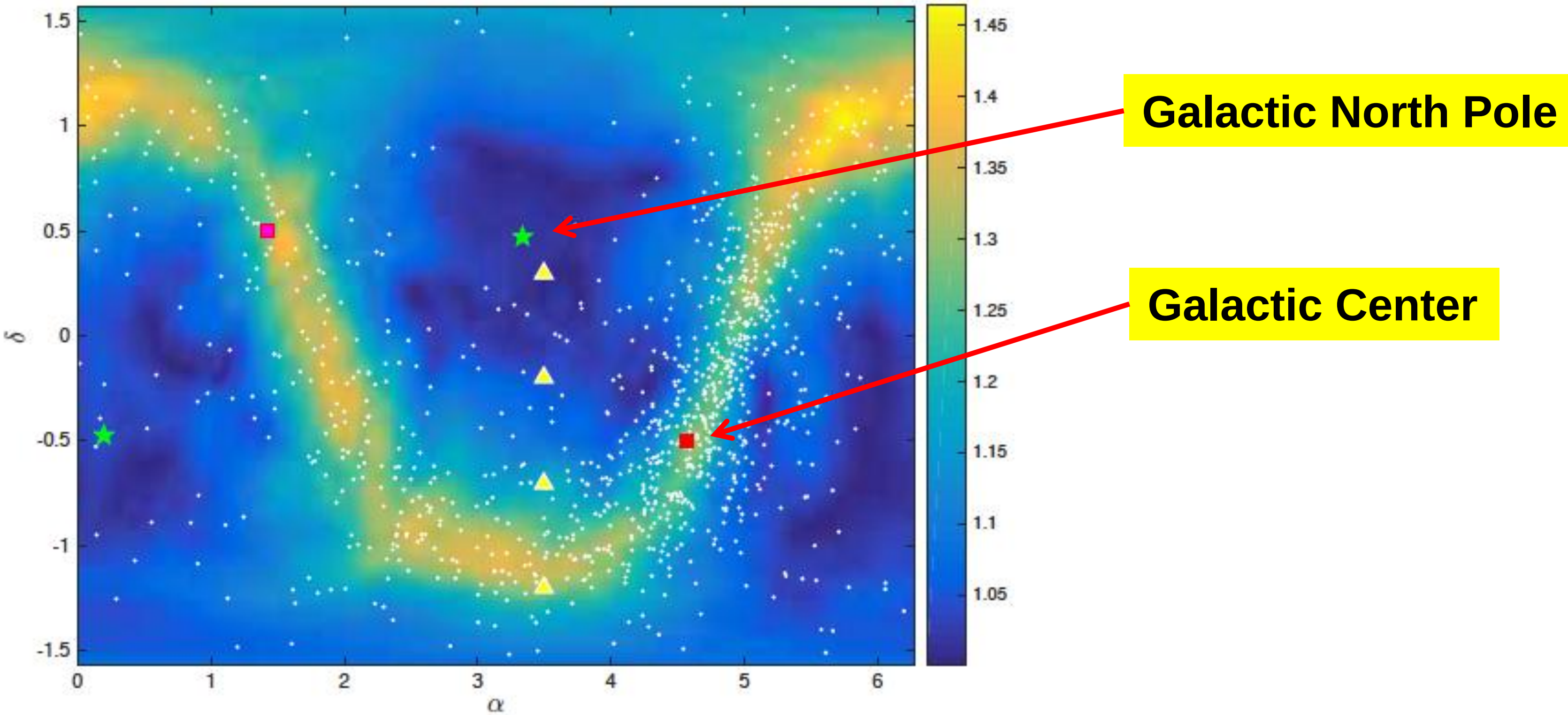
- 14000 canonic PSRs
- 6000 MSPs

- 1000 MSPs < 3 kpc
- 100 ns timing precision

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

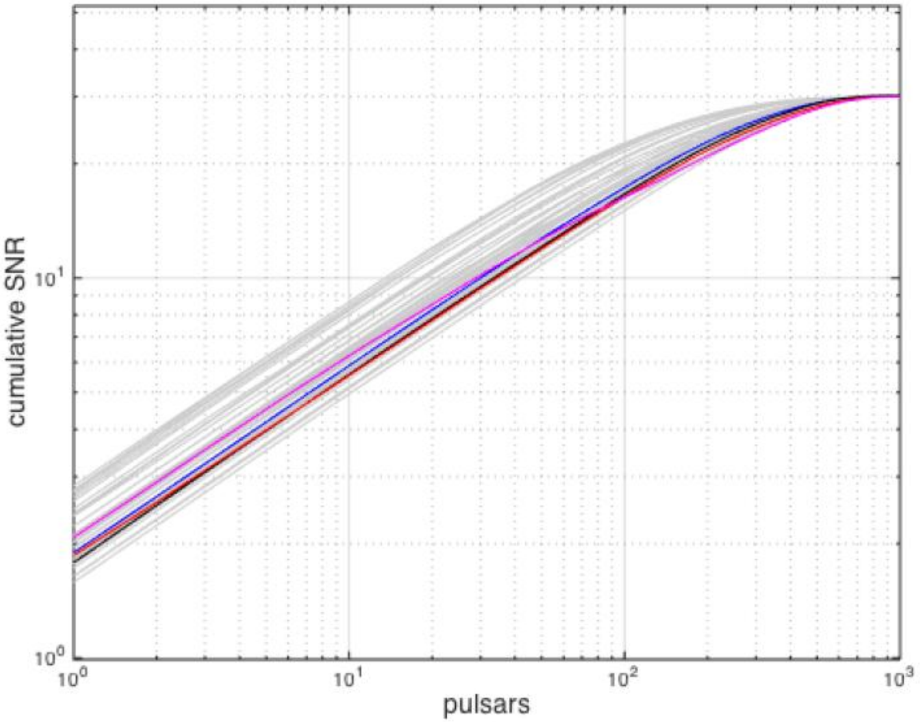
Data model for a network

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



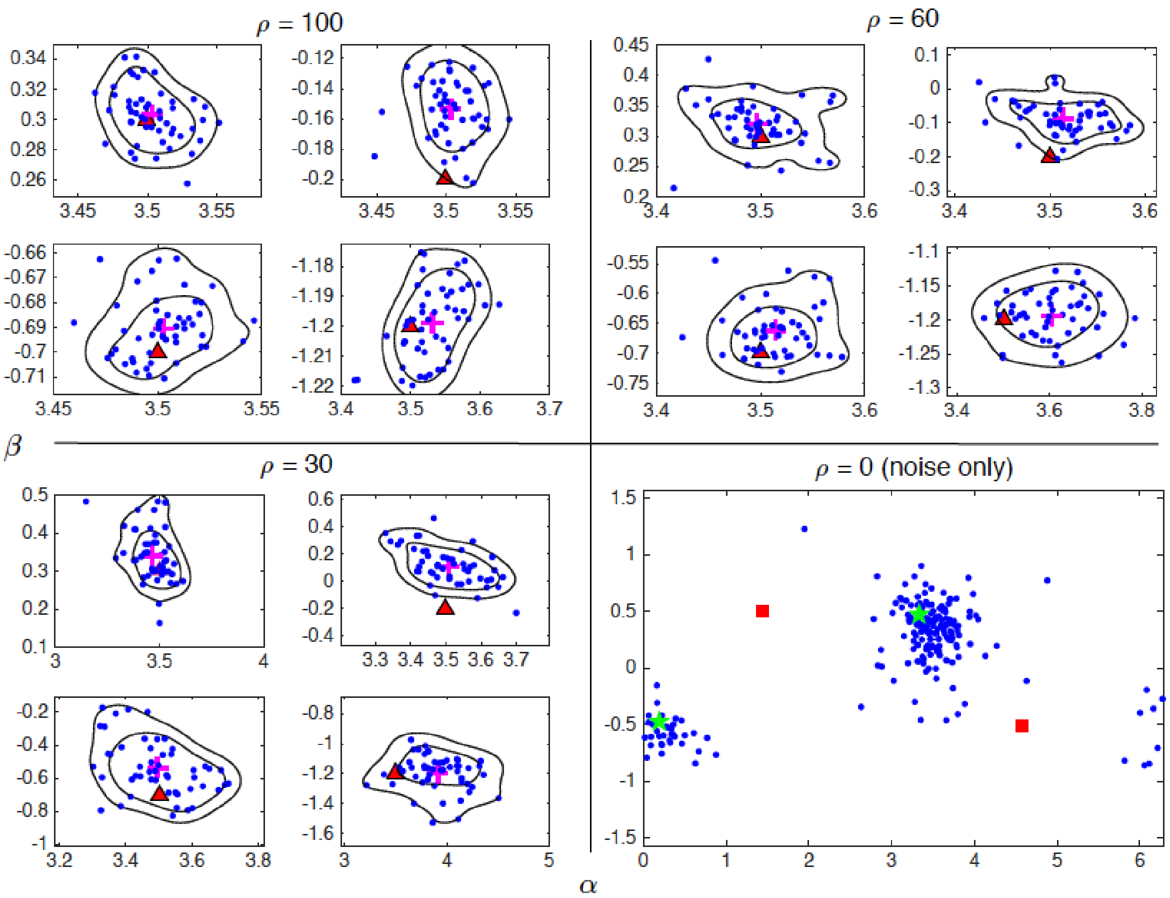
Wang & Mohanty, PRL (2017)

All sky search



- Marginal source for a 30 pulsar PTA has $\rho \sim 10 \Rightarrow \rho \sim 30$ for SKA
- Is $\rho = 30$ bright? (~ 1000 parameters to search $\Rightarrow$ False alarm quite high)
- **Simulation result**: 99.99% detection probability for False alarm probability of 10^{-4}
- Convert ρ to luminosity distance (signal frequency $2 \times 10^{-8}\ Hz$)
  - (Redshifted) chirp mass $10^9 M_\odot \rightarrow$ detectable to $z \leq 0.95$ to 1.55 (depending on sky location)
  - (Redshifted) chirp mass $10^{10} M_\odot \rightarrow$ detectable to $z \leq 28.03$ (averaged)
- Redshift of peak SMBHB formation rate: $z \sim 2$

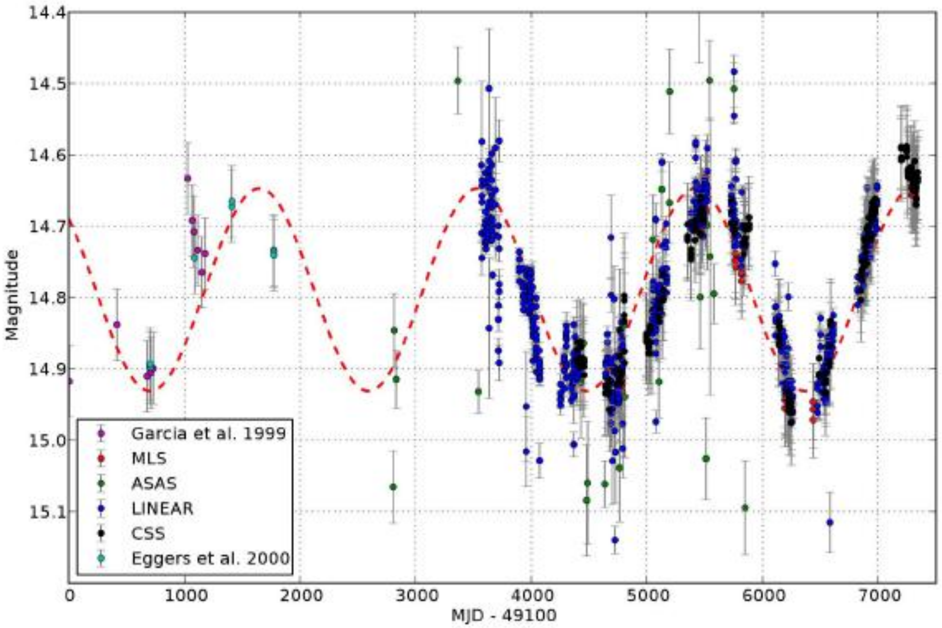
Direction estimation



- Conservative error area:
  $$2\sigma_\alpha \times 2\sigma_\delta \times \cos\delta$$
- Localization to within ~70 to 180 deg² at $\rho = 30$
- Search for PSO J334 (Liu et al. ApJL 2015): 80 deg² field from Pan-STARRS1 Medium survey
- Optical counterpart searches possible for even the most distant sources (SKA+LSST)

Wang & Mohanty, PRL (2017)

Known candidates

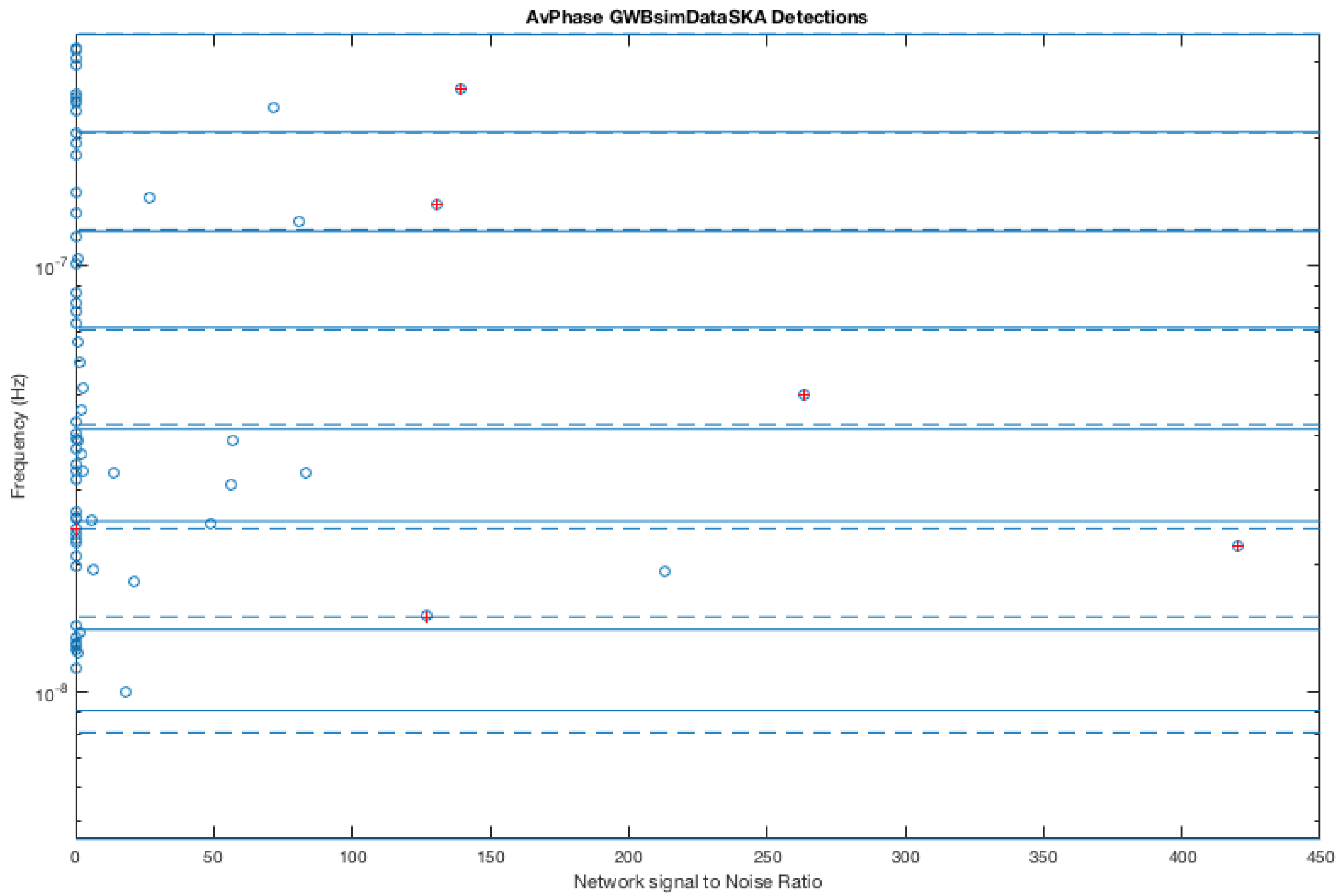


Light Curve for PG1302-102 for ~ 20 years (Graham et al. 2015, Nature)

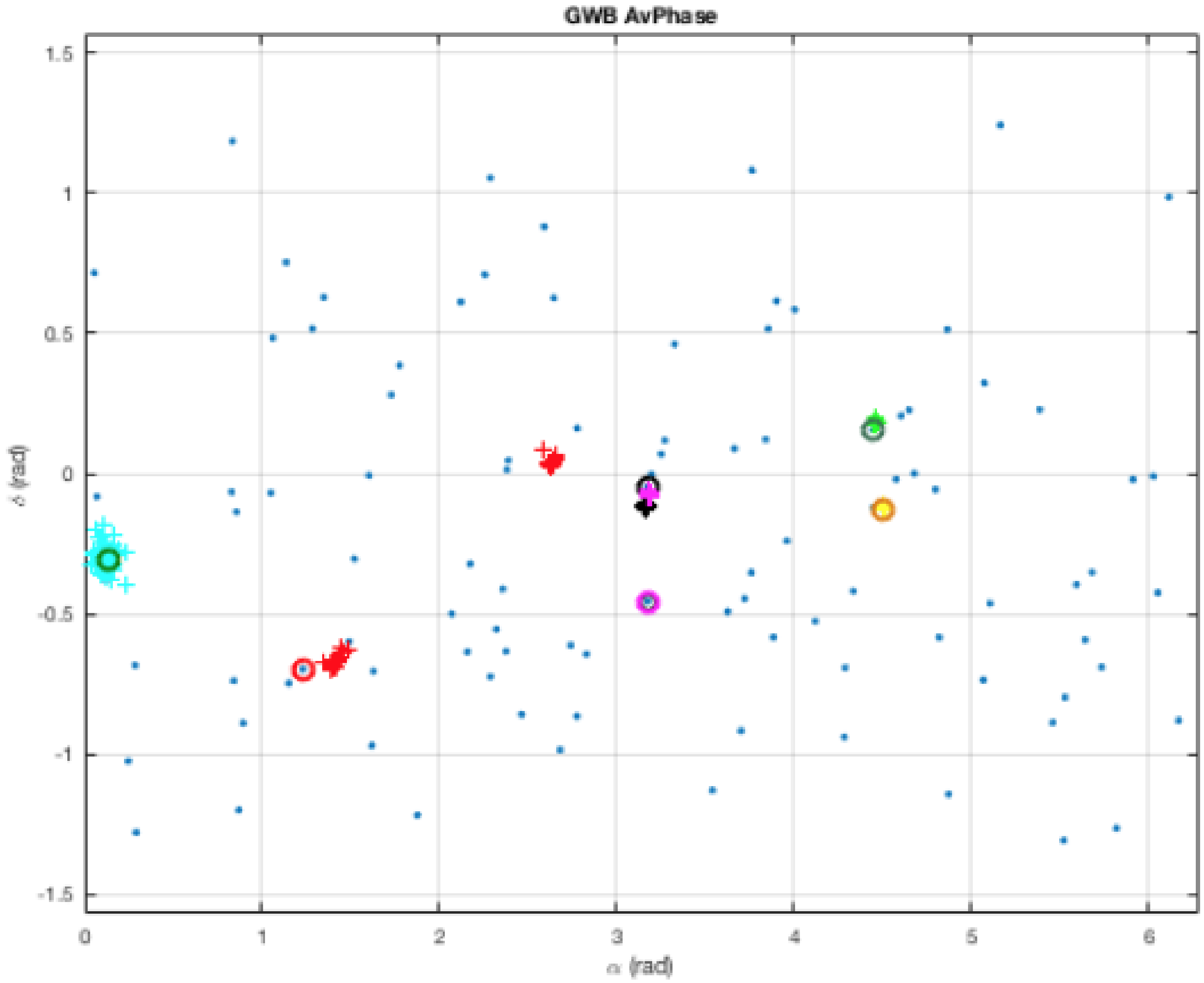
	PG 1302-102 Graham et al, Nat., 2015	**PSO J334+01** Liu et al, ApJL, 2015
Redshift (z)	0.2784	2.06
Resdshifted chirp mass $(1+z)M_c\ (M_\odot)$	$10^{8.0} - 10^{9.1}$	$10^{9.6} - 10^{10.0}$
Period (yr)	5.2	1.48

- PG 1302-102: A non-detection at $\rho = 30 \Rightarrow (1+z)M_c \leq 10^{8.67}\ M_\odot$ with very high confidence
  - Very strong constraint on system parameters from GW observations
  - $\Rightarrow$ rest frame total mass $\leq 10^{9.01}\ \mathrm{M}_\odot$.
- For PSO J334+01, $\rho \geq 100$
  - Guaranteed source for a SKA era PTA.
  - But predicted to coalesce before SKA!
  - More such systems should show up with LSST

Multiple source search – Frequency domain

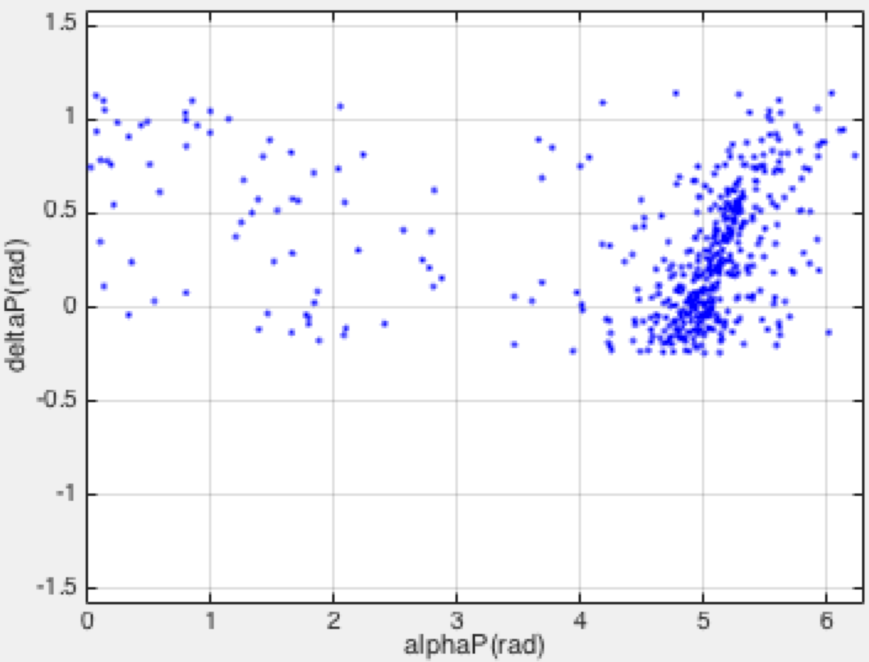


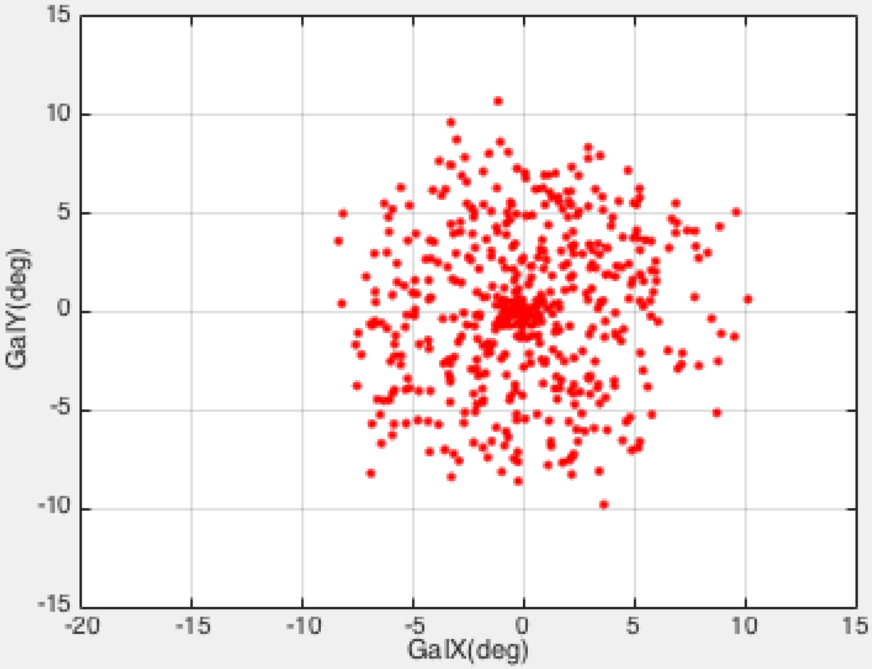
Multiple source search – Sky localization



Wang, Mohanty and Qian, 2017, in prep.

PTA in FAST era





R. Smits et al. A&A (2009)
L. Zhang et al. RAA (2016)
Qian, Mohanty and Wang, in prep.

Thank you!