The Large European Array for Pulsars: a **LEAP** of the **EPTA** for gravitational wave detection

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28th TEXAS Symposium, Geneva

05/01/2015

EPTA

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Radioastronomie

erc European Research Council

LEAP

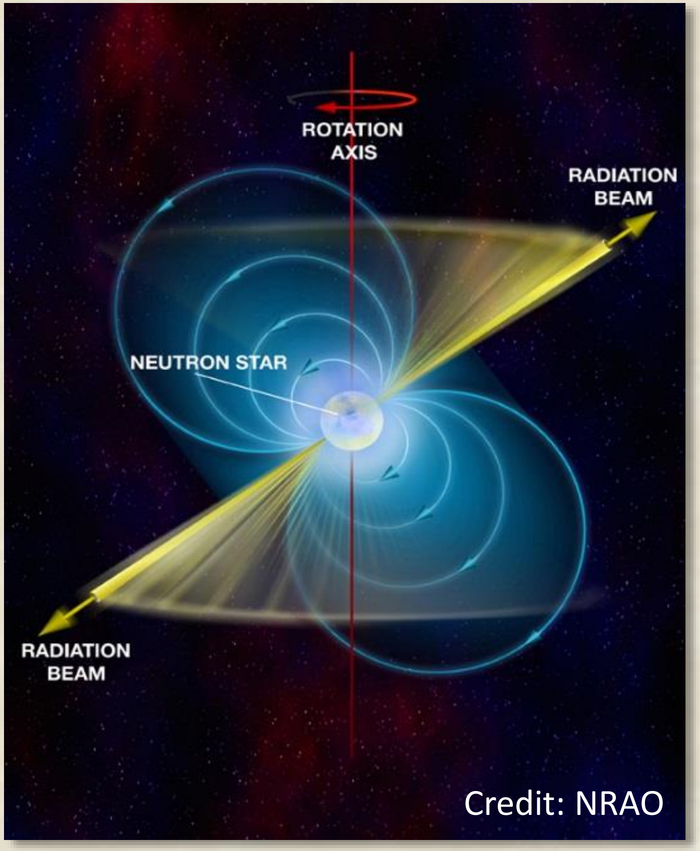
Outline

- Pulsars, Gravitational Waves, Pulsar Timing Array
- The European Pulsar Timing Array collaboration
- The Large European Array for Pulsars project
- Closing mark

Pulsars

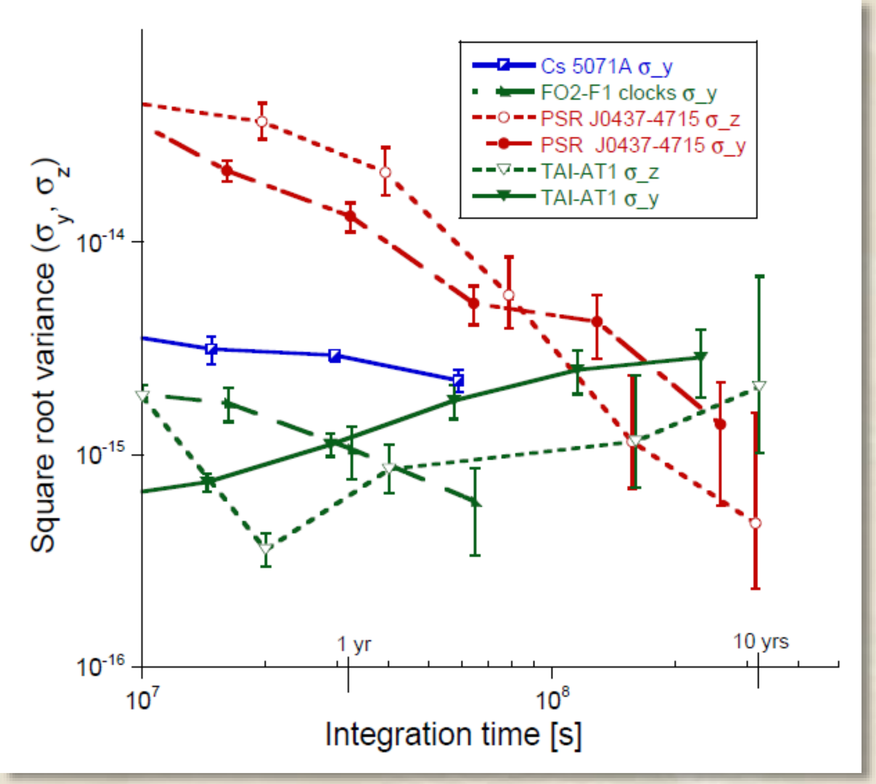
Pulsars are:

- Fast-rotating magnetic dipoles;
- Emitting electromagnetic wave at radio / X-ray / γ-ray…;
- Cosmic "light houses";



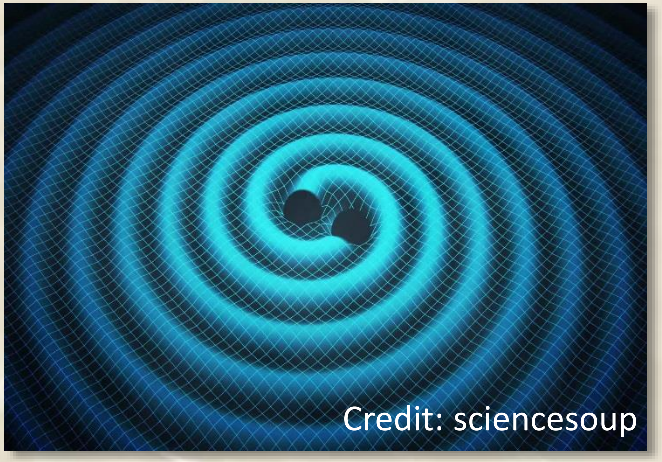
Millisecond Pulsars (MSPs) are:

- Rotational period < e.g. 20 ms;
- "Recycled" pulsars by accretion process;
- Highly stable rotators;
- Celestial "clocks";



[Hartnett & Luiten 2011]

Gravitational wave & Pulsar Timing Array

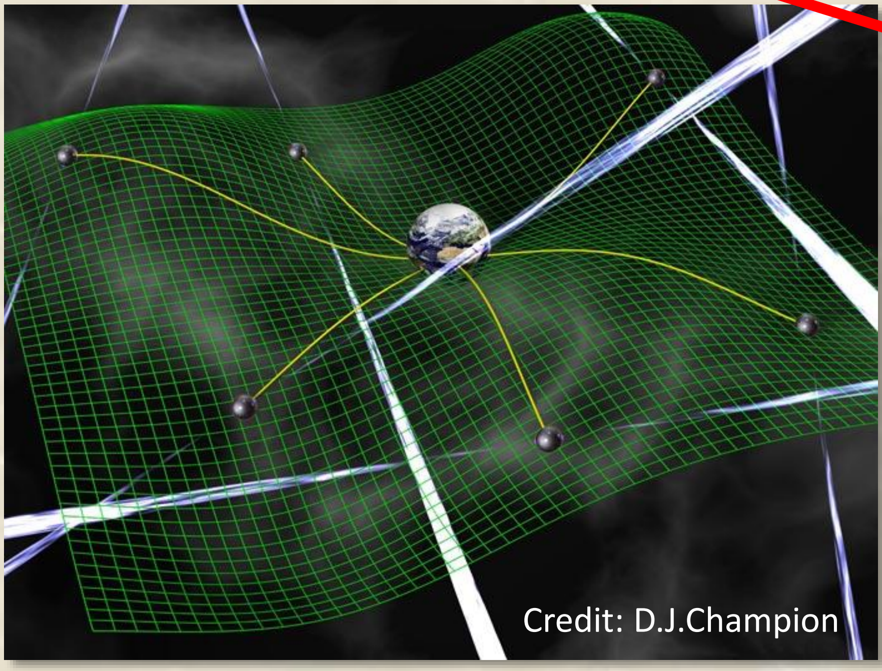


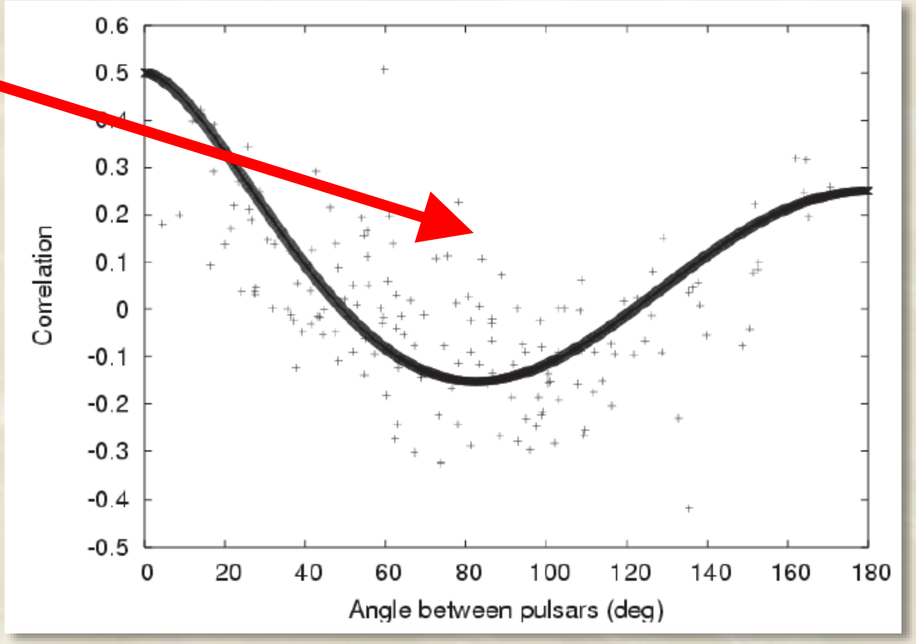
Gravitational waves are:

- Ripples in the curvature of space-time propagating as a wave;
- Predicted by General Relativity and alternative theories;
- From stochastic background (GWB) and single sources.

Pulsar timing array (PTA) is:

- A group of MSPs with high precision timing, at different sky directions;
- Looking for **a typical correlated timing signals** between pulsars.





[Helling & Downs 2011]

Gravitational wave & Pulsar Timing Array

Gravitational waves are:

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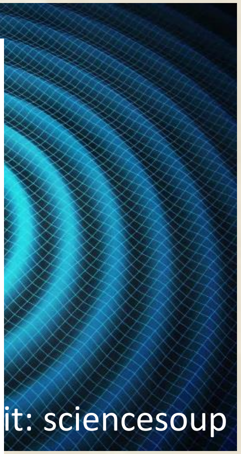
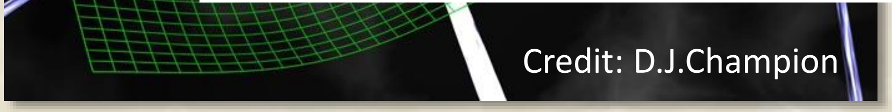
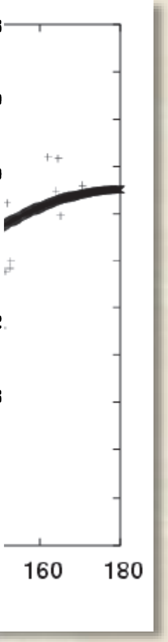
- From sto

Pulsar tin

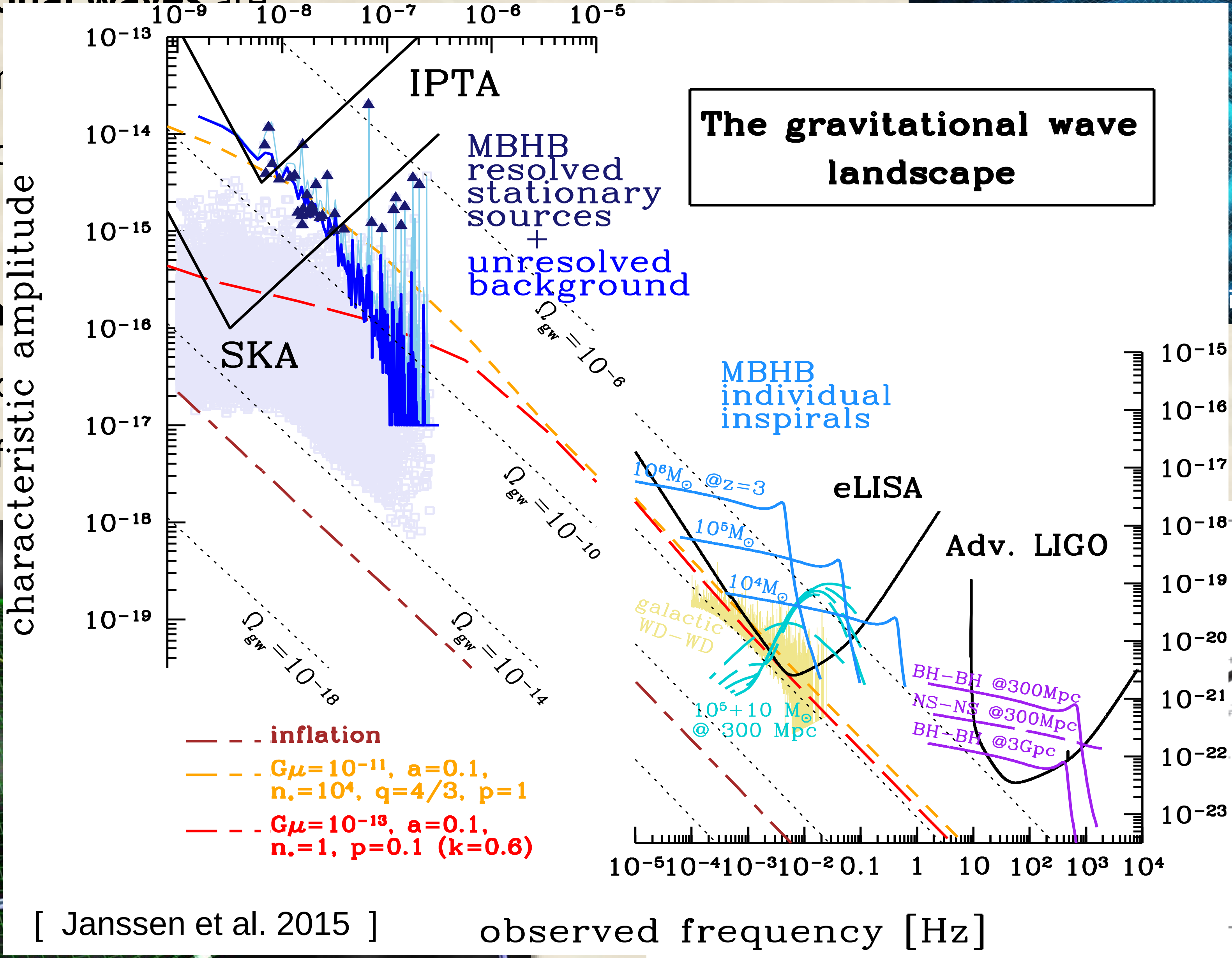
- A group c
- Looking f







[Helling & Downs 2011]



[Janssen et al. 2015]

The community in Europe

European Pulsar Timing Array (EPTA) is:

- A European pulsar timing collaboration to detect gravitaiont wave;
- Part of the International Pulsar Timing Array collaboration (with PPTA and NanoGrav);
- Combing pulsar timing data from the largest radio telescopes in Europe:


Effelsberg, 100-m, Germany


Lovell, 76-m, U.K.


Sardinia, 64-m, Italy;


Westerbork, 94-m, Netherlands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www.epta.eu.org

EPTA in 2015

The collaboration is busy publishing this year…

- "High-precision timing of 42 millisecond pulsars with the European Pulsar Timing Array"
  [Desvignes et al., recommended for publication]
- "Noise properties of 42 millisecond pulsars from the European Pulsar Timing Array and impact on gravitational wave searches"
  [Caballero et al., recommended for publication]
- "European Pulsar Timing Array limits on an isotropic stochastic gravitational-wave background"
  [Lentati et al., 2015]
- "Limits on Anisotropy in the Nanohertz Stochastic Gravitational Wave Background"
  [Taylor et al., 2015]
- "European Pulsar Timing Array limits on continuous gravitational waves from individual supermassive black hole binaries"
  [Babak et al., 2016]

EPTA in 2015

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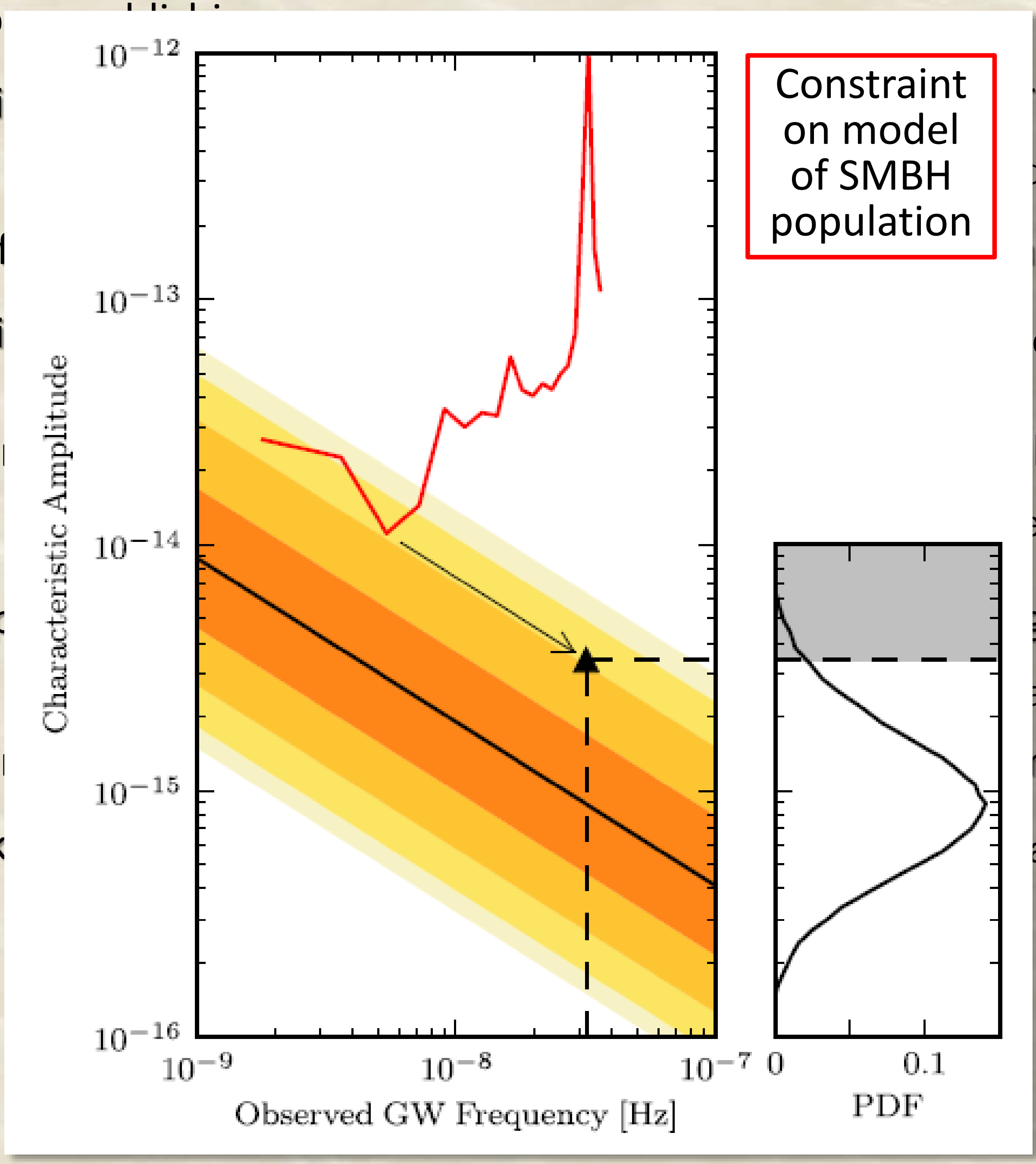

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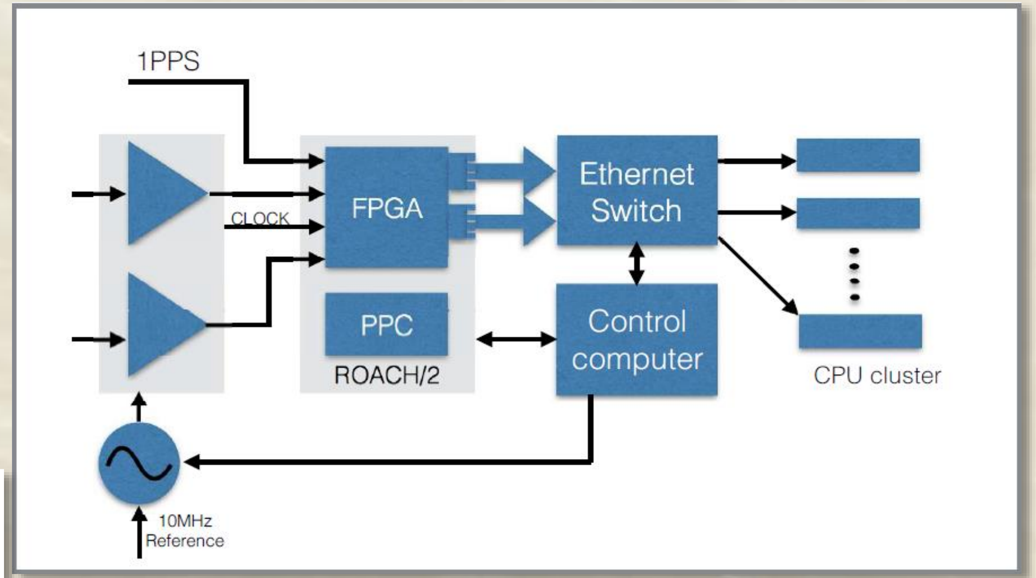
All the analysis were performed based on data from our legacy pulsar backend (narrow bandwidth, incoherent de-dispersion, low-bit sampling)…

We can do much better now !

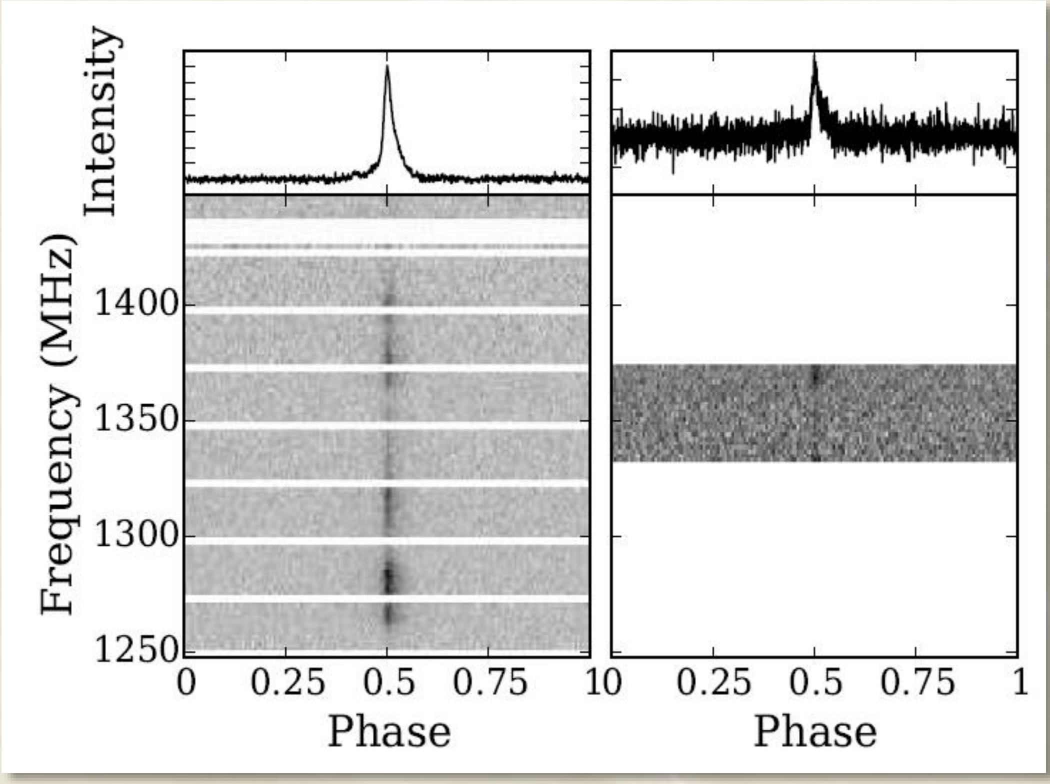
New generation EPTA pulsar instruments

ROACH Board technique from CASPER:

- 8-bit A/D converter at Nyquist rate;
- Maximum 512 MHz bandwidth;
- Flexible firmware / channelisation;



[Karuppusamy et al., in prep.]



[Lazarus et al., submitted]

Improvement on pulsar backends:

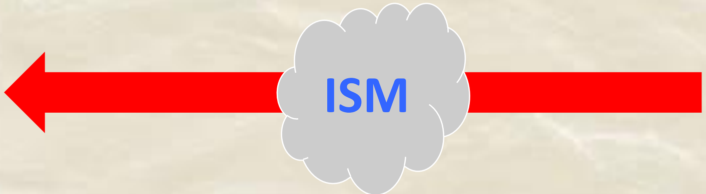
- Effelsberg: 64 MHz to 200 MHz bandwidth;

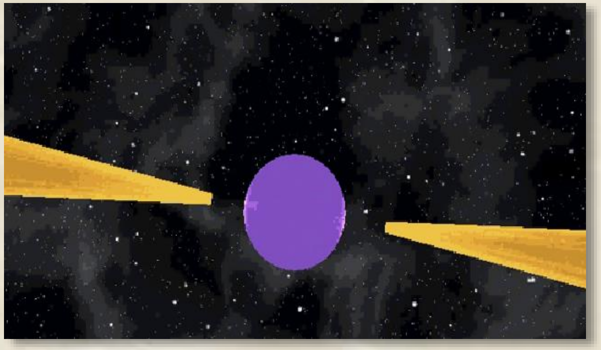
  2-bit to 8-bit sampling;
- Nancay: 128 MHz to 512 MHz bandwidth;

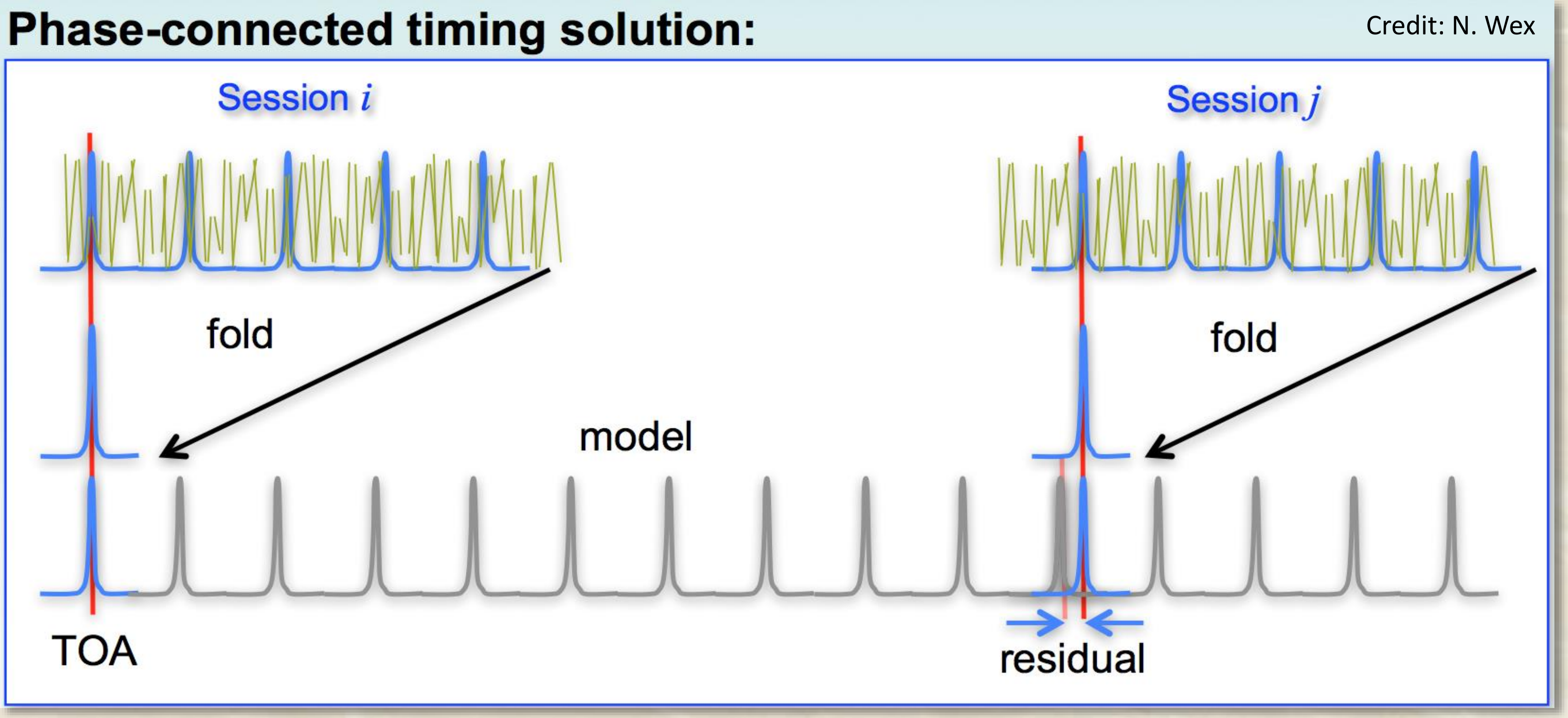
  2-bit to 8-bit sampling;
- Jodrell: 64 / 128 MHz to 400 MHz;

  1-bit to 8-bit sampling;
- Westerbork: 80 MHz to 200 MHz;

Pulsar timing

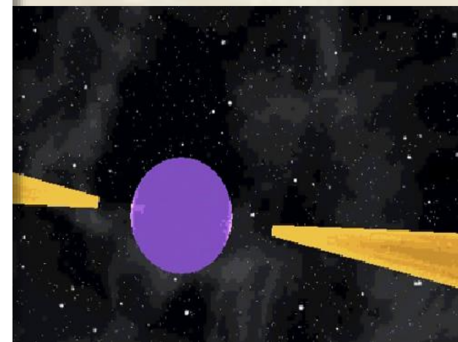


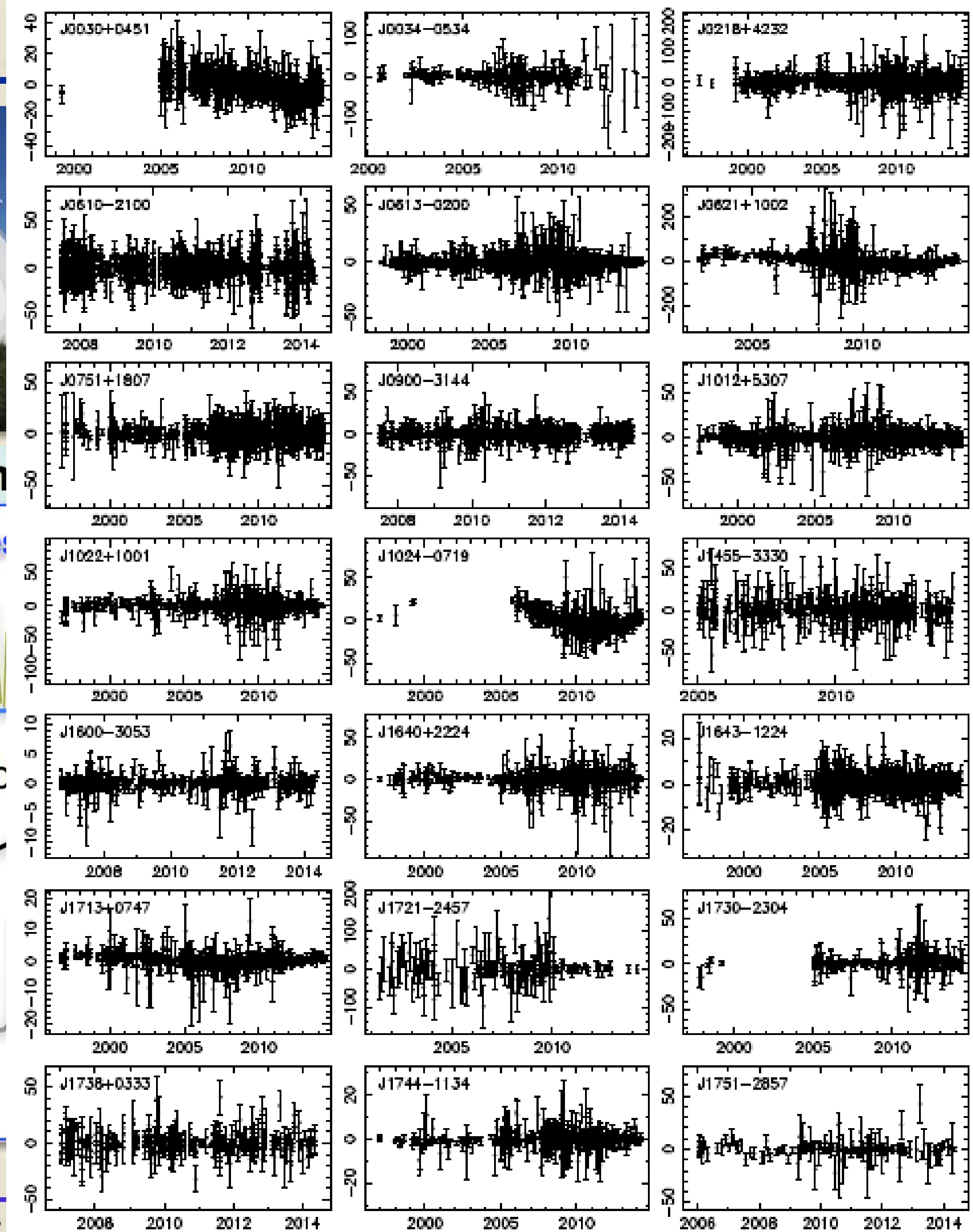




Pulsar timing is all about measuring the **pulse time-of-arrivals (TOAs)** precisely !

Pulsar timing

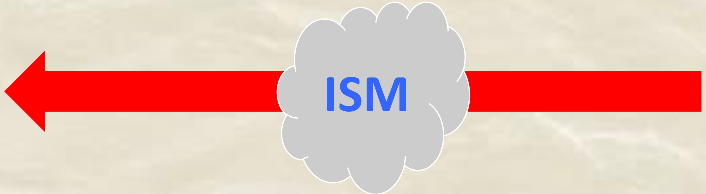


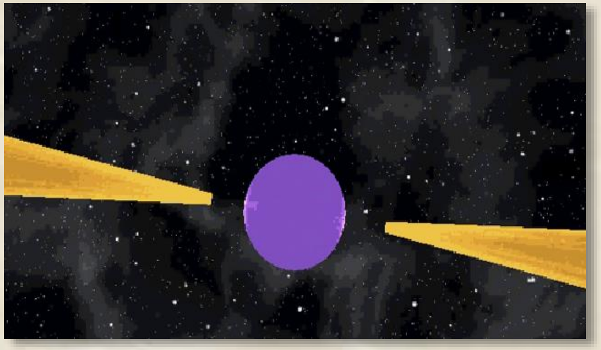


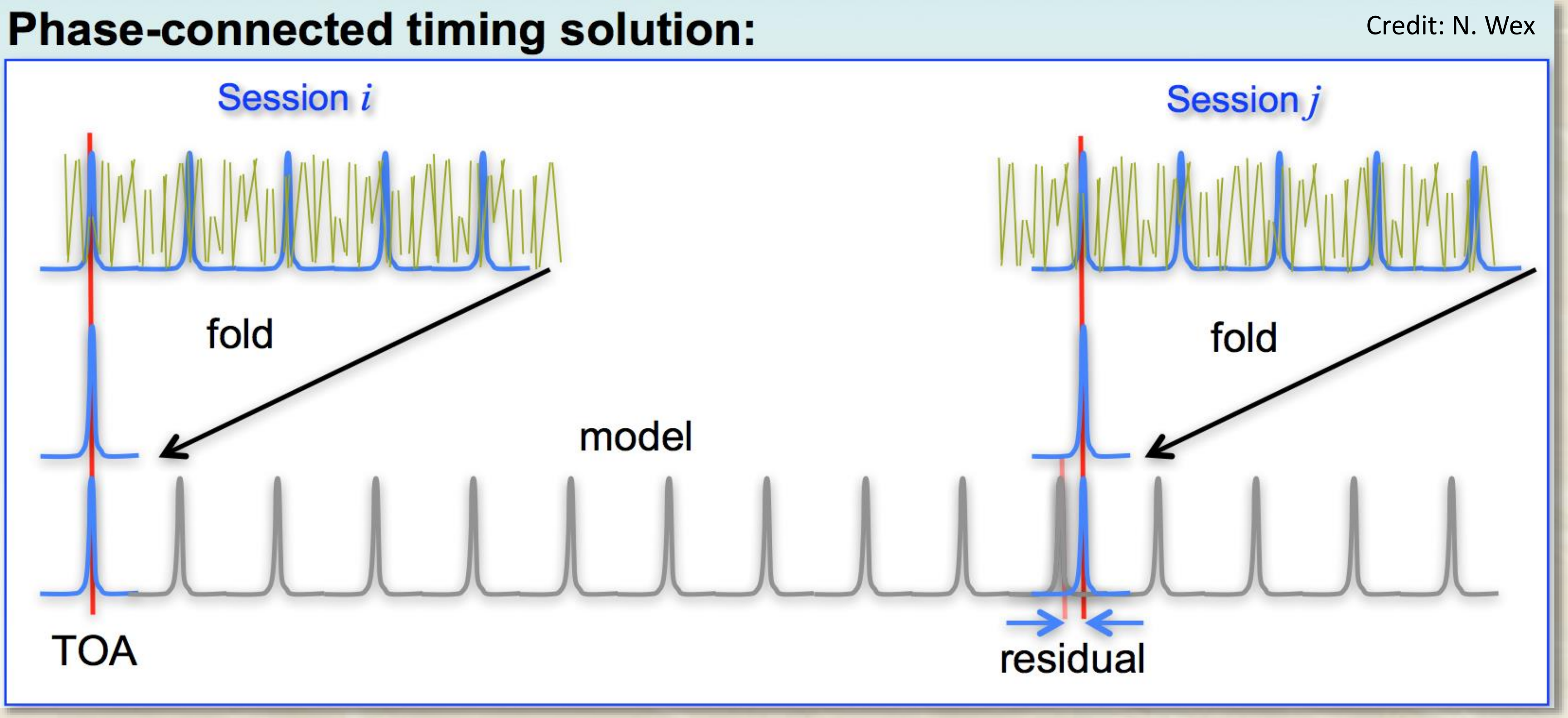
[Desvignes et al., submitted]

Pulsar timing ... **TOAs)** precisely !

Pulsar timing



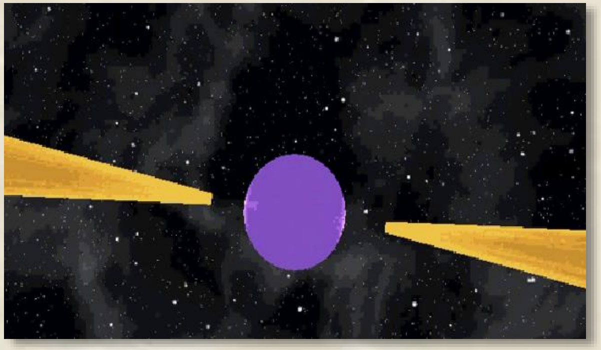


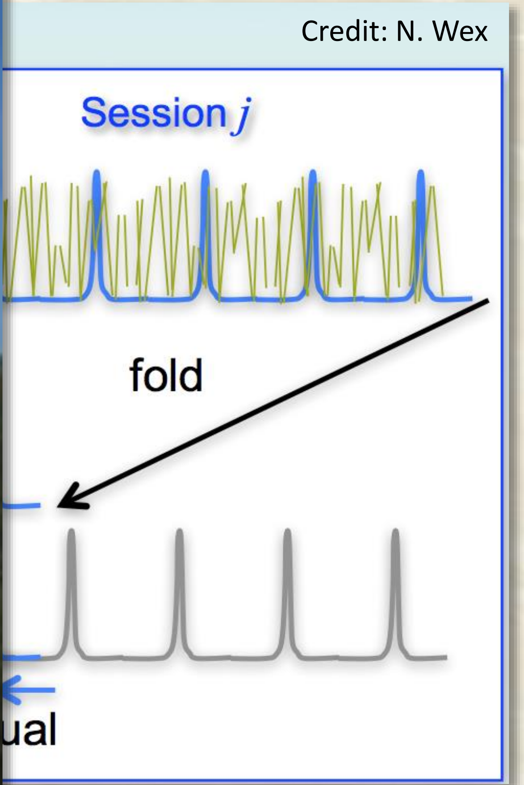


$$\sigma_{\rm TOA} \propto \frac{T_{\rm sys}}{A_{\rm eff}} \times \frac{1}{\sqrt{t_{\rm obs}\Delta\nu}} \times \frac{P\delta^{2/3}}{S}$$

To improve, make a **bigger** telescope !

Pulsar timing





σ ... ake a **bigger** telescope !

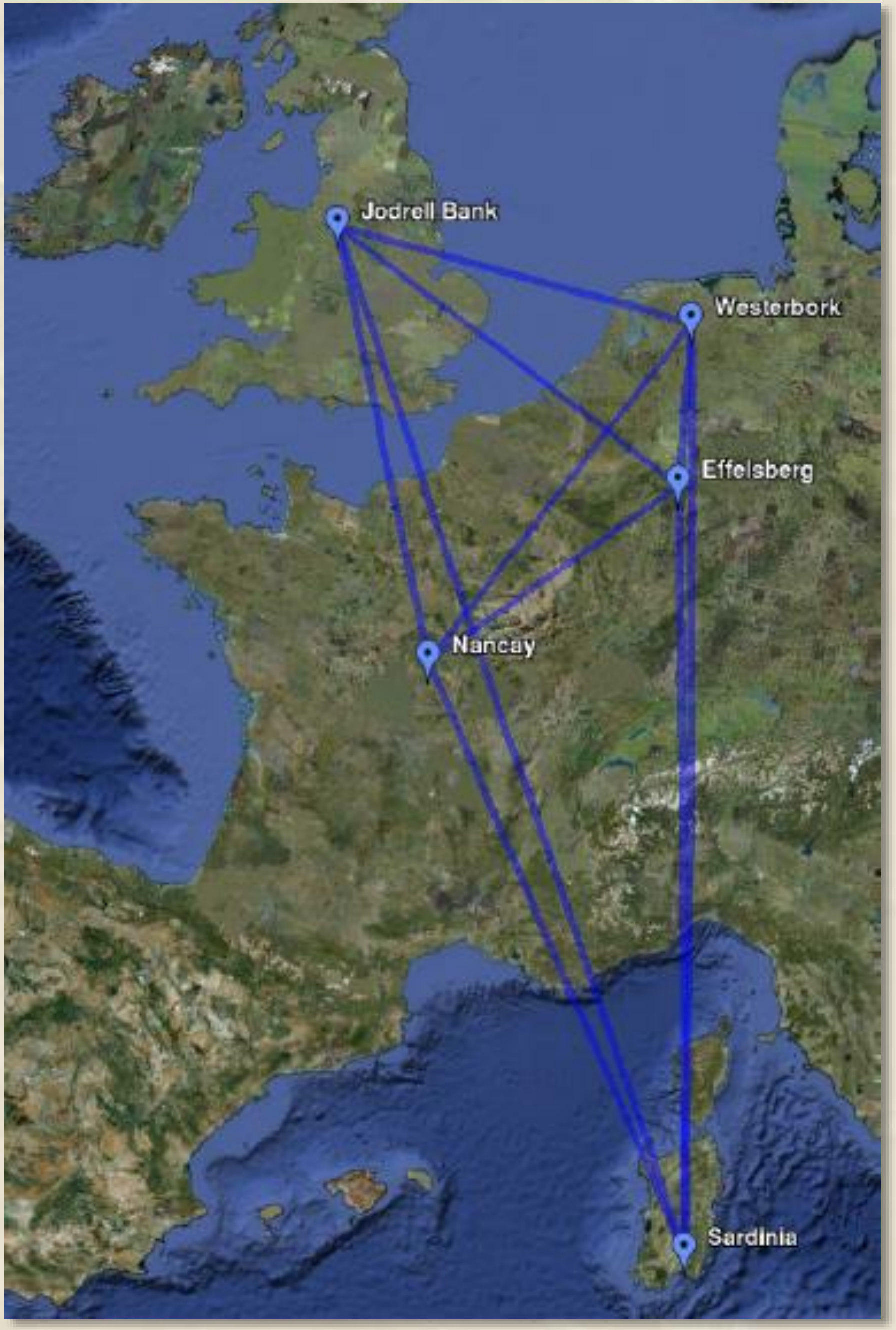
The Large European Array for Pulsars

The experimental design:

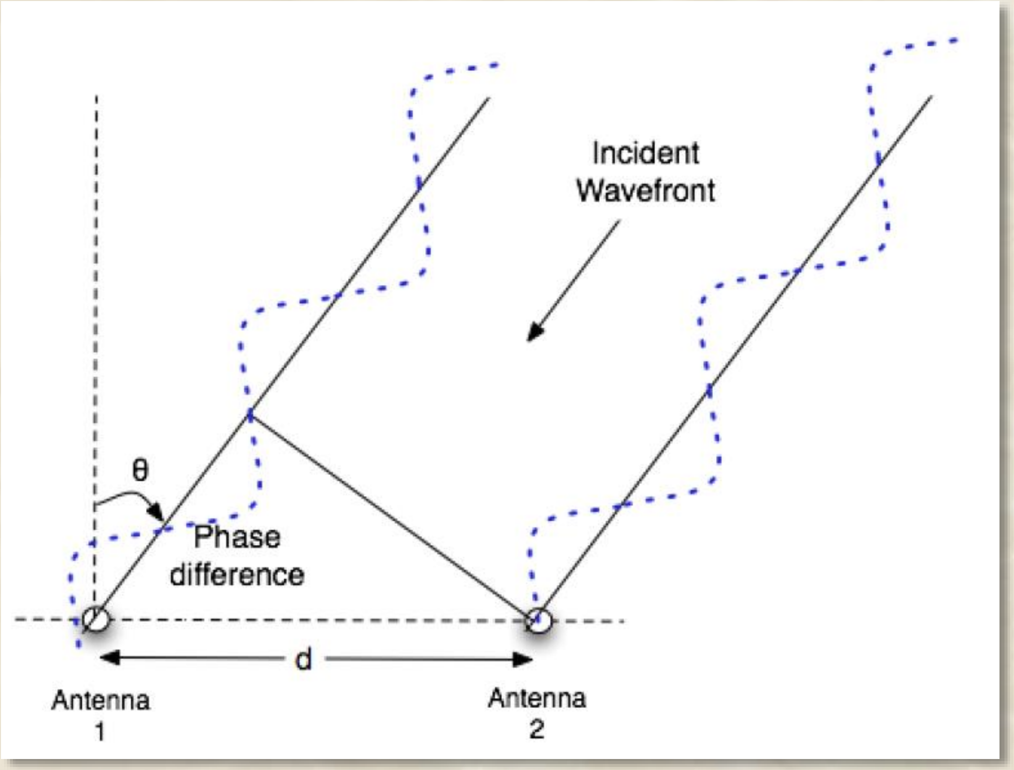
- Coherently combines raw voltage data from the five European telescope to form a **phased-array**, with reference to Effelsberg;
- Delivers sensitivity equivalent to a 192-m dish, similar to **SKA Phase I** → Pathfinder of the next generation radio telescopes !
- Enable declination range from +85 to -30 deg;

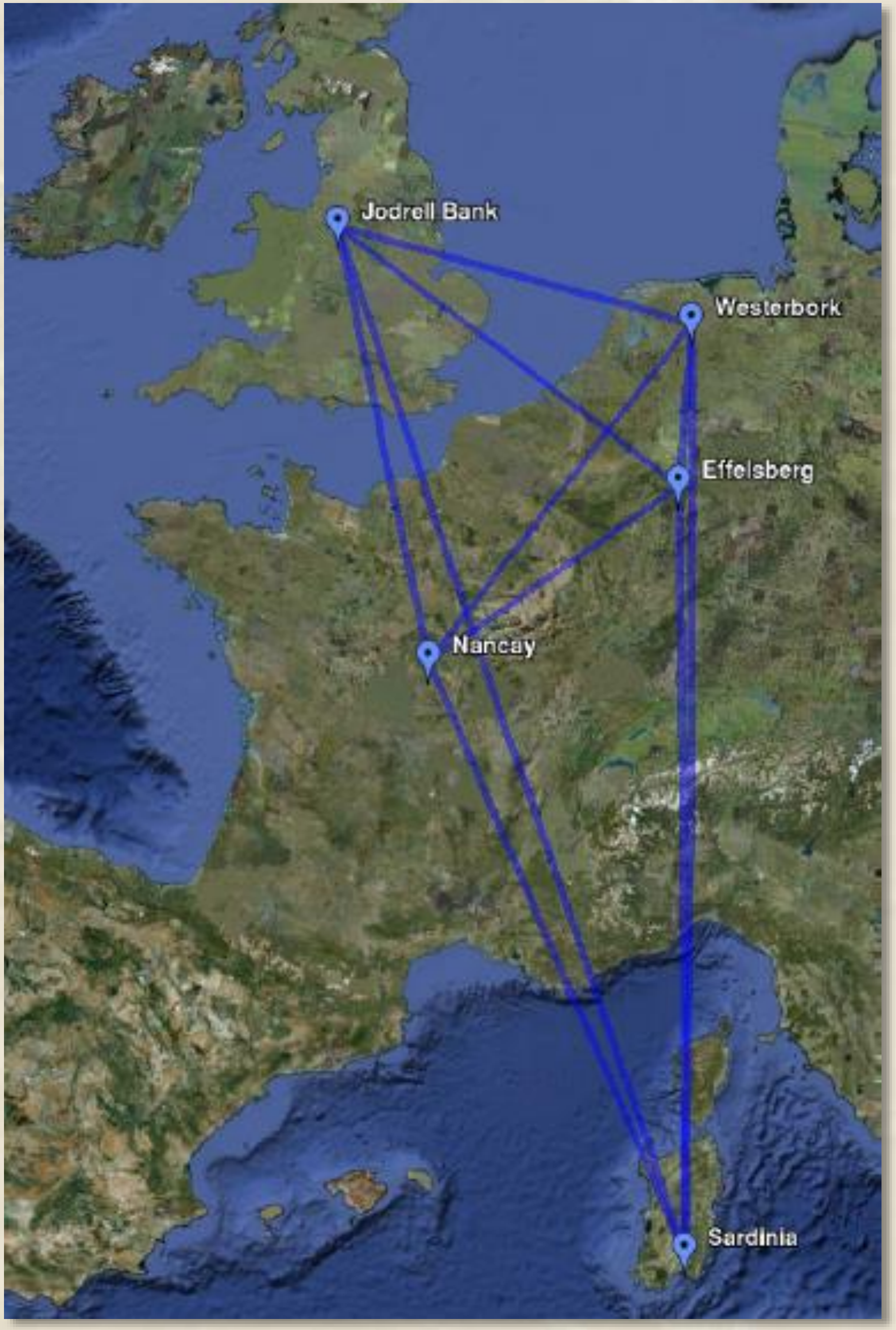
The project:

- Supported by ERC Advanced Grant (2M euro);
- Started on Sep. 2009;
- Funding ended officially on Sep. 2014;
- Now has 5 permanent staffs, 6 postdocs, 1 PhD student (another to join next year);



The Large European Array for Pulsars





Advantage from phasing-up:

- Improve TOA accuracy by number of telescopes;
- Calibrate instrumental offsets & instabilities;
- Flexible data form enabling many pulsar projects;

Project overview published this year !

Bassa et al. 2015, MNRAS

Observing setup & data management

Sampling bit	8
Central frequency	1396 MHz
Bandwidth	128 MHz
Polarisation	Calibrated, I Q U V
Bin number / period	… / 1024 / 2048 /…

Observations:

- Monthly 24 h sessions since Mar. 2012;
- 20-30 MSPs;
- Simultaneously with all 5 telescopes;
- Observe pulsars and phase calibrators;
- Use the ROACH-board backends to record data at Nyquist rate;
- Baseband voltage data stored on disk;

Data management:

- Transfer the data to Jodrell Bank, by either disk shipment or copying over internet;
- Place the data on storage cluster (with 288 slots) for processing;
- Store the coherent-added voltage data (with one backup) on tape archive;
- Store the timing data on both disks and tape archive;
- Ship back the disks for the future observations;
- Keep some voltage data on disks online for sub-projects.

Scheduling

Constraints:

- Sources at different hour angles;
- Phase calibrator in between pulsars;
- Maximise integration time on pulsars with minimal time on calibrators;
- Telescope specific slew speeds, cable wraps, and sky coverage constraints…

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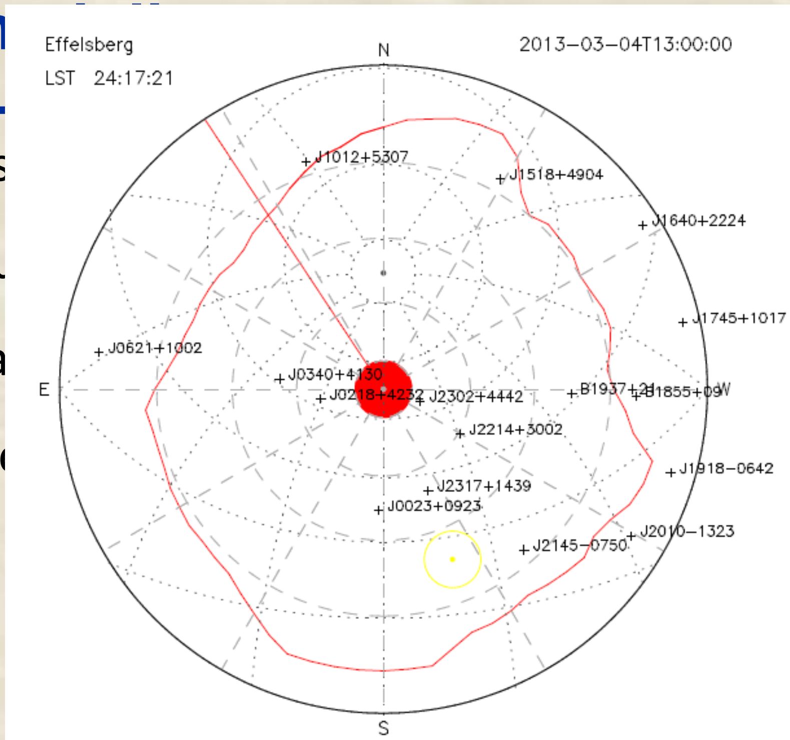

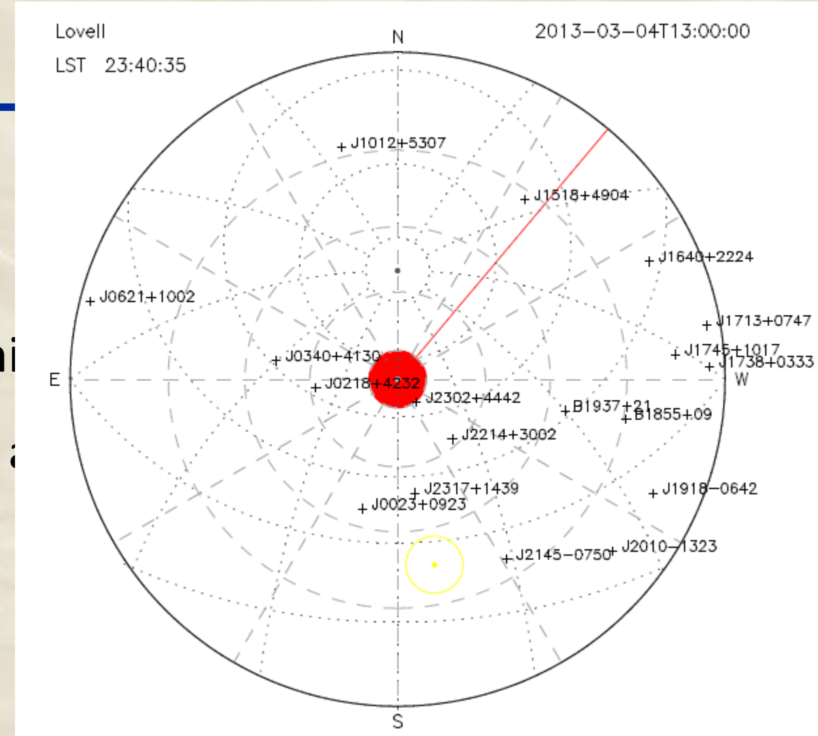

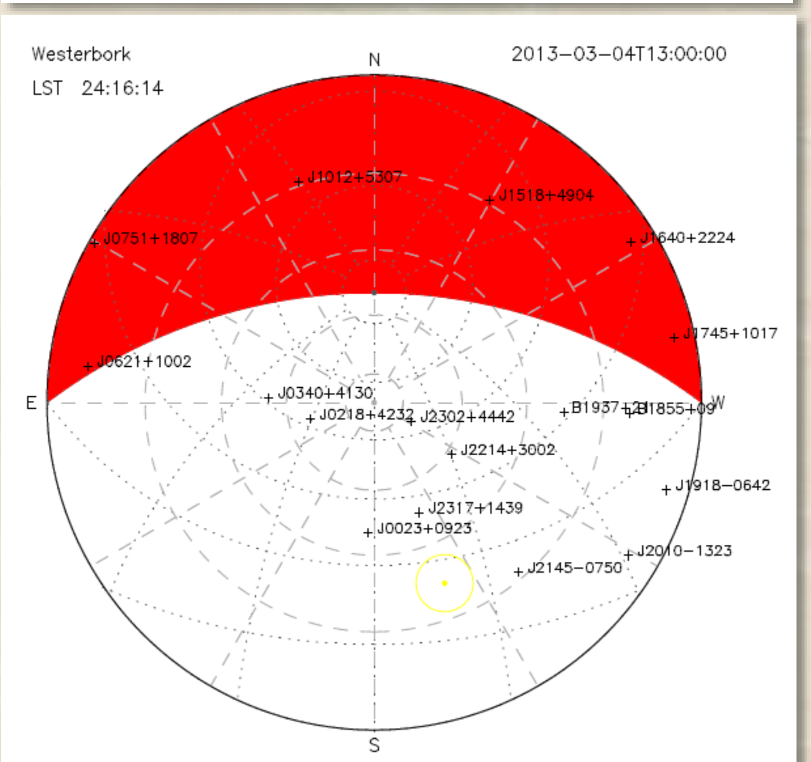

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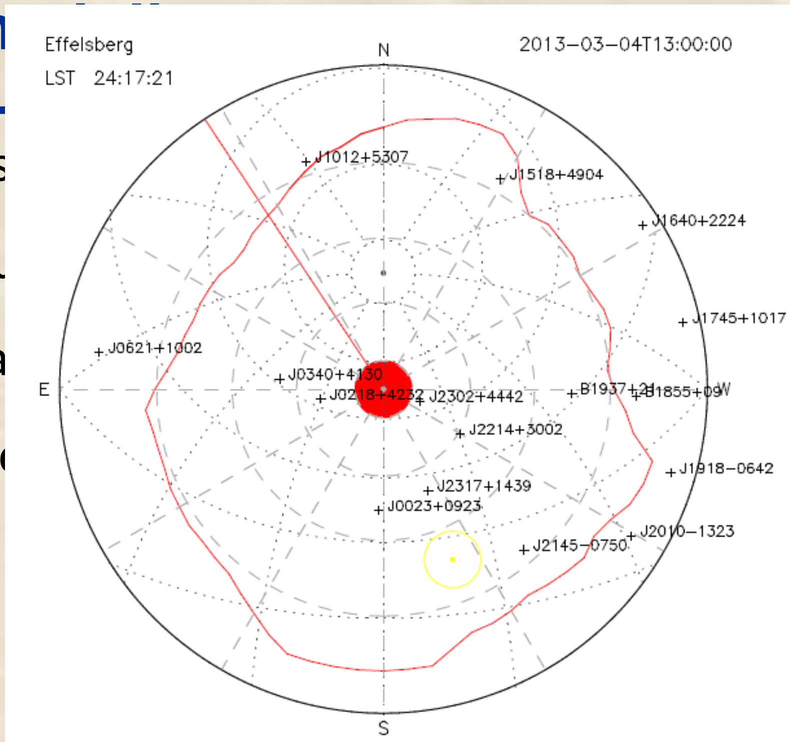
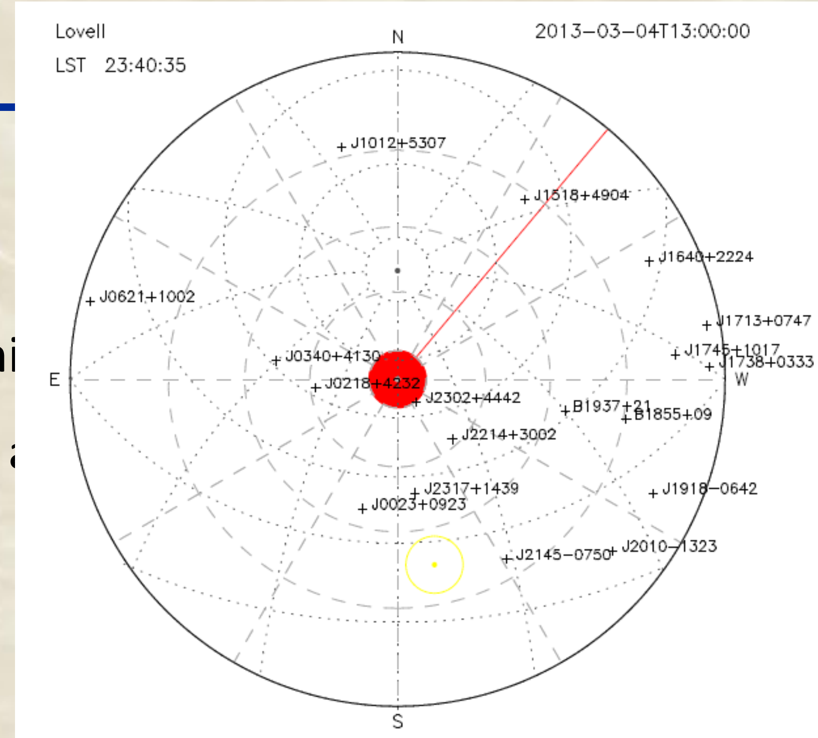
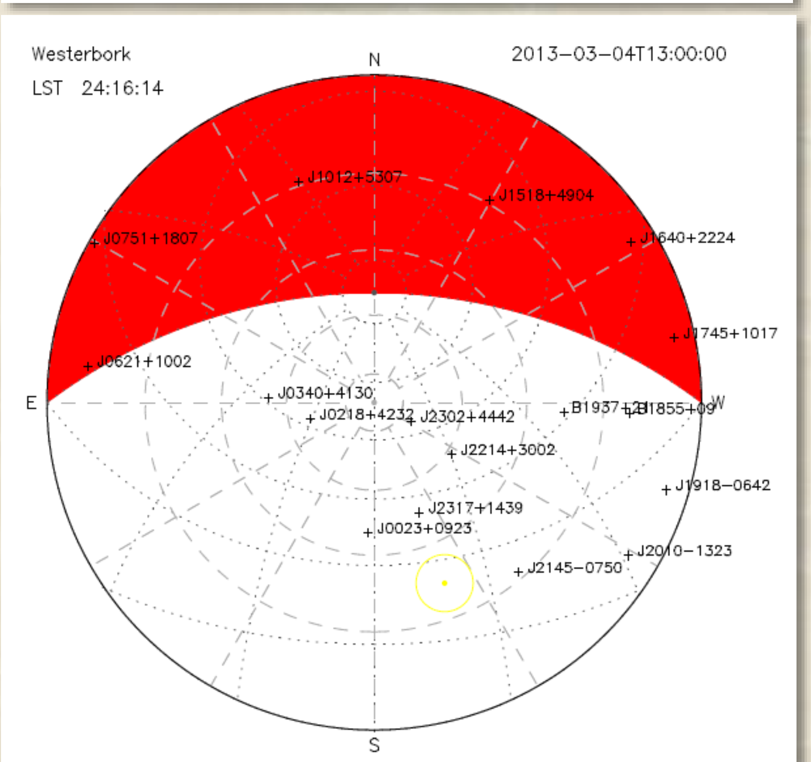
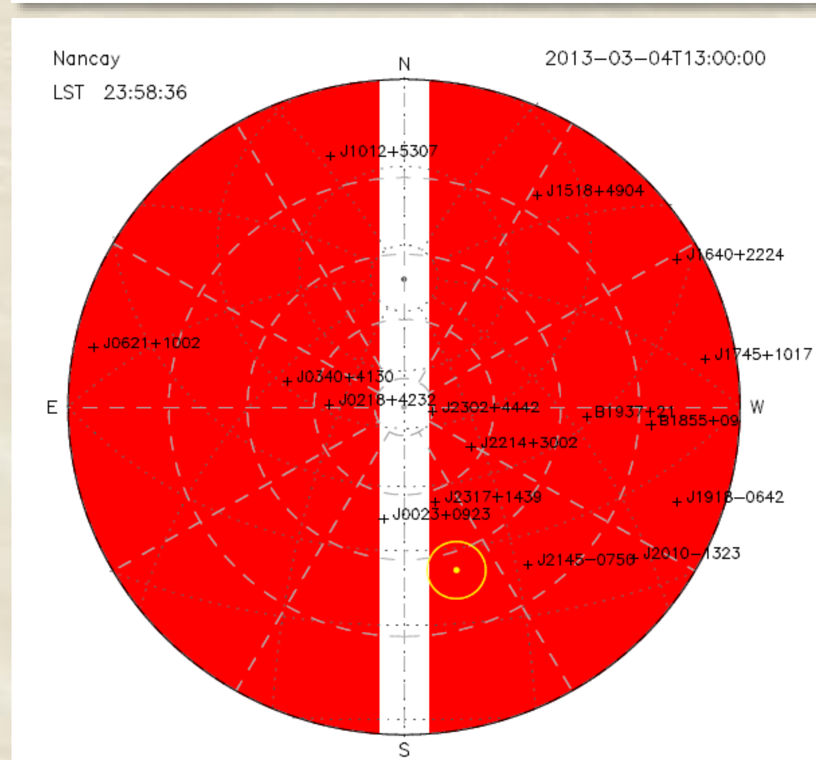








Scheduling

Constraints:

- Sources at different hour angles;
- Phase calibrator in between pulsars;
- Maximise integration time on pulsars with minimal time on calibrators;
- Telescope specific slew speeds, cable wraps, and sky coverage constraints…

Solution:

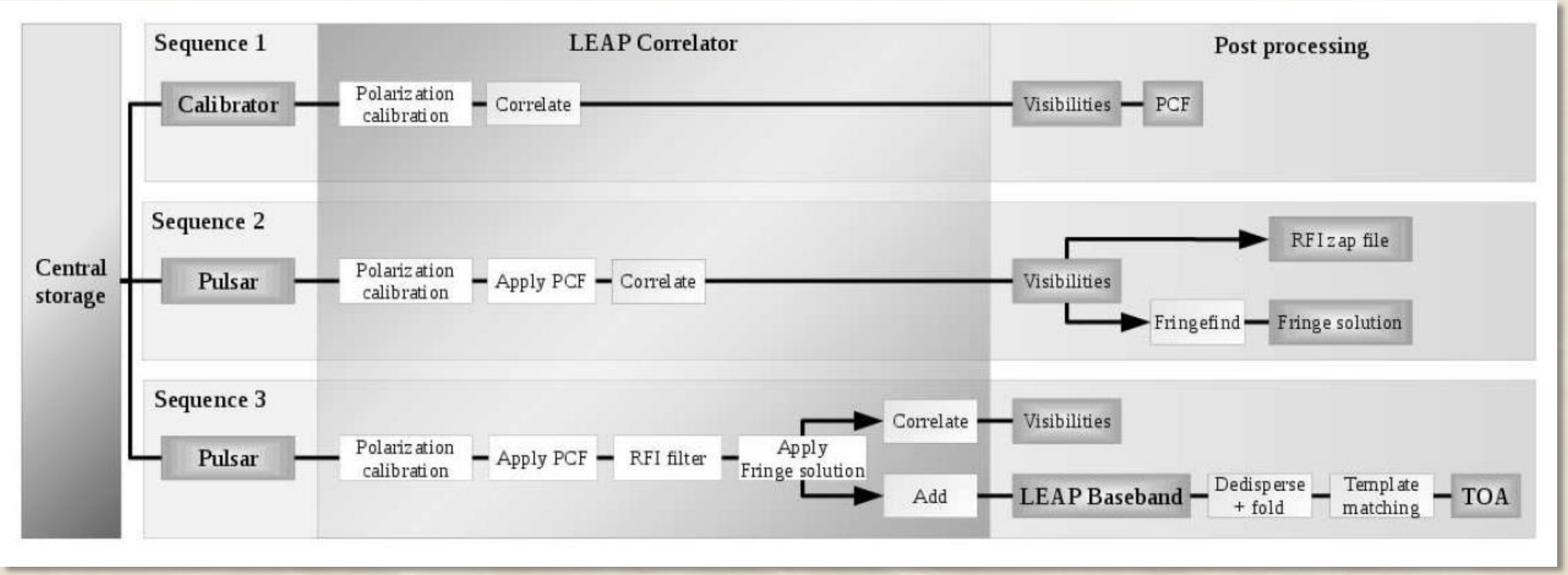
- 20h + 4h (15:30-19:30 LST twice);
- Fixed schedule with Nancay LSTs to get UT;

Source list:

• J0030+0451 (+NC)	• J0348+4320	• J1643-1224 (+NC)	• J1713+0747 (+NC)
• J0613-0200 (+NC)	• J0621+1001	• J1738+0333	• J1744-1134 (+NC)
• J0645+5158	• J0751+1807	• J1832-0836 (+NC)	• B1855+09 (+NC)
• J0931-1902 (+NC)	• J1012+5307	• J1918-0642 (+NC)	• B1937+21 (+NC)
• J1022+1001 (+NC)	• J1024-0719	• J2010-1323 (+NC)	• J2145-0750 (+NC)
• J1518+4904 (+NC)	• J1600-3053 (+NC)	• J2234+0944 (+NC)	• J2317+1439 (+NC)
• J1640+2224	• J0740+6620		

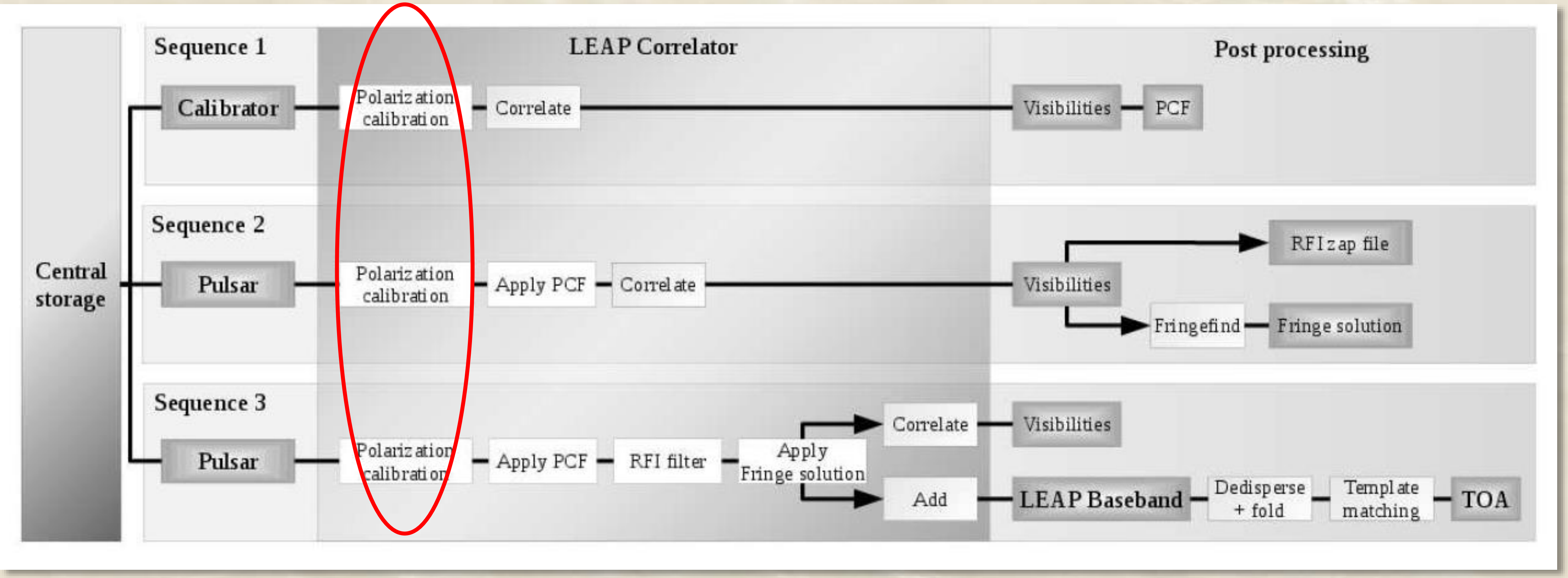
Red: EPTA sources with highest priority

Correlation pipeline



[Smits et al., in prep.]

Correlation pipeline

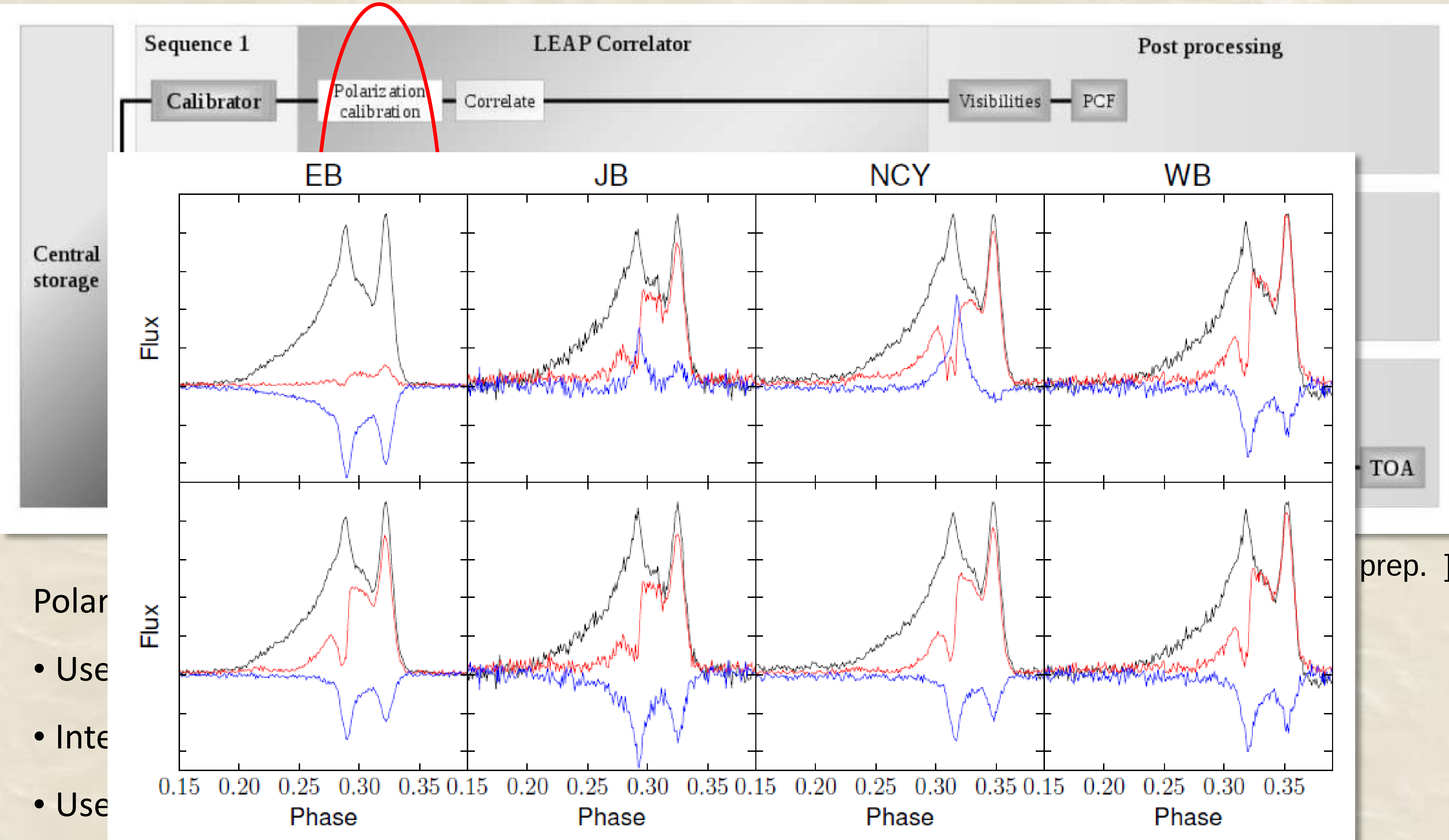


[Smits et al., in prep.]

Polarisation calibration:

- Use the template matching method developed by van Straten 2006;
- Integrated into software correlator and applied directly to baseband data;
- Use template from European Pulsar Network (EPN) database;
- Use a few bright pulsars as calibrator: B1933+16, J1022+1001, B1937+21, J1713+0747;

Correlation pipeline



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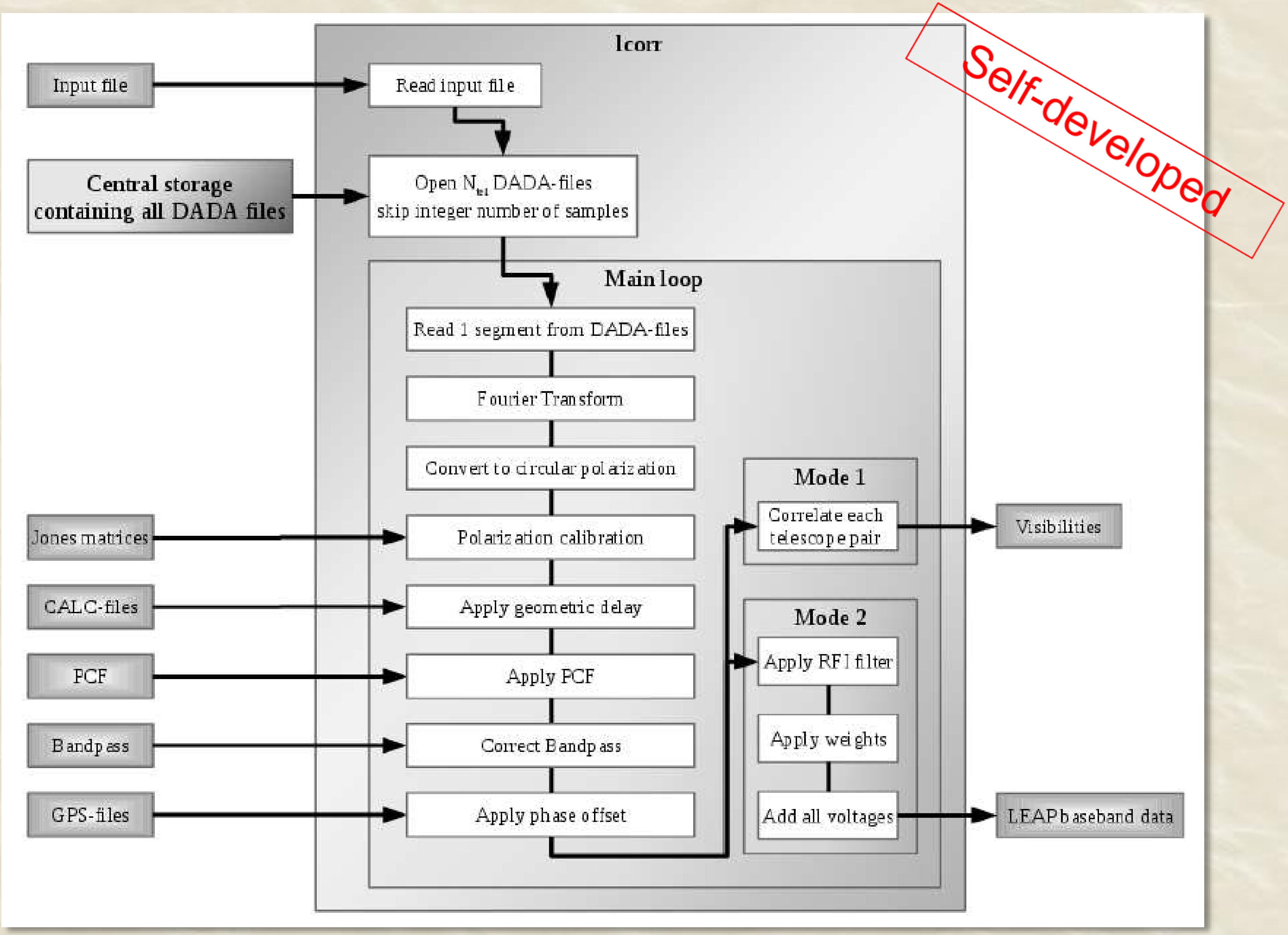
Software correlator



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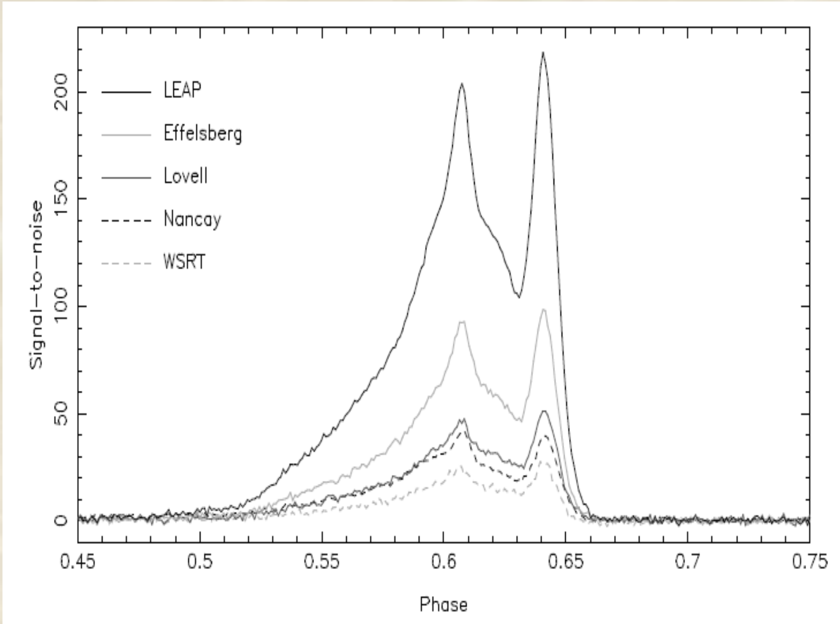
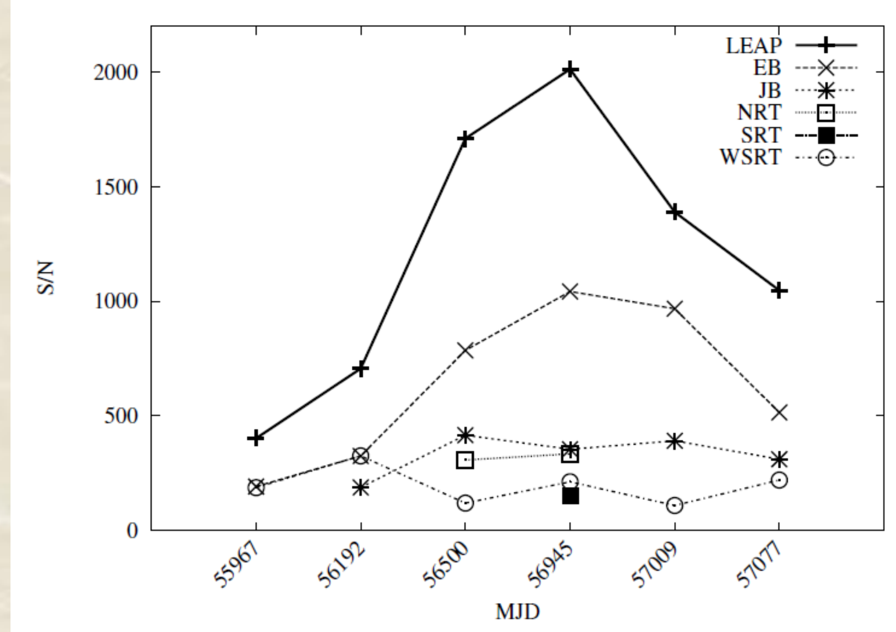
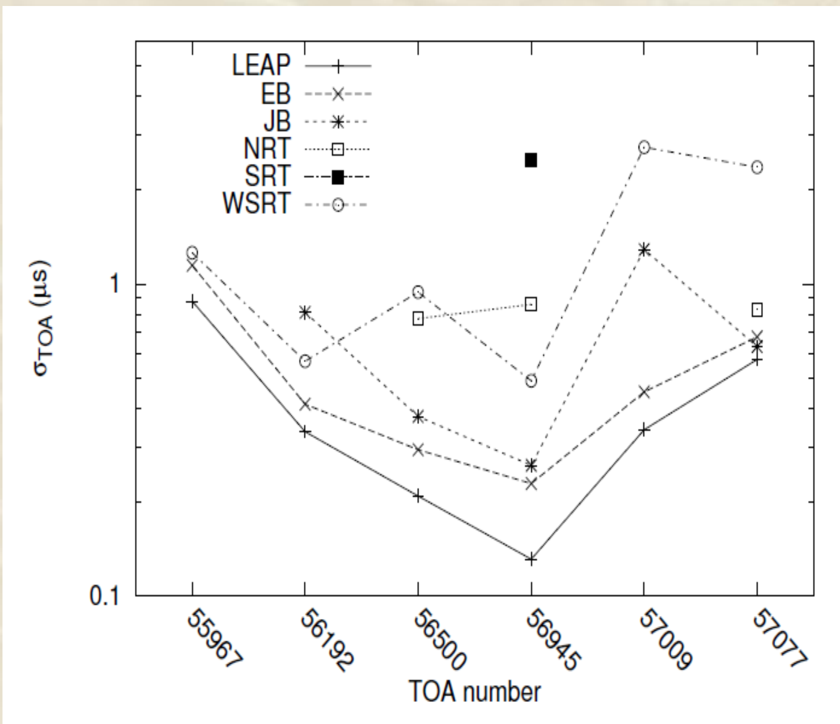
Effectiveness

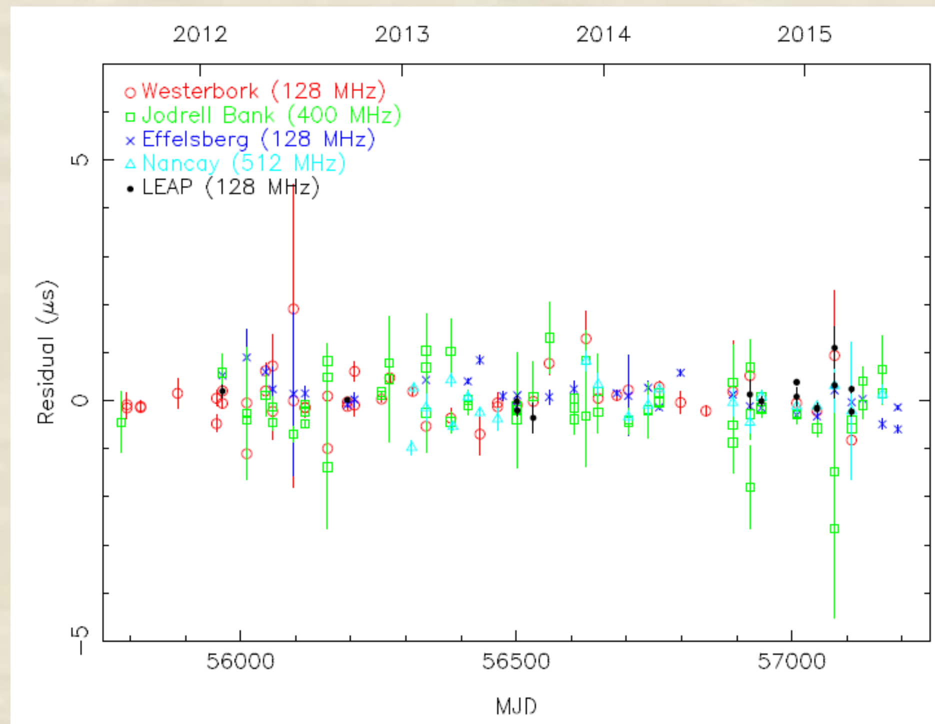
On profile data





On timing data

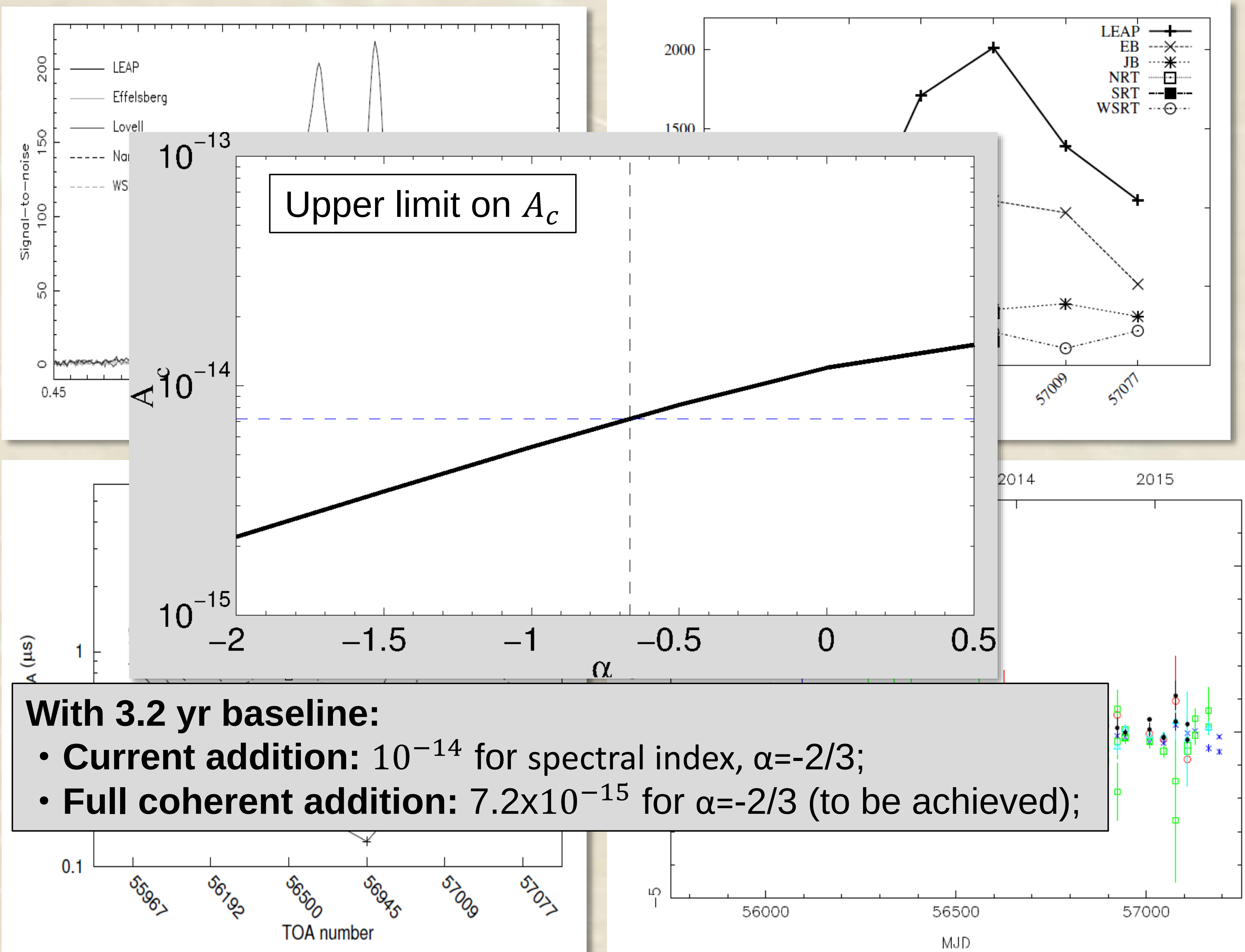




Effectiveness

On profile data

On timing data

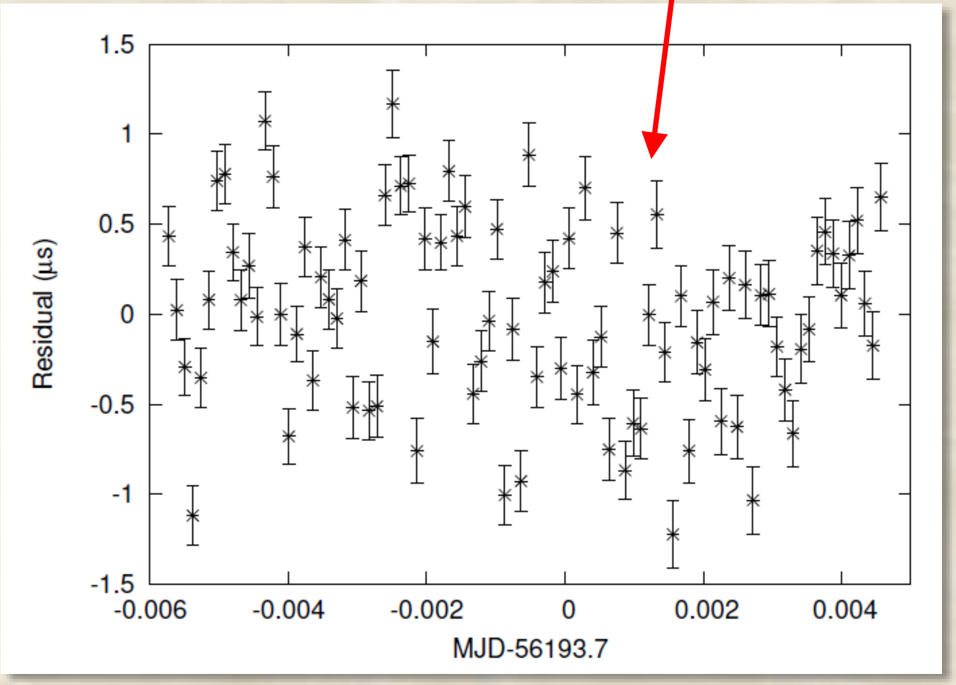


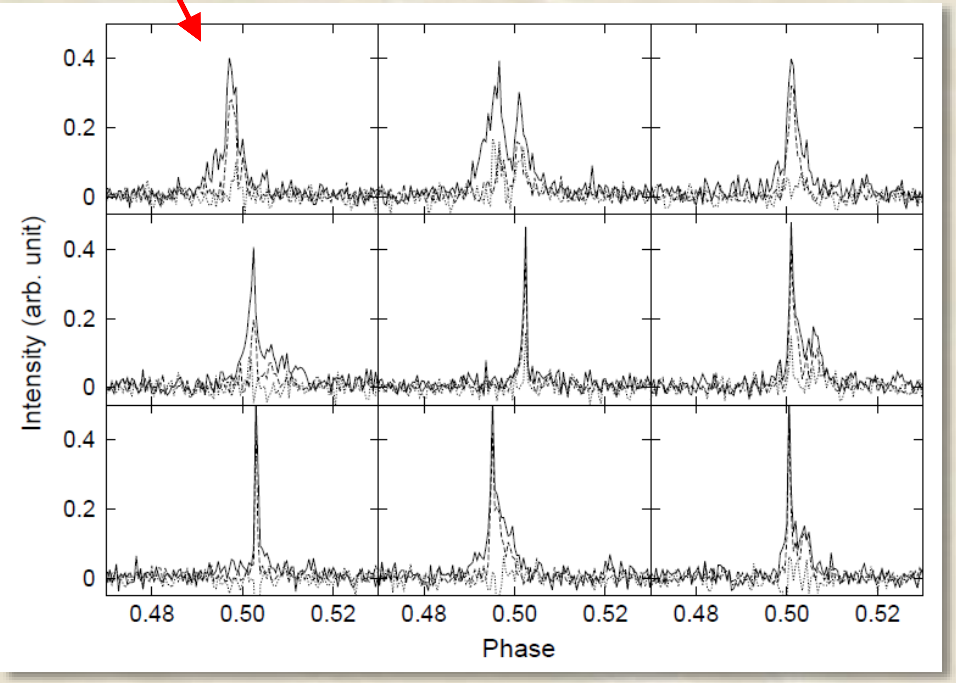
With 3.2 yr baseline:

- **Current addition:** 10^{-14} for spectral index, α=-2/3;
- **Full coherent addition:** 7.2x10^{-15} for α=-2/3 (to be achieved);

Other pulsar science: study of single pulses & "jitter" noise

- Single pulses of MSPs are seen to be variable, resulting in small phase variation in integrated pulse profiles (pulse phase jitter);
- MSP timing precision is now mostly limited by white noise, but will be limited by jitter noise with the next generation of radio telescopes (e.g., the SKA);
- Major aim: a). Quantify jitter noise; b). Characterize pulse variability; c). Mitigate jitter;





[Liu et al., in prep.]

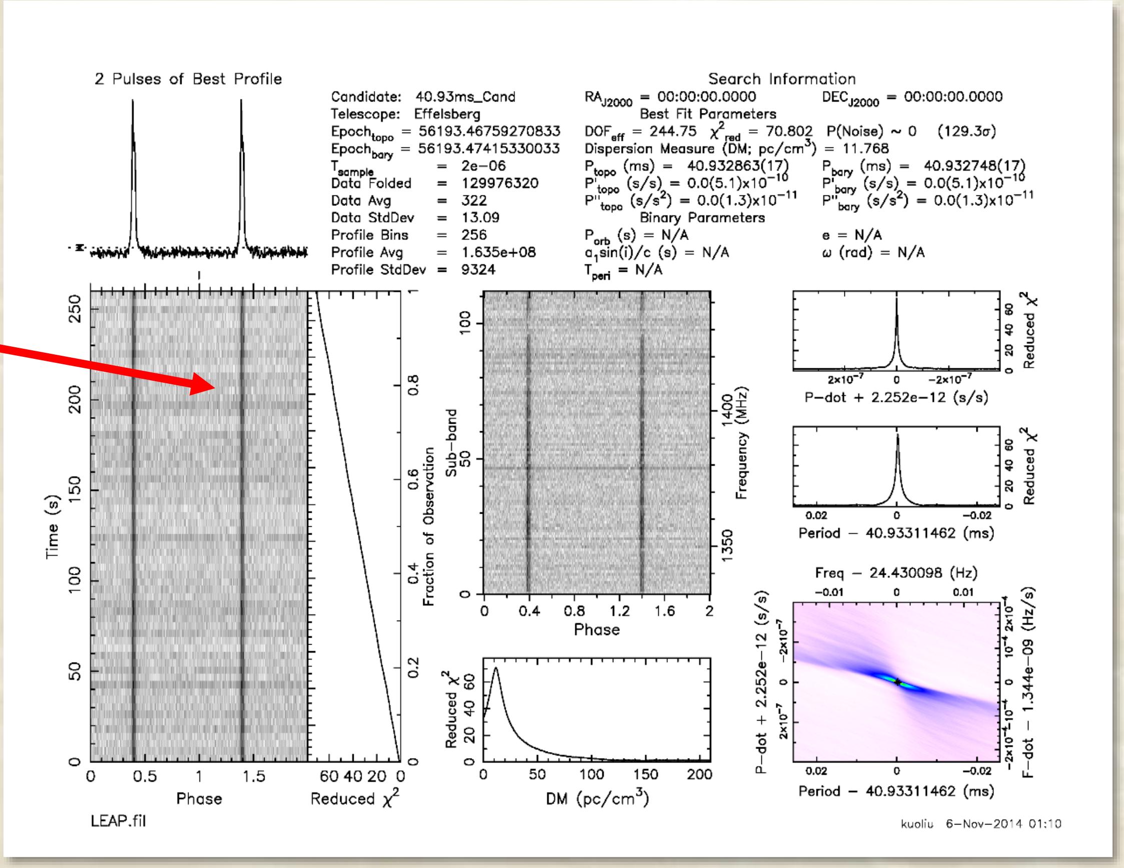
- **PSR J1713+0747**: 10-s integrations → 600 ns residuals, consistent with previous results (Shannon & Cordes 2013; Dolch et al. 2014) !

Other pulsar science: pulsar searching

Plan & strategy:

- Target search for unknown sources (e.g. Globular Cluster, known DNS system);
- Phase up with nearby / in-beam known pulsars / calibrators;
- Pulsation search & upper limit on flux density for companions in double-neutron-star;

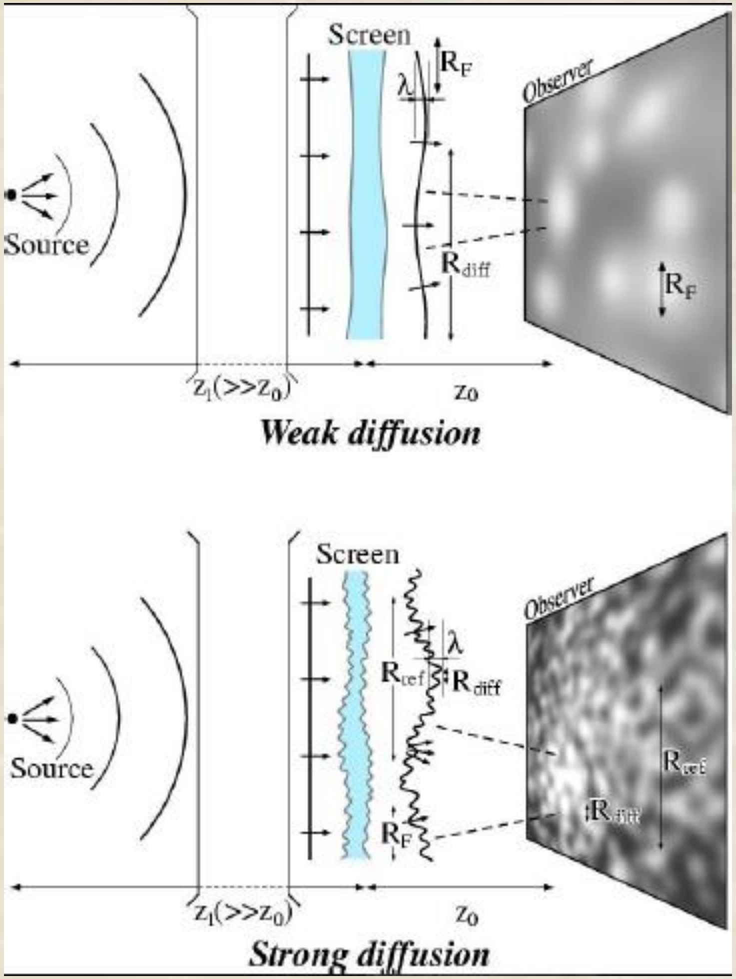
Redetection of J1518+4904 (a double-neutron star system) !

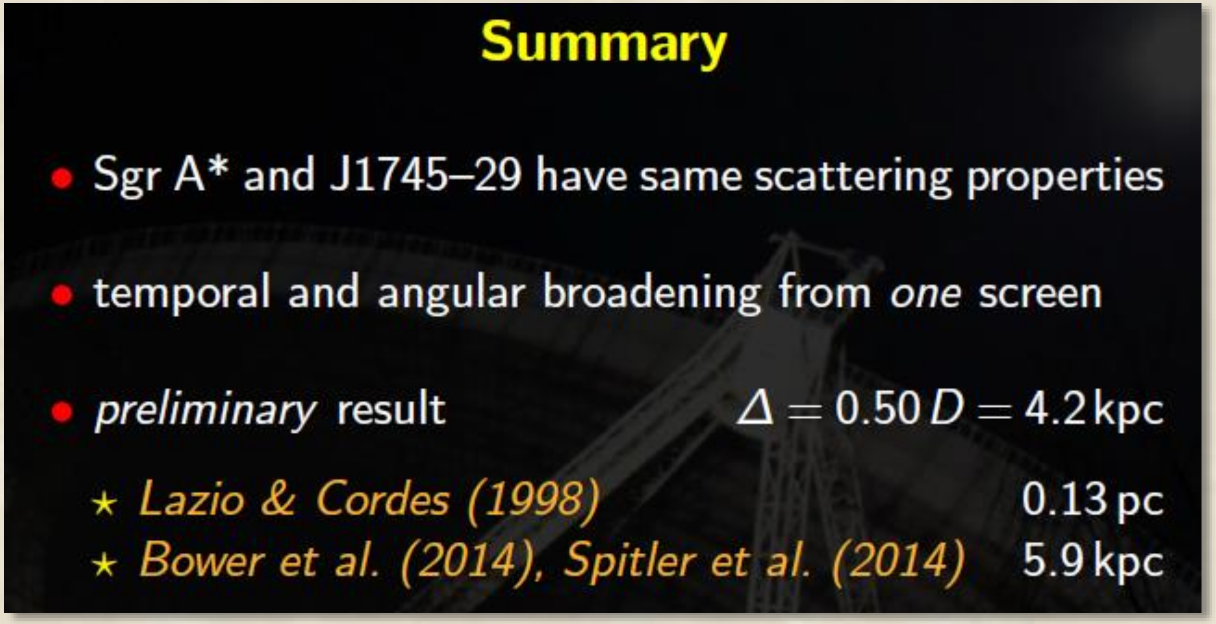


- Limit on the companion of J1518+4904: 0.31 mJy with 5-min integration;

Other pulsar science: study of interstellar medium

- Study the scattering screen along the line-of-sight, by looking at both pulse profile temporal broadening and imaging;
- LEAP observed the magnetar (J1745-2900) near the Galactic Centre, on Nov. 2013, repeated on Nov. 2014;

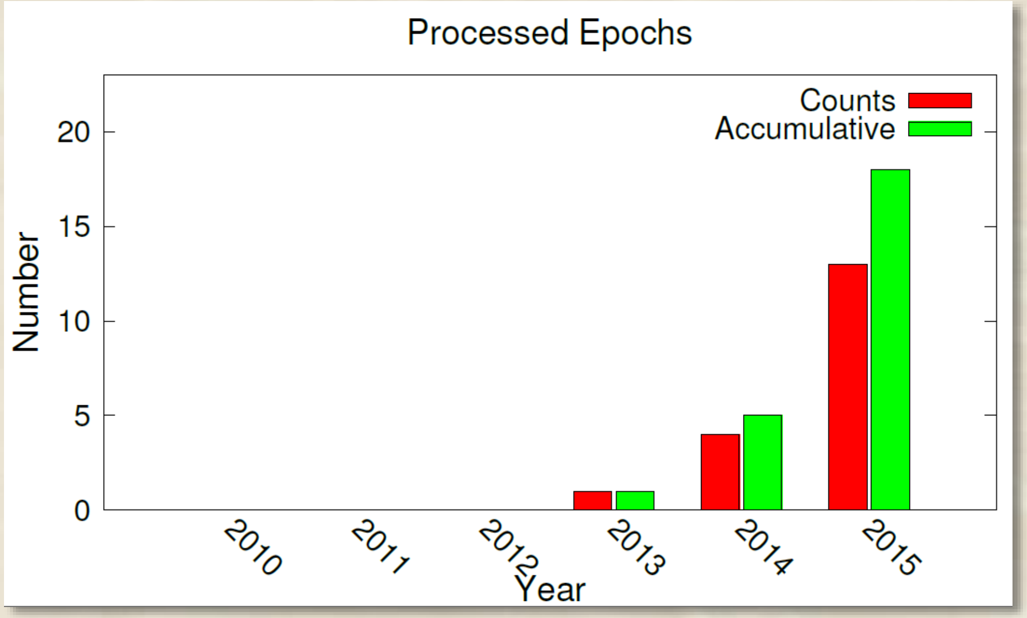


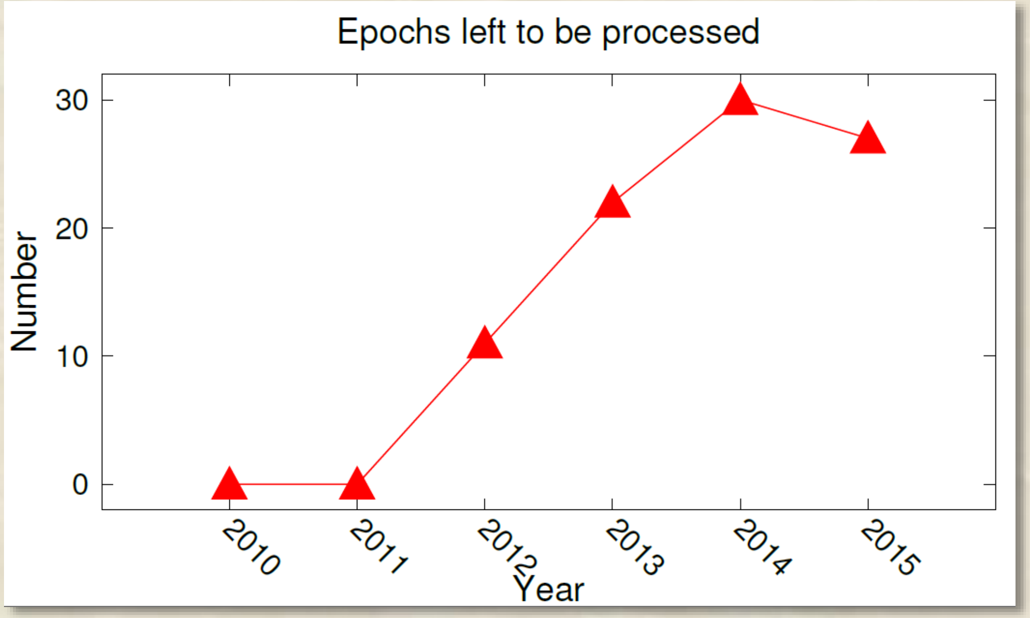


For more details, see http://evn2014.oa-cagliari.inaf.it/EVN2014/Talks/06%20Fri%20Morning/Wucknitz_EVN2014.pdf

Project status

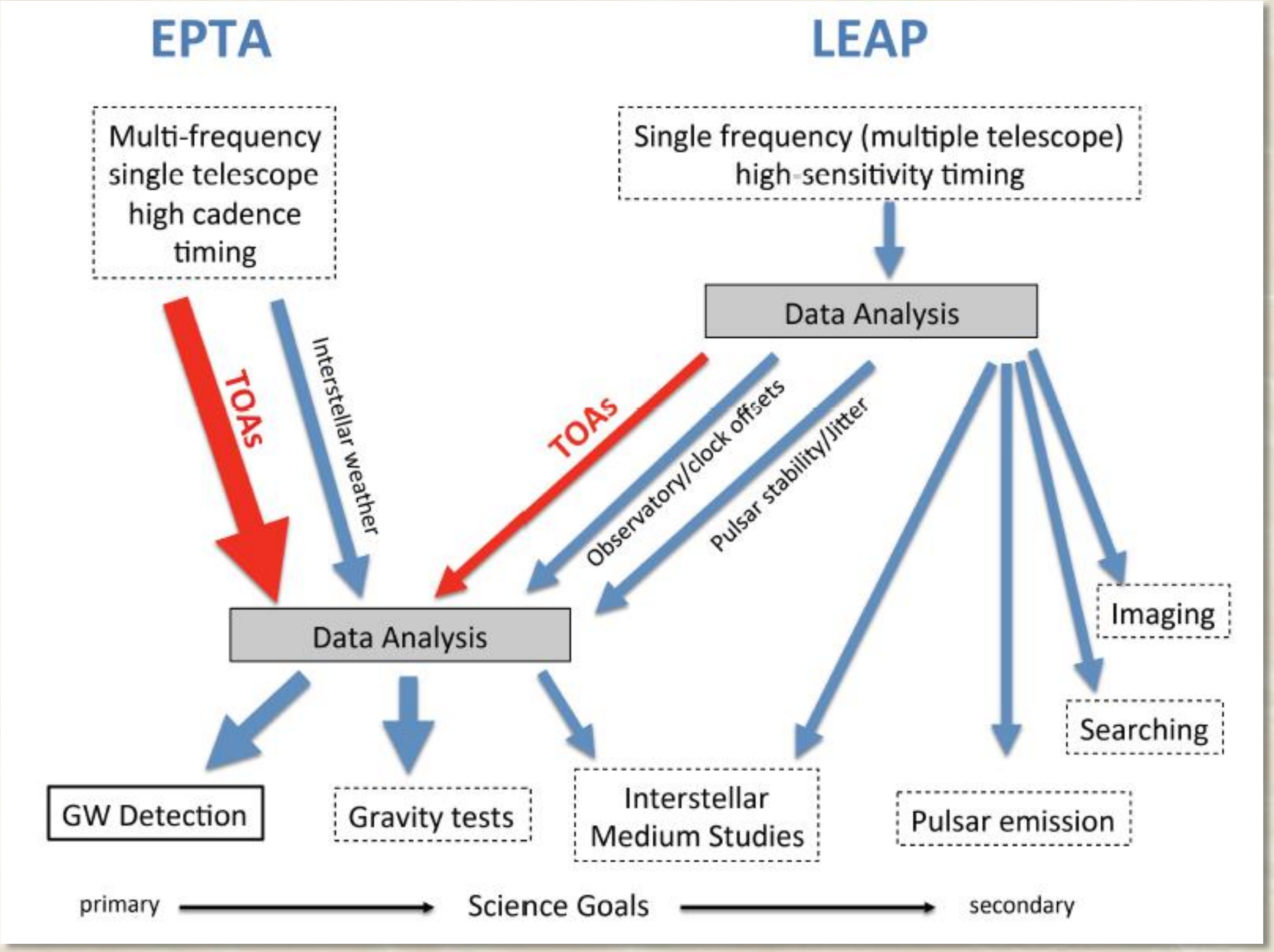
- Up to now, the project has collected 4.4 PB data !
- 2 PB (43%) have been processed !
- Currently performing three-week correlation campaign: No more backlogs !
- Started to reduce the amount of backlogs !





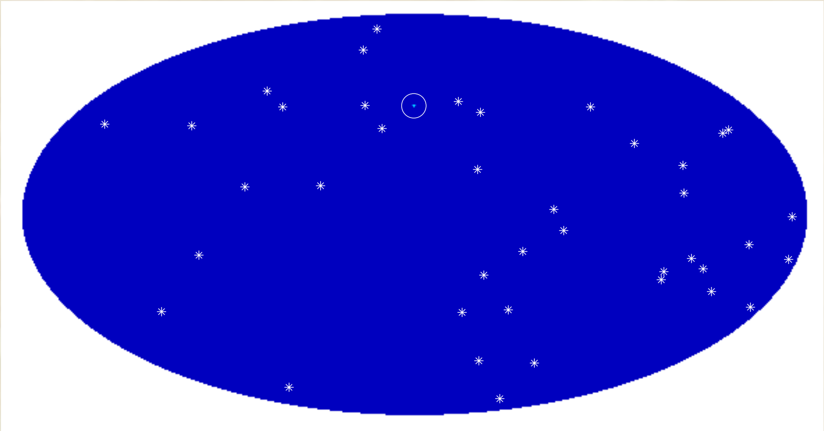
- LEAP has and will continue with multiple sources of funding support;
- LEAP data will be included in the next version of EPTA dataset;
- Interested in science with LEAP data ? Talk to one of the team members !

To summarize…

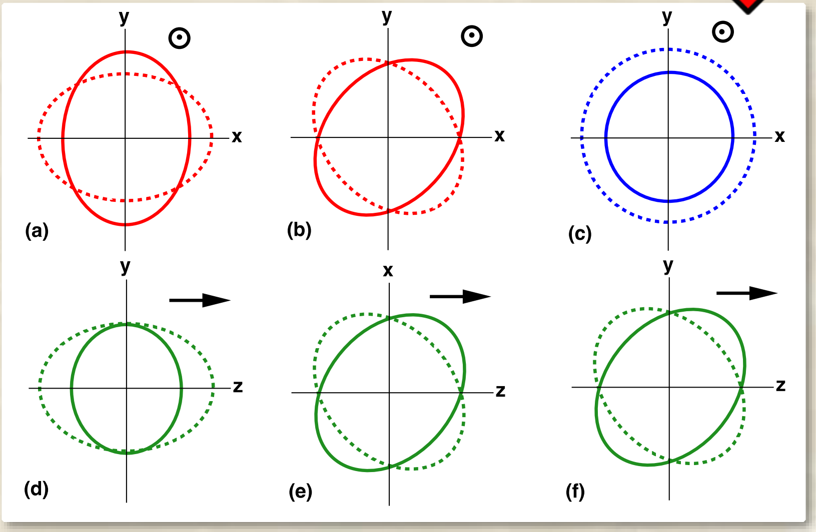


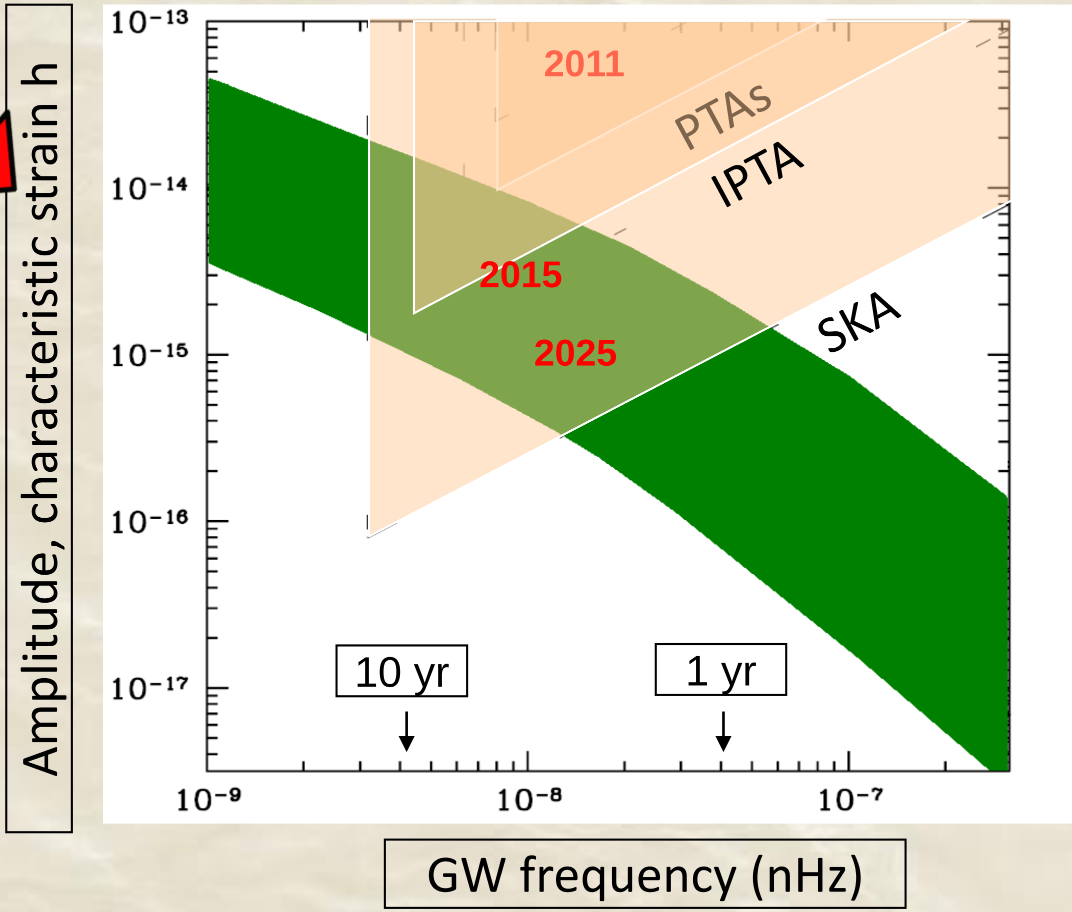
In the near future…

Locate the binary SMBH in the sky:



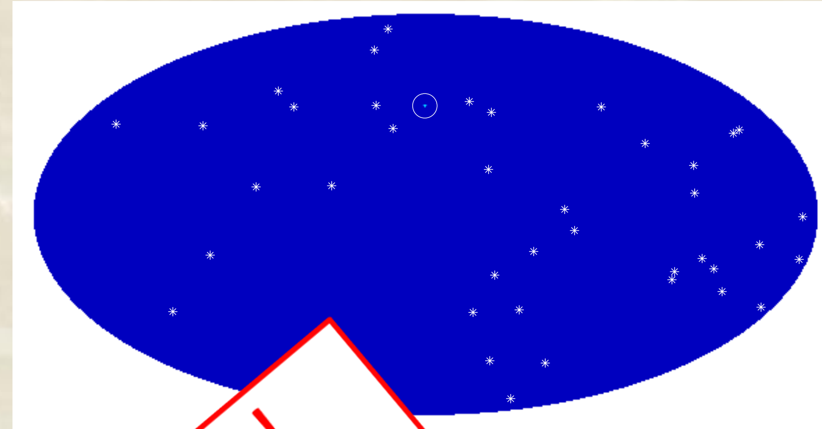
Polarization modes – Spin 2?



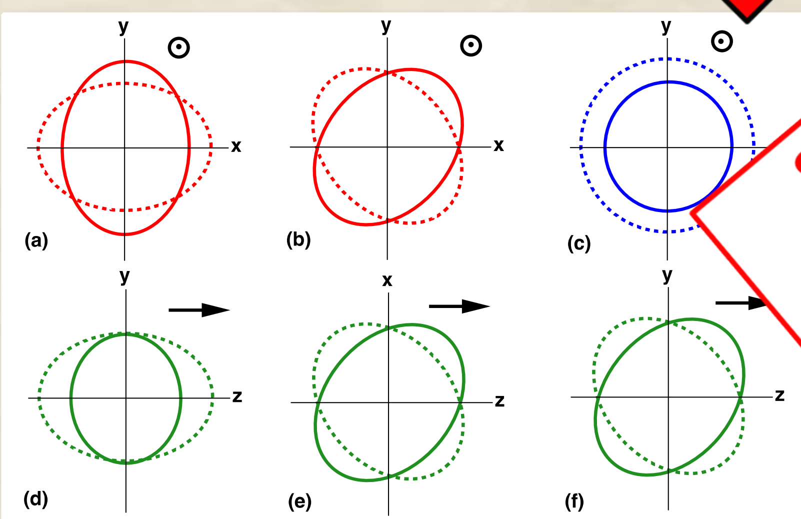


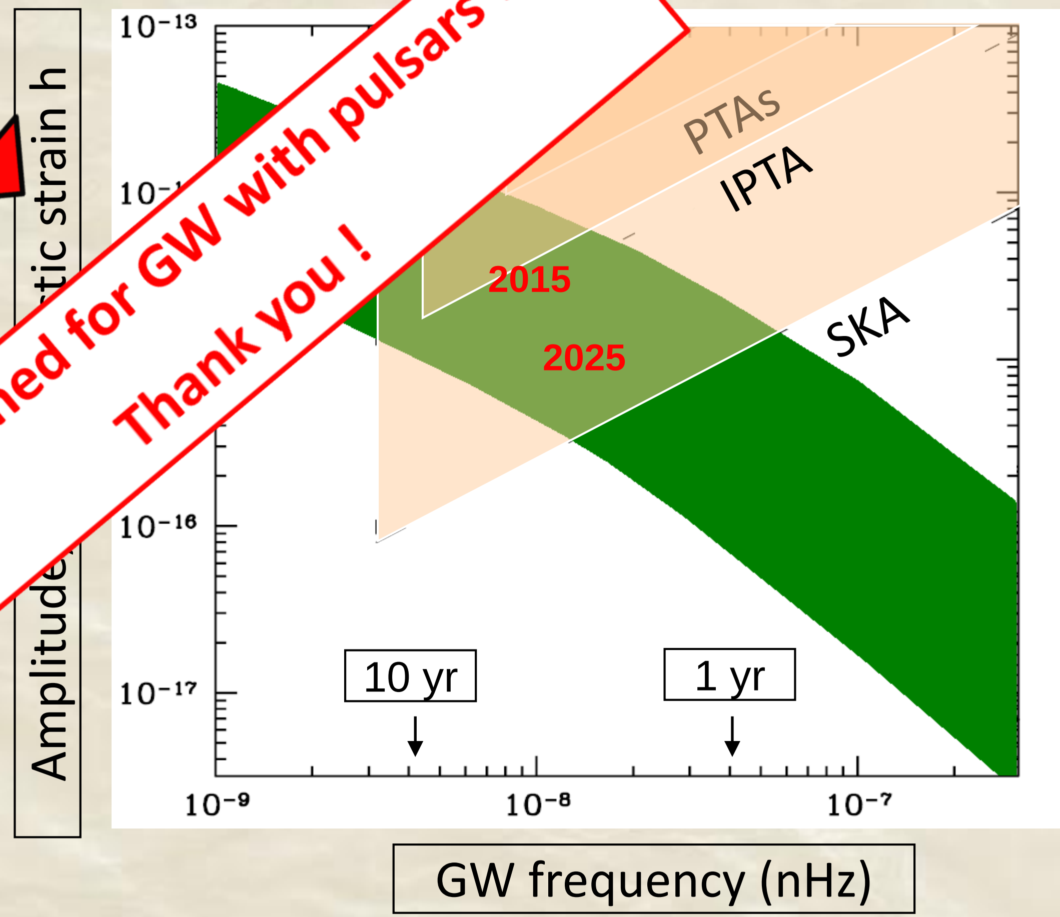
In the near future…

Locate the binary SMBH in the sky:



Polarization modes – Spin 2?





Stay tuned for GW with pulsars !

Thank you !