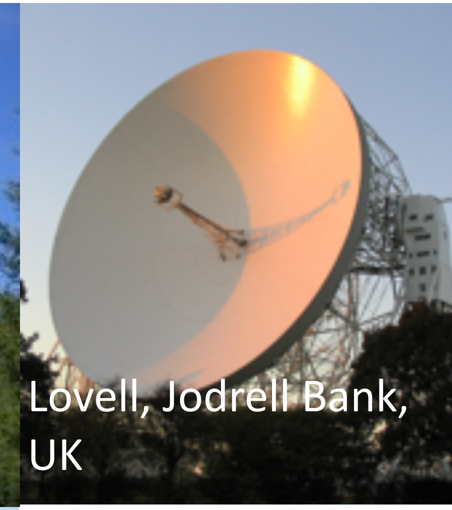
The European Pulsar Timing Array (EPTA)

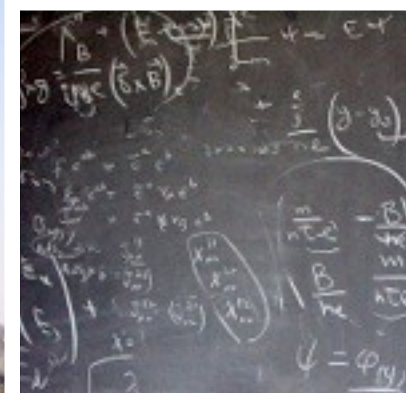
Ben Stappers, University of Manchester

on behalf of the EPTA members: http://www.epta.eu.org/

An array of 100-m class telescopes to form a pulsar timing array



Plus theory:



and ultimately forming the Large European Array for Pulsars (LEAP)

The EPTA partners





Mission: *"Perform high precision timing to study pulsar binaries, theories of gravity and to detect gravitational waves"*

Observational efforts:

- MPI for Radioastronomy, Bonn, Germany
- Jodrell Bank Centre for Astrophysics, Uni. Manchester, UK
- ASTRON, The Netherlands
- CNRS, France
- INAF, Italy

Complemented by *strong theoretical efforts* by these members:

- Albert Einstein Institut, Germany: limits, detection methods
- MPIfR, Germany: sources, detection & observing strategies, tests of theories of gravity
- Uni. of Birmingham, UK: sources, detection
- Uni. of Manchester, UK: cosmic strings

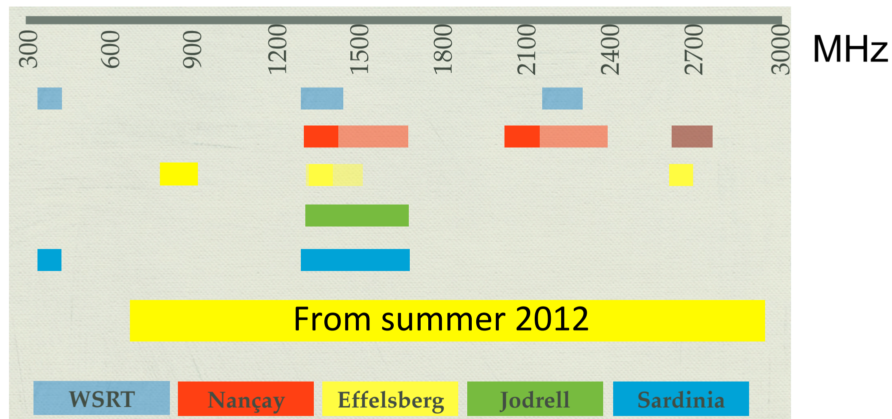
The EPTA observing systems





Observational advantages by having access to multiple telescopes:

- Increased cadence and source coverage, no gap in data
  - about 30 to 50 sources being monitored
  - Cadence per source: 7d (Nancay), 10d (Jodrell) to 30d (WSRT, EFF)
  - Time per source: 30-60min
- Increased frequency coverage to remove interstellar weather



- Inherit error checking by comparing different telescope data
- Reduction of systematic errors due to complementary observing systems
- Long time baseline: archives going back up to 25 years
- Current best published GW limit from EPTA (van Haasteren et al. 2011)
- Major hardware upgrade for data acquisition almost complete

The EPTA data acquisition systems

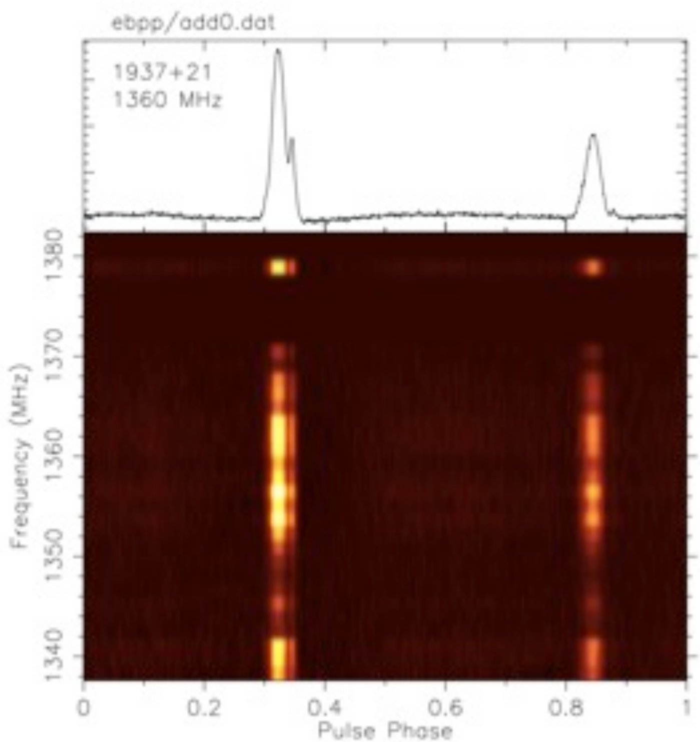


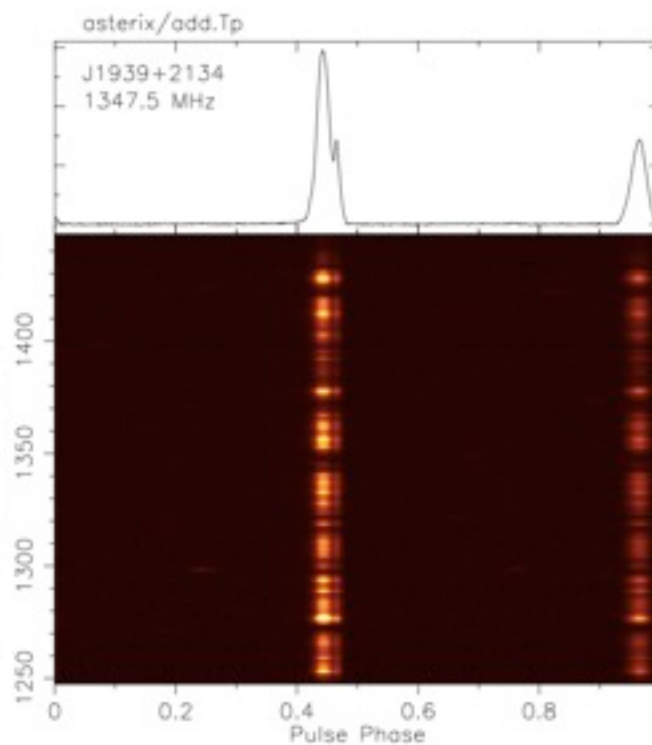


Combination of similar and complementary coherent dedisp. systems:

Effelsberg 100-m telescope:

- Legacy Effelsberg-Berkeley Pulsar Processor (EBPP, since 1995, ***Caballero Poster***): up to 112 MHz on-line coherent dedispersed BW, 4 bits
- Incoherent programmable FFT spectrometers, up to 2 GHz BW, 32 bits
- ASTERIX: Roach-board system for on- and offline coherent dedispersion, currently 200 MHz, soon 1000 MHz BW, 8 bits (***see Karuppusamy poster***)





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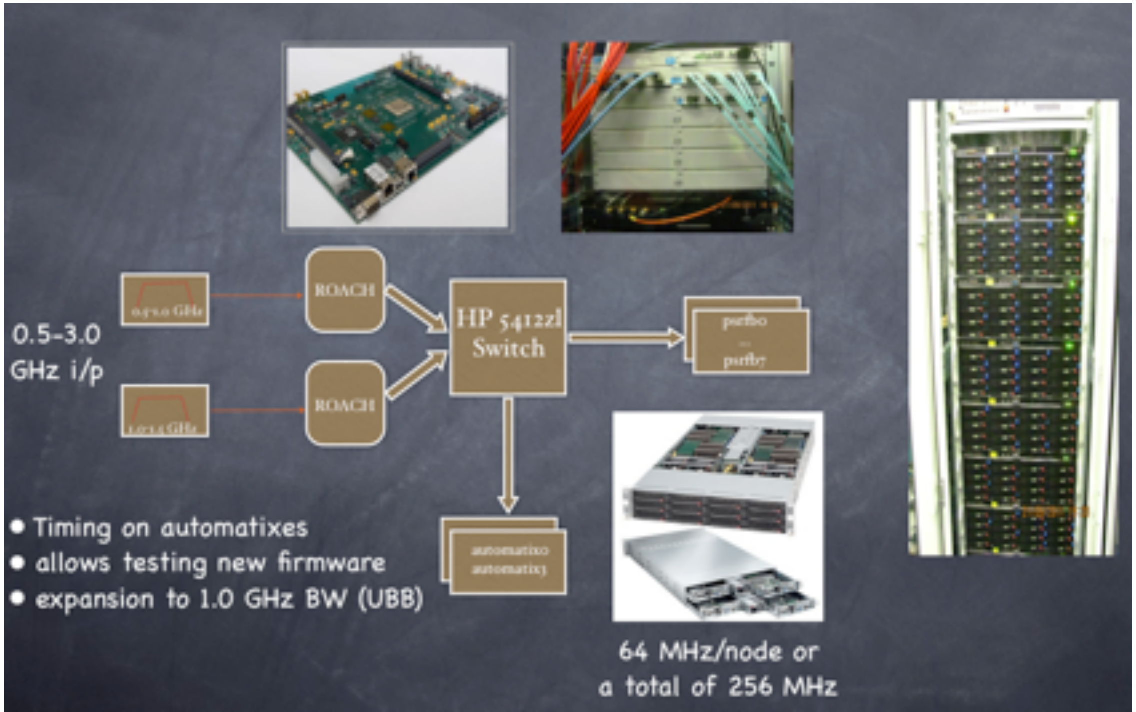
- ASTERIX: Roach-board system for on- and offline coherent dedispersion,
  currently 200 MHz, soon 1000 MHz BW, 8 bits
- Being built: GPU-based on-line coherent dedisperser, 3 GHz BW, 8 bits (***Verbiest talk***)



The EPTA data acquisition systems



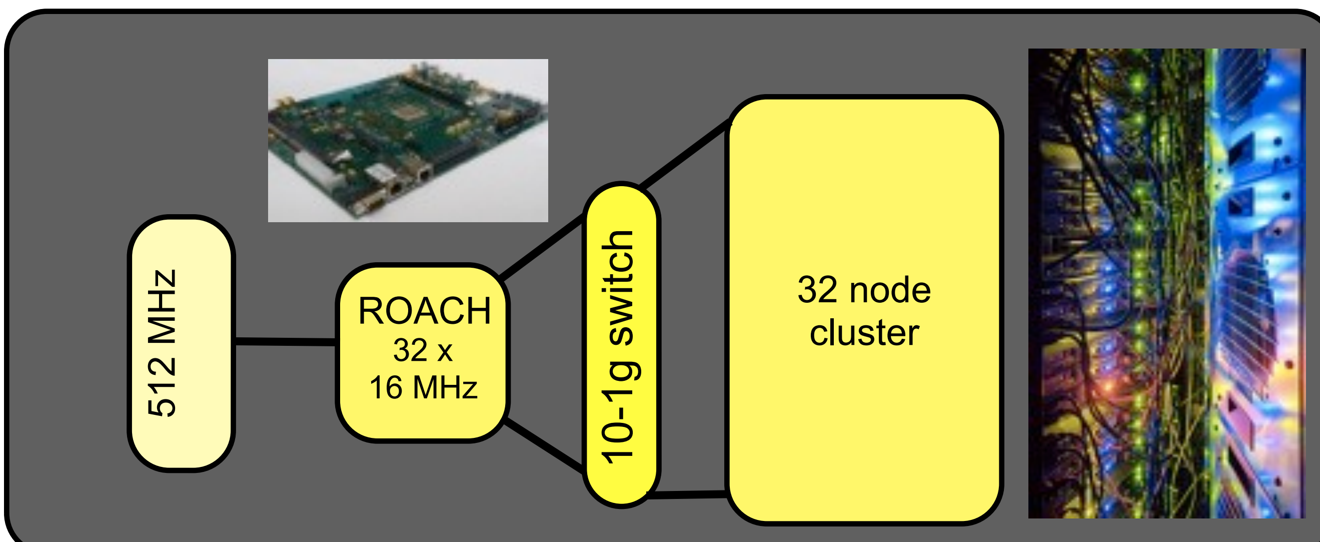


Combination of similar and complementary coherent dedisp. systems:

Effelsberg 100-m: 500/1000/soon 3000 MHz BW

Lovell 76-m telescope, Jodrell Bank:

- Legacy incoherent filterbank system, up to about 100 MHz (up to 28 yrs data!)
- ATNF Digital Filterbank (DFB), incoherent dedispersion, 384 MHz, BW, 8 bits
- ASTERIX-like ROACH-board system, 400 MHZ BW, 8 bits, Since early 2011 observing in two widely-spaced bands at L-band, baseband RFI rejection
- HPC computing cluster for ROACH and LEAP processing



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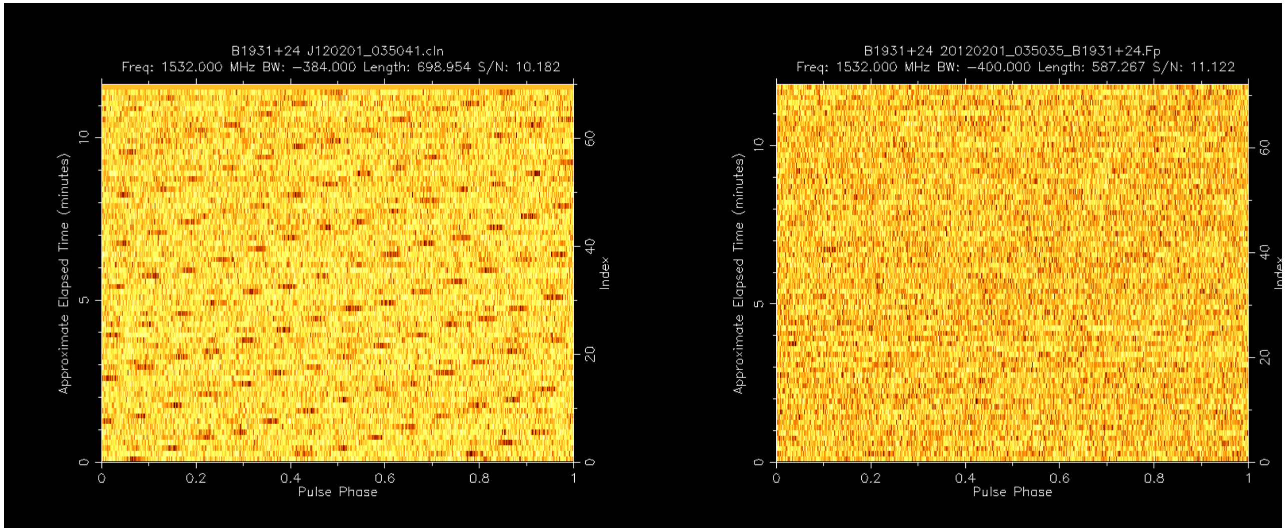
before and after RFI rejection scheme:



means you can do this.....

even when this is in your backyard....(almost)

Jodrell Bank Live June 23rd 2012

The EPTA data acquisition systems





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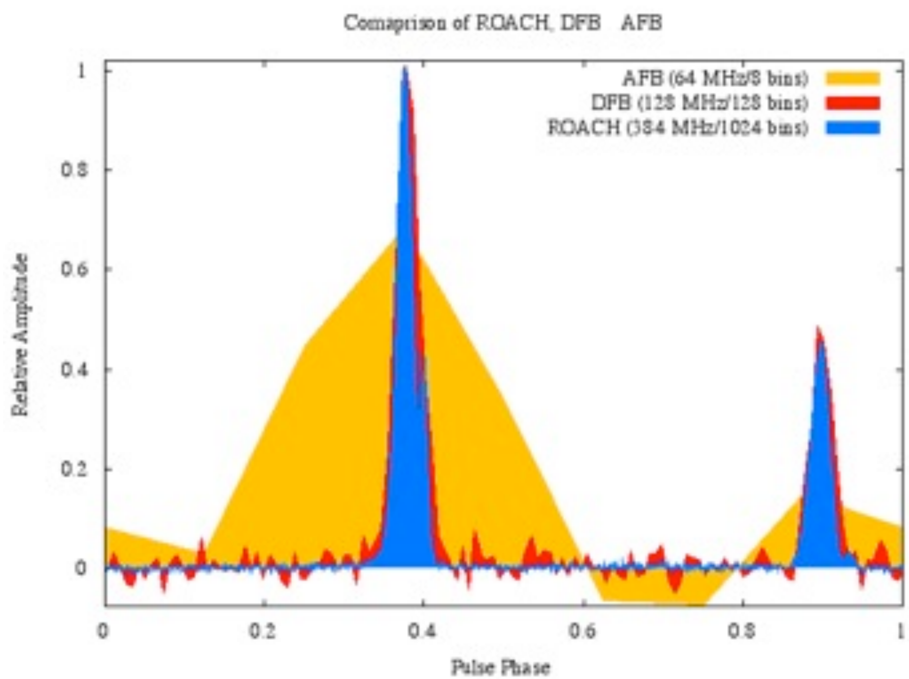


The EPTA data acquisition systems





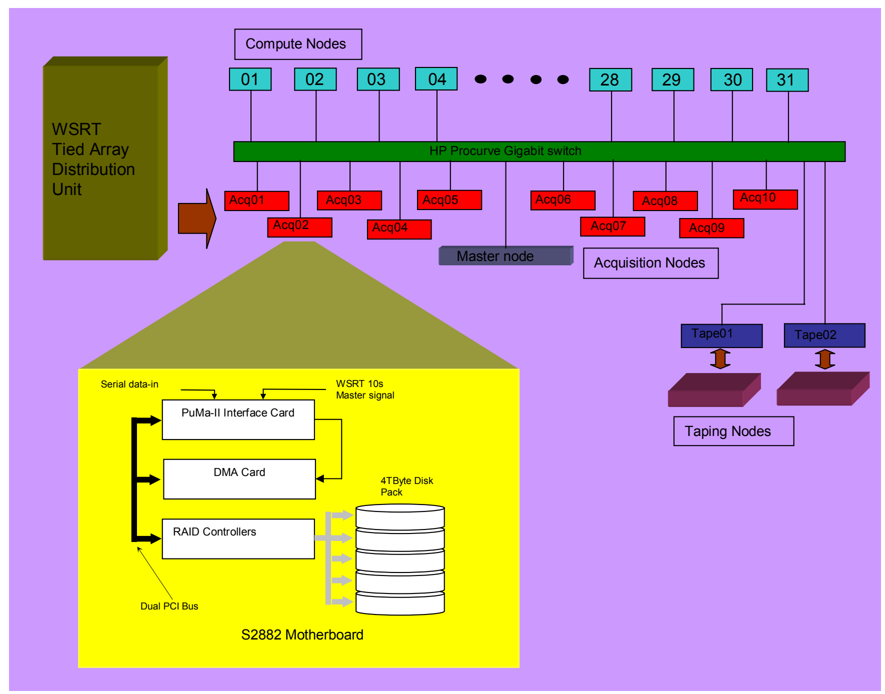
Combination of similar and complementary coherent dedisp. systems:

Effelsberg 100-m: 500/1000/soon 3000 MHz BW

Lovell 76-m telescope, Jodrell Bank: 400 MHz BW

Westerbork Radio Synthesis Telescope, 94-m equivalent:

- PuMaII baseband recorder for off-line coherent dedispersion, 80 (<1 GHz) /160 MHz (>1 GHz) BW, 8 bits (since 2006)
- Mulit-frequency frontends, observe from 300 - 2.3 GHz



The EPTA data acquisition systems

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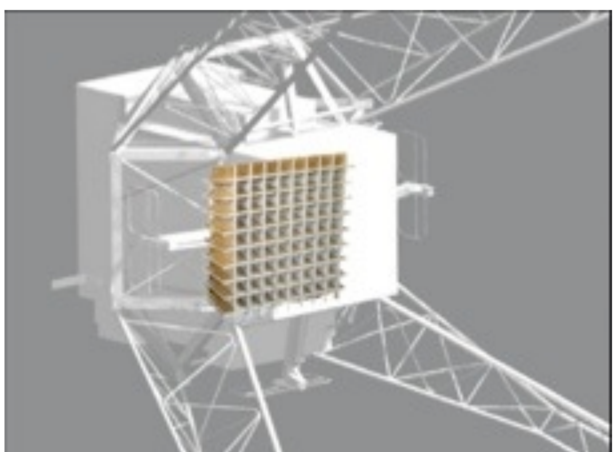
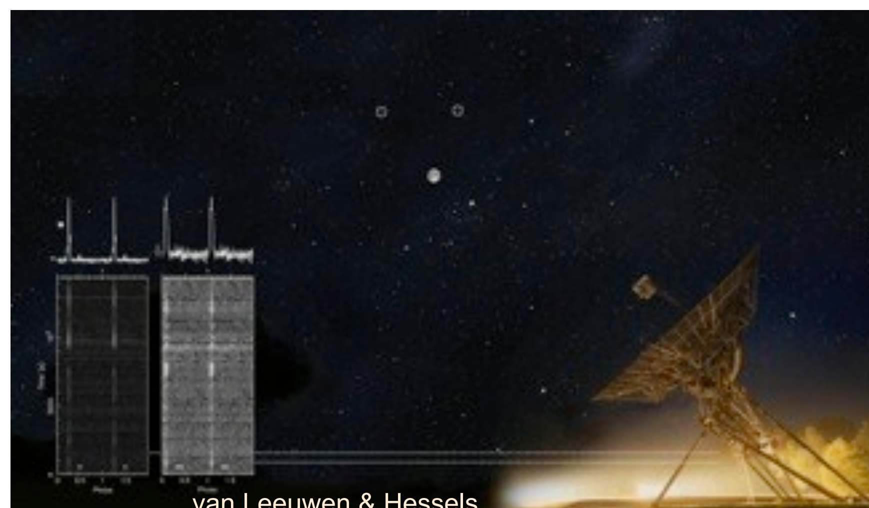
Westerbork Radio Synthesis Telescope, 94-m equivalent:

- PuMaII baseband recorder for off-line coherent dedispersion, 80/160 MHz BW, 8 bits
- Over next couple of years moving to APERTIF
  - PAF w/36 beams, >300 MHz BW, ~800-1600 MHz
  - Overall slight improvement in sensitivity, but no freq. agility





The EPTA data acquisition systems





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Effelsberg 100-m: 500/1000/soon 3000 MHz BW

Lovell 76-m telescope, Jodrell Bank: 400 MHz BW

Westerbork Radio Synthesis Telescope, 94-m equivalent: 160 MHz BW

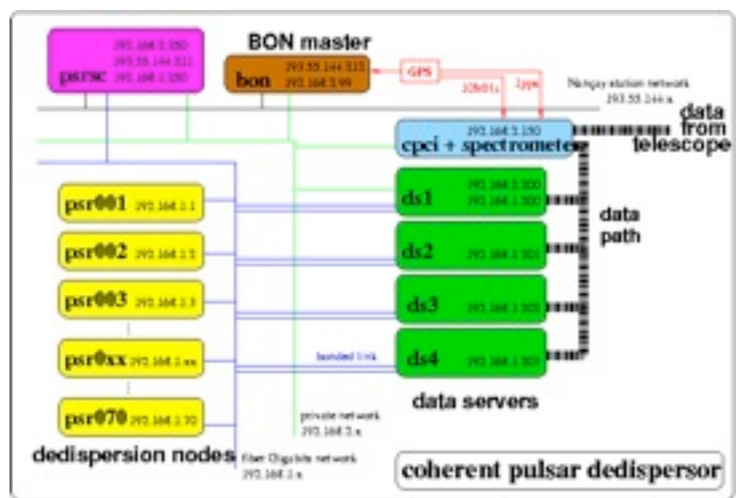
Nançay Radio Telescope, 94-m equivalent:

- Berkeley-Orleans-Nancay (Bon) on-line coherent dedisperser,

  ROACH + GPU based system, 512 MHz BW, 8 bits,

  also: digital filterbank mode for incoherent observations

  just implemented: base-band recording mode for LEAP

The EPTA data acquisition systems

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Westerbork Radio Synthesis Telescope, 94-m equivalent: 160 MHz BW

Nançay Radio Telescope, 94-m equivalent: 512 MHz BW

Sardinia Radio Telescope, 64-m (from Q4 2012):

- Dual band ATNF Pulsar Digital Filterbank (for single-band coherent dedispersion or dual 300/1400 MHz incoherent observations), up to 500 MHz BW, 8 bits – telescope being commissioned: smaller collecting area but only active surface telescope in EPTA
- ASTERIX-like system in 2013

The EPTA data acquisition systems





Combination of similar and complementary coherent dedisp. systems:

Effelsberg 100-m: 500/1000/soon 3000 MHz BW

Lovell 76-m telescope, Jodrell Bank: 400 MHz BW

Westerbork Radio Synthesis Telescope, 94-m equivalent: 160 MHz BW

Nançay Radio Telescope, 94-m equivalent: 512 MHz BW

Sardinia Radio Telescope, 64-m (from Q4 2012):

- H-maser arriving this week
- first light 7 GHz receiver: second half of july
- tests DFB with PSRs at 7 GHz: august
- first light L-P (now in Medicina) at the end of october
- test DFB (folding mode) with L-P from then till november
- base band mode with DFB as soon as we have the computational power on-site (likely dec/jan)

All of them combined

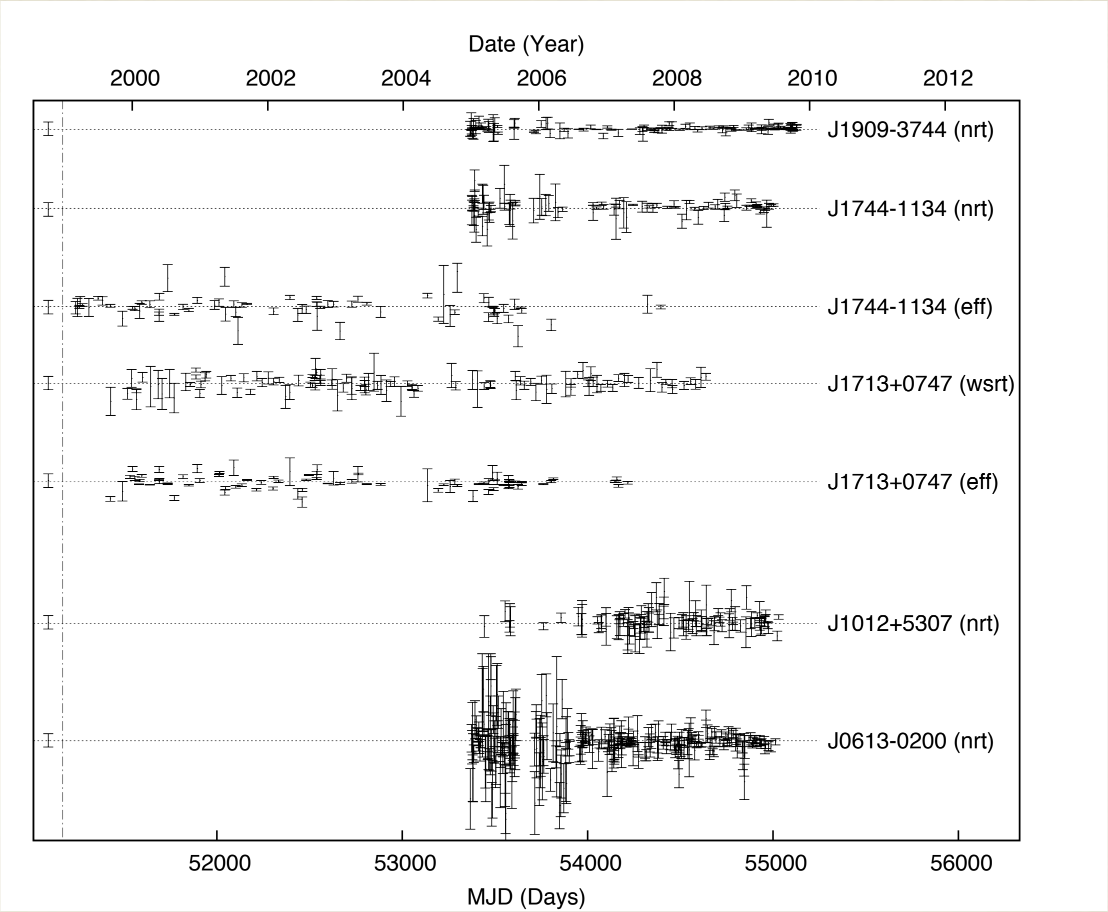
to form LEAP (***Bassa talk***)!

Observations & Residuals (see Gemma's talk)

Telescope	D(m)	Tsys	h/month	Dec(deg)	Freq
Effelsberg	100	24	43	>-30	1.4, 2.6
Lovell	76	30	50	>-35	1.4
Nançay	94	35	150	>-39	1.4, 2.1
Sardinia	64	25	?	>-46	0.3 simult 1.4
WSRT	96	29	48	>-30	0.35, 1.4, 2.3
LEAP	200	30	24	>-39	1.4

Pulsar	Eff(EBPP)	**Eff(Asterix)**	Jodrell(dfb)	Jodrell(R)	Nancay	WSRT(p1)	WSRT(PII)
0613-0200	2.0us(12yr)		3.5us(3.3yr)		1.1(7yr)	2.3us (11yr)	1.0us(5yr)
1022+1001	2.8us(12yr)		2.0us(3.3yr)		1.7(7yr)	1.6us(11yr)	1.0us(5yr)
1713+0747	0.5us(13yr)	0.17 (1 yr)	0.6us(3.3yr)	0.200 (1.2yr)	0.4(7yr)	0.7us(11yr)	0.23 us (5yr)
1937+21	0.23us(2yr)		1.4us(3.3yr)	0.33(1.2yr)		0.8us*(10yr)	0.5us(5yr)
1909-3744	-		-		0.11(7yr)	-	-

EPTA Limit - Data

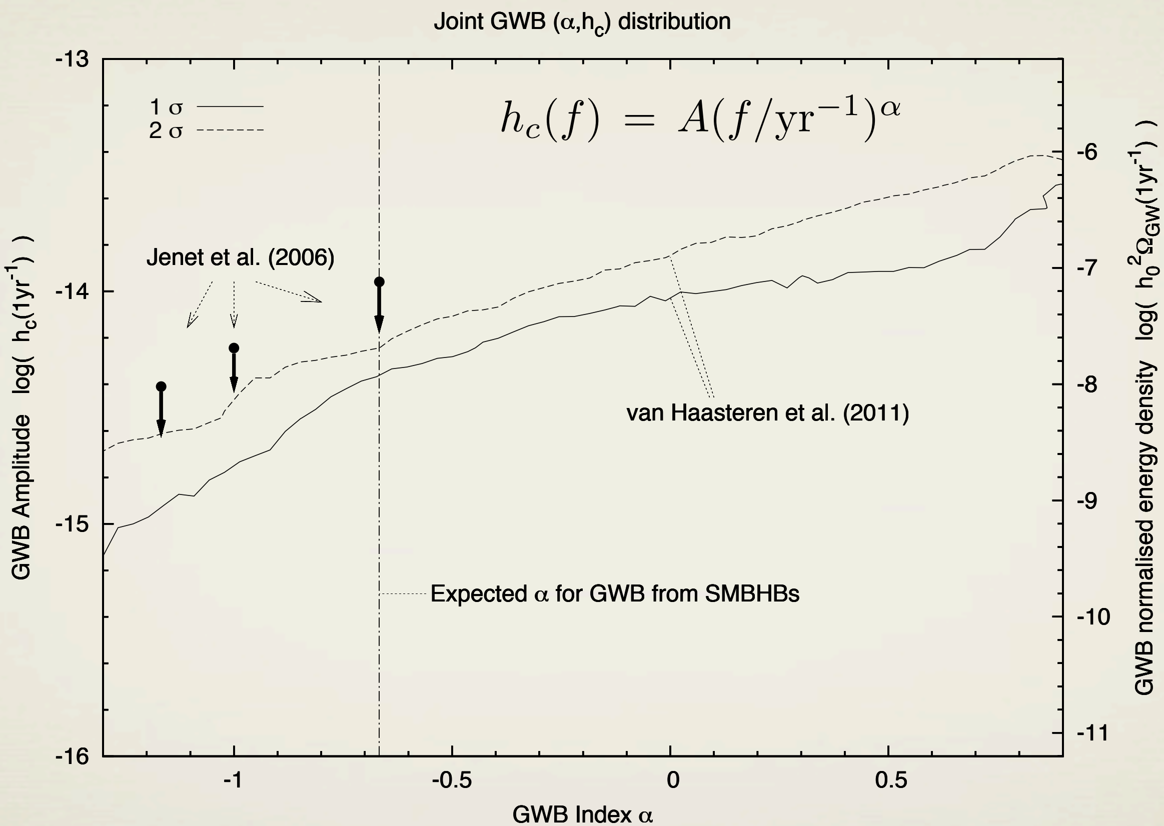


Uses data from multiple telescopes and multiple pulsars
Pulsars chosen by considering the GW limits they place individually
these five pulsars can individually limit the GWB well below $h_c(1yr) = 10^{-13}$ for $\alpha = -2/3$
Others are sufficiently worse that they don't improve the limit

van Haasteren et al 2011

EPTA Limit - Results (see Rutger's talk)

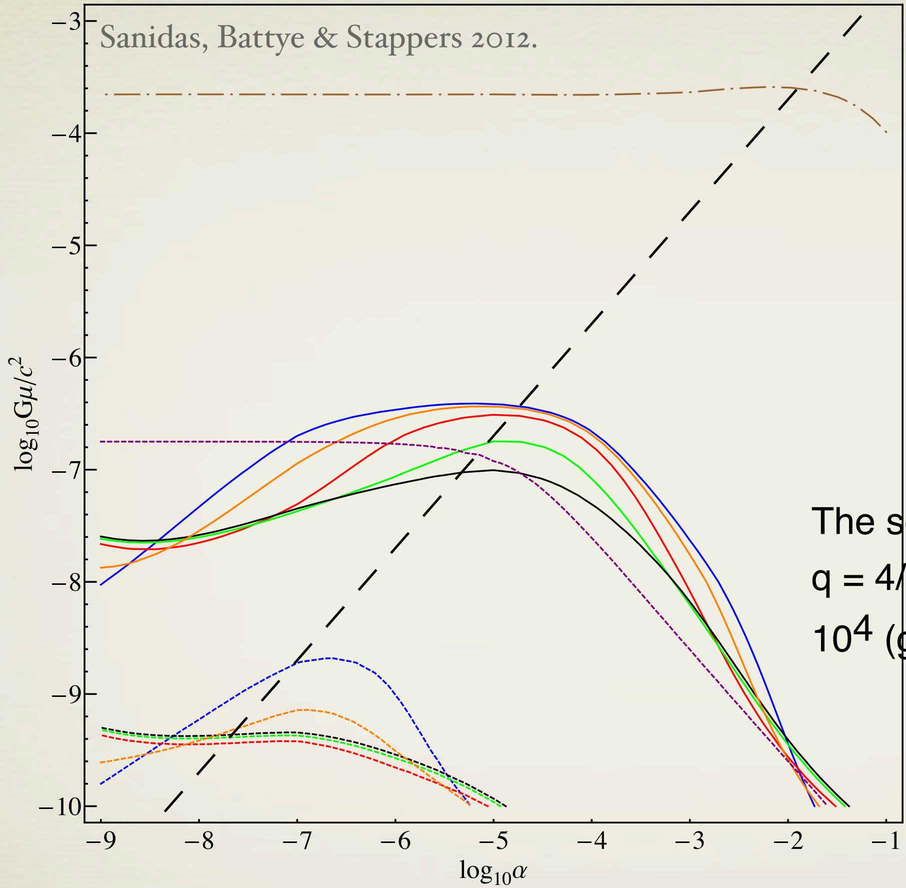
The marginalised posterior distribution as a function of the GWB amplitude, and spectral index.



For the case α = –2/3, which is expected if the GWB is produced by supermassive black- hole binaries, we obtain a 95% confidence upper limit on A of 6×10^{-15}, which is 1.8 times lower than the 95% confidence GWB limit obtained by the Parkes PTA in 2006.

van Haasteren et al 2011

Cosmic Strings (see Sotirios' Talk)



Ligo limit

The solid lines are for the EPTA $(1\text{yr})^{-1}$ limit for $q = 4/3$ and $n_* = 1$ (black), $n_* = 10^3$ (red), $n_* = 10^4$ (green) and for $q = 2$, $n_* = 10^2$ (orange).

Conservative upper bound limits on string tension and loop size based on the EPTA limit and different values for the number of modes and spectral index of the radiated power.

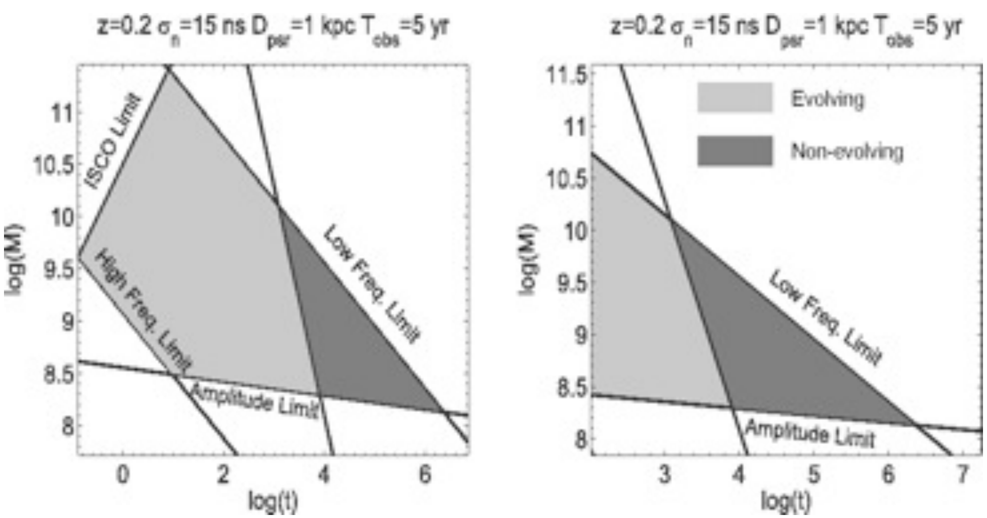
Single Source detection

Lee et al 2011

- Investigate the potential of detecting GWs from individual binary black hole systems using PTAs
- Calculate the accuracy for determining the GW properties.
- Accounting for the measurement of the pulsar distances via the timing parallax.
- At low redshift, a PTA is able to detect nano-Hertz GWs from SMBHBs with masses of $\sim 10^8 - 10^{10}$ M⊙ less than $\sim 10^5$ years before the final merger.
- Binaries $> \sim 10^3 - 10^4$ yrs before merger - effectively monochromatic GW emitters
- Such binaries may also allow us to detect the evolution of binaries.
- Also show how one can constrain distances

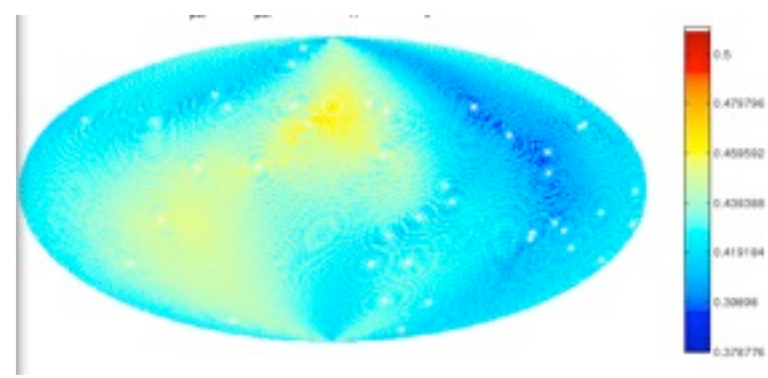
The parameter space of SMBHBs as detectable GW sources for a PTA

chirp mass of the SMBHB



'present' to the final merger in years

Constraining the GW source position



Profile Variations: J1022+1001

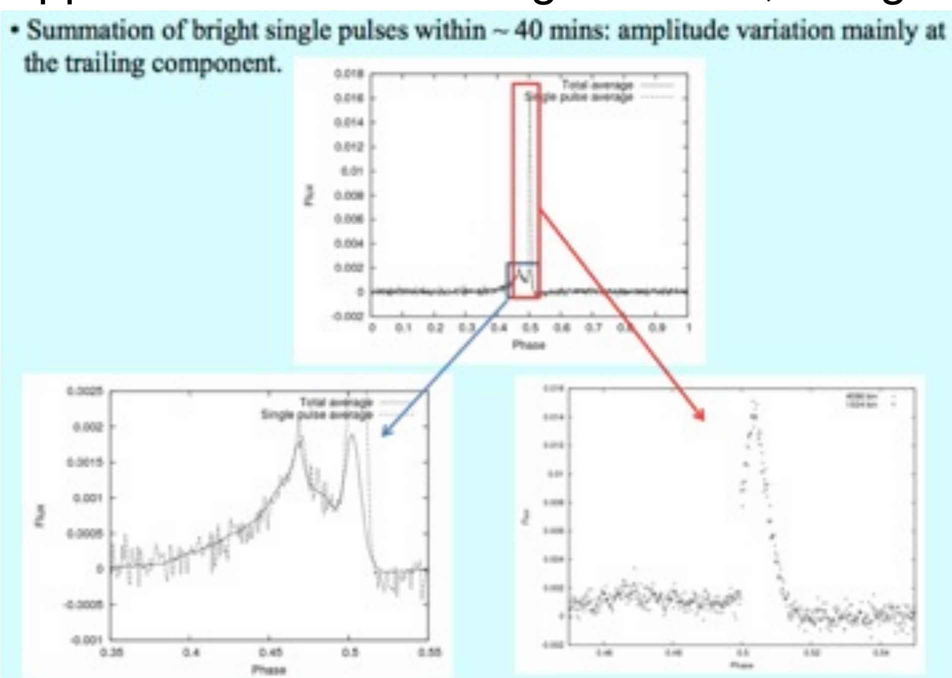
Liu, Purver et al 2012

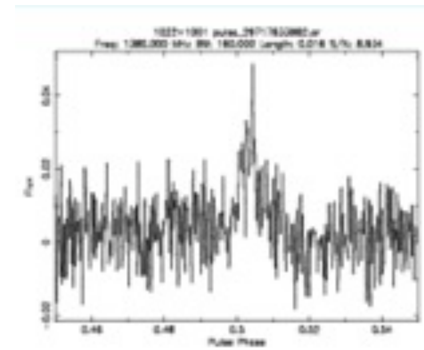
- Claims and counterclaims of profile evolution

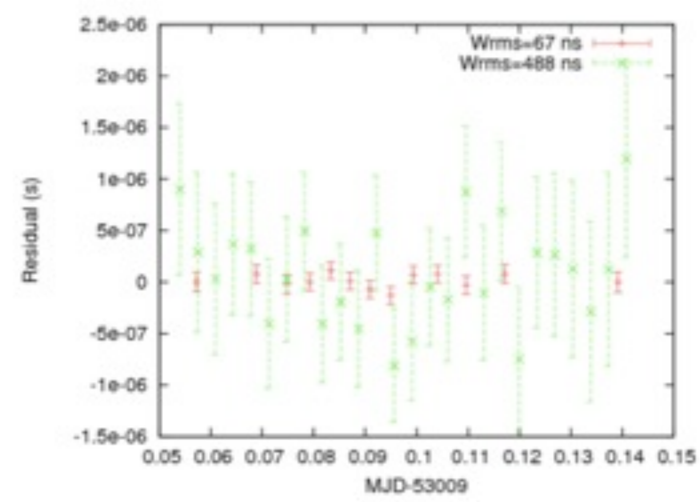
(Kramer et al 1999, Ramachandran & Kramer 2003, Hotan et al 2004, Purver 2010)

- Frequency (narrowband) and Time dependent
- Perhaps associated with polarisation calibration
- Purver's thesis seems to confirm variations
- Follow up observations simultaneous at 2 telescopes
- Data analysis ongoing, but
- Giant pulses found in the trailing component, which may be affecting the timing.
- Appear to be better timing with GPs, being repeated.

Edwards & Stappers (2003) showed modulation, now new WSRT obs show GPs seen in trailing component

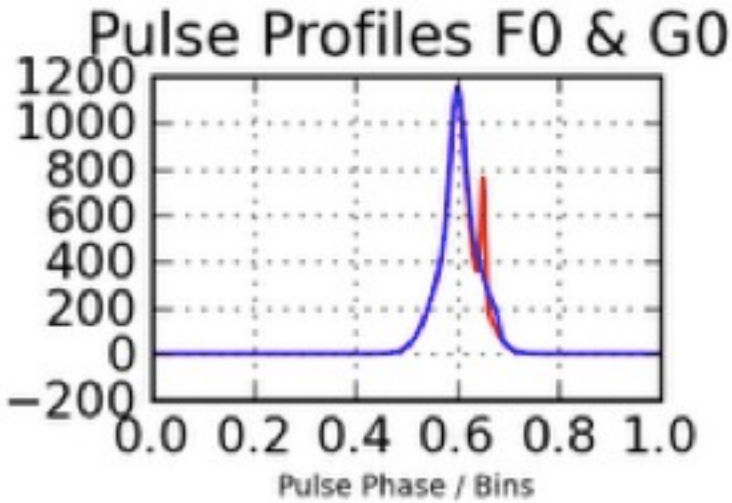


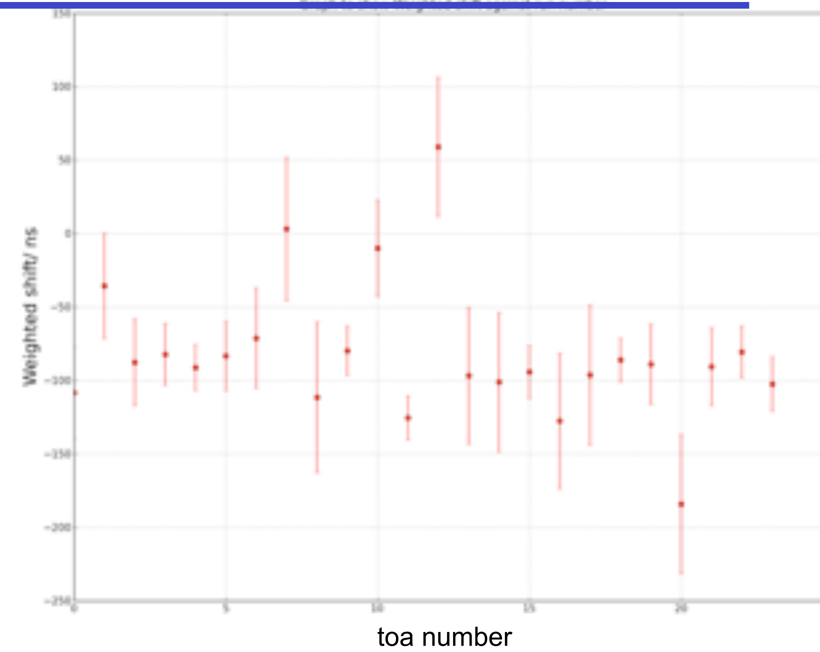


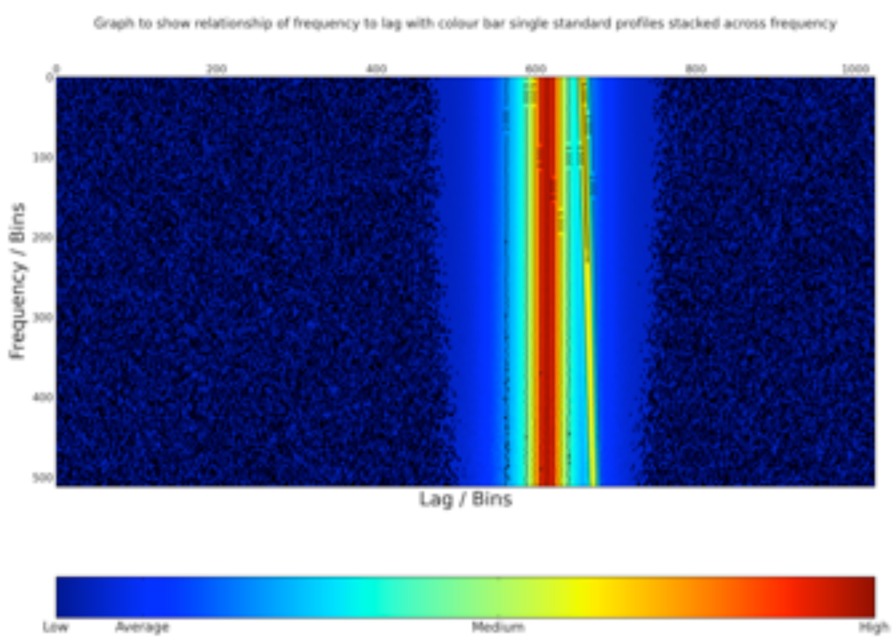


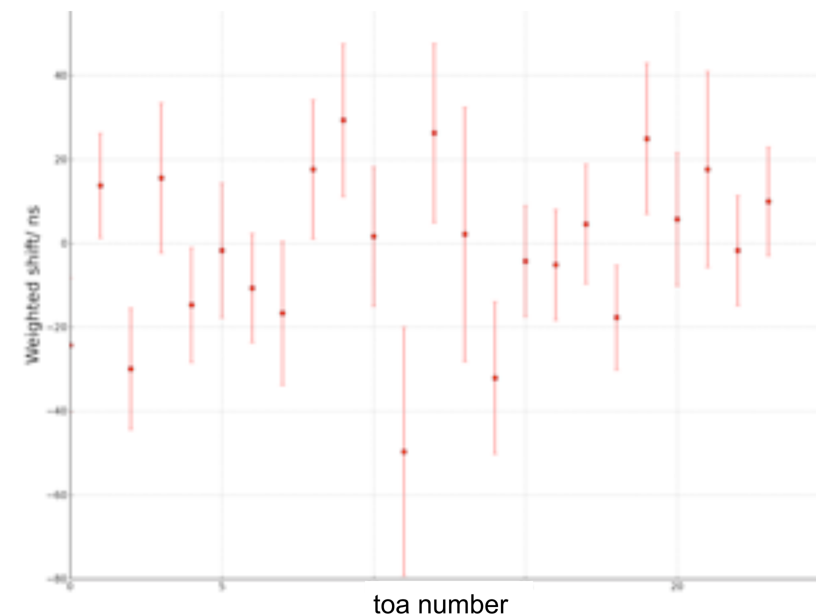
Profile Variations Simulations

Cook, Haster, Stappers et al 2012



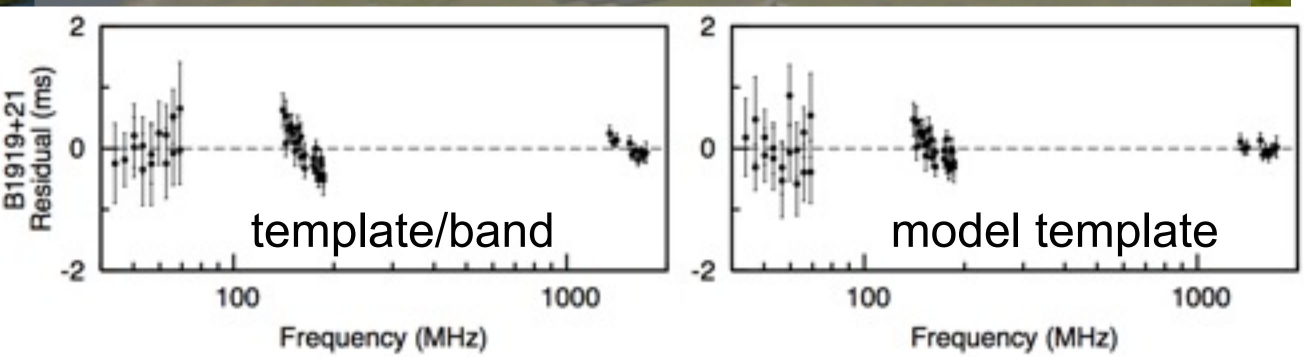


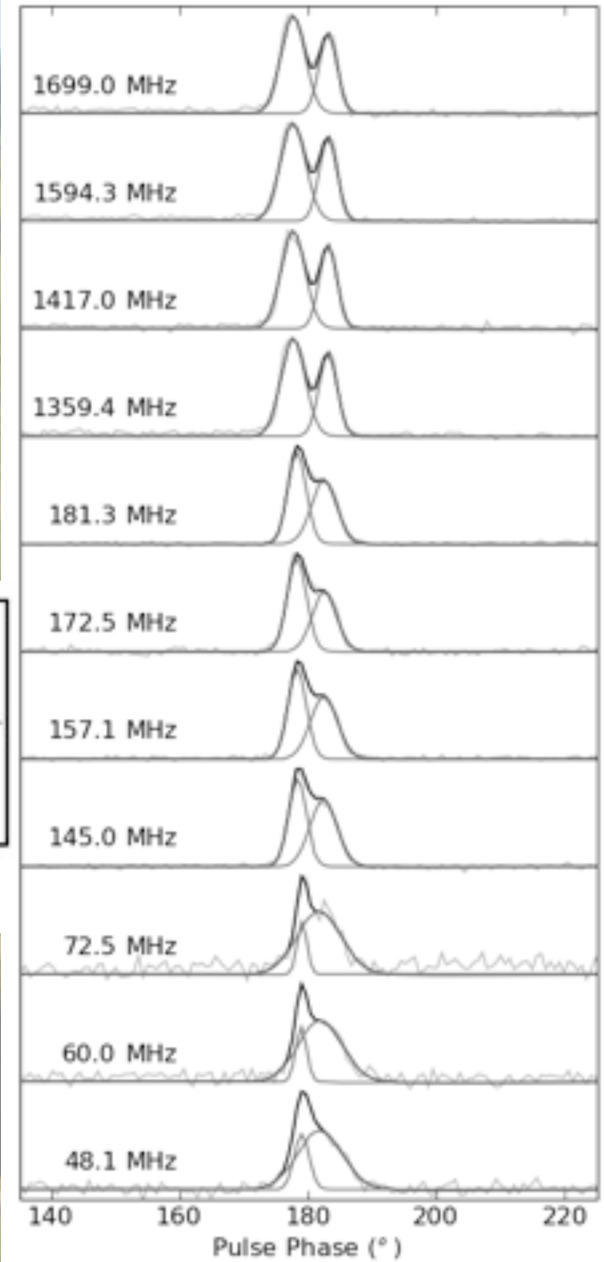




ISM, DM & Profile Evolution

- Simultaneous observations from 40 MHz to 8 GHz
- 4 relatively nearby pulsars (0329, 0809, 1133, 1919)
- Pulses at all frequencies arrive at the same time (apart from the dispersive delay)
- Able to find a “fiducial” point. Relatively simple model.
- Largest second-order ISM delay @40 MHz <4ms
- Extrapolating to pulsar timing frequencies <50ns (~100ns precision necessary for first generation of PTAs)
- ISM is relatively smooth
- No large “clumps” (at least along the sight-lines we probed)





Hassall, Stappers, PWG ++ 2012

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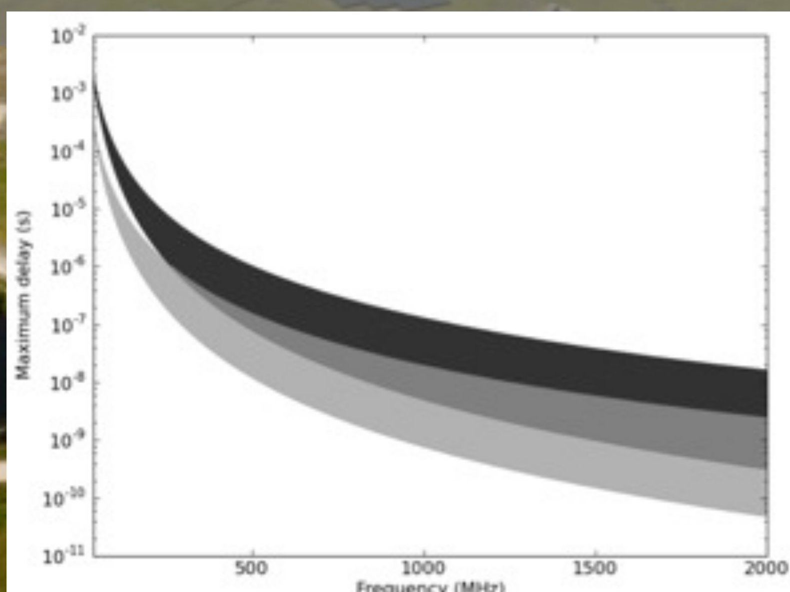

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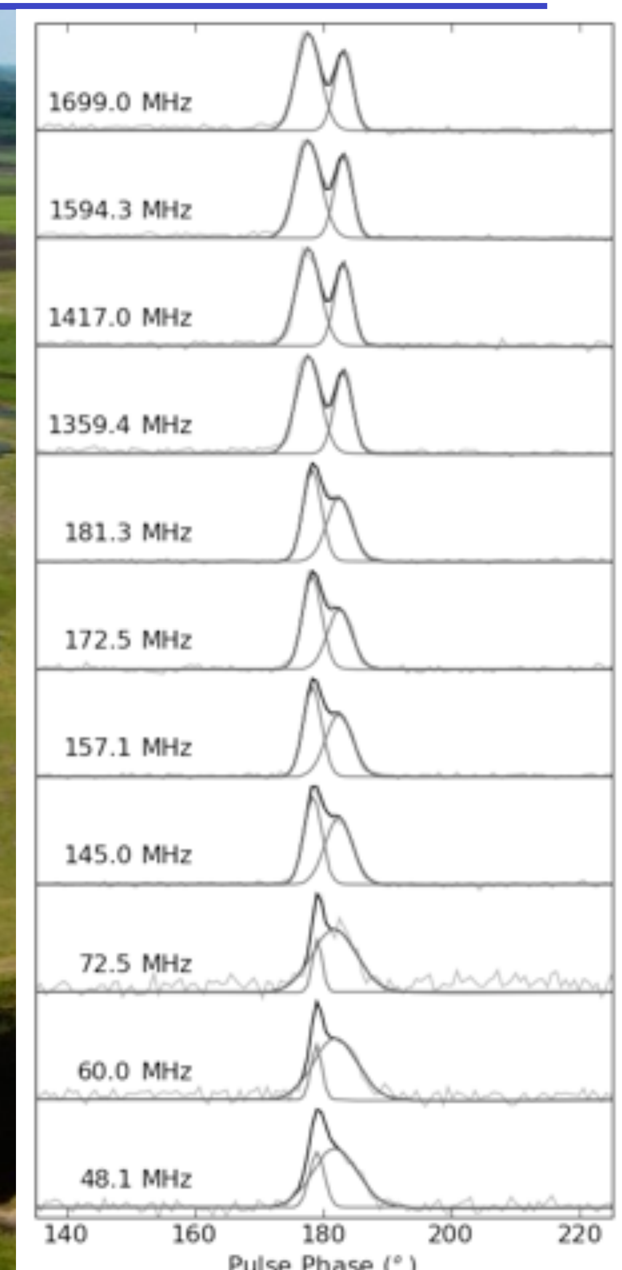
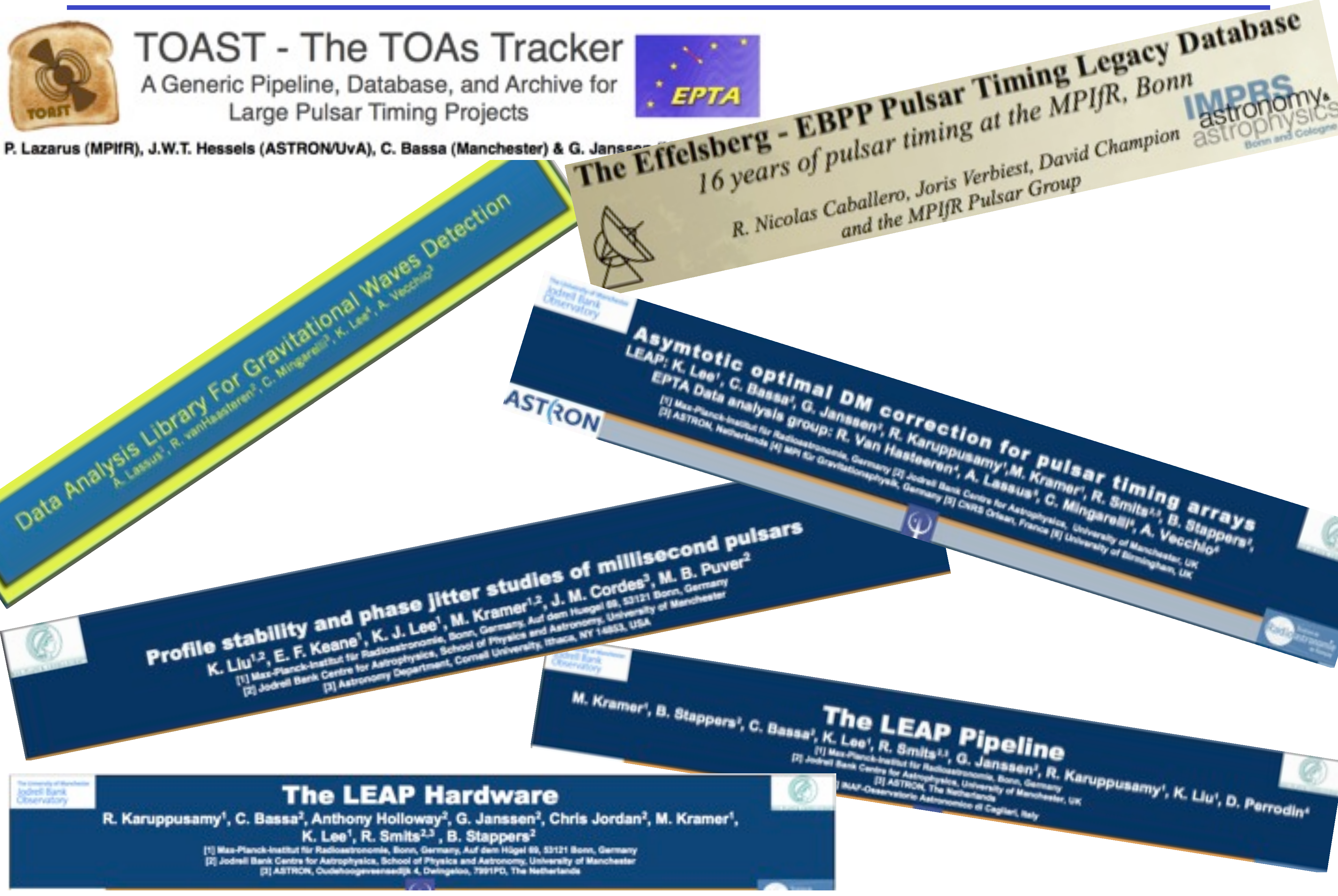


Hassall, Stappers, PWG ++ 2012

More information in these & other posters



Future work and developments

- Legacy data set release in a couple of months (Janssen Talk/Caballero Poster)
  - including papers on timing solutions, dm variations, profile variations
- Extension to profile/toa simulation work.
- TOAST(er) (Lazarus Poster) and Analysis pipeline (Lassus Poster)
- SRT observations to commence in Q1/2013 – access to 100 MHz @ 300 MHz
- First LEAP toas are coming online
- Completion of and full LEAP observations in Q1/2013 (Bassa Talk)
- Optimising observing time (Lee Talk)
- APERTIF being installed at WSRT starting 2013
- Ultra-broad receiver (UBB) at Effelsberg (Verbiest Talk)
- LOFAR (core + single-station) timing of MSPs: 48/80 MHz BW @ 110-240 MHz
- Much more on detection (van Haasteren talk) and analysis strategies (K.J. talk)
- Plus work on sources (Sesana, Sanidas, Babak and Mingarelli talks)