Recent pulsar timing highlights using the Lovell telescope and a look to the future

eMERLIN and EVN in the SKA era
11/9/2017

MANCHESTER
1824
The University of Manchester

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Outline

- Exploring the extremes of physics:
  some recent pulsar results based on Jodrell data
- Pulsars & eMERLIN
- Transients & eMERLIN

Pulsar Astrophysics: The Next Fifty Years

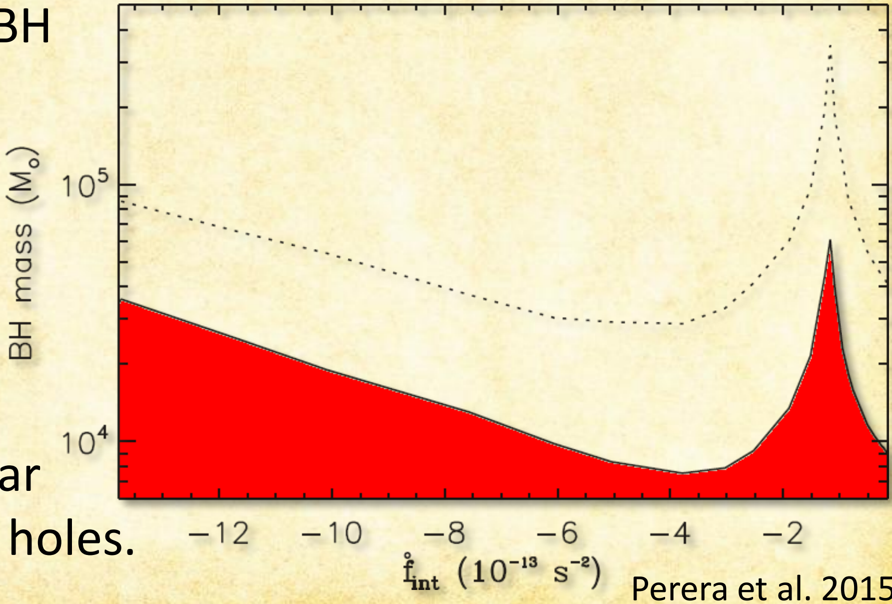
IAU Symposium 337 - 4th-8th September 2017 - Jodrell Bank Observatory, University of Manchester

Exploring the extremes of physics

Only possible because of the JBO unparalleled Pulsar Timing Database and the continuous improvements in sensitivity.

NGC 6624

- First dynamical evidence for an Intermediate Mass Black Hole (IMBH) in a Globular Cluster (GC) and perhaps anywhere!
- 25 years of high-precision timing of the closest known pulsar to the centre of any GC (PSR B1820-30A) revealed binary motion with a period of few kyr.
- Two families of degenerate solutions:
    1. Lowish eccentric orbit around stellar-mass companion
    2. Highly eccentric orbit around an IMBH
- 1st solution can only avoid tidal disruption by fine tuning → unlikely
- Minimum IMBH mass is 7500 $M_\odot$
- Gravitational modelling of the GC revealed that the likely mass exceeds 20,000 $M_\odot$
- IMBHs are the 'missing link' between stellar mass black holes and supermassive black holes.



Perera et al. 2015

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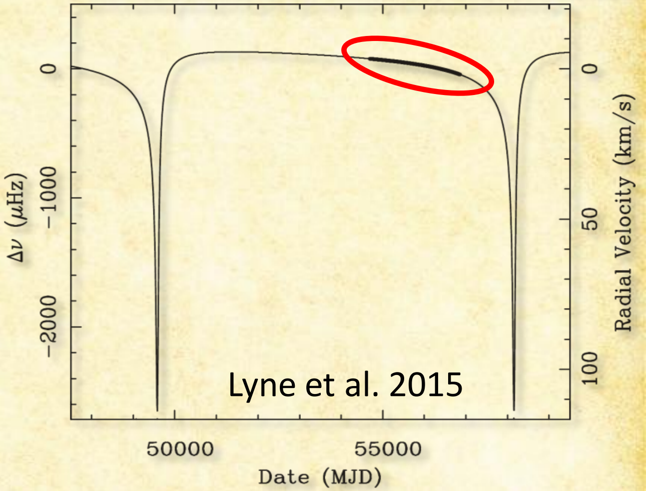
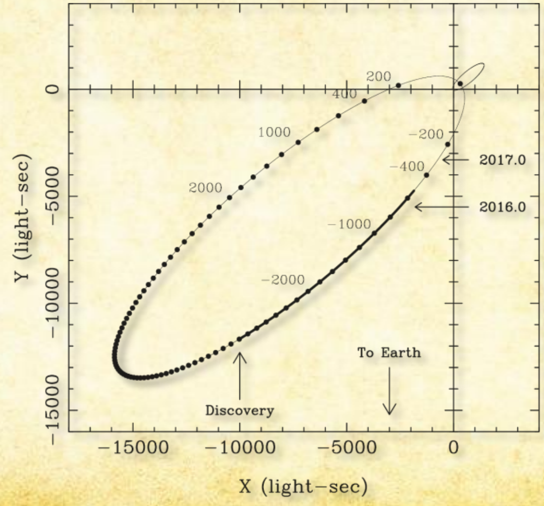
- PSR J2032+4127 was discovered in 2009 in γ-rays.
- Lovell observations: factor 2 change in spin-down rate.
- Reason: the gravitational pull of a ~15 $M_{\odot}$ Be star in the Cyg OB2 stellar association.
- High eccentricity initially prevented detection of the binary motion.
- Will plough through the disk in November 2017, which will result in high-energy "fireworks" (only 1.4-1.7 kpc away).
- Pulsar will move through and behind the disk: eclipses can occur because of the disk and atmosphere of the star (depends on unknown inclination of the system).





Ho et al. 2017

Exploring the extremes of physics

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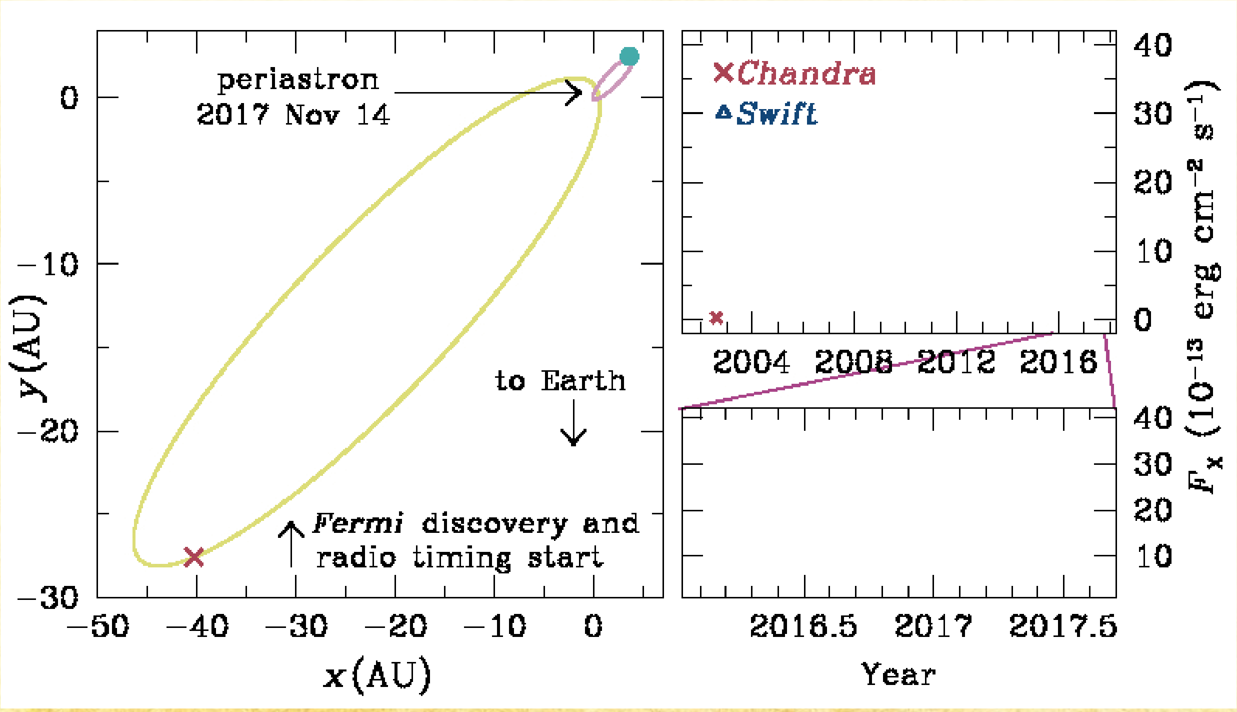
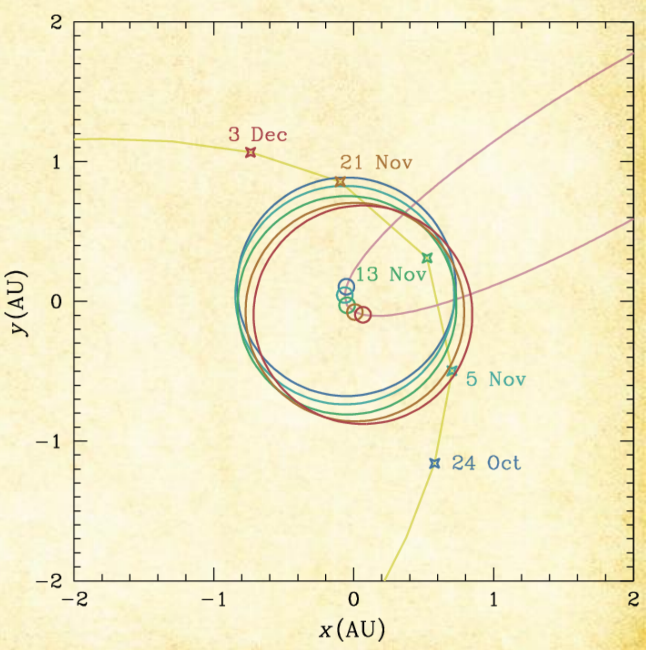
- X-ray activity because of interactions with the stellar wind already seen (Ho et al. 2017).
- Observations probe the Be star's gravity, magnetic field, the density of the wind flowing from the massive star and the structure of its disk.
- Important to understand the evolution of these systems as they are possible progenitors of double NSs which lead to NS-NS mergers!





Ho et al. 2017 & in prep.

Exploring the extremes of physics

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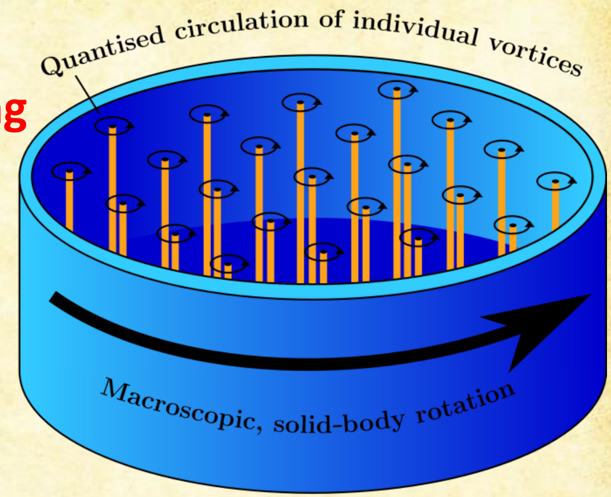
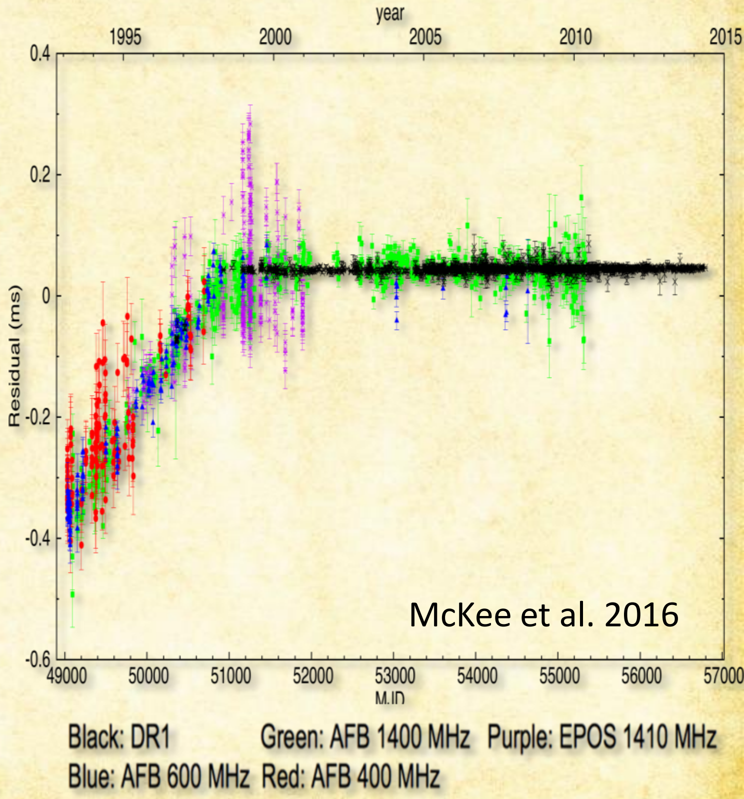


- Glitches: Coupling of superfluid circulation vortices in the neutron star interior with the crust result in discreet star spin-up events.
- Extremely rare in milli-second pulsars (MSPs): only one glitch detected before in a GC MSP.
- Lovell data in combination with Effelsberg and other European telescopes discovered a glitch in MSP J0613-0200.
- It is the smallest glitch ever detected:

  $$\Delta\nu/\nu = 2.5(1)\times10^{-12}$$

- Why so rare in MSPs – rate is ~0.2 glitches per century?
  - Do MSPs have a different stellar structure?
  - Is a different physical process involved?
- Accurate modelling of the glitch does not impact the timing precision for the detection of gravitational waves, but it takes longer to characterize them.



Exploring the extremes of physics

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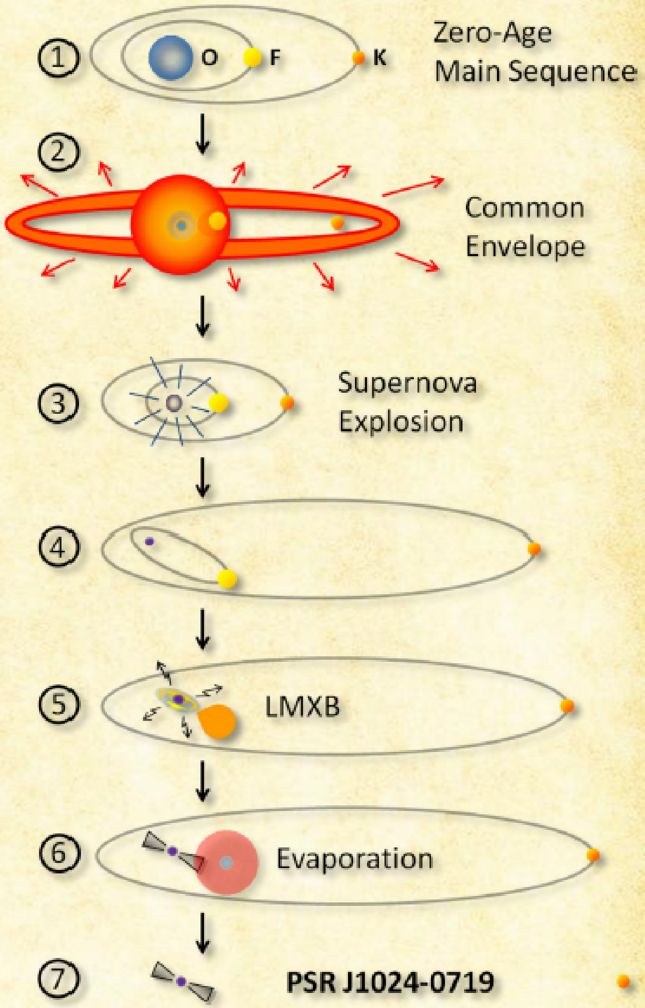
- 22 years of pulsar timing data of European telescopes discovered that MSP J1024-0719 is in an extremely wide orbit (> 200 years).
- Companion identified as a low metallicity K7V main-sequence star.
- Current main-sequence star cannot have recycled the MSP: exotic formation scenario required.
- Hypothesis: Hierarchical triple system → asymmetric SN explosion → evaporation of star responsible for the spin-up.
- Significant fine tuning required.



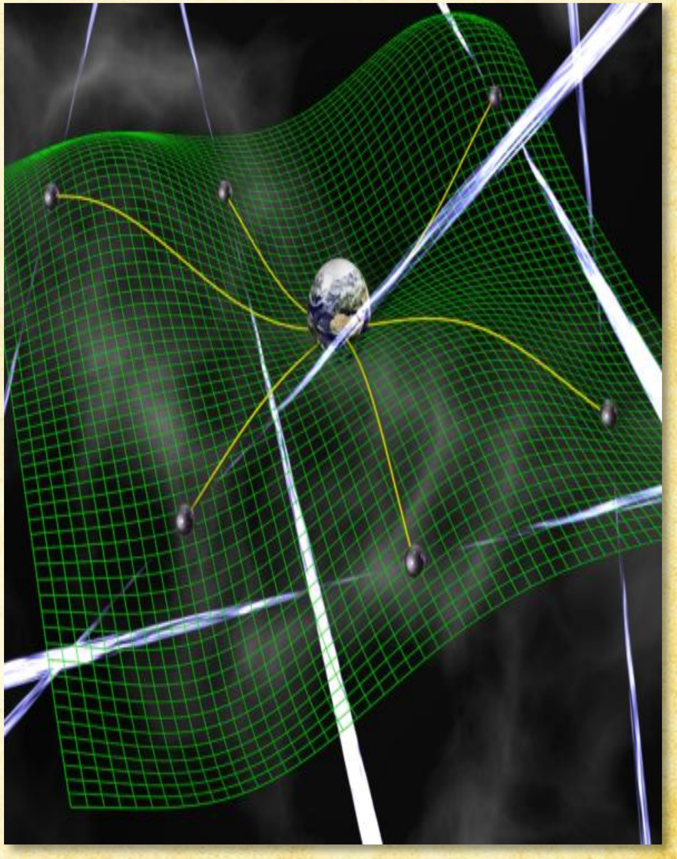
Bassa et al. 2017

Milli-second pulsars as ultra-precise clocks

Lovell telescope is the contributor of the largest number of pulsars the ***European & International Pulsar Timing Arrays***. It is a vital component of the ***Large European Array for Pulsars***, which combines the largest telescopes in Europe to make the world's largest steerable array for high precision pulsar timing.

The aims include:

- directly detect gravitational waves from supermassive black hole binaries, which is absolutely key to understand galaxy and structure formation in the Universe.



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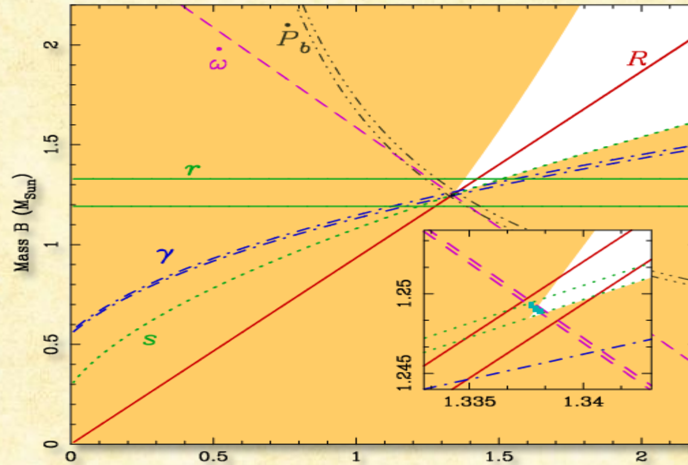
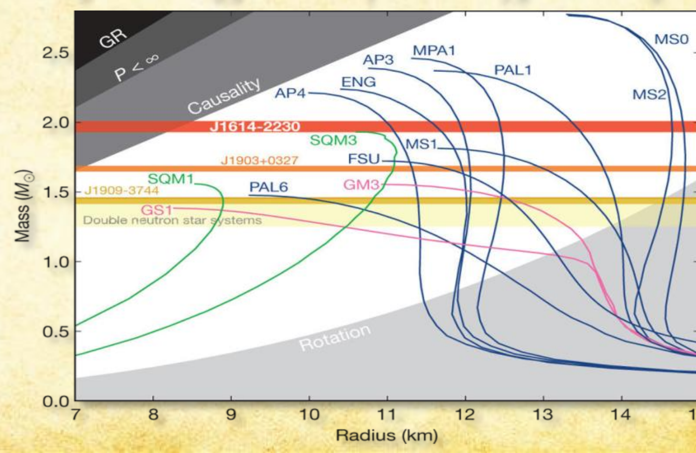
- Use post-Keplerian parameters of NS-NS and NS-WD binaries to test theories of gravity and the neutron star equation of state.
- For the Double pulsar: measure higher order light propagation effects, including a 'bending delay' as well as a relativistic deformation of the orbit never seen before.
- Lovell contributes vital high cadence data to the timing of even more relativistic systems that are still being discovered.





We have the opportunity now to enhance our science

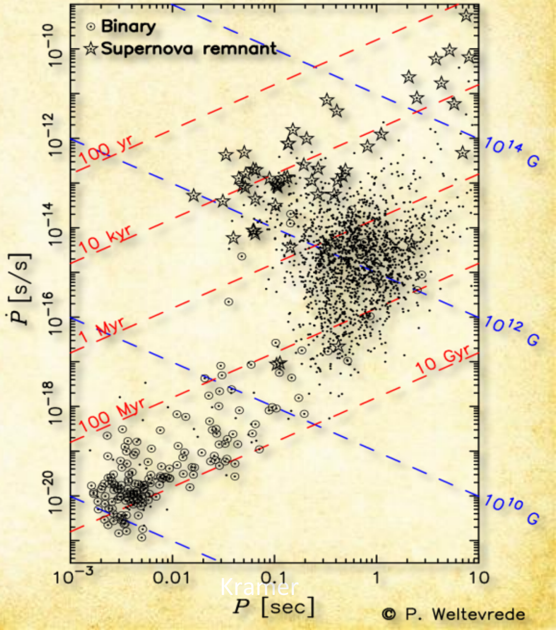
Improvement requires: Greater sensitivity, higher cadence, more sources, long time baselines – **combined e-Merlin & Lovell can give us all four!**

This would allow us to keep playing a vital role in extracting the physics from, and using, the new pulsars discovered with MeerKAT, FAST and also the SKA.

- combined Lovell and e-Merlin dishes:
  - Doubles the sensitivity for pulsar observations
  - Is equivalent to largest steerable telescopes in Northern Hemisphere
  - Increased sensitivity of the LEAP project, which can match Arecibo!
  - Significant improvement in contribution to Pulsar Timing Arrays (note detectability of many timing effects scales strongly with *t* and sensitivity)
  - We can improve the accuracy of cosmic clocks!

Questions we can Answer!

- What are the laws of physics in extreme conditions of gravity, density and magnetism?
- What is the velocity distribution of NSs and what does it mean for supernova physics and the total number of NSs in the Galaxy?
- What are the physical processes operating in the NS interior?
- Can we understand the NS zoo?
- How are millisecond pulsars formed?



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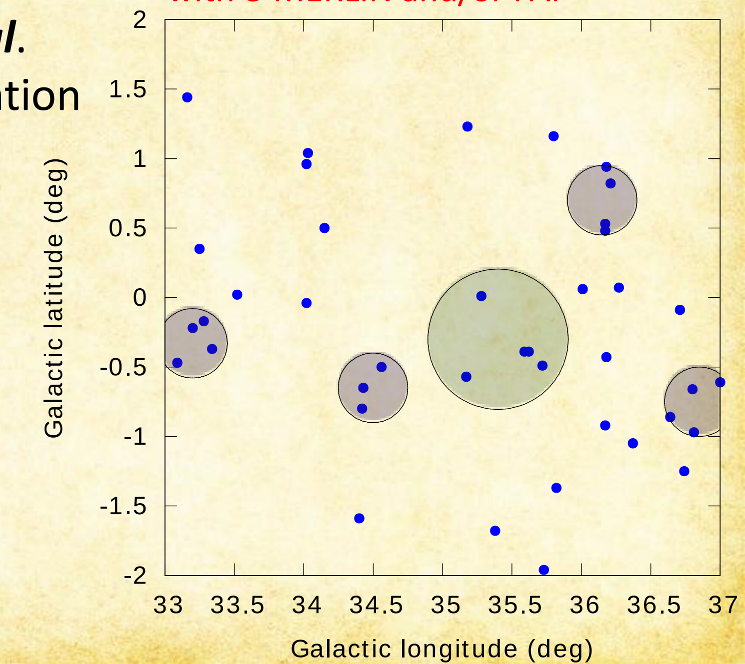
Adding a PAF and S-band system will really deliver the science!

The S-band system will give us exceptional timing precision while the PAF – uncooled and cooled will give us the wide field of view for improving the cadence and for a larger number of sources as the come in from the new facilities.

- Lovell does the timing of the majority of newly discovered pulsars (AO/Parkes/LOFAR) → ***essential to get the science***.
- SKA/FAST era > 20,000 known pulsars — how do we time them? ***An upgraded eMerlin telescope + PAF will be vital***.
- Observations at S-band dramatically reduce contamination from interstellar dispersion and scattering.
- S-band will become the optimal observing frequency for the majority of the pulsars used in the GW experiment.
- Combined with the sensitivity boost from the increased bandwidth this will be a step change in the contribution to precision pulsar timing.

Simultaneous multi-pulsar observing with e-MERLIN and/or PAF

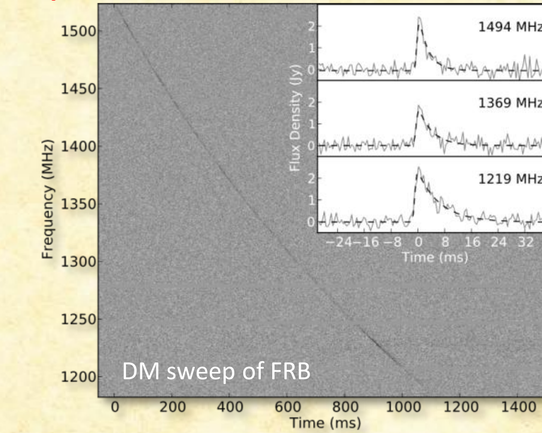


Fast Radio Transients

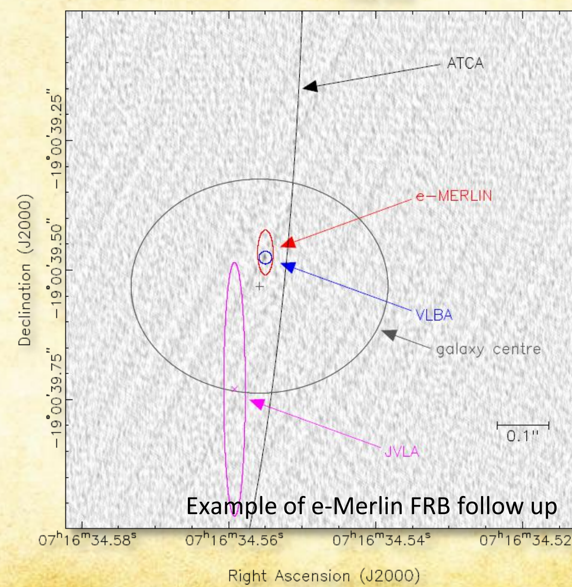
Fast radio transients is a rapidly growing field and crucially requires more detections, accurate localisations and detailed follow up – **We can achieve all three!**

This is possible through the increased sensitivity – combined telescopes
wider field of view -- use of smaller dishes & PAF(s)
and long baselines. -- inclusion of all array telescopes

- What is the origin and physics of the short duration extragalactic bursts (FRBs) of radio emission?
- What fraction of the missing baryons are in the IGM? How strong are the magnetic fields in the IGM?
- What are the prompt emission, afterglow and host galaxy properties of FRBs?
- Are FRBs standard candles? Can we use them to constrain the dark energy equation of state?
- Is there prompt radio emission associated with gravitational wave events?

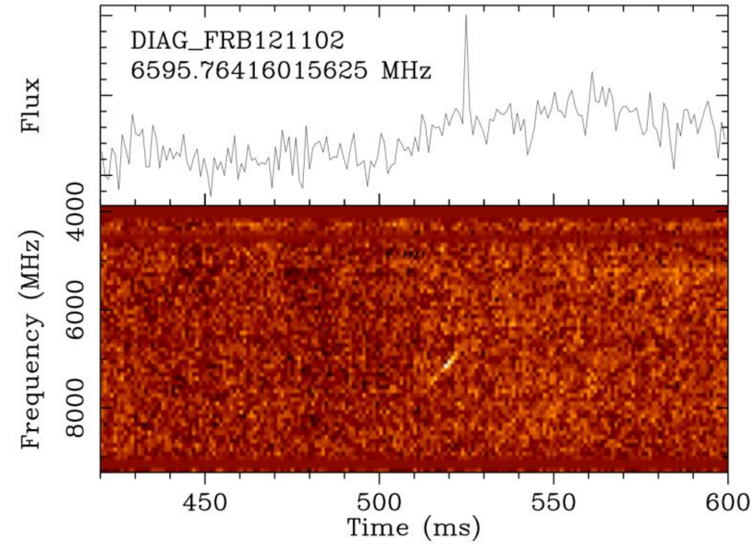


Thornton et al 2013



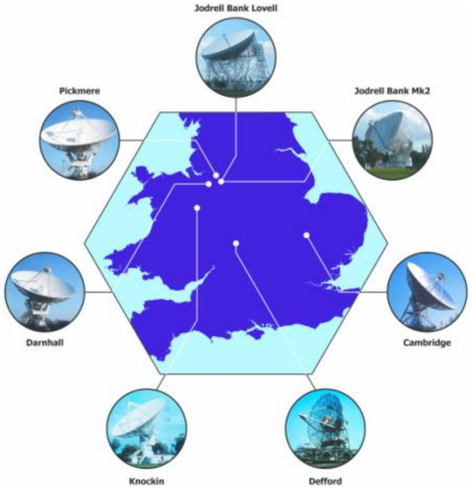
Bassa et al 2016

Transients & Lovell / e-Merlin



Breakthrough Listen (GBT) detection of repeating FRB:

- FRBs: ~10,000 sky/day! — but still only ~30 known.
- Unknown origin, localisation (PAF would be good for this) is essential to understanding what they are and for their use as cosmological probes!
- Current Lovell searches are piggyback on pulsar timing observations, but we really need a lager field of view
- e-MERLIN already being used for accurate localisation
- Large bandwidth is very beneficial (spectrum is variable and relatively flat)



LOFT-e *(Localisation Of Fast Transients with e-Merlin)*

- New project

- GPU/CPU software backend
- Real-time searching
- Buffering technology to enable raw data collection
- Interferometric localisation

Localisation of Fast Transients with e-MERLIN

- Poor FRB localisation hinders potential scientific yield
- LOFT-e will **commensally search for FRBs** in real-time
- Upon burst detection, store raw data for **sub-arcsecond localisation**
- Can also be used for analysis of **RRATs, giant pulses and other transients**.

L-band specifications:

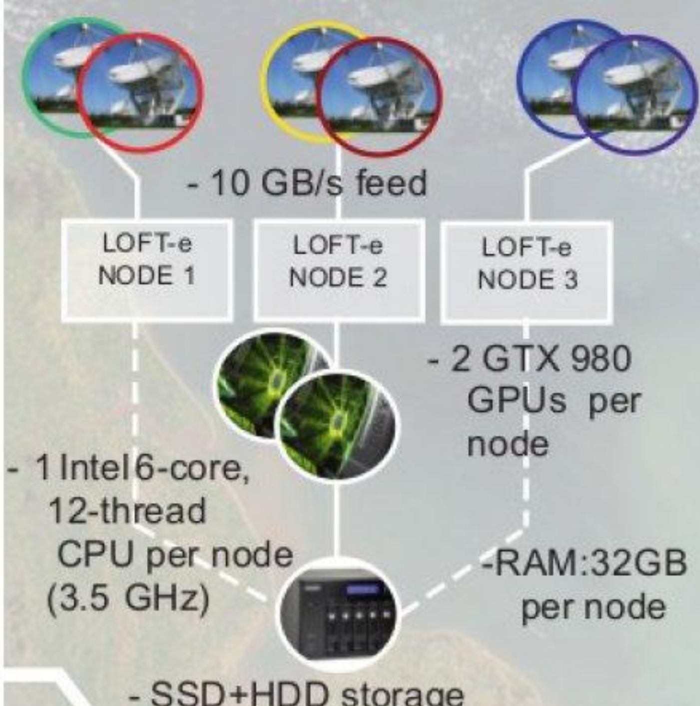
- **FOV:** 30' (25 m dishes)
- **Max angular resolution:** 150 mas
- **Max bandwidth:** 512 MHz

Our expectations:

~**1690 hrs** in L band per year from 220 days on sky (40:40:20 L:C:K band ratio)

~ **1 FRB per 400 hrs** based on 7,000 - 10,000 FRBs sky^{-1} day^{-1}

LOFT-e CONFIGURATION



LOFT-e STATUS

Completed work:

- **Commissioning** new correlator mode to record raw baseband data

Current efforts:

- **Recovering bright pulsars** at L-band and C-band
- **Observing single/giant pulses** e.g. B0329+54 to test single-pulse search and **anticoincidence** techniques
- Automating pipeline
- Investigating RFI environment

Next steps:

- **RFI-mitigation** techniques e.g. **MAD** may need implementation

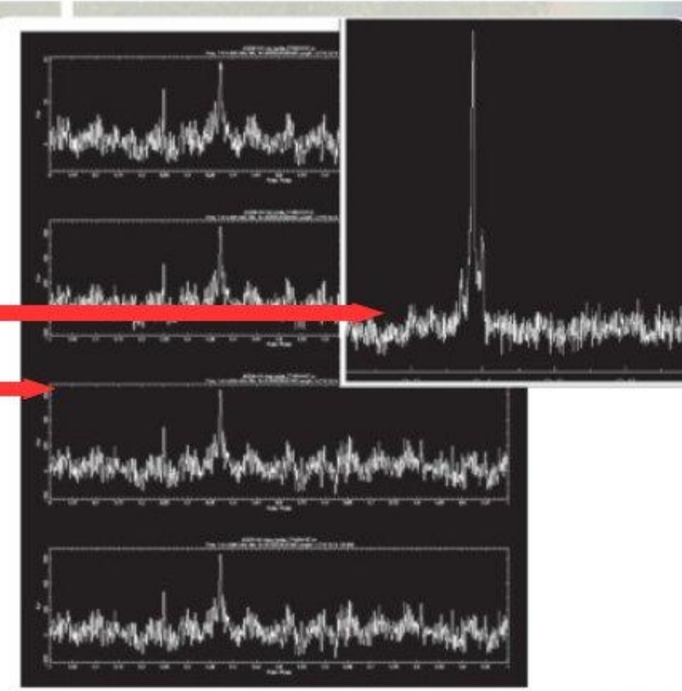
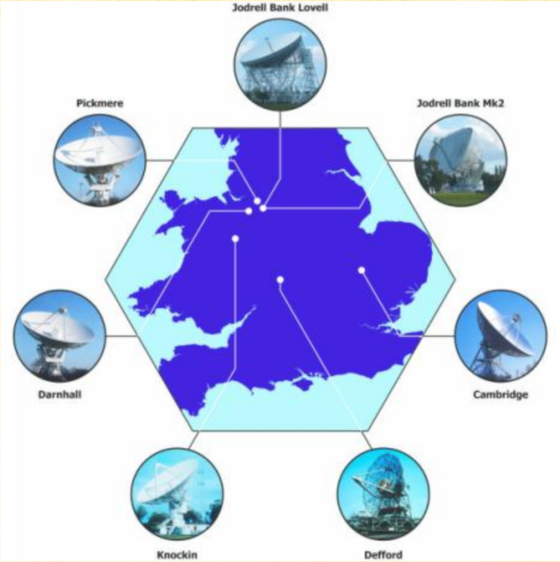


Figure 2: PSR B0329+54 single pulse as observed by four e-MERLIN antennae, centered at 1414 MHz over 64MHz bandwidth. ***Inset:*** Folded pulse-profile of 0329+54 formed from incoherent combination of antennae.

Conclusions



- There are many opportunities to make an e-Merlin upgrade successful, and pulsar/transient science will play a vital role.
- Jodrell Bank is a major part of (international & UK based) projects including high-energy and gravitational wave detectors.