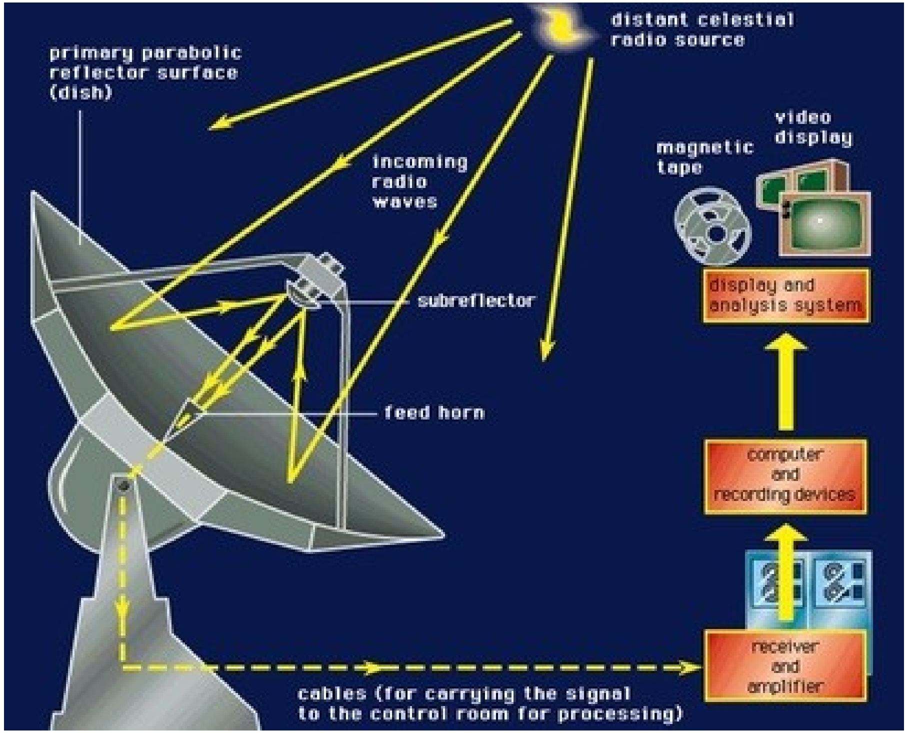
Pulsars with MeerKAT

Sarah Buchner
Commissioning scientist SARAO

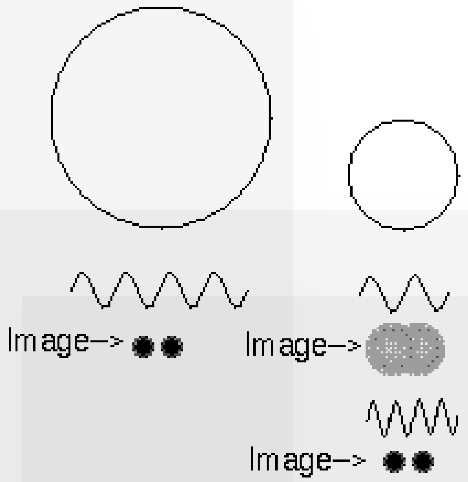
Outline

- 1 MeerKAT
- 2 Pulsars
- 3 Pulsars on MeerKAT
- 4 Meertime
- 5 Early results

Radio telescopes



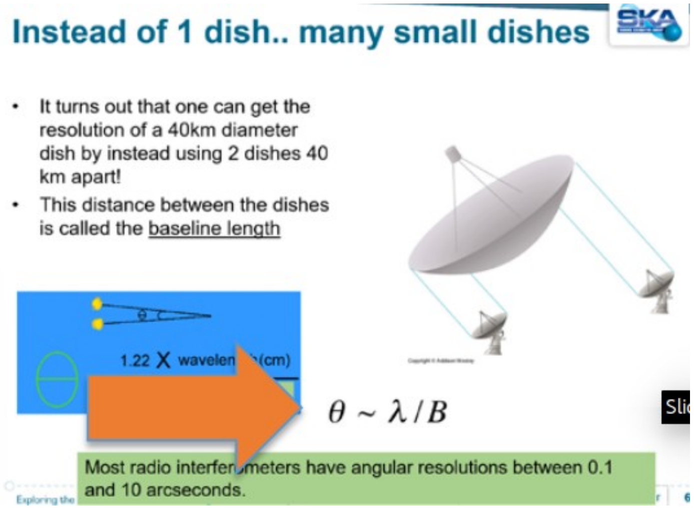
Increasing resolution

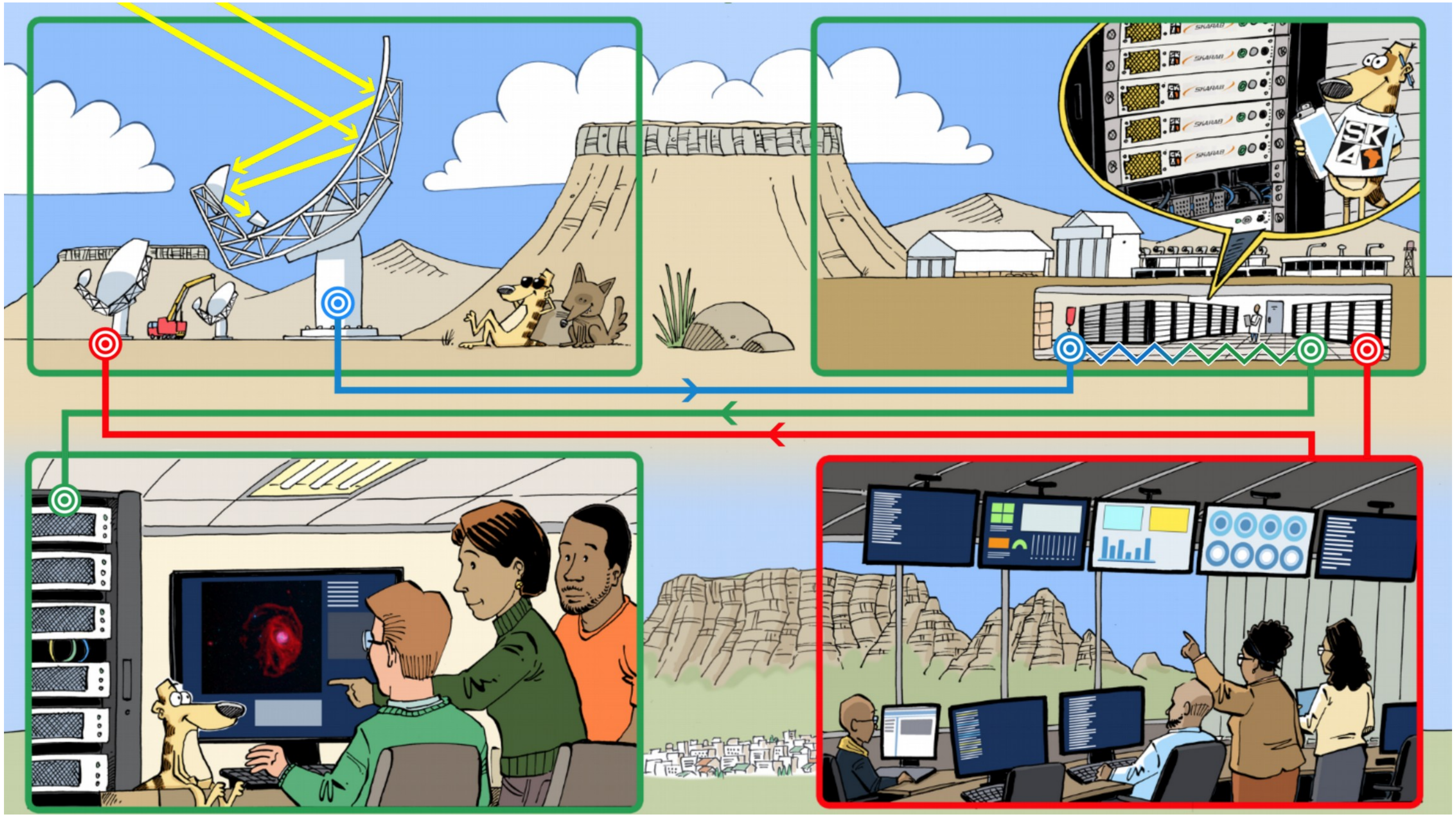


Bigger objective samples more of the light: sharper images! Depends on **diameter** of objective and **wavelength**: $\theta_R \sim (\lambda/D)$.

Make **diameter** *bigger* or **wavelength** *smaller* for sharper images.

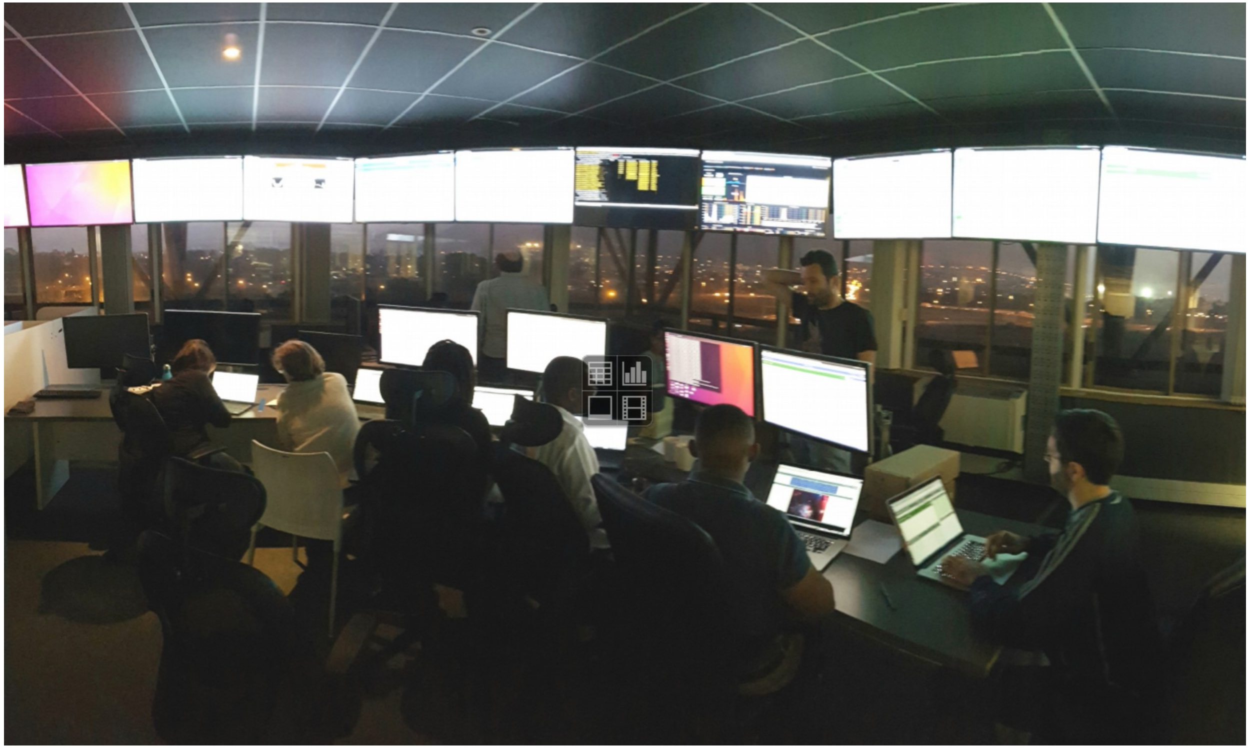
Images for same two stars are shown.





SARAO

Night before Easter weekend 2018

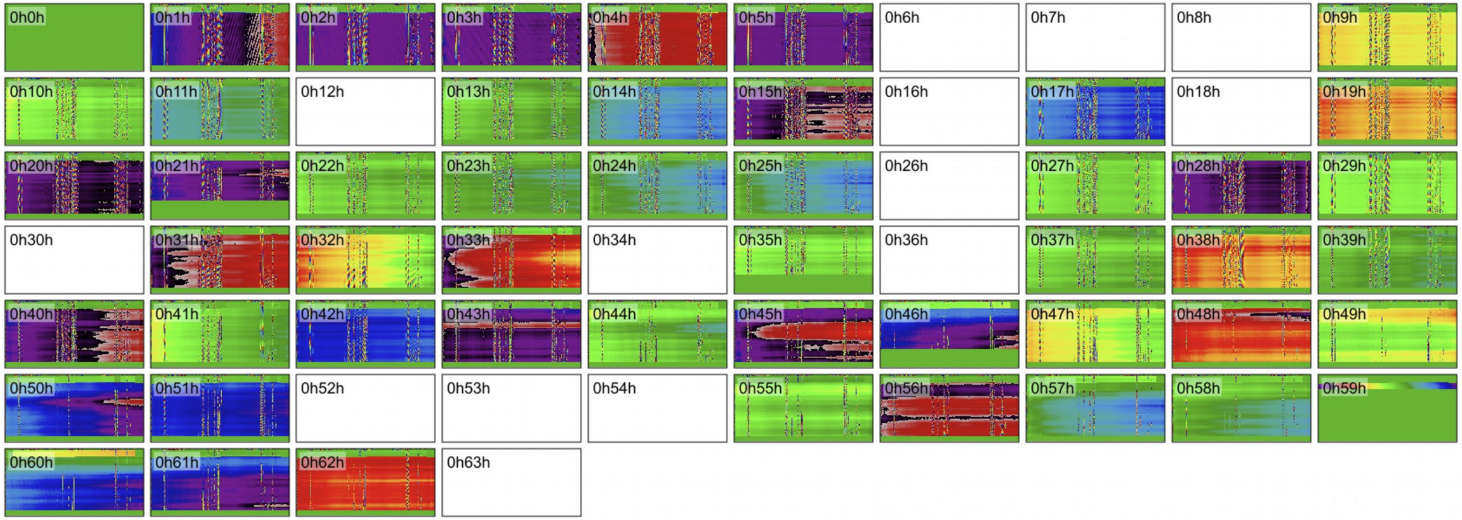


Galactic centre observations

Inauguration 13 July 2018

Beamformer

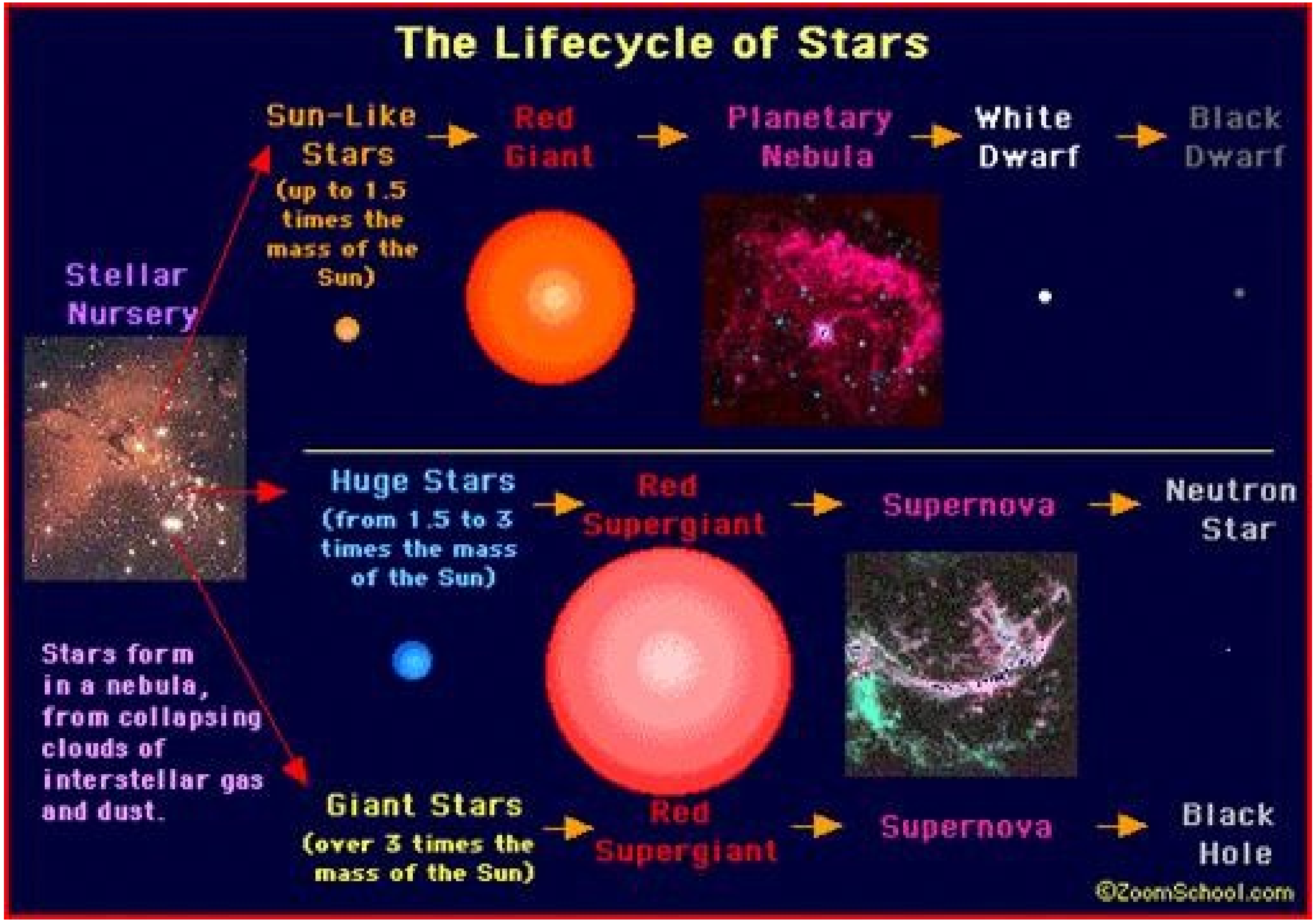
- Phase up on calibrator source
- Add antennas in phase to form a beam
- Record stream of data for each polarisation, frequency
- Pulsar timing has 1024 channels across 856 MHz



2: Pulsars

- What is a pulsar?
- Discovery of pulsars
- Why observe pulsars

Lifecycle of stars



White dwarf

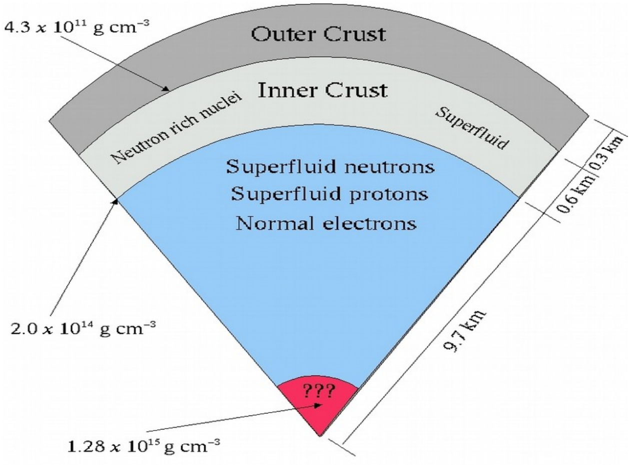
- White dwarf
  - Collapse halted by electron degeneracy pressure
    - Two electrons can’t occuy the same energy state (Pauli exclusion principle)
    - Maximum size given by Chandrasekhar limit 1.44 solar masses
    - A one solar mass white dwarf is about the size of earth

Neutron Star

- Neutron degeneracy
  - No two neutrons (fermions) can occupy identical state
  - This pressure prevents gravitation collapse for masses up to 2-3 solar masses.
    - Then form a black hole

Neutron Stars

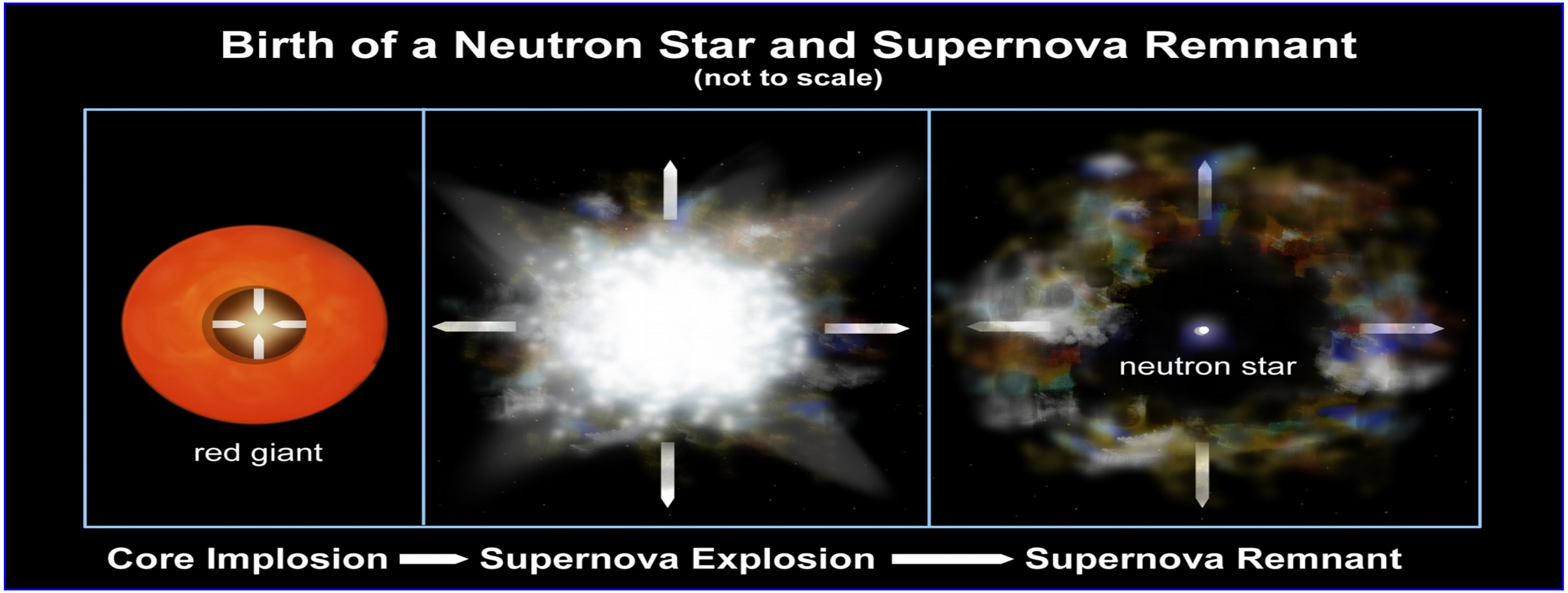
- The surface is crystalline iron, interior a neutron superfluid
- Magnetic field a billions times higher than anything on earth
- Surface rotation close to speed of light
- Ideal for studying extreme forms of matter



Neutron Star Pizza

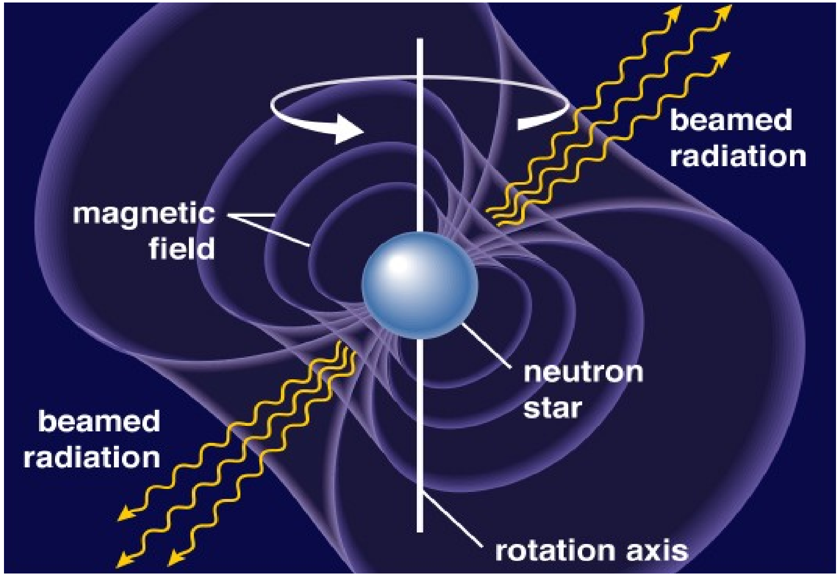
Neutron Stars

- Are the leftover cores from supernova explosions
- Almost black holes
- Very dense (1E17 kg / m3)
- 1.5 solar masses with a diameter of 10 to 20 km
- Mass 1E27 tons
- They rotate very rapidly: Period = 1.3 ms to 4 sec
- In the formation of neutron star – star collapses from 106 km → 10 km. Magnetic flux conserved so B increases → strong magnetic fields
- A teaspoon of neutron star material has the same mass as the population of the earth
- The work done in climbing a 1 cm high mountain = work done in climbing Everest
- If you drop a coin on the surface of a pulsar it will hit the surface at 0.6 c
-

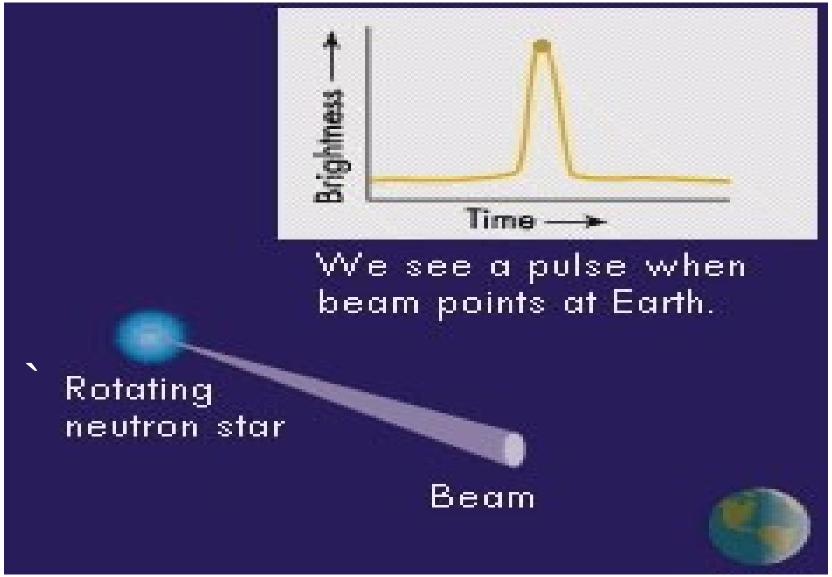


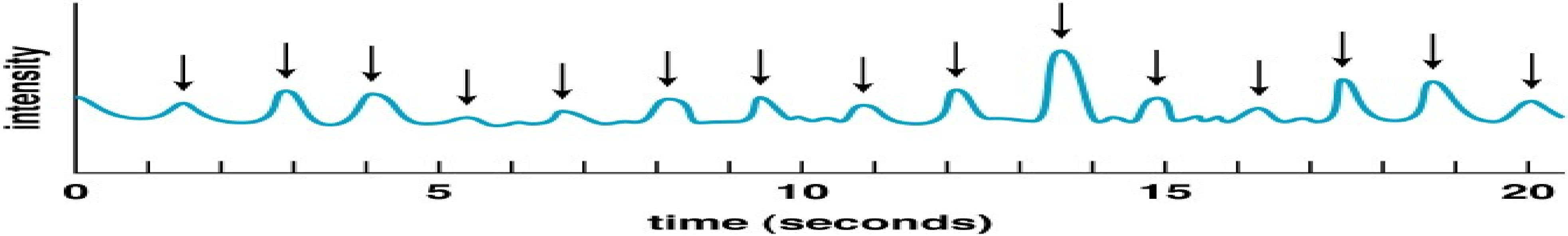
Birth of a Neutron Star and Supernova Remnant
(not to scale)
red giant
neutron star
Core Implosion
Supernova Explosion
Supernova Remnant

Pulsars



beamed radiation
magnetic field
neutron star
beamed radiation
rotation axis


Brightness
Time
We see a pulse when beam points at Earth.
Rotating neutron star
Beam


intensity
0
5
10
15
20
time (seconds)

Optical Pulsar

wavelength

Lucky Imaging

Cambridge University

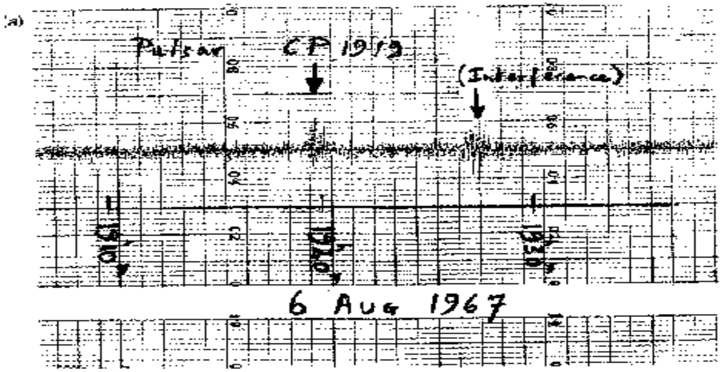
Discovery of Pulsars

Pulsars discovered in 1967 by PhD student Jocelyn Bell during a low frequency survery of scintillating extragalactic radio sources.

Pulsations at P=1.337s

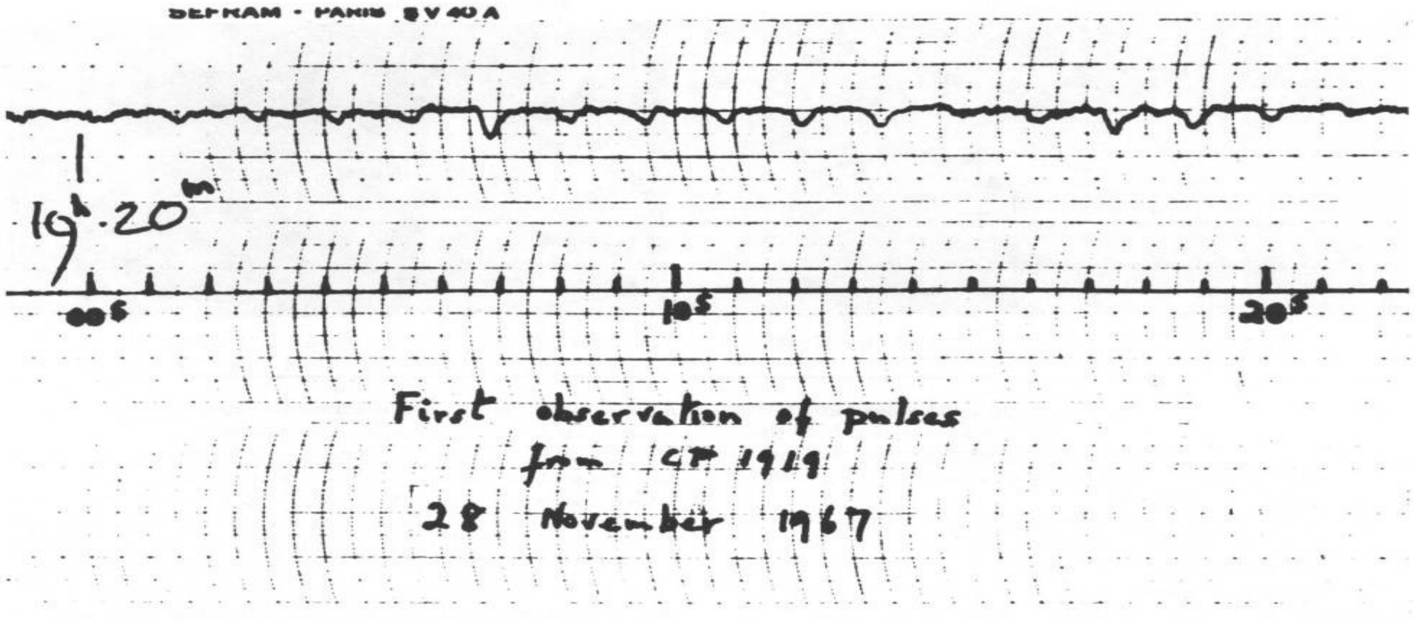
Source rises and sets sidereally (not local)

http://www.bigear.org/vol1no1/burnell.htm



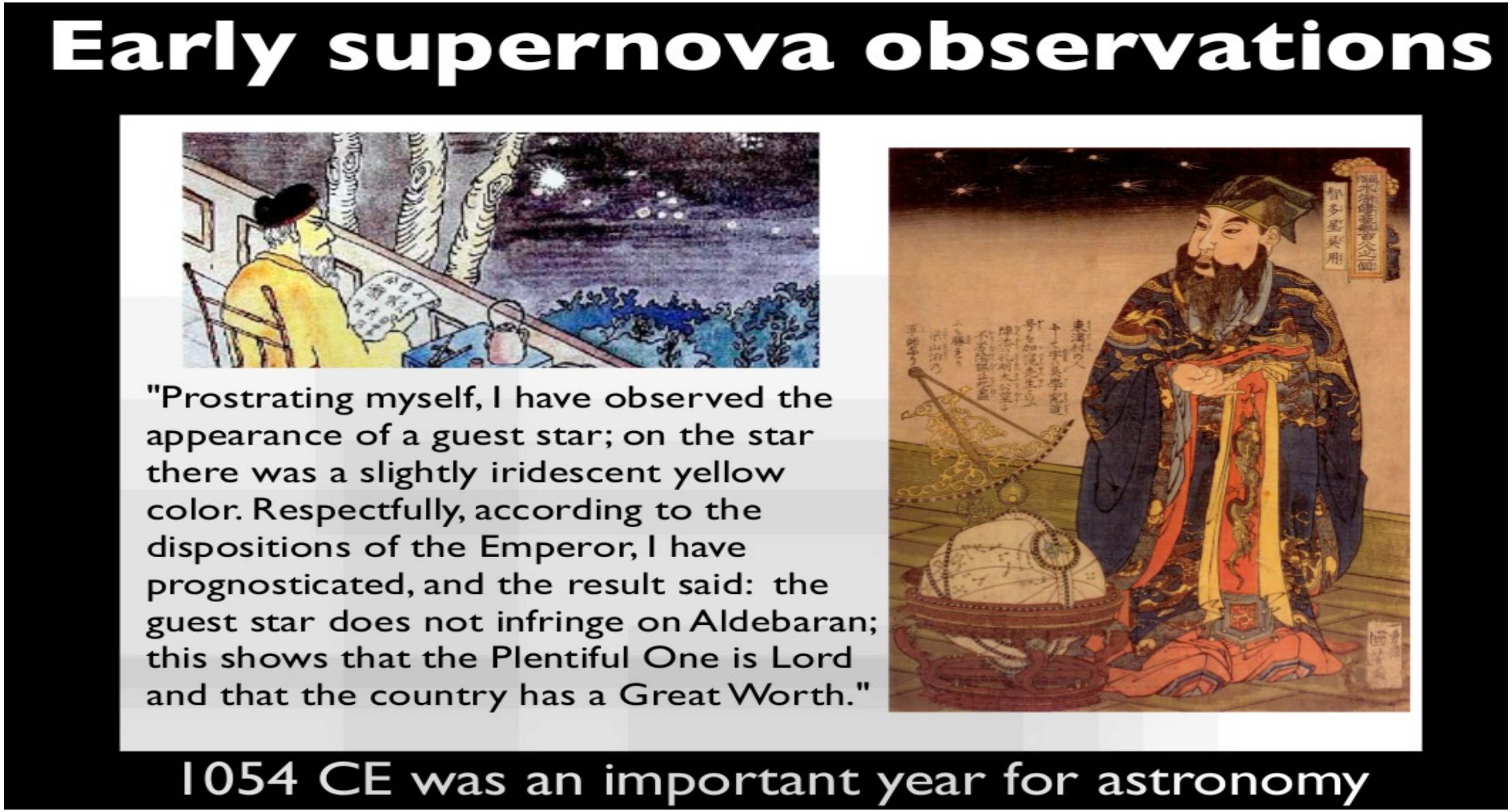
"The charts were analyzed by hand—by me."
Burnell and charts.

First observation of pulses

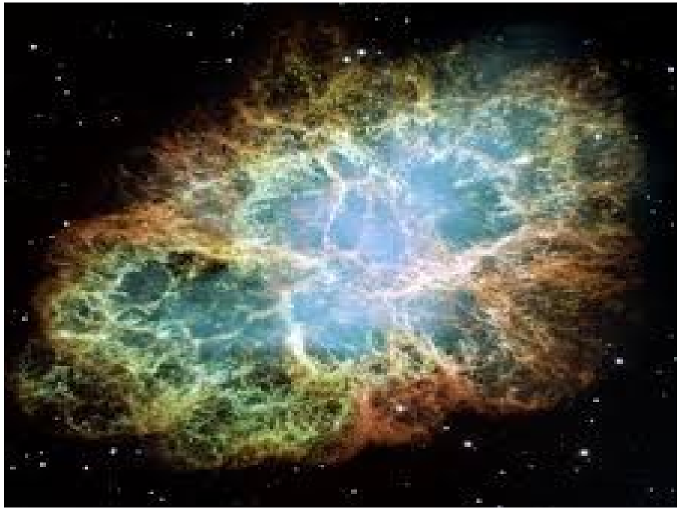


"I got it on a fast recording. As the chart flowed under the pen I could see that the signal was a series of pulses . . . 1⅓ seconds apart." (Deflections are down).

Crab supernova 1054



Crab pulsar



Guest star seen by the Chinese in 1054

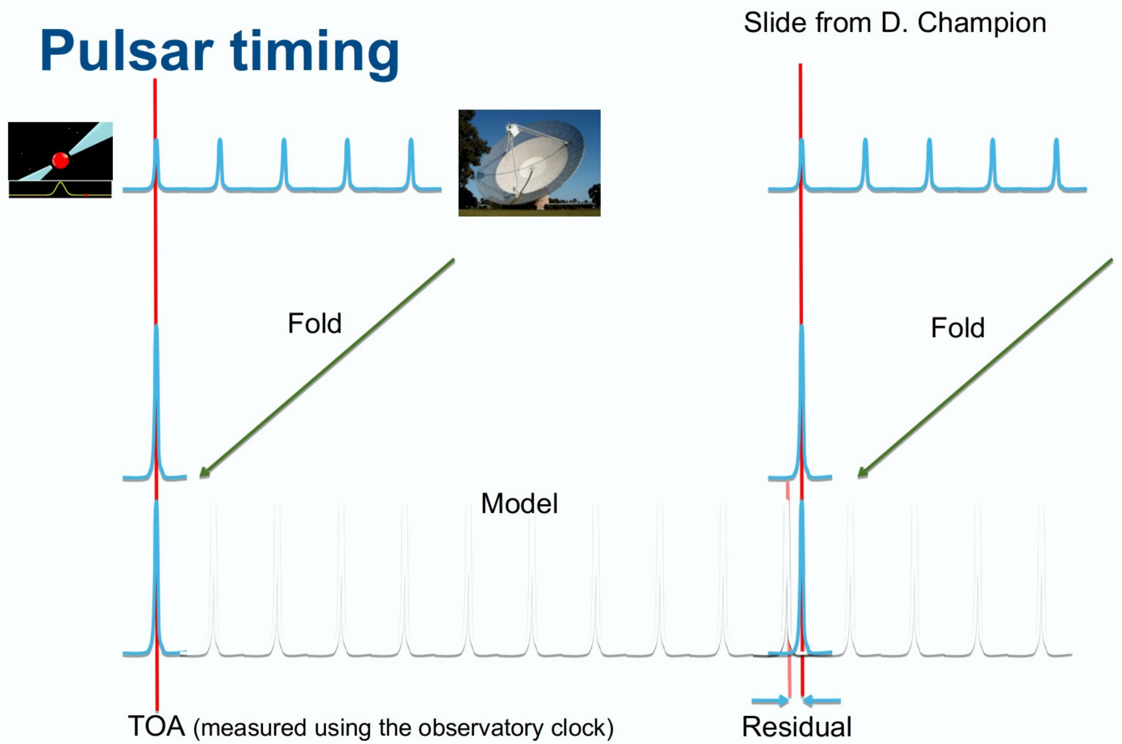
P = 0.033 s

When the crab pulsar was discovered (P = 0.033 s) its period implied a density too high for white dwarfs.

The pulse width is ~ 1 ms. This implies something a few hundred kilometres in size. Much smaller than white dwarf

It confirmed the Baade and Zwicky hypothesis that neutron stars were the remains of supernova remnants

Timing pulsars



Pulsars – cosmic clocks

- Massive stable flywheels - superb cosmic clocks

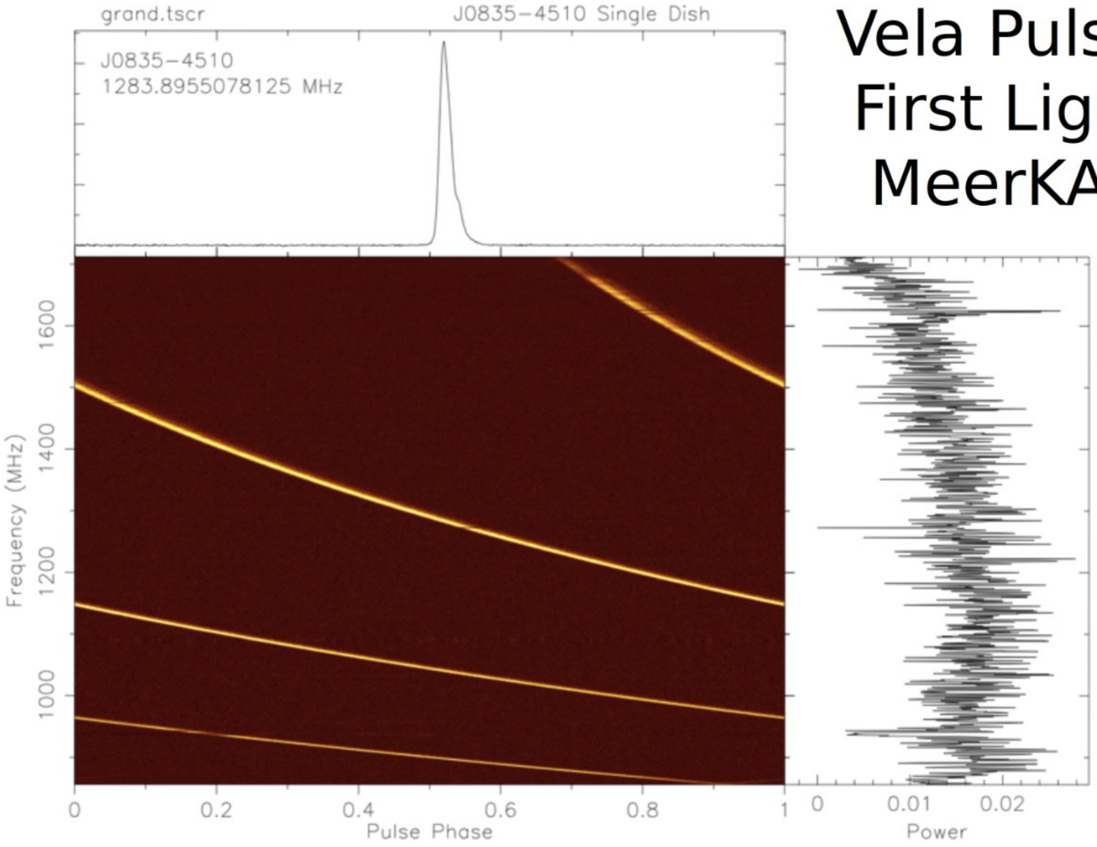
e.g. Vela:

$$\nu = 11.191072051817 \pm 0.000000000091 \, \mathrm{Hz}$$

$$\dot{\nu} = -156.20475(6) \times 10^{-13} \, \mathrm{Hz.s^{-1}}$$

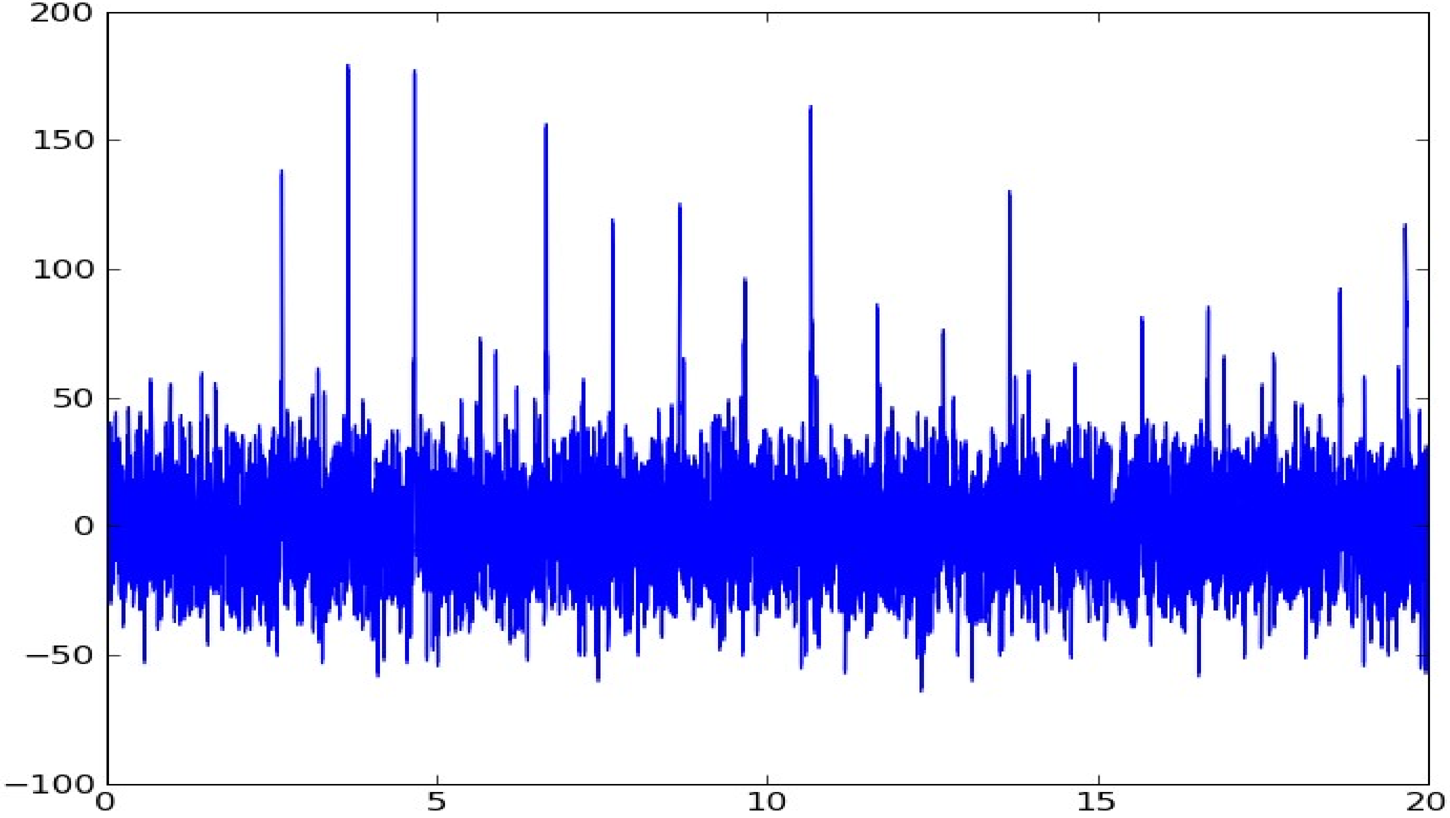
Unambiguously number each pulse

First light Vela Pulsar

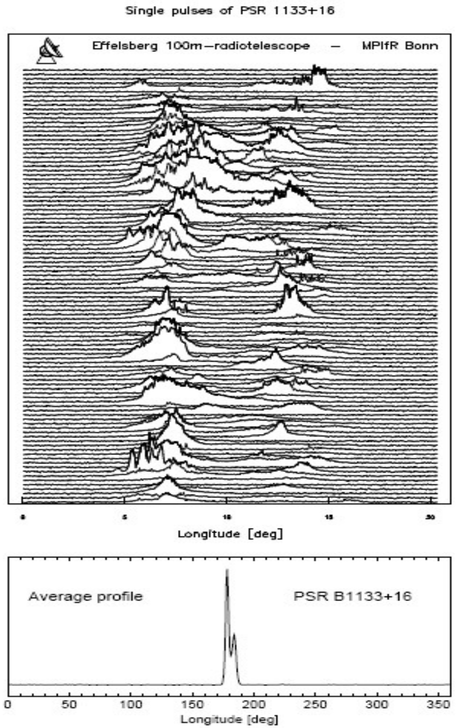


Vela Pulsar
First Light
MeerKAT

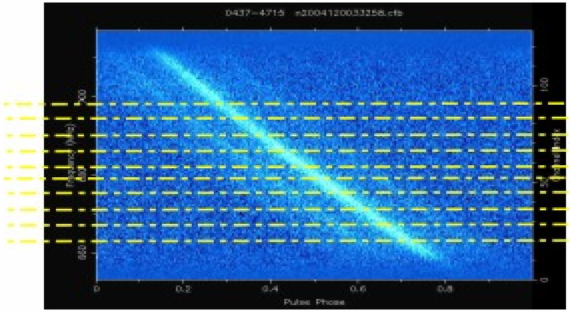
Actual pulse train



Integrate many pulses



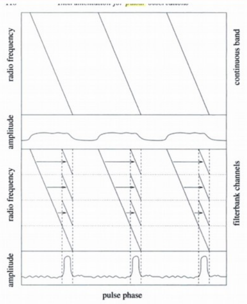
Incoherent dedispersion



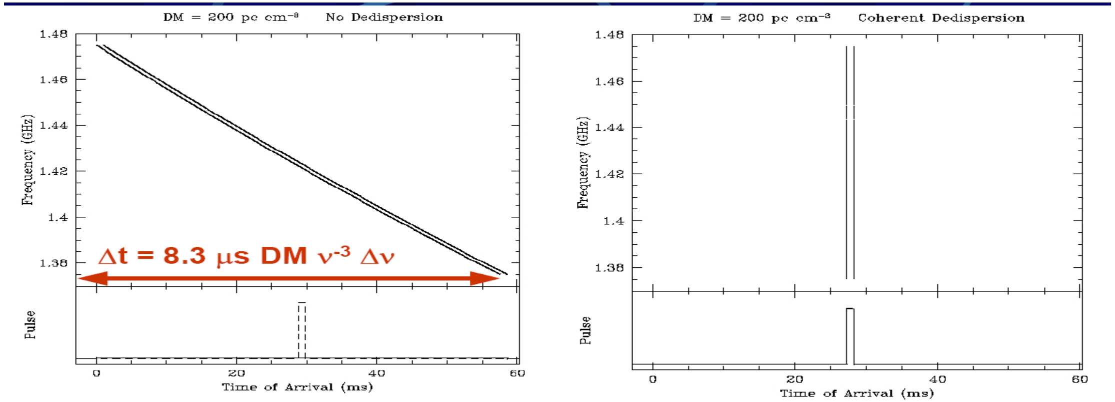
Incoherent dedispersion

The effect of dispersion can be removed by splitting the bandwidth i into a number of channels.

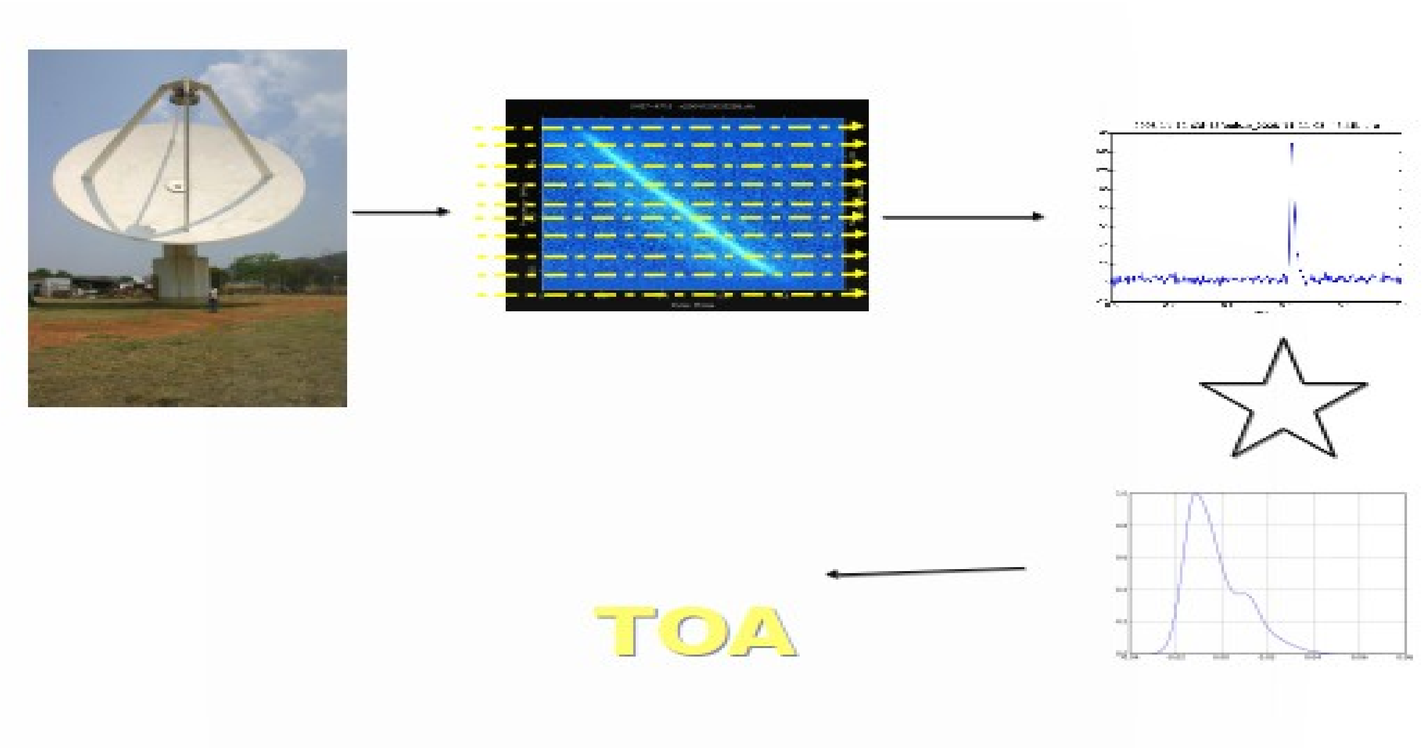
Each channel can be the corrected f dispersion. This process is known a incoherent dedispersion



From Lorimer and Kramer



Observing Pulsar



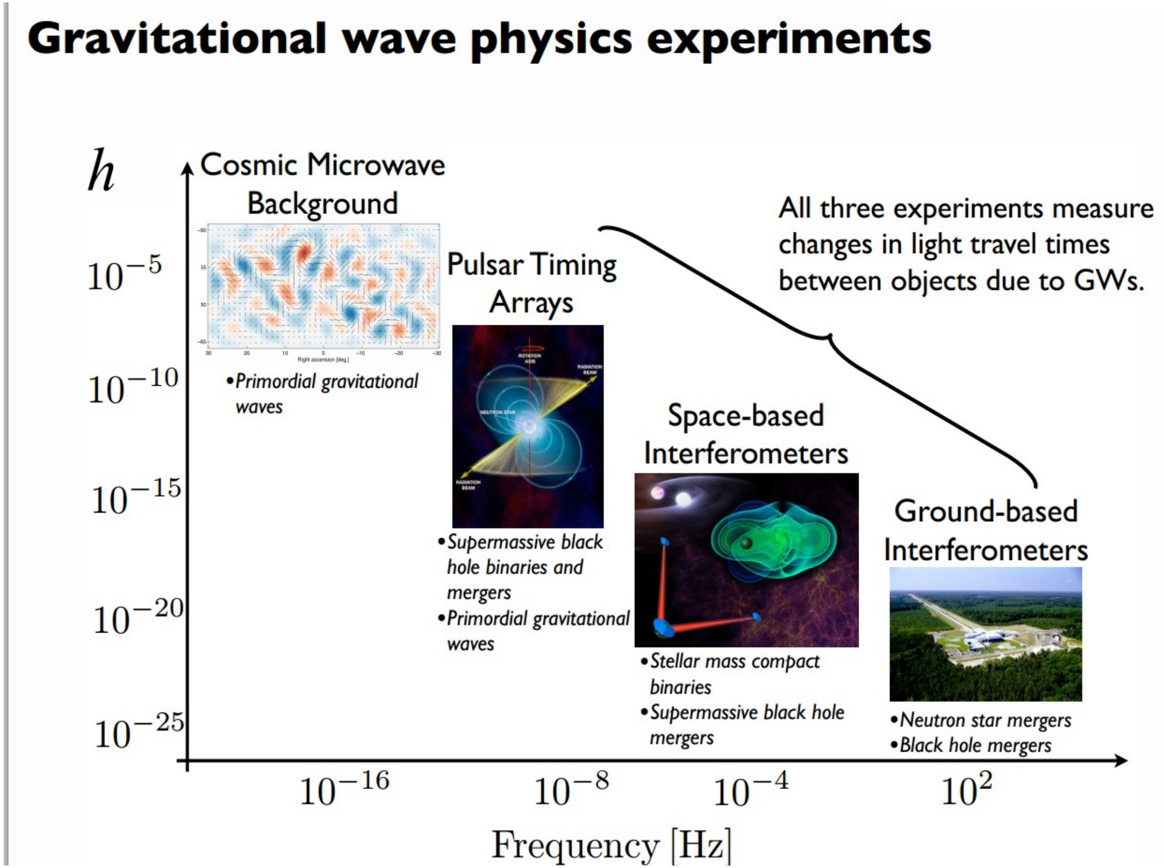
Meertime

- Four themes within MeerTime
  - Relativistic and Binary pulsars
  - Millisecond Pulsar Timing and Gravitational Wave Detection
  - Globular Cluster Pulsar Timing
  - The 1000 Pulsar Timing Array

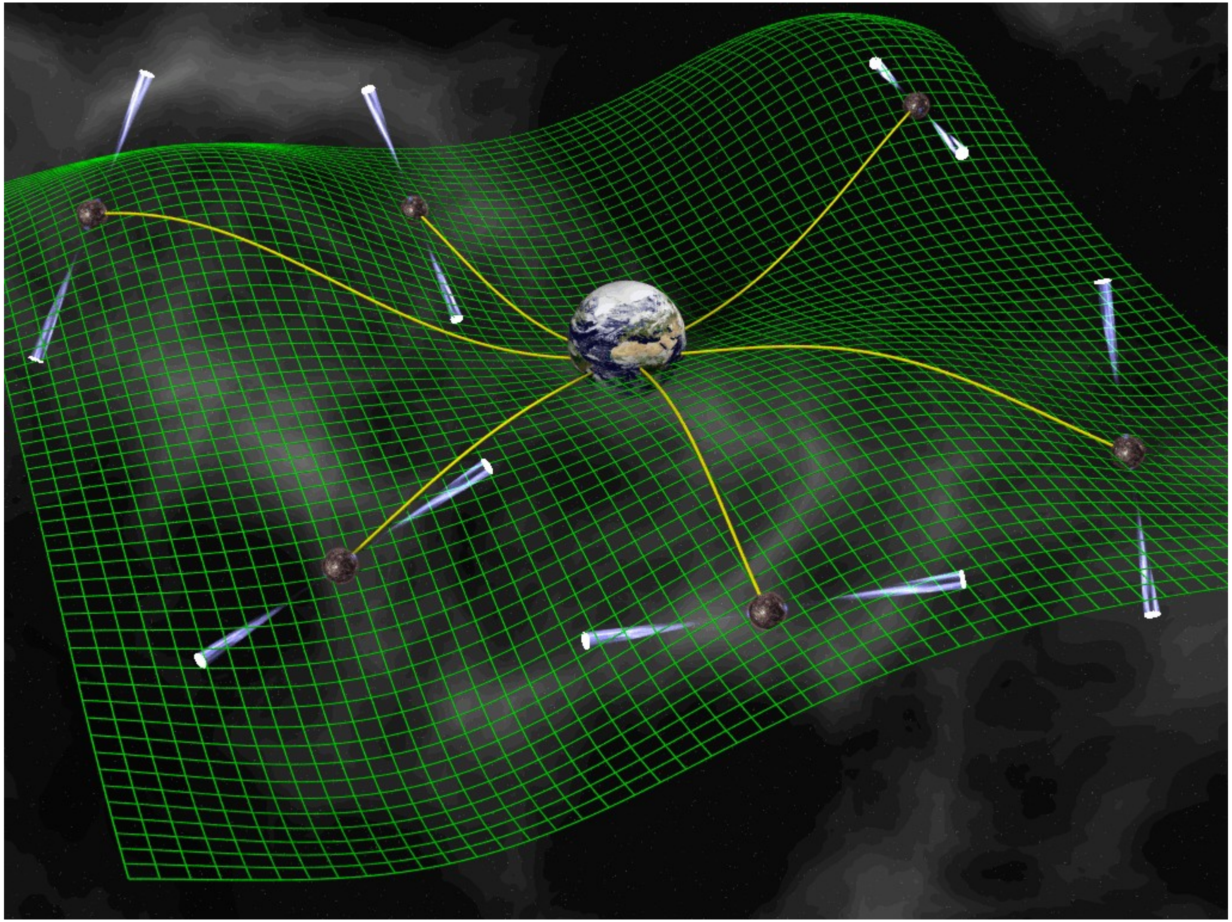
Relativistic and Binary Pulsars

- Pulsars are amazing laboratories for studying gravity.
  - In the strong gravity around a neutron star or black hole we can test Einstein's theory of gravitation (GR).

MSP timing and gravitational wave detection



Pulsar timing array

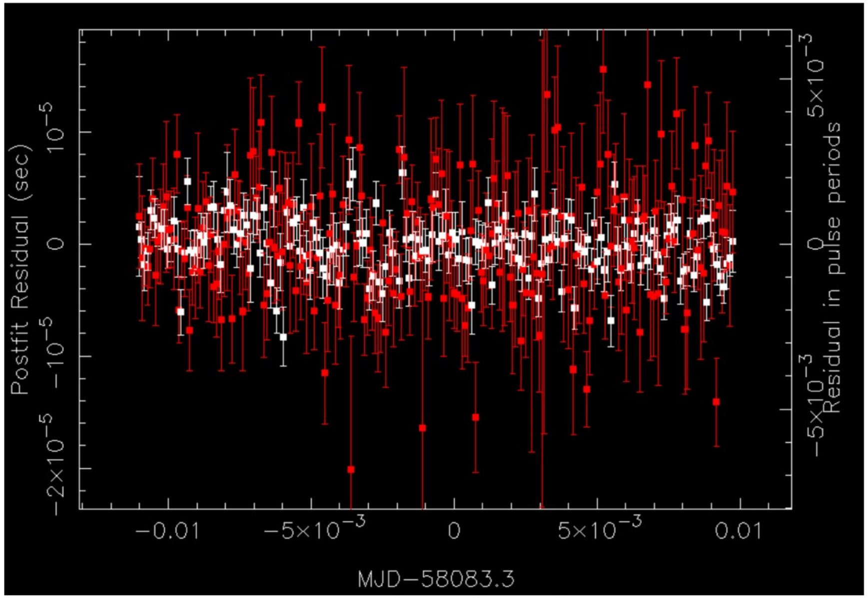


1000 pulsar array

- Observe 1000 pulsars across the sky

Comparing timing

Red = PKS_MB (340 MHz)
White = MeerKAT16 (850 MHz)



Early Meertime Science

- There have been 11 Meertime runs
- First on 12 Feb 2019, most recent on 20 May
- Still some teething issues but initial results are looking promising

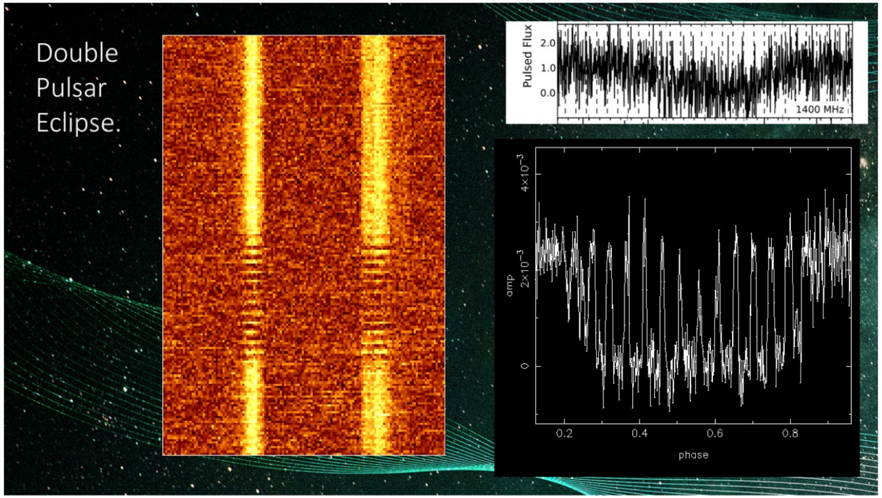
Double Pulsar Eclipse

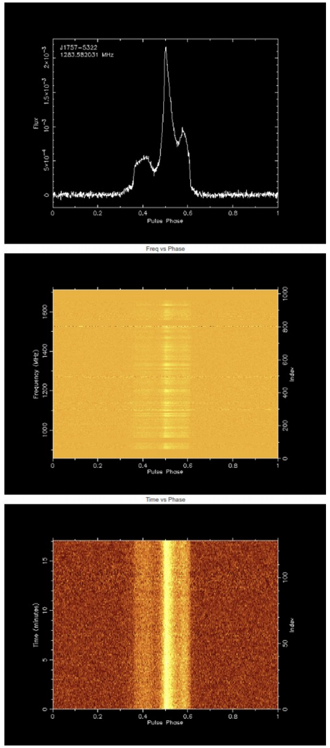
Dear Rob, Bernie, Justin and Fernando. (CC Thomas)

My colleagues and I have been working with SARAO staff to commission the pulsar processor for MeerKAT for many years now. In the last few weeks we've been given our first ~24h of telescope time and on Wednesday we received our first data on the celebrated double pulsar with high time resolution data.

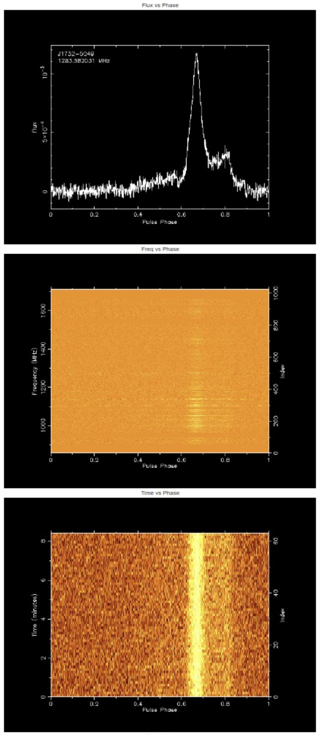
Once every 2.4 hours this pulsar goes behind the magnetosphere of the companion pulsar as it is a very edge on orbit. The plot below shows the pulse profile of the "A pulsar" as a function of time in the MeerKAT band (it has a double-peaked profile).

Remarkably, MeerKAT shows hitherto unseen detail of these eclipses. The A pulsar gets eclipsed by the rotating magnetosphere of the B pulsar which rotates every 2.7 seconds. So once every 2.7s the pulsar comes and goes, which will teach us about the opacity of a pulsar magnetosphere. The plot on the bottom right is the flux of the pulsar as a function of time. The plot on the upper right is from the GBT, showing the improvement MK provides!



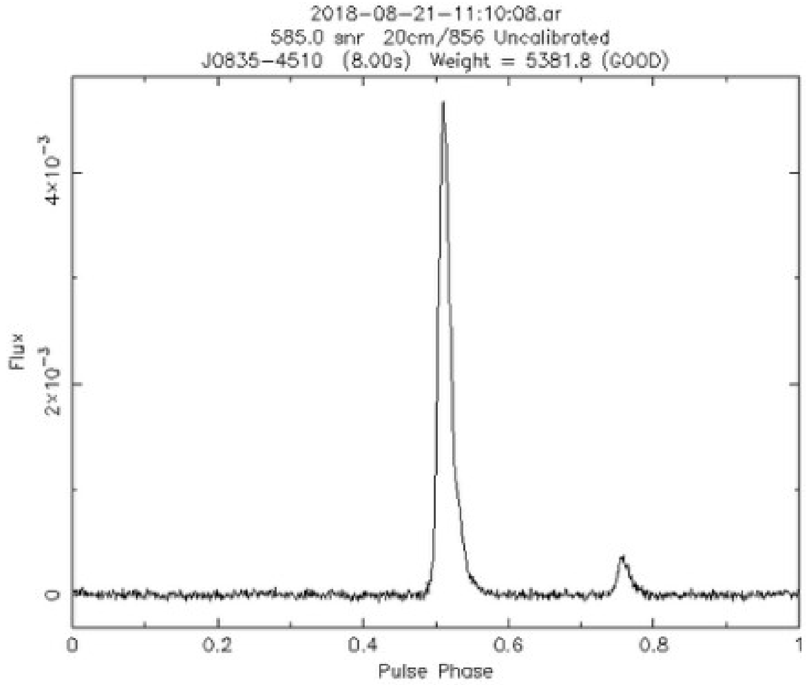


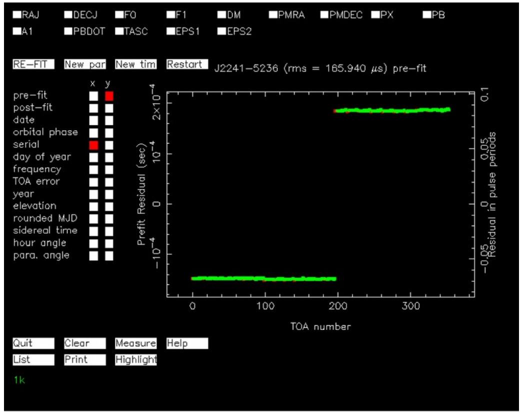
J1757−5322
1283.582031 MHz
Flux
Pulse Phase
Freq vs Phase
Frequency (MHz)
Index
Time vs Phase
Time (minutes)

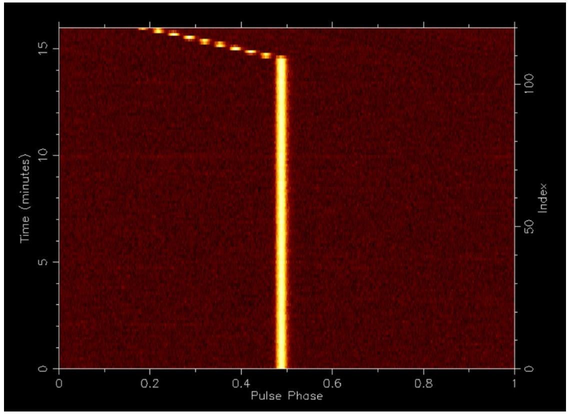


Flux vs Phase
J1732−5049
1283.582031 MHz
Flux
Pulse Phase
Freq vs Phase
Frequency (MHz)
Index
Time vs Phase
Time (minutes)

Issues


2018-08-21-11:10:08.ar
585.0 snr 20cm/856 Uncalibrated
J0835-4510 (8.00s) Weight = 5381.8 (GOOD)
Flux
Pulse Phase


J2241-5236 (rms = 165.940 μs) pre-fit
Prefit Residual (sec)
Residual in pulse periods
TOA number


Time (minutes)
Index
Pulse Phase

Matthew Bailes In theory, one minute of MeerKAT should achieve the same S/N ratio as about an hour of PKS with the multibeam receiver. These observations appear to confirm that relation which is very good news. SNR/minute for PKS is 12/sqrt(50) = 1.6. MeerKAT = 13. Ratio is 8.

1

Like · Reply · 8h

George Hobbs what is your Tsys and gain assumption?

Like · Reply · 7h

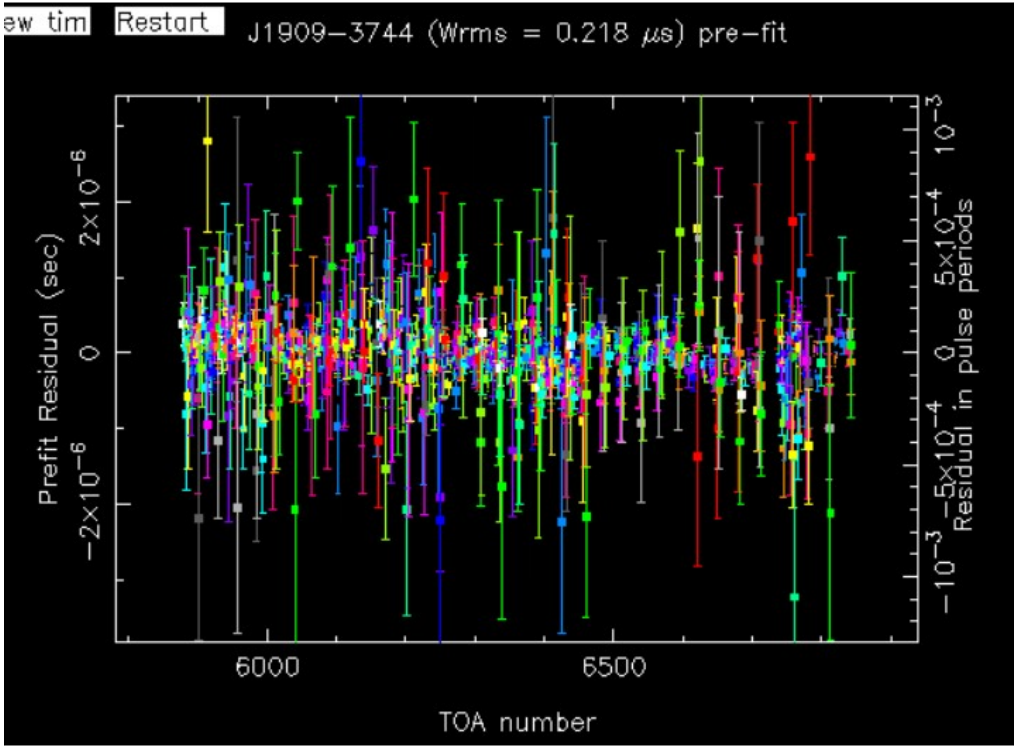
Froney Crawford The LMC awaits!

Like · Reply · 4h

Matthew Bailes George Hobbs Gain 2.8 K/Jy, Tsys maybe 18K, BW=850 MHz

1

Like · Reply · 1h



ew tim
Restart
J1909−3744 (Wrms = 0.218 μs) pre−fit
Prefit Residual (sec)
2×10⁻⁶
0
−2×10⁻⁶
Residual in pulse periods
10⁻³
5×10⁻⁴
0
−5×10⁻⁴
−10⁻³
6000
6500
TOA number

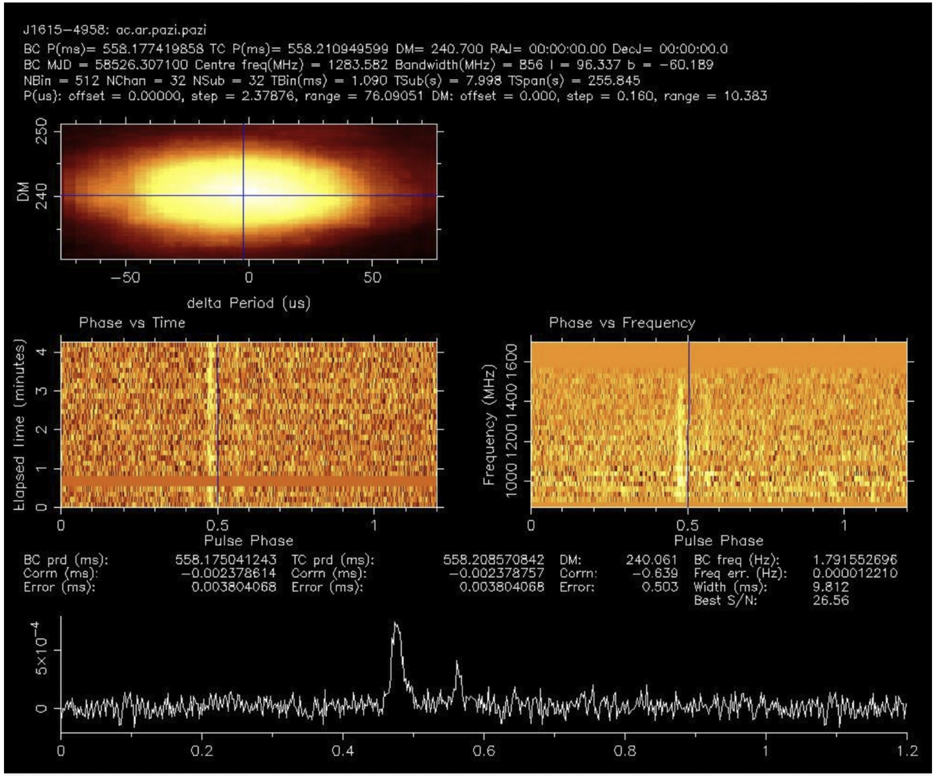
Gravitational waves

First meertime science run

Matthew Bailes

Admin · 23 hrs

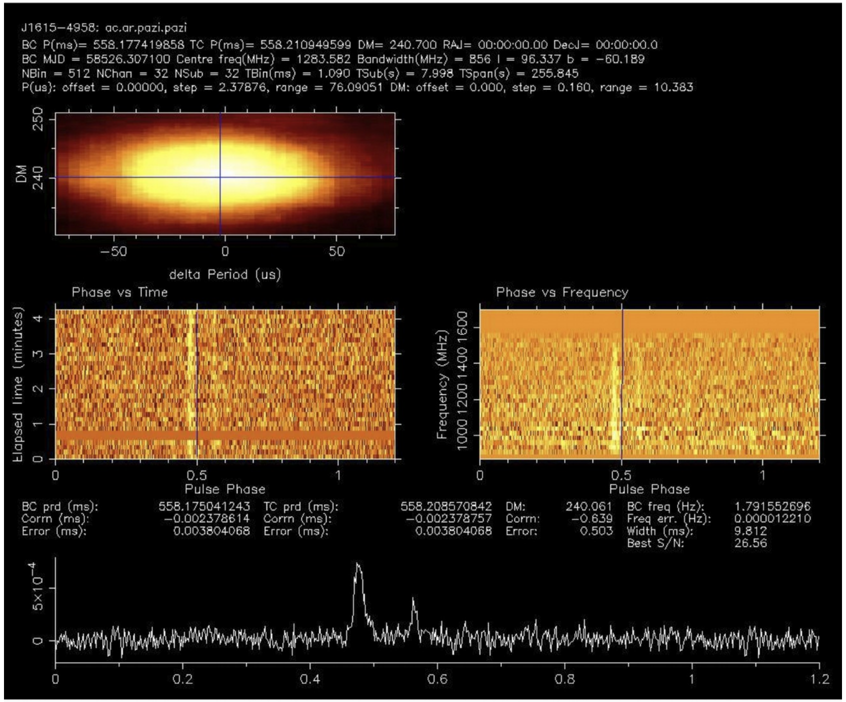
Today the first official MeerTime run was completed!



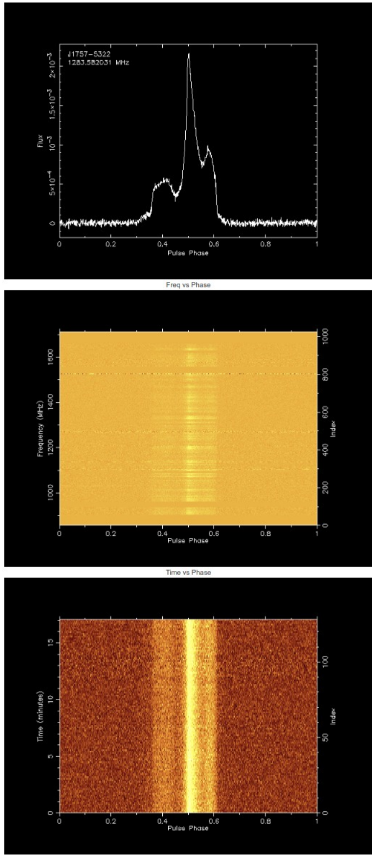
First Meerkat pulsar run 11 February 2019

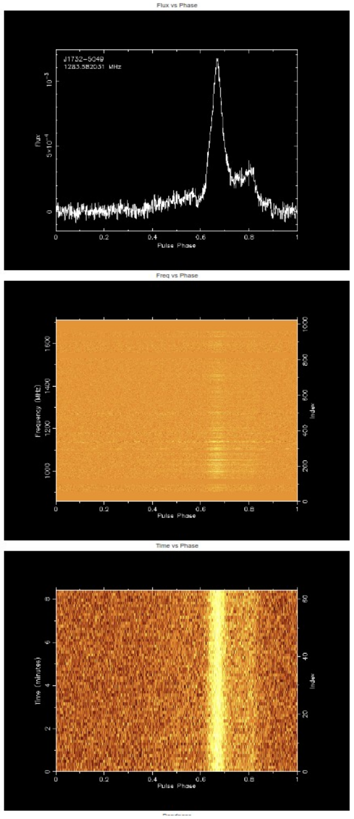
Matthew Bailes
Admin · 23 hrs

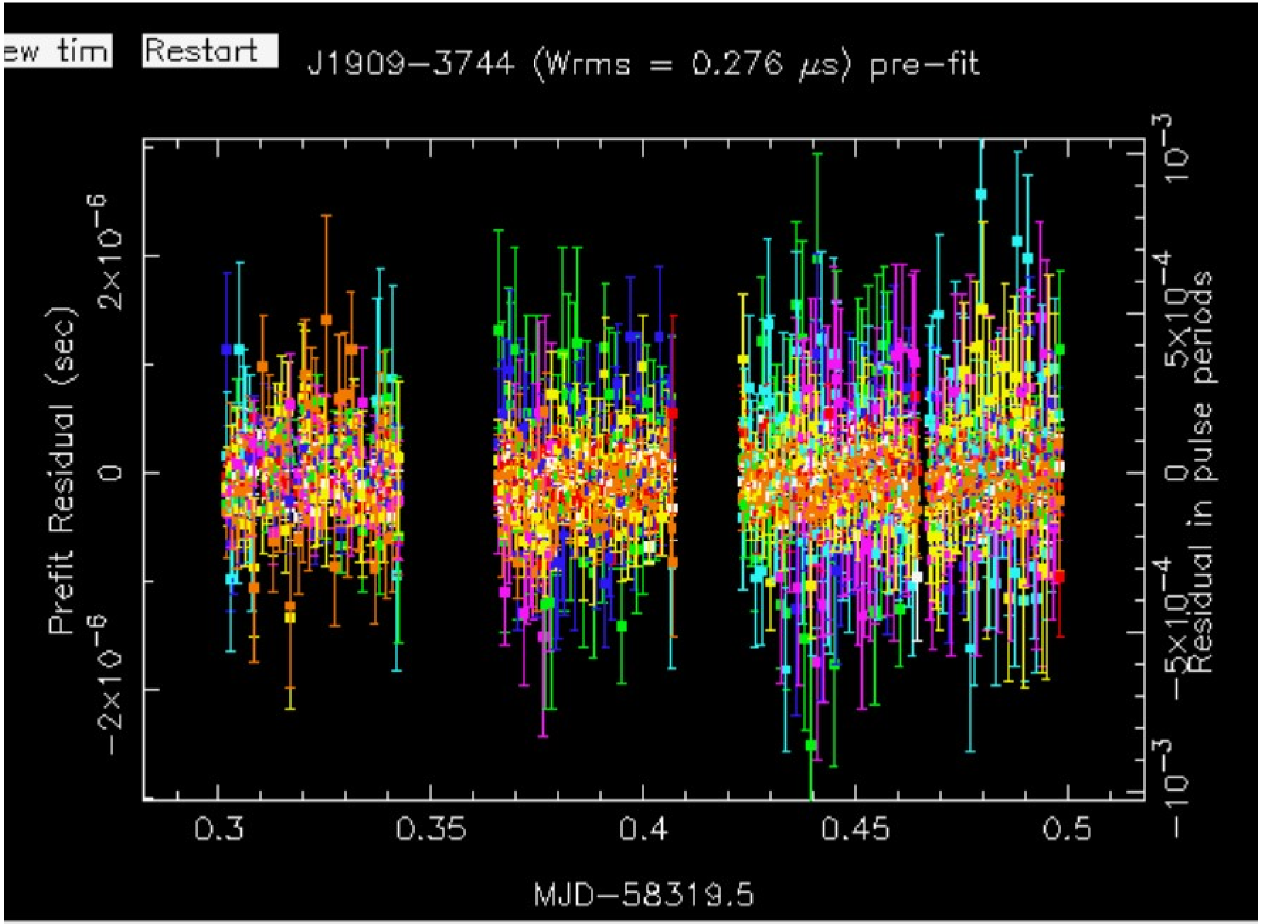
Today the first official MeerTime run was completed!



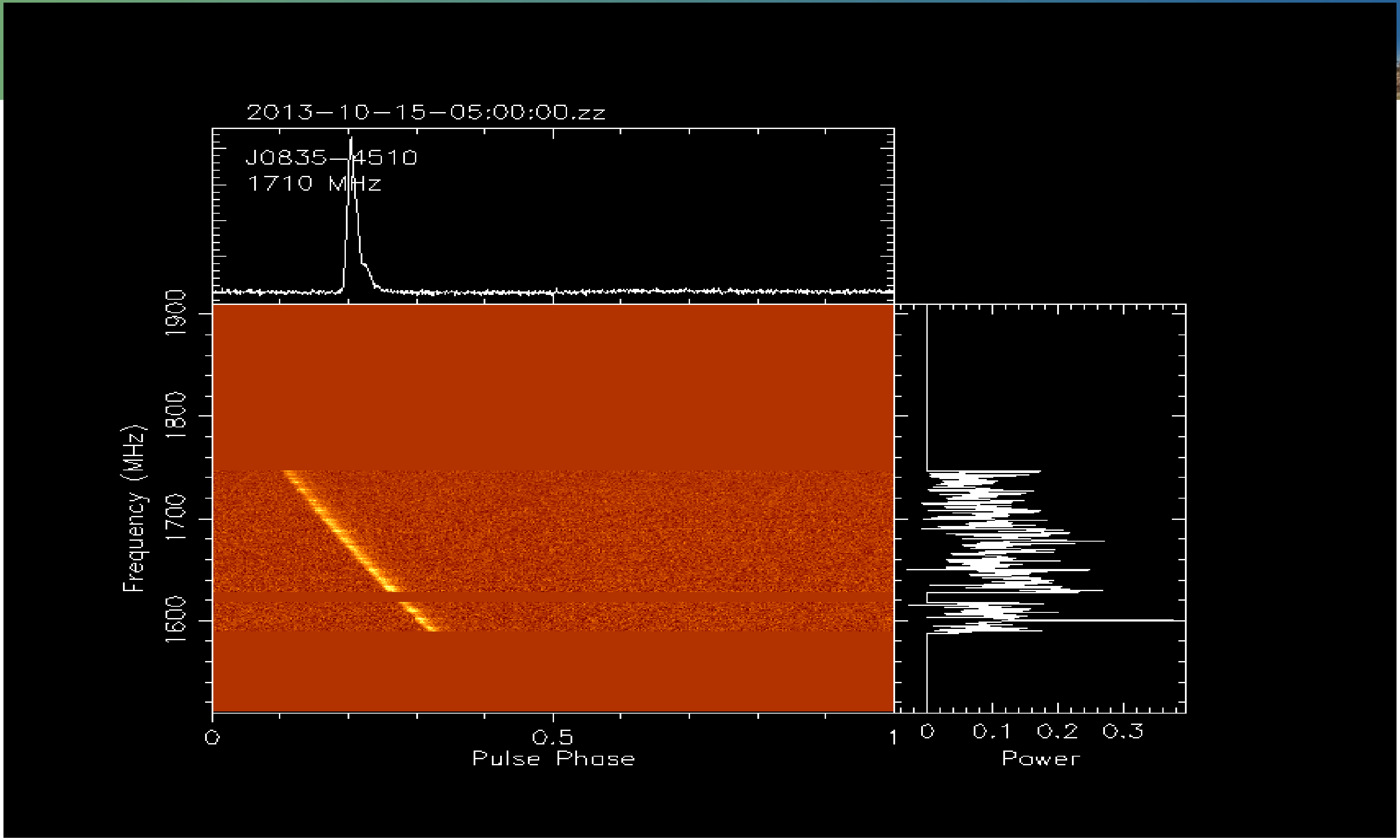
Some pulsars







ew tim
Restart
J1909−3744 (Wrms = 0.276 μs) pre−fit
Prefit Residual (sec)
2×10−6
0
−2×10−6
Residual in pulse periods
10−3
5×10−4
0
−5×10−4
−10−3
0.3
0.35
0.4
0.45
0.5
MJD−58319.5


2013−10−15−05:00:00.zz
J0835−4510
1710 MHz
Frequency (MHz)
1900
1800
1700
1600
0
0.5
1
Pulse Phase
0
0.1
0.2
0.3
Power