Applications & Challenges of multi-frequency and millimetre Pulsar Observations

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"Multi-Frequency mm-Wave Radio Telescope & Other Software Controlled Operations"

Contents

- (Very Brief) Introduction to Pulsars
- Motivation for millimetre Pulsar Studies
- Our experiences in multi-freq and millimetre pulsar observations & Challenges
- Future prospects

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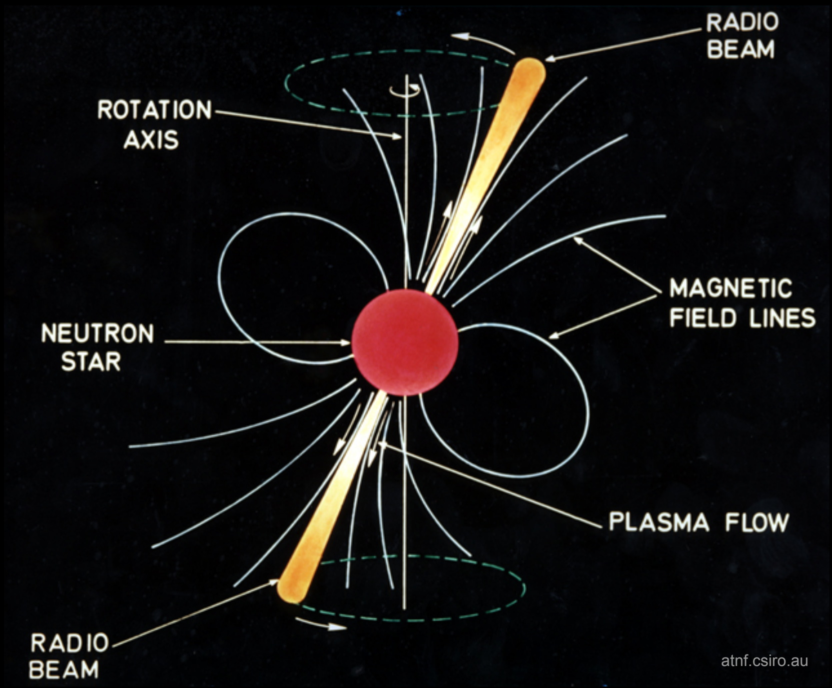
What is a pulsar?

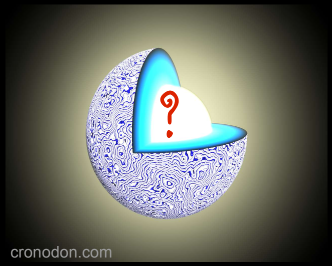
- Rotating neutron star with beamed, broadband electromagnetic radiation

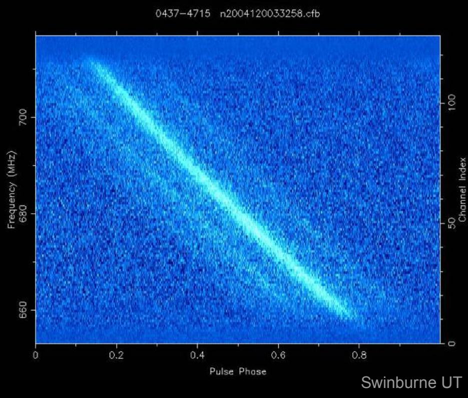


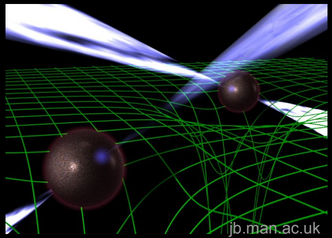
- Mass **[1.2-2.01]** M_sun
- Radii **[10-12]** km !
- Enormous densities > nuclear d.
- Strong gravity fields **(~10^{11} G_earth)**
- Strong magnetic fields **(10^{8}–10^{15} G)**
- Very stable and fast rotations

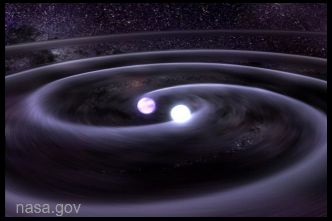
Pulsar Science Overview

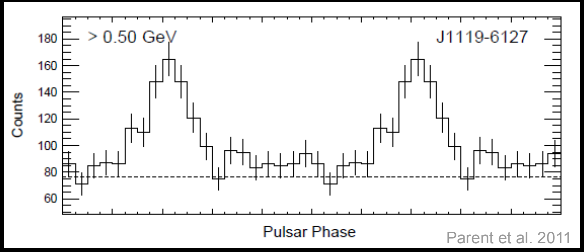
- Physics of super-dense matter
- Tests of gravity theories
- Gravitational waves
- Stellar population and evolution
- High energy astrophysics
- ISM properties
- Relativistic electrodynamics
- Magnetohydrodynamics
- Plasma physics
- Solid state physics
- ...

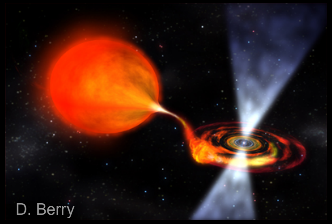












Pulsar Science Overview

- Physics of super-dense matter
- Magnetohydrodynamics
- Atomic physics
- Solid state physics
- ...

Benefit from mm- observations

"Pulsars allow studies in many fundamental fields of physics and they are unique tools!"

Contents

Multi-frequency & Millimetre data

- Physics of super-dense matter
- Tests of gravity theories ← Benefit from mm- observations
- Gravitational waves
- Stellar population and evolution ← Benefit from mm- observations
- High energy astrophysics
- ISM properties ← Benefit from multi-frequency observations
- Relativistic electrodynamics ← Benefit from mm- observations
- Magnetohydrodynamics ← Benefit from mm- observations
- Plasma physics ← Benefit from mm- observations
- Solid state physics
- ...

Example: Properties of the ISM

- Dispersion Measure. Free electrons in Line-of-Sight:

$$\Delta t_{DM} \approx 4.15\text{x}10^{6}\text{ms x } (f_1^{-2} - f_2^{-2}) \text{ x DM}$$

- Rotation measure. Magnetic field in Line-of-Sight:

$$\Delta PA \approx c^2 \, RM \, f^{-2}$$

$f \equiv$ frequency

- Scattering:

$$\Delta t_{scattering} \propto f^{-4}$$

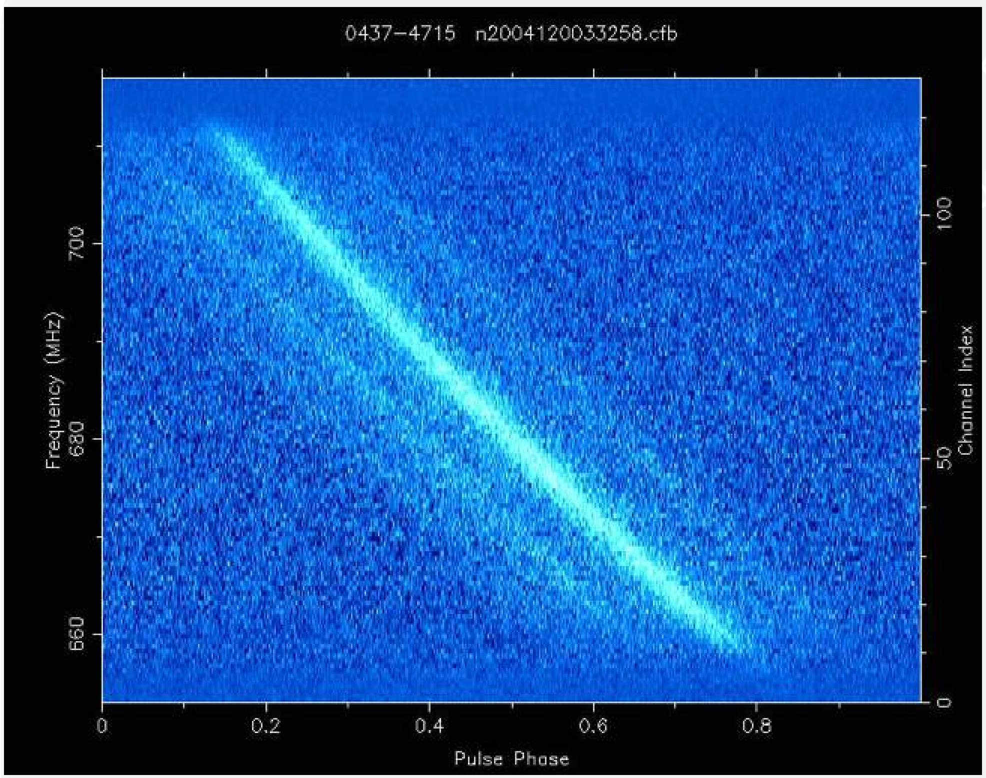
- Scintillation:

$$\Delta t_{scintillation} \propto \Delta t_{scattering} \propto f^{-4}$$

See Lorimer and Kramer (2005)

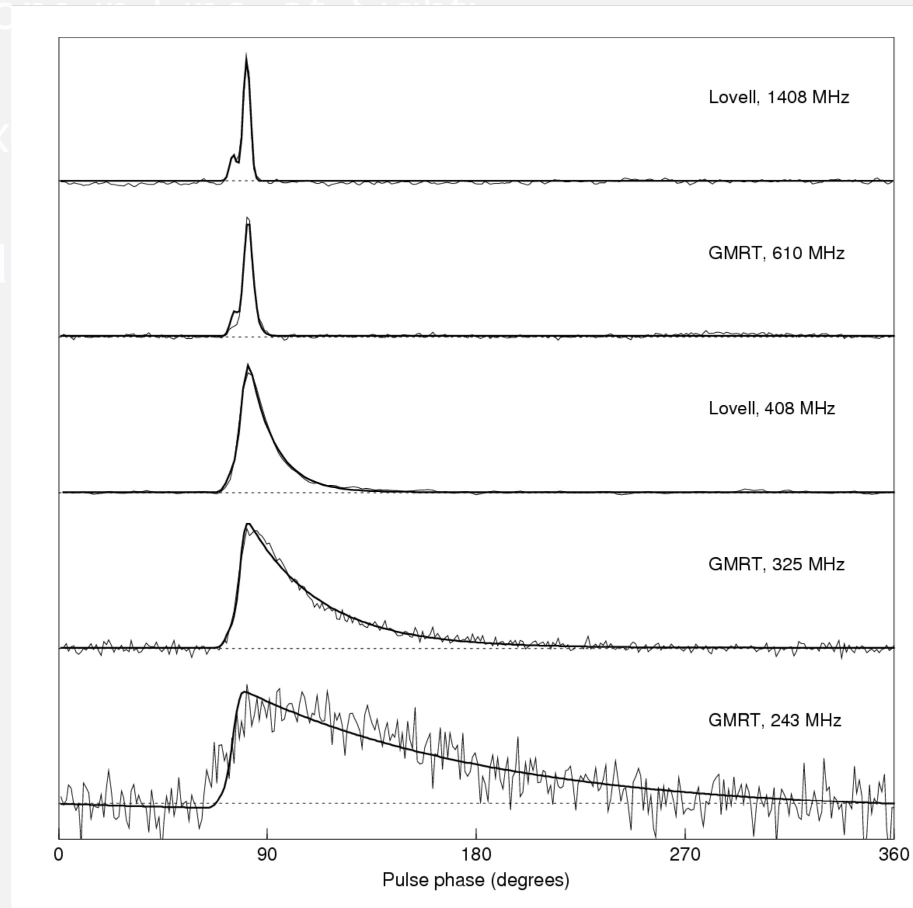
Example: Properties of the ISM

Example pulse dispersion



Swinburne UT

Example temporal scattering



From Lorimer and Kramer (2005). Figure by O. Löhmer.

Example: Tests of Gravity

- Many different possible experiments to test Gravity
- Most interesting: pulsars in the strong-field regime

Kramer et al. (2006)
Kramer et al. in prep.

- Strongest Gravity field in our Galaxy → Sgr A*
- Need to find a pulsar *closely* orbiting the supermassive black hole
- Scattering toward GC is a problem, and not yet well understood

Spitler et al. (2014)
Bower et al. (2014)

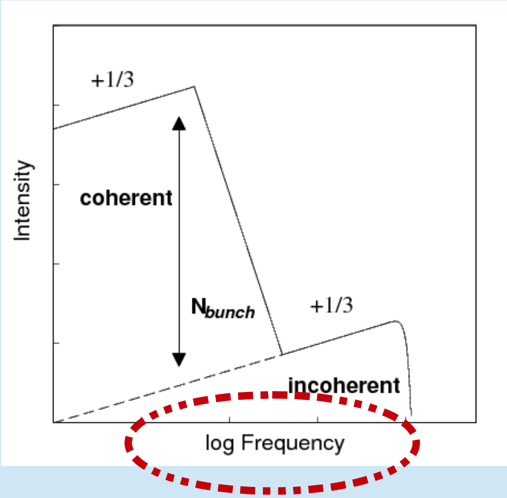
$$\Delta t_{scattering} \propto f^{-4}$$

High radio frequencies are greatly less affected by scattering, allowing to observe through very dense mediums: perfect to observe the Galactic Centre

Example: Pulsar Emission Mechanism

MODEL PREDICTION

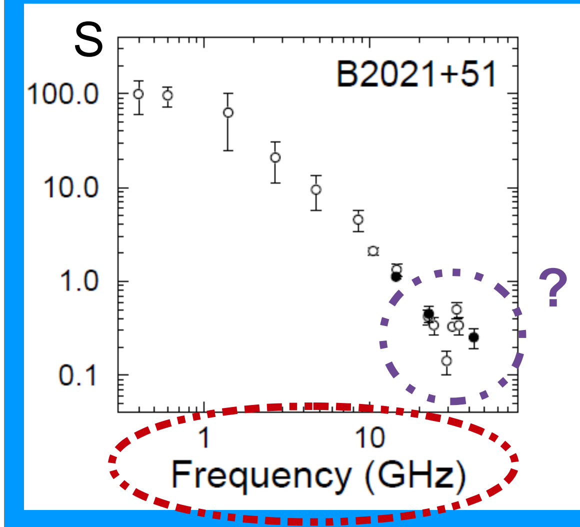
Coherence breakdown



(Figure adapted from Michel 1982, 1991)

OBSERVATION

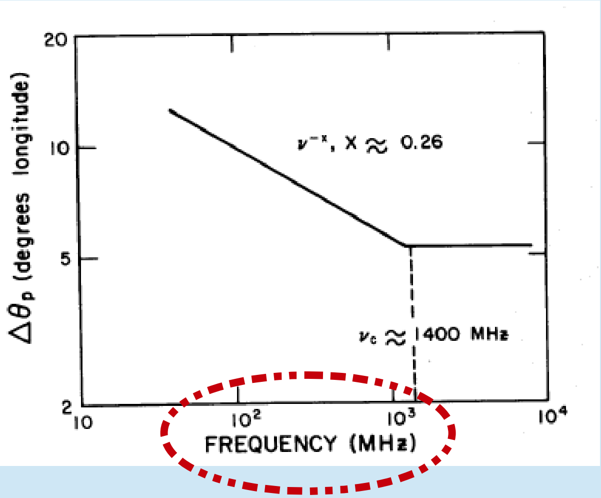
Spectrum turn-ups



Kramer et al. (1996)

MODEL PREDICTION

Profile Evolution Saturation



Cordes (1978)

+ unexpected depolarization at high radio frequencies (Xilouris 1996)
+ unexpected flux density variabilities (Kramer et al. 1997)

Example: Pulsar Emission Mechanism

"There is a strong frequency dependence in many effects.
Multi-frequency and millimetre data are very valuable for some experiments, (and key in some cases!)"

(Figure adapted from Michel 1982, 1991)

Kramer et al. (1996)

Cordes (1978)

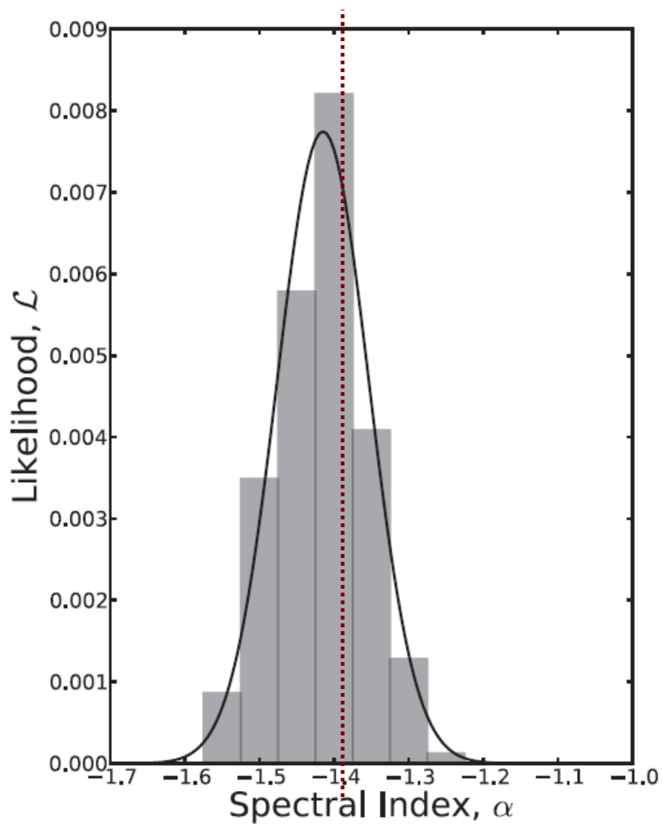
+ unexpected depolarization (Xilouris 1996)
+ unexpected flux density variabilities (Kramer et al. 1997)

Contents

Pulsar Spectra

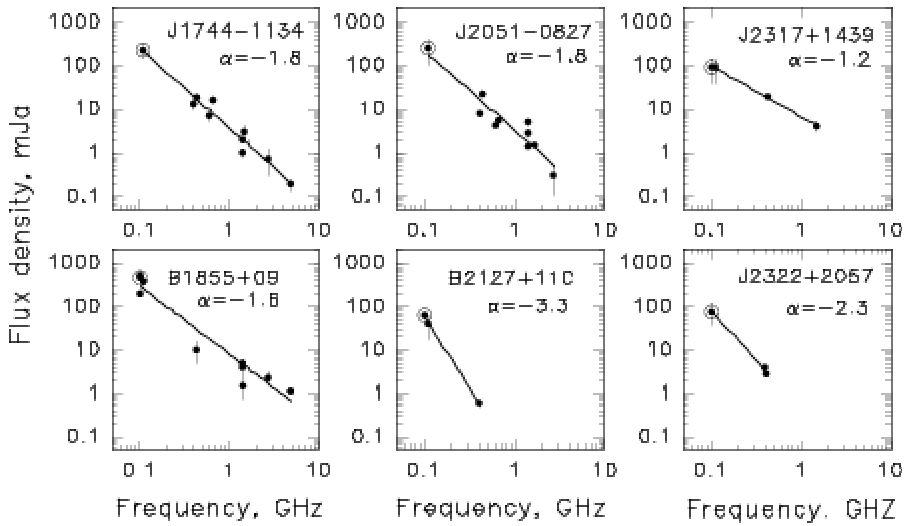
- Mean spectral index α ~ -1.4

Bates, Lorimer and Verbiest (2013)



$$S \propto \nu^{\alpha}$$

Spectral index · *flux density* · *frequency*



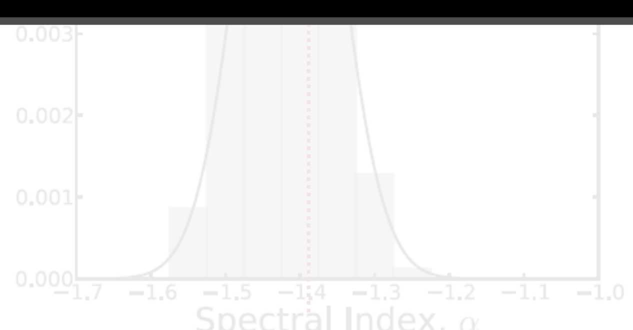
Kuzmin and Lozovsky (2001)

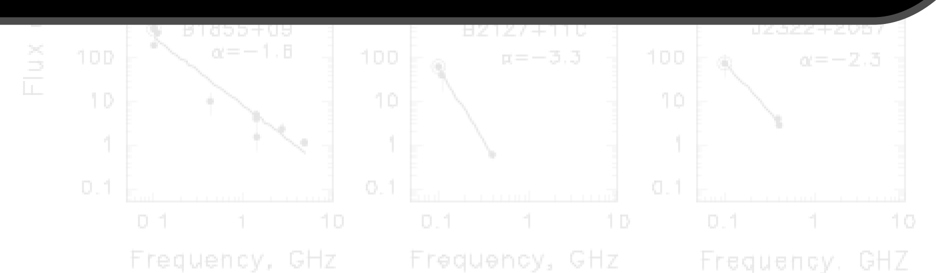
Pulsar Spectra

- Mean spectral index α ~ -1.4

"Pulsars are extremely faint at high radio frequencies."

Flux density down to μJy – pJy !!!

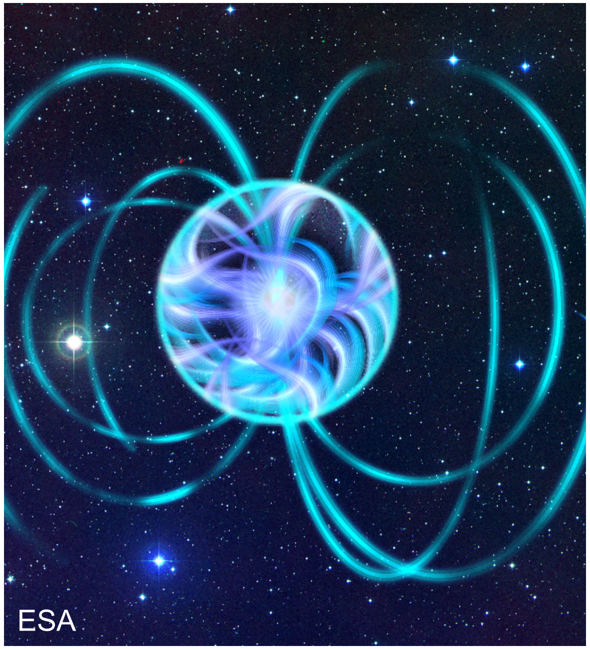




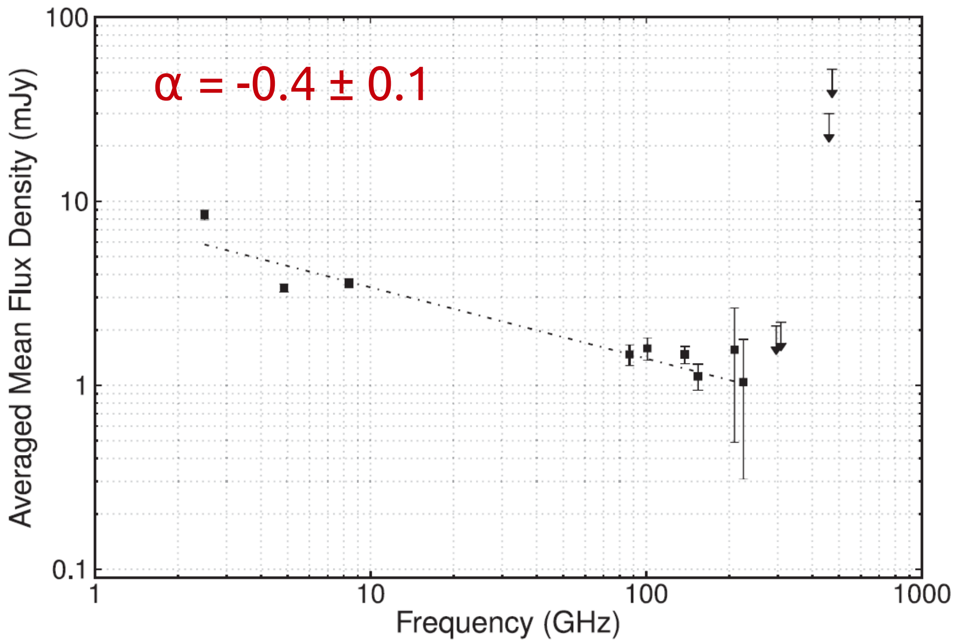
Kuzmin and Lozovsky (2001)

Radio-loud Magnetars

- Magnetars = Rare pulsars with extreme magnetic fields (~25 known)
- Radio-loud magnetars show ~flat spectrum!
- *Ideal for millimetre observations*



Torne et al. (2015)



A Magnetar in the Galactic Centre

- SGR J1745-2900, discovered in 2013 (Kennea et al. 2013, Mori et al. 2013)
- Radio-loud! (Eatough et al. 2013, Shannon & Johnston 2013)
- Location 0.1" from Sgr A* (Distance ~ 0.12 pc)
- *Ideal for millimetre observations*
- Regular monitoring by our team at centimetre wavelengths with Jodrell Bank (20 cm), Nançay (12 cm), Effelsberg (6 and 3 cm)
- *One campaign of simultaneous multi-frequency observations with Nançay (12 cm), Effelsberg (6 and 3 cm), IRAM 30m (3, 2, 1 mm)*
- Test observation with APEX (1, 0.9, 0.7, 0.6 mm)

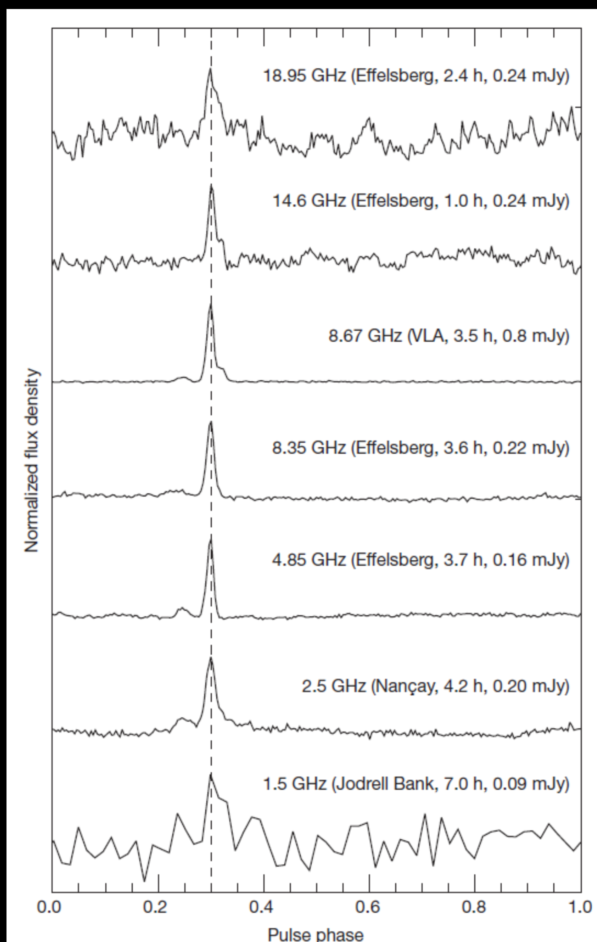
A Magnetar in the Galactic Centre

A number if nice results from this object:

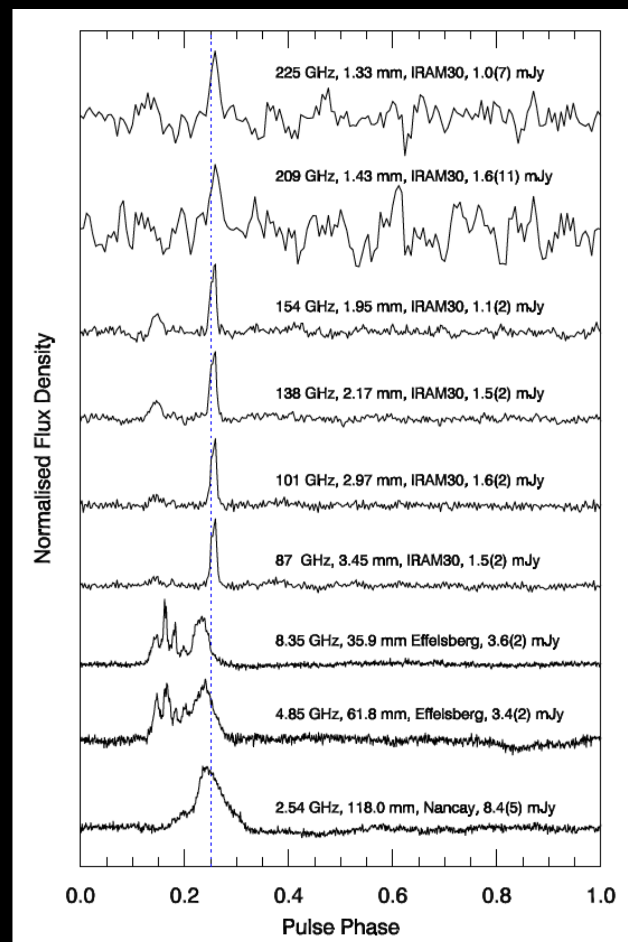
- A strong B-field around Sgr A* with implications for accretion and jet formation processes (Eatough et al. 2013, Nature)
- ISM scattering toward Galactic Centre revised, with measurements of scattering over three orders of magnitude lower than predicted (Spitler et al. 2014, Bower et al. 2014)
- Magnetar radio emission properties, with detection down to 0.9 mm doubling previous maximum frequency of detections (Torne et al. 2015, Torne et al. in prep.)

A Magnetar in the Galactic Centre

Eatough et al. 2013



Torne et al. 2015



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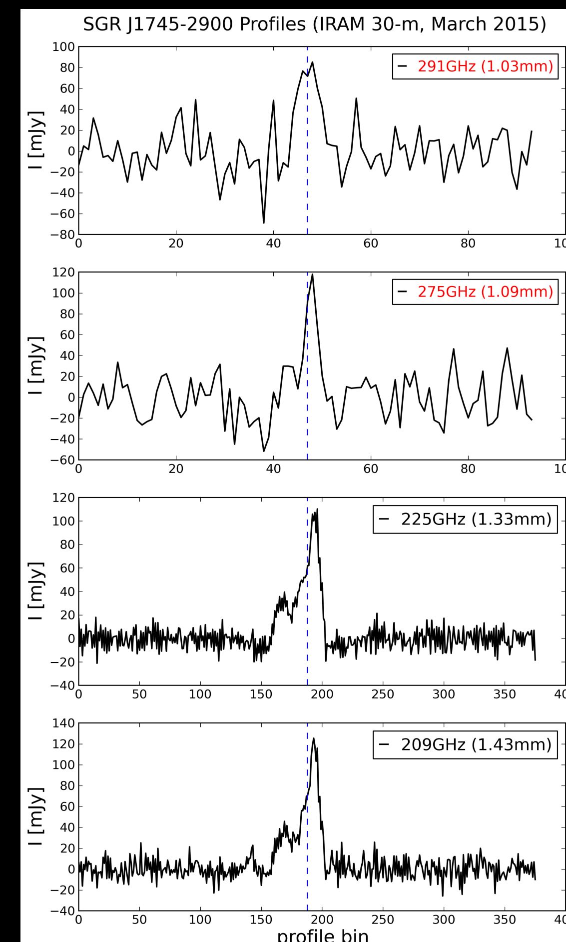

Preliminary results

Challenges Multi-λ + mm-

- Faintness of pulsars at high frequencies
  Require large collecting areas and long integration times
- Pulsars are broadband and transient objects. Thus, usual atmospheric removal and calibration techniques (freq., position switching, ...) are not applicable. Need new techniques for mm- pulsar data reduction
- Removing baseline variations and undesired signals present in the data (self-produced RFI, 1 Hz), and precise flux density calibration is tricky
- Different back-ends time stamp synchronization. Need to be 100% sure of correct times for certain (very interesting) experiments
- Weather and ON-source synchronization of different observatories

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(Near) Future of mm- Pulsar Astronomy

- More sensitive mm- facilities are opening new possibilities
- IRAM 30m, NOEMA, LMT, ALMA

(Near) Future of mm- Pulsar Astronomy

BlackHoleCam

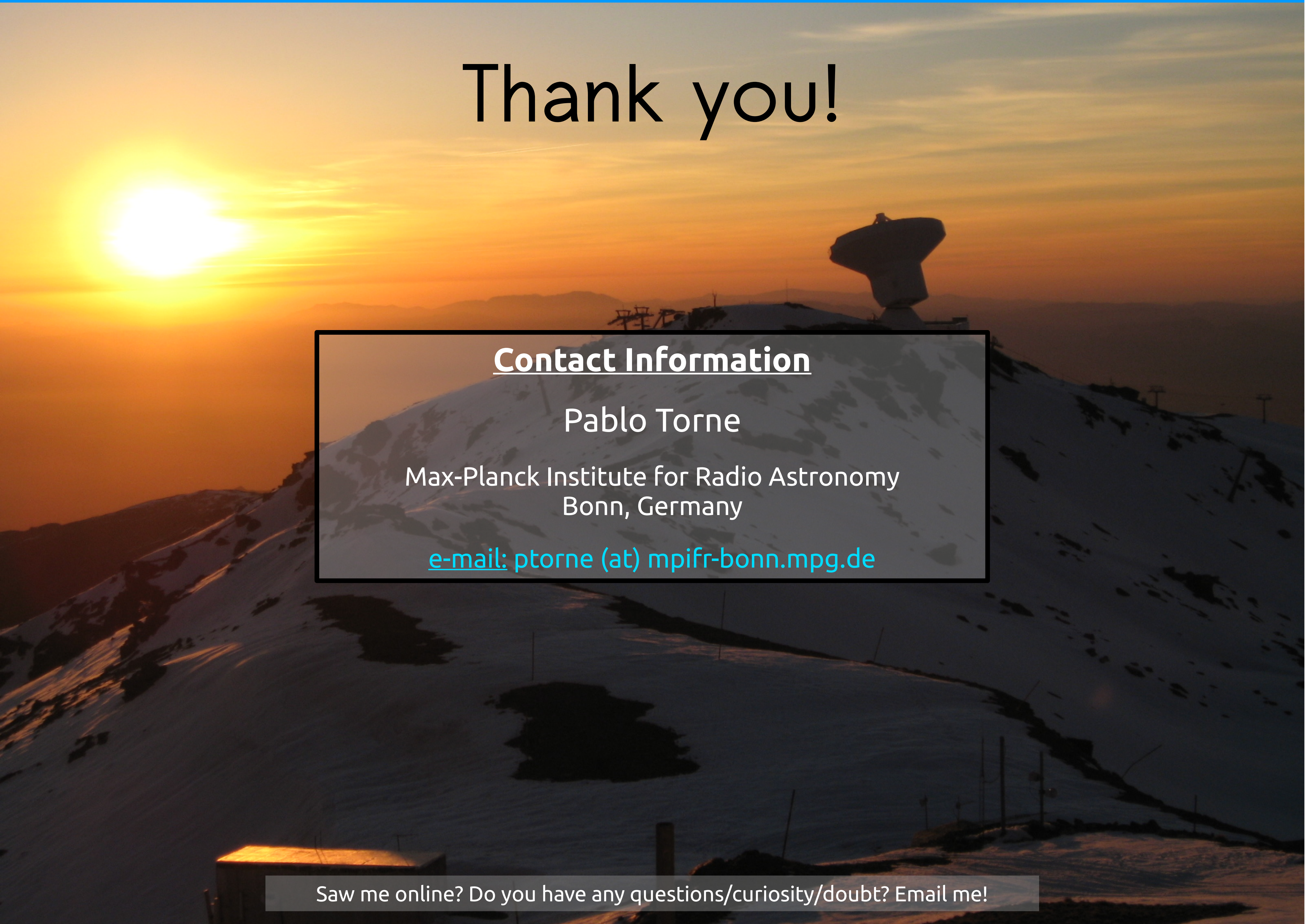
- Efforts to test General Relativity and other theories of Gravity by imaging directly Sgr A* with mm-VLBI
- Includes the search for pulsars around Sgr A*, complementing the results by the black hole imaging. Pulsars potentially allow to measure the mass, spin and quadruple moment of the black hole with unmatched precision (see Psaltis, Wex & Kramer 2015)
- Global collaboration within the Event Horizon Telescope (EHT)

More info: blackholecam.org || eventhorizontelescope.org

Summary

- Pulsars are very interesting tools for fundamental physics
- Millimetre observations of pulsars are not common, mainly due to the pulsars' faintness at high radio frequencies, but they are very interesting!
- Radio-loud magnetars are a special case with flat spectra. We found one very close to Sgr A*, excellent for pulsar GC experiments & tests
- New mm- facilities and upgrades on existing ones are opening new possibilities for experiments using pulsar mm- observations (also combining with lower/centimetre wavelengths)
- EHT and BlackHoleCam will revolutionize the studies of Gravity. Pulsars can be key in this fantastic project.

Thank you!



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Saw me online? Do you have any questions/curiosity/doubt? Email me!