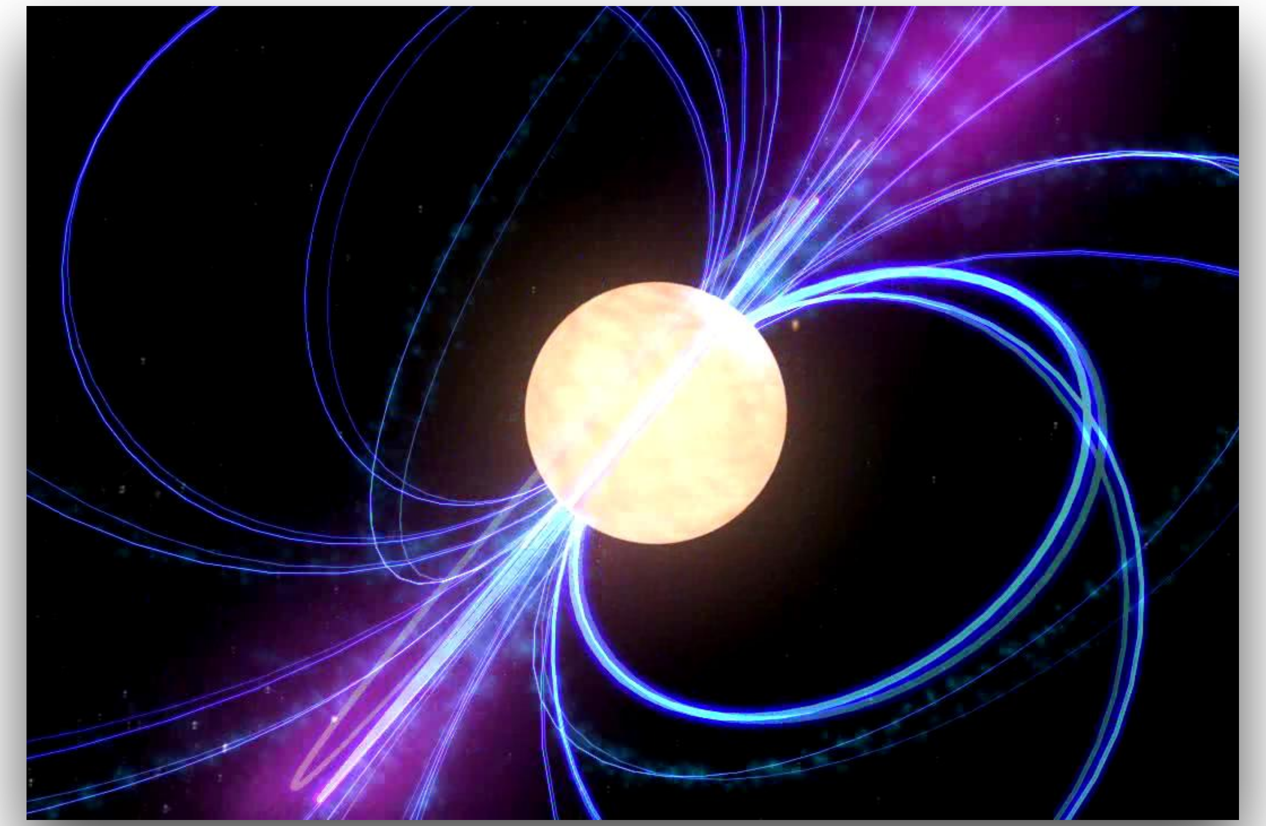
mm Universe @ NIKA2, Grenoble, 03–07 June 2019

The first pulsar detection with a KID camera (NIKA2)



Pablo Torne

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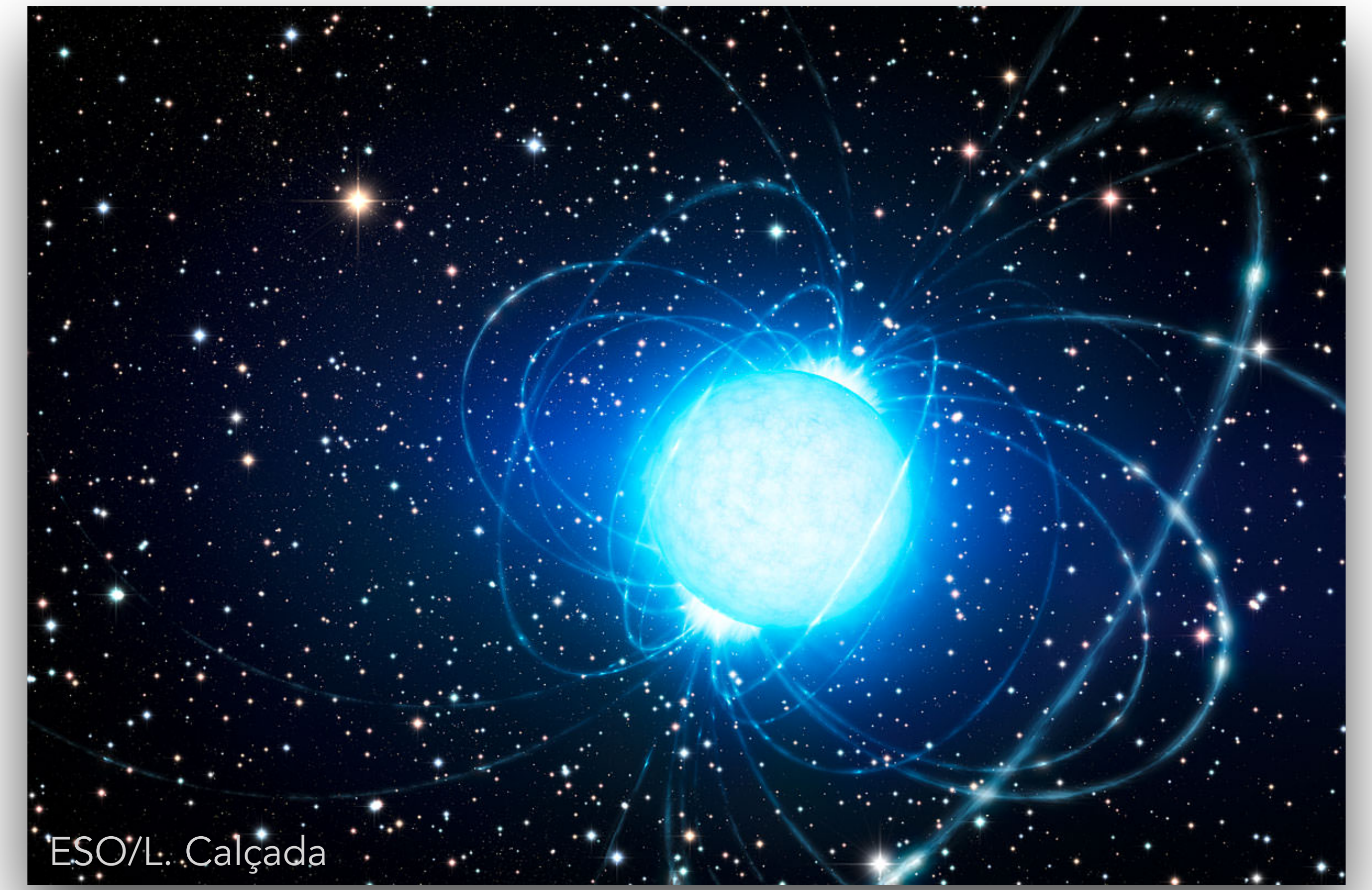
Instituto de Radio Astronomía Milimétrica

with Alessia Ritacco, Bilal Ladjelate, Juan Macias-Perez, Stefano Berta, Miguel Sanchez-Portal, Gabriel Paubert, Karl Schuster & *everyone making NIKA2 possible!*

Contents



Main Properties of Pulsars

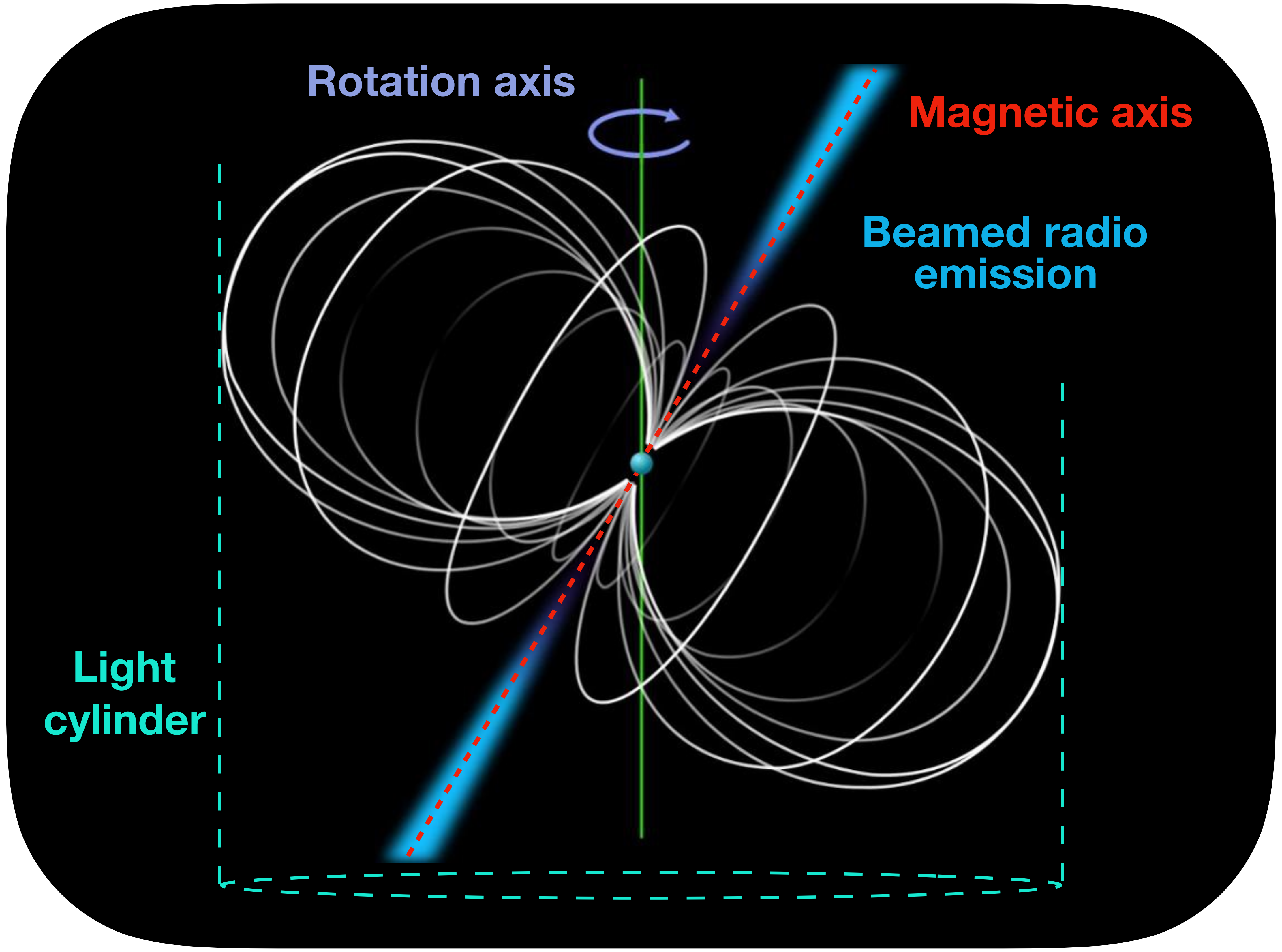


Image credit: Roy Smits (adapted)

- Neutron stars formed in supernovae
- Mass ~ [1 – 2] $M_\odot$
- Radius ~ 10 km
- Rapidly rotating (*P* ~ 10 – 0.001 seconds)
- Highly magnetised (B_s ~ 10^8 – 10^{15} G)
- Very stable rotators (ΔP down to 10^{-20} ss^{-1})
- Broadband emitters
- Steep spectral sources (<α> = -1.8 ± 0.2)
- Radio emission mechanism still unknown

  Pulses T_b ~ [10^{25} – 10^{43}] K (must be coherent)

They are almost black holes!

Pulsars

The Crab Nebula

Image credit: X-ray: NASA/Chandra; Optical: Nasa/Hubble; Infrared: NASA/Spitzer.

Pulsars

The Crab Nebula

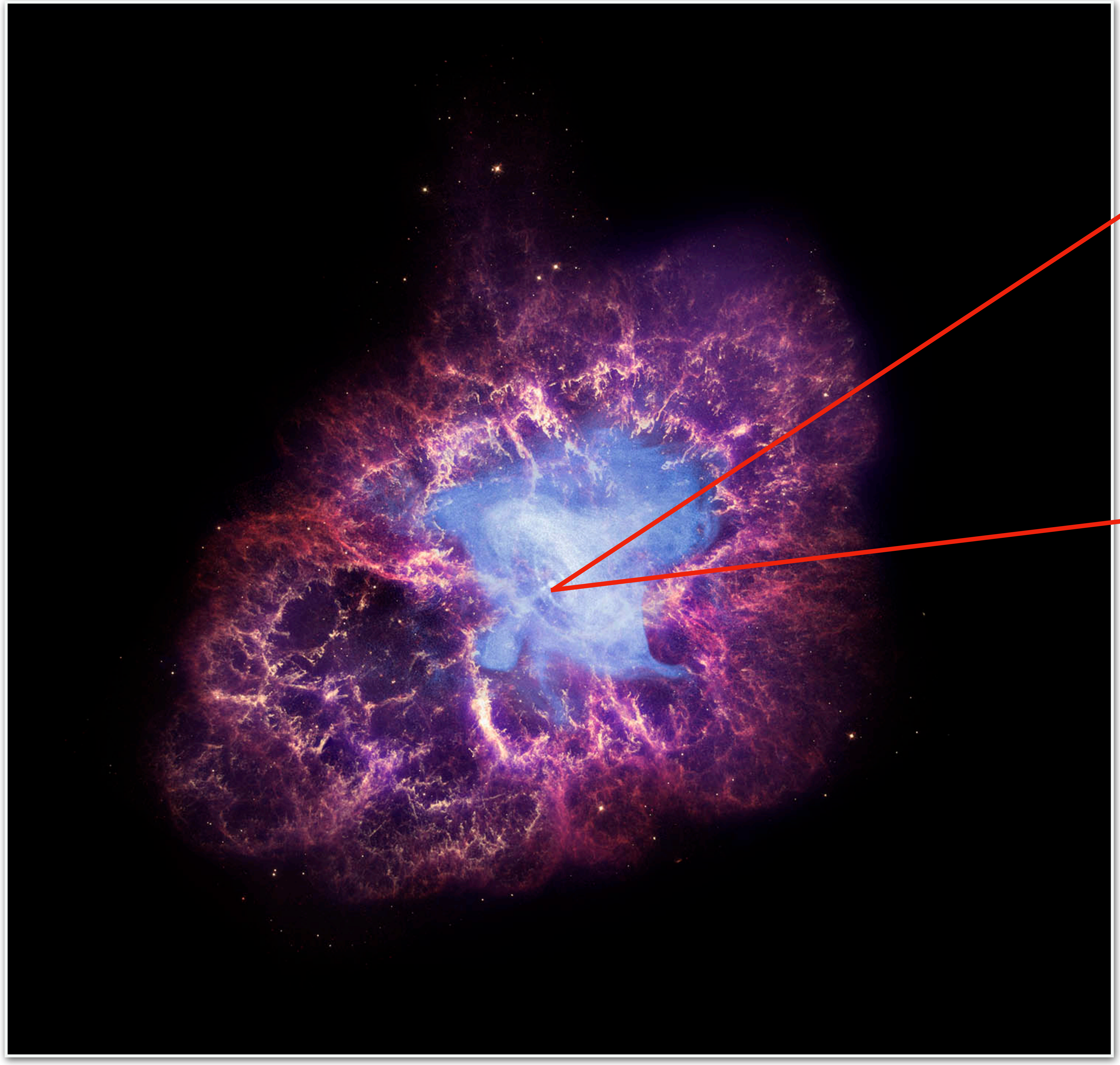
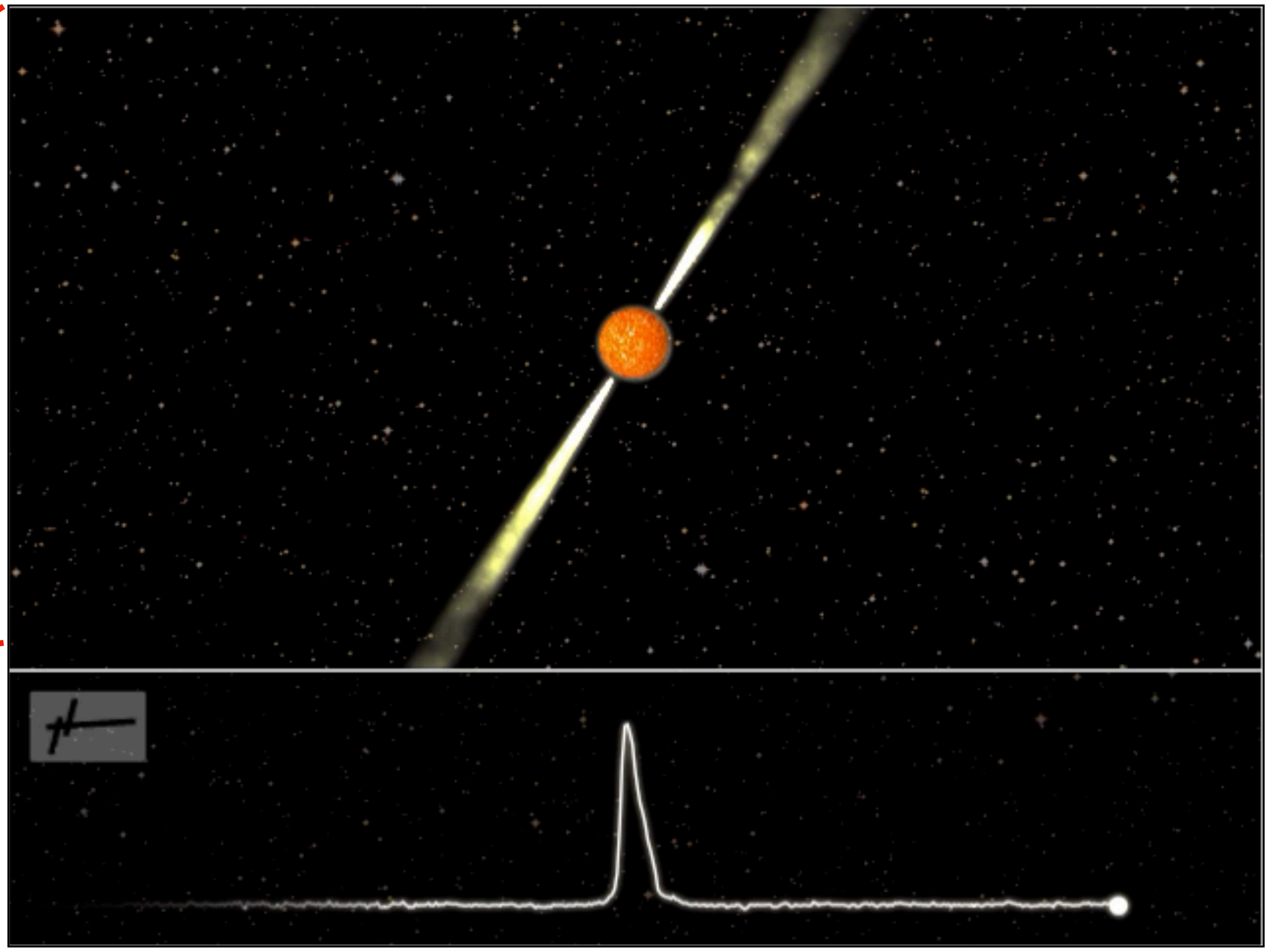
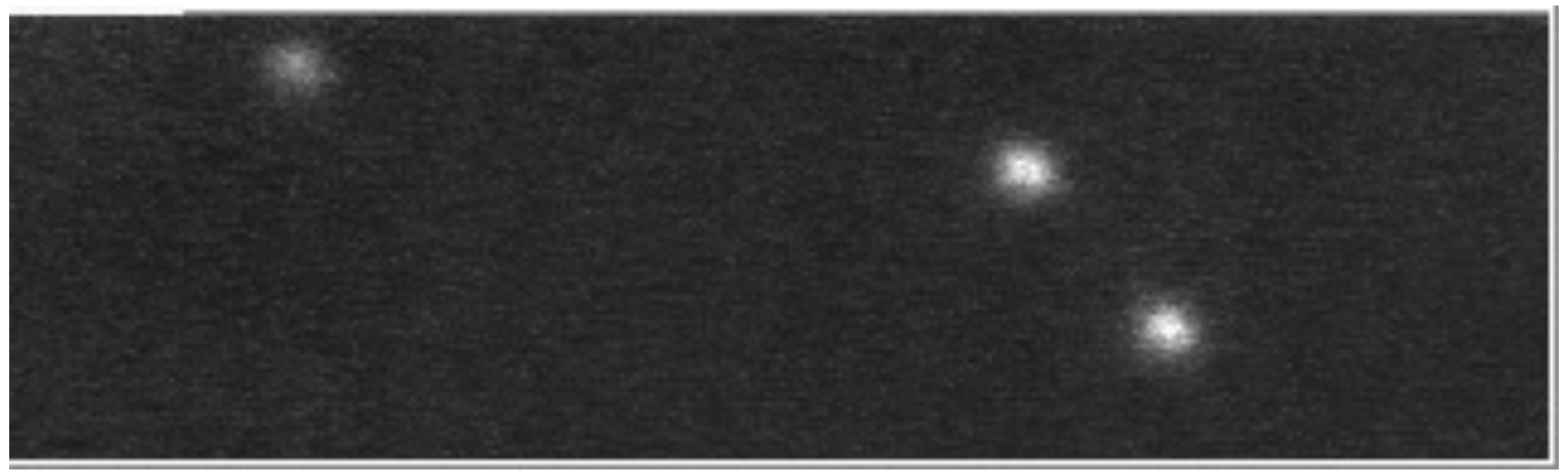


Image credit: X-ray: NASA/Chandra; Optical: Nasa/Hubble; Infrared: NASA/Spitzer.



Credit: J. van Leeuwen



Credit: Cambridge University

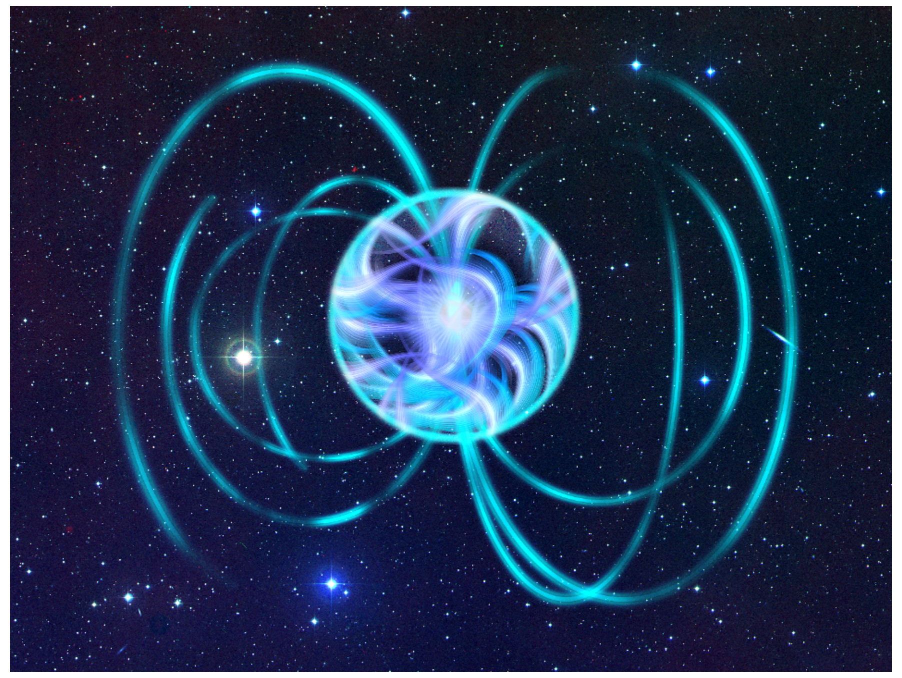
Pulsar Science

- Pulsars enable **high-precision astronomy in a wide variety of fields**, e.g.:

Interstellar medium

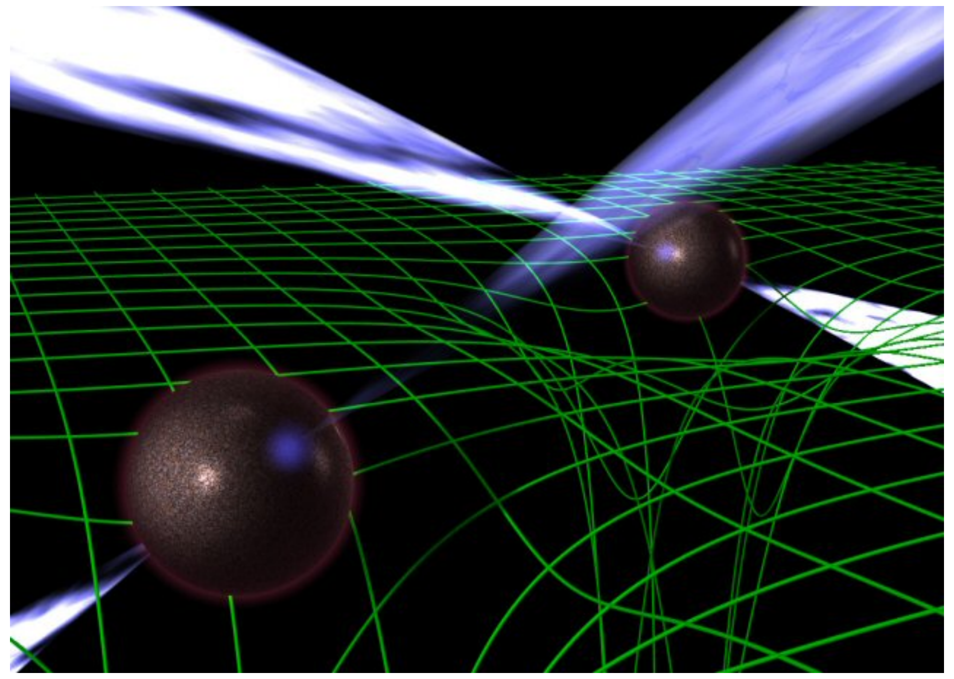
J. Williamson

Ultra-dense matter



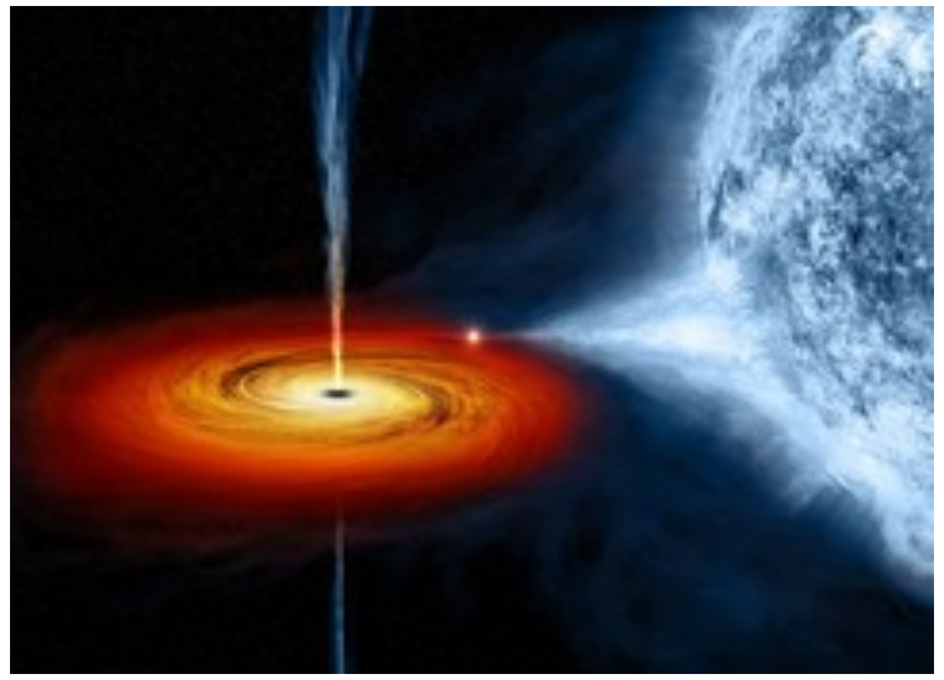
ESO

Gravity tests



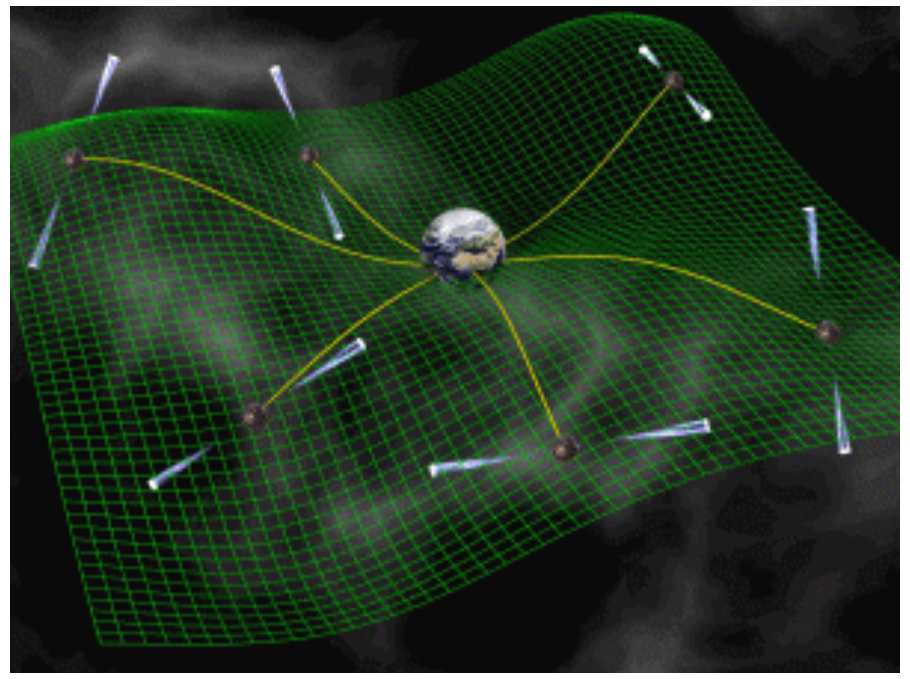
jb.man.ac.uk

Binary evolution



NASA/CXC/M. Weiss

Gravitational Waves



D. Champion (MPIfR)

- **Possible experiments depends on the pulsar systems known**, e.g.:
  - First binary pulsar ⇨ Gravitational Waves (Hulse & Taylor 1974) (Taylor & Weisberg 1982) 
  - 2-$M_\odot$ neutron star ⇨ Stringent constraints on EoS (Demorest et al. 2010) (Antoniadis et al. 2013)
  - Double pulsar ⇨ Most stringent tests of GR (Kramer et al. 2006)
  - Magnetar at Galactic Center ⇨ Strong B-field around Sgr A* (Eatough et al. 2013)

- **Discovering new pulsars expands our capabilities to do new science**

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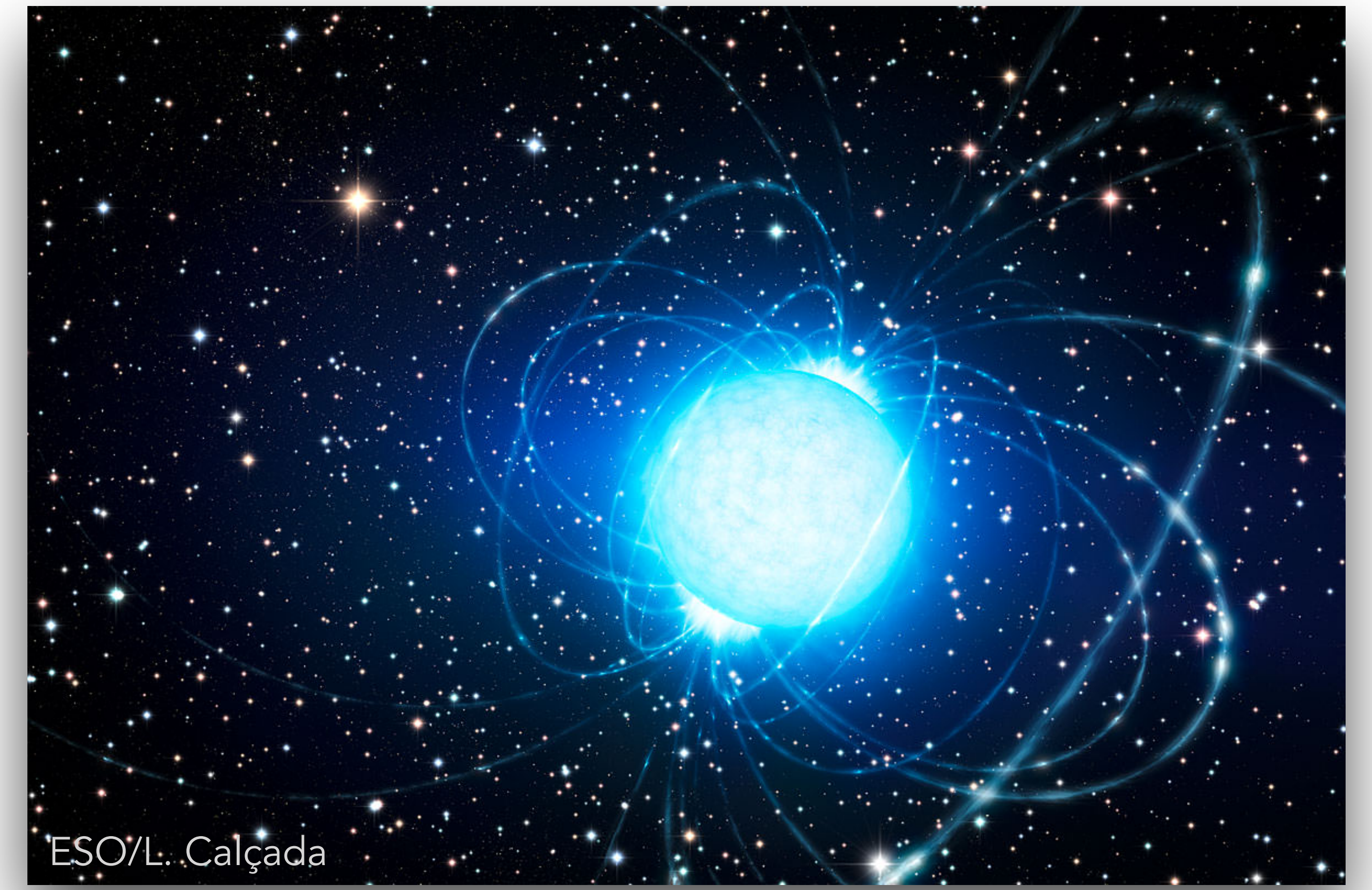


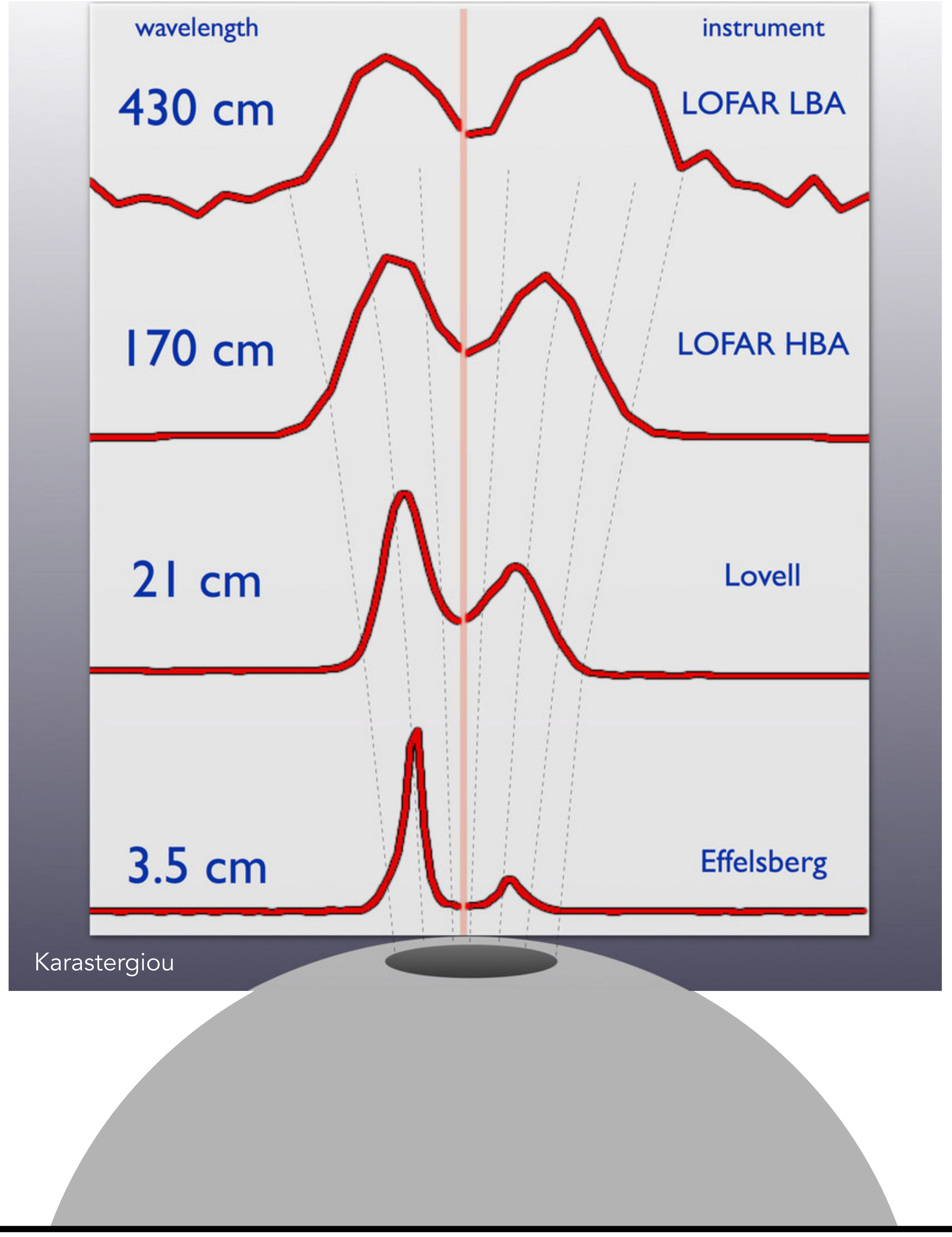
1. Understand Radio Emission Mechanism

- Models make predictions that we can try to test with observations
- Processes can be frequency dependent
- Some effects may be only observable at very high radio frequencies

⋆ **Millimetre regime is a very valuable input for models (and very scarce)**

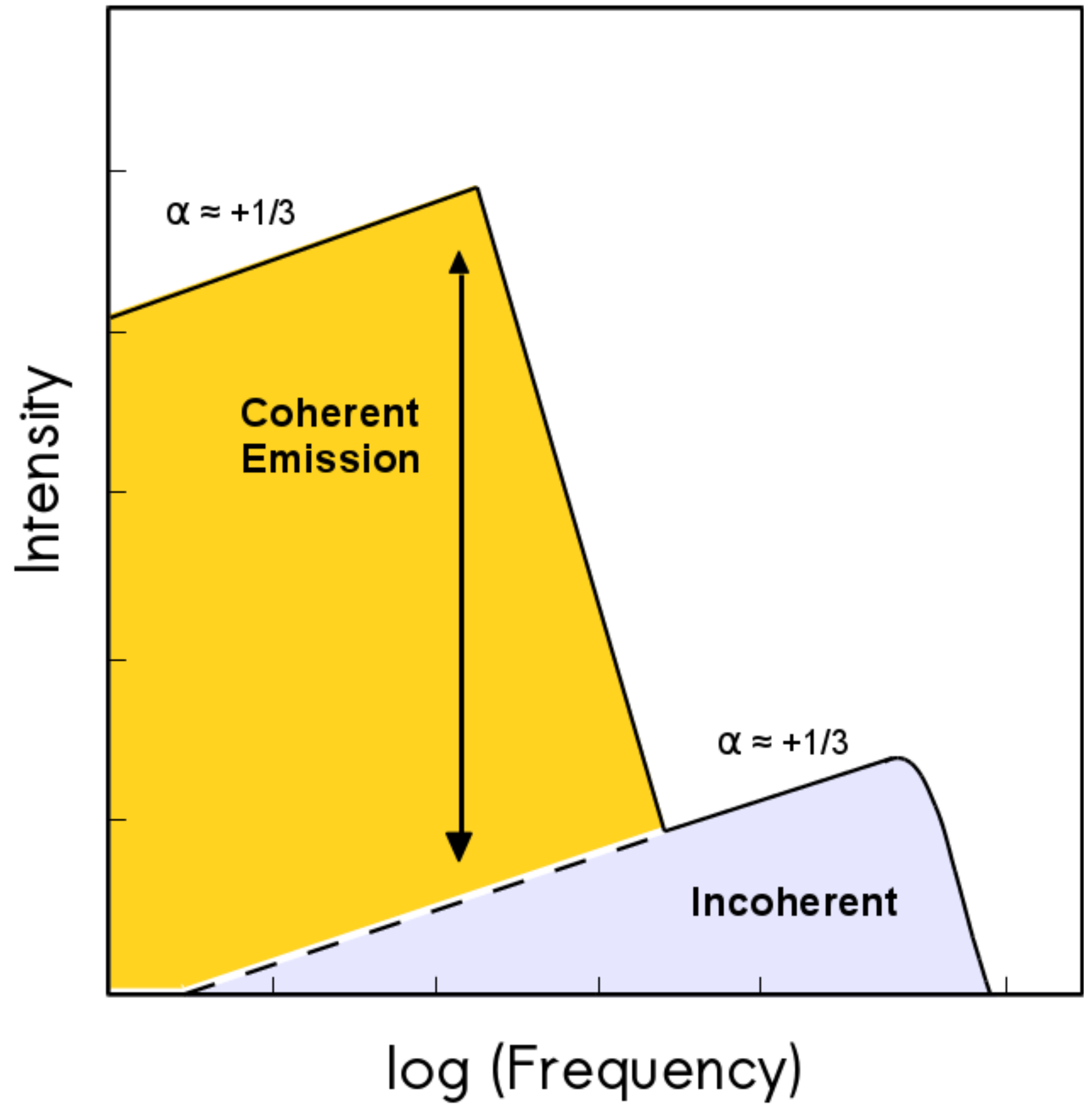
Radius-to-Frequency Mapping

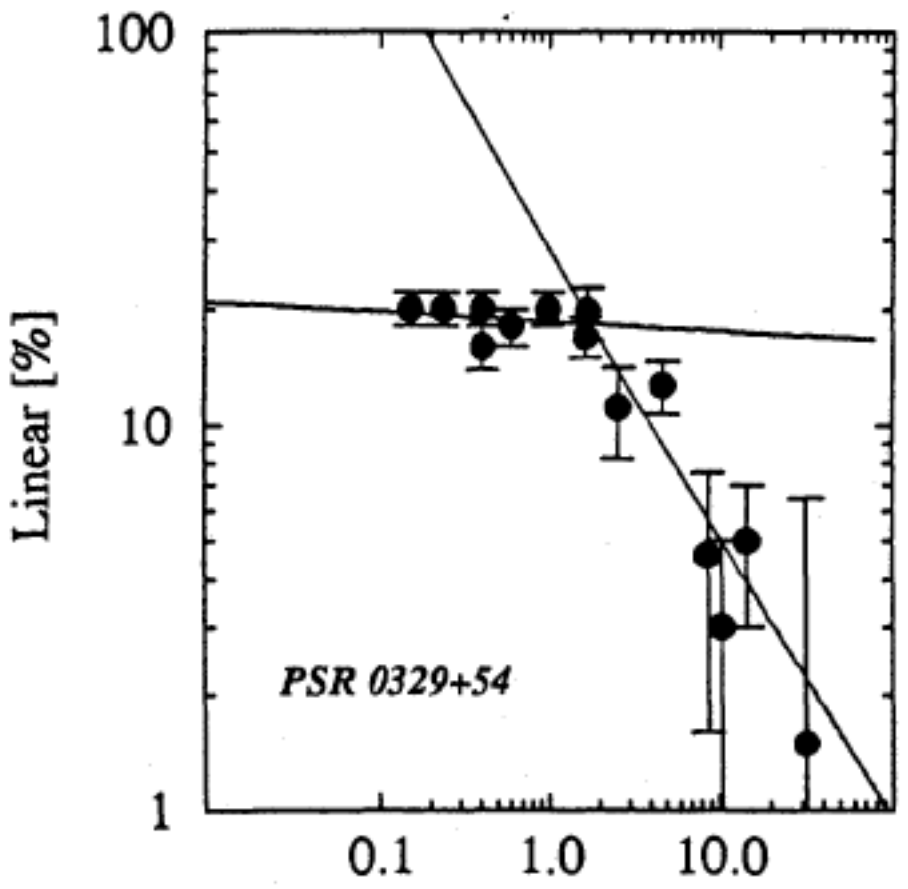
Radhakrishan and Cooke (1968), Cordes (1978)



Coherence breakdown

Michel (1982)



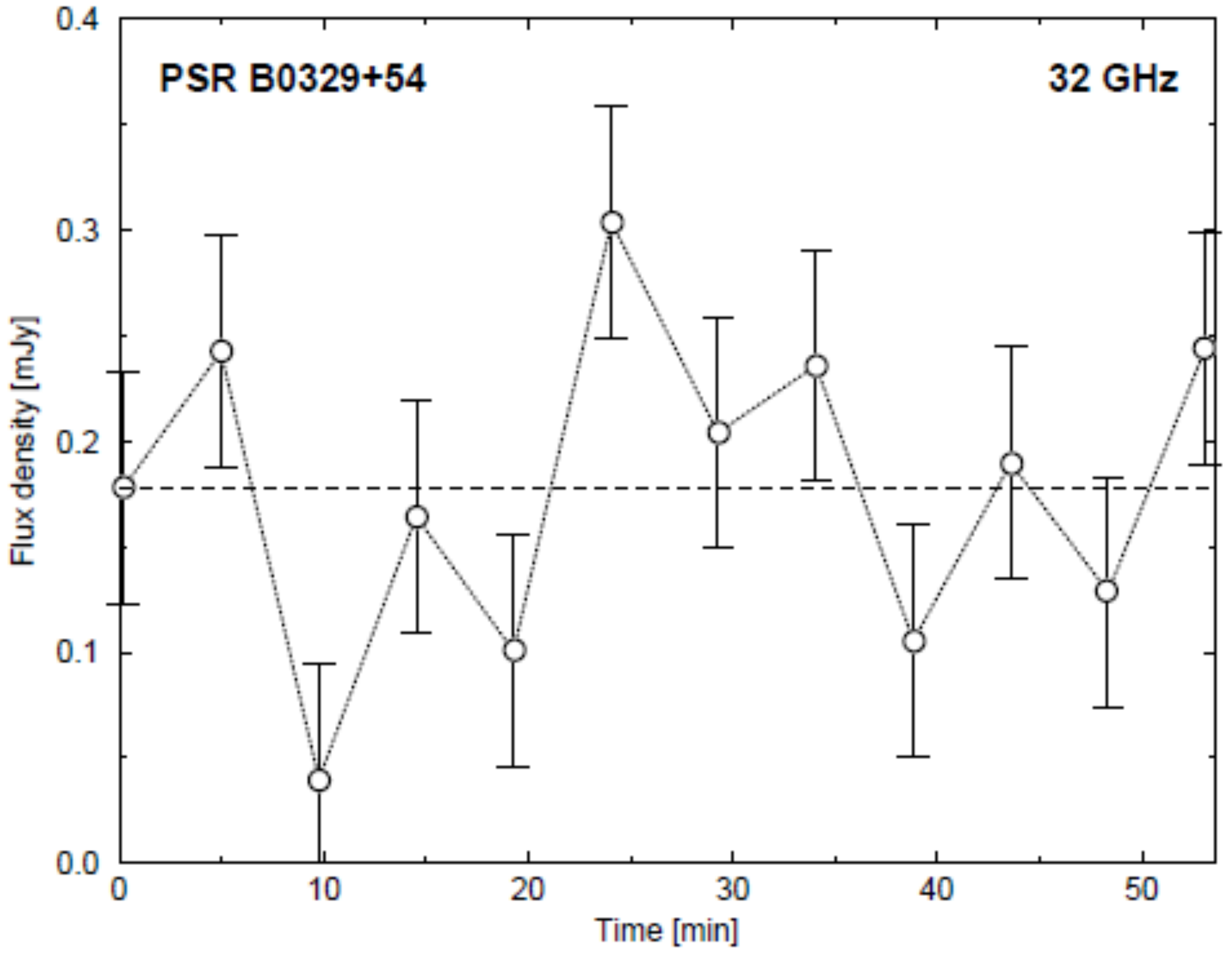


Decrease of polarisation

Xilouris et al. (1996)

Unexpected variability

Kramer et al. (1996, 1997)



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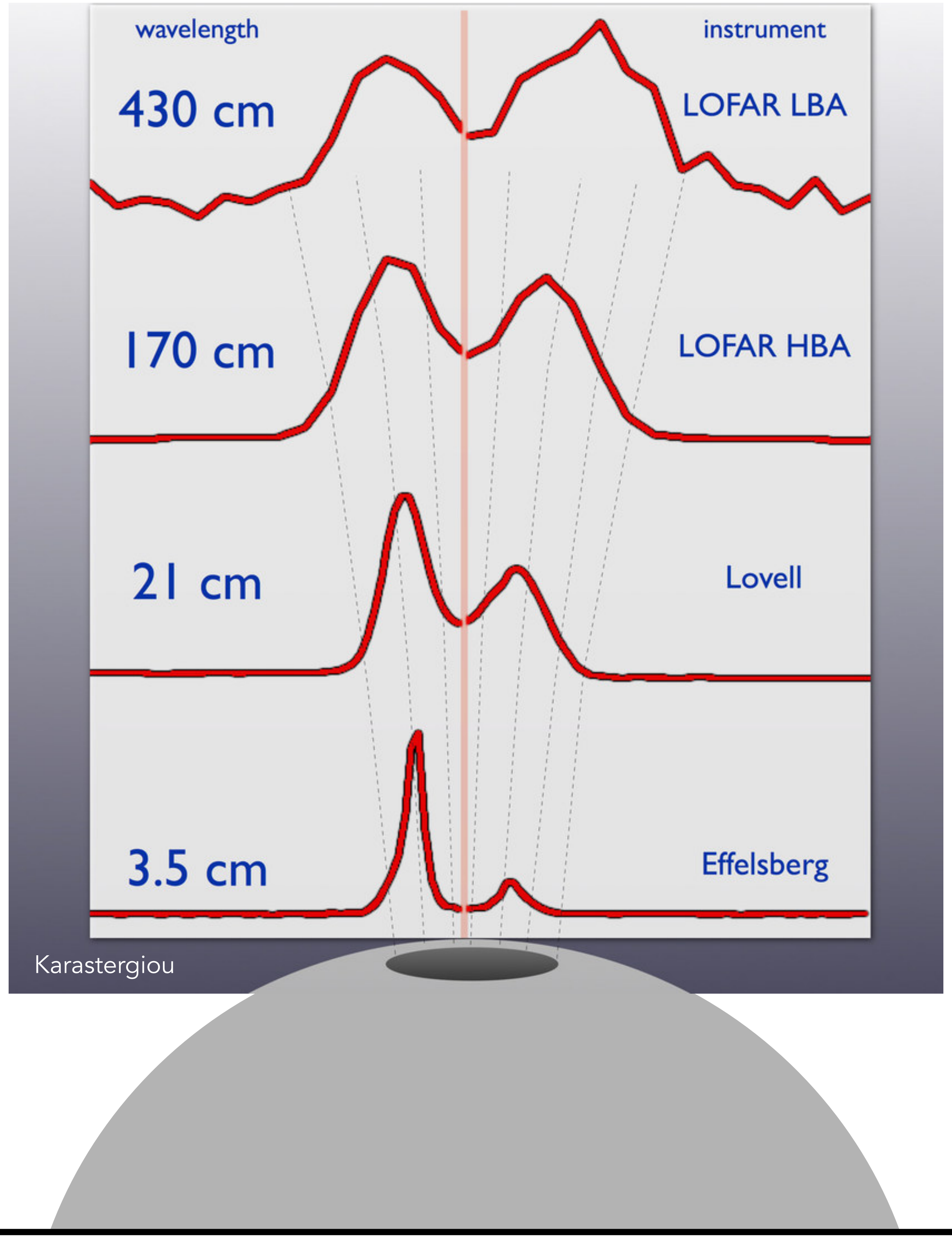

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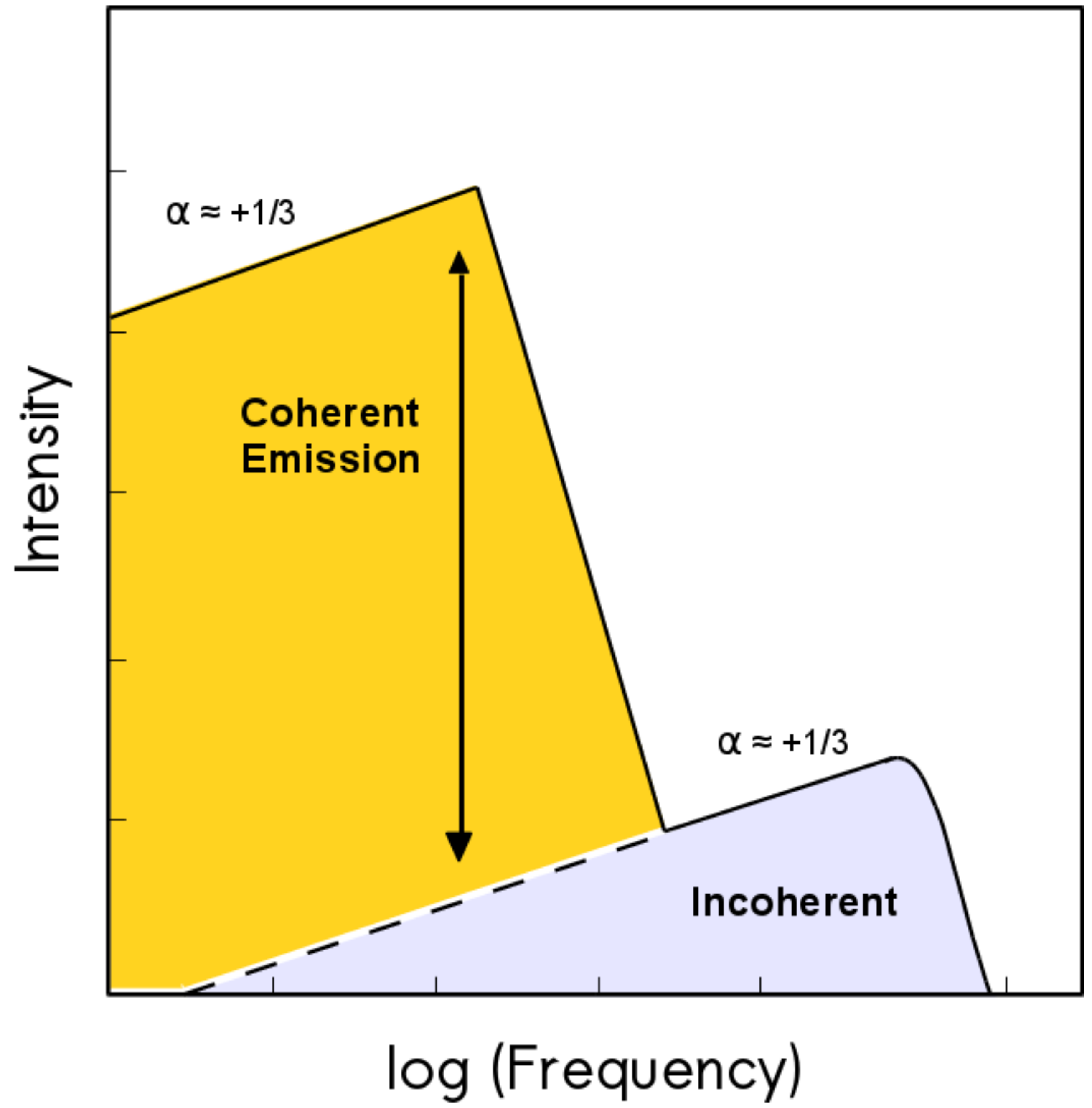
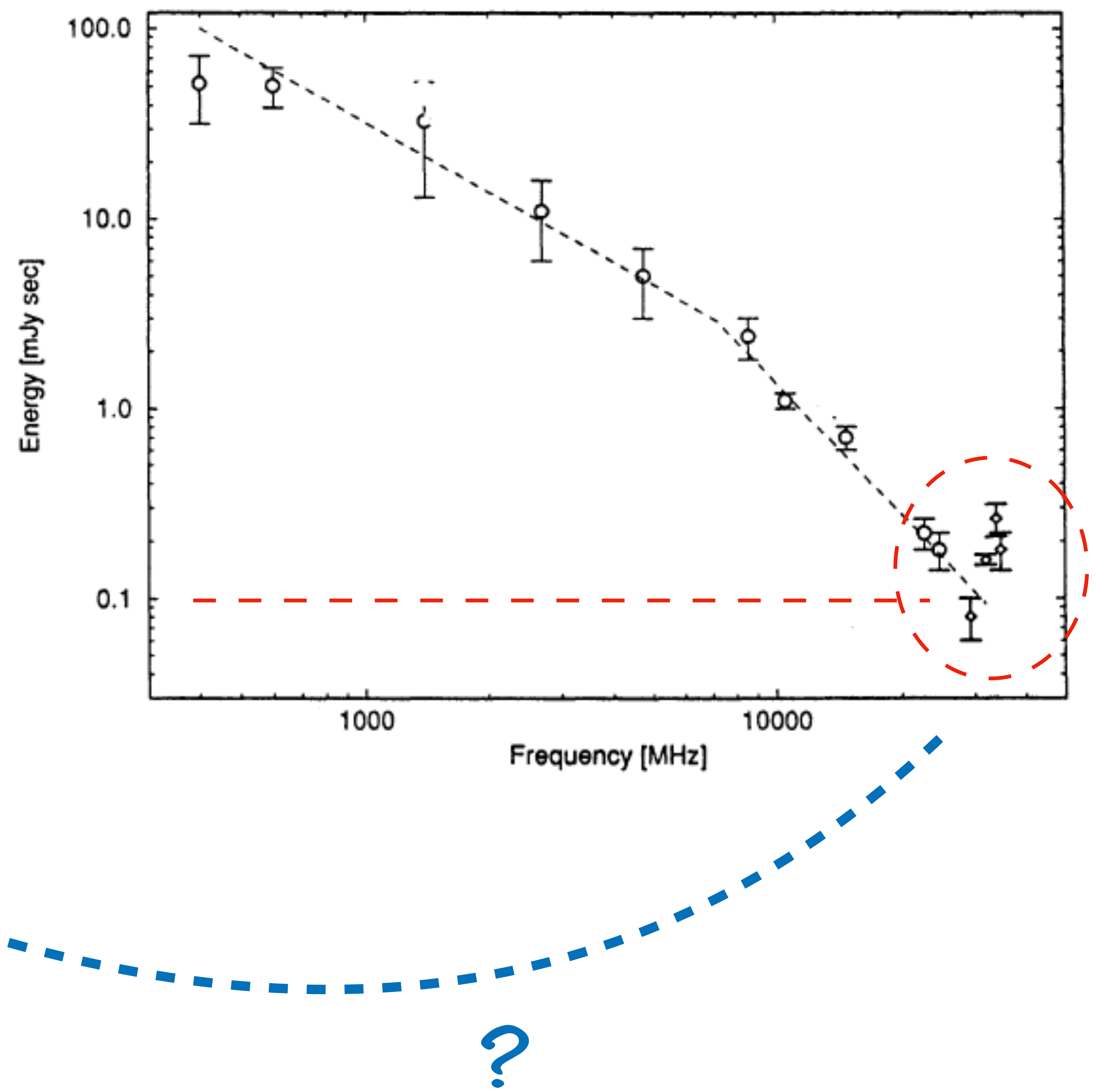


Apparent turn-up in spectrum

Kramer et al. (1996)



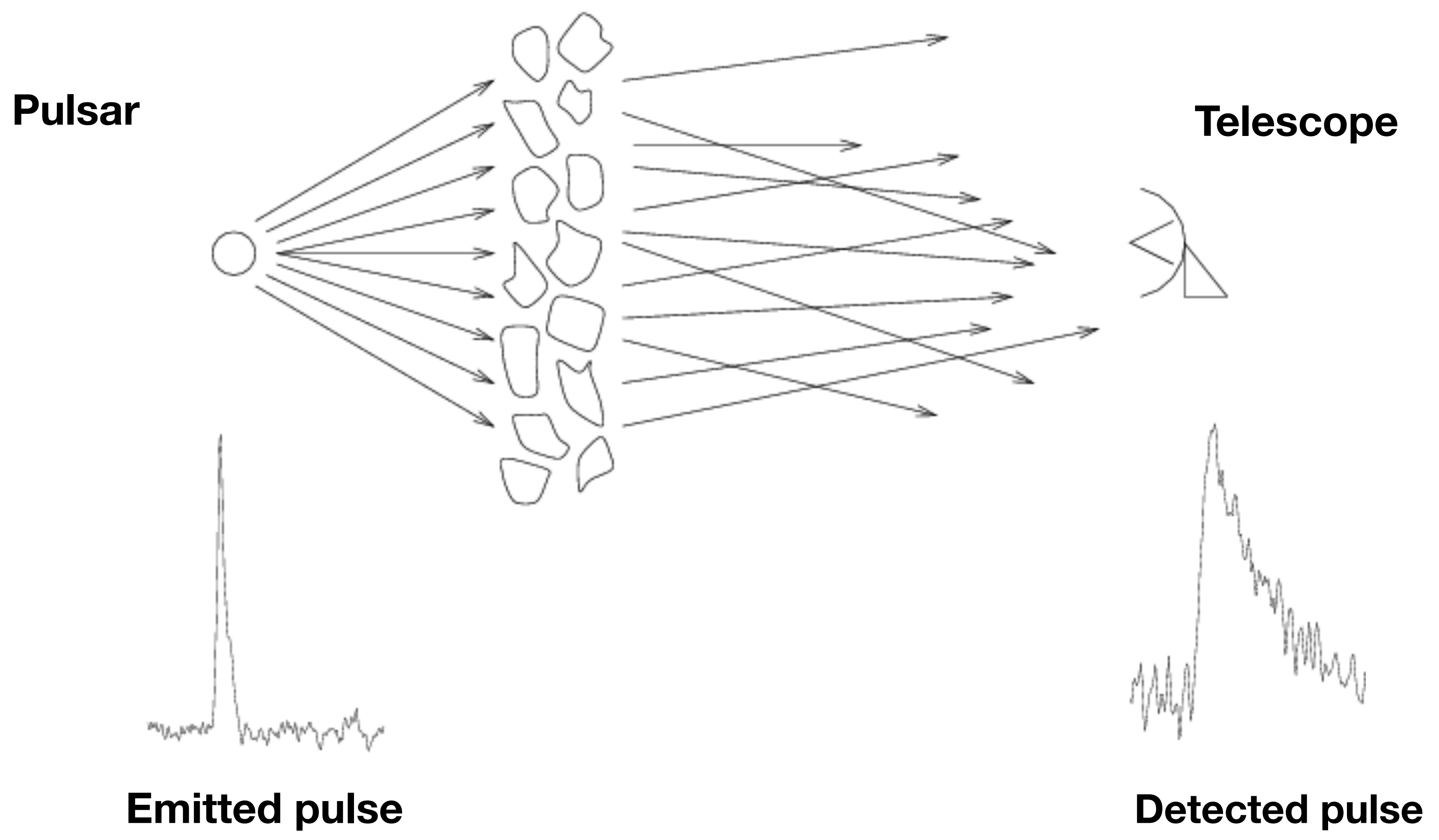
2. Observing Through Extreme Scattering Medium

- Extreme scattering can prevent the detection of pulsations !

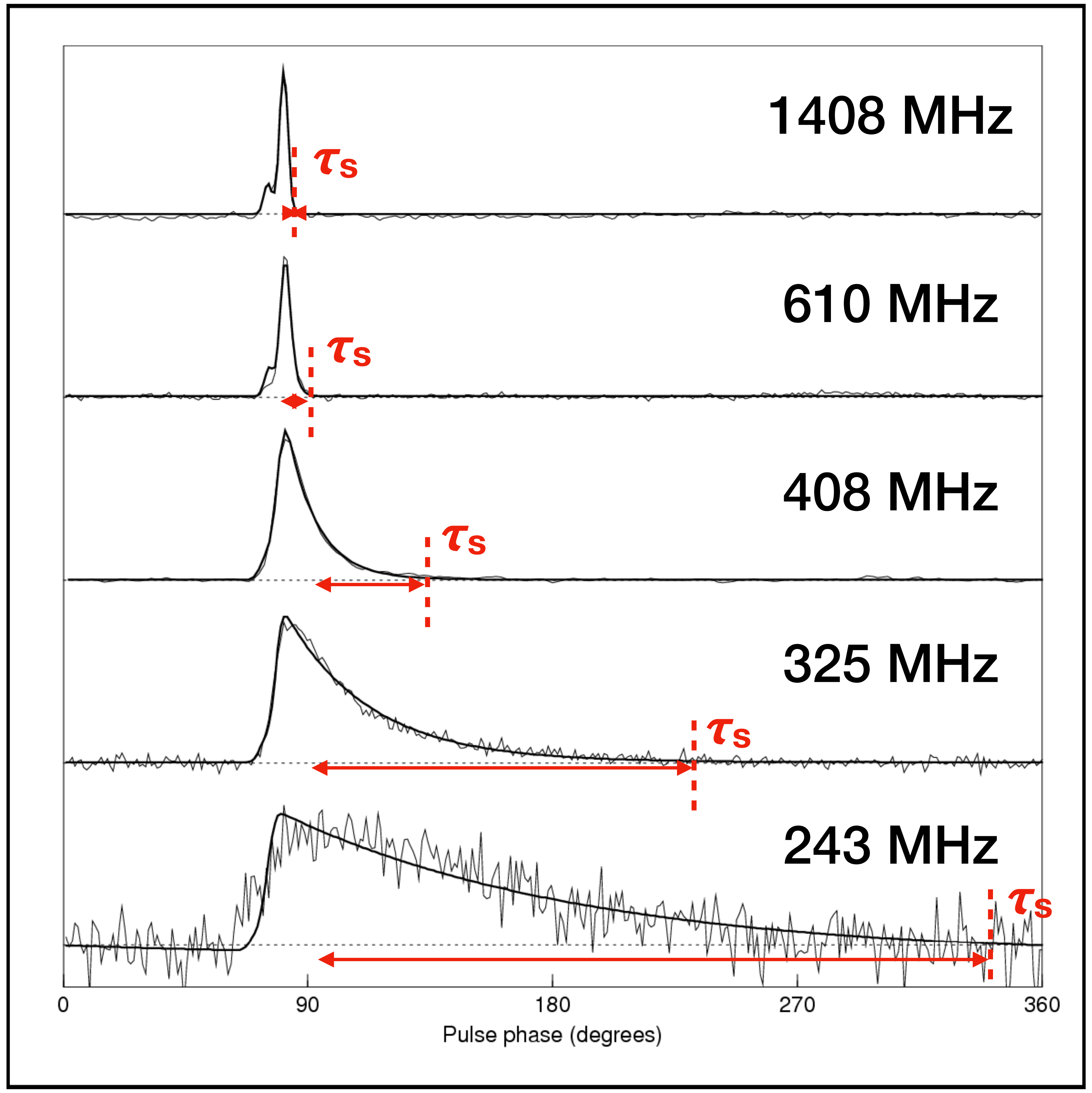
Scattering decreases very strongly with frequency: $\tau_s \propto f^{-4}$

$$I(t) \propto \exp(-c\Delta t/(\theta_d^2 d)) \equiv e^{-\Delta t/\tau_s}$$

$$\tau_s = \frac{\theta_d^2 d}{c} = \frac{e^4}{4\pi^2 m_e^2} \frac{\Delta n_e^2}{a} d^2 f^{-4}$$



Credit: D. Lorimer (WV Univ.)



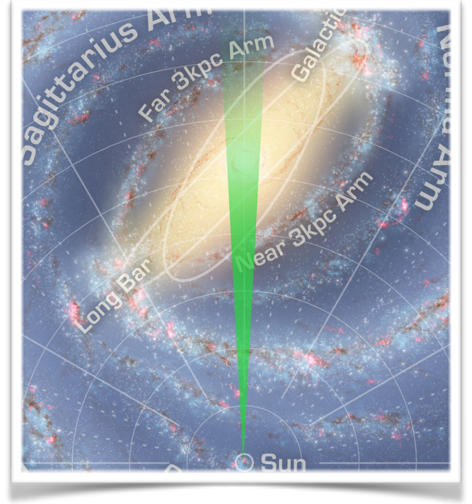
Credit: D. Löhmer et al. (2001)

2. → Pulsars in the Galactic Centre

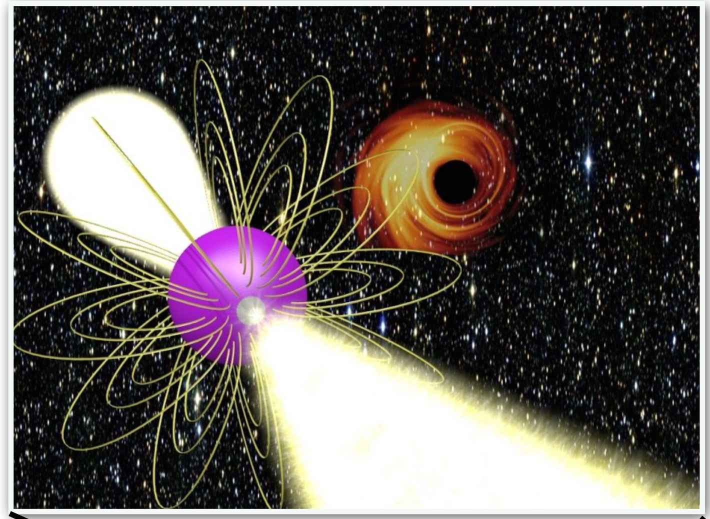
NASA/Spitzer

- Galactic Centre contains **very promising pulsar systems**
  - Probe gravitational potential of the region
  - Star forming history
  - Measure Galactic Centre gas properties with precision
  - Pulsar – Supermassive Black Hole system

★… and the **strongest scattering in the Galaxy**

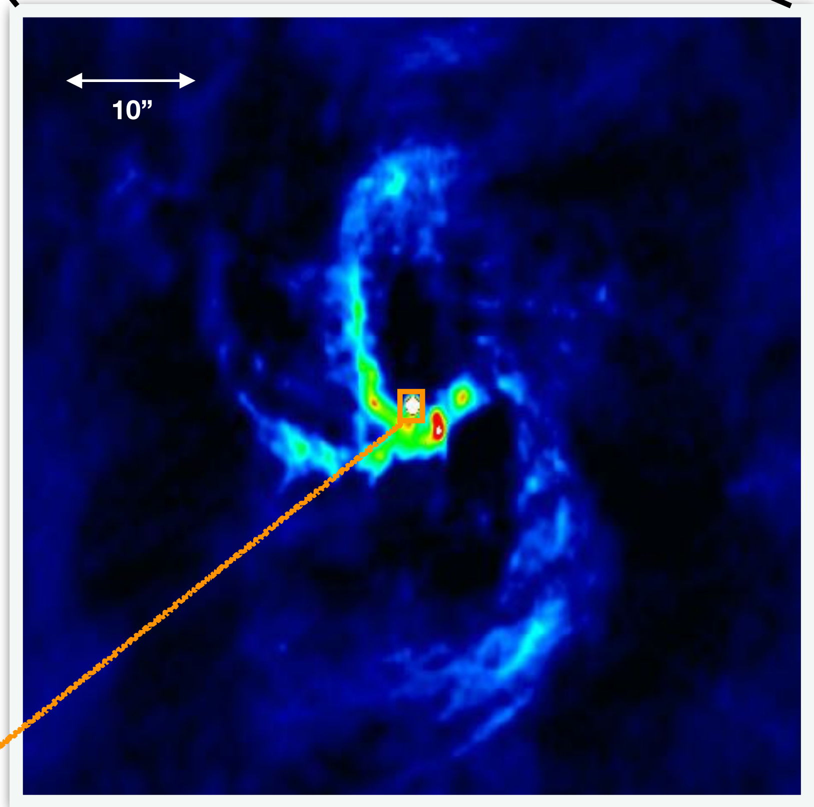


NASA/JPL

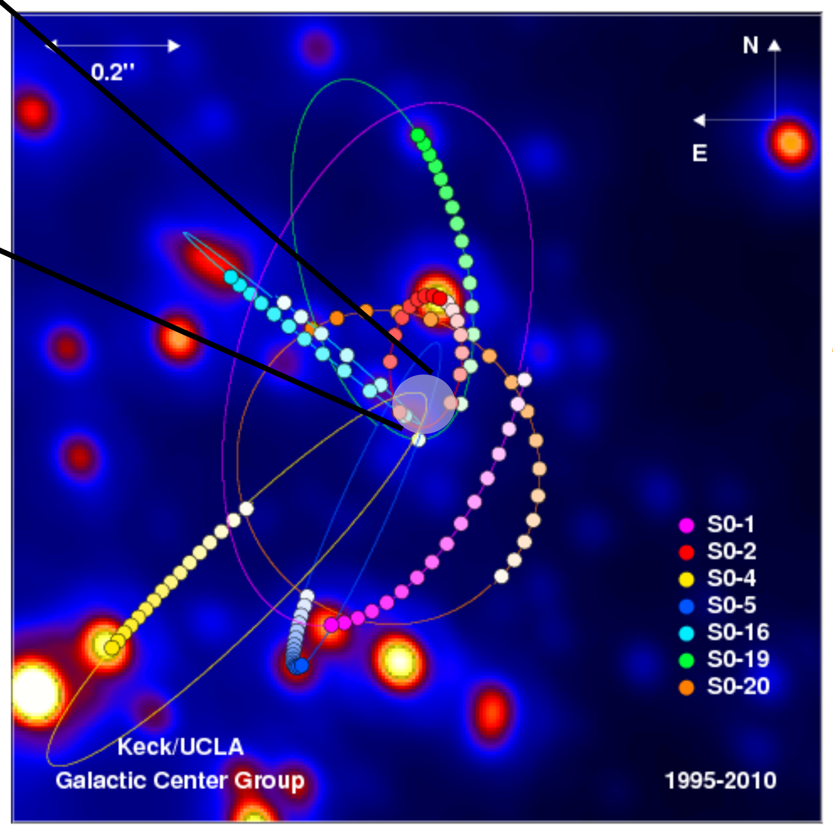


BlackHoleCam

Zoom into the Galaxy Centre



K.Y. Lo / VLA



2. → Pulsars in the Galactic Centre

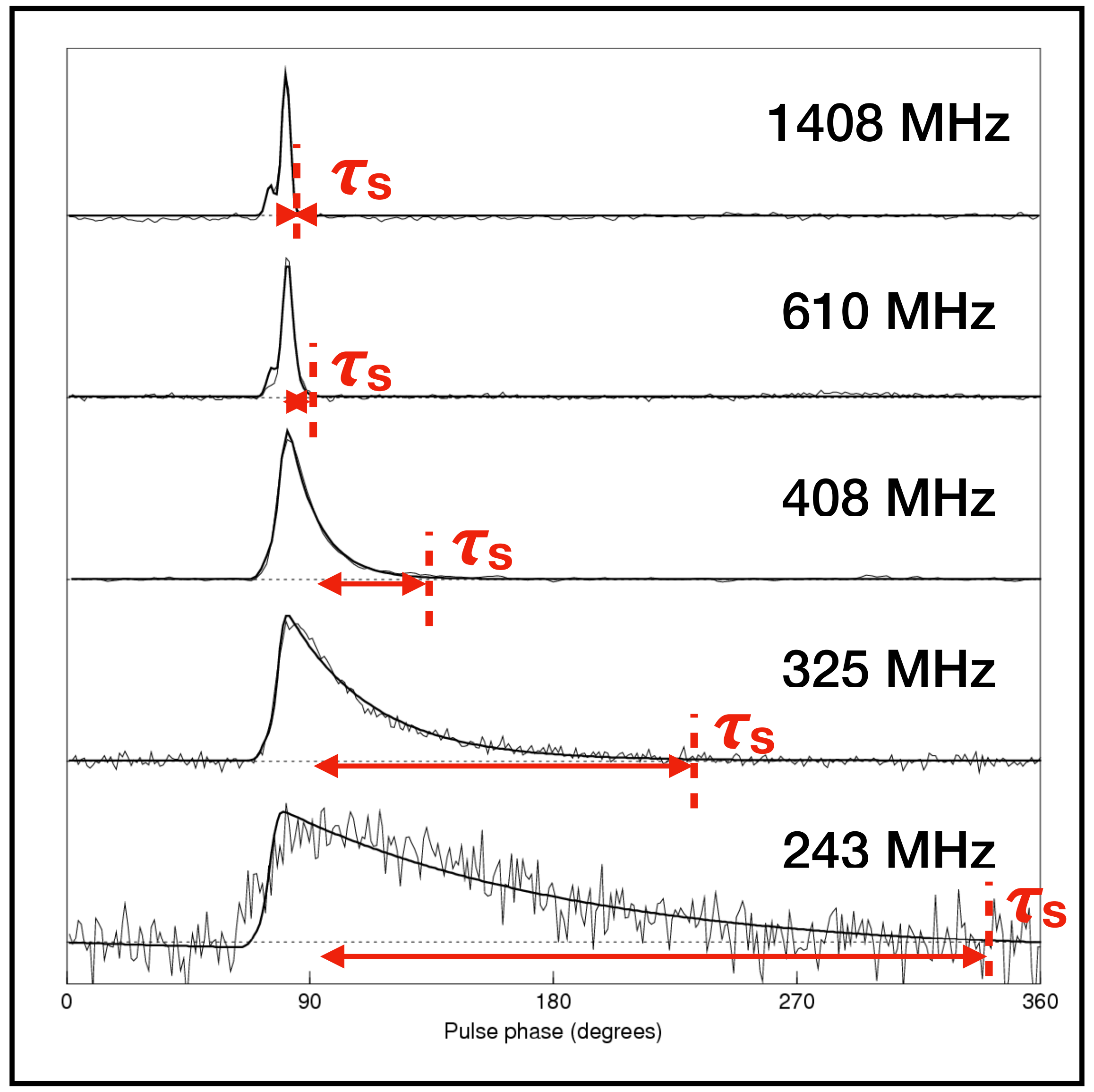
★ … and the **strongest scattering in the Galaxy**

Two main scenarios

***Hyper-strong scattering*:** τ_S @ GC ∝ **2000** seconds * f (GHz)$^{-4}$ — Lazio & Cordes (1997, 1998, 2002)

***"Weak" scattering*:** τ_S @ GC ∝ **1.3** seconds * f (GHz)$^{-3.8}$ — Spitler et al. (2014), Bower et al. (2014)

We likely do not fully understand the scattering medium in the Galaxy centre



Credit: D. Löhmer et al. (2001)

At short millimetre wavelengths scattering effect negligible

7 mm: τ_S @ GC ∝ 2000 seconds * 50 (GHz)$^{-4}$ = **320 µs**

3 mm: τ_S @ GC ∝ 2000 seconds * 87 (GHz)$^{-4}$ = **35 µs**

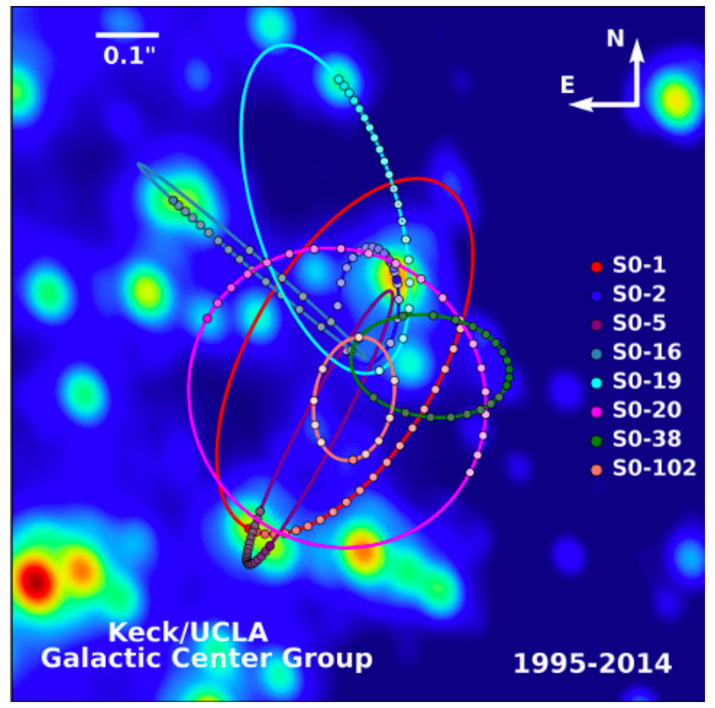
BLACK HOLE CAM

Event Horizon Telescope

2. → Pulsars in the Galactic Centre

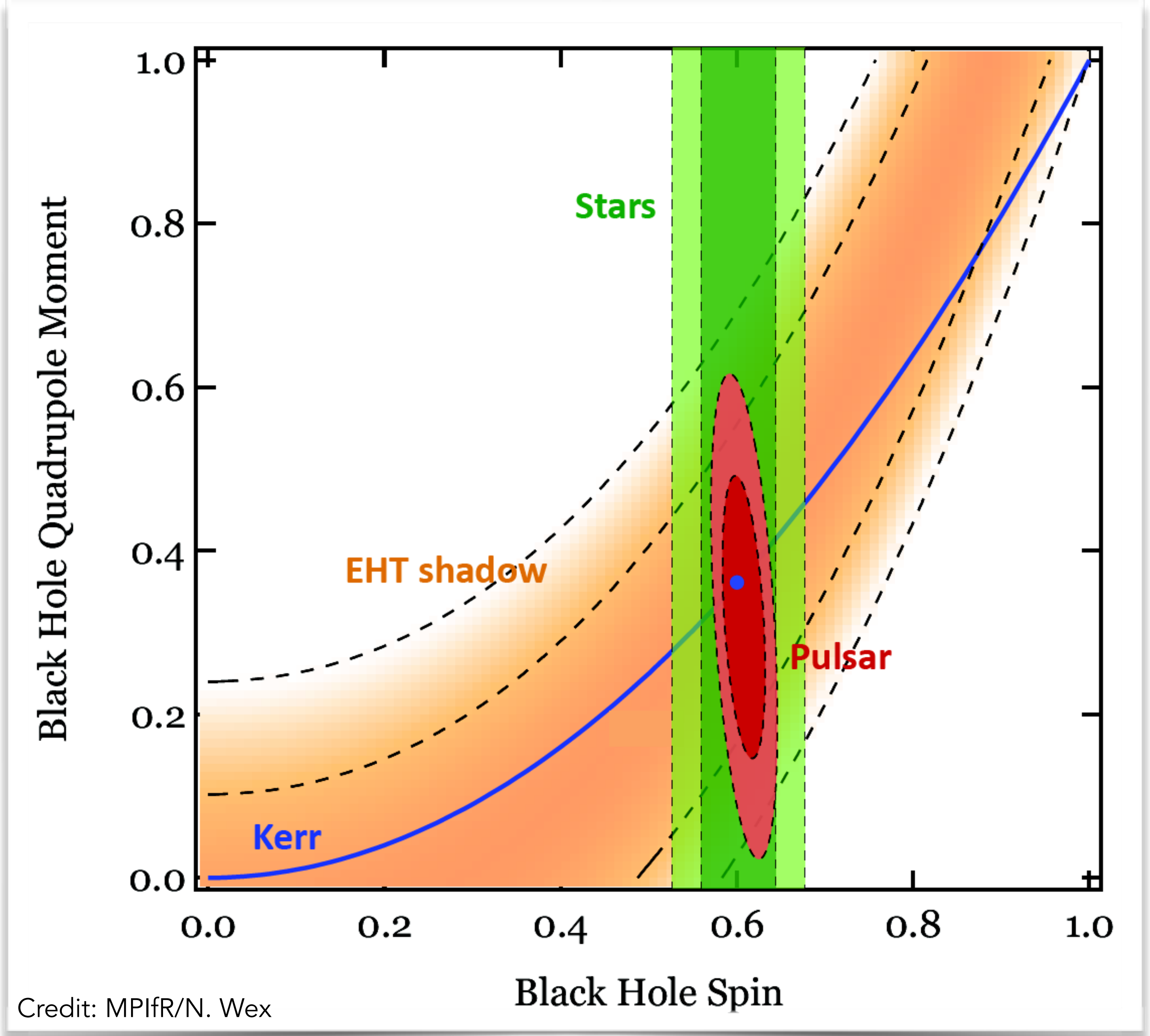
- Pulsar – Supermassive Black Hole = Best Gravity / Black Hole laboratory in the Galaxy
- A powerful synergy with the S-stars and the black hole shadow

Stars



EHT shadow

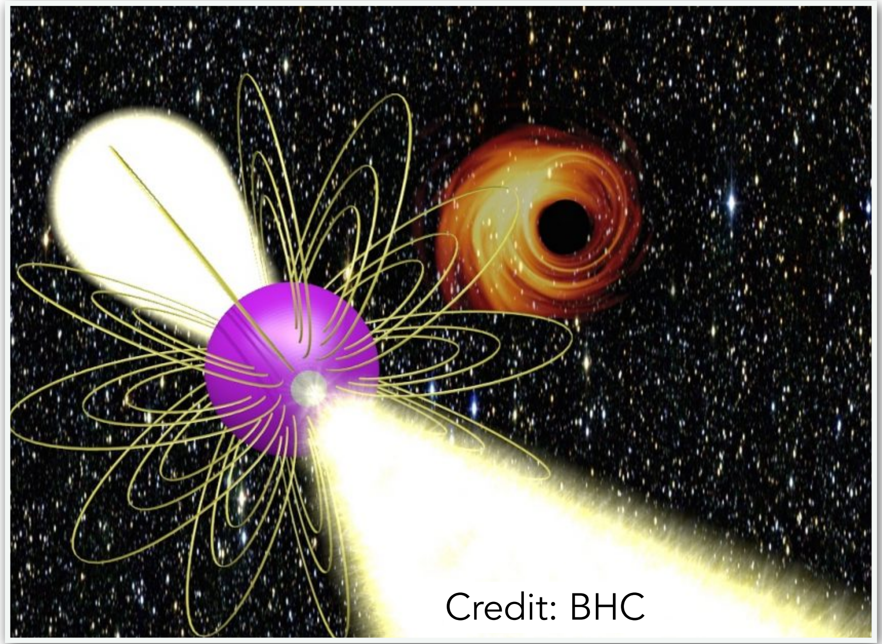
EHT Collaboration et al. (2019)



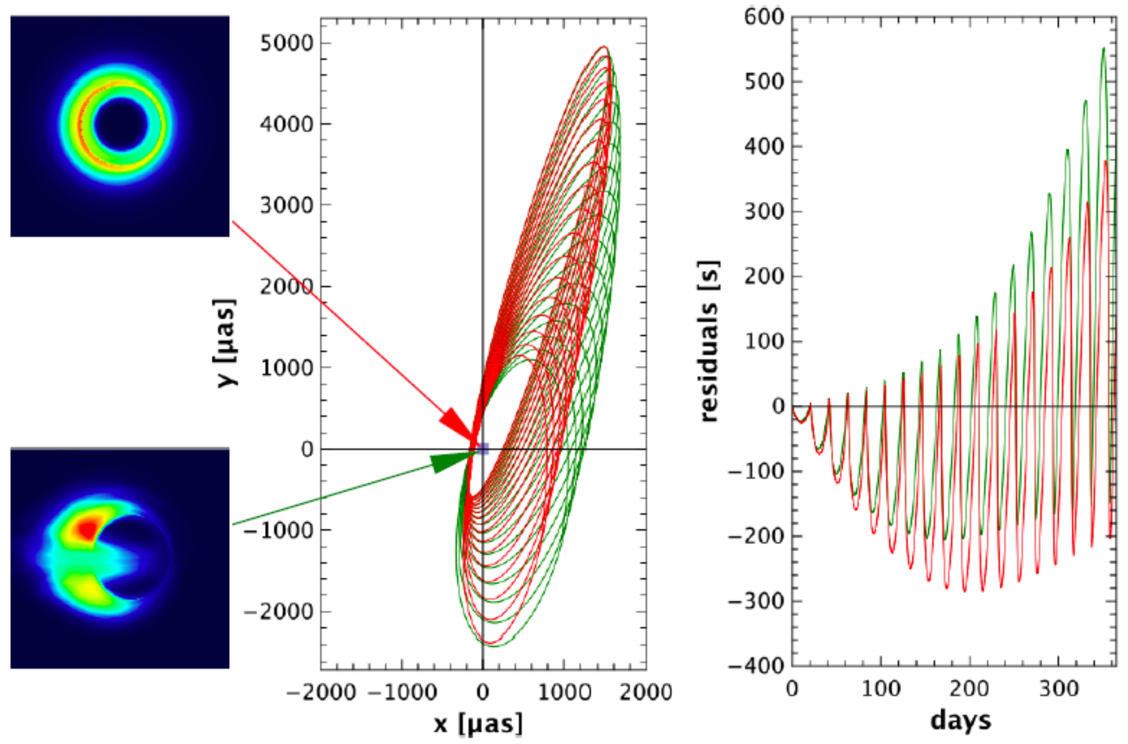
Credit: MPIfR/N. Wex

Event Horizon Telescope

Pulsars



Credit: BHC



Credit: MPIfR/N. Wex

3. Magnetars

- **Magnetars** are young pulsars with high B-fields
- Show peculiar and not-understood radio emission characteristics
  - Transient nature (turn on and off)
  - Extreme variability (factors of a few in tens of minutes!)
  - Very high degree of polarisation up to very high frequencies
  - Variable pulse profiles, spectral index

  ⋆ **Flat radio spectrum → Observable at short millimetre wavelengths !**

- Only 4 pulsars have been detected at 7 mm — Kramer et al. (1997)
- Only 3 at 3 mm (2 are magnetars) — Morris et al. (1997), Camilo et al. (2007), Torne et al. (2015)
- Only 3 at 2 mm (2 are magnetars) — Camilo et al. (2007), Torne et al. (2015), Torne et al. *in prep.*
- And 2 at 1 mm (both are magnetars) — Torne et al. (2015, 2017), Torne et al. *in prep.*

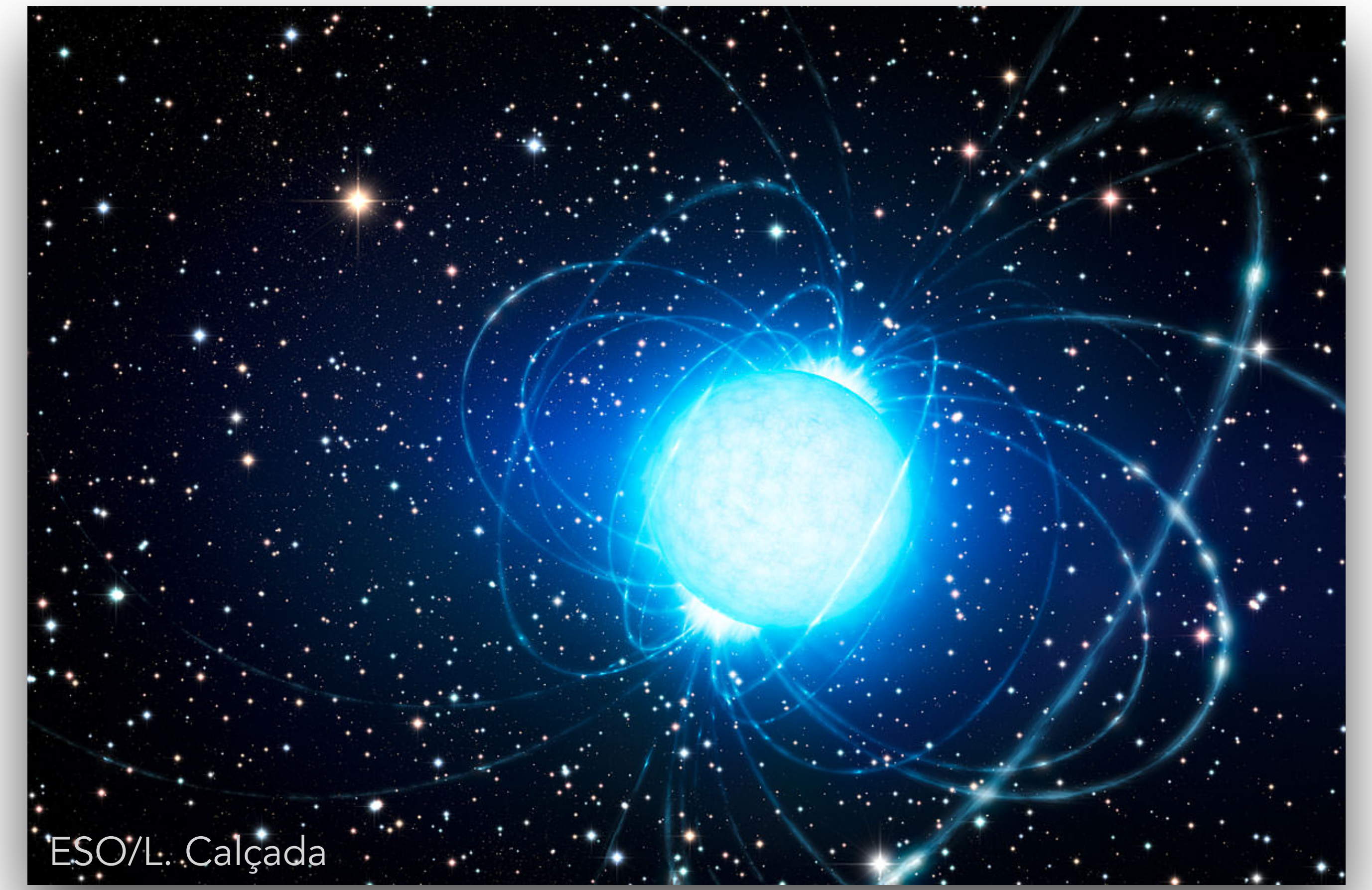
Image credit: IRAM / DivertiCimes

All done with the IRAM 30-m Telescope!

- Sometimes show inverted radio spectrum → Search for magnetar radio emission at mm- wavelengths !

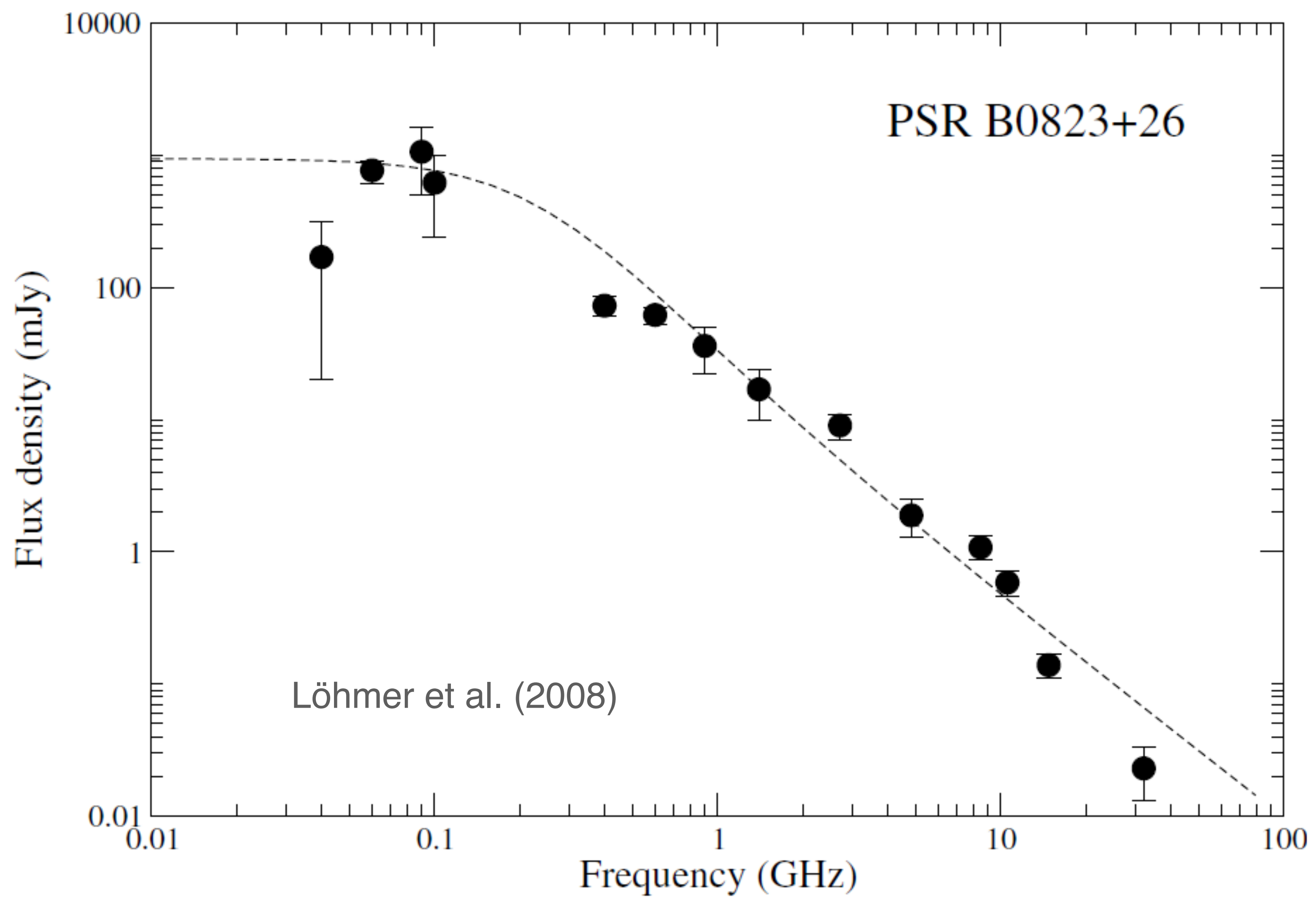
  Camilo et at al. (2007), Torne et al. (2017)

Contents



The Weakness of the Signals

- Pulsars are extremely faint radio sources
- Flux density down to ~ μJy – pJy → T_a^* ~ [10^{-6} – 10^{-12}] K !



Steep spectrum

on average

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

$<\alpha> = -1.8 \pm 0.2$

Maron et al. (2000)

Objectives at mm- wavelengths:

$\alpha > -1.2$ (70 pulsars)

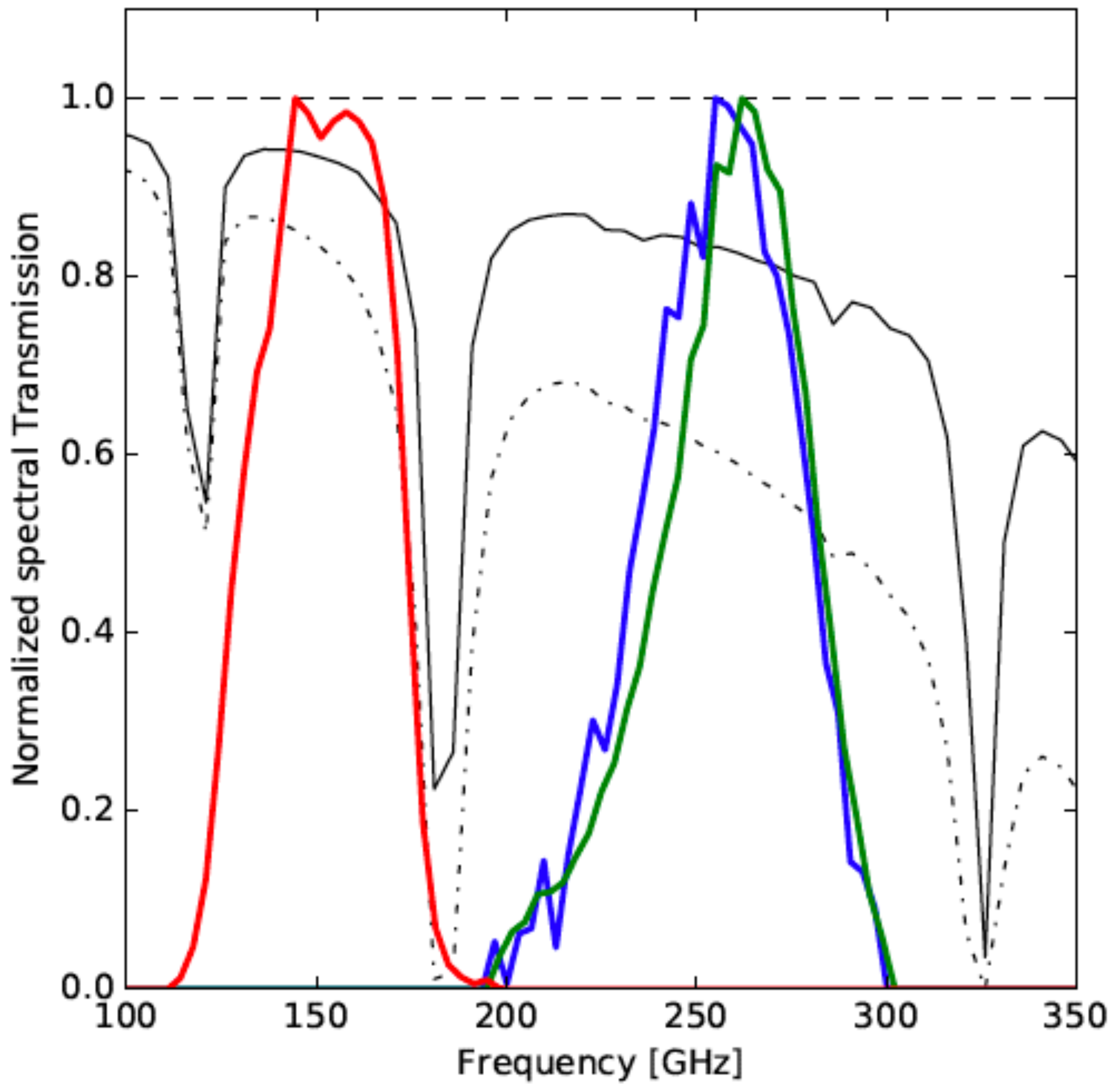
$-0.5 < \alpha < +1.0$ (Magnetars)

1. Visibility on sky
2. Flat spectrum pulsars
3. Brightest possible

The Weakness of the Signals

- NIKA2 can be extremely helpful here
- Large bandwidths = **Sensitivity!**

Adam et al. (2018)



Minimum detectable flux density at S/N level

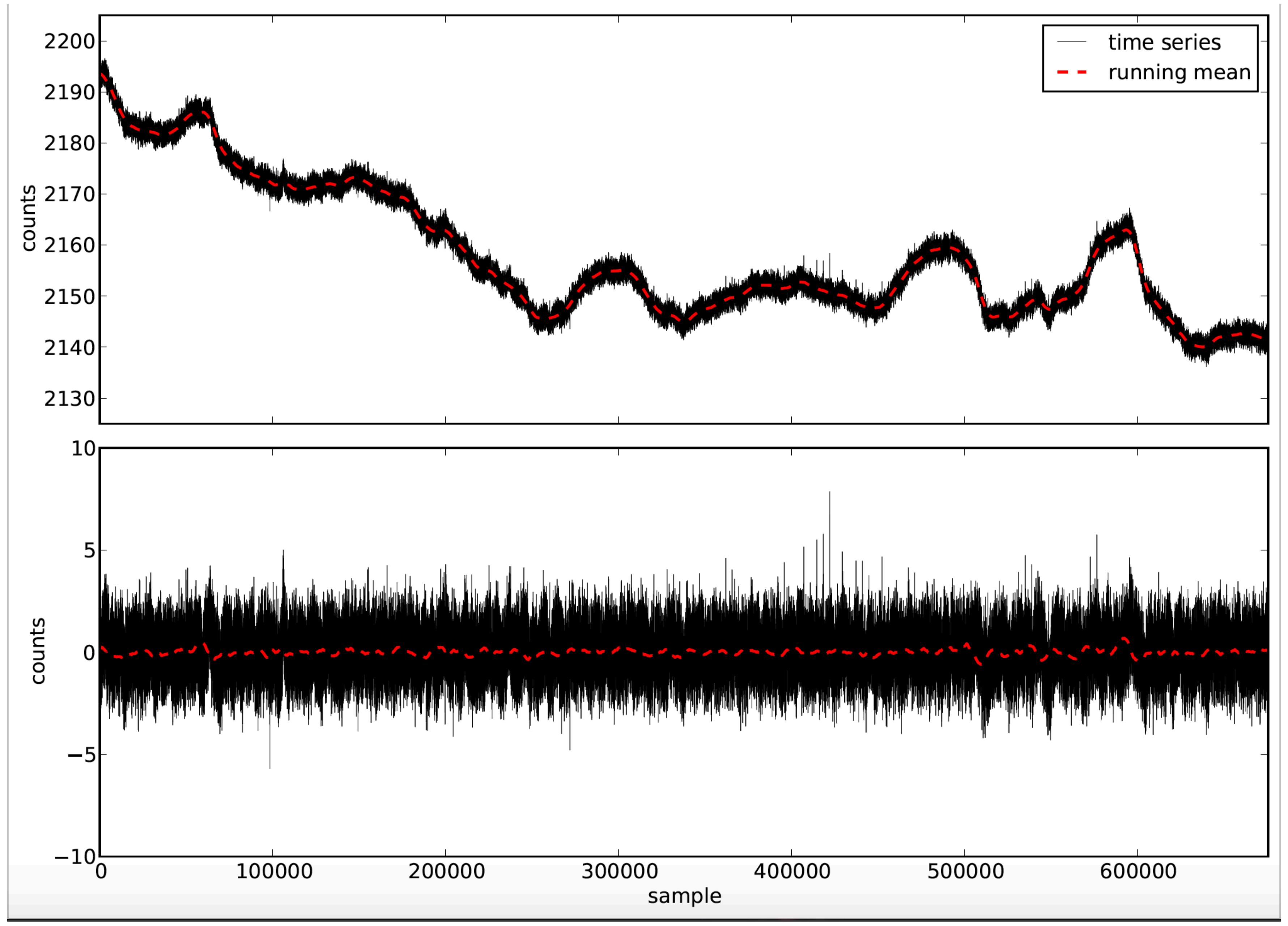
$$S_{\min} = \beta \frac{(S/N_{\min})\, T_{\mathrm{sys}}}{G\sqrt{n_{\mathrm{p}}\, t_{\mathrm{obs}}\, \Delta\nu}} \quad \text{[Jy]}$$

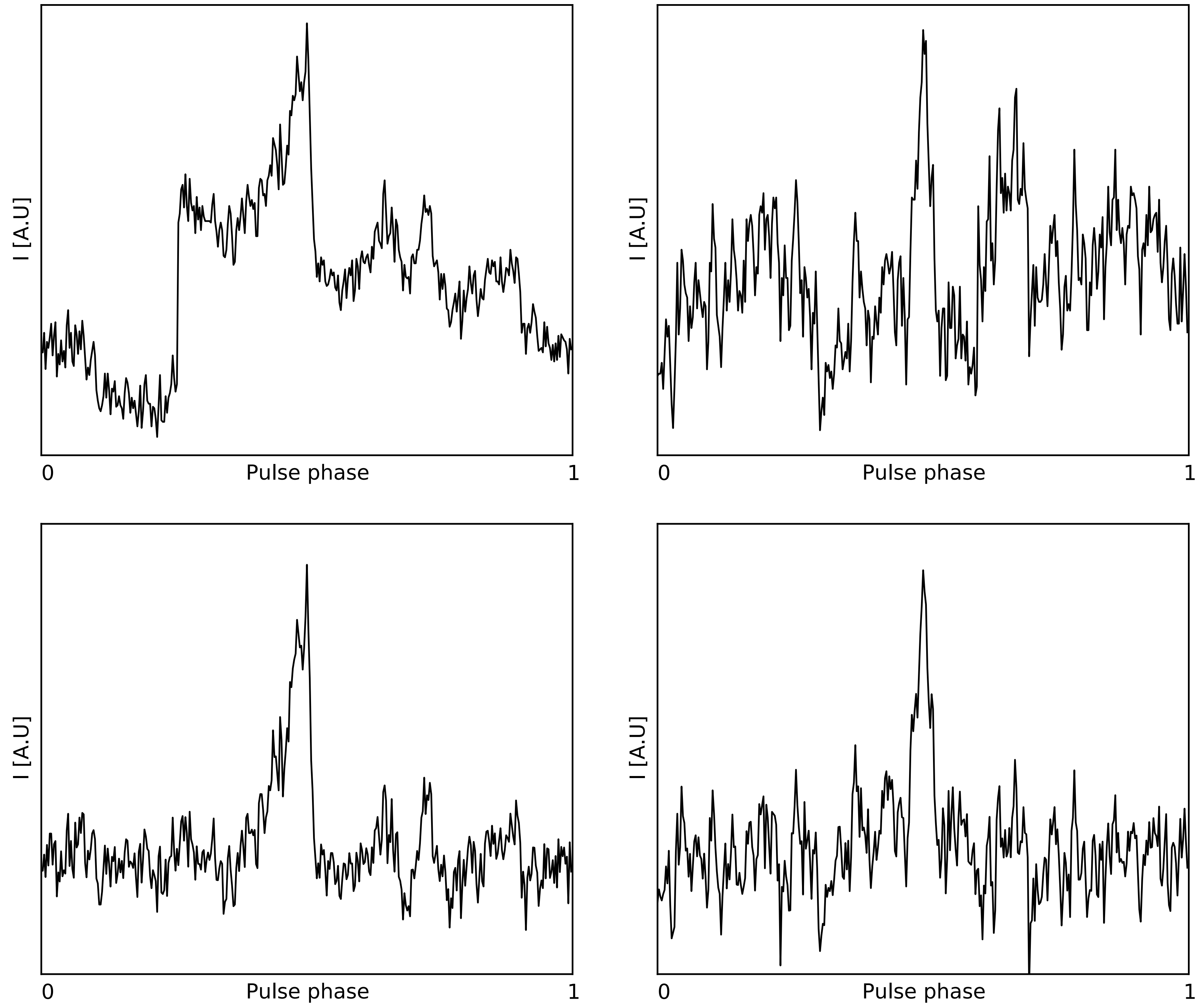
NIKA2: more radiometer-like noise than SiS Rx

To observe pulsars we want **as much bandwidth as possible!**
(and long integration times...)

The Variations of the Atmosphere

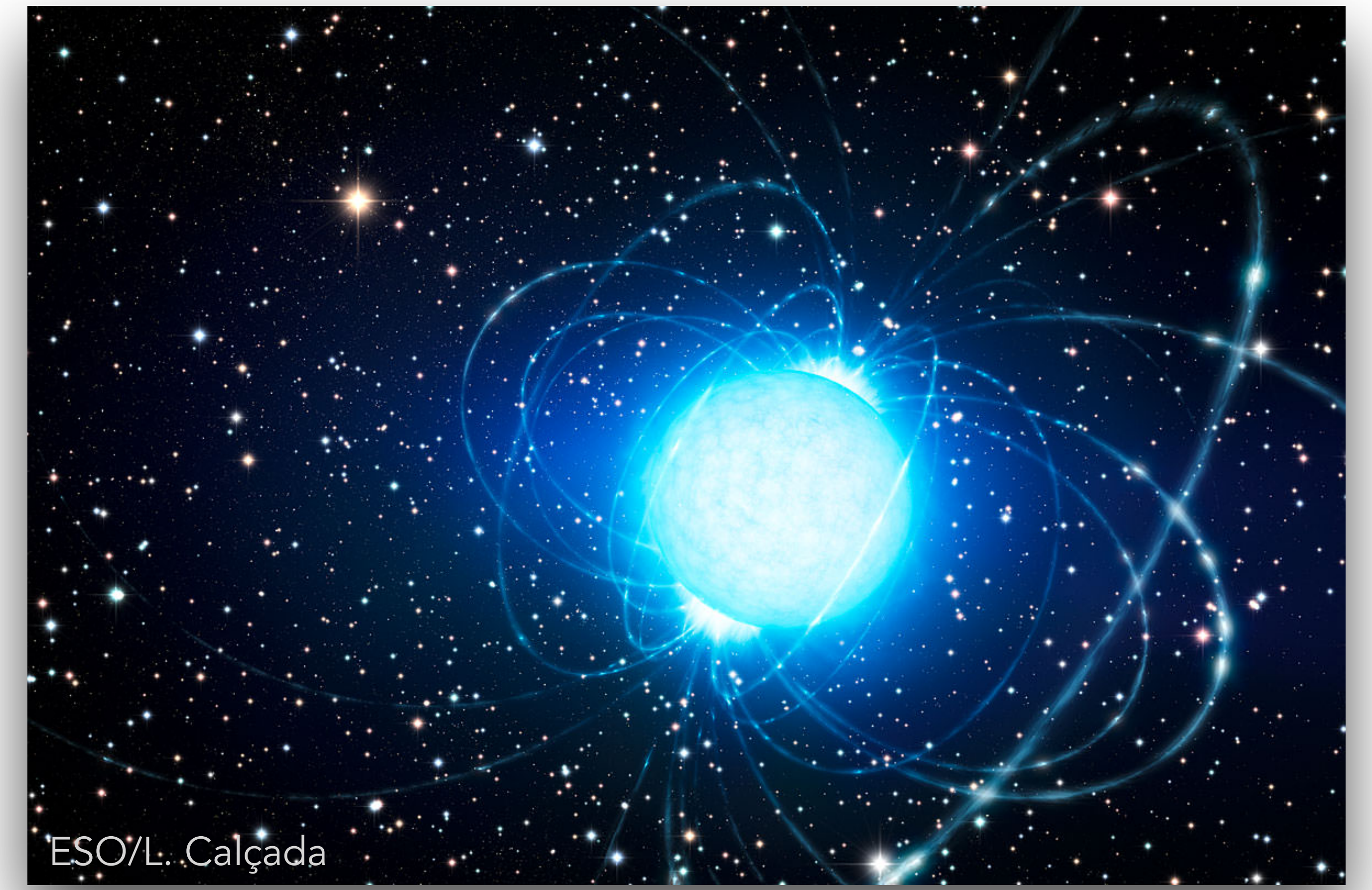
- Pulsars are observed in “track" mode, to avoid loss of coherency
- Subtracting the atmosphere is a critical step in data reduction
- Multiple pixels on sky can help tremendously!





Effective subtraction of atmosphere will **further increase our sensitivity!**

Contents

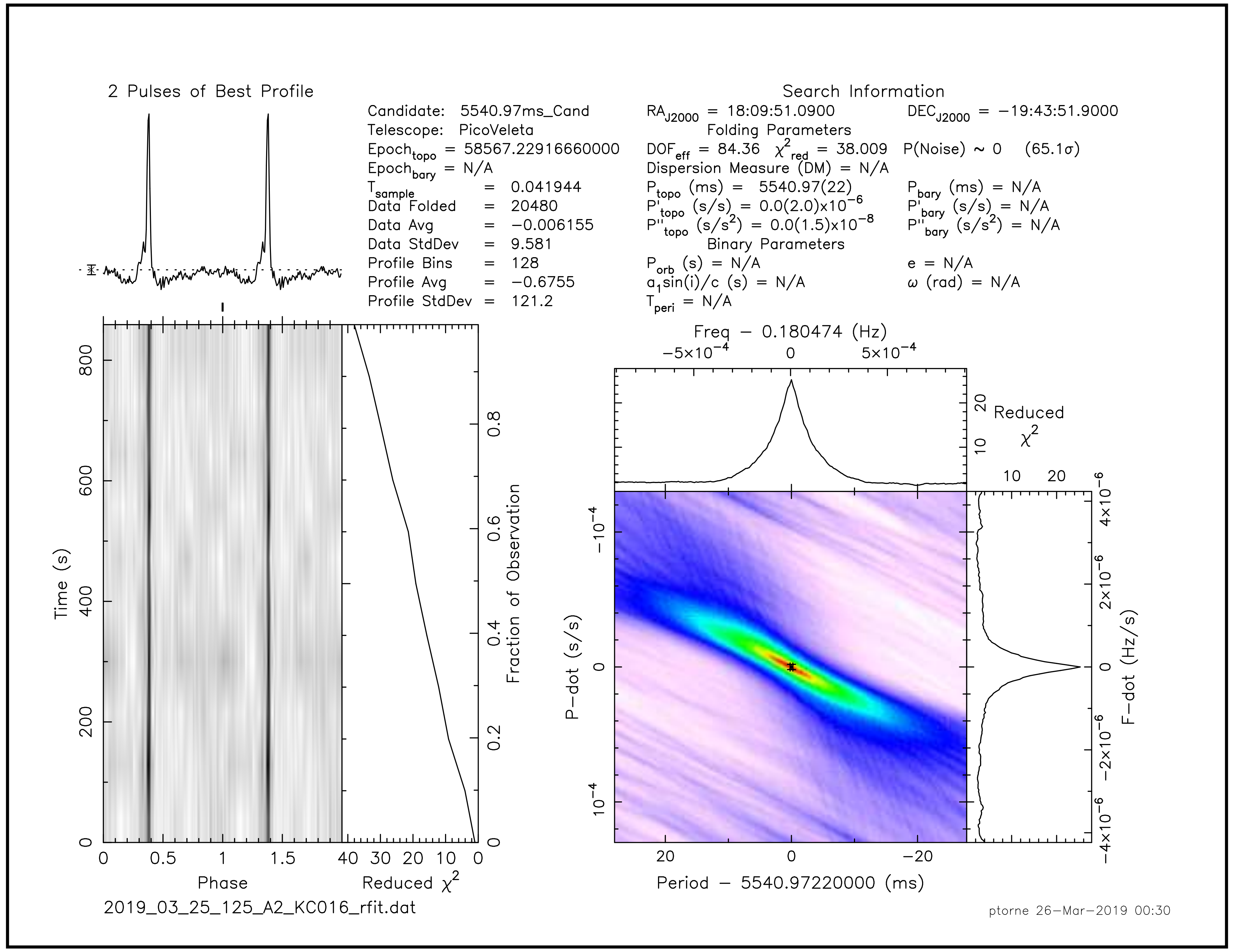


First Pulsar Detection with NIKA2 !

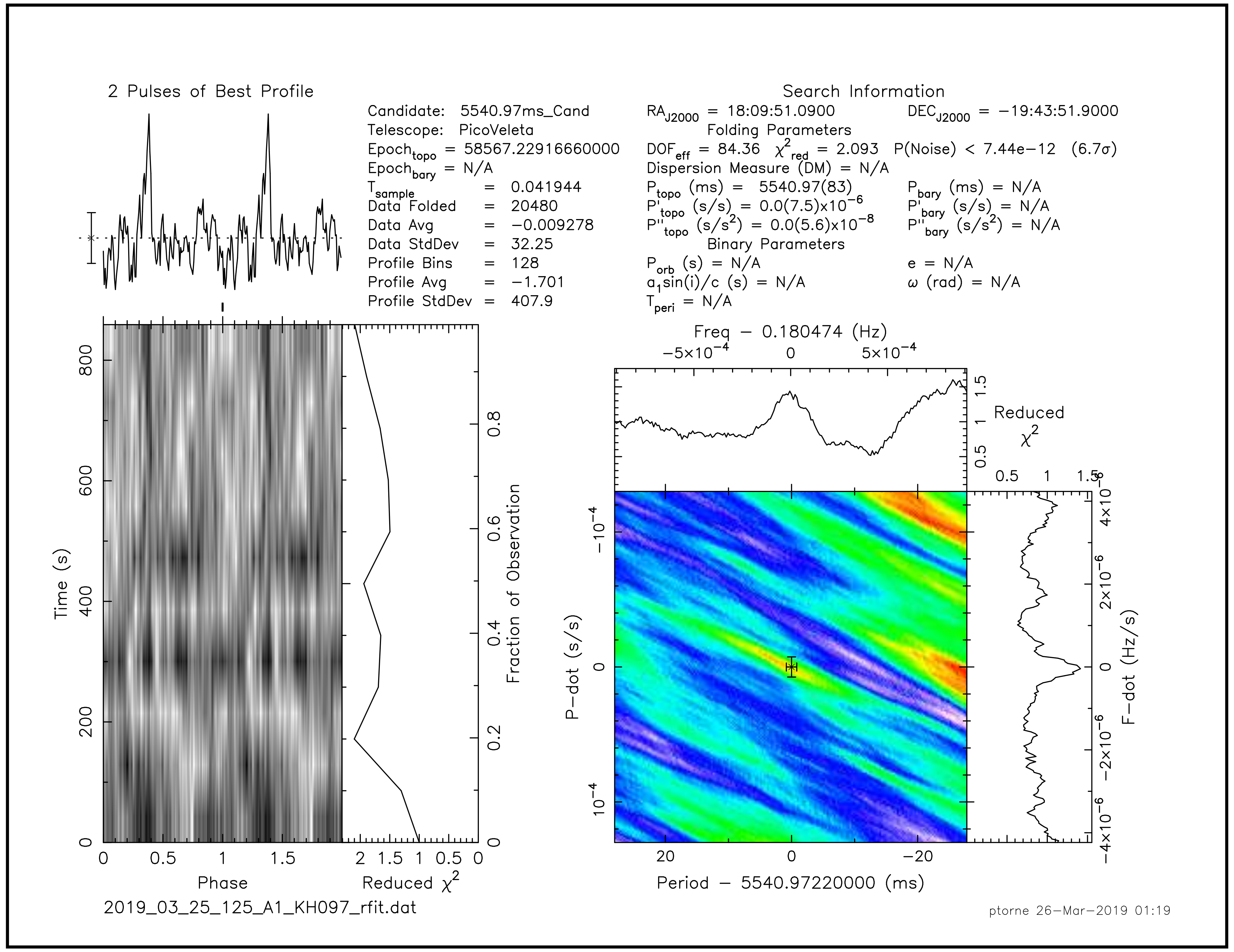
- 2019: Can a KID camera detect pulsars? YES, nicely!
- AXP1810−197 @ NIKA2, 1 hr obs. on 23-March-2019

Torne et al. *in prep*

Detection with 2 mm array



Detection with 1.3 mm array



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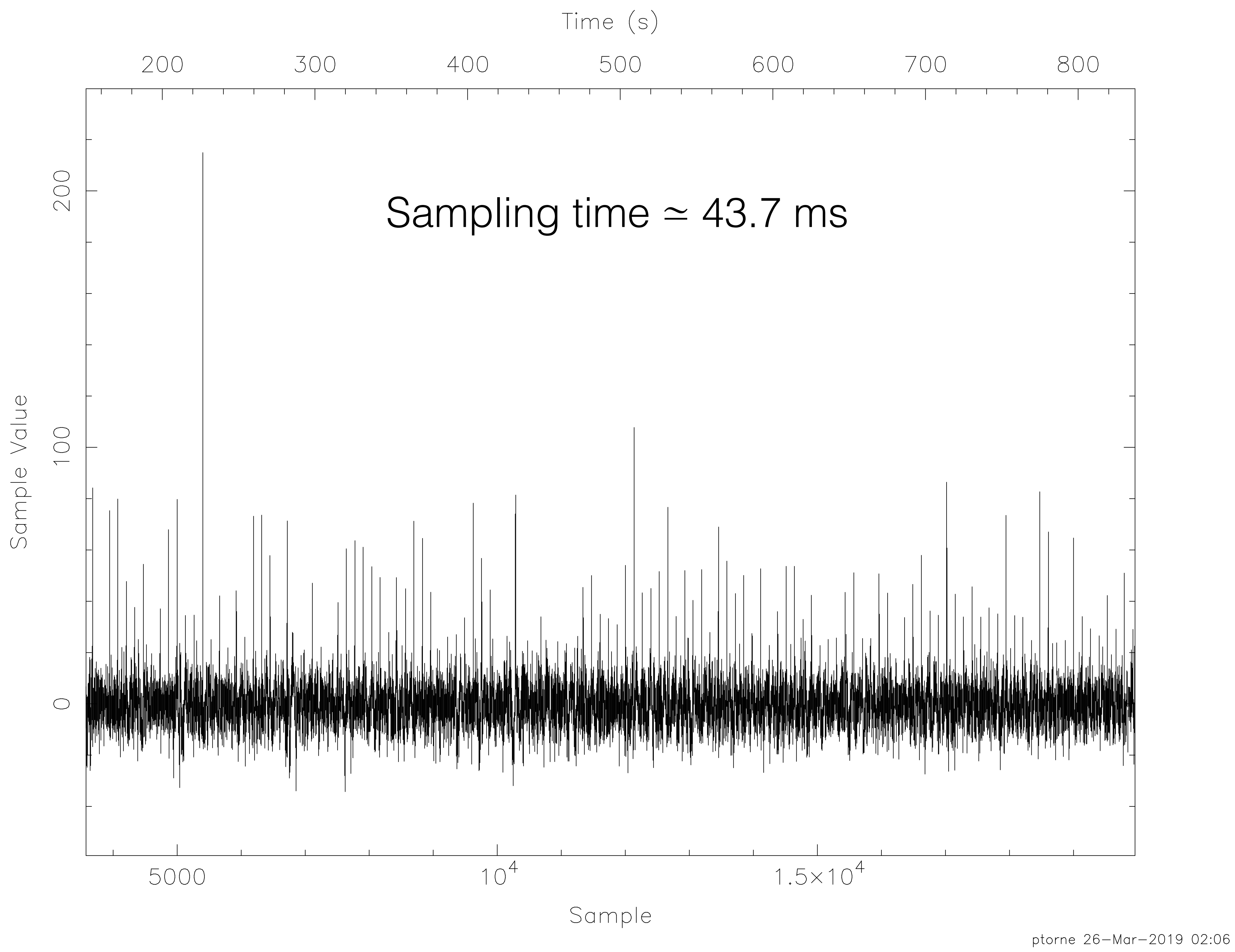
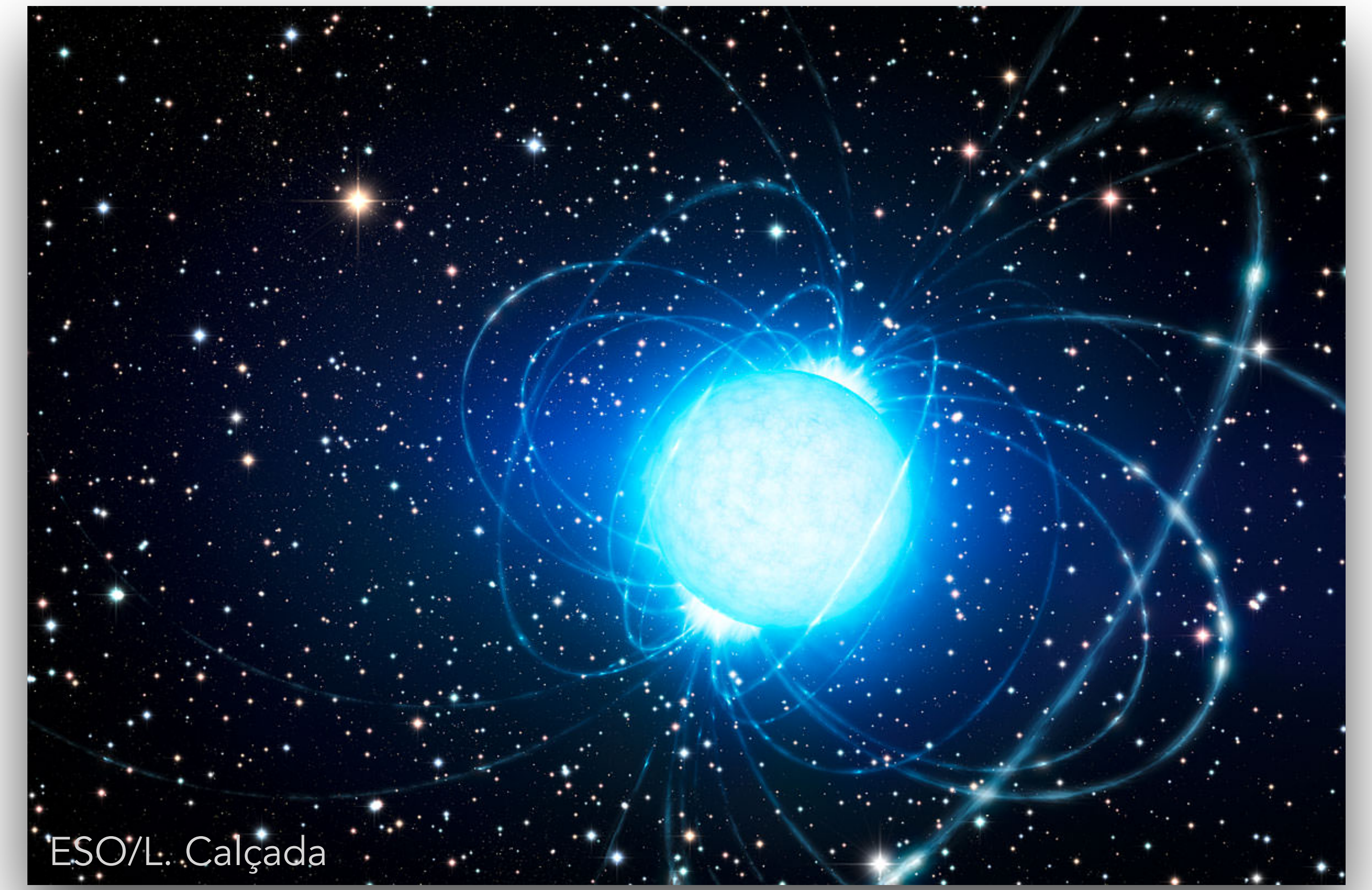
Time series with 2 mm array



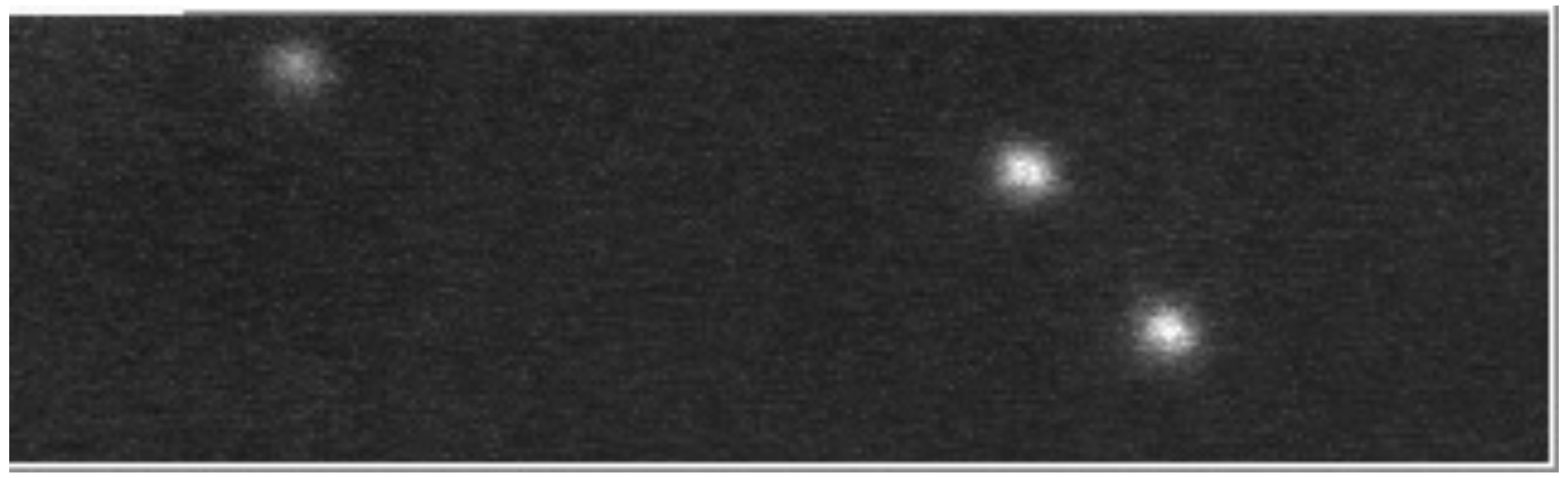
Individual rotations of the neutron star seen!

Contents

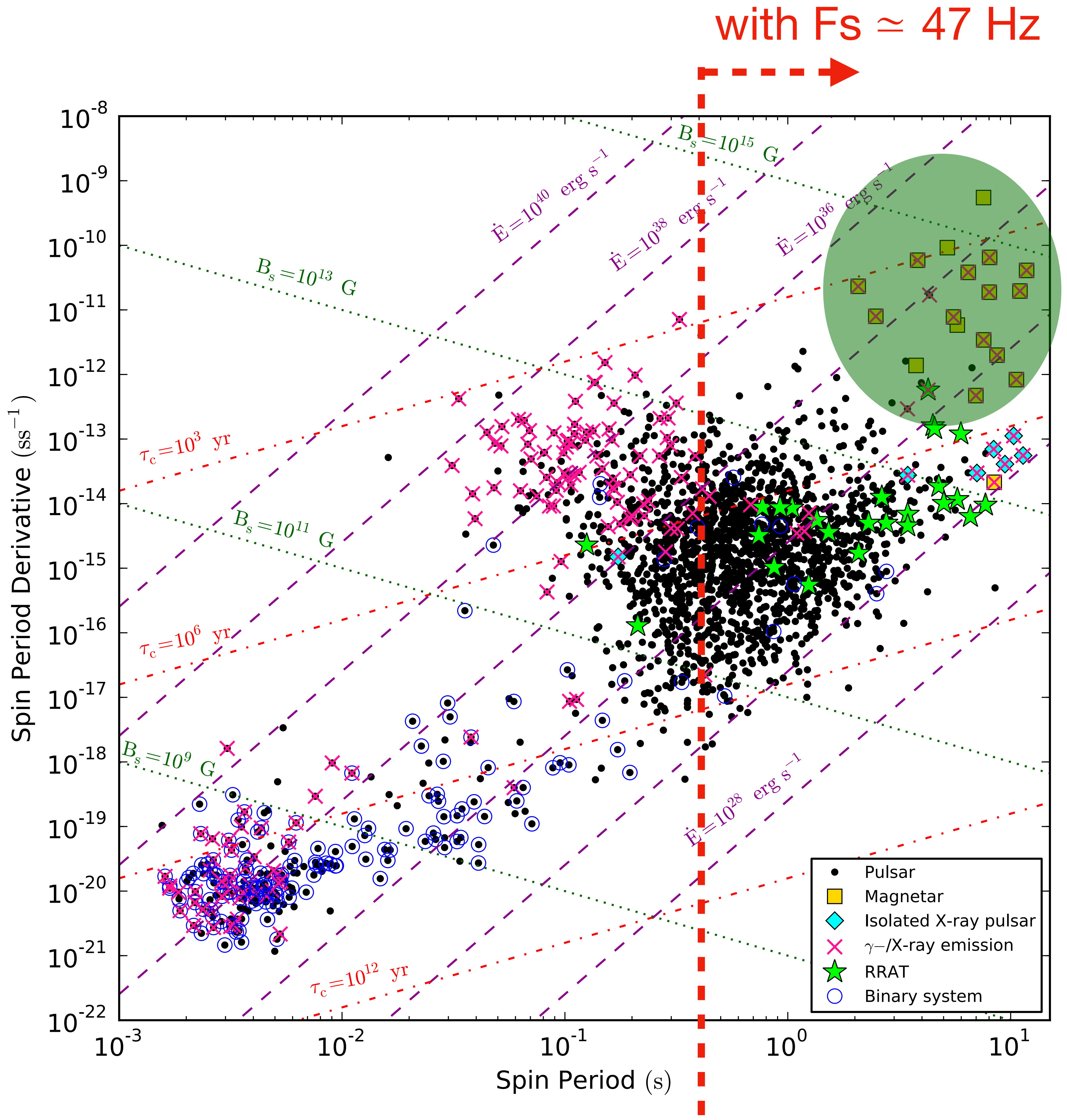


NIKA2 and Pulsars

- **NIKA2** is a powerful instrument, **very sensitive to detect pulsars**
- **Subtraction of atmosphere** can be done in new clever ways
- Rule of ~32 point per rotation of neutron star:
  - To observe the majority of pulsars we **need faster sampling**
- A **precise time stamp** of data is also a need
- In the radio band, lower frequency better: **3 mm sensor?**
- Infrared / Optical: KIDs may be a revolution for pulsar science



Credit: Cambridge University



Thank you !