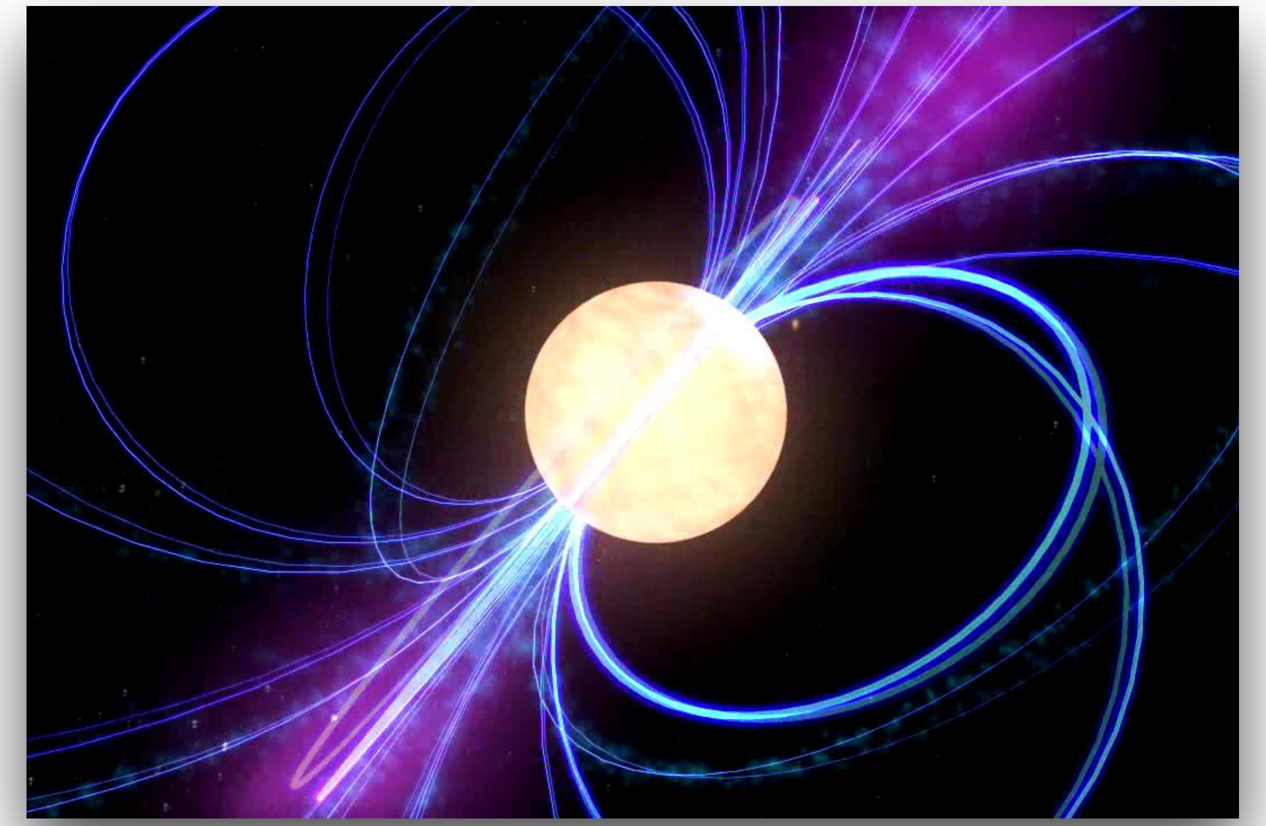
Exploring the properties of pulsar radiation at (sub)millimeter wavelengths



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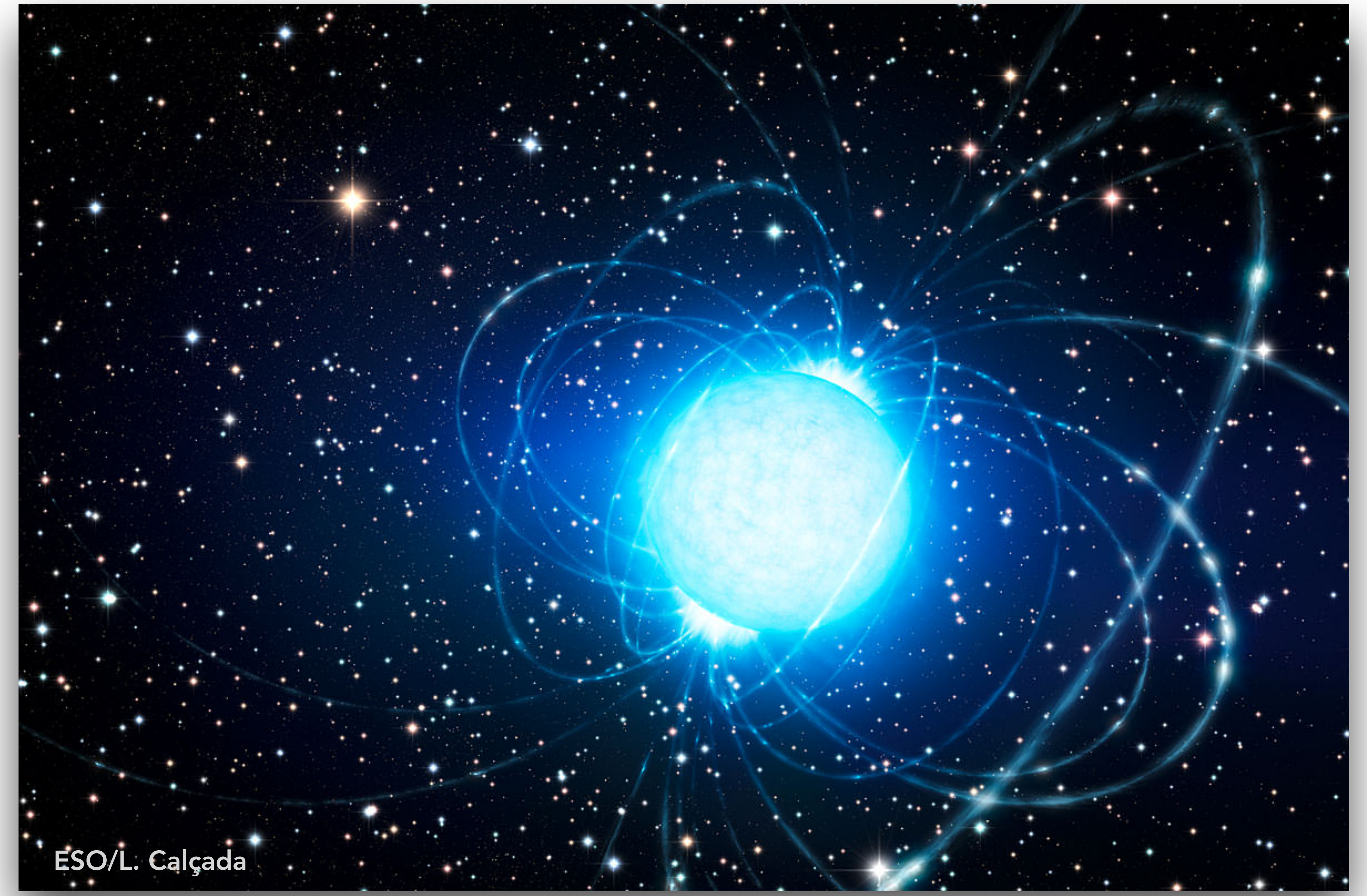
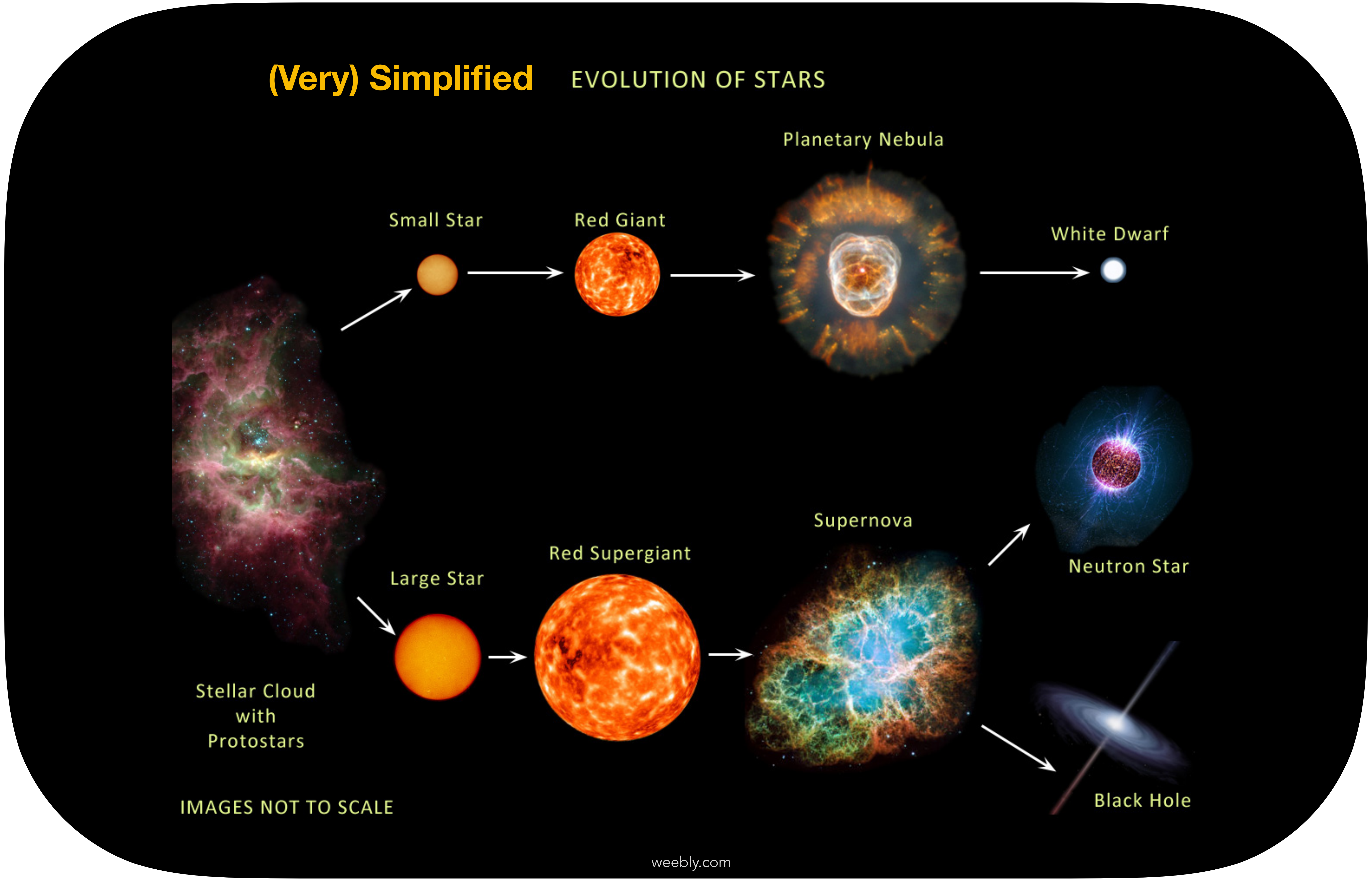
Contents



- Introduction to pulsars
- The radio emission mechanism problem
- Challenges to observe pulsars at short wavelengths
- Observations in the (sub)millimeter range
- Future, and how could the JCMT help
- Q&A

The Birth of Pulsars



Pulsars

The Crab Nebula

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

Pulsars

The Crab Nebula

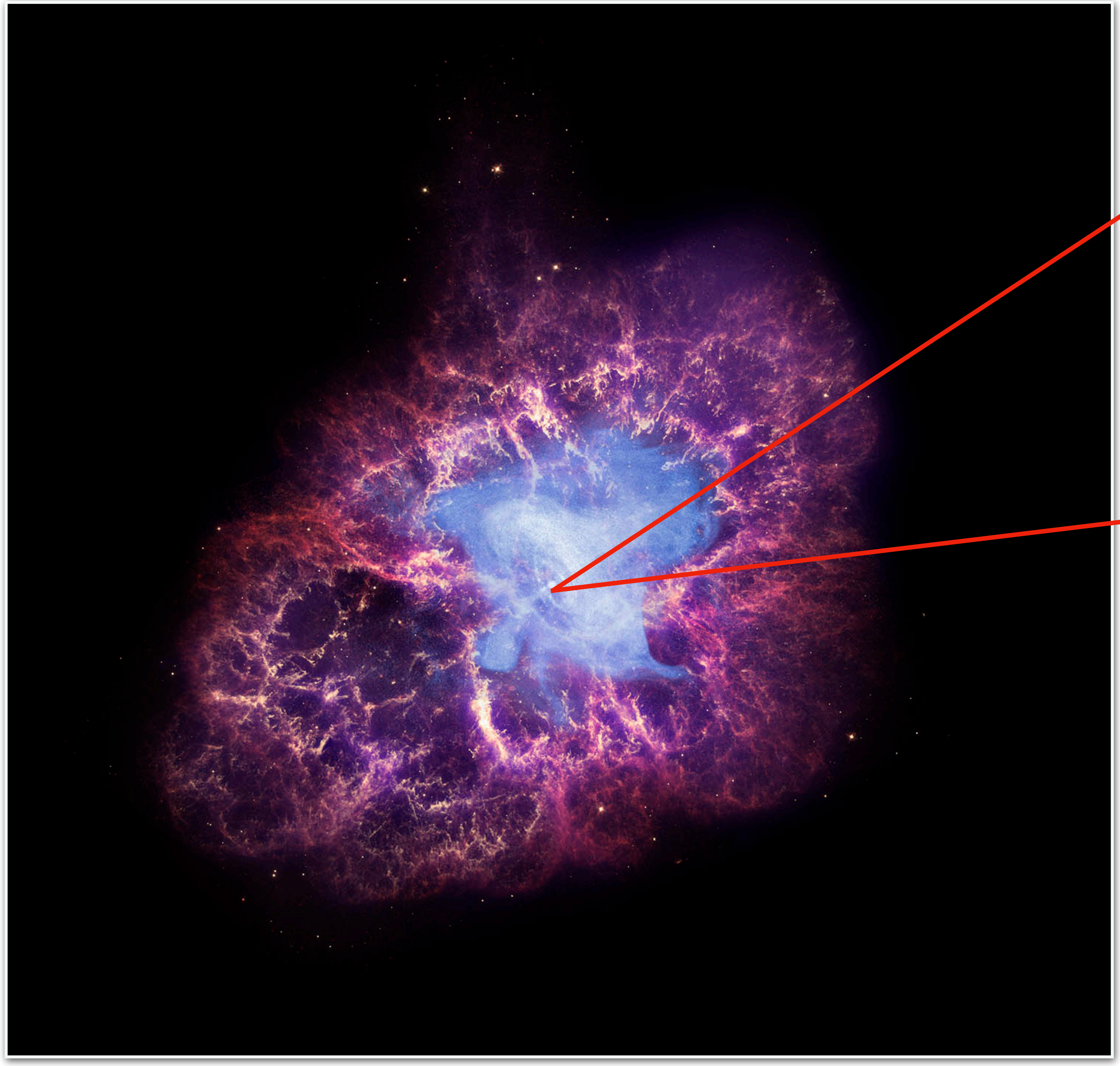
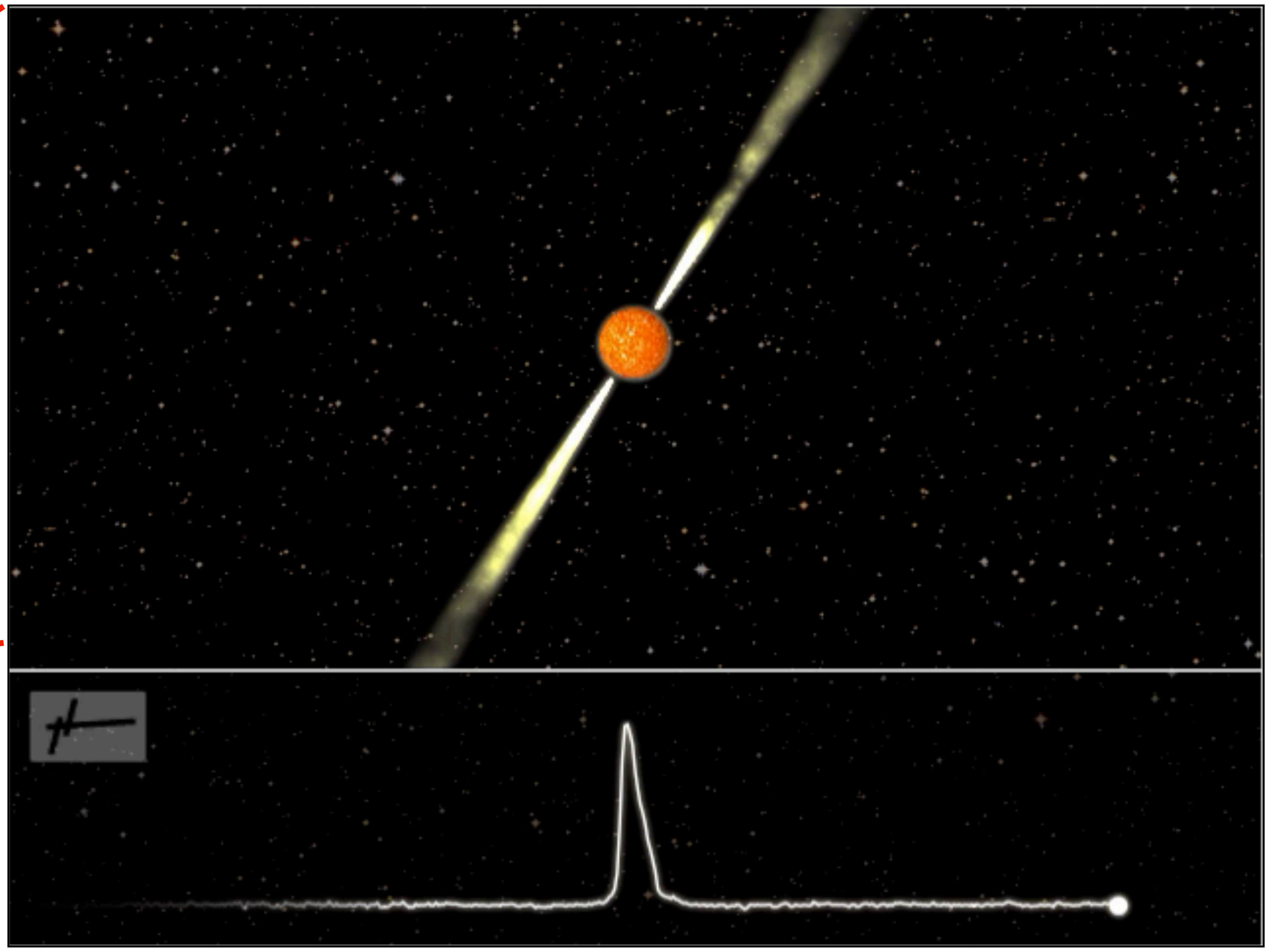
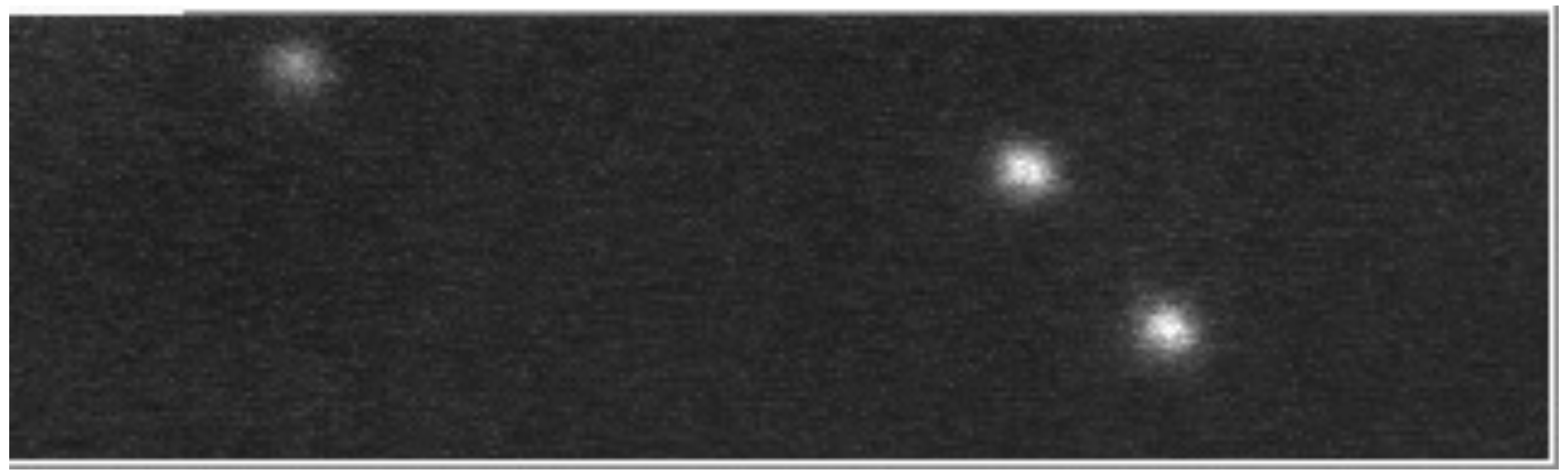


Image credit: X-ray: NASA/Chandra; Optical: Nasa/Hubble; Infrared: NASA/Spitzer.



Credit: J. van Leeuwen



Credit: Cambridge University

A (visible) gate to the unknown

A (visible) gate to the unknown

Properties of Pulsars

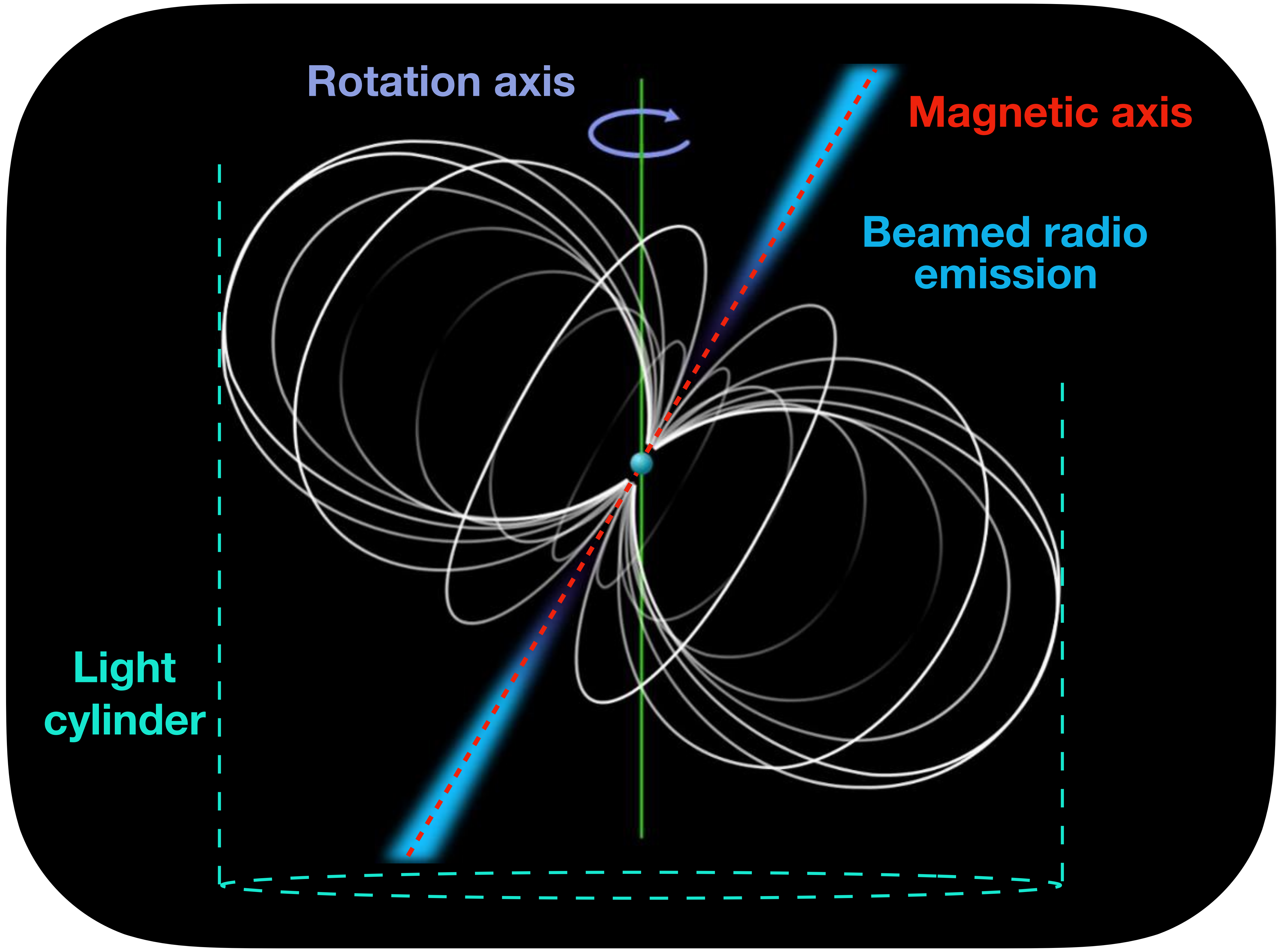


Image credit: Roy Smits (adapted)

- 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)

Point-like masses with ultra-precise clocks attached

Properties of Pulsars

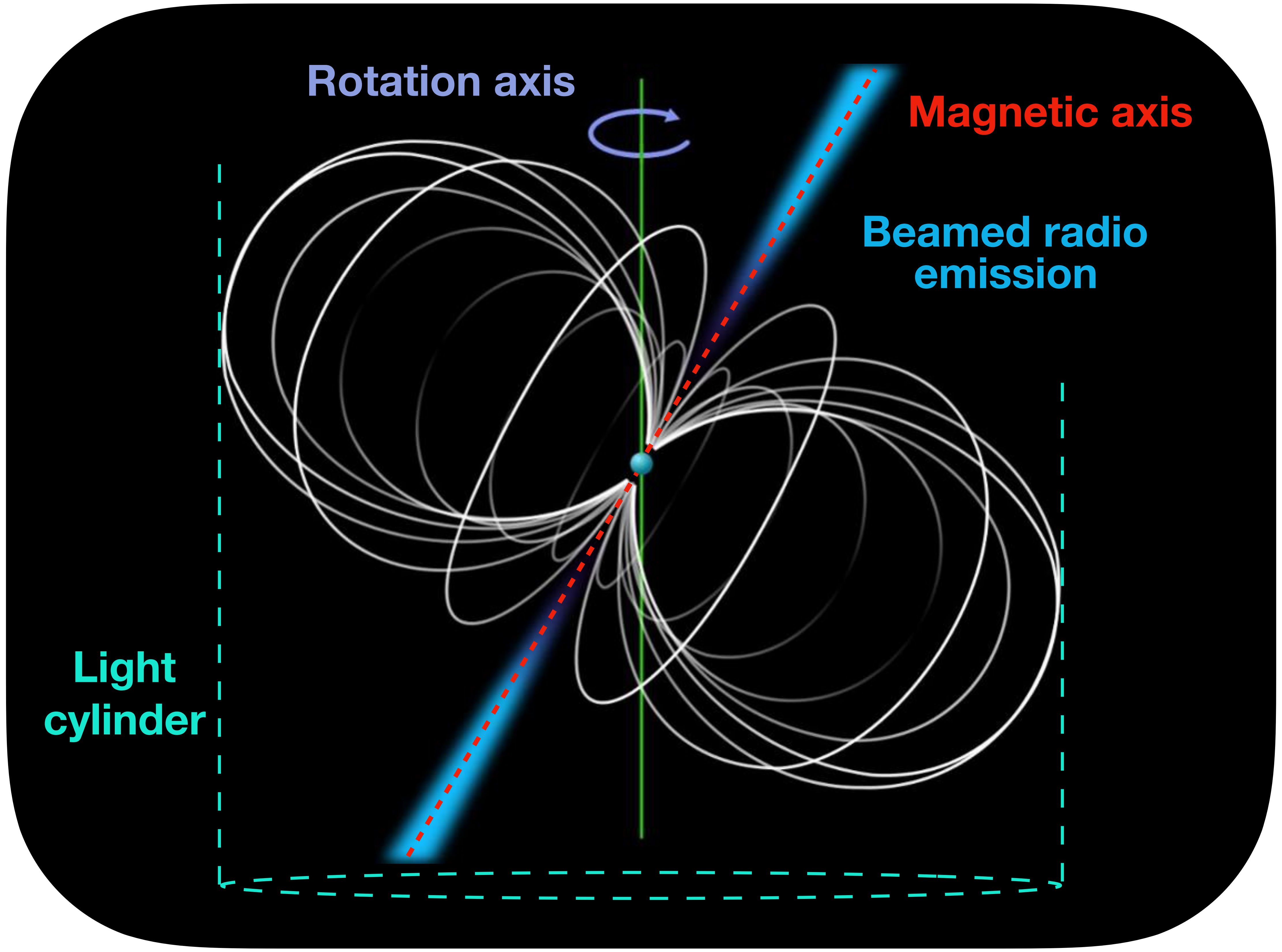


Image credit: Roy Smits (adapted)

• Neutron stars formed in supernovae

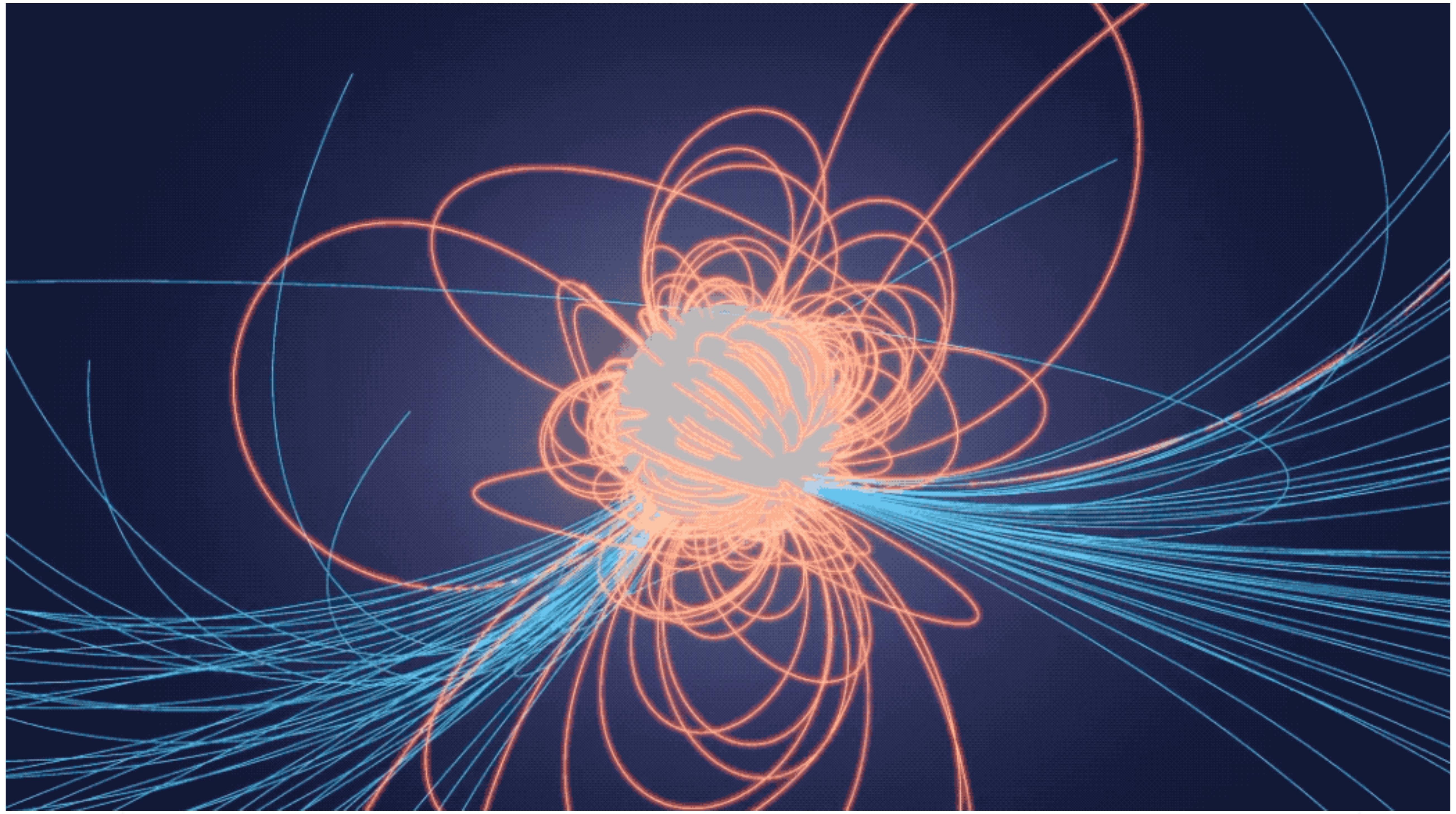
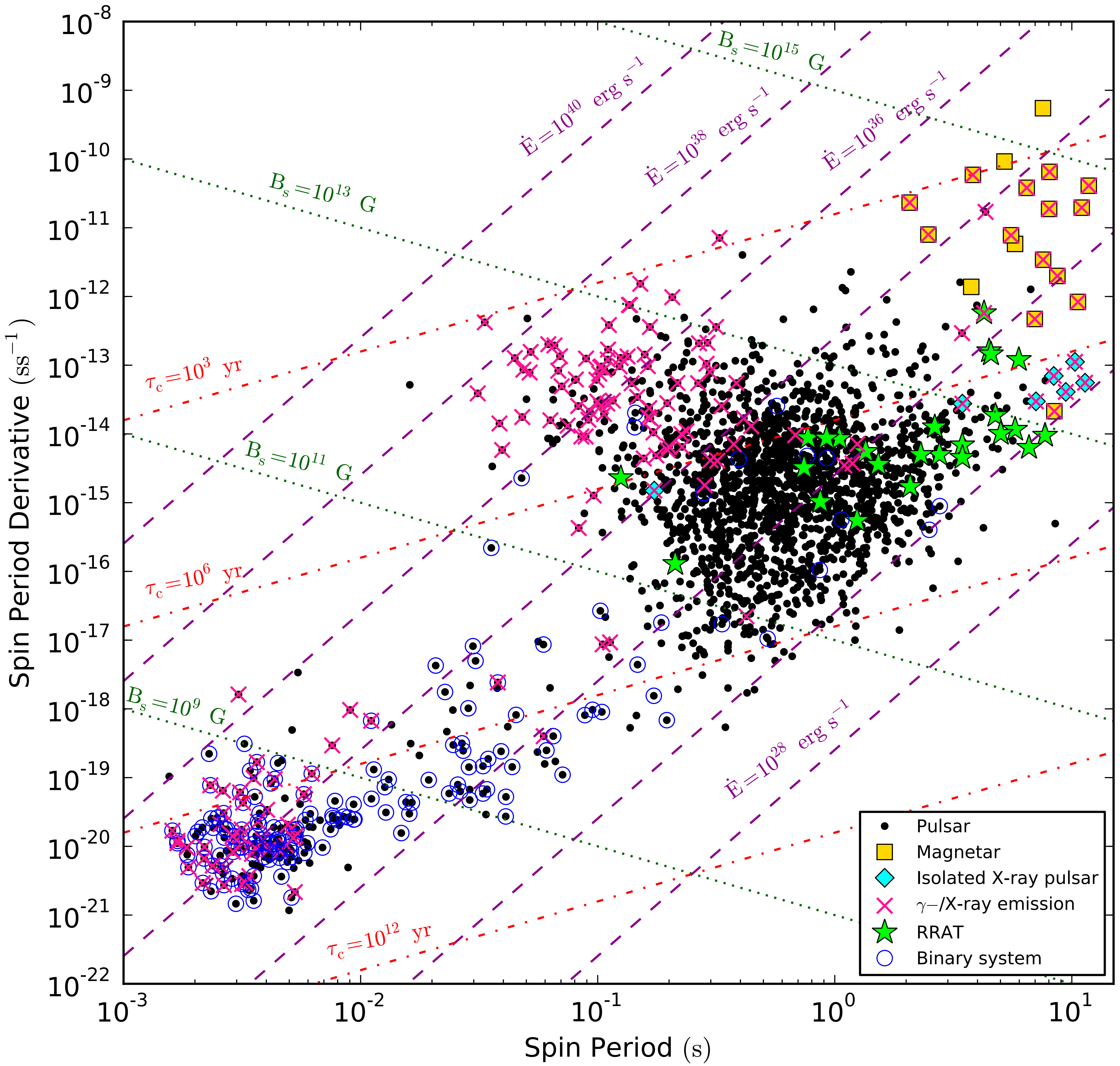


Image credit: Goddard Space Flight Center/NASA

Point-like masses with ultra-precise clocks attached

The Pulsar Population

- 2700+ pulsars known
- Different ways of classifying pulsars: B-field strength, Age, Energy, Binary/Isolated, Period, Period derivative, …
- Measurable quantities generally period (P) and its rate of change (Pdot)
- Three main subdivisions
  - Canonical / Normal
  - Millisecond
  - Magnetars



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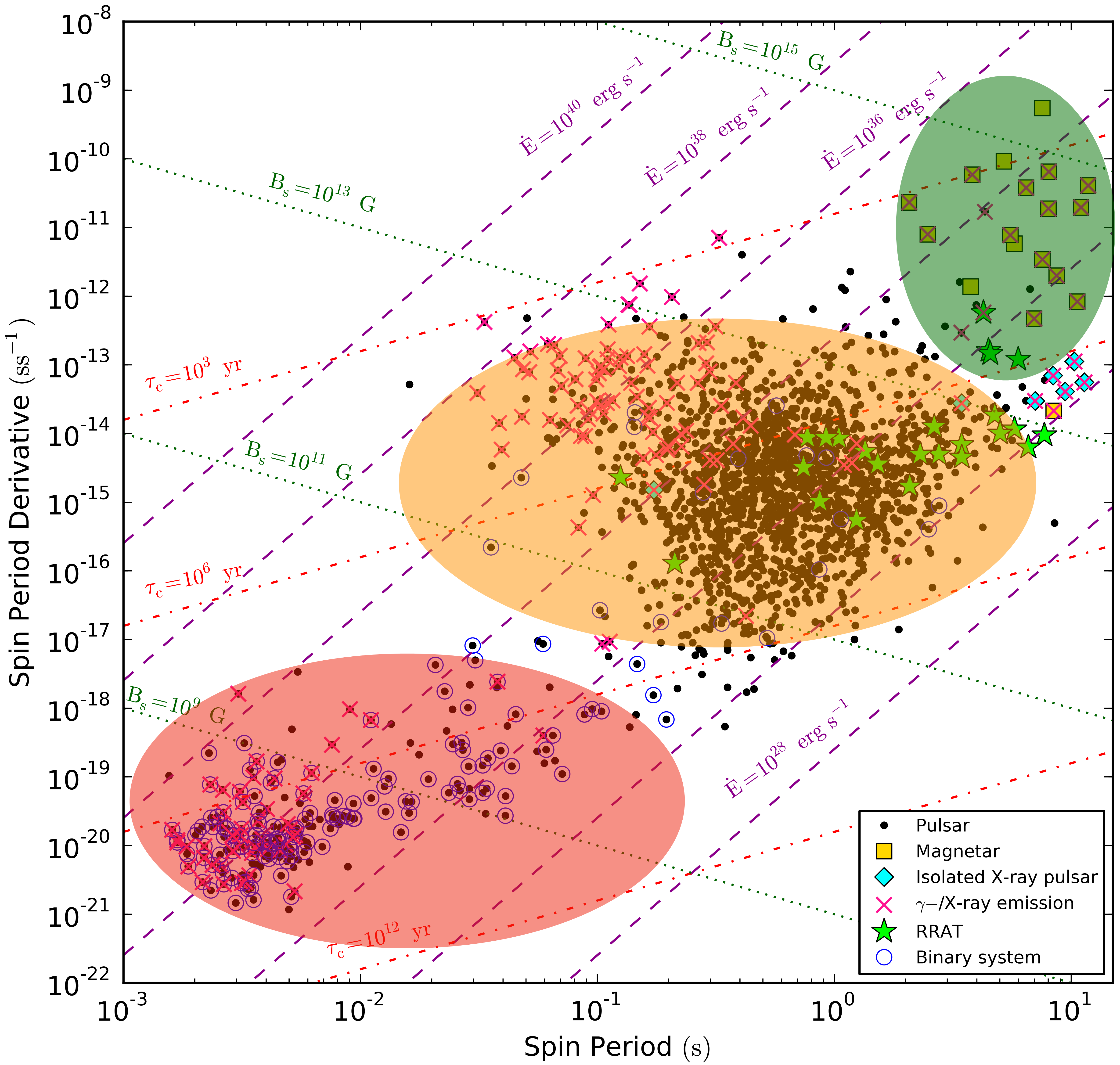


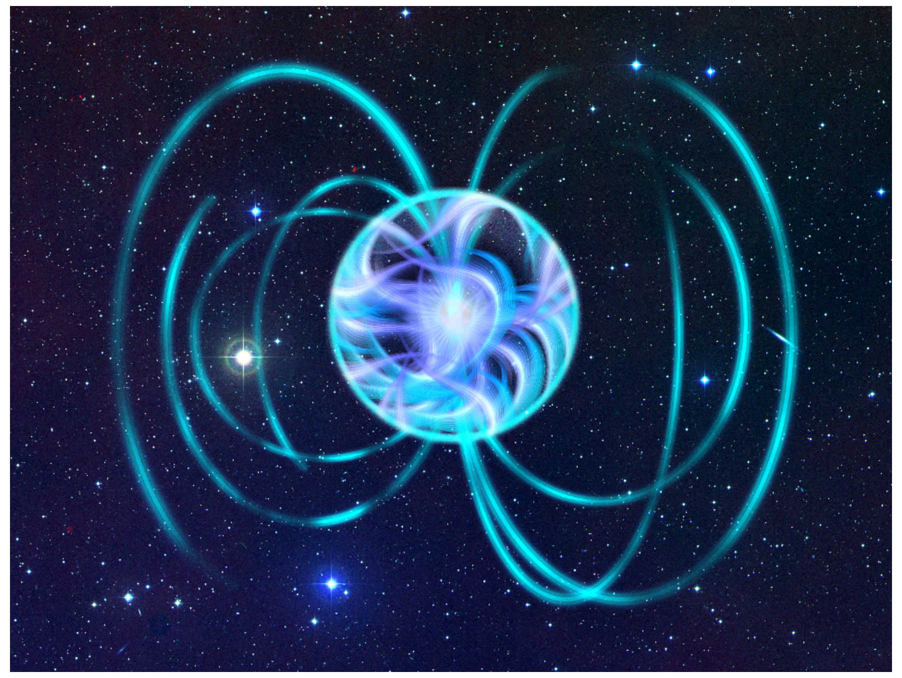
Pulsar Science

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

Interstellar medium

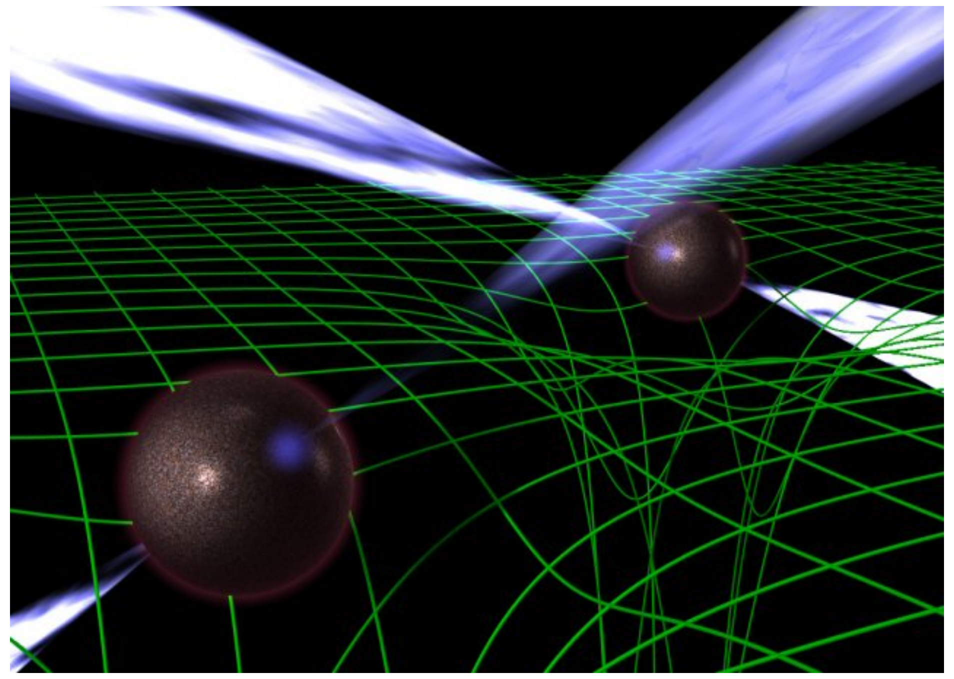
J. Williamson

Ultra-dense matter



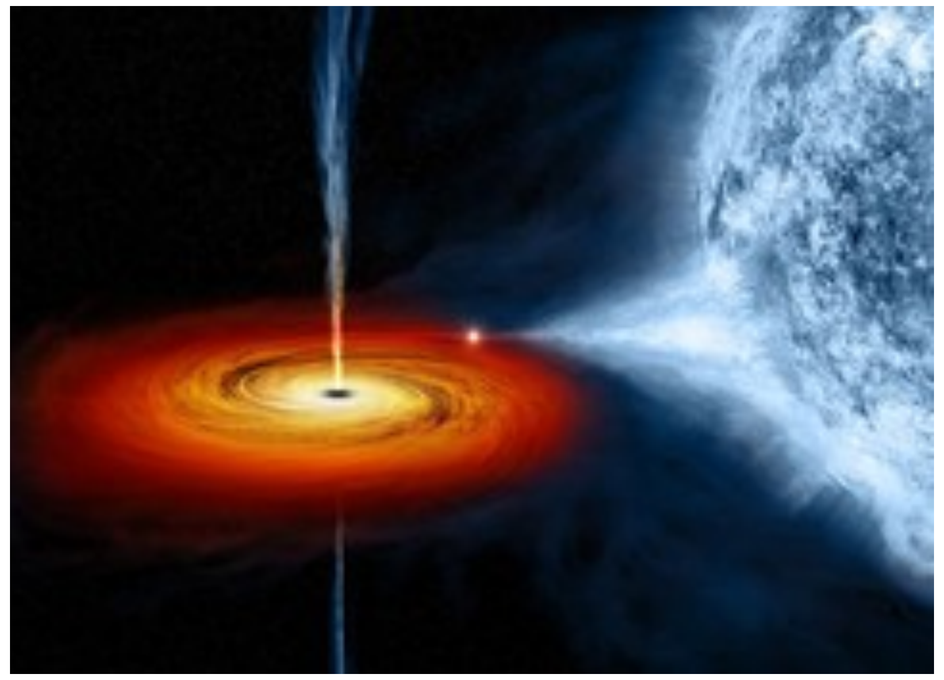
ESO

Gravity tests



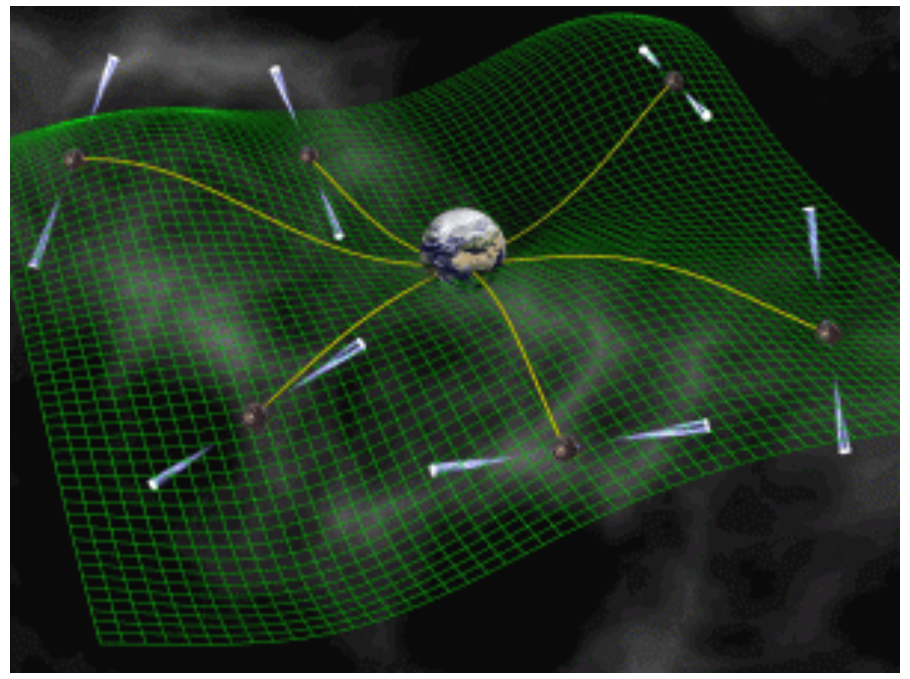
jb.man.ac.uk

Binary evolution



NASA/CXC/M. Weiss

Gravitational Waves



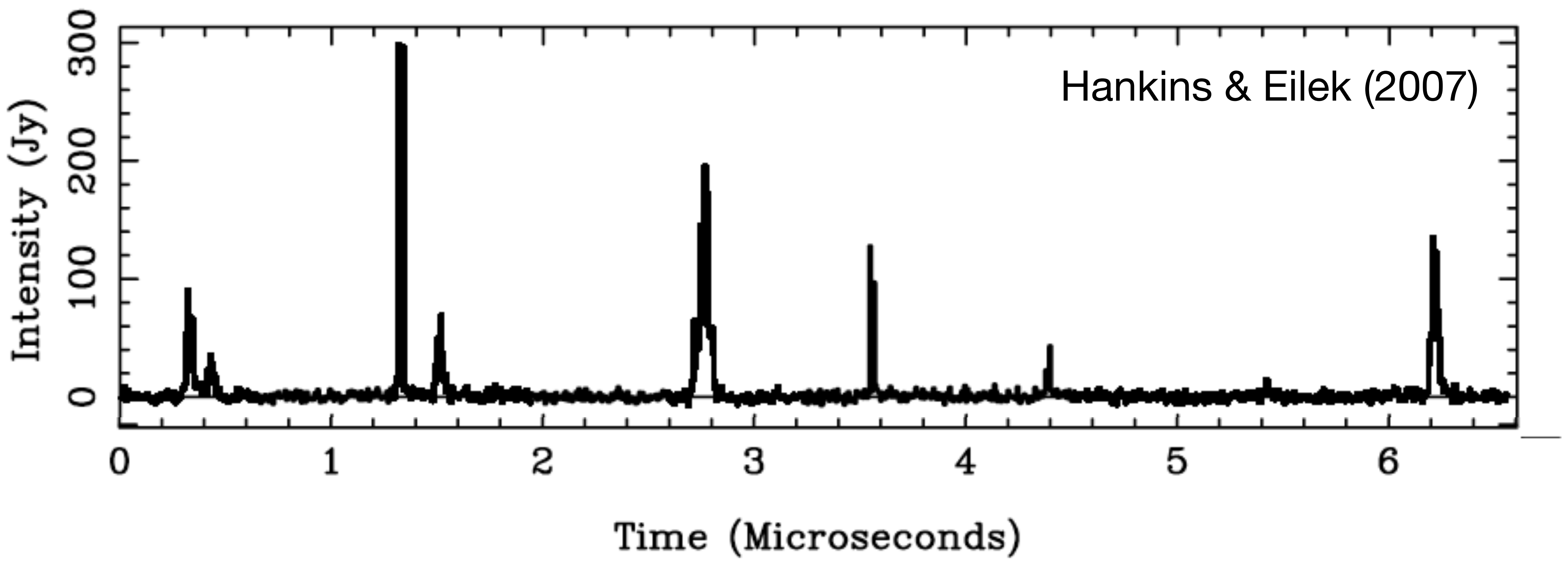
D. Champion (MPIfR)

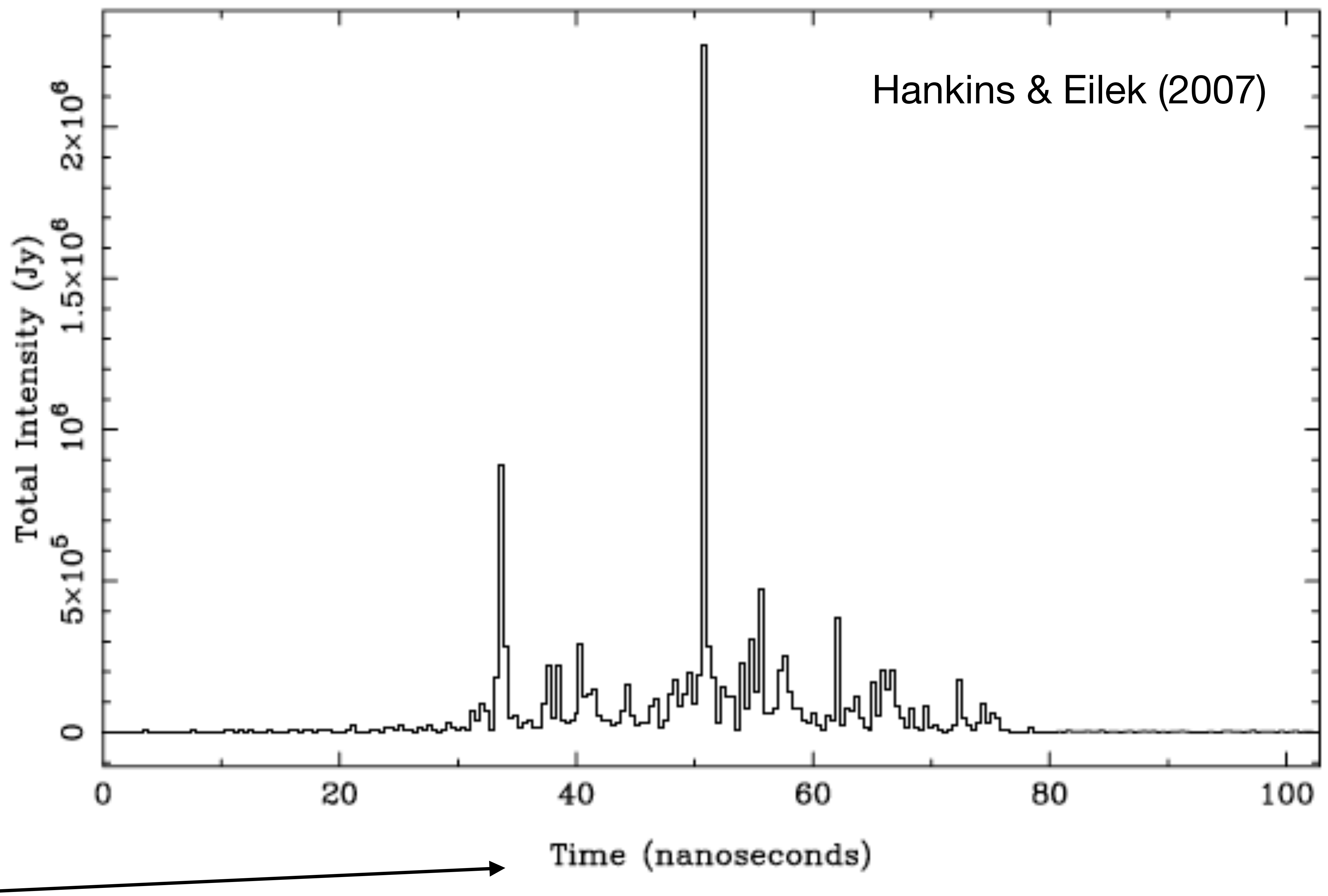
- **Possible experiments depends on the pulsar systems known**, e.g.:
  - First binary pulsar ⇨ Gravitational Waves (Hulse & Taylor 1974) (Taylor & Weisberg 1982)  Nobel prize
  - 2-$M_\odot$ neutron star ⇨ Stringent constraints on EoS (Demorest et al. 2010) (Antoniadis et al. 2013)
  - Double pulsar ⇨ 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**

Emission Characteristics in the Radio Band

- **Brightness temperatures above thermal limit.** Tb ~ [10^{25} — 10^{32}] K, up to $10^{37\text{-}41}$ K !
- Broadband emission, but with microstructure
- High degrees of linear and circular polarisation
- Spectral indices α ~ [-4, +1] → Not “pure" synchrotron …
- Pulses all different, but average to a stable mean pulse
- Nulling, Mode changing

Non-thermal / Coherent emission





Please note:

Emission Characteristics in the Radio Band

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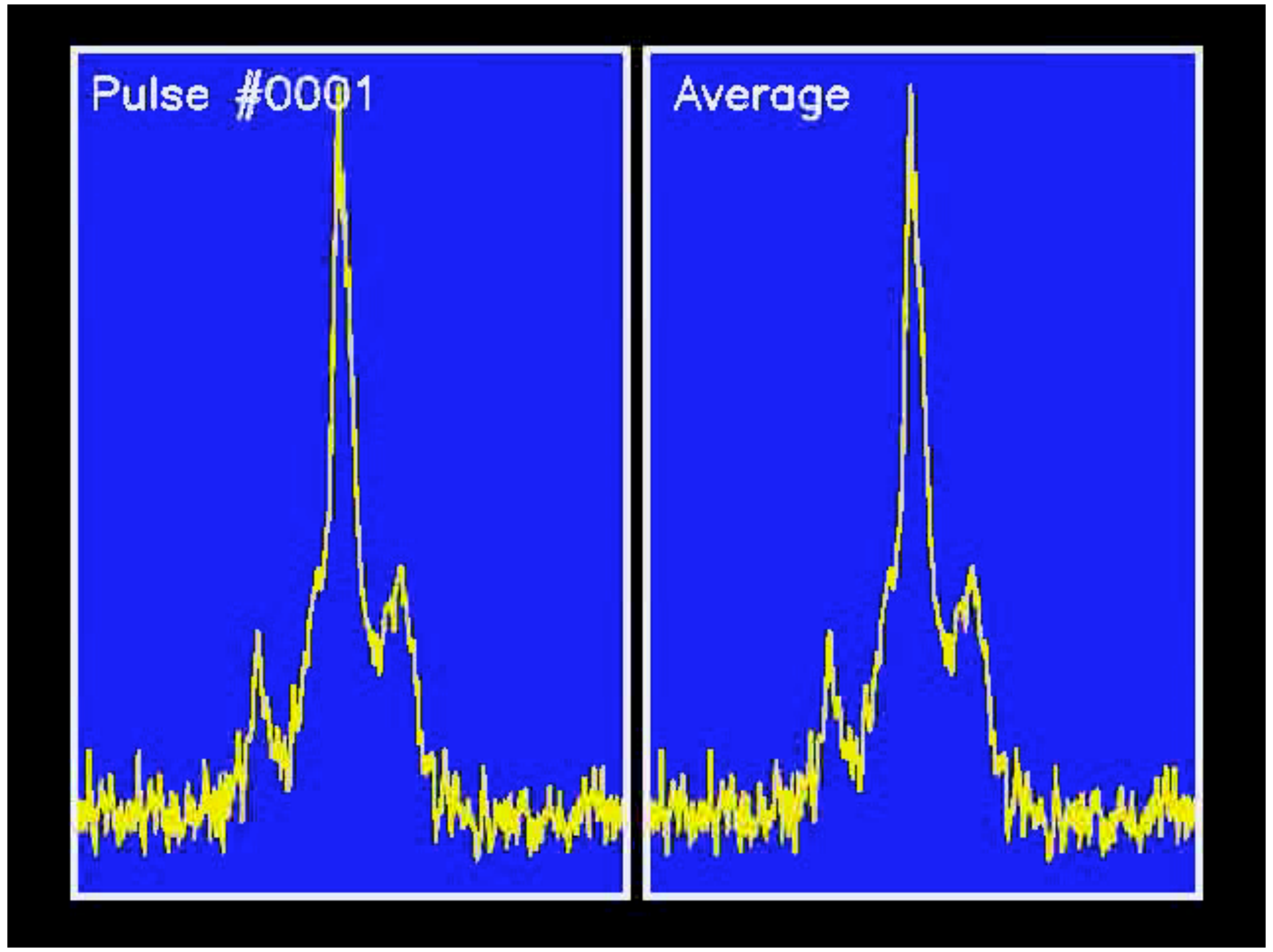
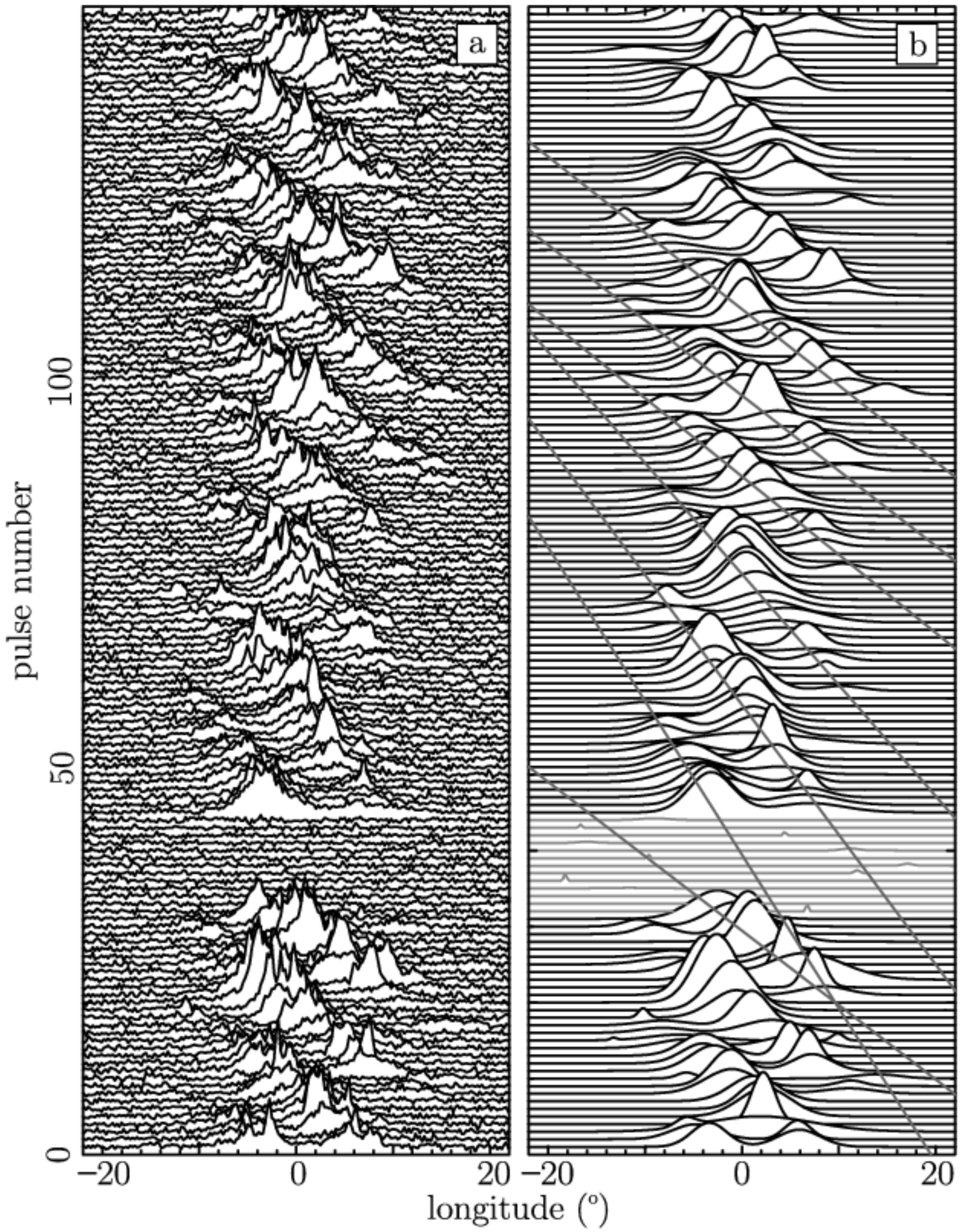


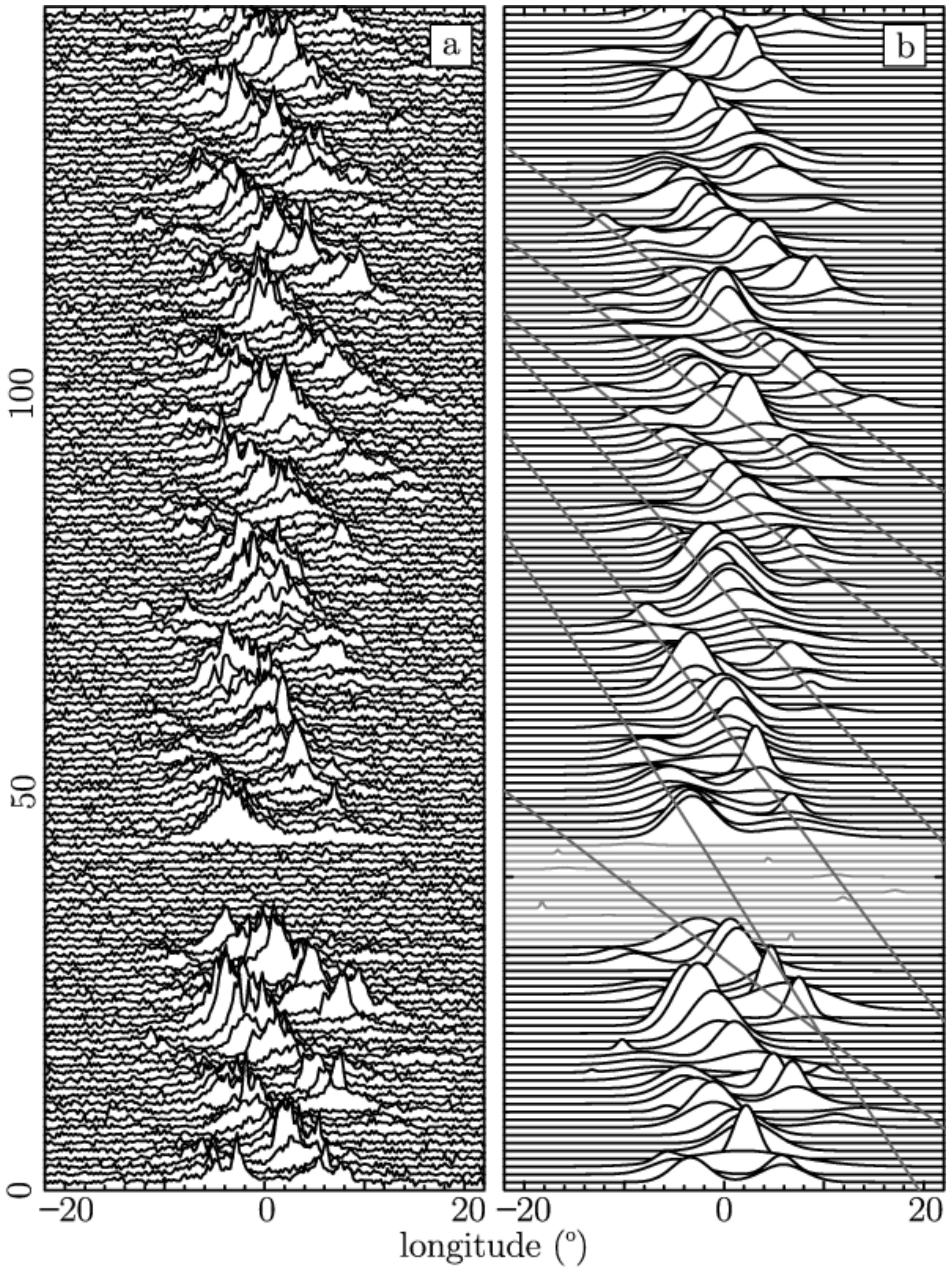
Jodrell Bank
University of Manchester

van Leeuwen et al. (2003)



Emission Characteristics in the Radio Band

van Leeuwen et al. (2003)



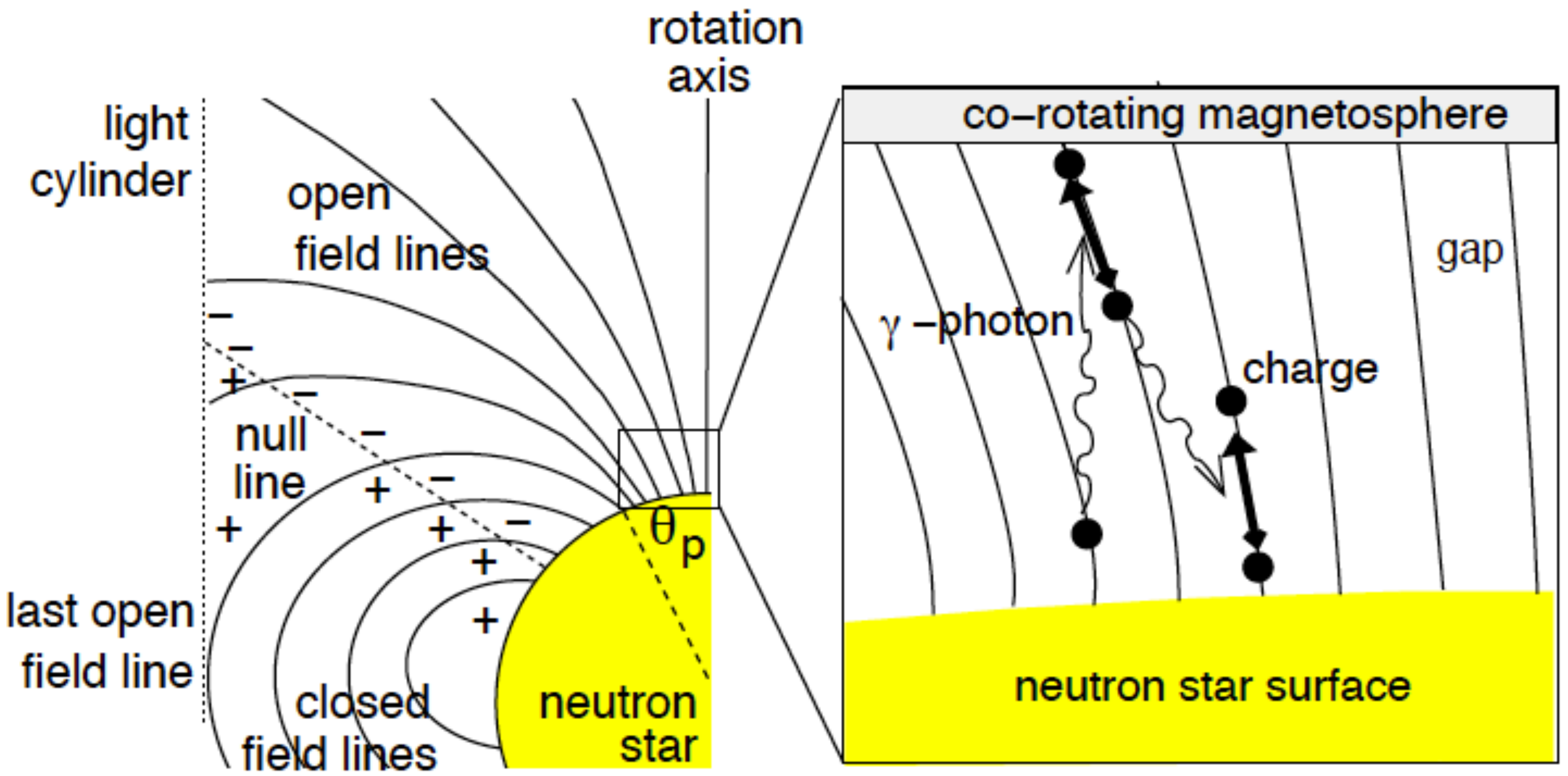
Unknown Radio Emission Mechanism

- Still a mystery after 50 years since the discovery of pulsars
- Models must explain coherency, high degree of polarisation
- Explain very broad emission (~ 10 MHz – 300+ GHz)
- Models must work over 4 orders of magnitude of spin period, and 7 orders of magnitude in B-field

- How do we think it happens:

"Antenna mechanism"

Curvature emission by bunched particles



Lorimer & Kramer (2005)

Cascade effect

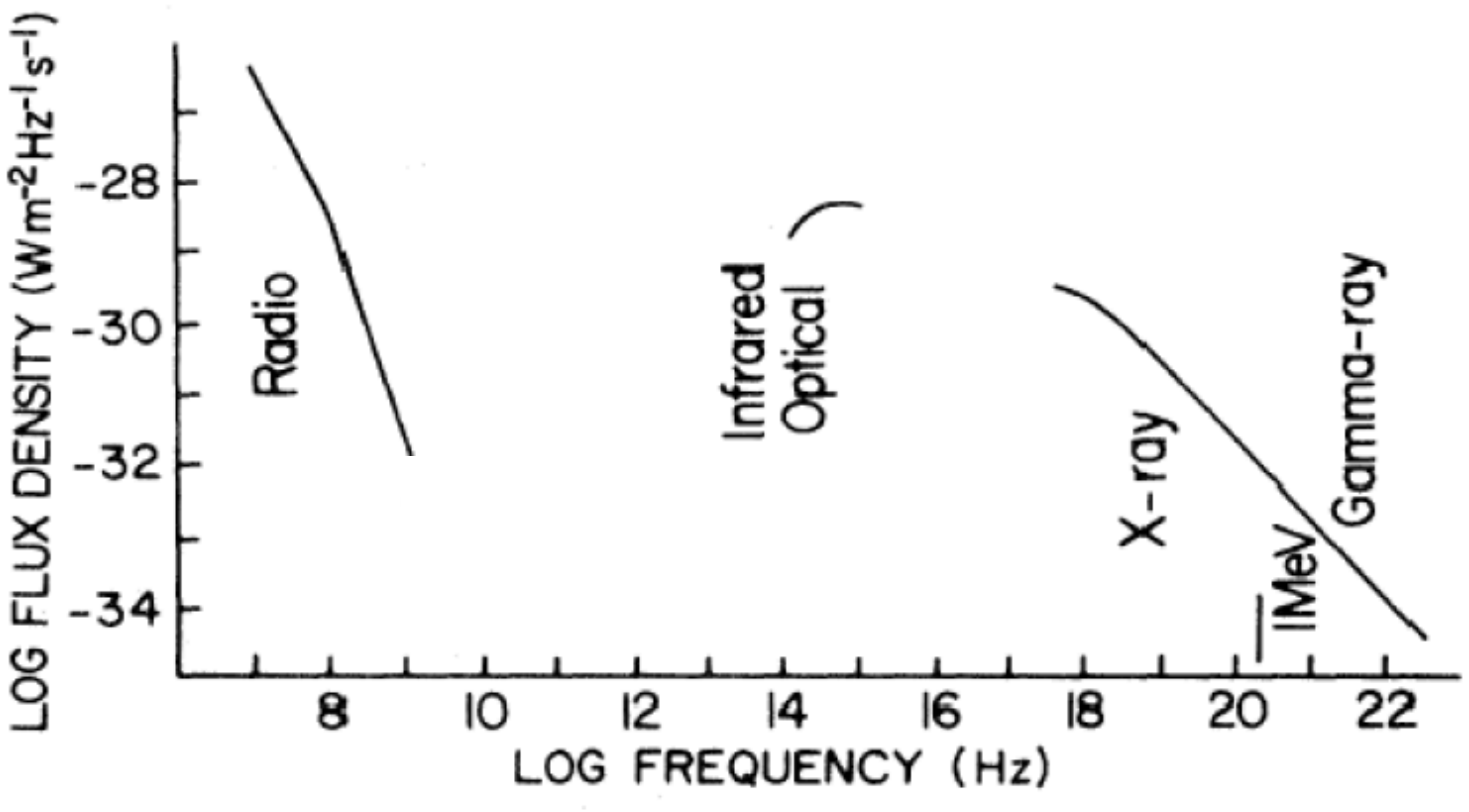
↓

Charged particles (e- / e+) grouped in small volumes and accelerated

- But there are alternative methods: relativistic plasma emission or maser mechanisms (see e.g. Melrose & Yuen 2016)

The Input from Observations

- Pulsar emission models make predictions that we can try to test with observations
- *Emission processes can be frequency dependent*
- **Some effects may only be observable at very short wavelengths (< ~few mm)**

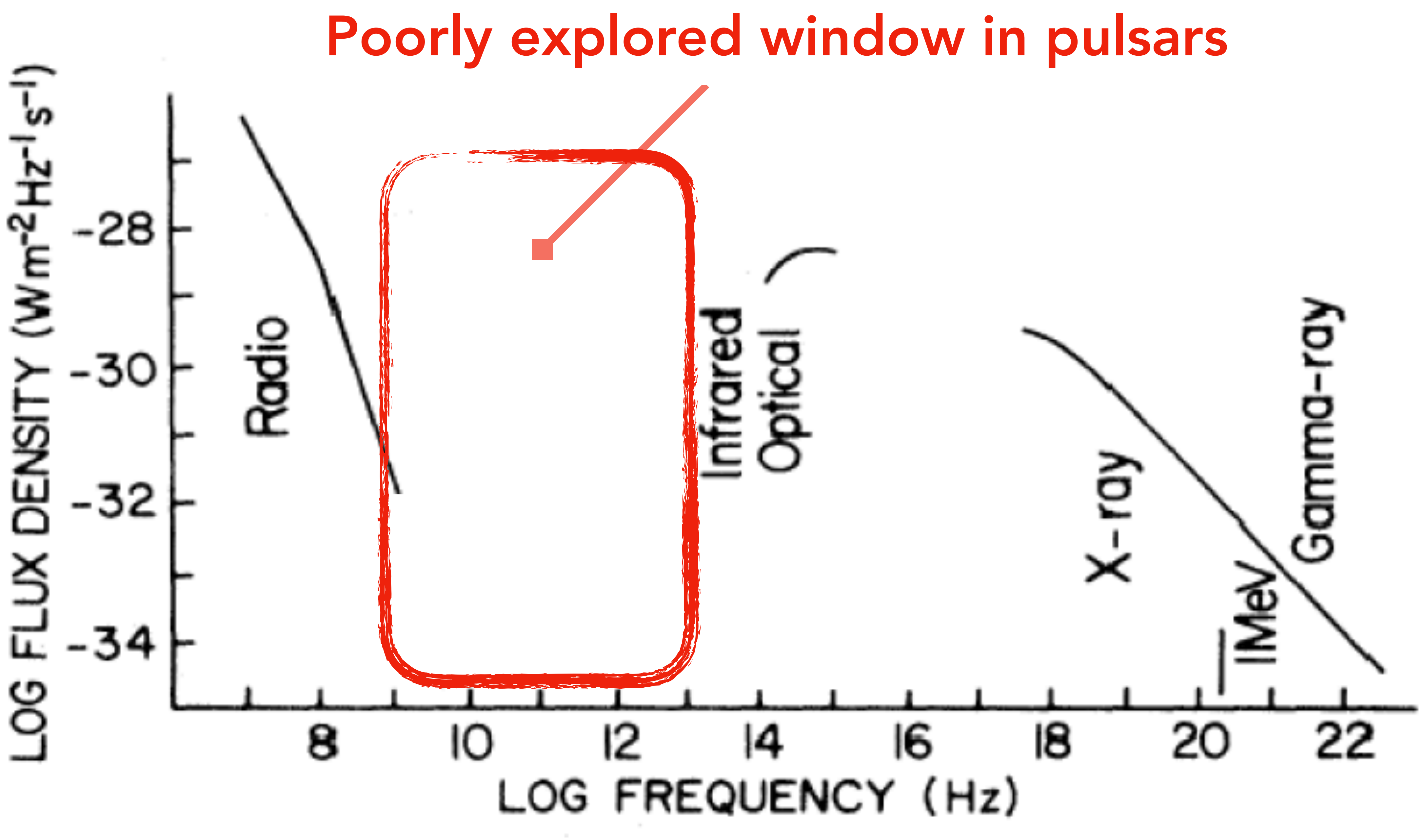


Adapted from Smith (1977)

The Input from Observations

- Pulsar emission models make predictions that we can try to test with observations
- *Emission processes can be frequency dependent*

(Sub)mm- observations cover a window of pulsar emission highly unexplored, enabling certain tests of emission models not possible at other wavelengths

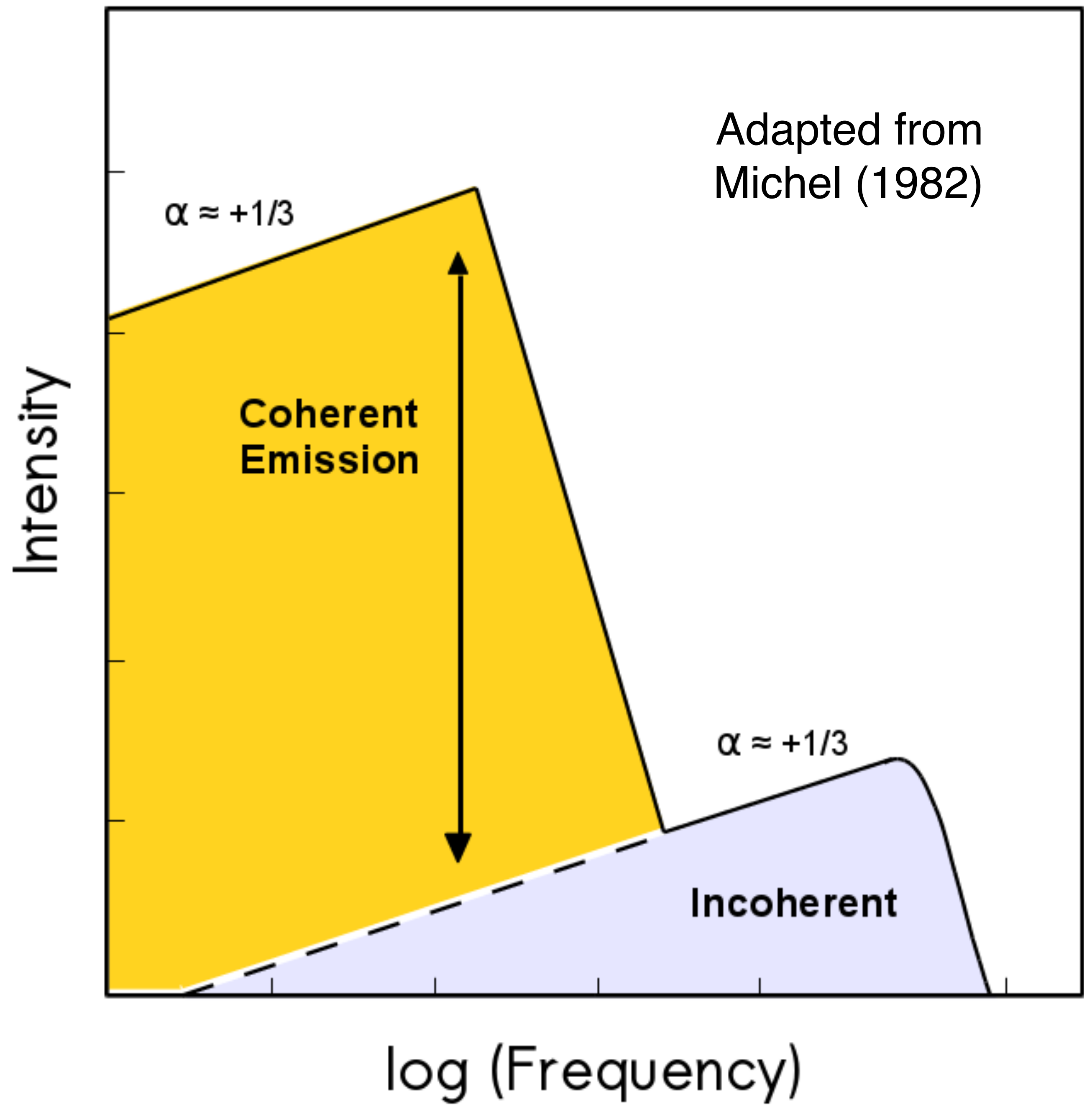


Adapted from Smith (1977)

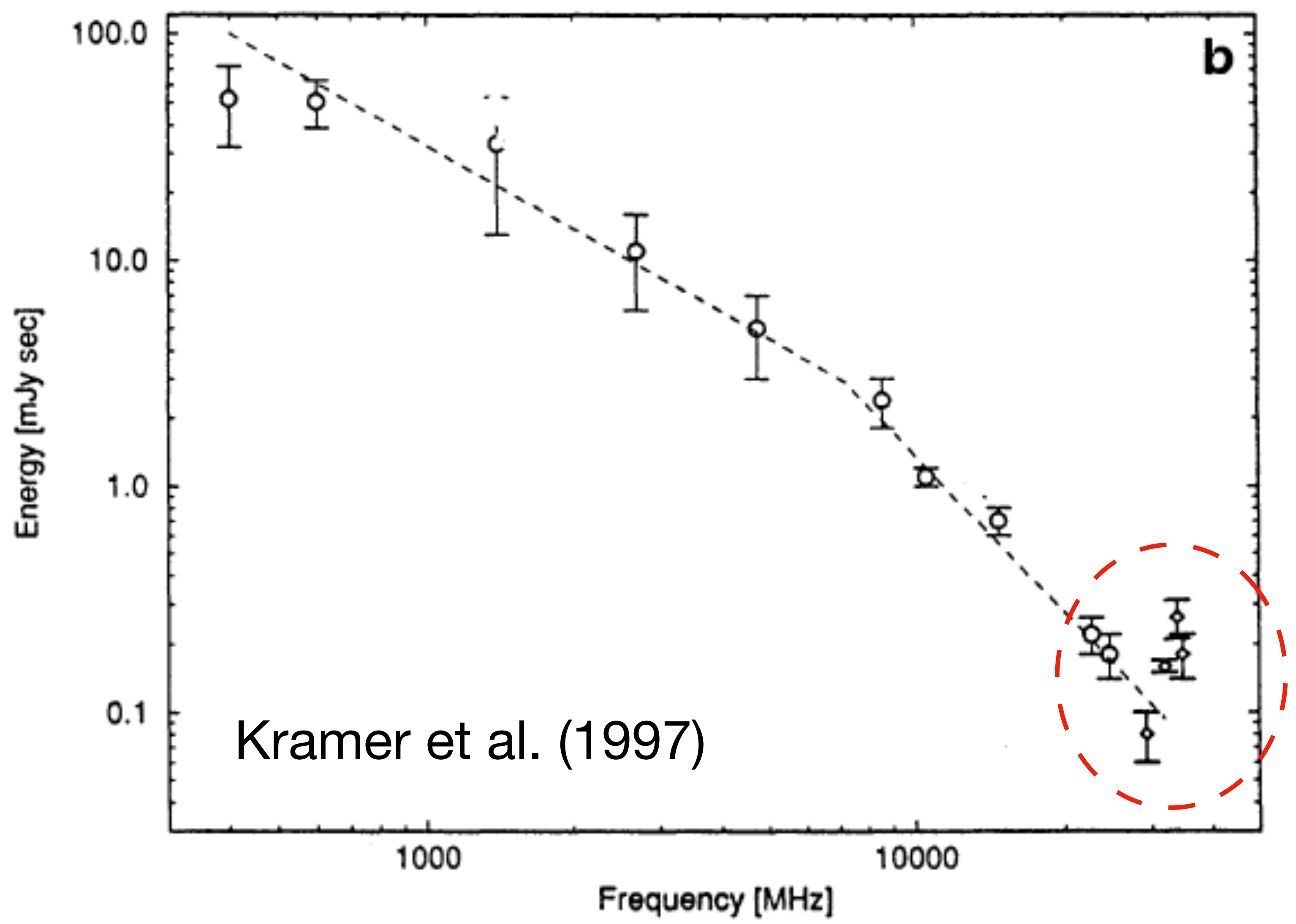
Examples

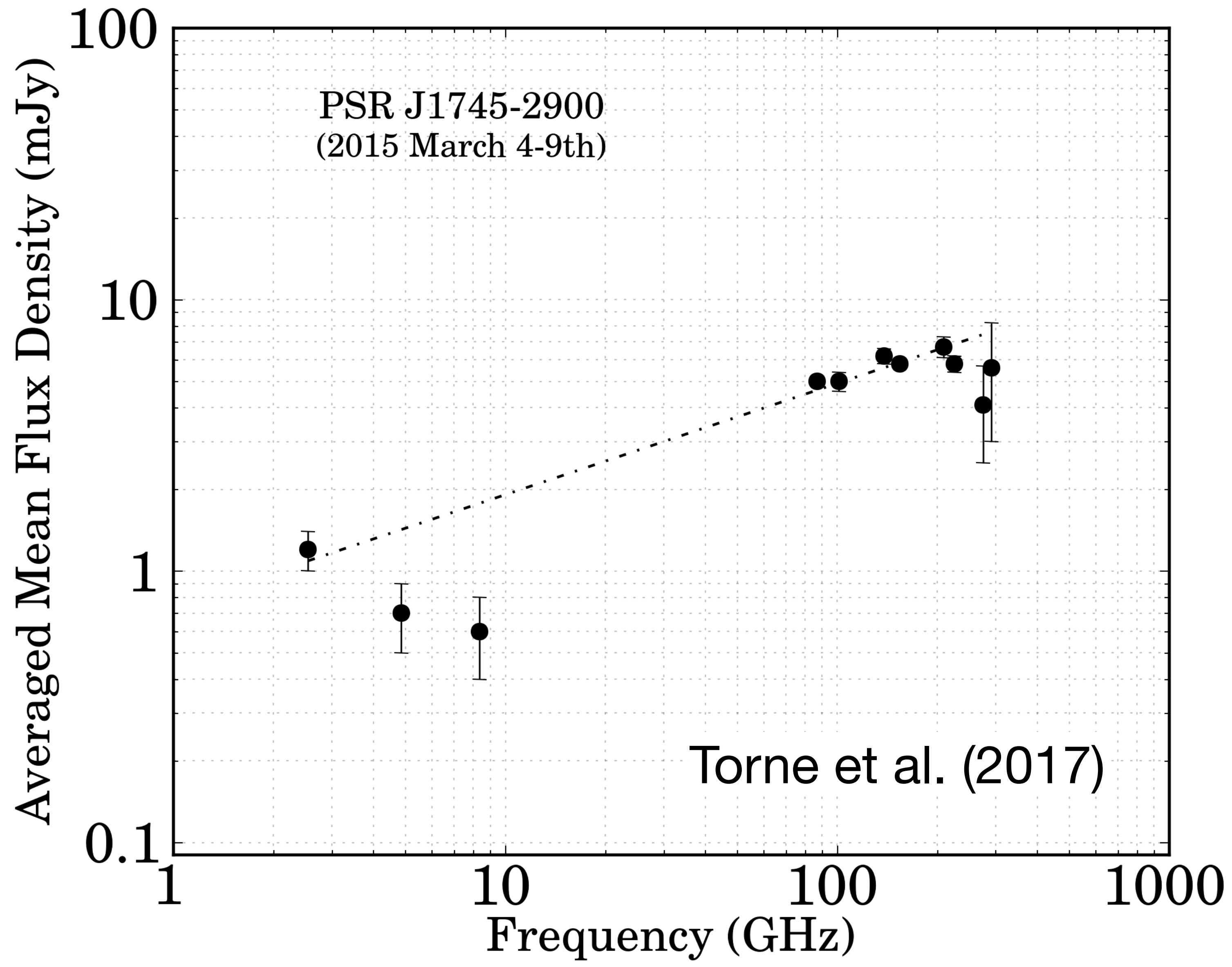
- **Coherence Breakdown**: coherent emission fails at sufficiently high frequency, incoherent emission takes over
- Features as a spectral turn-up in the spectrum
- Accompanying depolarisation ?

Coherence breakdown



Apparent turn-up in spectrum



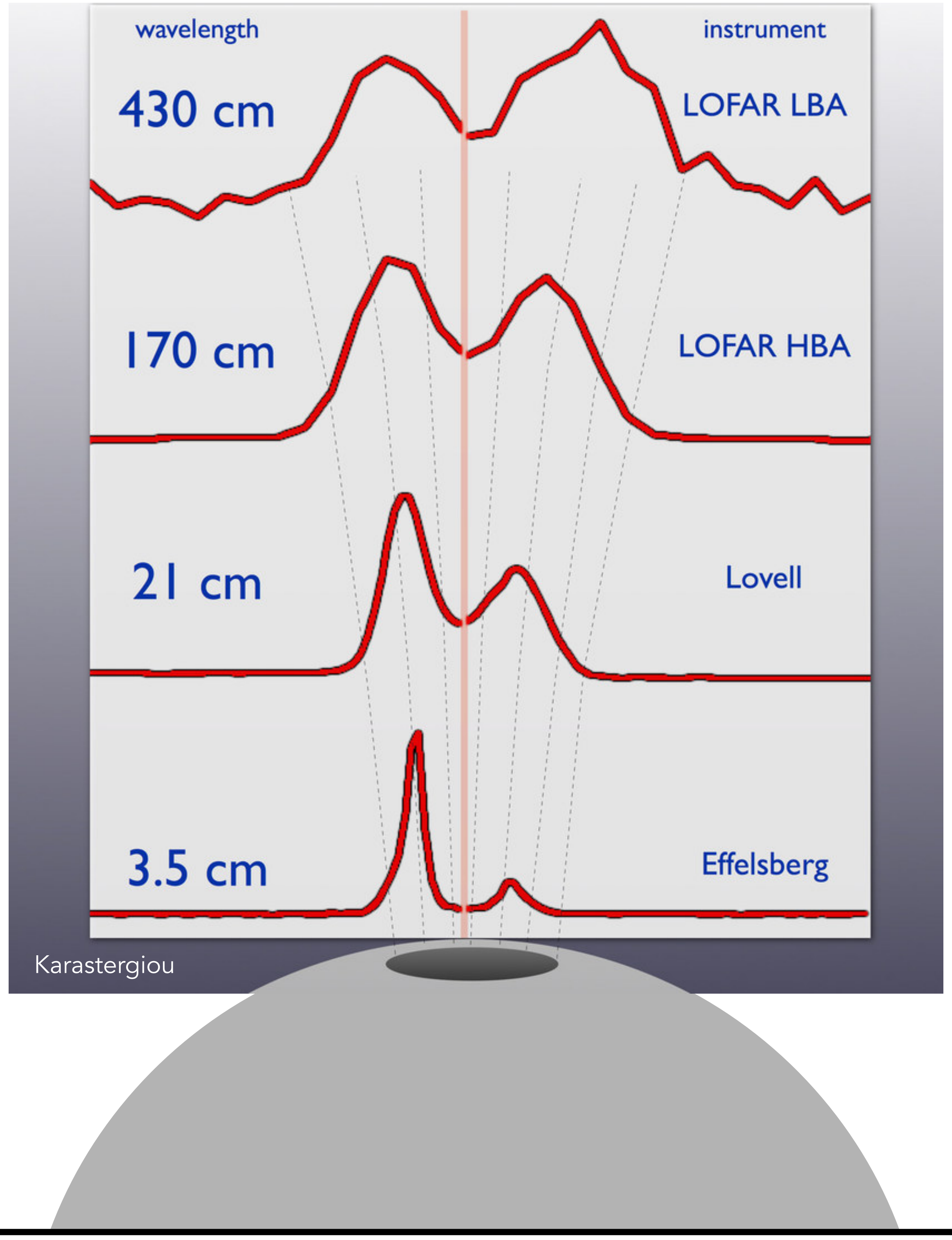


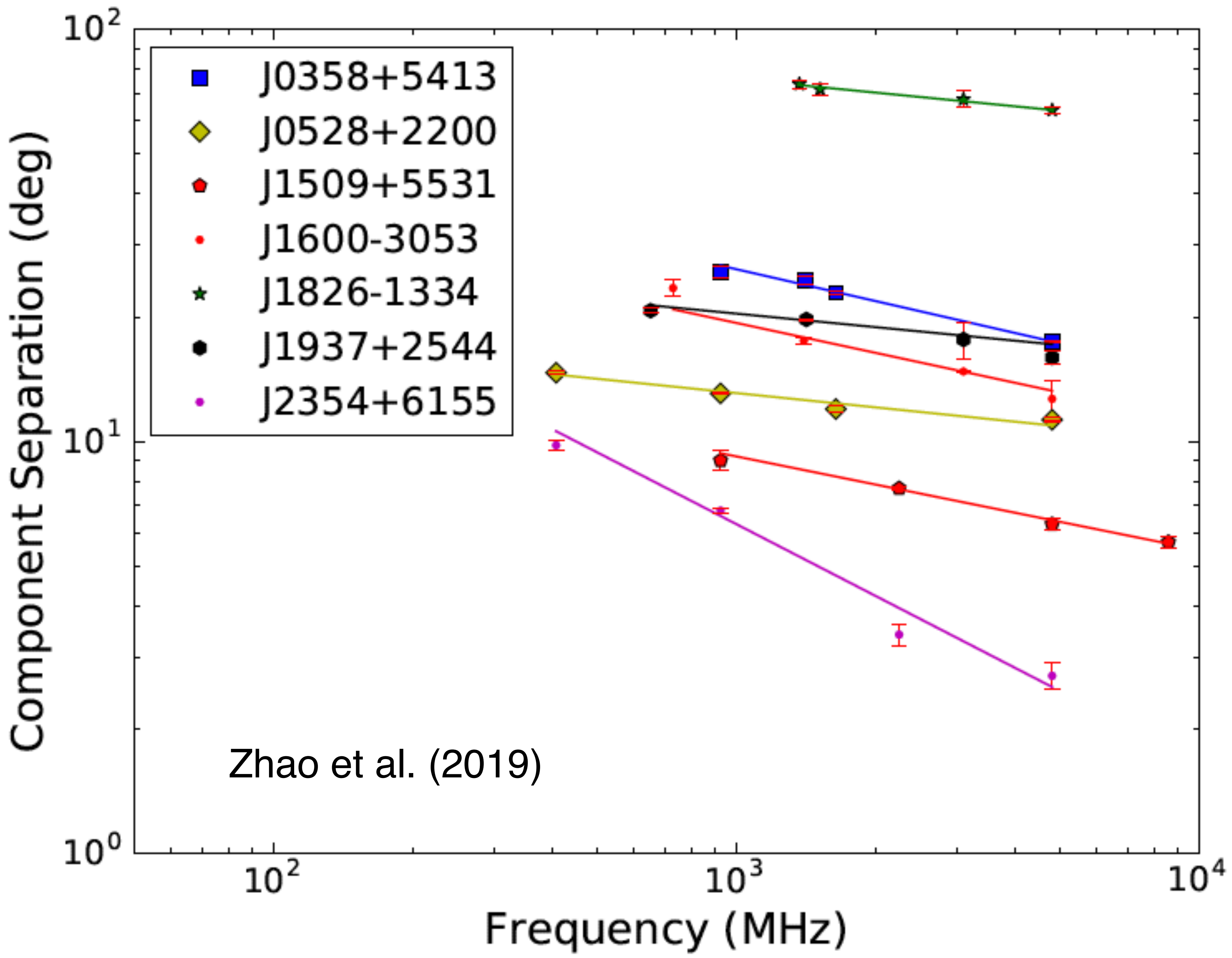
Examples

- **Radius-To-Frequency Mapping**
  - Dependence of height-of-emission ⟺ Observed Frequency
  - Implies narrower pulses at high frequency and depolarisation due to less ordered magnetic field

Radhakrishan and Cooke (1968)

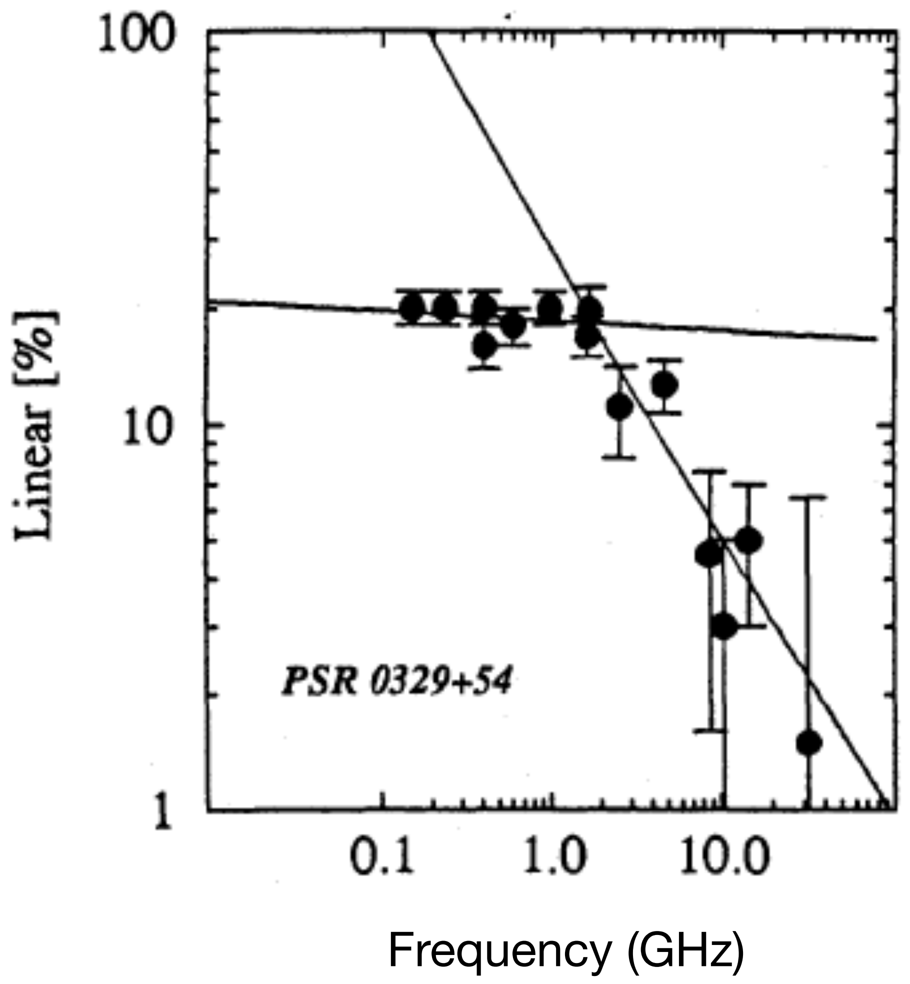
Cordes (1978)





Zhao et al. (2019)

Decrease of polarisation



Xilouris et al. (1996)

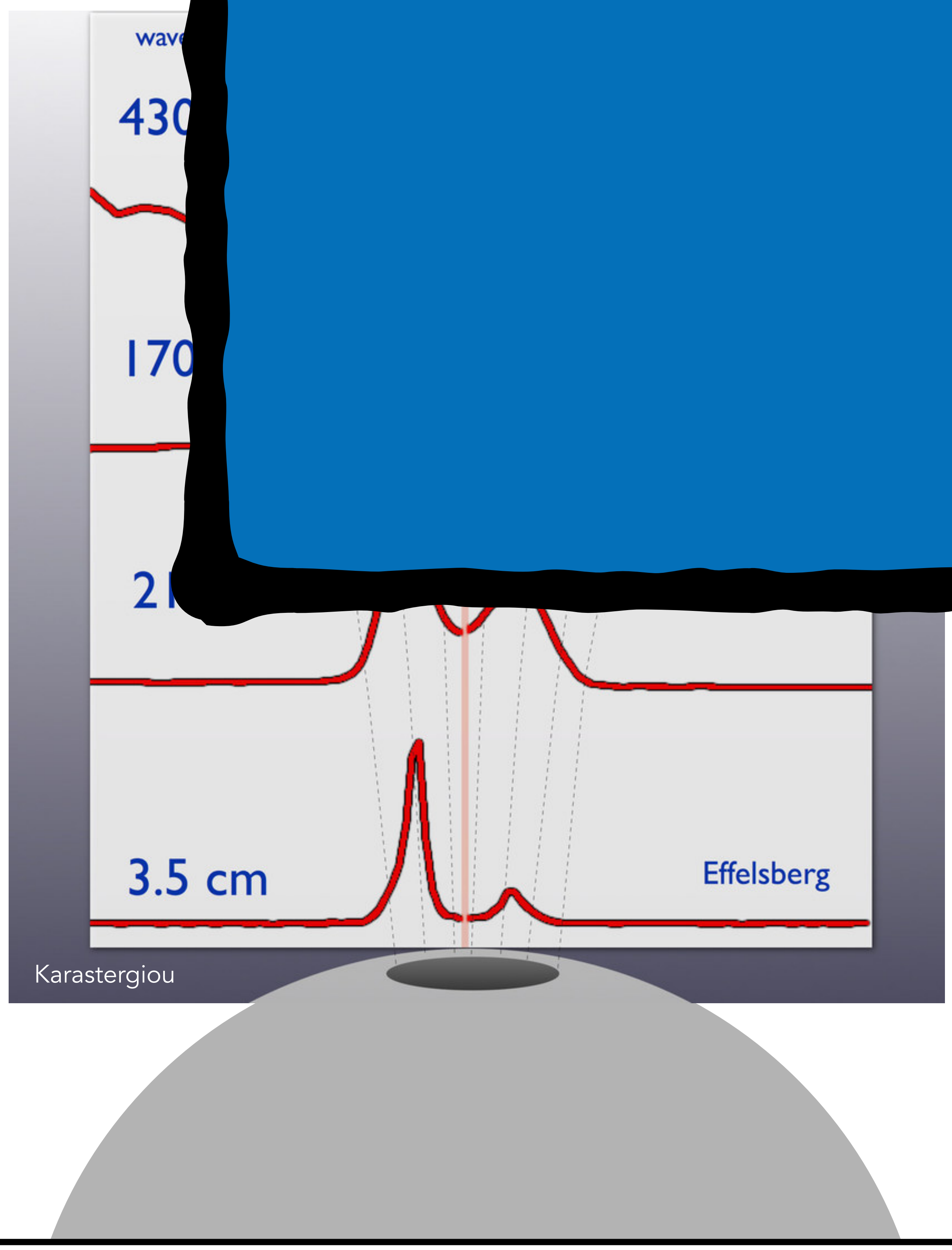
Examples

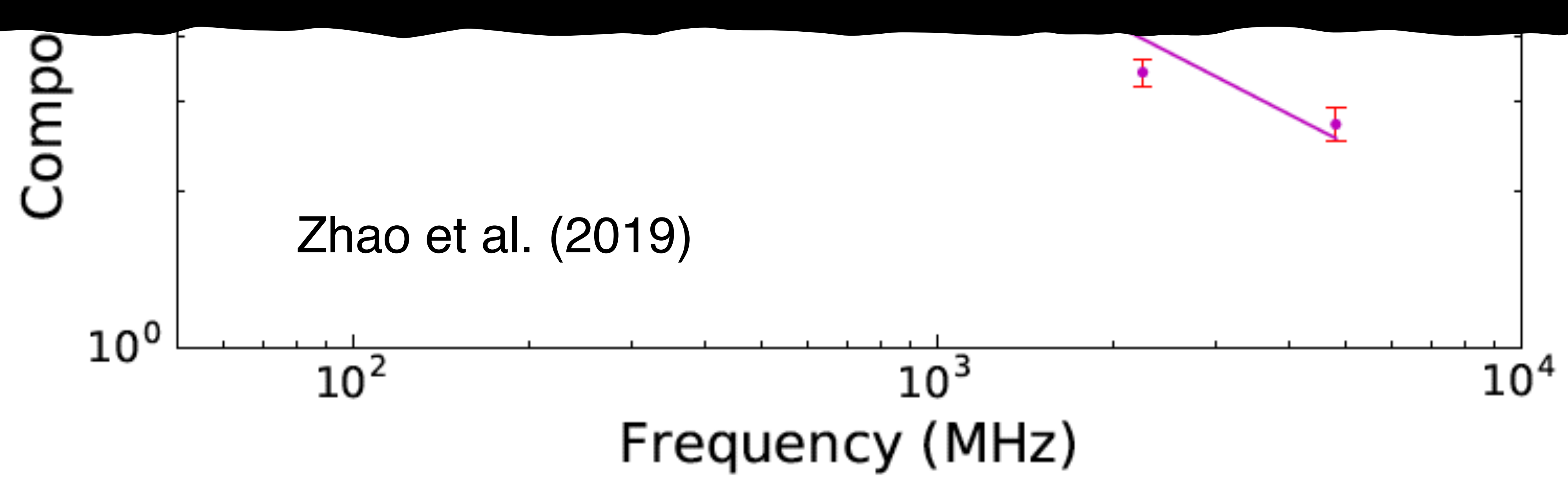
- **Radius-To-Frequency Mapping**
  - Dependence of height-of-emission ⟺ Observed Frequency
  - Implies narrower pulses at high frequency and depolarisation due to less ordered magnetic field

Found a model that seems to work?

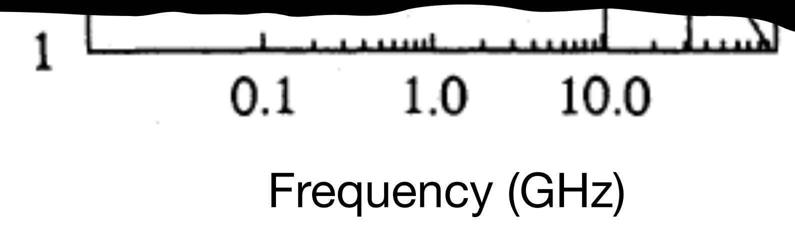
don't worry …

There will *always* be a pulsar out there that contradicts it …



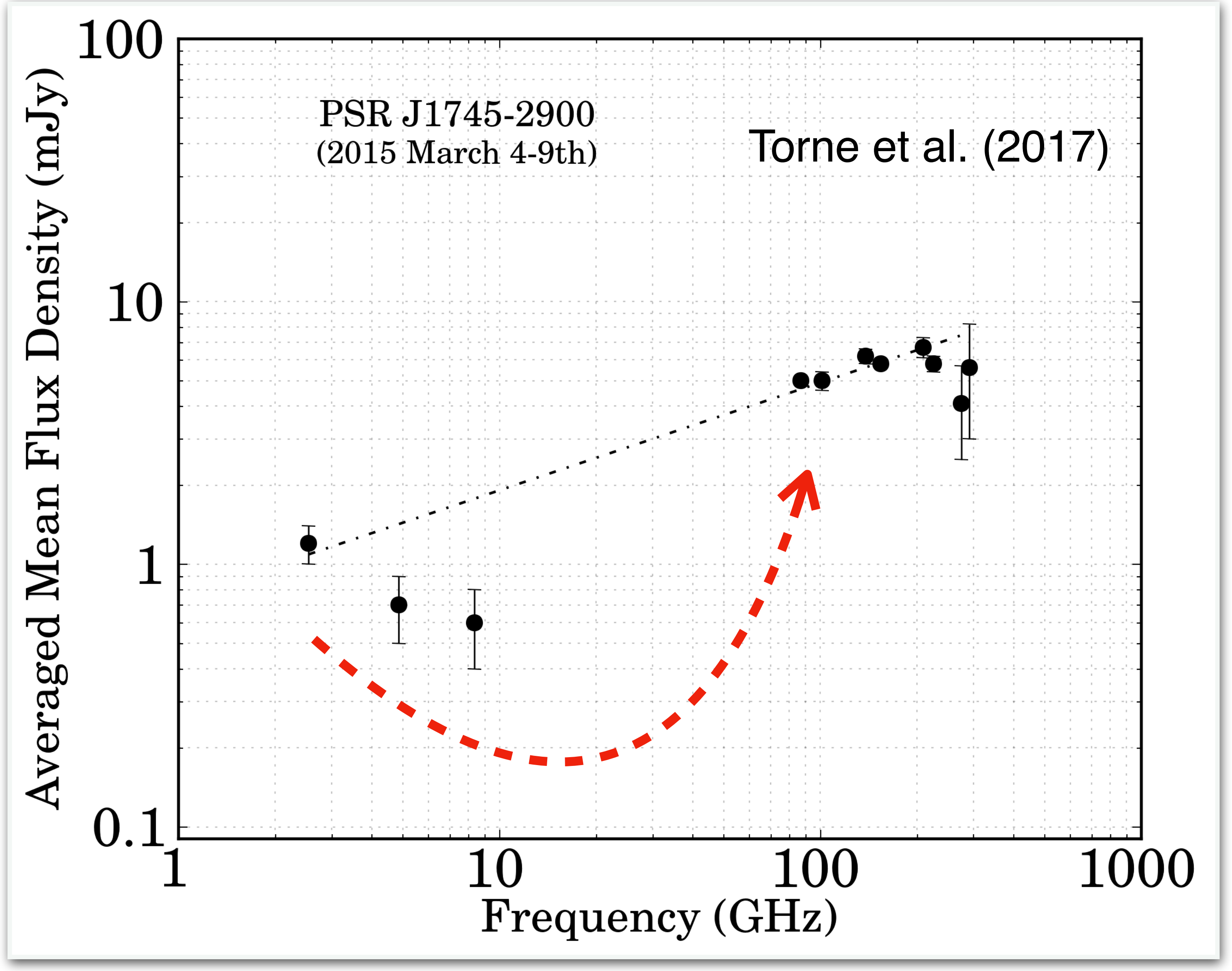


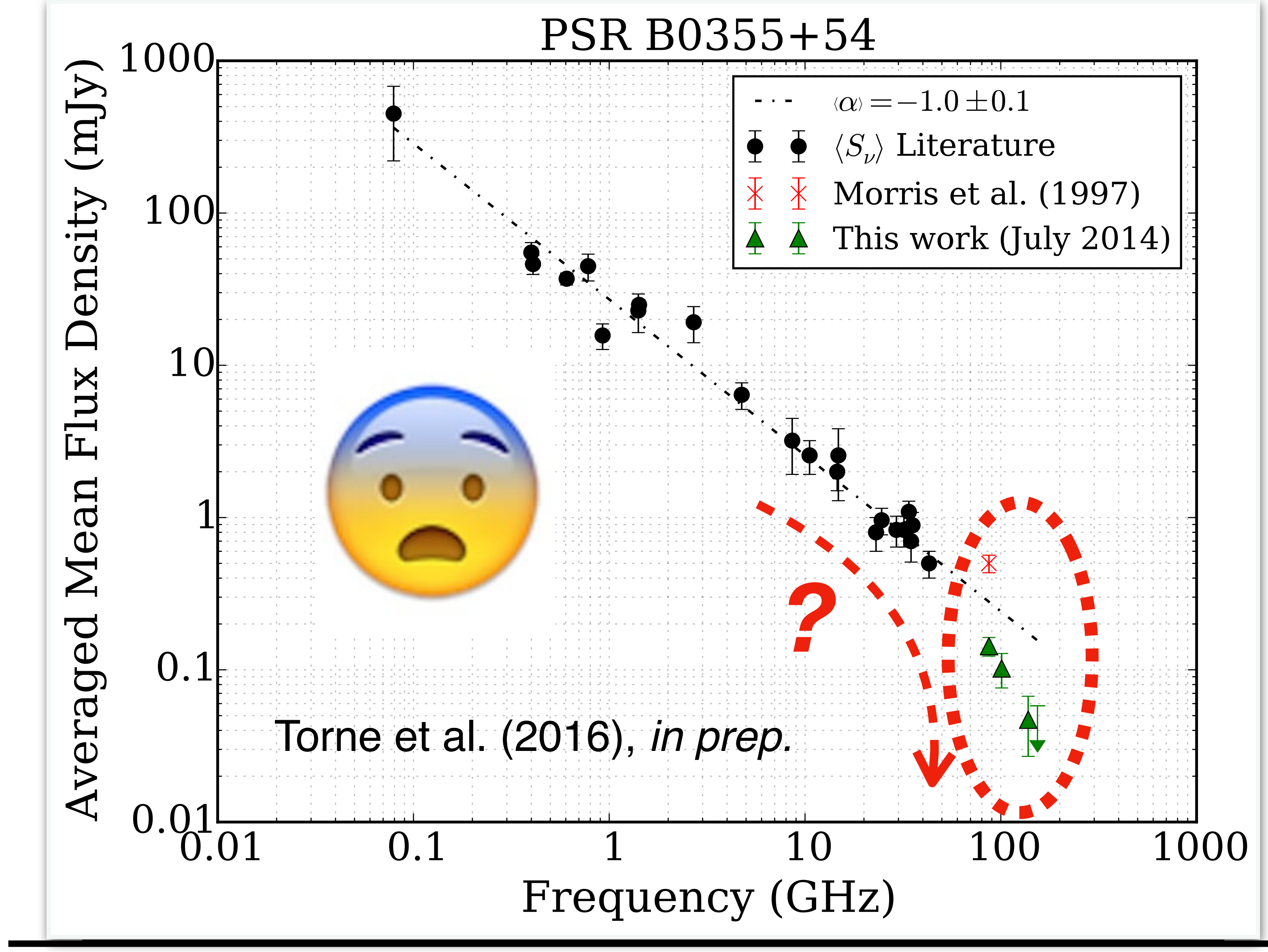
Zhao et al. (2019)

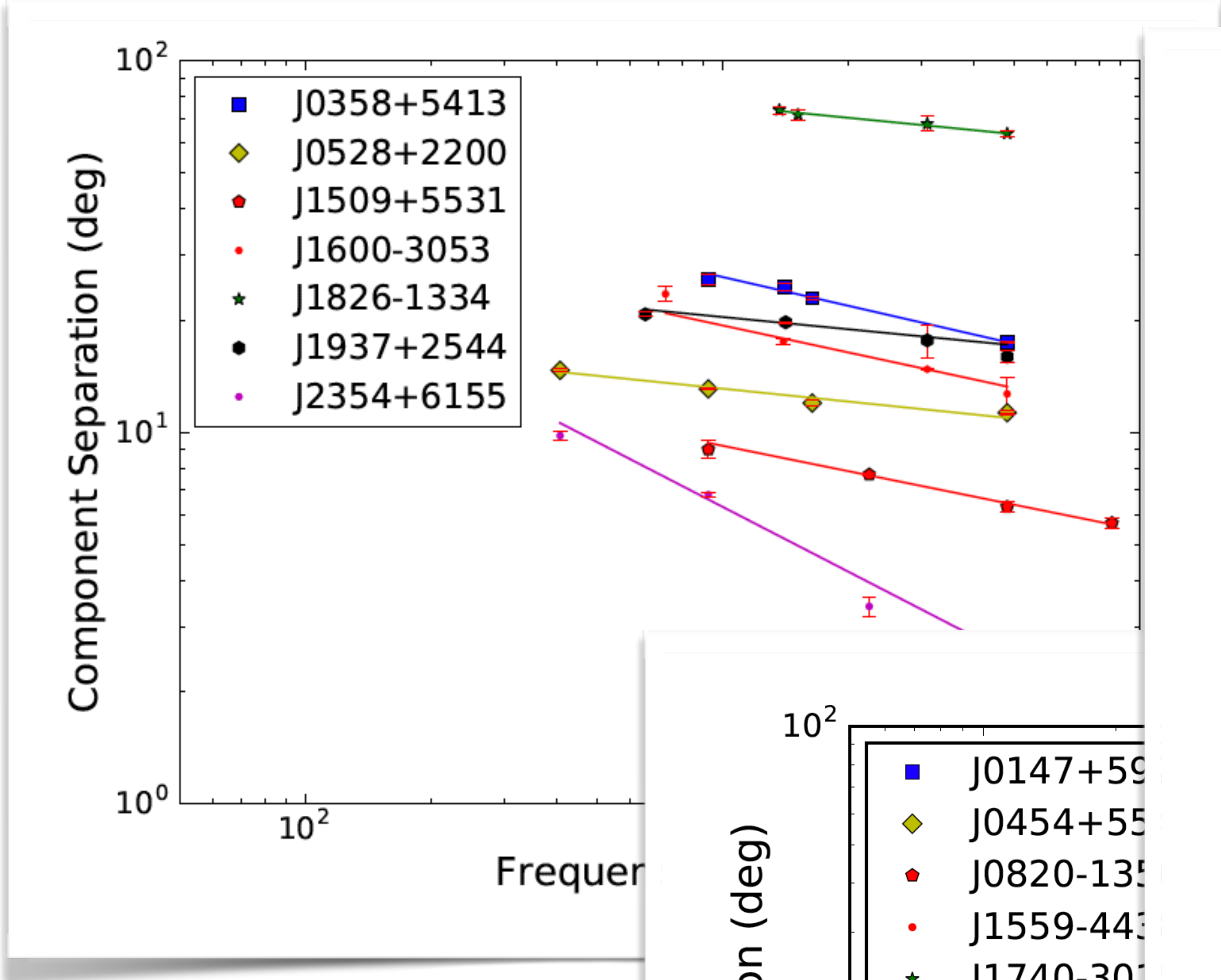


Xilouris et al. (1996)

The Big Puzzle: No Model Fits All







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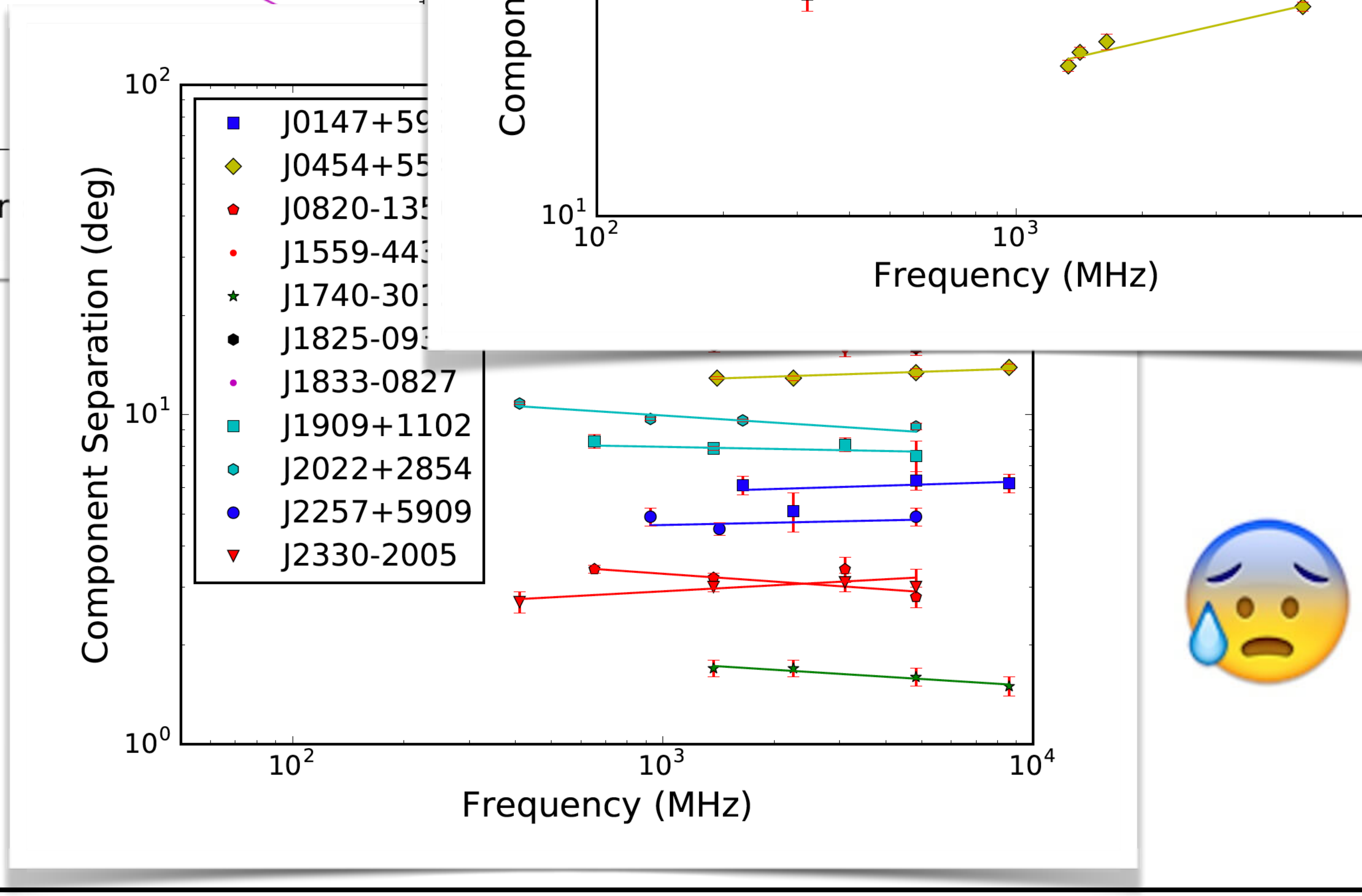
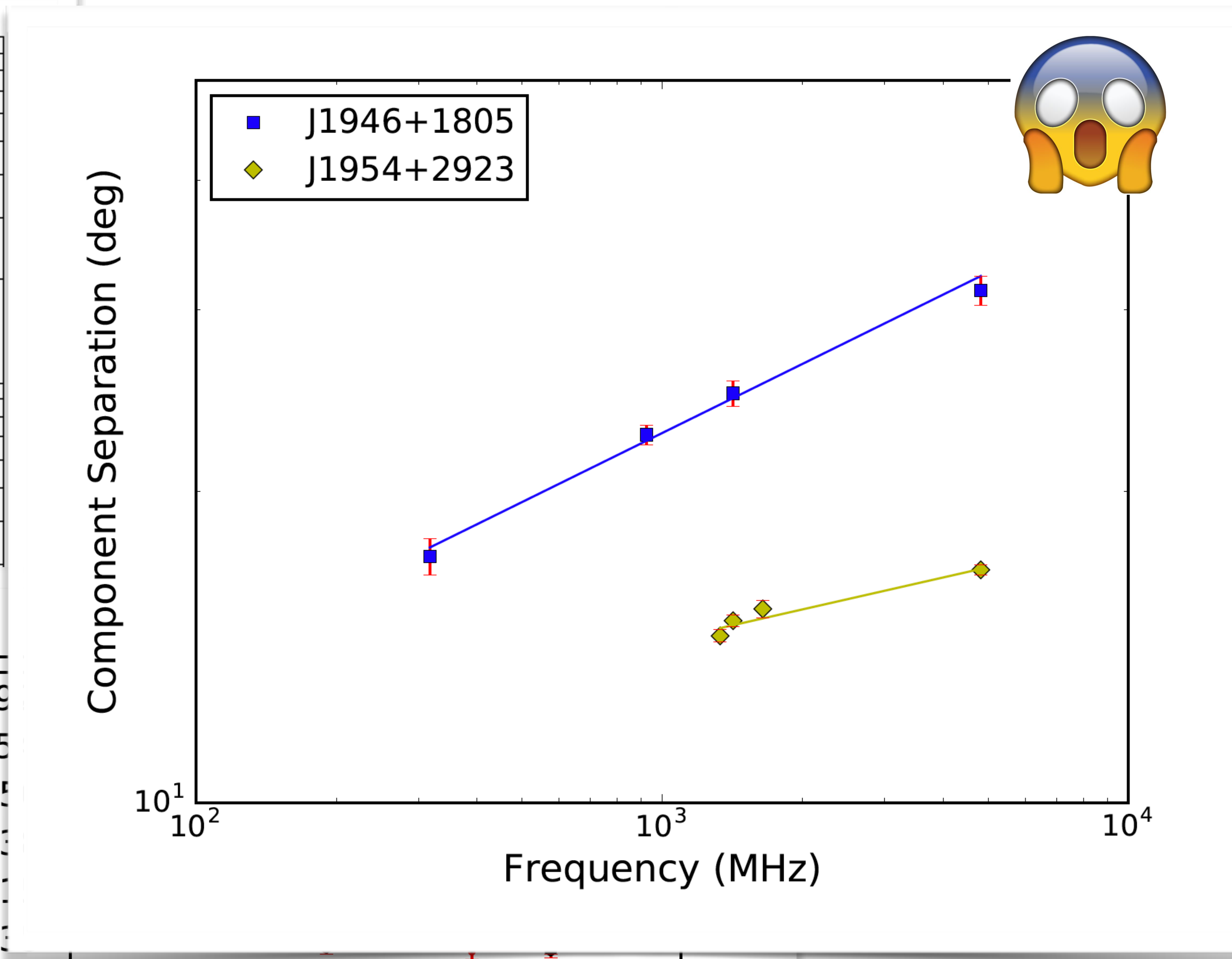
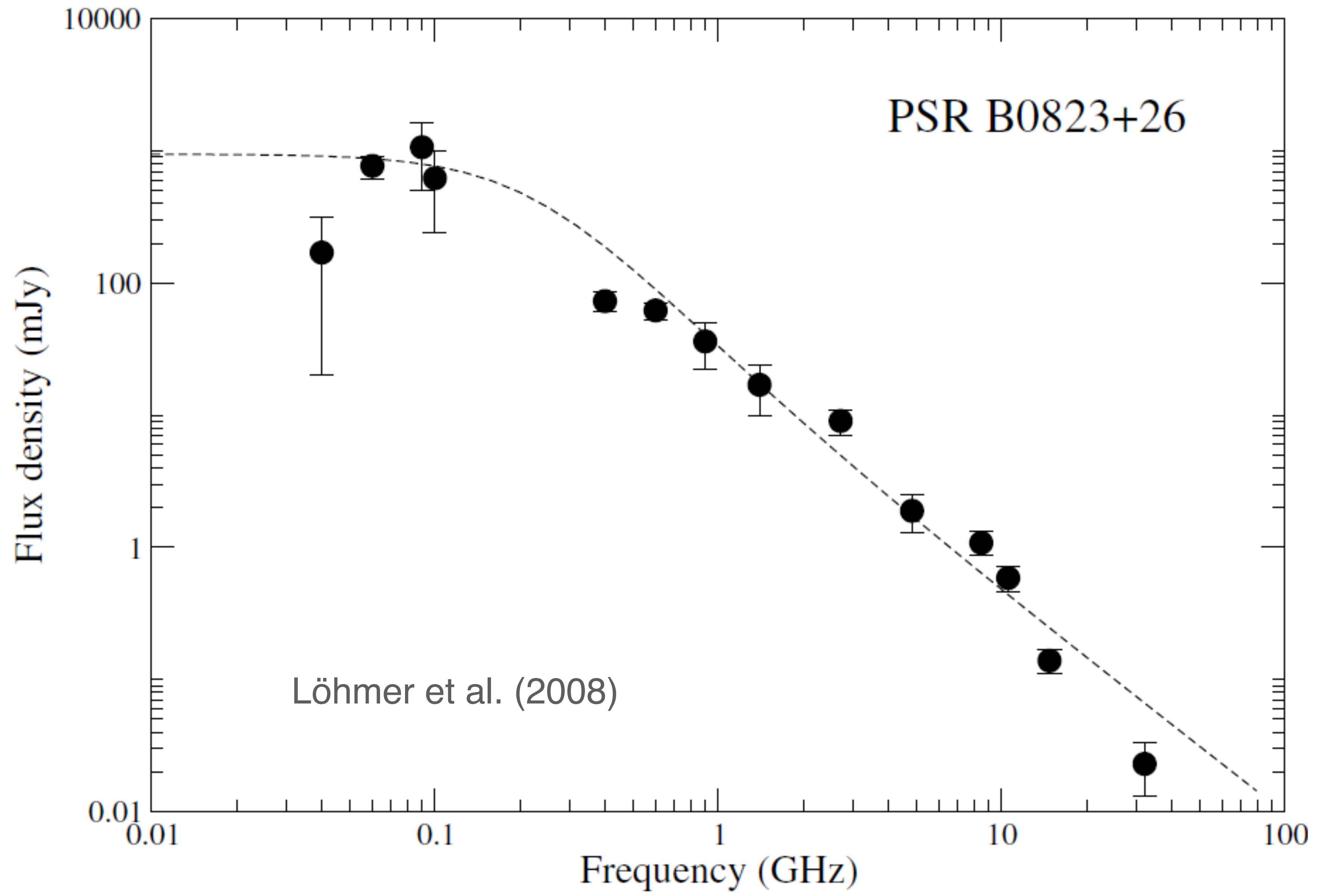




Observations and Challenges

“Natural” Issue: Signal Weakness

- **Pulsars are generally extremely faint radio sources**
- **Steep spectral sources → even weaker at short wavelengths**



Steep spectrum
on average

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

$$\langle\alpha\rangle = -1.8 \pm 0.2$$

Maron et al. (2000)

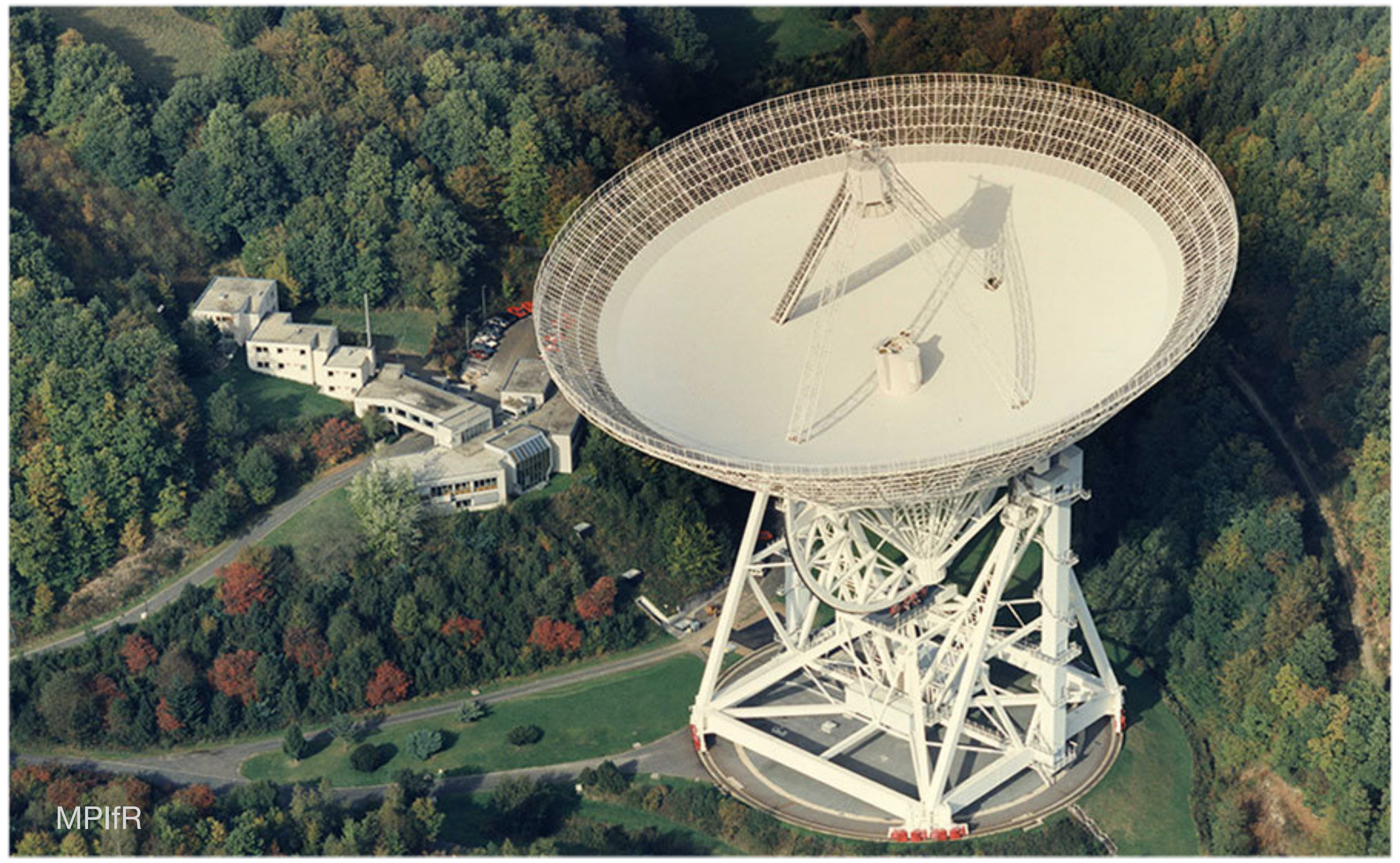
Objectives at (sub)mm-λ:

$\alpha > -1.2$ (70 pulsars)

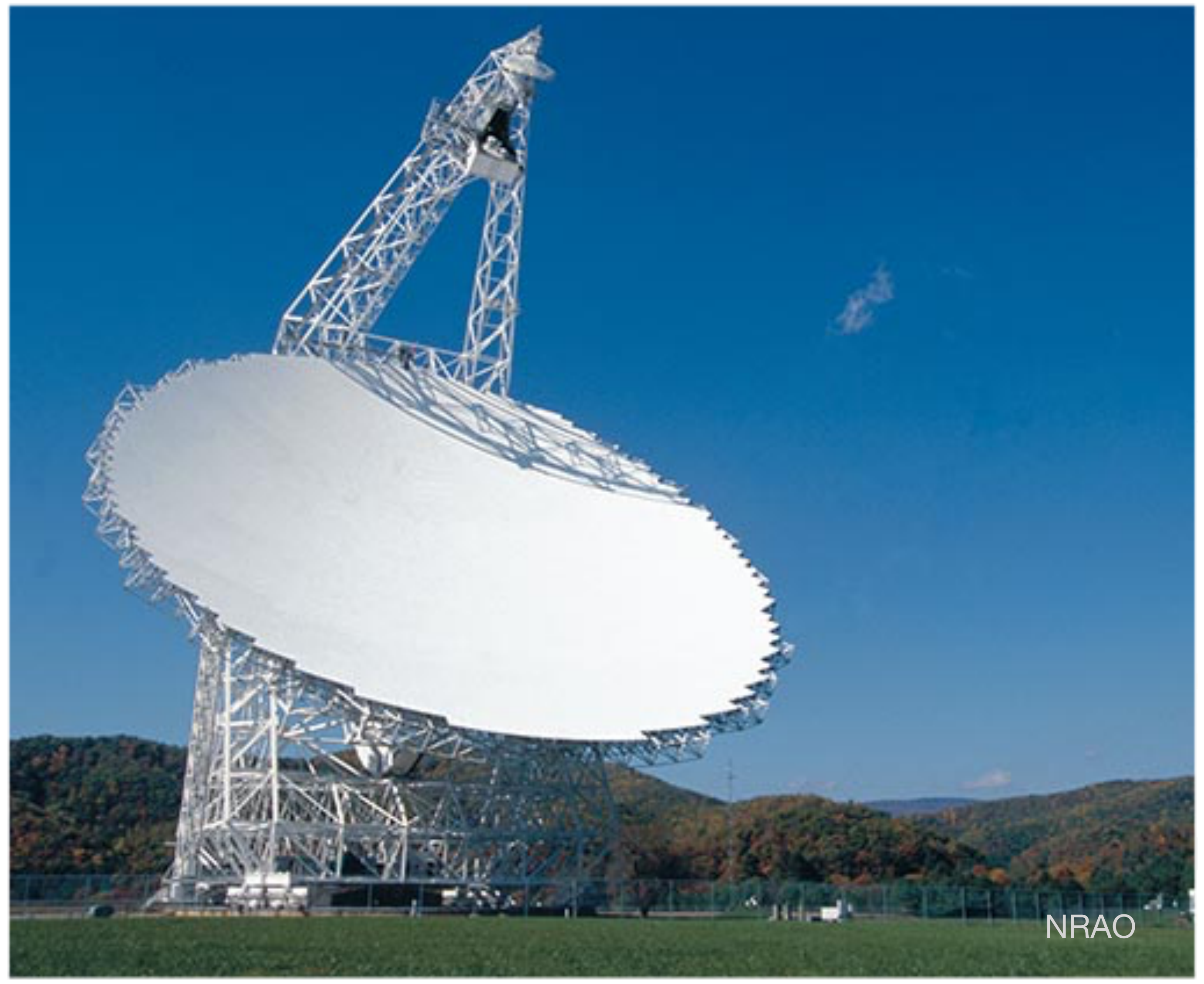
$-0.5 < \alpha < +1.0$ (Magnetars)

Pulsars are generally weak and steep spectral sources, making their detection and study at short radio wavelengths very challenging

“Natural" Issue: Signal Weakness



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



The Importance of Magnetars

Image credit: ESA

- **Magnetars** = young pulsars with very high B-fields
- Some show radio emission → **peculiar** and even less-understood **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 → Bright at short millimetre wavelengths !**

- Only 4 pulsars have been detected at 7 mm — Kramer et al. (1997)
- Only 4 at 3 mm (2 are magnetars) — Morris et al. (1997), Camilo et al. (2007), Torne et al. (2015), Liu et al. (2019)
- 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.*

Radio magnetars, due to their flat spectrum, are unique pulsars to study (sub)mm- radio emission characteristics. More telescopes with capability to detect pulsars at λ < 1.3 mm are of great application here ! (e.g., JCMT)

"Technological" Issue: Lack of Sensitivity

- To be able to detect the weak pulsations at short wavelengths **we need**:
  - Big collecting areas
  - Large bandwidths
  - "Nice" receivers -> Low Trec, "Gaussian' noise properties -> to integrate long times
  - Good sites for low Tsky

Gain is difficult to change, but we can improve:

Tsys, Tobs and Δ𝜈

→ the key to succeed if dish size ~medium-small

Minimum detectable flux density at S/N level

Good sites and state-of-the-art receivers

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

Big collecting areas

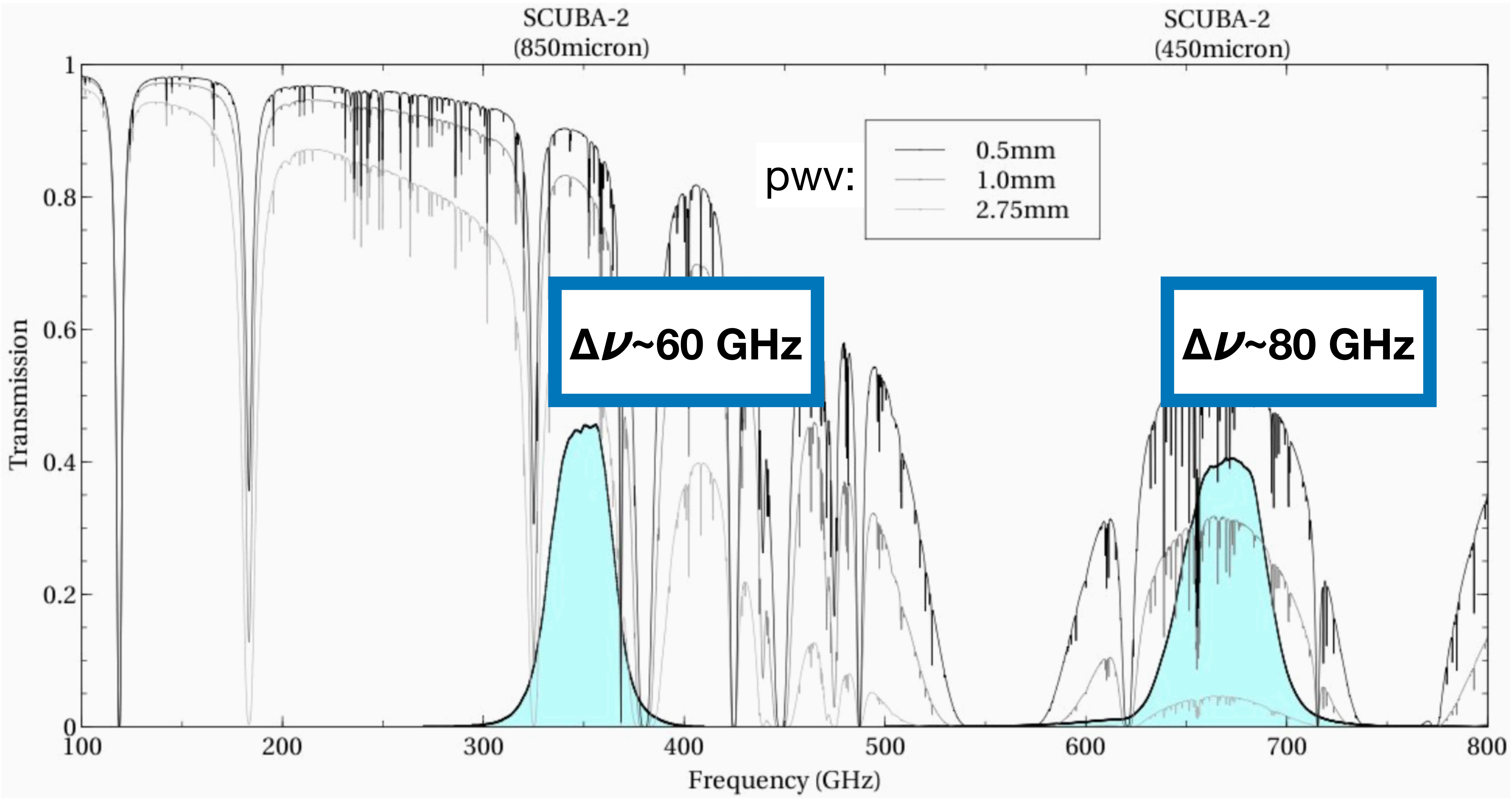
Long integration times

Large instantaneous bandwidths

Bolometer TES / KID Technology Promising

- TES Bolometer / Kinetic Inductance (KID) technology offering huge instantaneous bandwidths at (sub)mm-telescopes. See e.g., SCUBA2: Holland et al. (2013) + NIKA2: Adam et al. (2018) + LABOCA: Siringo et al. (2009)

SCUBA2 @ JCMT frequency coverage:



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

Bolometers / KIDs up to 2-3x more sensitive than typical SiS Rx

but can they be used for detecting pulsars?

https://www.eaobservatory.org/jcmt/instrumentation/

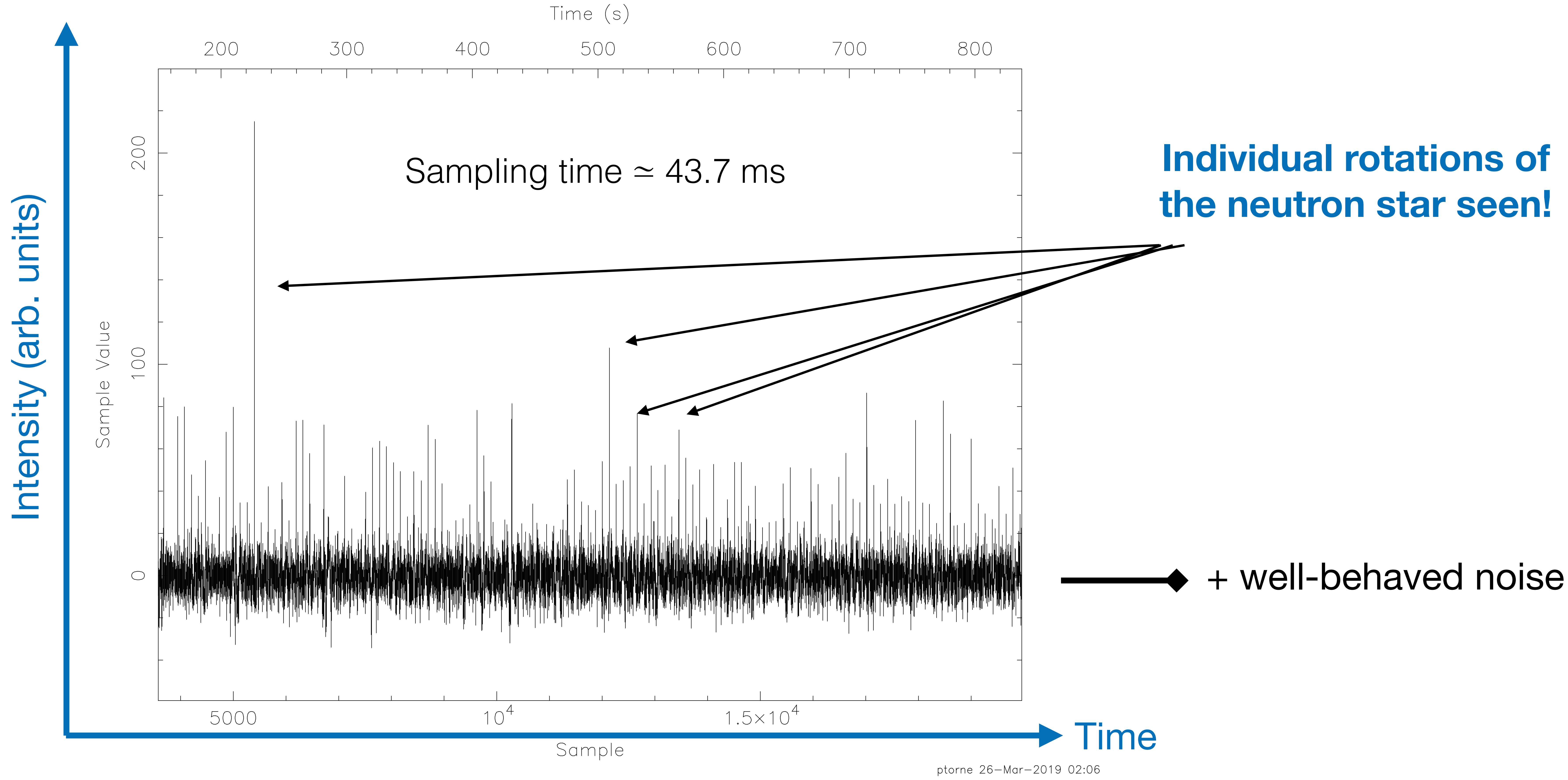
YES! ➙ First Pulsar Detection with a KID camera

Torne et al. *in prep*

- Magnetar AXP1810−197 with NIKA2 @ IRAM 30-m, 0.6 hr observation on 23-March-2019
- OK weather (tau225~0.3)
- Proof of concept, no major issues. Worked beautifully well!

Time series with 2 mm array

(1.3 mm not shown)



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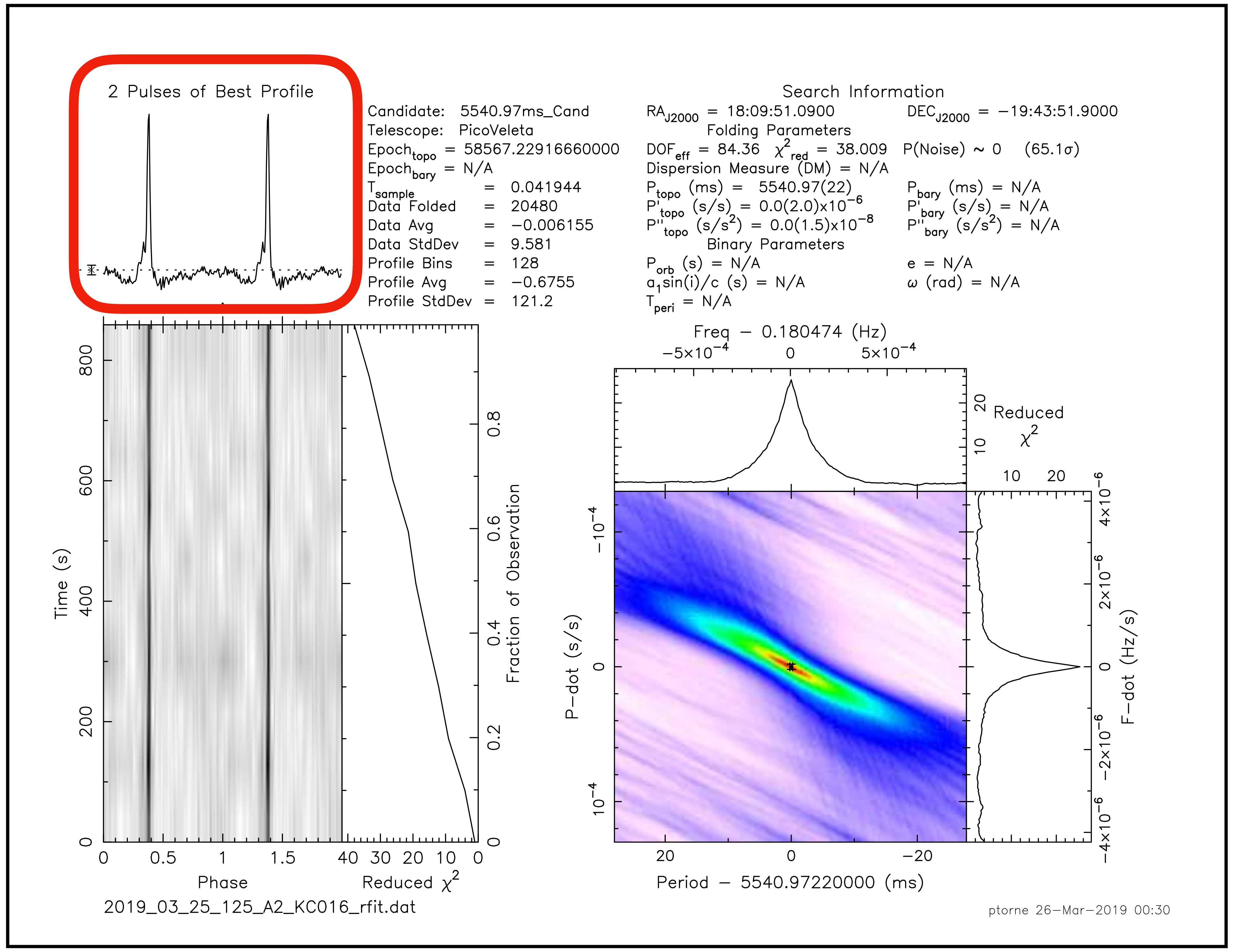
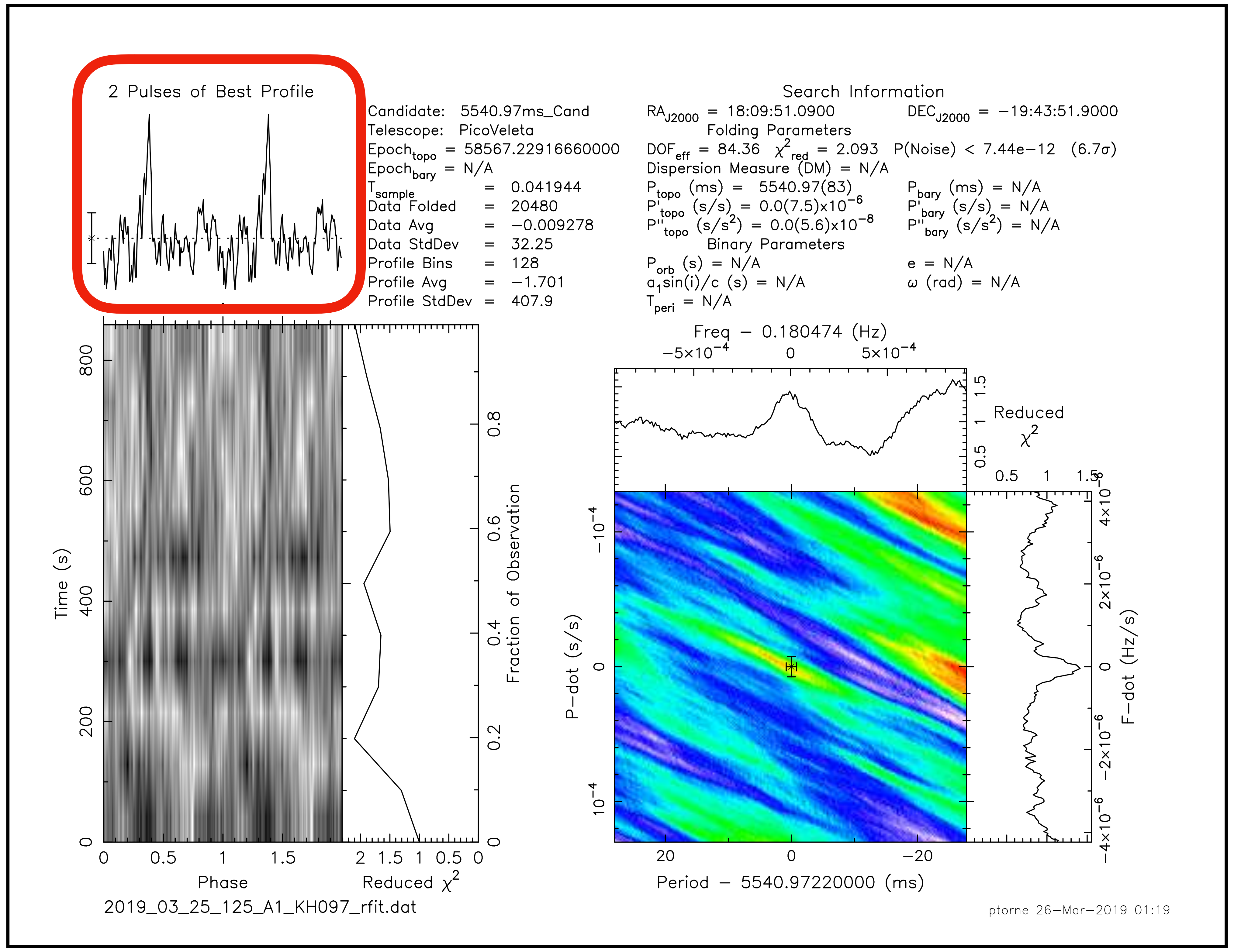
Torne et al. *in prep*

NIKA2

Detection with 2 mm array

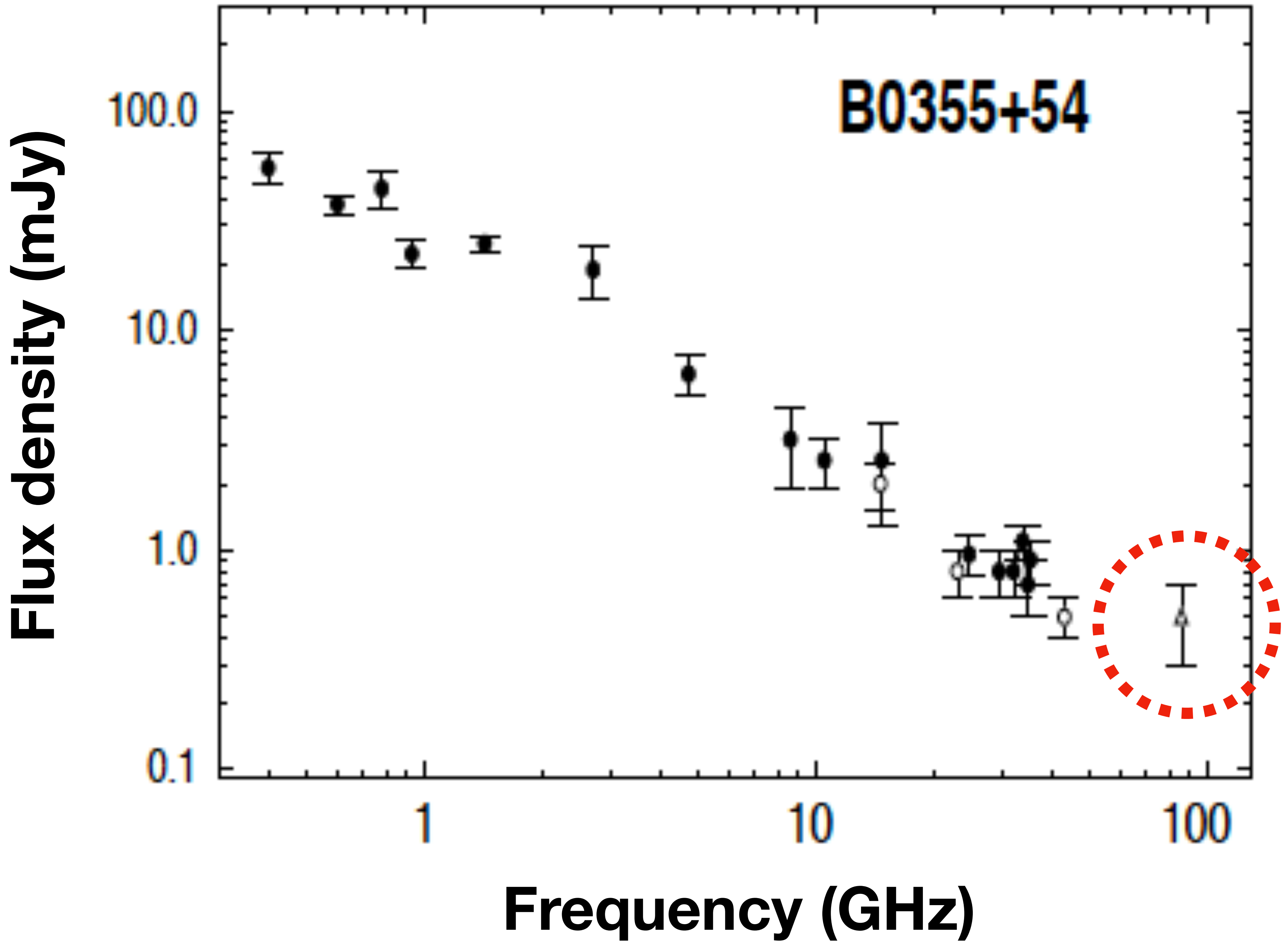


Detection with 1.3 mm array



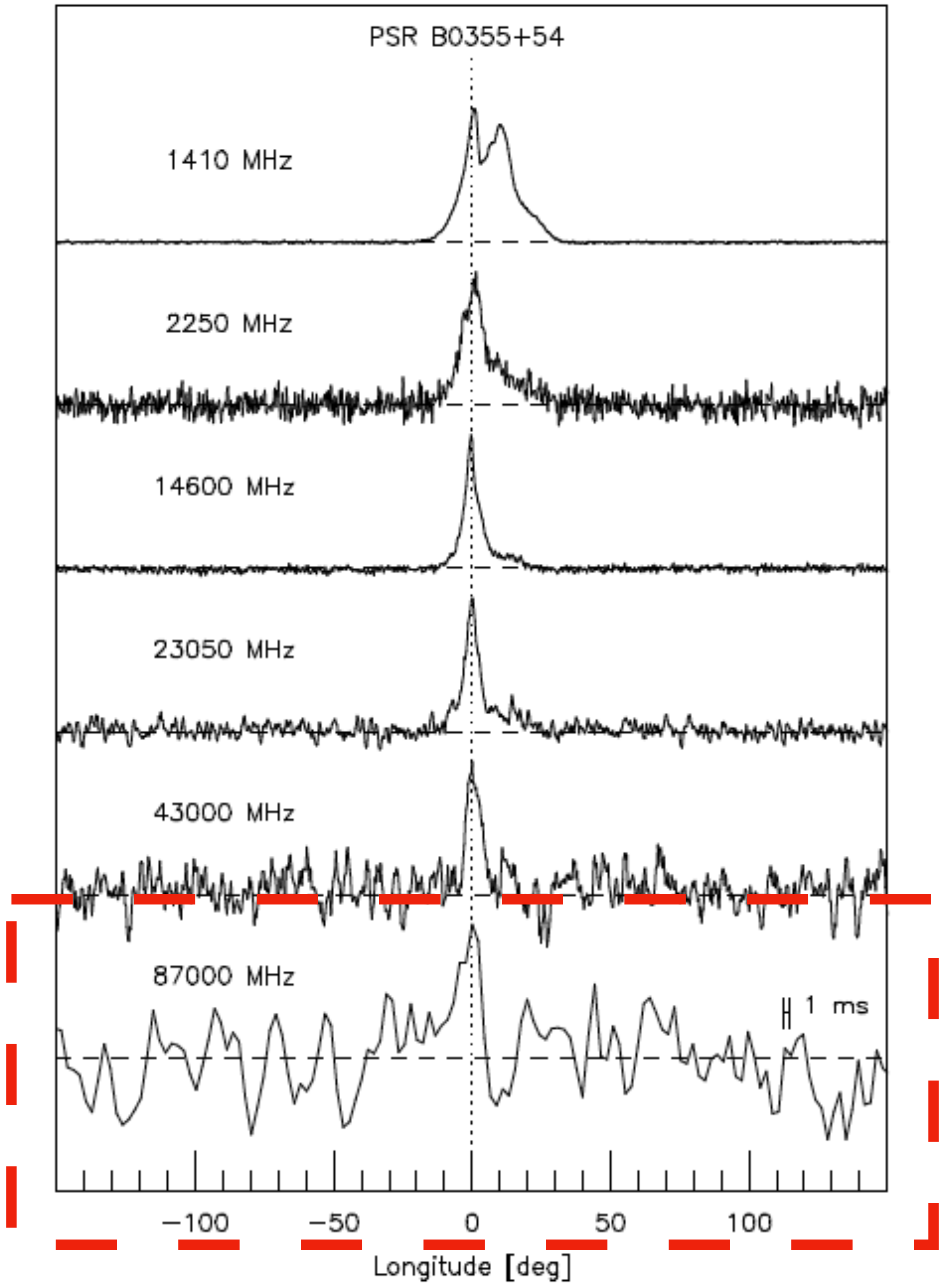
First Exploration of Range 3.4 – 1.1 mm

- 1997: Pulsars detected for the first time at 7 mm with Effelsberg 100-m
- **1997: Morris et al., detect PSR B0355+54 at 87 GHz (λ3.44 mm) with IRAM 30-m**
  - Single polarisation, 500 MHz bandwidth



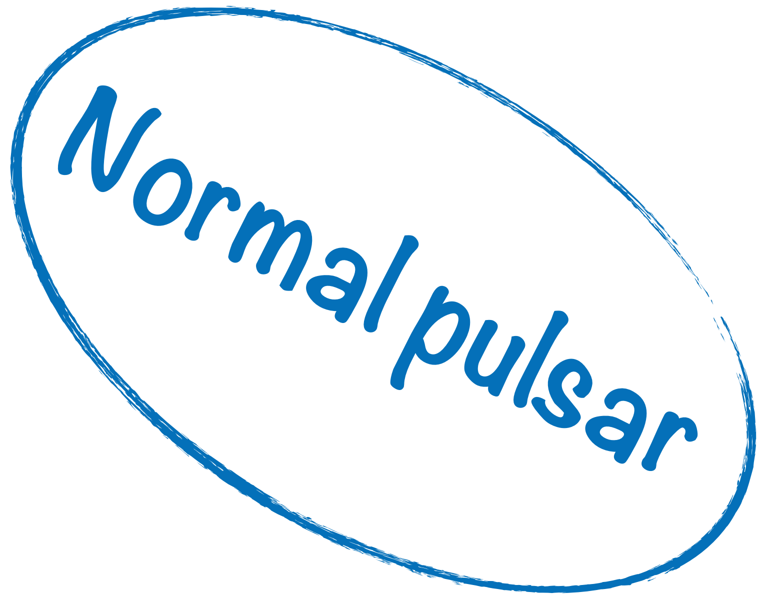
Morris et al. (1997)

Pulse profiles



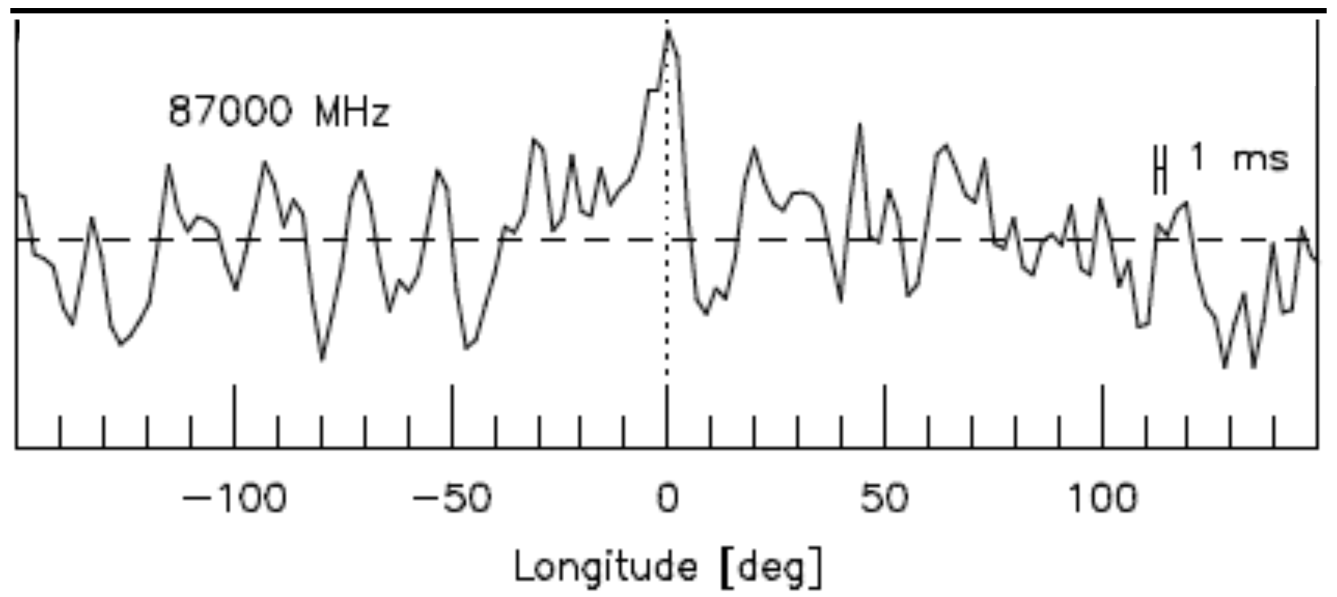
First Exploration of Range 3.4 – 1.1 mm

- **2014 - 2017: Torne et al., detect B0355+54 up to 138 GHz (λ2.17 mm) with IRAM 30-m**
- **Highest radio frequency detection to date** (for a normal pulsar) **!**
- BBC backend: 64 GHz bandwidth

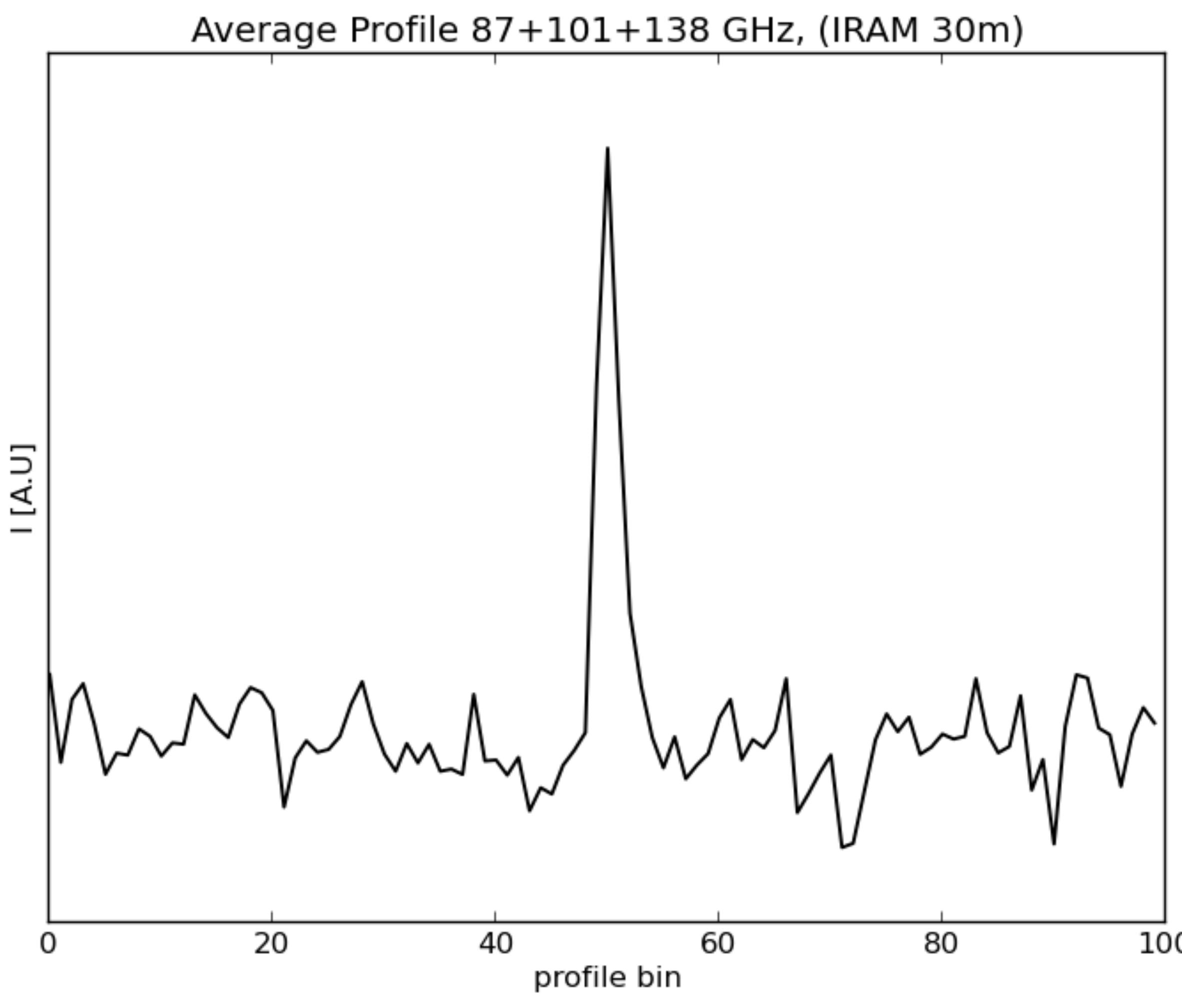


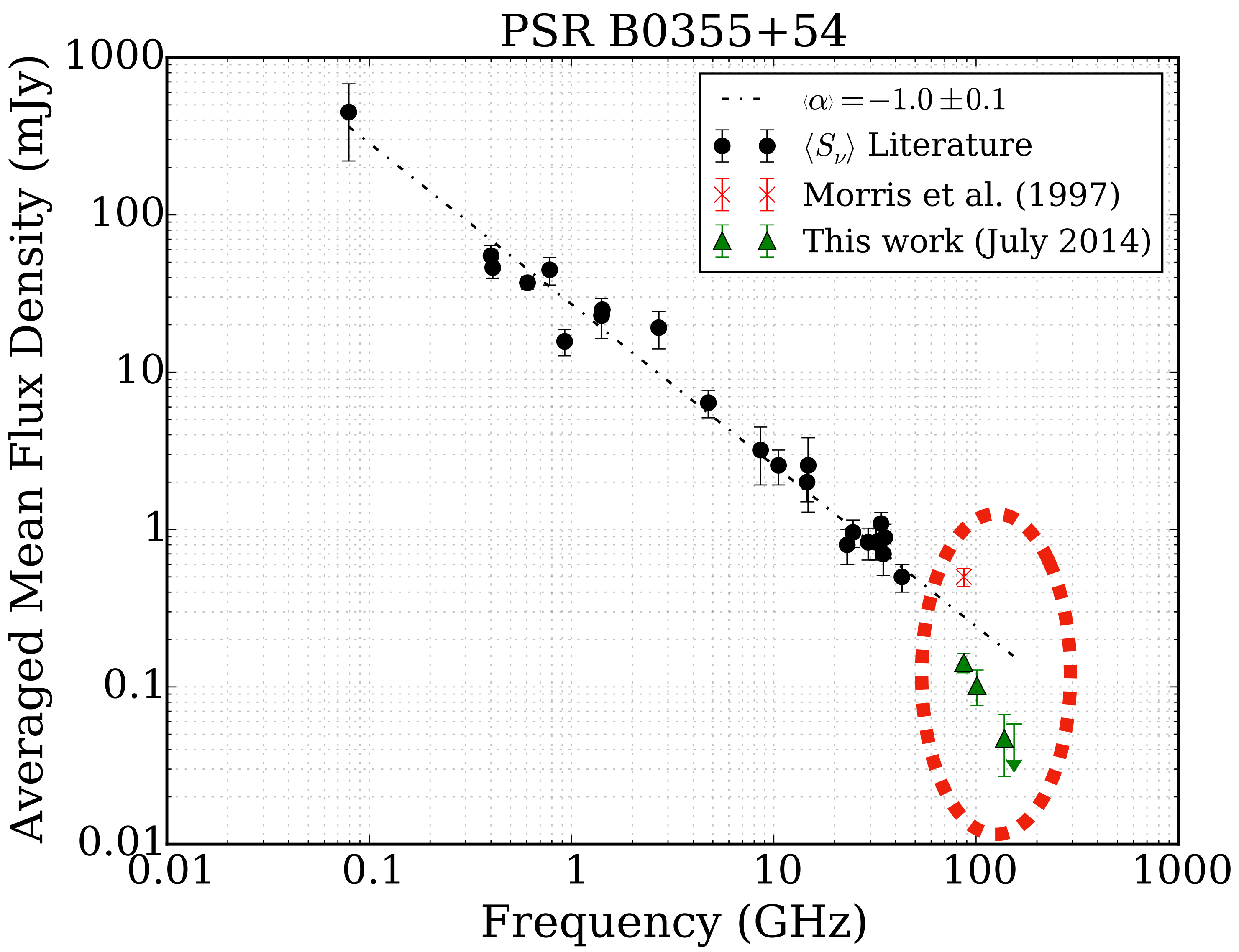
Significant technological progress

1997 → **2014 - 2019**



Morris et al. (1997)

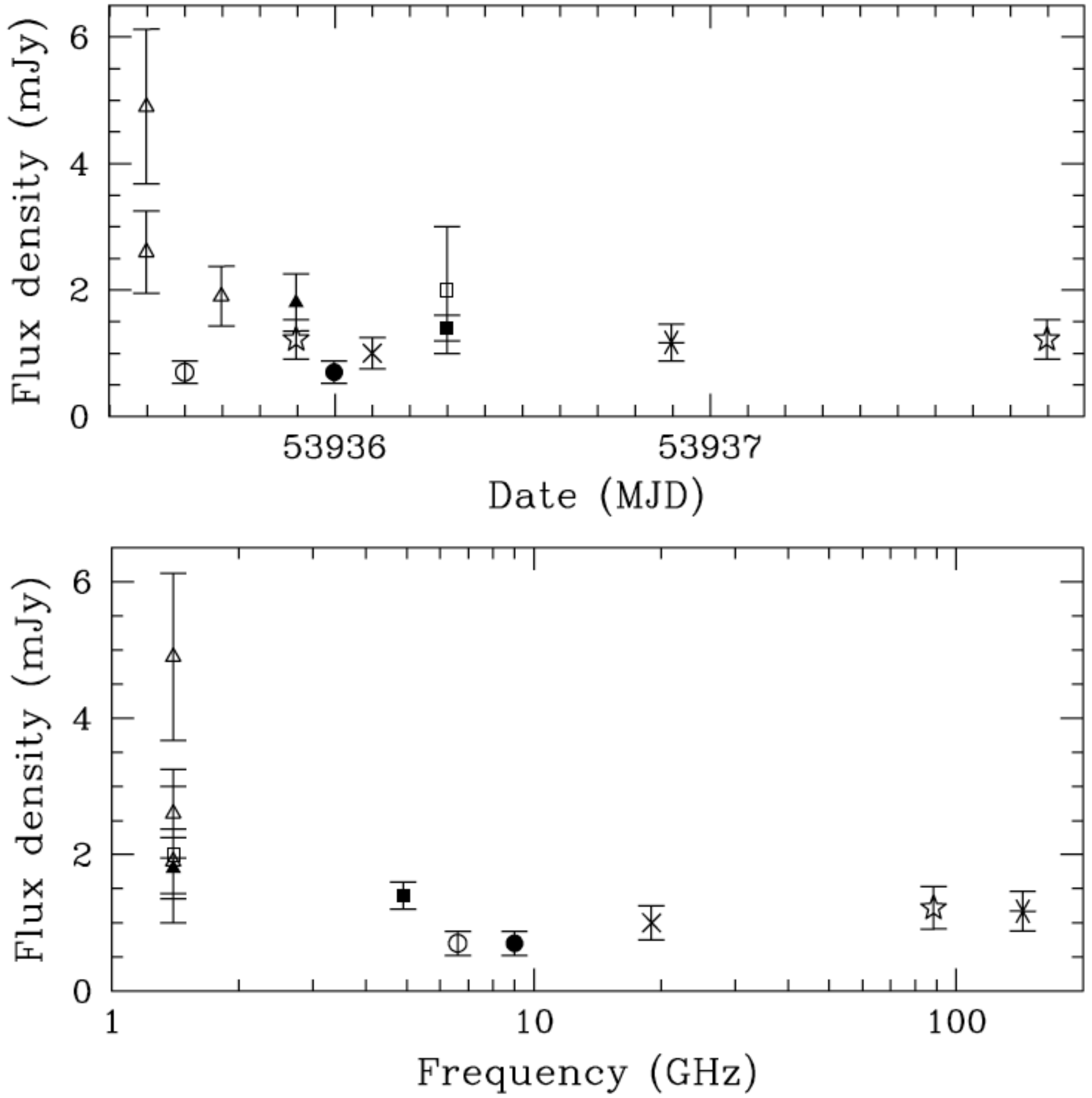




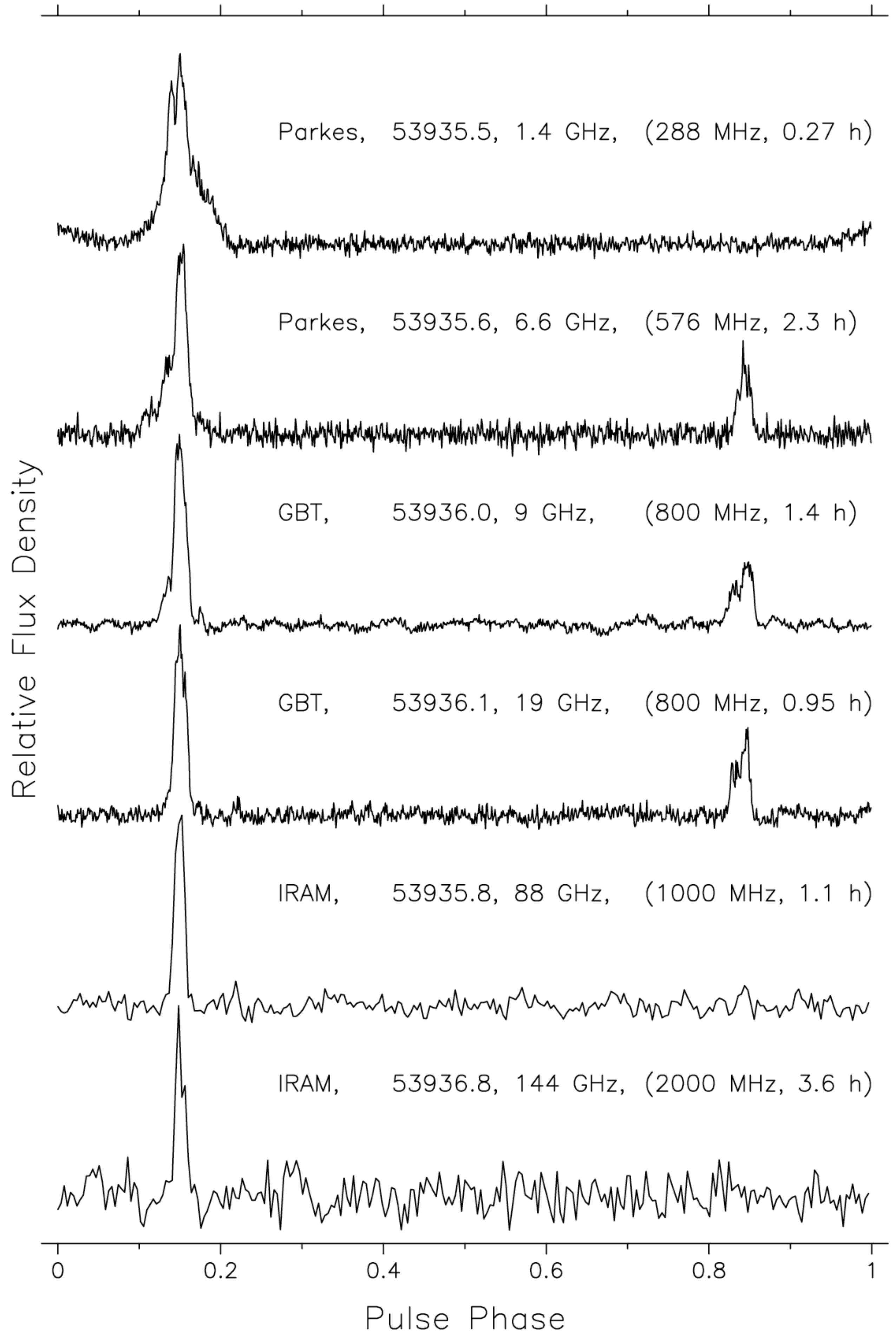
Torne (2017) PhD thesis, Torne et al. *in prep.*

First Exploration of Range 3.4 – 1.1 mm

- **2007: Camilo et al.: first detections of a magnetar (AXP 1810–197) up to 144 GHz (λ2.08 mm) with IRAM 30-m**
- Confirms variability (I, α) and flat spectrum into the mm- band

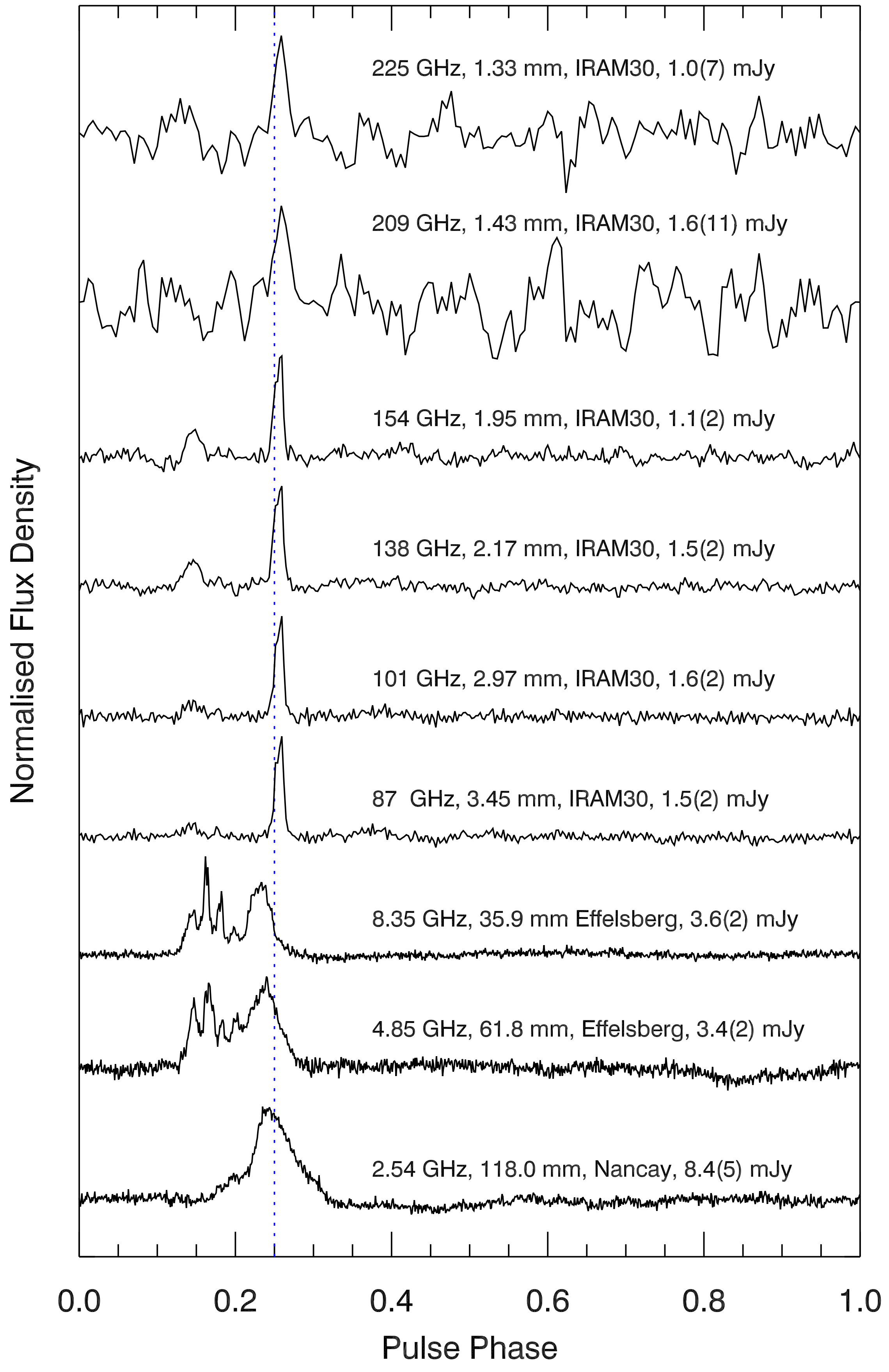


Camilo et al. (2007)



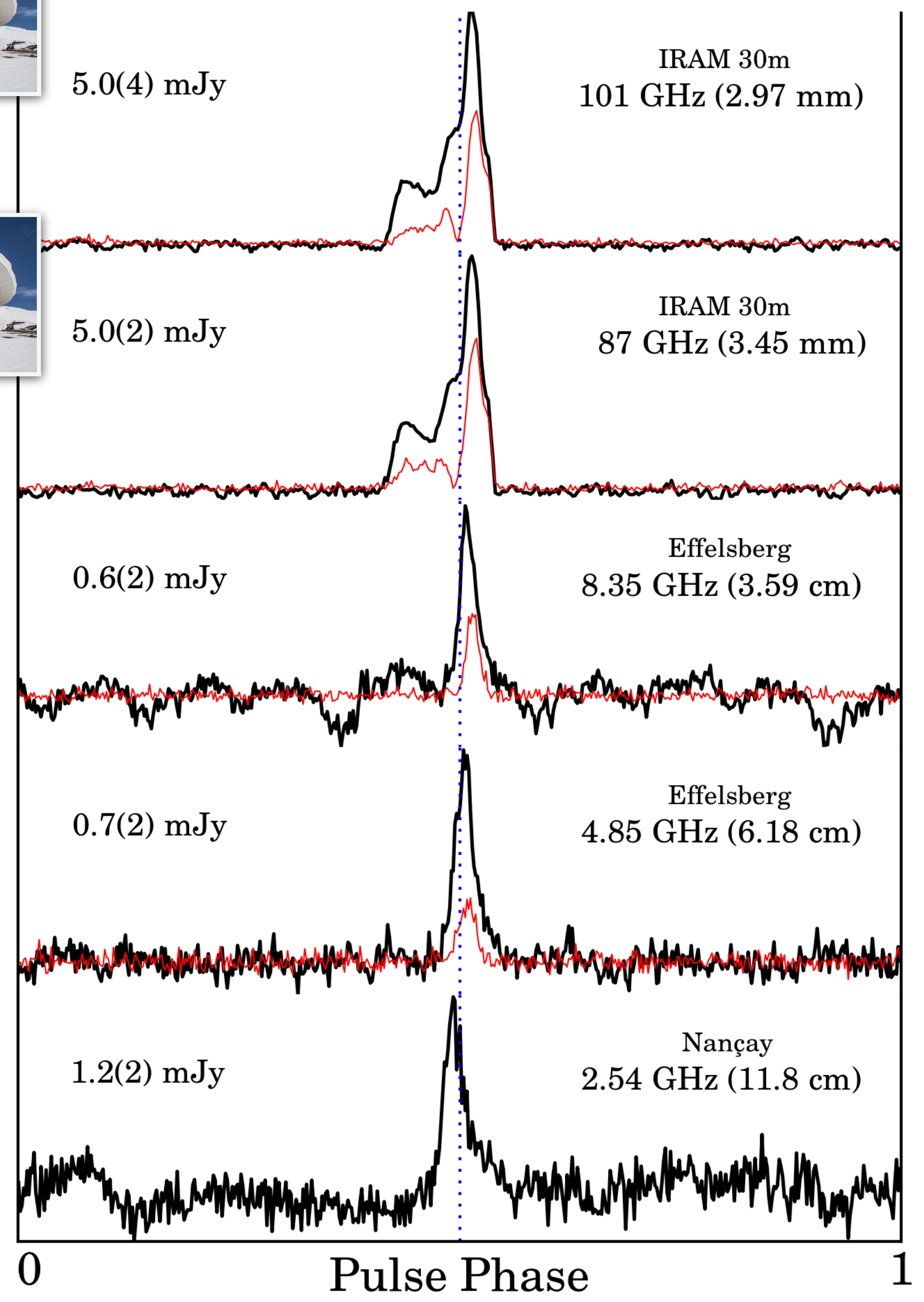
First Exploration of Range 3.4 – 1.1 mm

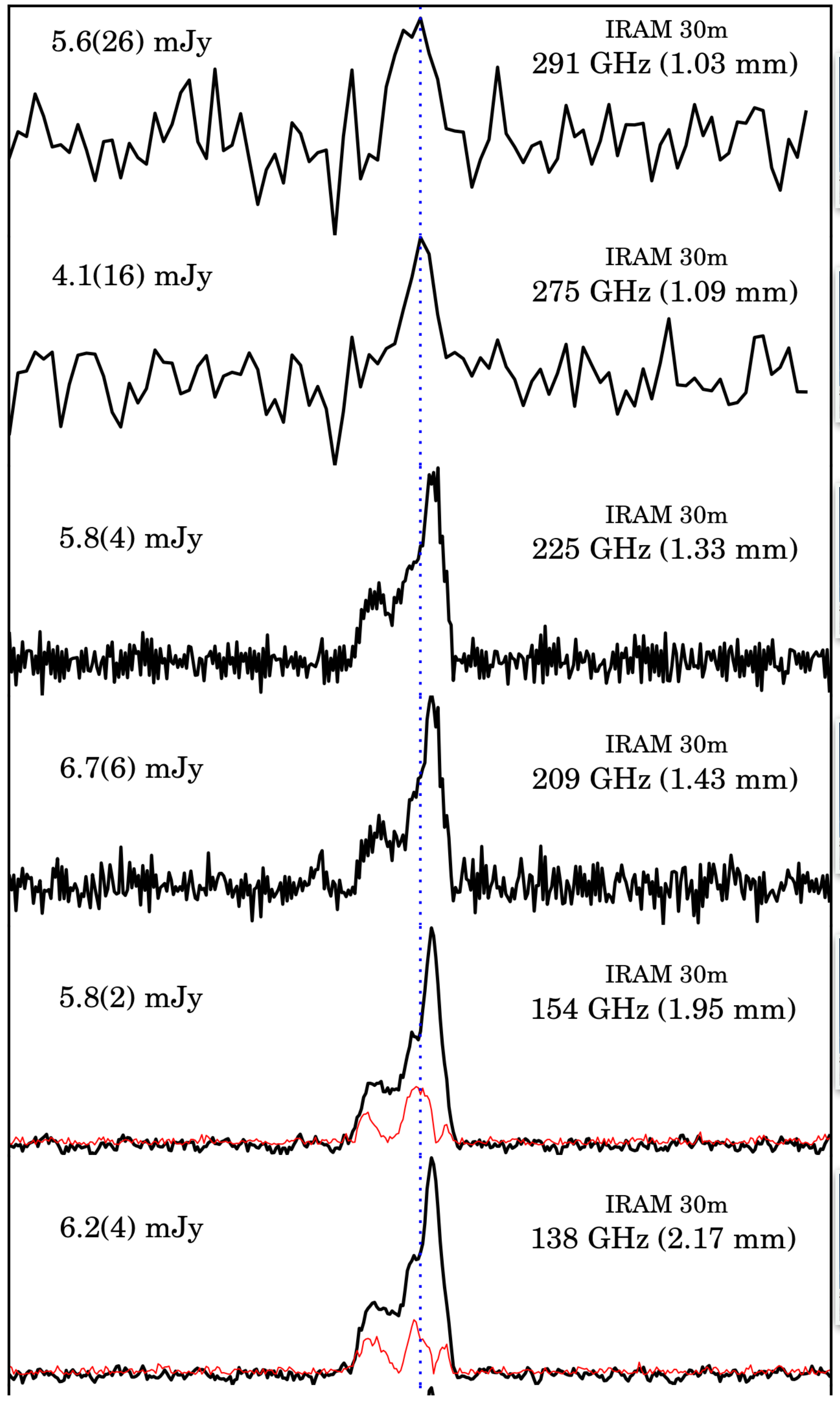
- **2015: Torne et al. detect Galactic Center magnetar (SGR J1745–2900) up to 225 GHz (λ1.33 mm)**
- **2017: detections up to 291 GHz (λ1.09 mm)** ⟶ Record to date



Torne et al. (2015) ⟵

Torne et al. (2017) ⟶

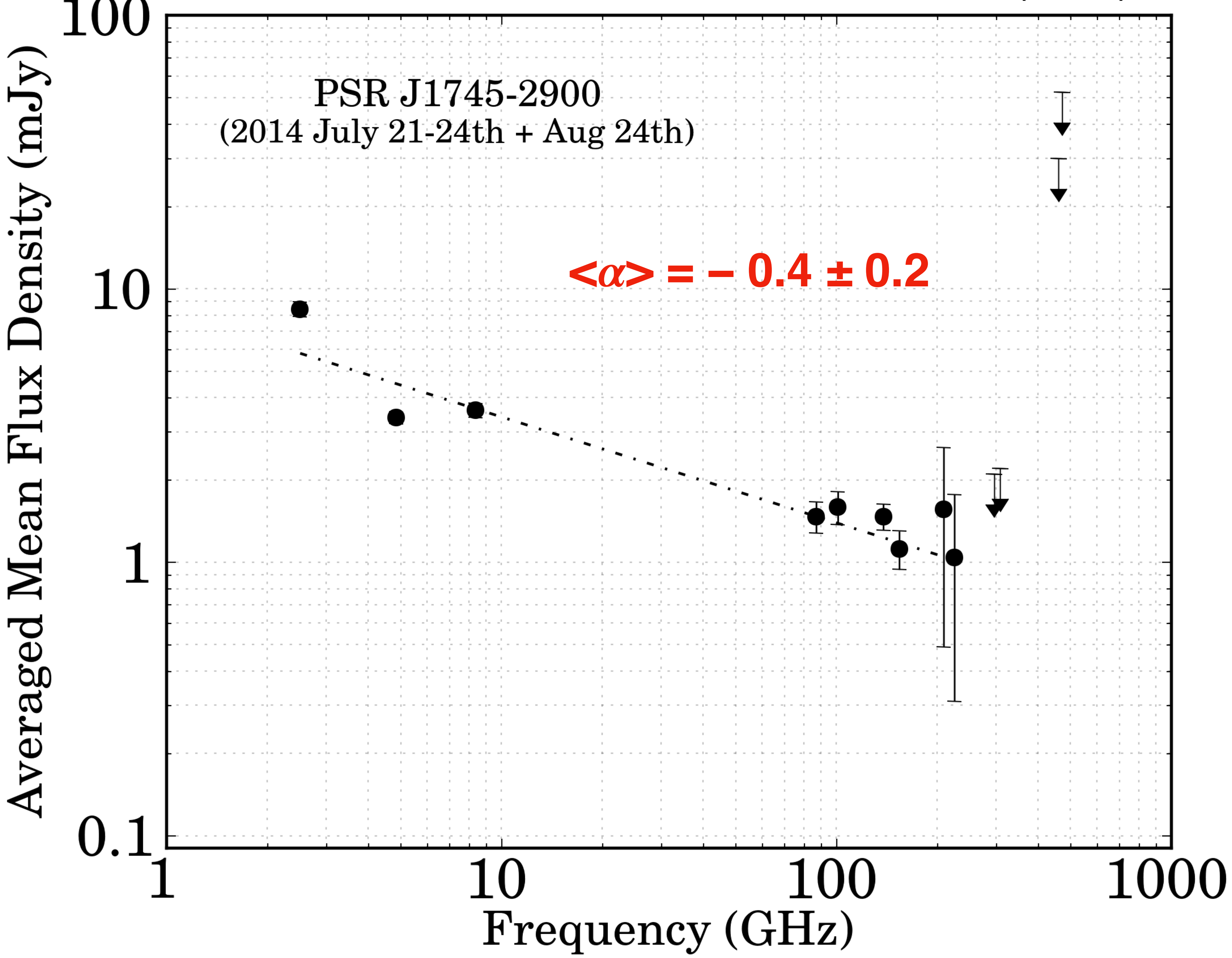




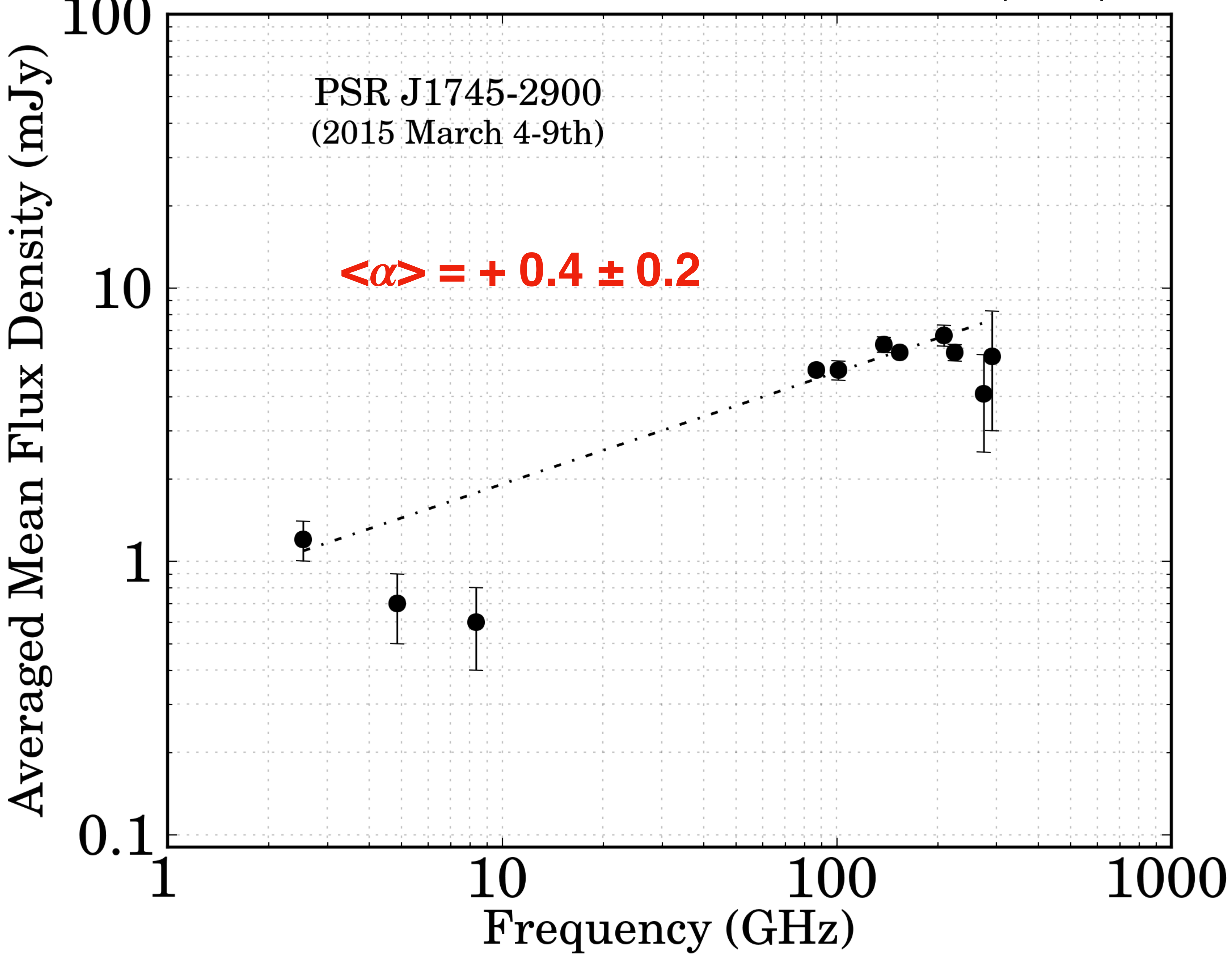
First Exploration of Range 3.4 – 1.1 mm

- Confirms variability (I, α) and flat spectrum into the mm- band for a second magnetar!

Torne et al. (2015)



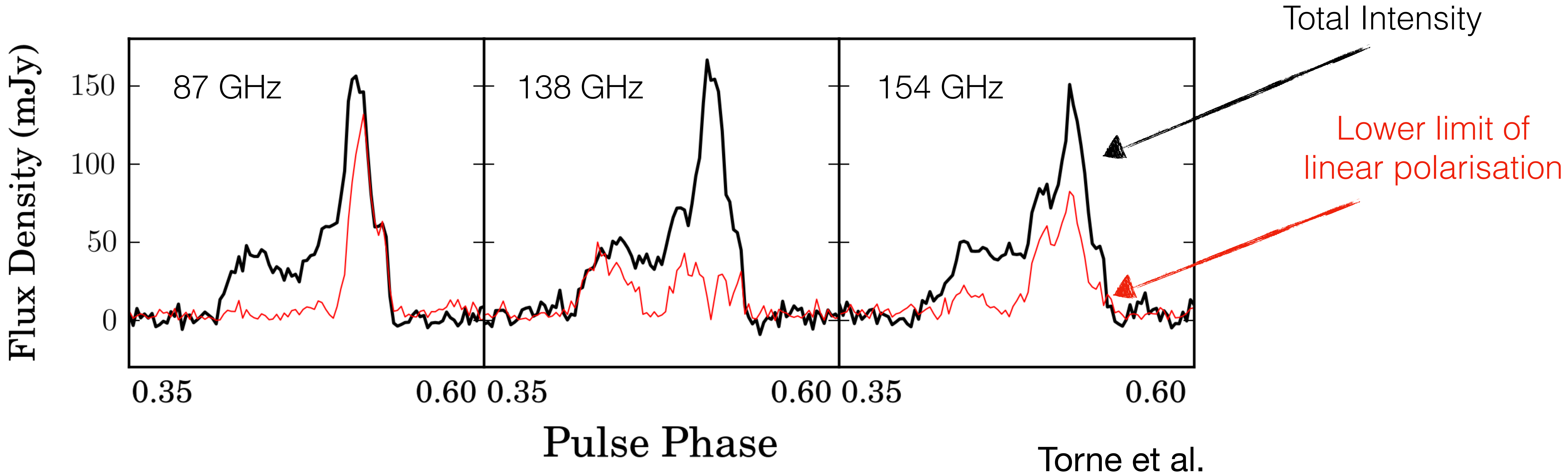
Torne et al. (2017)



First Exploration of Range 3.4 – 1.1 mm

- Confirms variability (I, α) and flat spectrum into the mm- band for a second magnetar!
- Evidence of high (up to 100%) **linear polarisation** up to 154 GHz (λ1.95 mm)

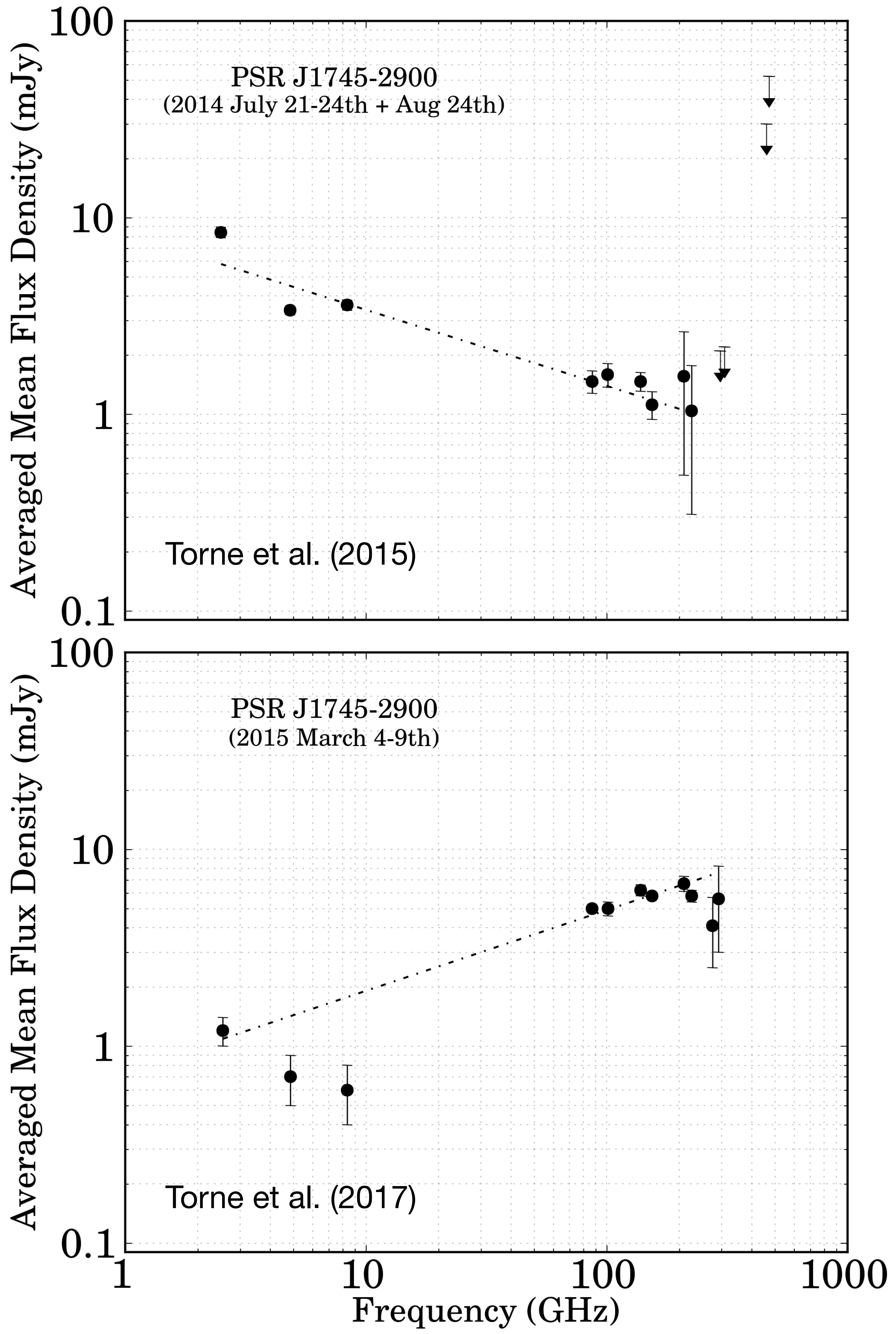
Highest degree of linear pol. at these frequencies?



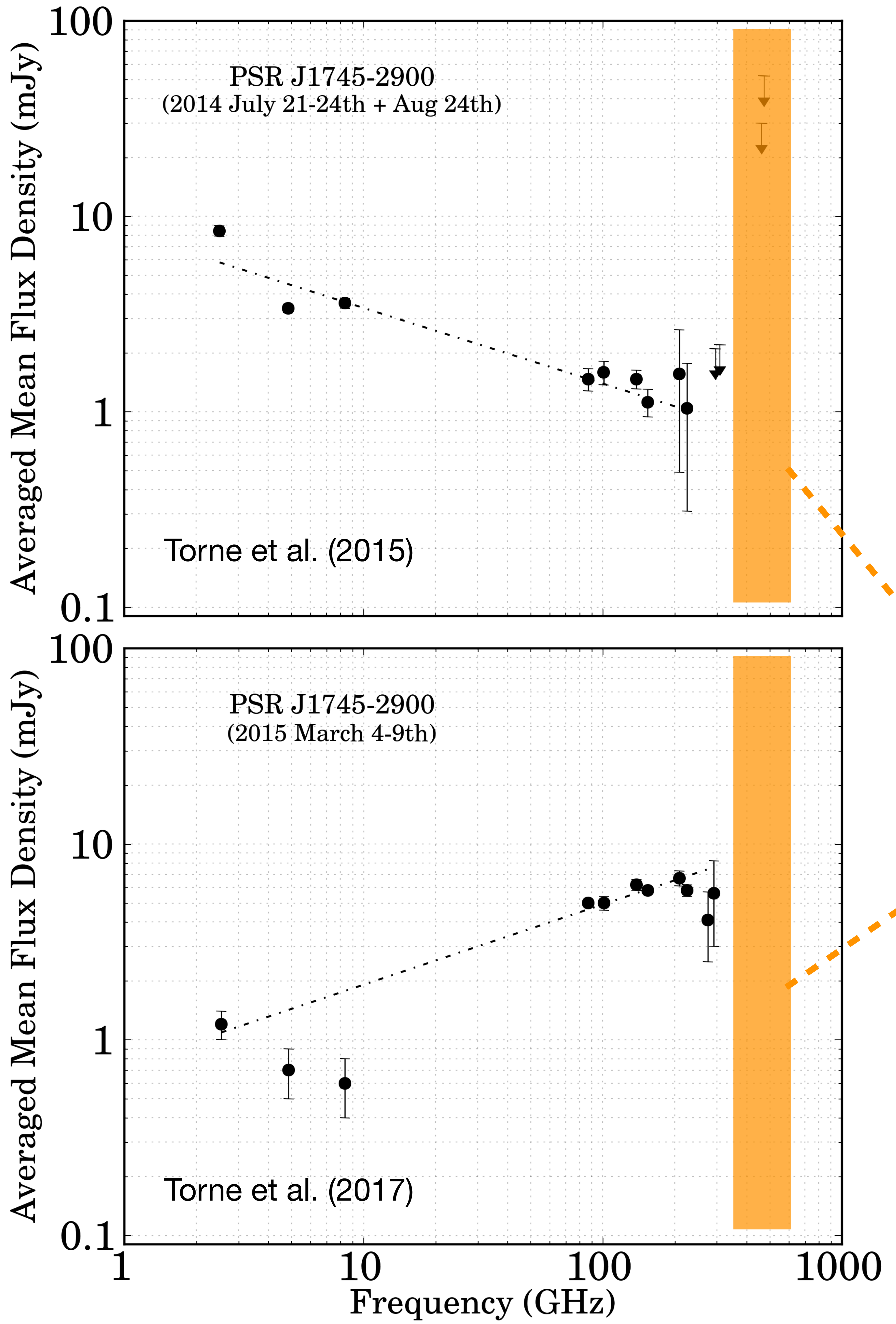
Torne et al. (2017)

What next?

JCMT very well suited for 0.9 — 0.4 mm window



JCMT very well suited for 0.9 — 0.4 mm window



- 15-m dish, high quality (good aperture efficiency at short wavelengths)
- Excellent site, Tsys very low and access to $\lambda < 0.8$ mm
- Large-bandwidth receivers, bolometer SCUBA2
- Atypical science case … pulsars never studied in [0.9 — 0.4] mm window
- Challenging, but worth trying !

JCMT is one of the few instruments in the world with potential for pulsar studies at (sub)mm- wavelengths

SCUBA2 Observations of a Radio Magnetar

Stay tuned !

- DDT: AXP1810−19, a recently reactivated radio magnetar with SCUBA2
- Goal: First-ever detection of pulsations from neutron stars at 0.85 and 0.45 mm → Check Coherence Breakdown!
- Requires special observing mode … tested on Friday: use of one array of SCUBA2, extract signal from Daisy pattern

Summary

Pulsars are fascinating objects and unique high-precision astrophysical tools

Extensively observed in the radio band, but the emission mechanism still a mystery

To aid in understanding the emission process: observations between millimeter and infrared

Bolometer TES / KID promising technology for pulsar observations in those ranges

JCMT well suited and observations of a radio pulsar with SCUBA2 planned (THANKS!)

Definitely more discoveries coming up with newer receivers and ALMA !

Thank you !