Observing pulsars with ALMA:
an unprecedented opportunity to explore the millimetre wavelength regime of pulsar emission

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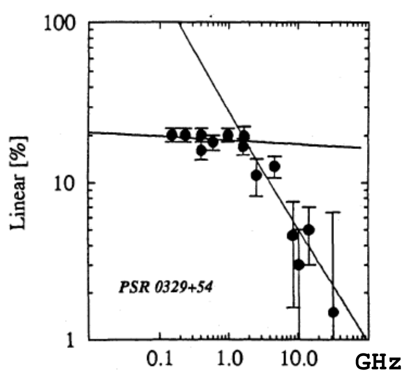
– 14th EVN Symposium –

Granada, Spain, October 2018

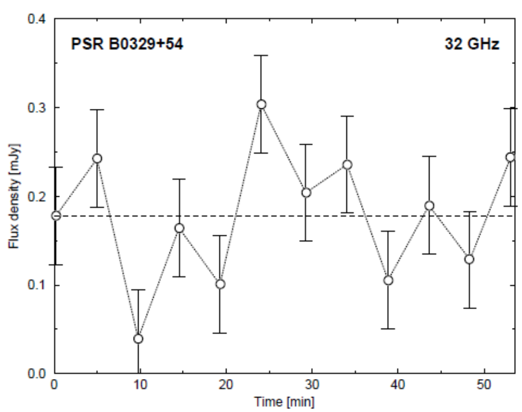
Advantages of mm-λ observations I

Observe under-explored region of pulsar spectrum

Emission properties



Xilouris et al. (1996)



Kramer et al. (1996, 1997)

Test emission models

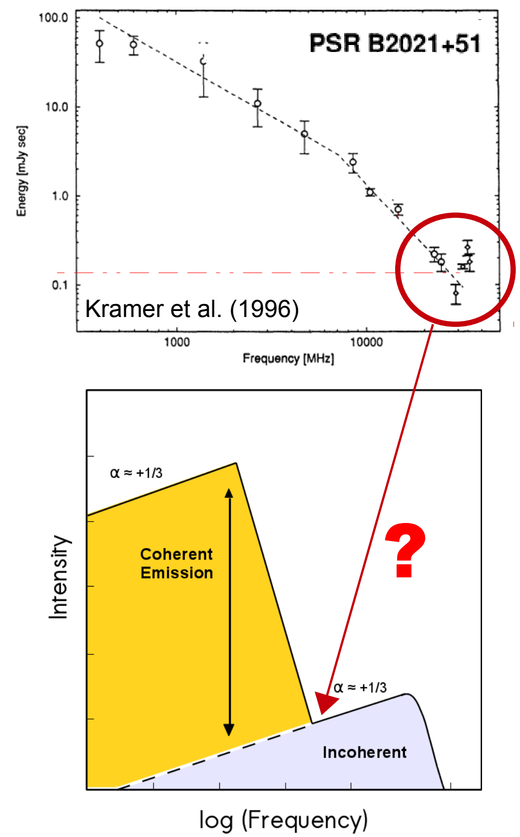


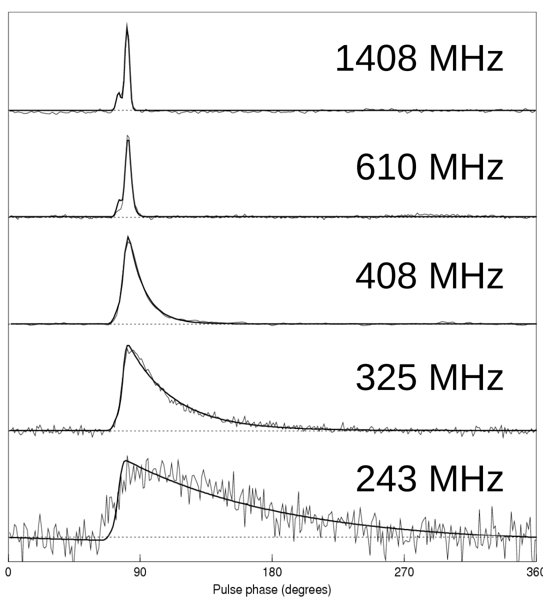
Figure adapted from Michel (1982)

Advantages of mm-λ observations II

Diminish (almost completely) the ISM effects

Scattering

$\Delta t_s \; \alpha \; (\nu^{-4})$

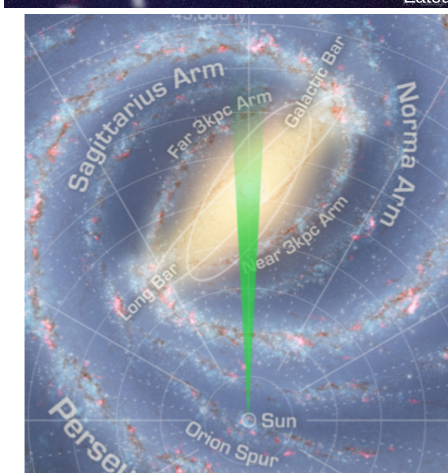


From Lorimer & Kramer (2005)

→ *Observe through dense-inhomogeneous media*

Galactic Centre

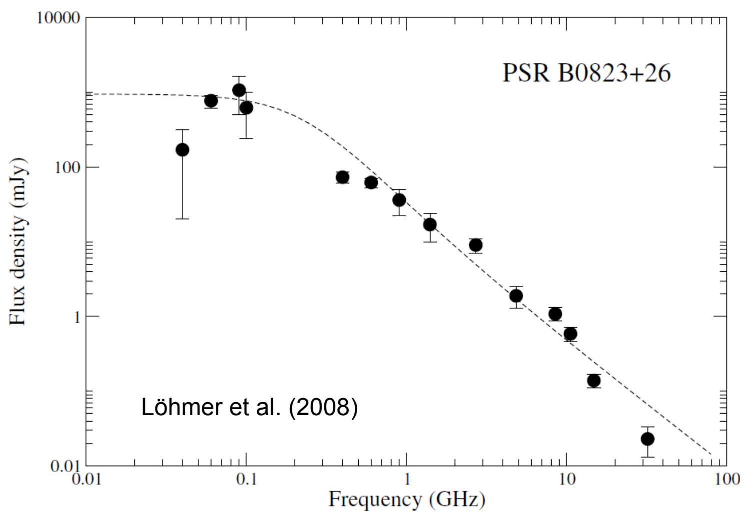
ISM effects ↑↑↑



NASA/JPL

Disadvantages / Challenges

Pulsars extremely faint at millimetre wavelengths



Steep spectrum

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

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

Maron et al. (2000)

Objectives

$\alpha > -1.2$ (~70 PSRs)

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

Pulsar backends not available at millimetre observatories

- Deploy pulsar machines
- Use VLBI recorder

Need large mm-telescopes

IRAM 30-m

D = 30 m

NOEMA

D ≈ 60 m (phased)

LMT

D = 50 m

ALMA

D ≈ 80 m (phased)

- Frequency coverage, effective bandwidth, geographical location, altitude, …
- Need versatile, broadband backends capable of detecting pulsars

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Need large mm-telescopes

IRAM 30-m NOEMA LMT ALMA

D = 30 m D ≈ 60 m (phased) D = 50 m D ≈ 80 m (phased)

- Frequency coverage, effective bandwidth, geographical location, altitude, …
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The “pathfinder”: Pico Veleta

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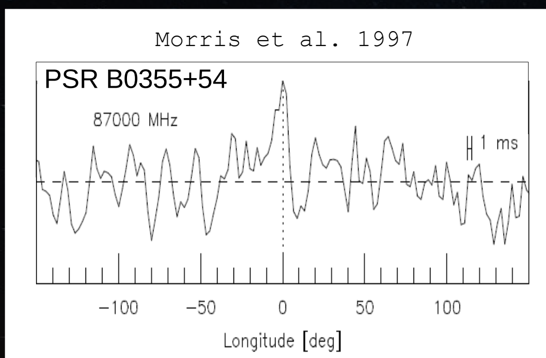
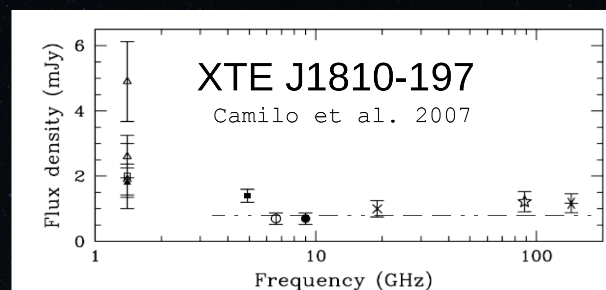
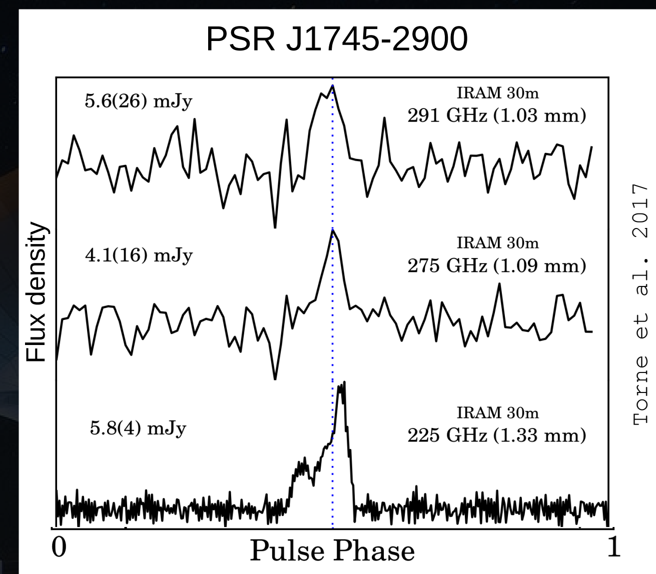
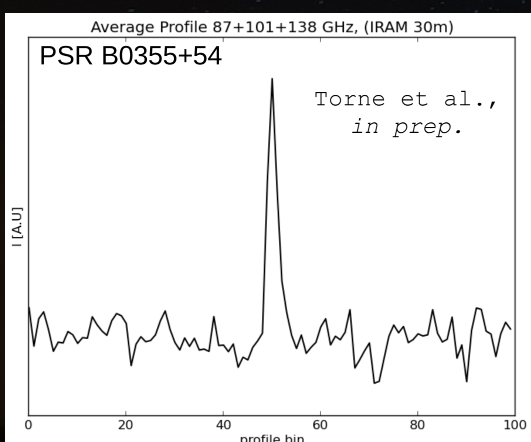
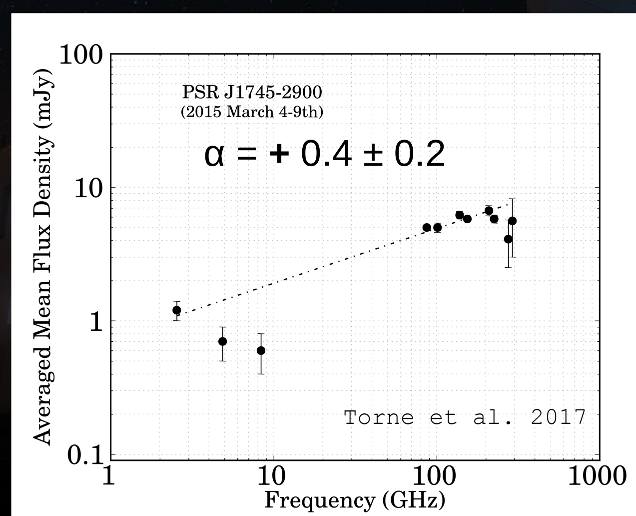
- First detection of PSR at 3.44mm (87 GHz) in 1997
- A magnetar up to 144 GHz in 2007
- 2015 to 2017: PSR up to 154 GHz, Magnetar up to ~300GHz

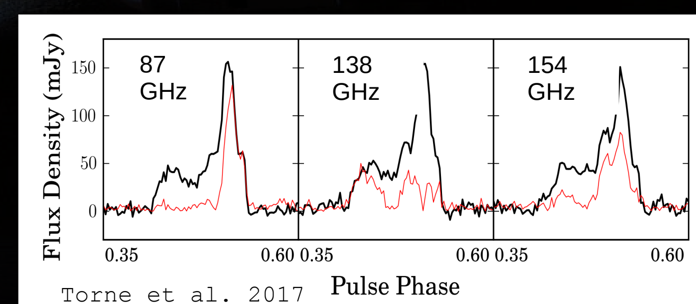












The “pathfinder”: Pico Veleta

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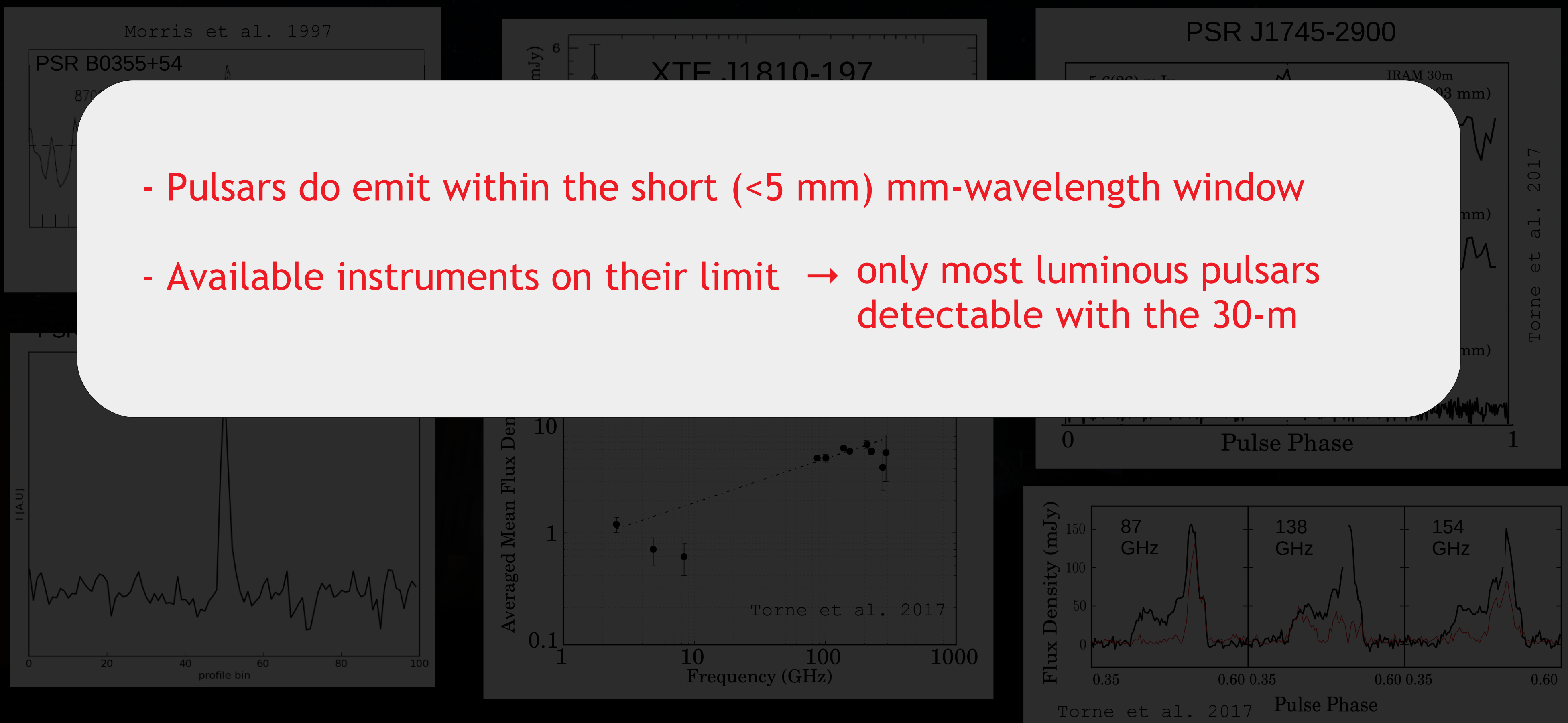


- Pulsars do emit within the short (<5 mm) mm-wavelength window

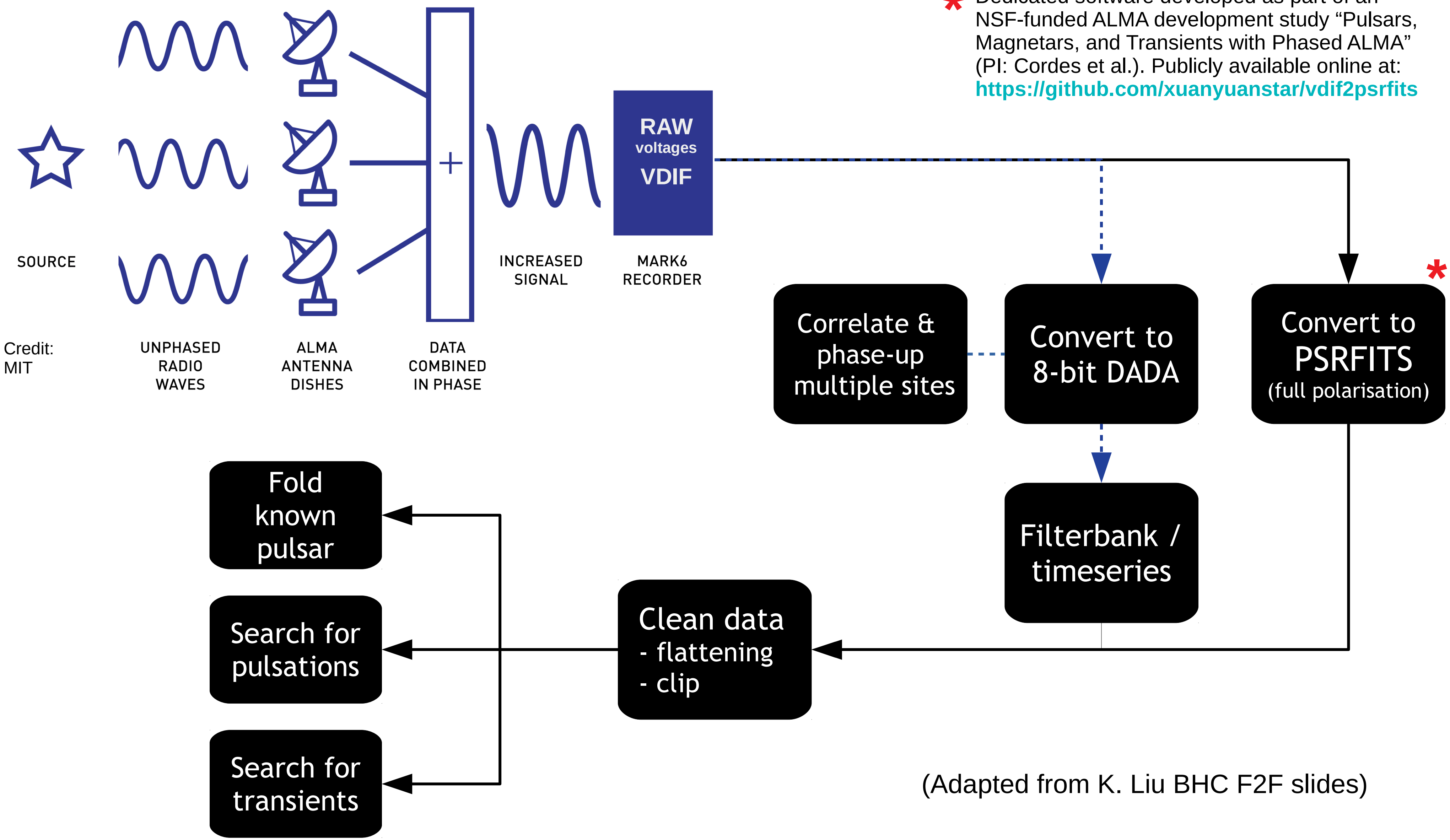
- Available instruments on their limit → only most luminous pulsars detectable with the 30-m

ALMA opens a new door

- Sensitivity
- Frequency coverage
- Location
- Pulsar detection capability

Credit: ESO/Y. Beletsky

The ALMA pulsar mode



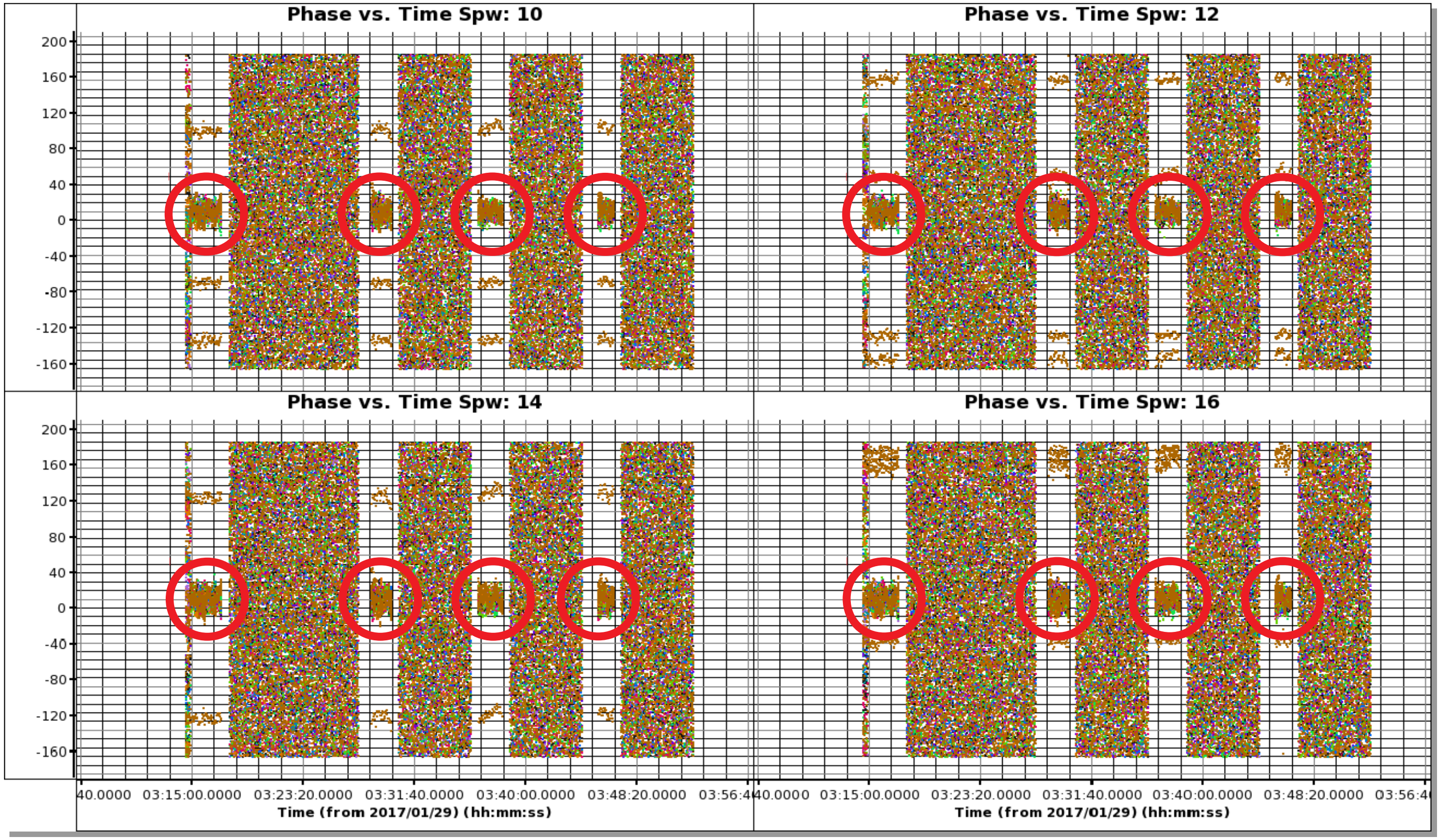
* Dedicated software developed as part of an NSF-funded ALMA development study "Pulsars, Magnetars, and Transients with Phased ALMA" (PI: Cordes et al.). Publicly available online at: **https://github.com/xuanyuanstar/vdif2psrfits**

(Adapted from K. Liu BHC F2F slides)

Phased ALMA observations on Vela

Jan. 29, 2017 ALMA (APP):

- Tobs ~ 30 min; Frequency = 86, 88, 98, 100 GHz; BW = 4x2 GHz
- Scans switching between Vela (**B0833-45**) ands calibrator (**J0828-3731**)
- Array phased in “**passive**” mode (no tuning of fringe solution when on source)

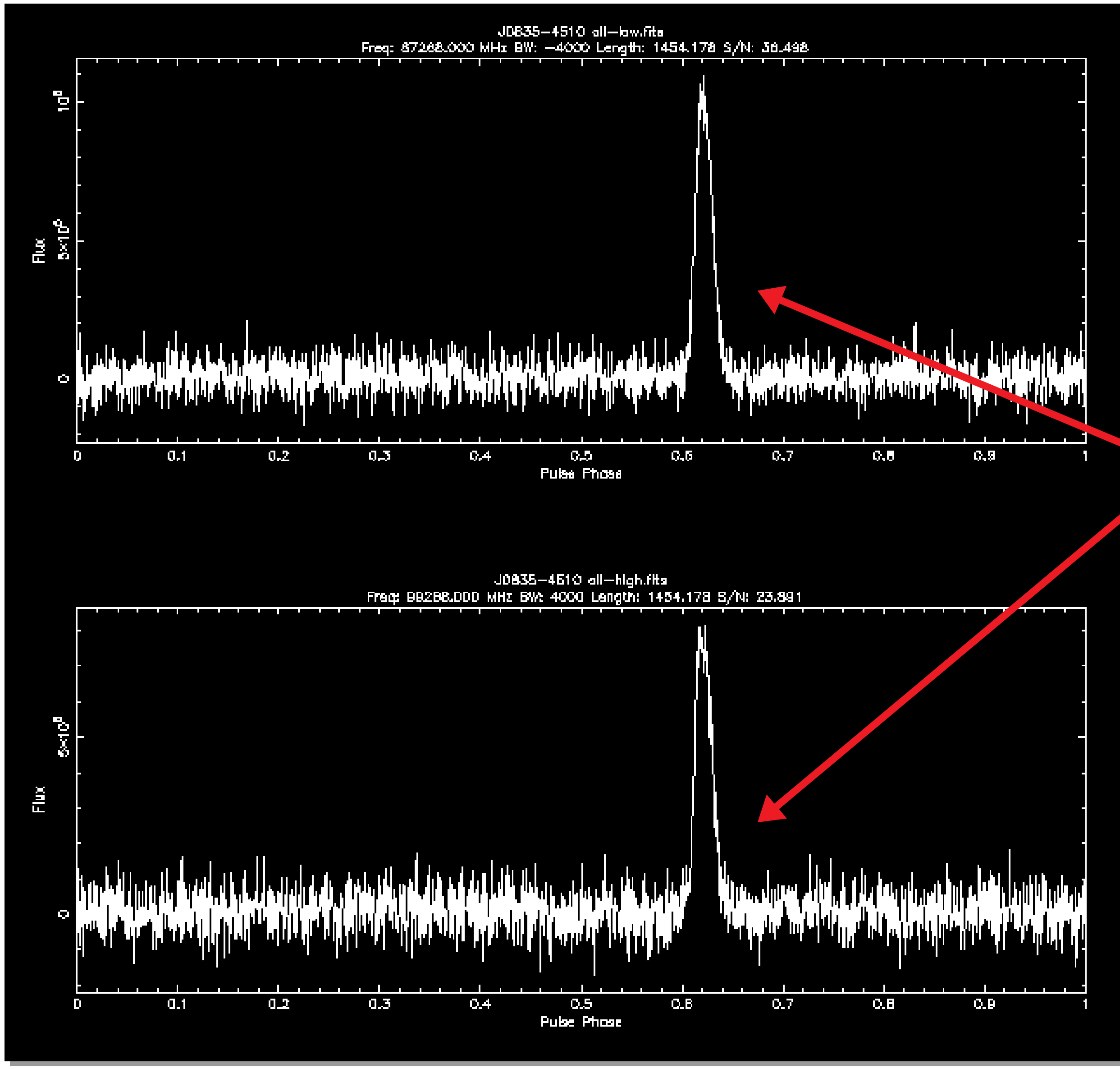


(Adapted from K. Liu BHC F2F slides)

Detections of the Vela pulsar

Lower side-band 87.27 GHz

Upper side-band 99.27 GHz

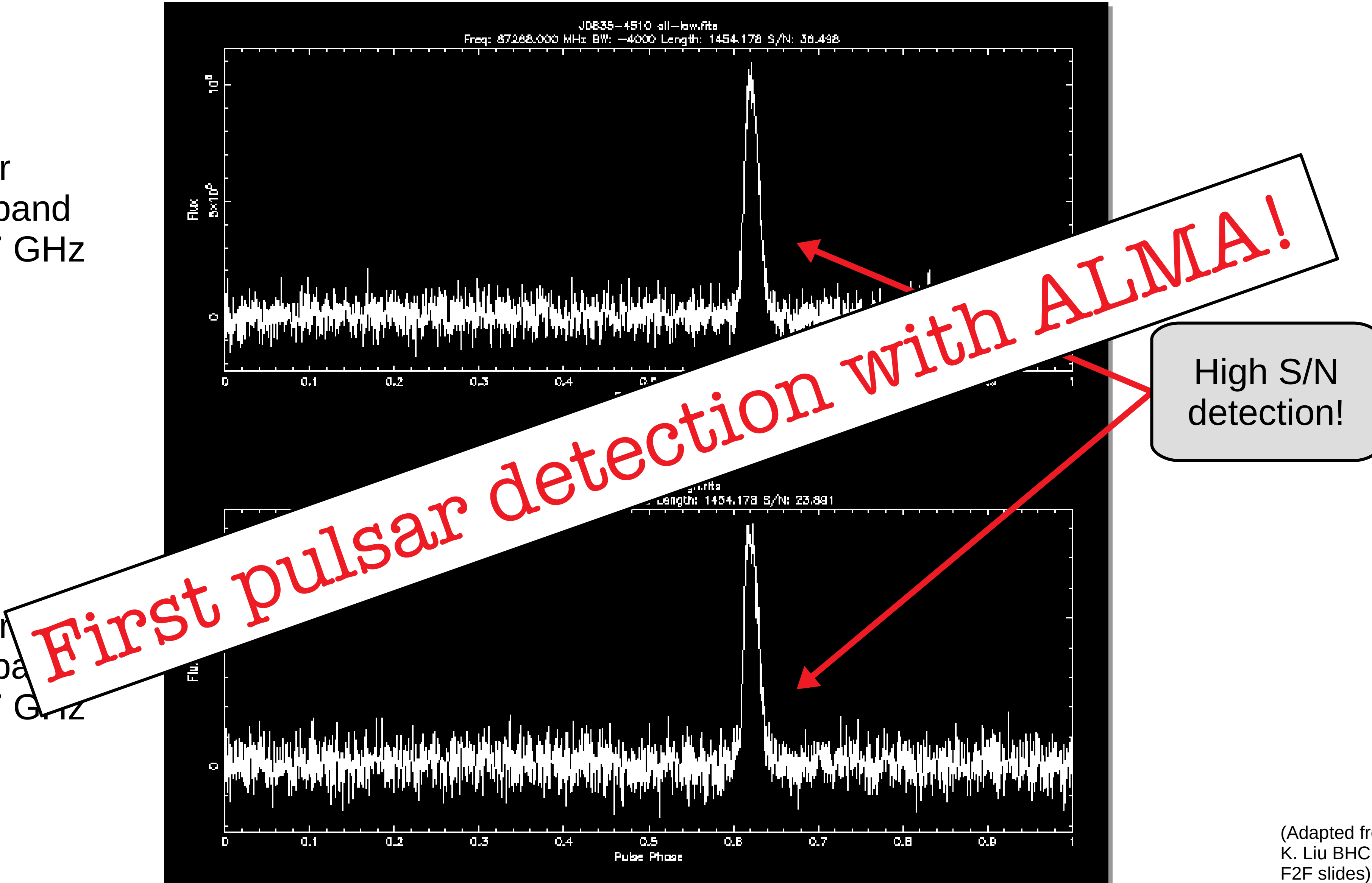


High S/N detection!

(Adapted from K. Liu BHC F2F slides)

Detections of the Vela pulsar

Lower
side-band
87.27 GHz



Upper
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(Adapted from
K. Liu BHC
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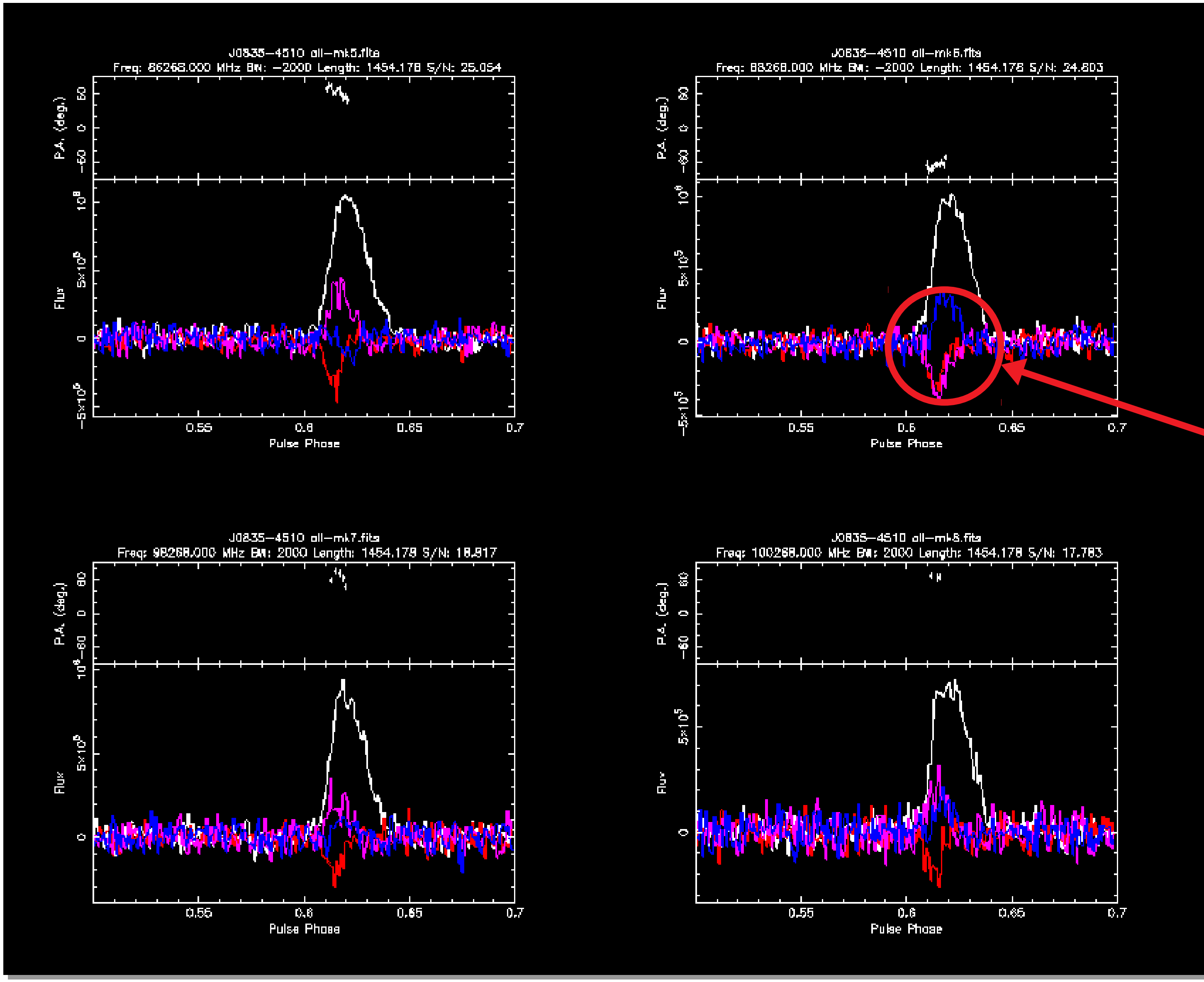
Detections of the Vela pulsar



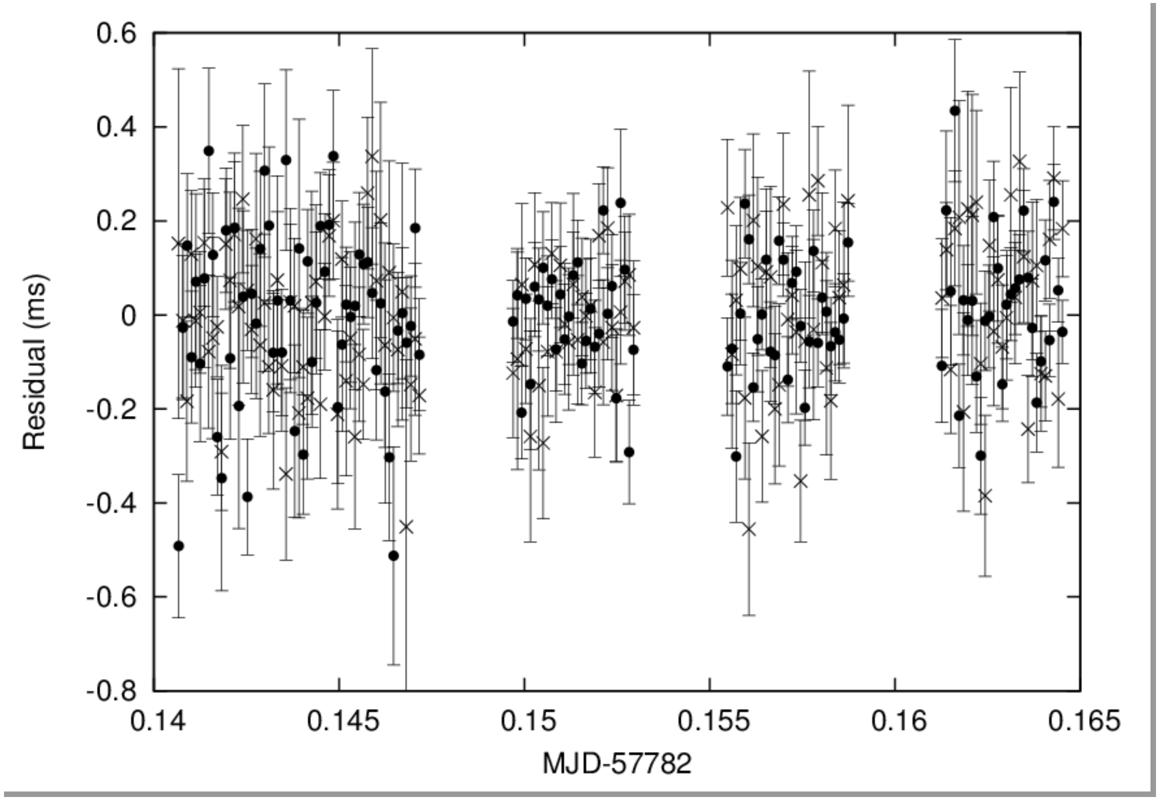
Stokes Q
Stokes U
Stokes V

Flipped sign in Stokes **U**, caused by 180 deg ambiguity in phase of two polarisations

(Adapted from K. Liu BHC F2F slides)

Final test: timing analysis

- Exact pulsar model from other-wavelength observations
- **Timing residuals = (Time-of-arrivals @ ALMA) – (model predictions)**



✔ **Residuals as white noise**: Model prediction works!

✔ **Aligned residuals between sub-scans**: No jumps introduced during source switching

(Adapted from K. Liu BHC F2F slides)

Final test: timing analysis

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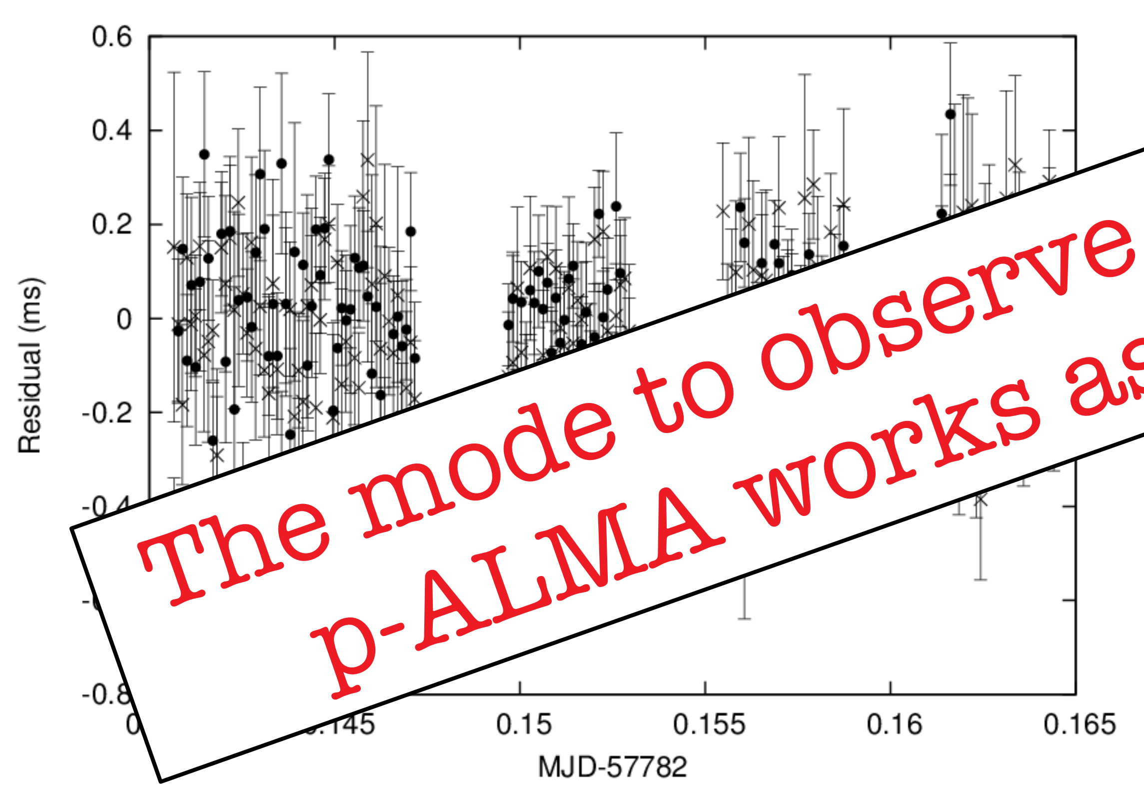


The mode to observe pulsars with p-ALMA works as expected!

…ation
…works!

✔ **Aligned residuals between sub-scans**: No jumps introduced during source switching

(Adapted from K. Liu BHC F2F slides)

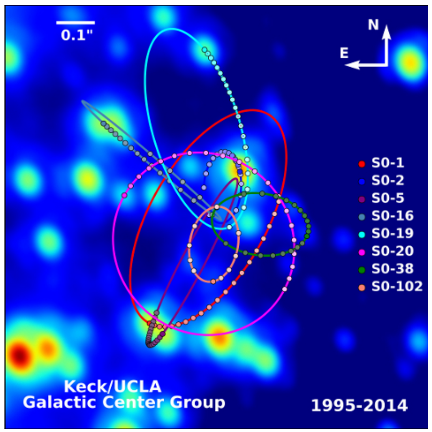
Summary

- Observations at short mm-λ are challenging, but can and should be done:
  - Unique insights into pulsar radio emission properties → test models
  - Possible way to probe dense ISM and find new pulsars and magnetars
  - Potential to be a tool for precision black hole physics @ Galactic Centre
- Pico Veleta showed feasibility of short mm-λ pulsar science
- Phased ALMA:
  - The most sensitive mm- telescope, with large frequency coverage
  - Access to the southern mm- pulsar sky: ~70% of all known pulsars have dec < 0 deg
  - Demonstrated its capability to detect and study pulsars

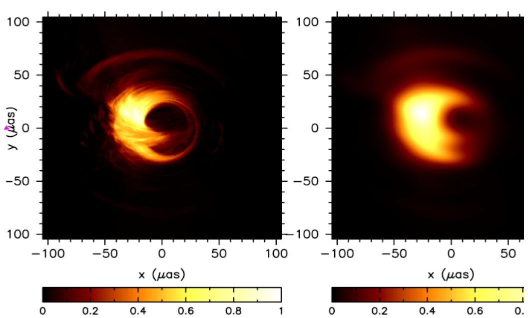
New findings to come!

Pulsars, complementary precision tools

Stars



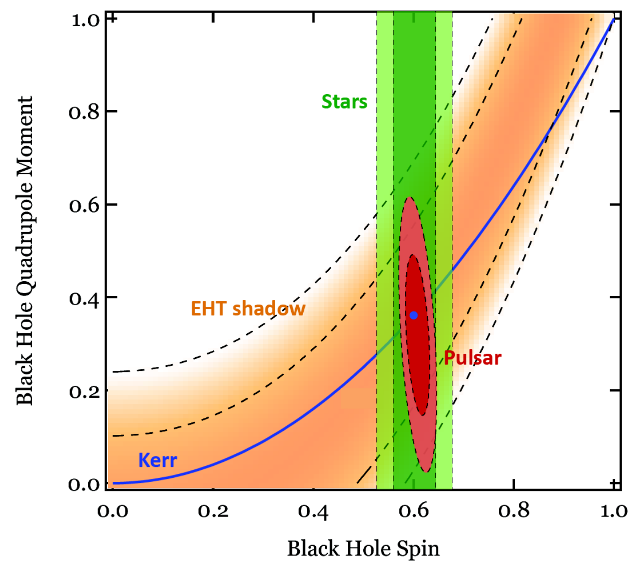
EHT shadow



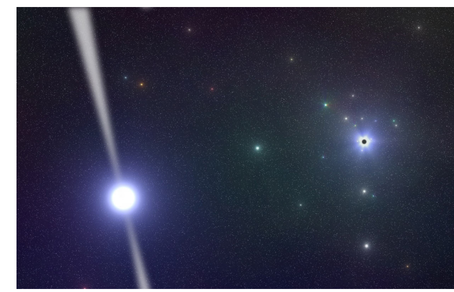
Mościbrodzka et al., 2014, A&A, 570, A7

- Independent measurements
- EHT shadow + stars/pulsars →
  test *near and far* gravitational field

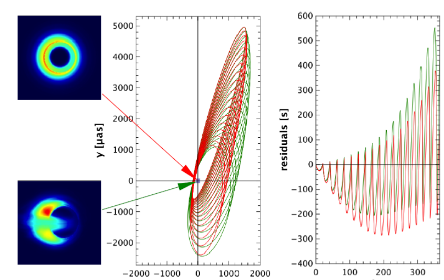
Credit: MPIfR/N. Wex



Pulsars

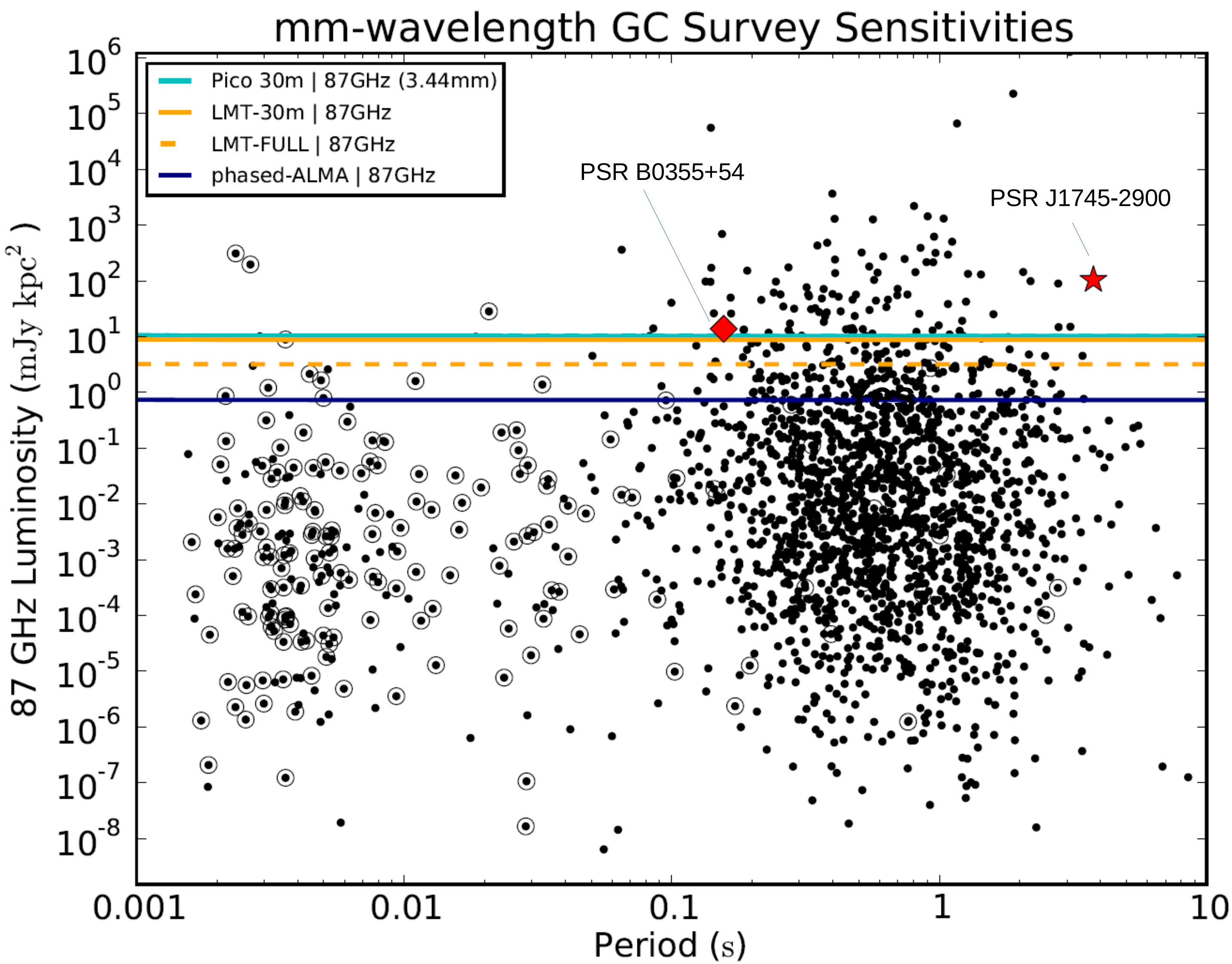


Credit: MPIfR/R. Eatough



Credit: MPIfR/N. Wex

Short mm-λ surveys at the GC



Detectable Population
Pico 30m ~ 5.9%
LMT 30m ~ 6.3%
LMT 50m ~ 9.7%
ALMA ~ 16.6 %

PSR J1745-2900 among the 2% brightest population
PSR B0355+54 among the 5% brightest population

↓

Lower-luminosity population still undetected!

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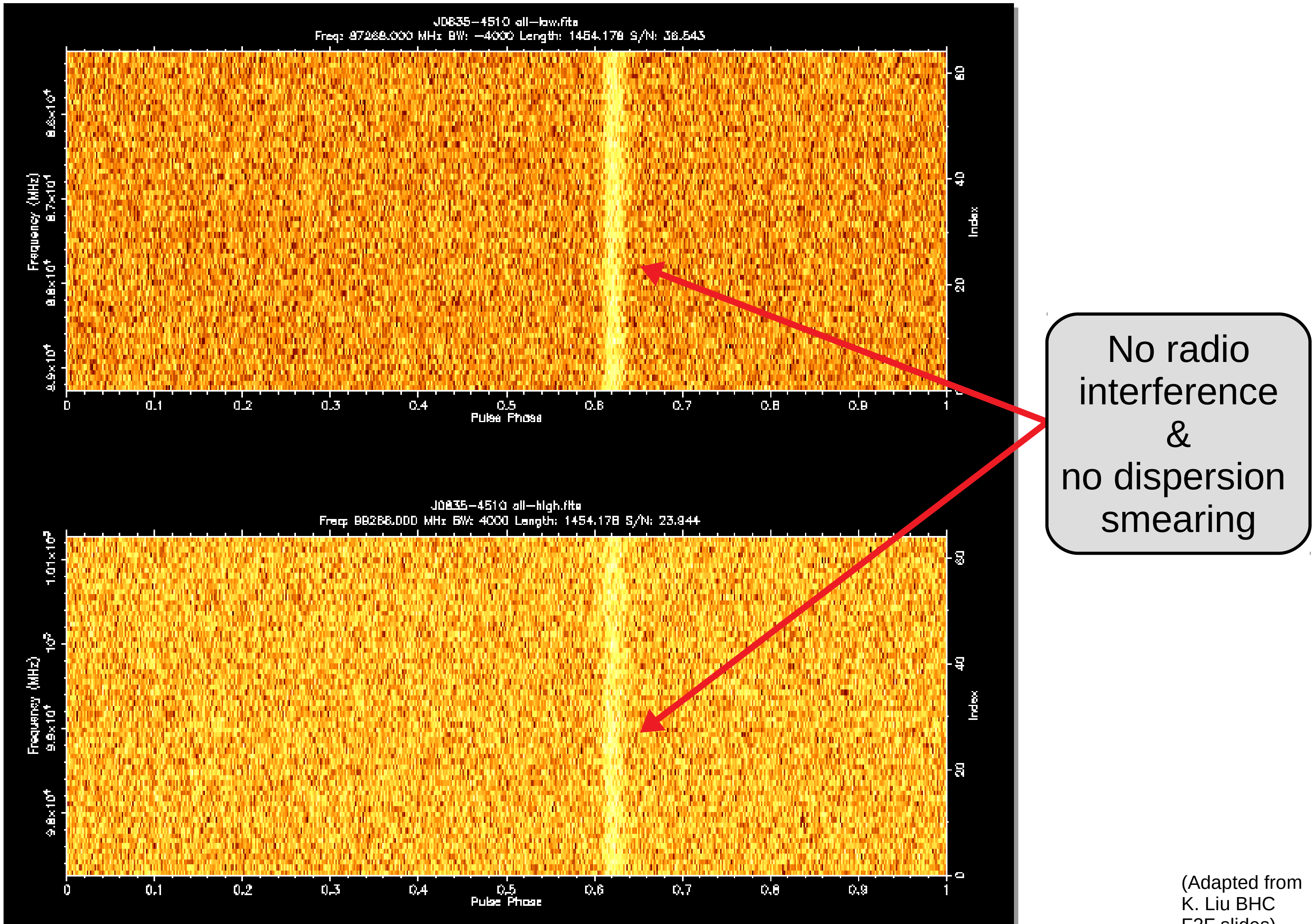
87.27 GHz



Upper
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Detections of the Vela pulsar

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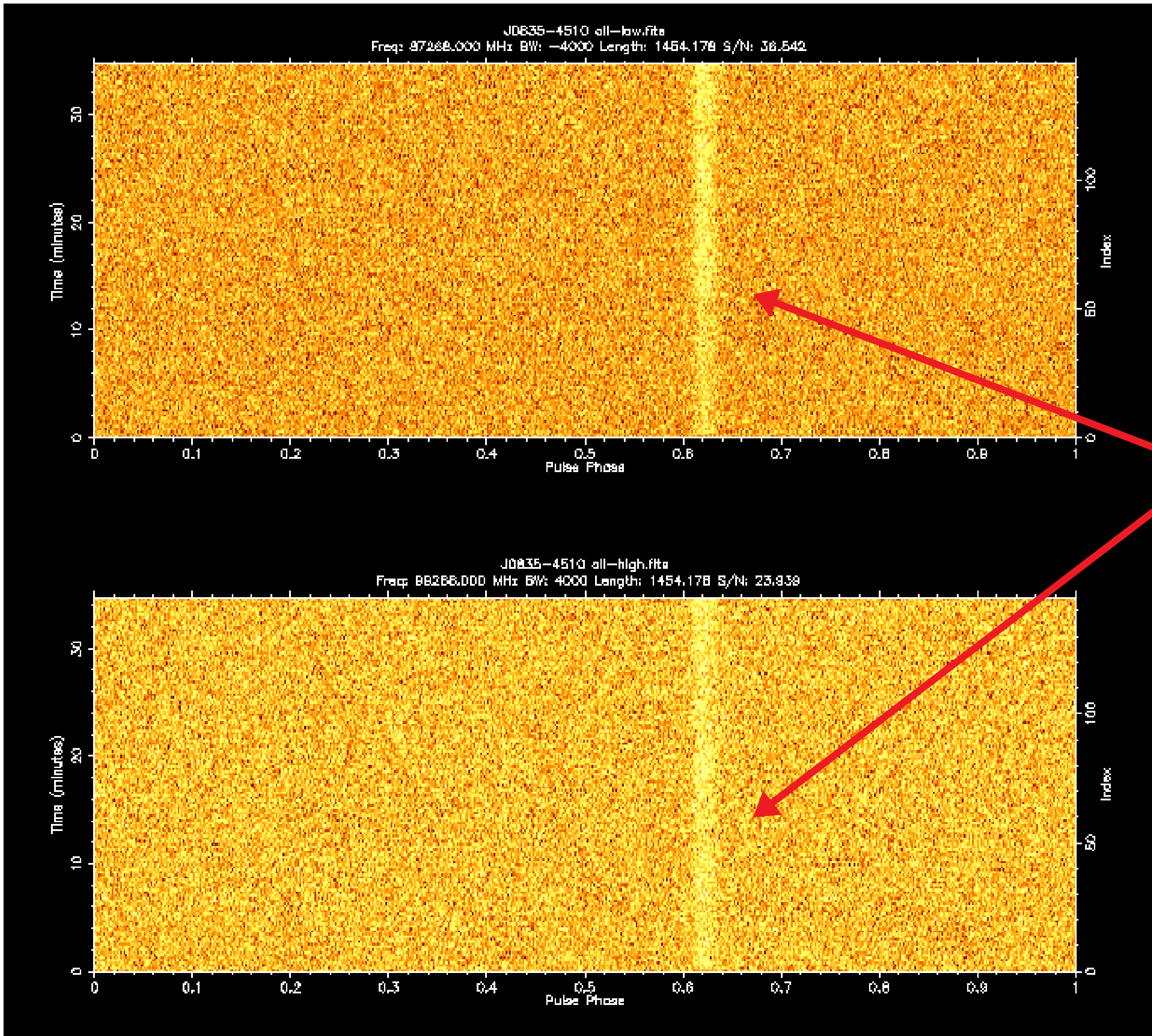

Upper
side-band
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Phase kept across the whole observation

(Adapted from K. Liu BHC F2F slides)