What do Scintillation Arcs Tell us About the Distribution of Scattering Material in the Interstellar Medium?

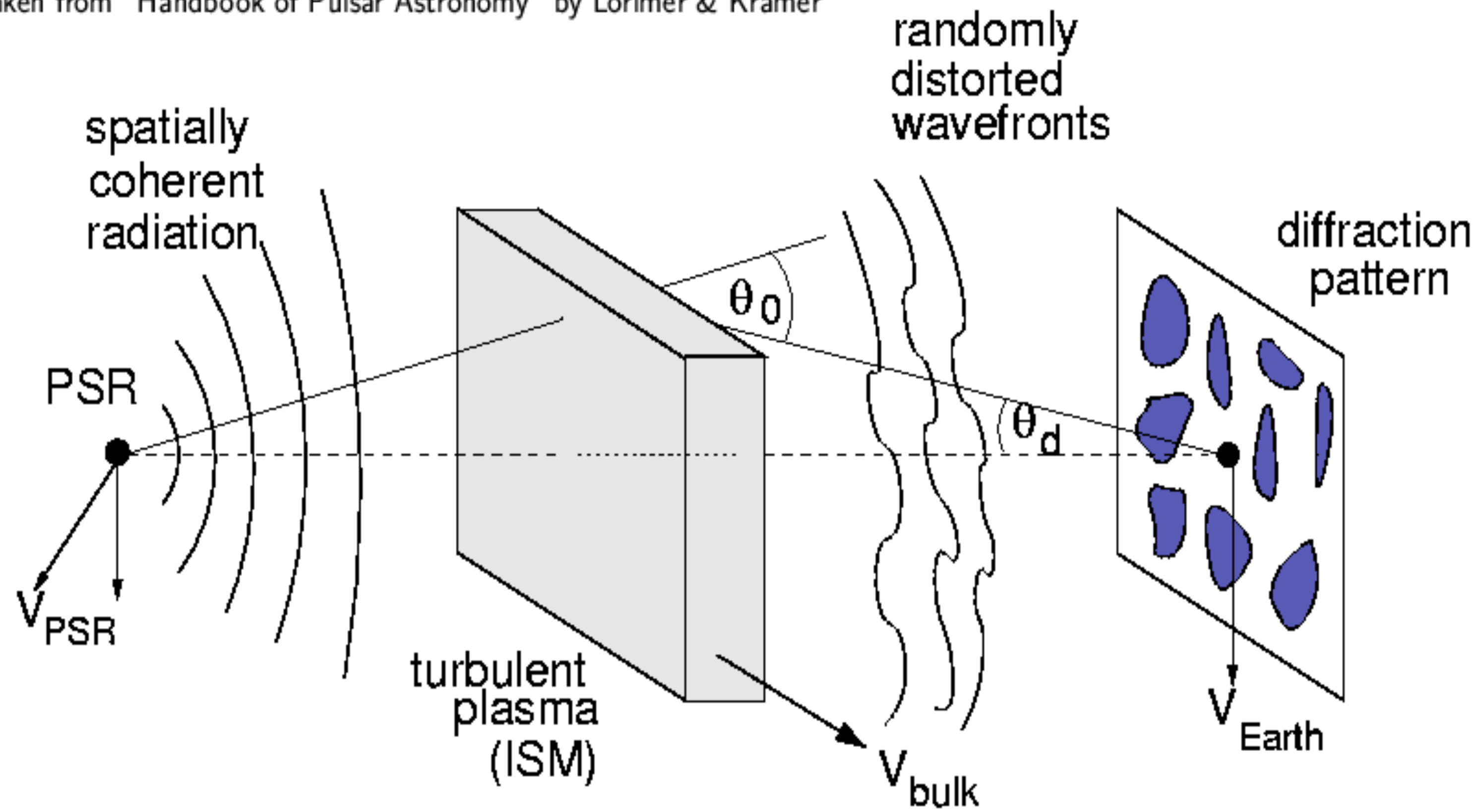
Dan Stinebring

Oberlin College

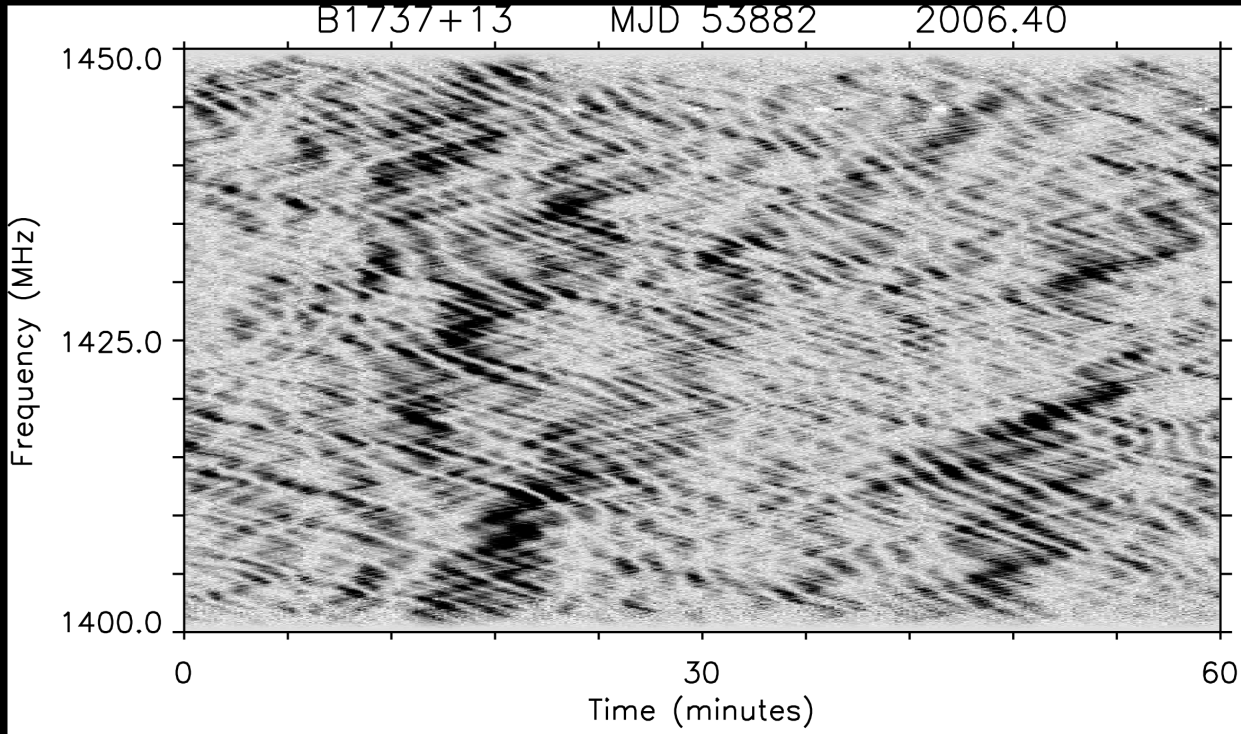
2019 July 16

NANOGrav

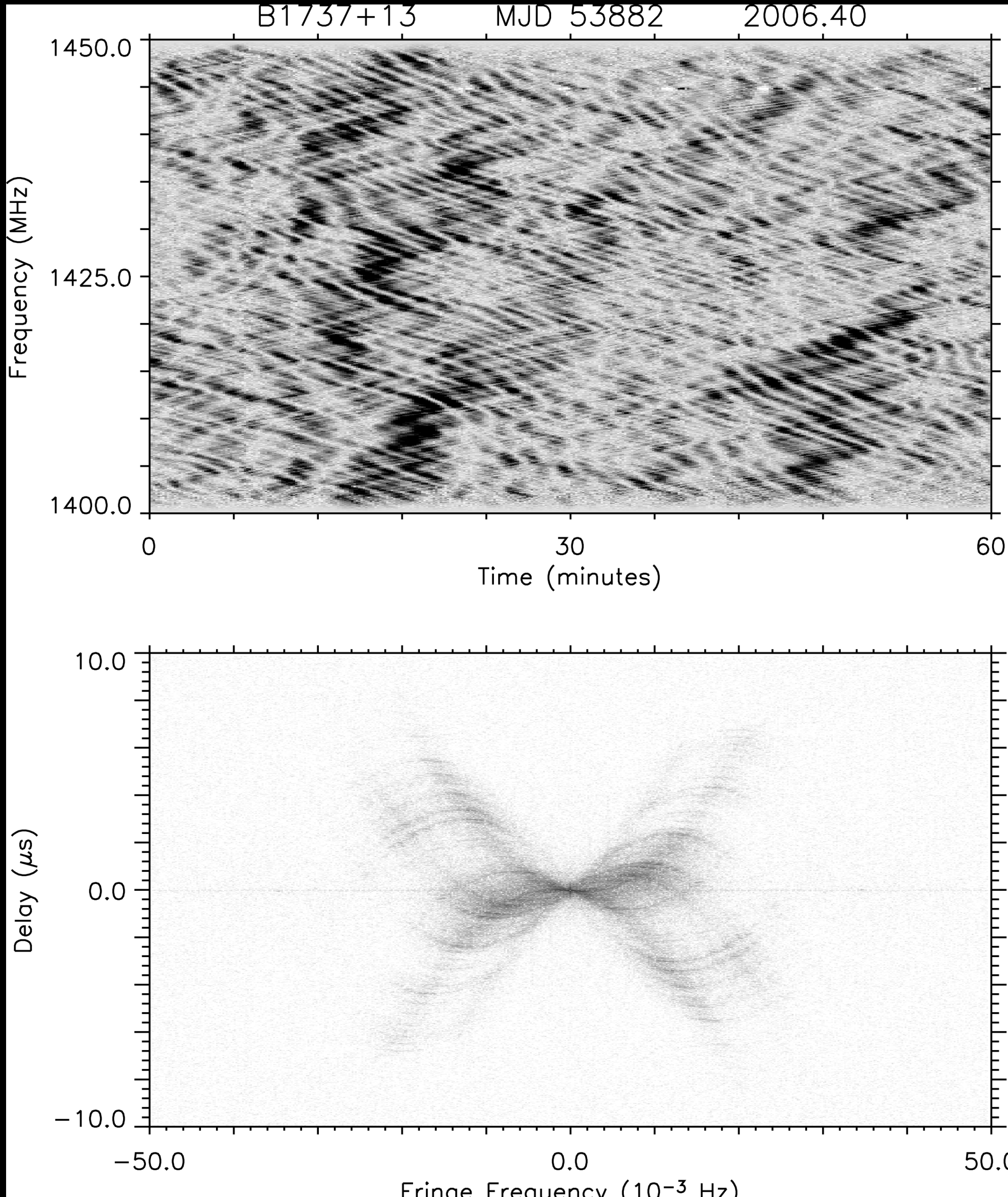
Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



Lorimer&Kramer (LK) Fig. 4.2 Sketch showing inhomogeneities in the ISM that result in observed scattering and scintillation effects.

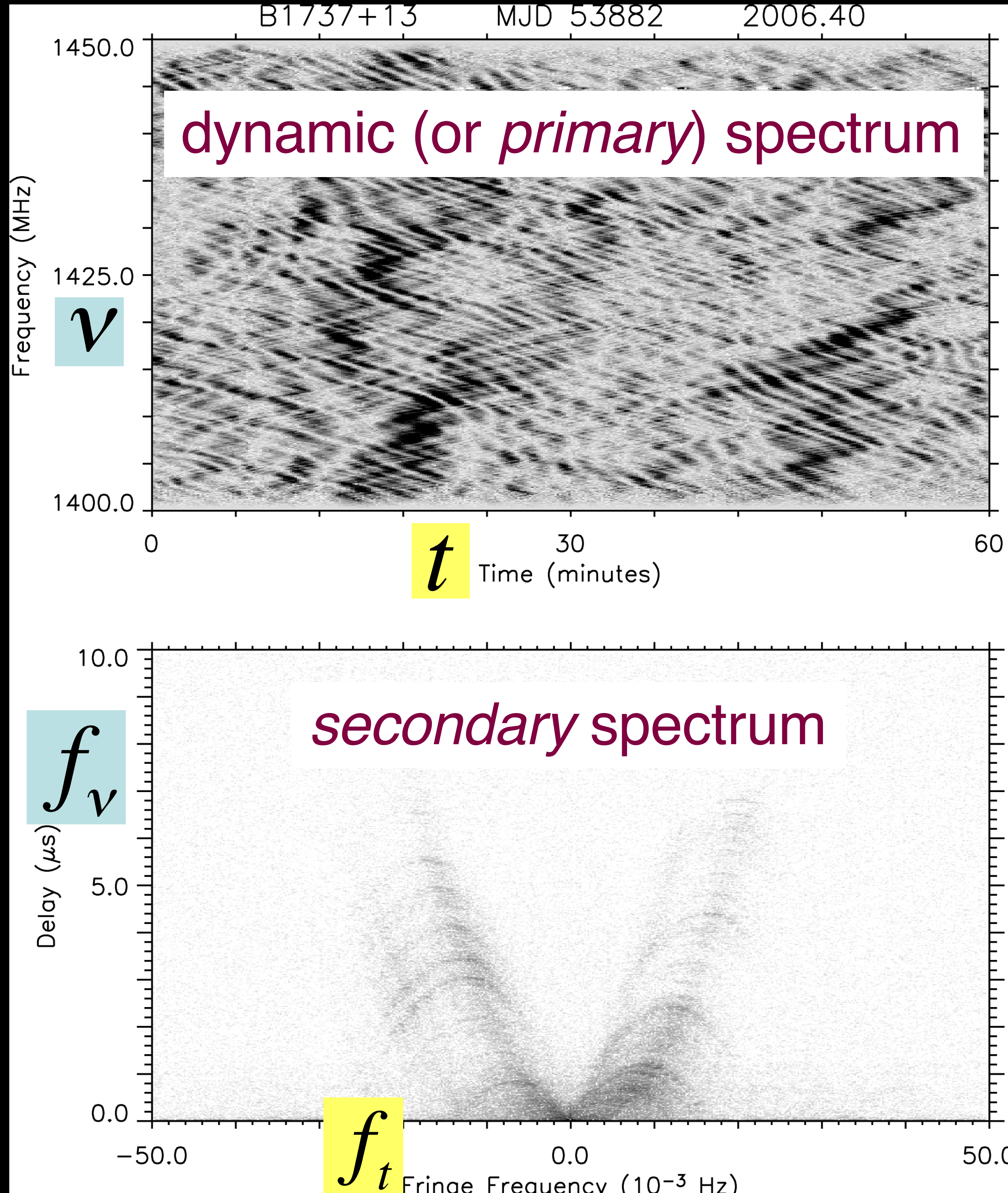


linear
grayscale



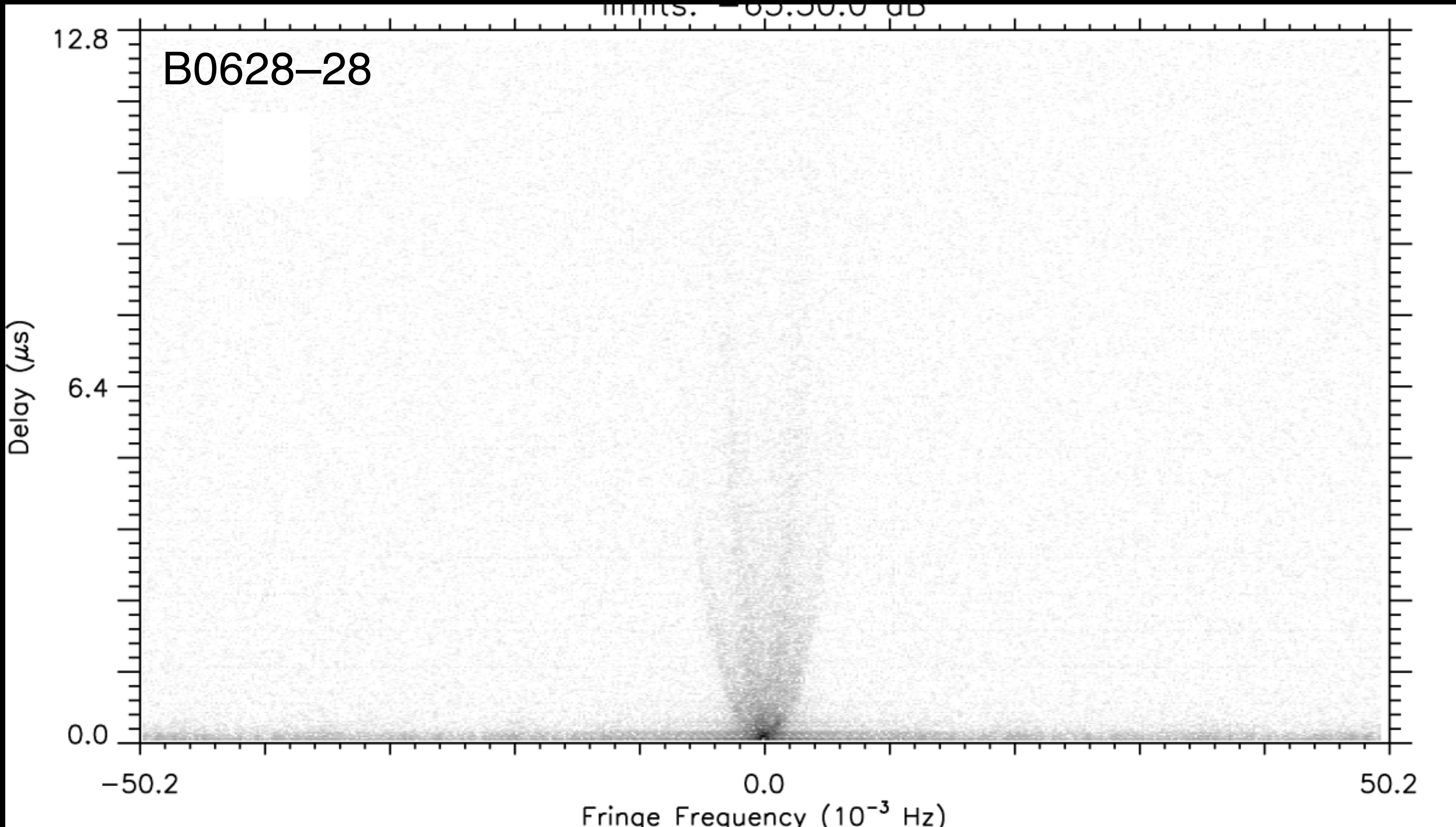
linear grayscale

logarithmic grayscale

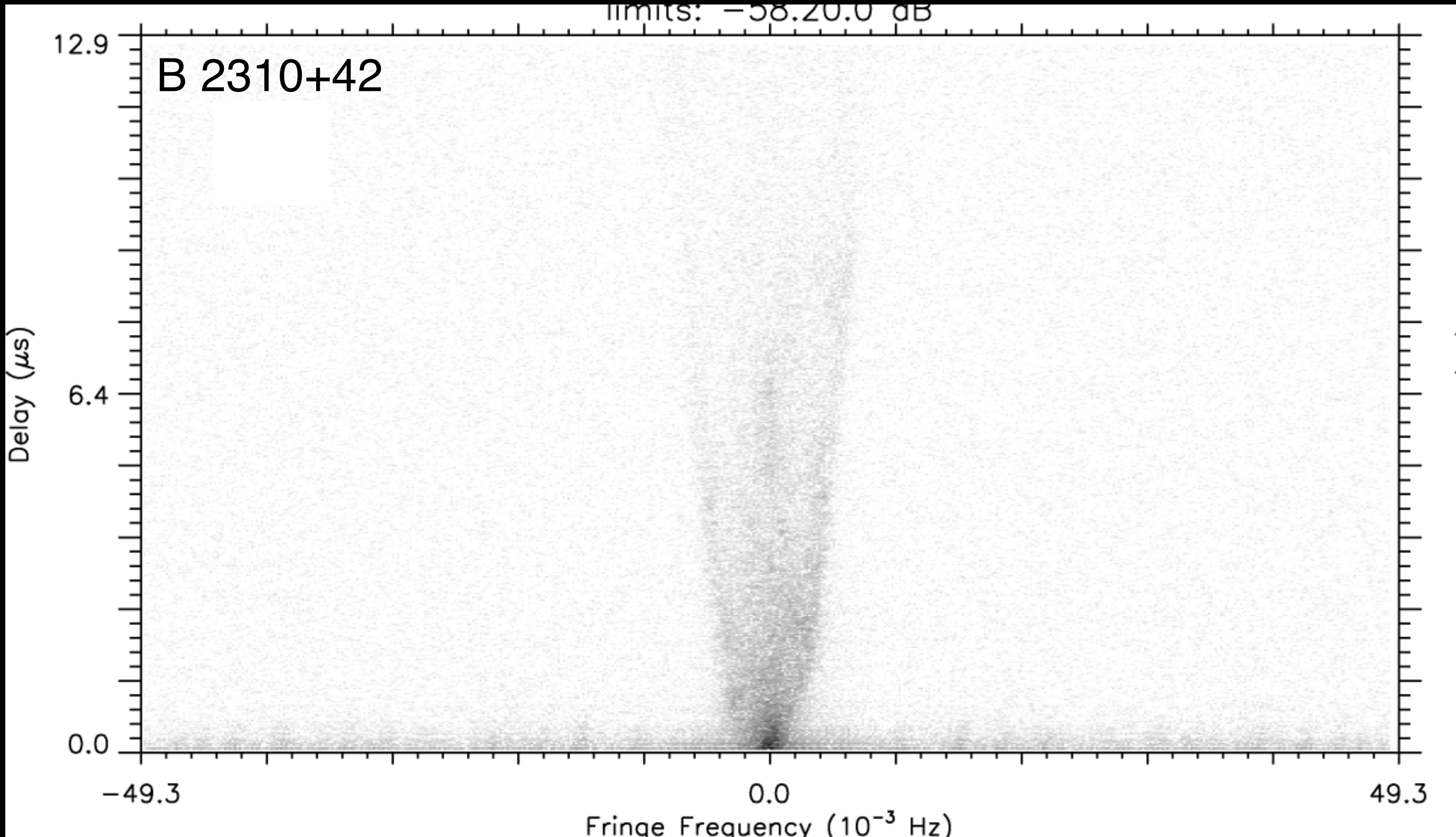


linear grayscale

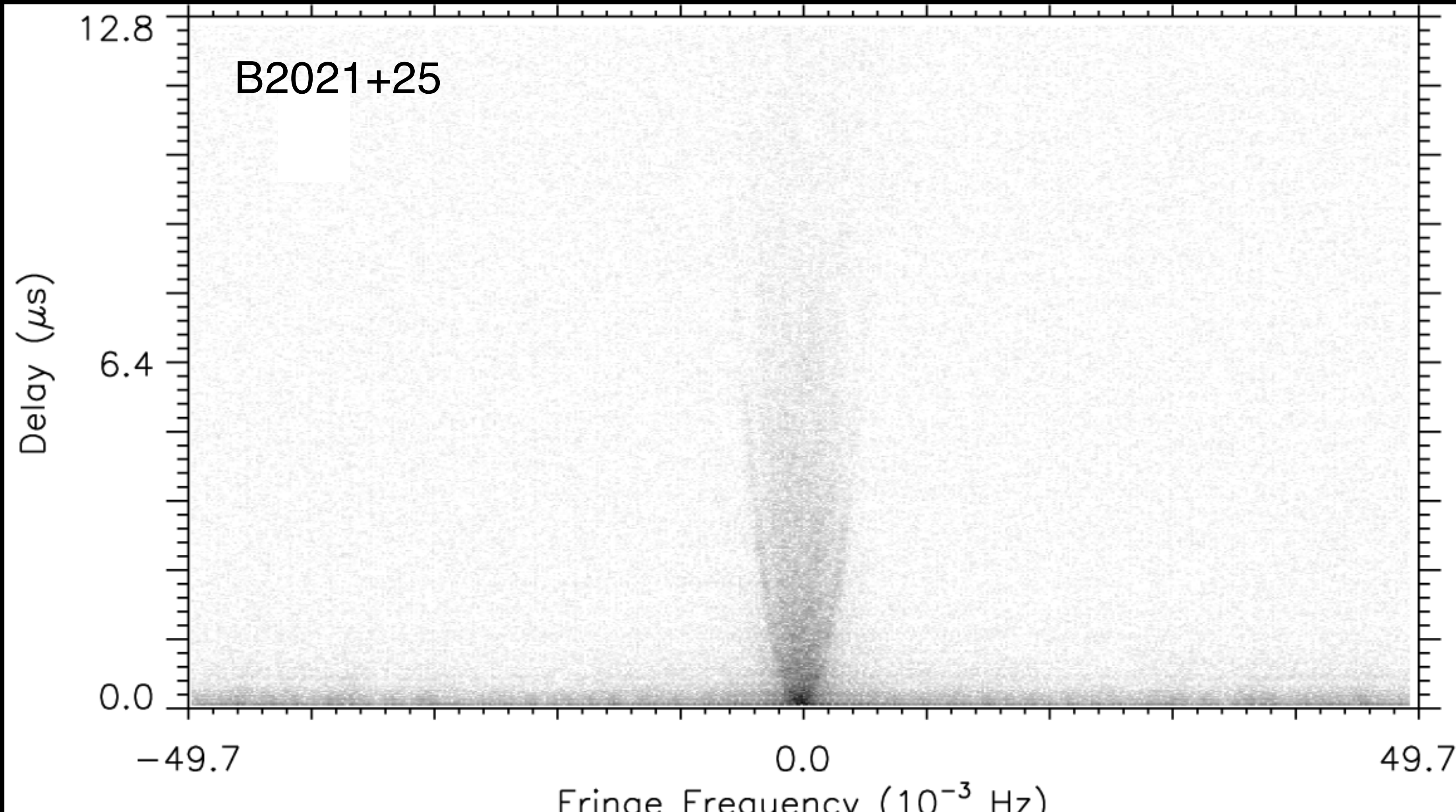
logarithmic grayscale



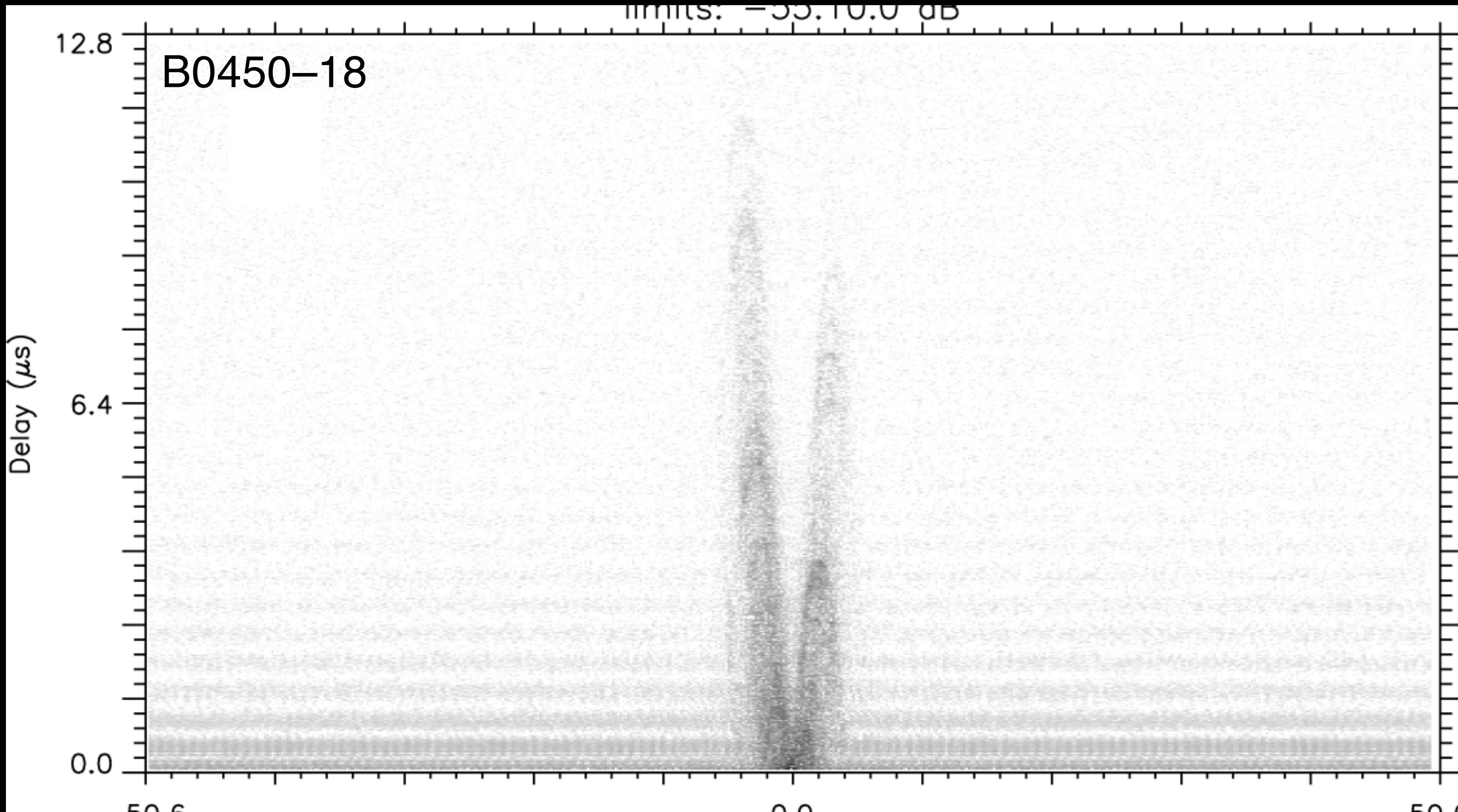
B0628–28
12.8
6.4
0.0
Delay (μs)
−50.2
0.0
50.2
Fringe Frequency (10⁻³ Hz)



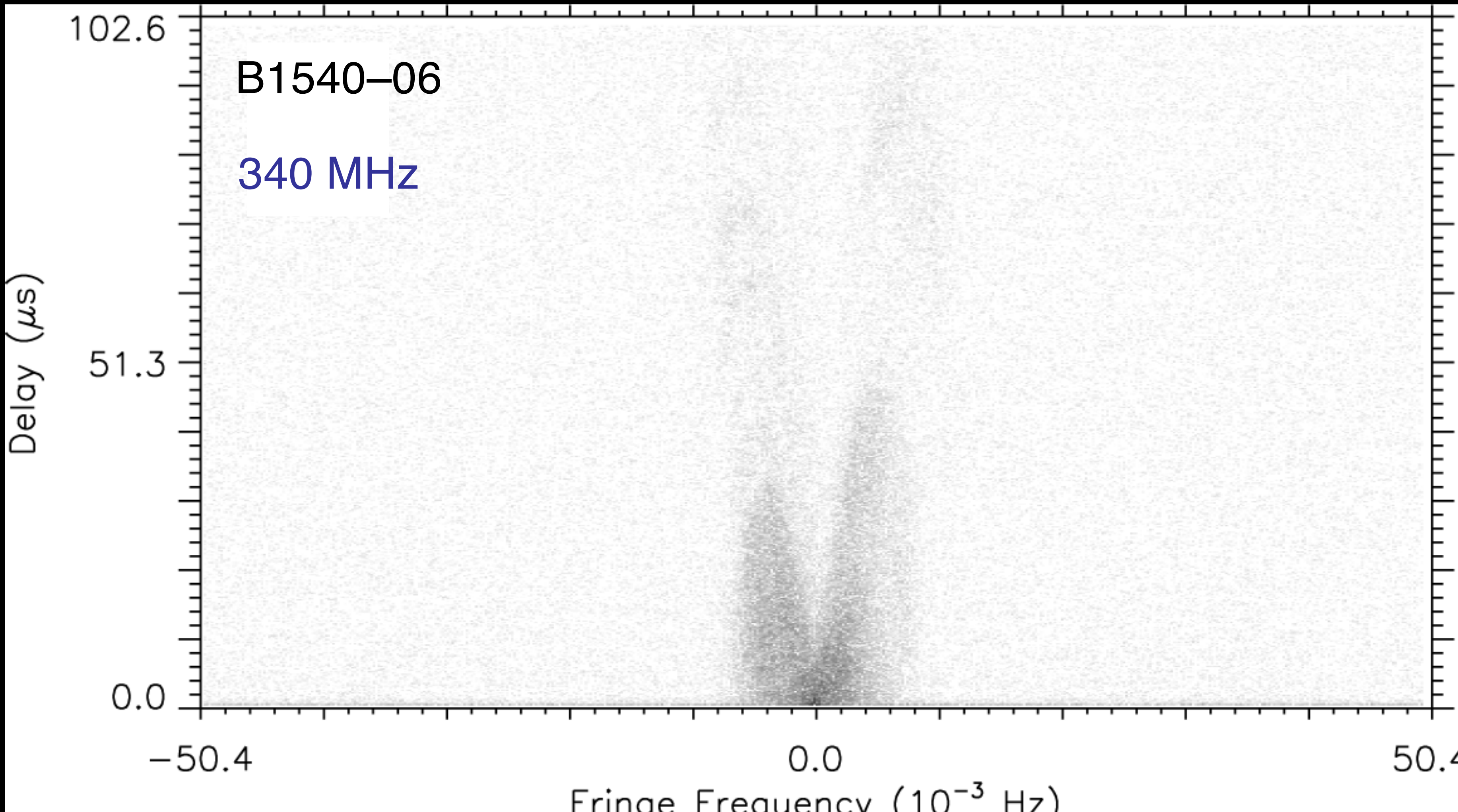
limits: −58.20.0 dB
B 2310+42
12.9
6.4
0.0
Delay (μs)
−49.3
0.0
49.3
Fringe Frequency (10⁻³ Hz)

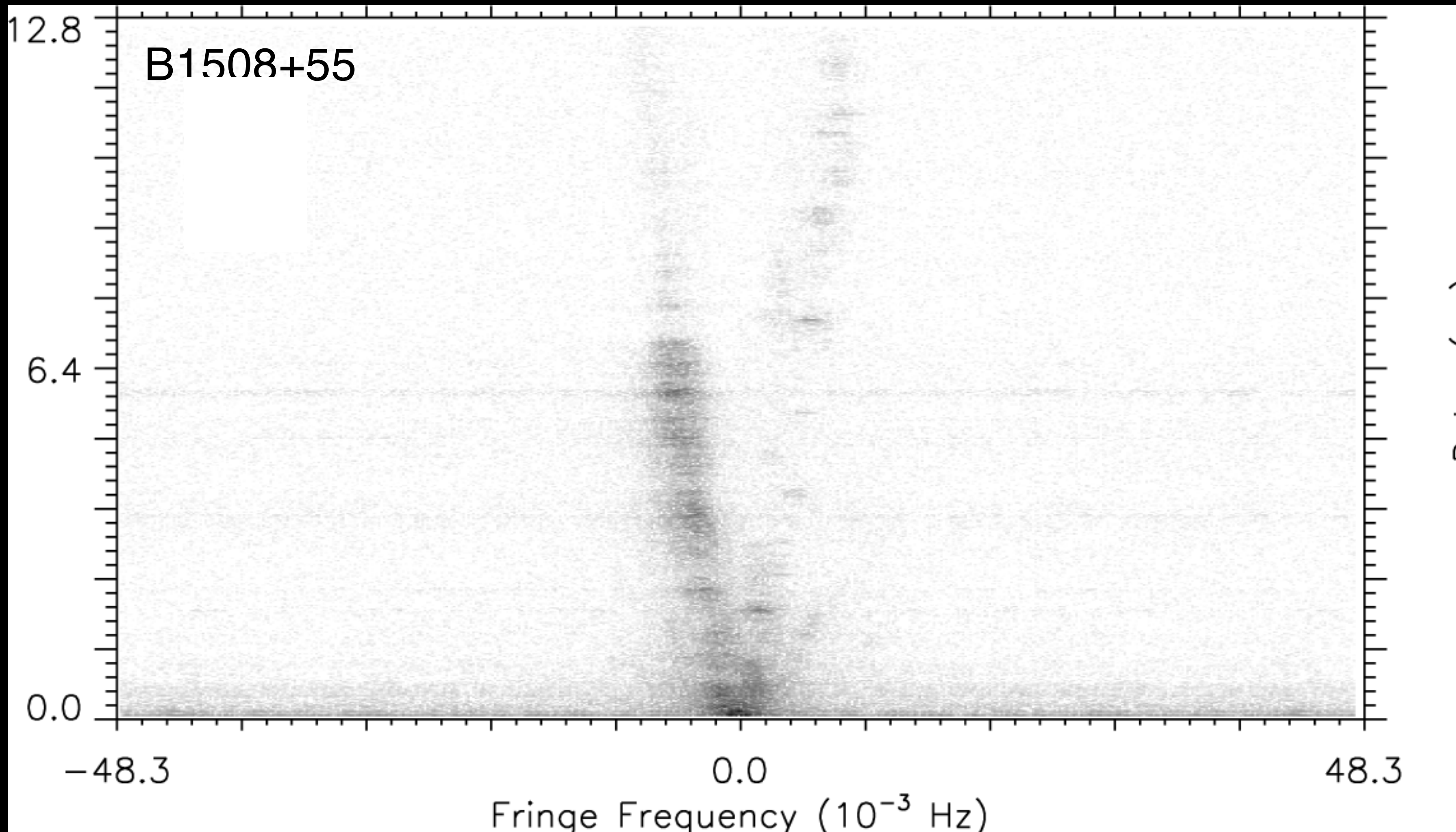


12.8
B2021+25
Delay (μs)
6.4
0.0
−49.7
0.0
49.7
Fringe Frequency (10⁻³ Hz)

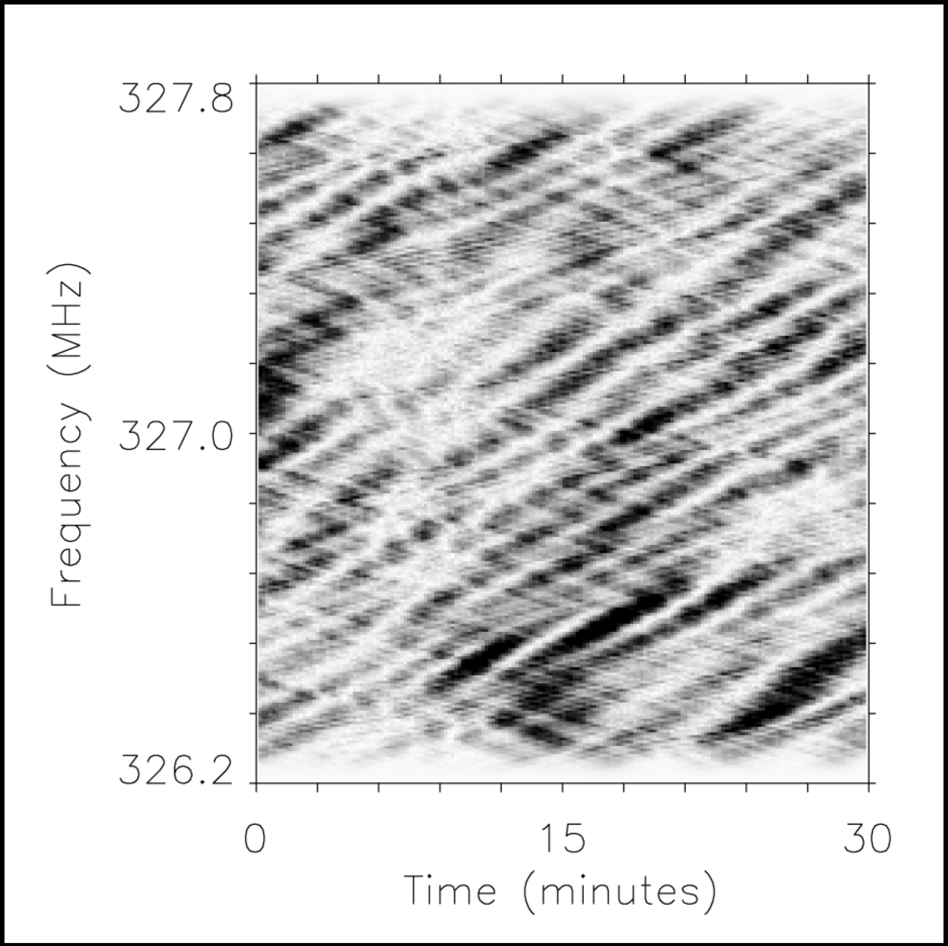


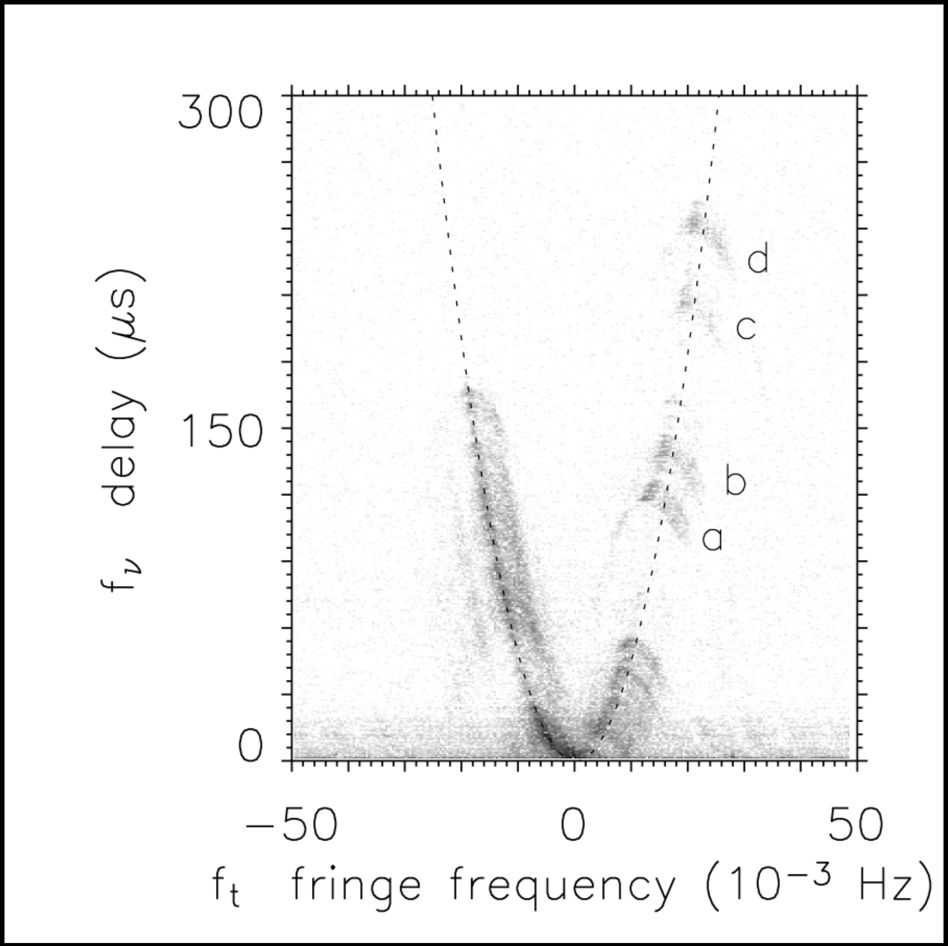
limits: −55.10.0 dB
B0450−18
Delay (μs)
12.8
6.4
0.0
−50.6
0.0
50.6


B1540–06
340 MHz
102.6
51.3
0.0
Delay (μs)
−50.4
0.0
50.4
Fringe Frequency (10⁻³ Hz)


B1508+55
12.8
6.4
0.0
−48.3
0.0
48.3
Fringe Frequency (10^{-3} Hz)

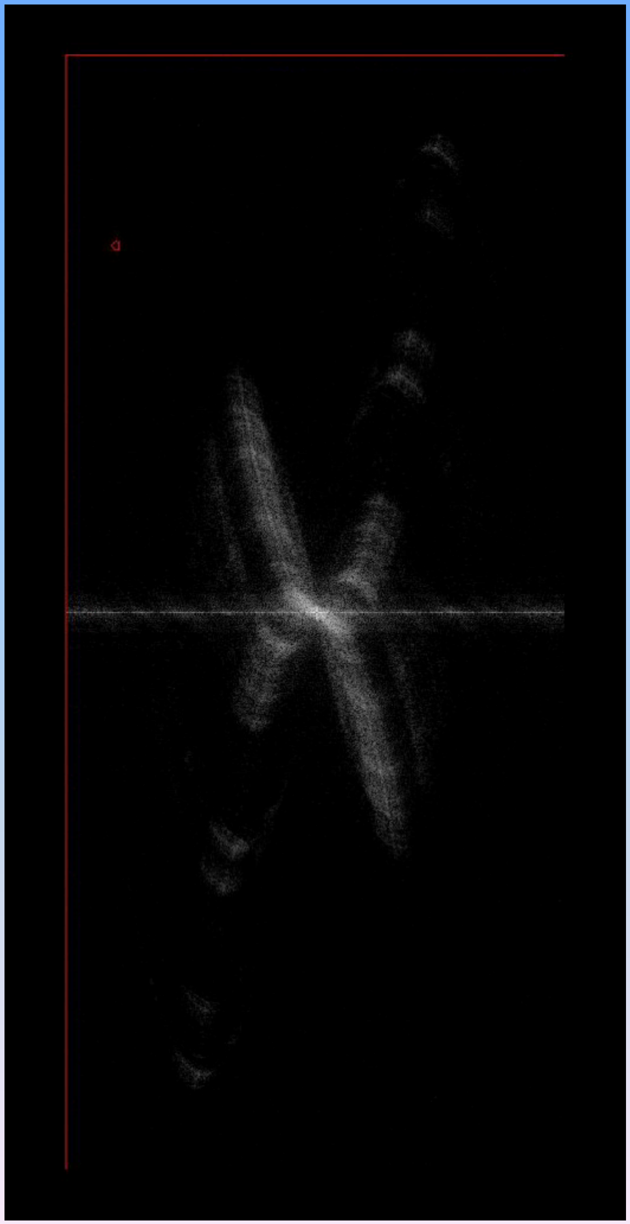
"Deflection of Pulsar Signal Reveals Compact Structures in the Galaxy," A. S. Hill et al. 2005, 619, L17

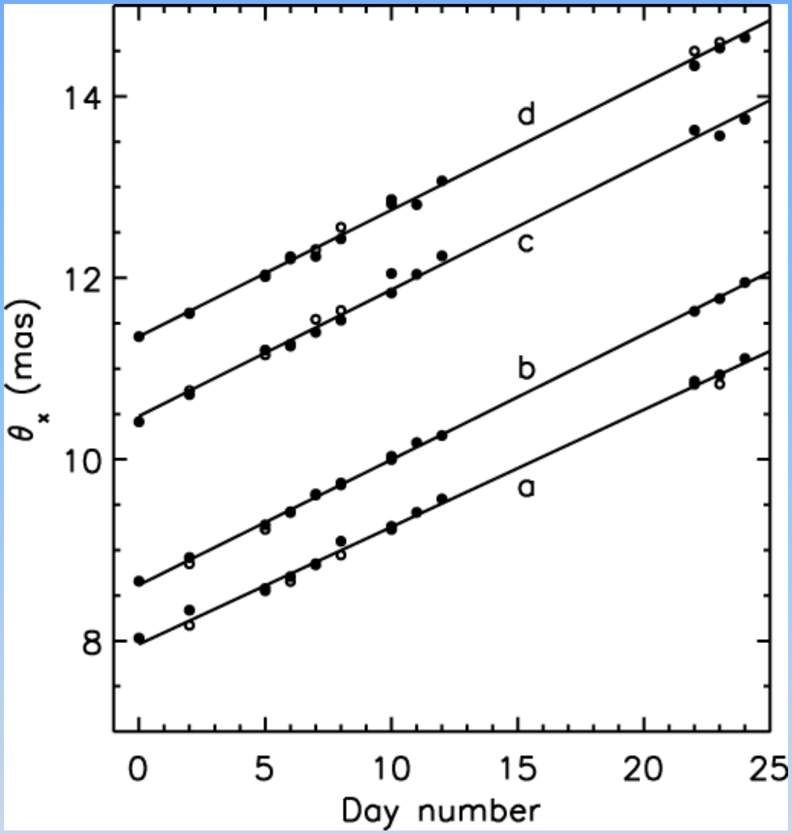




The substructure persists

and MOVES!





Hill, A.S., Stinebring, D.R., et al.

2005, ApJ,619, L171

This is the angular velocity of the pulsar across the sky!

The Earth Orbits
the Sun !!

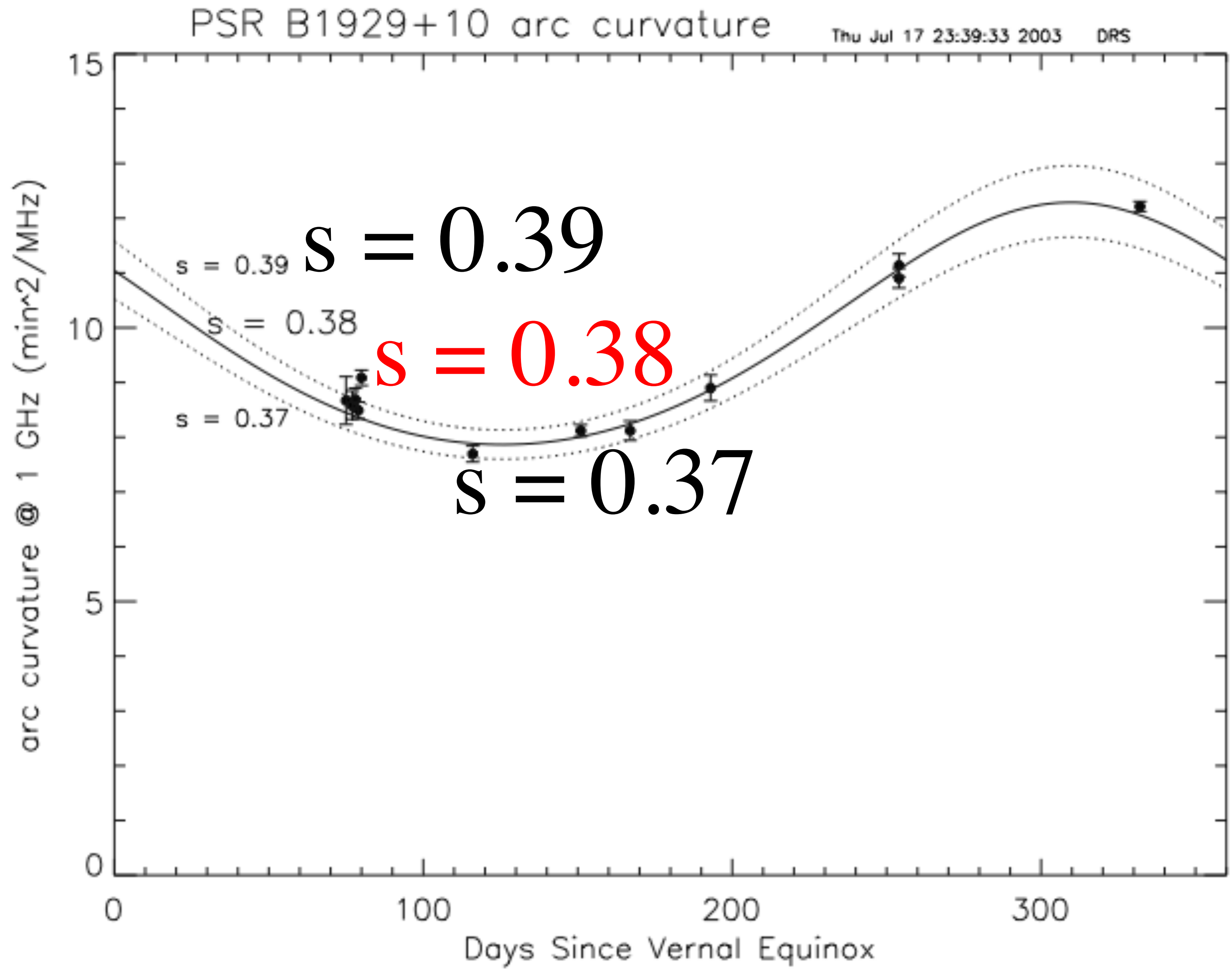
Effective Velocity

$$\mathbf{V}_{eff\perp} = (1-s)\mathbf{V}_{p\perp} + s\mathbf{V}_{obs\perp} - \mathbf{V}_{scr\perp}$$

Cordes and Rickett 1998, ApJ, 507, 846

$$s \equiv \frac{D_{\text{psr-screen}}}{D_{\text{total}}}$$

$$\eta = \frac{\lambda^2 D\, s\,(1-s)}{2cV_{eff}^2}$$



PSR B1929+10 arc curvature
Thu Jul 17 23:39:33 2003 DRS
s = 0.39
s = 0.38
s = 0.37
s = 0.39
s = 0.38
s = 0.37
arc curvature @ 1 GHz (min^2/MHz)
Days Since Vernal Equinox
0
5
10
15
0
100
200
300

Daniel Reardon (Swinburne, OzGrav)

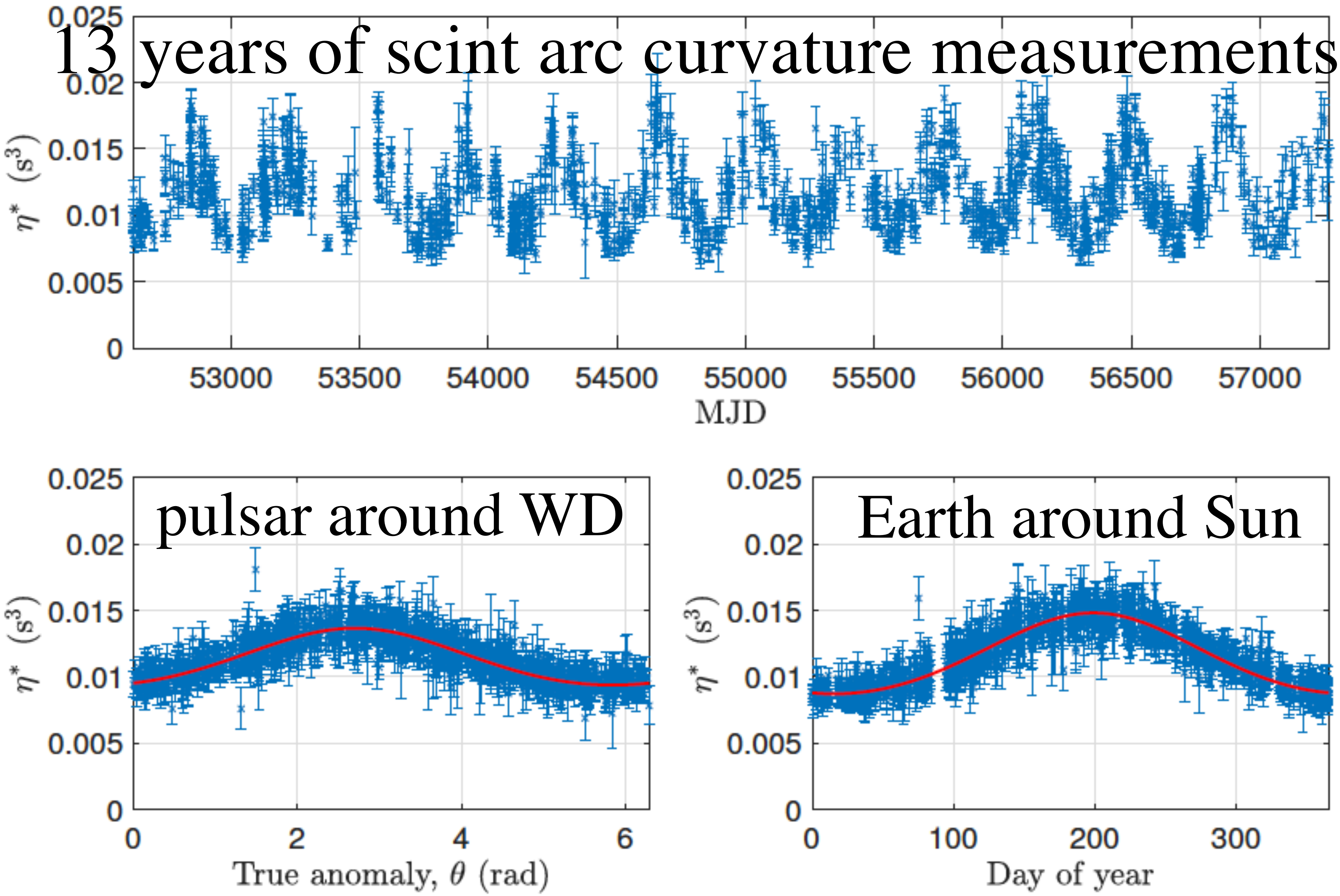
Precision radio-frequency pulsar timing & interstellar scintillometry

By

DANIEL JOHN REARDON

ANCORA IMPARO

MONASH University



Reardon, PhD thesis, 2018

distance to the pulsar J0437-4715

$$D = 156.79 \pm 0.25\,\text{pc}$$

distance to the primary screen

$$D_e = 90.6 \pm 0.7\,\text{pc}$$

(1 pc ≈ 3.3 light years)

Reardon, PhD thesis, 2018

Multiple Arcs —>

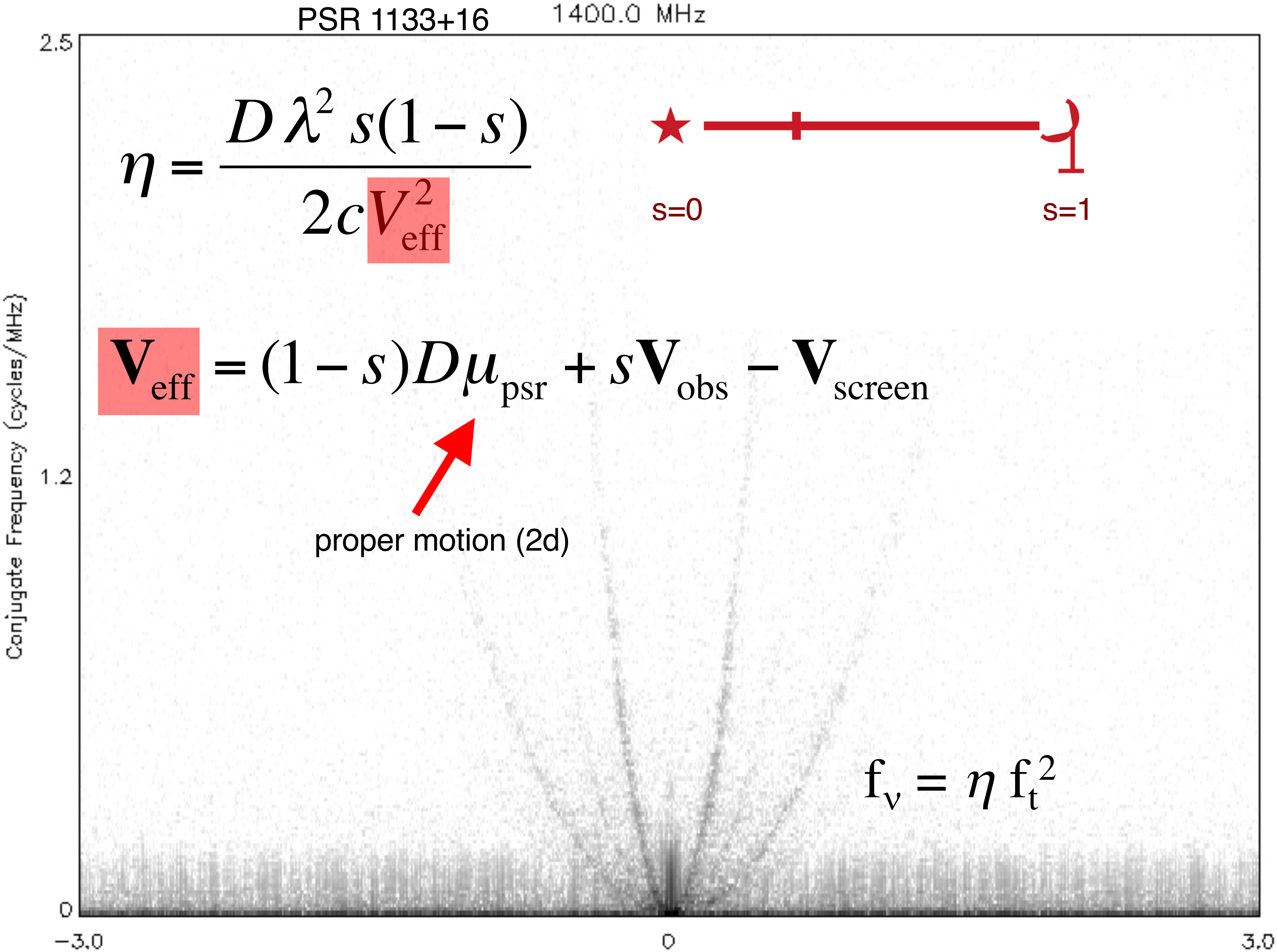
Multiple "Screens"

“Screen” Locations

$$f_\nu = \eta\, f_t^2$$

$$\eta = \frac{\lambda^2 D\, s\,(1-s)}{2cV_{eff}^2}$$

$$\mathbf{V}_{eff\perp} = (1-s)\mathbf{V}_{p\perp} + s\mathbf{V}_{obs\perp} - \mathbf{V}_{scr\perp}$$

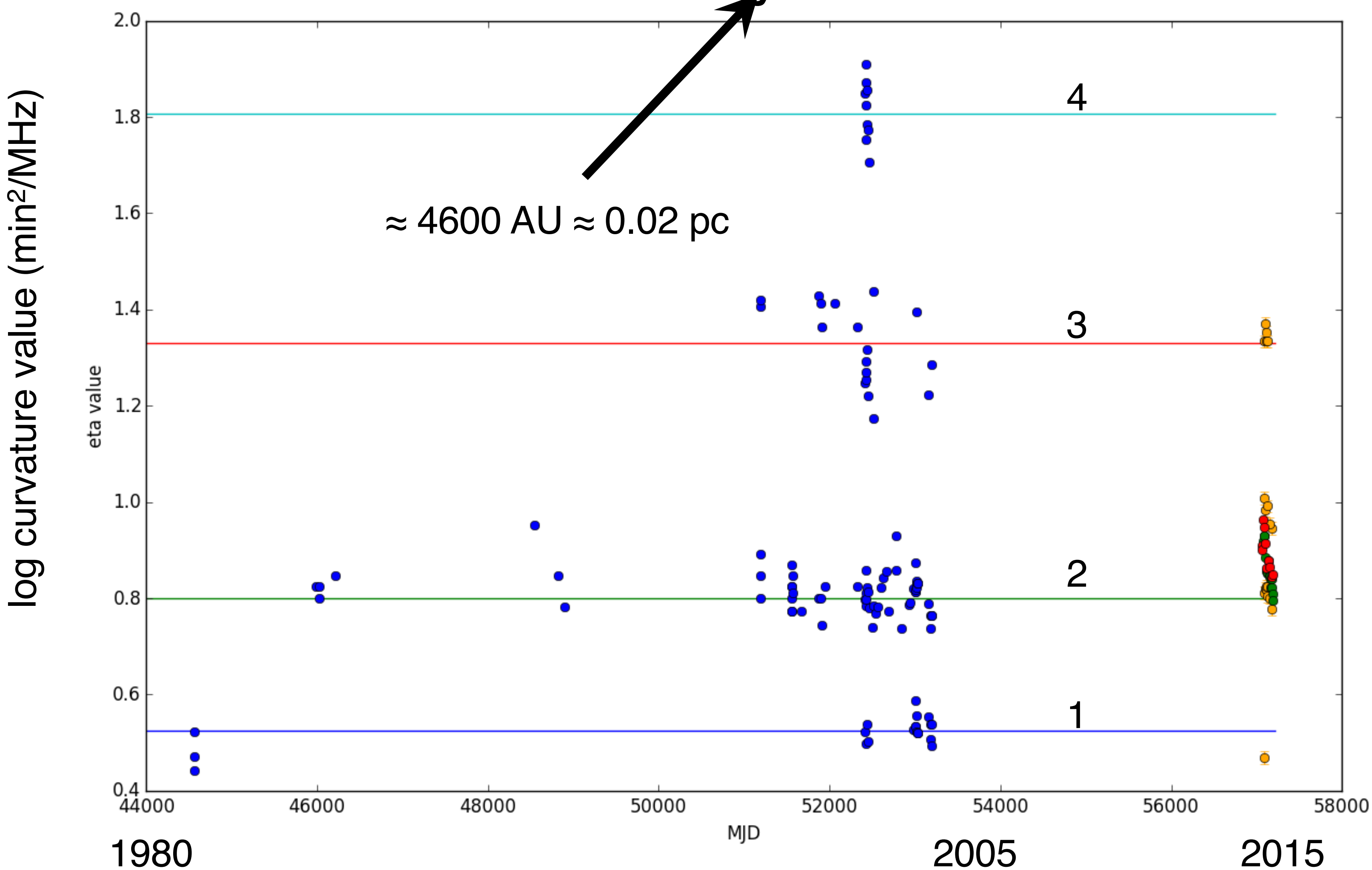


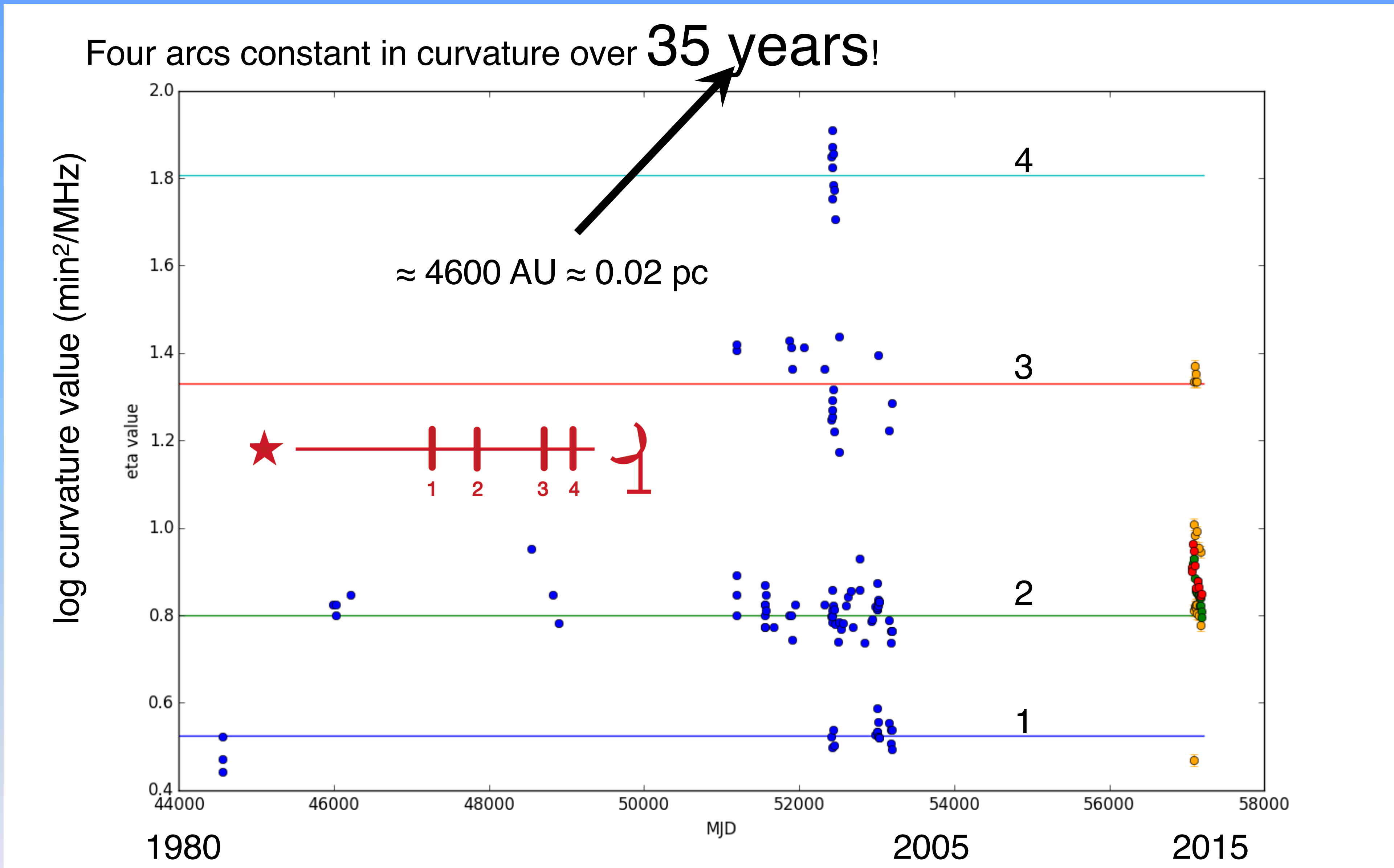
$$\eta = \frac{D\lambda^2 s(1-s)}{2cV_{\mathrm{eff}}^2}$$

$$\mathbf{V}_{\mathrm{eff}} = (1-s)D\mu_{\mathrm{psr}} + s\mathbf{V}_{\mathrm{obs}} - \mathbf{V}_{\mathrm{screen}}$$

$$\mathrm{f}_\nu = \eta\, \mathrm{f}_t^2$$

Four arcs constant in curvature over 35 years!





Four arcs constant in curvature over 35 years!
≈ 4600 AU ≈ 0.02 pc
log curvature value (min²/MHz)
eta value
MJD
1980
2005
2015
1
2
3
4

Pulsar and Screen Locations, Galactic Plane

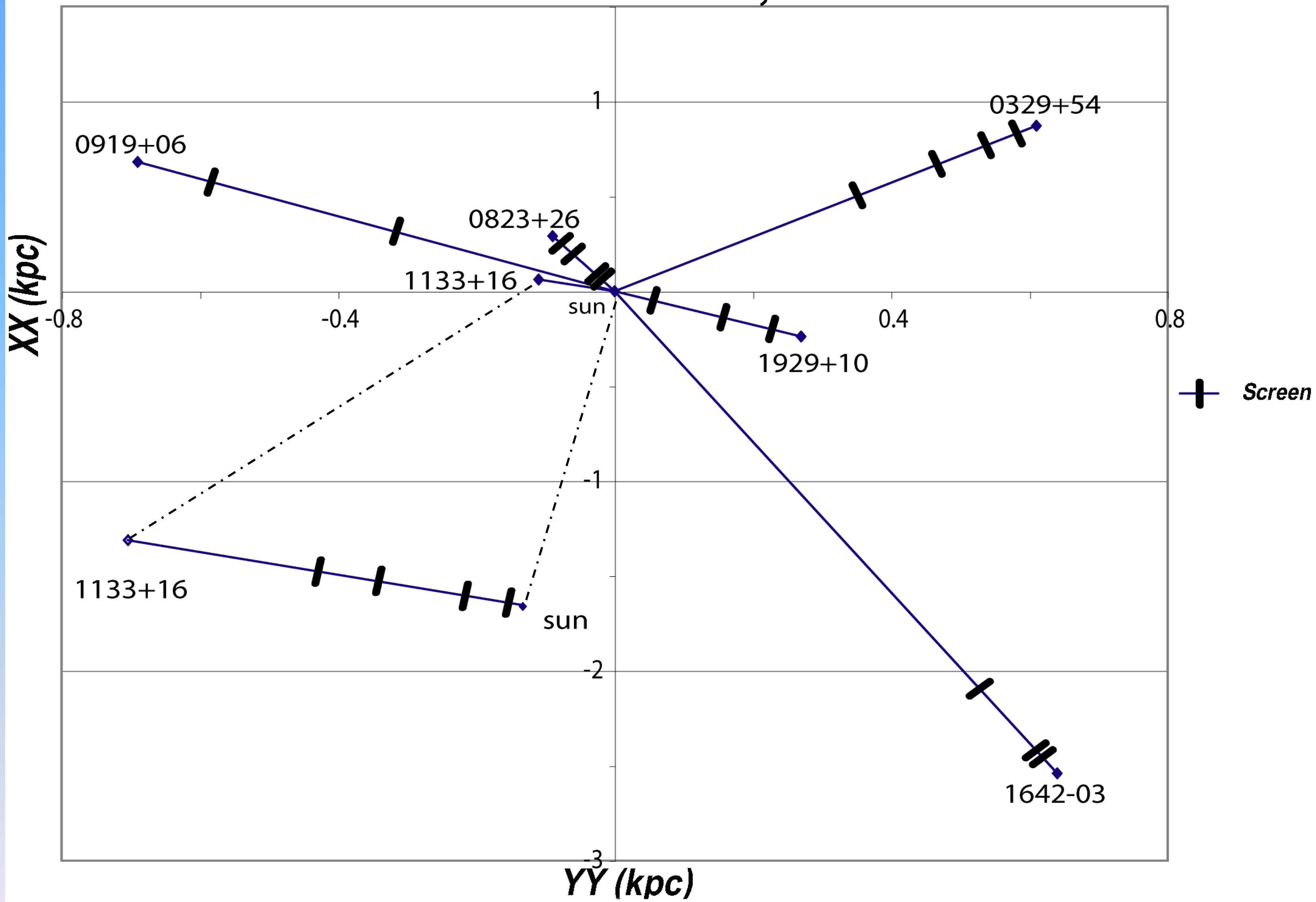
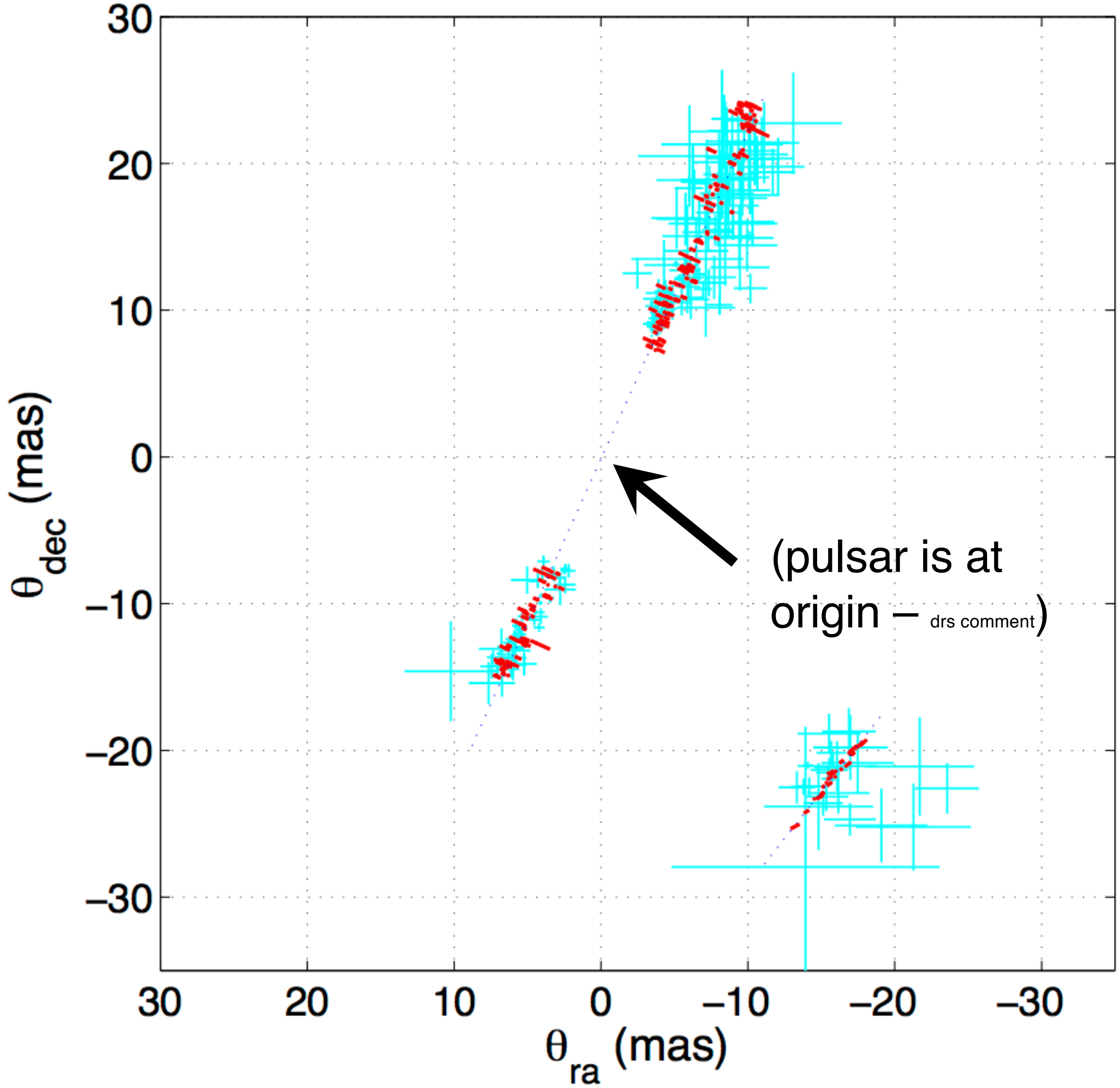


Image on the Sky



100 μas RESOLUTION VLBI IMAGING OF ANISOTROPIC INTERSTELLAR SCATTERING TOWARD PULSAR B0834+06

Brisken et al. 2010, ApJ, 708, 232

What produces the highly linear features in the scattered image?

- Pen and Levin 2014, MNRAS, 442, 3338
  corrugated plasma (reconnection) sheets
- Walker, Tuntsov, et al. 2017
  circumstellar structures around hot stars

from Ue-Li Pen ”Galt talk”

What produces the highly linear features in the scattered image?

- Pen and Levin 2014, MNRAS, 442, 3338
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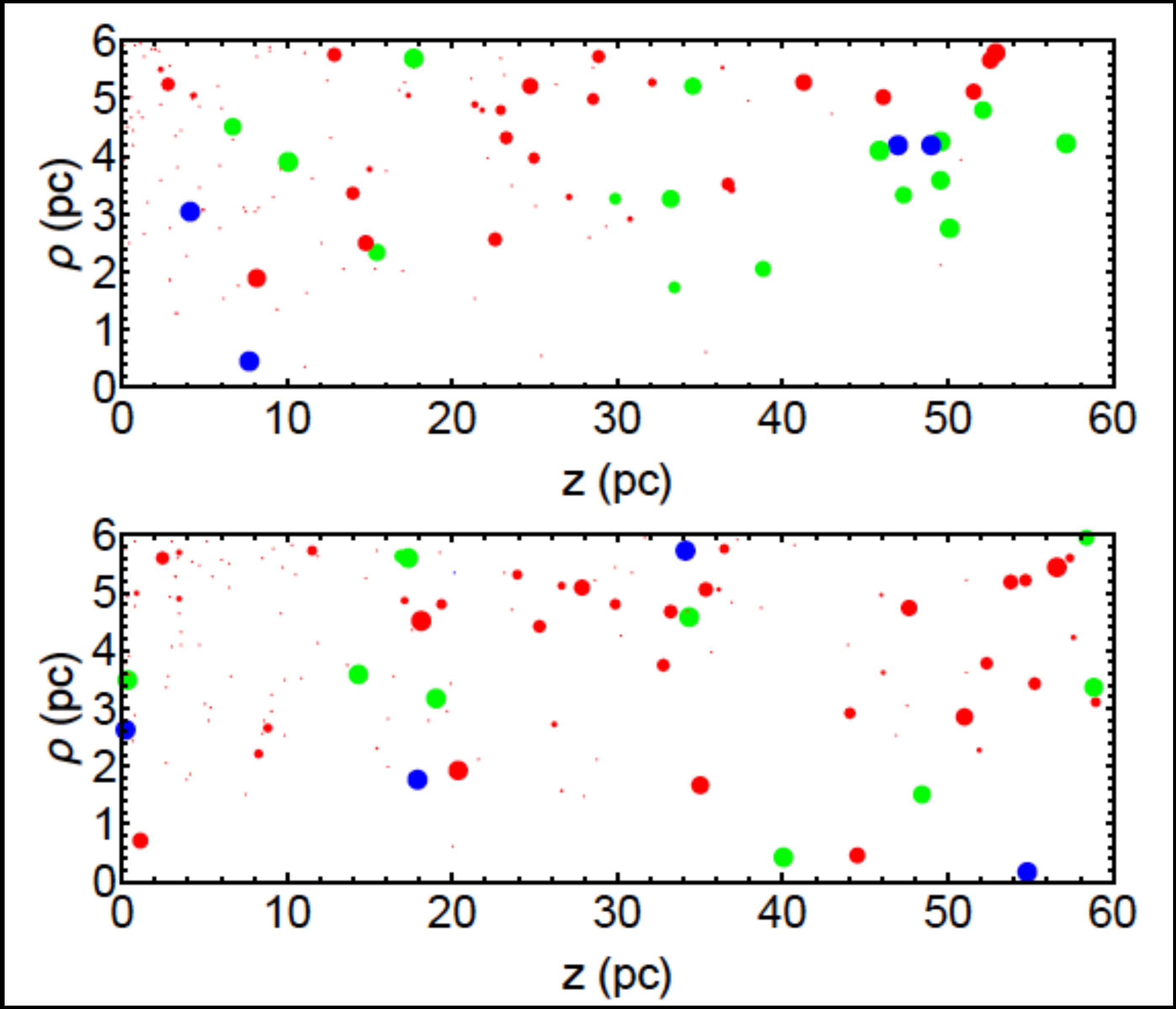


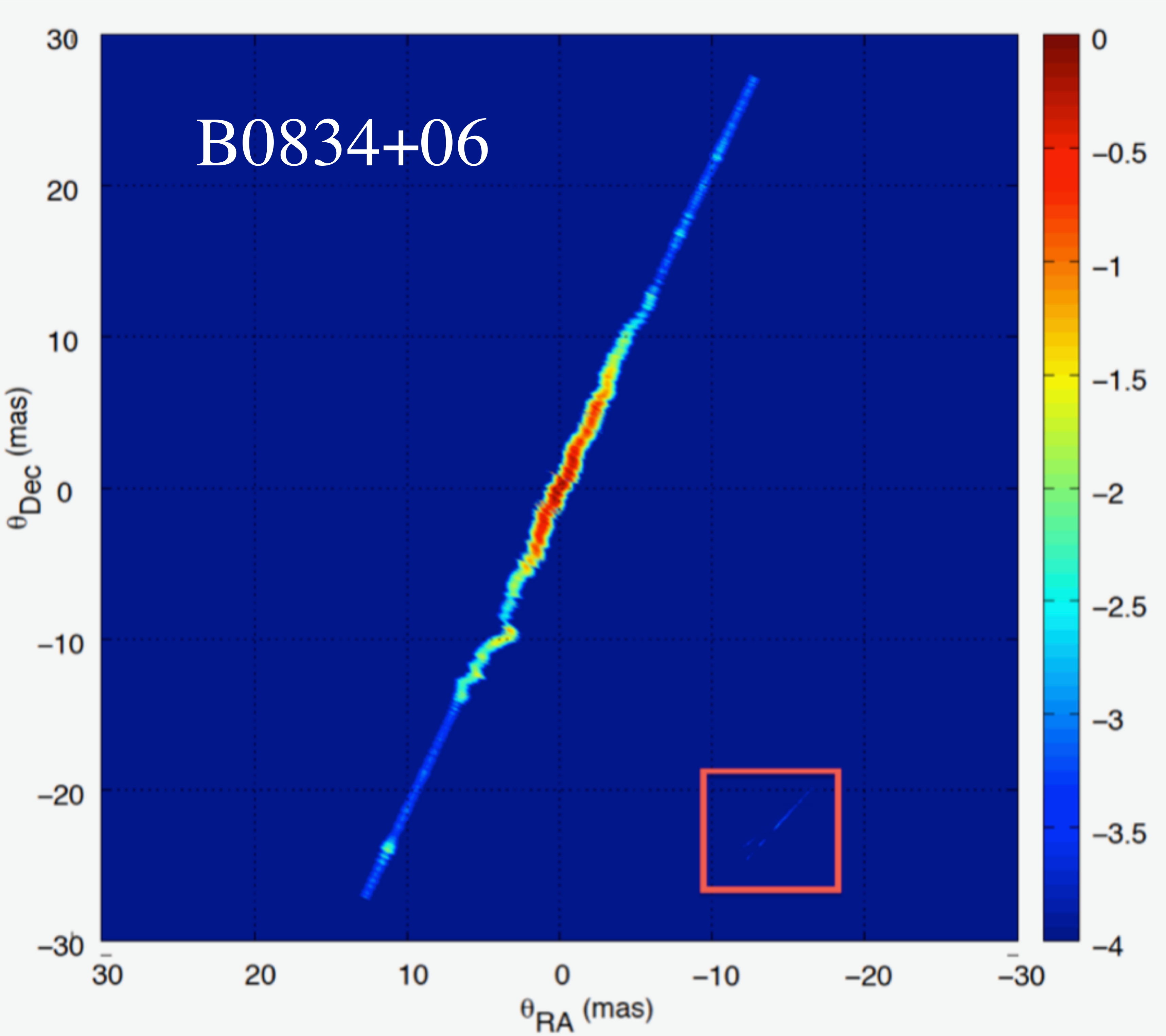
(cylindrical coordinates
size = luminosity
color = temperature)

Walker, Tuntsov, et al. 2017

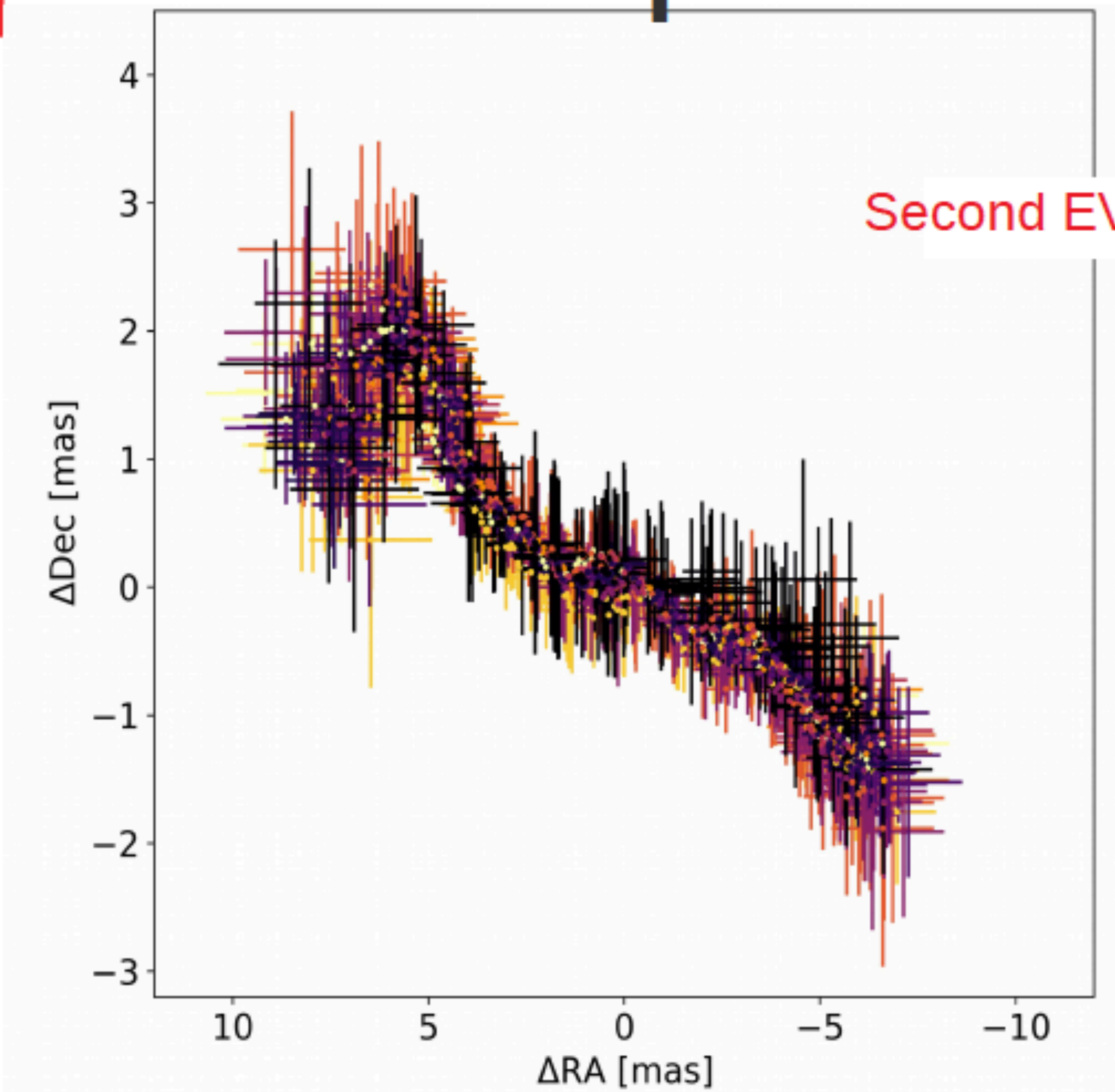
But, are they linear or mainly one-dimensional?

JJ Gao,
PhD
thesis

from
Barney
Rickett
(UCSD)



VELA – The speckle image



Second EVER speckle image!

Reminder: Beamsize > 20 mas

Seems speckle images do not lie on a line

Kirsten et al., in prep

Conclusions

- Most relatively nearby pulsars (DM < 50 pc cm^{-3}) exhibit one or more scintillation arcs
- Precision screen locations can be made by using orbital modulation
- Two models for what might be causing the highly linear scattering structures.

Conclusions

- Most relatively nearby pulsars (DM < 50 pc cm^{-3}) exhibit one or more scintillation arcs
- Precision screen locations can be made by using orbital modulation
- Two models for what might be causing the highly linear scattering structures. Let's get to the bottom of this!

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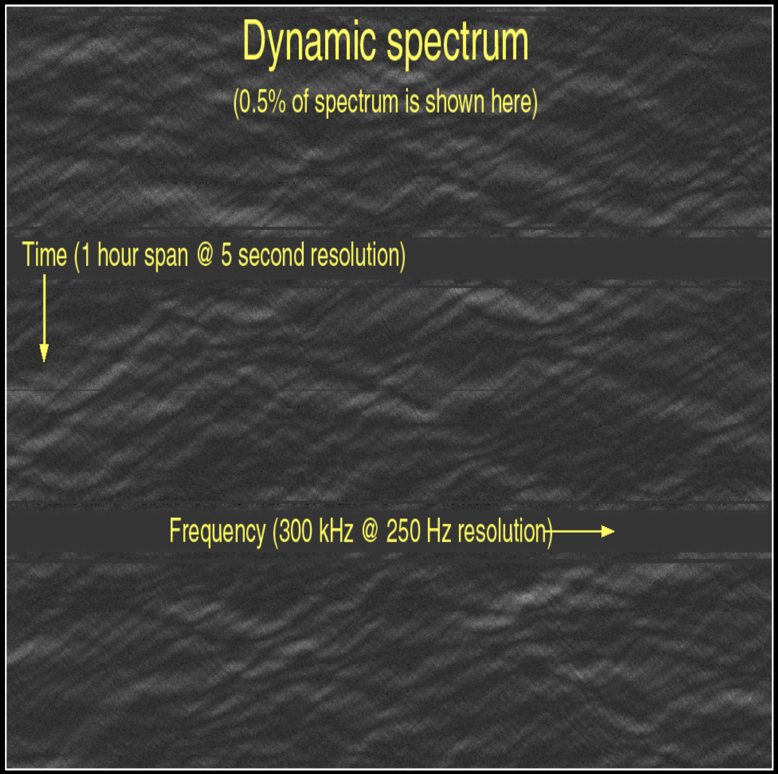
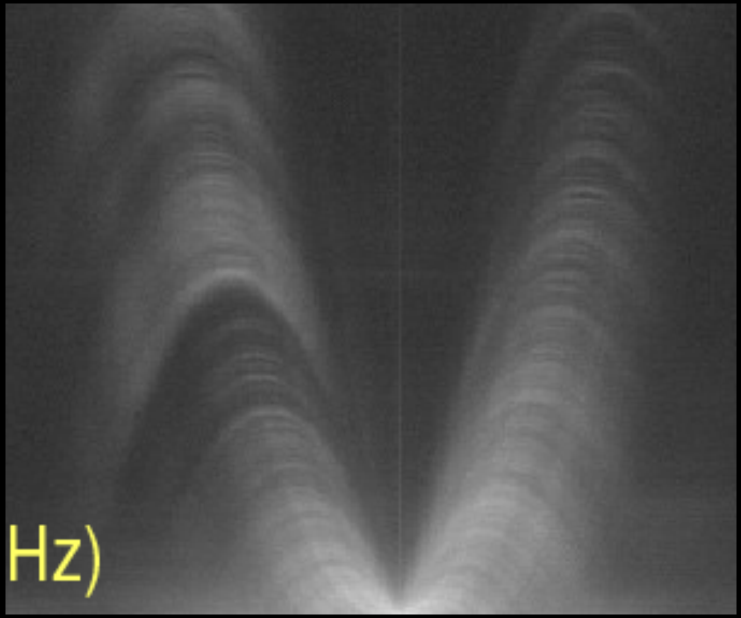
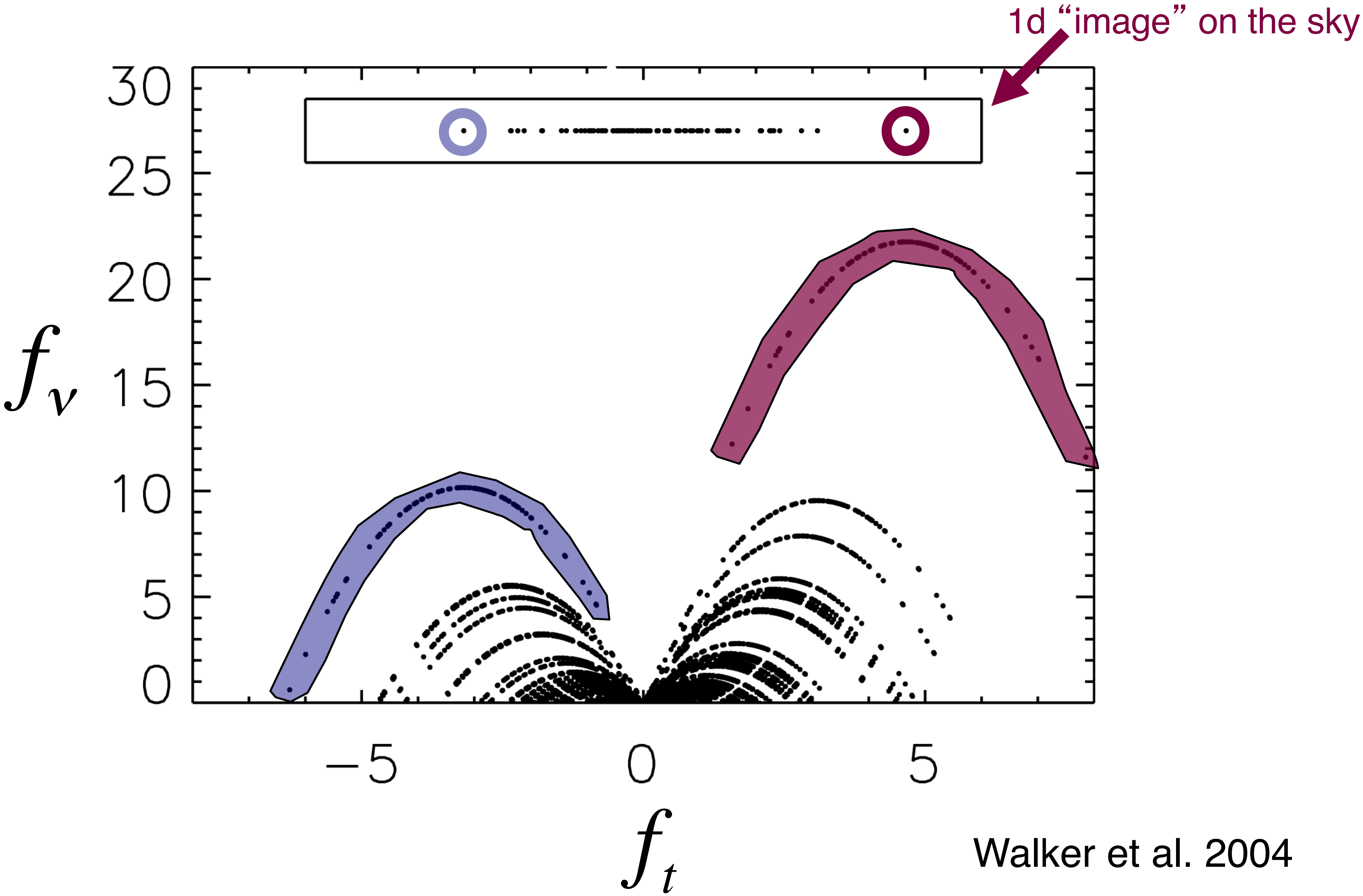


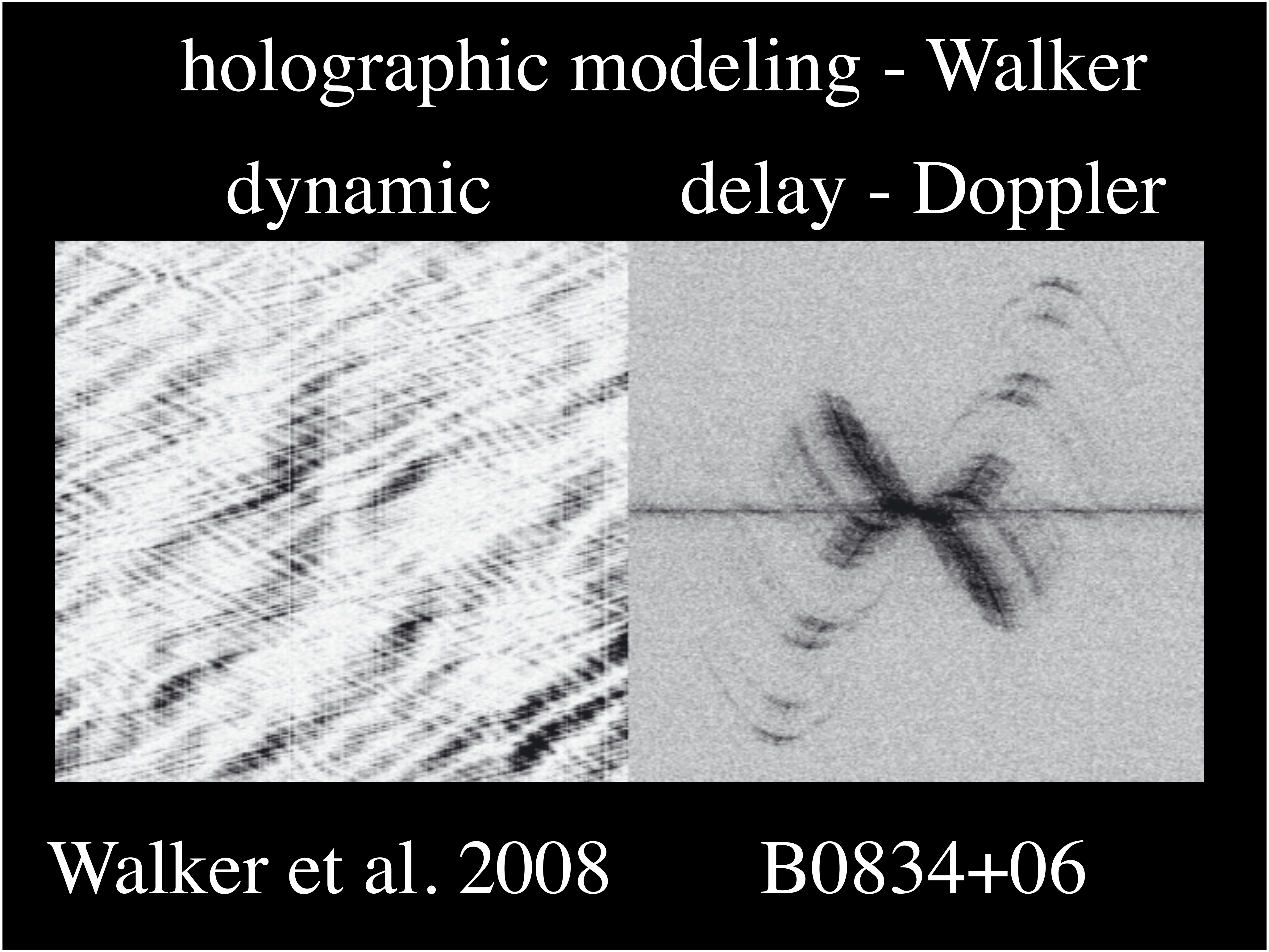
Walter Brisken (NRAO) et al.
"Small Ionized and Neutral Structures," Socorro, NM, 2006 May 23

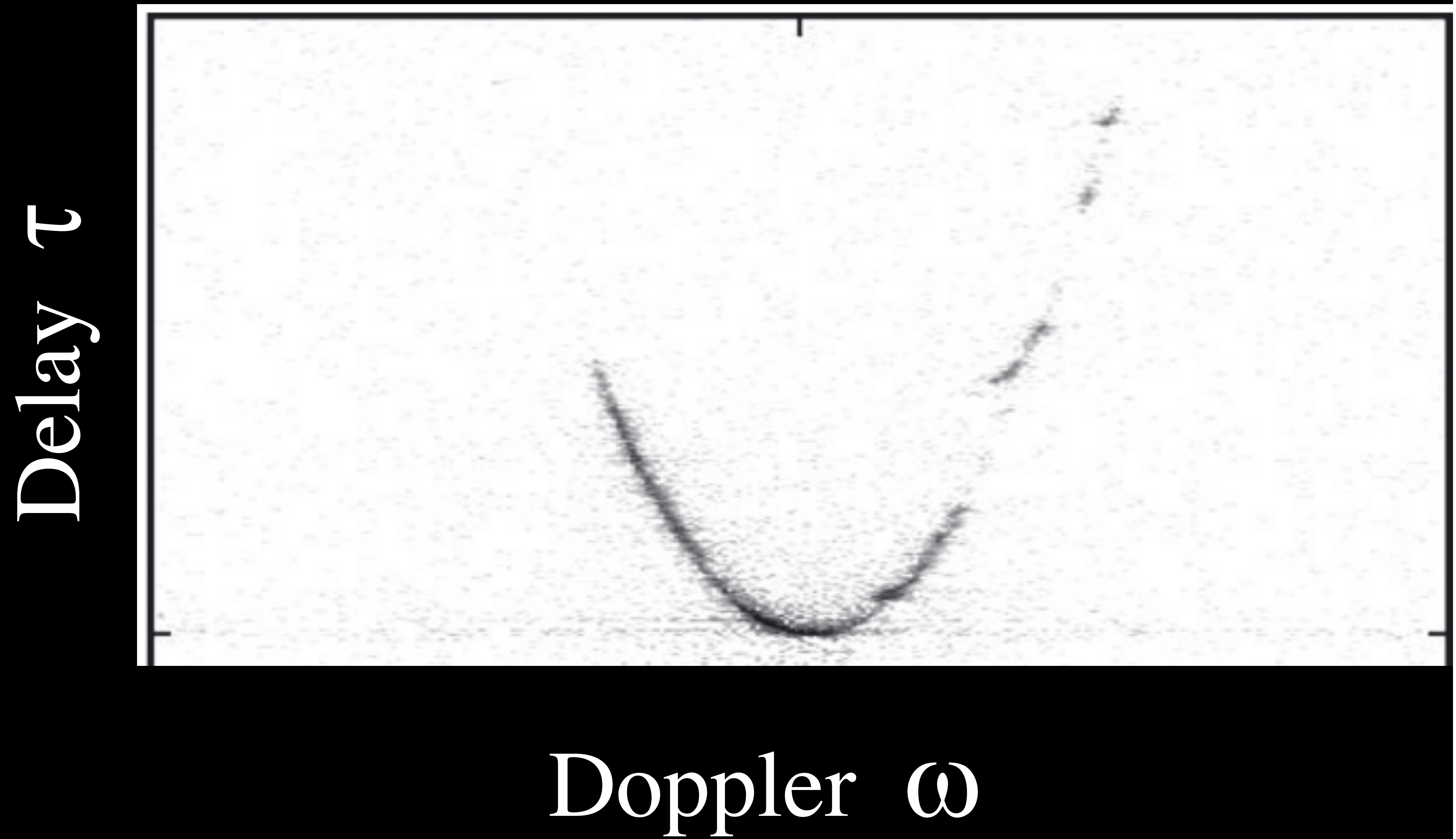


Where do the "arclets" (inverted parabolas) come from?

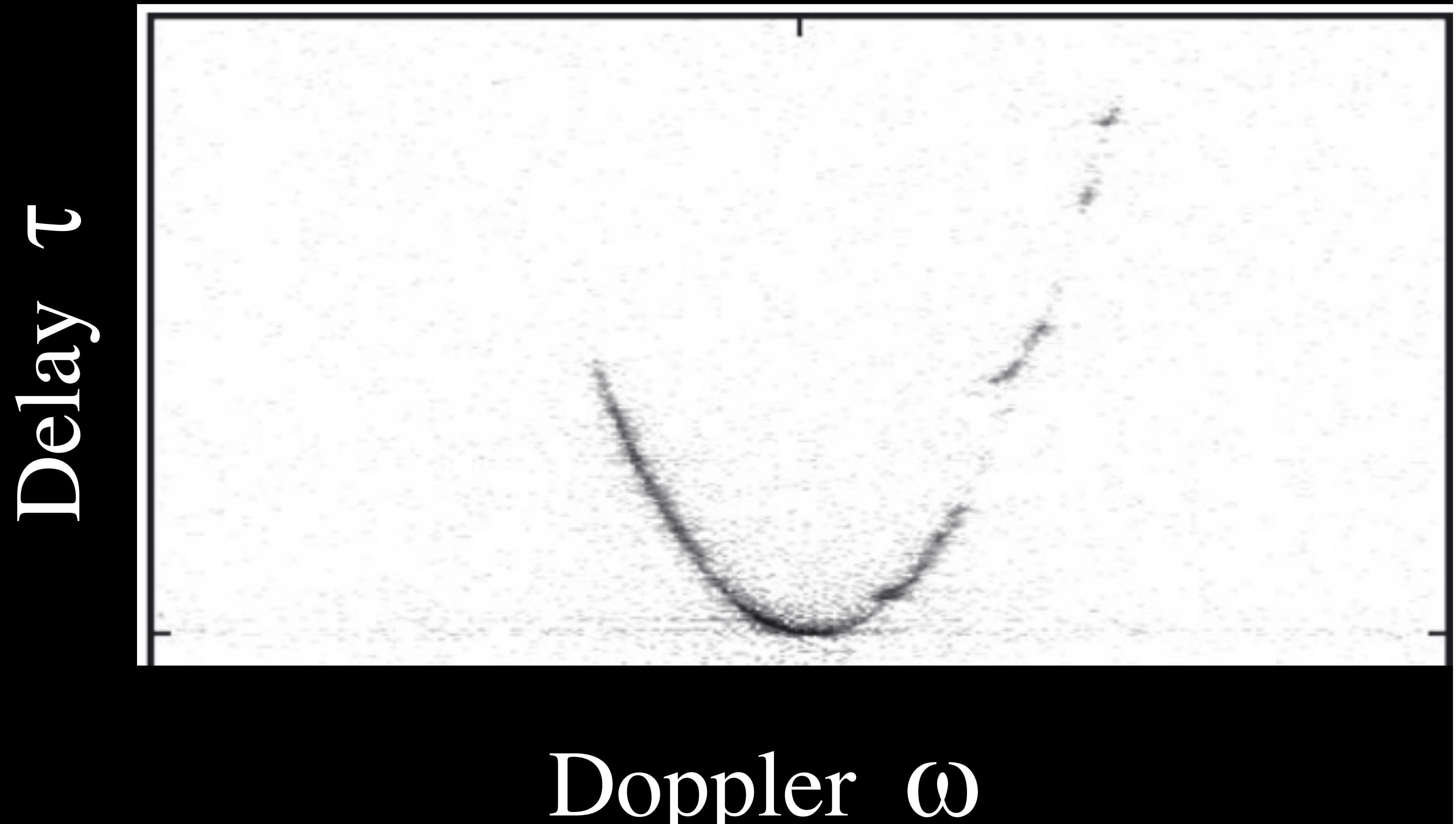


Walker et al. 2004


holographic modeling - Walker
dynamic
delay - Doppler
Walker et al. 2008
B0834+06

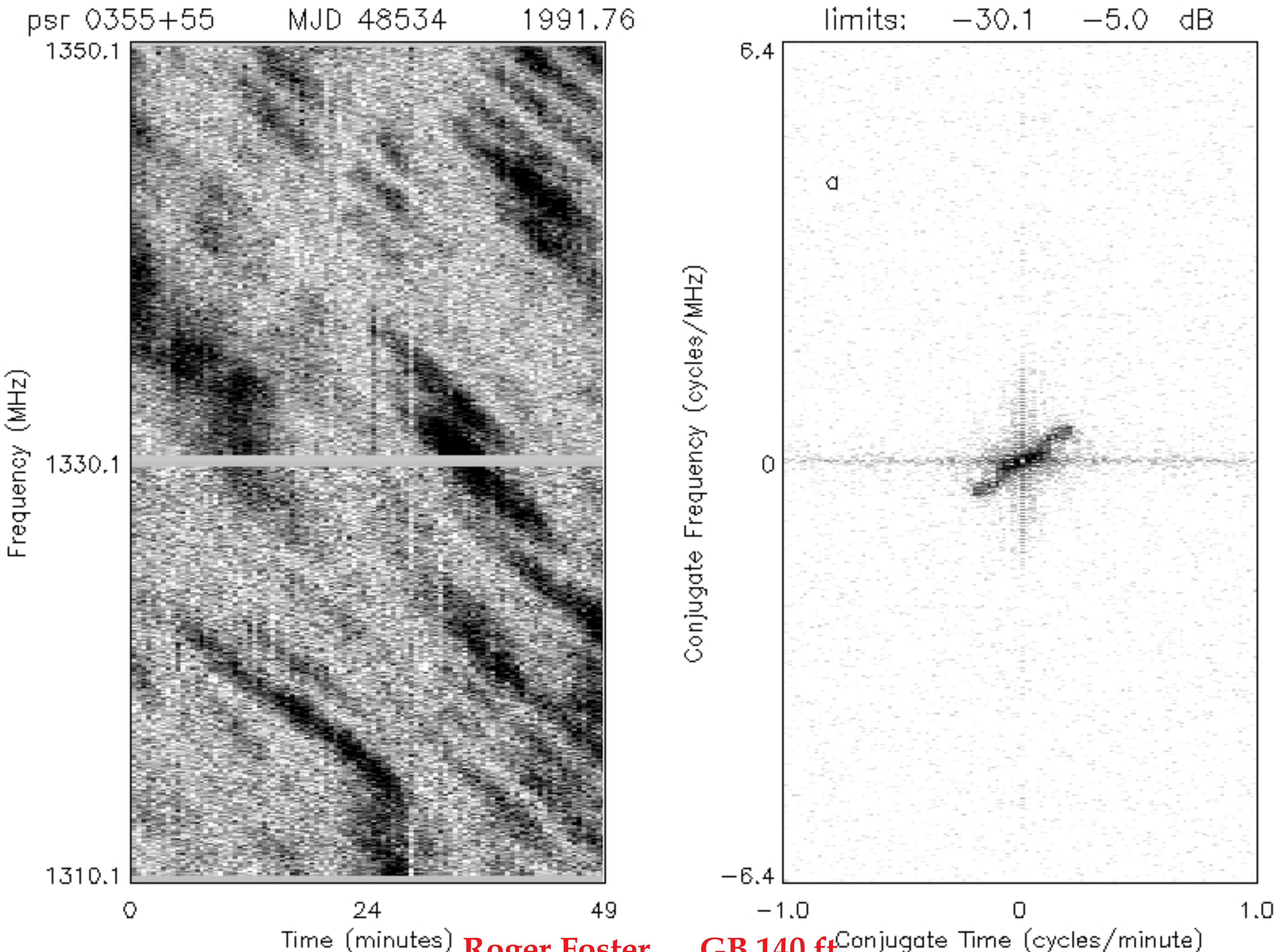


Walker et al. 2008

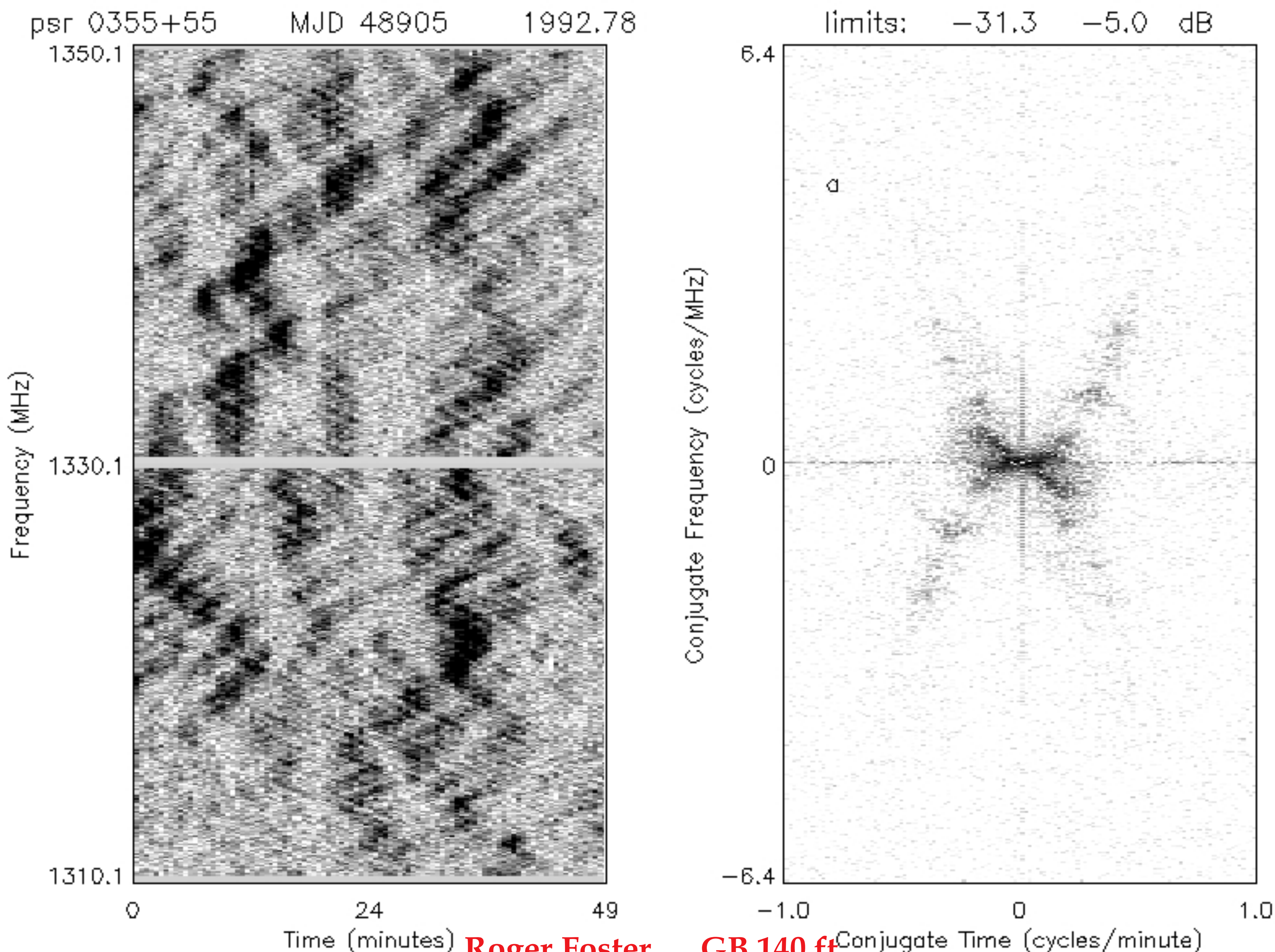


Wavefield representation
(no conjugate image)

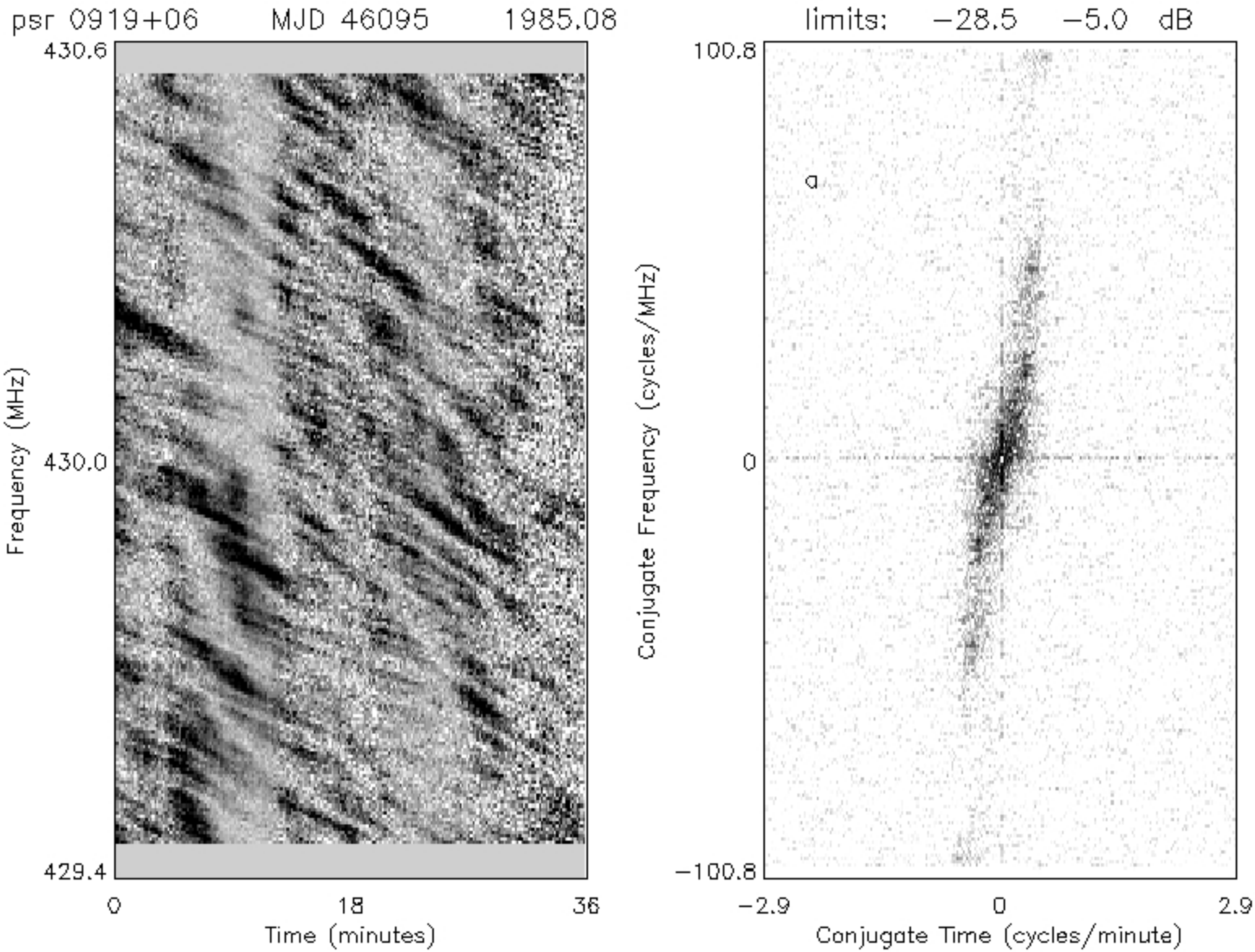
Walker et al. 2008

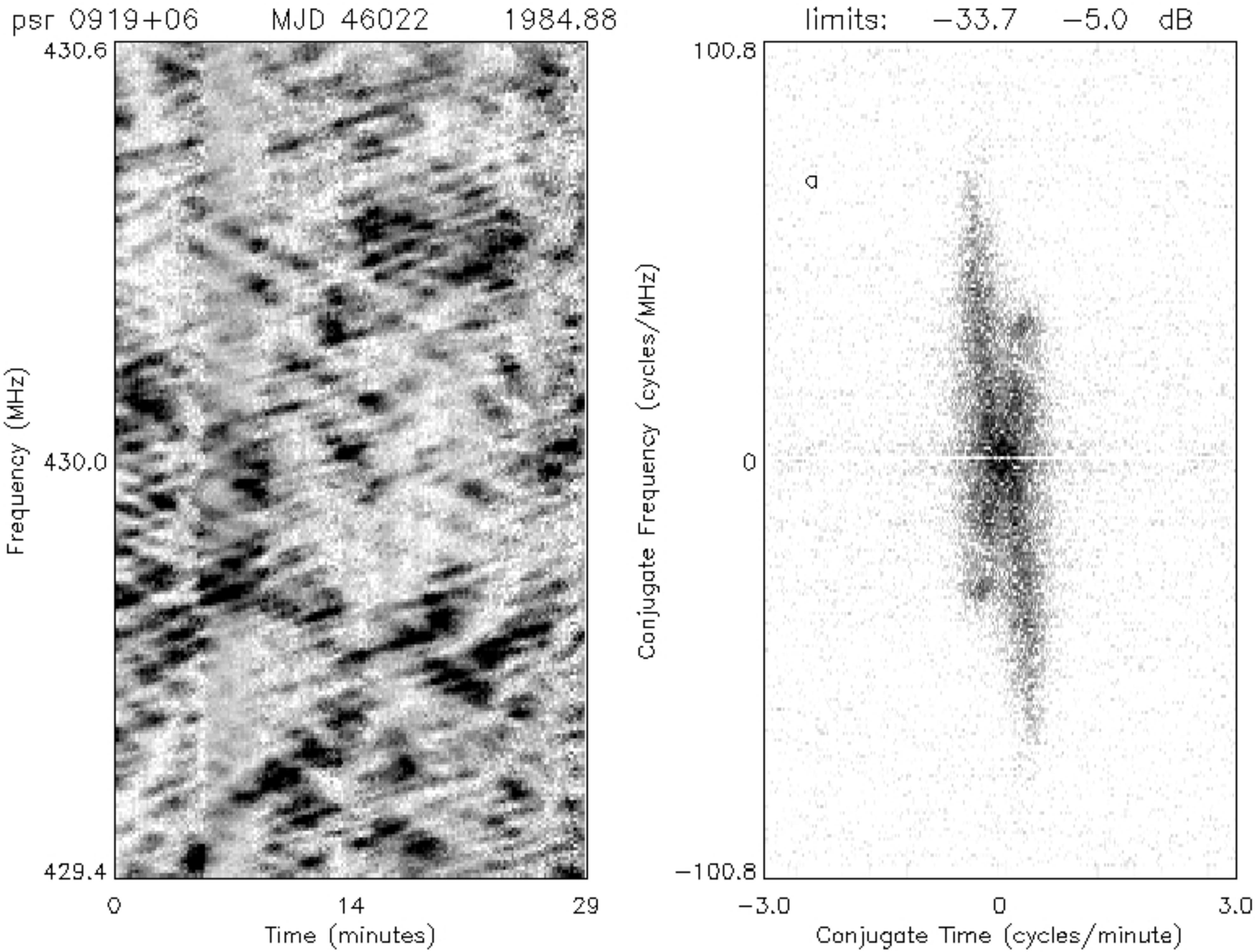


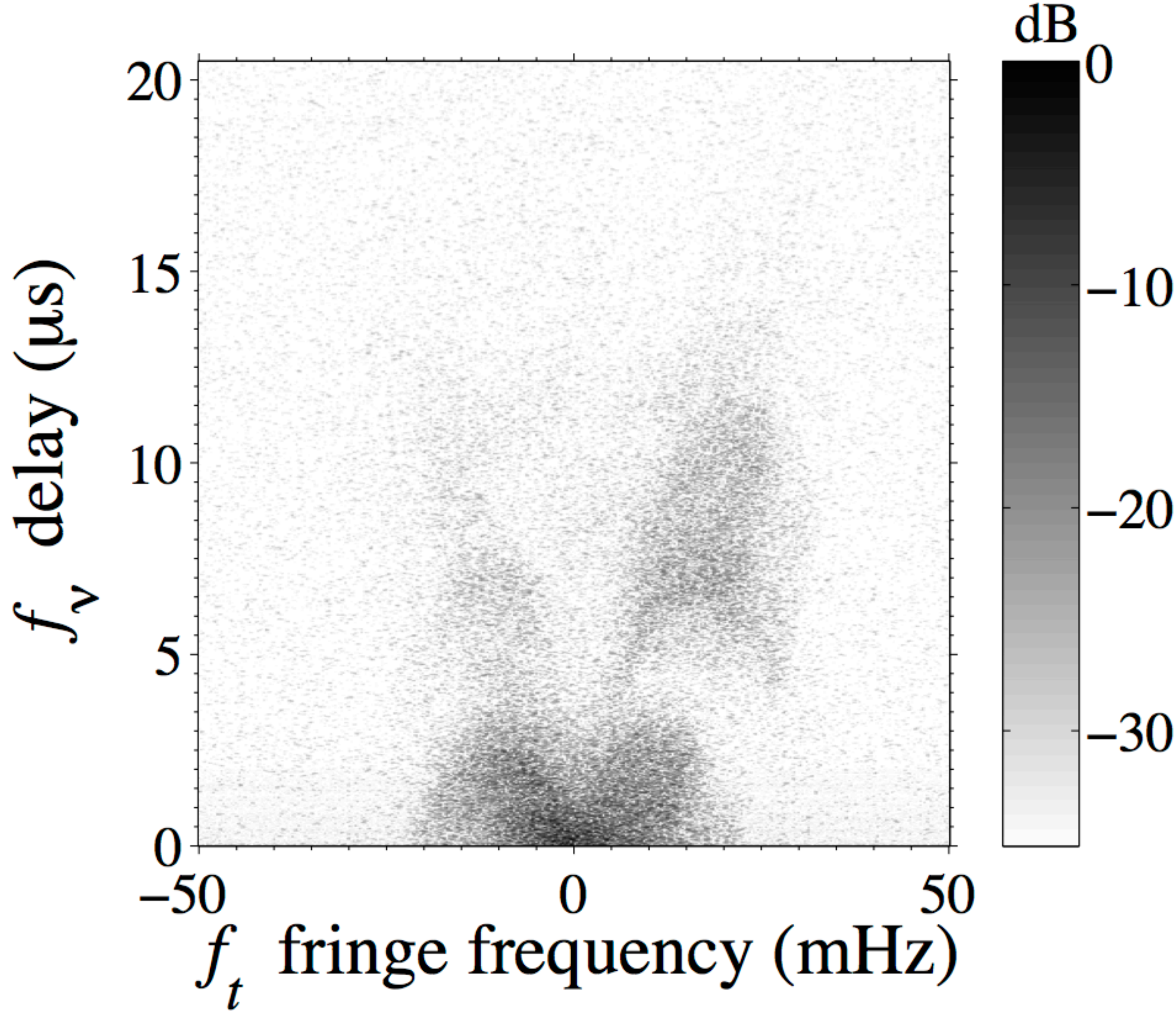
Roger Foster, GB 140 ft



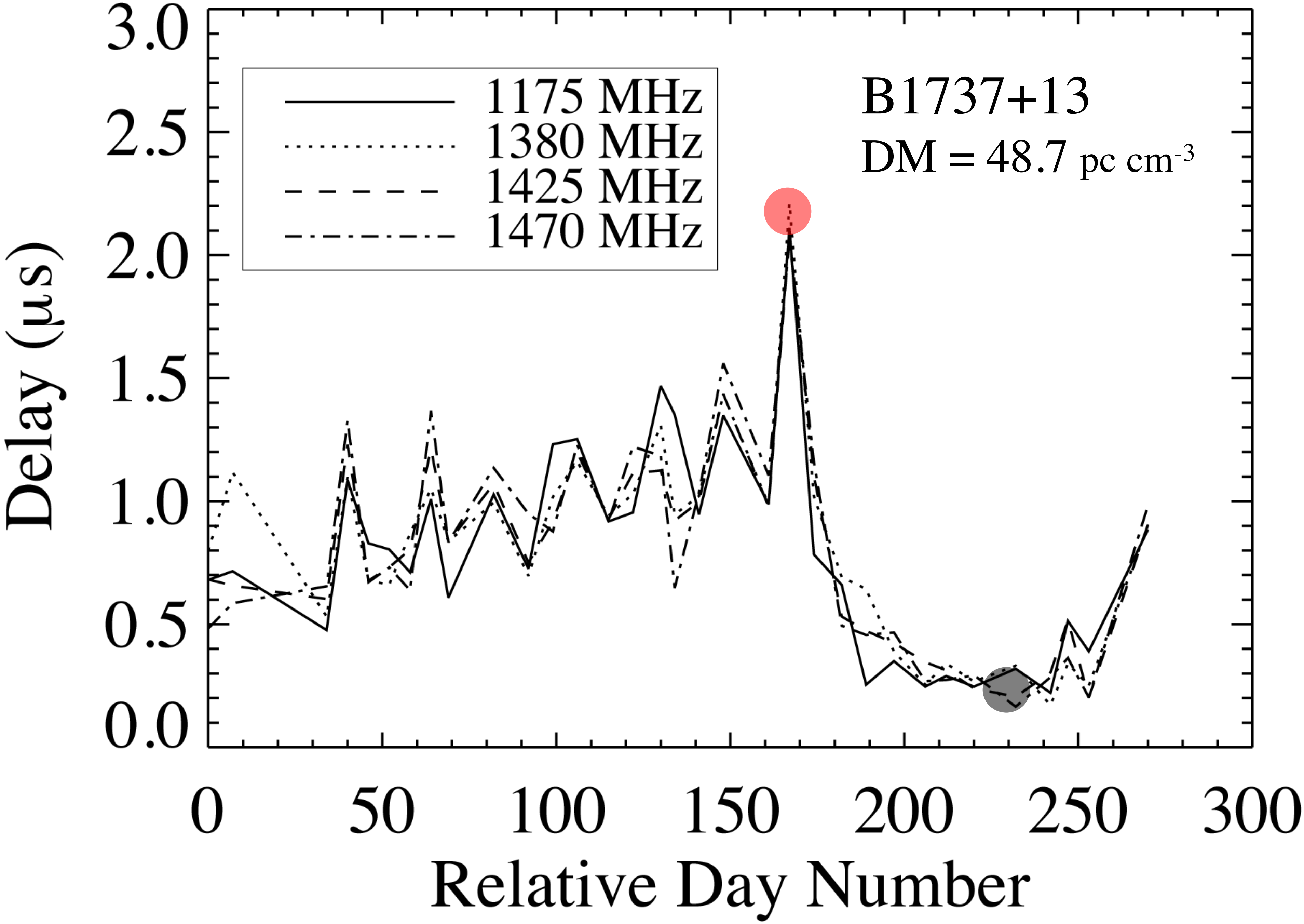
Roger Foster, GB 140 ft


psr 0919+06
MJD 46095
1985.08
limits: −28.5 −5.0 dB
430.6
430.0
429.4
Frequency (MHz)
0
18
36
Time (minutes)
100.8
0
−100.8
Conjugate Frequency (cycles/MHz)
a
−2.9
0
2.9
Conjugate Time (cycles/minute)

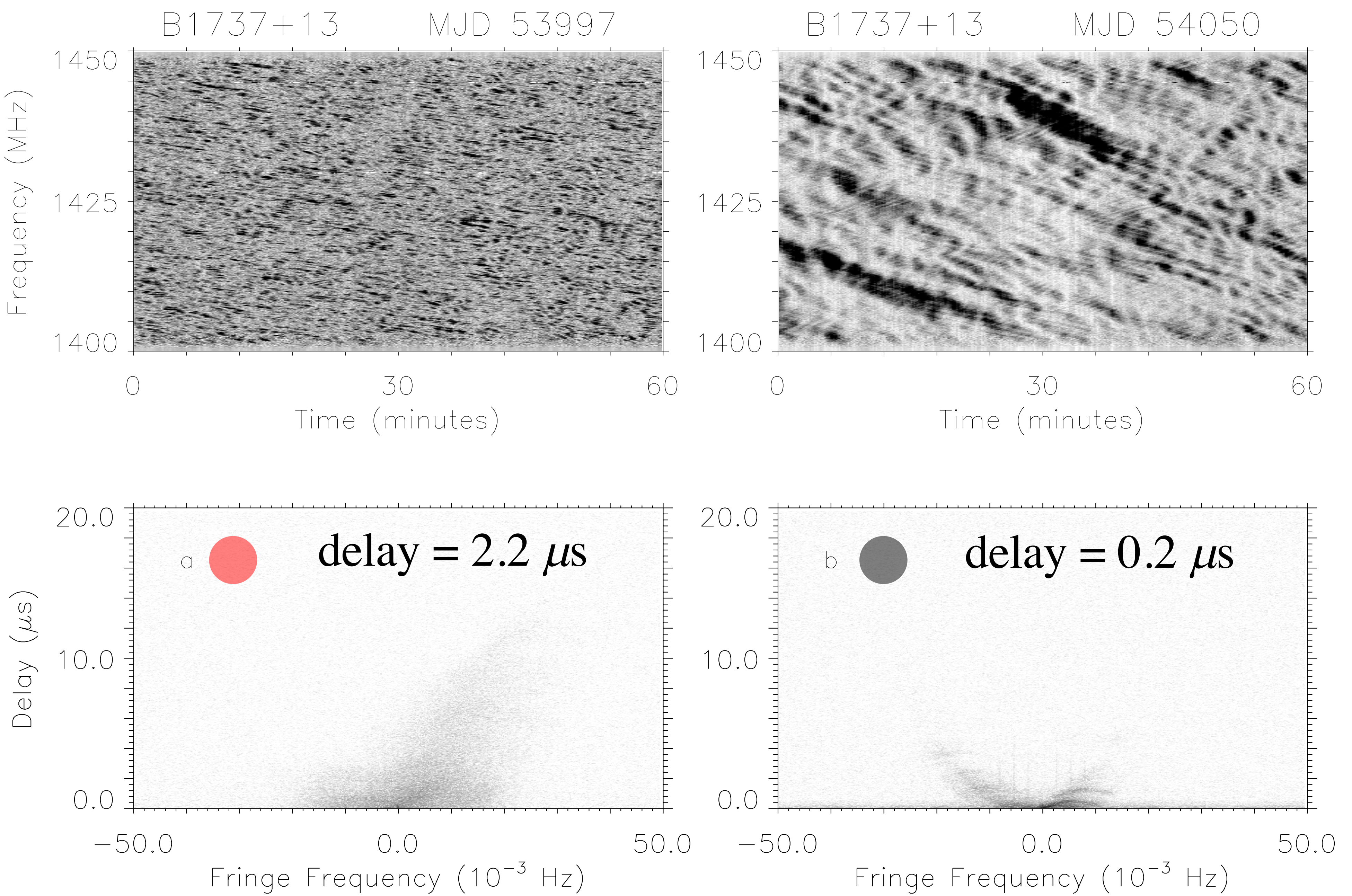

psr 0919+06
MJD 46022
1984.88
limits: −33.7 −5.0 dB
430.6
430.0
429.4
Frequency (MHz)
0
14
29
Time (minutes)
100.8
0
−100.8
Conjugate Frequency (cycles/MHz)
a
−3.0
0
3.0
Conjugate Time (cycles/minute)



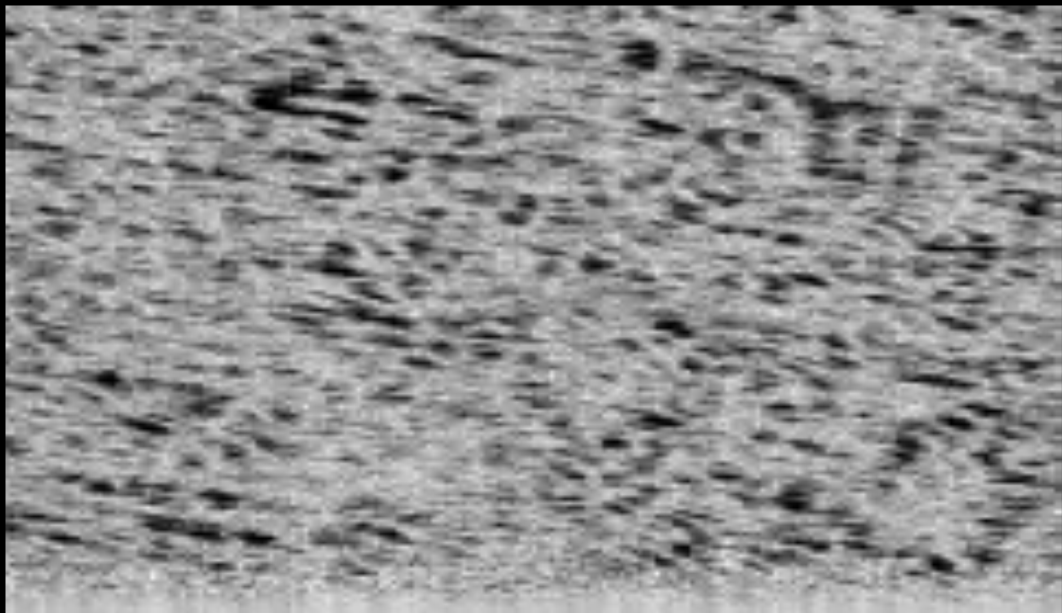
Hemberger and Stinebring 2008



Hemberger and Stinebring 2008



B1737+13 MJD 53997
B1737+13 MJD 54050
Frequency (MHz)
1450
1425
1400
Time (minutes)
0
30
60
a
delay = 2.2 μs
b
delay = 0.2 μs
Delay (μs)
20.0
10.0
0.0
Fringe Frequency (10^-3 Hz)
−50.0
0.0
50.0

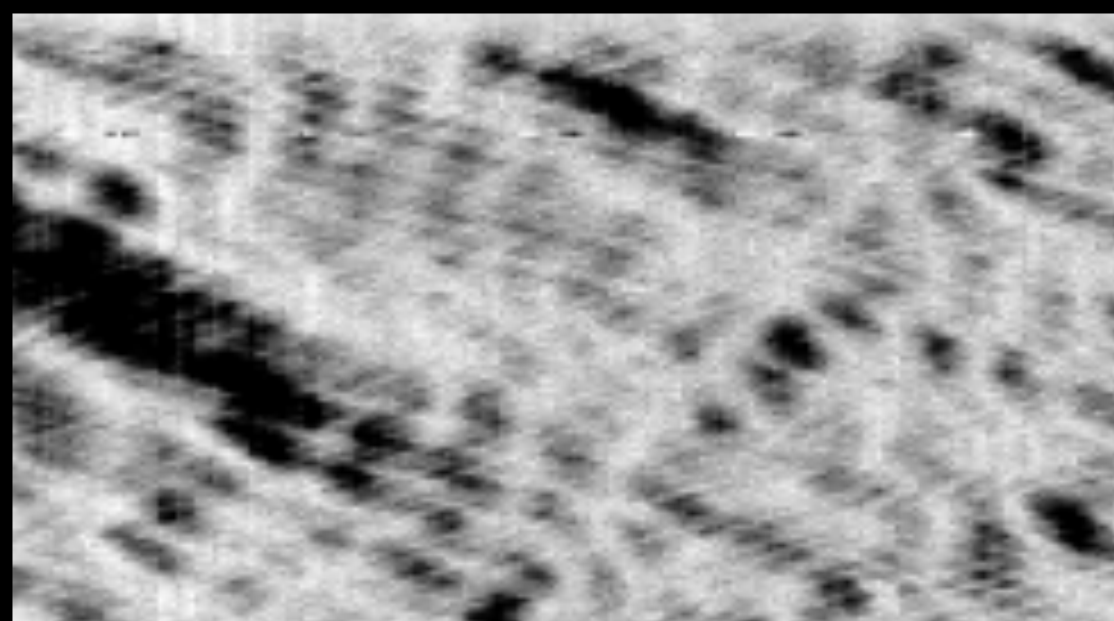


delay = 2.2 μs

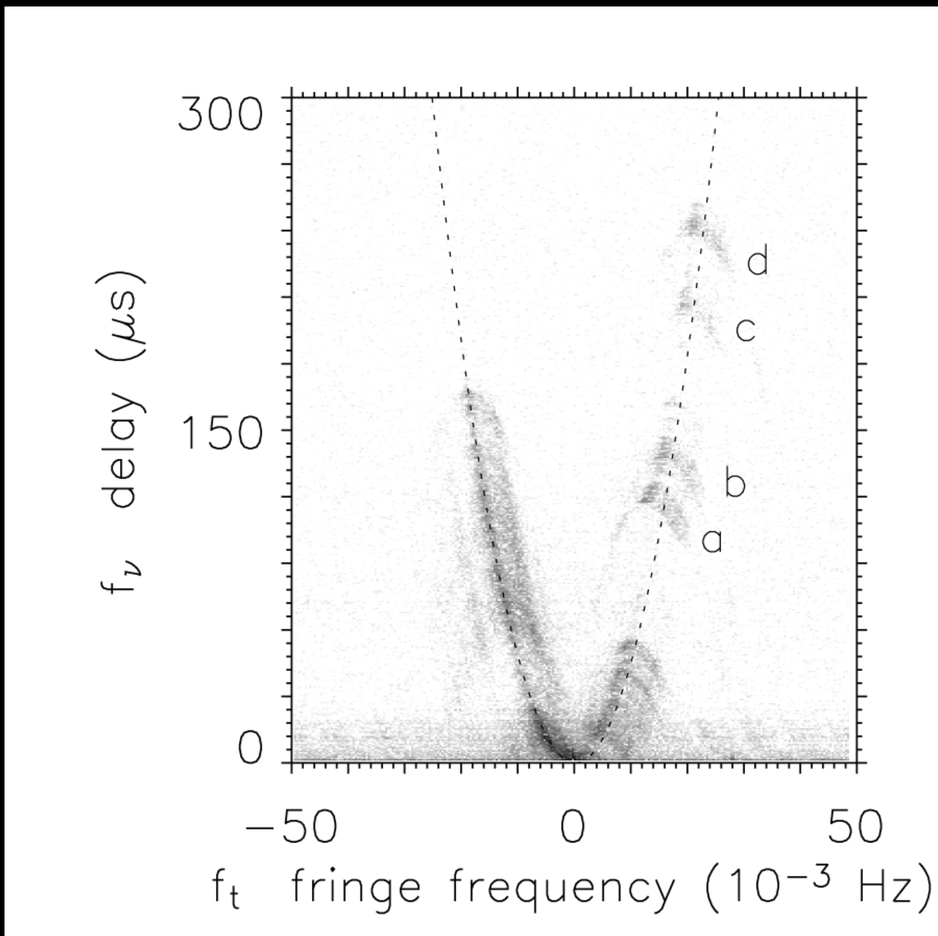
1400 MHz Arecibo

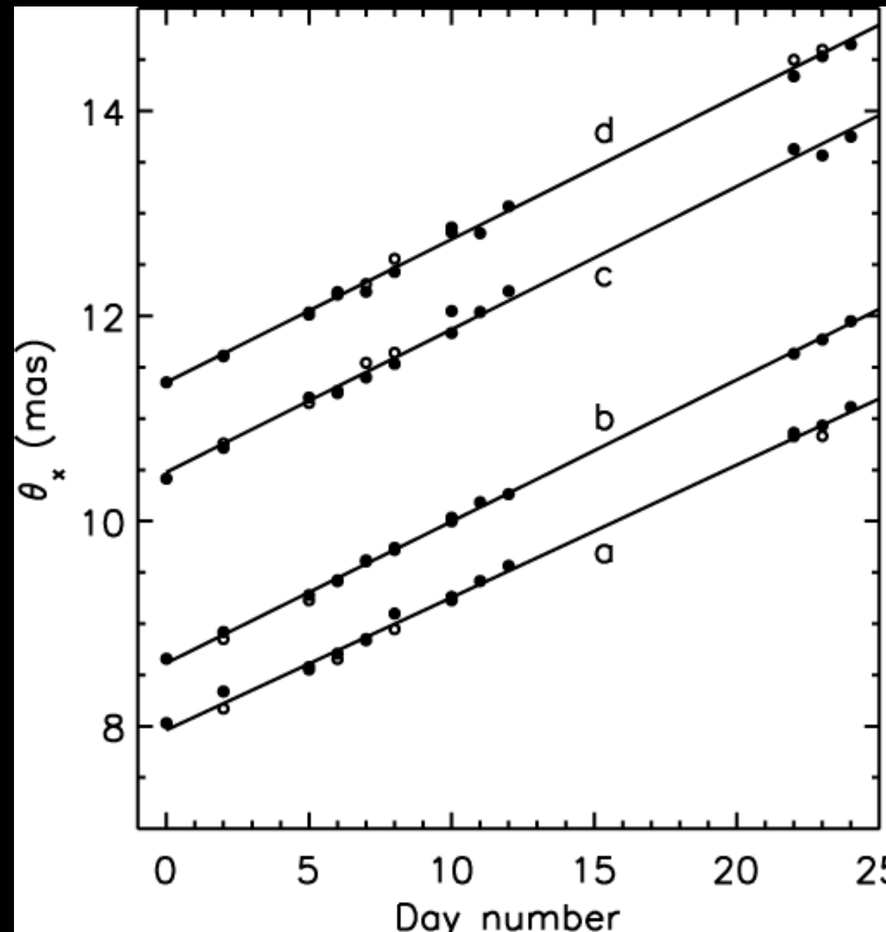
7 weeks later …

delay = 0.2 μs

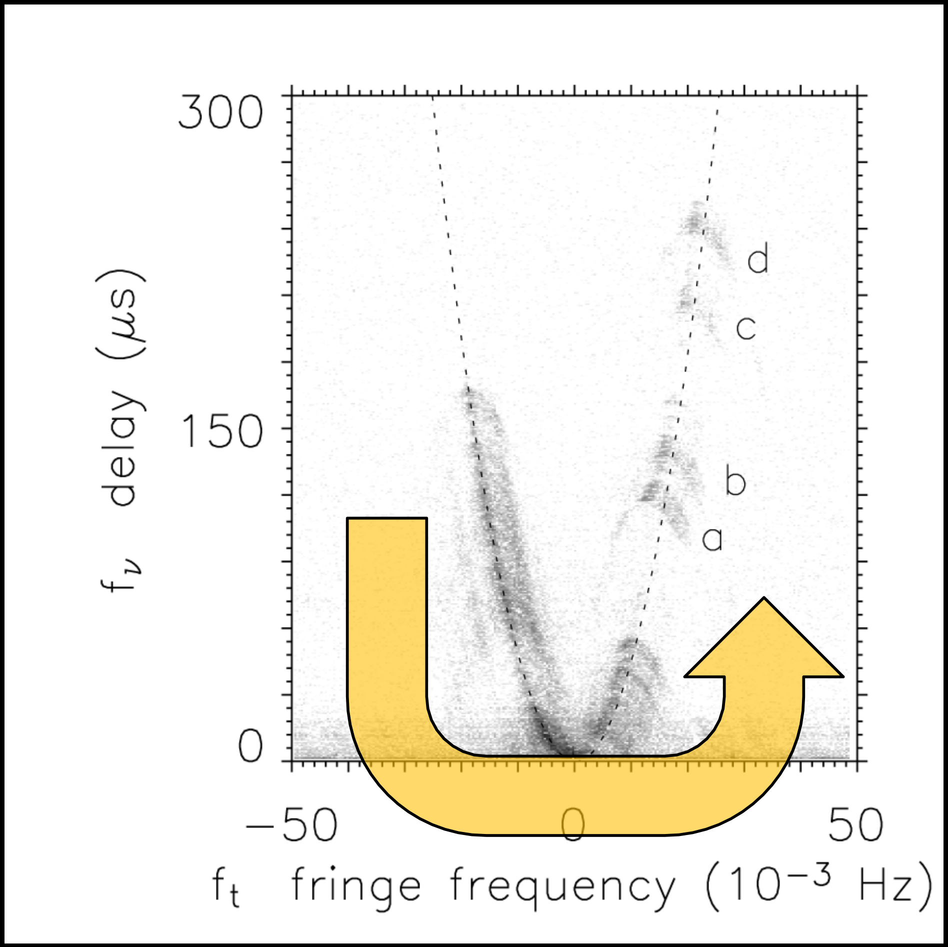


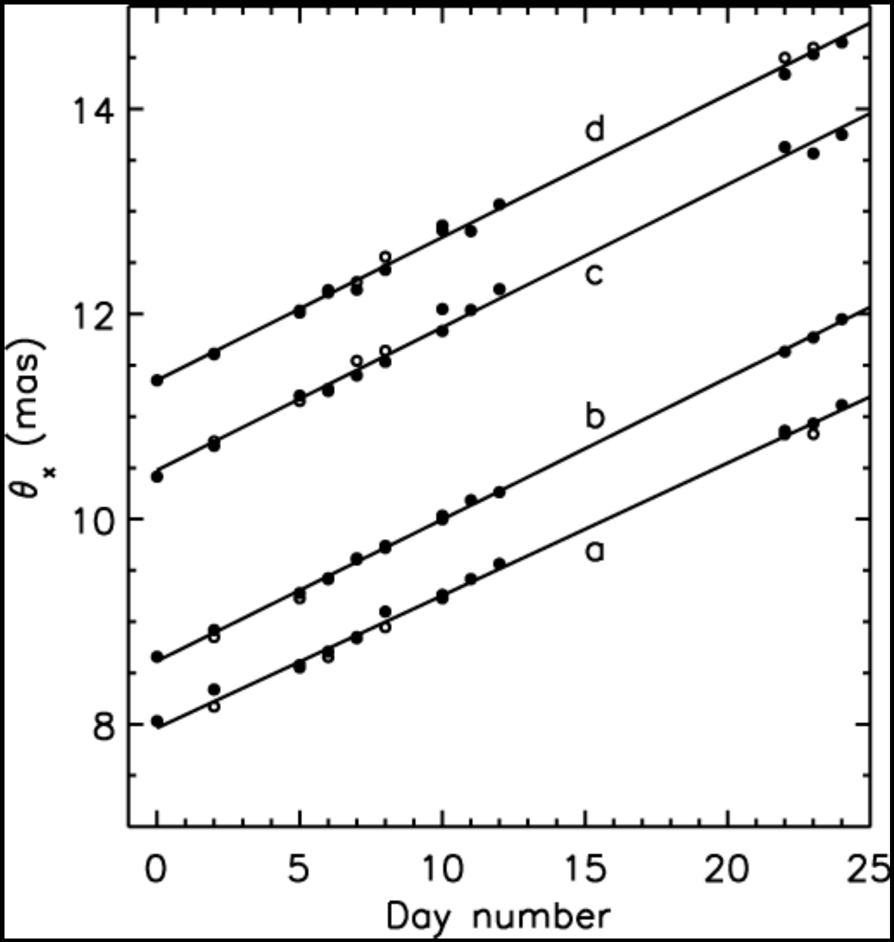
“Deflection of Pulsar Signal Reveals Compact Structures in the Galaxy,” A. S. Hill et al. 2005, 619, L17



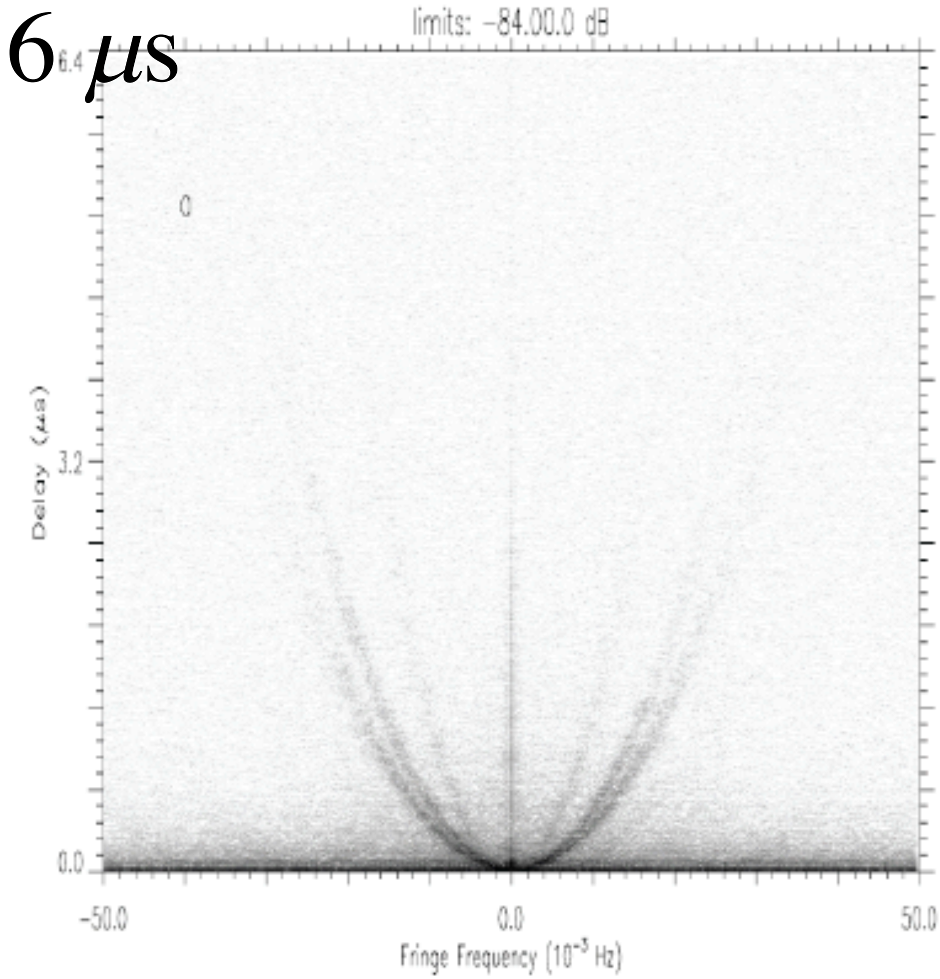


"Deflection of Pulsar Signal Reveals Compact Structures in the Galaxy," A. S. Hill et al. 2005, 619, L17

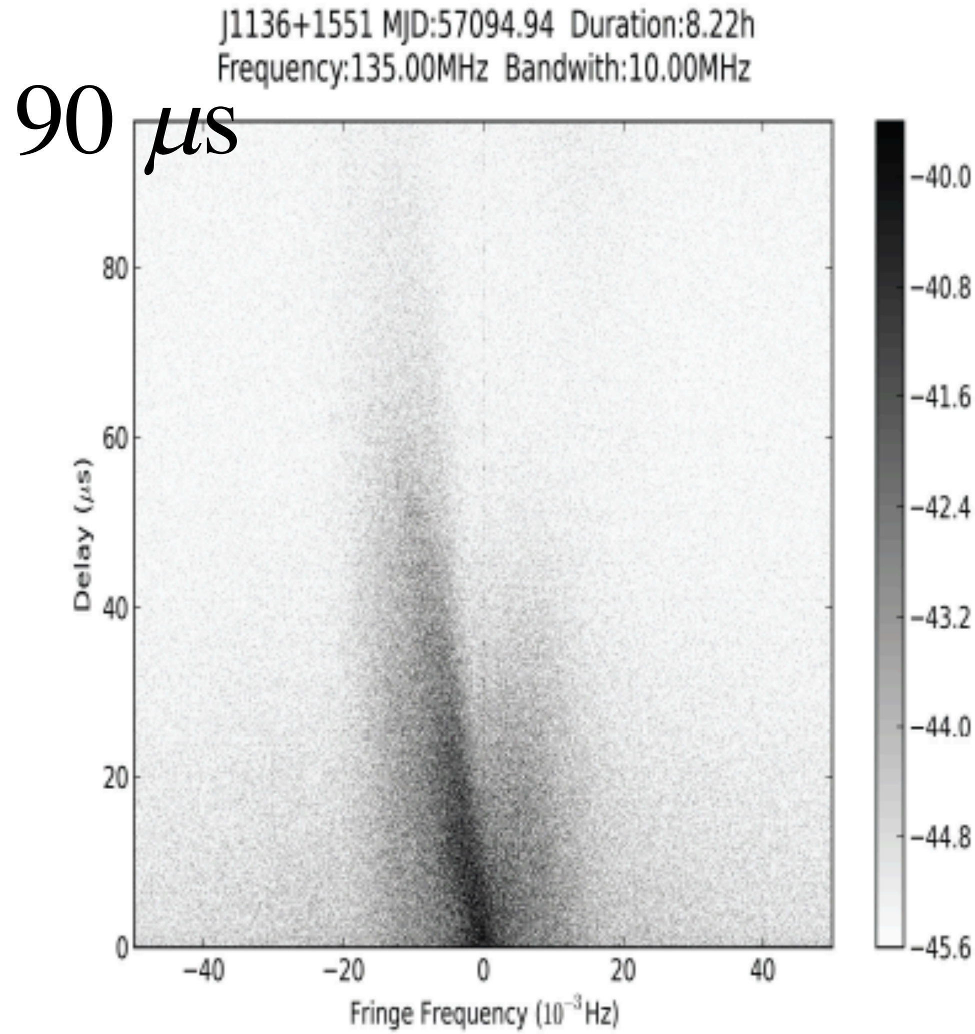




Asymmetry in the Scintillation Arcs of J1136+1551 I



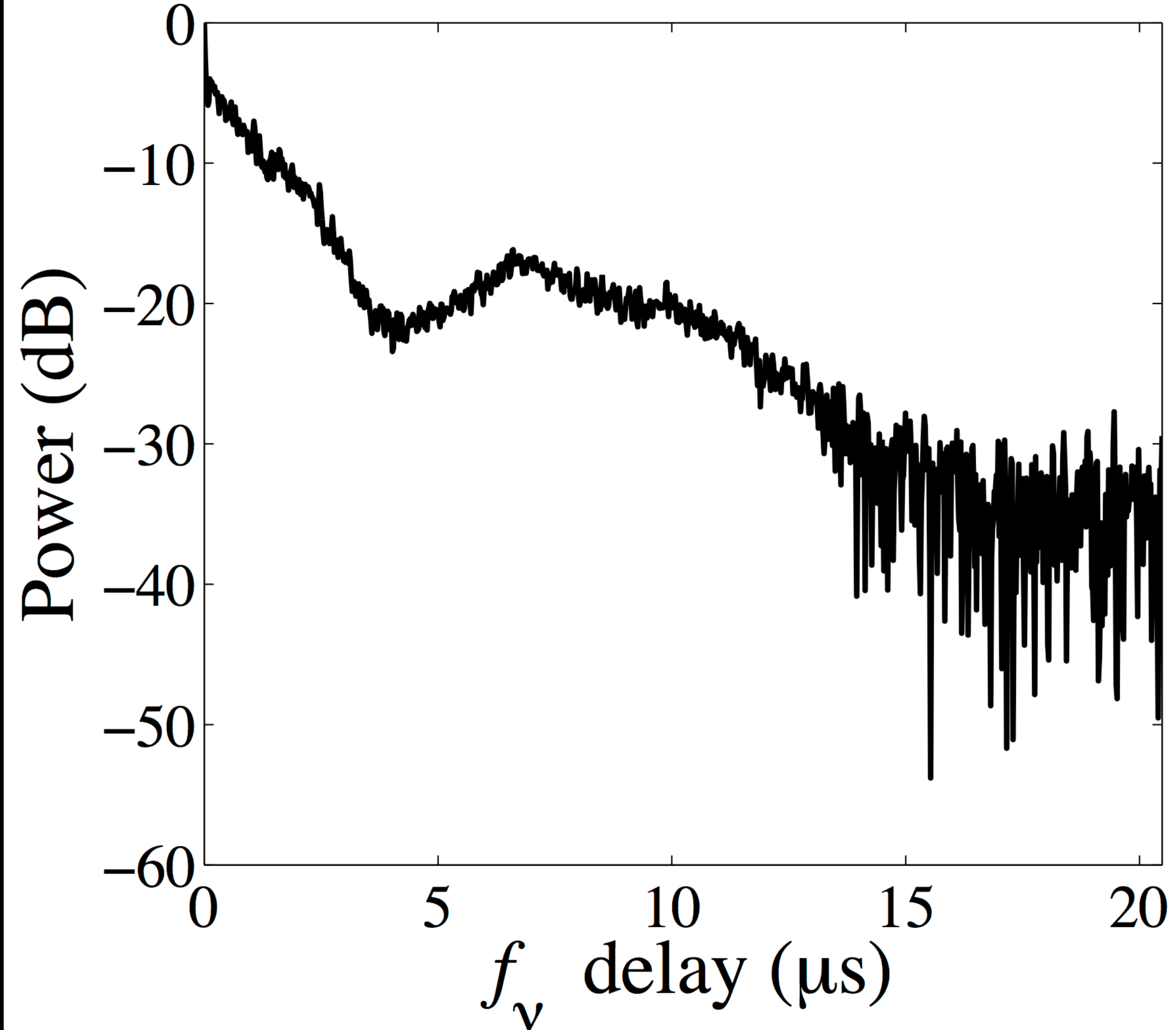
1450 MHz MJD: 57098



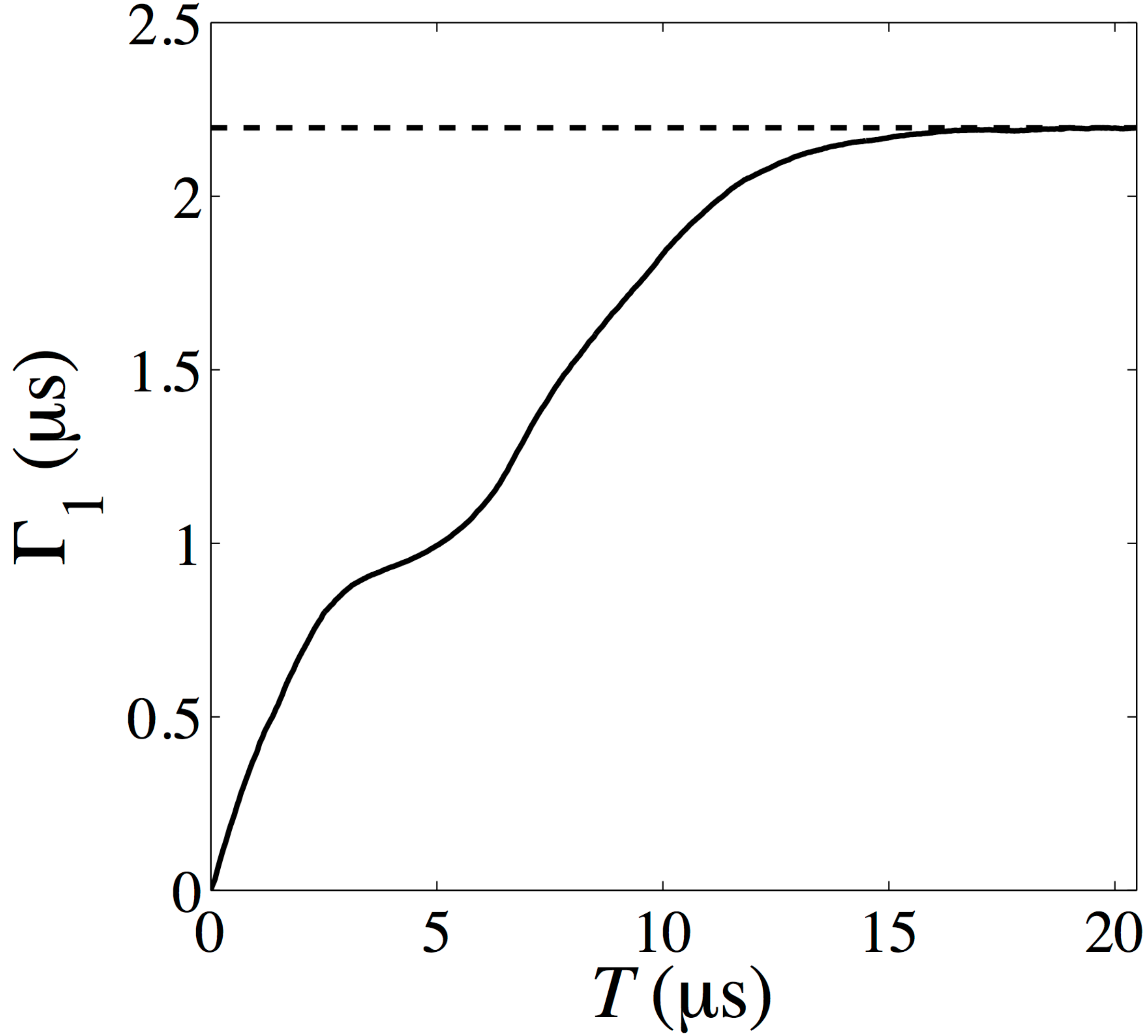
135 MHz MJD: 57095

[redacted]

[redacted]



Hemberger and Stinebring 2008



Hemberger and Stinebring 2008