Kinematics of Crab Giant Pulses

https://arxiv.org/abs/2105.08851

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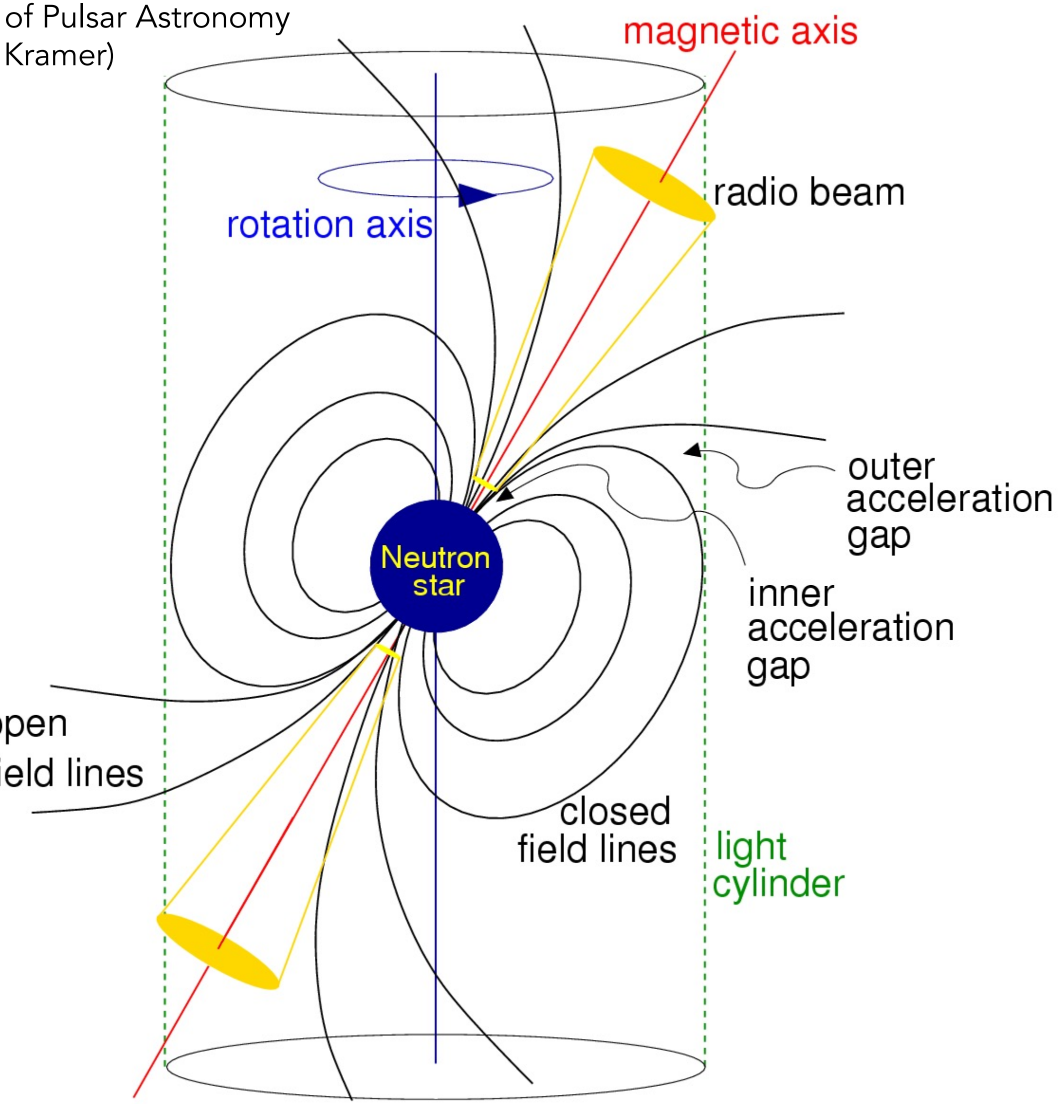
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

Overview

Handbook of Pulsar Astronomy
(Lorimer & Kramer)



First Direct Measurement

Lorentz Factor

$$\gamma \sim 10^4$$

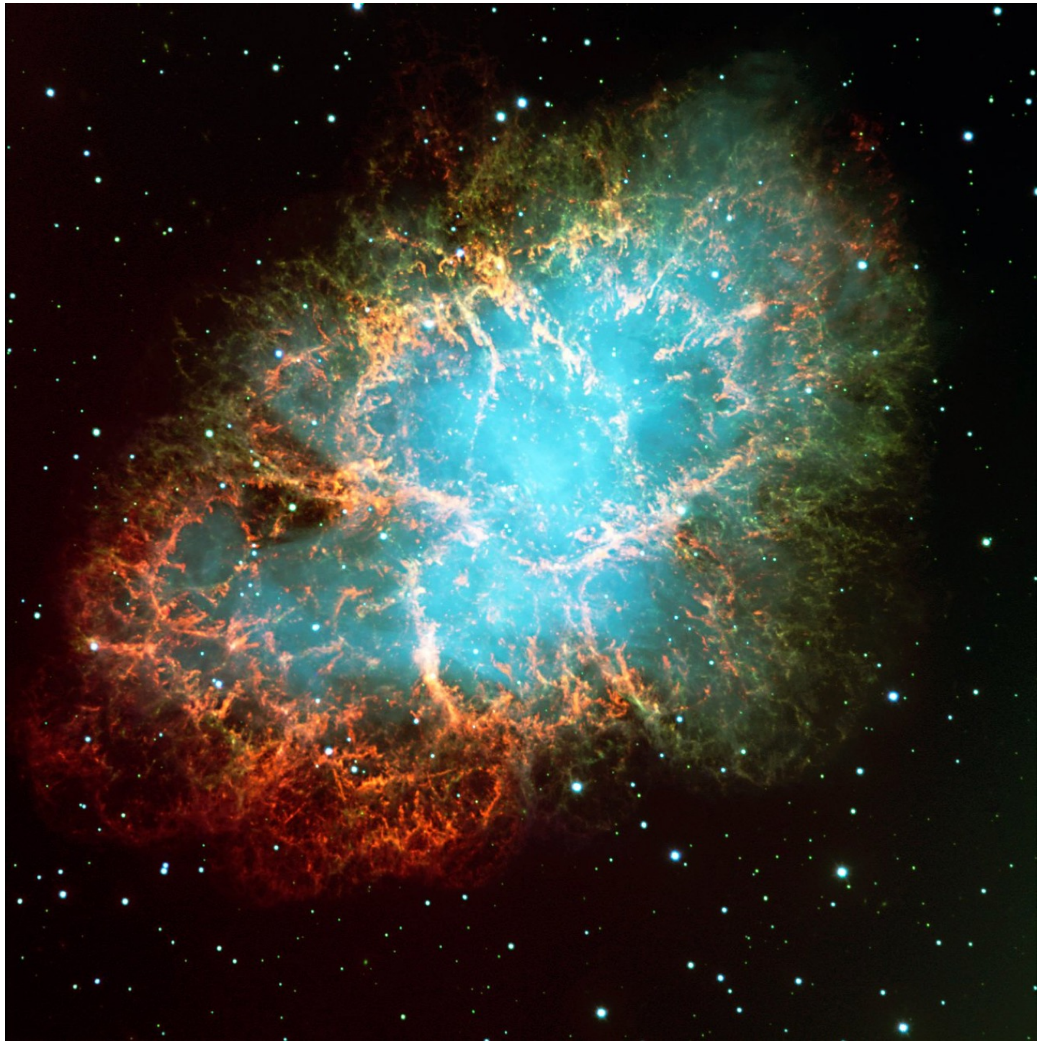
Highly Relativistic motion

Relatively cold plasma

Theoretical Predictions

$$\gamma = 1 - 10^7$$

Introduction: Crab Nebula & Pulsar

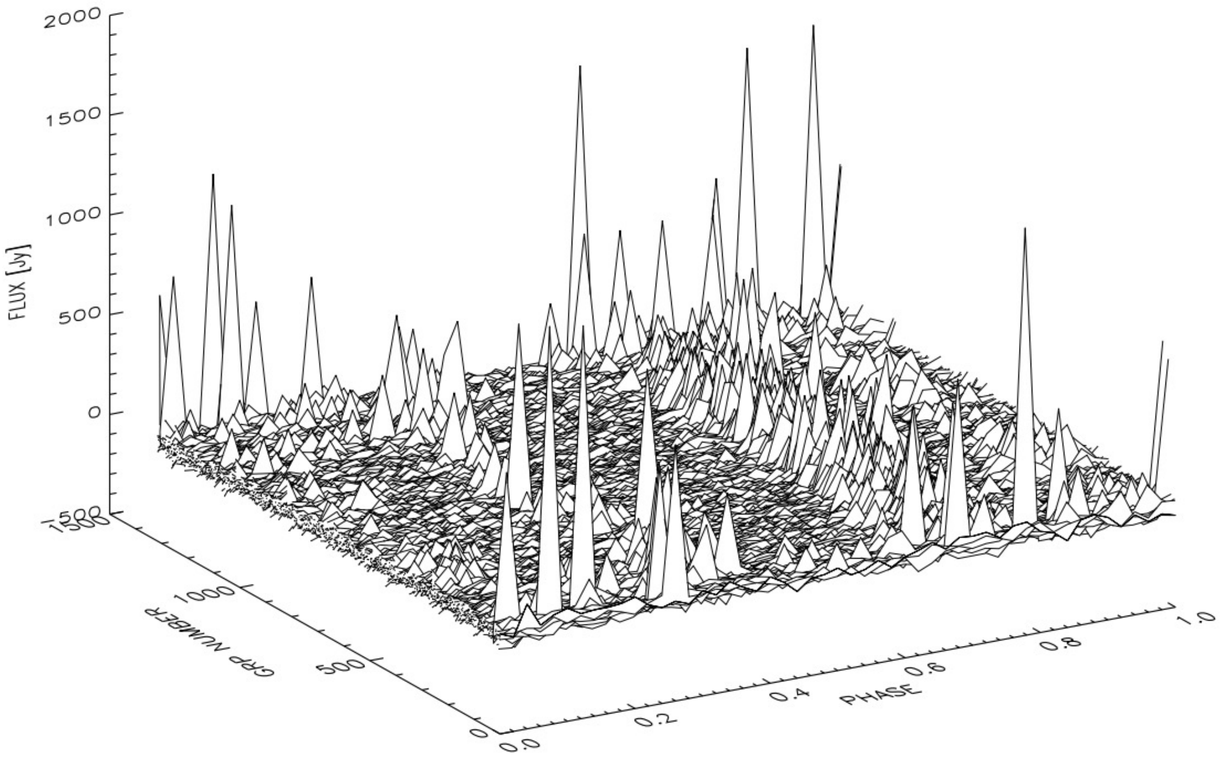


Remnant of SN 1054

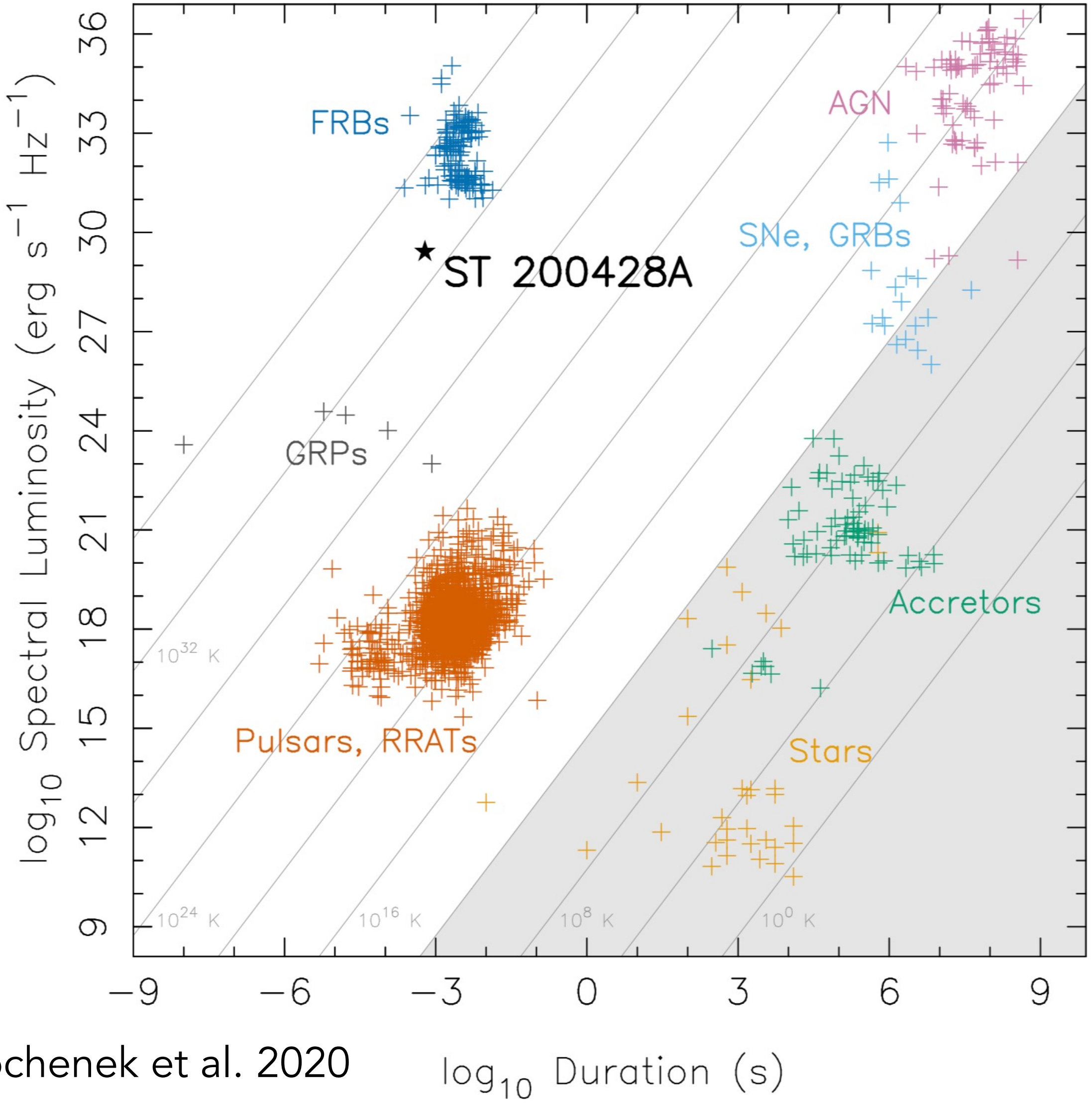
PSR B0531 +21

Giant Radio Pulse Behaviour

Can reach brightness temperatures of 10^{37} K



Jessner et al. 2005



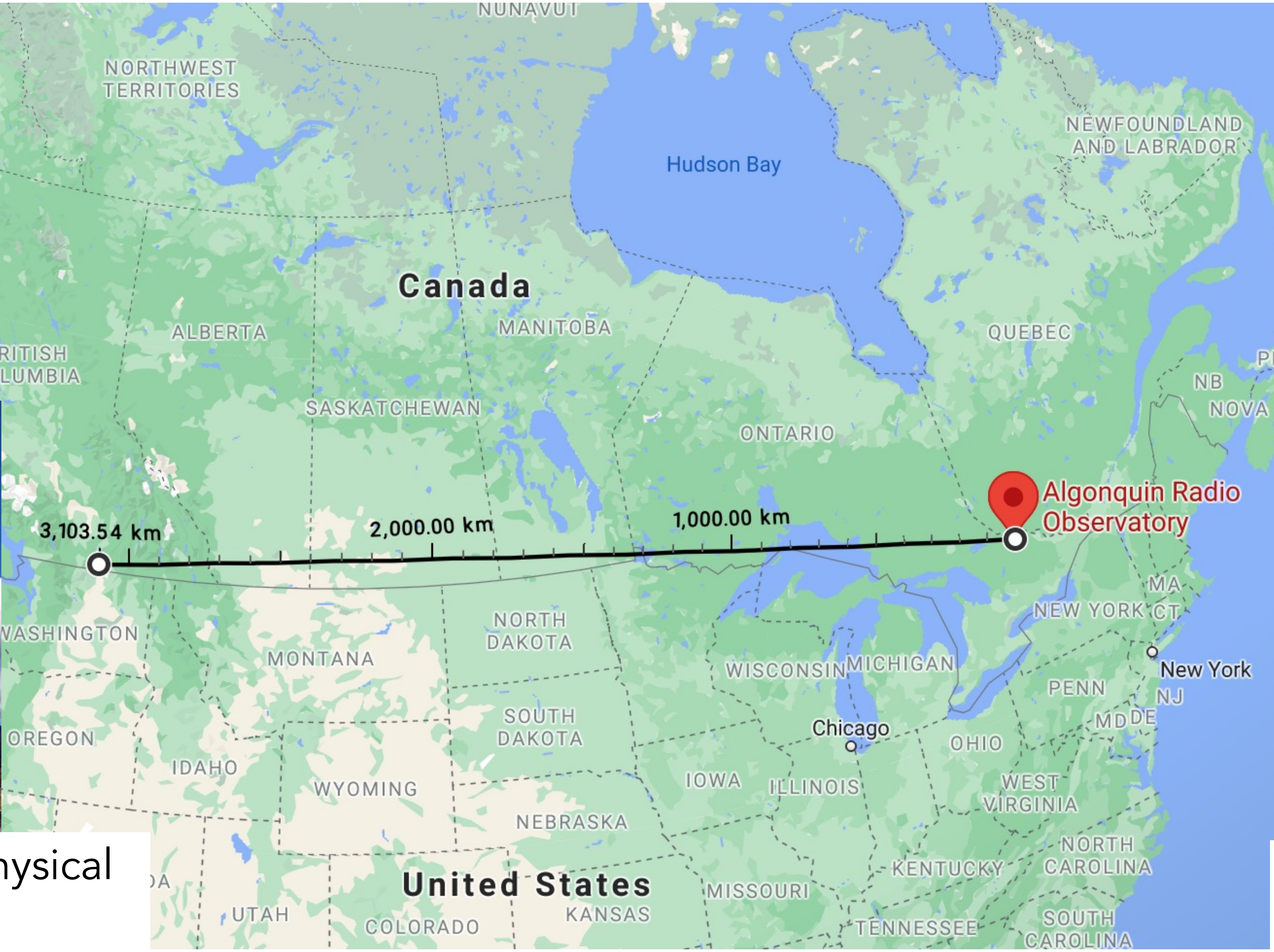
Bochenek et al. 2020

Observations

400-800 MHz (CHIME Band) Baseband

2015
2018

46 m

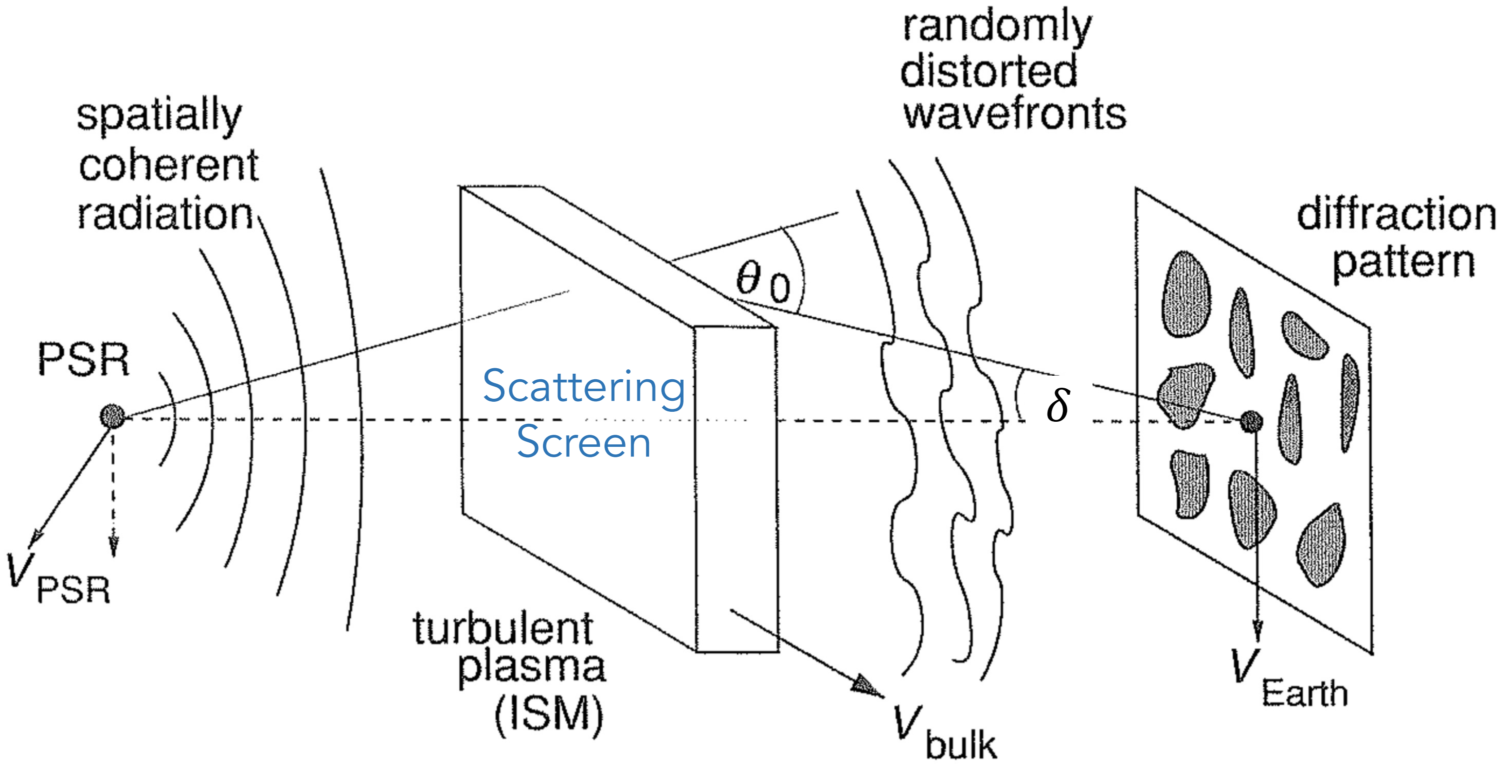


Dominion Radio Astrophysical Observatory (DRAO)

Algonquin Radio Observatory (ARO)

Interstellar Scattering

Variations in electron density n_e of size a



Handbook of Pulsar Astronomy
(Lorimer & Kramer)

Phase shift

$$\delta\Phi = \Delta k\ a$$

$$k = (2\pi/c)\ \mu\ f$$

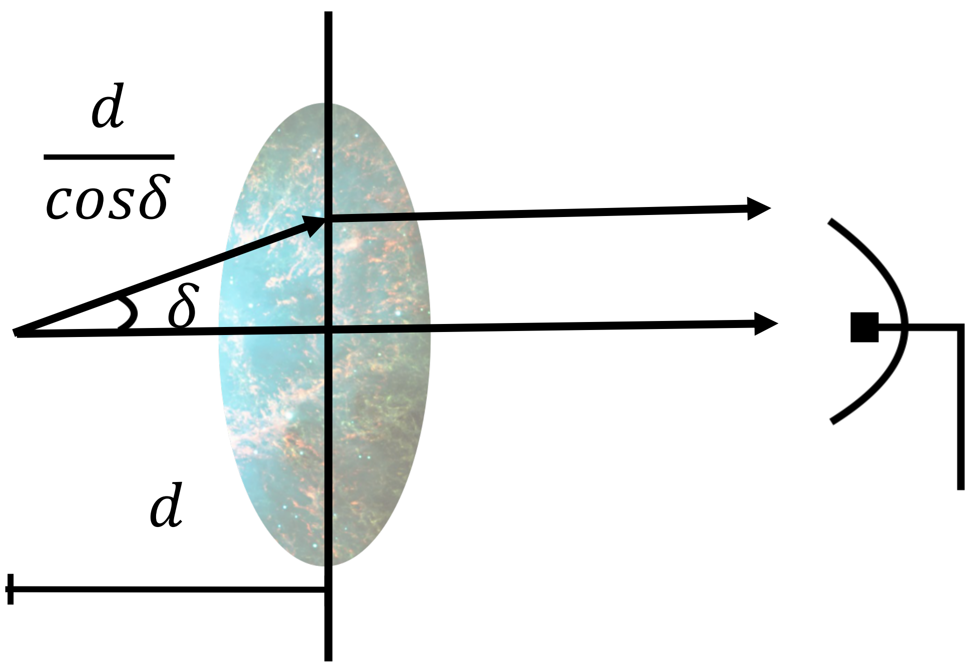
Model as bending by screen

$$\theta_0 \approx \frac{\Delta\Phi/k}{a} \propto f^{-2}$$

Frequency dependent

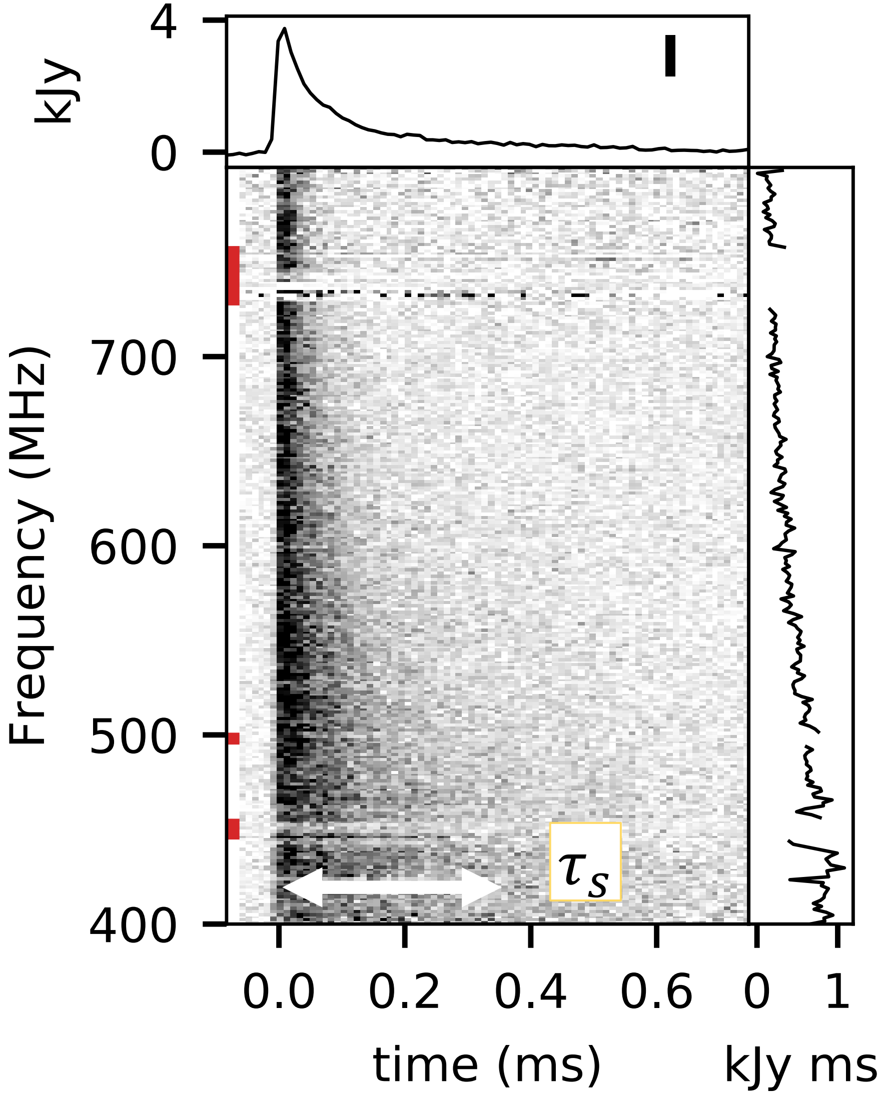
Scattering in Observations

Crab Nebula



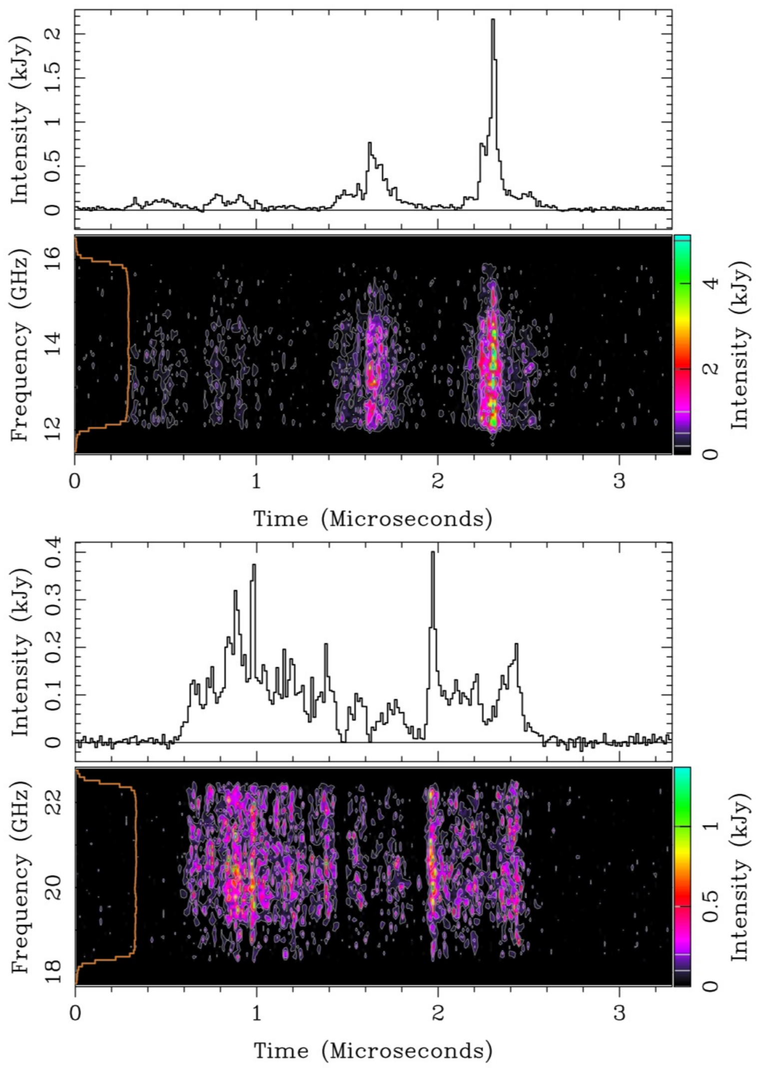
$$c\tau_s = \frac{d}{cos\delta} - d \qquad \tau_s \approx \frac{\delta^2 d}{2c}$$

$$\delta \propto f^{-2} \qquad \tau_s \propto f^{-4}$$



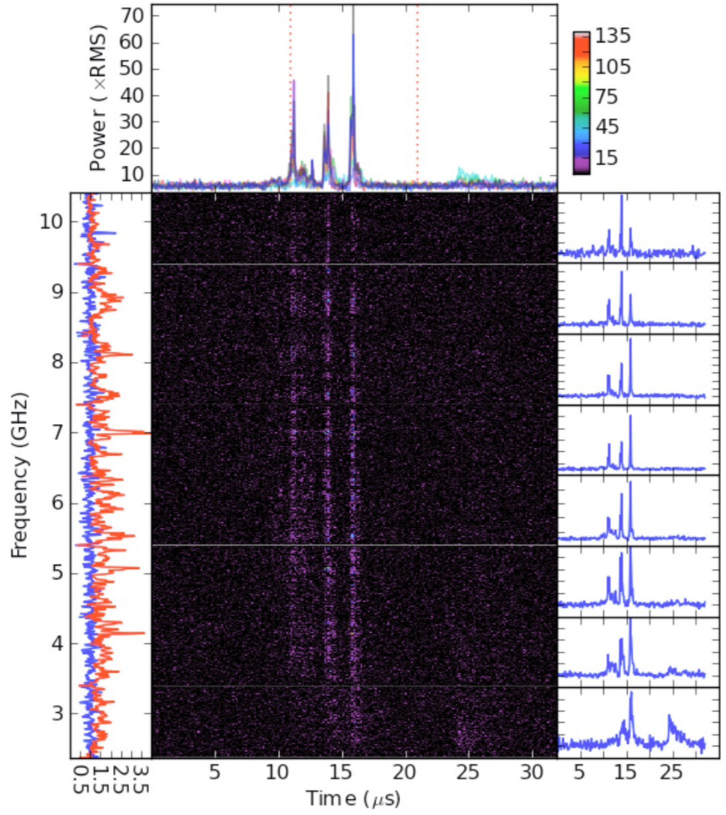
Crab Giant Pulses at High frequencies

"nanoshot" emission

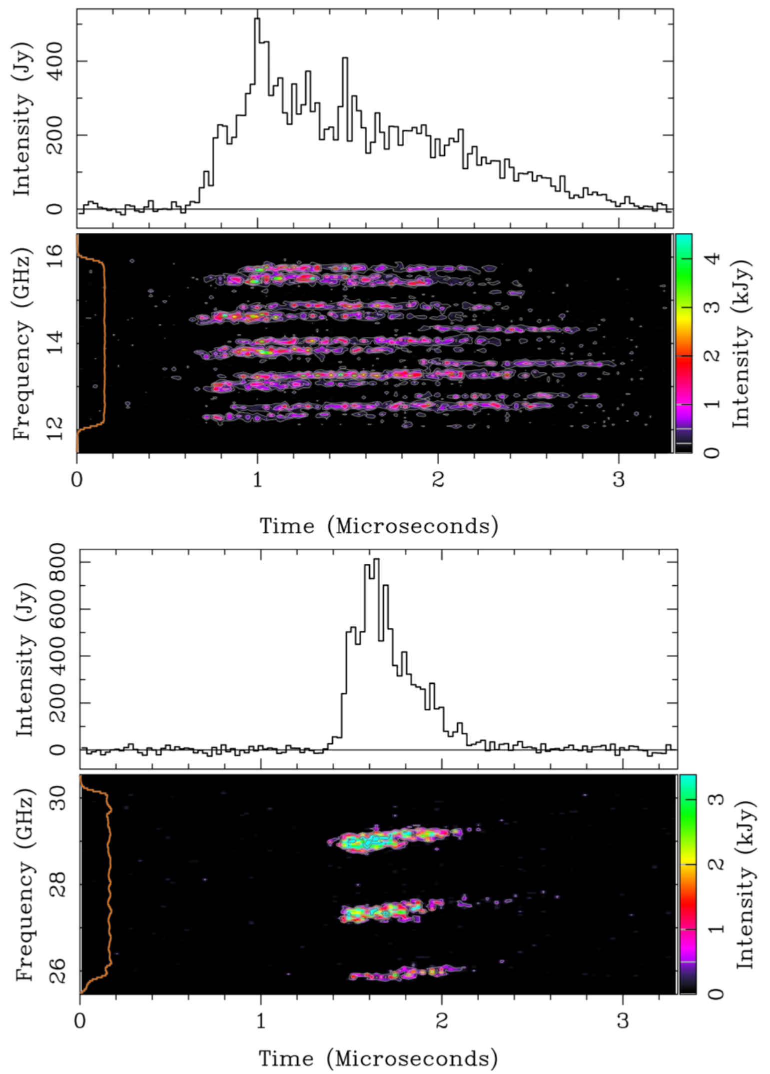


Hankins et. al 2016

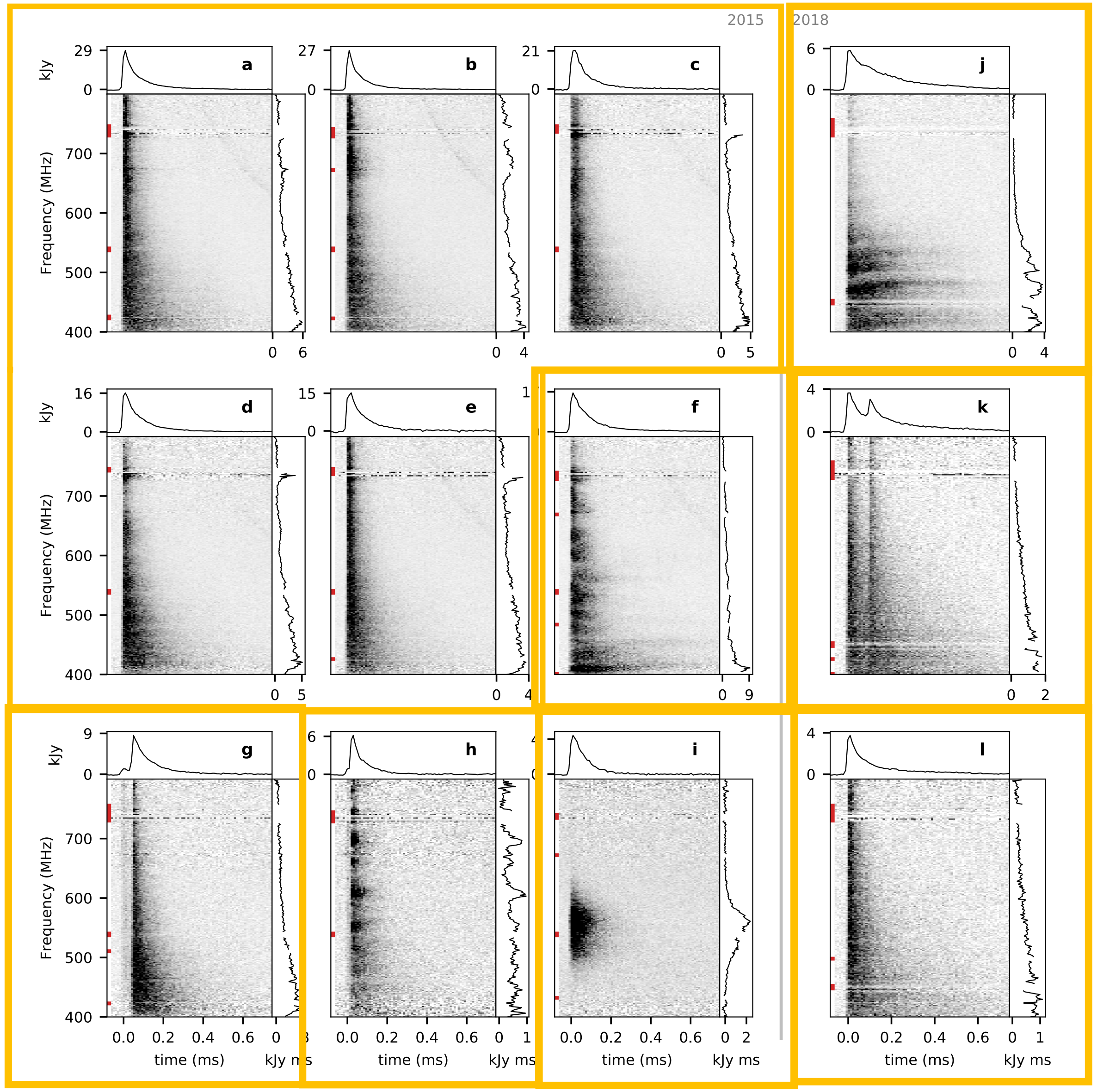
1-43 GHz



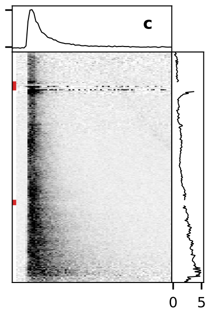
"spectral band" emission



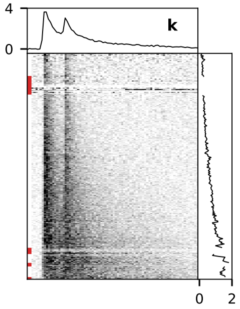
Pulse Gallery and Categorization



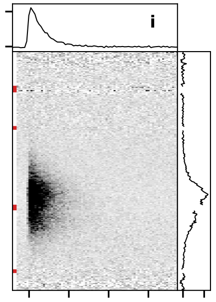
Regular



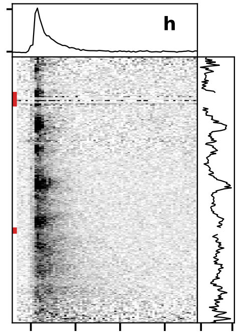
Double-Peak



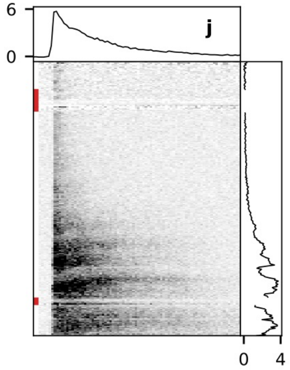
Partial



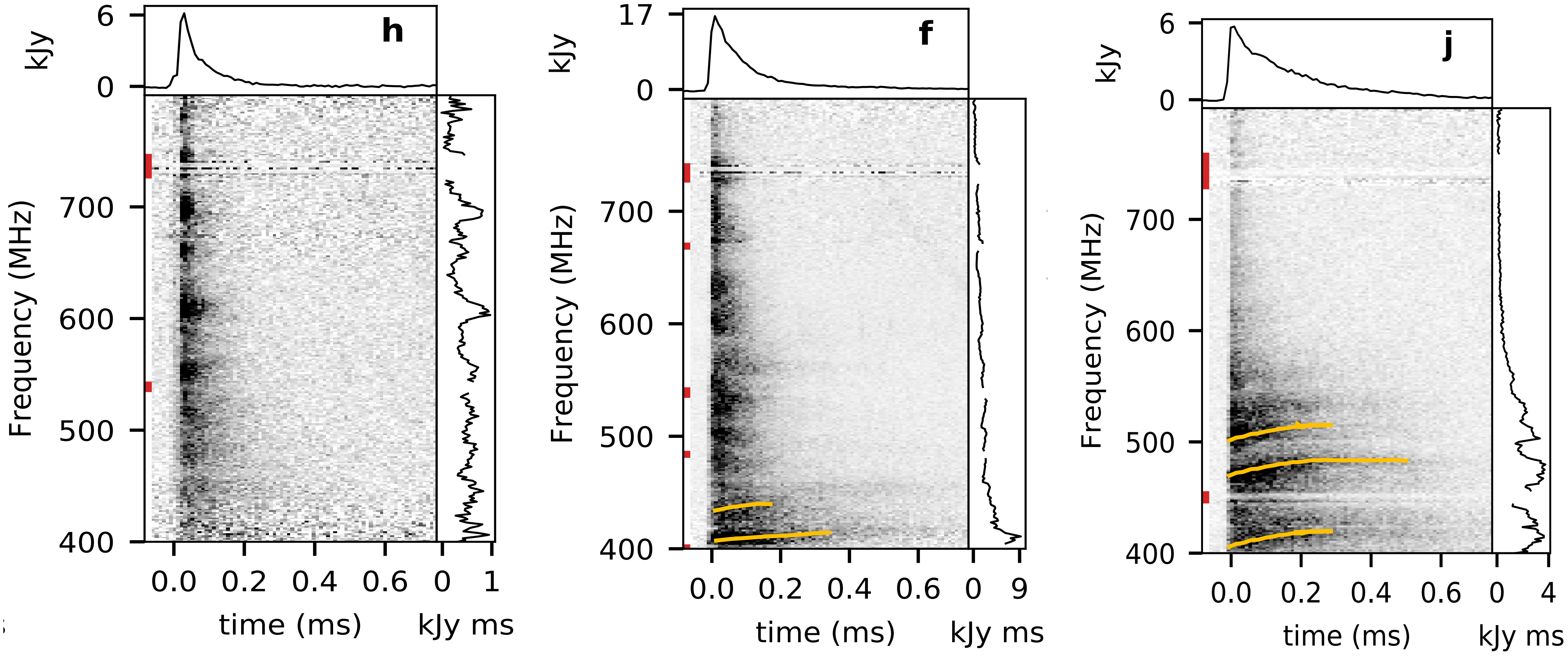
Banded



Drifting

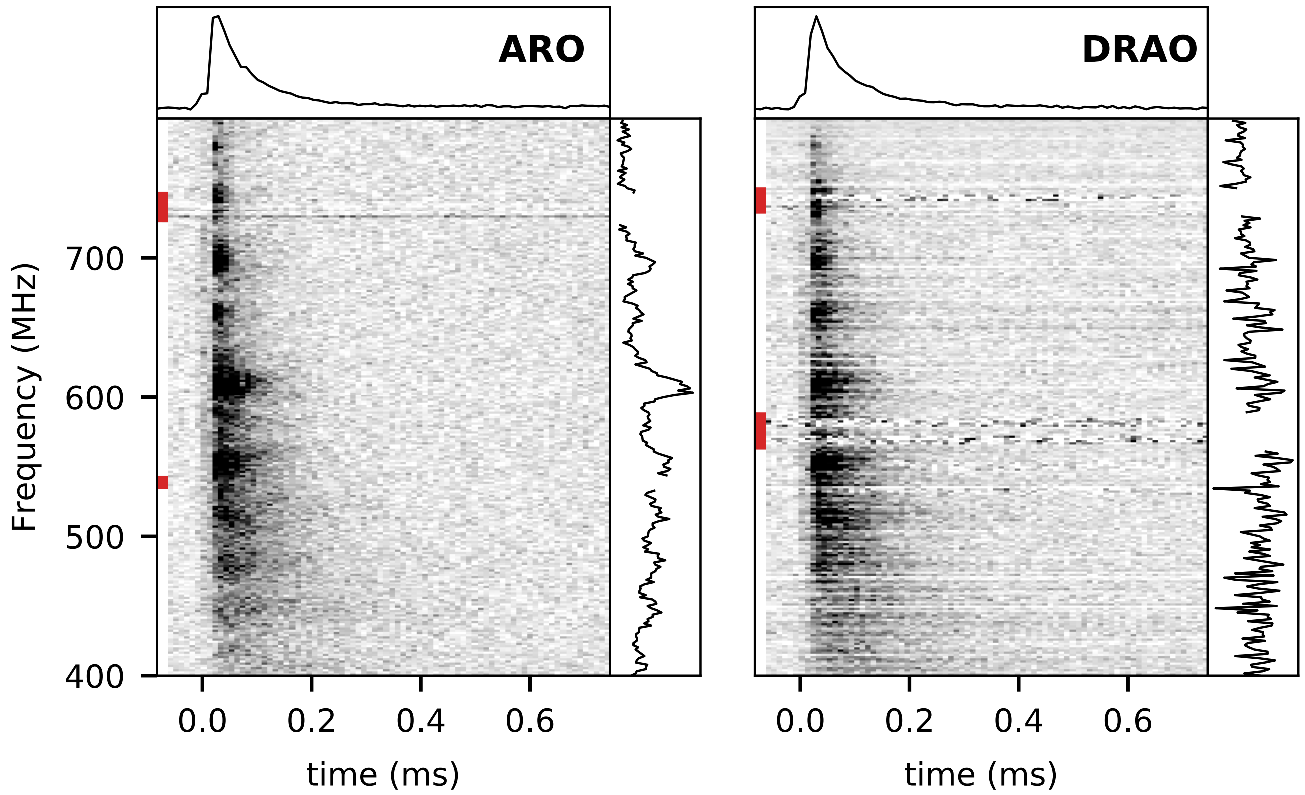


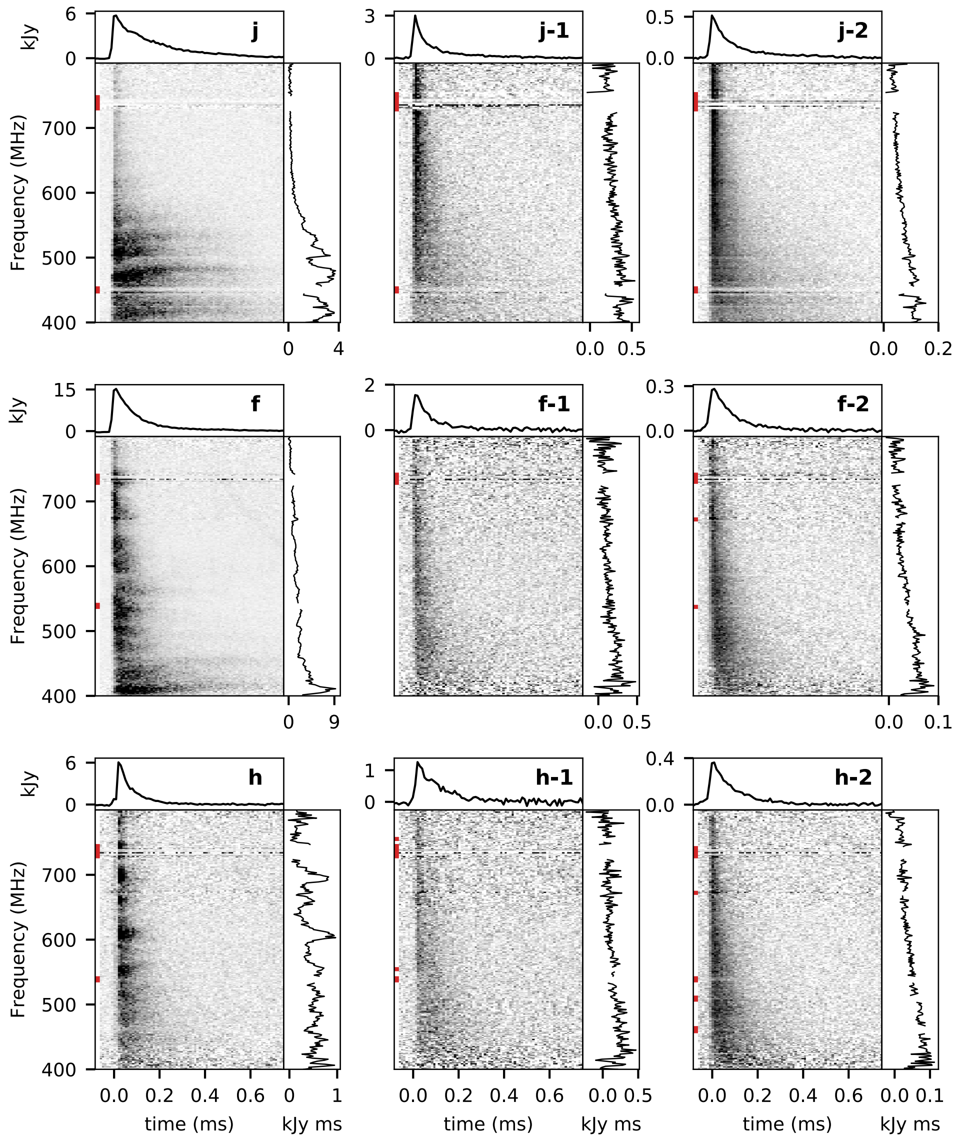
Observed shifts in frequency



Ruling out other interpretations

Instrumentation effect?

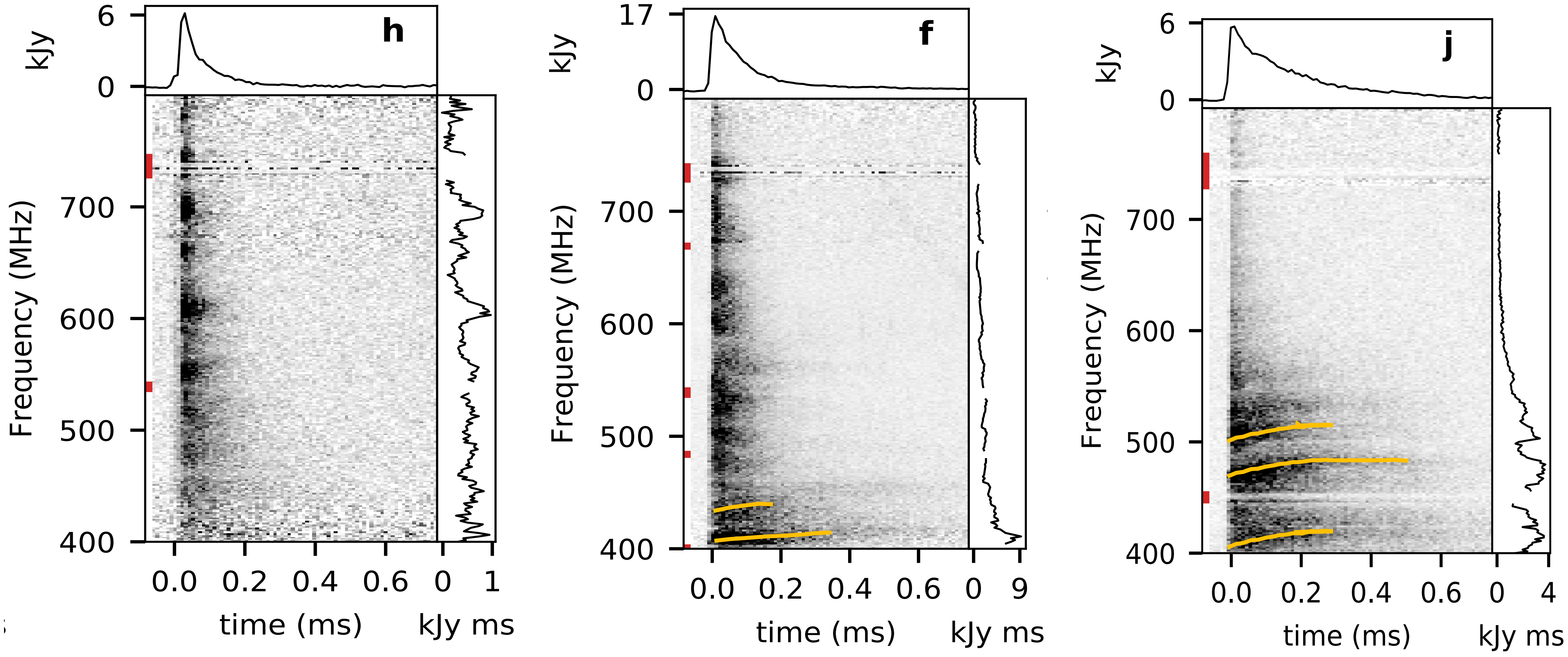




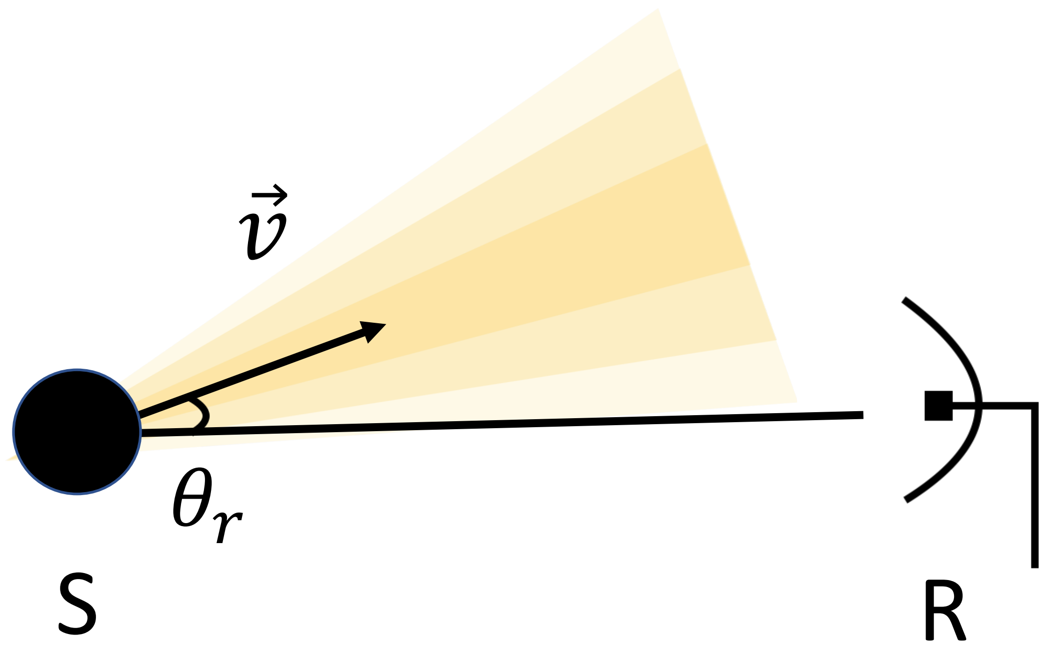
Scattering Environment?

Scintillation?

Observed shifts in frequency



Proposed Model – Doppler Shift



Doppler Shift

$$D = \frac{f_r}{f_s} = \frac{1}{\gamma(1 - \beta cos\theta_r)}$$

$$\beta = v/c$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Relativistic Beaming

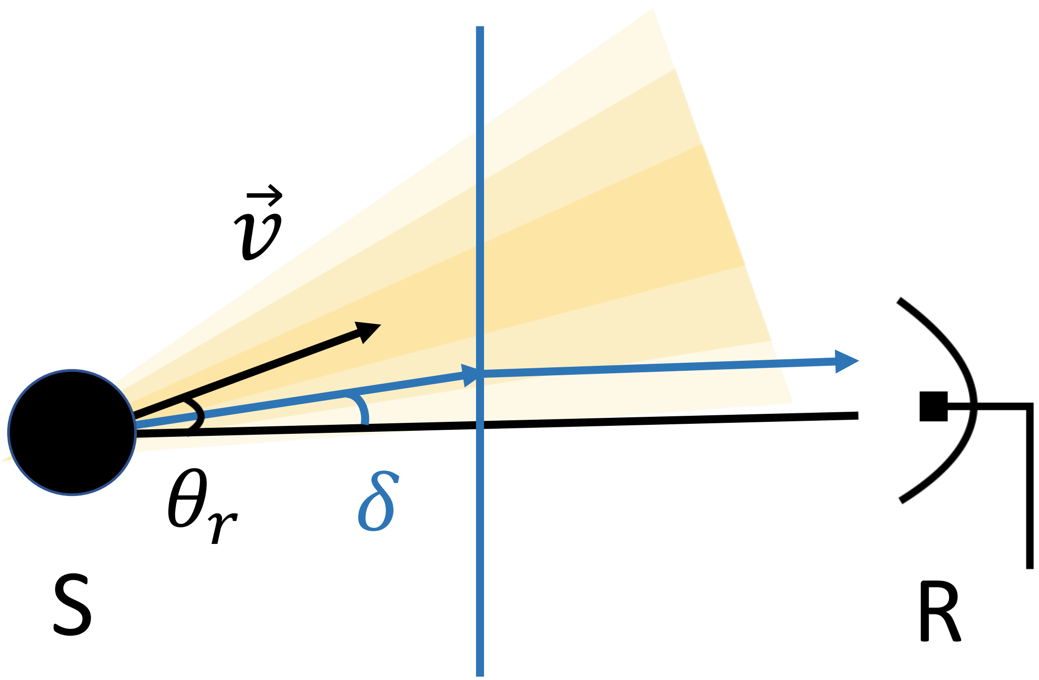
$$L_r = D^3 L_s$$

Small Angle Approximation

$$\gamma \gg 1$$

$$D = \frac{f_r}{f_s} \approx \frac{2\gamma}{1 + \gamma^2 {\theta_r}^2}$$

Proposed Model – Doppler Shift + Scattering



$$D = \frac{f_r}{f_s} \approx \frac{2\gamma}{1 + \gamma^2 {\theta_r}^2}$$

Scattering from Crab Nebula

$$\frac{\Delta f_r}{f_r} = \frac{\Delta D}{D} = \frac{-\gamma^2(2\theta_r\delta + \delta^2)}{1 + \gamma^2(\theta_r + \delta)^2}$$

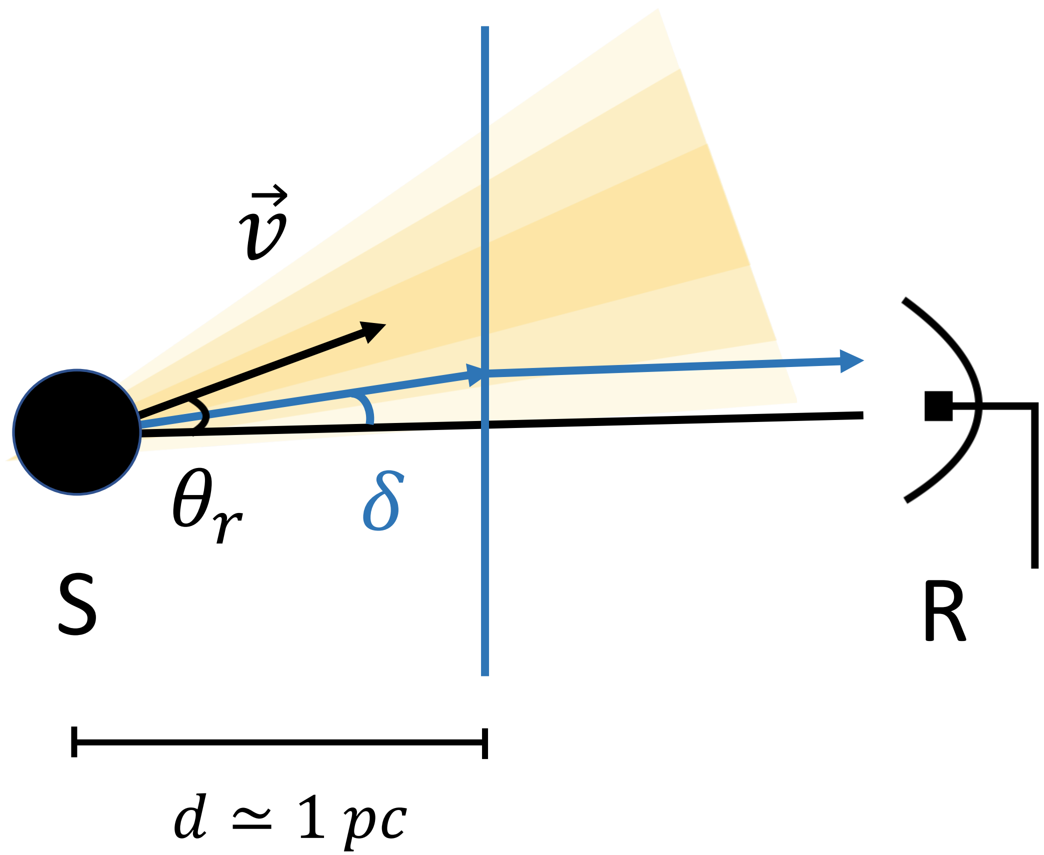
Center of beam

$\theta_r \simeq 0$ $\quad\quad$ $\Delta f_r / f_r \approx -\gamma^2\delta^2$

Edge of beam

$\theta_r \simeq 1/\gamma$ $\quad\quad$ $\Delta f_r / f_r \approx \gamma\delta$

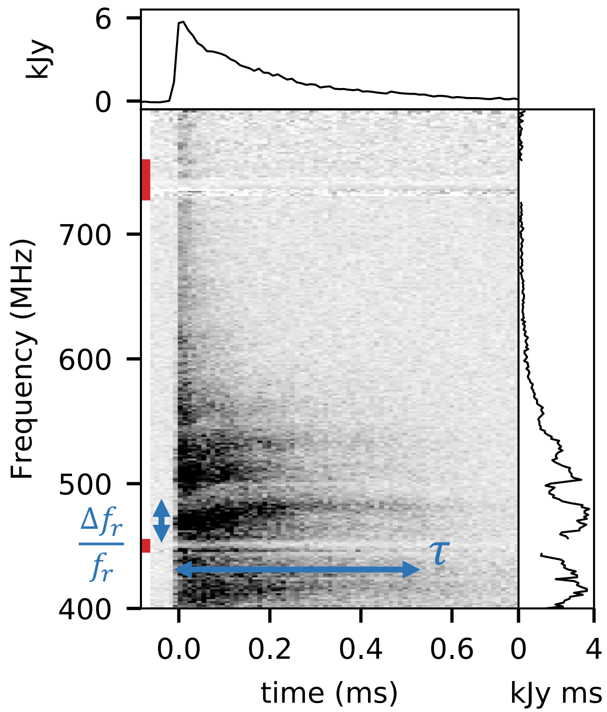
Proposed Model – Estimating Lorentz Factor



(Lawrence et al. 1995, Martin et al. 2021)

$$\frac{\Delta D}{D} = \frac{\Delta f_r}{f_r} \approx \gamma\delta$$

$$c\tau = \frac{d}{\cos\delta} - d \simeq \frac{d}{2}\delta^2$$



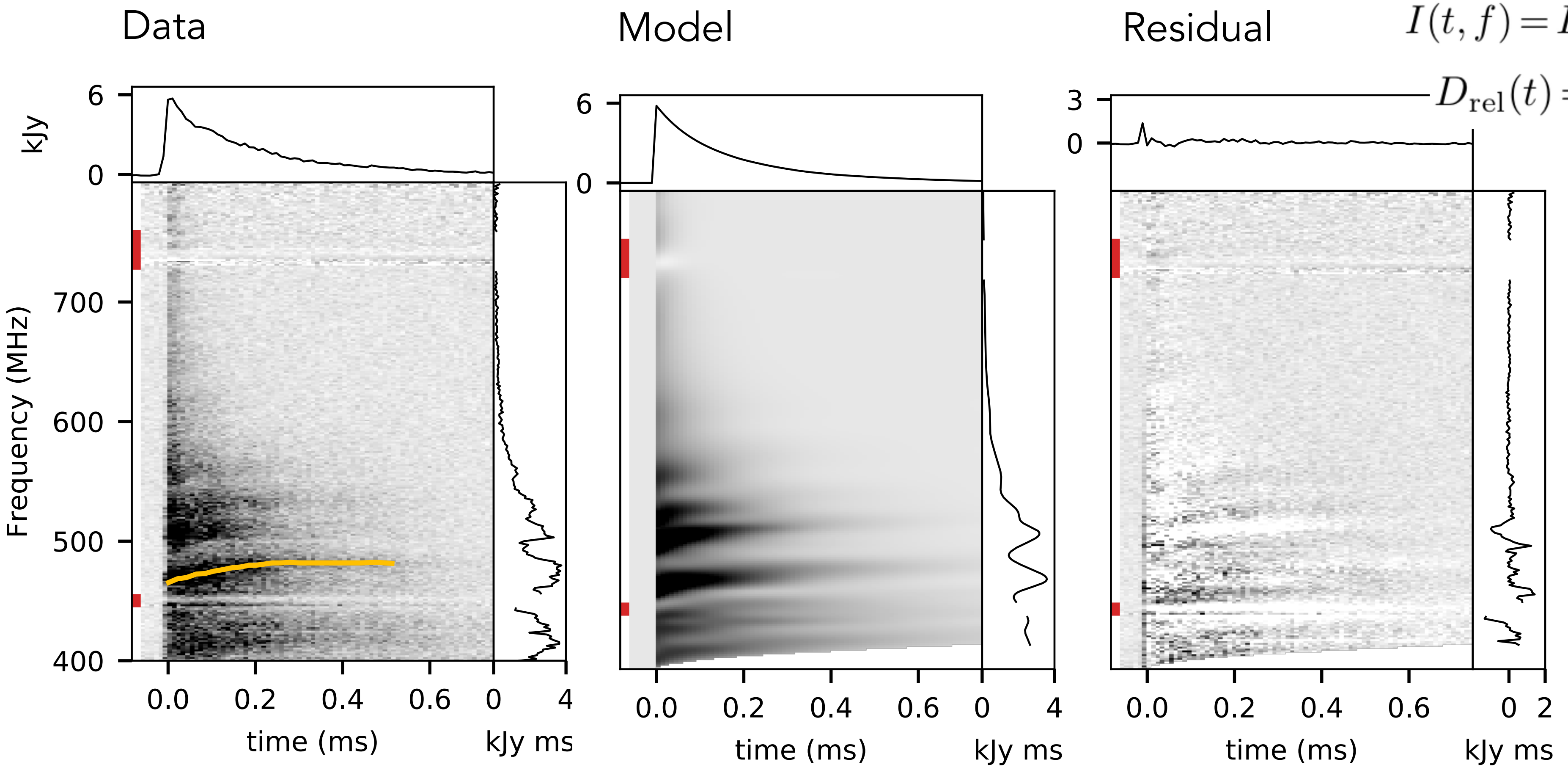
$\tau \simeq 0.5\,ms$

$\delta \simeq 0.6''$

$\frac{\Delta f_r}{f_r} \simeq 0.04$

$\gamma \simeq 10^4$

Does the model match the data?



$$I(t,f) = I(0, f/D_{\rm rel}(t))\ D^3_{\rm rel}(t)\ {\rm e}^{-t/\tau(f)}$$

$$D_{\rm rel}(t) = D(t)/D(0) = 1 + a\sqrt{t/\tau_{\rm ref}}$$

$$\tau(f) = \tau_{\rm ref}(f/f_{\rm ref})^{-4}$$

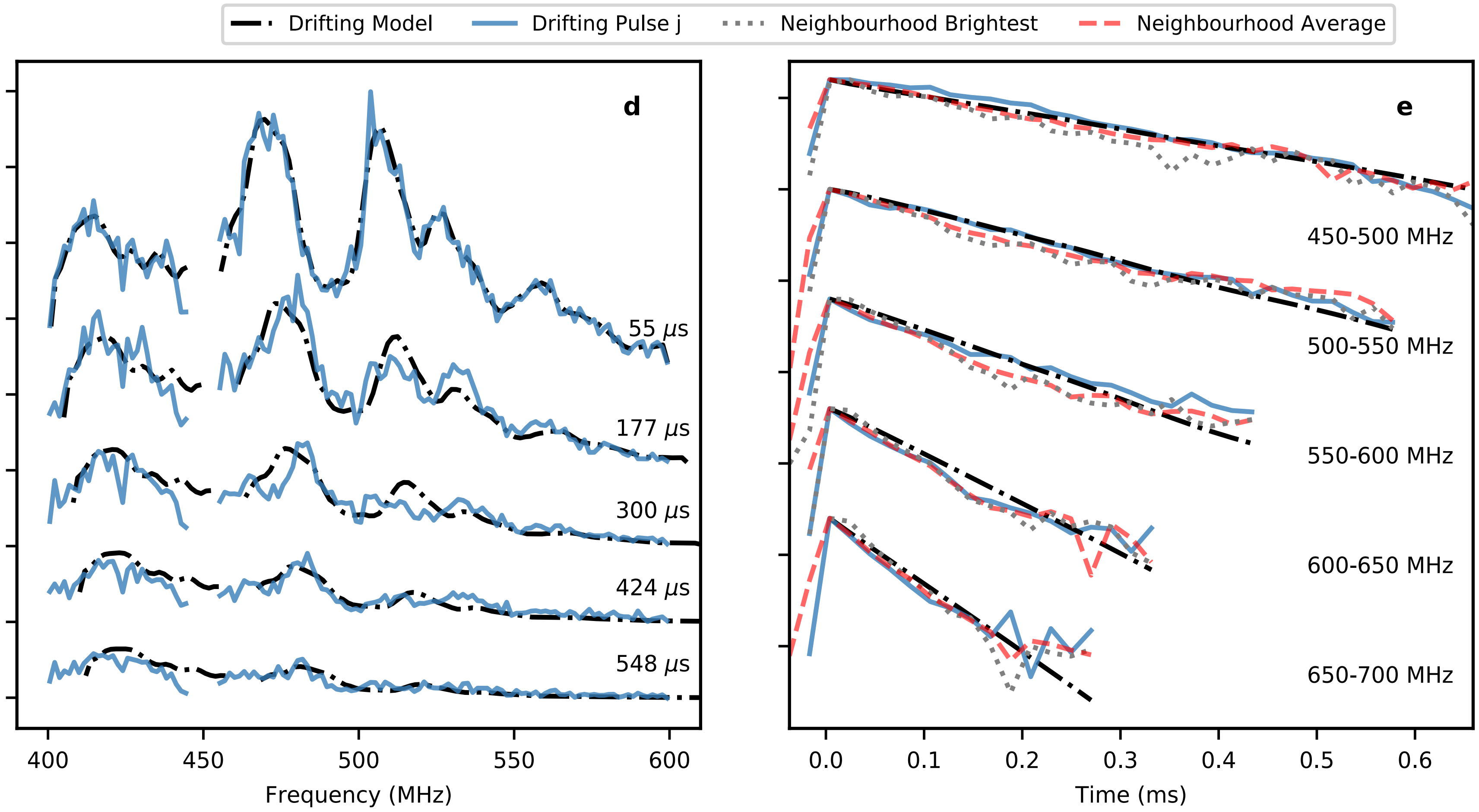
$$a \simeq 0.028$$

$$\frac{\Delta f_r}{f_r} \approx \gamma\delta \qquad \delta \propto \sqrt{t}$$

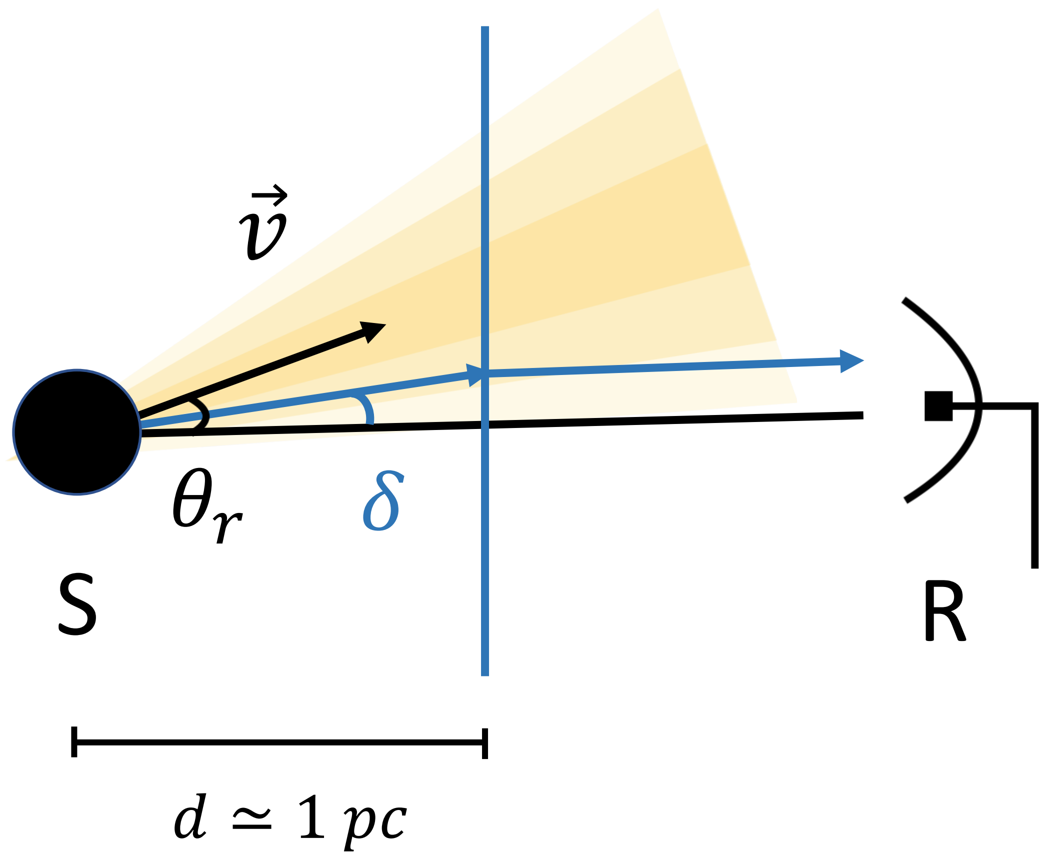
$$\frac{\Delta f_r}{f_r} \propto \sqrt{t}$$

Does the model match the data?

$$I(t,f) = I(0, f/D_{\rm rel}(t))\ D^3_{\rm rel}(t)\ {\rm e}^{-t/\tau(f)}$$

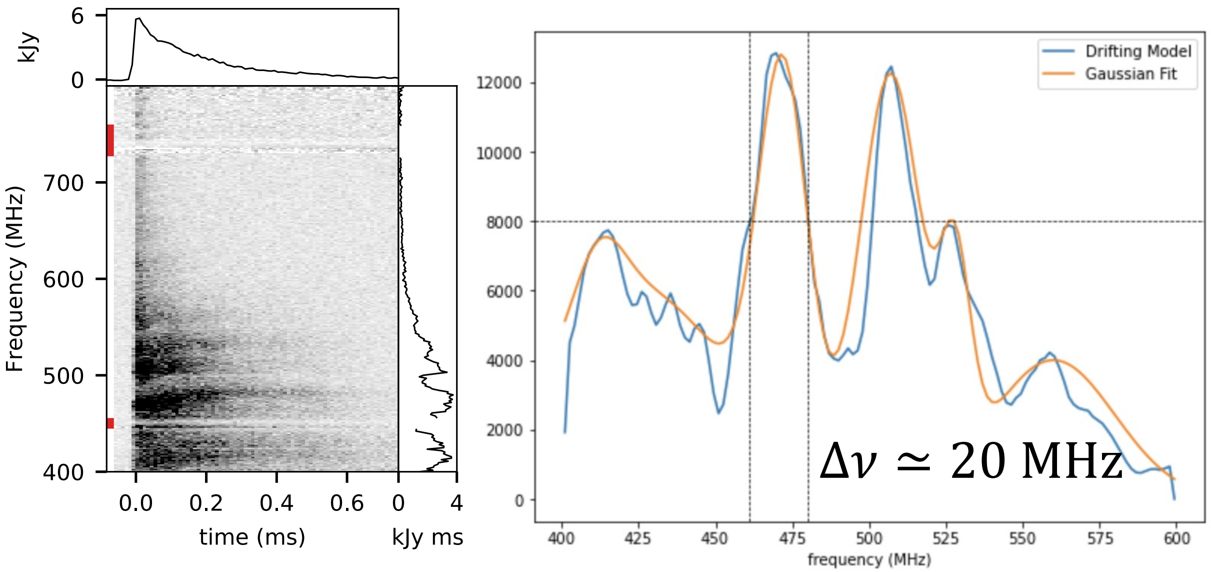


Proposed Model – Range in Lorentz Factor



$$\frac{\Delta D}{D} = \frac{\Delta f_r}{f_r} \approx \gamma\delta$$

$$\gamma \simeq 10^4$$



$$\Delta\gamma/\gamma \lesssim \Delta\nu/\nu \simeq 4\%$$

Relatively cold plasma

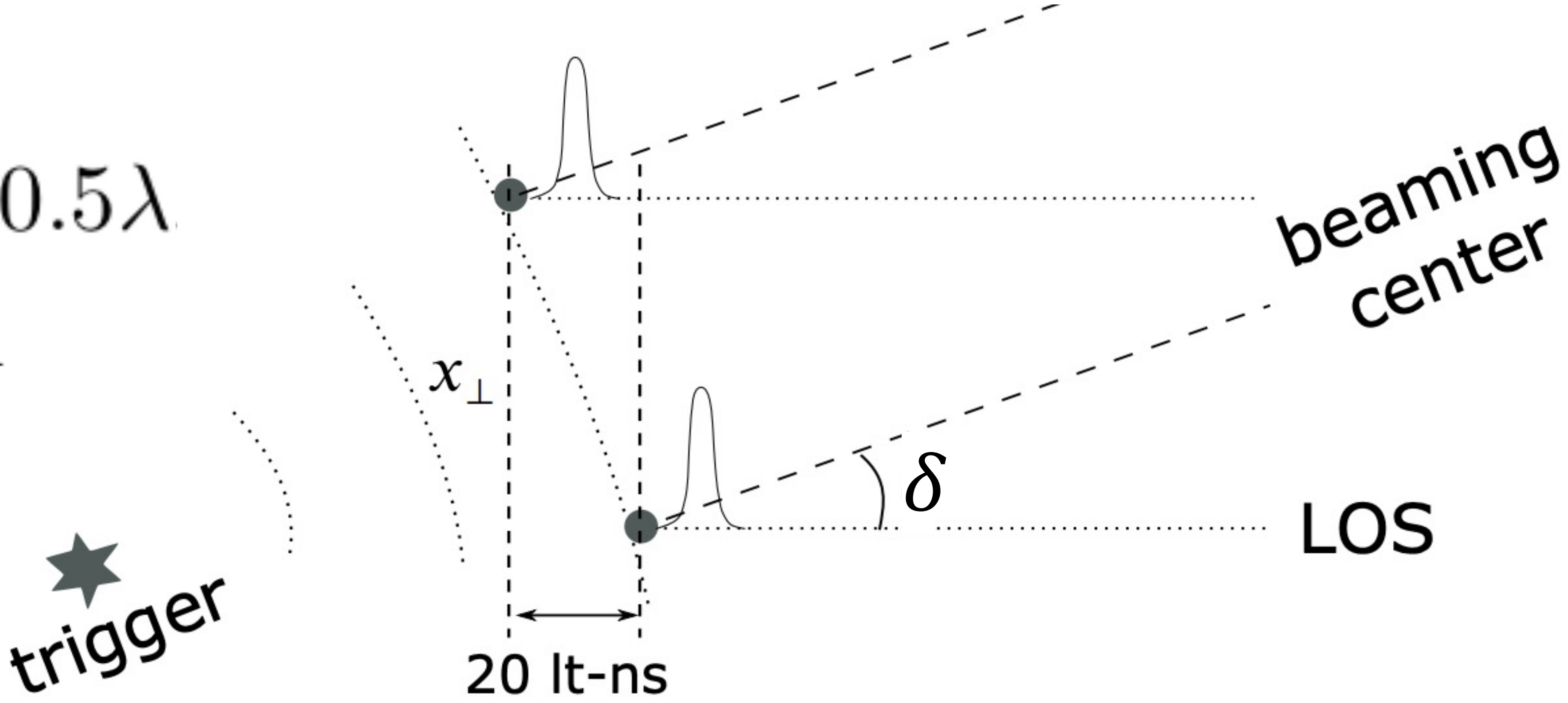
Alternative Interpretations

Interference between multiple nanoshots

$$x_\perp \delta \simeq 0.5\lambda$$

$$\lambda \simeq 0.5\,\mathrm{m}$$

$$\delta \simeq 0.6''$$

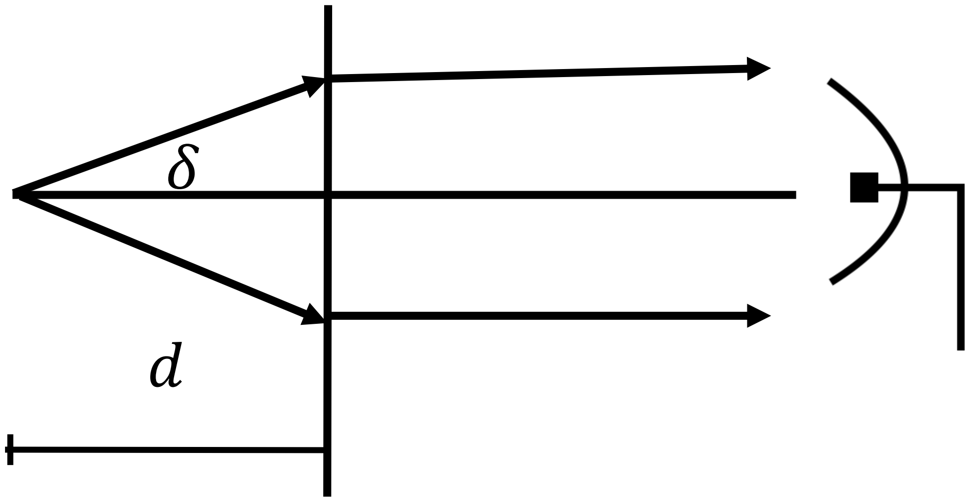


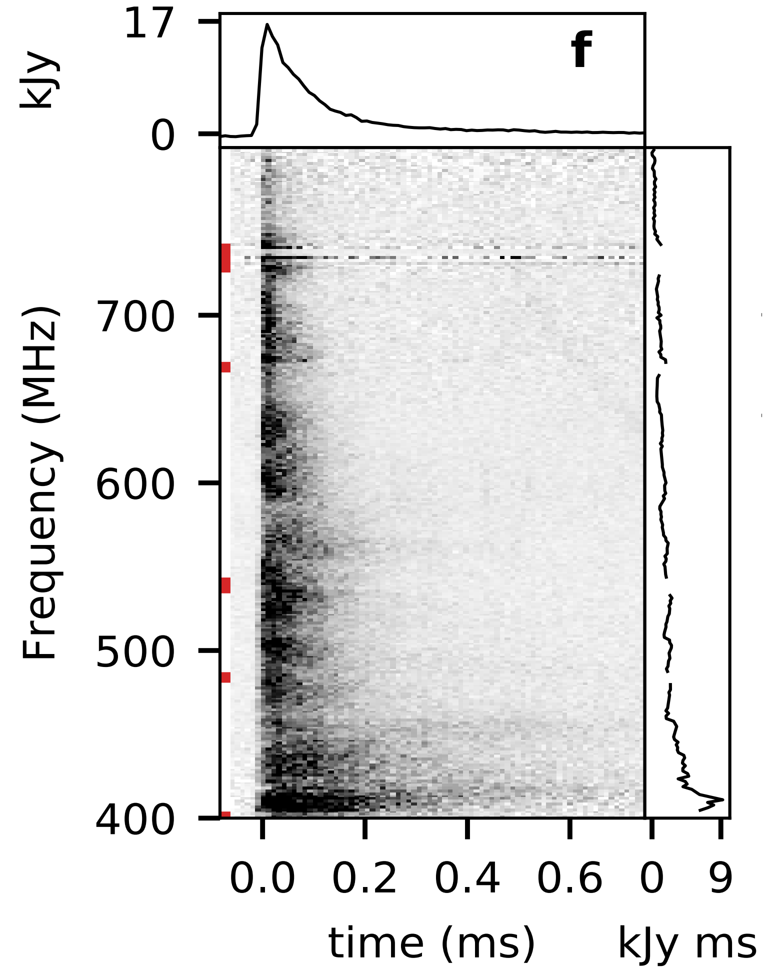
$x_\perp \sim 100\mathrm{km}$

Figure Credit: Wenbin Lu

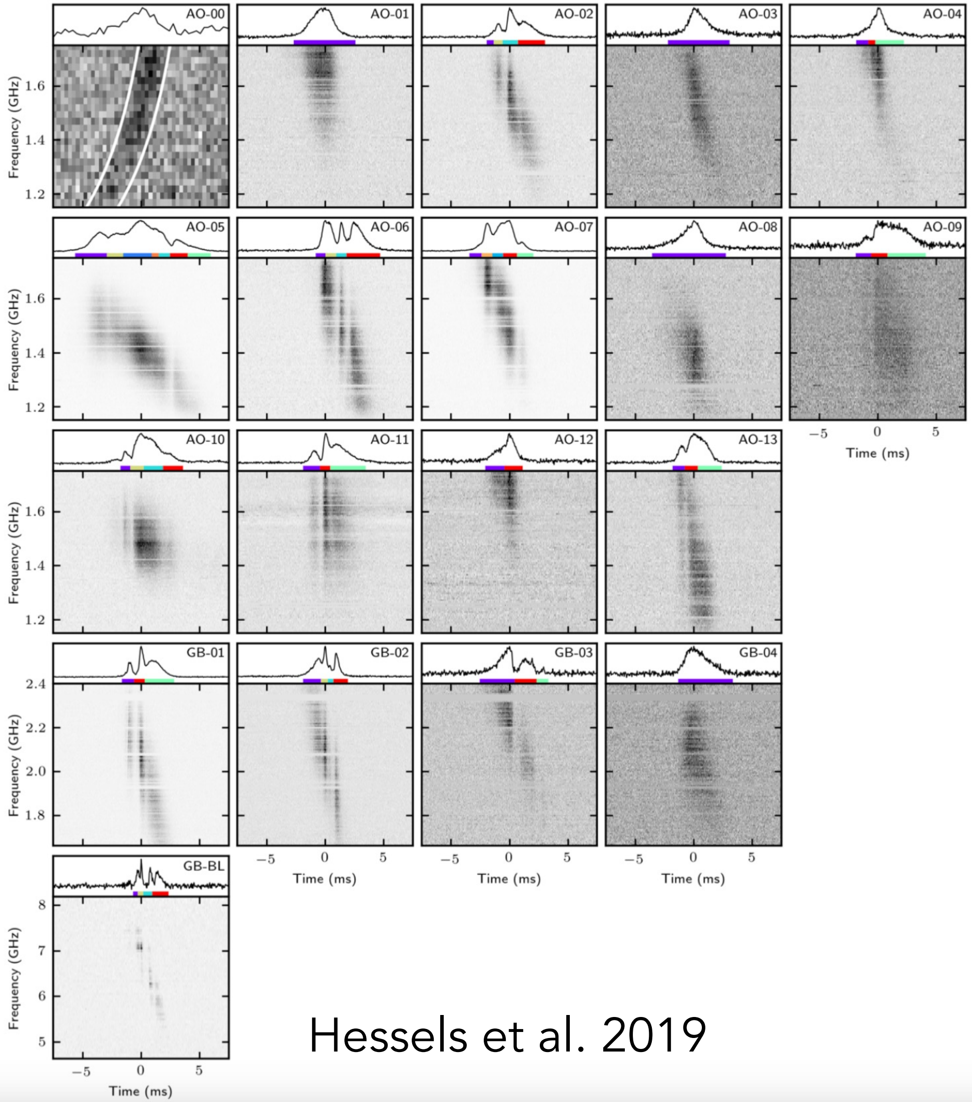
Implications + Model Predictions

- Different scattering geometries – upward + downward drift
- Small range in γ – cold plasma
- Boost in intensity in scattering tail by ~10%
- Physical separation 20 lt-ns

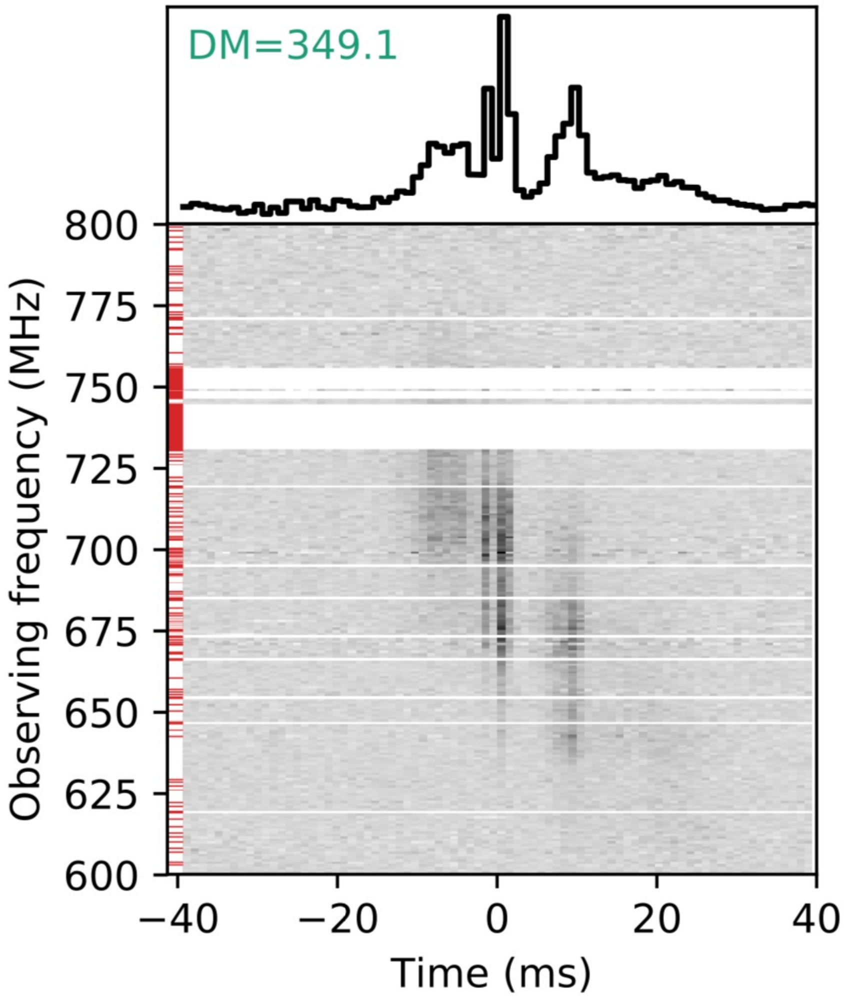




Implications for FRBs?



Hessels et al. 2019

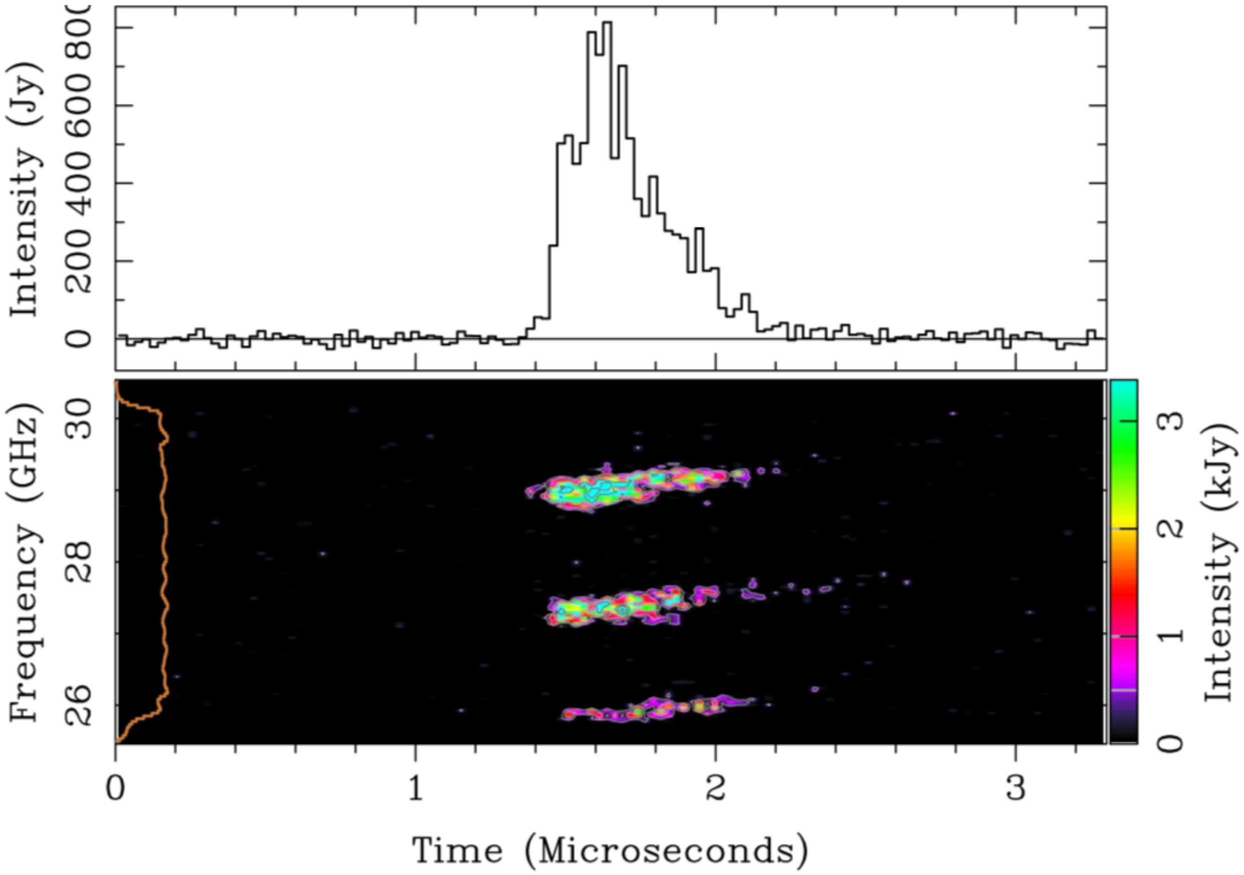


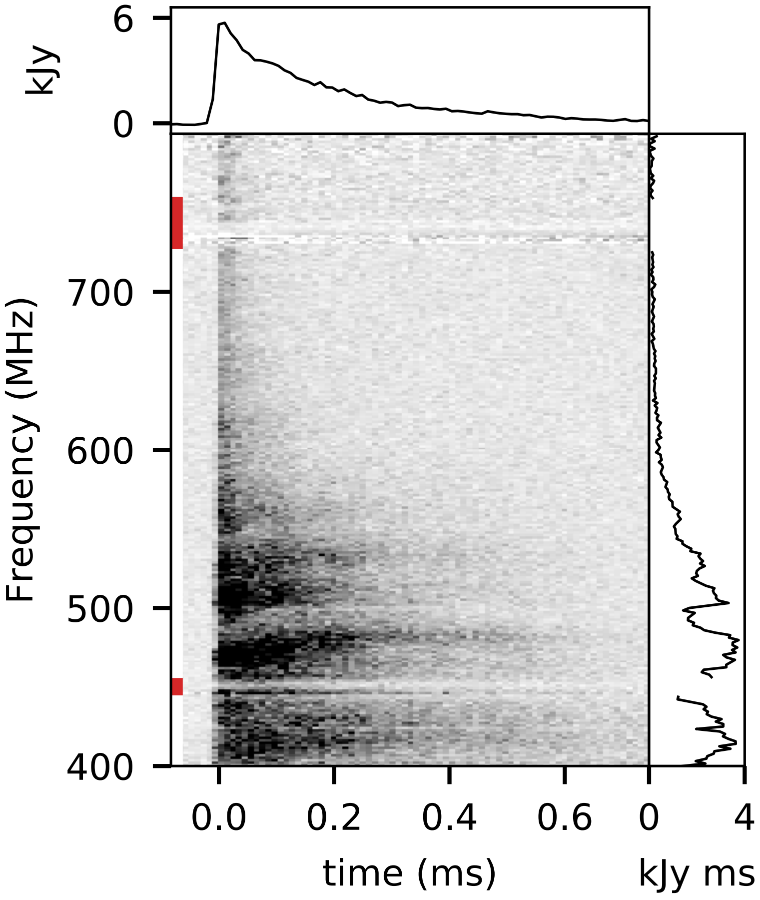
CHIME 2019

Crab Giant Pulses at High frequencies

Hankins et. al 2016

1-43 GHz





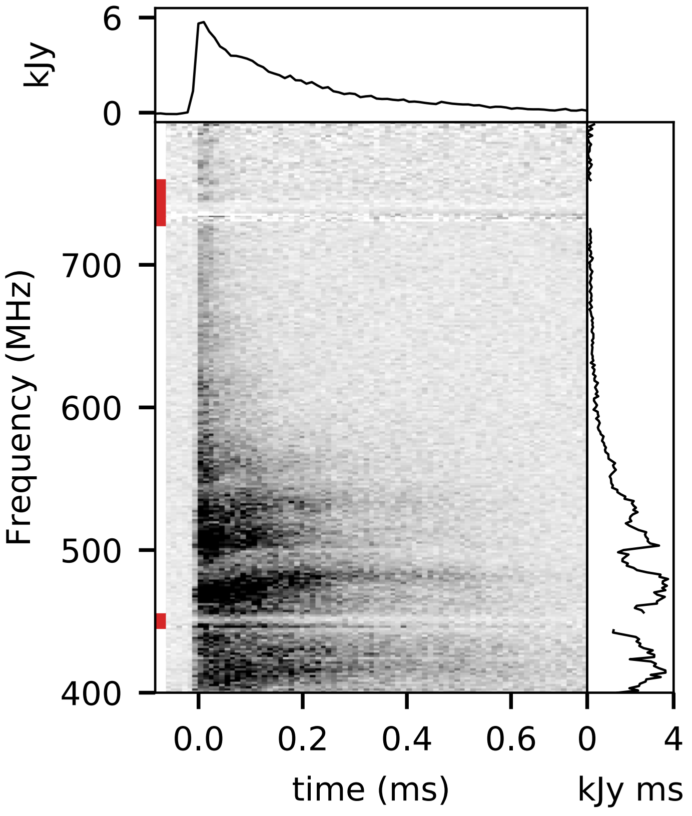
Next Steps

- Look for more “drifting” pulses – CHIME, LOFAR
- Lower frequency data where change in viewing angle is larger
- Downward drift or boosting?
- Statistical analysis of giant pulse characteristics
- FRBs with large scattering

Summary

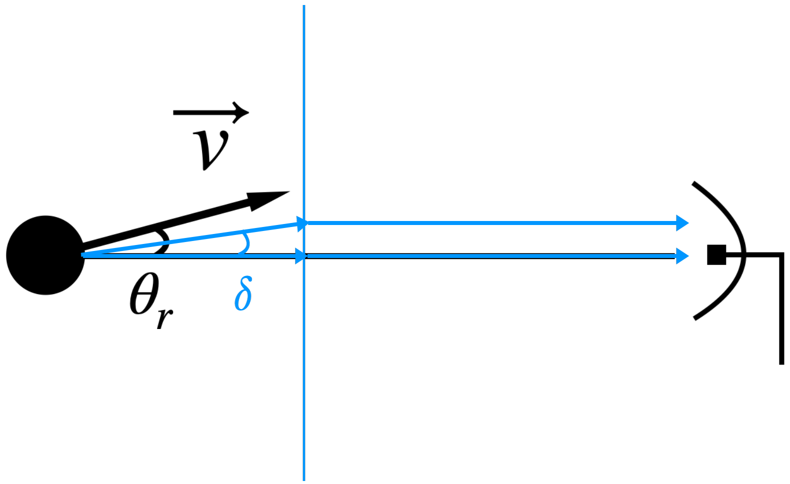
Crab Pulsar

400-800 MHz



Doppler Shift

Scattering screen



$$D = \frac{1}{\gamma(1 - \beta cos\theta_r)}$$

Lorentz Factor

Direct Measurement

$$\gamma \sim 10^4$$

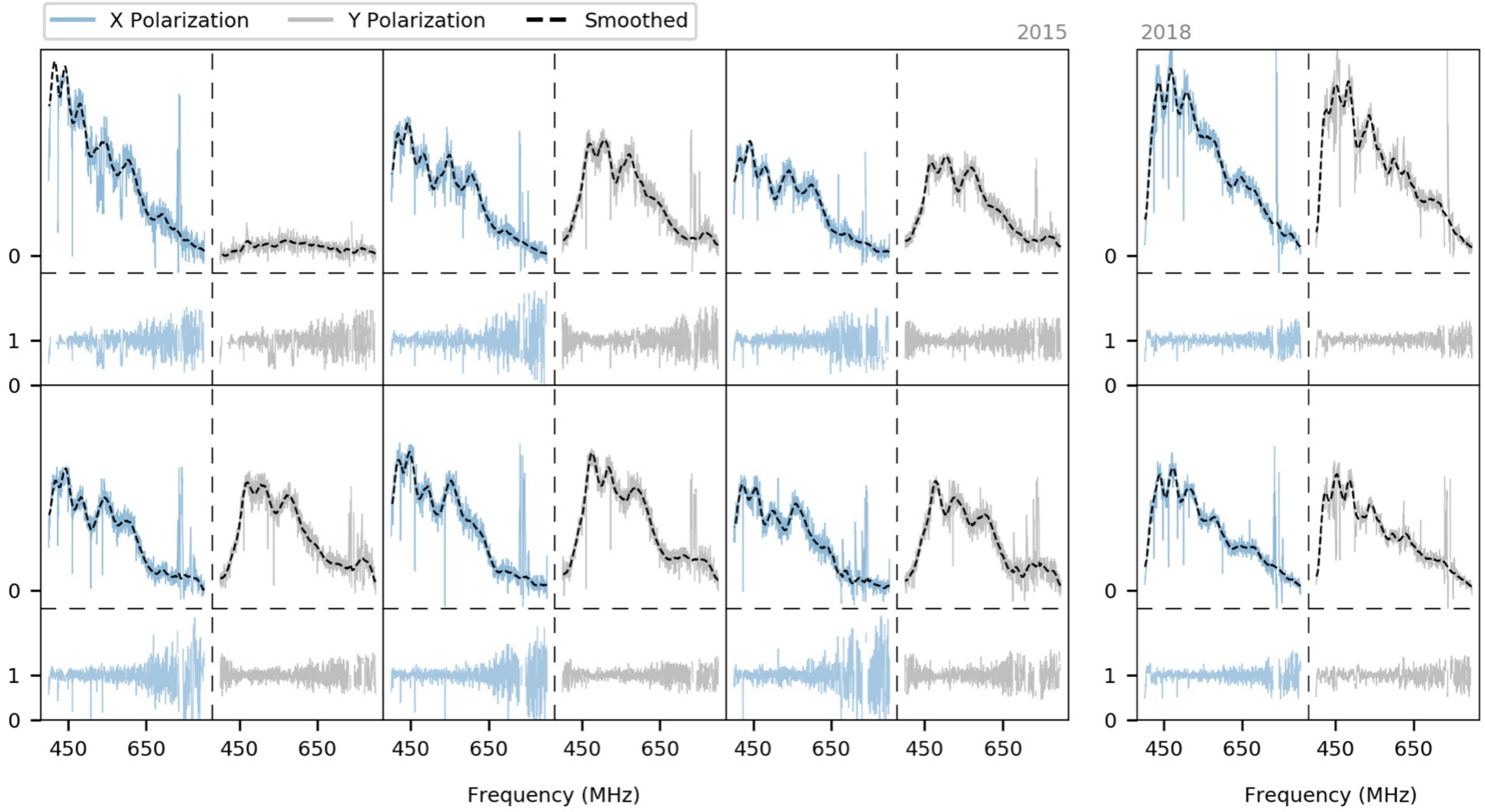
Theoretical Predictions

$$\gamma = 1 - 10^7$$

Thank you!

Any questions?

Appendix – Gain Correction and Flux Calibration



$$F_{\mathrm{GP}}(f) = F_{\mathrm{neb}}(f)\,\frac{I_{\mathrm{GP}}(f)}{I_{\mathrm{neb}}(f)}.$$

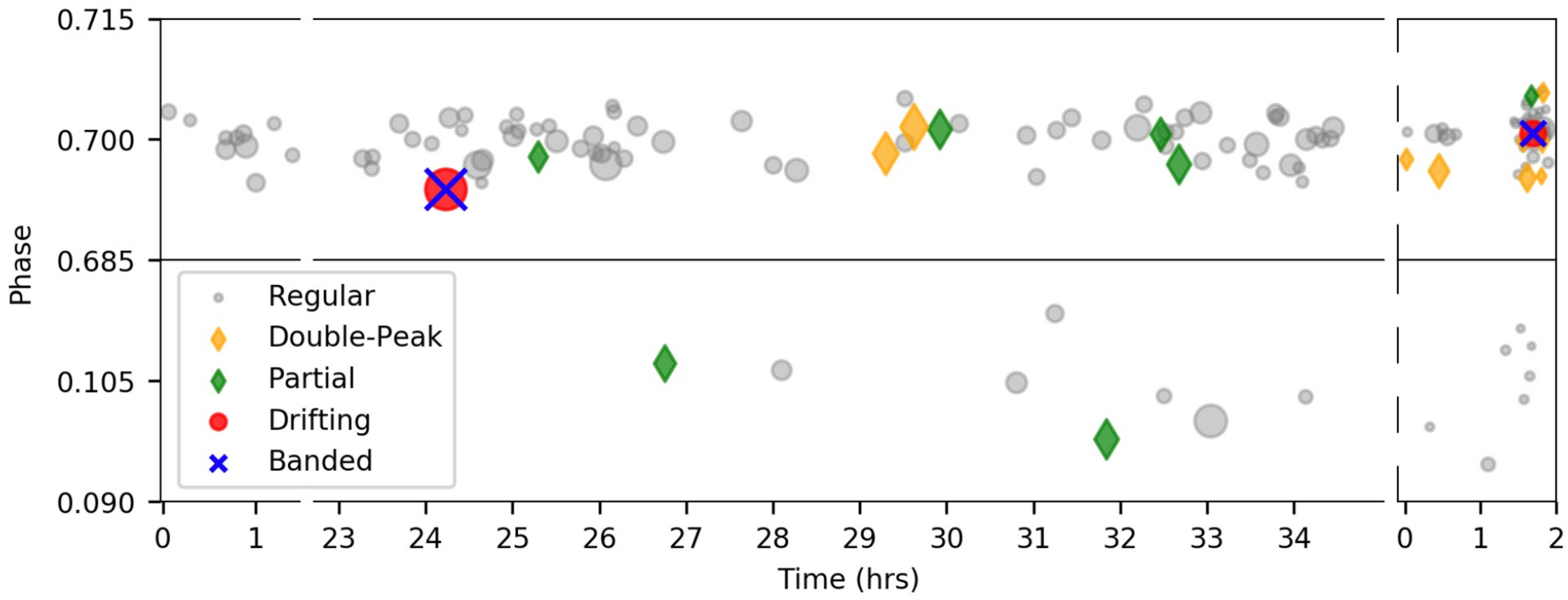
Appendix – Pulse Categorization

Table 1. Giant pulse categorization.

Feature	N	Fraction (%)	IP (%)
All.	148	100	10
Regular	129	87	10
Multi-peak	9	6	0
Partial.	7	5	30
Banded	3	2	0
Drifting[a]	2	1.3	0

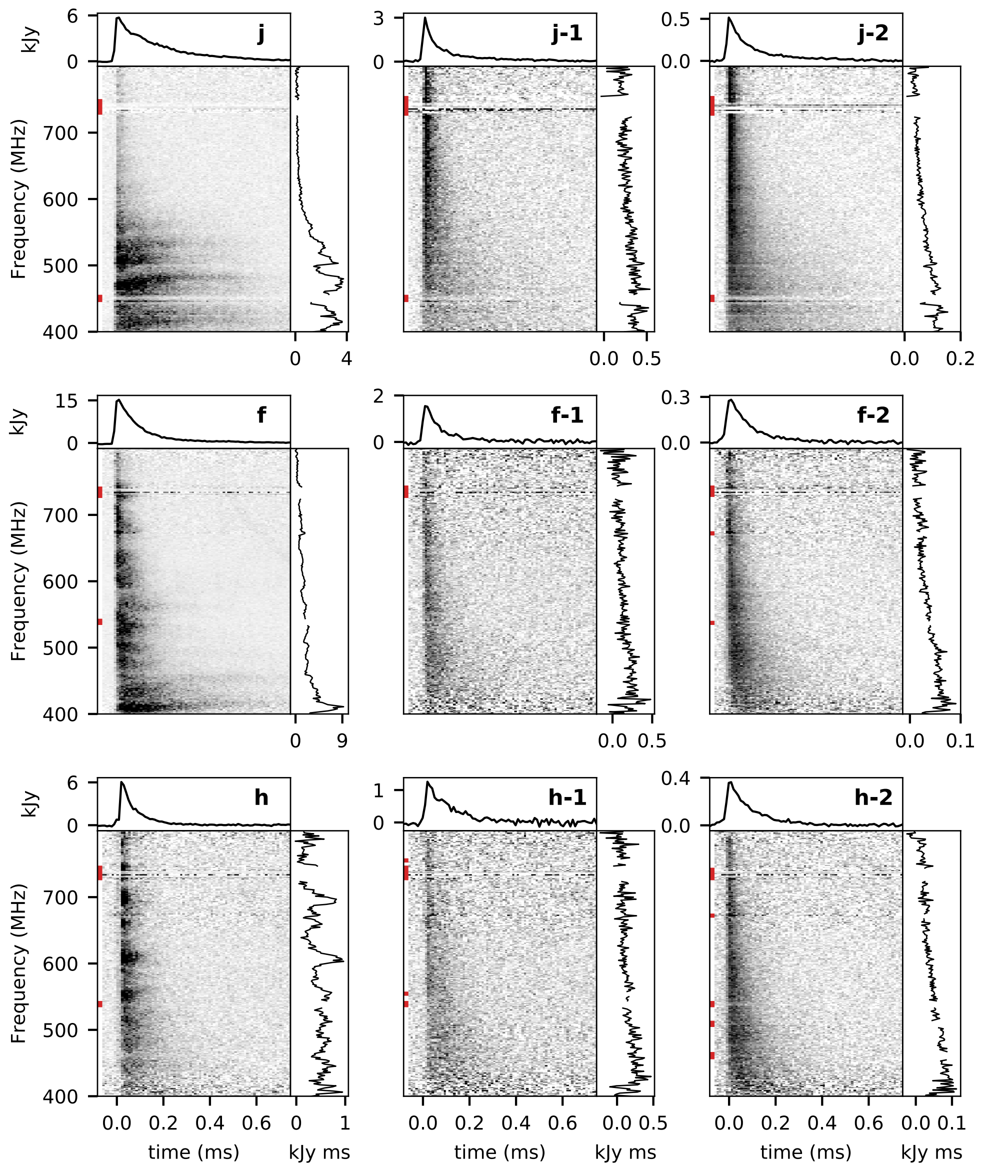
[a] 'Drifting' is a sub-category of 'Banded'.

NOTE—N is the number of pulses that have a given feature, fraction the relative occurence rate, and IP is the fraction that occurred in the interpulse phase.



Appendix - Ruling out other physical interpretations

- Interplanetary Scintillation
  - Expected De-correlation bandwidth 500 MHz
- Interstellar Scintillation
  - Expected De-correlation bandwidth 30 kHz
  - Not a point source



Appendix: Drifting Pulse Before de-dispersion